Recent measurements of W and Z bosons with the CMS experiment

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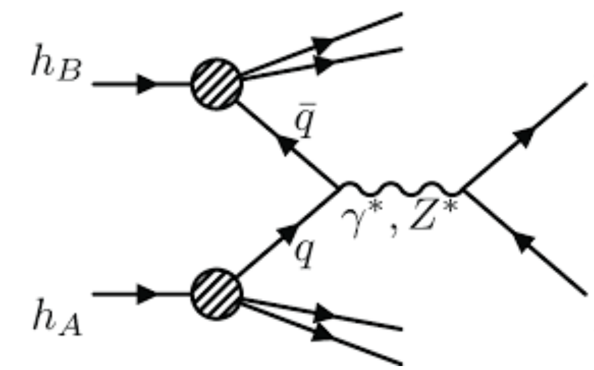
40 years of W and Z bosons at colliders!

Discovered at CERN in 1983 in $p\bar{p}$ collisions

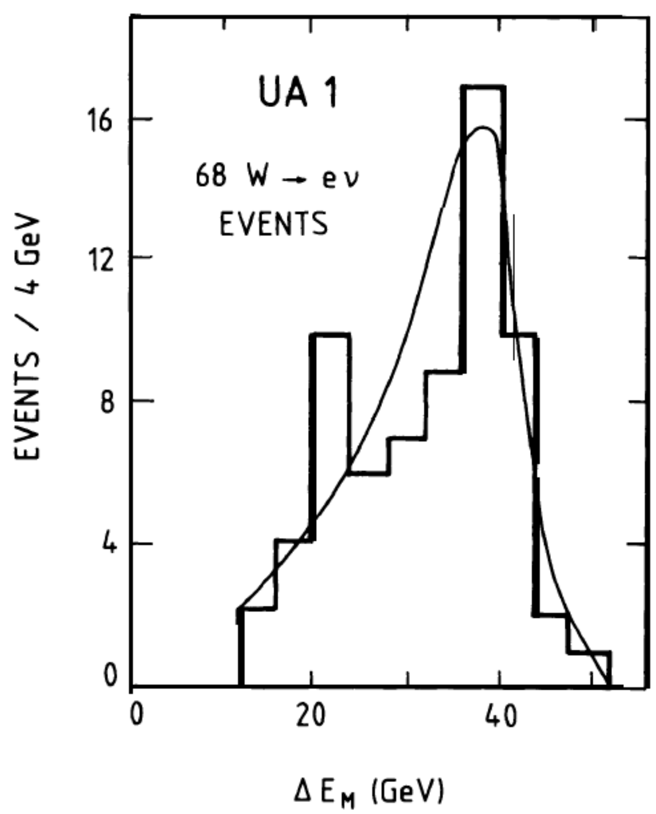
- still on the front line of the LHC physics program with pp

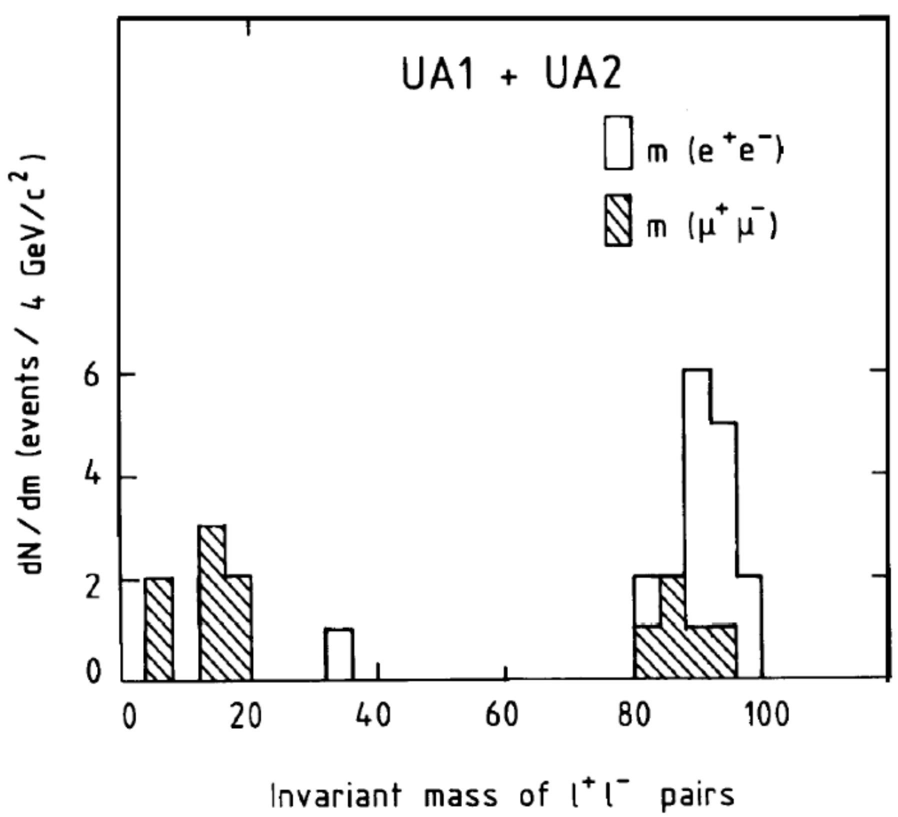
Drell-Yan process

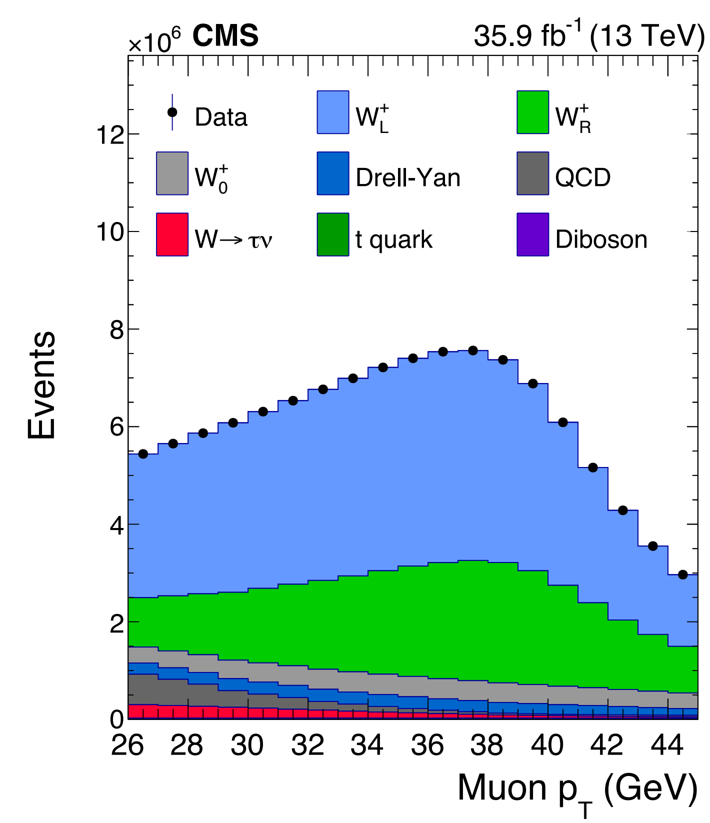


One of most prominent examples of hard scattering processes at hadron colliders

- tests of perturbative QCD and electroweak (EW) calculations to higher orders
- constraints on parton distribution functions (PDFs)
- validation of different generators to model hard scattering and parton shower



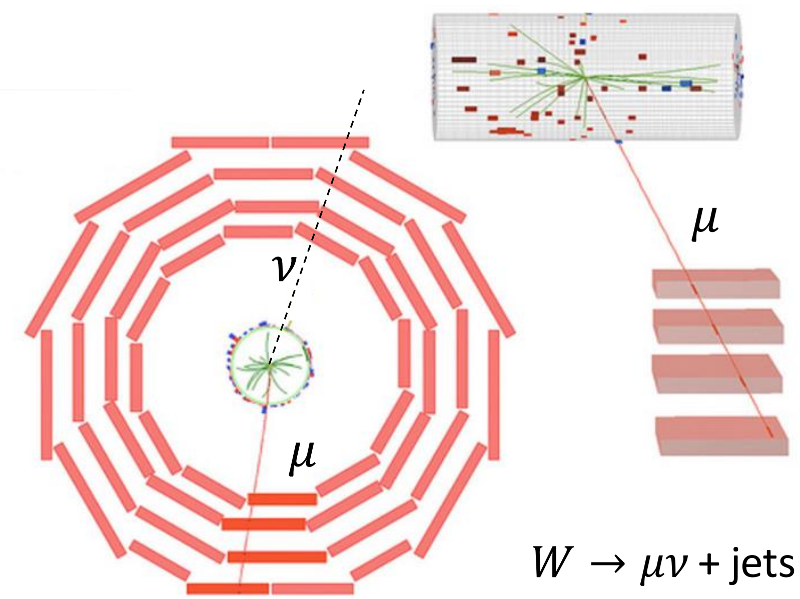




Experimental aspects of W and Z bosons

Clean experimental signatures because of leptonic decay to e, μ

- 1% uncertainty in efficiencies, ≈1% resolution, momentum scale better than 0.1%



Z bosons standard candles for detector calibration

- energy/momentum scale and resolution
- also luminosity calibration from Z counting

Large Run 2 LHC data sets

- multi-differential cross section measurements with negligible statistical uncertainty

