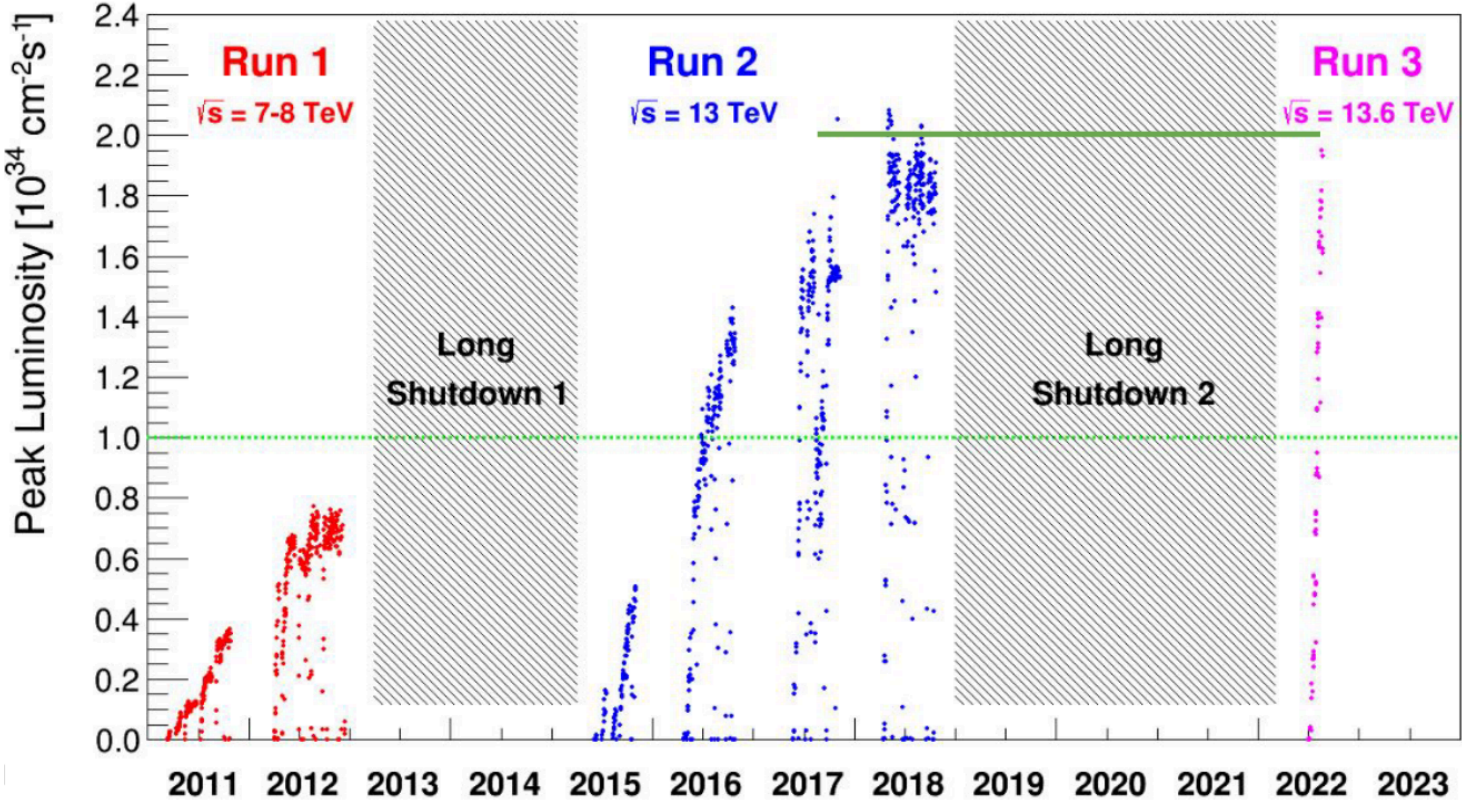
Standard Model measurements at the precision frontier at the LHC

Workshop on Tools for High Precision LHC Simulations

October 31st, 2022

Simone Amoroso (DESY)

Status of the Large Hadron Collider



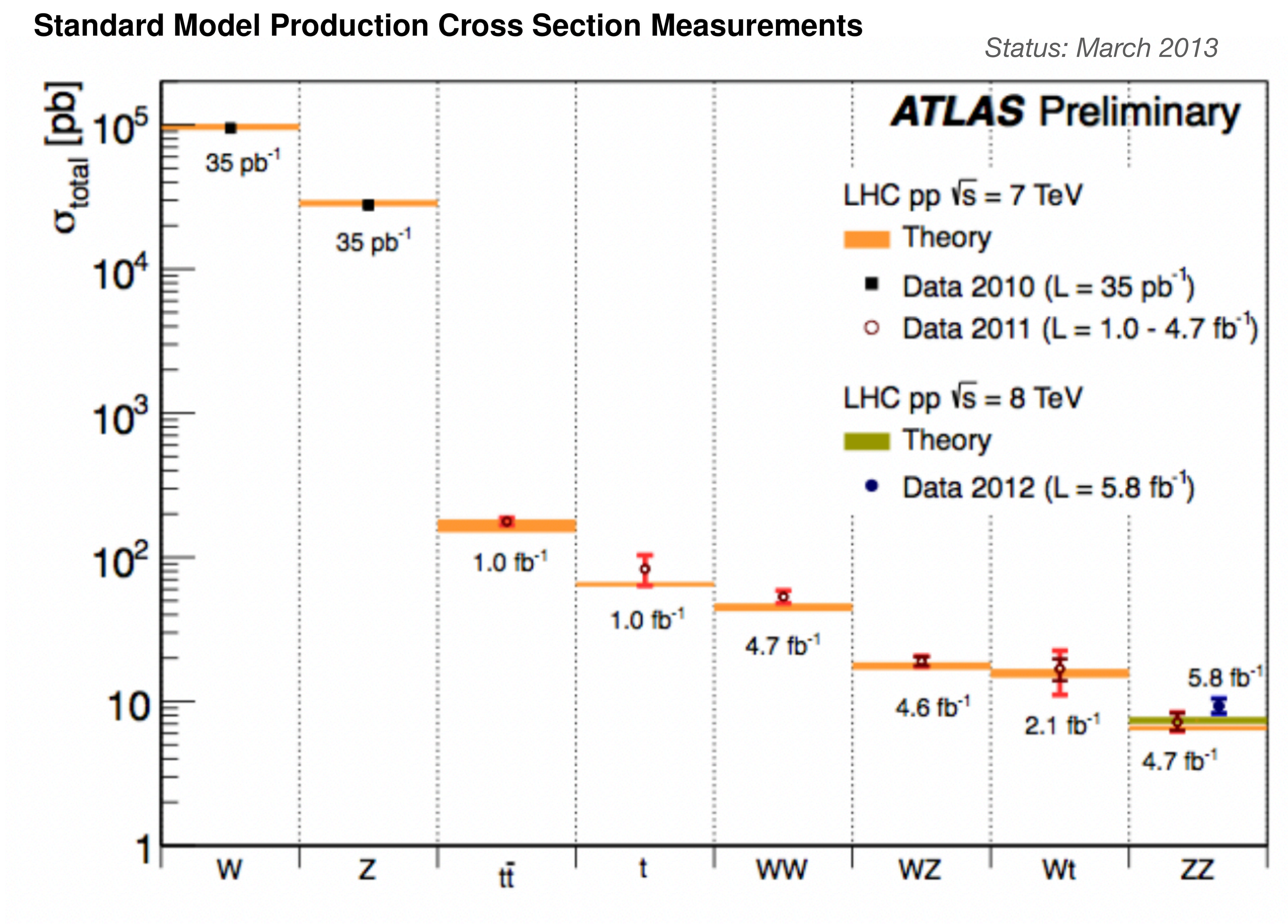
* Reliable operations at 6.8 TeV beams and double the design luminosity

The LHC: an "everything" factory

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 millions	
Top quark	275 millions	
Single top quark	50 millions	
Z boson	2.8 billions	290 millions leptonic
W boson	12 billions	3.7 billions leptonic
Bottom quark	~40 trillions	

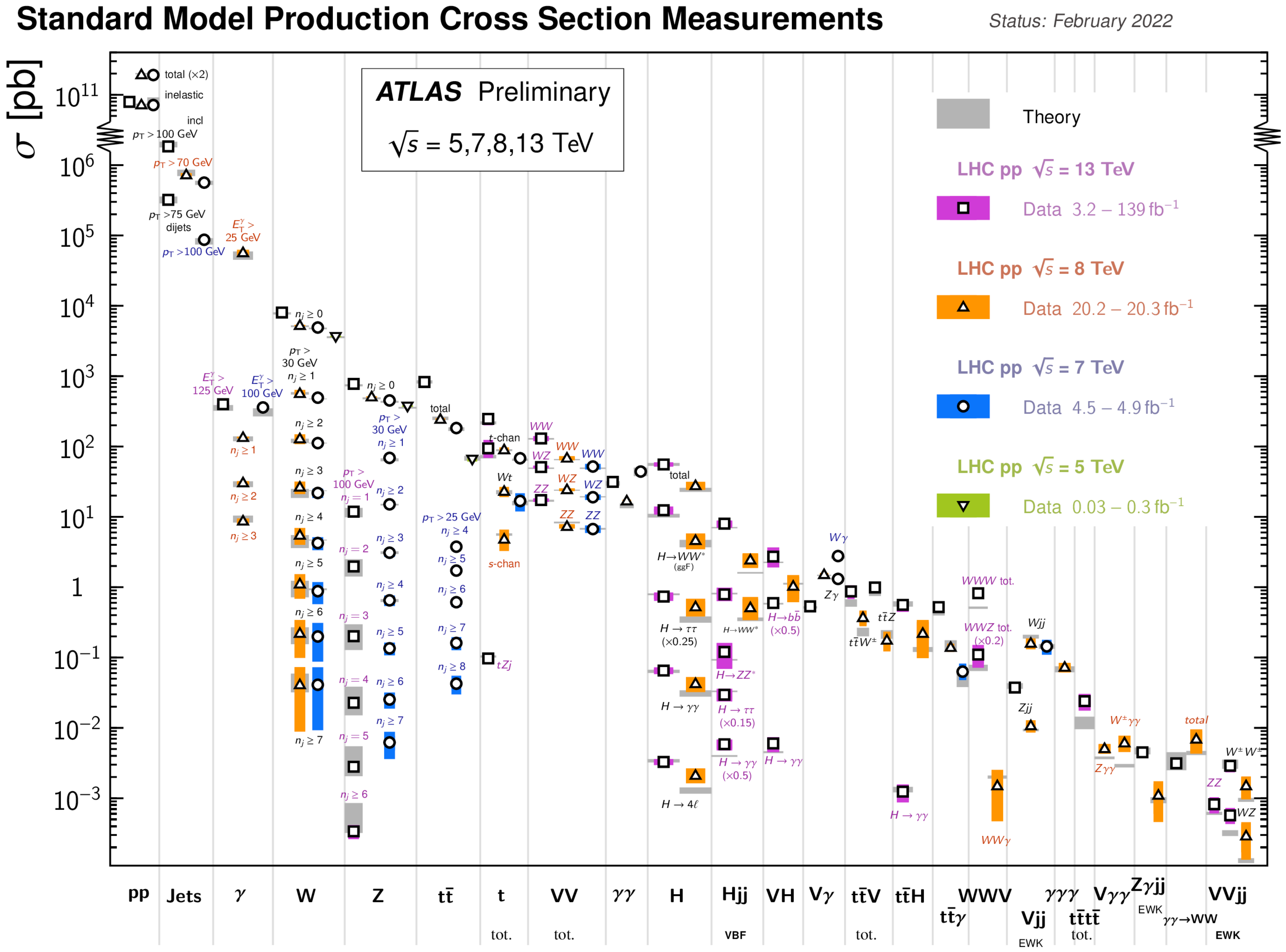
From A. Hoecker @ EPS 2019

Standard Model at the LHC: the beginnings



- Discovery of the Higgs
- Precision measurements of QCD and EW processes
- Exploration of BSM physics via direct and indirect searches

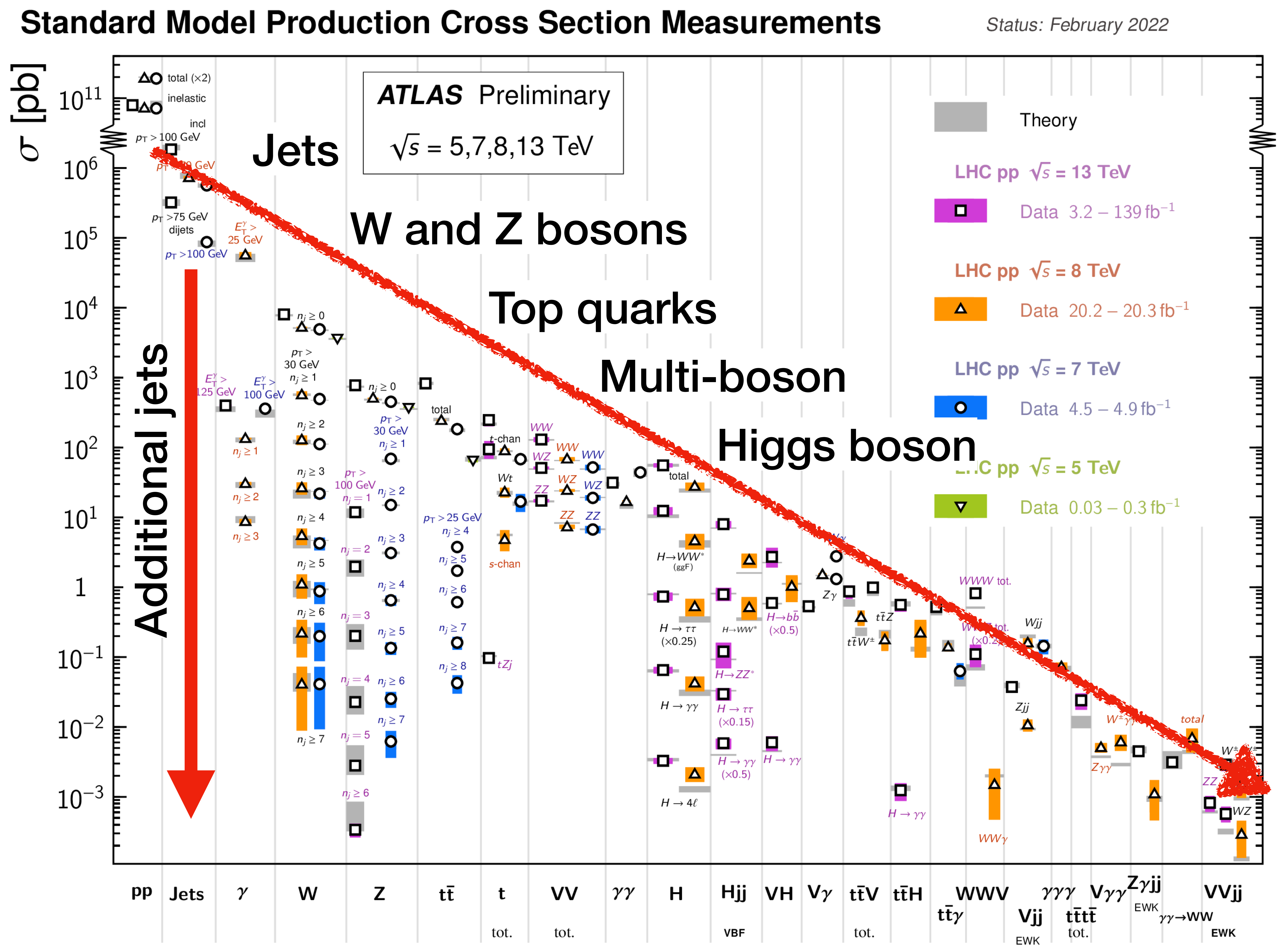
Standard Model at the LHC: now



- **Precision measurements** of Higgs and Standard Model processes
- Observation of very **rare SM processes**
- Direct BSM searches
- Indirect BSM searches through precision measurements

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

Standard Model at the LHC: now



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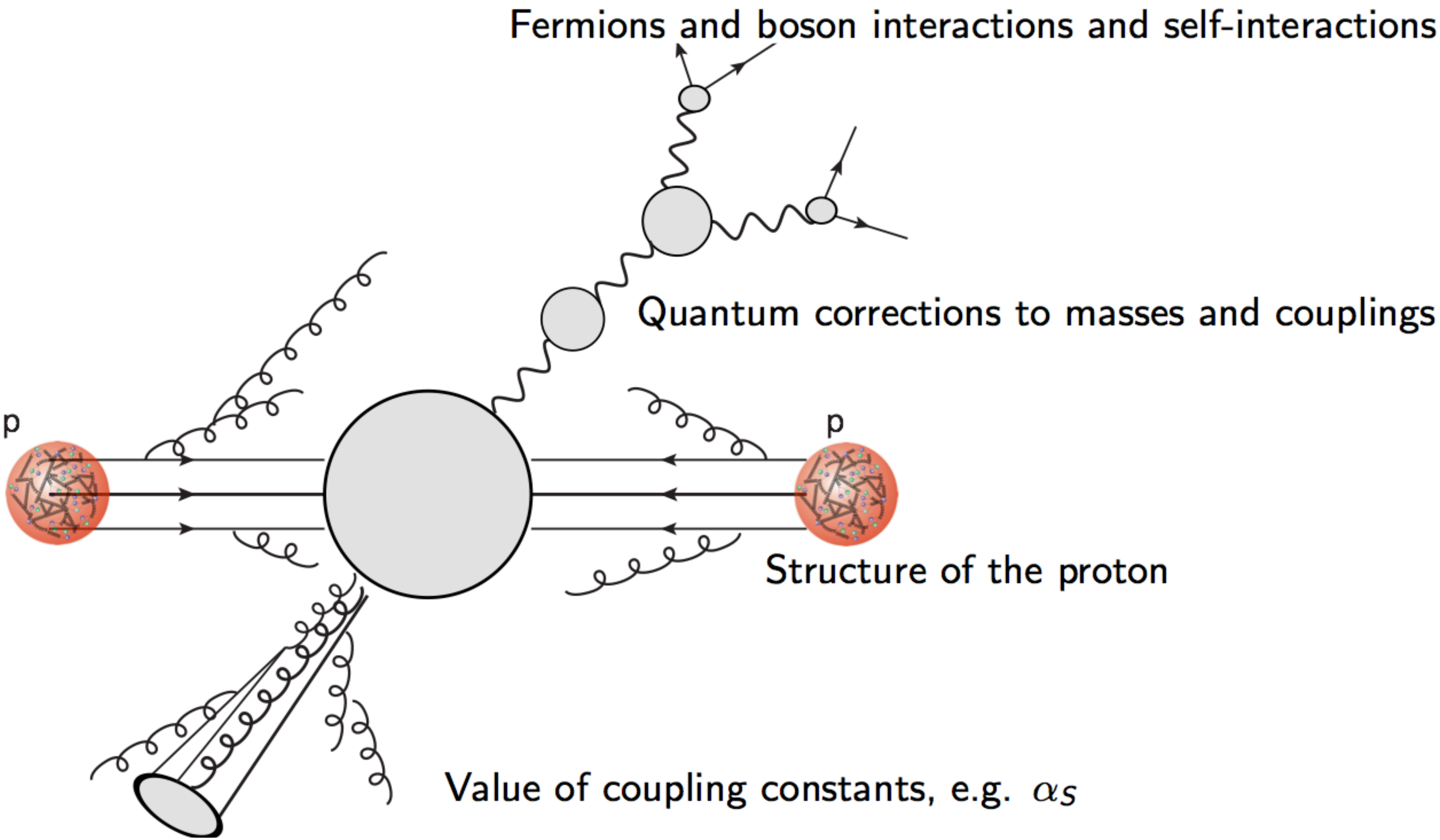
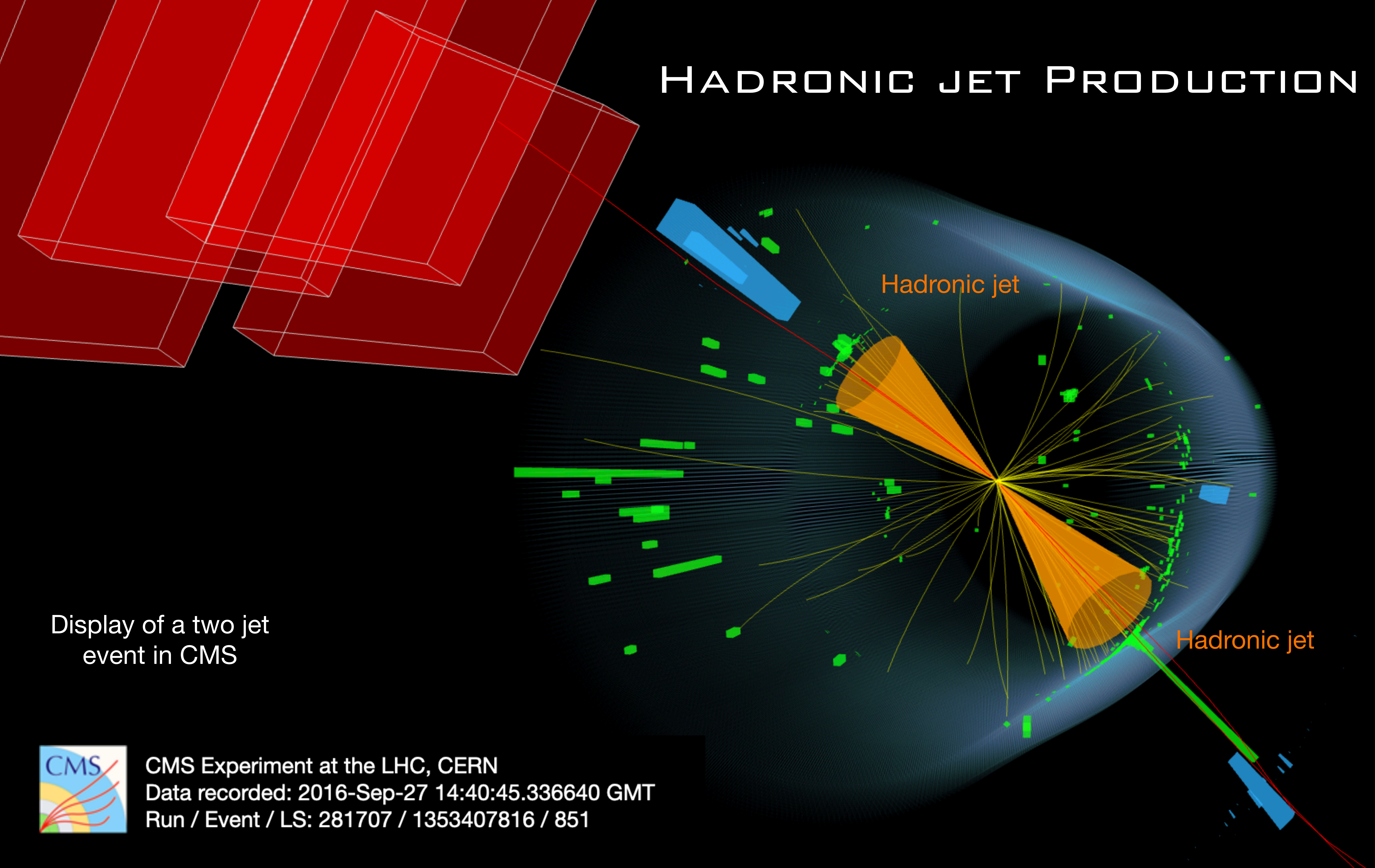
- **Precision measurements** of Higgs and Standard Model processes
- Observation of very **rare SM processes**
- Direct BSM searches
- Indirect BSM searches through precision measurements

Precision SM measurements at colliders



From J. Kretzschmar

Hadronic jet Production



Display of a two jet event in CMS

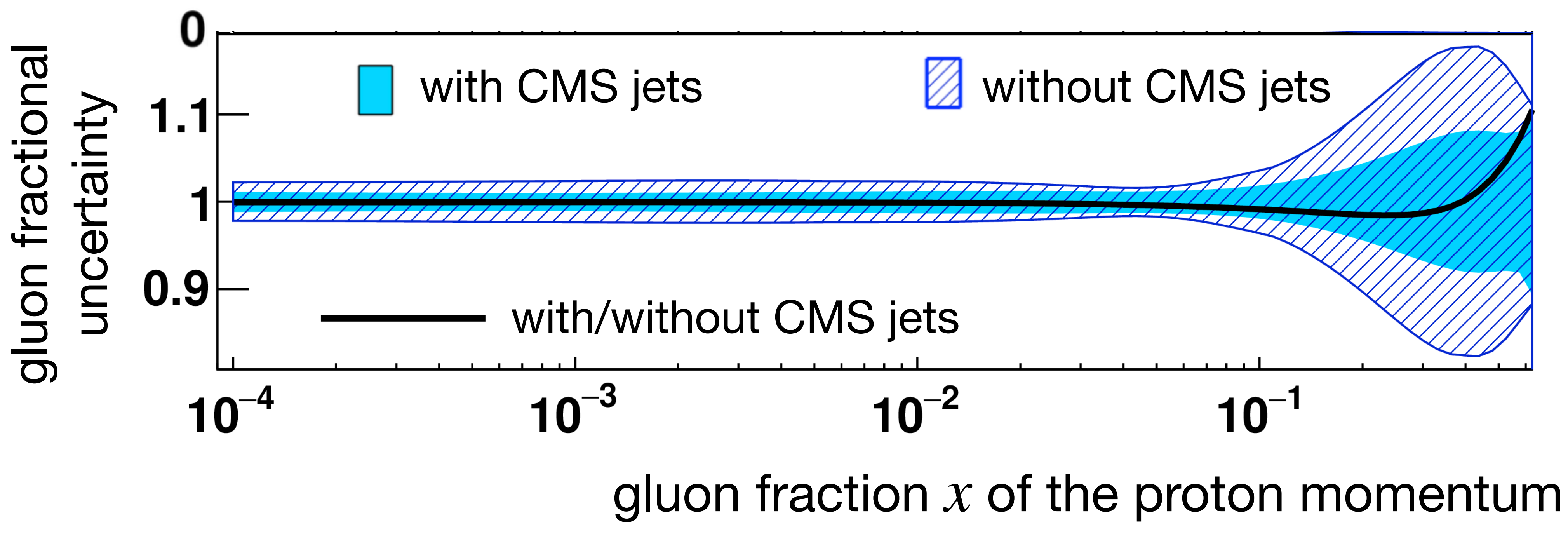
Inclusive jets and $\alpha_S(m_Z)$

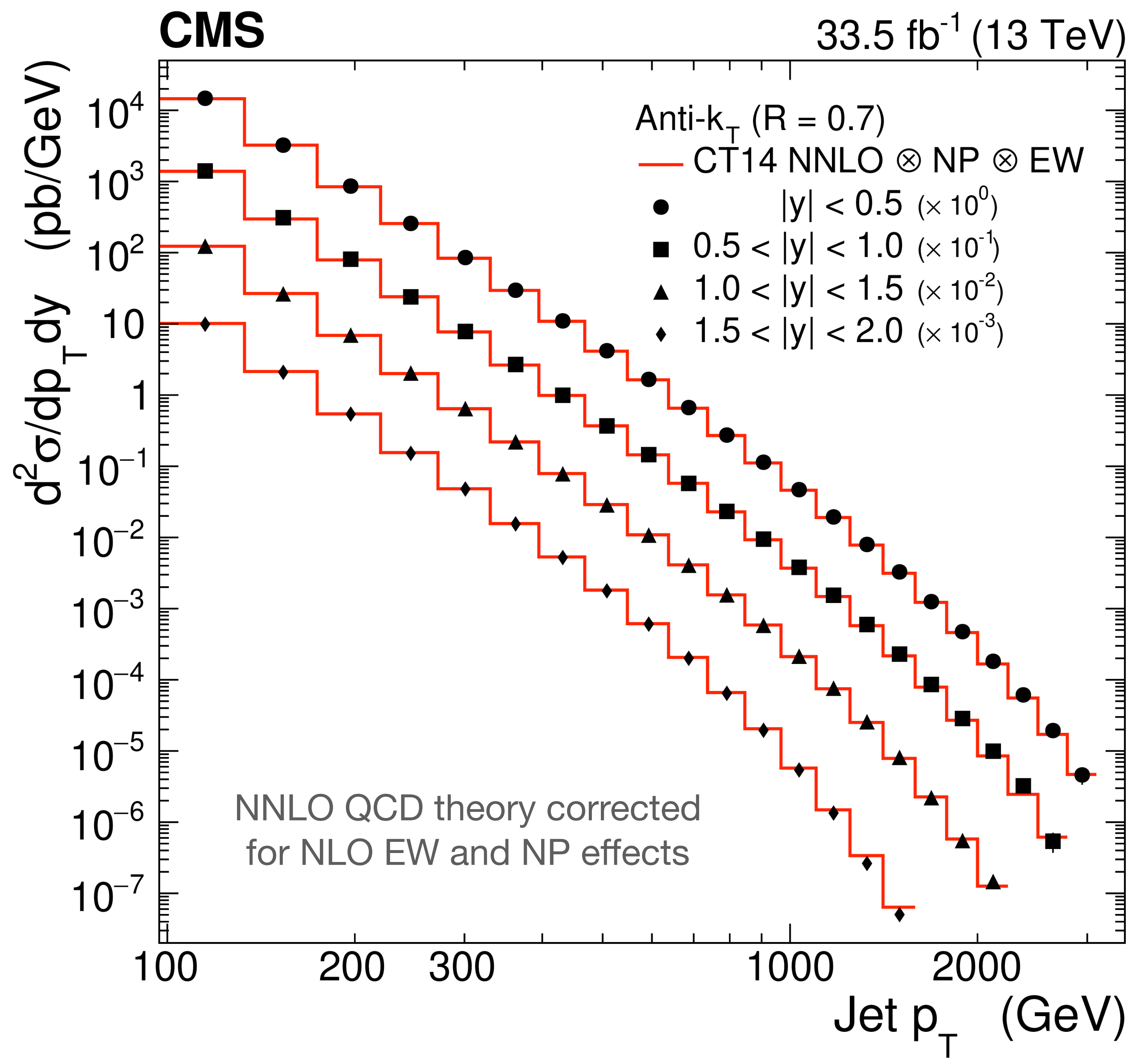
- New 13 TeV CMS measurement
  - Joint determination of the proton PDFs and $\alpha_S(m_Z)$ using the CMS jet and HERA2 DIS data
  - Avoid circularity: jets -> gluon PDF, jets -> $\alpha_S(m_Z)$

Data statistics — Parametric uncertainties

$$\alpha_S(m_Z) = 0.1170 \pm 0.0014(\text{fit}) \pm 0.0007(\text{model})$$
$$\pm 0.0008(\text{scale}) \pm 0.0001(\text{parametrisation})$$

QCD scale variations — PDF functional form





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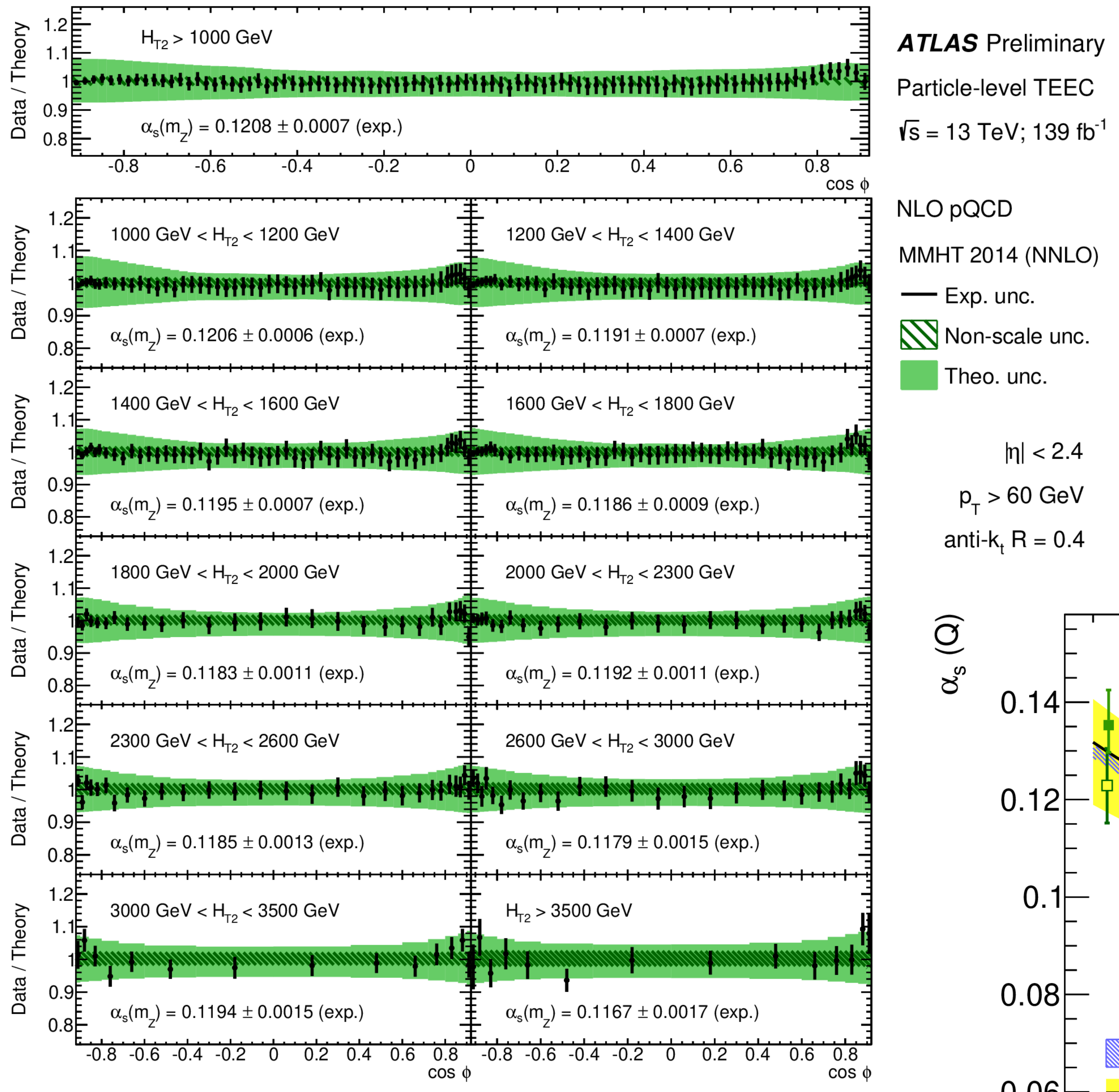
- Most precise $\alpha_S(m_Z)$ from hadron collider experiment, in agreement with world average

Event shapes and running of the strong-coupling



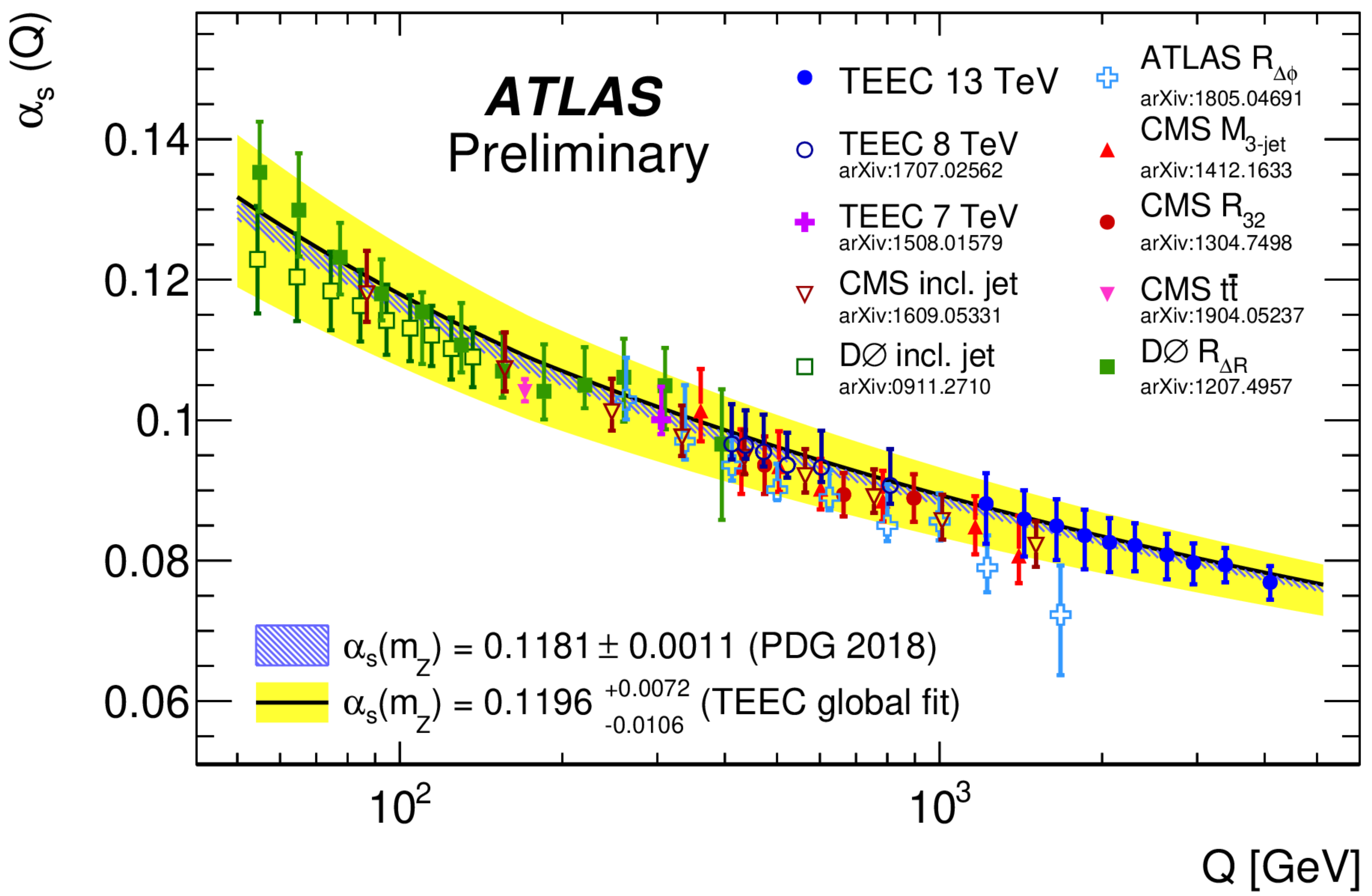
ATLAS-CONF-2020-025

- ATLAS measurement of the strong coupling from Energy-Energy Correlations in jet events

$$\frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi-\cos\phi_{ij}),$$

- NLO fixed-order predictions are used to get

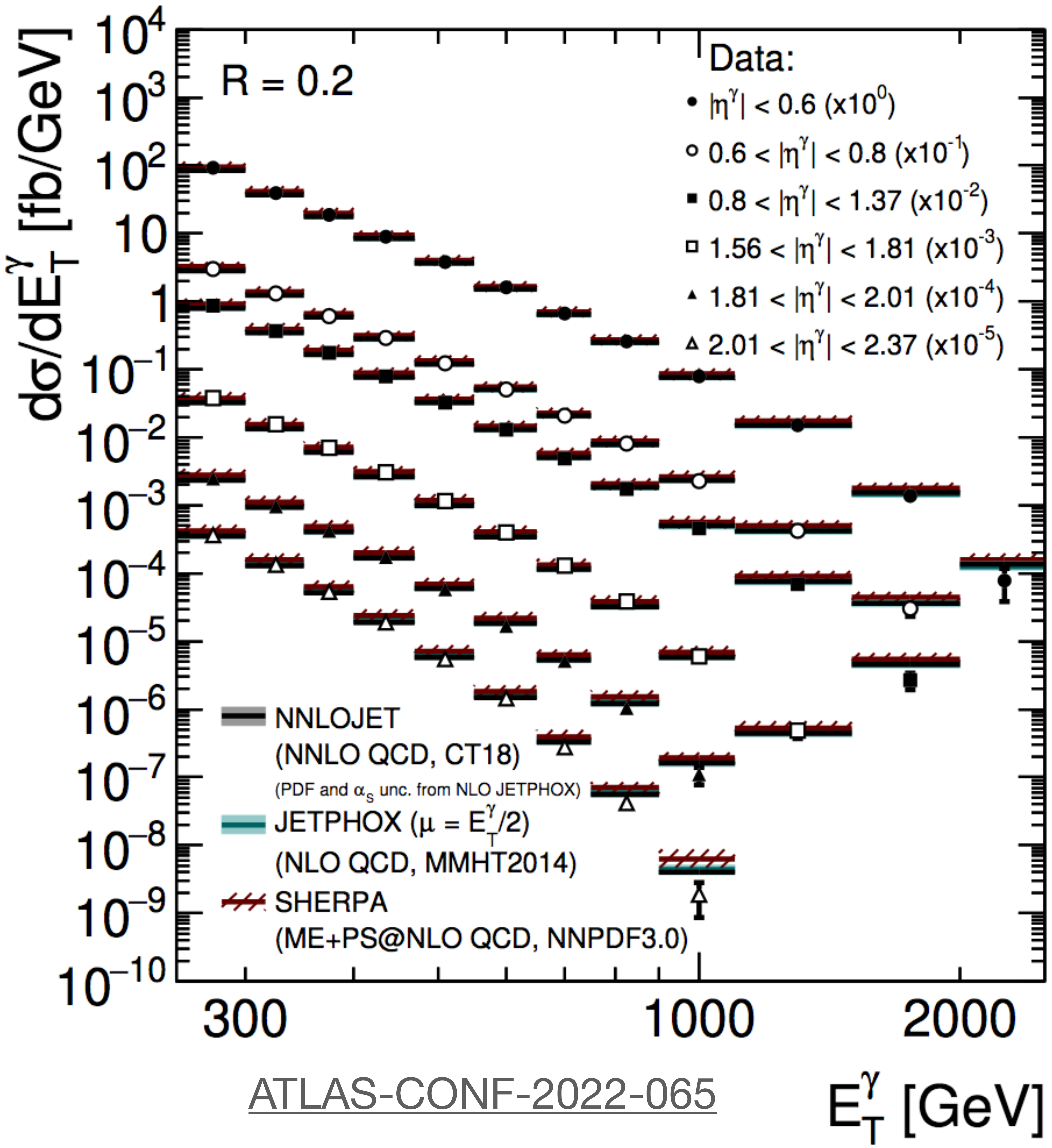
$$\alpha_s(m_Z) = 0.1196 \pm 0.0004\ (\mathrm{exp.})\ {}^{+0.0072}_{-0.0105}\ (\mathrm{theo.})$$



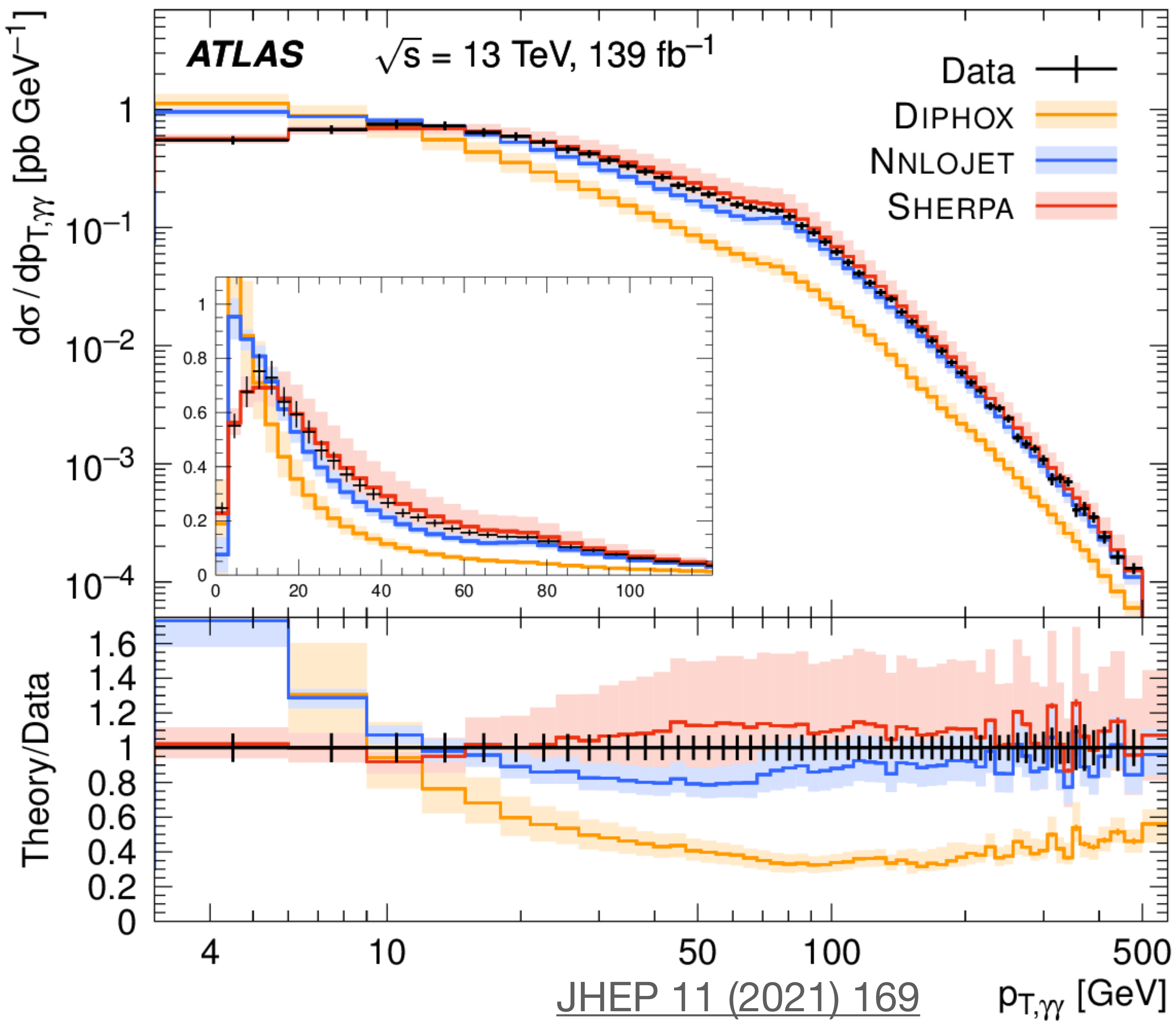
- Test the running up to highest scales
- But is the scale used in the predictions used appropriate?

