Precision W Measurements in CMS

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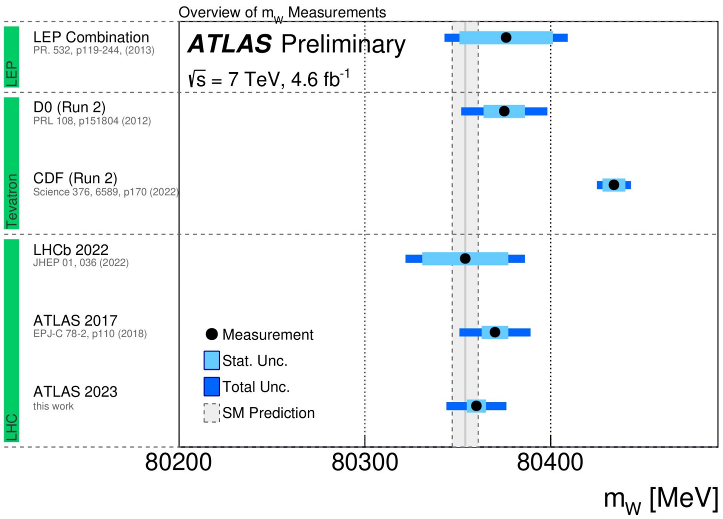
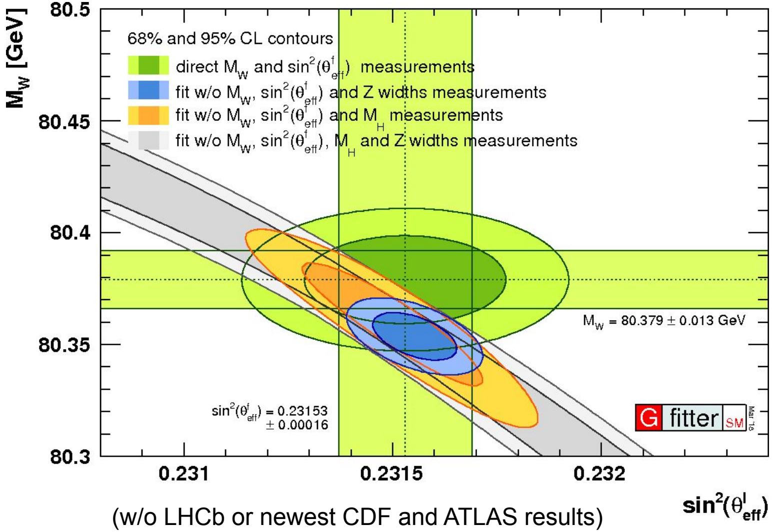
on behalf of the CMS Collaboration
MWDays23, CERN
April 17, 2023

m_W as a precision test of the SM



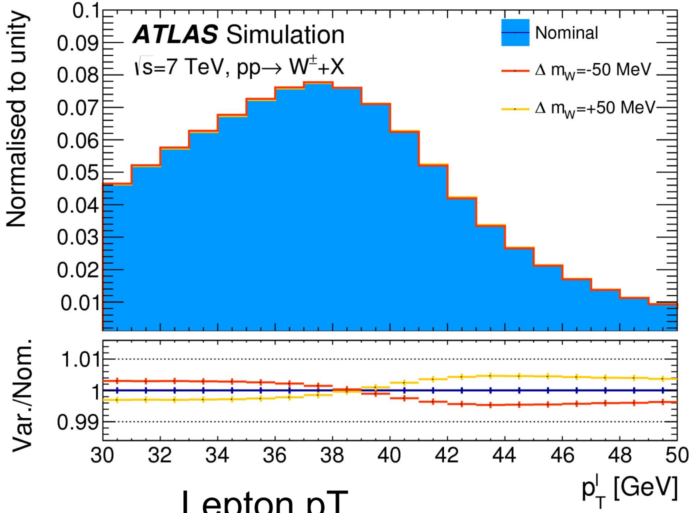


(w/o LHCb or newest CDF and ATLAS results)

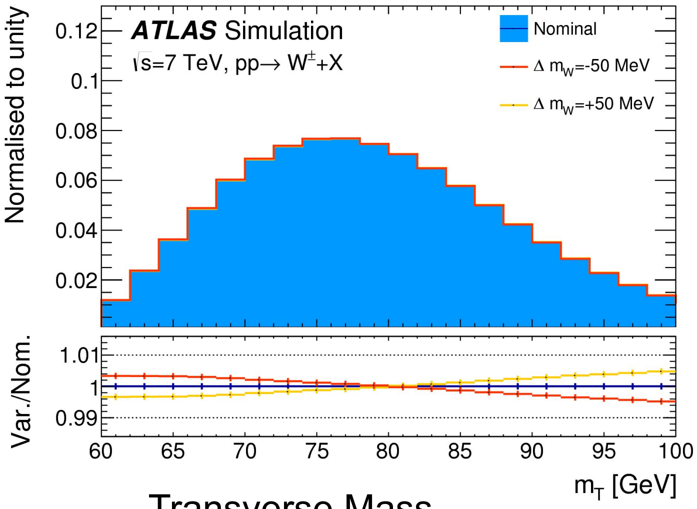
- The discovery of the Higgs and the measurement of its mass allowed (more) precise predictions of $m_W/\sin^2\theta_W/m_t$/etc from the global EW fit
- New CDF measurement in significant tension with SM prediction and other measurements

mW measurements at hadron colliders

- Hadronic channel not feasible due to huge QCD backgrounds/Jet energy scale
- W cannot be fully reconstructed in leptonic channel due to neutrino
- Mass must be inferred from lepton pT or transverse mass distributions (1D template fits)
- mW is sensitive to 0.1% level variations in templates
  - Extreme control needed over all experimental and theoretical aspects



Lepton pT

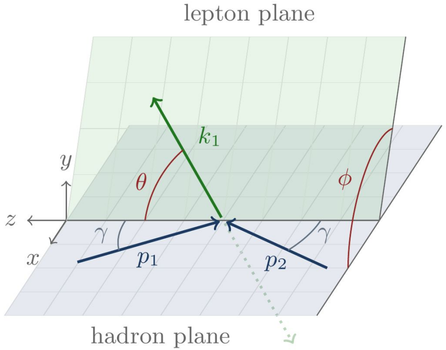


Transverse Mass

Theoretical Considerations

- W (and Z) production at hadron colliders described by PDFs + Perturbative QCD/EWK
    - Small additional non-perturbative effects from “intrinsic kT” (ie beyond-collinear-factorisation QCD effects in the proton)
- Relatively large theoretical uncertainties: usual strategy is to use precise Z->ll pT spectrum from data to tune the theoretical prediction
    - Potential residual uncertainties from Z->W extrapolation

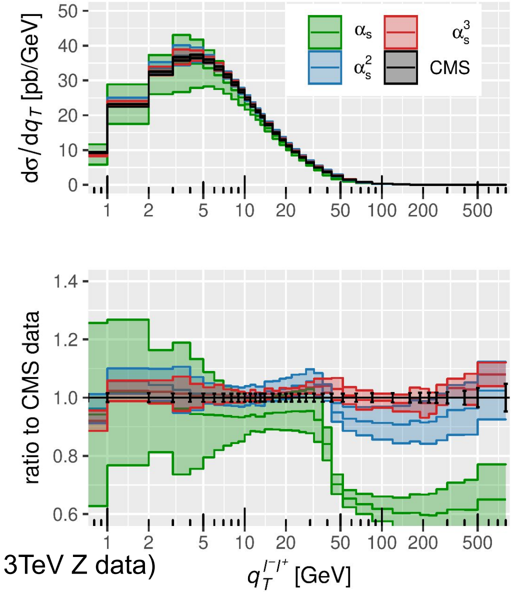
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_{\mathrm{T}}\,dy}\Big[\,(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,\Big],$$



JHEP 11 (2017) 003

W/Z production described by differential xsec + angular coefficients driven by polarization

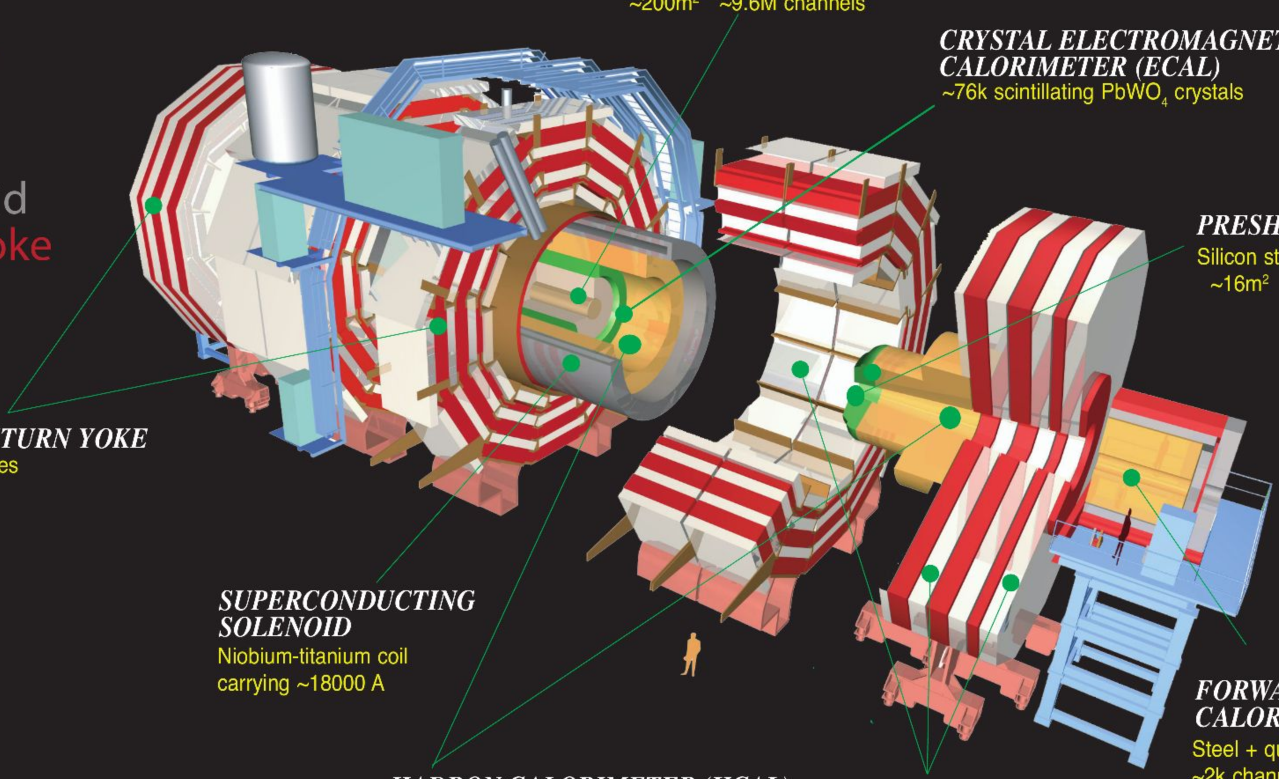
- Low pT region is challenging due to large logarithms
- Need resummed predictions
- State-of-the-art is N4LL+N3LO



arXiv:2207.07056
(comparison to CMS 13TeV Z data)

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm^2)
~1m^2 ~66M channels
Microstrips (80-180μm)
~200m^2 ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m^2 ~137k channels

STEEL RETURN YOKE
~13000 tonnes

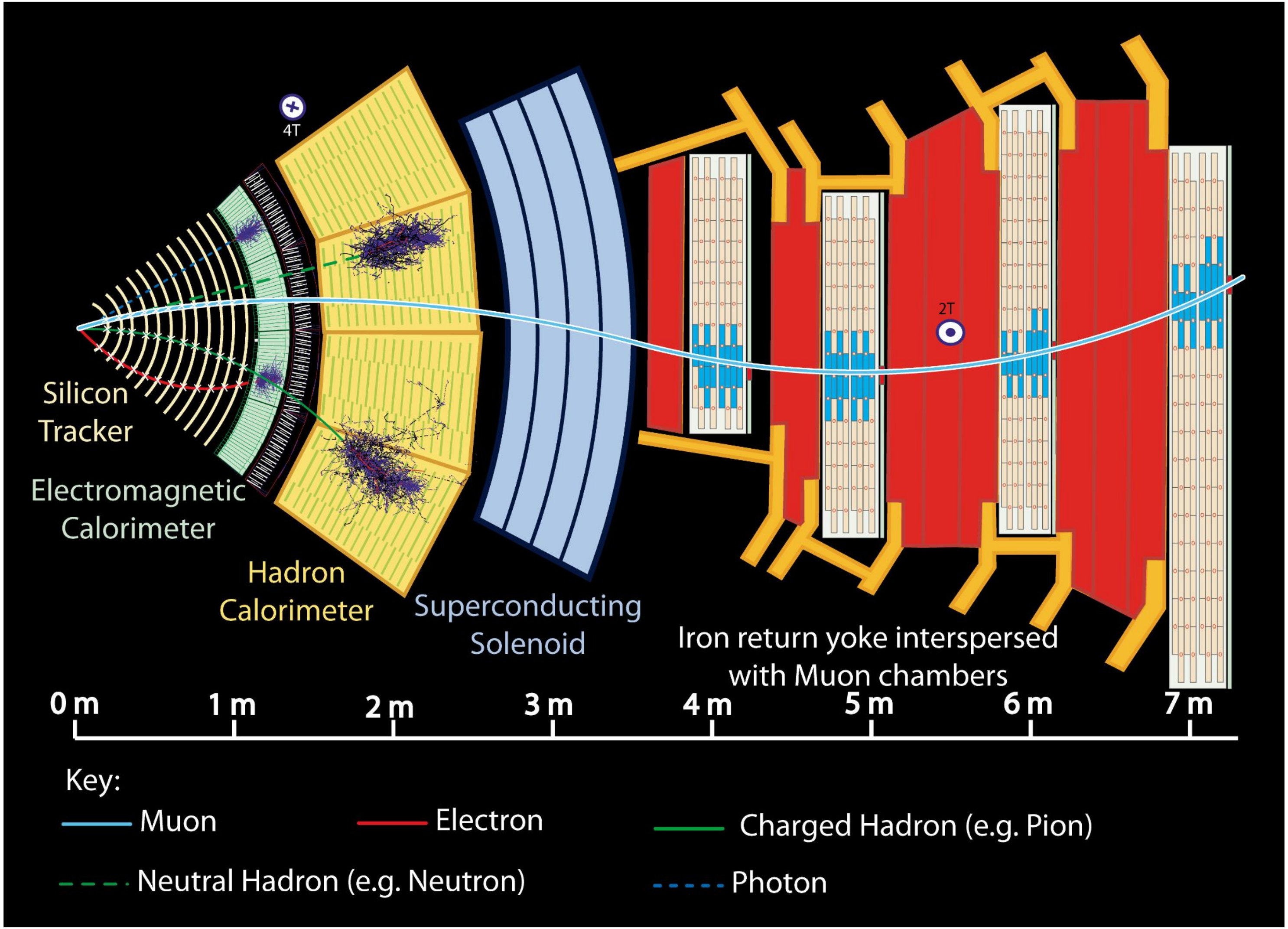
SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

