Role of theoretical uncertainties in the measurement of m_W and "wishlist" for theoretical inputs

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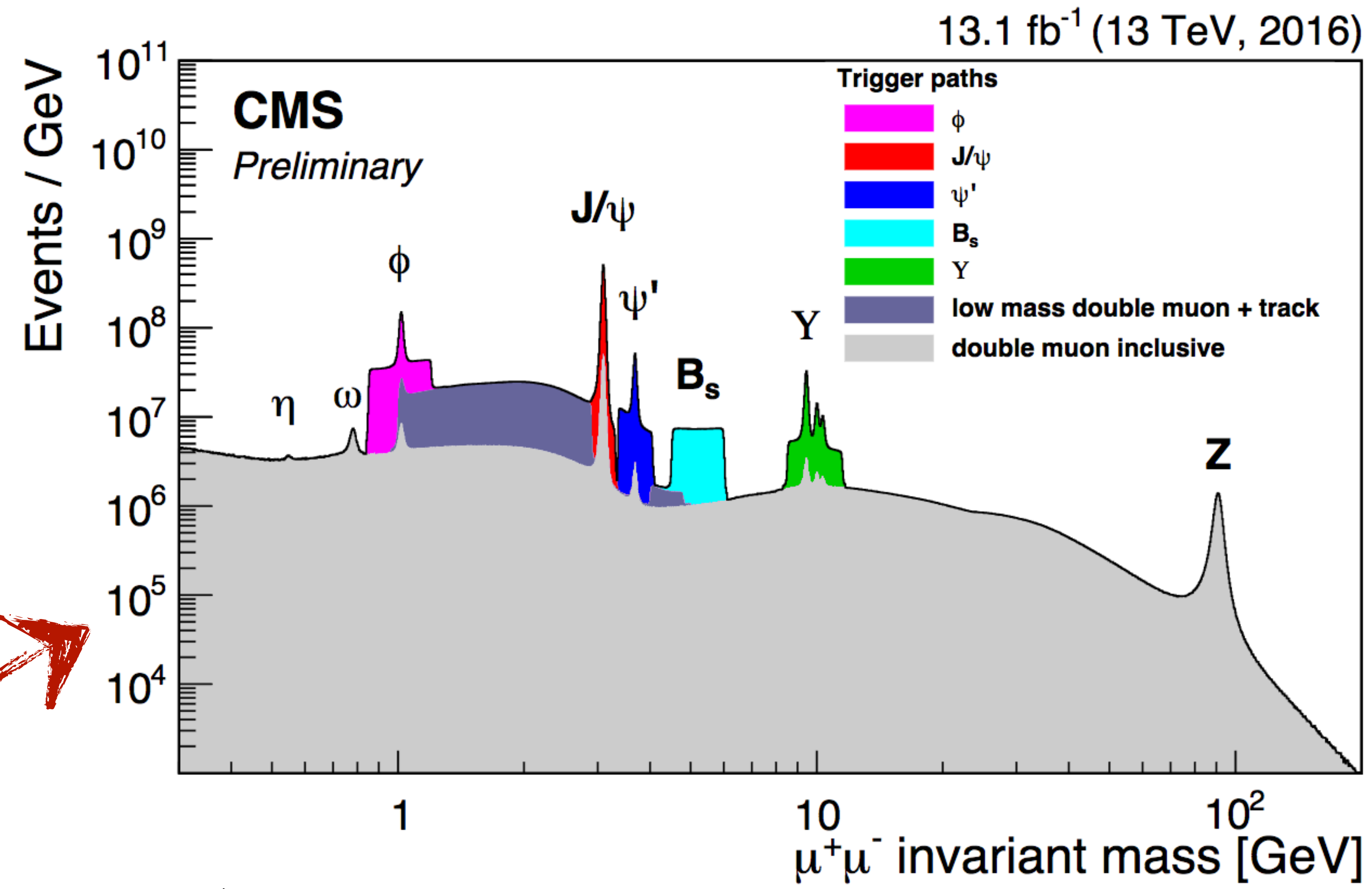
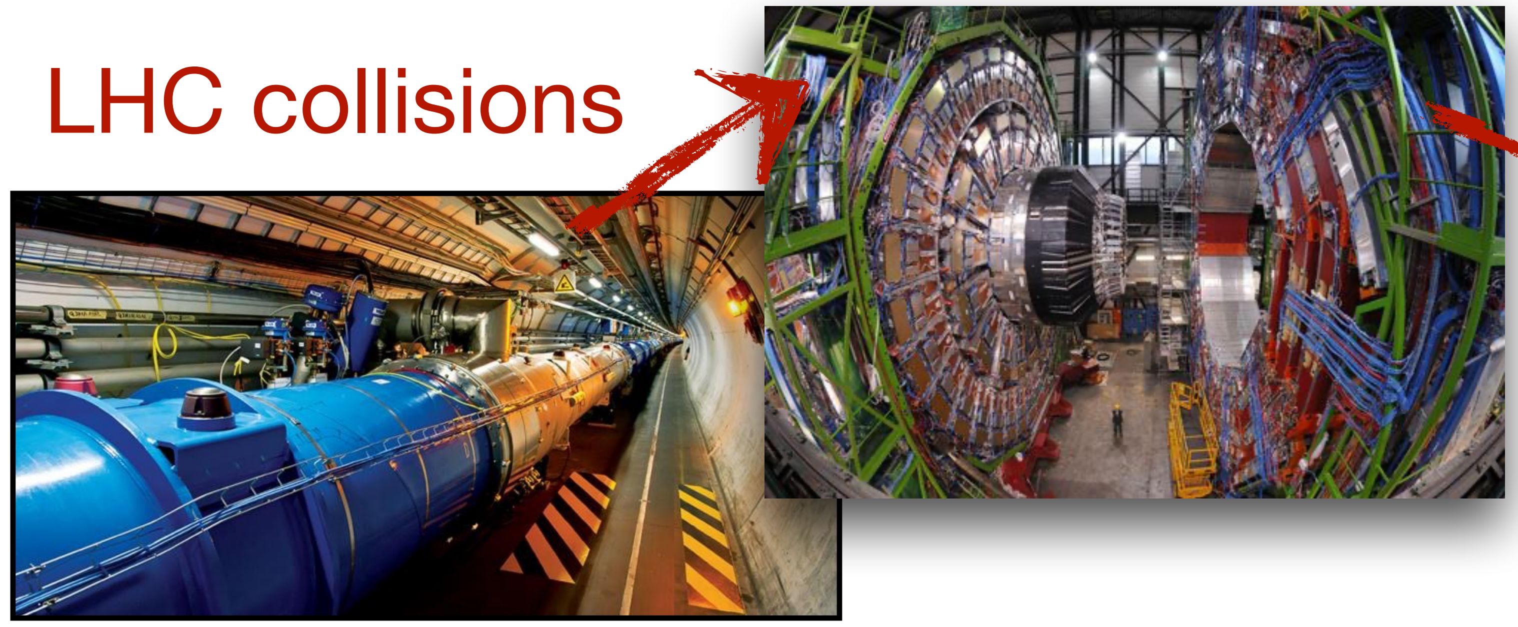
Introduction

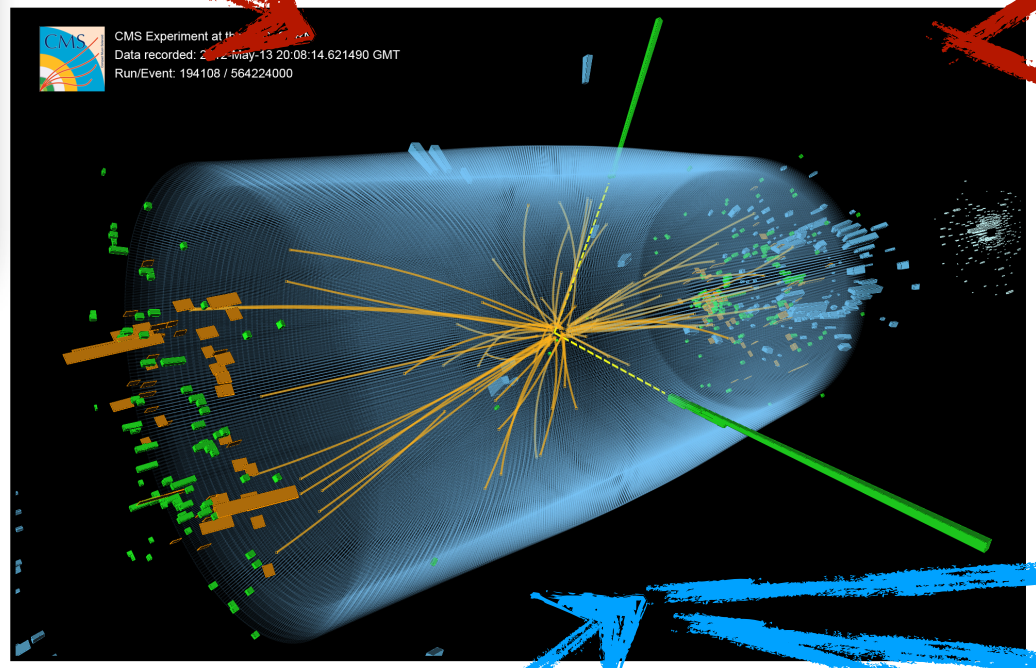
- Relationship between experimental and theoretical collider physics is multifaceted
  - Completely **theory independent** measurements
    - Theory guides interpretation
  - Minimally **theory dependent**: e.g., estimation of backgrounds
  - Theory-dependent conversion/extrapolation of from direct observation to indirect observable

