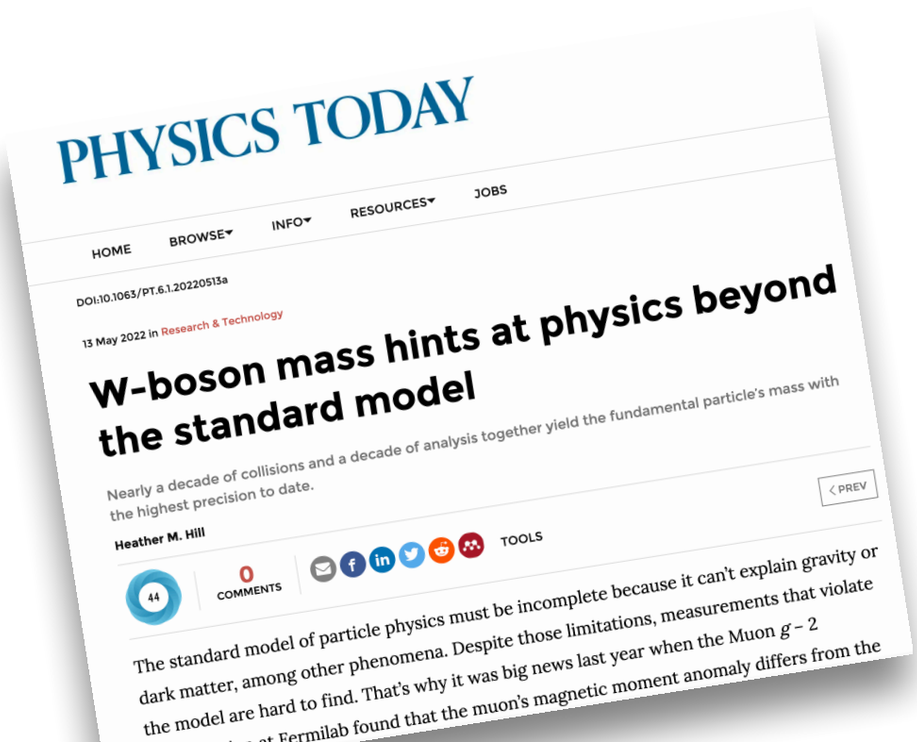
The W mass measurement at hadron colliders: a SM perspective

Juan Rojo, VU Amsterdam & Nikhef

Theory Meets Experiment mini-workshop

Nikhef, 03/06/2022



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13 May 2022 in Research & Technology

W-boson mass hints at physics beyond the standard model

Nearly a decade of collisions and a decade of analysis together yield the fundamental particle's mass with the highest precision to date.

Heather M. Hill

44 0 COMMENTS TOOLS PREV

The standard model of particle physics must be incomplete because it can't explain gravity or dark matter, among other phenomena. Despite those limitations, measurements that violate the model are hard to find. That's why it was big news last year when the Muon $g-2$ at Fermilab found that the muon's magnetic moment anomaly differs from the

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CHARLIE WOOD SCIENCE APR 17, 2022 8:00 AM

A Newly Measured Particle Could Break Known Physics

A new analysis of W bosons suggests these particles are significantly heavier than predicted by the standard model of particle physics.

