Top-quark Physics - Theory

- A unique laboratory to probe the SM and beyond -

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Outline

From prediction to discovery to precision, an incredible journey

Why top-quark physics is unique

- The multiple implications of the large top-quark mass.
- Short life-time and the access to an *unbound* quark state.

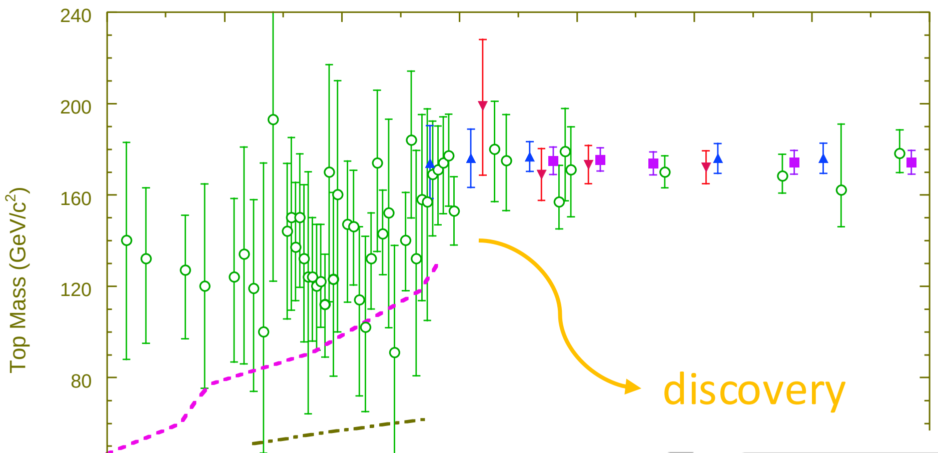
Theory predictions for top-quark physics at the LHC

- An incredibly rich program.
- Progress of theoretical predictions, meeting (HL-)LHC precision.

Constraining new physics via top-quark measurements

- Top-quark plays a special role in many models of new physics.
- Interesting to explore this connection in terms of effective interactions (EFT).

From prediction to discovery to precision



green dots → indirect fits

blue triangles → CDF

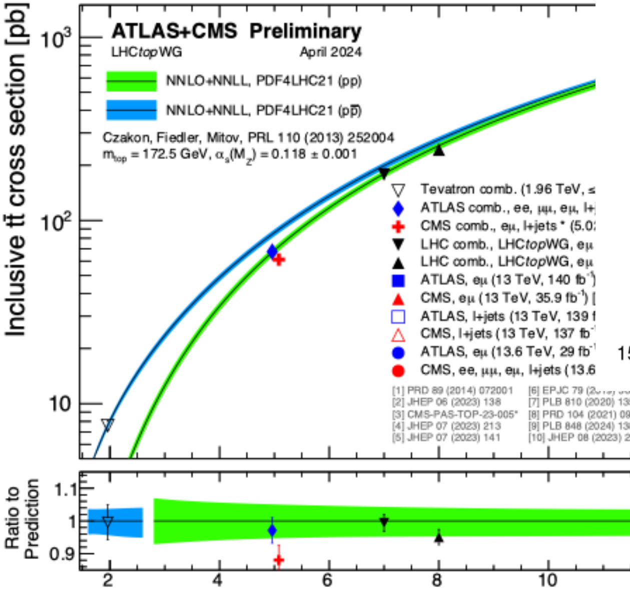
red triangles → D0

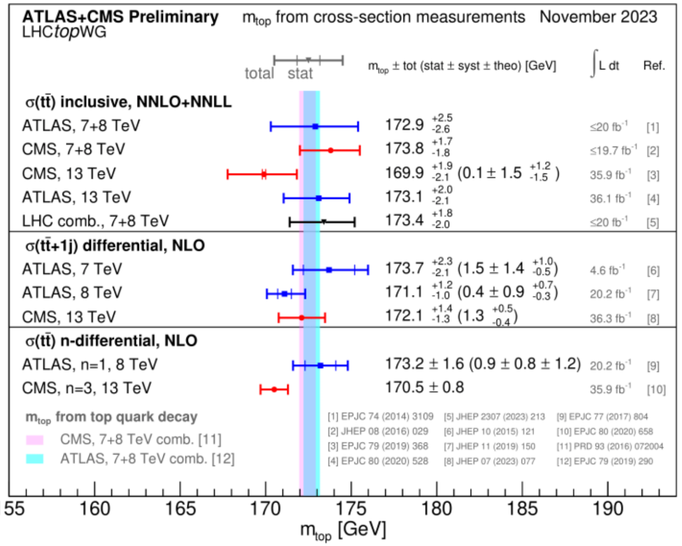
purple squares → world average

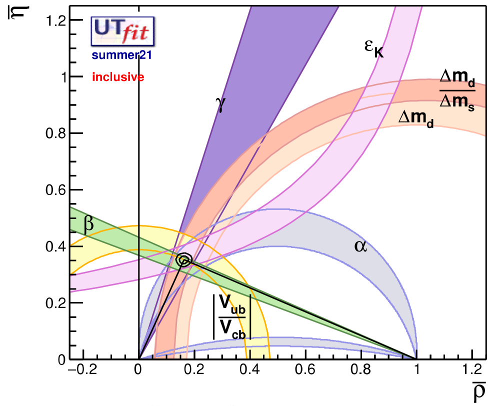
lines → various lower bounds

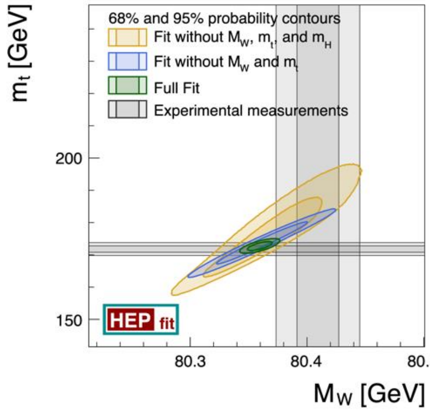
C. Quigg [hep-ph/0404228]

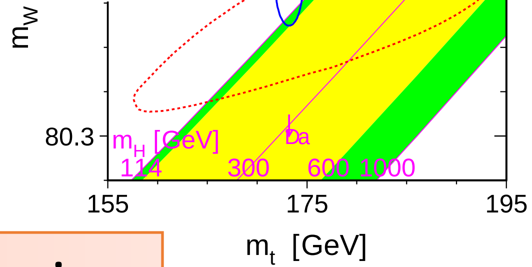
M_t becomes a crucial input in precision fits of the SM (including flavor)