Photon and diphoton production

- Testing QCD higher orders and subtleties with modelling of isolation



ATLAS-CONF-2022-065



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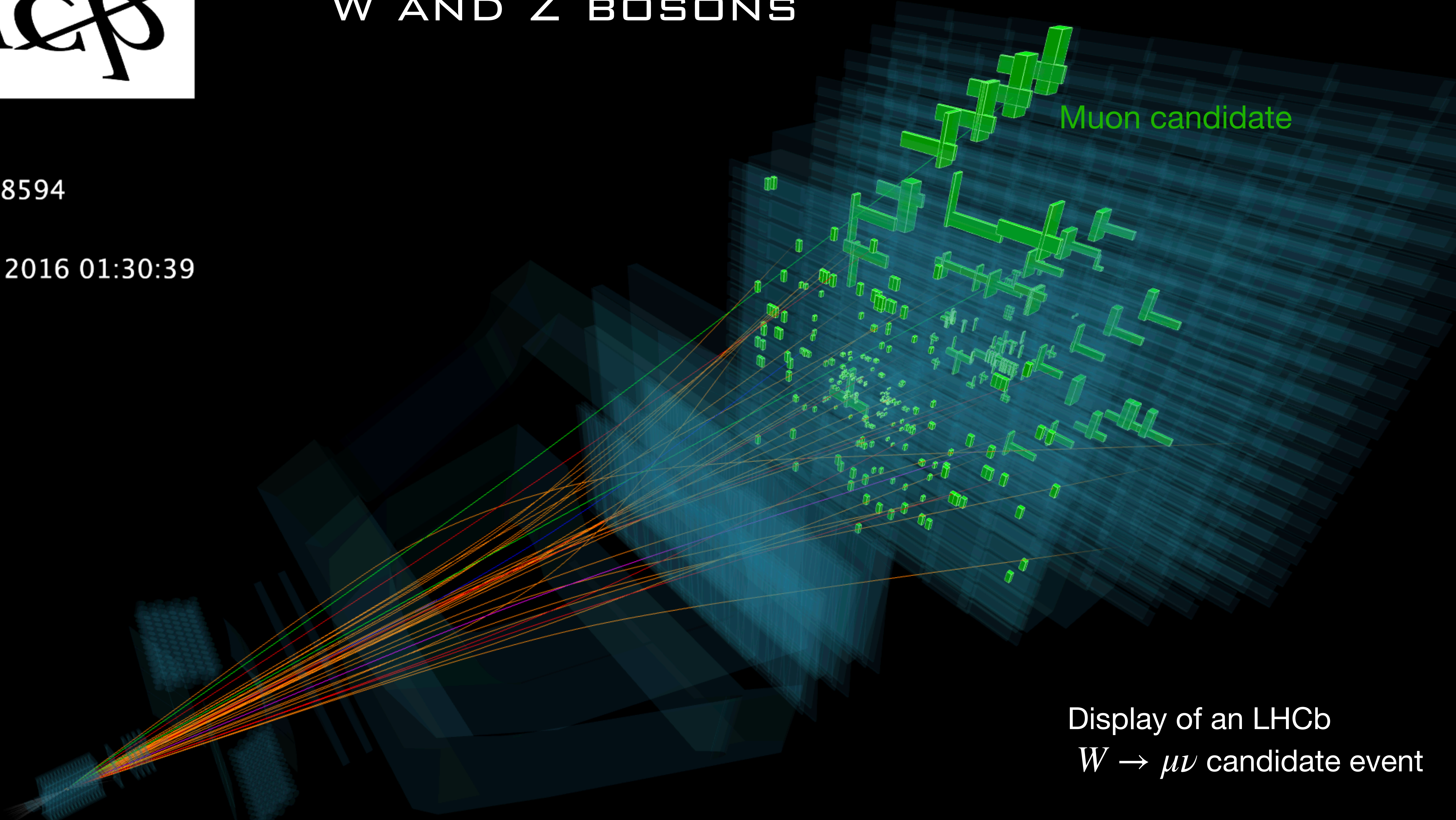
W and Z bosons

Event 506568594
Run 182153
Sun, 21 Aug 2016 01:30:39



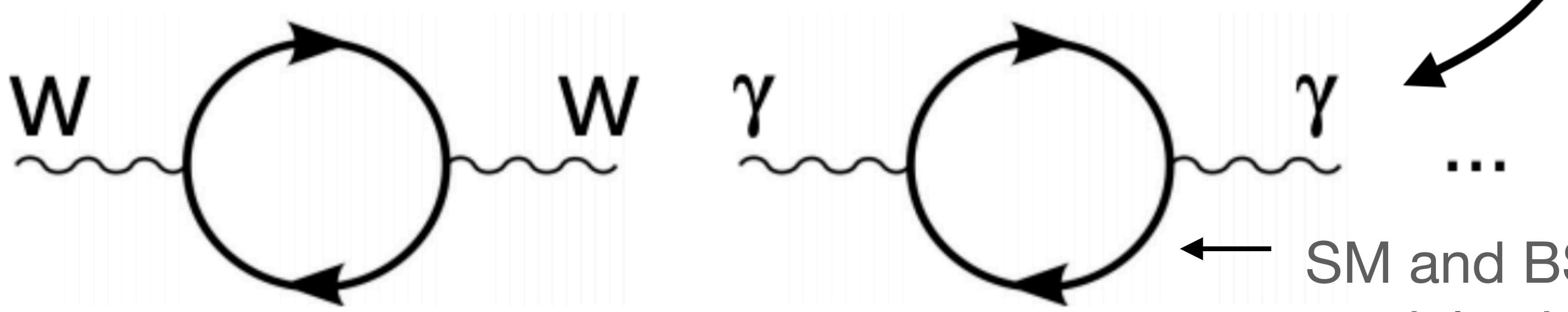
Display of an LHCb
$W \to \mu\nu$ candidate event

PRECISION ELECTROWEAK MEASUREMENTS

- Powerful way to access physics at very high energies

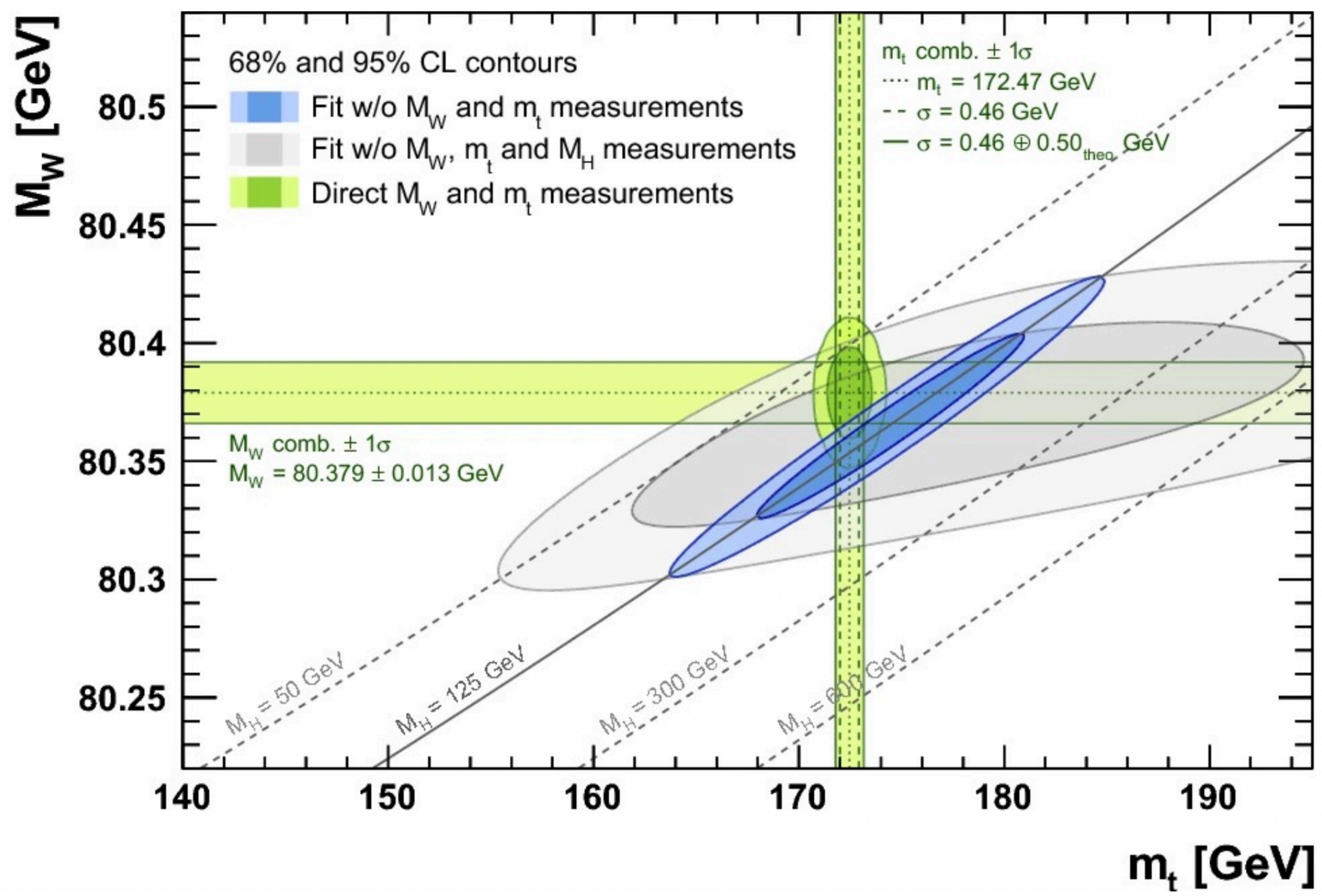
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

Radiative corrections



SM and BSM particles in loops

Global EW fit by the Gfitter group EPJC(2018)78:675



Parameter	Measurement	EW fit
m_H [GeV]	125.1±0.2	99.5±21
m_t [GeV]	172.47±0.68	175.2±2.4
m_W [GeV]	80.366±0.019	80.354±0.007
$\sin^2\theta^l_{eff}$	0.23152±0.00016	0.23153±0.00006

- Sensitivity to BSM primarily driven by the precision of direct m_W, $\sin^2\theta_W$ measurement

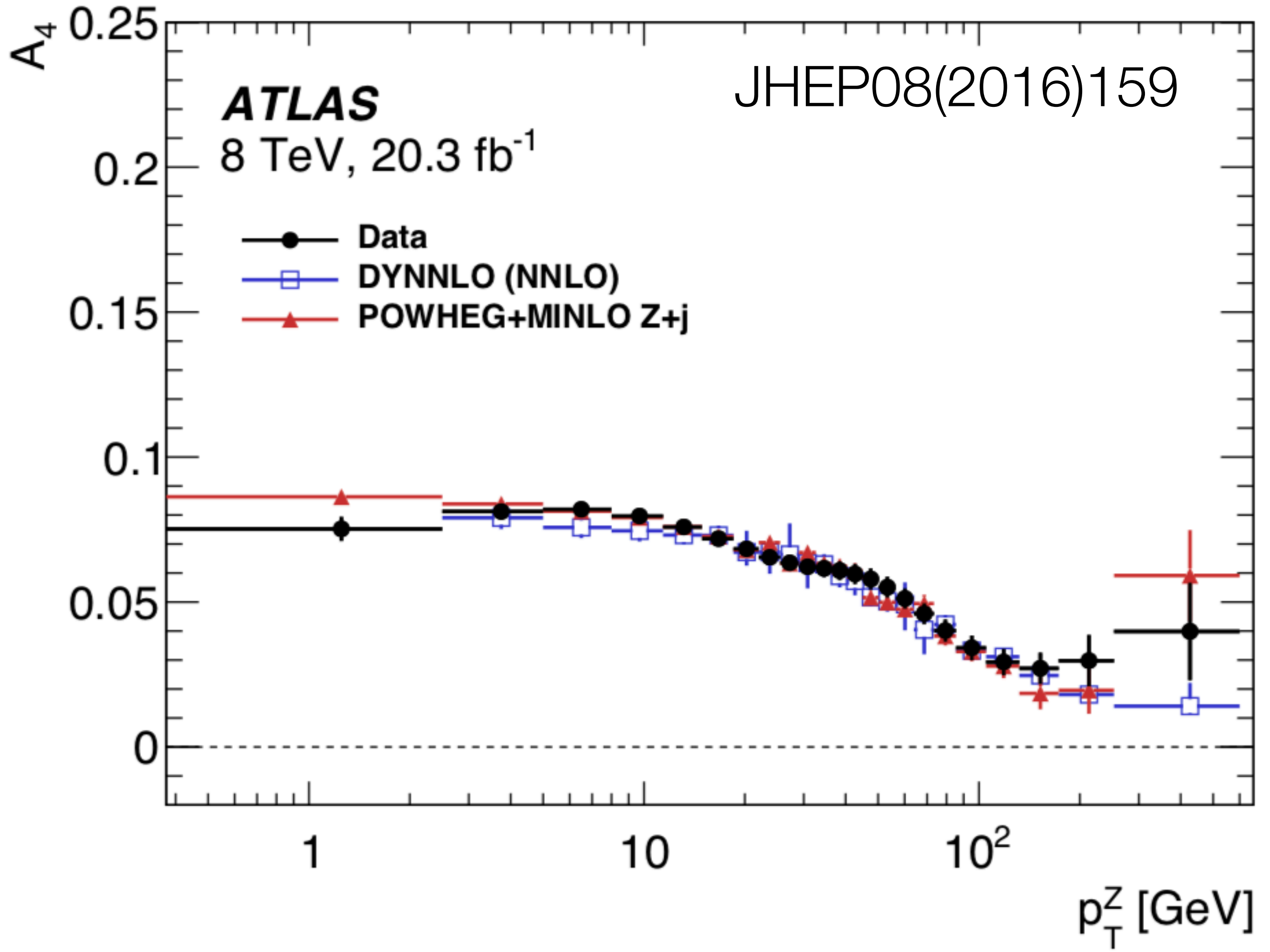
R. Kogler@ICHEP22

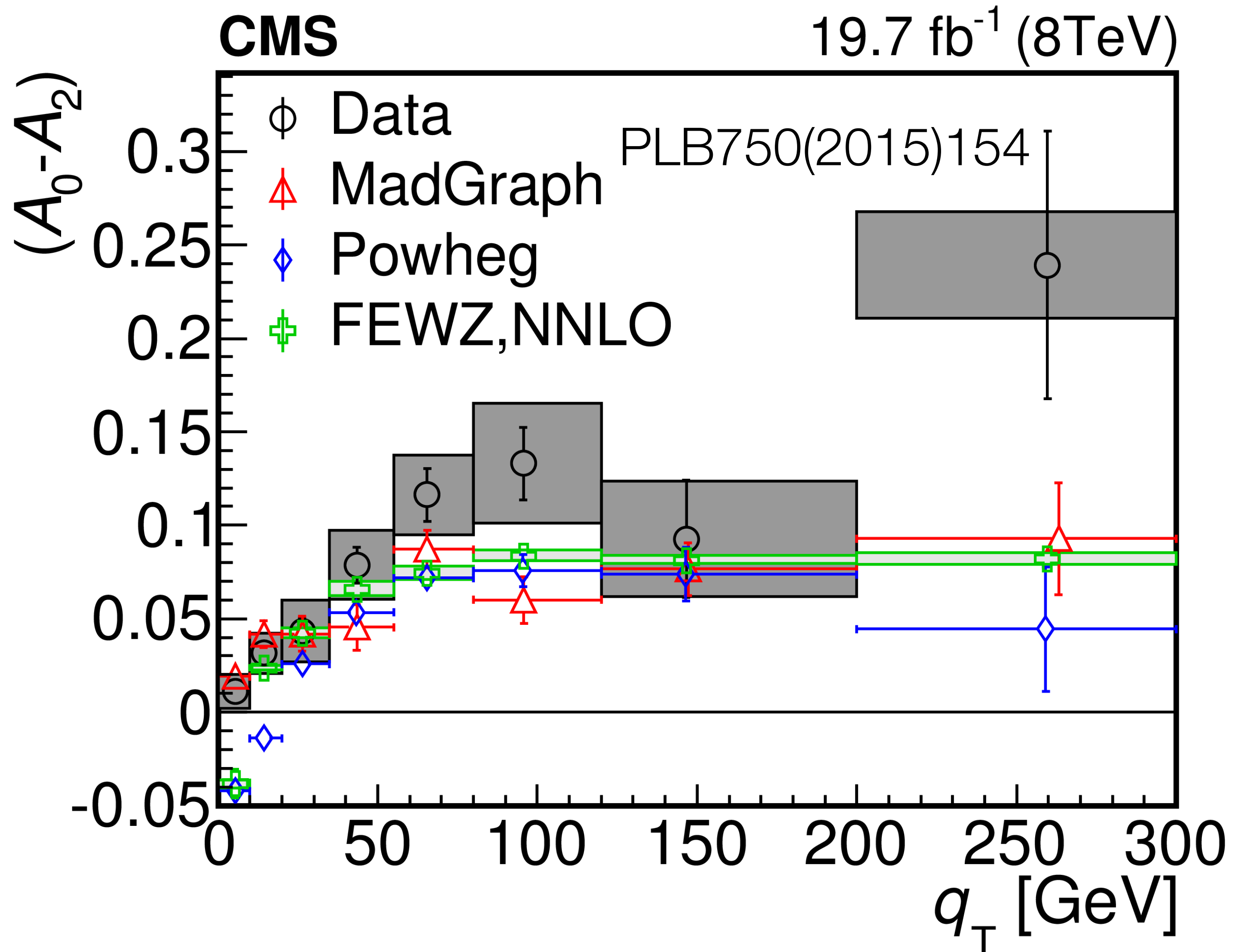
$\sin^2\theta_W$

- Drell-Yan cross-section can be decomposed into 9 harmonic polynomials

$$\frac{d\sigma}{dp_T^{\ell\ell}\,dy^{\ell\ell}\,dm^{\ell\ell}\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\,dy^{\ell\ell}\,dm^{\ell\ell}}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\,\sin 2\theta\,\cos\phi$$
$$+\frac{1}{2}A_2\,\sin^2\theta\,\cos 2\phi + A_3\,\sin\theta\,\cos\phi + \boxed{A_4\,\cos\theta}$$
$$+A_5\,\sin^2\theta\,\sin 2\phi + A_6\,\sin 2\theta\,\sin\phi + A_7\,\sin\theta\,\sin\phi\Big\}.$$

- Parity-violating A4 term sensitive to $\sin^2\theta^f_{eff}$
  - Related to $\sin^2\theta_W$ by radiative corrections: $\sin^2\theta^f_{eff}=\sin^2\theta_W\,K^f(s,t)$
  - Directly related to the forward-backward asymmetry; in full phase-space A_{FB} = 3/8 A4 (but EW corrections violate this)

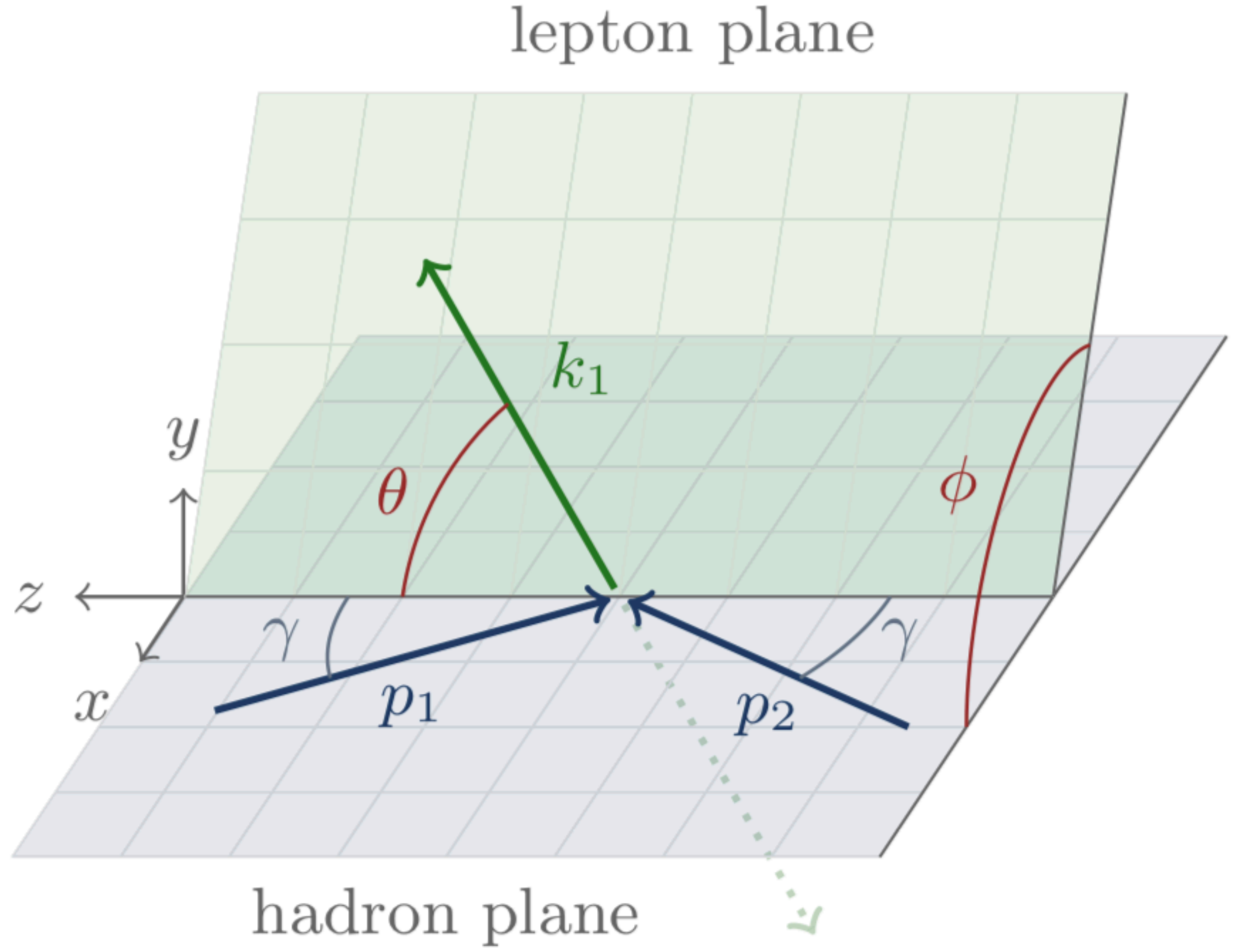




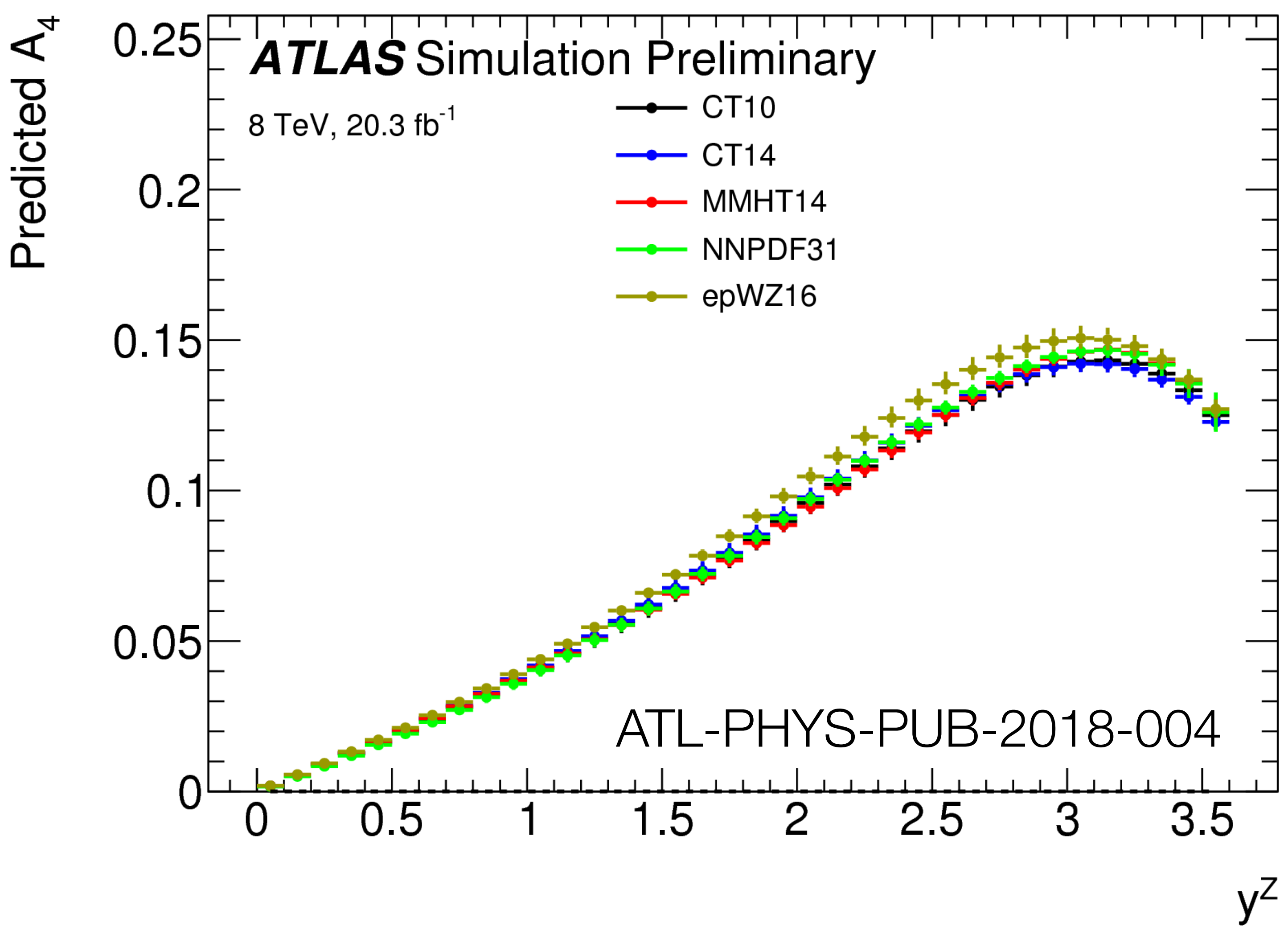
Multi-Differential Z->ll

- A_{FB}/A_4 is a parton-level effect that we measure at proton level
  - Introduces a strong dependence on PDFs

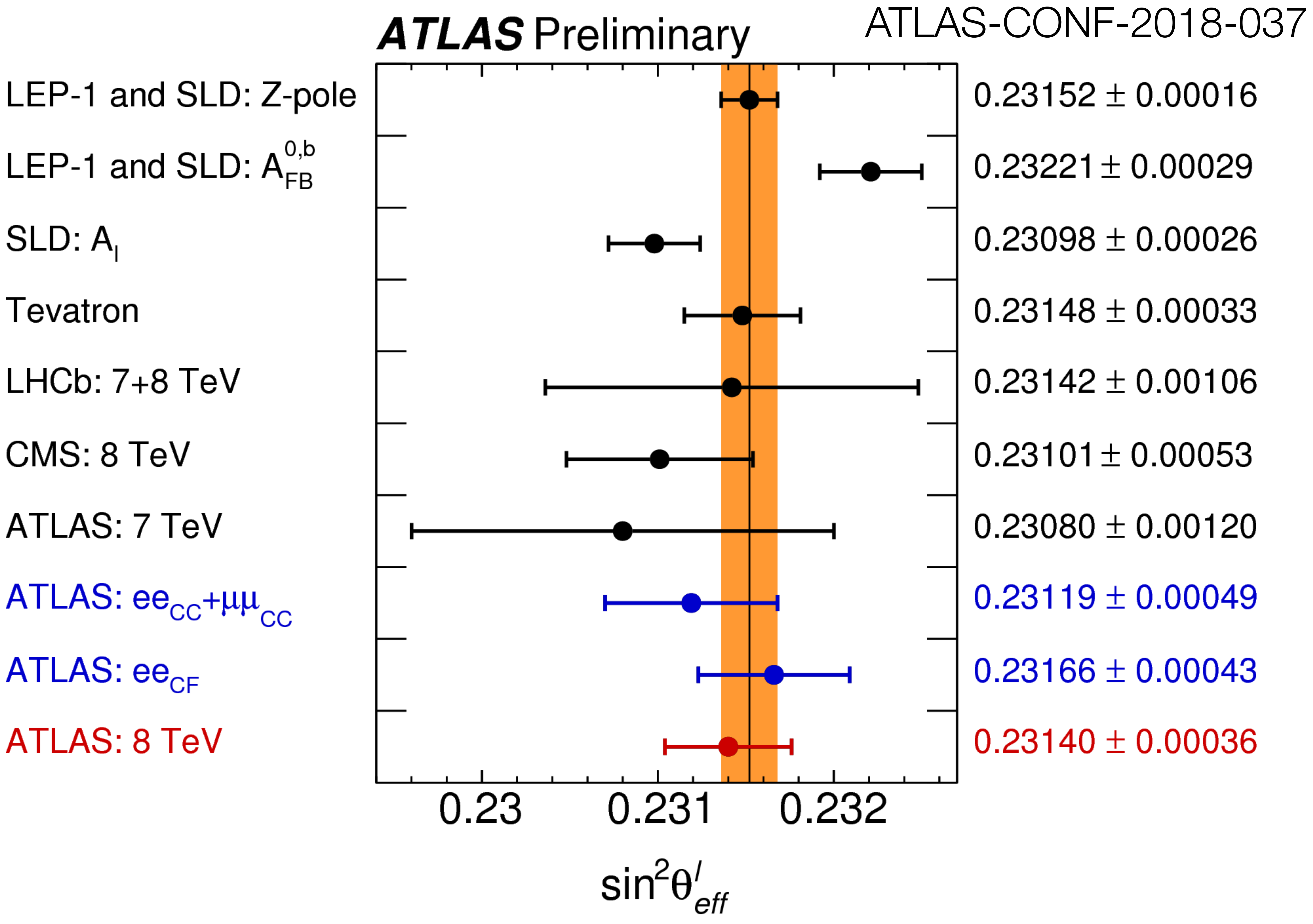
$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$



- Quark direction estimated from Z rapidity
  - Z mainly originate from valence quarks and have large x than antiquarks
  - Creates a “dilution of the asymmetry, larger at central rapidities
- Central leptons (|η|<2.4/2.5)
  - High statistics, helpful to constrain PDFs
- Central-forward leptons ($2.5<|\eta_e|<4.9$)
  - Challenging calibrations and large backgrounds but higher sensitivity



Results



- Higher order electroweak corrections through form-factors (ATLAS) or not included (CMS)
- LHCEWWG working to benchmark available codes at NLO+h.o. accuracy and get prescription for uncertainties

(0.16% precision)

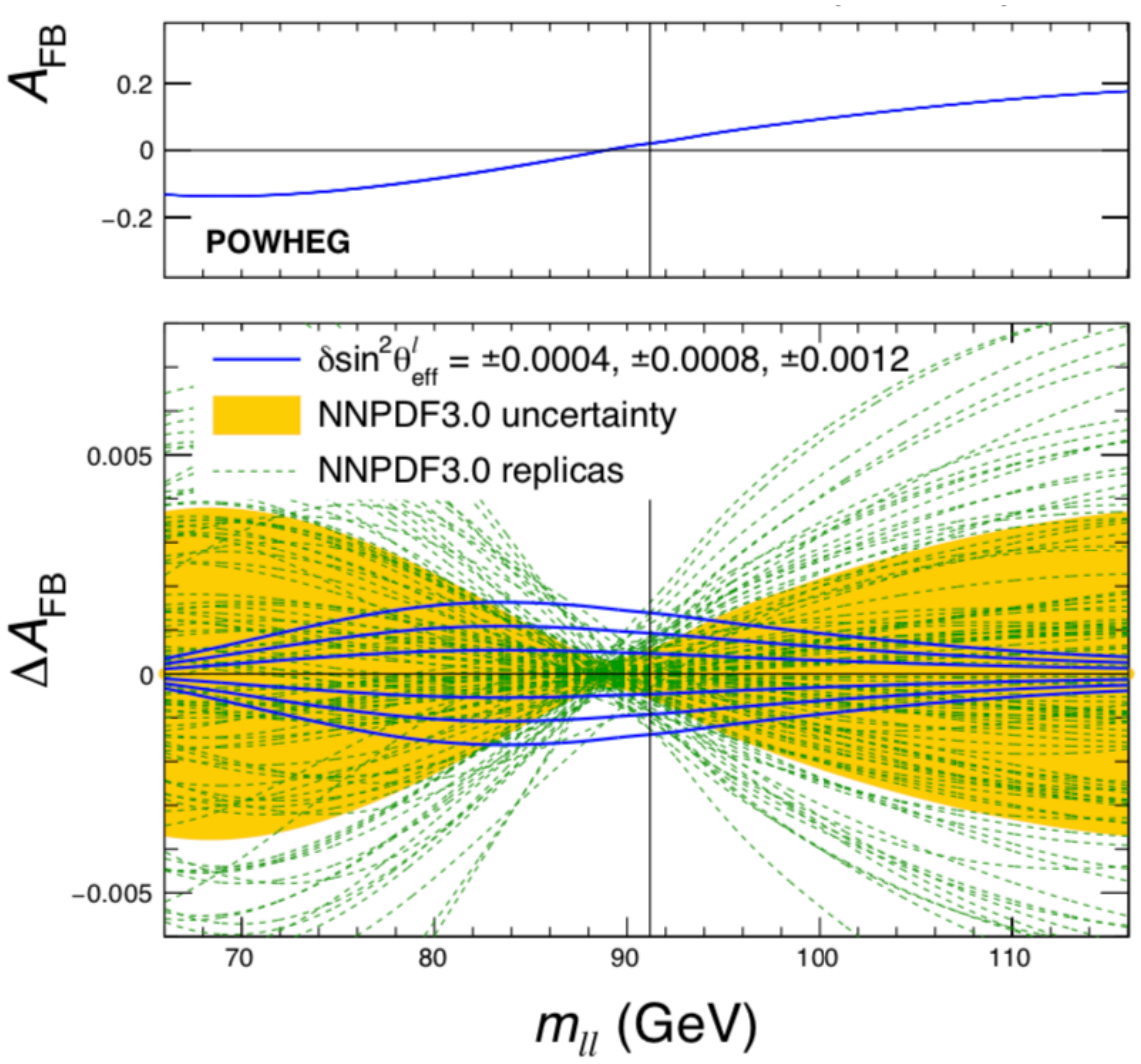
- Measurements dominated by stat and PDF uncertainties

CMS: 0.23101 ± 0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (th) ± 0.00031 (PDF)

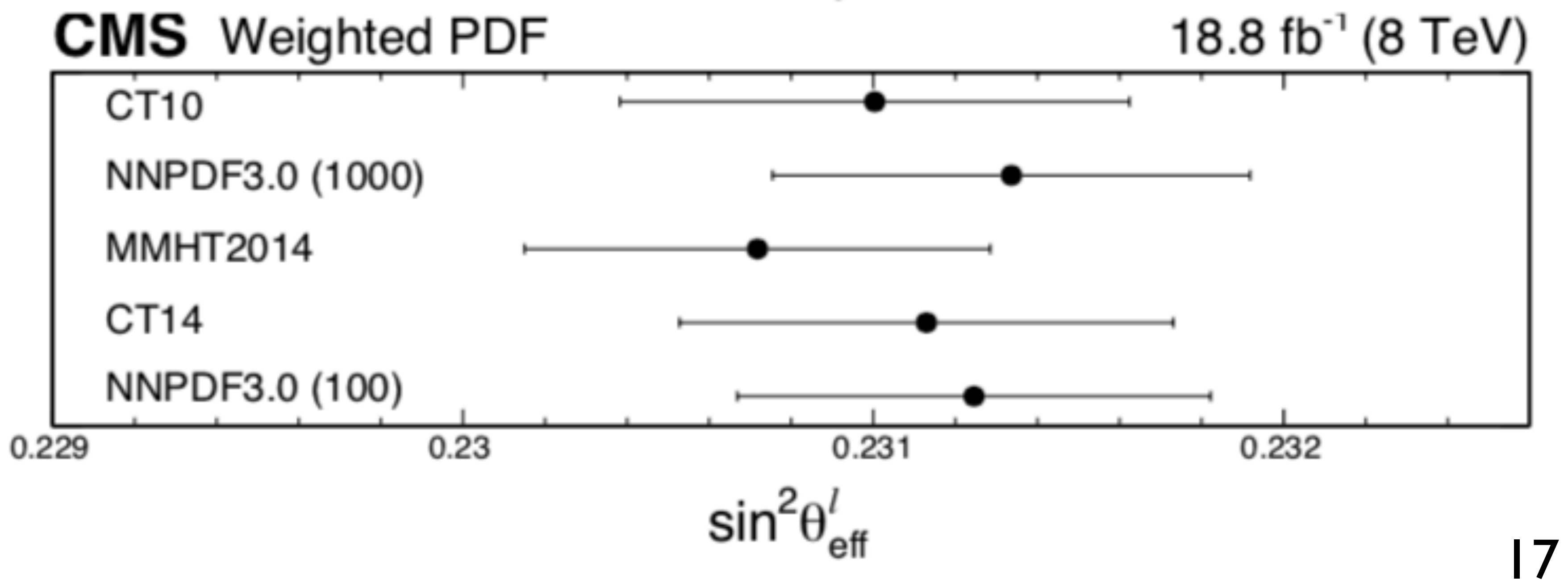
ATLAS: 0.23140 ± 0.00021 (stat) ± 0.00016 (syst) ± 0.00024 (PDF)

PDFs and $\sin^2\theta_W$

- PDF uncertainties are constrained in the interpretation exploiting their different dependence on mll, yll
  - ATLAS profiling of the Hessian eigenvectors
  - CMS Bayesian reweighing
- PDFs remain the largest source of uncertainty
  - CMS: PDF syst ±31, spread among sets ~65 [10^{-5}]
  - ATLAS: PDF syst ±24, spread among sets ~28 [10^{-5}]
- EFfort in the LHCEWWG to benchmark different global fits and provide correlations between different PDFs

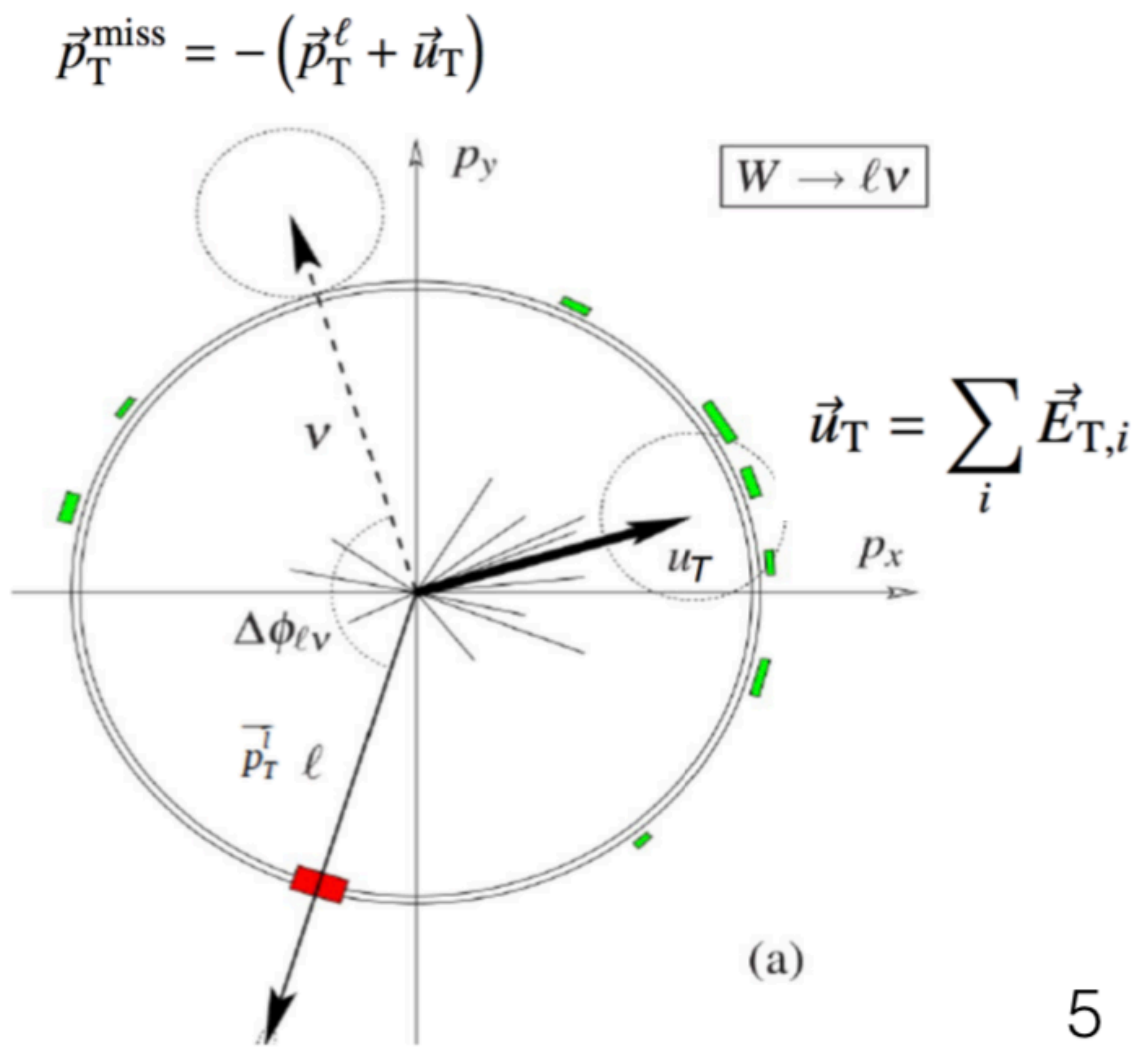


	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\mathrm{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31