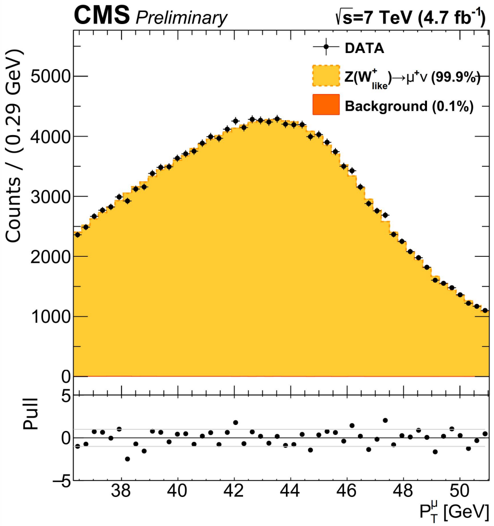
Introduction

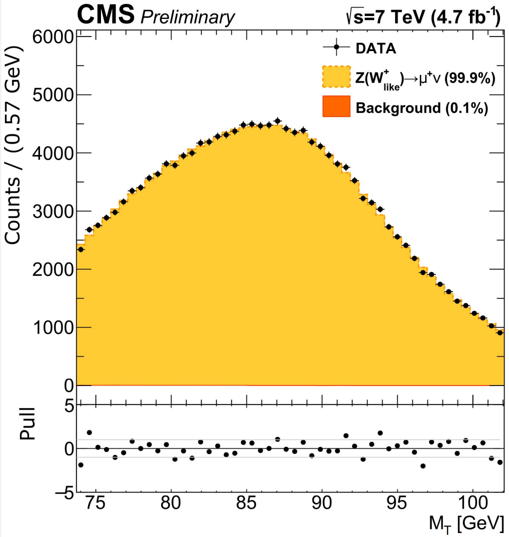
- CMS does not (yet) have a public mW measurement
- In this talk
  - Preliminary W-like measurement of the Z mass at 7TeV (CMS-PAS-SMP-14-007)
  - W helicity/rapidity measurement at 13TeV (Phys. Rev. D 102 (2020) 092012)
  - Various related aspects of detector performance, etc which are relevant/interesting

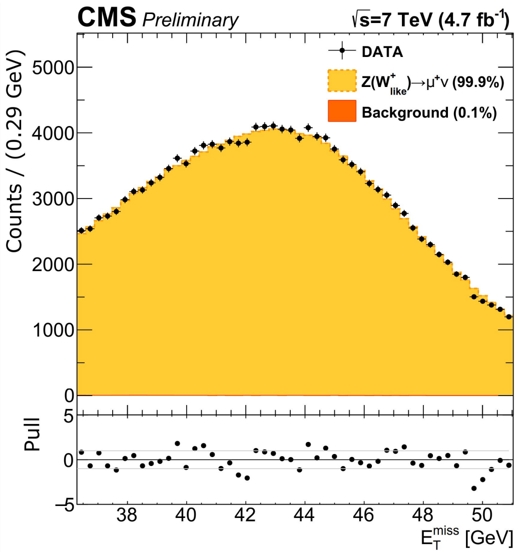
CMS-PAS-SMP-14-007

mW in CMS: W-like measurement at 7TeV

- “W-like” measurement of the Z mass
    - removing one lepton and treating as missing energy
- “Tevatron-like” like p_T^ℓ/m_T template fits using 7 TeV data from 2011 (4.7/fb with <μ> ~= 10)
- Central muons only (|η|< 0.9)
- Commissioning/demonstration of experimental techniques as a step towards an mW measurement
- Z production and decay re-weighted to data (theory aspects not the focus here)





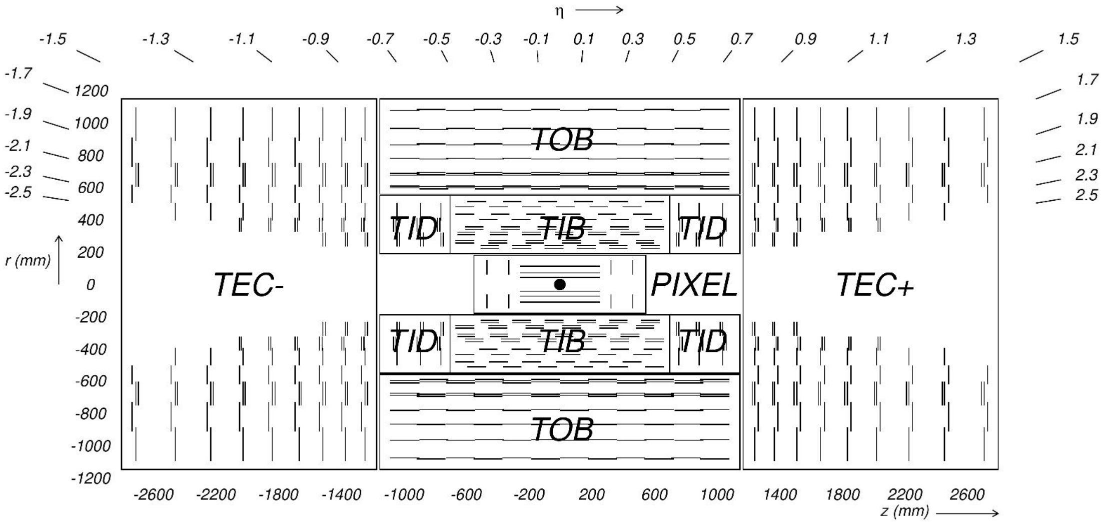


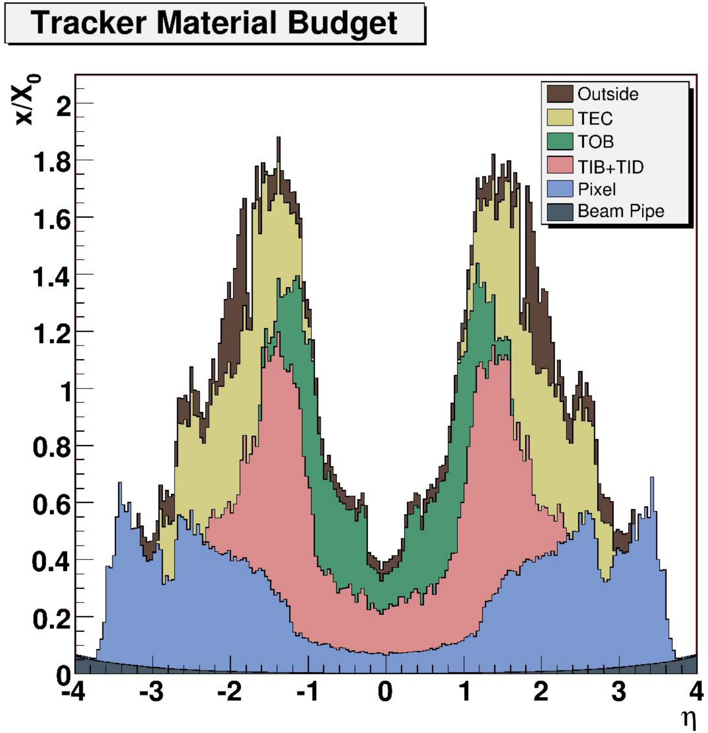
Muon Momentum Reconstruction/Calibration

- In nominal CMS reconstruction, muons with pT < 200GeV have their momentum reconstructed entirely from the strip and pixel detectors (“inner track”)
  - Magnetic field, material, and alignment are all **MUCH** more complicated when including the muon chambers -> additional lever-arm not worth the tradeoff for precision W and Z measurements
  - Muon chambers of course still essential for muon trigger and identification

Tracking in CMS (Phase-0)

[*JINST* 3 (2008) S08004](JINST 3 (2008) S08004)





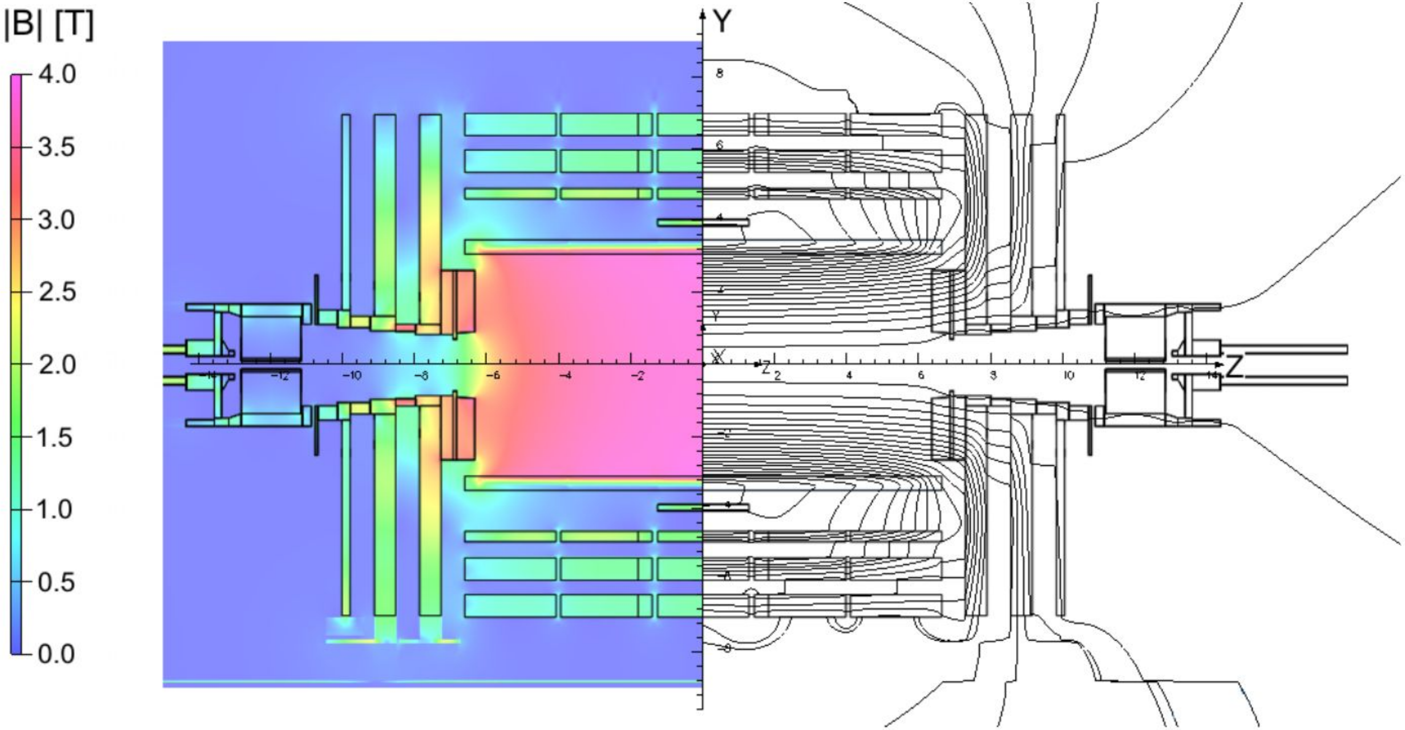
- All-Silicon tracker with measurements on up to 3 pixel layers and 9+ strip layers (typically 4+ stereo hits) for tracks from the IP
- Excellent measurement resolution: 15-53um depending on the layer
- But up to 1.8 radiation lengths of material…

