W mass measurement at LHCb

INFN-Genova seminar
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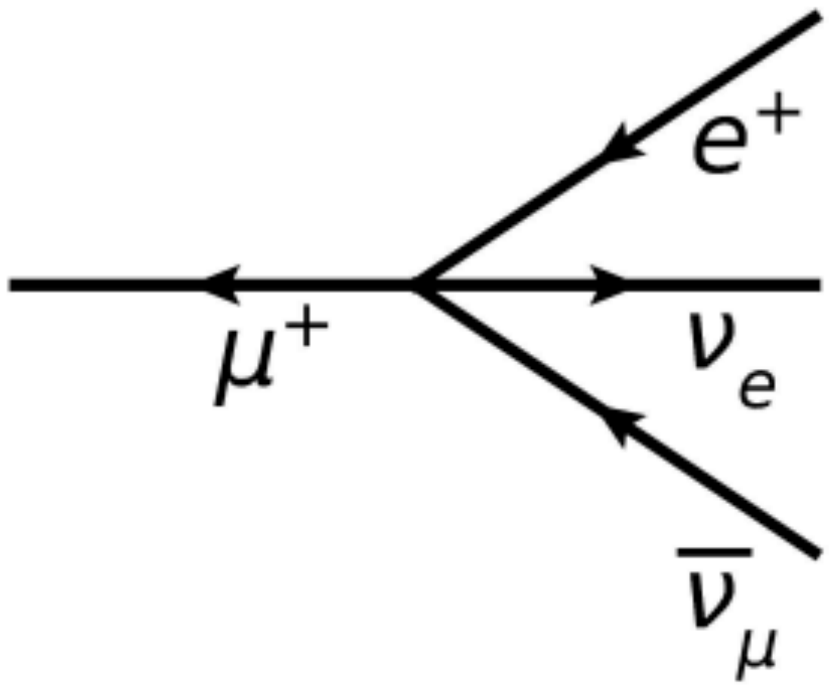
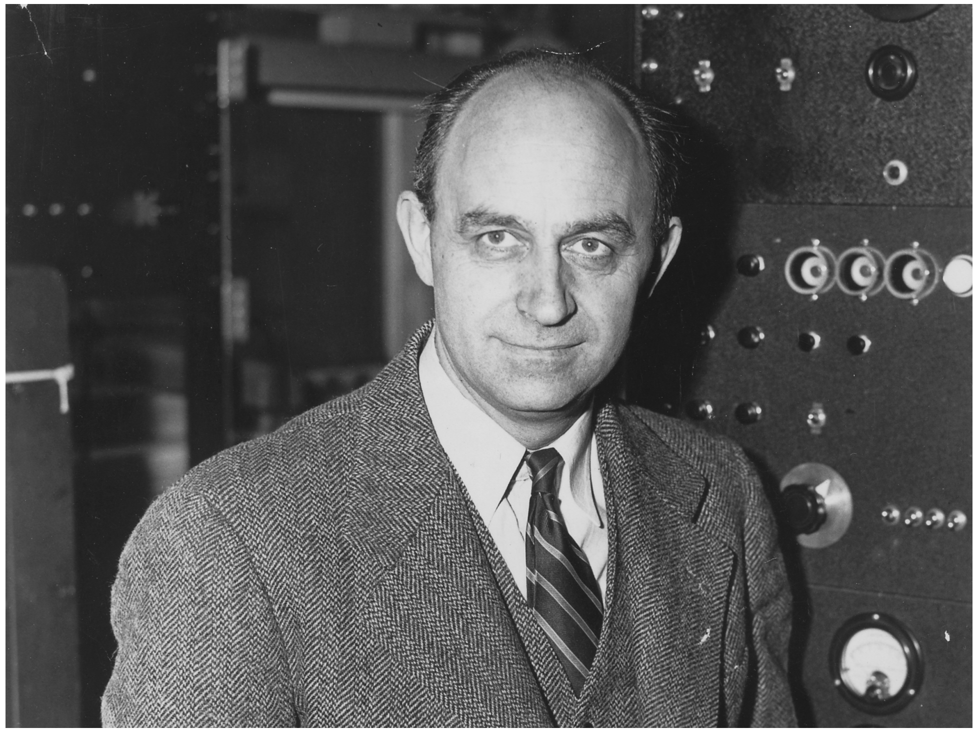
WARWICK
UKRI Science and Technology Facilities Council
erc European Research Council
LHCb

$$\tau_\mu \approx 2.2 \times 10^{-6}\ \mathrm{s}$$





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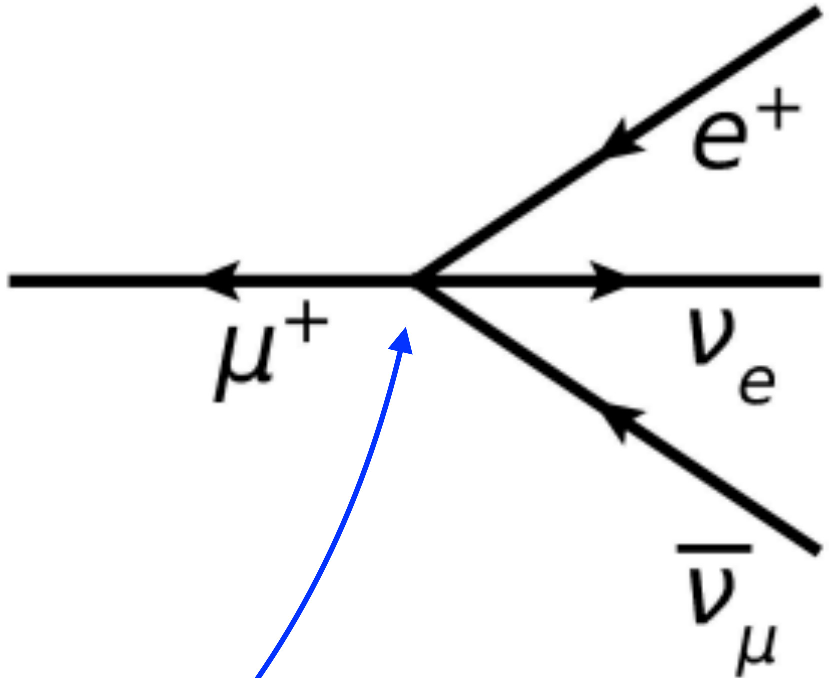
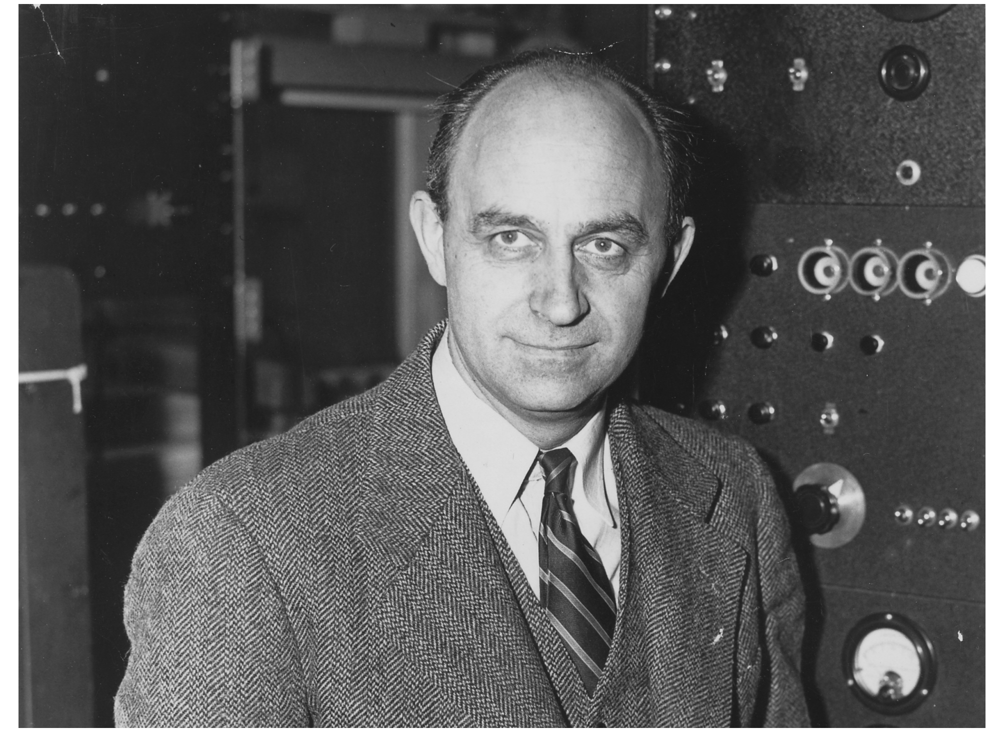
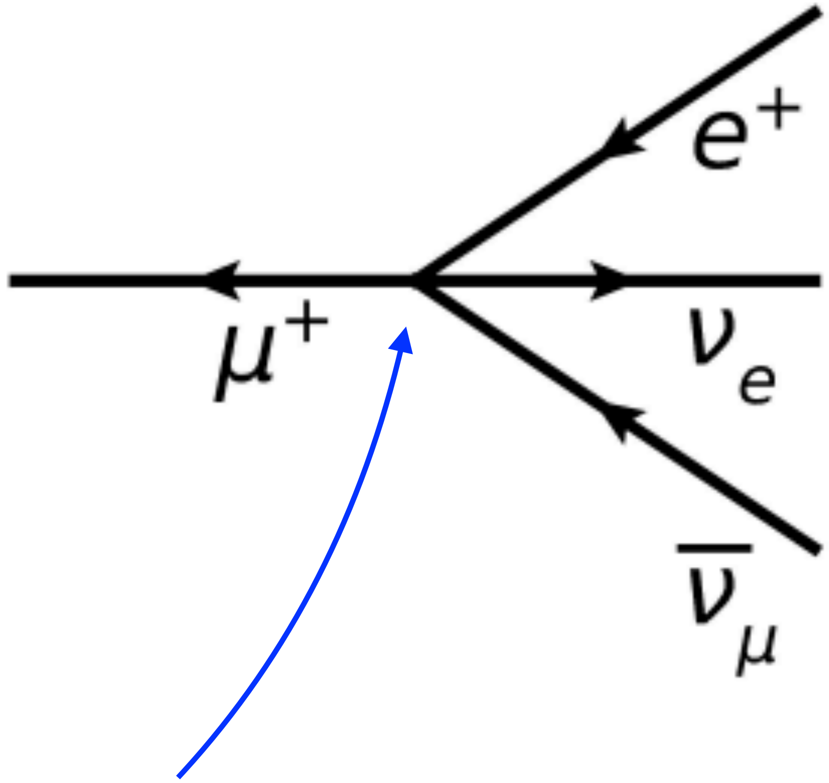




G_F^{-2}

$$\tau_\mu \approx 2.2 \times 10^{-6}\ \mathrm{s}$$

$$G_F \approx 1.2 \times 10^{-5}\ \mathrm{GeV}^{-2}$$



G_F^{-2} $\tau_\mu \approx 2.2 \times 10^{-6}\ \mathrm{s}$

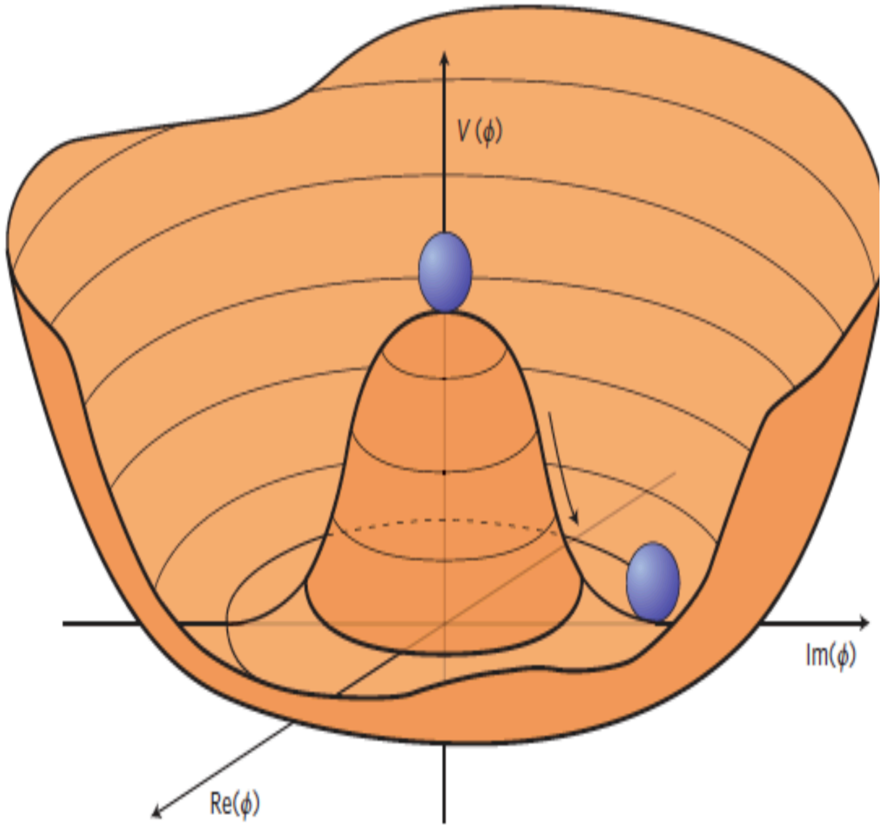
$$G_F \approx 1.2 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

How does this weak *charged* current interaction relate to QED?

Electroweak unification

$$W^{\pm} = \frac{1}{\sqrt{2}} \left(W_1 \mp i W_2 \right)$$

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$



- ✅ Massless photon
- ✅ Massive charged boson(s)

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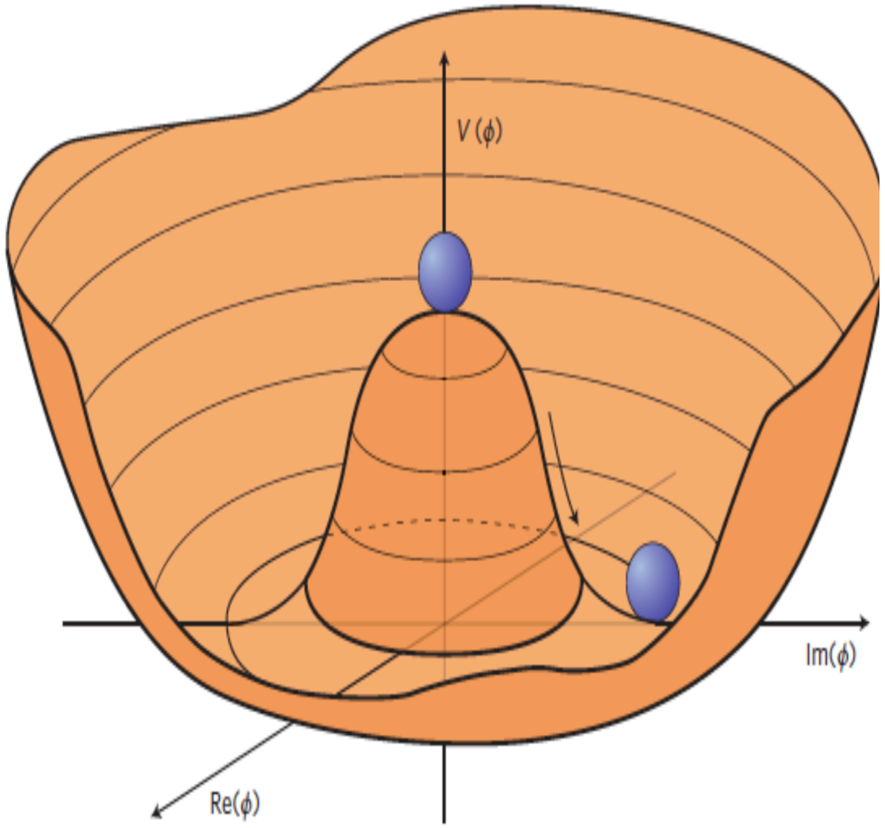
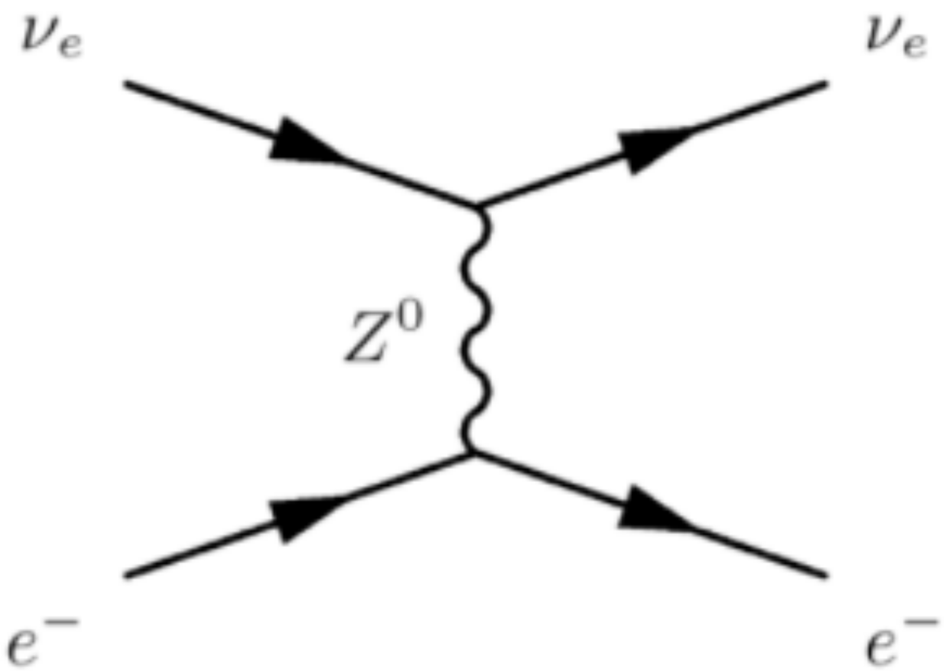


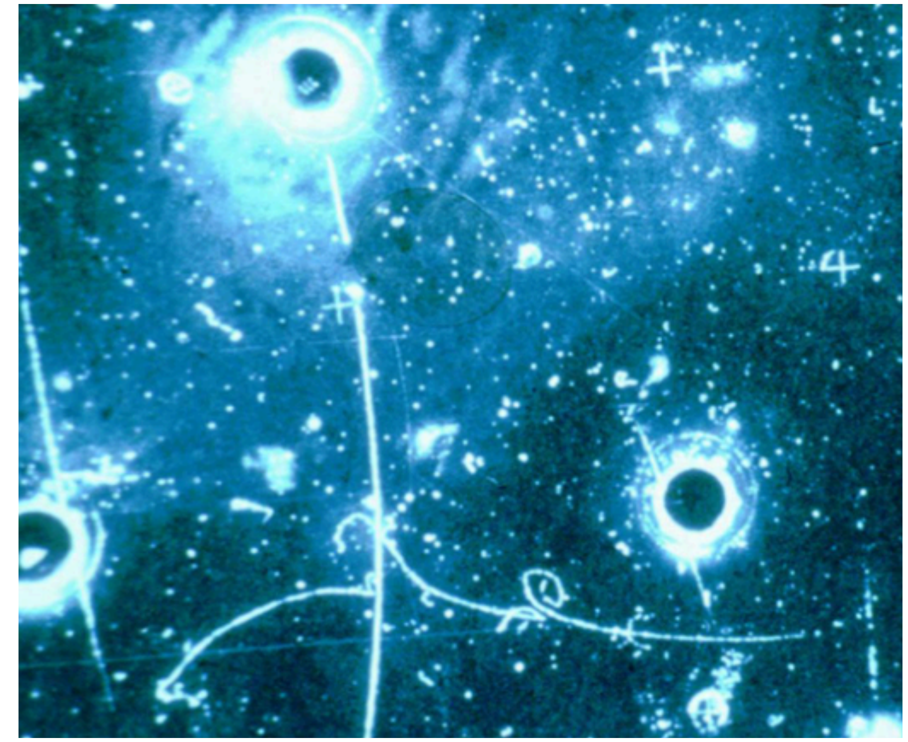
✅ Massless photon

✅ Massive charged boson(s)

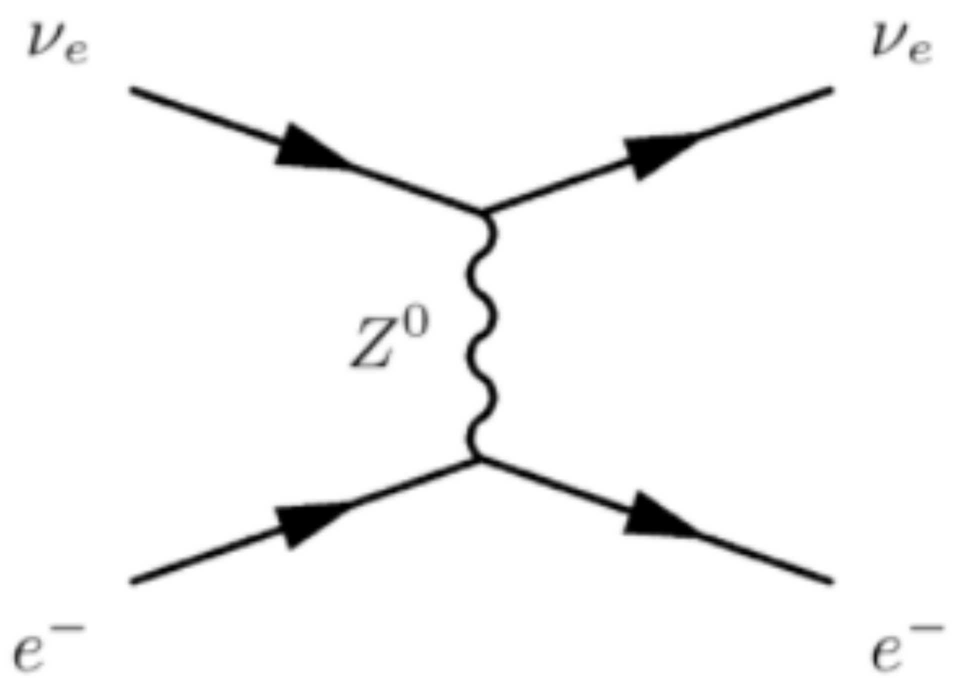
😮 A massive neutral boson

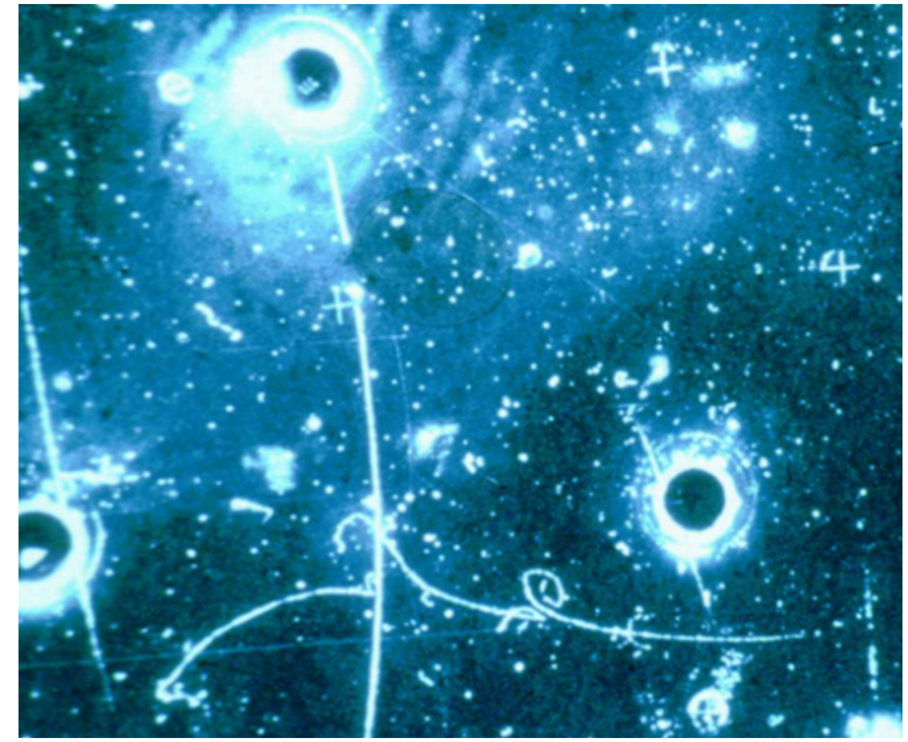
Weak neutral currents (1973)





Weak neutral currents (1973)





Can we predict the masses of these heavy weak bosons?

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

The largest group that leaves invariant the kinematic terms $-\overline{L}\gamma^{\mu}\partial_{\mu}L-\overline{R}\gamma^{\mu}\partial_{\mu}R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symhas mass

$$M_W = \tfrac{1}{2}\lambda g. \tag{9}$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \tag{12}$$

$$M_A = 0, \tag{13}$$

[the charged spin-1 field]
has mass

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[the neutral spin-1 field] masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \tag{12}$$

$$M_A = 0, \tag{13}$$

How to we determine (g, g', λ) ?

[the charged spin-1 field] has mass

$$M_W = \tfrac{1}{2}\lambda g. \qquad (9)$$

[the neutral spin-1 field] masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

$$G_W/\sqrt{2} = g^2/8M_W{}^2 = 1/2\lambda^2$$ muon lifetime again

$$e = gg'/(g^2 + g'^2)^{1/2}$$ fine structure constant

[the charged spin-1 field] has mass

$$M_W = \tfrac{1}{2}\lambda g. \qquad (9)$$

[the neutral spin-1 field] masses are

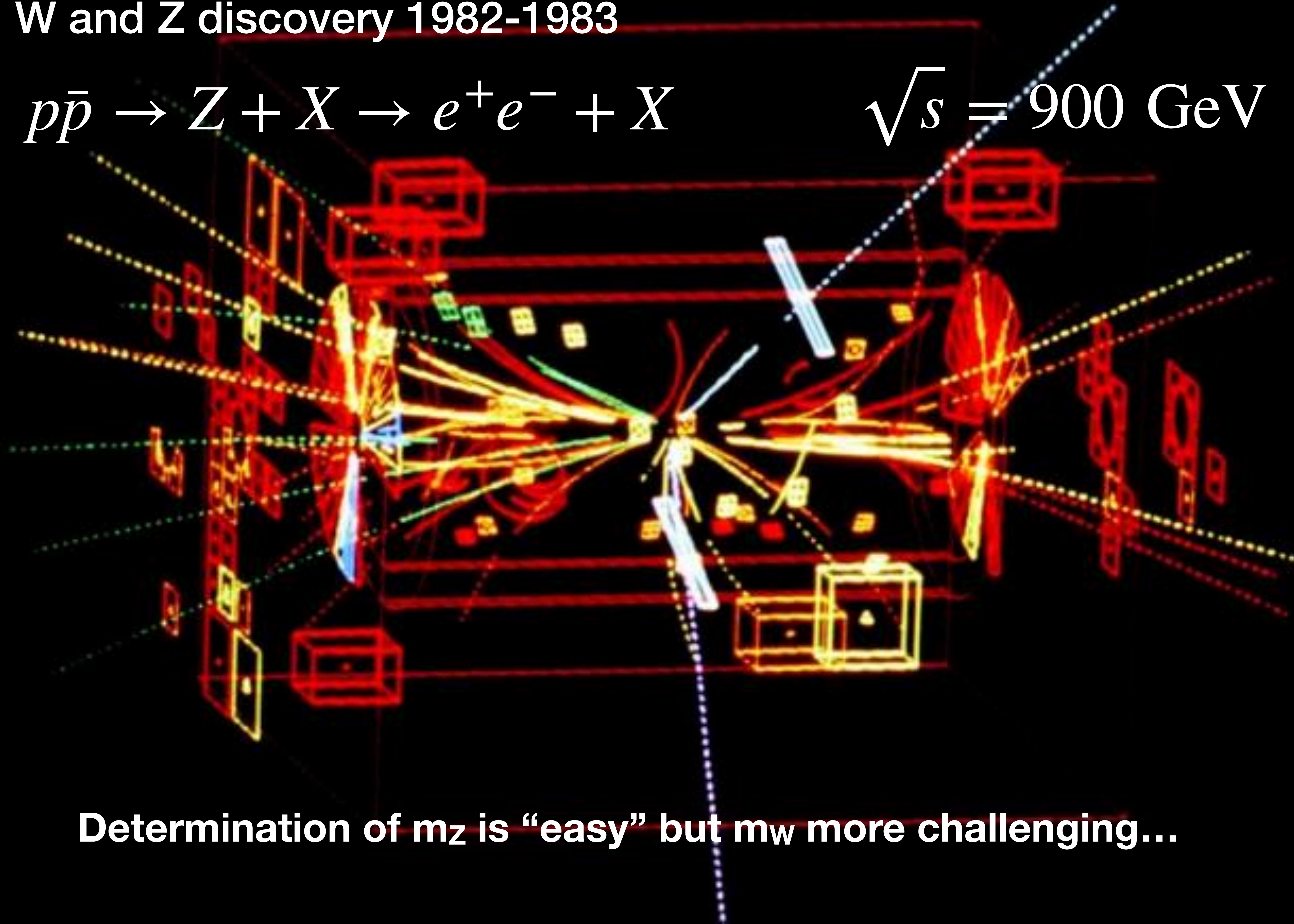
$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

so that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

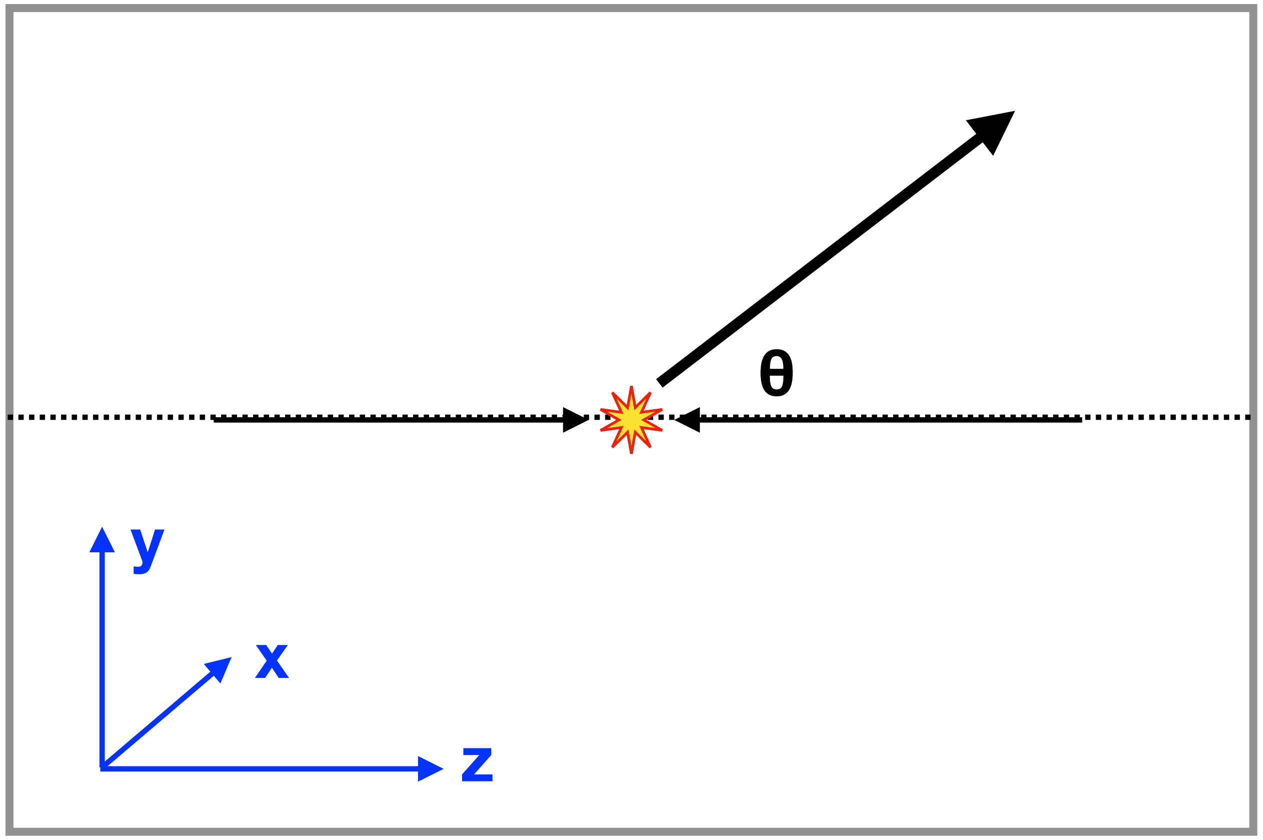
W and Z discovery 1982-1983

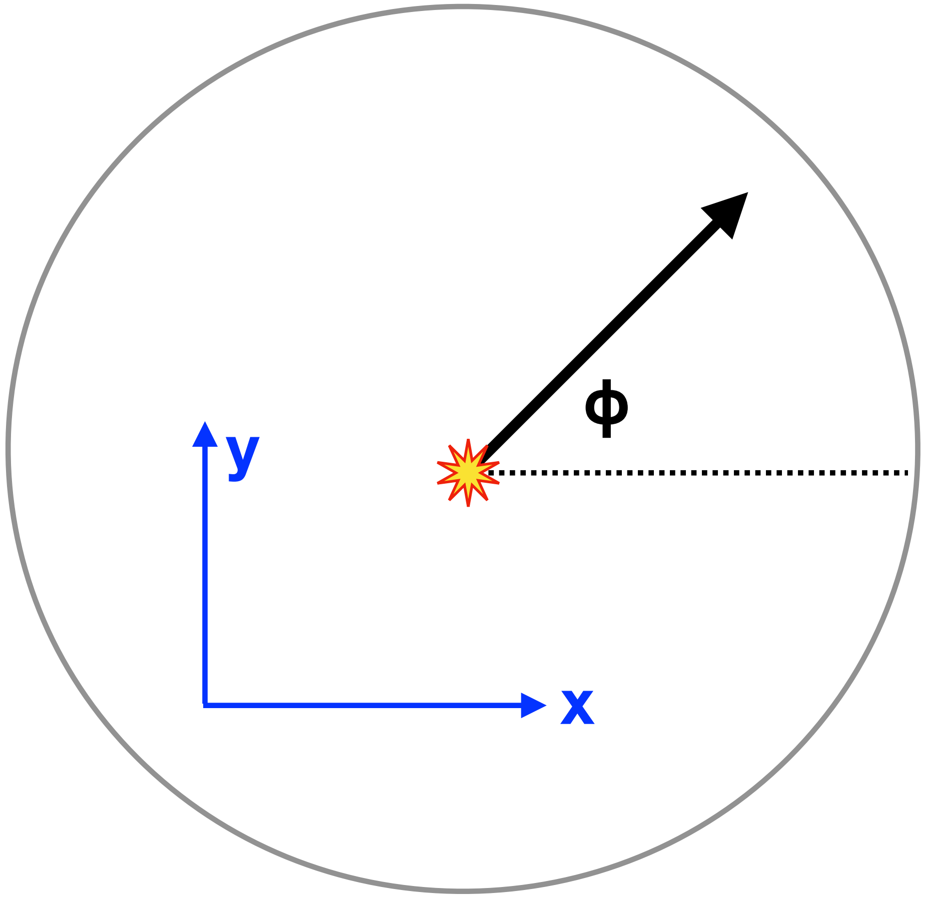
$$p\bar{p} \rightarrow Z + X \rightarrow e^+e^- + X \qquad \sqrt{s} = 900\ \mathrm{GeV}$$



