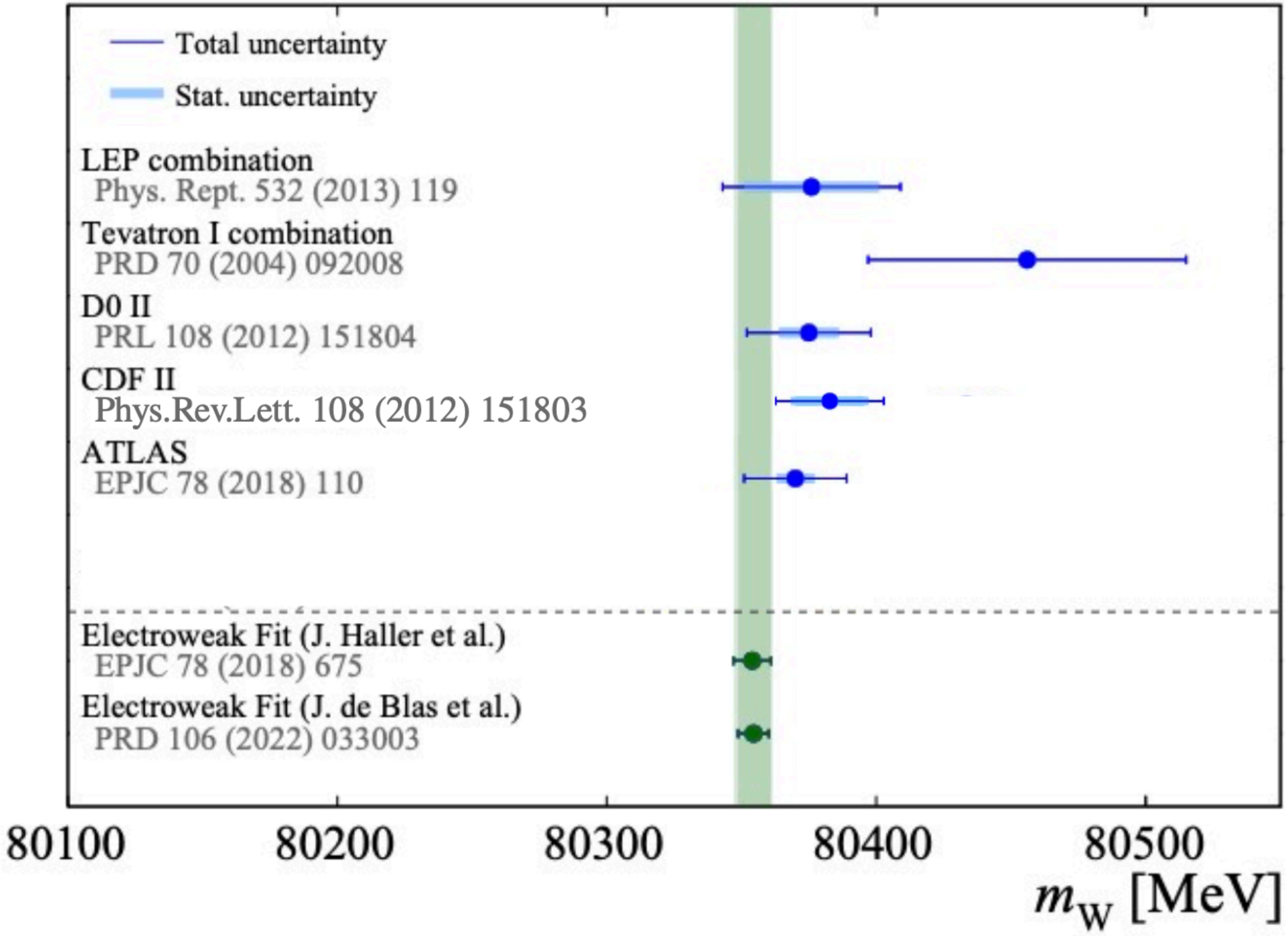
Status of the Tevatron/LHC W-boson mass combination

