Precision electroweak measurements using single boson events at CMS

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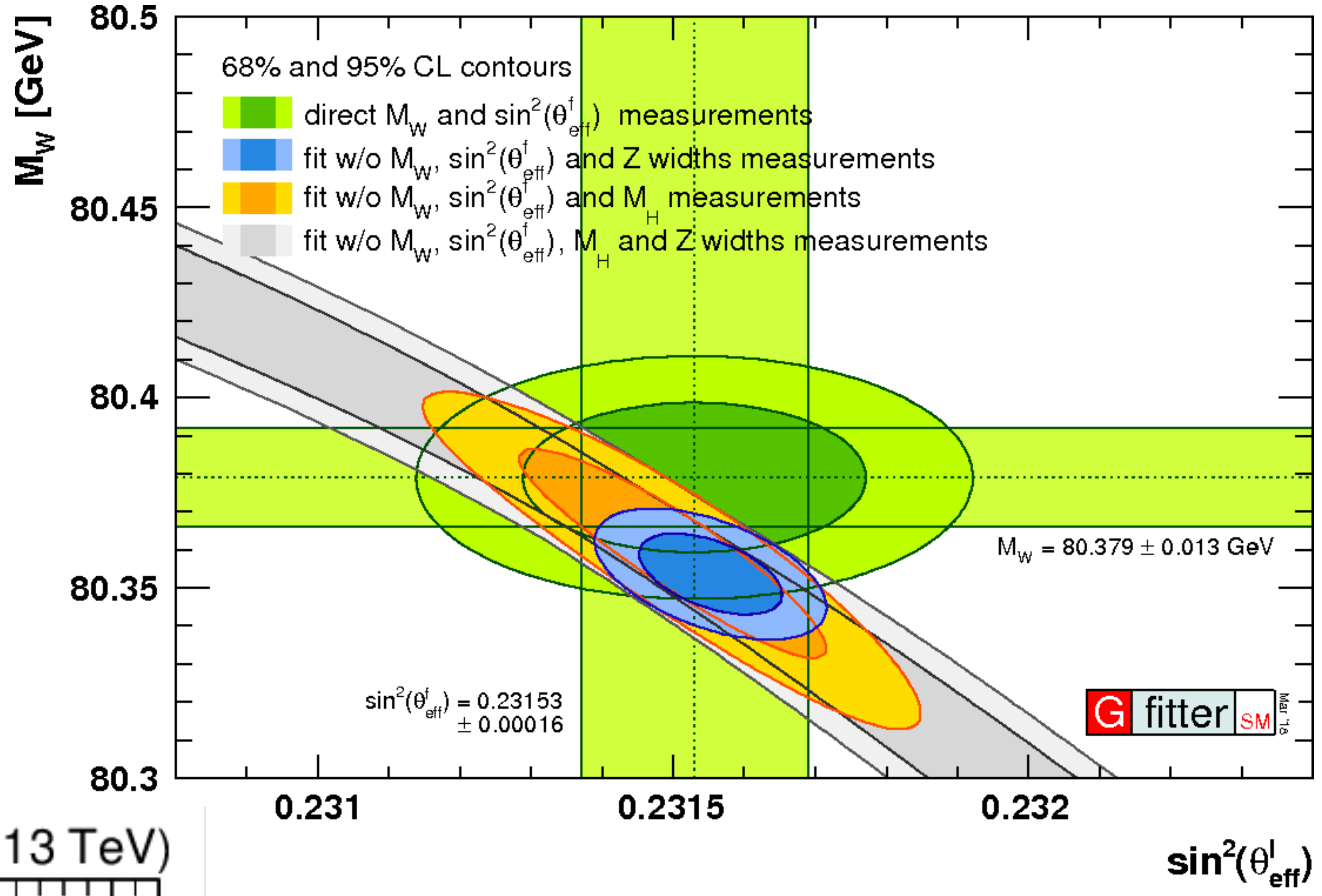
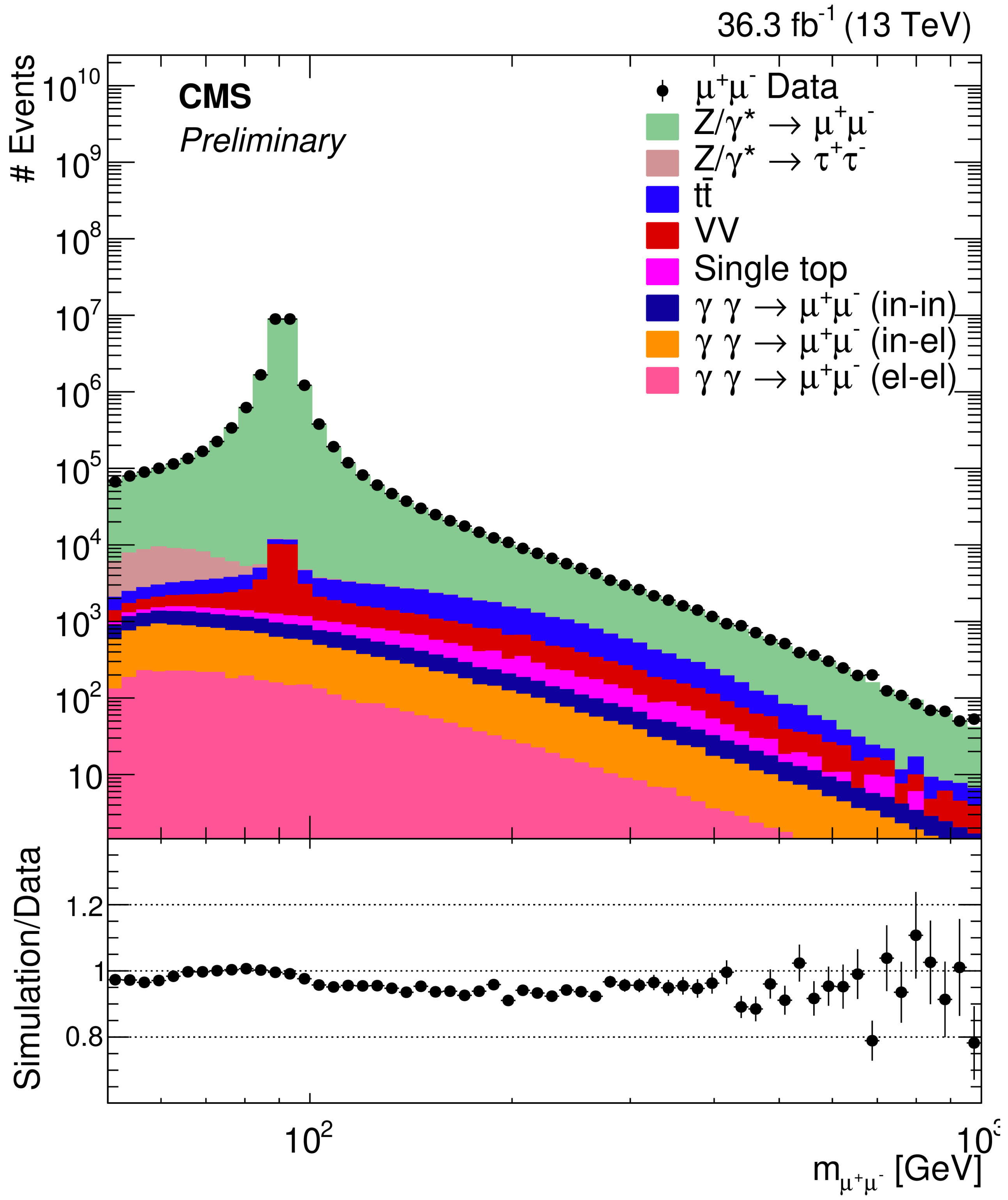
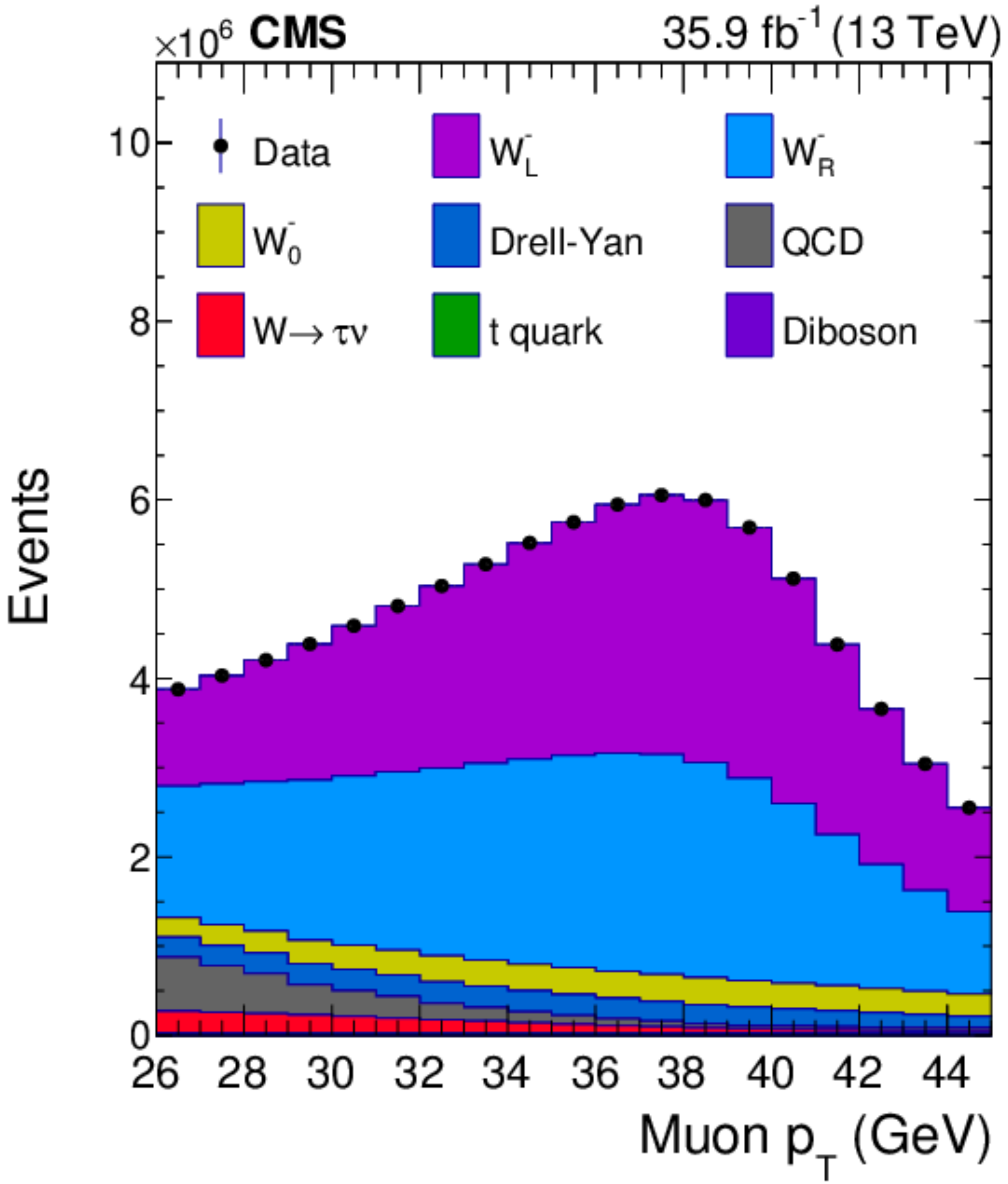
for the CMS Collaboration

Introduction

- Electroweak theory has been **extremely successful** over vast orders of magnitude
- Some parameters fundamentally experimental, but **relationships predicted by SM**
- Huge samples of W and Z boson production at LHC enable studies of SM self consistency
- *O*(billion) event data sets
- Understanding systematics take time, most results limited to 2016 data at present
- Studies with almost **4x more data** in progress







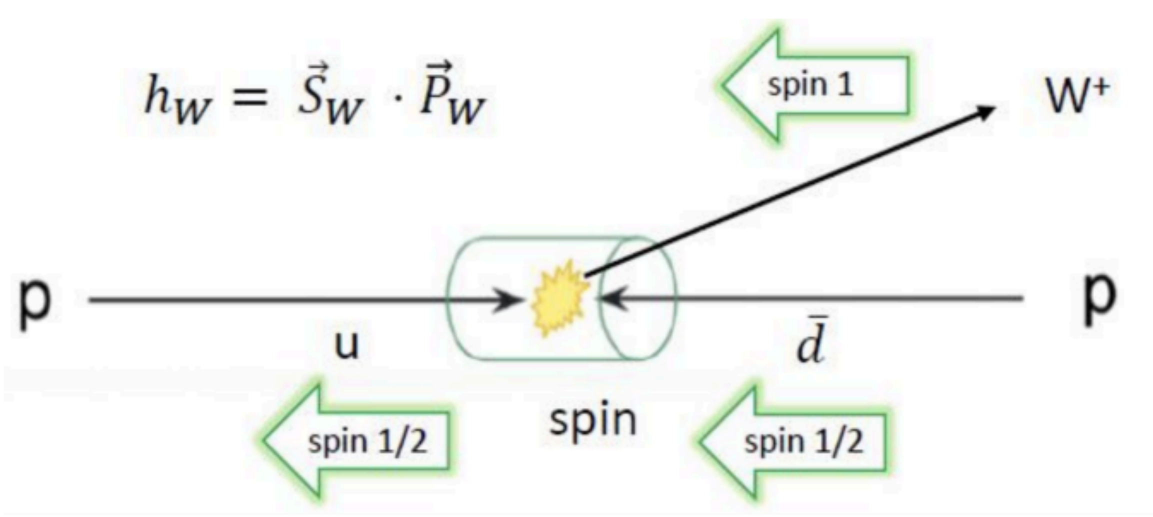
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

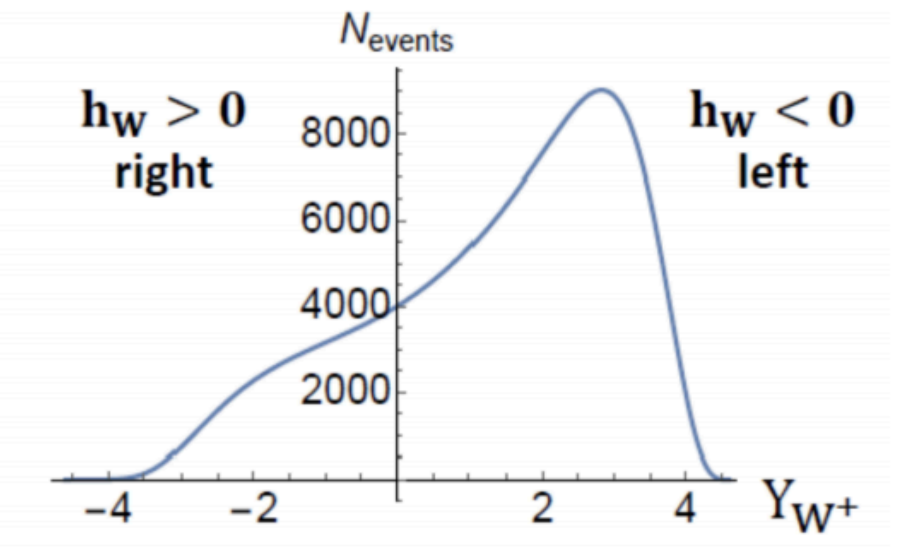
Higher-order corrections
Depend on m_t, m_H, … m_{BSM}?

