Recent precision W/Z measurements at the LHC, including full Run 2 and HL-LHC prospects

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17-22/10/2021

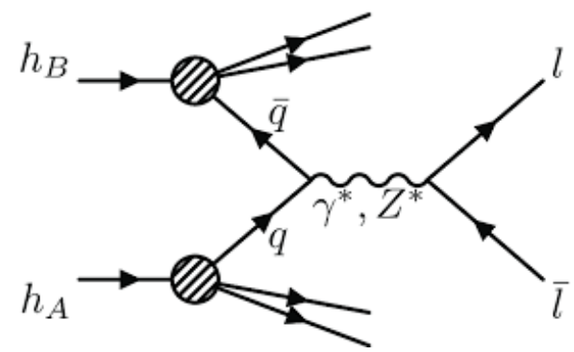
32nd Rencontres de Blois

W and Z bosons: why?

Building blocks of the standard model (SM) since early ’60s

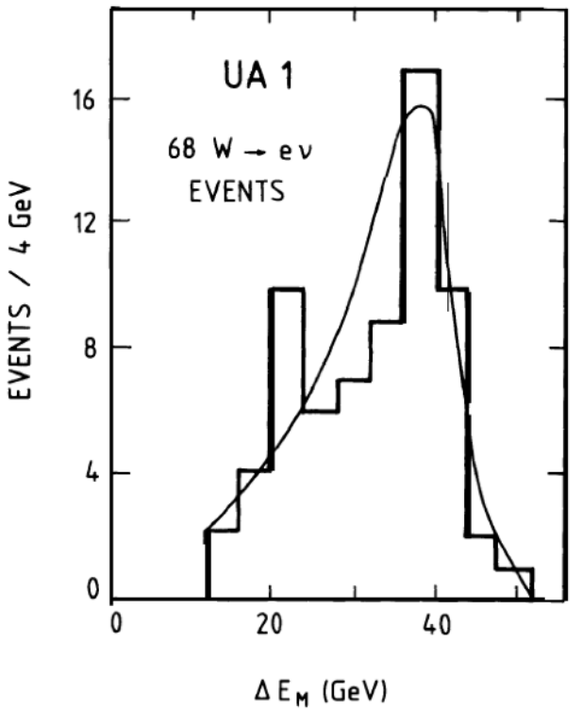
- discovered at CERN in 1983
- still on the front line of the LHC physics program

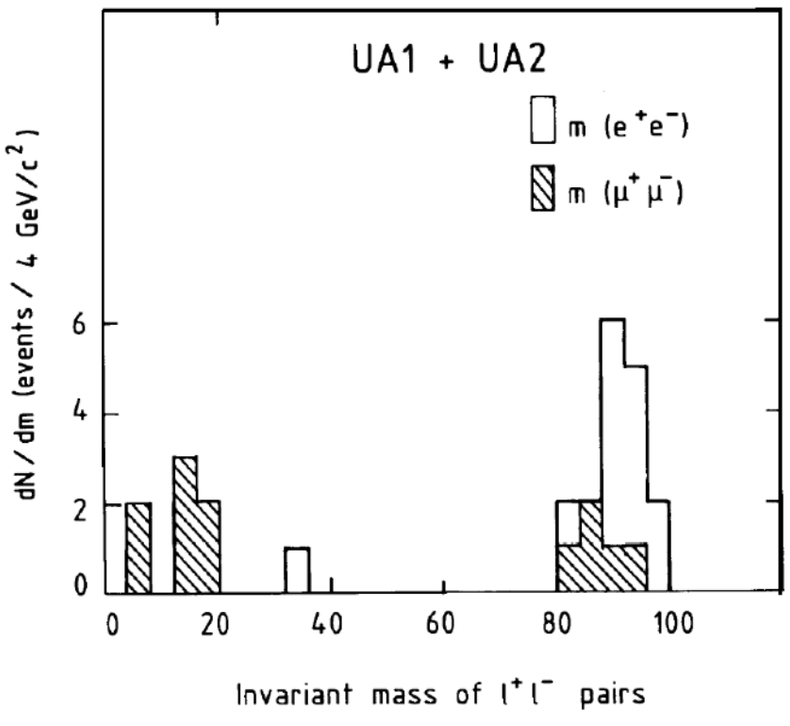
Drell-Yan process



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

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





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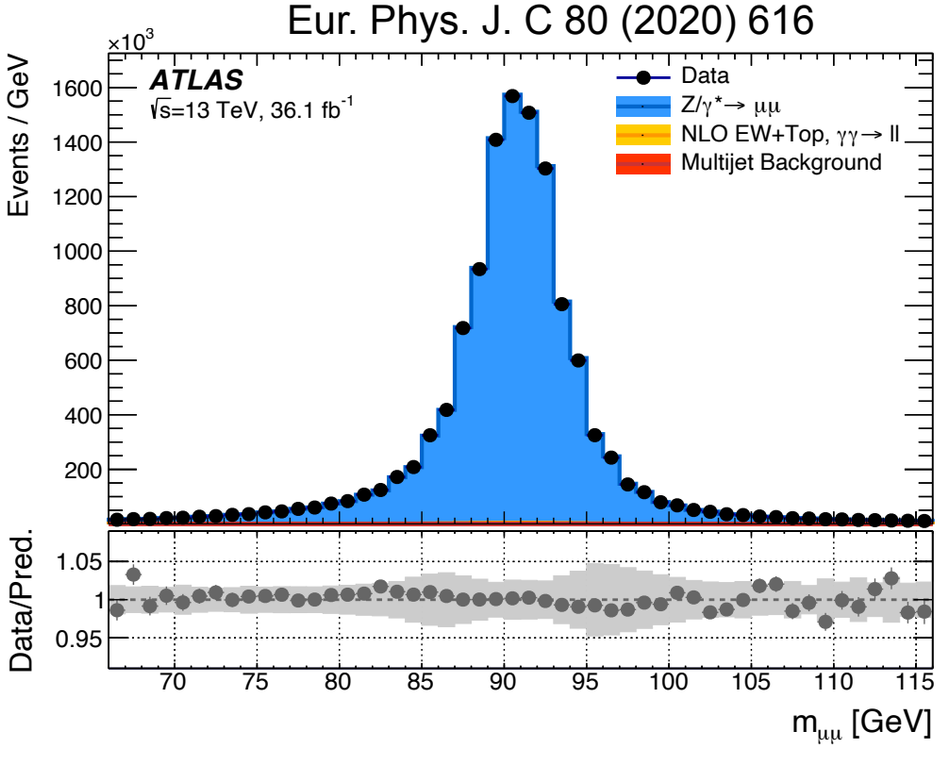


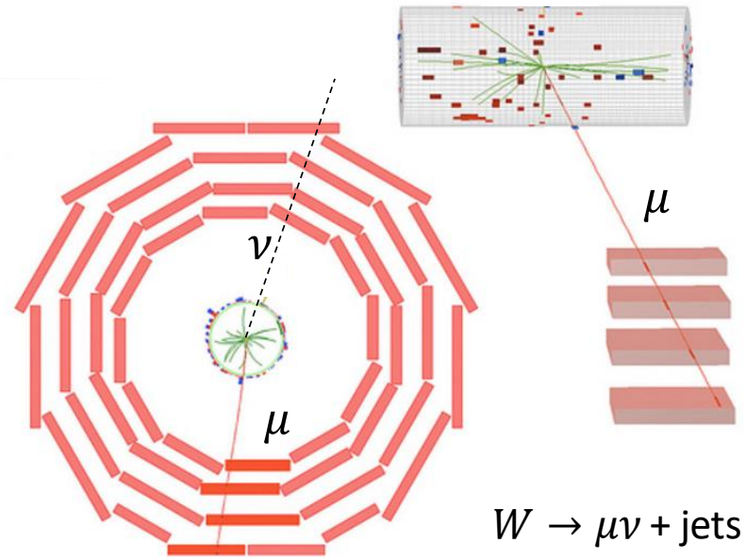
Experimental aspects of W and Z bosons

Clean experimental signatures because of leptonic decay to e, μ

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

Z bosons standard candles for detector calibration

- energy/momentum scale and resolution
- Z-counting method for luminosity calibration



$W \rightarrow \mu\nu$ + jets

Large Run 2 data sets

- multi-differential cross sections measurements with negligible statistical uncertainty
- sensitivity to rare decays or multi-boson production

Collaboration between theory and experiments paramount

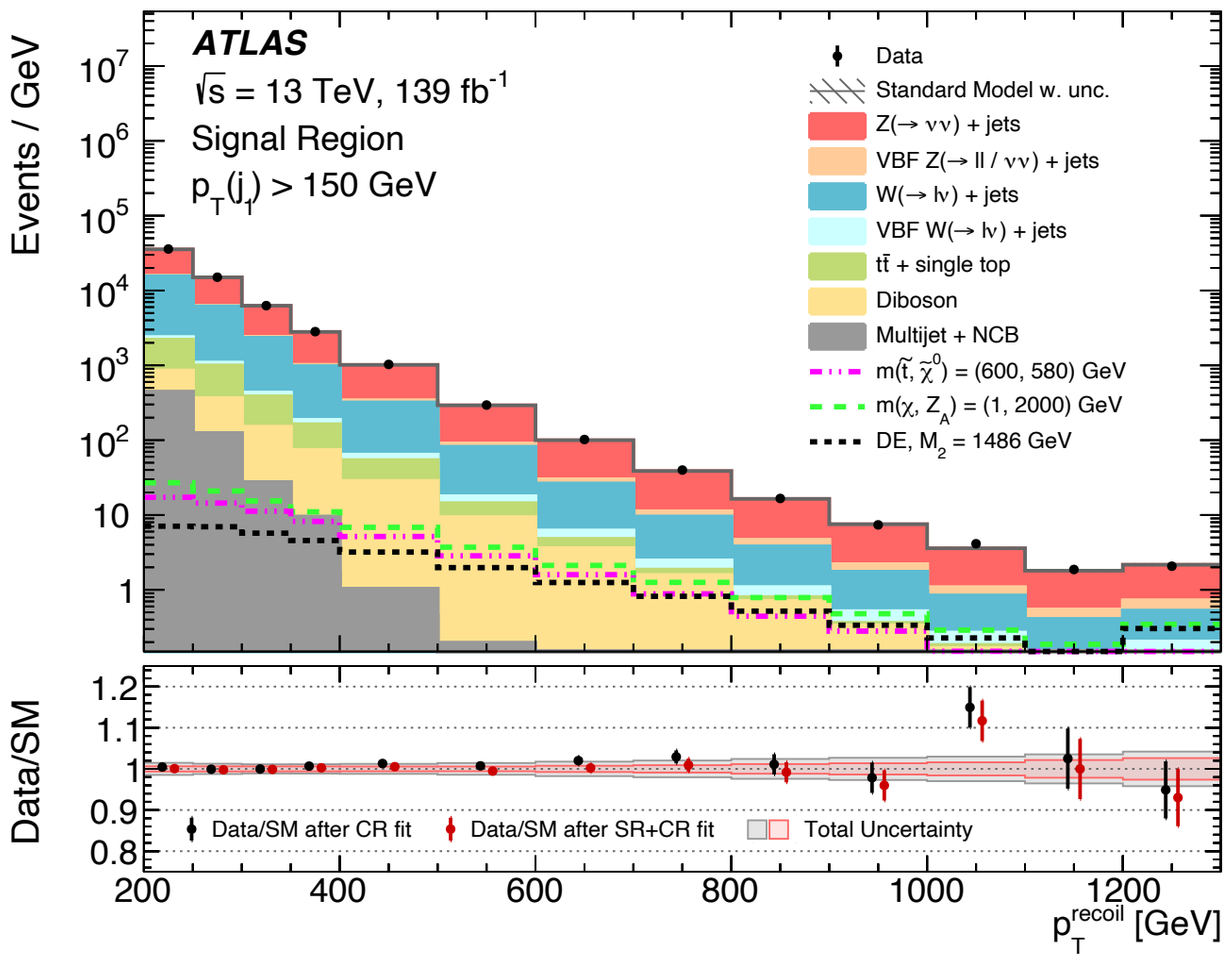
- calculations available at NNLO QCD/EW, often with % or better precision
- exciting challenges for detectors to reduce systematic uncertainties and keep up

Probing new physics with EW bosons

Phys. Rev. D 103, 112006 (2021)

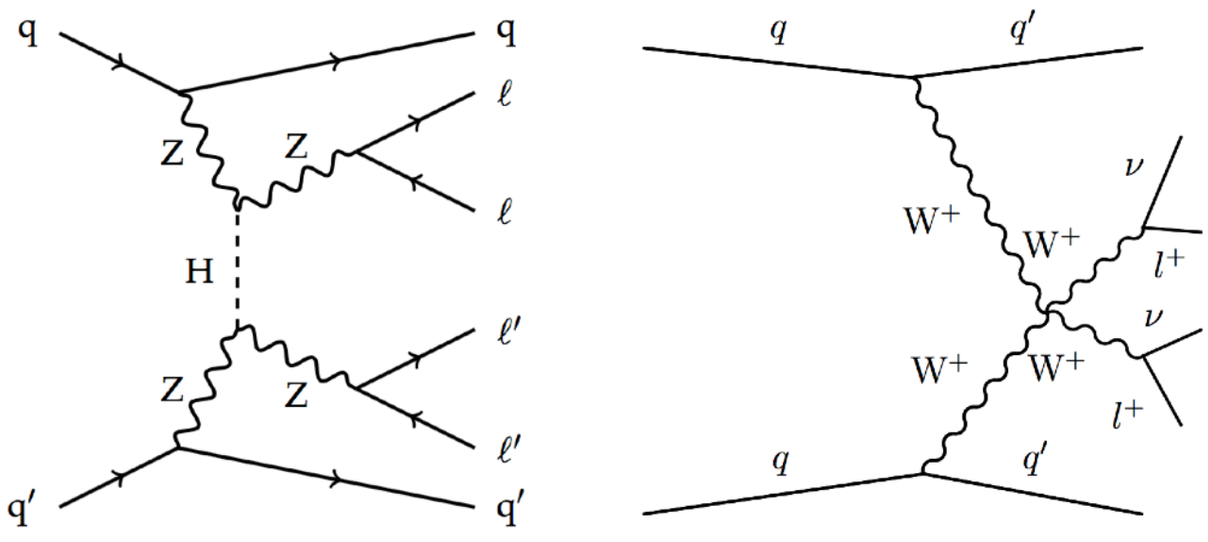
W/Z+jets often main backgrounds in searches for new physics (NP)

- decays into neutrinos indistinguishable from dark matter production topology



Multi-boson interactions sensitive to anomalous triple and quartic gauge couplings

- particularly appealing since they can provide hints on energy scale of NP



Z cross section from invisible decays

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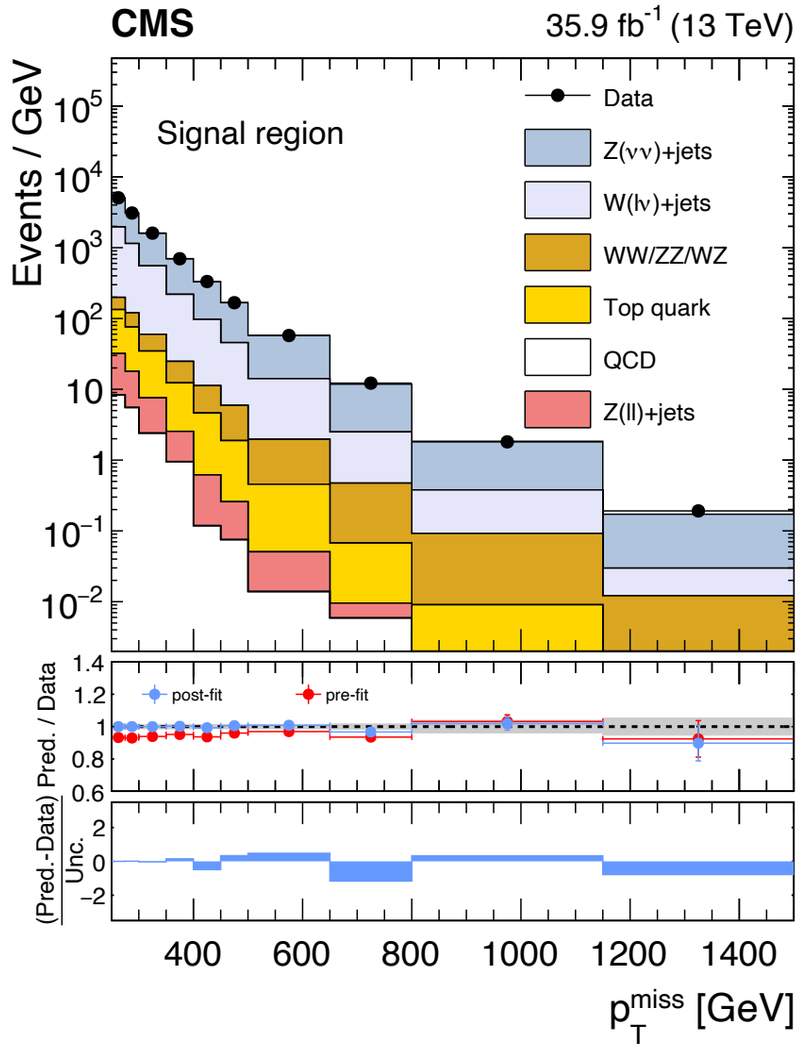
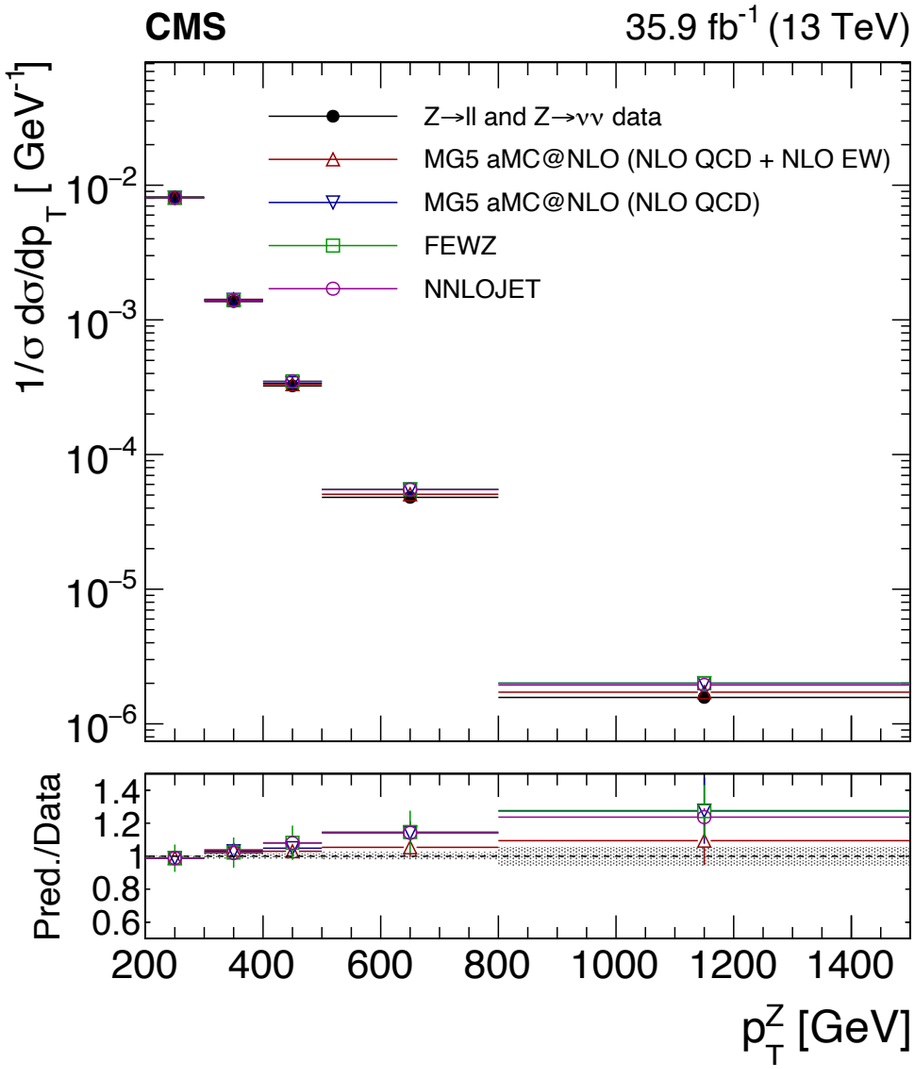
Knowledge of Z(νν)+jets cross section essential for NP searches

