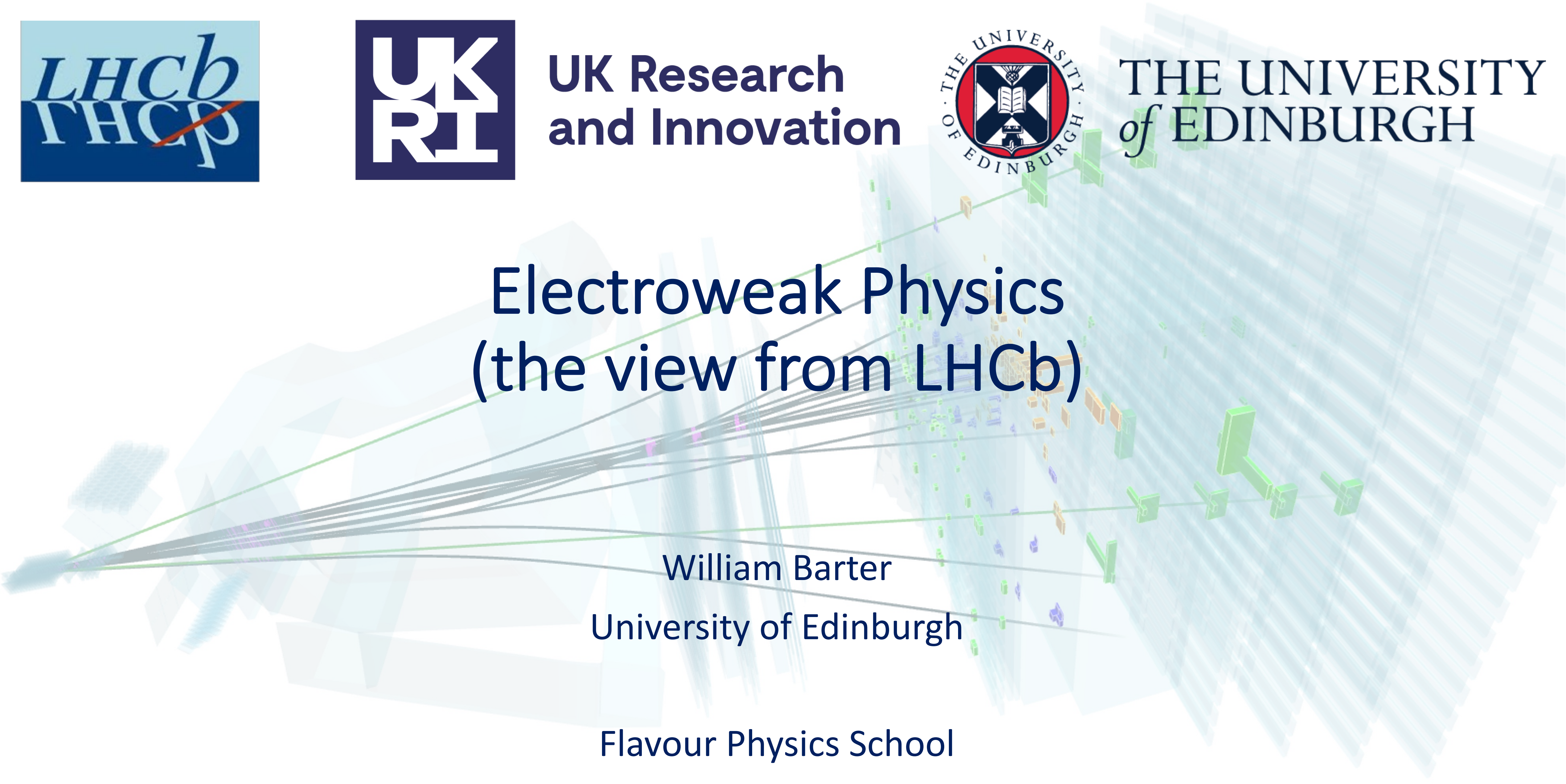

Electroweak Physics (the view from LHCb)

William Barter

University of Edinburgh

Flavour Physics School

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Today

- What are the goals of High Energy Physics?
- What is electroweak physics, and why should you care?
- What does a collision at the LHC look like?
- Probing QCD physics with Electroweak Bosons
- Probing fundamental EW physics

- Questions

Note: I will use examples from LHCb, but the content of what I say will be relatively general.

Please do interrupt with questions throughout.

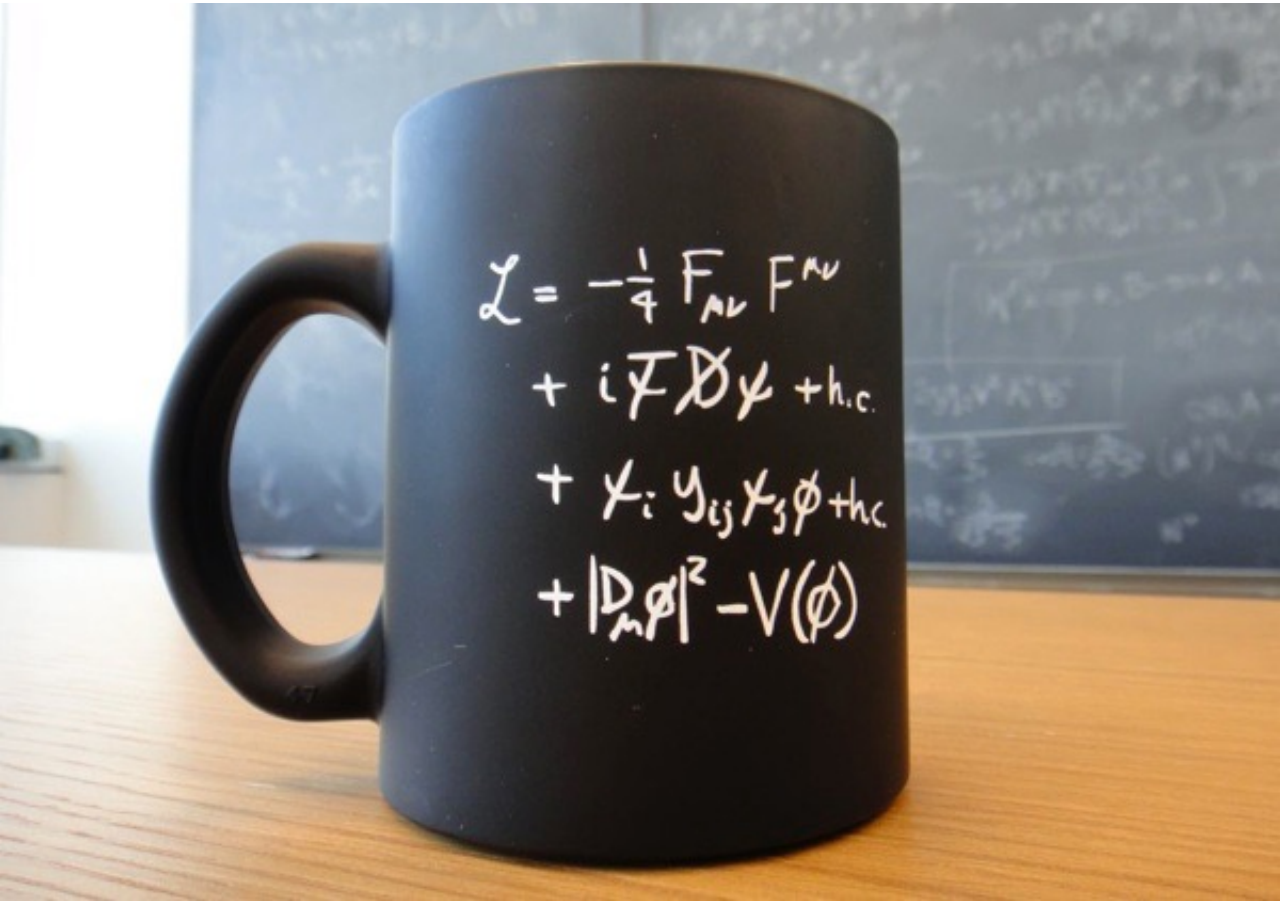
Disclaimer

- Lots of material on electroweak physics I will not have time to cover:
  - Multiboson physics
  - Angular Coefficients
  - Lepton Universality Tests with W and Z bosons
  - LEP measurements

- I will mostly talk about measurements from LHCb.
  - Though the underlying physics I present will be general, I will illustrate it using results from LHCb.

Introduction

Introduction



- High Energy Physics research studies the fundamental behaviour of nature:
  - Can we understand the already known forces of nature better? What are the values of the parameters in the terms on the mug? What are their consequences?
  - Can we find new physics that addresses major open questions? (e.g. the nature of dark matter) Are there new terms to add to the mug?
  - We often address these aspects at the same time.

What’s in the mug? - Standard Model Physics

- The Standard Model is made up of fermions and bosons.
  - We study the (heavy flavour) quarks and their interactions at LHCb.
- The vector bosons are the force carriers of electroweak physics, and of QCD physics.
  - We have the photon, the Z boson, 2 W bosons, and 8 gluons.
- The scalar Higgs boson completes the Standard Model.

What is Electroweak Physics?

- We separate out the W and Z boson from the field that gives them mass, and its excitation, the Higgs boson.
  - We label "Higgs physics" and "Electroweak" physics separately, despite key overlaps (and we will see these explicitly later).

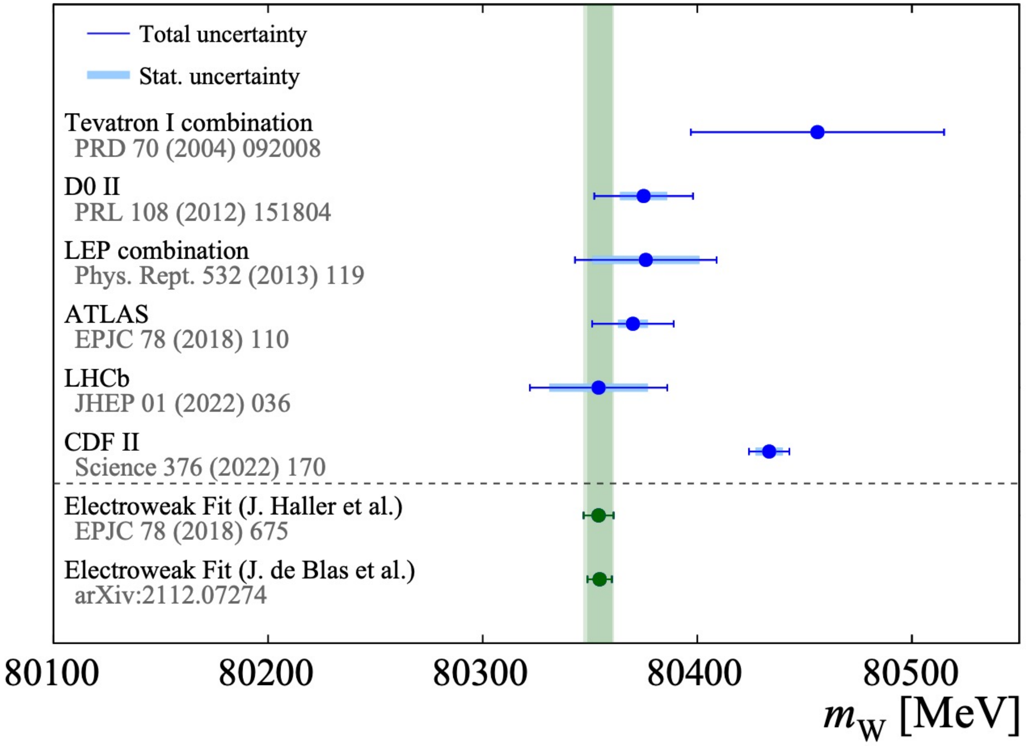
- Ultimately have one Standard Model, and there is considerable overlap between the different areas in it.
  - The physics of the CKM matrix is another perfect example of this.

Why should you care about Electroweak physics? I

- The EW sector is the highest fundamental scale we know of that we can access at colliders.
  - (Of course, one can argue that flavour offers access to much higher scales, and that the mystery of flavour is set at the highest scales)
- Measurements of EW physics let us access the SM Lagrangian directly and probe fundamental parameters of nature.
- Measurements with EW bosons let us understand our best theory of nature, better.

Why should you care about Electroweak physics? II

- High Precision measurements test the SM.
- Deviations from highly precise SM predictions potentially indicate the presence of BSM physics. (We will discuss how later)
- Two highly discrepant measurements of EW physics at the heart of our field at the moment:
  - CDF W boson mass – precision 9 MeV, discrepancy with SM is 80 MeV.
  - Muon g-2 – if you want to label this as EW.



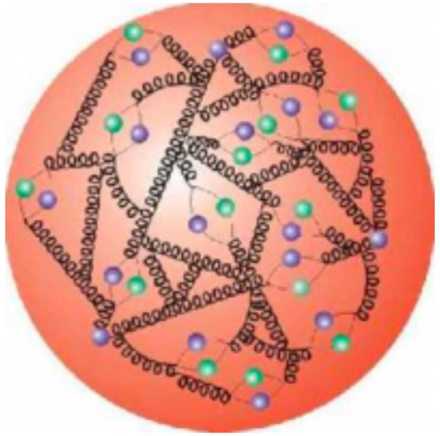
A note on language

- Electroweak physics v Physics with electroweak bosons

- We often label the fundamental physics (e.g. measurement of the W boson mass) as ‘electroweak physics’.
- We draw a subtle distinction with the physics we can do using electroweak bosons – e.g. measurements that probe QCD.
- This is similar to the difference between measuring e.g. a CP asymmetry, and measuring a Production Asymmetry for B meson production.

- We’ll talk about both today. Let’s try to understand this split a bit more.

Image from B. Heinemann



Collisions @ the LHC

- Collisions at the LHC access the whole of the Standard Model.

- Factorisation theorem (schematic):

Parton distribution functions (PDFs) describe the internal structure of the proton – these are QCD objects.

$$\sigma_{AB\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_a(x_1, Q^2) f_b(x_2, Q^2) \quad \sigma_{ab\to X}$$

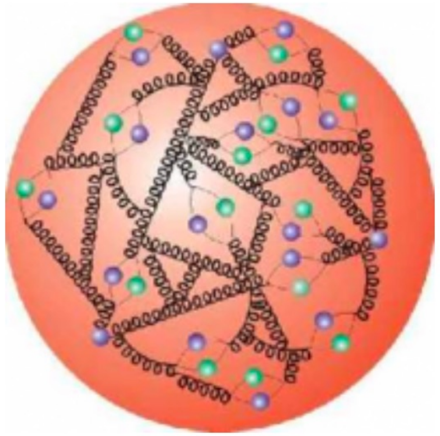
Fundamental partonic interaction / hard process

- Uncertainty on partonic cross-section is often small, but uncertainty on proton-proton cross-section can be much larger (via how well we understand the proton structure and PDF uncertainties).

- The LHC is a QCD-factory. QCD is inherently part of any measurement considering EW bosons at the LHC.

Image from B. Heinemann

Collisions @ the LHC



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Parton distribution functions (PDFs) describe the internal structure of the proton – these are QCD objects.

Fundamental partonic interaction / hard process

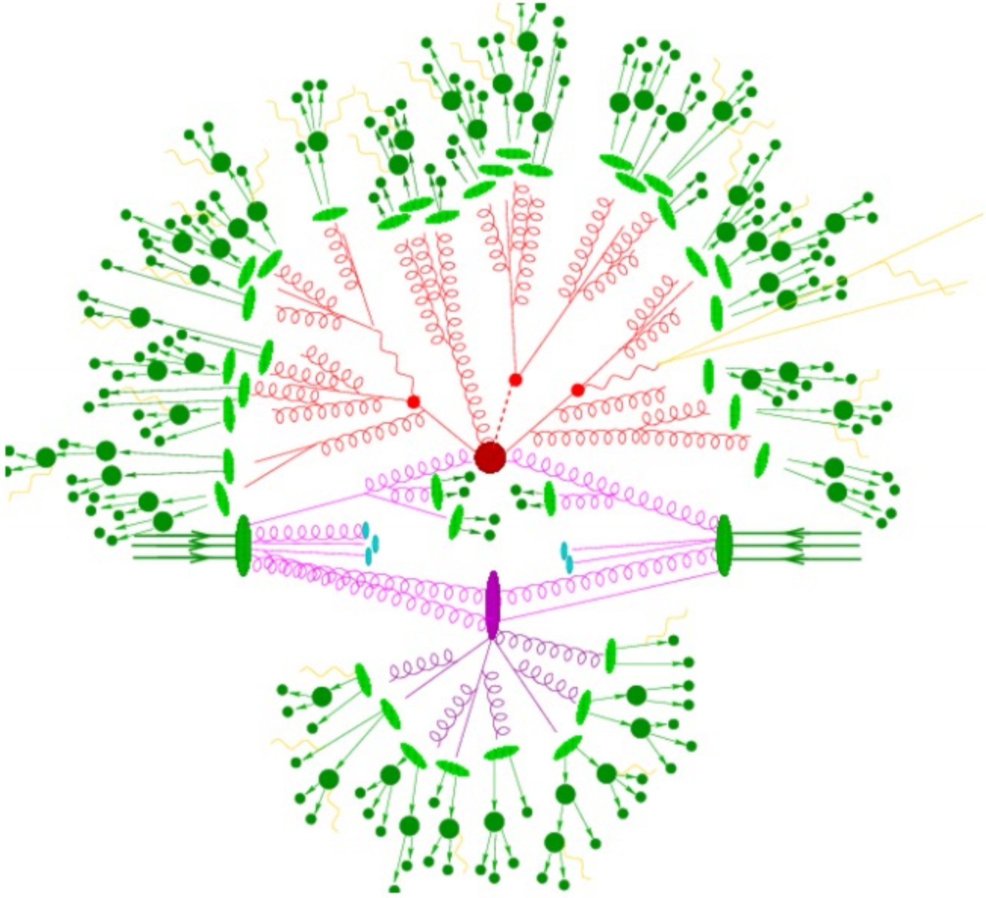
If you want to understand almost anything else at the LHC, then you need to understand QCD first.

Image from SHERPA collab.

Probing QCD Physics with W and Z bosons

QCD Physics – Probing the Strong Force

- Perturbative QCD leads to predictions for W and Z boson production rates with precision $O(\%)$, since α_s is large.
- Measurements of these rates can be used to make exciting studies on the modelling of:
  - e.g. internal proton structure (PDFs).
  - e.g. the evolution of the collisions.
- Relatively small datasets allow $O(1)\%$ precision.



Probing QCD and EW Physics with W and Z bosons

QCD Physics – Probing the Strong Force

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    - e.g. the evolution of the collisions.
- Relatively small datasets allow $O(1)\%$ precision.

EW Physics

- W and Z bosons also allow us to probe fundamental electroweak physics.
- Electroweak physics known at very good precision.
- Typically aiming for better than per mille level accuracy to provide exciting tests of the Standard Model.
- Need excellent understanding of QCD and the detector itself to achieve this precision experimentally.

Fundamental Differences between EW & HF ‘events’

- In most heavy flavour physics at the LHC, the proton-proton collision is typically “just” the source of the B-hadron under study.
    - What you care about is how the B-hadron decays, not how it is produced.
    - You can separate the production and the decay because the B-hadron is ‘long’-lived.
    - You mainly care about production from how it impacts e.g. the B-hadron pT.

- For EW bosons, they are intrinsically linked to the rest of the event.
    - How the EW boson is produced – the fundamental physics is linked directly to the overall event. EW bosons are not ‘long-lived’.

- The overall event is intrinsic to EW physics in a way that it isn’t for HF physics.
    - This has further implications, for example in “global event cuts”.

Some Numbers – how many events do we get?