W boson production: rapidity, helicity, and PDF constraints

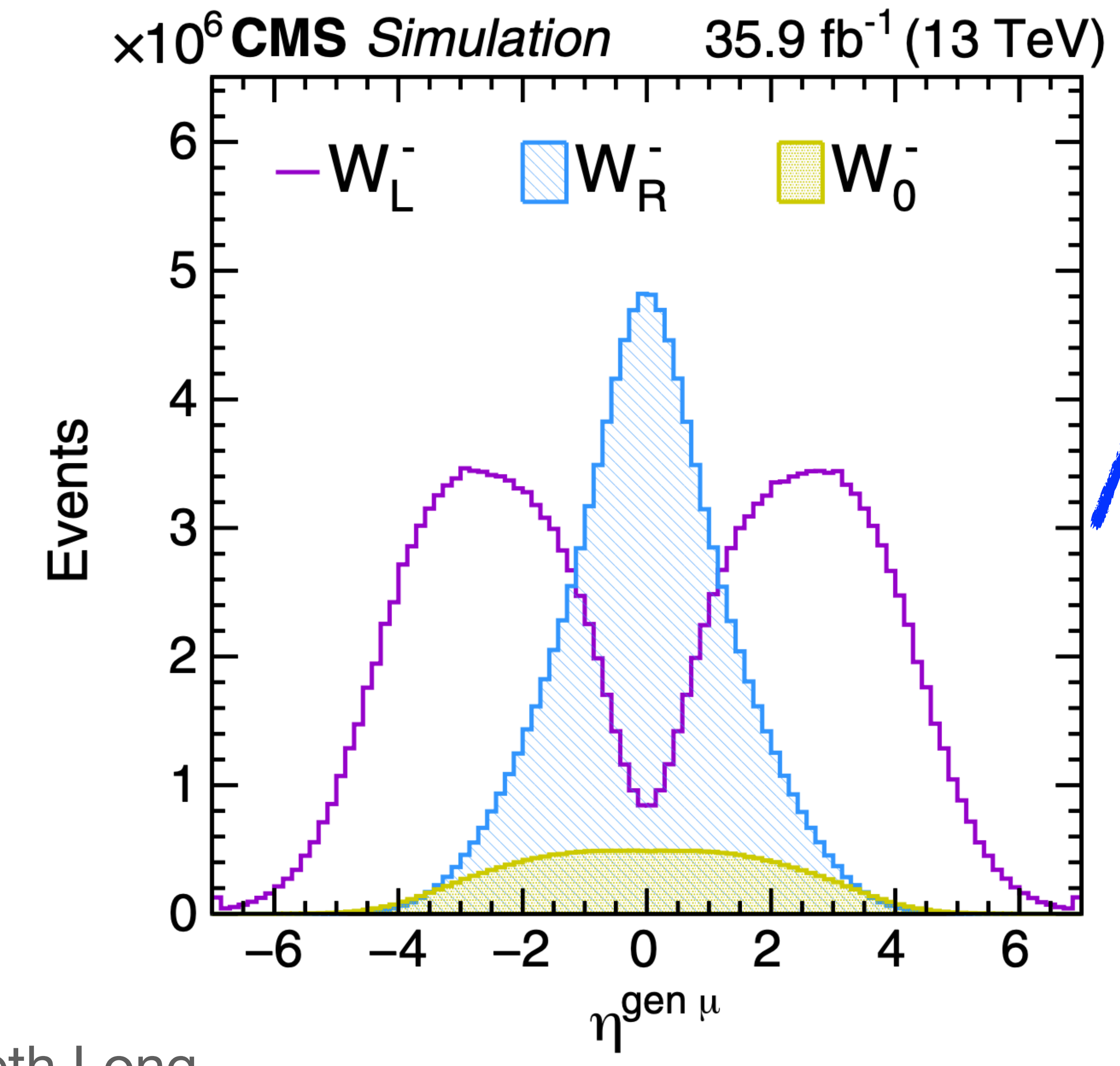
SMP-18-012

- W boson rapidity, and lepton pseudorapdity from decay, largely predicted by PDF
  - Opportunity to **constrain PDF** (for, e.g., m_W measurement)
  - Motivated by phenomenological study

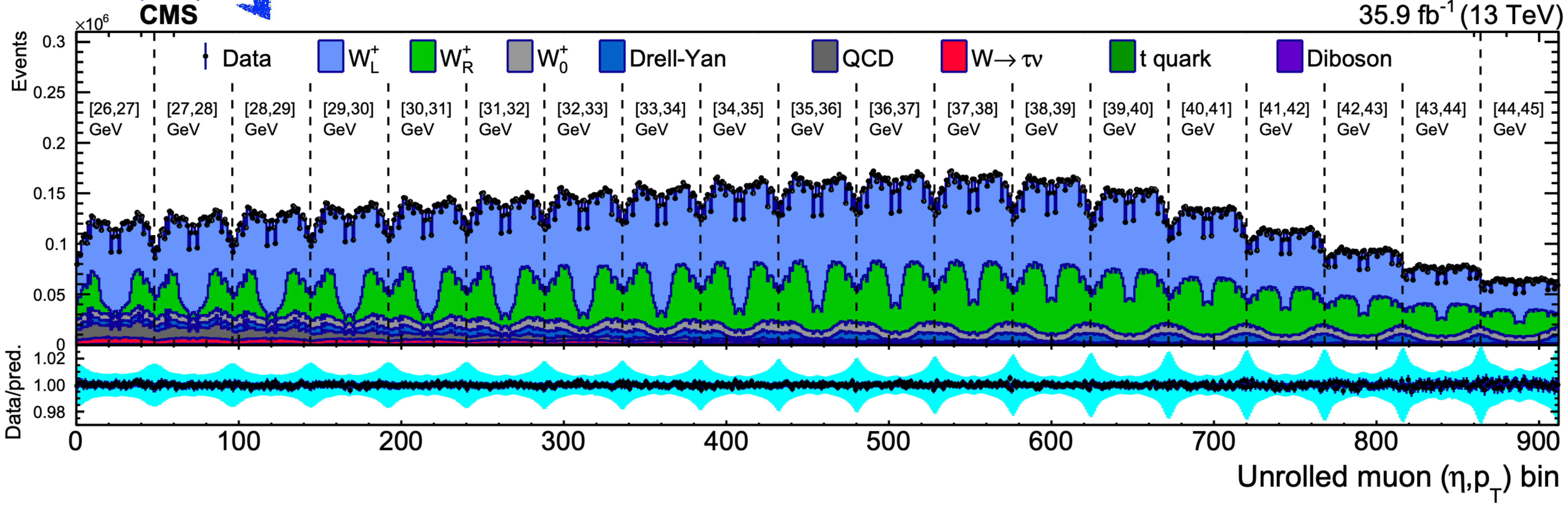




- Build complex **binned likelihood from 2D binning in (p_T, η)** sensitive to helicity fractions (and therefore PDFs)
  - Massive experimental (and technical) undertaking
  - > 3000 bins ($e^\pm$,$\mu^\pm$) with thousands of nuisance parameters
  - Dedicated optimisation framework developed for huge maximum likelihood fit



η^ℓ in 1 GeV slices of p_T^ℓ



Differential W boson measurements, PDF constraints

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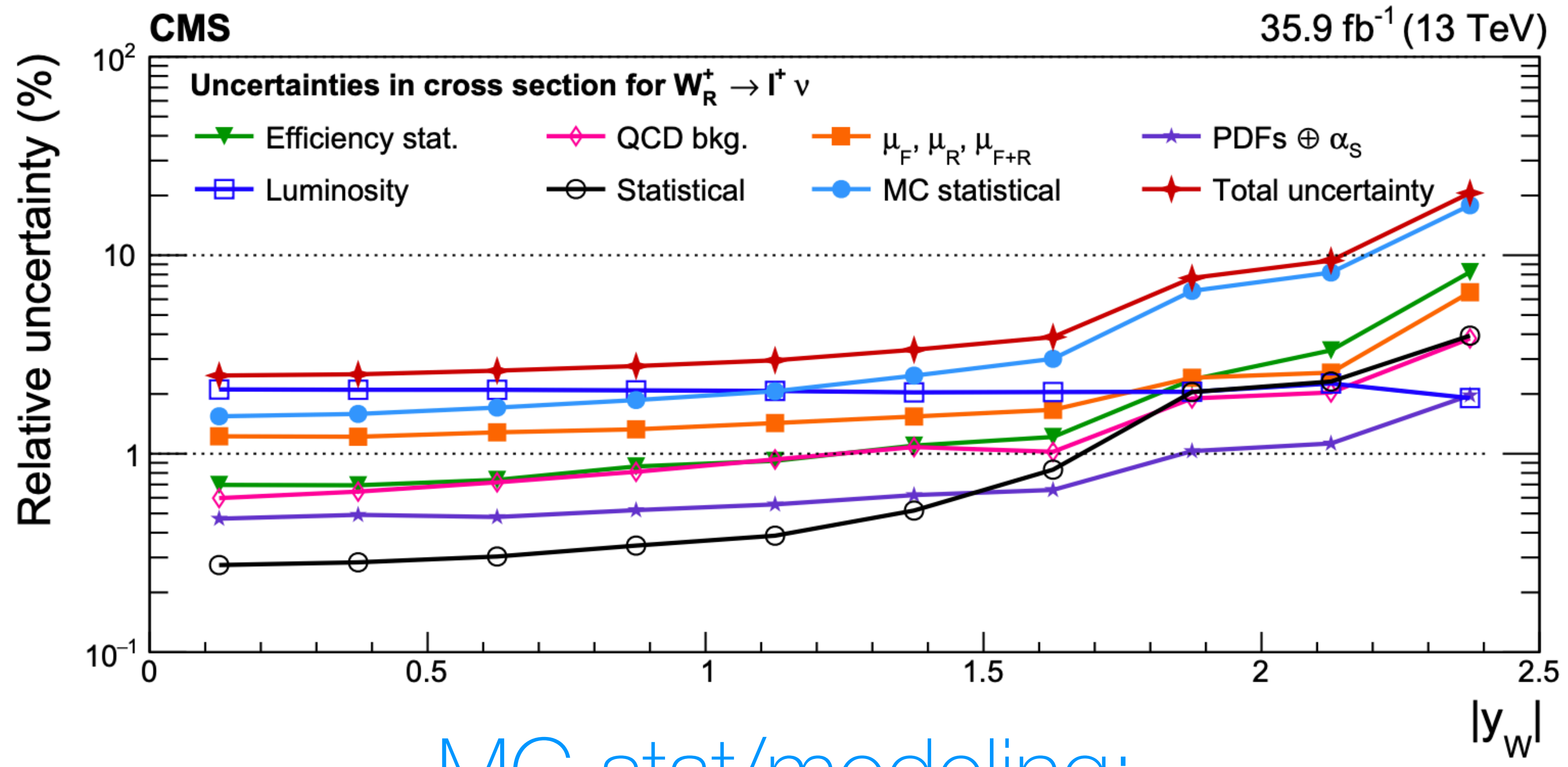
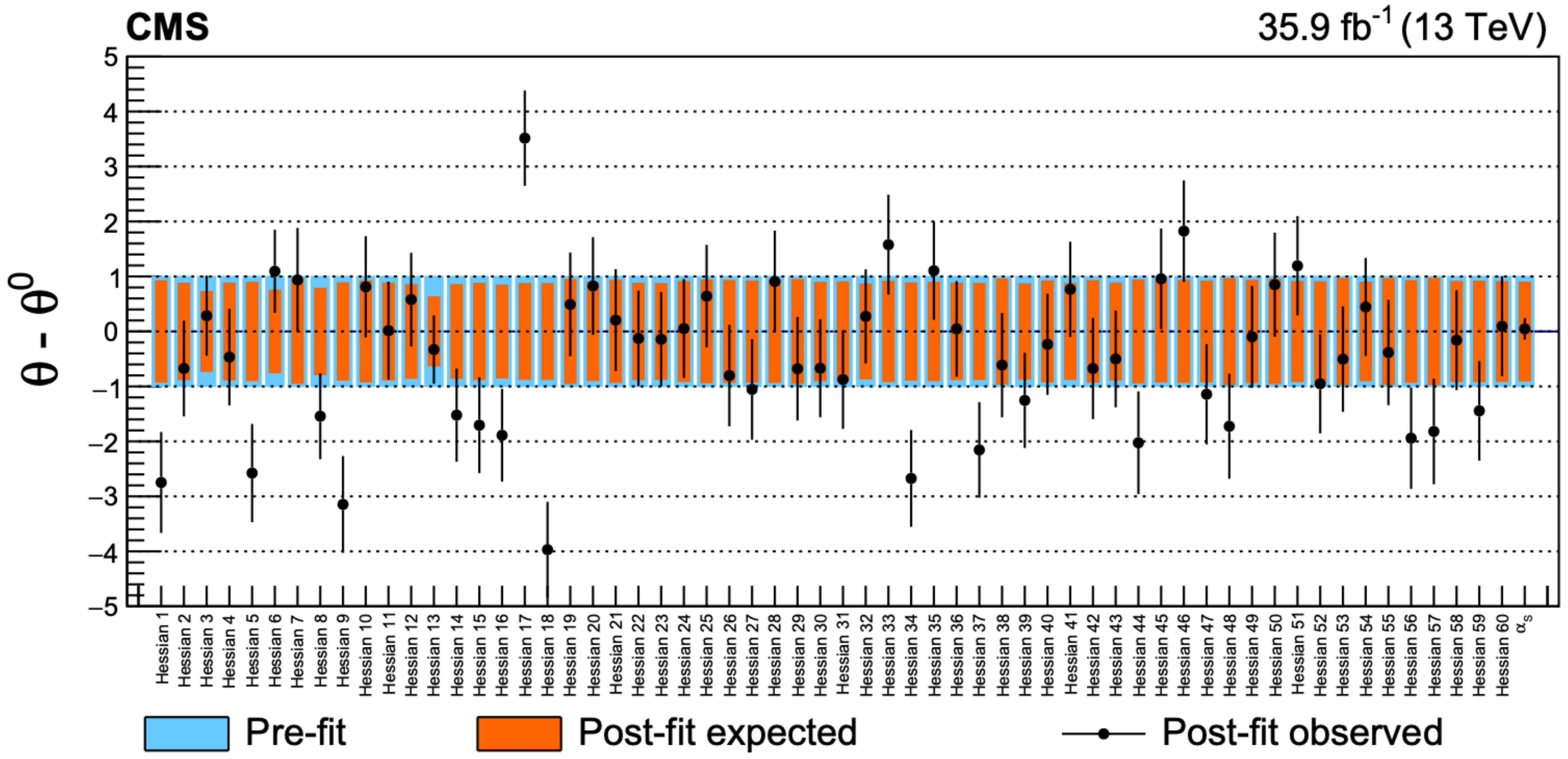
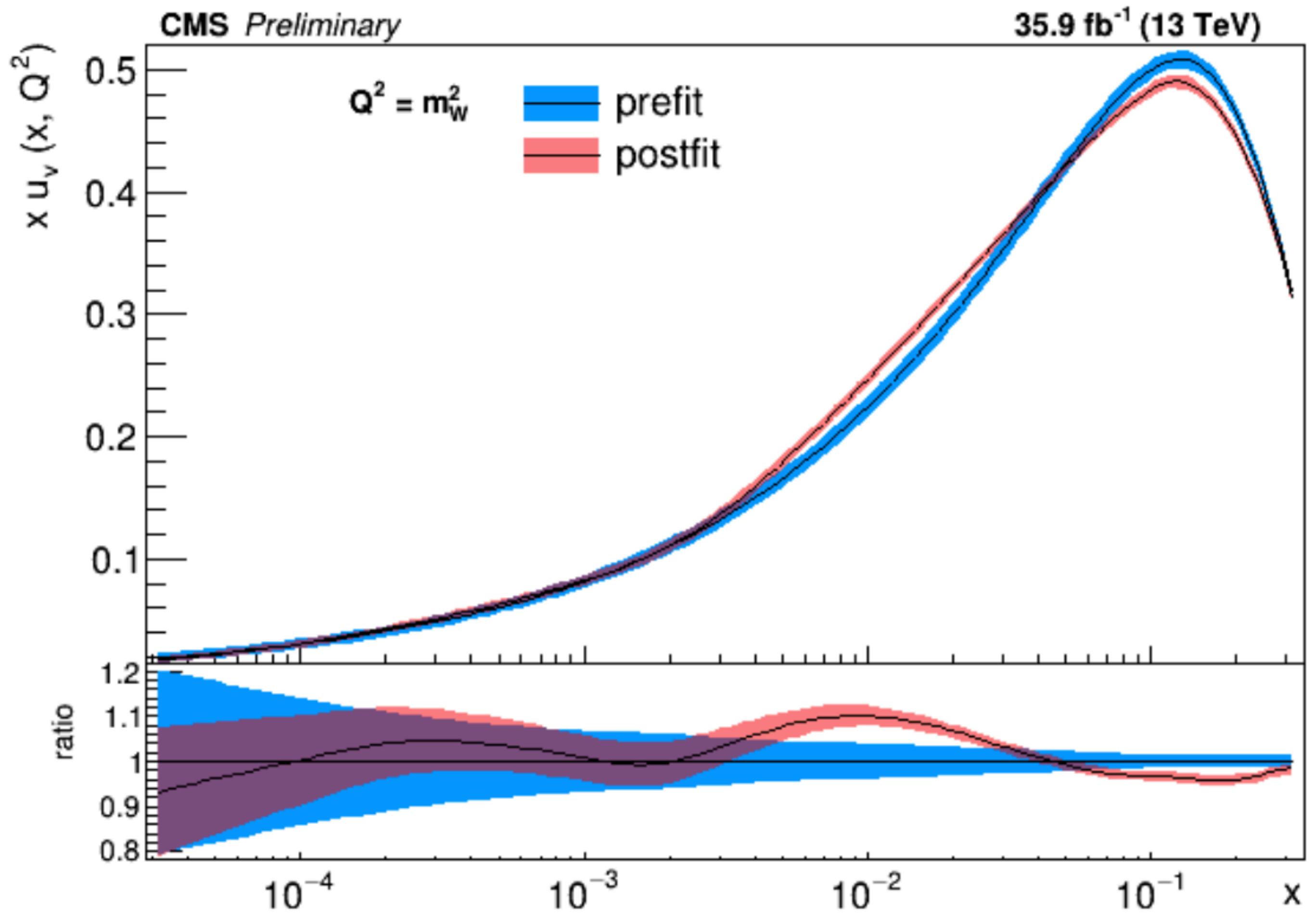
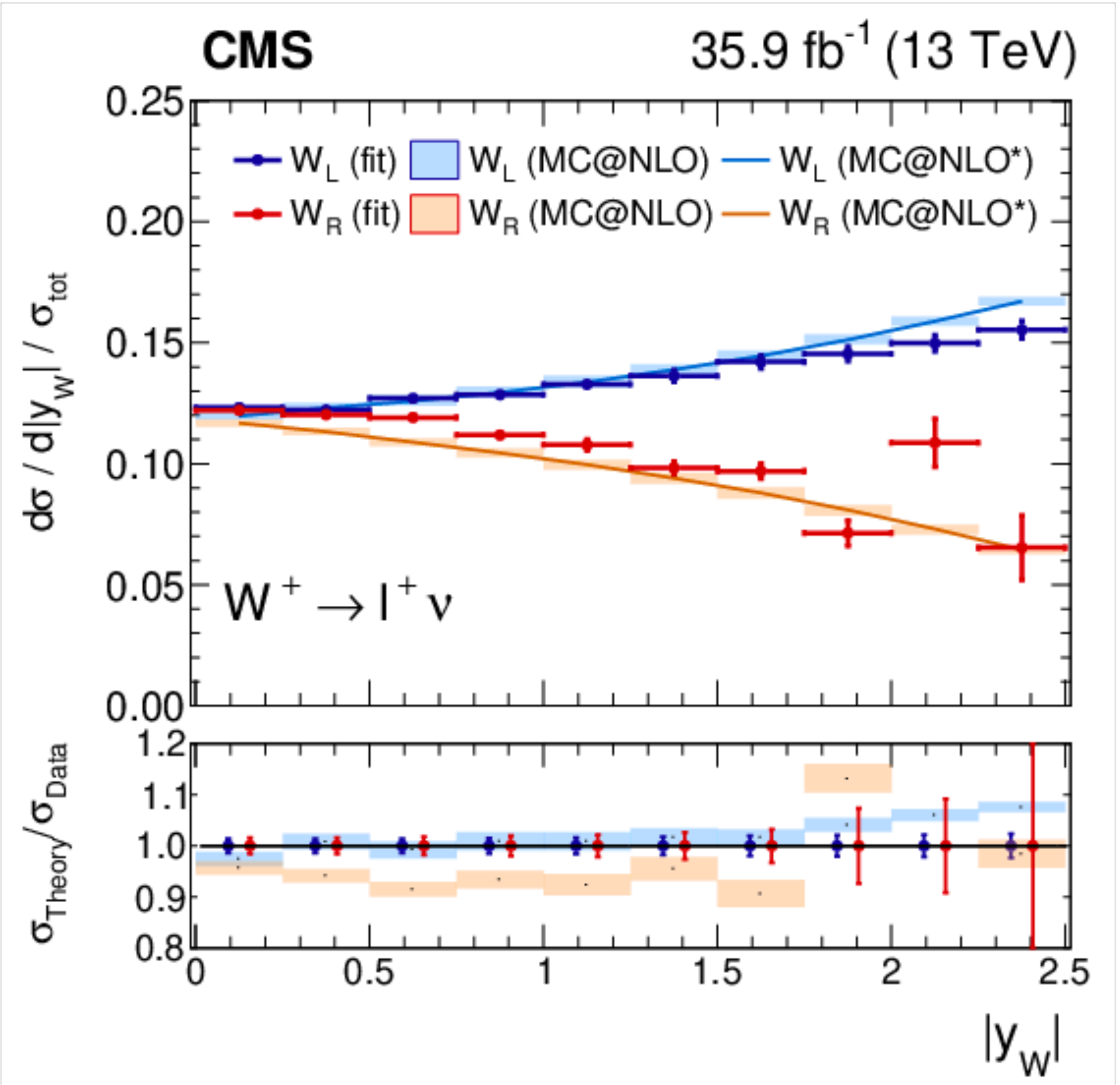
- **Many results** derived from exploiting this likelihood
  - Extensive **unfolded distributions**, including for W helicity fractions
  - PDF constraints from performing the fit with the signal cross sections fixed to prediction within theoretical uncertainties
    - NNPDF3.0 hessian vars using MC2Hessian
- Profiled PDF nuisances used to derive post-fit PDF
  - Should not be interpreted as a full PDF fit (uses NLO MC, old PDF set) but **clear constraining power**
    - Step towards reducing uncertainties in W mass measurement



