Precision Measurements at the LHC

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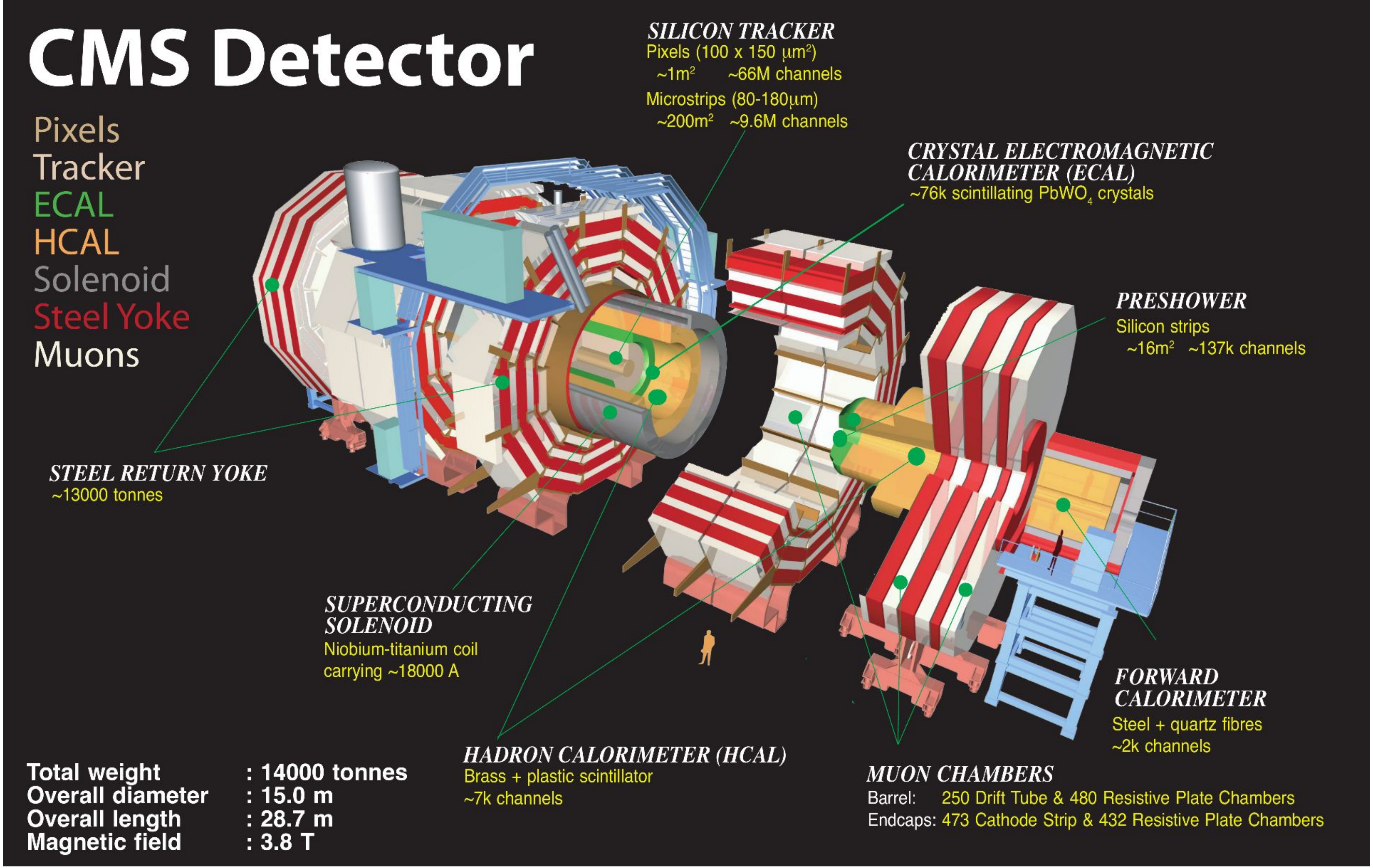
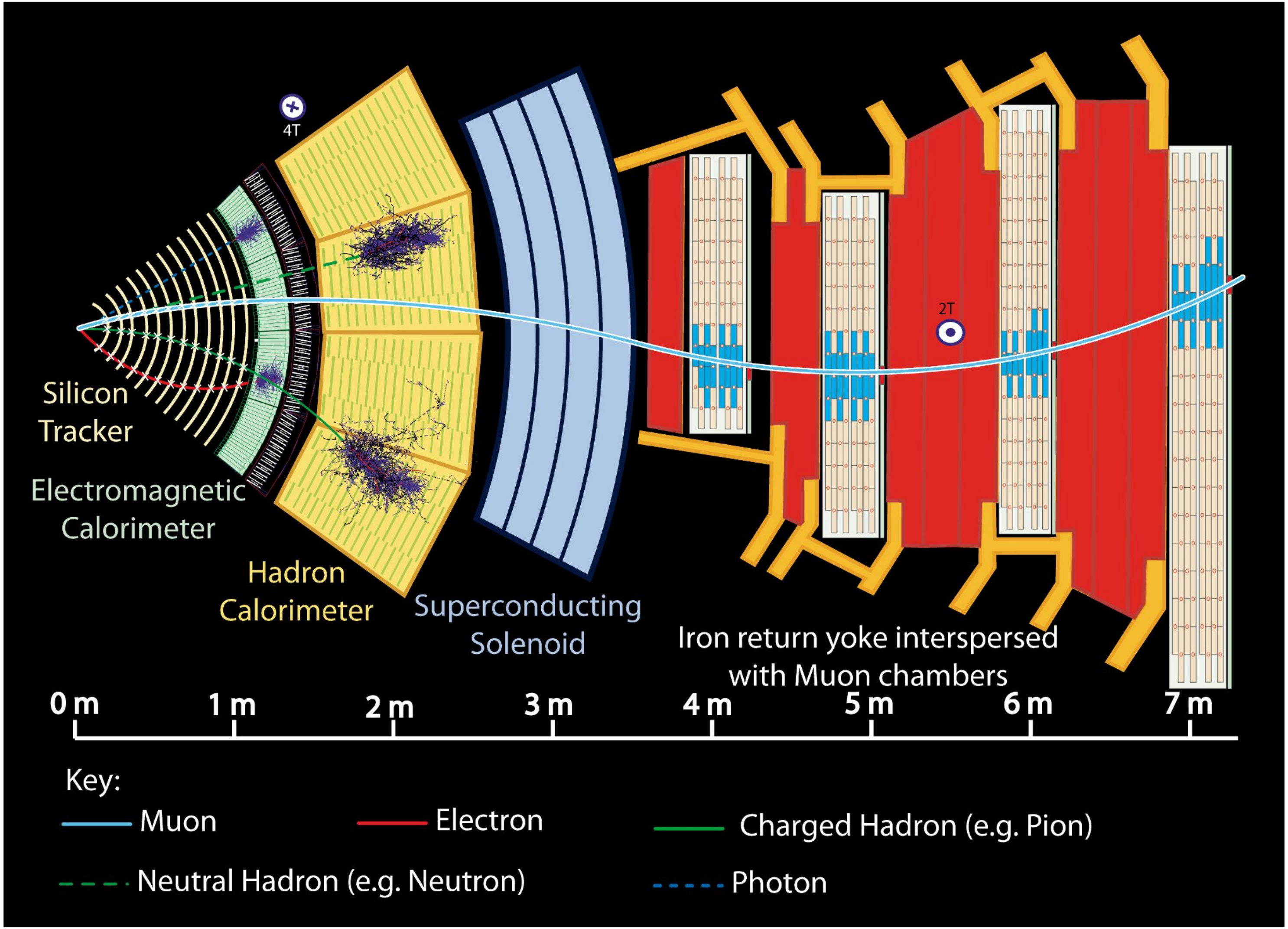
Introduction

- LHC experiments continue to push forward on experimental precision, driven by:
    - Large amount of data
    - Mature understanding of detectors and reconstruction algorithms
    - Continued advancements in reconstruction/analysis techniques, machine learning, etc
- Theoretical interpretation of precision data is critical
    - Extraction of fundamental parameters: mW, mtop, sin2theta, alphaS, etc
    - Constraints on PDFs
    - Validation of higher order perturbative predictions, or constraints on phenomenological models (hadronization, colour reconnection, etc)
- Challenges
    - Maximize utility of precision data/measurements for theoretical interpretation
    - Achieve corresponding reduction in theoretical uncertainties
        - Brute force? (More loops, more logarithms?)
        - In-situ constraints?

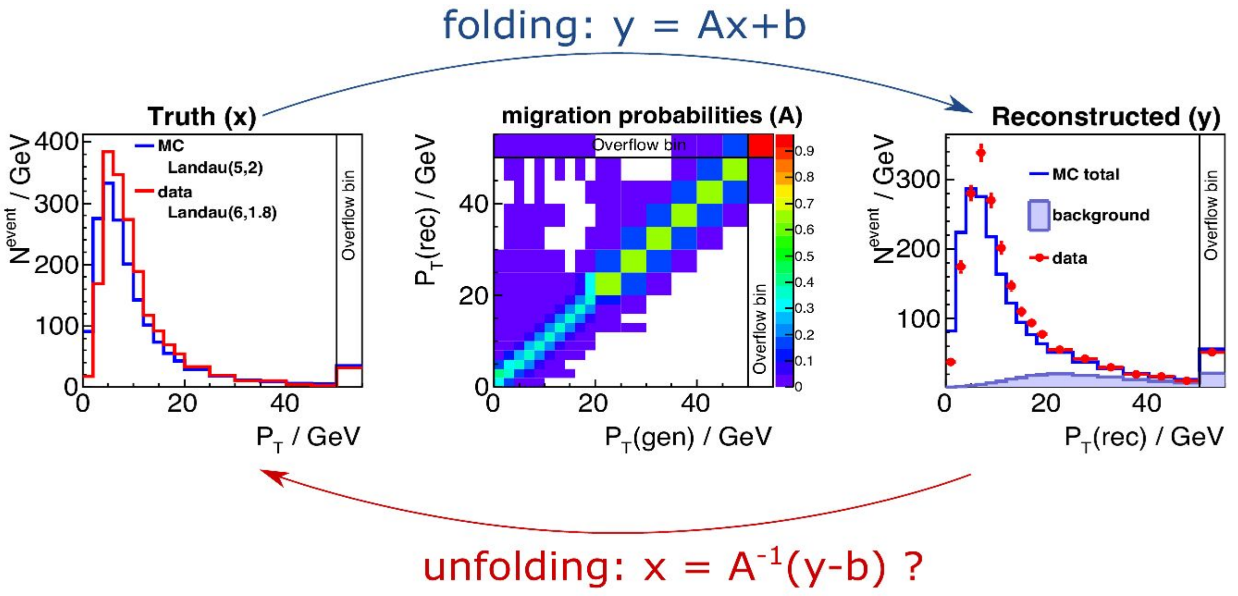
Introduction

- In this talk:
  - Some example measurements pushing the envelope in experimental precision and/or illustrating various important issues/topics
  - Challenges in theoretical uncertainties in the interpretation of precision LHC data


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k 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

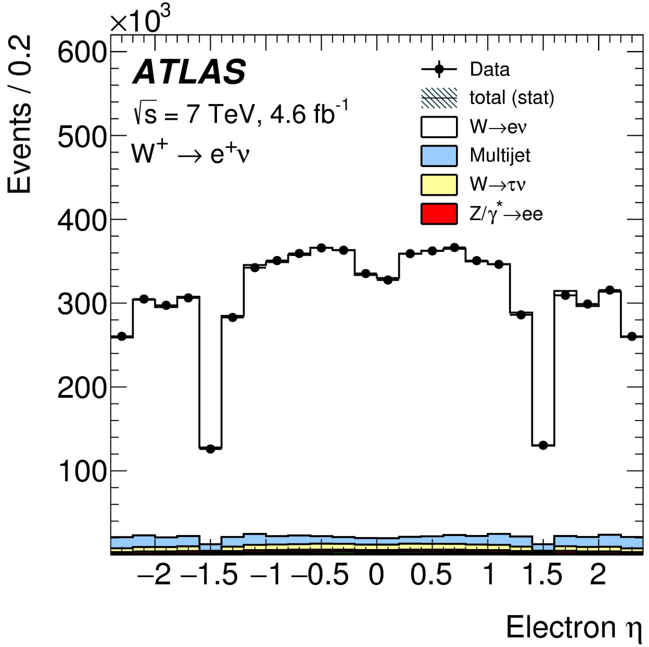

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Unfolding

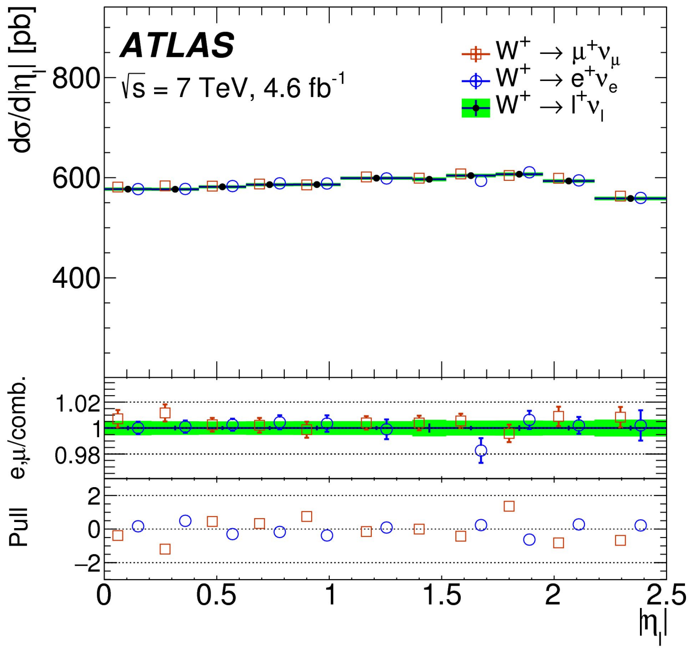


- Experiments measure event counts at “detector level”
- Accurate comparison of data and theory at this level possible (only) with full detector simulation
- Typically addressed with “unfolding”
    - Subtract background
    - Correct for detector resolution and efficiency

Unfolding

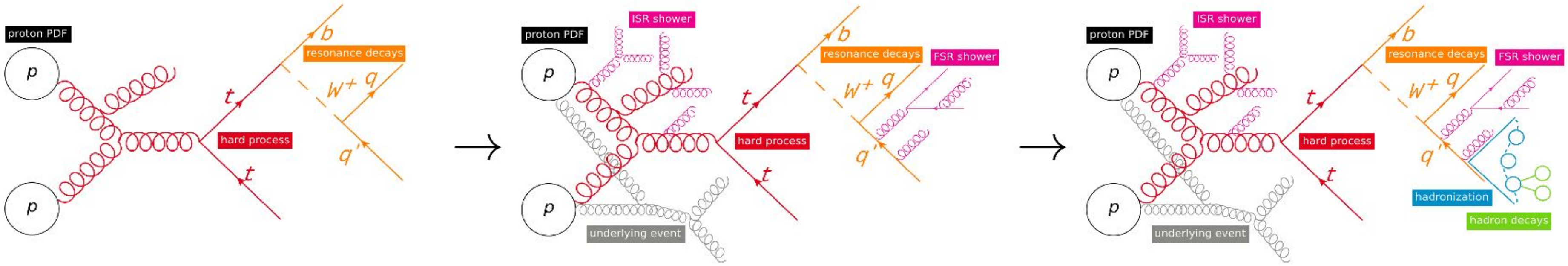


Detector Level



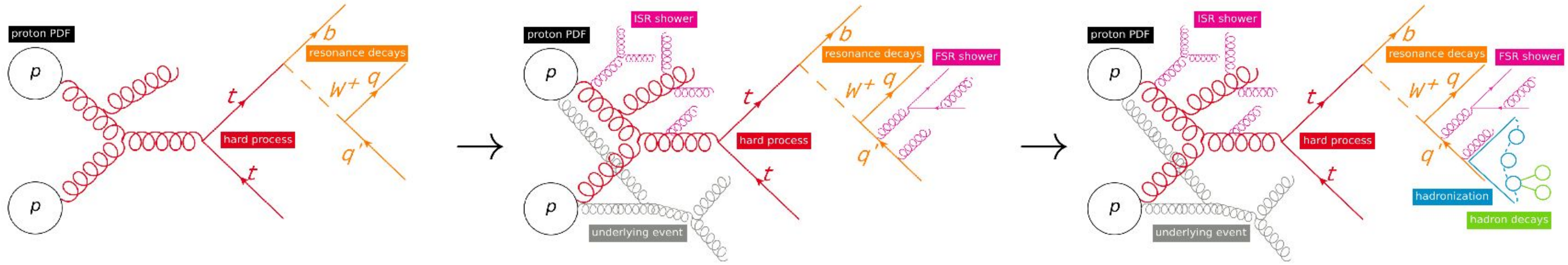
Unfolded Differential Cross Section

Unfolding Definition



- Unfolding relies on a “truth” definition to give a well defined meaning to the measured cross sections
    - Must be accessible event-by-event in the generated events passed through detector simulation in order to build the required response matrices
- Least model-dependent/closest to what is measured: “Particle-level” definition in terms of stable leptons, photons, hadrons
    - N.b “stable” with respect to boosted objects traversing the detector volume, ie muons and charged pions are “stable”, taus and pi0’s are “unstable”
- This implies that e.g. for top production, one needs a fully differential prediction with ISR/FSR, top decay, hadronization, decays in order to have a meaningful comparison