Standard Model at the LHC, FNAL

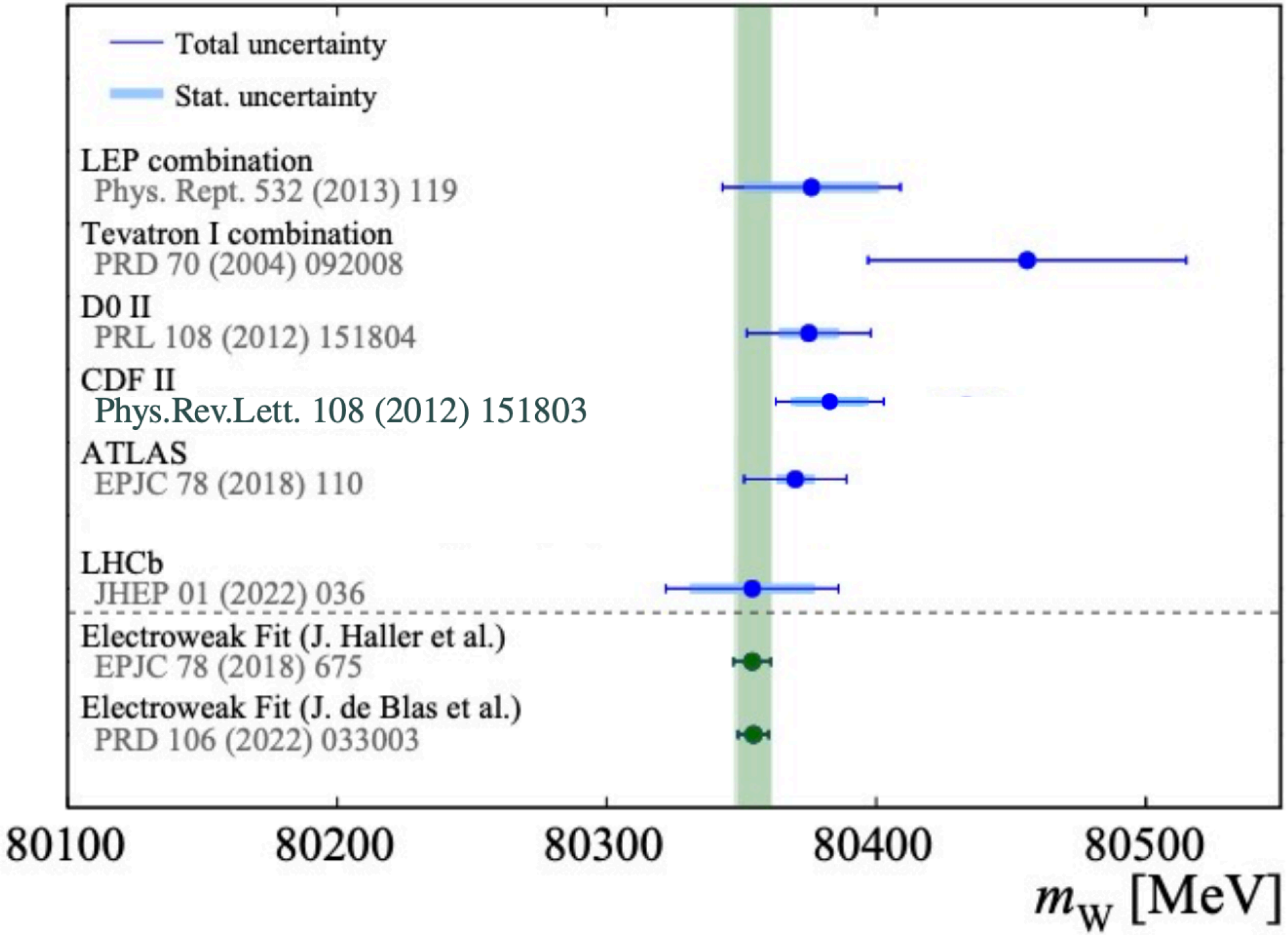
July 13th, 2023

Simone Amoroso (DESY)
for the Tevatron/LHC
mW combination WG

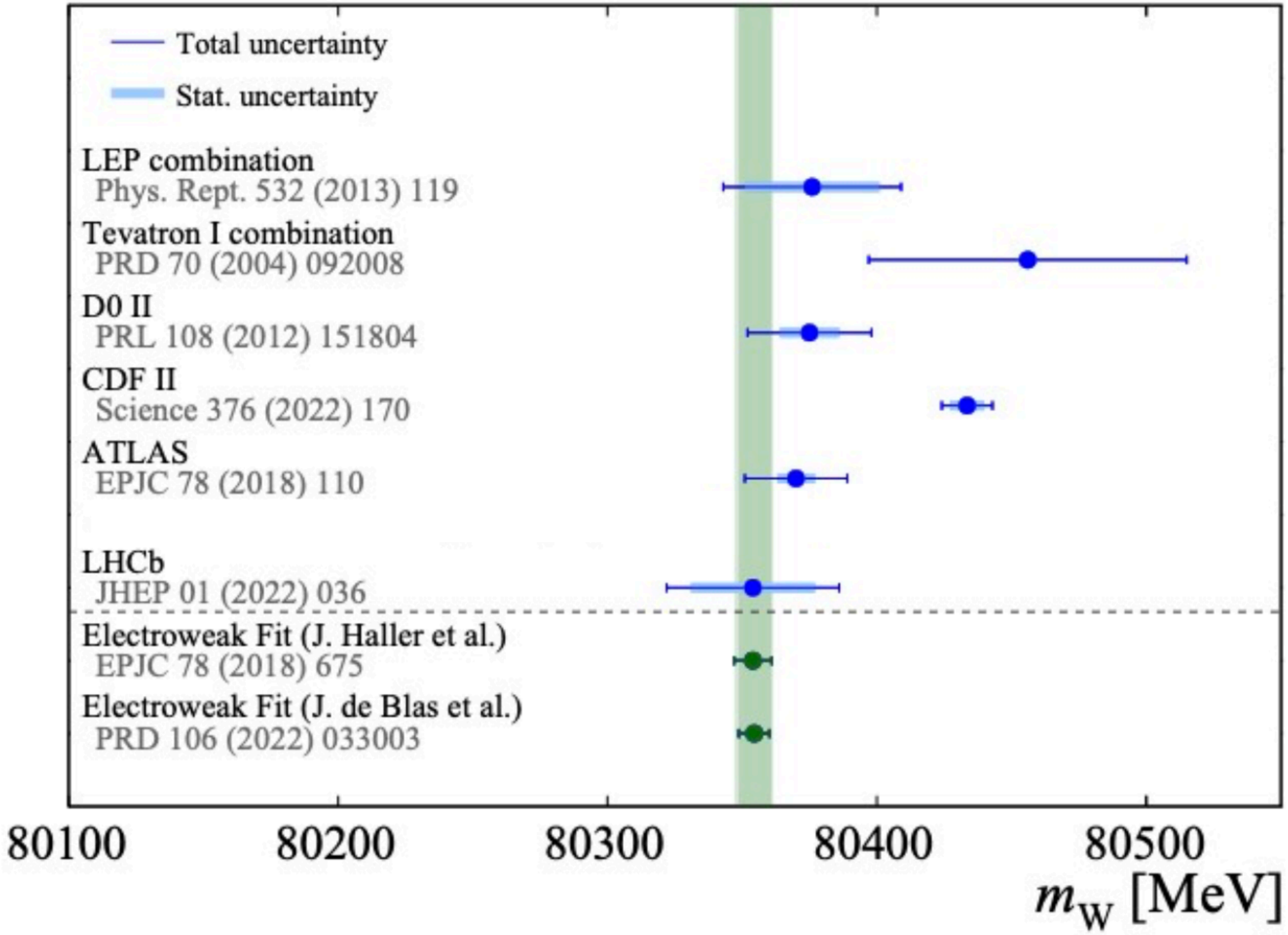
The M_W landscape: 2019-2020



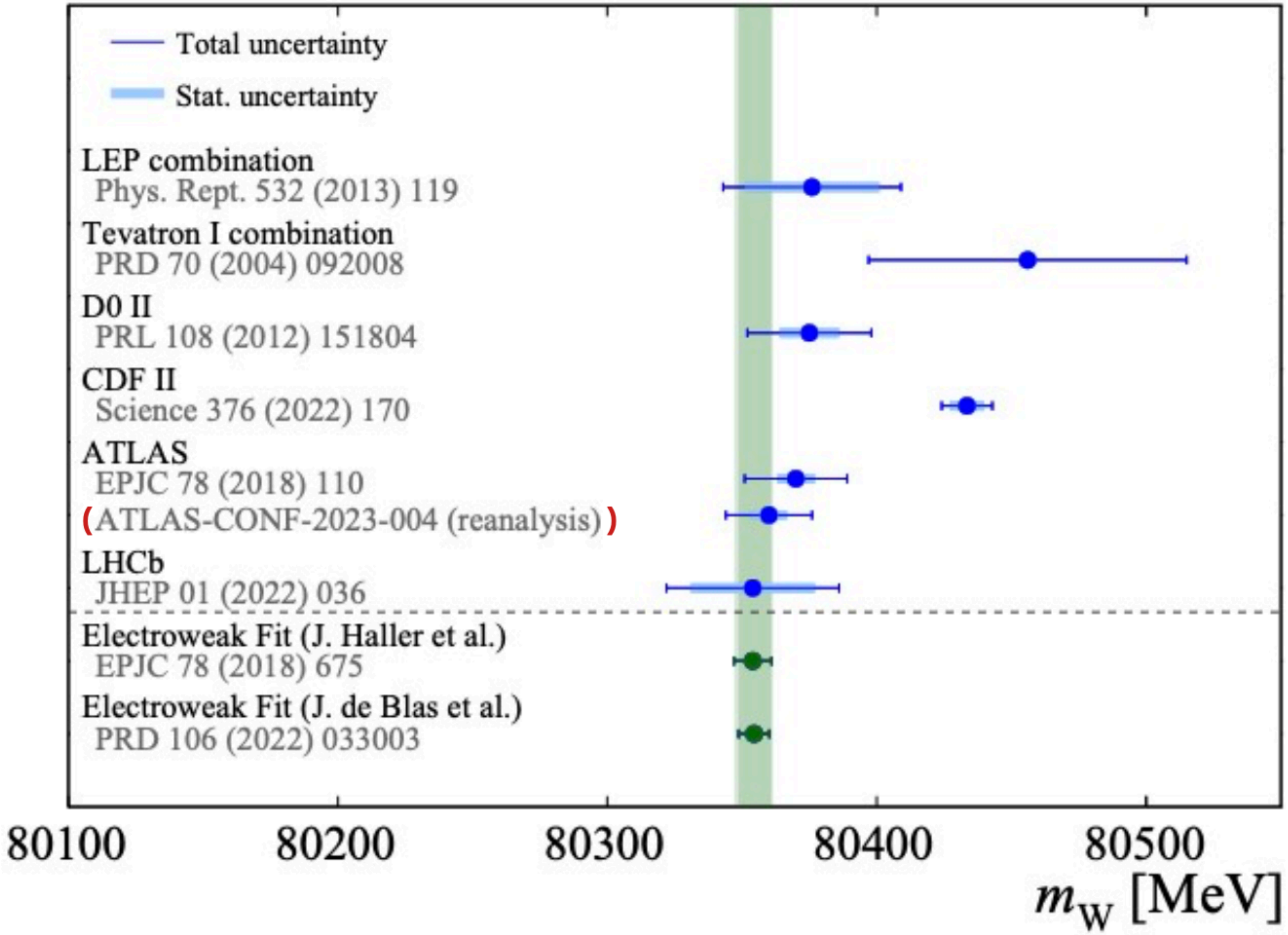
The M_W landscape: 2021



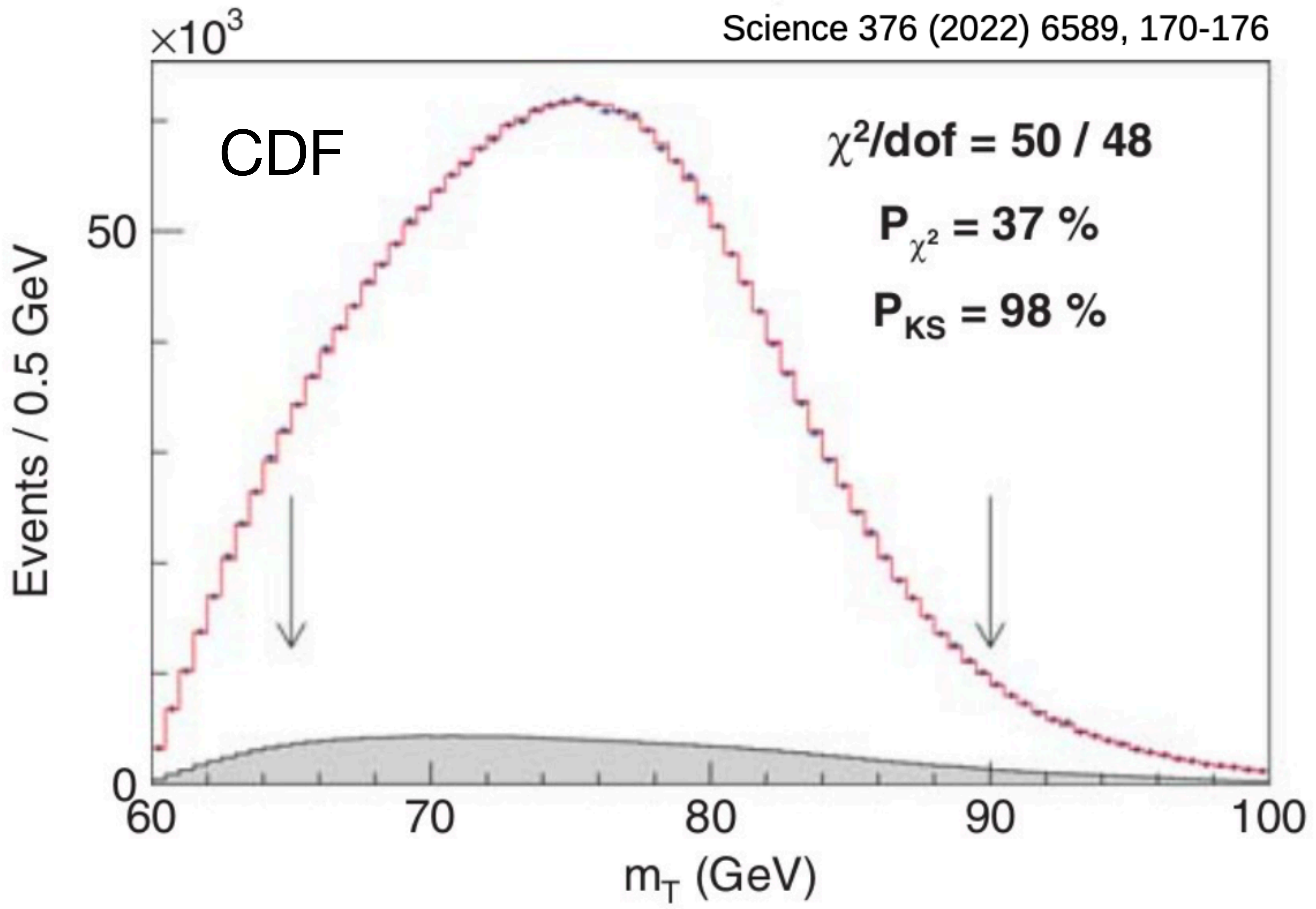
The M_W landscape: 2022

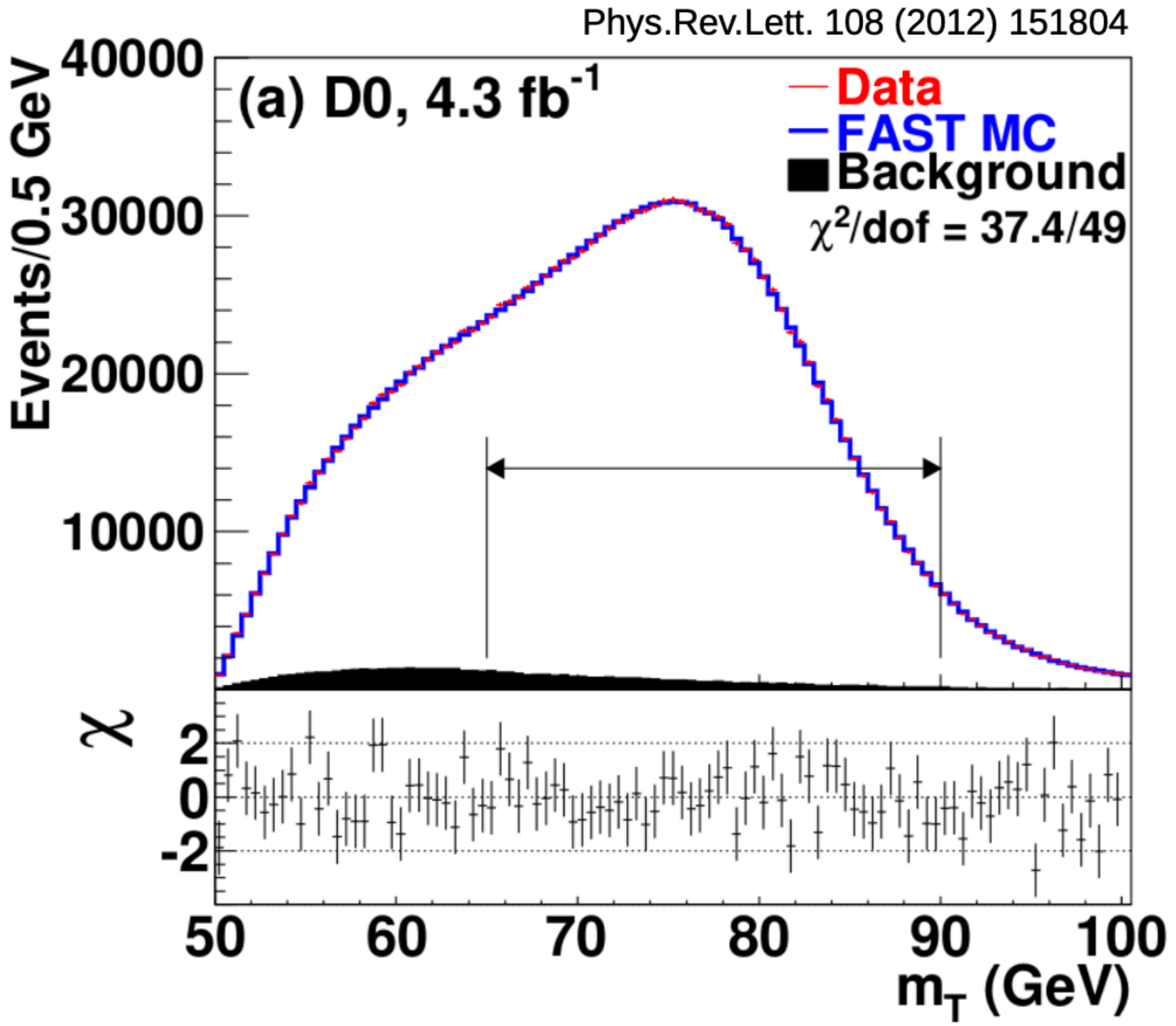


The M_W landscape: 2023



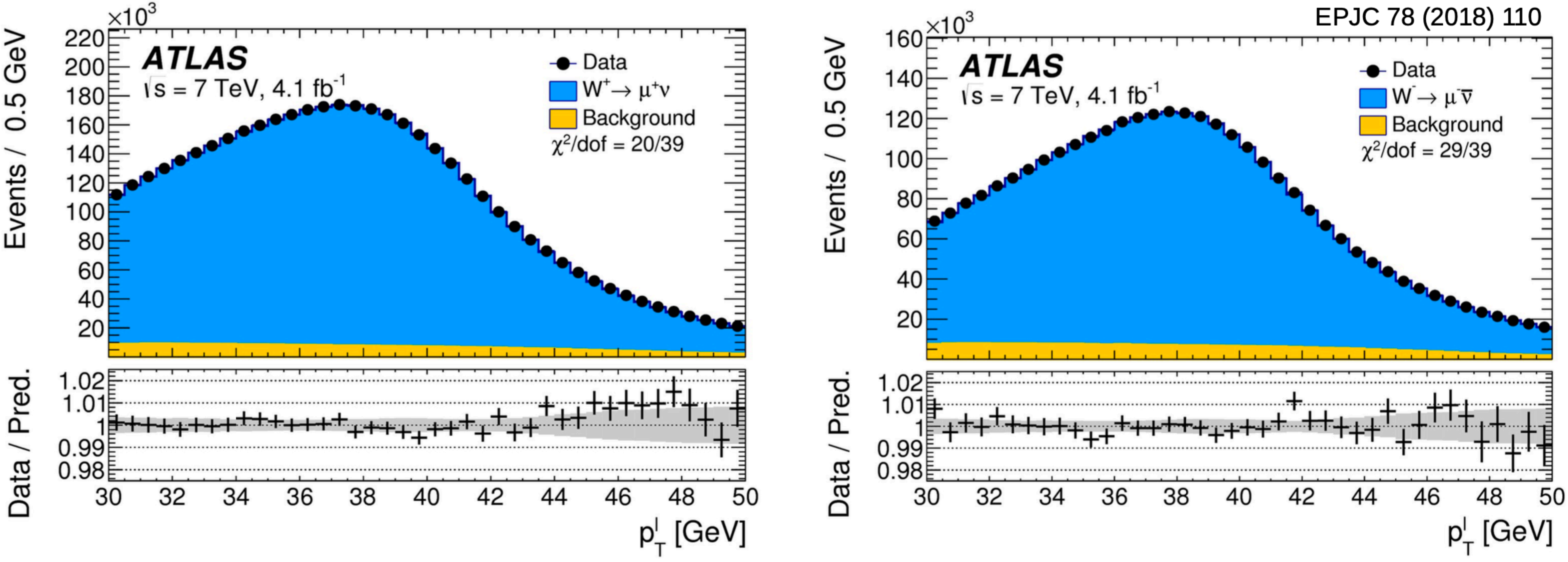
The measurements: CDF, D0





charge-blind p_T, m_T fits (CP-even initial and final states)

The measurements: ATLAS

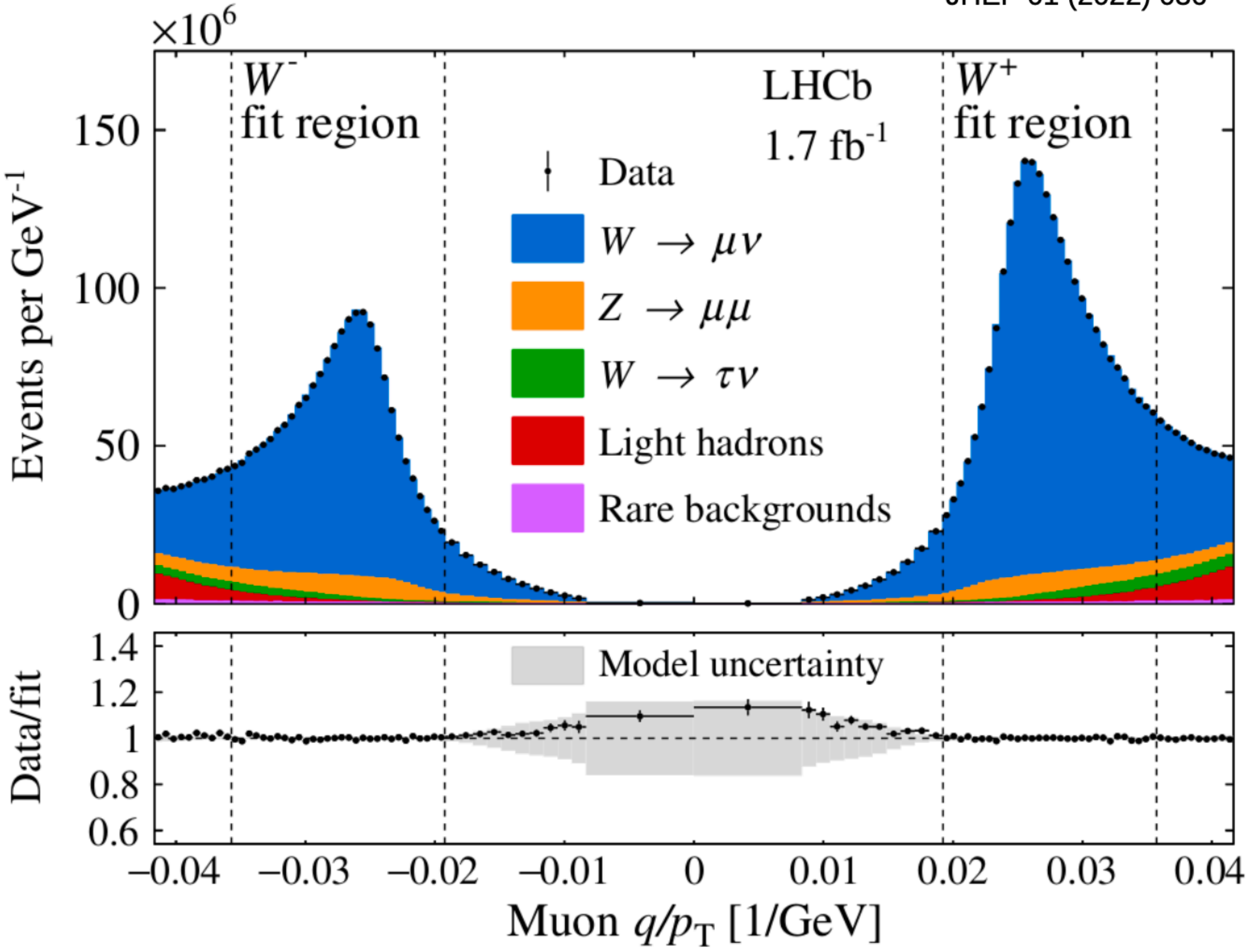


W+ W-

p_T, m_T fits separated by charge in bins of η

The measurements: LHCb

JHEP 01 (2022) 036



Fits to muon charge over p_T

Uncertainties comparison

	D0	CDF (old/new)	ATLAS (old/new)	LHCb
Momentum scale	15	7 / 3	8.4 / 6.8	7
Efficiency	-	- / 0.4	5.0 / 4.0	2
Background	2	3 / 3.3	4.6 / 2.4	2
EW ho	7	4 / 2.7	5.7 / 6.0	9
p_T,Y modelling	2	5 / 2	5.9 / 3.5	11
Ai modeling	-	- / -	5.8 / 3.5	10
PDF	10	10 / 3.9	9.0 / 7.7	9
Total sys.	20	15 / 6.9	17.2 / 15.5	22
Statistical	11	12 / 6.4	7.2 / 4.9	23
Total	23	19 / 9.4	18.7 / 16.3	32

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How correlated these numbers are ?

Aim of our effort

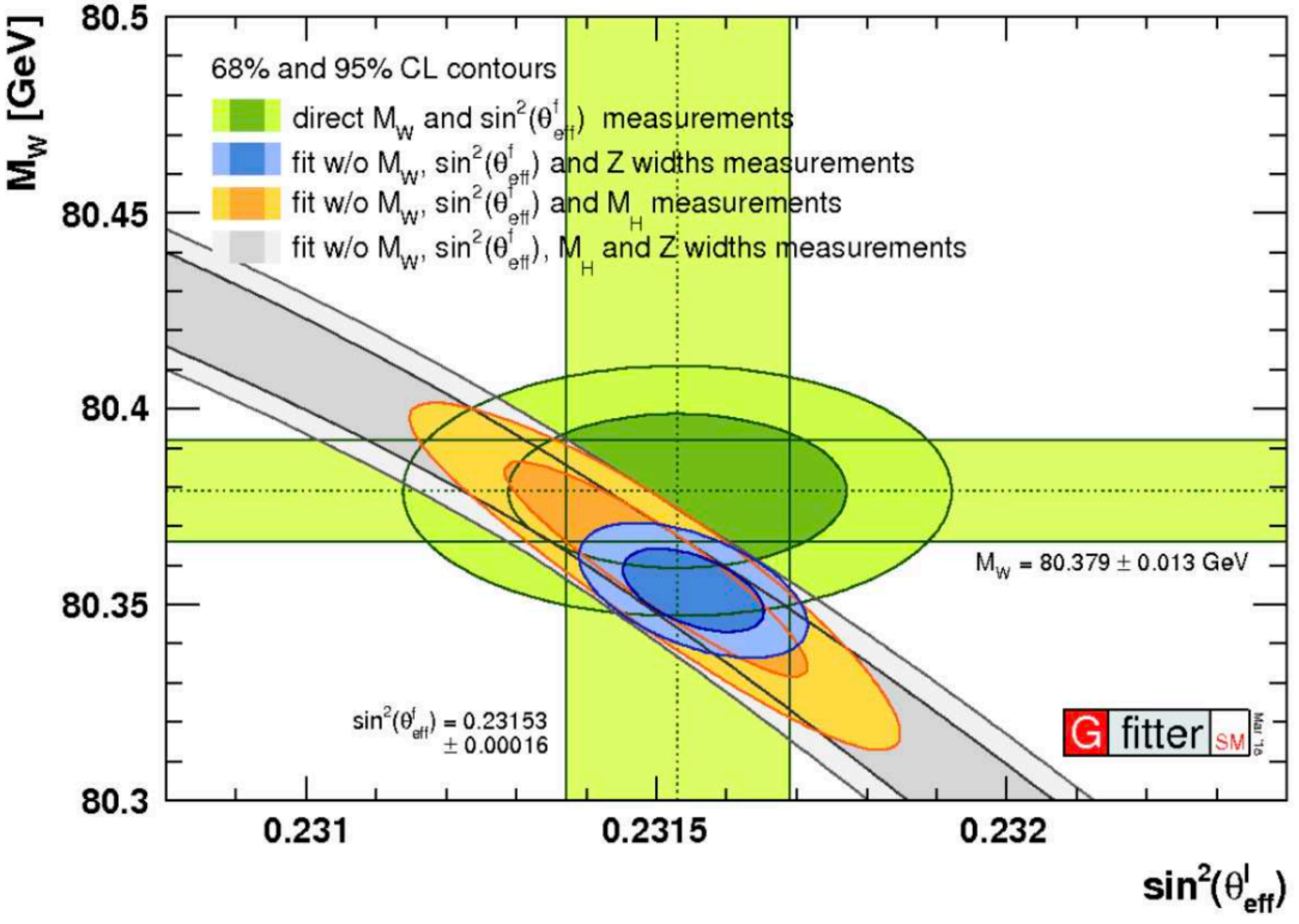
- Provide an endorsed ***world average combination*** of published* m_W measurements

[*Eur. Phys. J.* **C74** (2014) 3046]

- Establish combination methodology for present and future measurements

- Enable physics modelling updates (i.e. newer PDFs, QCD predictions)

- Properly correlate m_W, $\sin^2\theta_W$, and other PDF-dominated measurement in EW fits



So far not considering the ATLAS m_W reanalysis as not yet published in a journal

