Experimental Review of Electroweak and Higgs Physics

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
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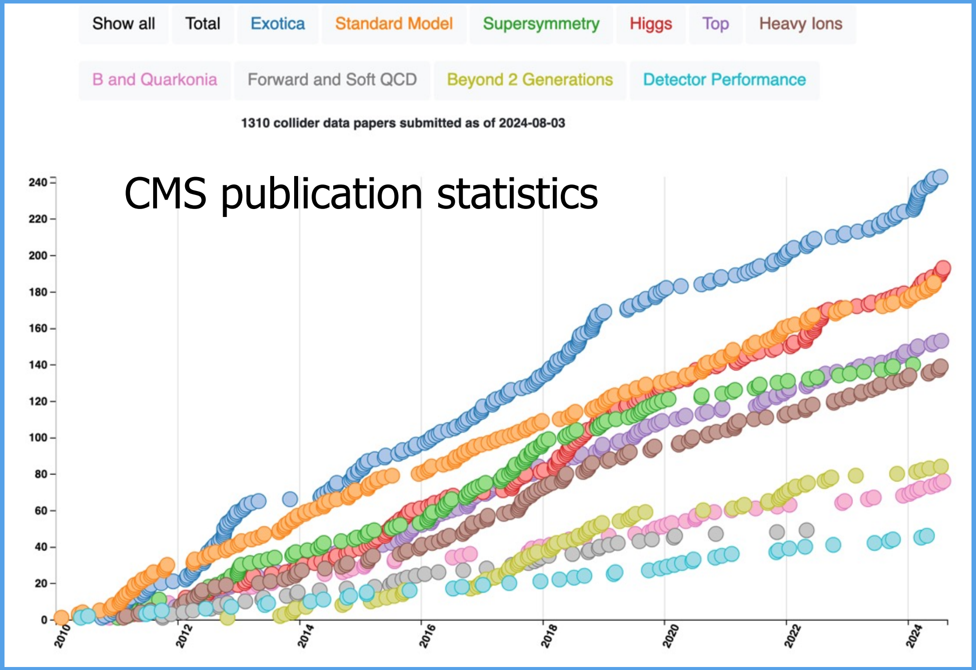
disclaimer

- we live in a time of enormous progress in Higgs and EW results
- the LHC is like an Eldorado for this field of physics
- a wealth of new results is becoming available



- in 2h we can only talk about a tiny fraction of these results
- results shown reflect a personal selection
  - mixture of historical review with latest results

for all the progress in the theory sector → lecture by D. Zeppenfeld

content of today and tomorrow

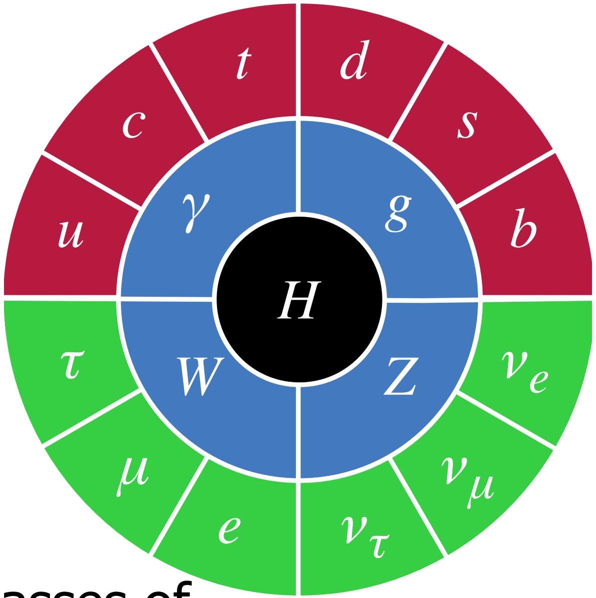
Lecture 1: Electroweak physics

- electroweak precision tests:
  - precisions measurement with single Z and W bosons
    - LEP legacy, new LHC results: $\sin^2\theta^l_{\text{eff}}$, $\Gamma(Z \to \text{inv})$, M_W , Γ_W, $\mathcal{B}(W \to \tau\nu_\tau)$
  - global checks of internal consistency, aka 'global EW fits'
- multiboson production at high energies: TGC and QGC
  - diboson production, triboson production
    - vector-boson scattering (VBS), towards polarized VBS

Lecture 2: Higgs physics

- Higgs boson properties (mass, spin and parity, width)
- Higgs boson couplings
  - signal strength, differential cross sections, Simplified Template Cross Sections (STXS), CP violation in the Higgs sector
- Probing the Higgs potential

The electroweak sector of the SM



- EW sector is based on local gauge symmetry

  $SU(2)_L \times U(1)_Y$

- electroweak gauge bosons:

  W^+, W^-, Z^0, γ (+H via spont. symmetry breaking)

  - tree level: fully described by 3 parameters:
    - g, g', v or α_{QED}, G_F, M_Z $\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$

- with HO: theory provides precise predictions of masses of gauge bosons and their interaction strengths

- allows rigorous tests of the theory

measurements of (pseudo-)observables and cross-sections involving these bosons

comparison

calculations of (pseudo-)observables and cross-sections as accurately as possible

focus of today

(cf. Lecture by D. Zeppenfeld)

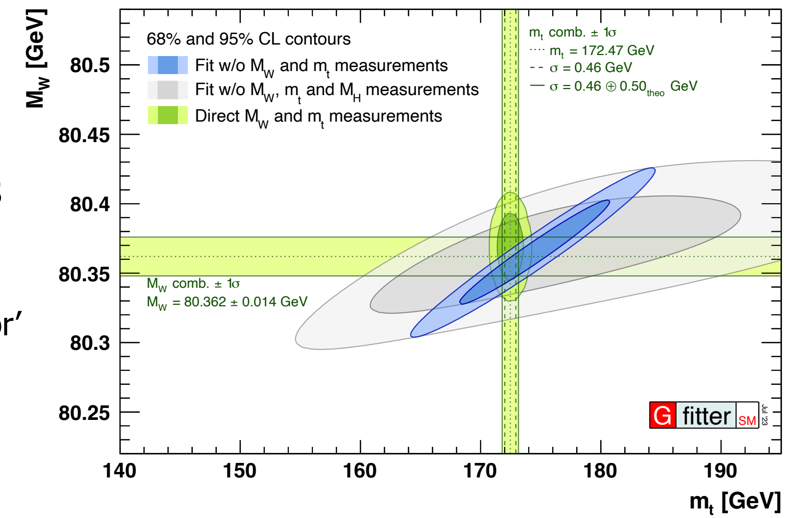
Tests of the electroweak theory

current HEP (at the LHC) follows two approaches:

1. precision frontier

measurement of EW precision observables and comparision with precision theory

global consistency checked in 'global fits of the ew sector'

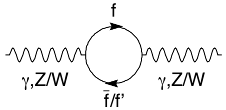


Gfitter group, Y. Fischer, EPS23

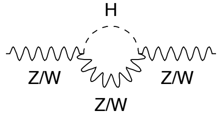
at loop level all fields enter the calculations

e.g. in boson propagators

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}G_F m_Z^2}\frac{1}{1-\Delta r}}\right).$$



$\propto m_t^2$



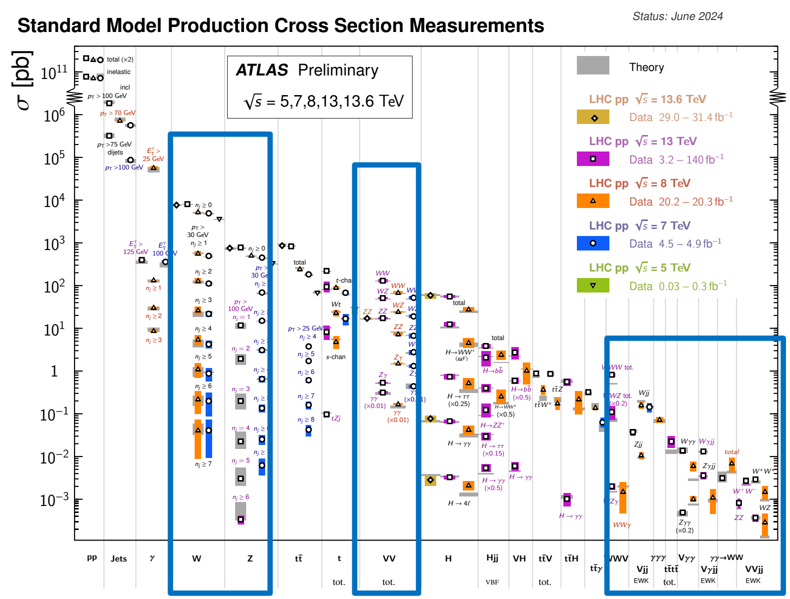
$\propto \log\frac{M_H}{M_Z}$

or couplings $\sin^2\theta^f_{\text{eff}} = \kappa_f\left(1-\frac{M_W^2}{M_Z^2}\right)$

detailed tests of non-trivial quantum effects and internal consistency of the electroweak sector

Tests of the electroweak theory

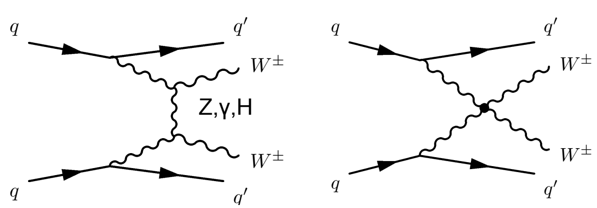
current HEP (at the LHC) follows two approaches:

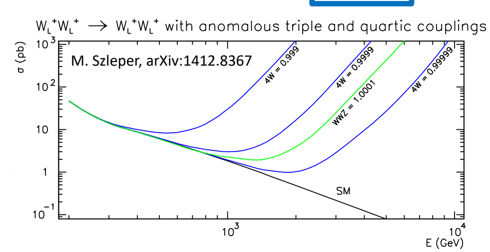


2. energy frontier

measurement of cross-sections for (multi-) boson production at high E and comparison with theory

note: SM often features exact cancellation of divergencies, e.g. via H-diagramms





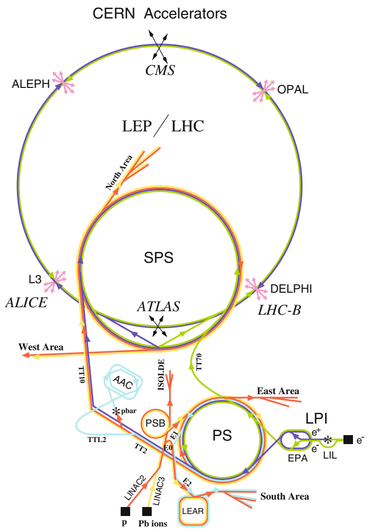
slight deviations from SM could lead to large effects

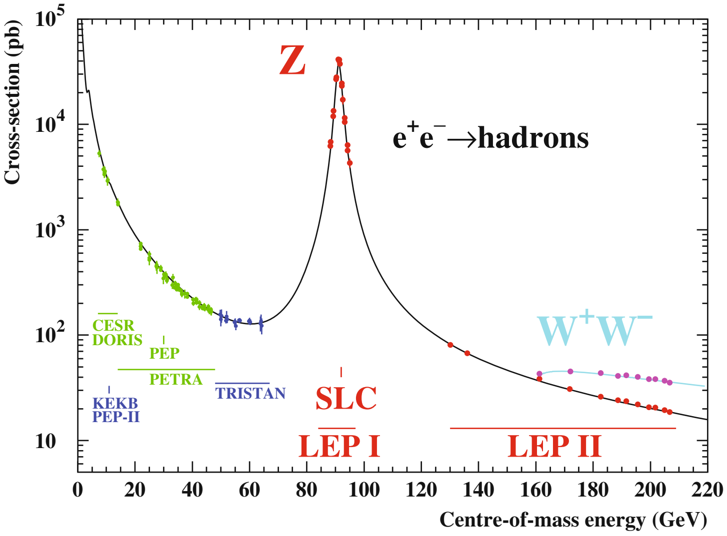
detailed tests of non-trivial quantum effects and internal consistency of the electroweak sector

precision measurements with Z bosons

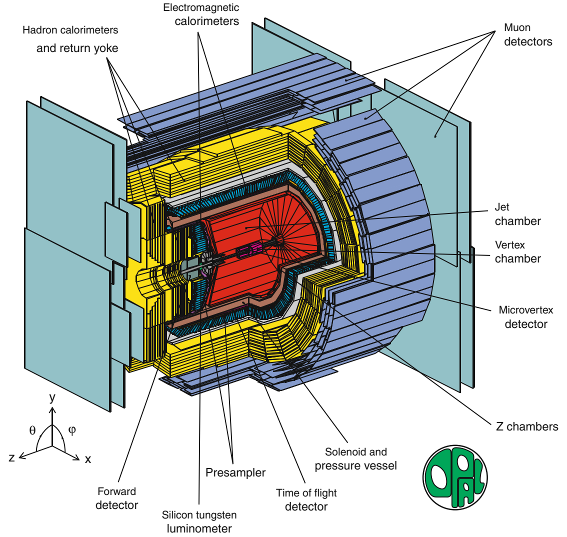
most important EW measurements done at LEP

- e^+e^- collider with four experiments: ADLO
- data taking phases (1989-2000):
  - LEP I:
    - high precision study of Z^0 pole
  - LEP II:
    - studies above WW threshold
    - search for the Higgs (up to $\sqrt{s} = 209$ GeV)





example dectector: OPAL



fanastic experimental conditions

- lepton collider is perfect maschine for electroweak precision measurements

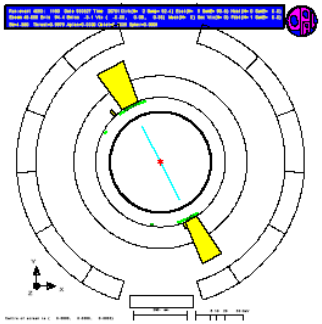
  - collision of known fundamental particles
  - centre-of-mass energy is exactly known in each event
  - events are experimentally clean
    - hardly any backgrounds (superb S/B ratio)
      - no pile-up or underlying event
    - EW processes have small cross-sections
      → basically no trigger preselection

- particles in energy reach can be studied with great precision (e.g. Z, W)

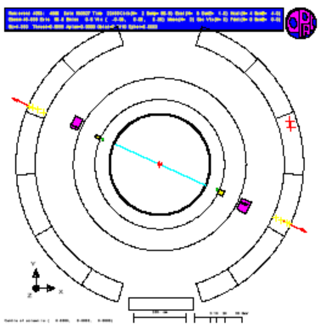
- only with LEP data, the SM entered the precision era

example events recorded by OPAL detector

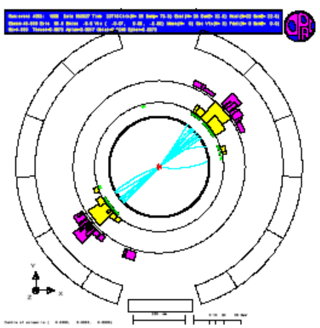
$e^+e^- \to e^+e^-$



$e^+e^- \to \mu^+\mu^-$



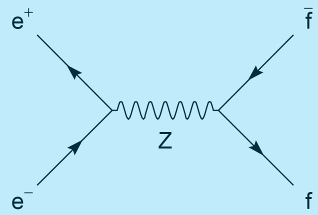
$e^+e^- \to q\bar{q}$

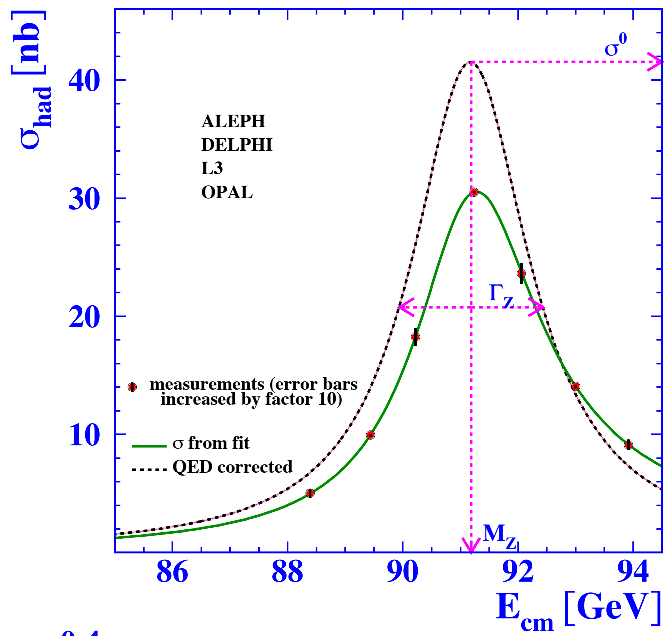


most precise EW measurement: Z^0 lineshape

ADLO, Phys.Rept.427:257-454,2006, hep-ex/0509008

- $E_{\rm cm}$ scan → measurement of hadronic cross-section

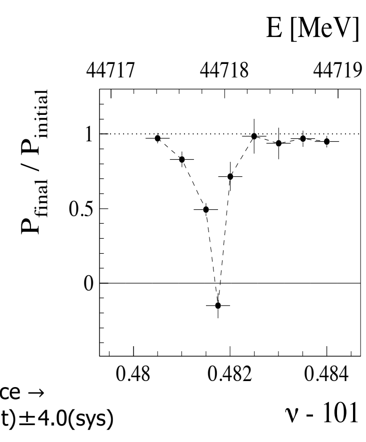




  - corrections of radiative effects, γ-exchange and γZ-interference yield 'pole' quantities

$$M_Z = 91.1875 \pm 0.0021 \text{ GeV}$$
$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$
$$\sigma^0_{\rm had} = 41.450 \pm 0.037 \text{ nb.}$$