Determination of m_Z is “easy” but m_W more challenging…

Coordinates





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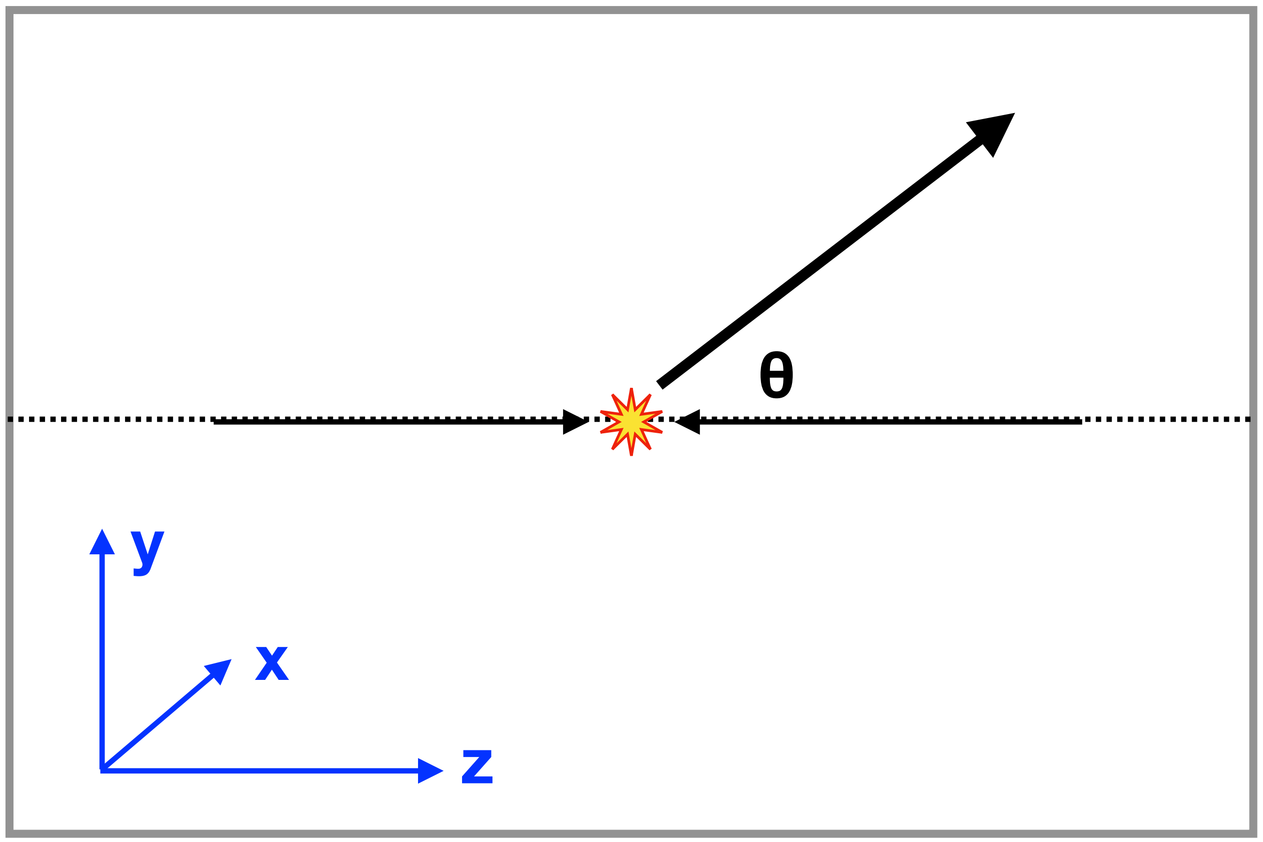
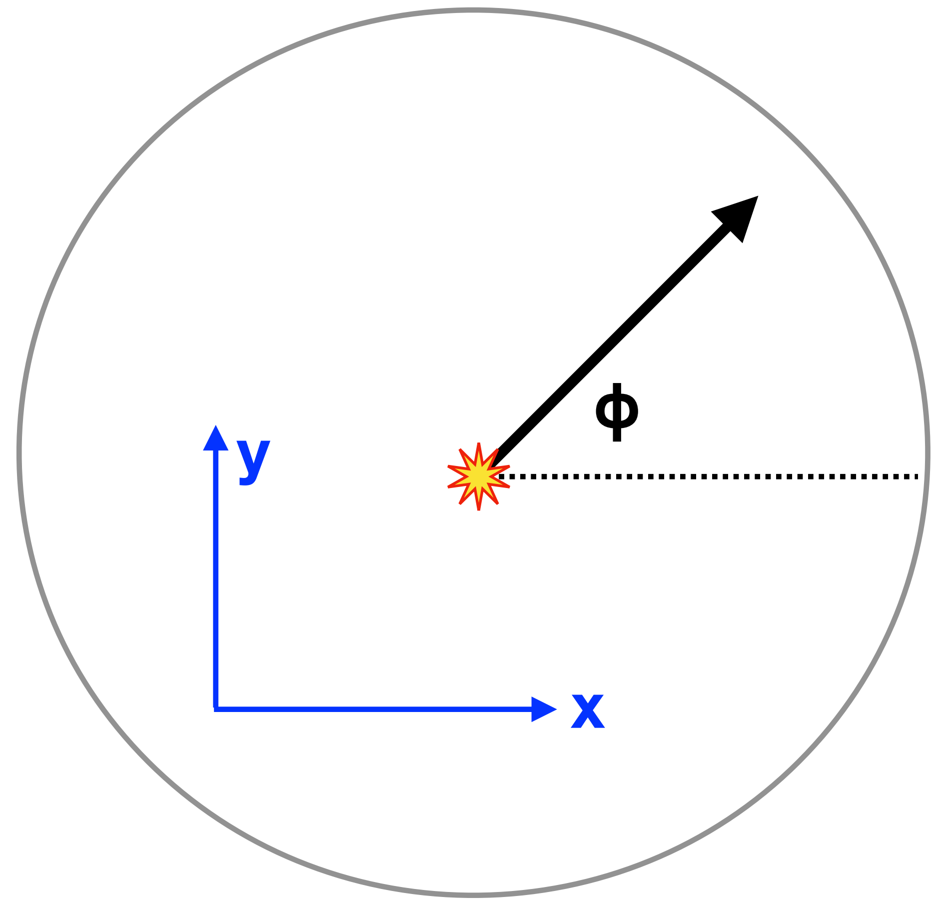


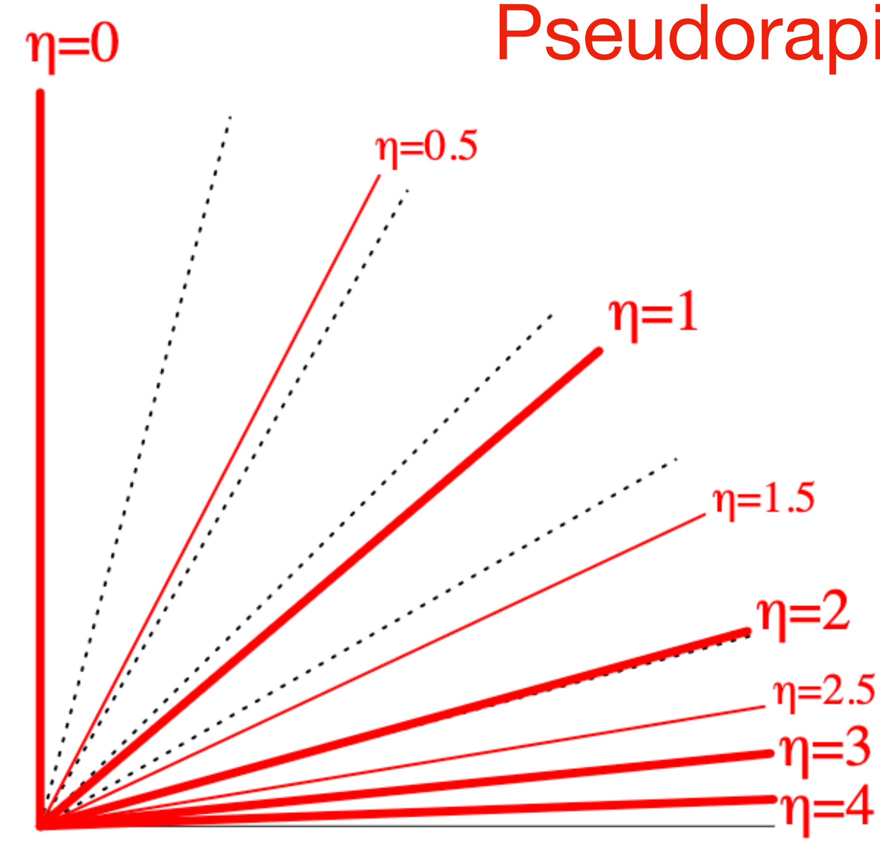


$$\eta \equiv -\ln\left[\tan(\theta/2)\right]$$

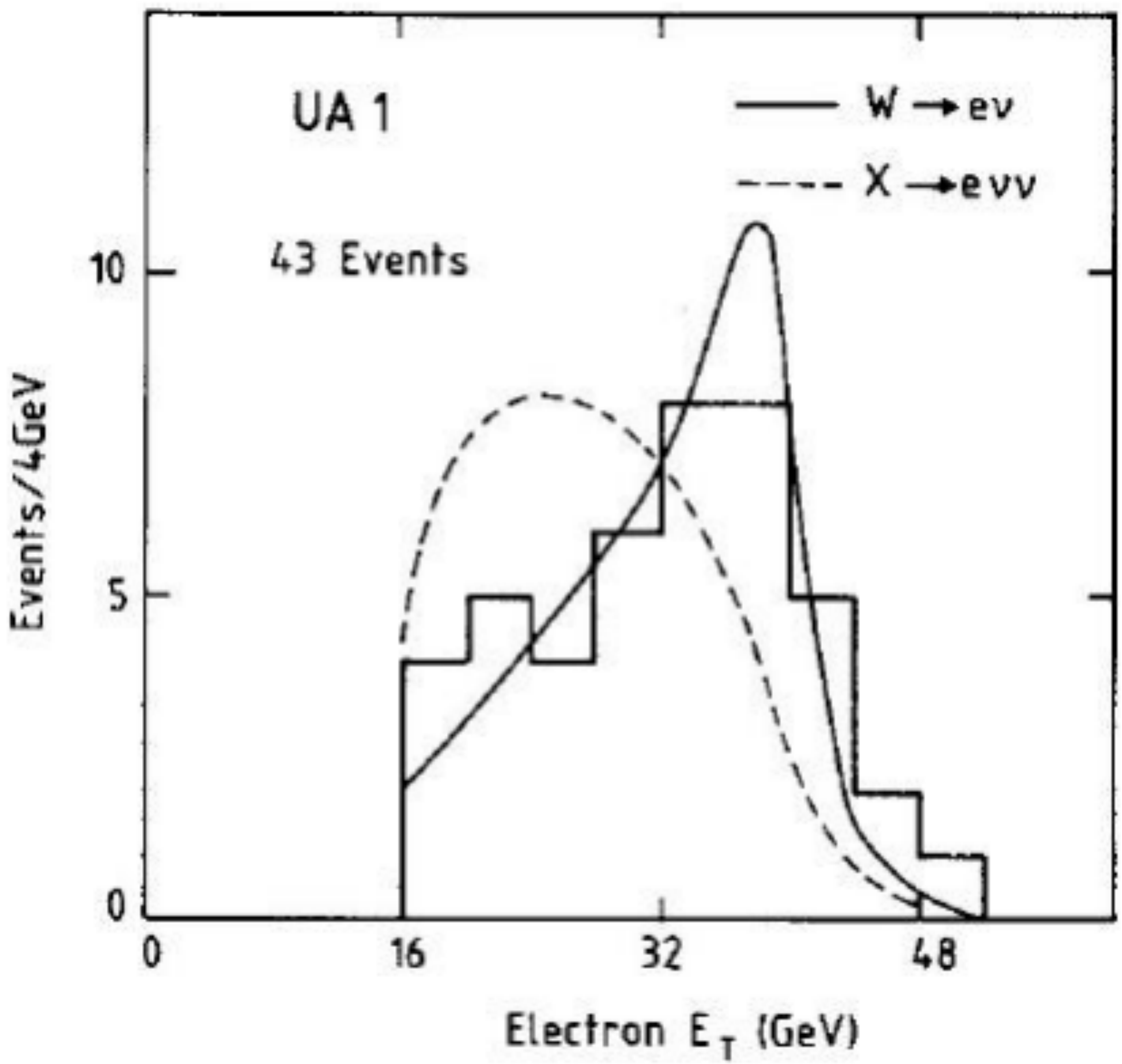
$$p_{\mathrm{T}} \equiv |p|/\cosh\eta$$

$$\phi$$

Pseudorapidity



W mass determination with charged lepton p_T



Note that there is also the “transverse mass” variable

Final UA1+UA2 results (~1983)

$$m_{W^\pm} = 82.1 \pm 1.7 \text{ GeV}$$

$$m_{Z^0} = 93.0 \pm 1.7 \text{ GeV}$$

Standard Model predictions confirmed [to a few %]!

Why are we still measuring the W mass then?

Modern prediction of m_W

Parameter	Measured value	Approx. precision
α^{-1}	137.035999084(21)	1 part in 10^{10}
G_F	$1.166\,3787(6) \times 10^{-5}$ GeV^{-2}	1 part in 10^{6}
m_Z	91.1876 ± 0.0021 GeV	1 part in 10^{5}

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

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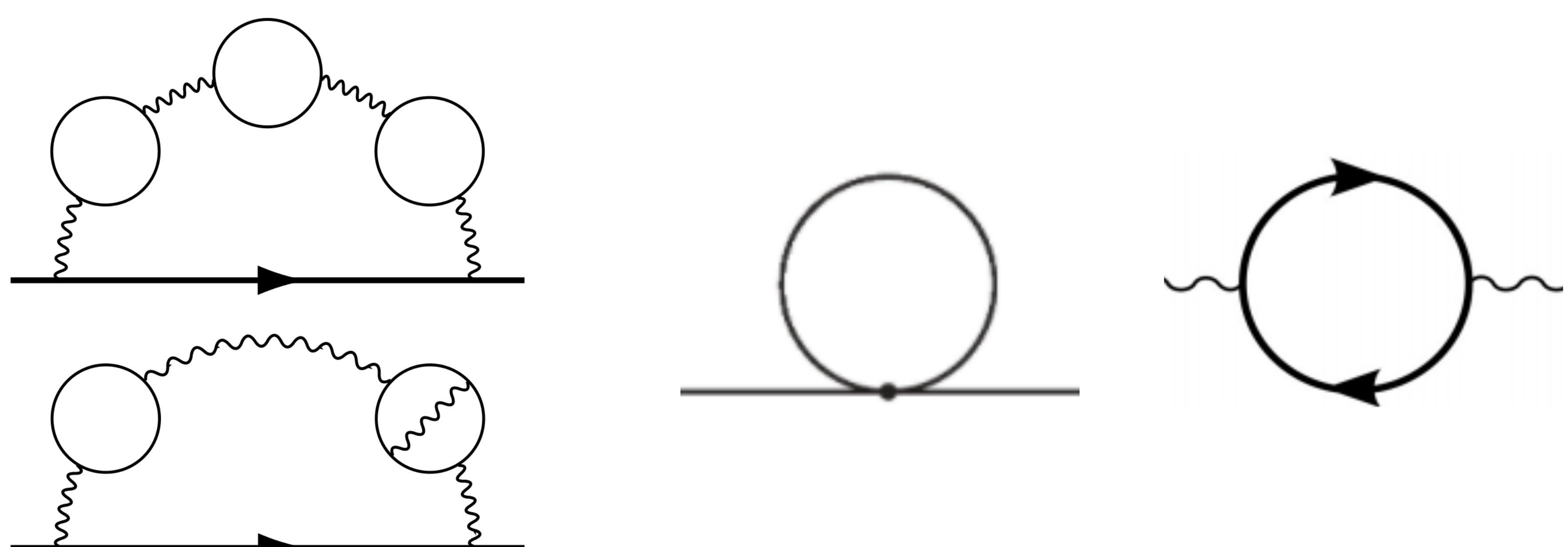
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(1+\Delta(m_t, m_H, m_b, \ldots, V_{\mathrm{CKM}}, \ldots)\right)$$



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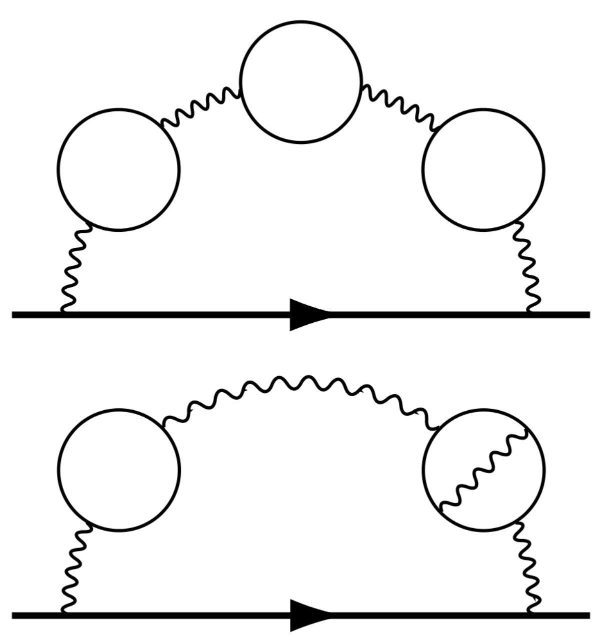
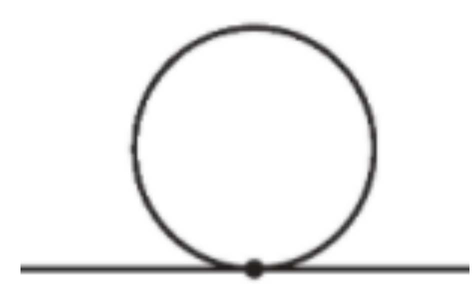
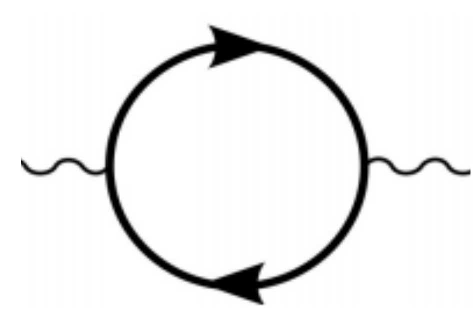
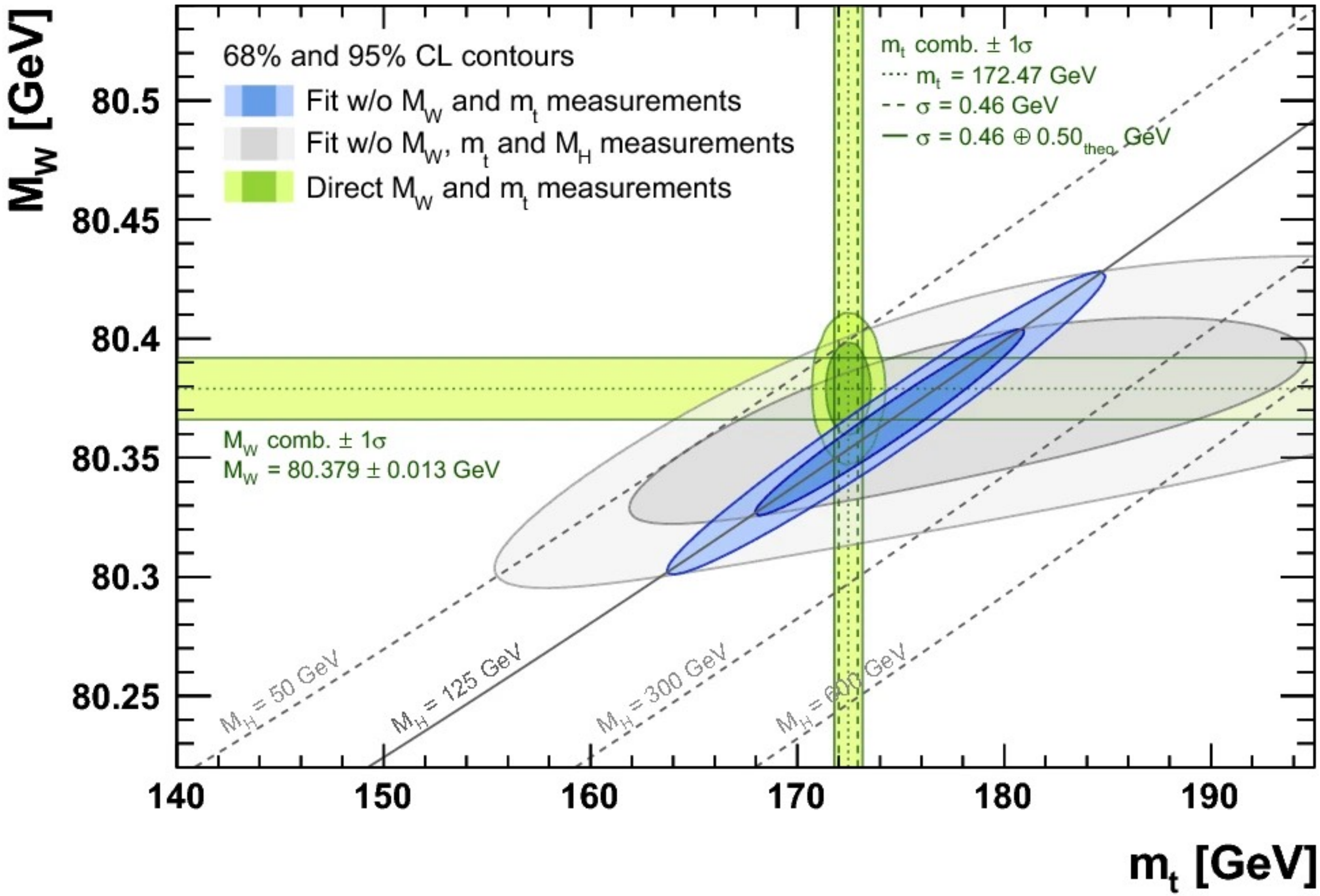
$$+\Delta_{\mathrm{BSM}}?$$





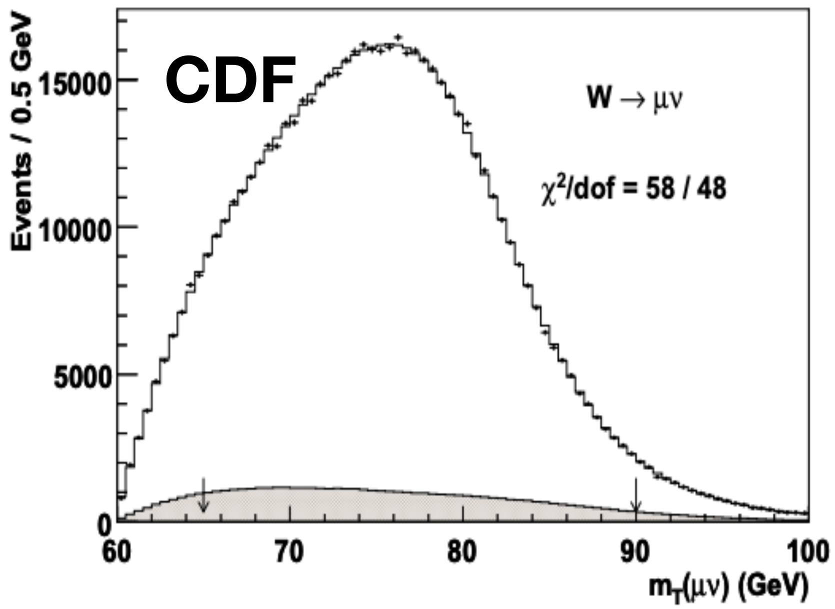




$$m_W^{\text{pred}} = 80354 \pm 7 \text{ MeV}$$

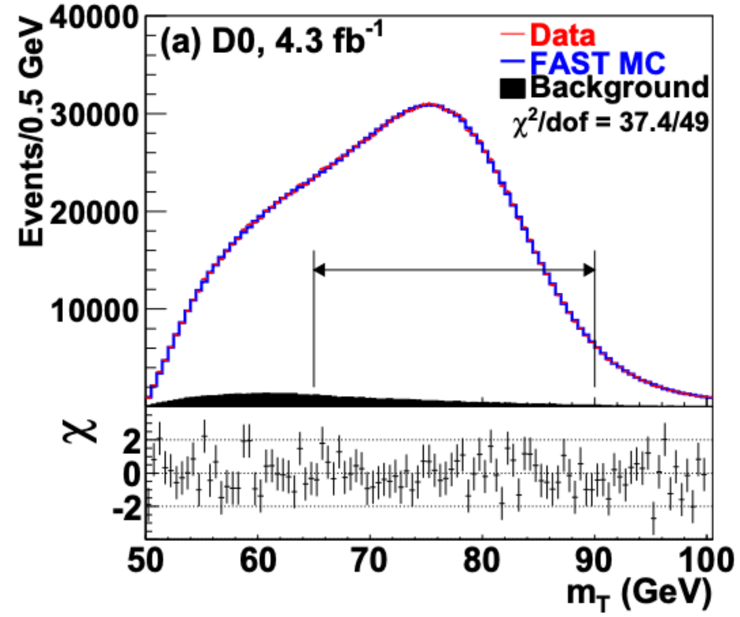
Global electroweak fit by the gFitter group EPJC 78, 675 (2018)

The three most precise measurements



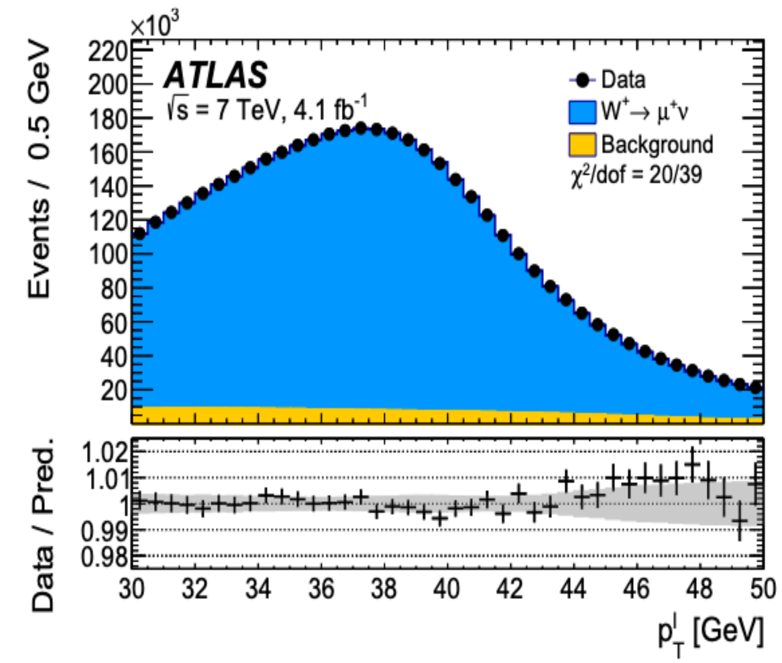
Phys. Rev. Lett. **108**, 151803 (2012)

$$80387 \pm 12_{\rm stat} \pm 15_{\rm syst}\ \text{MeV}$$



Phys. Rev. D 89, 012005 (2014)