- LHC Total Inelastic Cross-section (@13 TeV): 60 mb
- LHC Total W Cross-section (@13 TeV): 200 nb
  - In single muon channel: 20 nb
  - In ATLAS/CMS (muon): 8 nb
  - In LHCb (muon): 4 nb
- LHC Total Z Cross-section (@13 TeV): 54 nb
  - In dimuon channel: 2 nb
  - In ATLAS/CMS (dimuon): 0.8 nb
  - In LHCb (dimuon): 0.2 nb

Sums over W^+ and W^-

Integrated Lumi (@13 TeV):
ATLAS/CMS: 140/fb
LHCb: 6/fb

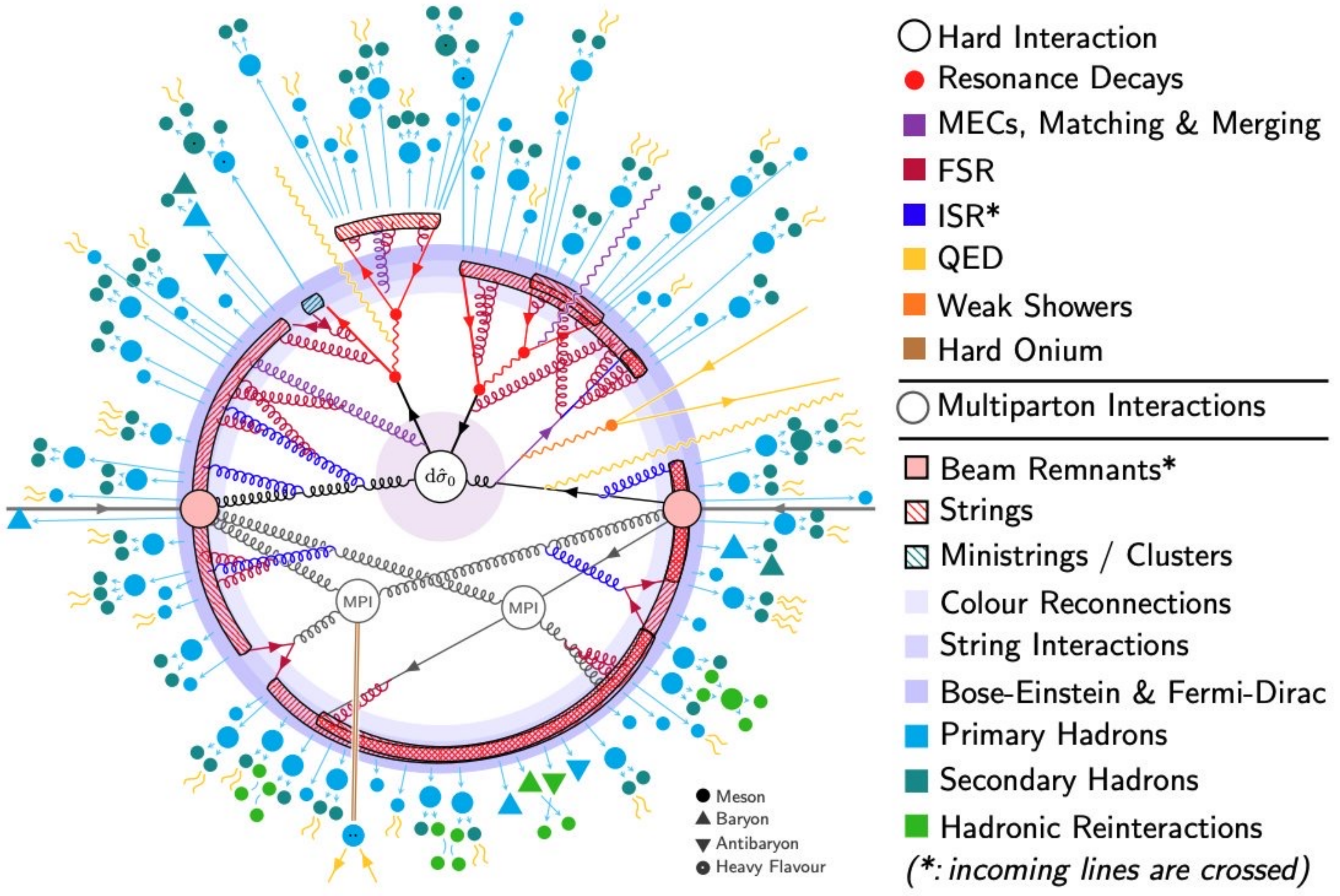
Enough events that studies will tend to be systematics limited.

Studying QCD with Electroweak Bosons

I’ll focus on LHCb measurements, but will discuss the broad goals of studying this physics at the LHC – the program of research I’ll discuss is very similar between the different LHC experiments.

Image from Peter Skands

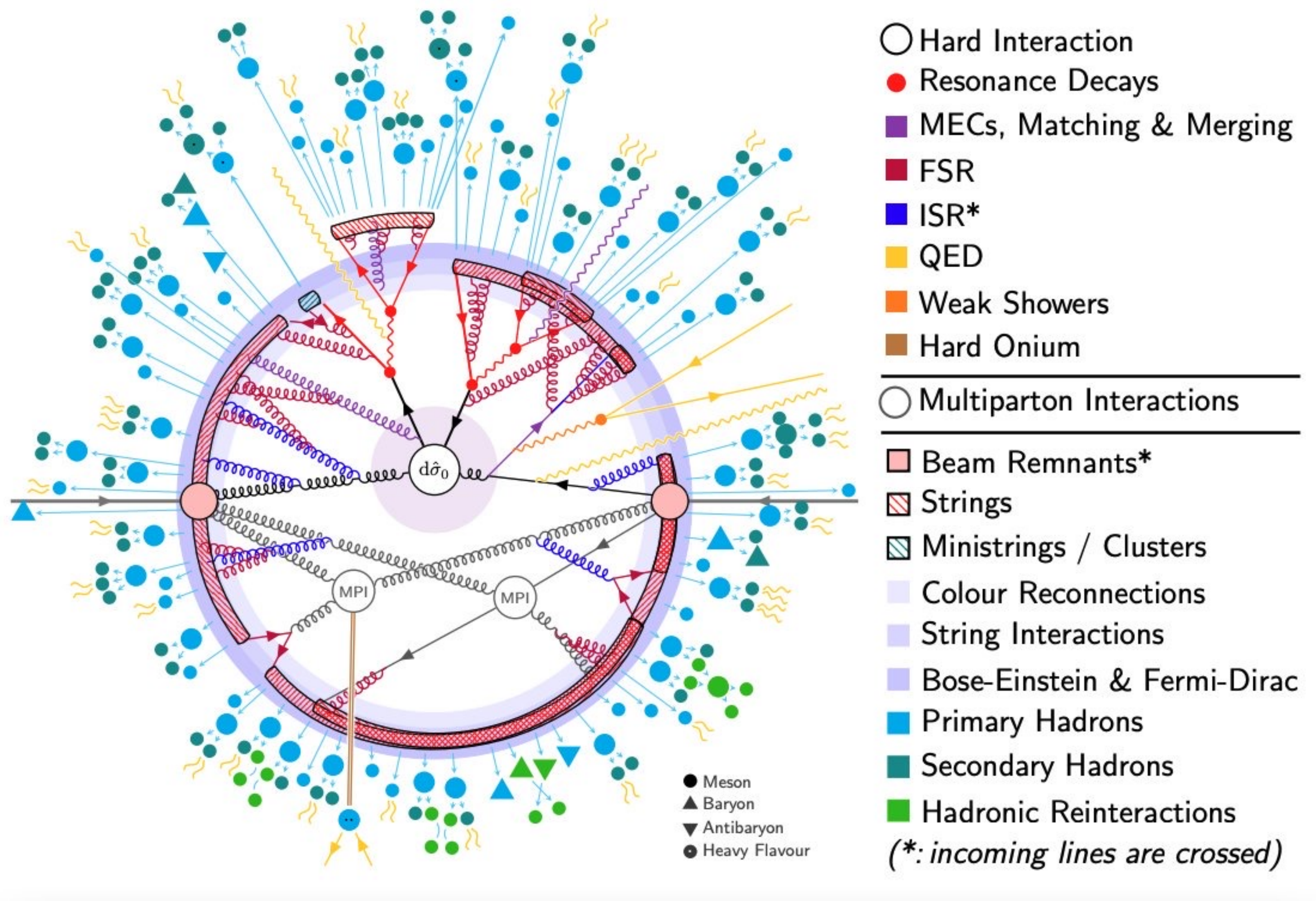
Summary of QCD I



- We separate collisions at the LHC into different pieces.
  - The hard interaction process is the highest energy part of the event.
  - It can be calculated using matrix elements.
  - The hard process then develops – parton showers, Final State Radiation.

Image from Peter Skands

Summary of QCD II



- We separate collisions at the LHC into different pieces.
  - Development of beam remnants – what happens to the rest of the proton.
  - The soft underlying event.
  - Multiple Parton Interactions.
  - Hadronisation + Decay

Getting Predictions

- We get meaningful predictions for hard process cross-sections via the factorisation theorem.

$$\sigma_{AB\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_a(x_1, Q^2) f_b(x_2, Q^2) \quad \sigma_{ab\to X}$$

- High-energy physics in the hard process (the partonic cross-section) calculated using perturbation theory for each process under consideration.
- Low-energy physics considered "universal" between processes, and considered part of the proton → captured using parton distribution functions (PDFs).

The hard process

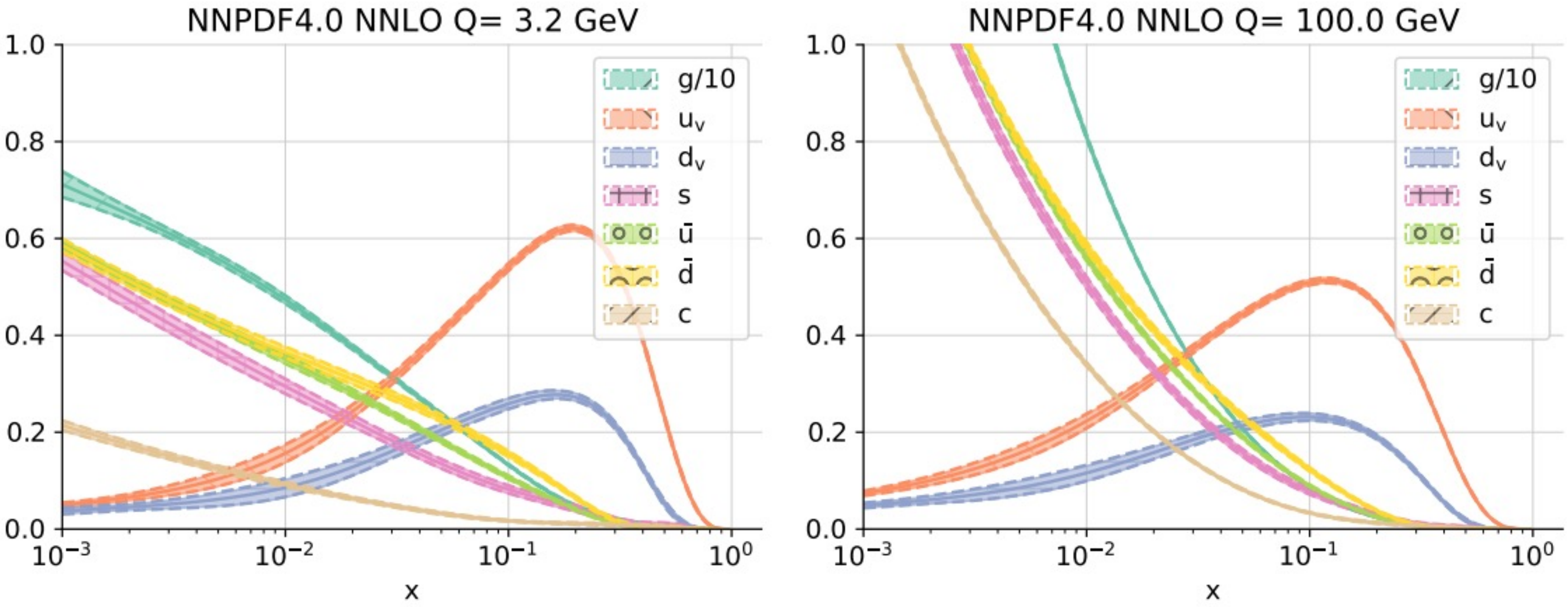
- Use Feynman diagrams to calculate the cross-section for some hard process.
  - Predictions made at fixed order: e.g. LO, NLO, NNLO etc.
  - Because α_s is large, we often need to consider multiple orders in perturbative QCD (pQCD).
  - Can also add in Electroweak corrections – e.g. additional emission.
  - Can also “resum” large logarithmic corrections to the process.
- Lots of different approaches including:
  - event generators (eg POWHEG, aMC@NLO interfaced with Parton Showers e.g. Pythia8)
  - numerical predictions (e.g. Resbos).
- Transverse momentum distributions at the LHC typically probe emission in QCD and modelling of QCD within the hard process.

$$\sigma_{AB\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_a(x_1, Q^2) f_b(x_2, Q^2) \quad \sigma_{ab\to X}$$

Proton Internal Structure

- Parton Distribution Functions capture the internal dynamics of the proton, and let us translate between partonic cross-sections and particle-level results.
- Determined as a function of x (fraction of proton’s momentum carried by parton) and Q^2 (energy scale).
- At Leading Order, PDFs just give the probability of finding the relevant parton in the proton. [This description becomes more complicated at NLO.]
- Not able to get a first principle prediction of the PDFs – instead rely on global fits to data that probe them. Multiple groups provide these (eg MSHT, CT, NNPDF…)
- Can however evolve the PDFs from one energy to another energy, using DGLAP equations – these are pertubative equations that describe how partons “split” as the energy scale changes.

Proton Internal Structure

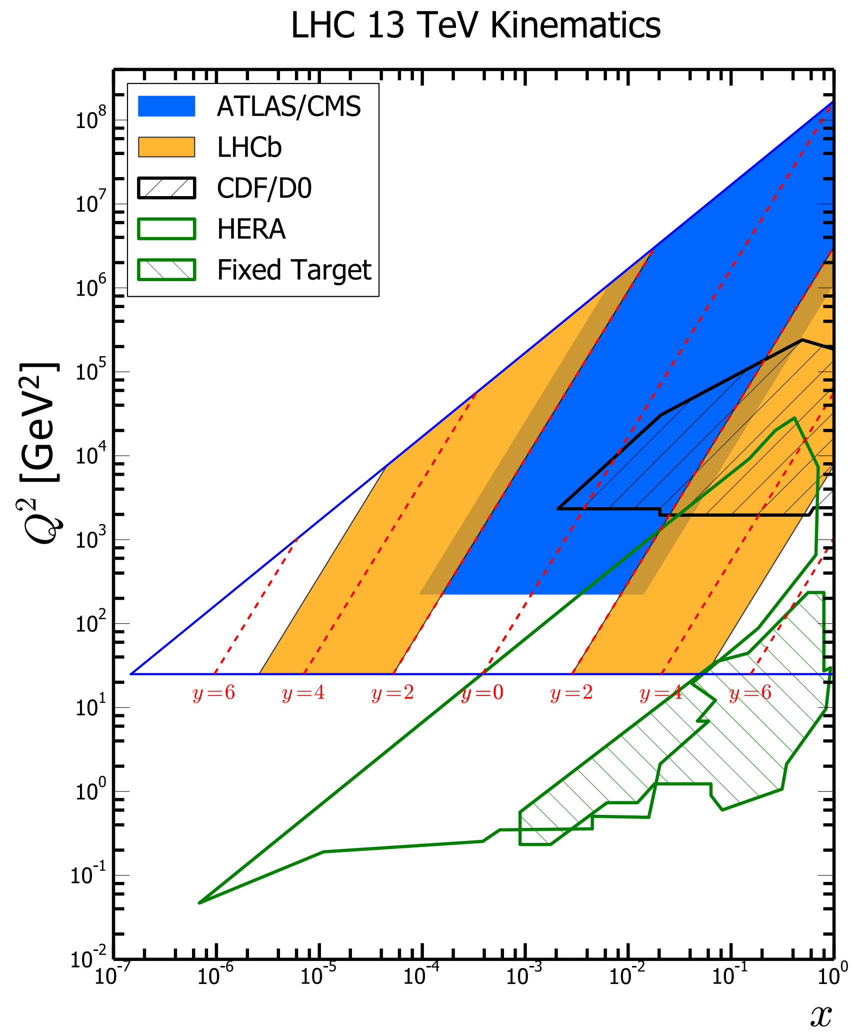


Probing the Proton Internal Structure

- To produce a particle of mass *m* at rapidity *y* [at Leading Order, with no pT]:

$$y \equiv \frac{1}{2}\log\frac{E+p_z}{E-p_z}\,; \quad y = \frac{1}{2}\log\frac{x_1}{x_2}\,; \quad x_{1,2} = \frac{m}{\sqrt{s}}\,e^{\pm y}$$

- Rapidity distributions most sensitive to PDFs since they directly probe *x.*
  - You can visualize this by seeing that rapidity increases when there is an imbalance in the initial state momenta.
- Note that LHCb probes different region of phase space to ATLAS+CMS.



A General Statement

Accurate modelling of QCD at the LHC is crucial if we are to learn fundamental physics at the collider. Electroweak bosons offer an excellent environment to test and refine this modelling – both for the hard process, and for PDFs – because Electroweak bosons are relatively well understood.

Since the partonic cross-section for Electroweak boson processes is known very well (often to better than 1% precision), Electroweak boson processes can provide crucial constraints on the PDFs.

