Precision measurements with Z boson decays at the LHC

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The importance of the Z precision measurements

Precision measurements with the Z boson are fundamental to understand the SM, complementary to those with W bosons:

- Electroweak model validation
- QED corrections and Final State Radiation (FSR)
- Perturbative and non-perturbative QCD
- Parton distribution functions (PDFs)

Pros and cons of doing precision measurements in a hadron collider like LHC:

- Higher production rates with access to the proton structure
- QCD takes an important role and events are more busy

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

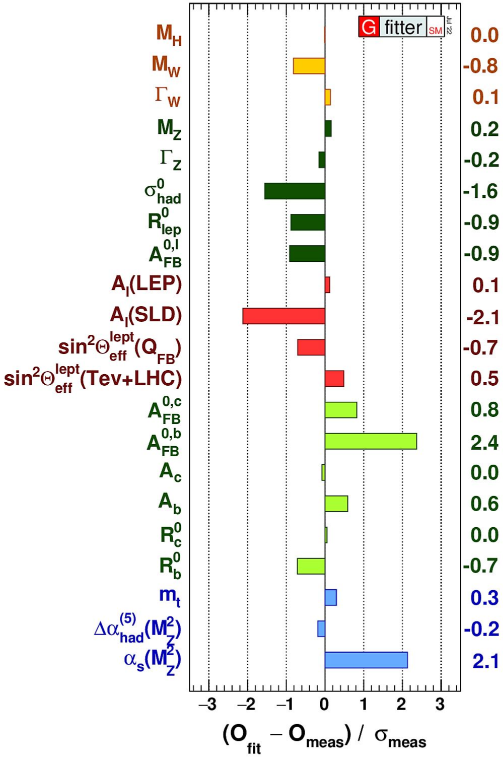
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

$$\Gamma_Z \propto G_F m_Z^3$$

$$\Gamma_W \propto G_F m_W^3$$

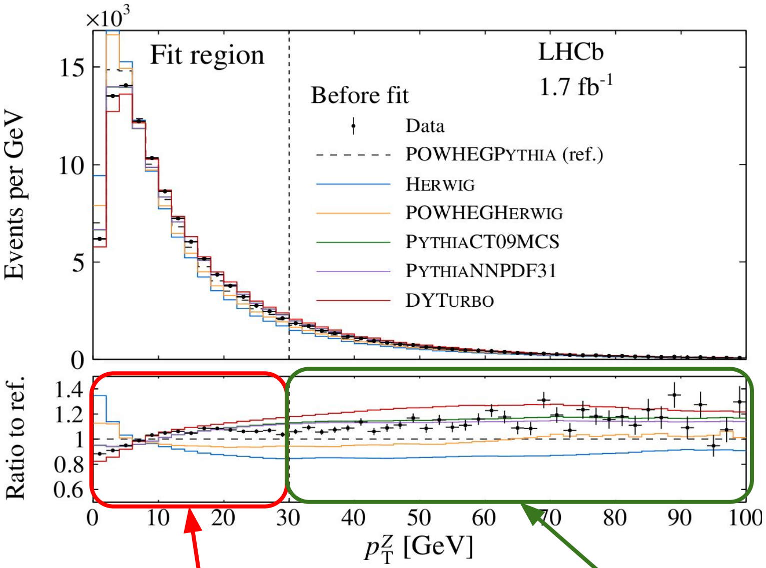
Higher order corrections

[arXiv:2211.07665]



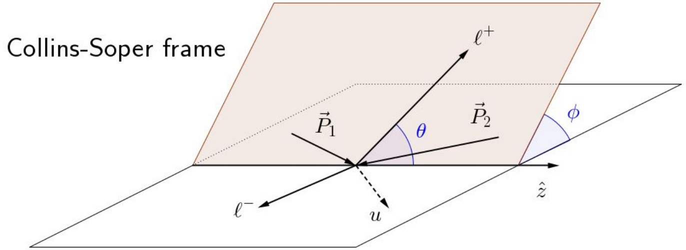
Studying processes with the Z boson

[JHEP 01 (2022) 036], [LHCB-PAPER-2021-024]

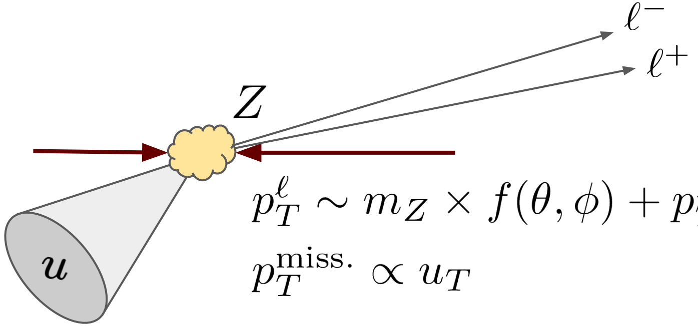


Better described at resummed high orders and by tuning the non-perturbative contributions and the strong-coupling constant

Predominantly affected by higher-order effects

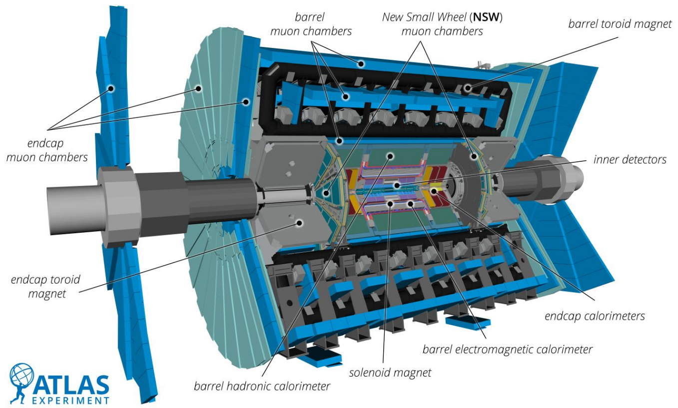


$$\frac{d\sigma}{dp_T^Z dy dM d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^Z dy dM}$$
$$\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi$$
$$+ A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\}$$



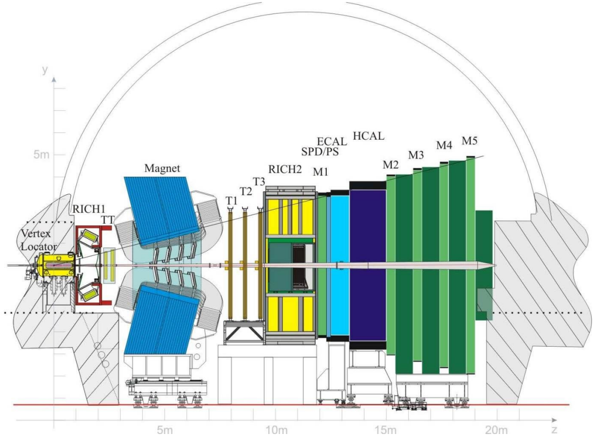
$$p_T^\ell \sim m_Z \times f(\theta,\phi) + p_T^Z \times g(\theta,\phi)$$
$$p_T^{\text{miss.}} \propto u_T$$