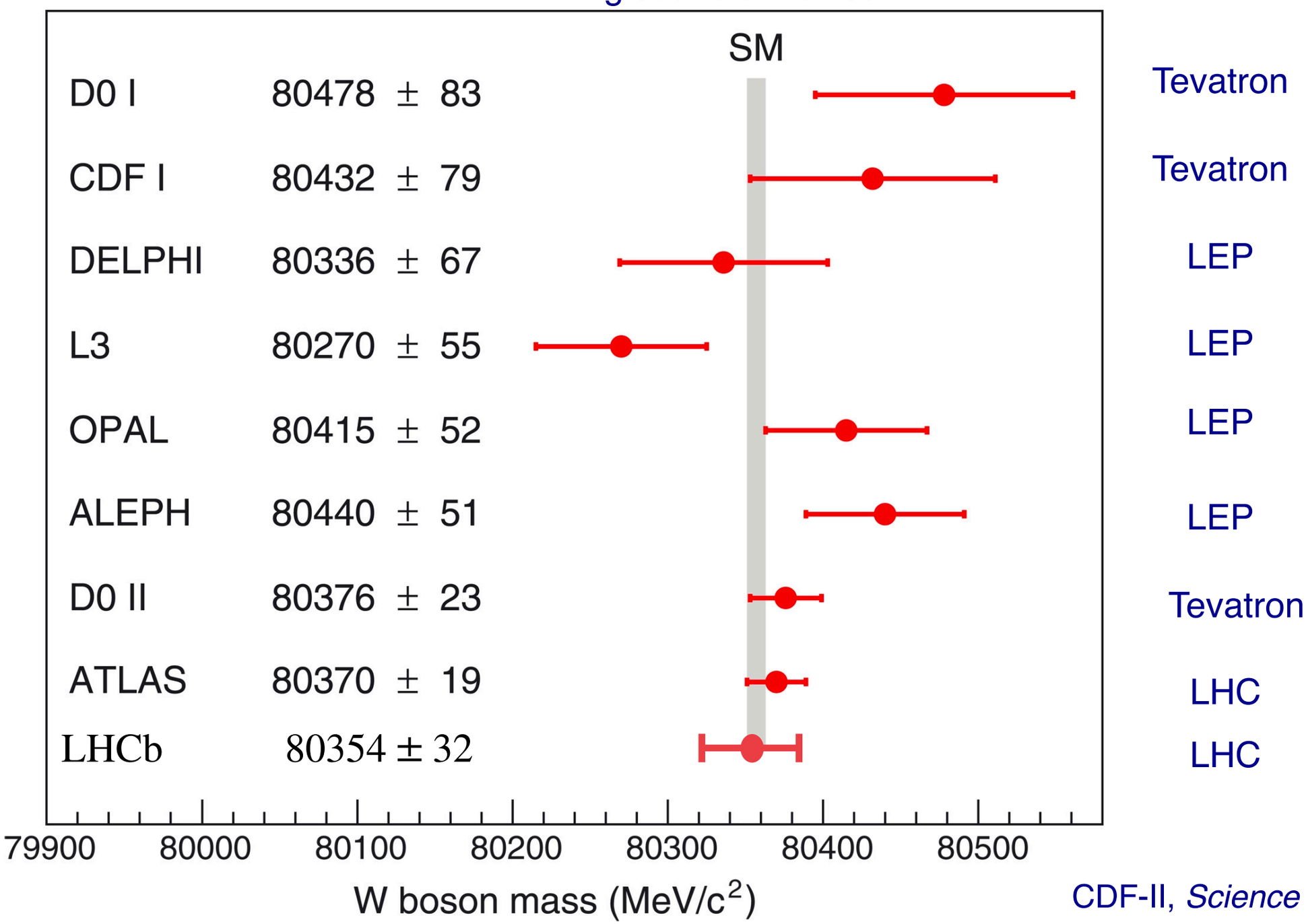
The curious heaviness of the W boson, one of 17 known elementary particles, may point to unknown particles or forces. ILLUSTRATION: SAMUEL VELASCO/QUANTA MA

Overview of W mass measurements

Within the Standard Model, measurements of a subset of its parameters can be used to **predict** the values of others such as the ***W* boson mass**

until recently, all direct measurements agreed with the SM prediction ….

``global electroweak fit”