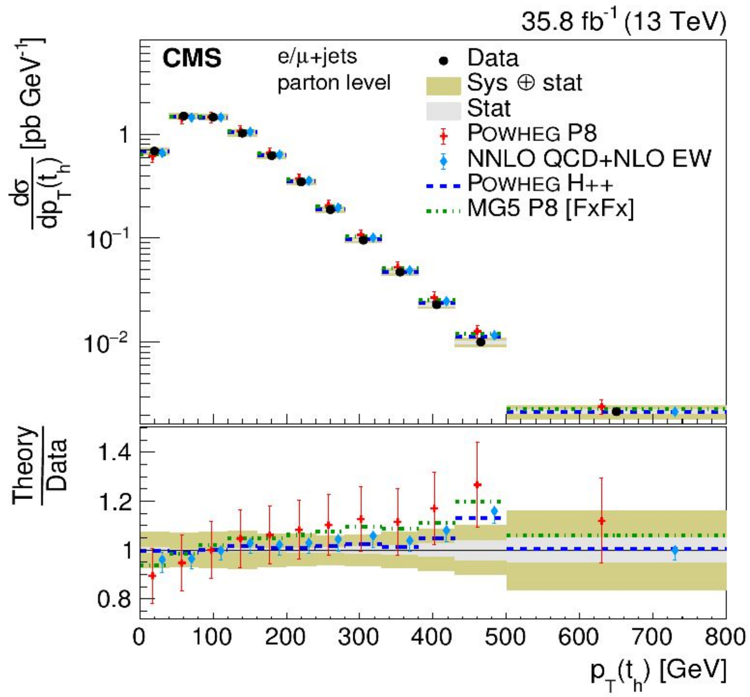
Unfolding Definition

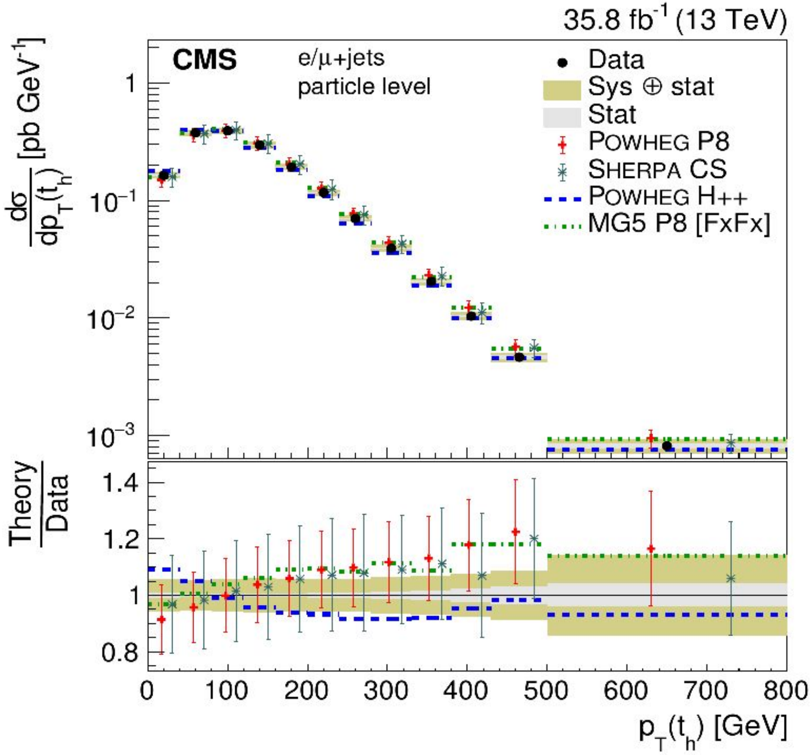


- Unfolding relies on a “truth” definition to give a well defined meaning to the measured cross sections
  - Must be accessible event-by-event in the generated events passed through detector simulation in order to build the required response matrices
- To facilitate comparison to e.g. fixed order predictions: “parton level”
  - E.g. top quark after parton shower but before decay
  - (For NLO MC kinematics may even be unphysical before first shower emission)
- Can be compared to fixed order predictions, but model dependence is (permanently) baked into the measurement

Phys. Rev. D 97, 112003 (2018)

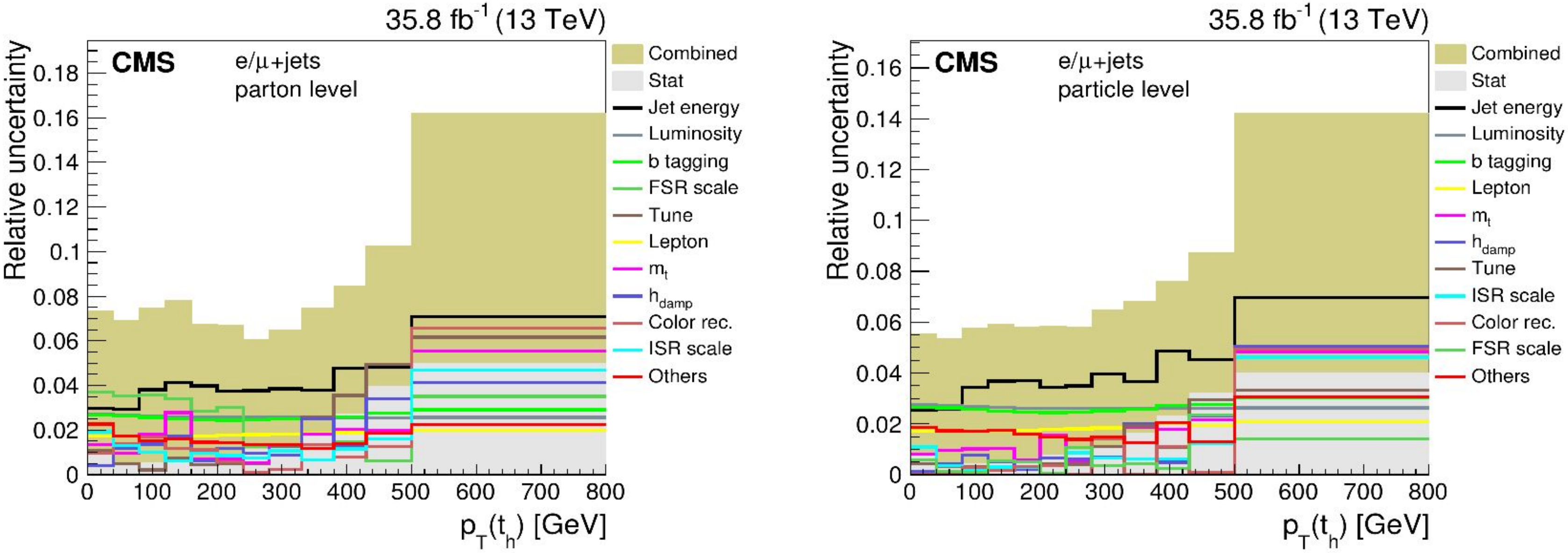
Parton vs particle level example





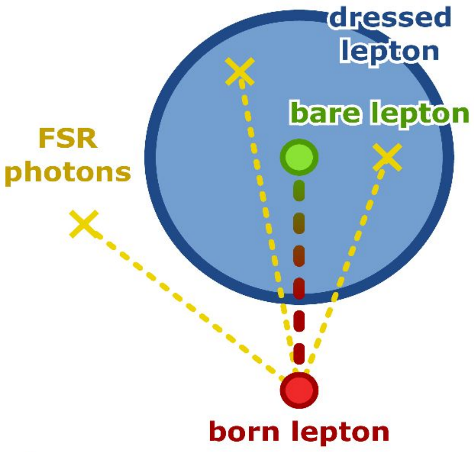
Phys. Rev. D 97, 112003 (2018)

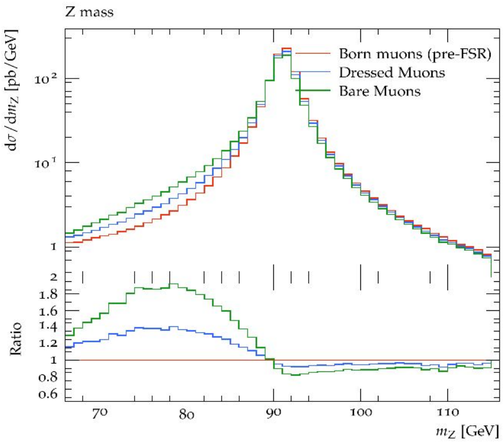
Parton vs particle level example

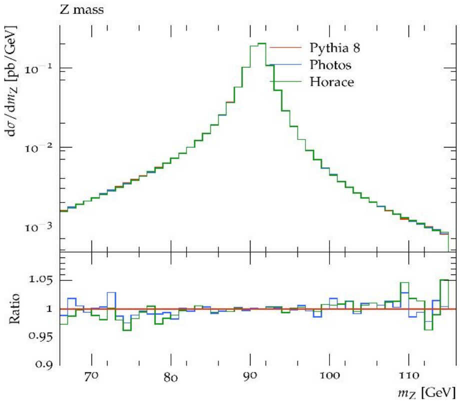


- Parton level result has 3-4% QCD FSR uncertainty, only Pythia 8 model considered
- Particle level result dominated by experimental uncertainties

Unfolding Definition: Charged Leptons





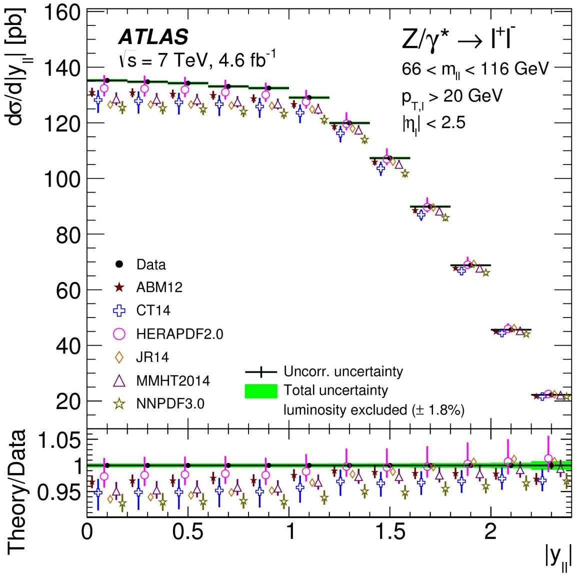


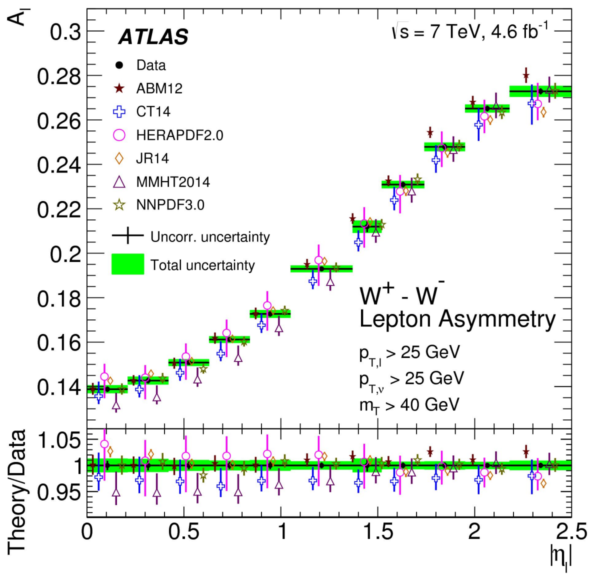
Bare leptons with different QED FSR models

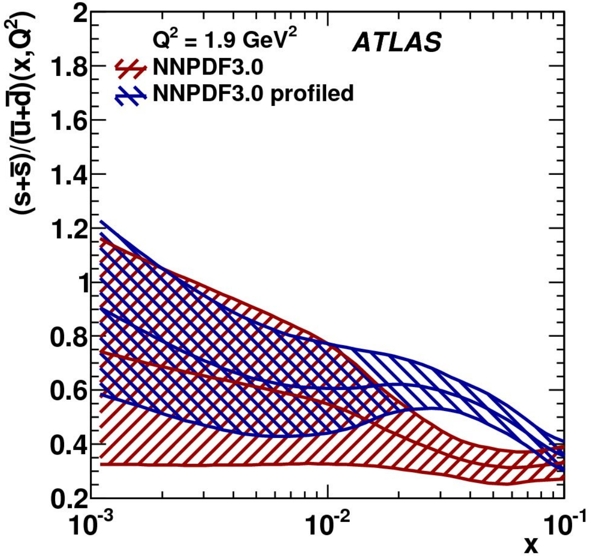
- Three common definitions:
  - “Born”: Parton-level definition where QED FSR is entirely unfolded
    - Facilitates comparison to pure QCD predictions
    - QED FSR being unfolded is reasonably well understood/stable between different models
    - In principle is ill-defined for any NLO EW prediction (ISR-FSR interference)
  - “Dressed”: Particle level definition in which photons are reclustered with the lepton (usually simple cone algorithm)
    - Roughly corresponds to how electrons are measured in the experiments, since bremsstrahlung photons are re-clustered and these are ~not experimentally distinguishable from QED FSR
  - “Bare”: Particle level definition in which the final post-fsr kinematics of the lepton are used
    - Directly corresponds to e.g. muons measured in CMS

ATLAS 7 TeV W/Z Cross Sections

Eur. Phys. J. C 77 (2017) 367







- This measurement provides high precision W and Z differential cross sections with significant constraining power for PDFs
- Results are unfolded to born lepton definition, so QCD-only predictions are valid for interpretation, but the fiducial cuts mean that resummation is relevant wrt fixed order predictions

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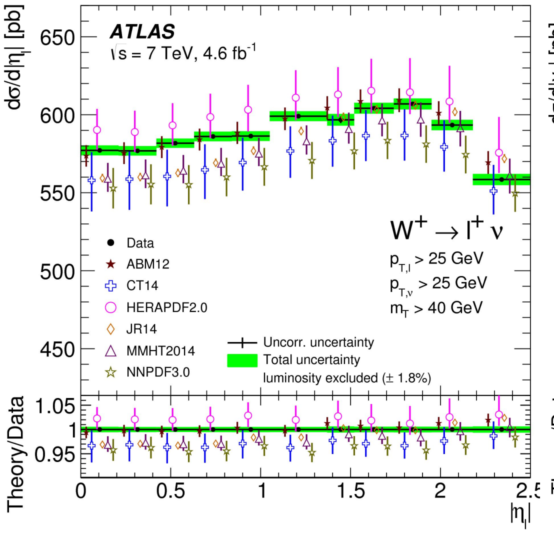
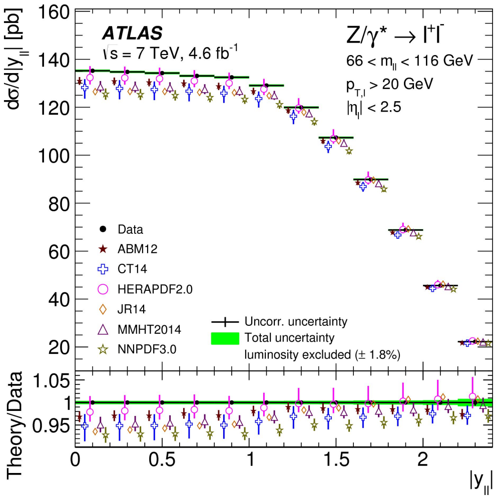
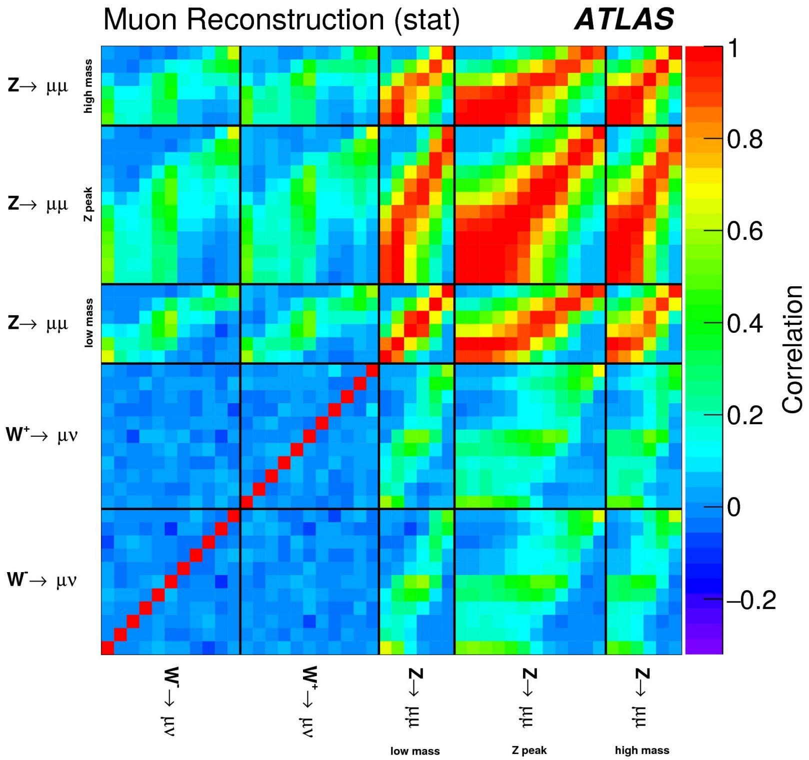
ATLAS 7 TeV W/Z Cross Sections

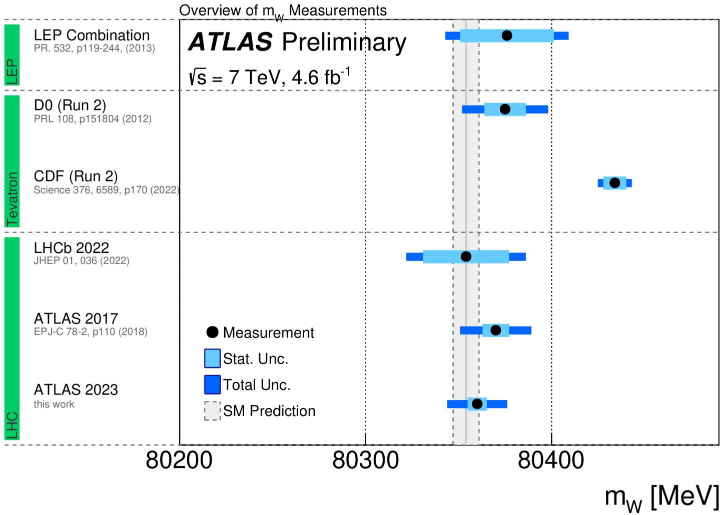


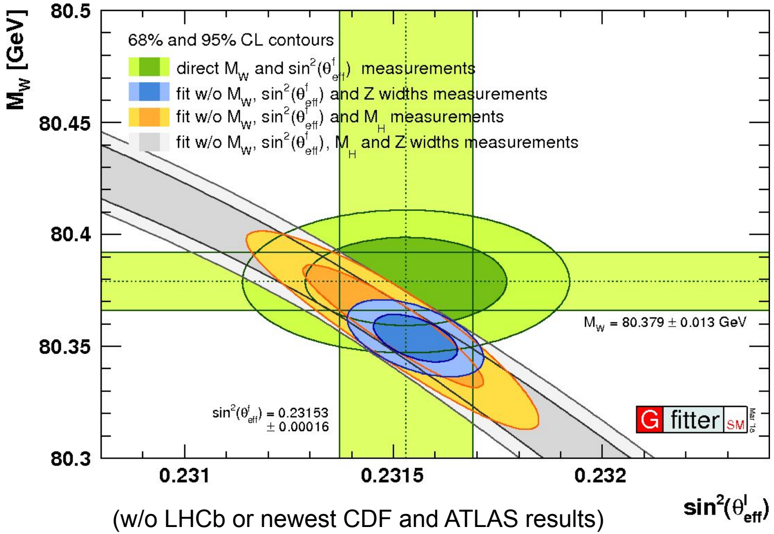




- Key feature of this measurement: **W and Z cross sections are measured together with careful accounting of the correlations for experimental uncertainties**

m_W as a precision test of the SM



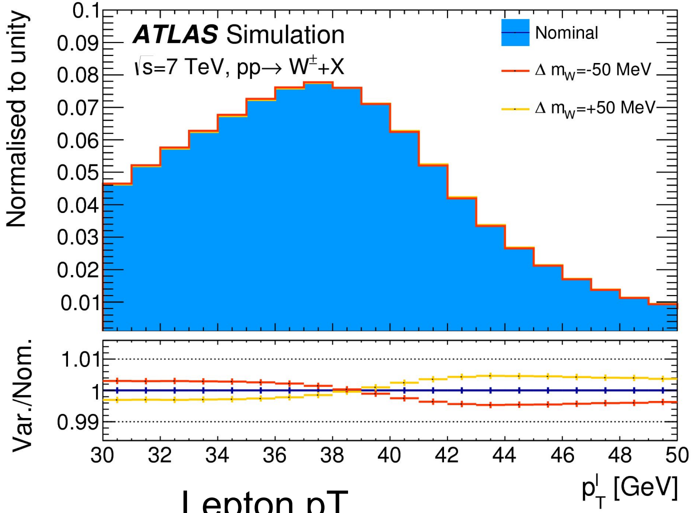


(w/o LHCb or newest CDF and ATLAS results)