  - crucial ingredient: knowledge of beam energy with excellent precision (via 'resonant depolarisation'): $\Delta E_{\rm beam} = \pm 0.2$ MeV



- impossible to be improve at hadron colliders

note: mass measurements at hadron colliders are conceptually different: measurement of invariant mass of decay products of the resonance → depends on energy/momentum resolution of detectors; best measurement reported by CDF alongside m_W measurement: 91192.0±6.4(stat)±4.0(sys) MeV (muon channel) and 91194.3±13.8(stat)±7.6(sys) MeV (electron channel), PDGl average: 91192.3±7.1MeV

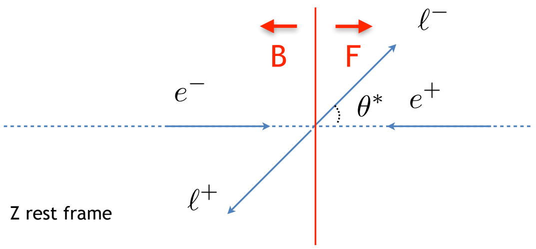
measurements of FB asymmetries at LEP

ADLO, Phys.Rept.427:257-454,2006, hep-ex/0509008

$$A_{FB}^{f} = \frac{N_F - N_B}{N_F + N_B}$$

N_F: number of events with $\cos\theta_f^* > 0$
N_B: number of events with $\cos\theta_f^* < 0$

- measure production polar angle wrt to initial electron and determine fermion (rather than antifermion)
  - easy in e^+e^-: Z rest frame = lab frame, electron direction known

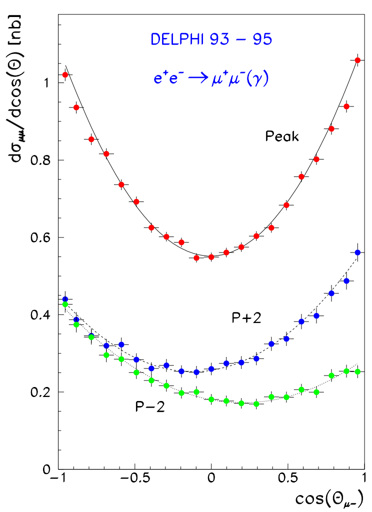


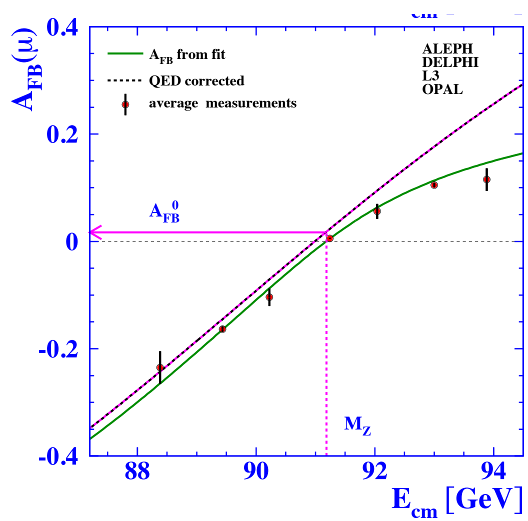
$$\frac{d\sigma}{d\cos\theta^*} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta^*) + B\cos\theta^*\right]$$

γZ interference

$$B \propto A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

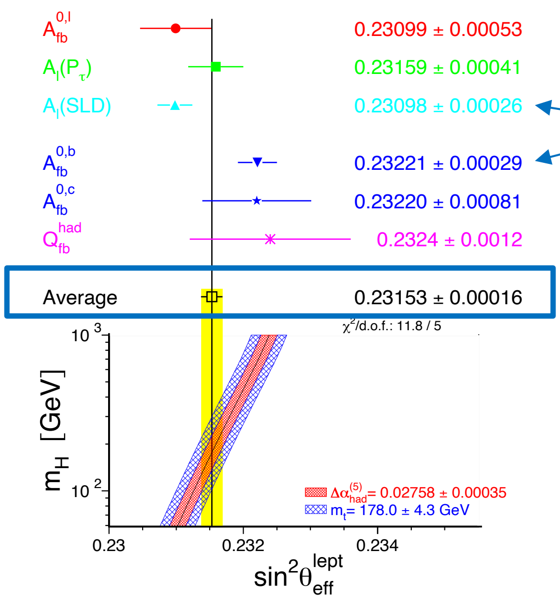
- asmmetry depends on E_{cm}
  - stronger effects off-peak





- asymmetries depend on $\sin^2\theta_{\rm eff}^{\rm lept}$

$$\sin^2\theta_{\rm eff}^{f} = \kappa_f\left(1 - \frac{M_W^2}{M_Z^2}\right)$$

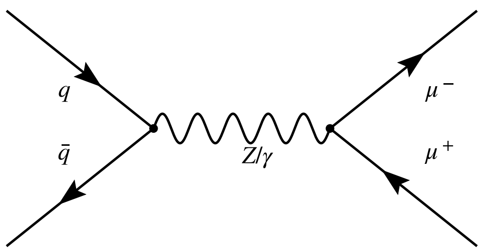


long standing issue: two most precise values differ by ~3σ
new physics?

physics with Z bosons at hadron colliders

Z bosons are studied at hadron colliders already for 40 years!

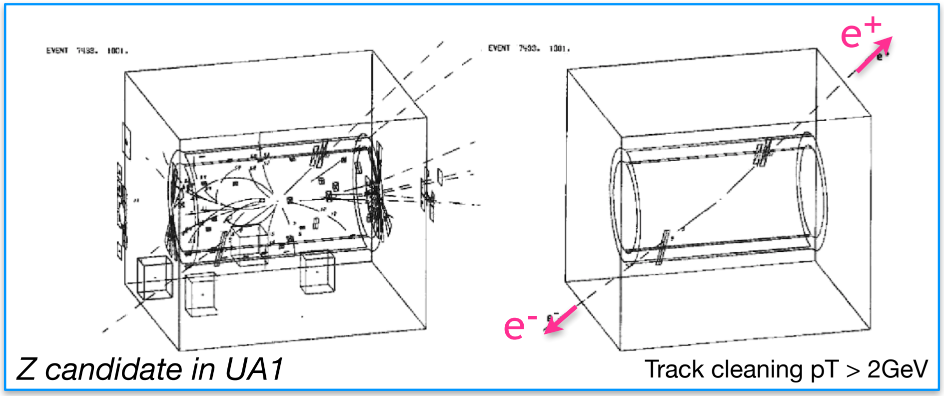
- discovery 1983/4 at UA1, UA2

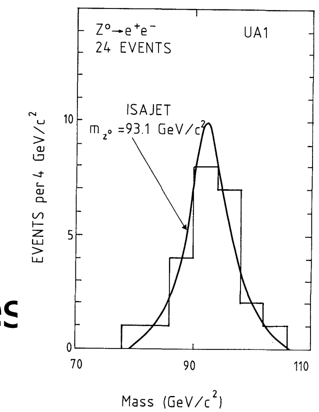


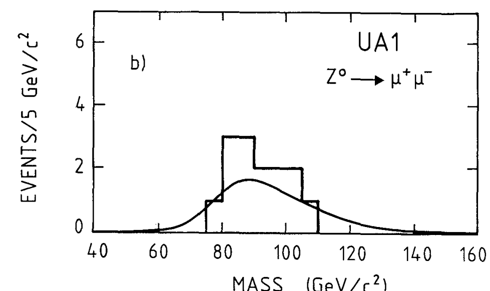
- very few events : in total O(100)
- measurements with large uncertainties

$$M_{Z\to\mu\mu} = 90.7 \,^{+5.2}_{-4.8} \pm 3.2\ \mathrm{GeV}/c^2.$$

$$M_{Z\to e^+e^-} = 93.1 \pm 1.0 \pm 3.1\ \mathrm{GeV}/c^2.$$







from 21 $Z \to ee$ and 12 $Z \to \mu\mu$ events via A_{FB}:
$\sin^2\theta_w$ of $0.24 \,^{+0.05}_{-0.04}$.

- principle of measurements same as today
- but the picture has completely changed

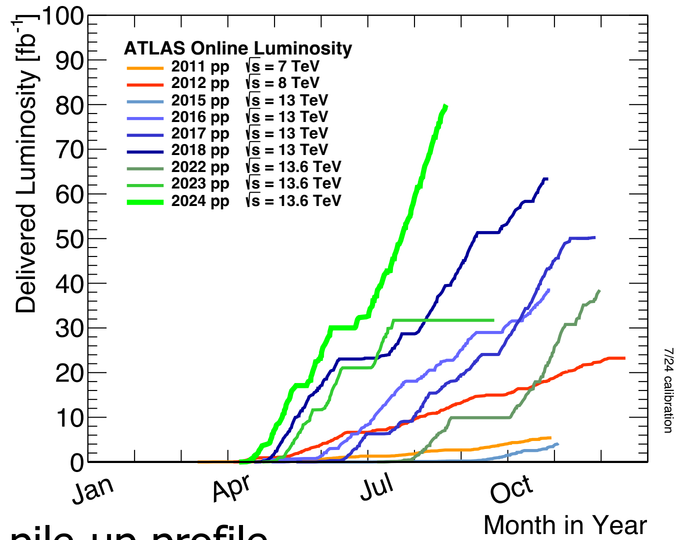
UA1 collaboration, Z. Phys. C 44 15-61 (1989)

the datasets collected at the LHC

LHC: fanatastic performance of accelerator and detectors

- Run 1: **7-8 TeV**, 2010-2012: ~25 fb^{-1}
- Run 2: **13 TeV**, 2015-2018: ~140 fb^{-1}
- Run 3: **13.6 TeV**, 2022-… >150 fb^{-1}

recorded luminosity

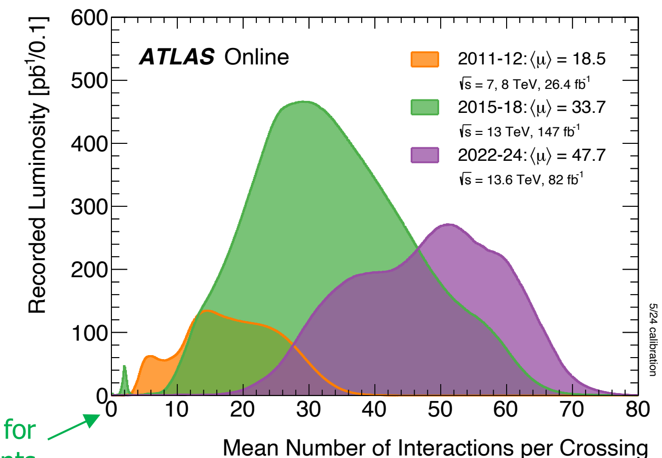


huge, well-calibrated datasets for a vast and diverse physics program

pile-up conditions are challenging for the experiments (reconstruction, calibration, triggering,…)

datasets at different energies: allow to probe energy dependence of SM predictions

pile-up profile

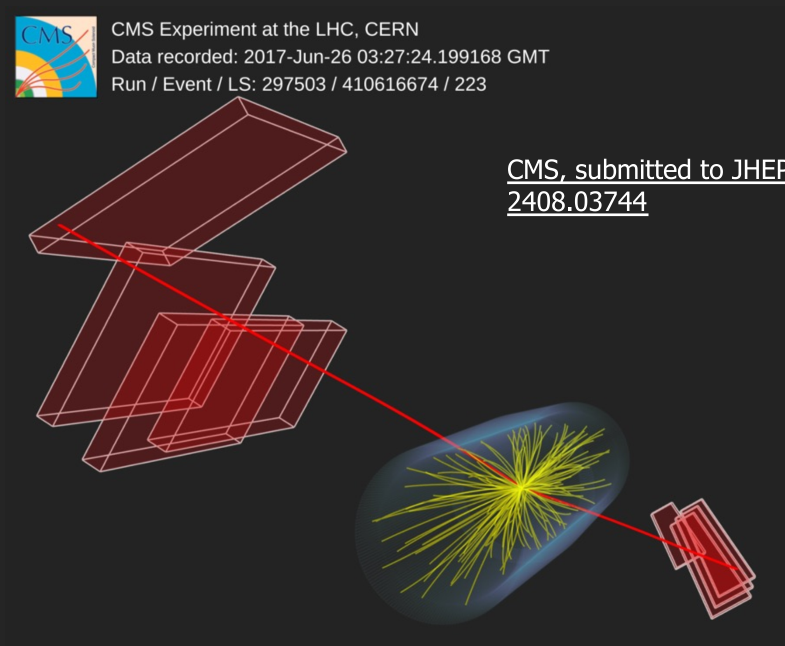


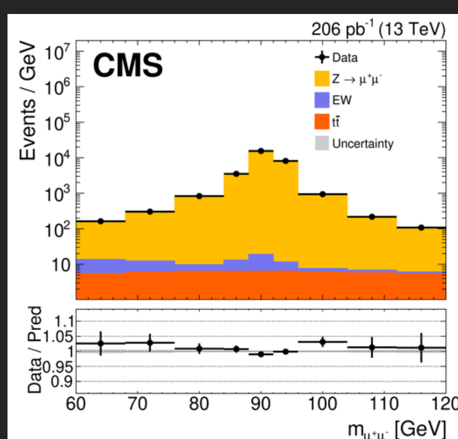
special low PU run in 2017 for EW precision measurements

lower trigger/reco thresholds, better reco of PU-impacted variables, e.g. W recoil, important for m_W

physics with Z bosons at hadron colliders

[CMS, submitted to JHEP, 2408.03744]





large + pure samples of Z (and W) events available at the LHC

- precise study of detector performance in large datasets possible ('tag & probe')
- already with subset of data: statistical uncertainty often negligible
  - e.g. recent CMS measurement of cross-section of inclusive Z production
    - o low PU run in 2017 → better p_T^{miss} resolution and lepton isolation→ less background

$$\sigma(\mathrm{pp} \to \mathrm{Z} + \mathrm{X})\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-) =$$
$$1952 \pm 4\,(\mathrm{stat}) \pm 18\,(\mathrm{syst}) \pm 45\,(\mathrm{lumi})\,\mathrm{pb}$$

  - dominant uncertainty from luminosity determination (2.3%)
  - often done: further reduction by building ratios of cross-sections

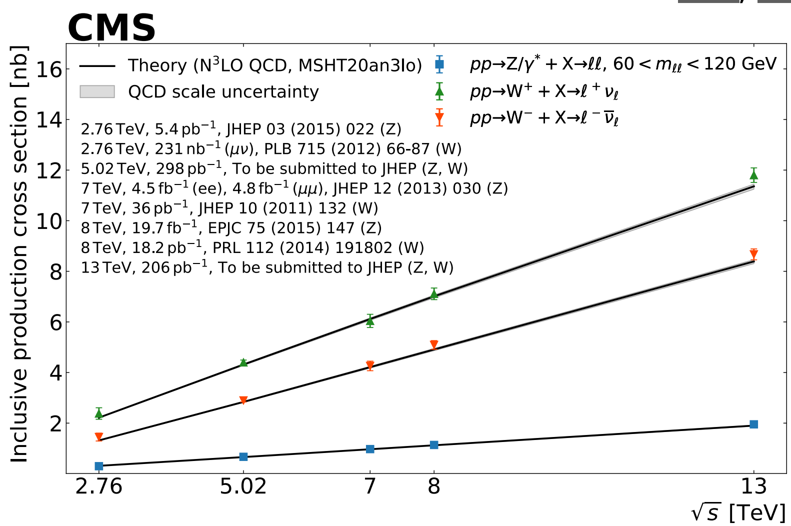
inclusive W and Z cross-sections at LHC

CMS review, subm. to PhysRep, 2405.18661

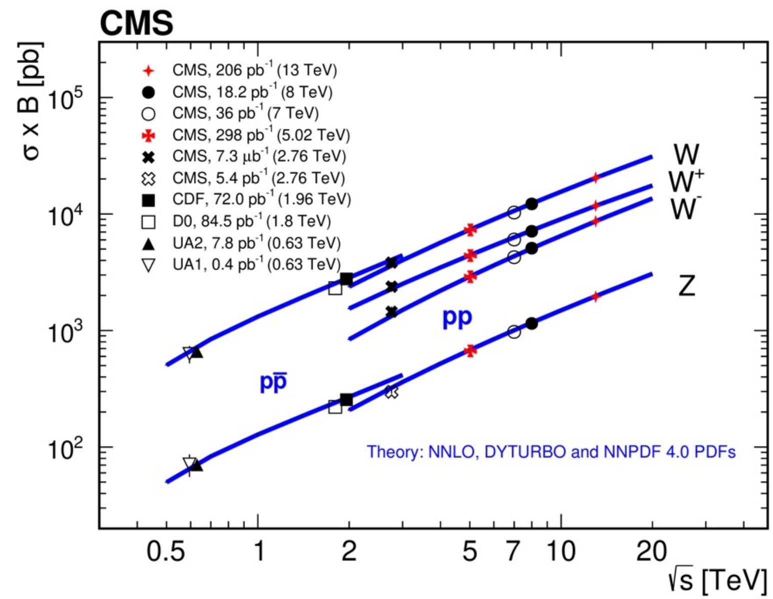
summary of inclusive measurements at different energies

these measurements represent most stringent tests of SM cross-section calculations at hadron colliders