W/Z are backgrounds in Higgs boson analyses and new physics searches

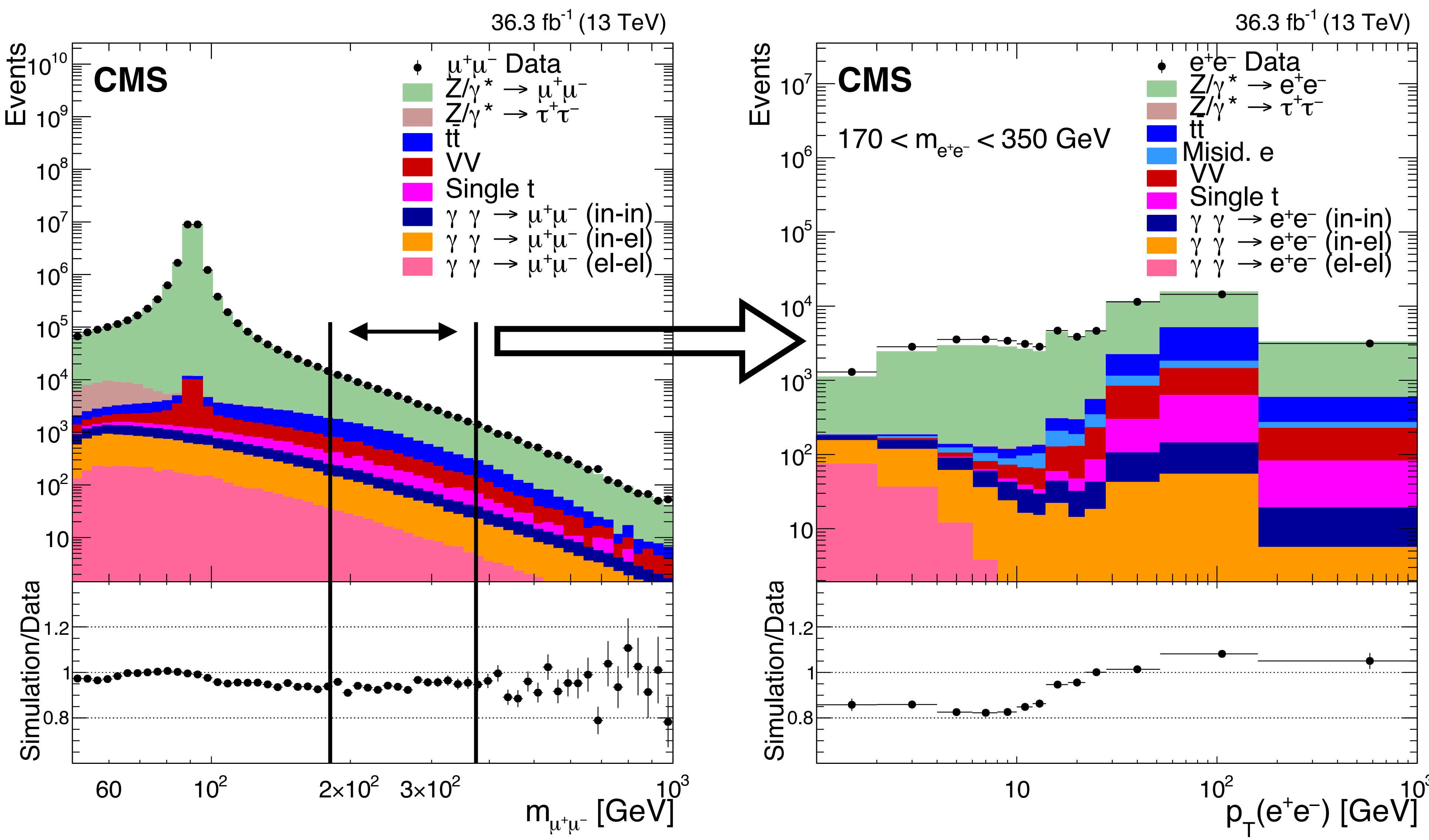
- as an example, missing transverse momentum (p_T^{miss}) from decays into neutrinos indistinguishable from dark matter production topology

Mass dependence of Z boson p_T

Reference

Measured differential cross section in p_T^Z or ϕ^* in bins of $m_{\ell\ell}$

- High p_T region usually well described by QCD higher orders in perturbation theory
- Low p_T region sensitive to soft gluon radiation, large log terms need resummation
  - predicted simple dependence on mass scale —> test validity of resummation approach and precision of different predictions



$$\varphi^*_\eta \equiv \tan\left(\frac{\pi - \Delta\varphi}{2}\right)\sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left[(\eta^- - \eta^+)/2\right]$$

ϕ^* correlated with Z p_T but better resolution especially at low p_T since only dependent on angular variables

$\phi^* \sim p_T^Z / m_{\ell\ell}$

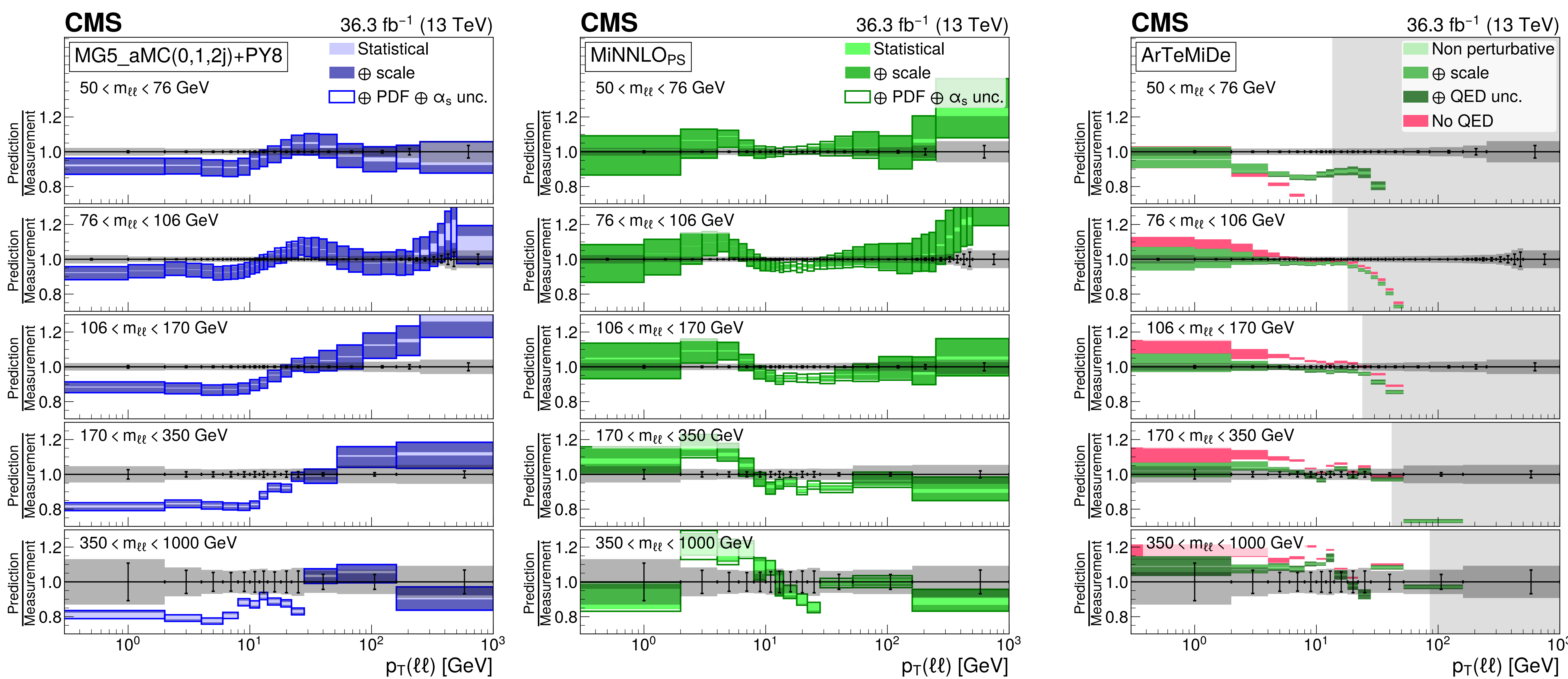
Mass dependence of Z boson p_T

Measurement performed using both ee and μμ decays

- for inclusive DY production or with at least one jet

Interesting to compare with multiple generators

- MiNNLO$_{PS}$ provides best global description of data



Showing (some) inclusive results (more on >=1 jets in Philippe's talk)

Forward-backward asymmetry in Drell-Yan

A_{FB} in $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ important feature of Z decay

- sensitive to many SM parameters
- was exploited to measure effective weak mixing angle $\sin^2\theta^f_{eff}$ at 8 TeV

$$\frac{d\sigma}{d\cos\theta} \propto \frac{3}{8}\left[1+\cos^2\theta+\frac{A_0}{2}\left(1-3\cos^2\theta\right)+A_4\cos\theta\right]$$

from interference of vector and axial-vector contributions (dependent on Z mass)

θ angle between ℓ^- and quark q in Collins-Soper frame

- quark's true direction unknown —> assume it is same as $\ell\ell$ pair —> dilution of A_{FB}