Tracking in CMS

- Final momentum determination from a Kalman Filter track fit in order to account for multiple scattering (+ stochastic component of energy loss) between measurements
- Material is approximated by infinitesimal planes concentrated on the active layers (averages for each layer computed from Geant 4 simulation model)
- Runge-Kutta propagation to account for non-uniform magnetic field (but no material interactions between layers)
- Global alignment of sensor positions/orientations/deformations using cosmics, tracks from IP, and constraints from known resonance masses
    - Remaining biases from systematic effects and/or weak modes

JINST 5:T03021,2010
Symmetry 14 (2022) 169

Magnetic Field Model



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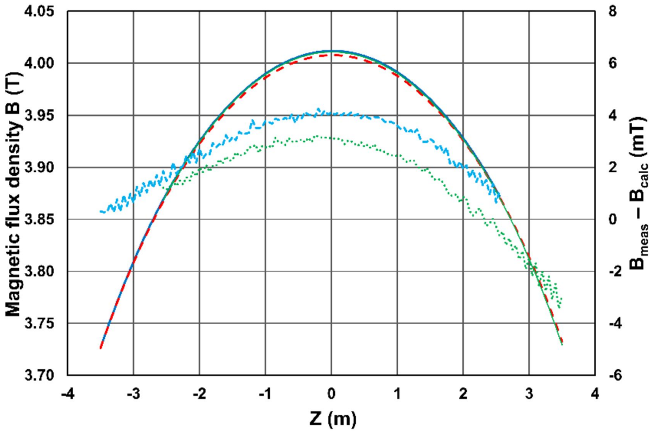
Symmetry 14 (2022) 169

Magnetic Field Model

- High granularity (33,840 space points) 3D field map taken in 2006 (but on the surface and without much of the detector)
  - NMR probes with relative accuracy better than 5e-5 and calibrated hall probes with accuracy of ~3e-4
- TOSCA model+parameterization used for track reconstruction reproduces field map data to +-0.1% with some variation vs z
- Possible future improvement: use the (interpolated) field map data directly
- Several NMR probes inside the solenoid (but outside the tracking volume) for monitoring
- **Magnetic field in tracking volume known to 0.1% a priori**
  - Residual corrections at this level not-unexpected
  - Uniformity could possibly be improved with direct use of field map data



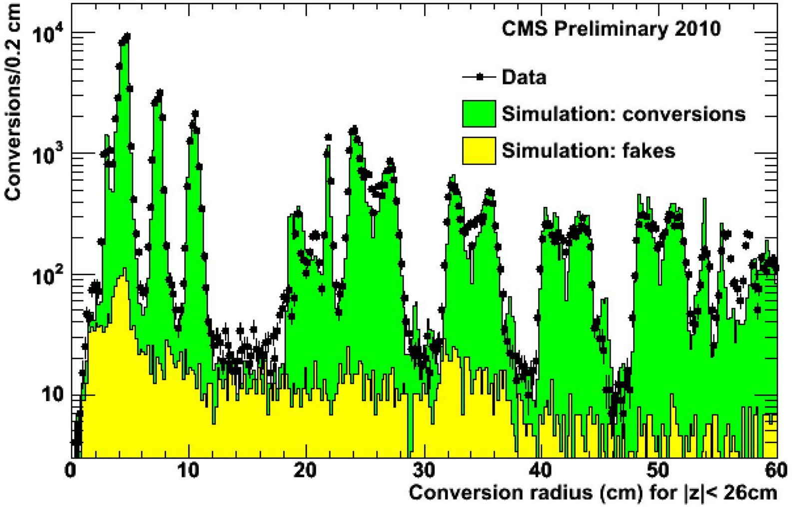
Model vs field map data at R = 0.1m (surface)

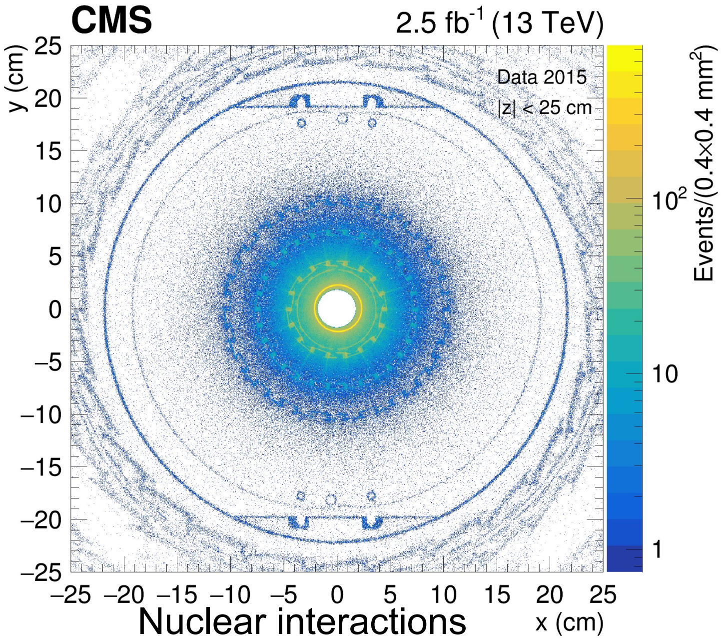
Source	**Field**	**Δ (rel.)**
Surface NMR (2006)	3.9176T	-8e-4
In-situ NMR (2008)	3.9206T	0
In-situ Model Prediction	3.9181T	-6e-4

Model vs NMR Measurements at R = 2.91m, z = -0.01m

CMS-TRK-10-003, CMS DP-2019/001

Material Model





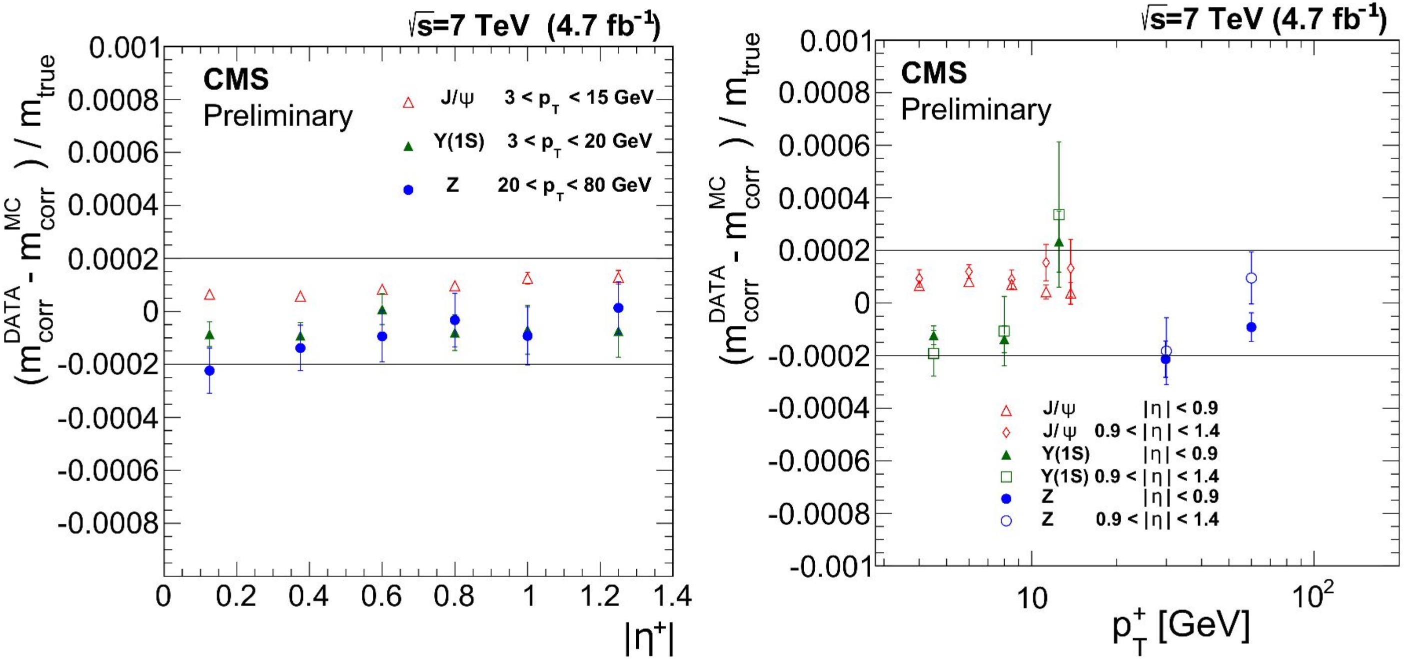
Nuclear interactions

- Material model in simulation is correct at the O(10%) level
- Additional corrections may be needed due to the infinitesimal plane approximation in the tracking

W-like measurement: Muon Momentum Calibration

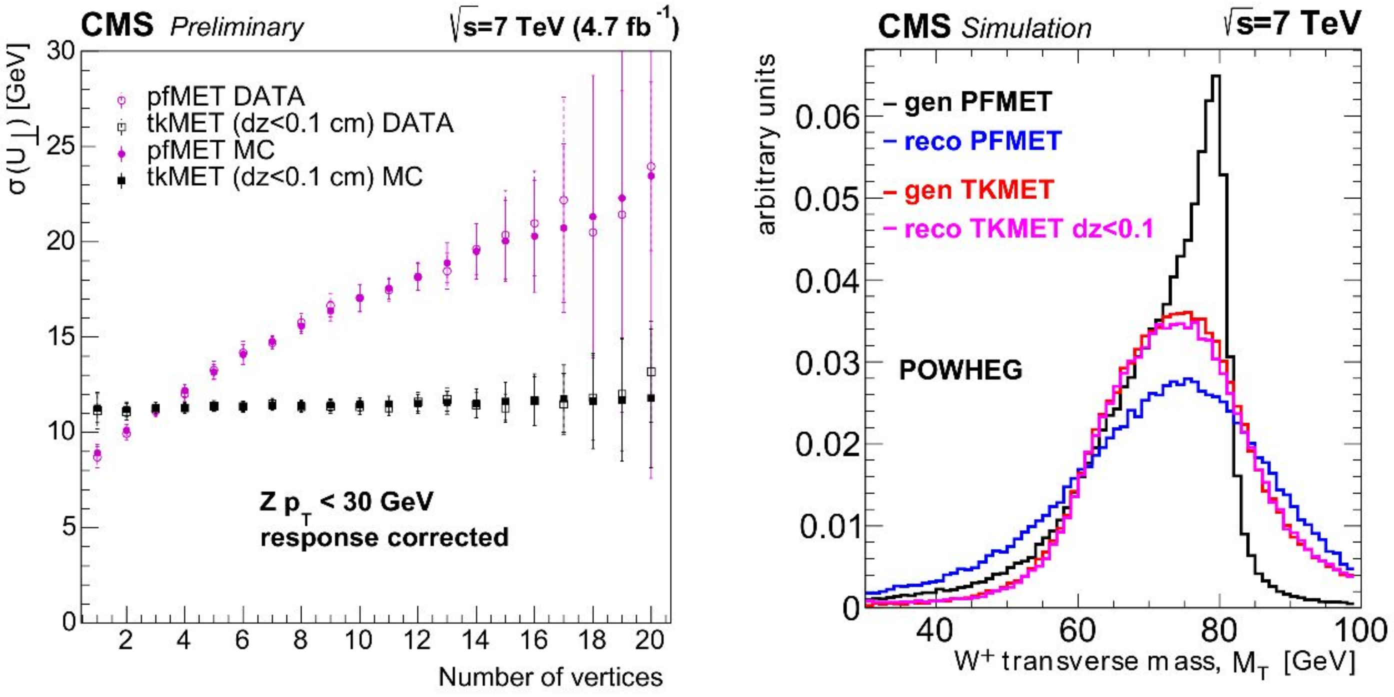
- Muon calibration derived from J/psi data
  - Pre-correction using 3d field map data ratio to TOSCA parameterization
- Parameterized corrections to account for residuals in magnetic field, energy loss (material) and alignment (with $k=1/p_T$):
  - $\delta k/k = A - ek + qM/k$
- Parameters A, e, M vary as a function of η and φ
  - $A = A1 + A2\ \eta^2$ (parabolic correction to magnetic field)
  - e binned in 12 bins of η
  - M as a sinusoid in φ, in 6 bins of η
- Parameters determined from J/psi mass via Kalman Filter procedure (events contribute to parameter gradients depending on η, φ, pT of the two muons)
- Field correction is consistent with unity within +-5e-4
- Energy loss corrections consistent with O(10%) changes in material

W-like measurement: Muon Momentum Calibration Closure



- Closure on Z and Upsilon within ~2e-4
- Clearly understanding of many aspects has improved in the meantime

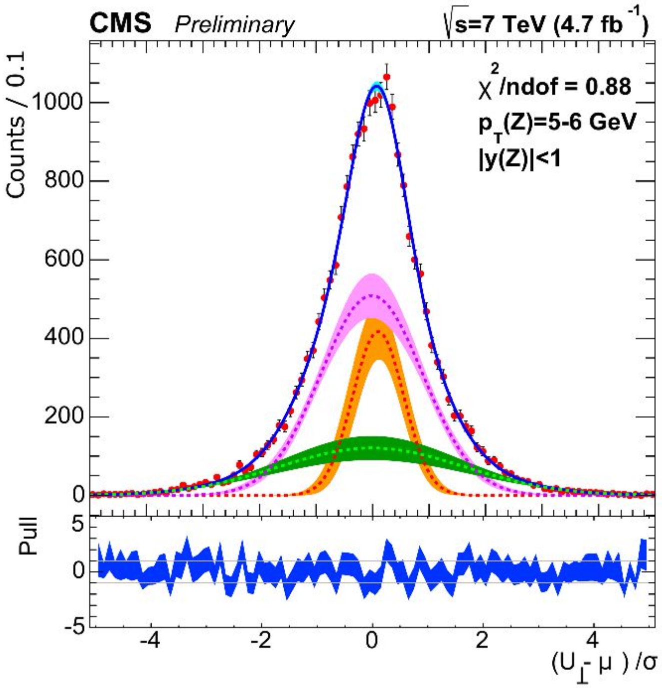
W-like measurement: Hadronic Recoil Calibration