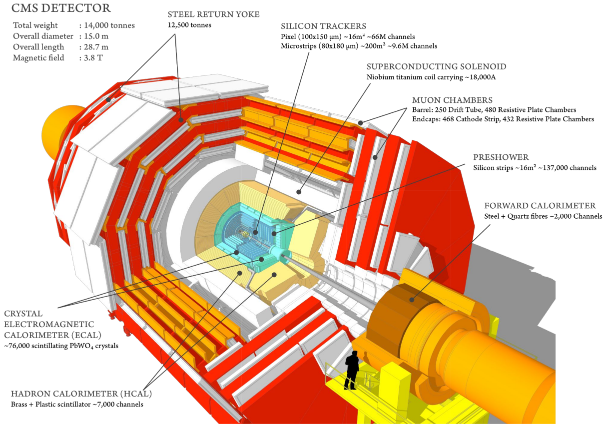
ATLAS, CMS and LHCb



[JINST 3 (2008) S08003]

[JINST 3 (2008) S08005]

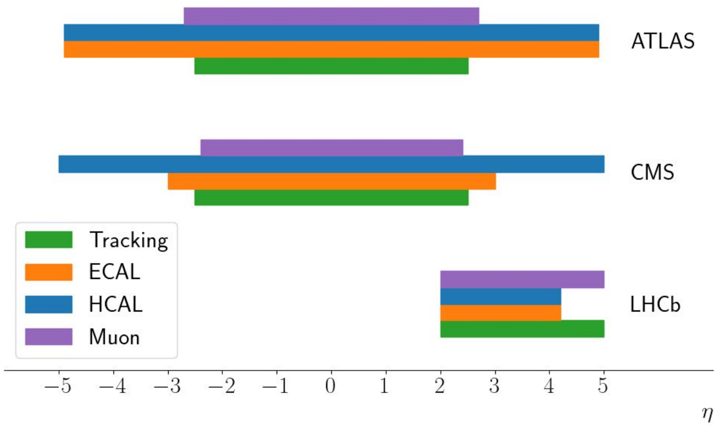


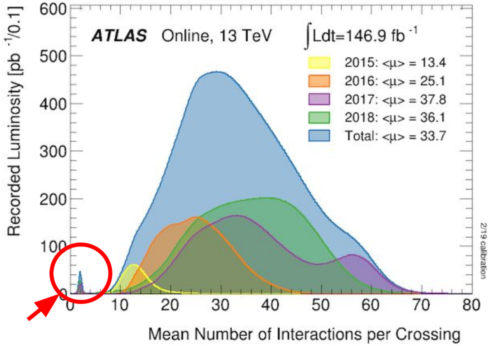


[JINST 3 (2008) S08004]

- Complementary detectors, which provide almost a 4π coverage
- Similar working environment: proton-proton, same energy, ...
- Interesting constraints on the physics modelling can be put combining the information from all of them (e.g. PDF uncertainties)

ATLAS, CMS and LHCb





Similar for CMS, to be compared with a value of ~2 for LHCb

[ATLAS public results]

Both ATLAS and CMS cover the central pseudorapidity region in a more hermetic environment

- Measurements of the hadronic recoil are possible with high precision (big implications in e.g. the measurement of the W transverse momentum)
- Electron modes can be studied in detail with the information from the ECAL
- The high pile-up can cause problems for some precision measurements, but dedicated runs are prepared for these

In LHCb the high pseudorapidity region is covered

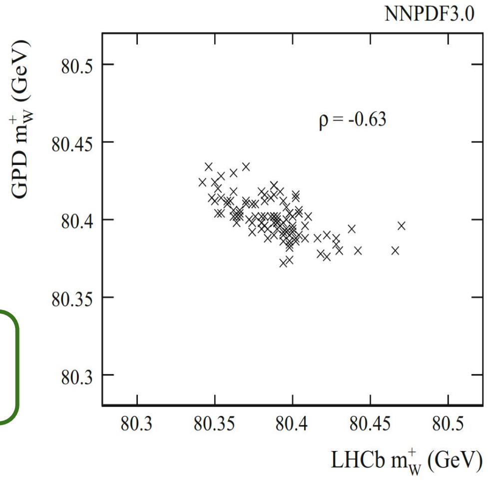
- Access to low and high Bjorken-x regions of the phase-space
- Provides valuable information for the physics modelling in the low transverse momentum region
- Complements the other detectors at the LHC
- Lower pile-up, but events are more populated in the high pseudorapidity range

The LHC combination: close to a 4π detector

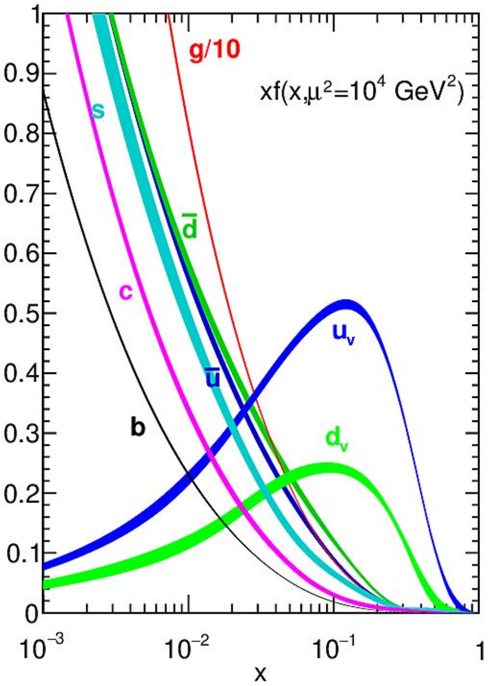
- Having three experiments with complementary coverage has big implications in the modelling and specially in the Parton Distribution Functions (PDFs)
  - Central Bjorken-x for ATLAS and CMS compared to low/high for LHCb
- Overall it provides useful information of the quark content of the proton:
  - In standalone Z processes we test quark/anti-quark interactions
  - With associated production we can directly test gluon and single-quark PDFs (e.g. Z + charm)

CMS & ATLAS

Up to a factor of 2 of reduced systematic uncertainty from PDFs in the W mass measurement



[EPJC 75, 601 (2015)]



NNPDF, [CERN-TH-2017-077]

Cross-section studies

The measurement of differential cross-sections is crucial to understand the modelling of the boson production cross-section

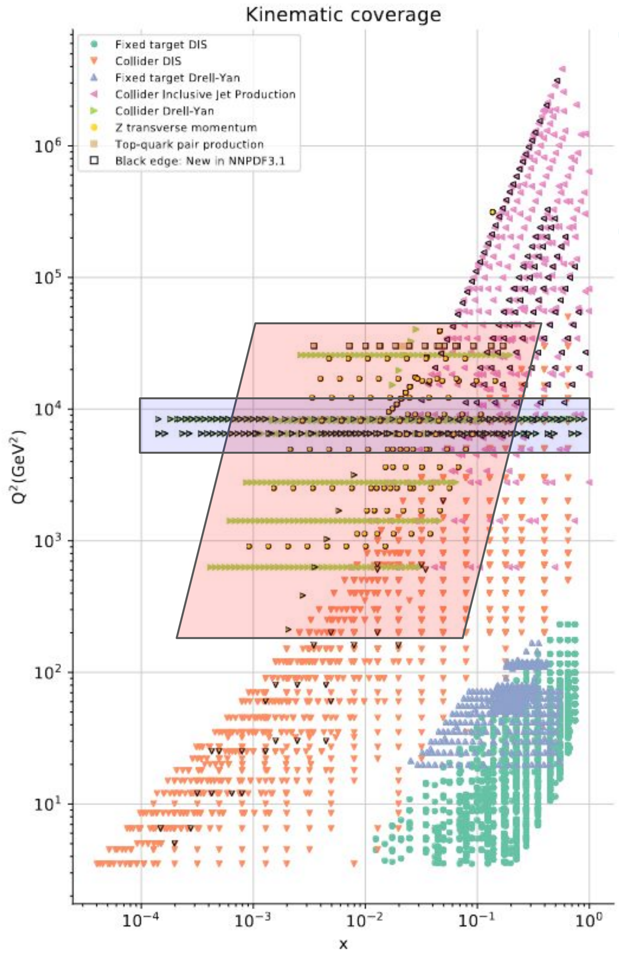
- Generator tuning: perturbative and non-perturbative contributions, resummation, scales...
- PDF fits of the different quark species as a function of Q^2 and Bjorken-x