- data consistent with N3LO QCD with approximate N3LO PDFs within uncertainties
  (limiting currently in theory: PDF unc., HO QCD and EW)
  new 13.6 TeV results also available: CMS, ATLAS



summary of inclusive measurements at different colliders

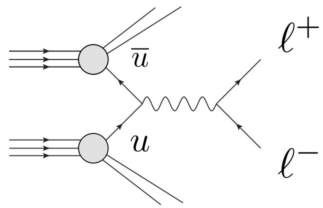


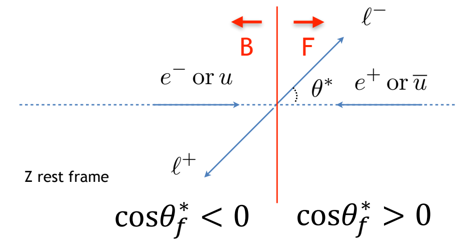
- measurements consistent with theoretical predictions across different energy scales and different collisions (pp vs $p\bar{p}$)
  - UA1 dataset collected within minutes at LHC

mainly tests of QCD-sector, but high-precision hadron collider data also enable high precision EW tests !

measurement of weak mixing angle at LHC

- principle: measure A_{FB} in
  $q\bar{q} \to Z/\gamma \to l^+l^-$ (ie. similar to e^+e^-):





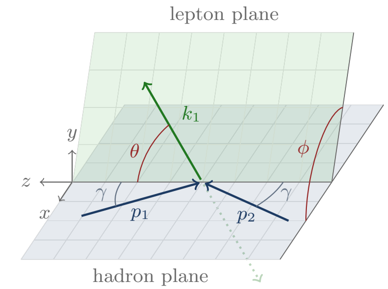
complications at LHC :

1) l^+l^- system can have p_T

→ 4-momentum of initial (anti-)quark not collinear with beam

approach: impact reduced in Collin-Soper frame

θ^*_{CS}: angle of l^- wrt to axis that bisects the angle between initial q and $\bar{q}$



2) ambiguity due to symmetric initial state pp

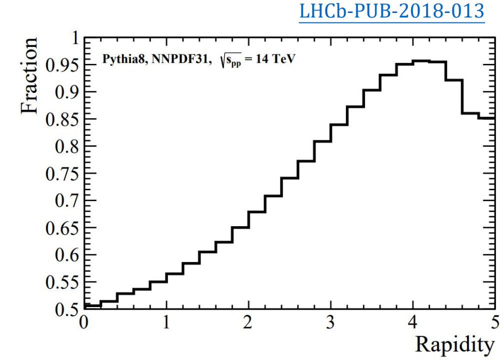
→ ambiguity in quark direction ($|\cos\theta^*_{CS}|$)

approach: assume: $q_{\text{val}}\bar{q}_{\text{sea}}$ process and $x_{\text{val}} > x_{\text{sea}}$, ie. longitudinal boost of l^+l^- = quark direction

- but: fraction of wrongly assigned quark directions leads to diluation of A_{FB}
- probability of correct assignment increases with boost

→ better sensitivity at high rapidities (advantage LHCb)

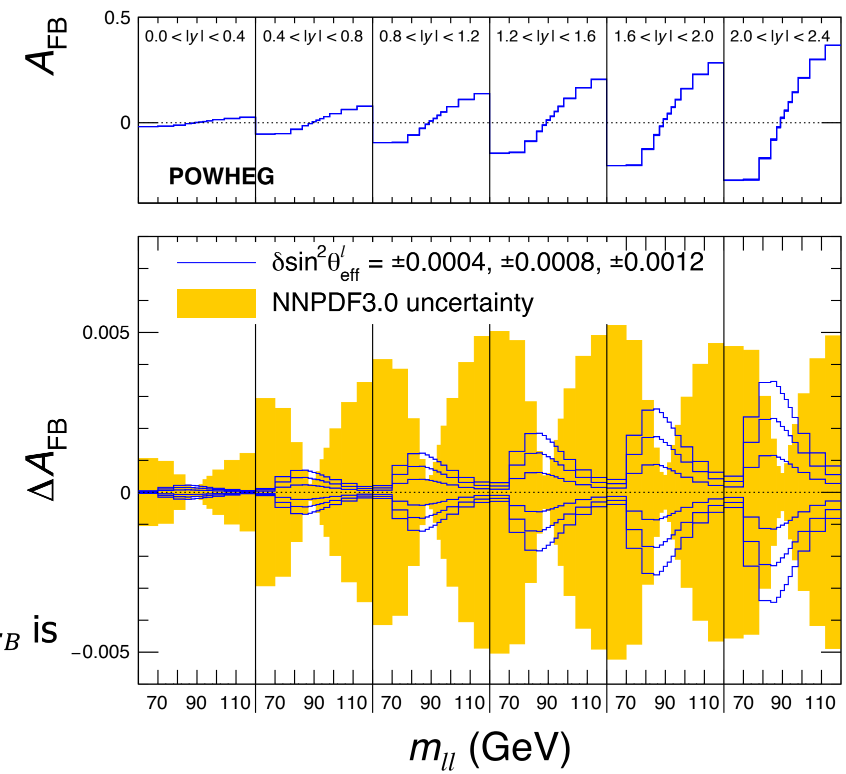
fraction of events where the Z boson travels in direction of initial state quark
LHCb-PUB-2018-013



measurement of weak mixing angle at LHC

value of A_{FB} depends on

- m_{ll}: electroweak effect
  - like $\sqrt{s}$ depedence in e^+e^-
  - most events in peak region
- $|y_{ll}|$: due to quark assignment
  - less dilution at high boosts
  - uncertainty from PDF increases as well



CMS, Eur.Phys.J.C 78 (2018) 9, 701, 1806.00863

different effects from PDF (largest when A_{FB} is large) and $\sin^2\theta^l_{\text{eff}}$ (largest close to pole)

- binning in m_{ll} is useful to profile PDFs (done in CMS, see next slide)
- LHCb measures inclusively since very forward sensitivity

high sensitivity on $\sin^2\theta^l_{\text{eff}}$ at high $|y|$

measurements of ATLAS, CMS and LHCb focus on forward region

measurement of weak mixing angle at CMS

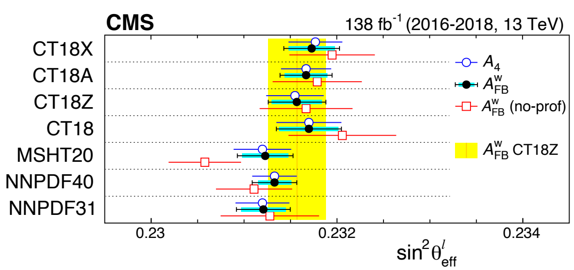
CMS, subm to PLB, 2408.07622

brand new result by CMS

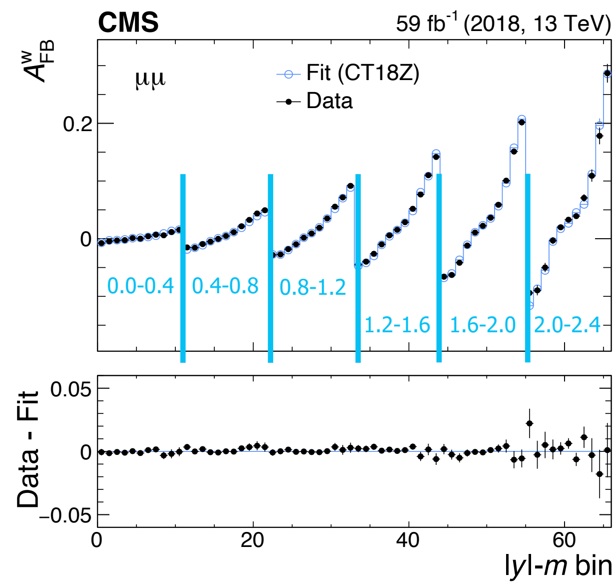
- special effort to cover high $|y|$ up to 3.4:
  - central electrons (e) and muons (μ): $|\eta| < 2.5$
  - electrons in fwd ECAL (g): $2.5 < |\eta| < 2.87$
  - electrons in fwd HCAL (h): $3.14 < |\eta| < 4.36$
- simultaneous fit of all $A_{FB}(|y|, m_{ll})$ values in all channels $(\mu\mu, ee, eg, eh)$ with varying $\sin^2\theta^l_{\text{eff}}$ (templates)

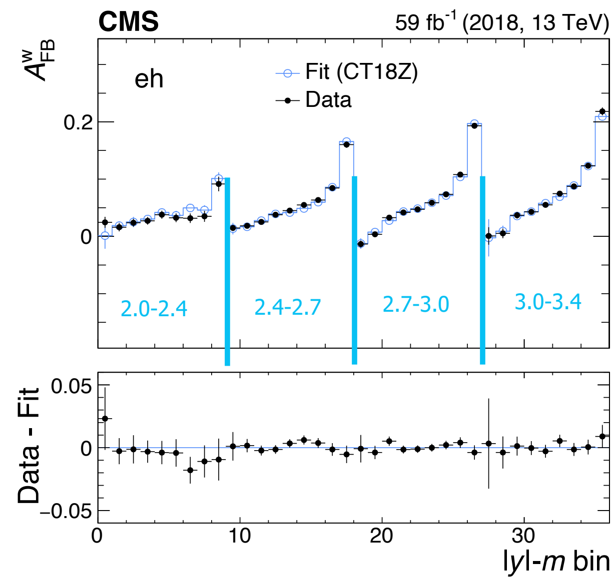
$$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{exp}) \pm 0.00009\,(\text{theo}) \pm 0.00027\,(\text{PDF}),$$

$$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00031$$



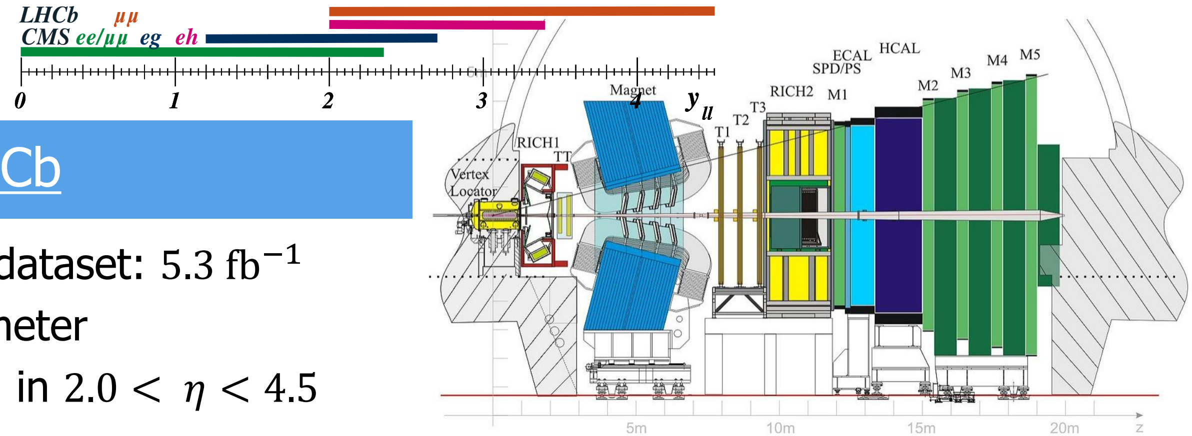
- single best measurement from hadron collider
- PDF uncertainties dominant, profiled in central result





measurement of weak mixing angle at LHCb

LHCb, presentend at ICHEP24



brand new analysis by LHCb

- $Z \to \mu^+\mu^-$ in full Run-2 dataset: $5.3\ \text{fb}^{-1}$
- LHCb: forward spectrometer
  - high quality μ reco: in $2.0 < \eta < 4.5$

➢ A_{FB} in 10 bins of $|\Delta\eta|$, inclusive in m_{ll}

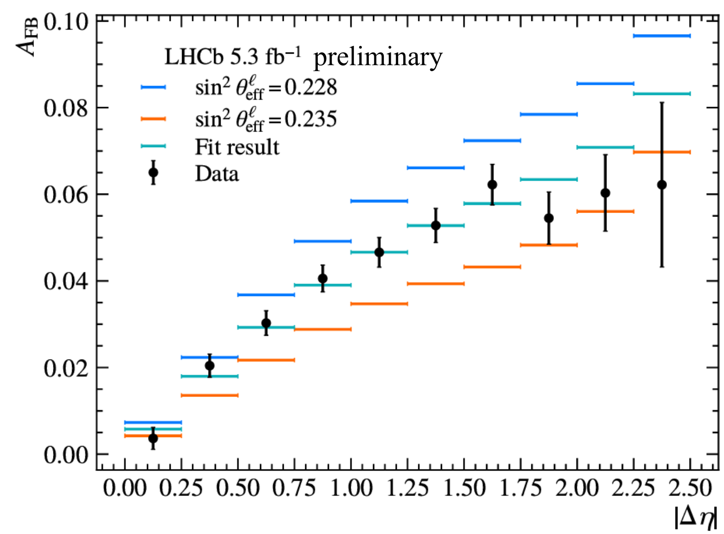
- best sensitivity on $\sin^2\theta^l_{\text{eff}}$ at high $|\Delta\eta|$

➢ $\sin^2\theta^l_{\text{eff}}$ extraction

- comparing with POWHEG-Box templates
- take average of PDF sets (NNPDF3.1, CT18, MSHT20)

$$\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23152 \pm 0.00044(stat.) \pm 0.00005(exp.) \pm 0.00022(theory)$$

$\chi^2/\text{ndof} = 7.6/9$



- result statistically limited, PDF unc. small
  → anticipate sign. improvement for run 3

paper in preparation: LHCb-paper-2024-028
more details in recent CERN seminar

summary: weak mixing angle

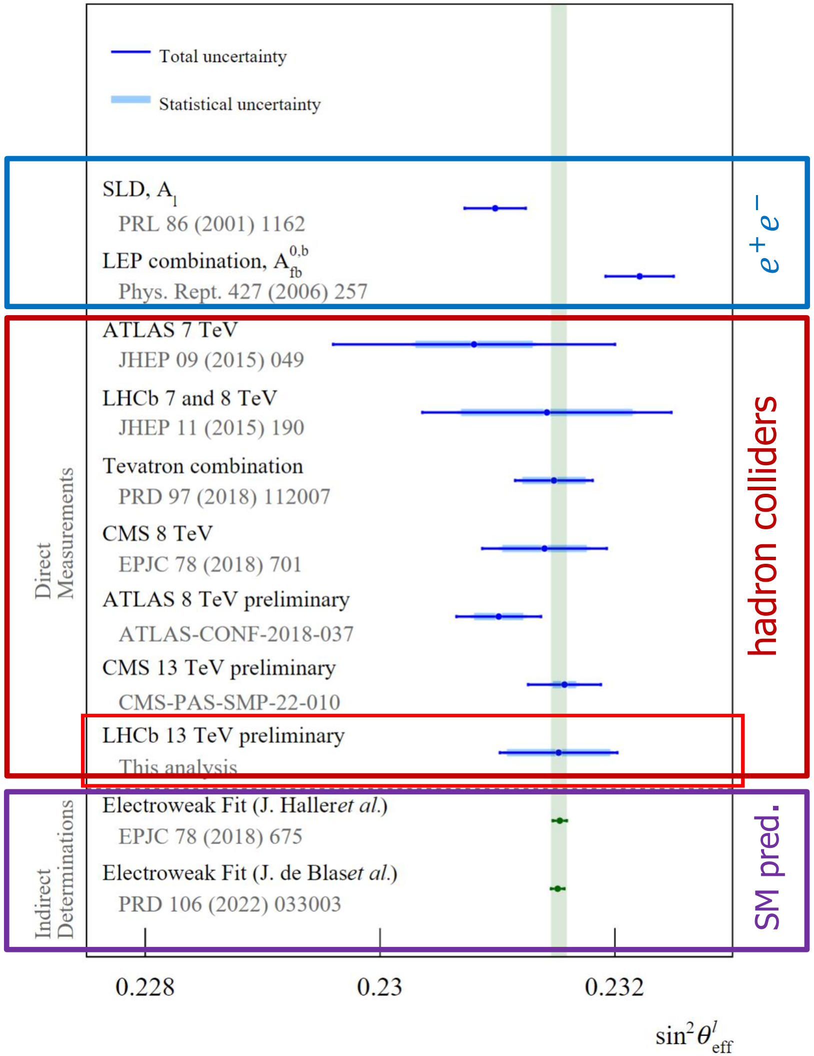
new hadron collider measurements with increasing precision

- nearing precision of LEP and SLD combined results !
- single best measurement from CMS
  - PDF uncertainties dominant
  - relative precision 0.13%

new measurements consistent with SM predictions from global fits

- midway between SLD and LEP

situation as of today

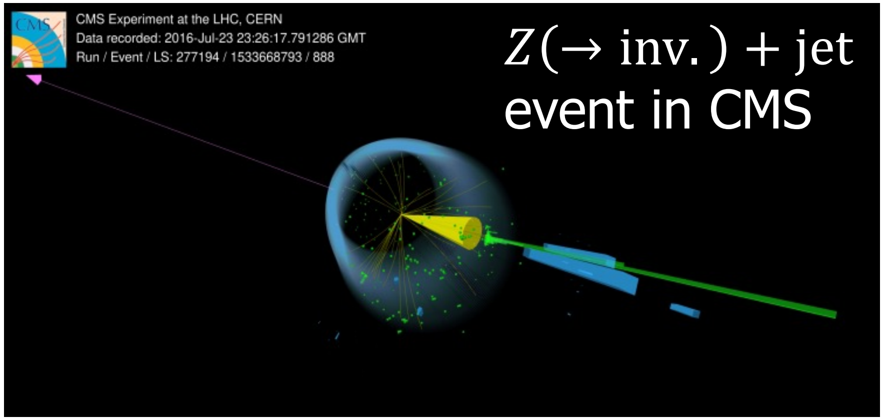


direct measurement of invisible Z width at LHC

CMS, Phys. Lett. B 842 (2023) 137563, 2206.07110
ATLAS, Phys. Lett. B 854 (2024) 138705, 2312.02789

fundamental test by measuring $\Gamma(Z \to \mathrm{inv})$

- SM: $Z \to \nu_{e,\mu,\tau}\bar{\nu}_{e,\nu,\tau}$
- BSM: additional invisible modes?