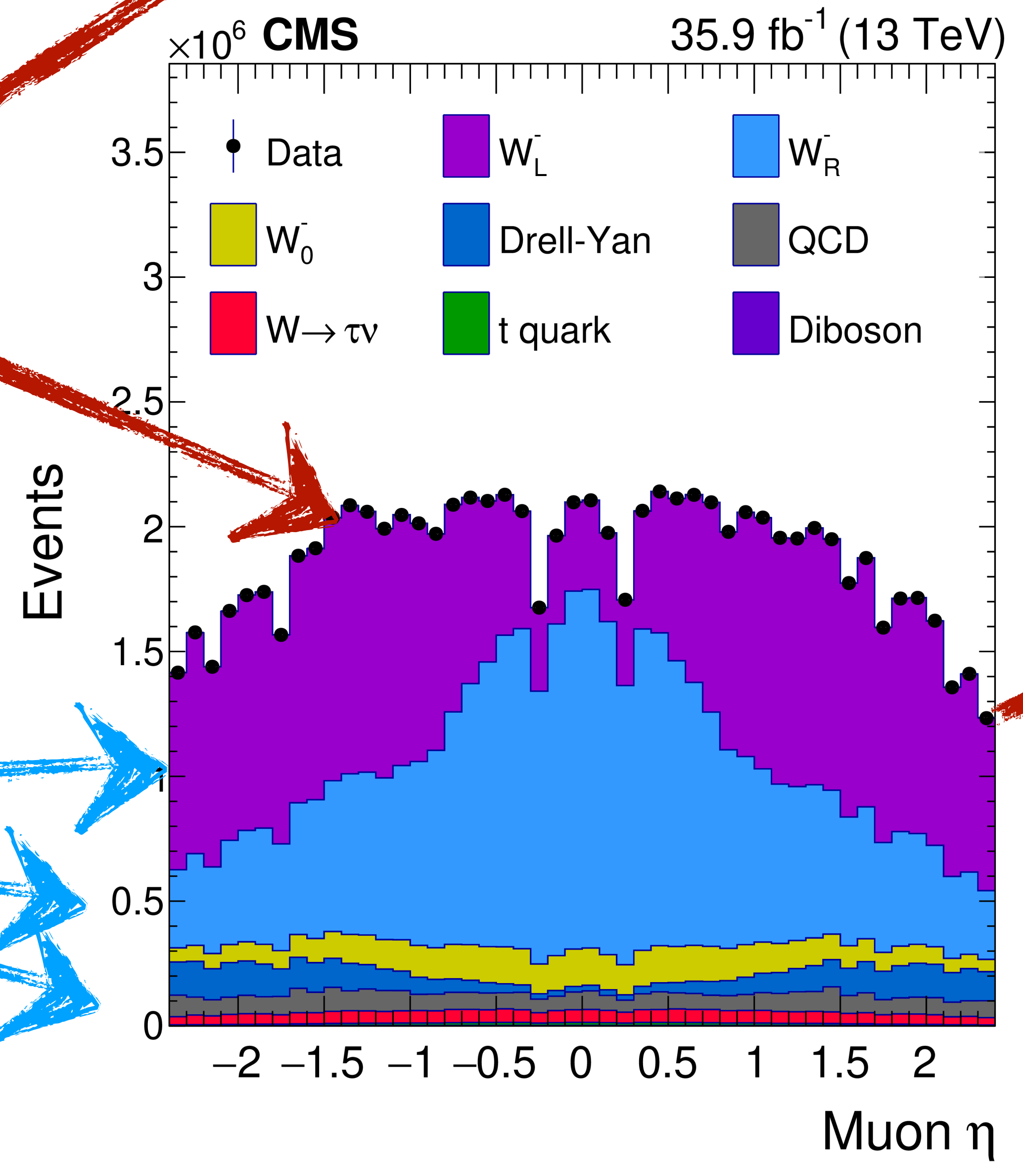


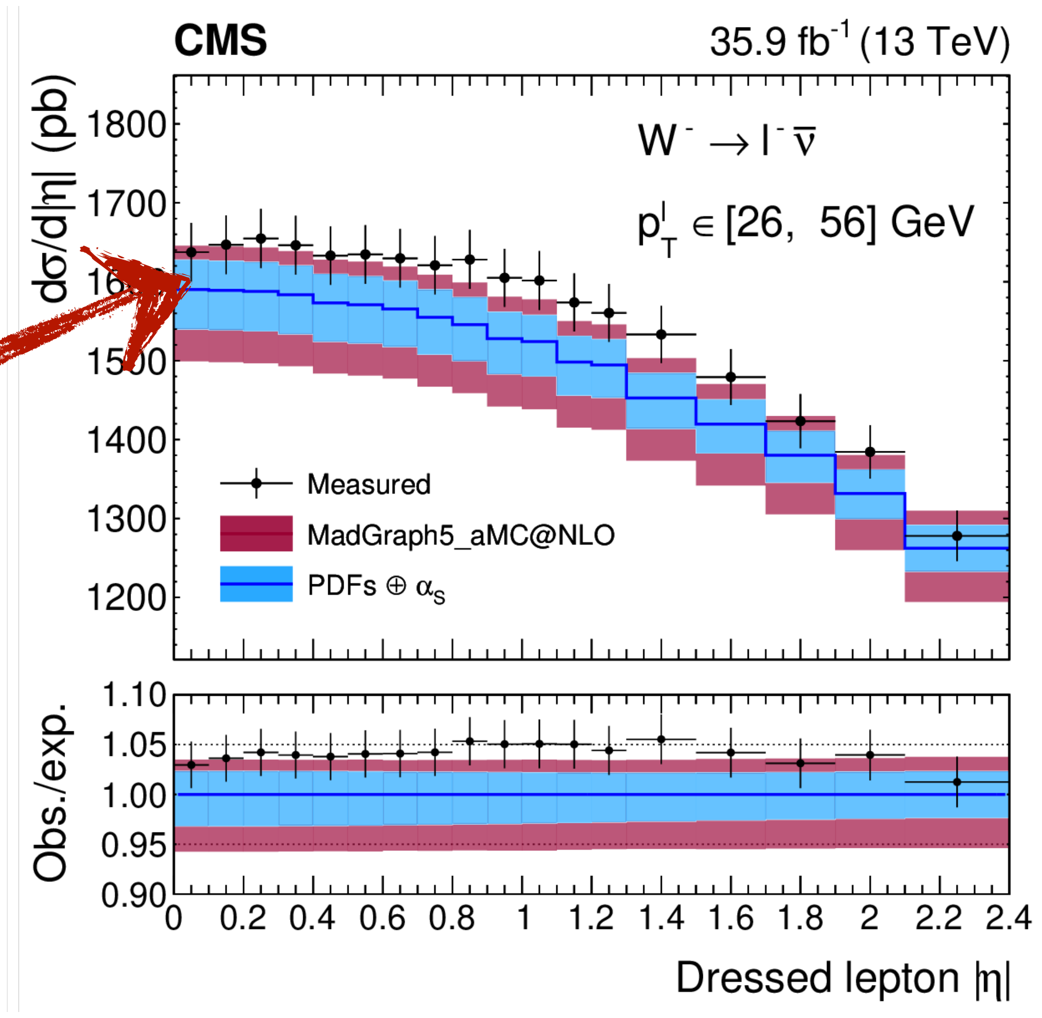
LHC collisions



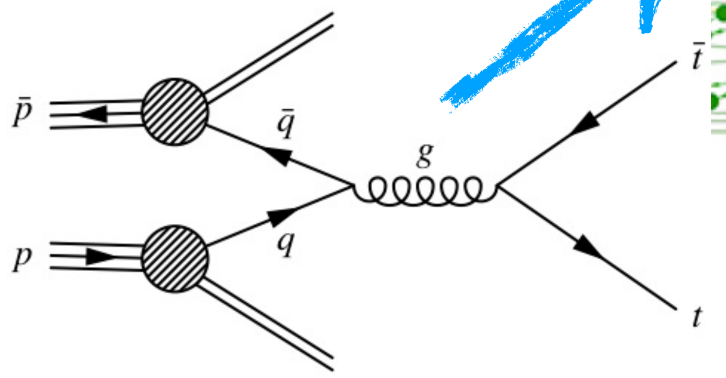
Event reconstruction

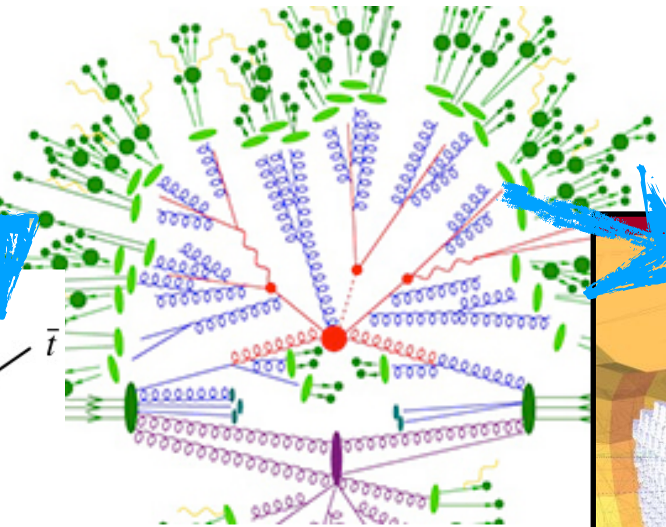


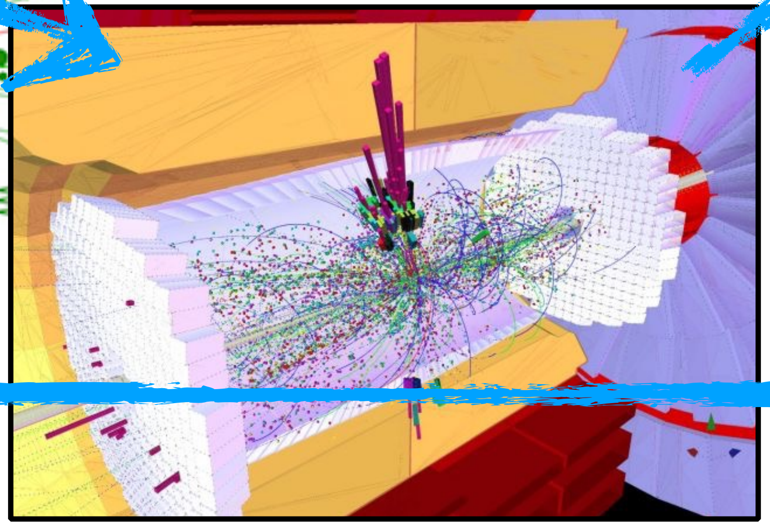




Event simulation



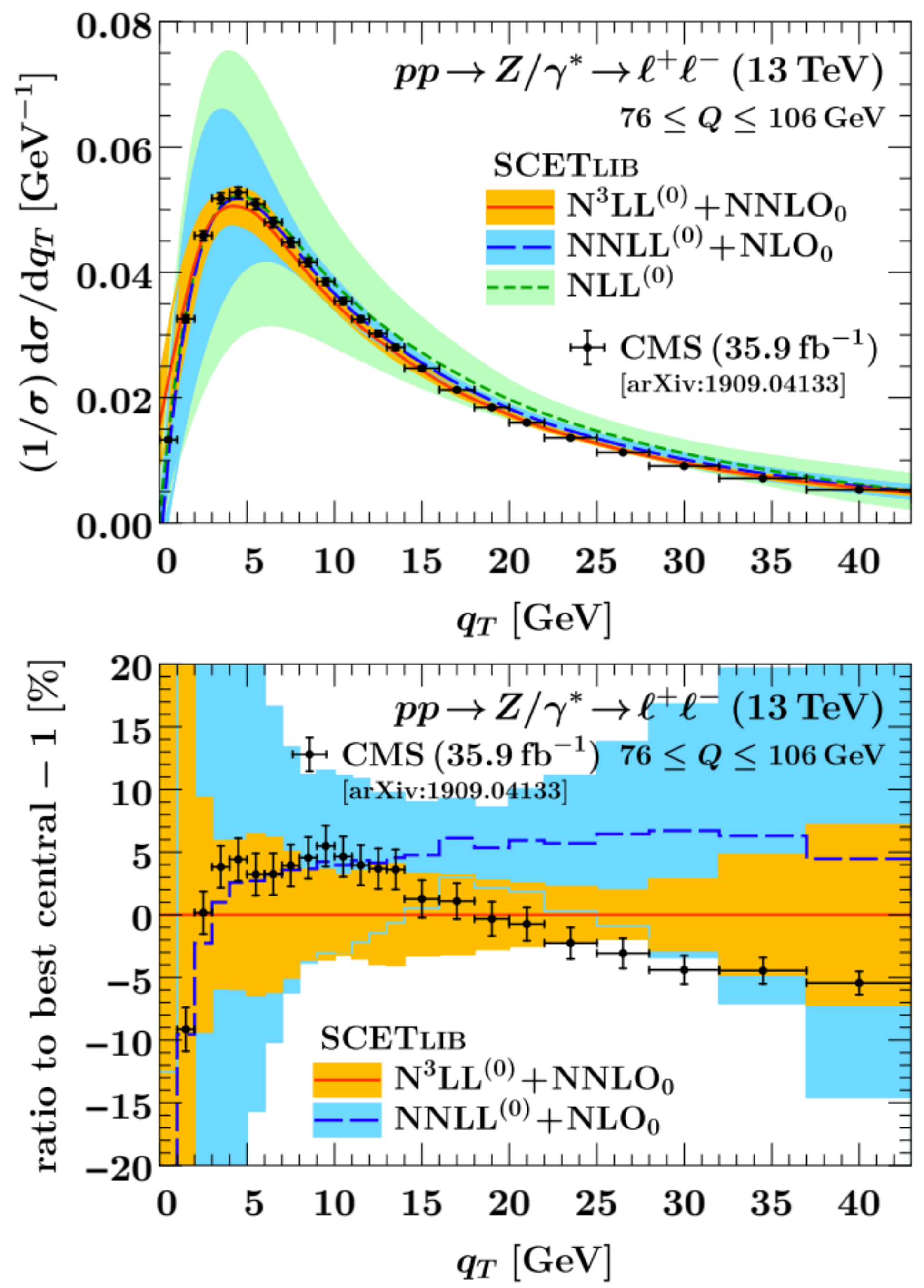


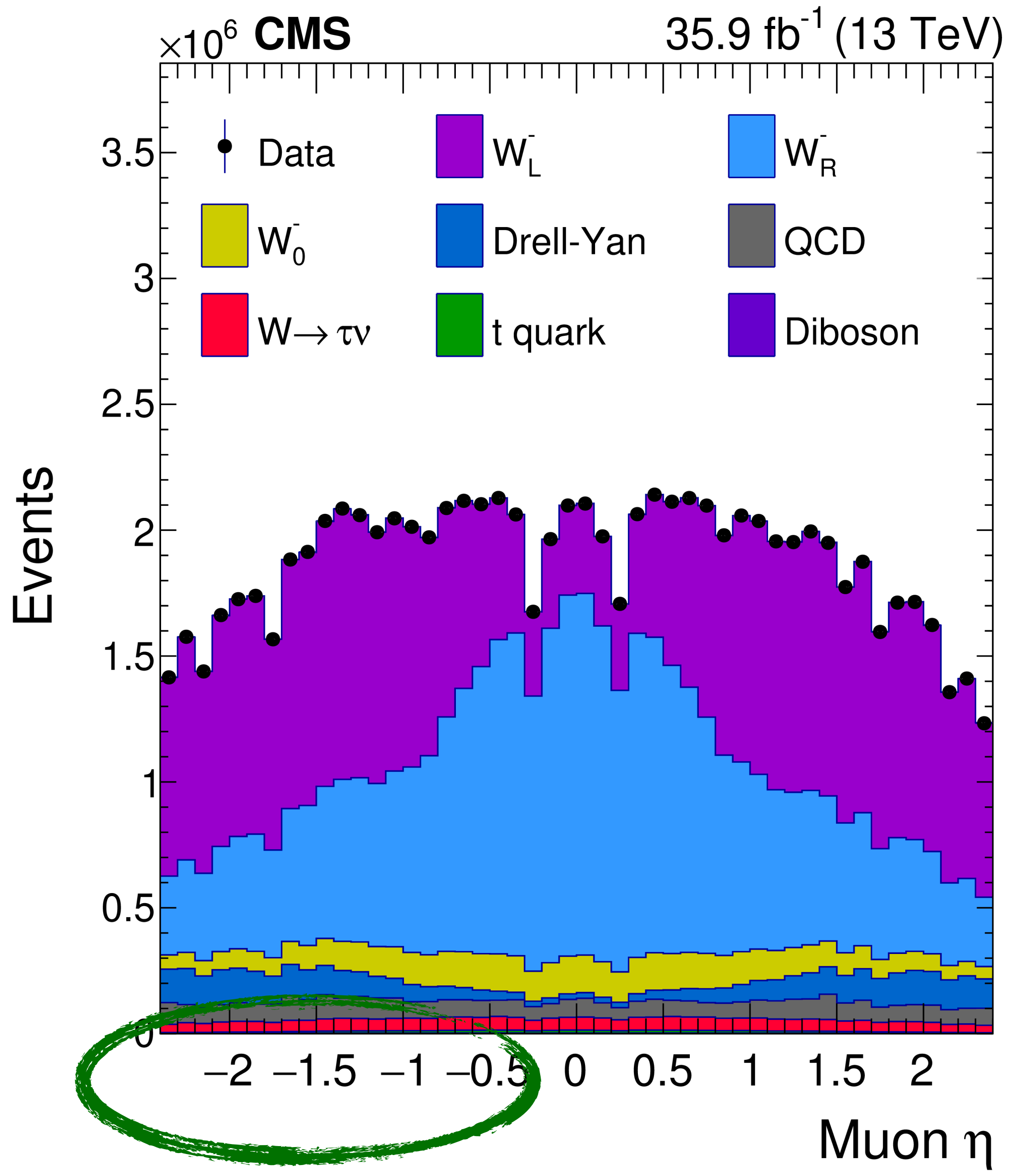


Detector simulation

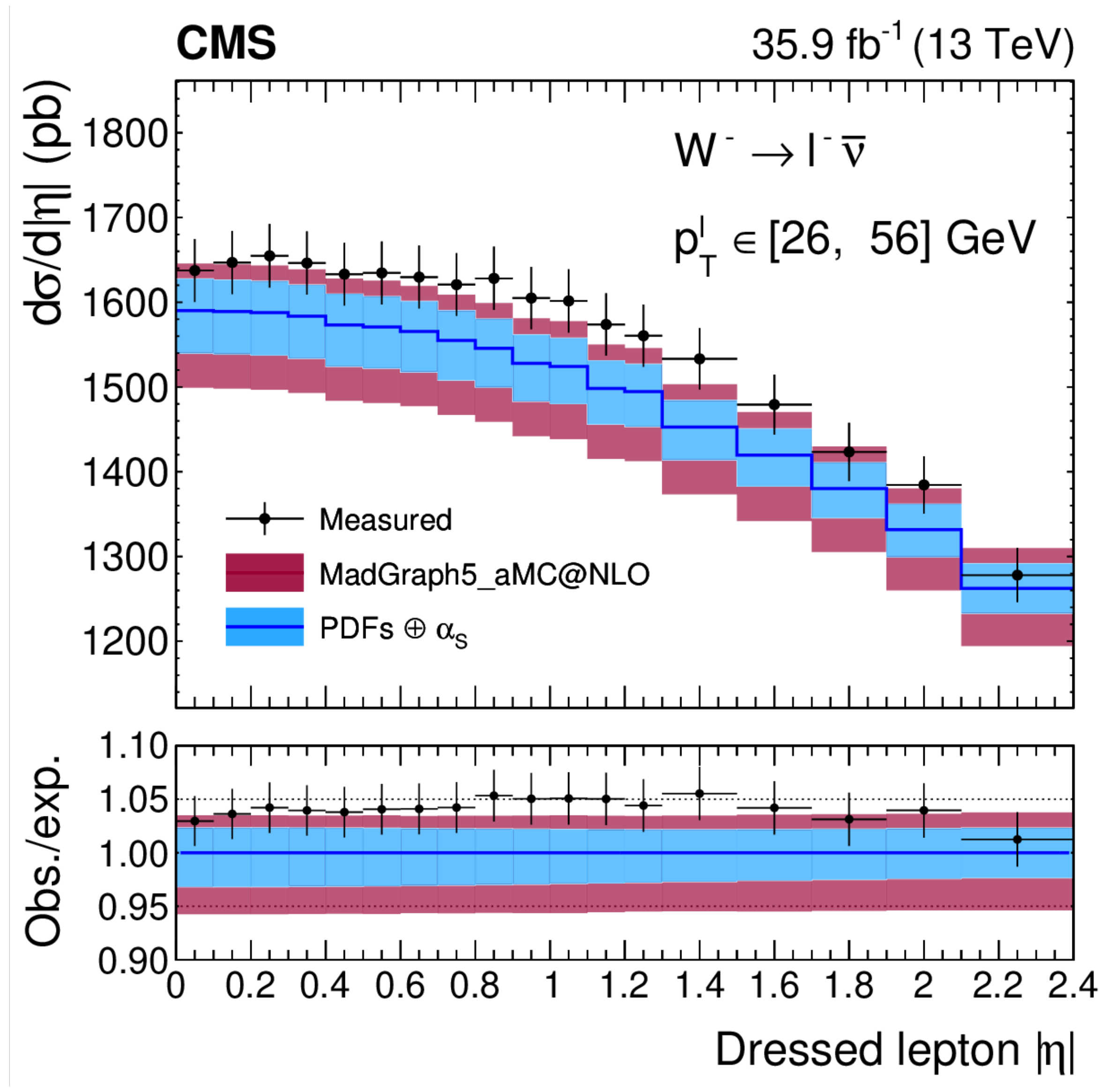
Theory and precision measurements

- Theory uncertainty in **directly measured observable** is minimal
  - Estimation of simulated backgrounds
  - Extrapolation from phase space of measurement to particle-level distribution
  - Correction for detector effects not strongly dependent on underlying physics
- Regardless, improved theory uncertainties, precision are **essential to our work**
  - Do results match expectation?
  - Are discrepancies real? Are they connected/from common underlying source?
- "Wishlist" item: **more accurate calculations everywhere!**