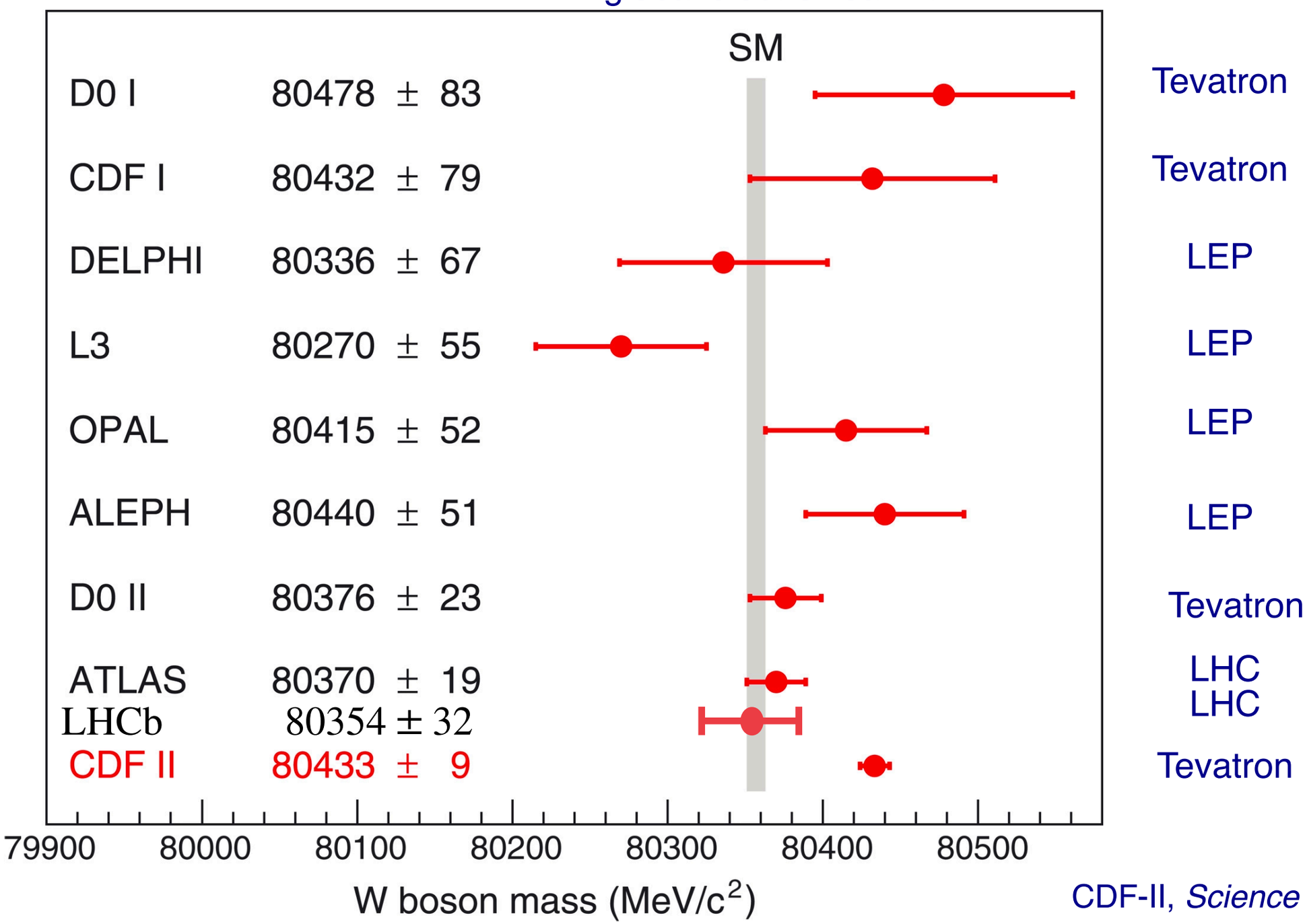
CDF-II, *Science* (2022)

Overview of W mass measurements

Within the Standard Model, measurements of a subset of its parameters can be used to **predict** the values of others such as the ***W* boson mass**

the new CDF-II result reduces the CDF-I error by almost a factor 10 (same central value)