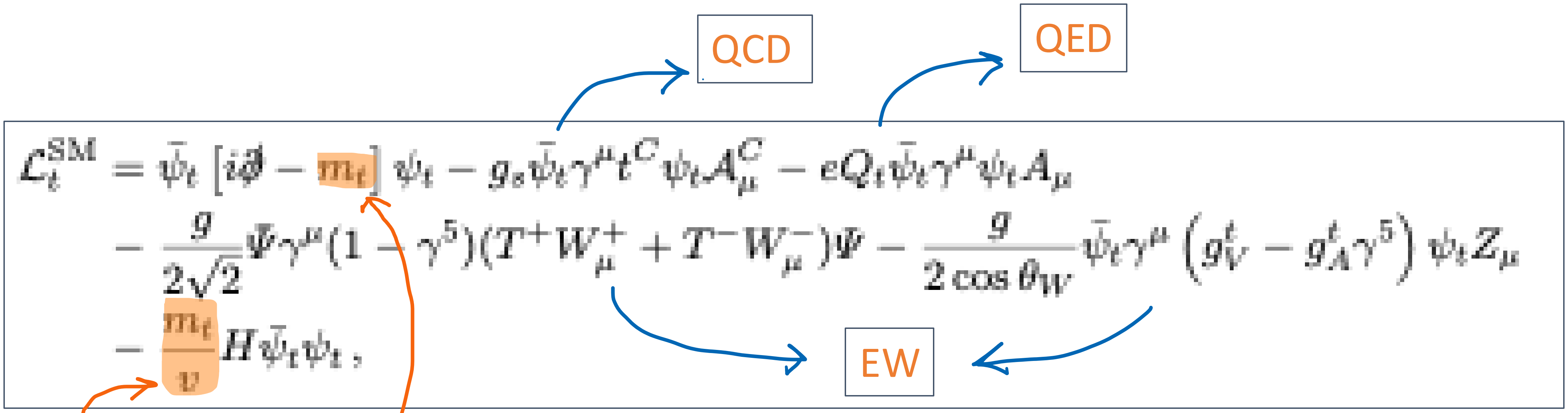
Anomalies in top-quark EW couplings (W,Z,H) possible hint of BSM physics

Why top-quark physics is unique

Many reasons to focus on top-quark physics and make it a core part of the (HL)-LHC physics program and a benchmark for future colliders.

Top quark intrinsically related to the most mysterious and probably least satisfactory aspects of the Standard Model (SM), namely the origin of the EW scale (why M_H?), the origin of the Yukawa interactions and its relation to the dynamic of flavor.

From the SM Lagrangian: yet another quark … not quite!



QCD

QED

$$\begin{aligned}\mathcal{L}_t^{\mathrm{SM}} = {} & \bar{\psi}_t \left[i\partial\!\!\!/ - m_t \right] \psi_t - g_s \bar{\psi}_t \gamma^\mu t^C \psi_t A_\mu^C - e Q_t \bar{\psi}_t \gamma^\mu \psi_t A_\mu \\ & - \frac{g}{2\sqrt{2}} \bar{\Psi} \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-) \Psi - \frac{g}{2\cos\theta_W} \bar{\psi}_t \gamma^\mu \left(g_V^t - g_A^t \gamma^5 \right) \psi_t Z_\mu \\ & - \frac{m_t}{v} H \bar{\psi}_t \psi_t \,,\end{aligned}$$

EW

$$y_{ij} \rightarrow \frac{m_t}{v}\,\delta_{ij} = {\sim}1$$

Large Yukawa coupling ⟷ Large mass

$$L_{Yuk} = y_{ij}\bar{\psi}_L^i \phi \psi_R^j + h.c.$$

Yukawa couplings

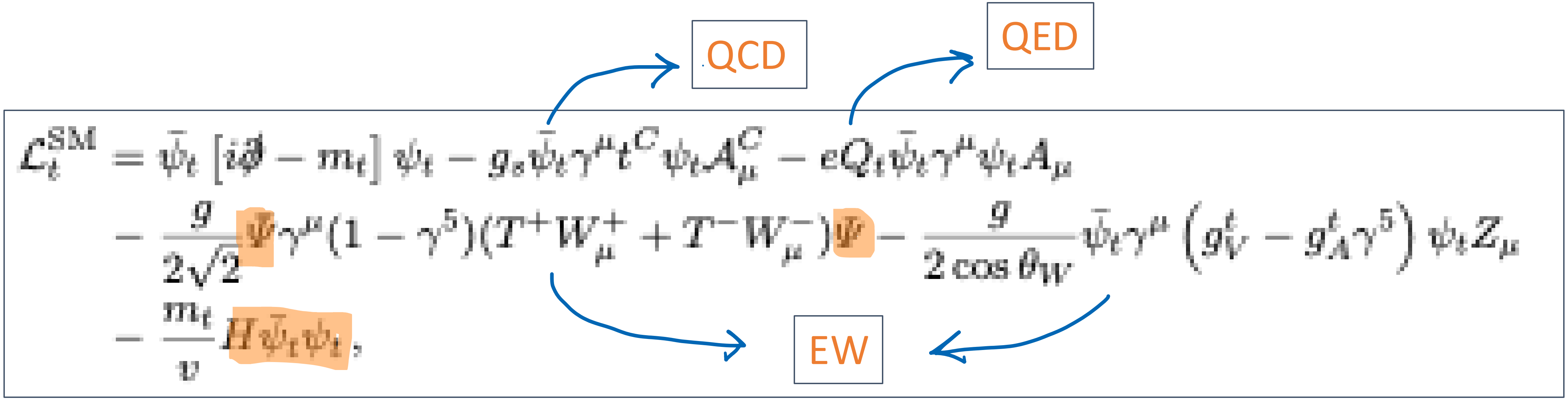
$$\phi \rightarrow H + v$$

fermion masses

Is this a new force?

- Why the hierarchy of fermion masses?
- Why the hierarchy of Yukawa couplings? (arbitrary in the SM)
- Why flavor-diagonal scalar couplings? ↔ Why one Higgs? (With more than one Higgs mass and current eigenstates can be different)

From the SM Lagrangian: yet another quark … not quite!



$$\mathcal{L}_t^{\mathrm{SM}} = \bar{\psi}_t \left[i\partial\!\!\!/ - m_t \right] \psi_t - g_s \bar{\psi}_t \gamma^\mu t^C \psi_t A_\mu^C - eQ_t \bar{\psi}_t \gamma^\mu \psi_t A_\mu$$

$$- \frac{g}{2\sqrt{2}} \bar{\Psi} \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-) \Psi - \frac{g}{2\cos\theta_W} \bar{\psi}_t \gamma^\mu \left(g_V^t - g_A^t \gamma^5 \right) \psi_t Z_\mu$$