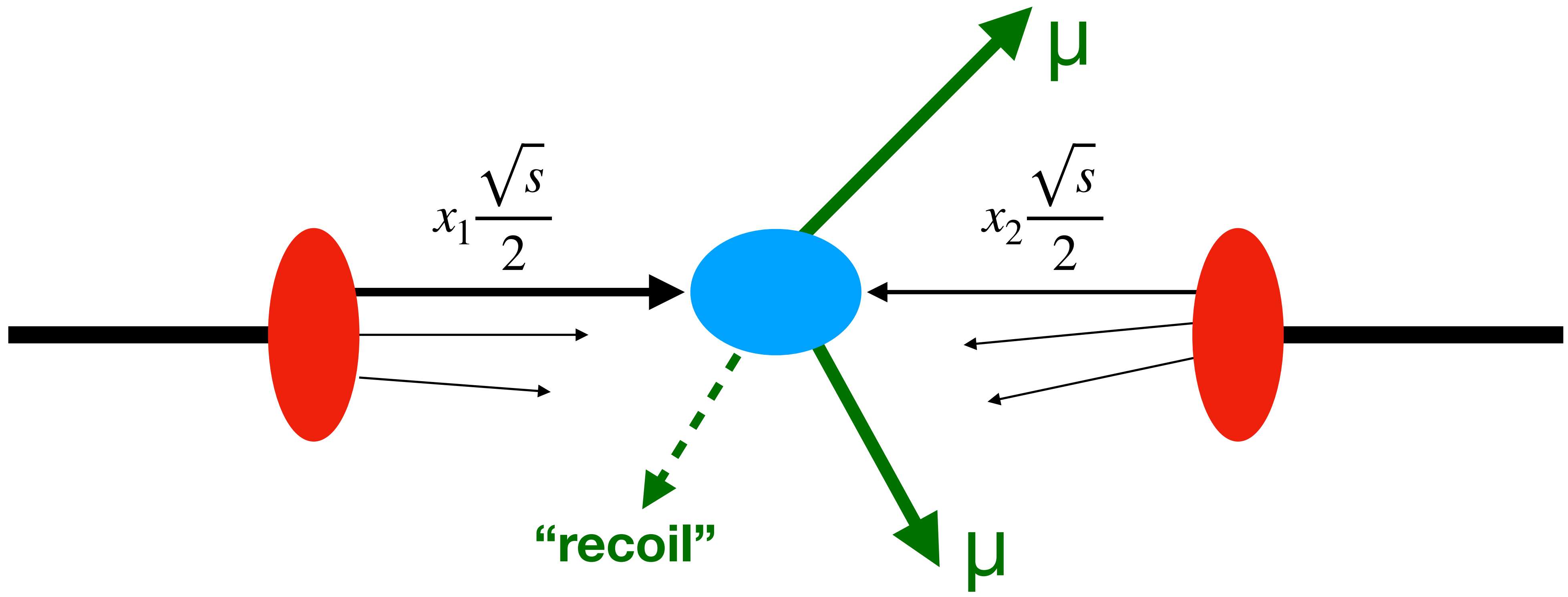
$$80375 \pm 23\ \text{MeV}$$

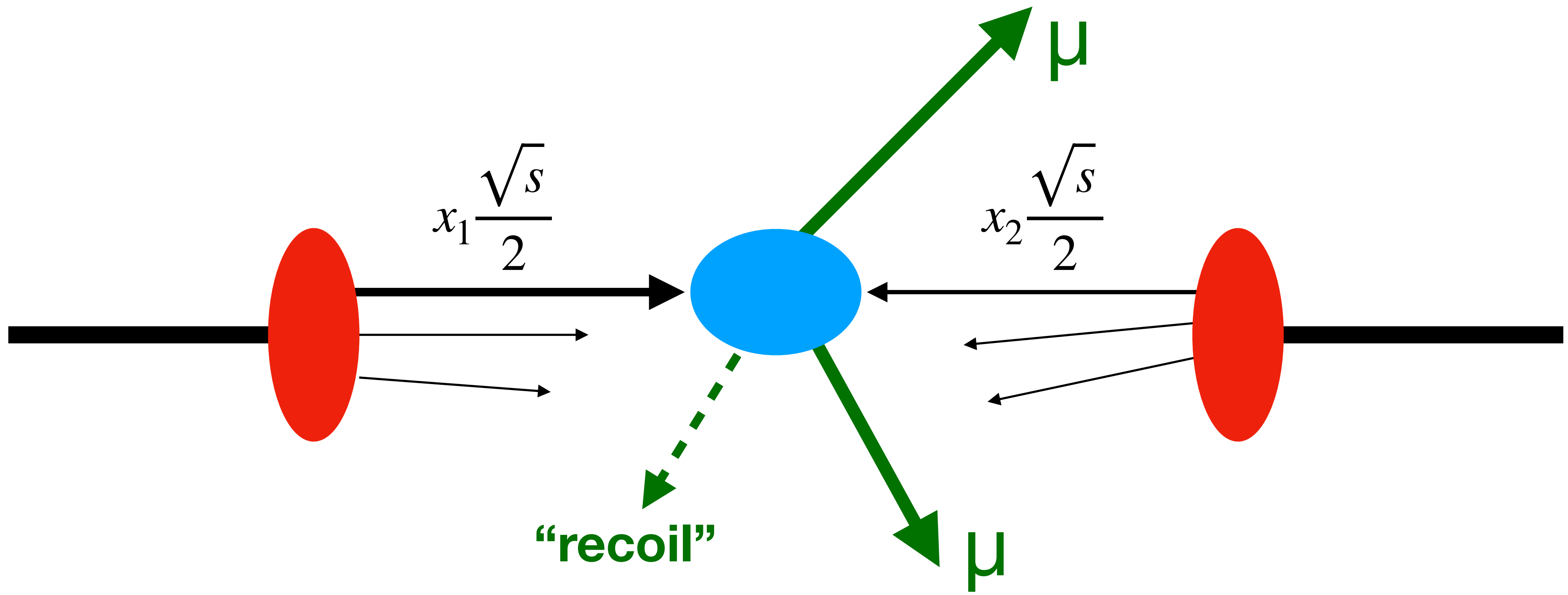


Eur. Phys. J. C 78 (2018) 110

$$80370 \pm 13_{\rm exp} \pm 14_{\rm model}\ \text{MeV}$$

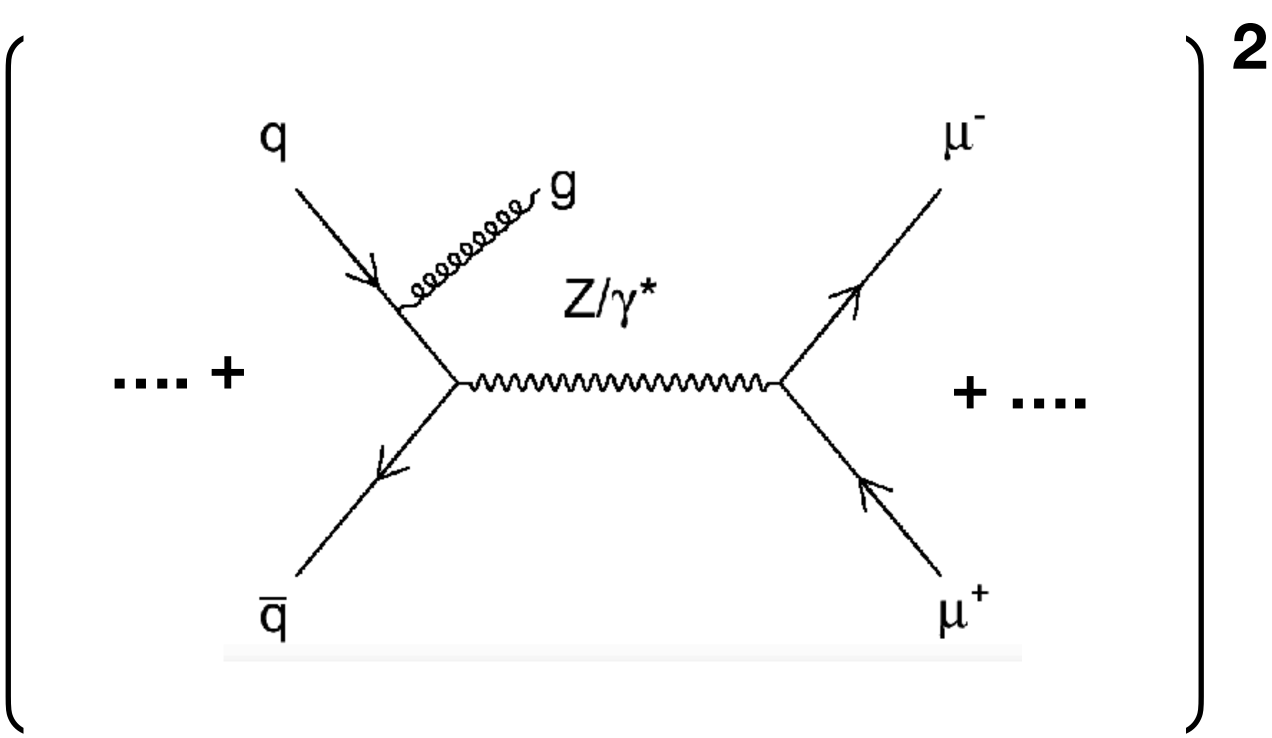
Extremely challenging measurements!

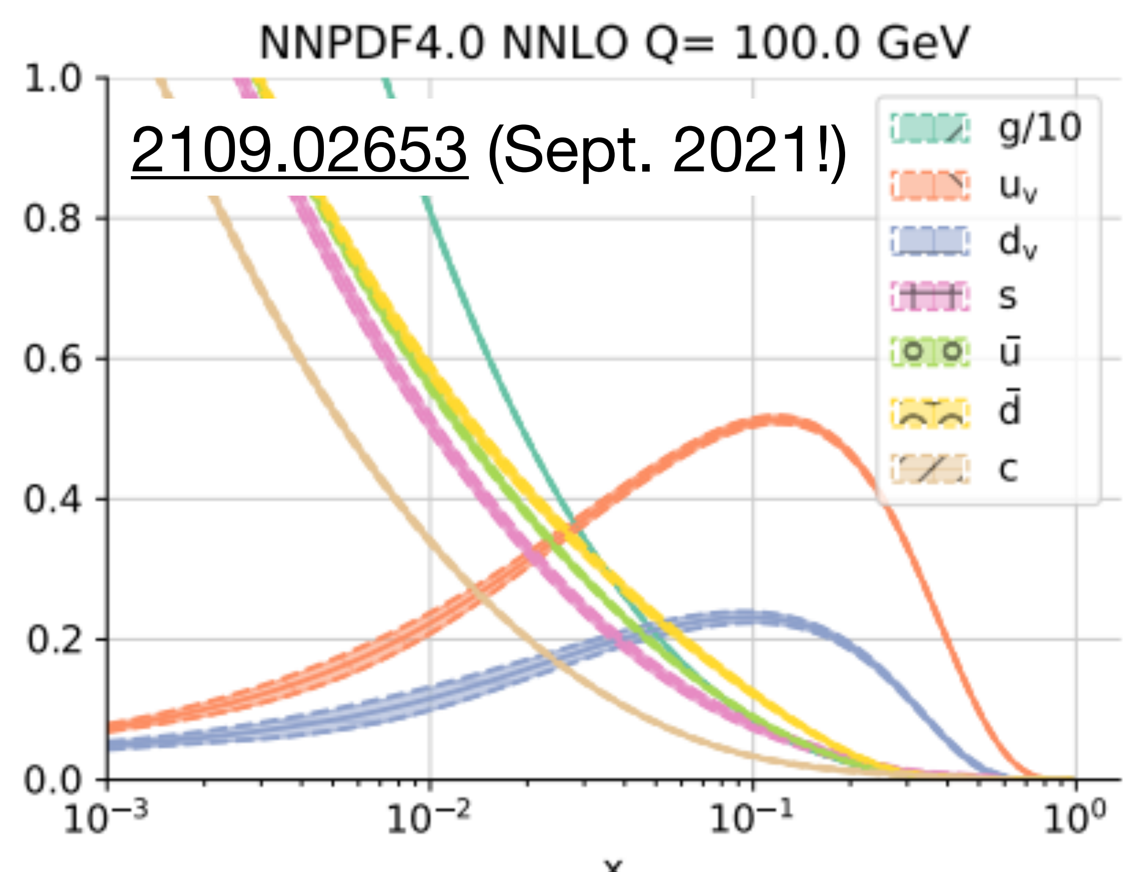

μ
$x_1\frac{\sqrt{s}}{2}$
$x_2\frac{\sqrt{s}}{2}$
"recoil"
μ



Parton-level hard process

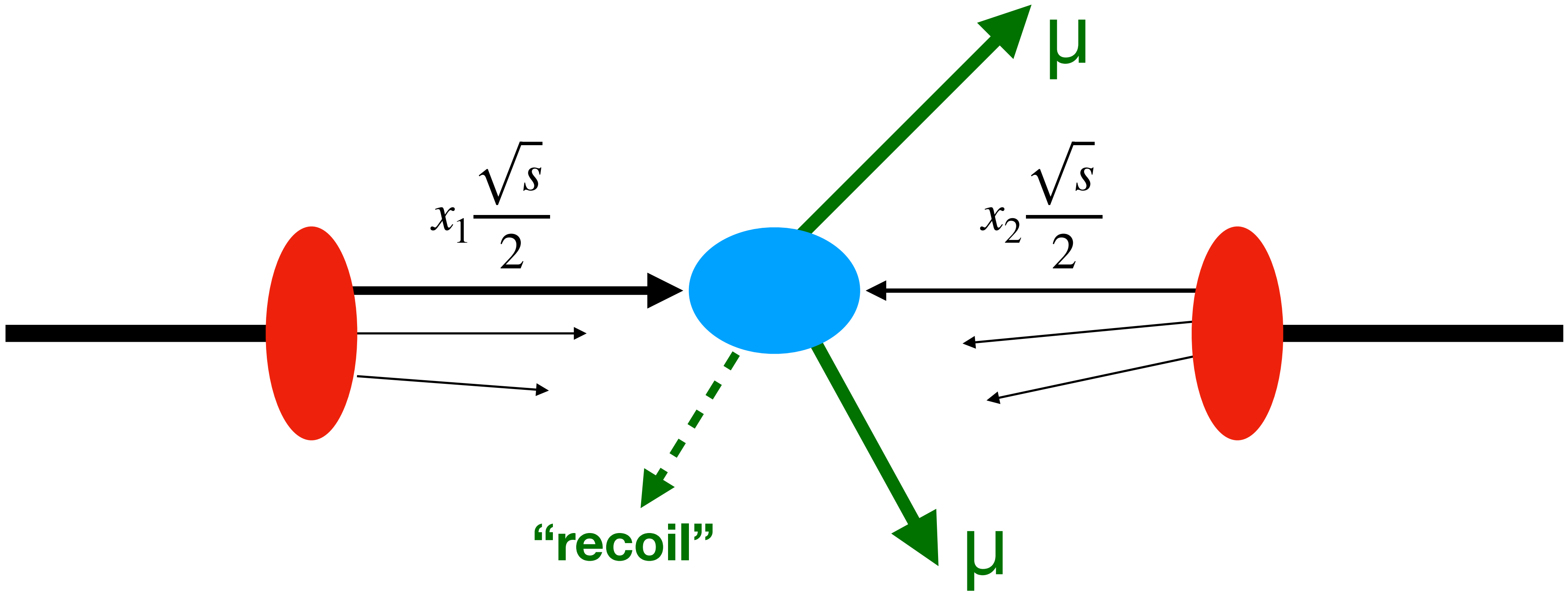
Parton Distribution Functions





Uncertainty from truncation of perturbative series.

Uncertainty from experiments, theory, parameterisations etc…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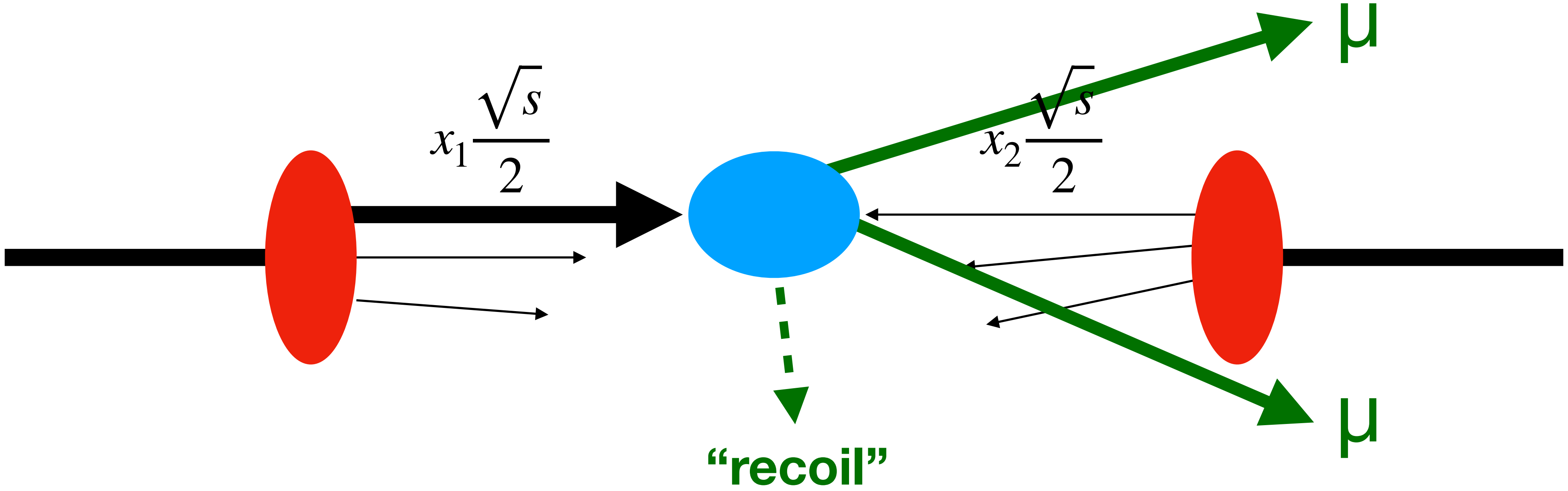
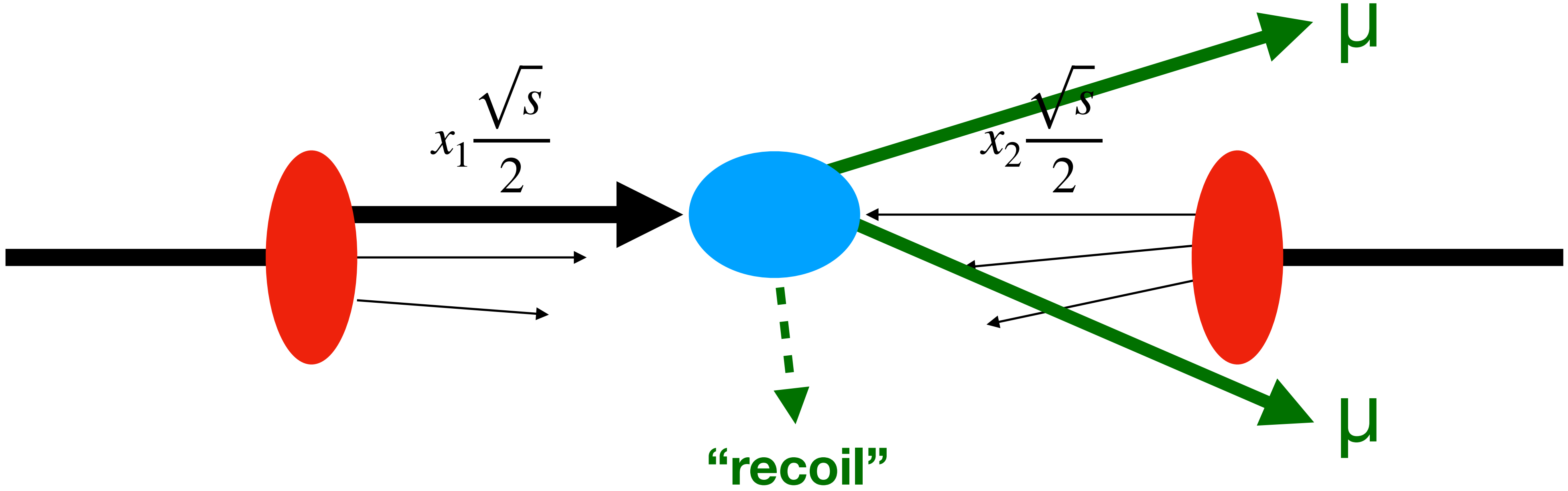
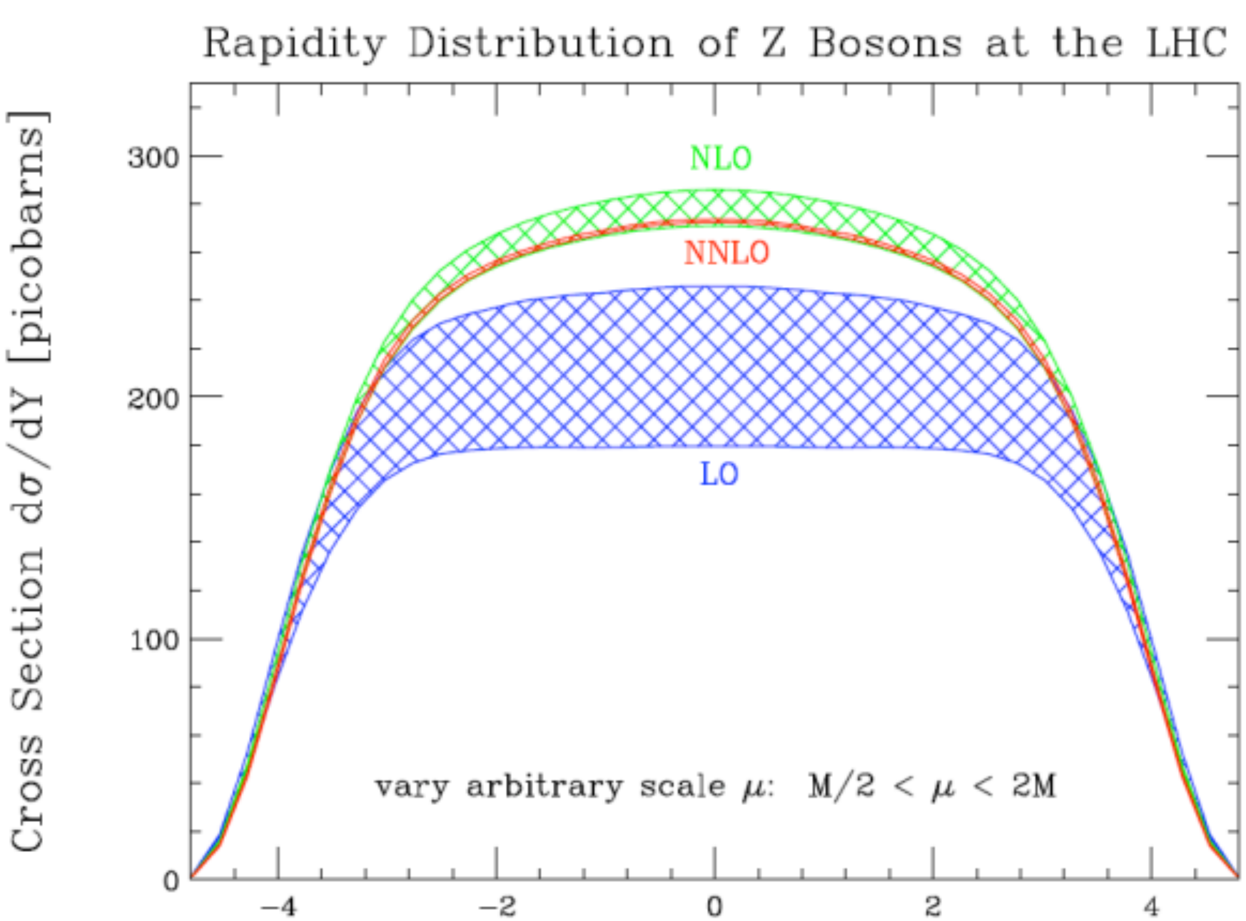
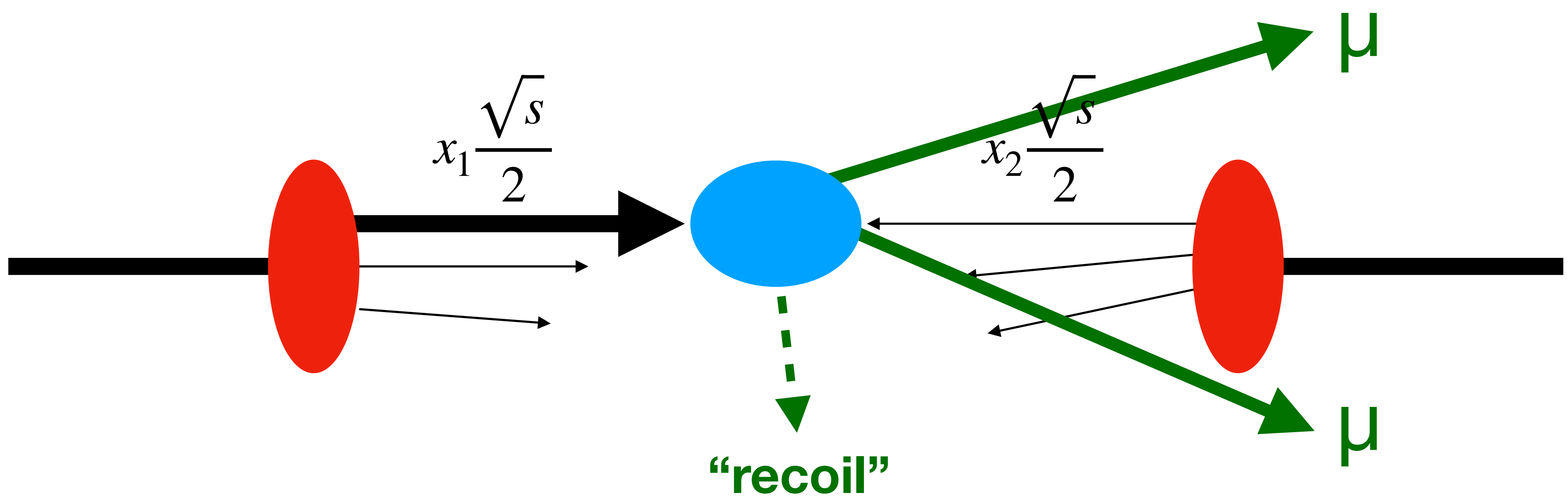
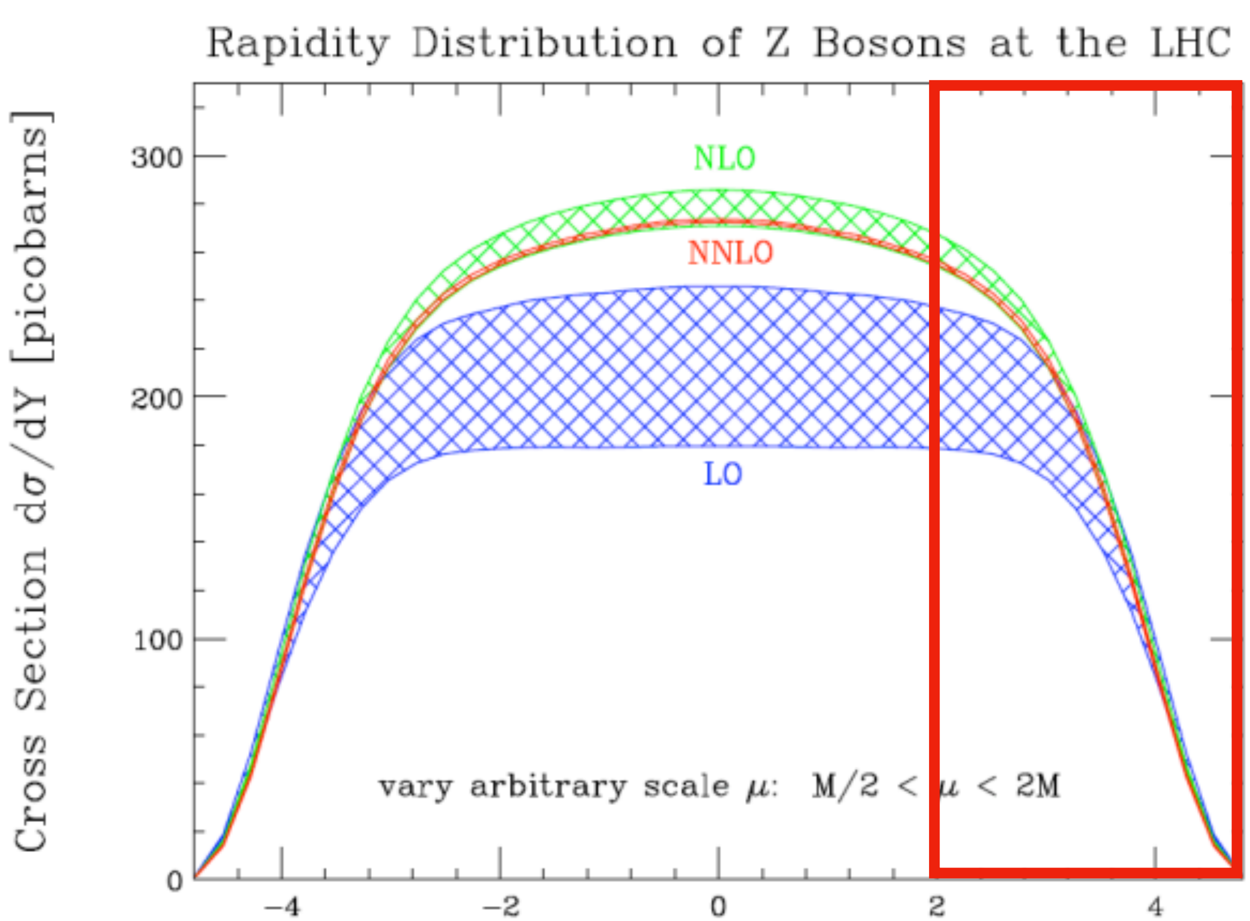

$x_1\frac{\sqrt{s}}{2}$
$x_2\frac{\sqrt{s}}{2}$
μ
μ
"recoil"