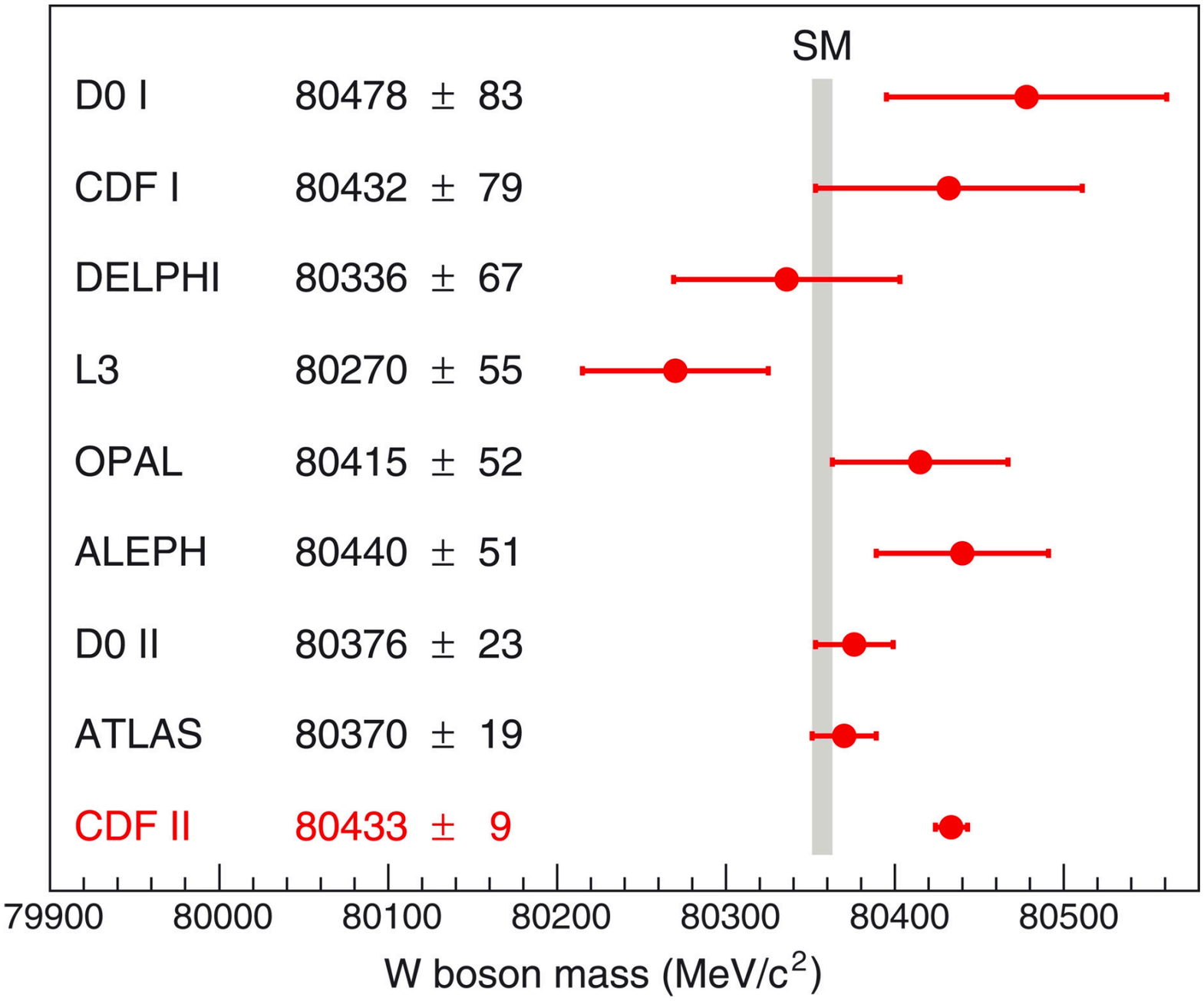
``global electroweak fit''



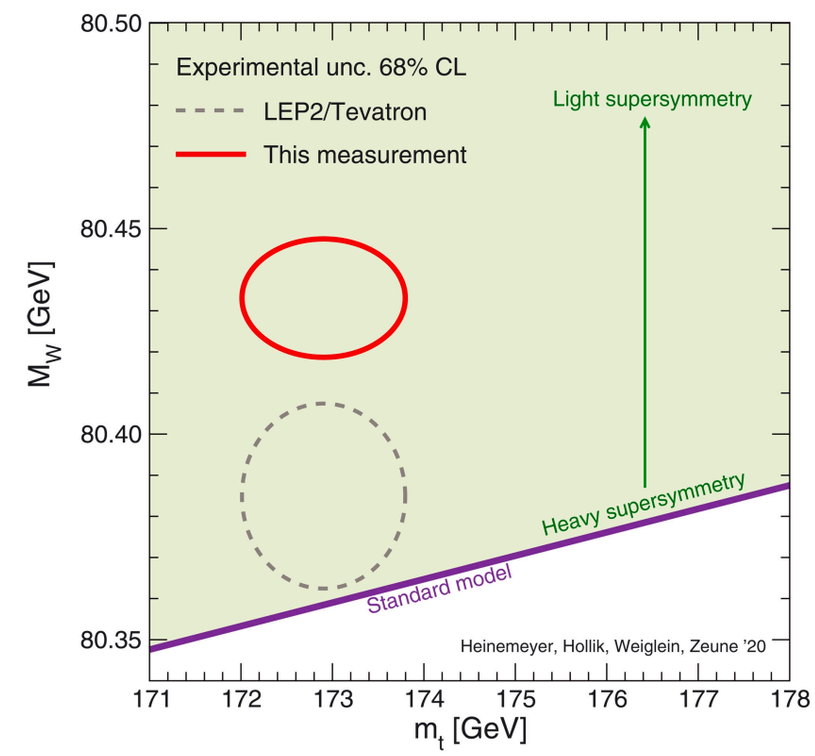
Clearly inconsistent with SM prediction!