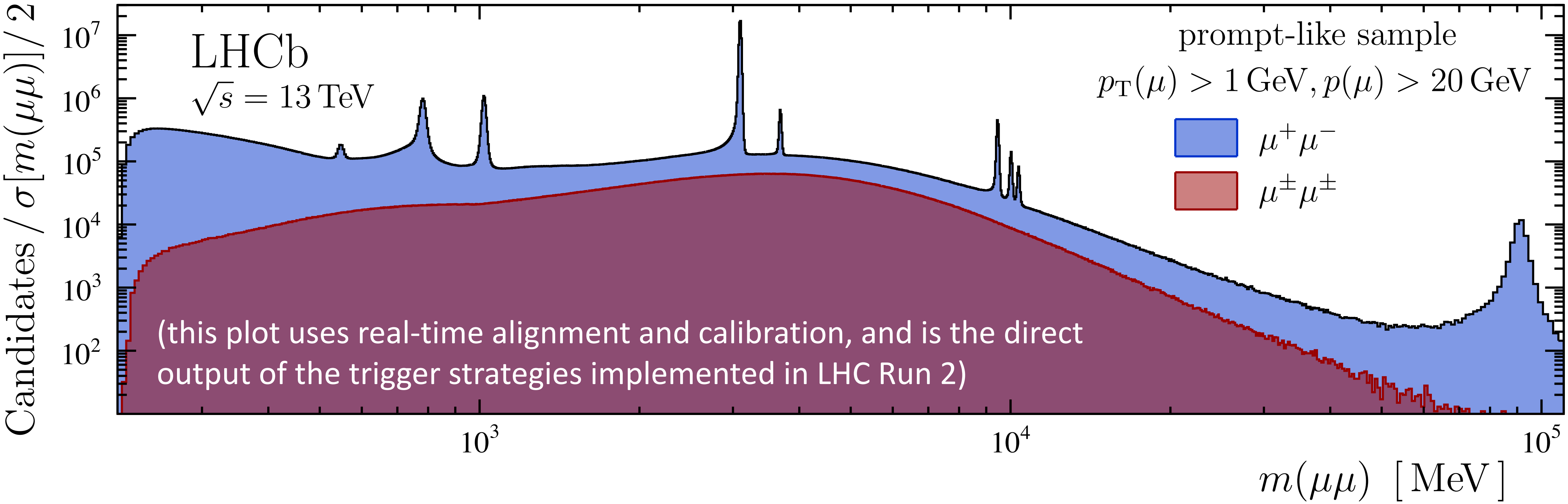
$$\sigma_{AB\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_a(x_1, Q^2) f_b(x_2, Q^2)\ \ \sigma_{ab\to X}$$

measure this

infer this

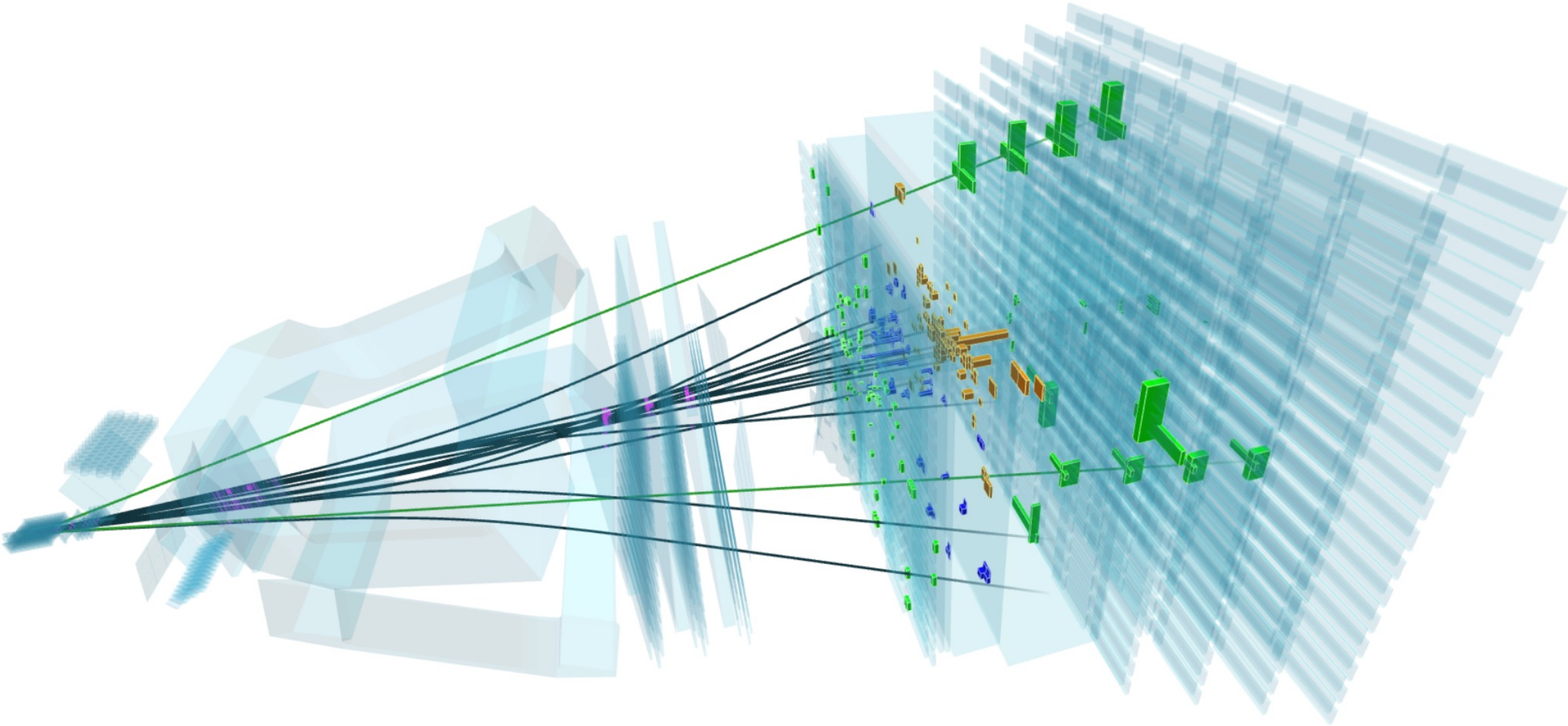
calculate this

And now: data



(this plot uses real-time alignment and calibration, and is the direct output of the trigger strategies implemented in LHC Run 2)

What an event at LHCb looks like!



Measuring W and Z bosons at LHCb

- Select events based on final state kinematics.
- Define a fiducial acceptance based on LHCb angular coverage:

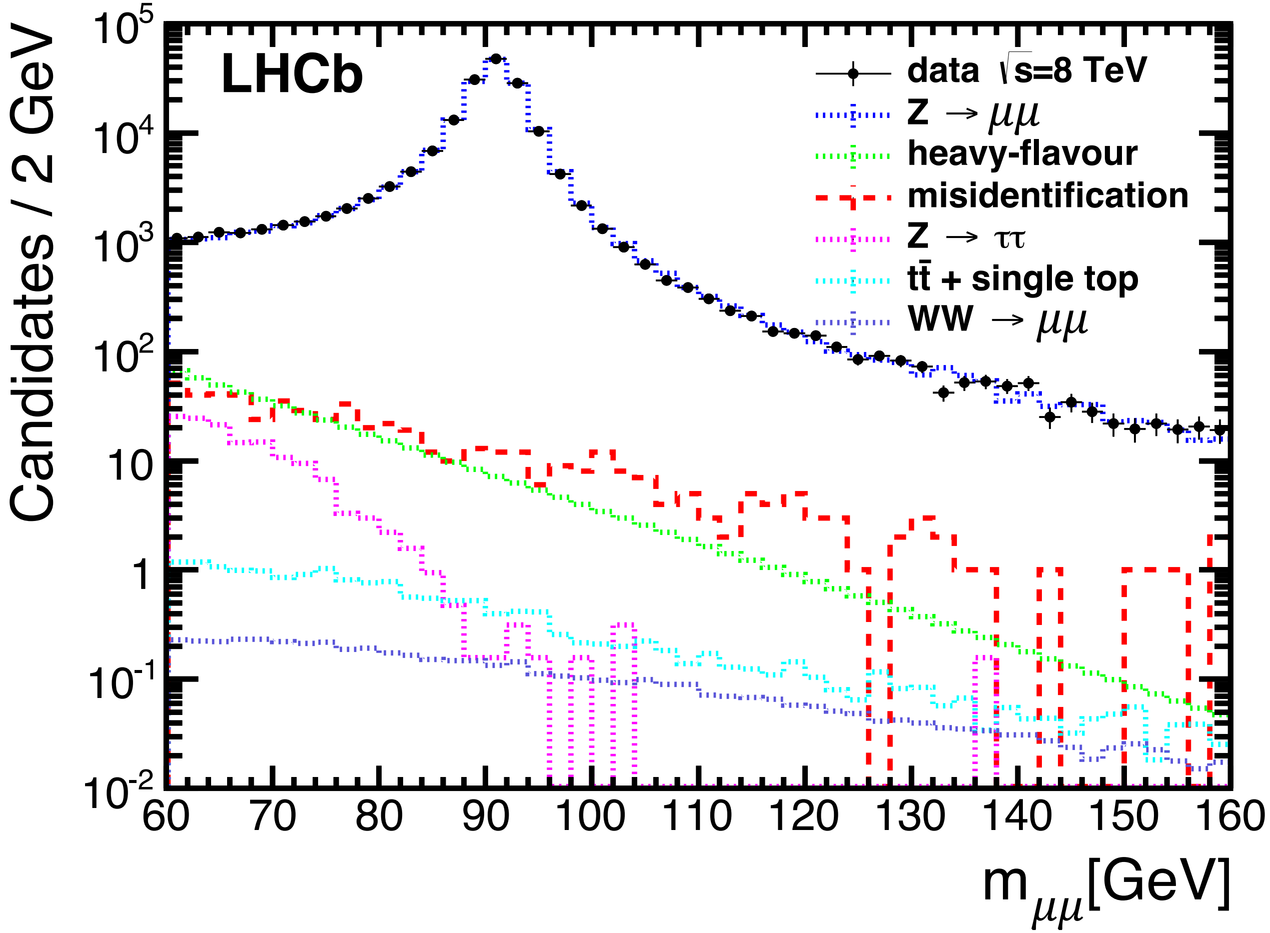
$$p_T(\mu) \;>\; 20\ \text{GeV};\; 2.0 \;< \eta(\mu) < 4.5$$

$$\text{Z: } 60 < m(\mu\mu) < 120\ \text{GeV}$$

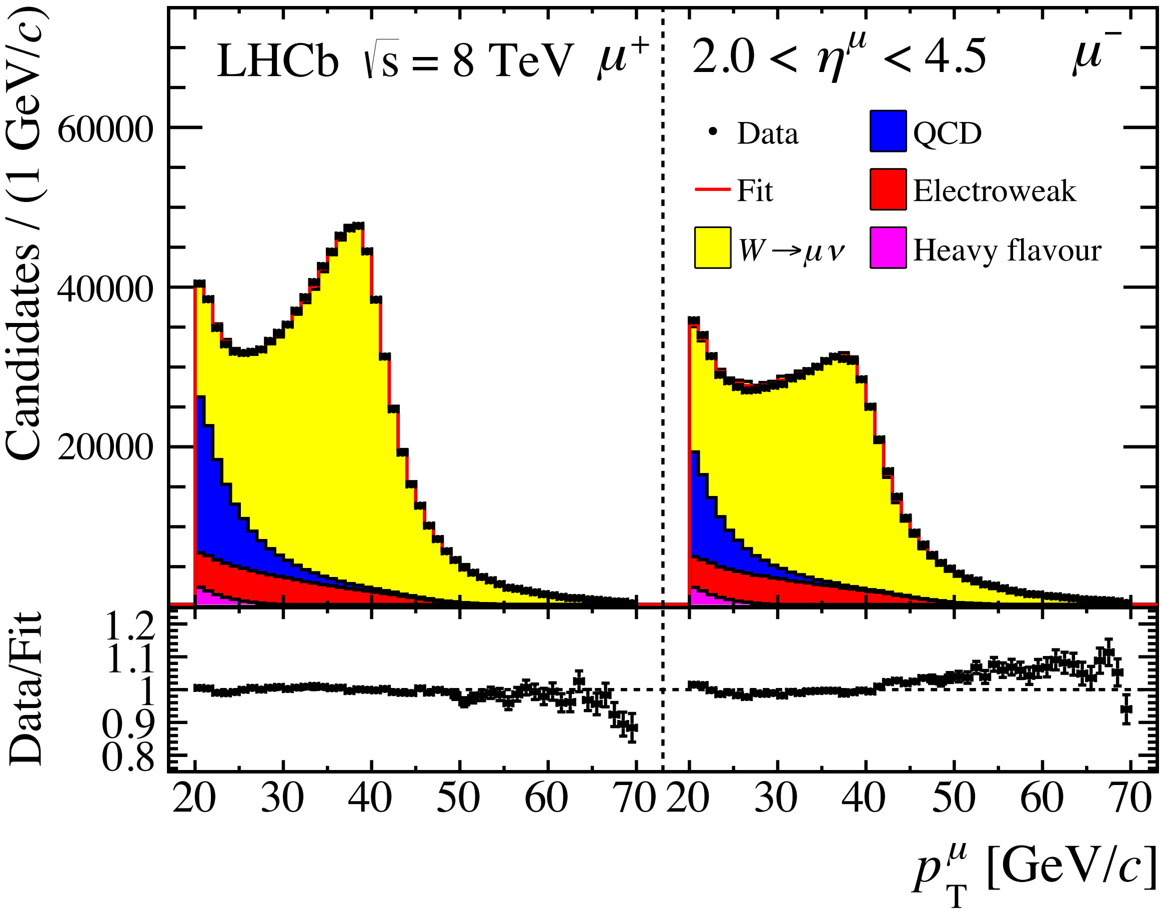
- Also place standard reconstruction quality requirements, require events are responsible for trigger selection.
- For muons produced in the decay of EW bosons, momentum resolution is $\sim 1\%$.
- Similar requirements made at ATLAS, CMS.

LHCb collab., JHEP 01 (2016) 155
LHCb collab., JHEP 11 (2015) 190

Measuring W and Z bosons at LHCb



Z selection: >99% purity

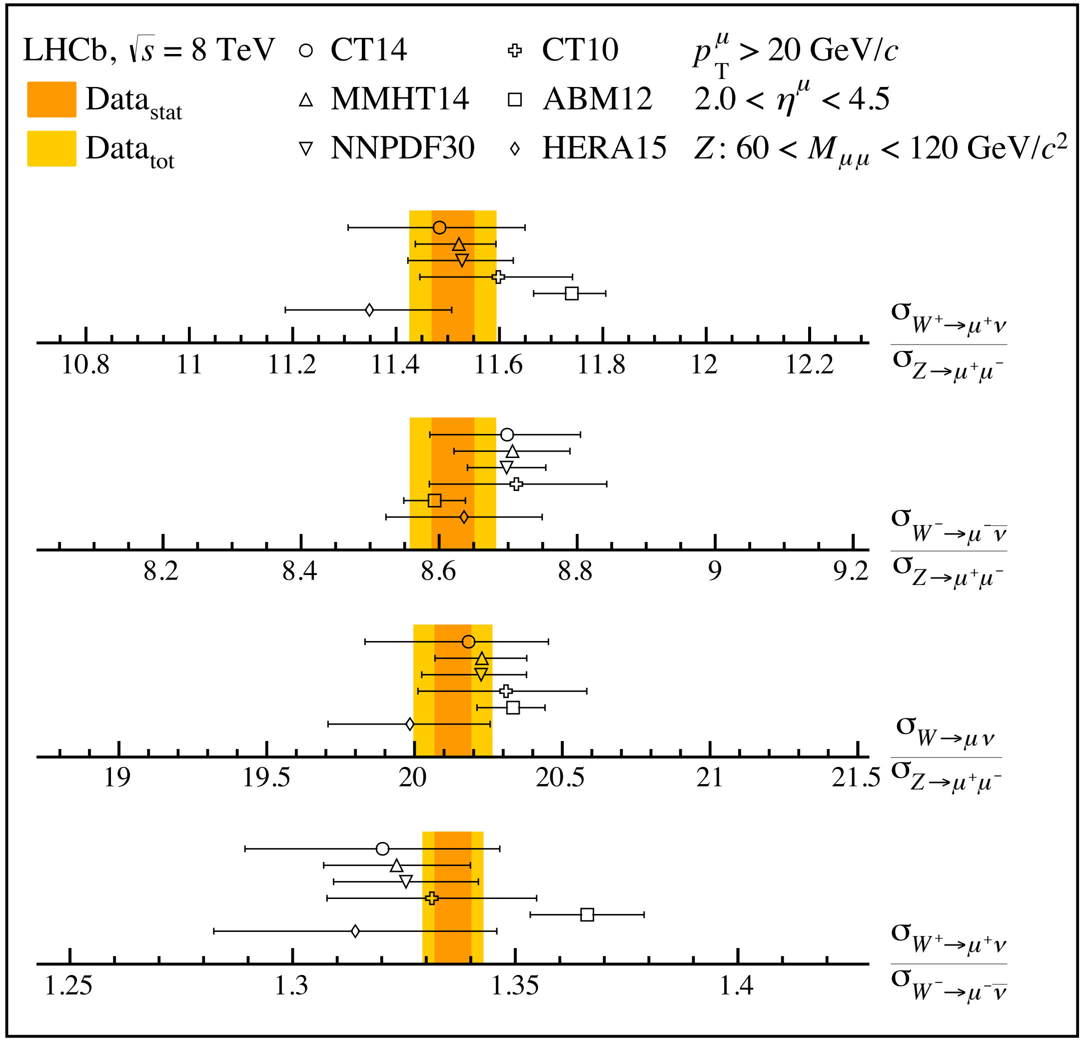


W selection: ∼80% purity

LHCb collab., JHEP 01 (2016) 155

W, Z boson fiducial cross-sections

- Cross-section ratios for W and Z boson production in the forward LHCb acceptance.
- Some ratios extremely sensitive to PDFs, others have PDF effects cancelling - allowing a more precise test of pQCD in the hard collision.
- Among the most precise measurements of W and Z boson production cross-sections at the LHC.
    - Systematics < 1% (without lumi); 1.3% (with lumi)

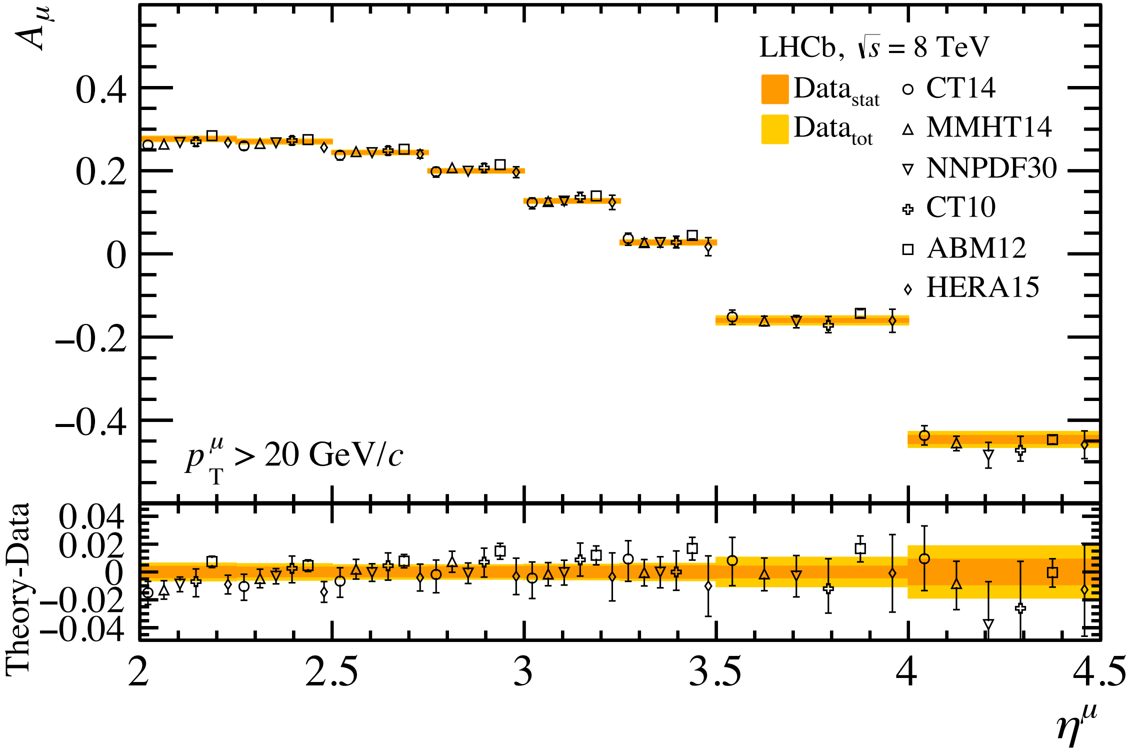


LHCb collab., JHEP 01 (2016) 155

W charge asymmetry

- Measure the relative cross-sections for W^+ and W^- production where the decay muons are produced inside LHCb.
- $A = \dfrac{\frac{d\sigma_{W+}}{d\eta} - \frac{d\sigma_{W-}}{d\eta}}{\frac{d\sigma_{W+}}{d\eta} + \frac{d\sigma_{W-}}{d\eta}}$
- Extremely sensitive to ratio of up and down PDFs.
- Variation with the lepton pseudorapidity arises from PDFs and V-A structure of the weak force.