$$\sigma(x, Q^2) \sim \sum_{a=g,u,\bar{u},\dots} C_a * f_{a,A}(x, Q^2) + \text{remainder } \mathcal{O}(1/Q^2)$$

cross-section — sum over all the species — calculable process — PDF — remainder contribution, negligible a a high energy scale (Q^2)

factorization of the hard process

define the PDF at a desired Q_0^2 for a process and evolve it up in Q^2 using the DGLAP equations, fitting it to data



NNPDF, [CERN-TH-2017-077]

Cross-section studies

At the LHC the three experiments have provide measurements at different energies, including Run 3 data!

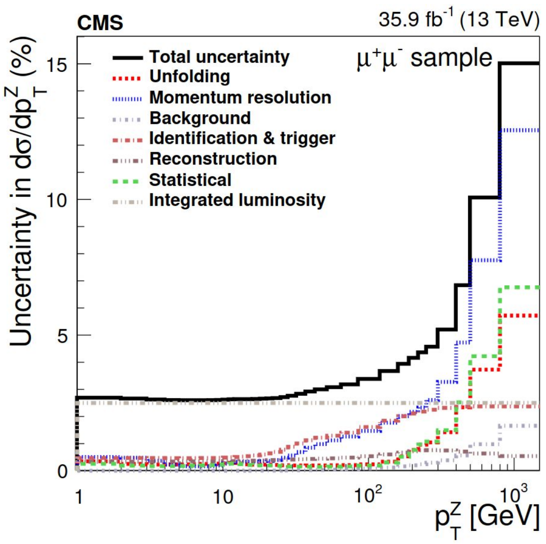
- ATLAS at 2.76, 5.02, 7, 8, 13 and 13.6 TeV
- CMS at 2.76, 5.02, 7, 8, 13 and 13.6 TeV
- LHCb at 5.02 , 7, 8 and 13 TeV

The measurement of the luminosity is crucial at the LHC, otherwise just a shape comparison can be made

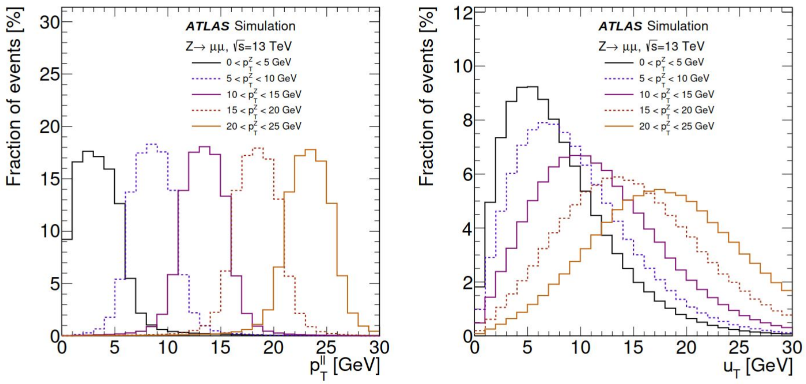
- Several developments done to construct luminometers in ATLAS [ATL-DAPR-PROC-2024-001], CMS [EPJC 83 (2023) 673], and LHCb [LHCB-TDR-022]
- Experiments target ~1% uncertainty for Run 3 and Run 4

The momentum and recoil resolution are the biggest sources of uncertainty

- Benefit from low pile-up runs
- Adopt new techniques for calibration (inputs from the W mass measurement?)



[JHEP 12 (2019) 061]



[CERN-EP-2024-080]

Angular coefficients

- The angular cross-section of bosons (S=1) can be expressed as a function of 9 harmonic spherics, with their accompanying coefficients A_i
- All the A_i are highly sensitive to next-to-leading order corrections, in such a way that all of them are close to zero at LO except for A_4 (related to the weak mixing angle)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$

Condenses information on the parity violation in weak interactions

$A_0 = A_2$ at LO for quark-antiquark and gluon-quark processes (Lam-Tung relation)

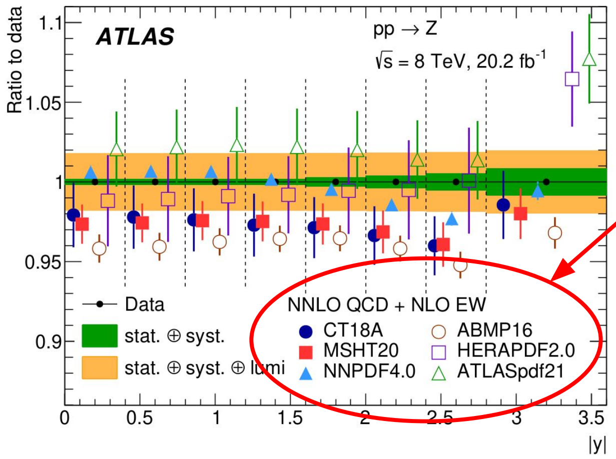
Angular coefficients

The analysis is similar to that of a cross-section measurement but:

- The cross-section is studied as a function of the decay angles as well as transverse momentum and rapidity
- More coarse binning is needed to optimize the sensitivity

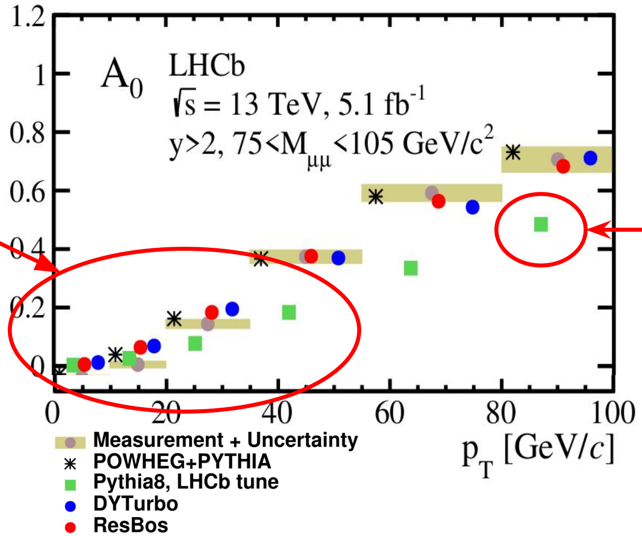
Pythia @ LO gives a poor description of the coefficients

[EPJC 84 (2024) 315]



Measurements are (almost) model independent, so comparison with different generators & conditions is relatively easy via folding the predictions

[PRL 129 (2022) 091801]