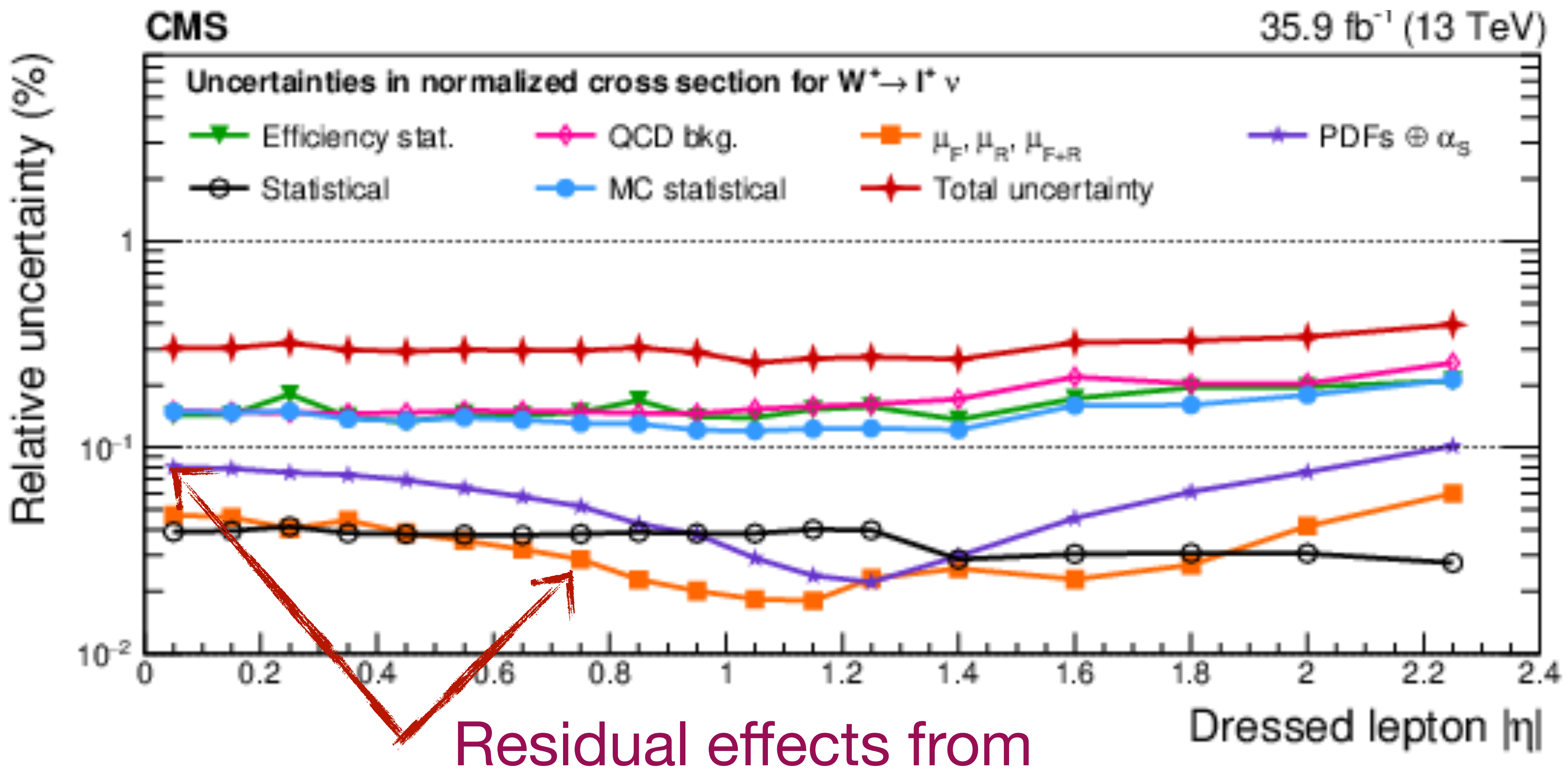




Simulated backgrounds subtracted



Minimal impact from theory on measurement, but improved theory unc. would improve comparison

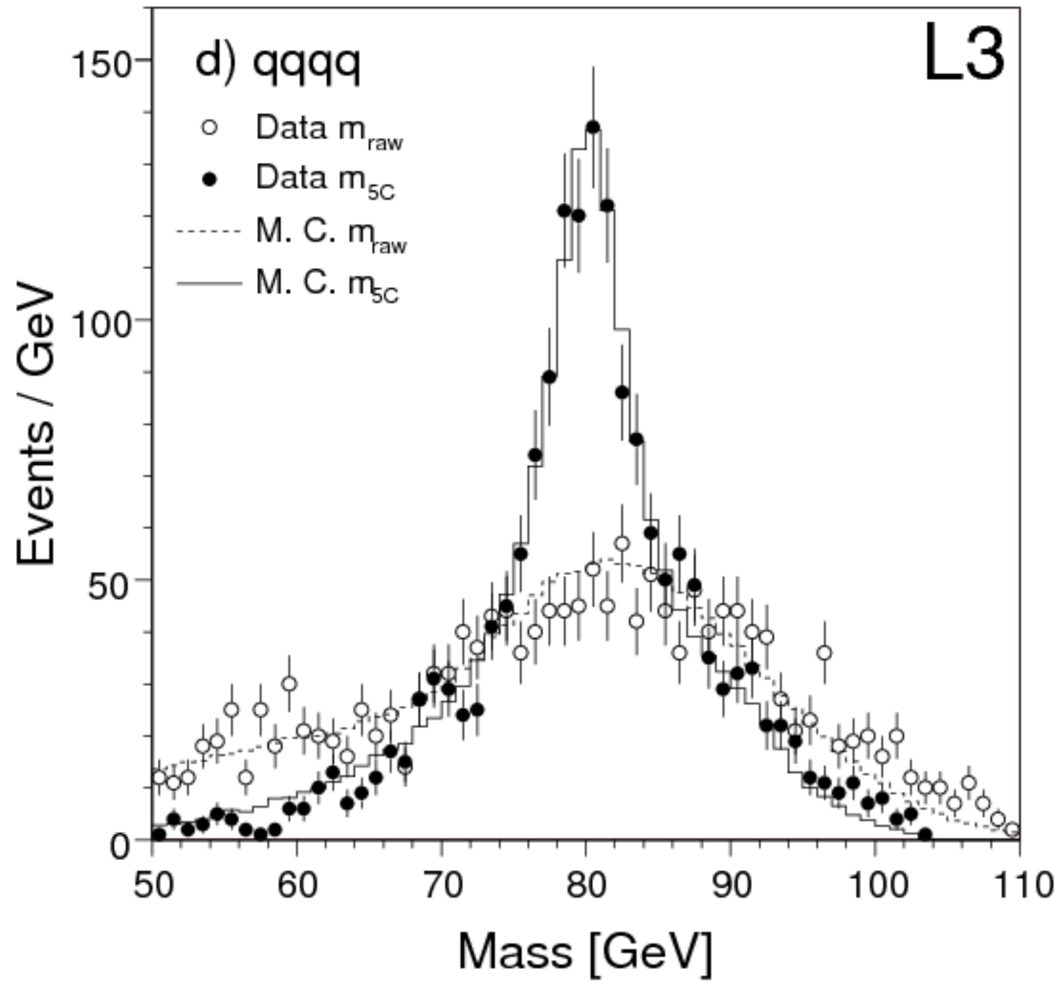


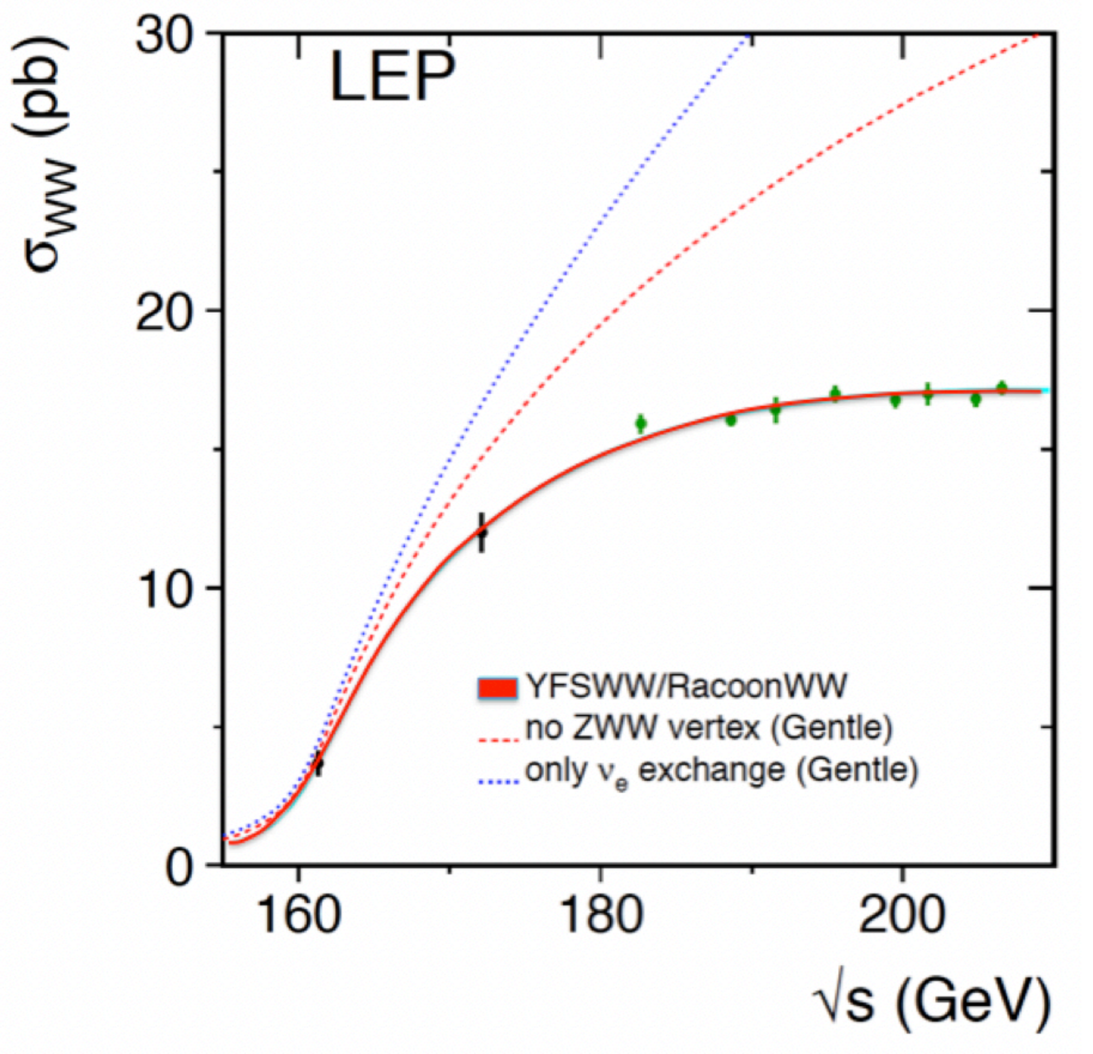
Residual effects from background, extrapolation

Theoretical dependence of m_W extraction at hadron colliders

- At e^+e^-, direct reconstruction of W mass in WW channel possible, but theory uncertainties still relevant
- WW vs. sqrt(s) is largely independent of theory, depends on theoretical knowledge of spectrum to infer m_W

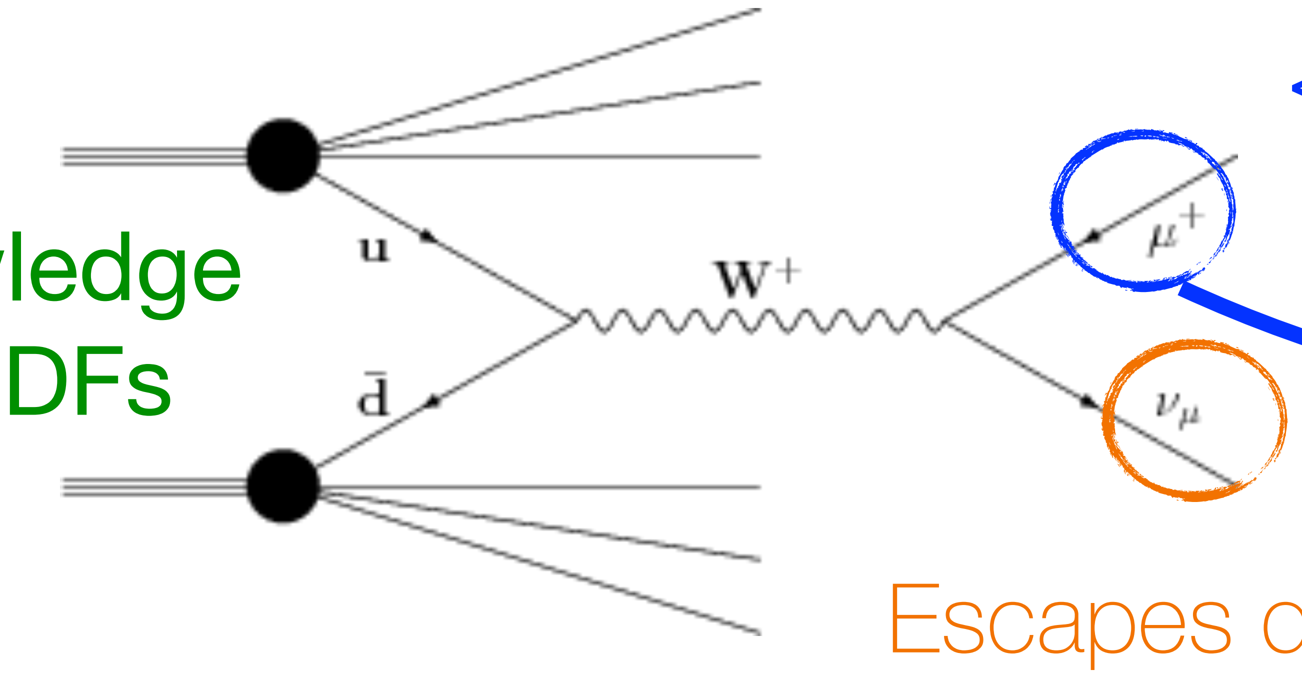
- At hadron colliders, **m_W is not a direct observable**
  - Hadronic decays of W cannot be reconstructed with sufficient resolution
  - Proxies sensitivity to m_W: m_T, p_T^ν (MET), p_T^ℓ