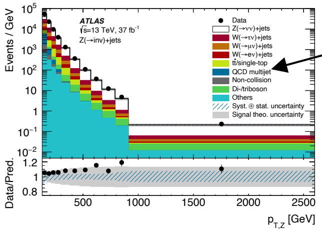
results from LEP

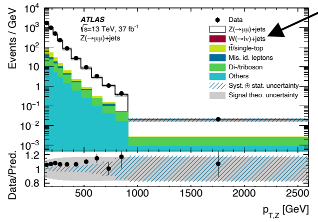
- indirect: total width from pole scan, subtract visible
- direct: recoil in $Z(\to \nu\nu) + \gamma$: O(10) less sensitive

new results from ATLAS + CMS

- use recoil in '$Z(\to \mathrm{inv}) + \mathrm{jet}$' events $\to p_T^{\mathrm{miss}} + \mathrm{jet}$
- measure ratio of '$p_T^{\mathrm{miss}} + \mathrm{jet}$' to '$ll + \mathrm{jets}$' in common phase space

$$\Gamma(Z \to \mathrm{inv}) = \frac{\sigma(Z+\mathrm{jets})\mathcal{B}(Z \to \mathrm{inv})}{\sigma(Z+\mathrm{jets})\mathcal{B}(Z \to ll)}\Gamma(Z \to ll)$$





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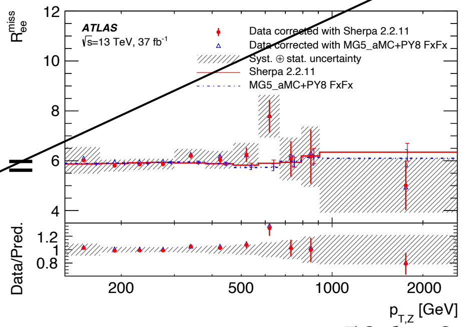
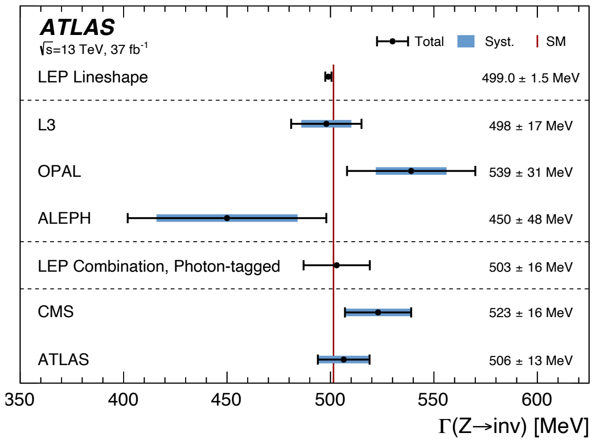


ATLAS: $\Gamma(Z \to \mathrm{inv}) = 506 \pm 2\ (\mathrm{stat.}) \pm 12\ (\mathrm{syst.})$

most precise recoil based measurements

ration: jet systematics greatly reduced

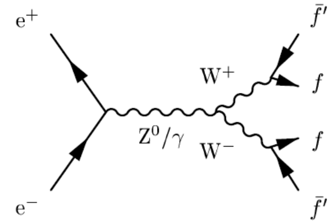


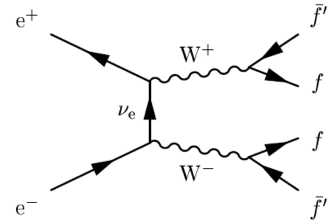
precision measurements with W bosons

measurement of the W mass at LEP II

ADLO, Phys.Rept. 532 (2013) 119-244, hep-ex/1302.3415

- with $\sqrt{s} > 2M_W$: $e^+e^- \rightarrow W^+W^-$



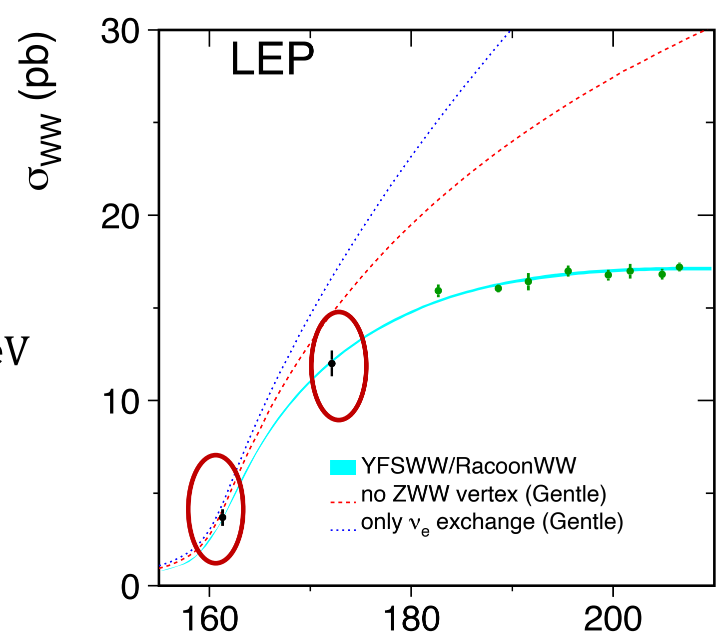


M_W measurement via $\sqrt{s}$ -scan of σ_{WW} threshold

- non-trivial cancellations experimentally confirmed

$$M_W(\text{thresh}) = 80.42 \pm 0.20(\text{stat}) \pm 0.03(E_{\text{LEP}})\text{GeV}$$

- statistical limitation as only very few data have been collected around threshold (3% of LEP II)



→ interesting running option for a future e^+e^- Higgs factory

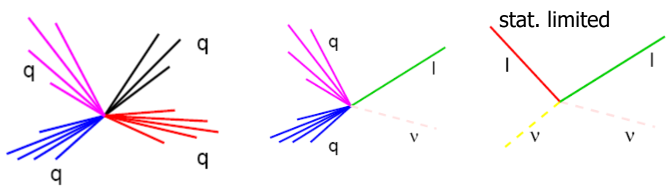
measurement of the W mass at LEP II

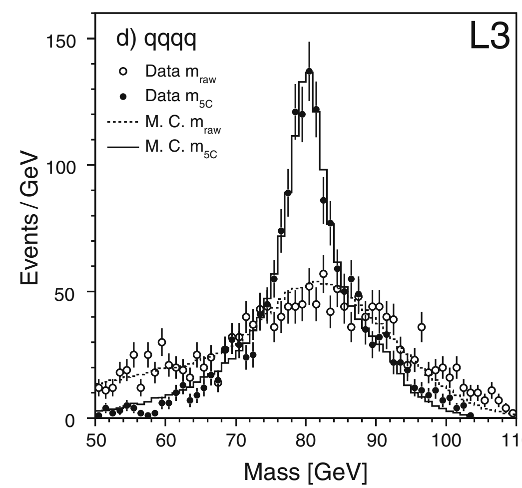
ADLO, Phys.Rept. 532 (2013) 119-244 ,hep-ex/1302.3415

M_W via direct reco of invariant mass of decay products

$$W^+W^- \to \quad q\bar{q}q\bar{q}, \quad q\bar{q}l\nu_l, \quad (l\nu_l l\nu_l)$$

use of all data with $\sqrt{s} > 2M_W$

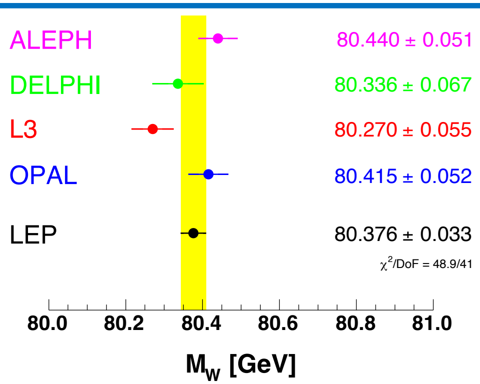




L3, Eur.Phys.J.C 45 (2006) 569-587, hep-ex/0511049

- crucial for reco: knowledge of $\sqrt{s}$
  - → neutrino momentum in $q\bar{q}l\nu_l$
  - → 'kinematic fitting' using constraints in $q\bar{q}q\bar{q}$ and $q\bar{q}l\nu_l$
- mass extraction from comparison of data with MC templates

$$M_W(\text{direct}) = 80.375 \pm 0.025(\text{stat}) \pm 0.022\ (\text{syst})\text{GeV}$$



final LEP combination (threshold + direct):

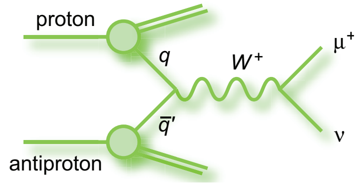
$$M_W(\text{LEP}) = 80.376 \pm 0.025(\text{stat}) \pm 0.022\ (\text{syst})\text{GeV}$$

physics with W bosons at hadron colliders

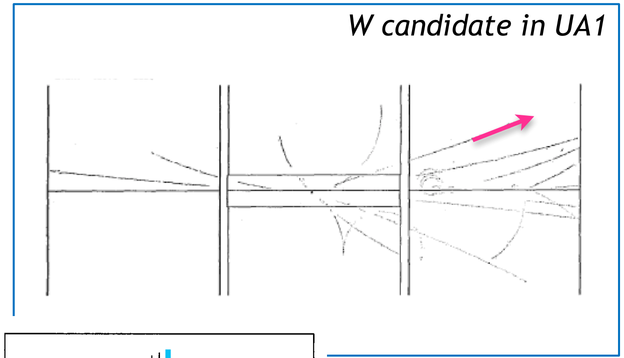
UA2 collaboration, Phys.Lett. B276 (1992) 354

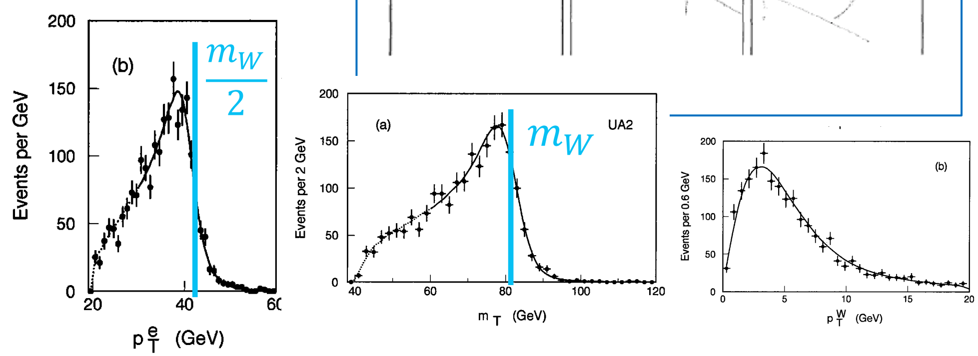
it all started 40 years ago

discovery of W bosons (UA1, UA2 1983/4)



final sample: O(2000) events only



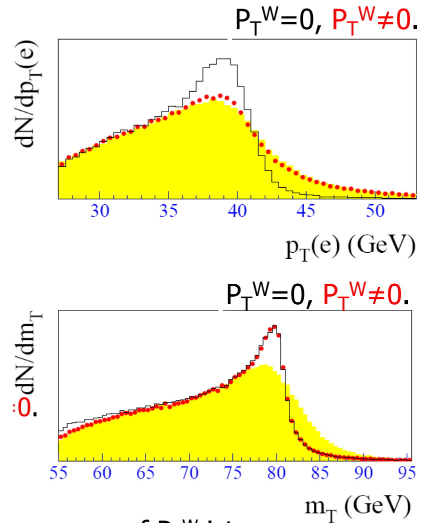


m_W measured from jacobean peak

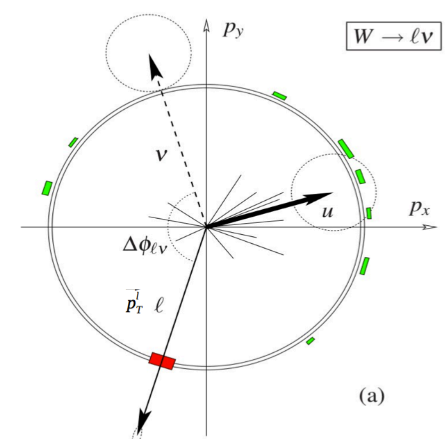
p_T^l clean momentum measurement, but sensitive to modelling of the W transverse momentum

m_T less sensitive to modelling, but more difficult to reconstruct (as based on p_T^{miss})

$$m_T = \sqrt{2 p_T^l p_T^{miss} (1 - cos\phi)}$$



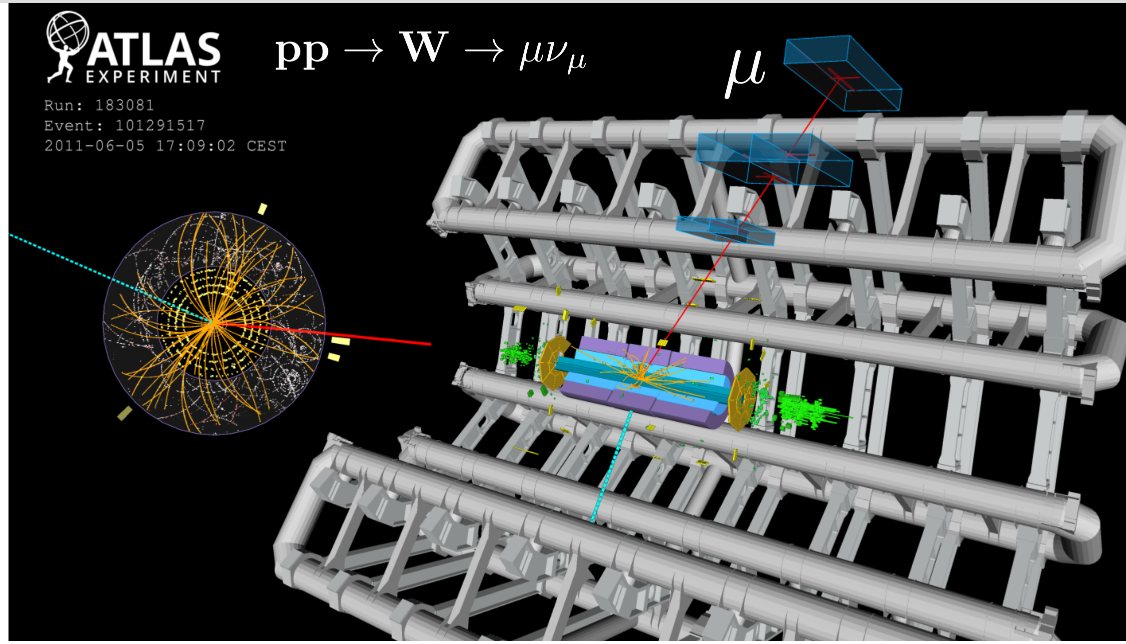
event topology: lepton, p_T^{miss} + hadronic recoil



measurement of W mass at ATLAS

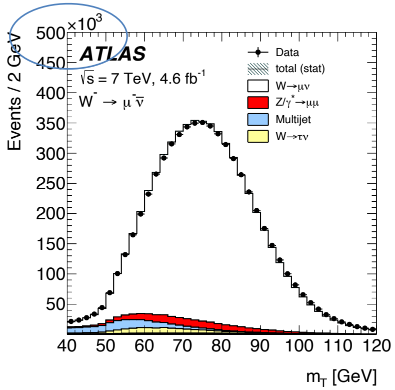
ATLAS, subm to EPJC, 2403.15085

ATLAS, Eur. Phys. J. C 78 (2018) 110, 1701.07240

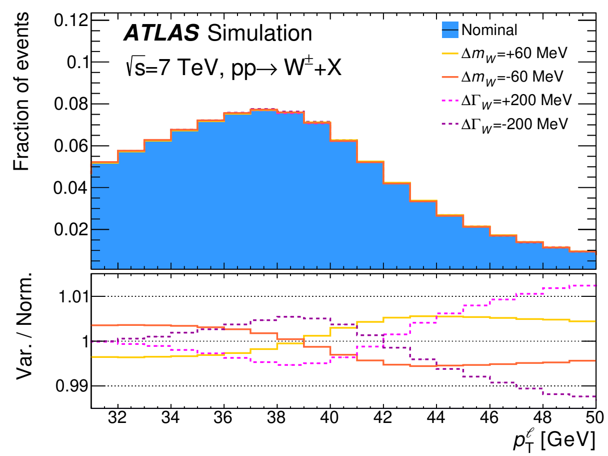


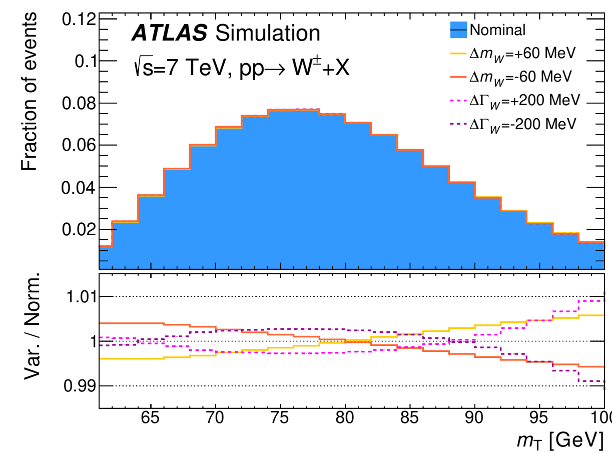
in ATLAS: this technique pushed to extreme precision

