EXPERIMENTAL TOP QUARK PHYSICS

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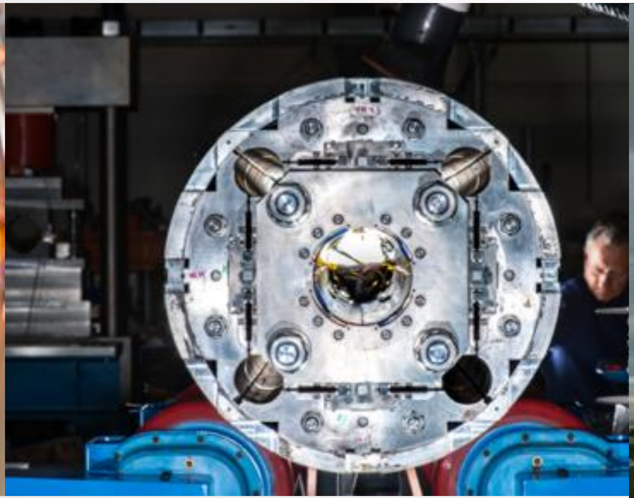
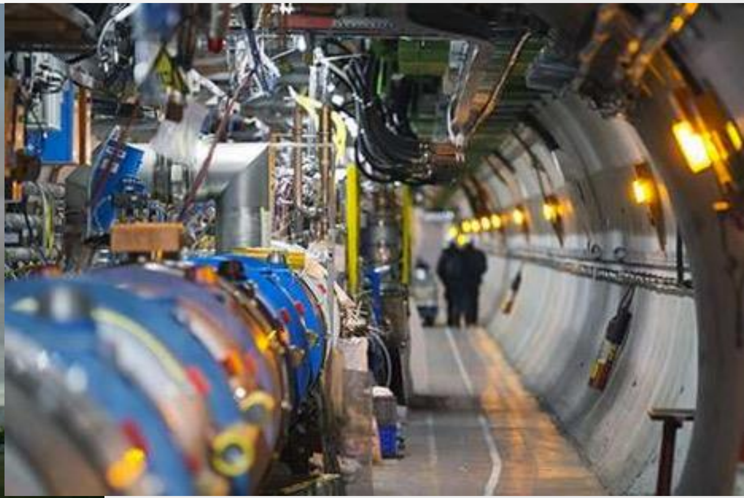




WHAT TO EXPECT

Today: *Top quark in the SM*

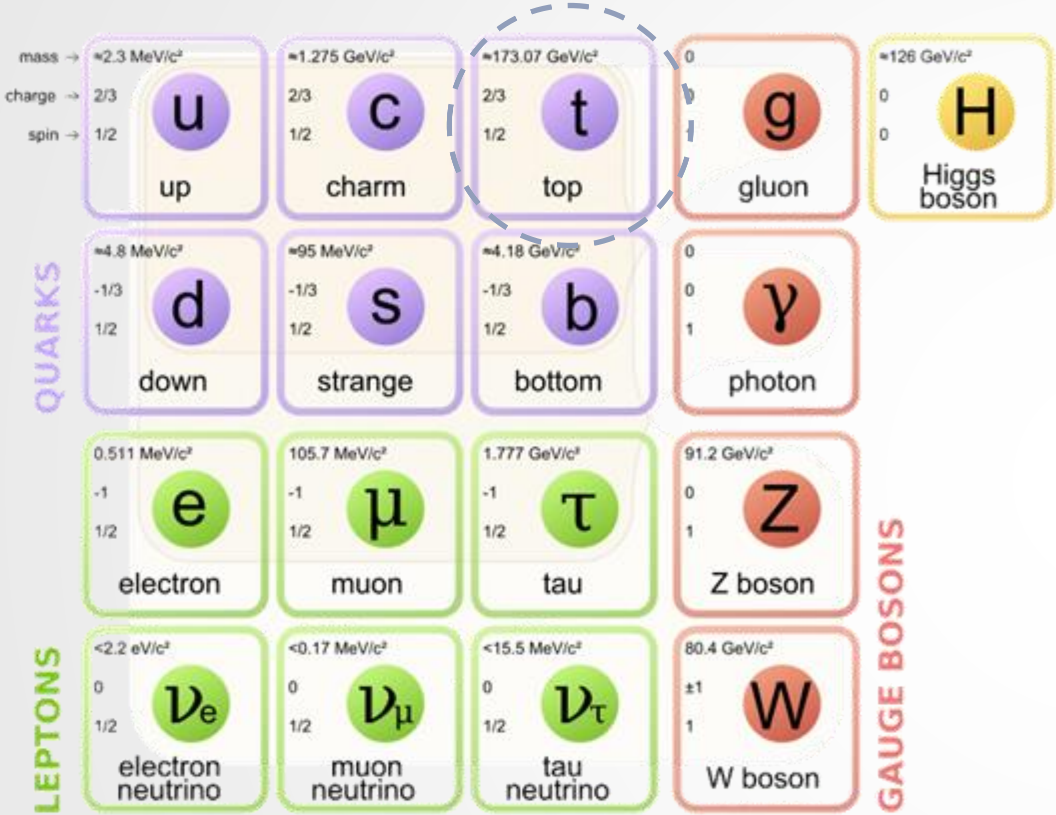
1. Introduction / Top quark overview
   - Production, Properties, Data taking, Decay, Modeling
2. Basics reconstructing top quarks
3. Cross section measurements [a selection]
4. Top quark mass
5. Prospects for HL-LHC

Tomorrow: *Beyond the SM*

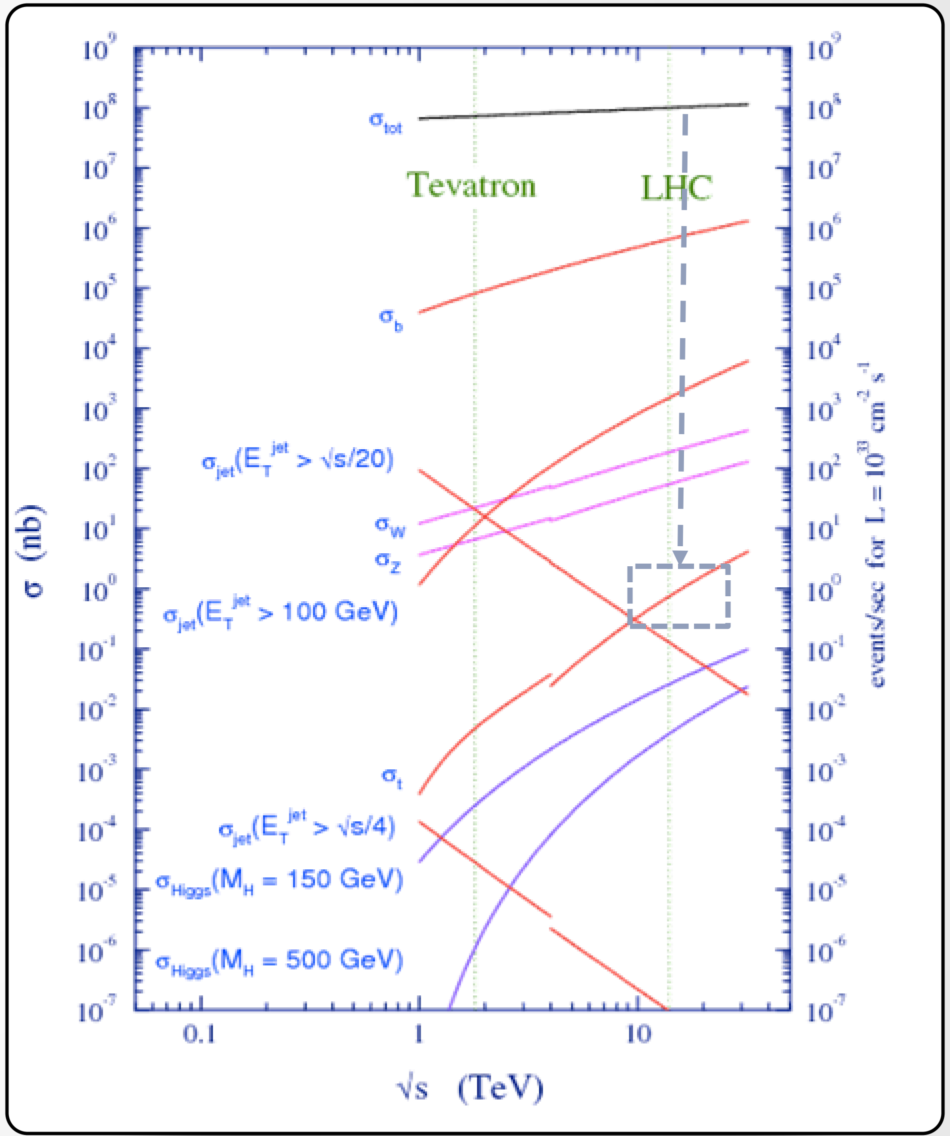
1. Example: Spin correlations (beyond the SM)
2. Effective Field theory
3. Top quark gauge couplings
4. Forces among quarks
5. Global Results
6. Machine-learning optimal top-quark observables

- Will focus on illustrative examples & concepts, no attempt at being comprehensive
- Focus on CMS, since this is my experiment

TOP QUARK OVERVIEW



- Discovered 1995 by CDF and Do at Tevatron
- The 6th & (probably?) last quark
- Large production cross section at hadron colliders

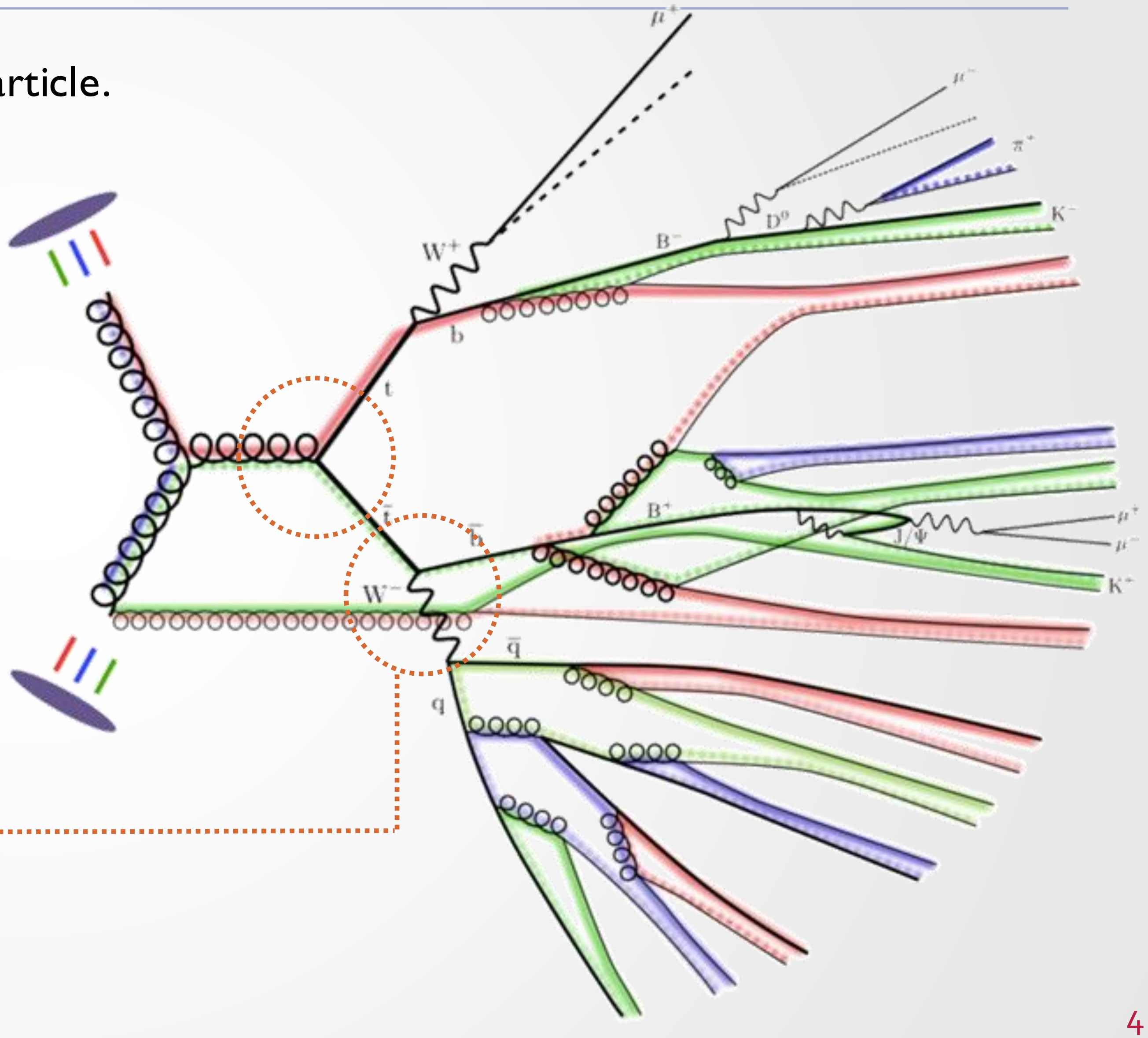


TOP QUARK OVERVIEW - PROPERTIES

- The top quark is the heaviest known fundamental particle. Interesting properties/problems appear at all scales

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

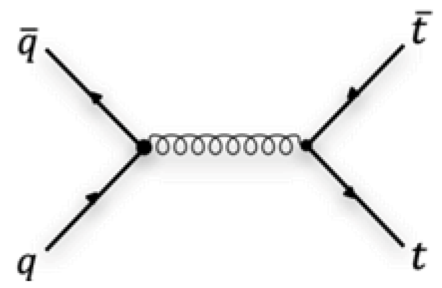
- x-sec measurements at high precision, interplay with PDFs
- mass measurements, hadronization effects, color reconnection, UE tune, …
- spin correlation, anomalous strong interactions
- weak interactions, vector couplings and dipole moments, …

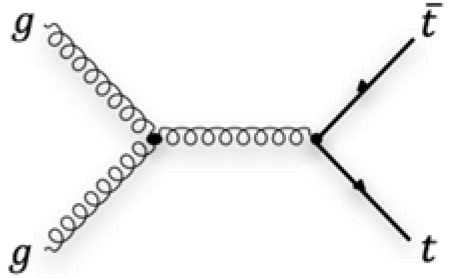


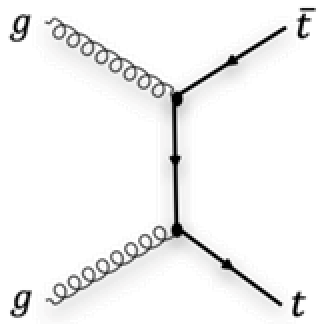
- All aspects under scrutiny at the LHC

TOP QUARK OVERVIEW - PRODUCTION

- Top quark pair production (791 ± 25 pb)



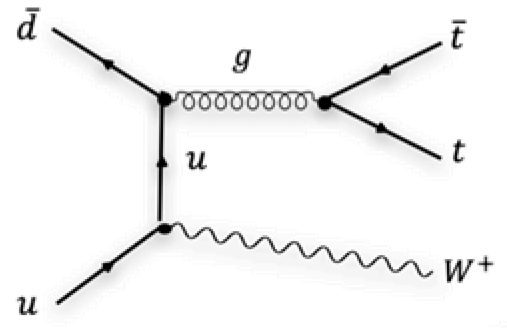




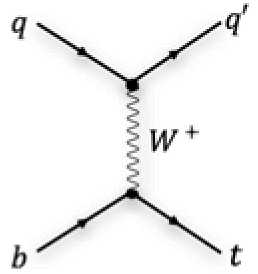
10% qq annihilation

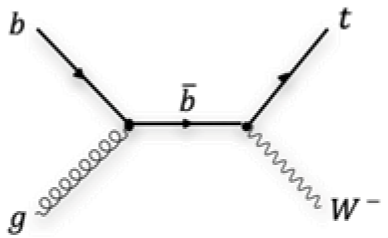
90% gluon fusion

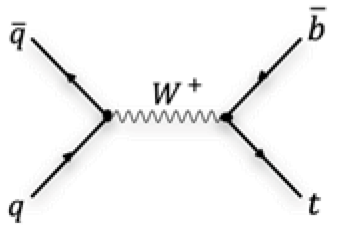
- ttW production (0.6 pb)

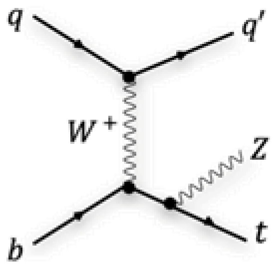


- Production of a single top quark









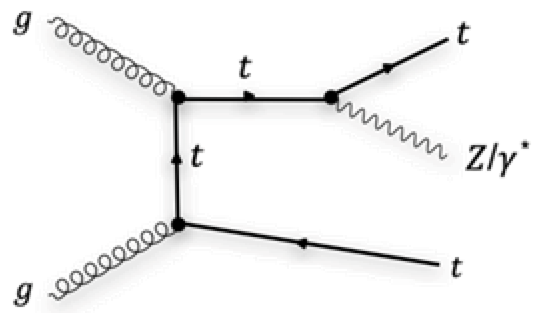
t-channel (73%)
238 pb

tW channel (24%)

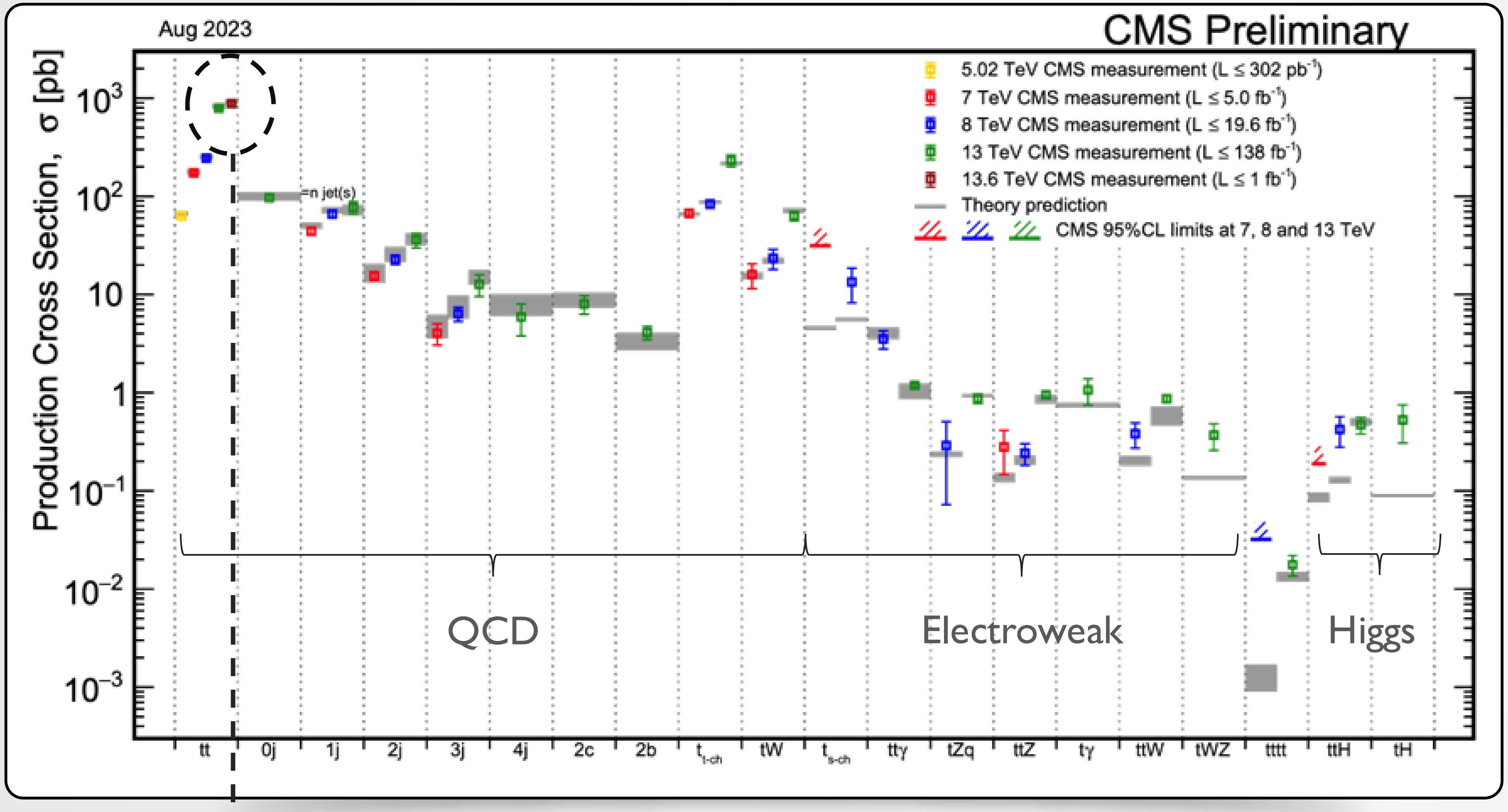
s-channel (3%)

tZq (<1%)

- ttZ production (0.9 pb)



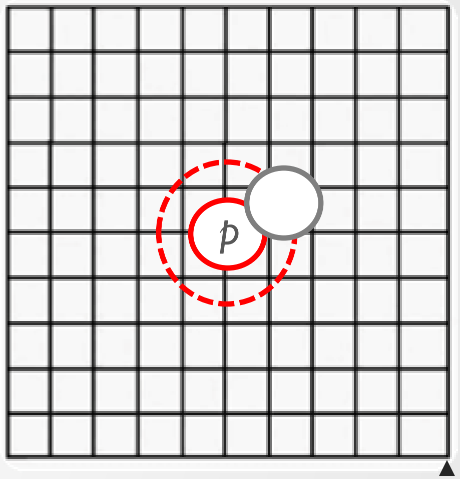
TOP QUARK OVERVIEW – PRODUCTION (13 TEV)



1b = 100 fm^2

R_p ~ 0.8 fm

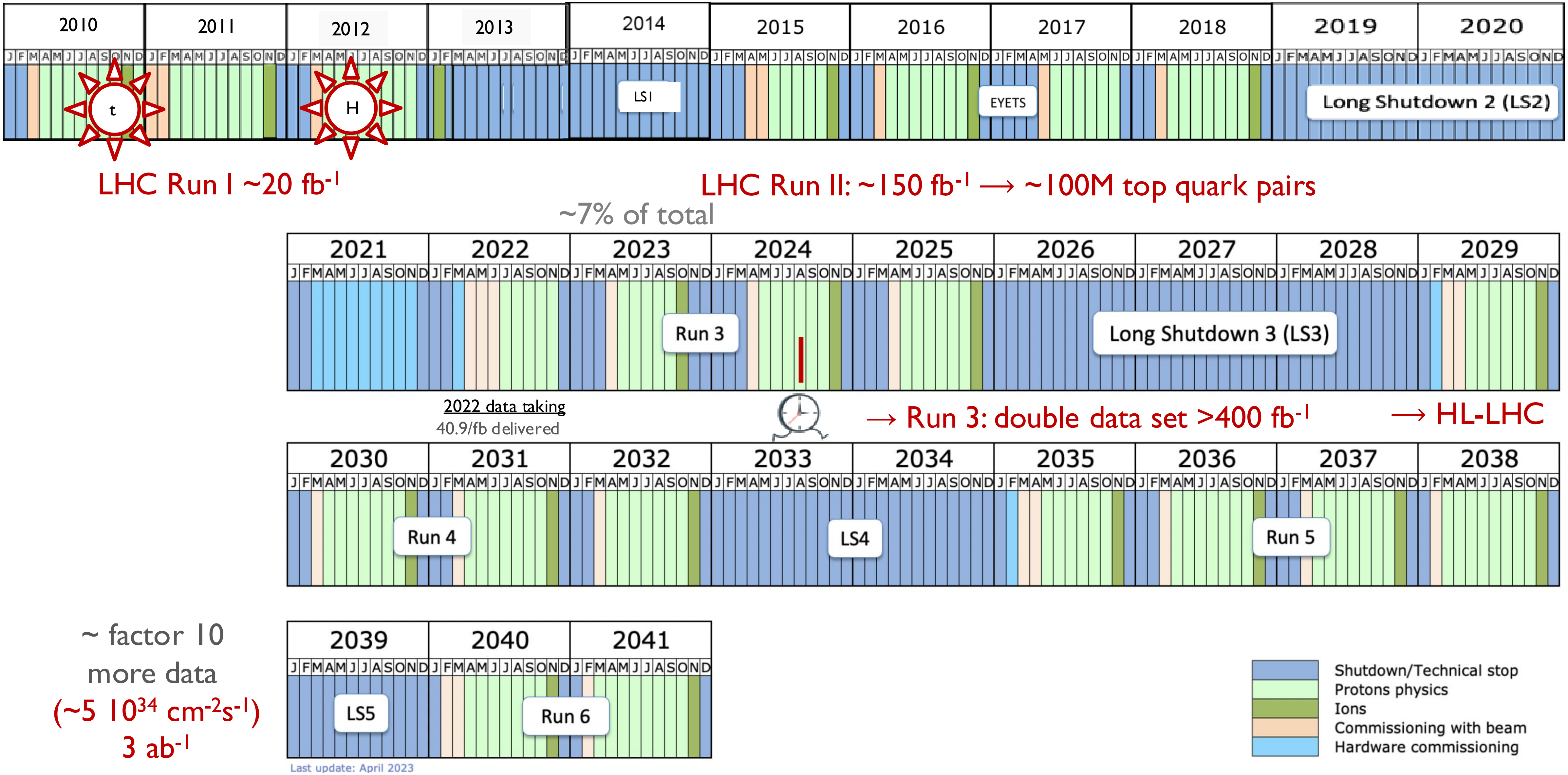
σ(pp) ~ 80 mb



1 barn = Unit of cross section

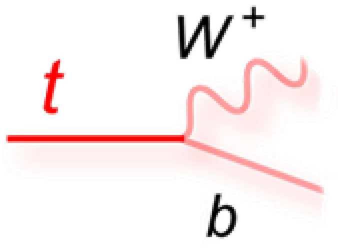
- **σ**(13 TeV) = 791 ± 25 pb; N_{Events} = $\mathcal{L}_{tot}$ x **σ** = 137/fb [Run II] x 791 pb ~ 100 x 10^6
- Rate = $\mathcal{L}_{inst}$ x **σ** = 20 kHz/**μ**b x 791 pb = 15.8 Hz

DATA TAKING & LHC SCHEDULE

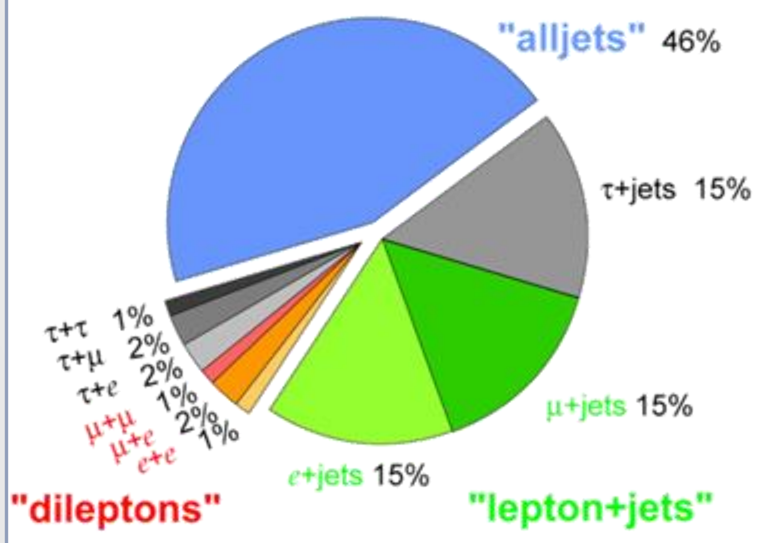


TOP QUARK OVERVIEW – DECAY

Decay: t⟶Wb
$|V_{tb}|^2 \sim 0.998$



top quark pair production



- Almost exclusively decays as t⟶ Wb. Simple pattern of branching ratios.
- Charged current coupling to fermions is universal BR(W → eν) ≈ 10%

2 lighter quark families → $2N_C$; 3 lepton families → 3

$$\Gamma_W = \Gamma_{\text{lep}} + \Gamma_{\text{had}} = (2N_C + 3)\,\Gamma(W \to \ell\,\nu) = 9\,\Gamma(W \to \ell\,\nu)$$

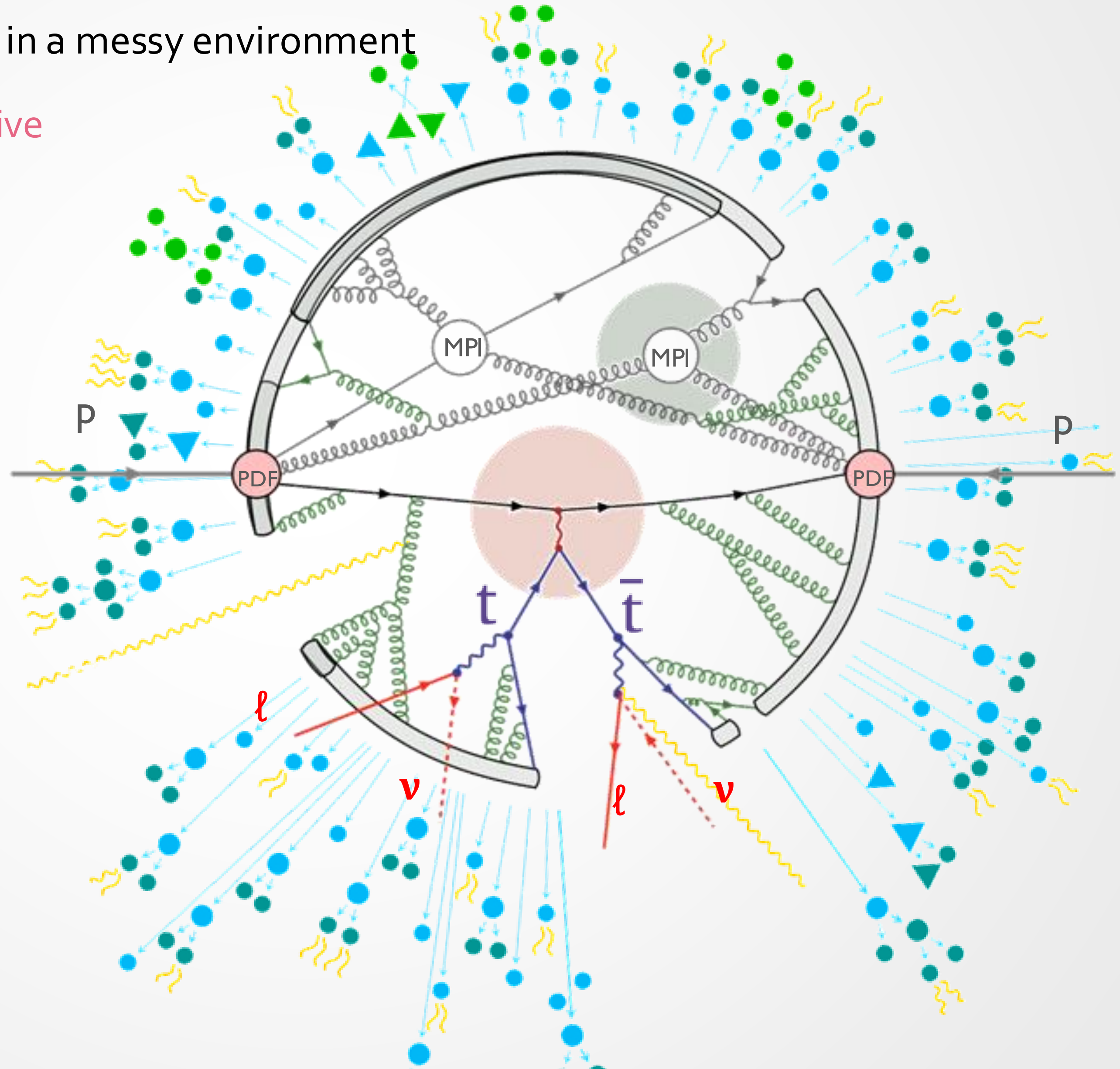
$$\text{BR}(W \to \ell\,\nu_\ell) = \frac{\Gamma_{\text{lep}}}{\Gamma_{\text{lep}} + \Gamma_{\text{had}}} = \frac{3}{2N_C + 3} = \frac{1}{3}$$

pair BR	e (≃1/9)	μ (≃1/9)	τ (≃1/9)	had (≃2/3)
e (≃1/9)	9% dileptonic			15% semi-lep.
μ (≃1/9)				15% semi-lep.
τ (≃1/9)				15% semi-lep.
Had (≃2/3)	-	-	-	46% all-had.

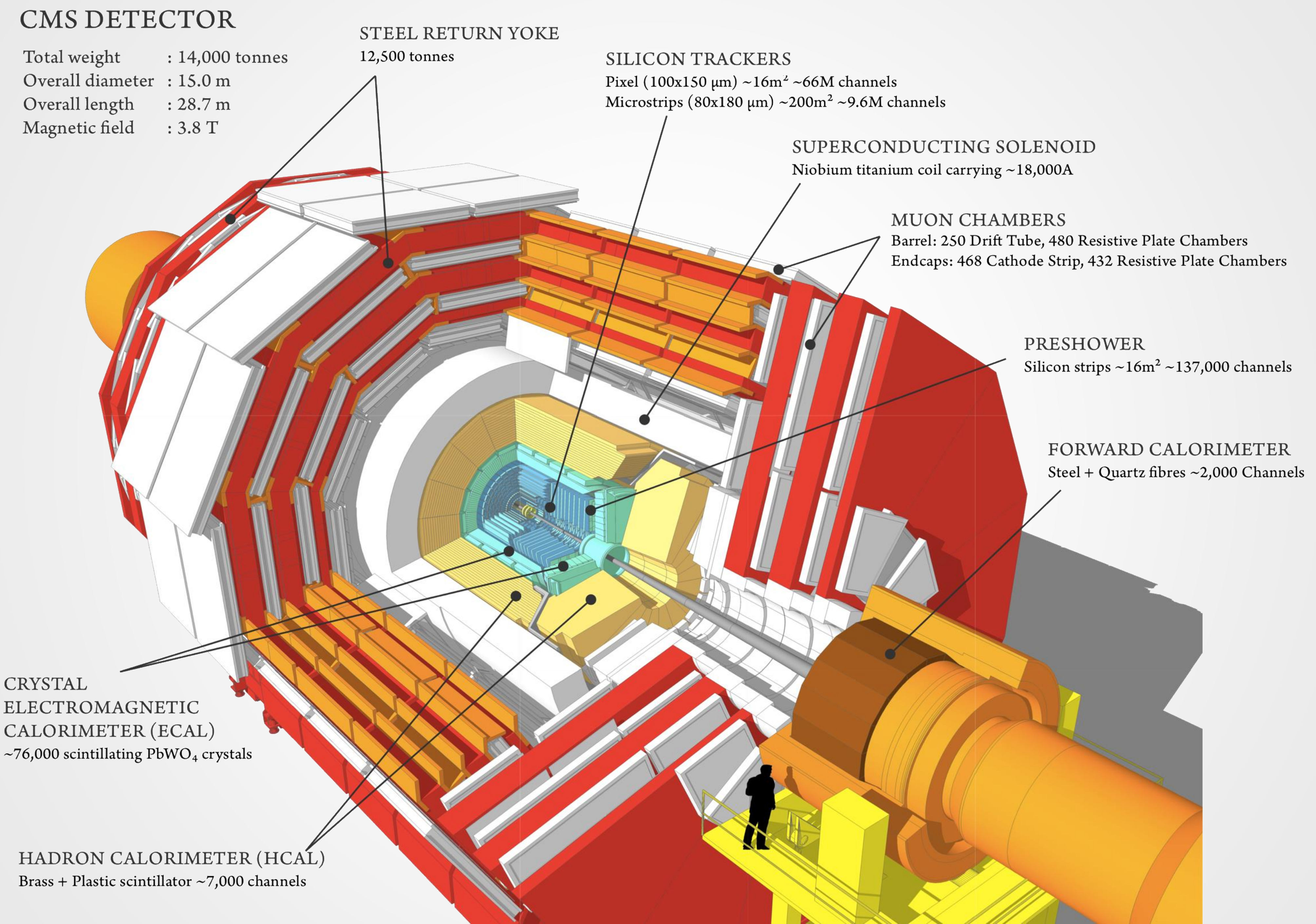
- "dileptons": small cross section, very clean. Up to 95% purity!
- "lepton+jets": large cross section, fairly clean
- "alljets": Only jets and b-tagged jets in the event; challenging!

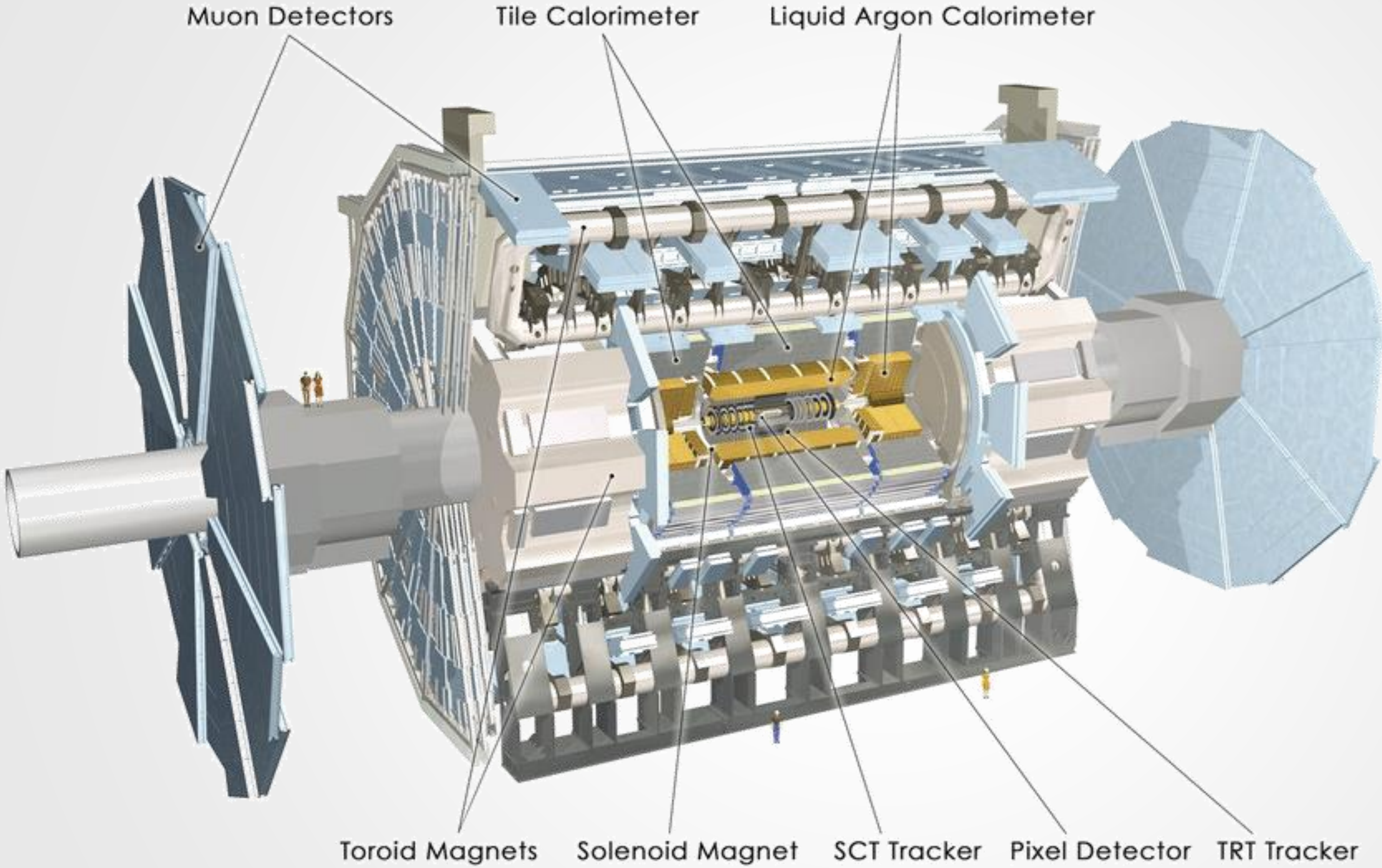
TOP QUARK OVERVIEW – MODELING

- Experimetally, tt(1/2ℓ) is a clean probe in a messy environment
- At low energies, QCD is non-perturbative
- LHC elevates the proton bound state to the perturbative regime
  - Expose the constituents' dynamics
  - Calculable short-distance phenomena
- Before & after the hard scatter: many uncertain effects
  - ME scales
  - Initial and final state radiation
  - Multi-parton interactions
  - Parton shower & ME matching
  - Color reconnection
  - Hadronization
  - Hadron decays



BASIC OF RECONSTRUCTION

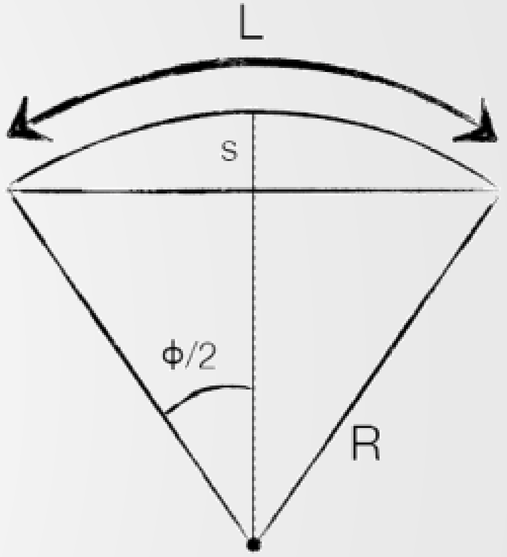

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels



ATLAS

Detector characteristics

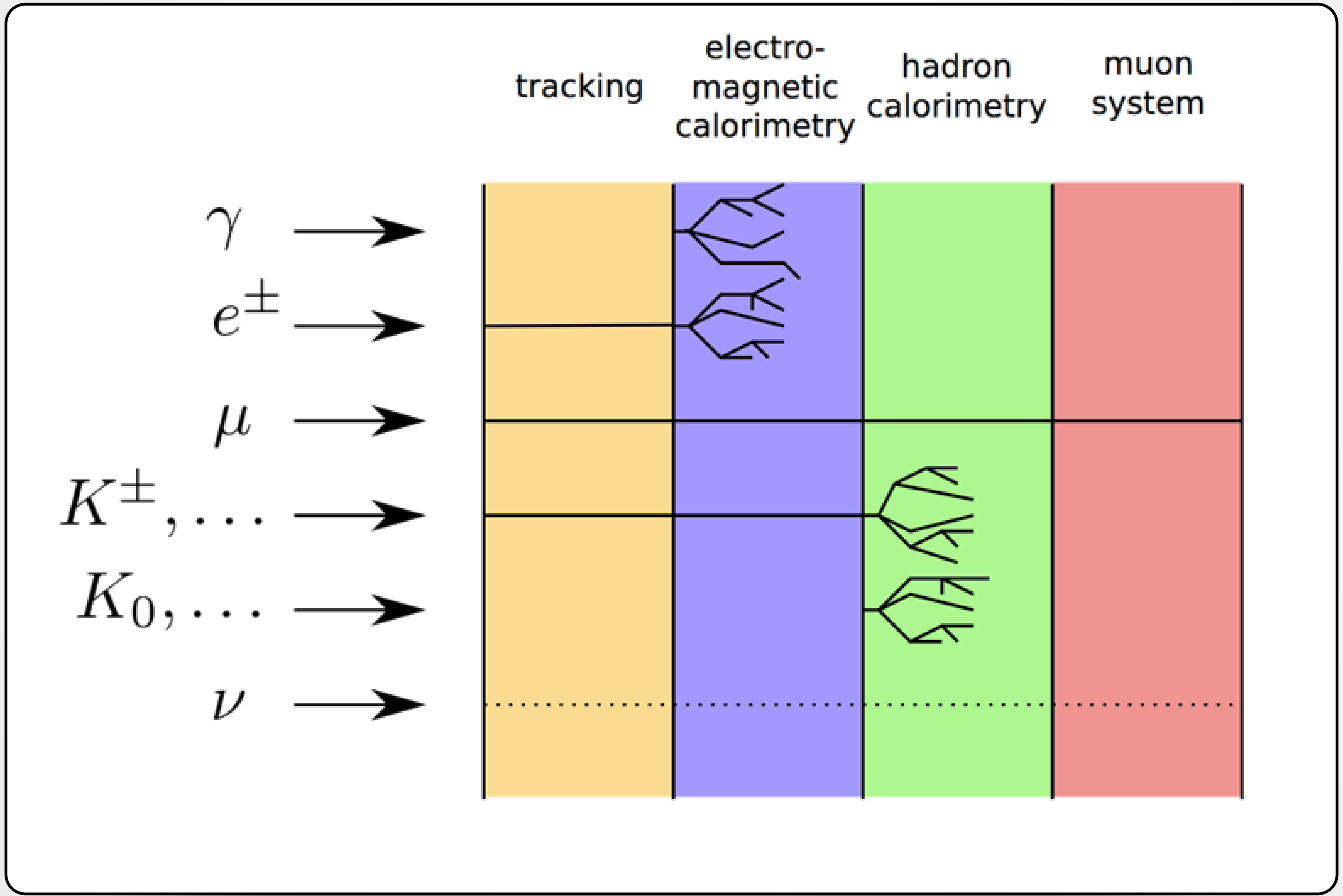
Width:	44m
Diameter:	22m
Weight:	7000t



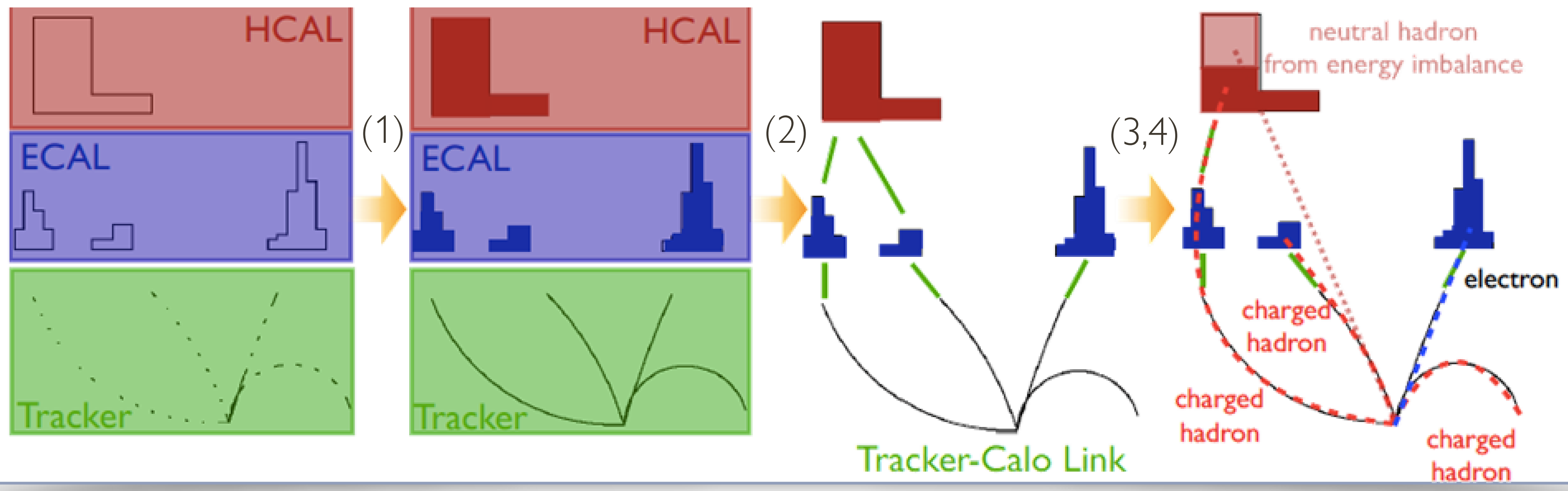
Spectrometer momentum resolution

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8\sigma_s}{0.3}\frac{p}{BL^2}$$