$$- \frac{m_t}{v} H \bar{\psi}_t \psi_t ,$$

Fermion mass eigenstates ⟷ Flavor mixing

$$\Psi = (t, V_{tb} b + V_{ts} s + V_{td} d)^T$$

Three generations ⟷ CP violation

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

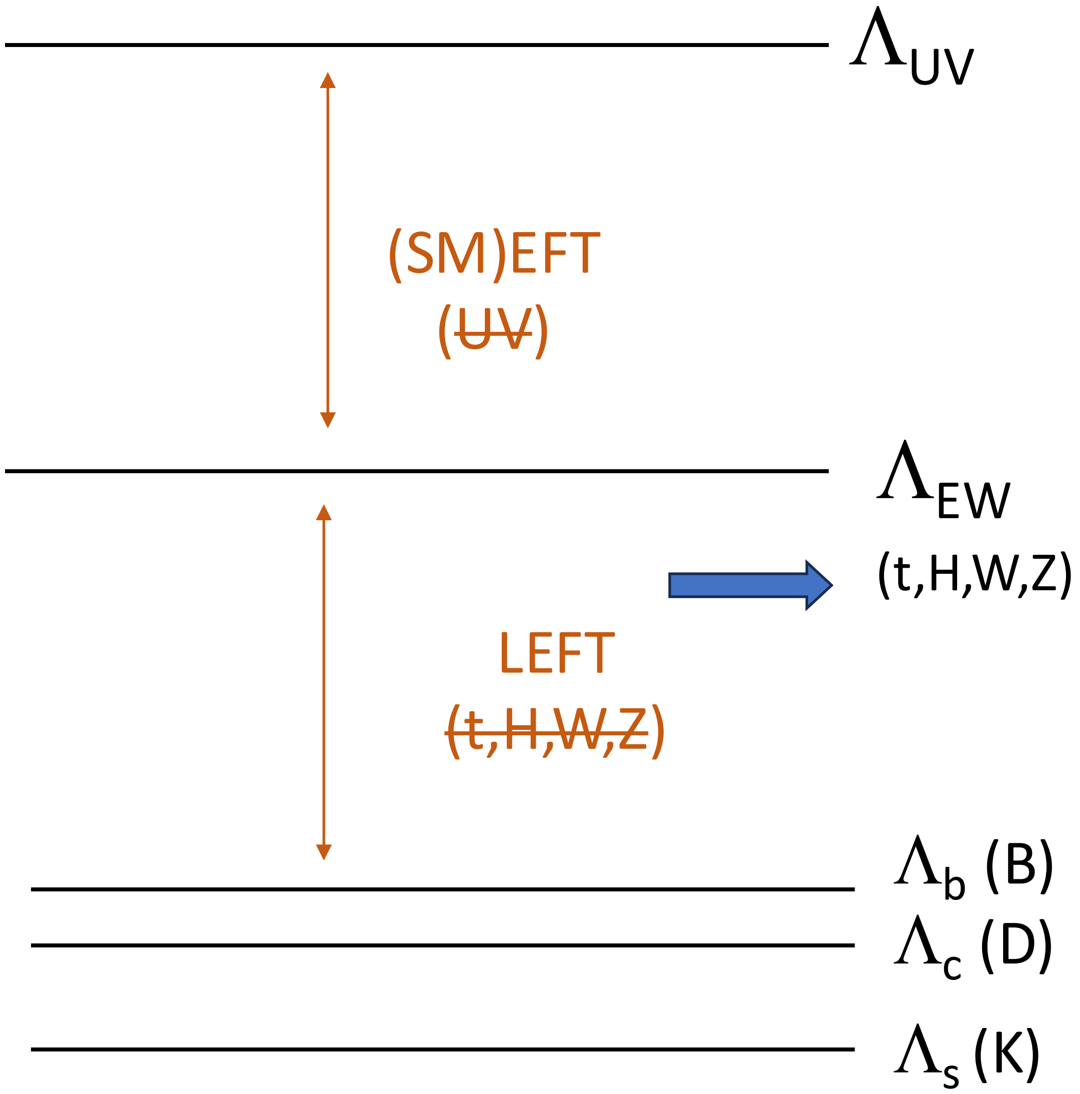
3x3 unitary matrix: 1 complex phase

Large mt effects in flavor physics

Historically:
Flavor physics has been one of the strongest constraints on m_t

Flavor physics: top quark belongs to the EW scale

Connecting far apart scales (from BSM to flavor) naturally lends itself to the EFT framework



Λ_{UV}

(SM)EFT

(~~UV~~)

Λ_{EW}

(t,H,W,Z)

LEFT

(~~t,H,W,Z~~)

Λ_b (B)

Λ_c (D)

Λ_s (K)

Heavy physics decouples and leaves
effective contact interactions of dim > 4

RGE

top-quark in
EFT operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,d} \frac{C_{i,d}^{\mathrm{SMEFT}}}{\Lambda^2} \mathcal{O}_{i,d}^{\mathrm{SMEFT}}$$

RGE

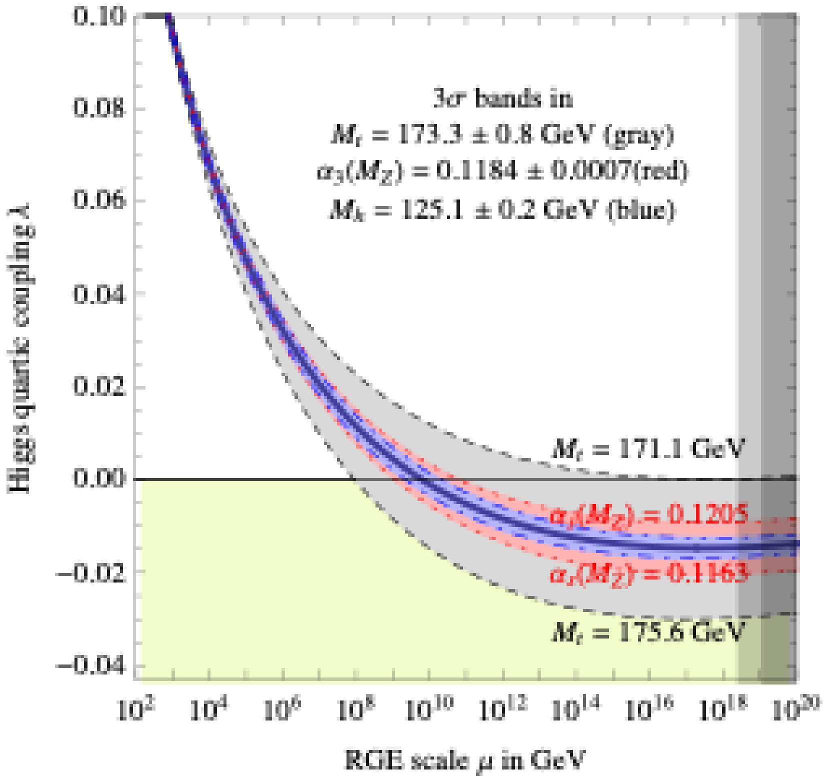
WC depend on m_t,
as well as
M_W,M_Z,M_H, … M_X