- large, pure samples of W available
- dataset at 7 TeV:
  - ~15.5M W^+, ~10.4M W^-
  - moderate PU



- first m_W analysis published 2018
- recently updated: determination of both m_W and Γ_W (constrained and simultaneously)
  - latest PDFs, better statistical method





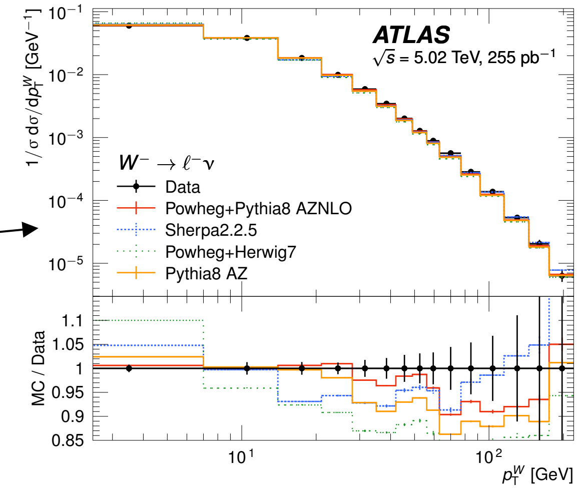
measurement of W mass at ATLAS

ATLAS, subm to EPJC, 2403.15085

ATLAS, subm to EPJC, 2404.06204

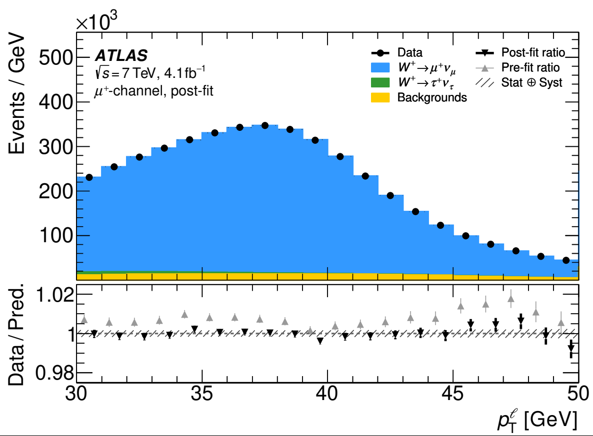
critical for m_W extraction: W production kinematics + hardonic recoil

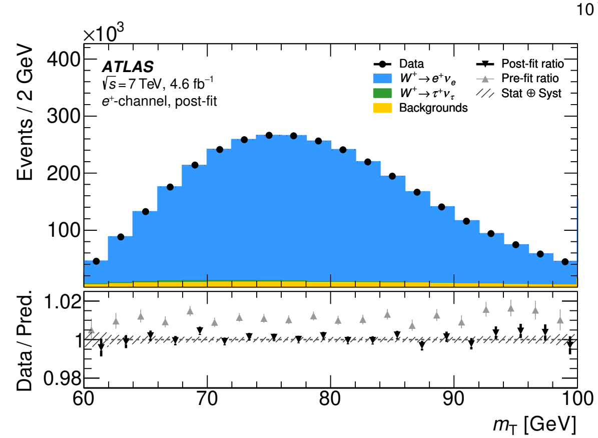
- best modelling used: NLO Powheg reweighted with NNLO calc., NNLO PDFs, Phythia 8 with AZNLO tune based on Z data
- describes p_T^W distribution in low PU runs at 5.02 and 13 TeV



profile likelihood fits of p_T^l and m_T distributions

28 categories (e^+, e^-, μ^+, μ^-, various $|\eta|$ bins): consistent results





Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

impressive precision!

$$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV},$$

$$\Gamma_W = 2202 \pm 32\ (\text{stat.}) \pm 34\ (\text{syst.})\ \text{MeV} = 2202 \pm 47\ \text{MeV}.$$

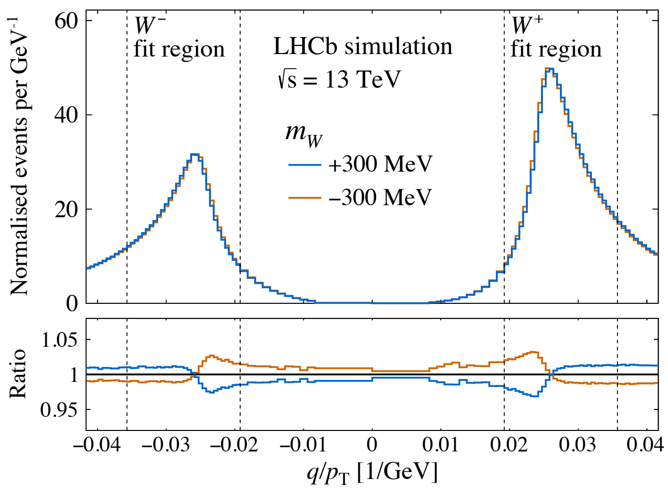
p_T^l measurement dominates, statistical uncertainty non-negligible, systematics distributed

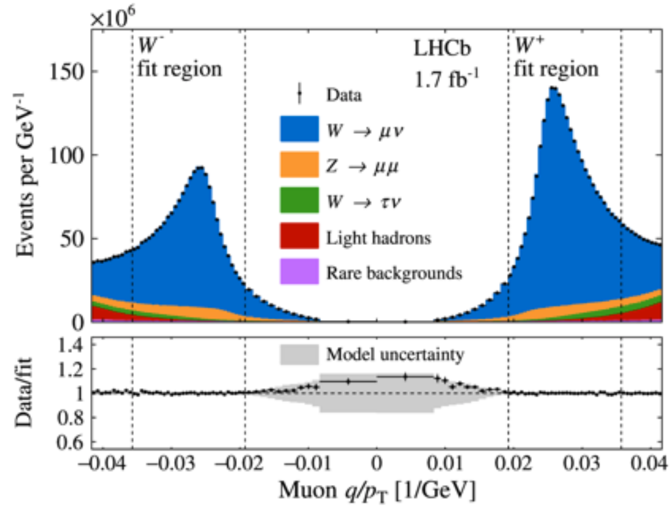
measurement of the W mass at LHCb

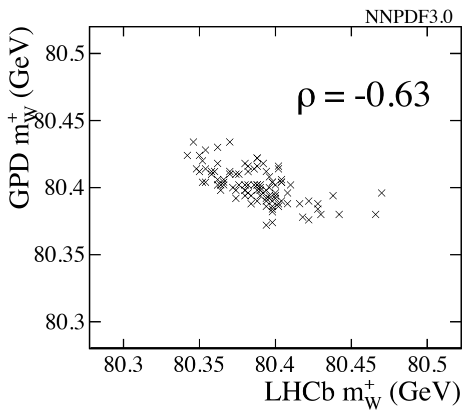
LHCb, JHEP 01 (2022) 036, 2109.01113

similar measurement principle also used at LHCb

(simultaneous fit of q/p_T in W events and Collin-Soper ϕ^* (proxy for p_T^Z) in Z events)







G. Bozzi et al., Eur.Phys.J.C 75 (2015) 12, 601, 1508.06954

m_W = 80354 ± 32 MeV

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

significant improvments expected:

- analysis uses only 1/3 of Run-2 data set
- effort on improving modelling and experimental systematics
- PDF uncertainties are anticorrelated with ATLAS due to forward configuration of LHCb → cancellation in combination

summary of W mass measurements

LHCb-FIGURE-2022-003

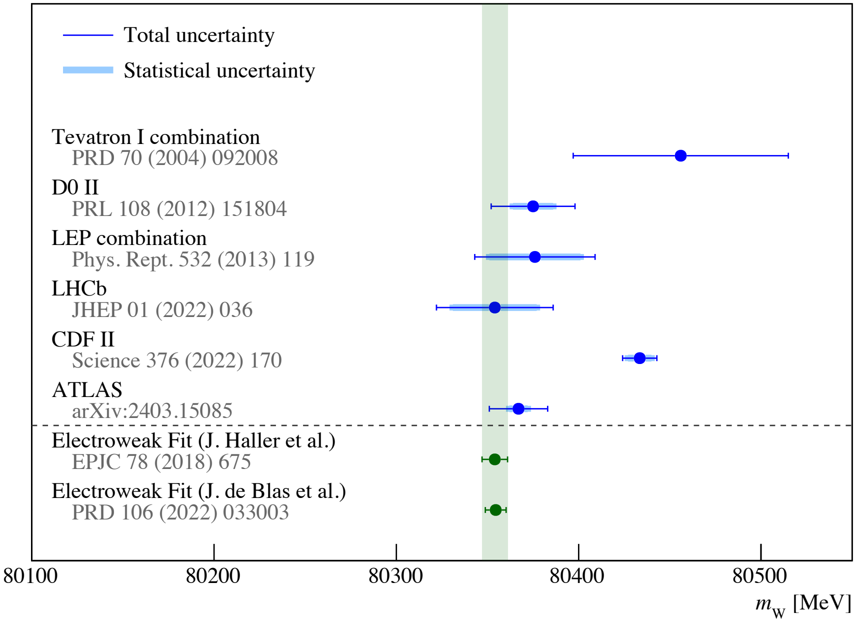
LHC-TeV MW Working group, subm to EPJC, 2308.09417

CDF, Science 376 (2022), 170

hadron collider surpass LEP in precision

measurements largely compatible with each other and with SM prediction

- exception CDF II: 7σ tension with SM prediction and 3-4σ inconstitency with other data



recent m_W combination paper (2308.09417):

- all results: $\mathrm{Prob}(\chi^2) = 0.02 - 0.5\ \%$ (depending on PDF set)
- all, excluding CDF II: $\mathrm{Prob}(\chi^2) = 91\%$

WA: $m_W = 80369.2 \pm 13.3\ \mathrm{MeV}$

precision: 0.016%

CMS measurement urgently awaited to resolve this puzzle

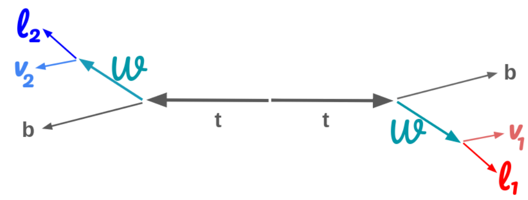
branching ratios of the W boson

ADLO, Phys.Rept. 532 (2013) 119, hep-ex/1302.3415
ATLAS, Nature Phys. 17 (2021) 7, 813, 2007.14040
ATLAS, subm to EPJC, 2403.02133
CMS, Phys. Rev. D 105 (2022) 072008, 2201.07861

leptonic decay widths of W from LEP II

$\mathcal{B}(W \to e\overline{\nu}_e)$ [%]	$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$ [%]	$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$ [%]
10.71 ± 0.16	10.63 ± 0.15	11.38 ± 0.21

- long standing $> 2\sigma$ excess of $\mathcal{B}(W \to \tau\bar{\nu}_\tau)$
- lepton flavour universality violation?
- related to B anomalies?



results also avialable for the other ratios using different methods in tt events

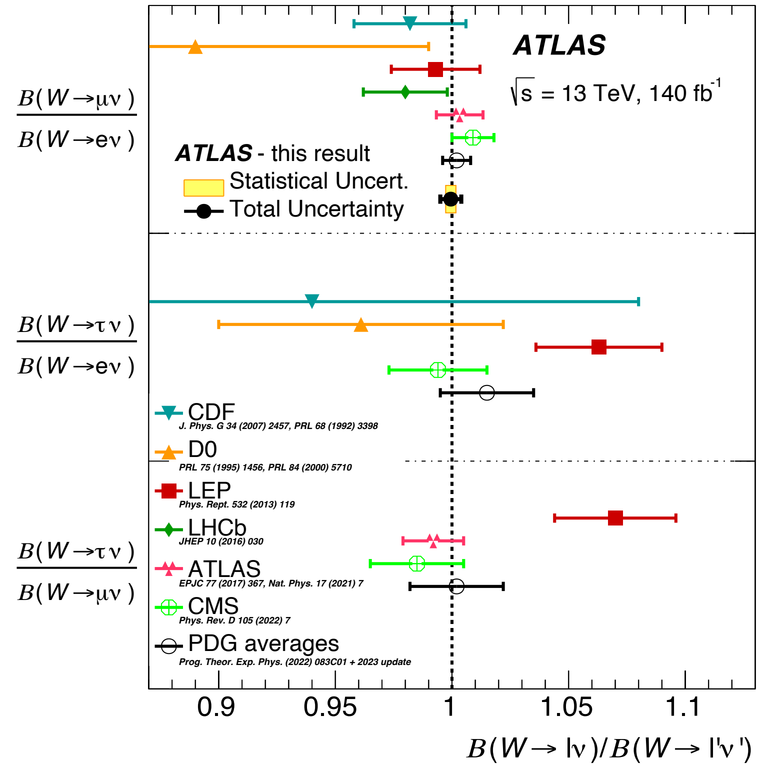
LHC: new measurements of ratios, e.g. $R(\tau/\mu)$

$$\frac{B(W\to\tau\nu)}{B(W\to\mu\nu)}$$

sys. unc. cancel in ratio

- selection of pure and unbiased W sample via dileptonic $t\bar{t}$ events
- tag (e or μ !) & probe (τ or μ ?)
  - e.g. $R(\tau/\mu)$ discriminate prompt μ's ($W \to \mu\nu_\mu$) from μ's from τ decays ($W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$)

ATLAS: $R(\tau/\mu) = 0.992 \pm 0.013$ [± 0.007 (stat) $\pm$ 0.011 (syst)], most precise single measurement



high precision LHC data agree with SM prediction of universal lepton couplings of W

global consistency of electroweak sector

crucial ingredient: mass of the top quark

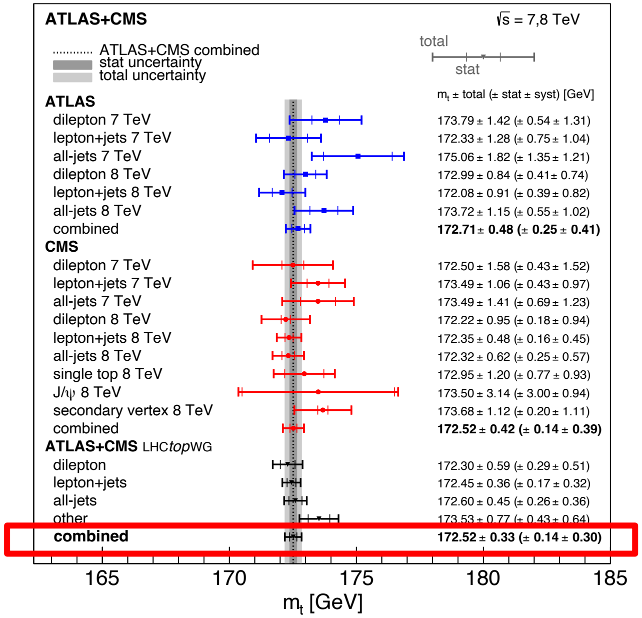
all details: R. Schöfbeck

mass of the top quark has measured at LHC using different methods

- most precise experimentally: direct kinematic reconstruction in $t\bar{t}$ events

legacy combination of ATLAS+CMS Run 1 measurements published recently

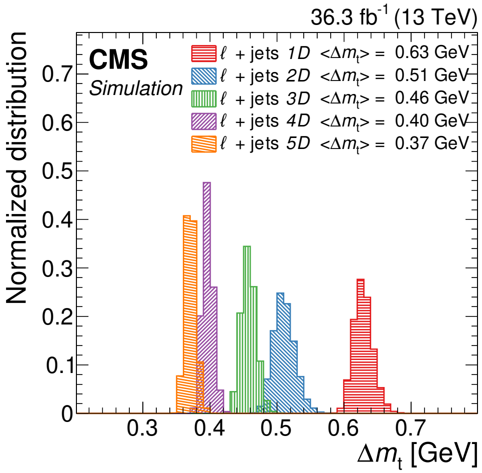
- experimental systematics dominates



ATLAS+CMS, Phys. Rev. Lett. 132 (2024) 261902, 2402.08713

further improvement from 13 TeV data

- e.g. most pricise single measurement (l + jets, CMS) $171.77 \pm 0.37\,\mathrm{GeV}$
  - sophisticated statistical methods to get most out of data