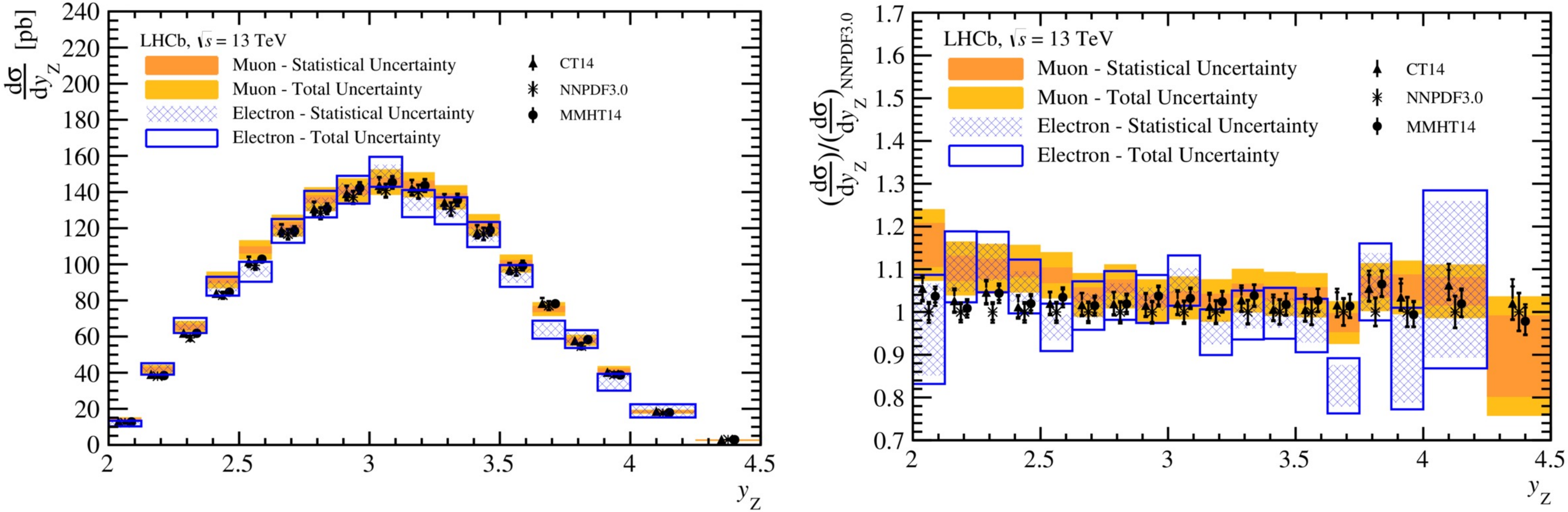
$$\eta \equiv -\ln(\tan(\frac{\theta}{2}))$$



LHCb collab., JHEP 09 (2016) 136

Z boson rapidity

- Also offers sensitivity to quark PDFs.
- Distribution also shows significant dependence on angular structure of Z boson decays.

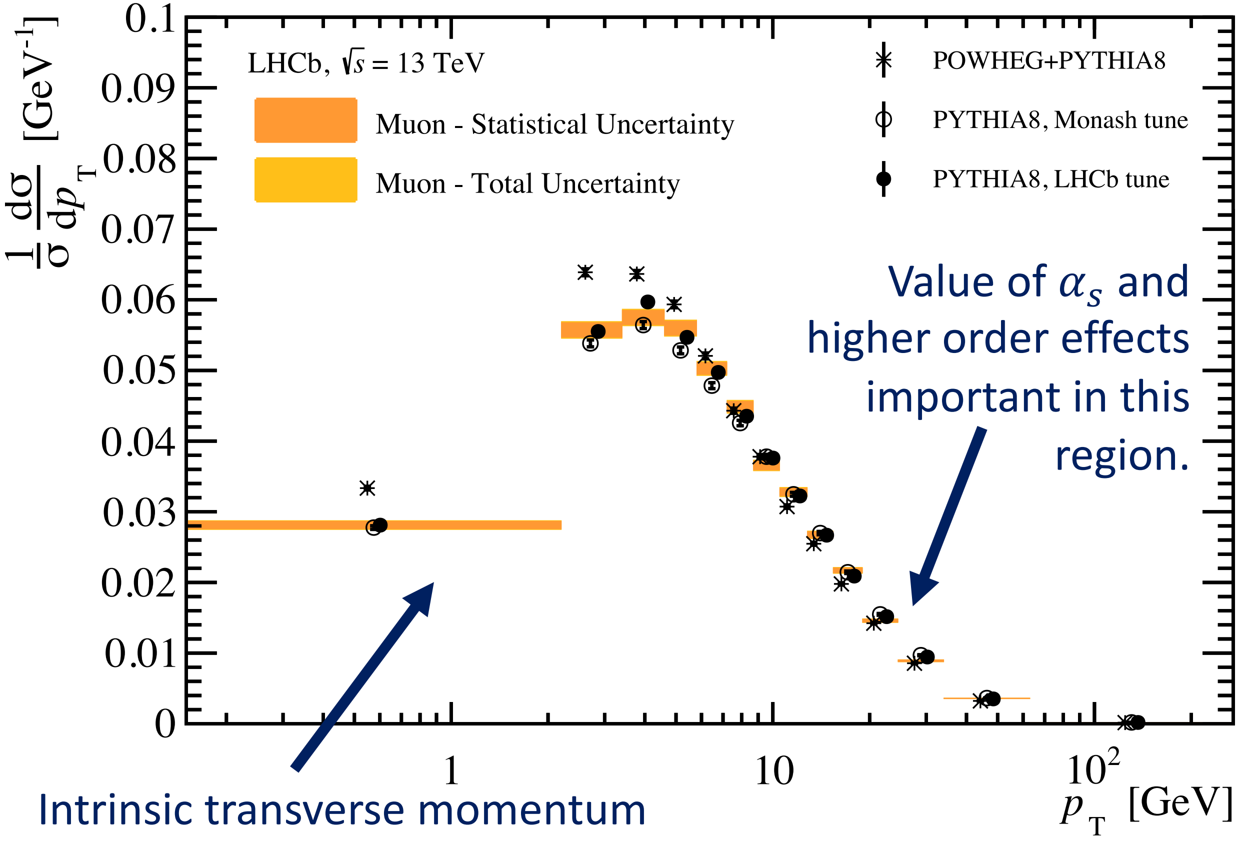


Note: Lepton cuts sculpt this distribution. Extrapolations to remove these cuts allow comparisons with ATLAS/CMS.

LHCb collab., JHEP 09 (2016) 136

Z boson pT

- Measurements of p_T and similar variables probe our understanding of QCD in the hard interaction
- Here LHCb measures the p_T distribution of forward Z bosons.
- PYTHIA 8 (LO in perturbative QCD) performs much better than POWHEG BOX (NLO) when interfaced with a parton shower.
- Also see good agreement with RESBOS (NLO+NNLL). Similar results seen at ATLAS and CMS.



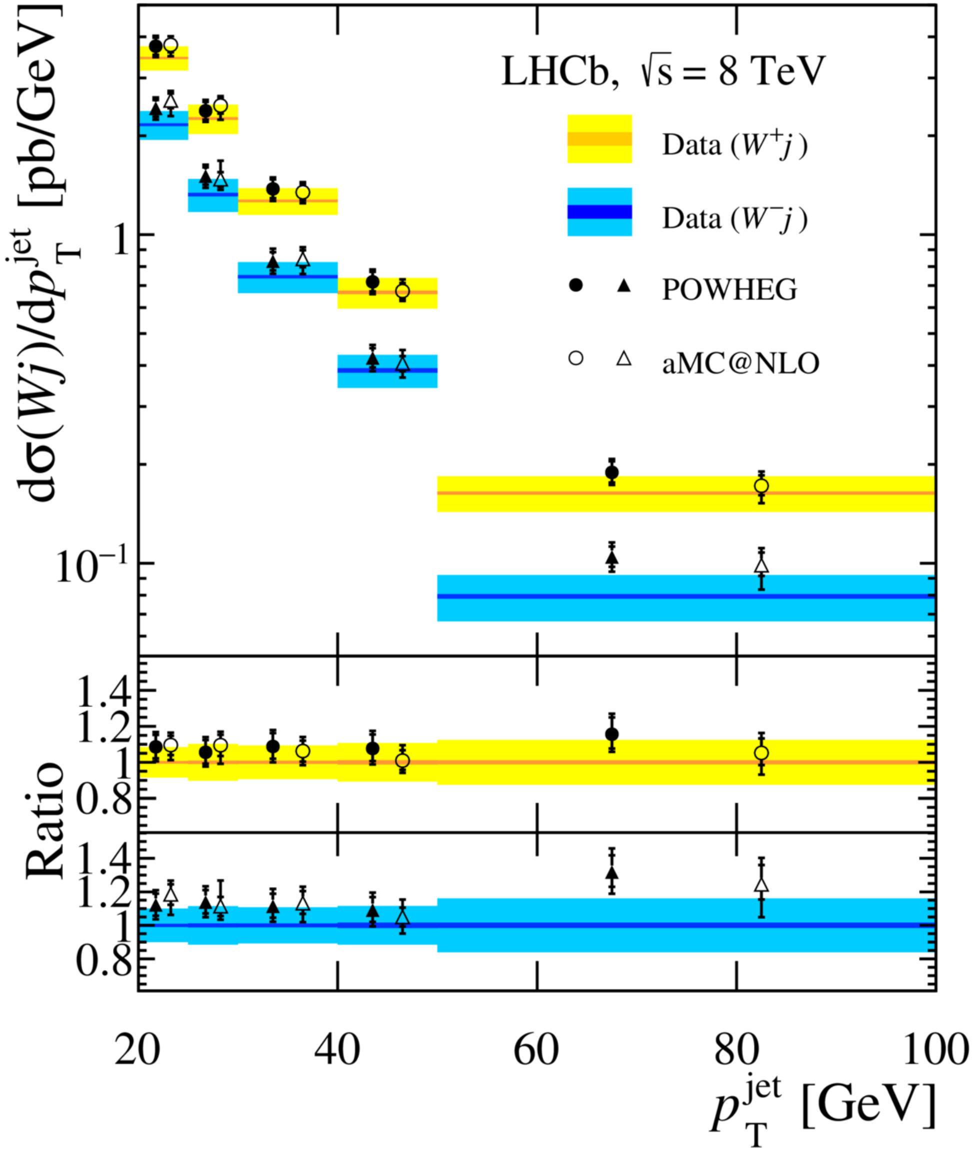
Value of α_s and higher order effects important in this region.

Intrinsic transverse momentum carried by quarks important in this region

LHCb collab., JHEP 05 (2016) 131

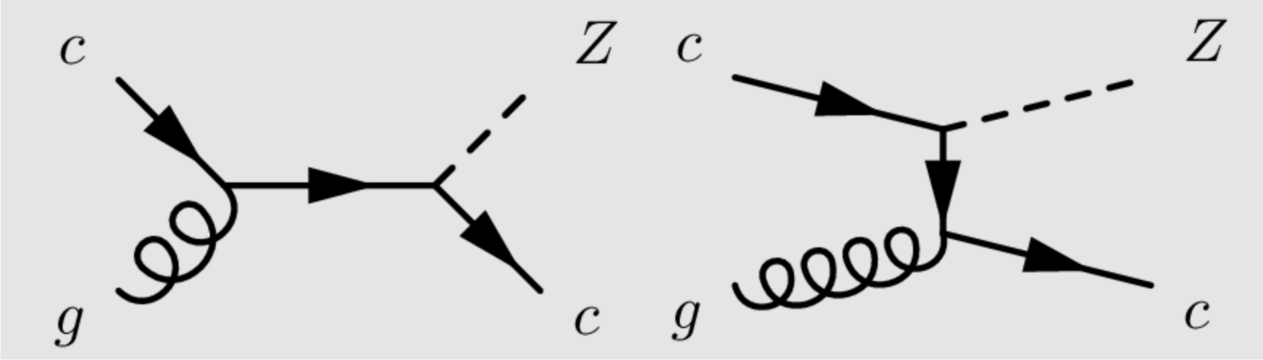
W, Z + jets

- Measure jet production in Z boson events.
- Probes events where the Z recoils against another parton - tests modelling of additional emission in the hard process.
- Compare to theoretical predictions – good agreement with predictions.



LHCb collab., PRL 128 (2022) 082001
NNPDF collab., Nature 608 (2022) 483

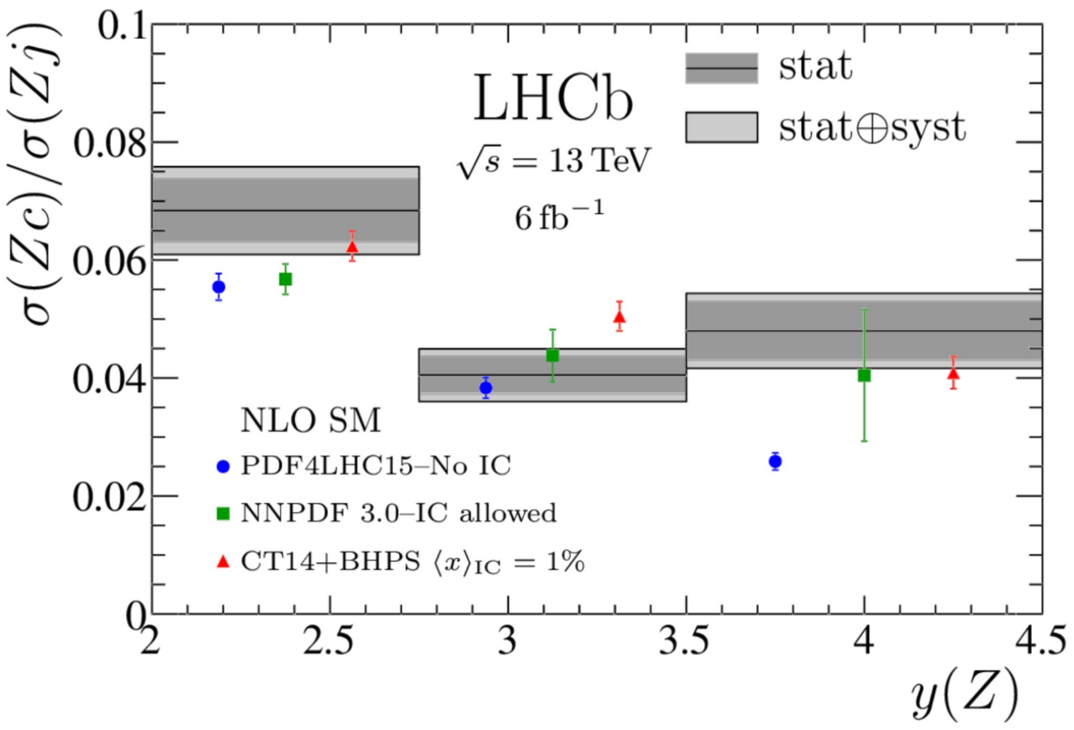
Z + charm-jet



- Tests intrinsic charm content in the proton – does the proton have "valence-like" charm content?

- Excess of events at high rapidity suggests presence of charm.

- Confirmed in follow-up global PDF analysis from NNPDF.



Summary – measuring QCD with EW bosons

- Measurements of electroweak boson production cross-sections (and related quantities) typically probe the modelling of QCD:
  - In the hard process – via the emission of additional partons.
  - Inside the proton – testing the proton's internal structure.

- Percent-level accuracy sufficient for these studies, since the theory is dependent on pQCD, typically at O(α_s^2), and $\alpha_s^2 \sim 0.01$.

Studying Fundamental EW Physics with Electroweak Bosons

Once again, I’ll focus on LHCb measurements and plans, but will discuss the broad principles of Electroweak Physics, and mention other important measurements.

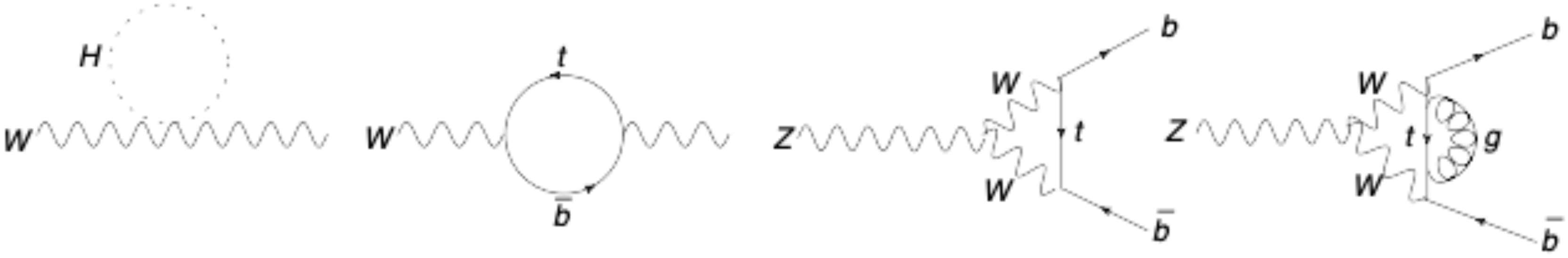
Fundamental EW Physics

- W and Z boson physics also probes fundamental interactions as described in the Standard Model Lagrangian.
- Today: will focus on W boson mass and the weak mixing angle, since extensive programs at the LHC (ATLAS, CMS, LHCb) seeking to measure these.
  - The Z boson mass is known from LEP with an order of magnitude better precision than the W boson mass.
- High precision necessary in order to be competitive – e.g. W boson mass currently known at precision of 1 part in 10^4.
  - To reach the necessary precision requires excellent modelling of both QCD, and detector performance.
  - This is not a small task: remember that when looking at QCD, we were only testing it at O(1%).

Feynman diagrams from here

Fundamental EW Physics

- You can set the entirety of the electroweak sector (at leading order) with three parameters (e.g. G_μ, m_W, m_Z or G_μ, α, m_Z or g, v, α or…).
  - e.g. at leading order $\sin^2\theta_W = 1 - {m_W^2}/{m_Z^2}$; $m_w = \frac{1}{2}gv$
  - Higher order effects then provide additional corrections – e.g. Higgs boson and top quark are important here.

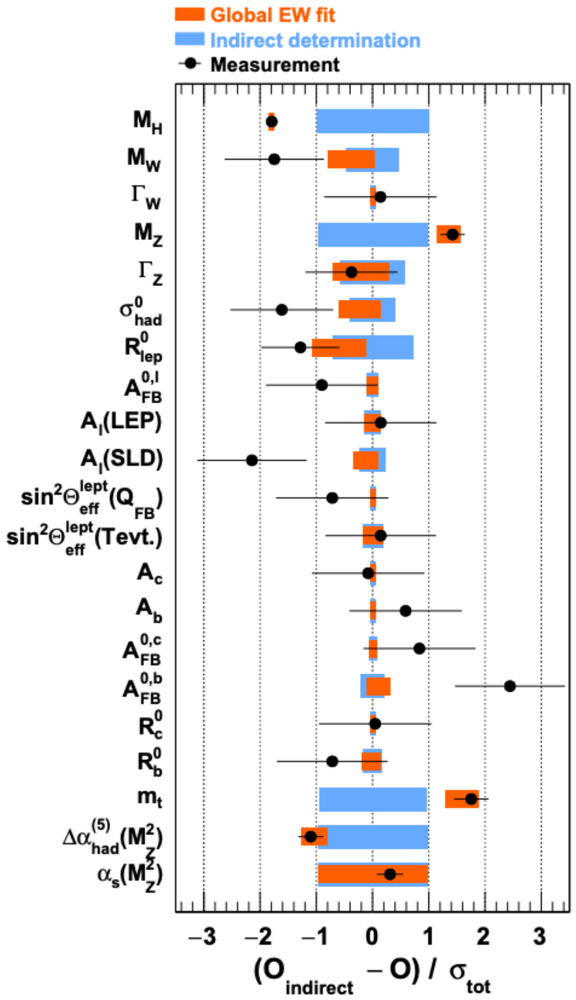


gFitter group, EPJC 78 (2018) 675

Fundamental EW Physics – global EW fit

Note – does not include CDF mW

- The Standard Model relates behaviour throughout the electroweak sector – e.g. the couplings of the W and Z boson are fundamentally related to the masses of the particles.
- This means that we can over-constrain the electroweak sector through related measurements.
- Global EW Fit compares directly measured values to “indirect measurements” (i.e. measurements of other quantities).
- If the Standard Model is valid, then we should get a consistent picture; New Physics would appear as discrepancies. Before CDF m_W measurement, everything seemed broadly consistent.
- Knowledge of W boson mass typically limits the interpretation of EW fit in terms of New Physics sensitivity.