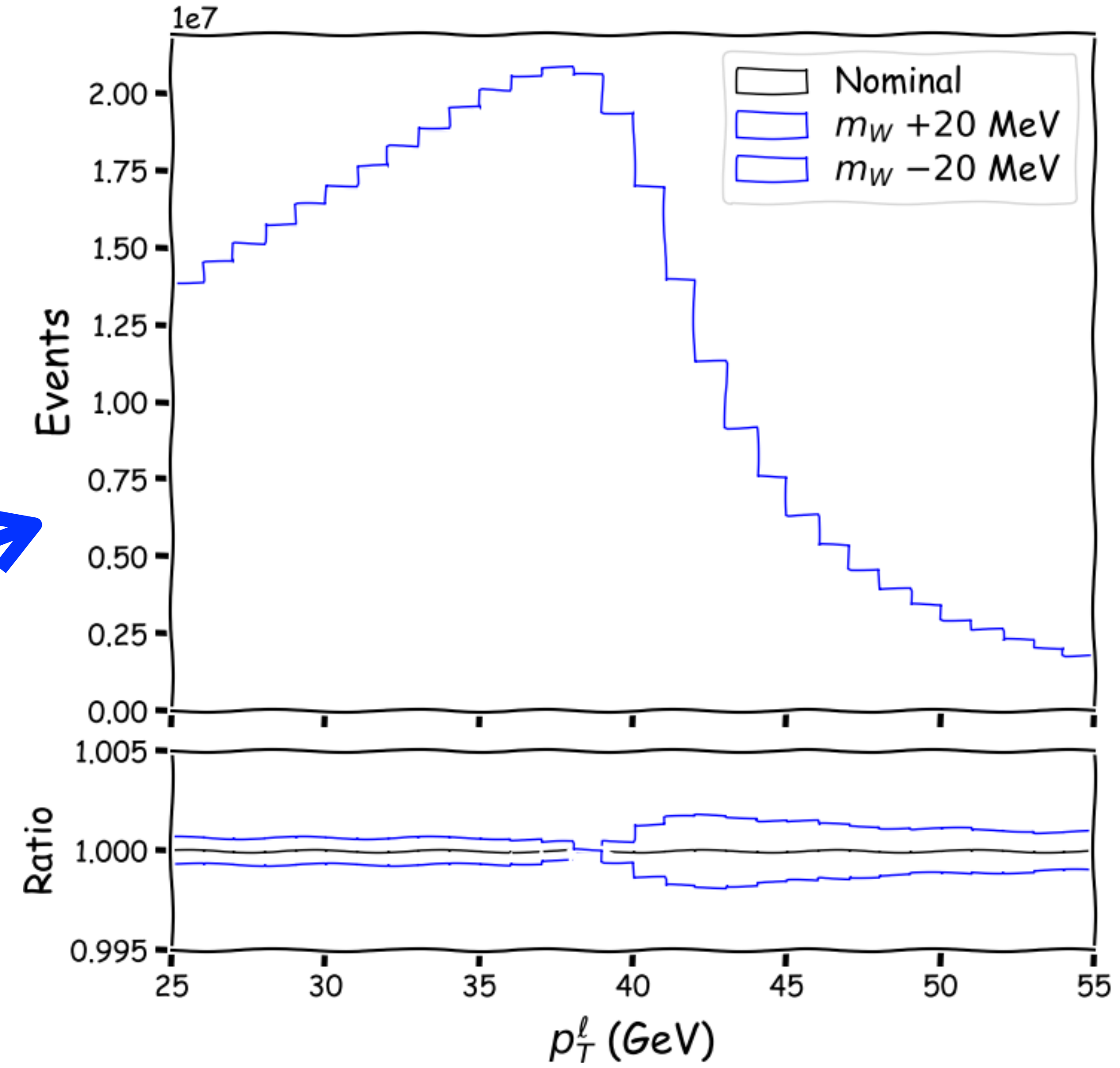
Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	–	35	8	27
Bose-Einstein Correlations	–	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

Knowledge of PDFs



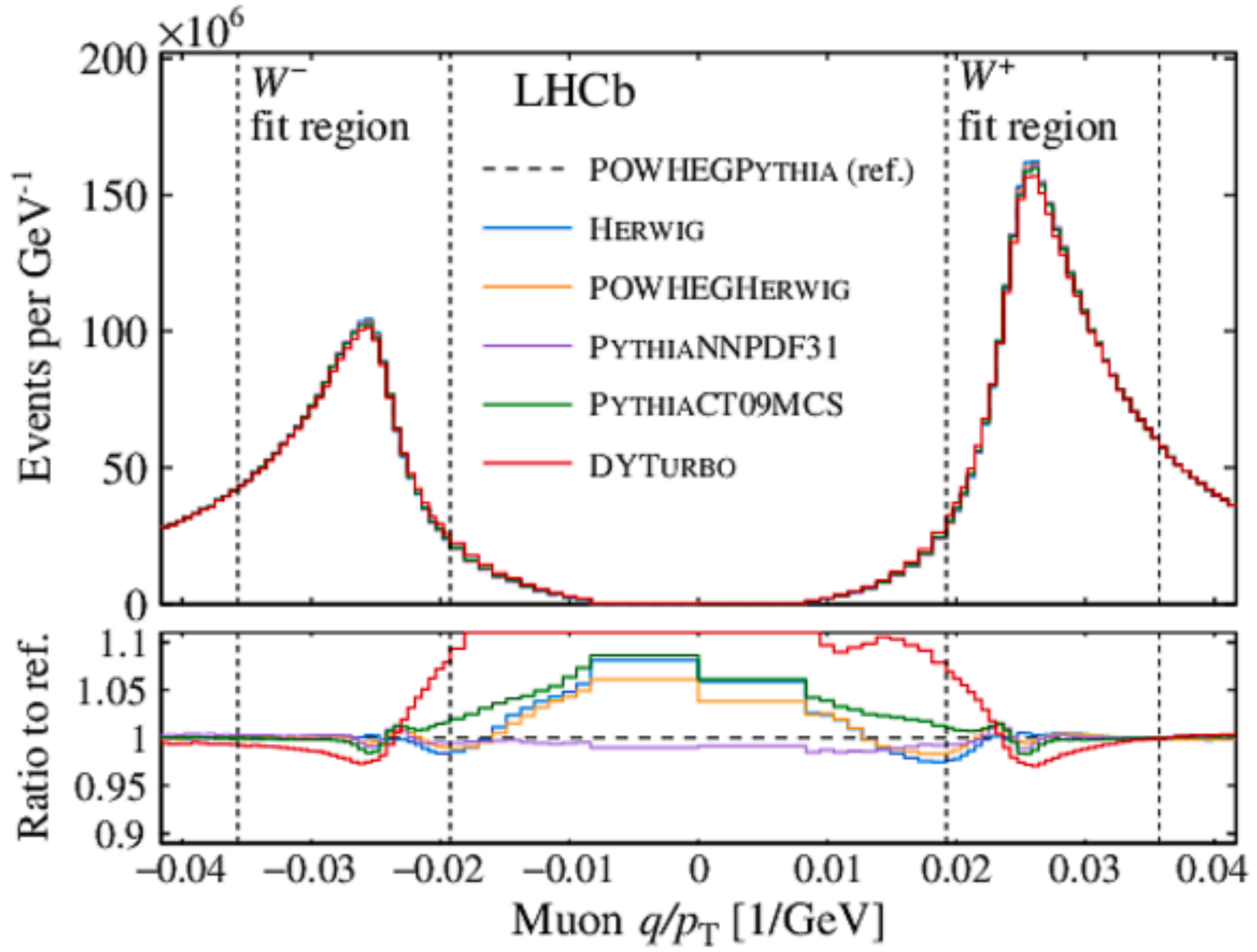
< per mille precision

Escapes detection
⇒Missing transverse mom.



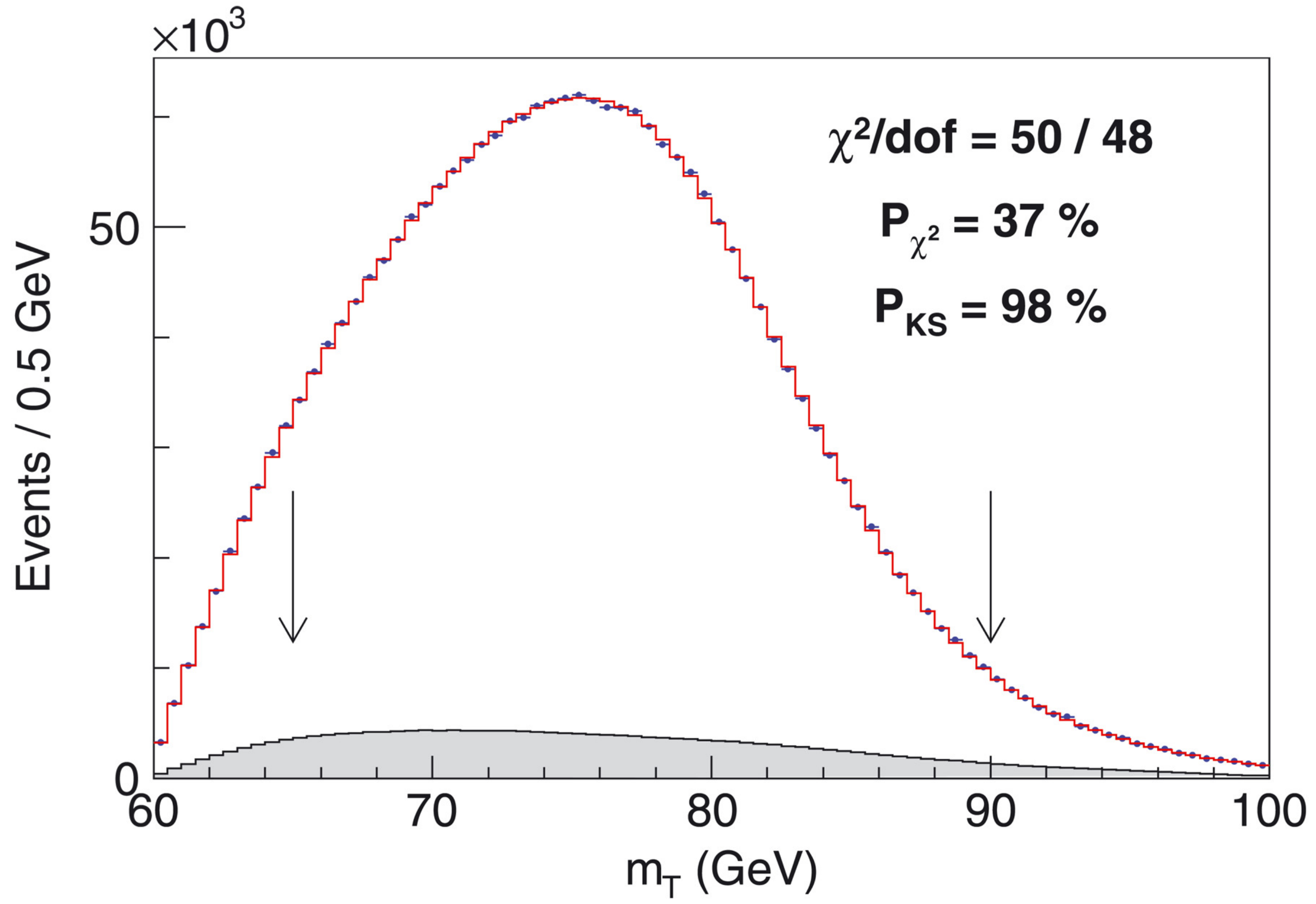
The role of theory in experimental extraction of m_W

- p_T^ℓ simplest experimentally, but **depends on (unmeasured) W kinematics**
    - Independent measurement at LHC limited by MET resolution
- m_T requires less theory extrapolation, but extremely challenging at high pileup
    - ATLAS dominated by p_T^ℓ ~90% power (at < 1/3 pileup in 7 TeV)
    - CDF has significantly better resolution due to lower energy, pileup, combination ~65% from m_T
- Machine-learning is promising for improving resolution/recoil, but **p_T^ℓ is the focus of short-term** CMS measurement



- Understanding of p_T^W to extract m_W from p_T^ℓ is a **leading challenge of the measurement**
    - State of the art calculations+auxiliary measurements+tuning+…?
    - Bulk of distribution at low values of p_T^W =>understanding of this region critical

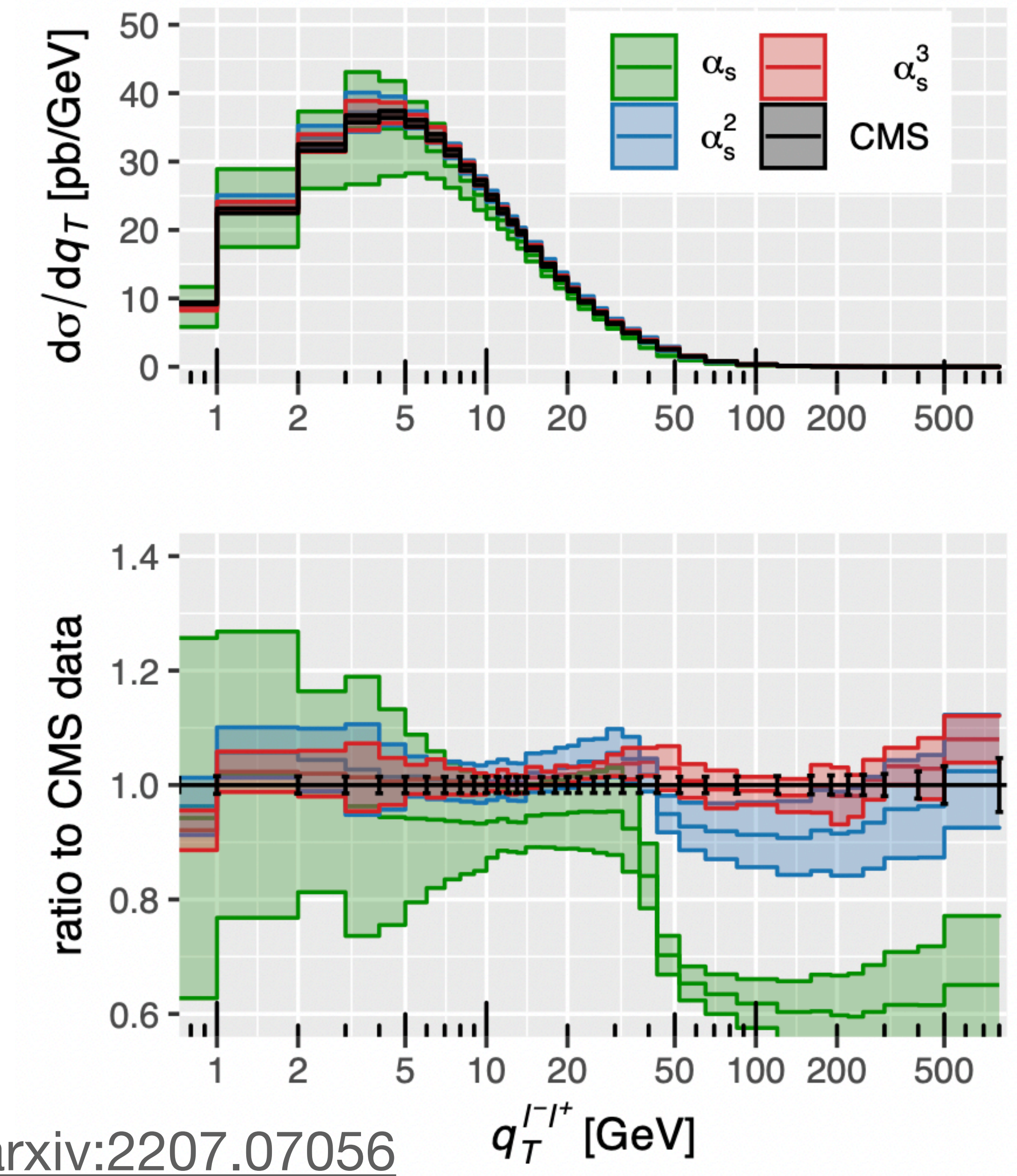
➡ Interplay with experimental uncertainties makes post-facto extraction of m_W impractical