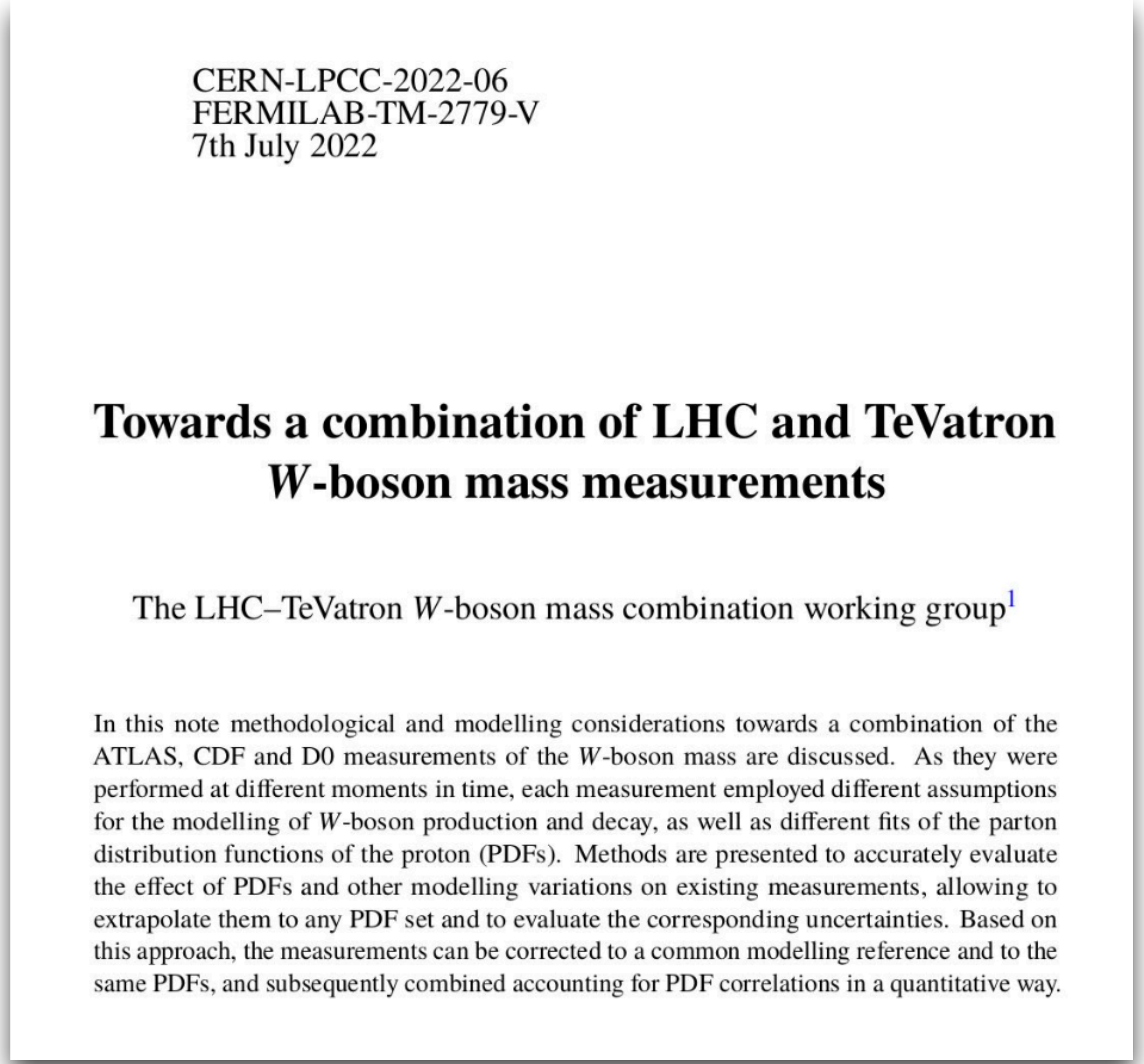
The Tevatron/LHC M_W combination WG

- Created in 2020 within the umbrella of the LPCC

- Primary goals
  - combinations of measurements with proper treatment of systematic correlations
  - Publications endorsed by corresponding collaborations

- Originally including ATLAS, CMS, CDF, D0; recently joined by LHCb

- Intermediate results presented at ICHEP2022 + public note released



CERN-LPCC-2022-06
FERMILAB-TM-2779-V
7th July 2022

Towards a combination of LHC and TeVatron *W*-boson mass measurements

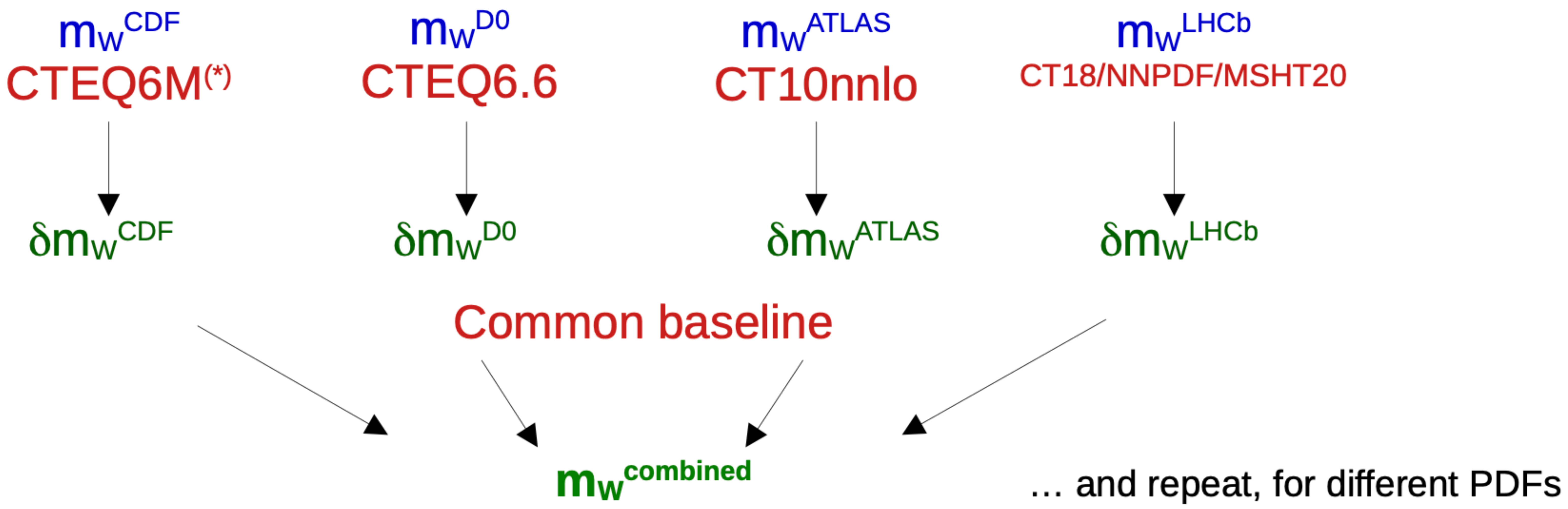
The LHC–TeVatron *W*-boson mass combination working group[1]

In this note methodological and modelling considerations towards a combination of the ATLAS, CDF and D0 measurements of the *W*-boson mass are discussed. As they were performed at different moments in time, each measurement employed different assumptions for the modelling of *W*-boson production and decay, as well as different fits of the parton distribution functions of the proton (PDFs). Methods are presented to accurately evaluate the effect of PDFs and other modelling variations on existing measurements, allowing to extrapolate them to any PDF set and to evaluate the corresponding uncertainties. Based on this approach, the measurements can be corrected to a common modelling reference and to the same PDFs, and subsequently combined accounting for PDF correlations in a quantitative way.

https://cds.cern.ch/record/2815187

Combination strategy

- Measurements performed at different times, using different PDFs and QCD models: need to translate them first to a common baseline
  - Correct all measurements to a *common PDF and QCD model*
  - *Combine* them with correlations



- Procedure decomposed into generator/QCD and PDF effects

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

published value — Improved predictions — PDF extrapolation

δm_W^{PDF} correction to reference PDF

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

Generator/QCD corrections

- Need to know the ***exact starting point*** to correctly estimate δm_W
- Fully reproduced the event generation chain of the original measurements

D0: ResBos CP (N2LO, N2LL) with CTEQ66 PDFs (NLO)

CDF: ResBos C (NLO, N2LL) with CTEQ6M PDFs (NLO)

ATLAS: POWHEG + Pythia8 (NLO + PS) combined with DYTurbo for A_i (N2LO) with CT10 PDFs (N2LO)

LHCb: POWHEG + Pythia8 (NLO + PS) combined with DYTurbo for A_i (N2LO) and averaging NNPDF 3.1, MSHT20 and CT18 PDFs (NLO)

- Variety of predictions used to compute δm_W shifts under PDF variations and to validate the QCD modeling
  - **Powheg** (NLO+PS), **MiNNLO$_{PS}$** (NNLO+PS), **DYTURBO** (NLO/NNLO)
  - Updated **Resbos** predictions at NLO+NNLL and NNLO+NNLL with improved treatment of spin correlations [2205.02788] (named here **Resbos2**)

Detector emulation

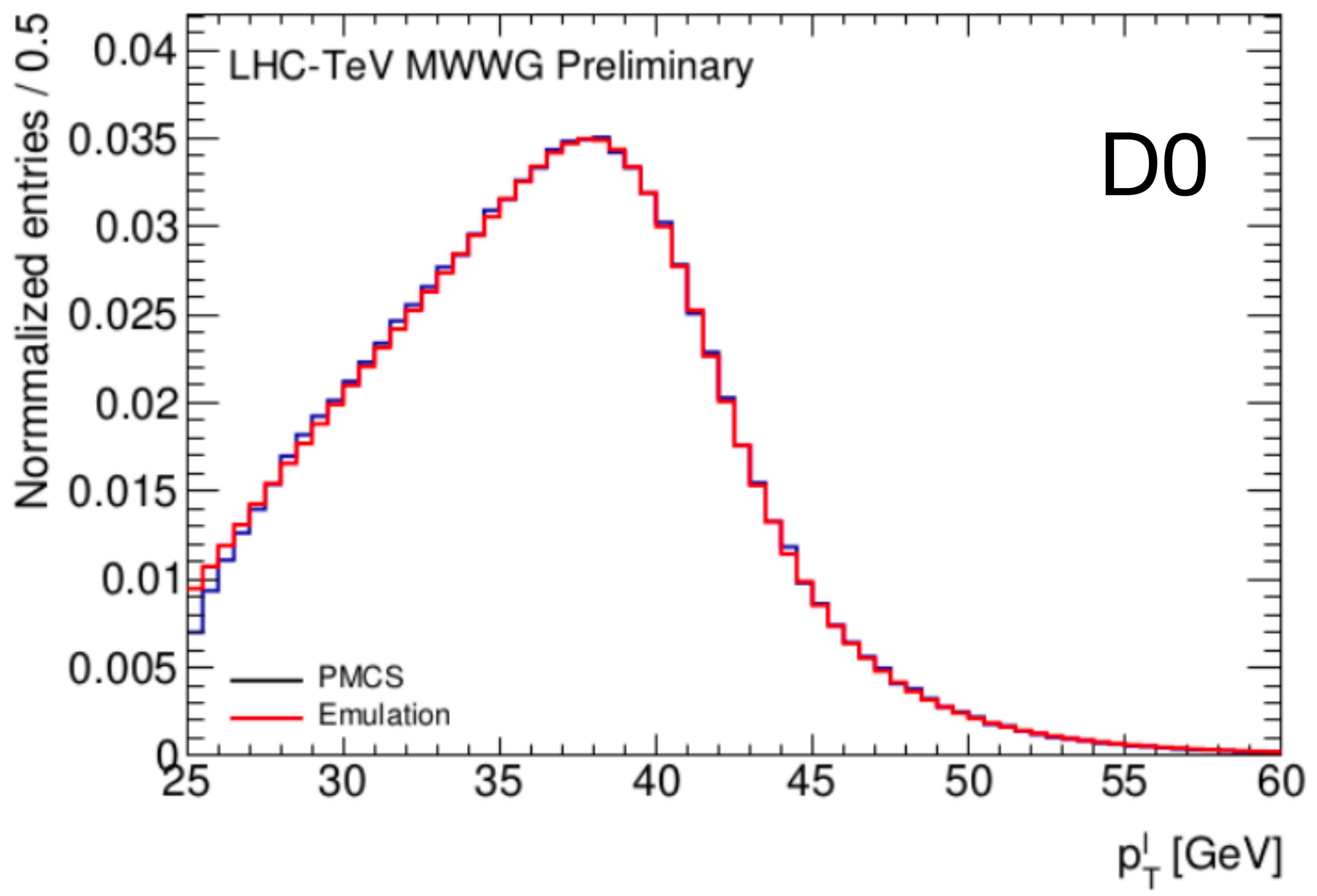
- Measurements performed at detector level: hard to reproduce

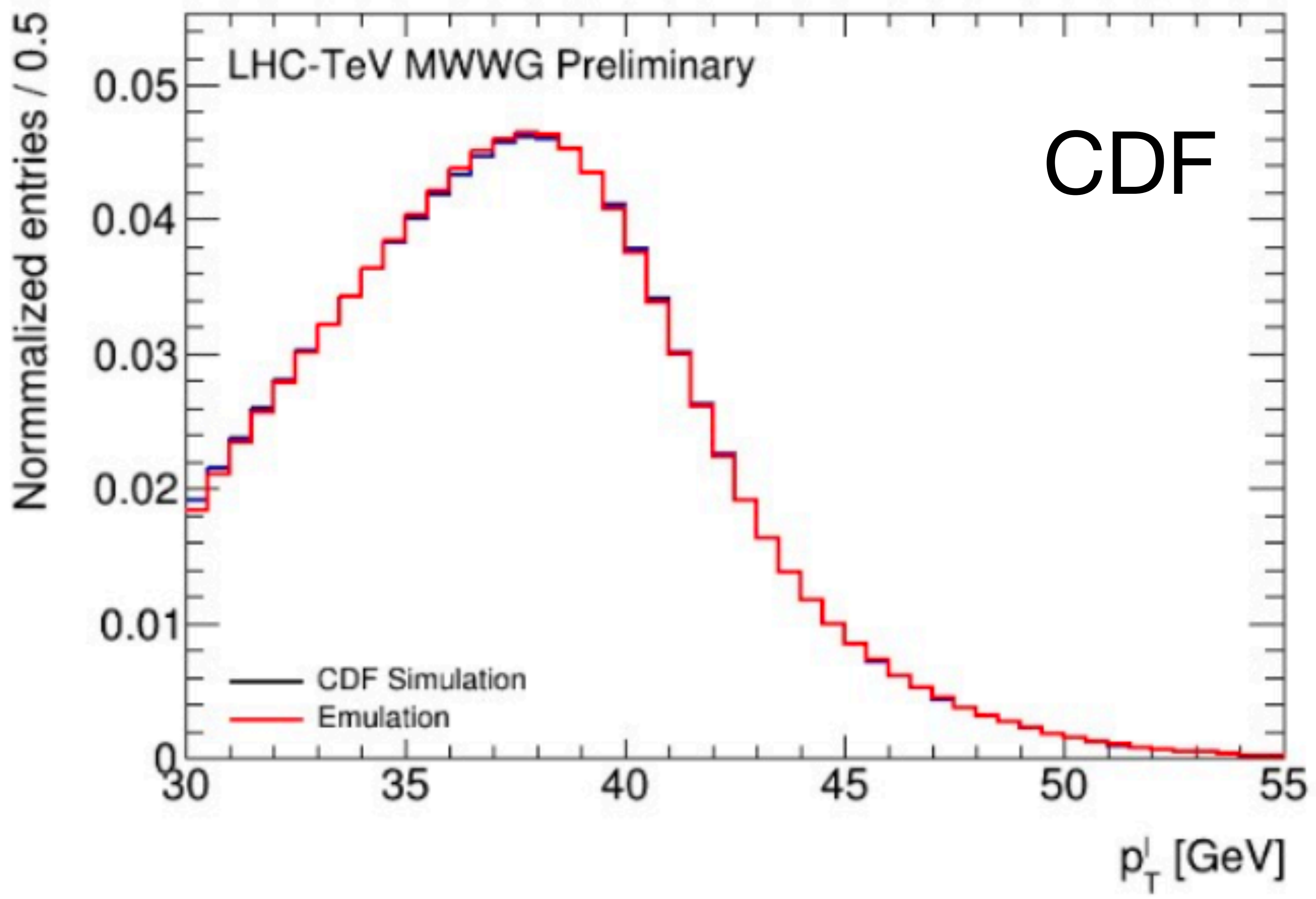
- For ATLAS, CDF and D0 use ***analysis emulation:***
  fast, parametrized detector response following published information

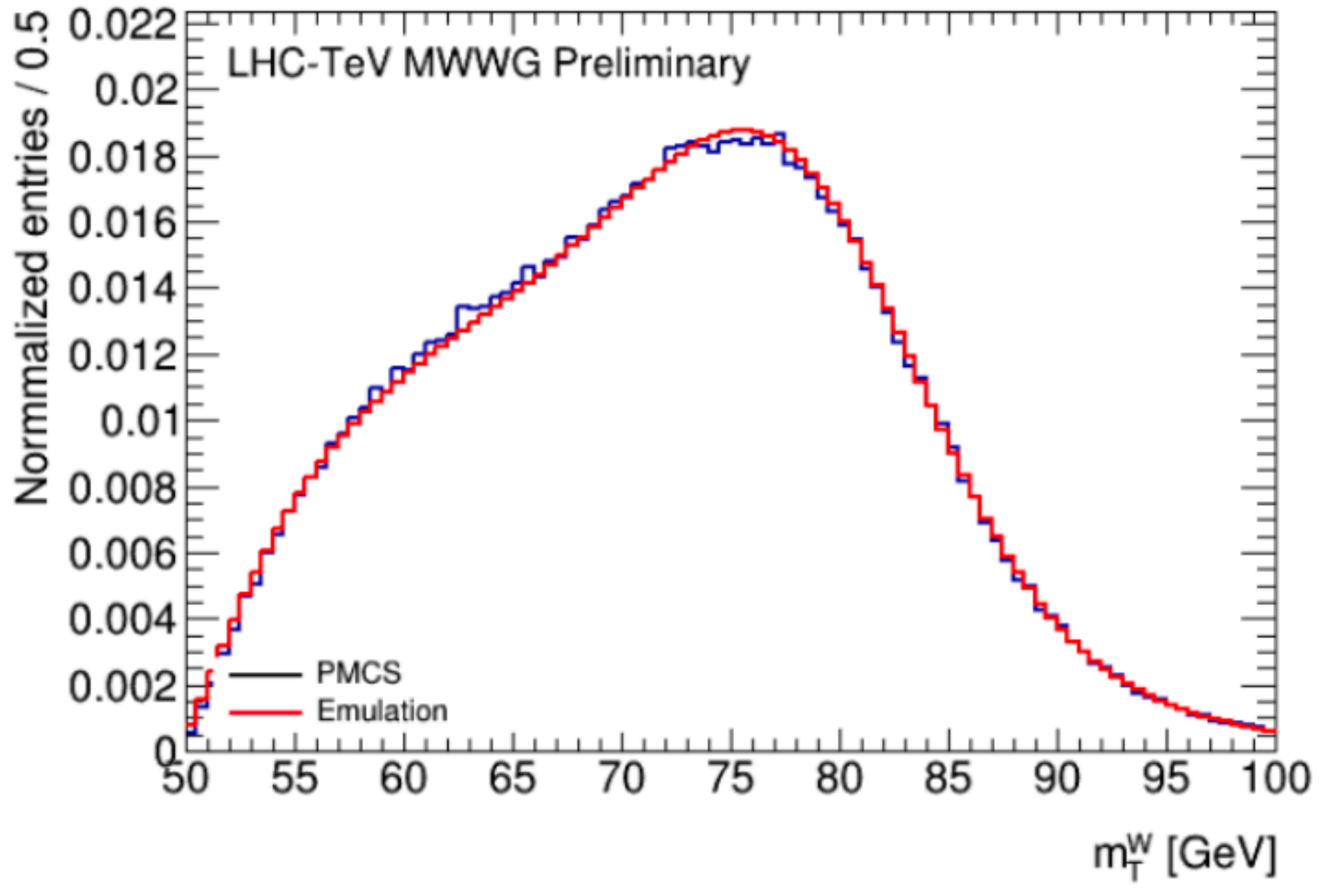
  - ***Leptons*** : η- and p_T-dependent energy/momentum scale and efficiencies
  - ***Recoil***: include "lepton removal" effects, dependence on p_T and event activity
  - Assume resolution effects cancel when making ratios of distributions
  - Event selection and fit ranges from publication fits