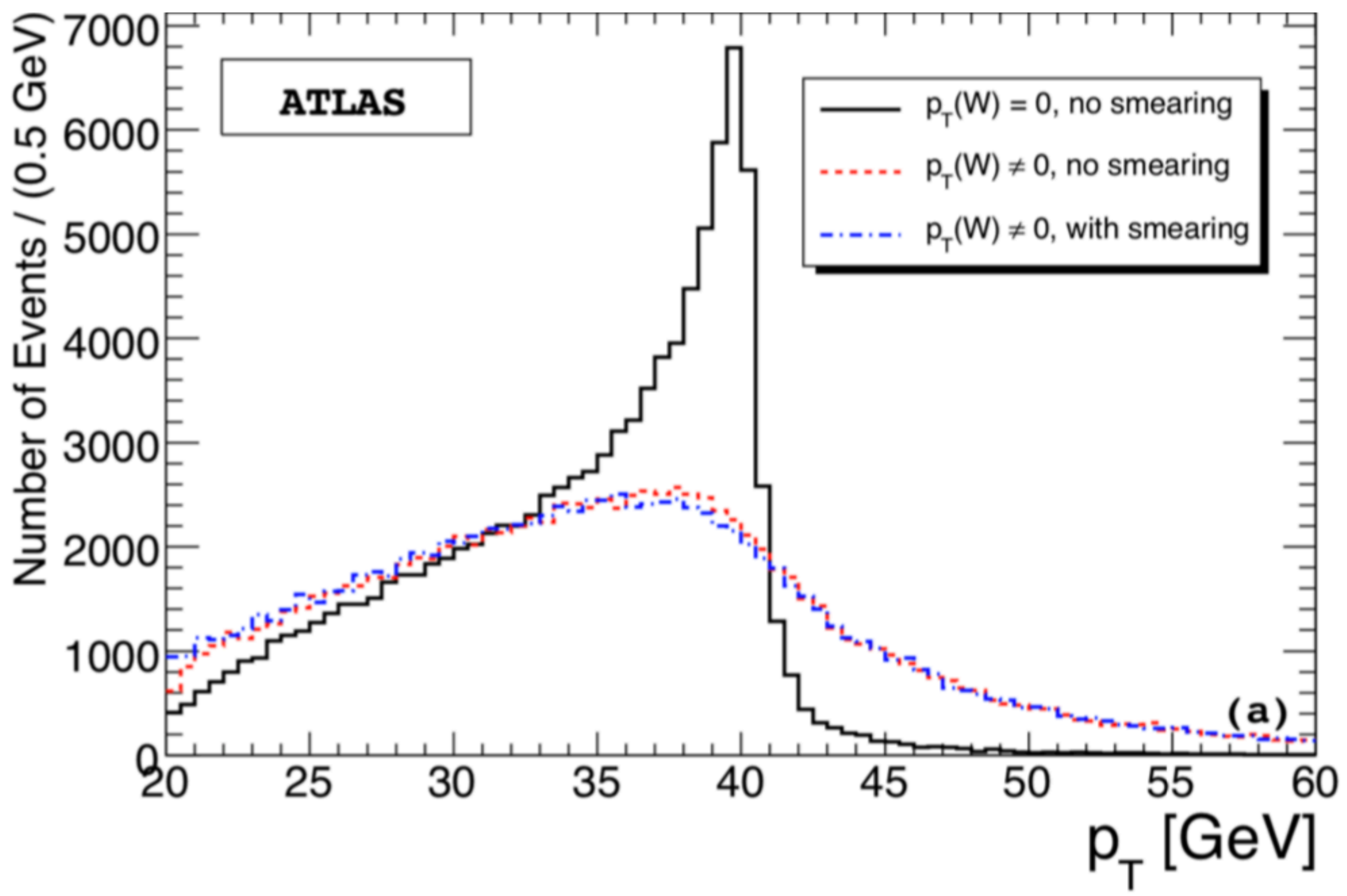
W-mass at hadron colliders

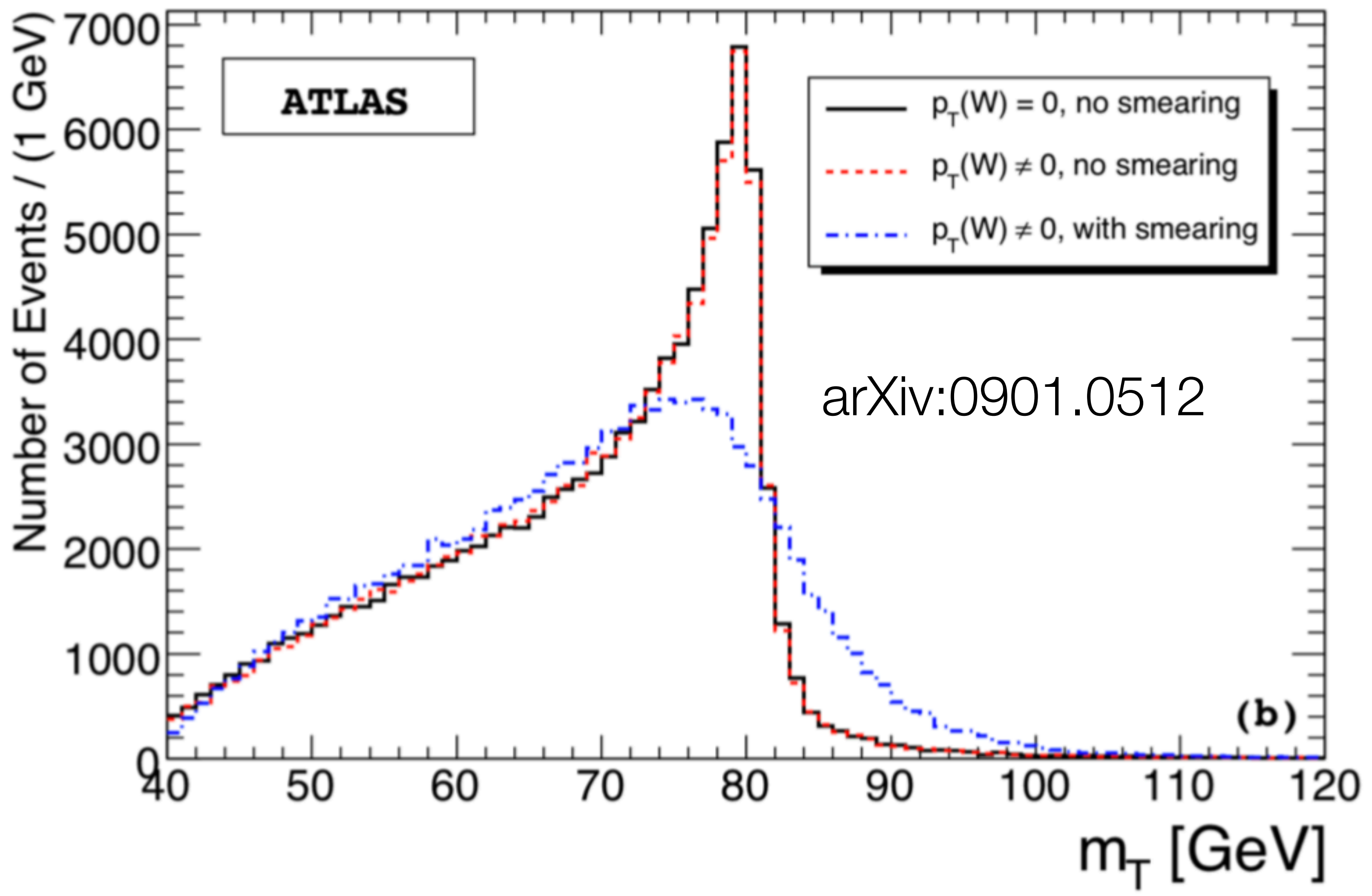
- Not possible to fully reconstruct W mass, m_W obtained through template fits to p_T^l and m_T
  - **p_T^l** sensitive to p_T^W modelling
  - **m_T** sensitive to the recoil resolution
- Extremely demanding on detector understanding
- Hard to control theory modelling



$$\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right) \qquad m_T = \sqrt{2 p_T^{\ell} p_T^{miss}(1 - \cos\Delta\phi)}$$

5



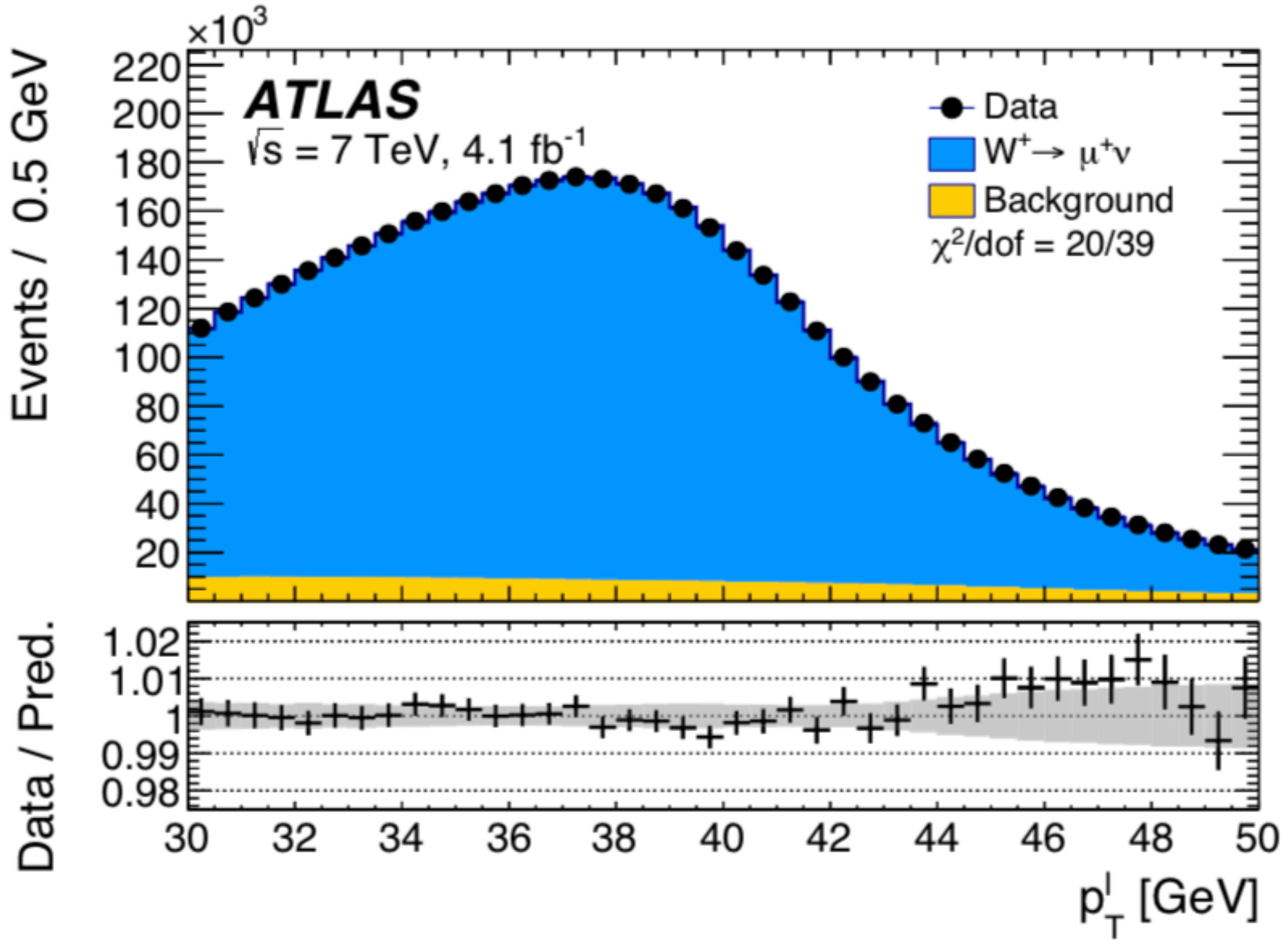


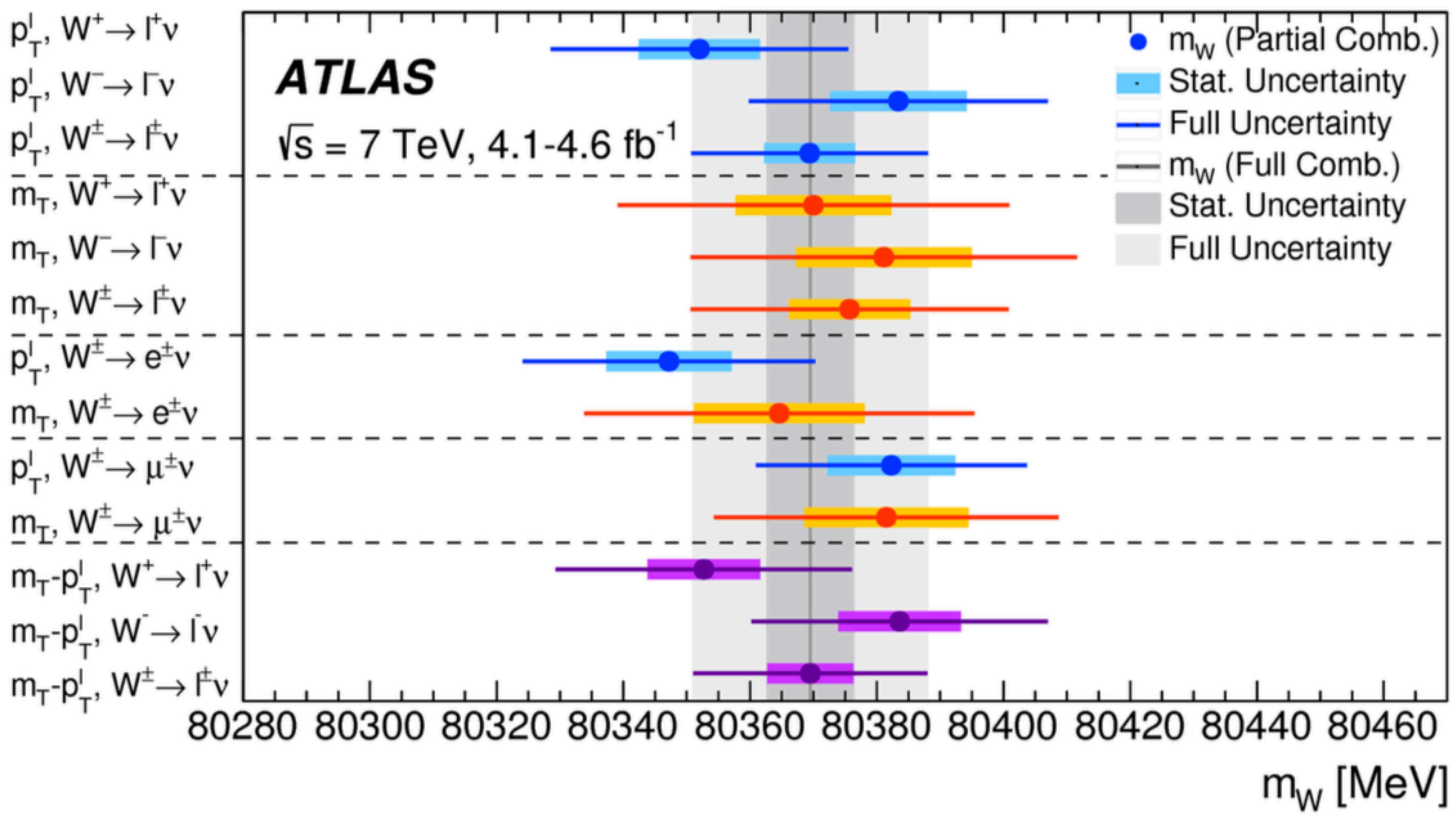
arXiv:0901.0512

ATLAS W-mass

- First LHC W-mass measurement at 7 TeV by ATLAS
  - 4.7 fb^{-1} with <mu>~9; $W\rightarrow e\nu$ and $W\rightarrow \mu\nu$ channels
  - Excellent agreement among the 28 categories (e/μ, eta, W^+/W^-, $p_{T,l}/m_T$...)

$$
\begin{aligned}
m_W &= 80369.5 \pm 6.8\ \text{MeV(stat.)} \pm 10.6\ \text{MeV(exp. syst.)} \pm 13.6\ \text{MeV(mod. syst.)} \\
&= 80369.5 \pm 18.5\ \text{MeV},
\end{aligned}
$$





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W-mass ancillary measurements

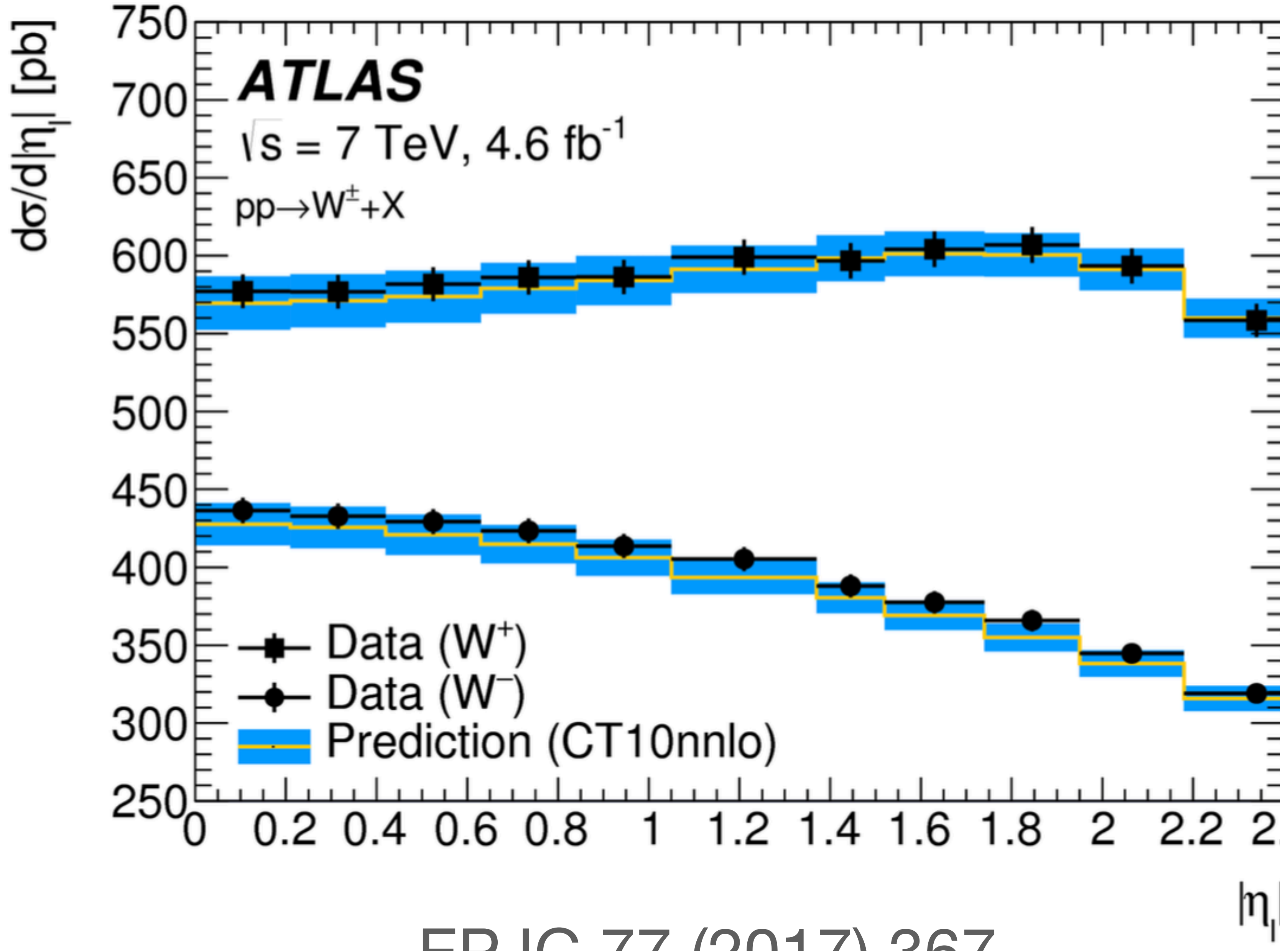
- The Drell-Yan cross-section can be reorganised factorising the dynamic of the boson production and the decay kinematic:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower



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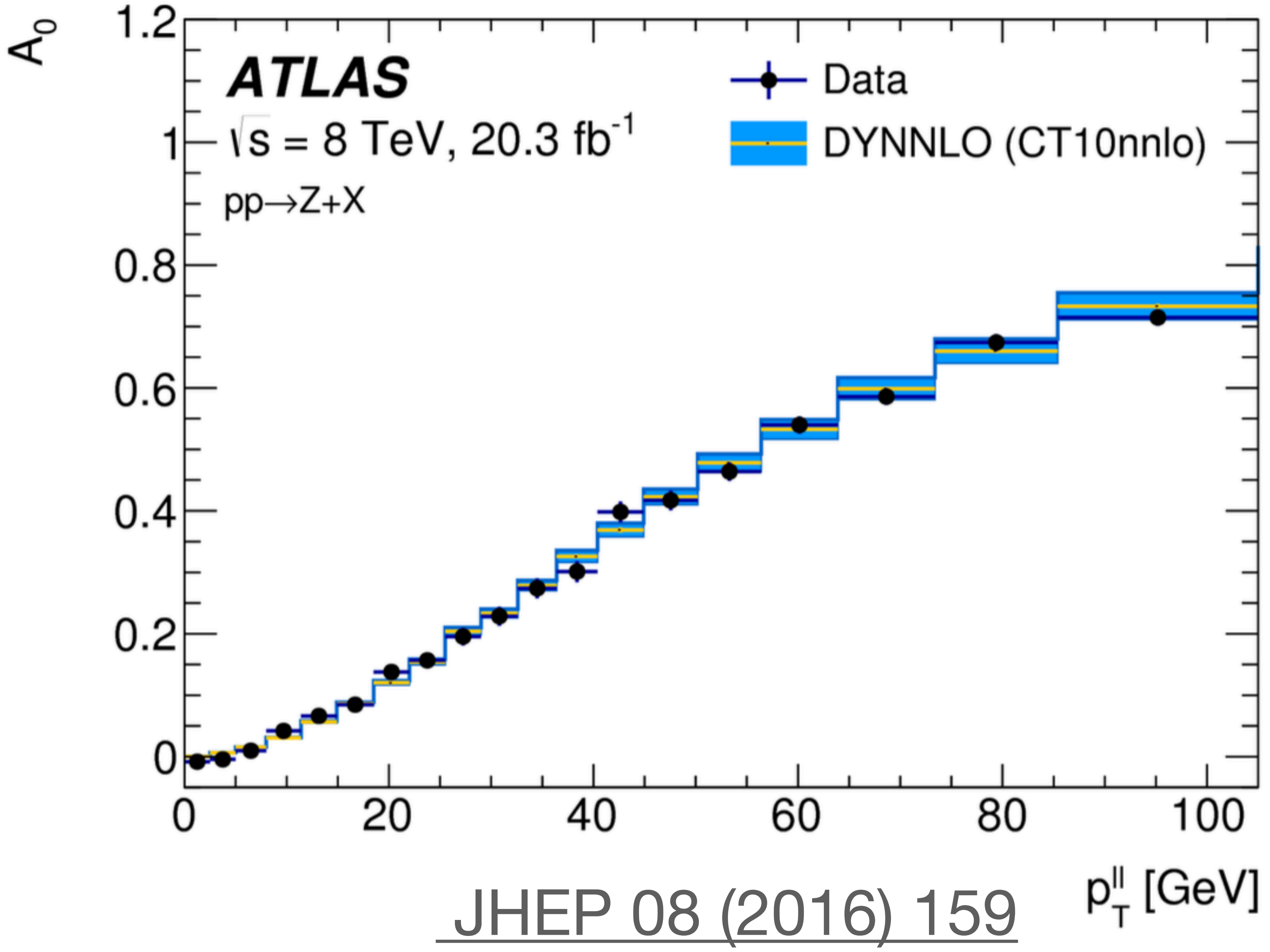

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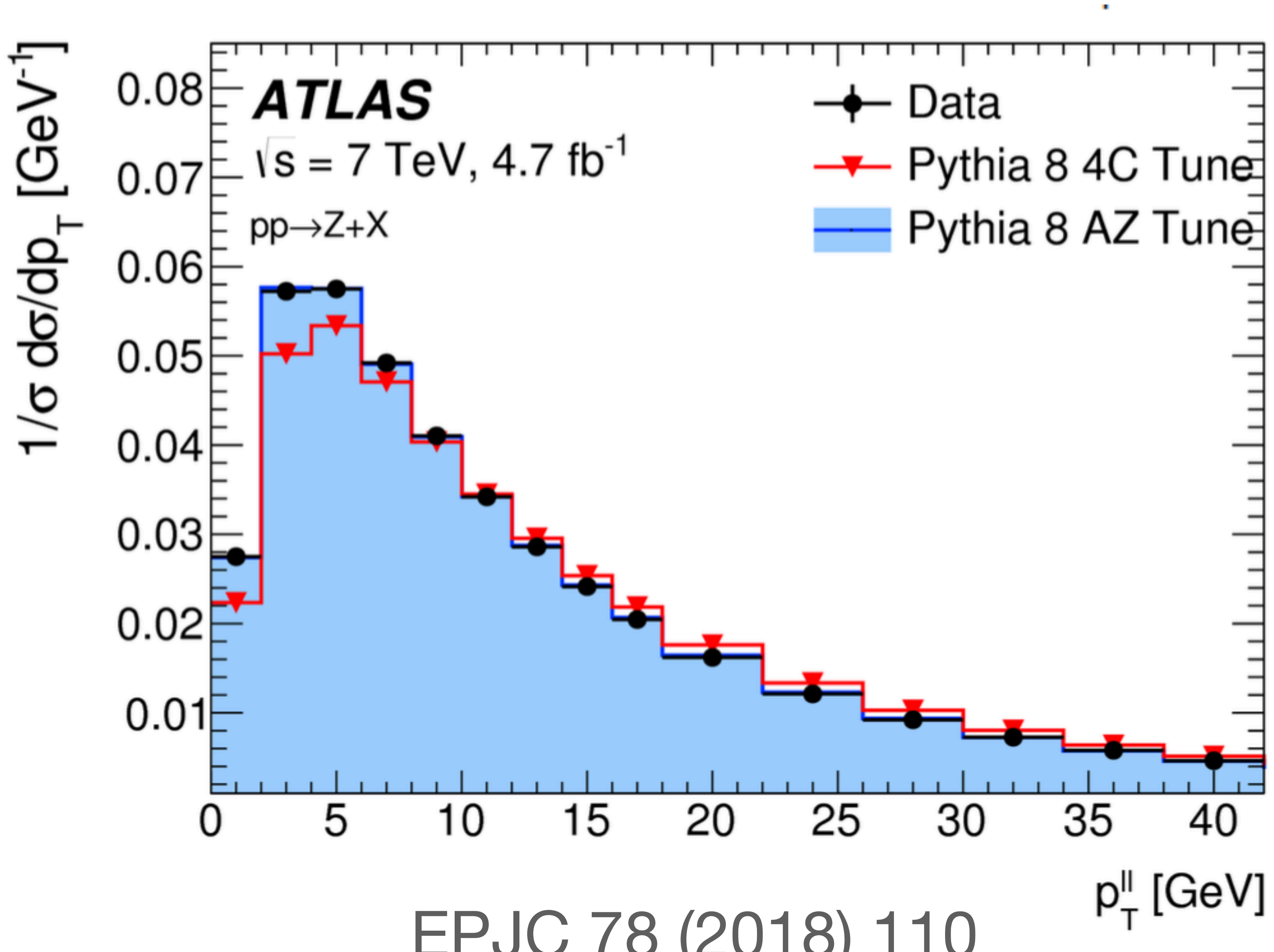


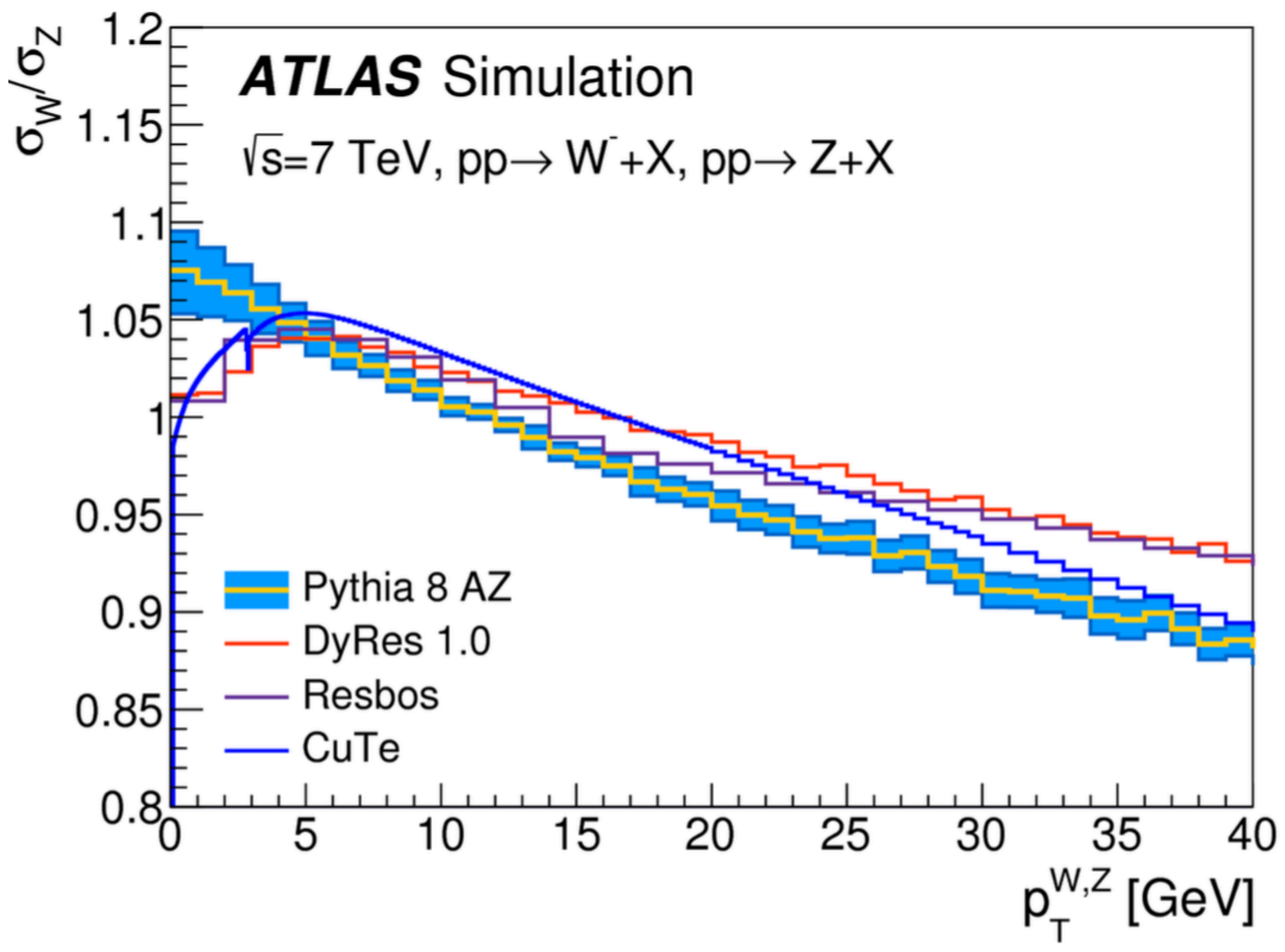
EPJC 78 (2018) 110

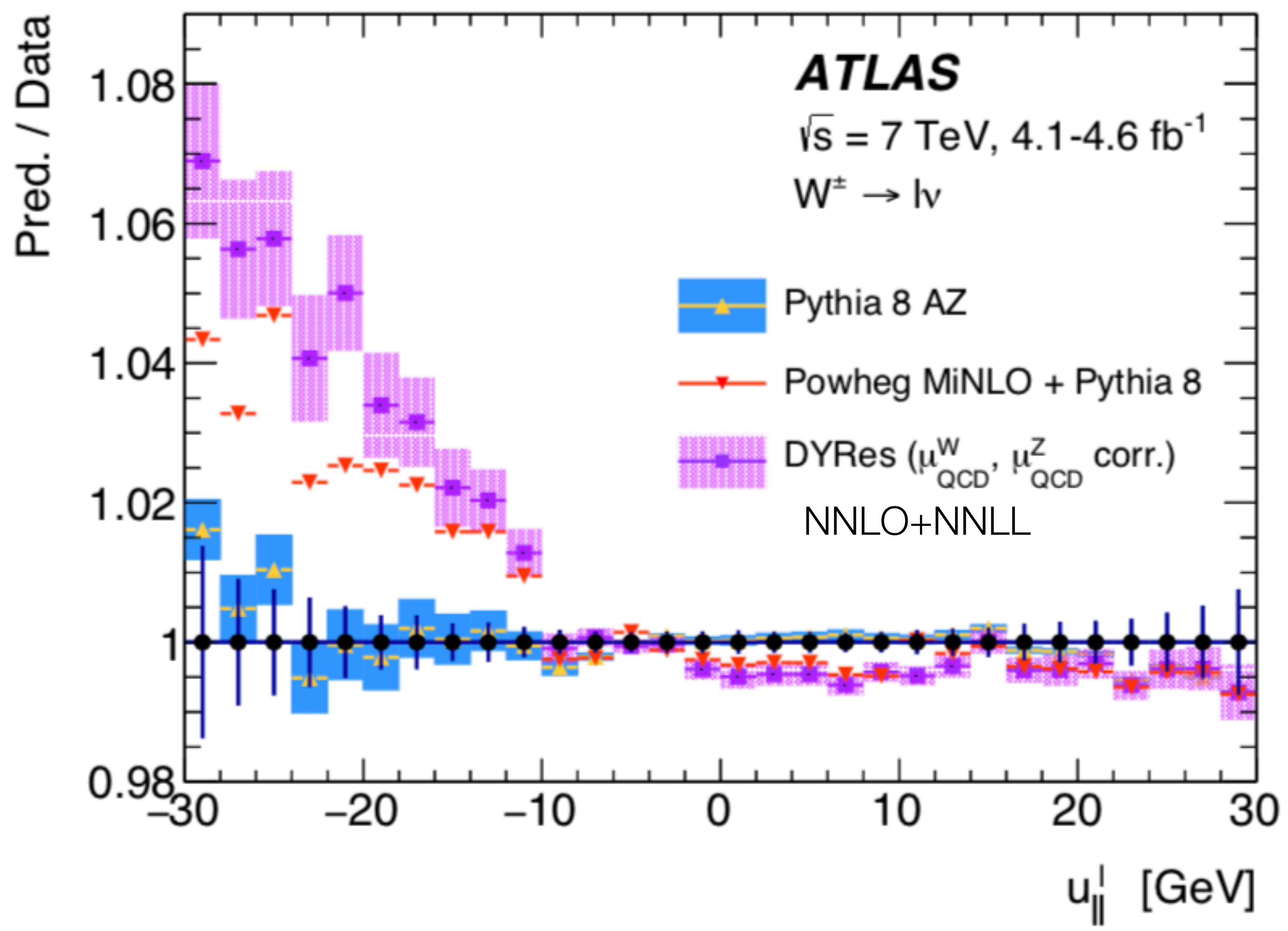
- Clean Z-boson sample essential to constrain experimental and theoretical uncertainties and extrapolate to the W

ATLAS W-mass uncertainties

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

* Result dominated by the p_T^l measurement with large QCD uncertainties
  - **PDF uncertainties** on light-quark sea decomposition from u, d, s (cs → W fraction) and well as valence-shape uncertainty (polarisation effects): W^+-W^-
  - **Modelling of small p_T^W** with significant uncertainties; NNLO+NNLL using W/Z-ratio in disagreement with data: $u^l_{||}$



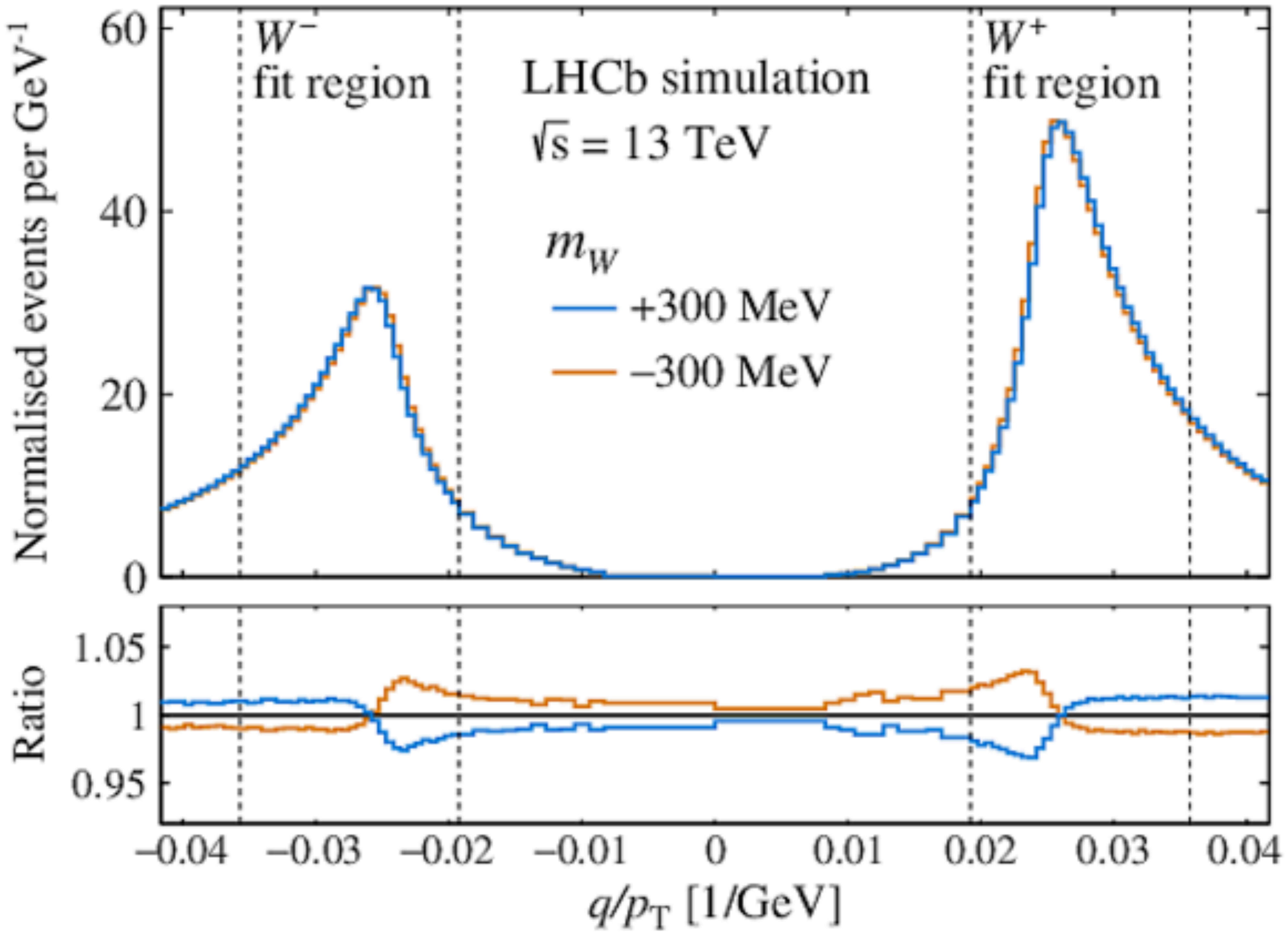


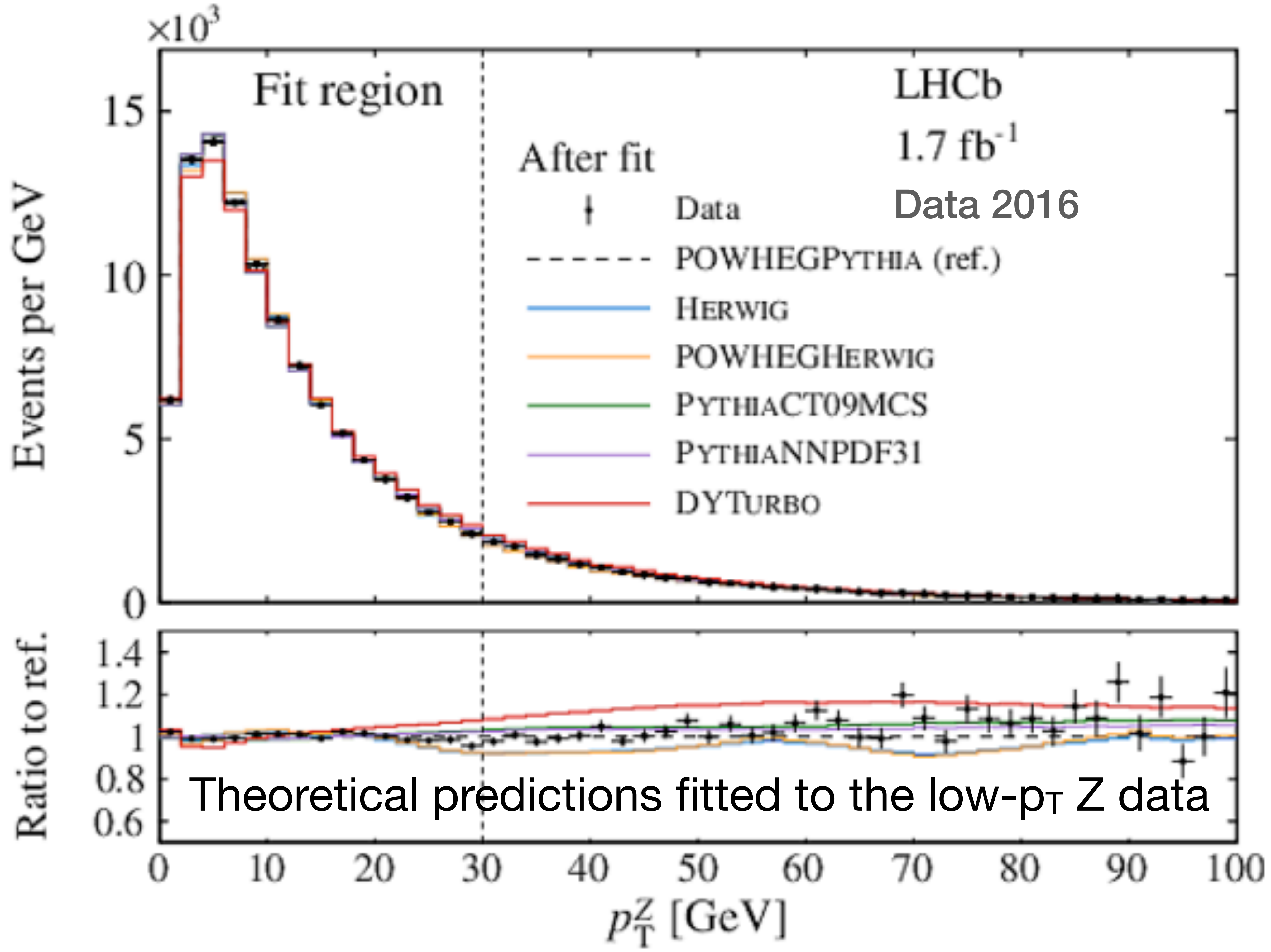
LHCb W-boson mass

JHEP 01 (2022) 036

- First m_W measurement in the forward region
  - ~2.4M $W \to \mu\nu$ events, $2.2 < \eta_\mu < 4.4$
  - m_W from template fits to q/p_T^μ distribution

Muon charge





Theoretical predictions fitted to the low-p_T Z data

- Constrain uncertainties using $\mu\mu$ resonances
  - Muon momentum calibration and modelling from Z, Υ(1S) and J/Ψ data and simulation
  - Z-boson sample used to constrain theoretical uncertainties and extrapolate to the W

LHCb W-boson mass

* Achieves a precision of ~32 MeV, consistent with other measurements and with SM

$$m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Muon momentum scale and resolution

Modelling of p_T^W and W polarisation

Average of PDF determinations

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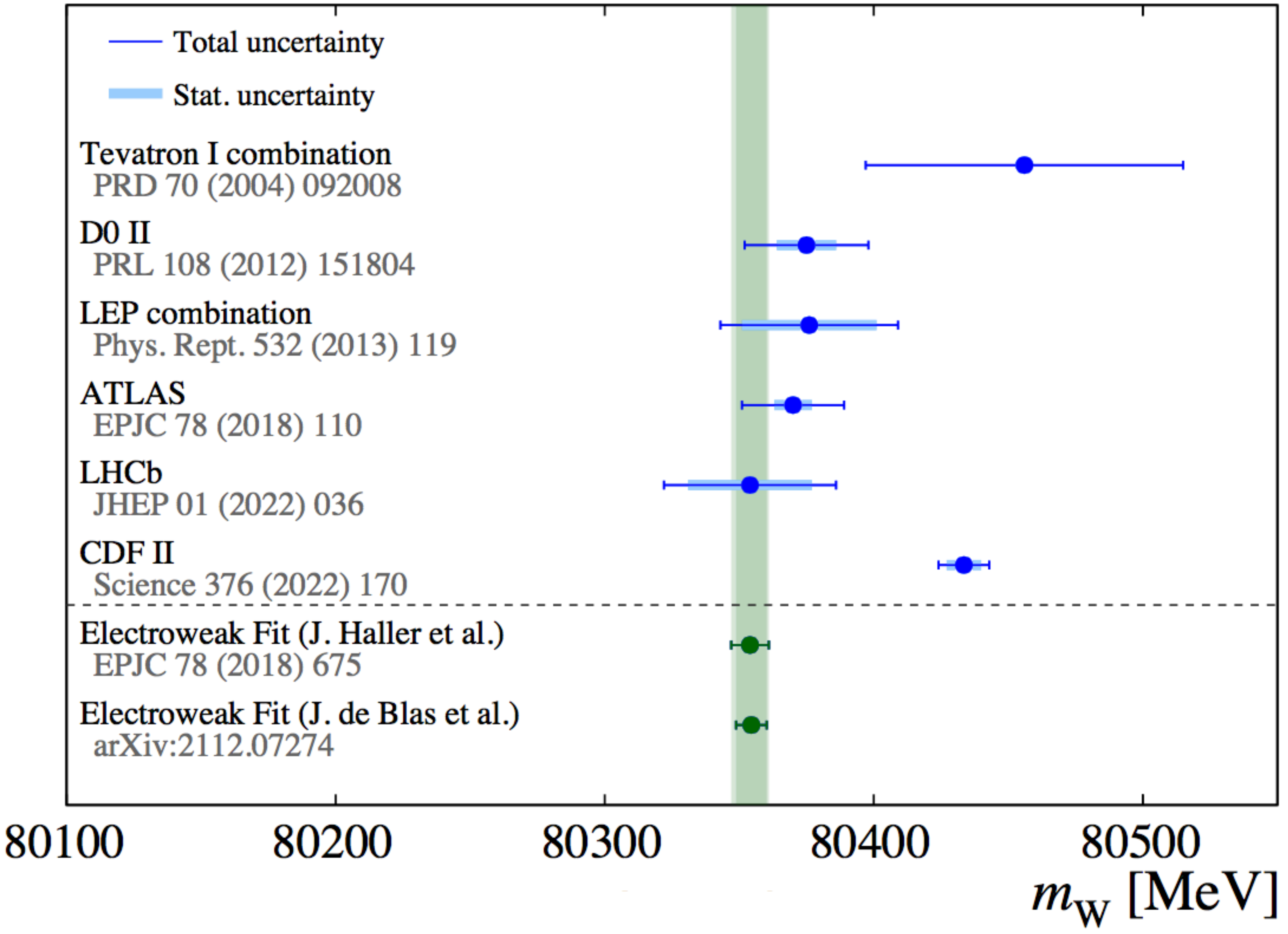


* Encouraging prospects for the future:
  - ~10 MeV statistical uncertainty with full Run2
  - But modelling systematics harder to reduce

* Expect factor ~2 reduction in PDF uncertainties combining with ATLAS/CMS

Tevatron/LHC W-mass combination

- Ongoing Tevatron/LHC EW WG effort towards a combination
  - Experiment endorsed world average, and update of past measurements to recent PDFs