OVERVIEW OF DETECTOR SIGNATURES



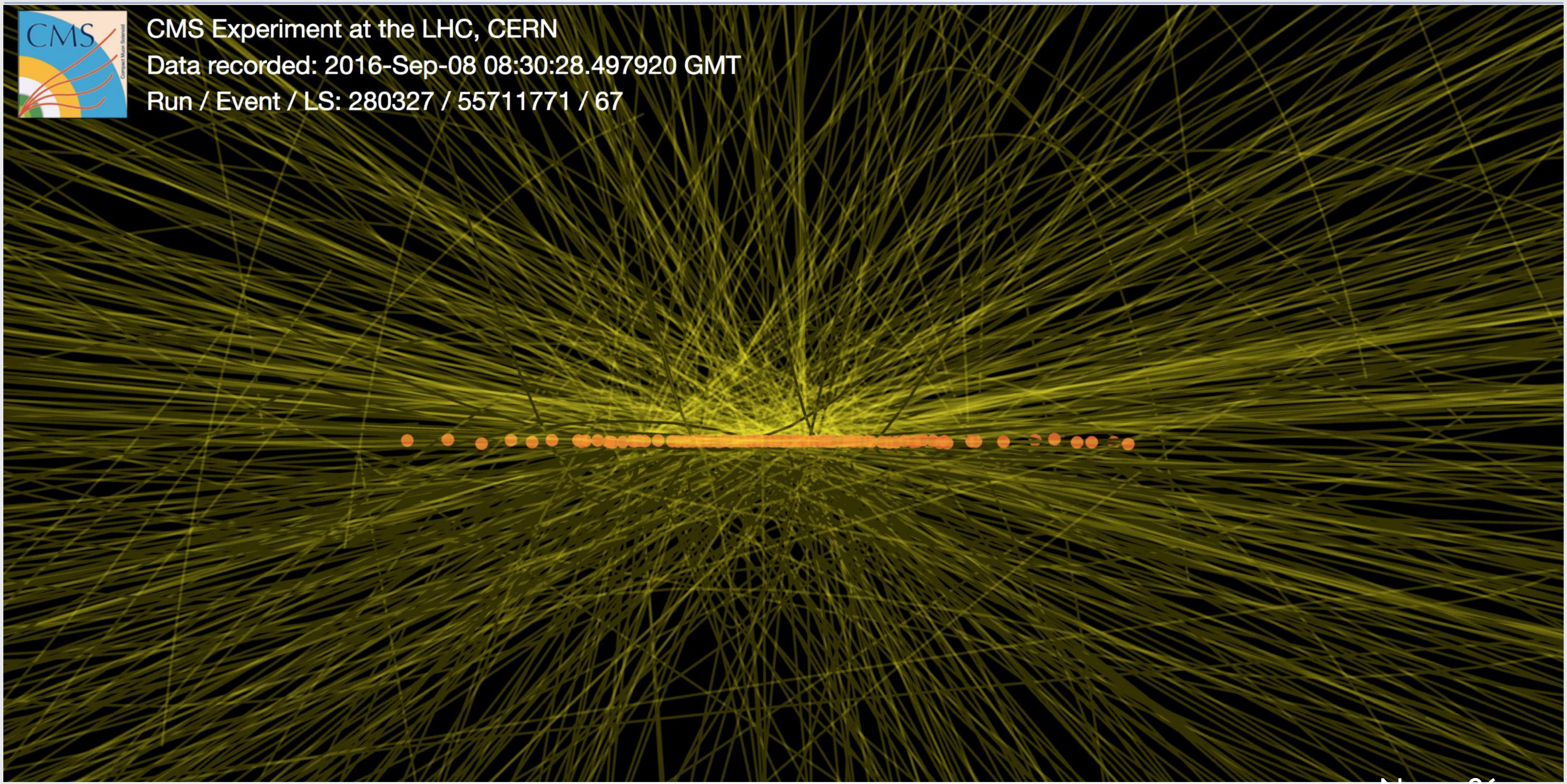
PRINCIPLES OF EVENT RECONSTRUCTION



When an event is recorded, the hits in the detector cells are stored. Main algorithmic steps are:

1. Build muon candidates, tracks, and calorimetry clusters
2. Link tracks and the calorimetry clusters based on spatial proximity
3. Identify 'charged hadron candidates' among the links by associating calorimetric energy to track momenta, when tracks are close
4. 'photon' and 'neutral hadron' candidates from excess energy

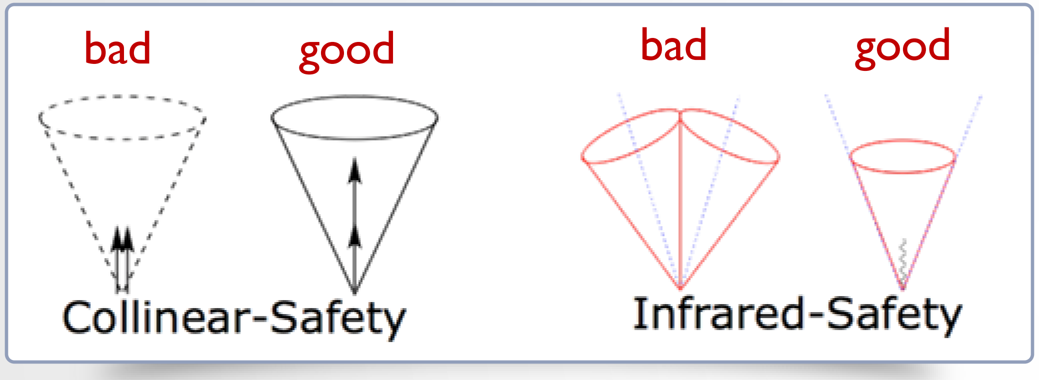
A HIGH PILE-UP EVENT

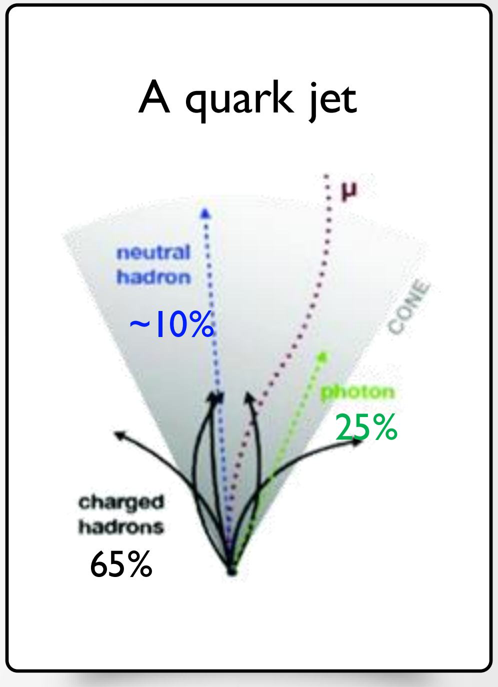


$N_{vtx} = 86$

JET RECONSTRUCTION

- Event: List of particles. A highly energetic parton hadronizes into a jet.
  - Correlate 'sprays' of particles with the initial partons
  - Theoretical properties of clustering algorithms are important for calculability



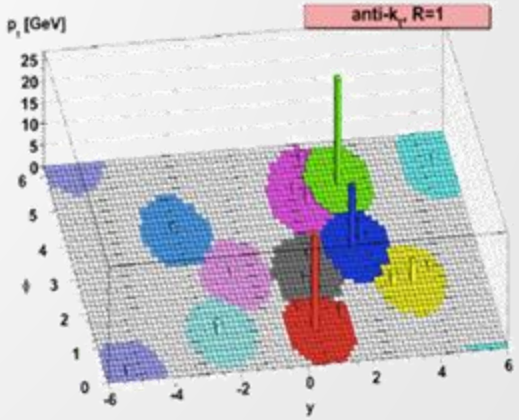


- Anti-k_T algorithm [JHEP 0804:063,2008] satisfies all criteria!
  1. Select a cone size R (e.g. R=0.4)
  2. For particle i, compute all distances d_{ij} and d_{iB}

$$d_{iB} = \frac{1}{p_{Ti}^2}, \qquad d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

p_T^{-2} prefers early merge of close & energetic particles

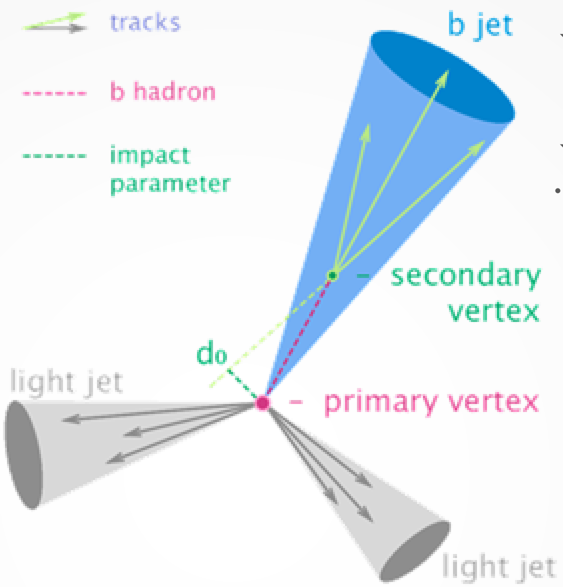
  3. If a pair (ij) has smallest distance in d_{ij}, merge & add momenta. Repeat step 2.
  4. Otherwise label jet, remove from list, start again with 2. until fully clustered.

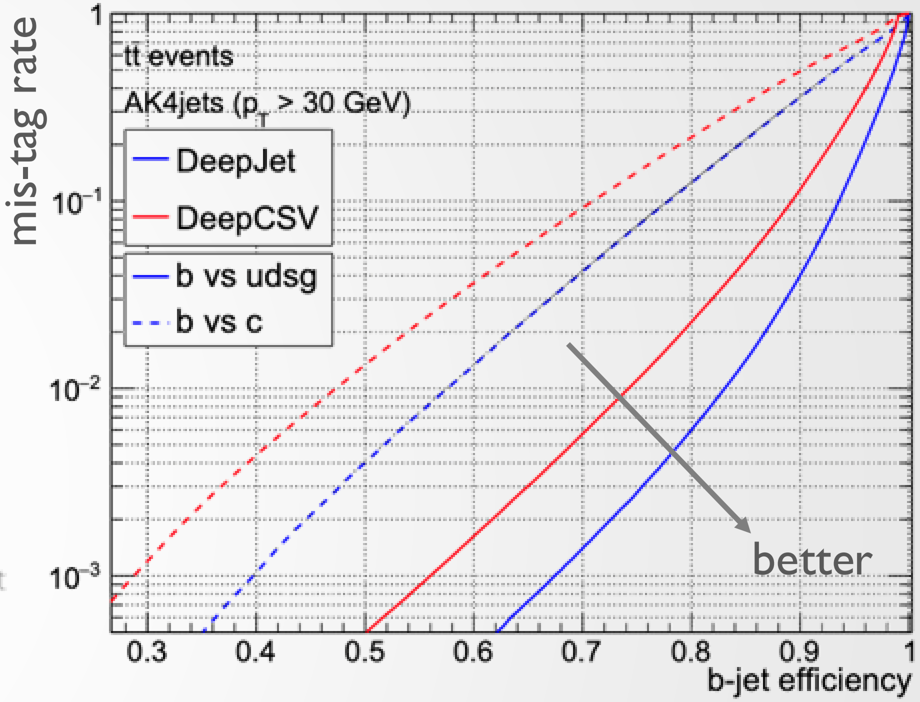


B-TAGGING AND TOP QUARK DECAY

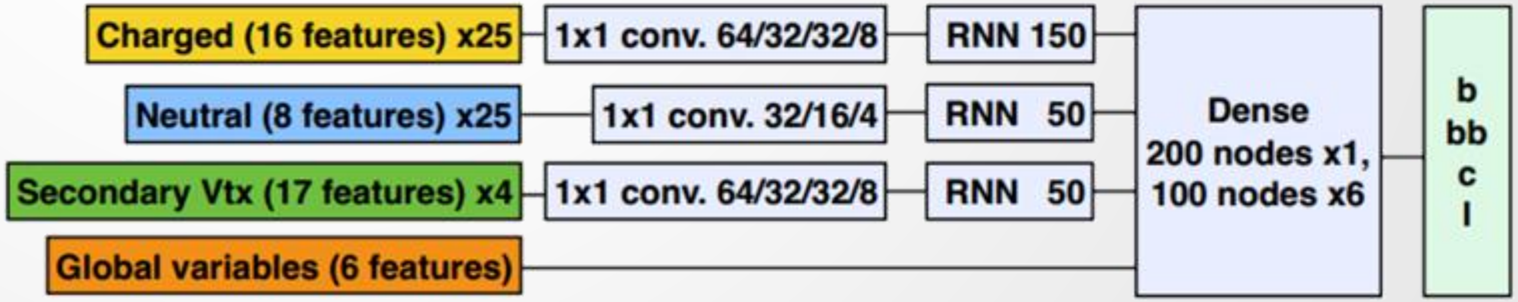
[DeepCSV]

- b-quarks are crucial role for top quark reco
  - b-quarks hadronize into B-hadrons
  - B-hadrons have a finite life time
    - $c\tau \approx 450\mu$m, at E=70 GeV: $\beta\gamma c\tau \approx$ 5mm
  - displaced particles are clustered in jet
- Global jet information achieves 65-70% tagging efficiency





- More information is encoded in the features of individual particles
  - Recurrent neural networks (LSTMs) read particle list
  - Exploit the full particle information
  - Typically find 75-85% at 1% mistag
  - Factor 5 background reduction (!)
- Transformer architectures for Run 3



DILEPTONIC EVENT RECONSTRUCTION

[arXiv:1811.06625]

- Initial partons carry a random proton momentum fraction!
  - No balance of measured z momenta
  - 6 unknowns in the neutrino momenta

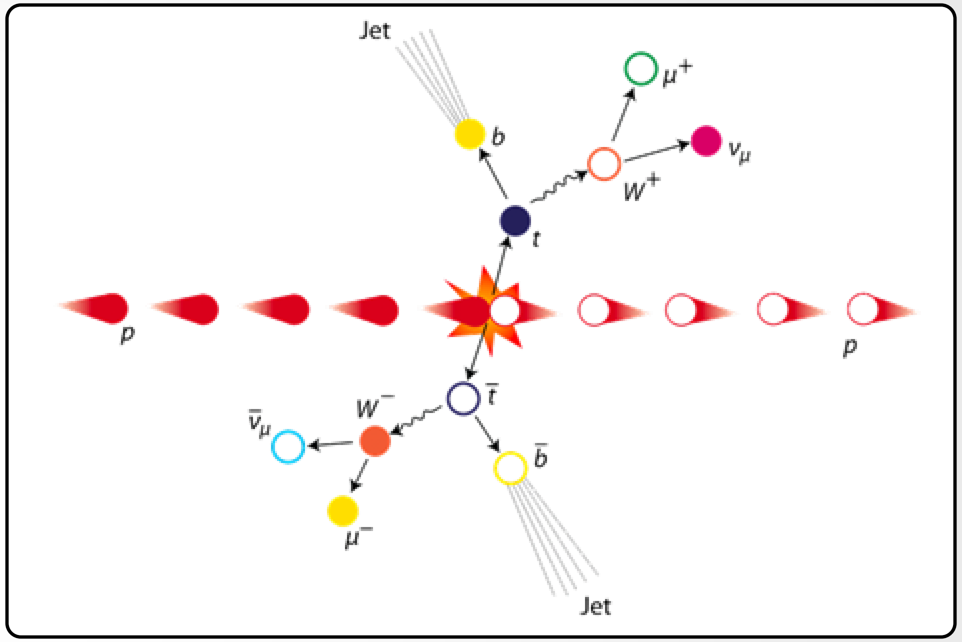
- Only x,y components are balanced; 2 equations.

$$\not{E}_x = p_{\nu_x} + p_{\bar{\nu}_x}$$
$$\not{E}_y = p_{\nu_y} + p_{\bar{\nu}_y}$$

measured

- Include 4 mass constraints:

$$m_{W^+}^2 = (E_{\ell^+} + E_\nu)^2 - (p_{\ell_x^+} + p_{\nu_x})^2, \\ -(p_{\ell_y^+} + p_{\nu_y})^2 - (p_{\ell_z^+} + p_{\nu_z})^2,$$
$$m_{W^-}^2 = (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell_x^-} + p_{\bar{\nu}_x})^2, \\ -(p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\ell_z^-} + p_{\bar{\nu}_z})^2,$$
$$m_t^2 = (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell_x^+} + p_{\nu_x})^2, \\ -(p_{b_y} + p_{\ell_y^+} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell_z^+} + p_{\nu_z})^2,$$
$$m_{\bar{t}}^2 = (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell_x^-} + p_{\bar{\nu}_x})^2, \\ -(p_{\bar{b}_y} + p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell_z^-} + p_{\bar{\nu}_z})^2.$$



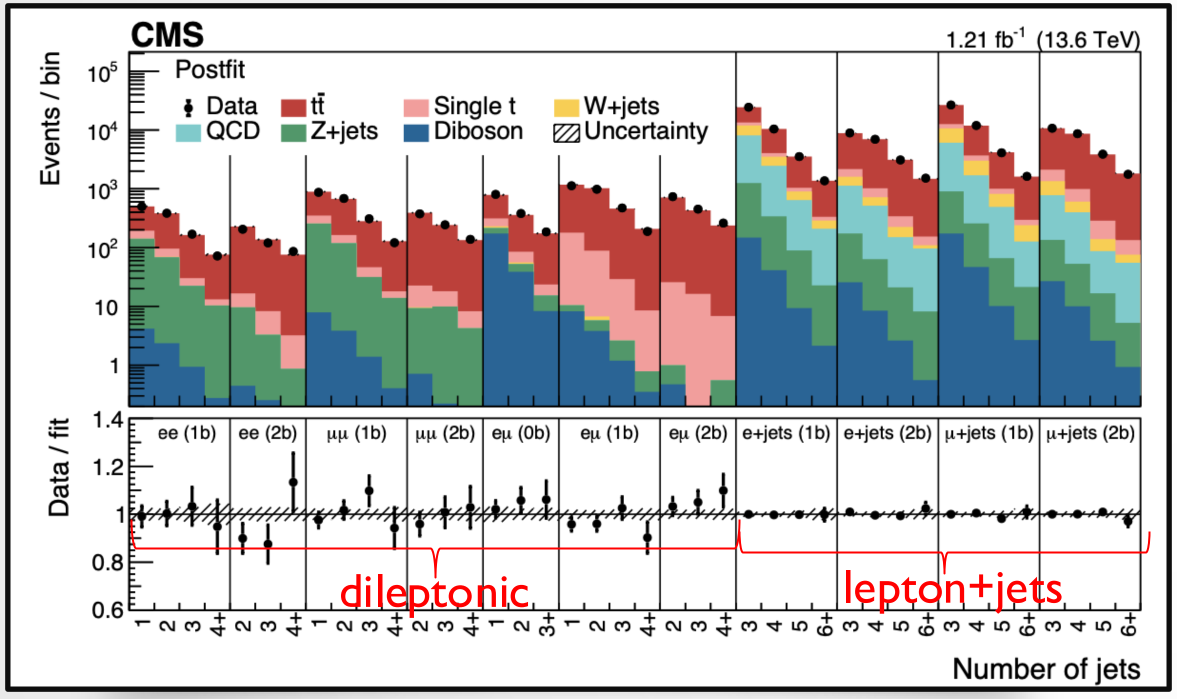
- Solve for the 6 unknown neutrino momenta
  - In general, 4 solutions
    - not counting ambiguities!
  - Take the smallest m(tt) of any real solution
  - Smear within uncertainties
  - Repeat 100 times
  - Average

CROSS SECTION MEASUREMENTS

INCLUSIVE CROSS SECTION MEASUREMENTS

[JHEP 08 (2023) 204]

- Inclusive top pair production cross section (Run 3, 13.6 TeV)
  - Predicted at 924 ± 40 pb (11% larger than at 13 TeV)



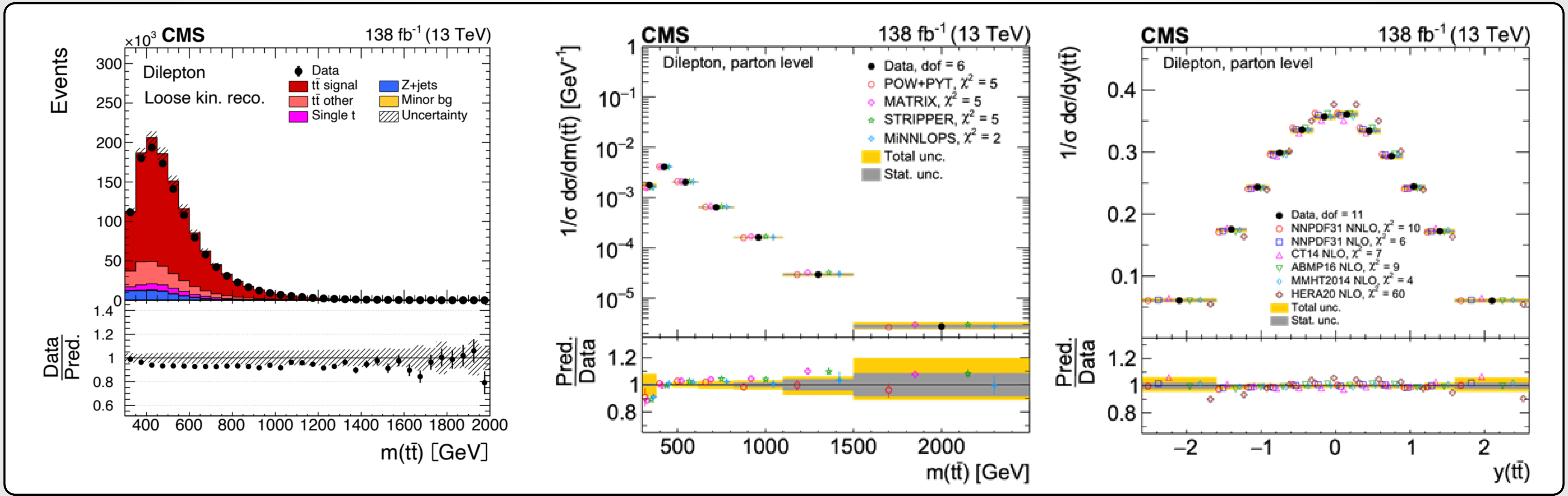
  - Measurement performed in bins of N_j, $N_{b\text{-tag}}$, and N_{lep}
  - Multiple bins constrain systematic uncertainties.
  - Result $\boldsymbol{\sigma}$ = 881 ± 23 (stat+sys) ± 20 (lumi) pb or ~3.5%

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.6
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.5
ME scale, backgrounds	0.2
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Top quark p_T	0.5
tW background	0.7
t-channel single-t background	0.4
Z+jets background	0.3
W+jets background	<0.1
Diboson background	0.6
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.5
Integrated luminosity	2.3

DIFFERENTIAL CROSS SECTION MEASUREMENTS

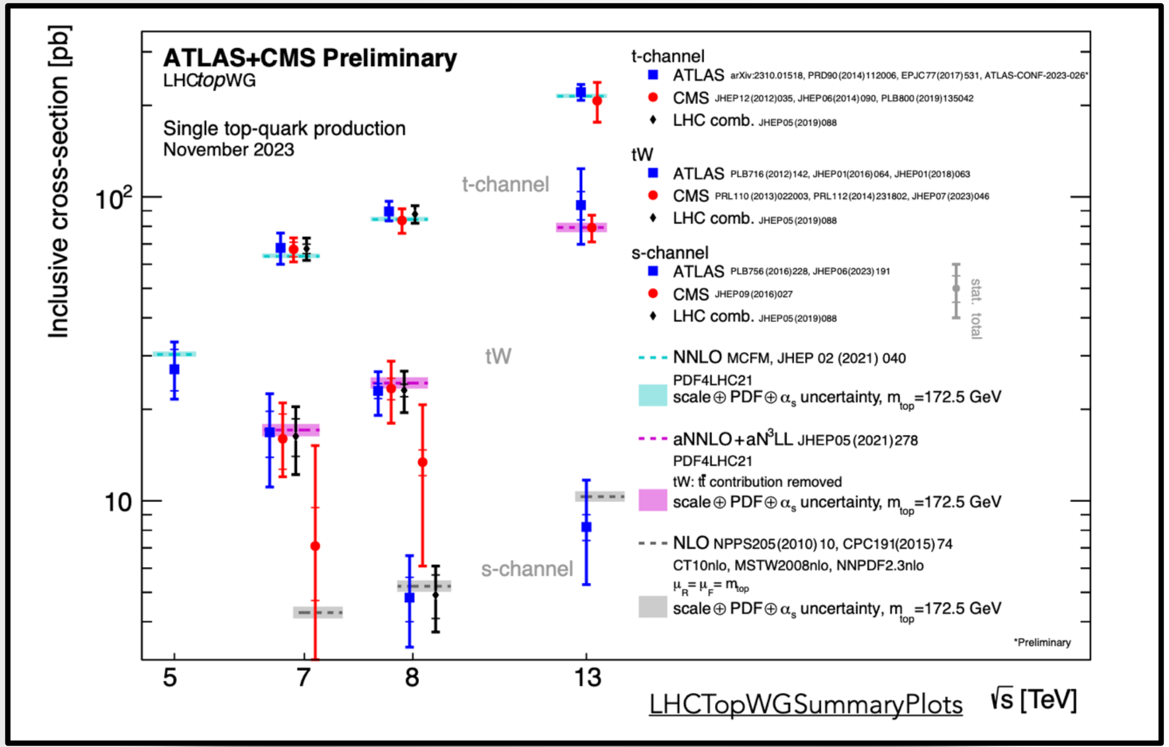
[2402.08486]

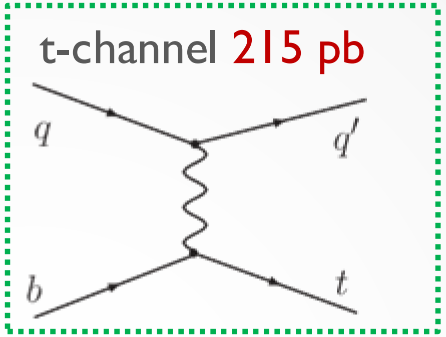
- Exhaustive single-, double-, triple-differential (p_T (tt), m(tt), |y(tt)|) measurement

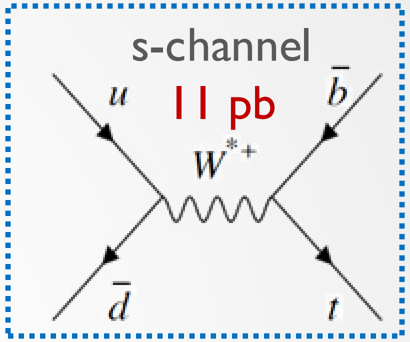


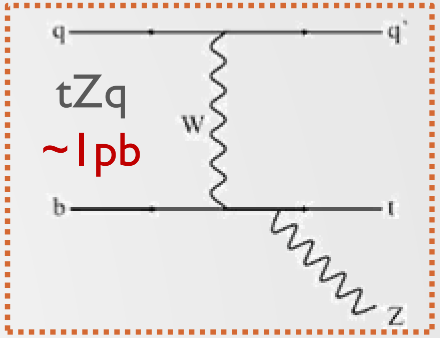
- Similar composition of uncertainties
- Comparisons with various PDF sets, event generators, theory predictions

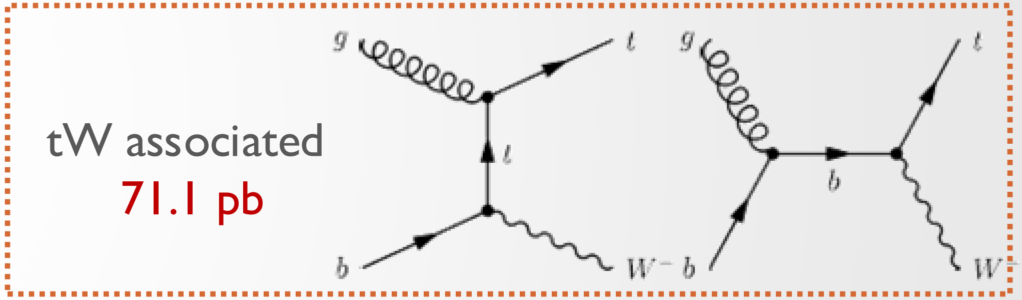
SINGLE TOP QUARK MEASUREMENTS







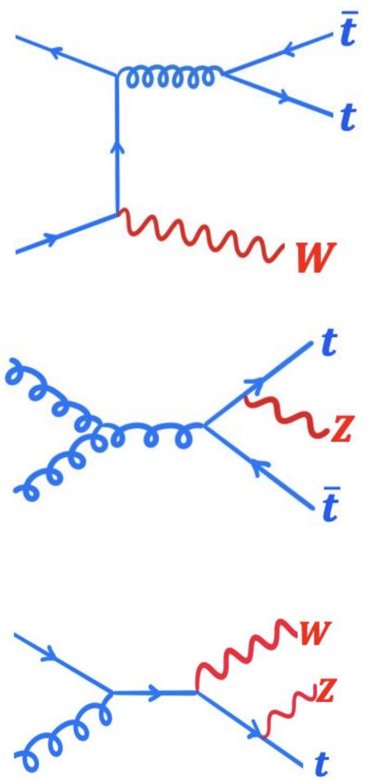


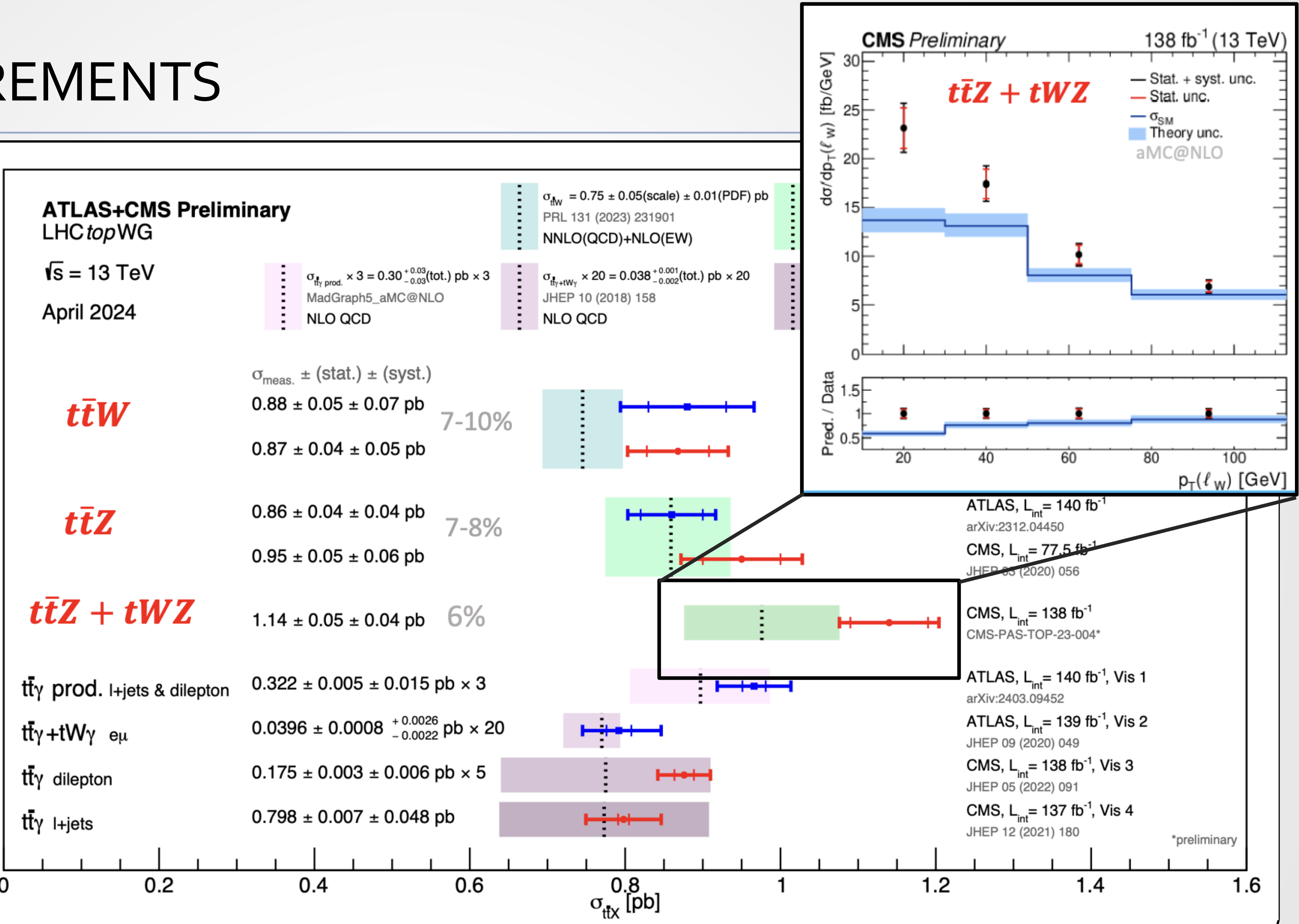


- t-channel, tW associated and electroweak s-channel production measured at various pp collision energy
- Including a 5.02 TeV ATLAS t-channel measurement from a short run in 2017
- Analyses rely heavily on MVA techinques for object reconstruction

TT+X MEASUREMENTS

First observed at the LHC





Now used for sensitive tests beyond the SM

TOP QUARK MASS

TOP QUARK MASS (OVERVIEW)

- Extremely simple tree level: SM masses from Yukawa coupling $y_t \approx 1$

$$-\mathcal{L}_{\text{Yukawa}} = y_d(\bar{q}_L \Phi)\, d_R + y_u(\bar{q}_L \widetilde{\Phi})\, u_R + y_\ell(\bar{\ell}_L \Phi)\, \ell_R + \text{h.c.}$$

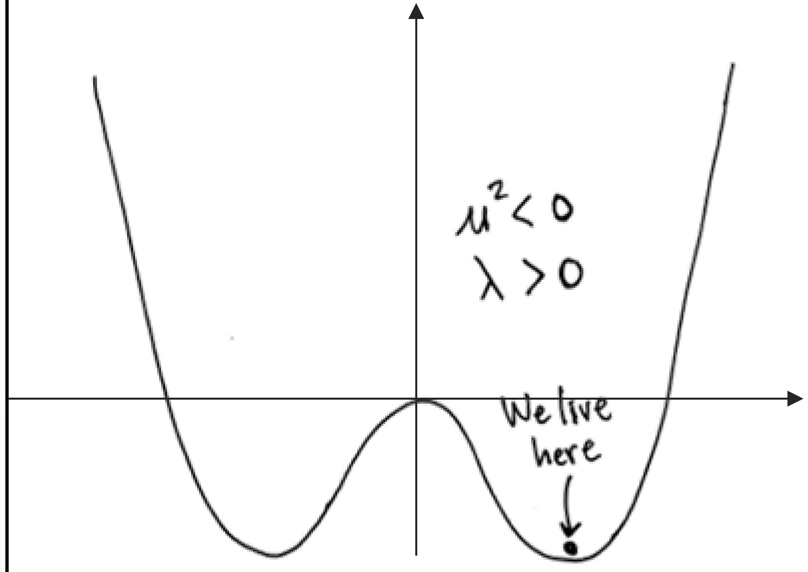
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ \phi + i\omega_3 \end{pmatrix} \qquad \langle \phi \rangle \equiv v = \sqrt{\frac{-\mu^2}{\lambda}} = 246 \text{ GeV}$$

- Tree level: $m_t = y_t\, v/\sqrt{2}$. Higgs mechanism impressively confirmed!

- Extremely complex picture at the loop level:
  - $\overline{\text{MS}}$ 'short distance mass' approx. 9 GeV lower than pole mass @N3LO
  - Experiments use 'MC mass' ⟷ *would* need a well defined perturbative expansion of parton showers ~ 1 GeV
  - Confinement : ambiguous (non-perturbative) relations to the pole mass of O(250 MeV)
  - Categories of top quark mass measurements (x-sec) relate differently to the Lagrangian parameters

Higgs potential

$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$



$\phi = \langle\phi\rangle + h = v + h$

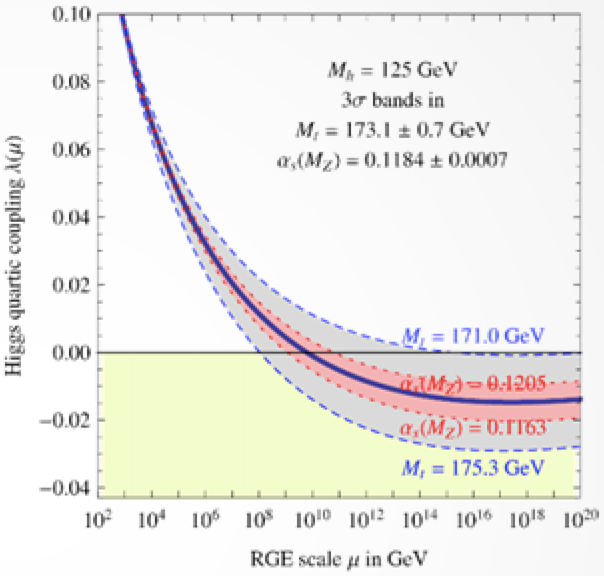
VACUUM STABILITY

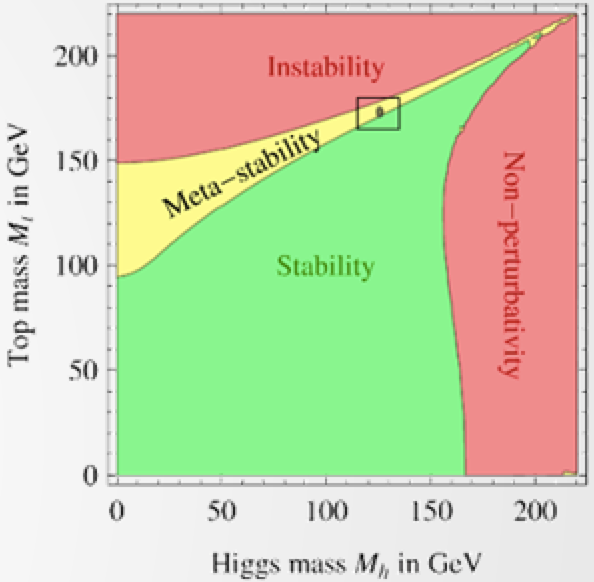
[1205.6497, 1207.0980, 1307.3536]

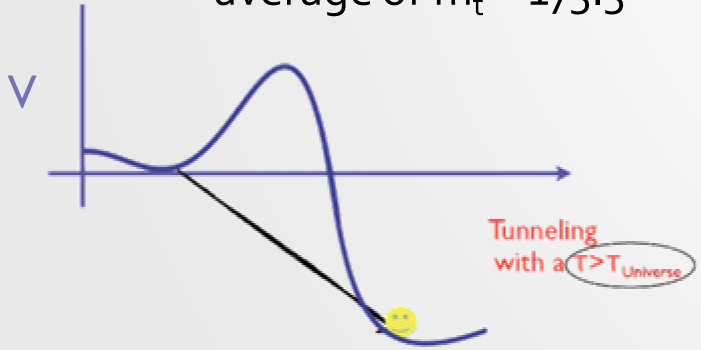
- Since 2012: Higgs self coupling $\lambda(m_t)$~0.14.
- NNLO SM RGE running of λ

$$\frac{d\lambda}{d\log\mu} = +\frac{3\lambda^2}{2\pi^2} - \frac{3}{8\pi^2} Y_t^4 \ldots$$

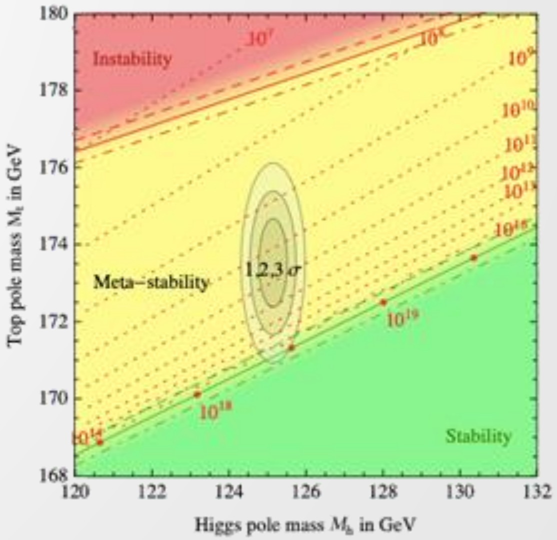
  finds the Higgs self-coupling λ remarkably small
- peculiar interplay of measured m_h and m_t on predicted vacuum stability
  - λ runs to negative values at Λ~10^{11} GeV for world average of m_t = 173.3

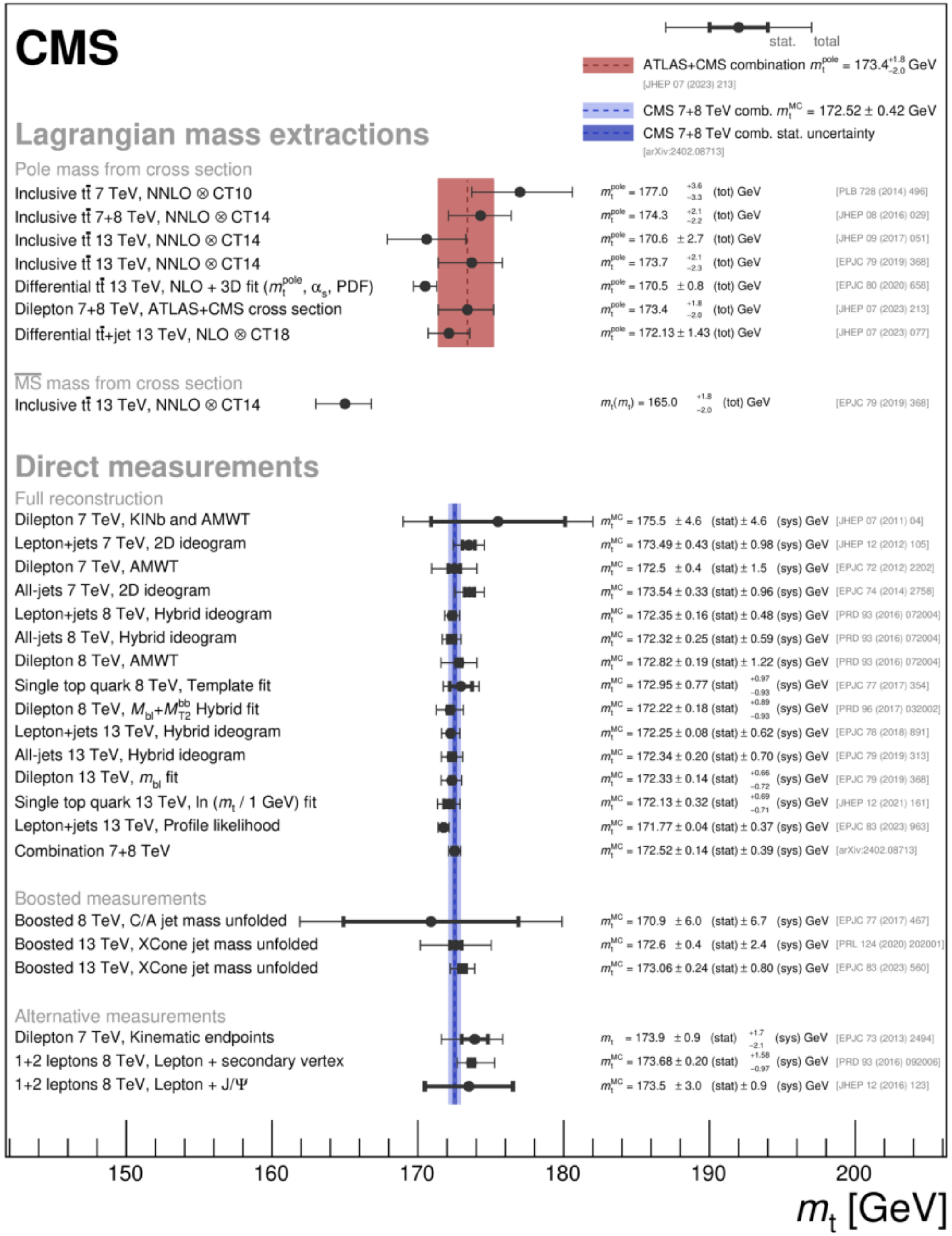




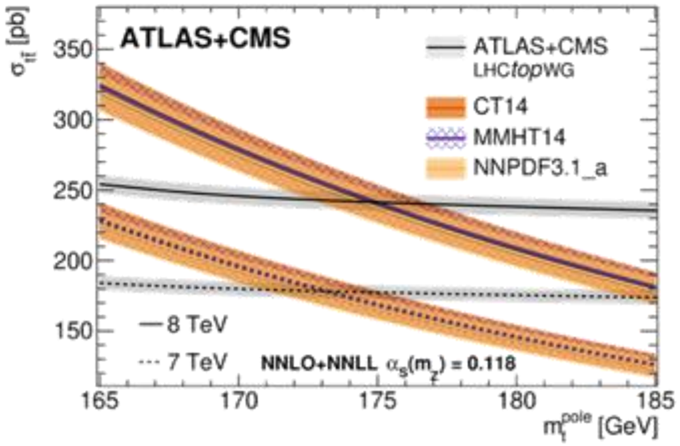


- High scale running could be affected by BSM
- Important implications for models of inflation

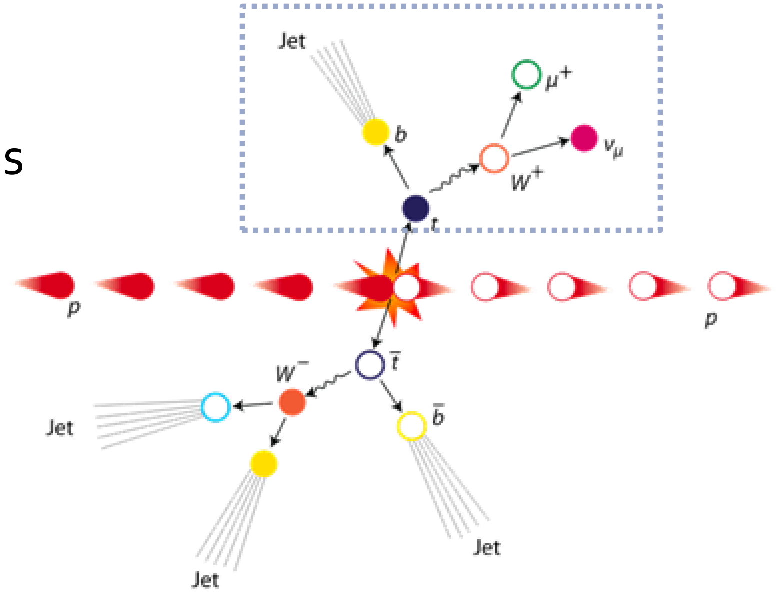




- Indirect meas. from cross section
  - Infer (pole) top quark mass from x-sec
  - ~1% precision, good theoretical control



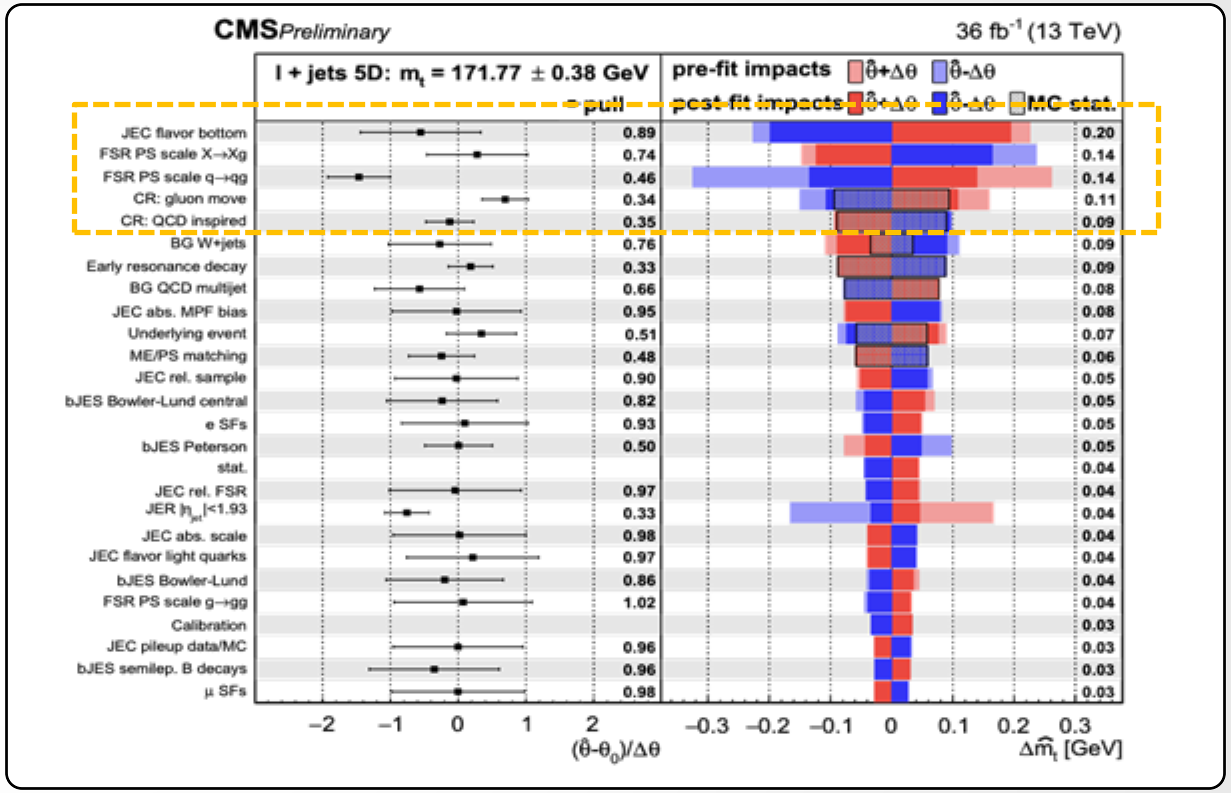
- Direct meas. from top quark decays
- Extract top quark mass from decay products
- Measures the "Monte Carlo" mass
- Better experimental precision: 0.2%