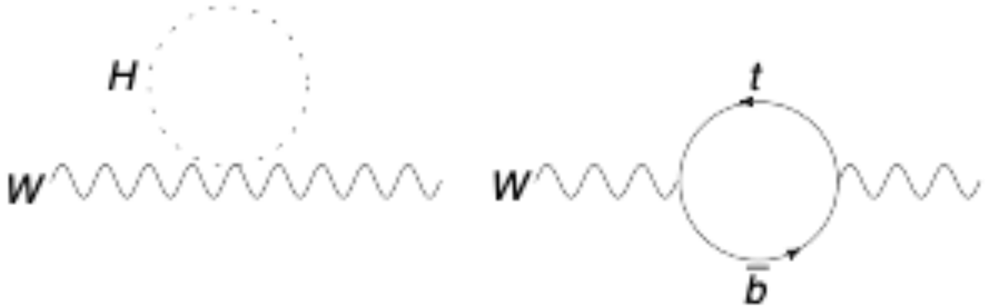


gFitter group, EPJC 78 (2018) 675

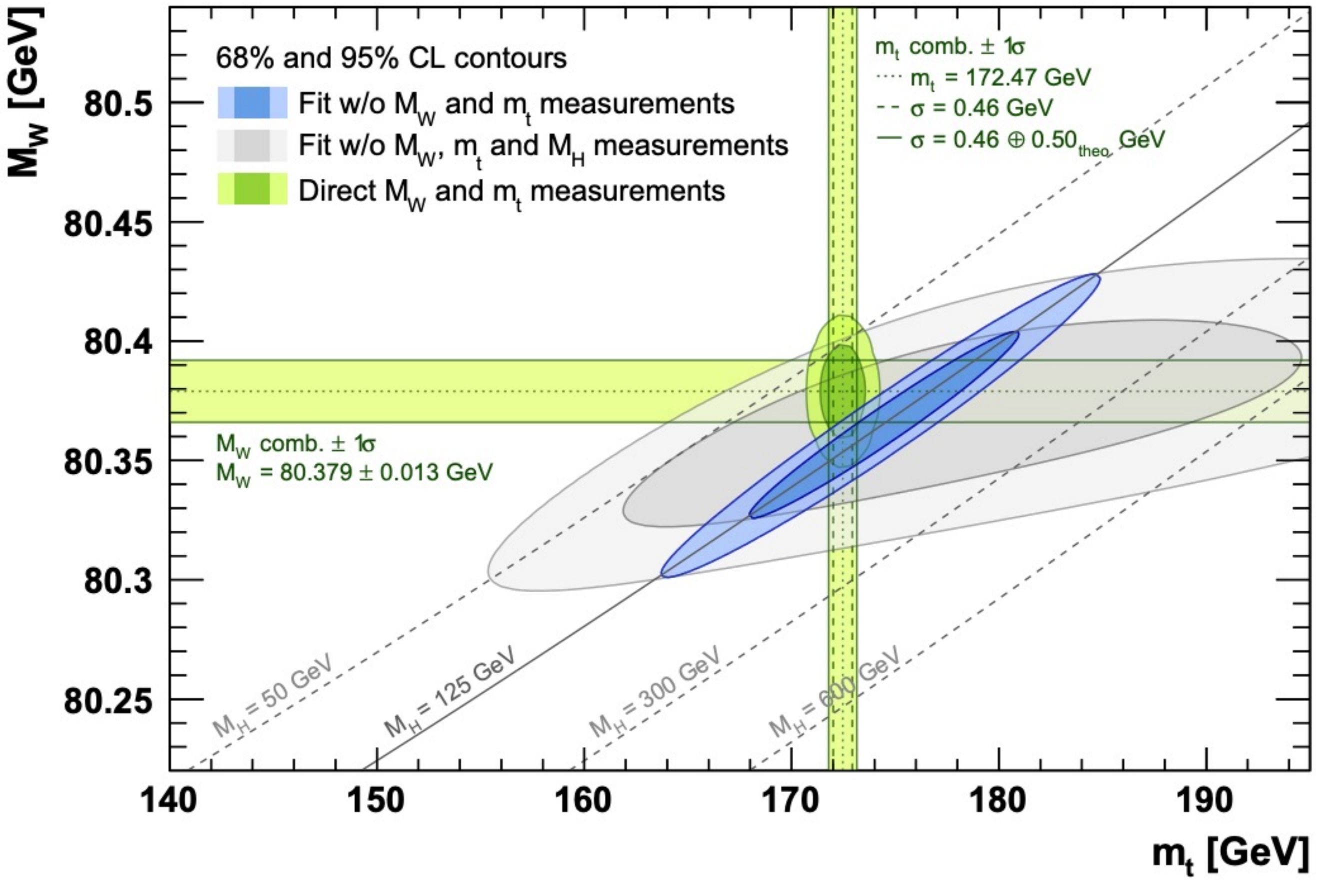
Fundamental EW Physics – global EW fit

$$m_W^2\left(1-{m_W^2}/{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\,\frac{1}{1-\Delta r(m_t,m_H,\dots)}$$

where Δr captures loop corrections.



Electroweak physics
IS
Higgs Physics



$$m_W=m_W^0+am_t^2+b\ln\left(\frac{m_H}{m_W}\right)$$

Further Reading: PDG has an excellent review covering Electroweak Physics constraints on New Physics

Impact of the CDF W mass measurement

- We can make a similar investigation with the CDF mW measurement (9 MeV precision), which disagrees with the Global EW Fit by 80 MeV.
- The CDF measurement, interpreted in the Standard Model framework, leads to a predicted Higgs boson mass of about 20 GeV! [S. Heinemeyer, arxiv:2207.14809]
- Inconsistency of CDF measurement with global EW picture can be interpreted as new physics impacting the W boson mass at loop level, moving it away from the Standard Model prediction.

$$m_W^2\left(1-{m_W^2}/{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\,\frac{1}{1-\Delta r(m_t,m_H,\dots,\mathrm{NP})}$$

In general, high-precision Electroweak Physics is sensitive to New Physics at multi-TeV scales.

Electroweak Physics at the LHC

- Let’s now consider how we can make high precision measurements, and achieve the necessary precision to probe fundamental electroweak physics!

- We’ll start by continuing our look at the W boson mass, before looking at the weak mixing angle.

How to measure m_W at the LHC

- Two main methods exploited at hadron colliders, considering $W \to l\upsilon$ events.

1. Measure lepton p_T distribution
    - W boson mass sets location of the peak
    - LHCb measurement makes use of this method, using muons.
    - Main method at ATLAS – receives weight of 86% in overall ATLAS analysis.

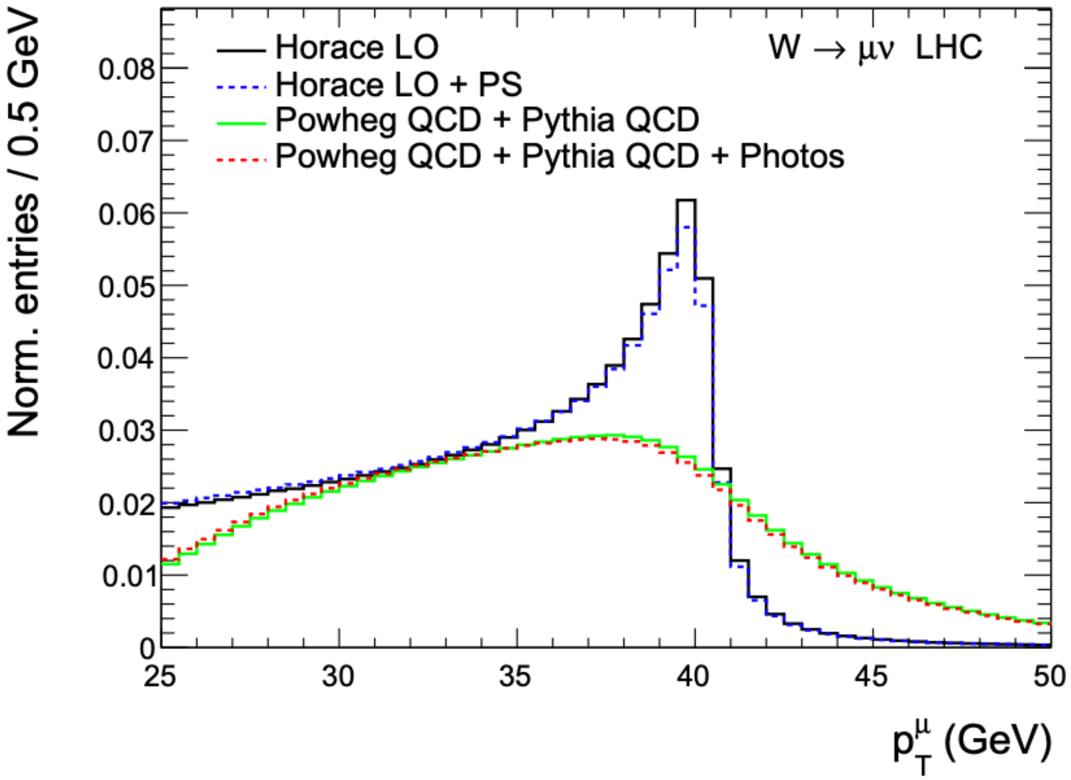
2. Measure W boson m_T distribution
    - Different uncertainties dominate with this method.
    - Not possible at LHCb – not a 4π detector – so no access to E_T^{miss}.

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

Plot From Phys. Rev. D 96, 093005 (2017)

Muon p_T distribution: theoretical ingredients

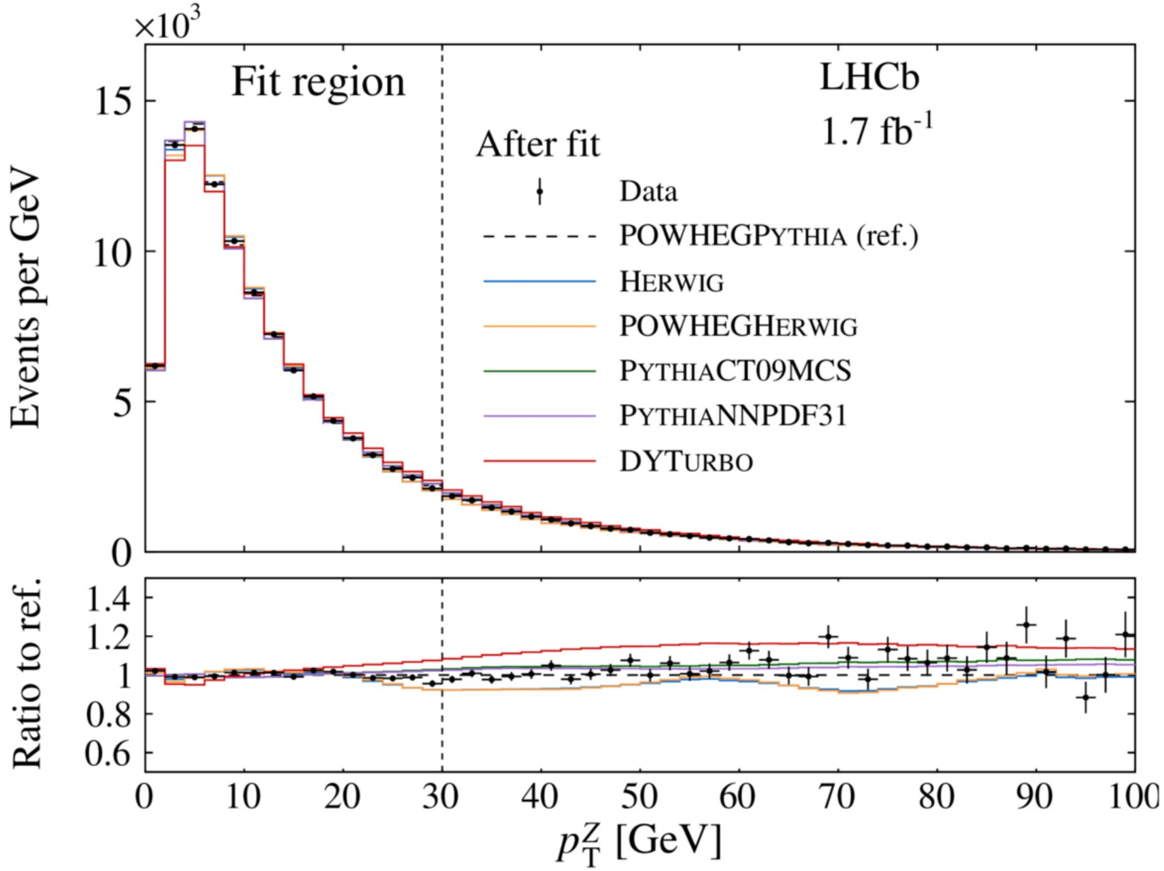
- Muon p_T distribution:
    - Depends on the W boson production model: how much p_T does the W boson transfer to the final state particles?
    - Depends on the angular distributions of W boson decays: what direction relative to the W boson does the muon travel in?
    - Need to understand the partonic environment – parton distribution functions.



LHCb collab., JHEP 01 (2022) 036

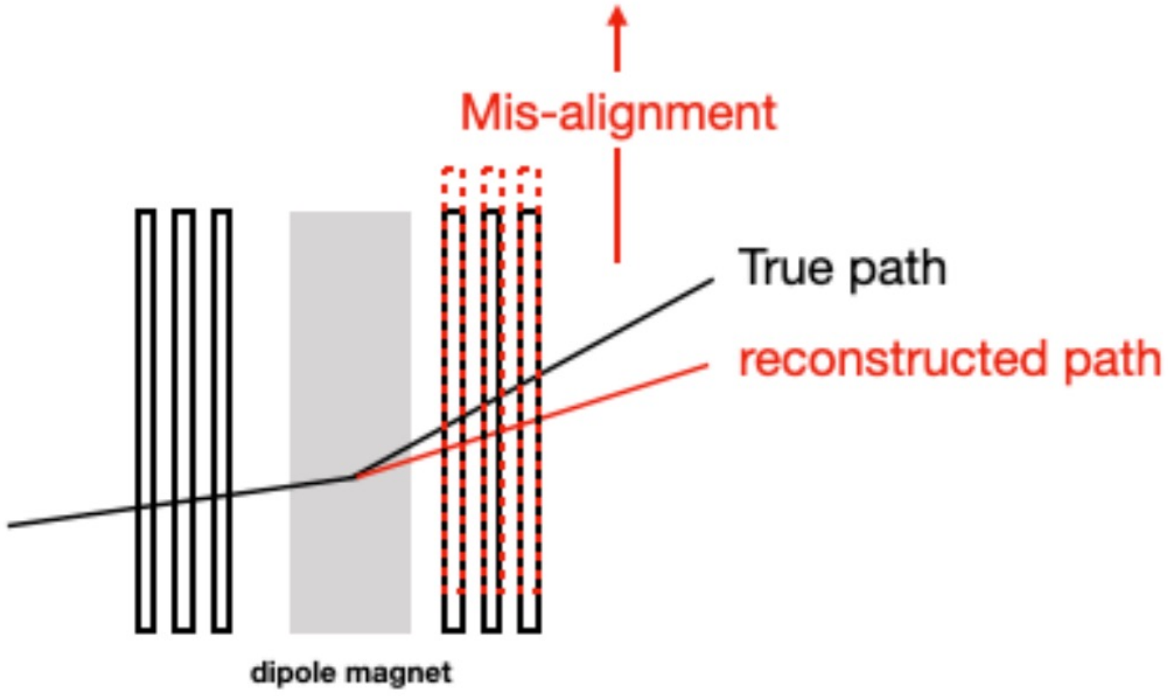
Muon p_T distribution: theoretical ingredients

- Typically use the Z boson – where you can measure the full differential cross-section – to tune/constrain the QCD physics for W boson production.
- Enables higher precision than possible using pQCD predictions directly.
- Can also float ‘nuisance parameters’ to capture theory effects and constrain them in situ.
- Need to be certain when doing this that it doesn’t bias the measured W boson mass.



Muon p_T distribution: experimental ingredients

- Crucial to understand the detector environment to a high degree of precision.

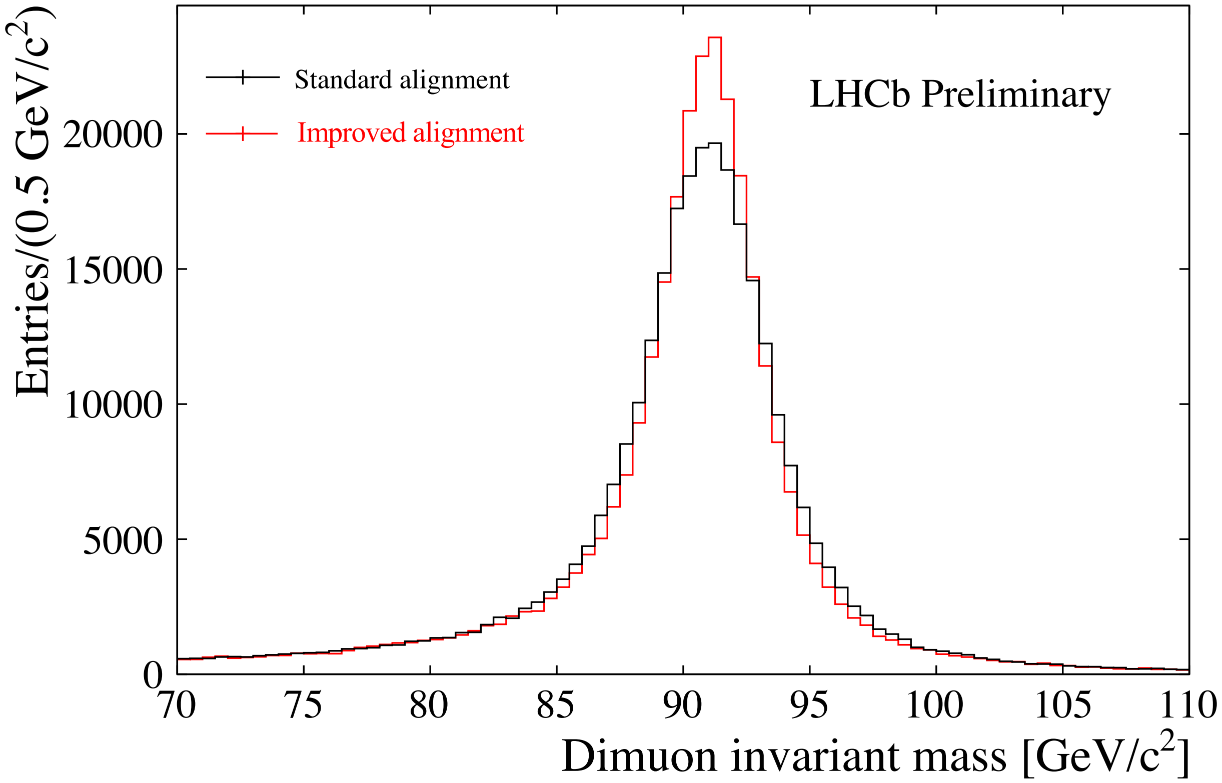


- Alignment effects particularly critical, since misalignments could shift the muon p_T peak.
  - At LHCb, a 5 micron misalignment could cause a 50 MeV bias in the W boson mass measurement.