From theory it is

$A_{FB} = 3/8 \cdot A_4$

Experimentally

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

$F: \cos\theta > 0$

$B: \cos\theta < 0$

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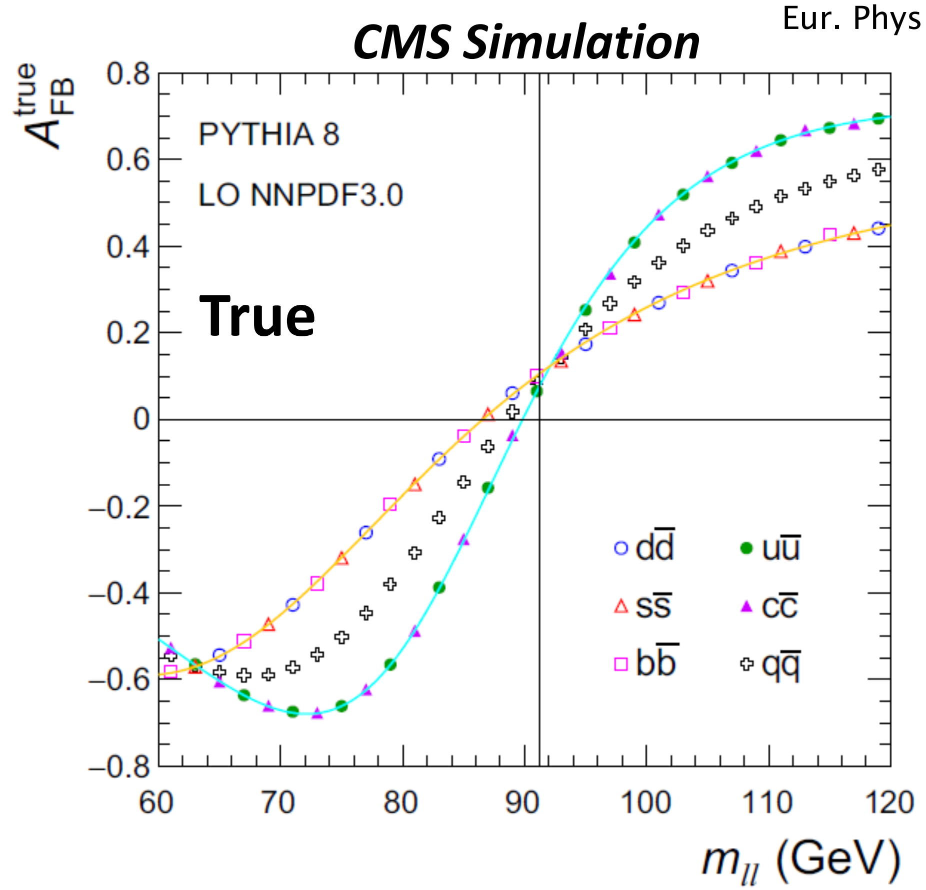
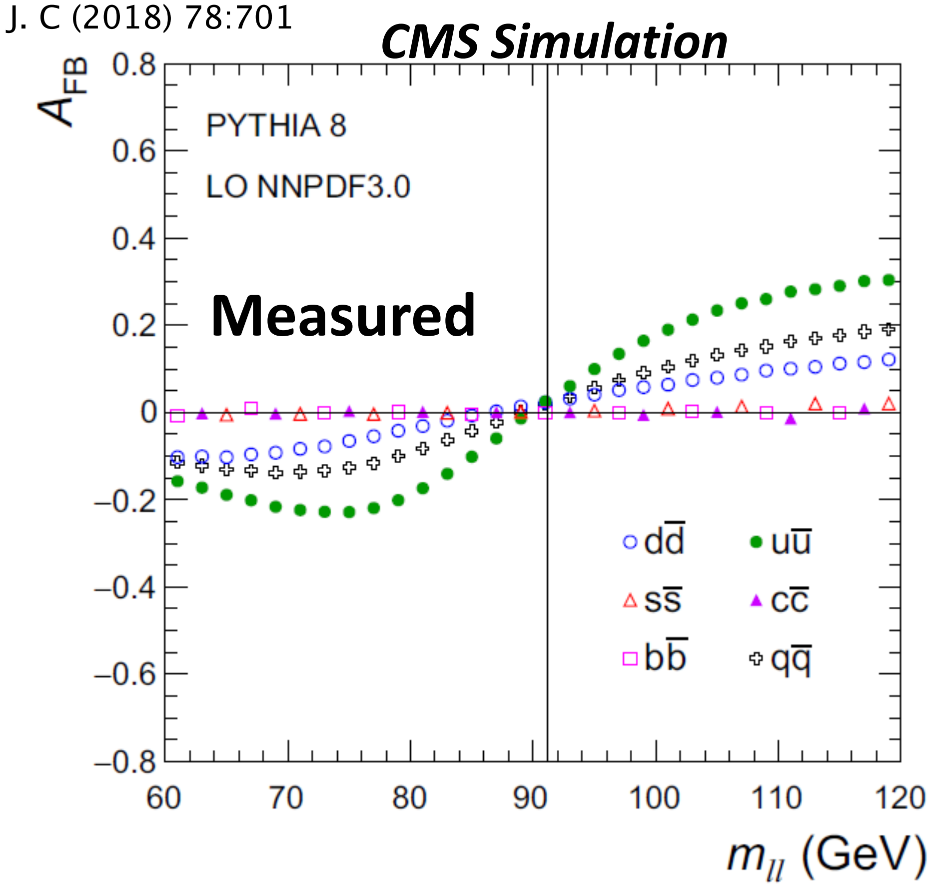




Reference

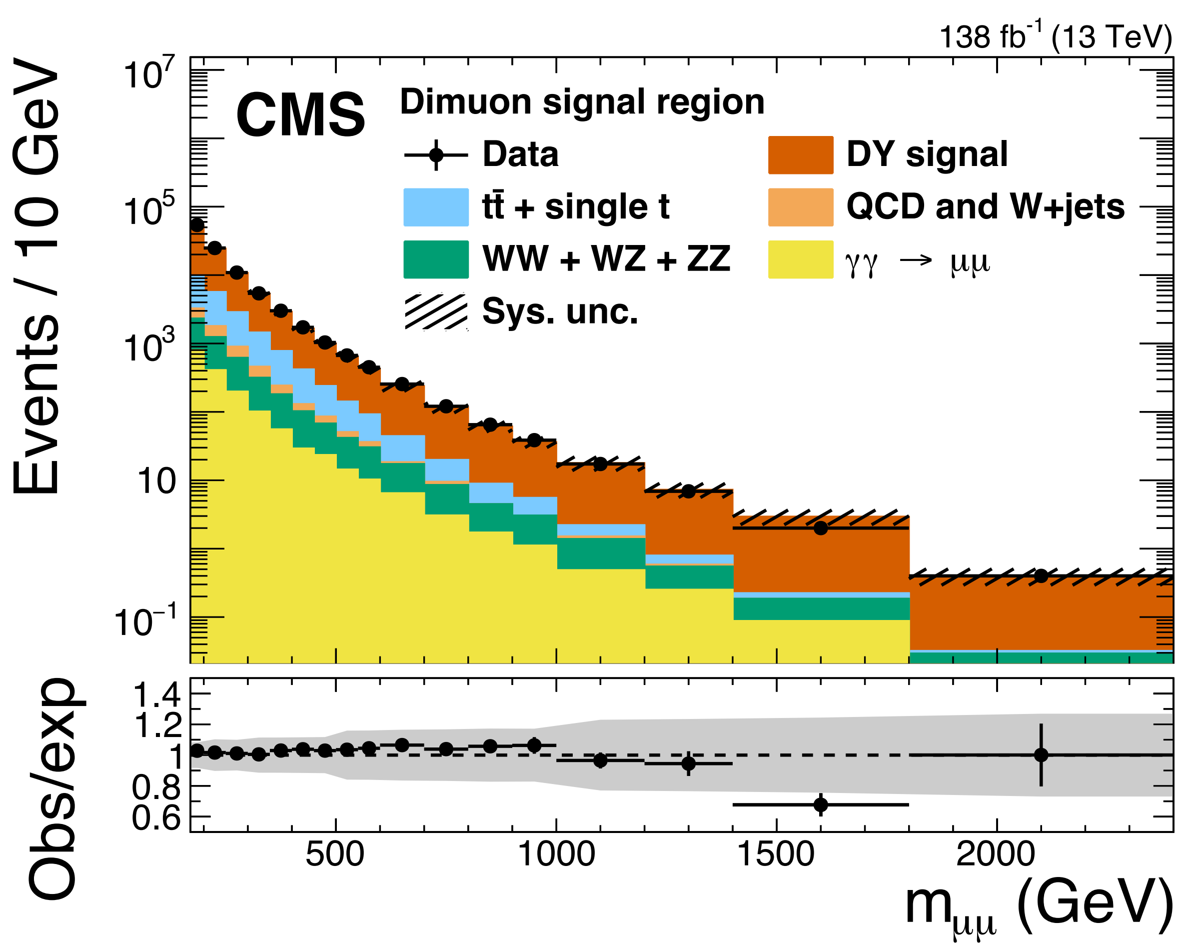
A_{FB} at high mass

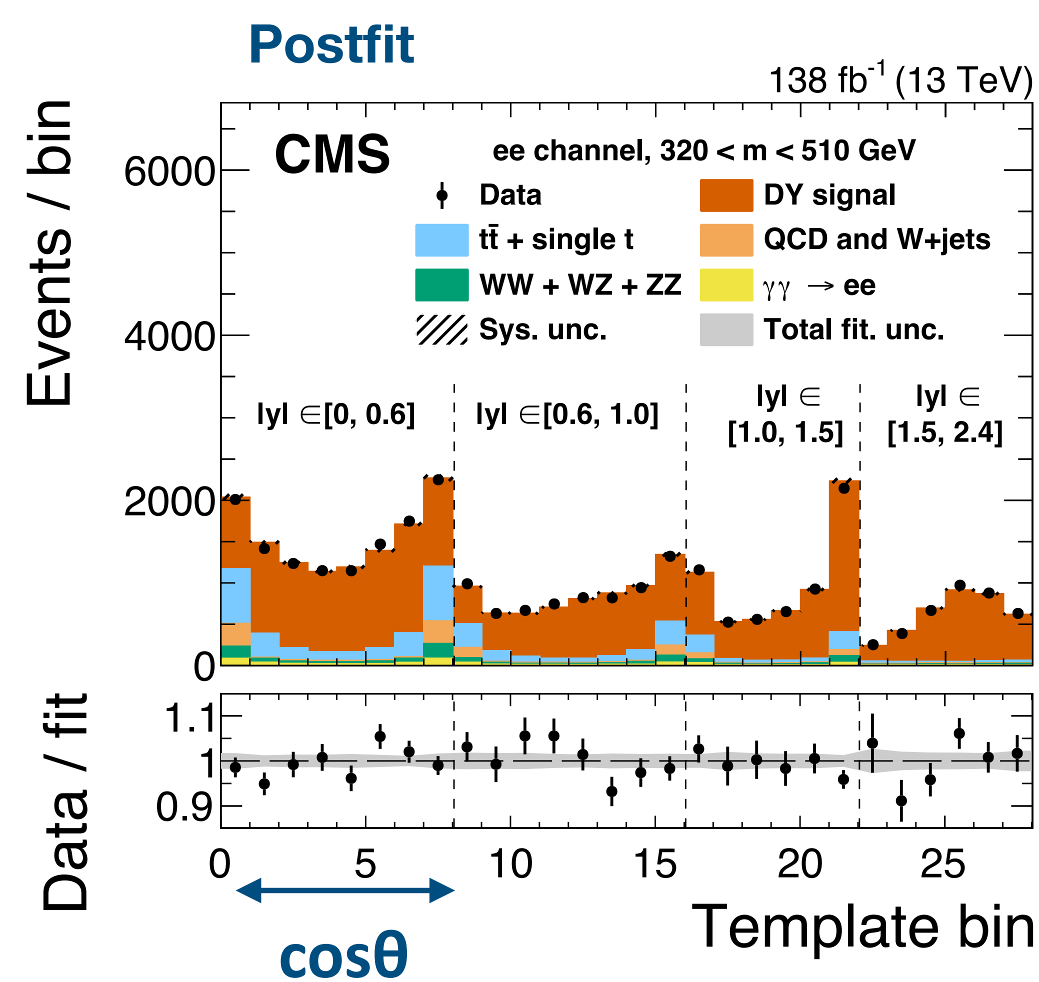
At dilepton masses well above Z peak (>170 GeV) A_{FB} ~ constant