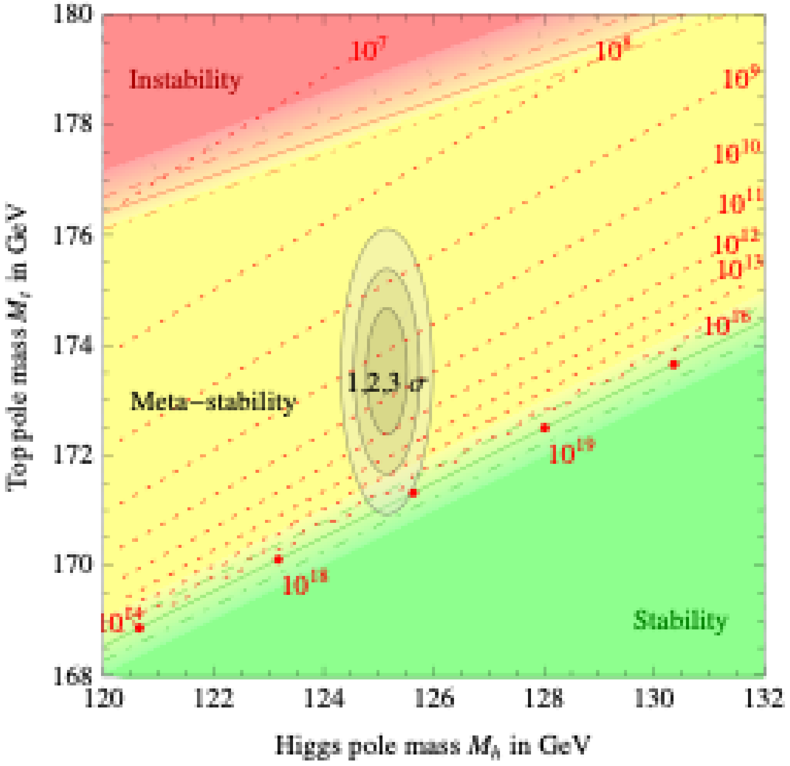
$$\mathcal{L}_{\mathrm{LEFT}} = \mathcal{L}_{\mathrm{QCD+QED}} + \sum_{i,d} \frac{C_{i,d}^{\mathrm{LEFT}}}{v^2} \mathcal{O}_{i,d}^{\mathrm{LEFT}}$$

Top-quark is part of the EW-scale dynamics

Large quantum effects on scalar potential

Top-quark effects are ubiquitous, and large, because of its large mass/Yukawa coupling.





[Buttazzo et al., arXiv:1307.3536]

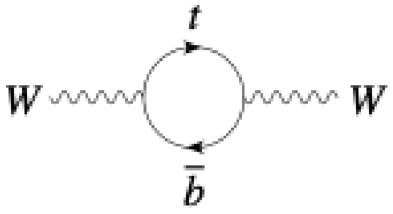
Including quantum effects induced by y_t in the study of the Higgs potential a condition of criticality is reached for a scale $\Lambda \sim 10^{11} - 10^{12}$ GeV.

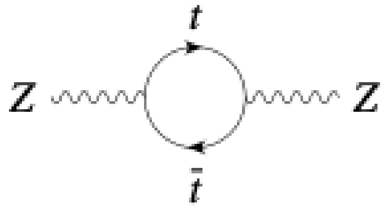
Top-quark mass and EW precision physics

- The symmetry structure of the Standard Model defines specific relations among couplings and masses.

- The renormalizability of the theory assures that tree-level relations are modified by finite calculable corrections.

- EW radiative corrections depend on m_t, e.g.





and similarly for all SM masses and couplings

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin\theta_W{}^2}\frac{1}{1-\Delta r(m_t, M_H)}$$

where,
at 1-loop

$$\Delta r(m_t, M_H) = c_t m_t^2 + c_H ln\left(\frac{M_H^2}{M_Z^2}\right) + \ \ldots$$

- **Precision measurements** of masses and couplings via multiple observables:
  - Test the consistency of the theory at the quantum level
  - Indirectly probe new physics via virtual effects

EW Global fit: general framework

- Set of input parameters (α or M_W scheme):
  - Fixed: G_F, α
  - Floating: M_W, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- Compute EW Precision Observables (EWPO), including all known higher-order SM corrections:
  - Z-pole observables (LEP/SLD): Γ_Z, $\sin^2\theta_{eff}$, A_l, A_{FB}, …
  - W observables (LEP II, Tevatron, LHC): M_W, Γ_W
  - m_t, M_H, $\sin^2\theta_{eff}$ (Tevatron/LHC)
- Perform best fit to EW precision data through different fitting procedures and compare with experimental measurements.
- Parametrize new physics effects on EWPO (tree-level) and constrain deviations in terms of chosen parameters:
  - Oblique parameters : S,T, U
  - Effective interactions: SMEFT
  - ….

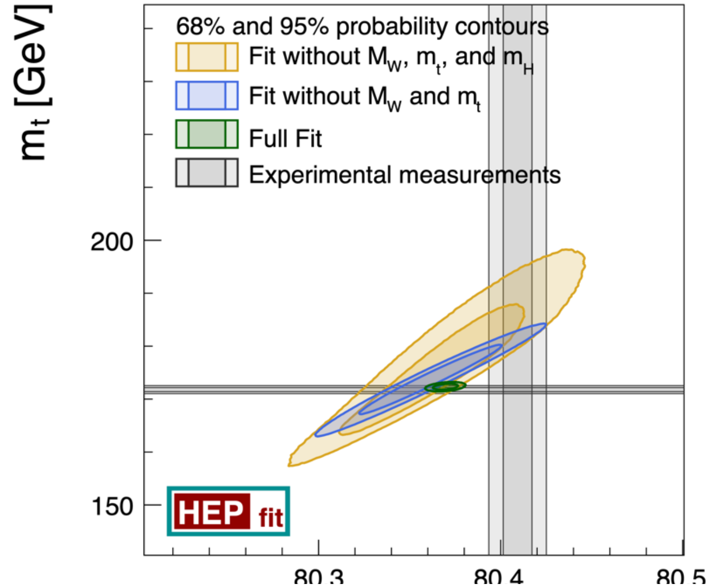
EW global fit of the SM - excerpt

J. de Blas et al. 2112.07274, 2204. 04204, plus updates

For M_W we combine:
- ☐ All LEP 2 measurements;
- ☐ Previous Tevatron average
- ☐ ATLAS and LHCb measurements
- ☐ CDF measurement [M_W=(80.4335±0.0094) GeV]
- ☐ ATLAS measurement [M_W=(80.360±0.016) GeV]

M_W = 80.409 ± 0.008 GeV (**standard**, with CDF)
M_W = 80.360± 0.012 GeV (**standard**, without CDF)

“standard”
(6.1 σ pull)

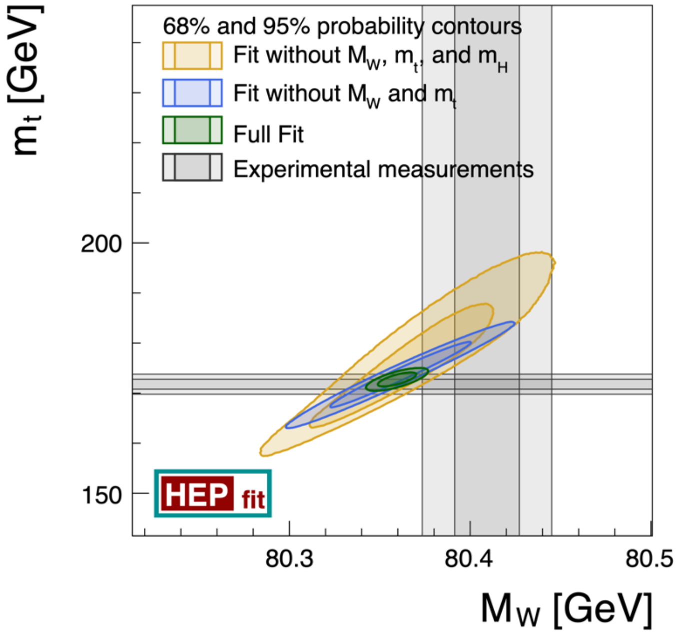


For m_t we combine:
- ☐ 2016 Tevatron combination
- ☐ ATLAS Run 1 and Run2 results
- ☐ CMS Run 1 and Run 2 results
- ☐ Recent CMS l+j measurement [m_t=(171.77±0.38) GeV]

m_t = 172.61 ±0.58 GeV (**standard**)