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

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



arxiv:2207.07056

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

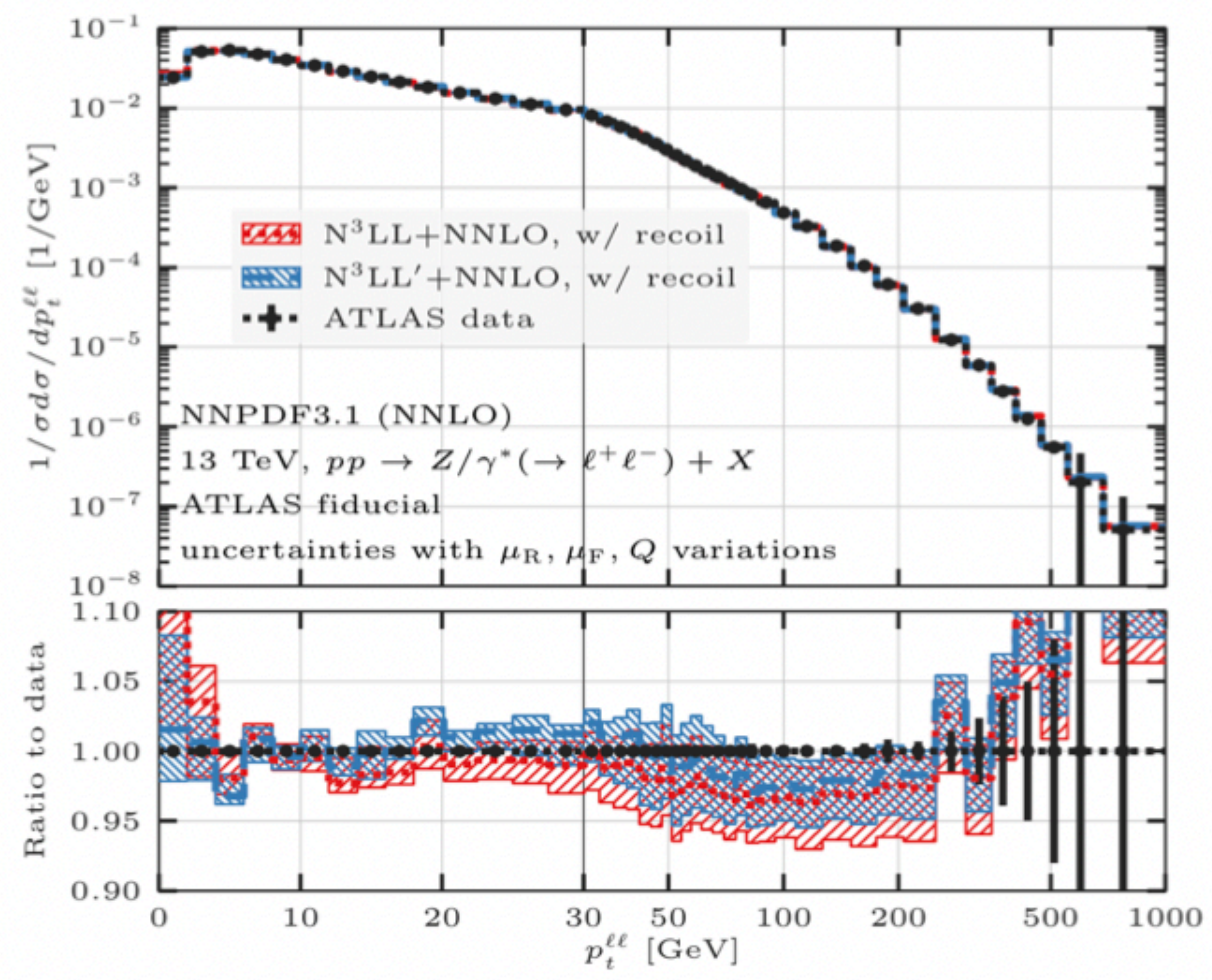
SCET-based tools:

`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

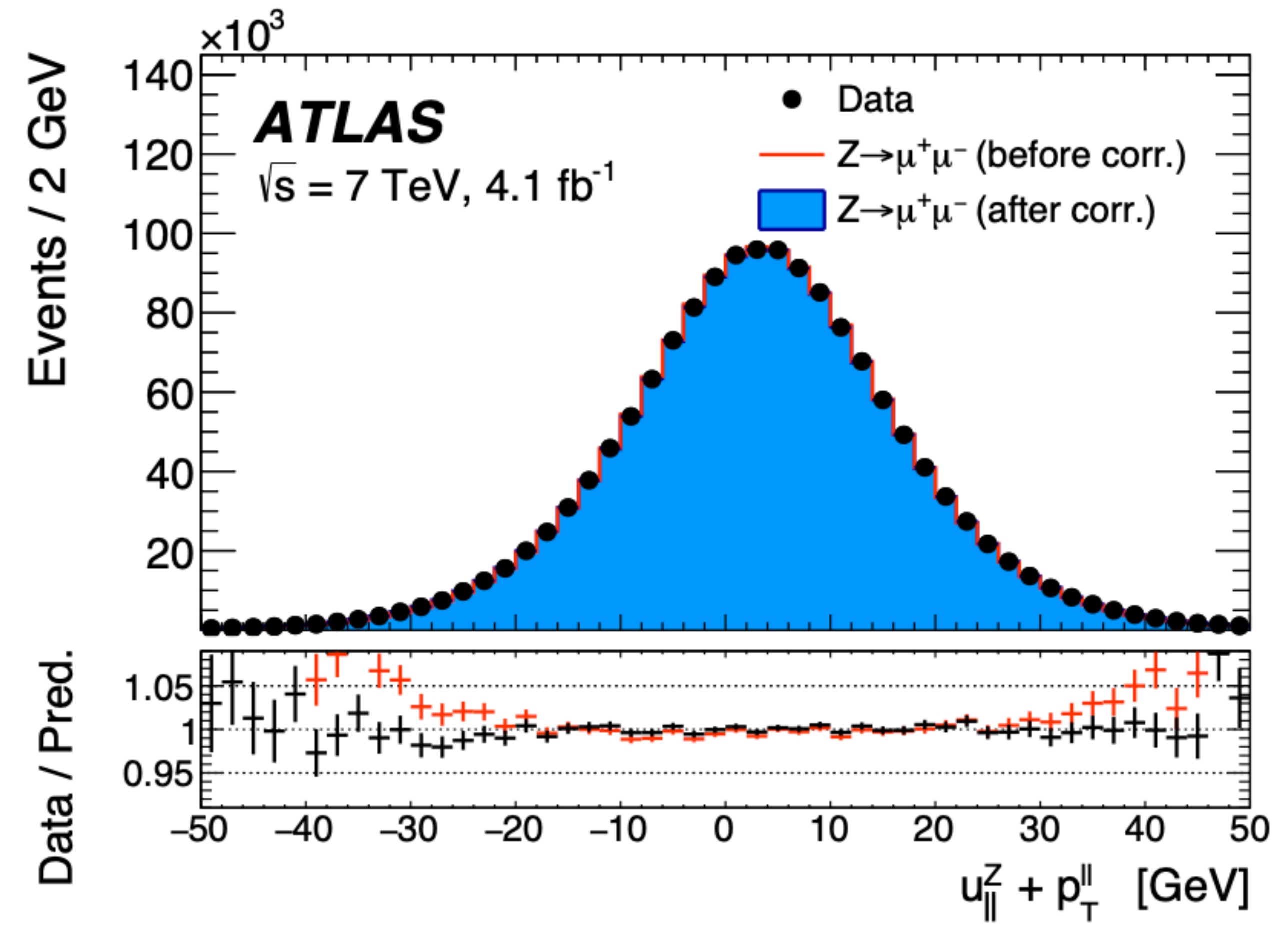


[RadISH, 2104.07509]

- "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?