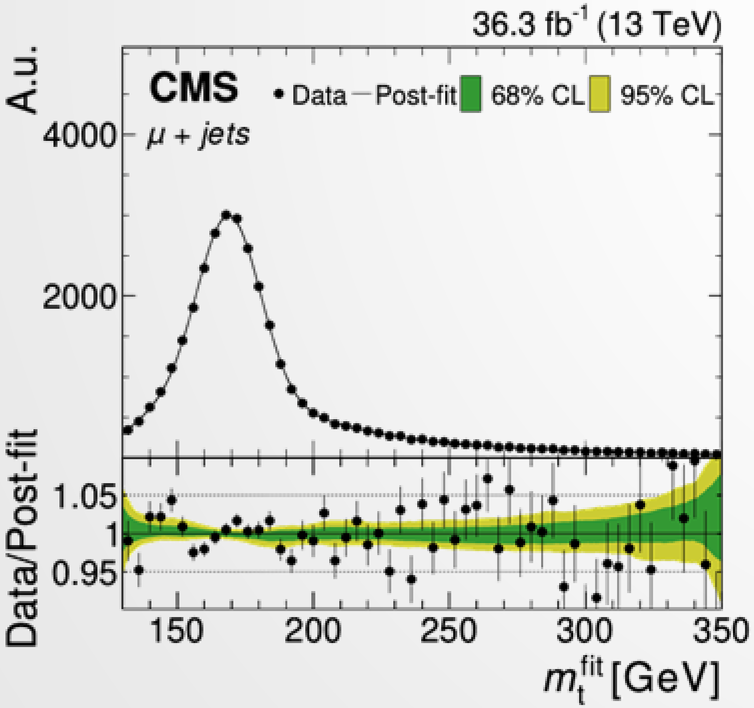


DIRECT TOP QUARK MASS MEASUREMENT

[Eur. Phys. J. C 83 (2023) 963]

- Best experimental strategy: "5D LL method" resolved jets & in-situ calibration on m_W
  - 380 MeV uncertainty (0.2%)
  - Exp: uncertainties:
    - response differs for light jets and b jets
    - modelling uncertainties



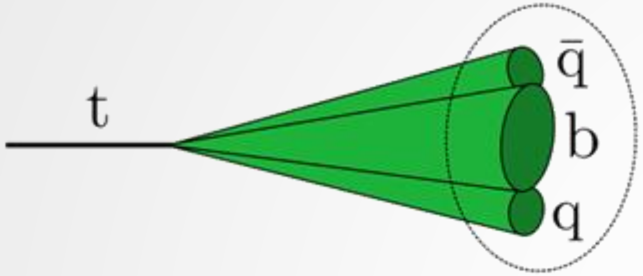


- Not a pole mass measurement!
- Plateau for any m_W calibration strategy
- Further improvements require *strategic change*

M_{JET} IN BOOSTED TOP QUARK DECAYS

[Eur. Phys. J. C 83 (2023) 560]

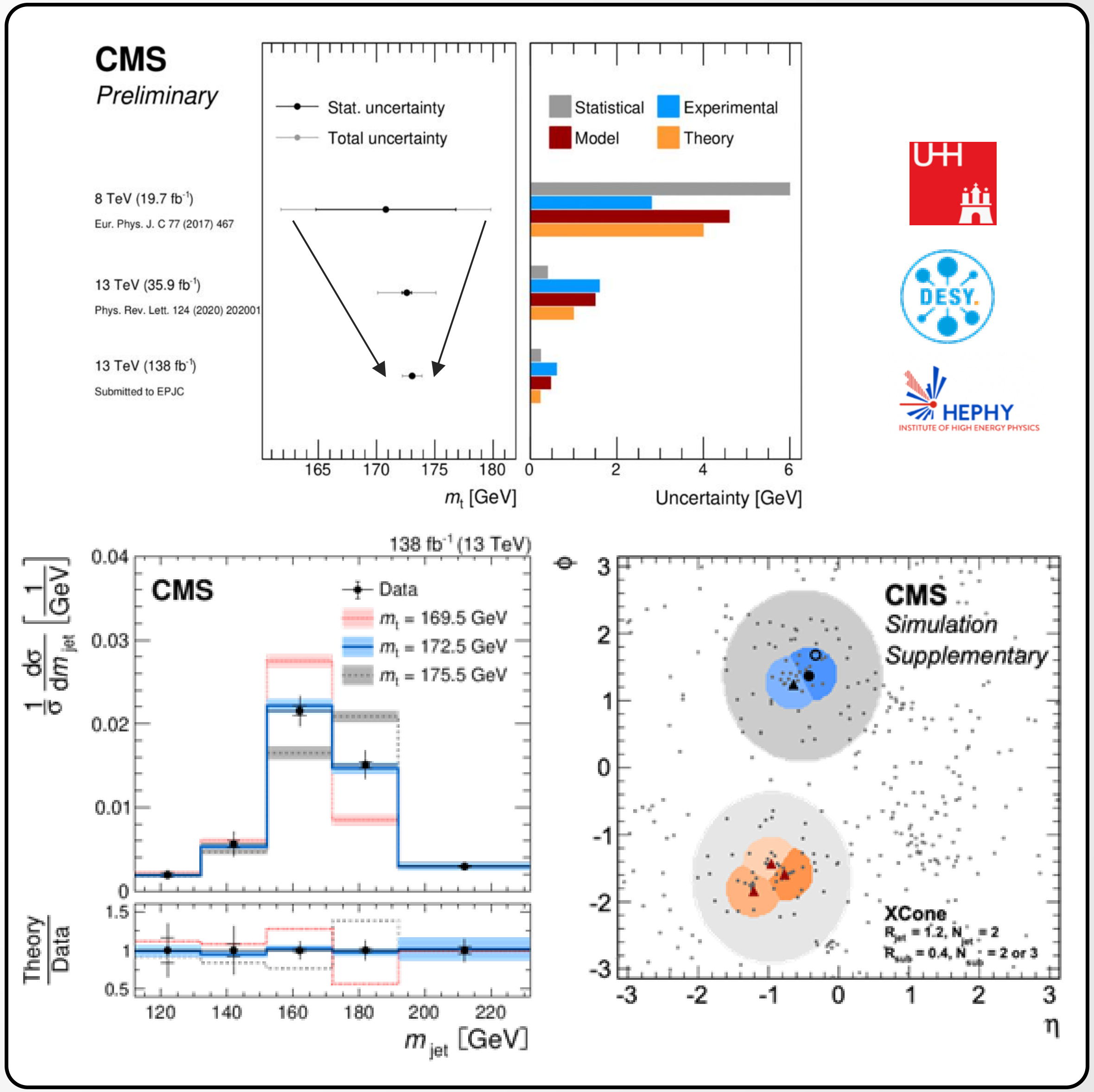
- Top quarks boosted → decay products merge



- Jet mass M(jet) sensitive to top quark mass M_t
- Jet mass (XCone) can be calculated *analytically* and allows an extraction of pole mass
  - For p_T(top)>750 GeV
- Measurement thought impossible after Run I
  - Careful calibration of jet mass scale and FSR modelling improve sensitivity to 800 MeV

$$m_t = 172.76 \pm 0.81 \text{ GeV}$$

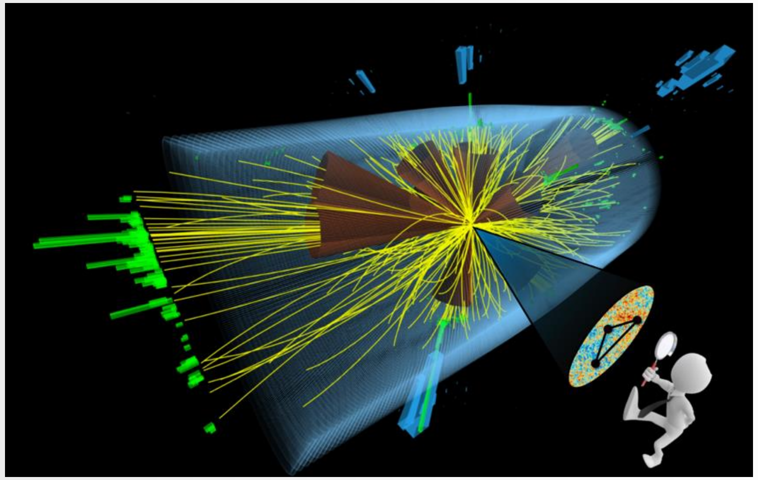
  - Using p_T(top)>400 GeV
- Theory phase space (p_T>750) accessible at HL-LHC



ENERGY CORRELATORS

[arXiv:0803.1467]

- So far, focus on exclusive processes [Compare slide 6!]
  - S-Matrix elements : Compare theory and prediction with a small number of particles
  - Is there an approach for large multiplicities? Energy correlators [overview]!



To make this idea more quantitative we define for any state a, an "angular energy current" in the e^+e^- CM frame:

$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \, \delta(\Omega - \omega_i) \qquad (1)$$

where the sum is over the n_a massless particles in a, with energies $\{\eta_i\}$ and momentum directions $\{\omega_i\}$ (ω_i stands for angles θ_i and φ_i).

[G.F. Sterman, 1975, 2 citations]

- What are energy correlators?
  - Energy flow into directions n(**θ**) at spacial infinity
  - Compute n-point correlation of momentum flux
  - Can *perturbatively* relate correlators to parameters of underlying theory [couplings, transport coefficients, HI, …]

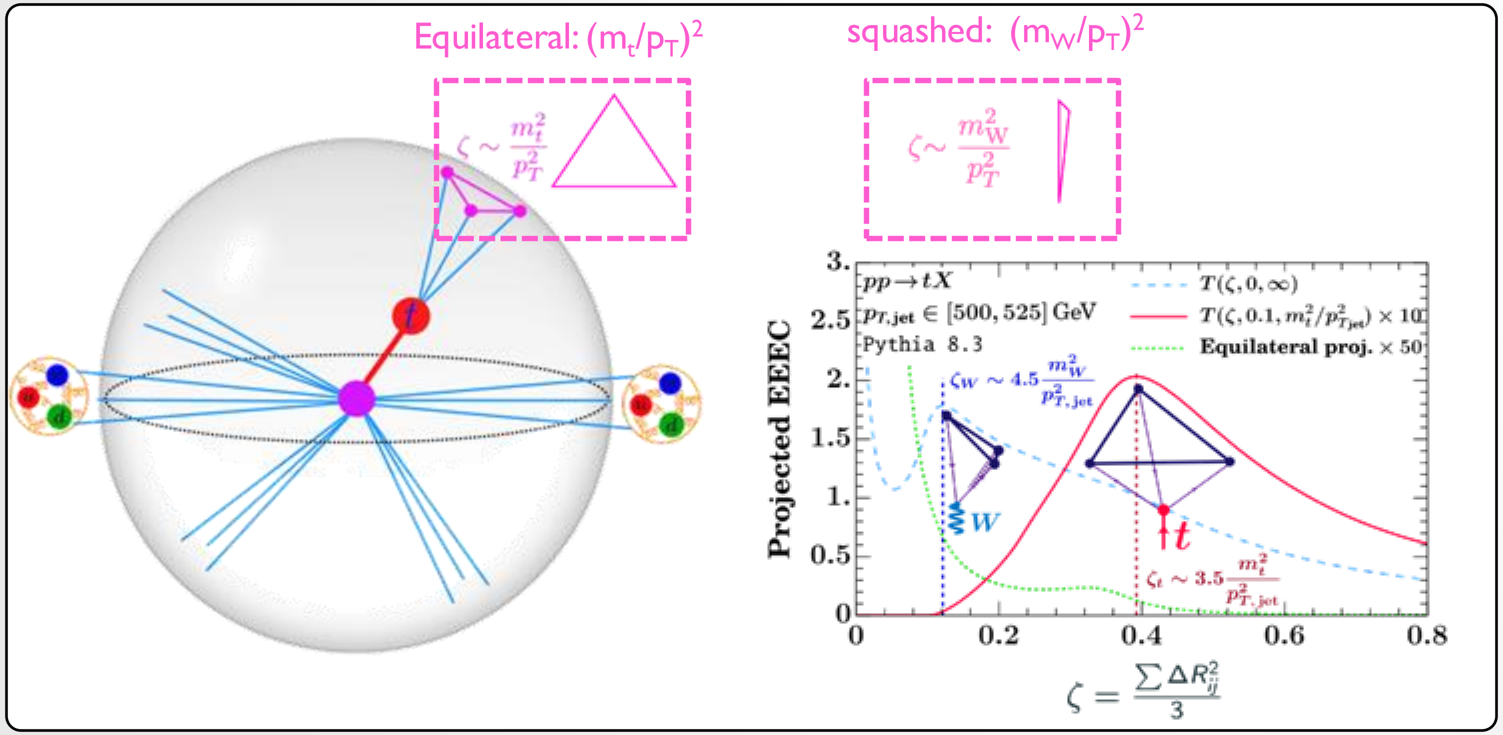
$$\mathcal{E}(\theta) = \lim_{r\to\infty} r^2 \int_{-\infty}^{\infty} dt\, n^i T^0_{\;i}(t, r\vec{n}^i)$$

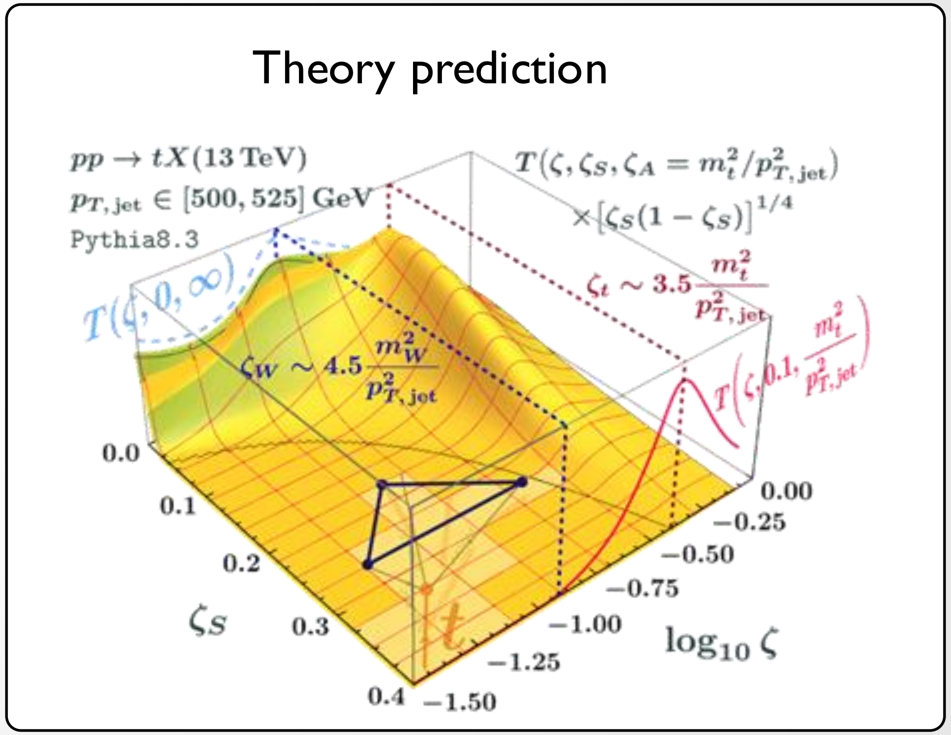
$$\langle \mathcal{E}(\theta_1)\cdots\mathcal{E}(\theta_n)\rangle \equiv \frac{\langle 0|\mathcal{O}^\dagger \mathcal{E}(\theta_1)\cdots\mathcal{E}(\theta_n)\mathcal{O}|0\rangle}{\langle 0|\mathcal{O}^\dagger\mathcal{O}|0\rangle}$$

M_T FROM TRACK-BASED ENERGY CORRELATORS [2201.08393, 2404.12900]

- 3-point energy correlators (EEEC) can be related to the top quark mass
  - Experimentally: A weighted histogram over the ensemble of triplets of particles in a jet: $w = \frac{(p_{T,1}p_{T,2}p_{T,3})^n}{p^n_{T,\mathrm{jet}}}$
  - Computed with *tracks* in boosted hadronic top jets

  Investigate total opening angle $\zeta = \frac{\sum \Delta R^2_{ij}}{3}$ ↔ sensitive to the M_t
- Track-based M_t measurement with (in principle) theoretical control. Will need HL-LHC stats!



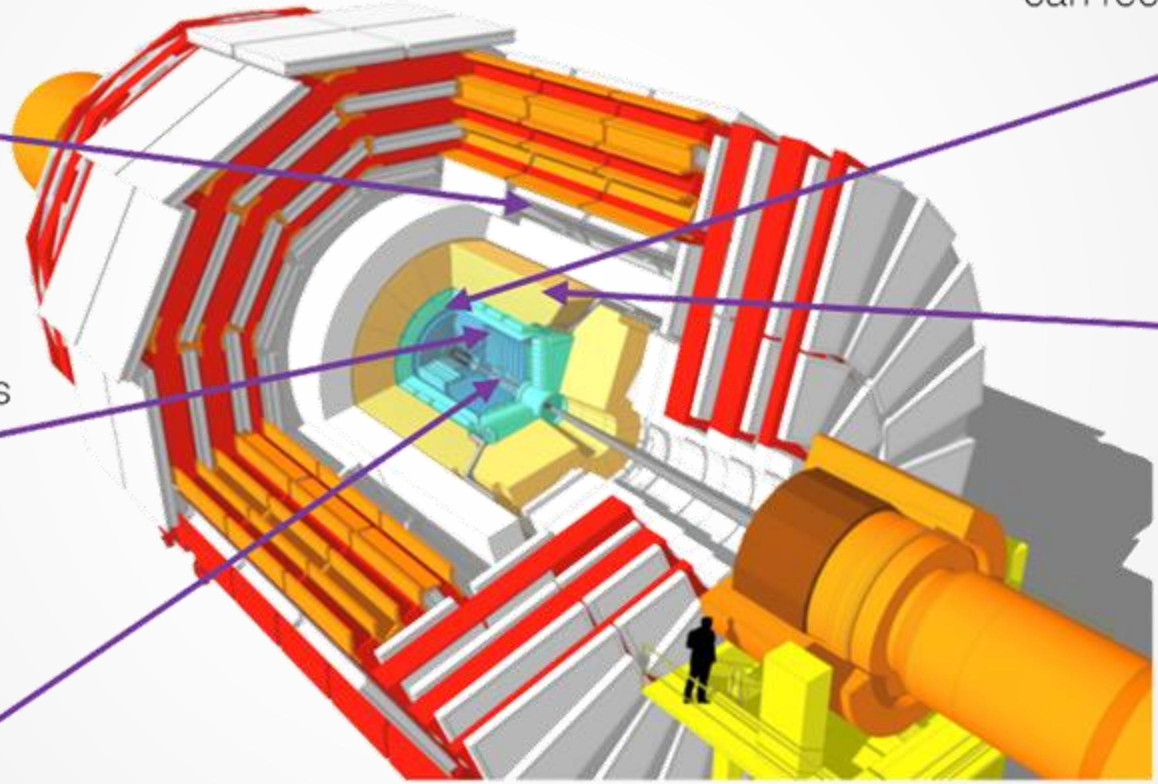


PROSPECTS FOR HL-LHC

CMS UPGRADES FOR HL-LHC

Improved muon coverage and trigger
increased RPC coverage ($1.5 < |\eta| < 2.4$)
new electronics
[CMS-TDR-016]

New endcap calorimeters
high granularity
can reconstruct showers in 3D
CMS-TDR-019



New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of $|\eta| < 3.0$
[CMS-TDR-020]

Updates to calorimeter and trigger
higher granularity
electronics for trigger

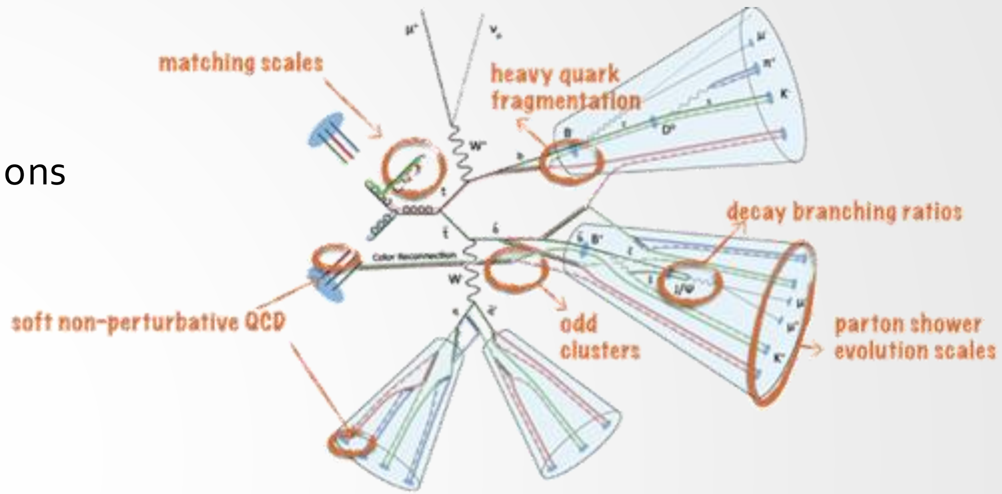
New inner tracker
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to $|\eta| < 4$ [CMS-TDR-014]

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1
[L1: CMS-TDR-021]
[DAQ/HLT: CMS-TDR-022]

EXPLOITING THE HL-LHC DATA SET

[Phys. Rev. Lett. 116, 082003 (2016)]

- A great many things have to come together
  1. State of the art theoretical tools/calculations
     - Factor 2 uncertainty reduction in most perturbative calculations
  2. Low-level understanding of sub-detector performance
  3. Object performance – realistic projections
  4. Novel analysis ideas that incorporate 1-3



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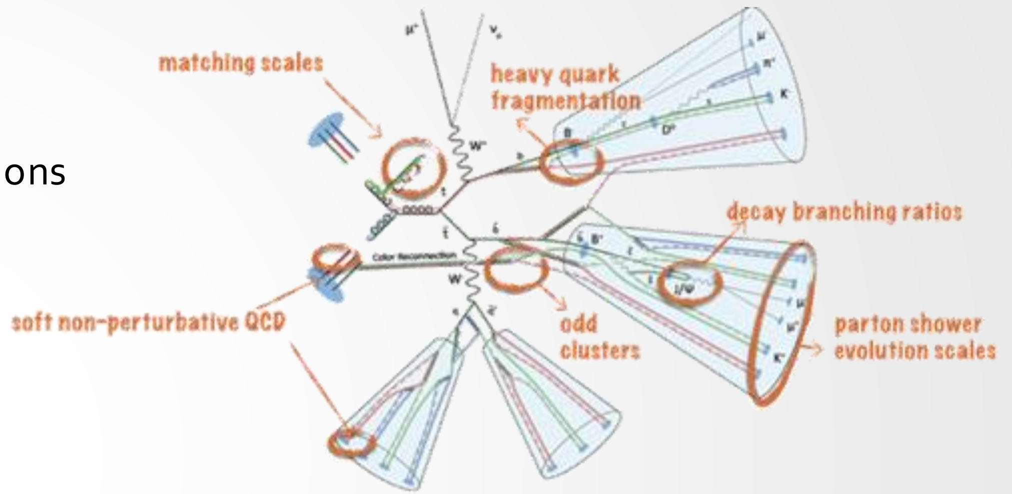
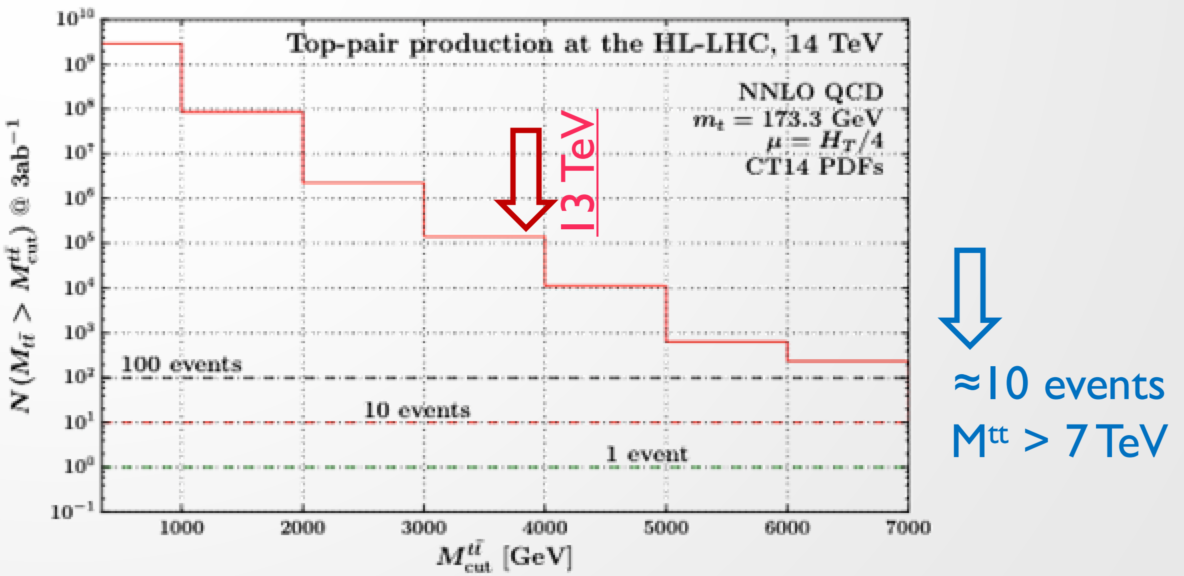


- kinematic reach HL-LHC 14 TeV with 3/ab
  - increase reach by several TeV
  - higher-order EWK corrections essential for precision

Cumulative M^{tt} distribution for HL-LHC



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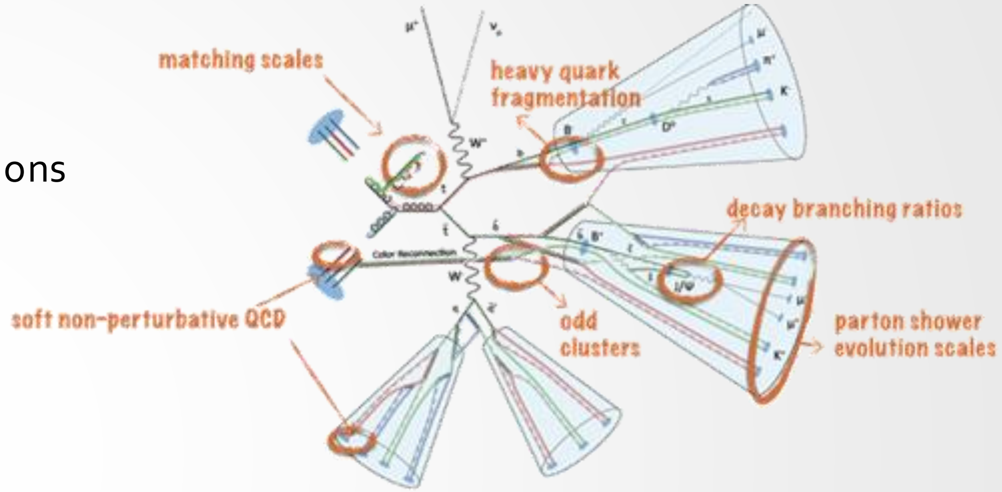

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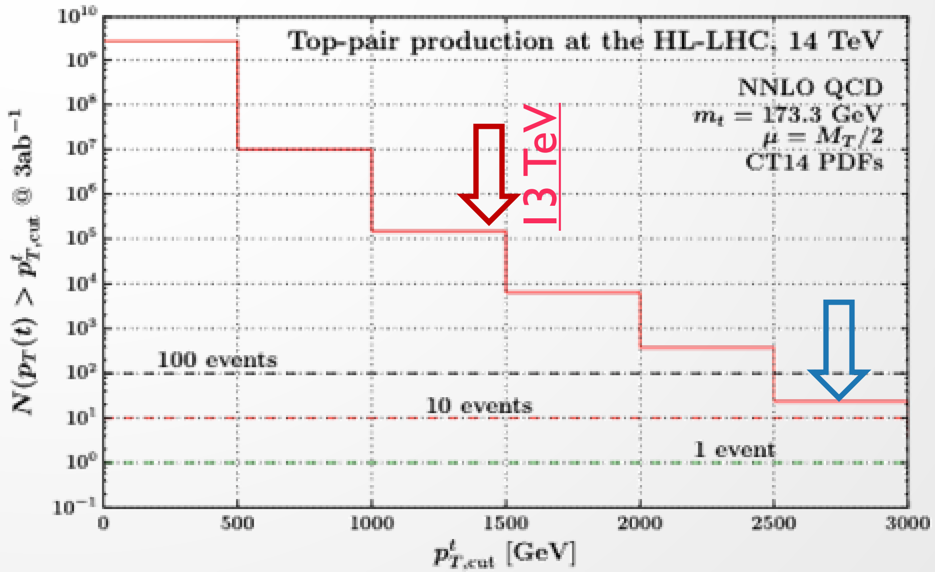
  - higher-order EWK corrections essential for precision

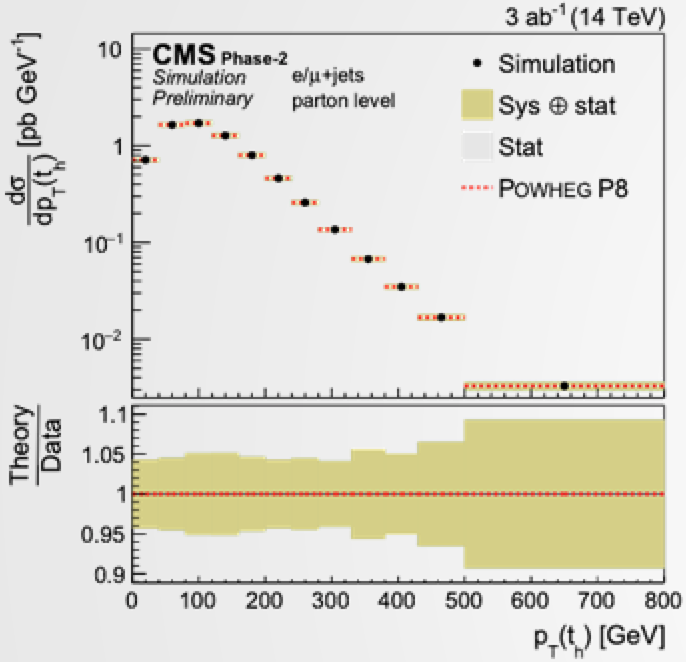
Cumulative $p_T(t)$ distribution for HL-LHC



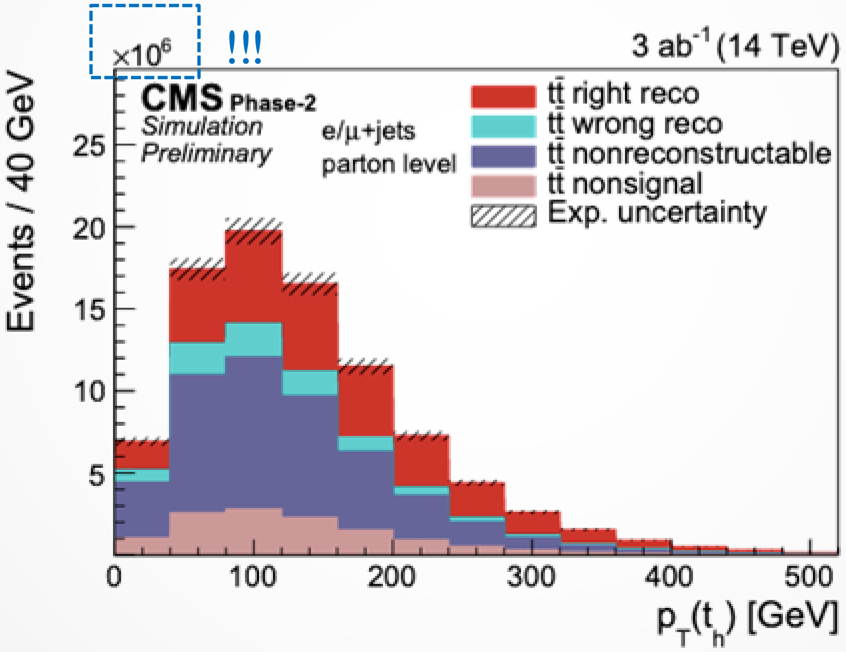
≈20 events
p_T > 2.5 TeV
TeV scale jets/leptons collimated to slim jets: $\Delta R \approx 0.13$
(16cm @ CMS ECAL)

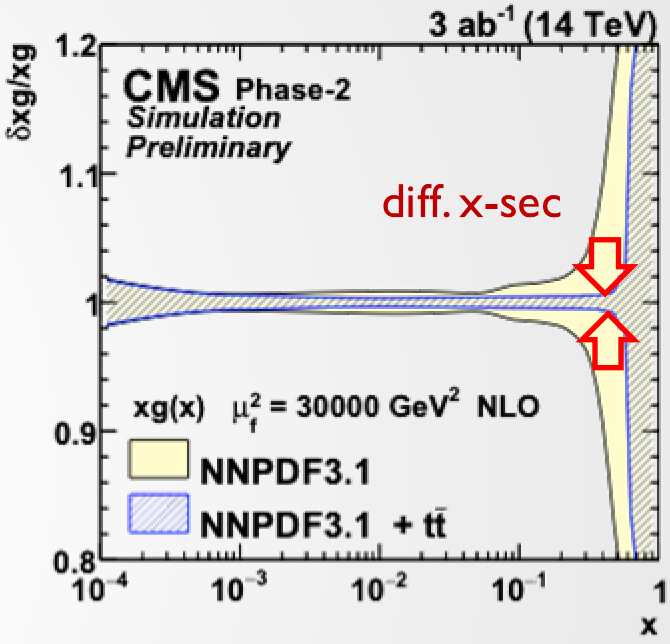
PRECISION FROM THE BULK AND FROM HIGH ETA

[CMS-FTR-18-015]
[arXiv:1311.1810]
[arXiv:1808.08865]



- uncertainty on differential top x-sec O(5%)
- significant impact on high x gluon PDF





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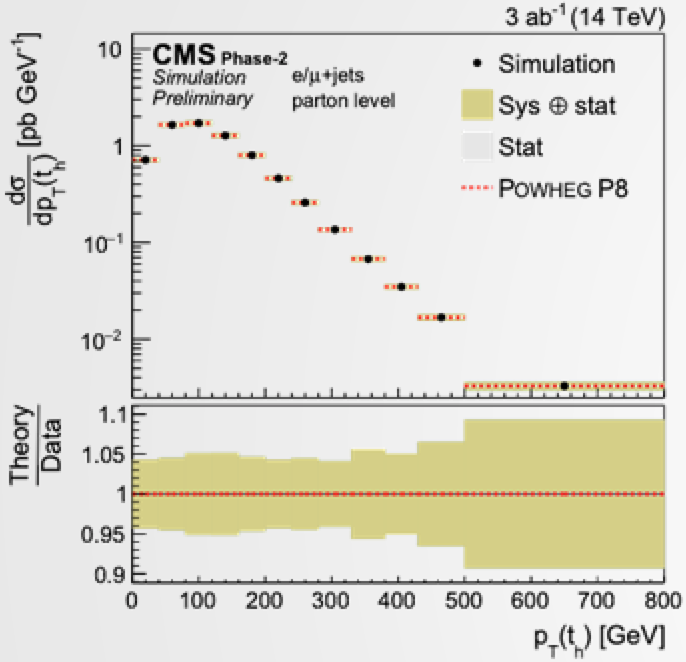
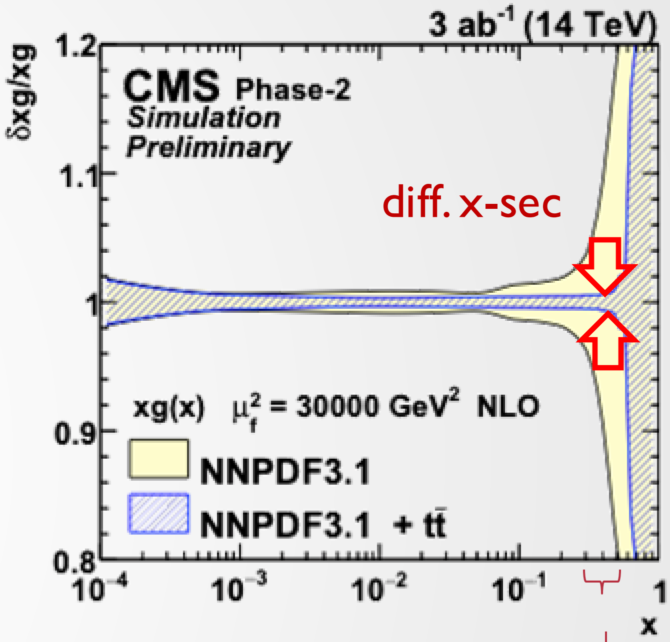
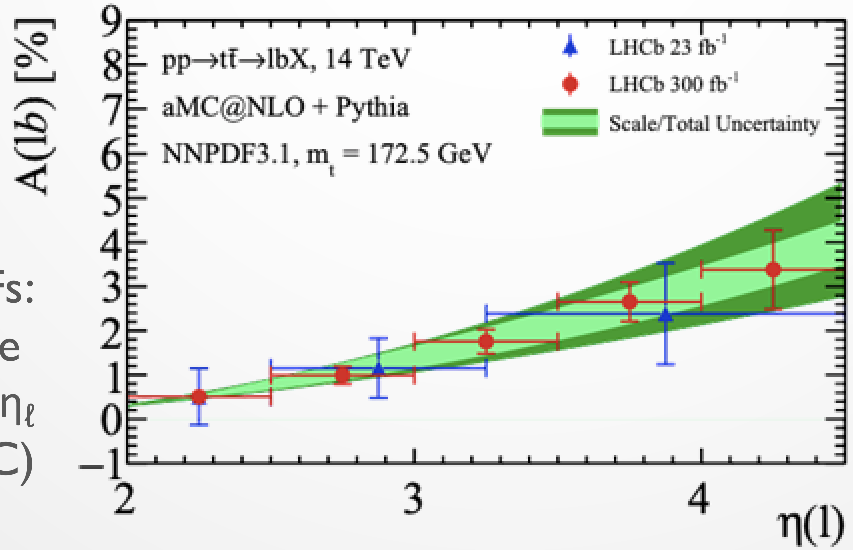


- uncertainty on differential top x-sec O(5%)
- significant impact on high x gluon PDF
- complemented with forward tops:
  1. 300/fb LHCb data probe high-x PDFs with partially reconstructed top quarks
  2. quark PDFs: use differential charge asymmetry vs. lepton **η**



quark PDFs:
differential l±b charge
asymmetry vs η_ℓ
(300/fb for HL/LHC)



sensitivity from 300/fb of LHCb data in (partial) t and tt final states

stat precision ↑ background level ↓

Final state	300 fb^{-1}	$<x>$
ℓb	830k	0.295
$\ell b\bar{b}$	130k	0.368
$\mu e b$	12k	0.348
$\mu e b\bar{b}$	1.5k	0.415

THE TOP QUARK BEYOND THE SM

TOP QUARK PROPERTIES

- The top quark is the heaviest known fundamental particle.
  Interesting properties/problems appear at all scales

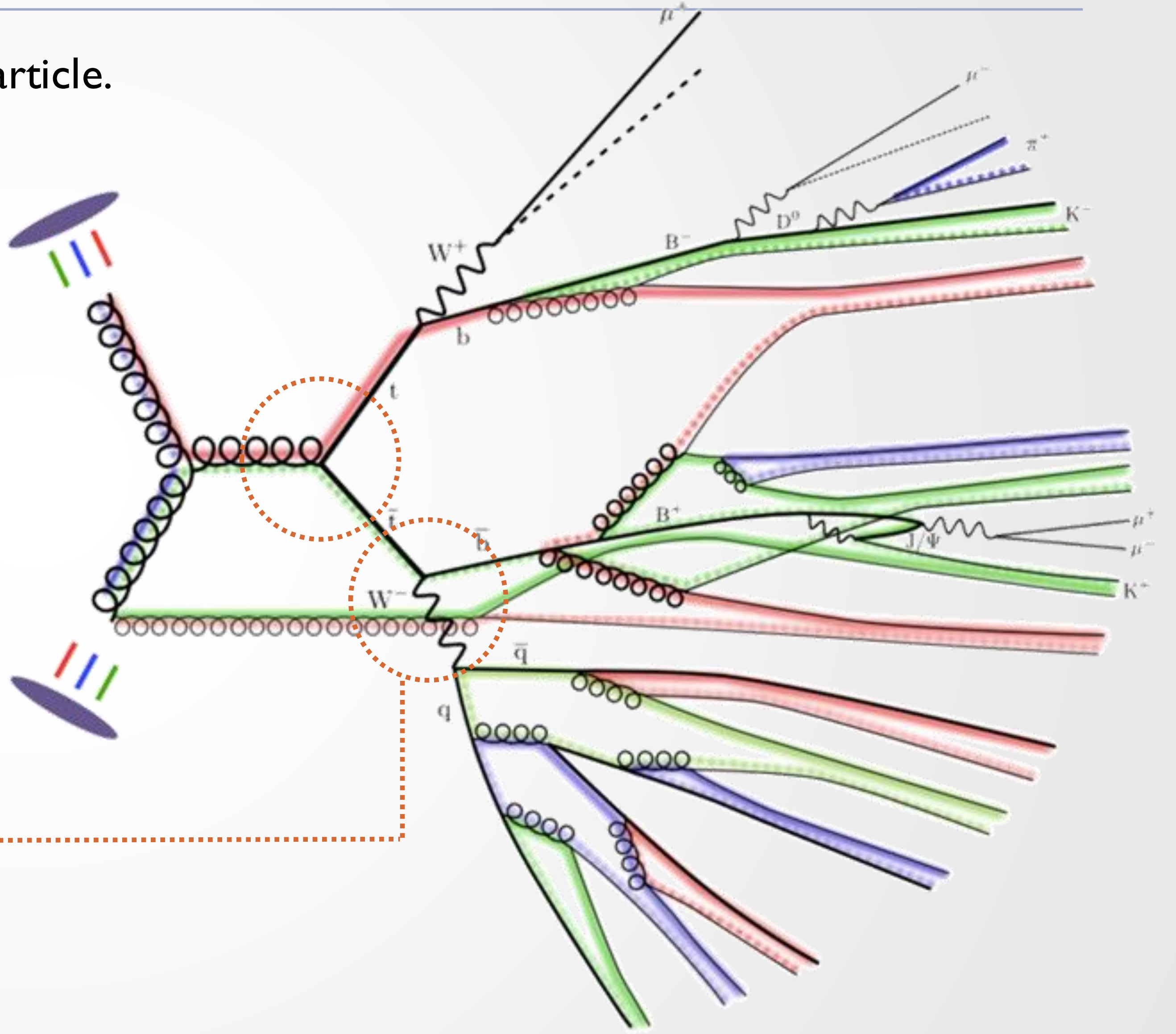
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

- x-sec measurements at high precision, interplay with PDFs

- mass measurements, hadronization effects, color reconnection, UE tune, …

- spin correlation, anomalous strong interactions

- weak interactions, vector couplings and dipole moments, …



- all aspects under scrutiny at the LHC; let us discuss an example

EXAMPLE: SPIN CORRELATION

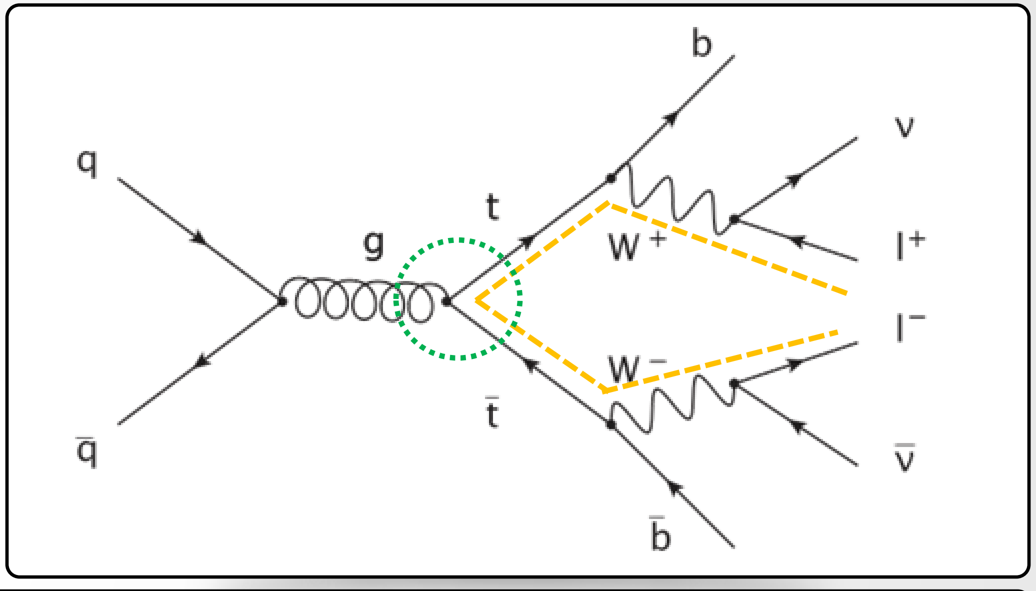
Phys. Rev. D 100, 072002 (2019)

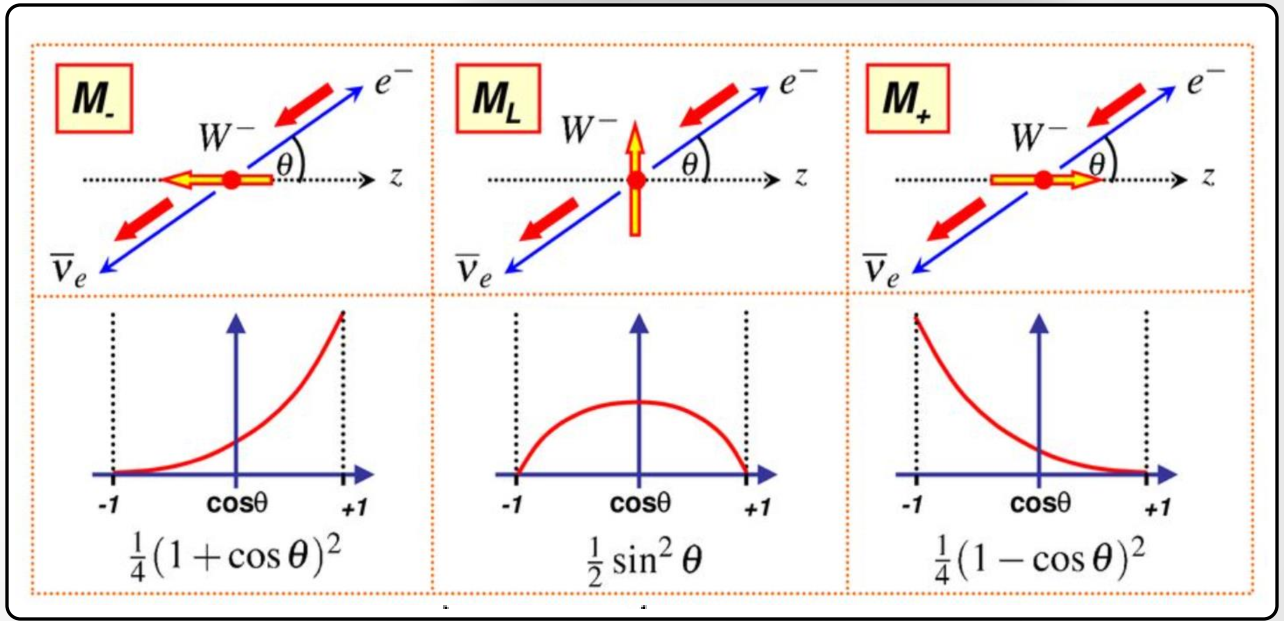
EPJC 80(2020)754

- Physics idea: ttbar unpolarized, but spins are correlated
- The long spin-flip timescale makes the leptons "spin-analyzers" of the top quark
  - ⟶ t/W/b spins are similarly correlated
  - Can we measure the spin or the correlation?
  - Transversely polarized W^- bosons eject the charged lepton *along the direction of motion*
  - For a $W^\pm$ pair originating from a top quark pair we expect *large relative lepton momenta*
- Rest-frame angle between leptons (p19!)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - \underbrace{D}_{-\frac{1}{3}\mathrm{tr}(C)} \cos \underbrace{\varphi(\hat{\ell}^+, \hat{\ell}^-)}_{\text{top rest frame}})$$

- Expect to see more often large lepton angles
  SM: tr(spin correlation matrix C) ≃ 1

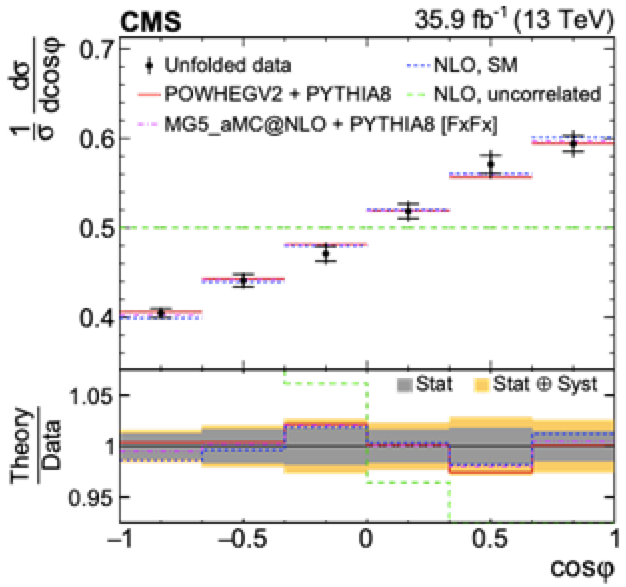




CHROMOMAGNETIC DIPOLE MOMENTS

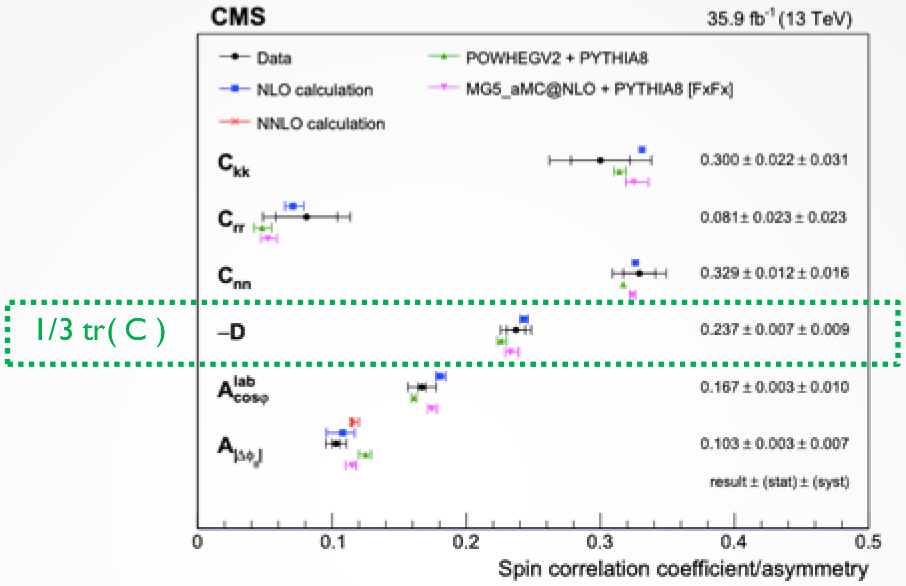
[Phys. Rev. D 100, 072002 (2019)]

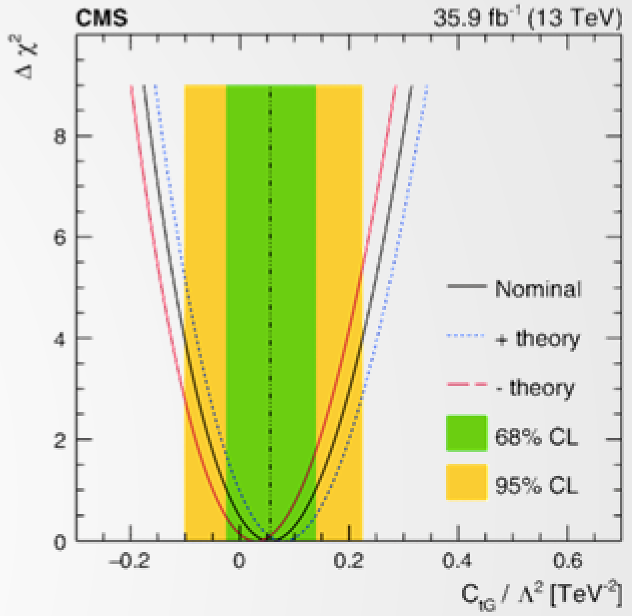
- Measurement as predicted!