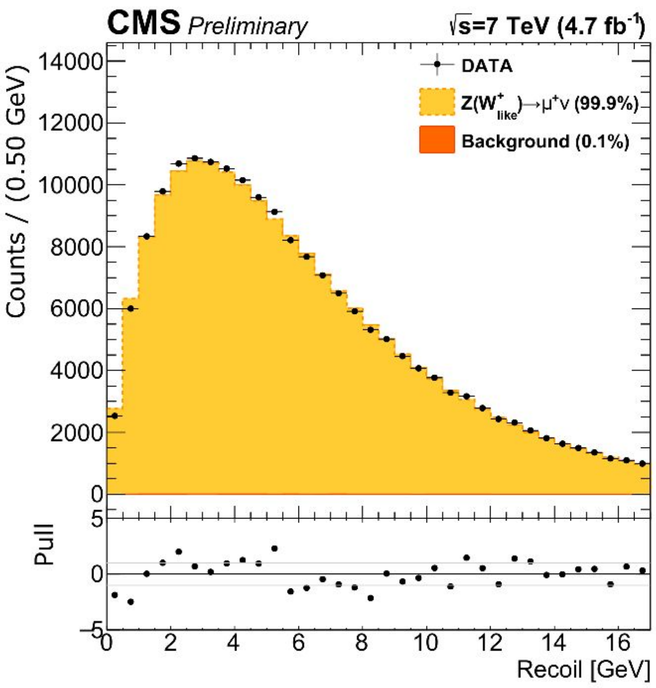


- MET formed with only tracks was favoured for this measurement since it's insensitive to pileup
- At the cost of smearing out of jacobian peak from fluctuation of charged vs neutral fraction in recoil

CMS-PAS-SMP-14-007

W-like measurement: Hadronic Recoil Calibration

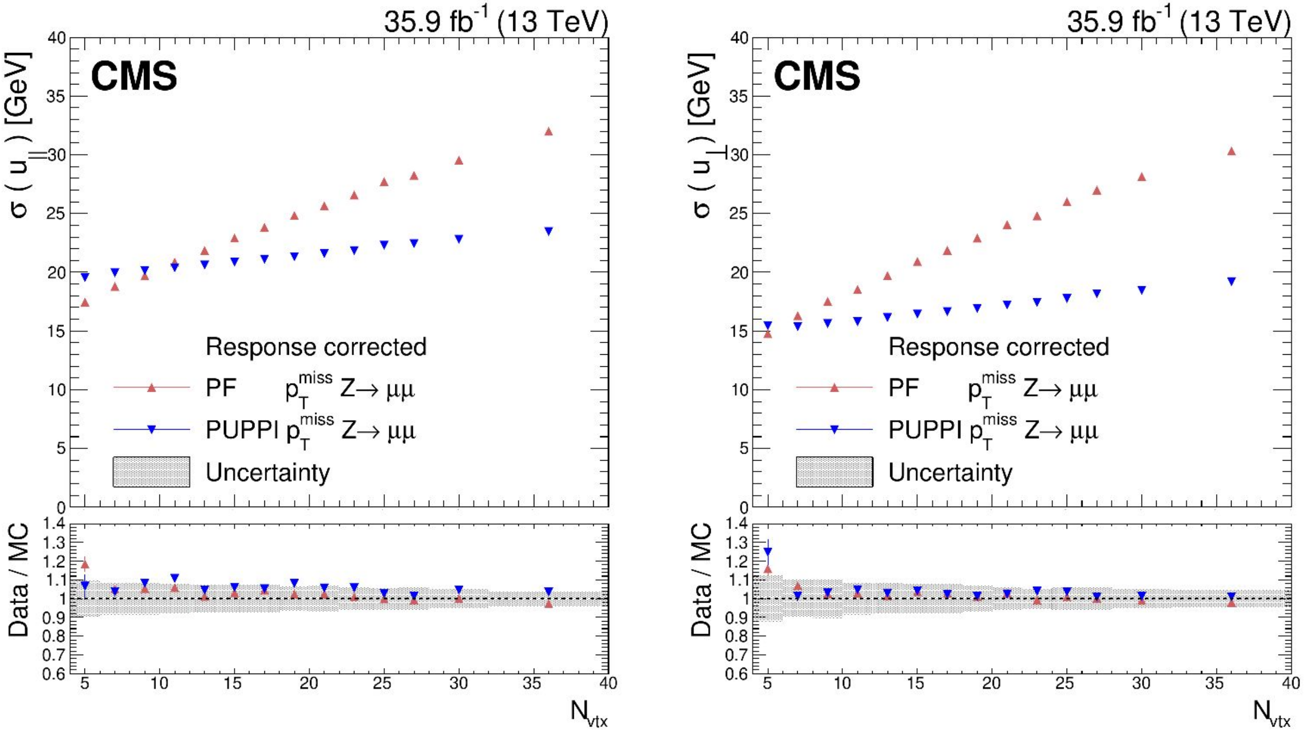




- Recoil calibrated from Z->μμ events in bins of boson pT
- Parallel and perpendicular components modeled by Gaussian mixtures -> modeling + statistical systematics
- Cumulative Distribution transform used to match simulation to data

Missing Energy Performance at 13 TeV

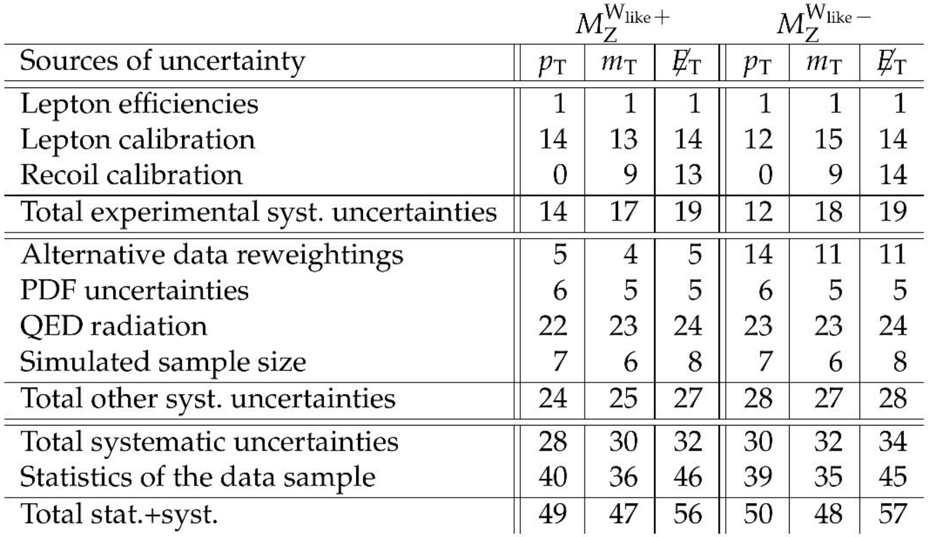
JINST 14 (2019) P07004



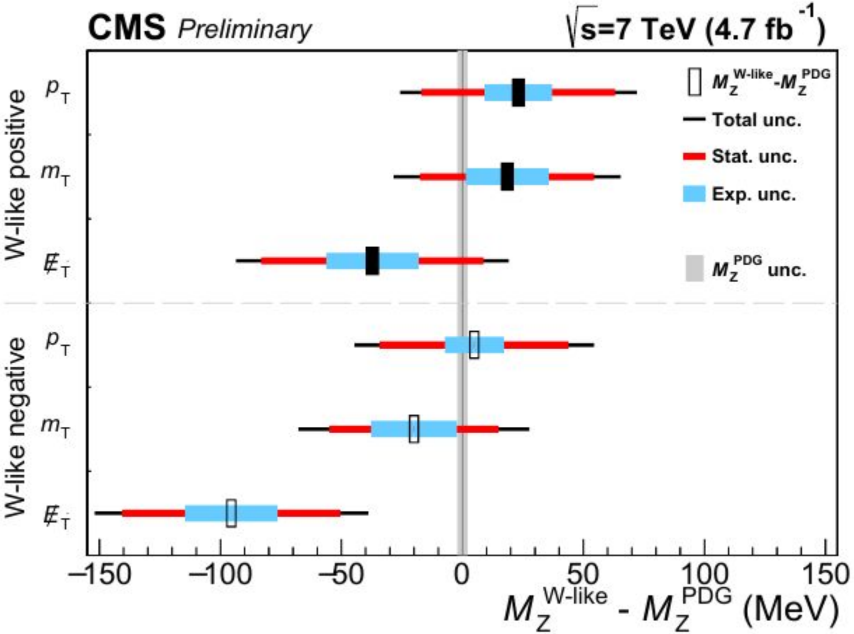
- Pileup mitigation techniques (e.g. pileup per particle identification here) can improve MET performance at high pileup
- Additional improvements are possible with machine learning

W-like measurement: Results

CMS-PAS-SMP-14-007



	$M_Z^{\mathrm{Wlike}+}$			$M_Z^{\mathrm{Wlike}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	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
Total experimental syst. uncertainties	14	17	19	12	18	19
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 other syst. uncertainties	24	25	27	28	27	28
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

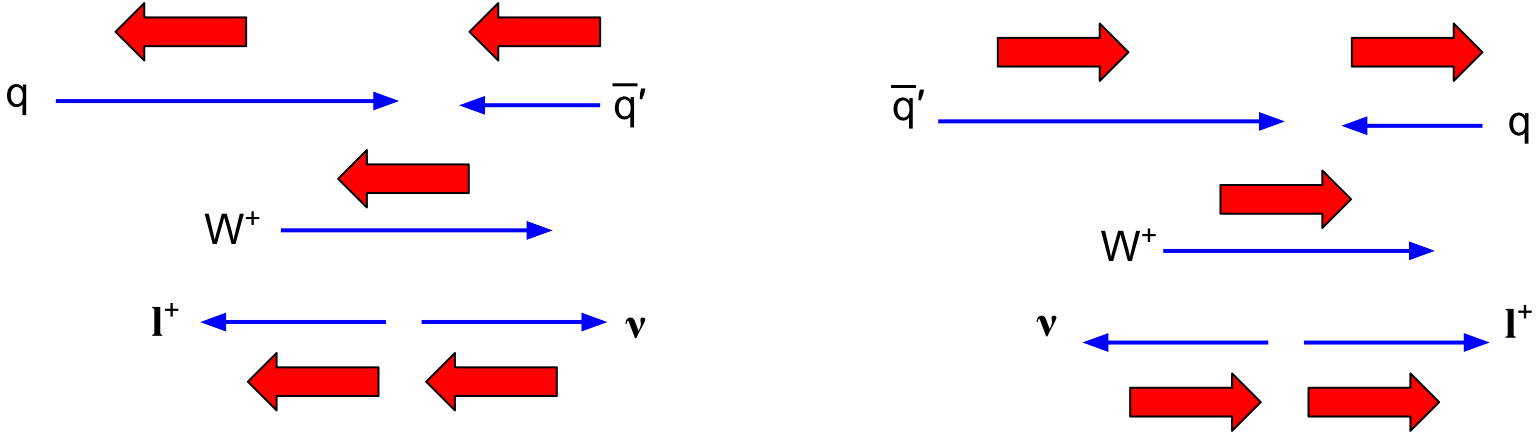


- Reasonable consistency with PDG mZ value
- **Dominant uncertainty 23 MeV on QED FSR due to issues with NLO EW matching in MC produced at the time**


ONE DOES NOT SIMPLY MEASURE THE W MASS
imgflip.com

Measurement of W helicity/rapidity

- Precision measurements of (polarized) W cross sections vs rapidity with sensitivity to PDFs -> **demonstrate physical and experimental basis of PDF constraints for future mW measurements**
- Pure left handed coupling of the W means that polarization and rapidity of the W are strongly correlated with the direction of the incoming quark vs antiquark, and subsequently with the direction of the outgoing charged lepton