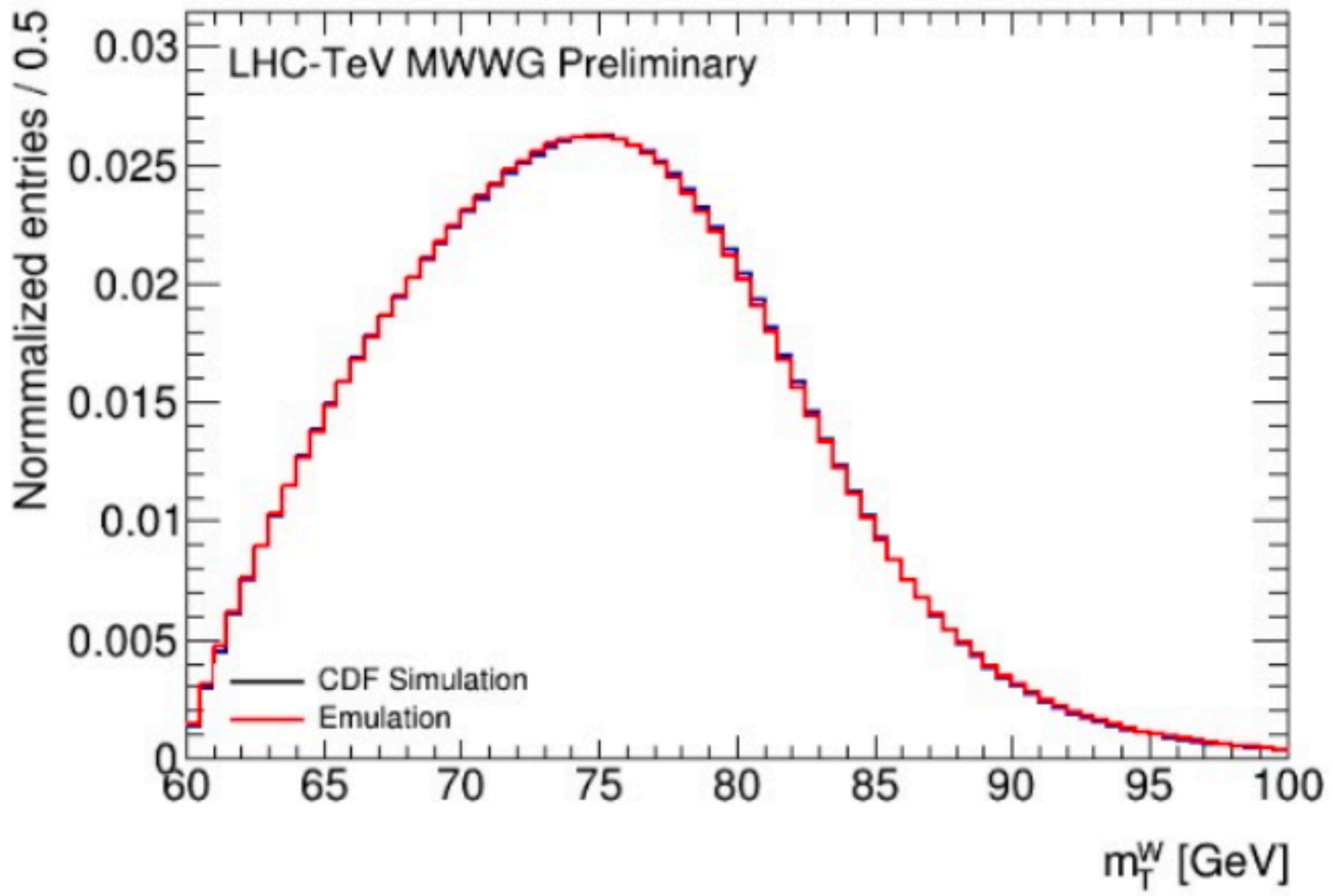
- LHCb analysis still alive, and can simply be rerun – much better!

Emulation: CDF and D0

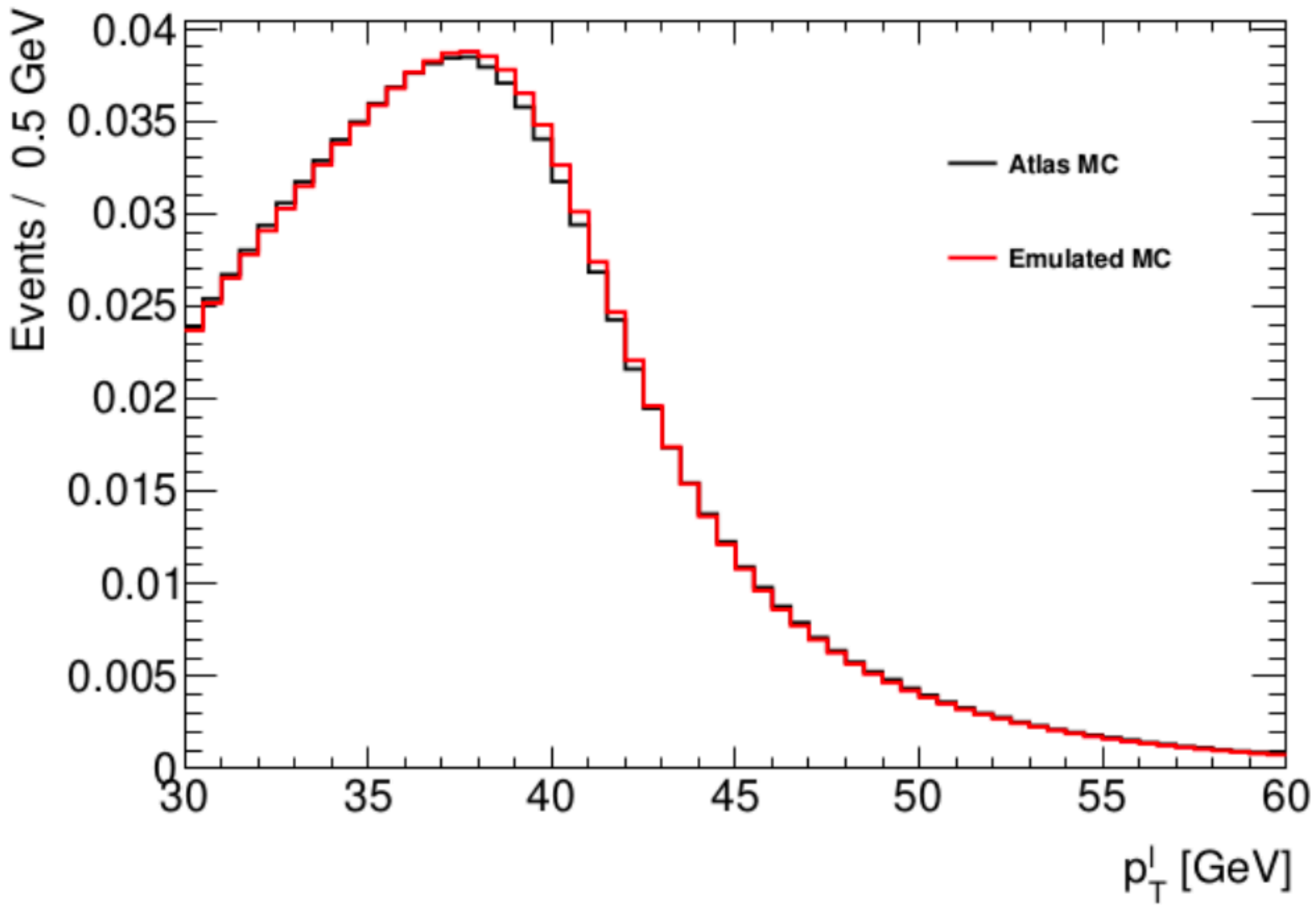


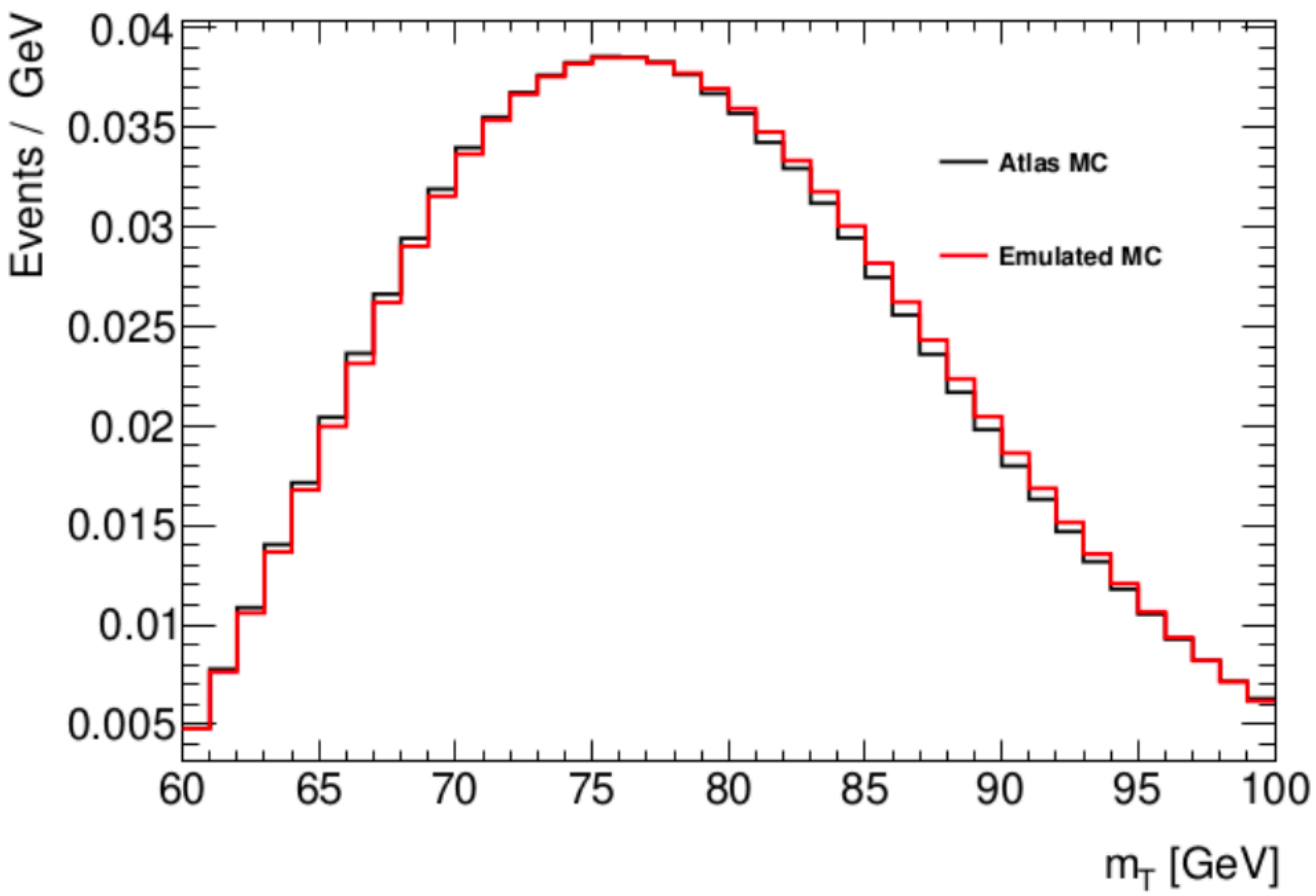






EMULATION: ATLAS

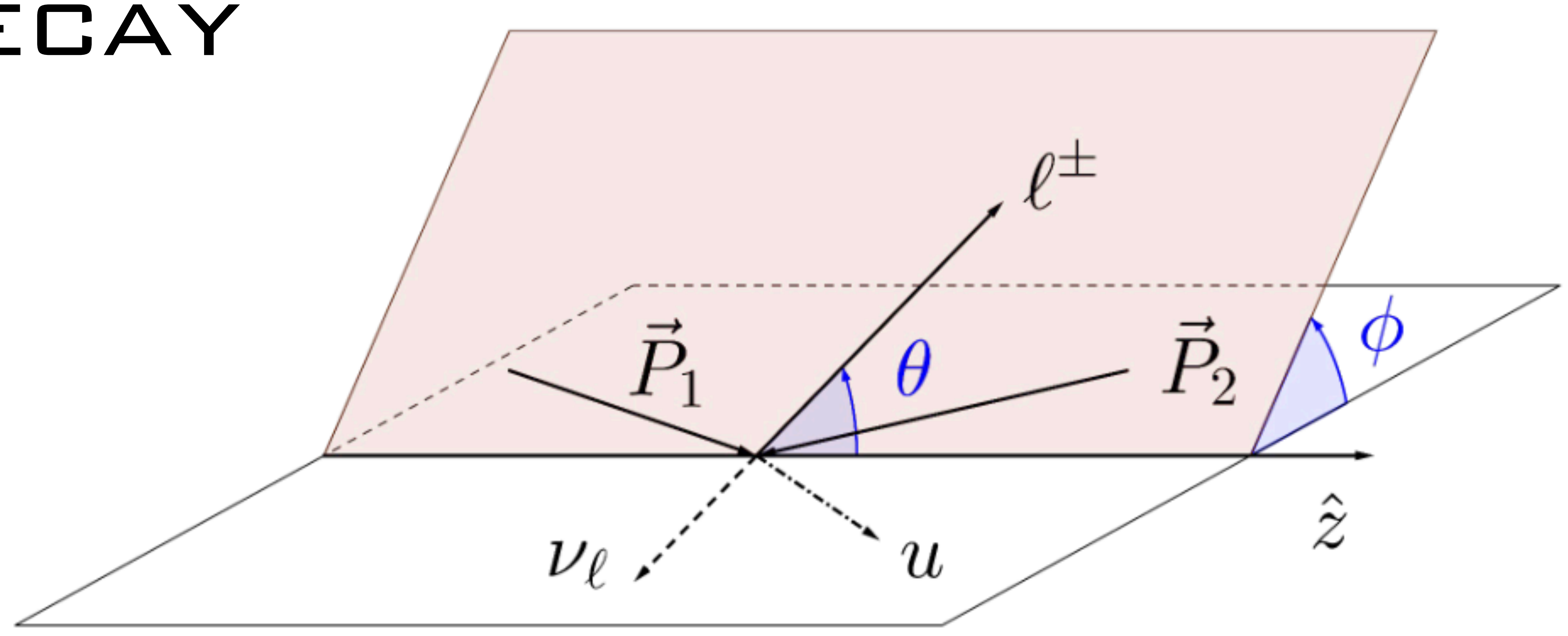




- Emulation reproduces published distributions after event selection at the % level
- Associated systematic uncertainty on m_W at the level of 1 - 2 MeV

W-boson production and decay

- Cross-section for the production of a spin-1 resonance can be decomposed into ***angular coefficients*** (to all-orders in QCD):



Collins-Soper frame

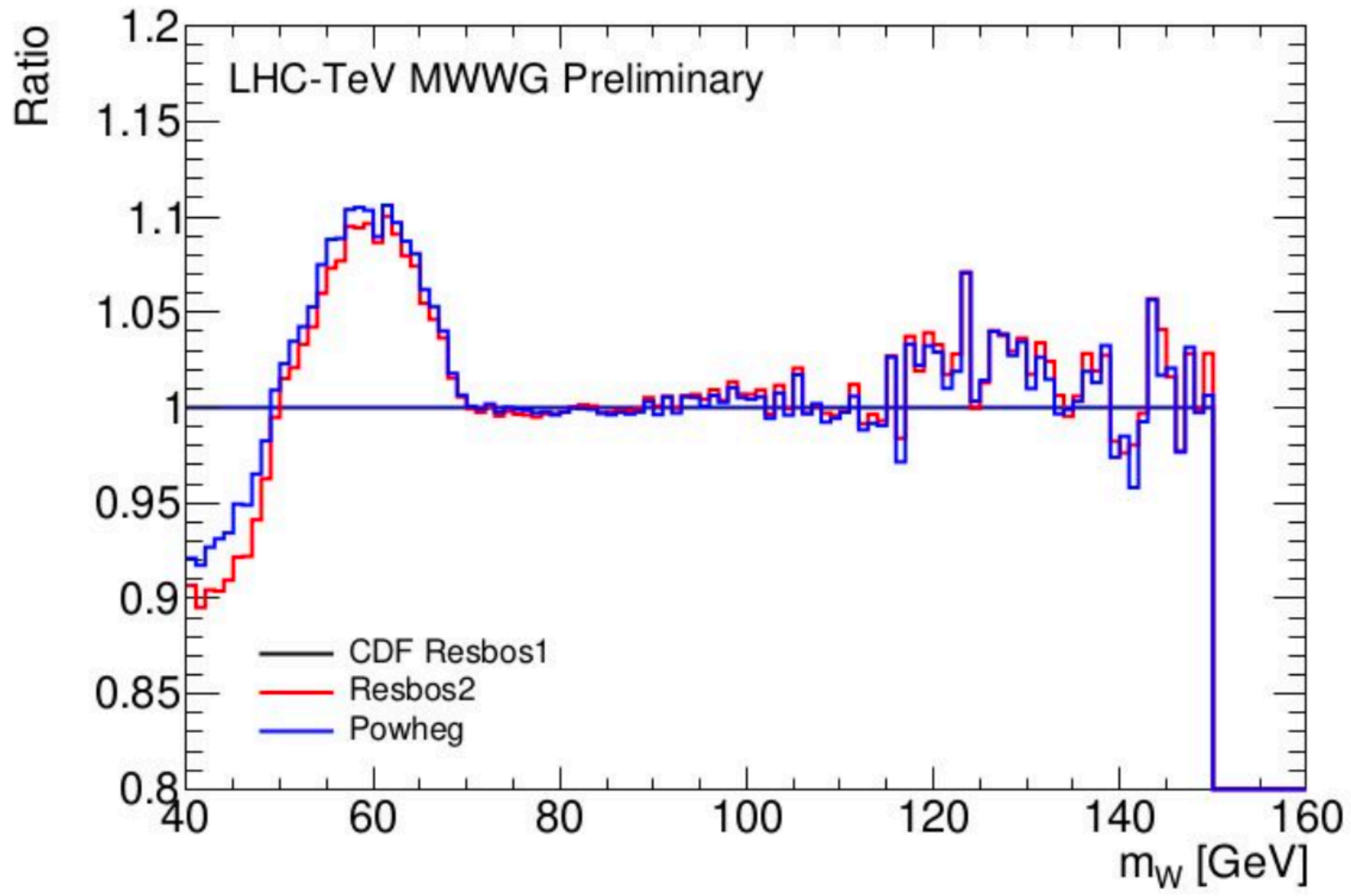
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_T\,dy}\Big[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi \Big],$$