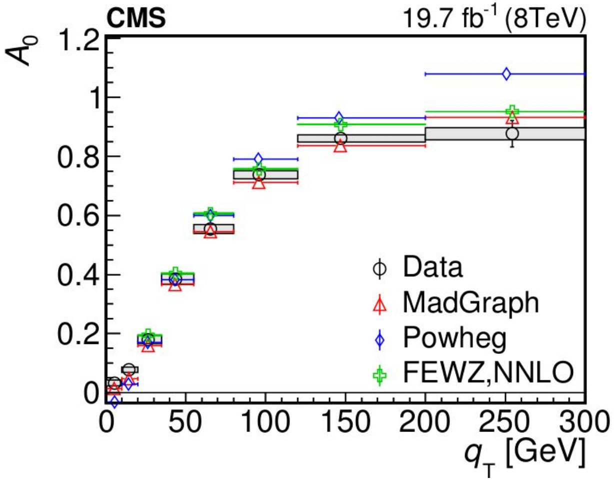
Angular coefficients

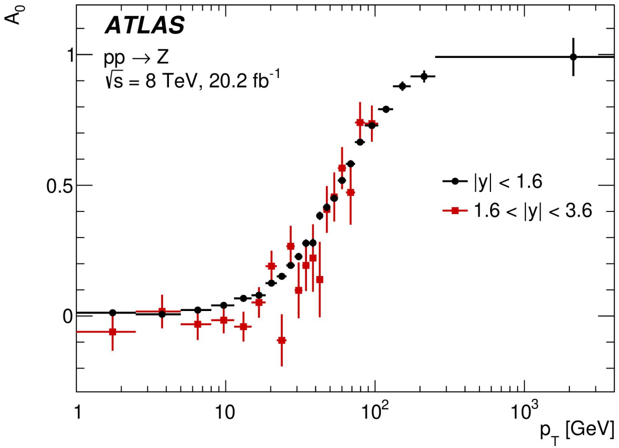
The angular coefficients have now been studied by the three experiments at different energies:

- ATLAS @ 8 TeV [EPJC 84 (2024) 315]
- CMS @ 8 TeV [PLB 750 (2015) 154]
- LHCb @ 13 TeV [PRL 129 (2022) 091801]

Useful information can be extracted to study calculations at N(N)LO

- In general, the angular coefficients are well predicted at fixed order
  - The only exception is A_4, which is highly affected by the PDFs
- Overall, it is an interesting area to study spin-momentum correlations of the proton, specially through the Lam-Tung relation





The weak mixing angle

- It is an useful quantity to test the custodial symmetry of the Standard Model

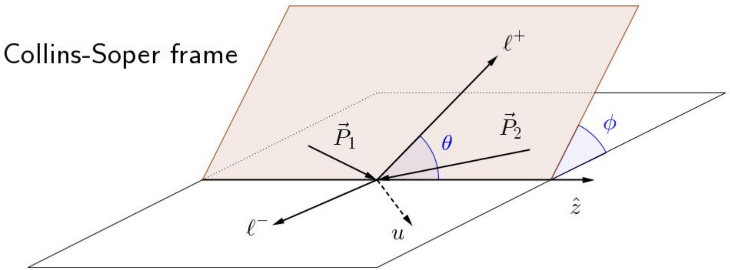
- Measuring the weak-mixing angle can be seen as an indirect measurement of the W boson mass:

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

- The treatment of A_4 deserves a special attention, since condenses information about the vector and axial-vector couplings of the Z boson

- It becomes interesting to perform singular measurements that maximize the sensitivity to the weak mixing angle (e.g. dilepton mass)

- The measurement is more challenging at the LHC compared to LEP, since it condenses information on the proton polarization



The definition of **"forward"** and **"backward"** is more ambiguous due to the **difference between quark** and **hadron level** information

$$A_{\rm fb} = \frac{\sigma_f - \sigma_b}{\sigma_f + \sigma_b} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$

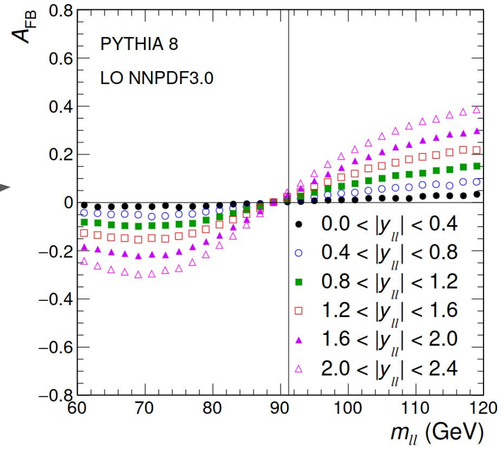
$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \cos^2\theta^* + \frac{8}{3} A_{\rm fb}\cos\theta^*$$

$$\cos\theta^* = \frac{2(p_\ell^+ p_{\bar{\ell}}^- - p_\ell^- p_{\bar{\ell}}^+)}{m_{\ell\bar{\ell}}\sqrt{m_{\ell\bar{\ell}}^2 + p_{T,\ell\bar{\ell}}^2}} \mathrm{sign}(p_{z,\ell\bar{\ell}})$$

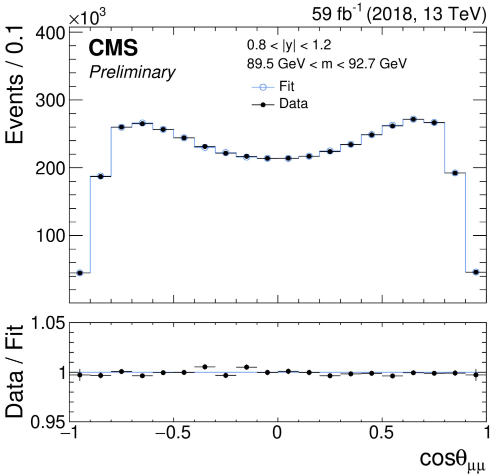
$$p_{\ell(\bar{\ell})}^{\pm} = \frac{1}{\sqrt{2}}\left(E_{\ell(\bar{\ell})} \pm p_{z,\ell(\bar{\ell})}\right)$$

The weak mixing angle

- There is a strong dependency of the forward-backward asymmetry with the mass of the dilepton system
  - This is caused by the interference between vector and axial-vector terms, hence the interference between the Z boson and virtual photon contributions
- The weak mixing angle is proportional to the cosine of the angle with respect to the quark parton, so events in the center of the distribution have less sensitivity (they dilute the measurement); therefore to enhance the sensitivity one can
  - weight events as a function of the cosine of θ^*
  - make a measurement as a function of the invariant mass, rapidity…



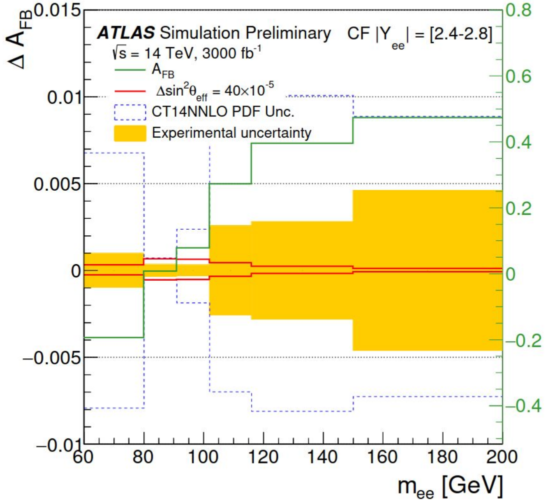
[EPJC 78 (2018) 701]