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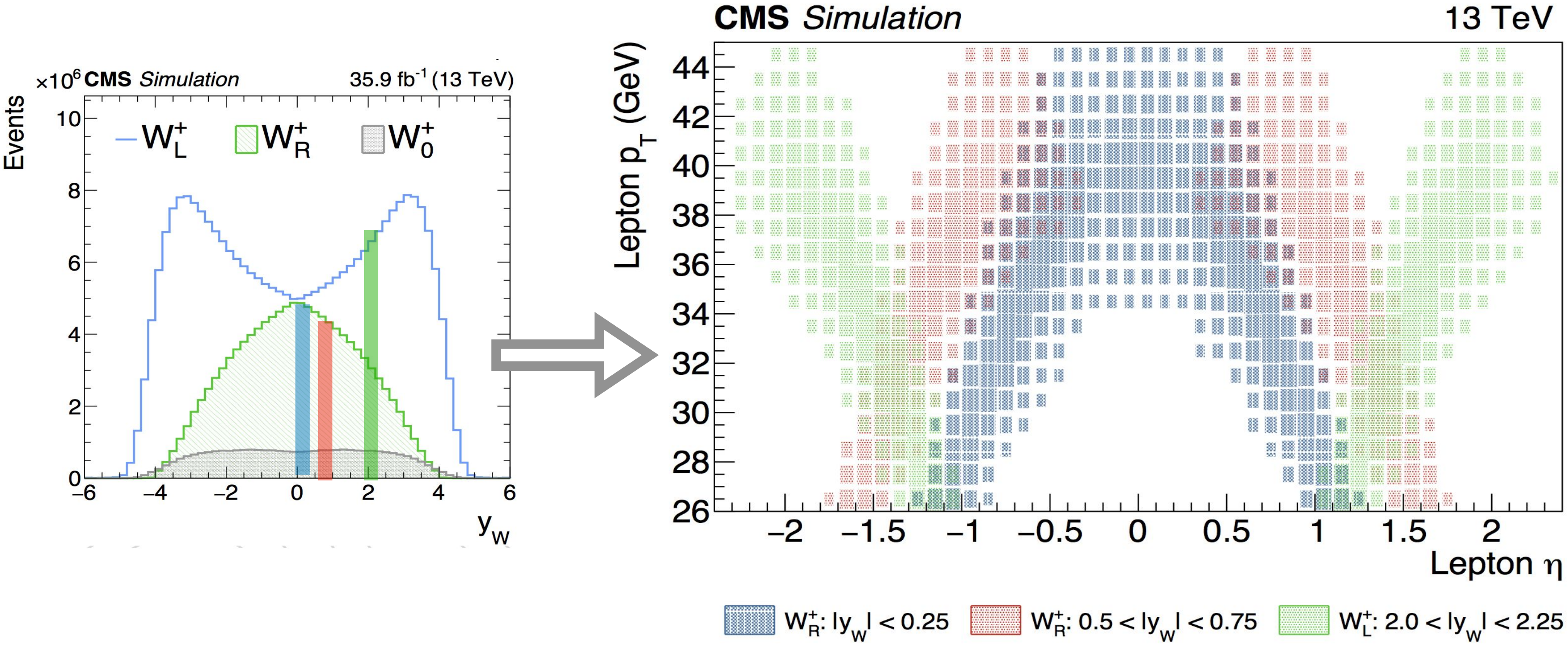
Measurement of W helicity/rapidity

- W rapidity and helicity are inferred statistically from lepton pT-eta distribution



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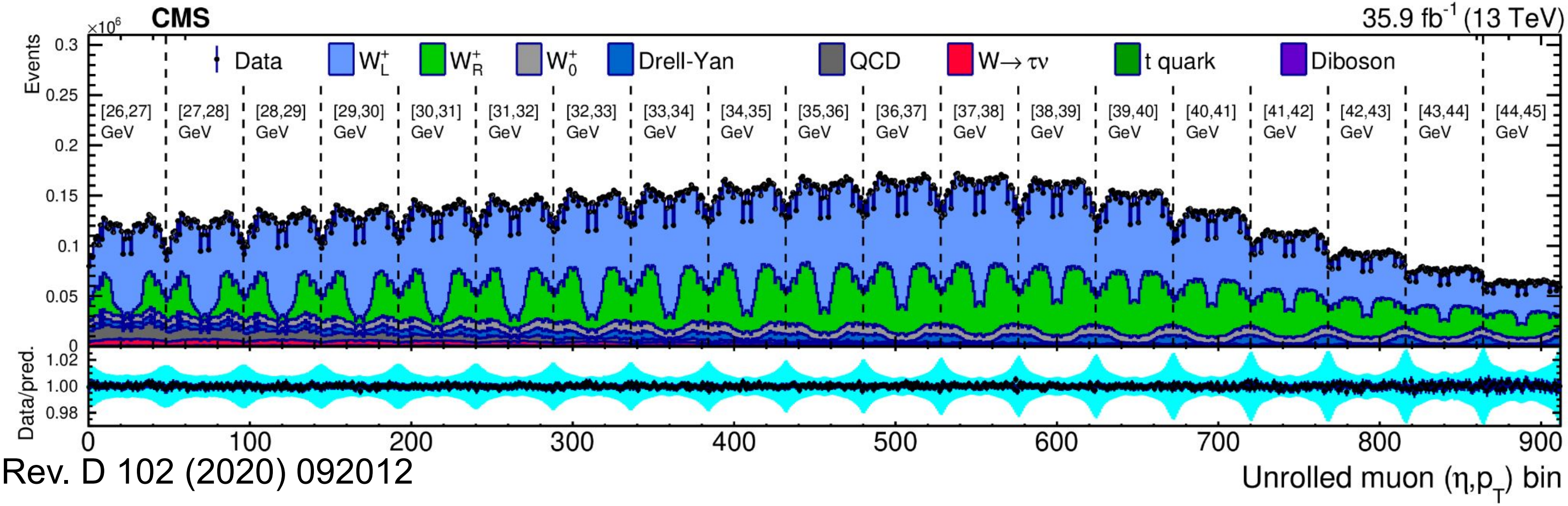
Measurement of W helicity/rapidity

- Develop physics, experimental and technical aspects towards an mW measurement with reduced PDF uncertainties
  - High precision efficiencies building on 13 TeV differential Z cross section publication
  - Less stringent requirements on MC/theory uncertainties/energy/momentum calibration compared to full m_W measurement
  - Complex profile likelihood fit to lepton pT-η distributions with ~300M W candidates, O(1000) nuisance parameters -> dedicated tensorflow-based implementation of likelihood and minimization



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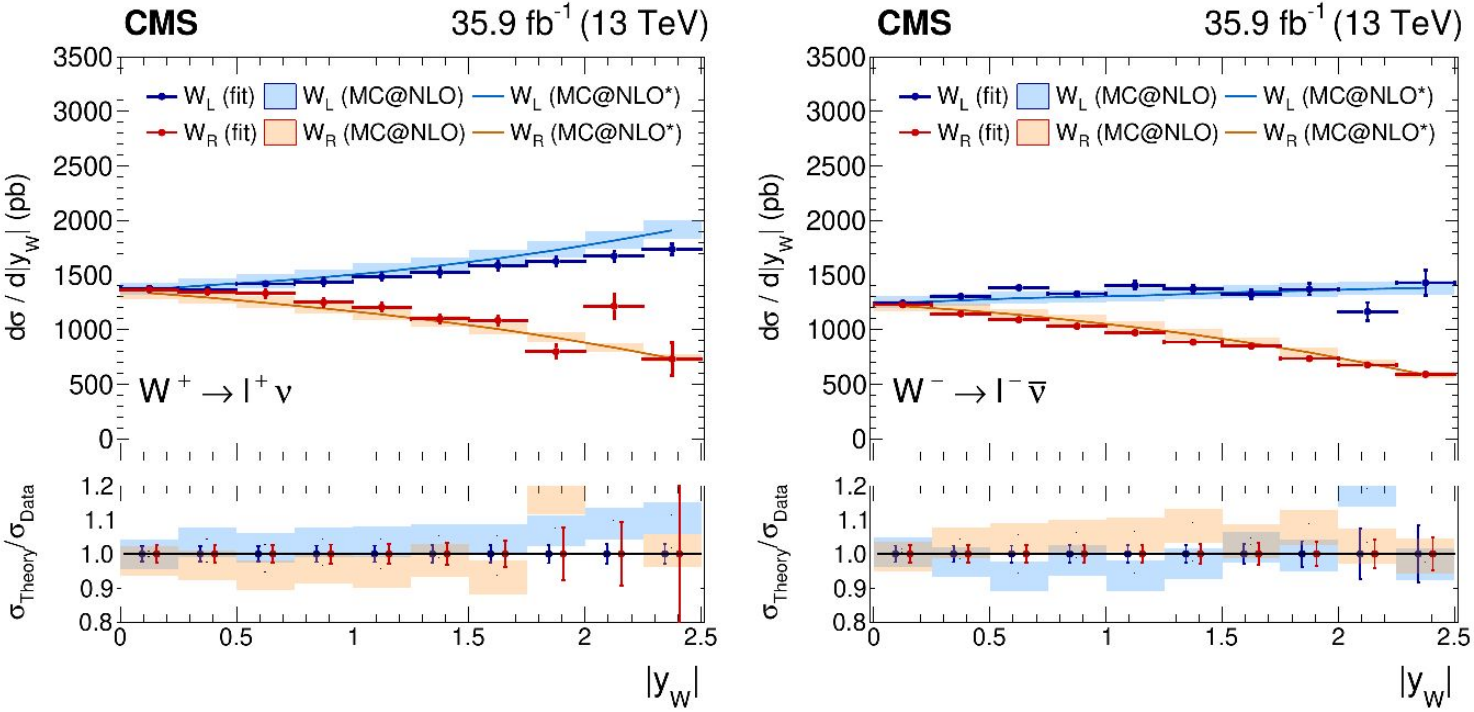
Results: Polarized W Cross Sections



- Some limitations in statistics and modeling for the MC available at the time (aMC@NLO with NNPDF3.0NLO and no alternate sets)

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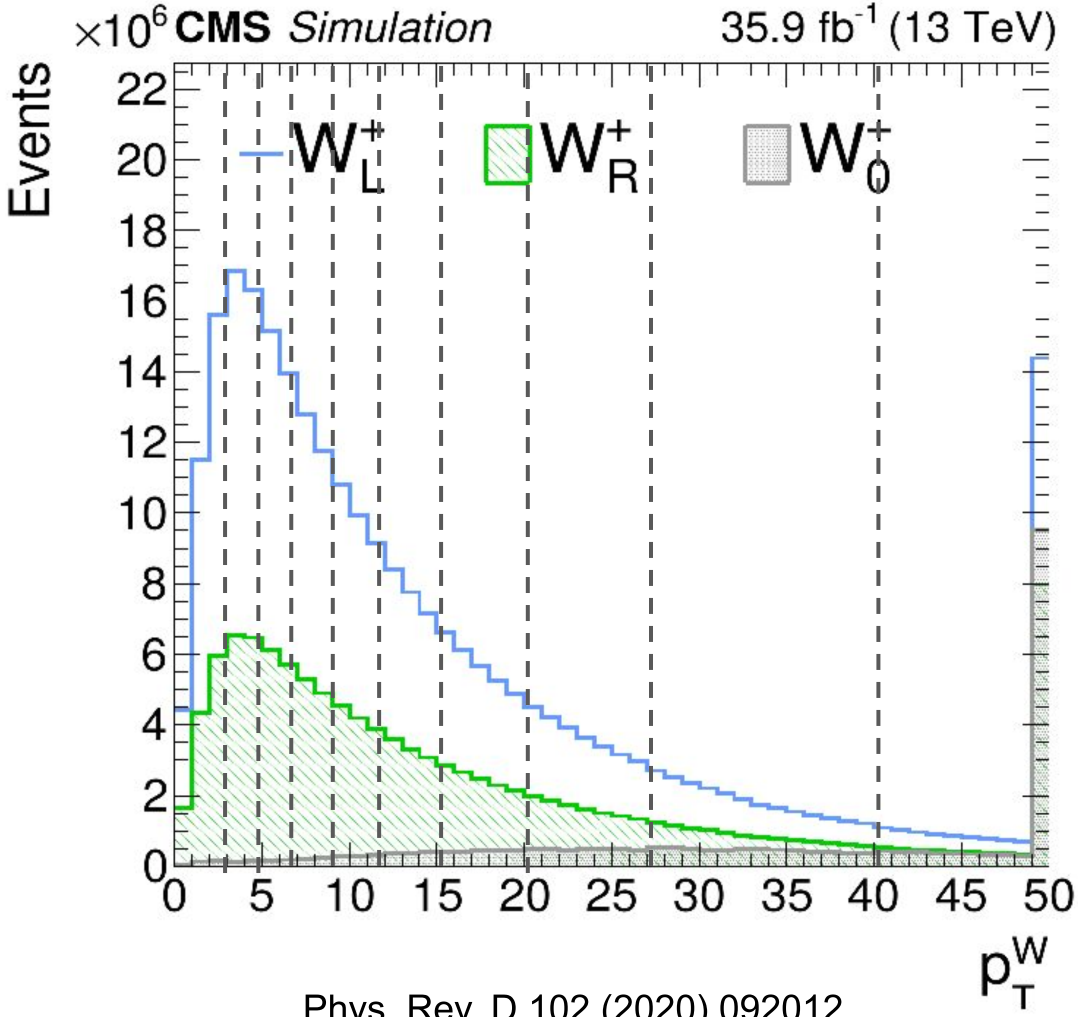
Theory Uncertainties

- Theory uncertainties sub-dominant here, but unfolded rapidity (and A4) do depend in principle on assumed W pT (and other Ai's)
- QCD renormalization and factorization scale variations decorrelated in 10 bins of pT, and by charge and helicity
- Longitudinal component (A0) fixed to MC prediction but with 30% uncertainty
- Other Ai's subdominant
- (Of course could also try to simultaneously measure W pT, additional Ai's, mW…)