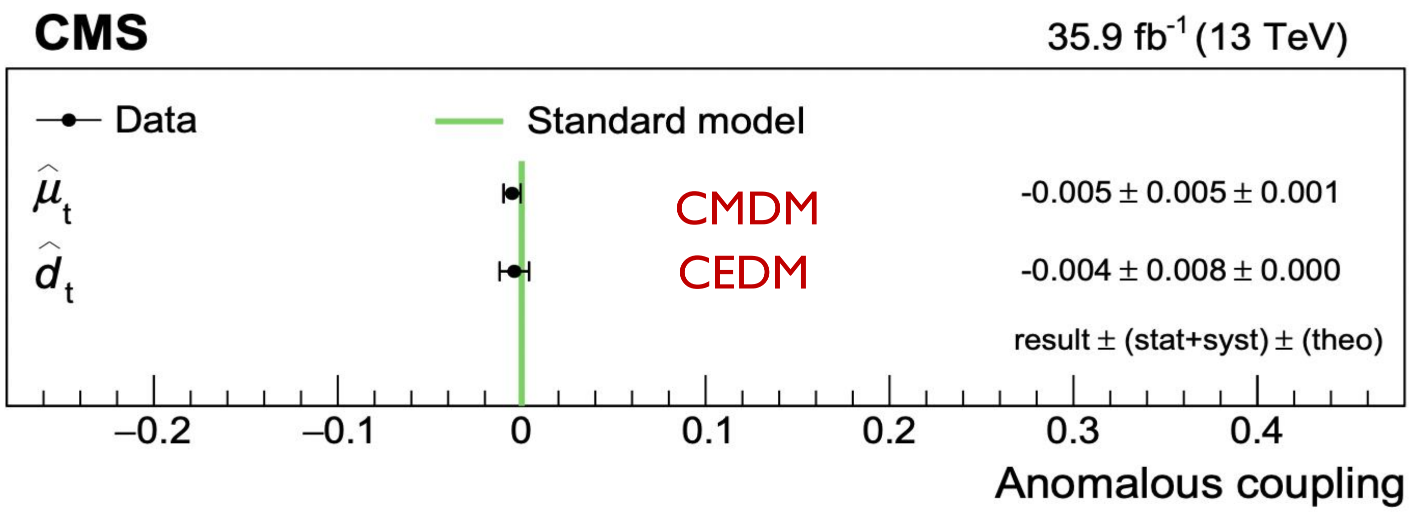


ratio to SM:

$$F_{\mathrm{SM}}(D) = 0.97 \pm 0.05$$





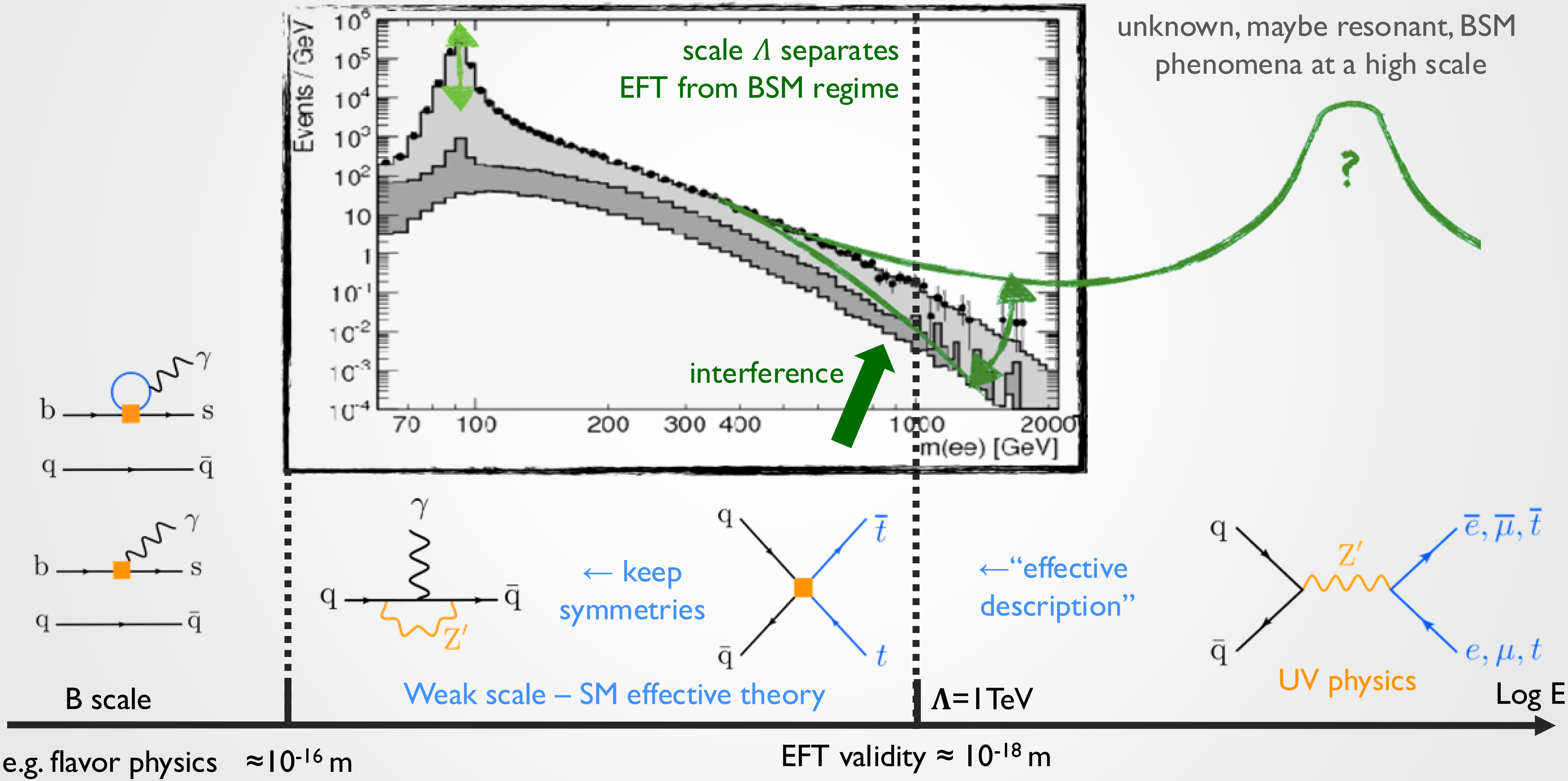


This is a limit on non-resonant BSM.
It could be invalidated by competing non-zerm effects.
We need a theoretically sound & complete approach!

(TOP) EFFECTIVE FIELD THEORY

GOING "LOW-LEVEL" IN THEORY LANDSCAPE

Sketch from F. Riva



THE STANDARD MODEL EFFECTIVE FIELD THEORY

- Organize the pieces in terms of mass dimension:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

1. Keep SM symmetries
   - $SU(3)_c \otimes SU(2)_L \otimes U(1)$
2. Keep particle content
3. Scale hierarchy

- 59 operators affect all SM predictions

$$\frac{C_{\phi W}}{\Lambda^2} \left(\phi^\dagger \phi\right) W_I^{\mu\nu} W_{\mu\nu}^I$$

$$\frac{C_{qq}^{(8)}}{\Lambda^2} (\bar{q}\, \gamma^\mu T^A\, q)\, (\bar{q}\, \gamma_\mu T^A\, q)$$

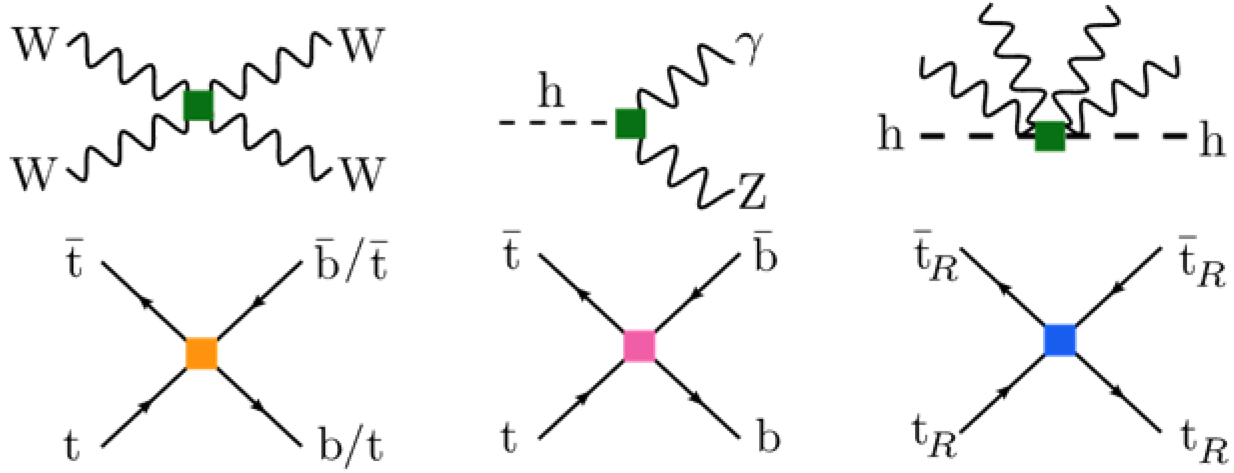
$$\frac{C_{qq}^{(3)}}{\Lambda^2} (\bar{q}\, \gamma^\mu \tau^I\, q)\, (\bar{q}\, \gamma_\mu \tau^I\, q)$$

unknown coefficients

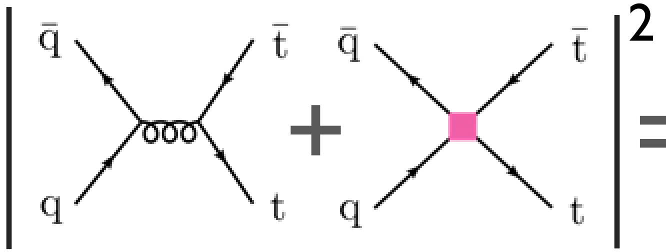
known SM particles

known SM symmetries

Anomalous couplings & new interactions (tiny selection!)



- Predicting rates from "squared" diagrams:



$$= \sigma^{SM} + \frac{C}{\Lambda^2}\sigma^{int} + \frac{C^2}{\Lambda^4}\sigma^{quad}$$

- Quite exceptional simplification!

SM-EFT AT MASS DIMENSION 6 (WARSAW BASIS)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$				

Table 3: Four-fermion operators.

Expansion of Higgs doublet: $$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\omega_1 + i\omega_2 \\ h + v + i\omega_3\end{pmatrix}$$

ω ⟶ modified/new interactions with longitudinal gauge bosons

h ⟶ modified/new interactions with the Higgs field

v ⟶ modified SM interactions of the order v^2/Λ^2

GAUGE COUPLINGS

TOP QUARK INTERACTIONS WITH BOSONS

Modification of SM vector interactions

$$
\begin{aligned}
&\mathcal{O}^{(3)}_{\phi q_L} && i\left(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi\right)\left(\bar{q}_L \gamma^\mu \tau^I q_L\right) \\
&\mathcal{O}^{(1)}_{\phi q_L} && i\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\bar{q}_L \gamma^\mu q_L\right) \\
&\mathcal{O}_{\phi \mathrm{t}} && i\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\bar{t}_R \gamma^\mu t_R\right)
\end{aligned}
$$

Tensor (dipole) interactions are 3-loop suppressed in SM down to ~10^{-3}

(W & B are DOF before EWSB →W/Z/γ)

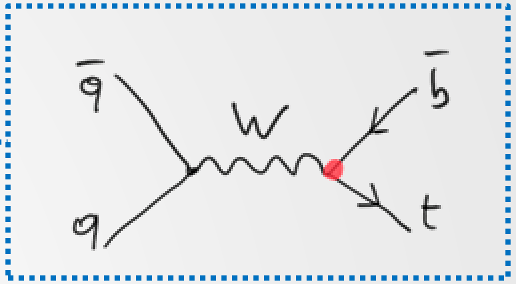
$$
\begin{aligned}
&\mathcal{O}_{\mathrm{tW}} && i\left(\bar{q}_L \sigma^{\mu\nu} \tau_I t_R\right) \tilde{\phi}\, W^I_{\mu\nu} + \mathrm{h.c.} \\
&\mathcal{O}_{\mathrm{tB}} && i\left(\bar{q}_L \sigma^{\mu\nu} t_R\right) \tilde{\phi}\, B_{\mu\nu} + \mathrm{h.c.} \\
&\mathcal{O}_{\mathrm{tG}} && i\left(\bar{q}_L \sigma^{\mu\nu} \lambda^a t_R\right) \tilde{\phi}\, G^a_{\mu\nu} + \mathrm{h.c.}
\end{aligned}
$$

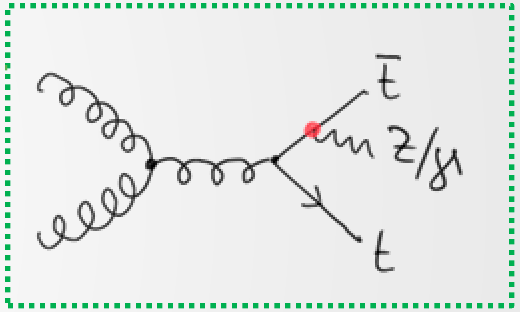
weak coupling to right handed fermions

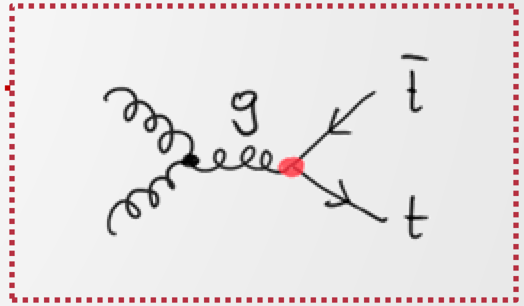
$$
\mathcal{O}_{\phi \mathrm{tb}} \quad i\left(\tilde{\phi} D_\mu \phi\right)\left(\bar{t}_R \gamma^\mu b_R\right) + \mathrm{h.c.}
$$

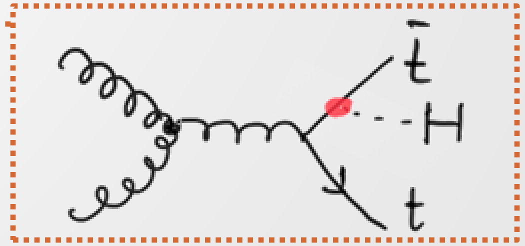
Yukawa term, Higgs interactions

$$
\begin{aligned}
&\mathcal{O}_{\mathrm{t}\phi} && \left(\phi^\dagger \phi\right) \bar{q}_L t_R \tilde{\phi} + \mathrm{h.c.} \\
&\mathcal{O}_{\Box} && |\Box H|^2
\end{aligned}
$$





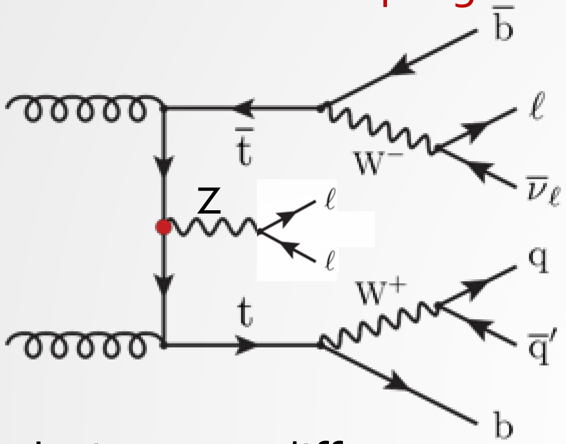




ELECTROWEAK TOP QUARK COUPLINGS

[JHEP 03 (2020) 056]
[sub. EPJC]

- Testing the electroweak couplings in associate Z/γ production



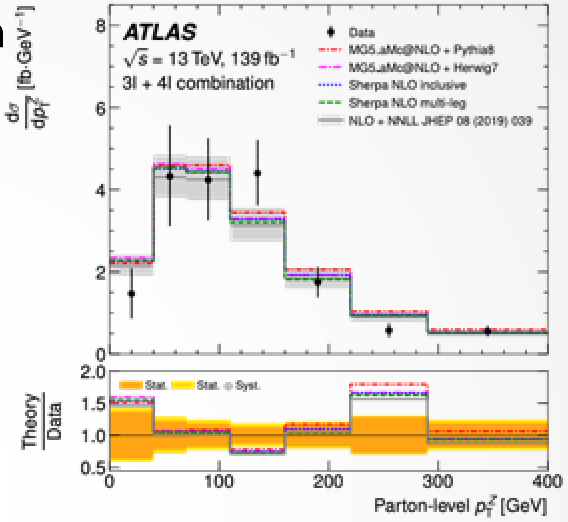
- For example: interpret diff. x-sec measurements
  - Some EFT effects grow with energy
  - Decay angle of Z boson also relevant cos(**θ***)

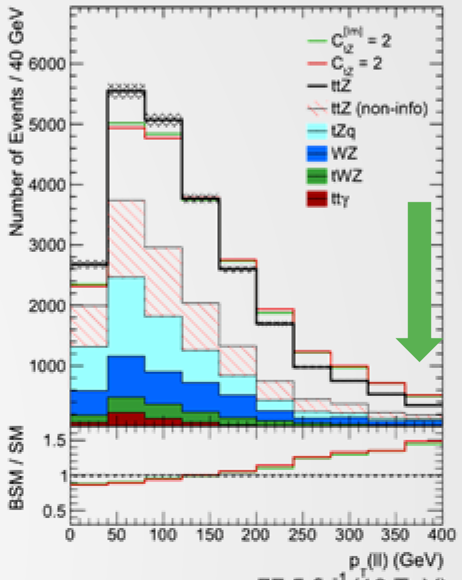
CMS $$\sigma(t\bar{t}Z) = 0.95 \pm 0.05\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}$$

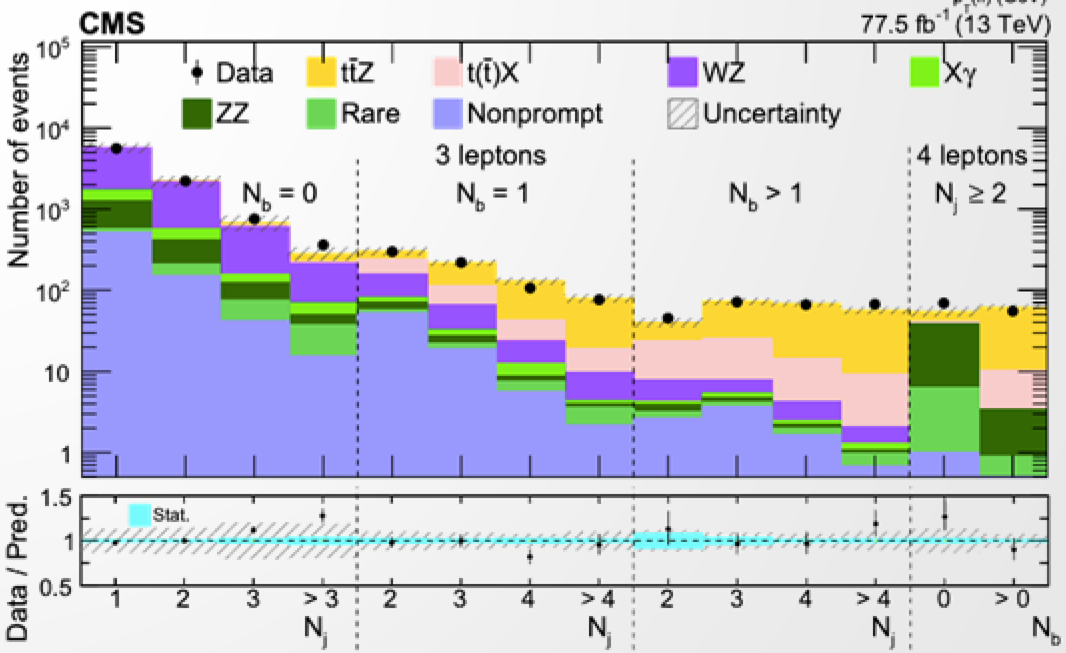
ATLAS EXPERIMENT $$\sigma(t\bar{t}Z) = 0.99 \pm 0.05\,(\text{stat.}) \pm 0.08\,(\text{syst.})\,\text{pb}$$

$$\sigma(\text{SM}) = 0.839 \pm 0.101\text{pb}$$

- SM NLO+EWK: 0.88 (ttγ interference, off-shell)
- Accurate SM predictions are a key ingredient!



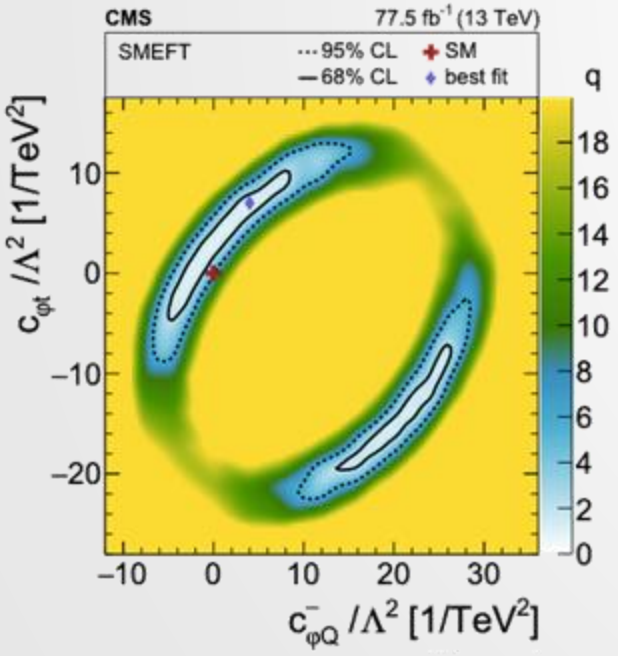


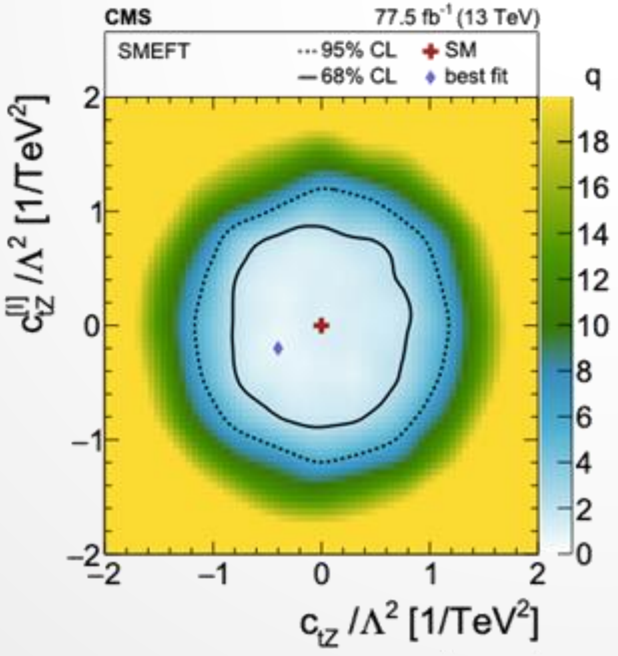


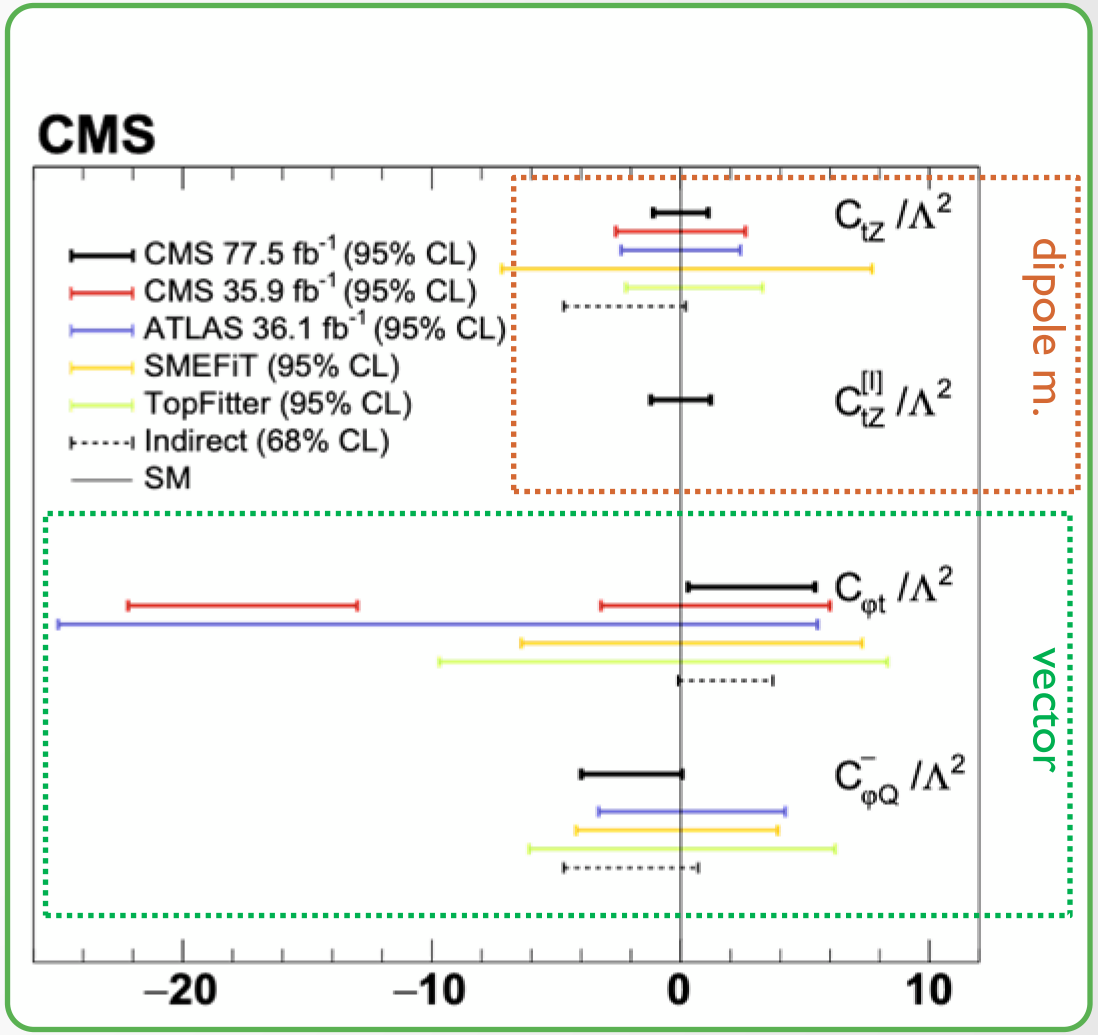
ELECTROWEAK TOP QUARK COUPLINGS

[JHEP 03 (2020) 056]

- ~~most~~ stringent direct constraints on the vector coupling and the dipole moments
  - differential measurement improves sensitivity by factor ~5
- vector-type couplings have large SM interference
- EFT tensor structure induces EWK dipole moments (quadratic)





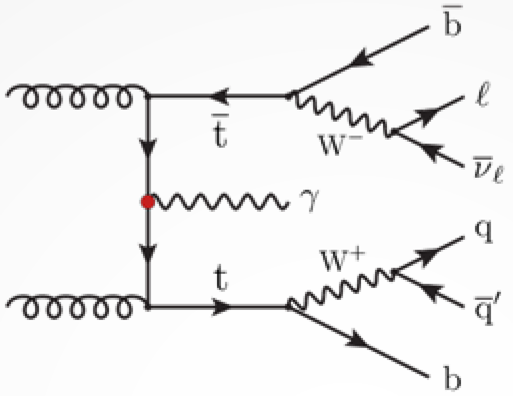


TT+ɣ DIFFERENTIAL CROSS SECTION

CMS-PAS-TOP-18-010

JHEP 09 (2020) 049

- SM gauge symmetry imposes linear relations among anomalous interactions
- Top dipole moments effect ttɣ stronger than ttZ

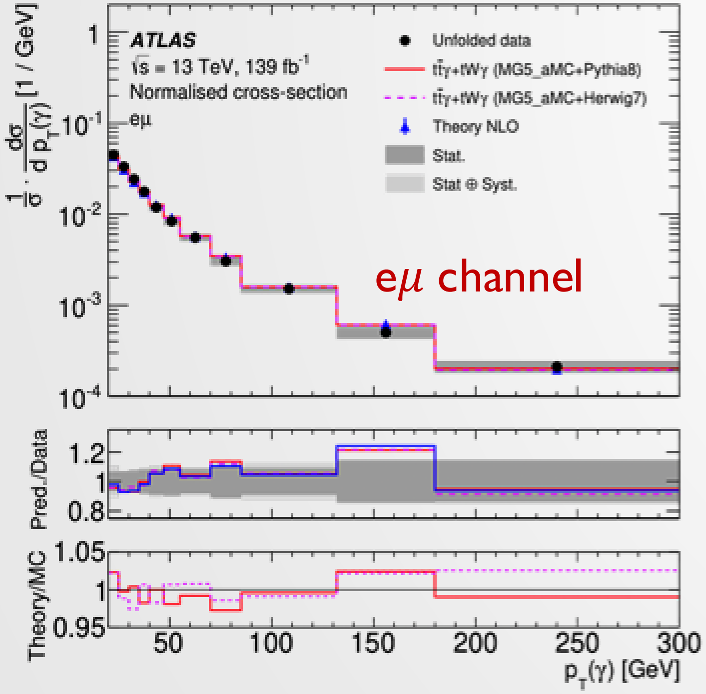


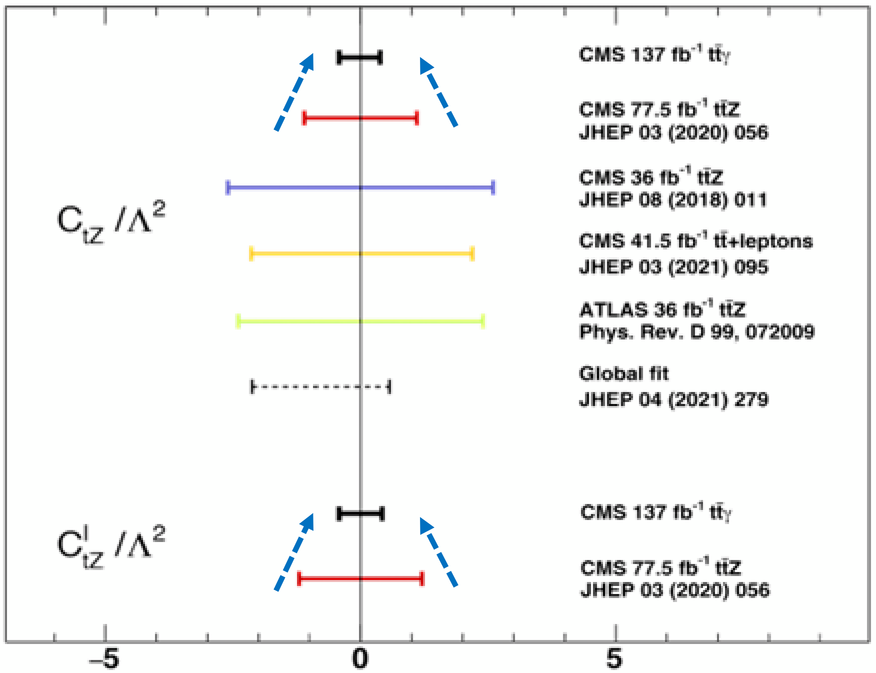
$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

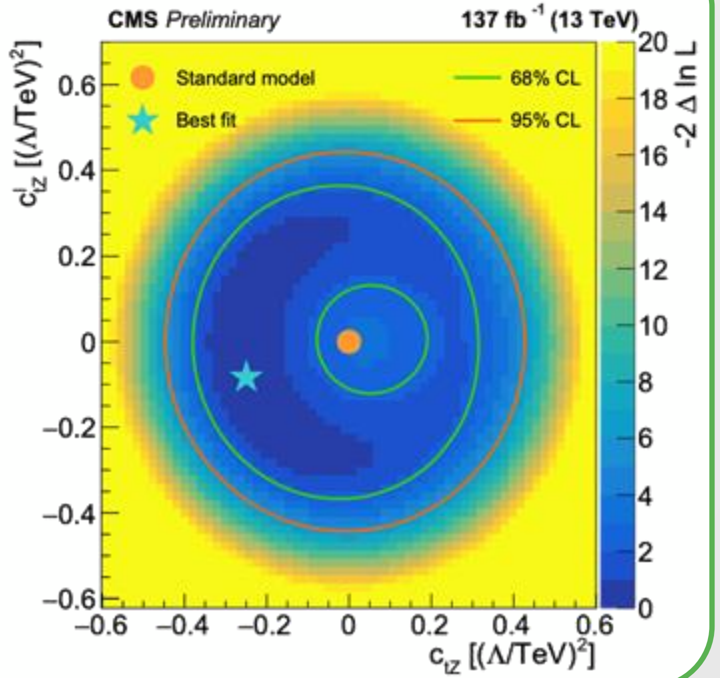
related by $SU(2)_L \otimes U(1)$

Constrained by W helicity fractions

$$c_{t\gamma} = \mathrm{Re}\left(\cos\theta_W C_{uB}^{(33)} + \sin\theta_W C_{uW}^{(33)}\right)$$



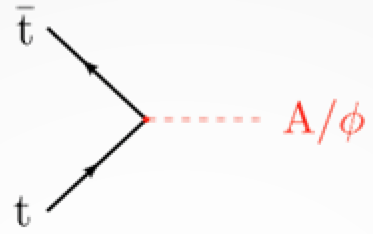




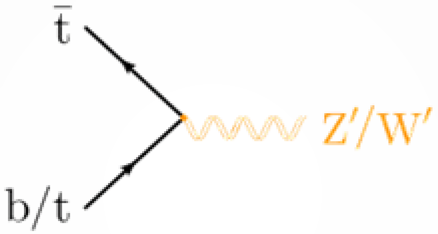
FORCES AMONG QUARKS

NEW FORCES INVOLVING TOP QUARKS?

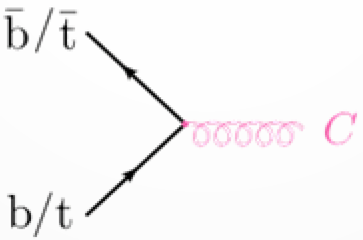
- Extended scalar sectors "two Higgs doublet models" from SUSY or other BSM physics [review]



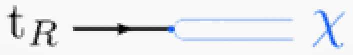
- High-mass force carriers similar to the W and Z bosons : Z' and W' bosons [review]



- Massive "chiral" colored force carriers, otherwise similar to the gluon: axigluons [Mimasu et.al.]



- Composite sector whose bound states mix with the SM particles: (right-handed) top-quark and/or Higgs compositness [review]



- Hypothetical UV models

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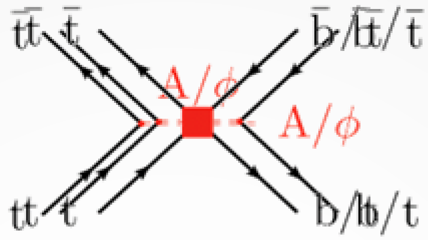

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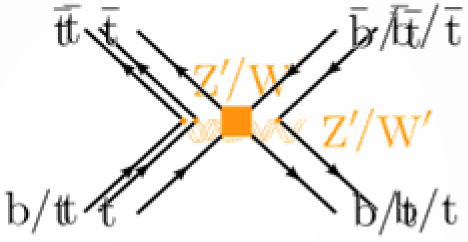

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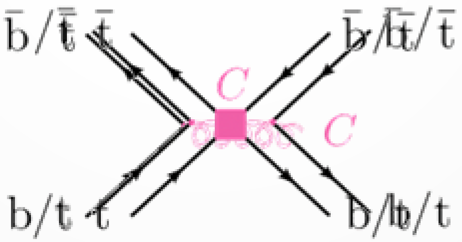

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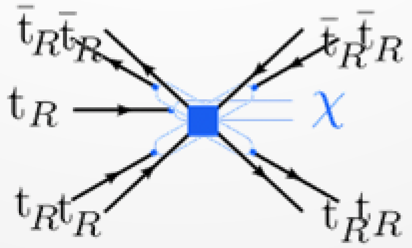
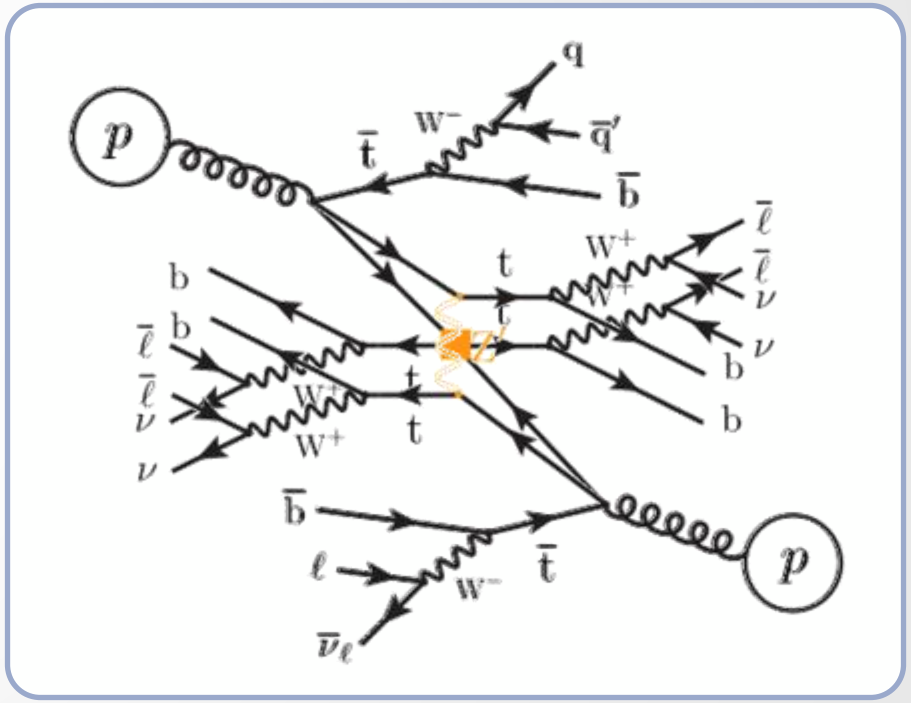


- Hypothetical UV models
  - predict force-carrier exchange
  - modify predictions for LHC processes
  - described by "effective theory"

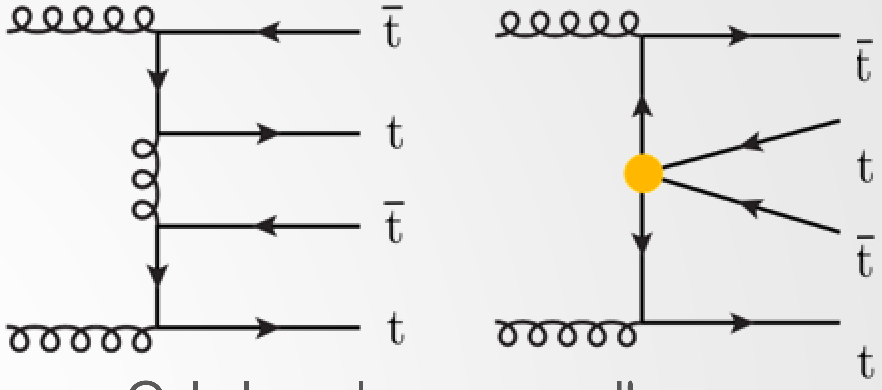


- Search for in LHC data!
- Combine t vs. t & t vs. b & t vs. light quarks

FOUR TOP QUARK PRODUCTION

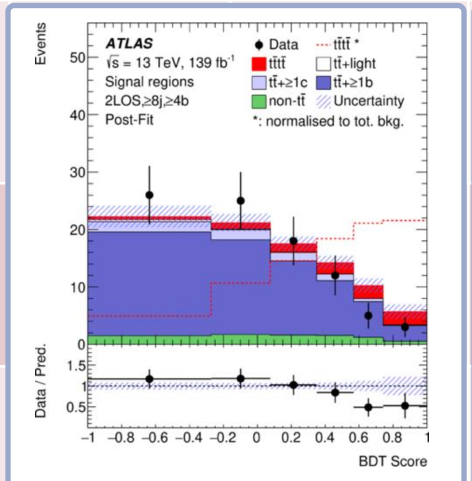
- ATLAS and CMS measure tttt in all decay channels – 0ℓ to 4ℓ
- Statistically limited: **σ**(SM) = 13.4 + 1 - 2.5 fb
  - most sensitive channel: 2ℓ with a same charge lepton pair
- Event-level BDTs, so far, are the workhorse classifiers.

  ATLAS with gNN $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}$

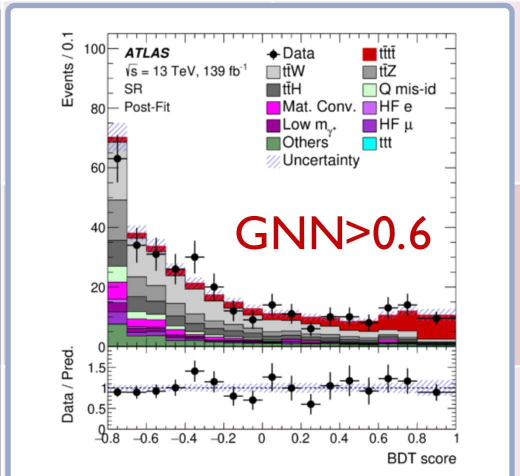


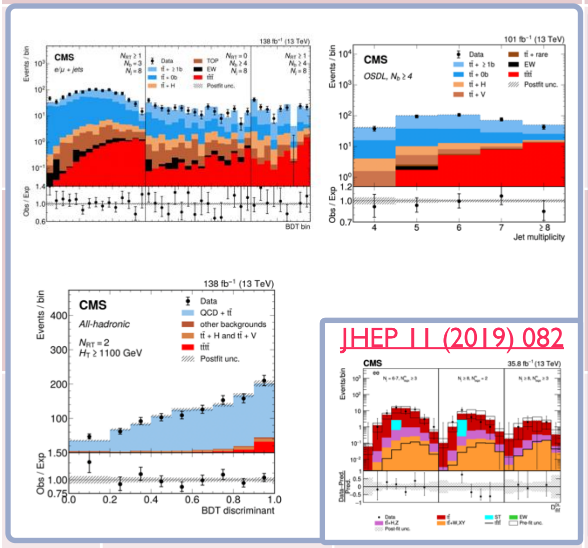
Only 1 number measured!