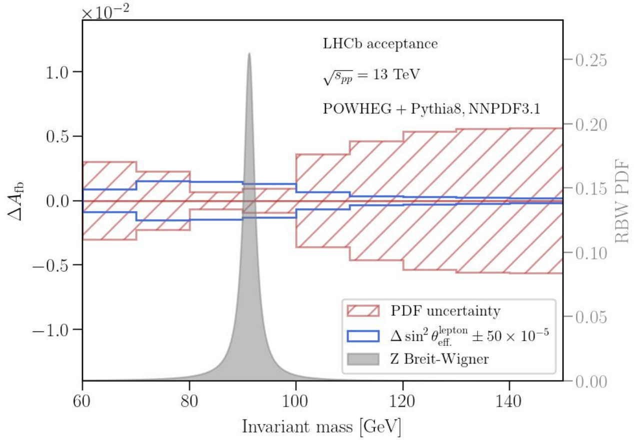
[CMS-PAS-SMP-22-010]

The weak mixing angle

- The measurement of the weak mixing angle at the LHC is highly dependent on the interplay between proton-level and quark-level quantities (especially in the definition of the *z* axis)
- These effects are reduced in the forward region (LHCb), where the dilution between proton and parton level is reduced
  - A high-*x* parton (typically a valence quark) interacts with a low-*x* parton (typically a sea anti-quark)
  - Enhanced sensitivity at ATLAS and CMS in the HL-LHC era due to the extended coverage in the forward direction
  - CMS used the forward calorimeters in its new measurement! [CMS-PAS-SMP-22-010]
- Mitigating the effect of the PDF uncertainties becomes crucial through e.g. profiling

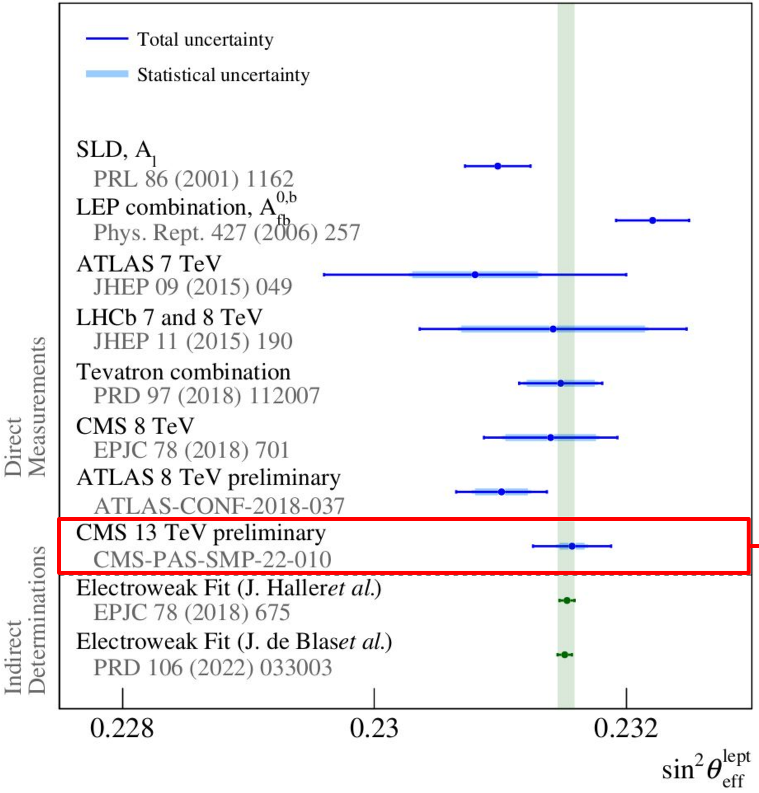


[ATL-PHYS-PUB-2018-037]



The weak mixing angle

0.00027 coming from PDFs!



- New measurement by CMS with 13 TeV data!

$$\sin^2\theta_{eff}^{lept}(\text{CMS @ 13TeV}) = 0.23157 \pm 0.00031$$

- ATLAS and LHCb still need to process the data collected at 13 TeV
- The HL-LHC has a big potential to drastically improve the accuracy
  - Improved detectors in the forward region
  - x10 more luminosity
- Beating the LEP experiments is possible in the future

$$\sin^2\theta_{eff}^{lept}(\text{LEP}) = 0.23221 \pm 0.00029$$

$$\sin^2\theta_{eff}^{lept}(\text{Tevatron}) = 0.23148 \pm 0.00033$$

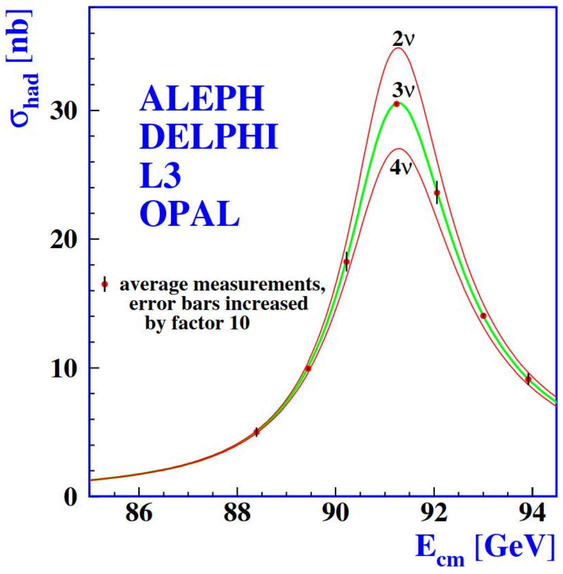
Z invisible width

[Phys.Rept.427:257-454,2006]

- The study of the invisible Z boson width has been important historically to determine the number of light neutrino families interacting through weak neutral currents
- For extracting the invisible width in a hadron collider, we need to compare the neutrino production to a known, well controlled, process like

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

- The measurement relies on having a hermetic detector and a precise measurement of the hadronic recoil, and therefore the missing transverse energy
    - To measure the recoil with high precision, the measurement must be restricted to values of the boson and jet transverse momentum higher than ~100 GeV



Much easier to do in an electron-positron collider via an energy scan

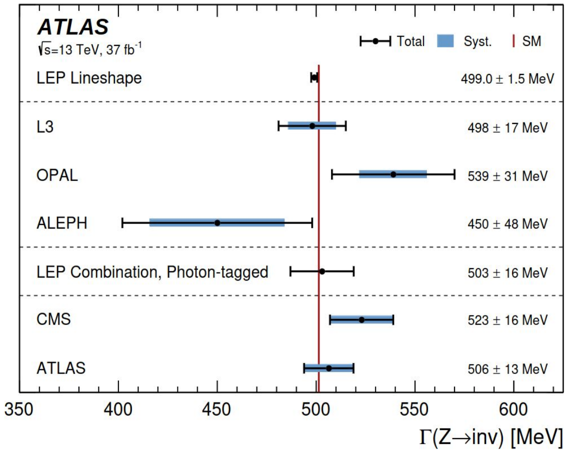
Z invisible width

[PLB 842 (2023) 137563]