- Deviations can be induced by new phenomena, such as a massive Z’ gauge boson
- off-shell interference can modify A_{FB} at $m_{\ell\ell}$ significantly lower than Z’ mass
  - Complementarity with direct Z’→ℓℓ searches

Template fit method rather than counting forward-backward events

- simulated templates represent terms in dσ/dcosθ and account for dilution effect



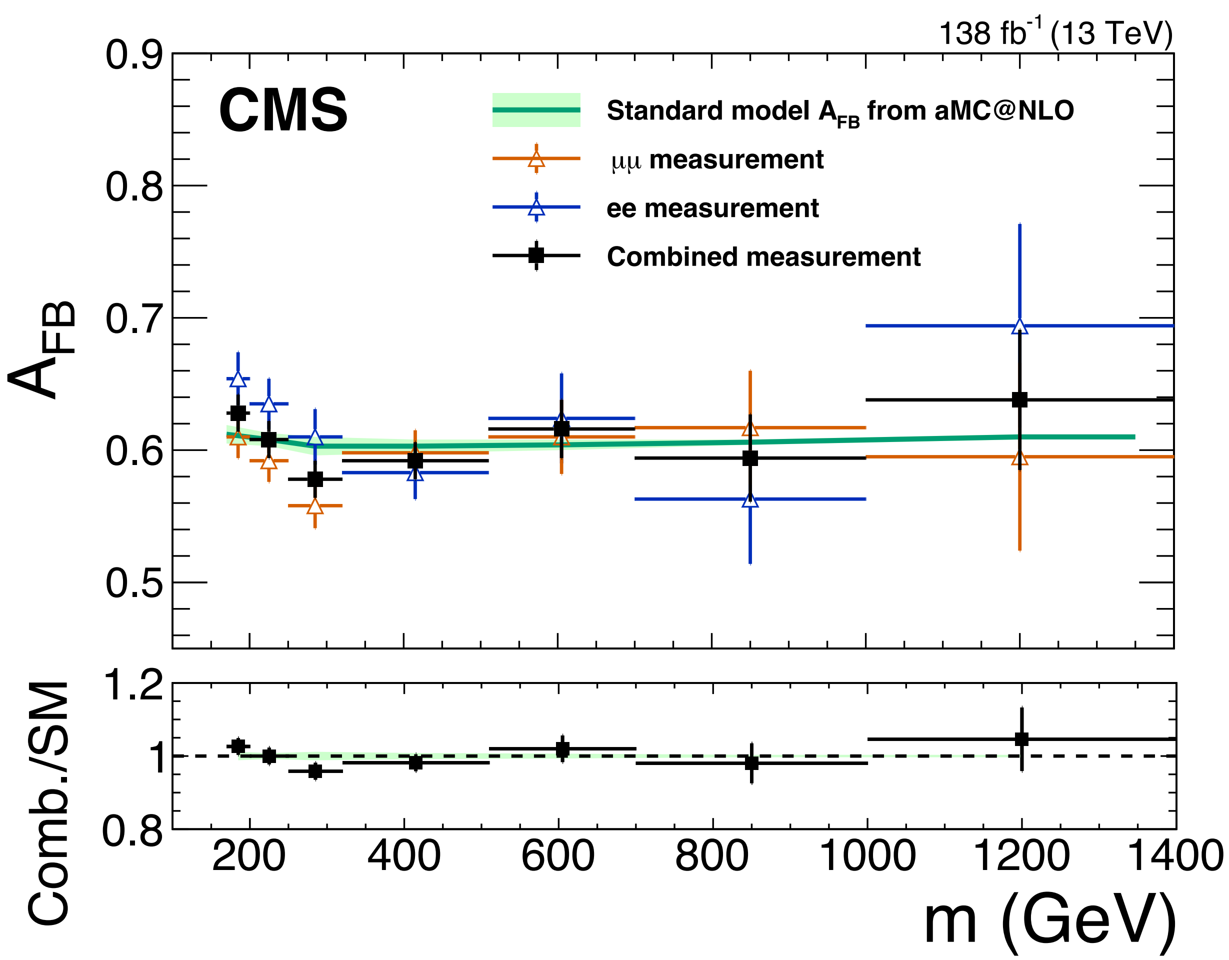


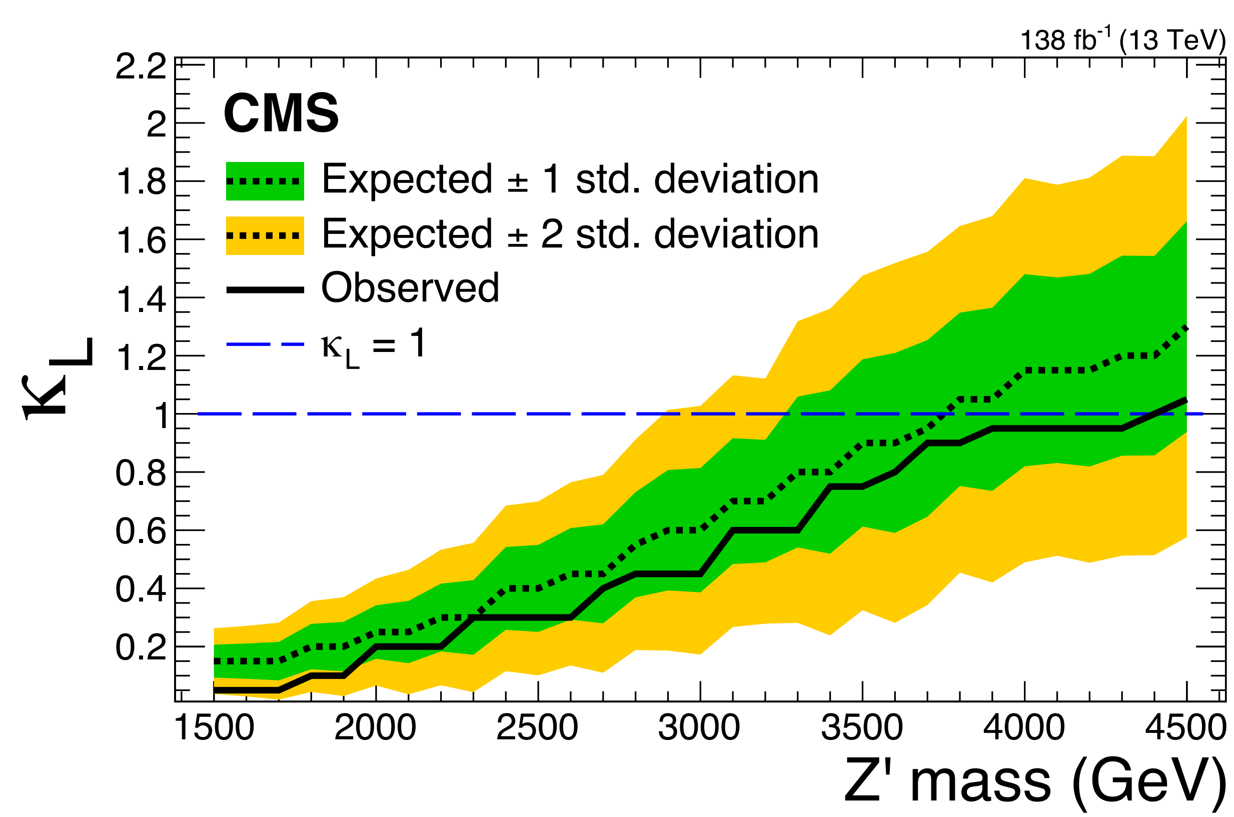
A_{FB} results

- A_{FB} and A_0 (also difference between e-μ channels) as a function of $m_{\ell\ell}$
- Exclusion of Z' with $m_{Z'}$ < 4.4 TeV assuming same coupling as SM Z
  - Less stringent limits than in direct searches, but also sensitive to wide resonances

