A New Era of Precision: Testing the Standard Model with Electroweak Measurements at LHCb

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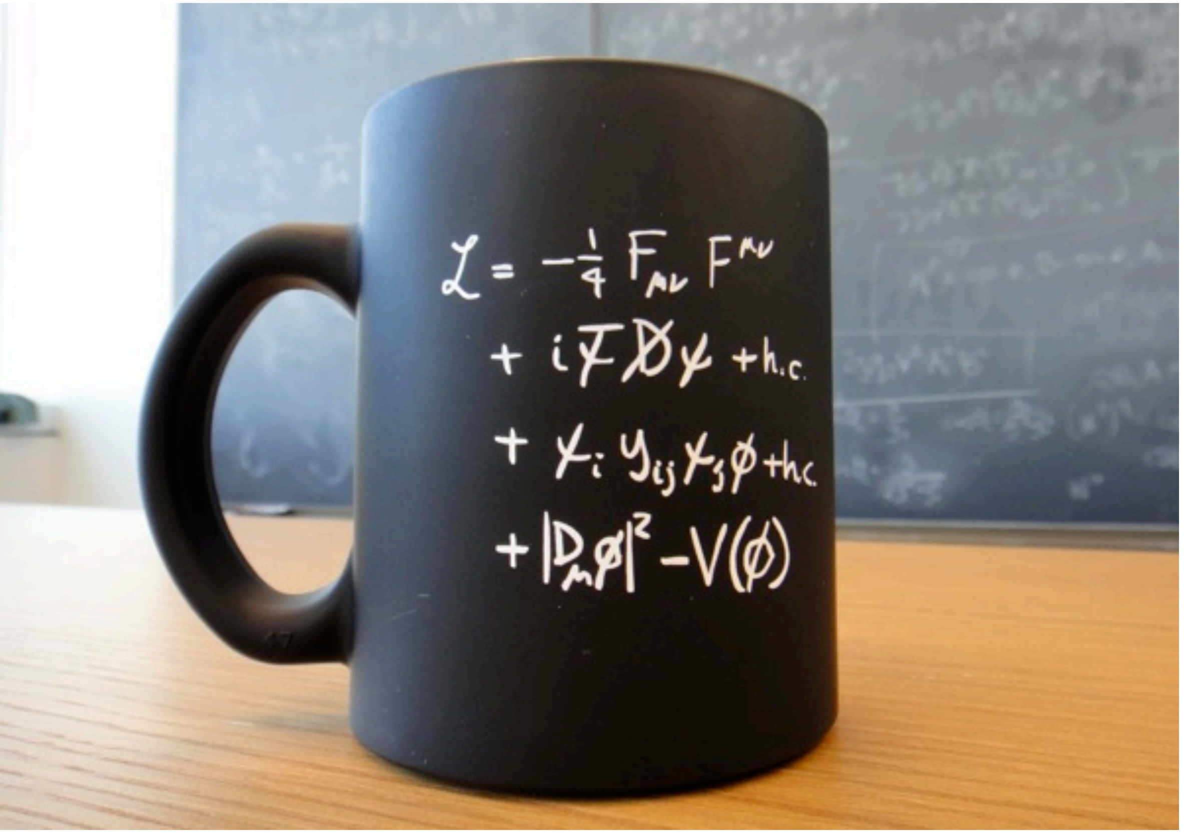
Introduction



- High Energy Physics research studies the fundamental behaviour of nature:
  - Can we understand the already known forces of nature better?
  - Can we find new physics that addresses major open questions? (e.g. the nature of dark matter)
  - We often address these aspects at the same time.
- The ways in which we address these questions change over time even at the LHC; the LHC offers a programme of research that will be multiple decades long.

Introduction – this talk

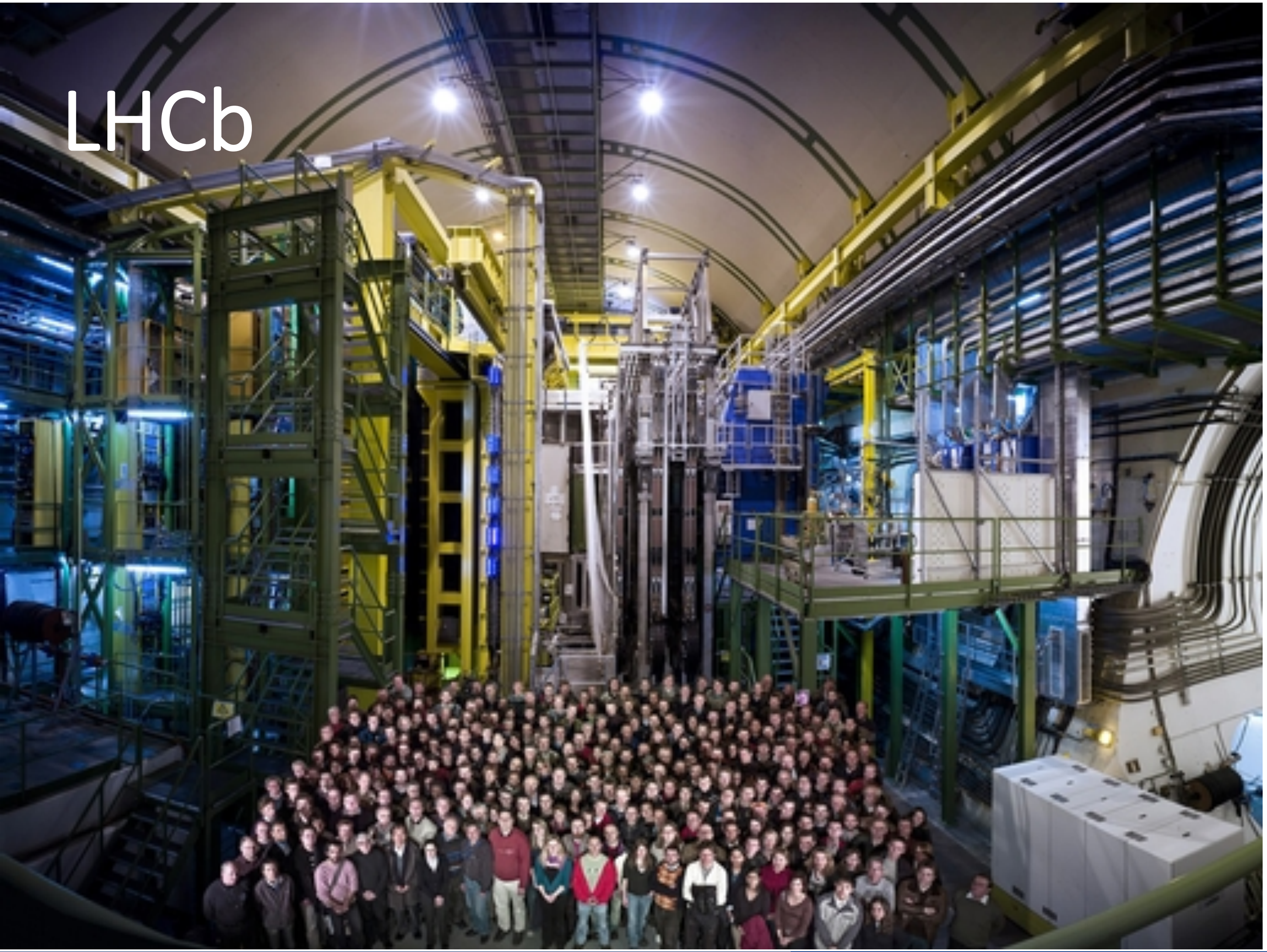
- First: the LHCb detector at the LHC, and its versatility.
- Physics at LHCb: focusing (here) on measurements that probe the Standard Model at Electroweak scales
- Probing QCD physics: studying the proton itself, and in the hard interaction, using electroweak bosons
- Probing Electroweak Physics at high precision: measuring fundamental parameters of nature – a journey that is just beginning at LHCb

Large Hadron Collider

Different experiments at the LHC test our understanding of nature in different ways.

- ATLAS and CMS are “General Purpose Detectors”.
- ALICE is designed to probe hot, dense matter in heavy ion collisions.
- LHCb designed to probe the decays of particles that contain b-quarks.

Large Hadron Collider



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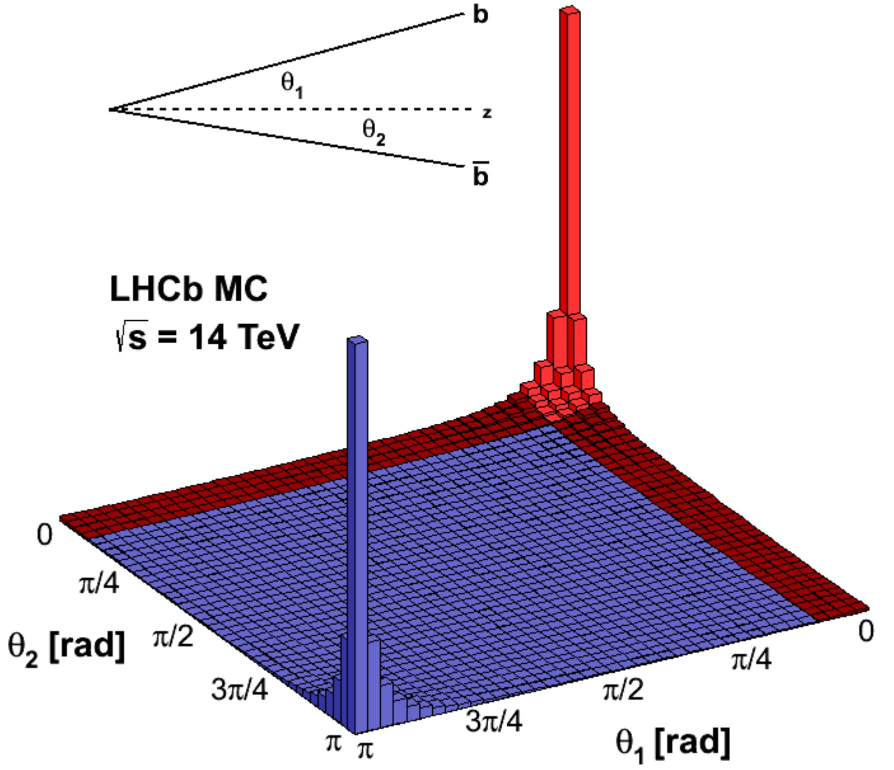
LHCb

- LHCb experiment designed to measure physics associated with b-quarks.
- b-quarks typically produced in the forwards and backwards direction at the LHC, with small angles to the beamline.
- LHCb experiment therefore covers the region close to the beamline (high η).
- Collect ∽30% of b-quarks produced by covering about 4% of the solid angle!

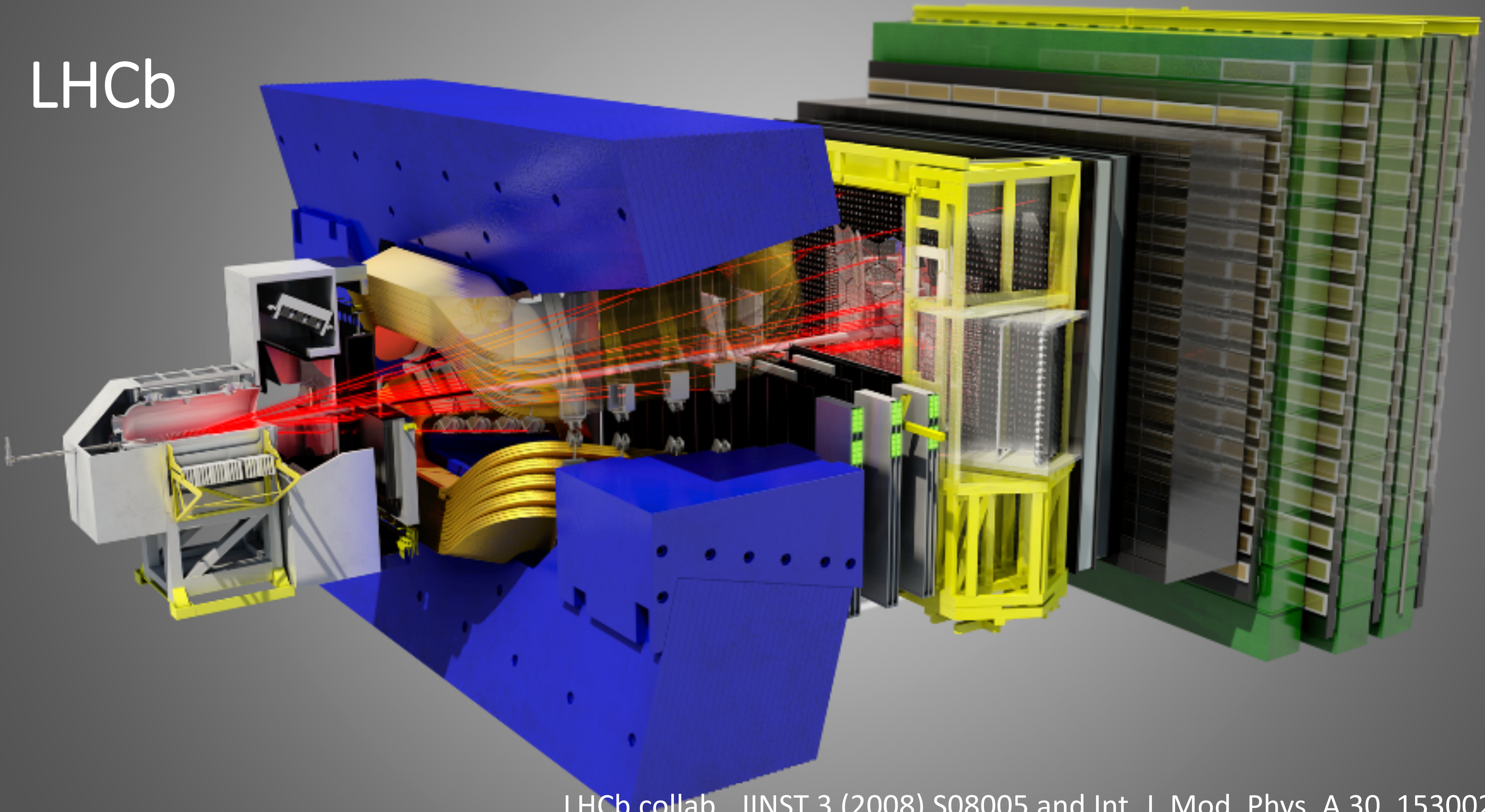


$$\eta = -\ln(\tan(\frac{\theta}{2}));$$
$$p_T = p\sin\theta$$

LHCb

Angular coverage of LHCb is roughly equivalent to instrumenting the Arctic circle were the proton collisions at the centre of the Earth!

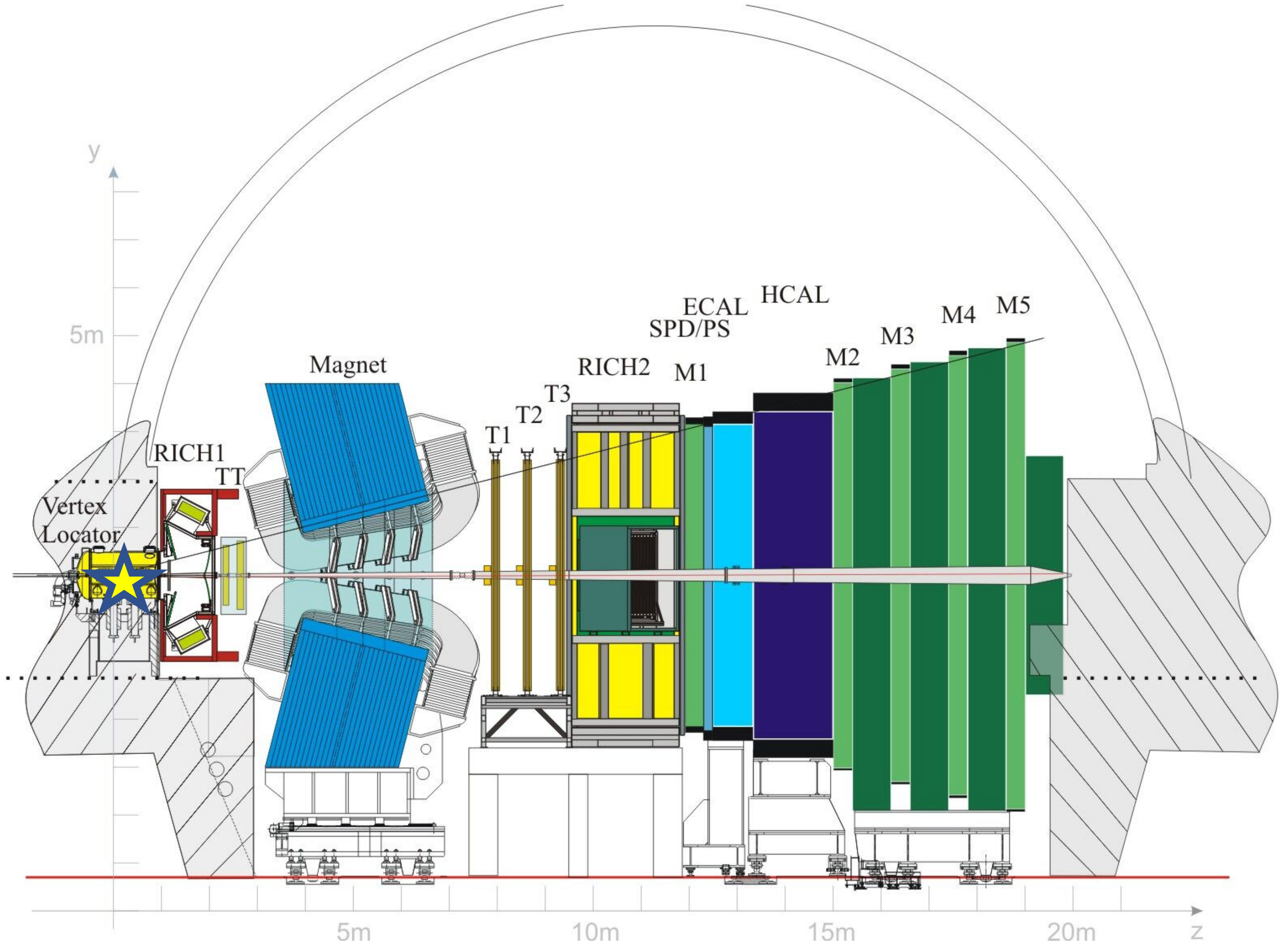
LHCb



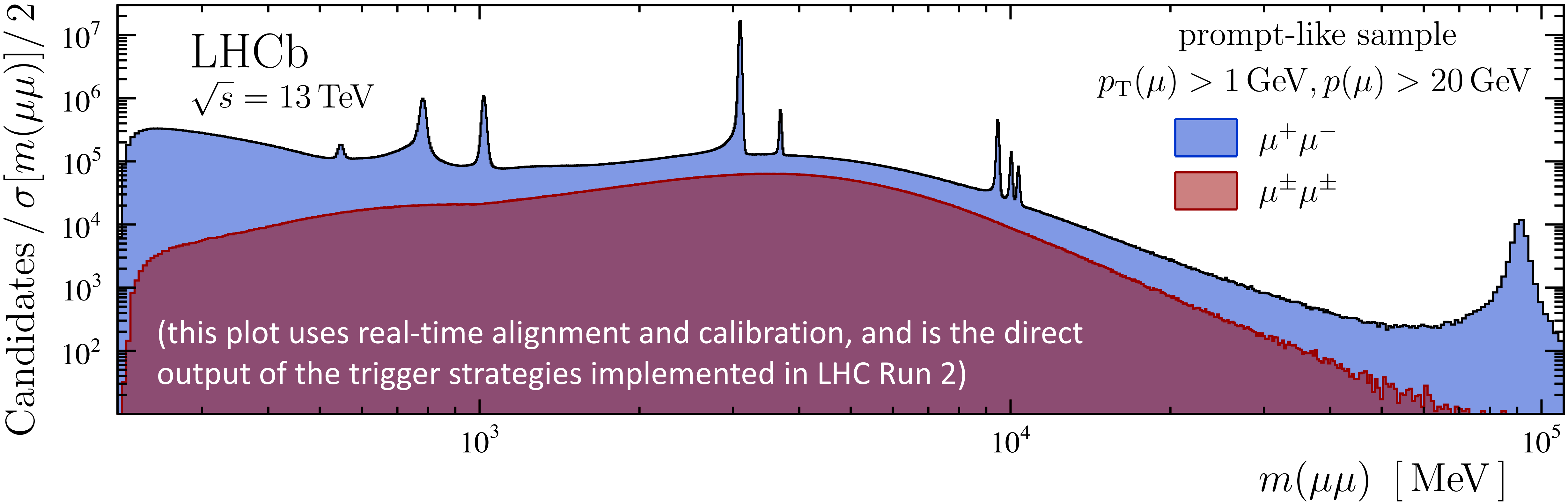
LHCb collab., JINST 3 (2008) S08005 and Int. J. Mod. Phys. A 30, 1530022 (2015)
and others, including R. Aaij *et al.*, JINST 14 (2019) P04013

LHCb

- Excellent vertexing (VELO), tracking, and particle identification ability.
- Flexible trigger
- Levelled luminosity

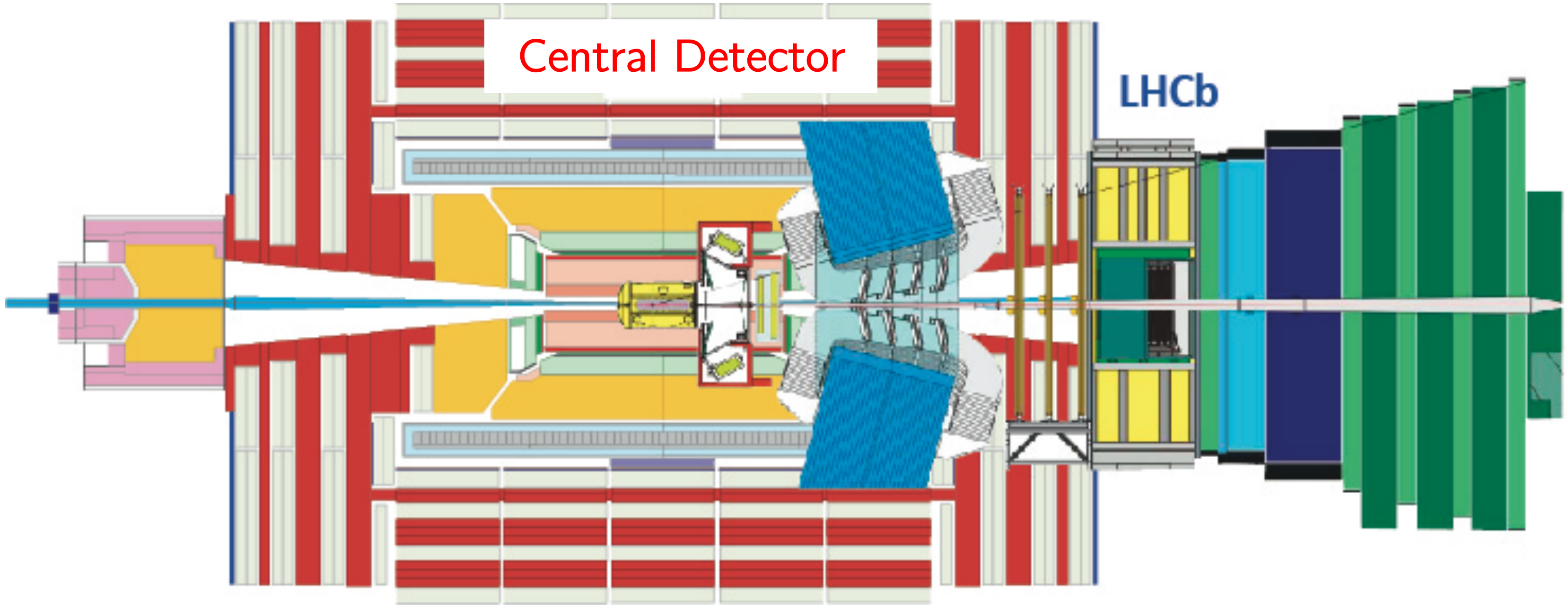


LHCb Detector Output - what we see



Excellent performance across a wide range of momenta!