MC stat/modeling; **lepton scale** still major challenges for m_W







W boson branching fractions

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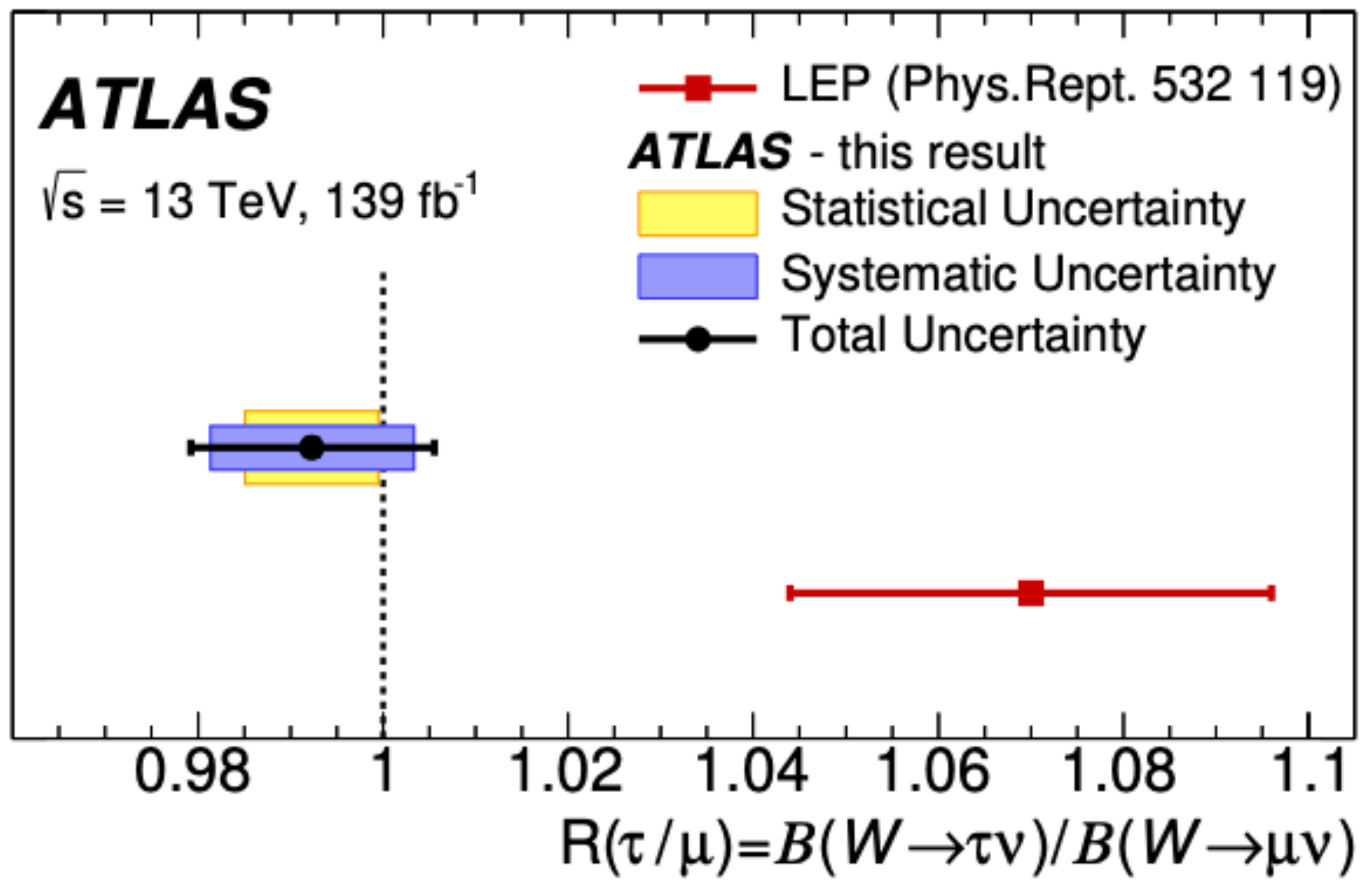
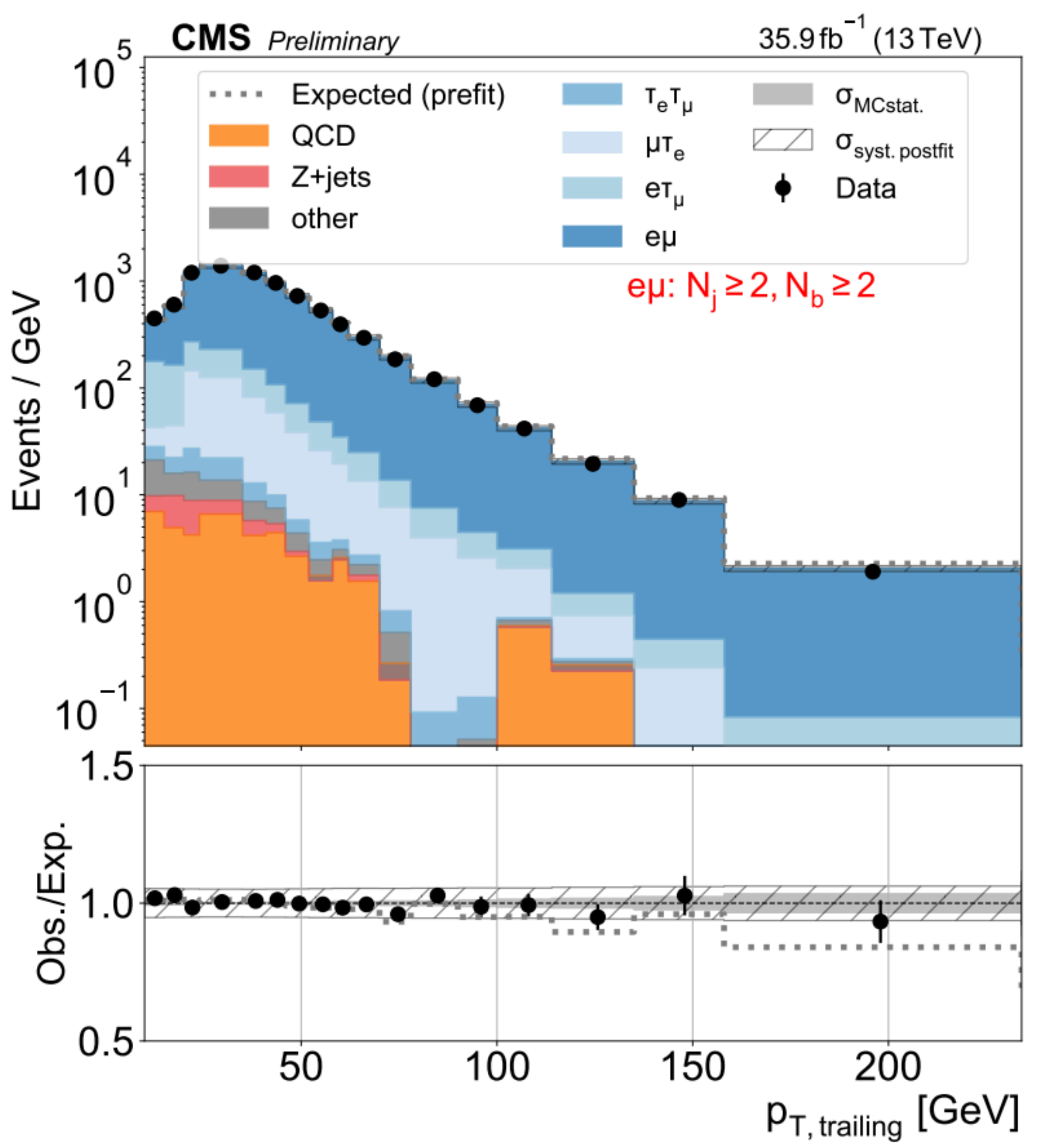
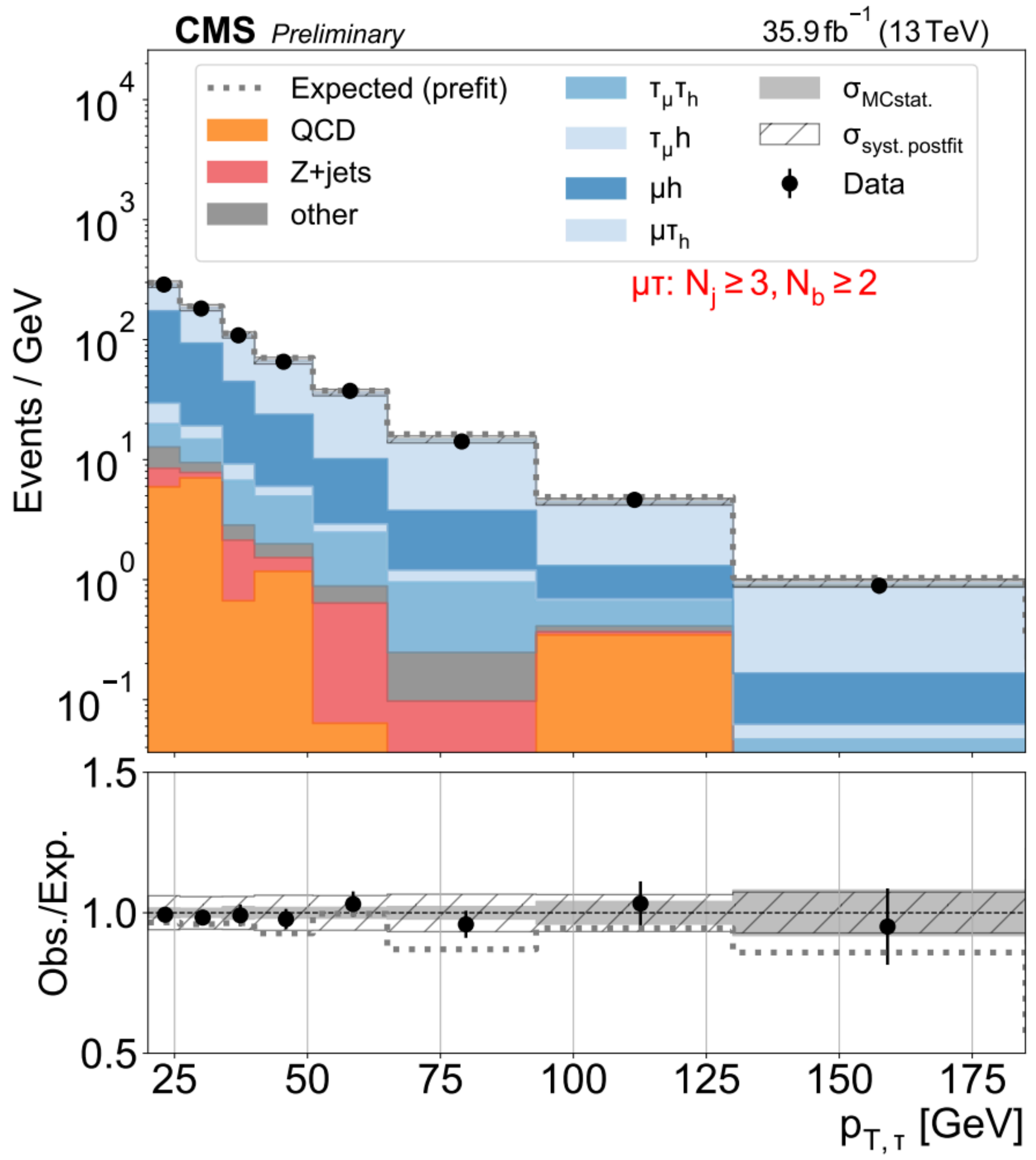
- Lepton universality (LU) predicts **equivalent decay rates of W to all ℓ**
  - Intriguing τ/μ difference seen at LEP, not confirmed by ATLAS
- Decay independent of production mechanism
  - **Use tt production** as primary source (no bias on non-triggering ℓ)
  - Categorize signal contributions: tt, tW, W all included
  - τ vs. light ℓ driven by p_T spectrum (different wrt ATLAS, uses vertex)
  - **Measure all W leptonic BRs**, including e, μ, τ hadronic or ℓ decay