- large missing transverse momentum (p_T^{miss}) and high energy jets
- complementary channel to Z(ℓℓ)+jets, but larger branching ratio
- measurement combined with dilepton data to improve precision

Normalized cross section relative to prediction

p_T^Z (GeV)	$Z \to \ell\ell$	$Z \to \nu\nu$	$Z \to \ell\ell + \nu\nu$
200–300	$1.012^{+0.006}_{-0.007}$	$1.019^{+0.009}_{-0.009}$	$1.011^{+0.004}_{-0.004}$
300–400	$0.943^{+0.025}_{-0.025}$	$0.979^{+0.015}_{-0.015}$	$0.963^{+0.015}_{-0.014}$
400–500	$1.006^{+0.031}_{-0.030}$	$0.963^{+0.019}_{-0.019}$	$0.971^{+0.017}_{-0.016}$
500–800	$0.993^{+0.036}_{-0.036}$	$0.942^{+0.024}_{-0.024}$	$0.949^{+0.021}_{-0.020}$
800–1500	$1.036^{+0.099}_{-0.095}$	$0.869^{+0.059}_{-0.057}$	$0.914^{+0.052}_{-0.051}$





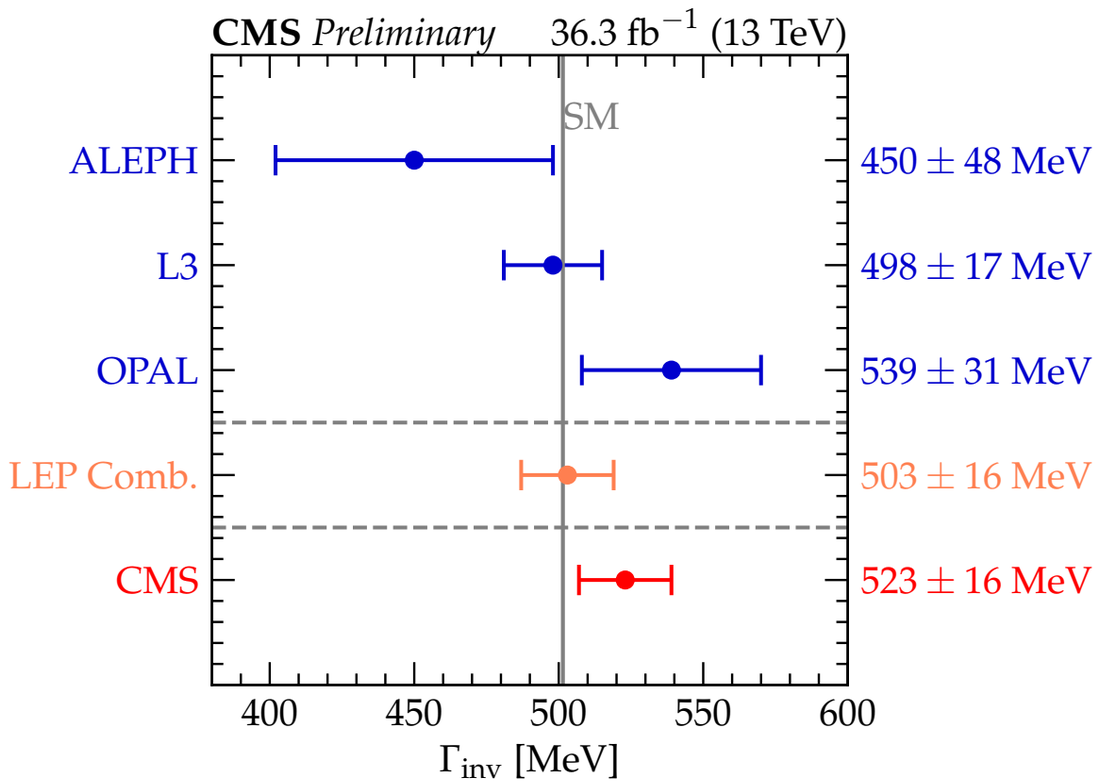
Invisible Z width

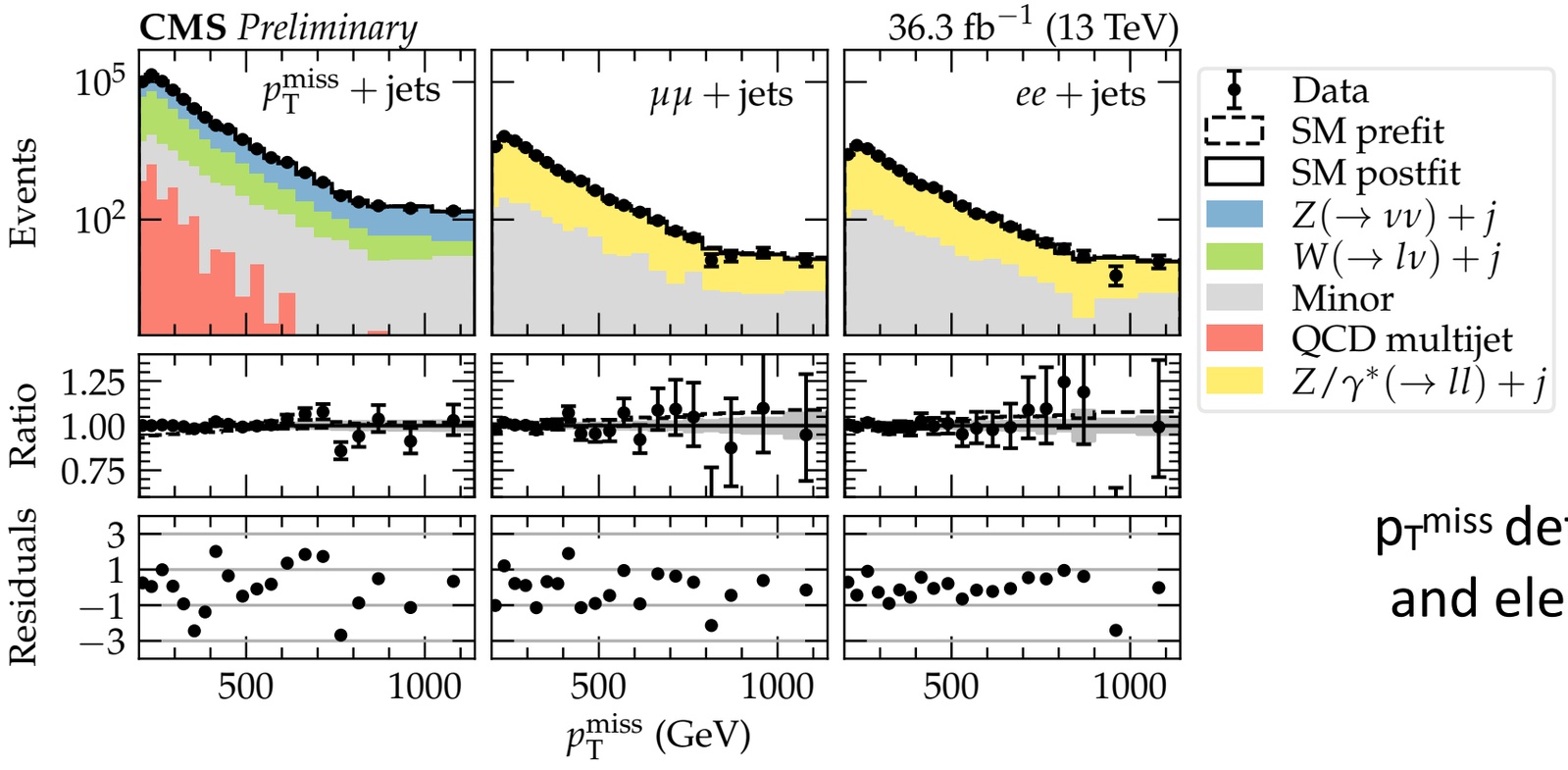
First measurement of Z invisible width at a hadron collider

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

Single most precise *direct* measurement

- negligible statistical uncertainty





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

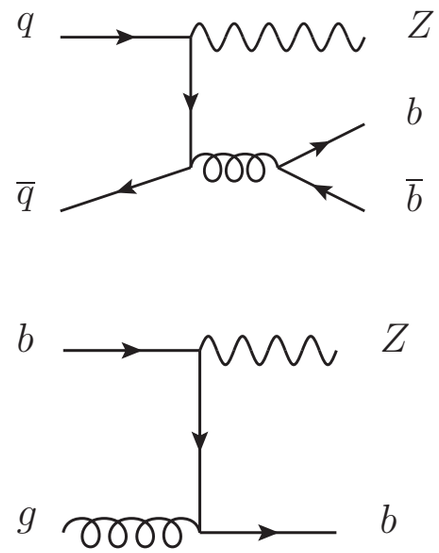
p_T^{miss} defined removing muons and electrons from the event

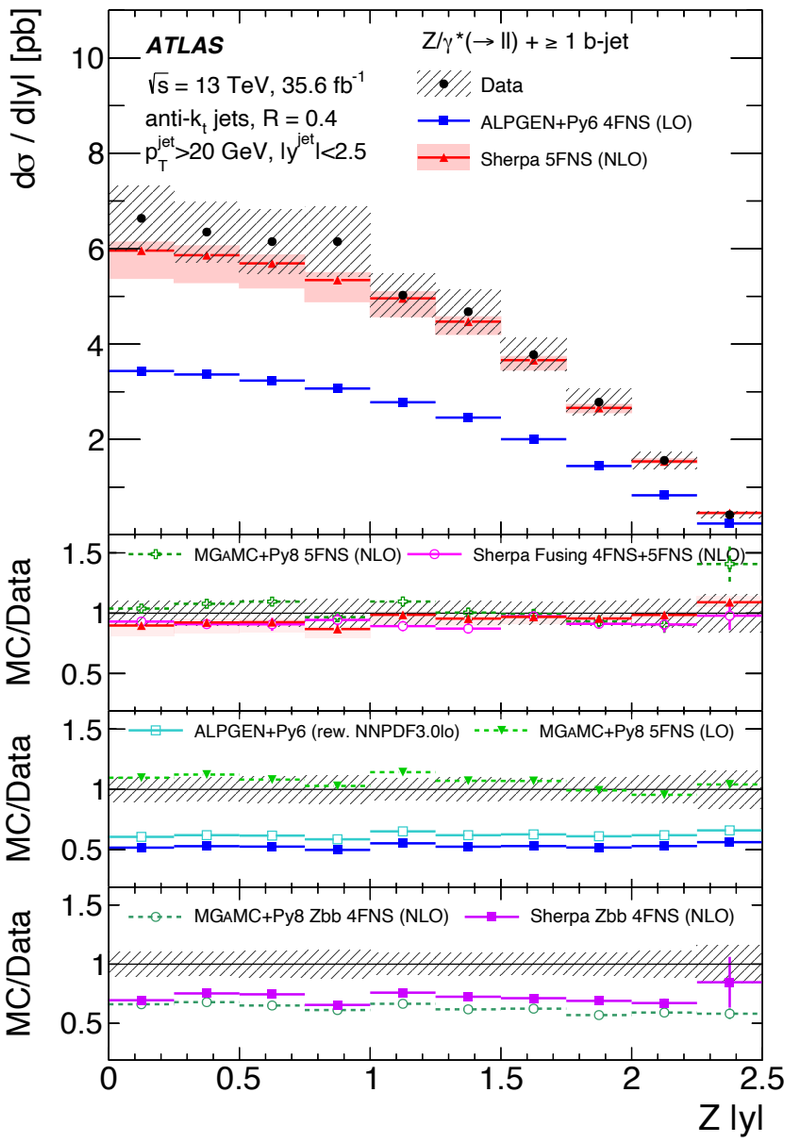
Z boson and heavy flavour jets

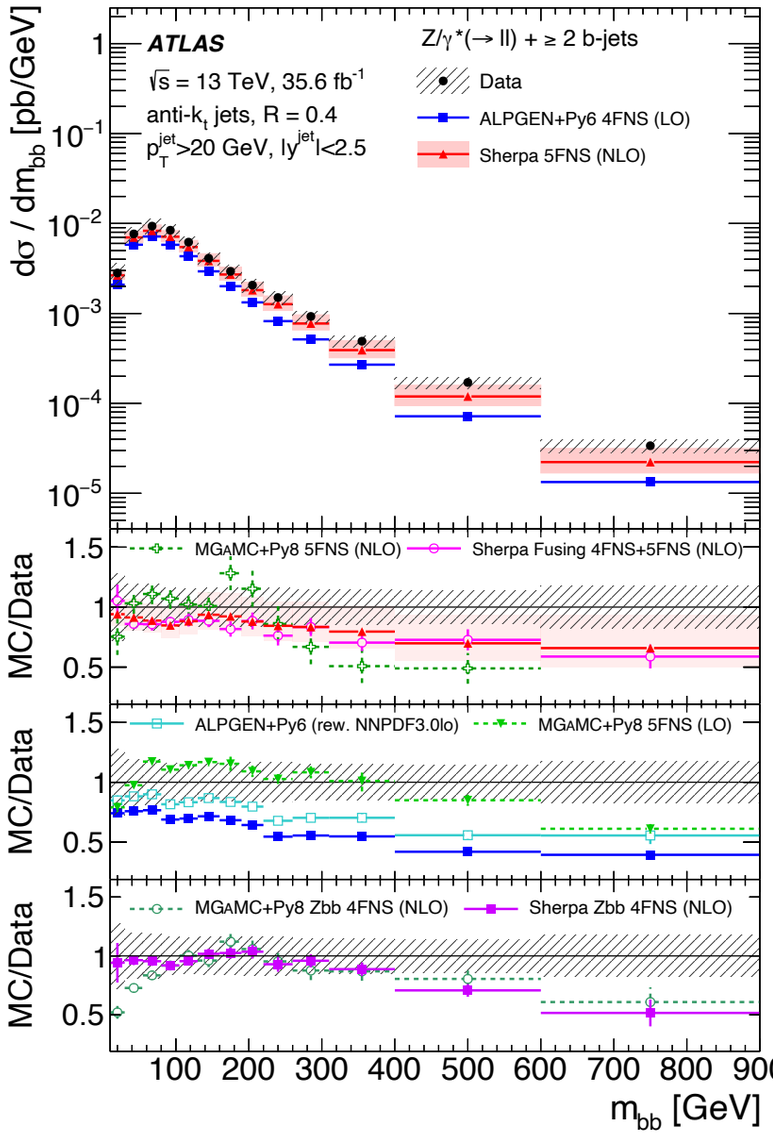
JHEP 07 (2020) 044
Phys. Rev. D 102, 032007

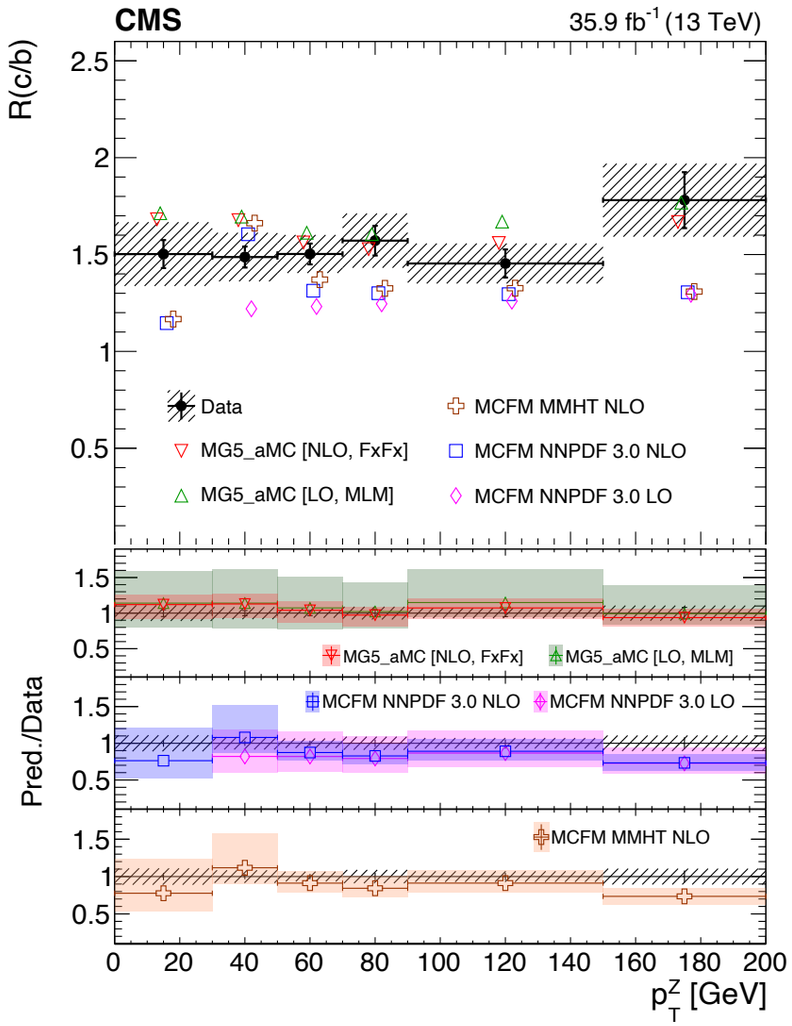
Sensitivity to c and b quark PDFs of proton

- check different b flavour schemes (4NFS or 5NFS)
- benchmark to validate MC predictions in VH topologies with H→c$\bar{c}$ or H→b$\bar{b}$
  - shape of m_{bb} at high mass not well described by most generators
- cross section ratios to different flavours valuable tests of perturbative QCD