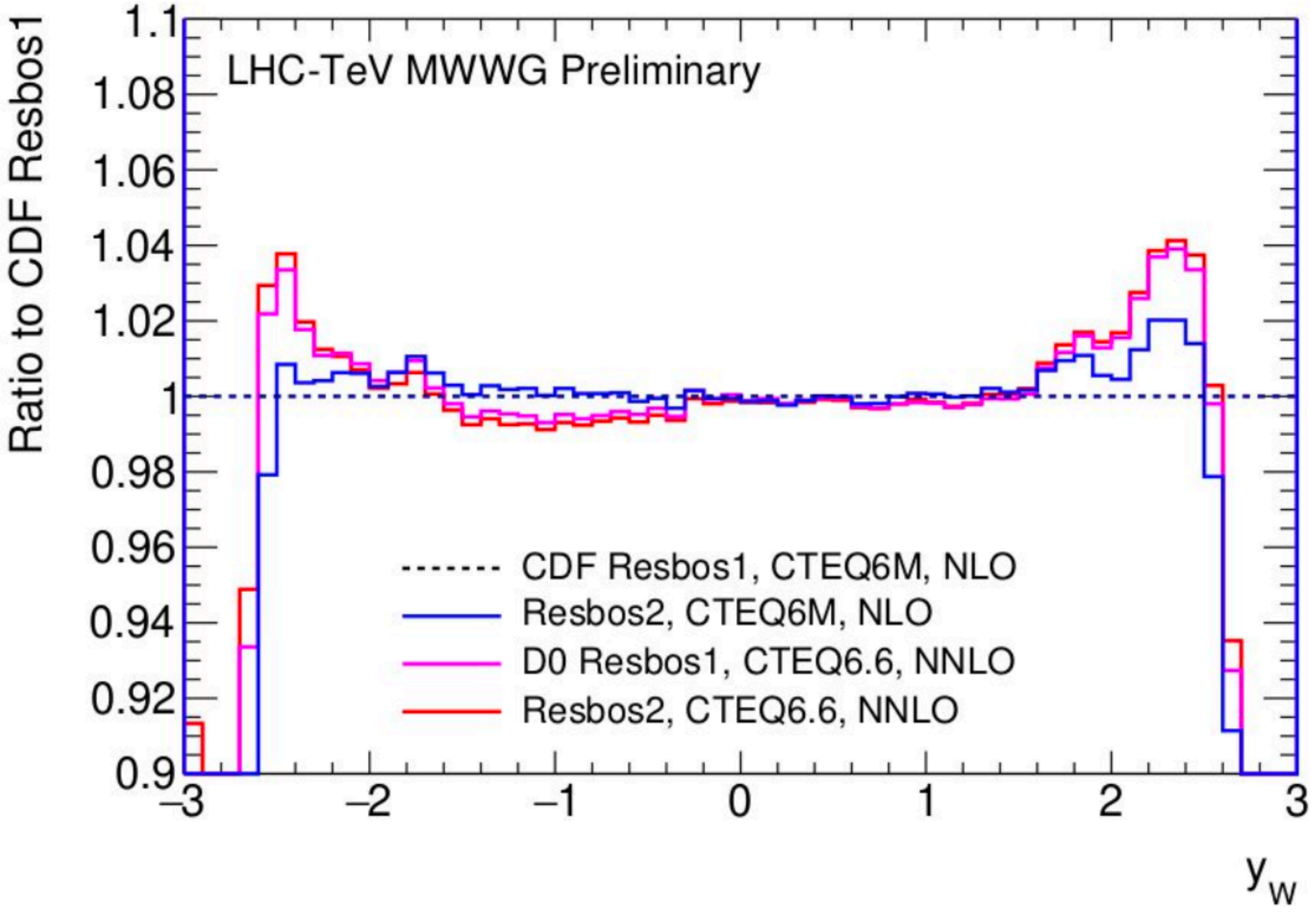
Unpolarised cross-section

Angular decomposition

W-boson invariant mass and rapidity

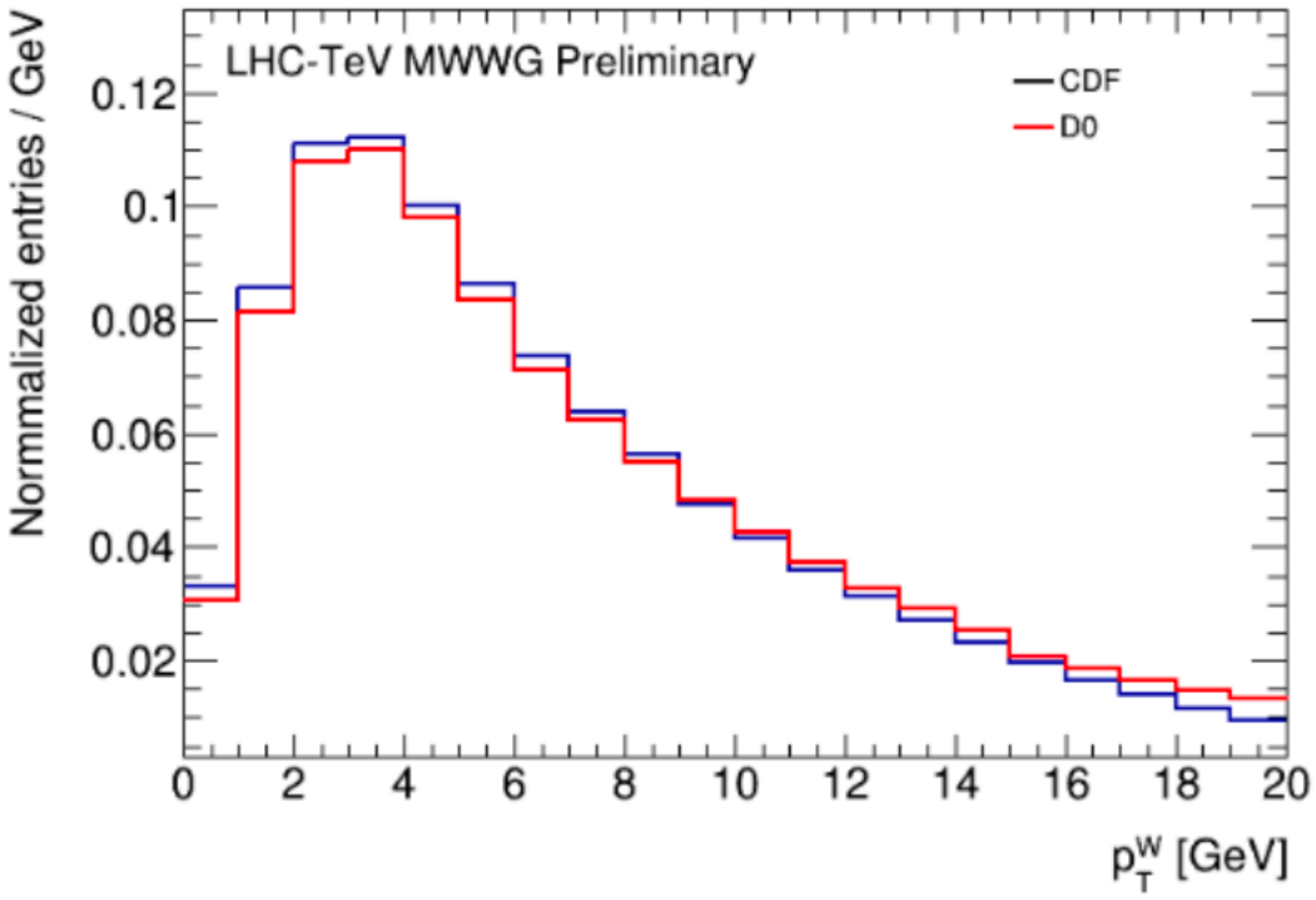
- Features and cuts in invariant mass distribution give a 1.4 – 2.7 MeV effect for CDF
- Distortions in the rapidity shape of legacy Resbos have a negligible impact

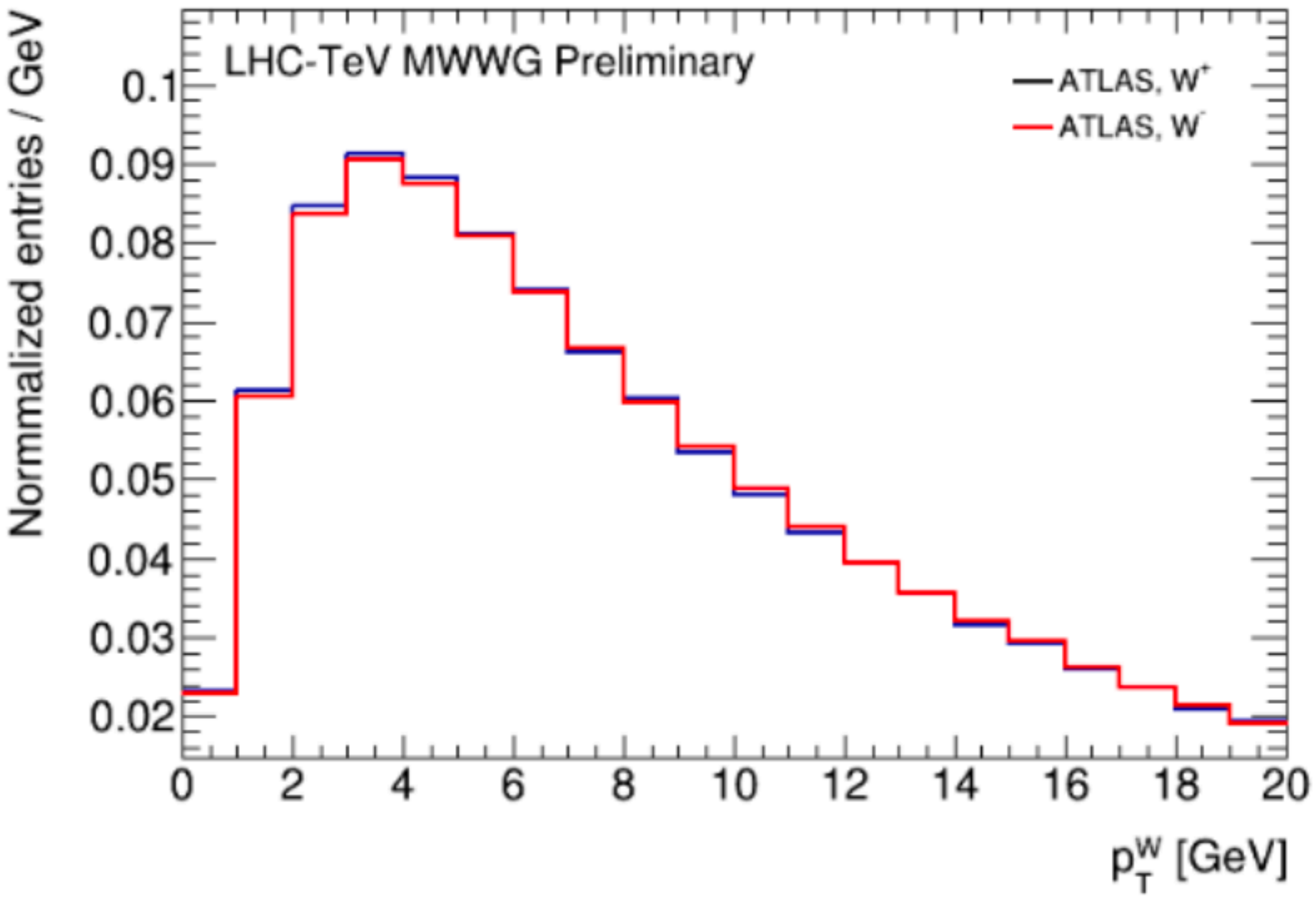




W-boson transverse momentum

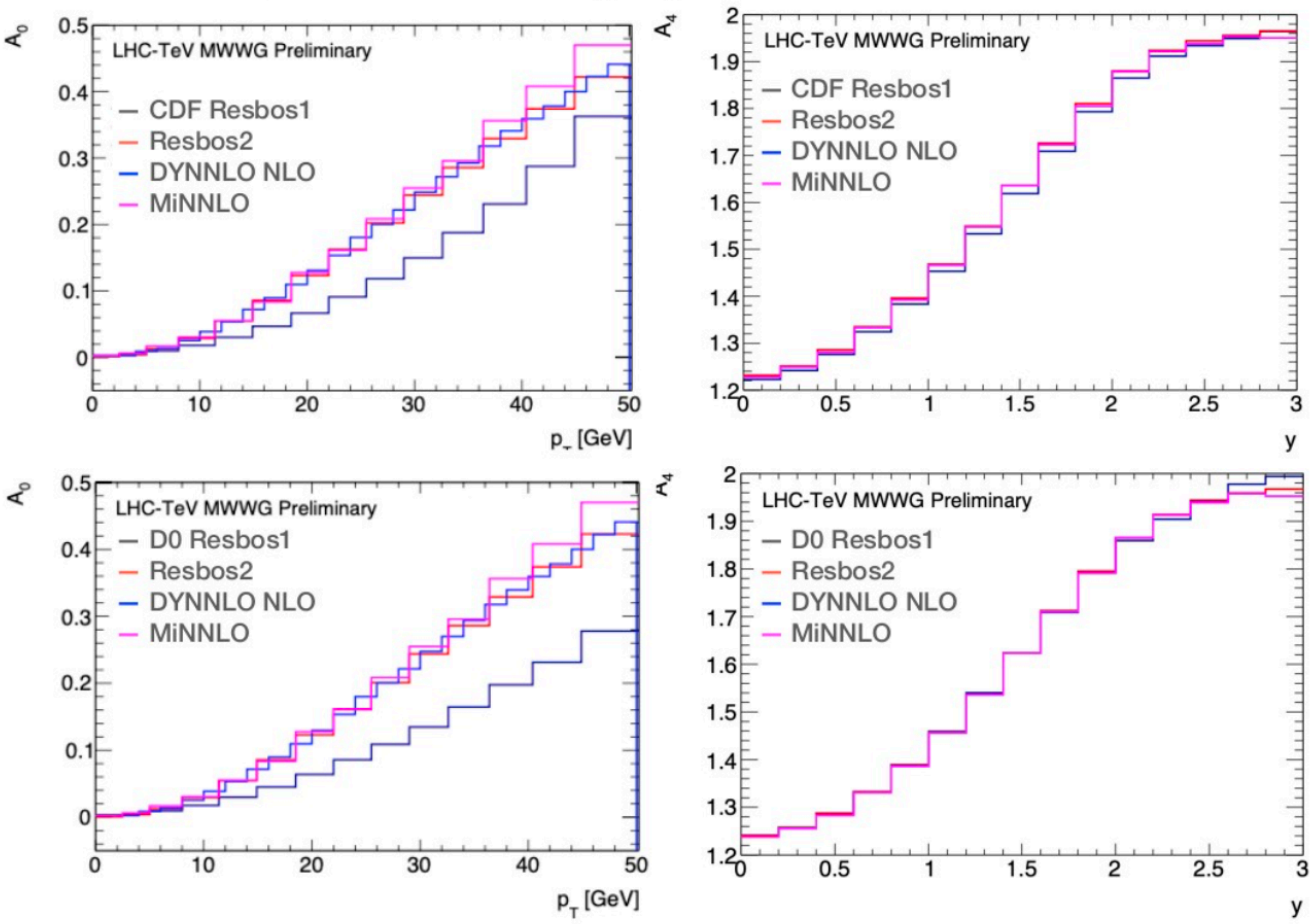
- The W boson p_T is fitted/constrained to data
- Assume published distribution; unchanged under QCD / PDF extrapolations
- CDF/D0: p_T^W distribution fixed; ATLAS: p_T^W/p_T^Z ratio fixed