LHCb as a General Purpose Forward Detector

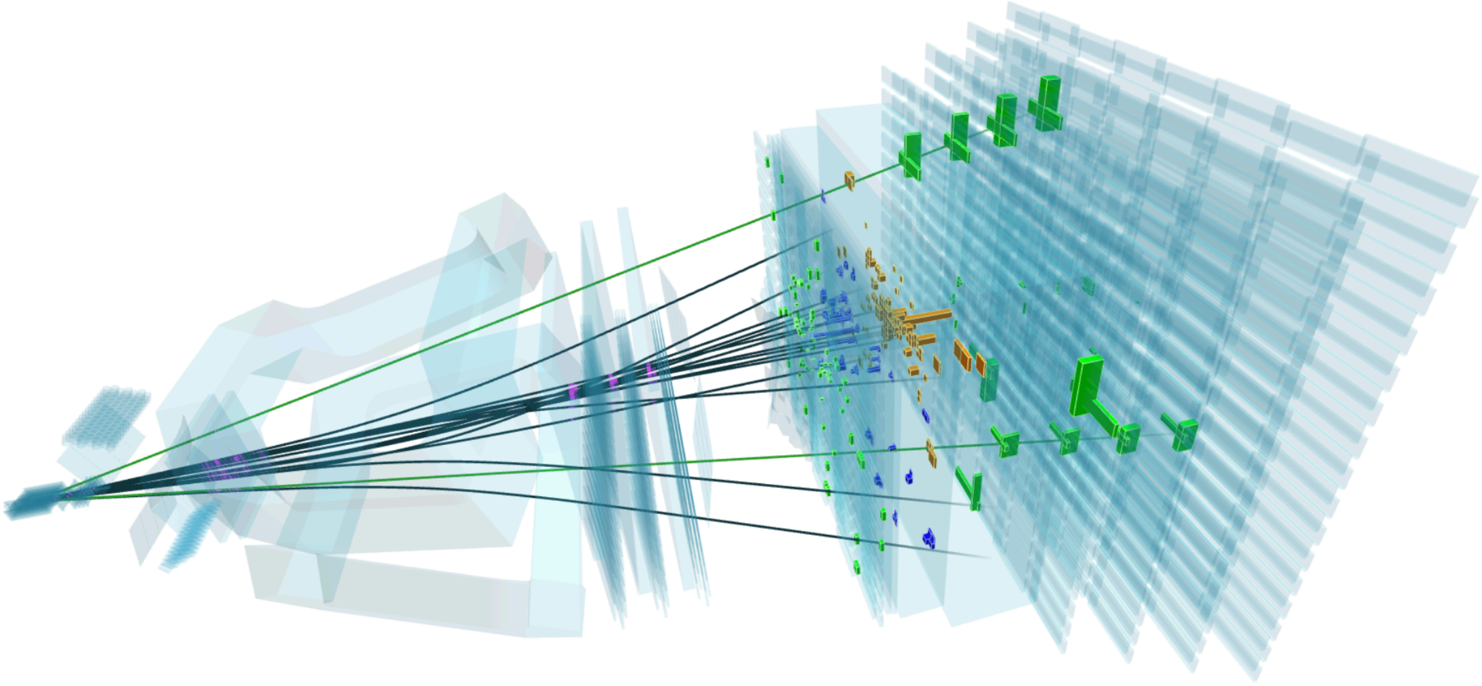


Precision instrumentation of forward region by LHCb means experiment also able to operate as a "General Purpose Forward Detector" in addition to performing heavy flavour physics studies.

Jets at LHCb

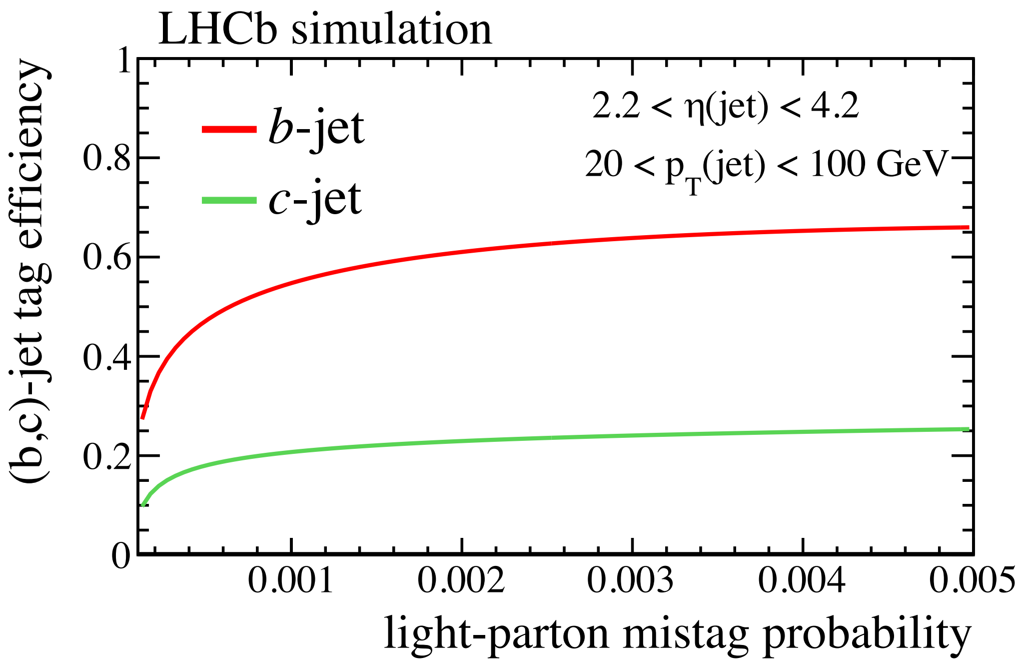
- High energy collisions typically produce collimated “streams” of particles – “jets”.

- To operate as a “General Purpose Forward Detector” it is crucial to reconstruct jets.



Jets at LHCb

- Reconstruct jets of particles by taking input particles from across the detector.
  - Remove potential double counting of particles on case-by-case basis, using full detector information.
- Cluster neighbouring particles into jets
  - For $20 < p_T$ (jet) < 100 GeV, p_T resolution is ∽ 10-15%.
- Able to classify ("tag") jets based on their content.
  - Able to separate jets containing Beauty and Charm hadrons.
  - For light jet mis-ID rate of ∽0.3%, achieve b-tag efficiency of ∽65% and a c-tag efficiency of ∽25%.



LHCb physics [a personal view]

- Measurements of matter/antimatter differences in Heavy Flavour hadron decays.
  - *Are our measurements of matter/antimatter asymmetries (CP violation) consistent with the Standard Model? If not, then we have evidence for New Physics.*
- Measurement of (rare) processes that are (relatively) suppressed in the Standard Model.
  - *Is there evidence for New Physics enhancing (or further suppressing) these processes?*
- Measurement of the properties of hadrons.
  - *Are measurements of these decays in agreement with predictions?*
  - *How do such hadrons fit into our understanding of the quark model?*
- Studies using the unique angular coverage of LHCb to probe physics beyond Heavy Flavour.
  - *e.g. Are measurements of the electroweak sector consistent with the Standard Model – can we indirectly see evidence for new physics?*
  - *e.g. Can we better understand QCD, for example through measuring jets and their content?*
  - *e.g. But also direct searches and tests: can we observe new particles, such as dark photons?*

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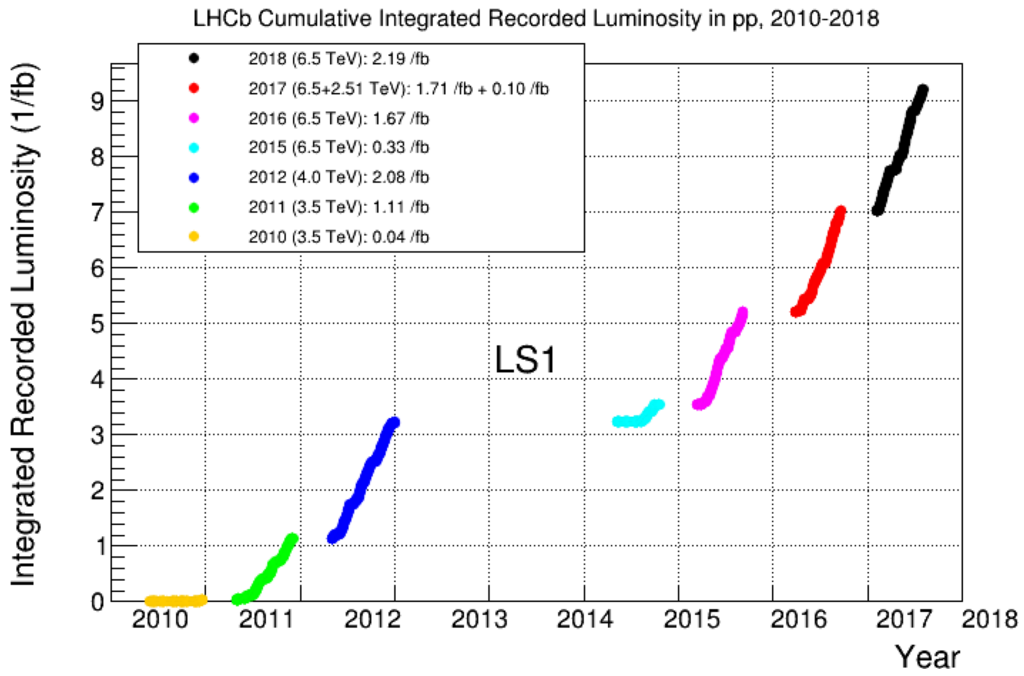
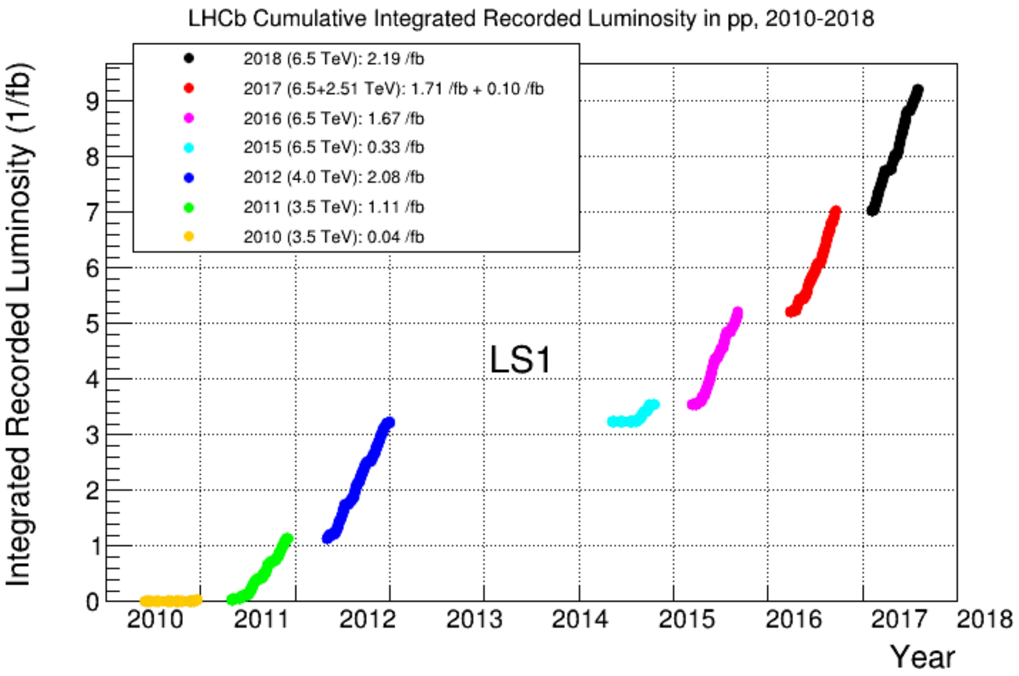
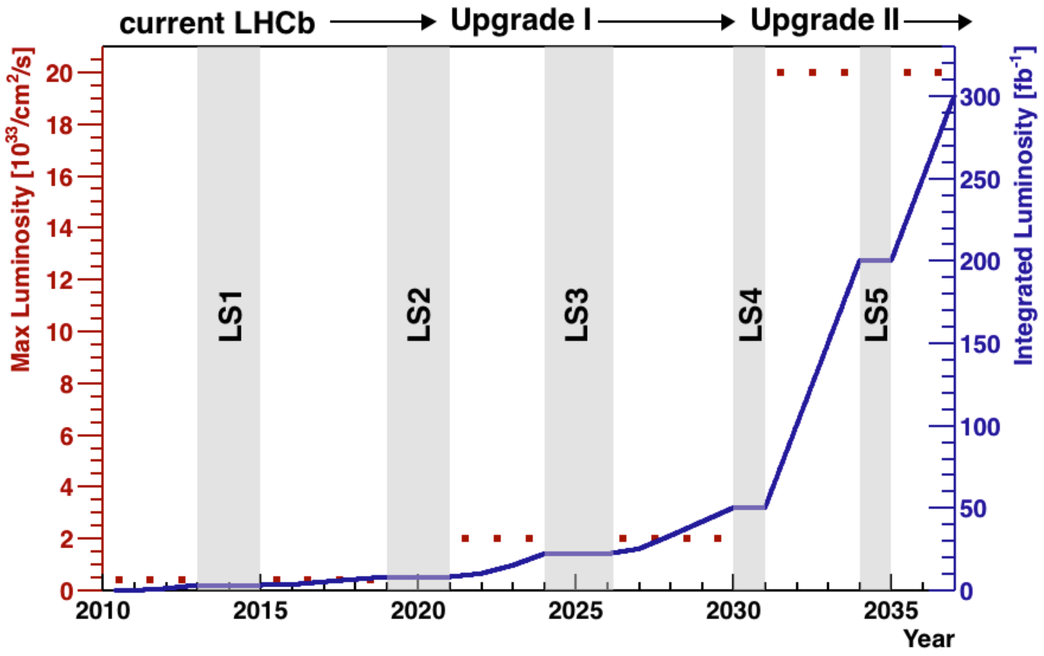
The data collected…



…and to come…



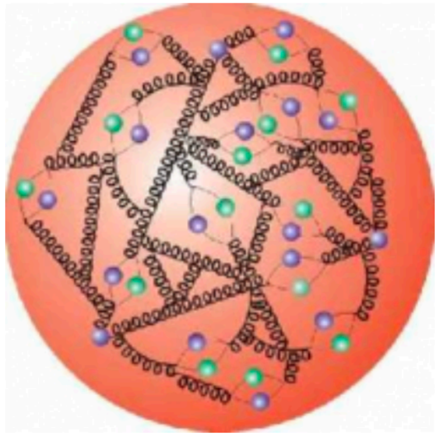


With increased data volumes, we are able to make more precise measurements – we are on the cusp of a new high precision era.

Anatomy of LHC collisions

- 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 PDF uncertainties).
- Since we can probe QCD with $\mathcal{O}$(%) level measurements, these studies are often among the first made.
- QCD is important:
  1. an inherently interesting topic – a key sector of the Standard Model.
  2. if we are to get precision information about the other fundamental interactions from proton-proton collisions, we first need to understand QCD.

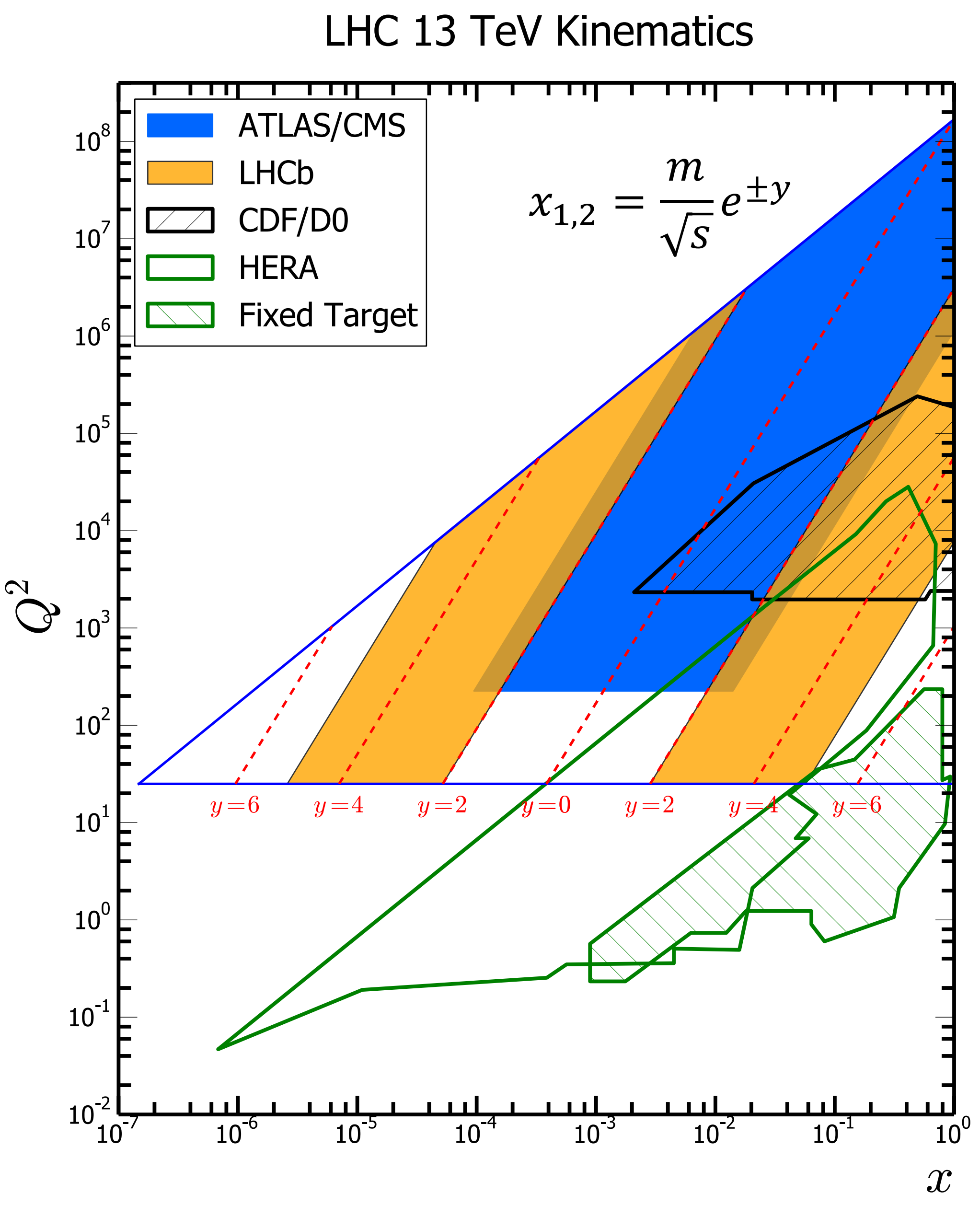
Collisions at LHCb

- Collisions in the LHCb acceptance are boosted 'forward':
  - One colliding parton has large momentum; the other has small momentum.
  - Collisions involve high-x and low-x partons.