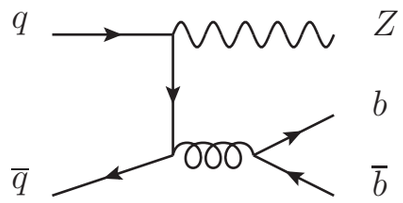


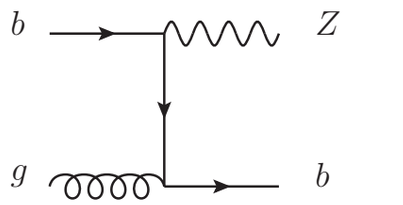


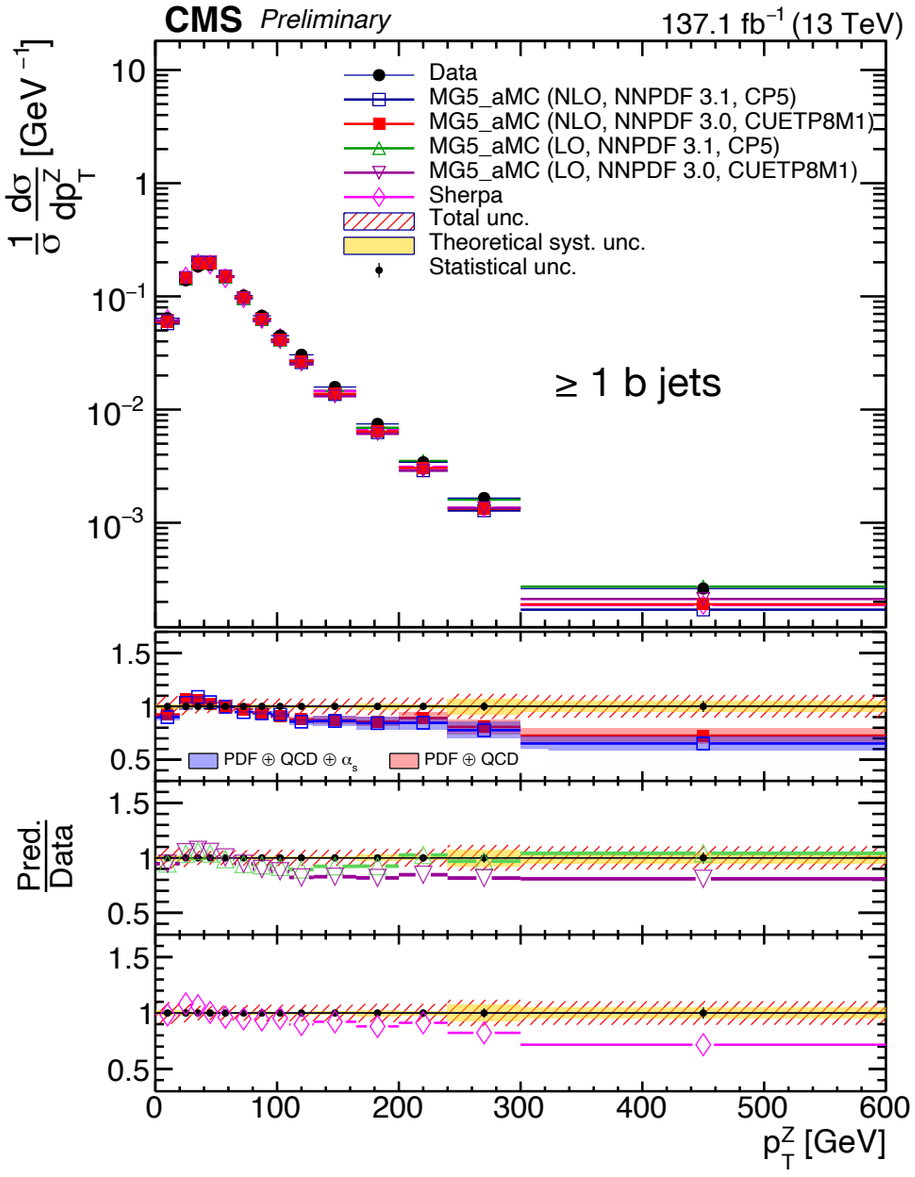
Z + b jet(s) with full Run 2 data

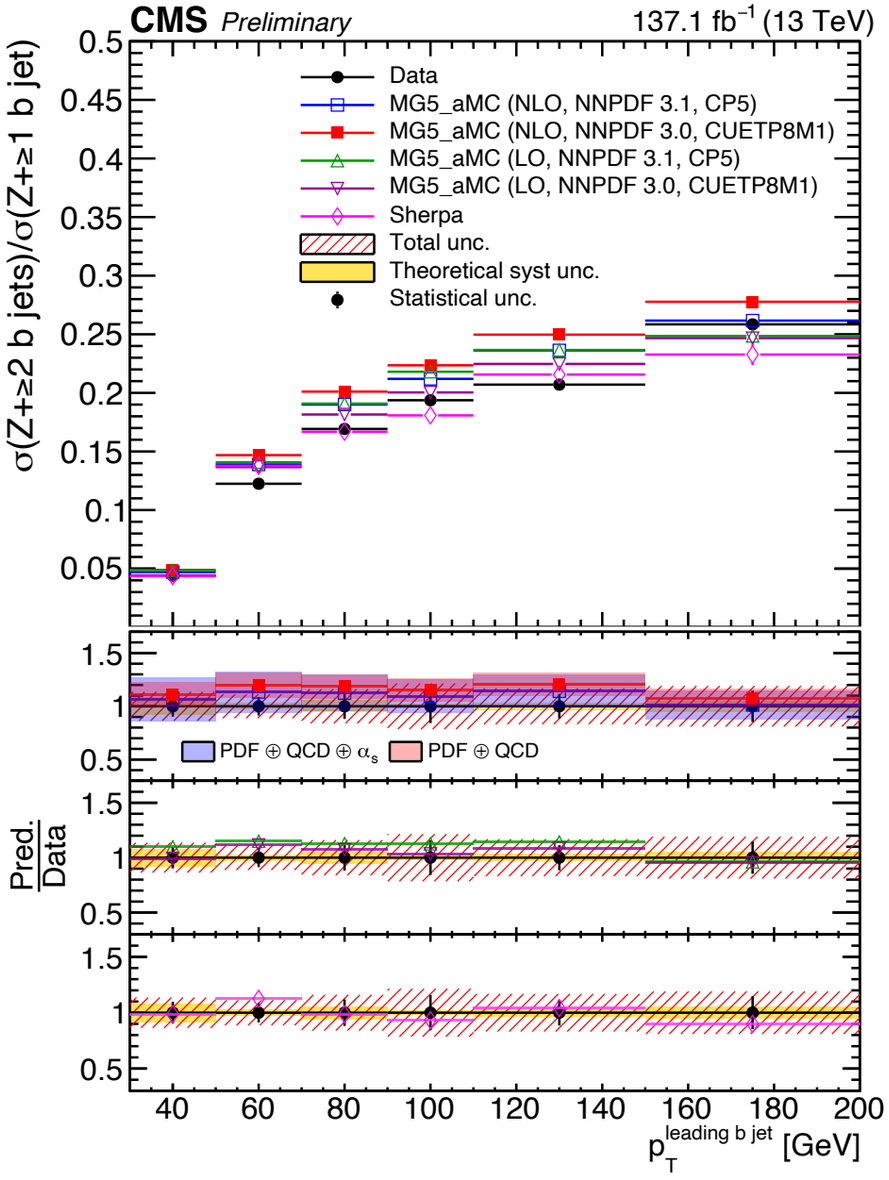
Statistical uncertainties usually negligible for 1 b jet, relevant for 2 b jets

- 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

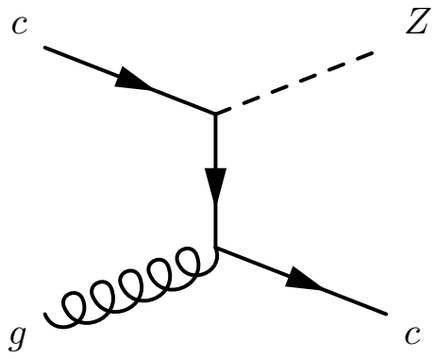


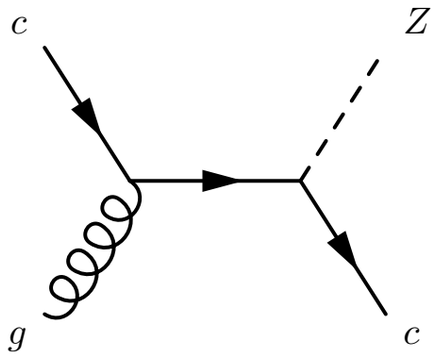






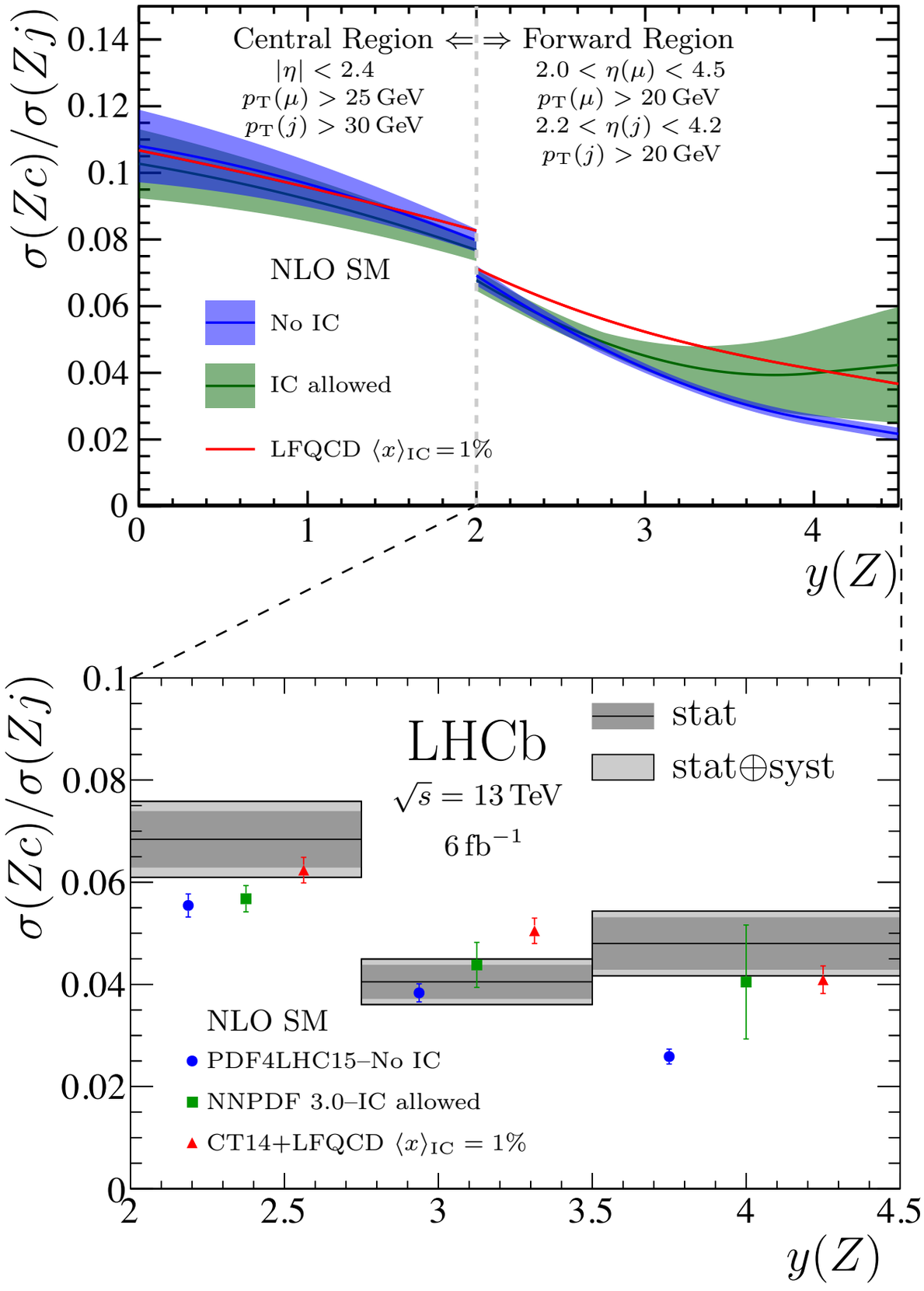
The charm of the proton





Long debate about possible charm component in proton wave function

- known as intrinsic charm (IC), as opposed to gluon splitting into $c\bar{c}$
- several phenomenological consequences from astrophysics to collider analyses
- largest sensitivity at forward Z rapidity (high Bjorken-x probes valence content), which ATLAS and CMS cannot explore
- LHCb results consistent with valence-like IC hypothesis

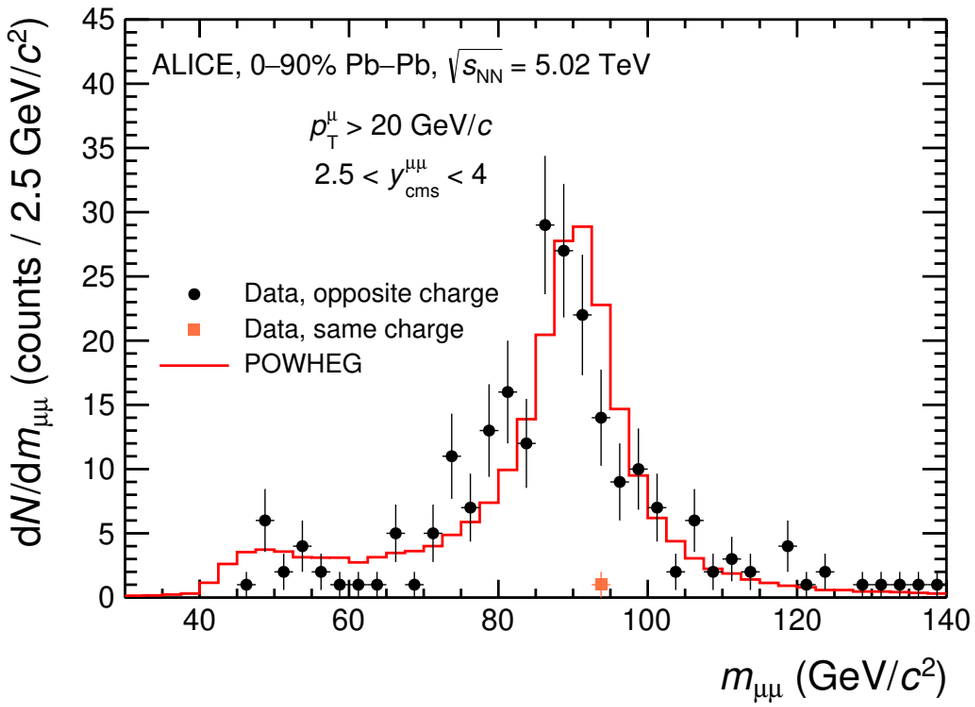


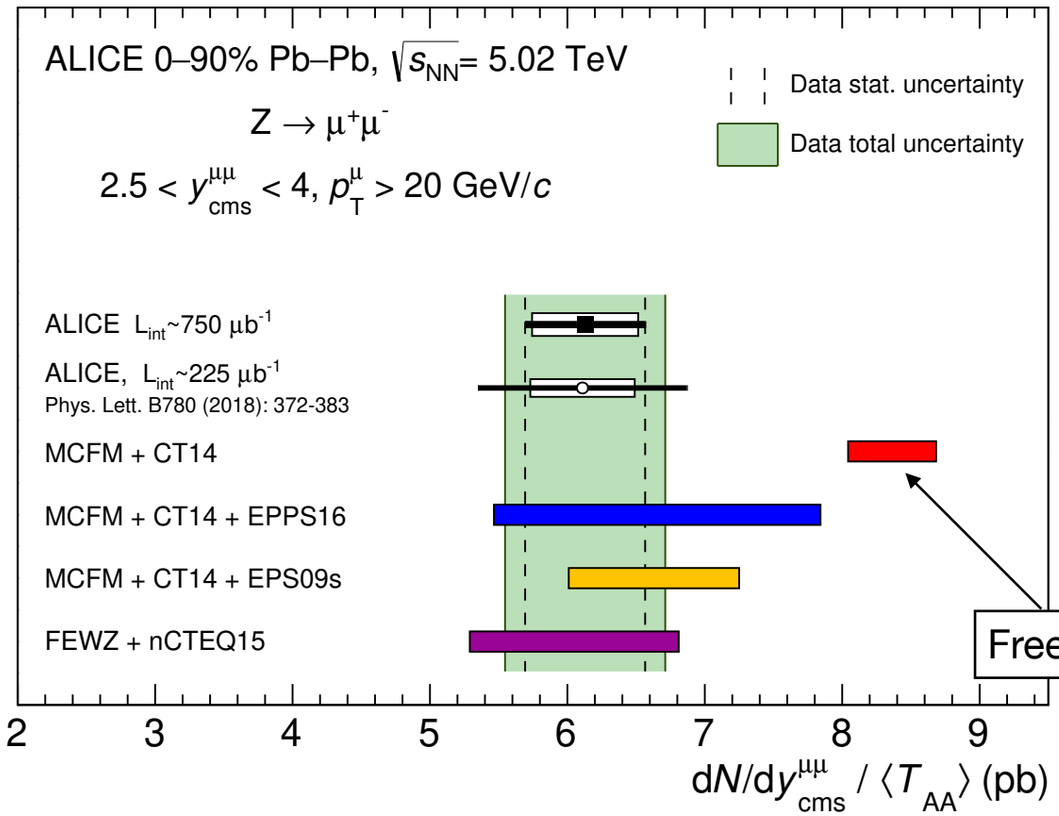
JHEP 09 (2020) 076

Z bosons with heavy ions

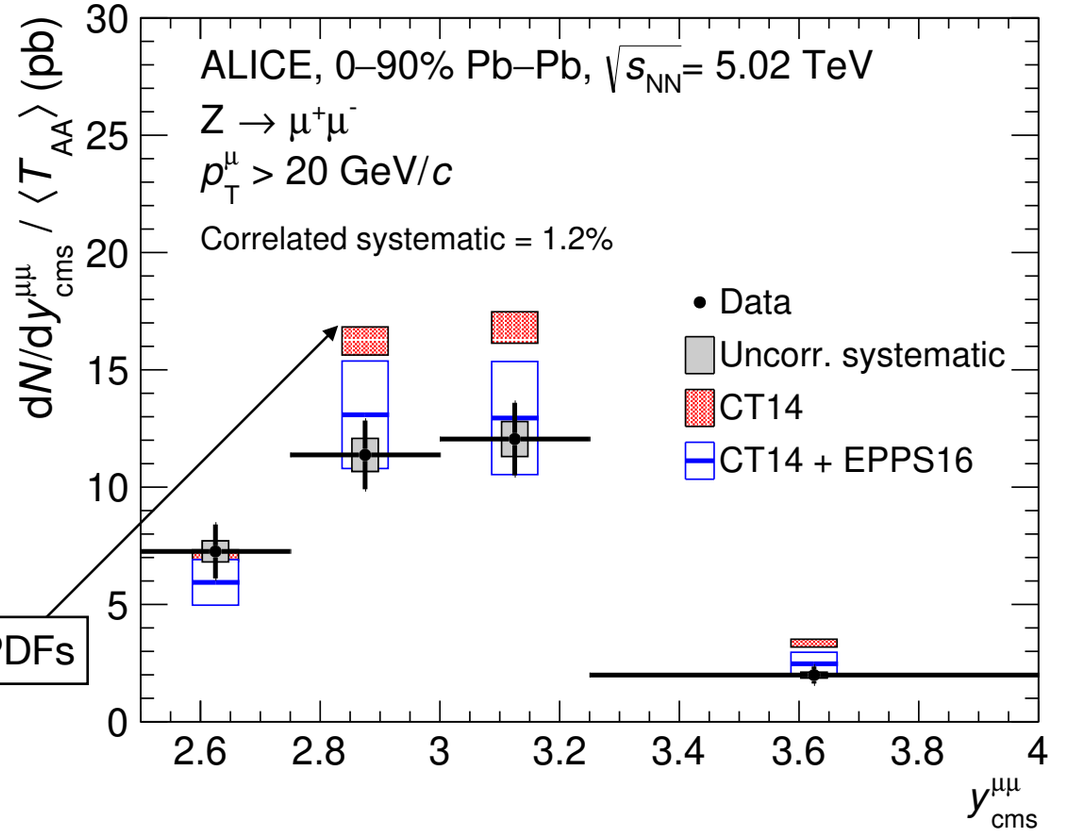
W and Z bosons useful probes to investigate PDFs with heavy ion collisions