Uncertainty dominated by statistical uncertainty in data and PDFs

- gain with more data and extended tracker acceptance at HL-LHC



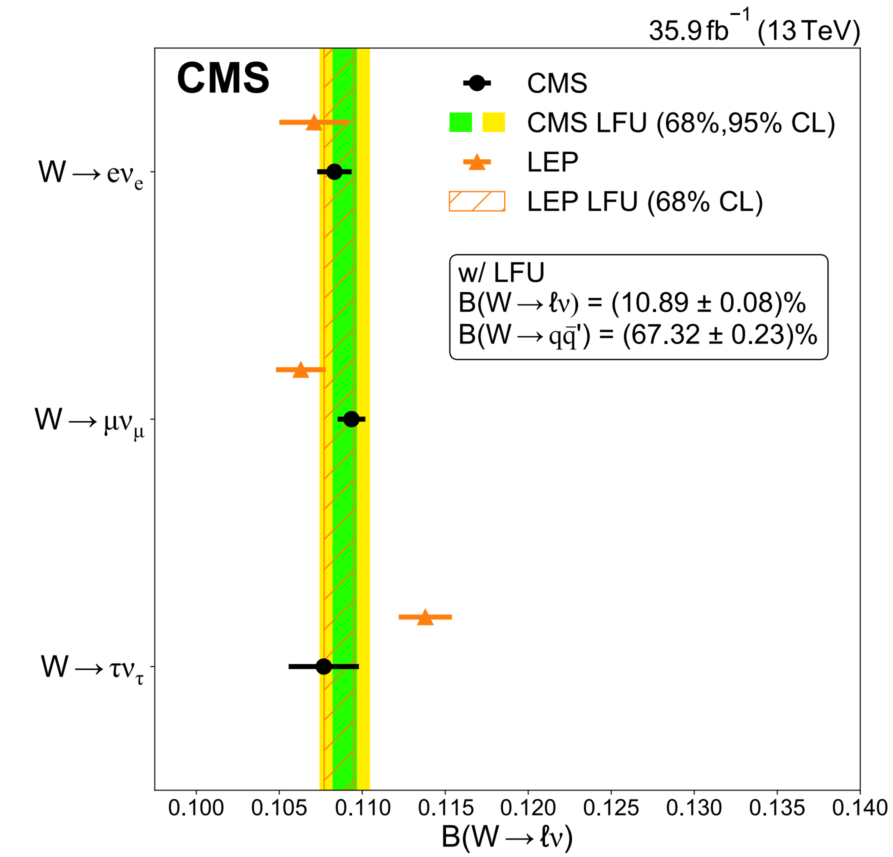


W decay branching fractions

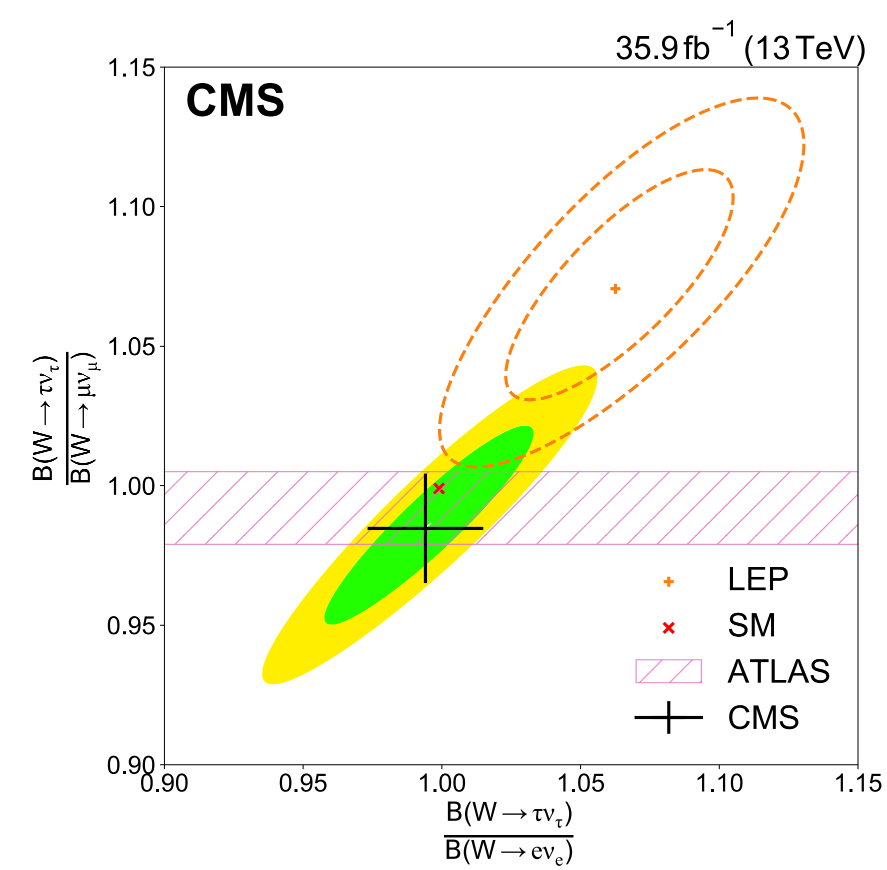
Reference

Measured leptonic and hadronic branching ratios $\mathcal{B}$ of W boson, and their ratios

- Stringent test of lepton flavour universality (LFU)
- Hadronic width depends on other SM parameters such as $\alpha_S(m_W)$ and CKM matrix elements V_{ij}
  - CKM unitarity requires $\sum_i |V_{ui}|^2 = \sum_i |V_{ci}|^2 = 1$ (i=d,s,b)
  - Indirect determination of these variables too



- Simultaneous fit in all decay channels in data using simulated templates for signal and backgrounds
  - **CMS more precise than LEP** (but limited by systs)



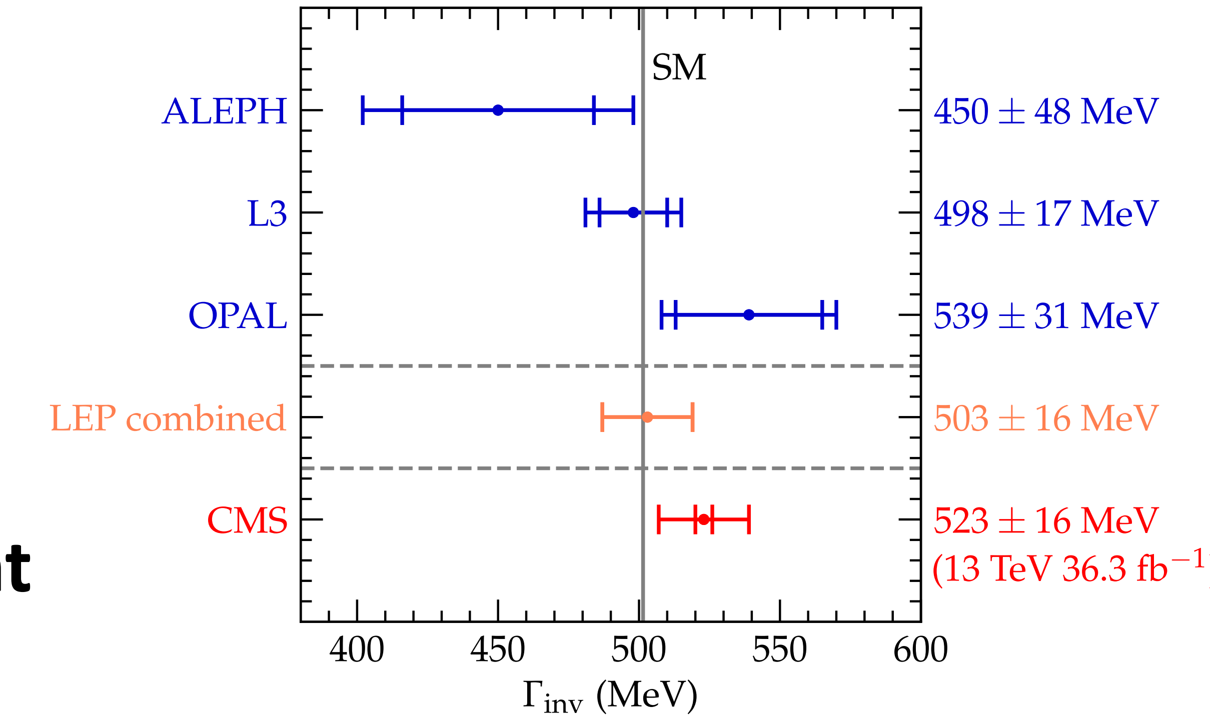
	CMS	LEP
$\mathcal{B}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e})$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)$ %
$\mathcal{B}(\mathrm{W} \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)$ %
$\mathcal{B}(\mathrm{W} \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)$ %
$\mathcal{B}(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(\mathrm{W} \to \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

Invisible Z width

Reference

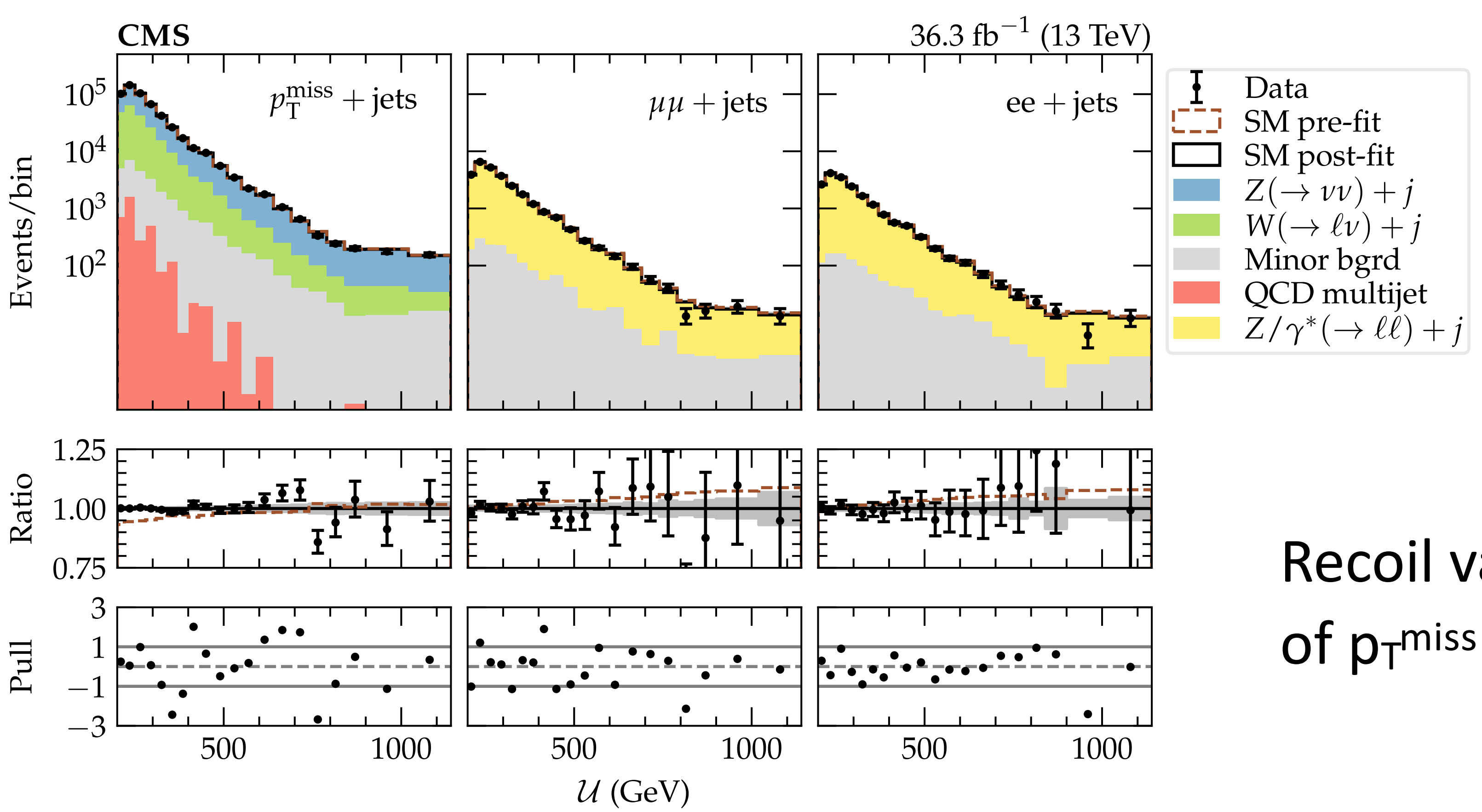
First measurement of Z invisible width at a hadron collider