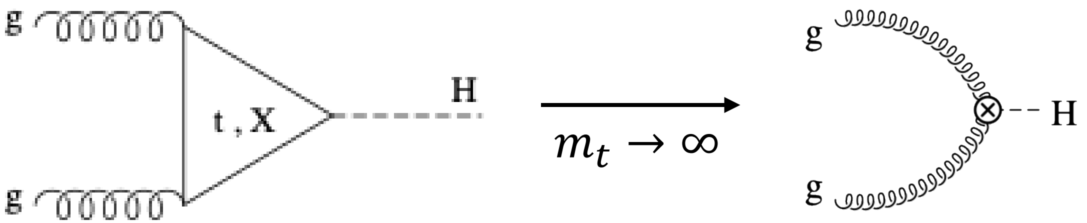
“conservative‘
(3.0 σ pull)

Due to tension between LEP, Tevatron, and LHC measurements consider also a **conservative** error of δM_W=18 MeV and δm_t=1 GeV (à la PDG)



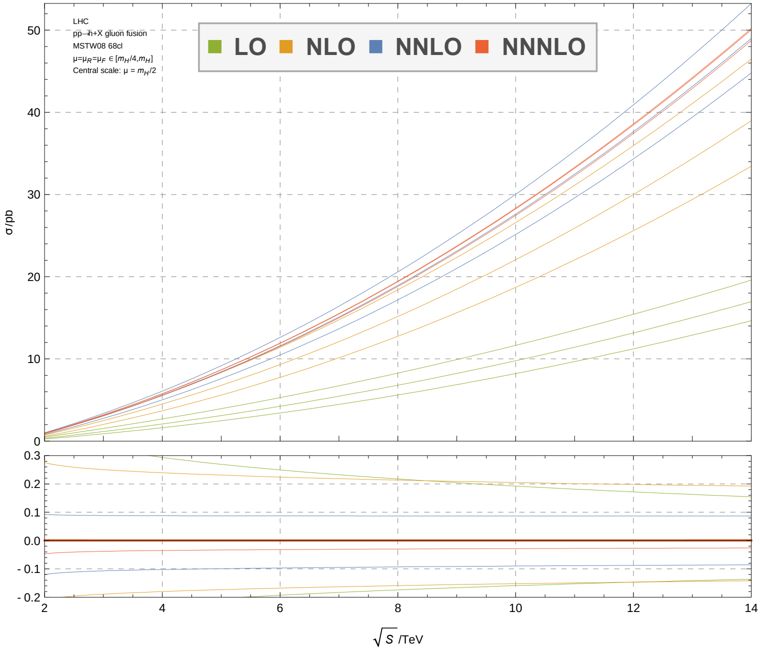
Dominant quantum effects in several processes

One of the most famous examples is Higgs-boson production via gluon fusion.
Loop-induced, dominated by top-quark loop, leading Higgs-boson production mode!



$$\mathcal{L}_{eff} = \frac{H}{4v} C(\alpha_{s,} m_t) G^{a,\mu\nu} G^{a}_{\mu\nu}$$

Calculate $C(\alpha_s, m_t)$



Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 1503.06056

Dominated by soft-dynamics: cannot resolve Higgs coupling to gluons

Allowed easier calculation of higher order corrections:
N^3LO QCD and NLO QCD+EW

Large width, short life-time

Very large width, $\Gamma_t \sim 1.5$ GeV $\gg \Lambda_{QCD}$

For $|V_{tb}| \gg |V_{td}|, |V_{ts}|$, dominated by $t \rightarrow Wb$ (with $W \rightarrow l\nu, q\bar{q}'$)

You should try to calculate it!

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

At NLO QCD, neglecting terms of order $m_b^2/m_t^2, \alpha_s^2, (\alpha_s/\pi)\, M_W^2/m_t^2$

Very short lifetime: $\tau_t \sim 10^{-25}$s, whereas $\tau_{QCD} \sim 10^{-24} s$

Check!

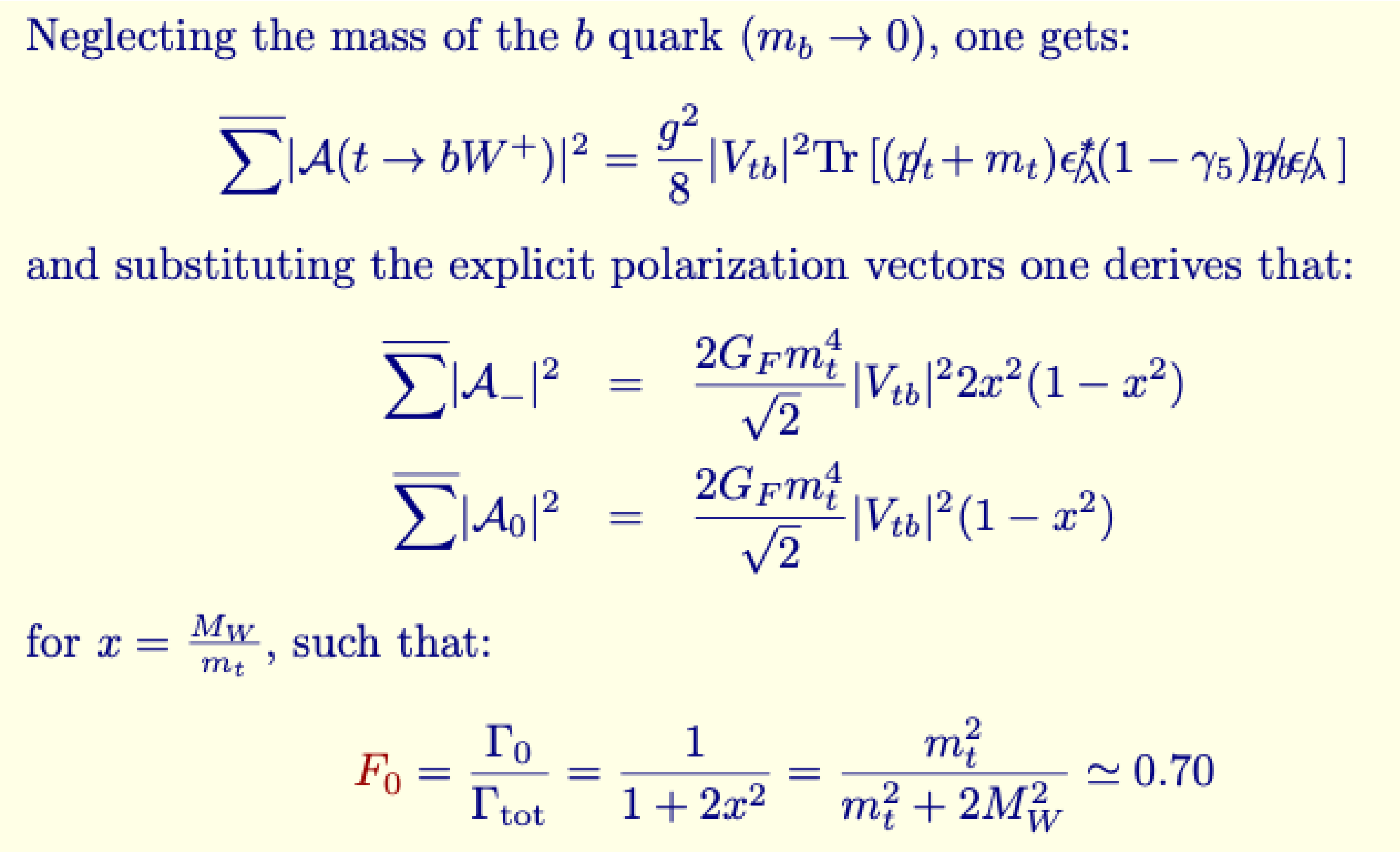
Top quarks decay before forming a bound state (meson): very clean laboratory to study its strong and electroweak interactions. Decay-product spin-correlation to parent top preserved.