- sensitive to nuclear modification factors of free nucleon PDFs $f_i^{nucleon}(x, Q^2)$
- in general, for nucleus with mass number A, it is $f_i^{A}(x, Q^2) \neq A\, f_i^{nucleon}(x, Q^2)$





Free nucleon PDFs

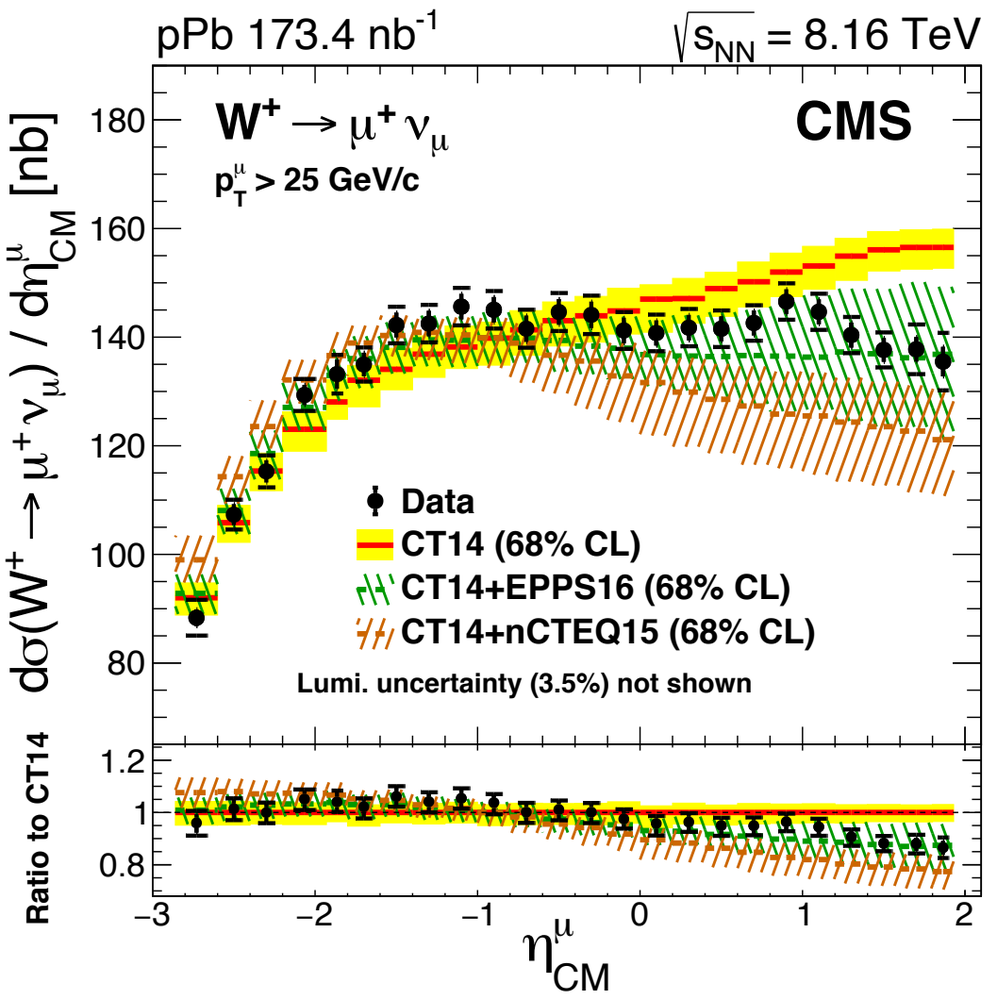


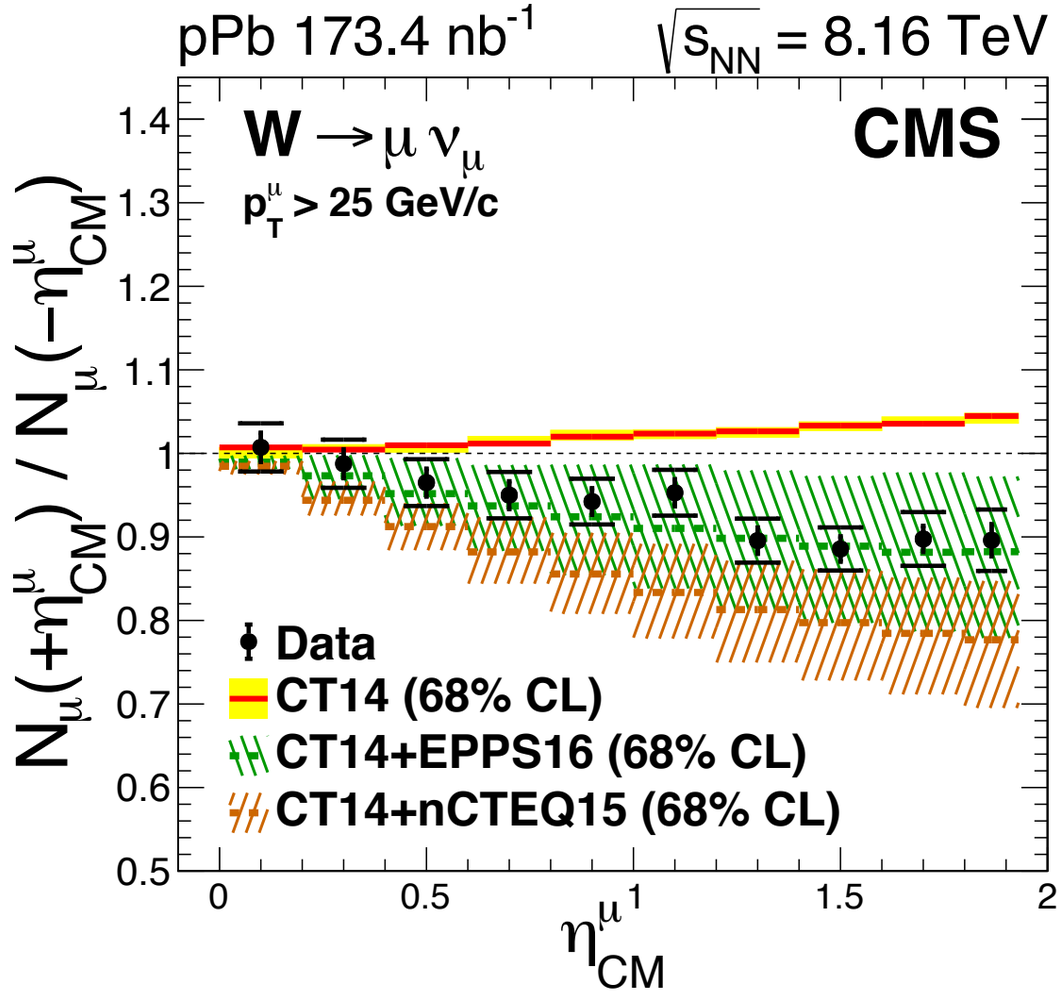
Phys. Lett. B 800 (2020) 135048

Heavy ion studies with W bosons

Differential cross section and asymmetry measurements allow for nuclear modification factor of PDFs to be studied with high precision

- calculations without nuclear modification factors (CT14) disfavoured by data
- Experimental uncertainties smaller than nuclear PDF uncertainties
  - constraints of quark and antiquark PDFs in nuclei





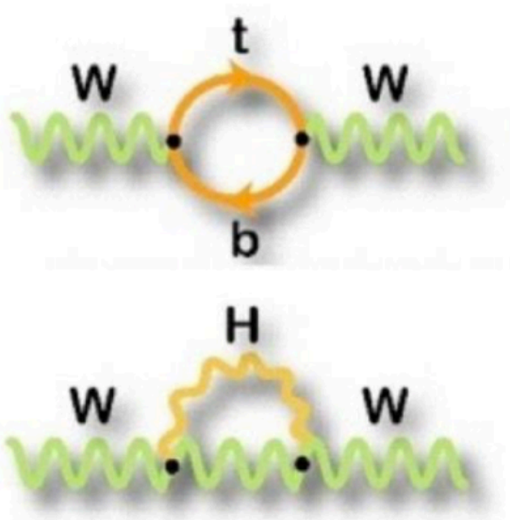
High precision measurements: W mass

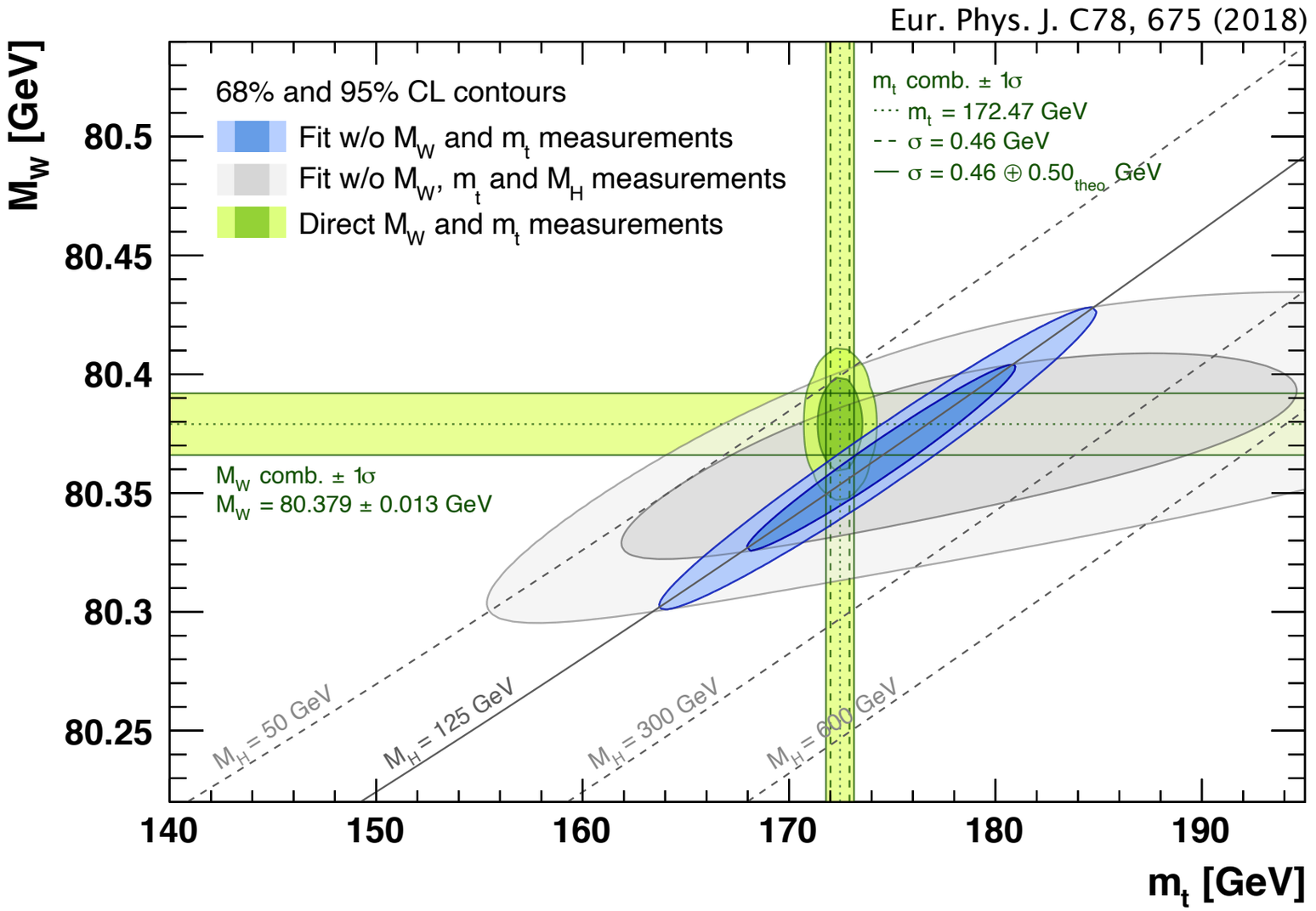
With no direct observation of NP at the LHC, precision measurements become crucial to test internal consistency of SM and explore NP scenarios

- heavy particles beyond SM can induce measurable corrections to W boson mass (m_W)
- global fit to EW parameters returns m_W with $\delta m_W \approx 8$ MeV (10^{-4} precision)
- experimental average has $\delta m_W \approx 13$ MeV (twice larger than global fit)

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

Δr = loop corrections, mainly induced by Higgs boson and top quark



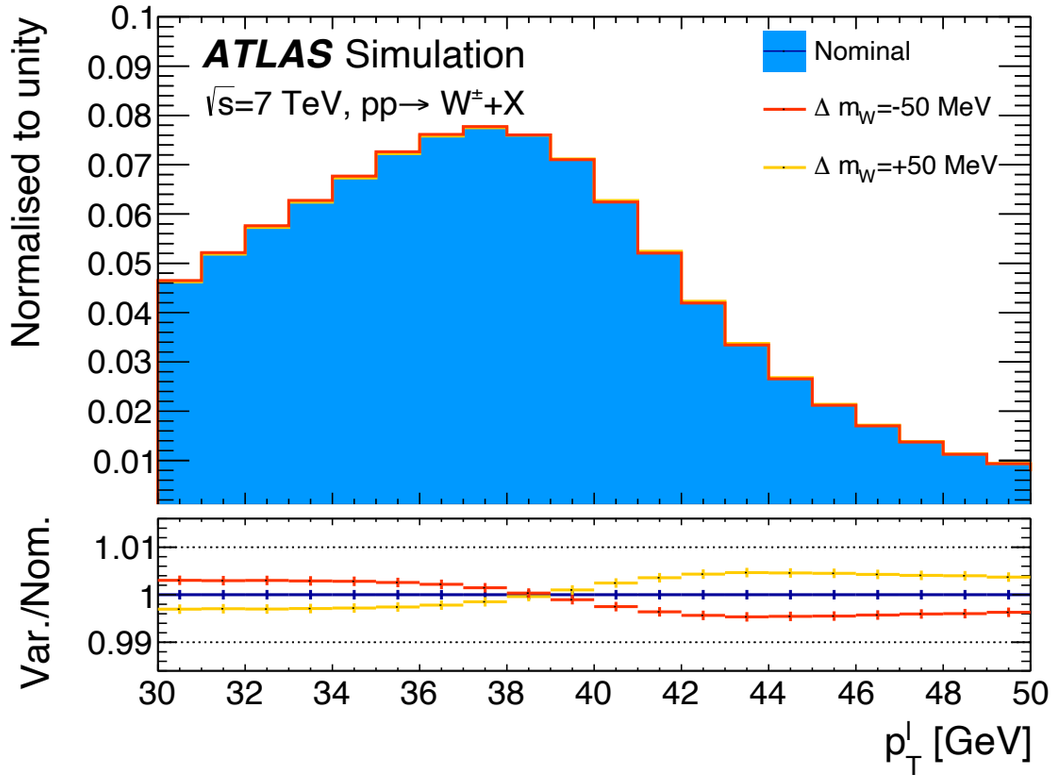


Eur. Phys. J. C 78 (2018) 110

Measuring m_W at hadron colliders

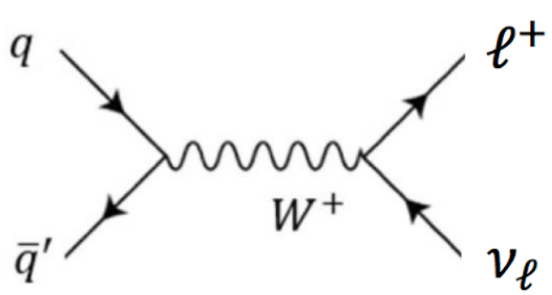
Standard technique based on template fits to p_T^{ℓ} and $m_T^{\ell\nu}$ distributions in data

- Jacobian peaks at $m_W/2$ or m_W
- p_T^{ℓ} experimentally more precise, but more sensitive to theoretical uncertainties related to W polarization (PDFs) and p_T^W (QCD higher orders)

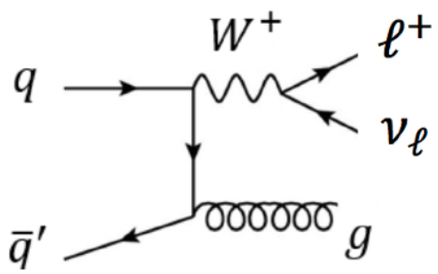


First LHC measurement from ATLAS

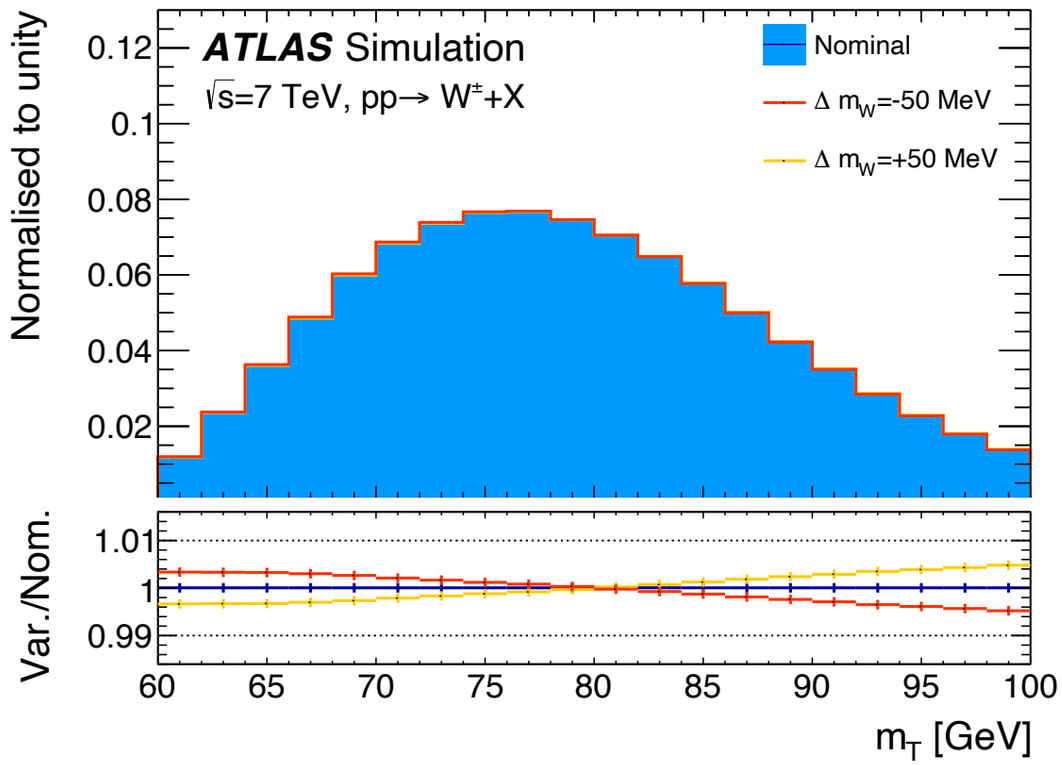
- $\Delta m_W = 7_{stat} \pm 11_{exp.syst} \pm 14_{mod.syst} = 19$ MeV
- about 9 MeV from PDFs and 8 MeV from p_T^W
- theoretical uncertainties dominate precision