- from Z(νν)/Z(ℓℓ) cross section ratio multiplied by Z(ℓℓ) partial width from LEP



Single most precise *direct* measurement

- negligible statistical uncertainty



$$\frac{\sigma(Z+jets)B(Z\to\nu\nu)}{\sigma(Z+jets)B(Z\to\ell\ell)} = \frac{\Gamma(Z\to\nu\nu)}{\Gamma(Z\to\ell\ell)}$$

Recoil variable $\mathcal{U}$ defined as vector sum of p_T^{miss} and reconstructed leptons' p_T

More in Philippe's talk

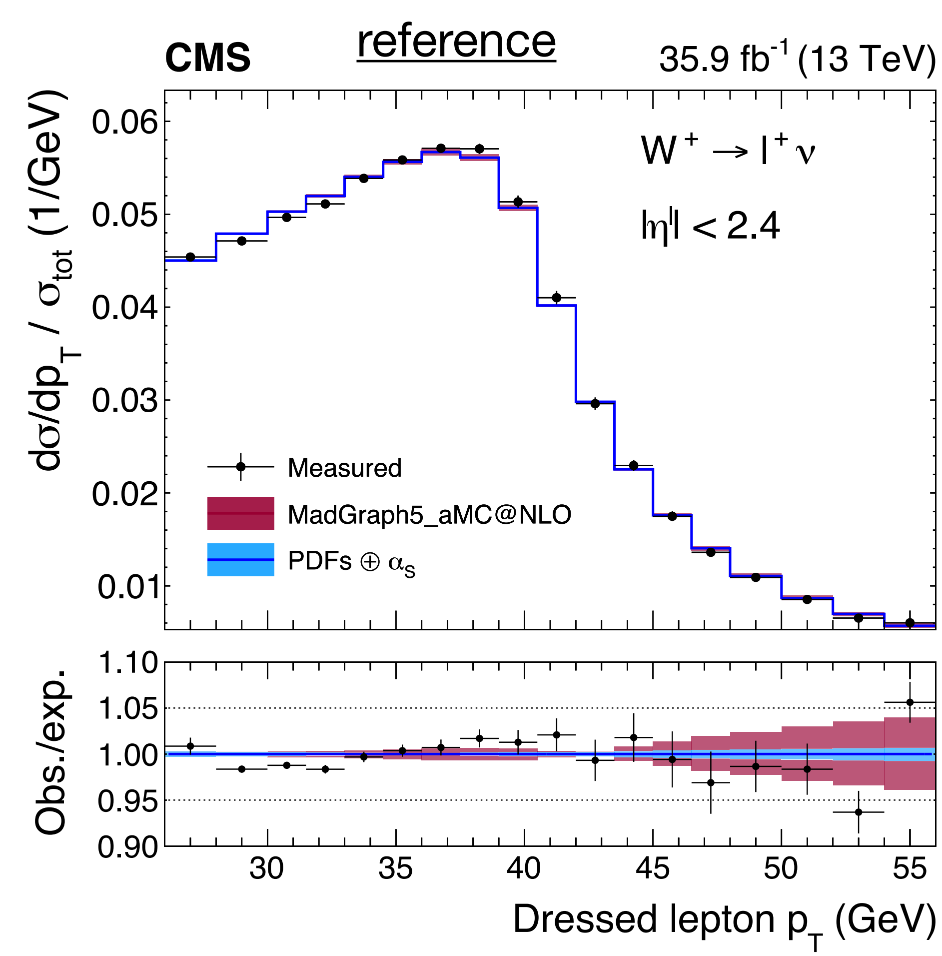
Physics prospects at the LH-LHC

20 times more data from HL-LHC phase than in Run 2

- but also daunting levels of pileup, higher trigger rates, intense radiation damage
- detector upgrade and complete overhaul of trigger and DAQ systems mandatory

Substantial improvements in first trigger stage (L1, hardware based)

- faster electronics, increased spacial granularity —> better particle identification
- maintain high signal purity and efficiency
  - W/Z physics requires leptons with p_T ~40 GeV
  - Keep low p_T thresholds in trigger



Extended tracker acceptance

- $|\eta| < 4$ instead of current 2.4
- better PDF constraints

Summary

Presented recent results on W and Z physics with CMS at the LHC

- valuable inputs to test theoretical calculations at higher orders
- precise knowledge of production cross sections guarantees more accurate background predictions for Higgs physics and is also vital in searches for new physics

Excellent performance of LHC and of CMS detector

- large data sets allow SM to be probed with unprecedented precision
- looking forward to Run 3 and future HL-LHC data and detector upgrades
- collaboration with theorists paramount to chart the course of future measurements

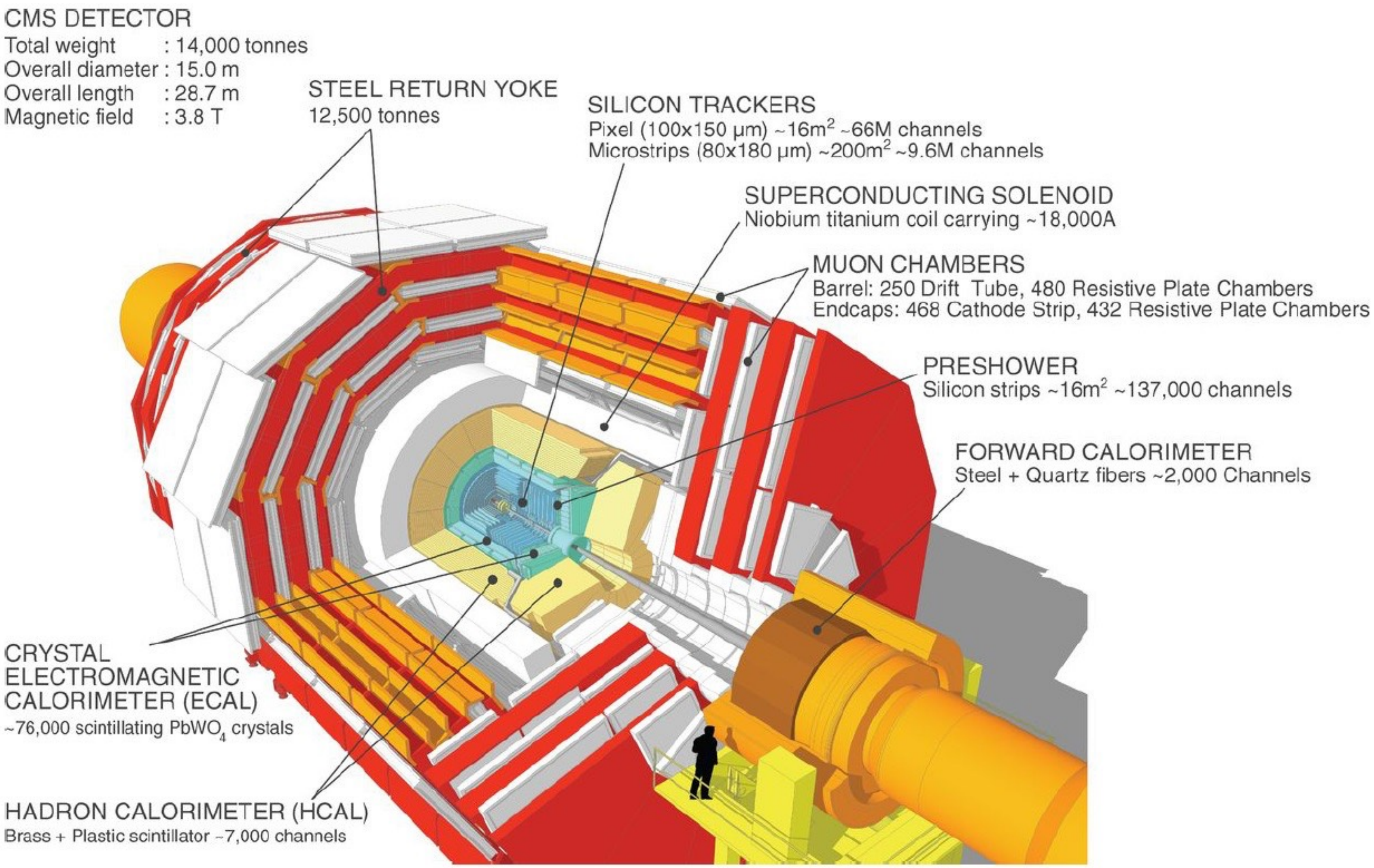
CMS standard model public results

- http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

More on W/Z + jets in Philippe's talk

BACKUP

CMS detector



Excellent tracking performance also thanks to 3.8 T magnetic field

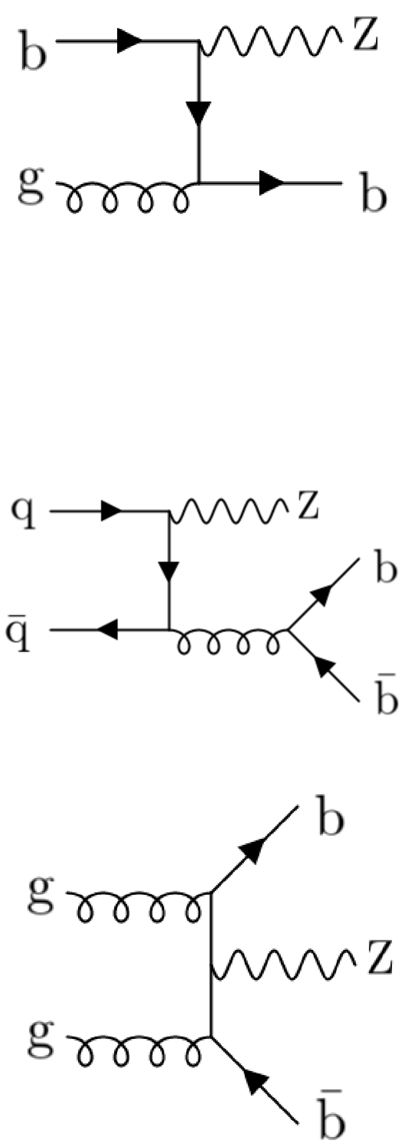
- Tracker coverage $|\eta| < 2.4$, precise p_T measurement and e/γ discrimination
- Electron reconstruction augmented with electromagnetic calorimeter