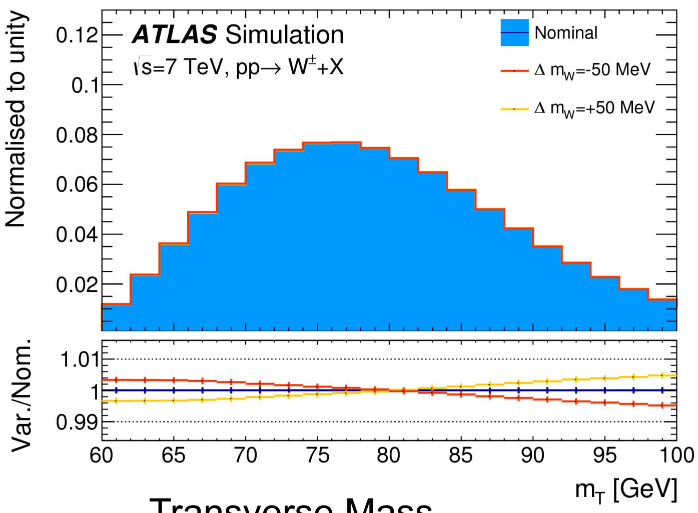
- The discovery of the Higgs and the measurement of its mass allowed (more) precise predictions of $m_W/\sin^2\theta_W/m_t$/etc from the global EW fit
- New CDF measurement in significant tension with SM prediction and other measurements

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

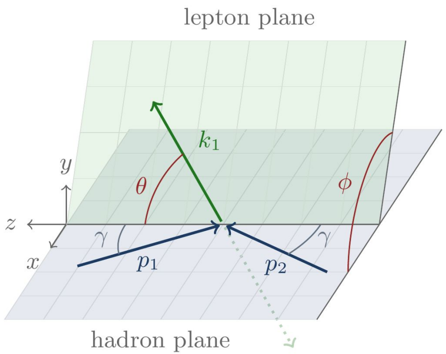


Transverse Mass

Theoretical Considerations

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

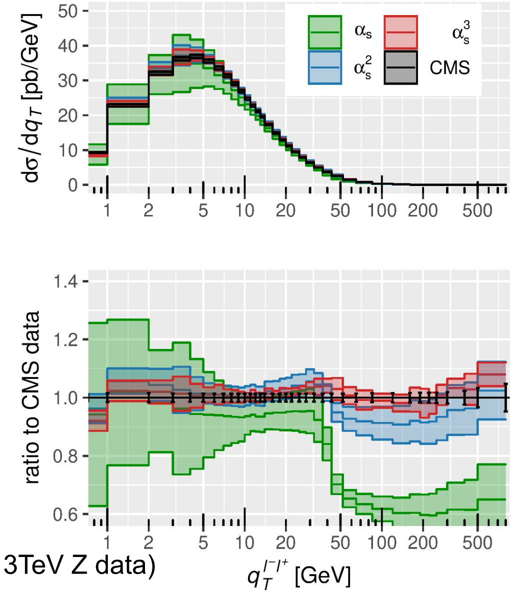
- W (and Z) production at hadron colliders described by PDFs + Perturbative QCD/EWK
  - Small additional non-perturbative effects from “intrinsic kT” (ie beyond-collinear-factorisation QCD effects in the proton)
- Relatively large theoretical uncertainties: usual strategy is to use precise Z->ll pT spectrum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



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



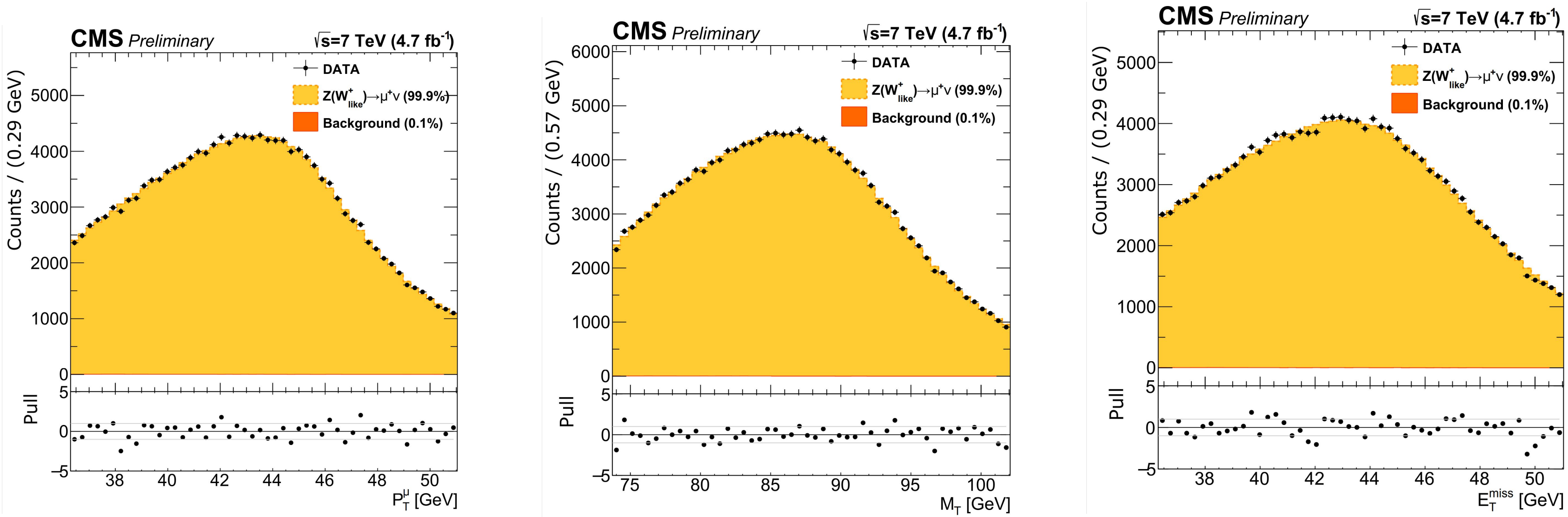
arXiv:2207.07056
(comparison to CMS 13TeV Z data)

mW in CMS

- 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

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)

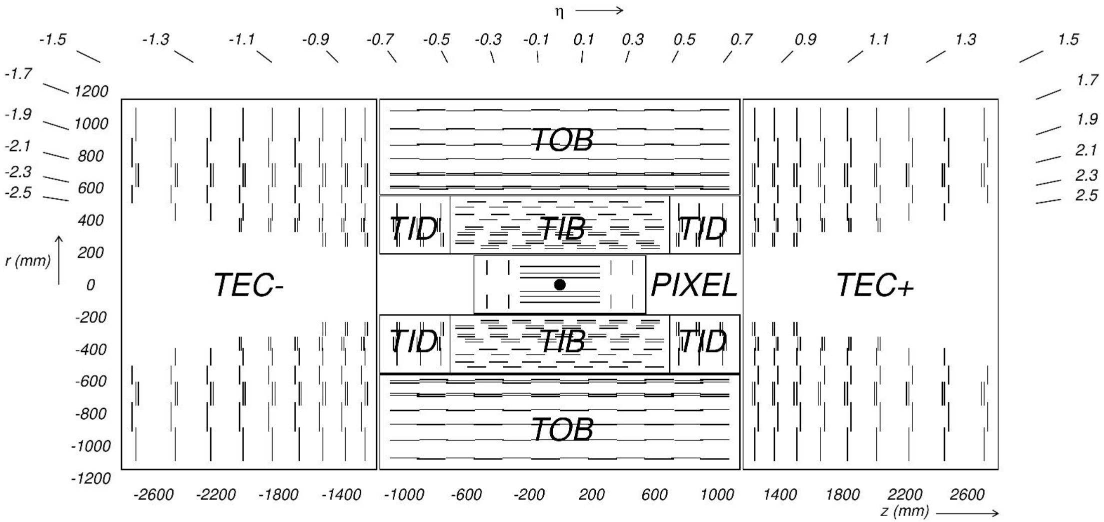


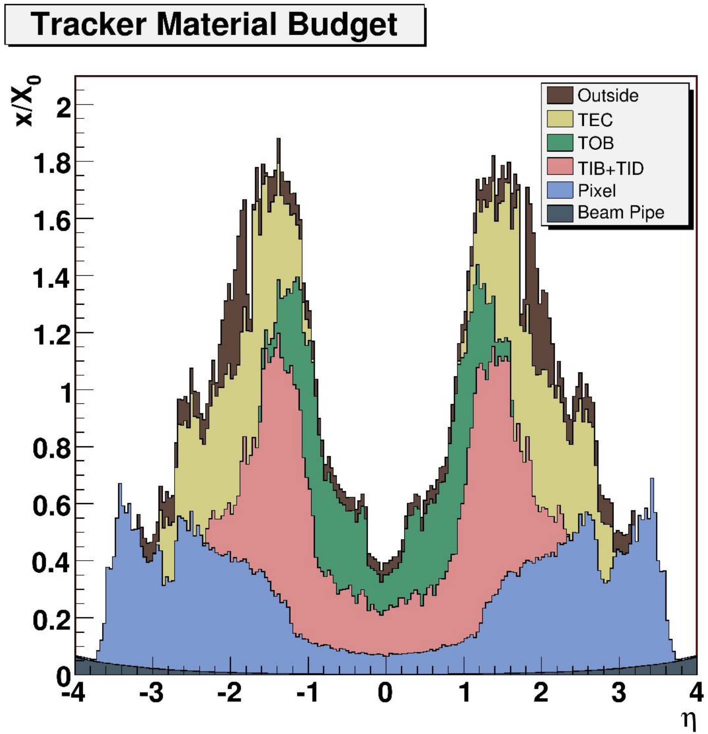
Muon Momentum Reconstruction/Calibration

- 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]





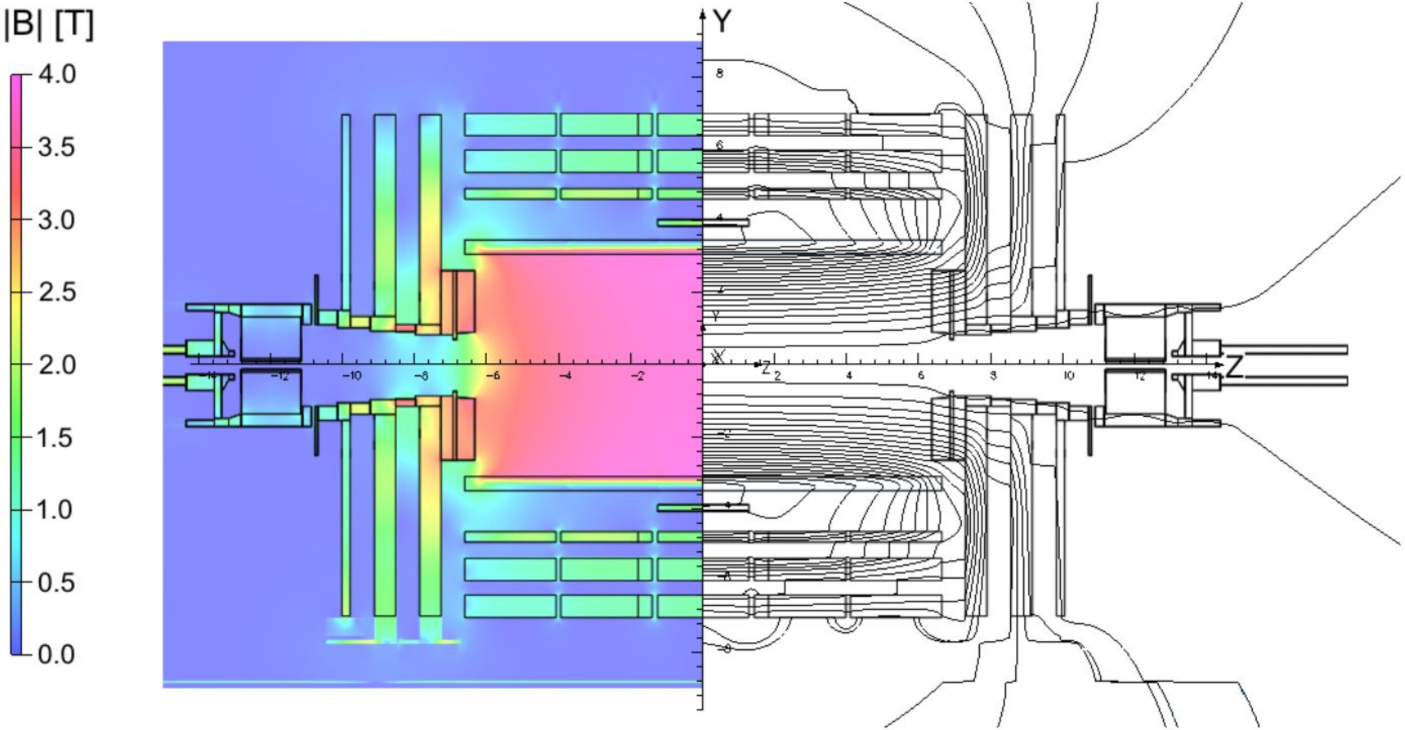
- All-Silicon tracker with measurements on up to 3 pixel layers and 9+ strip layers (typically 4+ stereo hits) for tracks from the IP
- Excellent measurement resolution: 15-53um depending on the layer
- But up to 1.8 radiation lengths of material…

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

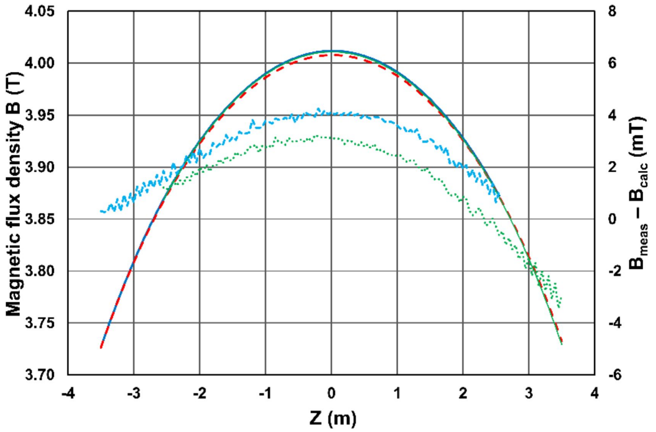
Magnetic Field Model



Magnetic Field Model

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

- 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

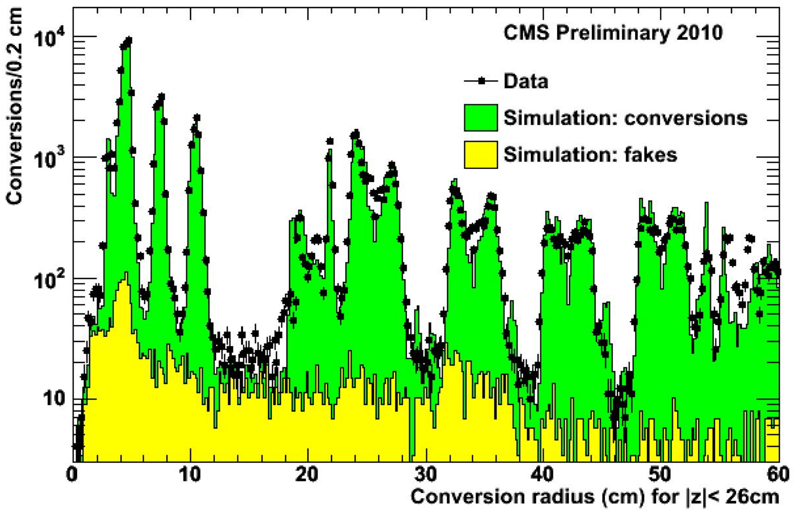


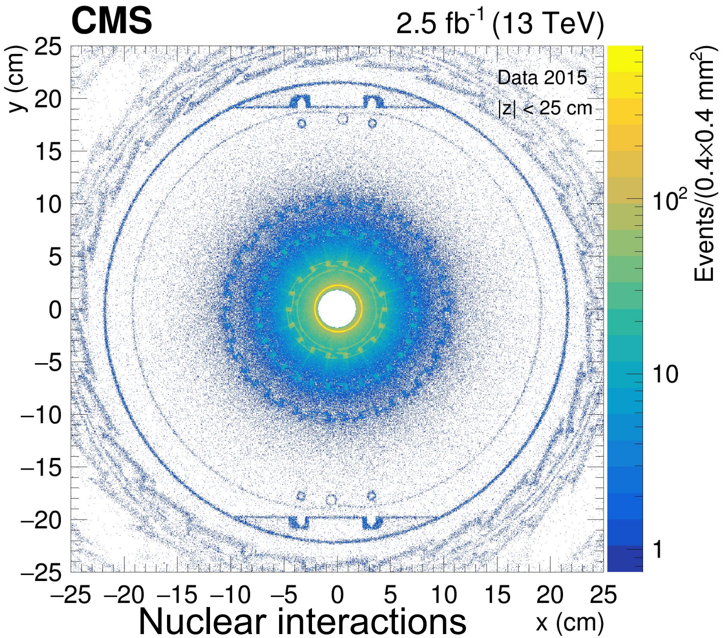
Model vs field map data at R = 0.1m (surface)

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

Material Model





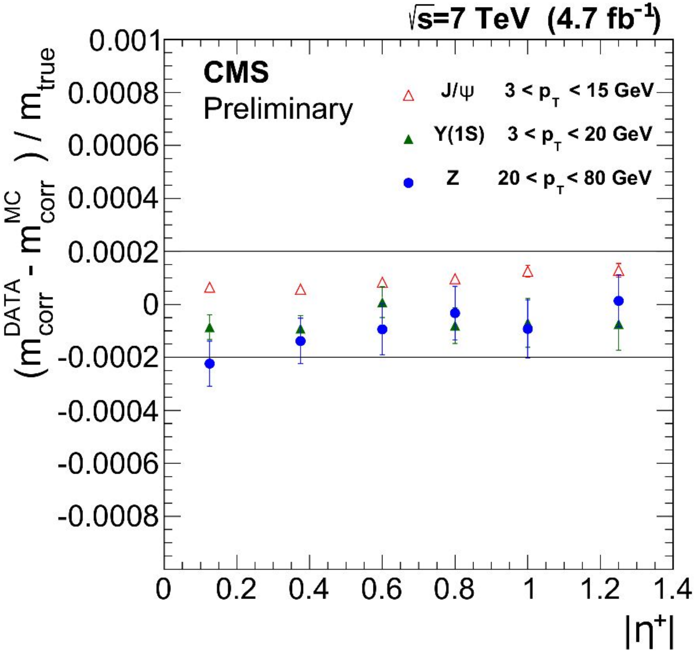
Nuclear interactions

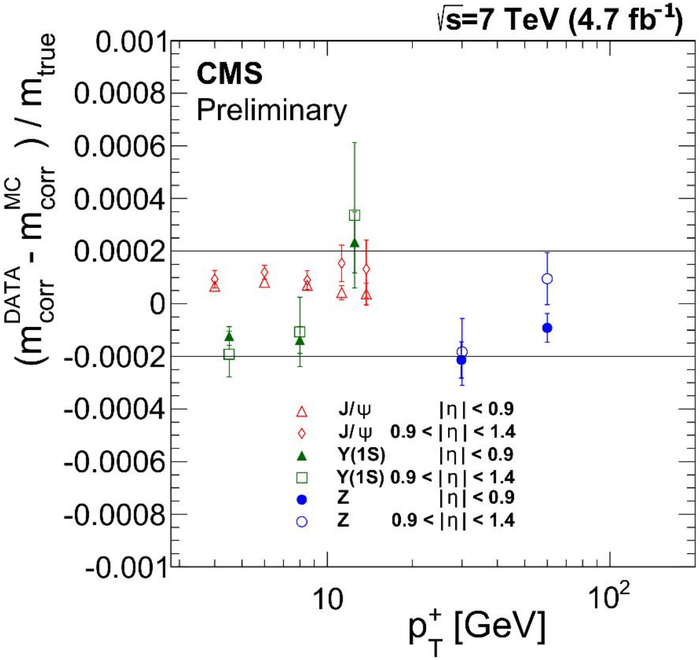
- Material model in simulation is correct at the O(10%) level
- Additional corrections may be needed due to the infinitesimal plane approximation in the tracking