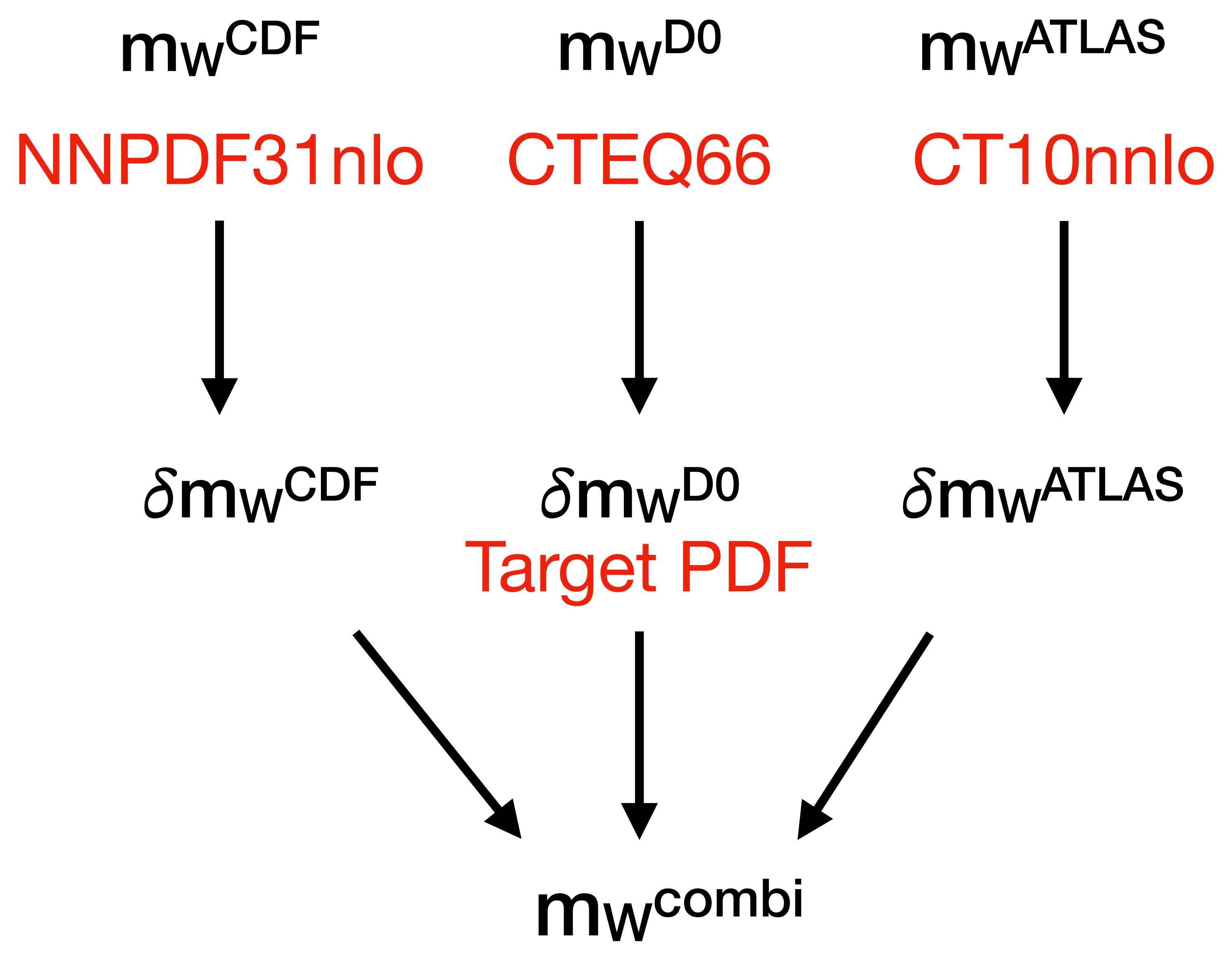
$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

published value — Improved predictions — PDF extrapolation

δm_W^{PDF} correction to reference PDF

δm_W^{QCD} correction to QCD modelling beyond quoted uncertainties

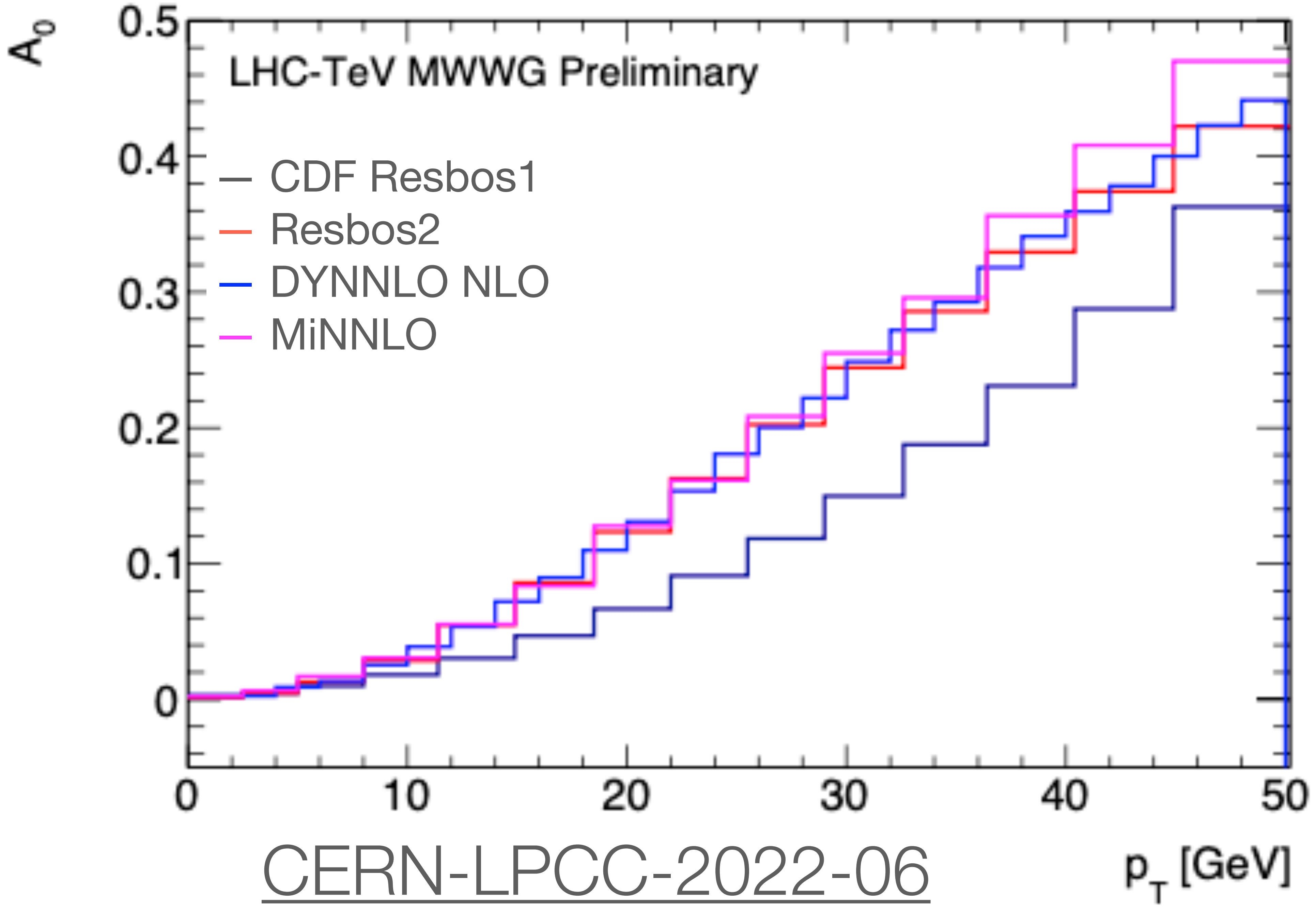
- PDFs main source of correction and uncertainty correlations
  - Other sources very small (EW corrections) or mostly decorrelated (p_T W/Z)
- Correction applied in a two-step procedure:
  1. Correct all measurements to a common PDF/QCD
  2. Combine them properly including correlations



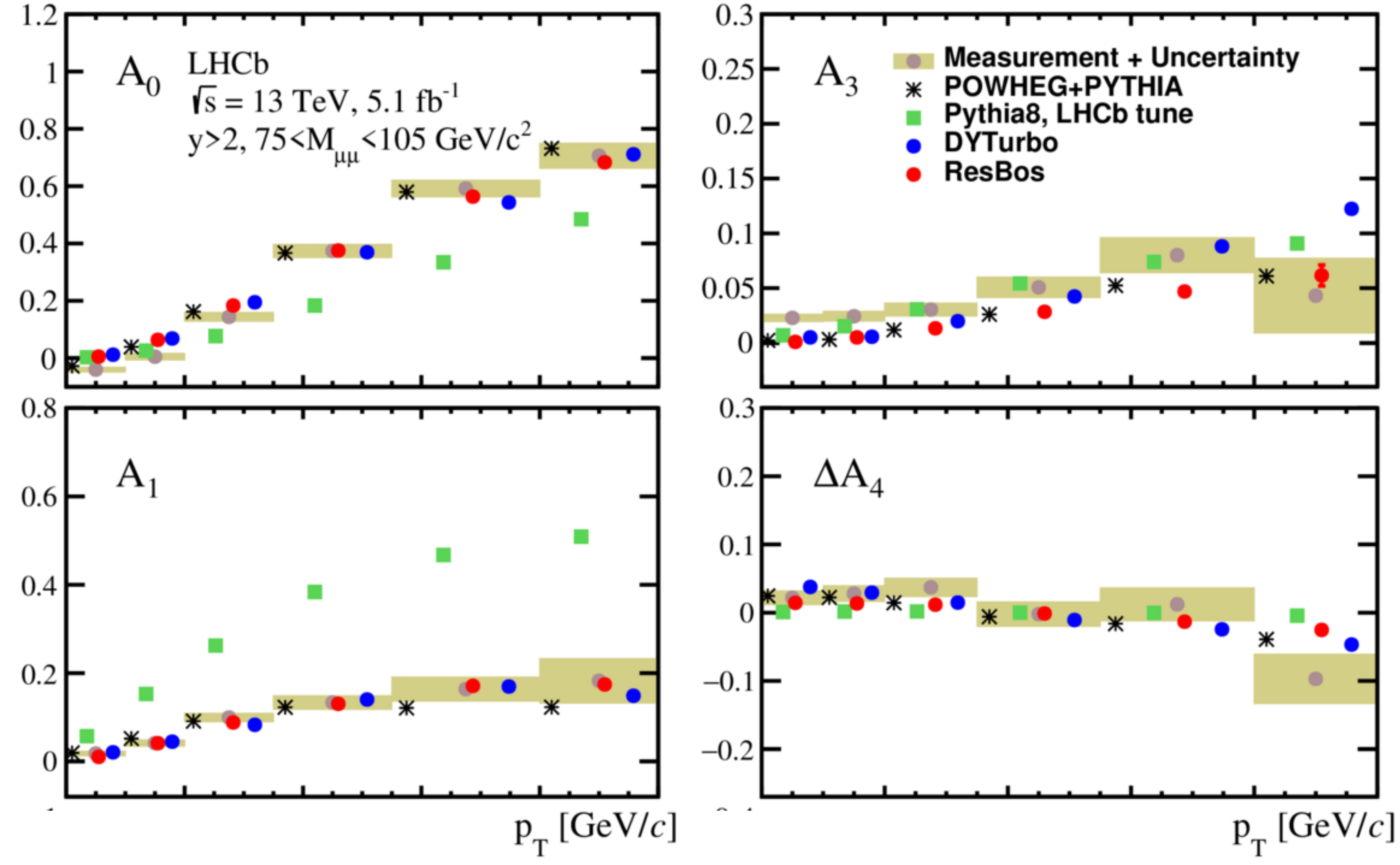
Angular coefficients in Drell-Yan

- Boson polarisation in legacy Resbos different from Resbos2 and other codes
  - NNLO matching in Resbos not fully differential and resummation only impacts A0, A4
  - Motivates a ~10 MeV correction of Tevatron measurements

PRL 129 (2022) 091801



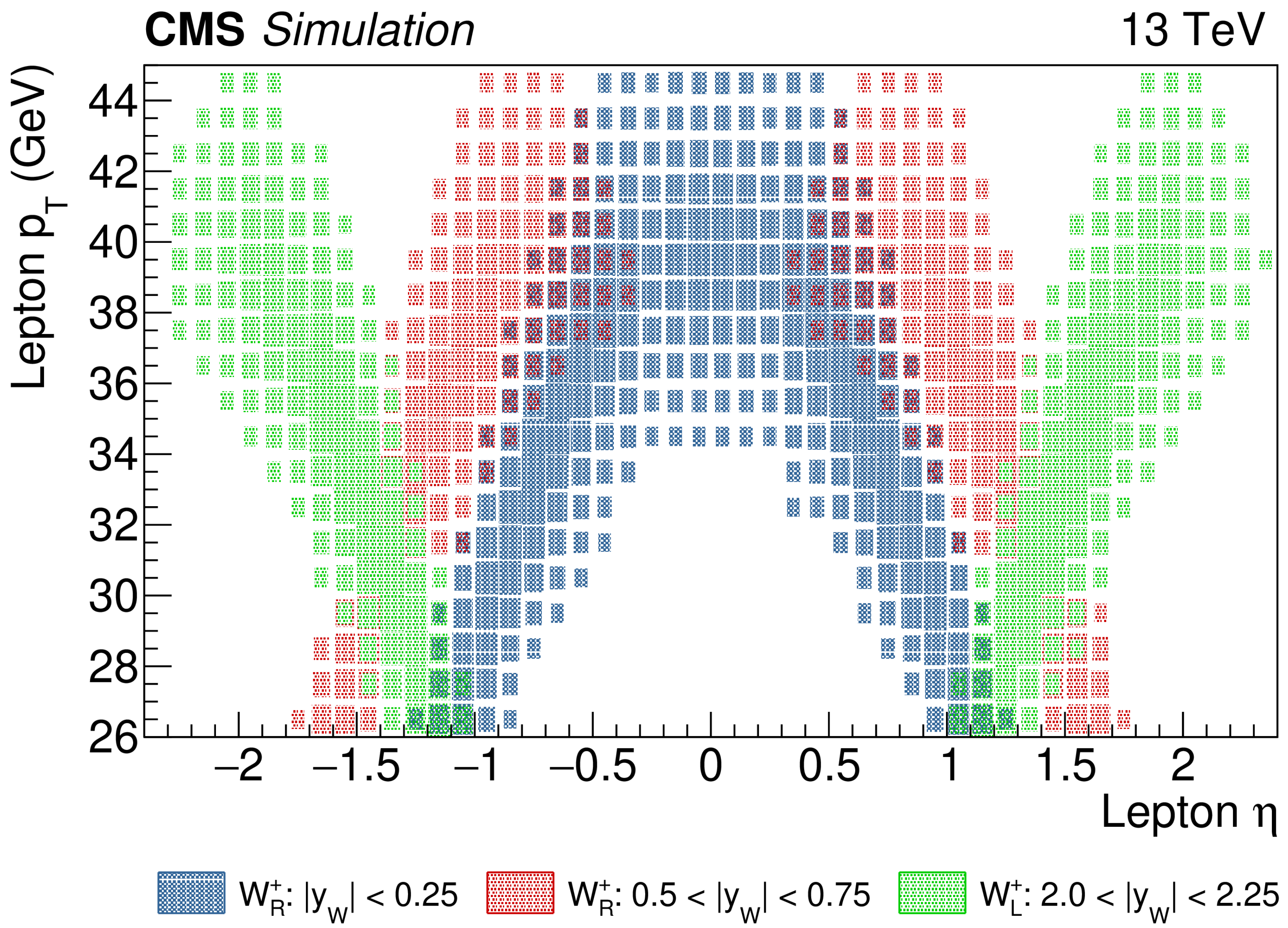
CERN-LPCC-2022-06

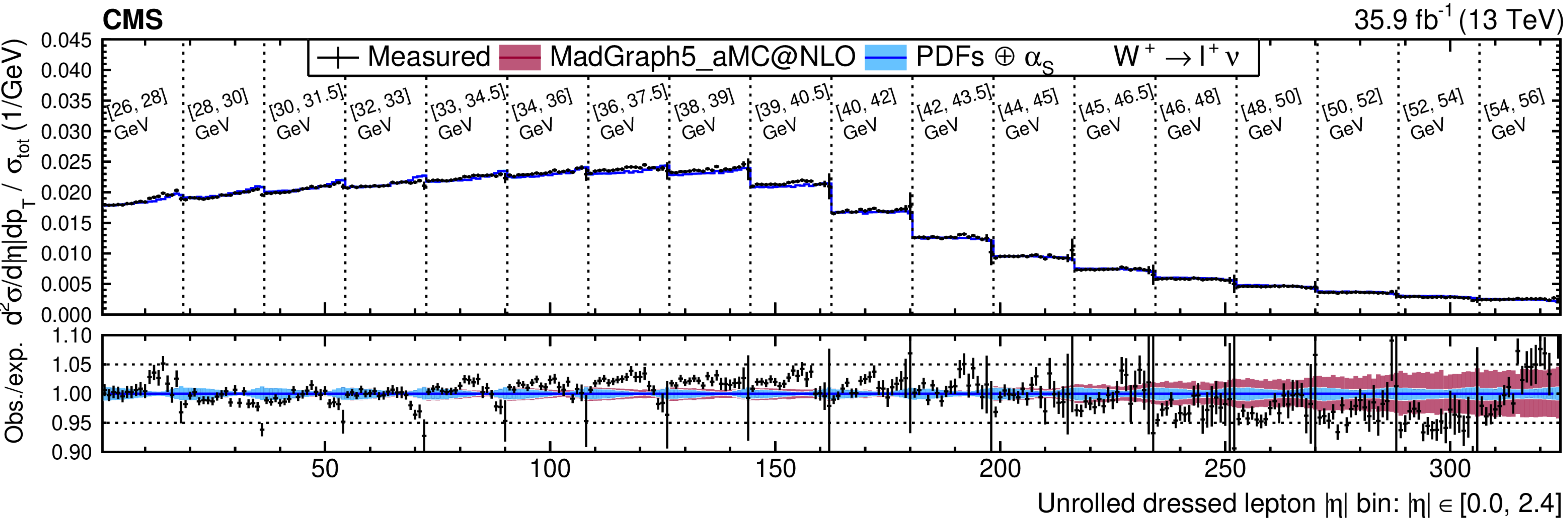


- First measurement of Ai in Zll in the forward region

CMS: from W-helicity to m_W

- Intermediate result towards an m_W measurement
- Multidifferential measurement of lepton p_T-eta and of W rapidity and helicity cross-section
  - Different bins in lepton p_T-eta retain information on the W-boson rapidity and helicity states
- Large sensitivity (and constraints) on valence-quark PDFs





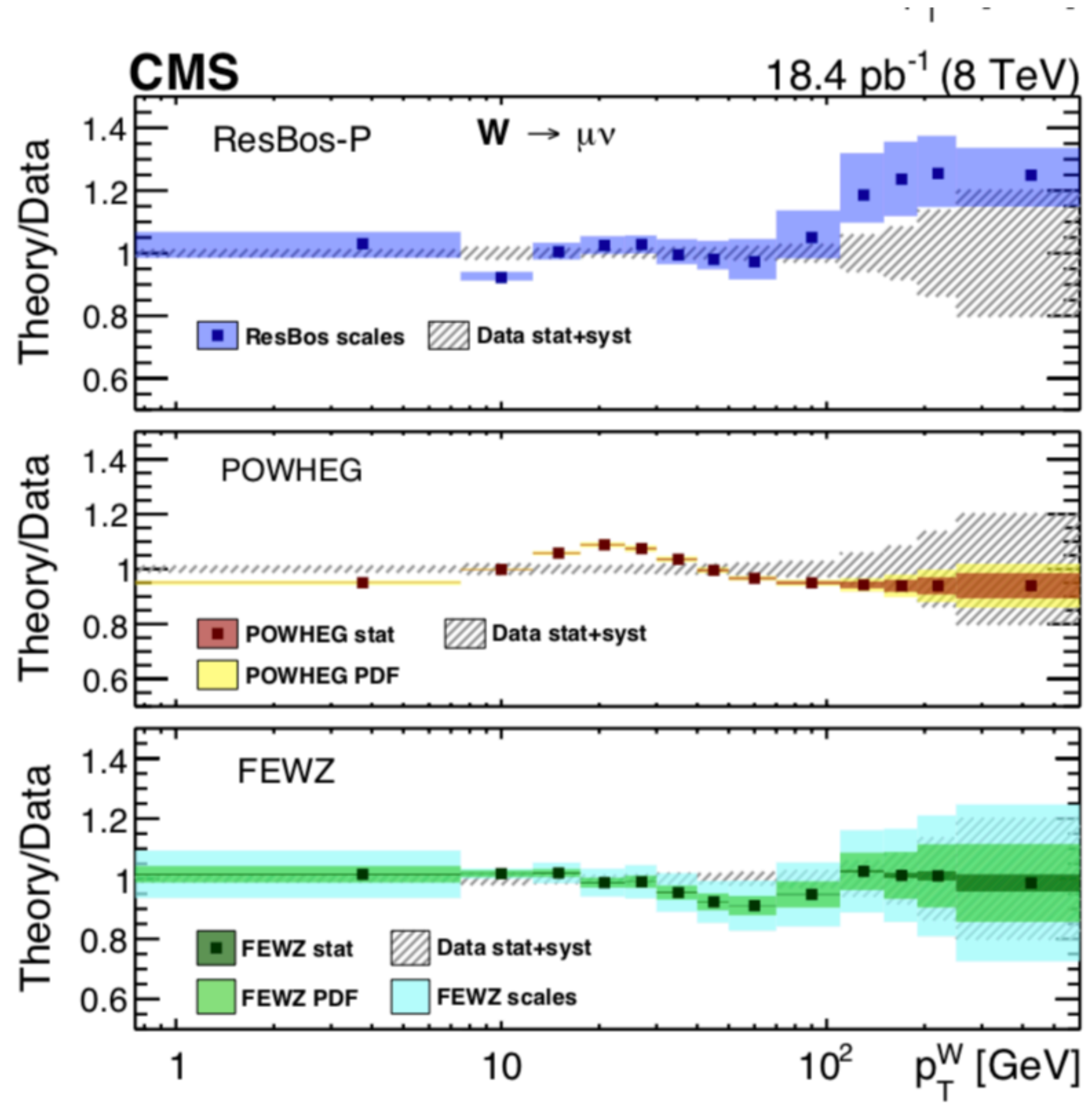
PRD 102 (2020) 092012

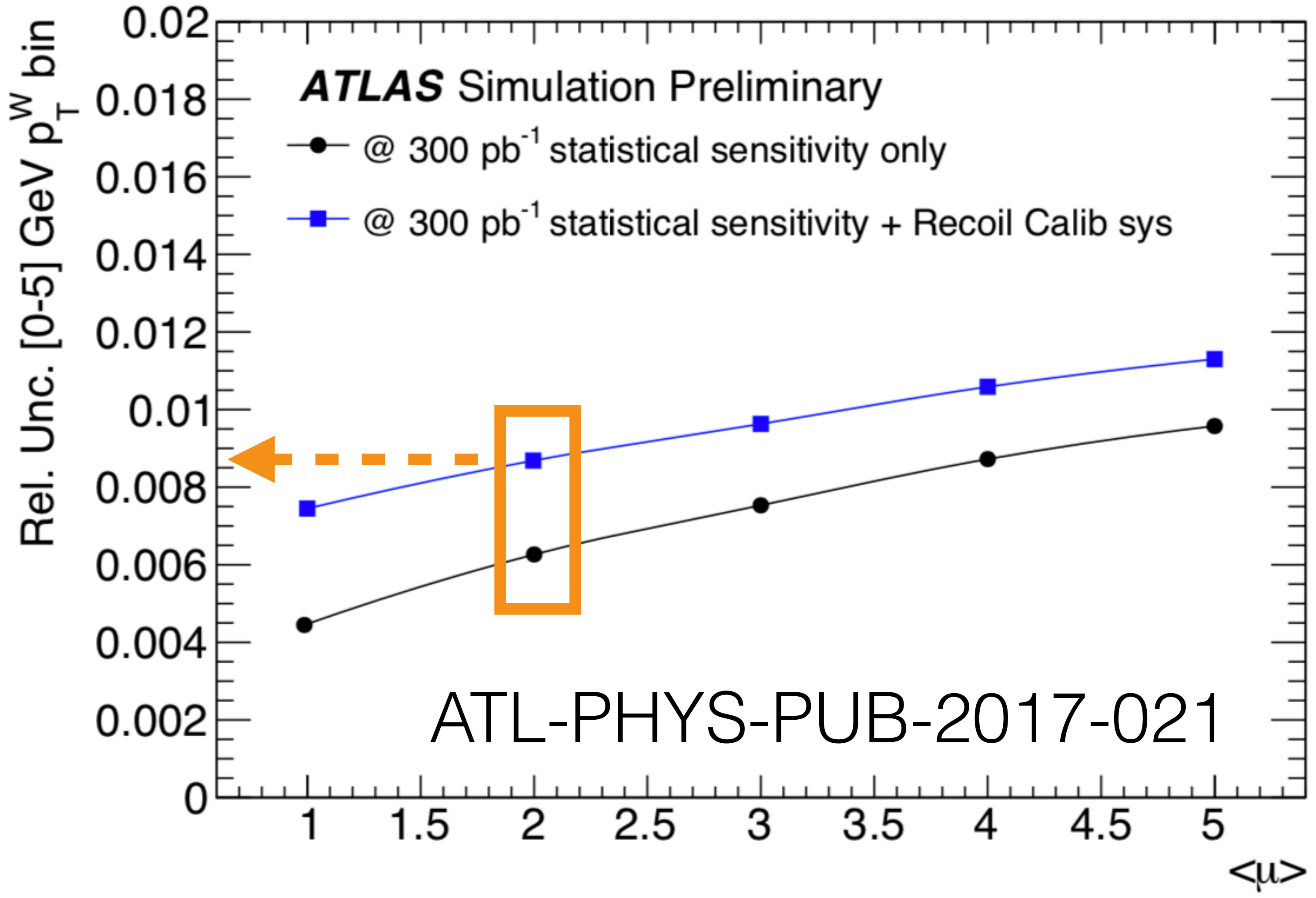
- Strategy for m_W
  - Make use of well-understood high-mu lepton p_T sample
  - Minimal assumptions on W vs Z uncertainties
  - Reduction of uncertainties through in-situ constraints

M_W PROSPECTS WITH LOW PILE-UP

- QCD systematics on p_T^l mainly due to uncertainties on p_T^W
  - ~2% uncertainty in p_T^W → ~10 MeV in m_W, at the LHC limited by recoil resolution
  - 2.5% uncertainty from fitting to Z and extrapolating to W
- Special low-μ datasets collected in Run 2
  - ATLAS/CMS: 380/200 pb^{-1} at 13TeV, 260/300 pb^{-1} at 5TeV; <μ>~2
  - Low pileup and special detector conditions to reach good recoil resolution
  - Aim for 1% precision in 5 GeV-bins of p_T^W at low pT
- Possible sample also for future m_W measurements (and more low pile-up data in Run3)

JHEP02(2017)096

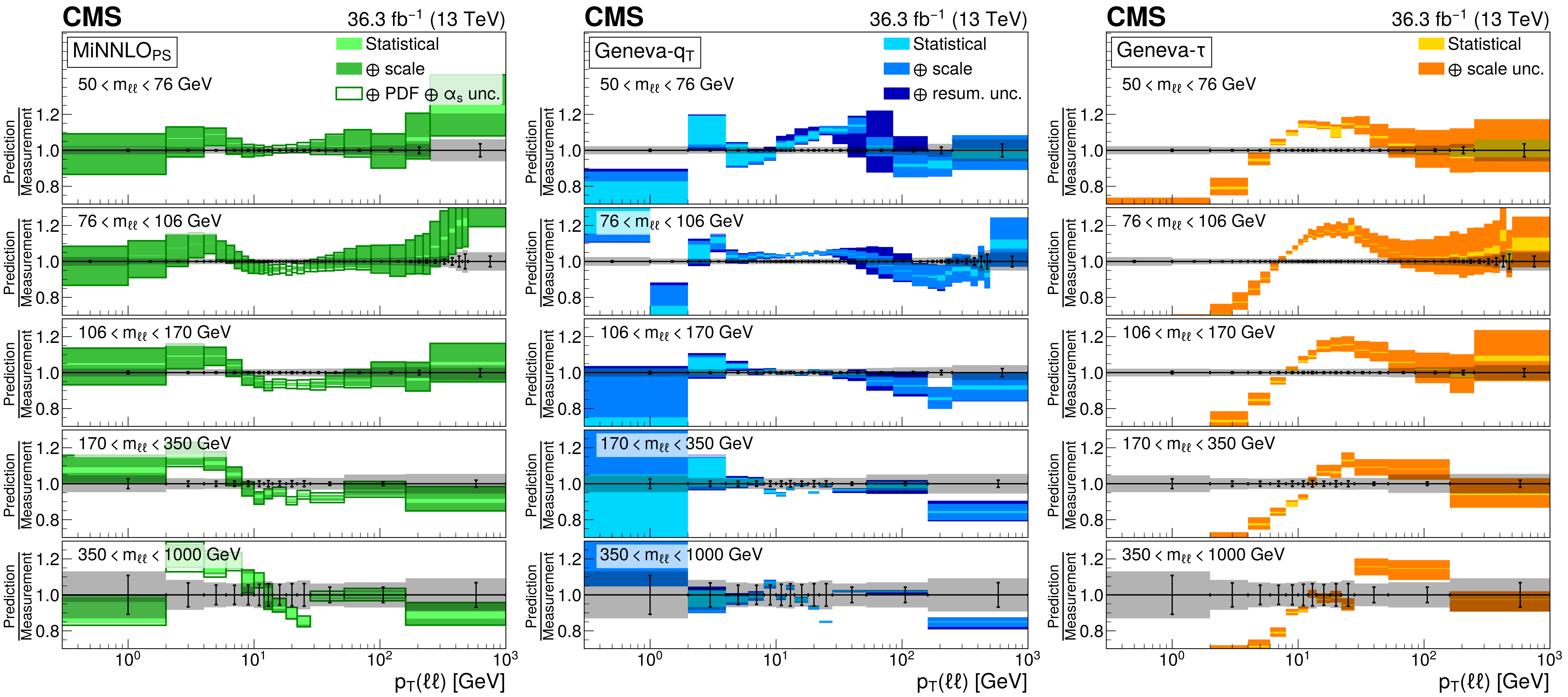




ATL-PHYS-PUB-2017-021

MASS DEPENDENCE OF THE Z p_T

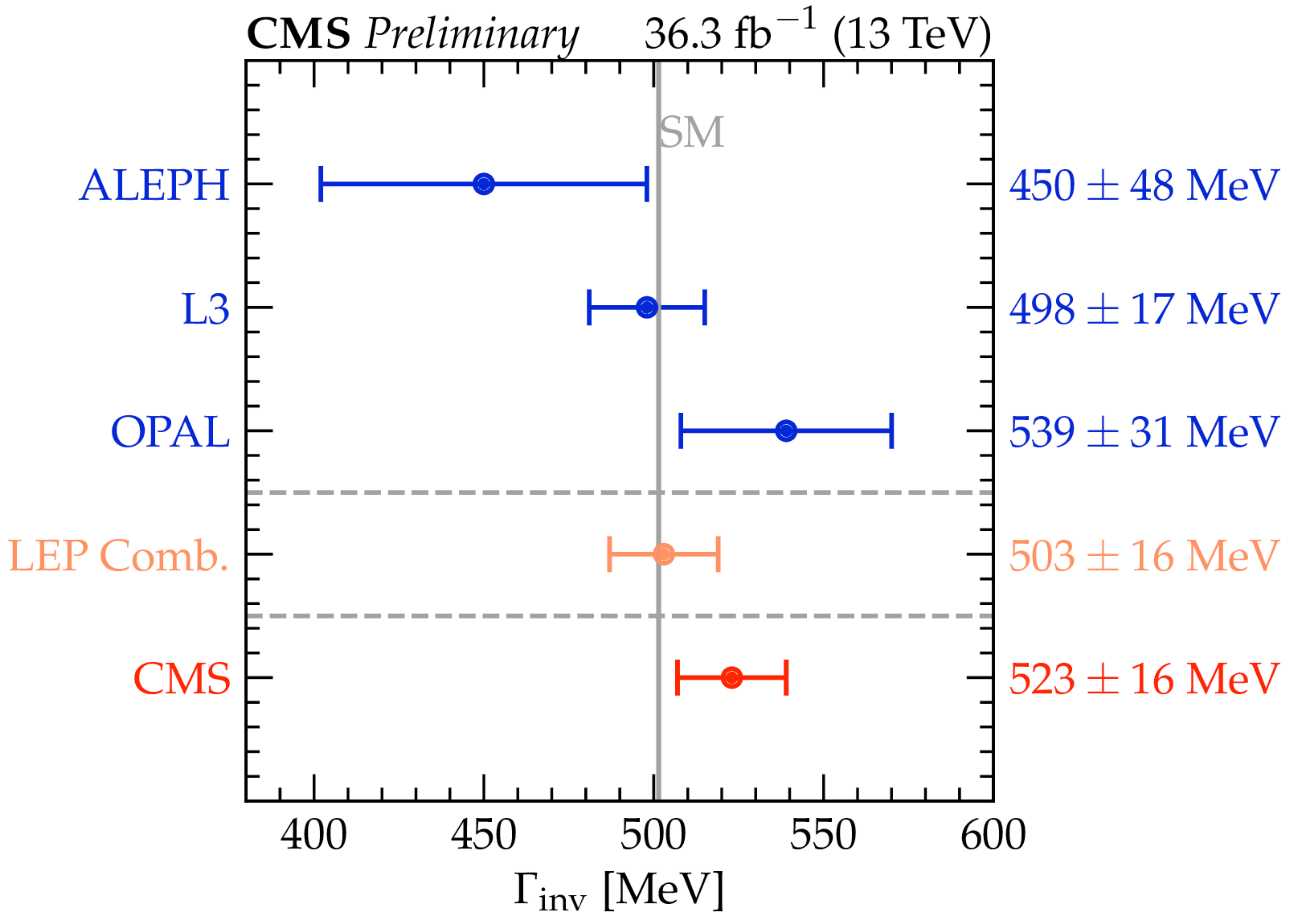
- New CMS result off the Z-peak, testing modern calculations

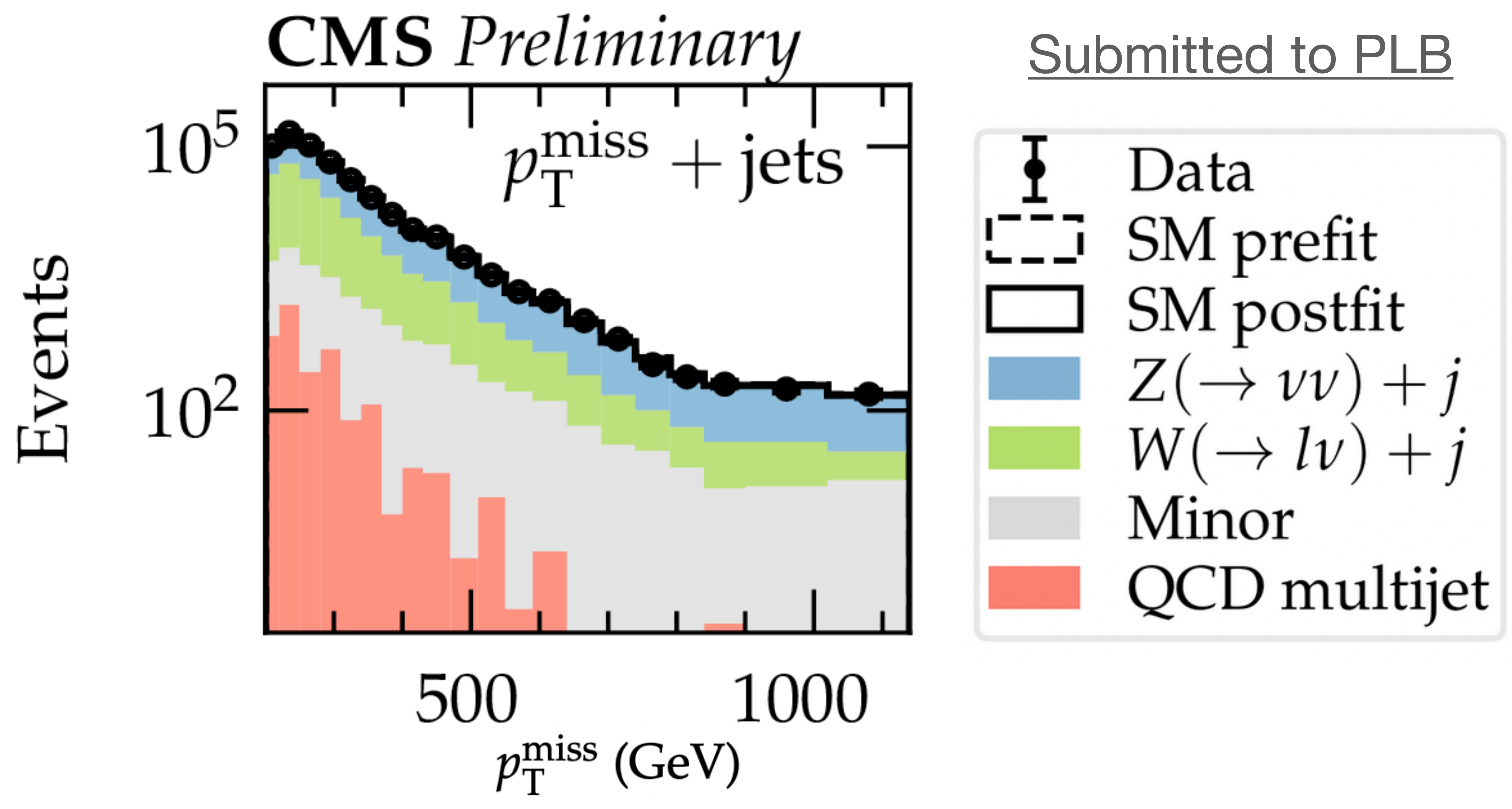


Accepted by EPJC

Z boson decays into neutrinos: invisible width

- Γ_Z^{inv} key parameter to constraint the number of light fermion families
- First direct measurement of Γ_Z^{inv} at a hadron collider from CMS





Submitted to PLB

- Γ_Z^{inv} from ratio of $Z \to \nu\nu$ to $Z \to ll$
  Jets+p_T^{miss} to select $Z \to \nu\nu$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

- Competitive with LEP direct measurement

Lepton Flavour Universality in $W \to \tau\nu$

- Lepton Flavour Universality at the core of the SM
  - W and Z branching ratios to $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$ should be equal
  - Long-standing LEP discrepancy for $W \to \tau\nu$ decays, $R(\tau/\mu) = B(W \to \tau\nu)/B(W \to \mu\nu)$ 2.7σ away from SM
- New ATLAS and CMS measurements weighting in
  - Exploit large unbiased sample of Ws from $t\bar{t}$ decays

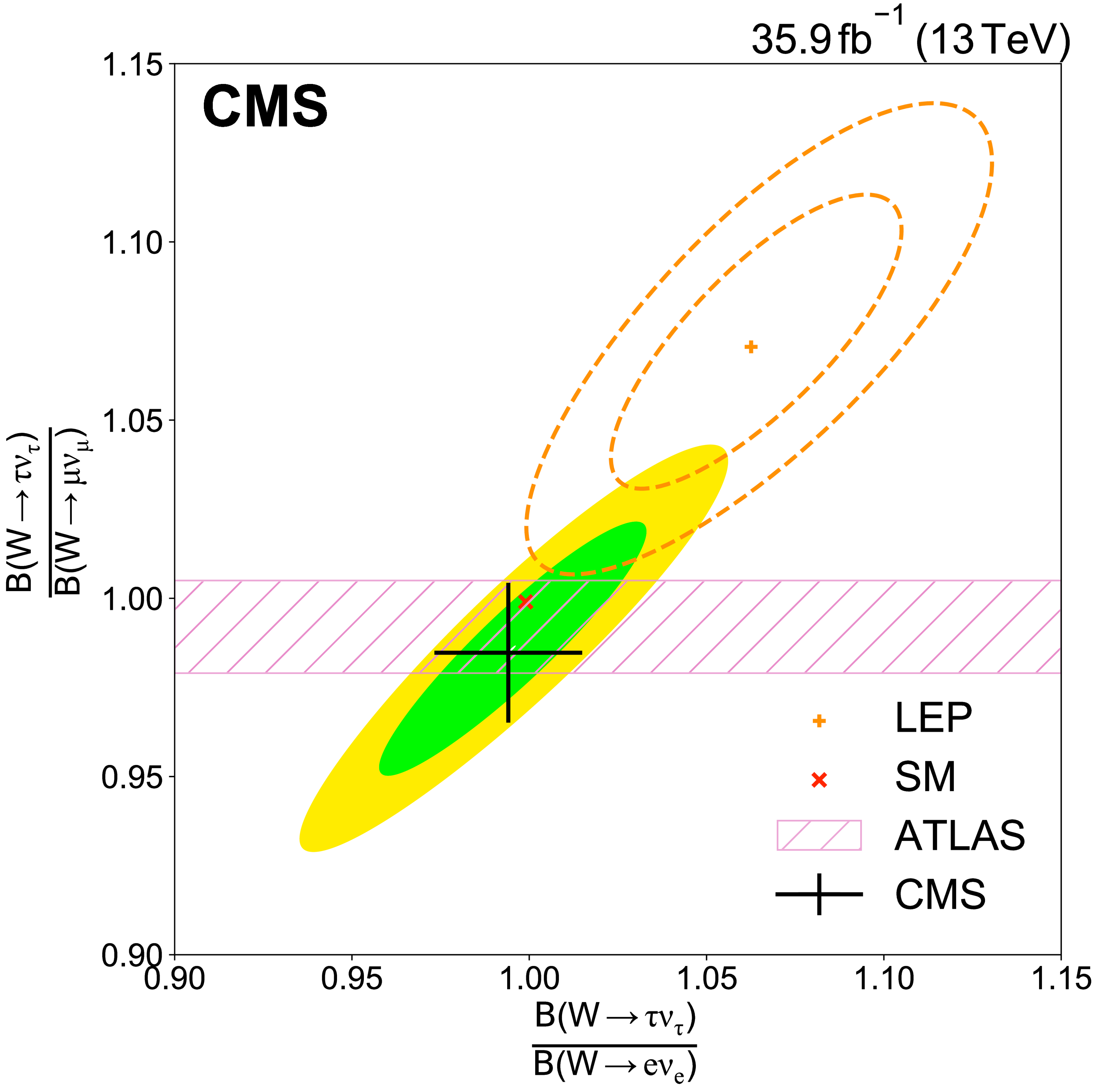
CMS Phys. Rev. D 105 (2022) 072008

$$R(\tau/\mu) = 0.985 \pm 0.020$$

ATLAS Nature Phys. (2021)

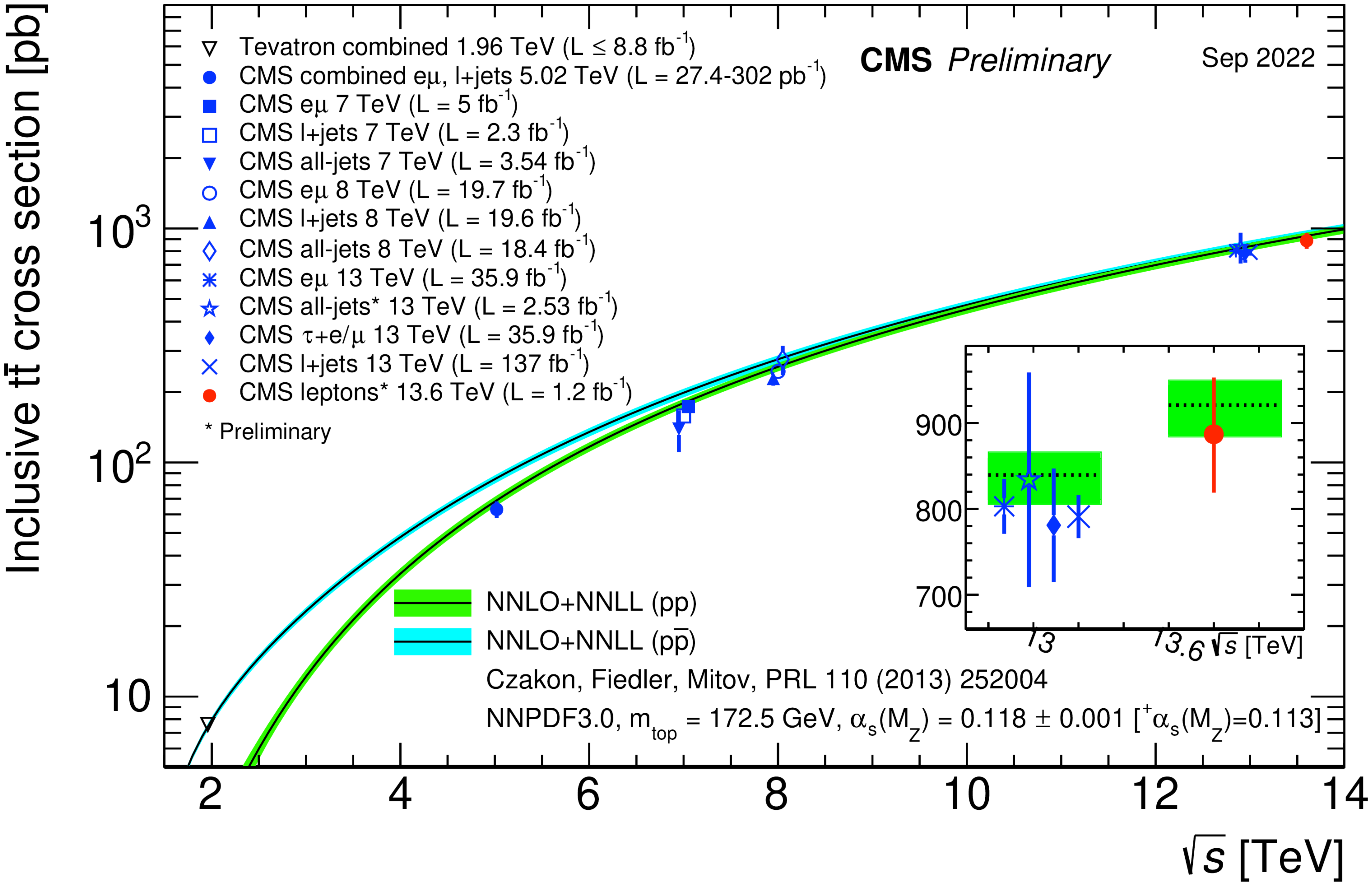
$$R(\tau/\mu) = 0.992 \pm 0.013$$

- $R(\tau/\mu)$ consistent with the SM and LFU and more precise than LEP!