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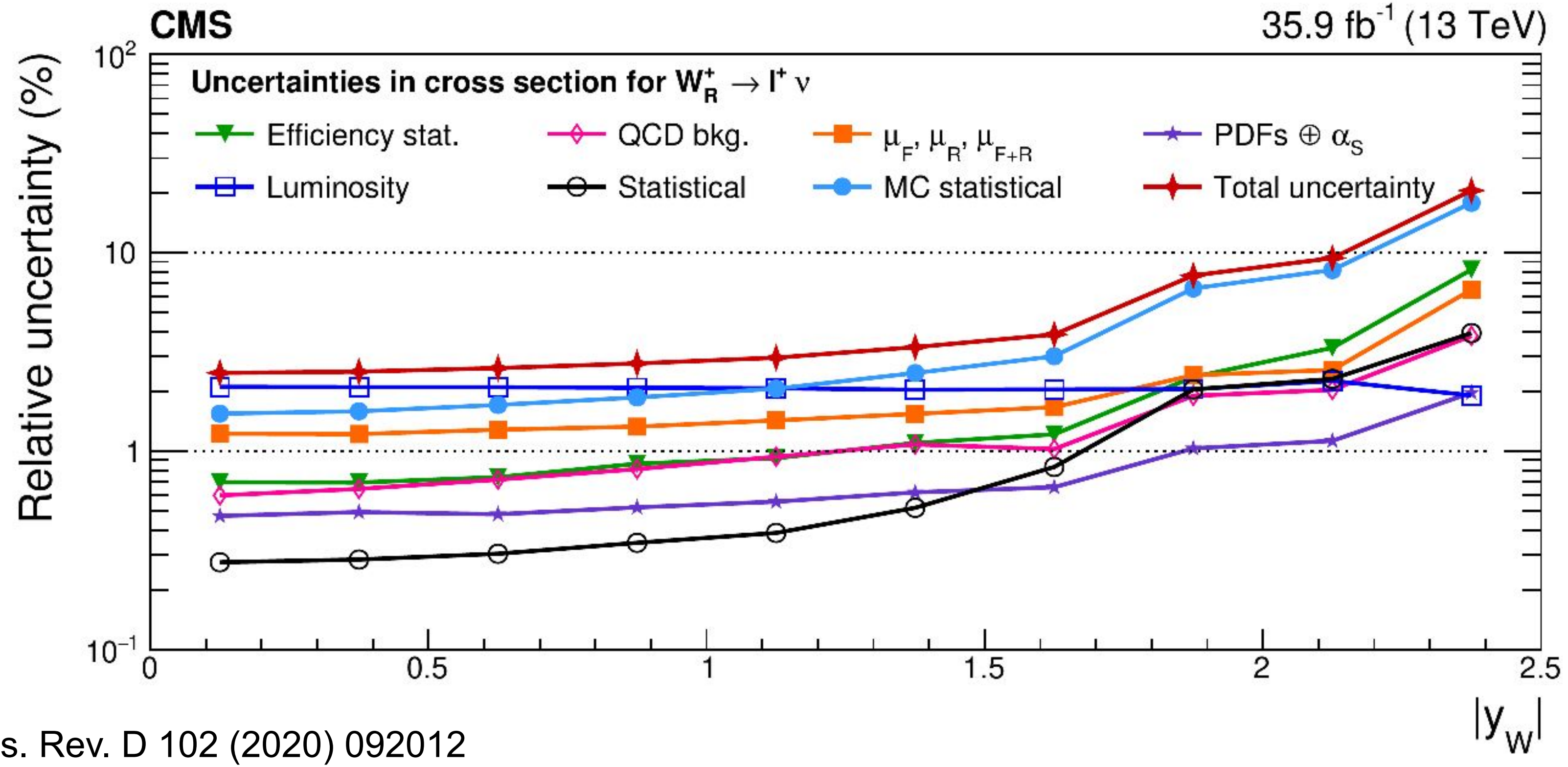
Results: Polarized W Cross Sections: Uncertainties



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“Derived” Results: A4

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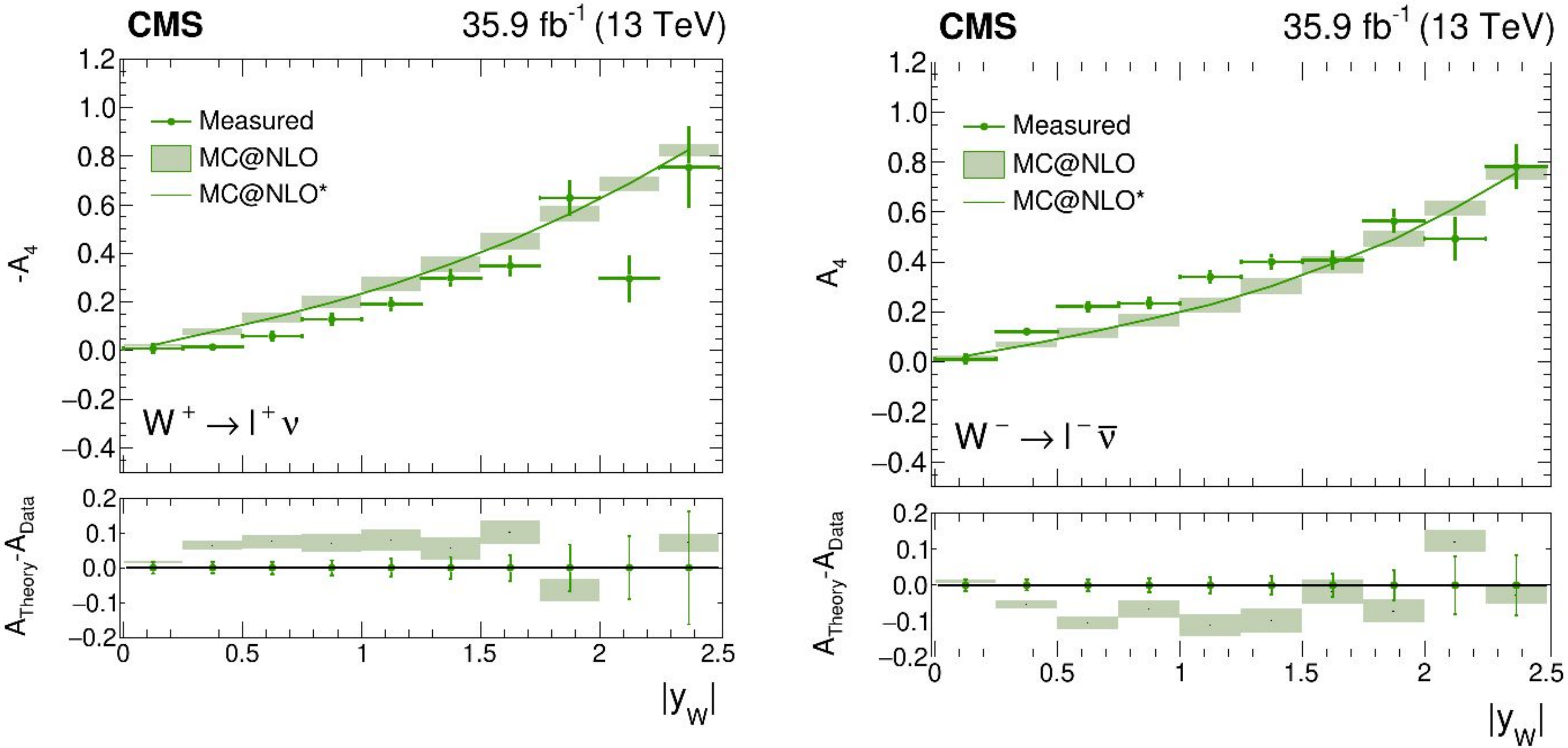

- Obtained taking the appropriate asymmetries of the polarized cross sections, taking into account the full covariance matrix

Helicity-Integrated Results

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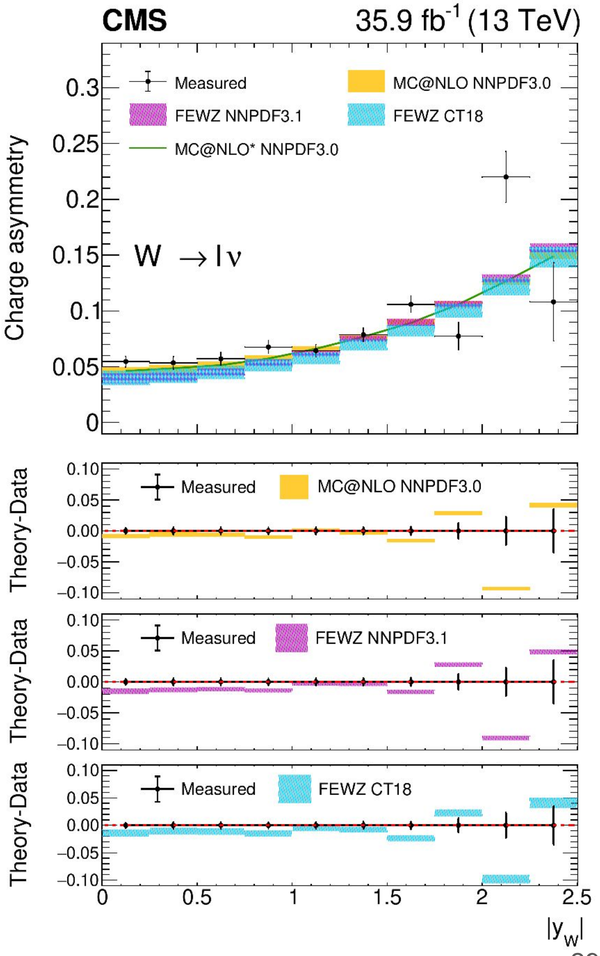
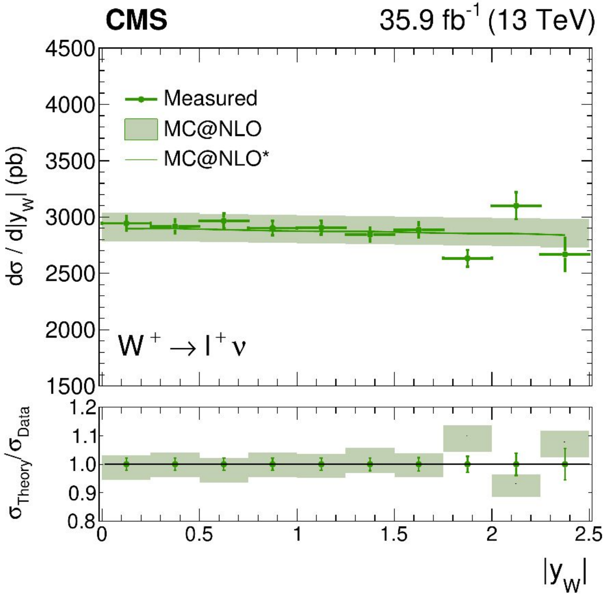
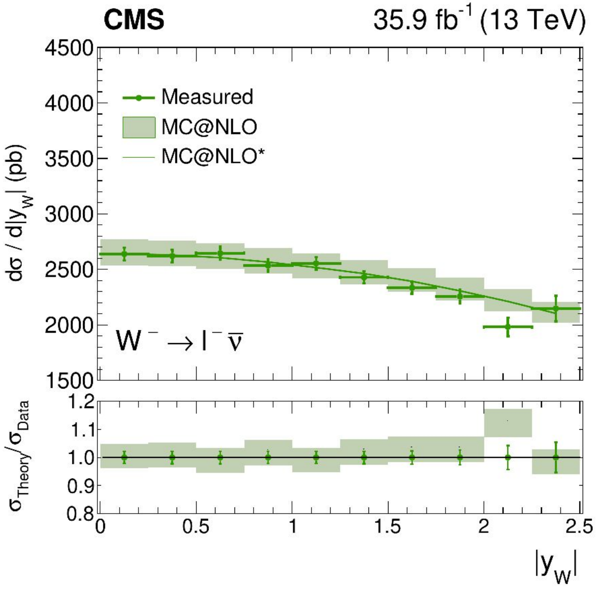
- Helicity-integrated quantities also measured without needing to make assumptions about underlying polarization
- This avoid entirely the issue of small circular pdf uncertainties which appear in e.g. the unfolded Tevatron W asymmetry measurements (which would also be larger at LHC)