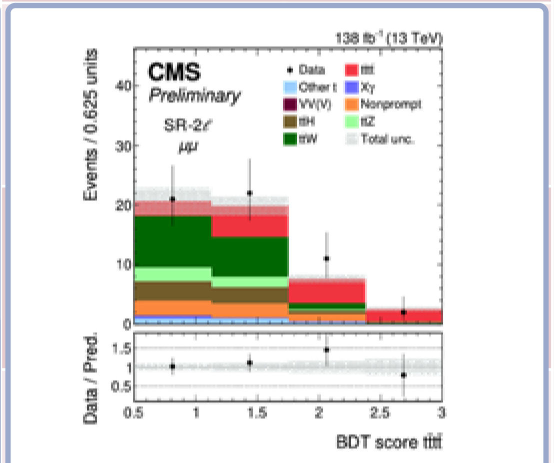
ATLAS EXPERIMENT	0ℓ	1ℓ	2ℓ(OS)	2ℓ(SS)	3ℓ+	CMS	0ℓ	1ℓ	2ℓ(OS)	2ℓ(SS)	3ℓ+
		JHEP 11 (2021) 118		EPJC 83 (2023) 496			TOP-21-005			TOP-22-006	
2018						2018					
2017						2017					
2016						2016					



μ(tttt) = 2.0 (+0.8-0.6), 4.7σ

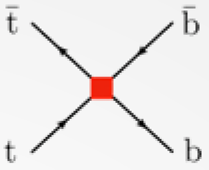






σ(tttt)=17.9 ±3.6 ± 2.5, >5σ

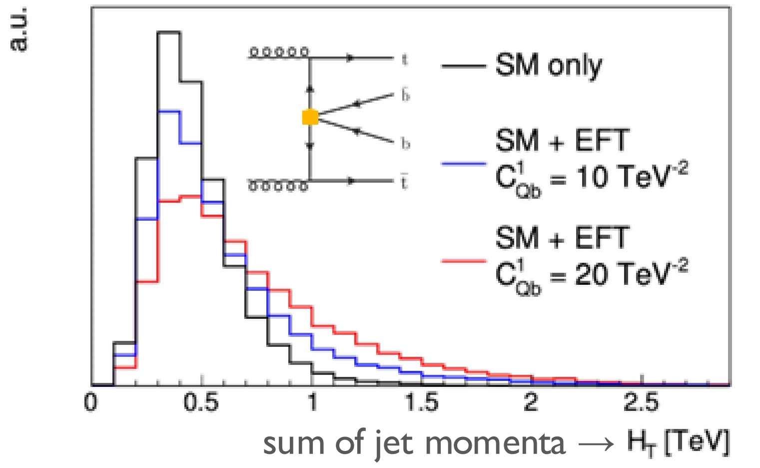
THE TT+BB PROCESS

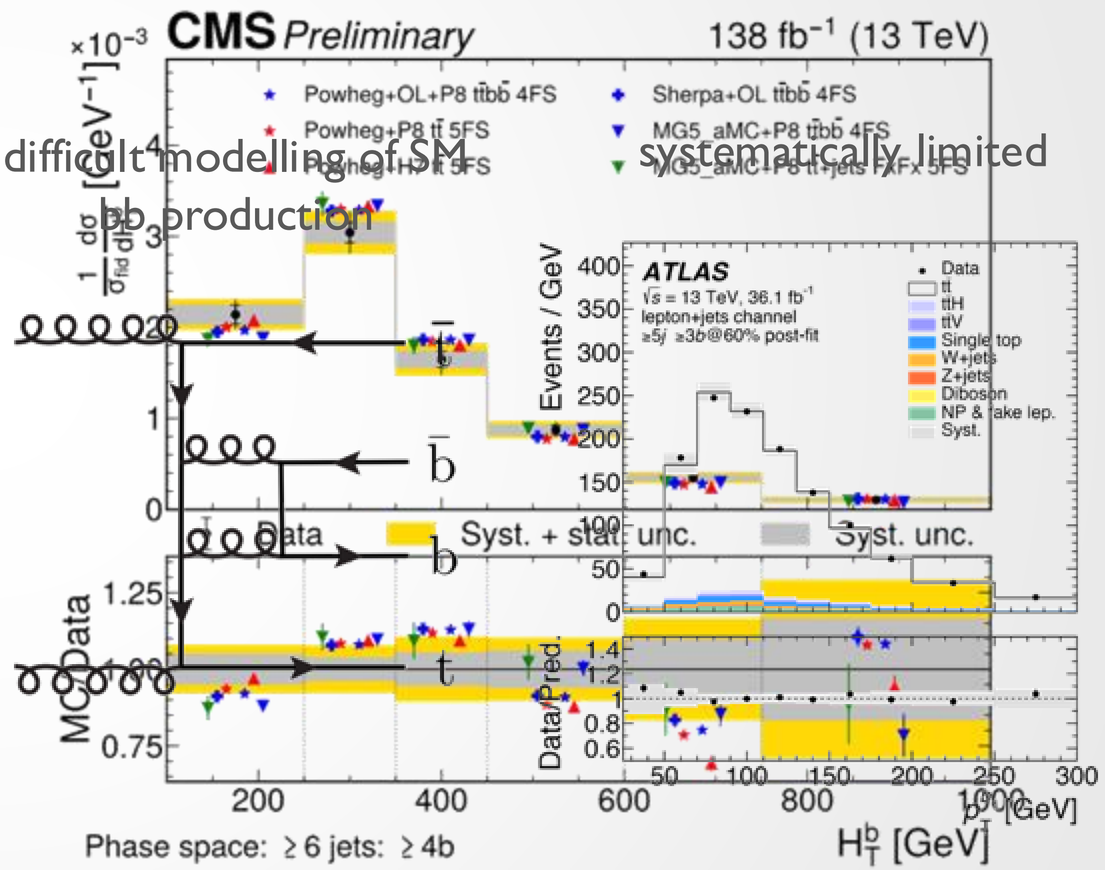


[JHEP 07 (2020) 125]
[PLB (2020) 135285]
[TOP-22-009]
[JHEP 04 (2019) 046]

- An example of how EFT shapes our interest:
  - Since Run 1, tt+bb studied mostly for *tuning*
  - Extra "bb" is a modeling challenge
- Significant EFT effects, constraining top-bottom interactions

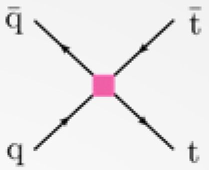
[Mimasu et.al. JHEP 11 (2018) 131]





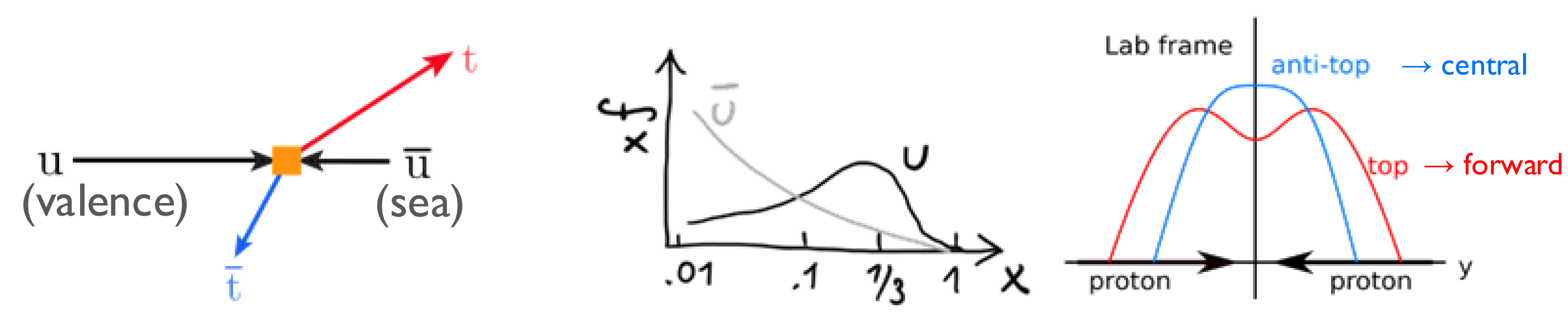
- Systematically limited

TOP QUARK CHARGE ASYMMETRY



[TOP-21-014] [arxiv:2208:12095]

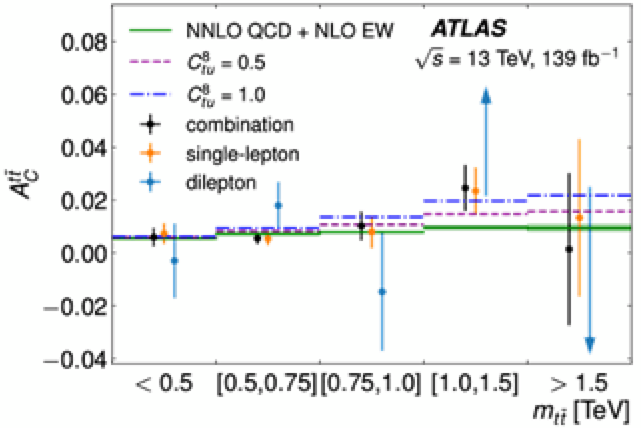
- Use subtle kinematic effects to target interactions with light quarks
- The "valence" light-quark carries, on average, a larger fraction of the protons momentum compared to anti-quarks

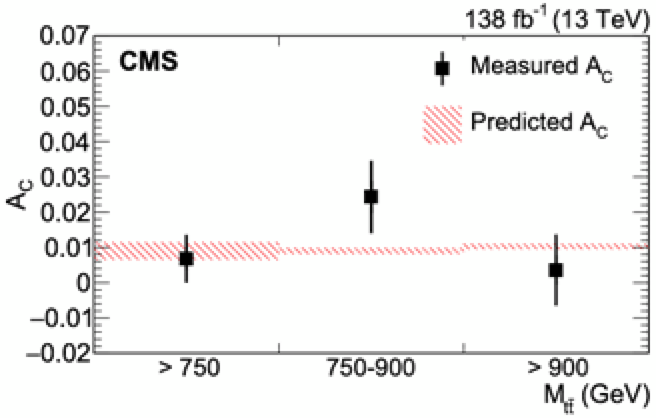


- The +t quark in pair production is more forward
- Charge asymmetry cancels overwhelming gluon-initiated background
  - Permille effect
- CMS (1ℓ) and ATLAS (1ℓ/ 2ℓ, resolved/boosted) have measured A_C(tt)
  - ATLAS A_C(tt) = 0.0068±0.0015 ↔ 4.7**σ** evidence

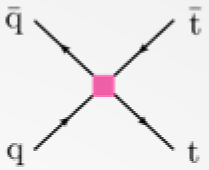
Exploit "forward-backward" symmetry:

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$





TOP QUARK CHARGE ASYMMETRY



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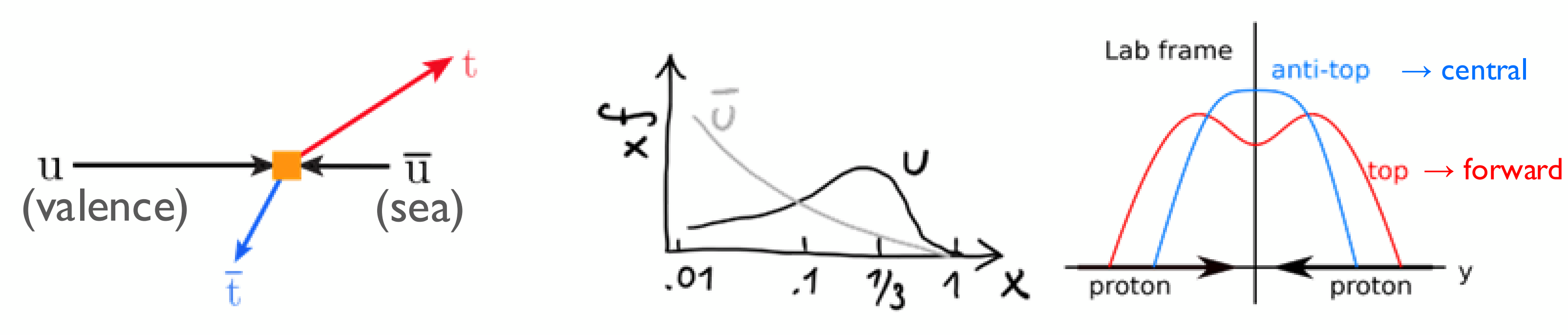

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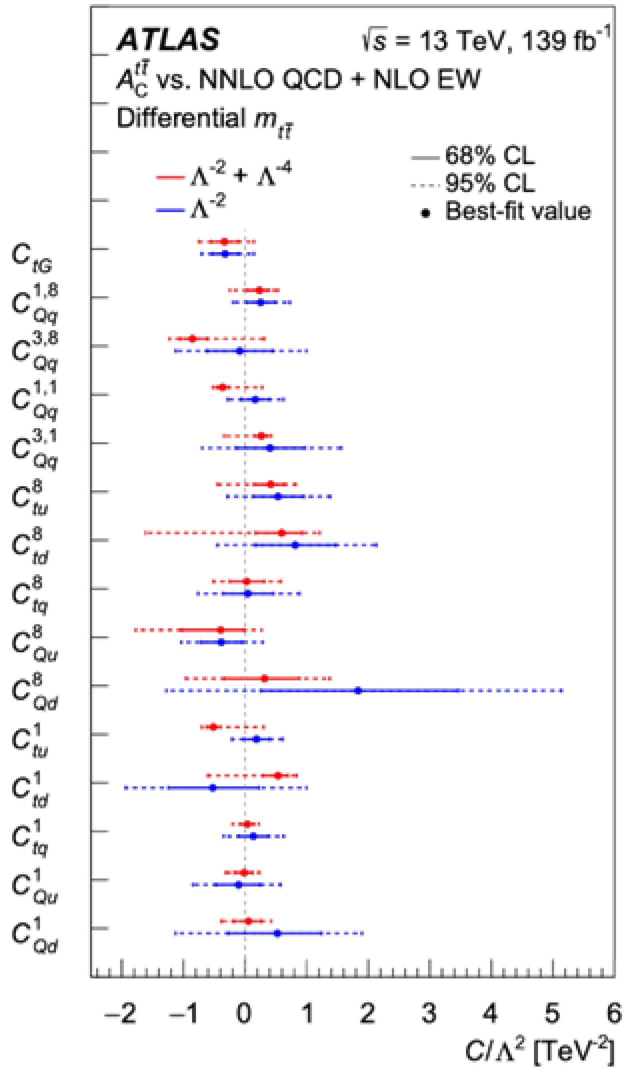
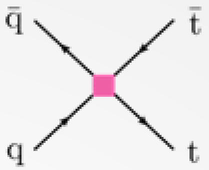
Comprehenseive EFT interpretation

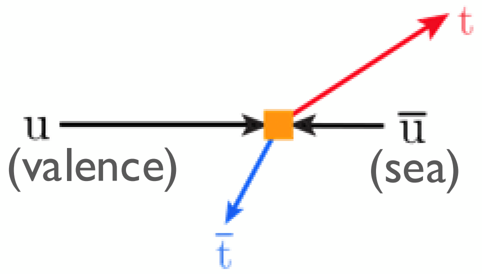


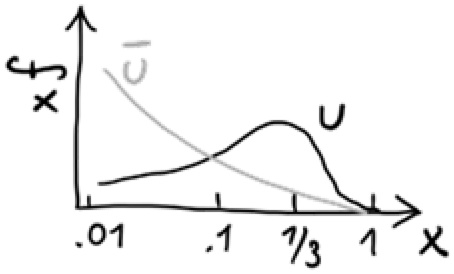
TOP QUARK CHARGE ASYMMETRY

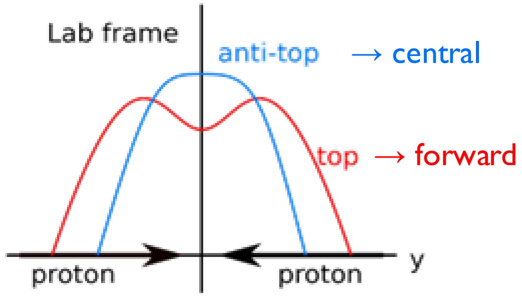


[TOP-21-014] [arxiv:2208:12095]

- Use subtle kinematic effects to target interactions with light quarks
- The "valence" light-quark carries, on average, a larger fraction of the protons momentum compared to anti-quarks



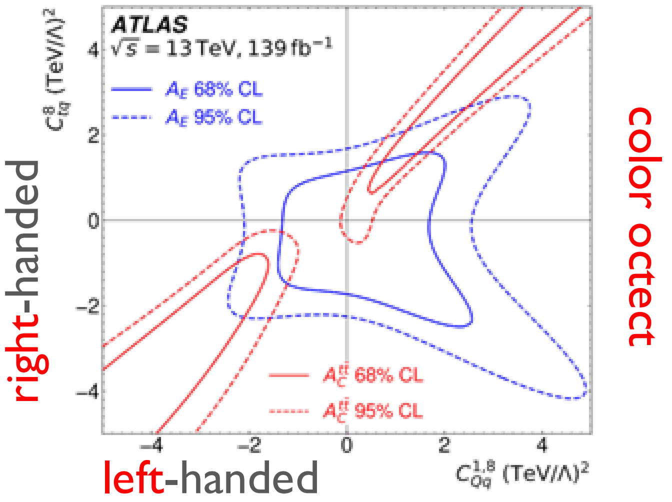




- The +t quark in pair production is more forward
- Charge asymmetry cancels overwhelming gluon-initiated background
  - Permille effect
- CMS (1ℓ) and ATLAS (1ℓ/ 2ℓ, resolved/boosted) have measured A_C(tt)
  - ATLAS A_C(tt) = 0.0068±0.0015 ↔ 4.7σ evidence

"Left-handed" vs. "Right-handed"
→ flat direction

→ resolved with Energy asymmetry



→ need to combine many measurements for unambigous results

GLOBAL RESULTS

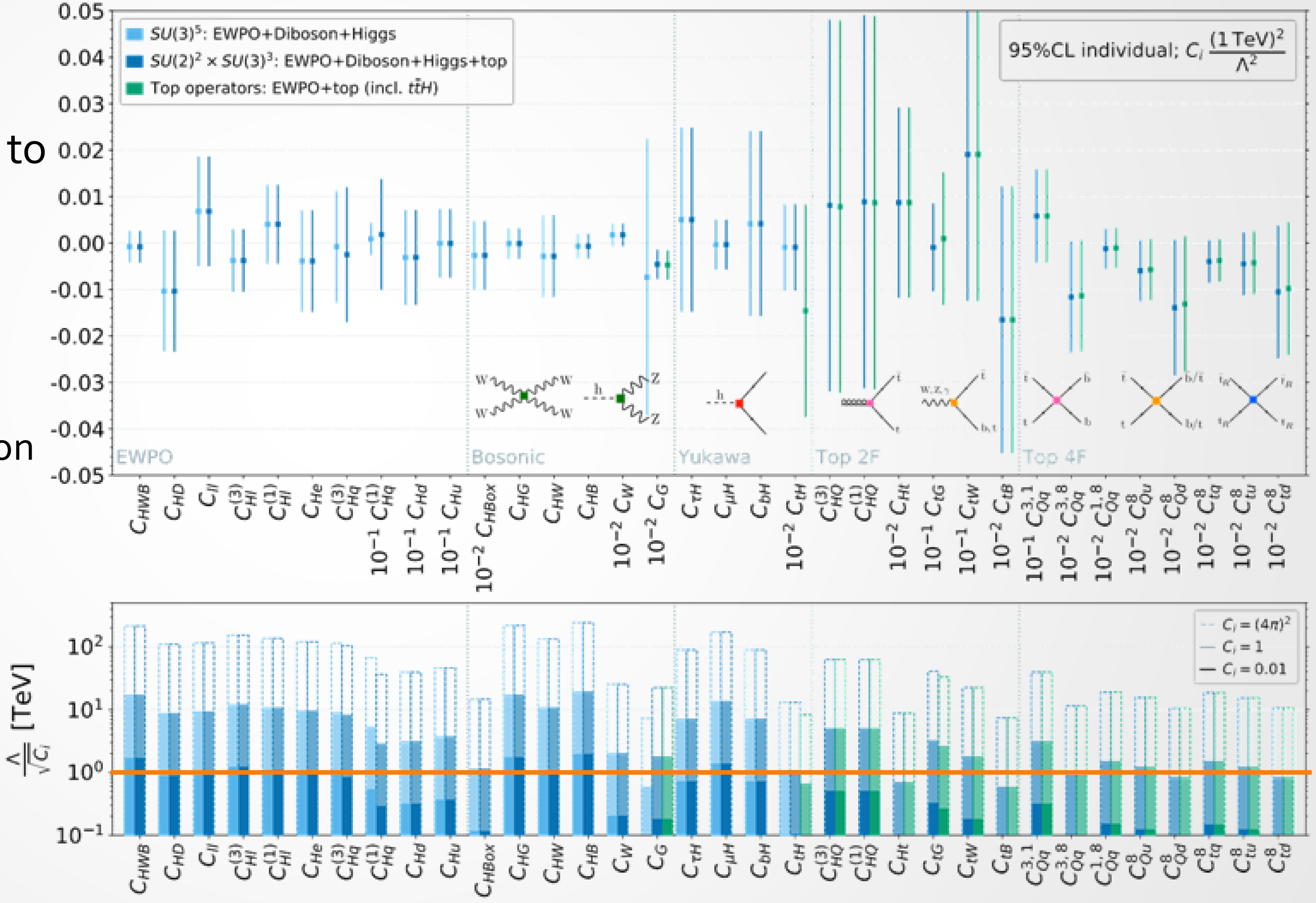
[Ellis, Sanz, et.al. FitMaker JHEP04(2021)279]

[Rojo, Maltoni et.al. SMEFiT JHEP11(2021)089]

GLOBAL FITS

- First global interpratations combining experimental results
- Individual operators constrained to ~ 1TeV regime: 10^{-18} m
- Caveats
  - background-subtracted inputs
  - simplified uncertainty correlation
- All-operator (marginalized) fits significantly less constraining
  - adding more processes → resolve ambiguities
- Experiments move towards more global fits

Fit one operator at a time



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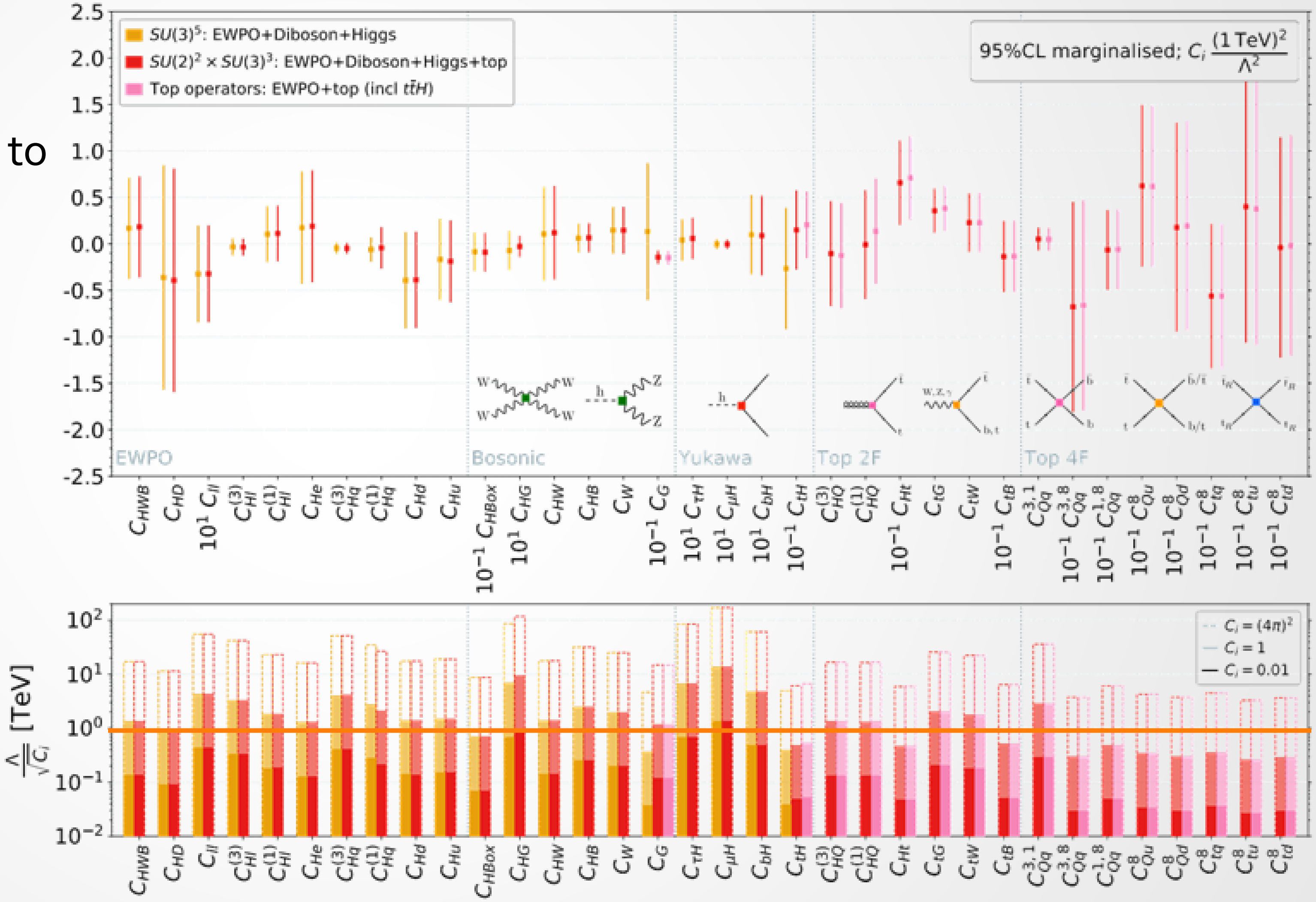
    - adding more processes → resolve ambiguities
- Caveats
    - Background-subtracted inputs
    - Simplified correlations
- Experiments move towards more global fits

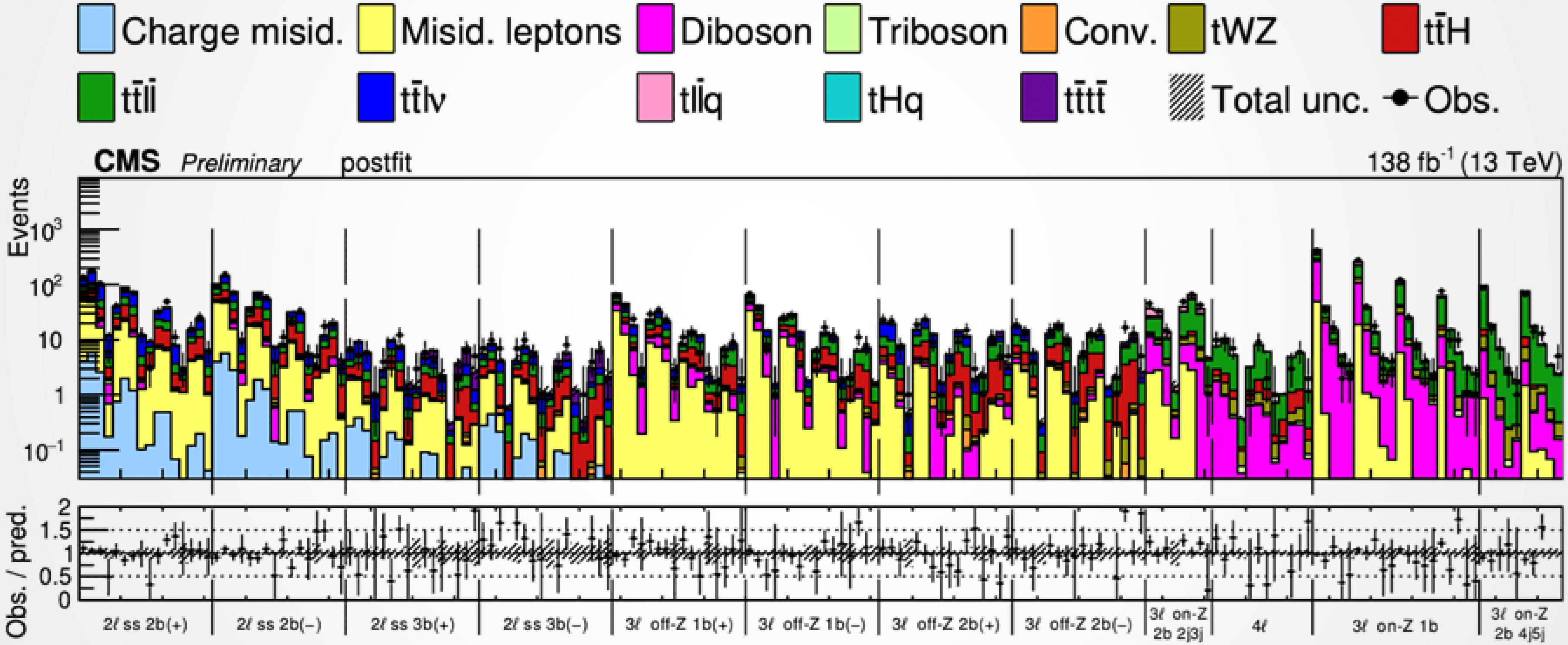
Fit of all operators



TOP QUARKS WITH ADDITIONAL LEPTONS

[TOP-22-006]

- CMS “top quark pair + Z/W/H” analysis [TOP-22-006]
  - 2ℓSS/3ℓ/4ℓ categories with different b-tag multiplicities and with/without on Z requirement



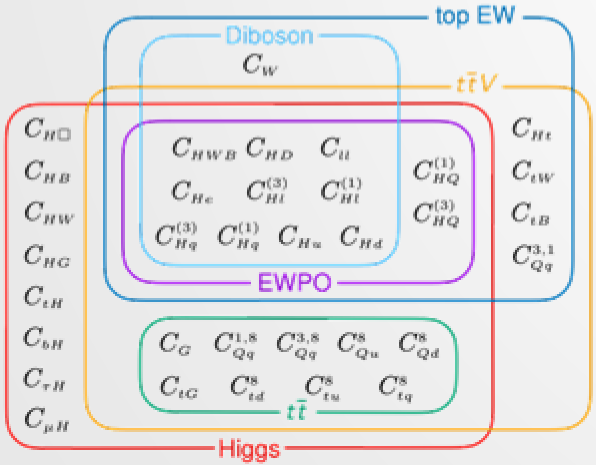
  - 178 measurements with full uncertainty correlation, constraining 22 operators
  - Some optimization to select an ‘optimal’ 1D observable that captures EFT energy dependence: $p_T(\ell jo)$
  - Most recent CMS step towards global in-experiment fit

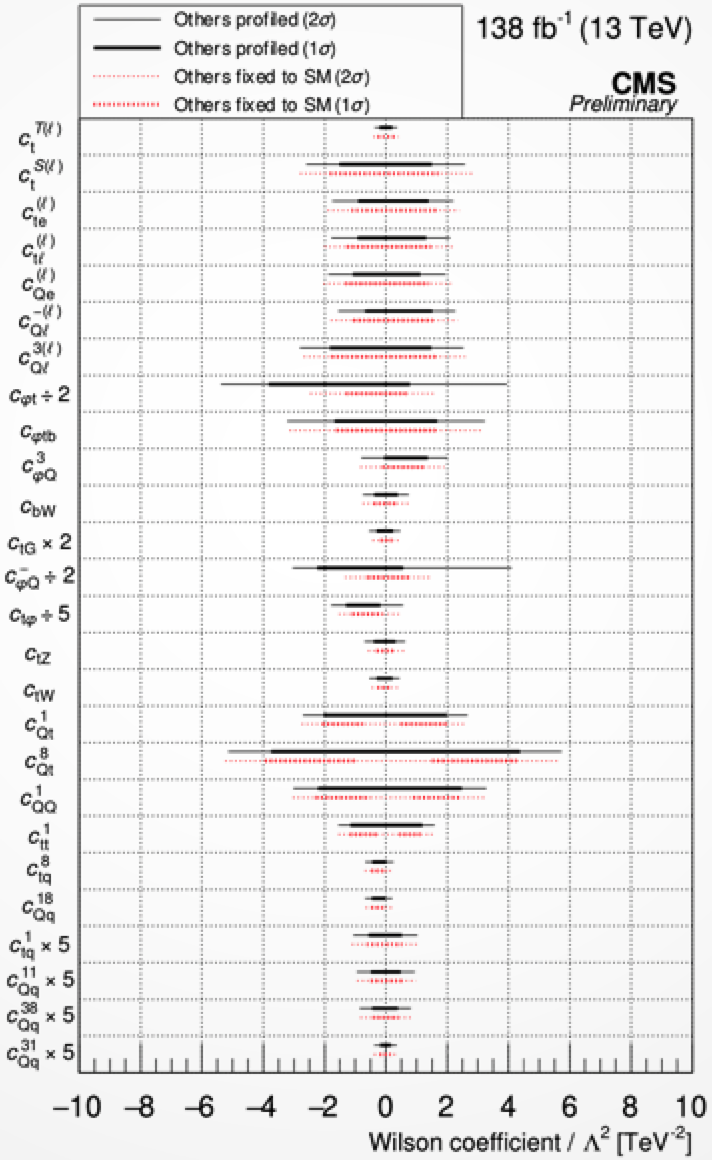
GLOBAL FITS (WITHIN EXPERIMENTS)

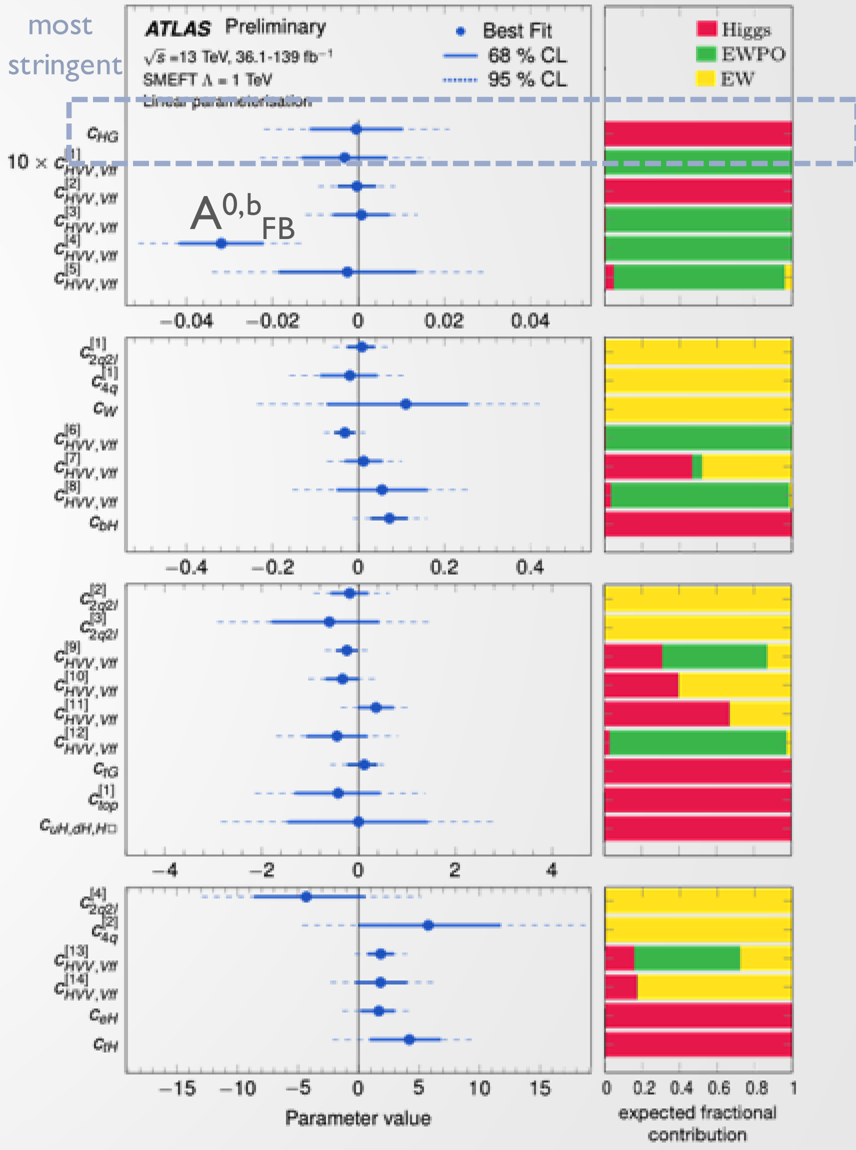
[ATLAS-PHYS-PUB-2022-037]

[TOP-22-006]

- CMS "top quark pair + Z/W/H"
  - full 22D uncertainty correlation
  - most recent step towards global in-experiment fit
  - 22 operators, 178 measurements
- ATLAS: Higgs+EWK+EWPO
  - LEP & SLC EW precision data
  - 6 coeff. + 22 lin. comb
  - mostly conistent with SM







SUMMARY!

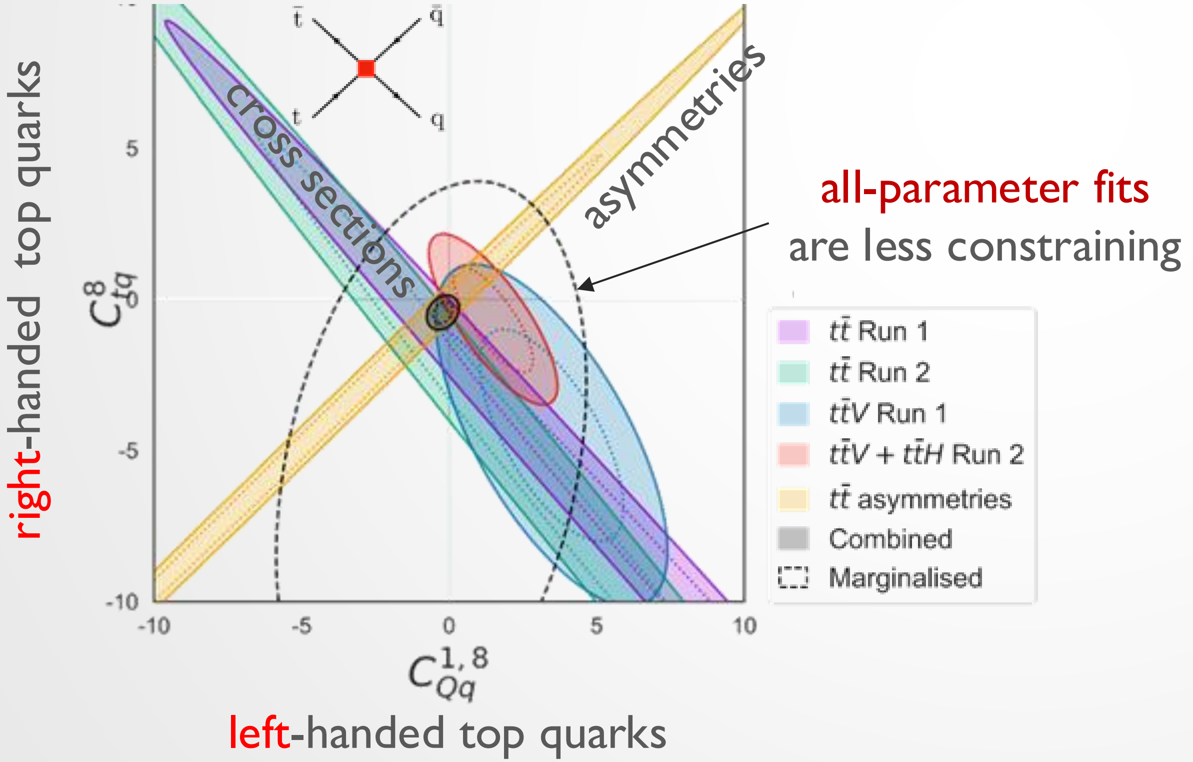
- Top quark properties precisely constrain many anomalous interactions
  - Need coherent theoretical approach (SMEFT) and many complementary processes
  - Must combine with other sectors
  - This way, we can answer the big questions!
- All couplings and properties in agreement with predictions (within uncertainties)
- Top quark physics still developing after 30 years!
  - New, rarer process, still become available: need to scrutinise as well
  - There is no single best M_t measurement, despite the relevancy for the universe's fate
- Looking forward to Run 3 & HL-LHC

MACHINE-LEARNING OPTIMAL TOP-QUARK OBSERVABLES

LOOKING INTO MANY DIRECTIONS AT ONCE

[Ellis, Sanz, et.al. FitMaker JHEP04(2021)279]

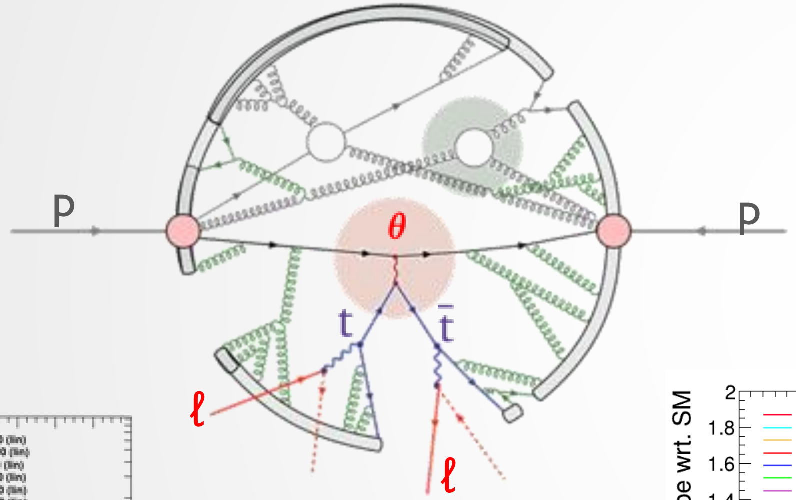
- Our earlier example: forces of left- and right-handed top quarks – start with two operators
- Many individual masurements, often with a “flat directions”
  - In combination, very tight constraint in 2D operator fit
- However(!) including all EFT operators leads to much less powerful
  - Physics question: Can we use the kinematic information in the events to resolve the ambiguities?

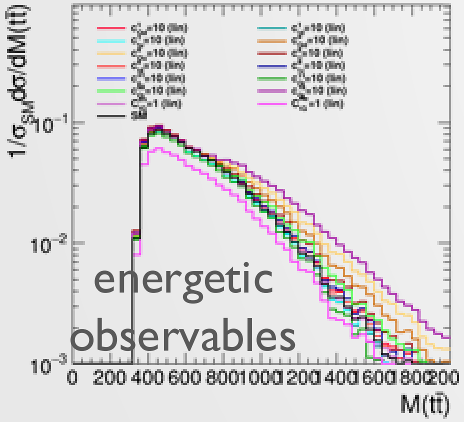


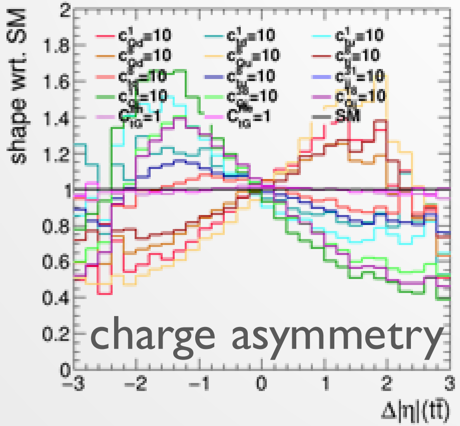
- Can we parametrize an EFT classifier?
- Can machine-learning help to improve the analysis strategy?
- How to achieve optimality?

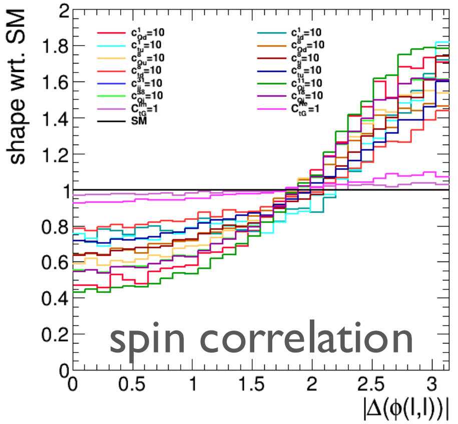
TOP QUARK PAIRS IN THE 2ℓ CHANNEL

- Top quark pair production with 2ℓ:
  - Clean probes of new physics in a messy environment



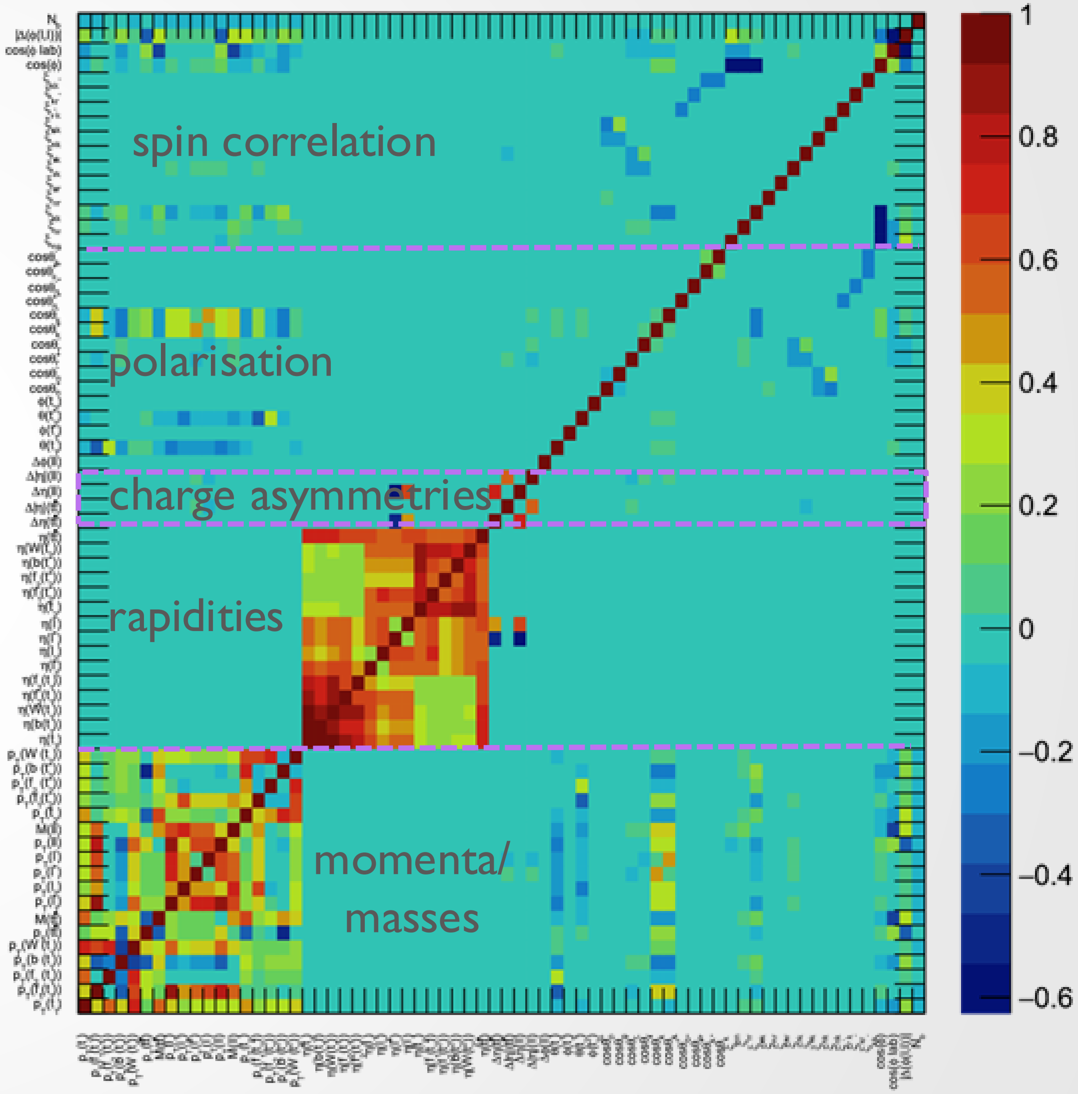






$\gtrsim$ 72 features

$\gtrsim$ 15 SMEFT POIs

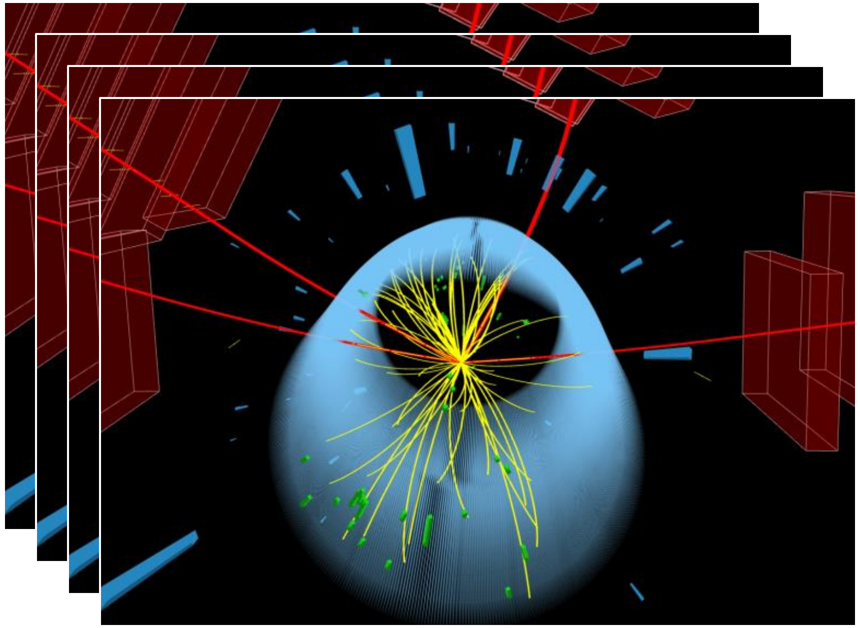


linear feature correlation in tt(2ℓ)

Typically use only 1 or 2 features!

NEYMAN-PEARSON & LIKELHOOD RATIO “TRICK”

arxiv:1503.0x7622



Neyman-Pearson Lemma: The *likelihood* ***ratio*** *test statistic is optimal*

data-set with feature vectors **x**

diff xsec ratio

$$q_{\boldsymbol{\theta}}(\mathcal{D}) \sim -\sum_{\boldsymbol{x}_i \in \mathcal{D}} \log \frac{\sigma(\boldsymbol{\theta})}{\sigma(\mathrm{SM})} \frac{p(\boldsymbol{x}_i|\boldsymbol{\theta})}{p(\boldsymbol{x}_i|\mathrm{SM})}$$

theory parameters

NEYMAN-PEARSON & LIKELHOOD RATIO "TRICK"

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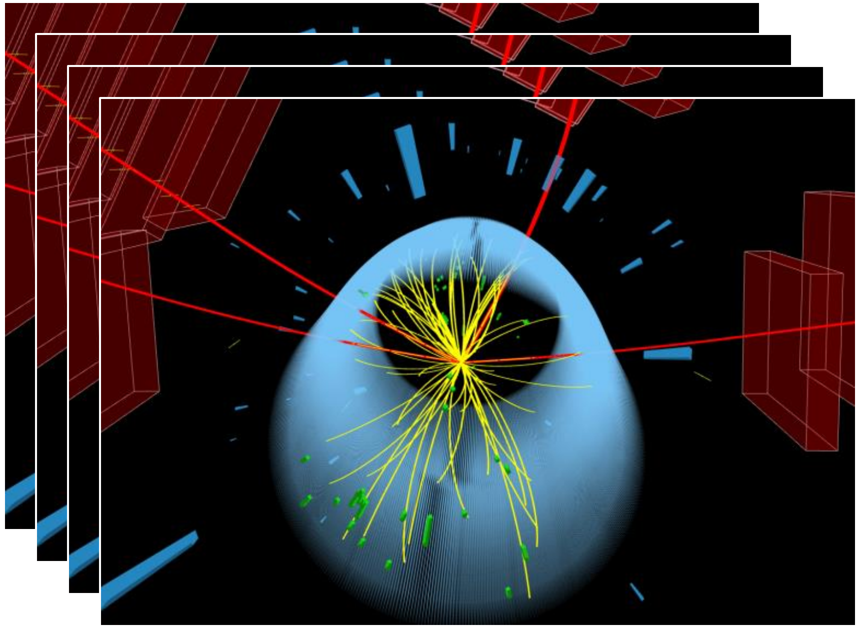

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theory parameters

Likelihood ratio "trick": label two values: **θ**, SM

$$L = \int \mathrm{d}\boldsymbol{x} \sum_{z \in \{0,1\}} p(\boldsymbol{x}, z) \left(z - \hat{f}(\boldsymbol{x})\right)^2$$

training samples

truth (supervised)

classifier

$$f^*(\boldsymbol{x}) = \frac{p(\boldsymbol{x}, \mathrm{SM})}{p(\boldsymbol{x}, \mathrm{SM}) + p(\boldsymbol{x}, \boldsymbol{\theta})} = \frac{1}{1 + \frac{\sigma(\boldsymbol{\theta})}{\sigma(\mathrm{SM})} r(\boldsymbol{x})}$$

supervised learning provides (close-to) optimal test statistiscs

What to do with the parameter dependence?