Display of an ATLAS top anti-top event in the emu decay channel

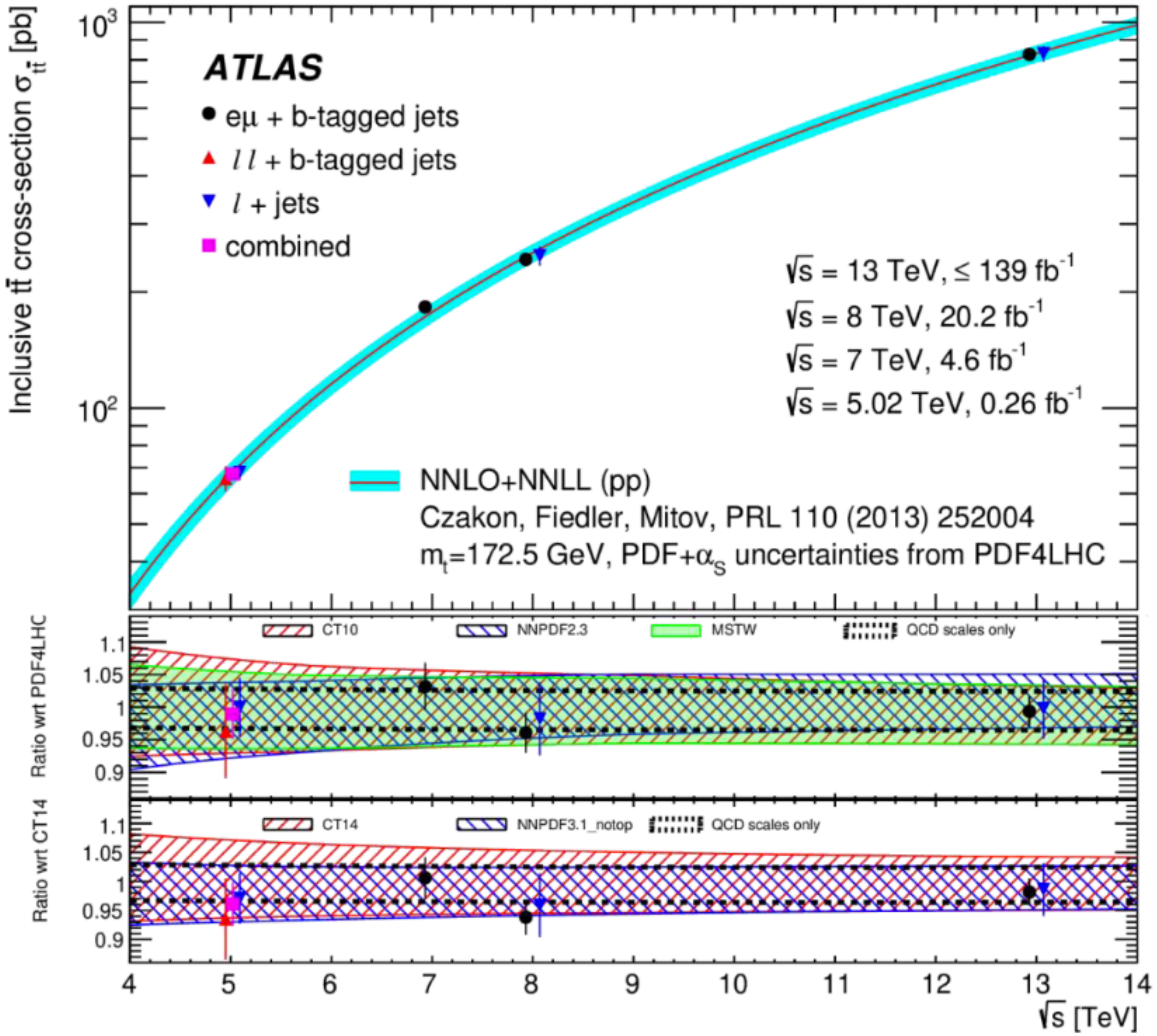
Top-pair cross-sections



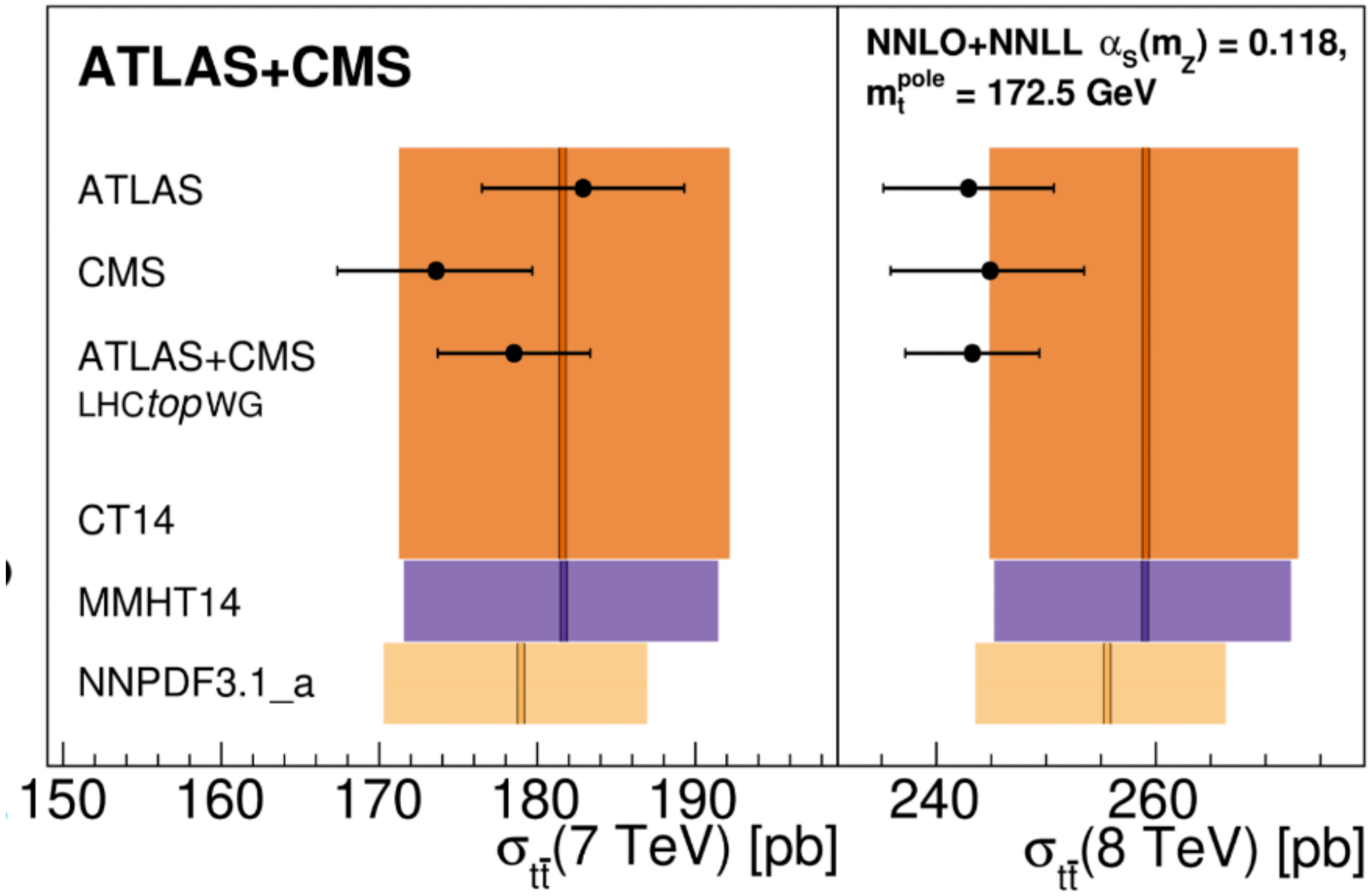
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP-22-012/index.html

Top-pair cross-sections

- New ATLAS measurement at 5.02 TeV (3.9 % precision)



Submitted to JHEP

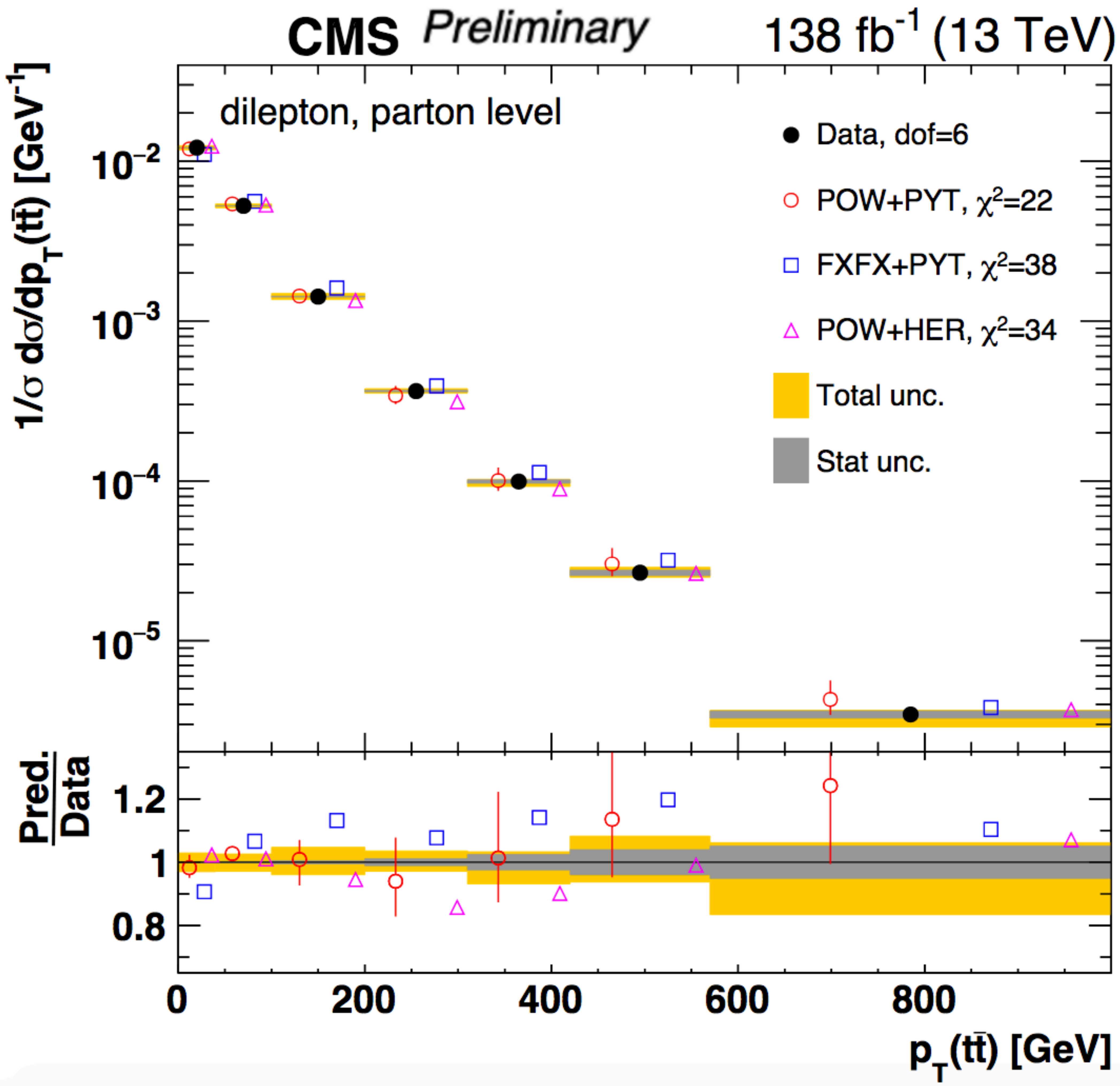


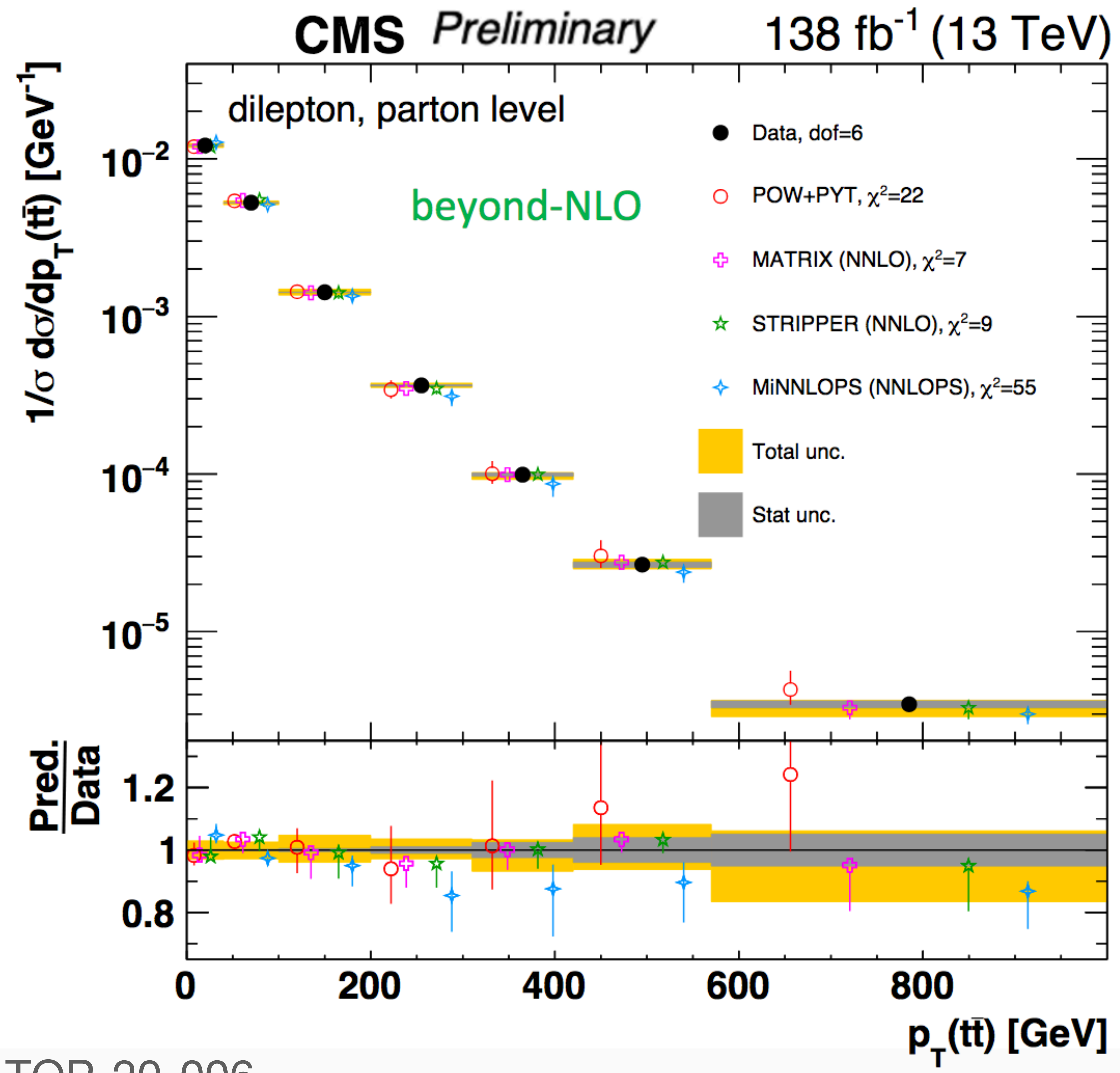
Submitted to JHEP

- ATLAS + CMS combination of Run1 results
  - 2.5% precision; 25% improvement from individual results

CMS dileptonic ttbar cross-sections

- Hundreds of distributions measured with unprecedented precision (between 2 - 20%)
  - Using both a parton level and a fiducial particle-level definition

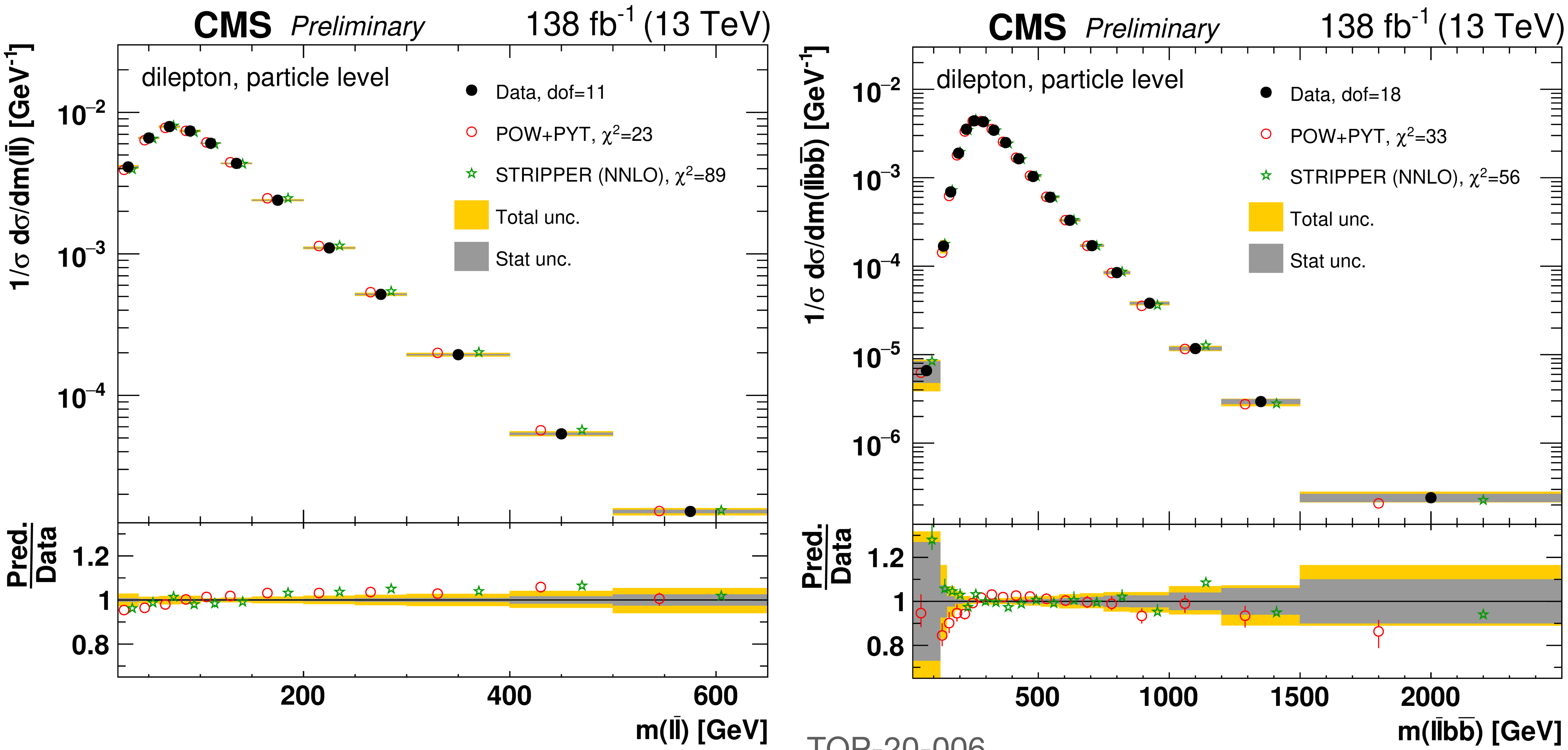




TOP-20-006

CMS dileptonic ttbar cross-sections

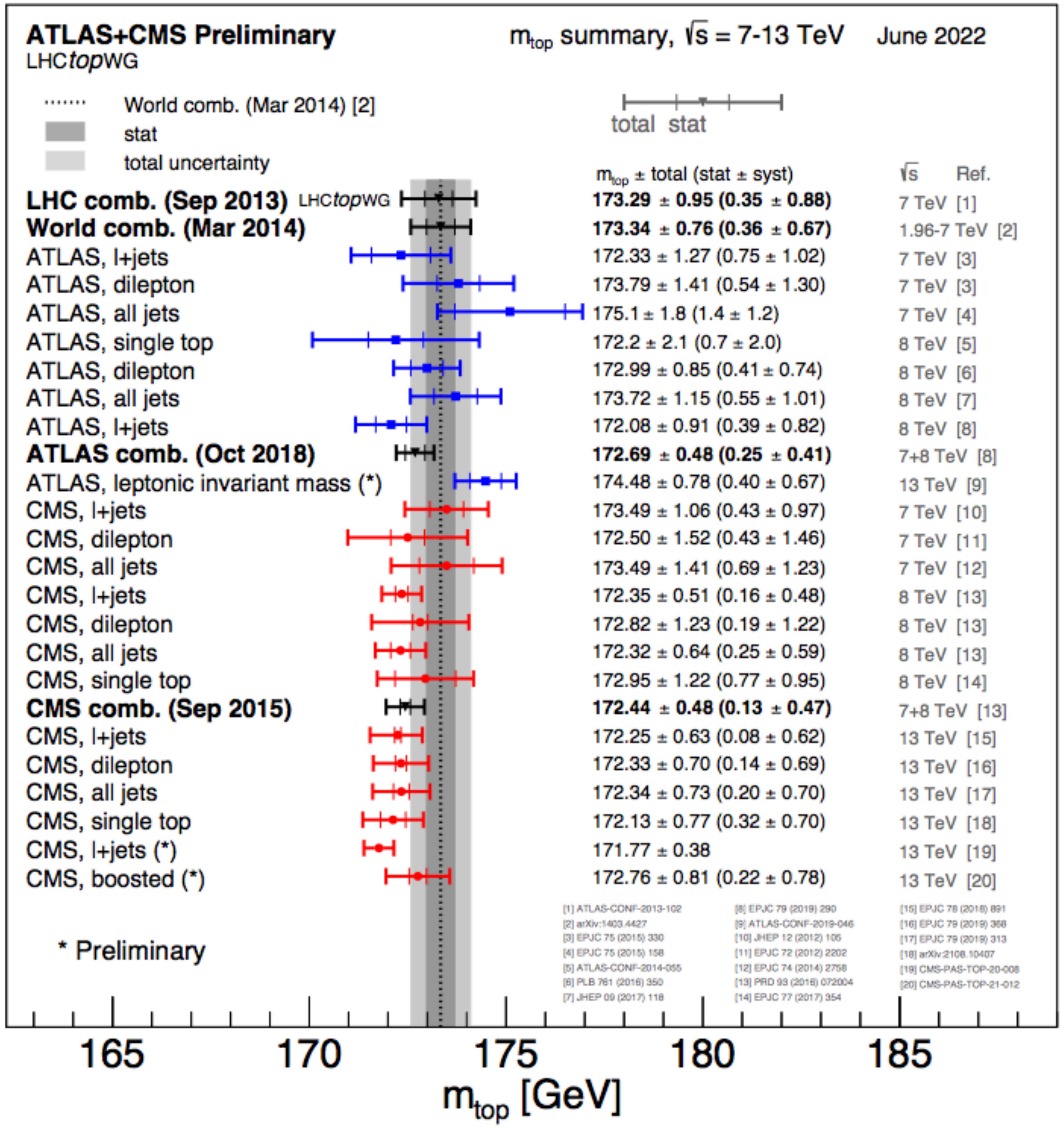
- Hundreds of distributions measured with unprecedented precision (between 2 - 20%)
  - Using both a parton level and a fiducial particle-level definition



TOP-20-006

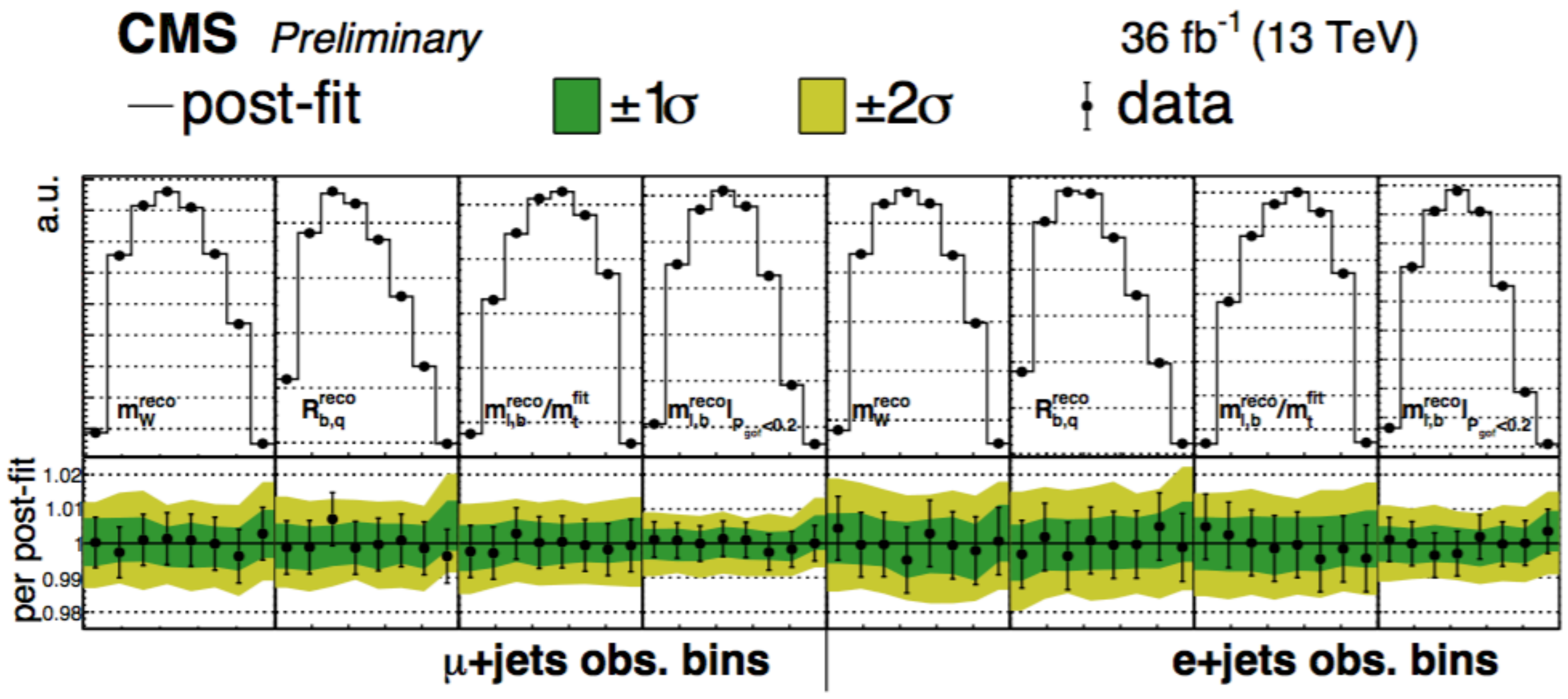
Top quark mass

- Direct measurement from reconstructed top decay products
  - MC mass m_t^{MC} (as defined in the Monte Carlo)
  - Highest sensitivity, now below 500 MeV (<0.3% precision)
  - Hard to improve without improved understanding of non-perturbative effects in MC
- Indirect measurements from sensitive observables (e.g. ttbar cross-sections) +theory
  - Use a well defined scheme (e.g. m_t^{pole}, $m_t(m_t)$)
  - Approaching <1 GeV precision
- Combinations of different measurements exploits anti-correlation in the uncertainties to constrain them

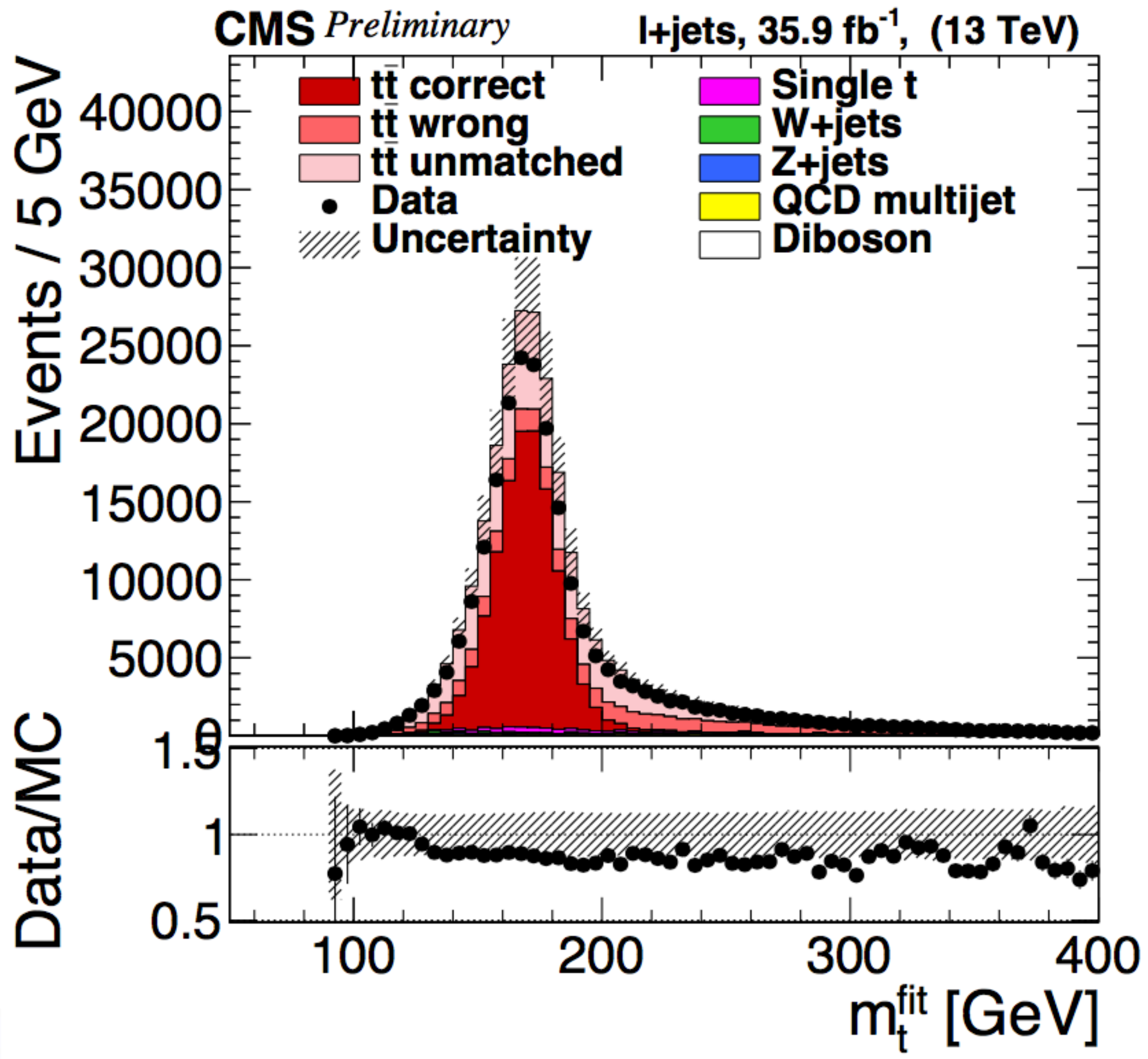


CMS direct mass measurement with a likelihood fit

- Profile likelihood fit using 5 input distributions using 2016 l+jets top data (36 fb^{-1})
- All modelling variations within Powheg+Pythia8 (QCD scales, PDFs, ME/PS matching, 32 ISR/FSR PS scales, CR, UE, top p_T, ...)



TOP-20-008

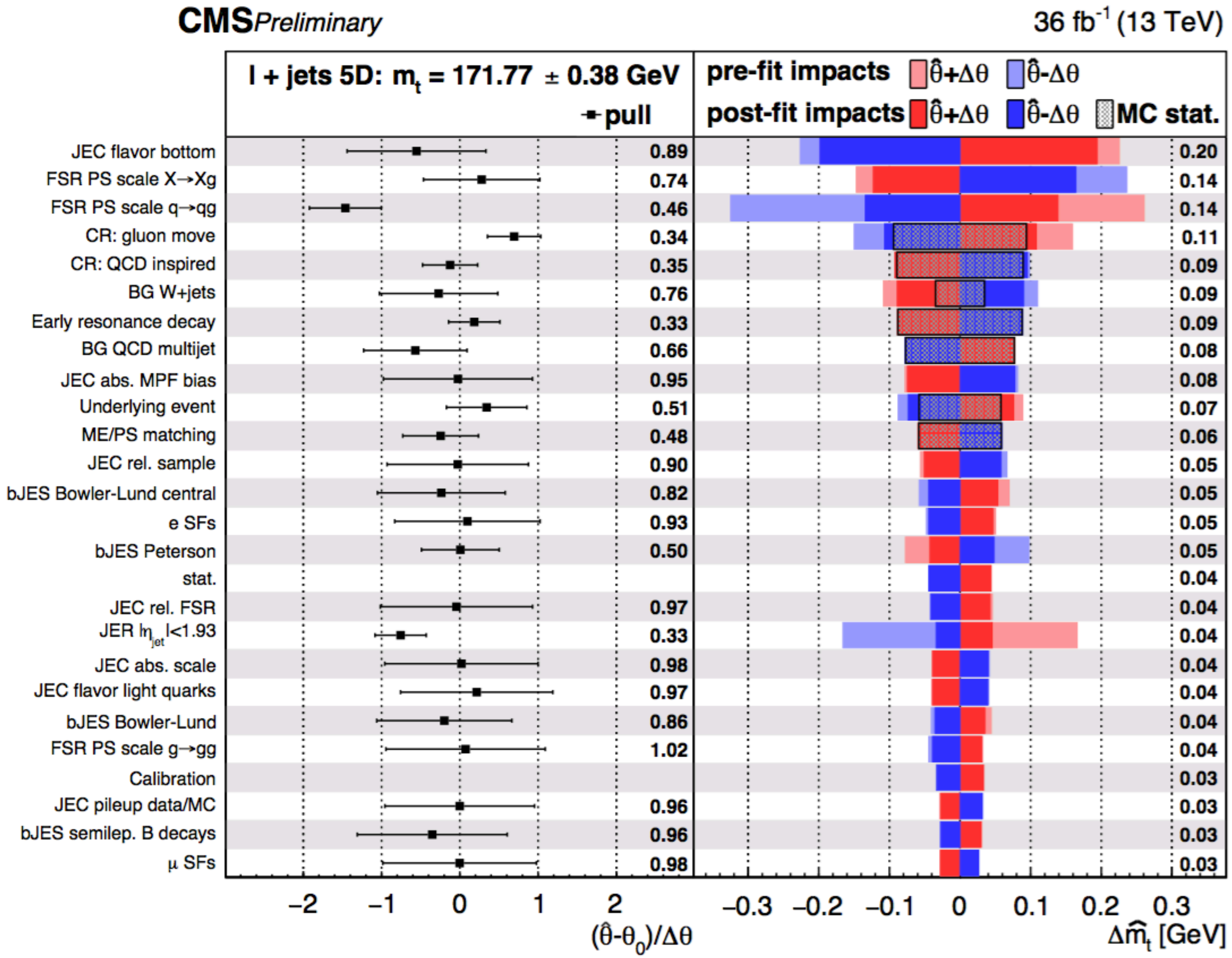


- Full 5D fit gives the best m_{top} to date

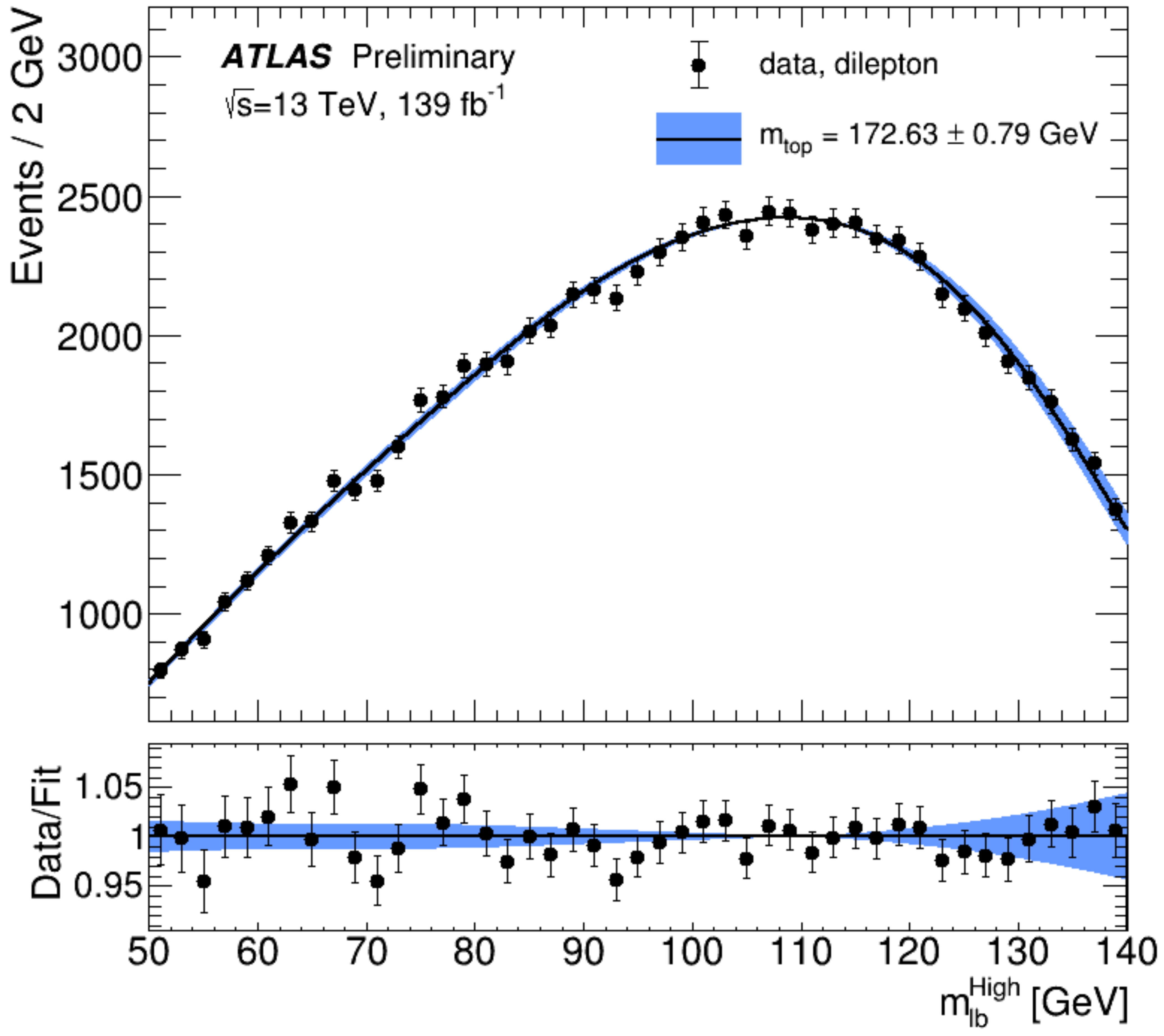
$$m_t = 171.77 \pm 0.38 \; (\pm 0.04 \text{ stat}) \text{ GeV}$$

CMS direct mass measurement with a likelihood fit

* But beware of the strong pulls and constraints observed on the nuisance parameters

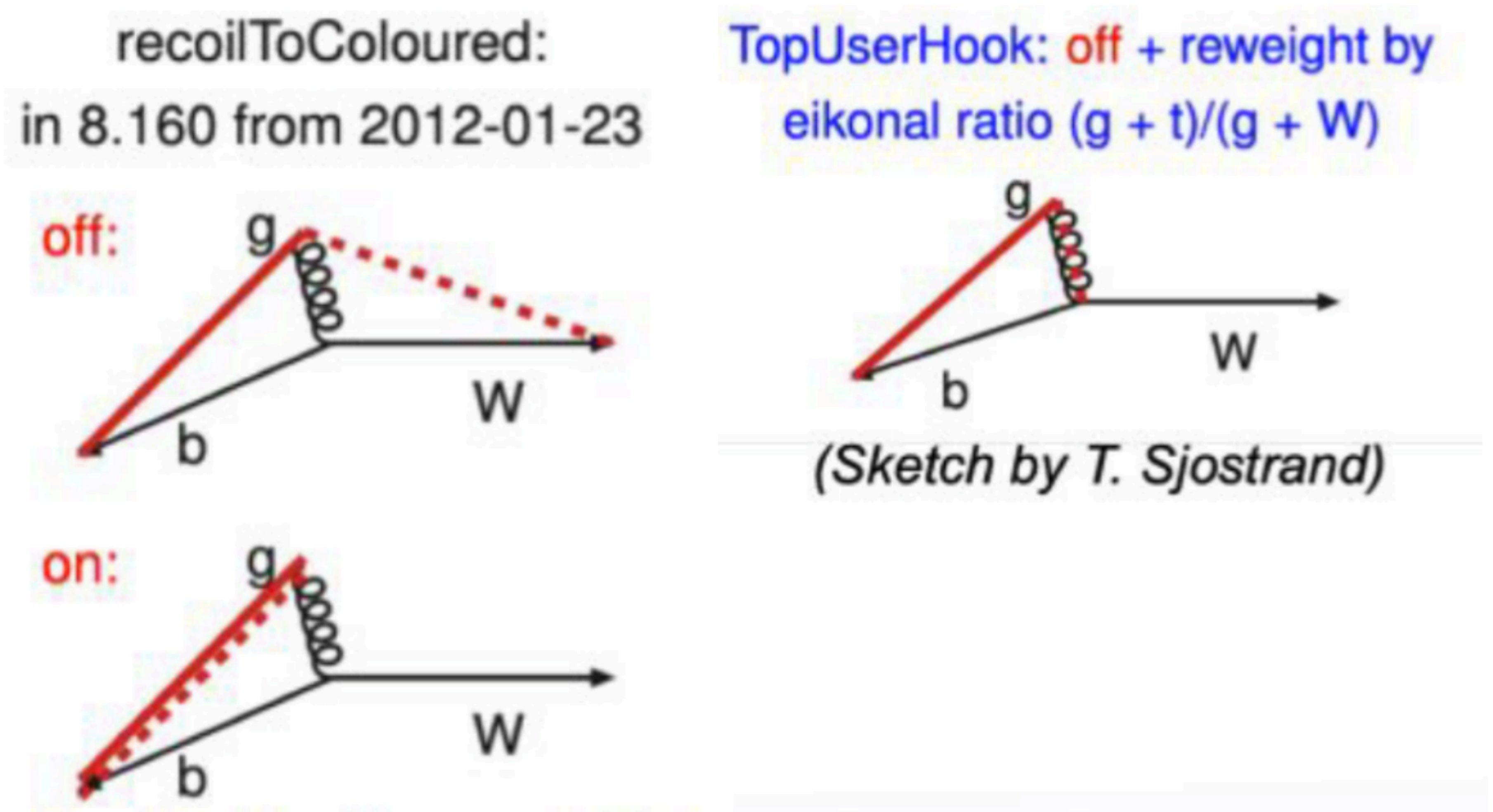


ATLAS top mass in dileptonic channel



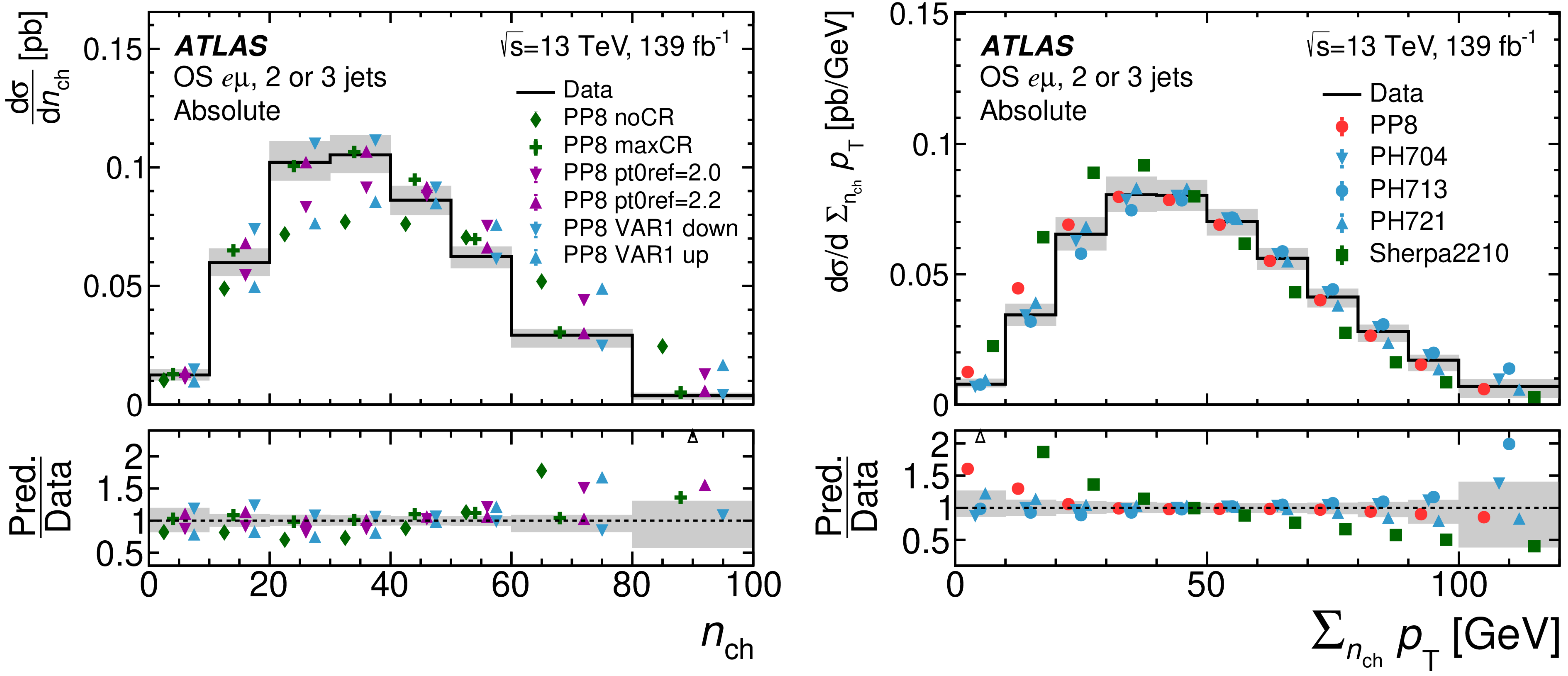
ATLAS-CONF-2022-058

- New full Run2 measurement in dileptonic decay channel
  - DNN to match the lepton, b-jet pairs
  - Unbinned likelihood fit to m_{bl} to extract m_{top}
  - Uncertainties dominated by JES, ME/PS matching, color reconnection, Pythia recoil settings



$$m_{top}^{dilepton} = 172.63 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.37\,(\text{recoil})\ \text{GeV}$$