Angular coefficients in Resbos-C/CP

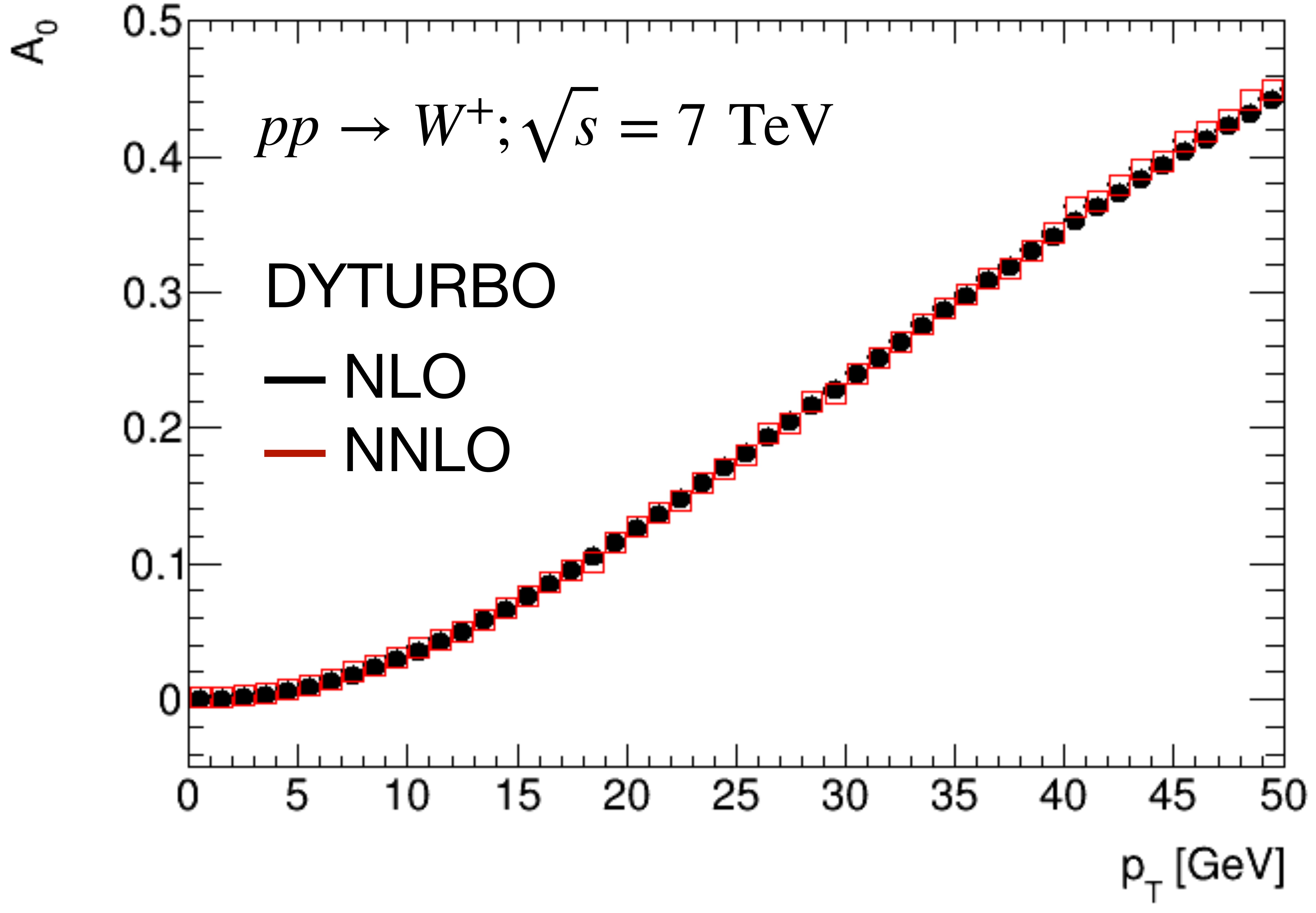
- Boson polarization in legacy Resbos-C/CP different to Resbos2 or other calculations

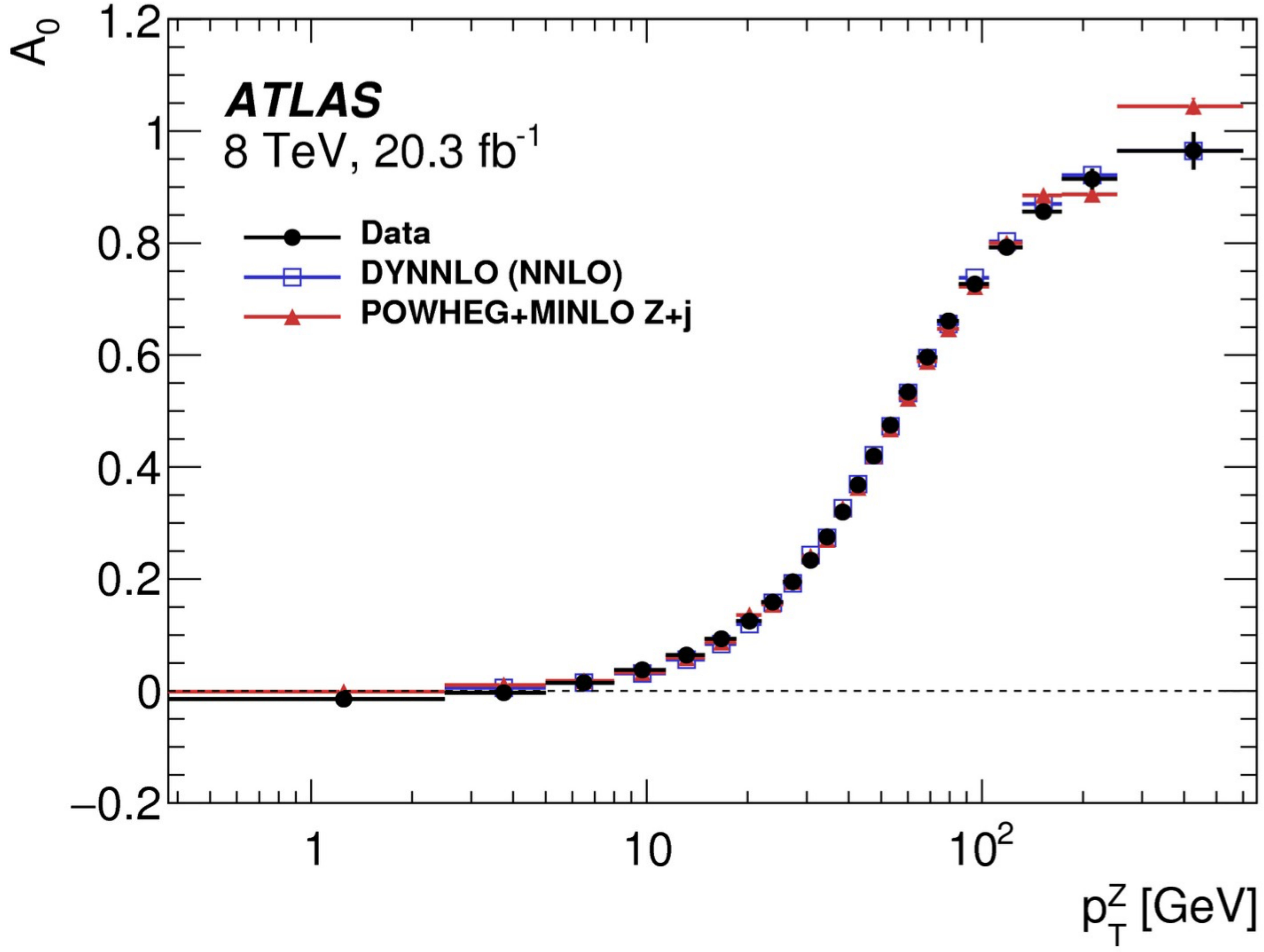


- Only the unpolarized cross-section and A_4 get resummation corrections in Resbos1
- Large differences Resbos1 and fixed-order or Resbos2
- Motivates a correction of Tevatron measurements to a common QCD model

Why disfavor the legacy ResBos ?

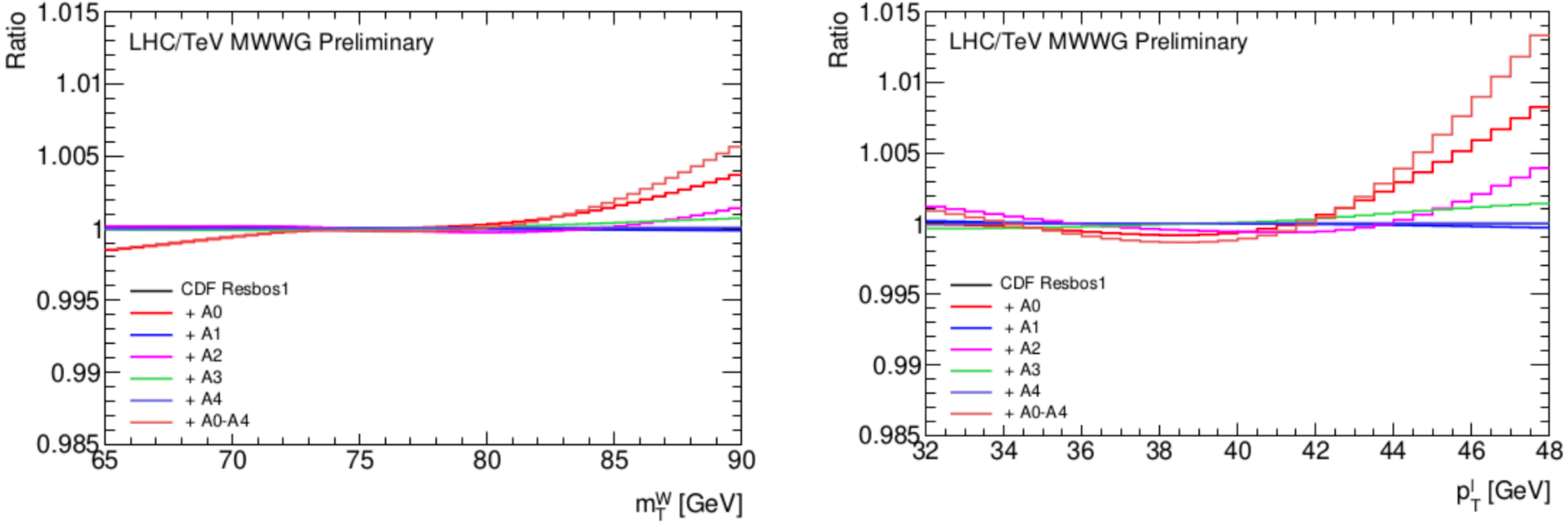
- Angular coefficients in Z production measured by ATLAS/CMS at $\sqrt{s} = 8$ TeV
- Data in good agreement with fixed-order and Monte Carlo predictions
- Fixed order extremely stable up to $O(\alpha_S^3)$ [*JHEP* 11 (2017) 003]





Spin correlations correction

- Impact of Ai correction to Resbos2 well reproduced by a reweighing of A_{0-4}
- Effect of up to 1% on detector-level distributions (dominated by A_0)
- Distribution of p_T^l become harder, m_W in data expected to decrease



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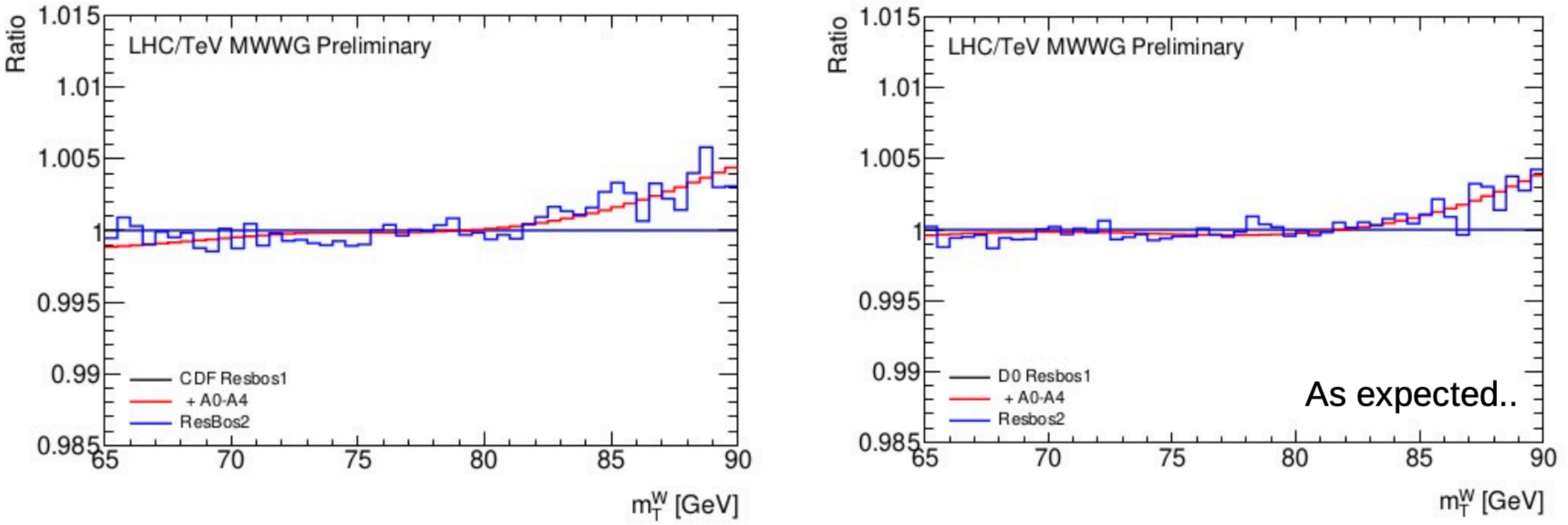


QCD/generator corrections

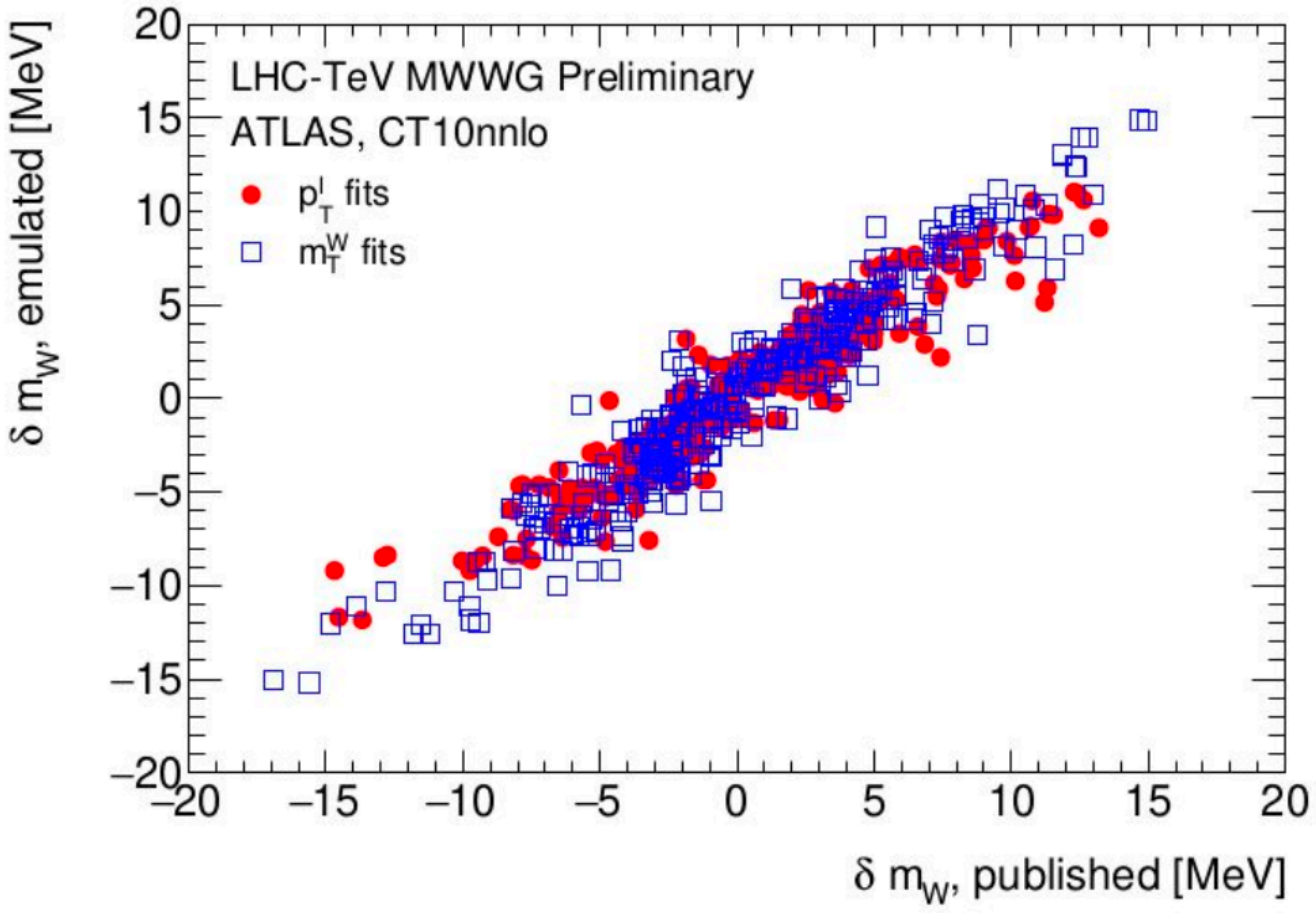
- Example impact for the D0 measurement (similar for CDF): δm_W^{QCD} **~ 7 - 14 MeV**