- Other effects also important – e.g. p_T dependent efficiency would sculpt the distribution

Muon p_T distribution: experimental ingredients

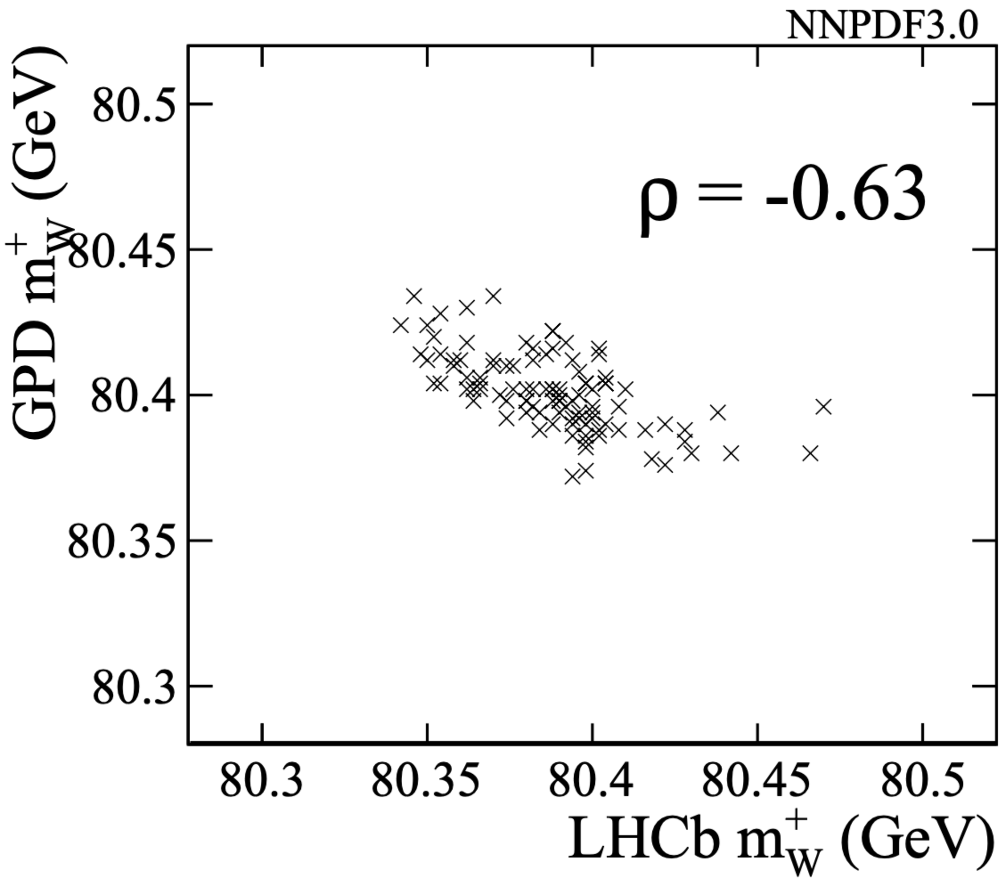
- Again, can use $Z \to \mu\mu$ events to study detector alignment directly.
- Able to improve dimuon invariant mass resolution significantly.



See EPJC 75 (2015) 601

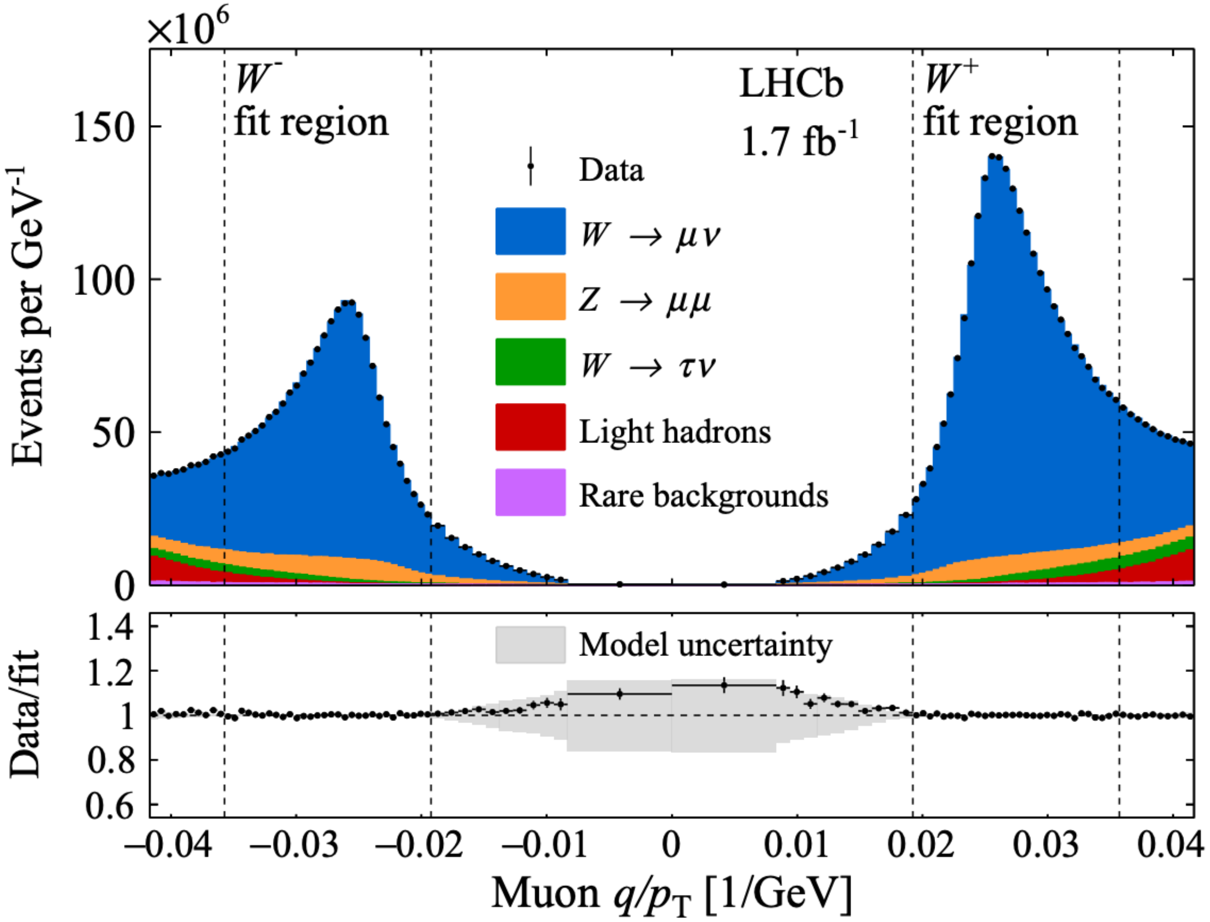
Why use LHCb for this physics?

- It's fair to ask 'what does LHCb add here?'
- The complementary forward coverage at LHCb is a significant advantage.
  - PDF uncertainties are expected to be anti-correlated in any W boson mass measurement between central and forward regions at the LHC.
- LHCb has the potential to contribute significantly in any LHC-wide average.
  - The overall average is ultimately the quantity that matters.



LHCb collab., JHEP 01 (2022) 036

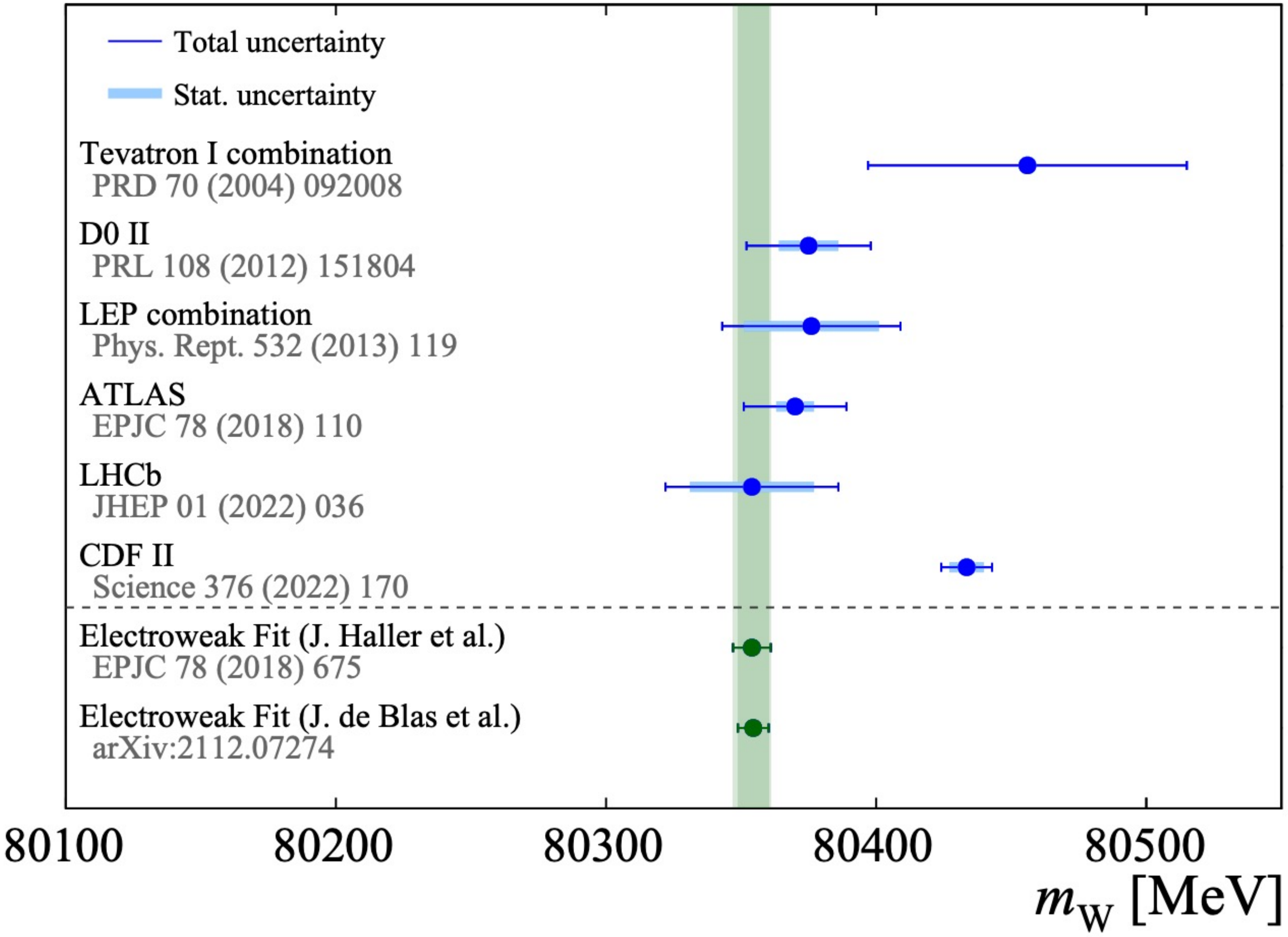
m_W @ LHCb – fit to data



Uncertainty	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

Note: LHCb uses 2016 dataset – factor 3 more data already available.

Fundamental EW Physics – all m_W results



Simple assumptions suggest 4σ discrepancy between CDF and the combination of results from other experiments.

Significant ongoing effort into combining LHC and Tevatron W mass measurements. See update at ICHEP 2022.

Weak mixing angle

- LHC also targeting measurement of the weak mixing angle at high precision.
- At leading order:

$$\sin^2\theta_W = 1 - {}^{m_W^2}\!/_{m_Z^2}\,; \quad \mathrm{e} = g_W \sin\theta_W = g_Z \sin\theta_W \cos\theta_W$$

$$c_{v,Z} = I_W^{(3)} - 2Q\sin^2\theta_W\,; \;\; c_{a,Z} = I_W^{(3)}.$$

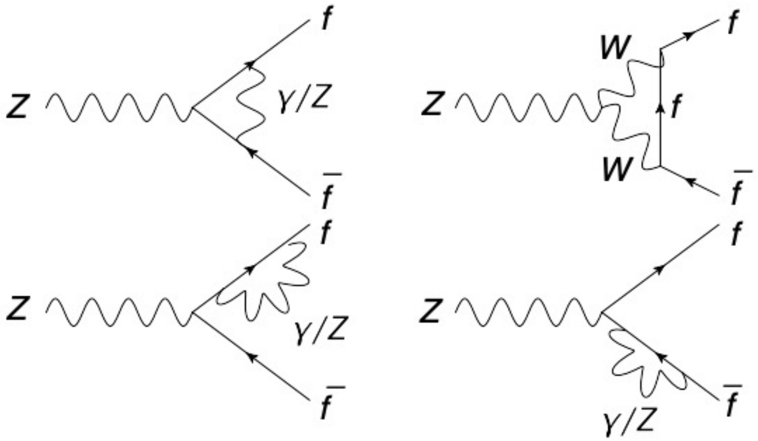
- Can measure couplings (and therefore the weak mixing angle) in many processes (and can also infer them from other measurements like m_W, m_Z as well).
- The consistency test of different measurements probing the same underlying physics (in the context of the Standard Model) is a fundamental test of the Standard Model.

Measuring the weak mixing angle

- We typically measure distributions which are sensitive to:

$$\sin^2\theta_{\text{eff}} = \frac{1}{4|Q|}\left(1 - \text{Re}\,\frac{c_{v,Z}}{c_{a,Z}}\right)$$

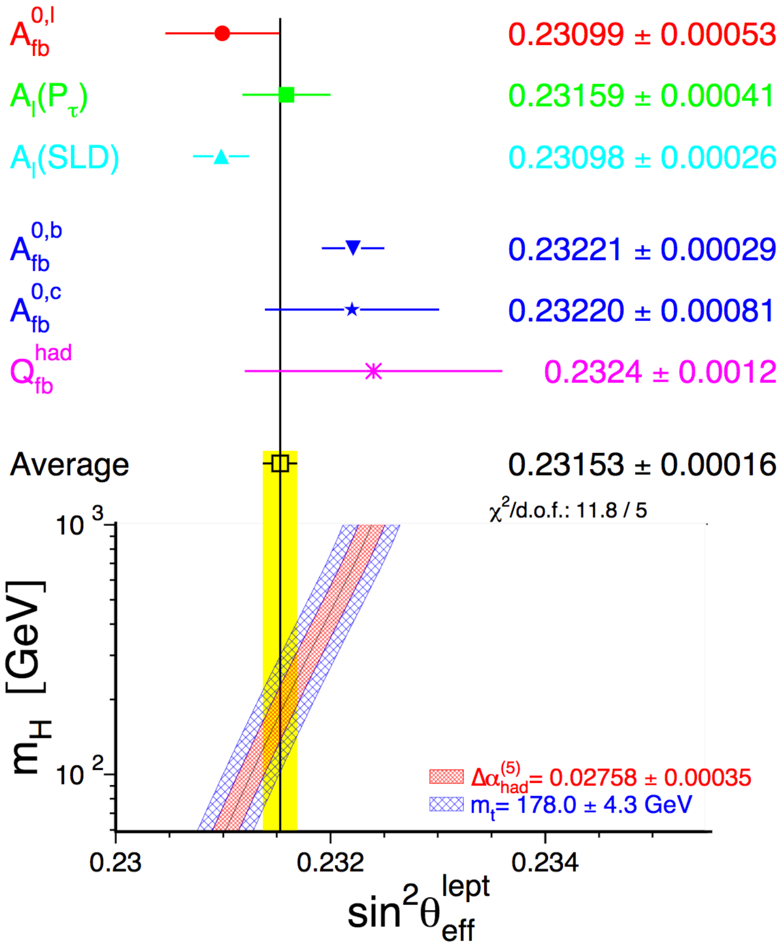
- Note this definition captures the impact of loop corrections compared to tree level – it's no longer the same as $1 - {}^{m_W^2}/_{m_Z^2}$ when you go beyond leading order.



LEP and SLD collaborations and Working Groups,
Phys. Rept. 427:257-454,2006

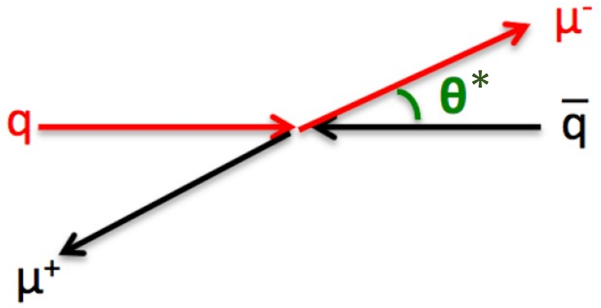
Measurements of the weak mixing angle in e^+e^-

- The two most precise measurements (made at LEP and SLD) measured different processes at similar precision ($(\sim 25 - 30 \times 10^{-5})$) – differ by $\backsim 3\sigma$.
- Raises prospect of interaction dependence of $\sin^2(\theta_W)$ – a non-SM effect!
- Might just be a statistical fluctuation, but crucial to measure at LHC – where we probe Z boson couplings to leptons.



Measuring the weak mixing angle at the LHC

- The vector and axial-vector couplings of the Z boson couplings introduce a forward-backward asymmetry at parton level:



(*z*-axis relative to direction of initial state quark)

Leading Order Formula

Virtual Photon

Z boson

$$\hat{\sigma}_{q\bar{q}}(\hat{s}, \cos\theta^*; \theta_W) \quad \propto \quad \frac{3\left(\rho_V^{q\bar{q}\to\gamma}\right)^2\left(\rho_V^{\gamma\to\ell\ell}\right)^2}{2\,\hat{s}} \times (1+\cos^2\theta^*)$$
$$+\frac{3}{2}\frac{\hat{s}}{(\hat{s}-m_Z^2)^2+m_Z^2\Gamma_Z^2} \times \left[\left(\left(\rho_V^{q\bar{q}\to Z}\right)^2+\left(\rho_A^{q\bar{q}\to Z}\right)^2\right)\left(\left(\rho_V^{Z\to\ell\ell}\right)^2+\left(\rho_A^{Z\to\ell\ell}\right)^2\right)(1+\cos^2\theta^*)\right.$$
$$\left. + 8\,\rho_V^{q\bar{q}\to Z}\rho_A^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}\rho_A^{Z\to\ell\ell}\cos\theta^*\right]$$
$$+\frac{3(\hat{s}-m_Z^2)\rho_V^{q\bar{q}\to\gamma}\rho_V^{\gamma\to\ell\ell}}{(\hat{s}-m_Z^2)^2+m_Z^2\Gamma_Z^2} \times \left[\rho_V^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}(1+\cos^2\theta^*)+2\,\rho_A^{q\bar{q}\to Z}\rho_A^{Z\to\ell\ell}\cos\theta^*\right].$$

Z/Virtual Photon Interference term

$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

Note vector/axial-vector interference term

CMS, CMS-PAS-SMP-16-007

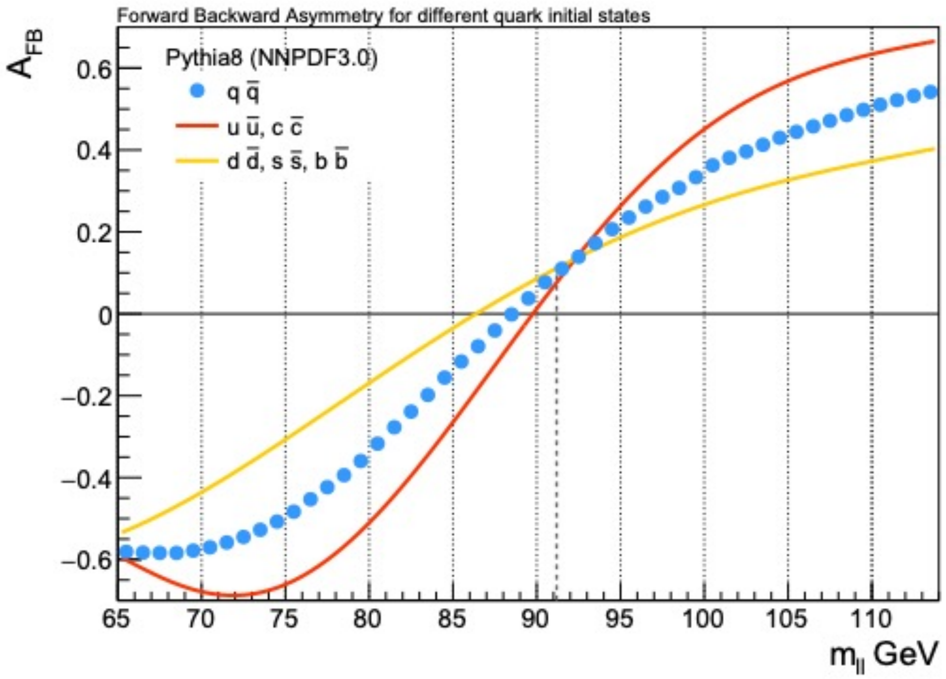
Measuring the weak mixing angle at the LHC

- The vector and axial-vector couplings of the Z boson couplings introduce a forward-backward asymmetry at parton level:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} \propto \frac{3}{8}A(1+\cos^2\theta^*) + \boldsymbol{B\cos\theta}^*$$

$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

- A_{FB} (and angular distributions) provide sensitivity to the weak mixing angle.
- Note – shape of A_{FB} mostly driven by Z/γ^* interference.