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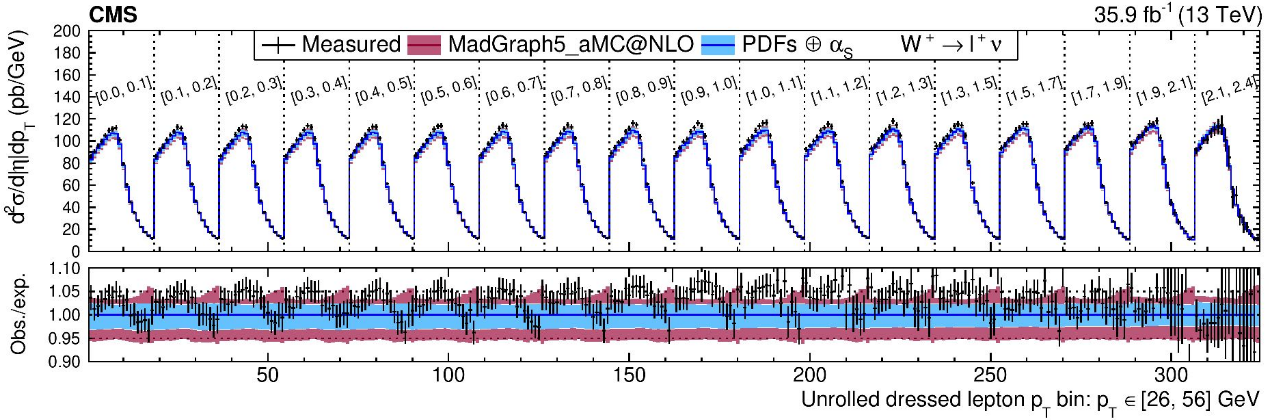
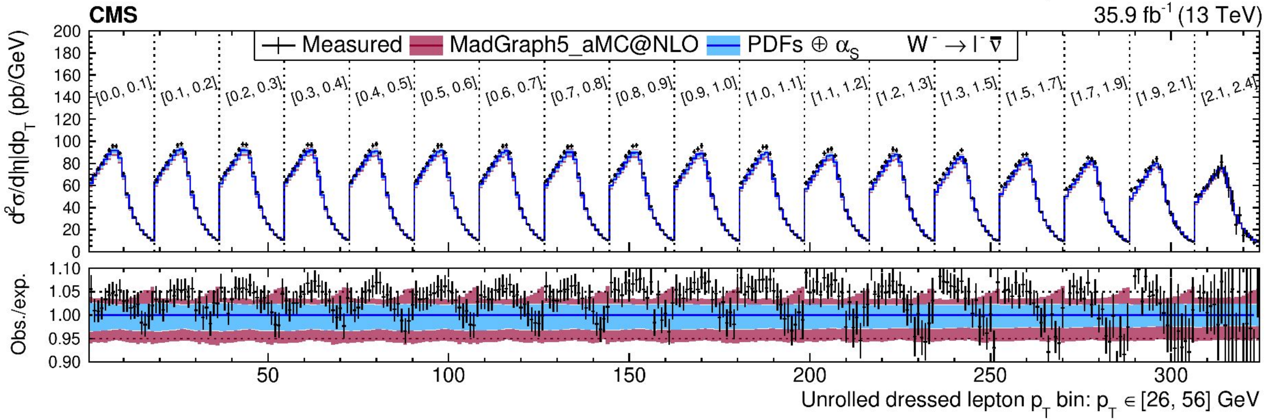
Results: Double-Differential Cross-Sections





- Results also provided directly in terms of unfolded double differential (dressed) lepton cross sections
- Closer to what is measured, but might be more difficult to use for PDF fits/theoretical comparisons

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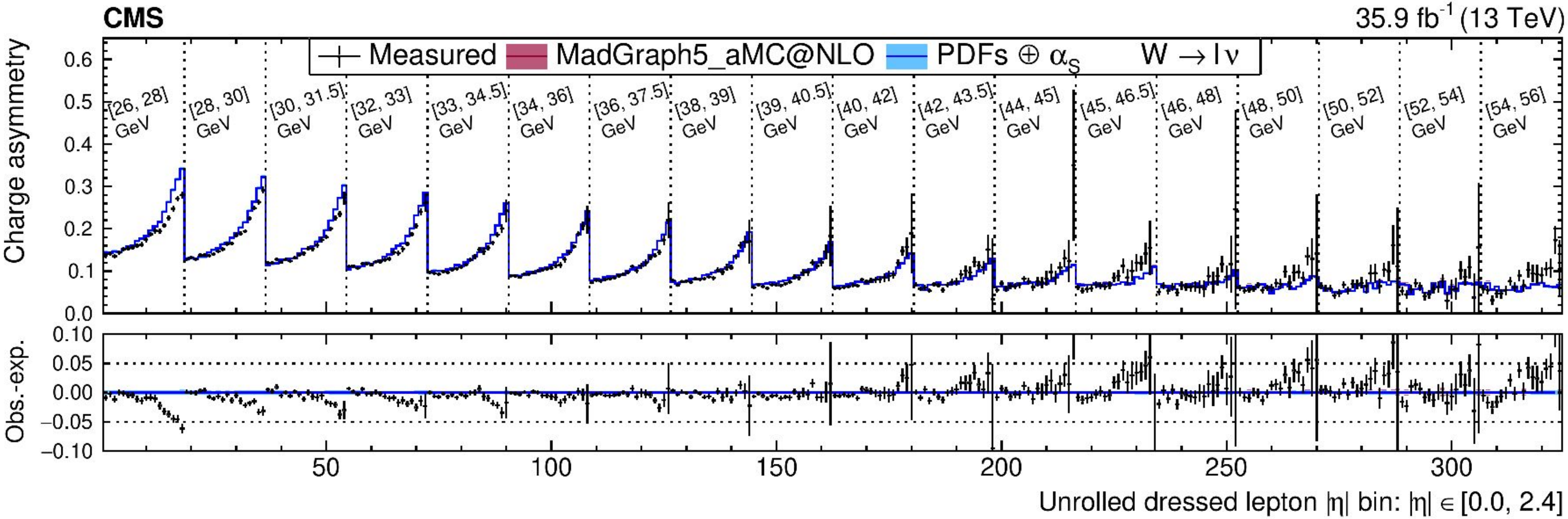
Results: Double-Differential Charge Asymmetry

- Results also provided directly in terms of unfolded double differential (dressed) lepton cross sections
- Closer to what is measured, but might be more difficult to use for PDF fits/theoretical comparisons



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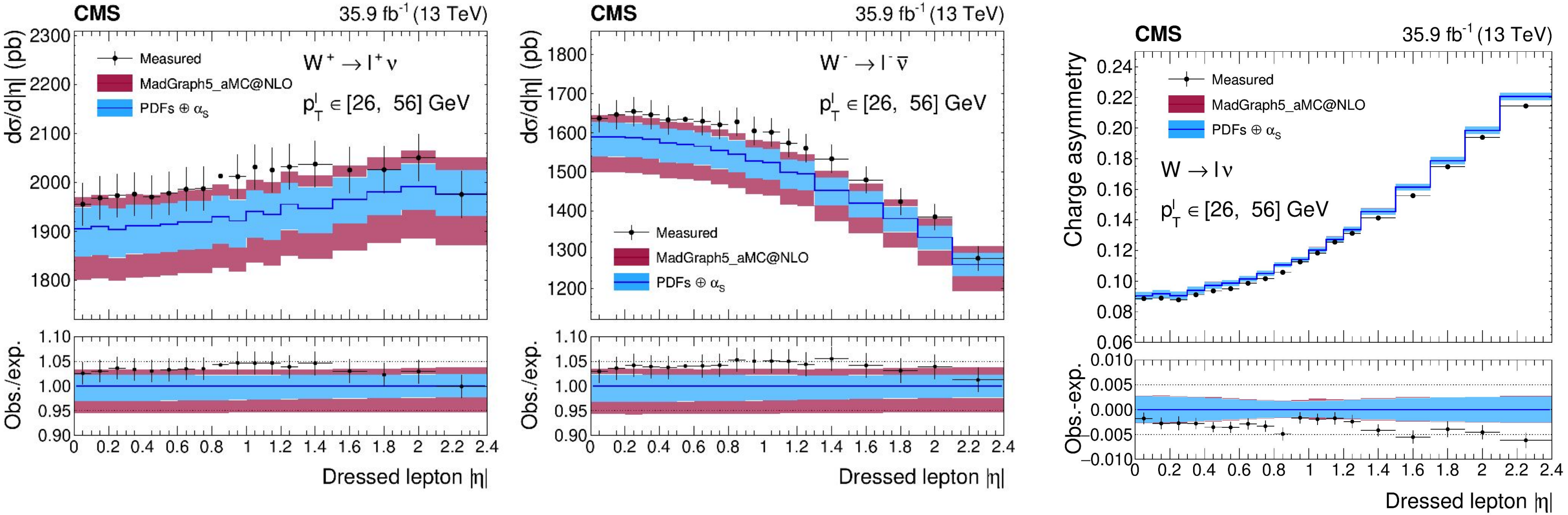
Results: 1D-integrated lepton cross sections



- Double-differential cross sections can be integrated over pT or eta to produce single-differential results (using the full covariance matrix)
- “Traditional” lepton charge asymmetry vs eta can be “recovered” in this way

PDF Constraints

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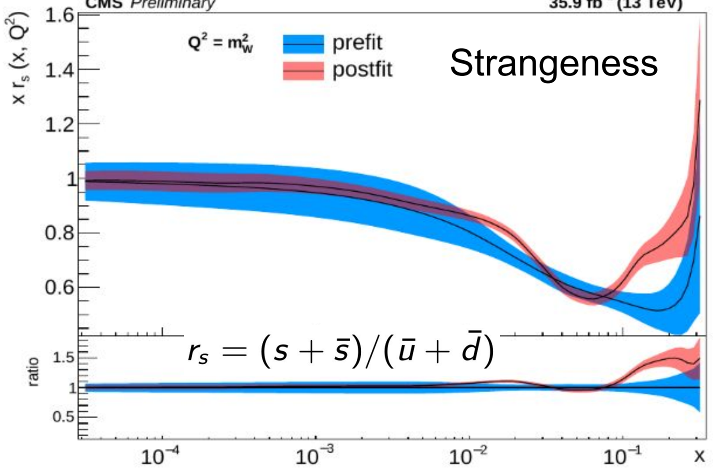
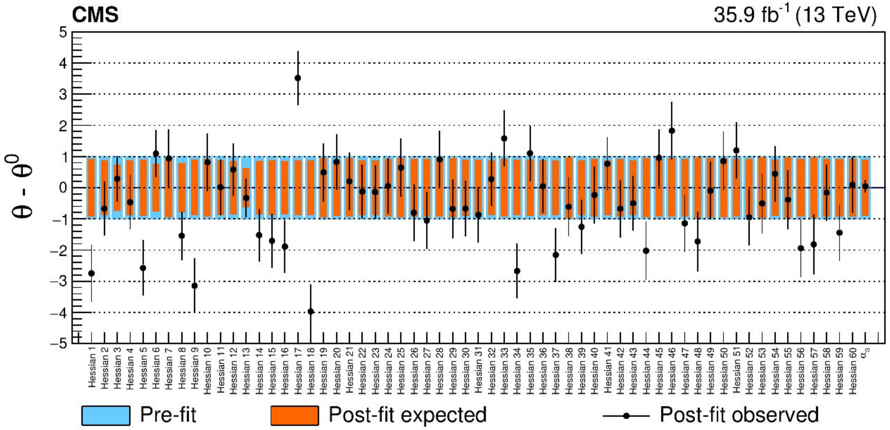
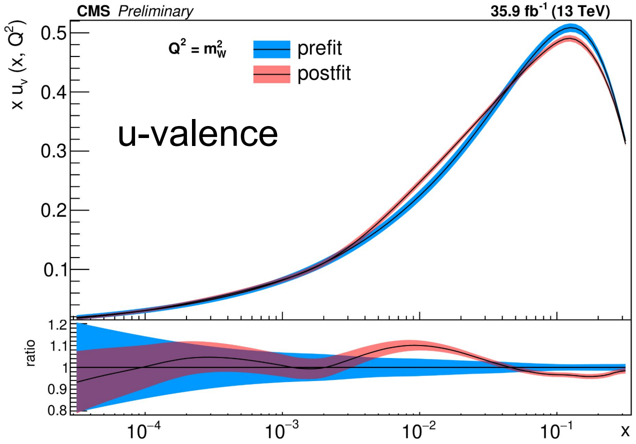
- PDF constraints obtained as proof-of-principle (e.g. for future mW measurement) by profiling PDF eigenvectors with cross sections fixed to their prediction within uncertainties
- NNLO predictions would give more meaningful results, but strong constraints on the PDFs are possible from this measurement given the sensitivity to sea vs valence quarks from the polarized cross sections



Strangeness

$r_s = (s + \bar{s})/(\bar{u} + \bar{d})$





u-valence

W Helicity/Rapidity in Hepdata

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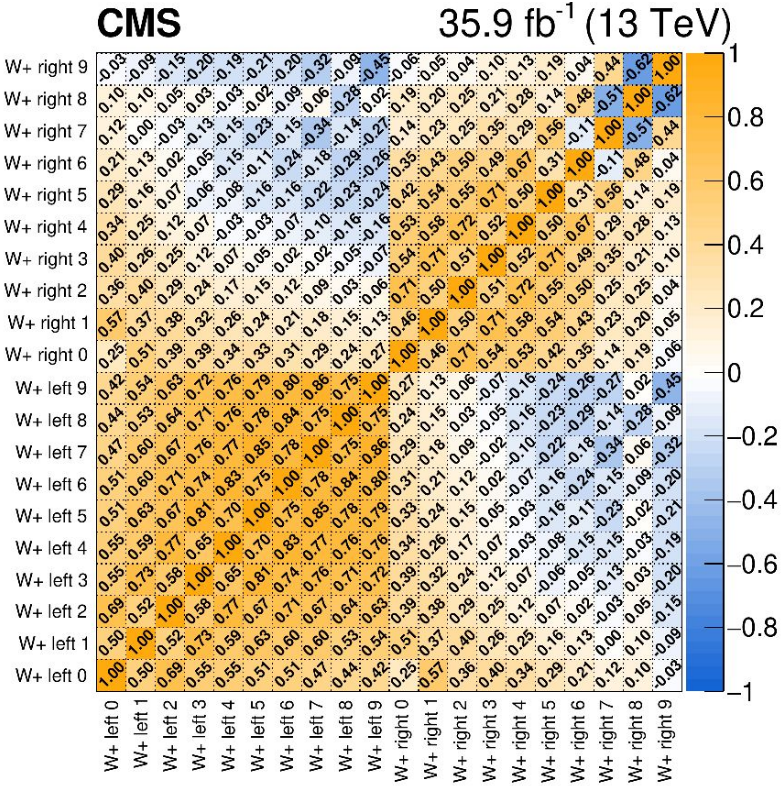
- Covariance matrices are essential for any interpretation of this data
- If not combining with other measurements, sufficient to have the e.g. 40x40 covariance matrix for the POI's (which have all the systematics included)
- If correlations with systematics are needed, then "full" ~1500x1500 covariance matrices for POI's + nuisances are provided
- "Impacts" are **not** sufficient because profile-likelihood fit induces postfit correlations
- This actually exceeded the Hepdata size limit and the larger matrices are linked from a CMS public twiki instead…
- **Maximally exploiting this data for PDFs is a non-trivial effort**

