Prospects for W-mass measurements at the LHC

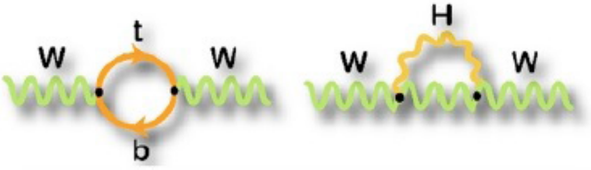
M. D'Alfonso (CERN)
On behalf of ATLAS, CMS and LHCb collaborations

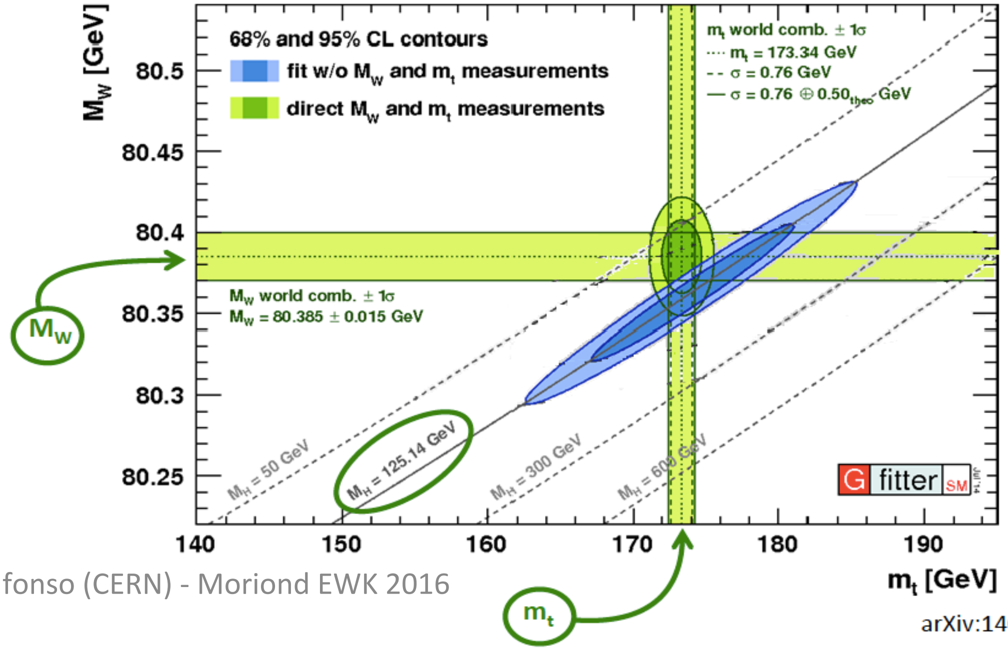
Moriond EWK 2016

The big picture, in the SM (or BSM)

A high-precision W mass measurement provides a crucial test of the SM !

- Direct measurements:
  - CDF 19 MeV, world average 15 MeV
- A competitive measurement is within reach @ LHC
- Complementary to the previous machine and detectors





arXiv:1407.3792

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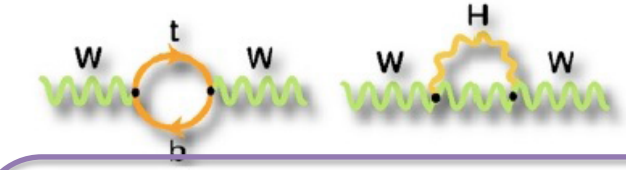
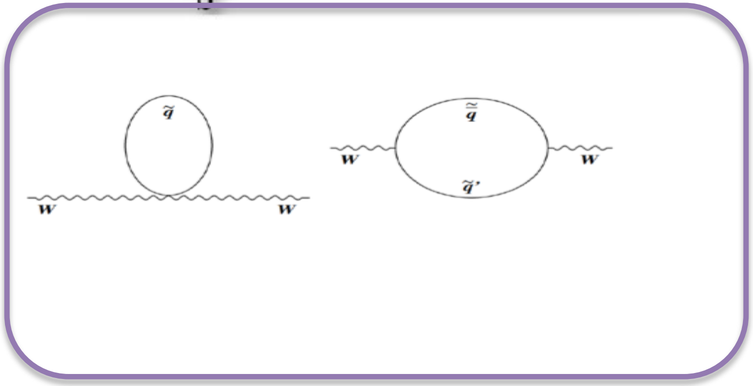
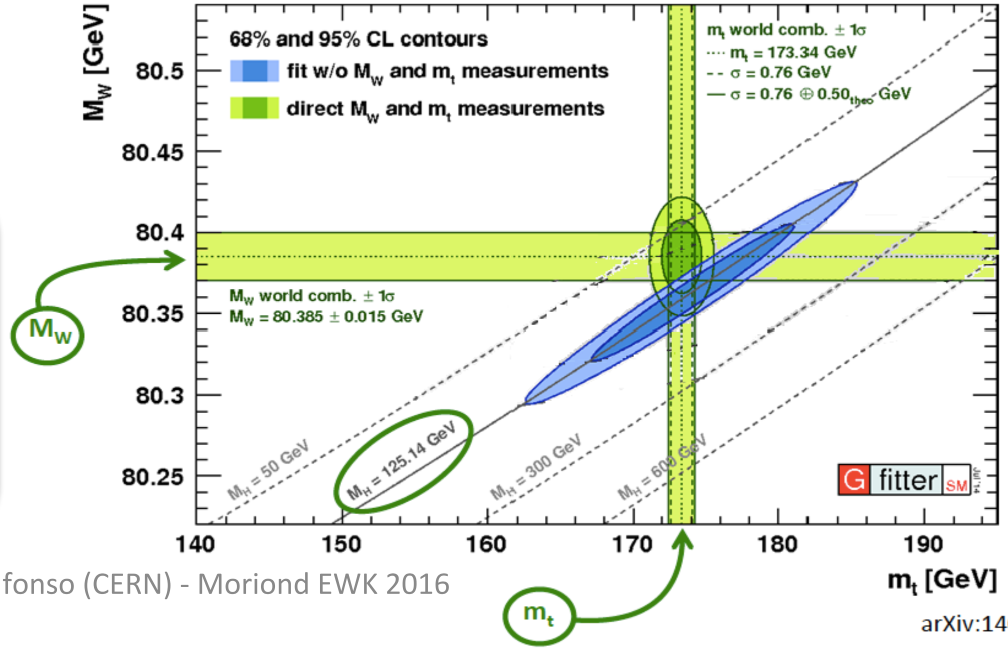






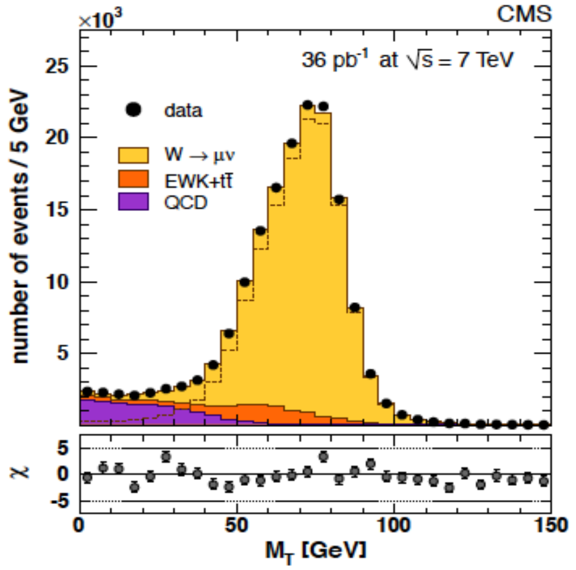
arXiv:1407.3792

Decomposing the W events

What we see in the detector
→ We can calibrate

lepton

JHEP 10 (2011) 132, arXiv:1107.4789



recoil=(PU+UE+jets)

What we try to describe with MC

Boson production/decay

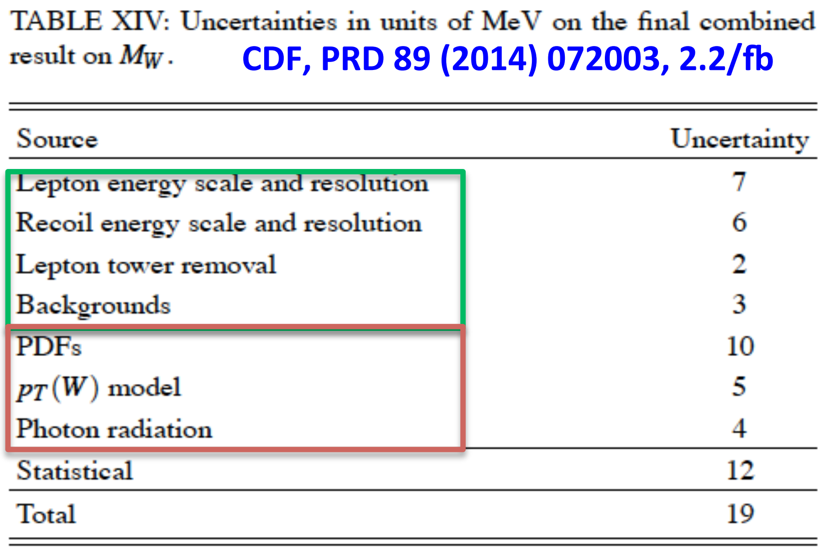
- proton PDF
- boson p_T (QCD and EWK, higher order)
- boson decay (polarization+ FSR)

Previous measurements

Previous measurements are based on the template fit of W transverse mass(M_T), leptonP_T (e, μ, MET)

→Different balance in the **experimental** and **theoretical** uncertainties.

→Each systematic uncertainty affects differently these variables.

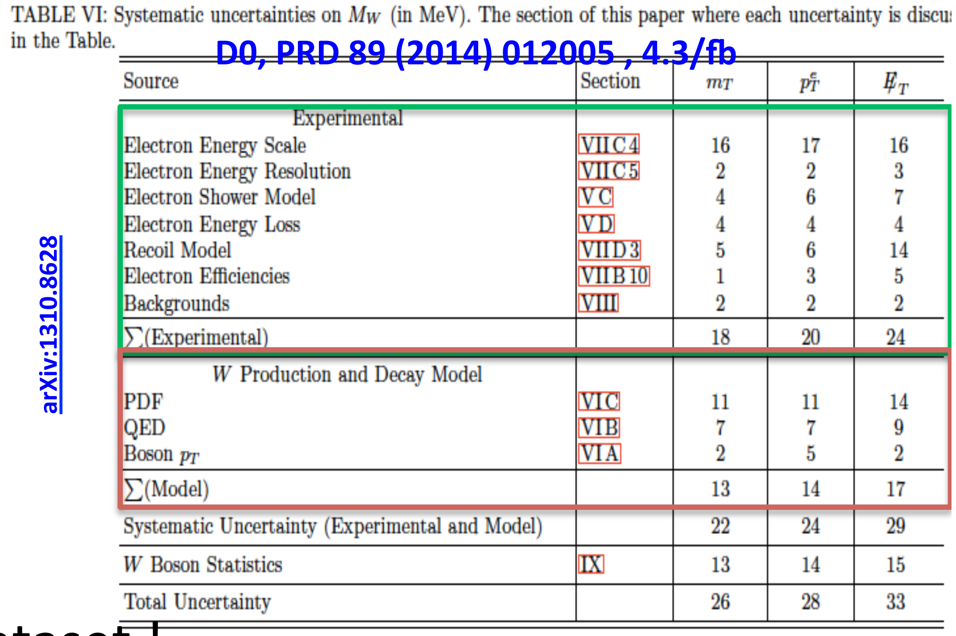


arXiv:1311.0894

TABLE XIV: Uncertainties in units of MeV on the final combined result on M_W.

CDF, PRD 89 (2014) 072003, 2.2/fb

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19



arXiv:1310.8628

TABLE VI: Systematic uncertainties on M_W (in MeV). The section of this paper where each uncertainty is discu
in the Table.

D0, PRD 89 (2014) 012005 , 4.3/fb

Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

Still to come full Tevatron Run-II dataset !