    (x is the fraction of the proton momentum carried by the colliding parton)

- At leading order (no p_T), to produce a particle of mass *m* at rapidity *y*:

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

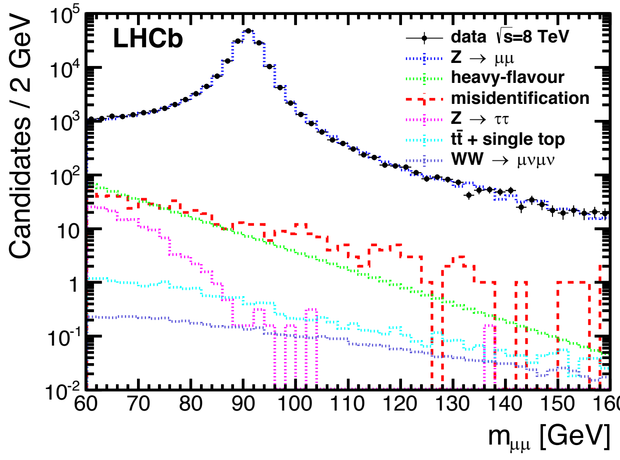


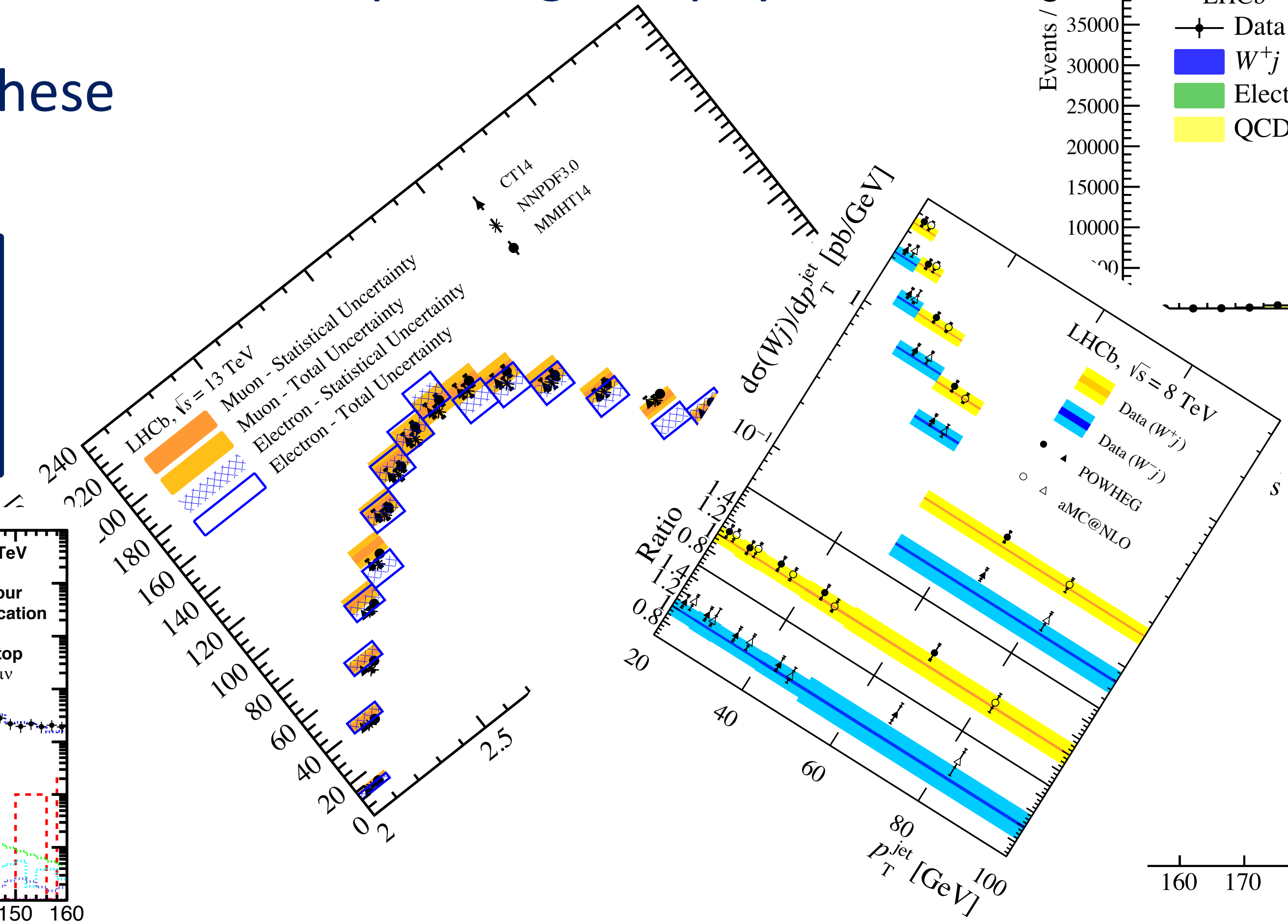
LHCb measurements

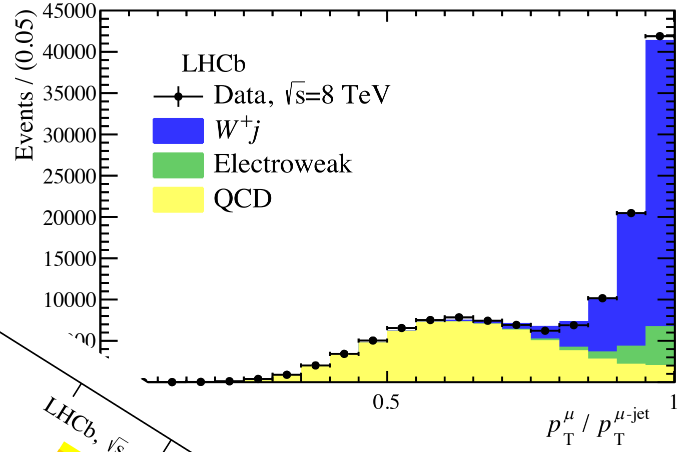
A large set of measurements at LHCb probing this physics!

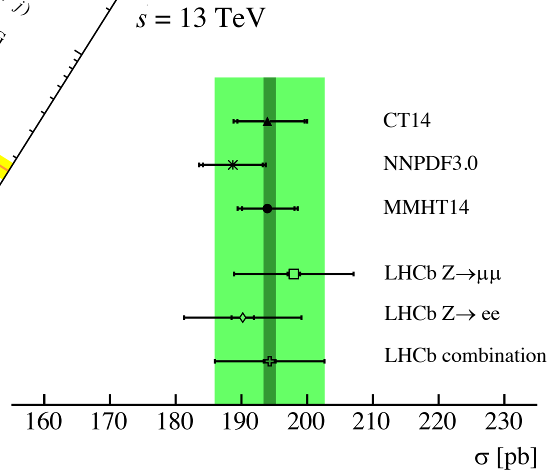
Will consider some of these measurements.

$\sigma_{\text{total, LHC}} \sim 100\ \text{mb}$
$\sigma_{Z\to ll,\ \text{LHCb}} \sim 200\ \text{pb}$
$\sigma_{W\to l\nu,\ \text{LHCb}} \sim 4000\ \text{pb}$









Measuring W and Z bosons at LHCb

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

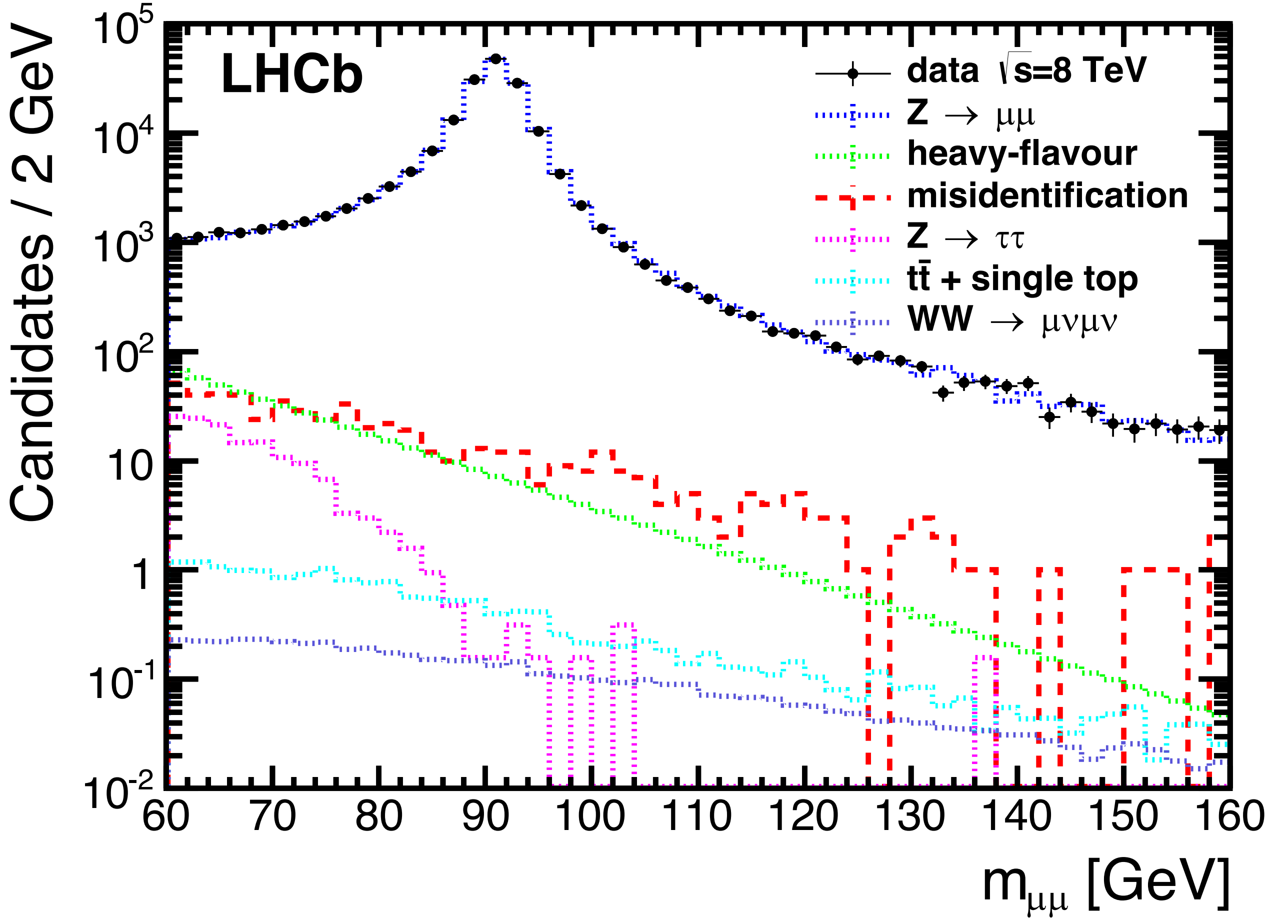
$$p_T > 20\ \text{GeV};\ 2.0 < \eta < 4.5$$

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

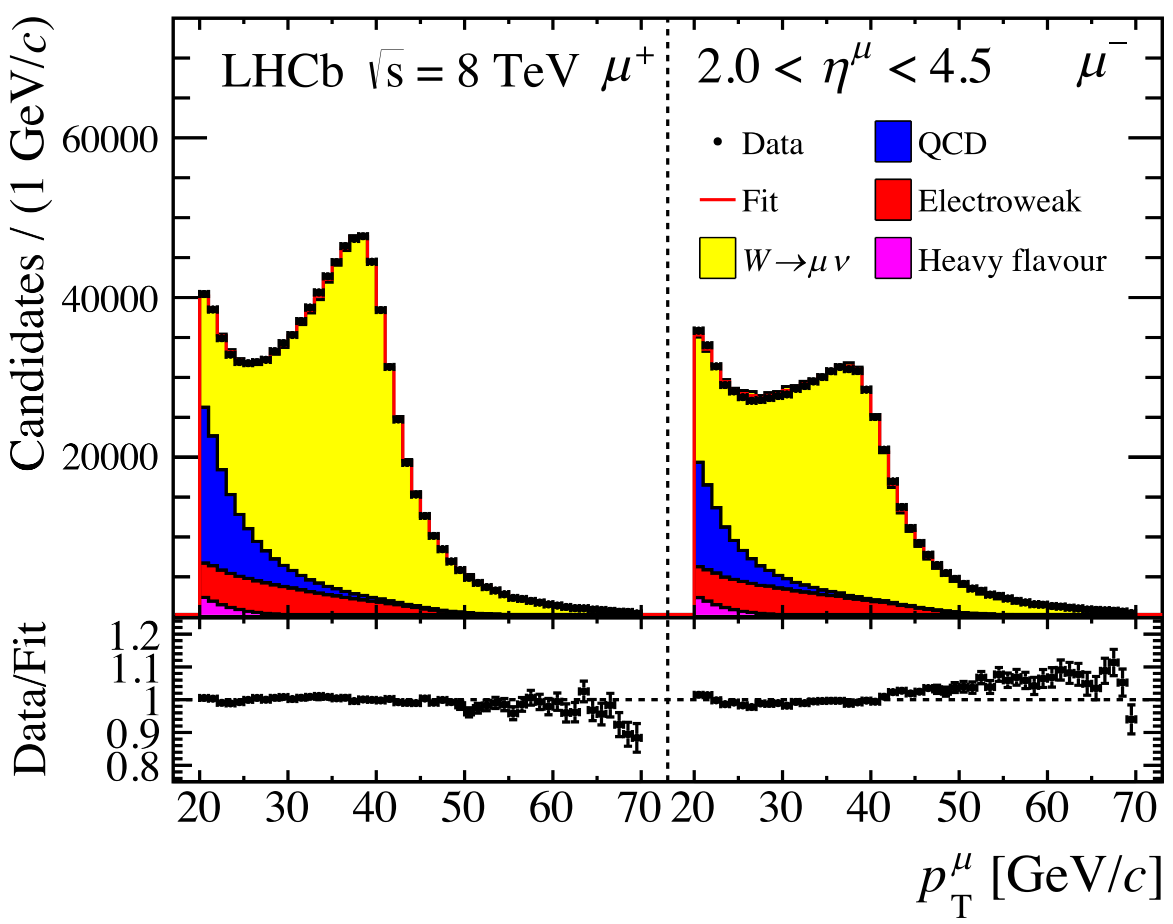
- Also place standard reconstruction quality requirements, require events are responsible for trigger selection.
- For muons produced in the decay of EW bosons, momentum resolution is $\sim 1\%$.

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

Measuring W and Z bosons at LHCb



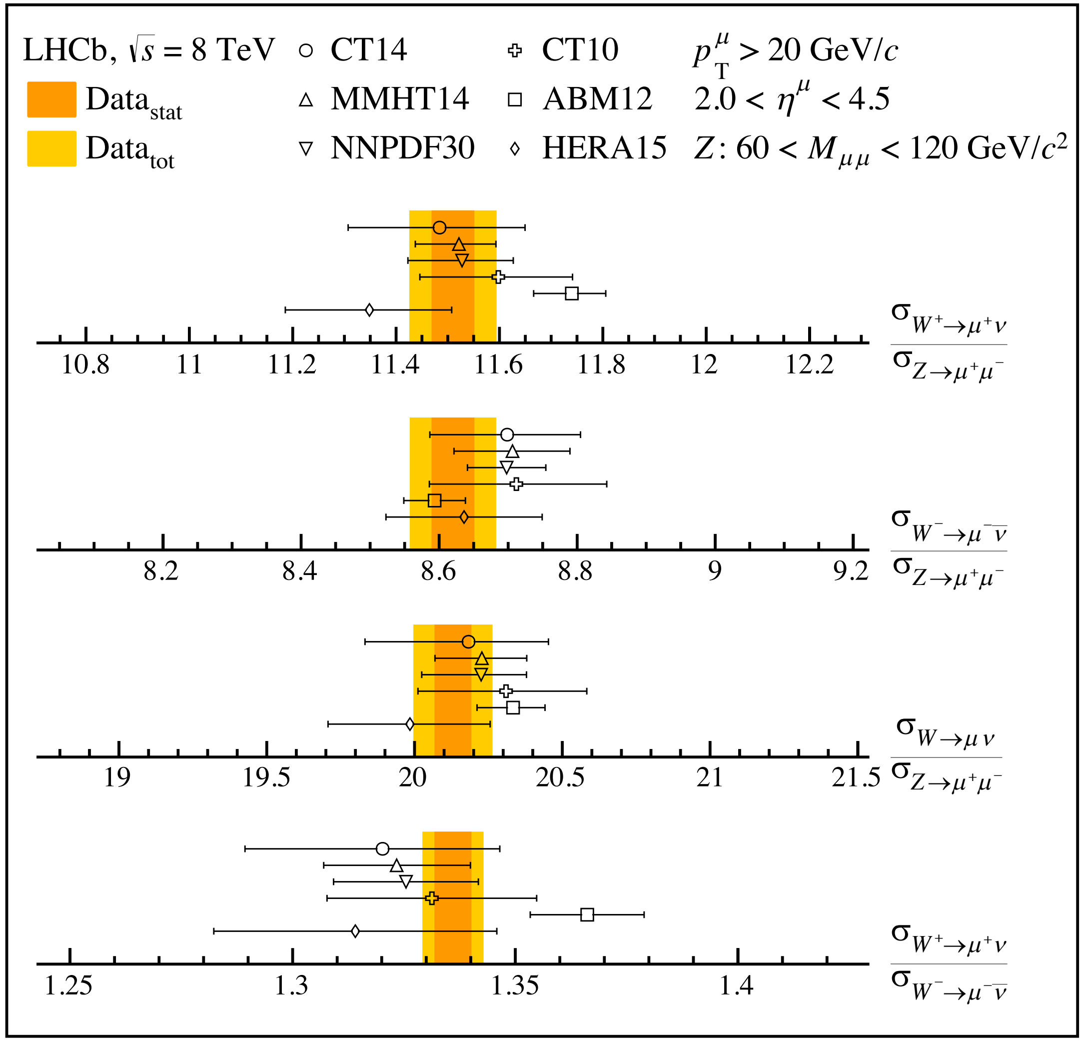
Z selection: >99% purity



W selection: ~80% purity

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)



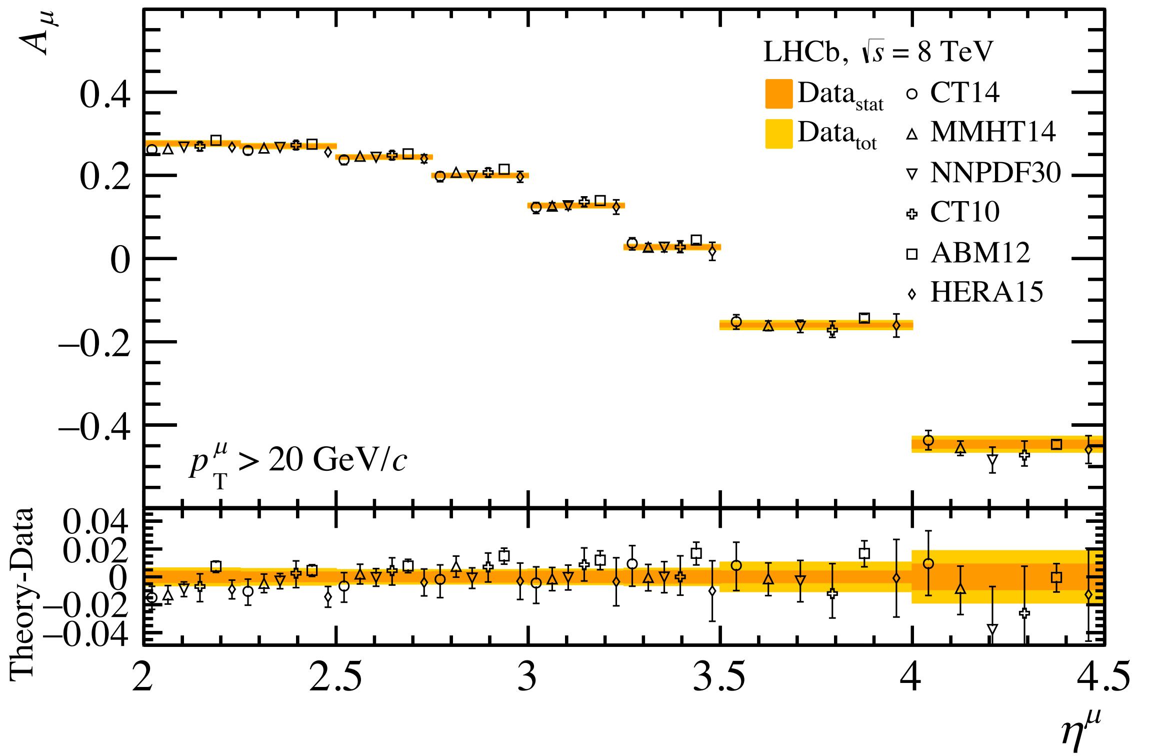
W charge asymmetry

- Measure the relative cross-sections for W^+ and W^- production where the decay muons are produced inside LHCb.