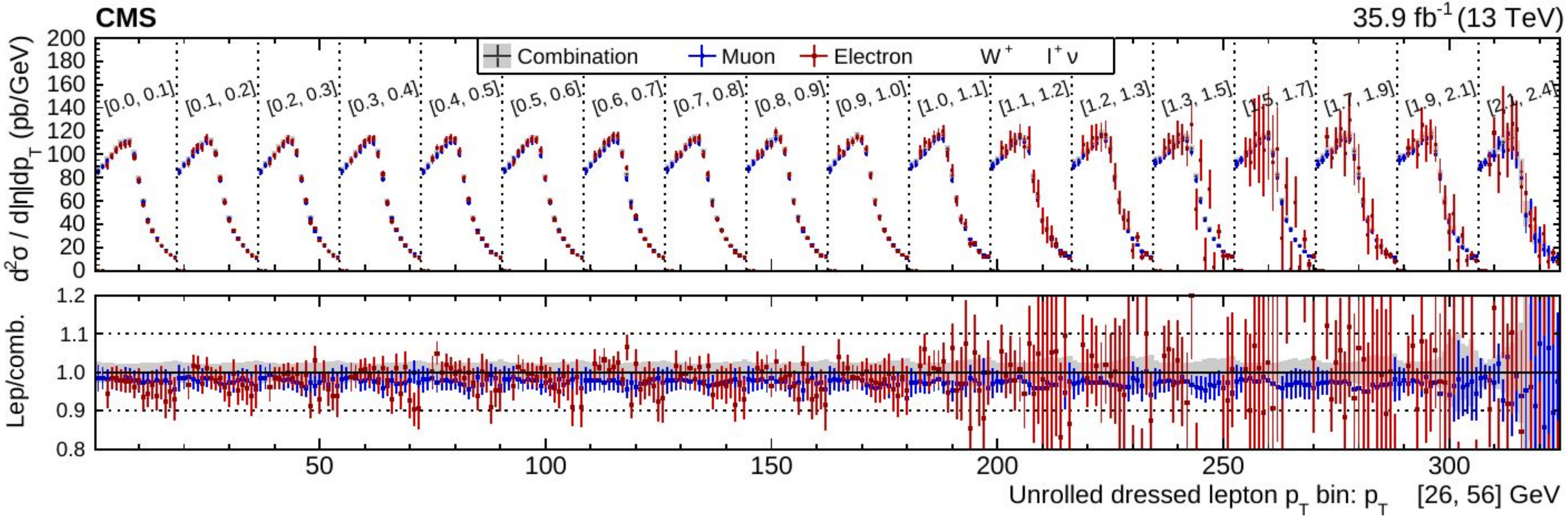


https://www.hepdata.net/record/ins1810913

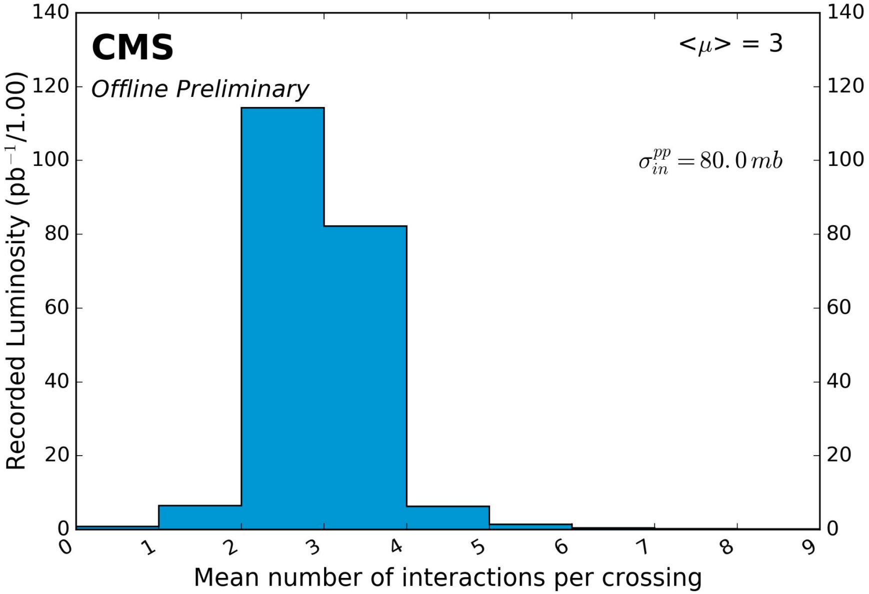
Electrons vs Muons

Phys. Rev. D 102 (2020) 092012

- Significantly larger statistical+experimental uncertainties for electrons already in W helicity measurement
- Energy calibration is also more challenging
- Will be difficult to be competitive with muons for mW measurements

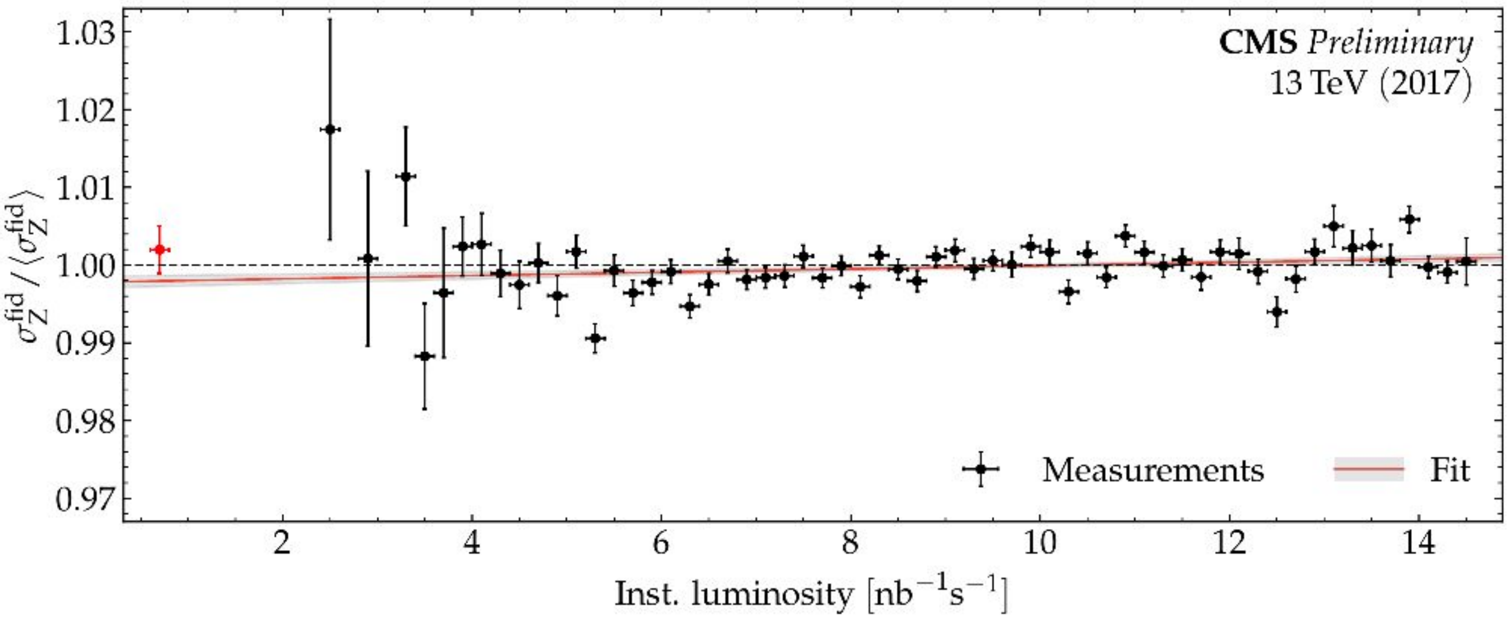


Low Pileup Data



- ~200/pb of data collected at <μ> = 3 in 2017
- Interesting for measurement of W pT distribution to validate and/or constraint theoretical models for mW measurements
- Direct mW measurement with transverse mass also interesting, especially with more data
- Possibility to collect more low pileup data in Run 3

Luminosity with Z counting in Low (and High) Pileup Data



- Using Z counting to extrapolate luminosity from low pileup to high pileup run conditions requires unprecedented control over systematic effects in muon efficiencies (also relevant for future mW measurement)

CMS-PAS-LUM-21-001

Conclusions

- mW measurements at hadron colliders are an extreme experimental and theoretical challenge
- CMS is actively working on an mW measurement, to be public as soon as possible
- CMS already officially participates in LHC-Tevatron mW Combination WG and CMS measurement is foreseen to be included in an updated combination as soon as it’s available
- Significant amount of precursor work has been done over the years and is already public
  - And much more which will be made public with our mW measurement
- CMS has collected ~200/pb of low pileup data in 2017 and is potentially interested in collecting more in Run 3 with definite relevance for mW
- Possible avenues for improvement of future mW measurements at LHC:
  - More data
  - Exploit different beam energy and pileup conditions
  - More advanced analysis techniques
  - More advanced theoretical inputs


WHEN WILL THEN BE NOW ?
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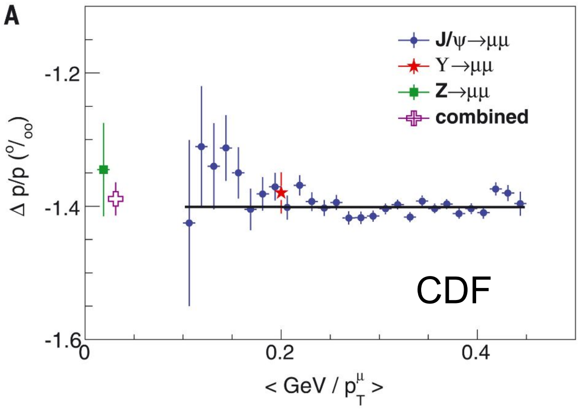
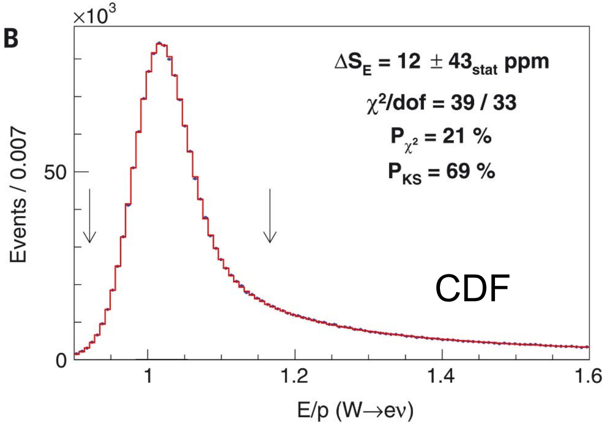
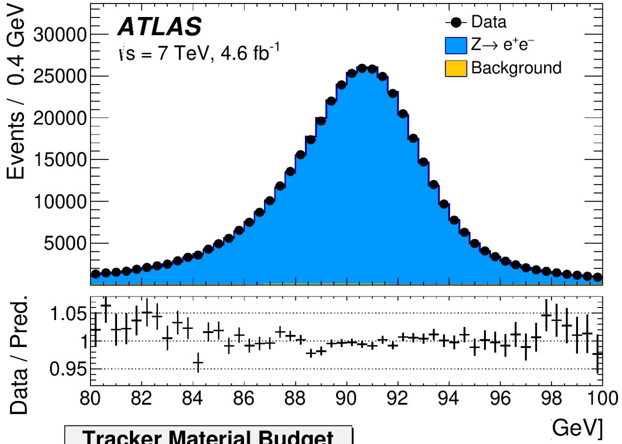
Backup

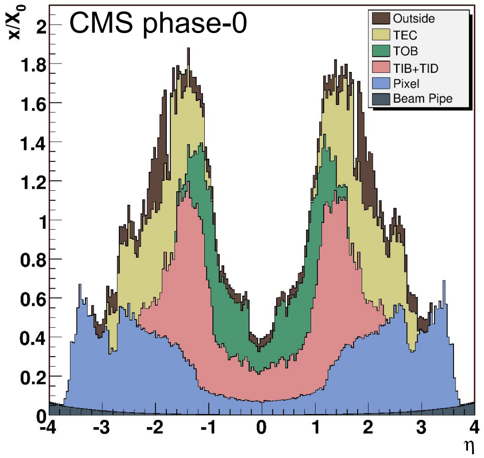
Electron Energy scale calibration in CDF and ATLAS







Tracker Material Budget



- CDF quotes systematic uncertainties on electron energy scale < 1e-4
- Achieved by transporting ultra high precision tracking calibration from muons to electron tracks and then using E/p
- CDF has < 0.2 radiation lengths of material in the tracking volume however…
- Quoted ATLAS electron energy scale uncertainties are approaching 1e-4, but rely maximally on Z->ee for calibration