For instance: the left-handed nature of weak interactions prefers for the W boson to be left-handed or longitudinal (conservation of angular momentum), modulus corrections proportional to m_b.

This can be calculated and measured: direct access to top interactions

Still, the top quark is colored, so we should not assume that we can treat it entirely as an on-shell physical state.

Exercise on helicity of W from top decay



Neglecting the mass of the b quark ($m_b \to 0$), one gets:

$$\overline{\sum}|\mathcal{A}(t \to bW^+)|^2 = \frac{g^2}{8}|V_{tb}|^2 \mathrm{Tr}\left[(\not{p}_t + m_t)\not{\epsilon}^*_\lambda(1-\gamma_5)\not{p}_b\not{\epsilon}_\lambda\right]$$

and substituting the explicit polarization vectors one derives that:

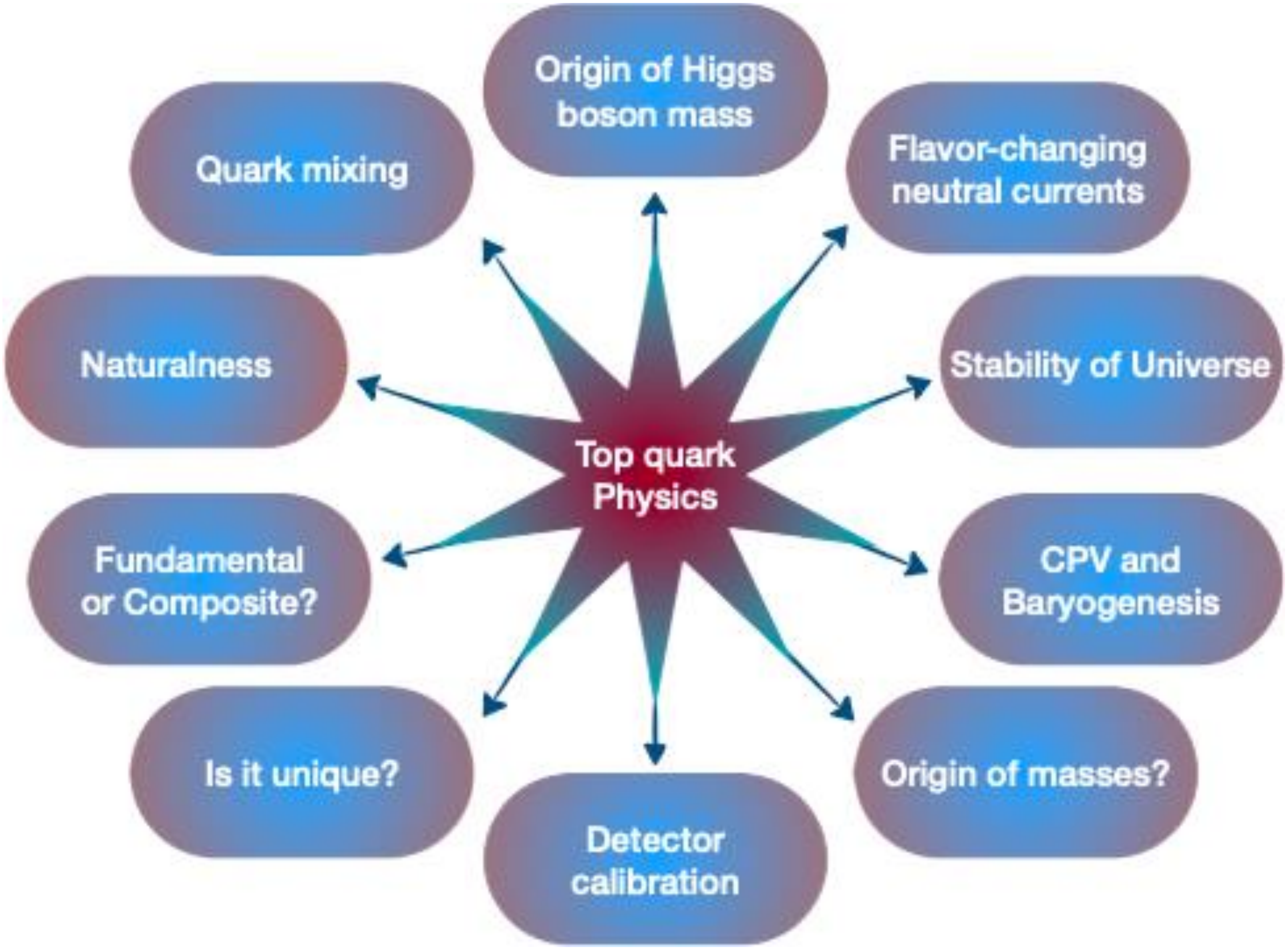
$$\begin{aligned} \overline{\sum}|\mathcal{A}_-|^2 &= \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2 2x^2(1-x^2) \\ \overline{\sum}|\mathcal{A}_0|^2 &= \frac{2G_F m_t^4}{\sqrt{2}}|V_{tb}|^2(1-x^2) \end{aligned}$$

for $x = \frac{M_W}{m_t}$, such that:

$$F_0 = \frac{\Gamma_0}{\Gamma_{\mathrm{tot}}} = \frac{1}{1+2x^2} = \frac{m_t^2}{m_t^2 + 2M_W^2} \simeq 0.70$$

Reproduce these results, including F_- and compare with experimental measurements