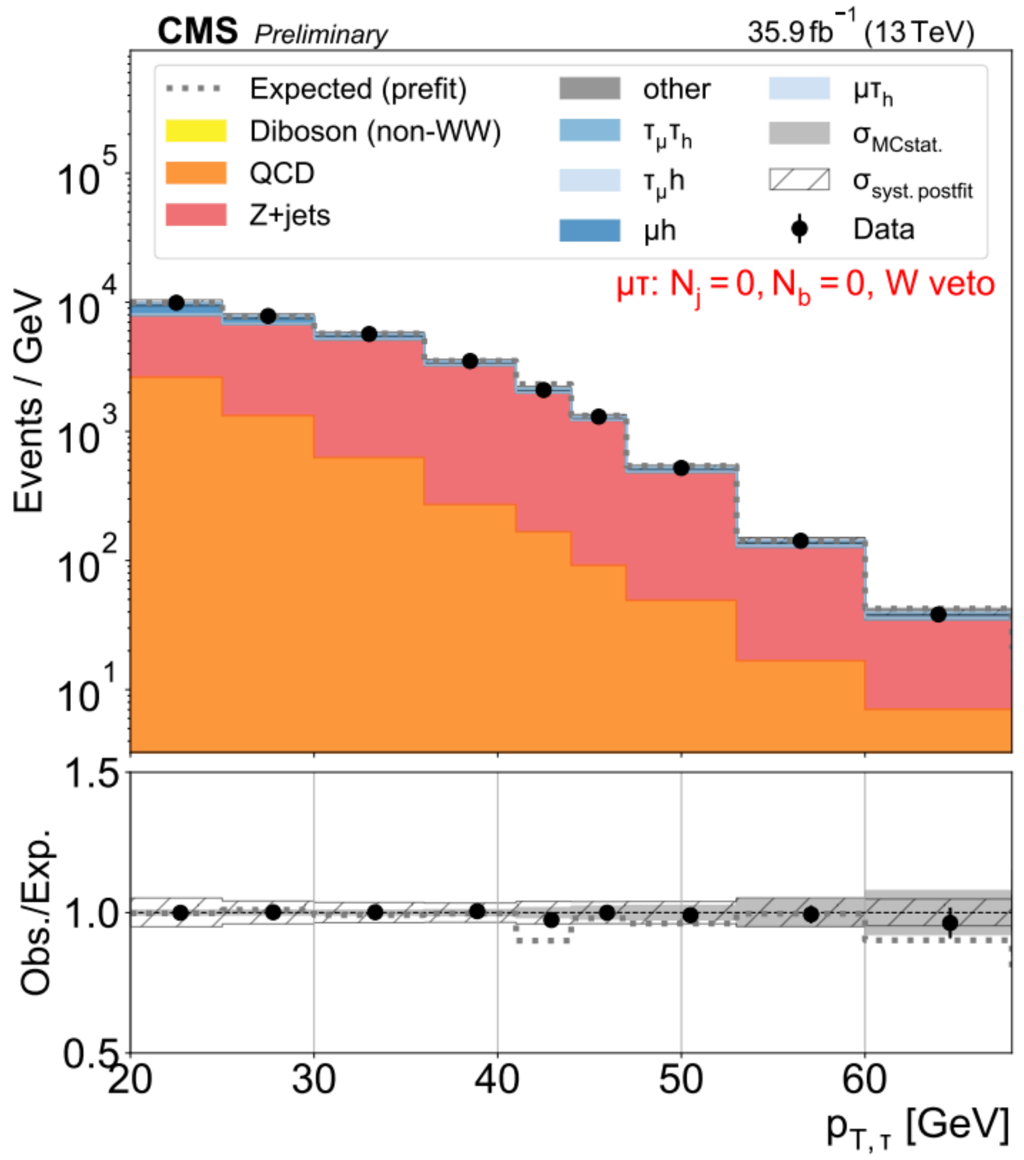




p_T to differentiate τ → e,μ from prompt e,μ



Important contribution from τ_h



Z CR for constraining τ reco. unc.

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau, \mu\tau$	$e\tau, \mu\tau,$	$e\tau, \mu\tau$		
	$e\mu$	$e\mu$	$ee, \mu\mu, e\mu$		
$N_b = 1$		$e\tau, \mu\tau$	$e\tau, \mu\tau$	$e\tau, \mu\tau$	
		$e\mu$	$ee, \mu\mu, e\mu$		
					$eh, \mu h$
$N_b \geq 2$			$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					$eh, \mu h$

W boson branching fractions

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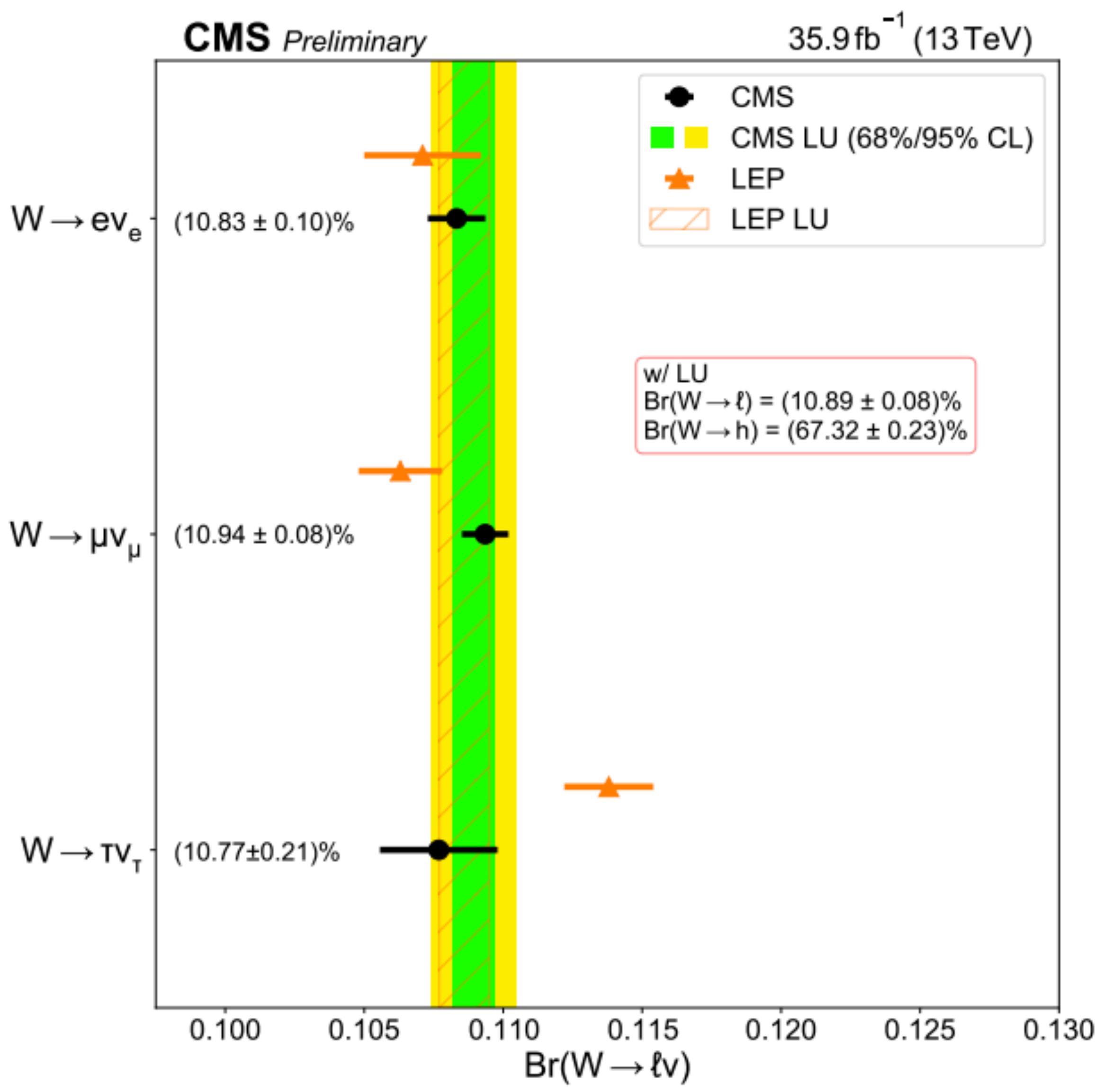
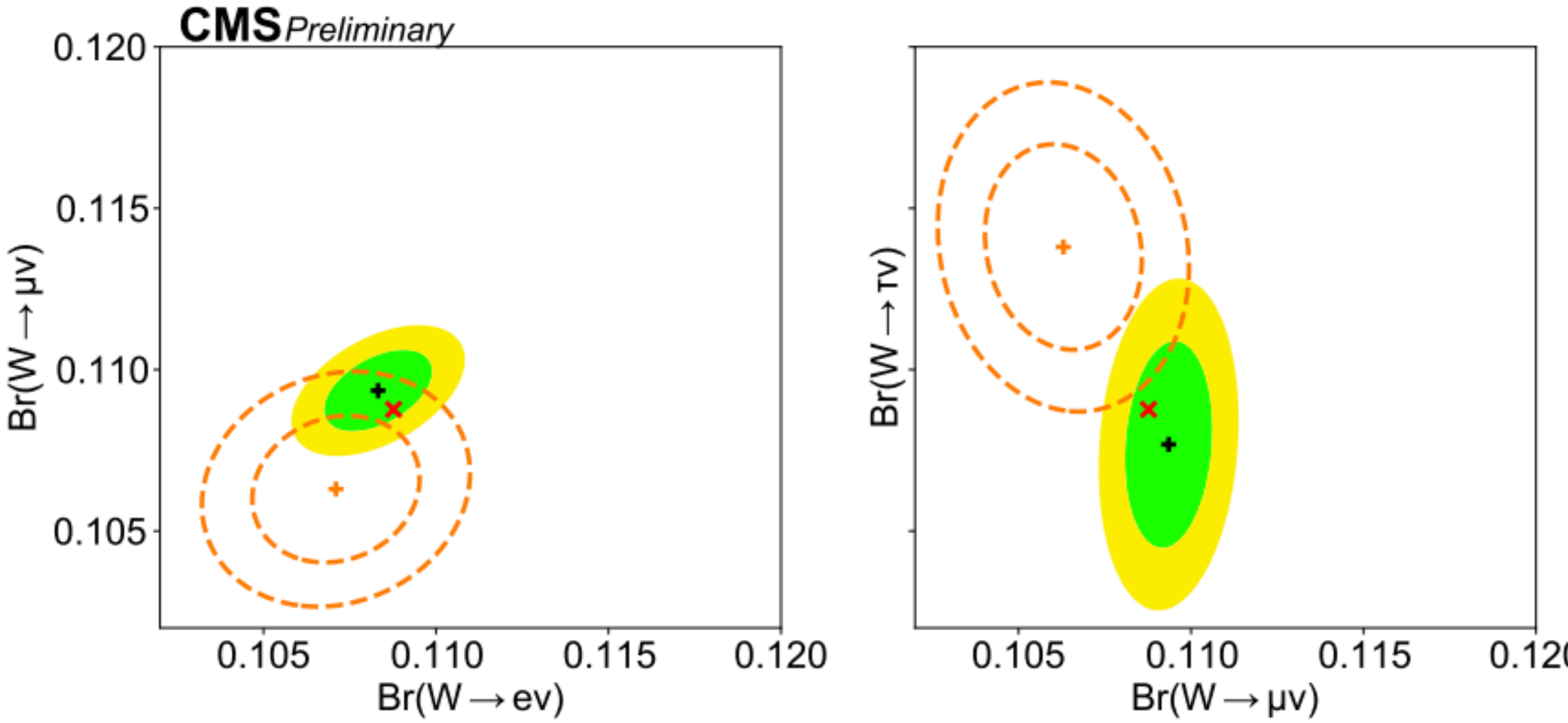
- Results obtained via maximum likelihood fit
  - Connect differential, relative yields to relative branching ratios (including e, μ, τ hadronic or leptonic decay)
  - **Multiple fits**: separately e, μ, τ; combined assuming LU; partial LU (e = μ)
- Dominant systematics
  - Lepton scale, reco eff.
  - Data driven background, tt modelling
- Very **consistent with LU and ATLAS** measurement
- Also derive SM parameters (V_{cs}, α_s) using measured branching ratios under SM assumption



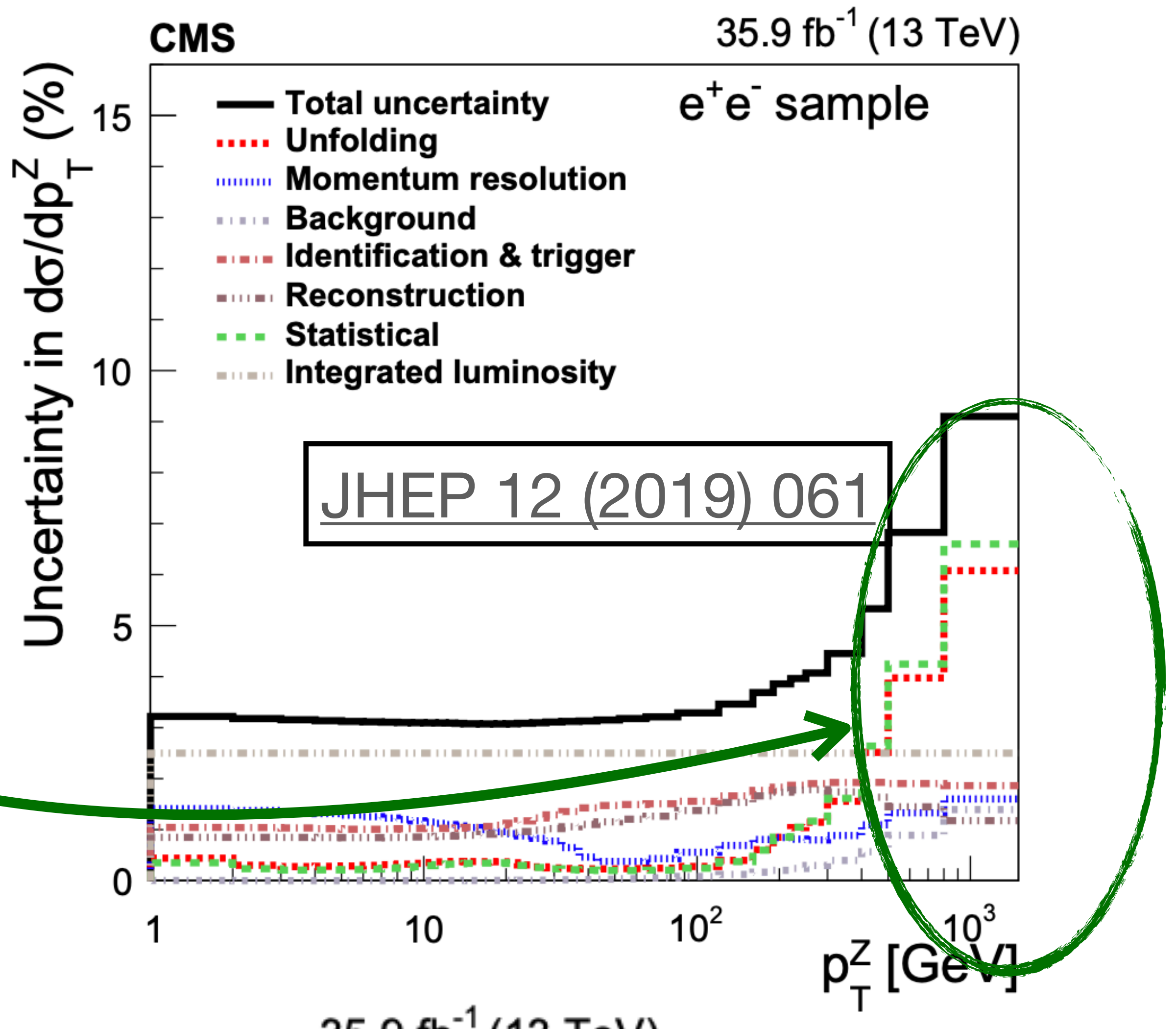
	CMS	LEP	CMS+LEP	ATLAS
$W \to \mu\nu / W \to e\nu$	1.009 ± 0.009	0.993 ± 0.019	1.008 ± 0.008	–
$W \to \tau\nu / W \to e\nu$	0.994 ± 0.021	1.063 ± 0.027	1.022 ± 0.016	–
$W \to \tau\nu / W \to \mu\nu$	0.985 ± 0.020	1.070 ± 0.026	1.014 ± 0.015	0.992 ± 0.013
$2W \to \tau\nu / (W \to e\nu + W \to \mu\nu)$	1.002 ± 0.019	1.066 ± 0.025	1.016 ± 0.015	–