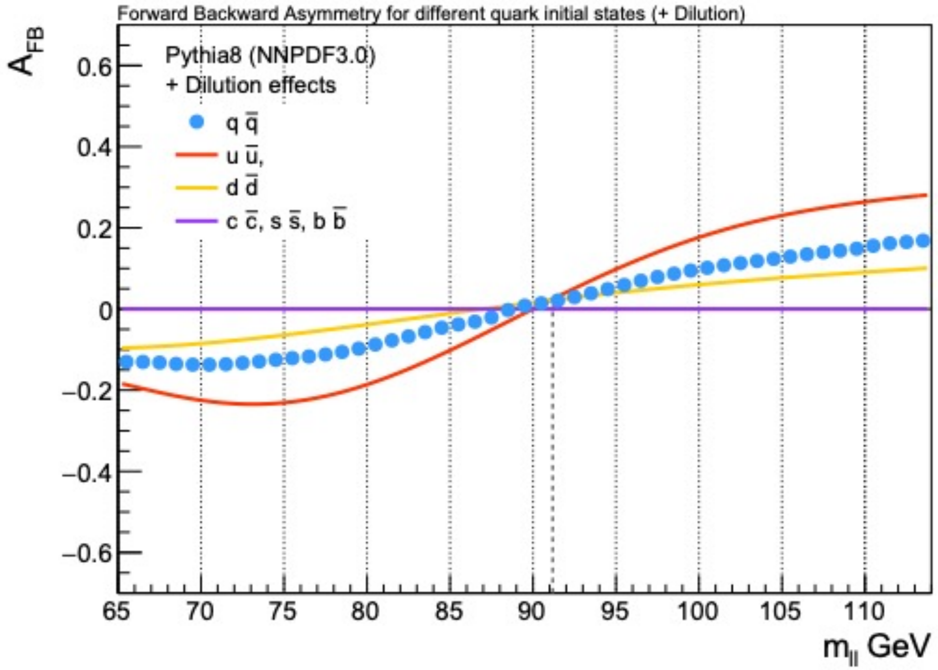


Measuring the weak mixing angle at the LHC

- Since the quark and anti-quark could be in either colliding proton at the LHC, the parton-level asymmetry is diluted at proton level.

- Best assumption is that the Z boson travels in the *z*-direction of initial state quark, so we therefore use this Z boson direction in the lab-frame to set the *z*-axis used to measure the asymmetry.

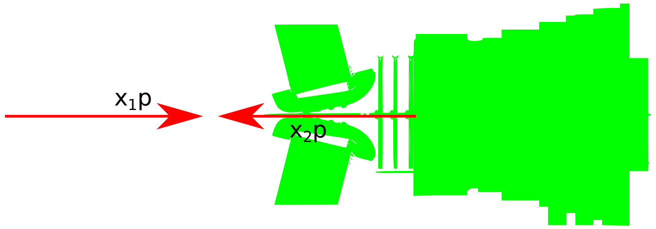
- Key uncertainties in any analysis using this data will come from PDFs – how to relate what we measure to fundamental parton-level asymmetry.



P. Azzi *et al.* in CERN-LPCC-2018-03

Measuring the weak mixing angle at LHCb

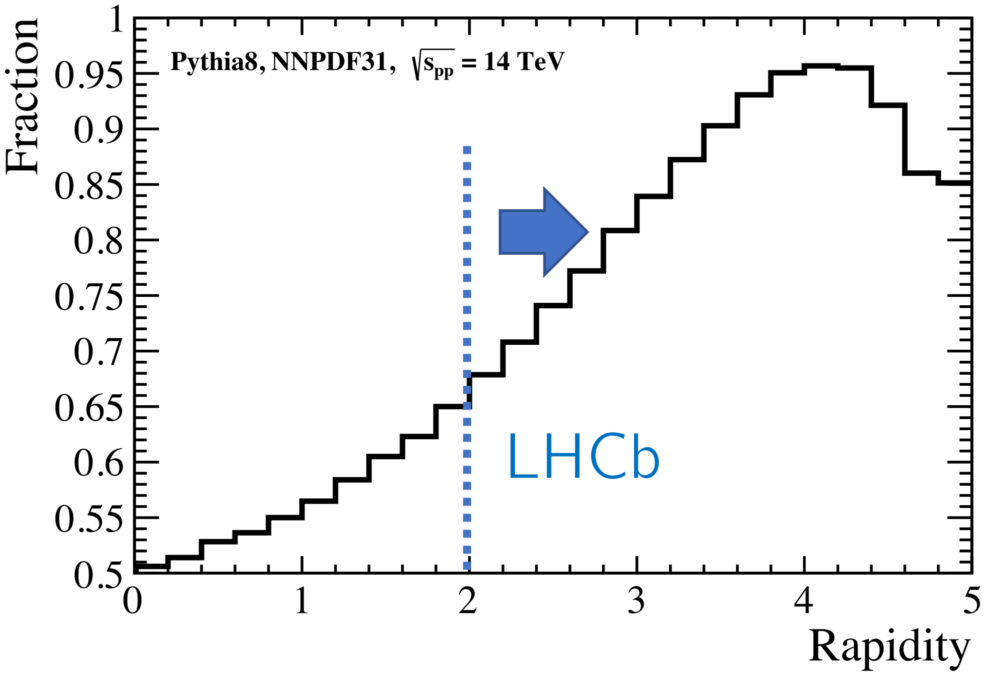
- This assumption becomes better at higher rapidities:
  - One parton at high x, one parton at low x.



$$x_{1,2} = \frac{m}{\sqrt{s}} e^{\pm y}$$

  - PDFs dictate that high-x parton tends to be a (valence) quark, and low x parton tend to be an anti-quark.
- At larger rapidities we therefore recover a larger asymmetry (proton-level is ‘closer’ to parton-level).

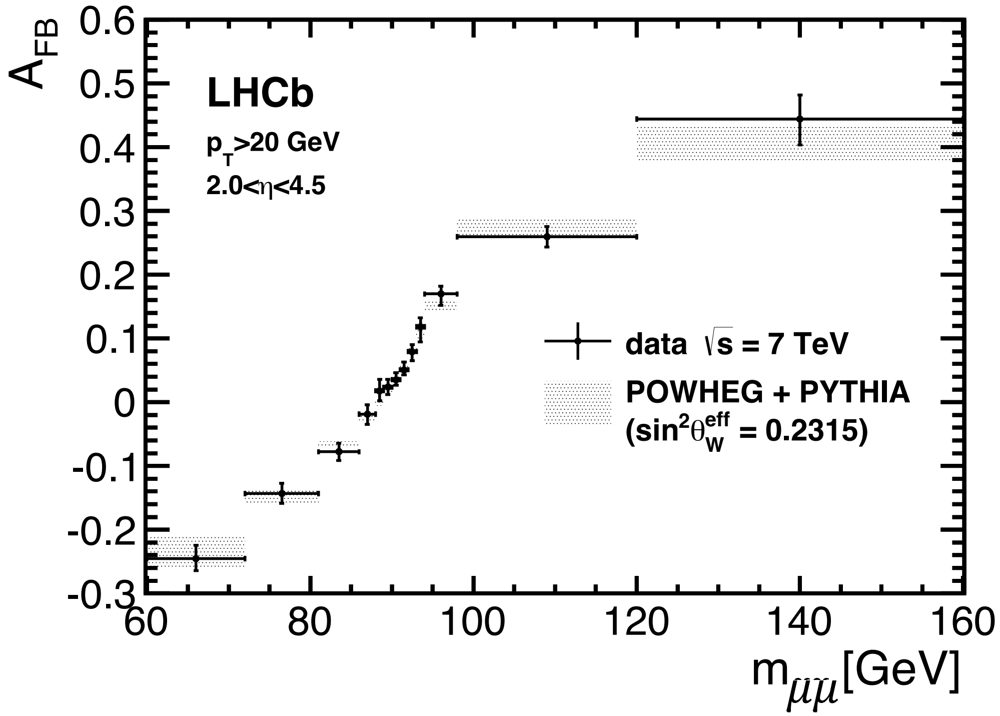
Fraction of events where the Z boson travels in direction of initial state quark.



Note: ATLAS and CMS calorimeters also provide forward coverage for electrons.

Measuring the weak mixing angle at LHCb

- LHCb has made a pathfinder measurement using Run 1 data.
  - From A_{FB} determine weak mixing angle, achieving precision of $\sim 100\times 10^{-5}$.
  - Largest uncertainty is statistical $(\sim 70\times 10^{-5})$; largest modeling / theory uncertainty arises from knowledge of PDFs $(\sim 30\times 10^{-5})$



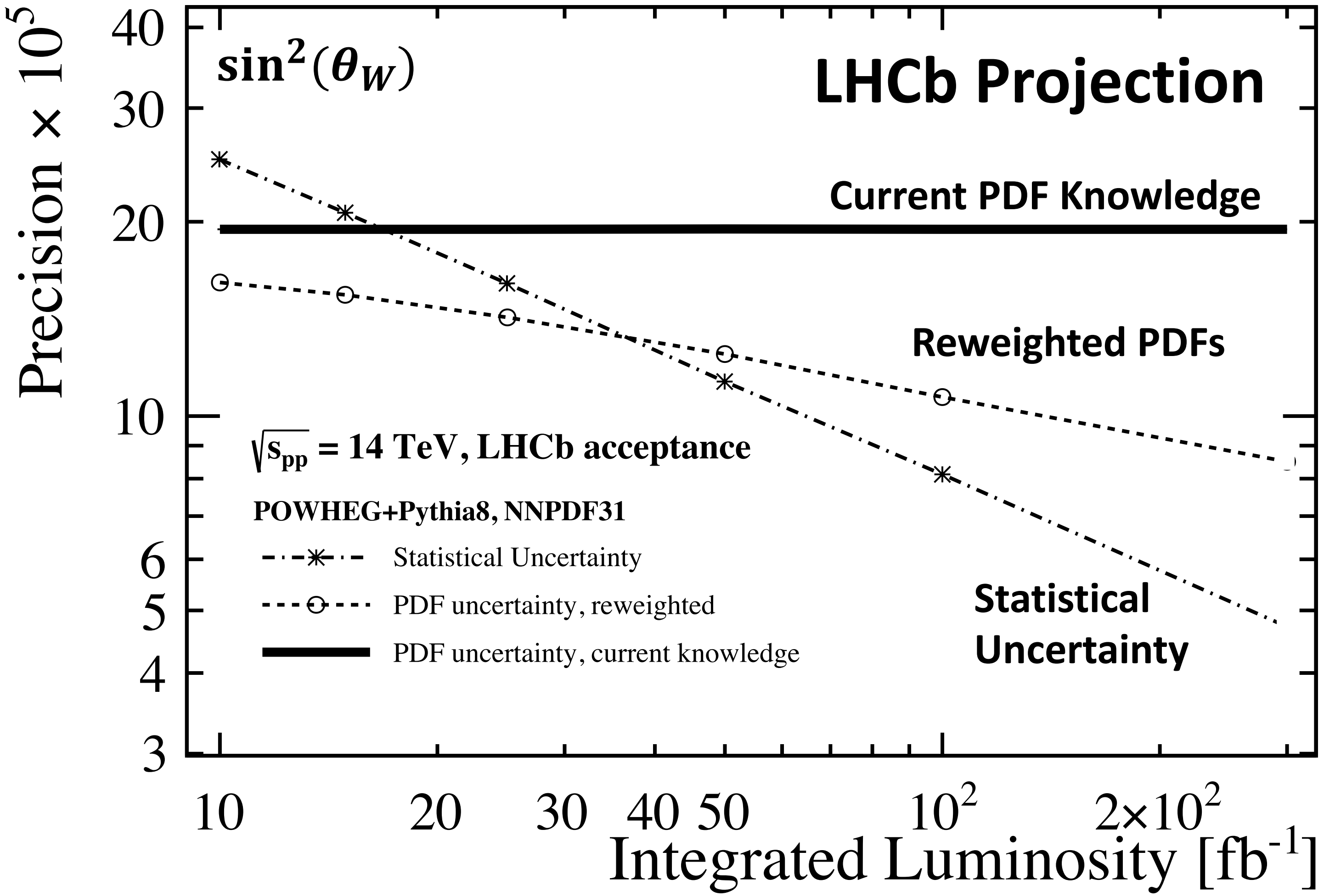
Note – existing ATLAS/CMS measurements achieve higher precision than LHC Run I

Measuring the weak mixing angle at LHCb

- Clear path to improve precision:
  - Larger datasets will reduce statistical uncertainties.
  - Better understanding of QCD from existing measurements.
  - Newer PDF fits – using LHCb data as inputs – have also reduced PDF uncertainty.
  - Profile over (or Bayesian reweight the) PDFs – using the data itself to constrain the size of potential PDF effects.

P. Azzi *et al.* in CERN-LPCC-2018-03

Measuring the weak mixing angle at LHCb



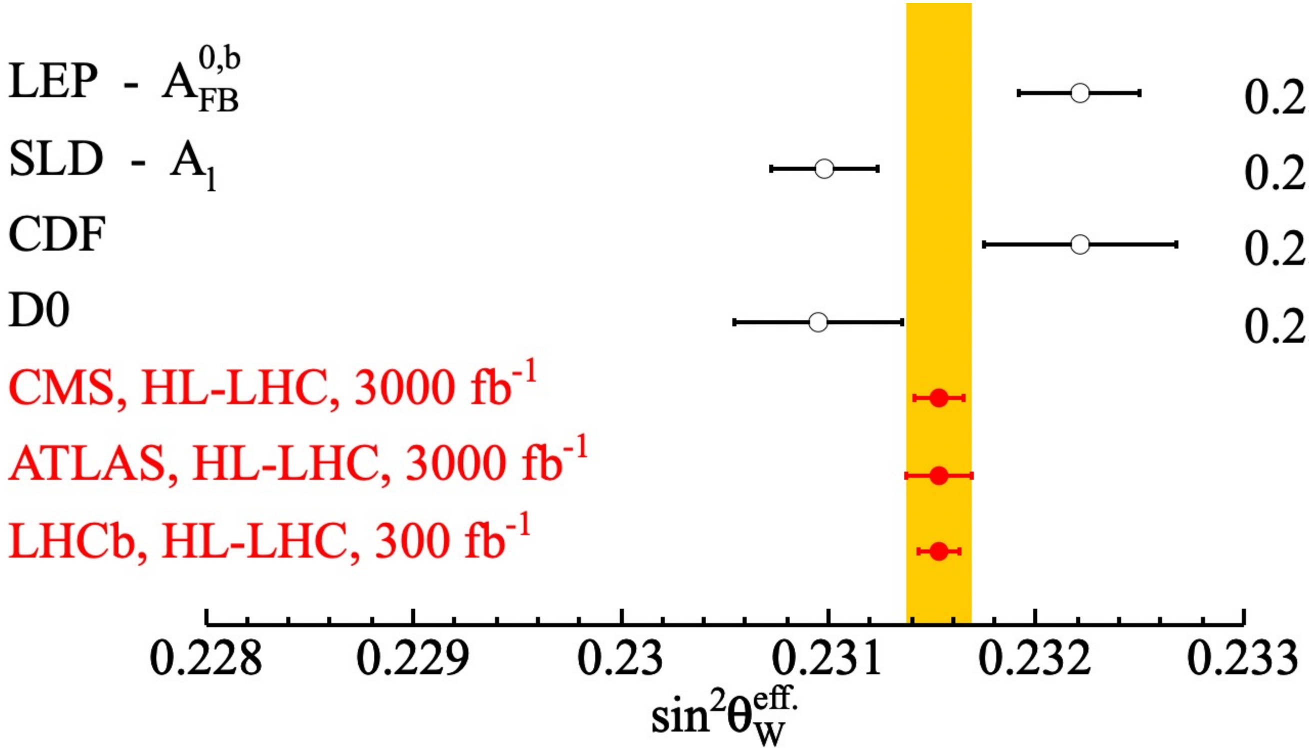
Uncertainties on weak mixing angle arising from PDF knowledge:

LHCb (300 fb^{-1}): 9×10^{-5}
(cf 20×10^{-5} without reweighting)

CMS (3000 fb^{-1}): 12×10^{-5}
(cf 57×10^{-5} without reweighting)

P. Azzi *et al.* in CERN-LPCC-2018-03

Measuring the weak mixing angle at the LHC



0.23221 ± 0.00029
0.23098 ± 0.00026
0.23221 ± 0.00046
0.23095 ± 0.00040
± 0.00012
± 0.00016
± 0.00010

(expected precision from PDF and statistical uncertainties)

An exciting future – precision of 16×10^{-5} on the weak mixing angle is equivalent to **8 MeV** precision on the W boson mass.

Note – existing ATLAS/CMS measurements currently achieve similar precision to Tevatron experiments.

Linking Fundamental EW Physics to Flavour + More

- Constraints from EW physics significantly influence model building in flavour physics in general – see e.g. B. Allenach & J. Davighi, arXiv:2205.12252.
  - Any new Z’ boson that exhibits Z-Z’ mixing will directly impact EW physics. It’s usually easier to absorb these non-SM effects into the W boson mass, since it is the ‘least’ well known parameter in the EW sector.
  - Current knowledge of the W boson mass typically limits interpretation of the electroweak sector in terms of new physics.
- Some models of New Physics in the flavour sector also seek to explain the anomalous coupling of the Z boson to beauty quarks. See e.g. M. Carena *et al.*, JHEP 12 (2018) 43; A. Crivellin *et al.*, PRL 127 (2021) 011801.
- Existing constraints from the EW sector typically rule out (relevant) New Physics models at multi-TeV scales. See e.g. J. Ellis *et al.*, JHEP 03 (2015) 157

Summary – measuring fundamental EW physics

- Measurements of the electroweak sector at high precision allow us to probe the fundamental parameters of the Standard Model Lagrangian.
  - Requires fine control of both the detector environment AND knowledge of the QCD.