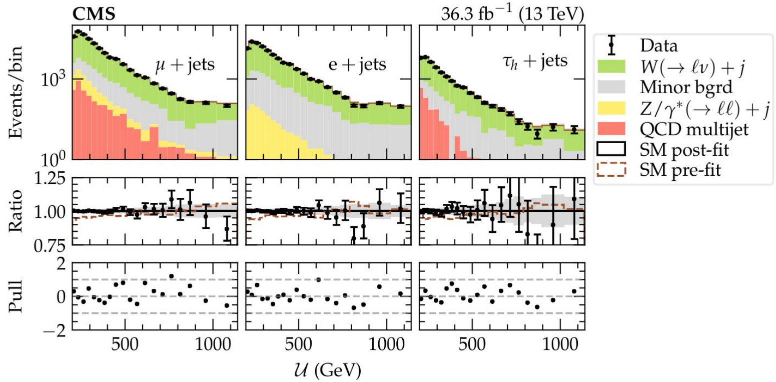
The measurement is highly dependent on the $p_T^{miss.}$ measurement, so the modelling needs to be validated as a function of a quantity sensitive to it:

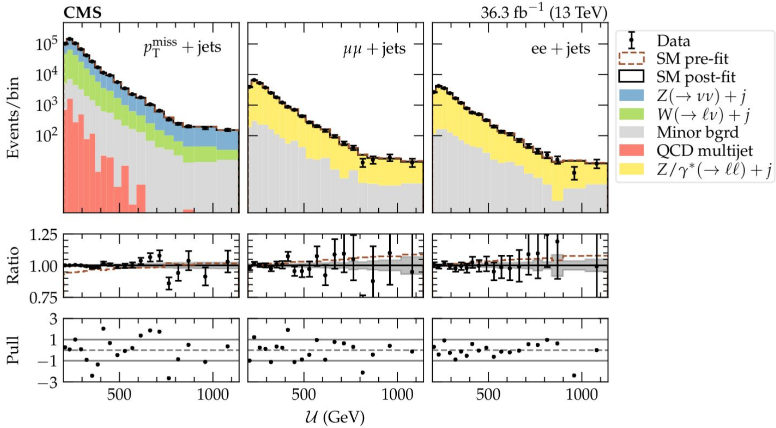
- ATLAS used the Z boson transverse momentum
- CMS used the measurement of the recoil

The dominant background from W+jets can be efficiently controlled with simulation and verified on data (~38% of the events). Other backgrounds (~15% of the events) can be controlled through data-driven approaches or from simulation



[STDM-2019-01]





Conclusions

The different experiments at the LHC offer a wide variety of ways of checking the consistency of the Standard Model with an unprecedented level of precision:

- Fundamental parameters, via model-dependent measurements
- Differential unfolded distributions, for which having more data and adopting new calibration techniques becomes crucial to reduce the experimental uncertainties

The study of Z bosons at the LHC constitutes a very important area to understand the Standard Model and redefine its boundaries

- We can efficiently validate procedures through different channels: electrons/muons, transverse momentum/recoil...
- It allows to understand backgrounds and the detector response in searches for physics beyond the standard model
- Has a nice interplay with W boson precision measurements (see the next talk by Marco Cipriani)

Many important measurements to come in the near future, and a very promising scenario awaits with HL-LHC, where beating LEP is possible in measurements like the weak mixing angle!

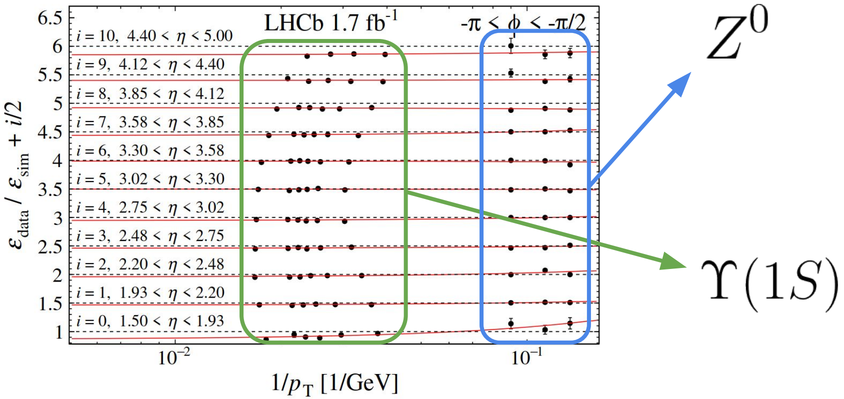
Thank you!

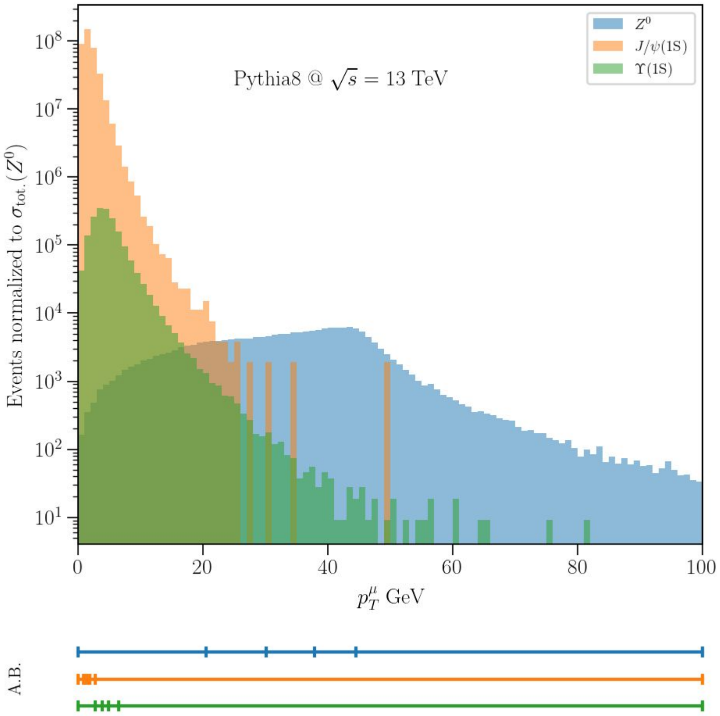
Backup

Calibrations using quarkonia

- The challenging part is to control with high accuracy the detector aspects
  - Momentum scaling (momentum)
  - Corrections to the resolution (momentum)
  - Efficiencies (transverse momentum in mass measurements)
- Corrections are typically applied as a function of η and φ to account for detector biases in bins of the transverse momentum
- Benefit from new quarkonia mass measurements e.g. Υ(1S) [Phys. Lett. B839 (2023), 137766] (reduction of the uncertainty by a factor of two)