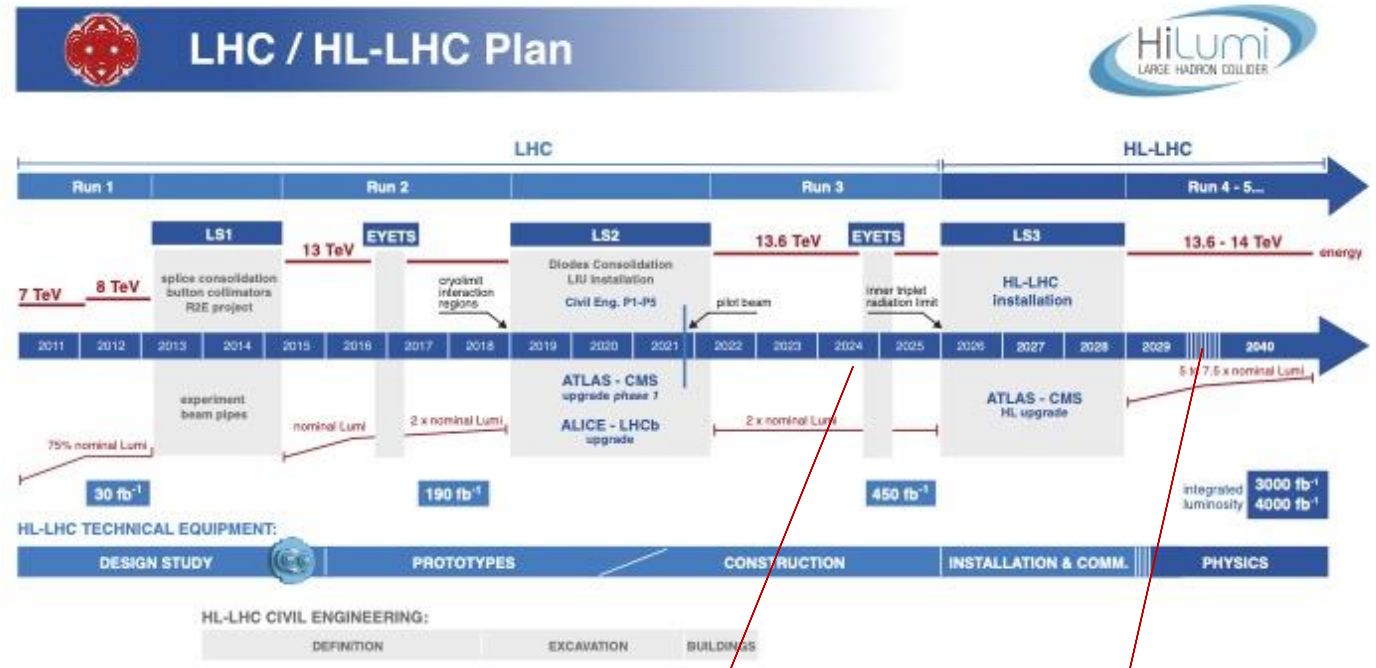
Top-quark physics central to most of the big open questions in particle physics



Theory predictions for top-quark physics at the LHC

- Top-quark physics is central and unique to the physics program of the (HL-)LHC. A growing spectrum of top-physics observables is being measured with higher precision and theoretical predictions are being improved to match the experimental accuracy.

The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

Indirectly via Top (Higgs, etc.)

- More than 100 millions top quarks produced so far.
- LHC will define top physics till the next high-energy collider
  - e^+e^- > 500 GeV
  - pp@100 TeV
  - $\mu^+\mu^-$ > 10 TeV

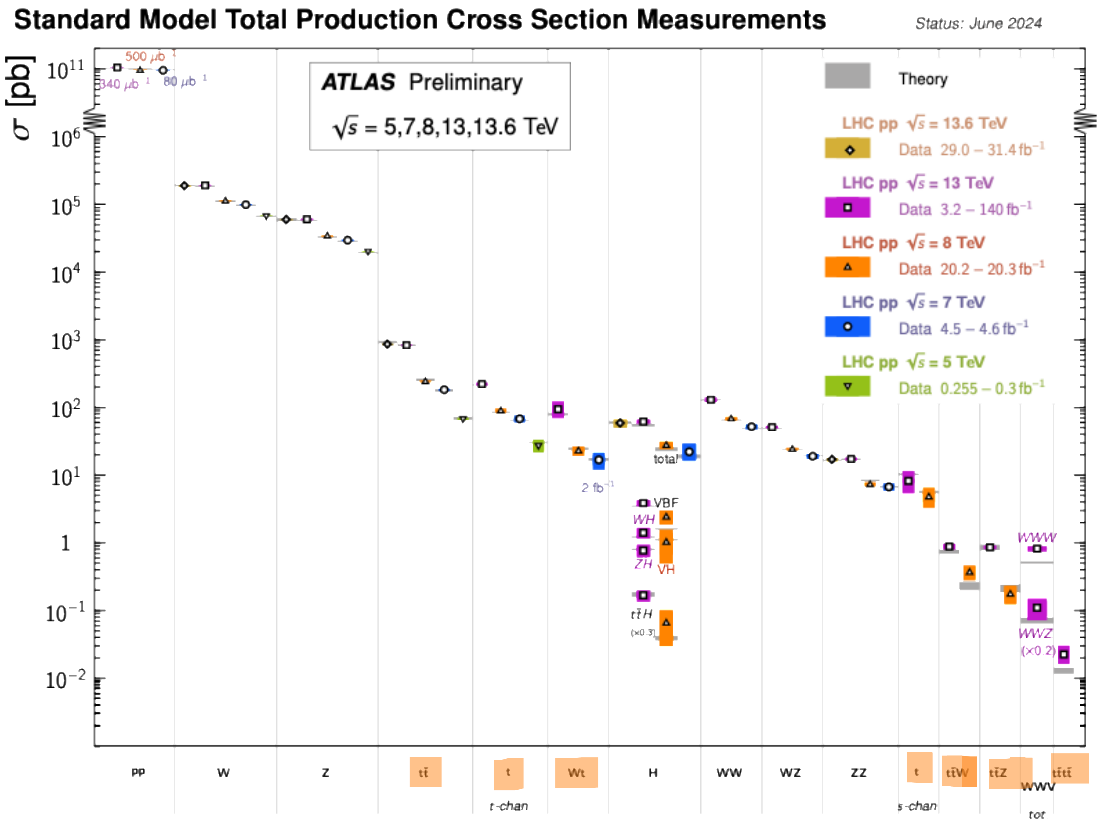
Statistical limitations will be overcome for a very large number of observables