LHC strategy

W production at the LHC is relatively abundant;
7(8) TeV, 5(20) fb-1 → ~15(75)x10^6 in W → $l\nu$ ($l = e, \mu$)

The **statistical error** scales with the amount of W data:
For example: considering the W+ and Muon decay channel
@ 7eV Lint = 4. 5 fb^{-1} → Stat uncertainty O(10 MeV)
@ 8TeV Lint = 19.5 fb^{1} → Stat uncertainty O(5 MeV)   ***:: important to analyze the 8TeV data***
@ 13TeV a lot more

The MW measurement at the LHC follows a strategy similar to the Tevatron.

Important differences:

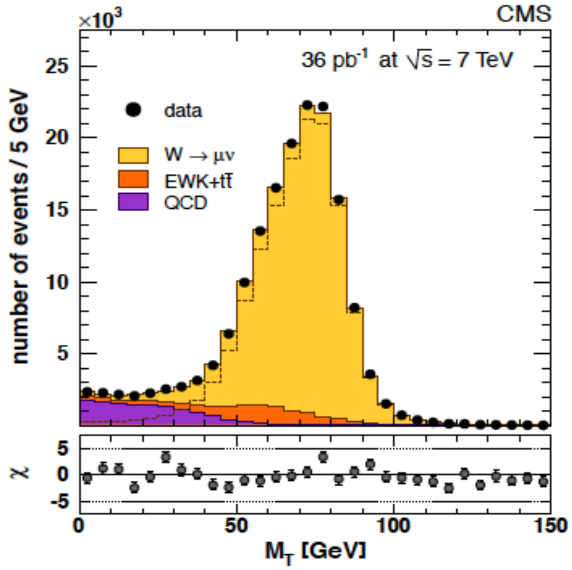
1. Higher pile-up environment → affect hadronic recoil calibration
2. Both ATLAS and CMS construct their MC template with detector full simulation.
3. Different theoretical uncertainties due to pp instead of ppbar collisions
4. Different energy regime 2 TeV vs 7/8/13 TeV → potentially larger theoretical uncertainties
5. W^{+} and W^{-} production is not symmetric → Requires a charge-dependent analysis

Experimental calibrations

What we see in the detector
→ We can calibrate

lepton

JHEP 10 (2011) 132, arXiv:1107.4789



recoil=(PU+UE+jets)

From experimental side effort went to understand and control detector effects:

→To have a competitive measurement, shapes must be known below the per mill level to get MW with better than 10 MeV accuracy

$$E_T^{miss} = -\sum_i \vec{p_t^i} = -\vec{p_t^\mu} - \vec{h}$$

where h the recoil

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

$$m_W \sim 2 p_T + h_{||}$$

Where $h_{||}$ is the projection of the recoil on lepton axis

40 GeV	few GeV	←typical values
10^-4	10^-3	←target precision

Lepton momentum scale calibration

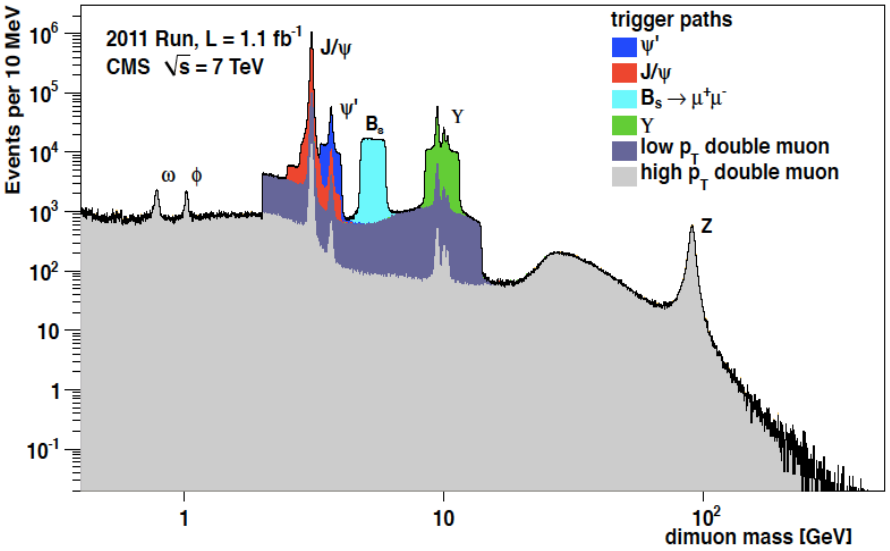
$$m_T^2 = 2p_T E_T^{miss}(1 - cos(\Delta\phi))$$
$$m_W \sim 2p_T + u_{||}$$

The lepton momentum scale enters linearly in the Lepton p_T and MT fits.

In ***CMS***, the first Wmass measurement will come in the ***muon*** final state. ***ATLAS*** is performing in parallel the ***muon and electron***.

- This will lead to a statistical improvement of order sqrt(2) on the W mass.
- Also provide a cross check of the robustness results

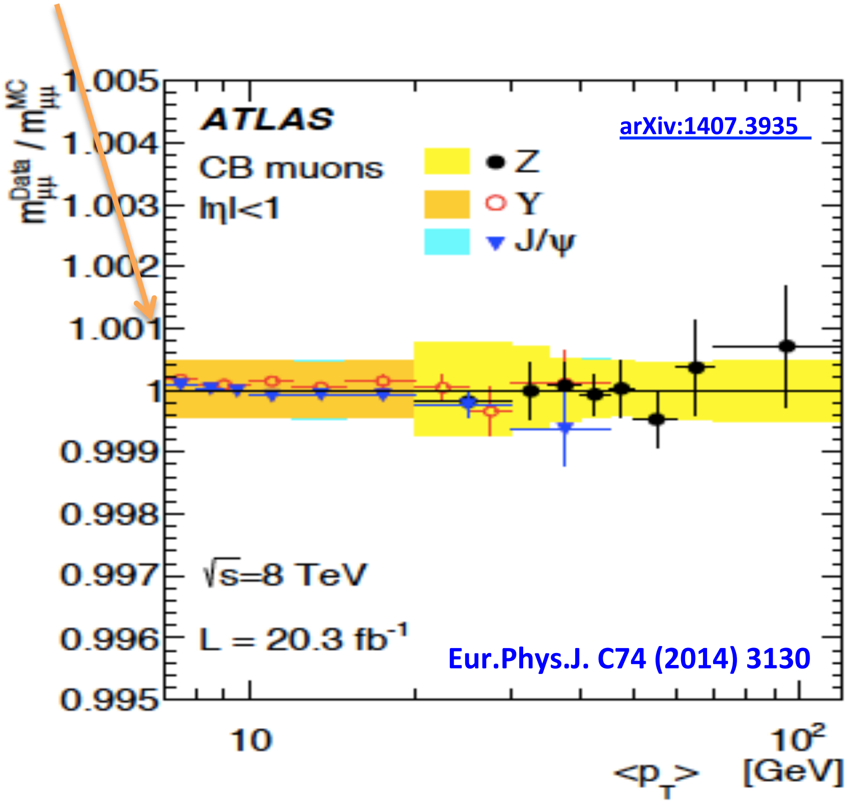
Calibration in situ with J/psi, Y



The starting point

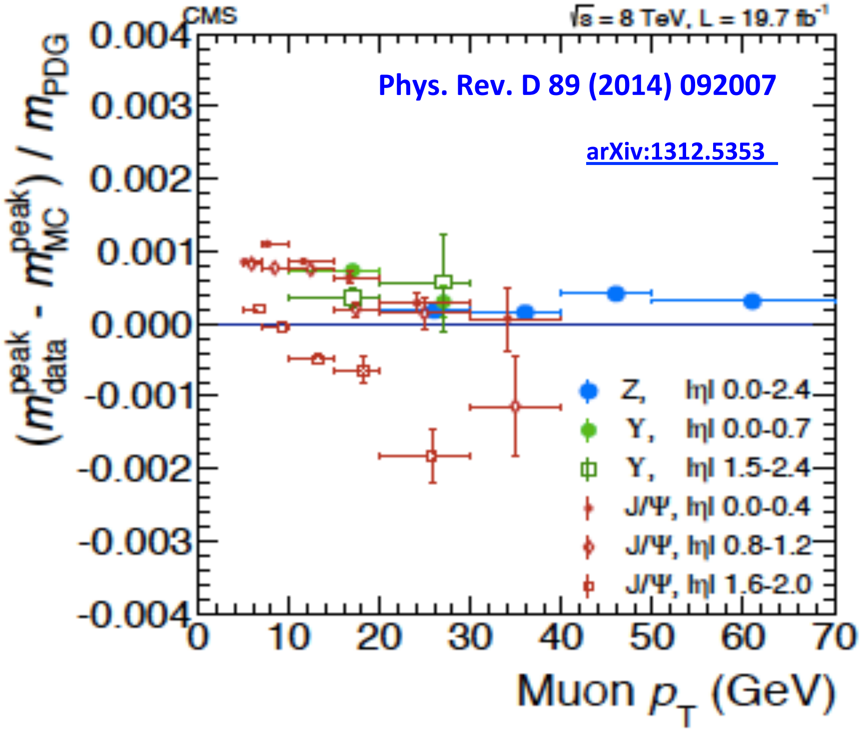
~ 100 MeV

Looking at the run1 Higgs results *(muons)*: ATLAS had 2 times better scale



arXiv:1407.3935

Eur.Phys.J. C74 (2014) 3130



Phys. Rev. D 89 (2014) 092007

arXiv:1312.5353

New techniques are being developed to calibrate the muon momentum scale with the required precision O(10 MeV).

CMS-SMP-14-007

“W-like” mass milestone

First step: use the Z→ll events as test sample to measure the Z mass as if it was a W-like system.

i.e. we build a W-like system removing one lepton and recalculating MET and M_T.

Statistical erros		
Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	**NO**	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
μ momentum scale	✓ YES	✓ YES
μ tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	**NO**	✓ YES
Background to 1-l	**NO**	✓ YES

Advantages:

- low background
- can use the dilepton system to anchor the theory part

  Zmass, Z momentum, Zrapidity and angular distribution

  → Adopted a temporary re-weighting of the distributions

→ *For W-like measurement used half of the sample for the calibration and the other half for the measurement*

Convince:

- *The HEP community that we are on track on the experimental calibration.*
- *the theory community to invest more efforts on the M_T variable*

CMS-SMP-14-007

Muon momentum scale calibration

Dedicated muon momentum scale calibration using J/ψ, Y mass

- Correct the curvature of the track: $K=1/p_T$
- Three effects to be corrected :
  - Magnetic field (**A**) Dedicated solenoid map corrections+parabolic symmetric function of η

    For the typical muon p_T from W, in CMS the inner tracker drives the measurement of the muon momentum scale, in ATLAS combination from the tracker/muon spectrometer.
  - Misalignment (**M**) Fourier terms vs ϕ in eta, separating μ+ and μ-
  - Material (**ε**) in bins of η

New technique employed using a Kalman filter.

$$K_c = (\boxed{A} - \underline{1})K + \boxed{\frac{K}{1 + \epsilon \sin\theta K}} + q\underline{M}$$