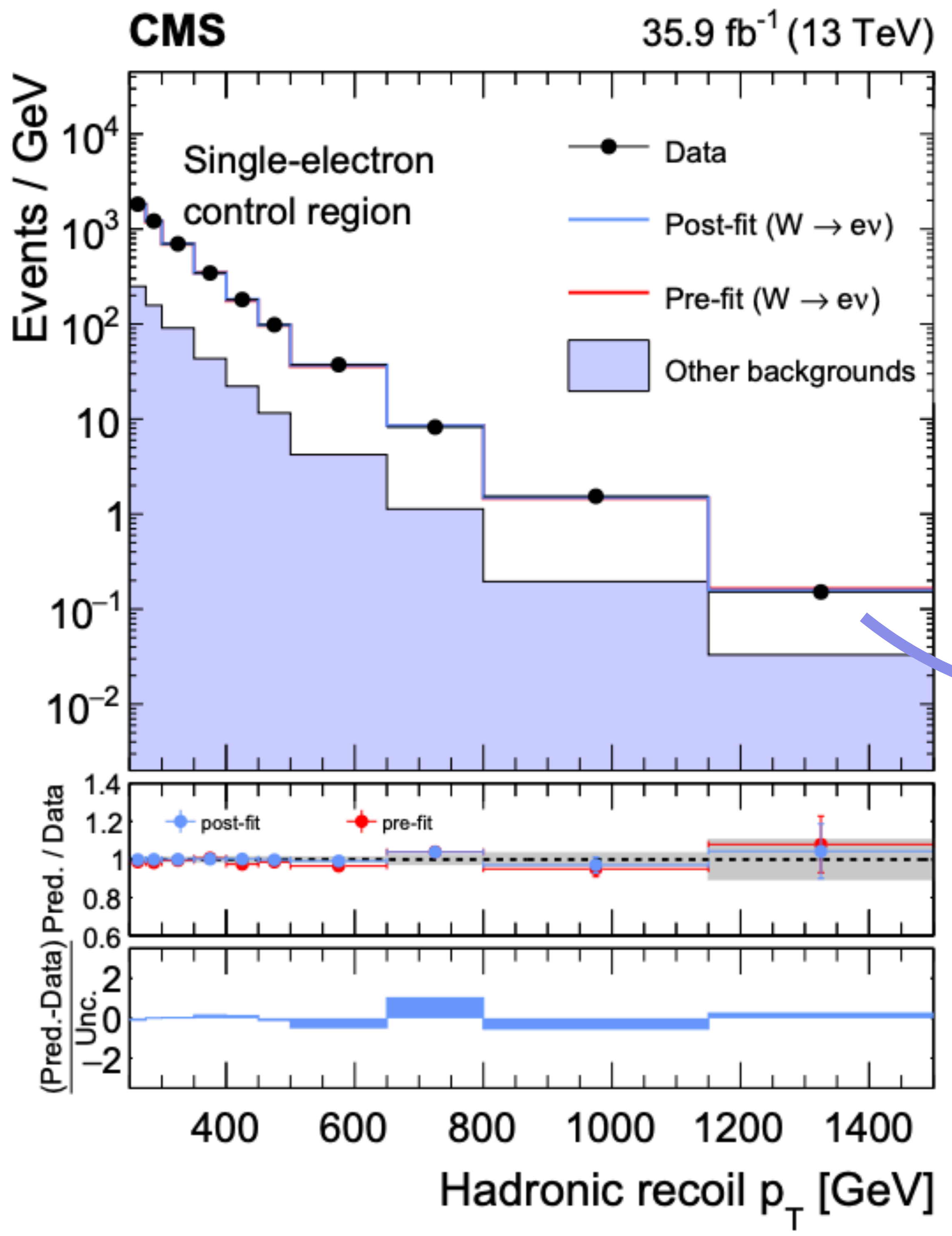
Z boson production: p_T distribution

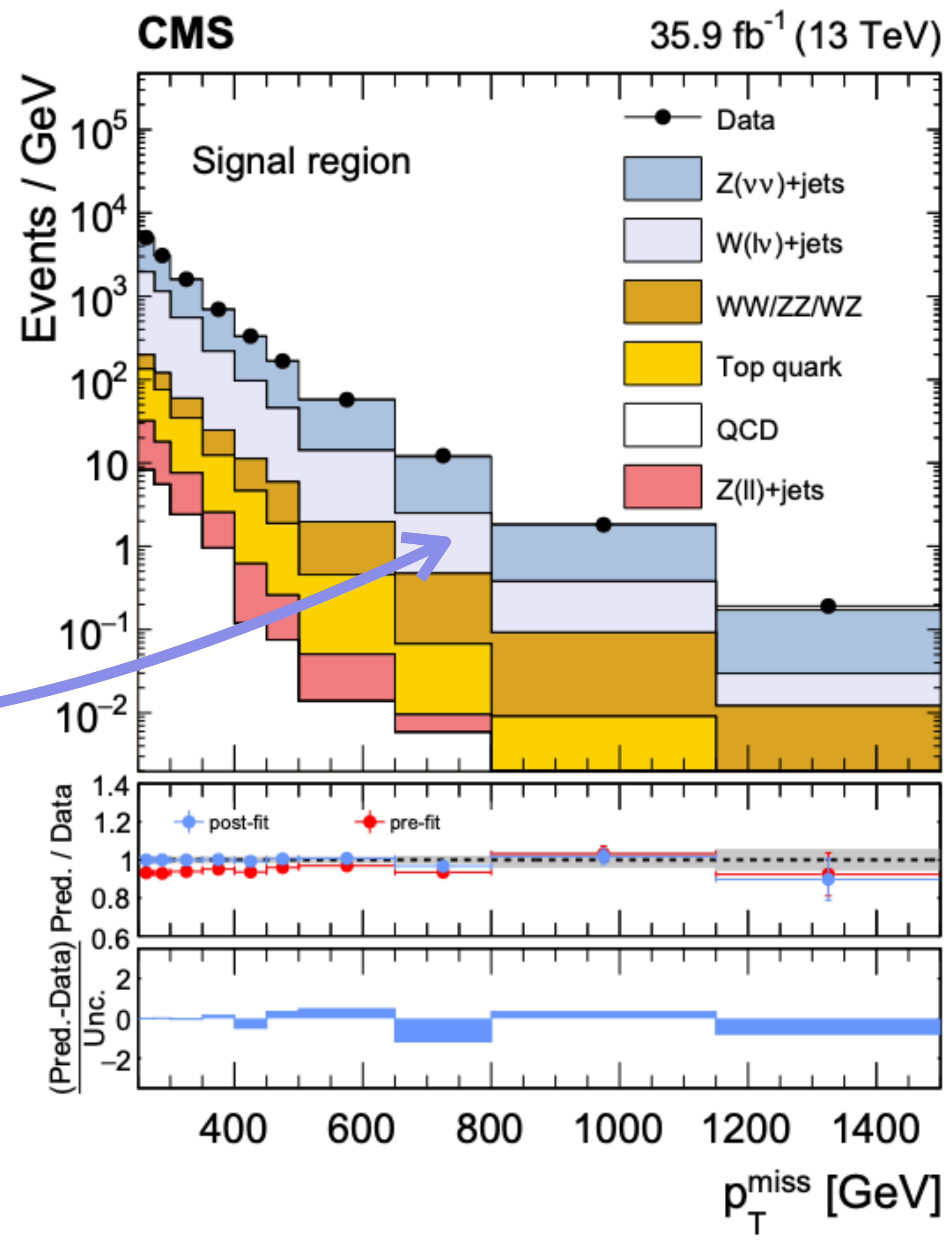
JHEP 05 (2021) 205

- p_T^Z "simple" but **critical observable**
  - Sensitive to PDFs, higher-order QCD, EW corrections
  - Background for many BSM searches, standard candle for H, exotics
  - Insight into p_T^W spectrum, crucial for m_W measurement in high pileup
- **Z(νν) channel**: increase stats in tails wrt classic precision Z(ℓℓ) measurement



- Principle challenge estimation of W(ℓν) background
  - **Estimate from data** with single lepton control regions, simultaneously in likelihood fit
  - Theoretical predictions for extrapolation (same approach as for monojet searches)
  - arxiv:705.04664





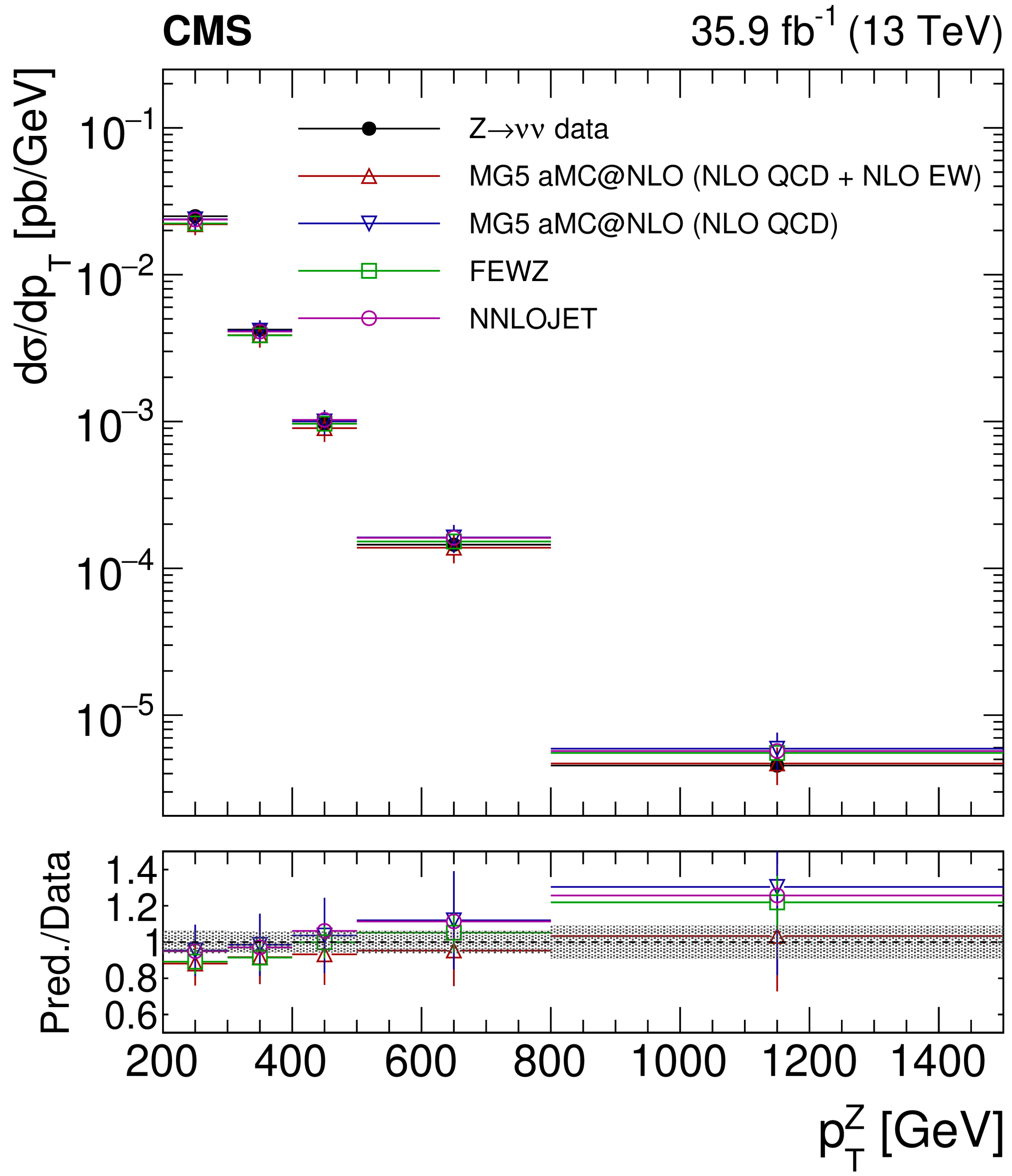
Z boson production: measured p_T distribution

JHEP 05 (2021) 205
JHEP 12 (2019) 061

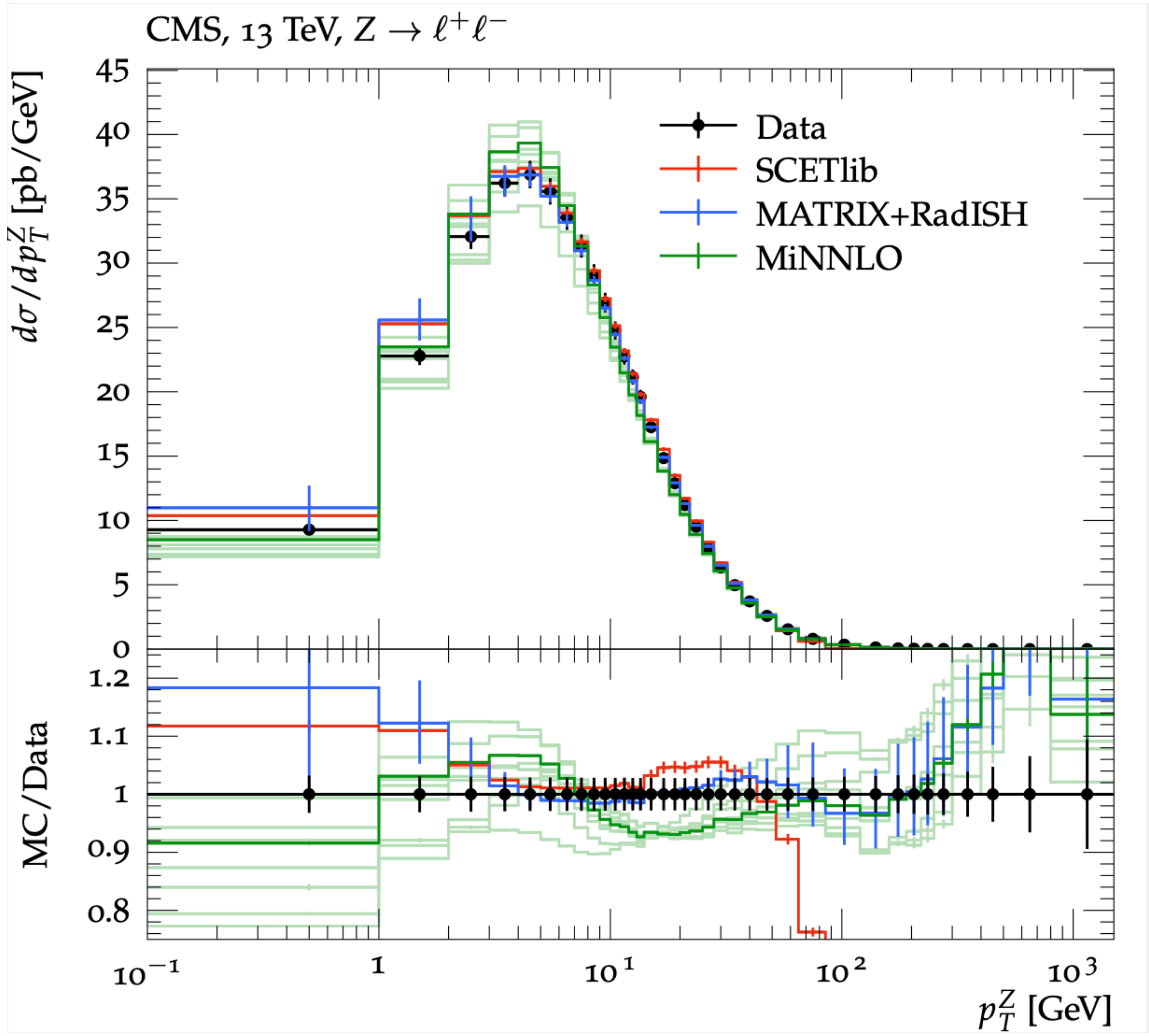
- Z(νν) channel important at high mass
- Confirms **excellent performance of theoretical tools**
  - NLO EW corrections evident
  - Rivet routine available: comparison to **any** prediction
    - **Using current measurements to guide simulation** for future precision measurements (weak mixing angle, W mass) and BSM (boosted H backgrounds)

p_T^Z (GeV)	$Z \to \ell\ell$	$Z \to \nu\nu$	$Z \to \ell\ell + \nu\nu$
200–300	$1.012^{+0.006}_{-0.007}$	$1.019^{+0.009}_{-0.009}$	$1.011^{+0.004}_{-0.004}$
300–400	$0.943^{+0.025}_{-0.025}$	$0.979^{+0.015}_{-0.015}$	$0.963^{+0.015}_{-0.014}$
400–500	$1.006^{+0.031}_{-0.030}$	$0.963^{+0.019}_{-0.019}$	$0.971^{+0.017}_{-0.016}$
500–800	$0.993^{+0.036}_{-0.036}$	$0.942^{+0.024}_{-0.024}$	$0.949^{+0.021}_{-0.020}$
800–1500	$1.036^{+0.099}_{-0.095}$	$0.869^{+0.059}_{-0.057}$	$0.914^{+0.052}_{-0.051}$