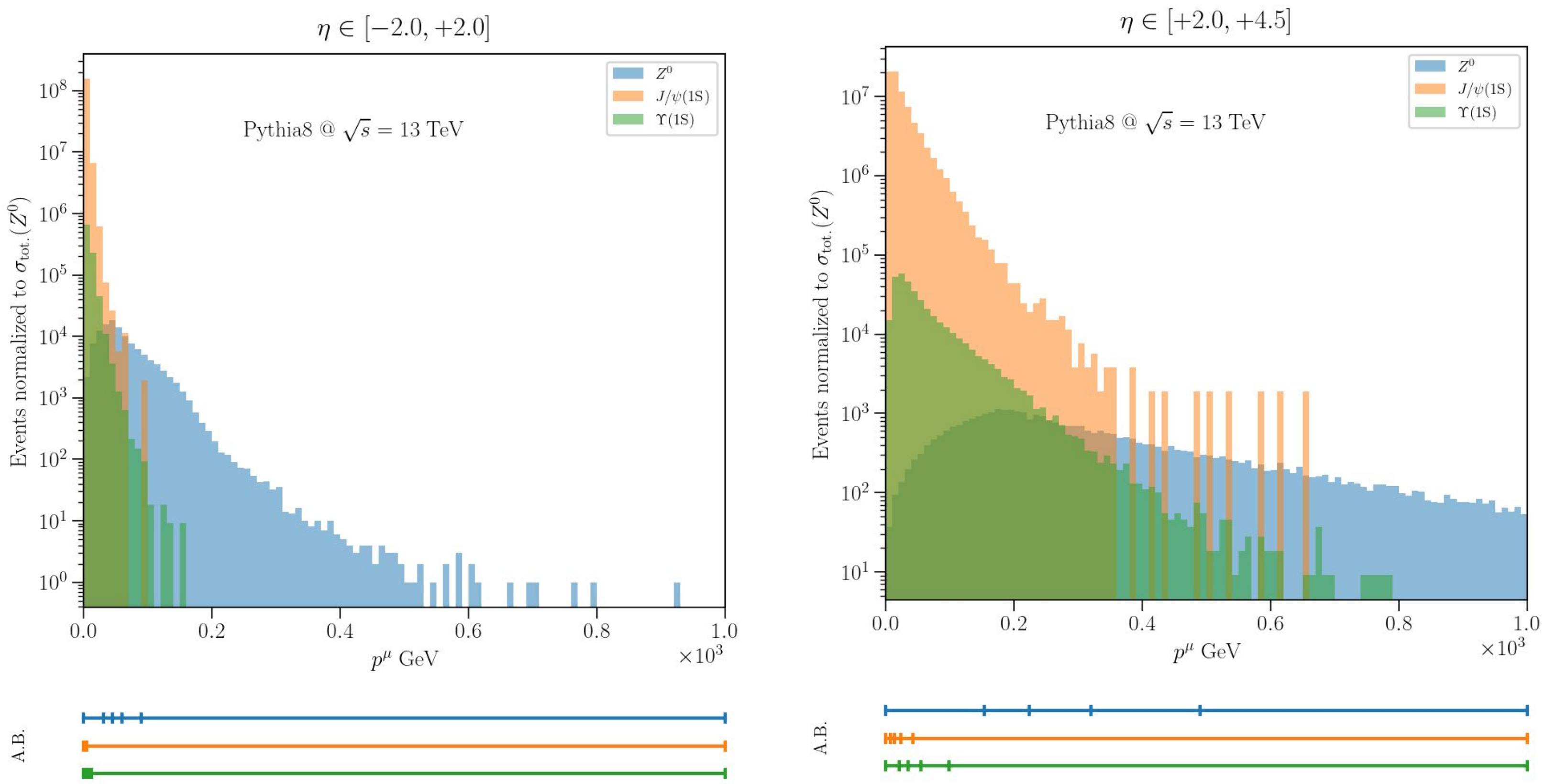
[JHEP 01 (2022) 036]





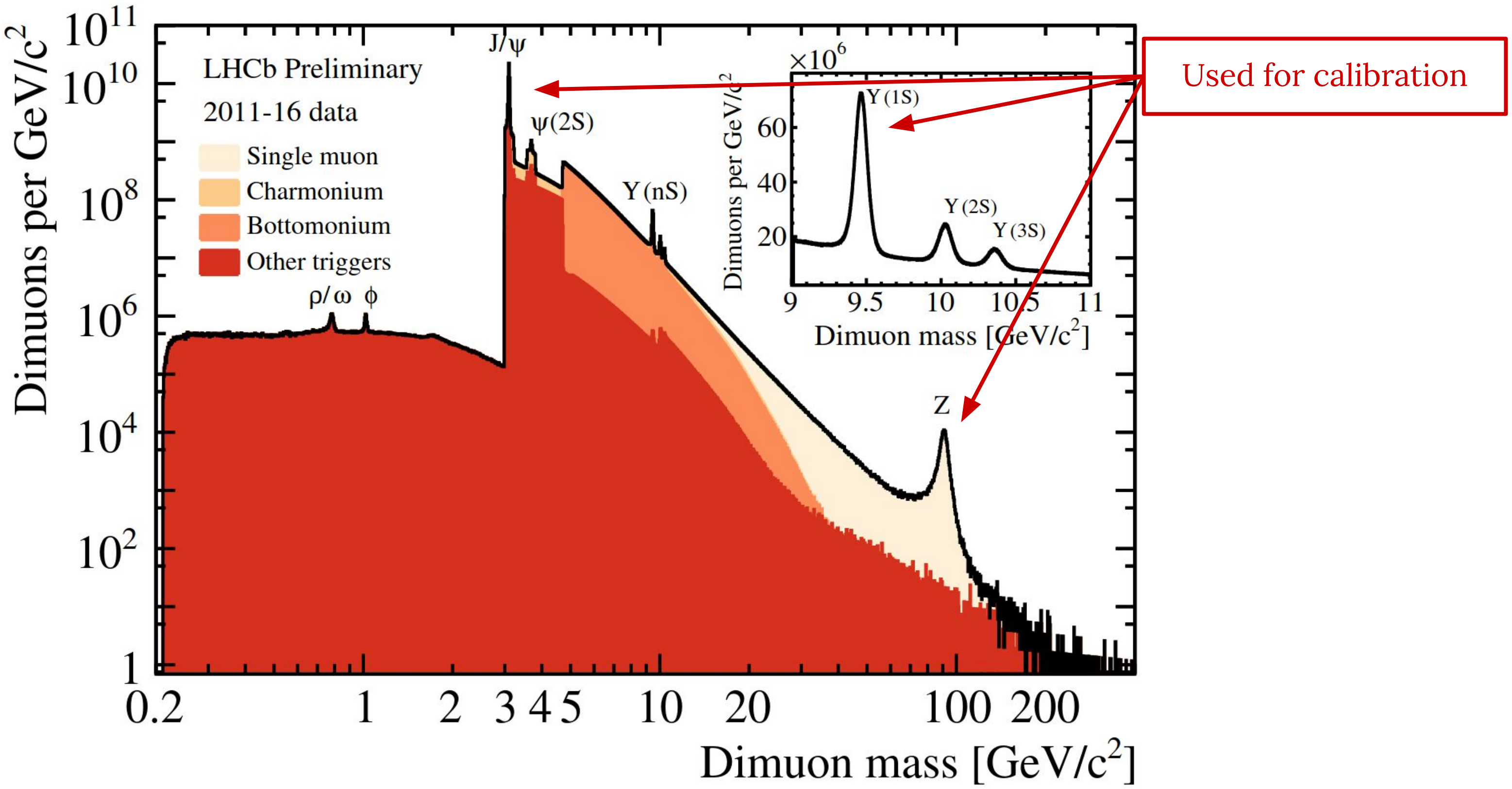
Very different binning schemes w.r.t. the Z