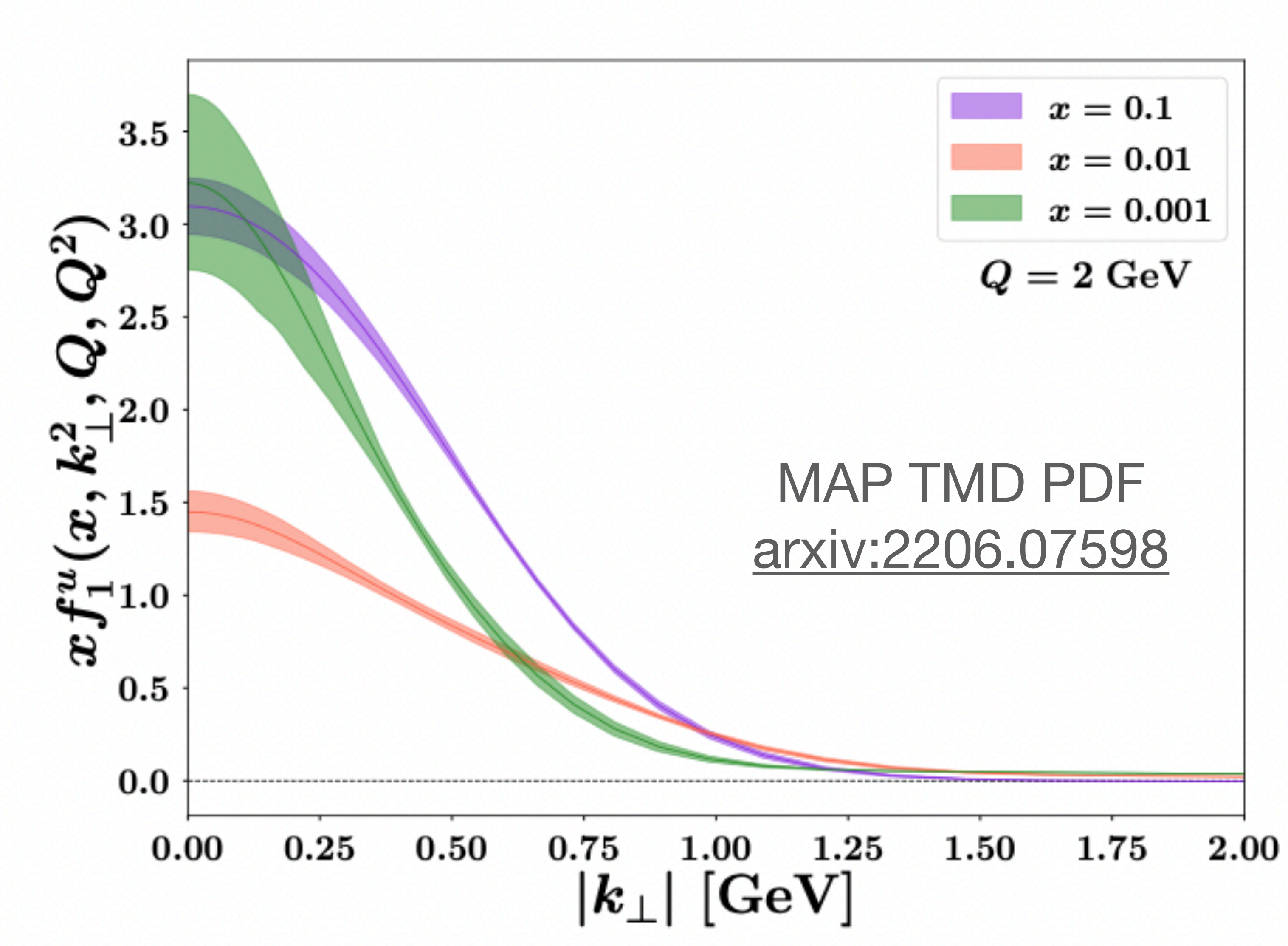
Non-perturbative effects in m_W

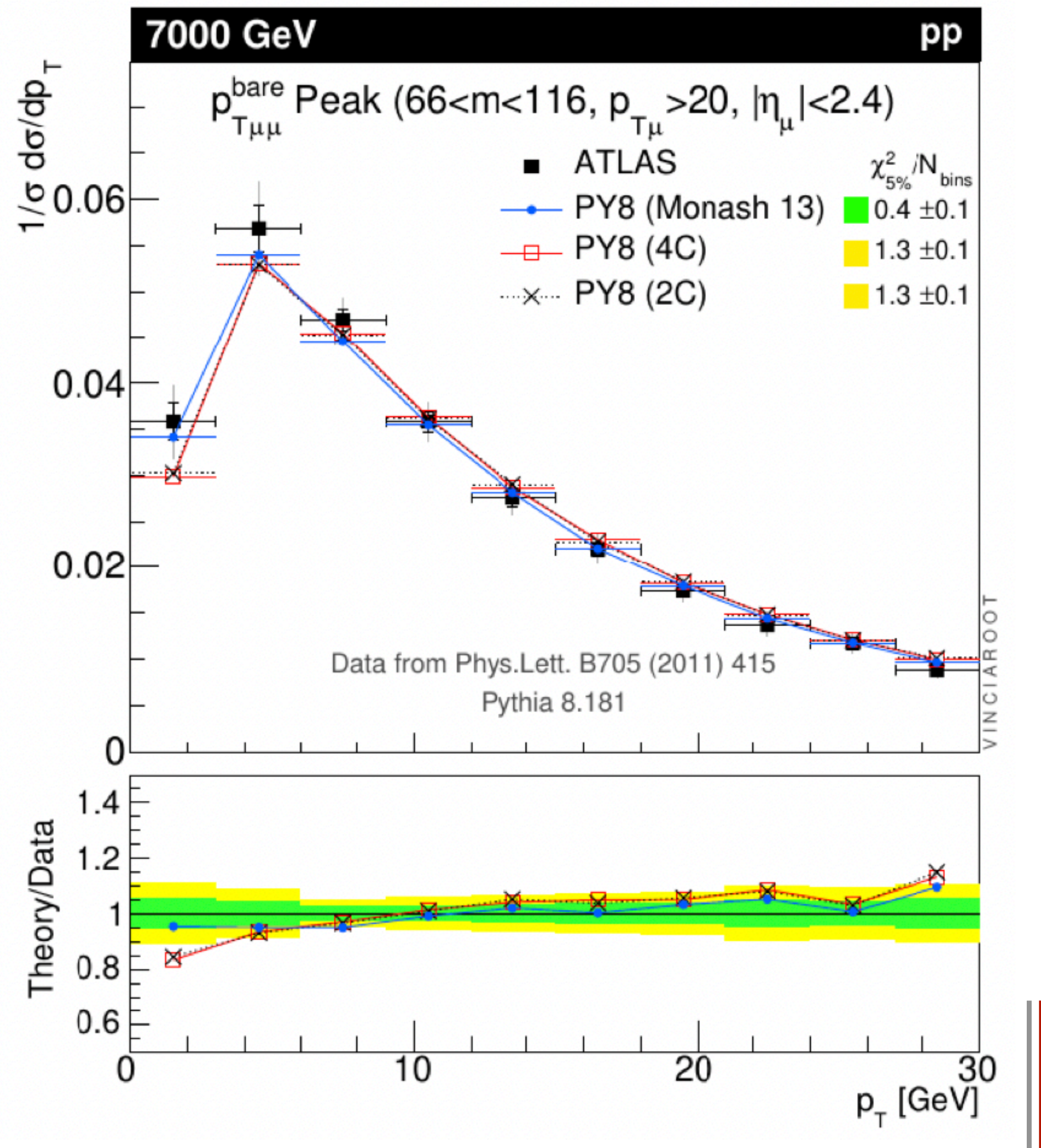
- Huge progress in resummed and FO perturbative calculations, but very low W p_T is **sensitive to independent, less understood NP** effects
  - Tune to measurements => robust, flexible parameterisation needed
    - Simple Gaussian model of Pythia commonly used in event generation
    - BLNY form used in CDF: $S = \left[g_1 - g_2 \log\left(\frac{\sqrt{\hat{s}}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right)\right] b^2$



- Transportation of Z-derived recoil correction to W sensitive to flavour differences, composition
- “Wishlist” item: towards recommendations for NP parameterisation
  - Applicability across processes
  - Uncertainty (from parameterisation?)
  - Wider development/use of TMD PDFs

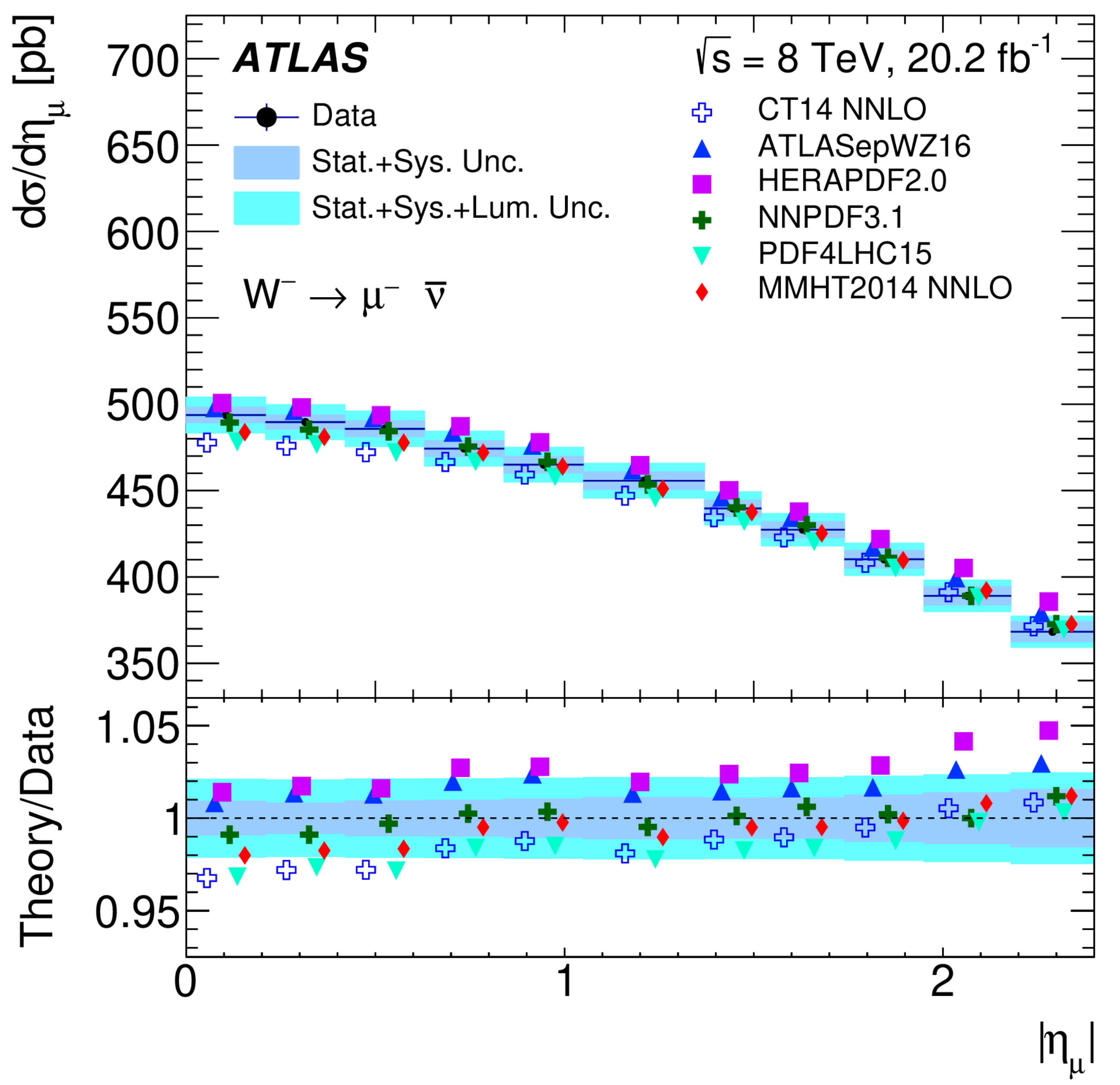
https://indico.cern.ch/event/1194333

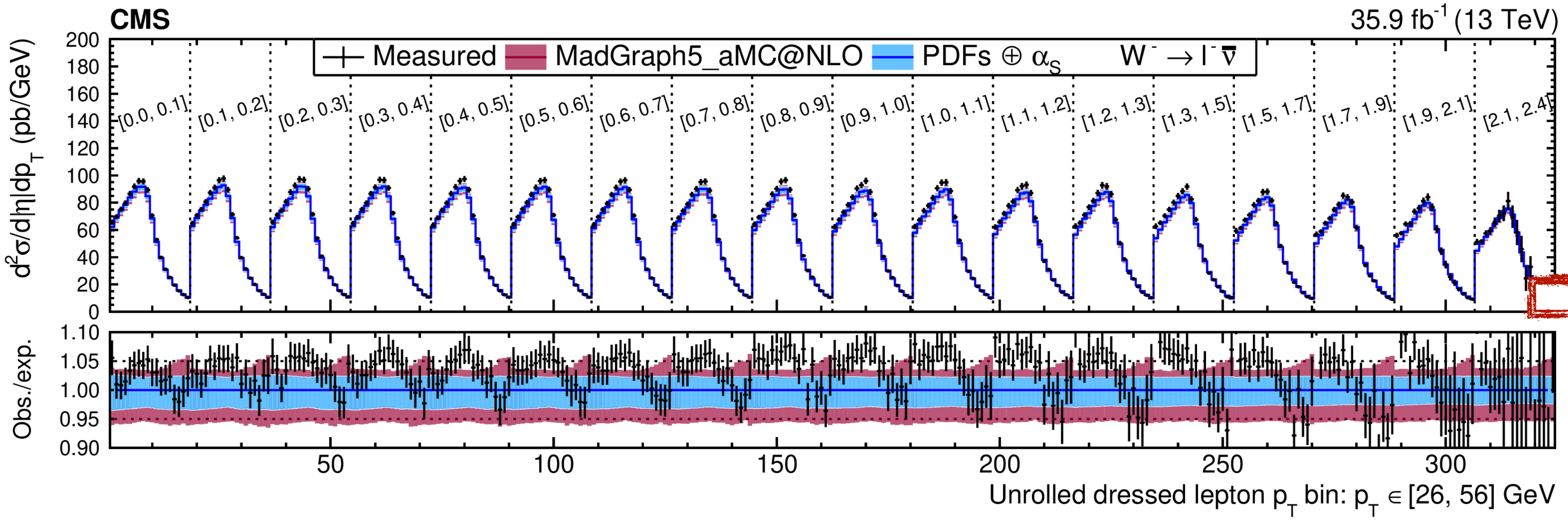


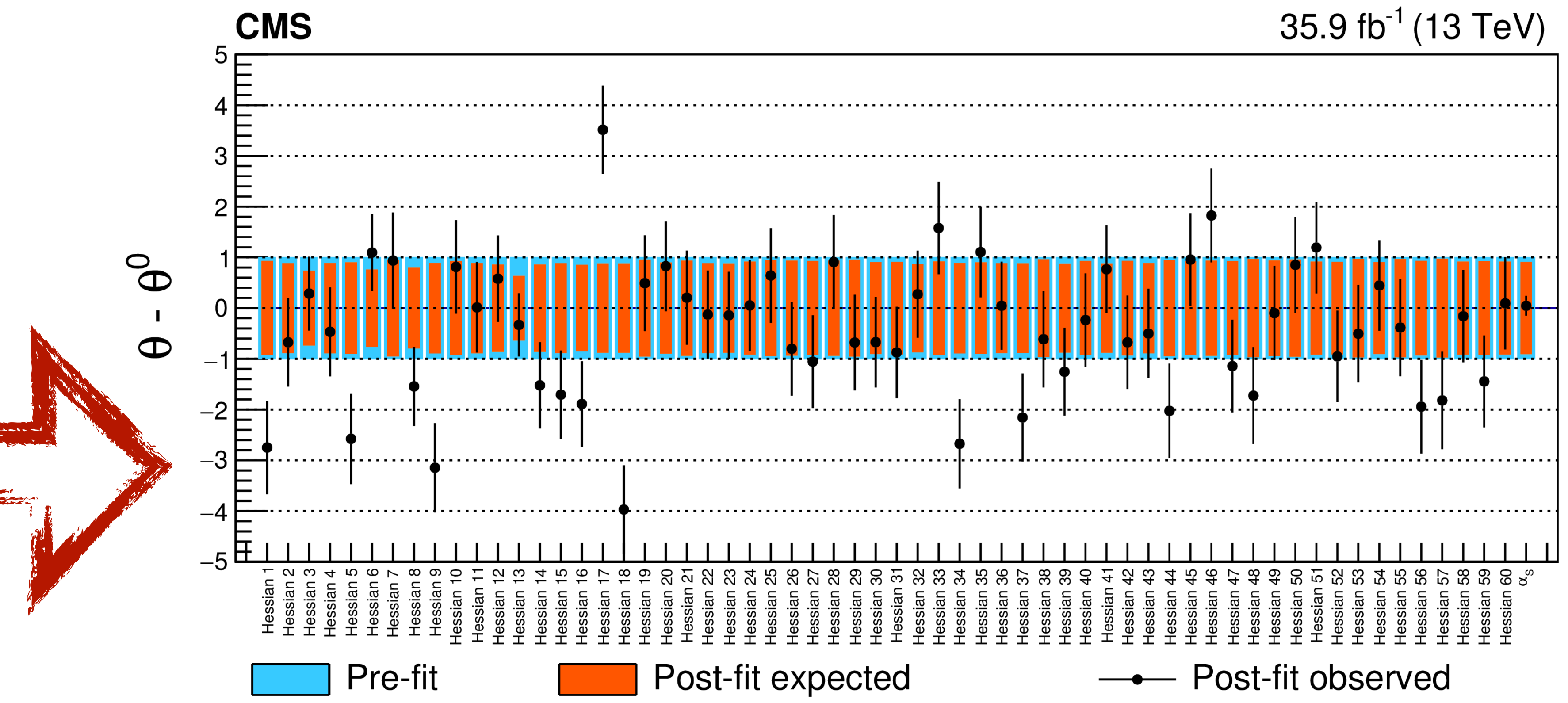


Experimentally constraining theoretical uncertainties

- Experiment always seek to provide **results that drive/improve theory**
  - e.g., comparison of measured result to predictions from many PDFs
  - Incorporate published, unfolded results into future PDF fits
- Ideally would **short circuit this process**
  - Profile hessian PDF uncertainties or weight MC replicas (arxiv.org:1902.04323)
- CMS-SMP-18-012: Profiled PDF nuisances used to derive post-fit PDF
  - Not a full PDF fit (uses NLO MC, old PDF set) but **clear constraining power**
- Wishlist items
  - Direct tests of procedure (theory+exp collaboration)
  - Improved perturbative accuracy. Theoretical uncertainties in PDFs.