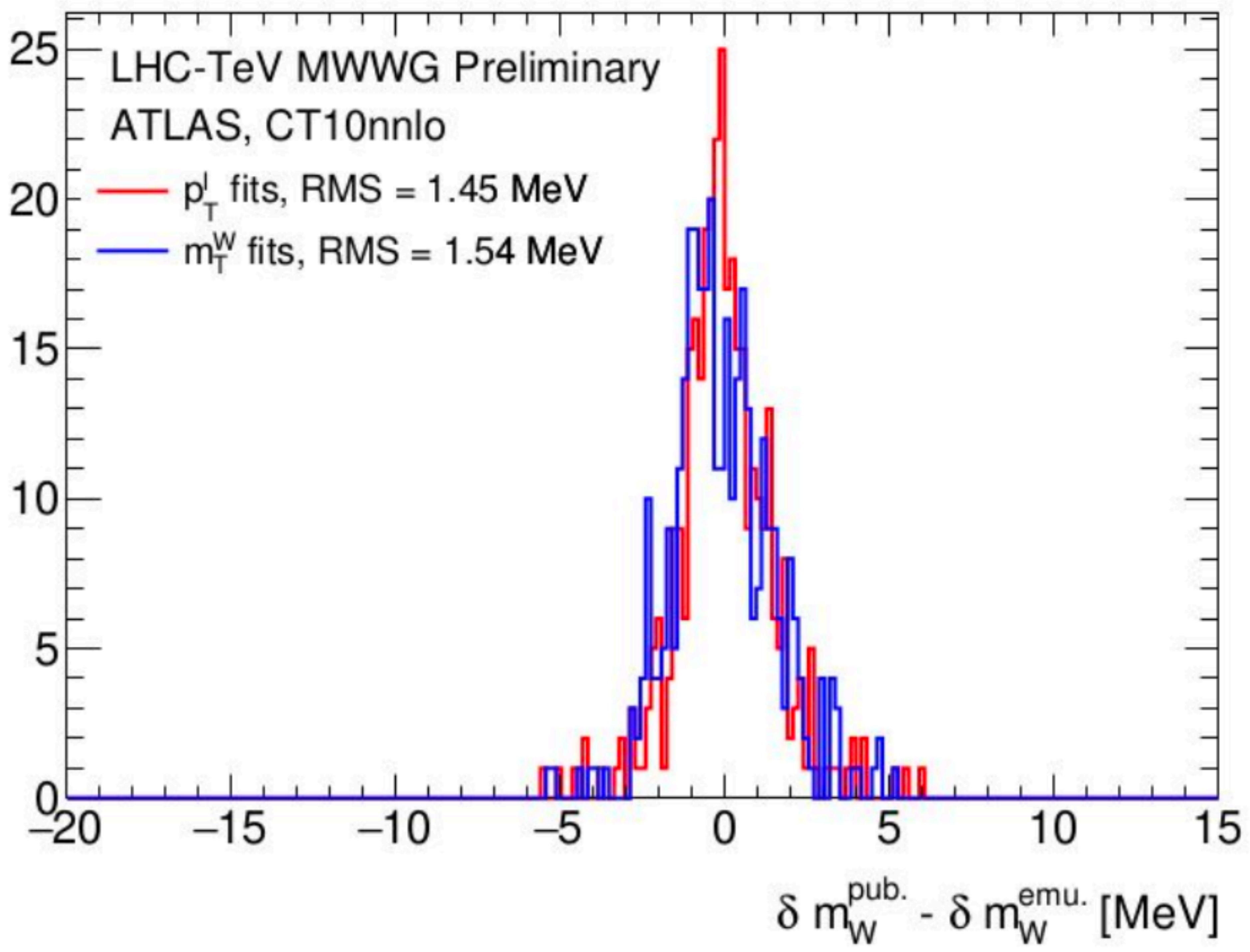
Correction	Shift [MeV]					
	p_T^W-constrained			No constraint		
	p_T^ℓ	m_T	p_T^ν	p_T^ℓ	m_T	p_T^ν
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
A_0	7.6	10.0	15.8	16.0	12.6	19.4
A_1	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
A_2	-3.0	-2.6	2.9	-4.2	-3.0	2.3
A_3	2.9	1.6	-0.5	3.5	1.8	-0.2
A_4	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
ResBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

Measured value decreases by this amount

PDF extrapolations and uncertainties

- PDF extrapolations calculated for a wide variety of PDF sets
  - Legacy PDFs: CTEQ6, CTEQ6.6, CT10nnlo
  - Newer NNLO sets: ABMP16, CT14, CT18A/Z/X, MMHT14, MSHT20, NNPDF3.1/4.0





- Validation of the emulated vs published PDF shifts gives closure of ~1.5 MeV in m_W

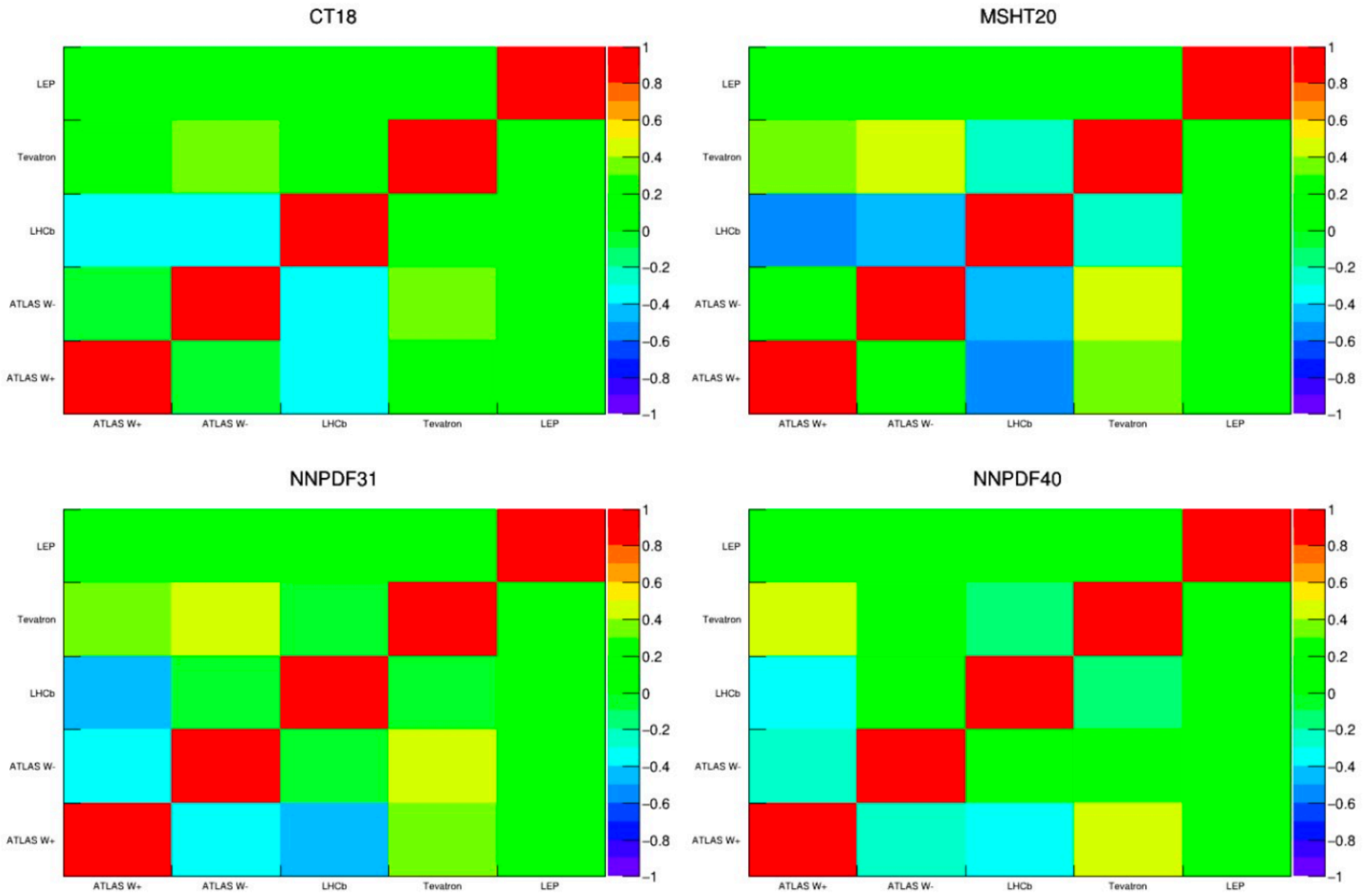
Example PDF Extrapolations for Tevatron

Generator	Powheg	Powheg	MiNNLO	Resbos
Sample type	Reweighted	Direct	Reweighted	Direct
QCD accuracy	NLO+NLL	NLO+NLL	NNLO+NLL	NLO+NLL
PDF set			Shift	
CTEQ6M	0	0	0	0
CTEQ66	-15.4 ± 0.8	-15.8 ± 0.8	-14.0 ± 1.3	-17.8 ± 1.0
CT10	-6.3 ± 0.8	-6.2 ± 0.8	-4.2 ± 1.3	–
CT10nnlo	-16.2 ± 0.8	-16.6 ± 0.8	-16.8 ± 1.3	–
CT14	-4,1 ± 0.8	-3.9 ± 0.8	-6.8 ± 1.3	-7.1 ± 1.0
CT18	-6.2 ± 0.8	-6.6 ± 0.8	-8.5 ± 1.3	-9.4 ± 1.0
CJ15	7.7 ± 0.8	7.9 ± 0.8	10.1 ± 1.3	–
MMHT14	-6.2 ± 0.8	-6.4 ± 0.8	-6.9 ± 1.3	-8.1 ± 1.0
MSHT20	-5.0 ± 0.8	-4.9 ± 0.8	-4.9 ± 1.3	–
ABMP16	5.2 ± 0.8	5.0 ± 0.8	-0.2 ± 1.3	–
NNPDF3.1	-13.8 ± 0.8	-14.3 ± 1.4	-14.1 ± 1.3	-15.8 ± 1.0

ABMP showing a larger spread

- Preliminary outdated numbers, shown for illustration only
- Generator dependence of PDF extrapolations within ~1-2 MeV in m_W

PDF correlations

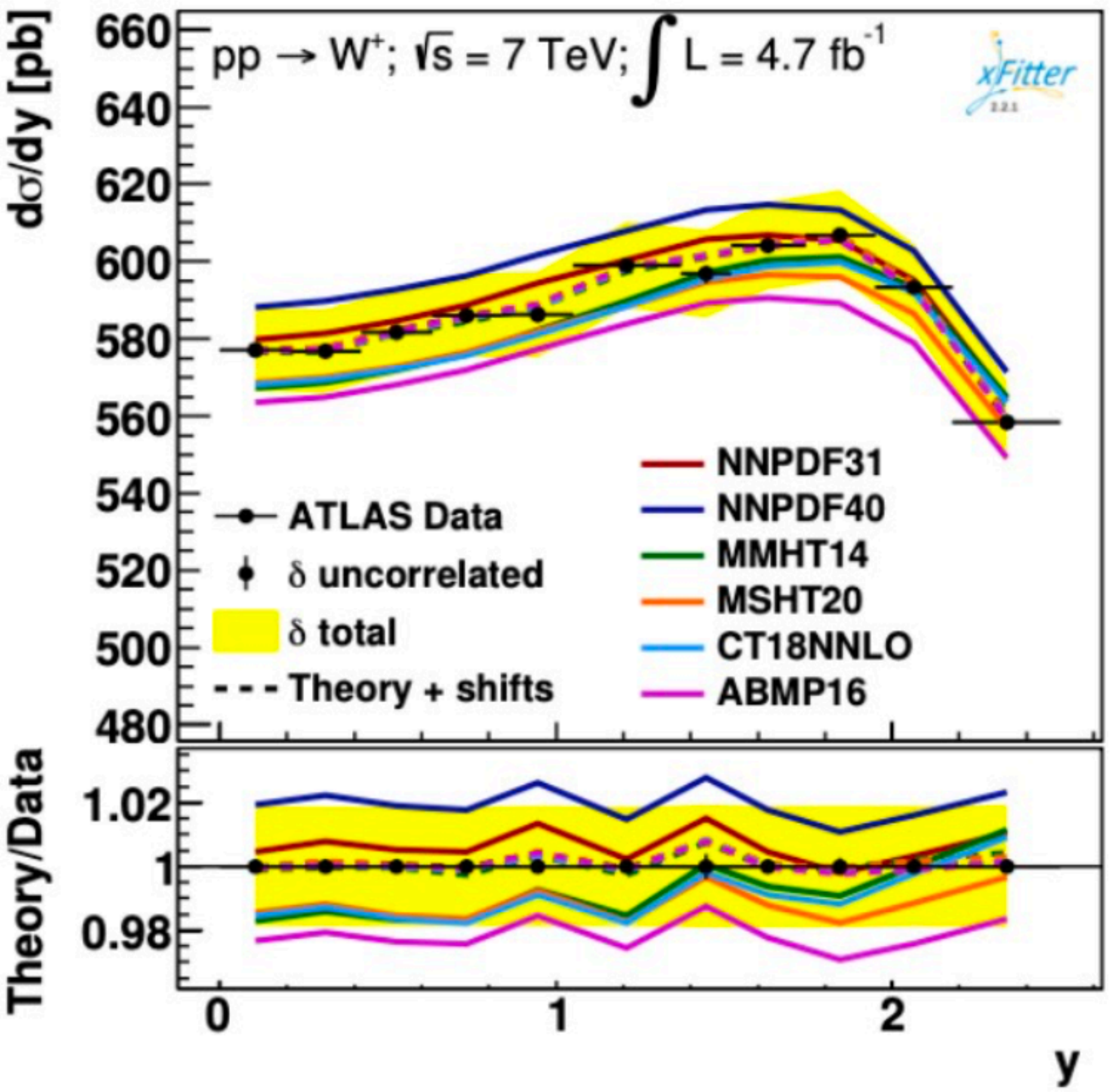


Non trivial PDF correlations and a significant model dependence

Which PDF set to choose ?

- Benchmark considered PDFs agains relevant Tevatron and LHC data
  - W, Z production cross-sections at the energies and phase-spaces of m_W measurements
  - Using NNLO QCD x NLO EW theory

PDF set	Chi2/ndf	PDF set	Chi2/ndf
Cteq66	231/126	CT18NNLO	163/126
CT10	179/126	CT18ANNLO	170/126
NNPDF31	200/126	MSHT20	270/126
NNPDF40	195/126	ABMP16	236/126



- Best description by modern NNLO sets, but no fit gives a $\chi2$/ndf~1
- Decision on the final PDF will account for this and the $\chi2$ of the combination itself

Combinations

- Finally, combinations are performed using the BLUE method
  - Validated by reproducing published combinations (CDF/D0, ATLAS subchannels)

- Planned results for each experiment:
  - Published value
  - Correction for QCD modeling
  - PDF extrapolations

- Combinations: Tevatron-only, LHC-only, “N-1” and world combination (with LEP)
  - QCD correction applied wherever appropriate
  - Combinations reported for all PDFs considered

- Still discussing how exactly to present and discriminate among the final results

Summary

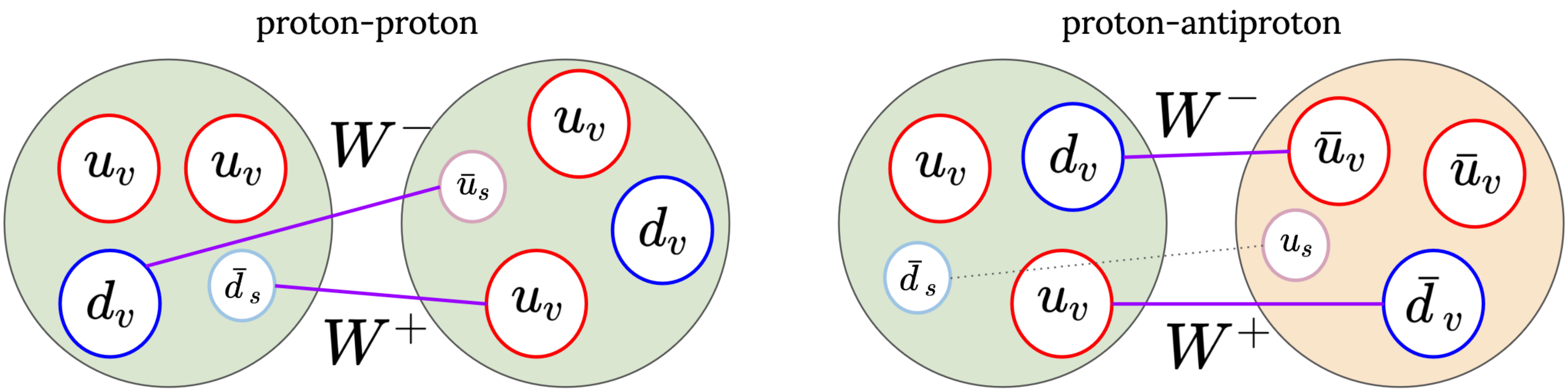
- Significant progress towards a first combination (and understanding) of existing m_W measurements
  - Current status documented in a public note CERN-LPCC-2022-06
- Final combination results expected to be public within a few months
- Expect remaining tensions even after ~10 MeV QCD correction to Tevatron results
- Aim to extend in the future this methodology to upcoming m_W measurements and to other PDF dominated EW parameters
  - Planned complication, combine uncertainty components of likelihood fits

Backup

Event selection and fit ranges

Experiment	Event selections	Fit ranges
CDF	$30 < p_{\mathrm{T}}^{\ell} < 55$ GeV, $\lvert\eta_\ell\rvert < 1$	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV
	$30 < E_{\mathrm{T}}^{\mathrm{miss}} < 55$ GeV, $60 < m_{\mathrm{T}} < 100$ GeV	$32 < E_{\mathrm{T}}^{\mathrm{miss}} < 48$ GeV
	$u_{\mathrm{T}} < 15$ GeV	$65 < m_{\mathrm{T}} < 90$ GeV
D0	$p_{\mathrm{T}}^{\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 1.05$	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV
	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 50$ GeV	$65 < m_{\mathrm{T}} < 90$ GeV
	$u_{\mathrm{T}} < 15$ GeV	
ATLAS	$p_{\mathrm{T}}^{\ell} > 30$ GeV, $\lvert\eta_\ell\rvert < 2.4$	$32 < p_{\mathrm{T}}^{\ell} < 45$ GeV
	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, $m_{\mathrm{T}} > 60$ GeV	$66 < m_{\mathrm{T}} < 99$ GeV
	$u_{\mathrm{T}} < 30$ GeV	
LHCb	$p_T^{\mu} > 24$ GeV	$28 < p_T^{\mu} < 52$ GeV
	$2.2 < \eta_\mu < 4.4$	

W production at hadron colliders



- m_W measurements in proton-proton collisions are challenging
  - In proton-proton Ws are mostly produced in the same helicity state
  - In proton-antiproton Ws are equally distributed between helicity states