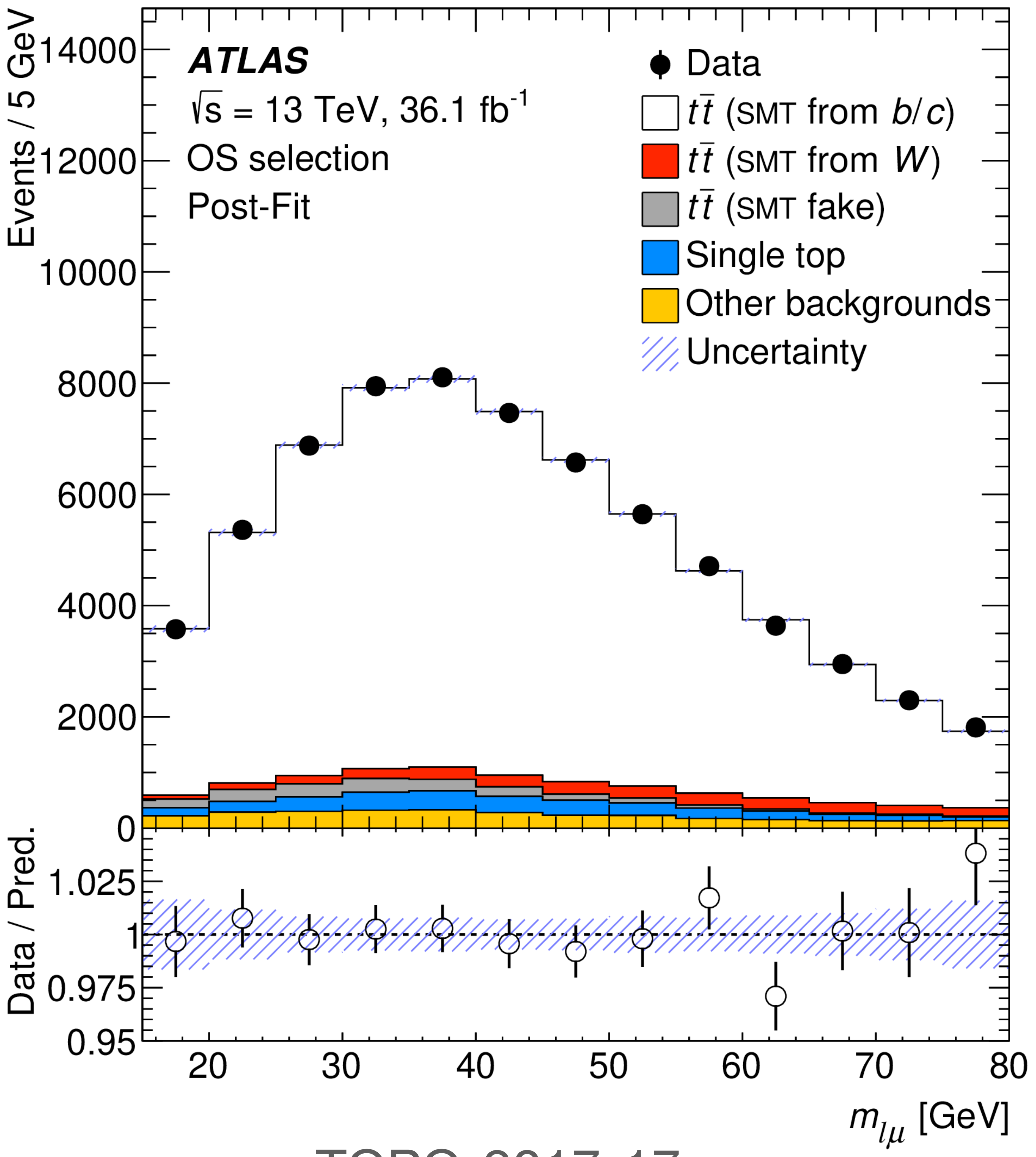
Color reconnection in ttbar events



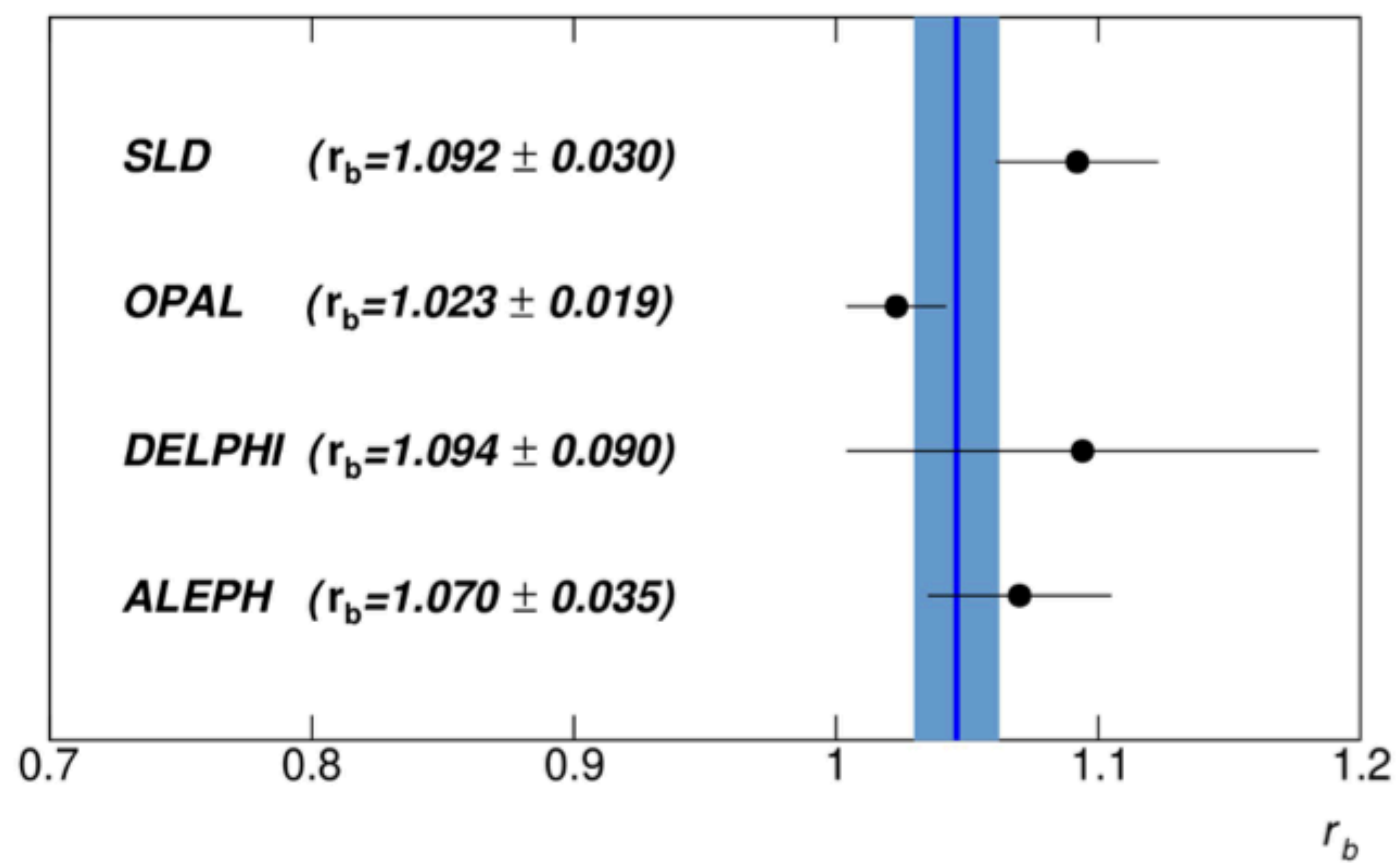
Submitted to EPJC

Direct mass measurement with a soft muon

- Avoid large uncertainties from hadronic jet reconstruction using a fully leptonic quantity
- Use a soft lepton from a semileptonic decay of a B-hadron



TOPQ-2017-17

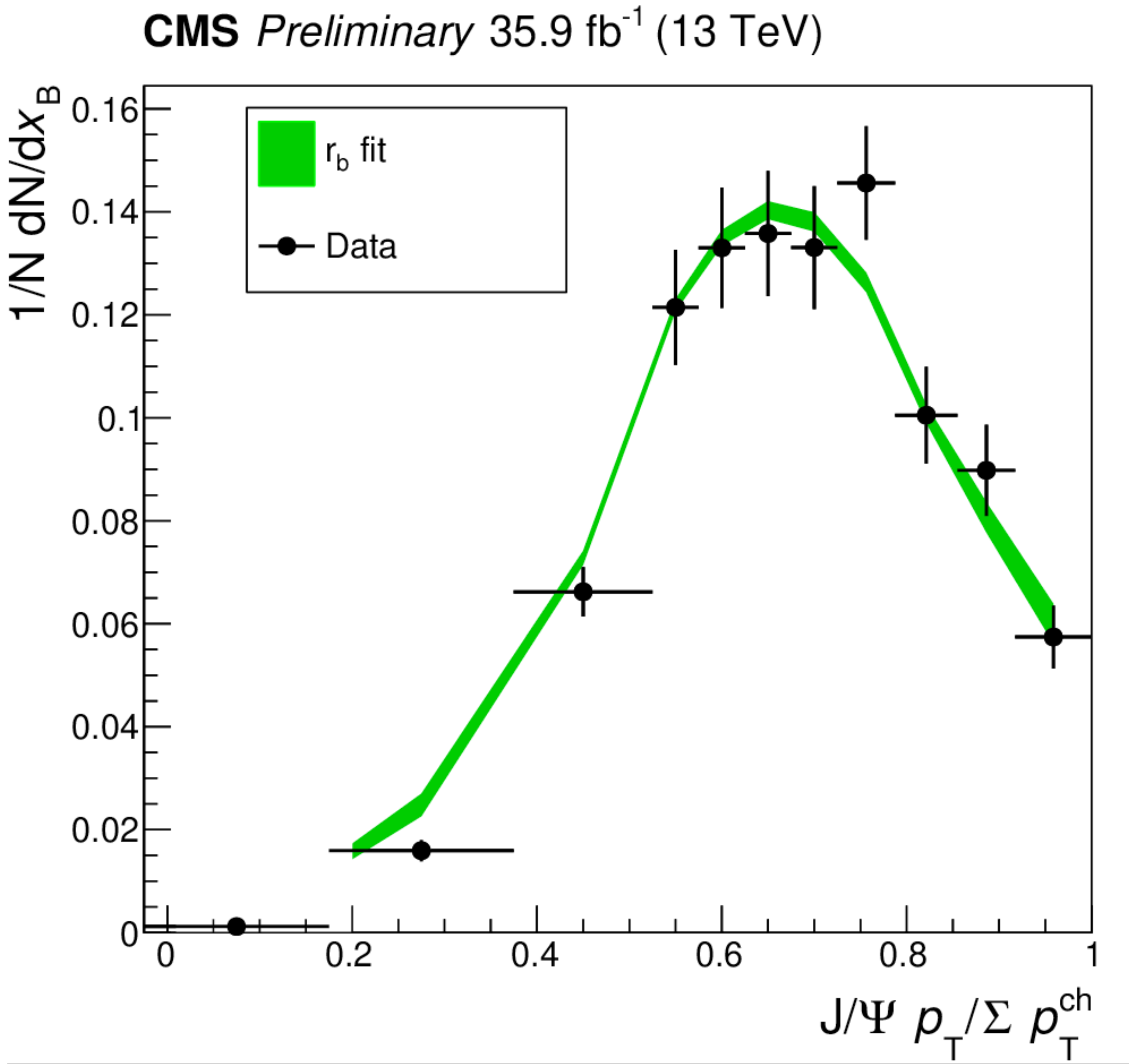


- Dominant uncertainties from knowledge of branching-ratios and fragmentation
  - Fit of r_B parameter of Pythia8 Lund-Bowler FF
  - BR and fragmentation fractions reweighted to world average
- m_{top} from likelihood fit to m_{lmu} distribution

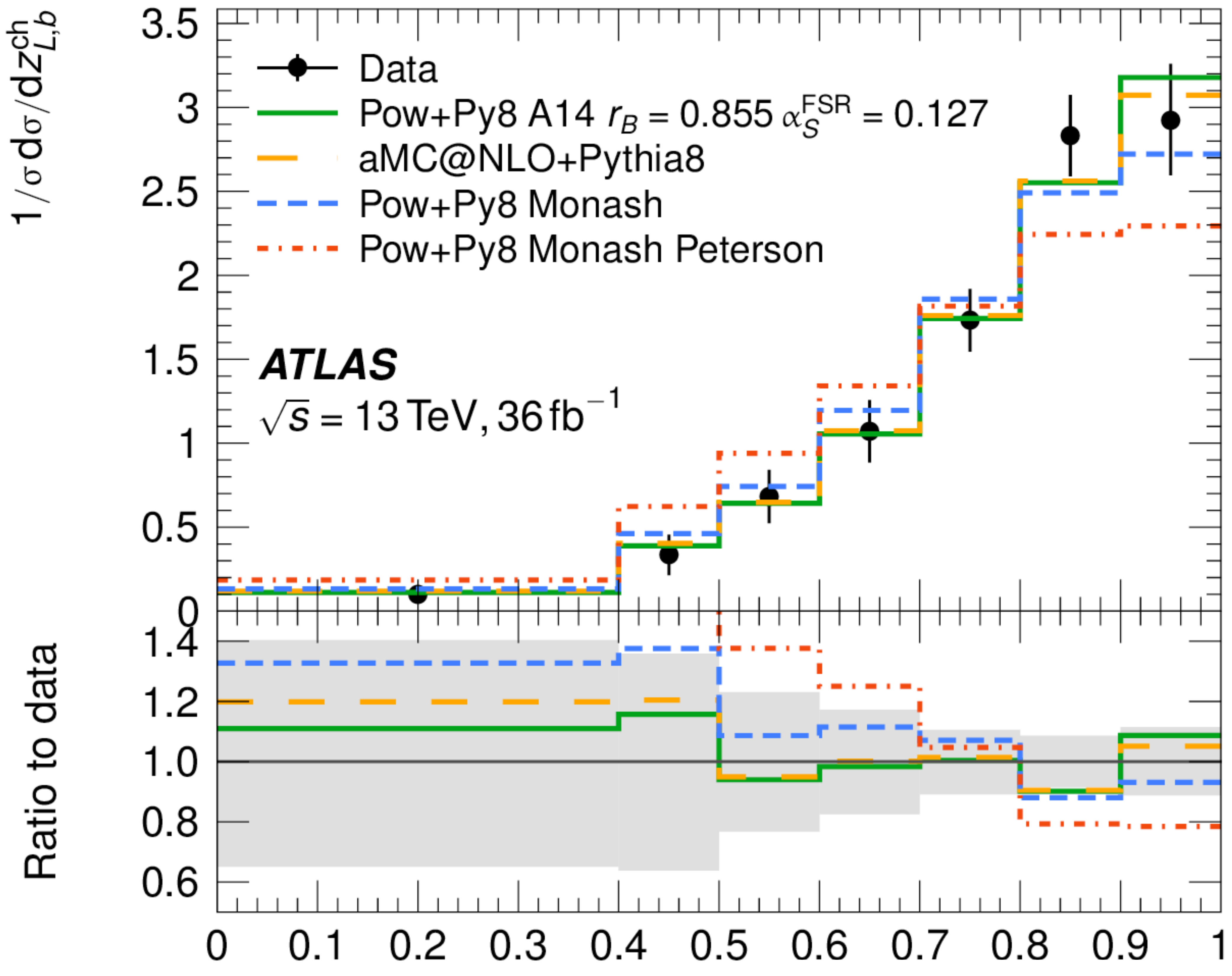
$$m_t = 174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

B-fragmentation in TP eventso

* Run2 measurements from ATLAS and CMS can now be used to validate and constrain the models



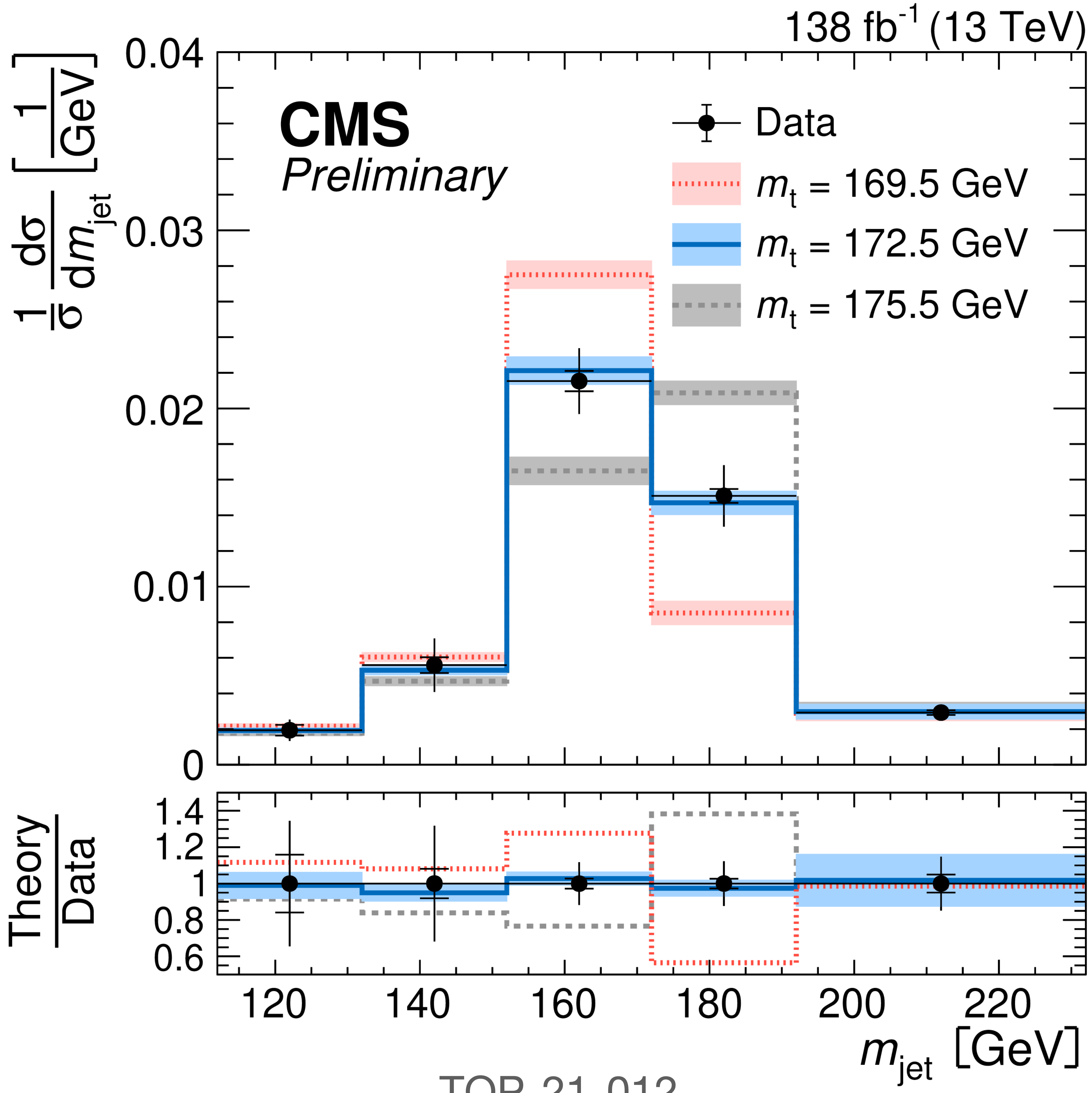
TOP-18-012



PRD (2022) 032008

$$z^{ch}_{L,b} = \frac{\vec{p}^{\,ch}_b \cdot \vec{p}^{\,ch}_{jet}}{|p^{ch}_{jet}|^2}$$

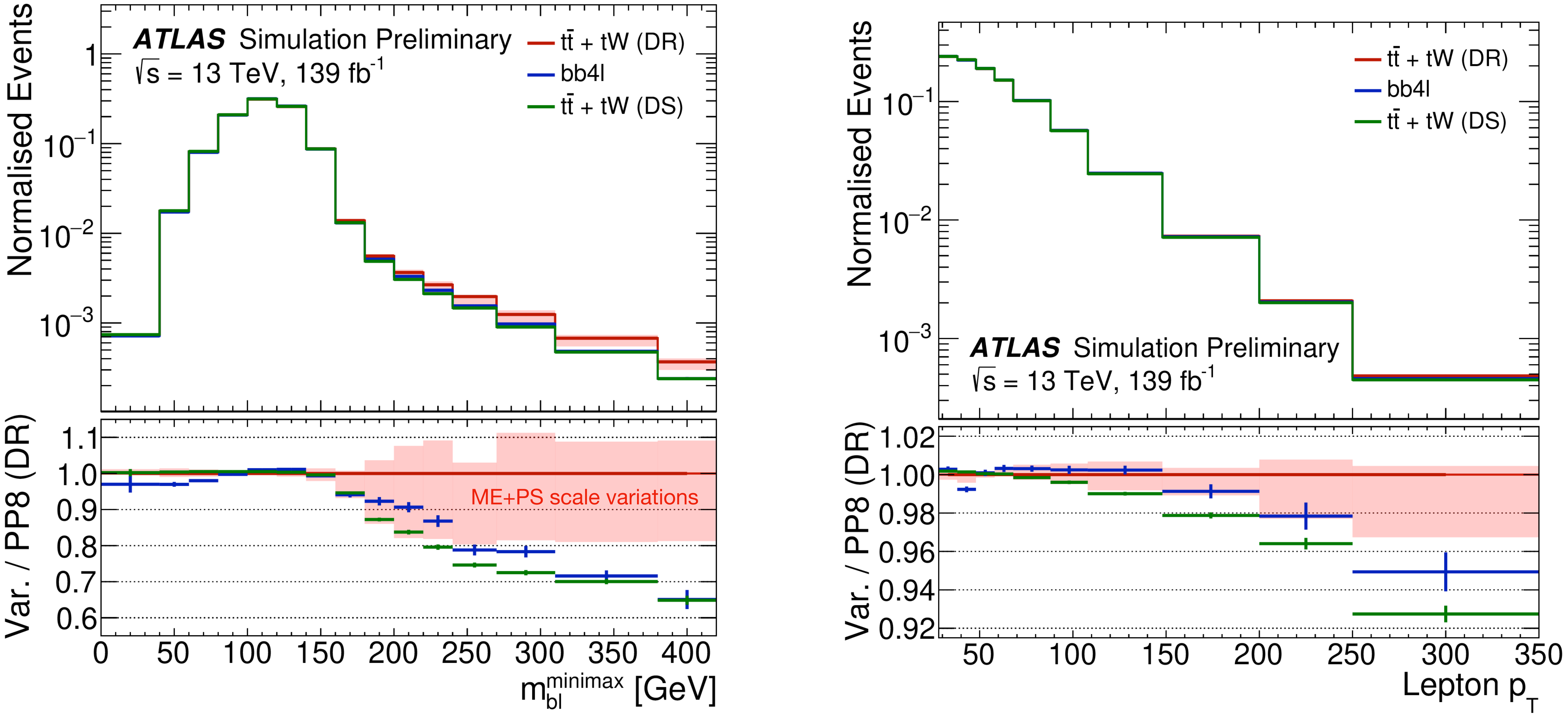
Top quark mass from boosted jet mass



TOP-21-012

- Measurement of the unfolded normalised jet mass in hadronic decays of a boosted top quark
  - XCone with R=1.2 for jets reclustering at particle level
  - Require a jet with $p_T > 400$ GeV
- Linear template fit to extract m_{top}
  m_{top} = 172.76 pm 0.81 GeV (0.22 stat)
- Paves the way to future m_{top} extractions using analytic calculations

How narrow a width is enough?

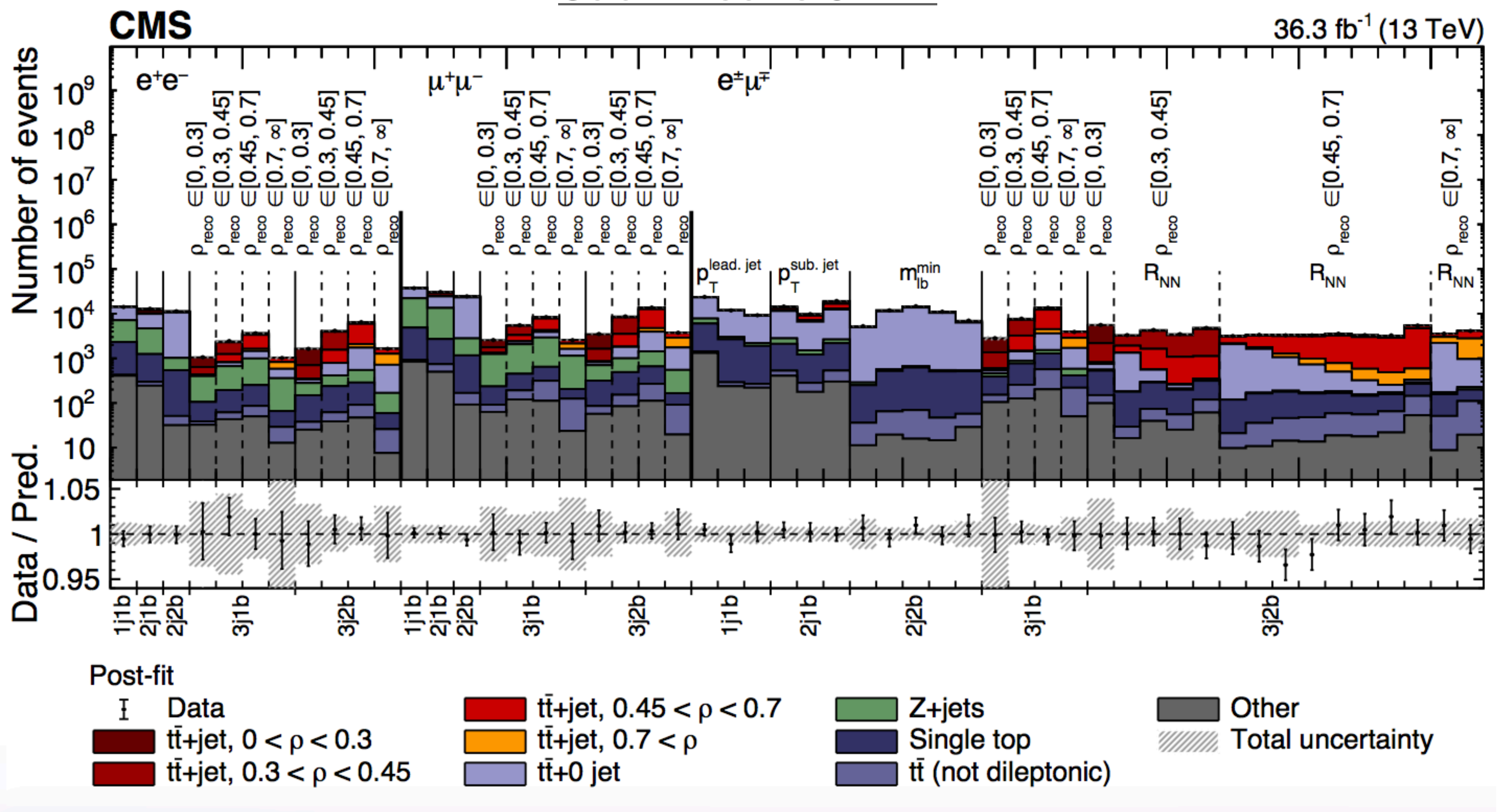


ATL-PHYS-PUB-2021-042

TOP POLE MASS WITH TTBAR+JET

- Pole mass from differential measurement of dileptonic ttbar+jet cross-sections
- NN used to reconstruct the ttbar kinematics and discriminate against Z+jets background
- Measurement binned in ρ = 2 × $m_0/m_{tt+jets}$ (m_0=170 GeV) EPJC 77 (2017) 794
- Simultaneous profile likelihood fit in four rho bins to extract the signal

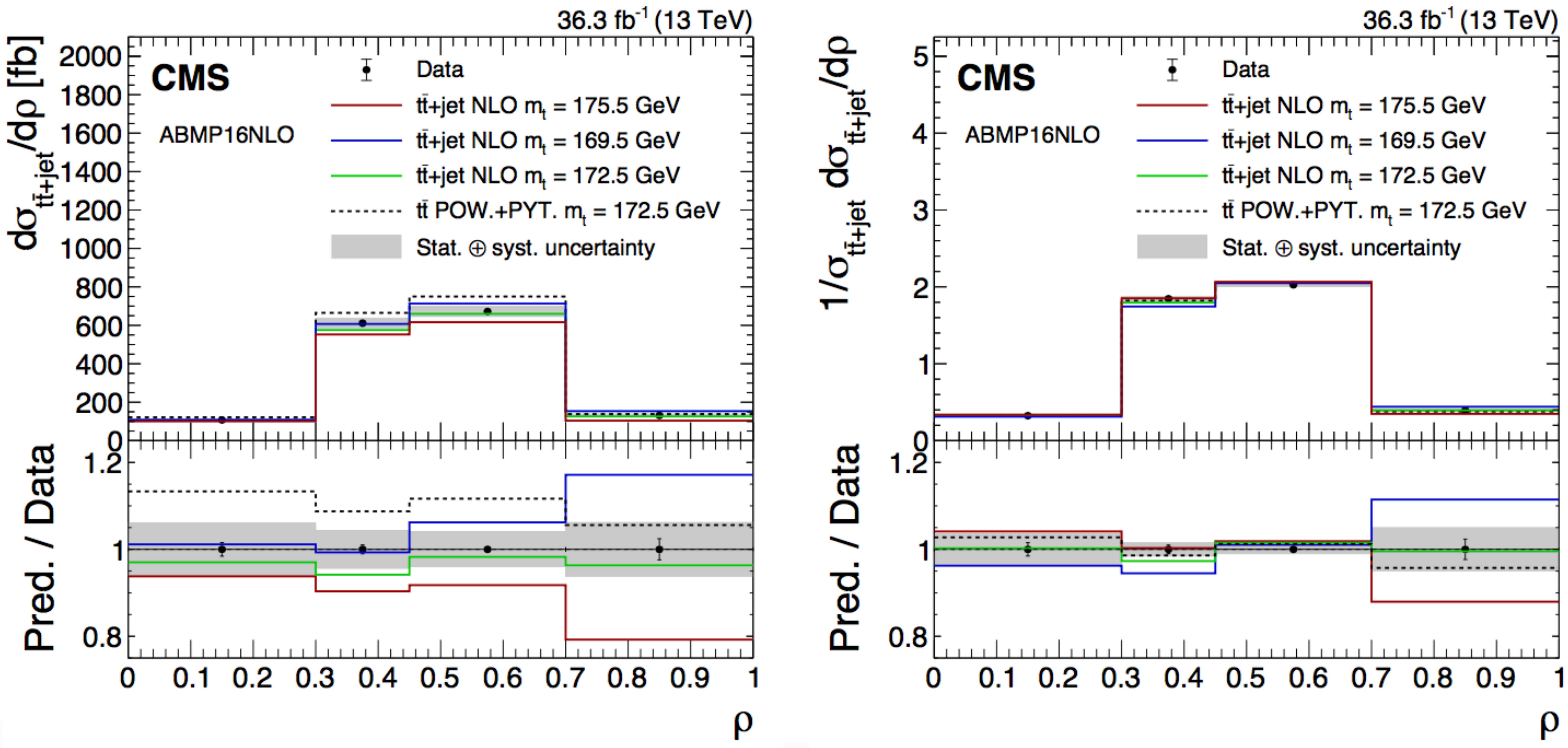
Submitted to JHEP



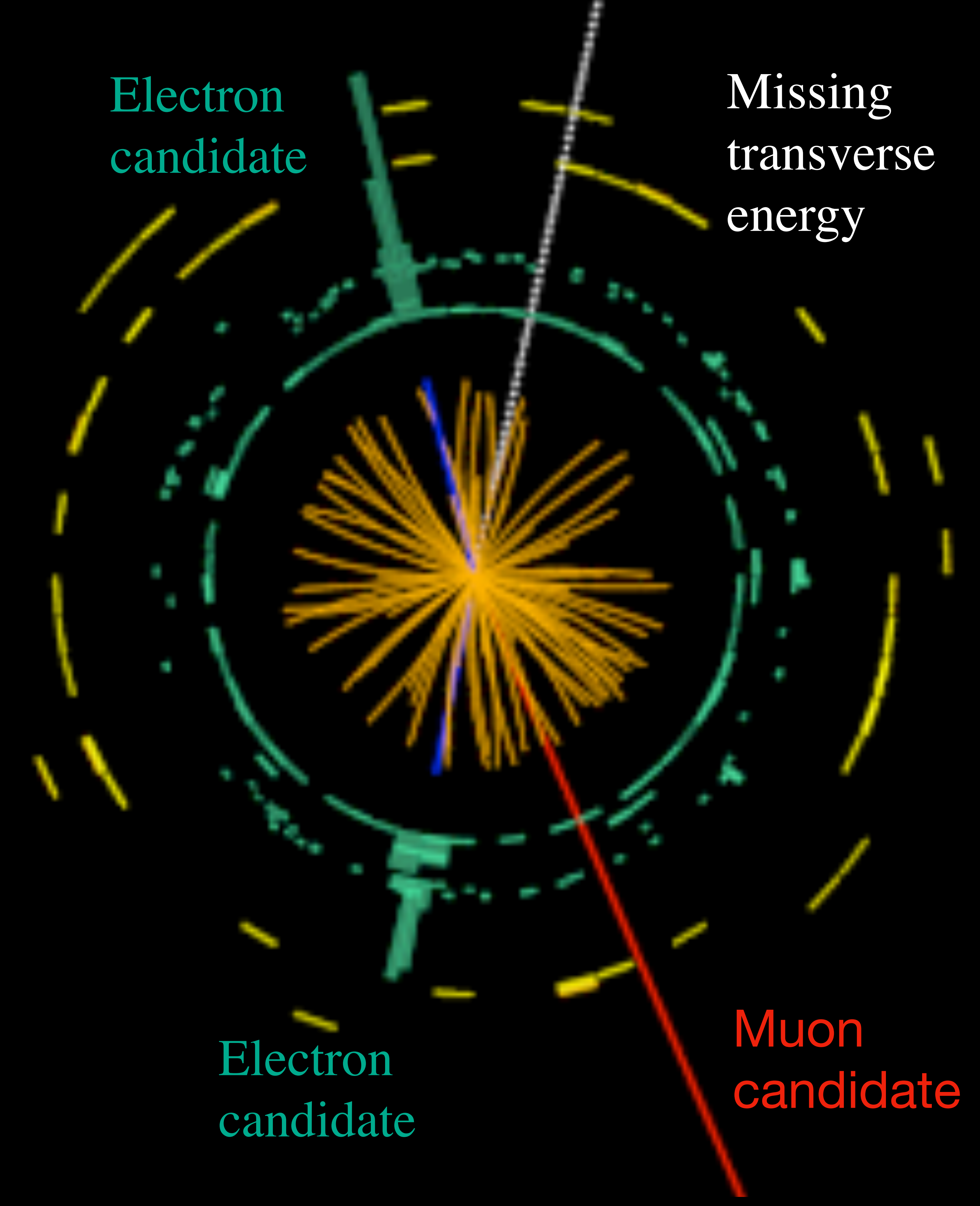
- Pole mass extracted from a template fit to the unfolded normalised cross-section
- Fixed order NLO (tt+jet) predictions from Powheg to build templates

$$m_{\mathrm{top}}^{\mathrm{pole}} = 172.94 \pm 1.27\,(\mathrm{fit})\,^{+0.51}_{-0.43}\,(\mathrm{scale})\ \mathrm{GeV}$$ ➡ ABMP16NLO

$$m_{\mathrm{top}}^{\mathrm{pole}} = 172.16 \pm 1.35\,(\mathrm{fit})\,^{+0.50}_{-0.40}\,(\mathrm{scale})\ \mathrm{GeV}$$ ➡ CT18NLO

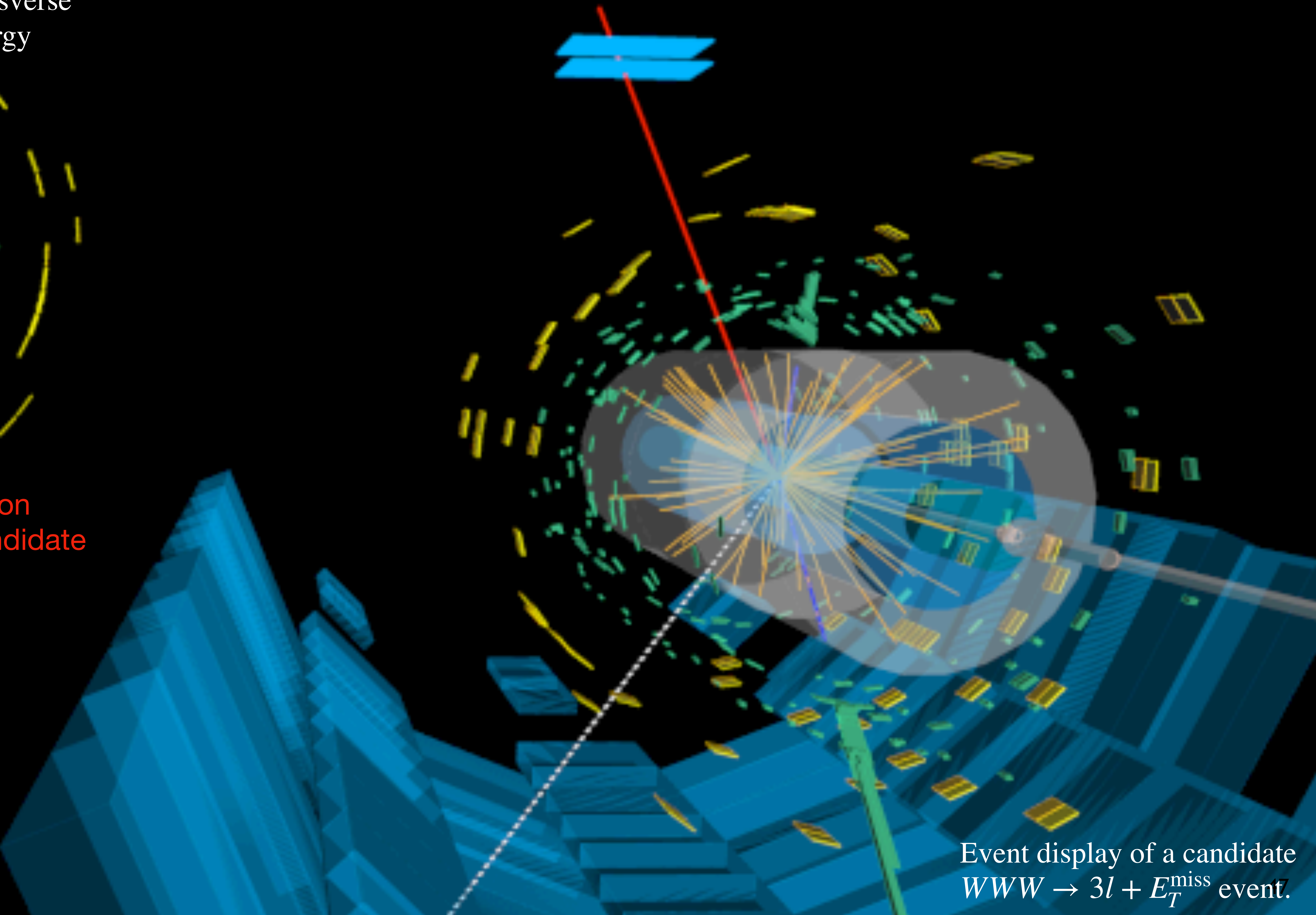


Multi-boson production



ATLAS EXPERIMENT

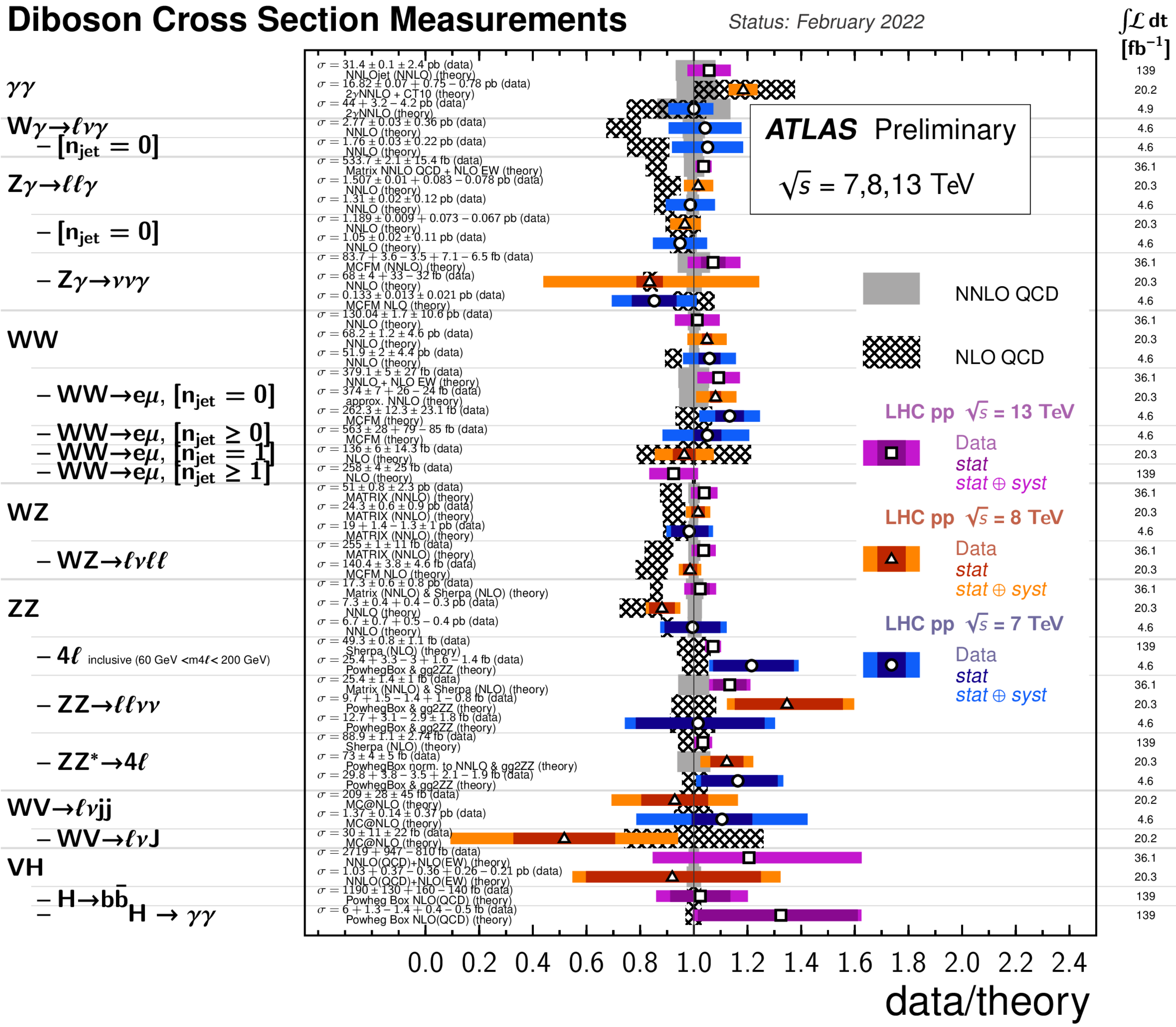
Run: 349169
Event: 1043374730
2018-04-30 01:58:32 CEST

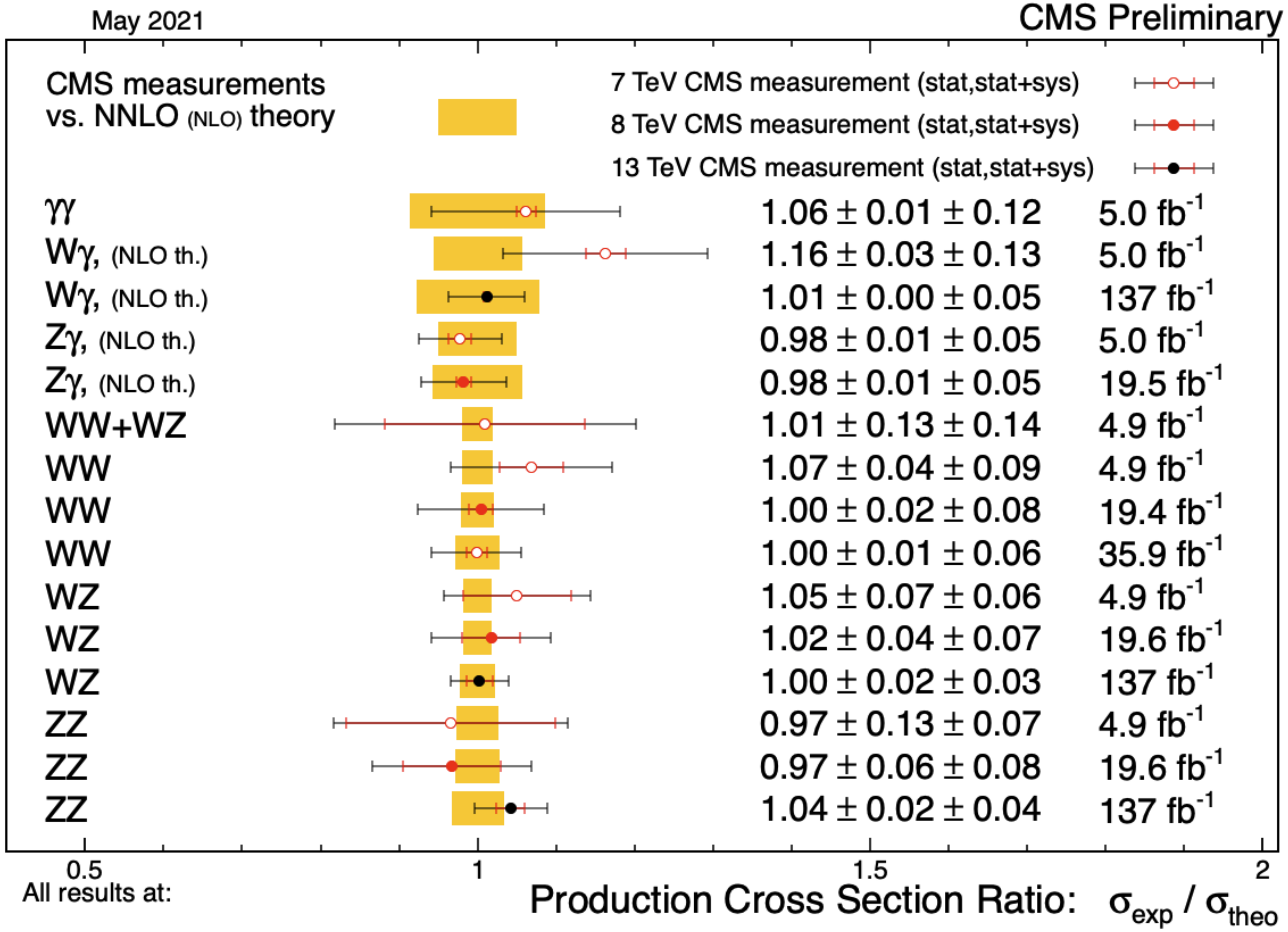


Event display of a candidate $WWW \to 3l + E_T^{\text{miss}}$ event.