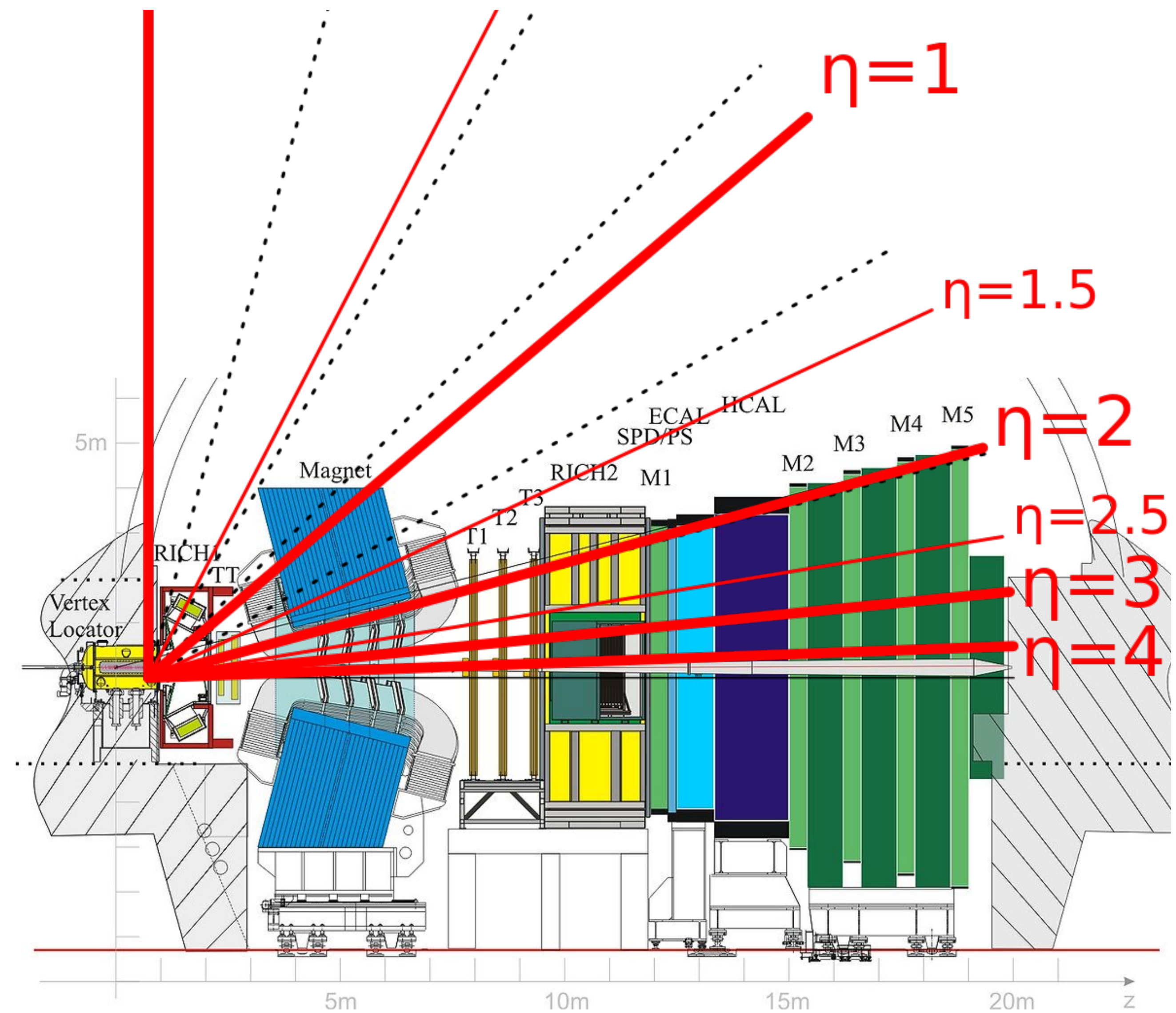




Rapidity $Y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$







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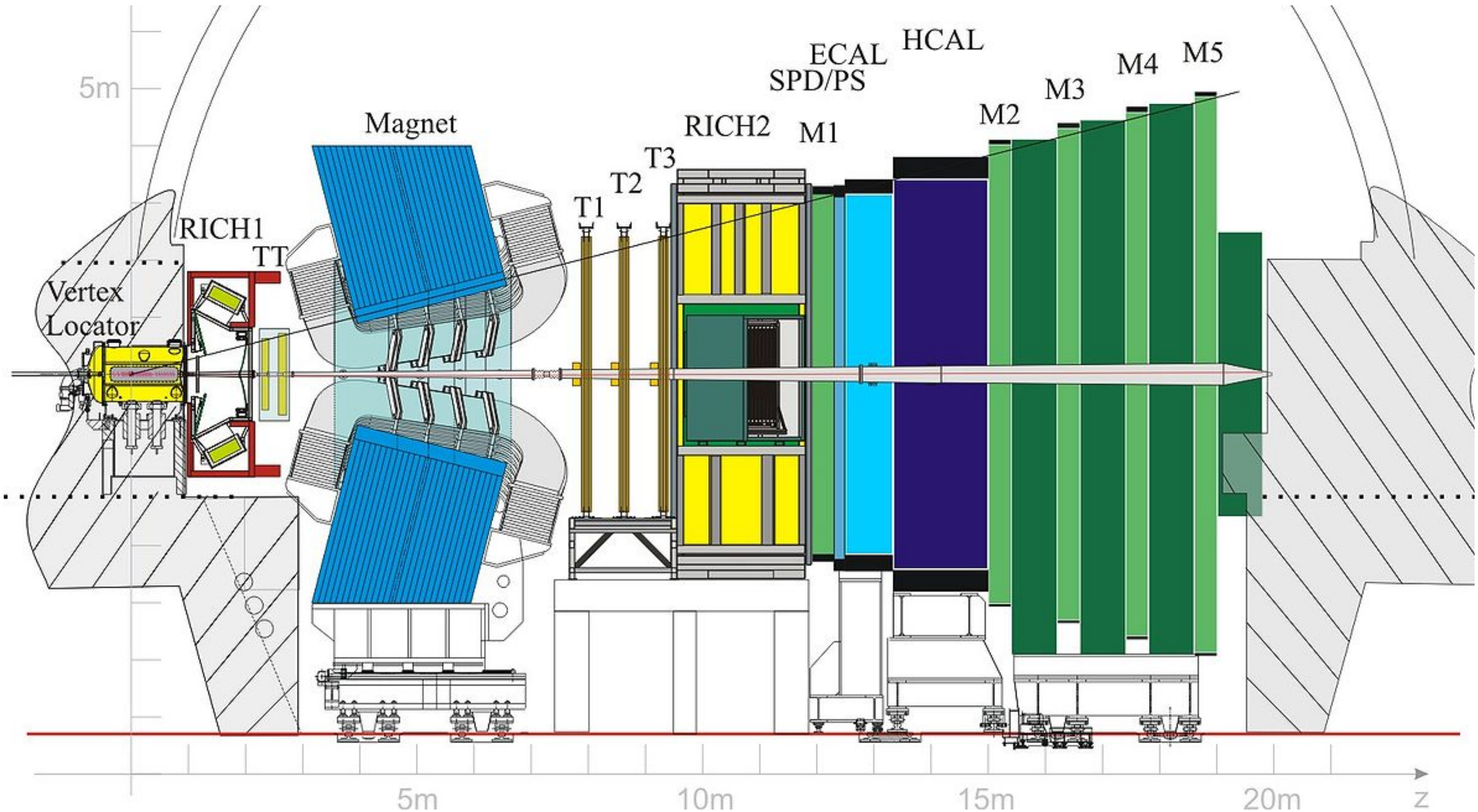


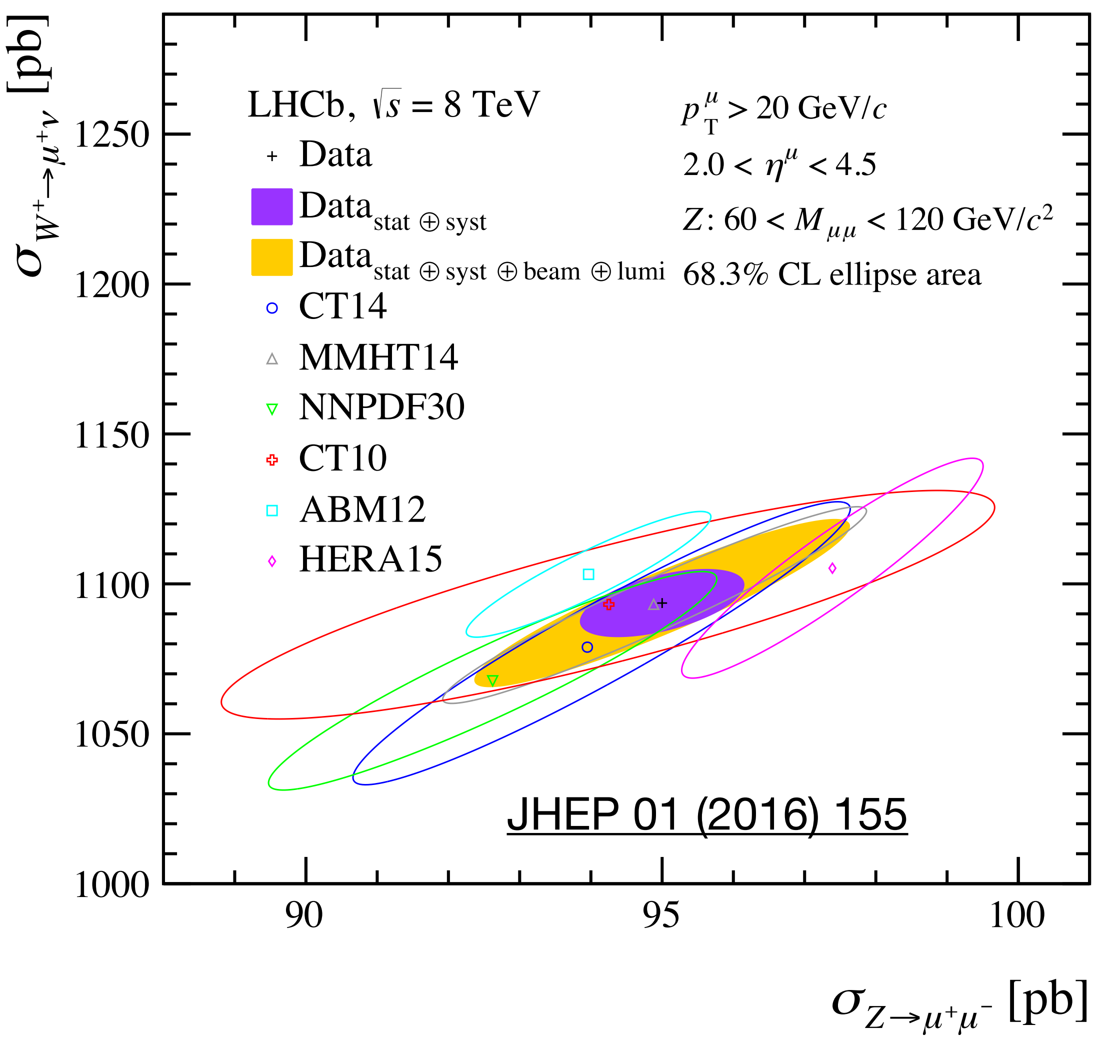
At p_T ~ 40 GeV:

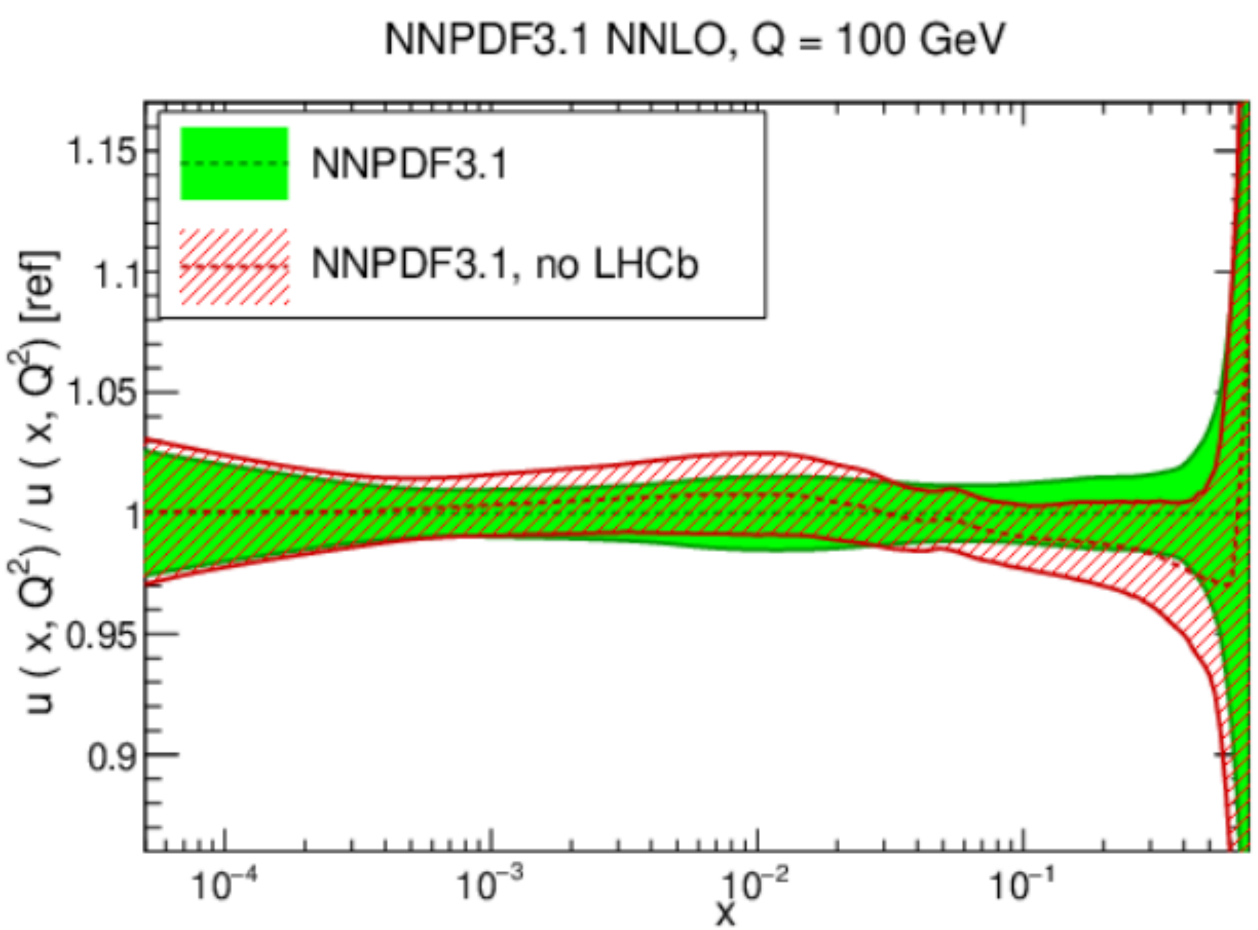
✅ Momentum resolution ~ few %

✅ $\epsilon(\pi/K \rightarrow \mu) \sim 10^{-3}$ for $\epsilon(\mu \rightarrow \mu) \sim 95\%$

LHCb can help with the W mass in **two** ways…

1) Constrain the PDFs with cross-section measurements



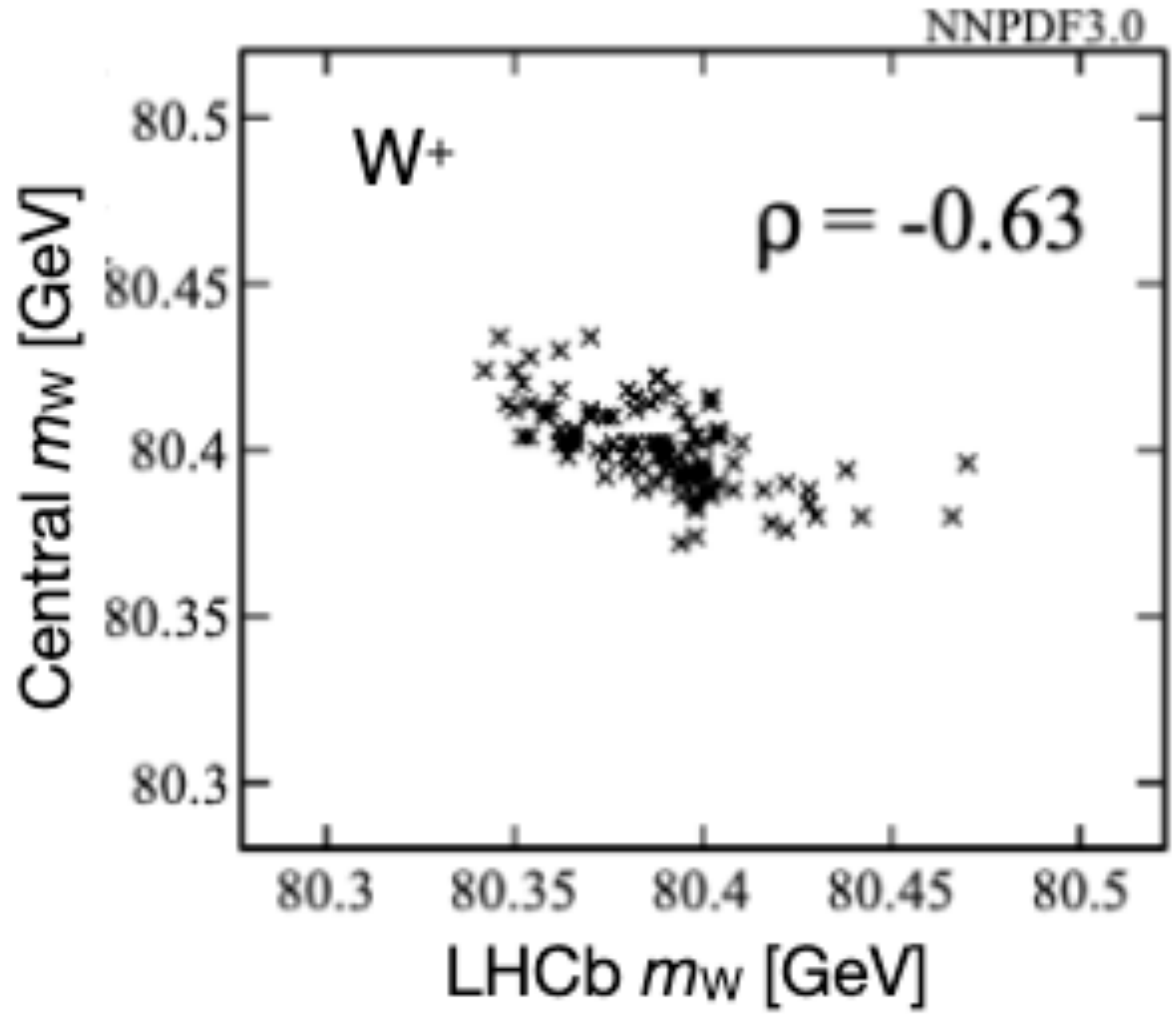


$$x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

2) Measuring the W mass ourselves!

EPJC 75 (2015) 12, 601

Use muon p_T distribution in $pp \to W + X \to \mu\nu + X$

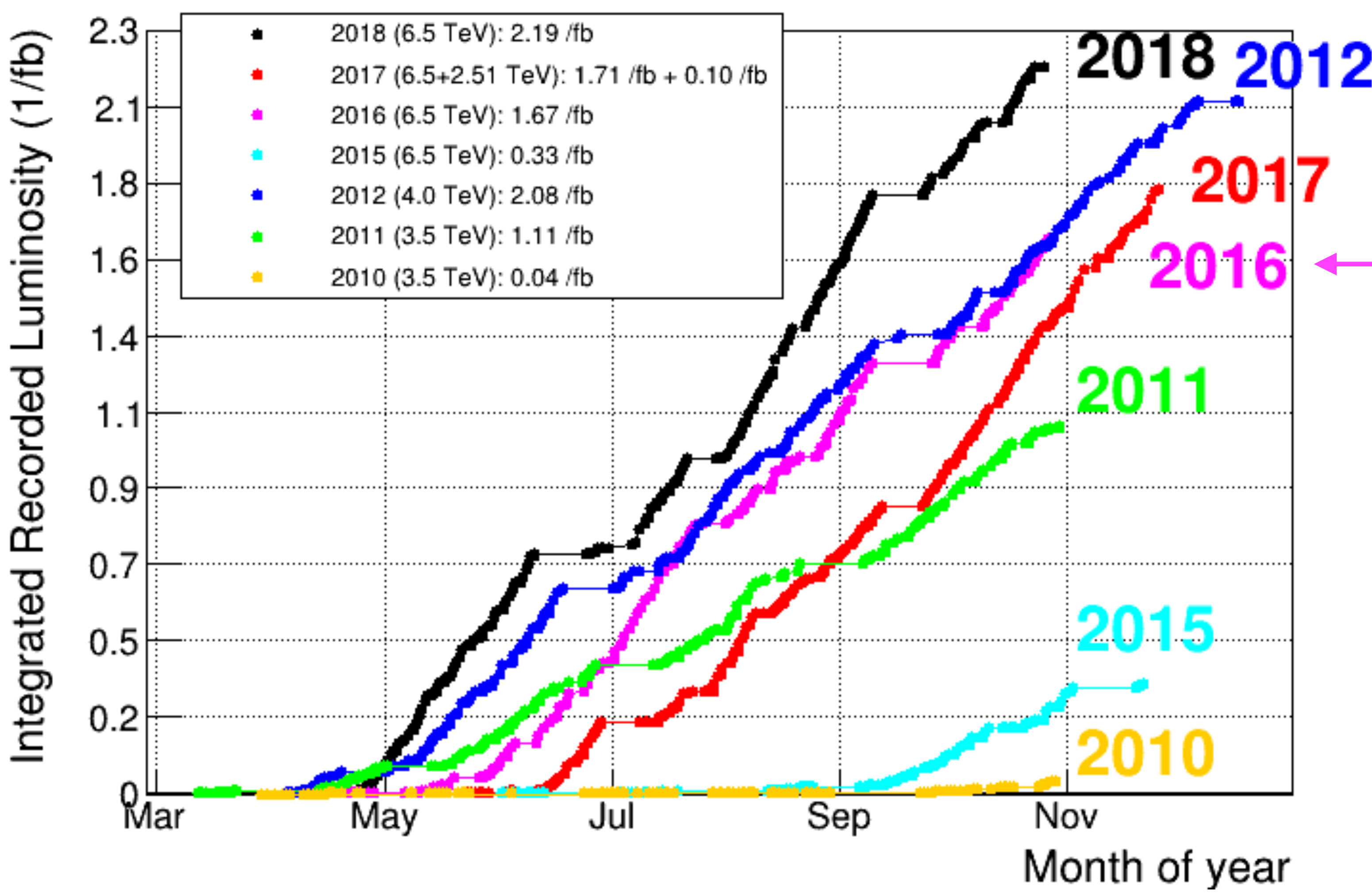


	Run-I $3\ \text{fb}^{-1}$		Run-II $7\ \text{fb}^{-1}$	
	W^+	W^-	W^+	W^-
Signal yields, $\times 10^6$	1.2	0.7	5.4	3.4
Z/γ^* background, (B/S)	0.15	0.15	0.15	0.15
QCD background, (B/S)	0.15	0.15	0.15	0.15
δm_W (MeV)				
Statistical	19	29	9	12
Momentum scale	7	7	4	4
Quadrature sum	20	30	10	13

1. Partial anticorrelation of the PDF uncertainty
2. Plenty of statistics
3. W p_T distribution will be challenging…

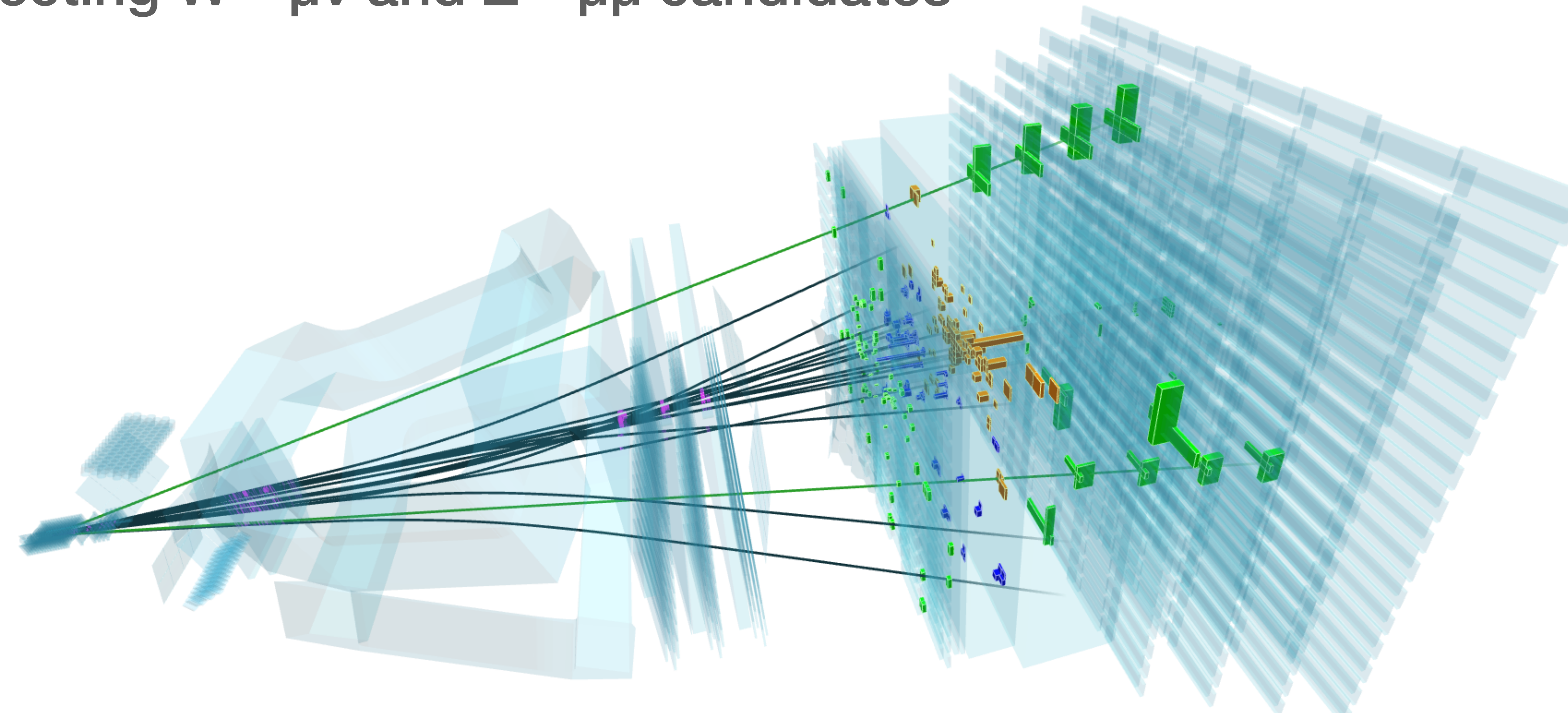
Part 2: Proof-of-principle measurement of m_W with LHCb

hep-ex:2109.01113 LHCb-PAPER-2021-024



This analysis (1.7 fb^{-1})

Selecting $W \to \mu\nu$ and $Z \to \mu\mu$ candidates

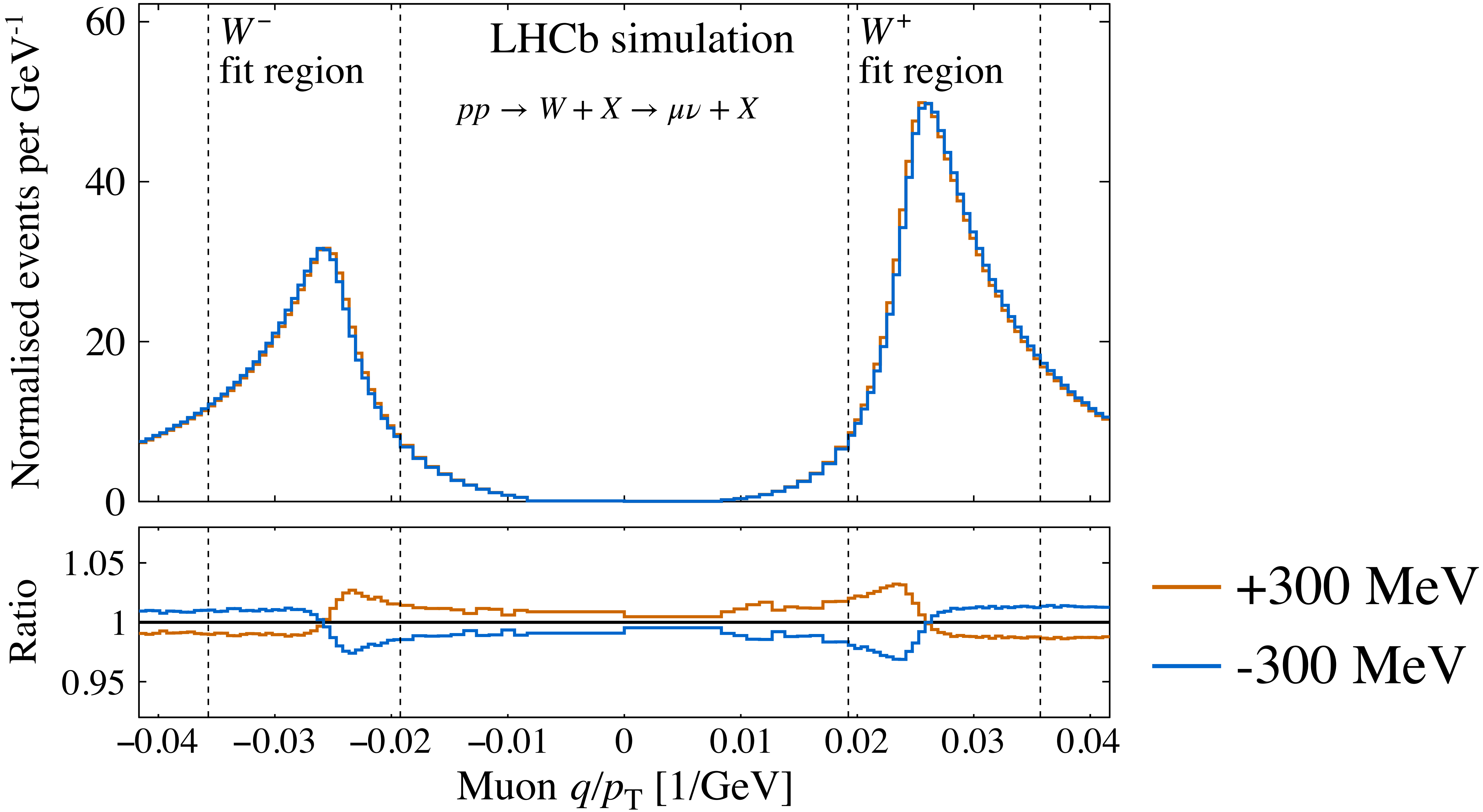


$W \to \mu\nu$	2.4 million*
$Z \to \mu\mu$	0.2 million**

$$\sigma_{\text{stat}}(m_W) \sim 20 \text{ MeV}$$

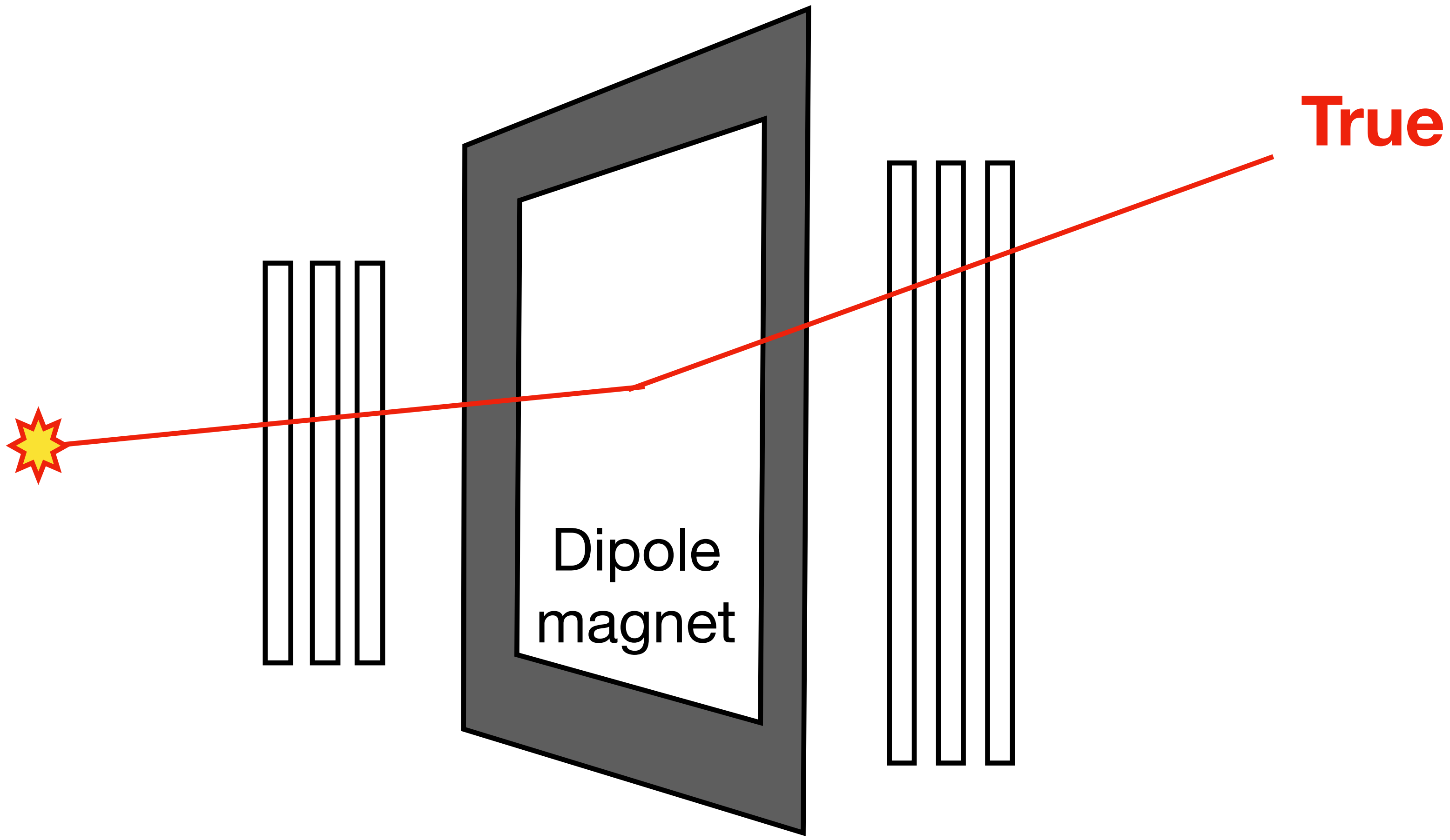
*In $28 < p_T < 52$ GeV and $2.2 < \eta < 4.4$ region used for m_W fit
**Mass within ±14 GeV of nominal Z mass