CMS, Eur.Phys.J.C 83 (2023) 10, 963, 2302.01967

PDG avarage: $m_t = 172.57 \pm 0.29\ \mathrm{GeV}$

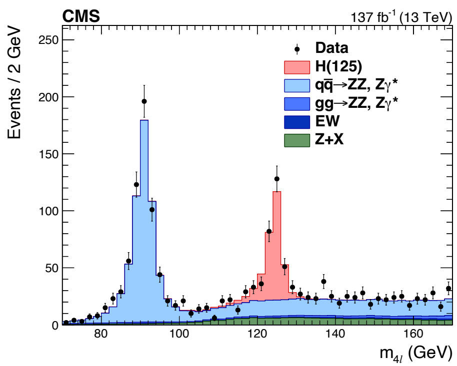
rel precision: 0.17%

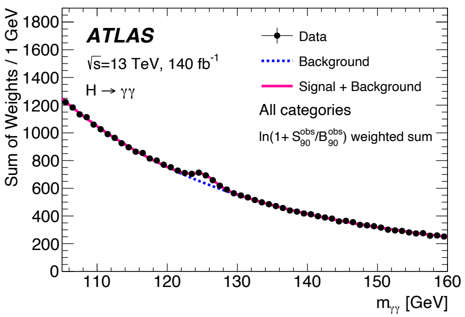
crucial ingredient: mass of the Higgs boson

all details: tomorrow

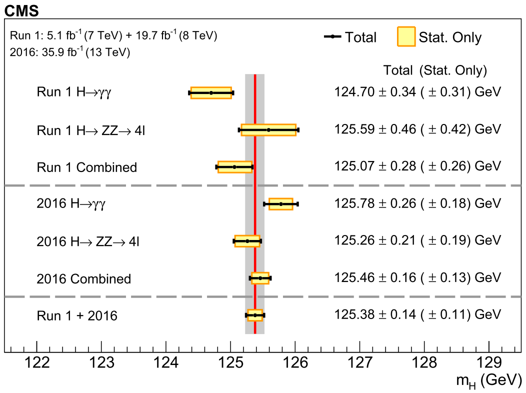
mass of the H boson measured by ATLAS and CMS with great precision

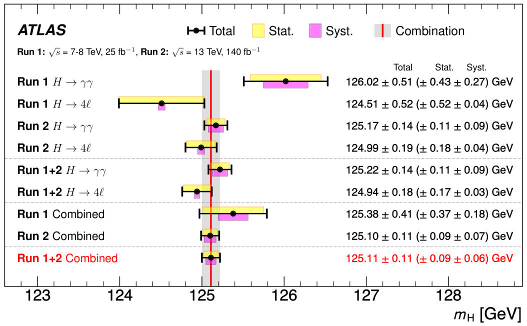
- using high-resolution channels $H \to 4l$ and $H \to \gamma\gamma$





and combinations





PDG avarage: $m_H = 125.20 \pm 0.11$ GeV

ie. 0.08 % relative precision

- statistical uncertainty still substantial
- exact value not crucial for EW test

(due to $\ln m_H$ dependence of HO corrections)

CMS, Eur. Phys. J. C 81 (2021) 488, 2103.04956

ATLAS, Phys. Lett. B 847 (2023) 138315, 2308.07216

CMS, Phys.Lett.B 805 (2020) 135425, 2002.06398

ATLAS, Phys. Rev. Lett. 131 (2023) 251802, 2308.04775

global tests of the internal consistency

precision tests done for a long time

- huge effort of theo and exp community
  - definition of (pseudo-)observables
  - measurements
  - HO calculations

ever increasing precision (both exp. and theo.)

system is overconstrained

- all free parameters measured meanwhile
- most important inputs from e$^+$e$^-$ colliders
  - mainly LEP: partly extreme precision
    - e.g M_Z: 0.002 %
- crucial inputs from hadron colliders (LHC):
  - M_W, $\sin^2\theta^l_{\text{eff}}$, m_t, M_H

m_W from CDF not used in the following

experimental input

Parameter	Input value	
		LEP
M_H [GeV]	125.1 ± 0.2	LHC
M_W [GeV]	80.362 ± 0.014	LEP, LHC, (Tev.)
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4955 ± 0.0023	
σ^0_{had} [nb]	41.500 ± 0.037	
R^0_l	20.767 ± 0.025	
$A^{0,l}_{\text{FB}}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^l_{eff}(Q_{\text{FB}})$	0.2324 ± 0.0012	
$\sin^2\theta^l_{eff}(\text{Tev} + \text{LHC})$	0.23141 ± 0.00026	Tev. LHC
A_c	0.670 ± 0.027	
A_b	0.923 ± 0.020	
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	SLD
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	low E
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]$^{(\triangledown)}$	172.47 ± 0.68	(Tev.) LHC
$\Delta\alpha^{(5)}_{had}(M_Z^2)$ $^{(\dagger\triangle)}$	2761 ± 9	low E

α_s unconstrained, G_F fixed

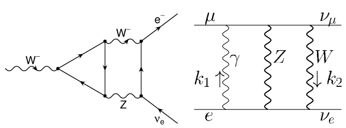
Gfitter group, Y. Fischer, EPS23

global tests of the internal consistency

- enormous effort by theory community to calculate the respective observables

Calculations

All observables calculated at 2-loop level



"fermionic" "bosonic"

- **M_W** : full EW one- and two-loop calculation of fermionic and bosonic contributions
  [M Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002)]
  + 4-loop QCD correction [Chetyrkin et al., PRL 97, 102003 (2006)]
- **$\sin^2\theta^l_{eff}$** : same order as M_W, calculations for leptons and all quark flavours
  [M Awramik et al, PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009)]
- **partial widths Γ_f**: fermionic corrections in two-loop for all flavours (includes predictions for σ^0_{had}) [A. Freitas, JHEP04, 070 (2014)]
- **Radiator functions**: QCD corrections at N³LO
  [Baikov et al., PRL 108, 222003 (2012)]
- **Γ_W** : only one-loop EW corrections available, negligible impact on fit
  [Cho et al, JHEP 1111, 068 (2011)]
- **all calculations**: one- and two-loop QCD corrections and leading terms of higher order corrections

Gfitter, R. Kogler, ICHEP22

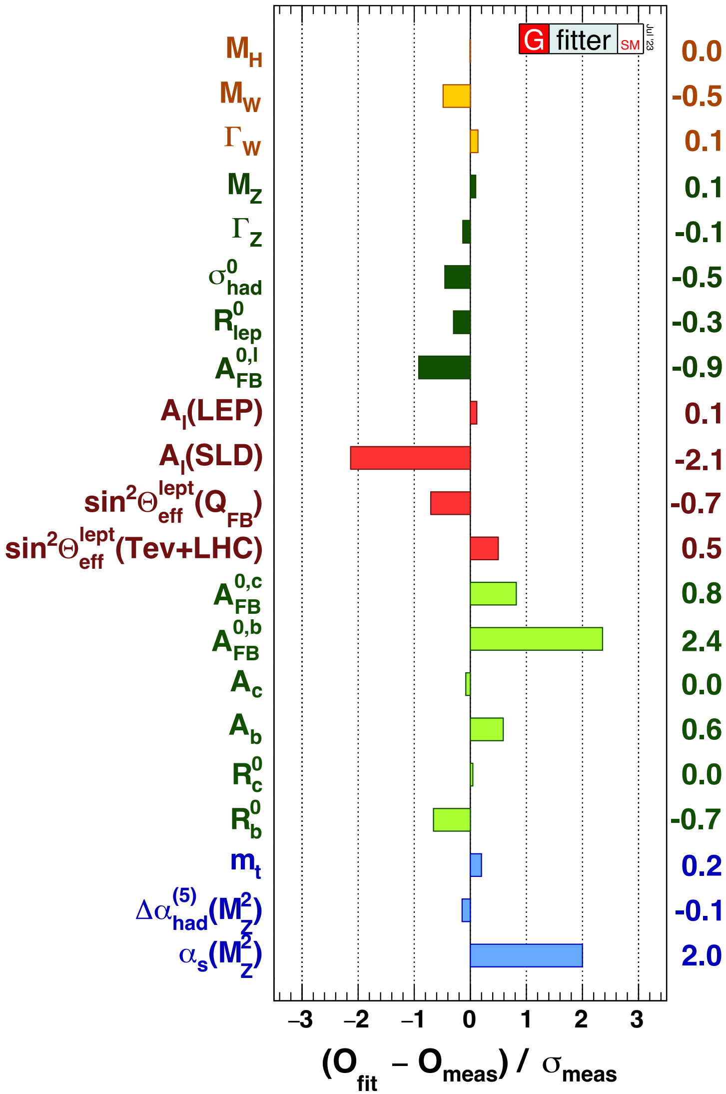
Gfitter, Y. Fischer, EPS23

- New corrections for Γ_Z und σ^0_{had} by Voutsinas et al., PLB 800, 135068 (2018)
- Full two loop calculations for Z decay by Dubovyk et al., PLB 783, 037 (2018)

- details not discussed in this experimental lecture, used for comparison with measurements

global fit of the electroweak sector

Gfitter, Y Fischer, PoS EPS-HEP2023 (2024) 304



report here status of 2023 (party 2018), global picture does not change

global fit able to describe the EWPO, internal consistency

fit converges with

$$\chi^2_{\min}/\mathrm{ndf} = 13.8/15$$
$$\rightarrow p - \mathrm{value} = 0.55$$

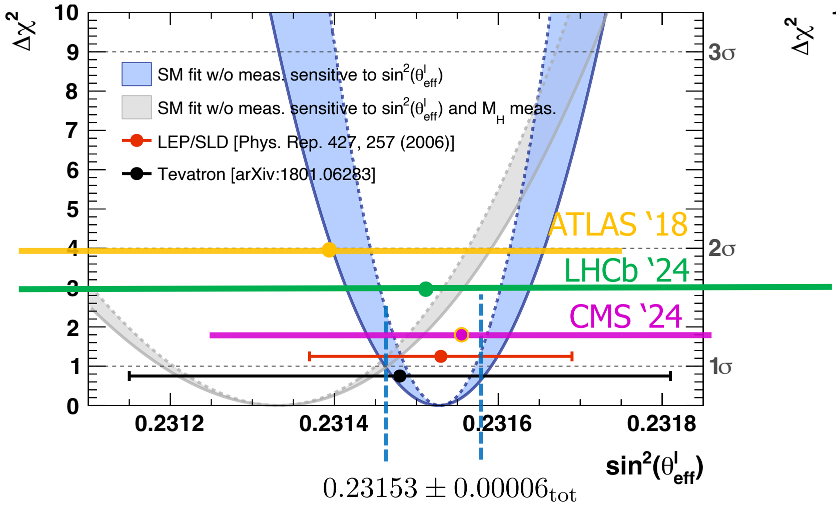
largest tension remains $A_{FB}^{0,b}(\mathrm{LEP})$ and $A_l(\mathrm{SLD})$.

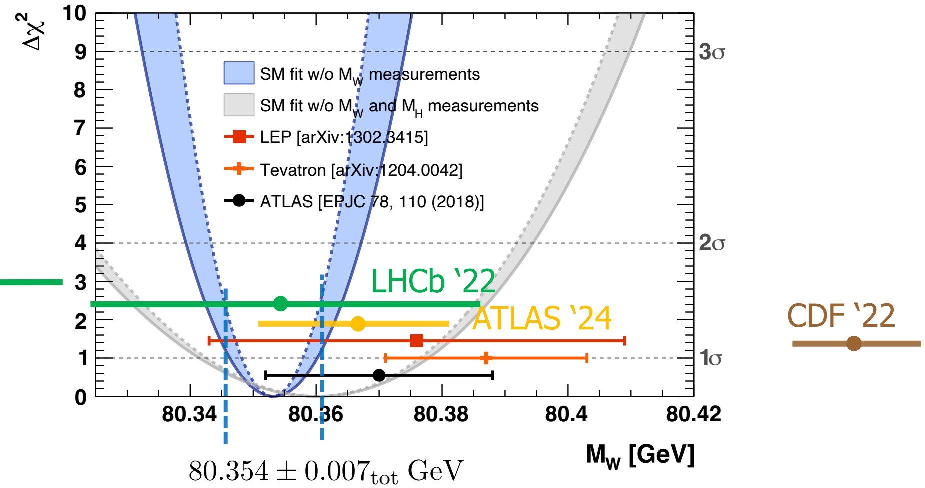
m_W from CDF II not used in the following

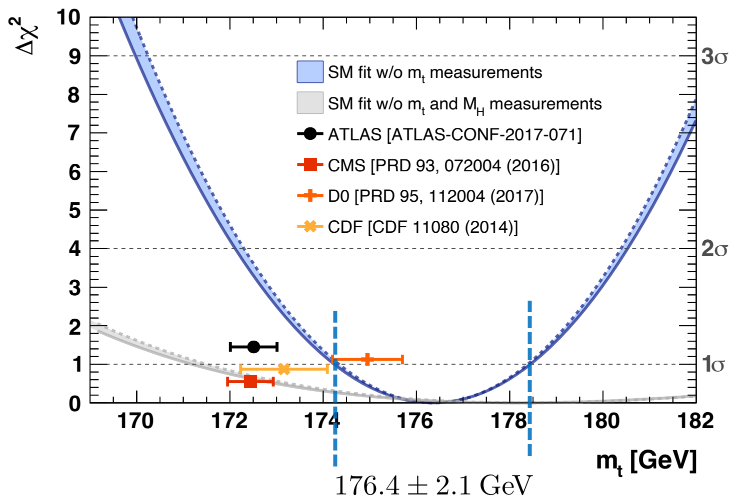
global fit of the electroweak sector

Gfitter, Eur.Phys.J.C 78 (2018) 8, 675, 1803.01853

comparison of SM predictions from 2018 fit with recent direct measurements







$\sin^2\theta^l_{\rm eff}$: prediction from fit more precise than direct measurements, important to improve the measurements, agreement found

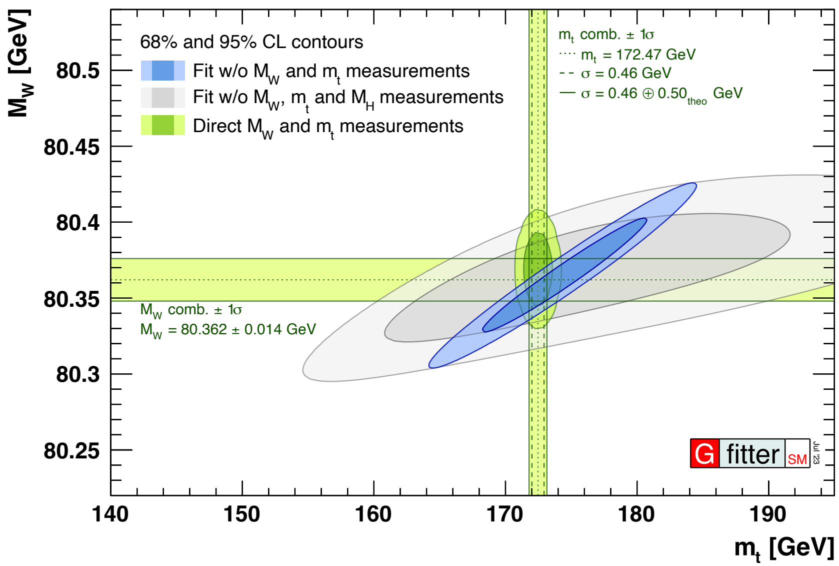
M_W: fit yields precision of 7 MeV, much better than direct measurements, agreement (except CDF)

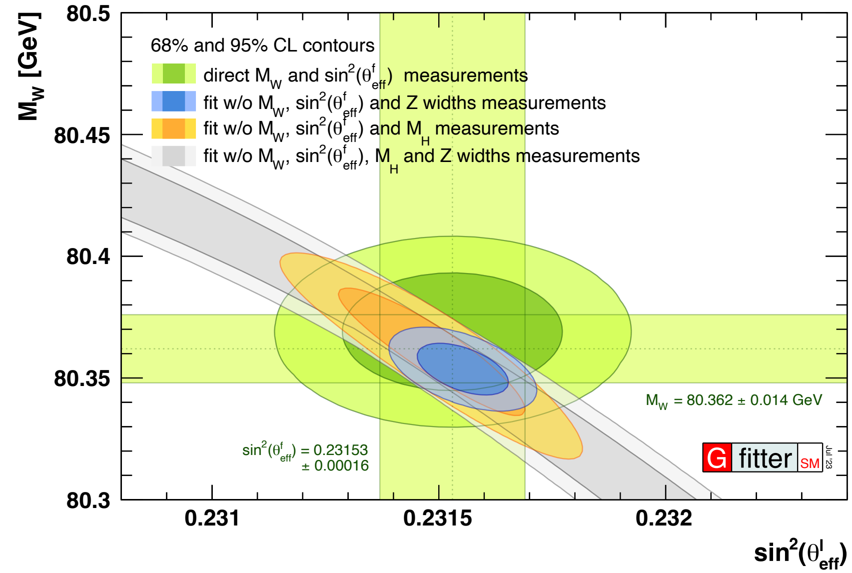
m_t: different situation, direct measurements already significantly better than direct prediction, agreement

knowing the Higgs mass precisely is not of greatest importance (due to weak $\ln m_H$ dependence of HO corrections)

global fit of the electroweak sector

Gfitter, Y Fischer, PoS EPS-HEP2023 (2024) 304





electroweak sector very consistent (using M_W from LEP+LHC)

hadron collider input (M_W , $\sin^2\theta^l_{\text{eff}}$, m_t , M_H) driving the exp progress