Calibrations using quarkonia



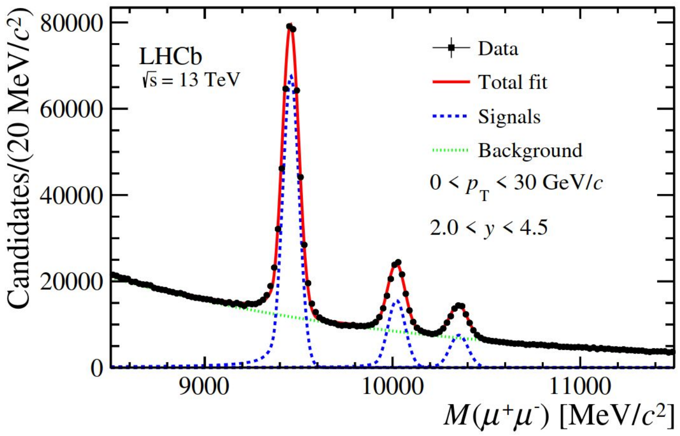
Overview of the dimuon samples (@ LHCb)

[LHCb-CONF-2016-005]

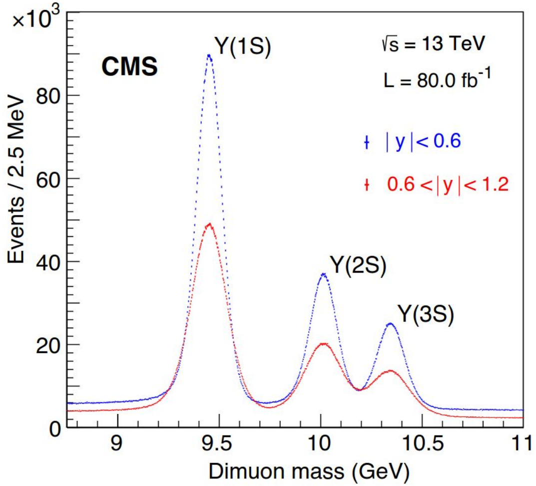


Upsilon resonances for calibration

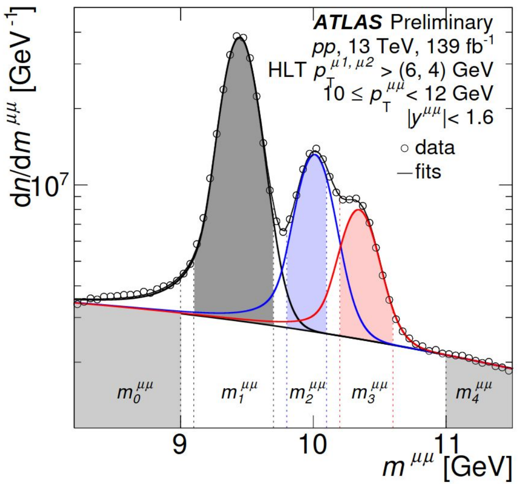
[JHEP 07(2018)134]



[PRL 121, 092002 (2018)]



[ATLAS-CONF-2022-023]



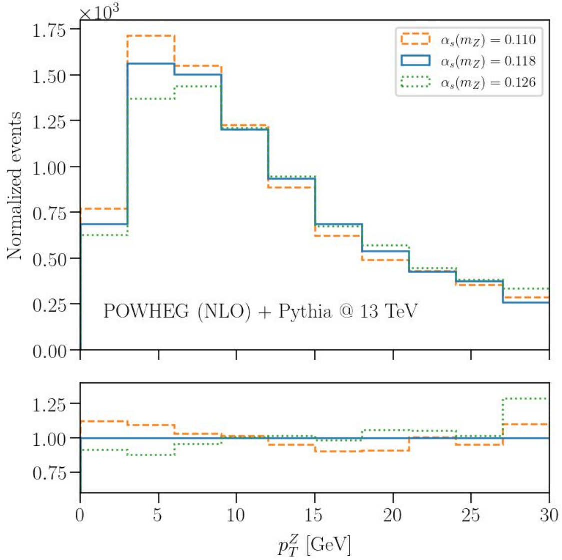
The strong coupling constant

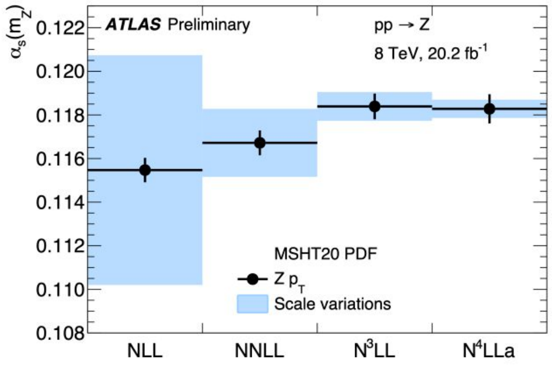
	Electromagnetism	Weak interaction	Gravitation	Strong interaction
Relative uncertainty	10^{-10}	10^{-7}	10^{-5}	10^{-2}

The least well known!

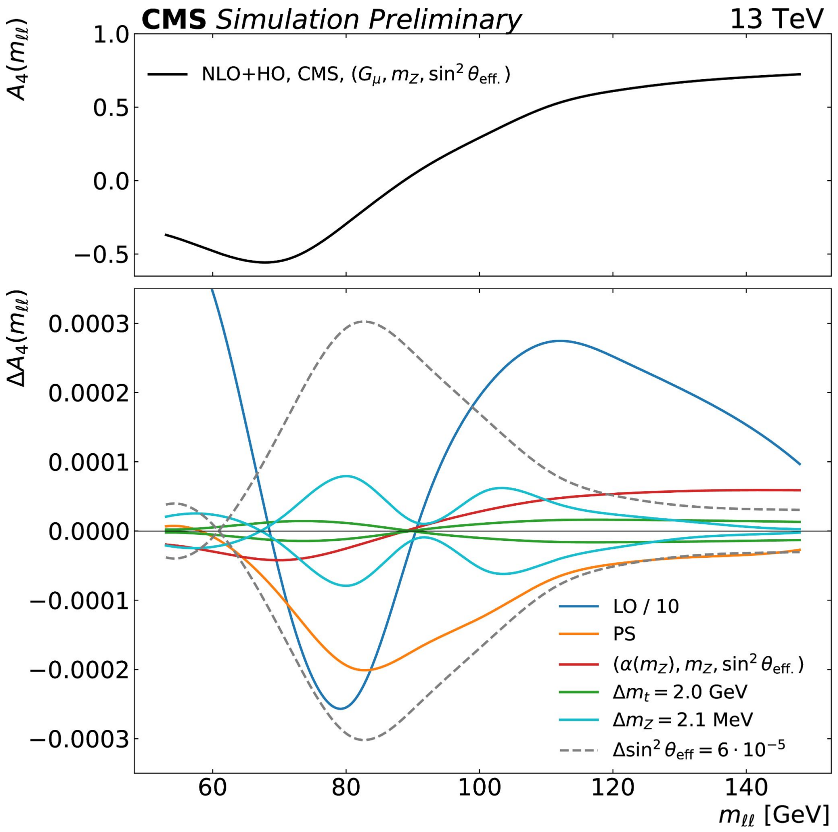
- Measurement by ATLAS [CERN-EP-2023-200 (submitted to Nature)] (Z-only), previous [JHEP 07 (2023) 85] (multijet)
- Measurement by CMS [JHEP 06 (2020) 018] (W and Z)
- No measurement yet at LHCb, but different possibilities are being explored
    - Find jet observables sensitive to the strong-coupling constant
    - Using the Z boson transverse momentum sounds challenging due to the partial reconstruction of the recoil

Dedicated talk on measurements at ATLAS and CMS by Massimo Corradi after the coffee break





Dependency of the weak mixing angle



[CMS-PAS-SMP-22-010]

Modelling the Z transverse momentum

[EPJC (2020) 80:251]