Our m_W-sensitive observable



The challenge is *modelling* the data, but first…

Curvature biases



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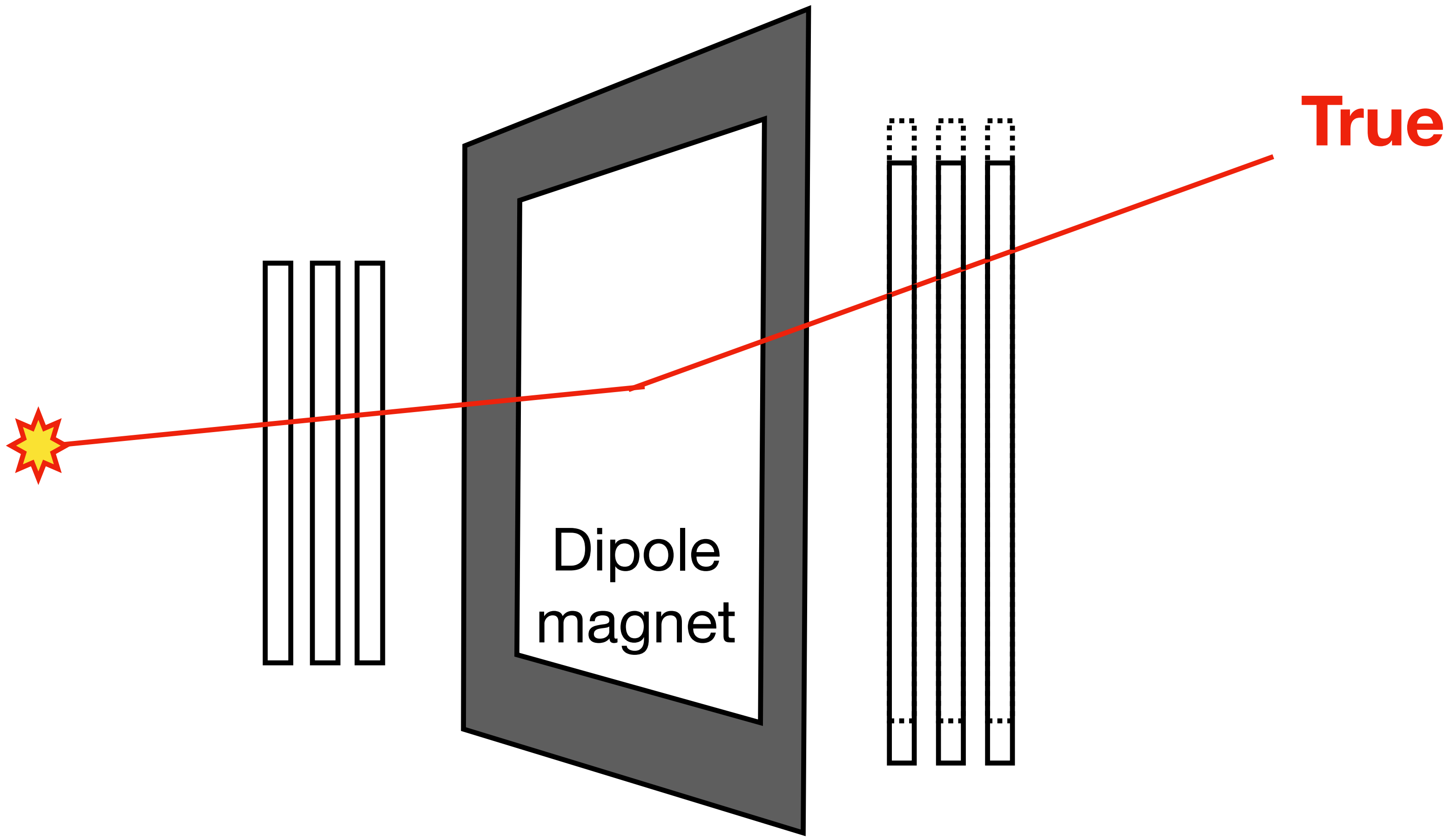

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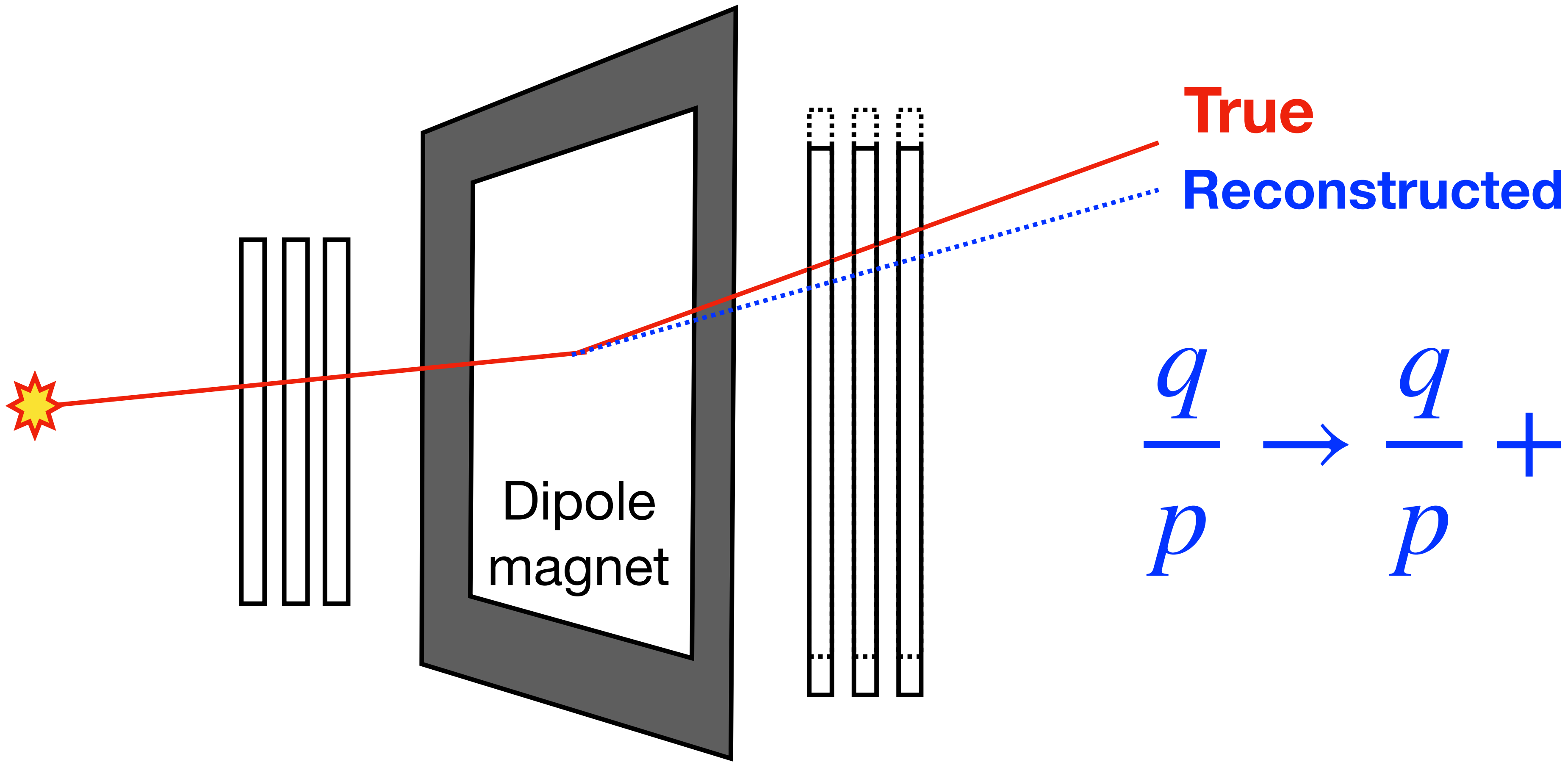


$$\frac{q}{p} \to \frac{q}{p} + \text{bias}$$

Using the *pseudomass*[*]

EPJC 81 (2021) 3, 251

$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

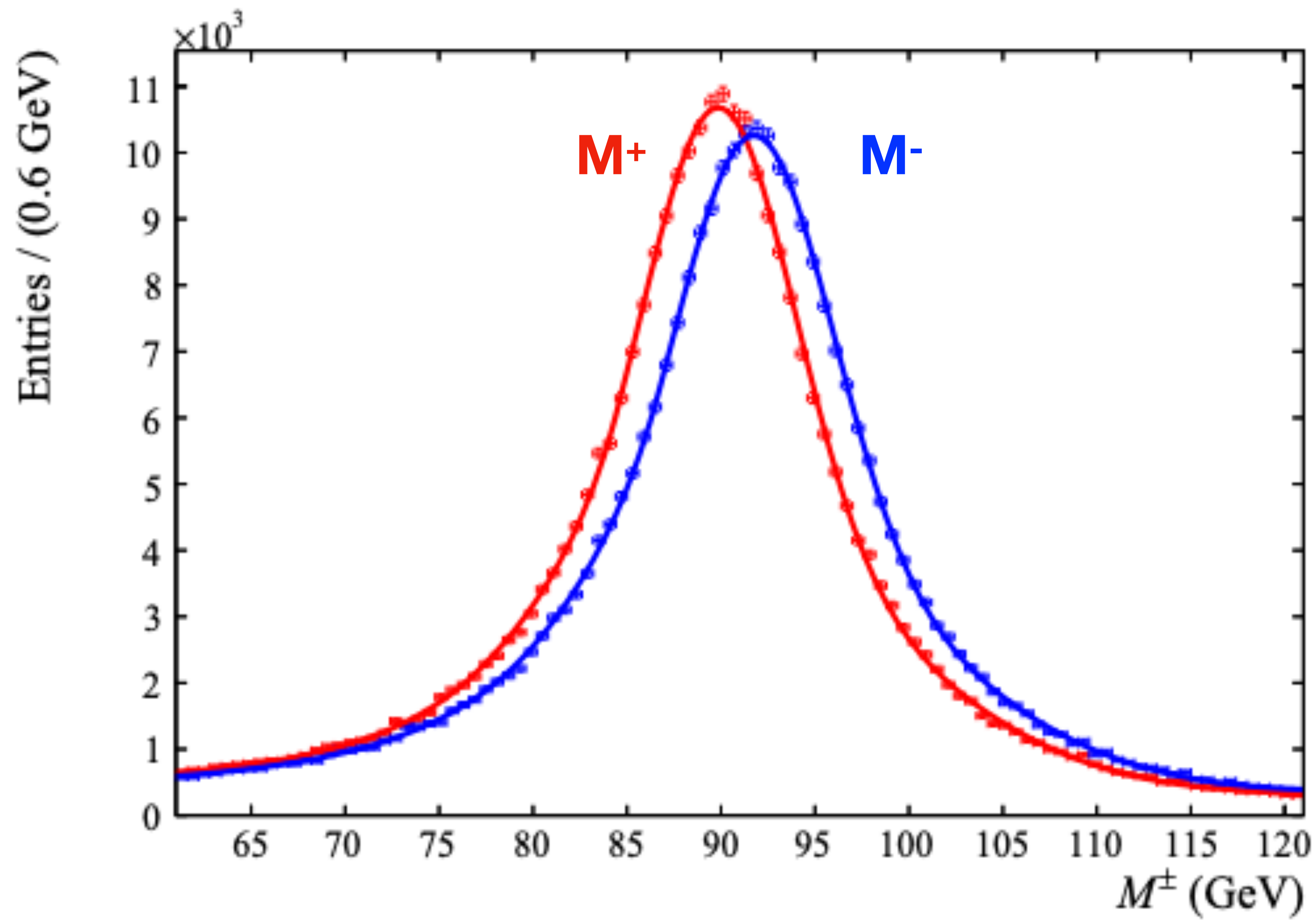
*Inspired by similar variable used in PRD **91**, 072002 (2015)

Using the *pseudomass**

EPJC 81 (2021) 3, 251

$$M^{\pm} = \sqrt{2p^{\pm}p_T^{\pm}\frac{p^{\mp}}{p_T^{\mp}}(1-\cos\theta)}$$

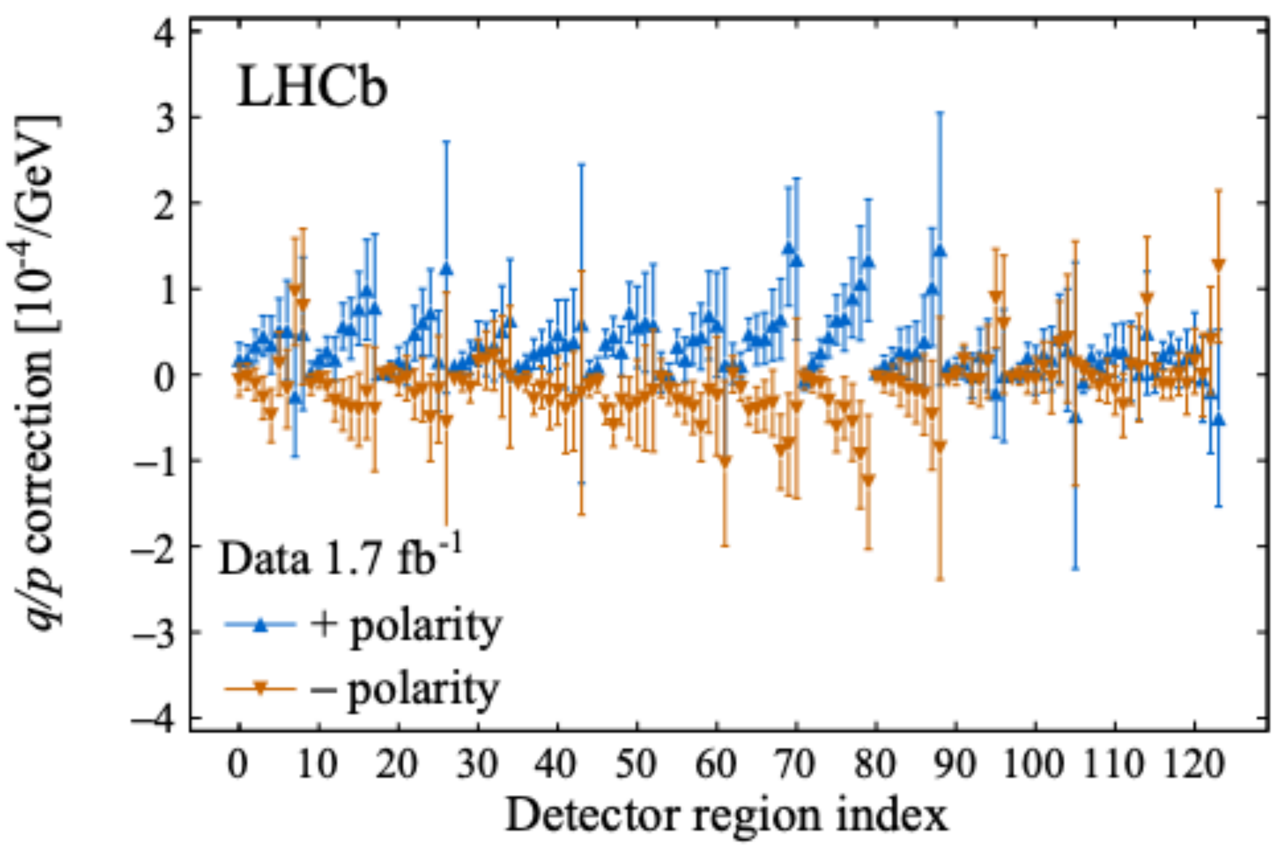
Z→μμ simulation with 50 micron global mis-alignment

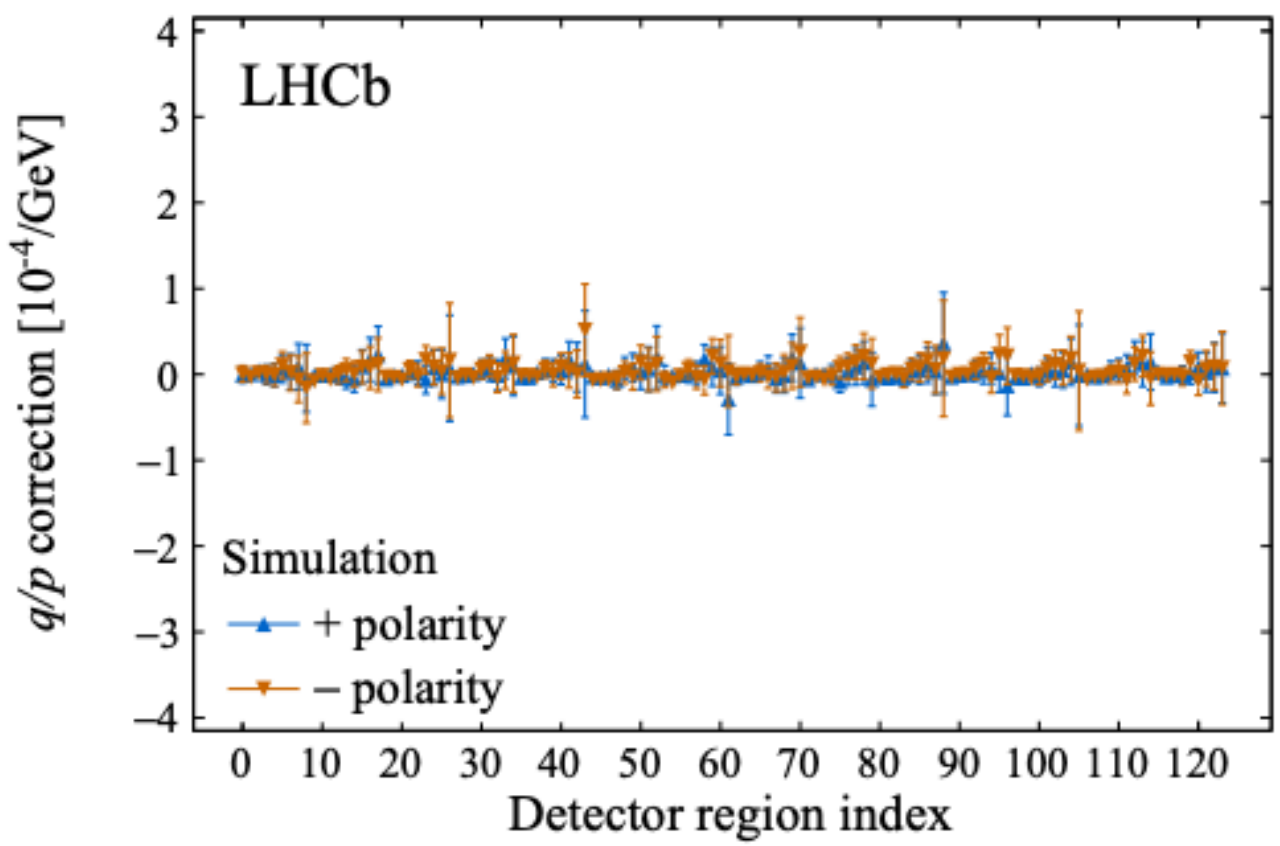


The μ^+ and μ^- are now independent "probes" of q/p biases!

*Inspired by similar variable used in PRD **91**, 072002 (2015)

Curvature corrections from the pseudo mass





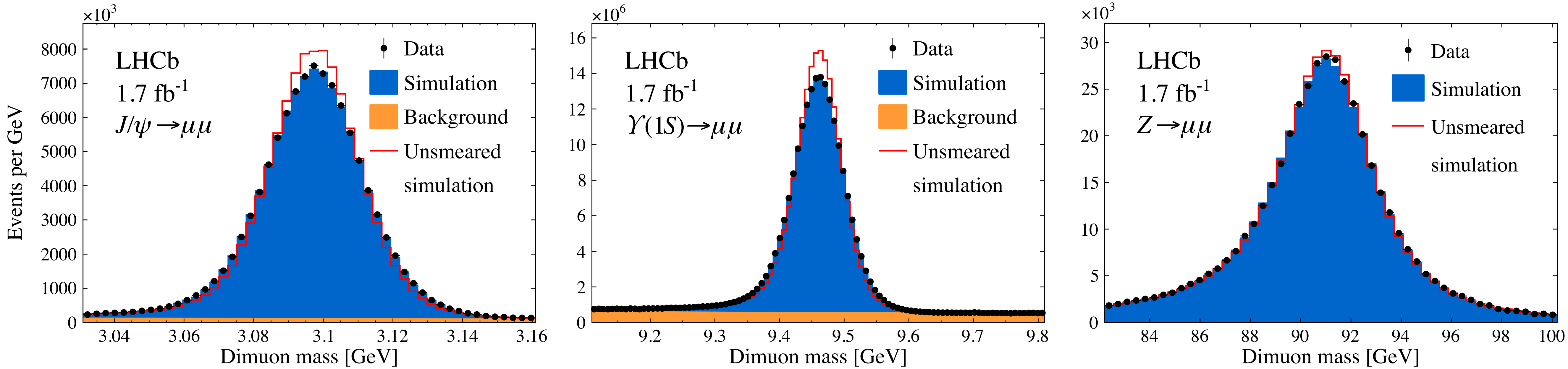
Typical size of q/p corrections ~ 10^{-5} GeV^{-1}

Now the data are easier to model.

Muon momentum smearing

$$\chi^2_{\mathrm{total}}/\mathrm{ndf} = 1862/2082$$

$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh \eta}\right)$$



Simultaneous fit of Z, Υ(1S) and J/Ψ data (and simulation) in many categories[1]

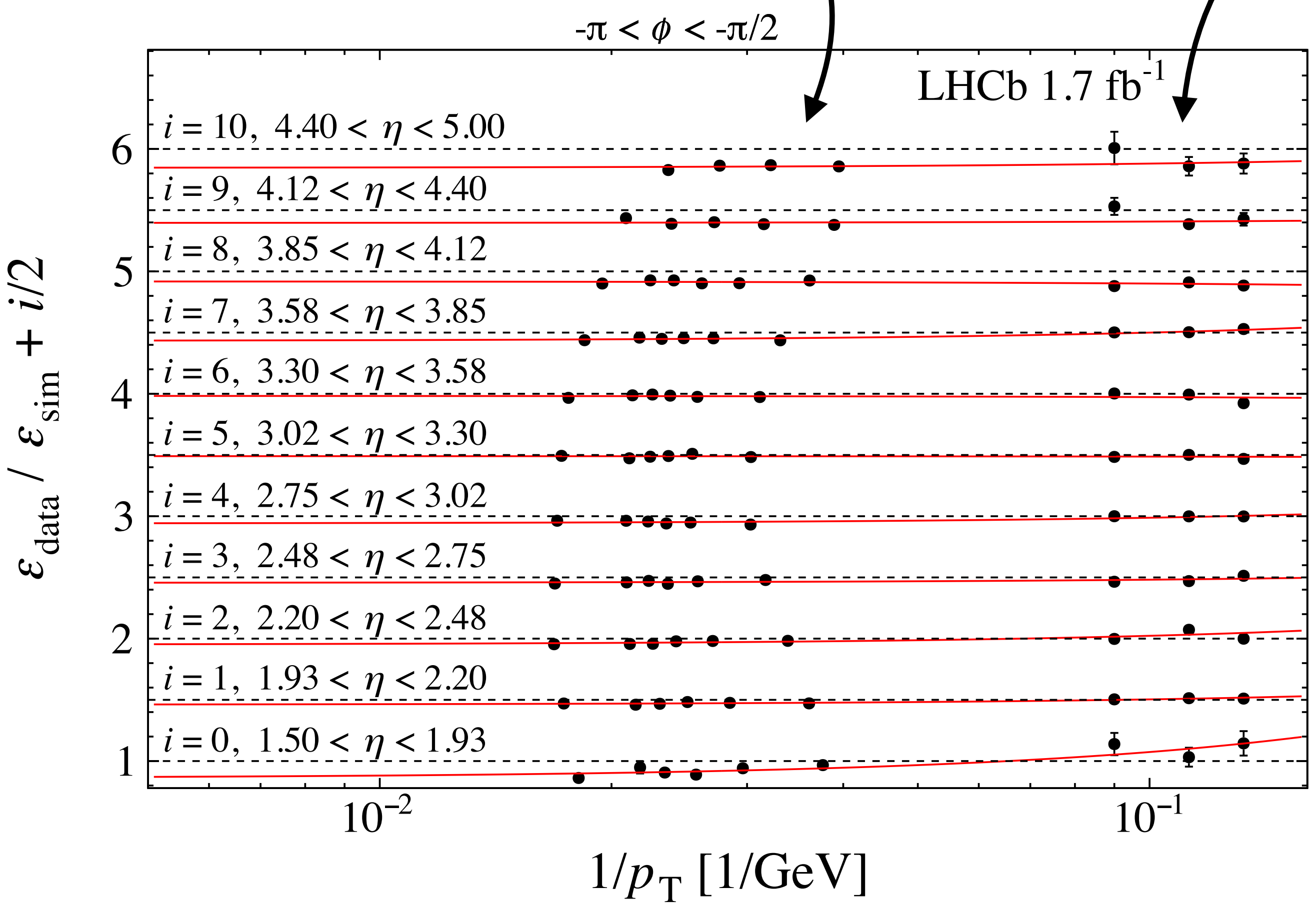
Contributes **7 MeV** uncertainty on m_W

[1] 36 fit categories (based on species, magnet polarity, η of the two muons).
[2] Includes statistics, variations in the PDG resonance masses, detector material budget, final state radiation and the form of the smearing function.

Muon (trigger, tracking, ID) efficiency modelling

Sufficient sub detector redundancy to measure the efficiencies.

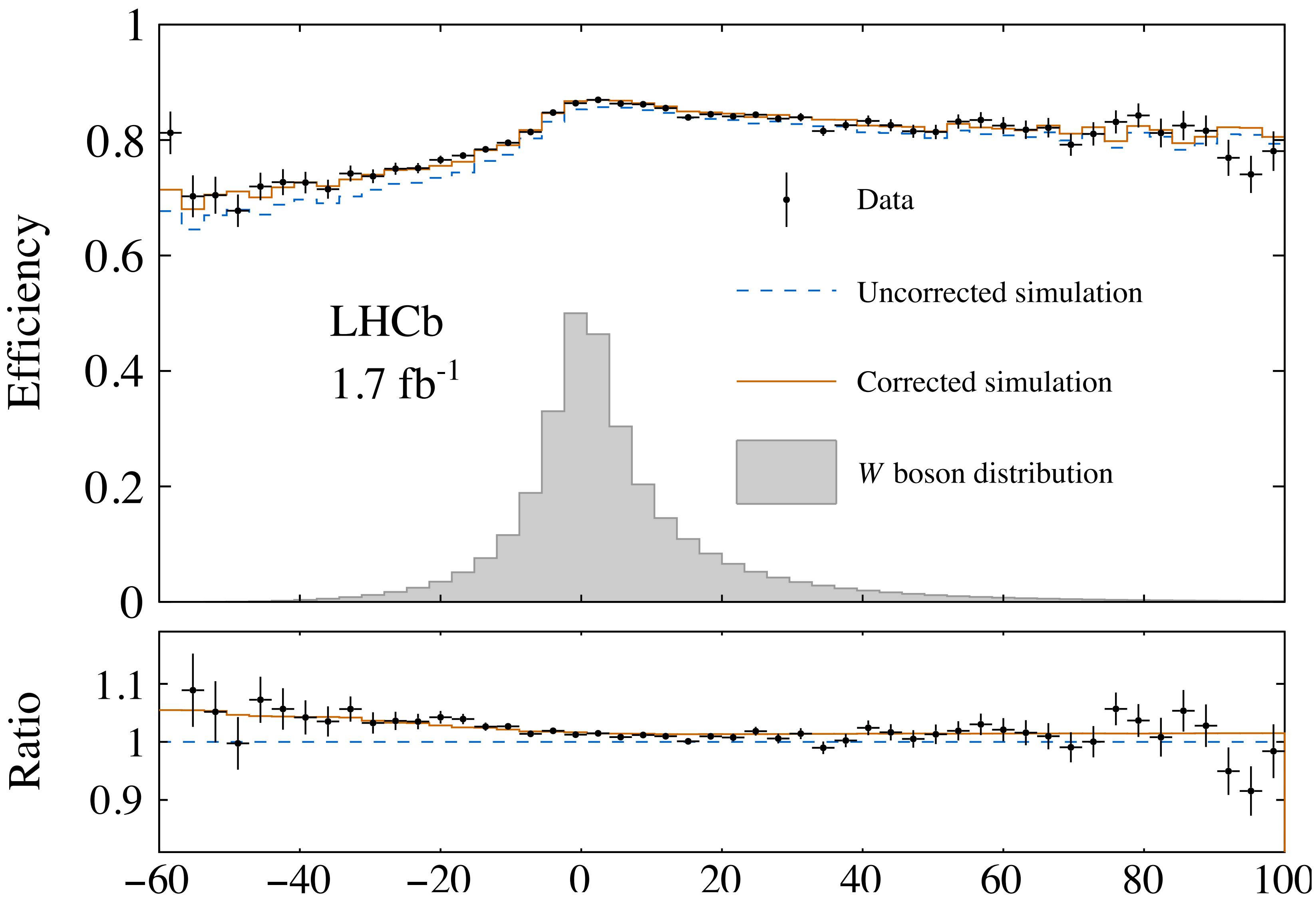
$Z \rightarrow \mu\mu$ $\Upsilon(1S) \rightarrow \mu\mu$