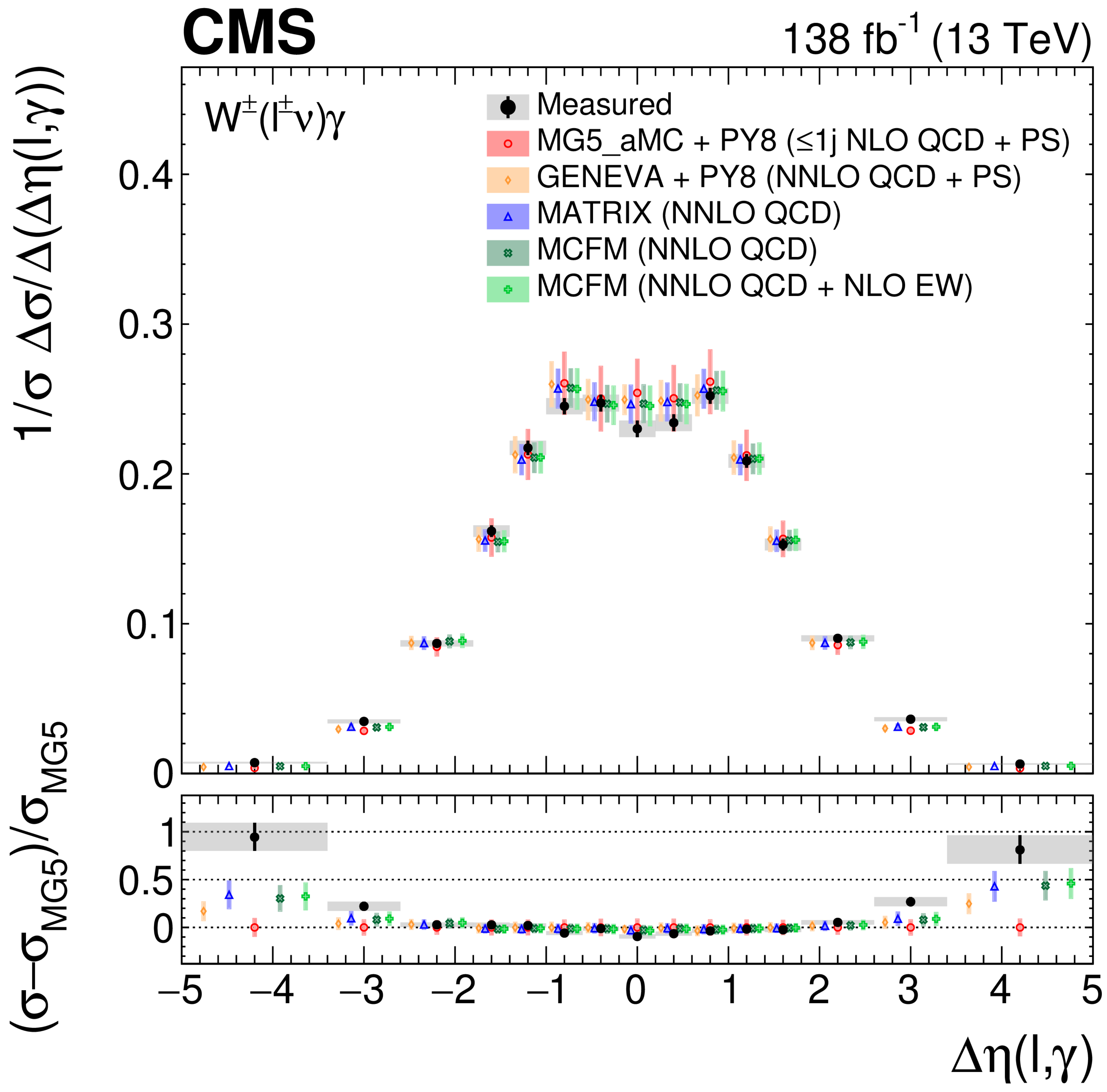
Diboson cross-sections status

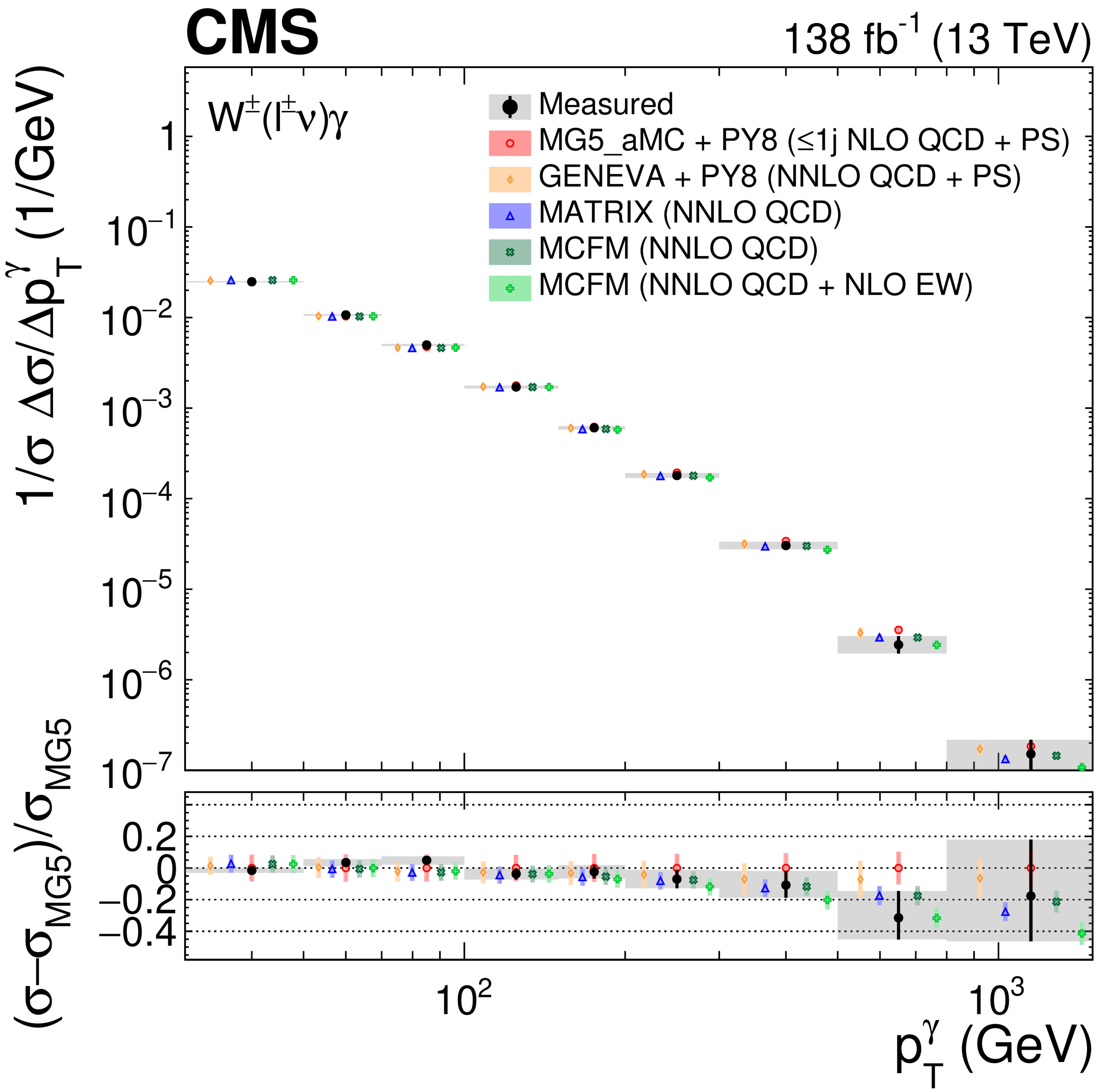
- Reaching few percent accuracies for di-boson production





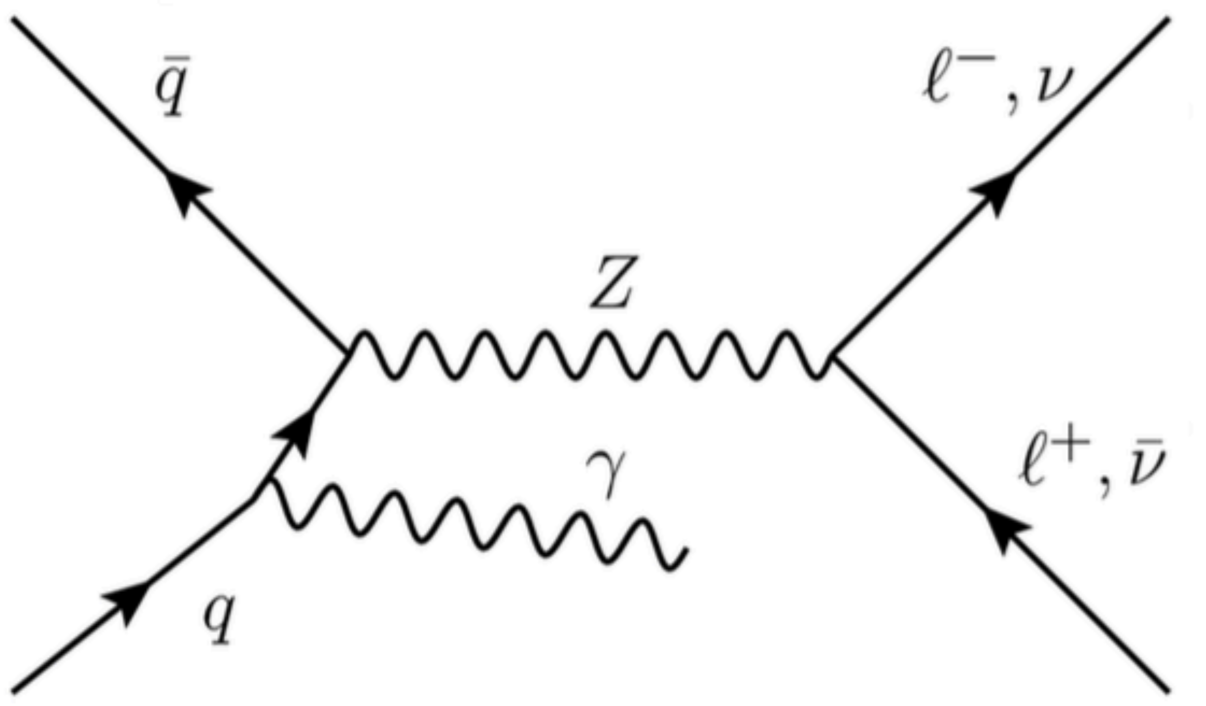
CMS full Run2 W+gamma cross-sections



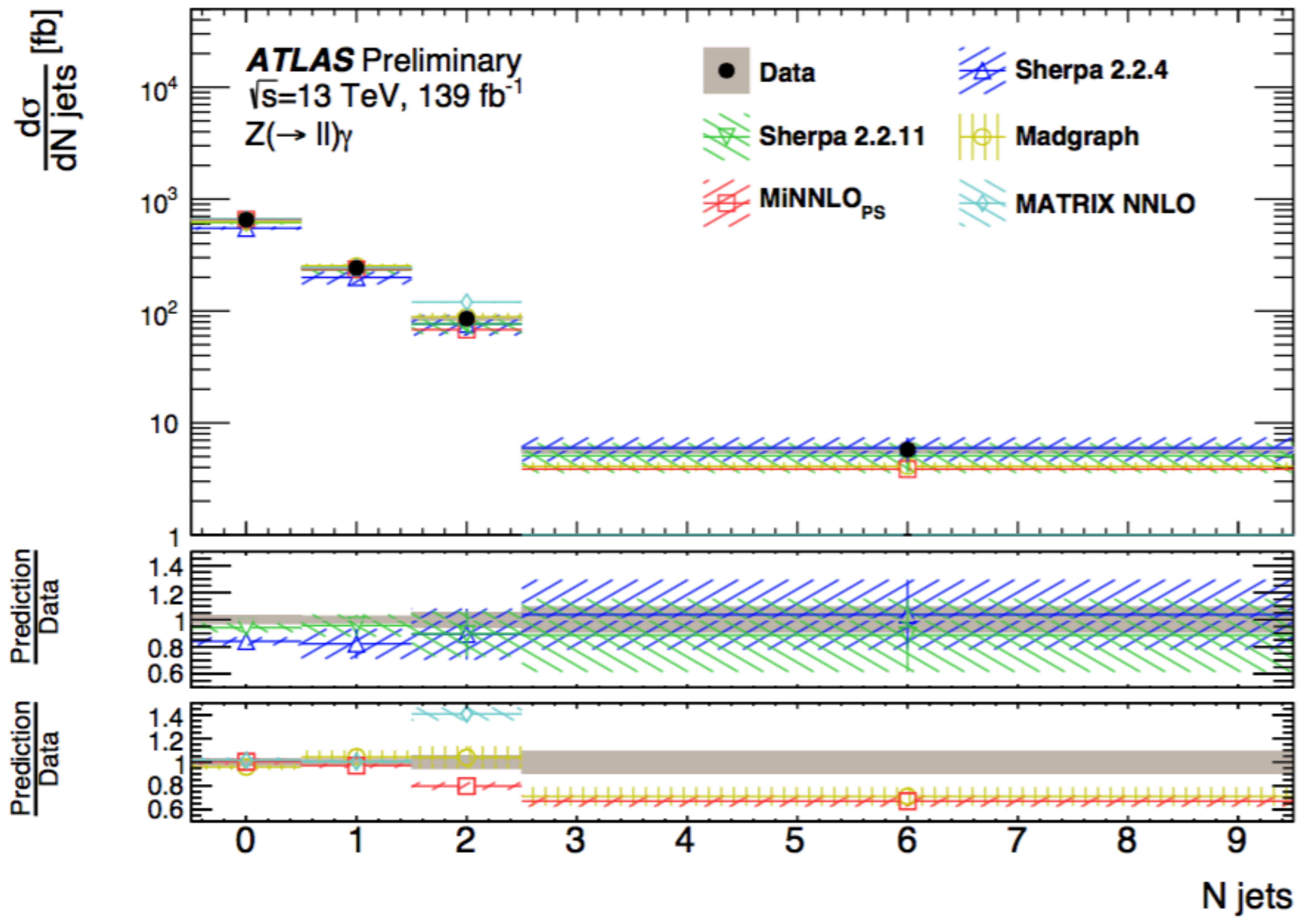


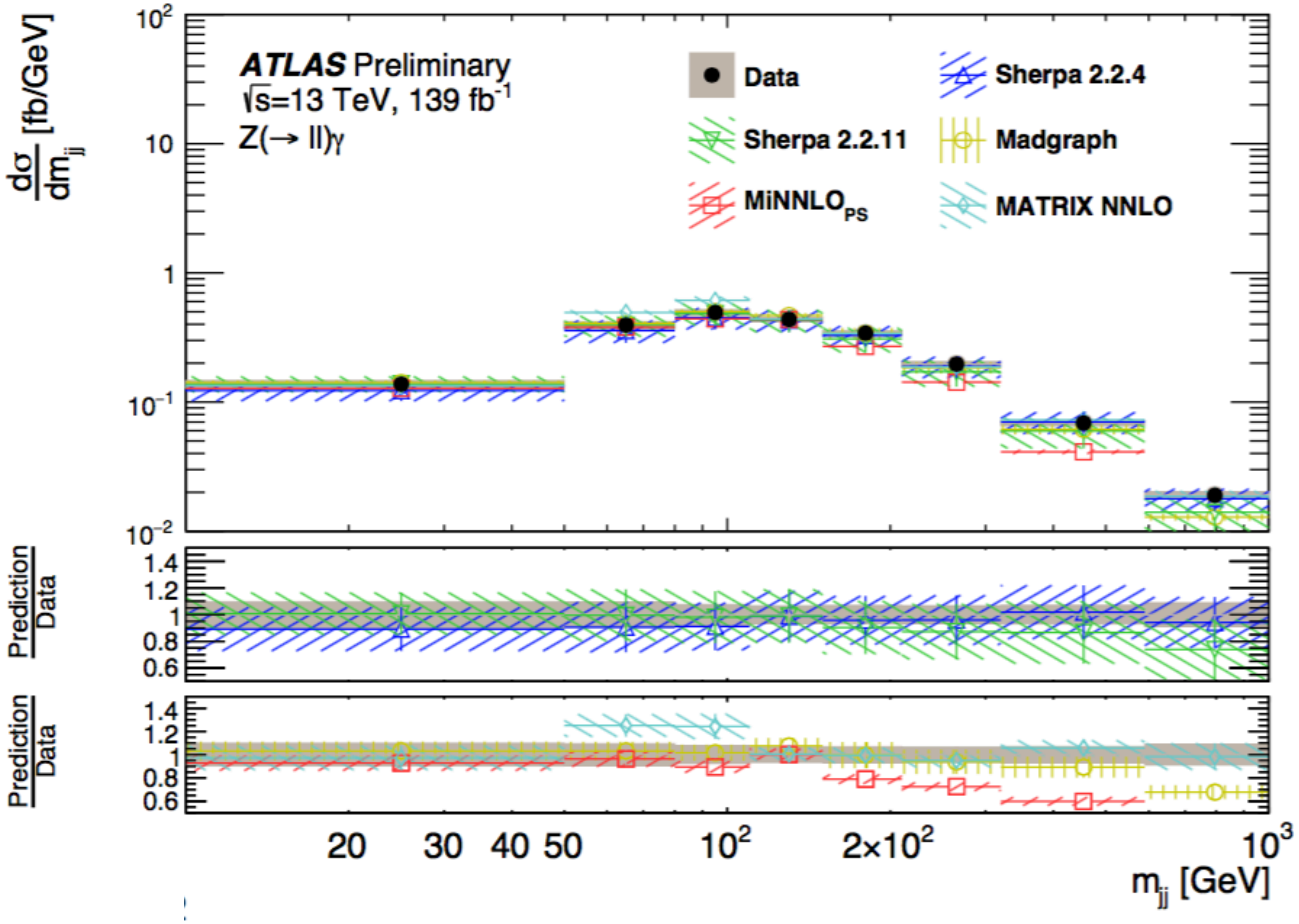
PRD 105 (2022) 052003

ATLAS Z+gamma



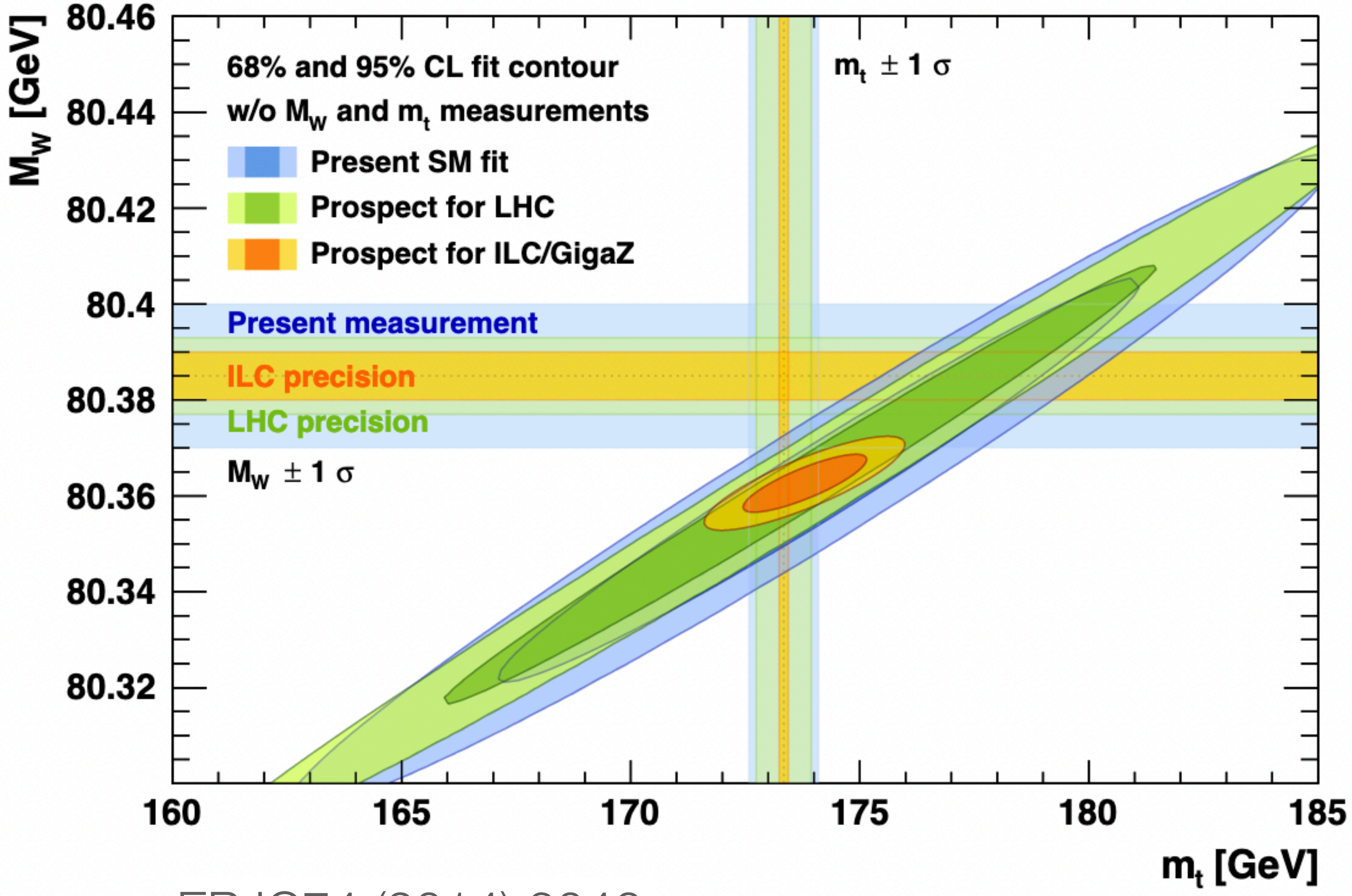
- ATLAS measurement of Zgamma+jets using full Run2 data
  - Reaching 4-10% uncertainties
  - Selection enriched in QED ISR





ATLAS-CONF-2022-047

Standard Model at the LHC: the future



EPJC74 (2014) 3046

Parameter	Current precision	HL-LHC expected
m_H	170 MeV	10-20 MeV
$\sin^2\theta_{eff}$	50 10^{-5}	15 10^{-5}
m_W	20 MeV	4 MeV
m_t^{MC}	500 MeV	200 MeV
m_t^{pole}	~1 GeV	< 500 MeV
$\alpha_S(m_Z)$	~2%	~1%

Summary

* Remarkable opportunities for precision physics at the LHC

* Mounting precision allows for **stringent SM tests** which can (and start to) **surpass the LEP/Tevatron** legacy

* Many **novel ideas and methodologies** that are/will be pursued, also with the coming datasets

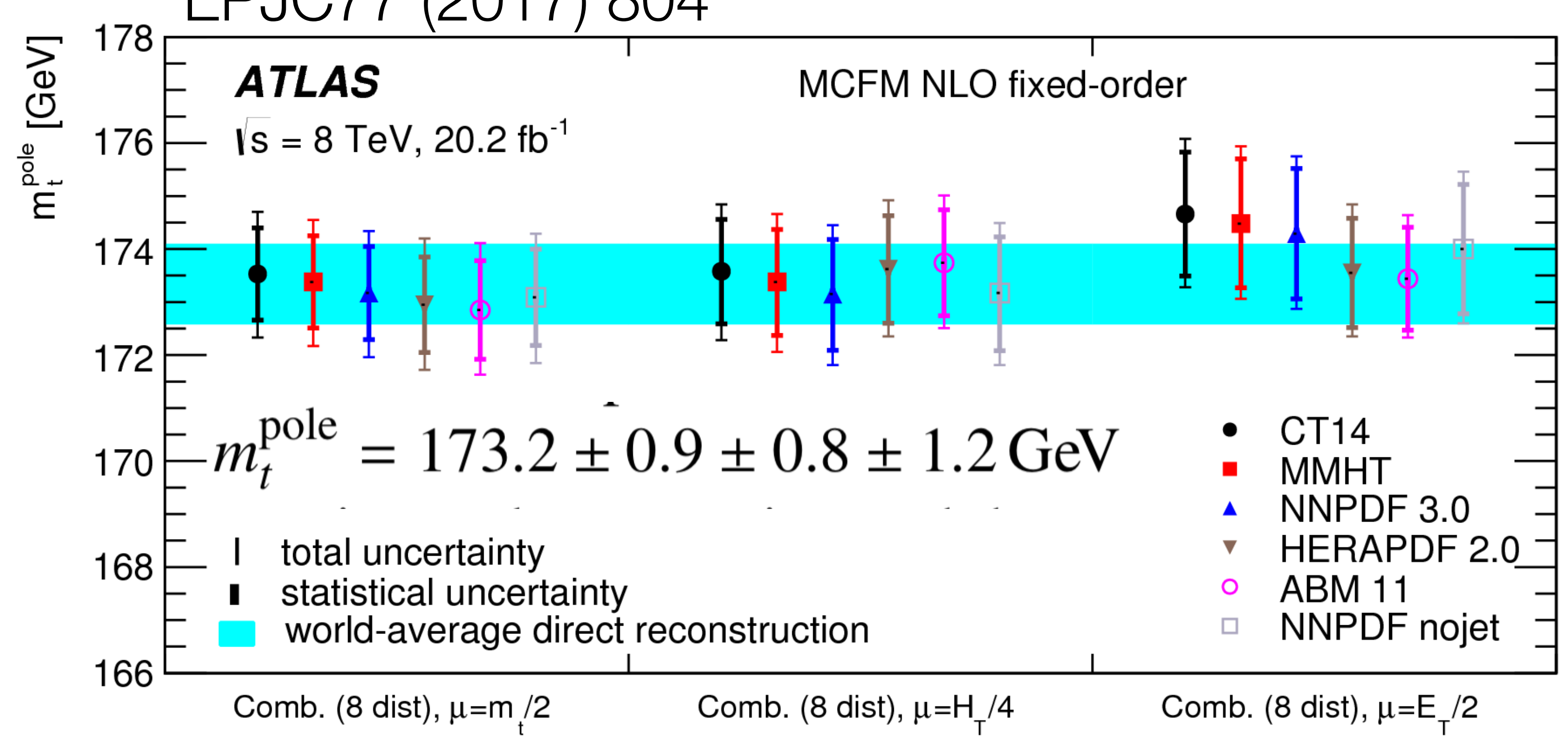
* Theory uncertainties and knowledge of PDFs main bottlenecks for future improvements

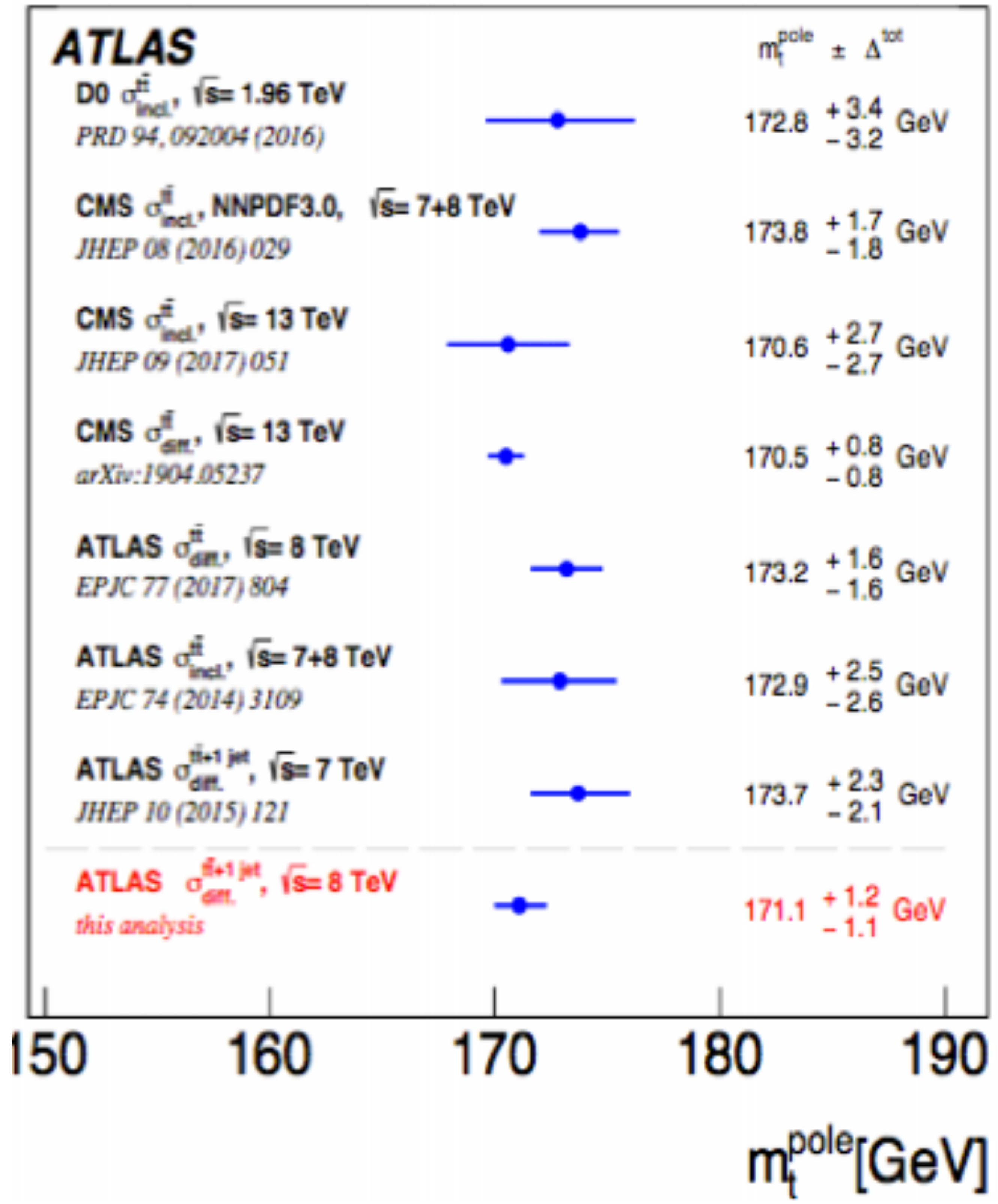
Backup

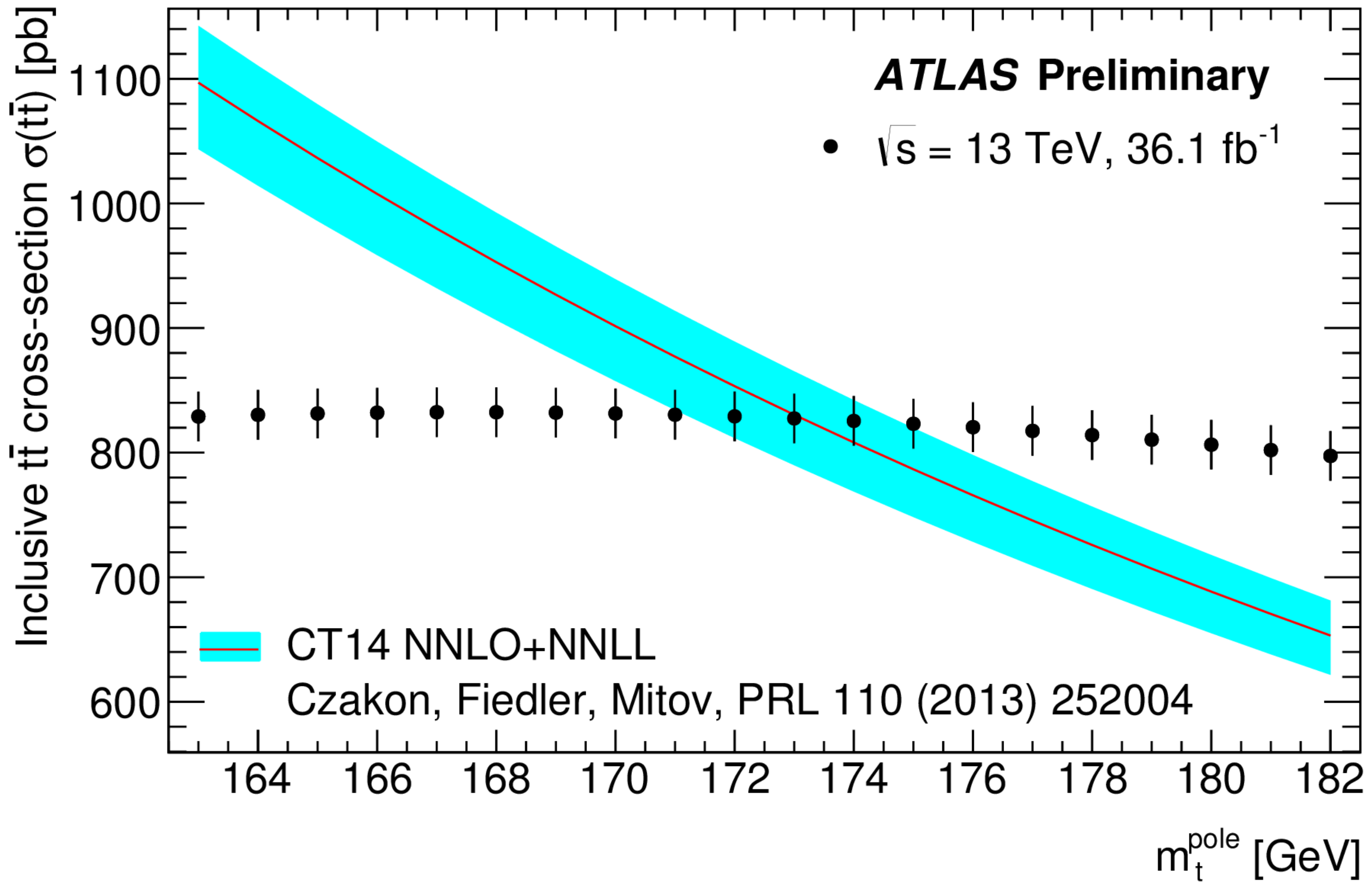
Indirect measurements

- Lepton differential distributions at 8TeV can achieve a very precise measurement of the pole mass and simultaneously constrain PDFs

EPJC77 (2017) 804



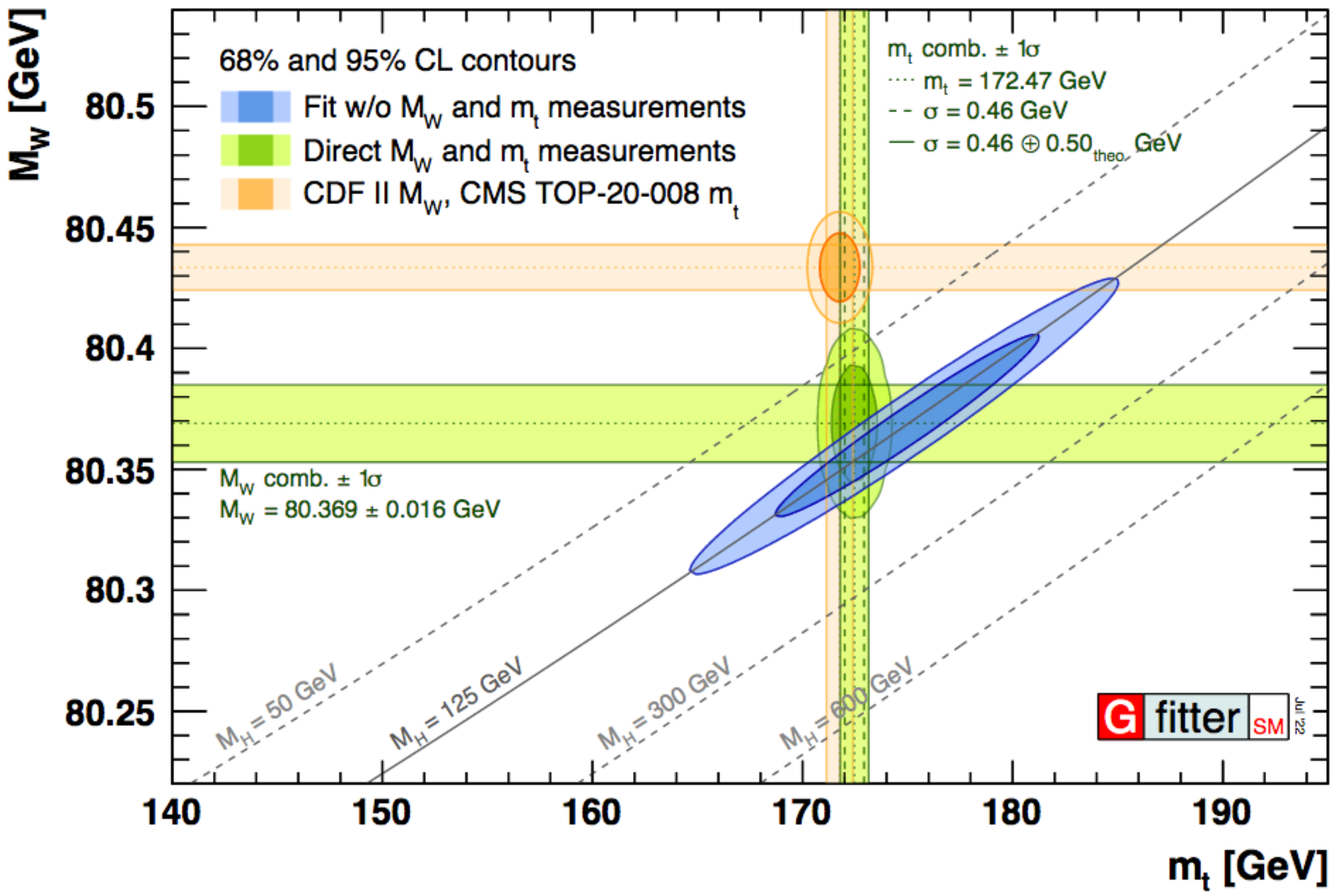




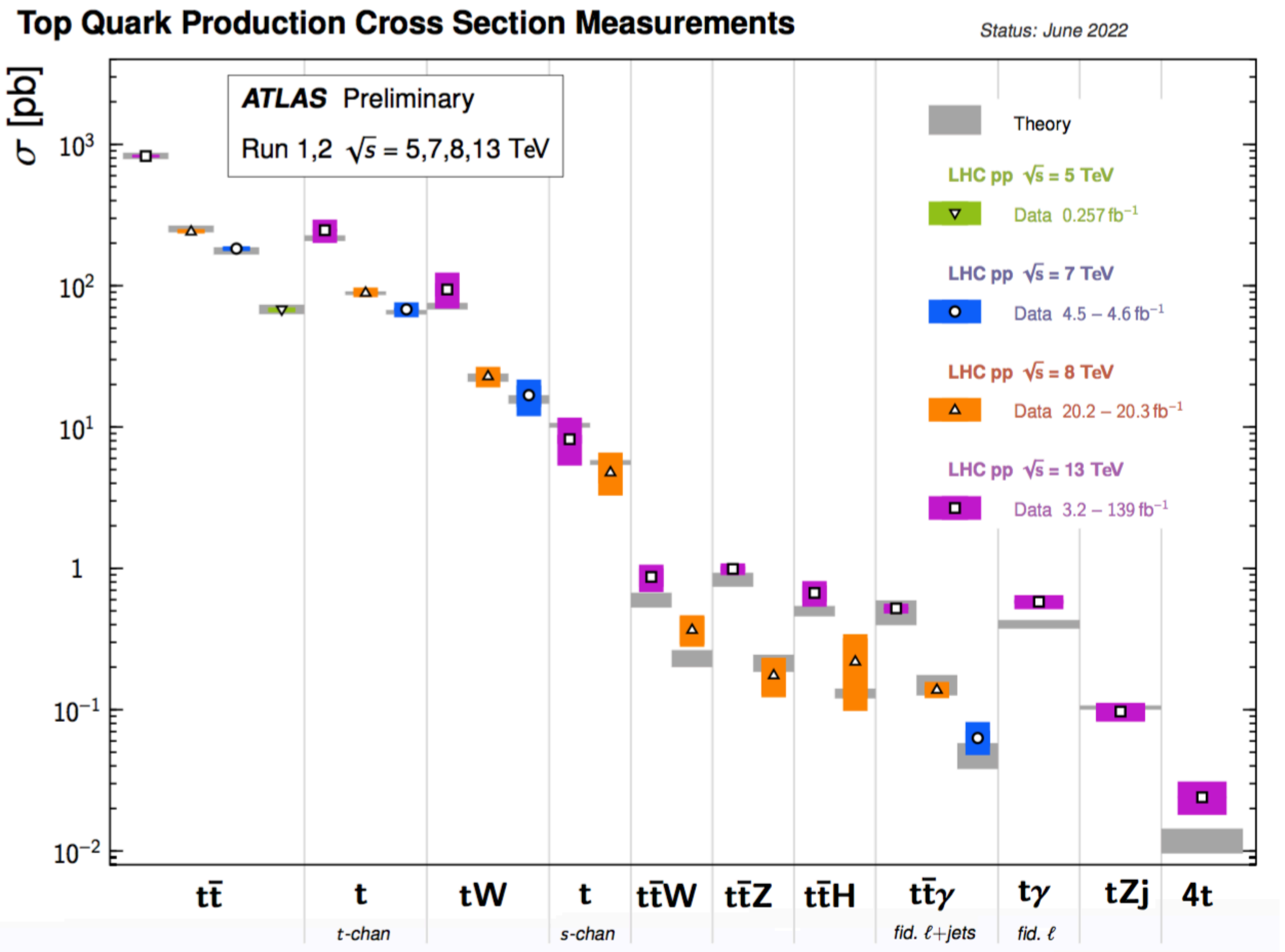
- Dominated by data statistics and lepton systematics after constraining theory scales
- New 13 TeV measurement using inclusive σ(tt) and NNLO+NNLL theory achieves

$$m_t^{\text{pole}} = 173.1^{+2.0}_{-2.1}\ \text{GeV} \qquad (1.15\%)$$

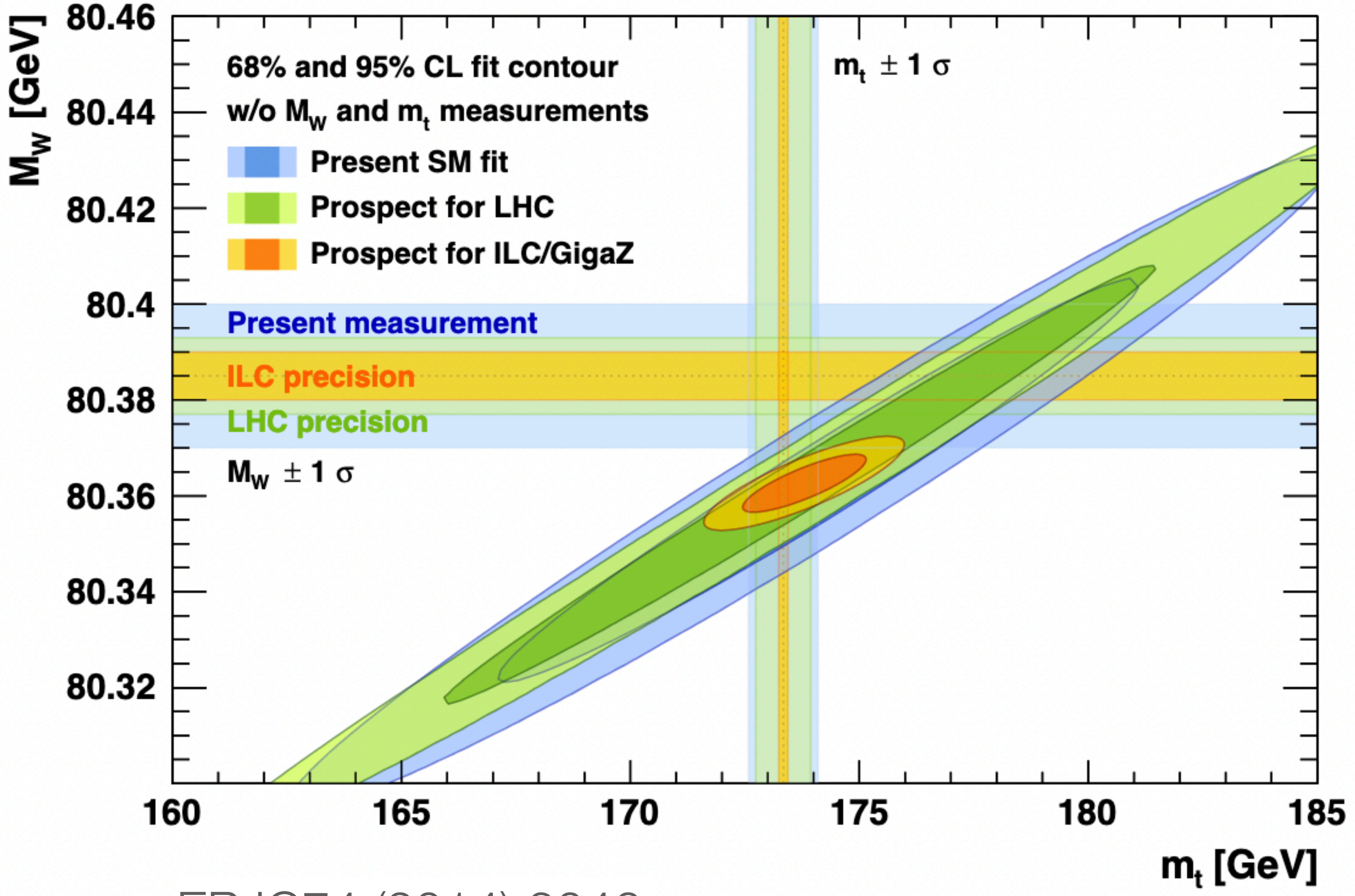
Ttbar cross-sections (dileptonic)