- Large PDF induced W-polarization uncertainty on the lepton p_T distribution

W candidate events

Experiment	Muon channel	Electron channel	Result (MeV)	Stat. Unc. (MeV)	Total Unc. (MeV)
ATLAS	7.8×10^6	5.9×10^6	80370	7	19
LHCb	2.4×10^6	N/A	80354	23	32
CDF-II	2.4×10^6	1.8×10^6	80433.5	6.4	9.4

ATLAS: [EPJC 78 (2018) 110]

LHCb: [JHEP 01 (2022) 036], [LHCB-PAPER-2021-024] (supplementary)

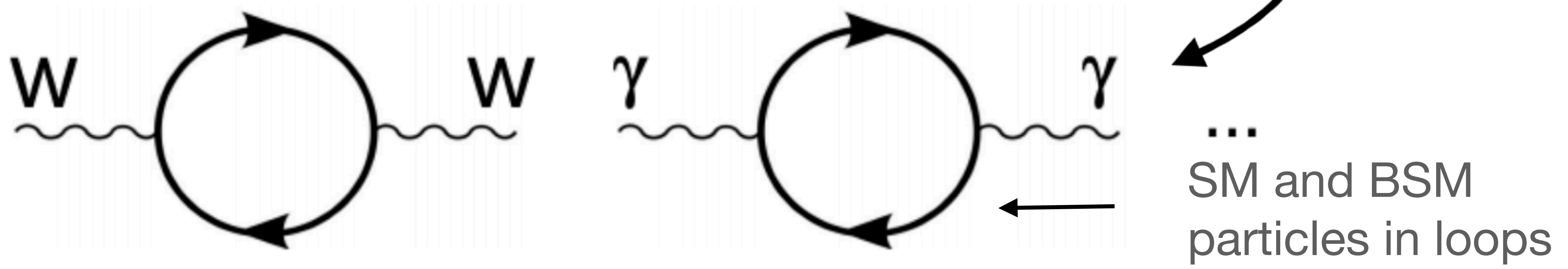
CDF: [Science, 376, 6589, (136-136), (2022)]

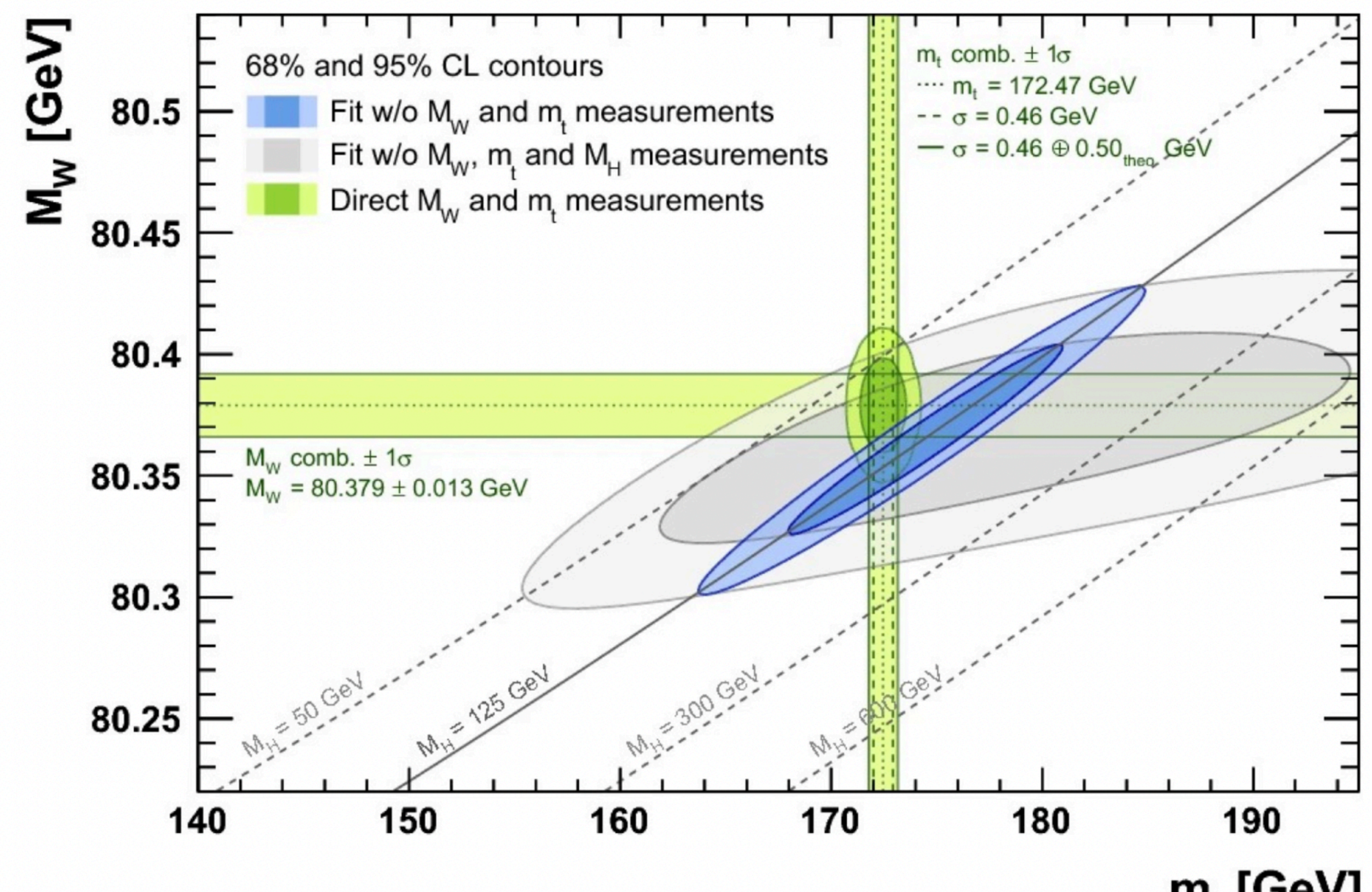
PRECISION MEASUREMENTS

- **Indirect tests** are a powerful way to access physics at very high energies
  - electroweak theory fully determined by three parameters
  - I.e. given m_Z, α, G_F, the W mass can be predicted by the SM

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

Radiative corrections





Global EW fit by the Gfitter group

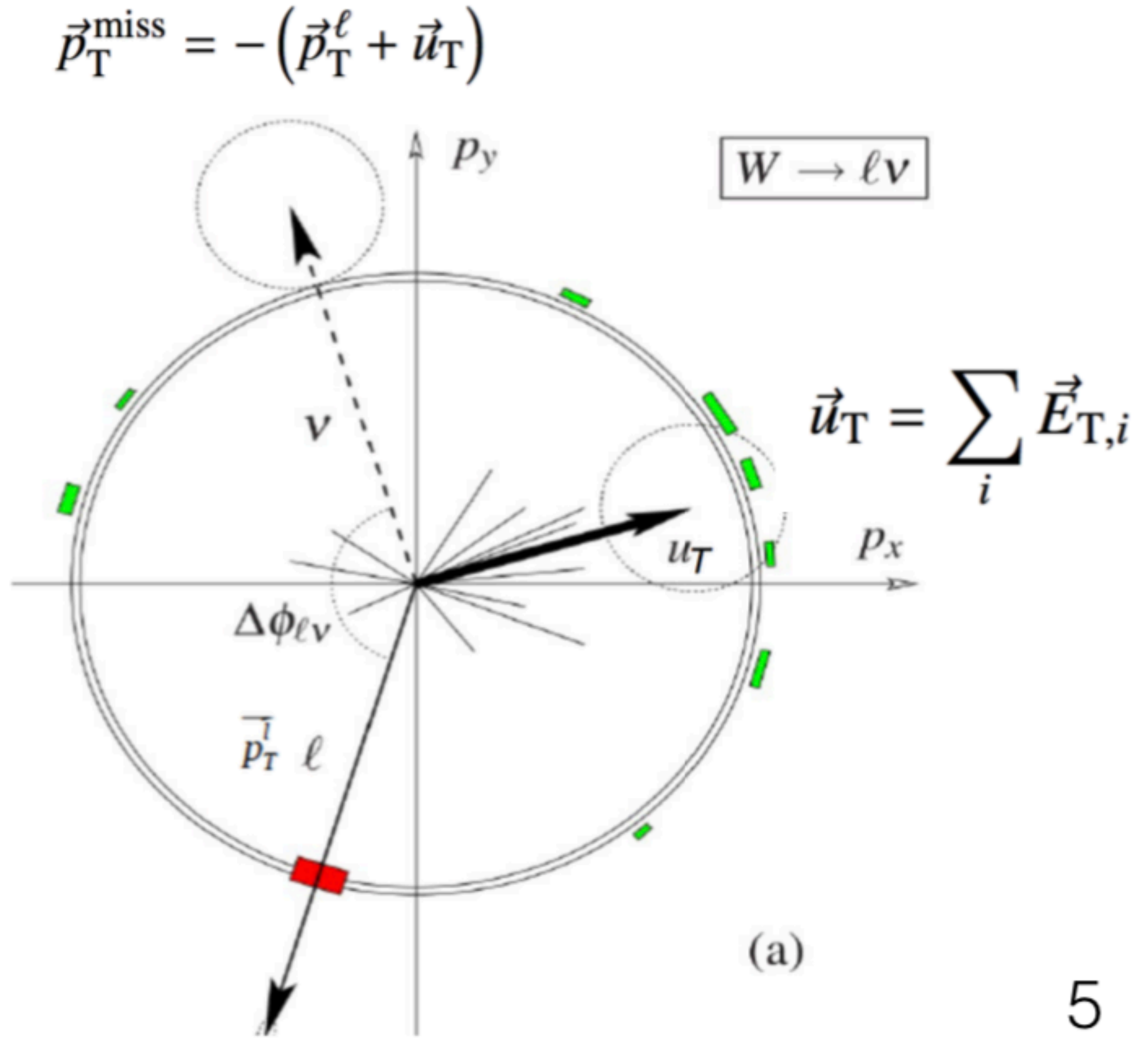
EPJC(2018)78:675

- Sensitivity to BSM primarily driven by the precision of direct m_W measurement

Parameter	**Measurement**	**EW fit**
m_H [GeV]	125.1±0.2	90±21
m_t [GeV]	172.47±0.68	176.4±2.1
m_W [GeV]	80.379±0.013	80.354±0.007
$\sin^2\theta_{eff}$	0.23152±0.00016	0.23153±0.00006

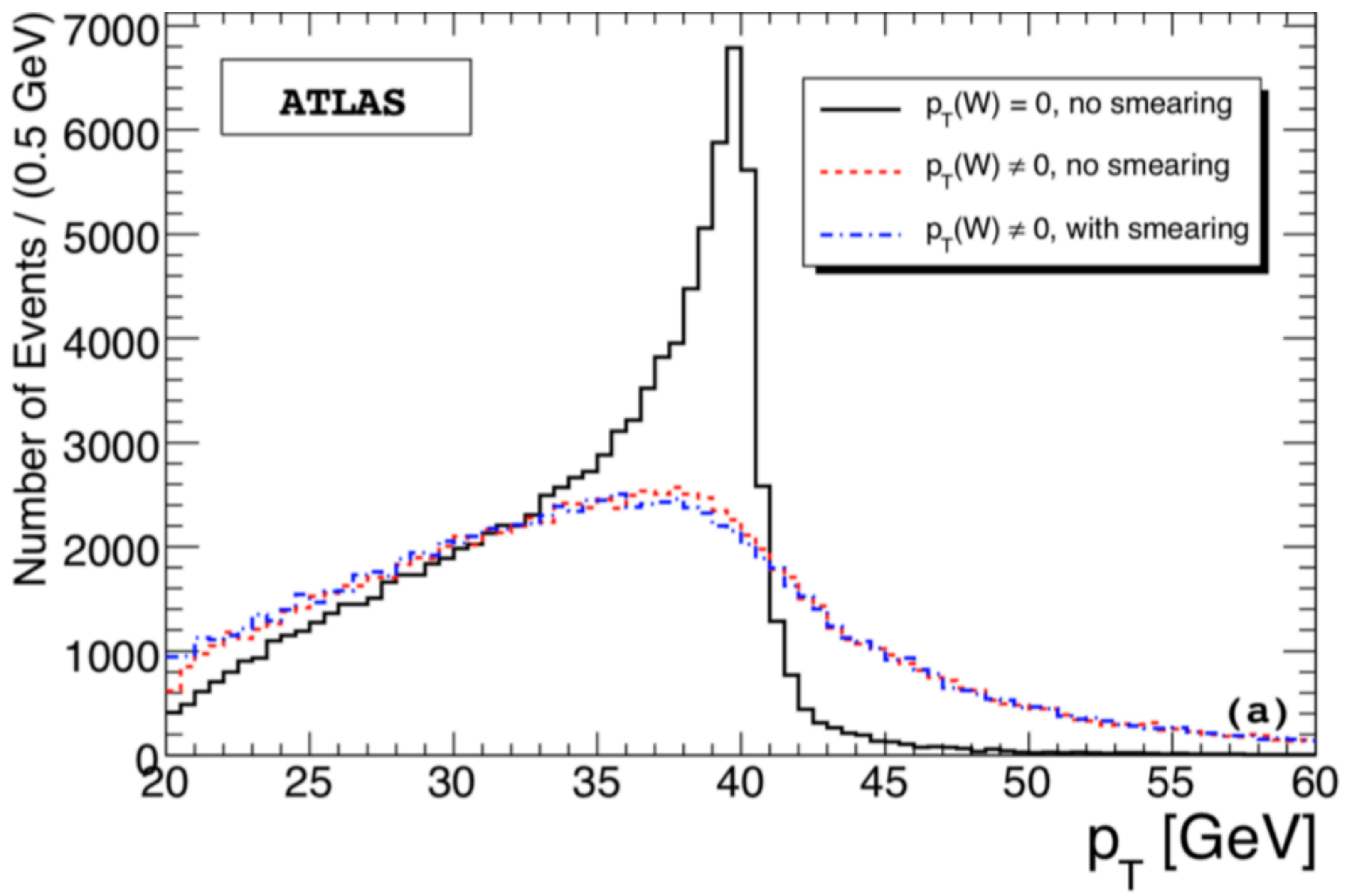
W-mass at hadron colliders

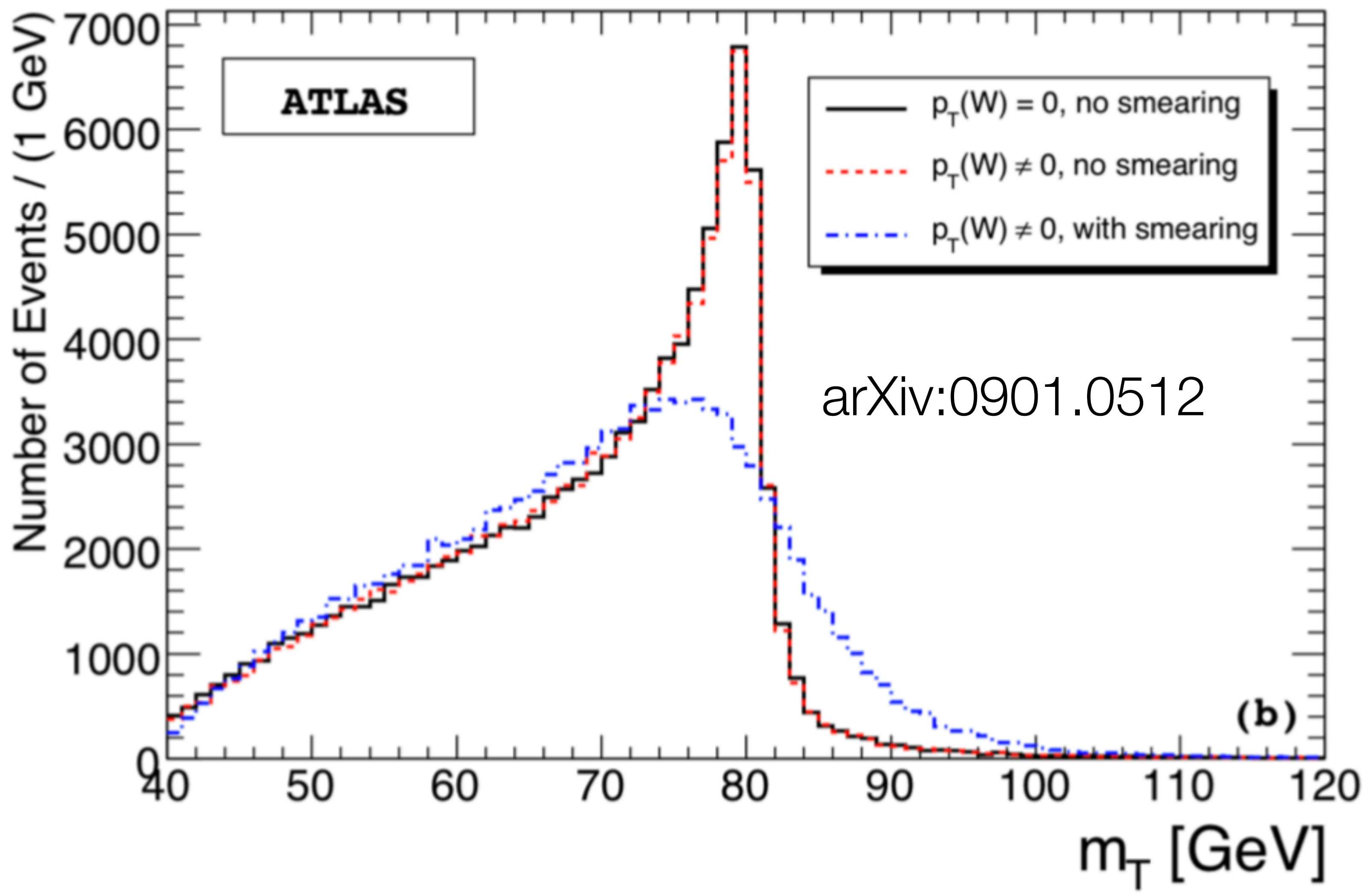
- Not possible to fully reconstruct W mass, m_W obtained through template fits to p_T^l and m_T
  - **p_T^l** sensitive to p_T^W modelling
  - **m_T** sensitive to the recoil resolution
- Extremely demanding on detector understanding
- Hard to control theory modelling



5

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





NNLOJET A0, A2 predictions