- $$A = \frac{\frac{d\sigma_{W+}}{d\eta} - \frac{d\sigma_{W-}}{d\eta}}{\frac{d\sigma_{W+}}{d\eta} + \frac{d\sigma_{W-}}{d\eta}}$$

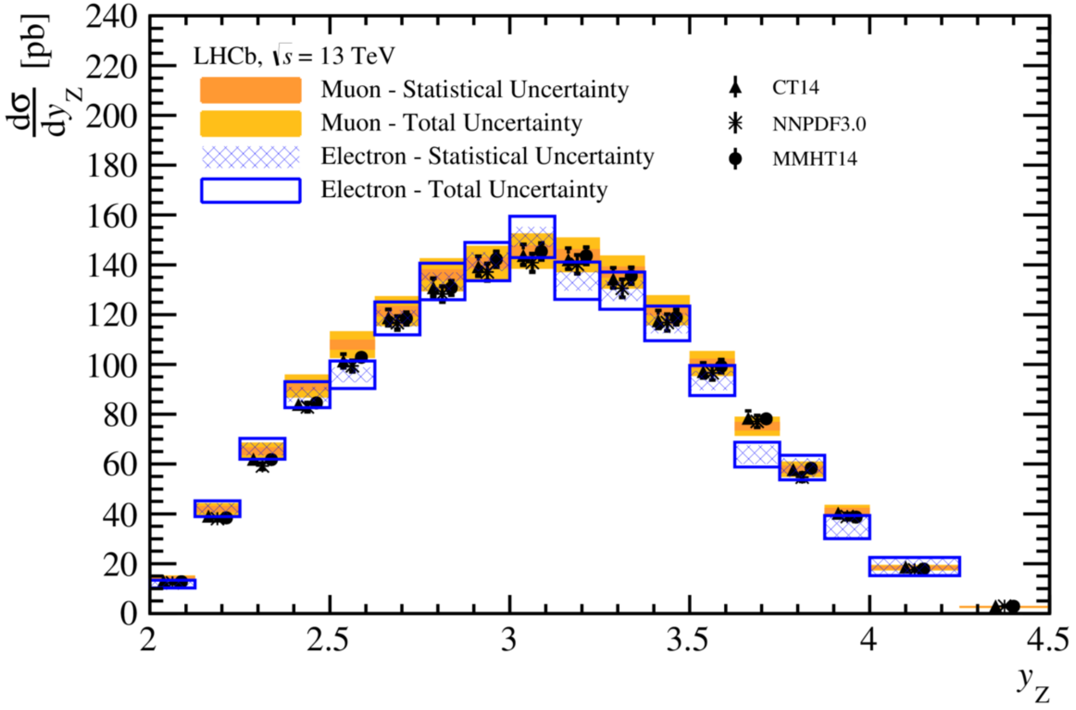
- Extremely sensitive to ratio of up and down PDFs.

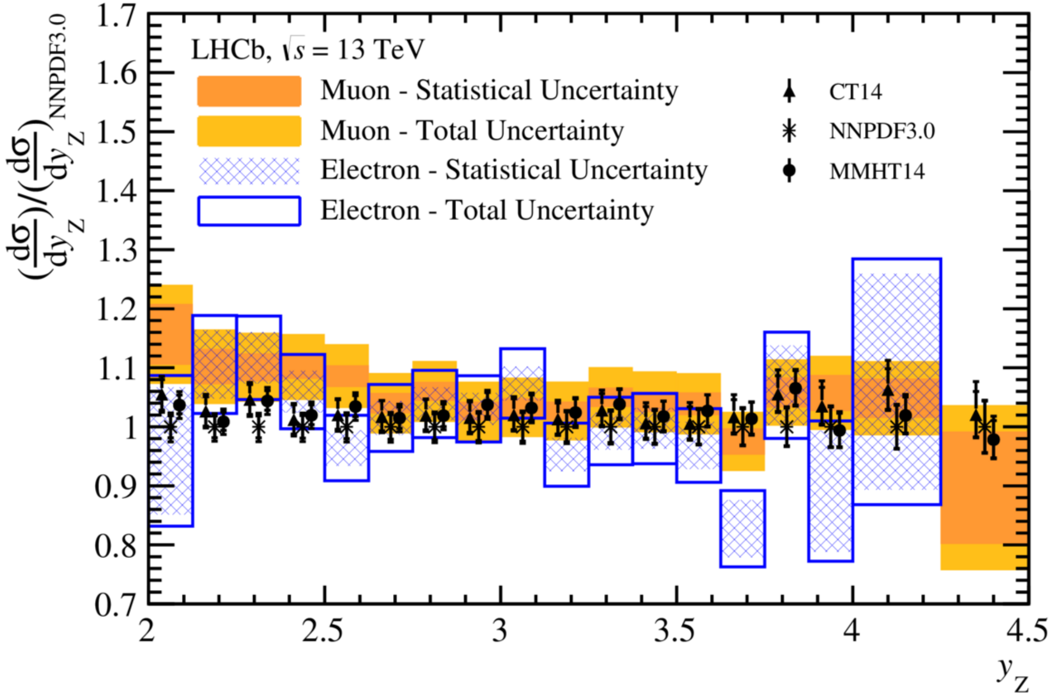
- Variation with the lepton pseudorapidity arises from PDFs and V-A structure of the weak force.



Z boson rapidity

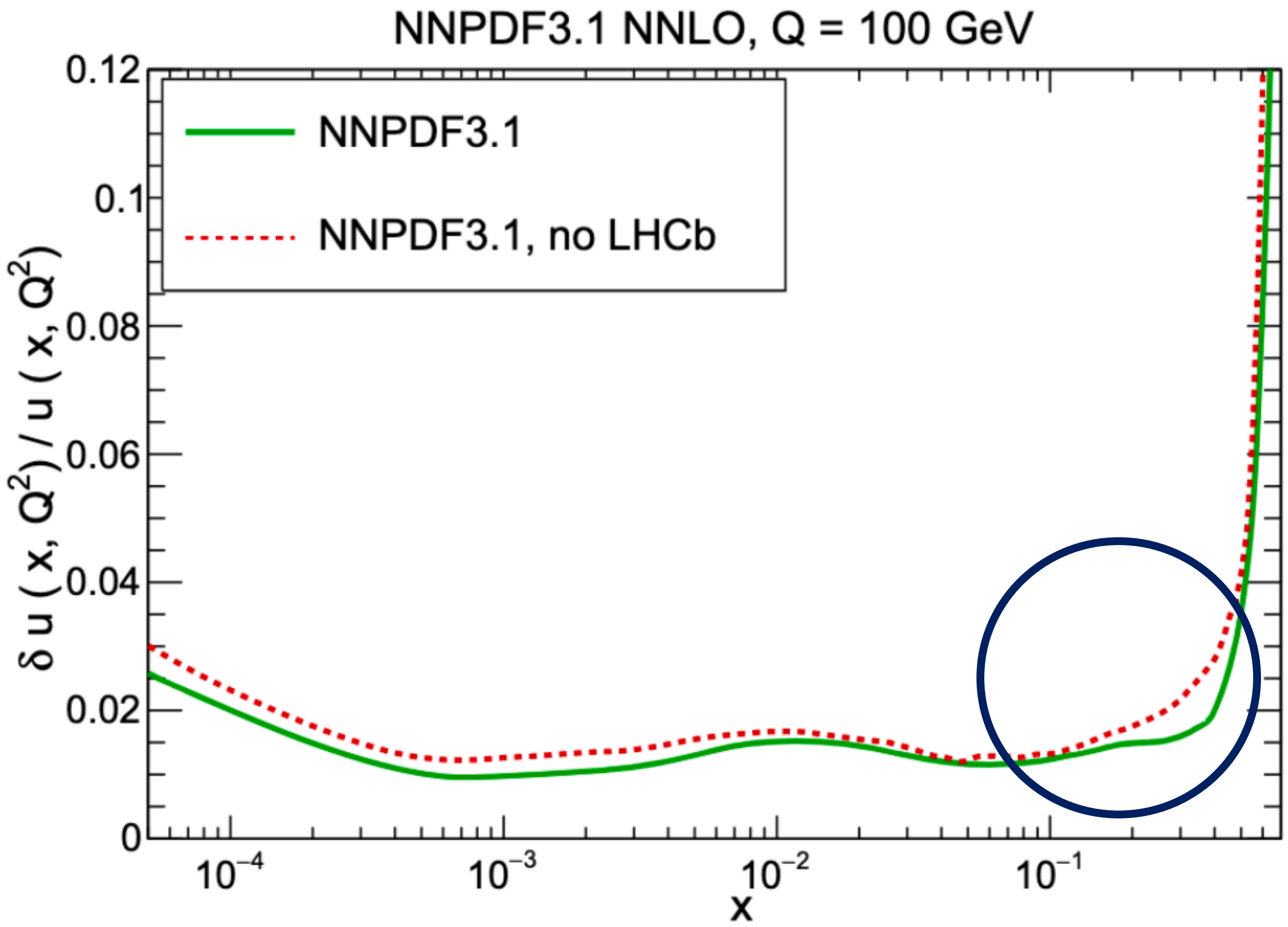
- Also offers sensitivity to quark PDFs.
- Distribution also shows significant dependence on angular structure of Z boson decays.





LHCb measurements – impact on PDFs

- LHCb results routinely included in global fits to data to extract PDFs – shown here NNPDF.
- Up to factor two reduction of uncertainties at high-*x*, with 10-20% reduction at other *x* values (in addition to ATLAS/CMS impact).

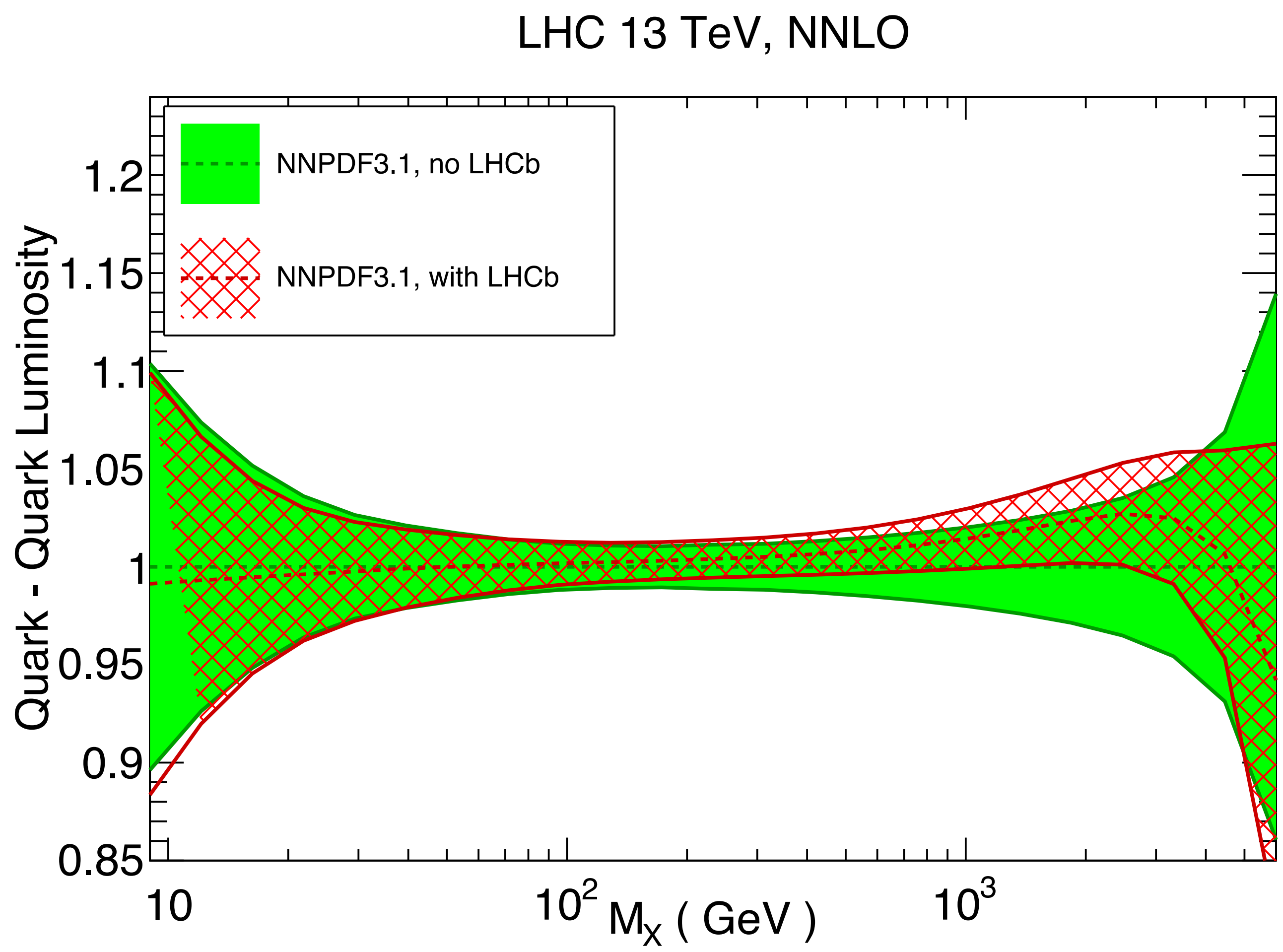


NNPDF collab., EPJC 77 (2017) 663

LHCb measurements – impact on PDFs

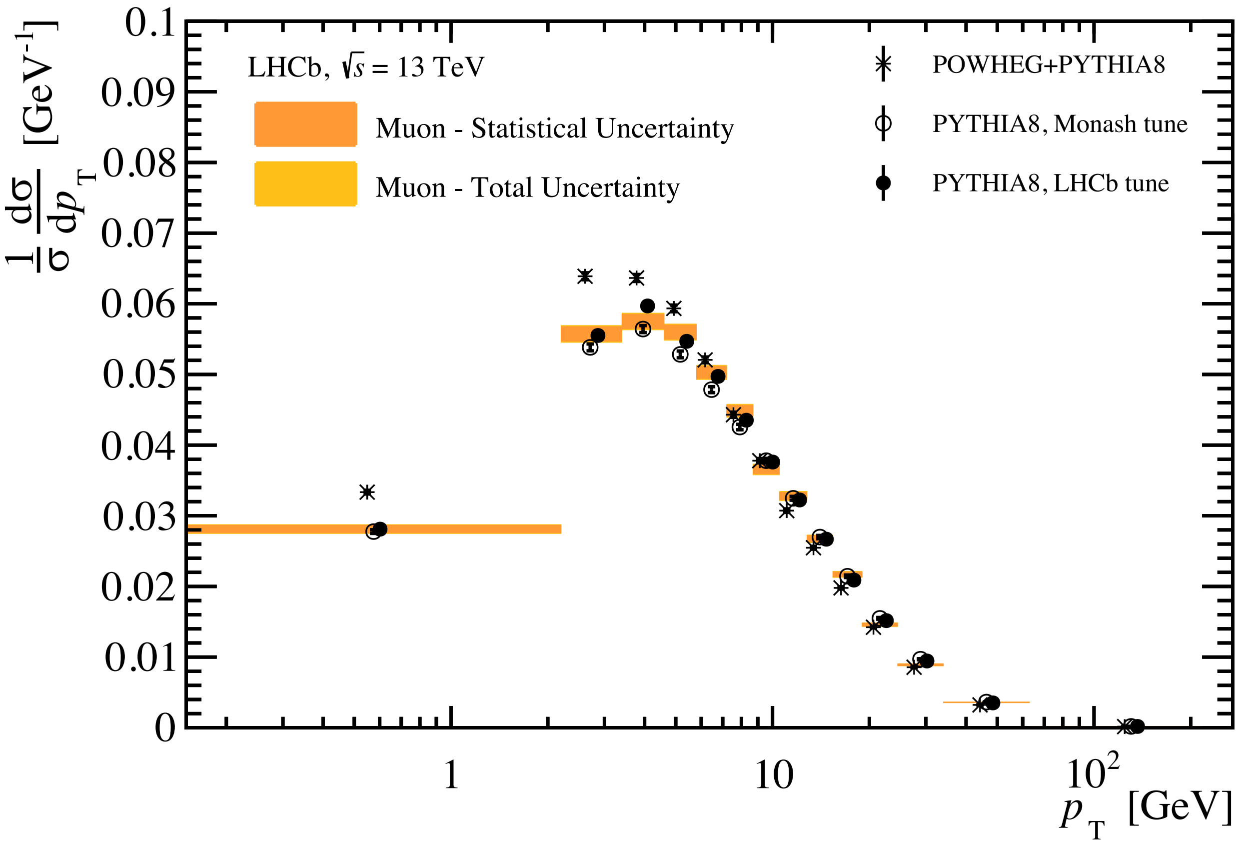
- Significant uncertainty reduction on relative $q\bar{q}$ luminosity at high masses.

- Useful input for understanding production of new states at high mass.



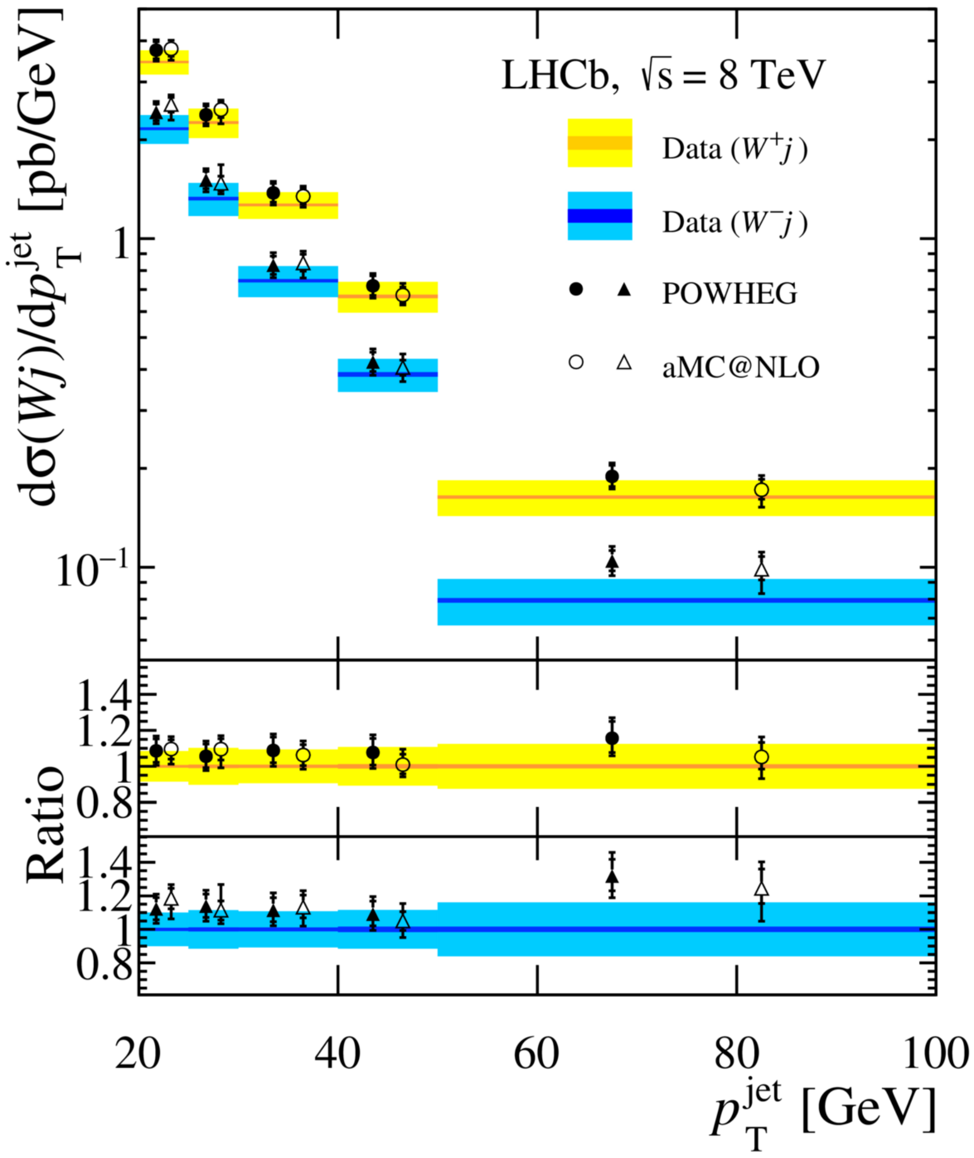
Probing QCD in the hard interaction

- Measure the p_T distribution of forward Z bosons.
- PYTHIA 8 (LO) performs much better than POWHEG BOX (NLO). Also see good agreement with RESBOS (NLO+NNLL). Similar results seen at ATLAS and CMS.
- Understanding boson p_T distribution crucial for measurements of the W boson mass – at any detector.



W, Z + jets

- Measure jet production in Z boson events.
- Compare to theoretical predictions – good agreement with NLO + PS predictions.
- Key measurement: unlocks other studies e.g. Top @ LHCb.