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

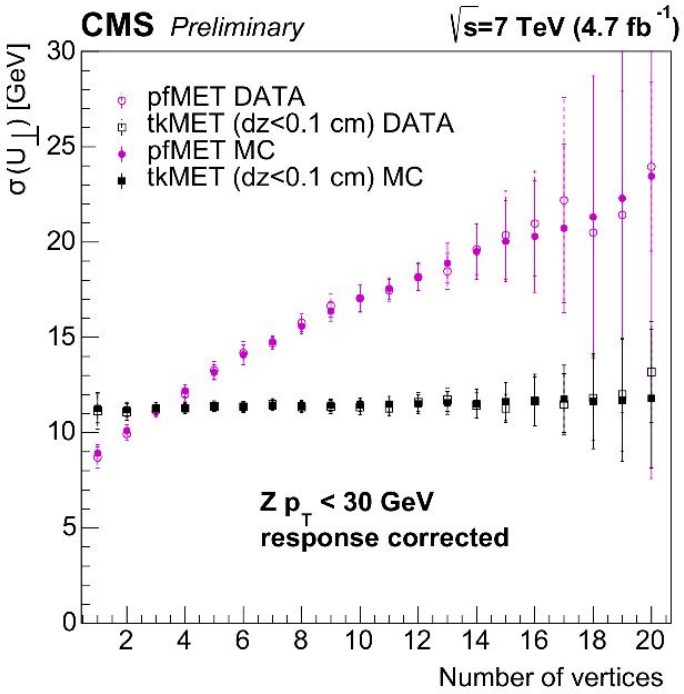
W-like measurement: Muon Momentum Calibration Closure

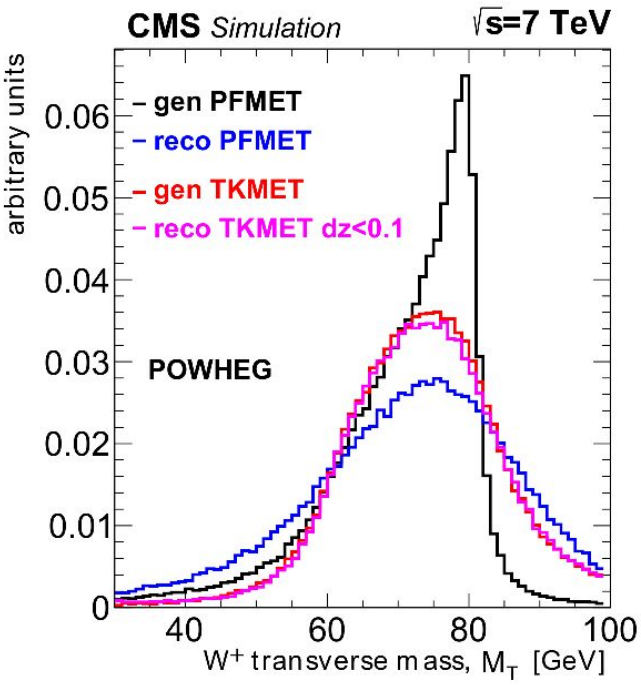




- Closure on Z and Upsilon within ~2e-4
- Clearly understanding of many aspects has improved in the meantime

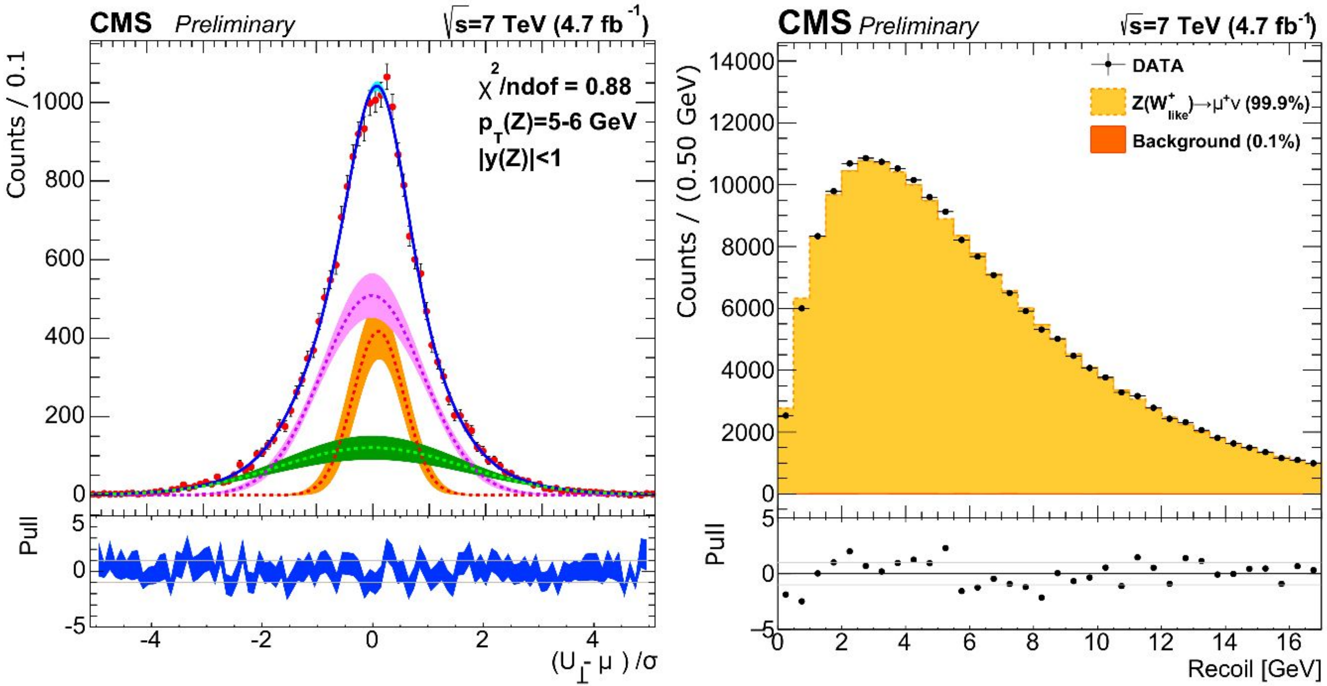
W-like measurement: Hadronic Recoil Calibration





- 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

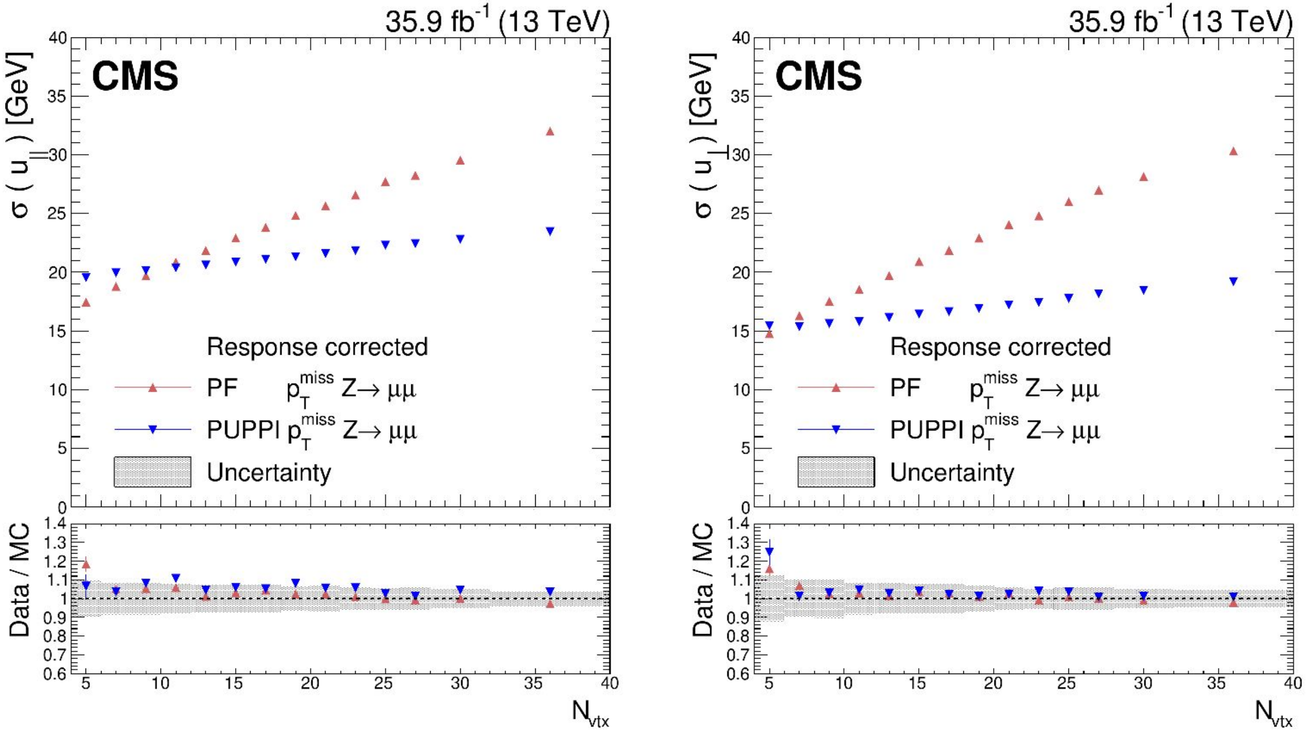
W-like measurement: Hadronic Recoil Calibration



- 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

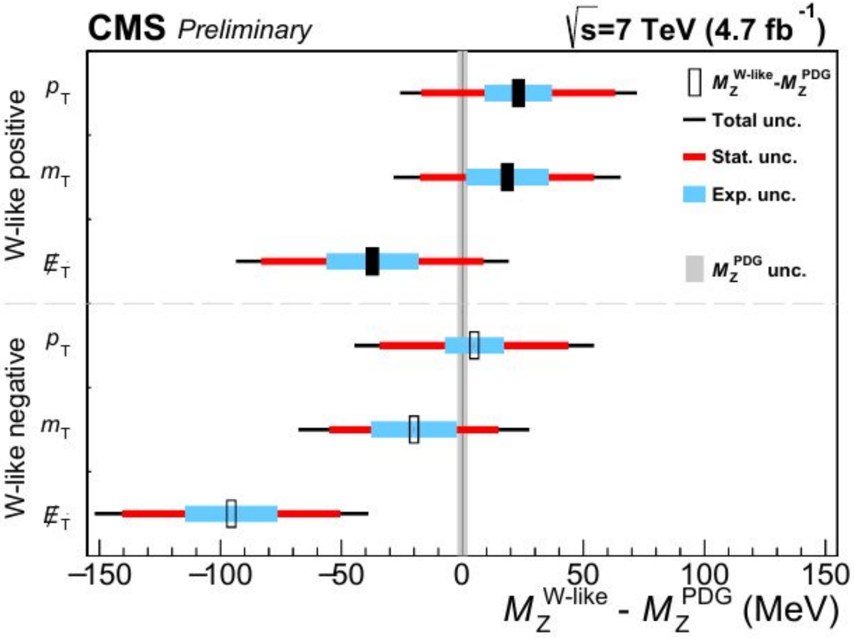
JINST 14 (2019) P07004



- 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

	$M_Z^{\mathrm{W like}+}$			$M_Z^{\mathrm{W like}-}$		
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

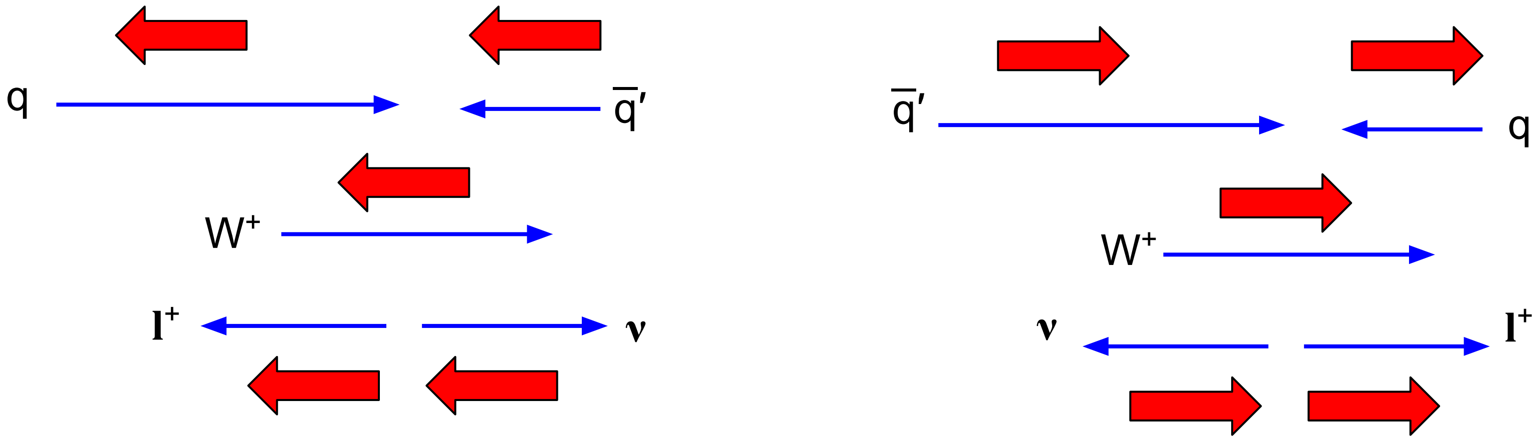


- Reasonable consistency with PDG mZ value
- **Dominant uncertainty 23 MeV on QED FSR due to issues with NLO EW matching in MC produced at the time**


ONE DOES NOT SIMPLY MEASURE THE W MASS
imgflip.com

Measurement of W helicity/rapidity

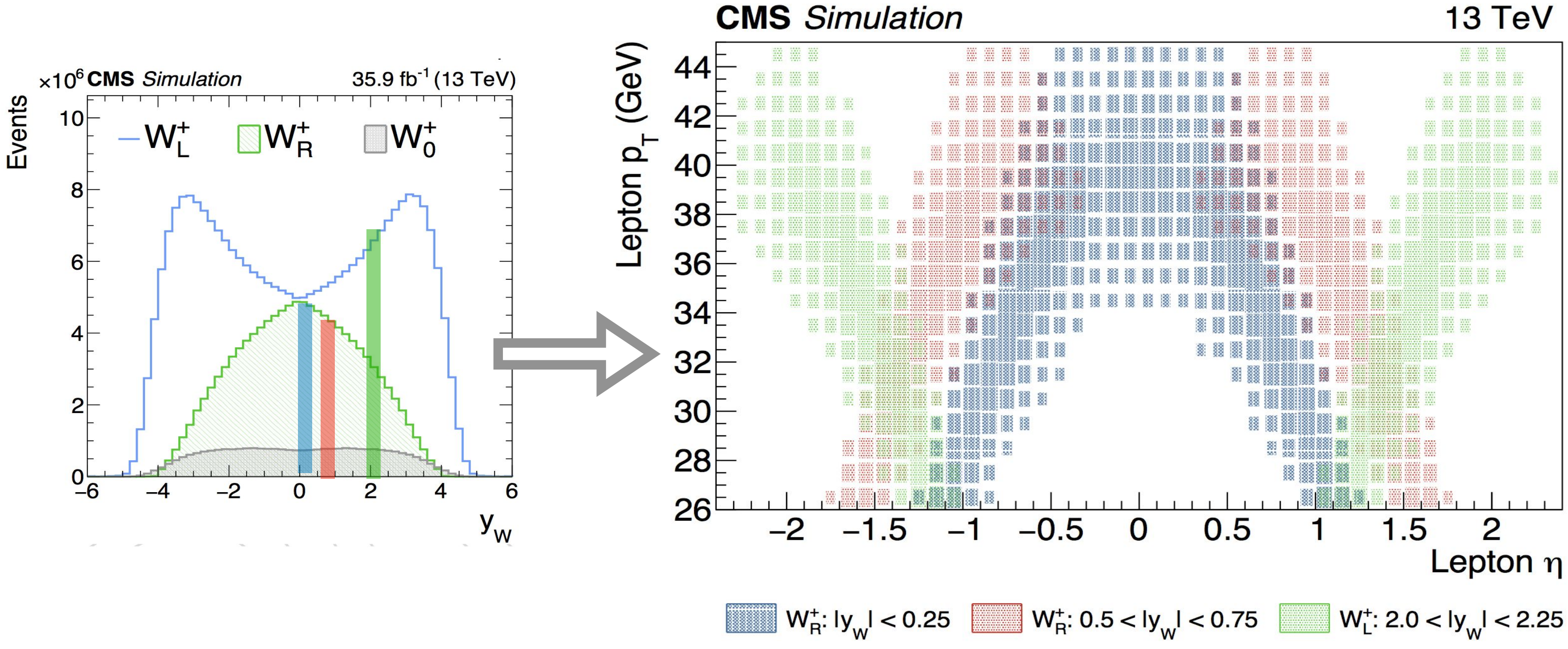
- Precision measurements of (polarized) W cross sections vs rapidity with sensitivity to PDFs -> **demonstrate physical and experimental basis of PDF constraints for future mW measurements**
- Pure left handed coupling of the W means that polarization and rapidity of the W are strongly correlated with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



Phys. Rev. D 102 (2020) 092012

Measurement of W helicity/rapidity

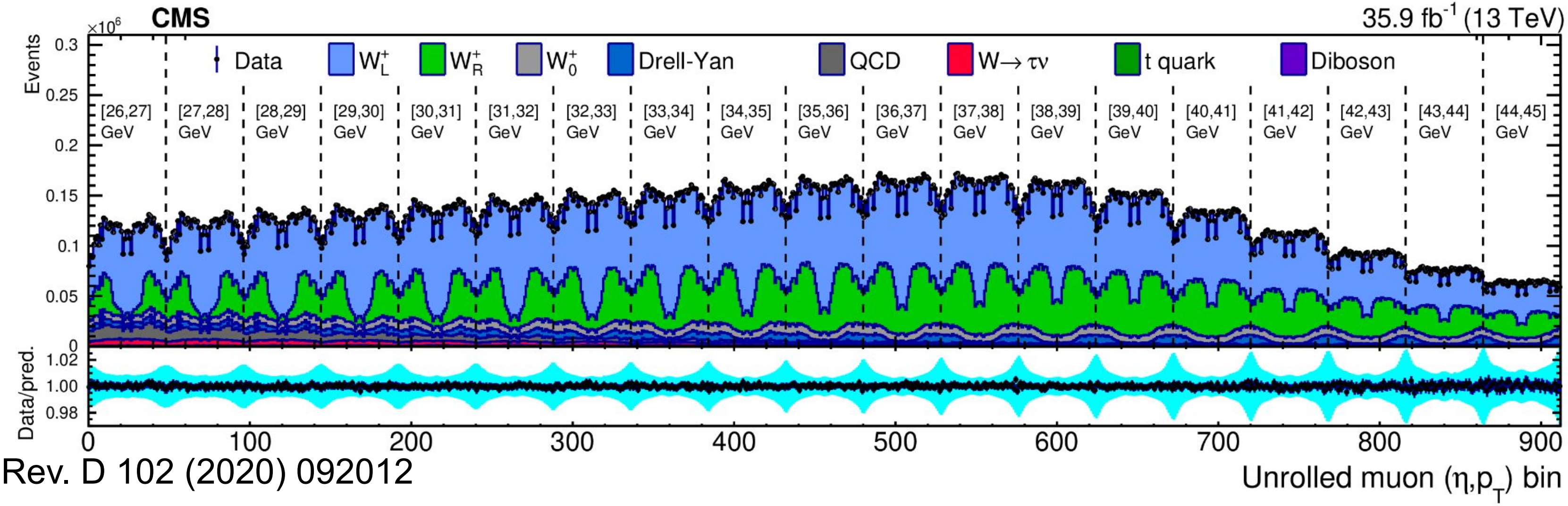
- W rapidity and helicity are inferred statistically from lepton pT-eta distribution