- MG5_aMC ≤2j@NLO +NLO EW via arxiv.org:705.04664
- FEWZ NNLO QCD
- NNLOJET (Z+1j @NNLO)



- MATRIX+RadISH (NNLO+N3LL)
- MiNNLO (NNLO+PS)
- SCETlib (N3LL) (FO matching supported, but not included here)

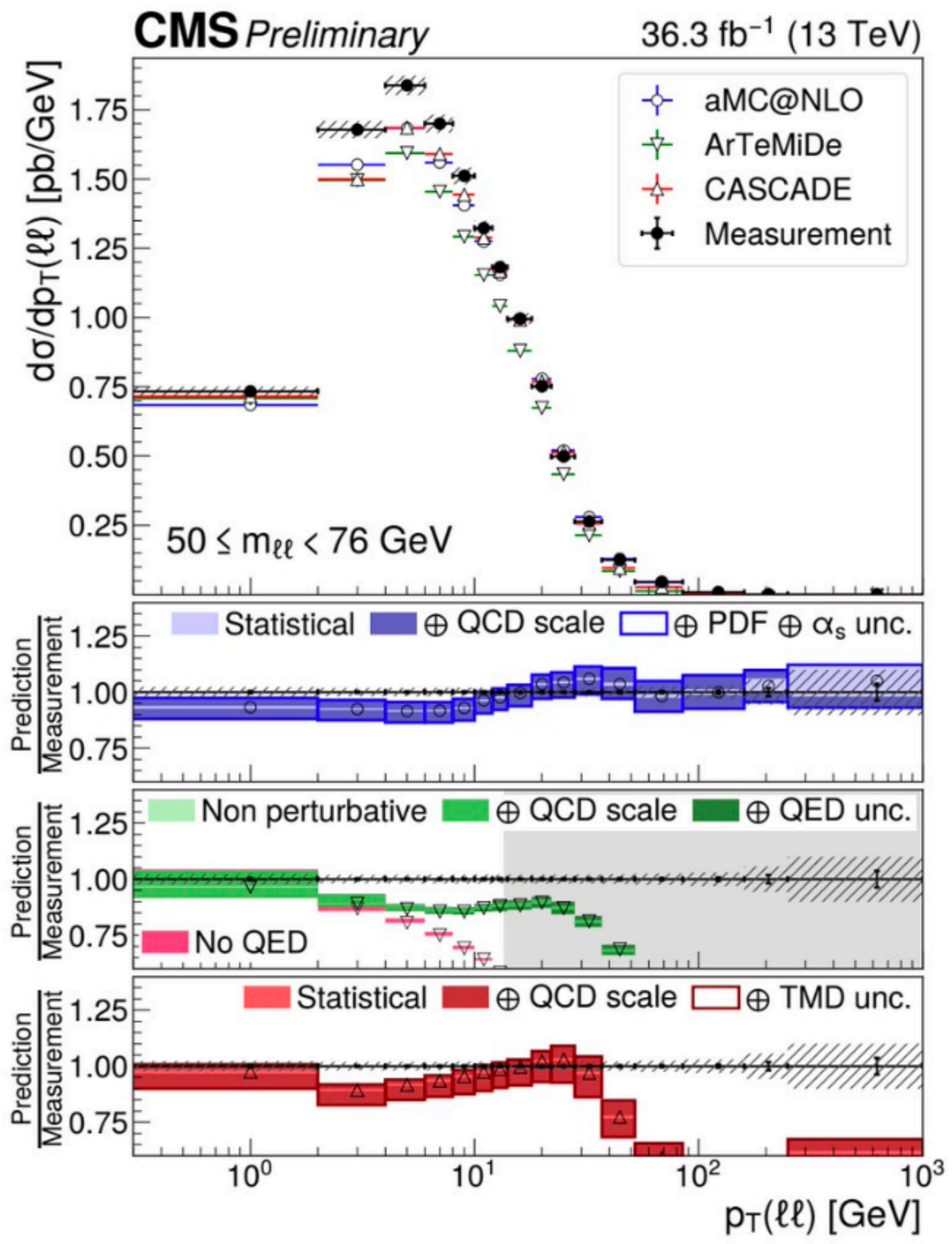


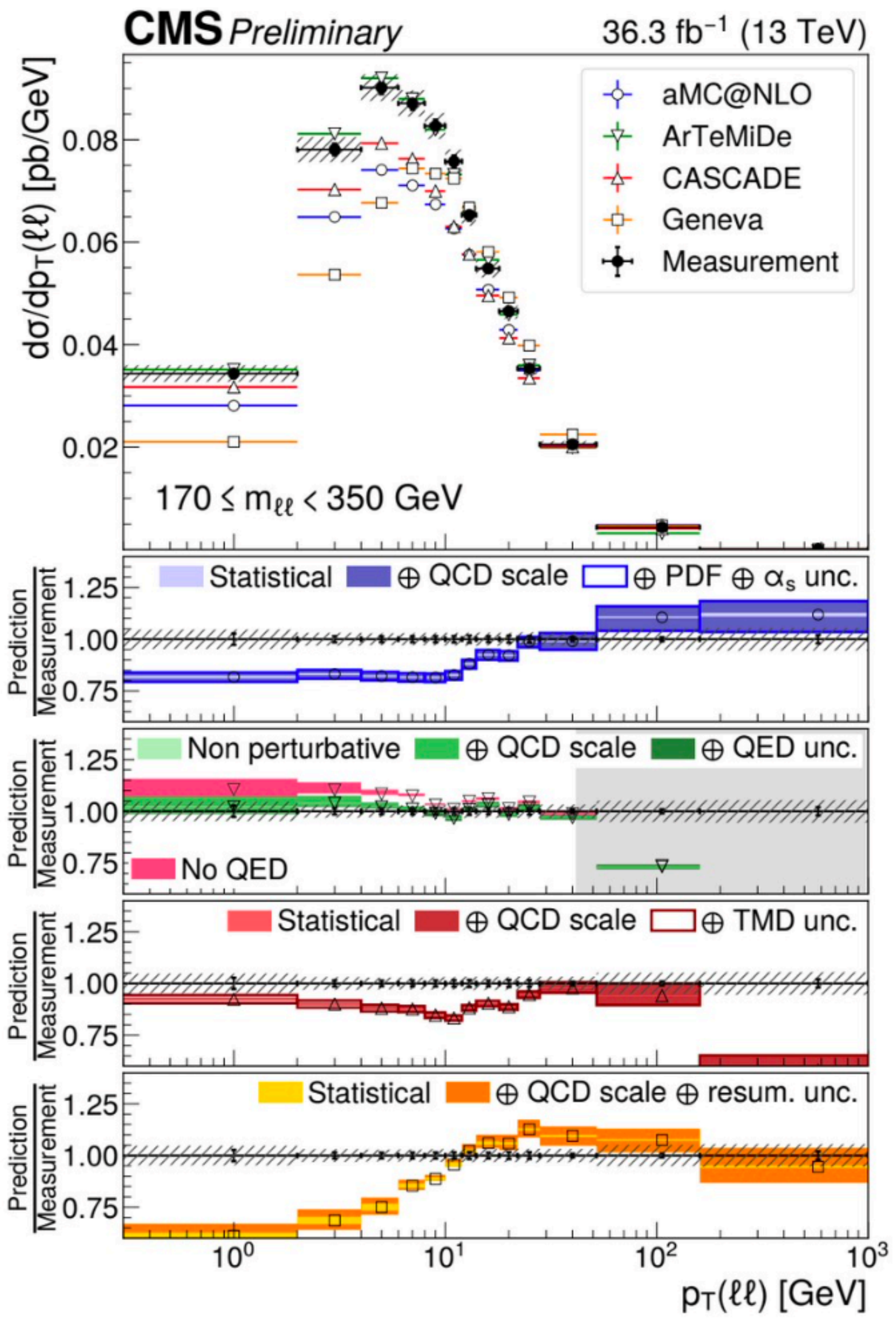
Leptonic measurement

Z boson production: multi-differential pT distribution

SMP-20-003
SMP-21-003

- Fully leptonic channels also used for **multi-differential p_T measurement** over $m_{\ell\ell} \in$ [50, 76, 106, 170, 350, 1000] GeV + multi-differential with jets (SMP-21-003)
  - Background relevant off Z-peak, estimate from data (opposite sign)
  - Extensive **study of modern MC predictions** + Rivet routine to be released soon



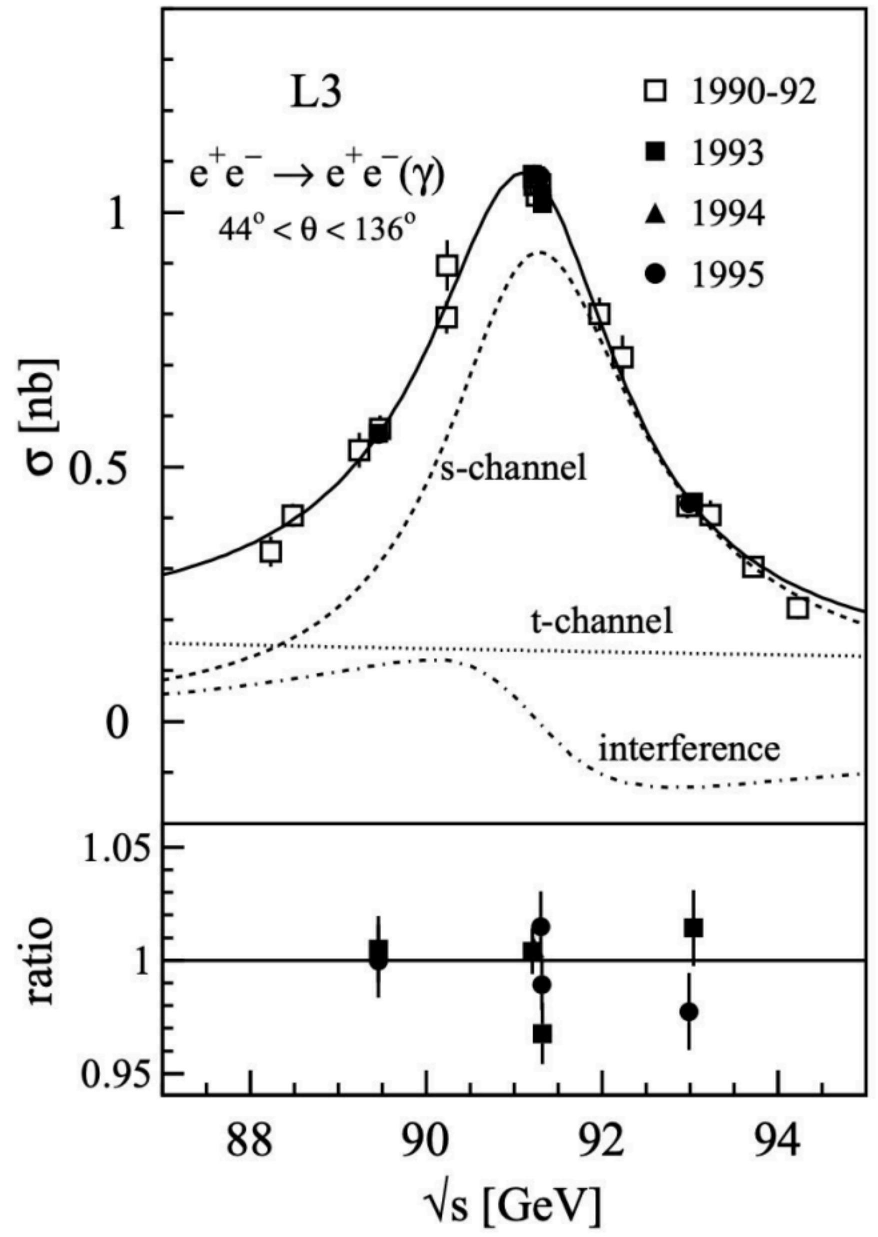


- MG5_aMC@NLO ≤2j@NLO
- ArTeMIDe: Parton branching with NNLO TMD PDFs+QED FSR correction from Pythia
- CASCADE: parton branching with TMD PDF+Pythia6
- Geneva: N^{3}LL'+NNLO+Pythia8

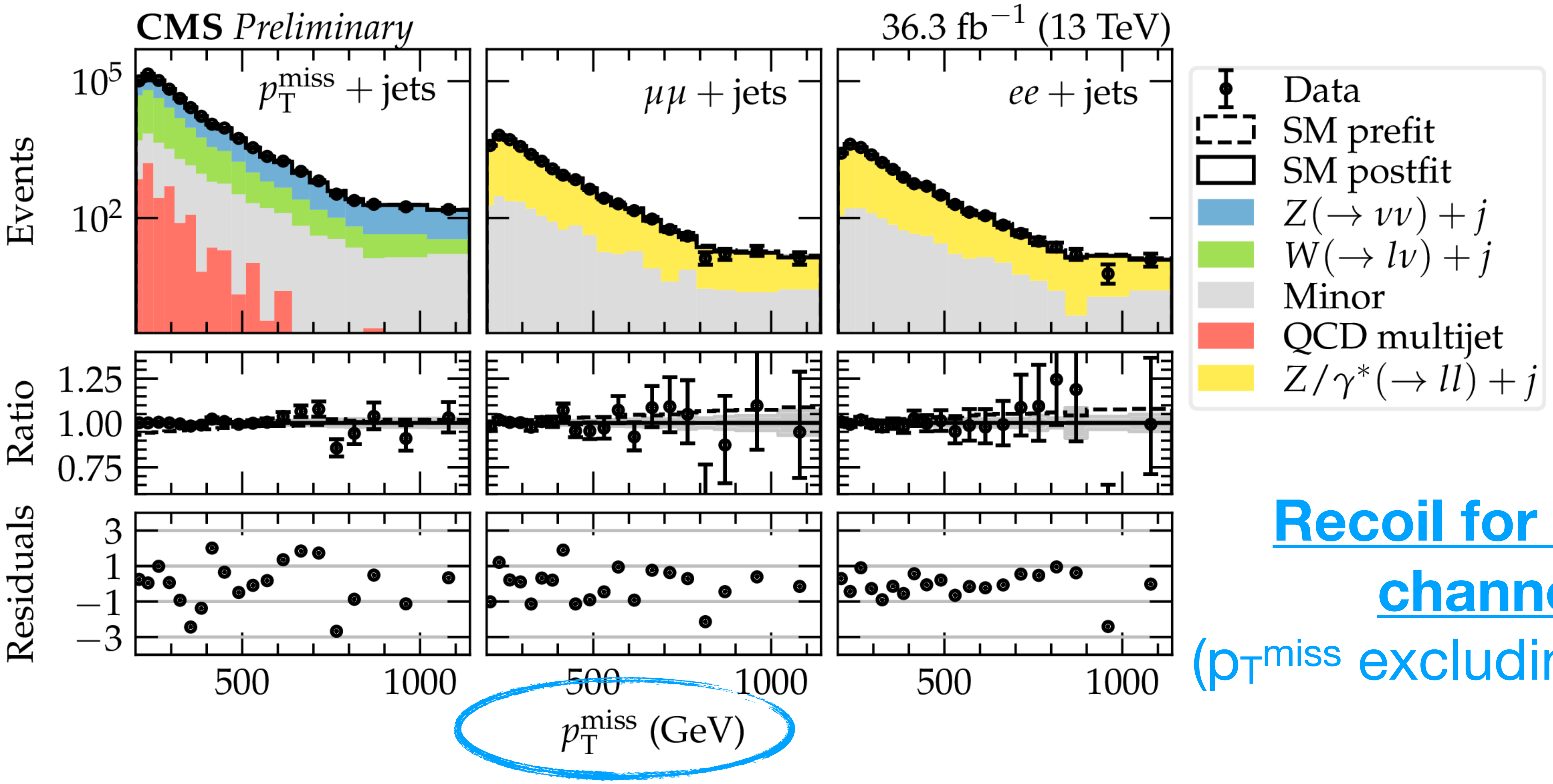
Z boson invisible branching fraction

SMP-18-014

- Branching ratios fundamental, **independent of production mechanism**
  - In practice, produce at collider, correct for (hopefully small) assumptions
- Indirect Z(νν) measurement
  - At LEP (e^+e^-): **measure width from energy scan**, all visible partial widths, subtract.
  - ➡ Very accurate, this is the number in the PDG
- Direct measurement
  - At LEP: Z(νν)+γ. O(10x) less sensitive than indirect
  - At LHC: only indirect possible. **Use Z(νν)+j**