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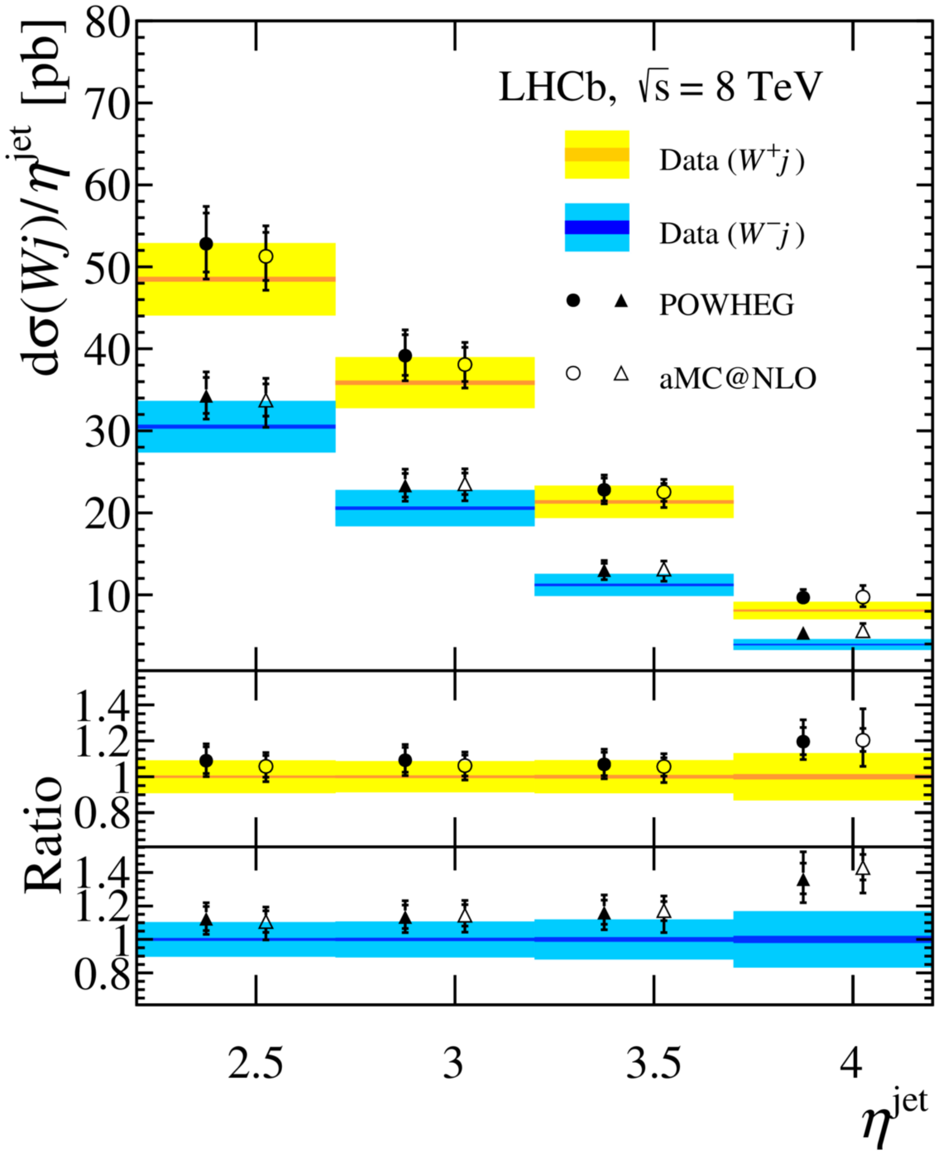


More details at
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

Selected LHCb Measurements

- Wide selection of measurements at different $\sqrt{s}$ and for different final states – including:
  - $Z \to \mu\mu$ JHEP 09 (2016) 136, JHEP 01 (2016) 155, JHEP 08 (2015) 039, JHEP 06 (2012) 058
  - $Z \to ee$ JHEP 05 (2015) 109, JHEP 02 (2013) 106
  - $Z \to \tau\tau$ JHEP 09 (2018) 159, JHEP 01 (2013) 111
  - $W \to \mu\nu$ JHEP 01 (2016) 155, JHEP 12 (2014) 079
  - $W \to e\nu$ JHEP 10 (2016) 030
  - Z + jets, W + jets JHEP 05 (2016) 131, JHEP 01 (2014) 33
  - Z + HF, W + HF PLB 767 (2017) 110, PRD 92 (2015) 052001, JHEP 01 (2015) 064, JHEP 04 (2014) 091
  - $Z \to b\bar{b}$ PLB 776 (2018) 430

Studying the Standard Model at EW scales

- Measurements of production cross-sections and ratios:
  - small deviations from predictions can be challenging to interpret in terms of New Physics – theory uncertainties are typically large.
  - Percent-level measurements extremely useful for the study of QCD phenomenology, and can be made with relatively little data.

- High Precision Measurements:
  - to interpret (typically) sub-percent precision, we first need to understand and control larger theory effects (e.g. those arising in QCD).
  - If this is possible, these measurements can then have a very clear interpretation – e.g. EW theory is very well understood. Consistent deviations can reasonably be interpreted as new physics, even if the effects are small.

Precision EW parameters

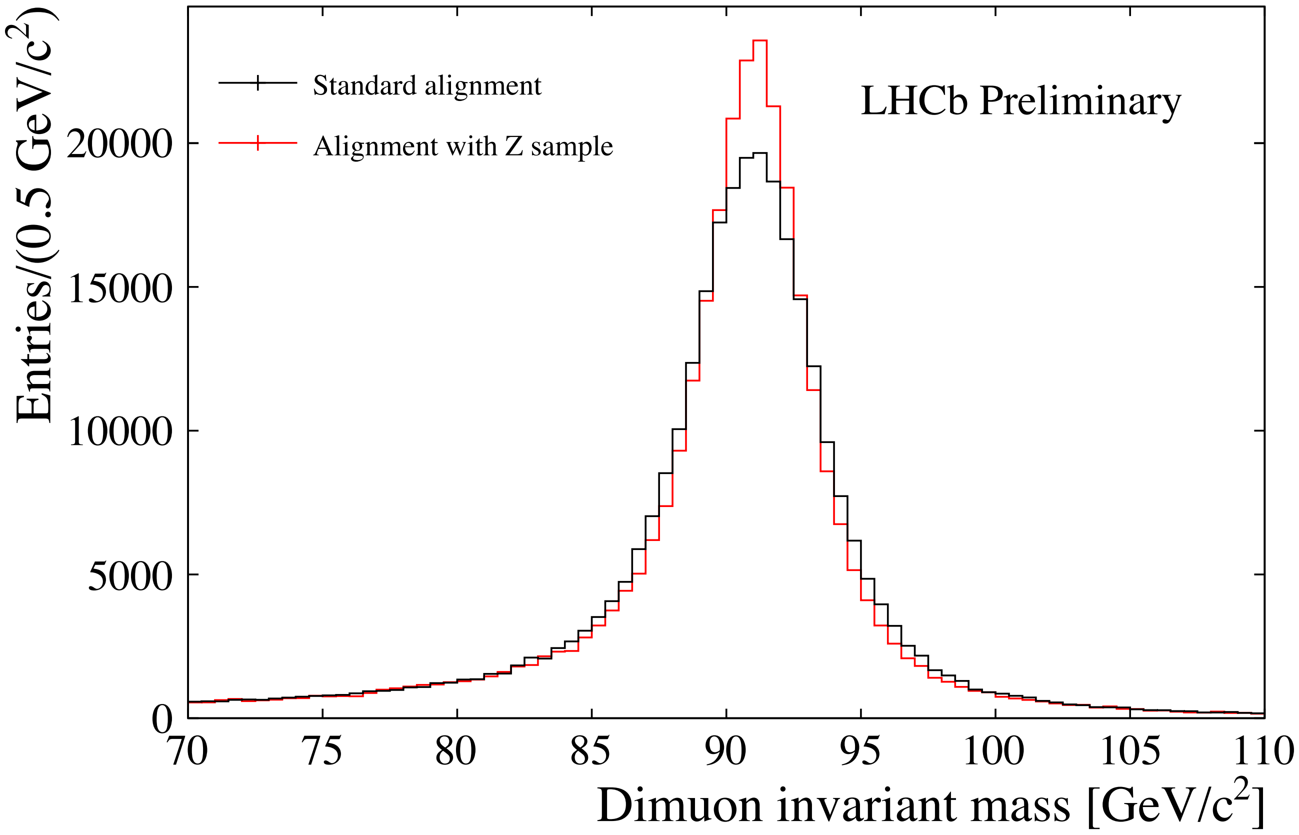
- Measurement of the W boson mass and the weak mixing angle form the next phase of (part of) this research programme.
  - Some preliminary measurements and studies, but work very much ongoing (but will be for next decade and beyond).
- The global EW fit provides sensitivity to potential new physics at multi-TeV scales – LHCb has a crucial role to play.
- To access regime of interest need large datasets – LHCb Upgrade(s) crucial.
- And understanding QCD (e.g. PDF effects) crucial – expected to provide largest theory uncertainties in precision EW measurements.

Achieving Precision

- Also need excellent understanding of detector performance.

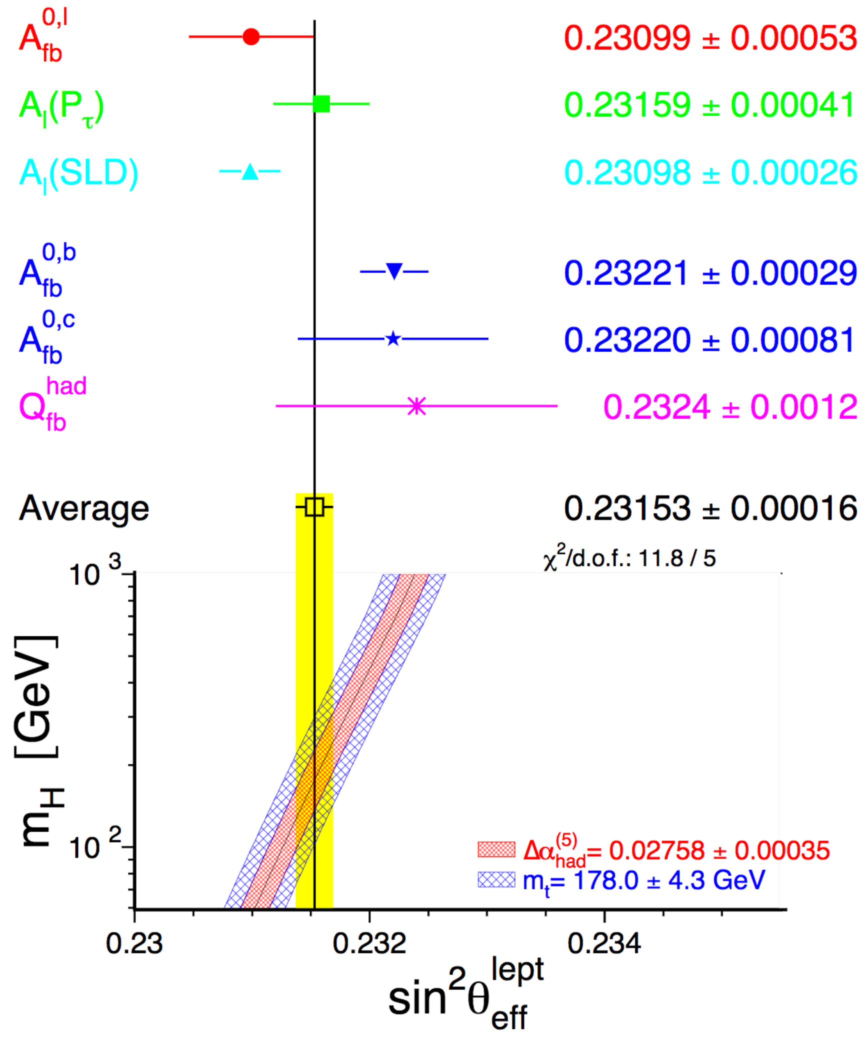
- Crucial to minimise differences (and corrections) between detector level and particle level results.

- Detector alignment revisited – invariant mass resolution improved by ~40%.



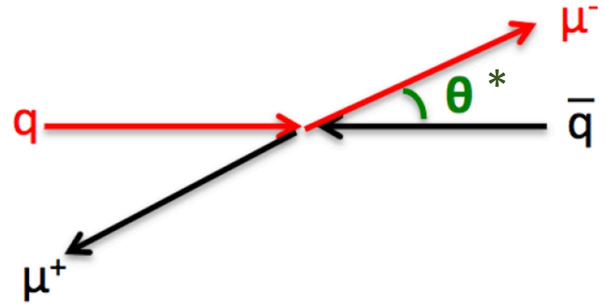
Weak mixing angle

- Encapsulates mixing of different fields in Standard Model, at heart of Electroweak theory.
- Takes a unique, process independent value – combination of measurements achieves a precision of $16{\times}10^{-5}$ on $\sin^2(\theta_W)$.
- Two most precise measurements (LEP and SLD) measured different processes at similar precision ($\sim 25 - 30 \times 10^{-5}$) – but differ by $\backsim 3\sigma$.
- Raises prospect of interaction dependence of $\sin^2(\theta_W)$ – a non-SM effect!



Measuring the weak mixing angle at the LHC

- Vector and axial-vector couplings of Z boson are determined by the weak mixing angle.



- These couplings introduce a forward-backward asymmetry at parton level (present at leading order):

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

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

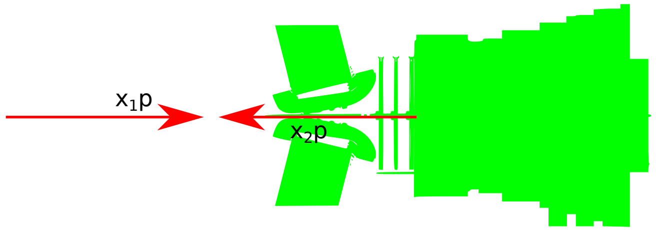
$$A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}$$

- Since the quark could be in either colliding proton at the LHC, the integrated asymmetry is zero – as is asymmetry at $y_Z = 0$. But not the case at larger rapidities.

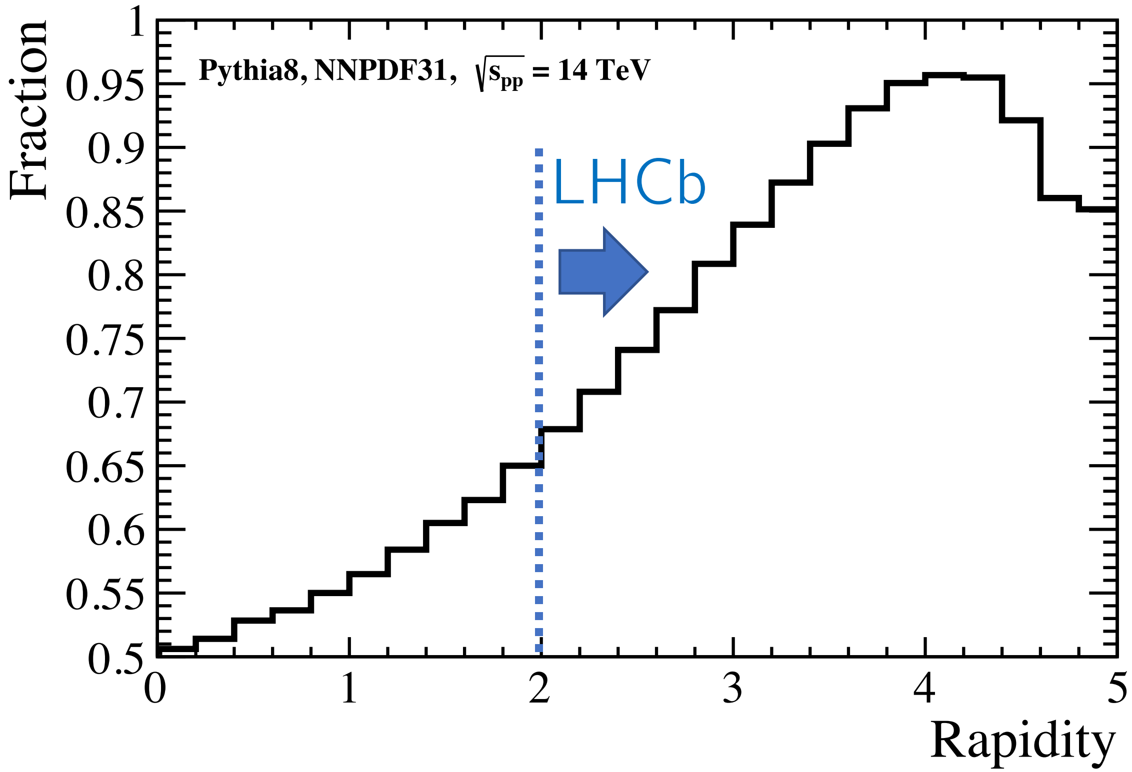
$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + {}^1/_2\,A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + \boldsymbol{A_4\cos\theta} + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$

Measuring the weak mixing angle at LHCb

- At large rapidities have asymmetric initial state:
  - One parton at high x, one parton at low x.



  - PDFs dictate that high-x parton tends to be a (valence) quark, and low x parton tend to be an anti-quark.
  - At large rapidities we therefore recover a well-defined *z*-axis about which we can measure the asymmetry.



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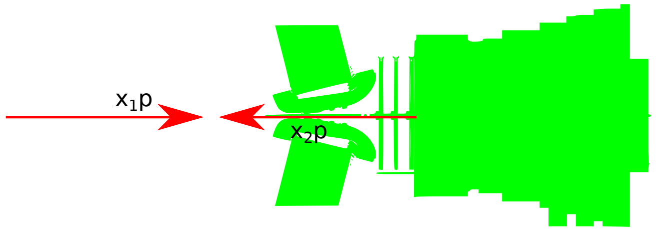

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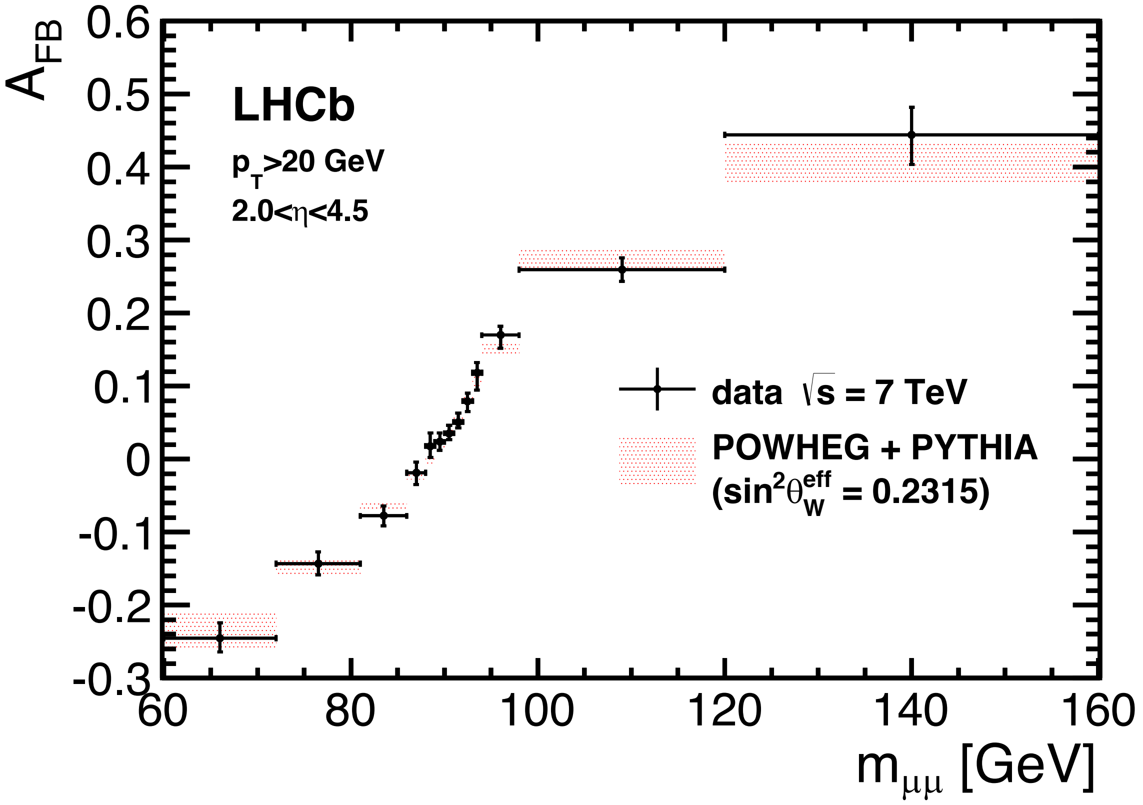