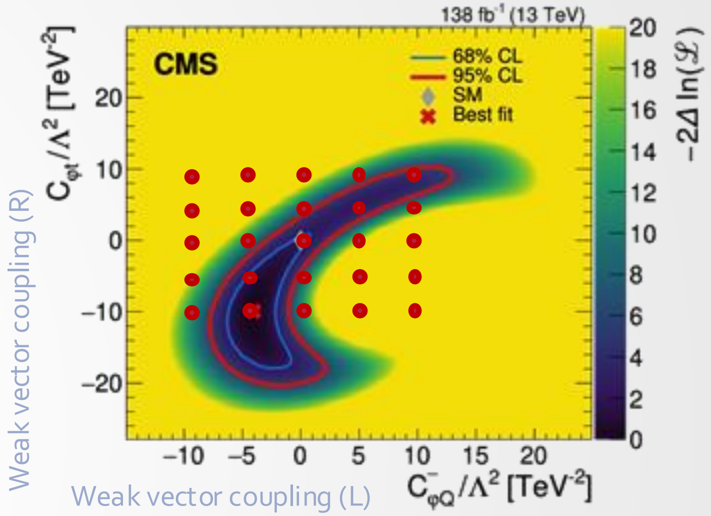
SENDING MIXED SIGNALS TO THE LOSS FUNCTION

$$L = \sum_{\theta \in \mathcal{B}} \int \mathrm{d}\boldsymbol{x} \left(p(\boldsymbol{x}|\boldsymbol{\theta}) \hat{f}(\boldsymbol{x})^2 + p(\boldsymbol{x}|\mathrm{SM})(1 - \hat{f}(\boldsymbol{x}))^2 \right)$$

$\boldsymbol{\theta}$ - ignorant

mixing signals &
case dependent mixes

$$f^*(\boldsymbol{x}) = \frac{1}{1 + r_{\mathcal{B}}(\boldsymbol{x})} \qquad r_{\mathcal{B}}(\boldsymbol{x}) = \frac{\frac{1}{|\mathcal{B}|} \sum_{\theta \in \mathcal{B}} p(\boldsymbol{x}|\boldsymbol{\theta})}{p(\boldsymbol{x}|\mathrm{SM})}$$



- Sending 'mixed signals' to the loss function
  - Averages the training data set
  - linear effects cancel in the training
  - Classifier does not reflect knowledge on the $\boldsymbol{\theta}$-dependence
- Definition: *SMEFT-specific ML exploits the quadratic structure of the SMEFT predictions*

PARAMETRIZED CLASSIFIERS: NETS & TREES

Wulzer et.al. [JHEP 05 (2021) 247]

RS et. al., [2107.10859], [2205.12976]

$$L=\sum_{\theta\in\mathcal{B}}\int \mathrm{d}\boldsymbol{x}\,\left(p(\boldsymbol{x},\boldsymbol{z}|\boldsymbol{\theta})\hat{f}(\boldsymbol{x};\boldsymbol{\theta})^2+p(\boldsymbol{x},\boldsymbol{z}|\mathrm{SM})(1-\hat{f}(\boldsymbol{x};\boldsymbol{\theta}))^2\right)$$

Make loss function aware of analytic SMEFT structure

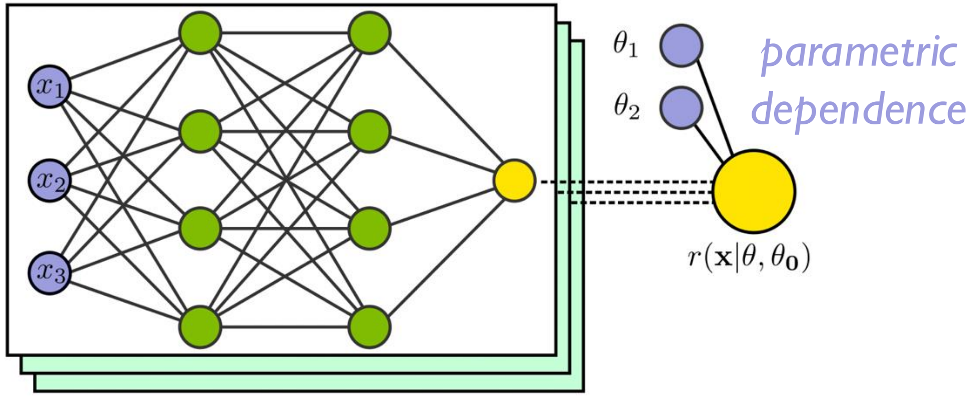
Invert likelihood trick
with positive polynomial of NN -outputs

$$\hat{f}(\boldsymbol{x};\boldsymbol{\theta})=\frac{1}{1+\hat{r}(\boldsymbol{x};\boldsymbol{\theta})}$$

$$\hat{r}(\boldsymbol{x};\boldsymbol{\theta})=\left(1+\sum_a\theta_a\hat{n}_a(\boldsymbol{x})\right)^2+\sum_a\left(\sum_{b\geq a}\theta_b\hat{n}_{ab}(\boldsymbol{x})\right)^2$$

Fit NNs simultaneously

inject new technology here ↴



$$L=\sum_{\theta\in\mathcal{B}}\int \mathrm{d}\boldsymbol{x}\,\mathrm{d}\boldsymbol{z}\,p(\boldsymbol{x},\boldsymbol{z}|\mathrm{SM})\left(r(\boldsymbol{x},\boldsymbol{z}|\boldsymbol{\theta},\mathrm{SM})-\hat{F}(\boldsymbol{x},\boldsymbol{\theta})\right)^2$$

Tree ansatz with polynomial SMEFT dependence

$$\hat{F}(\boldsymbol{x},\boldsymbol{\theta})=\sum_{j\in\mathcal{J}}\mathbb{1}_j(\boldsymbol{x})F_j(\boldsymbol{\theta})$$

Can solve for trainable parameters of the predictor
→ *Large training speedup*

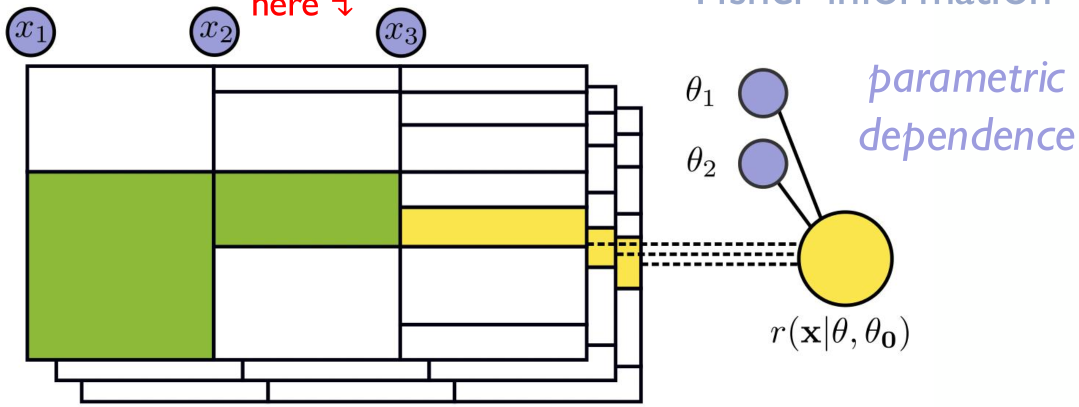
$$F_j(\boldsymbol{\theta})=\frac{\sum_{i\in j}w_i(\boldsymbol{\theta})}{\sum_{i\in j}w_i(\boldsymbol{\theta}_0)}\equiv\frac{w_j(\boldsymbol{\theta})}{w_j(\boldsymbol{\theta}_0)}$$

Obtain loss function for optimal partitioning, solved by e.g. CART algorithm → Boost

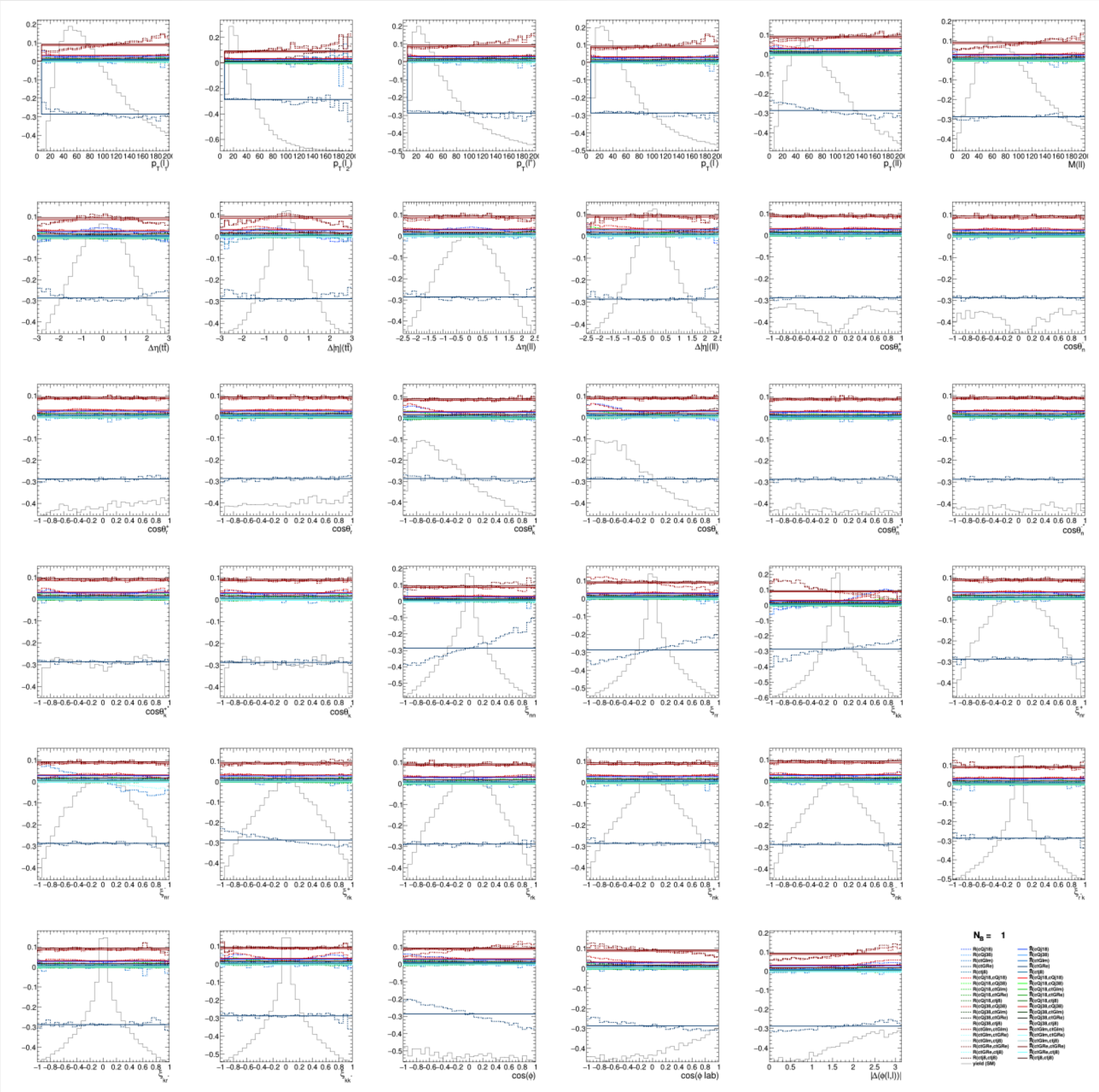
$$L=-\sum_{\theta\in\mathcal{B}}\sum_{j\in\mathcal{J}}\frac{w_j^2(\boldsymbol{\theta})}{w_j(\boldsymbol{\theta}_0)}$$

linear truncation: optimize Fisher information

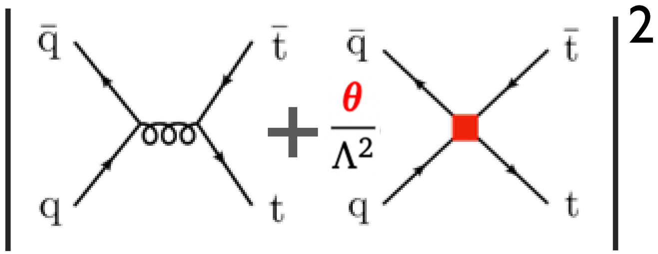
inject new technology here ↴



LEARNING SMEFT IN TTBAR



- 35 features top quark pairs (2ℓ)
- "Boosted Information Tree (BIT)"
  - NN are equivalent
  - 5 POIs, 20 functions simultaneously learned
  - 300 trees, D=5, ~9 hrs of training
  - also more realistic study, including backgrounds [2107.10859], [2205.12976]
- Learning coefficient functions to compute parametrized optimal oberables



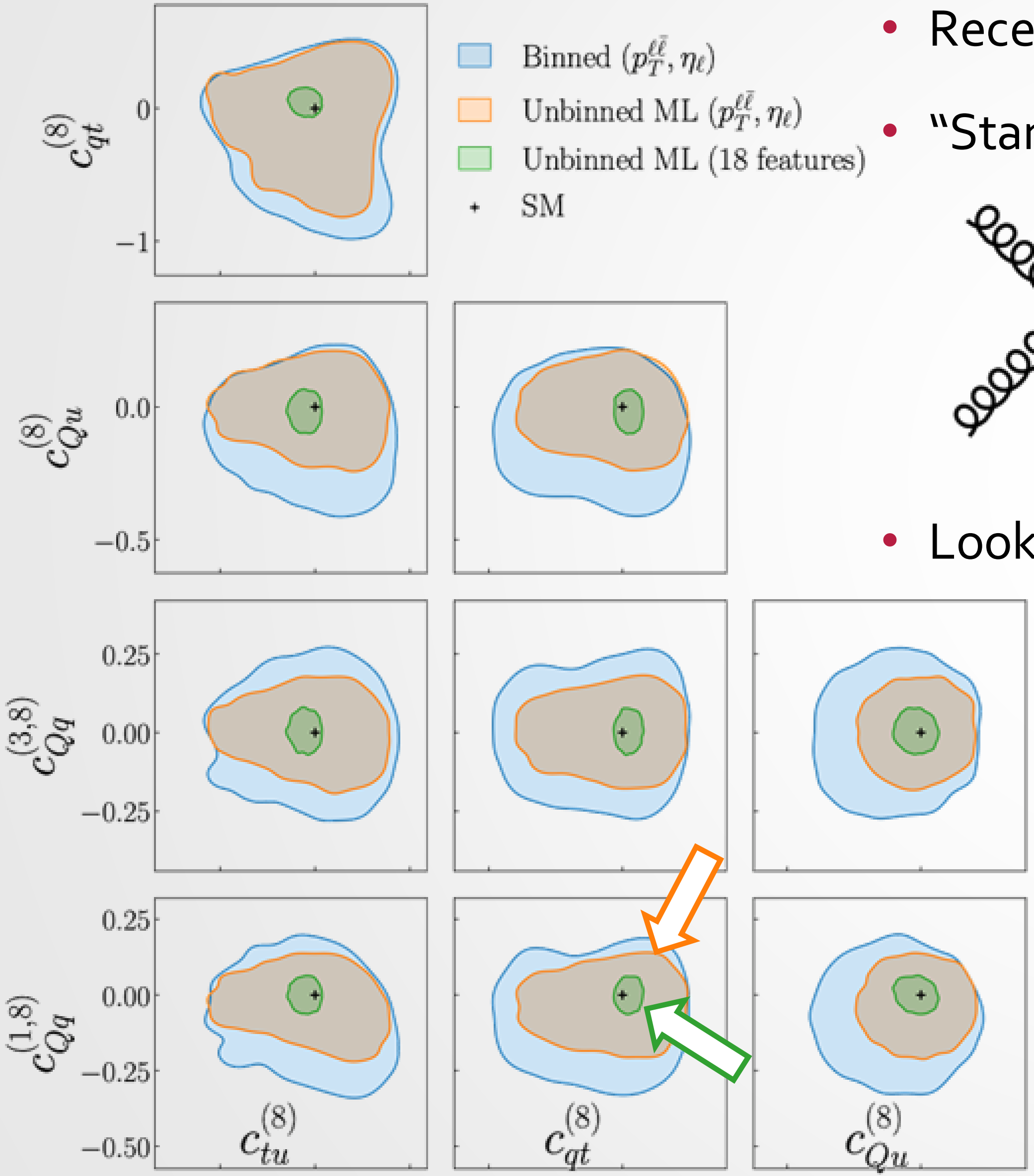
$$=$$

$$\mathrm{d}\sigma(\boldsymbol{x}) + \frac{\boldsymbol{\theta}}{\Lambda^2}\mathrm{d}\sigma_{\mathrm{int}}(\boldsymbol{x}) + \frac{\boldsymbol{\theta}^2}{\Lambda^4}\mathrm{d}\sigma_{\mathrm{quad}}(\boldsymbol{x}) =: R(\boldsymbol{x}|\boldsymbol{\theta})\mathrm{d}\sigma(\boldsymbol{x})$$

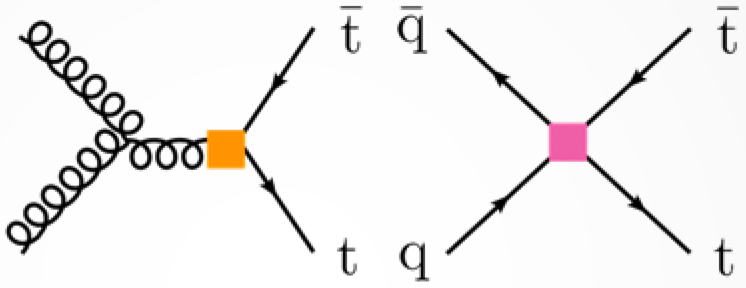
$\rightarrow$ parametrized $q(\boldsymbol{\theta}|\mathcal{D})$

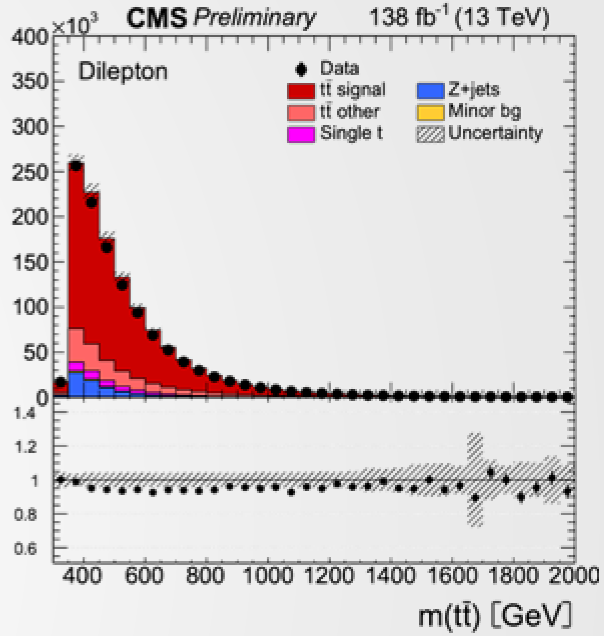
IMPROVING HIGH DIMENSIONAL LIMITS

[CMS-TOP-PAS-20-006]



- Recent [ML4EFT] on,e.g., top quark pairs
- "Standard model candle" – 95% purity





- Look at 2D limits while 6 more floating
- Physics case: forces among top quarks & light quarks
- 2 features; binned vs. unbinned tests: Some gain w/ unbinned
- What about using the full event information? (*18 features*)
  - Large improvement
  - High dimensional observation (N_{feat}=18) in a 'standard model candel' can constraining a high-dimensional (N_{coef}=8) model

THE END!

ANATOMY OF TOP QUARK BSM IN SM-EFT

Modification of SM vector interactions

$$\mathcal{O}^{(3)}_{\phi q_L} \quad i\left(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi\right)\left(\bar{q}_L \gamma^\mu \tau^I q_L\right)$$

$$\mathcal{O}^{(1)}_{\phi q_L} \quad i\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\bar{q}_L \gamma^\mu q_L\right)$$

$$\mathcal{O}_{\phi \mathrm{t}} \quad i\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\bar{t}_R \gamma^\mu t_R\right)$$

Tensor (dipole) interactions are 3-loop suppressed in SM down to ~10^{-3}

$$\mathcal{O}_{\mathrm{tW}} \quad i\left(\bar{q}_L \sigma^{\mu\nu} \tau_I t_R\right) \tilde{\phi} W^I_{\mu\nu} + \mathrm{h.c.}$$

$$\mathcal{O}_{\mathrm{tB}} \quad i\left(\bar{q}_L \sigma^{\mu\nu} t_R\right) \tilde{\phi} B_{\mu\nu} + \mathrm{h.c.}$$

$$\mathcal{O}_{\mathrm{tG}} \quad i\left(\bar{q}_L \sigma^{\mu\nu} \lambda^a t_R\right) \tilde{\phi} G^a_{\mu\nu} + \mathrm{h.c.}$$

weak coupling to right handed fermions

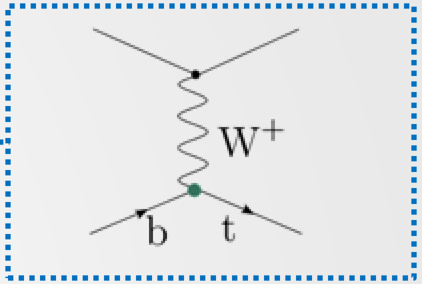
$$\mathcal{O}_{\phi \mathrm{tb}} \quad i\left(\tilde{\phi} D_\mu \phi\right)\left(\bar{t}_R \gamma^\mu b_R\right) + \mathrm{h.c.}$$

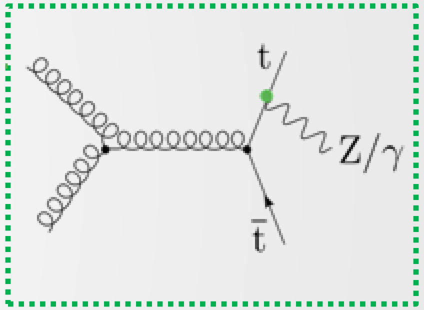
modification of top-quark Yukawa term (Higgs without Higgs)

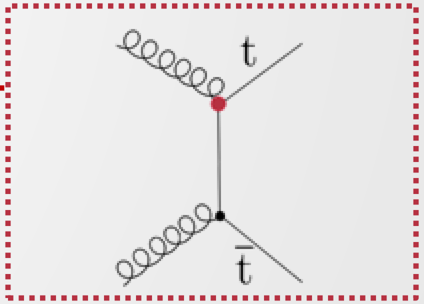
$$\mathcal{O}_{\mathrm{t}\phi} \quad \left(\phi^\dagger \phi\right) \bar{q}_L t_R \tilde{\phi} + \mathrm{h.c.}$$

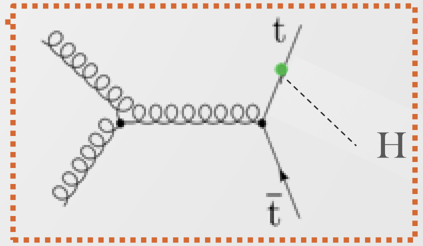
'oblique' Higgs operator modifying h propagator

$$\mathcal{O}_{\Box} \quad |\Box H|^2$$





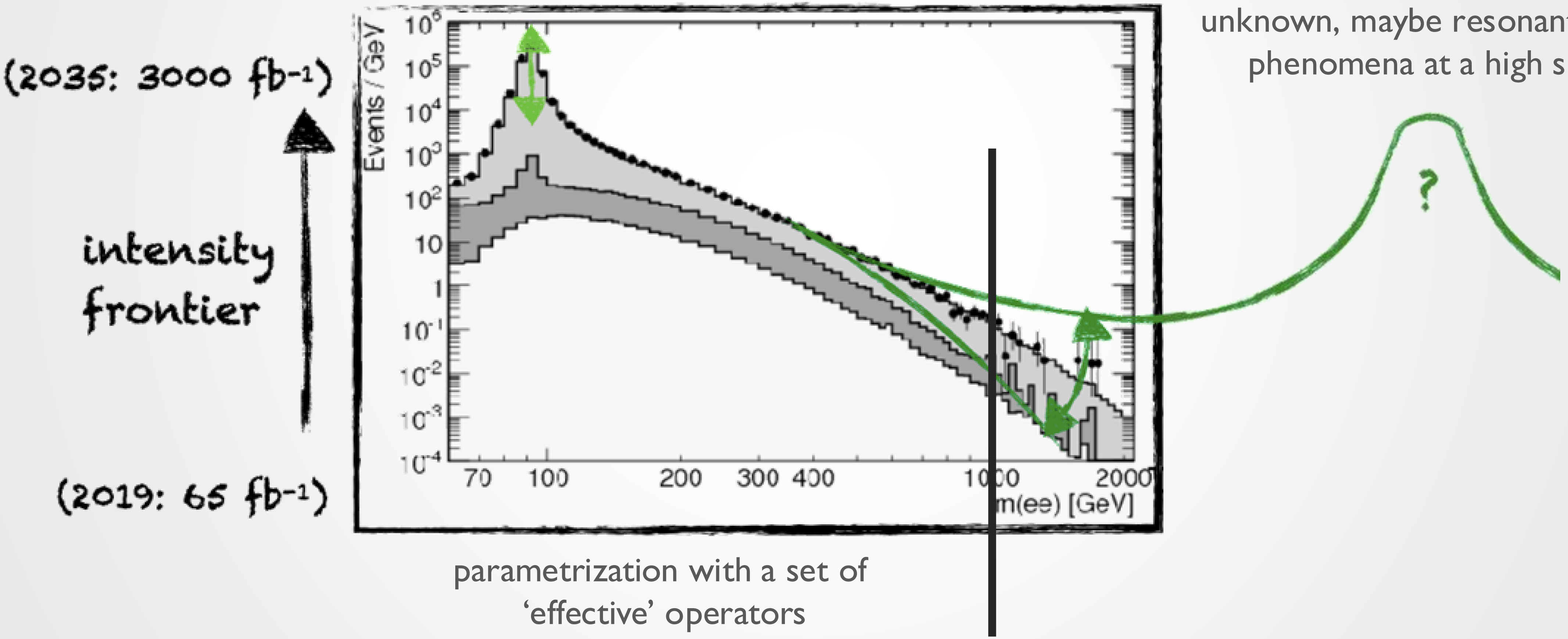




EFFECTIVE DESCRIPTION

Sketch from F. Riva

unknown, maybe resonant, BSM phenomena at a high scale



parametrization with a set of ‘effective’ operators

scale Λ separates EFT from BSM regime

EFFECTIVE FIELD THEORY

- generic extension of the Standard Model

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

  - all gauge invariant combinations and use EOM to remove redundancy
- limited & well defined approximations
  - global way to look for NP in SM measurements
  - parameterizes deviations from higher-order SM predictions
  - organizing principle is the mass dimension of the operators
- defined in unbroken phase of SM → complex pattern after EWSB
- EFT provides guidance to exp. searches
  - e.g. on combination strategy in TT+X (respects gauge symmetries)
  - e.g. on where to include include 4-f ops (global hierarchy)
  - can derive σ(C) on event level analytically ⟶ curse of dimensionality is lifted.

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

C_x Wilson coefficients (complex)
Λ scale of dim-6 interactions
$O_{6,x}$ 59 dim-6 gauge-invariant ops.
most general flavor structure: 2599 dof

Compare with anomalous coupling approach:
- often break gauge symmetries
- no global hierarchy of effects
- less well defined assumptions
- pro: simpler interpretation

Disadvantages
- unintuitive (read: ugly)
- few different basis around

RECENT REFERENCES

top Yukawa coupling from kinematic distributions in the l+jets channel, 36 fb^{-1}, 13 TeV
Phys. Rev. D 100, 072007 (2019)

4 top single-lepton + opposite sign dilepton, 36 pb^{-1}
JHEP 11 (2019) 082

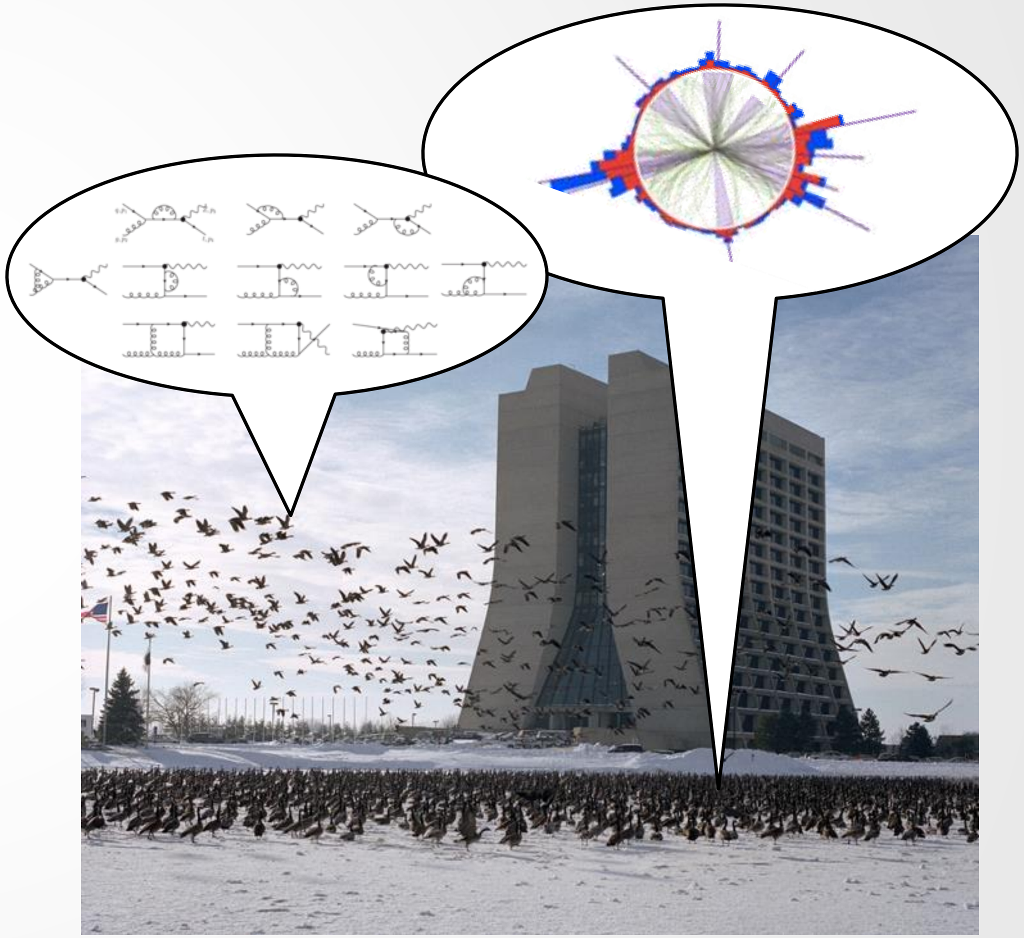
4 top same-sign and multilepton channels, 137 fb^{-1}
Eur. Phys. J. C 80 (2020) 75

ttZ differential in 3/4 lepton channels, 77 fb^{-1}
accepted by JHEP

tt spin correlation in 2 lepton final state, 36 fb^{-1}
Phys. Rev. D 100, 072002 (2019)

top quark charge asymmetry 36 fb^{-1}
JHEP 02 (2019) 149

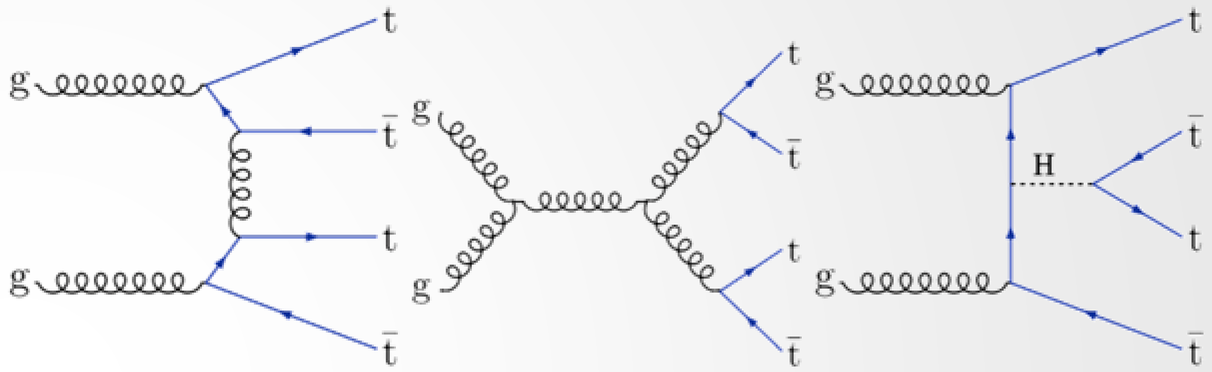
new physics in ttbar dilepton events 36 fb^{-1}
Eur. Phys. J. C 79 (2019) 886



4 TOP QUARK PRODUCTION RUN II

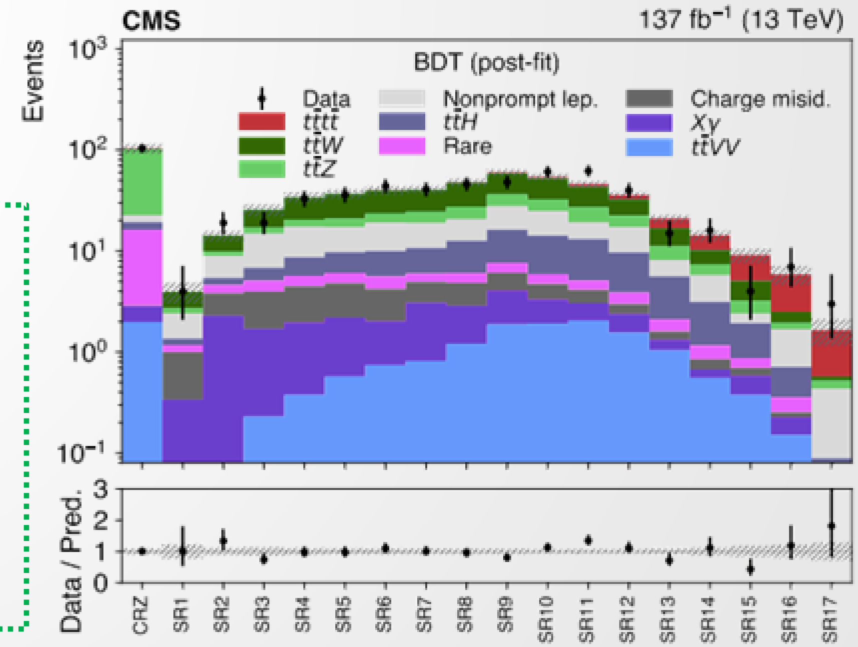
Eur. Phys. J. C 80 (2020) 75

- tttt is an unobserved very rare process: σ(tttt) ≈ 12 fb
- very large jet and b-jet multiplicities
- large hadronic activity
- CMS (and ATLAS): two main channels



1. single lepton + OS dilepton
   - 40% branching fraction
   - relatively large backgrounds
2. same-sign dilepton + multilepton
   - 12% branching fraction
   - low backgrounds
   - most sensitive channel!
   - full Run II data 137 fb^{-1}

- MVA & cut-based analysis
- main backgrounds: ttW , ttZ and ttH
- interesting process from BSM perspective!



4 TOP QUARK PRODUCTION RUN II

[Eur. Phys. J. C 80 (2020) 75]

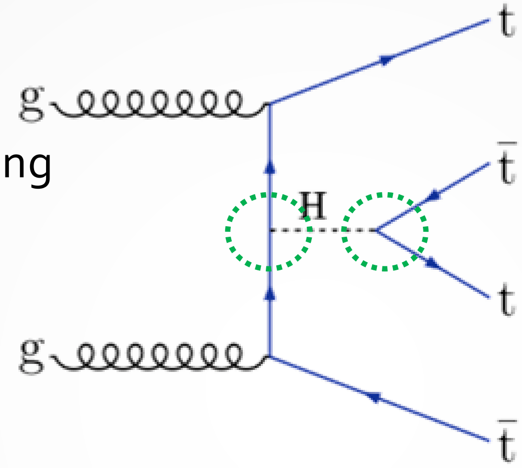
- Result: significance of 2.6 (2.7) s.d.
- rich set of interpretations!
  - constraint on the SM Yukawa coupling

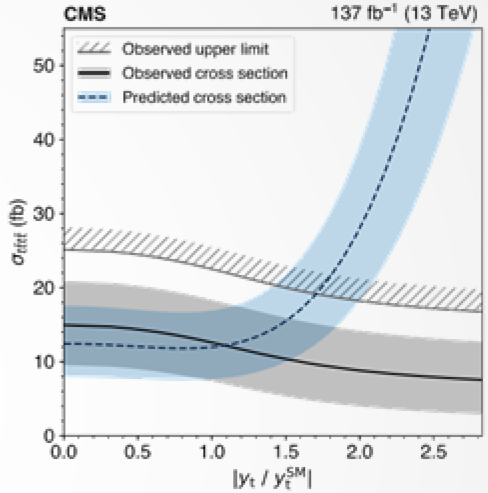
$$|y_t| / |y_t^{SM}| < 1.7 \text{ (95\% C.L.)}$$

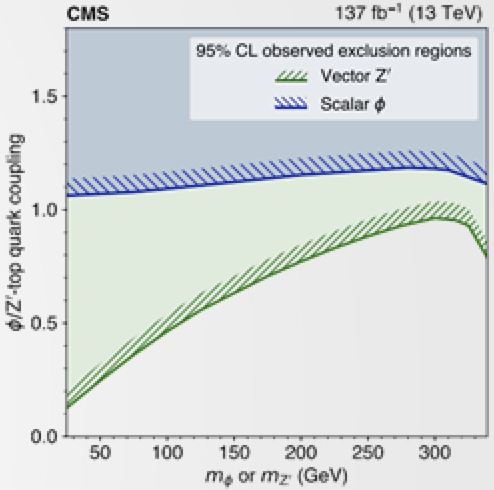
  - BSM scalar ϕ or vector Z′ $m<2m_t$
  - 2HDM ($m>2m_t$) and DM SMS including tqH/A, tWH/A contributions
  - 'oblique' Higgs parameter affecting the H propagator $\hat{H}$ [Giudice et.al. JHEP 09 (2019) 41] (albeit not the H-VV signatures)

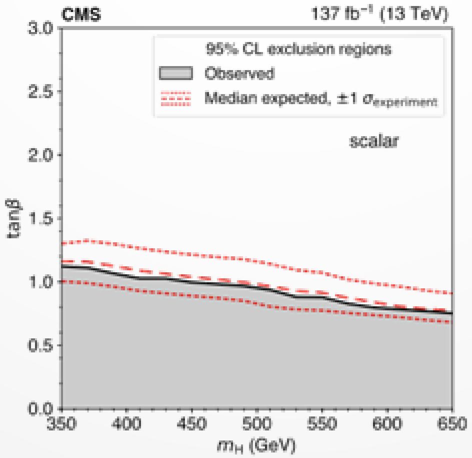
$$\hat{H} = C_{\Box}\frac{m_h^2}{\Lambda^2} < 0.12$$

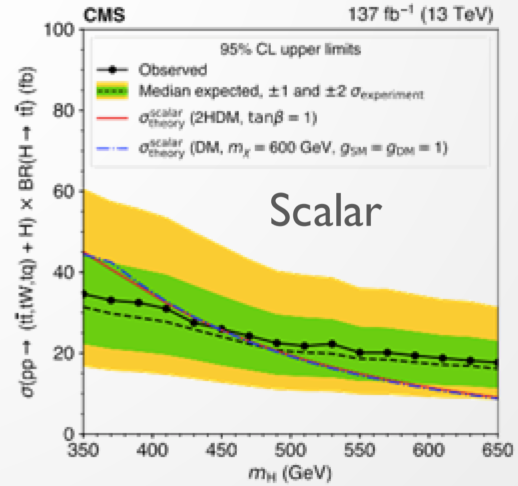
    - constrain (pure) H physics
    - (not in Warsaw basis)

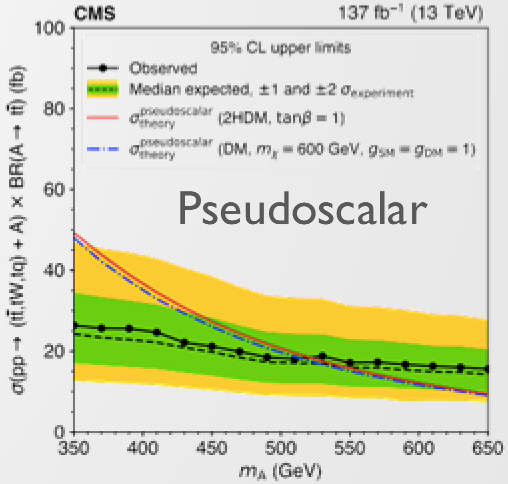












EFT IS NOT A SIMPLE BSM MODEL

- Can use 4t production to constrain qqtt 4-fermion operators
  - e.g. $\mathcal{O}_{tu}^{(8)} = (\bar{t}_R \gamma_\mu T^a t_R)(\bar{u}_R \gamma^\mu T^a u_R)$
- There are two operator insertions necessary to produce 4 top quarks
  - (can neglect genuine dim-8 operators for wide class of BSM)
- Compare this to a single operator insertion.
  - i.e. modification of the qq⟶tt process
  - Can the tiny 4t signal compete in sensitivity?
- because $\sigma \propto |M|^2$ two insertions give a 4th order polynomial

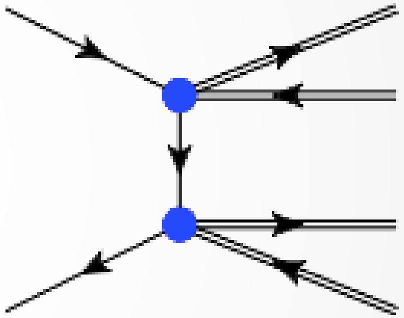
$$\sigma_{LO}(4t) = 6.1 + 0.10\tilde{C}_{tu}^{(8)} + 0.081\tilde{C}_{tu}^{(8)2} + 0.016\tilde{C}_{tu}^{(8)3} + 0.0048\tilde{C}_{tu}^{(8)4}$$

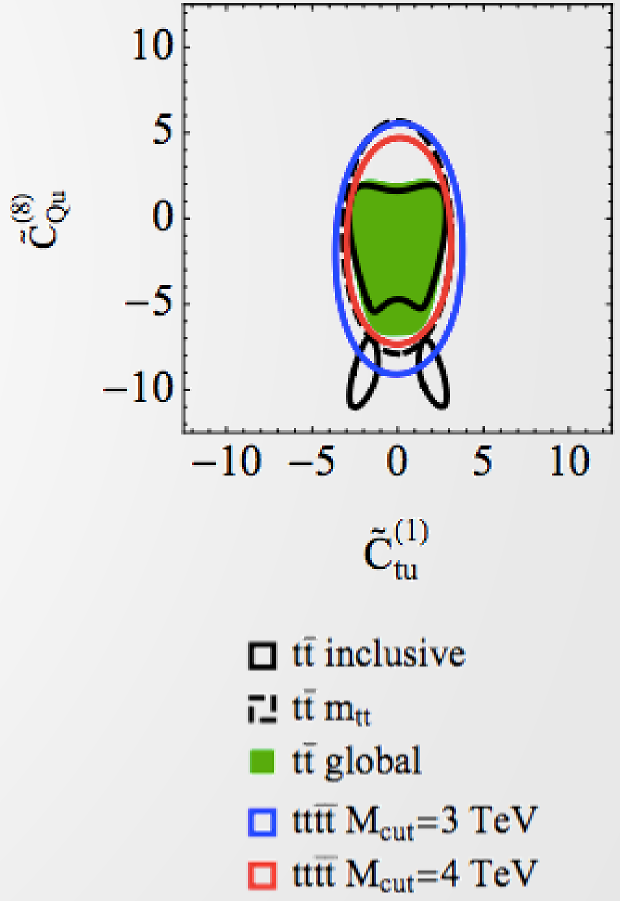
- Comparing inclusive tt xsec

4t xsec: $-8.8 < \tilde{C}_{tu}^{(8)} < 7.1$

inclusive tt x-sec: $-11.8 < \tilde{C}_{tu}^{(8)} < 4.6$

C. Zhang, 2017
https://arxiv.org/pdf/1708.05928.pdf
TOP-17-009
https://arxiv.org/pdf/1710.10614.pdf

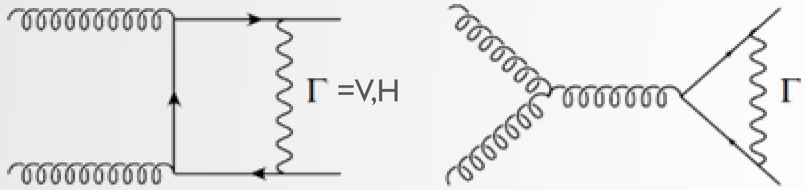


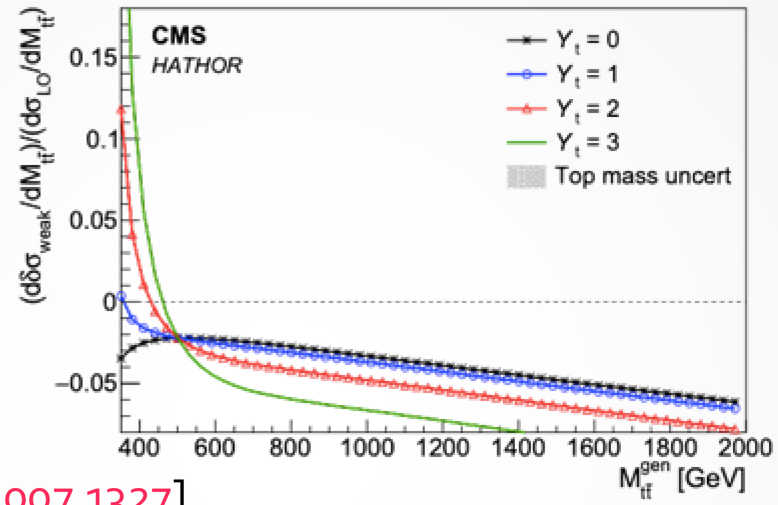


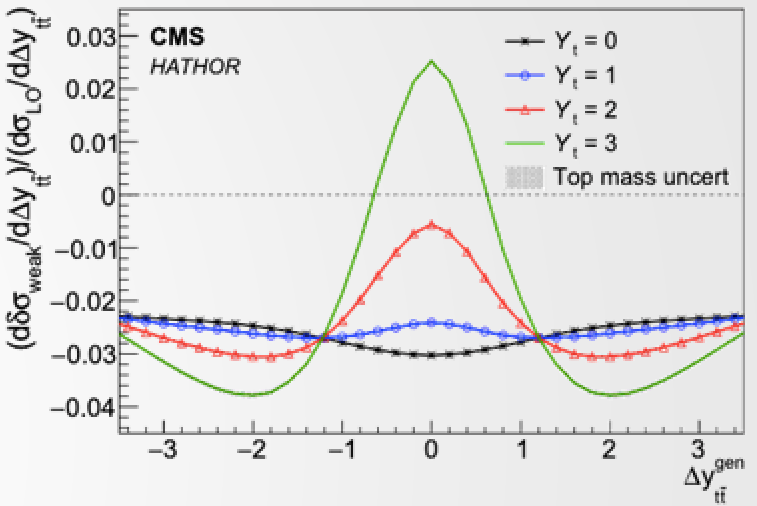
CONSTRAINING THE TOP YUKAWA COUPLING

Phys. Rev. D 100, 072007 (2019)

- idea: use differential single-leptonic x-sec to constrain top Yukawa coupling Y_t
- exploit EWK corrections at $\alpha_s^2\,\alpha_{weak}$