CDF-II, *Science* (2022)

Overview of W mass measurements

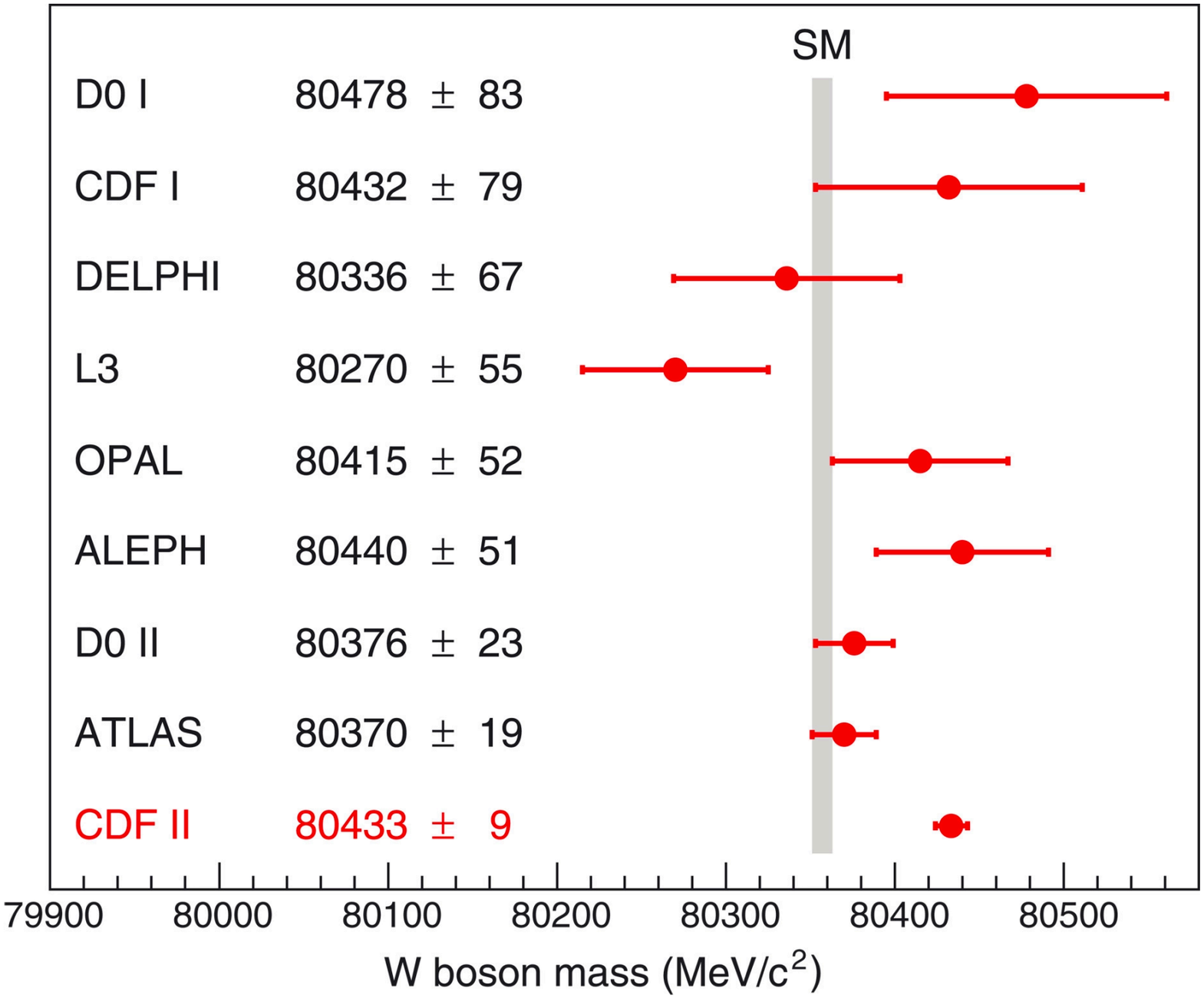


Explanation A: New Physics!