Magnetic field

material

misalignement

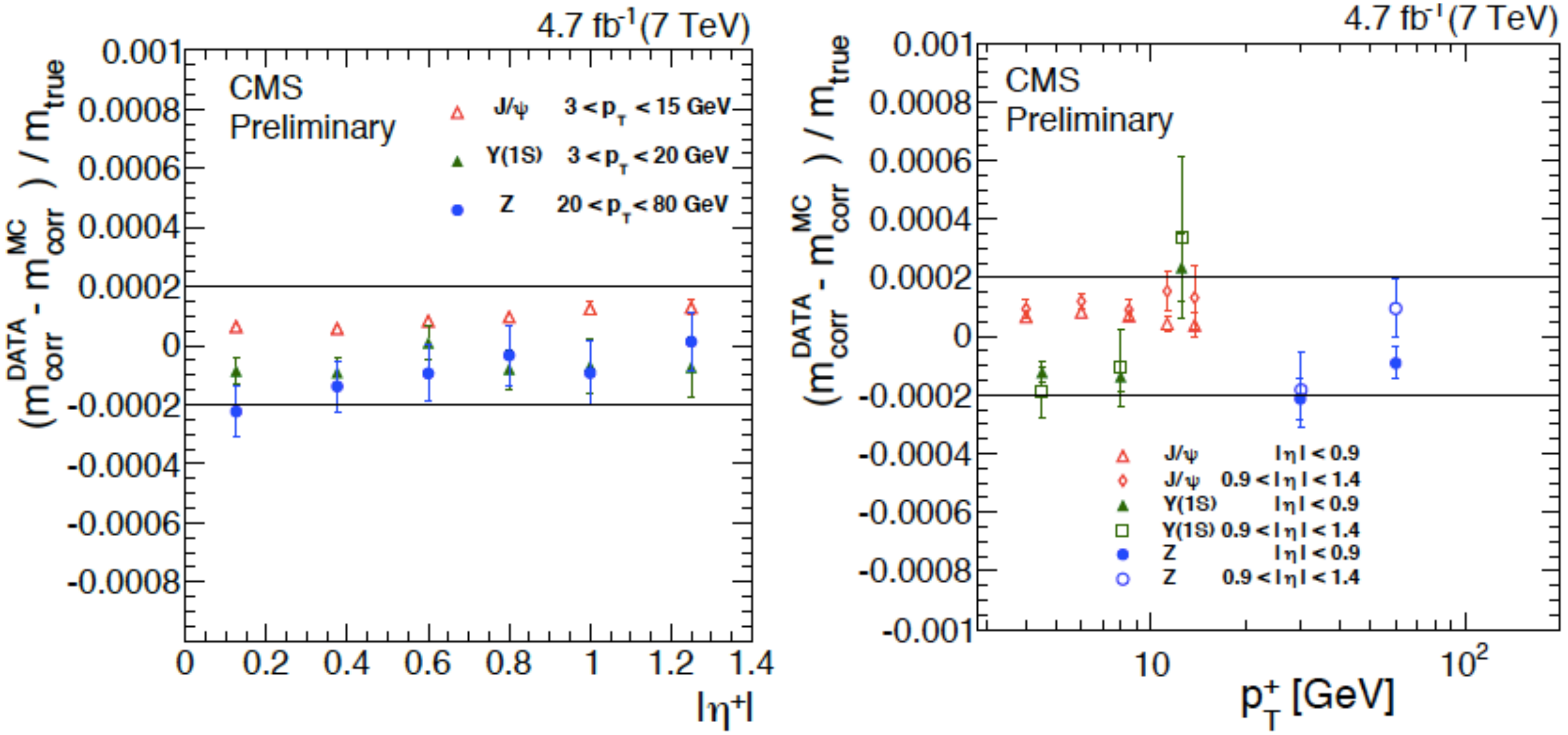
CMS-SMP-14-007

Closure of the scale

Muons momentum resolution important to verify the closure:

calibrate on J/ψ and Y widths

closure verified on Z events

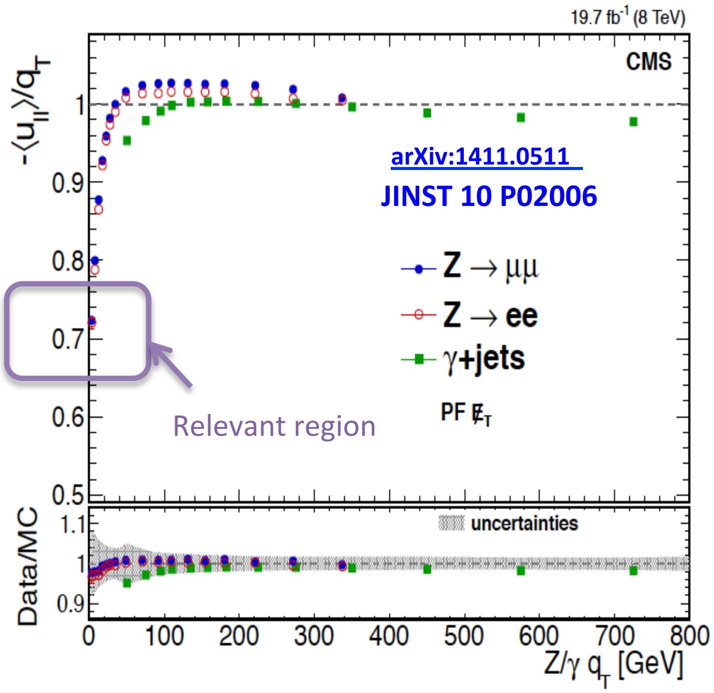


Very good performance → closing at <8 MeV

MET in CMS and ATLAS

Reconstruction:

- The **CMS** experiment uses **particle-flow (PF)** event reconstruction, which consists of reconstructing and identifying each particle with an optimized combination of all subdetector information. (more in ***JINST* 10 P02006**)
- **ATLAS** starts from **calorimeter clusters** (more in **Eur.Phys.J. C72 (2012) 1844**)

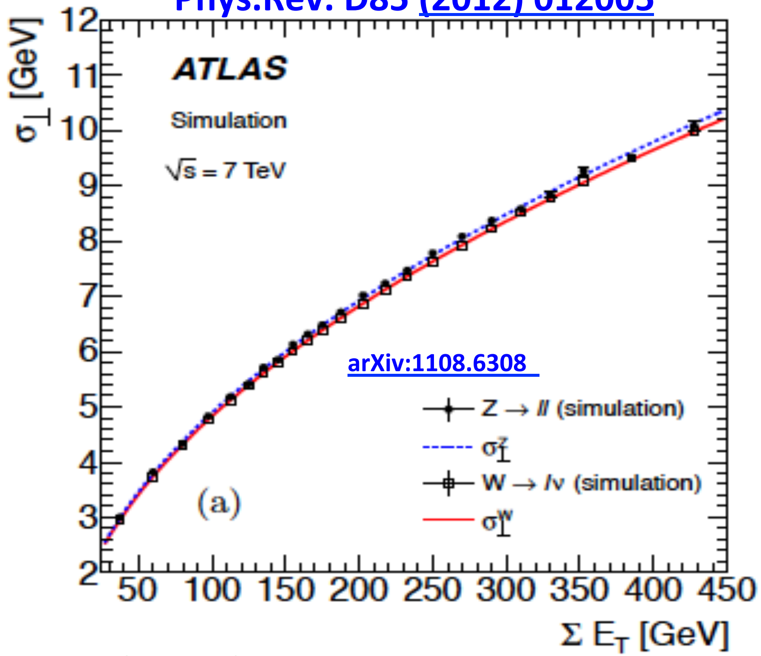


arXiv:1411.0511

JINST 10 P02006

Relevant region

Phys.Rev. D85 (2012) 012005

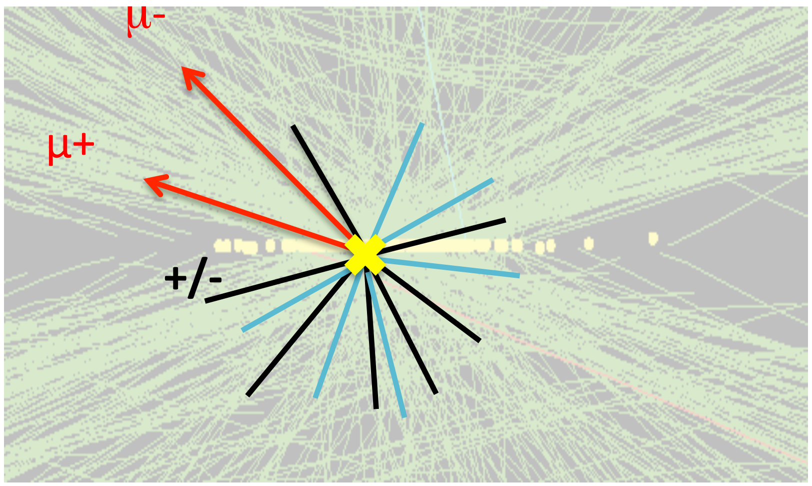


arXiv:1108.6308

Similar resolution between ATLAS and CMS to start with.

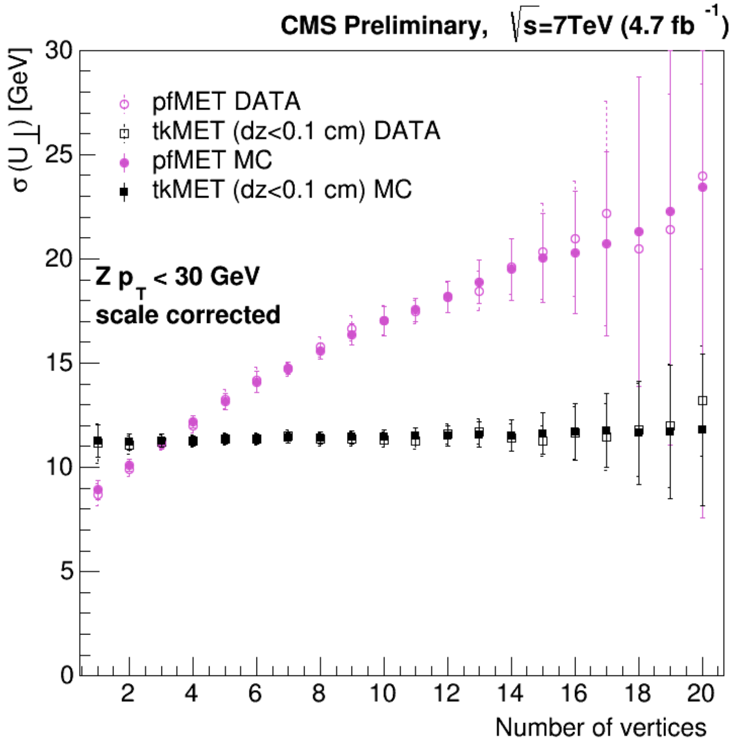
CMS-SMP-14-007

recoil resolution and PU



tkMET = vectorial sum of the PF chargedHadron with dz<0.1 cm

pfMET = vectorial sum of the PF charged + neutral particles

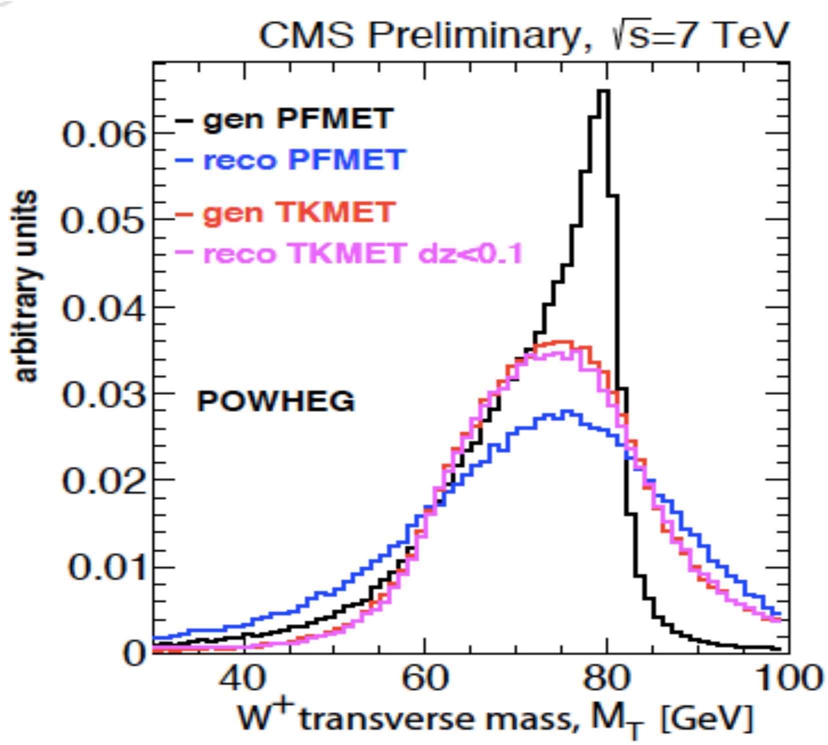


Suppress in-time pile-up at reconstruction level not considering PF hadrons/clusters associated to vertices other than the Primary Vertex.