LO diagram: $p_T^W = 0$



NLO diagram: $p_T^W \neq 0$, additional hadronic activity



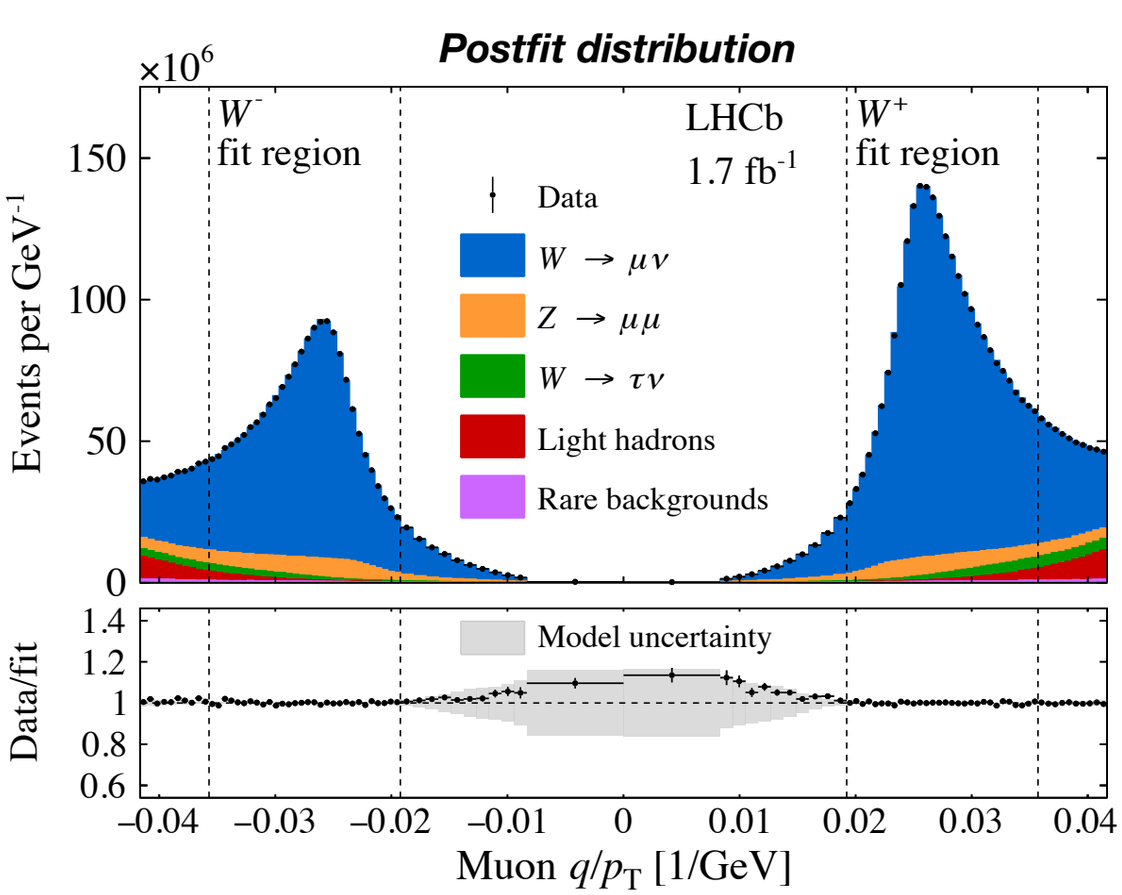
LHCb-PAPER-2021-024
arXiv:2109.01113v1

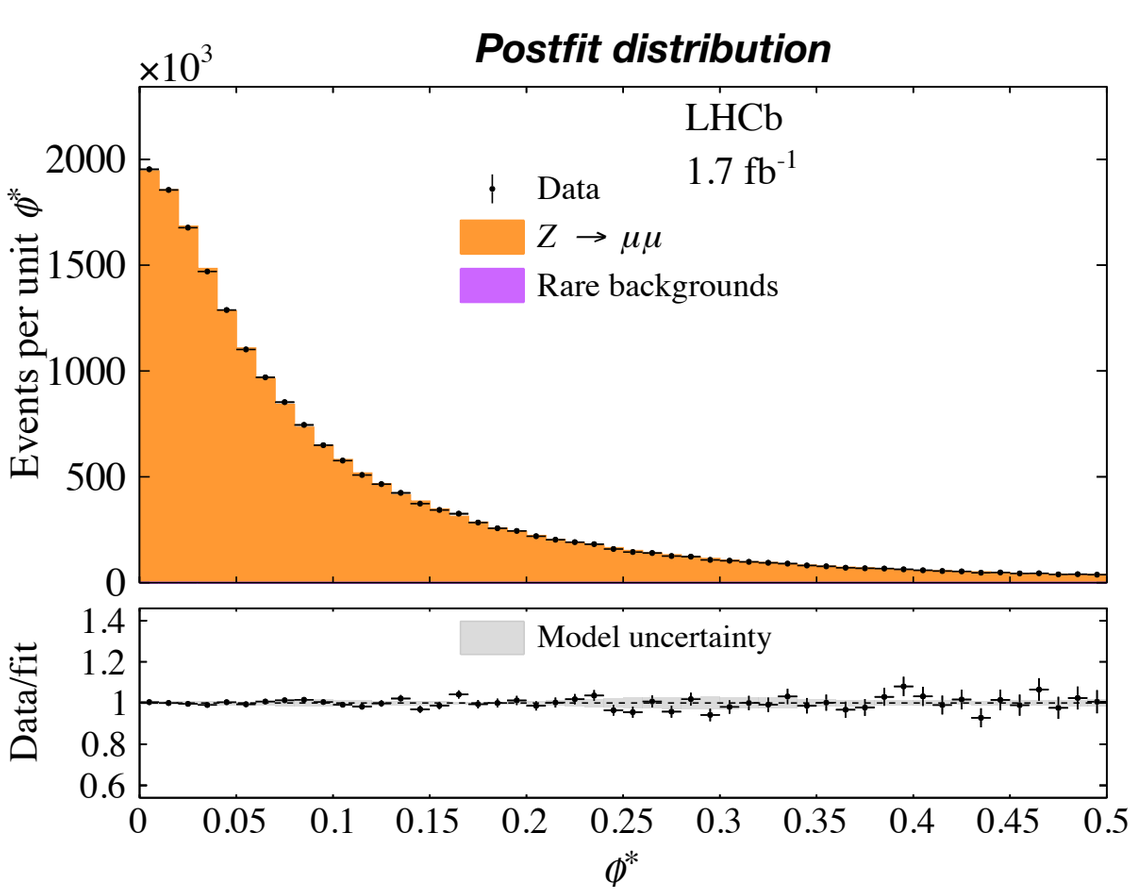
W mass at LHCb

LHCb has recently released a new measurement of m_W

- $W \to \mu\nu$ events from 1.7 fb^{-1}, only 1/3 of full Run 2 dataset
- simultaneous fit of muon p_T (actually charge/p_T) and Z boson ϕ^* (correlated to Zp_T but only dependent on angular variables, less susceptible to modelling uncertainties)
  - partial constraints on Wp_T thanks to in-situ Zp_T measurement
- $\Delta m_W = 23_{stat} \pm 10_{exp.syst} \pm 17_{theory} \pm 9_{PDF}$ MeV = 32 MeV

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



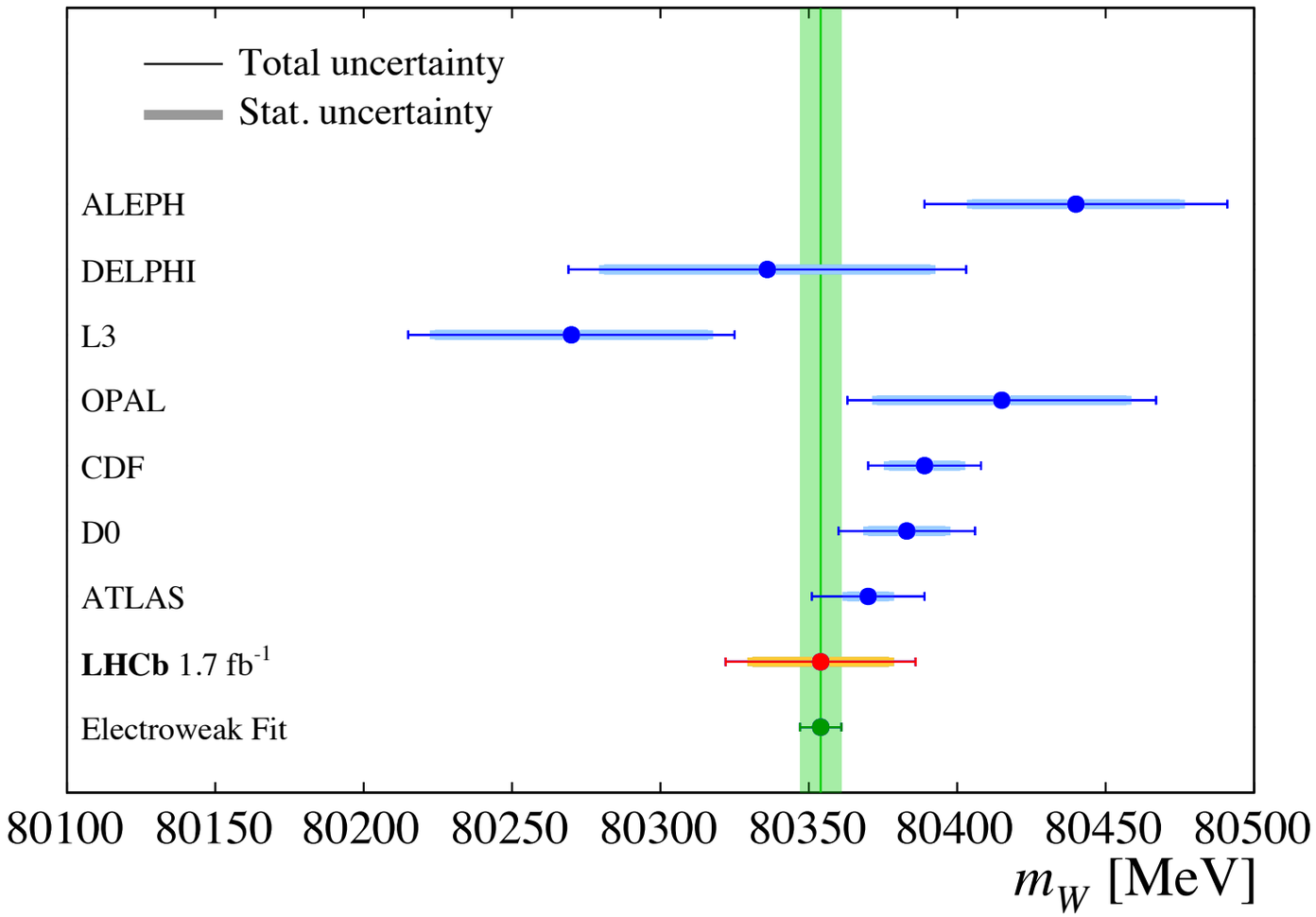


Status of W mass measurements

arXiv:2109.01113v1
EPJC 79 (2019) 497

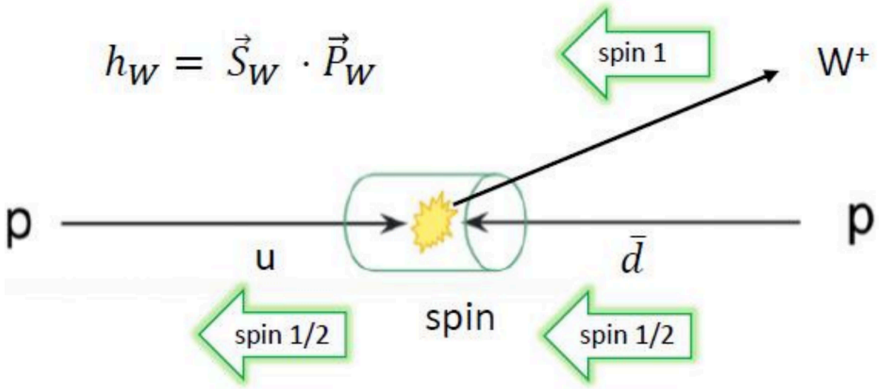
LHCb measurement less precise than Tevatron/ATLAS (but no m_T or W→eν)

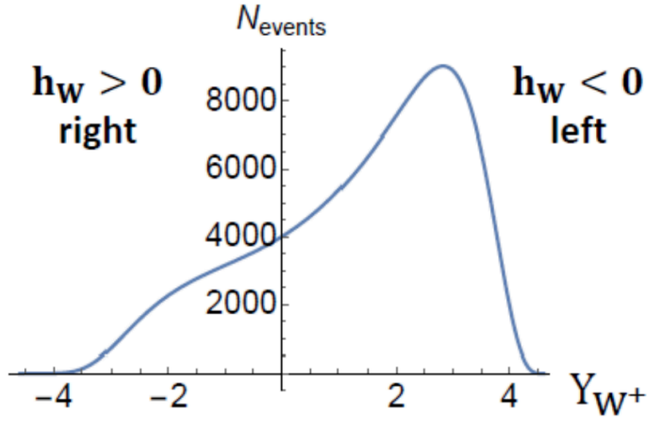
- but explores complementary rapidity region compared to ATLAS and CMS, and can help constrain PDF uncertainties in future LHC combinations
- new LHCb measurement in progress with full Run 2 data (stat. unc. ~10 MeV)
  - will exploit a 2D fit of muon q/p_T and η to reduce PDF uncertainties

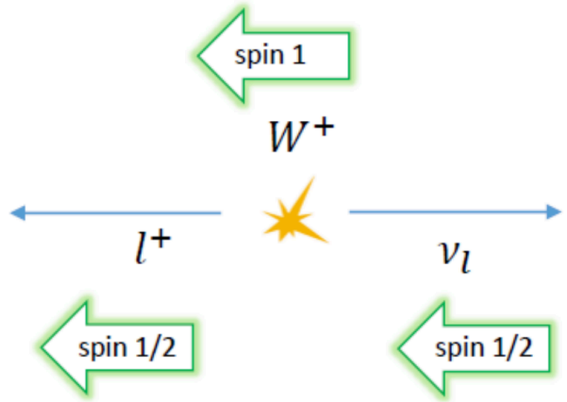


- motivation for ancillary measurements to investigate feasibility of in-situ constraints of theoretical uncertainties

W polarization and rapidity at the LHC



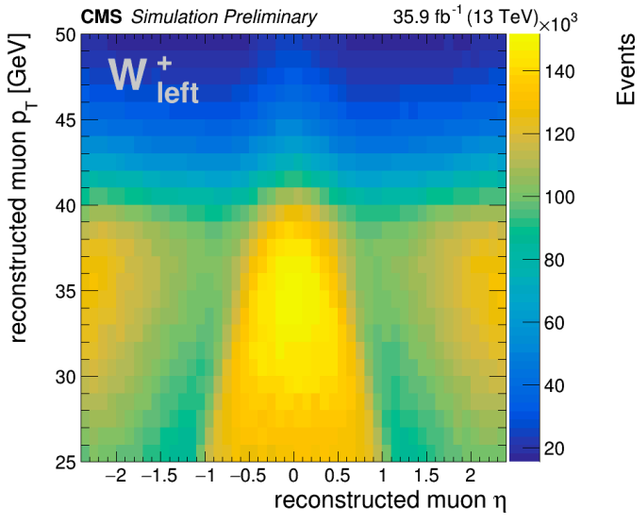


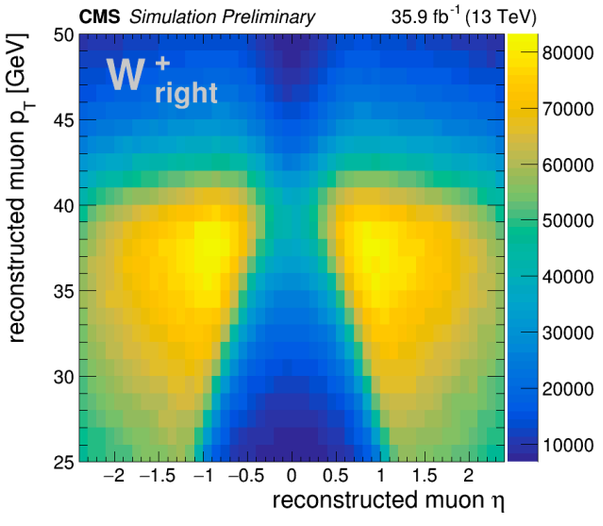


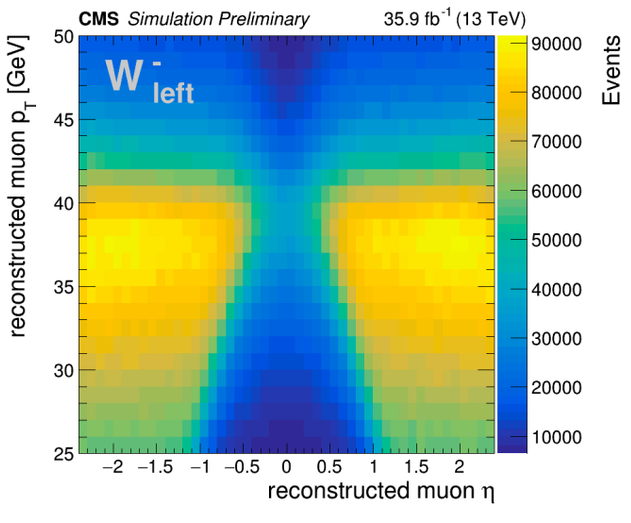
- W boson helicity h_W and rapidity Y_W determined by PDFs
- h_W/Y_W affect lepton p_T-η through spin correlations
- **lepton p_T-η distribution carries information on PDFs**