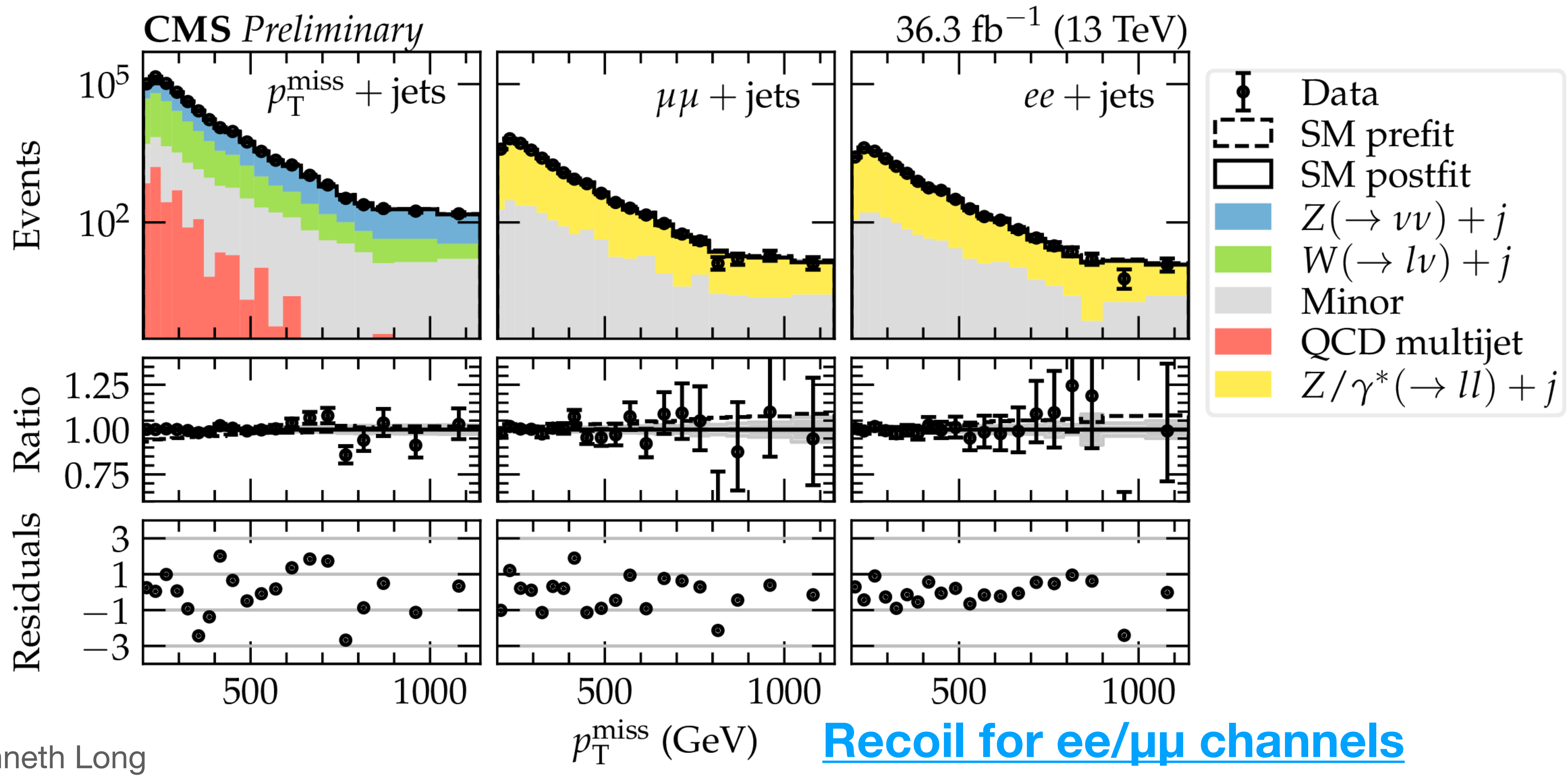
- Procedure at CMS
  - Z(νν) channel with ptmiss > 200 GeV
  - **Recoil** in ee/μμ channels > 200 GeV
  - W(ℓν) from single lepton CR
    - Transfer factors from MC (lost lep.)
    - Validate consistency of e/μ/τ

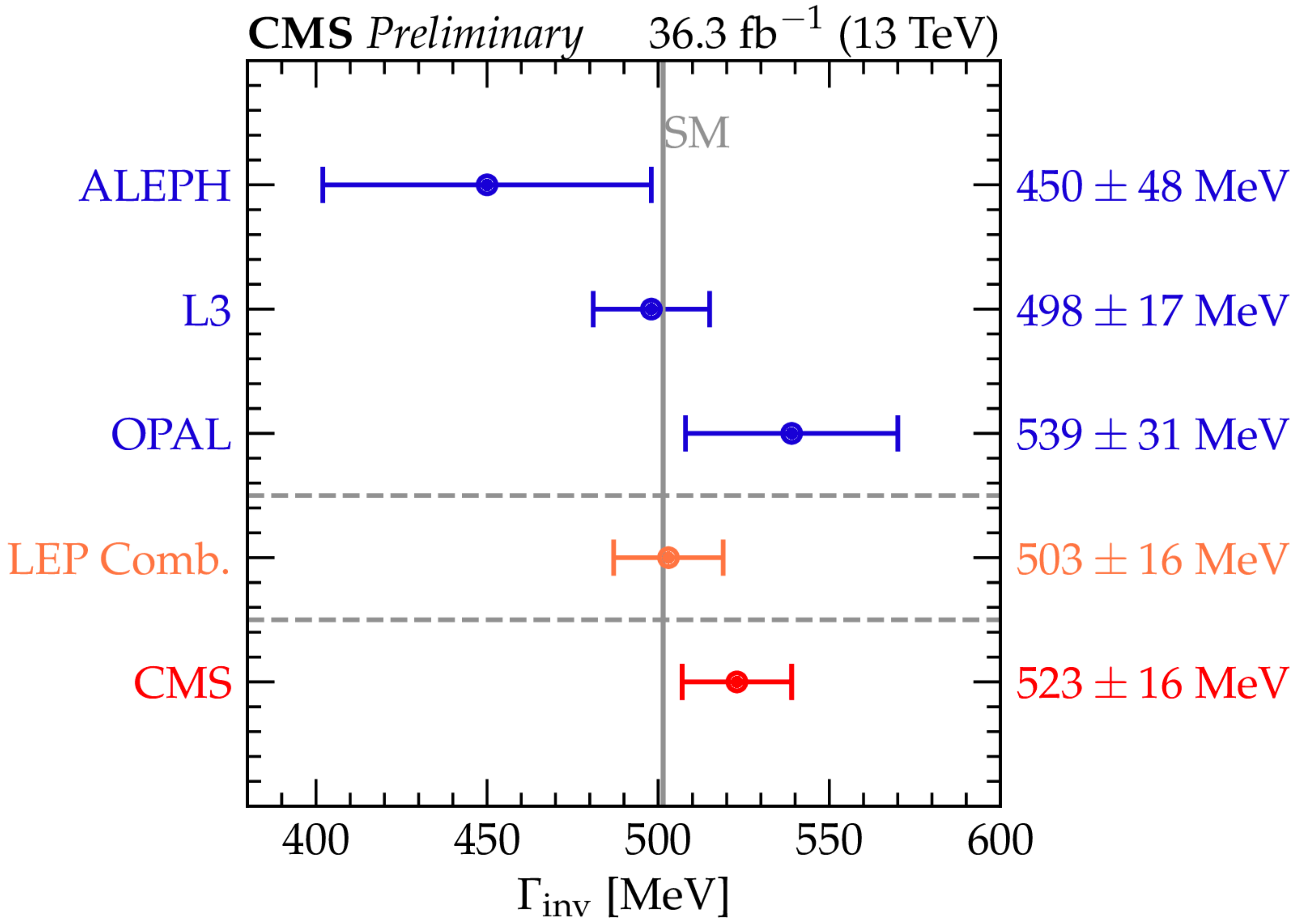


Recoil for ee/mm channels,
(p_T^{miss} excluding leptons)

Z boson invisible branching fraction: results

- Measurement via **simultaneous fit to 3 signal regions** + norm. In W CRs (unconstrained norm.)
  - True observable is ratio of Z(νν)/Z(ℓℓ) in fiducial (high p_T^Z) region
  - Corrections to p_T spectrum separately for each channel via "monojet approach": arxiv:705.04664
    - Rely on theory prediction such that ratio in fiducial region = ratio in inclusive (~0.5% unc.)
- **Jet uncertainties strongly reduced** in ratio. Similar importance to lepton efficiency unc. (Each ~2%)
- Precision directly **competitive with LEP** direct measurement





Recoil for ee/μμ channels

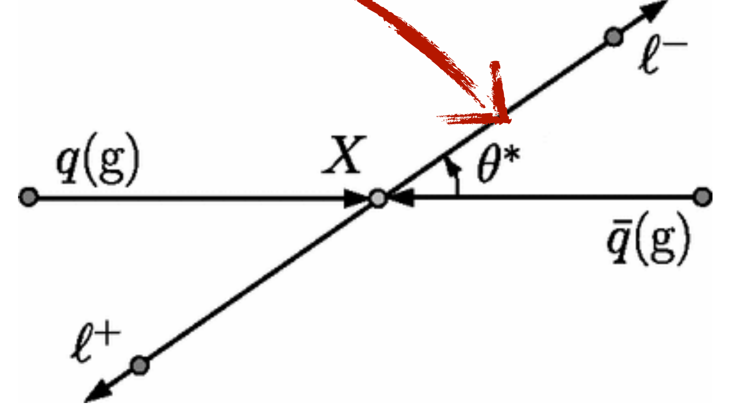
Z boson forward backward asymmetry

SMP-21-002

- Drell-Yan angular properties are a function of Z/γ* vector/axial-vector couplings
- Non-zero A_{FB} arises from different Z/γ* couplings, interference
  - $\sin\theta_W^{eff}$ measurement from A_{FB} via coupling dependence (around Z peak)
  - Additional **heavy vector interactions could lead to A_{FB} deviations** at high $m_{\ell\ell}$
- Study A_{FB} in mass range $m_{\ell\ell}$ in [170, 1400] GeV
  - Parameterize (CS frame) angular dependence, **extract A_{FB} from maximum likelihood fit**
  - Exact direction of quark unknown, guess from $p_T^{\ell\ell}$: $\cos\theta^* \to \cos\theta_r$

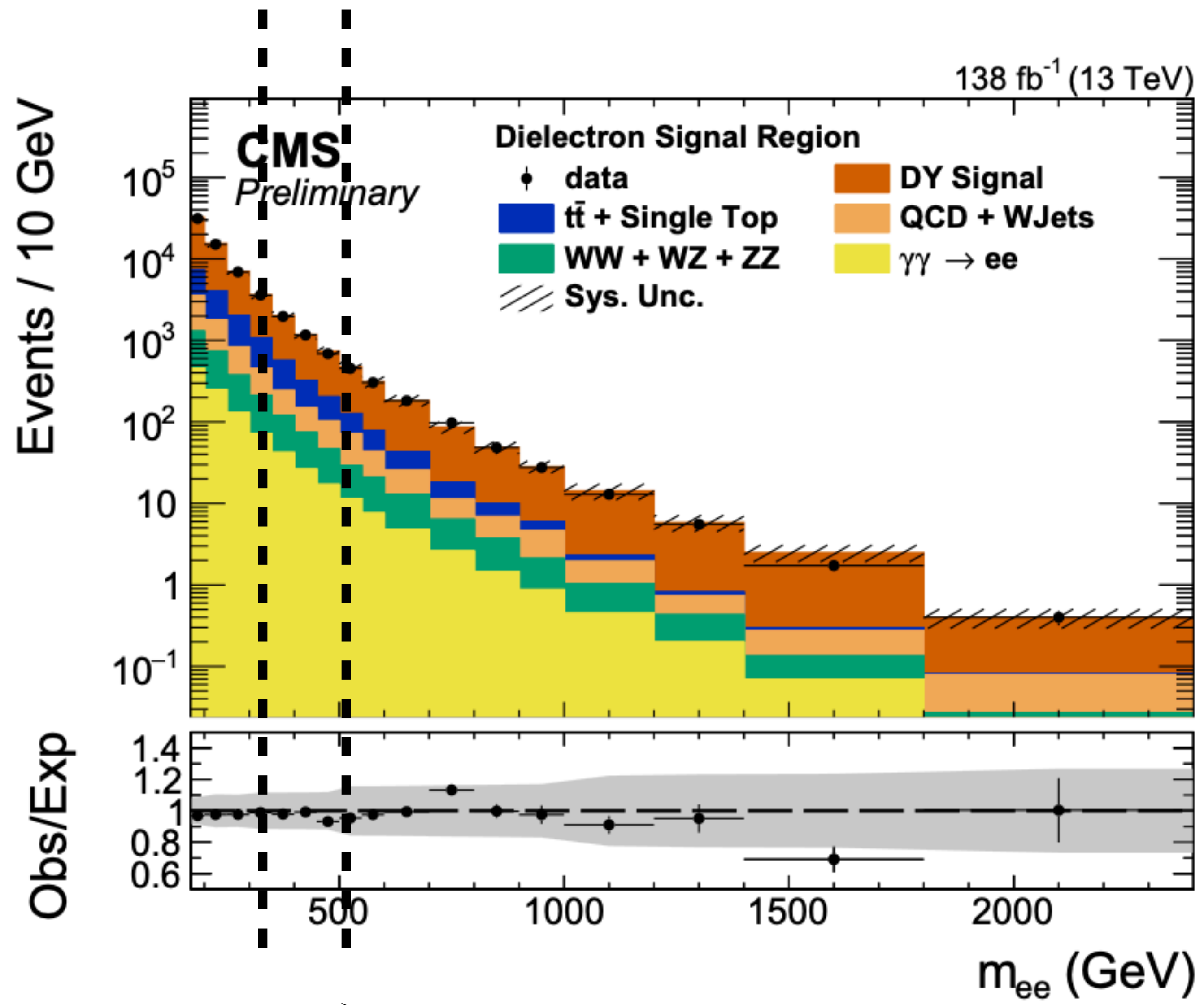
$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*\right]$$