tkMET insensitive to the PU also at the high PU regime of the 8 TeV

CMS-SMP-14-007

recoil resolution and PU



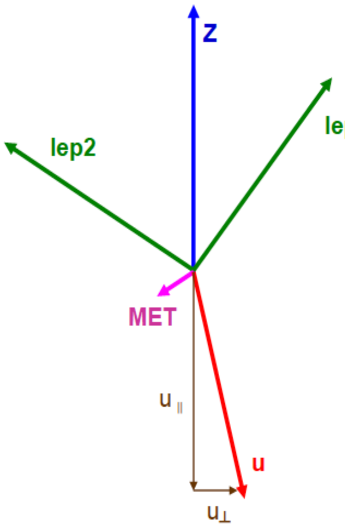
- Comparing of the reconstructed vs the ideal case, we have more difference between the standard PFMET definition (***genPFMET*** vs ***recoPFMET***) than in the charged ones (*genTKMET* vs ***recoTKMET***)
  - → tkMET is robust against PU contamination
  - → CMS reconstructs 80% of the tracks with 300MeV

- Looking at the ideal case (***genPFMET*** vs *genTKMET*) the jacobian peak is not sharp anymore
  - → The charged recoil scale hasn't unity response

- Overall the reconstructed jacobian peak is sharper in the charged case (*genTKMET* vs ***recoTKMET***) width respect to the inclusive case (***genPFMET*** vs ***recoPFMET***)
  - → We are protected by the ptW << ptNeutrino

CMS-SMP-14-007

Recoil calibration



Approach:

- ➢ **do not fine tune each single piece (pile up, underlying event, soft/hard radiation) *since we cannot really disentangle them***
- ➢ **take the overall response of the detector from the Z+jets events.**
  - Closest topology to the signal sample W->$\mu\nu$
  - Any Met is purely due to resolution effects of the hadronic activity
  - Precise candle p_T(Z) m(Z)

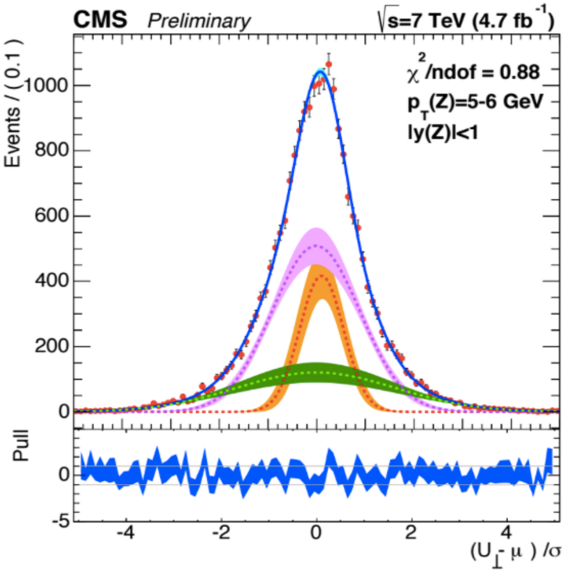
The recoil is projected respect to the boson p_T

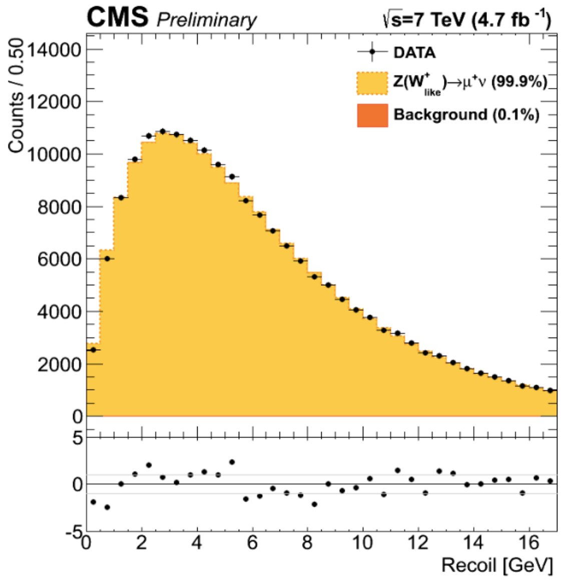
Parallel to the boson p_T mainly affected by the hadronic recoil

Perpendicular mainly affected by the underlying event

Example of 3-Gaussian with parameters dependent on Zp_T done in bins of Zy

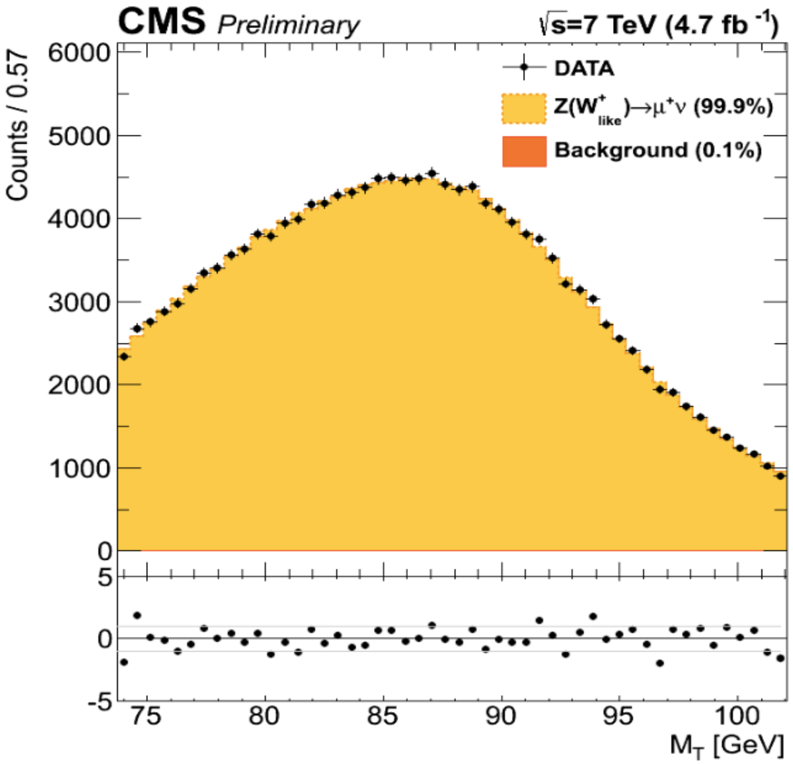
Alternative model with an adaptive kernel.

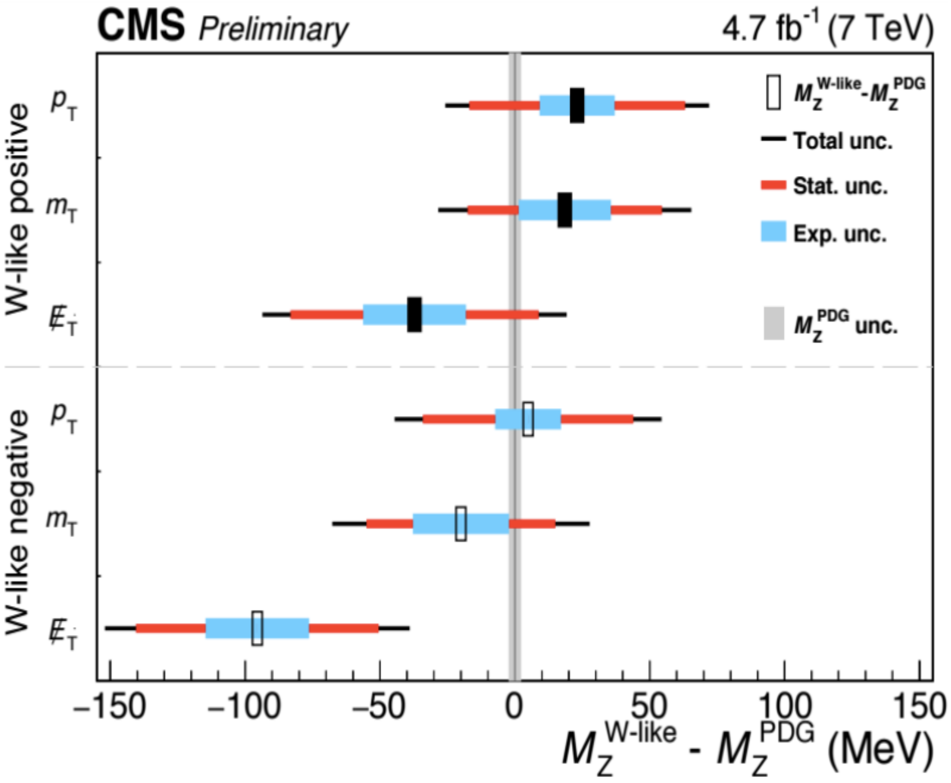




CMS-SMP-14-007

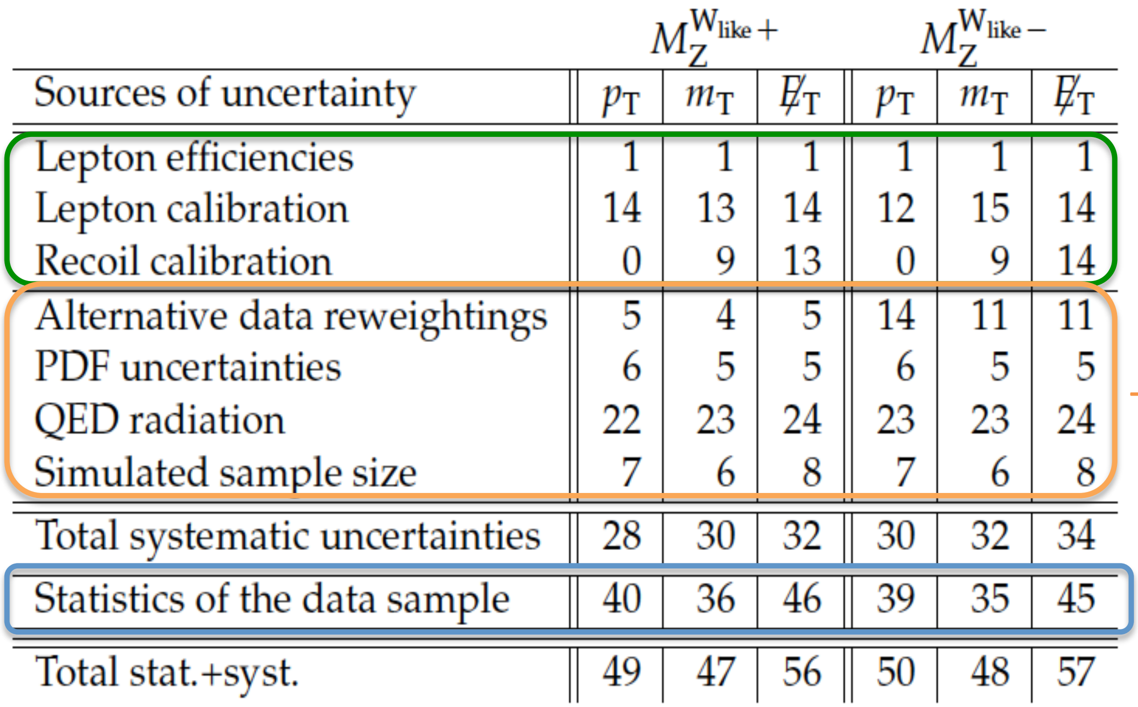
“W-like” mass results





CMS-SMP-14-007

"W-like" mass results



Sources of uncertainty	$M_Z^{\mathrm{W like}+}$ p_T	m_T	$\not{E}_T$	$M_Z^{\mathrm{W like}-}$ p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