Phys. Rev. D 102 (2020) 092012

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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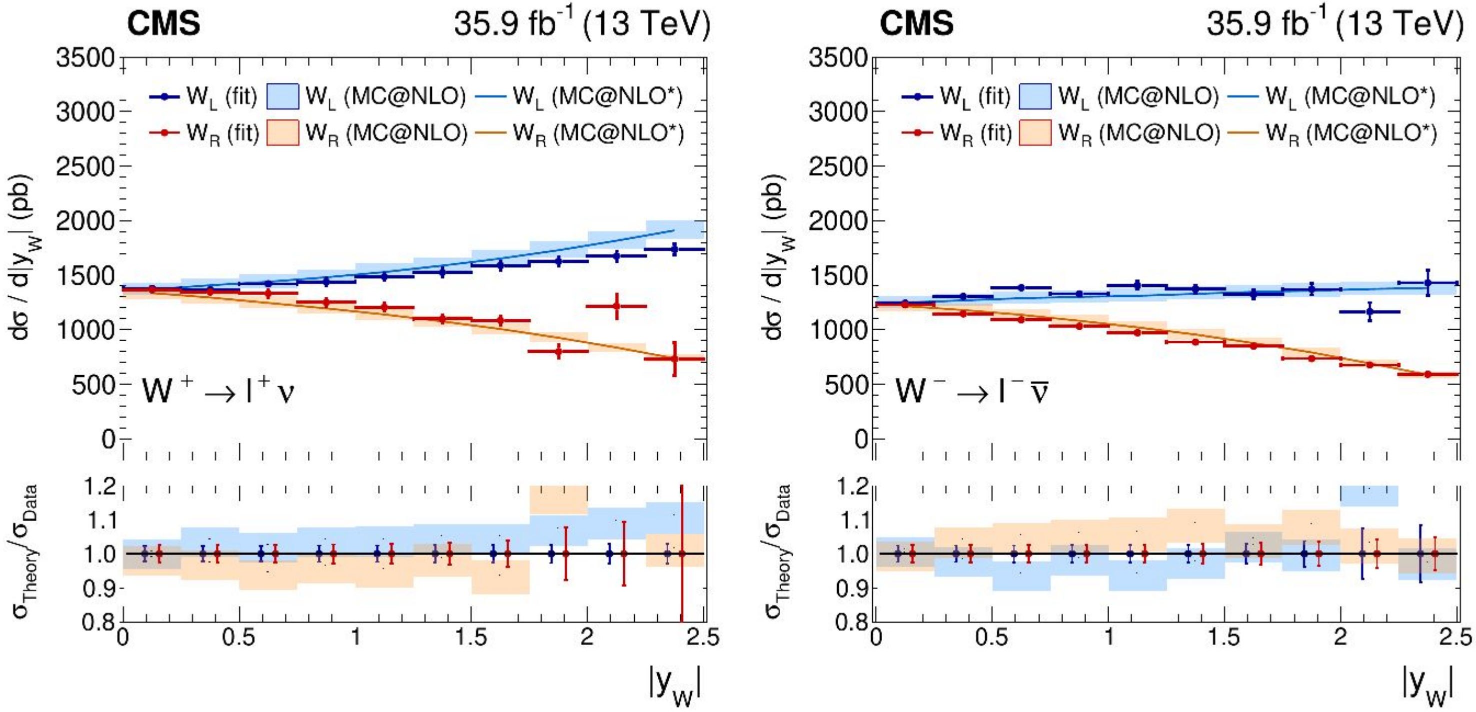
Results: Polarized W Cross Sections



- 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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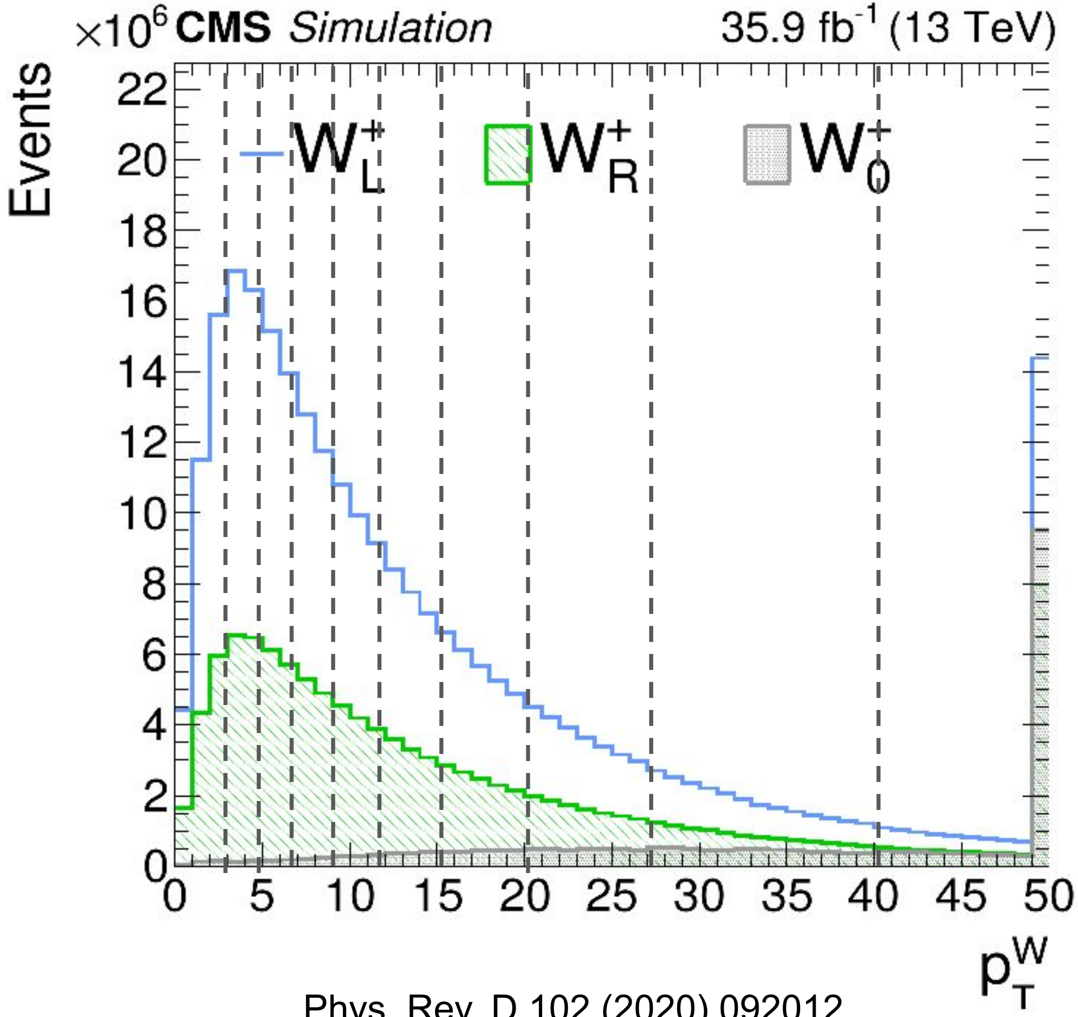
Theory Uncertainties

- 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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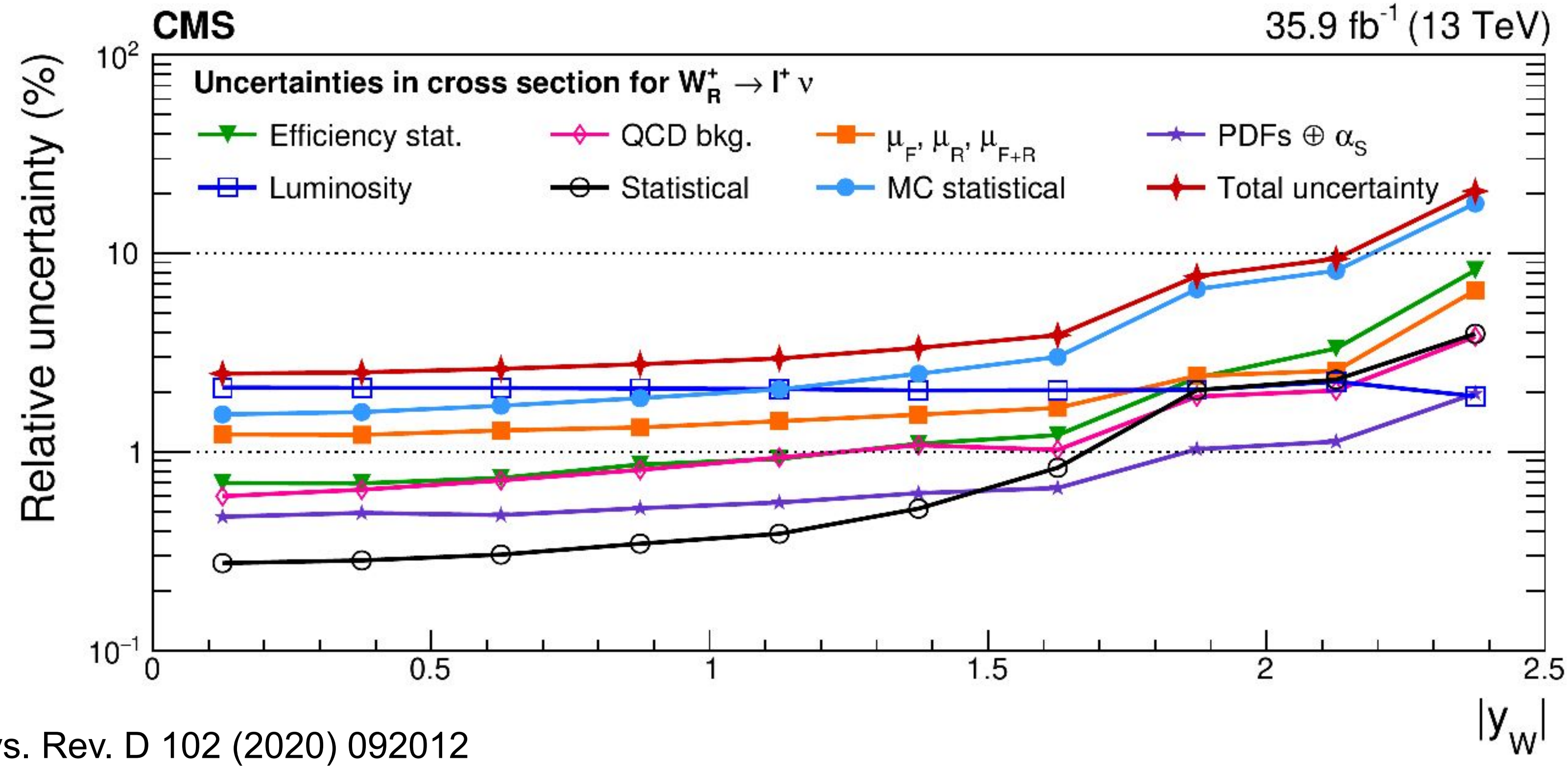
Results: Polarized W Cross Sections: Uncertainties



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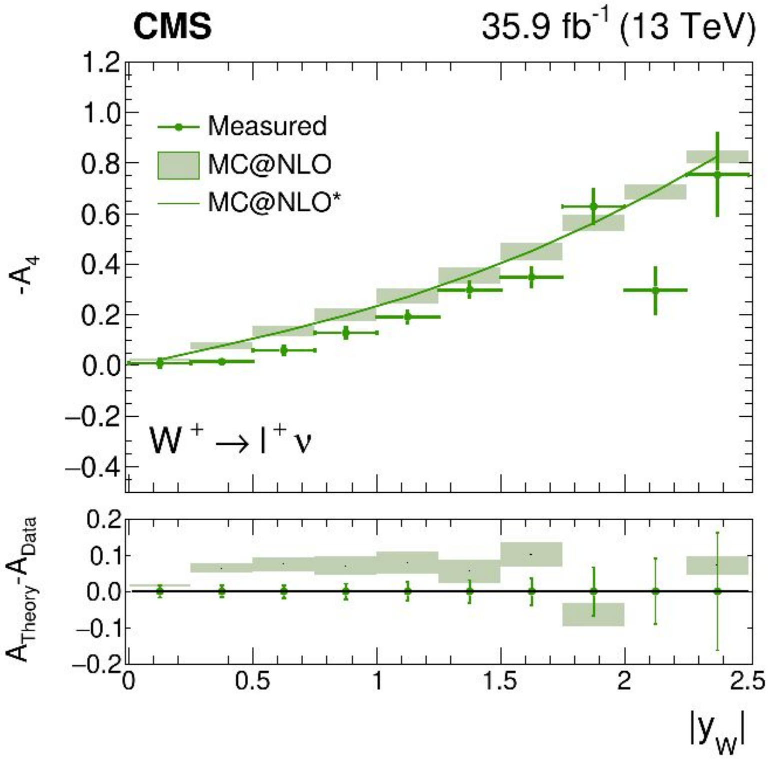
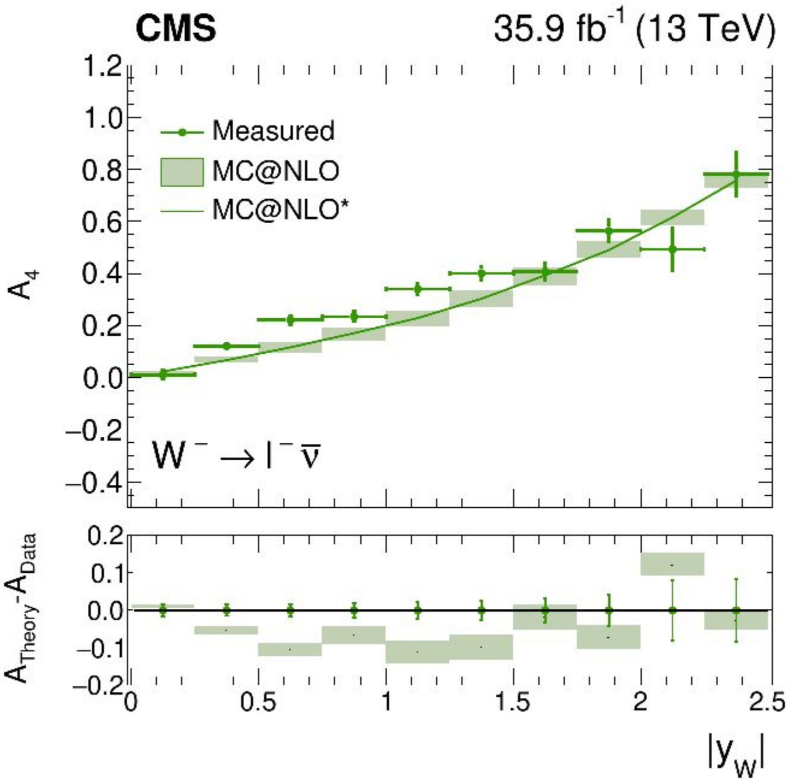
“Derived” Results: A4