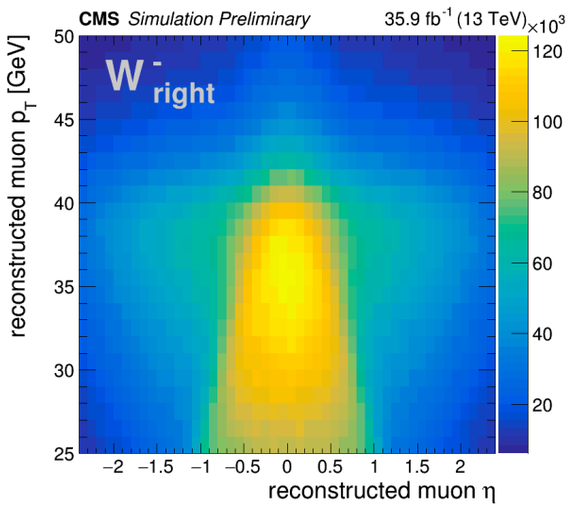
$$Y_W = \frac{1}{2} \cdot \log \frac{E + p_z}{E - p_z}$$

$$\eta_\ell \approx Y_W \pm 0.5$$









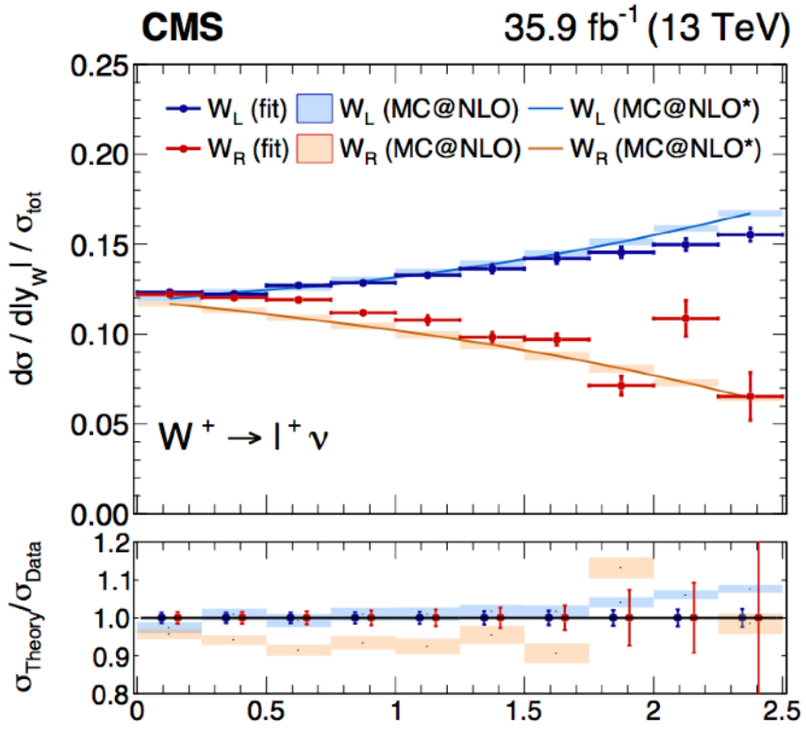
+ a smaller component from longitudinal polarization …

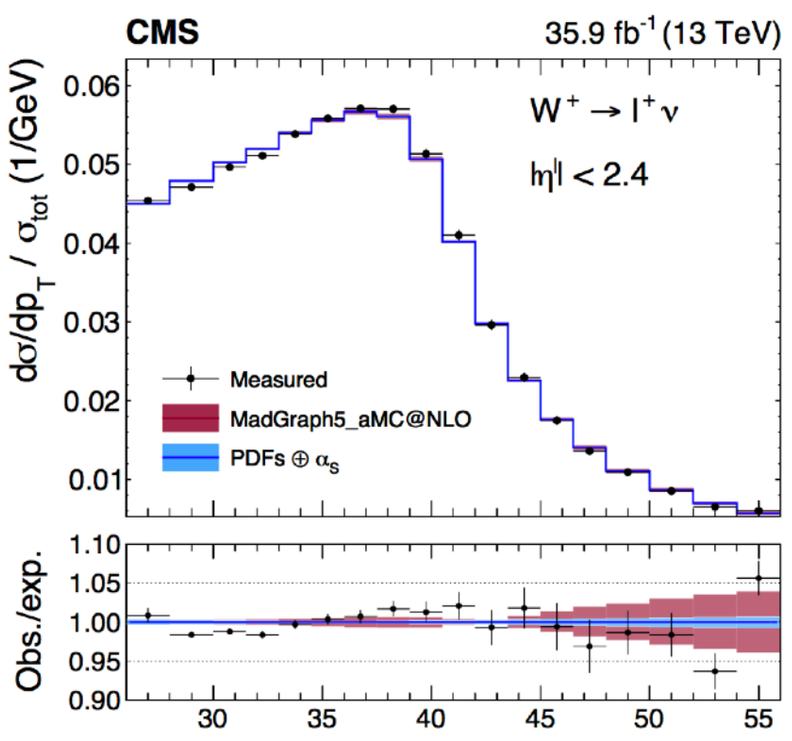
PRD 102 (2020) 092012

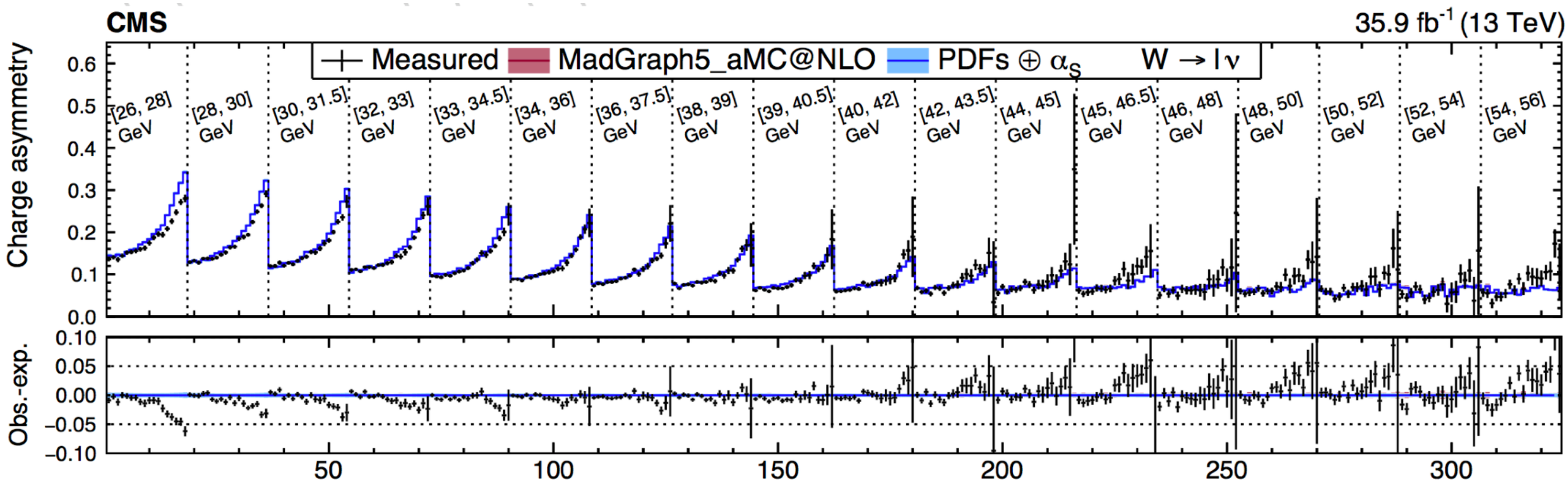
W helicity, rapidity, cross sections, asymmetries

Wide range of results

- fitting p_T^{ℓ}-η^{ℓ} in data with simulated templates in bins of particle-level quantities
- measurement precision ≈1% or better in most bins







W helicity and PDF constraints

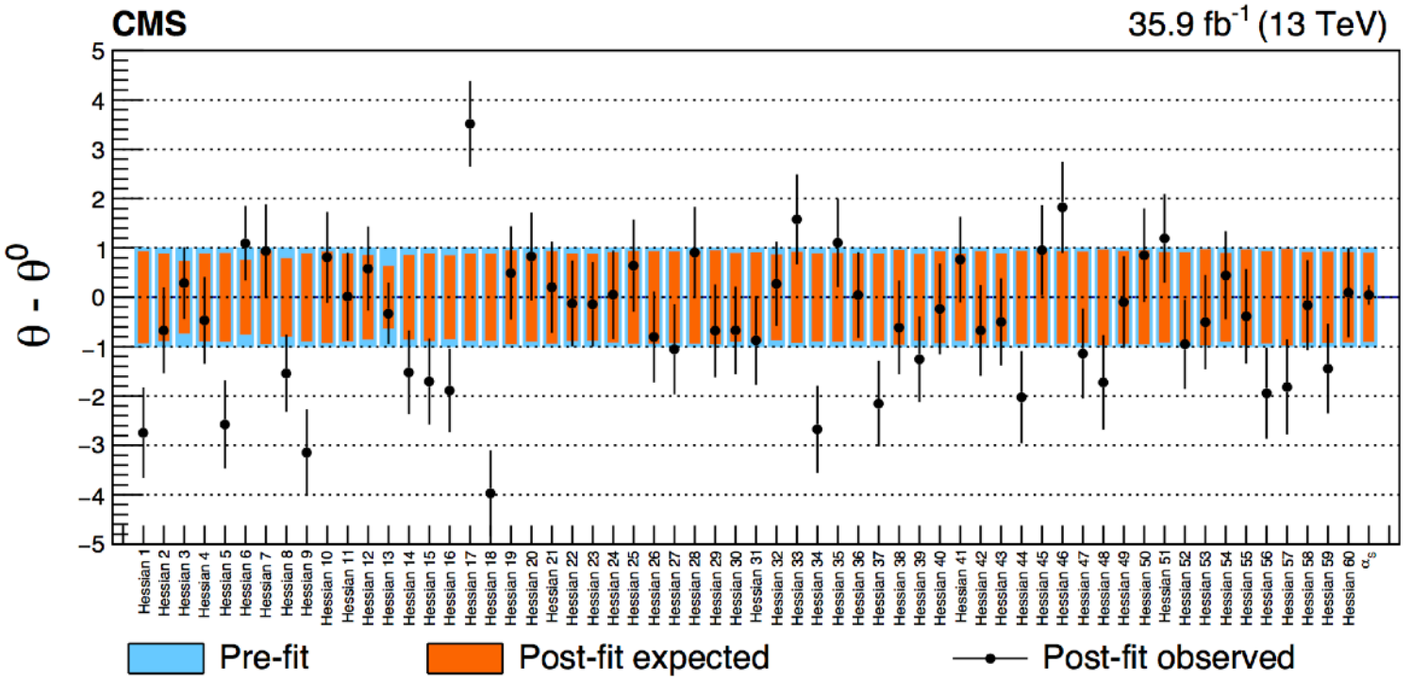
PRD 102 (2020) 092012
CMS-SMP-18-012

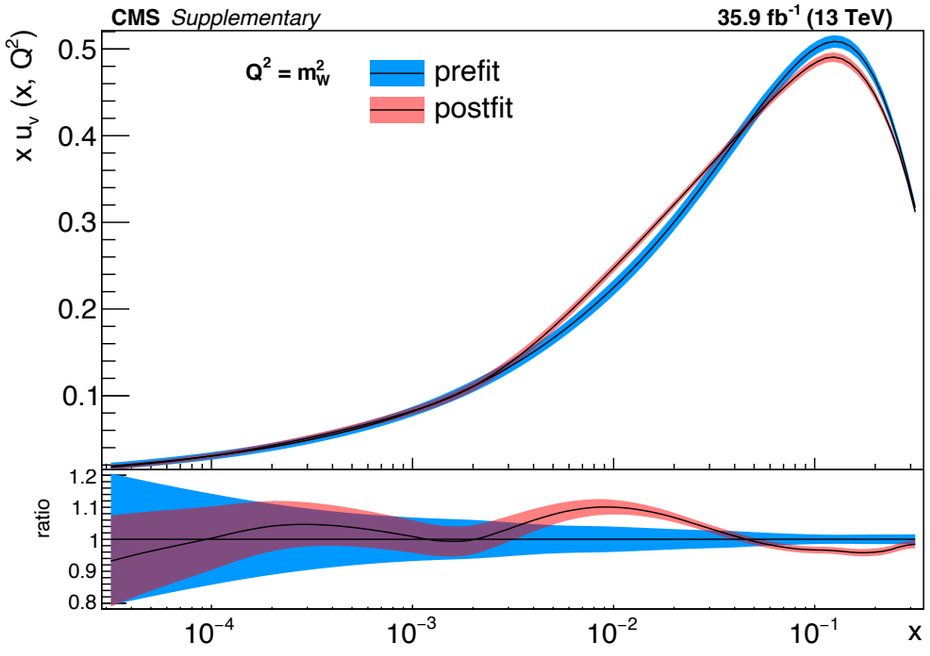
Analysis based on NNPDF3.0 PDFs, with uncertainties represented by 100 MC replicas

- converted into 60 Hessian eigenvectors using mc2hessian , then treated as nuisance parameters in the fit and profiled in the likelihood minimization
  - average 10% constraints thanks to information embedded in lepton η
  - benchmark to reduce PDF uncertainties in m_W measurement at the LHC

PDF parameters translated back into PDF shapes versus Bjorken-x

- not an actual QCD analysis: profiling procedure implies that one cannot interpret results as a rigorous PDF determination in case they are far from input PDFs
- possible limitations of NNPDF3.0 PDF set with respect to newer sets





Eur. Phys. J. C (2018) 78:701

Effective weak mixing angle: $\sin^2\theta^f_{eff}$

Forward-backward asymmetry A_{FB} in $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ sensitive to $\sin^2\theta^f_{eff}$

- mixing angle from ratio of vector and axial-vector couplings

$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$

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

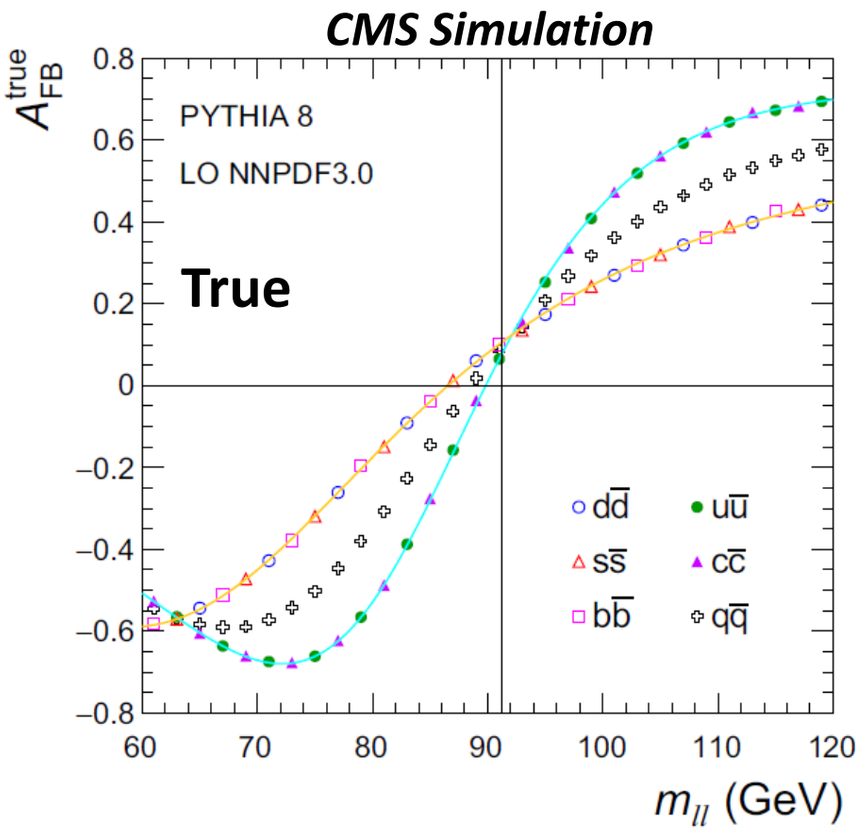
θ^* angle between ℓ^- and quark in Collins-Soper frame

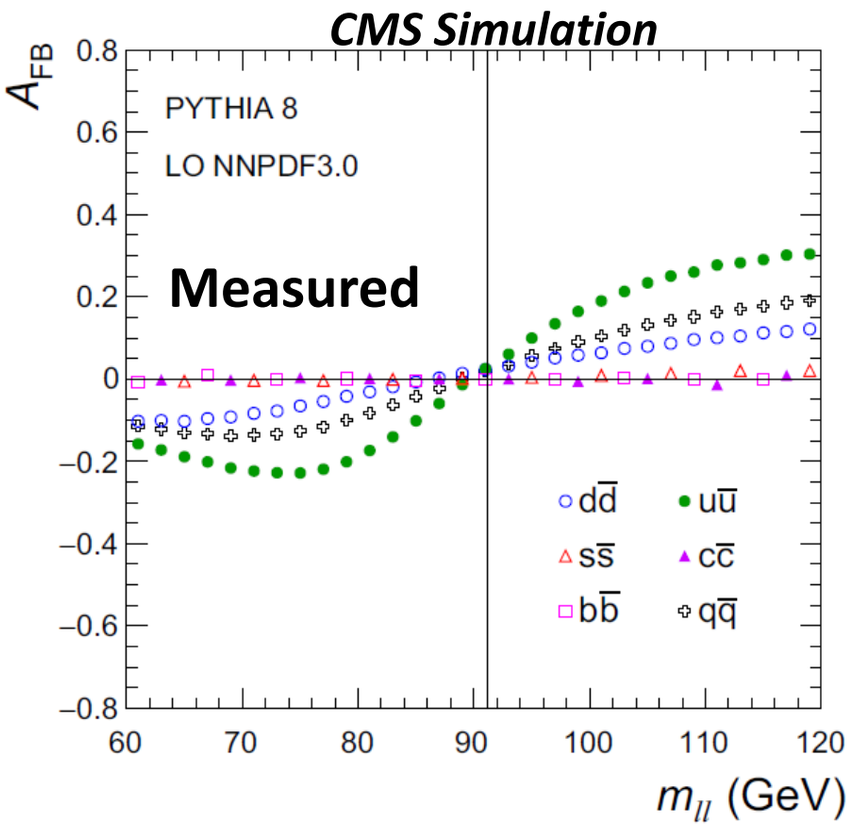
- definition of θ^* assumes lepton pair produced along quark's direction
- quark's true direction unknown —> dilution of A_{FB} —> sensitivity to PDFs (large-x $\bar{q}$)