Include the statistical and systematic component of the calibrations

These do not directly translate to the W

Expected to decrease to few MeV for the W

Measured mass compatible with the PDG value

δ(stat) ~ 40MeV

$\delta(\text{calib})_{\text{mu/recoil}}$ < 20MeV

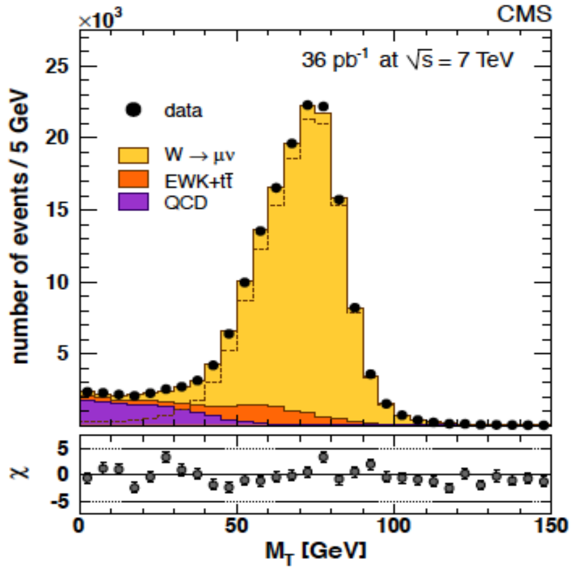
δ(other) ~ 30MeV

Decomposing the W events

What we see in the detector

lepton

JHEP 10 (2011) 132, [arXiv:1107.4789]



recoil=(PU+UE+jets)

What we try to describe with MC

Boson production/decay

- proton PDF
- boson pt (QCD and EWK, higher order)
- boson decay (polarization+ FSR)

Main themes of research:

1) Have state of the art MC

→*What is a good enough description ??*

2) Ancillary measurements

→constrain physics model

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
https://twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.htm

3) Analysis strategy

→minimize model-dependence

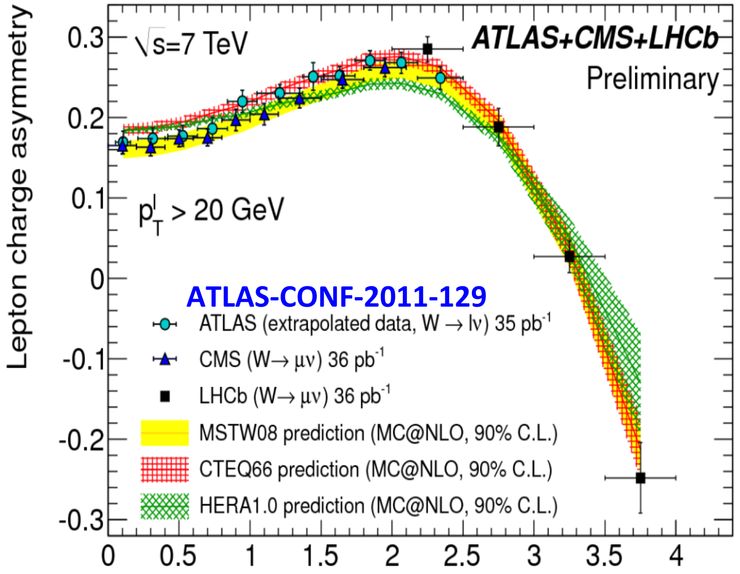
PDF

Production mainly $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$ with x from 10^{-3} to 10^{-1}

- Similar between W and Z
- Measurements done to constraint:
  - Improvements in some region from the LHC@13
  - *Need to create a dedicated PDFset that is not correlated to the W*

u/d valence /sea quark density

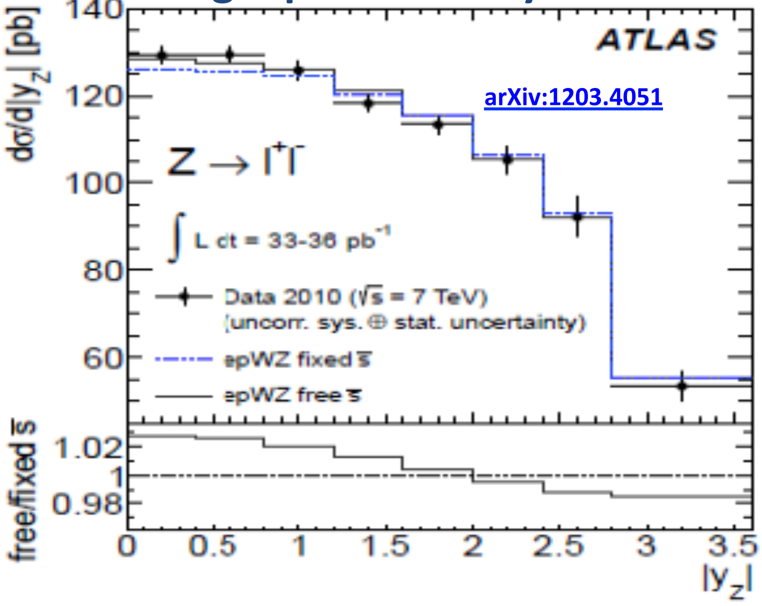
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})},$$



ATLAS-CONF-2011-129

See also CMS:Phys. Rev. D 90 (2014) 032004

Strange quark density



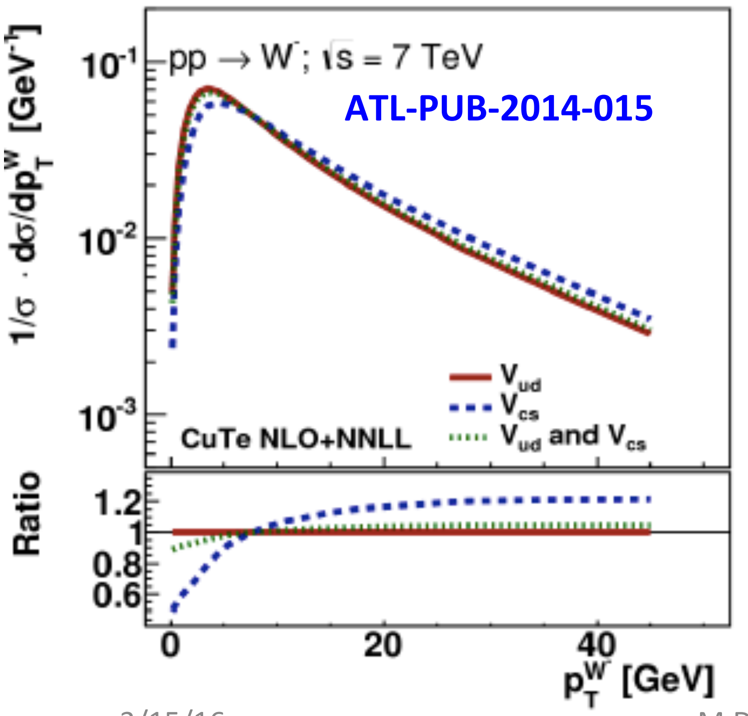
arXiv:1203.4051

Phys.Rev.Lett. 109 (2012) 012001

Physical origin of the PDF uncertainty

Studied the physical origin of the PDF uncertainty to design a roadmap to reduce them.

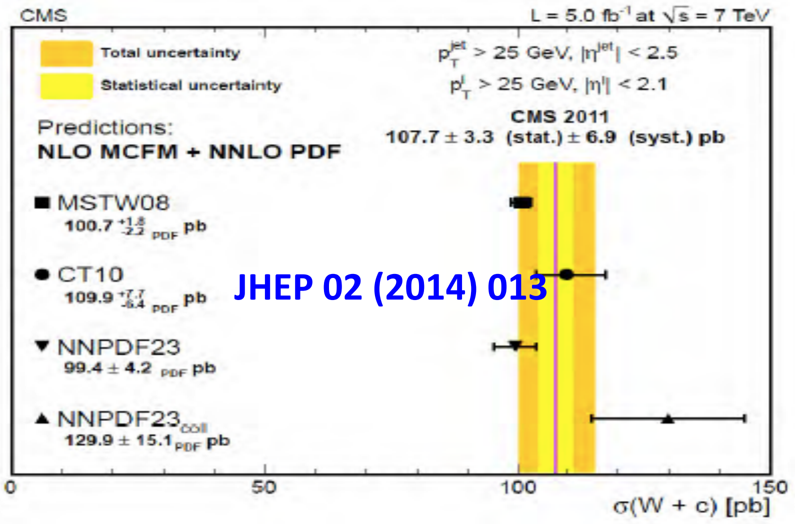
Strange PDF and charm initiated W-production:
estimated δ(mW) :7-9 MeV



ATL-PUB-2014-015

Charm dedicated PDF fits
This is different in W and Z:

The charm quark contribution
significant to W production (~ (Vcscs¯+Vcdcd¯+c.c.)),
smaller for Z production (~ cc¯).
the b-quark content
contributes to Z production (~ b¯b),
negligible to W production (~ (Vcbc¯b +c.c.))



JHEP 02 (2014) 013

Physical origin of the PDF uncertainty

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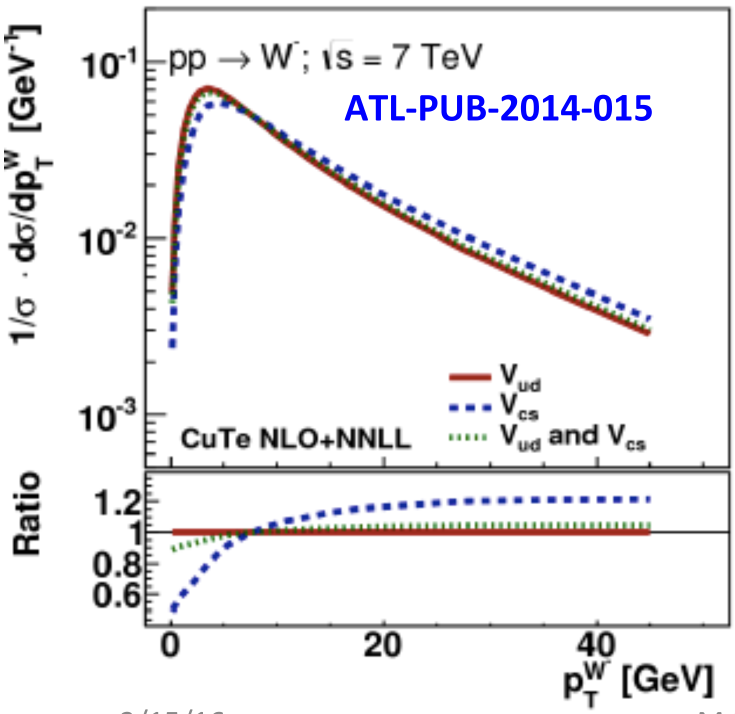
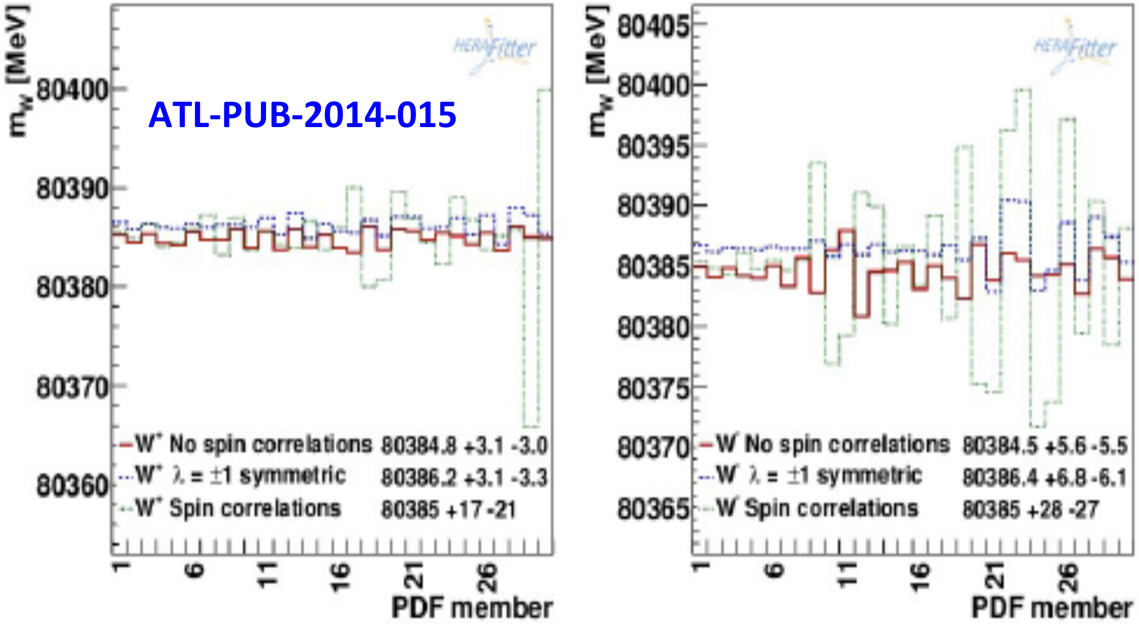
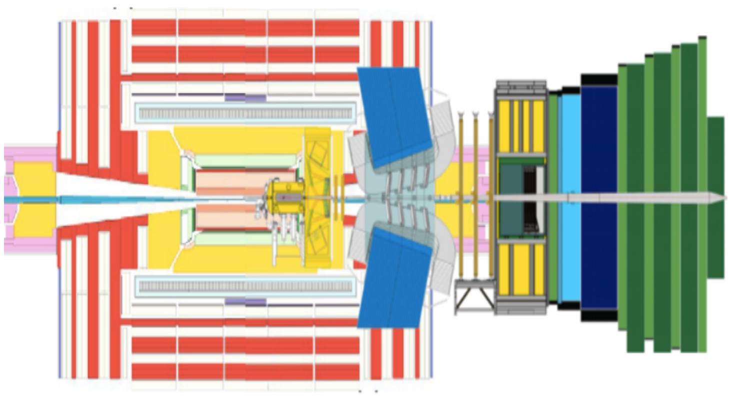