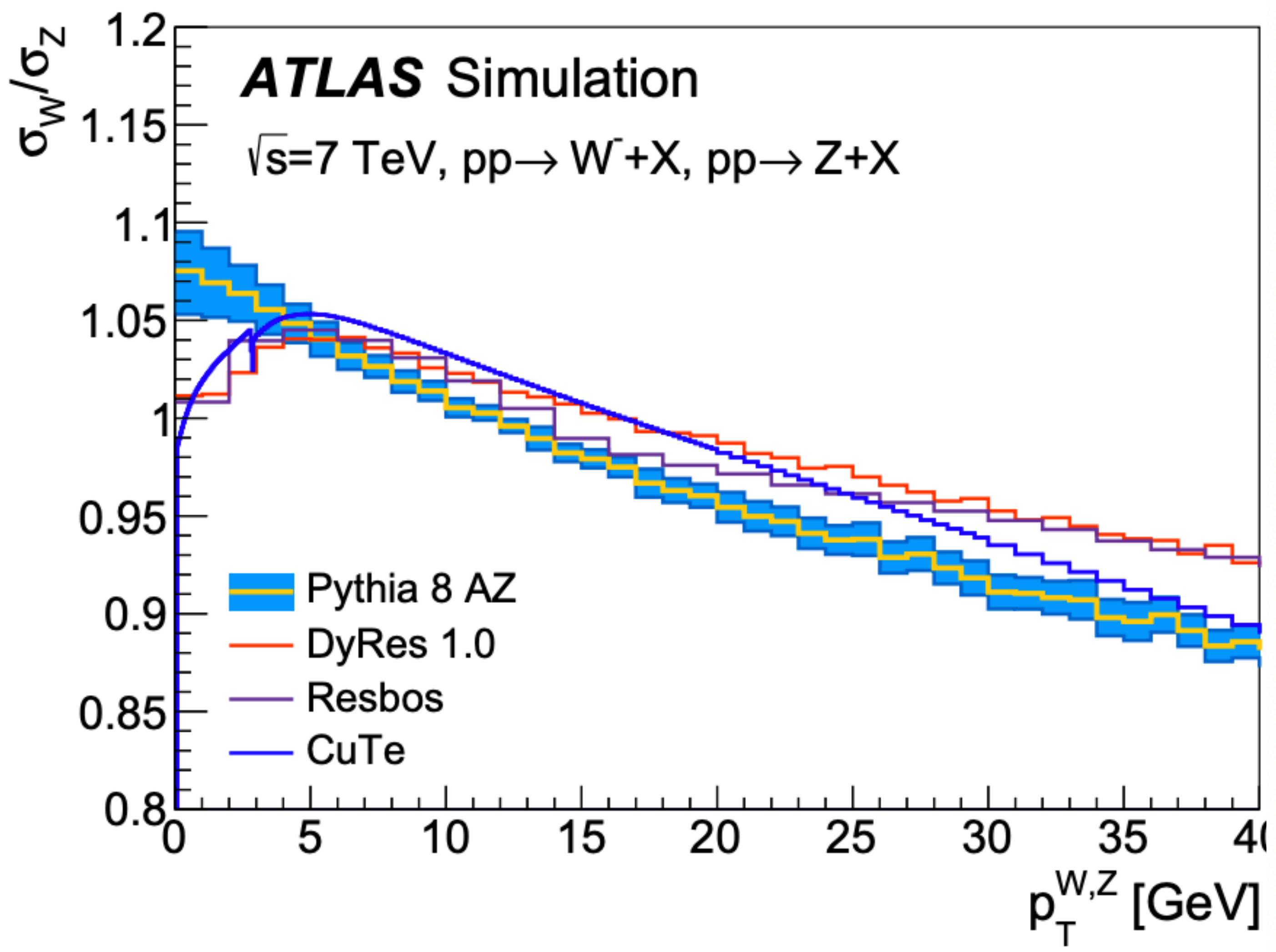


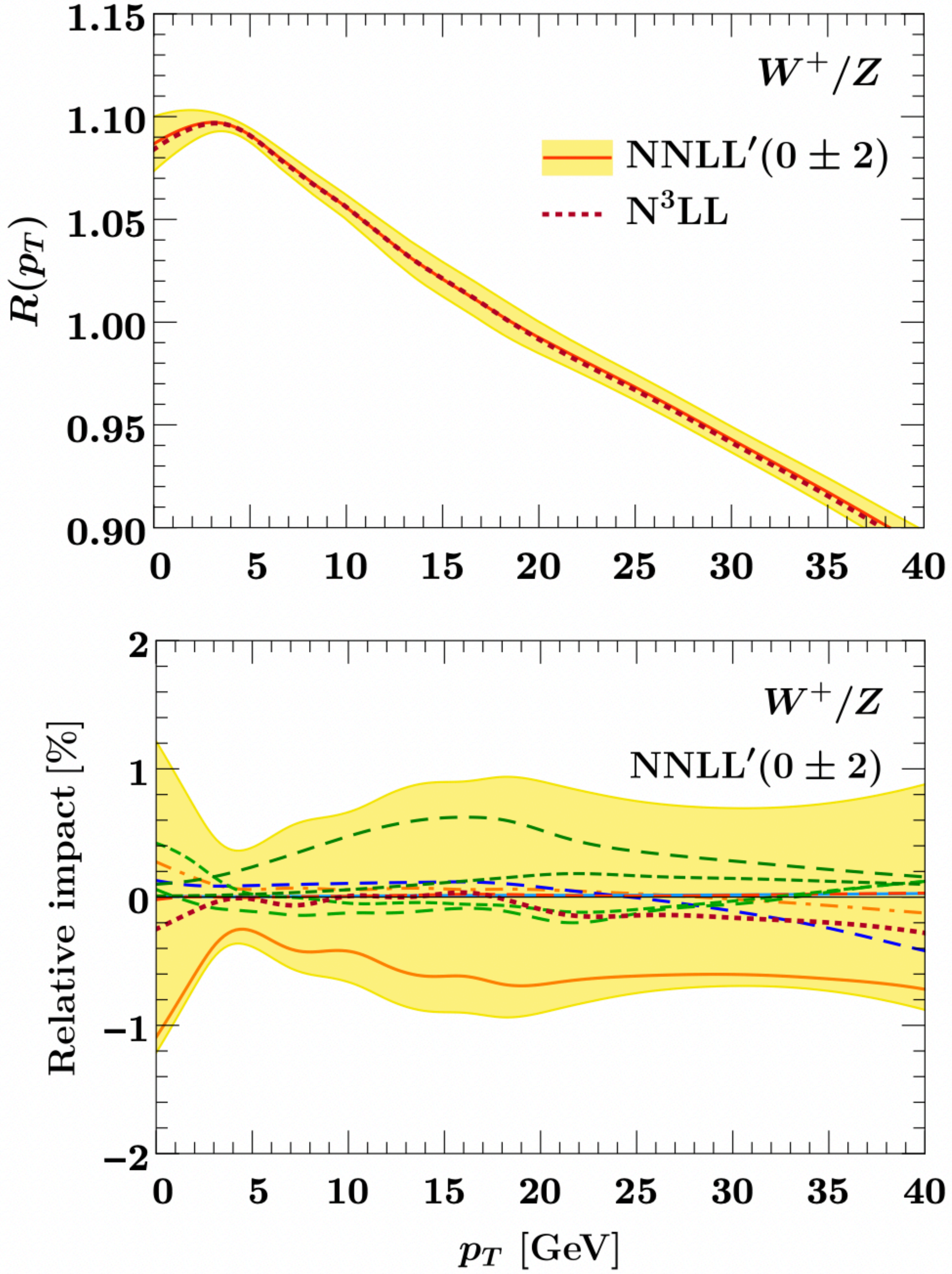


Experimentally constraining theoretical uncertainties: beyond PDFs

- Z boson is extremely well understood experimentally
  - Can we **exploit this to learn more about W** production (especially p_T^W)?
  - Ideally posed as a statistical problem: define uncertainties which connect underlying parameters of Z and W in a meaningful way

- "Wishlist" items
  - "Recipe" for transporting Z measurements to W
  - Optimally: **well-defined nuisance parameters** that can meaningfully be profiled in a likelihood fit
    - Expose parameters of a calculation that have "true" values (experimentally determinable)
    - Aware of "theory nuisance parameter" implementation in SCETlib, but not available in public implementations