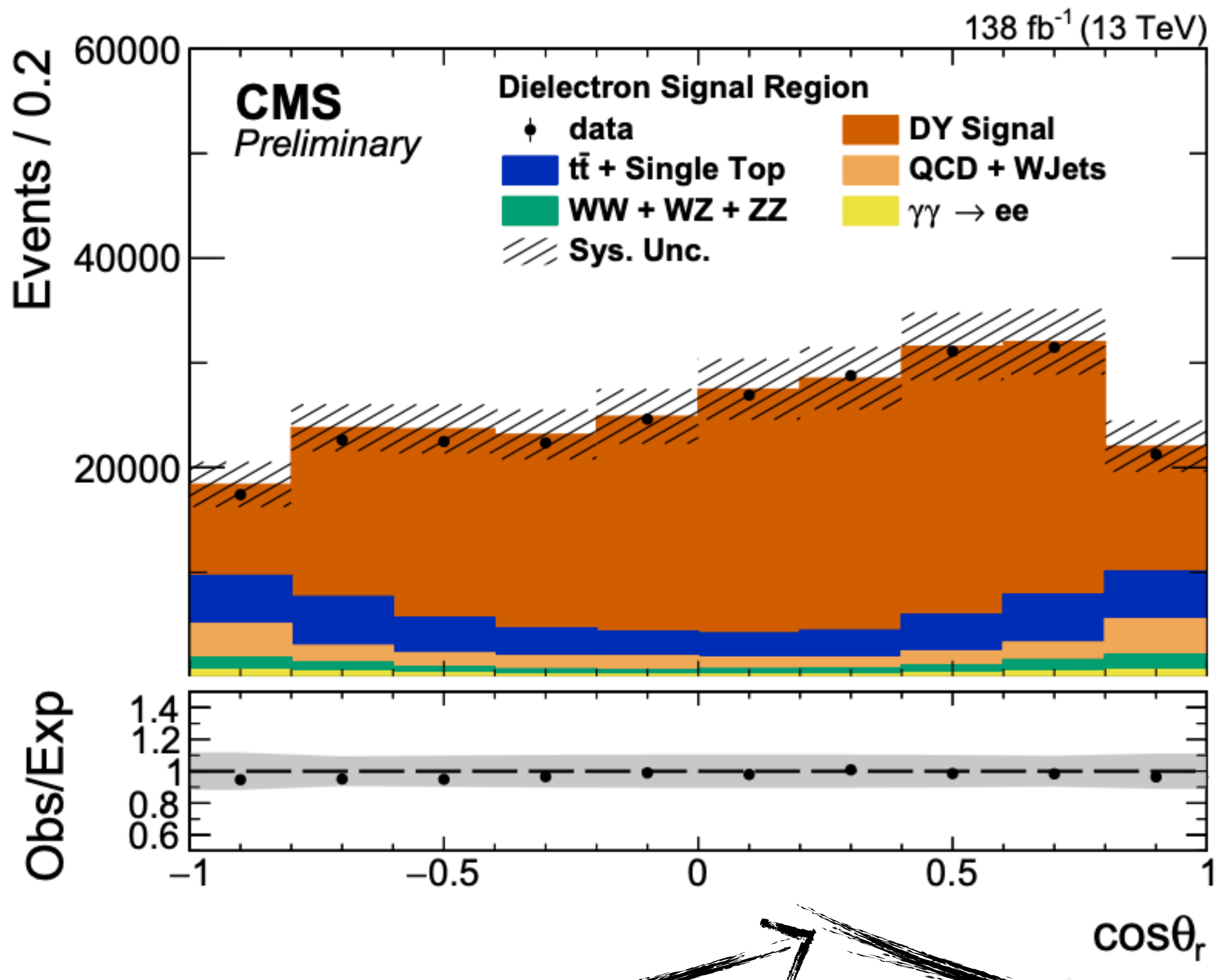
Vector — Axial vector/ vector interf.

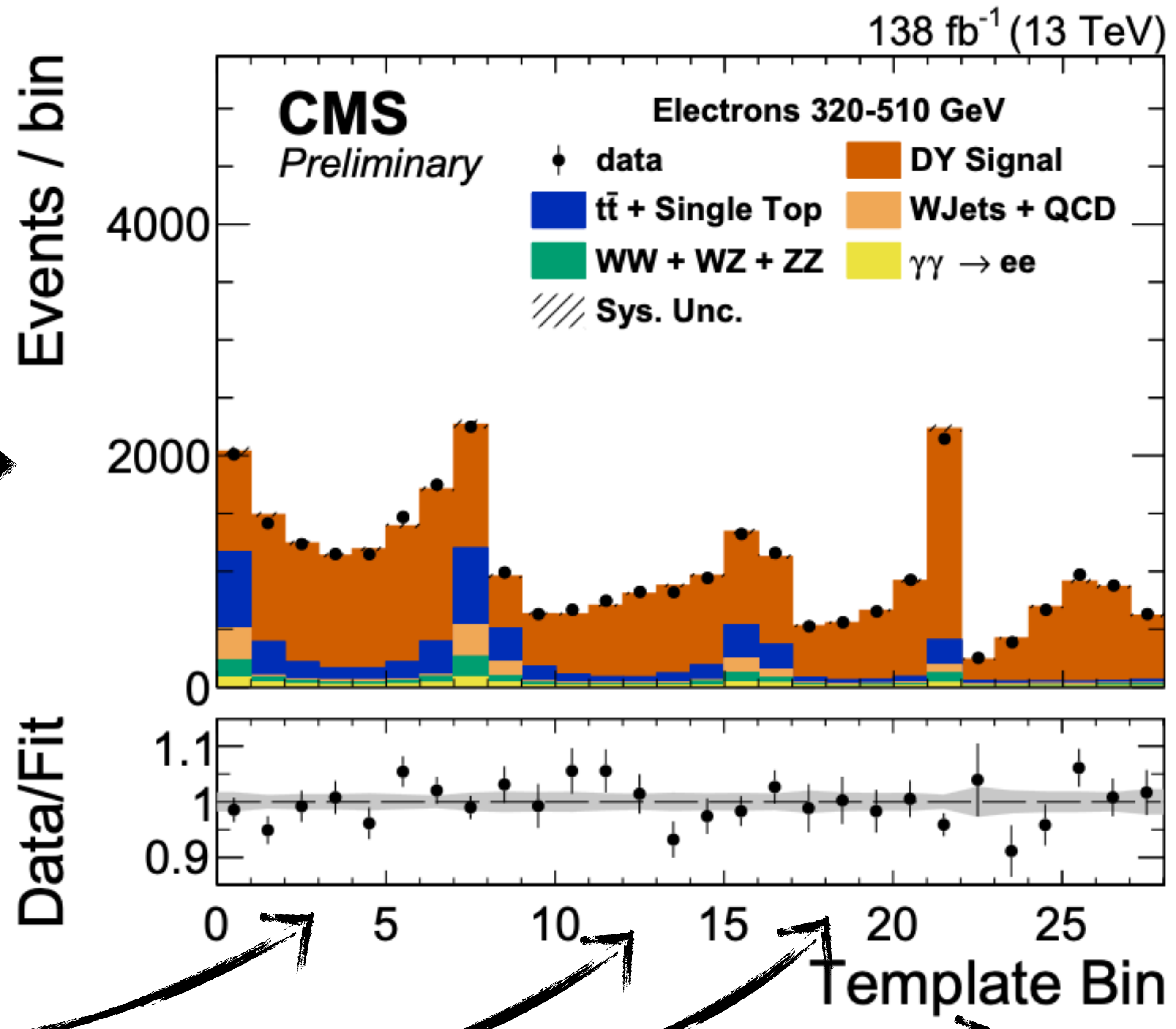


$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

σ_F ($\theta^* > 0$)
σ_B ($\theta^* < 0$)



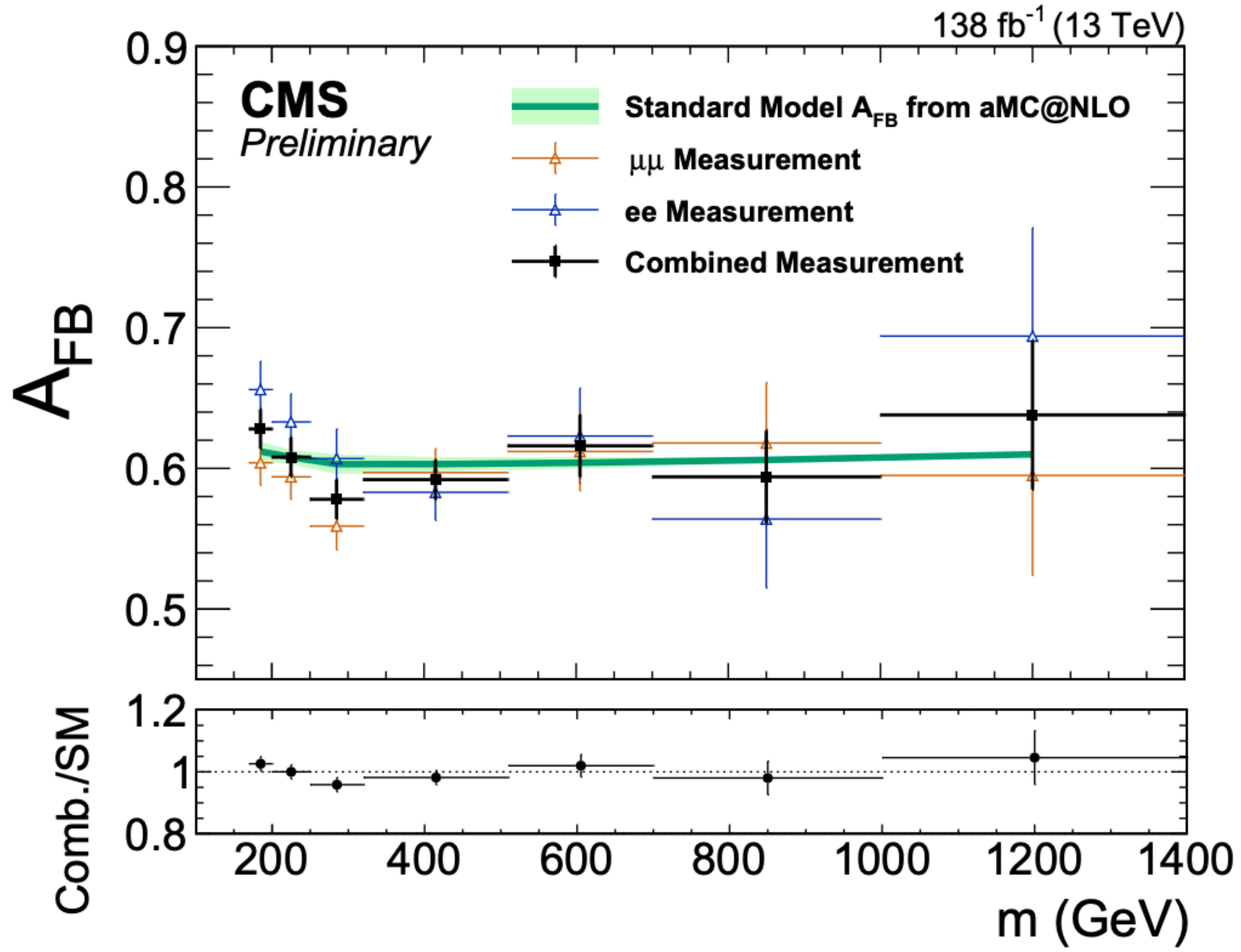


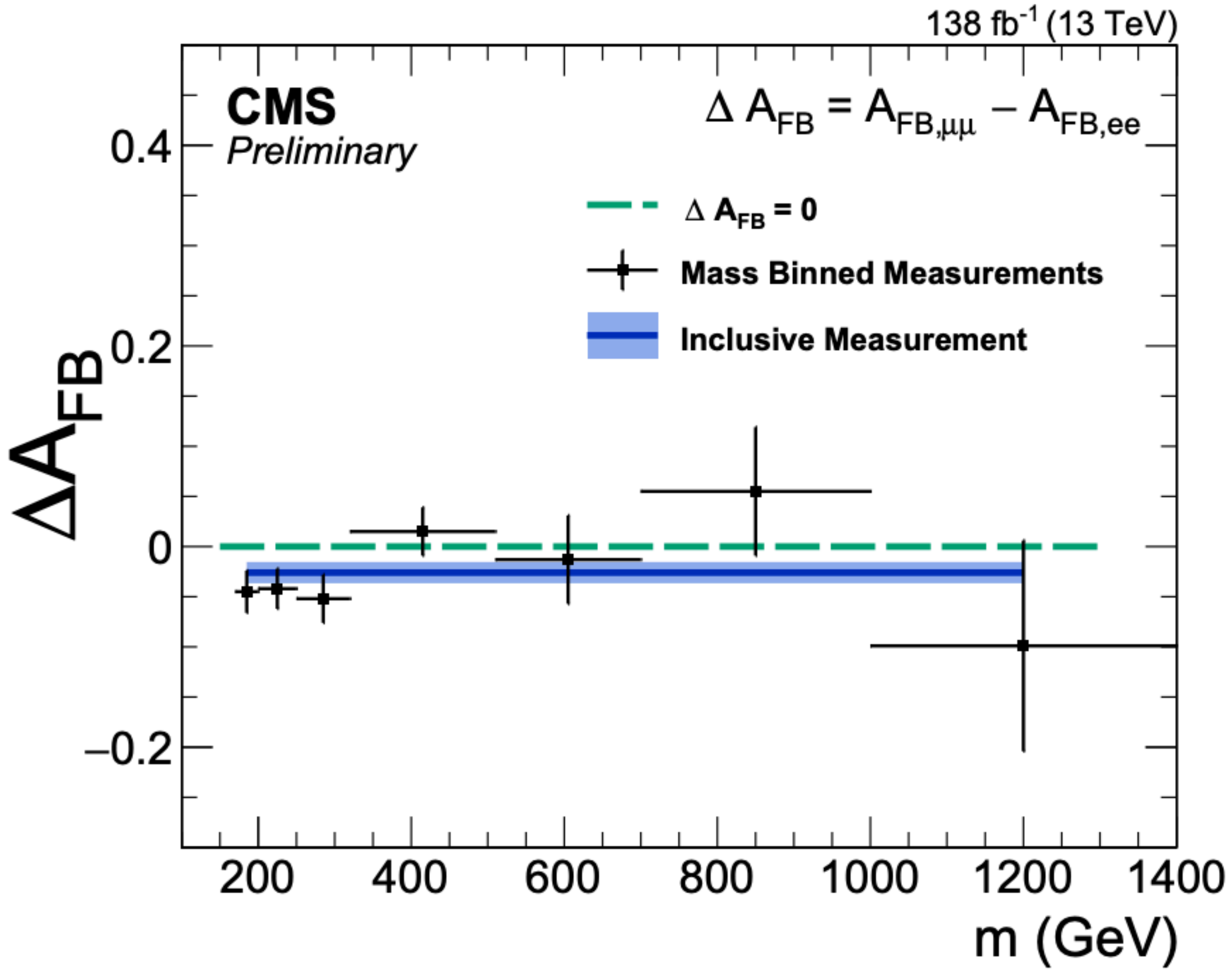


Z boson forward backward asymmetry: results

- Fit distribution per mass bin
  - Separately for ee/μμ + combined
  - Separate fits test ee/μμ consistency (lepton universality)
- A_{FB} **consistent with SM** over wide mass range
- Inclusive ΔA_{FB} (difference between e, μ) differs from expectation by 2.4σ
- Dominant uncertainties from fake background est. and PDF

Source	Frac. of total sys. unc. on A_{FB}	Frac. of total sys. unc. on ΔA_{FB}
PDFs	50%	1%
MC and MisID Backgrounds Stat. Unc.	13%	42%
α_s + μ_F/ μ_R Scales	8%	9%
DY Cross Section	7%	1%
Pileup	6%	13%
$t\bar{t}$ Cross Section	6%	< 1%
DY p_T Correction	3%	1%
$e\mu$ Shape Corrections	2%	<1%
Luminosity	1%	1%
Electron Identification/Isolation	1%	6%
Electron MisID Normalization	1%	17%
Electron MisID Shape	<1%	6%





Conclusions

- The LHC, and CMS, have **proven to be precision tools**, competitive with measurements of fundamental parameters at LEP

➡Thanks to years of collecting very high quality data, developing understanding of detector, and **incredible performance of theoretical tools**

- Exploiting full Run II data and beyond will take time, but clear road map in place for updated results and **new studies at high precision**

- **New frontiers of precision** also opening up (e.g., diboson measurements, P. Vischia's talk)