Valence PDF and W polarization:
estimated δ(mW) : 20-30 MeV

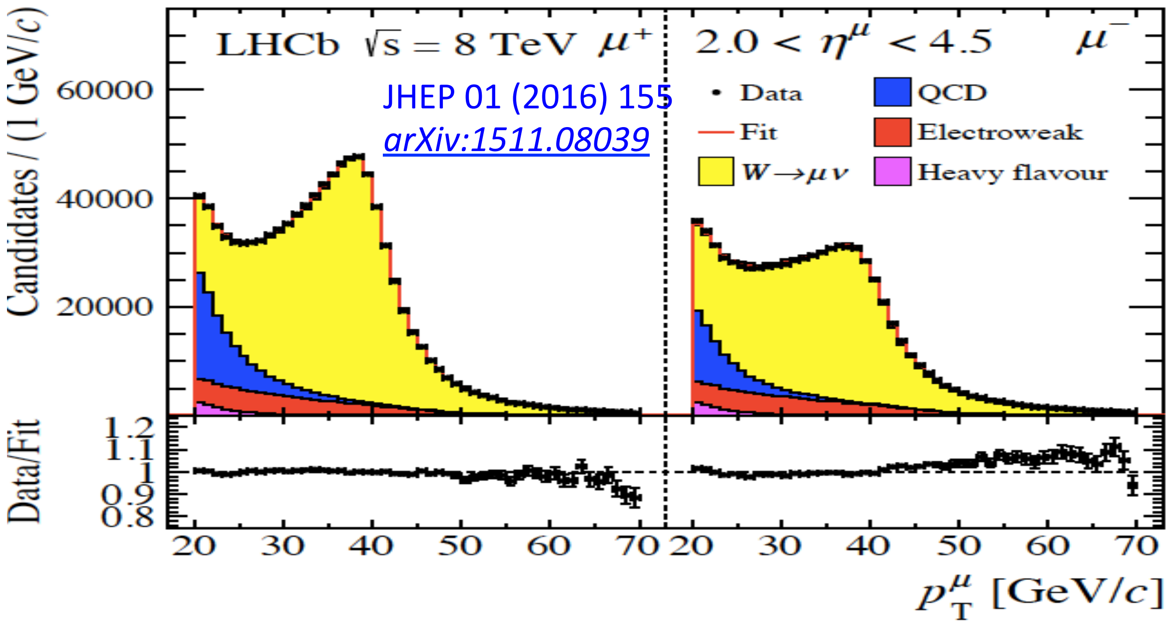


PDF and Phase Space

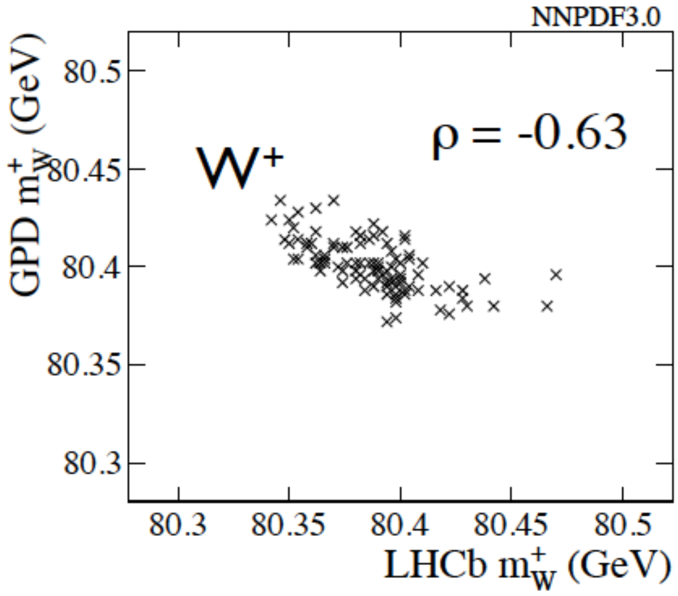
$|\eta_{lept}| < 2.5$ $+\ 2 < \eta_{lept} < 5$



- ➢W Analysis phase space (large η lepton and low ptW) important to limit the PDF uncertainty on W mass (Vicini et al. *arXiv:1501.05587 , arXiv:1508.06954*)



JHEP 01 (2016) 155
arXiv:1511.08039



Large anti-correlation between the CMS/ATLAS and LHCb
➔ Can reduce of 30% the impact of the PDF uncertainty

Production

Two main sources:

1 Intrinsic momentum in the partons in the proton

2 Non-perturbative parton radiation

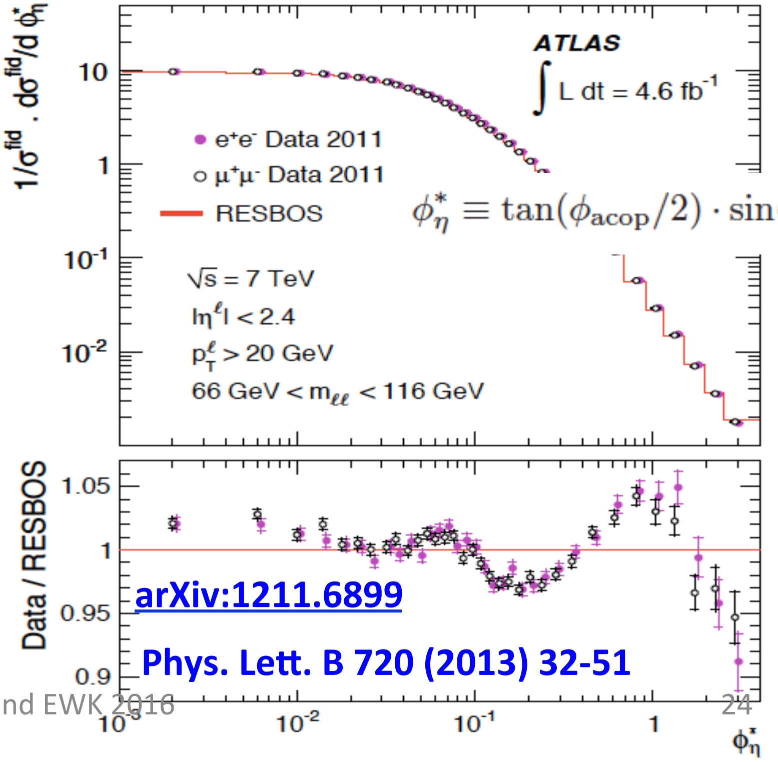
Occurring in the transition from the low-**Q**2 proton towards the hard process.

Those are expected to be common to W and Z.

Two general methods for combining Shower MC with perturbative calculation at NLO (avoiding double counting):
POWHEG and MC@NLO

-> NNLO corrections and analytic QCD resummation needed to allow a good control of theoretical uncertainties.

Studied also outside the Zmass peak with 8TeV dataset arXiv:1512.02192



$$\phi^*_\eta \equiv \tan(\phi_{\rm acop}/2)\cdot\sin(\theta^*_\eta)$$

arXiv:1211.6899

Phys. Lett. B 720 (2013) 32-51

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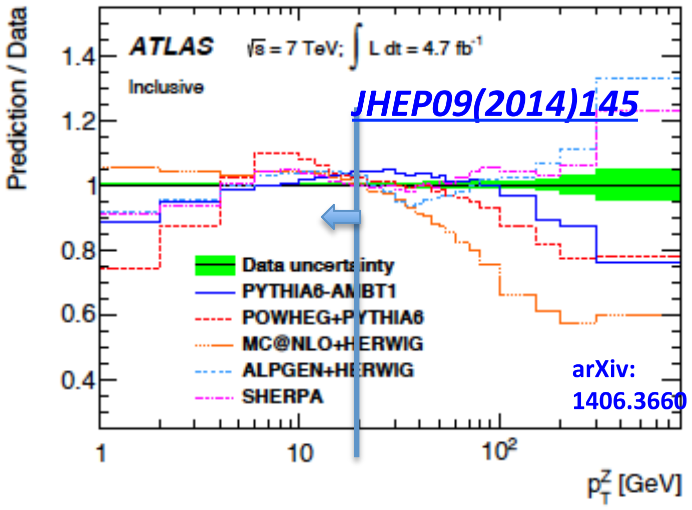
Those are expected to be common to W and Z.

Not easy the interplay in the PDF, QCD higher order, tune in the MC description.



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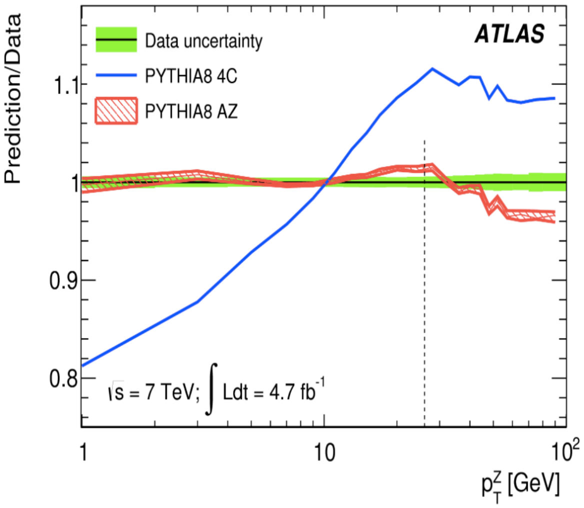
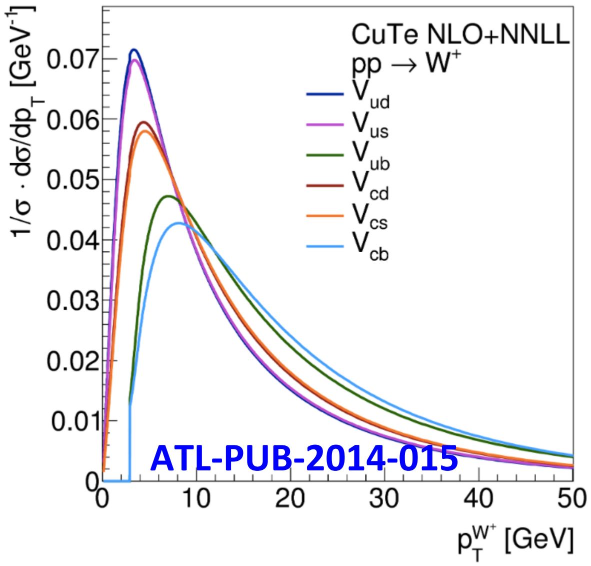
arXiv: 1406.3660