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

Helicity-Integrated Results

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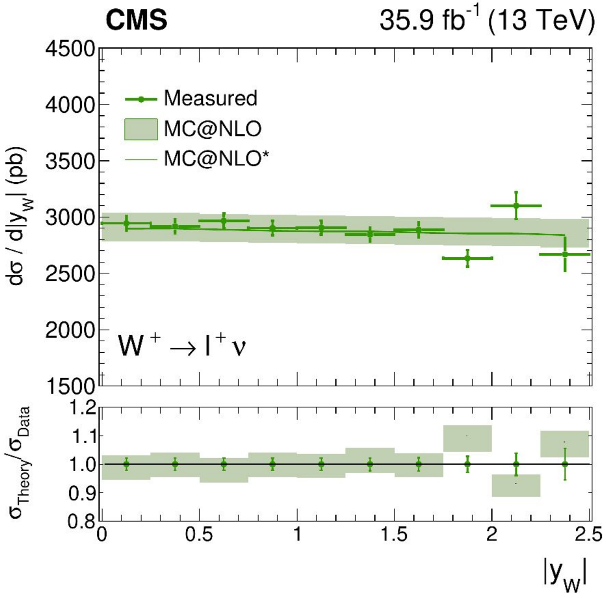
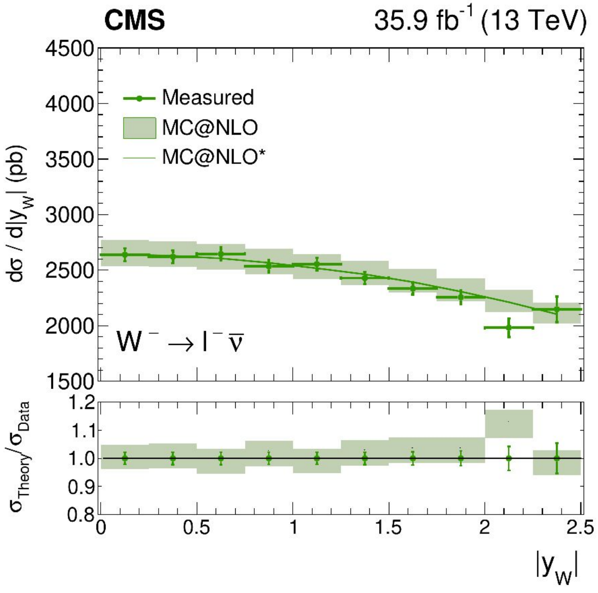
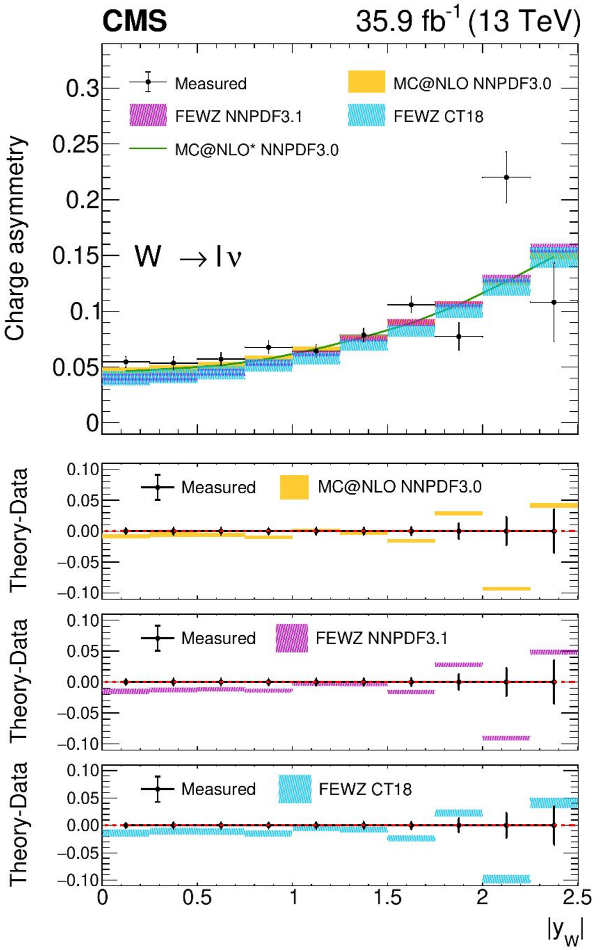
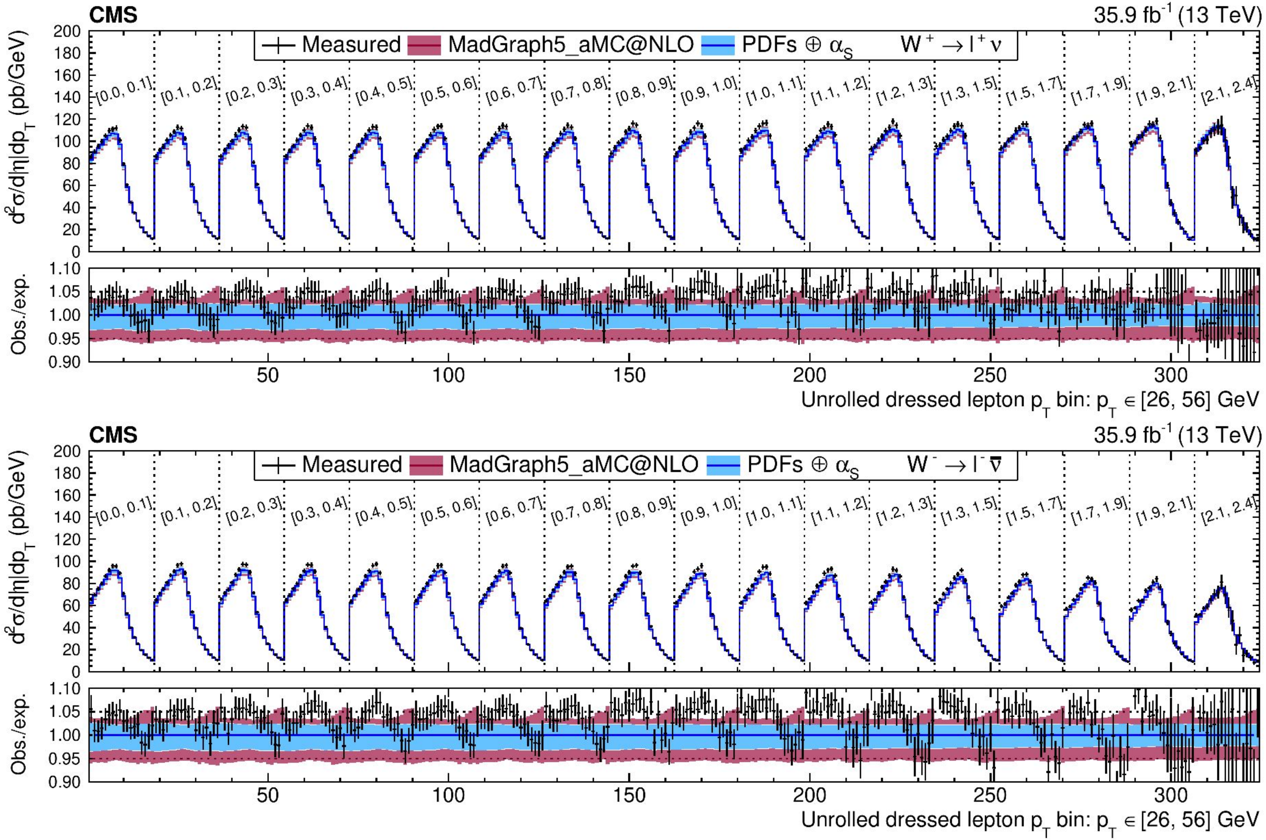
- Helicity-integrated quantities also measured without needing to make assumptions about underlying polarization
- This avoid entirely the issue of small circular pdf uncertainties which appear in e.g. the unfolded Tevatron W asymmetry measurements (which would also be larger at LHC)







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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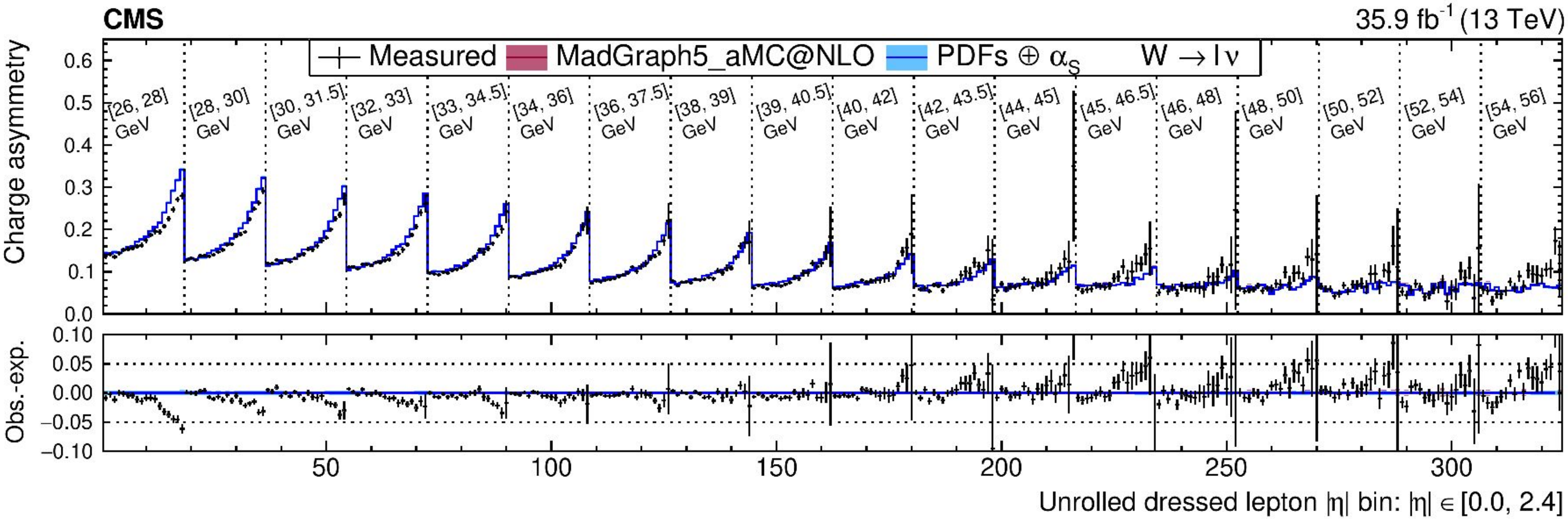
Results: Double-Differential Charge Asymmetry

- 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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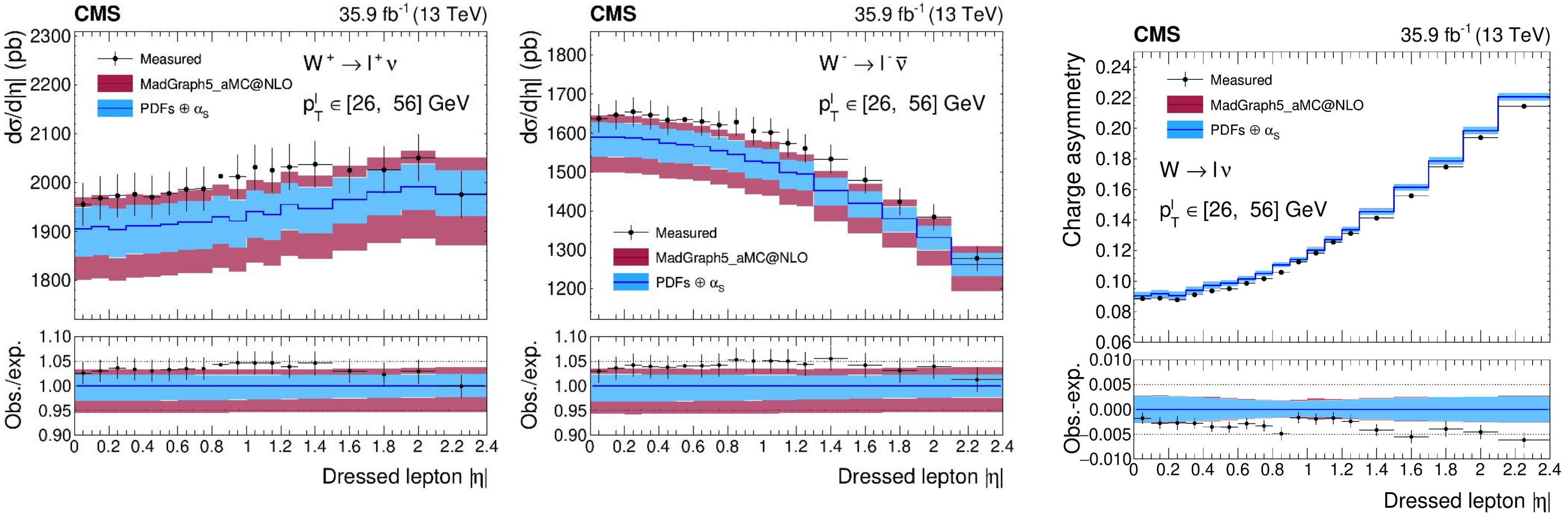
Results: 1D-integrated lepton cross sections



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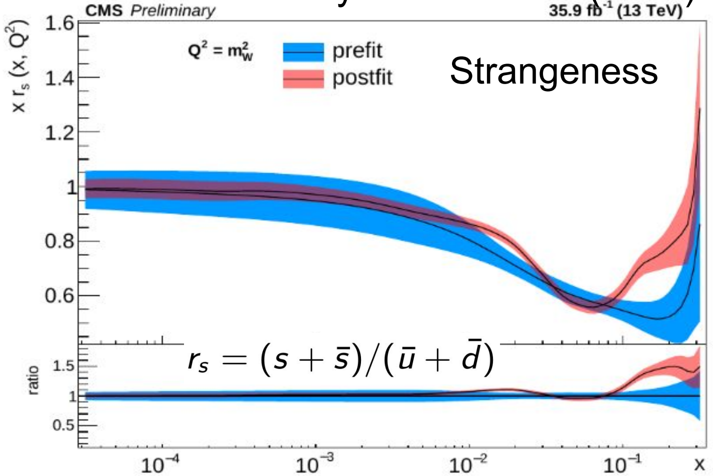
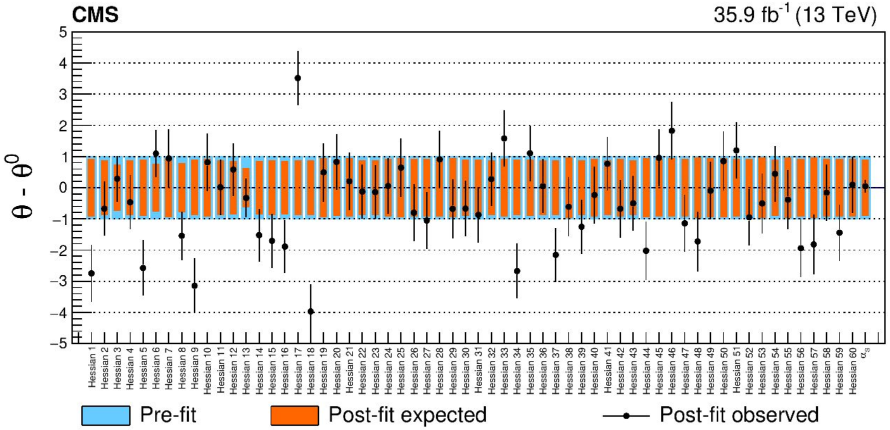
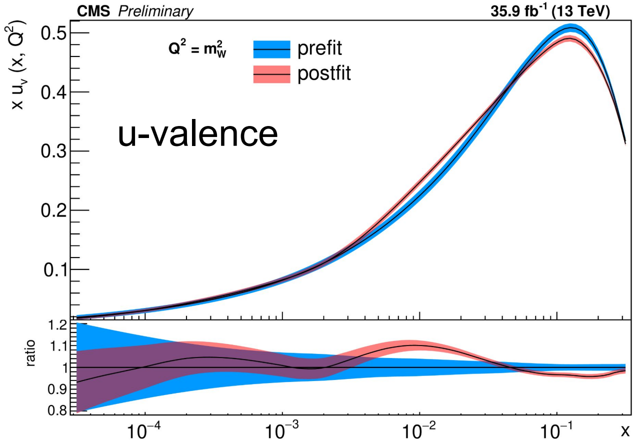
- PDF constraints obtained as proof-of-principle (e.g. for future mW measurement) by profiling PDF eigenvectors with cross sections fixed to their prediction within uncertainties
- NNLO predictions would give more meaningful results, but strong constraints on the PDFs are possible from this measurement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







W Helicity/Rapidity in Hepdata

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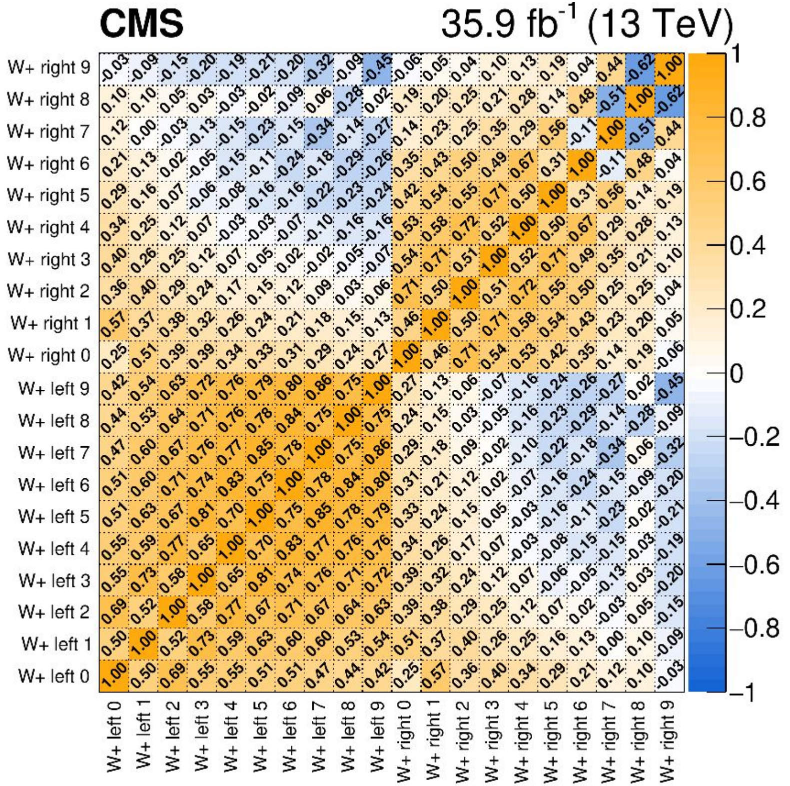
- Covariance matrices are essential for any interpretation of this data
- If not combining with other measurements, sufficient to have the e.g. 40x40 covariance matrix for the POI's (which have all the systematics included)
- If correlations with systematics are needed, then "full" ~1500x1500 covariance matrices for POI's + nuisances are provided
- Simple "Impacts" are **not** sufficient because profile-likelihood fit induces postfit correlations
  - To be understood if/how arXiv:2307.04007 changes the picture
- 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

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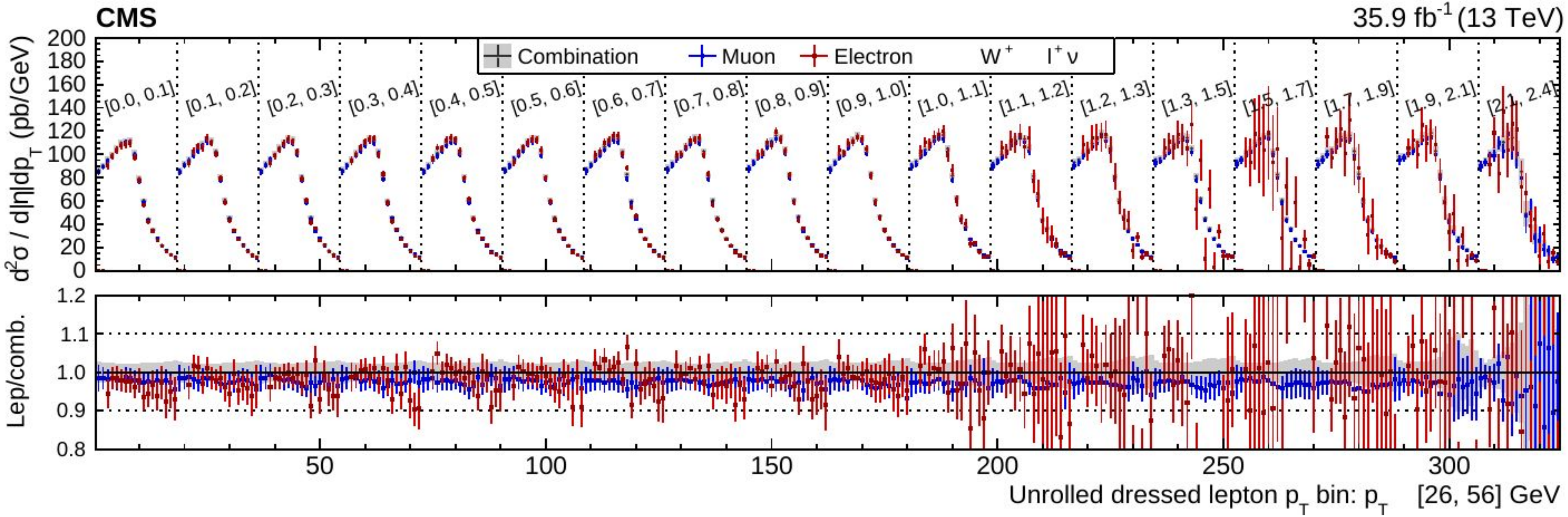
- Significantly larger statistical+experimental uncertainties for electrons already in W helicity measurement
- Energy calibration is also more challenging
- Will be difficult to be competitive with muons for mW measurements



Aside: High Performance Analysis

- Inclusive W production has a high cross secton at the LHC -> more than 3 x 10^9 W->lv events produced per lepton flavour per experiment in LHC run 2
- Example analyiss for ¼ of total run 2 integrated luminosity and one lepton flavour:
  - 800M single lepton triggered data events with little to no scope for skimming
  - 1.5B **Signal** MC events with little to no scope for skimming
- For this type of analysis **HL-LHC is now**

High Performance Analysis

- Broad analysis steps
  - Production of NANOAOD (on the grid)
  - Preparation/measurements of calibrations and corrections
  - **NANOAOD -> histograms (nominal + systematic variations)**
  - Statistical analysis (maximum likelihood fit)
    - More details on tensorflow-based likelihood fit: https://indico.cern.ch/event/882824/contributions/3932491/attachments/2075631/3485248/tffit-pyhep-Jul16-2020.pdf
- In CMS leverage “NANOAOD” data format
  - 1-2 kBytes/event
  - High level format with e.g. four-vectors of leptons, jets, etc, with corrections either already applied, or applicable on the fly