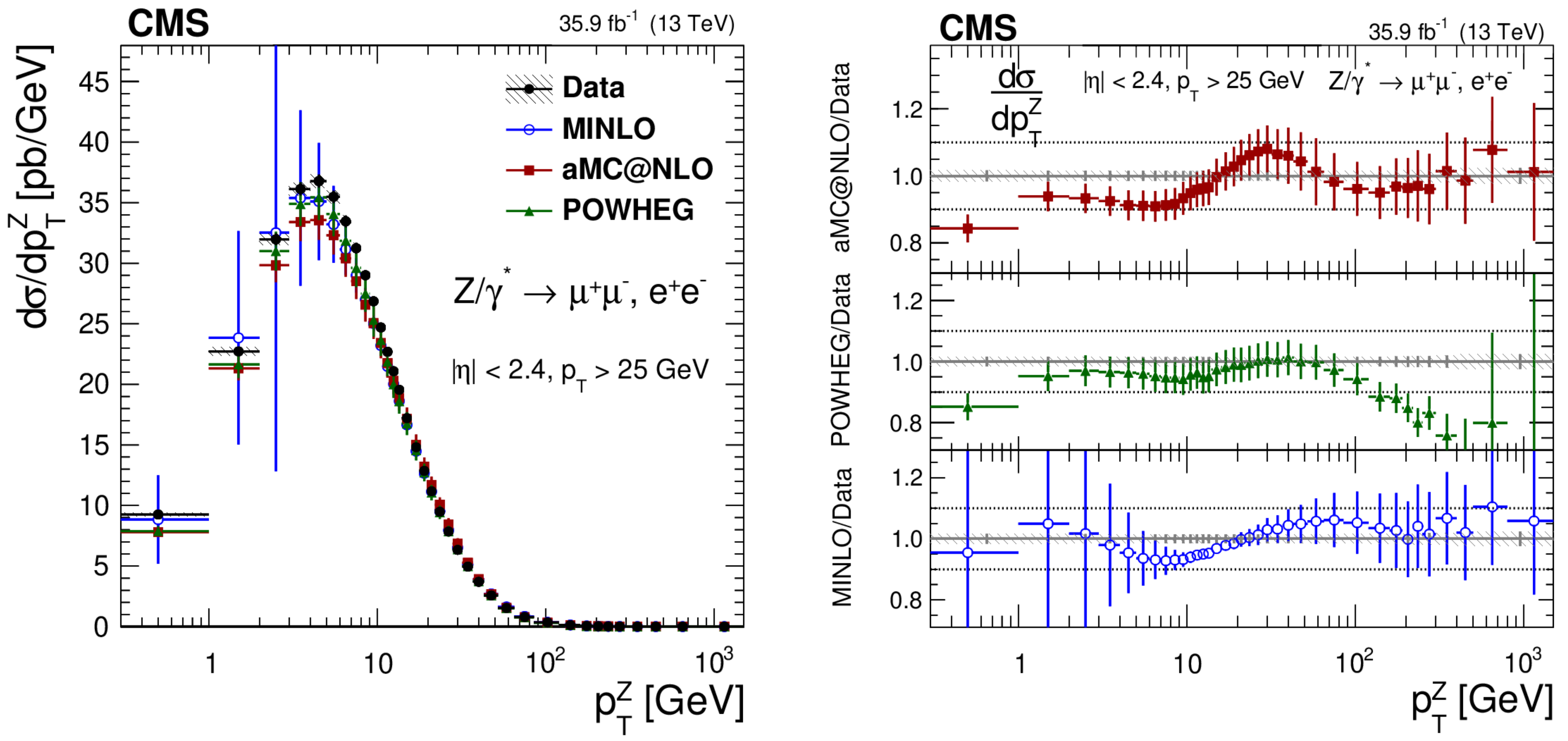


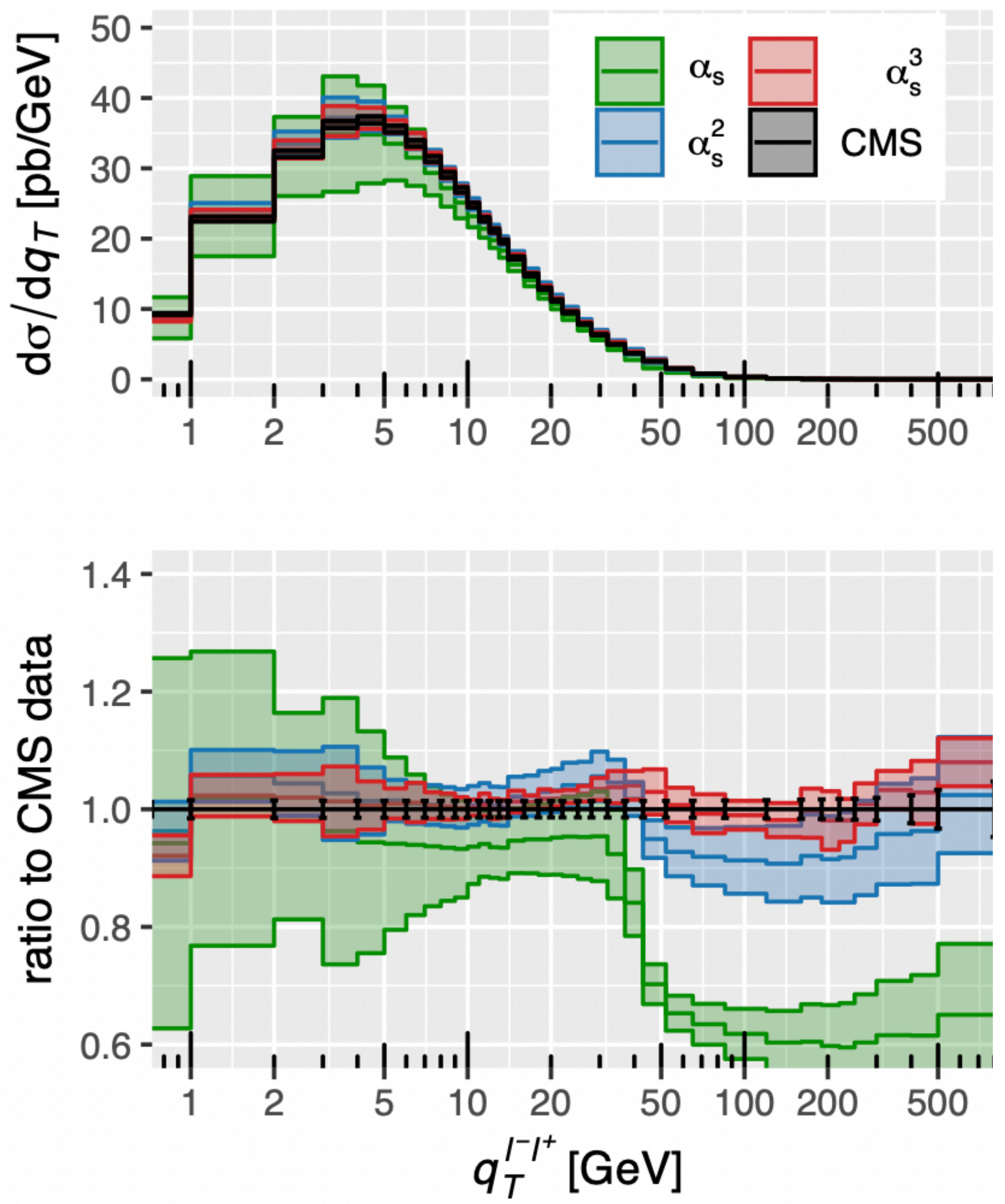


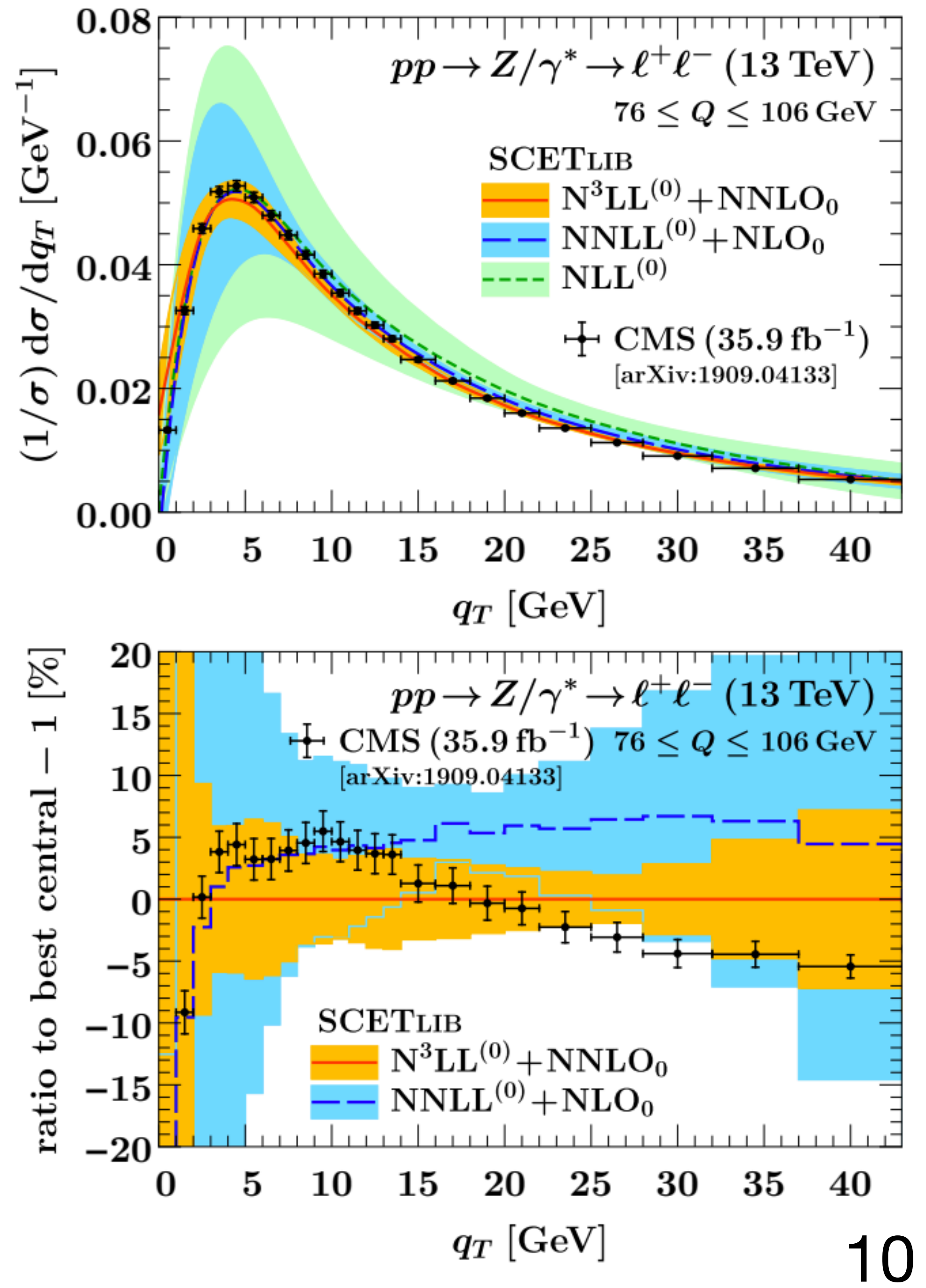
F. Tackmann
https://indico.cern.ch/event/801961/contributions/3334772/

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

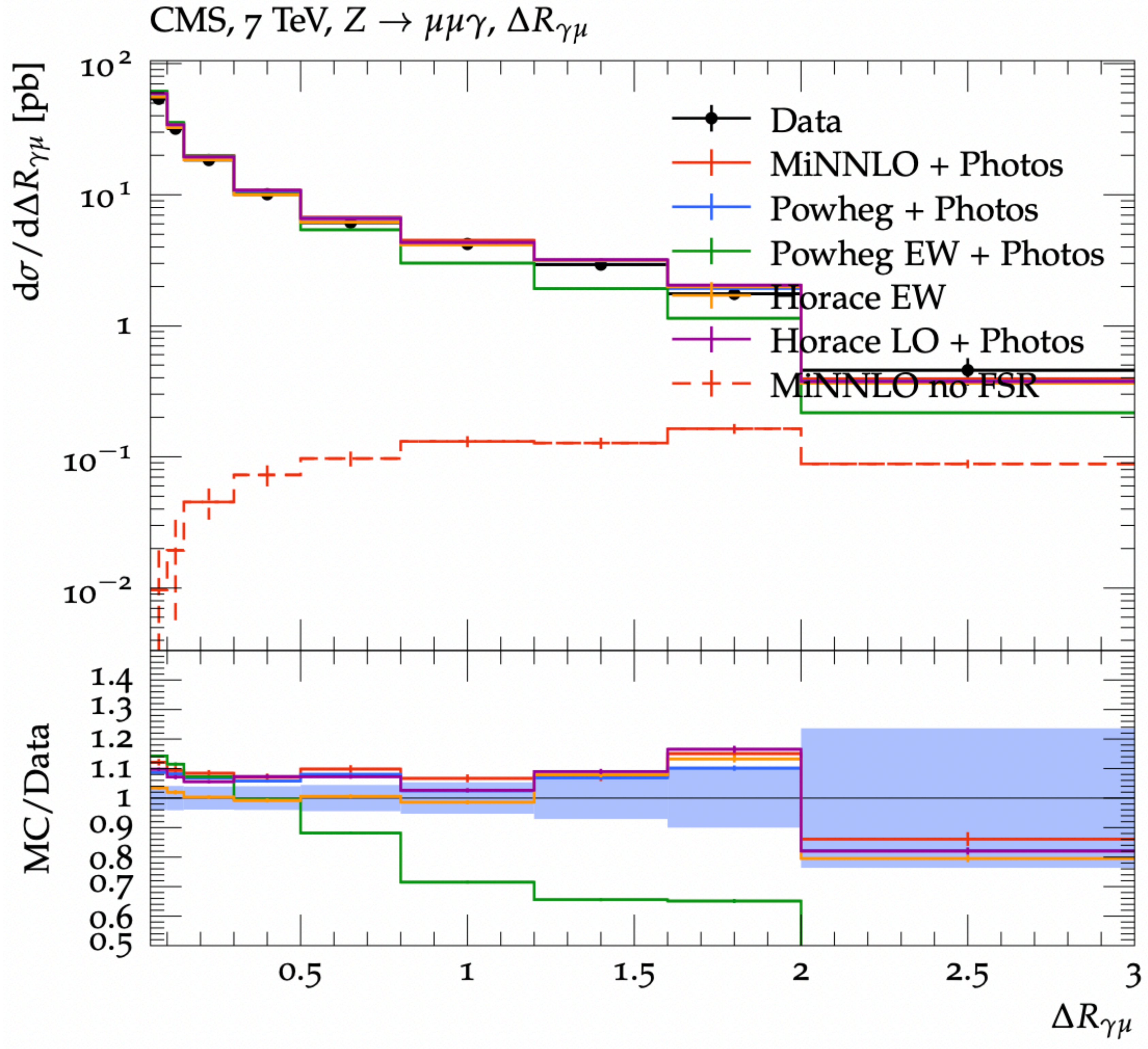






Further benchmarking and technical considerations

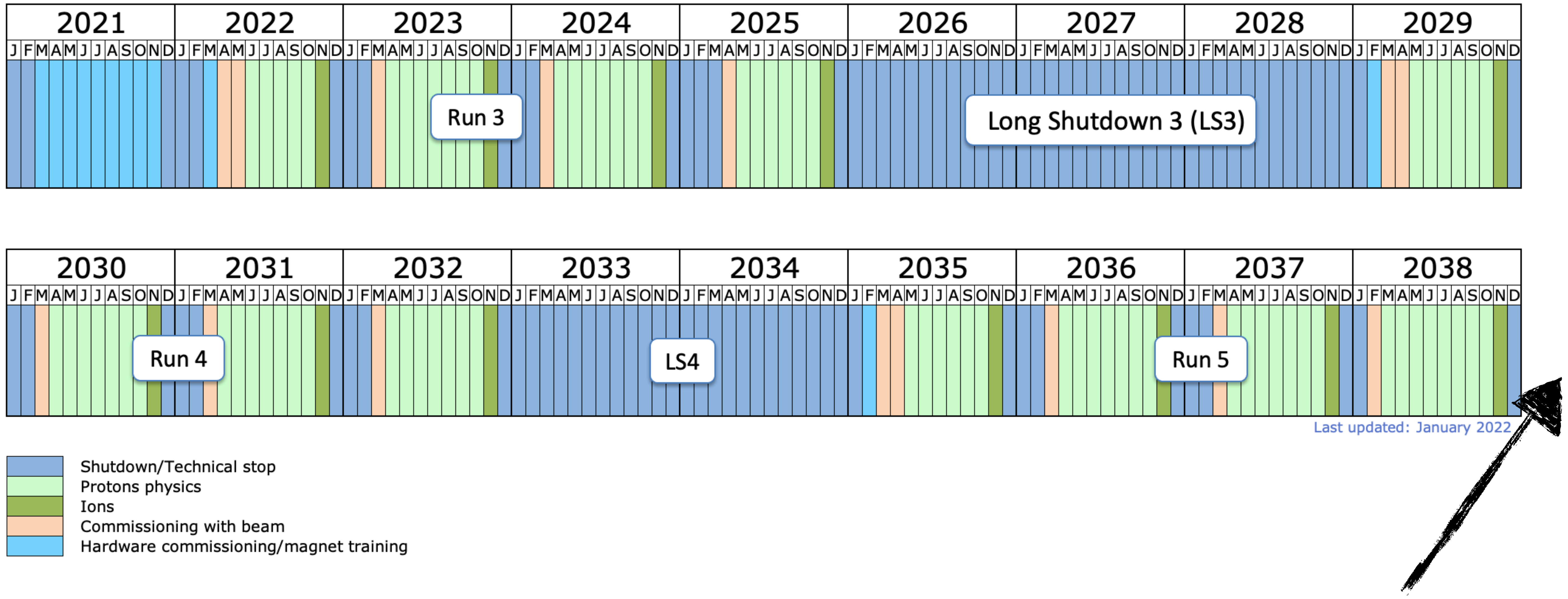
- Benchmarking of resummed predictions is a huge service to the field
- Landscape of other calculations (FO QCD, higher-order EW, mixed corrections) is perhaps not as vast, but would **still benefit from careful benchmarking**
  - Difficult for us to know if differences are expected/acceptable or not
  - 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

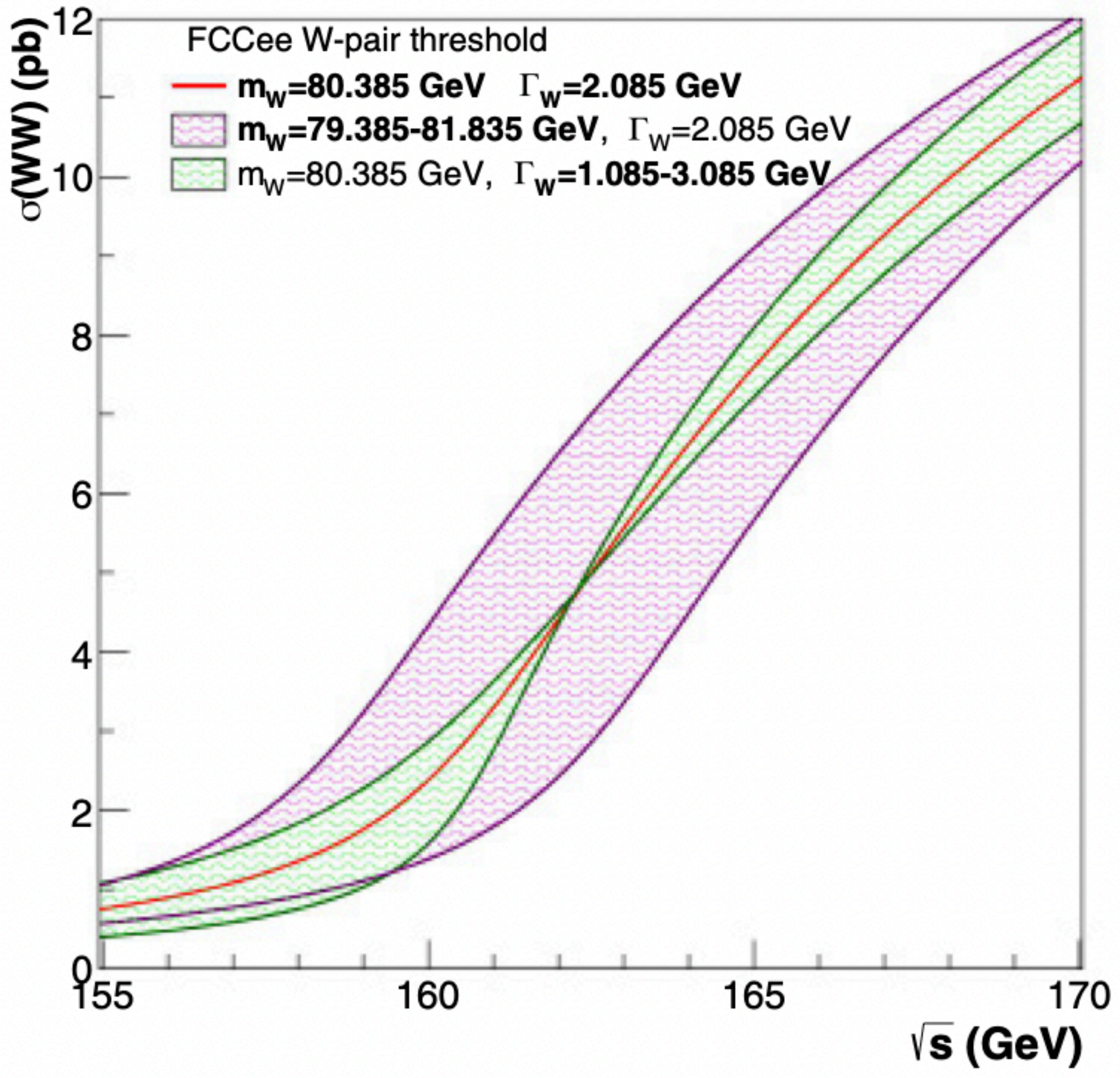
Looking forward

- In the near (and not so near) future, **hadron colliders are our main probe of m_W**
  - Can envision huge theoretical progress in next 20 years
  - Enormous data set will come with increased experimental challenges due to high-pileup and detector aging
  - Mitigate with special runs, detector upgrades, reconstruction advancements



- Future e^+e^- collider provides more direct, less theory-dependent measurement from threshold scans
  - FCC-ee anticipates < 1 MeV unc. in m_W

FCC-ee?



- "Wishlist" items
  - Experimental+theory hadron collider communities must meet the challenge of providing results that stand the test of time
  - Publish/maintain analyses that can be reinterpreted with improved theory

https://doi.org/10.1140/epjst/e2019-900045-4

Conclusions

- The interplay between theory and experiment is **critical to the advancement of our understanding**
- Extracting the W boson mass at hadron colliders requires and exceptional level of interplay between theory and experiment
  - Our goal is always to reduce the theoretical dependence of our measurements
  - Requires care, validation, and guidance
- **We always "wish" for better**, more accurate, more precise calculations.
- … that are fast, easy to use, robust…
- We're in this together: **how can experimentalists help**?
  - Measurements can improve calculations, which can then improve our measurements
  - Always valuable to know if additional measurements, auxiliary material, or method of presentation could benefit the development and validation of theoretical tools
- The achievable precision in m_W at lepton colliders is staggering, but **hadron colliders still have a long road ahead**