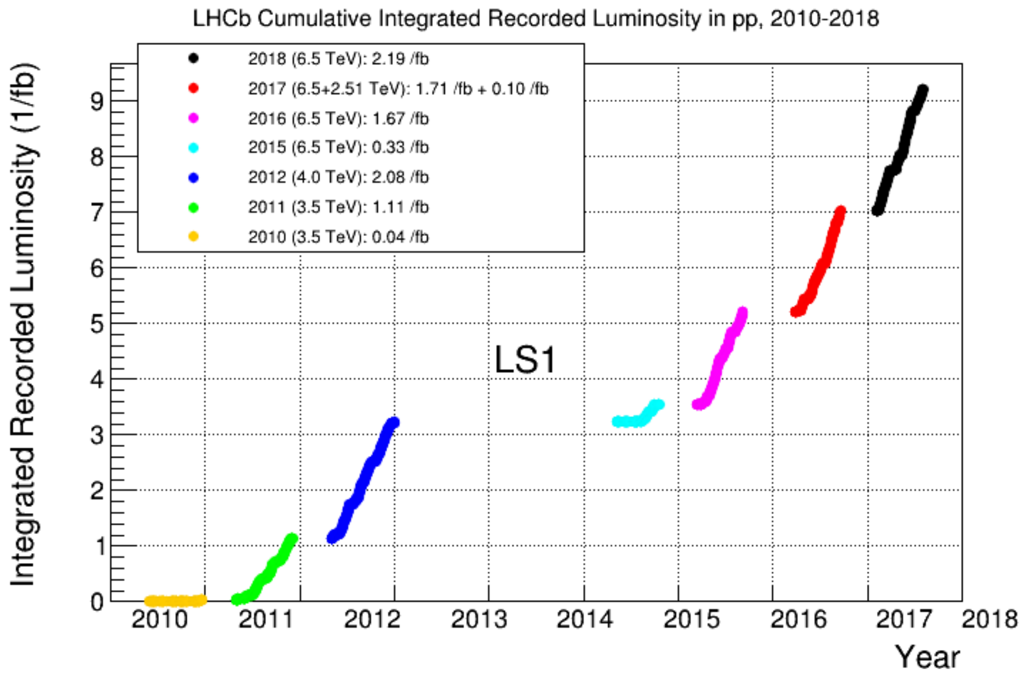
- The electroweak sector of the Standard Model can be over-constrained by making multiple measurements of (related) quantities.
  - The consistency of these measurements in the global electroweak fit then provides an indirect search for the effects of New Physics.

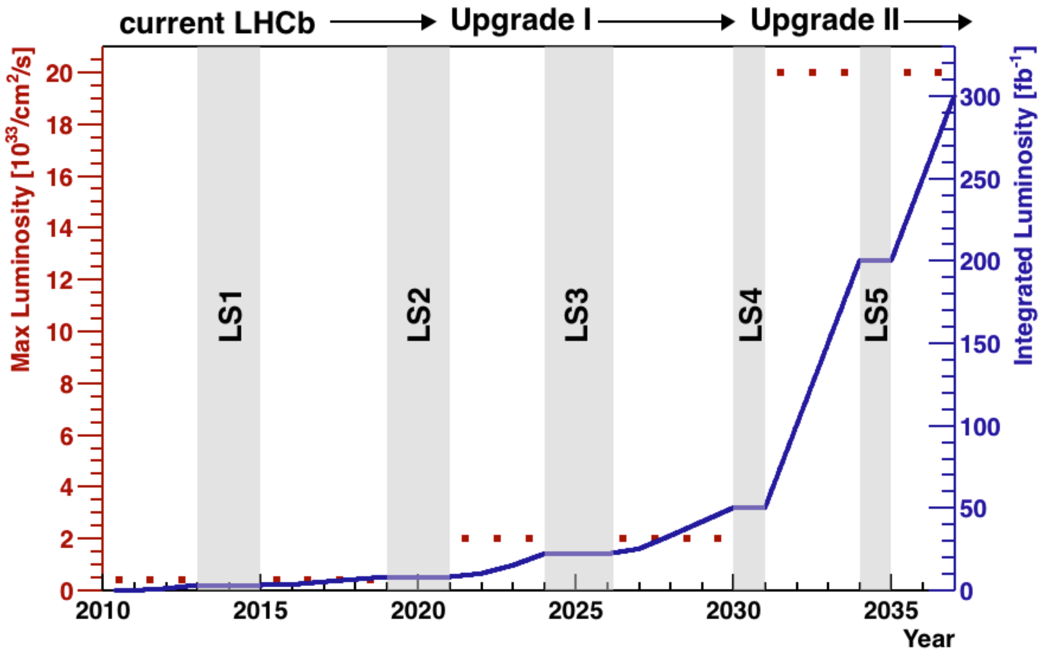
- LHC targeting measurements of the W boson mass and the weak mixing angle – LHCb playing an important role.

The Future

LHCb collab., CERN-LHCC-2018-027

Far more to come…





With increased data volumes, we are able to make more precise measurements – we are on the cusp of a new era of high-precision.

Data Samples Recorded and To Come

Muon Final States	W boson	Z boson
Run 1	3M	200k
Run 1+2	20M	1M
Run 1+2+3	100M	5M
LHCb Total (inc. Upgrade 2)	1200M	60M

LHCb Upgrades – relevance for EW programme

- Upgrade I:
  - Increase in instantaneous luminosity by more than a factor of 5 (and associated detector upgrades to achieve this).
  - Removal of hardware trigger – full event readout and software-based analysis of every event.

- Upgrade II:
  - Further increase in instantaneous luminosity by a factor of 10.
  - Improved calorimetry potentially allows electron channels to contribute equivalent precision to muon channels. To date, yields in electron channels at LHCb are roughly 1/2 of yields in muon channels.

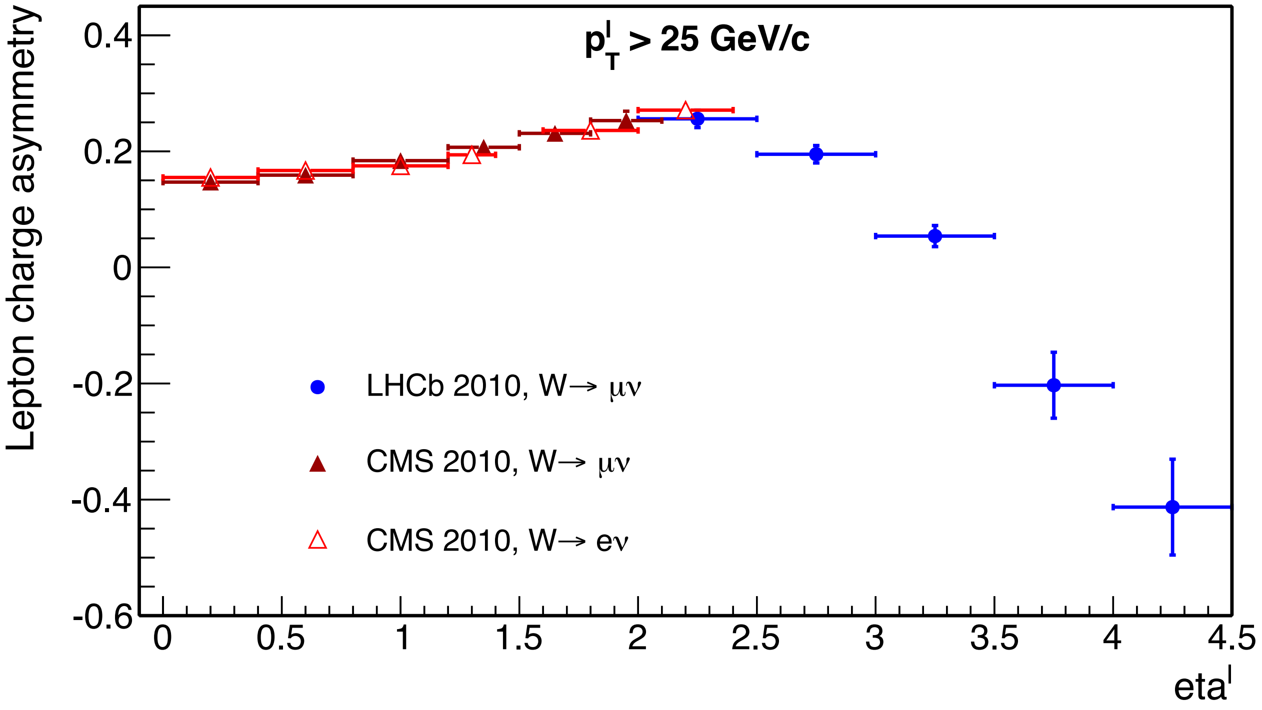
Conclusions

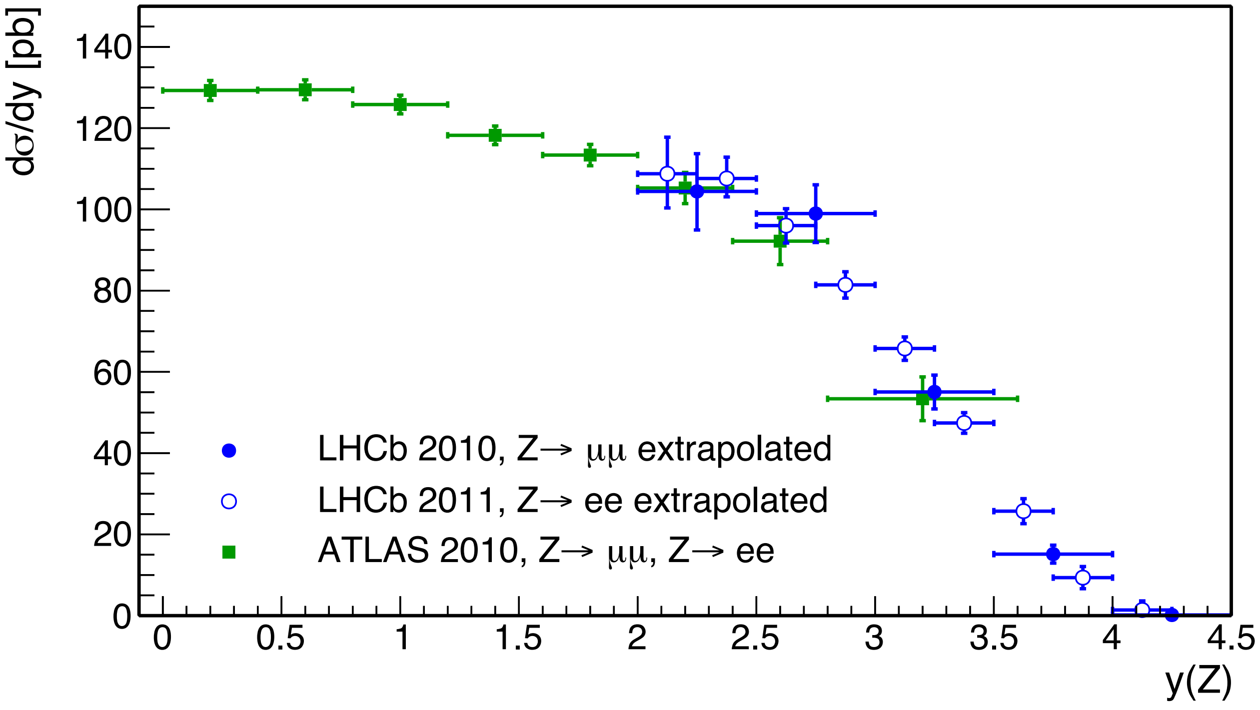
The Standard Model at EW scales

- Electroweak bosons are a key tool for studying the physics of the Standard Model at the LHC.
- Production measurements typically test QCD in both the hard interaction and in the proton internal structure.
- High-precision measurements of fundamental electroweak physics test the overall consistency of the Standard Model.
- High-precision measurements typically probe New Physics at multi-TeV scales.
- LHCb playing a key role in studies of this physics, with much more to come!

Backup

Comparison of LHCb/ATLAS/CMS Results





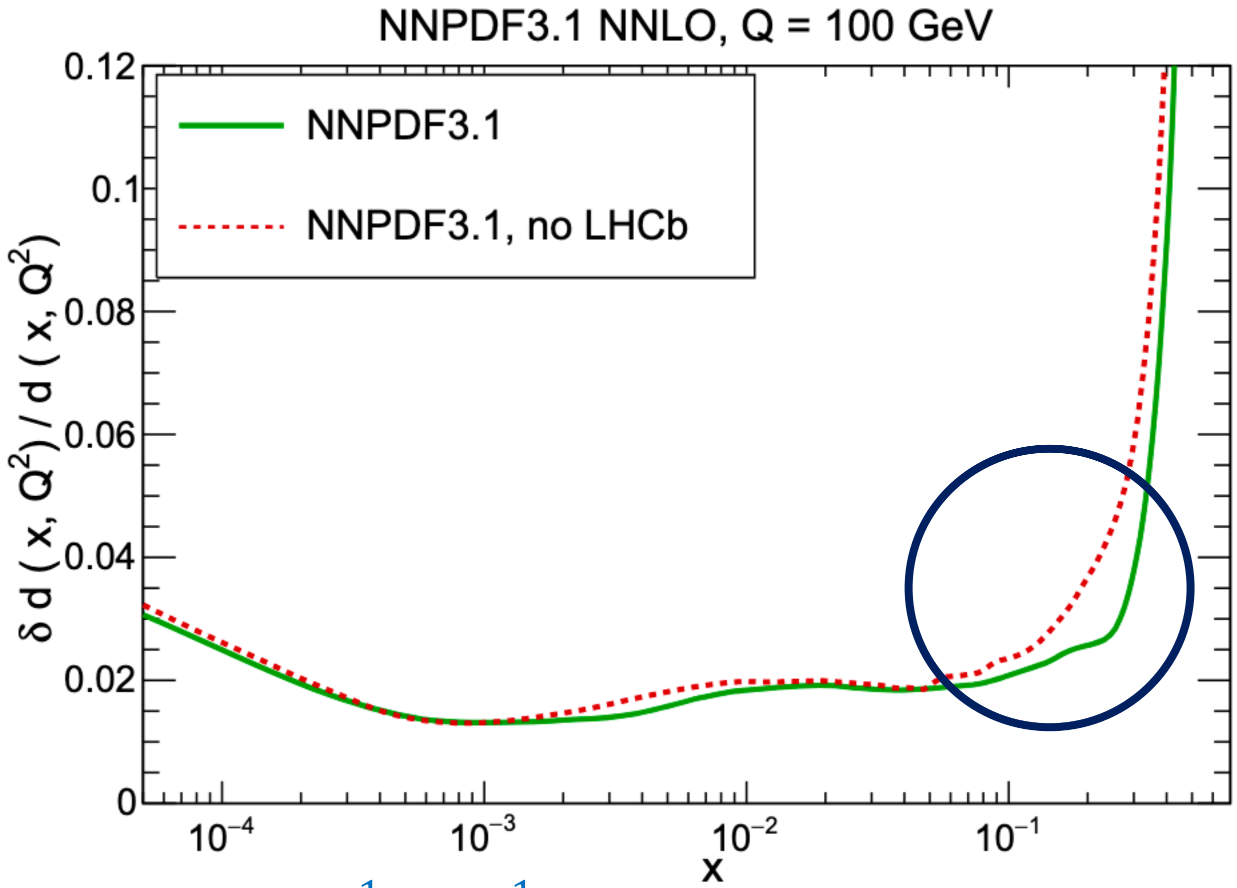
NNPDF collab., EPJC 77 (2017) 663

Impact on PDFs

- LHCb results routinely included in global fits to data to extract PDFs – shown here NNPDF.

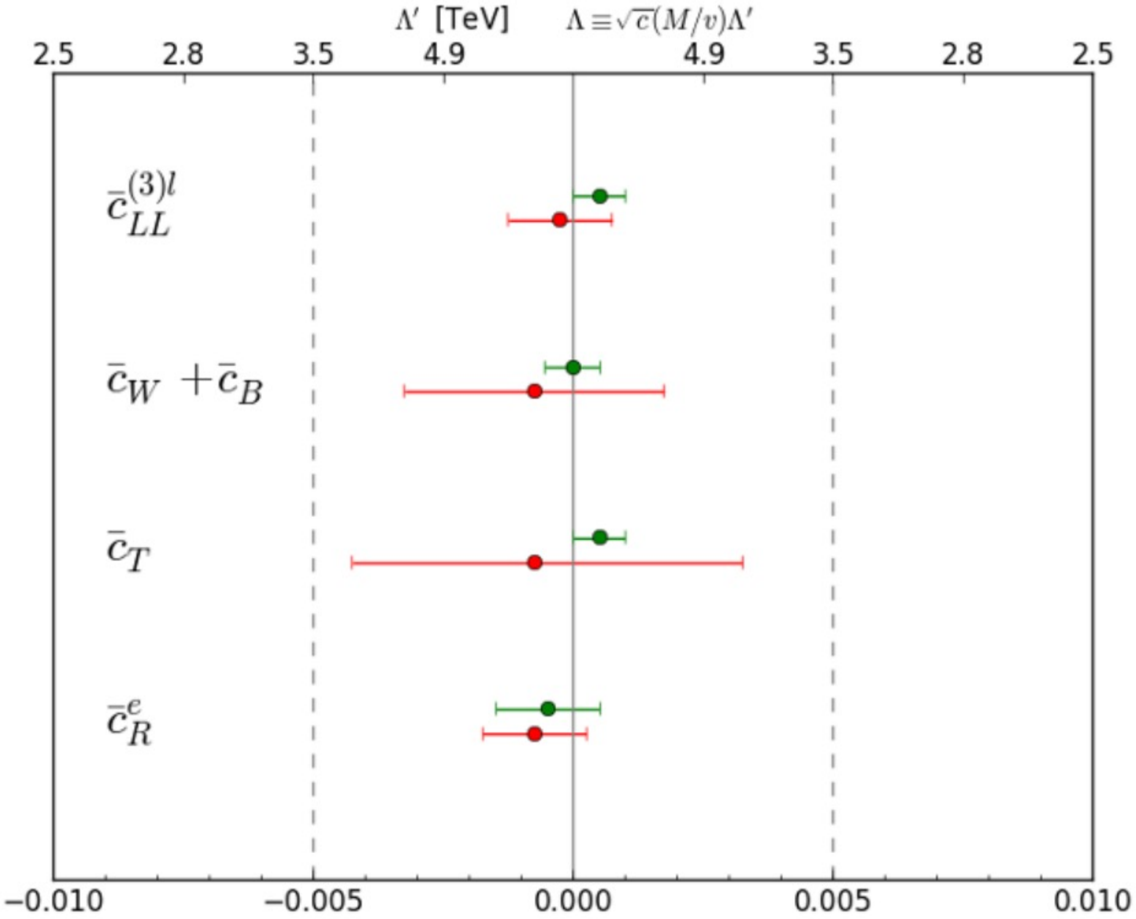
- Up to a factor of two reduction of PDF uncertainty at high-*x*, with 10-20% reduction at other *x* values (in addition to ATLAS/CMS impact).

- Will aid understanding of any high mass states found at ATLAS and CMS (produced in high-*x* collisions).



$$\sigma_{AB\to X} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2\, f_a(x_1,Q^2) f_b(x_2,Q^2) \quad \sigma_{ab\to X}$$

New Physics Reach



95% CL ranges
For individual coefficients
and for multi-coefficient fits

LHCb collab., JHEP 01 (2022) 036

LHCb W mass Combination Study