Ttbar cross-sections



Precision prospects for HL-LHC



EPJC74 (2014) 3046

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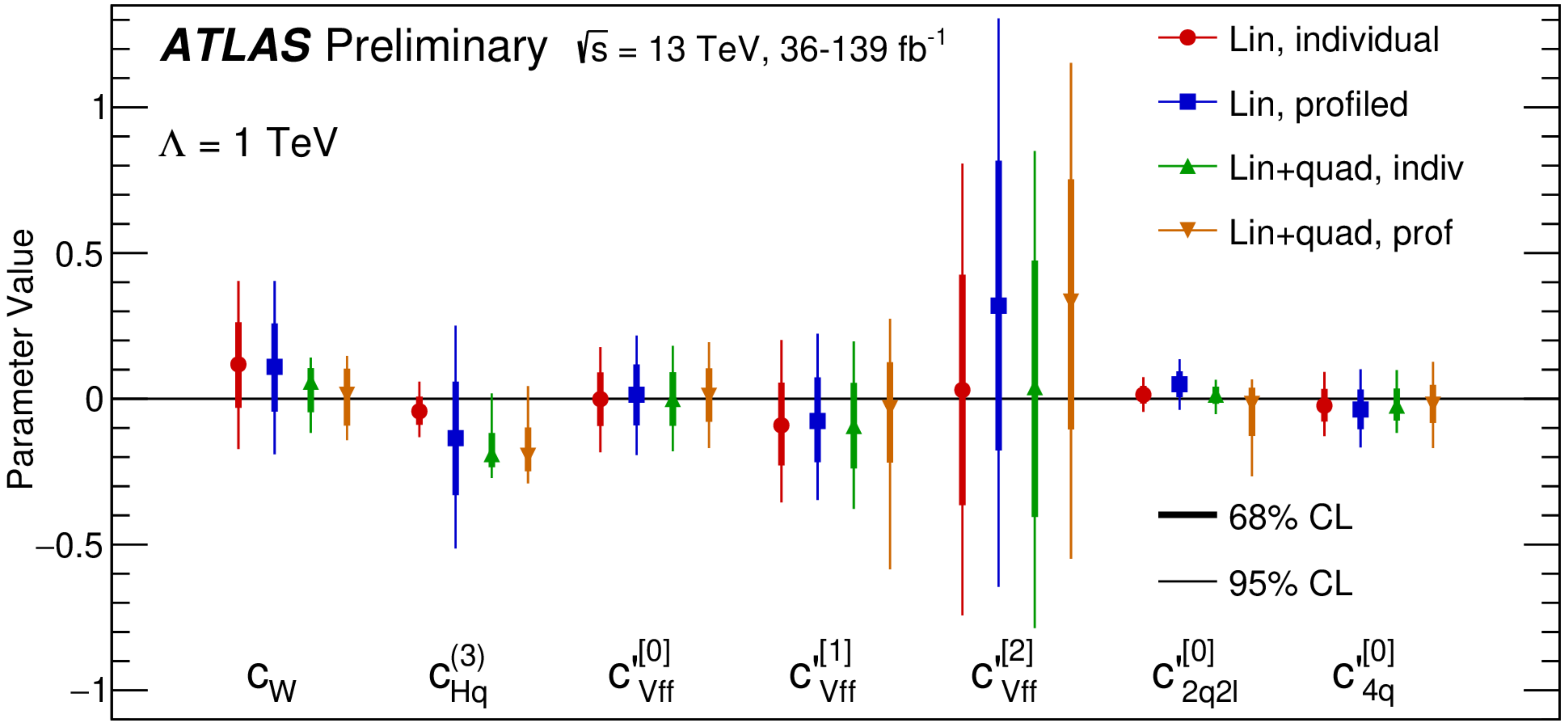
m_t^{pole}	~1 GeV	< 500 MeV
$\alpha_S(m_Z)$	~2%	~1%

ATLAS diboson EFT Combination

- ATLAS combined fit of WW, WZ, 4l, and VBF Z measurements : **6 differential inputs**
- First step towards global EFT interpretations



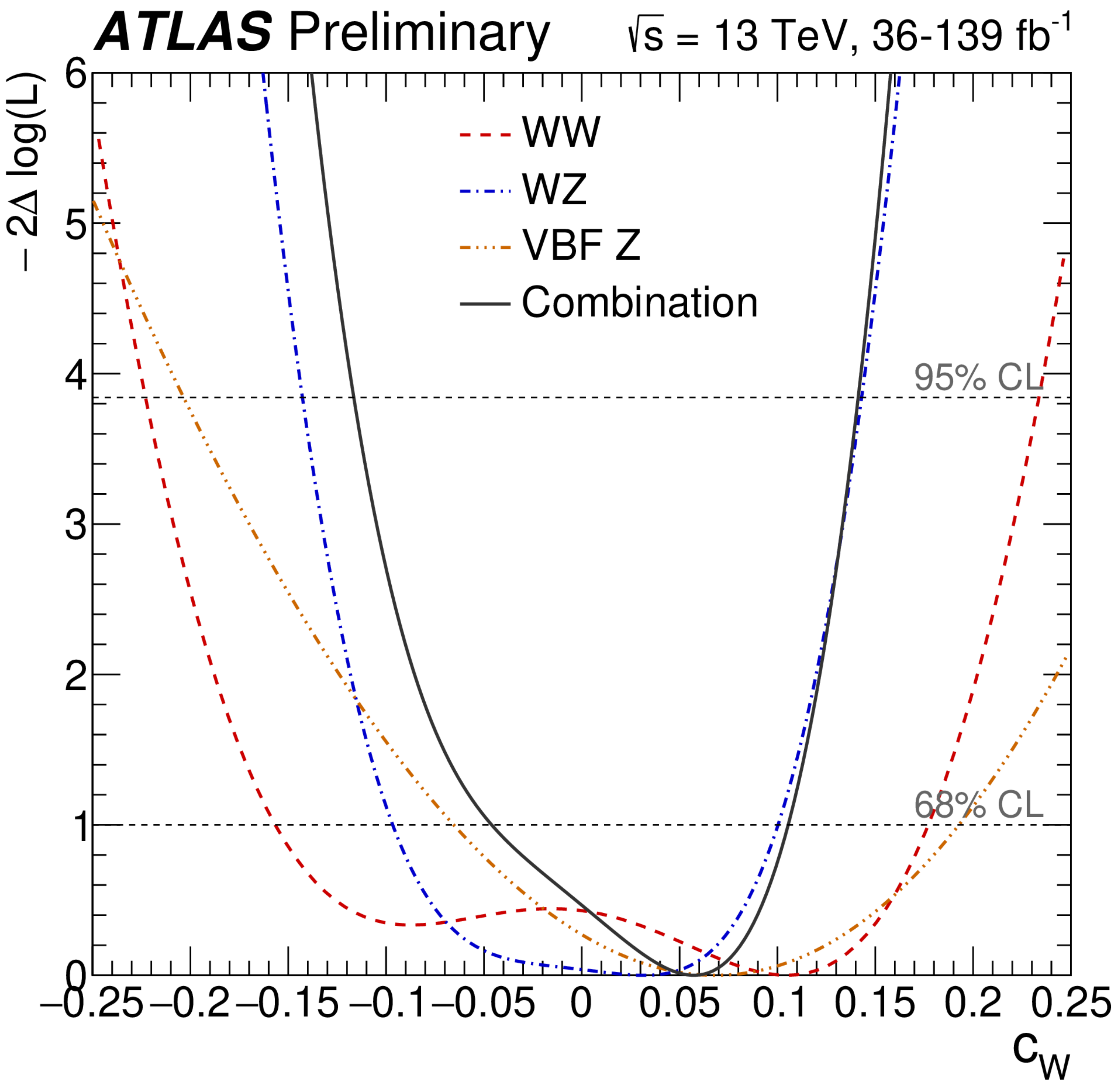
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

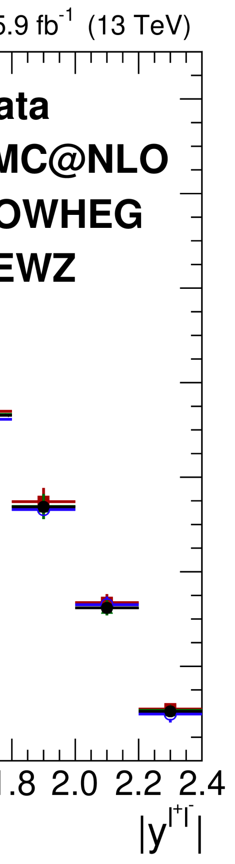
$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

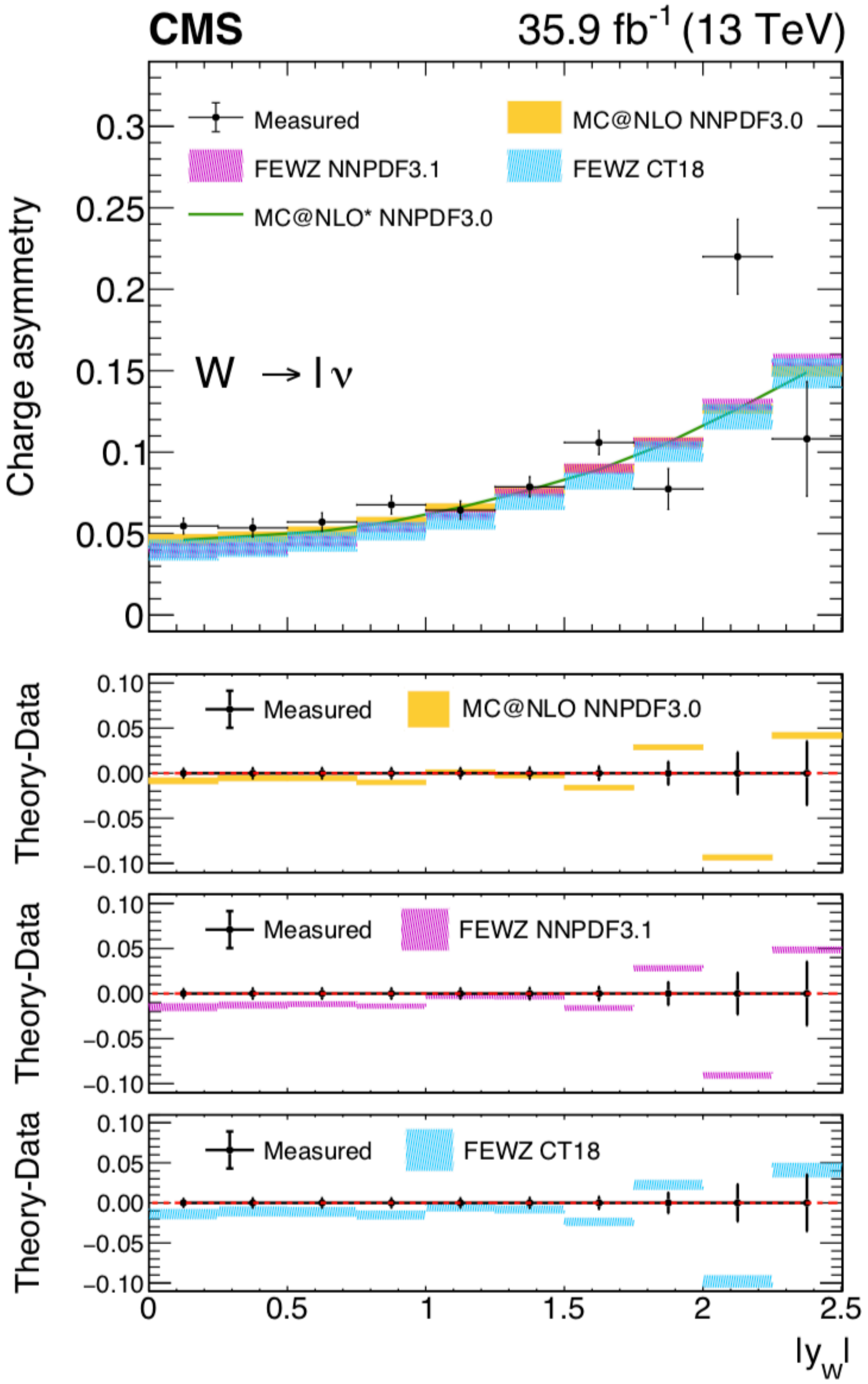
$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$





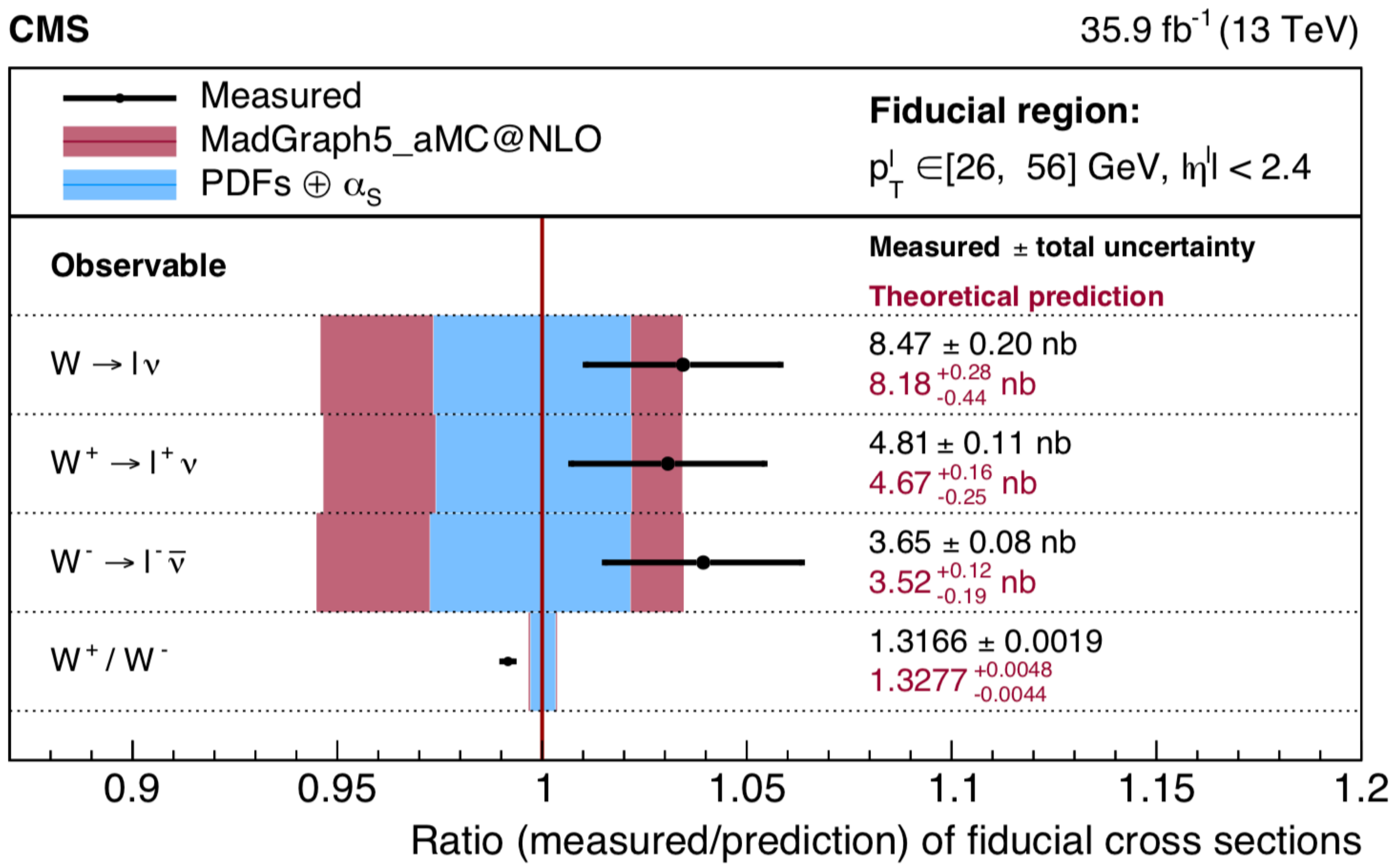
W polarisation at 13 TeV

- Novel CMS measurement of differential cross-sections and charge asymmetry for the two W helicity states



- Cross-sections measured as a function of p_T^l and η^l
- Integrated W cross-sections and charge asymmetry sensitive to valence quark PDFs

$$A_W \sim \frac{u_V(x_0) - d_V(x_0)}{u(x_0) + d(x_0)}$$



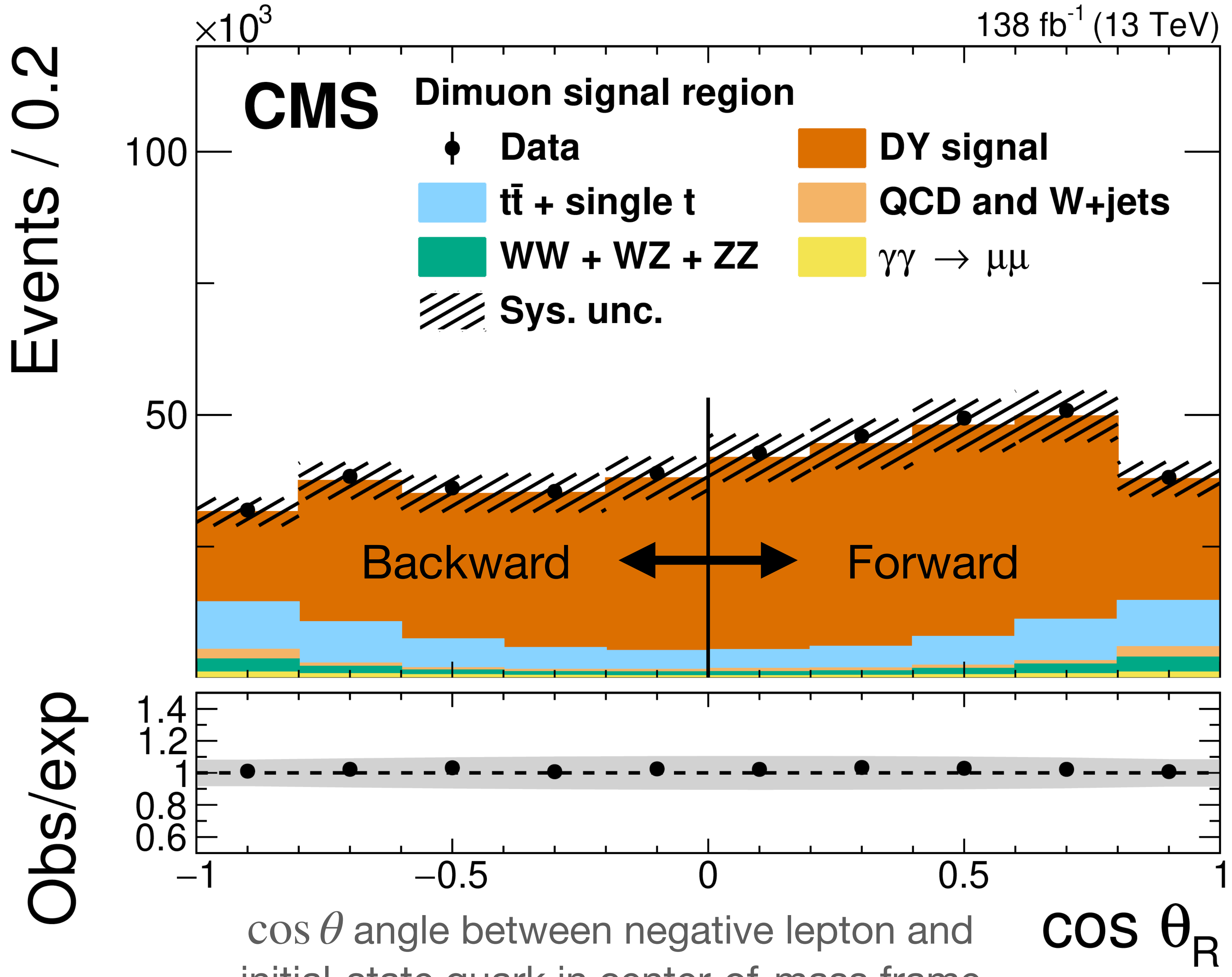
2008.04174, accepted by PRD

HIGH-MASS AFB IN $Z \to l^+l^-$

- Forward-backward asymmetry in Drell-Yan probe of the V-A structure of weak interactions
  - At high-masses, probe extra massive gauge bosons

Forward-Backward asymmetry:

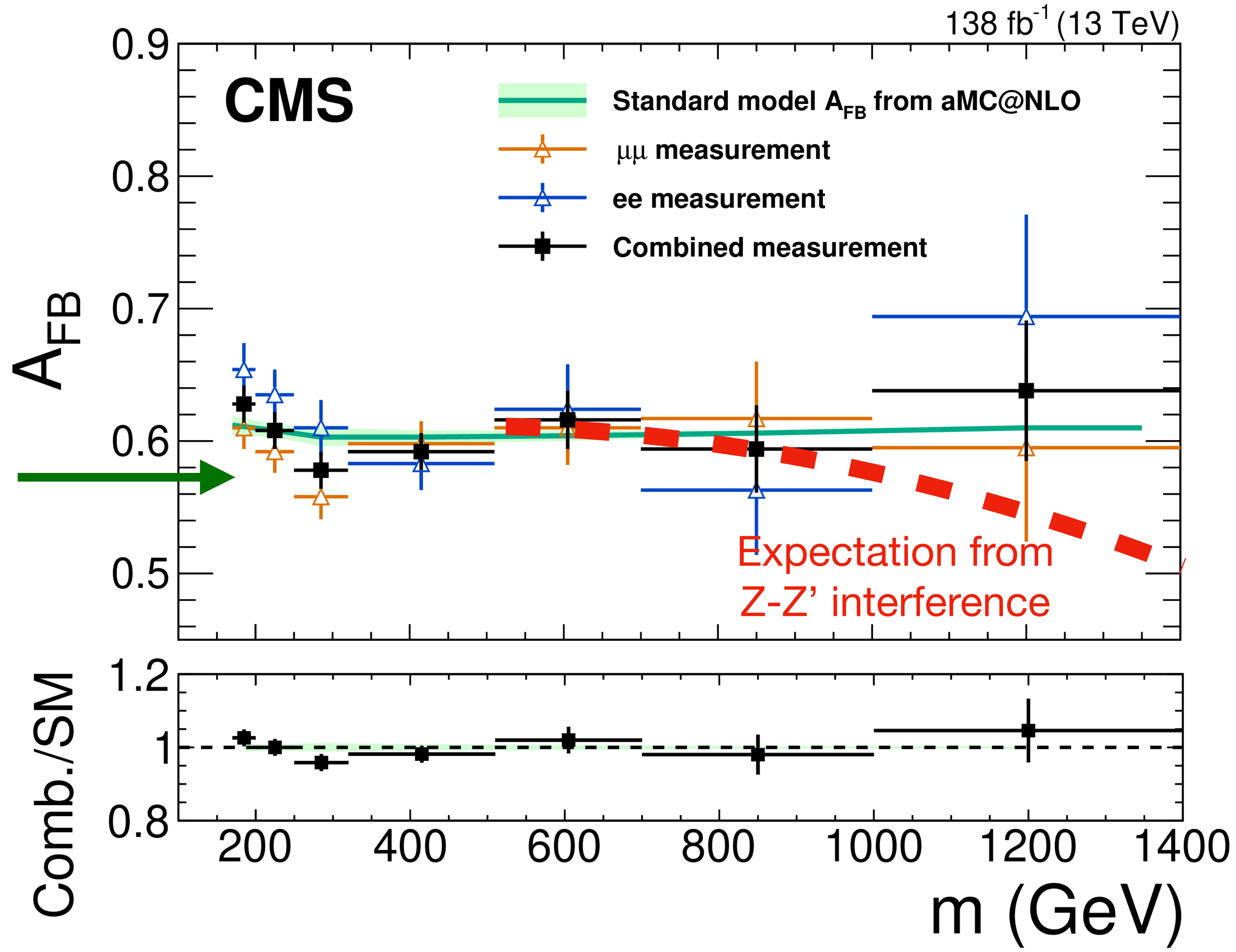
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



$\cos\theta$ angle between negative lepton and initial-state quark in center-of-mass frame

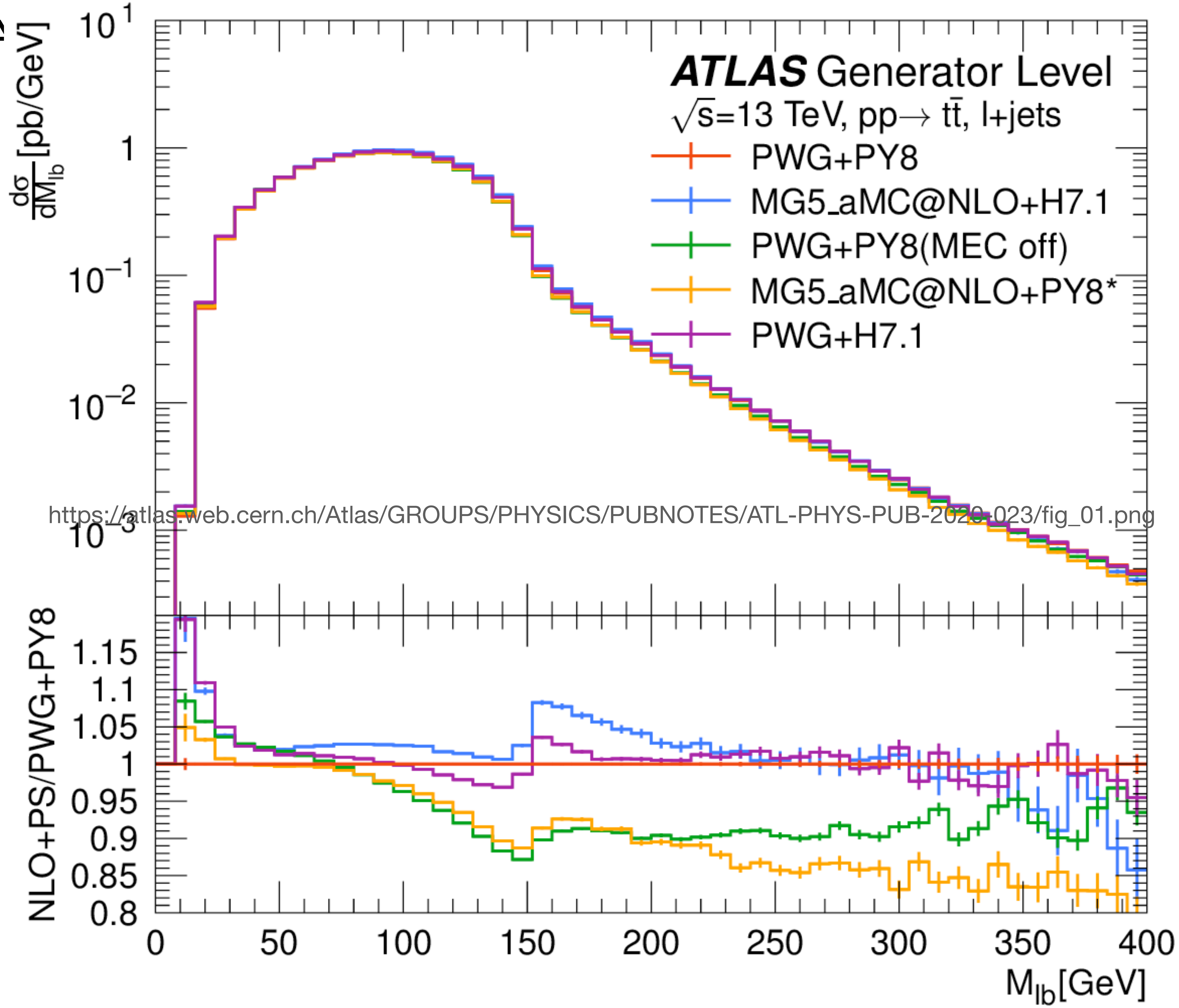
Submitted to J. High Energy Phys.

AFB positive at high-mass due to γ^*/Z interference

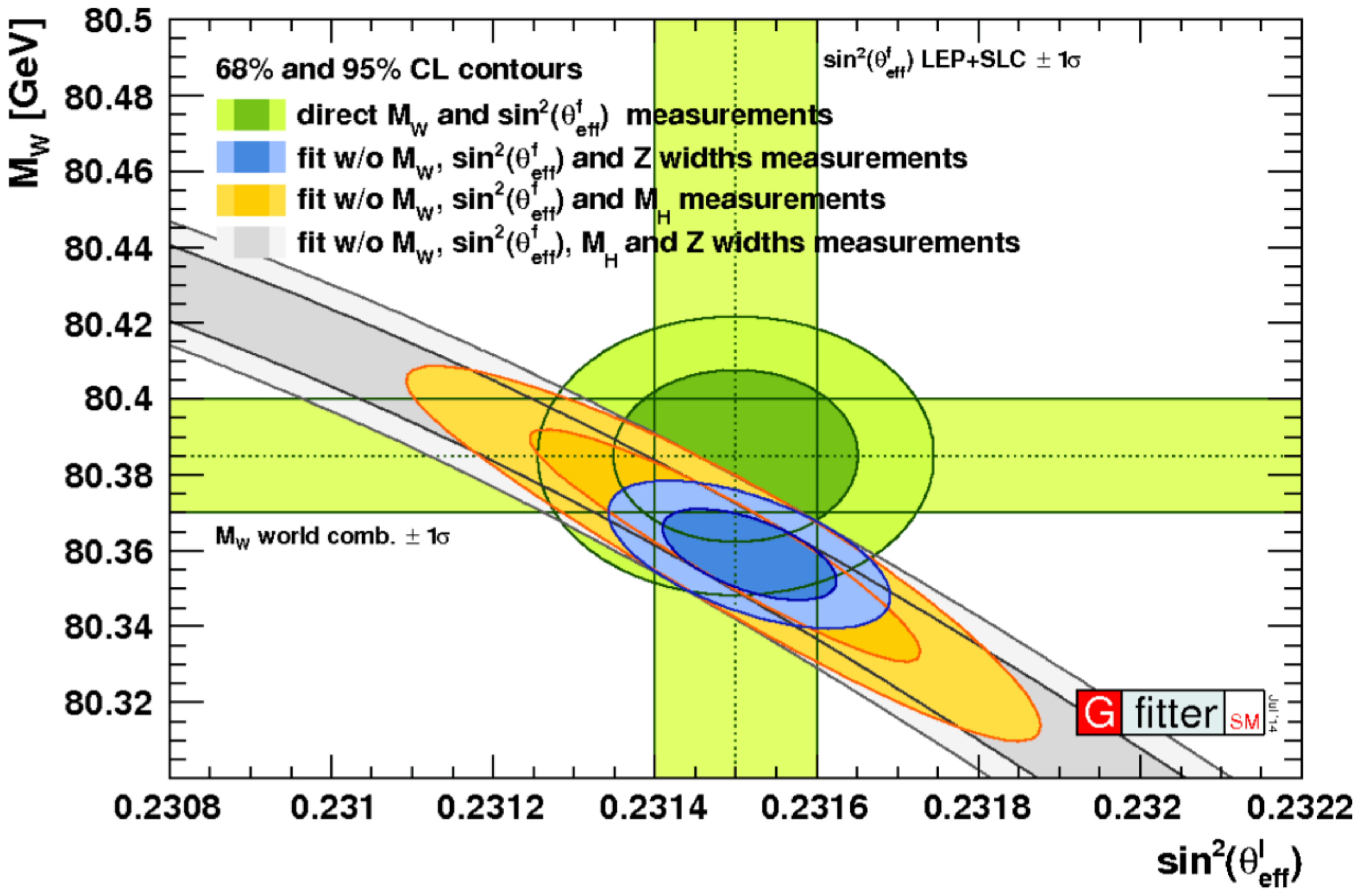


- Measurement in agreement with NLO QCD
- Derive limits on Z' in the Sequential SM
  - Excludes $m_{Z'} < 4.4$ TeV at 95% CL
  - Comparable with ~ 5 TeV from direct searches

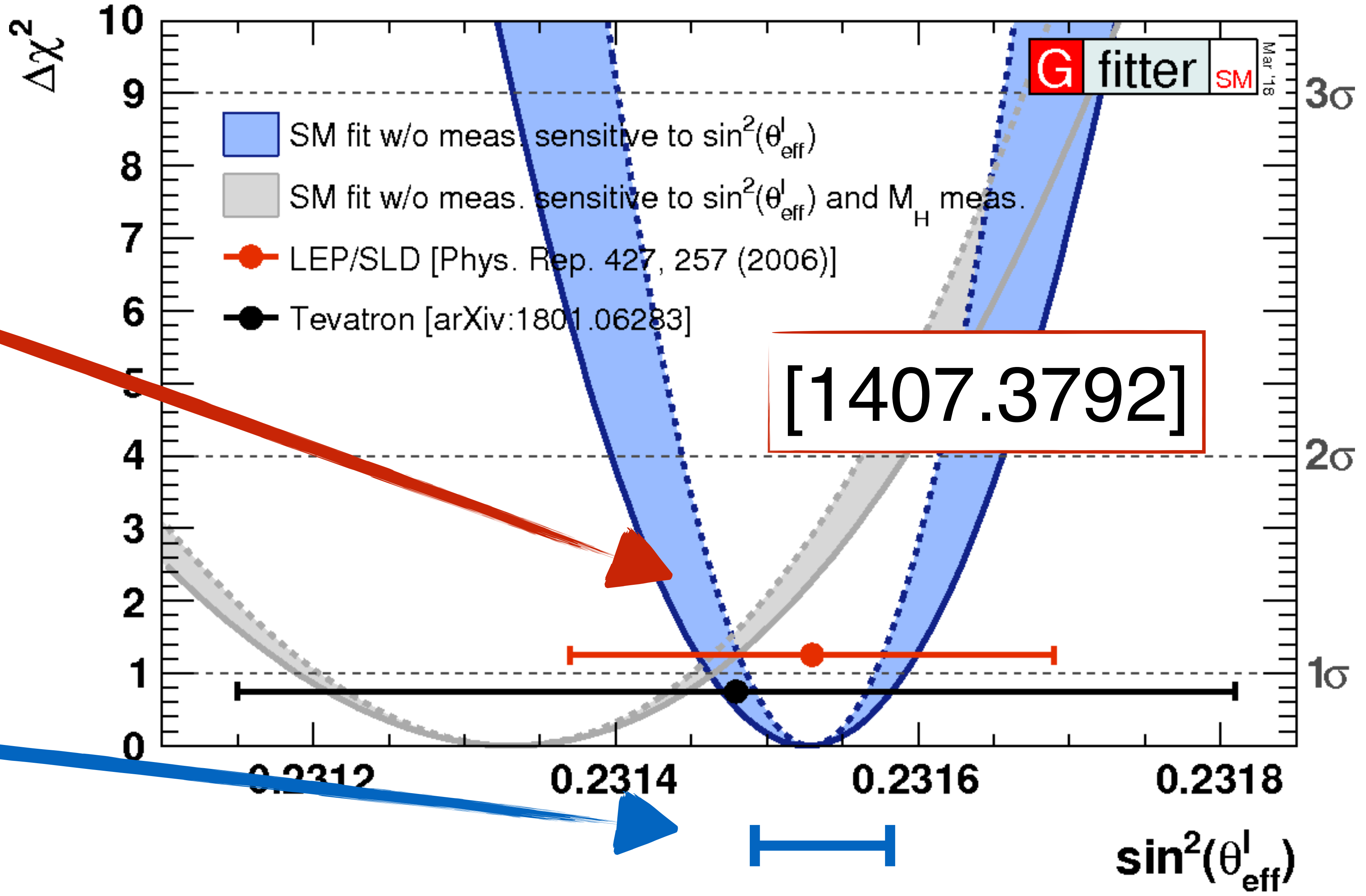
W-MA


ATLAS Generator Level
$\sqrt{s}$=13 TeV, pp→ $t\bar{t}$, l+jets
PWG+PY8
MG5_aMC@NLO+H7.1
PWG+PY8(MEC off)
MG5_aMC@NLO+PY8*
PWG+H7.1
$\frac{d\sigma}{dM_{lb}}$ [pb/GeV]
NLO+PS/PWG+PY8
M_{lb}[GeV]
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-023/fig_01.png

The weak mixing angle

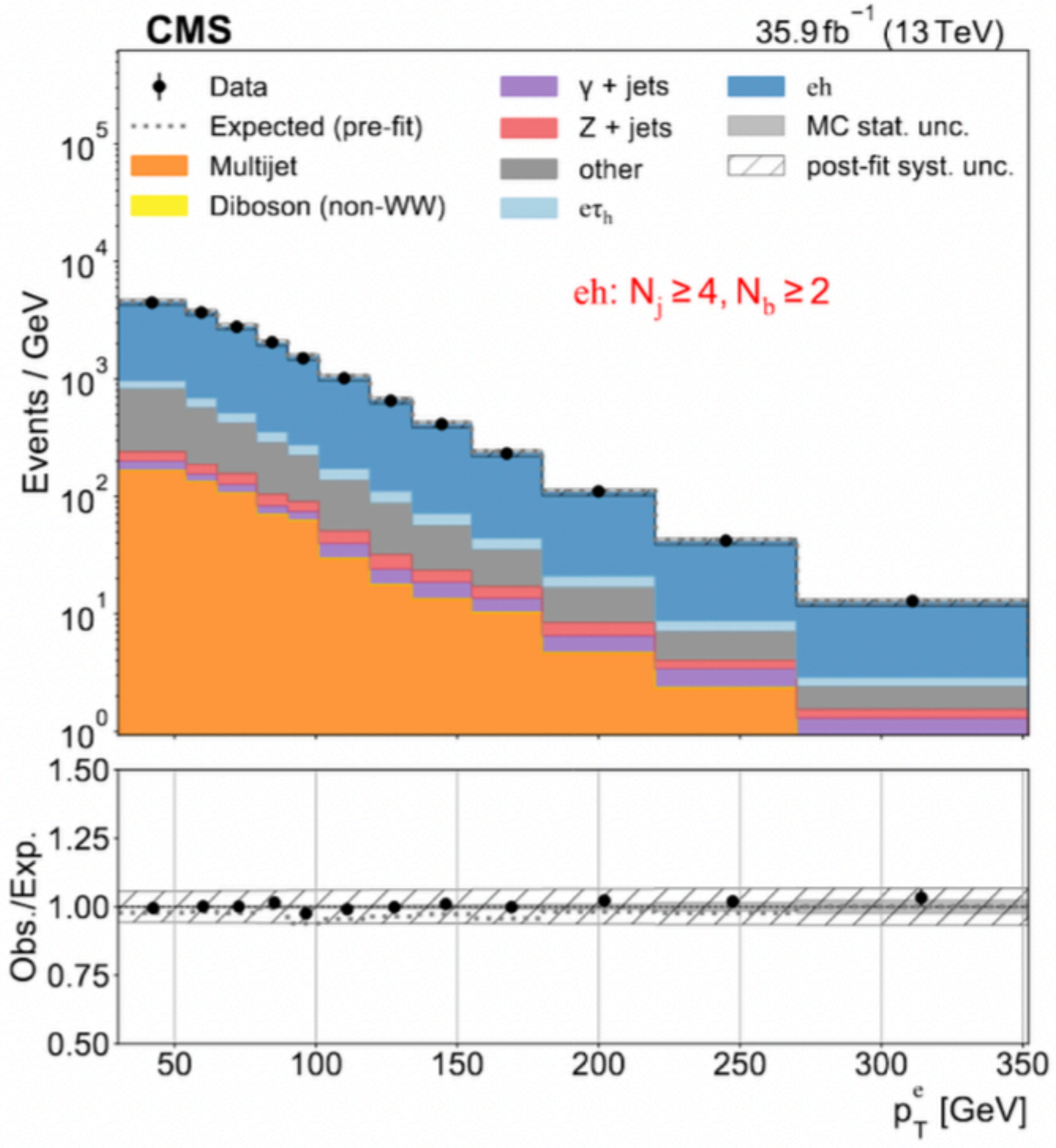


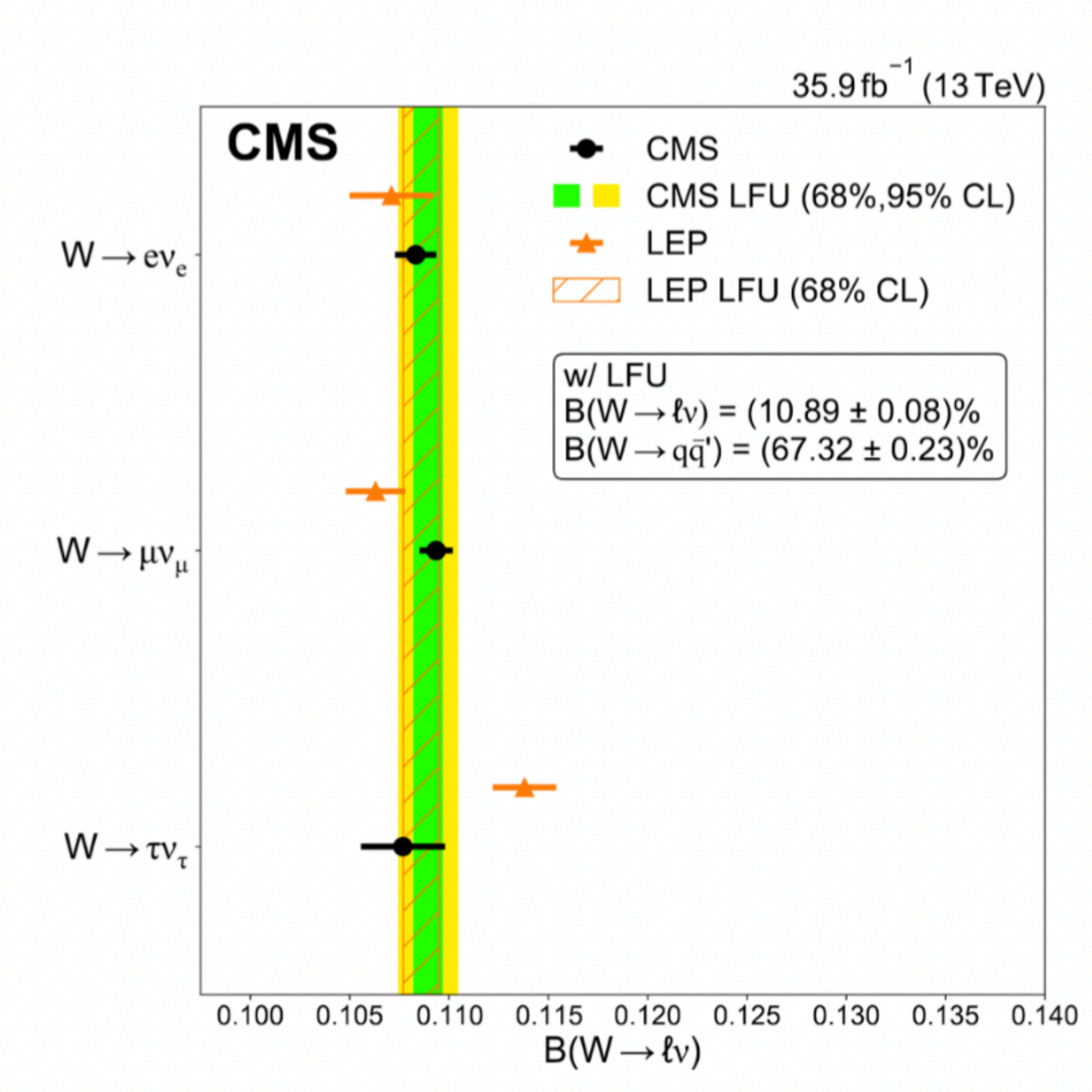
- The weak mixing angle in the SM parametrises the mixing between the EM and weak fields
- And provide and indirect determination of the W-boson mass
- Direct measurements have an average precision of ~16x10^-5
- Removing the direct measurements the indirect determination has a precision of ~6x10^-5



CMS W branching fractions

- Maximum likelihood fit using templates
  - Categories based on numbers of leptons, jets, b-jets
  - tW and WW processes considered as part of the signal
  - Kinematic discriminant in each category used to separate





$$\frac{\mathcal{B}(\mathrm{W}\to \mathrm{q\bar{q}'})}{1-\mathcal{B}(\mathrm{W}\to \mathrm{q\bar{q}'})} = \sum_{\substack{i=(\mathrm{u,c}),\\ j=(\mathrm{d,s,b})}} |V_{ij}|^2\left[1+\sum_{i=1}^{4} c_i\left(\frac{\alpha_S}{\pi}\right)^i + c_{\mathrm{EW}}(\alpha) + c_{\mathrm{mix}}(\alpha\alpha_S)\right]$$

$\alpha_S(m_W^2)$	$\lvert V_{cs}\rvert$	$\sum_{ij}\lvert V_{ij}\rvert^2$
0.095 ± 0.033	0.967 ± 0.011	1.984 ± 0.021

Accepted by PRD