- we cannot know M_W and $\sin^2\theta^l_{\text{eff}}$ precisely enough
- further experimental improvements highly desirable
  - CMS M_W measurement awaited to clarify tension

measurements of EW processes at high E: multi-boson production

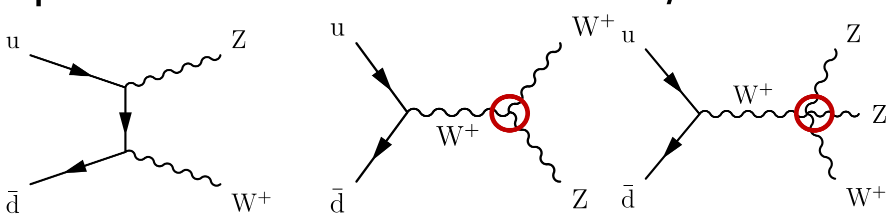
Multi-Boson production at LHC

CMS review, subm. to PhysRep., 2405.18661

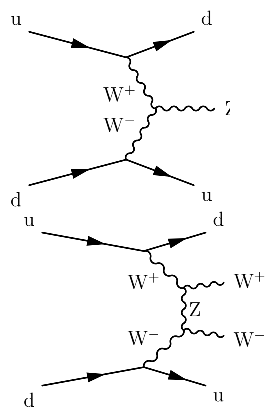
Multi-boson production provides detailed insights into VV interactions

single, double, triple production

production modes for multi-W/Z:



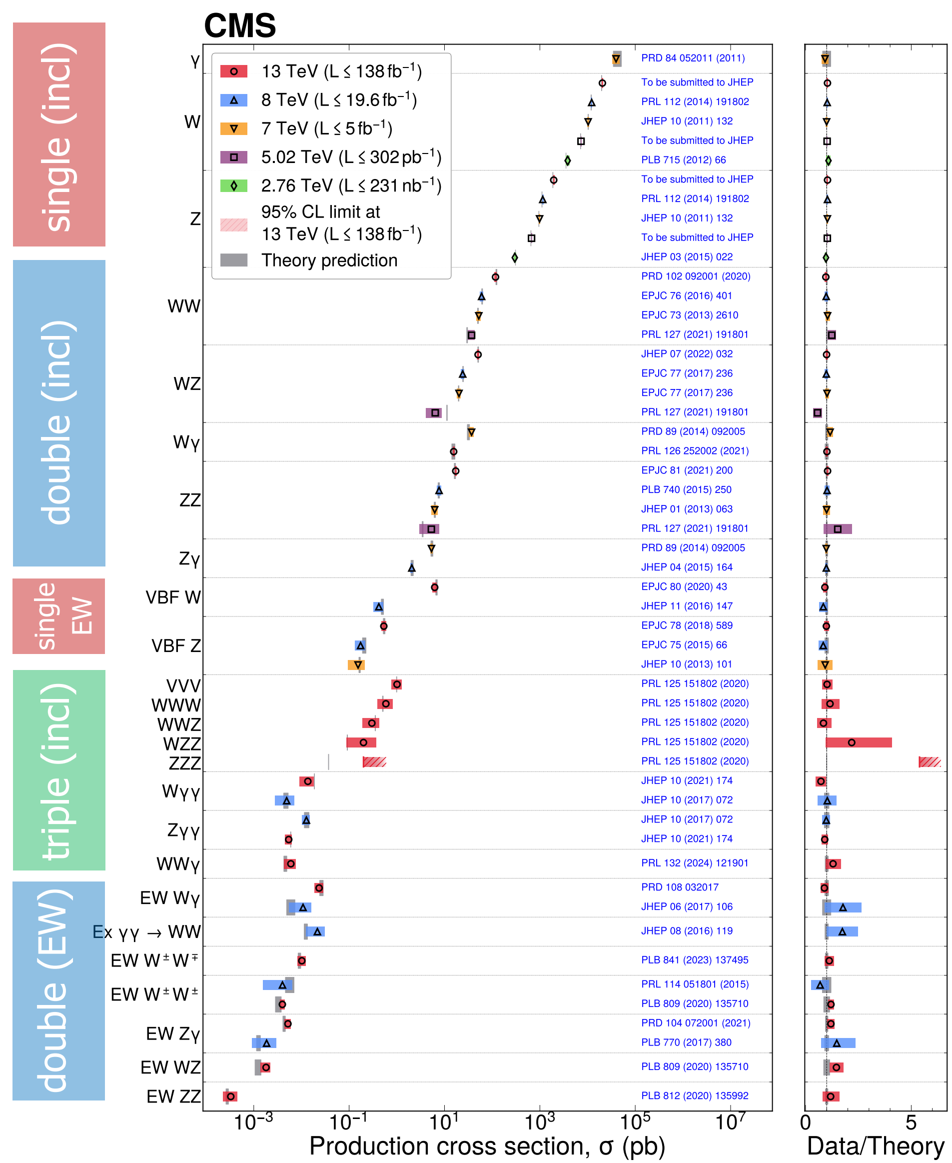
- q/g-ind.: DY, radiative, g-induced
- multi-boson-interactions ('EW prod')
  - test of TGC and QGC
  - Vector Boson Fusion (VBF)
  - Vector boson scattering (VBS)



large variety of final states,

broad range of cross-sections probed

can only cover a tiny fractions



Diboson production at LHC

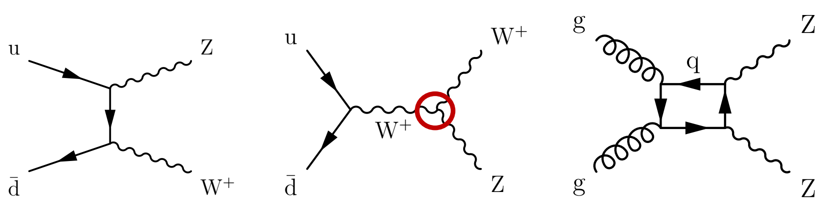
CMS review, subm. to PhysRep., 2405.18661

several production modes:

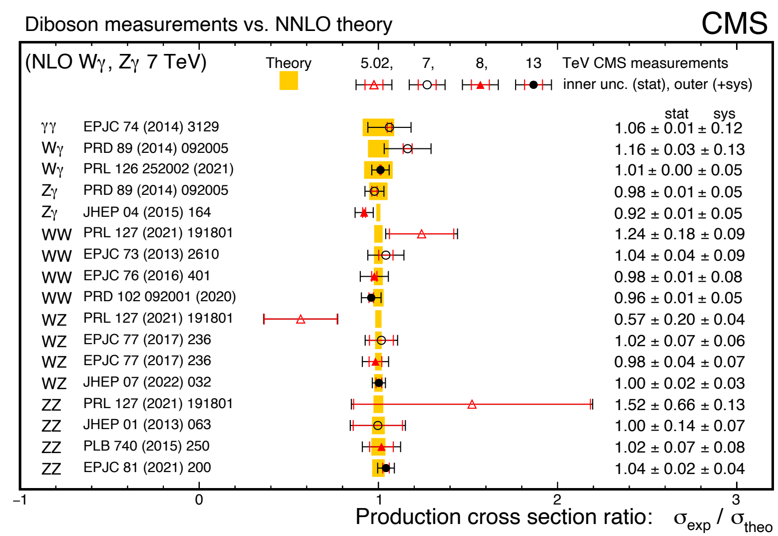
radiative production

TGCs

NNLO QCD



- first observed at TeVatron



precision results available at LHC

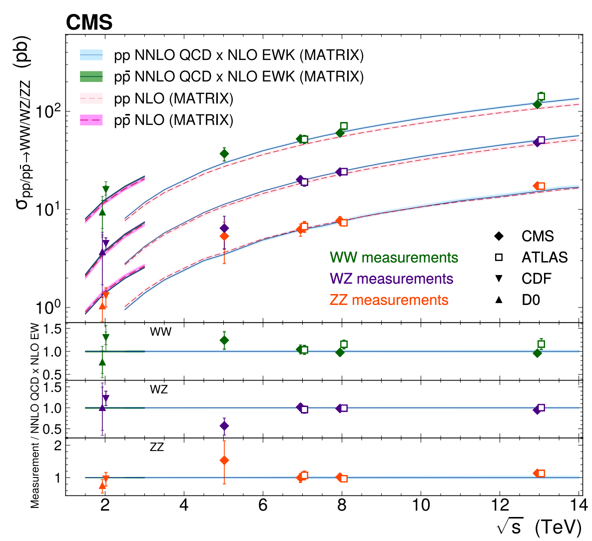
- pure $W \to l\nu$ and $Z \to ll$ reconstruction + large datasets

→ already in Run-1: studies of major modes

$\gamma\gamma, W\gamma, Z\gamma$, OS $W^{\pm}W^{\mp}, WZ, ZZ$

→ Run-2: high precision measurements at several % level

- – most precise: WZ, ZZ with 3-4 % precision
- – need NNLO QCD + NLO EW calculations for comparison
  - o good agreement seen



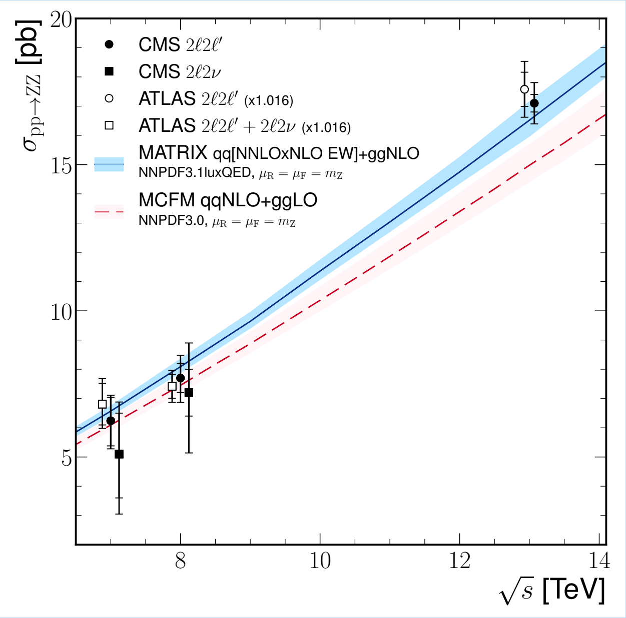
Diboson production at LHC

<u>importance of accurate SM predictions</u>

- comparising precise σ_{ZZ} measurements with:
  - NLO QCD for $q\bar{q}$, LO QCD for gg
  - NNLO QCD + NLO EW for $q\bar{q}$, NLO QCD for gg

→ contribution from NLO and NNLO QCD substantially increase cross sections

- needed for agreement with experimental data



differential measurements for all diboson final states also done

- variety of variables: $p_T^l, p_T^V, n_{\text{jet}}, p_T^{\text{jet}}, m_{VV}, \ldots$ (with sensitivity for HO QCD, HO EW or BSM)
- not covered here, in general decent agreement observed.

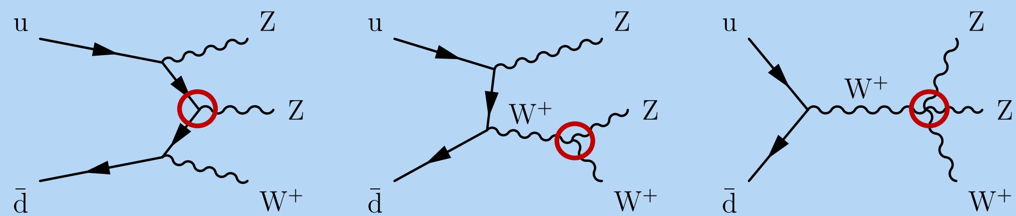
Triboson production at LHC

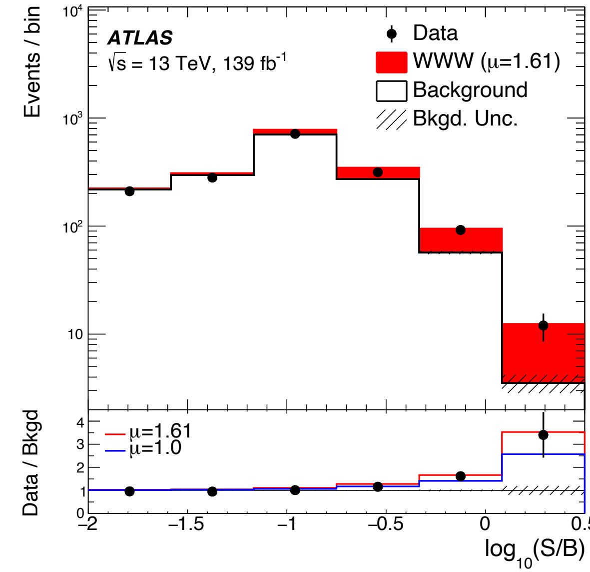
ATLAS, Phys. Rev. Lett. 129 (2022) 061803, 2201.13045

CMS, Phys.Rev.Lett. 125 (2020) 15, 151802, 2006.11191

most difficult: VVV with very small cross-sections

- probe of TGCs and QGC
  - smaller TGC sensitivity than in diboson



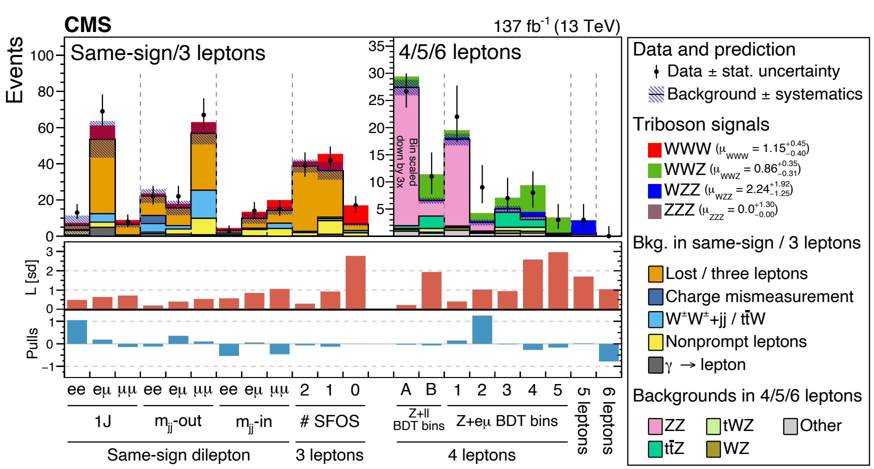


at LHC Run-2: large $\sqrt{s}$ and large $\int L\mathrm{d}t$

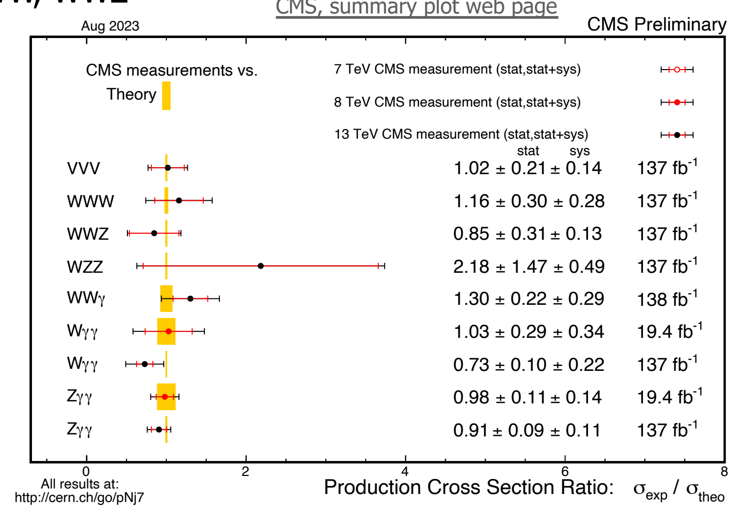
first time discovery, signature: multi-lepton (SS) events

ATLAS: WWW observed (significance: $8\sigma, 2.6\sigma$ above SM (NLO QCD, EW LO))^