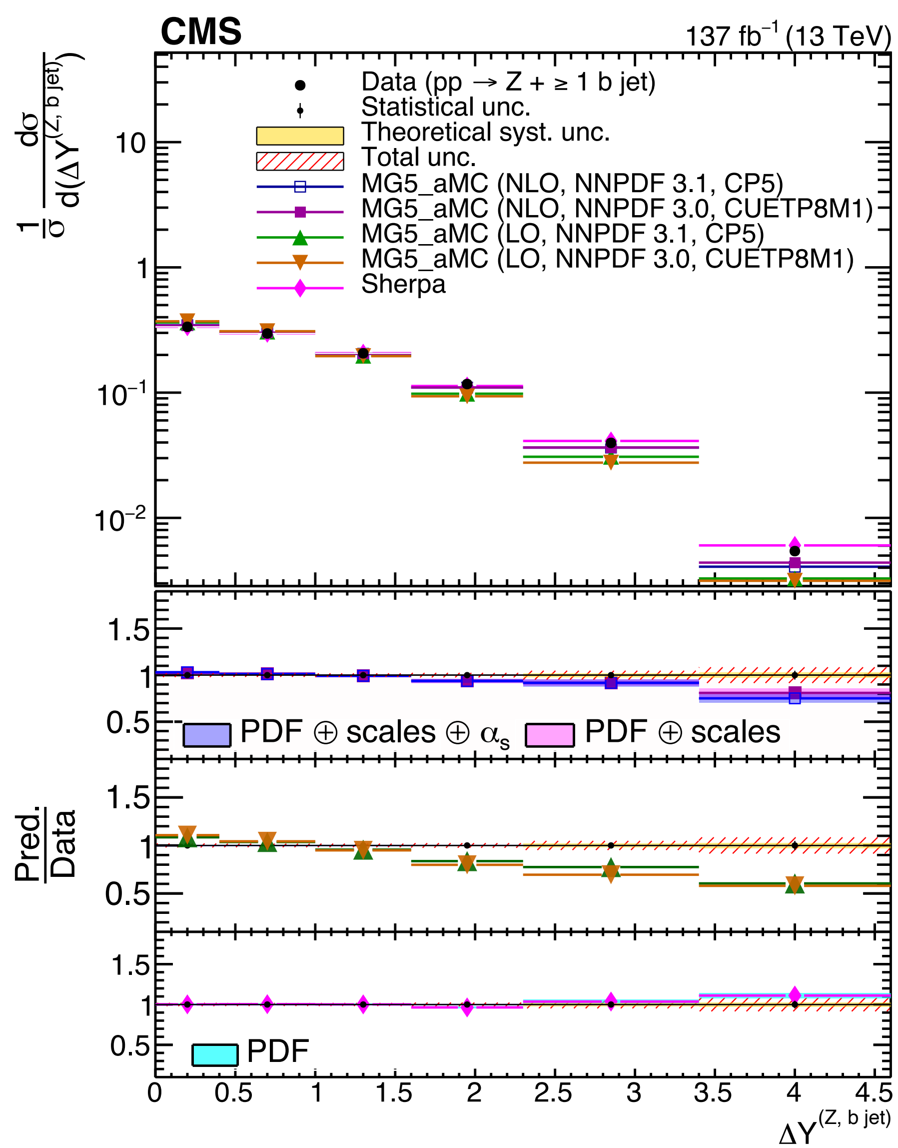
Calorimeters coverage up to $|\eta| < 5$, crucial for jets and p_T^{miss}

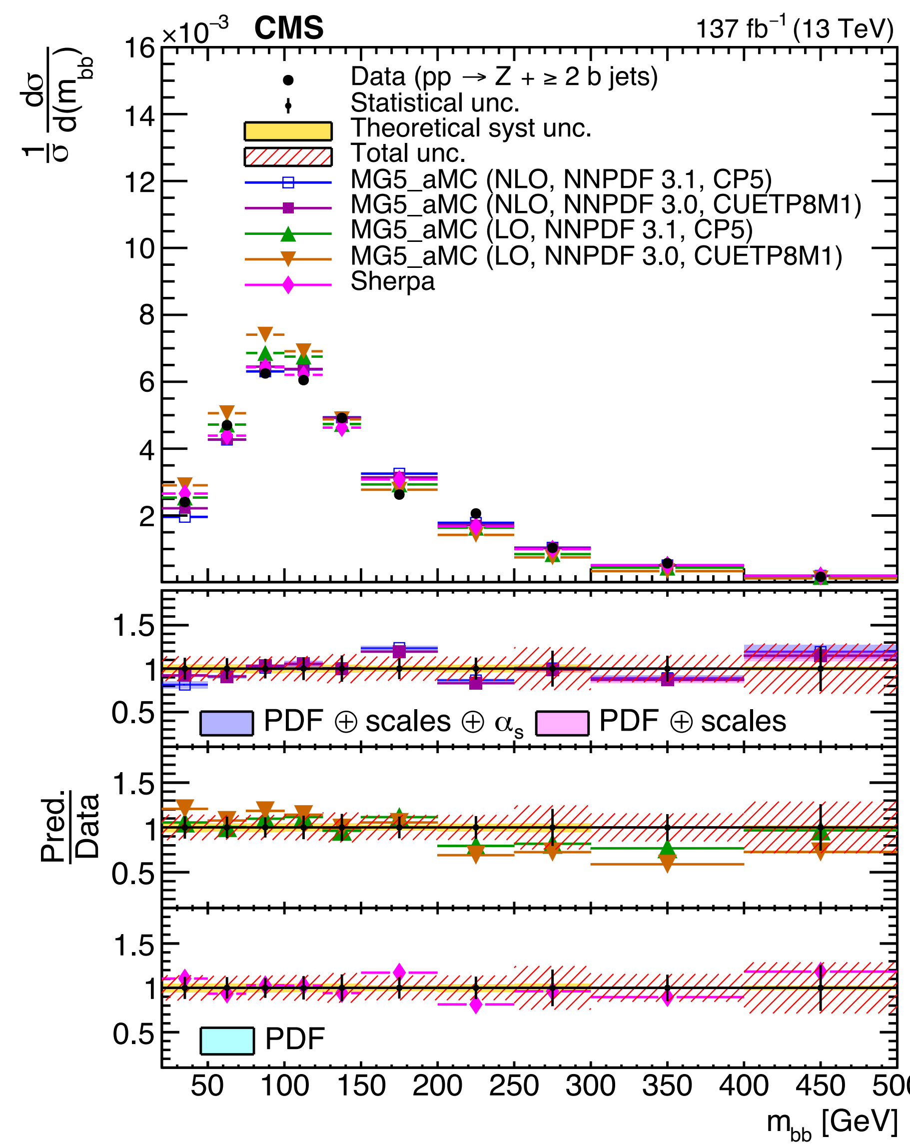
Z boson and heavy flavour jets

Sensitivity to c and b quark PDFs of proton

- check different b flavour schemes (4NFS or 5NFS) that affect number of final state b
- benchmark to validate MC predictions in VH topologies with $H \rightarrow c\bar{c}$ or $H \rightarrow b\bar{b}$
- compare angular or p_T distributions with calculations at different orders