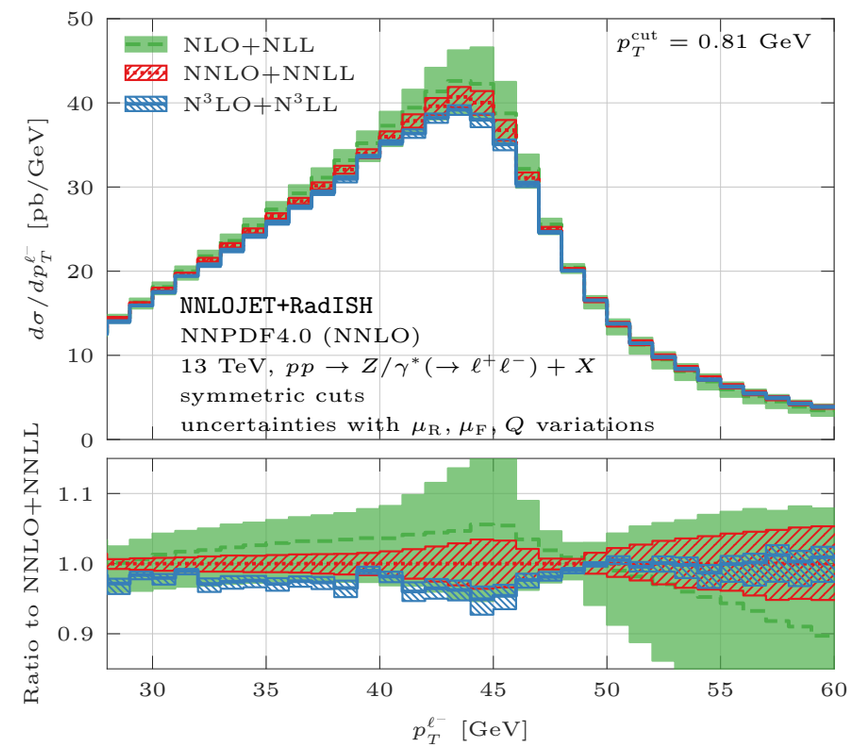


Jordy's talk

Overview of W mass measurements

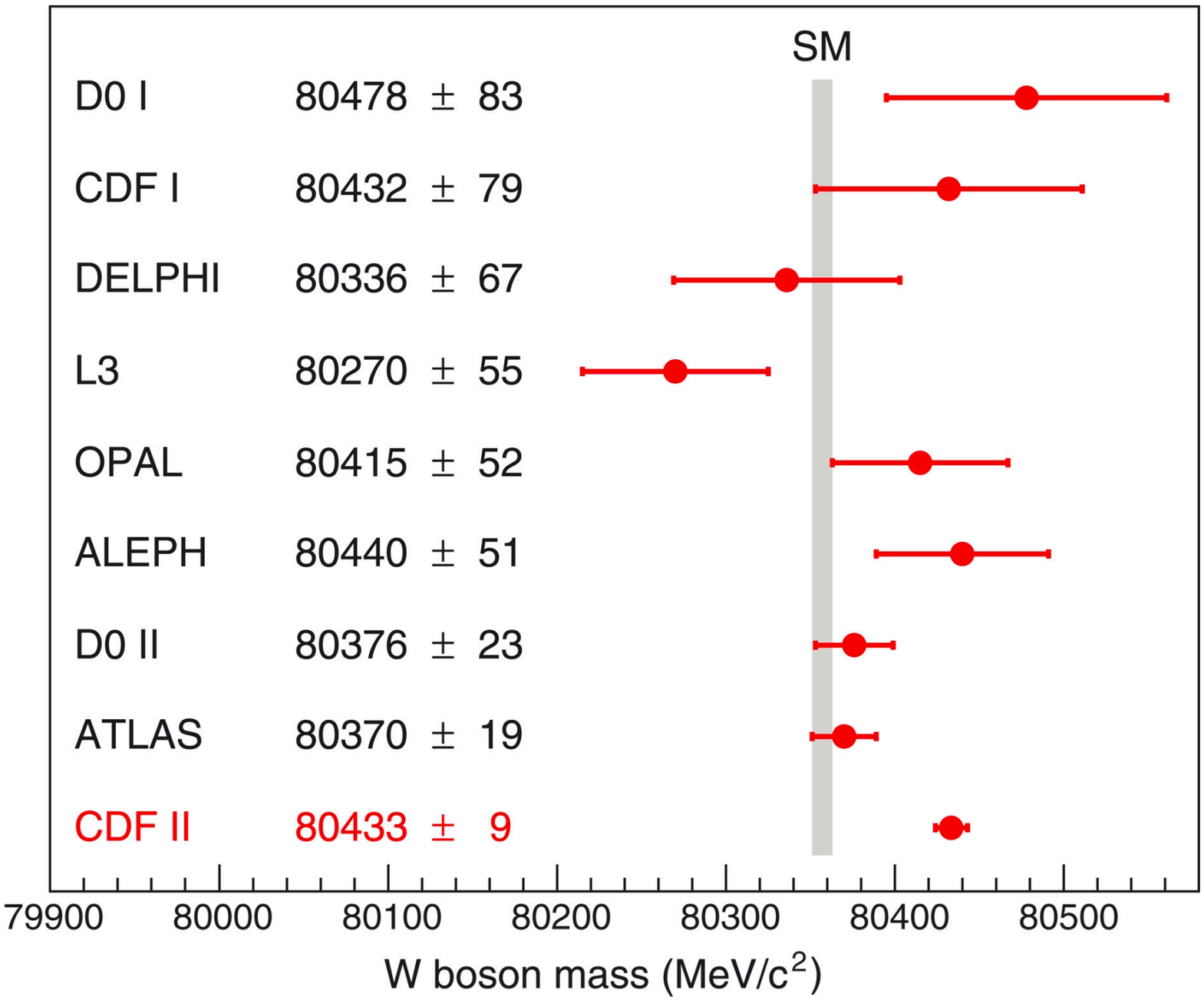


Explanation B: Mismodeling of SM predictions



some possible explanations considered in this talk

Overview of W mass measurements



Explanation C: issues with the experimental analysis

local ATLAS & LHCb experts!

Template fits for the *W* mass

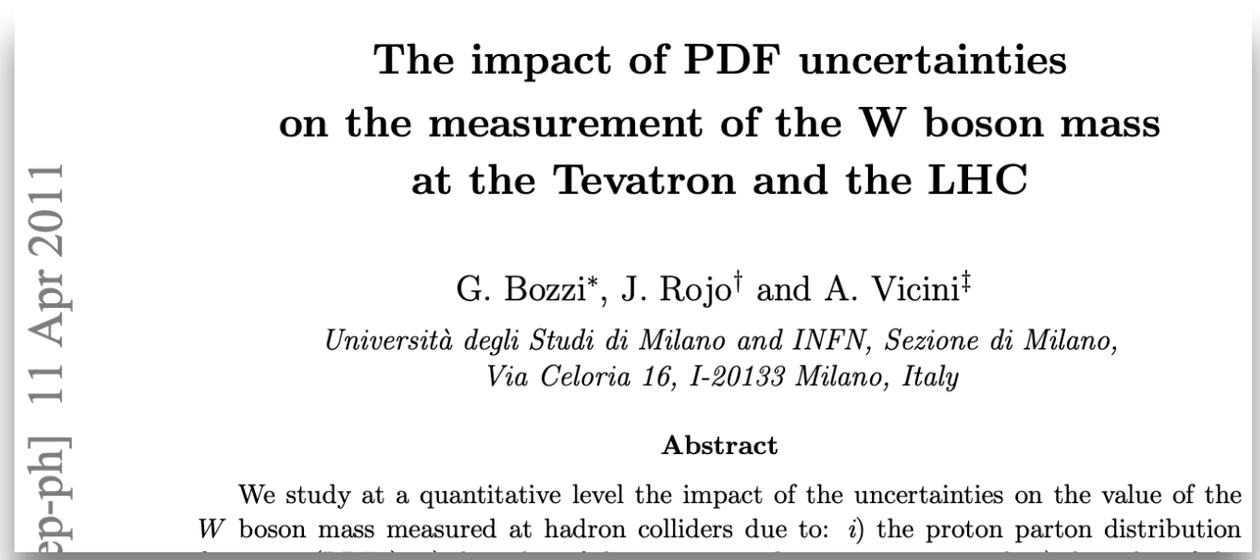
As opposed to other SM parameters, measurements of the ***W* boson mass** at hadron colliders rely heavily on theoretical modelling (of the Drell-Yan process)

Why this is the case?

The mass of the *W* boson can be extracted from data by means of **template fits**

- Start from a **baseline theoretical model** of final-state distributions sensitive to M_W
- Produce **theory templates** of this distribution with a given binning and a range of M_W values
- Measure the same distributions, and compare them with your templates
- The template that **agrees better with data** corresponds to your central M_W value
- Repeat the process for additional templates generated by **varying experimental systematic errors or theory parameters** to estimate the systematic (theory+exp) error on M_W

challenge: small variations in the templates can propagate into large shifts in M_W


ep-ph] 11 Apr 2011

The impact of PDF uncertainties on the measurement of the W boson mass at the Tevatron and the LHC