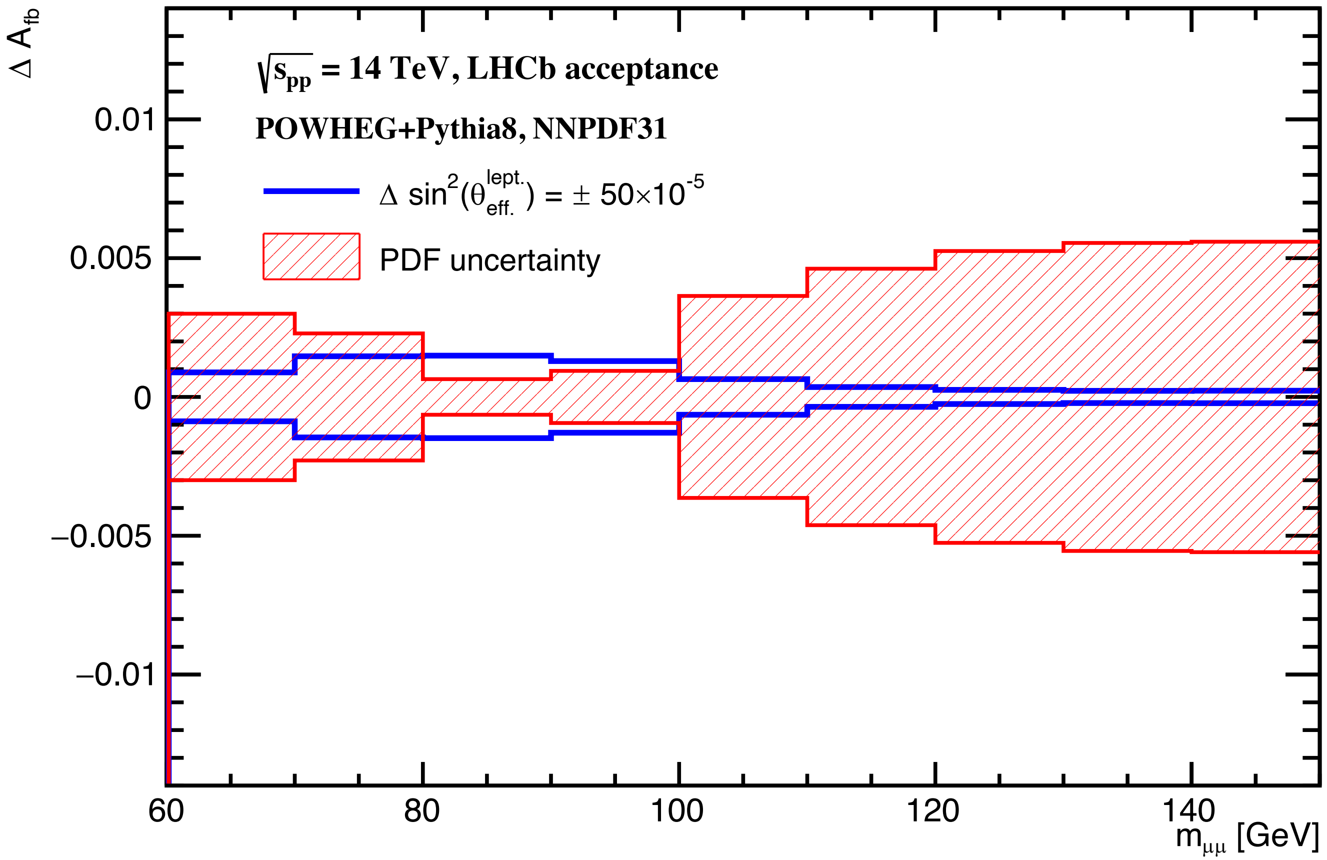
NNPDF collab., Nucl. Phys B. 849 (2011) 112 and Nucl. Phys B. 855 (2012) 608
LHCb collab., JHEP 11 (2015) 190; P. Azzi, WB, *et al.* in CERN-LPCC-2018-03

Measuring the weak mixing angle at LHCb

- LHCb has made a pathfinder measurement using Run 1 data.
  - From A_{FB} determine weak mixing angle using template fit, 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 ($\sim 30\times 10^{-5}$)

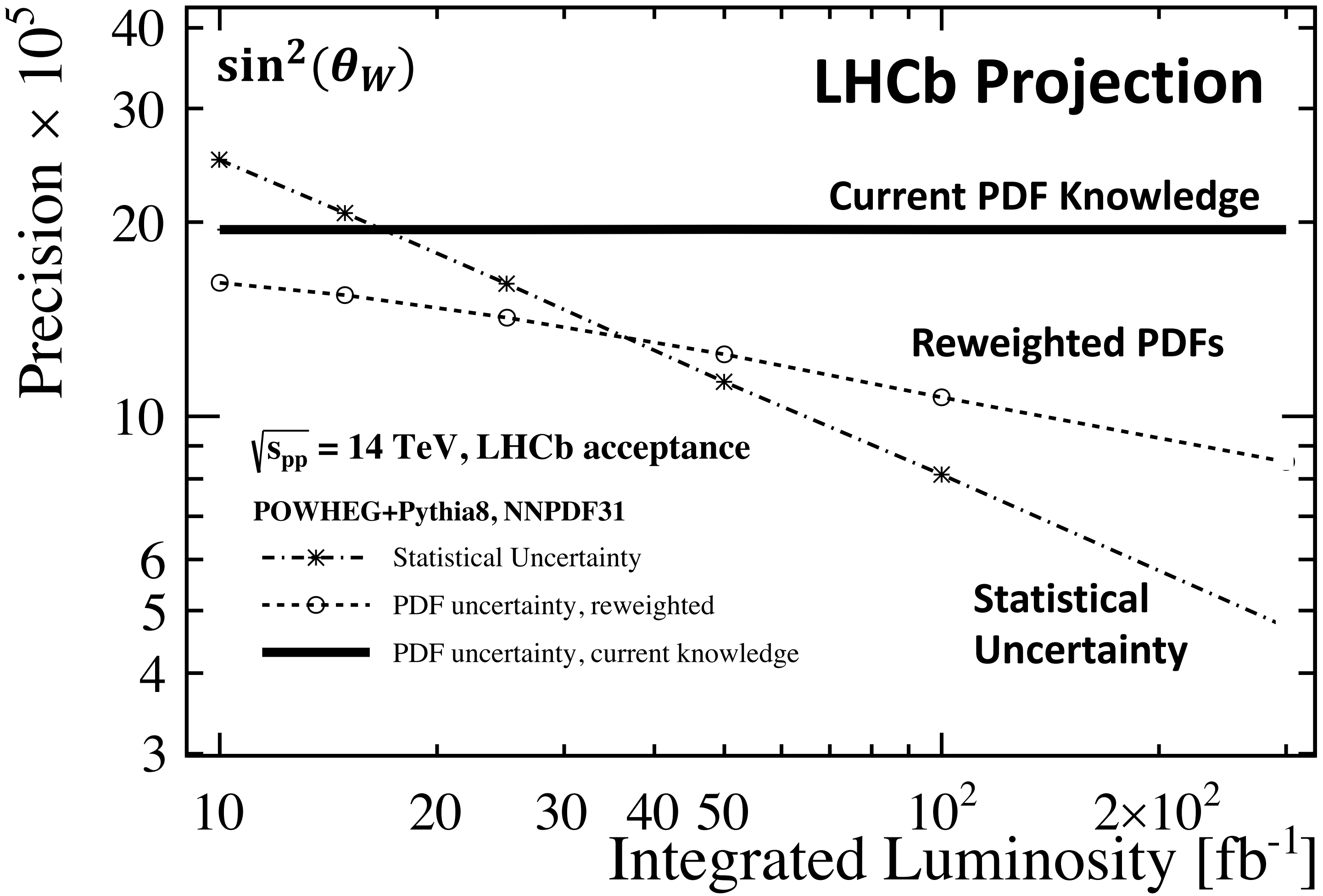
- Clear path to improve precision:
  - Larger datasets will reduce statistical uncertainties.
  - Better understanding of QCD from existing measurements.
  - Newer PDF fits – using LHCb data as inputs – have also reduced PDF uncertainty.
  - Profile over (or Bayesian reweight the) PDFs – using the data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

Measuring the weak mixing angle at LHCb



- PDF profiling/reweighting:
  - PDFs themselves bring about variations in A_{fb}, different in form to those arising from the weak mixing angle.
  - Can use the data to constrain the PDF effects.

Measuring the weak mixing angle at LHCb



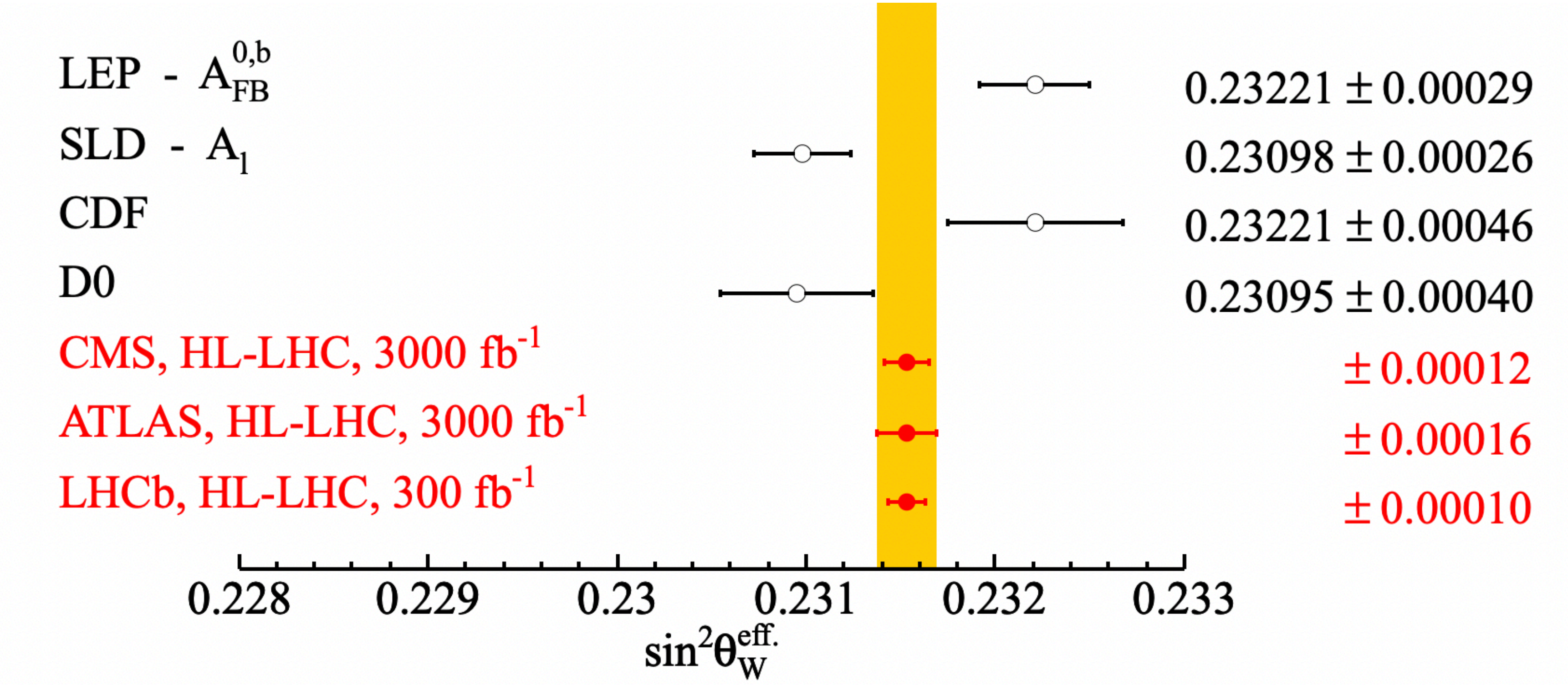
<u>Uncertainties on weak mixing angle arising from PDF knowledge:</u>

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, WB *et al.* in CERN-LPCC-2018-03

Measuring the weak mixing angle at LHCb



(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.

W boson mass at LHCb

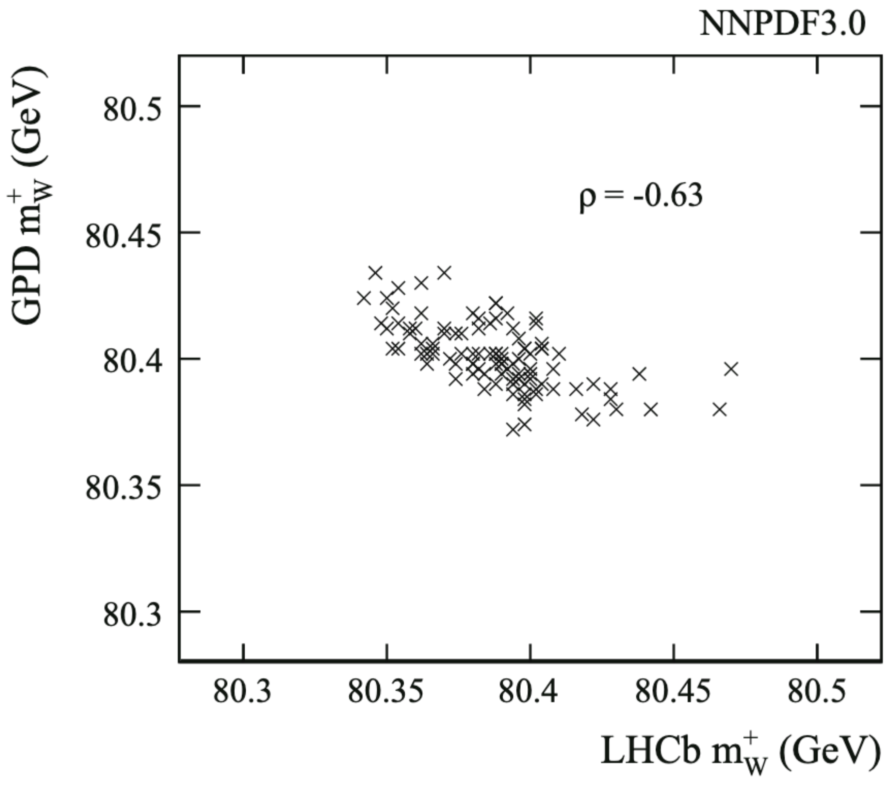
- Another crucial parameter in the Electroweak Sector.
- Direct measurements are currently a factor 2 less precise than predictions from the global electroweak fit, leaving room for new physics.

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

- Existing high precision measurements from ATLAS, D0 and CDF.
- LHC (roughly) targeting 8 MeV precision on the W boson mass.

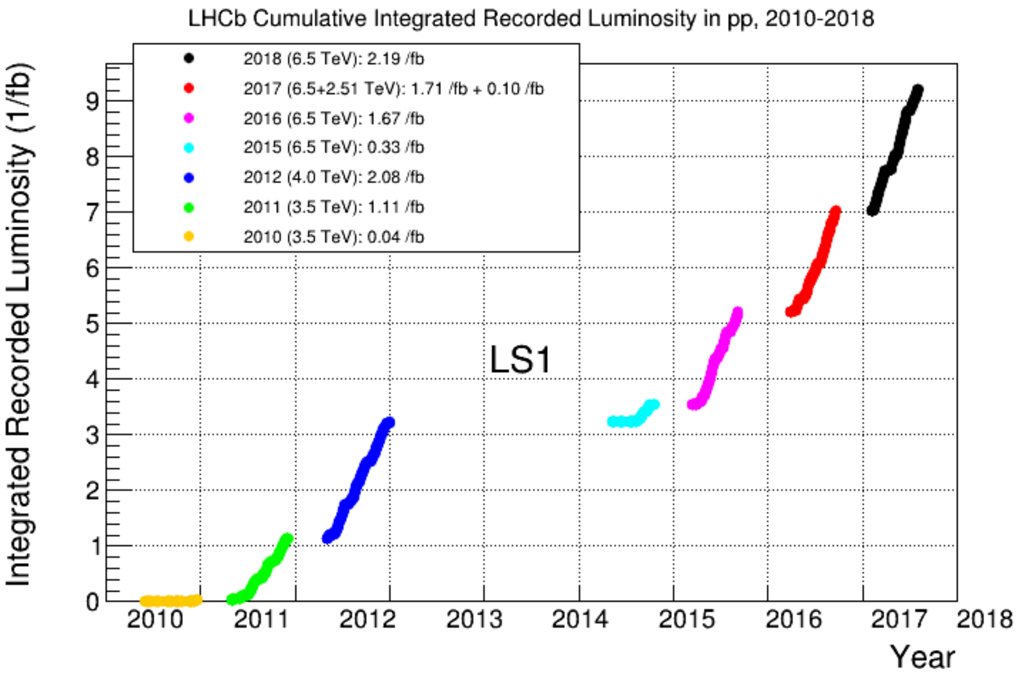
Prospects for the W boson mass at LHCb

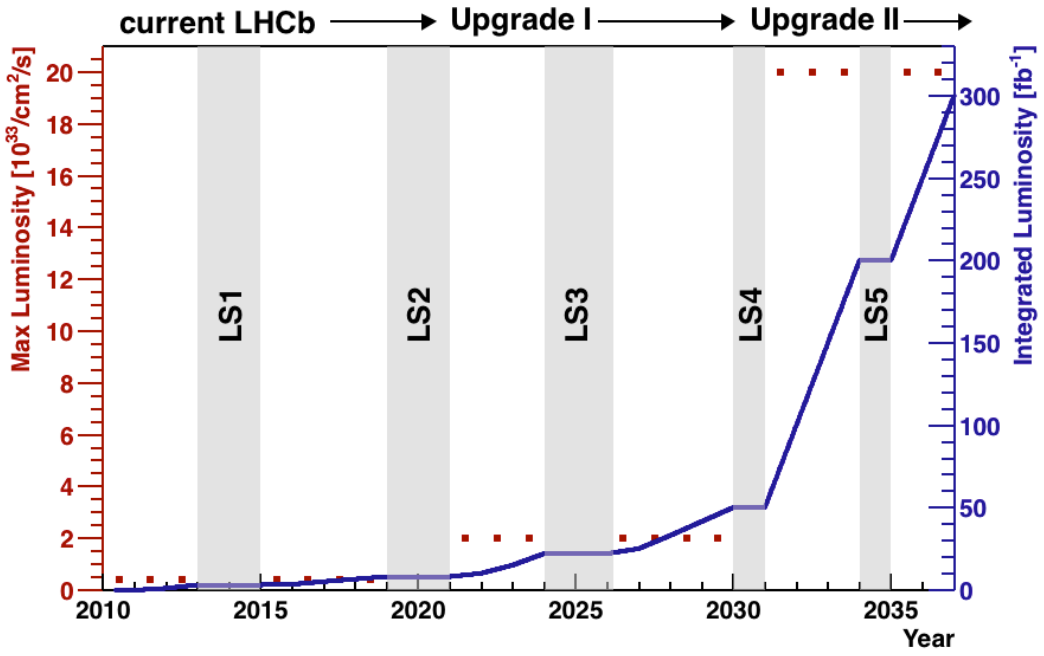
- At LHCb, lack of 4π information means we aim to determine W boson mass through a fit of the muon p_T spectrum.
- Why LHCb? PDF uncertainty anti-correlated with ATLAS/CMS – LHCb will have crucial impact in LHC-wide combination, potentially reducing the uncertainty on any LHC-wide combination by up to 30%.
- The existing dataset will allow m_W measurement with statistical uncertainty $\mathcal{O}$(10MeV), and PDF uncertainty $\mathcal{O}$(10MeV) - enabling a high precision measurement.



Analysis in Progress

Far more to come…





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

LHCb Upgrades

- 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.

LHCb collaboration, CERN-LHCC-2018-027
R. Aaij *et al.*, JINST 14 (2019) P04013

Taking stock – key dates for LHCb

2008-2010

LHC startup and initial collisions

2010-2012

LHC Run 1: pp collisions at $\sqrt{s} = 7$ and 8 TeV. Beams have 50ns bunch spacing.

2013-2015

Long Shutdown 1: Upgrade to higher energies and luminosities; LHCb Trigger Upgrade

2015-2018

LHC Run 2: pp collisions at $\sqrt{s} = 13$ TeV. Beams have 25ns bunch spacing.

2019-2022

Long Shutdown 2: Includes LHCb Upgrade I

2022-2024

LHC Run 3: LHCb achieves more than 5 times the instantaneous luminosity

2025-2027

Long Shutdown 3: Upgrade Ib for LHCb (Major Upgrade for ATLAS and CMS)

2027-2030

LHC Run 4: HL/LHC era begins. LHCb records at least 50/fb.