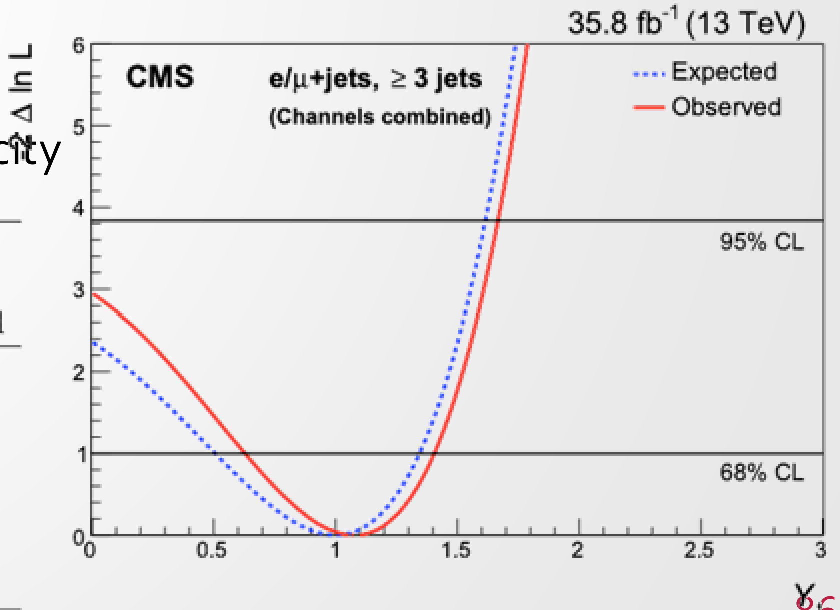




- compute correction factors with Hathor [1007.1327] in M(tt) and |Δy(tt)| and apply to simulation at parton level
- Top-Yukawa coupling extracted from 57 bins in M(tt) , |Δy(tt)|, and jet multiplicity
- Low M(tt) and small |Δytt | regions are the most sensitive to Y_t

use e/μ events with likelihood based event reconstruction for neutrino momentum

Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67



CONSTRAINING EWK COUPLINGS

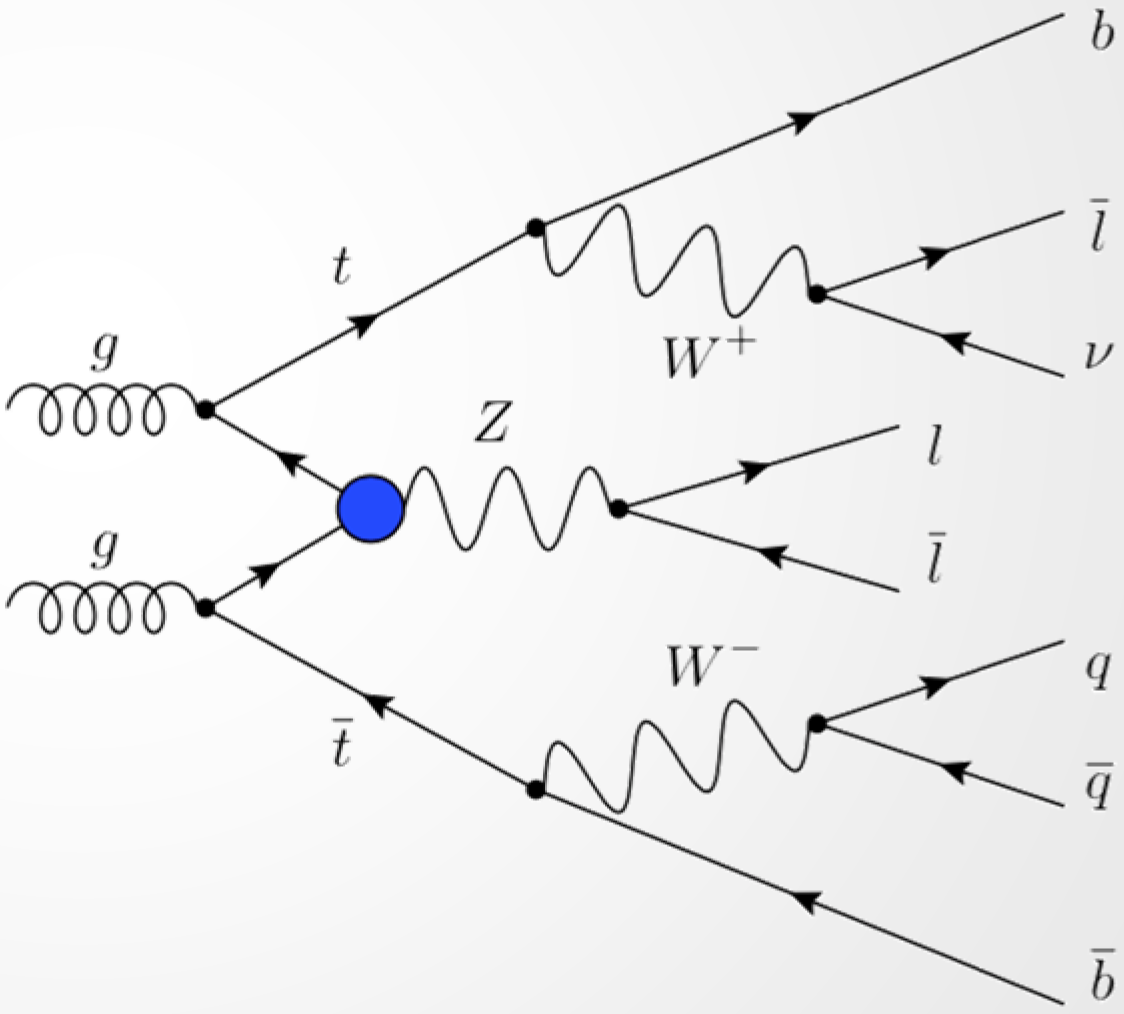
accepted by JHEP

- use associate production of tt with Z bosons to constrain electroweak interactions
- interpret x-sec measurements
  - 77.5/fb tt+Z in 3+4 lepton final states
  - binned in N_j, N_b
  - differential x-sec in $p_T(Z)$, cos(**θ***)
- modelling, tagging efficiencies, background estimates contribute to systematics

$$\sigma(\mathrm{SM}) = 0.839 \pm 0.101\mathrm{pb}$$

1 NLO+EWK

$$\sigma(\mathrm{t\bar{t}Z}) = 0.95 \pm 0.05\,\mathrm{(stat)} \pm 0.06\,\mathrm{(syst)}\,\mathrm{pb}$$



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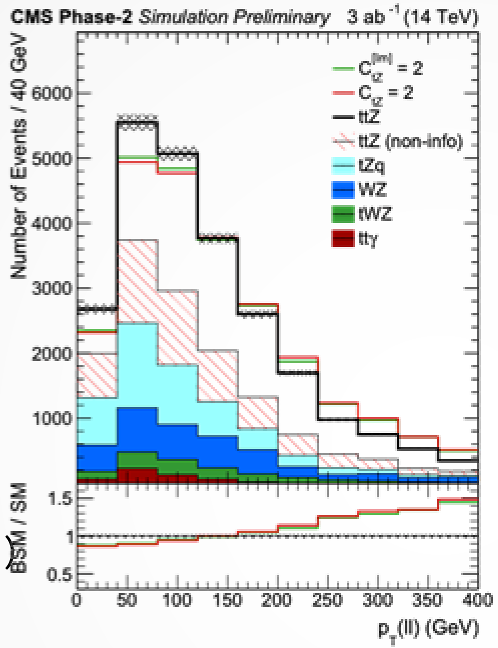
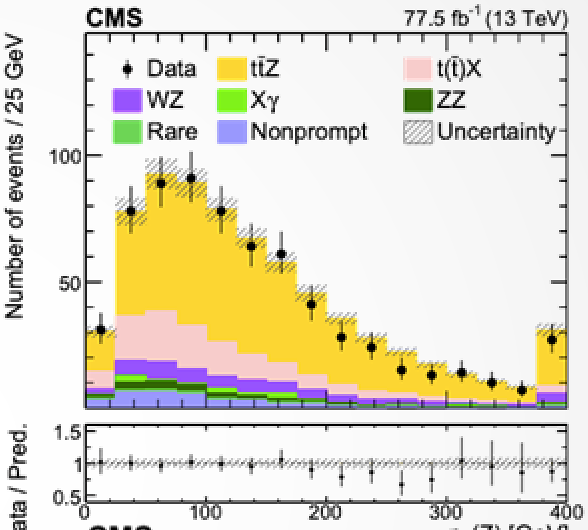
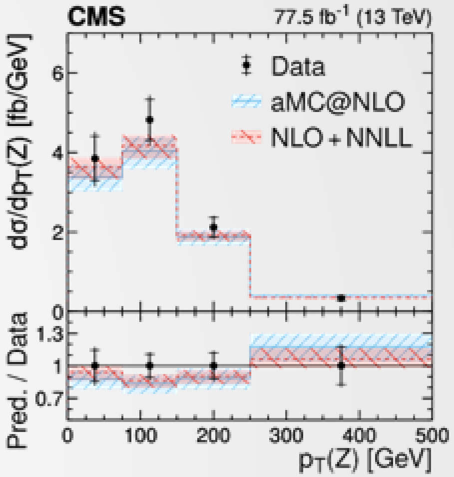
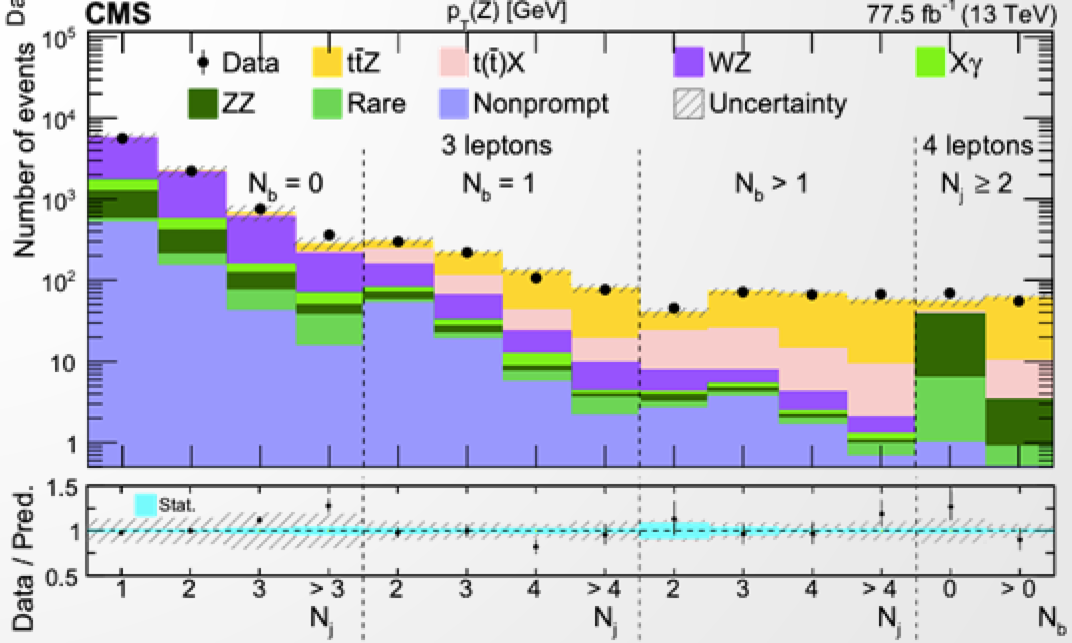


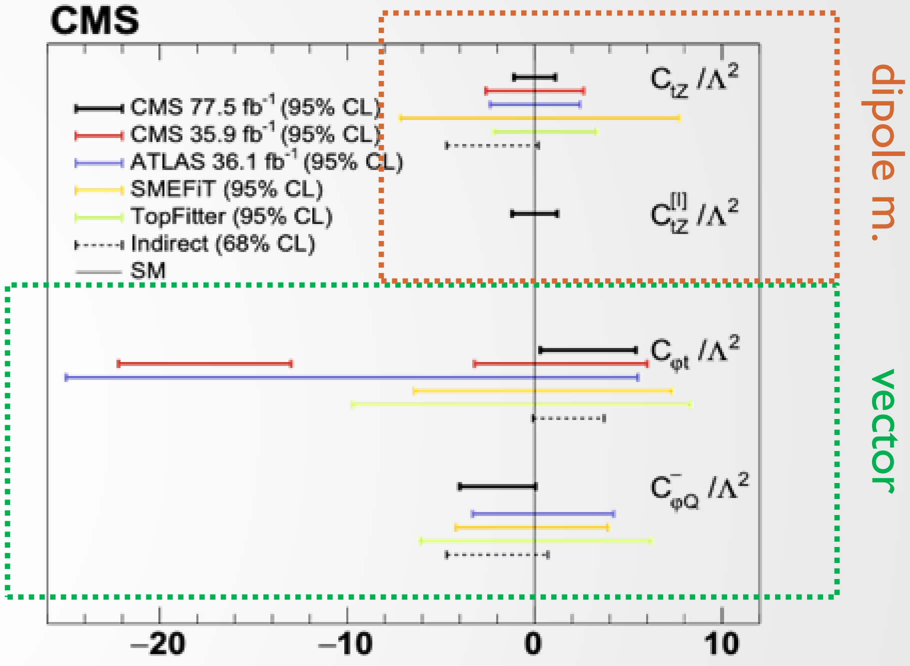






CONSTRAINING EWK COUPLINGS

- consider single operator insertions
- interference term is important for vector-type couplings.
- EFT tensor structure induces EWK dipole moments (quadratic dependence of x-sec)
- most stringent direct constraints on the top-Z vector coupling and the EWK dipole moments
  - simple linear relations exist at tree level
  - differential measurement improves sensitivity
  - small interference for dipoles



Coefficient	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL	Previous CMS constraints Exp. 95% CL	Previous CMS constraints Obs. 95% CL	Indirect constraints 68% CL
c_{tZ}/Λ^2	[−0.7, 0.7]	[−1.1, 1.1]	[−0.8, 0.5]	[−1.1, 1.1]	[−2.0, 2.0]	[−2.6, 2.6]	[−4.7, 0.2]
$c_{tZ}^{[I]}/\Lambda^2$	[−0.7, 0.7]	[−1.1, 1.1]	[−0.8, 1.0]	[−1.2, 1.2]	—	—	—
$c_{\phi t}/\Lambda^2$	[−1.6, 1.4]	[−3.4, 2.8]	[1.7, 4.2]	[0.3, 5.4]	[−20.2, 4.0]	[−22.2, −13.0] [−3.2, 6.0]	[−0.1, 3.7]
$c^{-}_{\phi Q}/\Lambda^2$	[−1.1, 1.1]	[−2.1, 2.2]	[−3.0, −1.0]	[−4.0, 0.0]	—	—	[−4.7, 0.7]

anomalous coupling Lagrangian:

$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V} + \gamma_5 C_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C_{2,V} + i\gamma_5 C_{2,A}\right)\right] v(p_{\bar{t}})\, Z_\mu.$$

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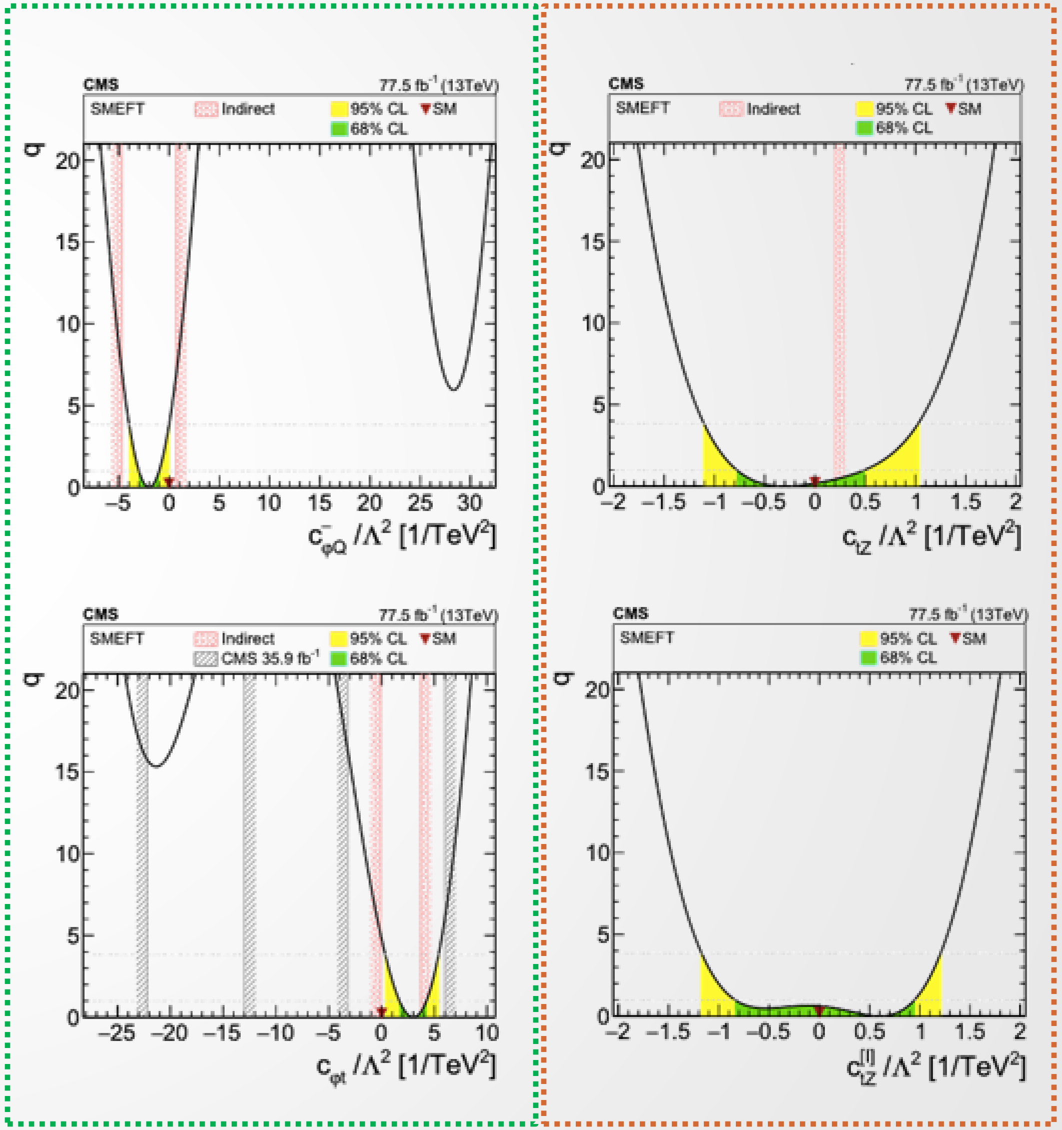

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$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^{\mu}(C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu}q_{\nu}}{M_Z}(C_{2,V} + i\gamma_5 C_{2,A})\right] v(p_{\bar{t}})\, Z_{\mu}.$$

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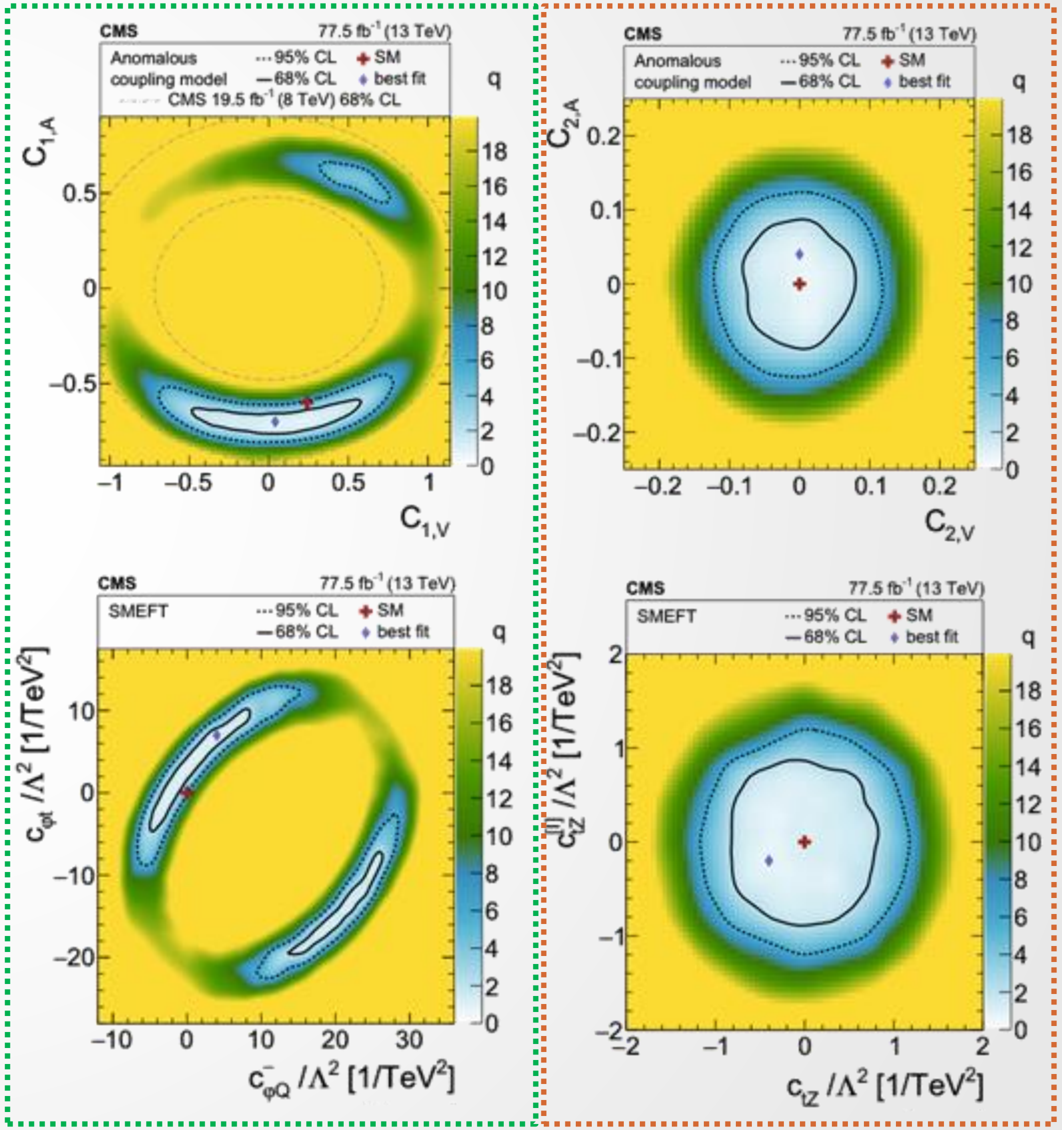


CHROMOMAGNETIC DIPOLE MOMENTS

Phys. Rev. D 100, 072002 (2019)

- top decay products are a probe of the ttbar spin correlation

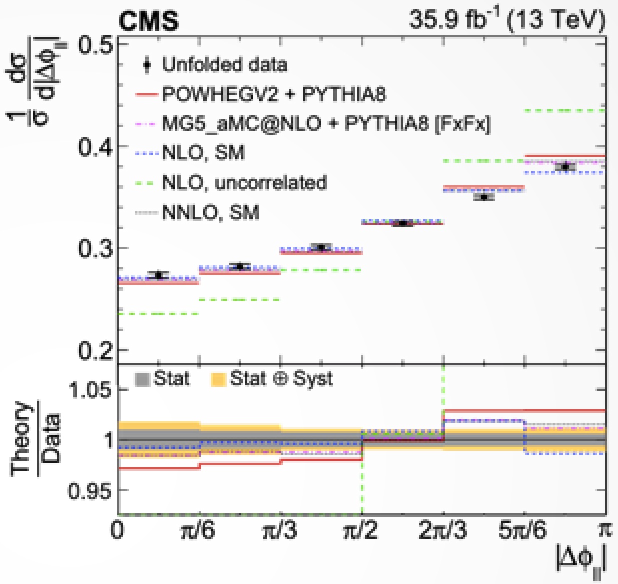
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\10^{-21}\ \text{s}}}$$

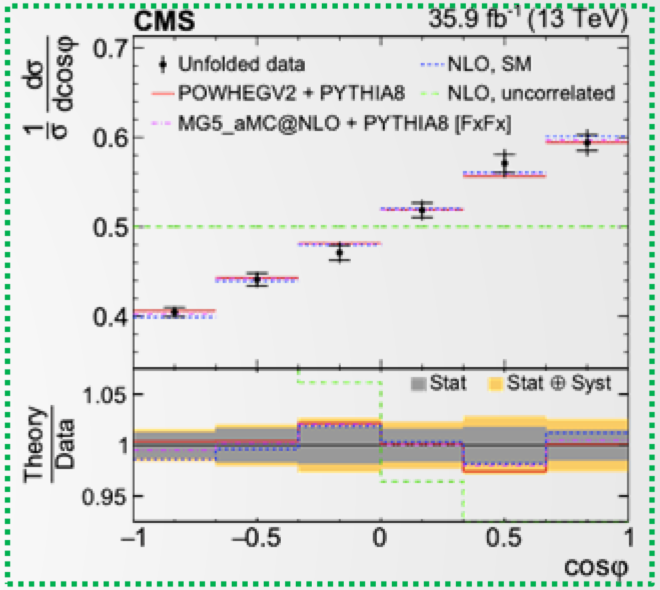
- directly measure spin correlation matrix
  - reconstruct the top momenta; e/**μ**, ee, **μμ**
  - probe top spin in 3D (15 observables)
  - fully consistent with SM
- Most sensitive direct result: D coefficient

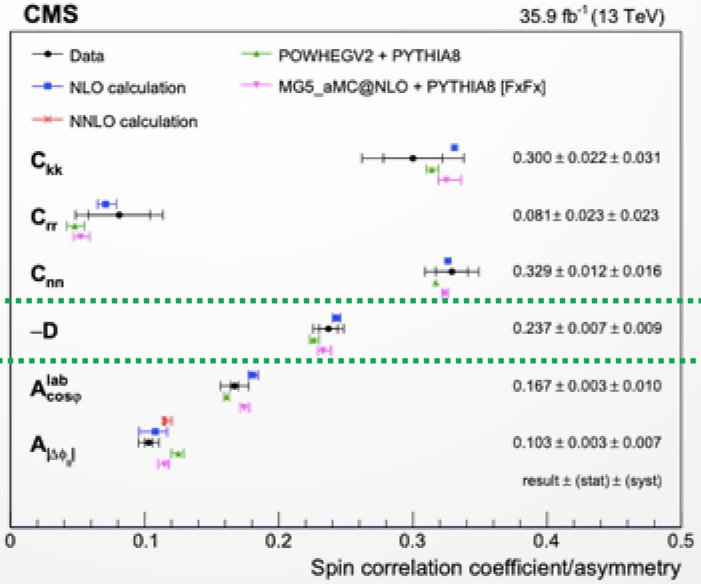
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}\left(1 - \underbrace{D}_{-\frac{1}{3}\mathrm{tr}(C)}\ \cos\ \underbrace{\varphi(\hat{\ell}^+,\hat{\ell}^-)}_{\text{top rest frame}}\right)$$

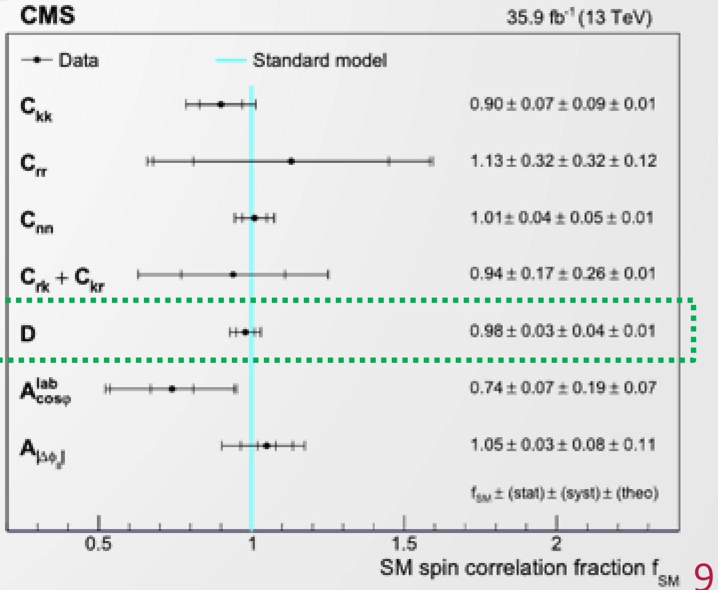
$$F_{SM}(D) = 0.97 \pm 0.05$$

- Spin correlation is sensitive to the strong production vertex









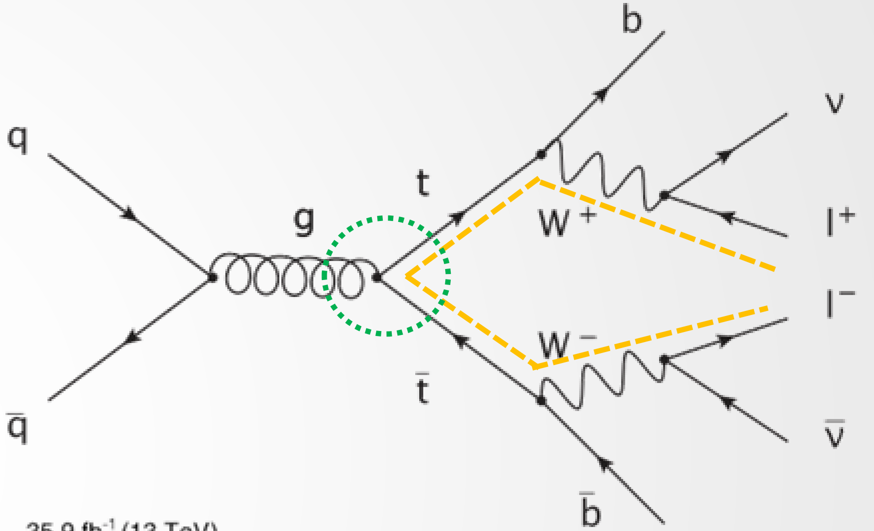
TOP CMDM AND CHARGE ASYMMETRIES

Phys. Rev. D 100, 072002 (2019)

- Constrain the top chromo-magnetic & electric dipole moment

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{\phi}G^a_{\mu\nu} \qquad C_{tG}/\Lambda^2 = \hat{\mu}_t/(2m_t^2)$$

  - 2HDM, SUSY, technicolor, compositeness
  - perform simultaneous fit to all distributions
  - currently best limit: $-0.10 < C_{tG}/\Lambda^2 < 0.22\ \text{TeV}^{-2}$

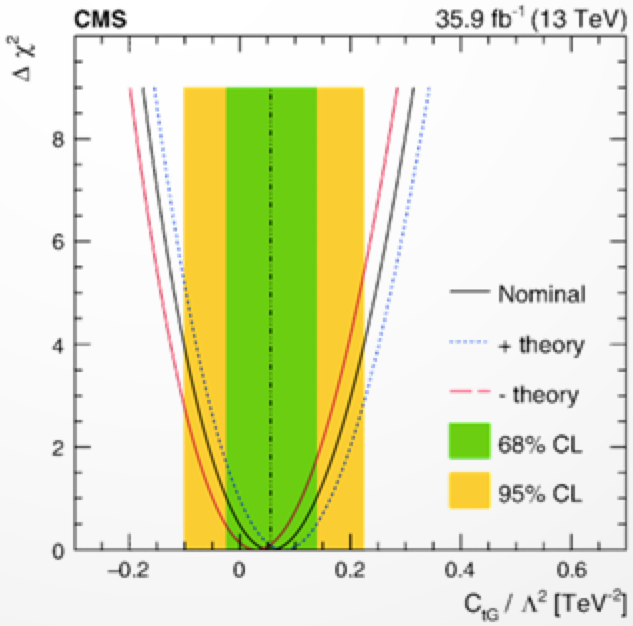


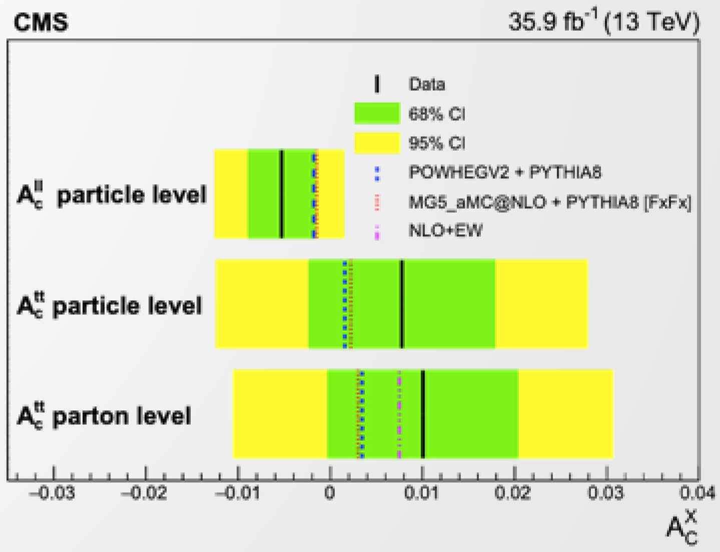
  - In the same dataset, measure top charge asymmetries

$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}$$

$$A_c^{\ell\bar{\ell}} = \frac{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) - \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}{\sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) > 0) + \sigma_{t\bar{t}}(\Delta\eta(\ell,\bar{\ell}) < 0)}$$

- sensitive to axigluon, Z′, W′ coupled to top
- first measurement at 13 TeV





CONSTRAINING SM-EFT WITH TTBAR

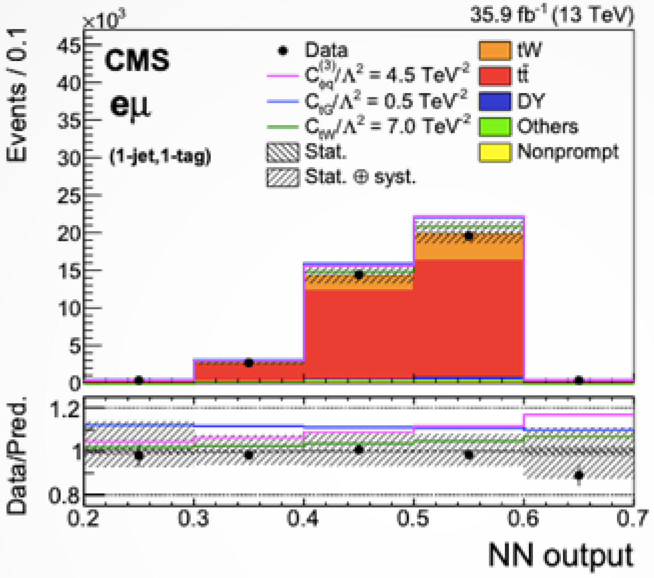
Eur. Phys. J. C 79 (2019) 886

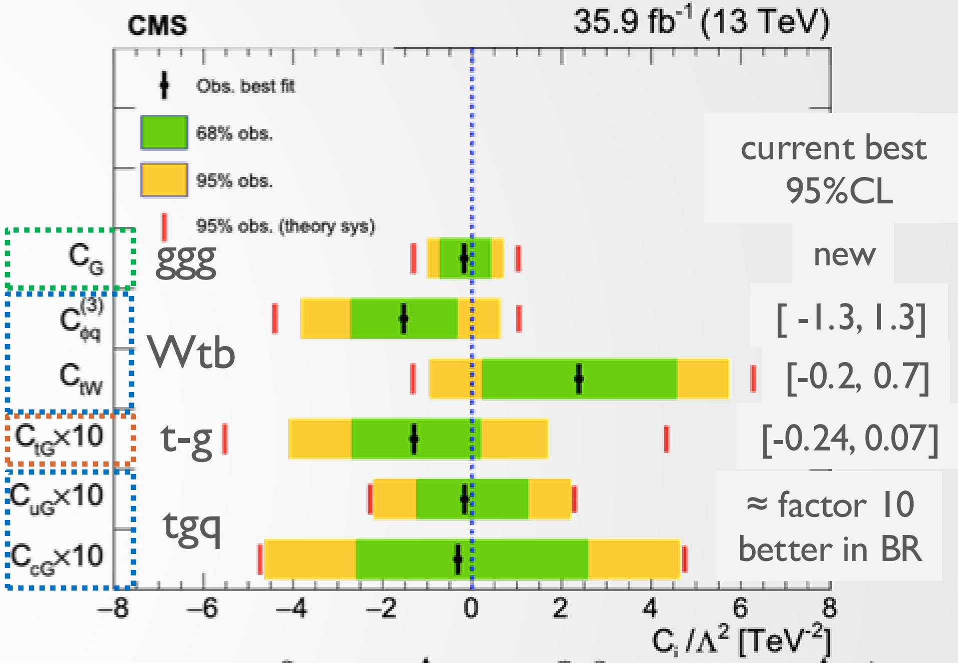
- using the dilepton channel, directly constrain EFT with tW and $t\bar{t}$ final states

Single Top (tW) | $t\bar{t}$

Single Top (tW) + $t\bar{t}$

- split in e/μ lepton flavor
  - $t\bar{t}$ ≥ 2 jets (≥ 2 b jets)
  - tW: 1-2 jets (0-1 b jet).





- test separately 6 Wilson coeff:
  - Wtb vertex, top-gluon coupling, 3g vertex, FCNC couplings

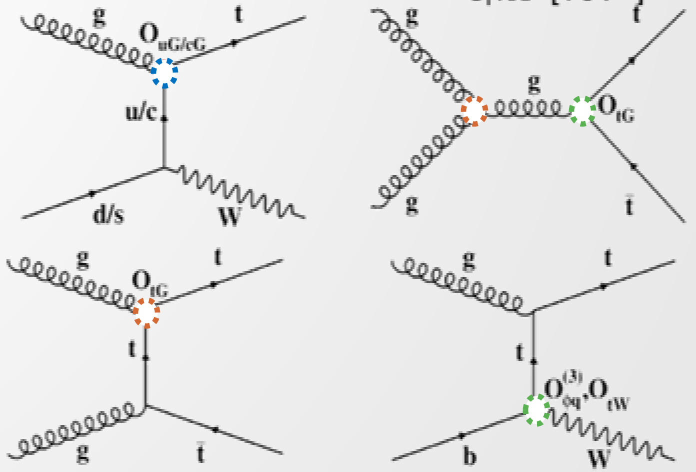
$$O^{(3)}_{\phi q} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu},$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$

$$O_G = f_{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu},$$



- Signal extraction via per-channel neural networks
- first attempt of a global analysis at CMS

FCNC

- FCNC suppressed to $10^{-12} - 10^{-15}$ in SM by GIM mechanism
- sensitive probe BSM models: 2HDM, SUSY, etc.
- anomalous coupling Lagrangian:

theory summary:
Snowmass 2013 WG report

$$\mathcal{L}_{FCNC} = \sum_{q=u,c}\Bigg[\frac{\sqrt{2}}{2}g_s\,\frac{\kappa_{\rm tgq}}{\Lambda}\,\left(\bar{q}\sigma^{\mu\nu}T^a(f^L_{gq}P_L + f^R_{gq}P_R)t\right)G^a_{\mu\nu}$$

7+8 TeV, JHEP 02 (2017) 028

$$+\frac{eQ_t}{\sqrt{2}}\,\frac{\kappa_{\rm tq\gamma}}{\Lambda}\,\left(\bar{q}\sigma^{\mu\nu}(f^L_{\gamma q}P_L + f^R_{\gamma q}P_R)t\right)F_{\mu\nu}$$

8 TeV, JHEP 04 (2016) 035

$$+\frac{g}{\sqrt{2}}\,\kappa_{\rm tqH}\,\left(\bar{q}(f^L_{Hq}P_L + f^R_{Hq}P_R)t\right)H$$

13 TeV, JHEP 06 (2018) 102
8 TeV, JHEP 02 (2017) 079

$$+\frac{\sqrt{2}g}{4c_W}\,\frac{\kappa_{\rm tqZ}}{\Lambda}\,\left(\bar{q}\sigma^{\mu\nu}(\hat{f}^L_{Zq}P_L + \hat{f}^R_{Zq}P_R)t\right)Z_{\mu\nu}$$

8 TeV, JHEP 07 (2017) 003
13 TeV TOP-17-017

$$+\frac{g}{4c_W}\,\zeta_{\rm tqZ}\,\left(\bar{q}\gamma^{\mu}(\bar{f}^L_{Zq}P_L + \bar{f}^R_{Zq}P_R)t\right)Z_\mu\Bigg] + \text{h.c.}$$

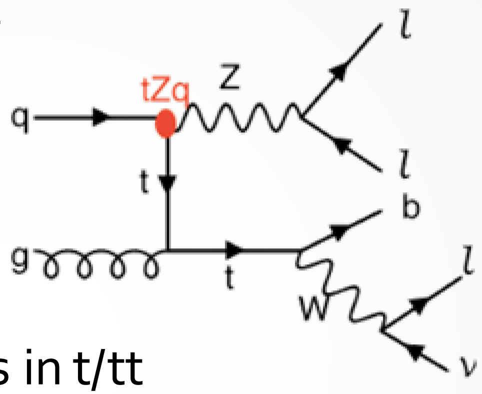
nevermind prefactors - different conventions in use. Compare BR.

- often simplify chiral structure, e.g. $f^R = 1$.
- q can be u or c, with more sensitivity to u (higher x-sec)

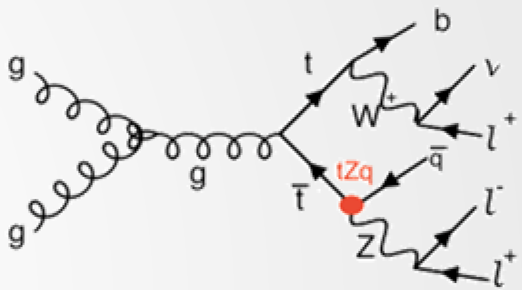
FCNC T/TT QZ

- combine t & tt FCNC channels
- consider all flavor combinations eee/μee/μμe/μμμ
  require same-flavor opposite-sign Z candidate
- consider only tensor coupling κ_{tqZ}
- train BDTs to separate t and tt-FCNC signal,
  fit output discriminator in CR and SR simultaneous in t/tt

13 TeV TOP-17-017
http://cds.cern.ch/record/2292045



8 TeV TOP-12-039
JHEP 07 (2017) 003
https://arxiv.org/abs/1702.01404

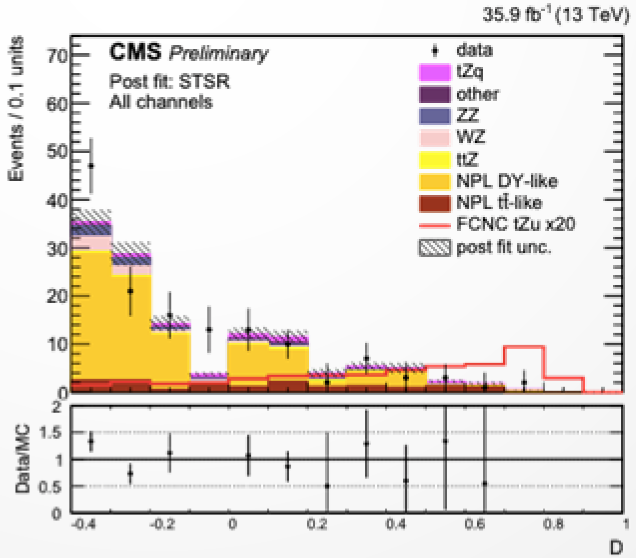


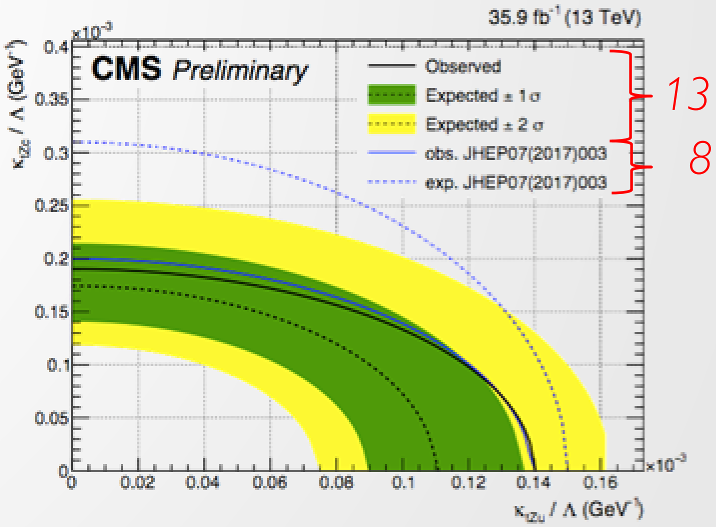
8 TeV

Branching fraction	Expected	68% CL range	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.027	0.018 – 0.042	0.022
$\mathcal{B}(t \to Zc)$ (%)	0.118	0.071 – 0.222	0.049

Branching fraction	Expected	Observed
$\mathcal{B}(t \to Zu)$ (%)	0.015	0.024
$\mathcal{B}(t \to Zc)$ (%)	0.037	0.045

13 TeV





13 TeV
8 TeV

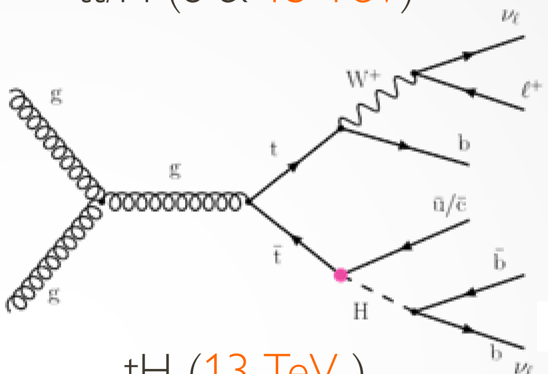
- statistics dominated; profit from energy and lumi; excluded BR ~ $O(10^{-4})$

FCNC TQH

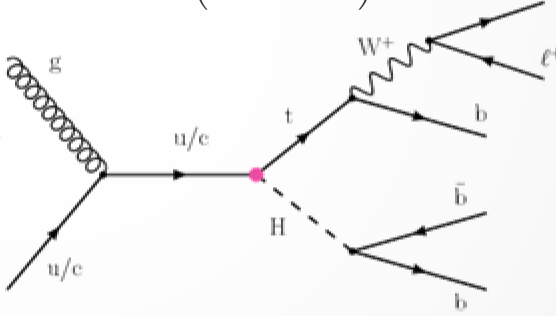
- Combine 8 TeV results from top quark pair production in H→bb/γγ/WW+ττ(+ZZ)
  - H→γγ most sensitive
  - For H→WW+ττ(+ZZ) combine SS and multi-lepton channels
- H→bb has largest branching but large combinatorial background BDT to select correct assignment in FCNC signal, ANN (8 TeV) or BDT (13 TeV) to selecting signal
- At 13 TeV, focus on H→bb but include tH production (+20% sensitivity from PDF enhancement when q=u)

13 TeV TOP-17-003
https://arxiv.org/abs/1712.02399
8 TeV TOP-13-017
JHEP 02 (2017) 079
https://arxiv.org/abs/1610.04857

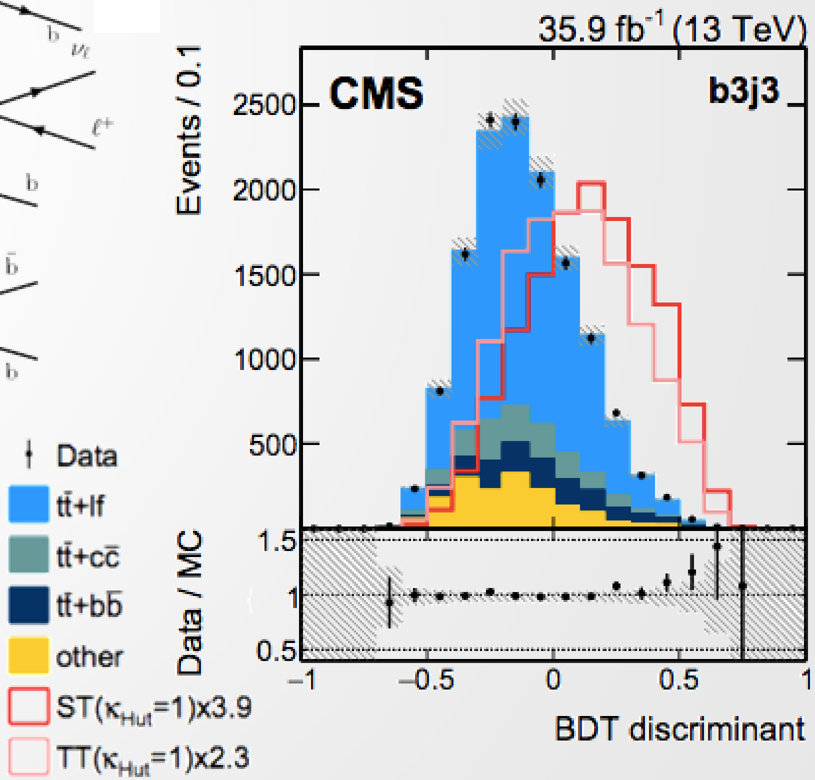
tt/H (8 & 13 TeV)



tH (13 TeV)



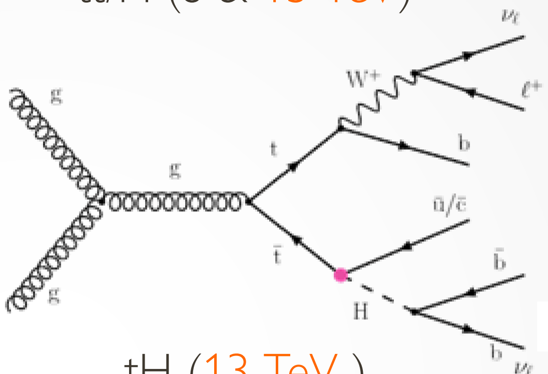
UL[%]	8 TeV	13 TeV (bb)
BR(t→Hu)	0.55(0.40)	0.47(0.34)
BR(t→Hc)	0.40(0.43)	0.47(0.44)