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 : $cos\theta^* < 0$



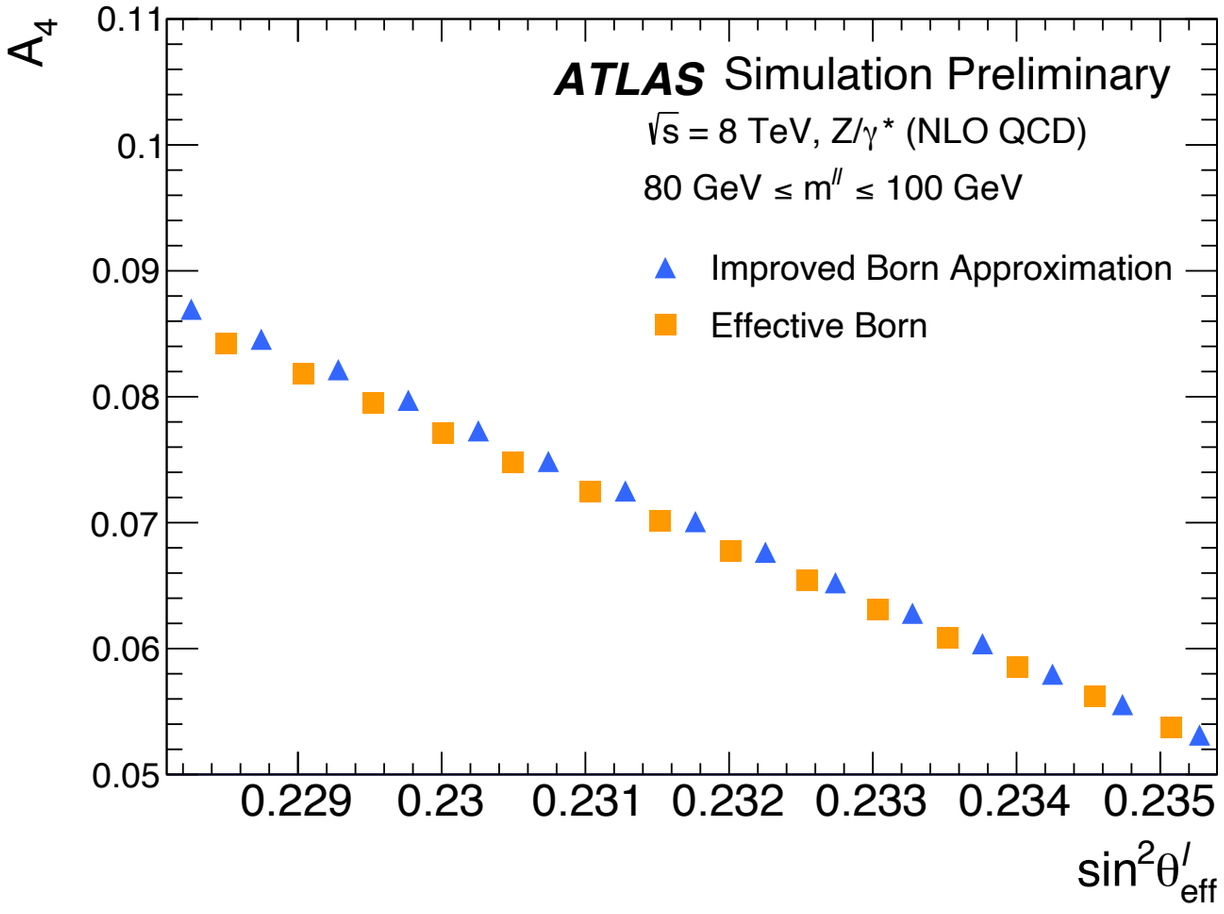


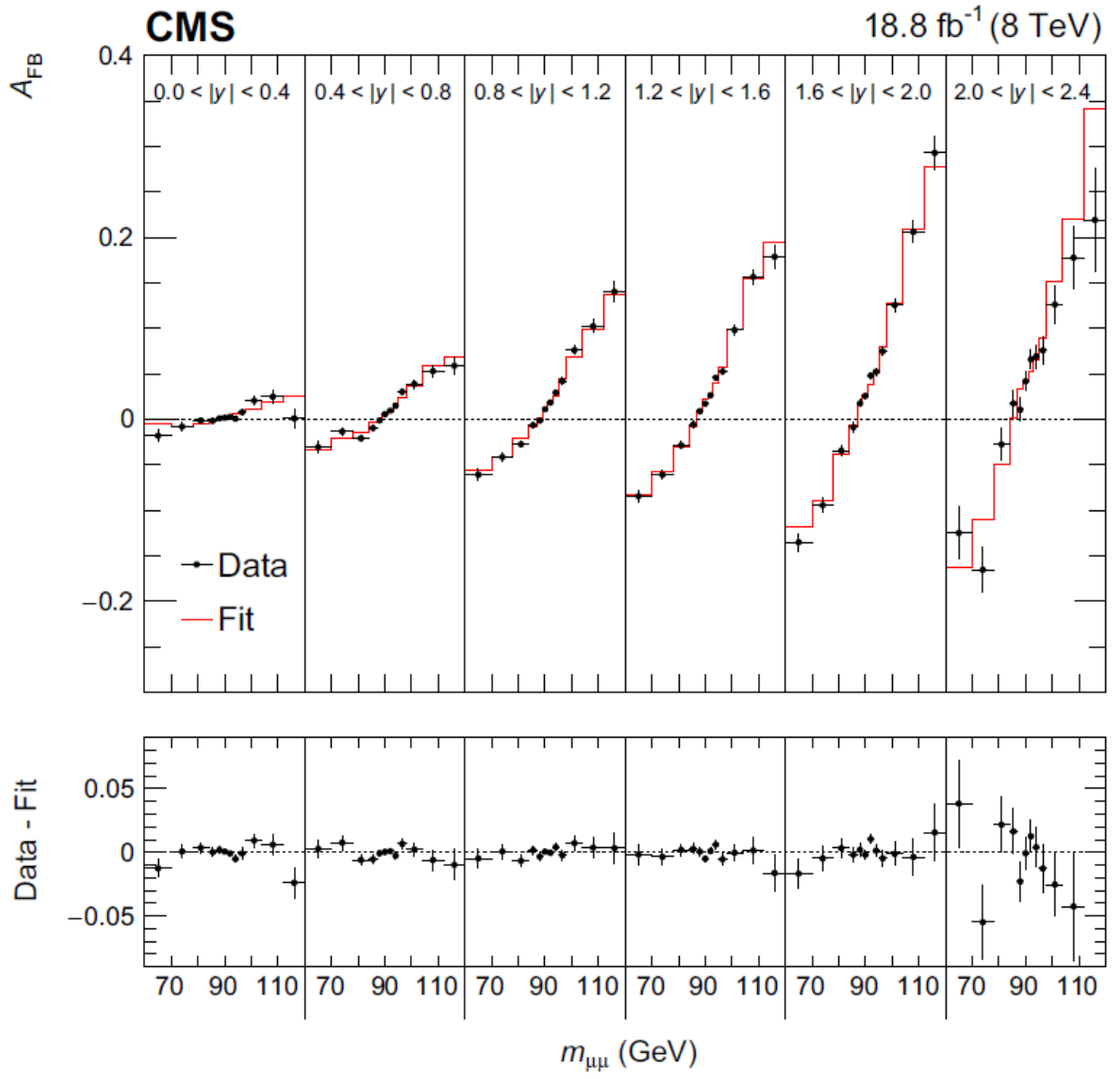
Measuring $\sin^2\theta^f_{eff}$

ATLAS-CONF-2018-037
Eur. Phys. J. C (2018) 78:701

Different approaches pursued by ATLAS and CMS to measure $\sin^2\theta^f_{eff}$

- ATLAS: from A_4 angular coefficient through effective linear relation
- CMS: fitting $A_{FB}(m_Z,y)$ in data to SM predictions obtained for different values of $\sin^2\theta^f_{eff}$





Status and prospects with Run 2 data

ATLAS-CONF-2018-037
Eur. Phys. J. C (2018) 78:701

Current LHC measurements of $\sin^2\theta^f_{eff}$ based only on Run 1 data

- uncertainties dominated by PDFs and limited size of data and MC samples
- ATLAS more precise than CMS thanks to additional category with one forward electron (no track, measured only with calorimeters), which helps constrain PDFs

ATLAS and CMS working on new measurement with all Run 2 data

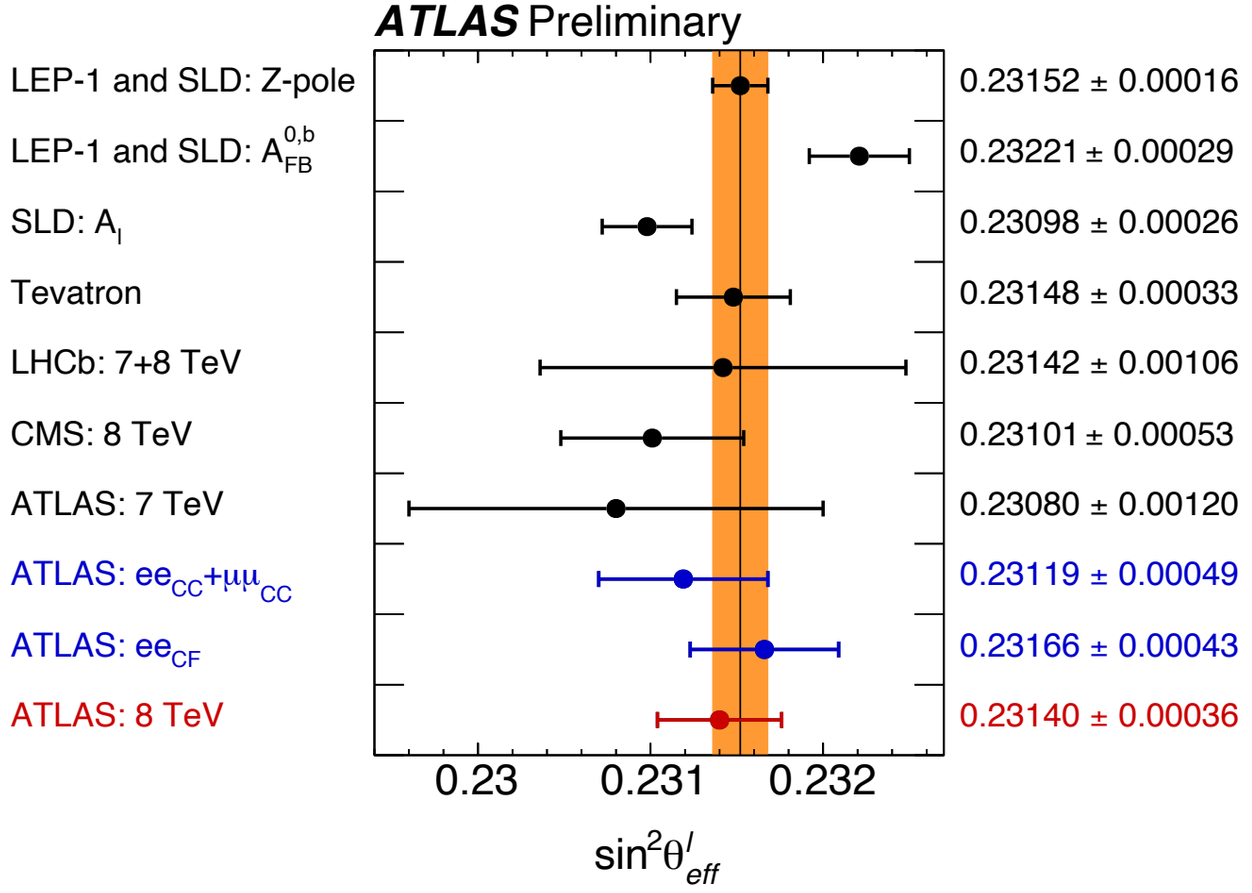
- lower statistical uncertainty, especially in high rapidity bins (more sensitive to PDFs)

ATLAS (Run 1):

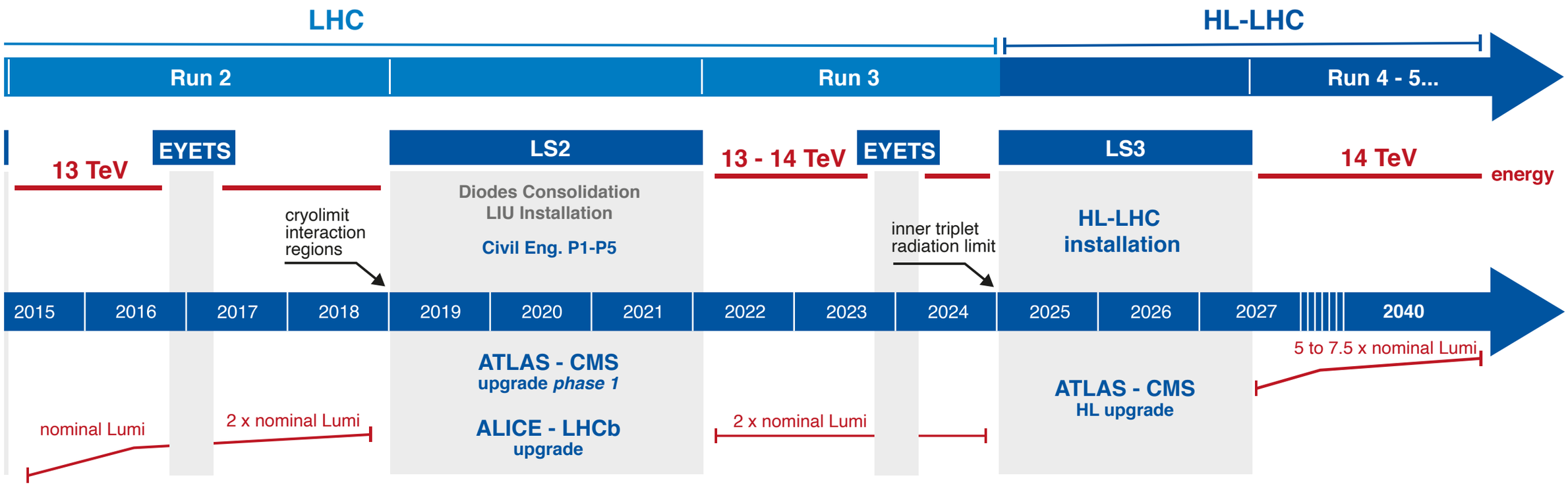
$\sin^2\theta^f_{eff} = 0.23101 \pm 0.00021\,(stat) \pm 0.00016\,(syst) \pm 0.00024\,(PDF)$

CMS (Run 1):

$\sin^2\theta^f_{eff} = 0.23101 \pm 0.00036\,(stat) \pm 0.00018\,(syst) \pm 0.00016\,(theory) \pm 0.00031\,(PDF)$



Towards HL-LHC



HL-LHC will provide us with 20 times more data than in Run 2

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

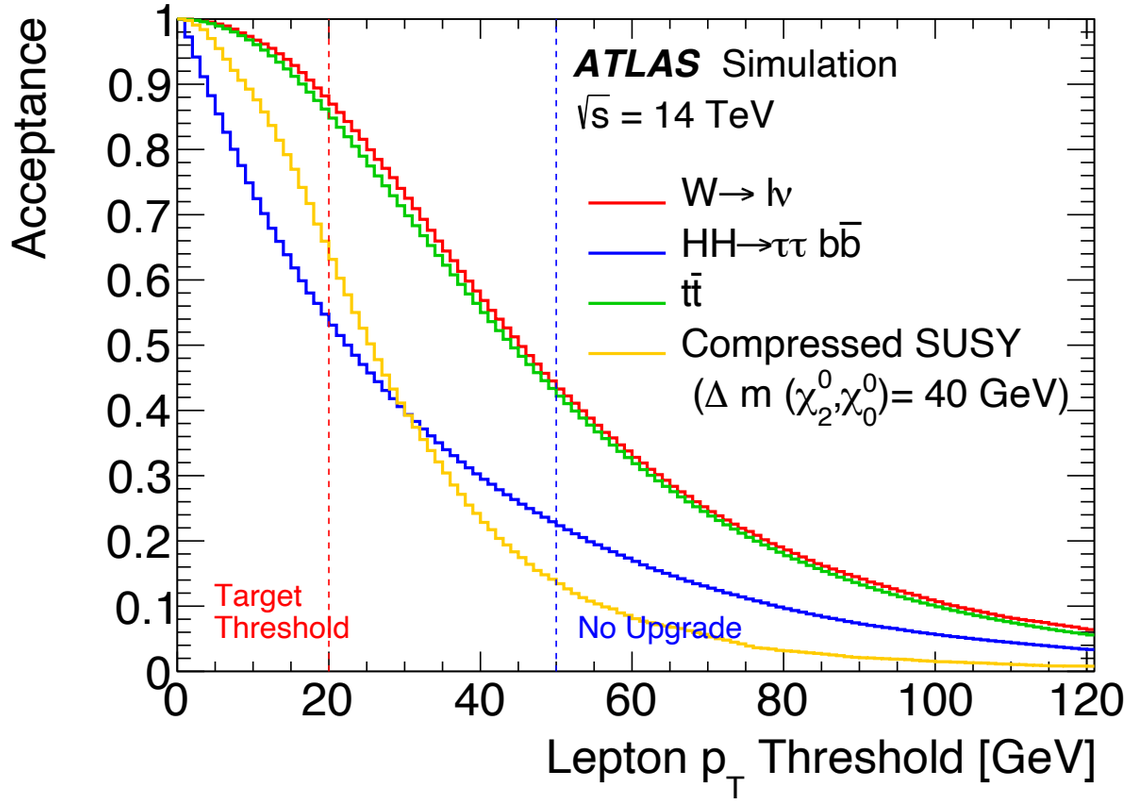
Major challenges to reap this benefit

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

Physics prospects

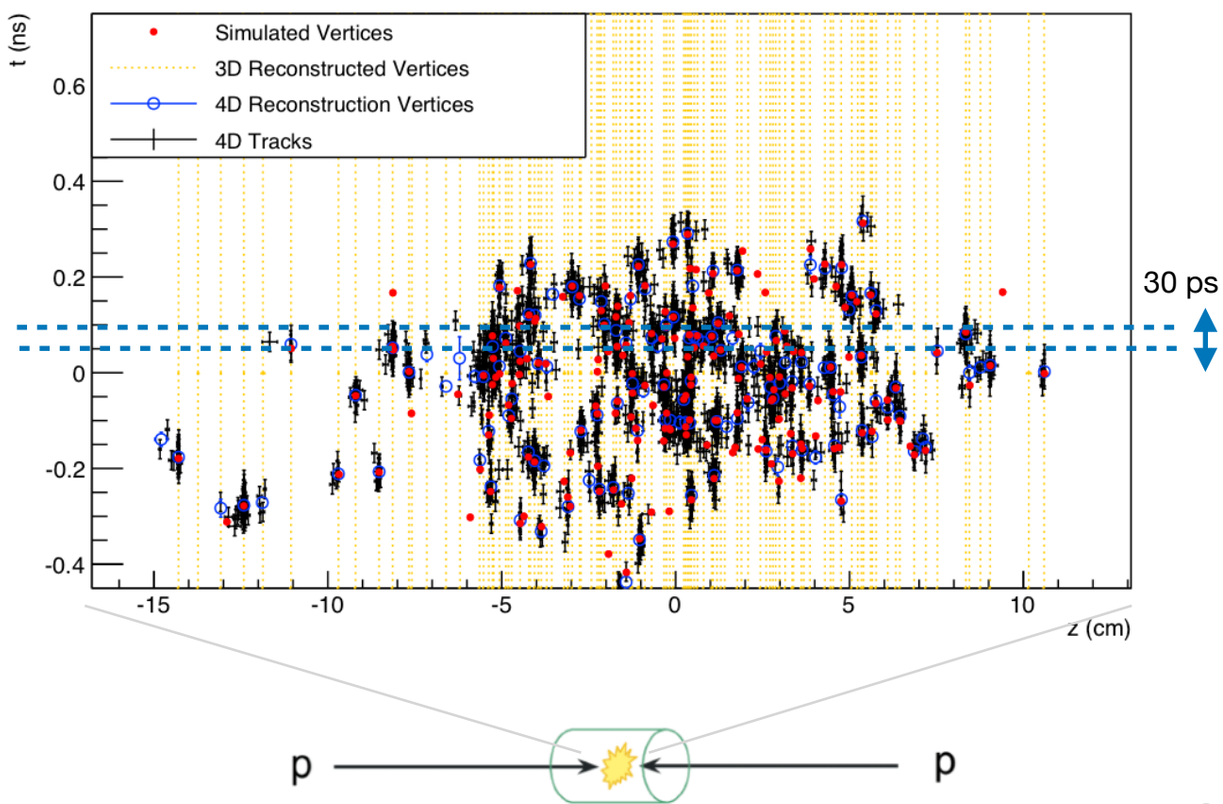
Substantial improvement in the first trigger stage (hardware based)

- faster front-end electronics
- increased spacial granularity to allow for more sophisticated particle identification
- track reconstruction at this stage
- maintain high signal purity and efficiency
  - W/Z physics requires low p_T leptons!