ATL-PUB-2014-015

Decay

MC description substantially improved recently

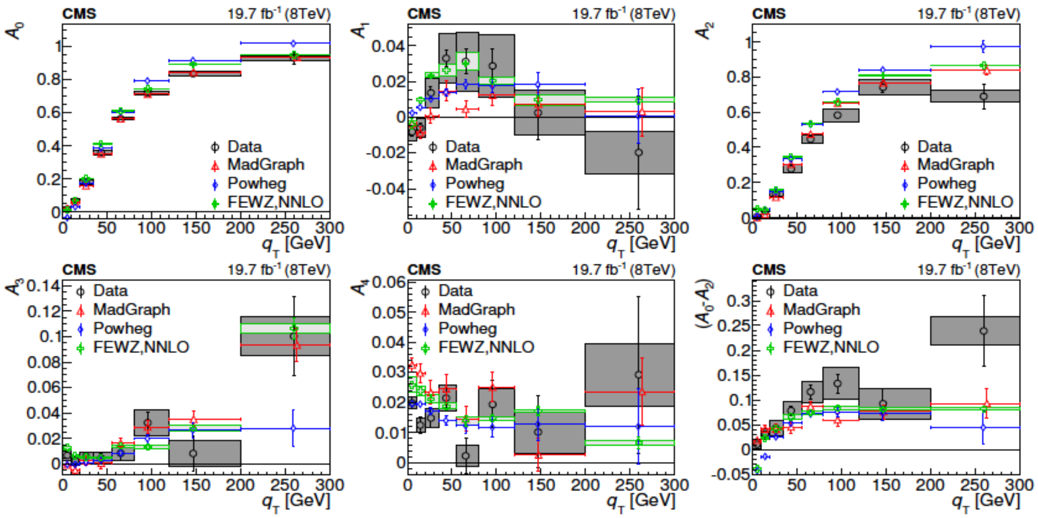
https://indico.cern.ch/event/367442/other-view?view=standard

Angular coefficients:

arXiv:1504.03512, Phys. Lett. B 750 (2015) 154

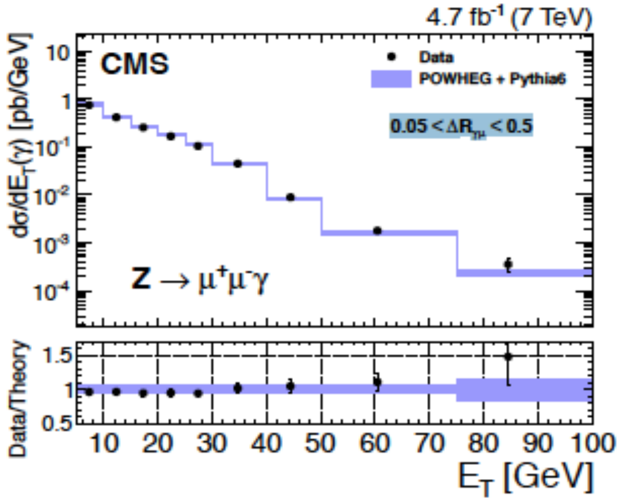
Comparison of the angular coefficient in the Collin Soper frame in bins of qt and |Y|<1 and |Y|>1

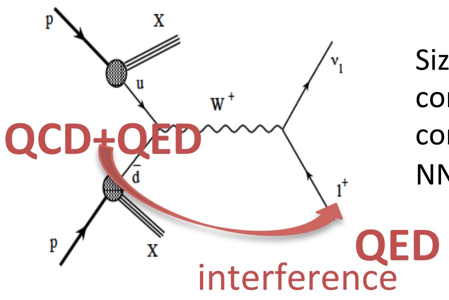
$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$
$$+A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$



FSR in Z decay:

arxiv:1502.07940 Phys. Rev. D 91 (2015) 092012





Size of NLO EWK corrections comparable to the NNLO QCD

Summary and Outlook

Experiments working on the lepton and MET calibration to the required precision.

Presented the status of the art calibration with the W-like measurement of Z mass*.*

Physics modeling is a major challenge:

Ancillary measurements to constrain physics model and analysis strategy to minimize model dependence and tune state of the art MC.

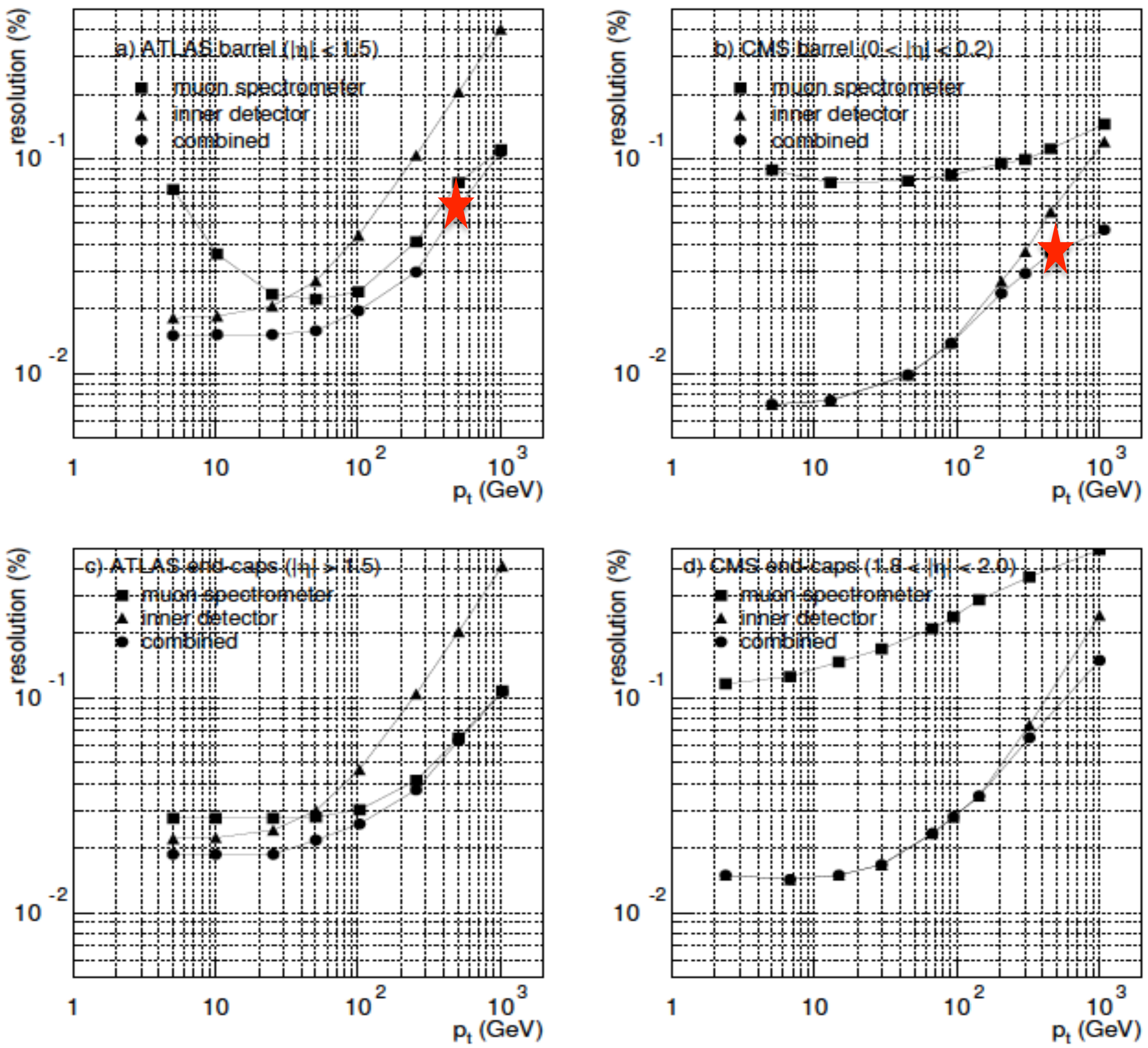
Current status

Tevatron δ(stat)~δ(theo) ~δ(calib)
LHC δ(theo)>δ(calib) >δ(stat)