High Performance Analysis: Histogramming

- **Problem:** With a suitably complex analysis with full set of systematic variations, the total size of the histograms to be filled can exceed 1-2GBytes of memory typically available to a single thread
- **Solution:**
  - Multithreaded analysis (**not multiprocess**) in ROOT RDataFrame
  - Share histograms between threads (Boost histograms with std::atomic storage to allow concurrent filling)
- More details: https://indico.fnal.gov/event/23628/contributions/237985/attachments/154987/201732/highPerfAnalysis-May11-2022.pdf

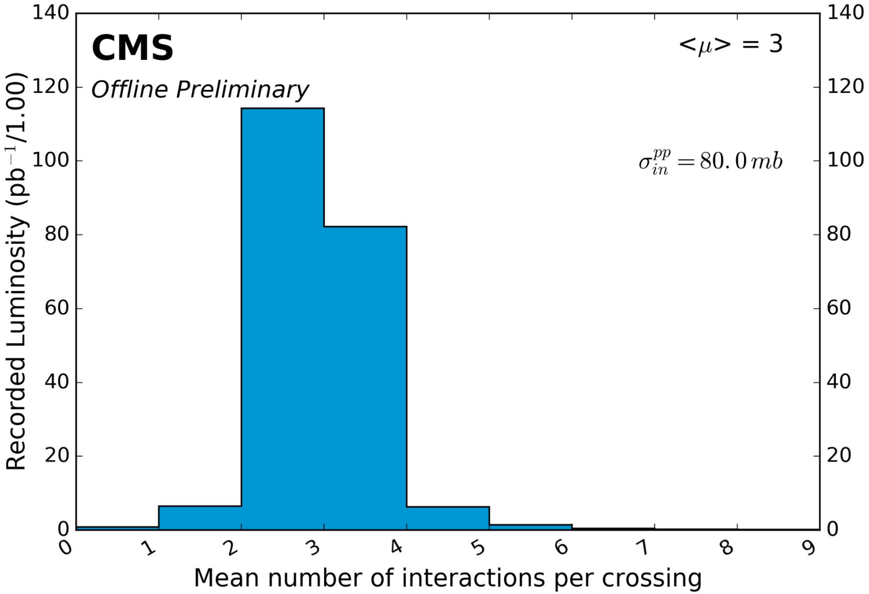
High Performance Analysis: Histogramming

- Benchmark example:
  - 411M events of CMS NANOAOD (W+->mu v)
  - Nominal histogram with ~11,000 bins, filling 10 copies of the pdf variation histograms
  - Dual EPYC (Zen 2) machine with 256 threads, 1TB memory and fast SSDs
- Optimized configurations achieve 50x reduction in CPU and memory usage
- Analysis event rates in the MHz

Hist Type	Hist Config	Evt. Loop	Total	CPUEff	RSS
ROOT THnD	10 × 103 × 5D	59m39s	74m05s	0.74	400GB
ROOT THnD	10 × 6D back	7m54s	25m09s	0.27	405GB
ROOT THnD	10 × 6D front	13m52s	30m27s	0.42	406GB
Boost ("sta")	10 × 6D back	7m07s	7m17s	0.90	9GB
Boost ("sta")	10 × 6D front	3m22s	3m33s	0.86	9GB
Boost ("sta")	10 × (5D + 1-tensor)	1m54s	2m04s	0.81	9GB
Boost ("sta")	1 × (5D + 2-tensor)	1m32s	1m42s	0.77	9GB

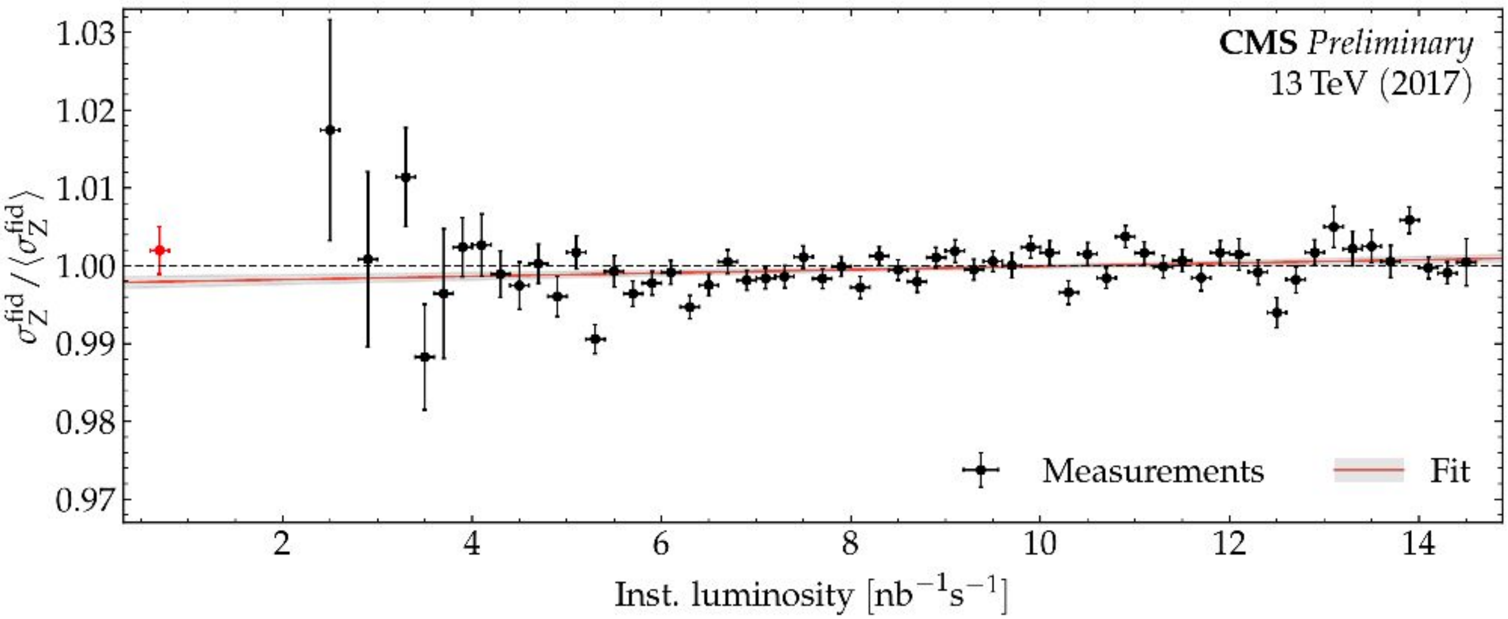

WHEN WILL THEN BE NOW ?
SOON.
memecenter.com
MemeCenter

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

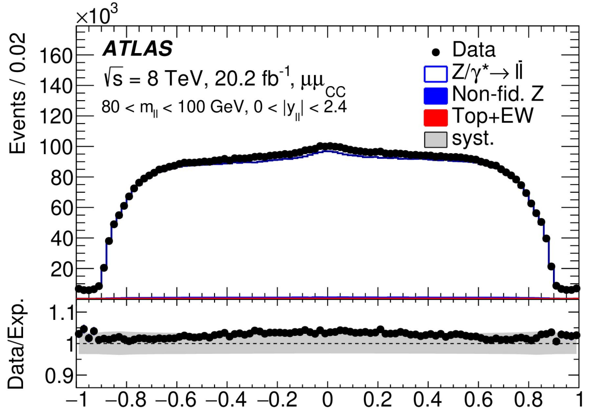
Luminosity with Z counting in Low (and High) Pileup Data

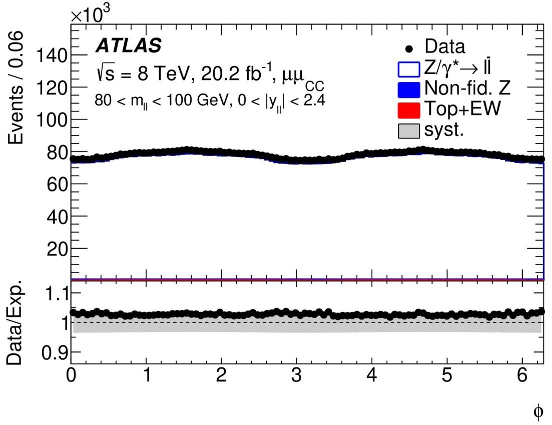


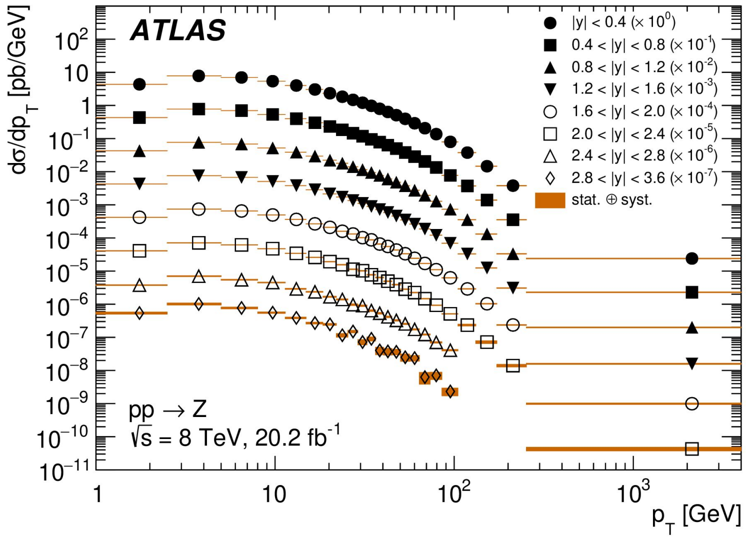
- Using Z counting to extrapolate luminosity from low pileup to high pileup run conditions requires unprecedented control over systematic effects in muon efficiencies (also relevant for future mW measurement)

CMS-PAS-LUM-21-001

ATLAS 8 TeV Z pT measurement + alphaS extraction

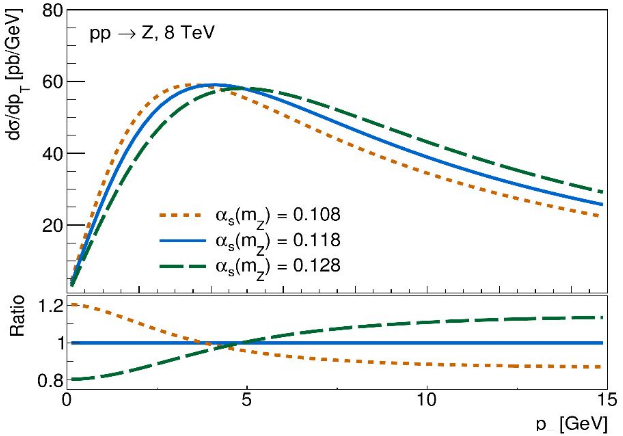


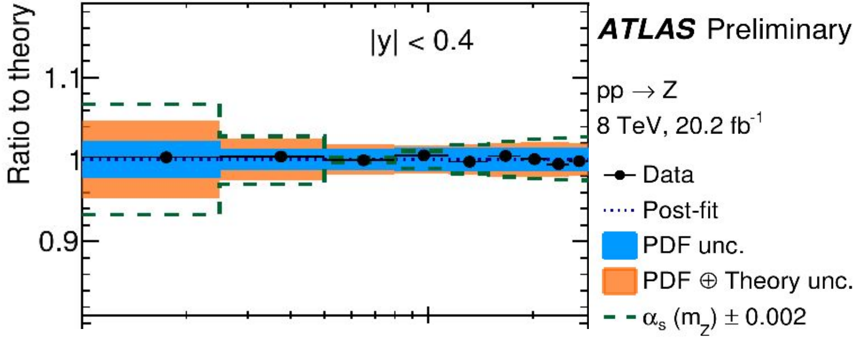


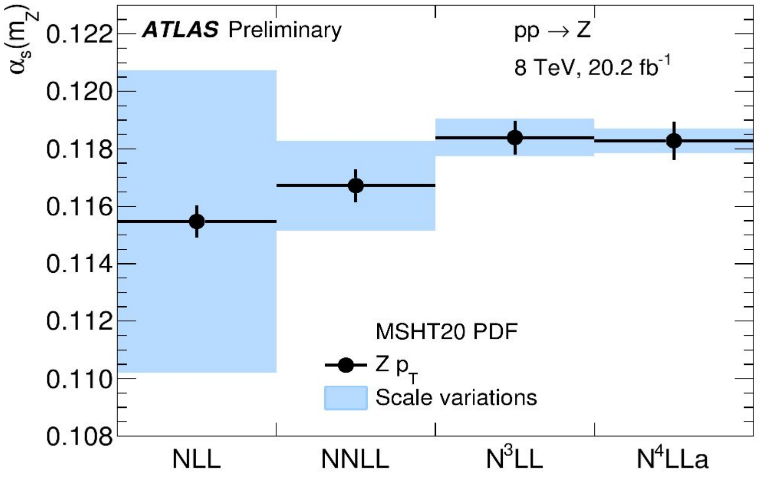


- Decay angle distributions are used to simultaneously measure angular coefficients and inclusive cross section (model-independent extrapolation to full phase space)

ATLAS 8 TeV Z pT measurement + alphaS extraction







- Unfolding to full phase space facilitates use of computationally challenging N3LO+N4LLa predictions
- High levels of control needed over both perturabtive and non-perturbative theory uncertainties

Wishlist for p_T^W modeling

- Since the ATLAS m_W measurement in 2016, **major progress has been made** to push the state of the art in resummed and FO perturbative calculations
  - Progress in **resummed calculations** critical due to importance of low pT region
  - Many calculations at N3LL on the market, with new results at **N3LL', N4LL**
  - **NNLO V+j** known and matched to resummed results
- Almost equally important is the community effort to validate procedures and codes

Currently participating groups and codes

TMD global fit tools (Collins/Soper/Sterman formalism):

artemide	Scimemi, Vladimirov '17, '19
NangaParbat	Bacchetta et al. '19
ResBos2	Isaacson '17

Direct QCD (Catani/de Florian/Grazzini formalism):

DYRes/DYTurbo	Camarda et al. '15, '19, '21
reSolve	Coradeschi, Cridge '17

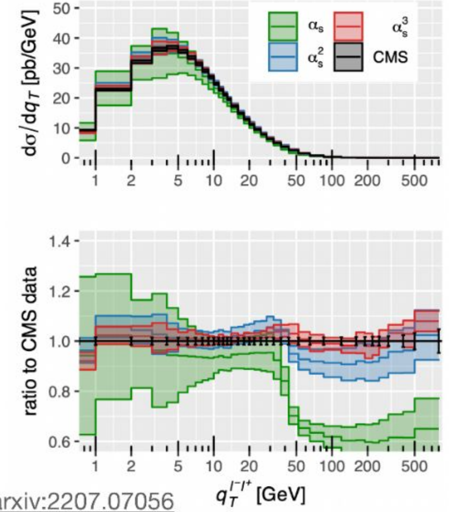
SCET-based tools:

CuTe-MCFM	Becher, Neumann '11, '20
SCETlib	Billis, Ebert, JM, Tackmann '17, '20

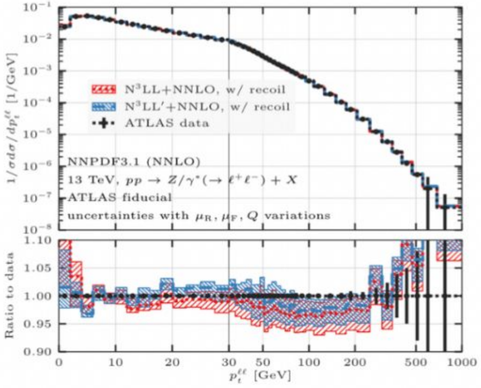
Coherent branching/momentum-space resummation:

RadISH	Monni, Re, Rottoli, Torrielli '16, '17, '19, '21

EWWG resummation benchmarking report, J. Michel https://indico.cern.ch/event/1194333/contributions/5025856



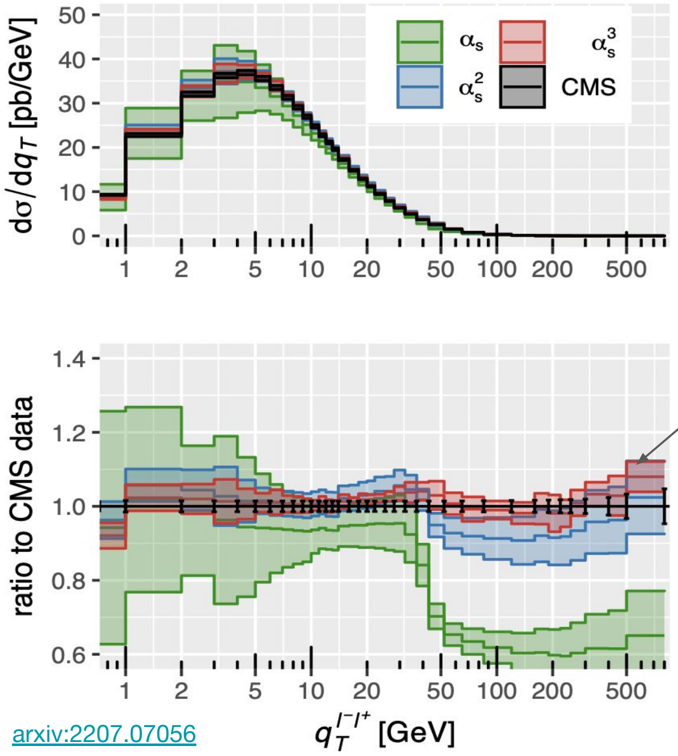
arxiv:2207.07056



[RadISH, 2104.07509]

- "Wishlist" item
  - Keep up the excellent work!
  - Do differences constitute uncertainties? Are individual uncertainty procedures **sufficient to capture the true uncertainty** of our knowledge of the process?