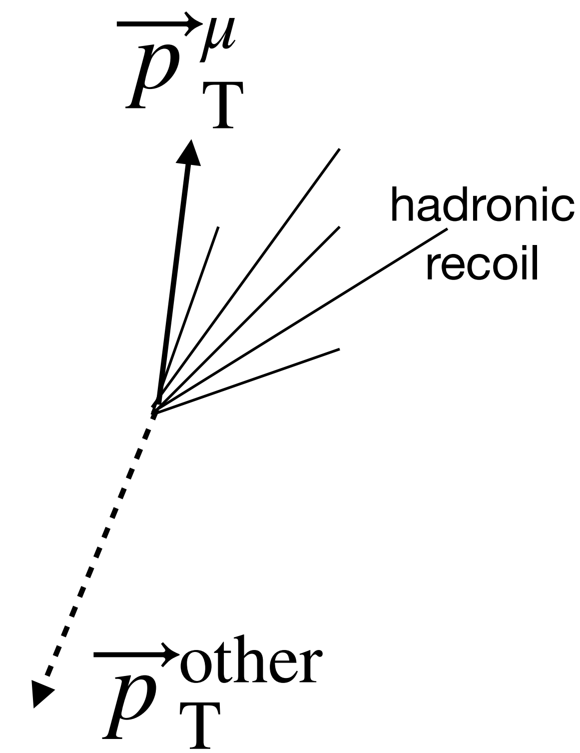
E.g. Trigger efficiency corrections

Contributes **6 MeV** to uncertainty on m_W

Isolation efficiency modelling



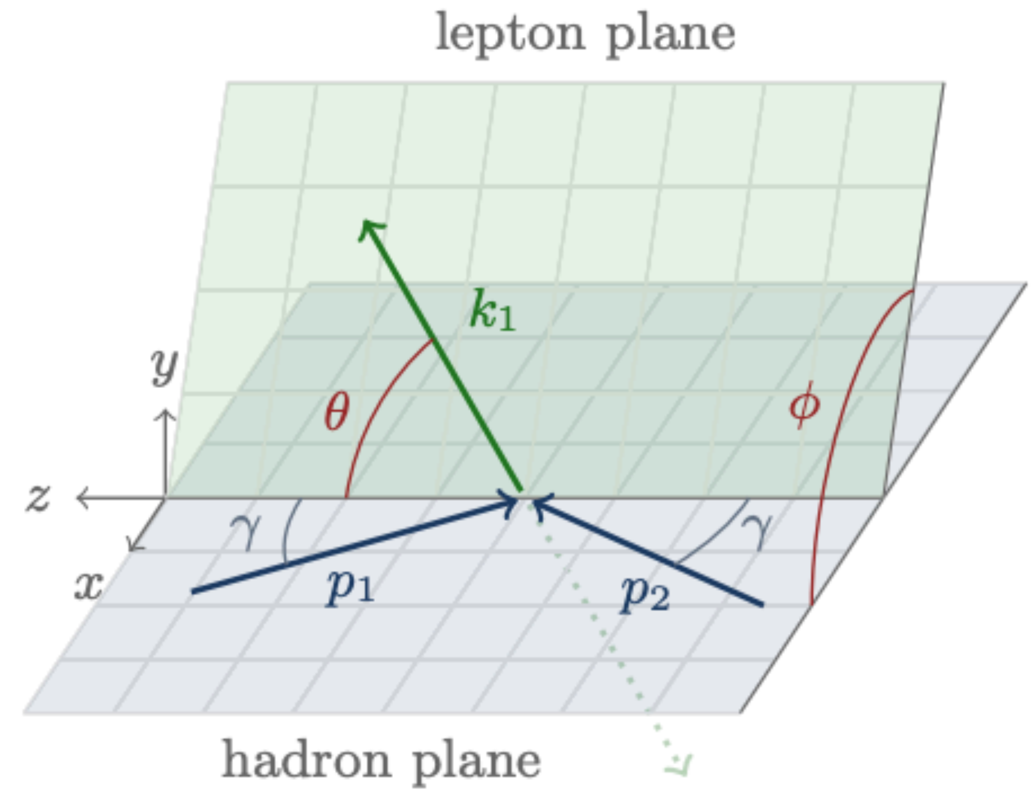
$$u = \frac{\vec{p}_T^{\,V} \cdot \vec{p}_T^{\,\mu}}{p_T^{\mu}}$$ [GeV]



Contributes **4 MeV** uncertainty on m_W

Vector boson production model

θ and ϕ in the Collins-Soper frame



Electroweak part:
QED FSR →**7 MeV uncertainty**
Missing EW corrections → **5 MeV uncertainty**

General **QCD** form of kinematics:

$$\frac{d\sigma}{dp_T^W \, dy \, dM \, d\cos\theta \, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{dp_T^V \, dy \, dM}$$

$$\Big\{(1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$

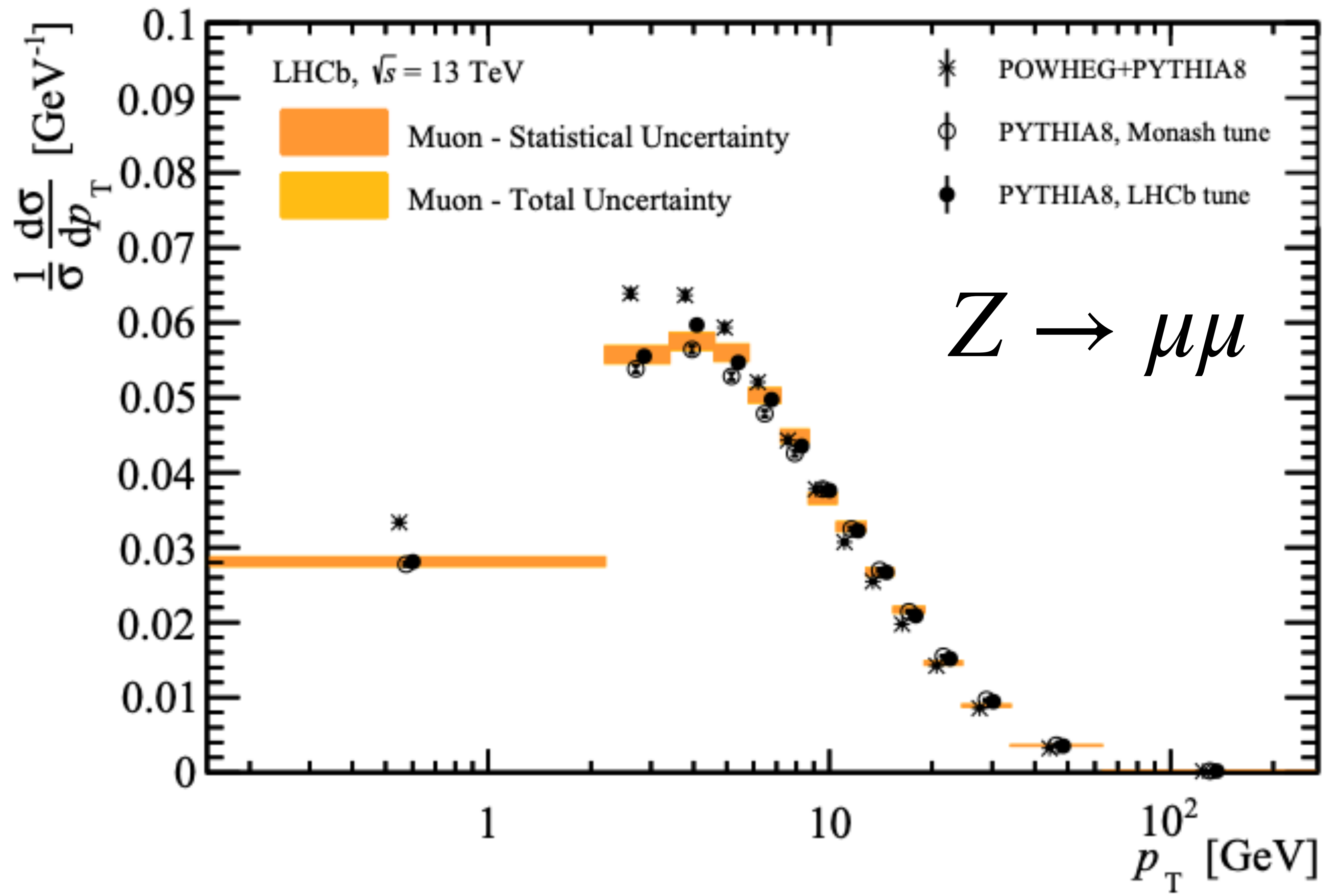
$$+ A_2 \frac{1}{2}\sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4 \cos\theta$$

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\},$$

The p_T dependence of the cross section is particularly important…

1708.00008 acknowledged for the figure.

Boson p_T distribution



Related observable with better experimental resolution:

$$\phi^* \equiv \tan\left(\frac{\pi - \Delta\phi}{2}\right)/\cosh\left(\frac{\Delta\eta}{2}\right) \sim \frac{p_T}{M}$$

EPJC 71:1600 (2011)

Modelling the boson p_T distribution

Convergence of perturbative series spoiled by large logs.

Order by order corrections ~ $$\frac{\alpha_s^n}{p_T} \sum_m^{2n-1} \ln^m \frac{M}{p_T}$$

Resummation to all orders is required.

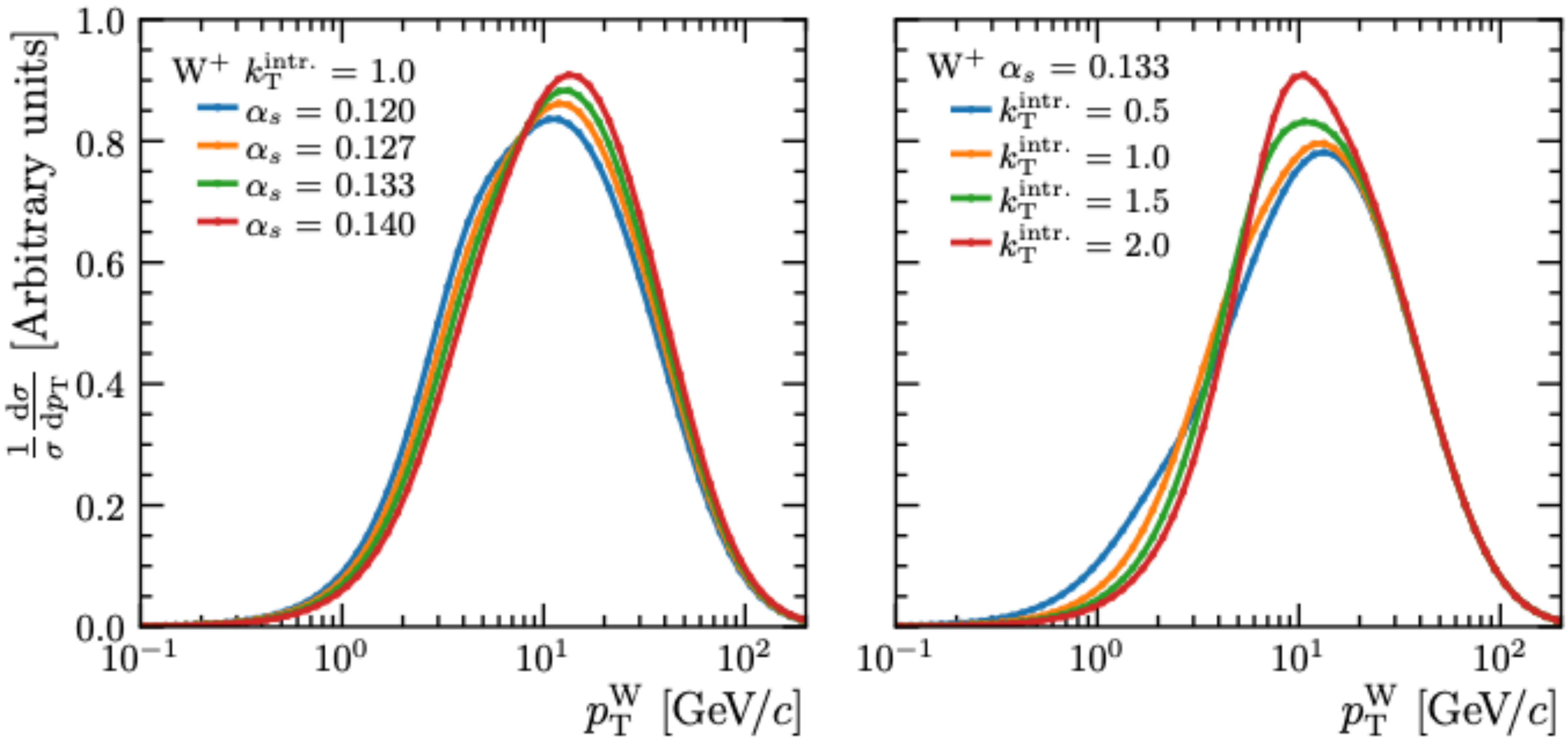
Parton showers (Pythia, Herwig etc…) effectively resum the *leading* logs.

Limited accuracy can be compensated by “tune” of α_s and the “intrinsic k_T”

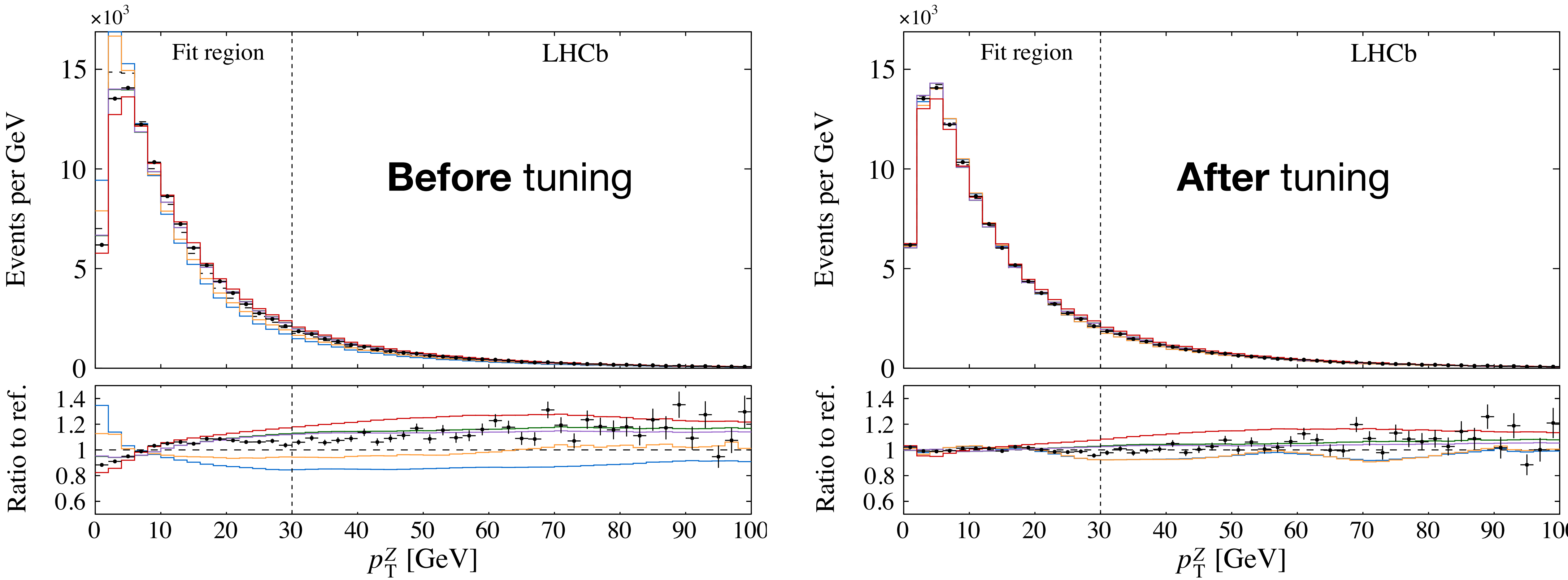
Effect of α_s and intrinsic k_T variation [in Pythia]

1907.09958 (2019)

Varying α_s | or intrinsic k_T



Tuning and validation with Z p_T data



- - - - POWHEGPYTHIA (ref.)
HERWIG
POWHEGHERWIG
PYTHIACT09MCS
PYTHIANNPDF31
DYTURBO

Note that the W boson model gets an independent tune in the m_W fit 1907.09958 (2019)

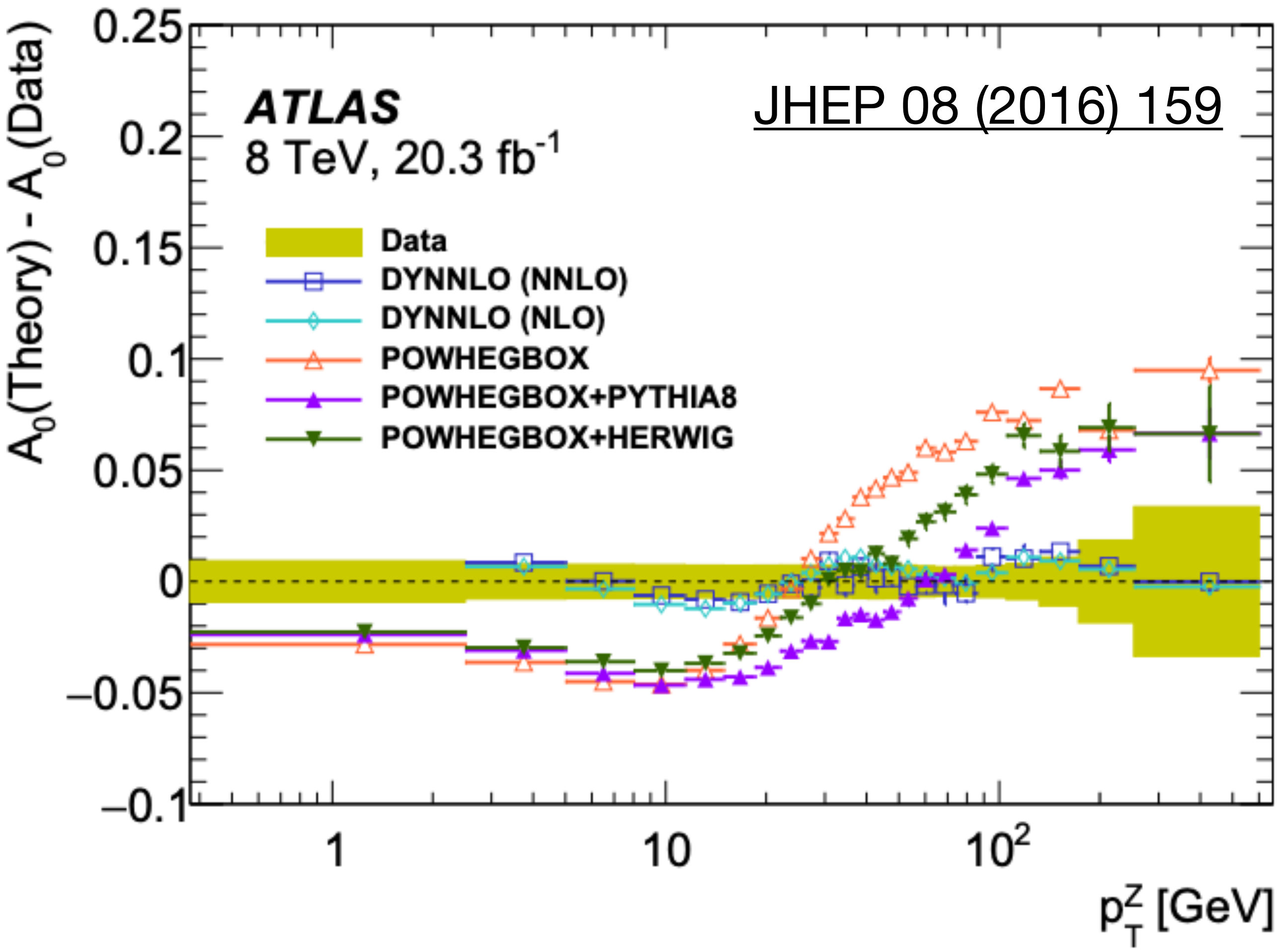
Best description from POWHEG+Pythia with $\alpha_s \approx 0.125$

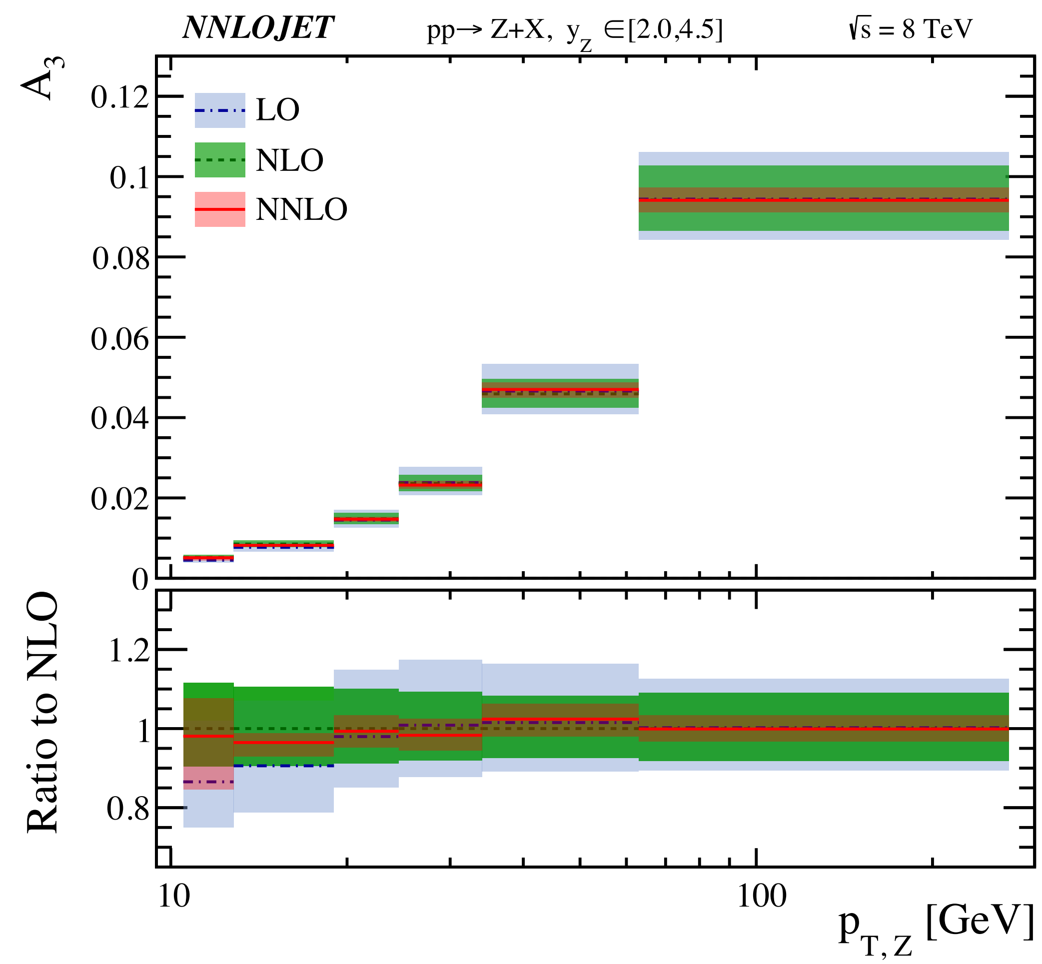
Uncertainty from envelope of m_W fits based on 5 models.

Contributes **11 MeV** uncertainty on m_W

Angular coefficients

JHEP 11 (2017) 003





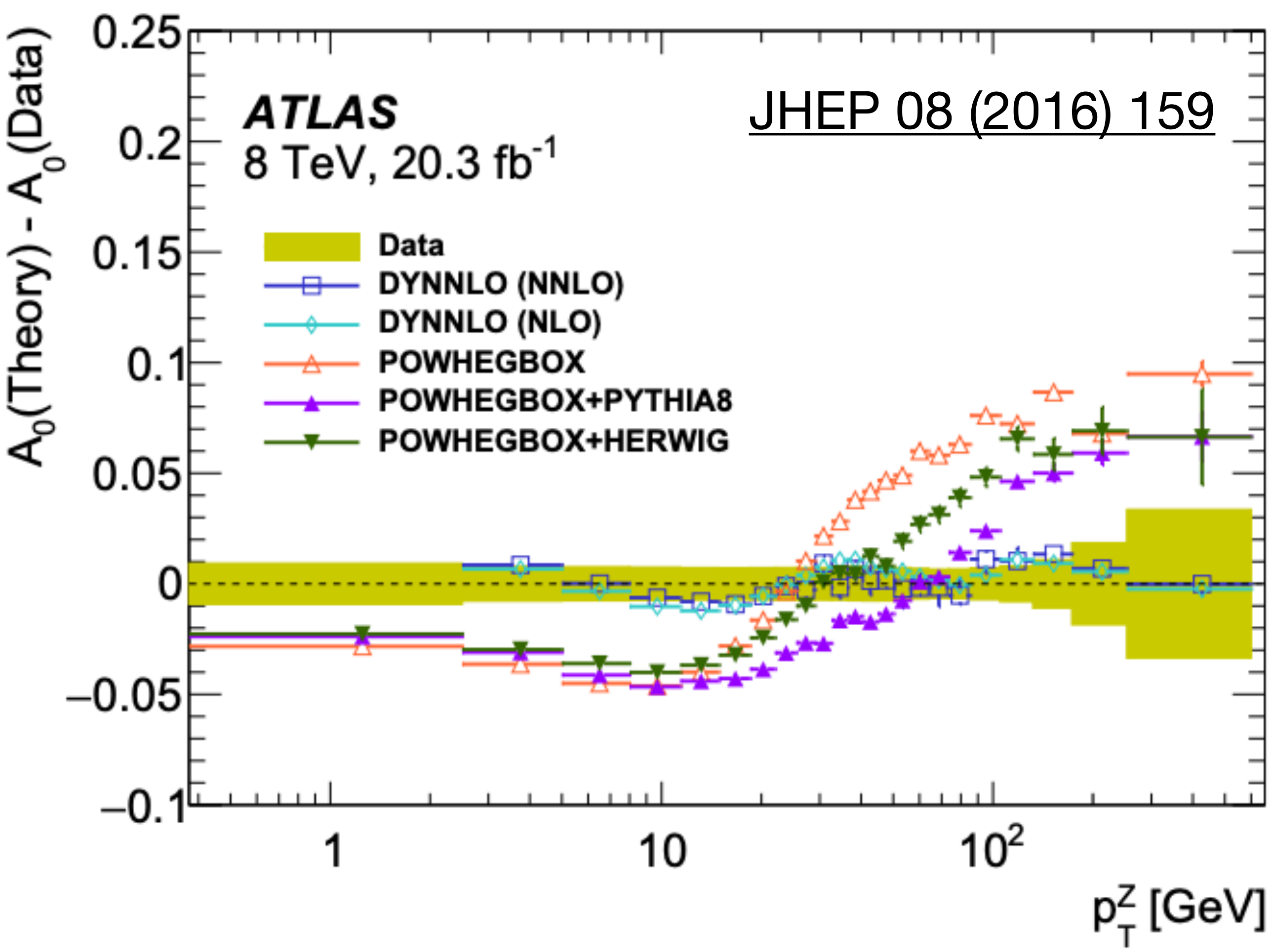
❌ Event generators (e.g. POWHEG)

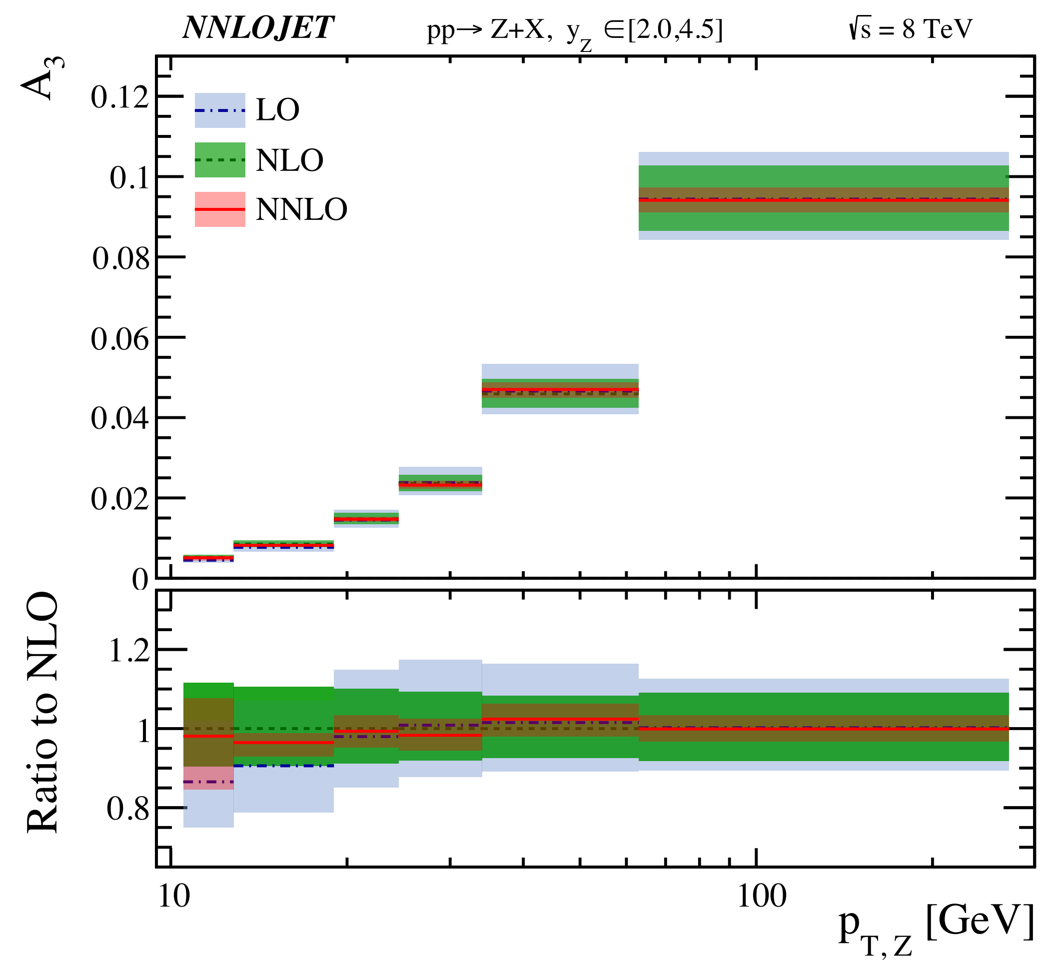
✅ Fixed order QCD

For the renormalisation and factorisation scale uncertainties we use the *uncorrelated* (31-point) scheme.

Angular coefficients

JHEP 11 (2017) 003





Using α_s^2 fixed order predictions from DYTurbo

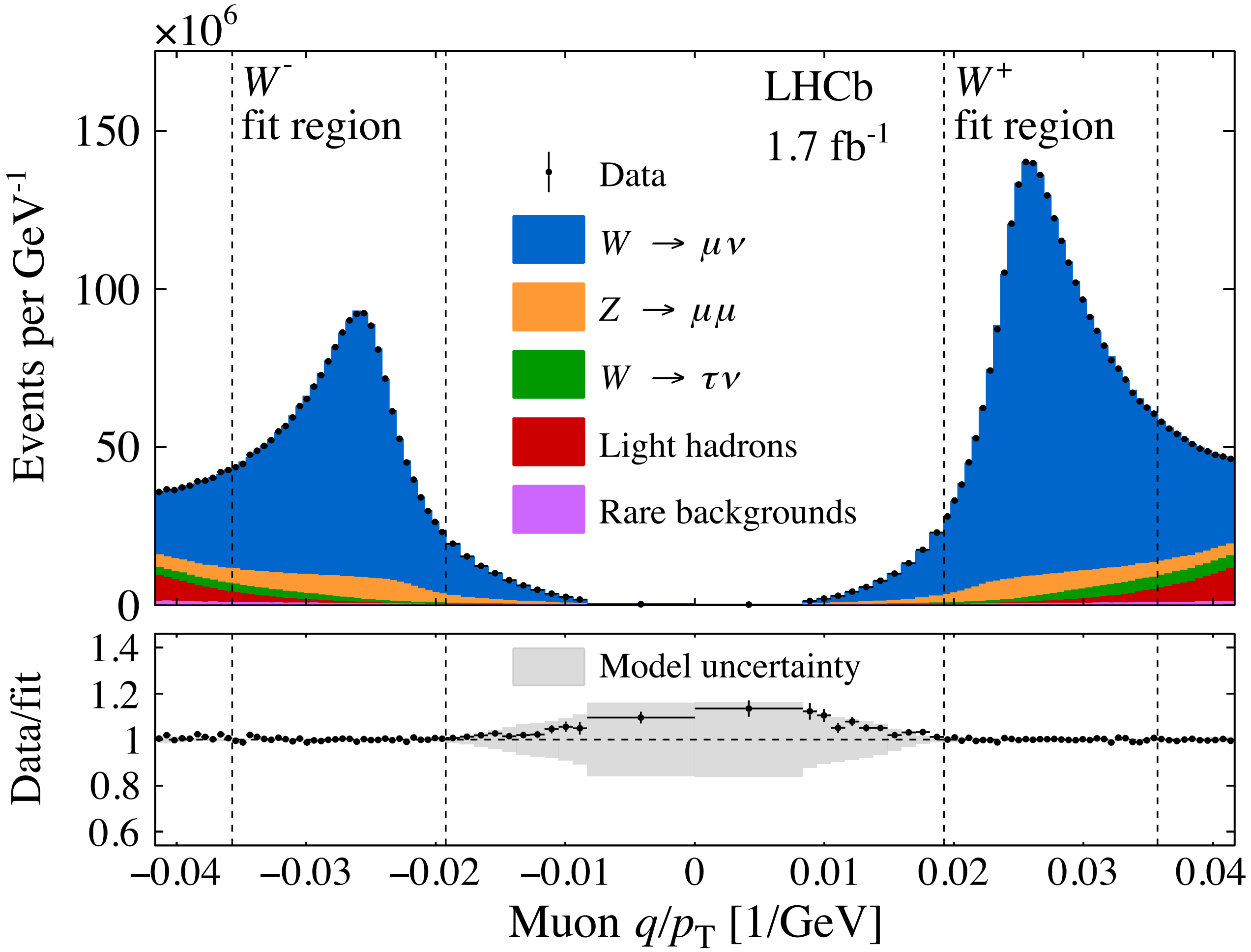
31-point scale variations → 20-30 MeV uncertainty on m_W.