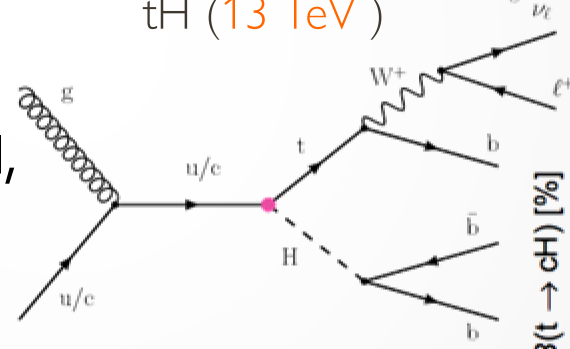
FCNC TQH

- Combine 8 TeV results from top quark pair production in H→bb/γγ/WW+ττ(+ZZ)
  - H→γγ most sensitive
  - For H→WW+ττ(+ZZ)
    combine SS and multi-lepton channels
- H→bb has largest branching
  but large combinatorial background
  BDT to select correct assignment in FCNC signal,
  ANN (8 TeV) or BDT (13 TeV) to selecting signal
- At 13 TeV, focus on H→bb but include tH production (+20% sensitivity from PDF enhancement when q=u)

tt/H (8 & 13 TeV)

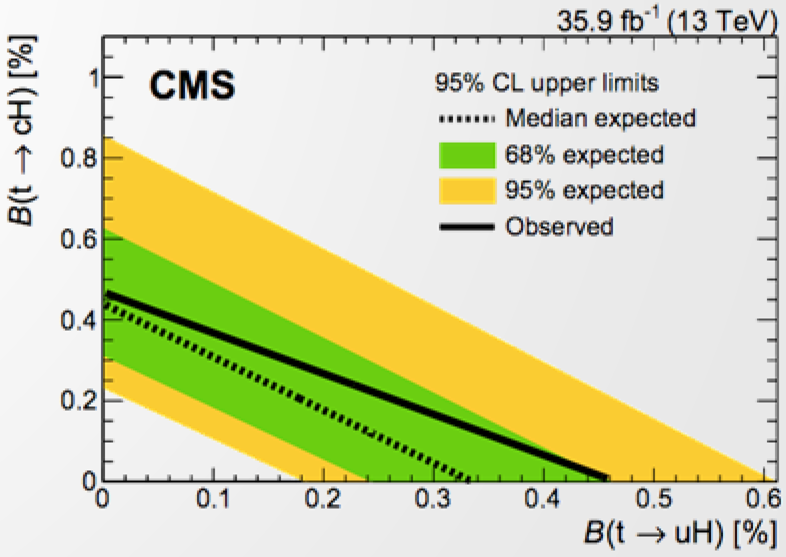


tH (13 TeV)



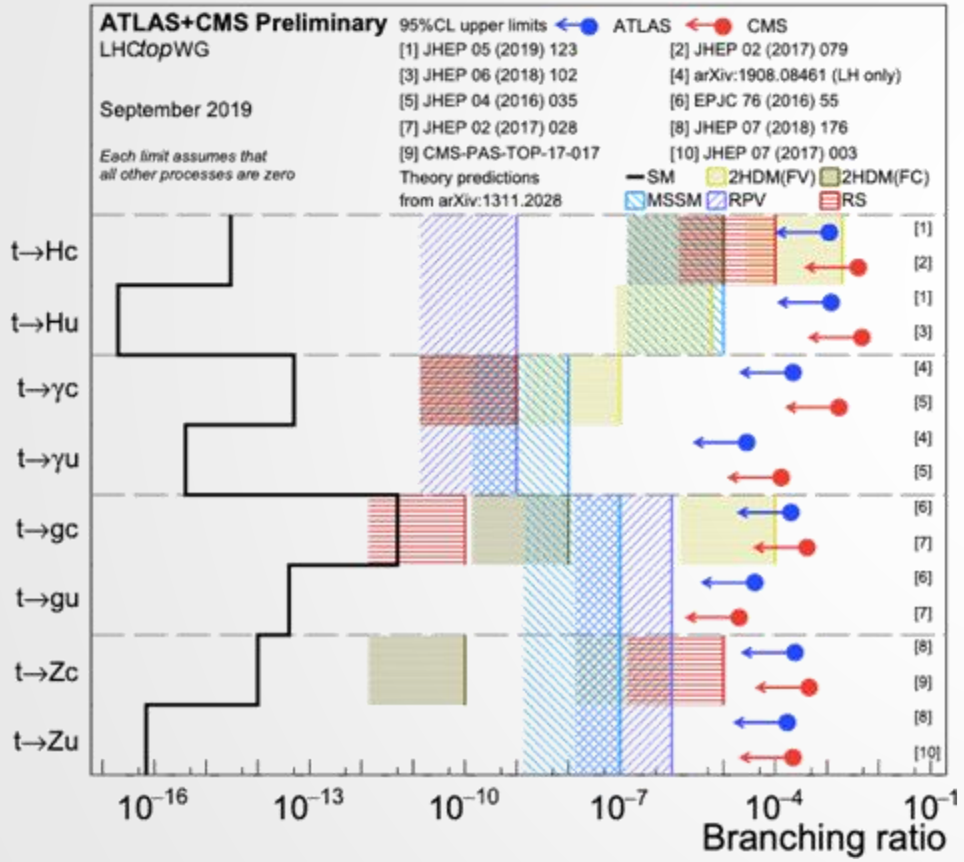
13 TeV TOP-17-003
https://arxiv.org/abs/1712.02399
8 TeV TOP-13-017
JHEP 02 (2017) 079
https://arxiv.org/abs/1610.04857

UL[%]	8 TeV	13 TeV (bb)
BR(t→Hu)	0.55(0.40)	0.47(0.34)
BR(t→Hc)	0.40(0.43)	0.47(0.44)



FCNC STATUS & OUTLOOK

- common language pragmatic choice: branching ratios



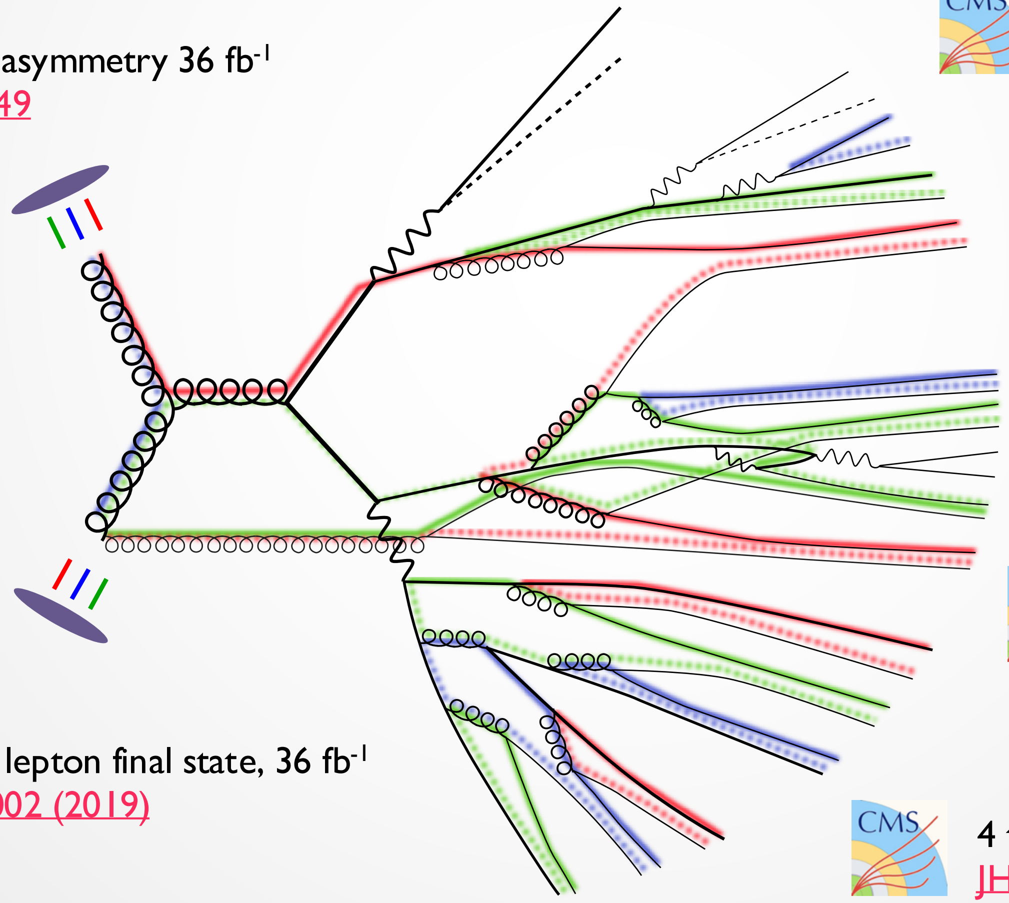
- EFT approach in: *G. Durieux, F. Maltoni, C. Zhang Phys. Rev. D 91, 074017 (2015)* https://arxiv.org/pdf/1412.7166.pdf
  - points out few missed contributions, e.g. dilepton final states off the Z-peak that disentangle EWK contributions from 4f operators

REFERENCES

new physics in ttbar dilepton events 36 fb^{-1}
Eur. Phys. J. C 79 (2019) 886

top quark charge asymmetry 36 fb^{-1}
JHEP 02 (2019) 149

top Yukawa coupling from kinematic distributions in the l+jets channel, 36 fb^{-1}, 13 TeV
Phys. Rev. D 100, 072007 (2019)



ttZ differential in 3/4 lepton channels, 77 fb^{-1}
accepted by JHEP

4 top same-sign and multilepton channels, 137 fb^{-1}
Eur. Phys. J. C 80 (2020) 75

tt spin correlation in 2 lepton final state, 36 fb^{-1}
Phys. Rev. D 100, 072002 (2019)

4 top single-lepton + opposite sign dilepton, 36 pb^{-1}
JHEP 11 (2019) 082

BIRD'S EYE VIEW: TOP EFT OPERATORS @ LO

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

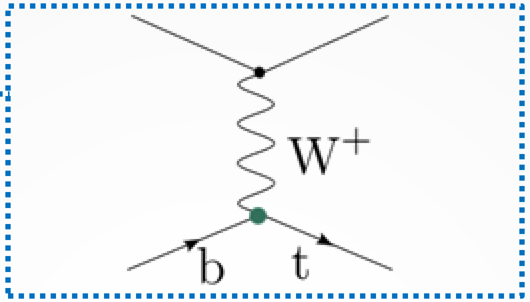
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

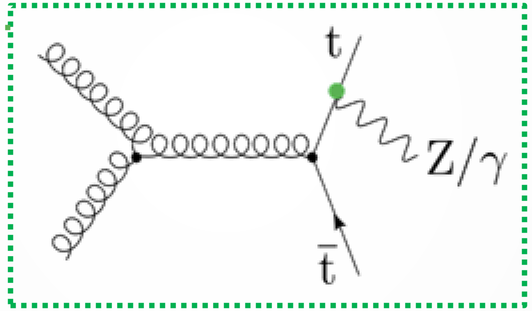
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

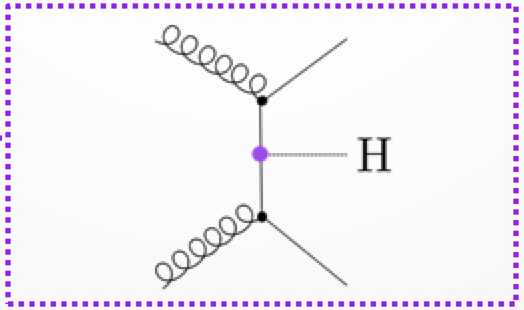
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

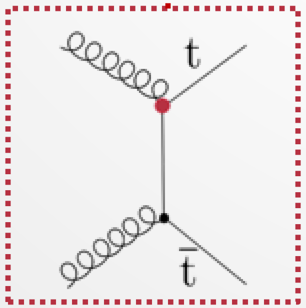


tightest Wtb constraints from W polarization and single-t measurements



tt+Z and tt+γ constraint different linear combinations





+ 4 fermion operators
+ FCNC
+ operator mixing

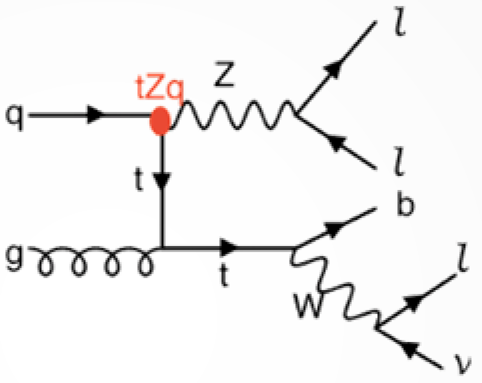
FCNC T/TT QZ

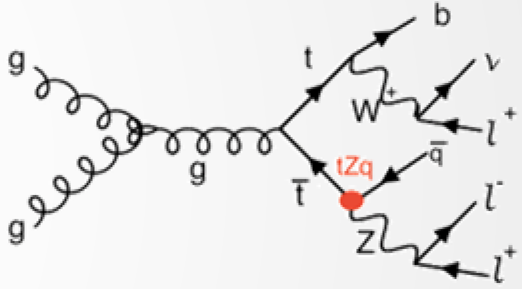
- combine t & tt FCNC channels

8 TeV TOP-12-039
JHEP 07 (2017) 003
https://arxiv.org/abs/1702.01404

13 TeV TOP-17-017
http://cds.cern.ch/record/2292045

FCNC signal single-top-quark	FCNC signal $t\bar{t}$
1 jet, $\lvert\eta\rvert<2.4$ 1 b tag	$\geqslant 2$ jets, $\lvert\eta\rvert<2.4$ $\geqslant 1$ b tag
$m_T^W > 10$ GeV $p_T^{miss} > 40$ GeV	$m_T^W > 10$ GeV $p_T^{miss} > 40$ GeV





- consider all flavor combinations eee/μee/μμe/μμμ
  require same-flavor opposite-sign Z candidate
- consider only tensor coupling κ_{tqZ}
- three low njet/nbjet SB for (1) non-prompt leptons and W+Jets (separated by m_T(W) and per flavor) and for NPL + (2) t and (3) tt
- train BDTs to separate t and tt-FCNC signal,
  fit output discriminator in CR and SR simultaneous in t/tt

HARD-SCATTER MODELING

Madminer [1506.02169] [1805.00013] [1805.00020] [1805.12244] [1907.10621] [1908.06980] [2109.10414]

1. Analytic predictions for the SMEFT predictions at the parton level - easily recalcuable

$$d\sigma_{\mathrm{SMEFT}}(\boldsymbol{z}_p|\boldsymbol{\theta}, \nu_R, \nu_F, \boldsymbol{\nu}_{\mathrm{PDF}}) \propto \sum_{f_1, f_2} \left|\mathcal{M}_{\mathrm{SMEFT}}(\boldsymbol{z}_p|\boldsymbol{\theta}, \mu_R(\nu_R), \mu_F(\nu_F))\right|^2$$
$$\times \mathrm{PDF}(f_1, x_{\mathrm{Bjorken},1}, \mu_F(\nu_F), \boldsymbol{\nu}_{\mathrm{PDF}})\mathrm{PDF}(f_2, x_{\mathrm{Bjorken},2}, \mu_F(\nu_F), \boldsymbol{\nu}_{\mathrm{PDF}})d\boldsymbol{z}_p$$

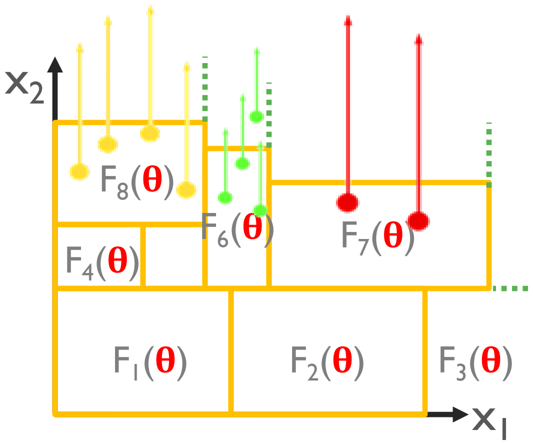
2. Phenomena at lower energy scales largely factorize:
   - → Conditional propabilities factor out [*Madminer*, full Refs. in backup]
   - → Access to the 'joint likelihood' ratio for POIs and some systematic effects.

$$r(\boldsymbol{x}_i, \boldsymbol{z}_i|\boldsymbol{\theta}, \boldsymbol{\nu}) = \frac{\sigma(\boldsymbol{\theta}, \boldsymbol{\nu})}{\sigma(\mathrm{SM})}\frac{p(\boldsymbol{x}_i, \boldsymbol{z}_{\mathrm{reco},i}, \boldsymbol{z}_{\mathrm{ptl},i}, \boldsymbol{z}_{\mathrm{p},i}|\boldsymbol{\theta}, \boldsymbol{\nu})}{p(\boldsymbol{x}_i, \boldsymbol{z}_{\mathrm{reco},i}, \boldsymbol{z}_{\mathrm{ptl},i}, \boldsymbol{z}_{\mathrm{p},i}|\mathrm{SM})} = \frac{\sigma(\boldsymbol{\theta}, \boldsymbol{\nu})}{\sigma(\mathrm{SM})}\frac{p(\boldsymbol{x}|\boldsymbol{z}_{\mathrm{reco}})}{p(\boldsymbol{x}|\boldsymbol{z}_{\mathrm{reco}})}\frac{p(\boldsymbol{z}_{\mathrm{reco}}|\boldsymbol{z}_{\mathrm{ptl}})}{p(\boldsymbol{z}_{\mathrm{reco}}|\boldsymbol{z}_{\mathrm{ptl}})}\frac{p(\boldsymbol{z}_{\mathrm{ptl}}|\boldsymbol{z}_{\mathrm{p}})}{p(\boldsymbol{z}_{\mathrm{ptl}}|\boldsymbol{z}_{\mathrm{p}})}\frac{p(\boldsymbol{z}_{\mathrm{p},i}|\boldsymbol{\theta}, \boldsymbol{\nu})}{p(\boldsymbol{z}_{\mathrm{p},i}|\mathrm{SM})} \sim \frac{\left|\mathcal{M}(\boldsymbol{z}_{\mathrm{p},i}, \boldsymbol{\theta}, \boldsymbol{\nu})\right|^2}{\left|\mathcal{M}(\boldsymbol{z}_{\mathrm{p},i}, \mathrm{SM})\right|^2}$$

TREE ALGORITHM FOR SMEFT LEARNING

[arXiv:2107.10859, arXiv:2205:12976]

Phase-space partitioning



A simple tree

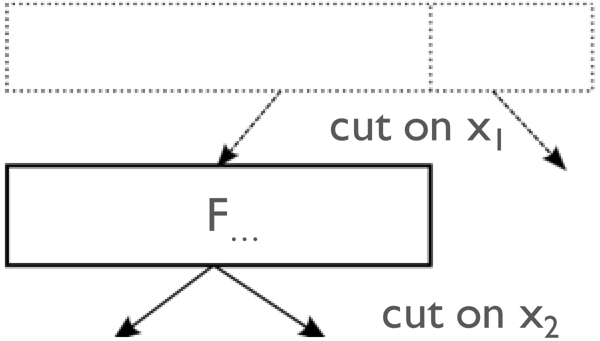
$$\hat{F}(\boldsymbol{x},\boldsymbol{\theta}) = \sum_{j\in\mathcal{J}} \mathbb{1}_j(\boldsymbol{x}) F_j(\boldsymbol{\theta})$$

non-linearity)

phase space partitioning J

prediction F_j

Cart algorithm

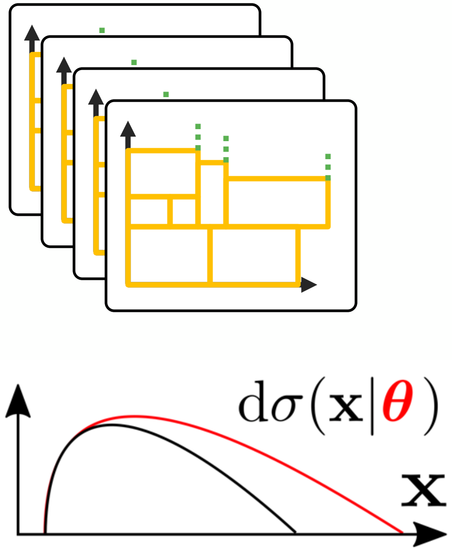


$$F_j(\boldsymbol{\theta}) = \frac{\sum_{\boldsymbol{x}_i\in j} w_j(\mathrm{SM})\, r_i(\boldsymbol{\theta})}{\sum_{\boldsymbol{x}_i\in j} w_j(\mathrm{SM})}$$

$$= \frac{\int \mathrm{d}z \frac{\mathrm{d}\sigma_{\boldsymbol{\theta}}}{\mathrm{d}(x,z)}}{\int \mathrm{d}z \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}(x,z)}}$$

"magic" (Kyle C.)

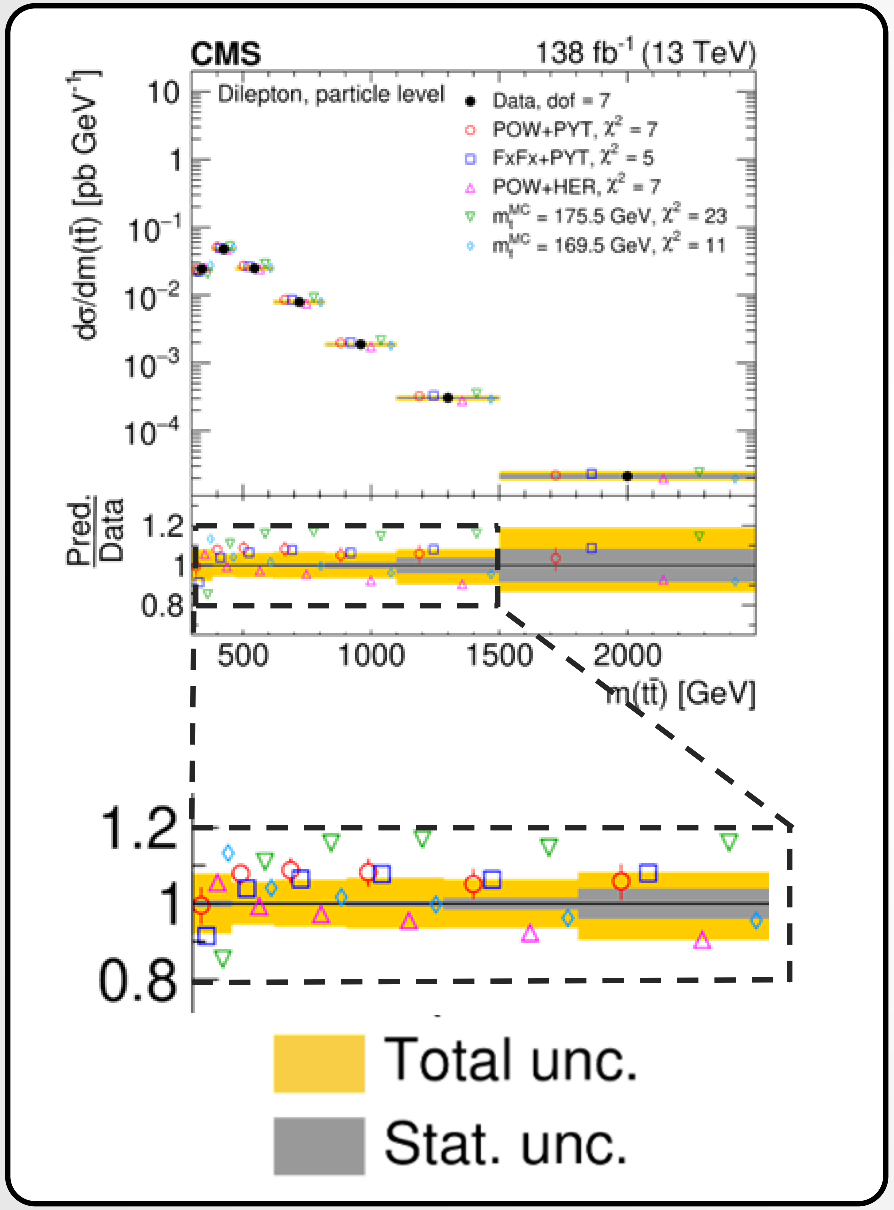
Boosting



- A tree is a hierarchical phase-space partitioning
  - Boosted Information Tree: Associate each region j with a polynomial $F_j(\boldsymbol{\theta})$
  - The non-linearity is in the change across node positions
  - Fitting tree: Optimize "node split positions" on some loss. Can compute $F_j(\boldsymbol{\theta})$ from events in node.
- Boosting elevates tree to an arbitrarily expressive regressor for $\mathrm{d}\sigma(\mathbf{x}|\boldsymbol{\theta})$ - ratios

BACK TO REALITY!

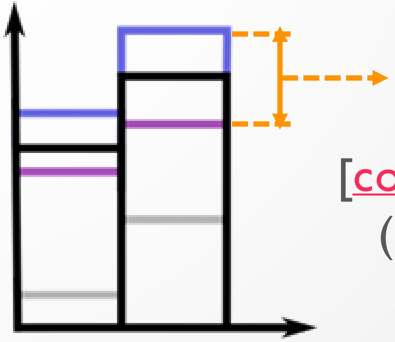
[CMS-TOP-20-006]



- Systematics dominate in many/most applications
- Binned analyses? Use additive model with exponentials

$$\text{prediction}(\boldsymbol{\theta}, \boldsymbol{\nu}) = \sum_{p=1}^{N_p} R_{n,p}(\boldsymbol{\theta}) \exp\left(\boldsymbol{\nu}^\top \Delta_{n,p,1} + \boldsymbol{\nu}^\top \Delta_{n,p,2}\, \boldsymbol{\nu}\right) \sigma_{n,p}(\text{SM})$$

- How to find the parameters Δ?
  - "Vary simulation" ⟷ Generate synthetic datasets
  - shift JEC, scale b-tagging efficiencies, PS weights, hDamp



$\Delta_{n,p}$

[combine paper]
(N. Wardle)

- Decades of experience with modeling choices

REFINABLE MODELING IN 3-STEPS

1. Let's write an unbinned *additive* model

$$\mathrm{d}\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu}) = \sum_{p=1}^{N_p} \underbrace{R_p(\boldsymbol{x}|\boldsymbol{\theta})}_{\text{SMEFT}} \underbrace{\alpha_p^{\nu_p}}_{\text{normalisation ("k-factors")}} \underbrace{\exp\left\{\boldsymbol{\nu}^\intercal \Delta_{n,p,1}(\boldsymbol{x}) + \boldsymbol{\nu}^\intercal \Delta_{n,p,2}(\boldsymbol{x})\boldsymbol{\nu} + \ldots\right\}}_{\text{systematics } S_p(\boldsymbol{x}|\boldsymbol{\nu})} \mathrm{d}\sigma_p(\boldsymbol{x}|\mathrm{SM})$$

2. The experimentalist (not the framework) decides on further specification

TT(2ℓ) has 90% purity: We have a single EFT process and a number of small backgrounds (DY, non-prompt,…)

$$\mathrm{d}\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu}) = R_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\theta}) S_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\nu}) \mathrm{d}\sigma_{\mathrm{EFT}}(\boldsymbol{x}|\mathrm{SM}) + \sum_{p=1}^{N_{\mathrm{bkgs}}} \alpha_p^{\nu_p} S_p(\boldsymbol{x}|\boldsymbol{\nu}) \mathrm{d}\sigma_p(\boldsymbol{x}|\mathrm{SM})$$

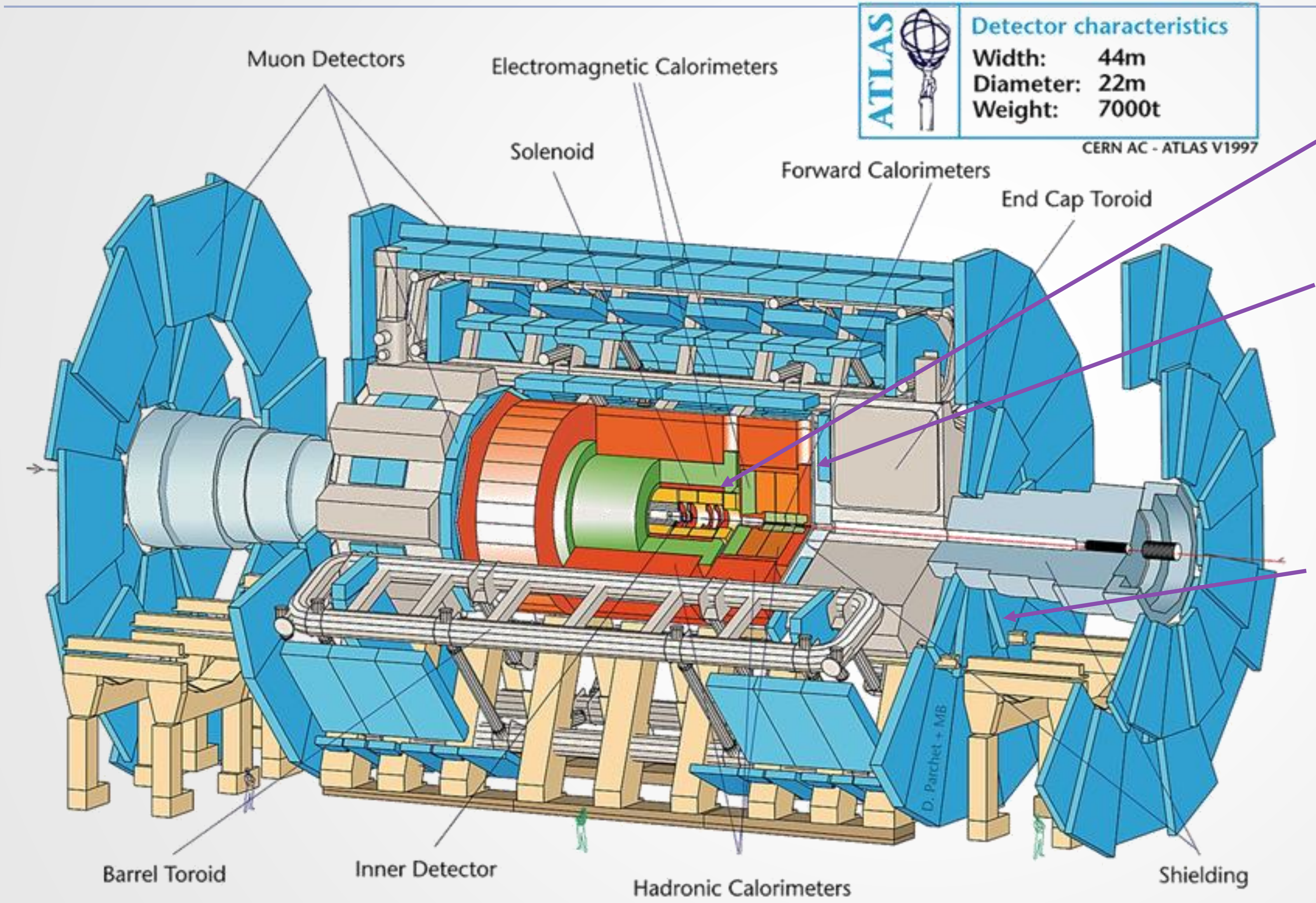
3. Form the ratio & learn the factors!

1) SMEFT learning — 2) systematics learning — 3) classifiers

$$\frac{\mathrm{d}\Sigma(\boldsymbol{x}|\boldsymbol{\theta},\boldsymbol{\nu})}{\mathrm{d}\Sigma(\boldsymbol{x}|\mathrm{SM})} = \frac{R_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\theta}) S_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\nu}) + \sum_{p=1}^{N_{\mathrm{bkgs}}} \alpha_p^{\nu_p} S_p(\boldsymbol{x}|\boldsymbol{\nu}) \frac{\mathrm{d}\sigma_p(\boldsymbol{x}|\mathrm{SM})}{\mathrm{d}\sigma_{\mathrm{EFT}}(\boldsymbol{x}|\mathrm{SM})}}{1 + \sum_{p=1}^{N_{\mathrm{bkgs}}} \frac{\mathrm{d}\sigma_p(\boldsymbol{x}|\mathrm{SM})}{\mathrm{d}\sigma_{\mathrm{EFT}}(\boldsymbol{x}|\mathrm{SM})}} \approx \frac{\hat{R}_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\theta}) \hat{S}_{\mathrm{EFT}}(\boldsymbol{x}|\boldsymbol{\nu}) + \sum_{p=1}^{N_{\mathrm{bkgs}}} \alpha_p^{\nu_p} \hat{S}_p(\boldsymbol{x}|\boldsymbol{\nu}) \hat{g}_p(\boldsymbol{x})}{1 + \sum_{p=1}^{N_{\mathrm{bkgs}}} \hat{g}_p(\boldsymbol{x})}$$

Adding systematics or processes *doesn't invalidate* partial training!

ATLAS UPGRADES FOR HL-LHC



Inner Tracking Detector (ITk)

All silicon, strips and Pixels up to $|\eta| \leq 4$
[ATLAS-TDR-025, ATLAS-TDR-030]

Muon system upgrade
New chambers in the Inner barrel region ($|\eta| \leq 2.7$)
[ATLAS-TDR-026]

High granularity timing detector (HGTD) $2.4 \leq |\eta| \leq 4.0$ with 30ps
[ATLAS-TDR-031]

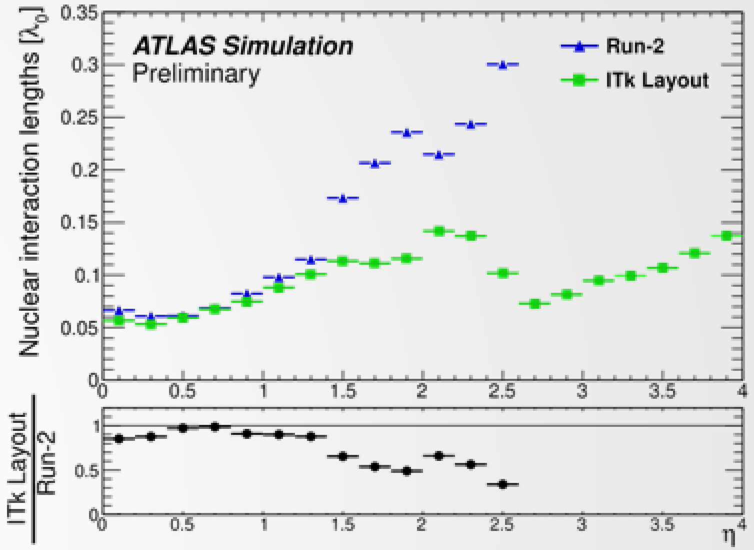
Upgraded Trigger and
Data Aquisition System
[ATLAS-TDR-029]

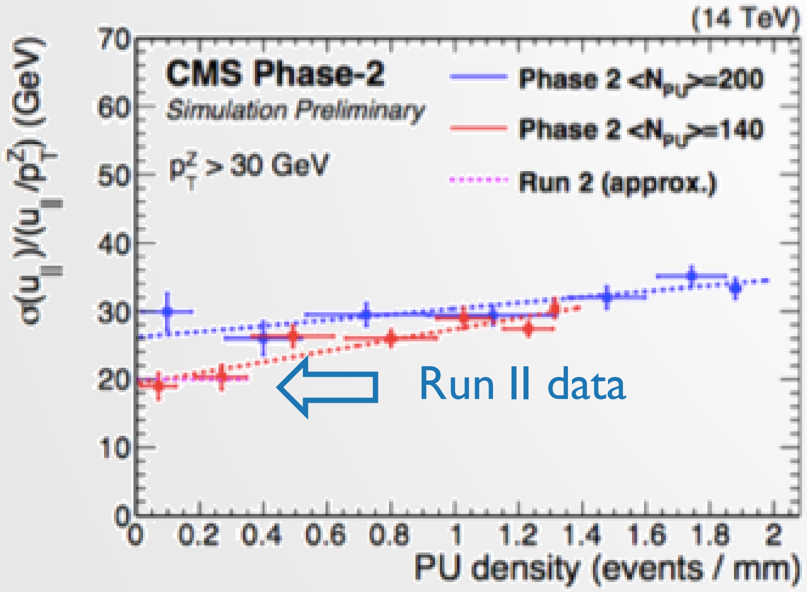
RECONSTRUCTION PERFORMANCE

[CMS-FTR-18-015, CMS-NOTE-2018-006]

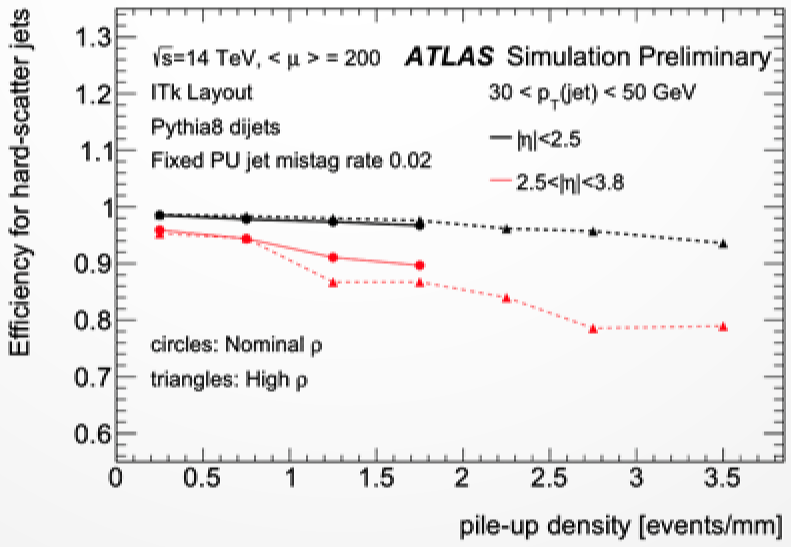
[ATL-PHYS-PUB-2021-024, ATL-PHYS-PUB-2021-023]

- ATLAS ITk nuclear interaction length vs. η with extended tracking coverage
- impacts b-tagging performance similar to Run II (200PU & up to |η| < 4)
- Excellent & stable PU jet rejection across all PU densities
- E_T^{miss} resolution not much worse than in Run II

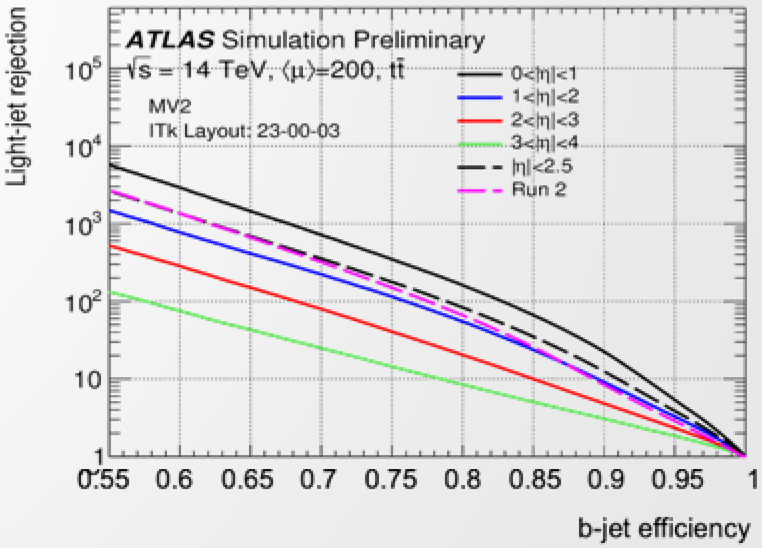




Puppi E_T^{miss} resolution for $p_T(Z)>30$



Hard-scatter jet efficiency vs. PU density

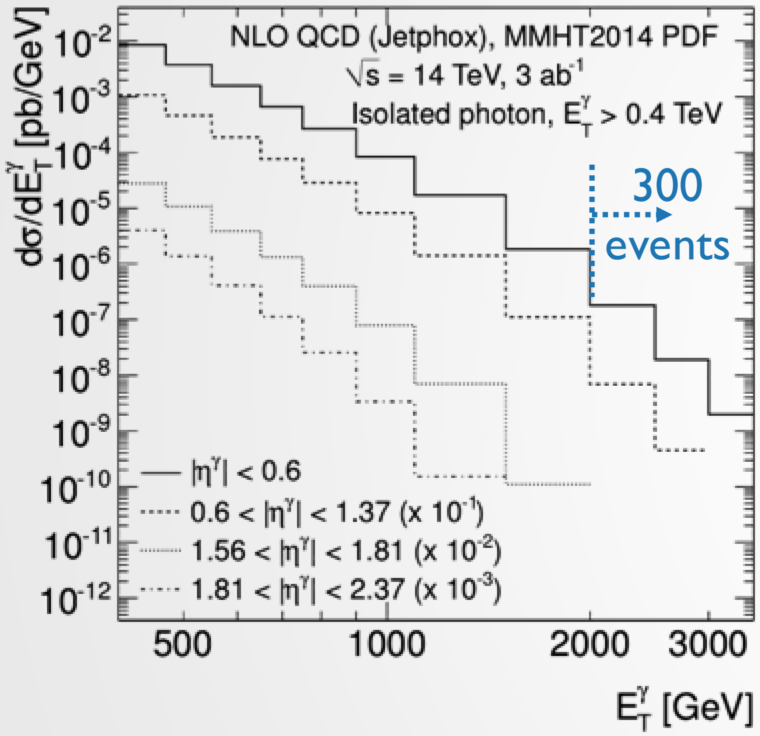


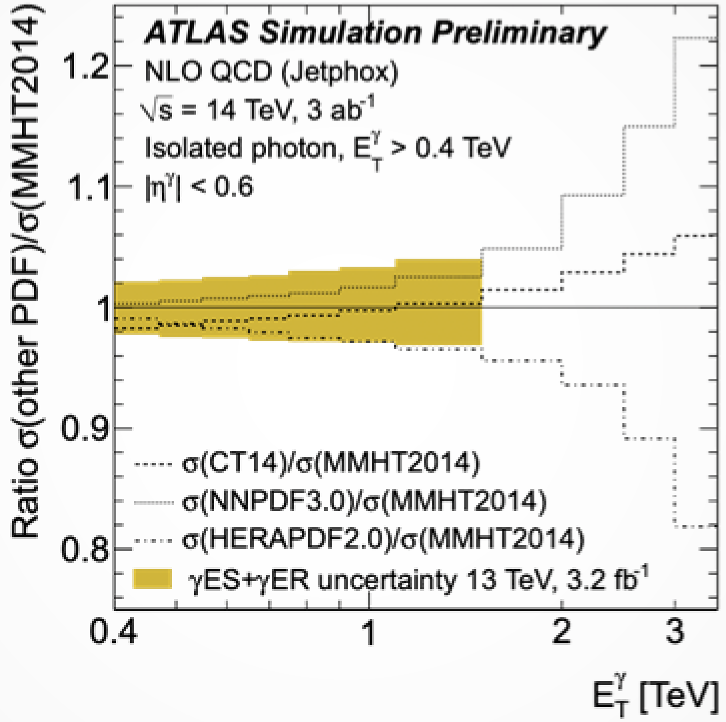
PDFs AT HL-LHC

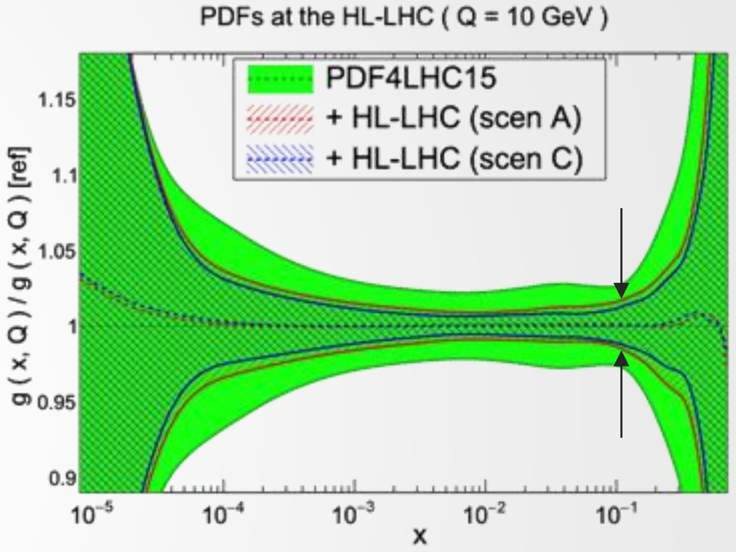
[arXiv:1810.03639]
[ATLAS-PHYS-PUB-2018-051]

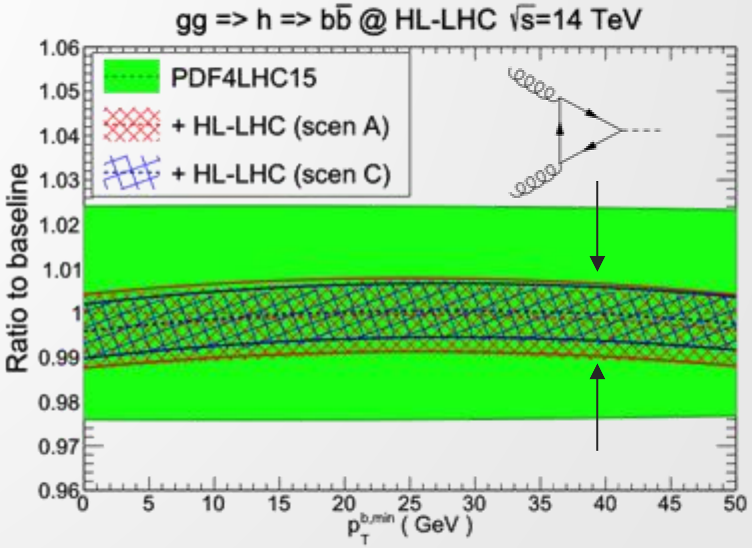
ATLAS EXPERIMENT

- ultimately: Drell-Yan at all m(ℓℓ), top quarks, W+charm, direct γ, forward W+Z, inclusive jets









- ATLAS direct γ up to $E_T^{\gamma} \approx 2$ TeV with good statistics
- differential high- E_T^{γ} x-sec ratio for different PDF sets
- "ultimate" PDF precision for projected measurements: > factor 2

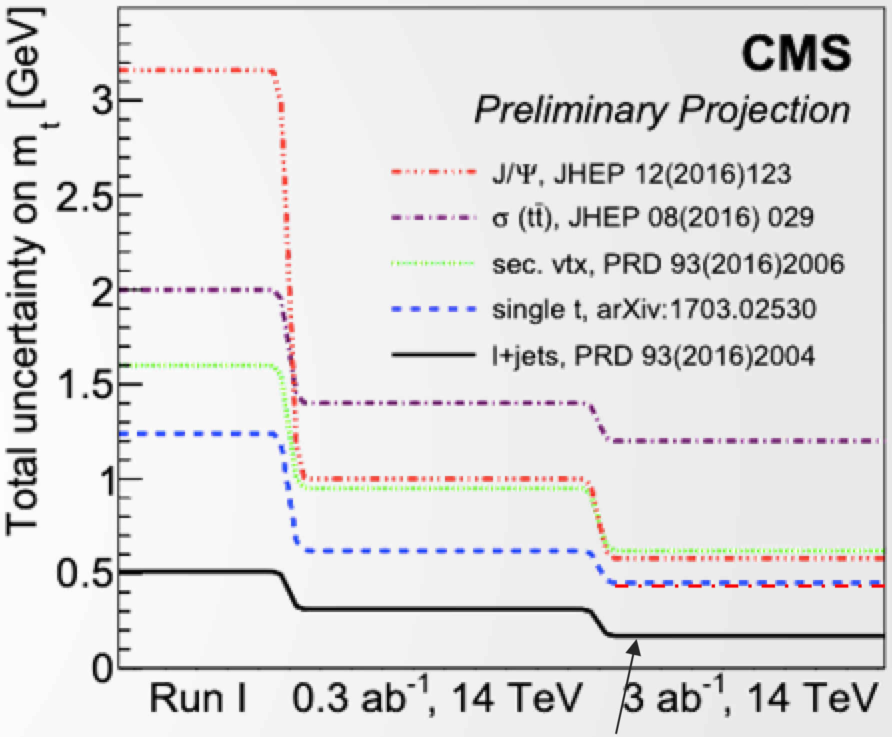
TOP QUARK MASS (OVERVIEW)

- Extremely simple tree level: SM masses from Yukawa coupling $y_t \approx 1$

$$-\mathcal{L}_{\text{Yukawa}} = y_d(\bar{q}_L\Phi)\, d_R + y_u(\bar{q}_L\widetilde{\Phi})\, u_R + y_\ell(\bar{\ell}_L\Phi)\, \ell_R + \text{h.c.}$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \omega_1 + i\omega_2 \\ \phi + i\omega_3 \end{pmatrix} \qquad \langle\phi\rangle \equiv v = \sqrt{\frac{-\mu^2}{\lambda}} = 246\ \text{GeV}$$

- Tree level: $m_t = y_t\, v/\sqrt{2}$. Higgs mechanism impressively confirmed!
- World average (Tev.+LHC): $m_t = 173.34 \pm 0.24$ (stat) ± 0.71 (sys)
- Extremely complex picture at the loop level:
  - $\overline{\text{MS}}$ 'short distance mass' approx. 10 GeV lower than pole mass @N^{3}LO
  - experiments use 'MC mass' ⟷ *would* need a well defined perturbative expansion of parton showers
  - direct and indirect top quark mass measurements (x-sec) relate differently to the Lagrangian parameters
  - confinement : ambiguous (non-perturbative) relations to the pole mass of O(250 MeV)



0.17 GeV ⟶ 0.1 %
dominated by JES