CMS: VVV collectively observed, individual evidence for WWW, WWZ



CMS, summary plot web page

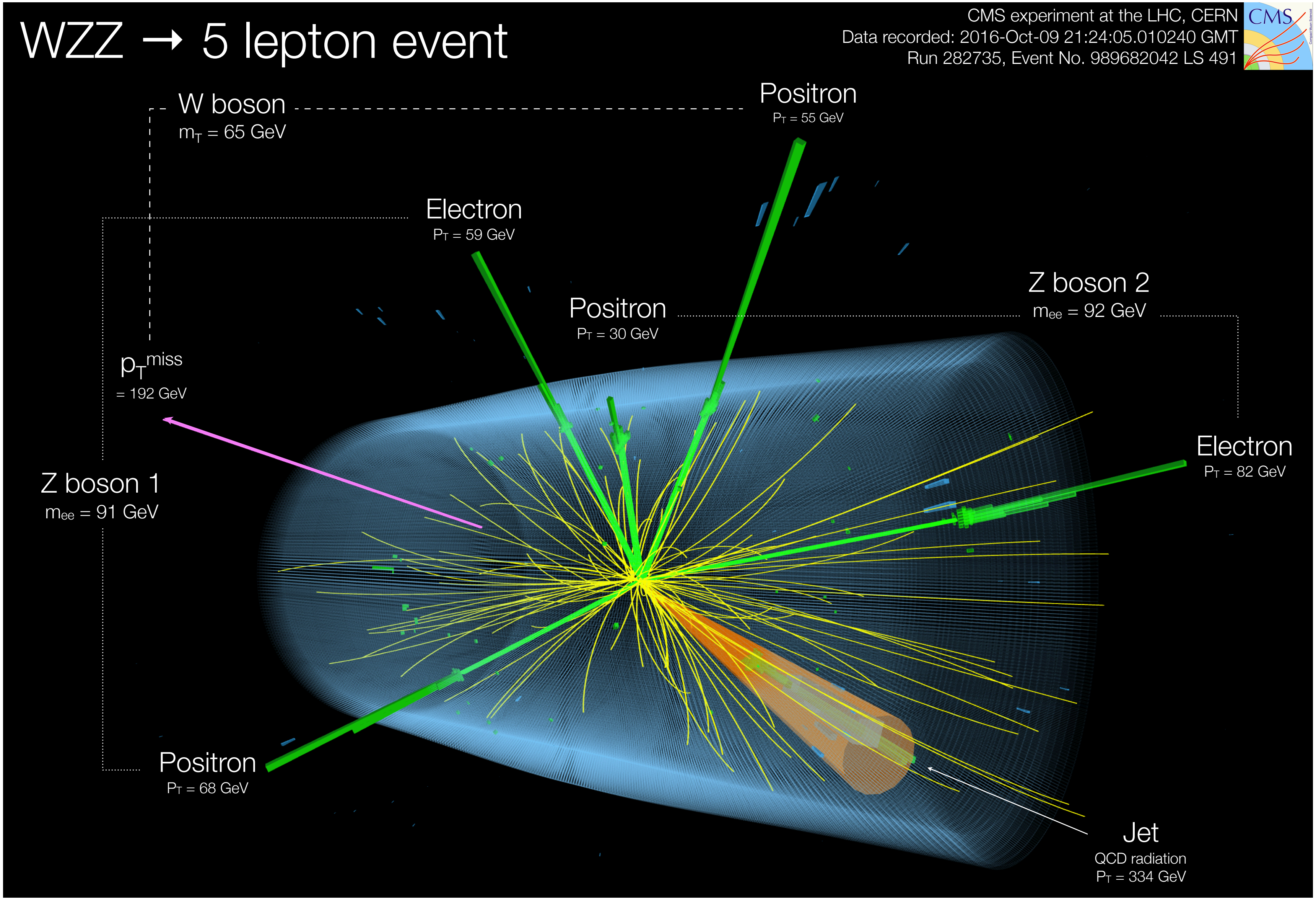


O(30)% precision

decent agreement with SM prediction

Triboson production at LHC

CMS, additional material



Vector-Boson scattering (VBS)

ATLAS, Phys. Rev. Lett. 123, 161801 (2019), 1906.03203

CMS, Phys. Rev. Lett. 120, 081801 (2018), 1709.05822

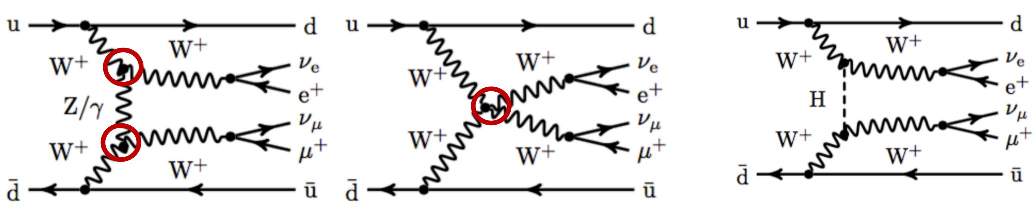
Vector-Boson scattering is unique at LHC

production modes:

double TGC in t- and s- channel

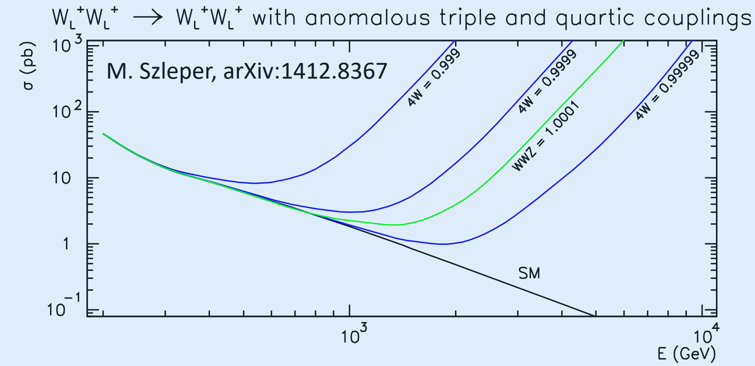
quartic gauge couplings

t-channel Higgs (needed to unitarize cross-section of logitudinal VBS)



highly interesting, purely EW interactions

SM: cancellations of contributions in $W_L^+ W_L^+ \rightarrow W_L^+ W_L^+$

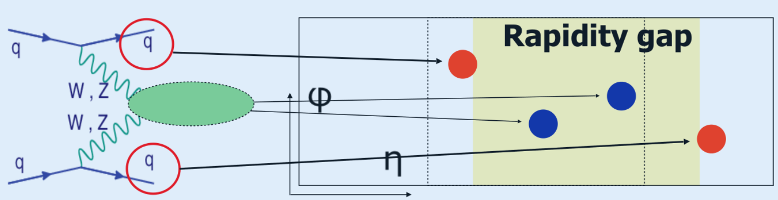


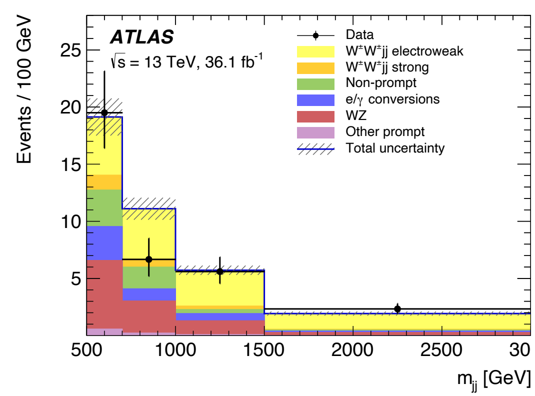
first obs. in SS WW in early Run-2

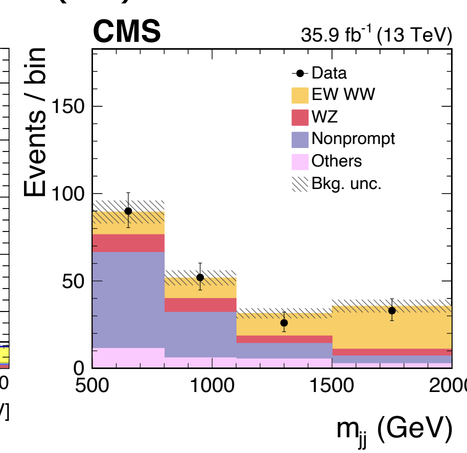
ATLAS: 6.5 (4.4) σ, CMS: 5.5 (5.7) σ

experimental features: very rare, O(fb)

- 2 jets, large rapidity gap, high mass



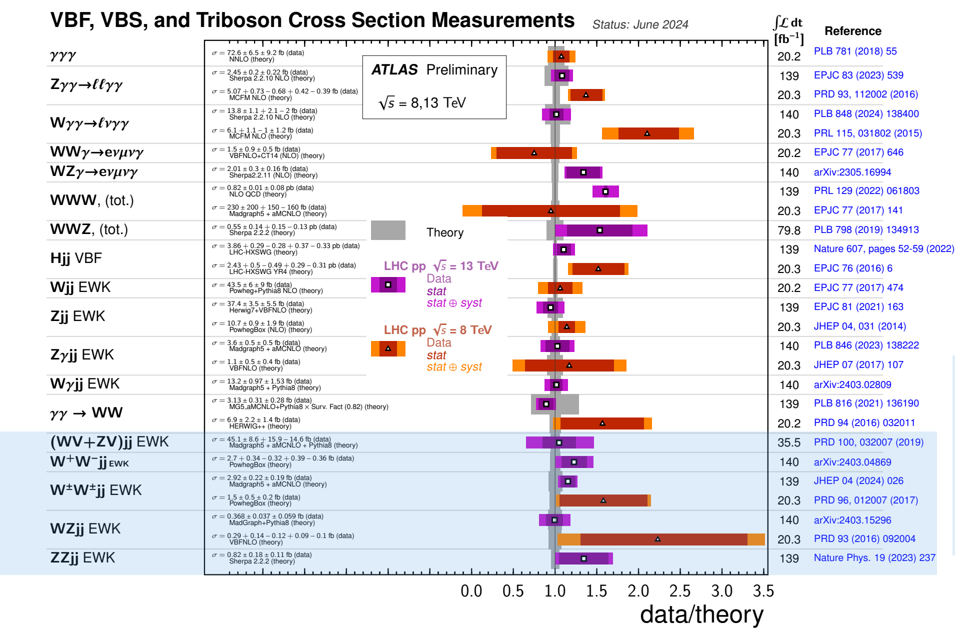


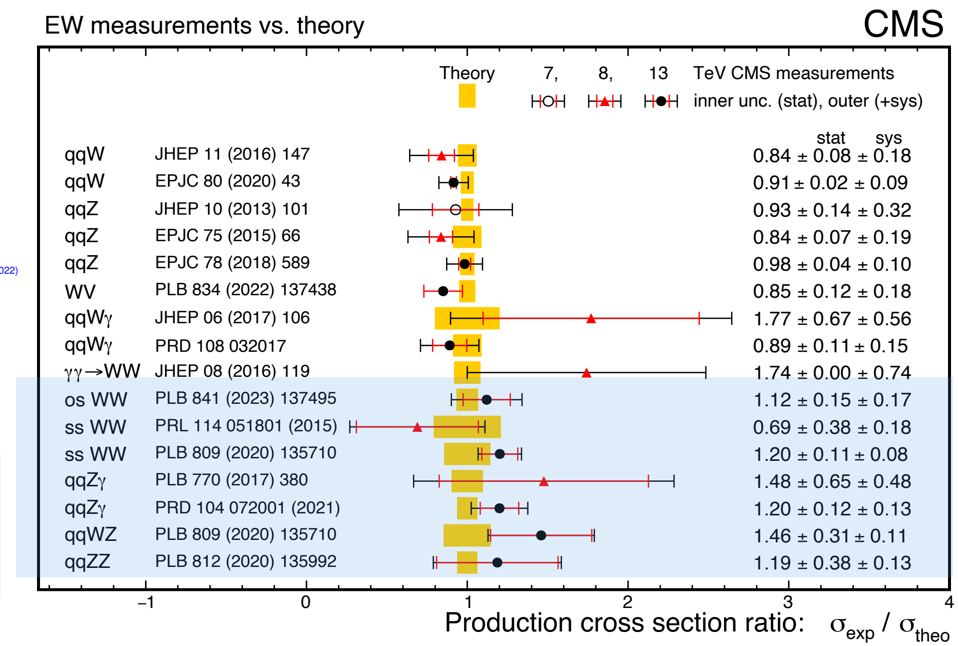


Vector-Boson scattering (VBS)

CMS review, subm. to PhysRep., 2405.18661

with full Run-2 data, VBS observed in all major channels:





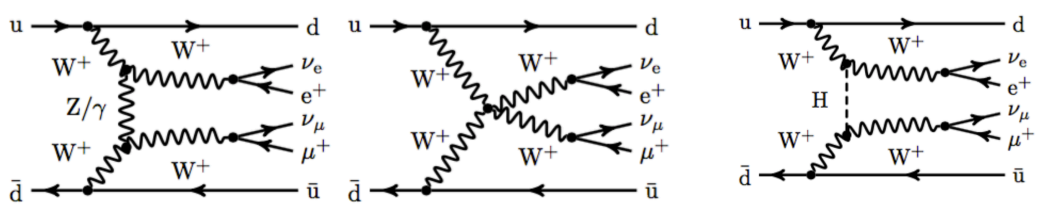
- plenty of results (incl. and differential): see ATLAS and CMS presentations at ICHEP24
- decent agreement with theoretical predictions within significant uncertainties
- constraints on aQGCs (EFT dim-8 operators)
- results are statistically dominated
- improved precision expected with more data (Run-3)

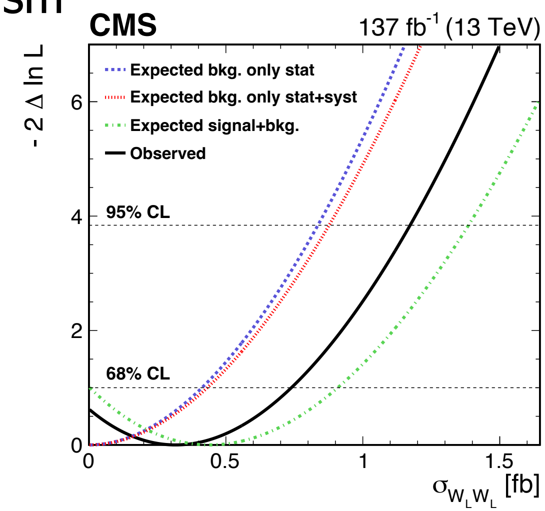
the next level: polarized Vector-boson scattering

CMS, Phys. Lett. B 812 (2020) 136018, 2009.09429

identification of scattering of longitudinally polarized WW: clear sign of presence of Higgs interaction in VBS

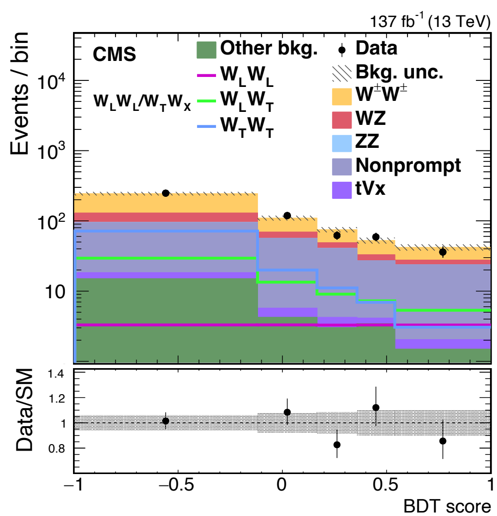
considered one of the crucial tests of EWSB mechanism





current analyses use distinctive SS channel of $W^{\pm}W^{\pm}$

- multivariate discriminant to separate polarisation contributions



run-2 data not enough for evidence:

- significance for VBS $W_L^{\pm}W_X^{\pm}$ is 2.3σ
  - obs. 95% CL: $\sigma(W_L^{\pm}W_L^{\pm}) < 1.17$ fb
  - SM prediction: $\sigma(W_L^{\pm}W_L^{\pm}) = 0.44$ fb

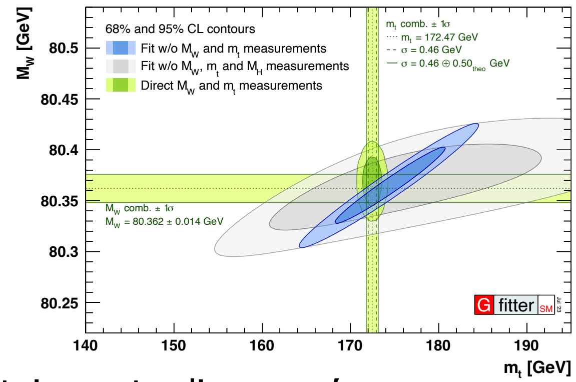
MADGRAPH5_aMC@NLO LO + $\mathcal{O}(\alpha_S\alpha^6)$ and $\mathcal{O}(\alpha^7)$ corrections

stay tuned !

summary of first part (EW)

LHC provides a broad range of EW results (often far beyond initial expectations)

- recently many new, highly precise measurements of EW parameters (M_W , $\sin^2\theta^l_{\text{eff}}$)
  - in combination with EWPO from e^+e^-
    → impressive internal consistency



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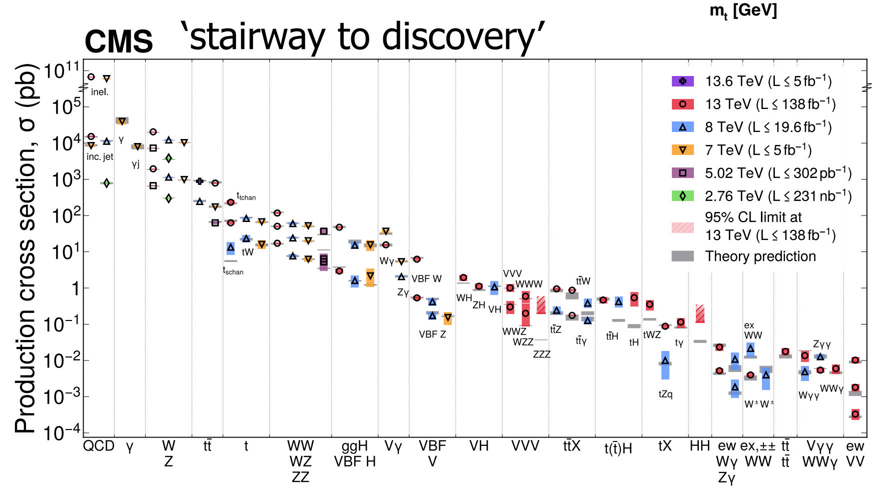
- wide variety of EW processes identified; cross sections being measured with increasing precision
  - reaching few %-level in some cases
  - good agreement with SM prediction
  - testing non-trivial HO effects of theory

CMS ‘stairway to discovery’



CMS review, subm. to PhysRep., 2405.18661

LHC Run-3 + HL-LHC: results will get even more precise → SM confirmation or BSM ?