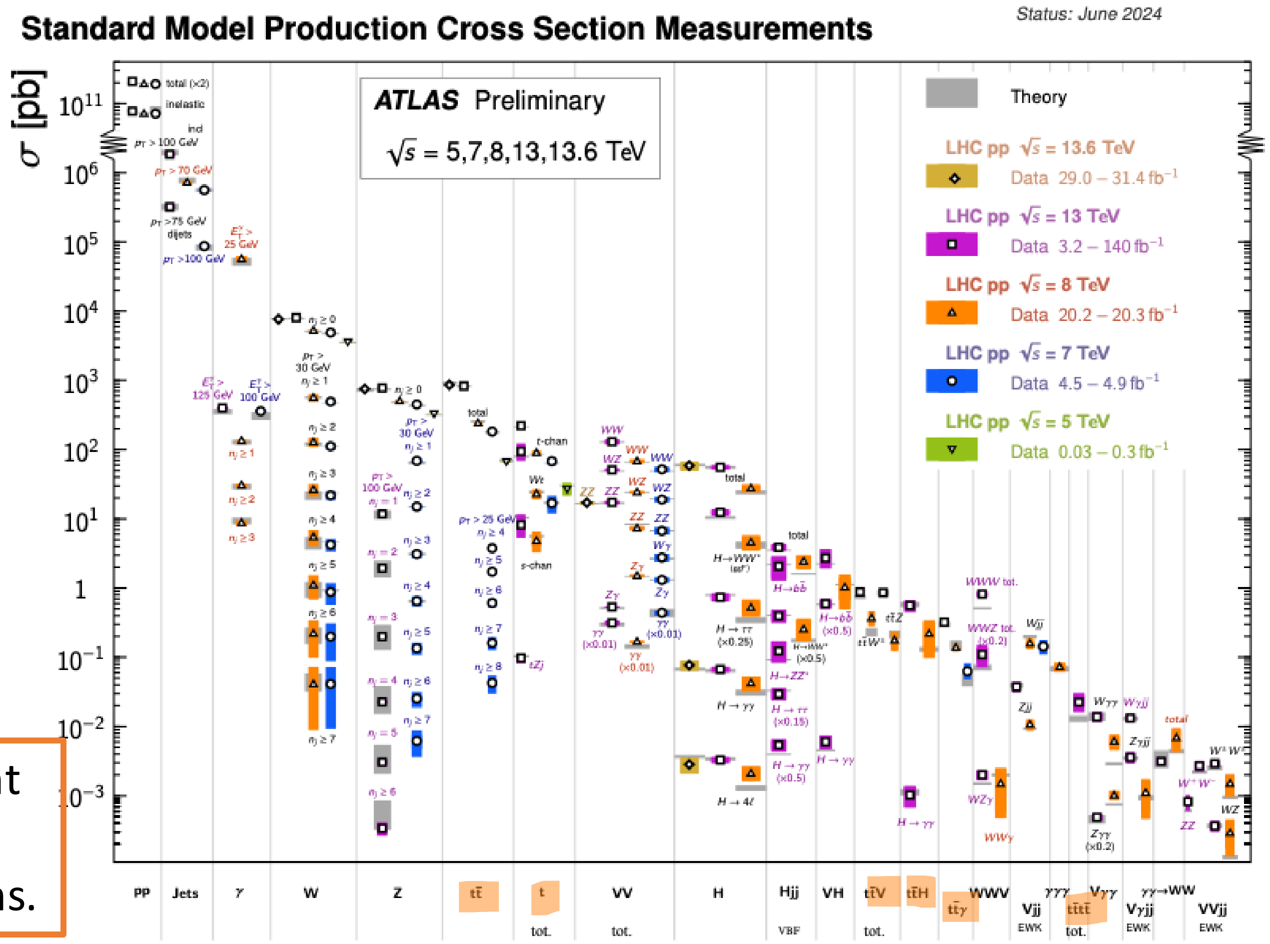
Reach % level precision

→ 2-fold increase in statistics by the end of Run 3

→ 20-fold increase in statistics by the end of HL-LHC!

The breadth of LHC measurements

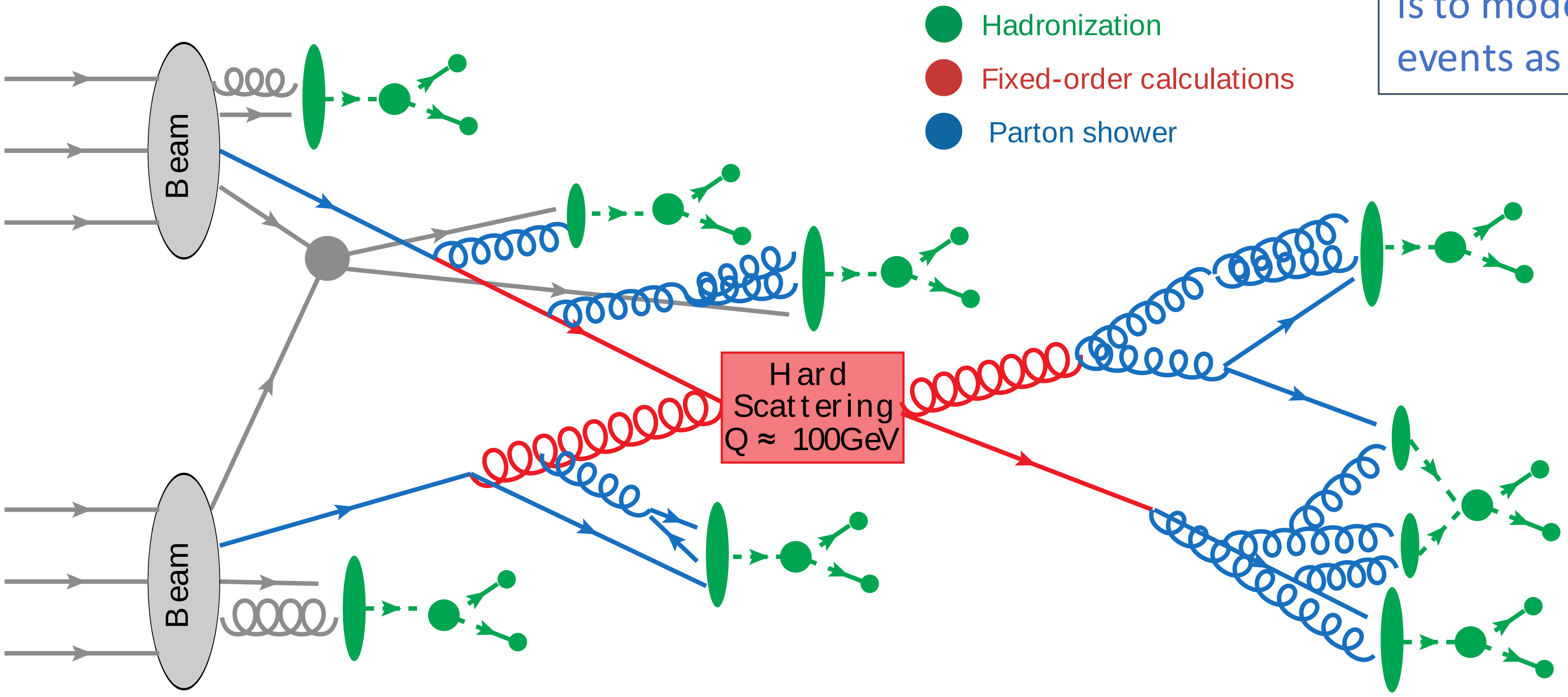




Top-quark properties are extracted from the measurement of processes that involve direct top-quark production or receive indirect top-quark dependent quantum corrections.

Dissecting the challenge

The goal of theoretical predictions is to model the complexity of LHC events as closely as possible



Huge progress in the last two decades for all components of hadronic event modeling

From S. Ferrario Ravasio, RADCOR 2023

$$d\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \widehat{d\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution Functions (PDF)

hard-scattering partonic xsection (pQCD+EW)

Hadronization, non-p QCD