Bonus slides

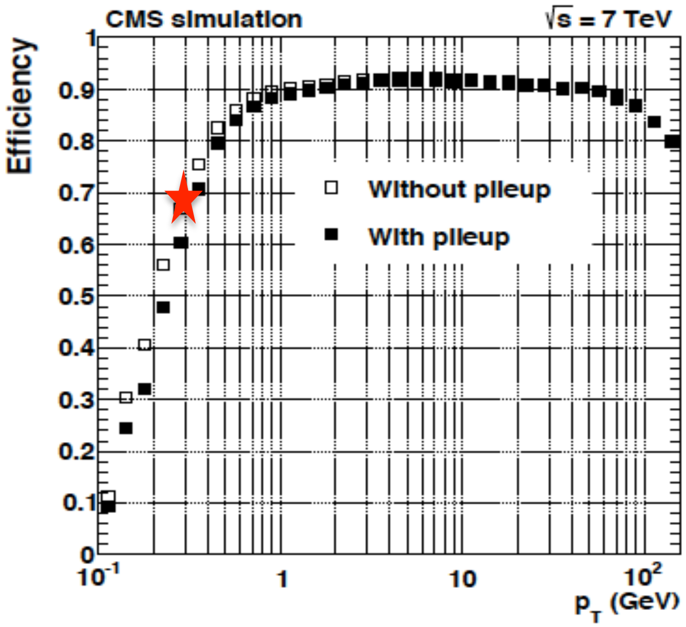
http://cds.cern.ch/record/1048974

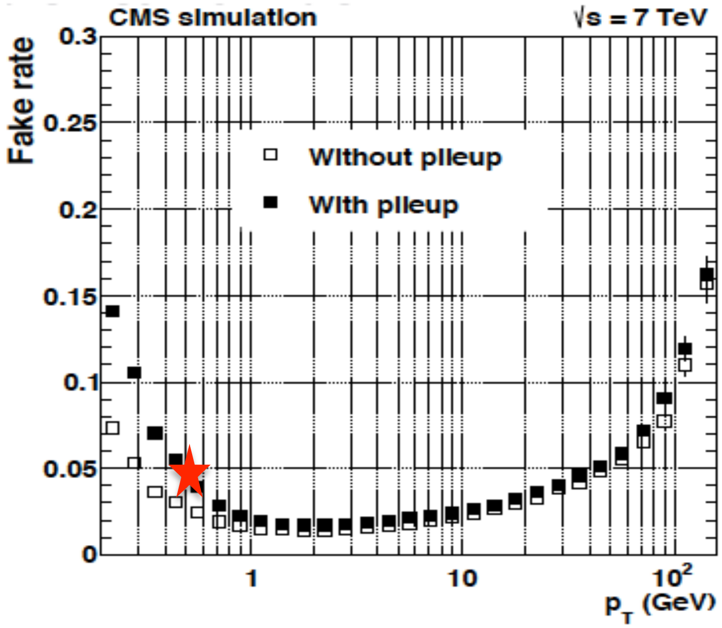
Muon scale



Tracking efficiency/fake rate

CMS-TRK-11-001





@pt=300 MeV

Very high efficiency 80%

Low fake rate 5%

PDF

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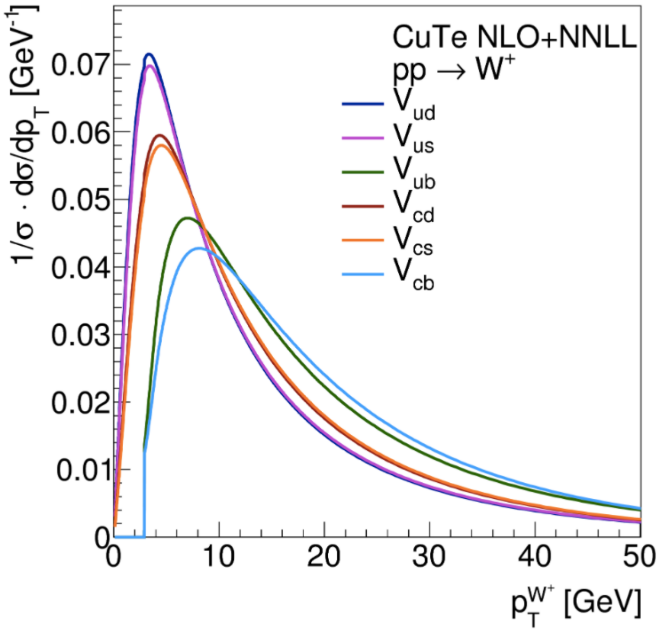
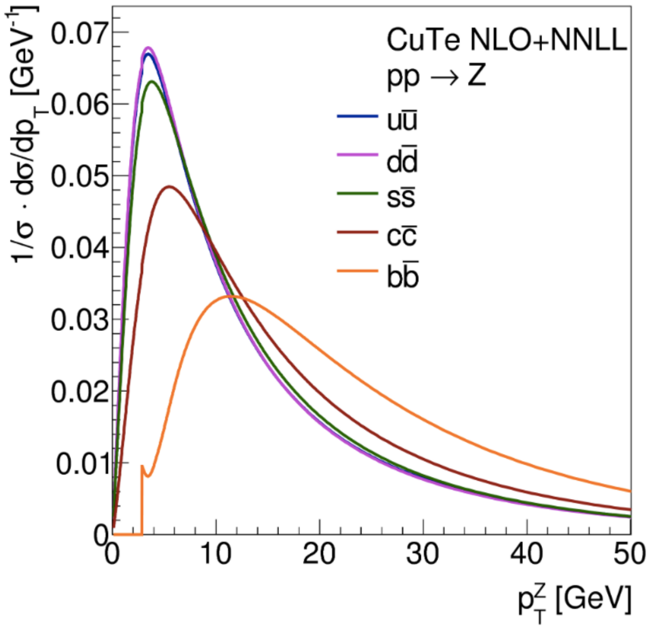
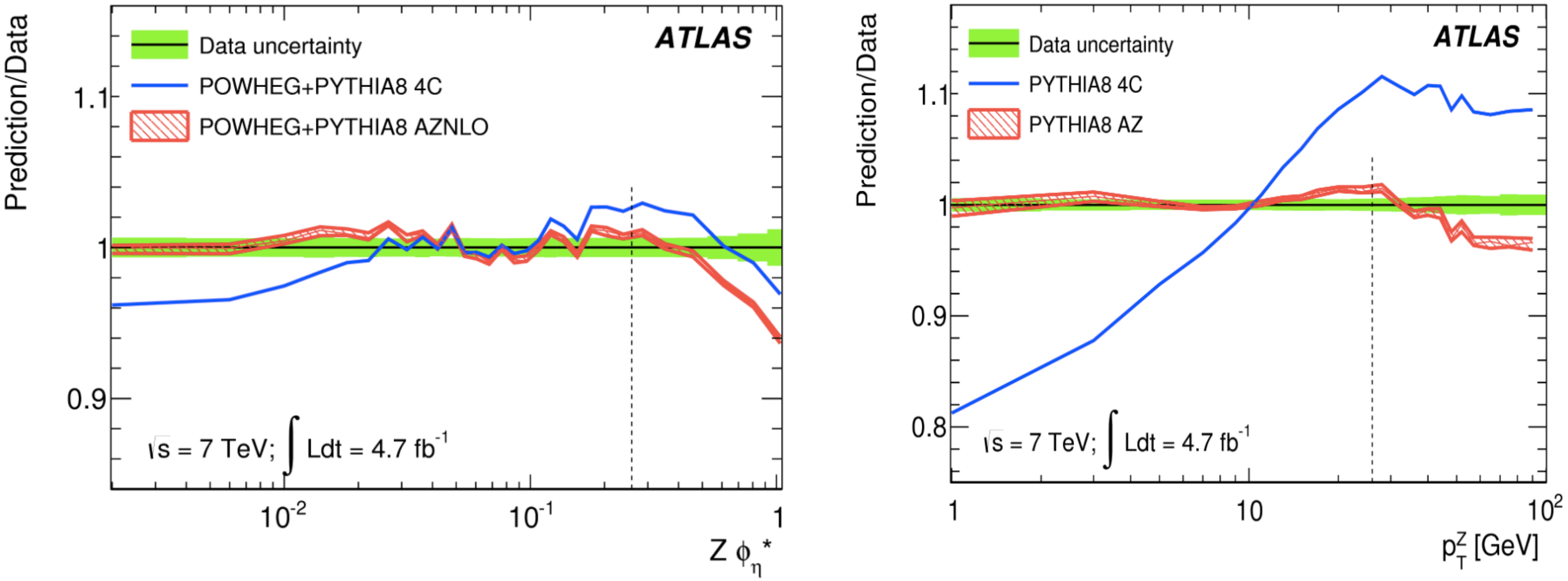




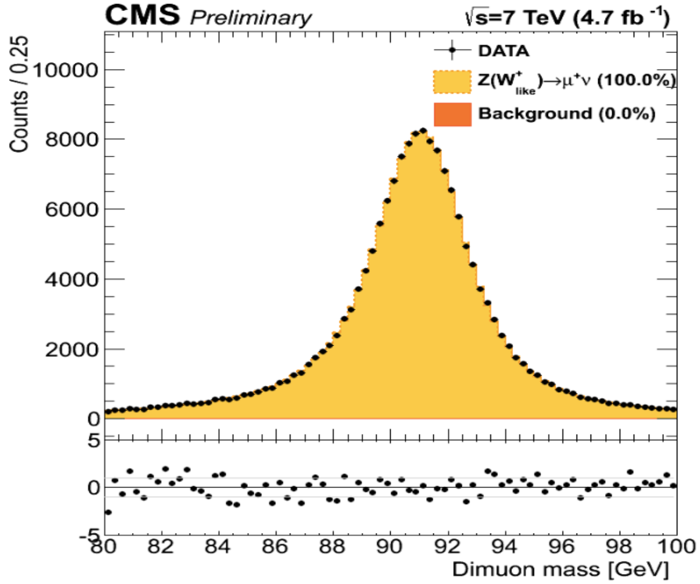
Parton shower tunes

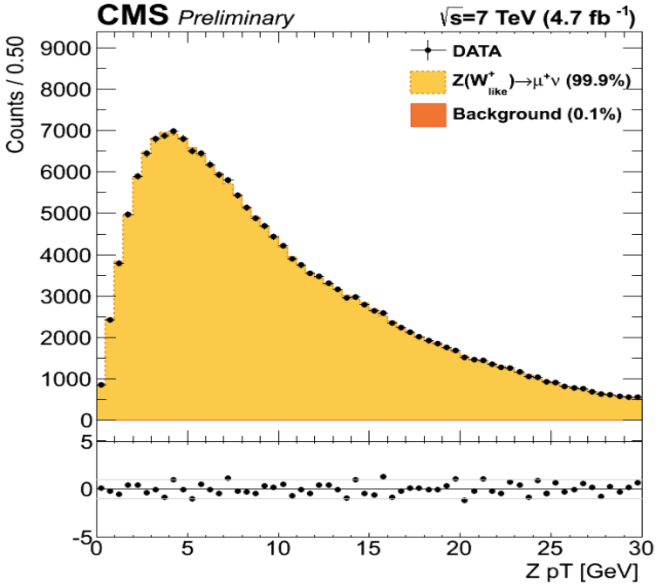
ATLAS: Comparison of the PYTHIA8 generator with the 4C and AZ tunes to the muon-channel $p_T z$ data and electron-channel ϕ*;

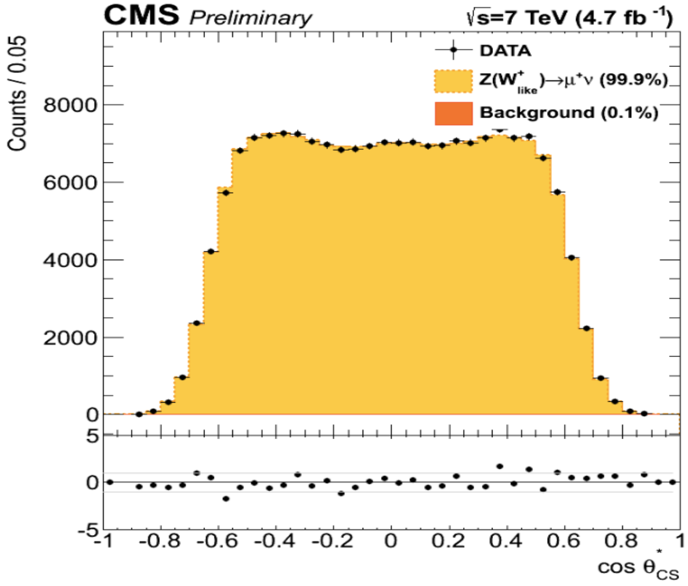
JHEP09(2014)145

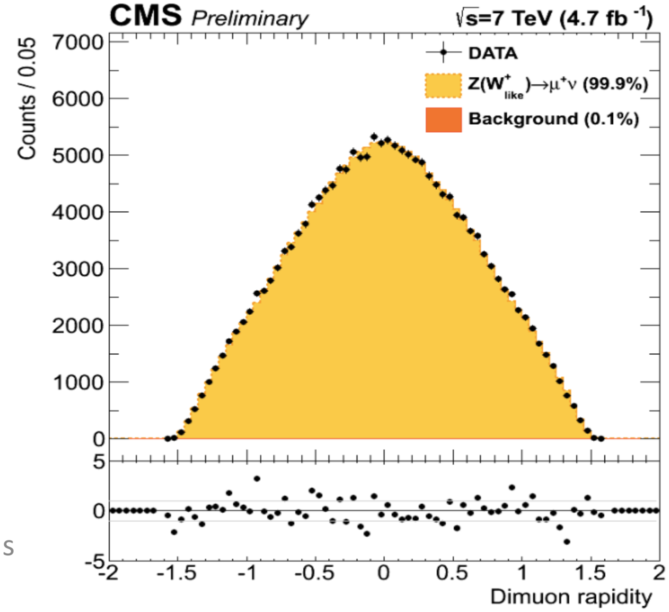


Properties of the W-like system









W-like - correlations

Events in the various w-like variables statistically correlated

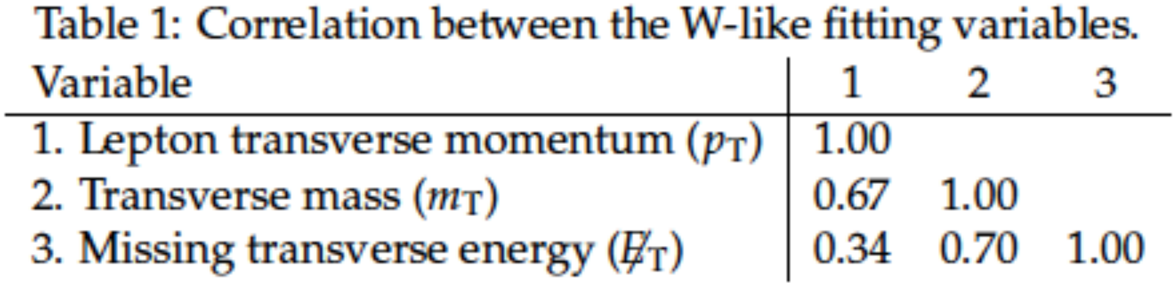


Table 1: Correlation between the W-like fitting variables.

Variable	1	2	3
1. Lepton transverse momentum (p_{T})	1.00		
2. Transverse mass (m_{T})	0.67	1.00	
3. Missing transverse energy ($\not{E}_{\mathrm{T}}$)	0.34	0.70	1.00

We have 50% of common events between the W-like Pos dataset and W-like Neg dataset.