Early 2030s

Long Shutdown 4: LHCb Upgrade II To allow collisions in LHCb with 10 times higher lumi

2030s+

LHC Run 5+: To infinity and beyond! LHCb dataset at least 300/fb

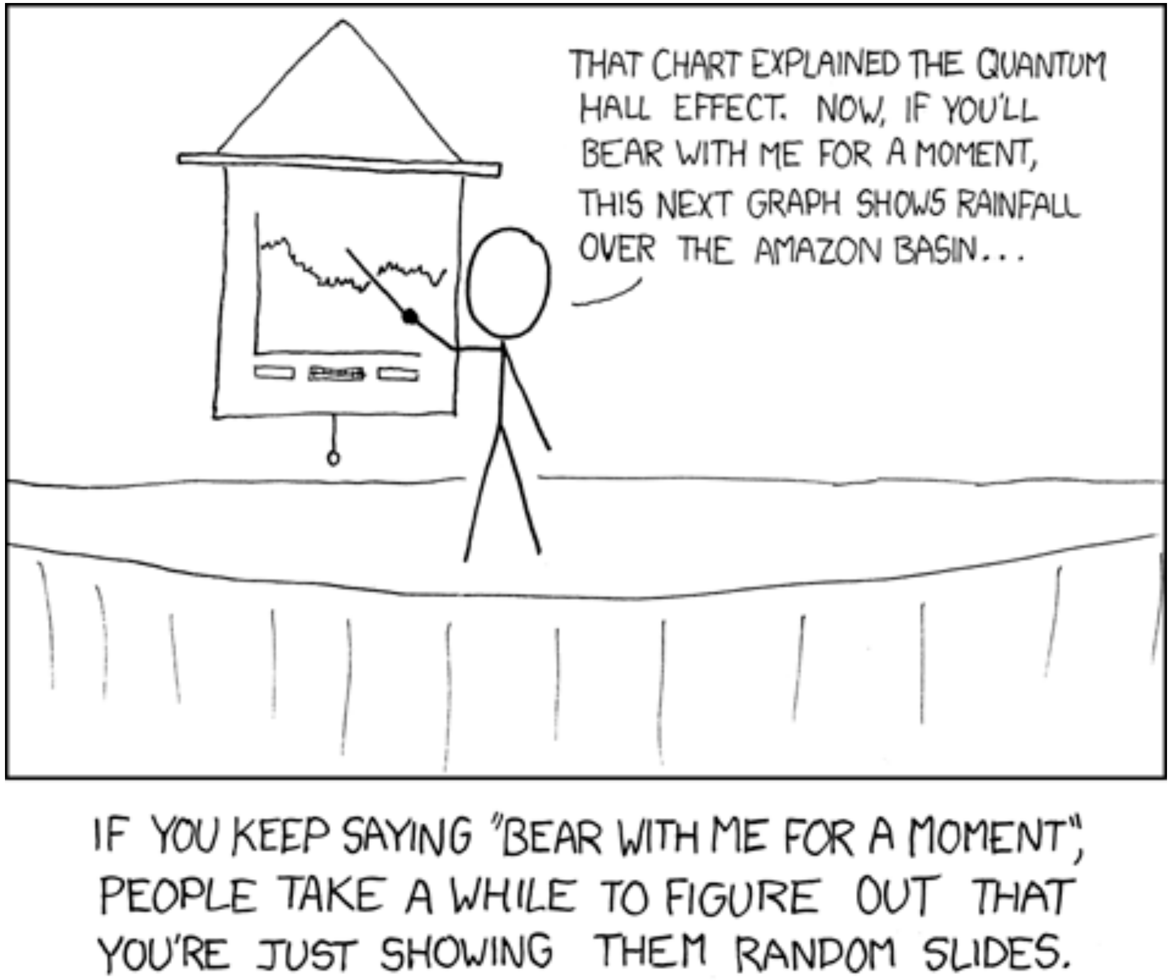
We are 10 years into a decades-long programme!

Summary

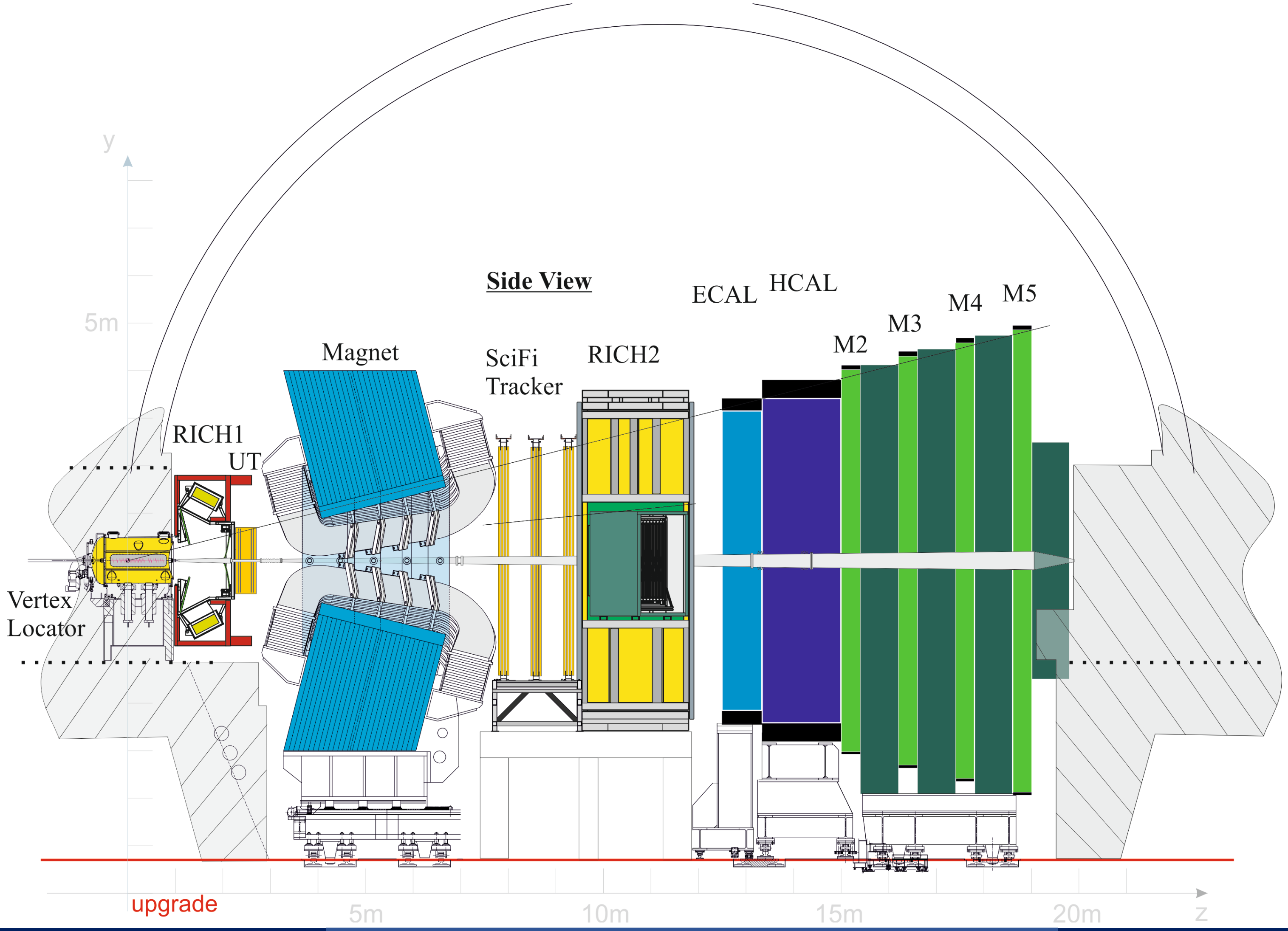
- LHCb has a diverse programme of research:
  - Designed for flavour physics, and with an impressive and key flavour physics research programme…
  - …but making important contributions to the study of QCD, Electroweak, BSM physics and more.
- Covered studies we have made using electroweak bosons:
  - With the coming upgrades, LHCb has crucial and unique role to play making precision studies.
- We are roughly 10 years into a decades-long programme – and are entering an exciting new high-precision era.

xkcd.com/365/

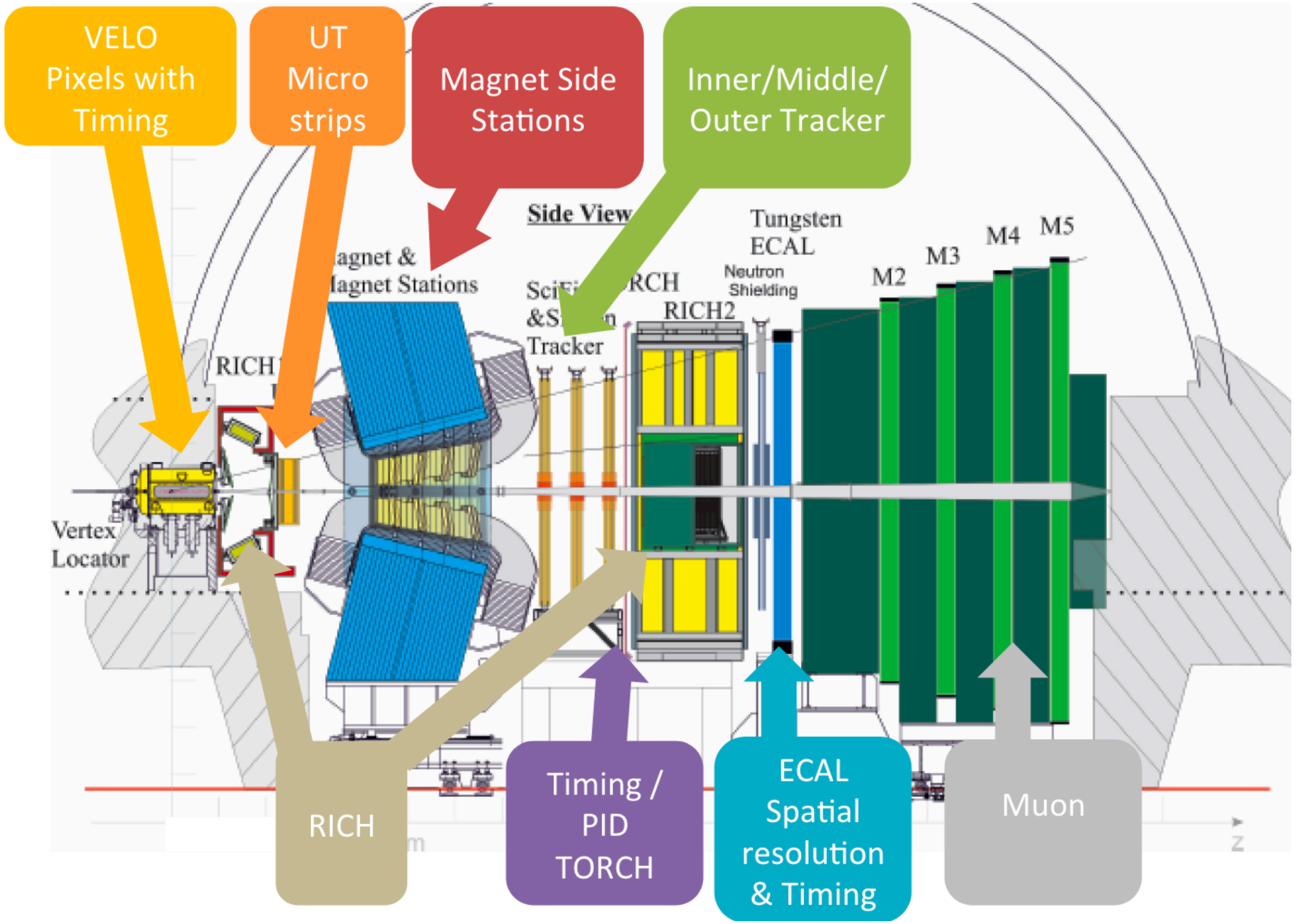
Backup Slides



Upgrade I Detector



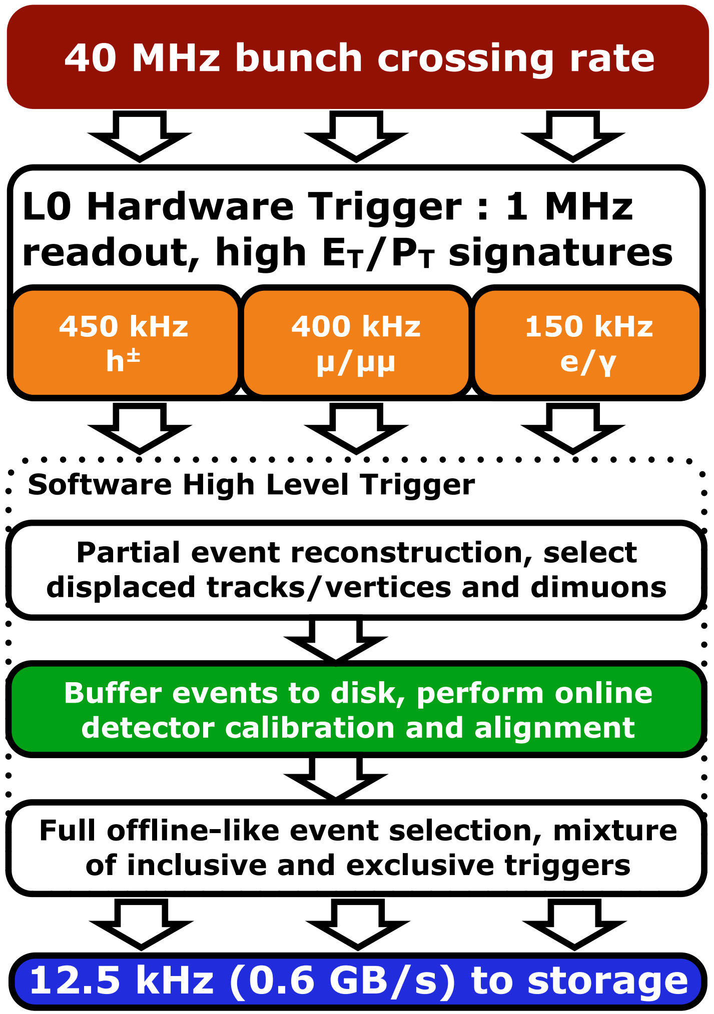
Upgrade II Detector



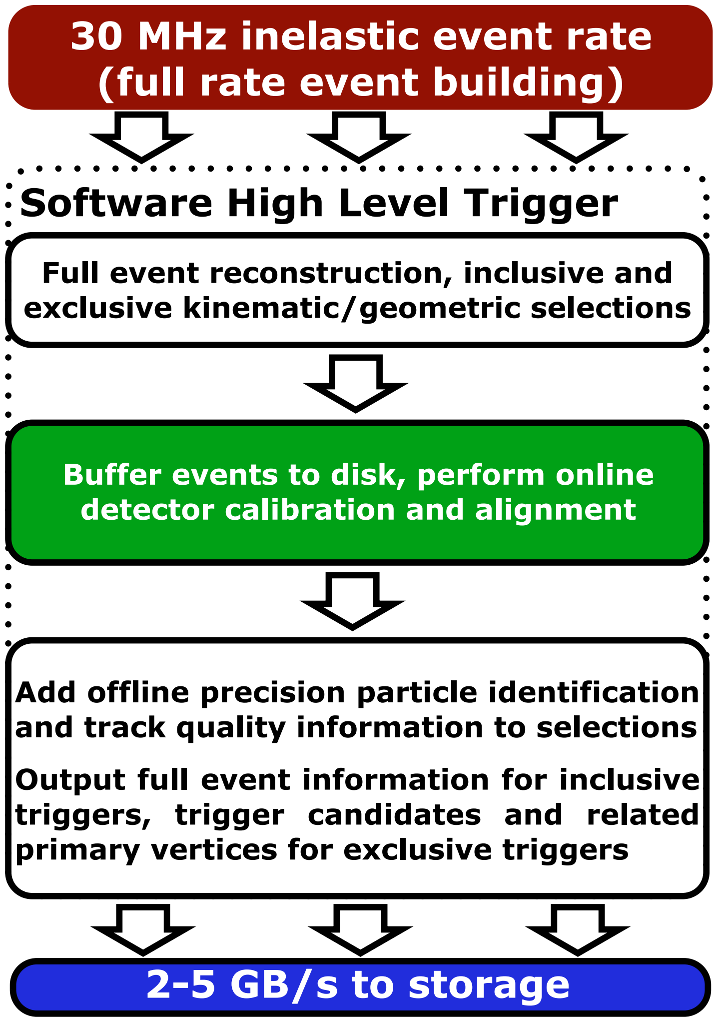
LHCb collab., JINST 3 (2008) S08005
R. Aaij, WB, *et al.*, arxiv: 1812.10790, submitted to JINST

Trigger – design and performance

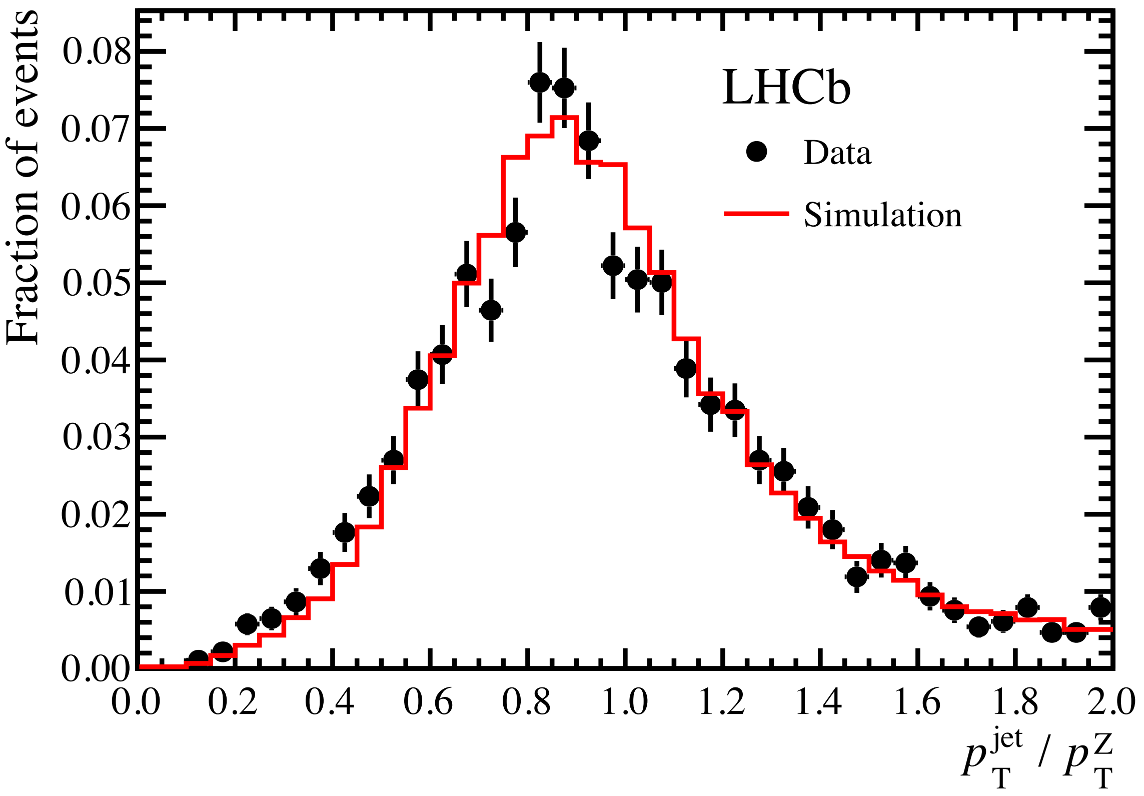
LHCb 2015 Trigger Diagram



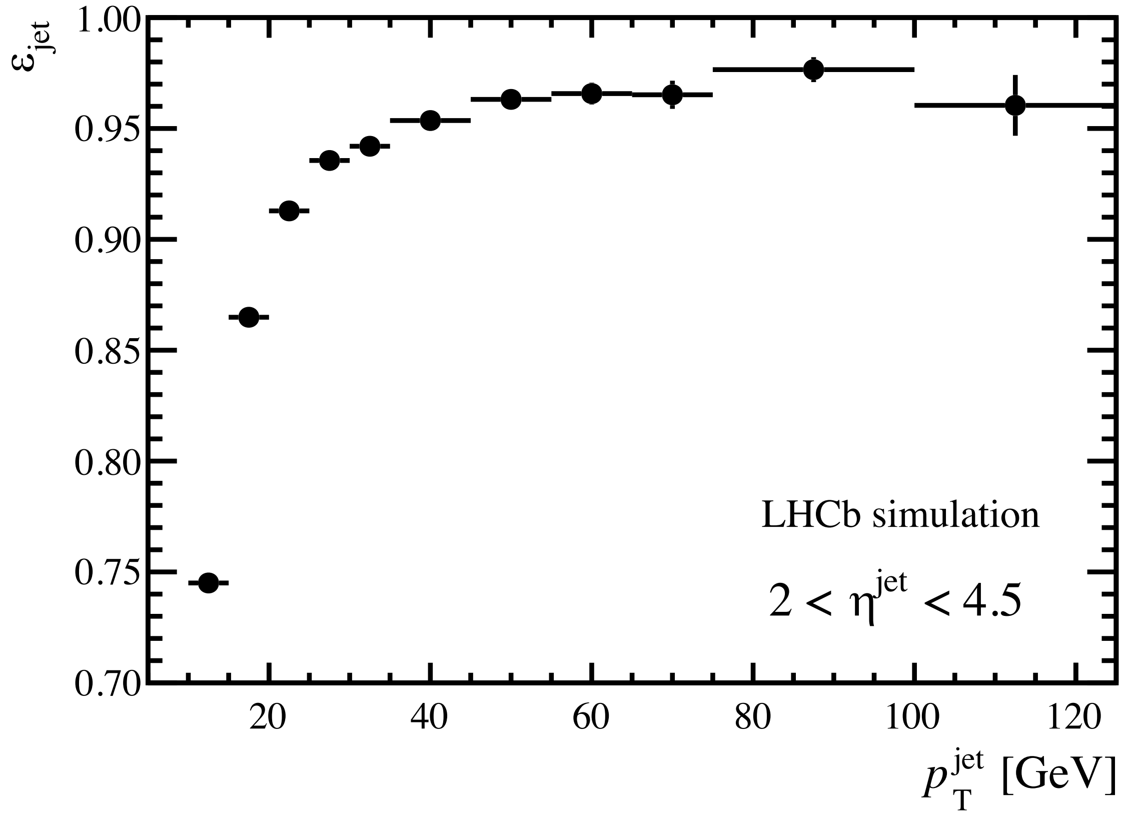
LHCb Upgrade Trigger Diagram



Jets at LHCb

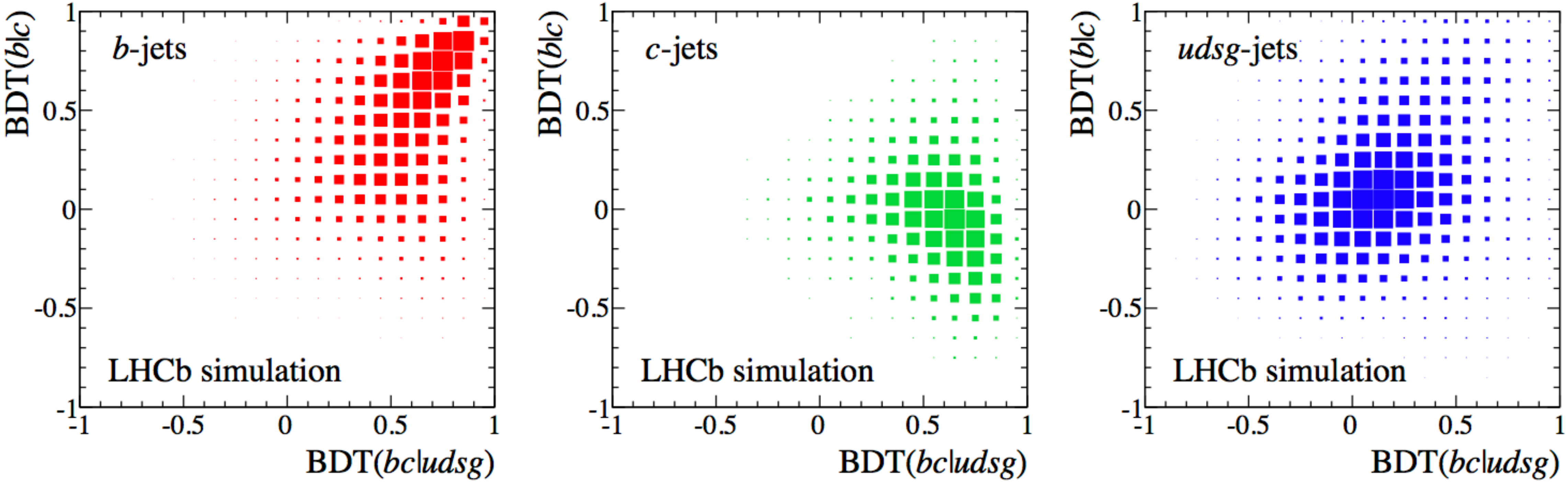


Fraction of events
LHCb
Data
Simulation
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
p_T^{jet} / p_T^Z