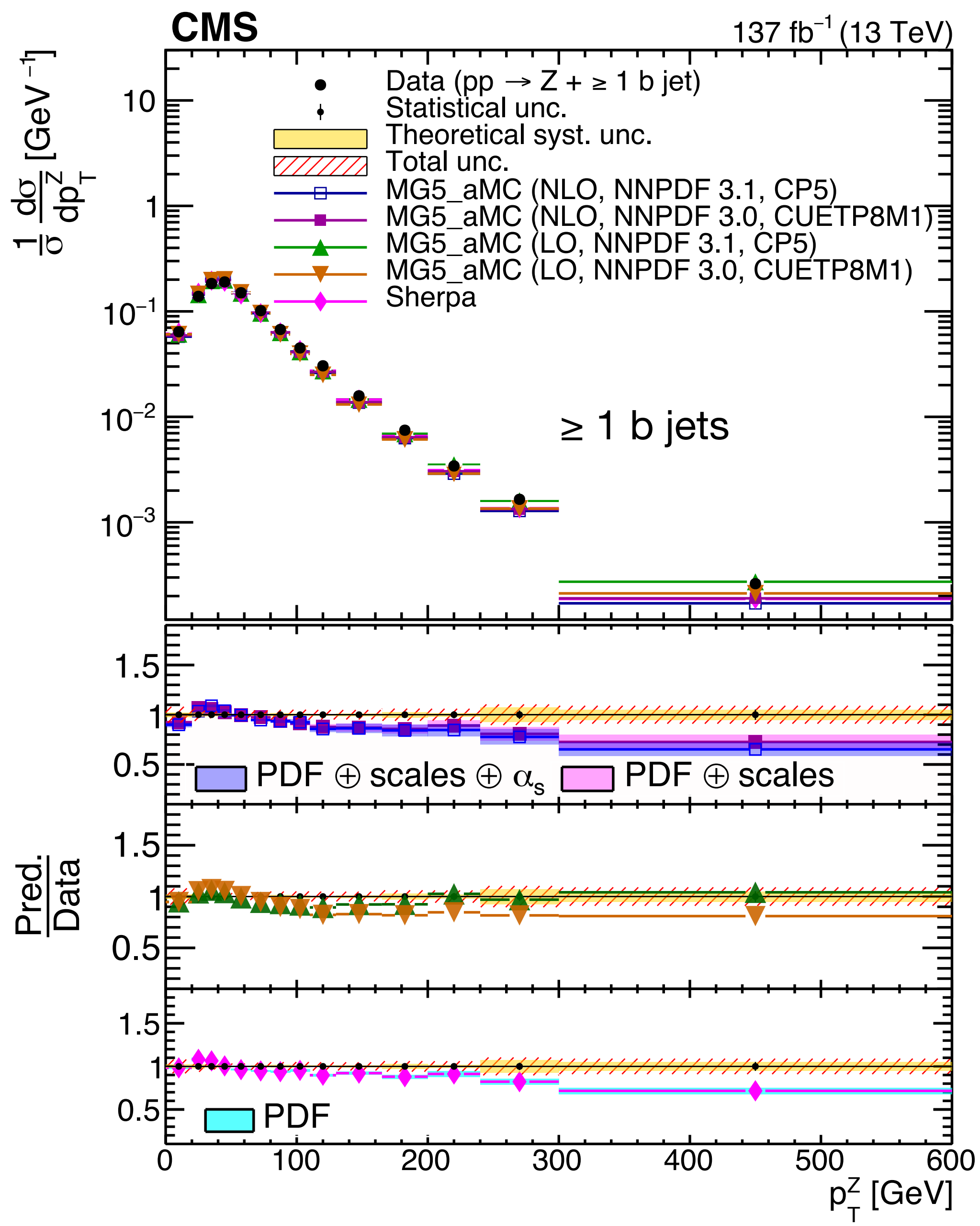


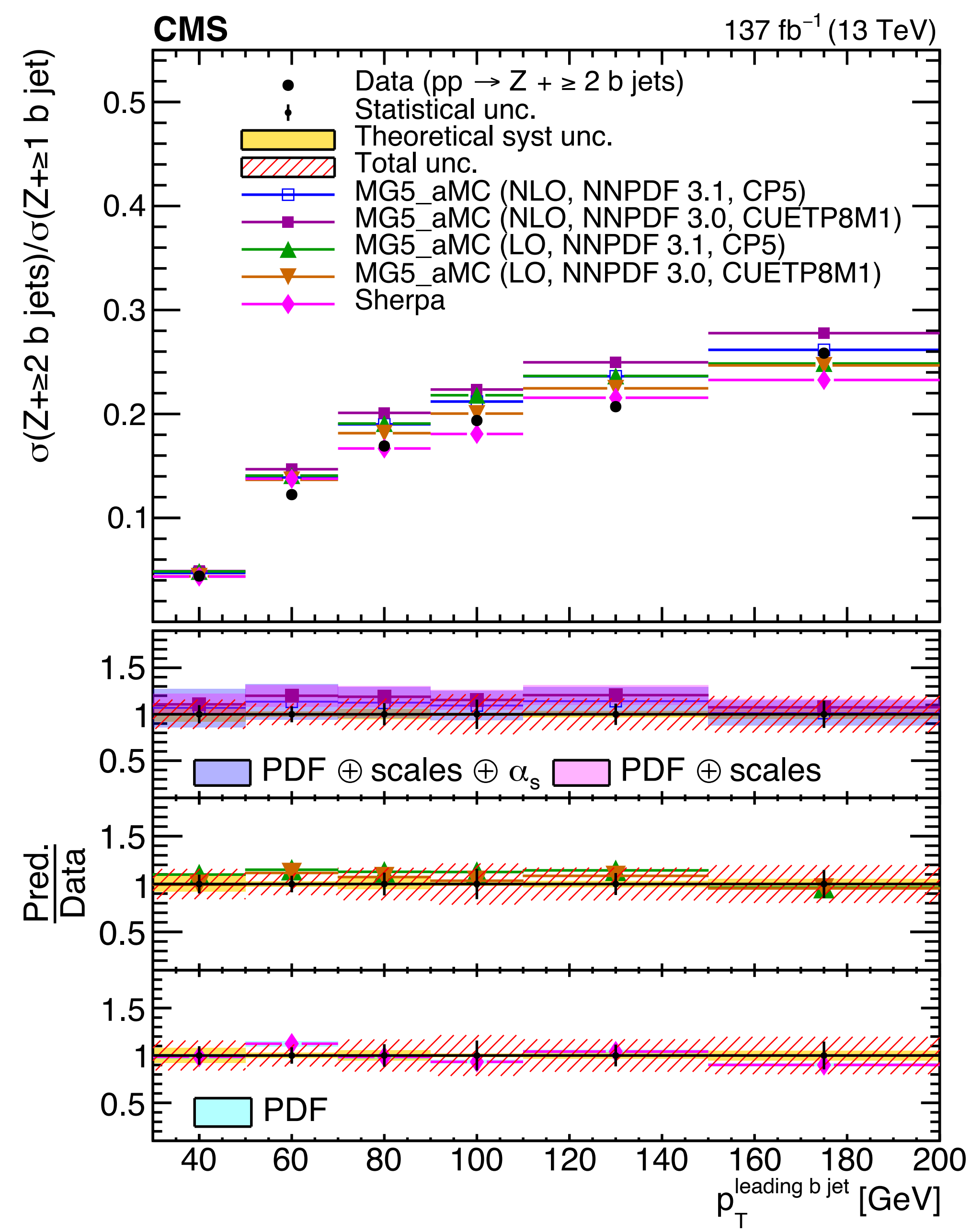


Z + b jet(s) with full Run 2 data

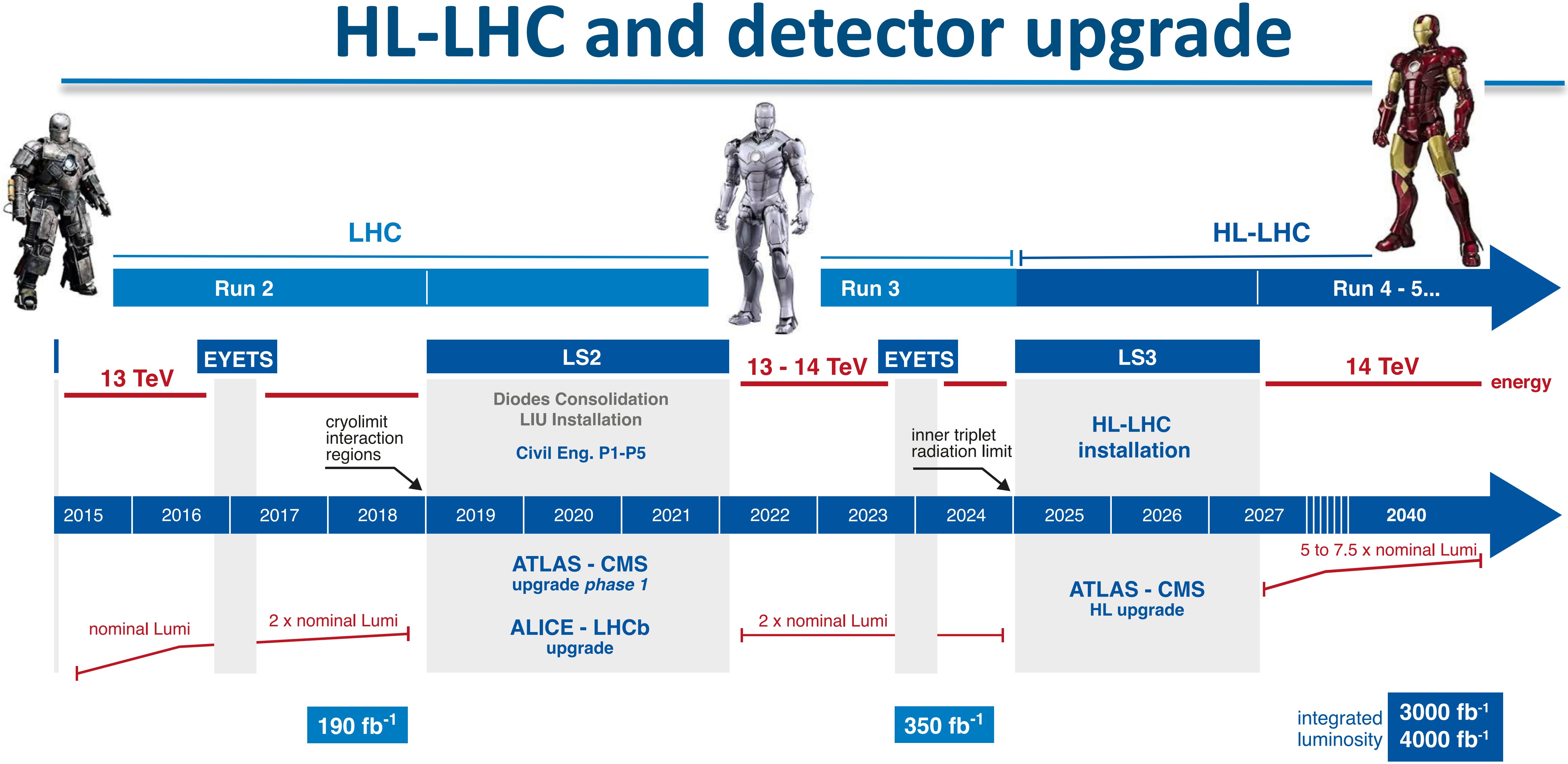
Statistical uncertainties usually negligible for 1 b jet, relevant for 2 b jets

- main systematic uncertainties from jet energy scale and resolution, and b tagging
- Total σ(Z + ≥ 1 b jets) = 6.52 ± 0.04 (stat) ± 0.40 (syst) ± 0.14 (theo) pb
- Total σ(Z + ≥ 2 b jets) = 0.65 ± 0.03 (stat) ± 0.07 (syst) ± 0.02 (theo) pb





HL-LHC and detector upgrade



20 times more data from HL-LHC phase than in Run 2

- but also daunting levels of pileup, higher trigger rates, intense radiation damage

Major challenges to reap this benefit

- upgrade detectors for improved granularity and more robust particle identification
- complete overhaul of trigger and DAQ systems

Future physics at the HL-LHC: $\sin^2\theta^f_{eff}$

ATL-PHYS-PUB-2018-037
CMS-PAS-FTR-17-001
LHCb-PUB-2018-013

- A_{FB} diluted at larger √s (valence quarks contribute less), but significant gain from extended detector acceptance

- With 1000/fb statistical uncertainty becomes negligible compared to PDFs