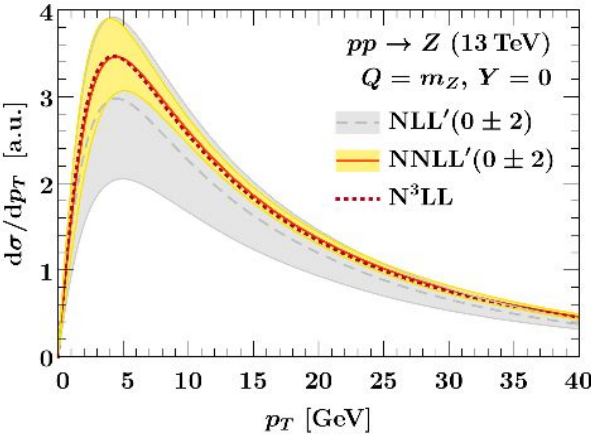
Limitations and Challenges for Theory Uncertainties

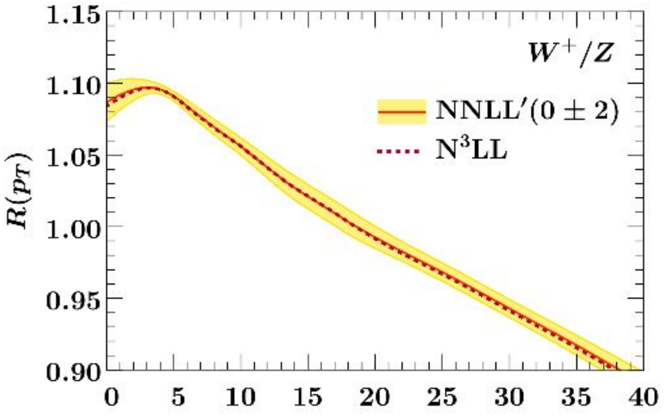


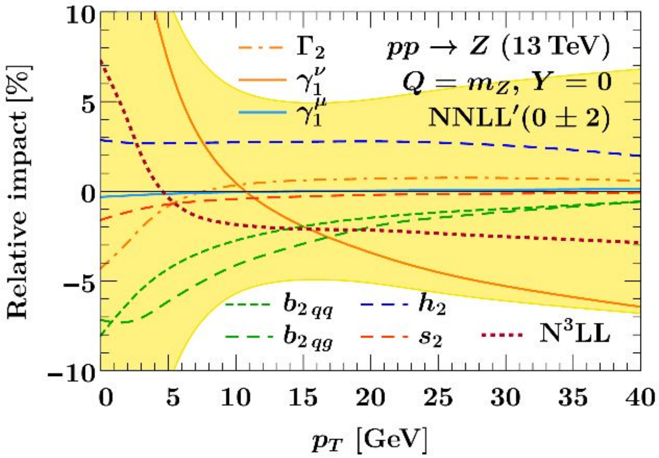
arxiv:2207.07056

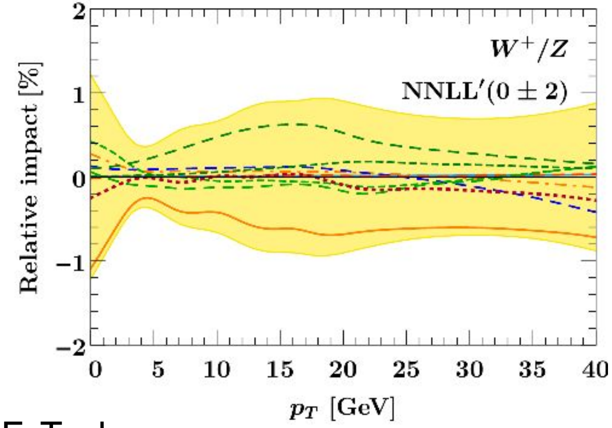
- Critical point: What is the **correlation** of theory uncertainties between different regions of phase space, distributions, or processes
- What's the correlation matrix of the red uncertainty band here? This matters a great deal for:
  - Quantifying agreement with data
  - **Constraining** theoretical uncertainties in-situ in a robust way
  - Maximally disentangling theoretical uncertainties from experimental ones and from underlying physics parameters (e.g. mW, alphaS)
- Uncertainties from scale variations in perturbative QCD (EW) calculations generally not well suited to this

Beyond Scale Variations?







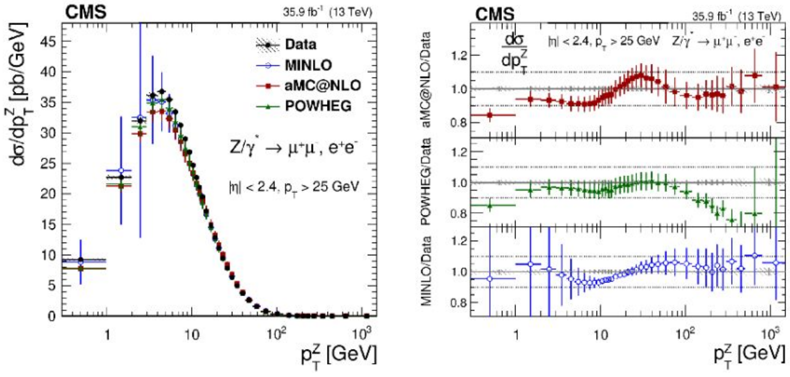


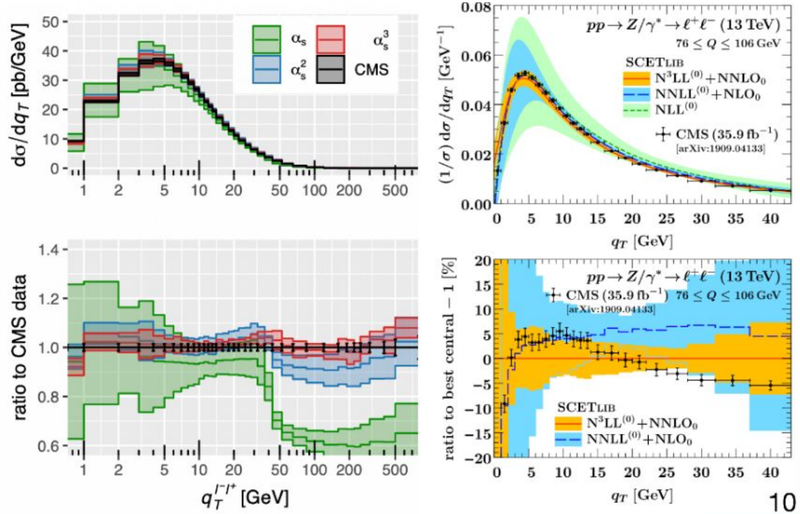
- Ongoing work to re-parameterize missing higher order perturbative QCD uncertainties in terms of "Theory Nuisance Parameters" instead of scale variations
- Potentially much better-defined correlations across phase space and between W and Z
- A significant step towards what is needed for precision measurements

F. Tackmann
https://indico.cern.ch/event/801961/contributions/3334772/

Theory vs. experiment for precision results

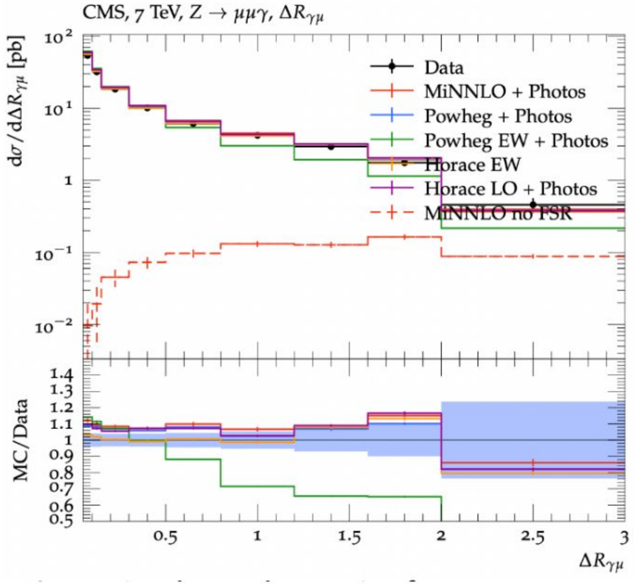
- Optimally, new measurements would be published with comparisons to state-of-the-art predictions. Practically:
  - Development cycle of new theoretical predictions often exceeds new precision measurements
  - Software may not be publicly available
  - Technical issues/resources/time constraints (or laziness) limit scope of comparisons in published paper
  - HepData/Rivet essential for ease of comparison
- "Wishlist" for theorists
  - Public codes, **open access development** highly preferable
  - Better usability => more likely to be used by non-experts
    - In practice overlap of authors at an institute etc. also plays a role
  - Example processes for validation, quick start instructions always useful
  - **Computationally performant**
    - Native multicore support
    - Easy scale out to batch/wide batch support





Further benchmarking and technical considerations

- Benchmarking of resummed predictions is a huge service to the field
- Landscape of other calculations (FO QCD, higher-order EW, mixed corrections) is perhaps not as vast, but would **still benefit from careful benchmarking**
  - Difficult for us to know if differences are expected/acceptable or not
  - e.g., discrepancies in NLO EW predictions
- **Computational performance** also an overlooked aspect
  - Do we know how fixed order and resummation codes compare in speed and efficiency?
  - Multithread vs. MPI?
  - DYTurbo developed with performance in mind. Other tools?
  - Experimental use case (e.g., PDF weights in POWHEG MiNNLO) can hammer performance



- **Development practices**
  - Significant software expertise, and relatively higher person power, are present in experimental collaborations
  - To our knowledge, most theoretical codes don't accept contributions (e.g., pull requests) directly
    - We often "fix" things that annoy us
    - Challenging to get these modifications into the upstream code. Diverging development cycles make maintenance and preservation a major headache

LHC -> FCC-ee

FCC-ee projections

arXiv:2106.13885

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate

- Future circular e+e- collider allows measurements of EW parameters with orders of magnitude better precision than LHC
- Reinterpretation of LHC measurements possible in terms of **ultra precise tests of QCD and constraints on PDFs** given experimental input from FCC-ee and future theoretical developments **but requires careful preparation of legacy LHC results**
- Incorporate experience and limitations of high accuracy detector/simulation calibration from LHC experiments into FCC-ee experiment design
  - E.g. physics benefits and limits of high *accuracy* tracking cross-calibrated with beam energy constraints and known resonance masses

Theory Uncertainties at FCC-ee

Freitas, Heinemeyer, et al. '19

	CEPC	FCC-ee	perturb. error with 3-loop†	Param. error scen. 1*	Param. error scen. 2*
M_W [MeV]	0.5	0.4	1	2.1	0.6
Γ_Z [MeV]	0.025	0.025	0.15	0.15	0.1
R_b $[10^{-5}]$	4.3	6	5	< 1	< 1
$\sin^2\theta^{\ell}_{eff}$ $[10^{-5}]$	<1	0.5	1.5	2	1

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$, leading 4-loop

(N_f^n = at least n closed fermion loops)

Parametric inputs:

***Scenario 1:** $\delta m_t = 600$ MeV, $\delta\alpha_s = 0.0002$, $\delta M_Z = 0.5$ MeV, $\delta(\Delta\alpha) = 5 \times 10^{-5}$

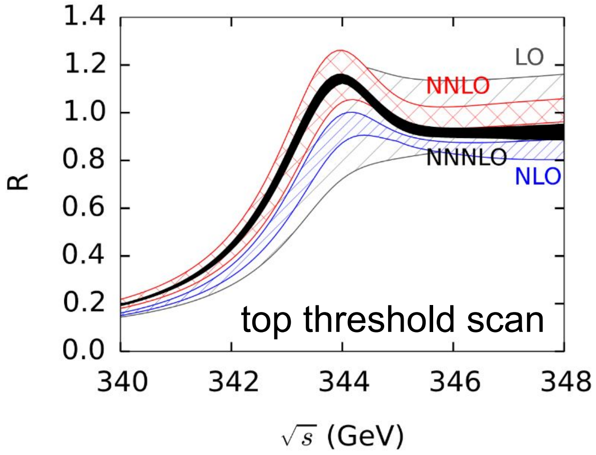
***Scenario 2:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0002$, $\delta M_Z = 0.5$ MeV, $\delta(\Delta\alpha) = 3 \times 10^{-5}$

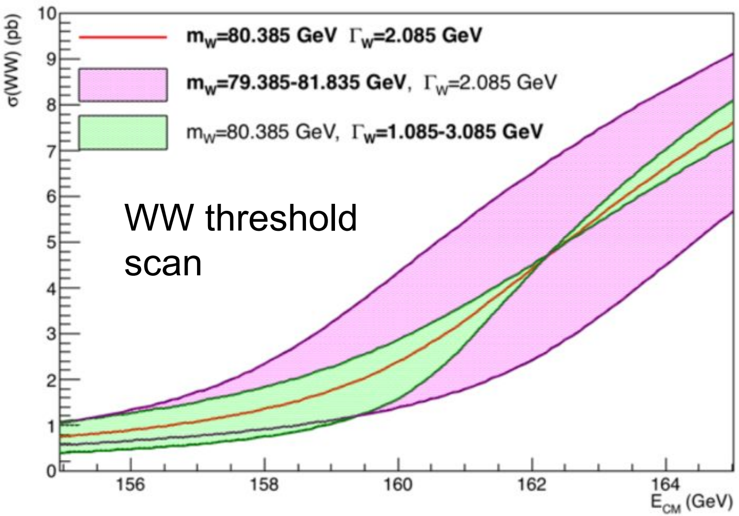
A. Freitas, Precision calculations for future e+- colliders
https://indico.cern.ch/event/1140580/contributions/4863864/

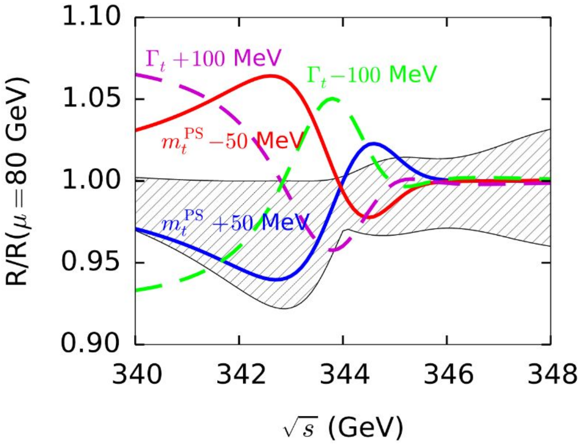
- Extreme experimental precision requires theoretical calculations at 3-4 loops to keep up
- Perturbative EW/QCD uncertainties may still be the dominant ones

Theory Uncertainties at FCC-ee

arXiv: 1703.01626







- Top and W mass at FCC-ee most precisely extracted from threshold scans
- Fit the **shape** of production cross section vs √s
- Perturbative EW+QCD uncertainties could be the limiting factor
- **Must** know the correlation of theoretical uncertainty between √s points to properly interpret the data!
  - Directly related to current challenges with QCD uncertainties at the LHC

Conclusions

- LHC experiments continue to push forward on experimental precision
- Theoretical interpretation of precision data is critical
- Challenges
    - Maximize utility of precision data/measurements for theoretical interpretation
    - Achieve corresponding reduction in theoretical uncertainties
        - Brute force? (More loops, more logarithms?)
        - In-situ constraints?
- Significant progress in both experimental techniques and theoretical predictions
- Great care is needed at the interface as the precision of both theory and experiment improve
- Significant related challenges potentially ahead at FCC

Backup

“Data-Driven” vs a priori theory uncertainties

- Even if neutral current data is not used, profiling and in-situ constraints are inevitable
- Ideal world: work towards improving the validity/applicability of theory uncertainties in this context
  - Make the resulting constraints interpretable by theorists as well!
  - Super ideal world: Well defined correlations -> simultaneous in-situ constraints between neutral and charged current

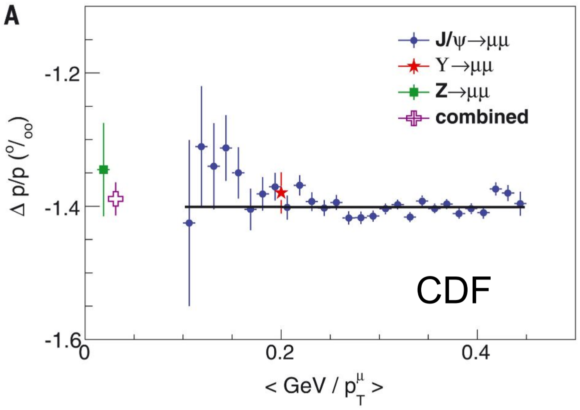
Experimental use of state-of-the-art predictions: Technical/Physics

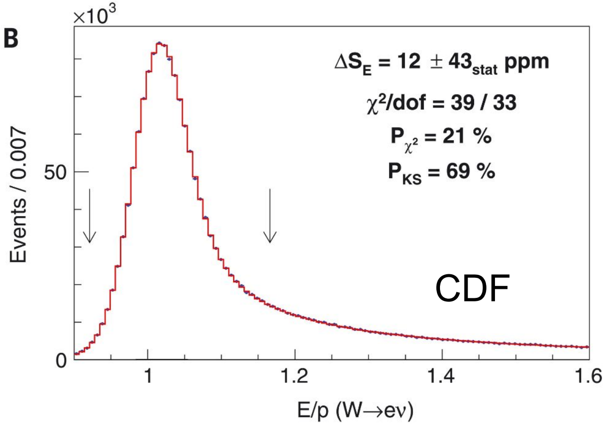
- LHC Experiments have excellent detector simulations and significant computing power -> significant benefit to using showered events with detector simulation
- Historically (and currently) significant gap/lag in accuracy available in standalone calculations (pointwise/binned cross sections, event generators) vs those matched to shower
- Experiments typically employ reweighting with some suitable binning in boson pT, y, m (+ angular coefficients)
- Prospects for improved matched shower MC predictions?
- Improvements possible in interfacing of less accurate shower MCs with more accurate calculations? (event-wise/point-wise reweighting?)
- Improve speed of predictions? (especially for large number of scale/pdf variations, angular coefficients)

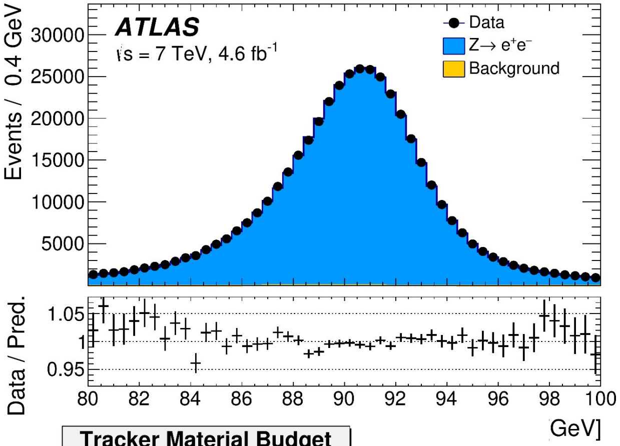
Experimental use of state-of-the-art predictions: Sociological

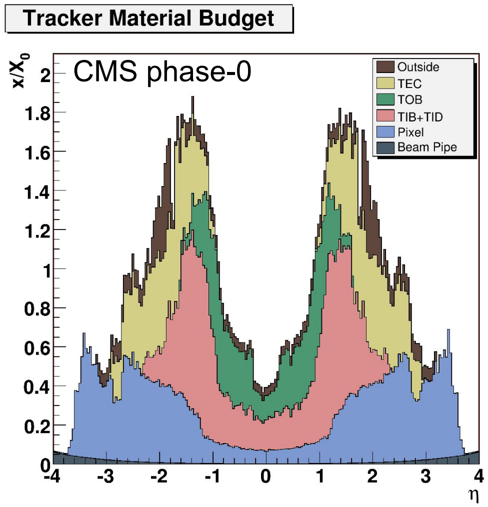
- A few possible models:
    - Theorists run predictions on request for the experimentalist
        - Mismatches in timescales, person-power, computing power
    - Experimentalists run private versions of code provided by theorists
        - Potentially serious problems with reproducibility (c.f. different private versions of Resbos + grids provided to CDF and D0 at different points in time)
    - Code is publicly available for experimentalists to run
        - Imposes documentation and support burdens on theorists
        - +10: Code available in public github or gitlab repository, with issues, pull requests, open development model
            - Experimentalists can and will help with technical aspects of the code! (compiler support, parallelization, etc)
            - Open development and public code likely to improve robustness and maintainability
            - Major reproducibility and open-science benefits
        - When can/should this happen with respect to theory publications?
        - Can/should funding agencies and large experiments pressure/coerce/incentivize theorists to do this?

Electron Energy scale calibration in CDF and ATLAS









- 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

HL-LHC -> FCC-hh

- Future hadron collider designs foresee 1000 interactions per crossing -> **HL-LHC must be maximally exploited as proving ground for detectors, reconstruction, computing, analysis techniques**
  - Maximize impact of high granularity, precision timing, advanced analysis, statistical and computing techniques