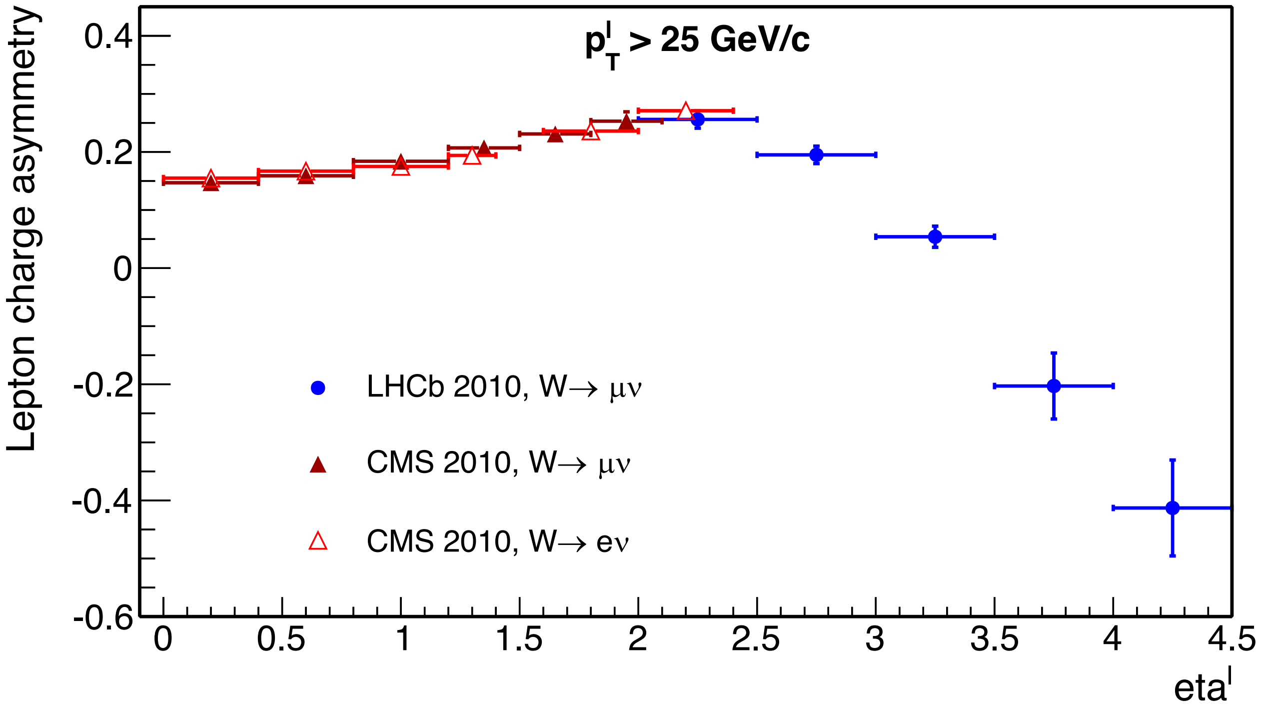


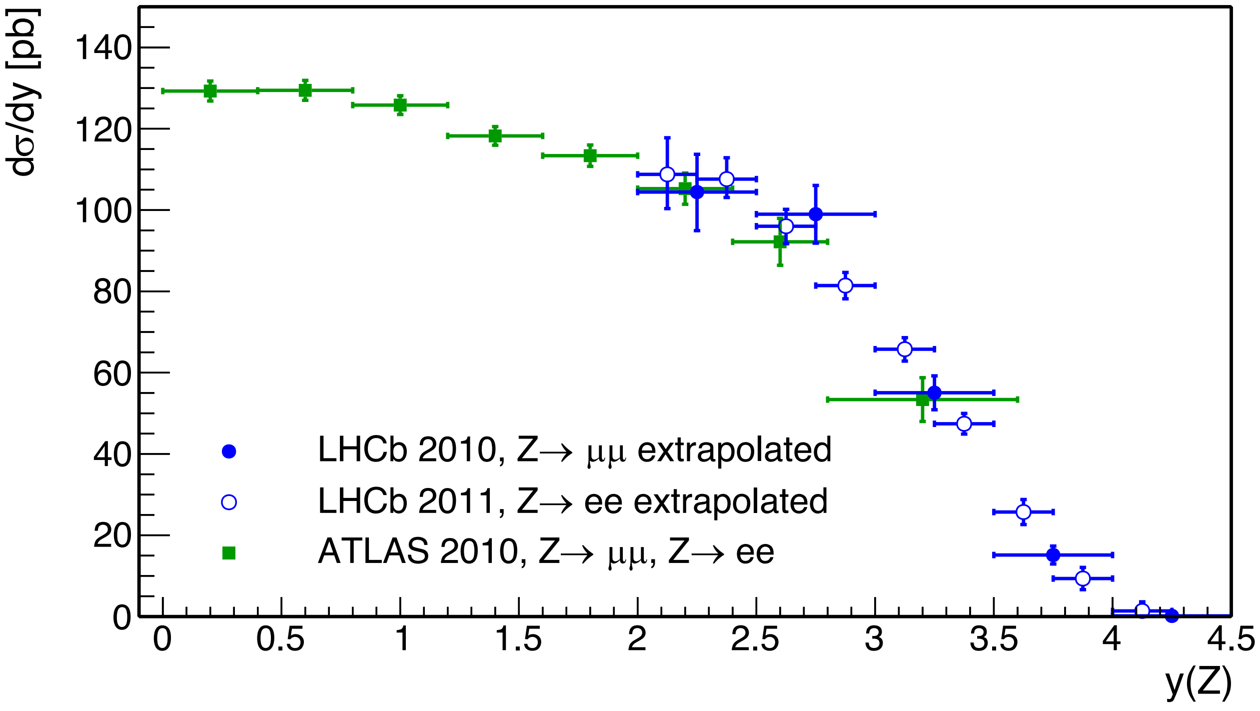
ε_{jet}
1.00
0.95
0.90
0.85
0.80
0.75
0.70
20
40
60
80
100
120
LHCb simulation
$2 < \eta^{jet} < 4.5$
p_T^{jet} [GeV]

Jets at LHCb

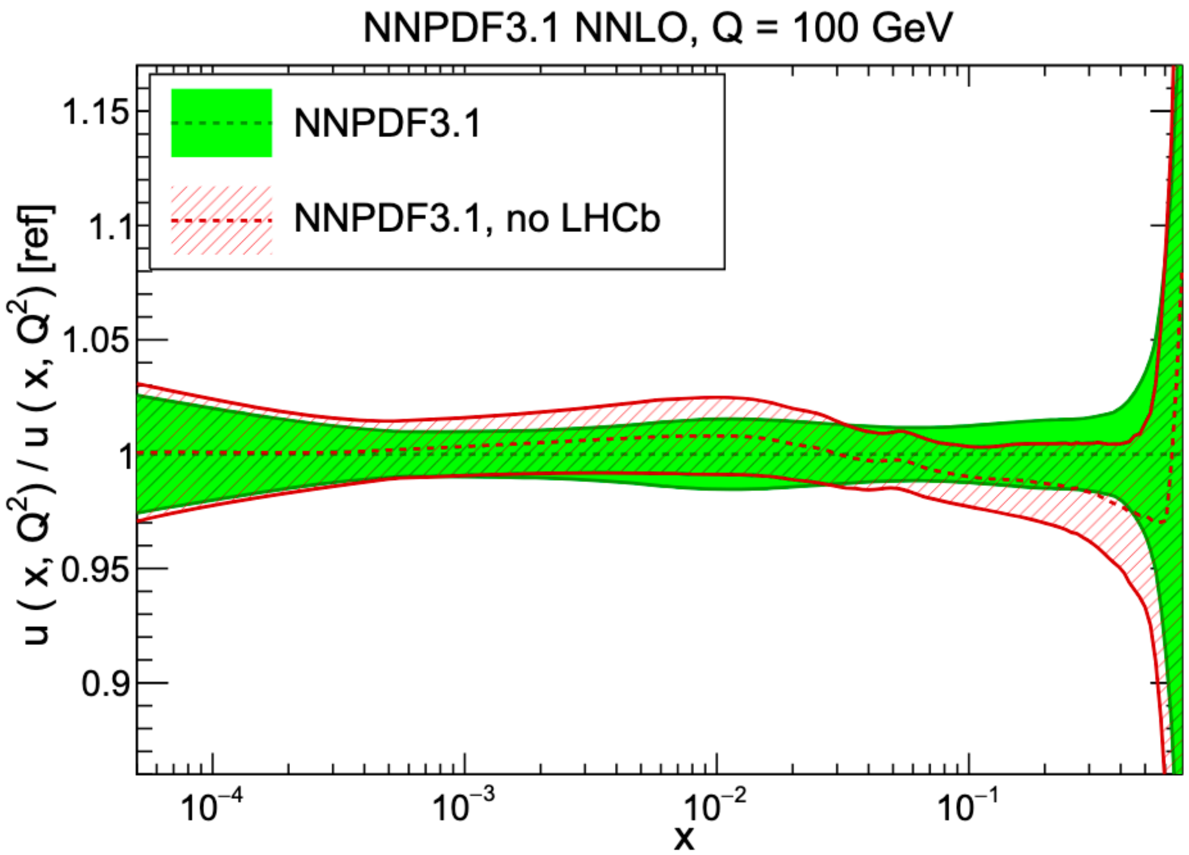

b-jets
c-jets
udsg-jets
LHCb simulation
LHCb simulation
LHCb simulation
BDT(b|c)
BDT(bc|udsg)
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1

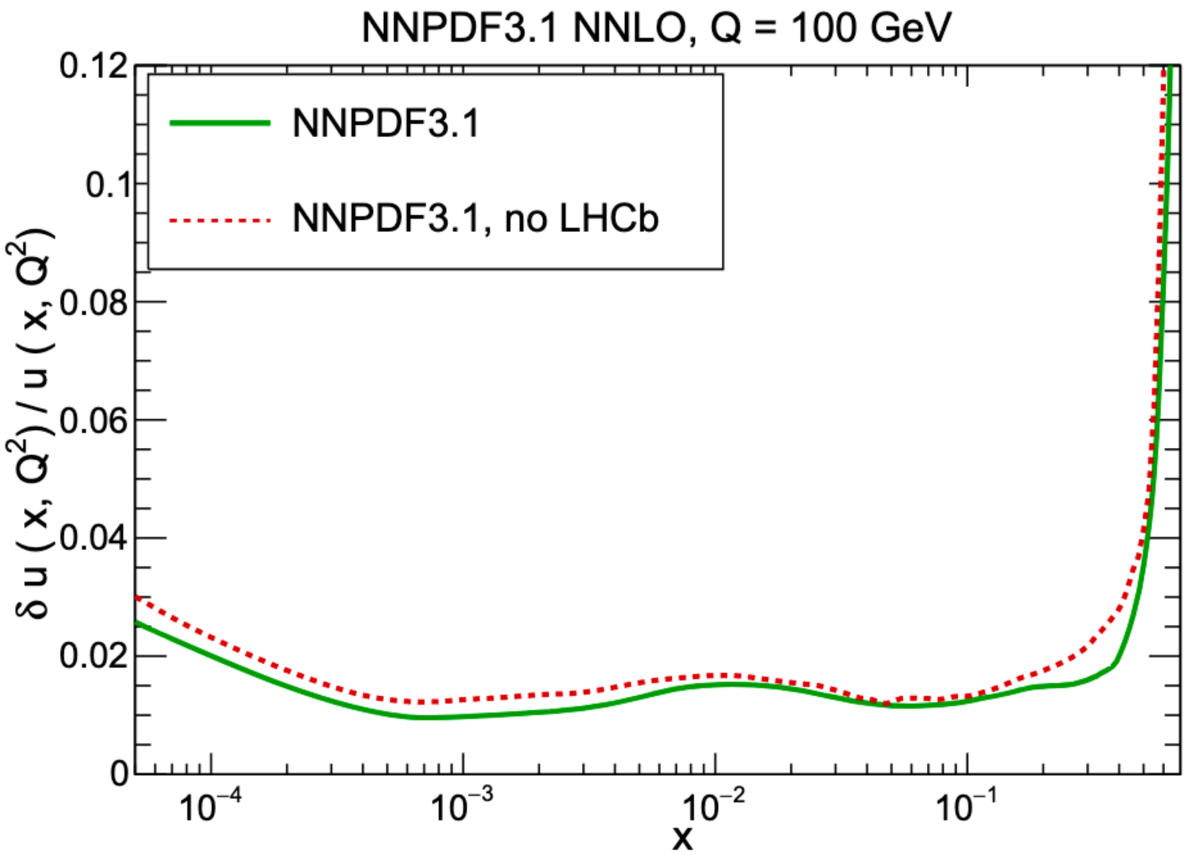
Comparison of LHCb/ATLAS/CMS Results





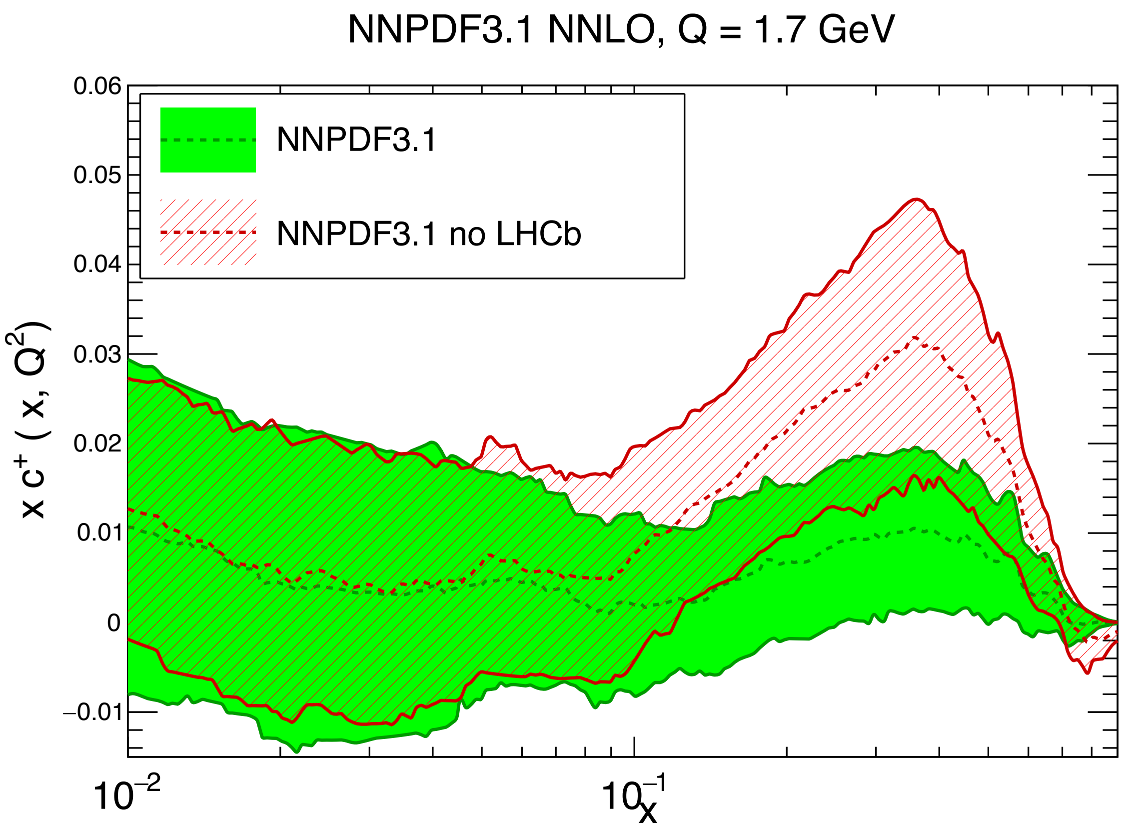
PDF constraints



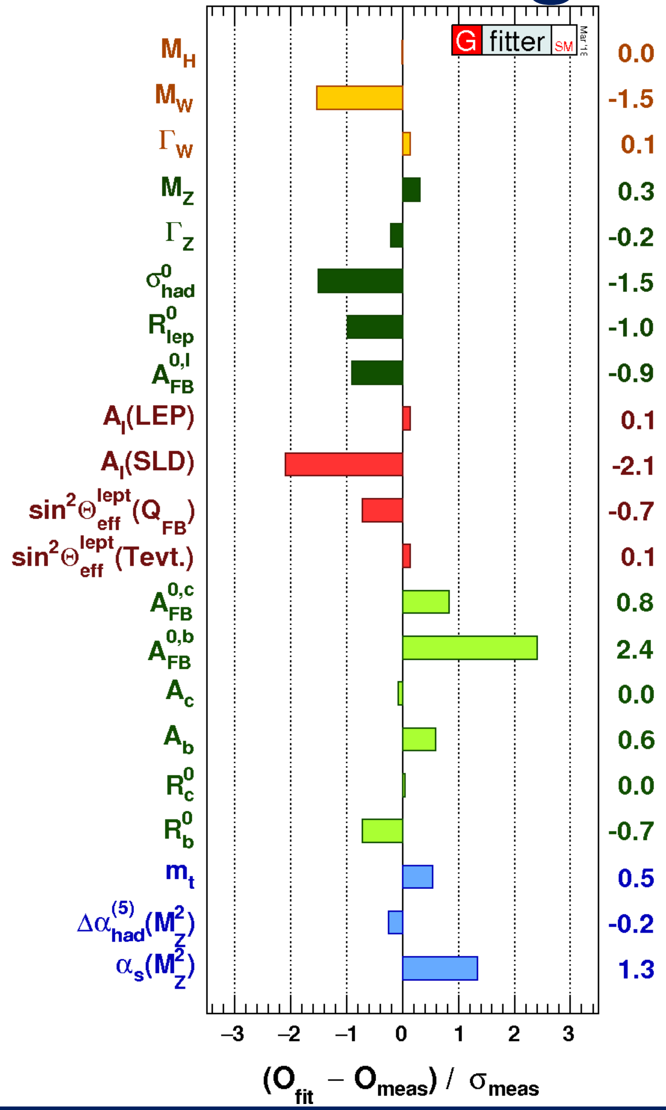


NNPDF collab., EPJC 77 (2017) 663

PDF constraints



Weak mixing at LHCb



$$\mathcal{G}_{\mathrm{Vf}} = \sqrt{\mathcal{R}_{\mathrm{f}}}\,(T_3^{\mathrm{f}} - 2Q_{\mathrm{f}}\mathcal{K}_{\mathrm{f}}\sin^2\theta_{\mathrm{W}})$$

$$\mathcal{G}_{\mathrm{Af}} = \sqrt{\mathcal{R}_{\mathrm{f}}}\,T_3^{\mathrm{f}}\,.$$

$$\frac{g_{\mathrm{Vf}}}{g_{\mathrm{Af}}} = \Re\left(\frac{\mathcal{G}_{\mathrm{Vf}}}{\mathcal{G}_{\mathrm{Af}}}\right) = 1 - 4|Q_{\mathrm{f}}|\sin^2\theta^{\mathrm{f}}_{\mathrm{eff}}$$

Weak mixing at LHCb