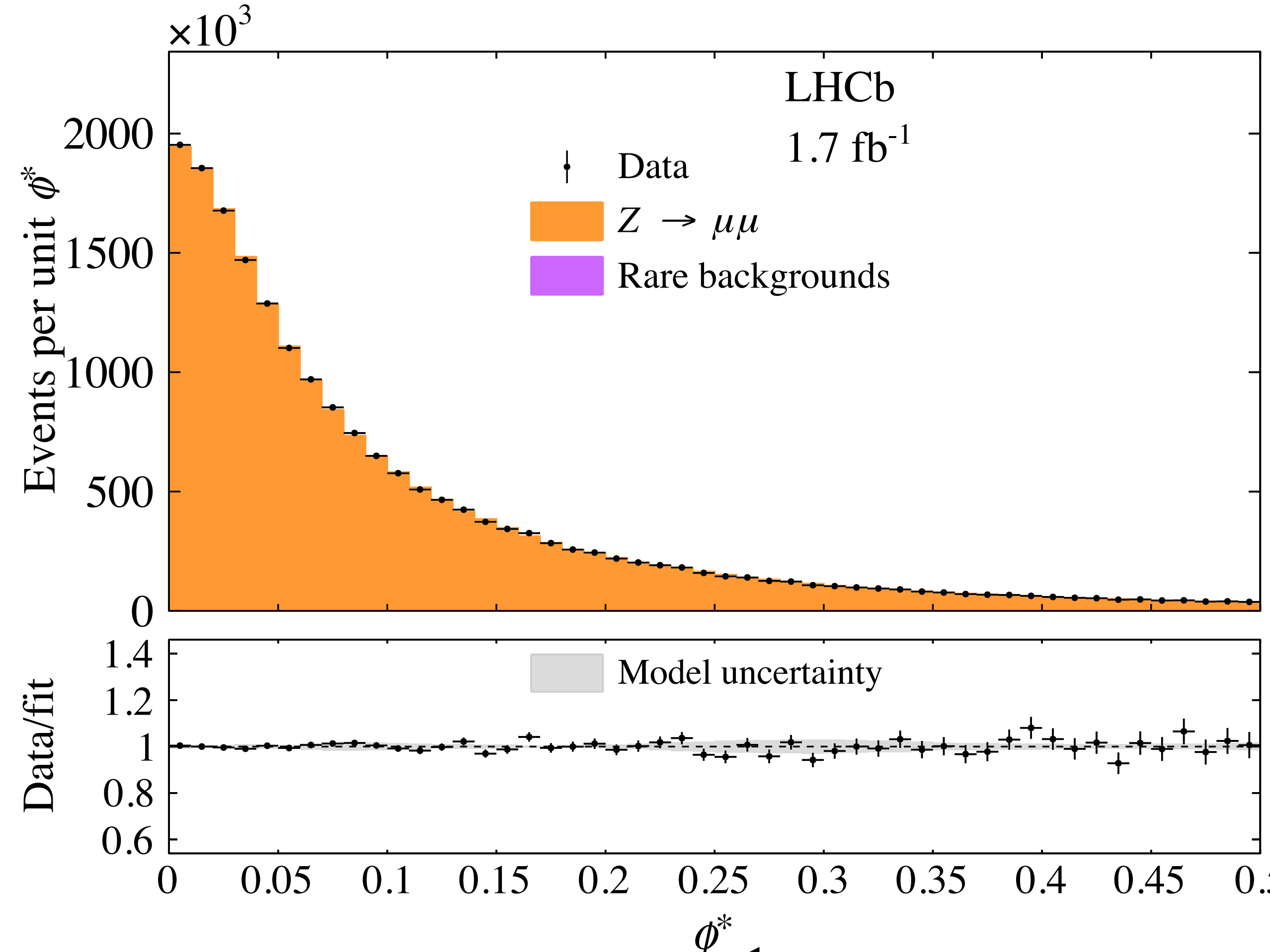
Mitigate by introducing a floating A_3 scale factor in the m_W fit.

Contributes **9 MeV** uncertainty on m_W

The simultaneous fit to W and Z data

$\chi^2/\mathrm{ndf} = 105/102$



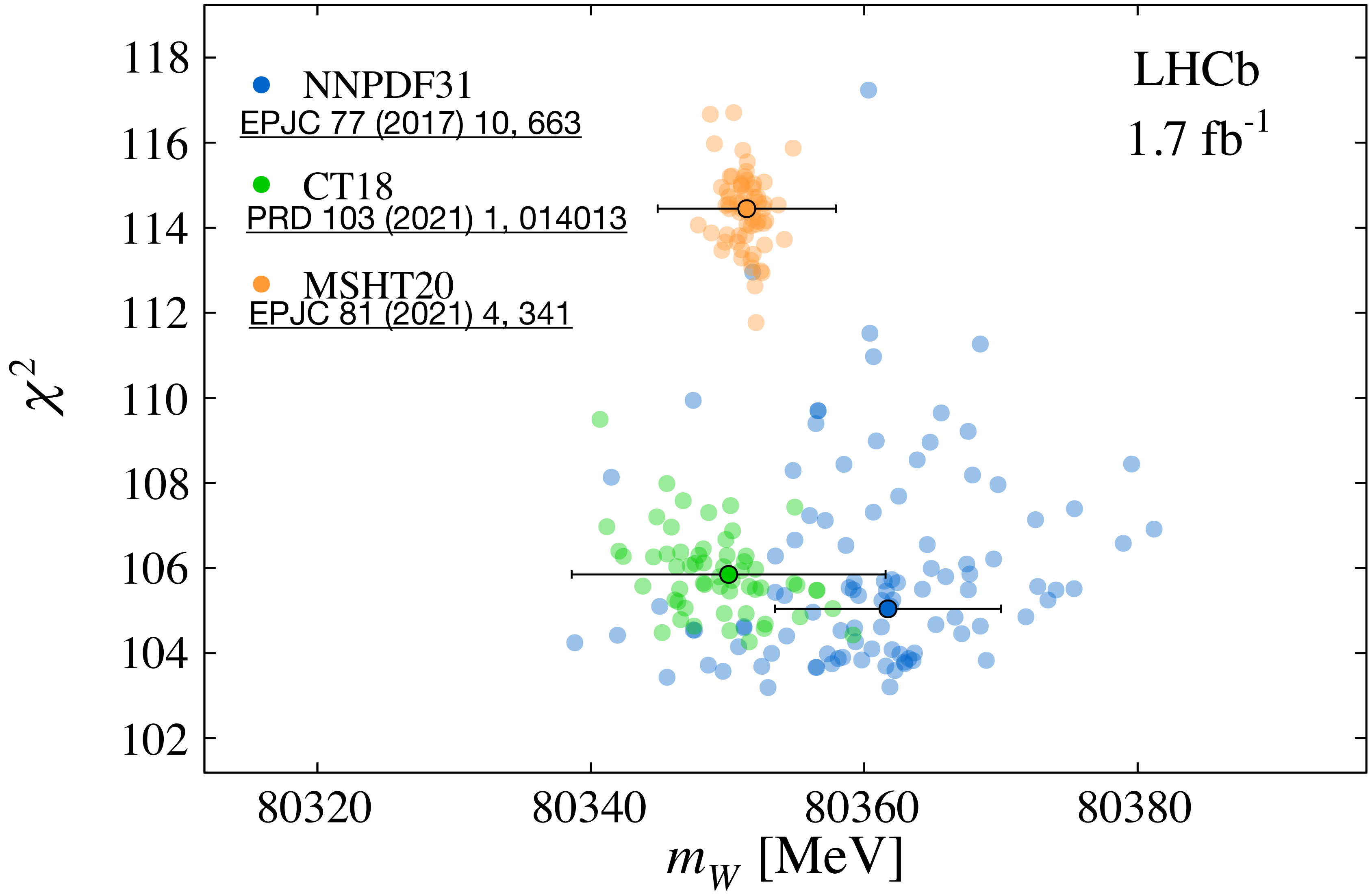


EPJ C71 1600 (2011)

Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
$k_\mathrm{T}^\mathrm{intr}$	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026
m_W	80362 ± 23 MeV

With NNPDF31 PDFs, but there are alternatives…

Democratic PDF average and uncertainty



Three separate results are reported in the paper.

Central result is a simple average of the three.

Contributes **9 MeV** uncertainty on m_W

Measurement uncertainty summary

Source	Size [MeV]	
Parton distribution functions	9	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	17	
Transverse momentum model	11	Envelope from five different models
Angular coefficients	10	"Uncorrelated" 31 point scale variation
QED FSR model	7	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5	Test with POWHEGew
Experimental total	10	
Momentum scale and resolution modelling	7	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6	
Isolation efficiency	4	
QCD background	2	
Statistical	23	
Total	32	

[Pre-unblinding] Cross checks

1. **Orthogonal splits:** Five ~50:50 splits of the data (polarity, charge $\times$ polarity, etc…) all result in [m_W] differences within 2σ.

2. **Fit range:** The result is stable w.r.t. variations in the upper/lower limits.

3. **Fit freedom:** The result is stable w.r.t. variations in the model freedom (e.g. 3 independent α_s values instead of 2, etc…)

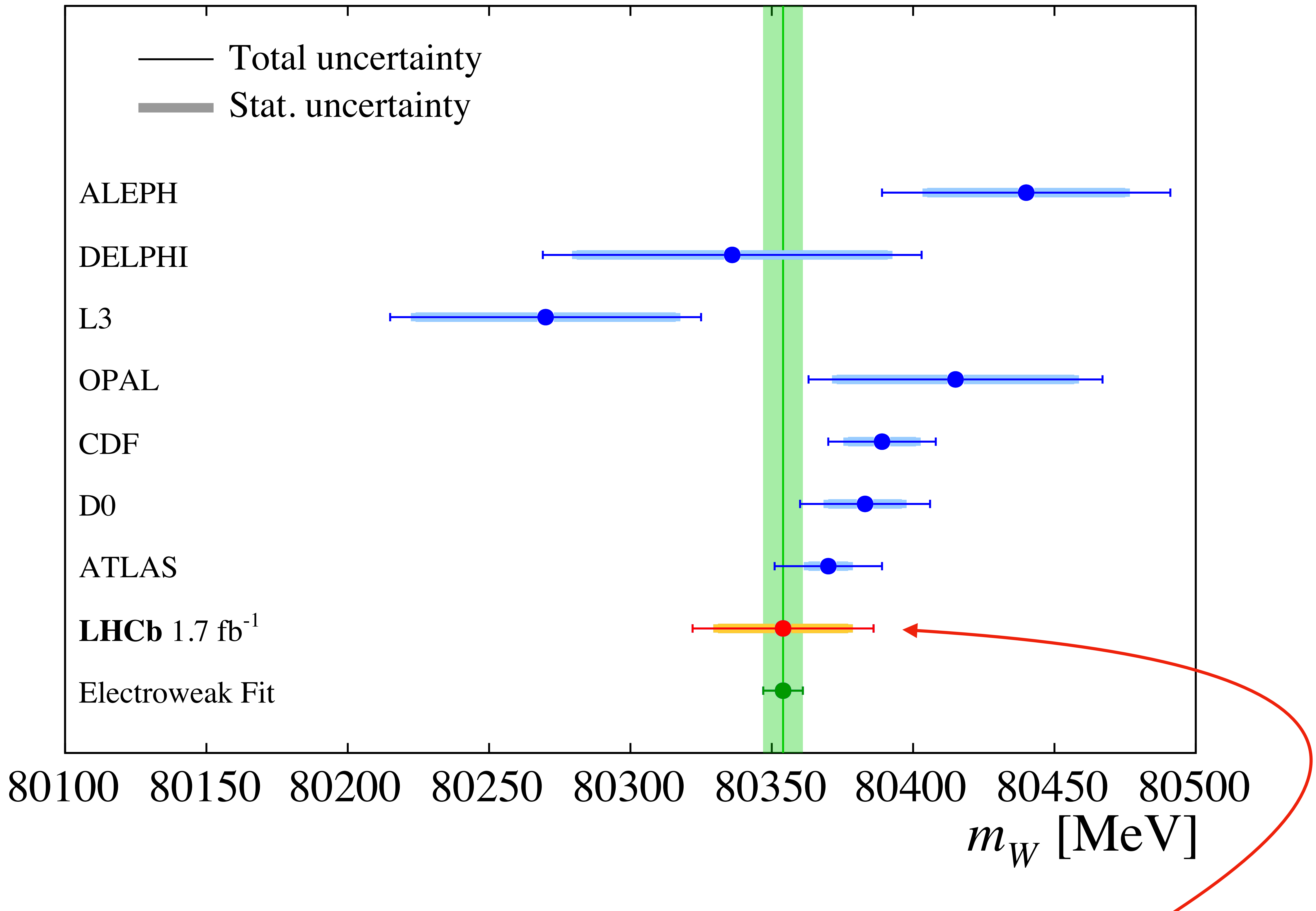
4. **W-like fit of the Z mass:** Measurements with μ^+ and μ^- agree to better than 1σ and their average agrees with the PDG value to better than 1σ.

5. **δm_W fit:** Alternative fit with the difference between the W^+ and W^- masses as another floating parameter: this parameter is consistent with zero within 1σ.

6. **Additional tests** with NNLO PDFs instead of NLO PDFs, variations in the charm quark mass, etc… affect m_W at the $\lesssim$ 1 MeV level.

7. **Pseudodata challenges:** fitting the default POWHEG+Pythia model to pseudo data with DYTurbo, Herwig, etc… based models of the boson p_T. Results are commensurate with our 11 MeV uncertainty.

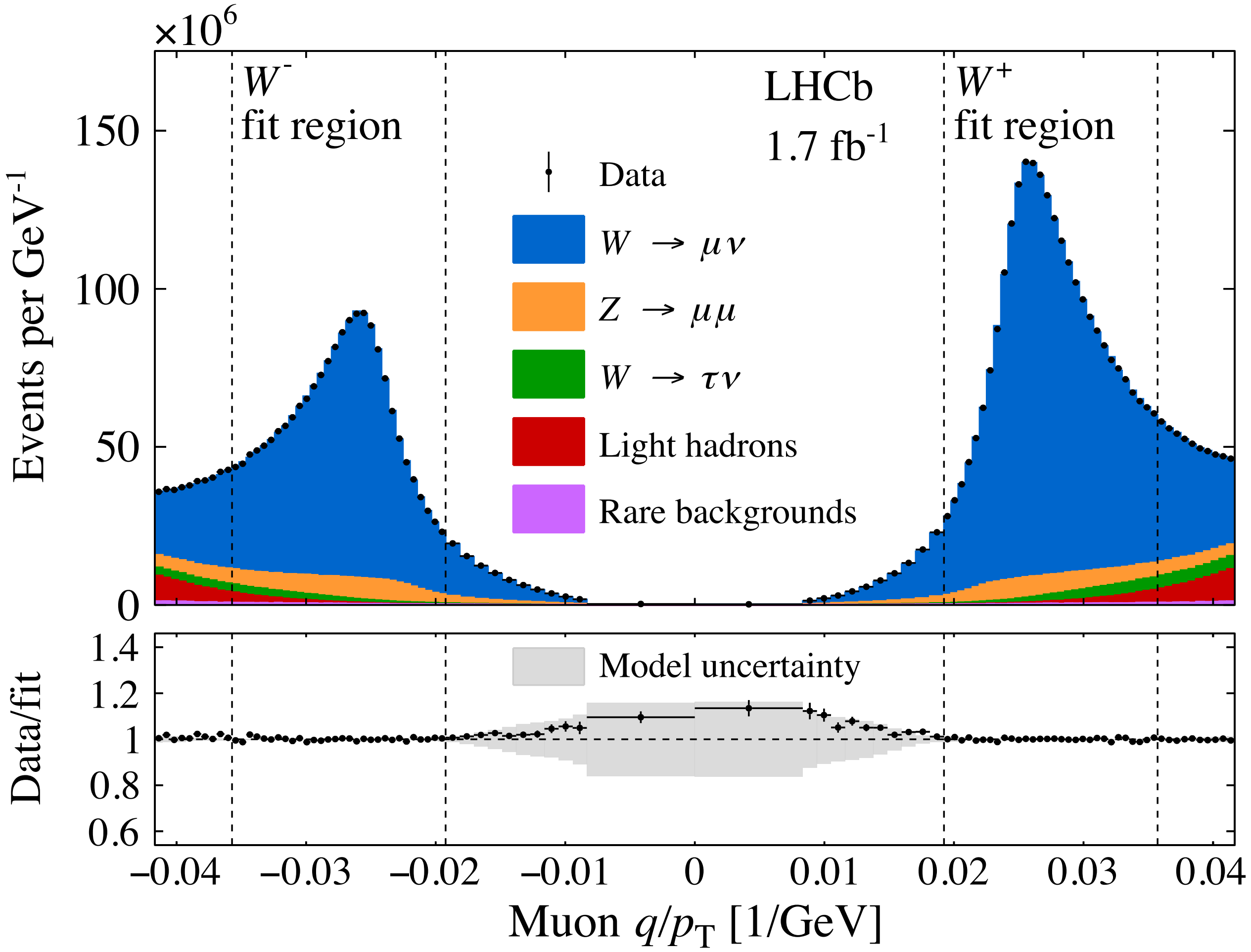
8. ….

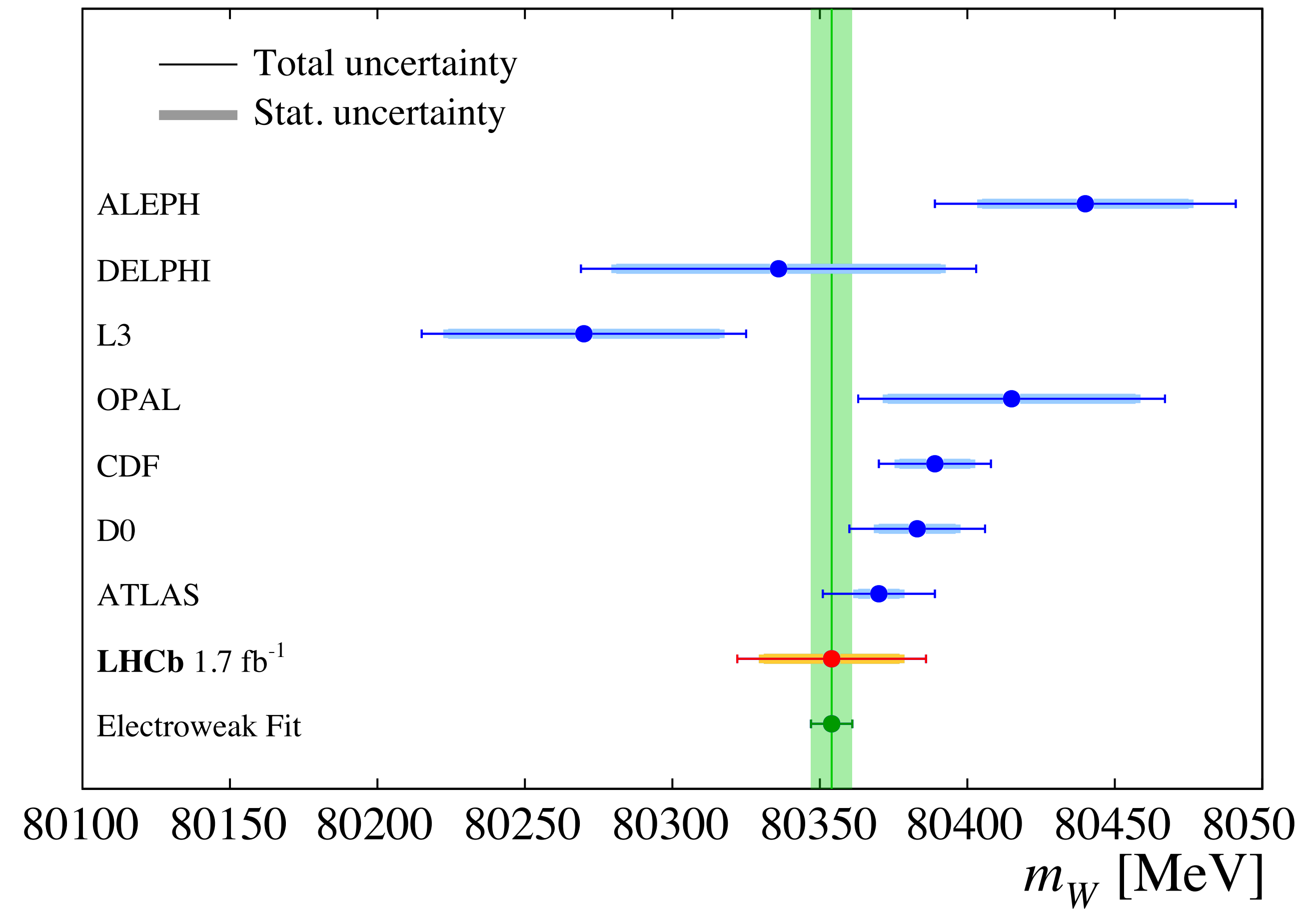


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Conclusions and outlook

[JHEP 01 (2022) 036, hep-ex:2109.01113, LHCb-PAPER-2021-024]





First measurement of m_W from LHCb with 32 MeV uncertainty is consistent with previous measurements and with the prediction.

A total uncertainty of ≲ 20 MeV looks achievable with existing LHCb data.

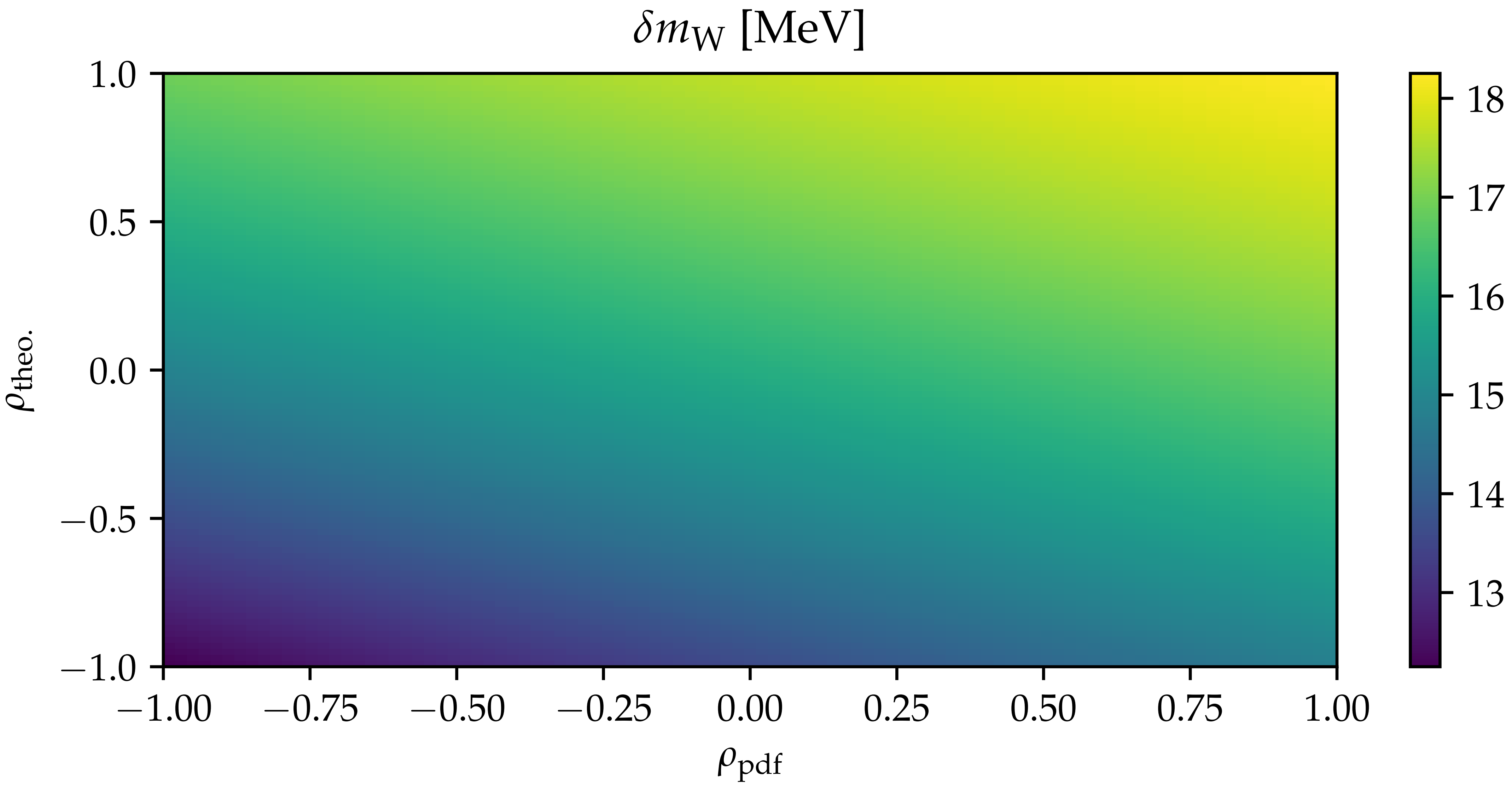
EPJC 79 (2019) 6 encourages us to upgrade to a double-differential fit.

We look forward to working with the other LHC experiments, and the theory community, to fully exploit LHCb's unique/complementary rapidity coverage to achieve the ultimate precision on m_W.

Backup slides

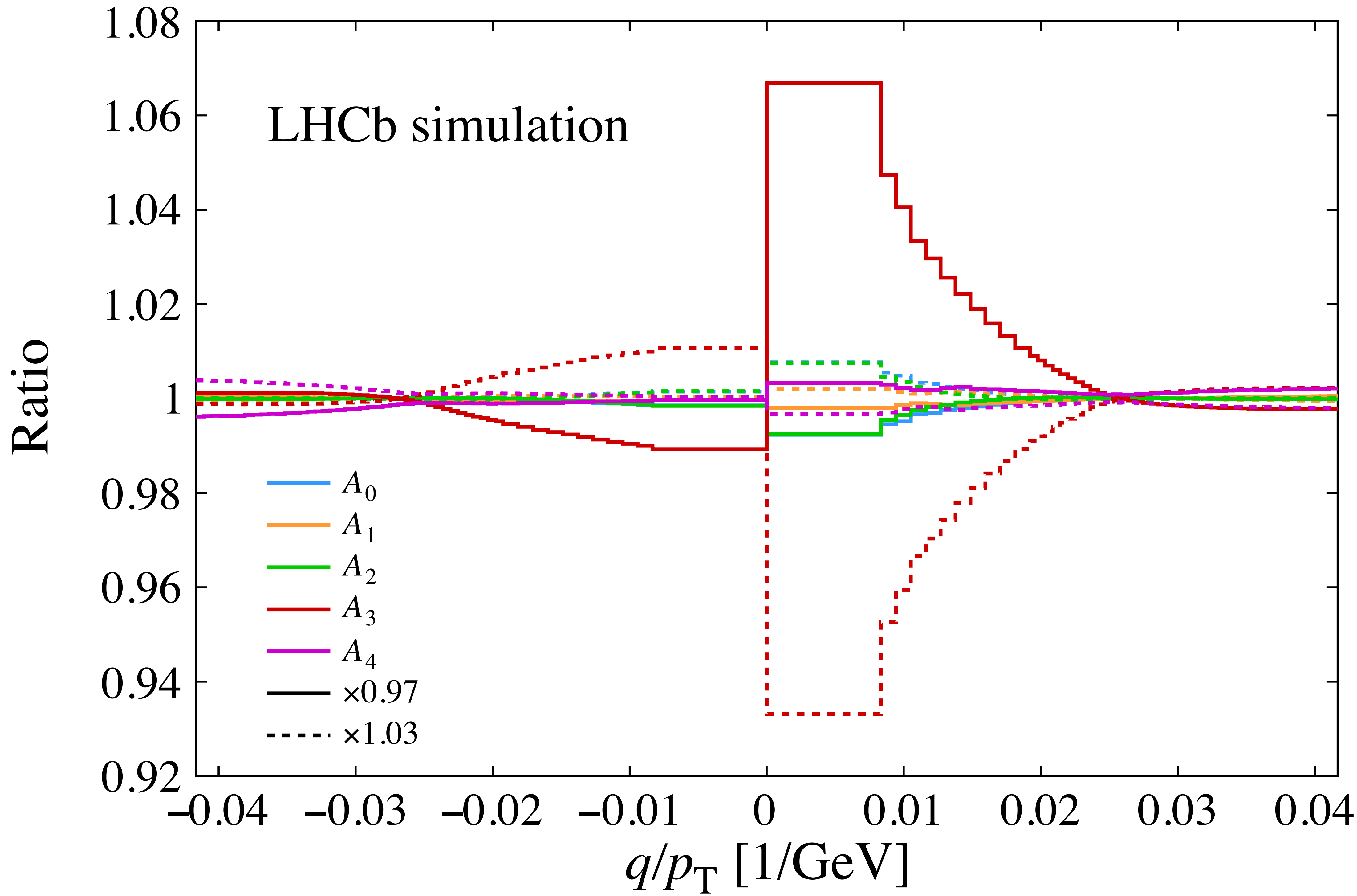
Prospects for LHC average

ATLAS+LHCb average under the simplest assumptions:

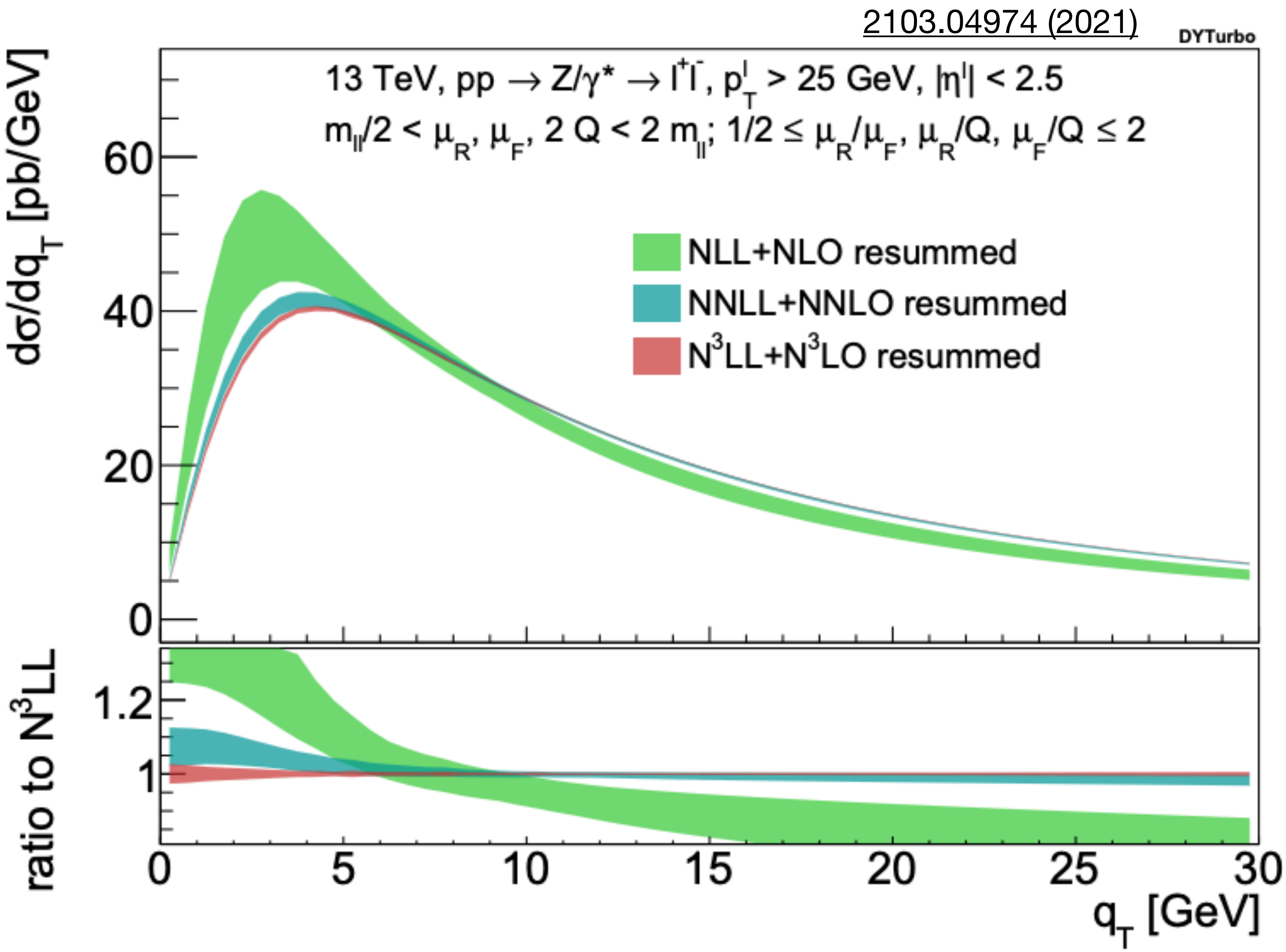


A detailed ATLAS+LHCb collaborative effort will be required to precisely determine these two correlation coefficients but it seems likely that ρ_{PDF} will be negative 1508.06954 while the (non-PDF) theory uncertainty will have a positive coefficient.