New detector paradigms at HL-LHC

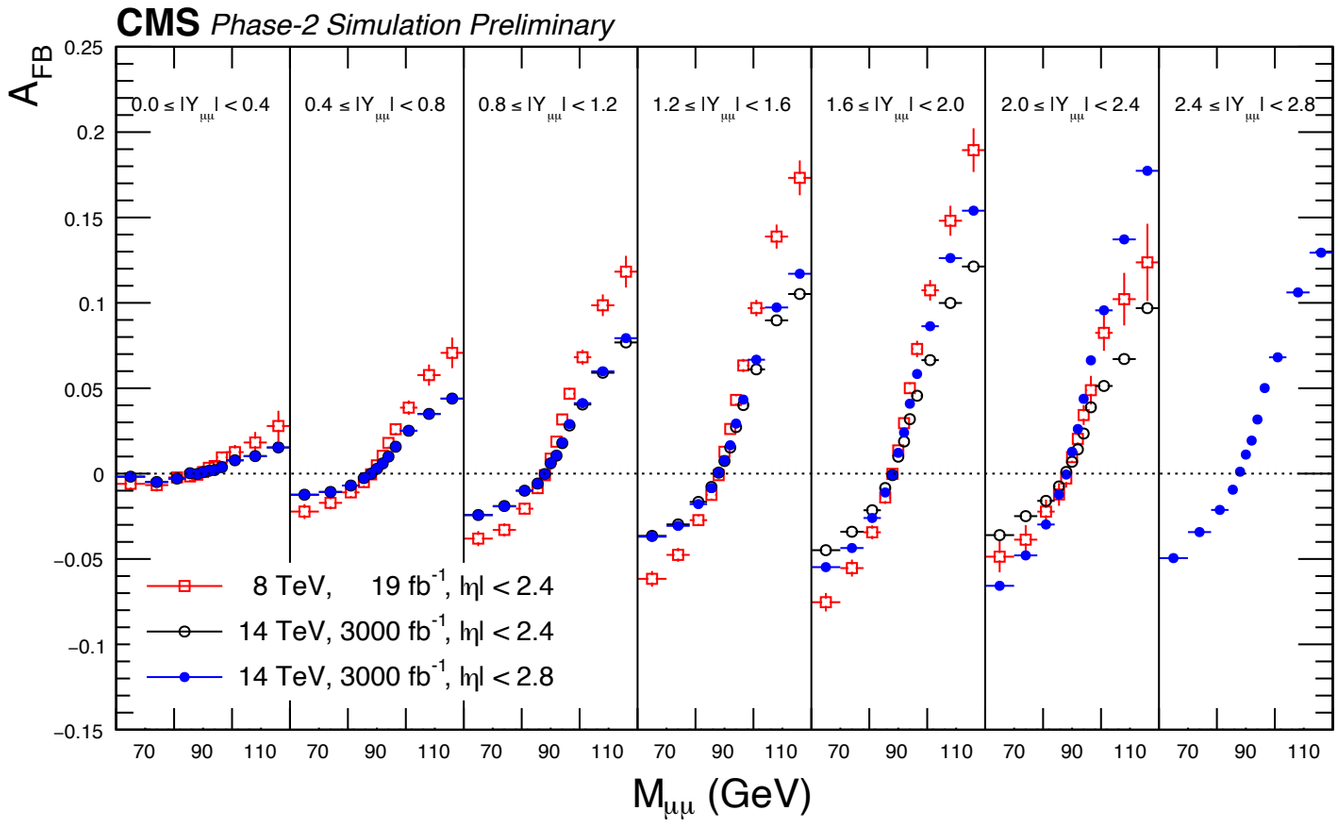
- timing detectors for pileup mitigation
  - will also contribute to better tagging of secondary vertices and improved particle reconstruction
- tracking systems with extended coverage up to $|\eta| < 4$ (against current 2.5)

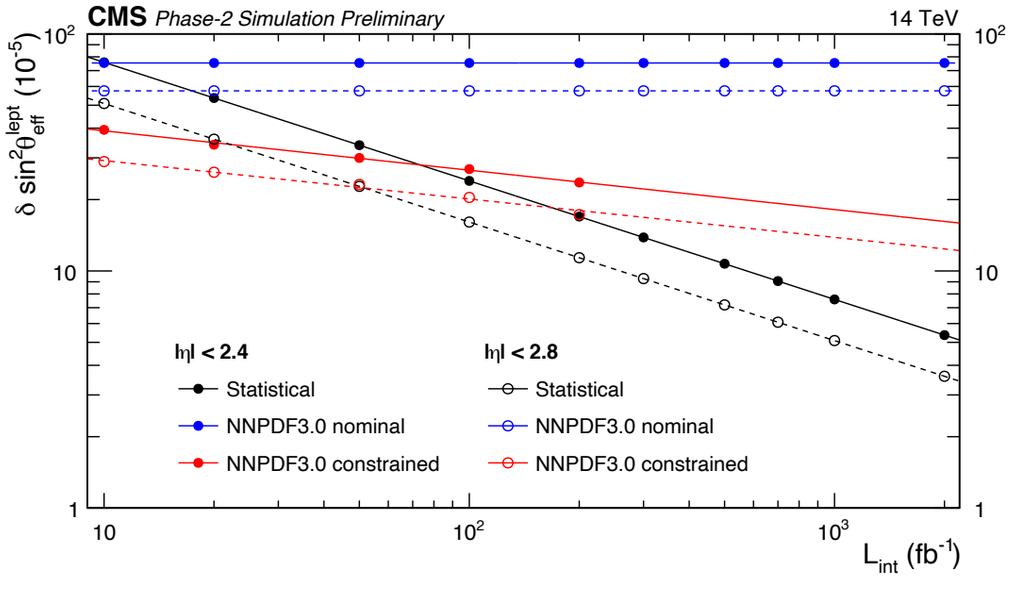


An example: $\sin^2\theta^f_{eff}$ at the HL-LHC

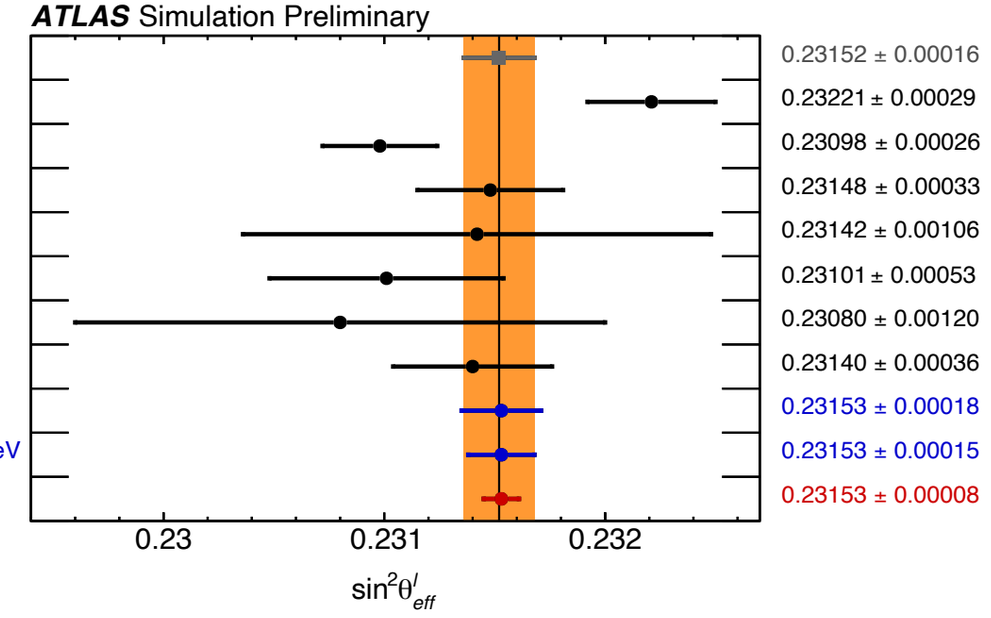
ATL-PHYS-PUB-2018-037
CMS-PAS-FTR-17-001
LHCb-PUB-2018-013

- 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





LEP-1 and SLD: Z-pole average
LEP-1 and SLD: $A^{0,b}_{FB}$
SLD: A_l
Tevatron
LHCb: 7+8 TeV
CMS: 8 TeV
ATLAS: 7 TeV
ATLAS Preliminary: 8 TeV
HL-LHC ATLAS CT14: 14 TeV
HL-LHC ATLAS PDF4LHC15$_{HL-LHC}$: 14 TeV
HL-LHC ATLAS PDFLHeC: 14 TeV



Summary

Presented small selection of recent results on W and Z physics 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 the LHC and experiments

- large data sets allow SM to be probed with unprecedented precision
- reducing systematic uncertainties mandatory
  - theoretical uncertainties to be constrained using data whenever possible

Looking forward to HL-LHC data and detector upgrades

- new physics opportunities to further constrain SM
- collaboration with theorists paramount to chart the course of future measurements

Public pages

ATLAS

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS

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

LHCb

- https://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

ALICE

- https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

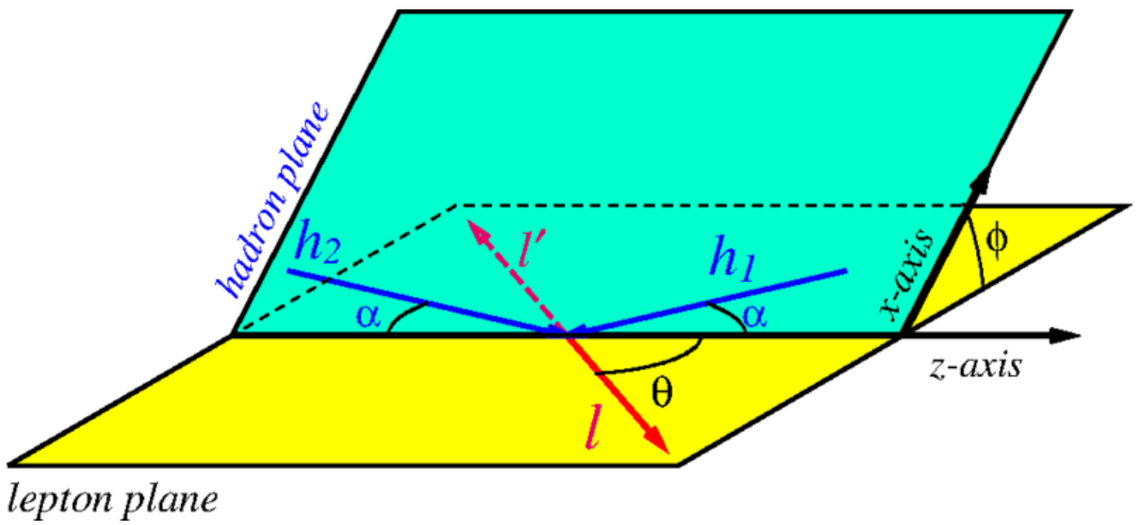
BACKUP

W and Z boson cross section

W/Z production and leptonic decay characterized by 5D cross section

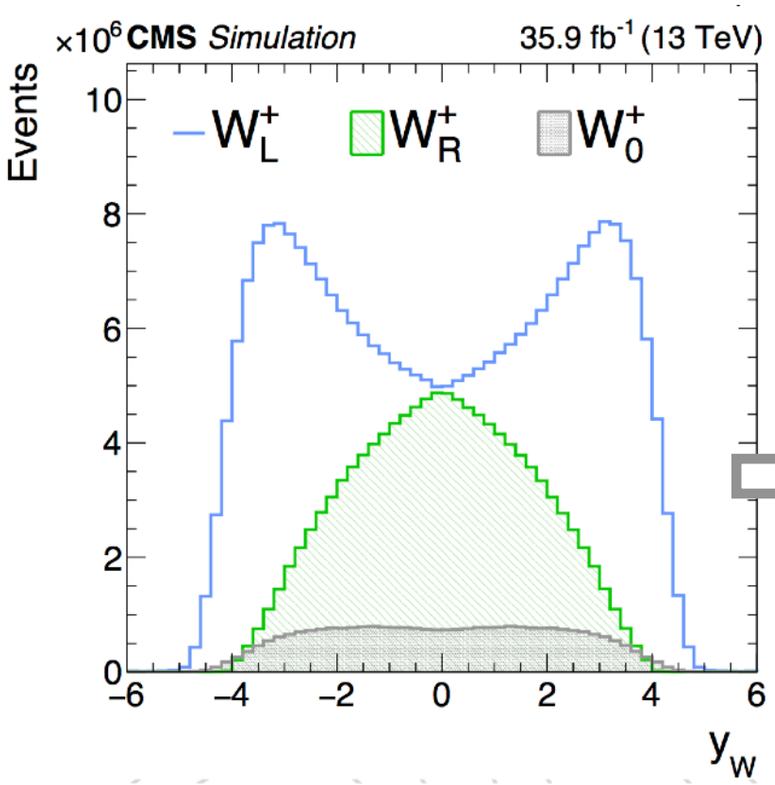
- Full information encoded in boson mass m, rapidity Y, transverse momentum p_T, and lepton θ-ϕ angles defined between negative lepton (or neutrino or W^+) and boson
- angular coefficients A_i strongly depends on Y and p_T

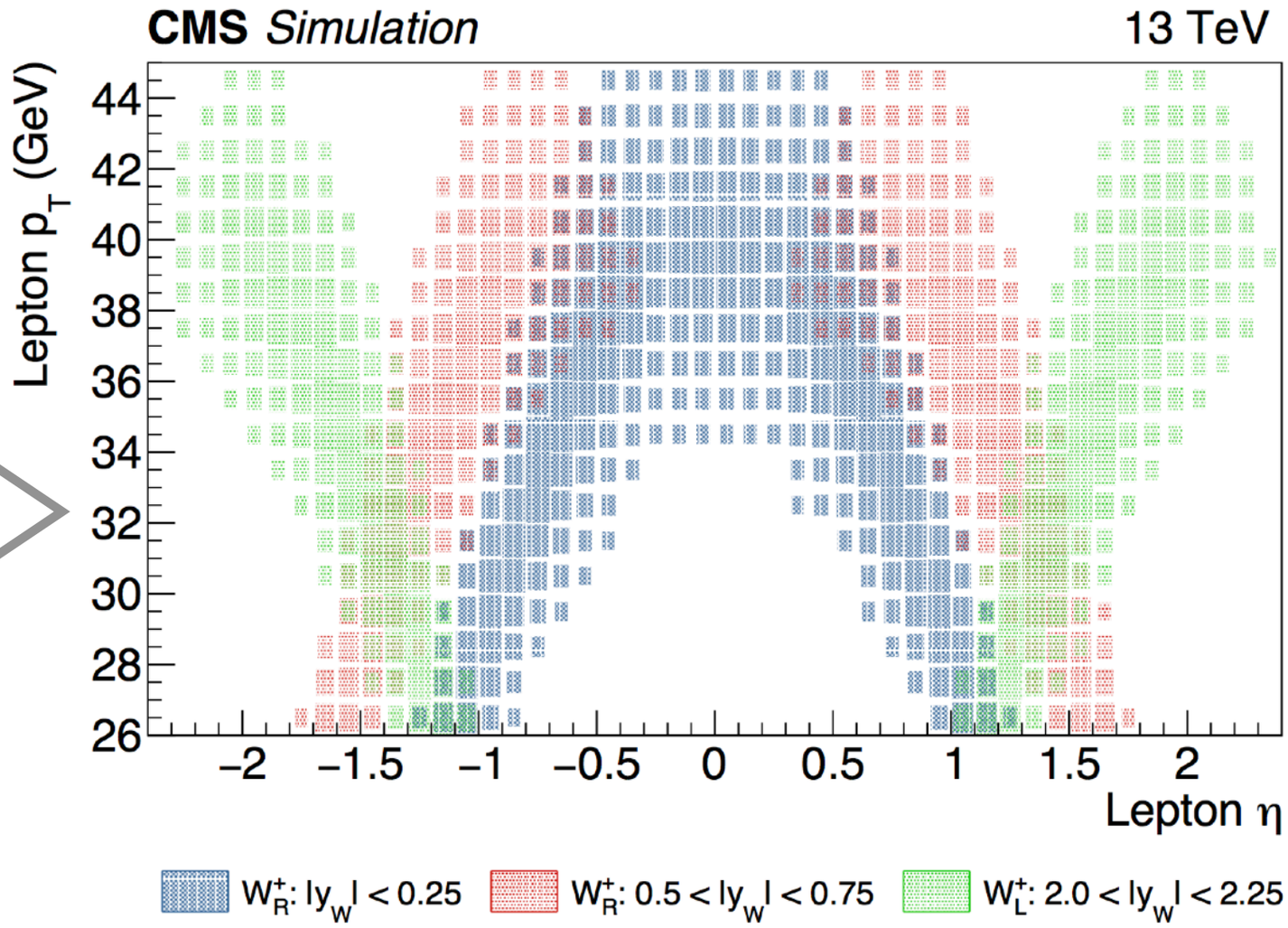
Given the mass, the cross section is predicted by SM up to uncertainties associated with PDFs and missing higher orders in QCD and EW calculations



$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}p_T^2\,\mathrm{d}Y\,\mathrm{d}m\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T^2\,\mathrm{d}Y\,\mathrm{d}m} \times \Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

Kinematics of polarized W decays





- different bins of Y_W/h_W correlate with well-defined regions of lepton p_T-η (with some overlap -> expect statistical correlations among Y_W/h_W bins)
- can measure h_W/Y_W fitting η-p_T distribution in data with simulated signal templates defined in bins of h_W/Y_W
- conceptually like solving an equation

$$N_{data} - B = \sum_i a_i \cdot S_i$$

- N_{data}: p_T-η template in data
- B: p_T-η templates for backgrounds
- $a_i \cdot S_i$: p_T-η templates for i-th signal category (a bin of Y_W/h_W)

THE LORD OF THE LHC RING

… one does not simply measure the W mass …