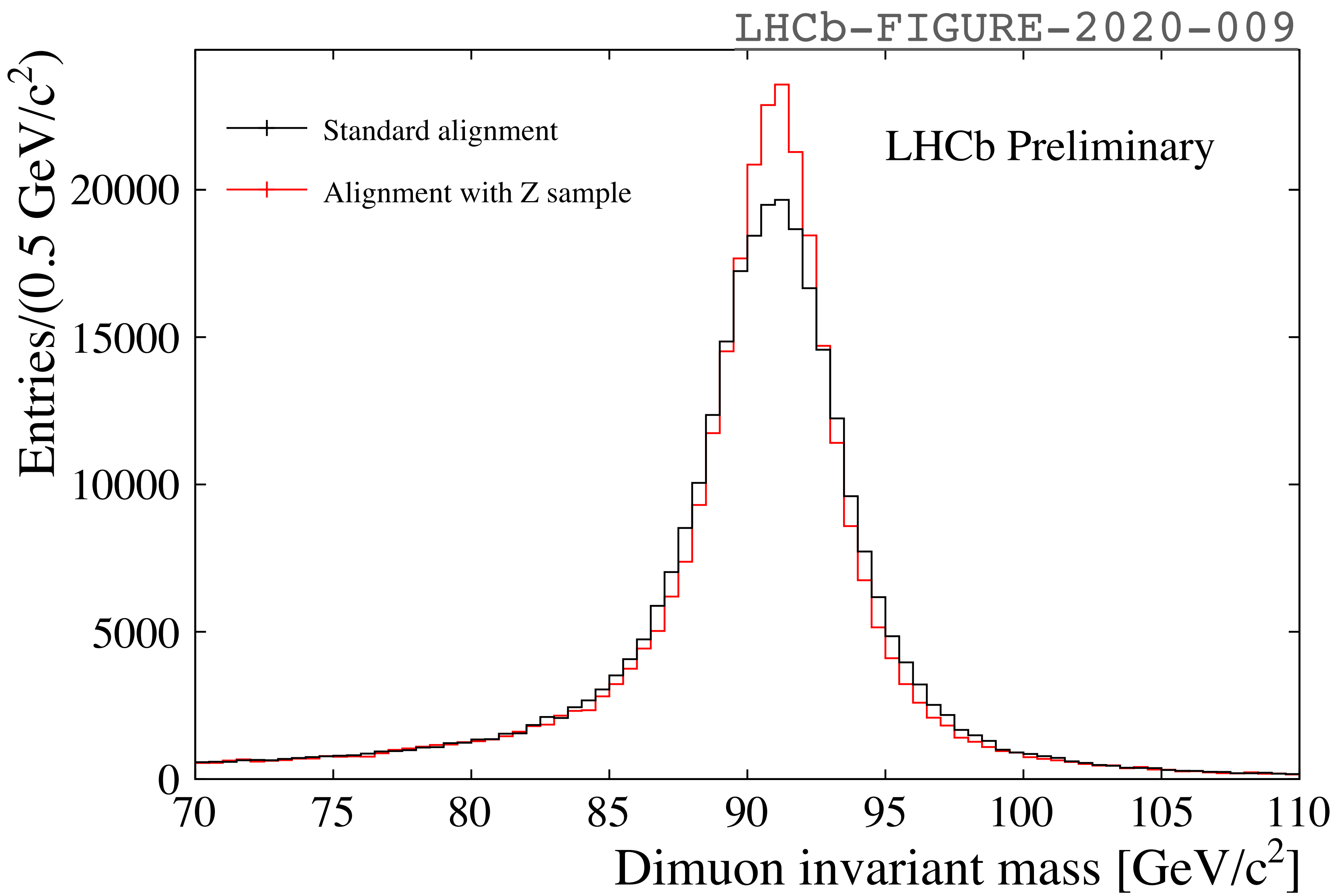
Sensitivity to other angular coefficients



Boson p_T state-of-the-art (example, of many groups)



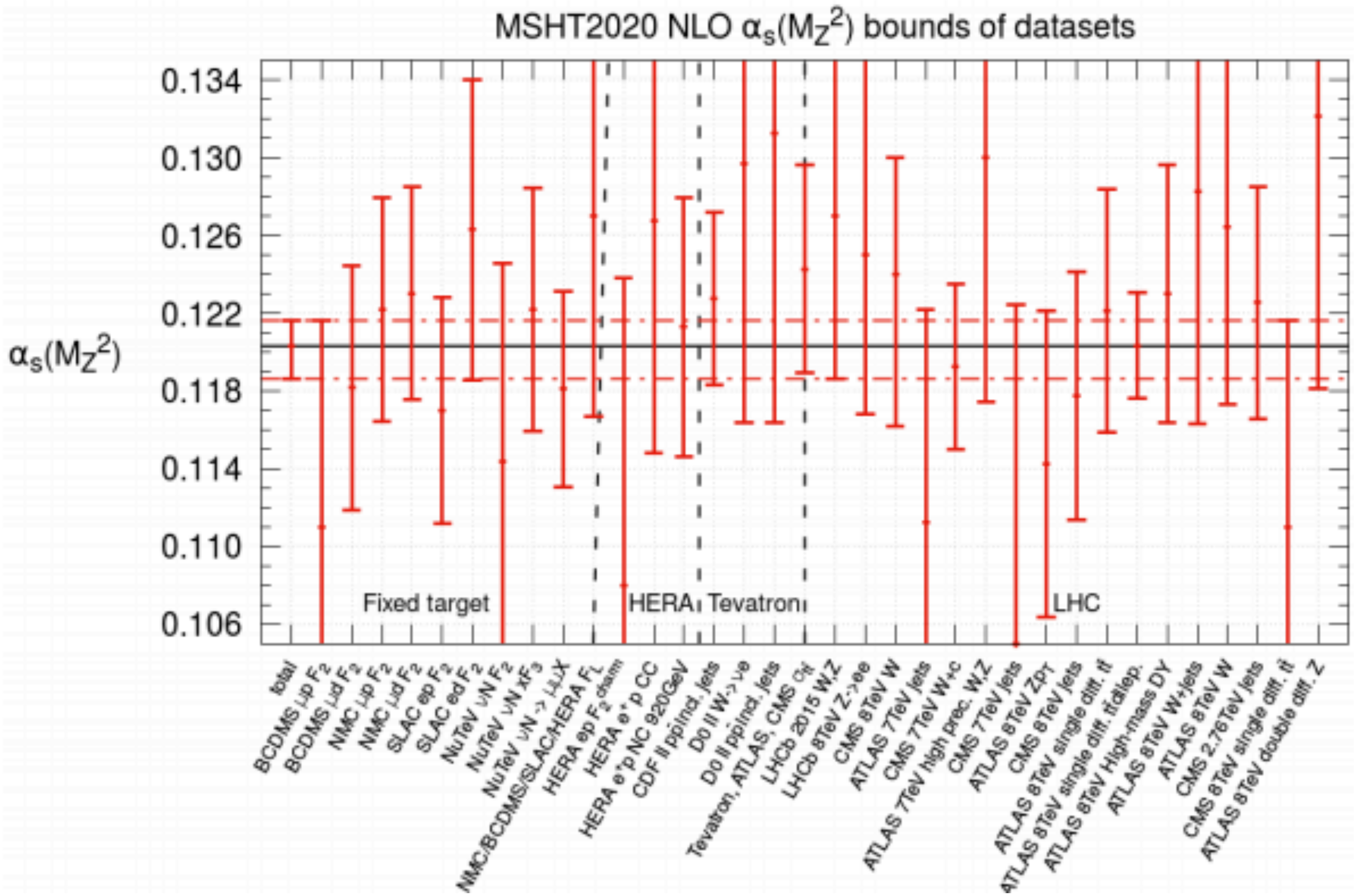
Custom alignment for high p_T analyses



LHCb's successful real-time alignment and calibration was commissioned in Run-2 JINST 14 (2019) P04013

For the very high (up to ~1 TeV) momentum muons in EW processes the resolution could be improved with a custom alignment including mass-constrained Z candidates.

Recent study on α_s 2106.10289



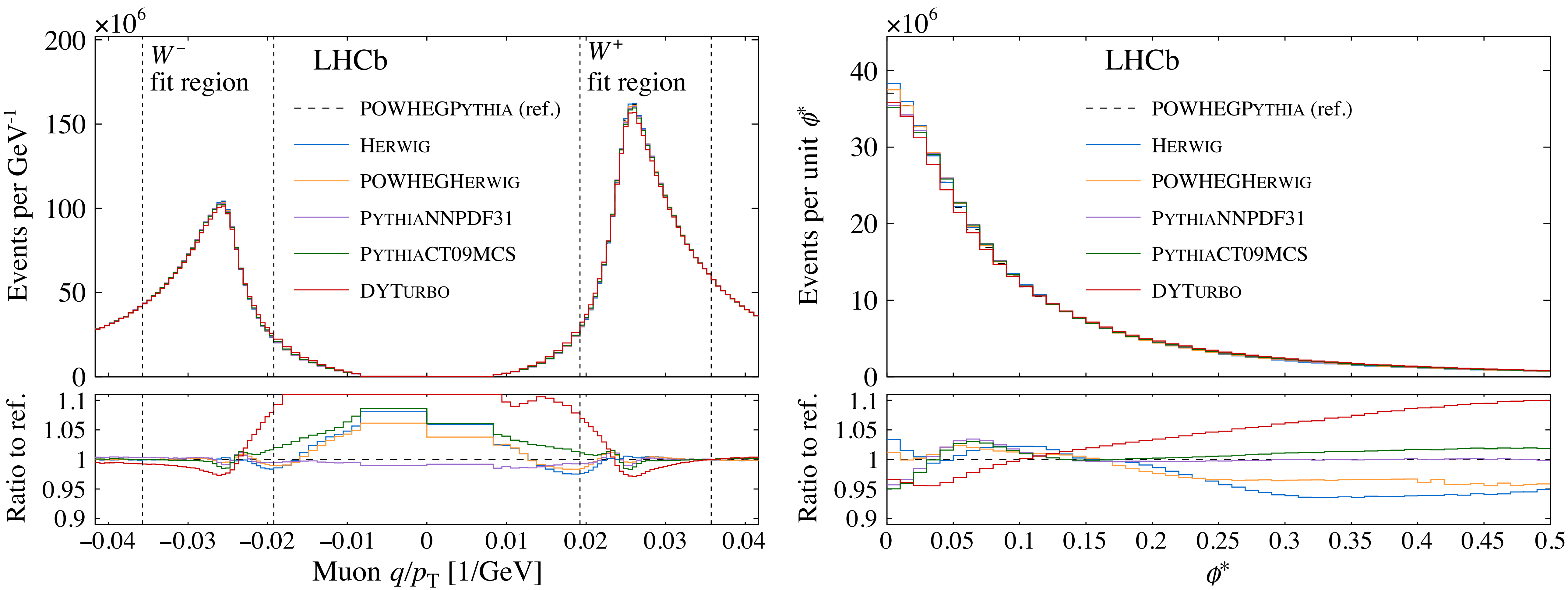
[Submitted on 18 Jun 2021]

An investigation of the α_S and heavy quark mass dependence in the MSHT20 global PDF analysis

T. Cridge, L.A. Harland-Lang, A.D. Martin, R.S. Thorne

We investigate the MSHT20 global PDF sets, demonstrating the effects of varying the strong coupling $\alpha_S(M_Z^2)$ and the masses of the charm and bottom quarks. We determine the preferred value, and accompanying uncertainties, when we allow $\alpha_S(M_Z^2)$ to be a free parameter in the MSHT20 global analyses of deep-inelastic and related hard scattering data, at both NLO and NNLO in QCD perturbation theory. We also study the constraints on $\alpha_S(M_Z^2)$ which come from the individual data sets in the global fit by repeating the NNLO and NLO global analyses at various fixed values of $\alpha_S(M_Z^2)$, spanning the range $\alpha_S(M_Z^2) = 0.108$ to 0.130 in units of 0.001. We make all resulting PDFs sets available. We find that the best fit values are $\alpha_S(M_Z^2) = 0.1203 \pm 0.0015$ and 0.1174 ± 0.0013 at NLO and NNLO respectively. We investigate the relationship between the variations in $\alpha_S(M_Z^2)$ and the uncertainties on the PDFs, and illustrate this by calculating the cross sections for key processes at the LHC. We also perform fits where we allow the heavy quark masses m_c and m_b to vary away from their default values and make PDF sets available in steps of $\Delta m_c = 0.05\ \mathrm{GeV}$ and $\Delta m_b = 0.25\ \mathrm{GeV}$, using the pole mass definition of the quark masses. As for varying $\alpha_S(M_Z^2)$ values, we present the variation in the PDFs and in the predictions. We examine the comparison to data, particularly the HERA data on charm and bottom cross sections and note that our default values are very largely compatible with best fits to data. We provide PDF sets with 3 and 4 active quark flavours, as well as the standard value of 5 flavours.

[Pseudo]data challenges



Can our [POWHEG+Pythia] model adapt itself to pseudo data corresponding to *other* models of the W/Z p_T distributions?

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]
POWHEGPYTHIA	64.8	34.2	–
HERWIG	71.9	600.4	1.6
POWHEGHERWIG	64.0	118.6	2.7
PYTHIA, CT09MCS	71.0	215.8	−2.4
PYTHIA, NNPDF31	66.9	156.2	−10.4
DYTURBO	83.0	428.5	4.3

✅ No more than 10 MeV bias on m_W!

Momentum smearing fit parameter values

$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh \eta}\right)$$

Parameter	Fit value
α $(\eta < 2.2)$	$(0.58 \pm 0.10) \times 10^{-3}$
α $(2.2 < \eta < 4.4)$	$(-0.0054 \pm 0.0025) \times 10^{-3}$
δ	$(-0.48 \pm 0.37) \times 10^{-6}$ GeV^{-1}
σ_δ $(\eta < 2.2)$	$(17.7 \pm 1.2)\,\mathrm{keV}^{-1}$
σ_δ $(2.2 < \eta < 4.4)$	$(14.9 \pm 0.9)\,\mathrm{keV}^{-1}$
σ_{MS}	$(2.015 \pm 0.019) \times 10^{-3}$

Our tunes to the Z p_T data

Program	χ^2/ndf	α_s	
DYTurbo	208.1/13	0.1180	$g = 0.523 \pm 0.047\,\mathrm{GeV}^2$
POWHEGPythia	30.3/12	0.1248 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 1.470 \pm 0.130\,\mathrm{GeV}$
POWHEGHerwig	55.6/12	0.1361 ± 0.0001	$k_\mathrm{T}^\mathrm{intr} = 0.802 \pm 0.053\,\mathrm{GeV}$
Herwig	41.8/12	0.1352 ± 0.0002	$k_\mathrm{T}^\mathrm{intr} = 0.753 \pm 0.052\,\mathrm{GeV}$
Pythia, CT09MCS	69.0/12	0.1287 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 2.113 \pm 0.032\,\mathrm{GeV}$
Pythia, NNPDF31	62.1/12	0.1289 ± 0.0004	$k_\mathrm{T}^\mathrm{intr} = 2.109 \pm 0.032\,\mathrm{GeV}$

Data challenge exercise

Data config.	χ^2_W	χ^2_Z	δm_W [MeV]	α_s^Z	α_s^W	A_3 scaling
POWHEGPythia	64.8	34.2	–	0.1246 ± 0.0002	0.1245 ± 0.0003	0.979 ± 0.029
Herwig	71.9	600.4	1.6	0.1206 ± 0.0002	0.1218 ± 0.0003	1.001 ± 0.029
POWHEGHerwig	64.0	118.6	2.7	0.1206 ± 0.0002	0.1226 ± 0.0003	0.991 ± 0.029
Pythia, CT09MCS	71.0	215.8	-2.4	0.1239 ± 0.0002	0.1243 ± 0.0003	0.983 ± 0.029
Pythia, NNPDF31	66.9	156.2	-10.4	0.1225 ± 0.0002	0.1223 ± 0.0003	0.967 ± 0.029
DYTurbo	83.0	428.5	4.3	0.1305 ± 0.0001	0.1321 ± 0.0003	0.982 ± 0.028

Consistency between orthogonal subsets of data

Subset	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]
Polarity $= -1$	$92.5/102$	–
Polarity $= +1$	$97.3/102$	-57.5 ± 45.4
$\eta > 3.3$	$115.4/102$	–
$\eta < 3.3$	$85.9/102$	$+56.9 \pm 45.5$
Polarity $\times\ q = +1$	$95.9/102$	–
Polarity $\times\ q = -1$	$98.2/102$	$+16.1 \pm 45.4$
$\lvert\phi\rvert > \pi/2$	$98.8/102$	–
$\lvert\phi\rvert < \pi/2$	$115.0/102$	$+66.7 \pm 45.5$
$\phi < 0$	$91.8/102$	–
$\phi > 0$	$103.0/102$	-100.5 ± 45.3

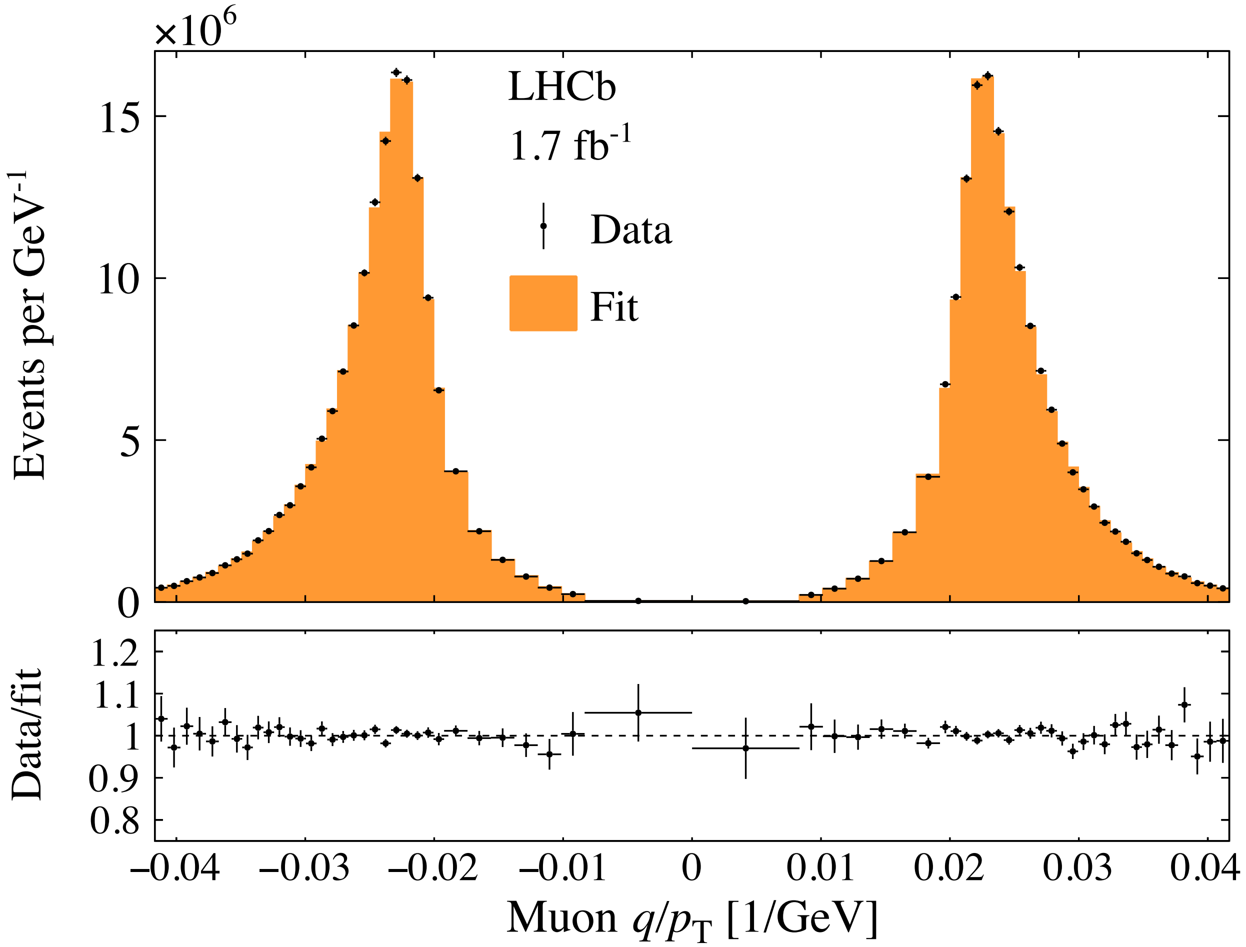
Varying the freedom of the fit model

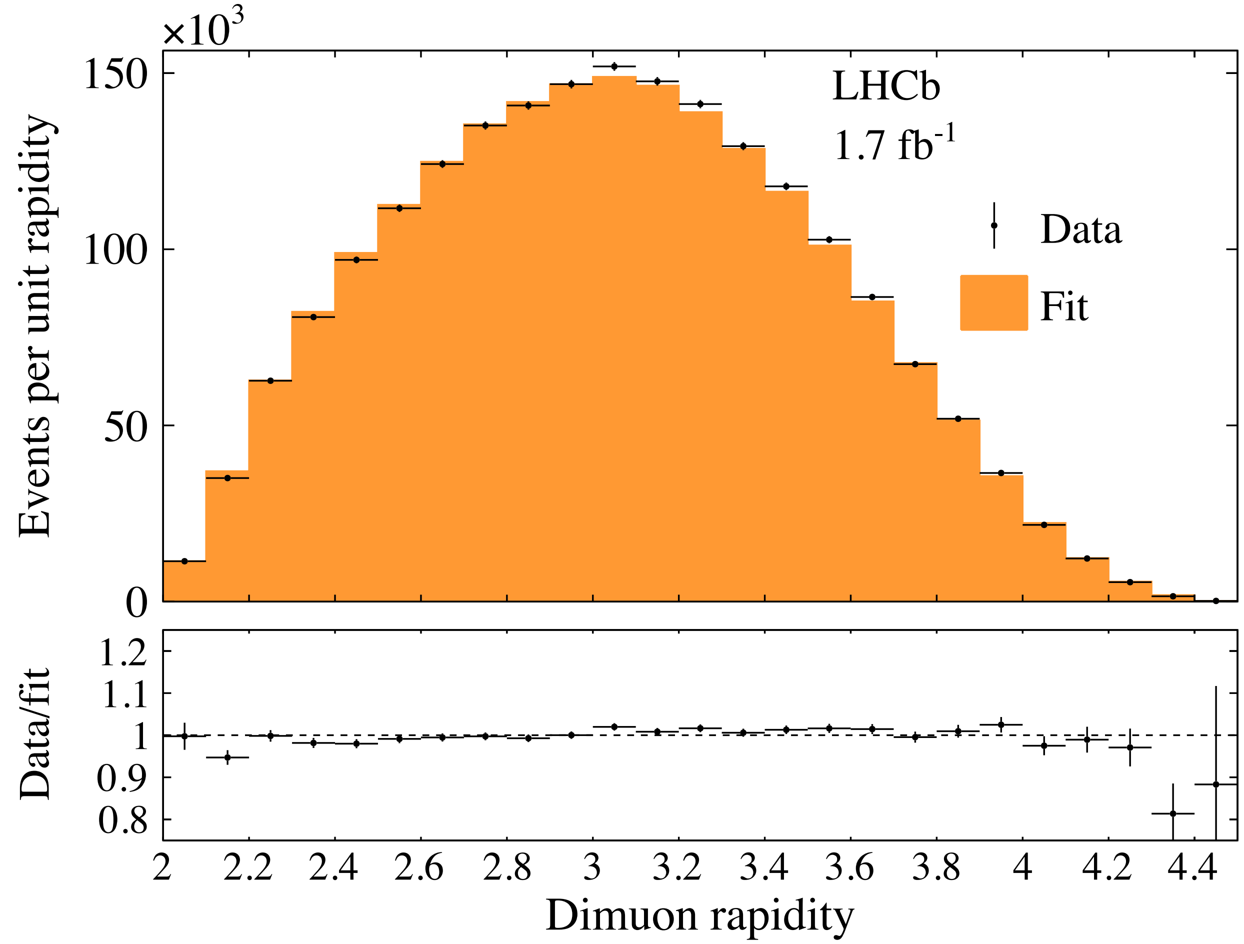
Configuration change	$\chi^2_{\text{tot}}/\text{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$2 \to 3$ α_s parameters	103.4/101	-6.0	± 23.1
$2 \to 1$ α_s and $1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	116.1/102	$+13.9$	± 22.4
$1 \to 2$ $k_{\text{T}}^{\text{intr}}$ parameters	104.0/101	$+0.4$	± 22.7
$1 \to 3$ $k_{\text{T}}^{\text{intr}}$ parameters	102.8/100	-2.7	± 22.9
No A_3 scaling	106.0/103	$+4.4$	± 22.2
Varying QCD background asymmetry	103.8/101	-0.7	± 22.7

Stability w.r.t. varying the [q/p_T] fit range

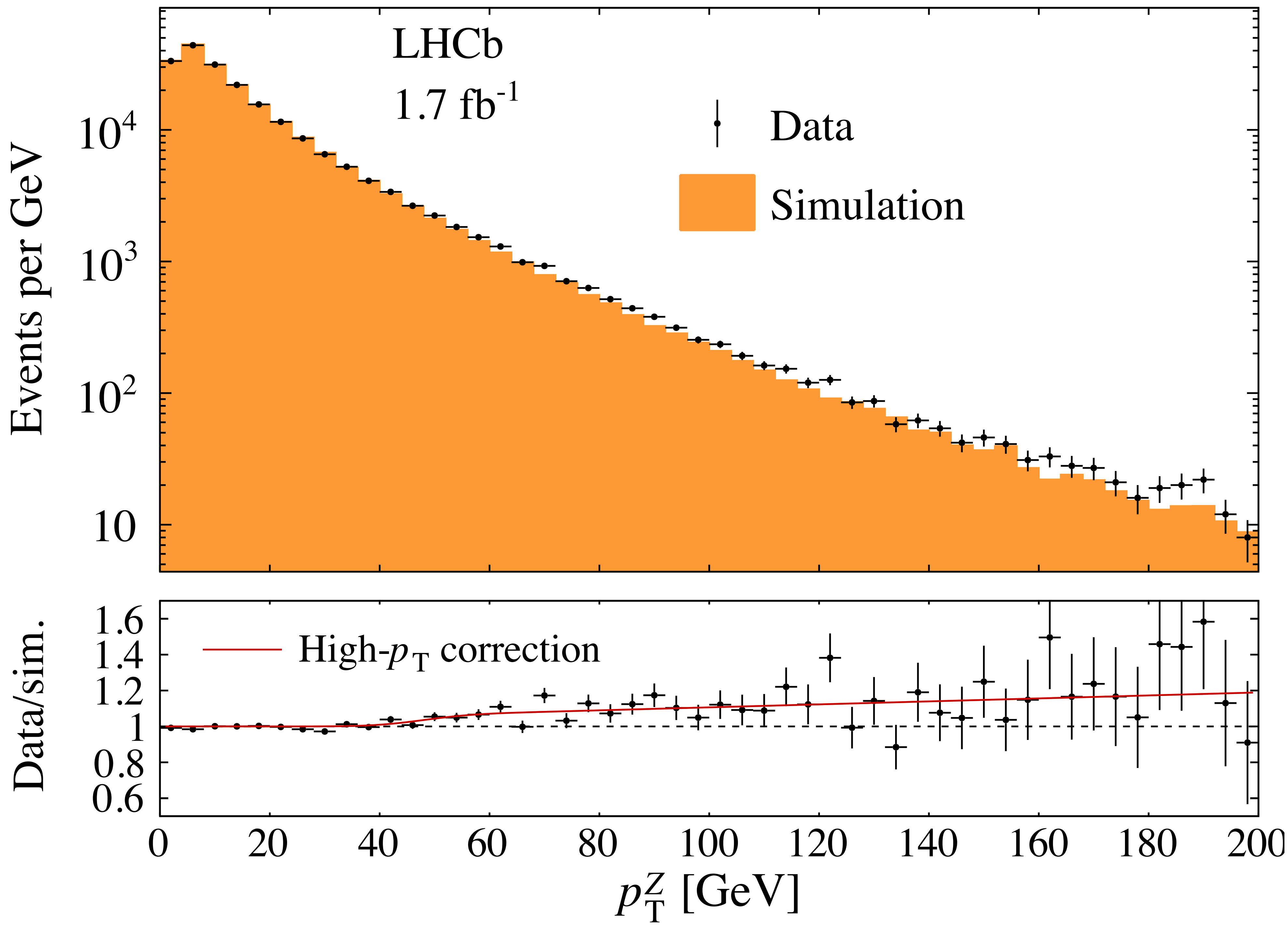
Change to fit range	$\chi^2_{\mathrm{tot}}/\mathrm{ndf}$	δm_W [MeV]	$\sigma(m_W)$ [MeV]
$p_{\mathrm{T}}^{\mathrm{min}} = 24$ GeV	96.5/102	+6.8	19.7
$p_{\mathrm{T}}^{\mathrm{min}} = 26$ GeV	97.7/102	+9.6	20.9
$p_{\mathrm{T}}^{\mathrm{min}} = 30$ GeV	102.7/102	+3.0	25.7
$p_{\mathrm{T}}^{\mathrm{min}} = 32$ GeV	84.9/102	−21.6	30.8
$p_{\mathrm{T}}^{\mathrm{max}} = 48$ GeV	105.3/102	−3.8	23.2
$p_{\mathrm{T}}^{\mathrm{max}} = 50$ GeV	103.0/102	−2.1	23.0
$p_{\mathrm{T}}^{\mathrm{max}} = 54$ GeV	96.3/102	−8.6	22.6
$p_{\mathrm{T}}^{\mathrm{max}} = 56$ GeV	103.7/102	−14.3	22.4

Example postfit projections





Parametric correction at high boson p_T



Also applied to the model of W production but with 100% uncertainty => ~1 MeV on m_W.

Hadronic background model