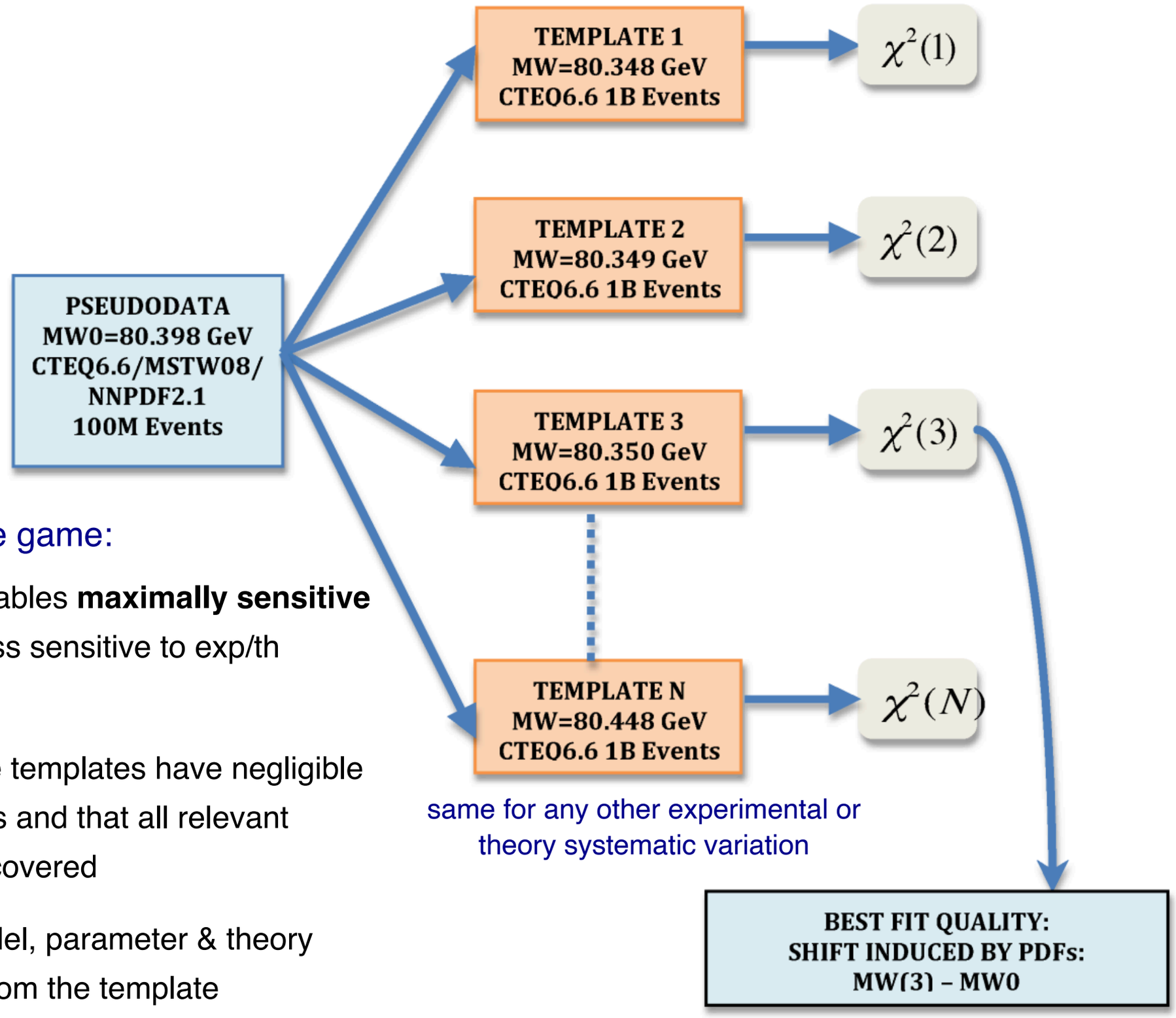
G. Bozzi*, J. Rojo† and A. Vicini‡

Università degli Studi di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy

Abstract

We study at a quantitative level the impact of the uncertainties on the value of the *W* boson mass measured at hadron colliders due to: *i*) the proton parton distribution

Template fits for the *W* mass



The name of the game:

- Identify observables **maximally sensitive to M_W** while less sensitive to exp/th uncertainties
- Ensure that the templates have negligible stat fluctuations and that all relevant variations are covered
- Propagate model, parameter & theory uncertainties from the template calculation to the final measurement

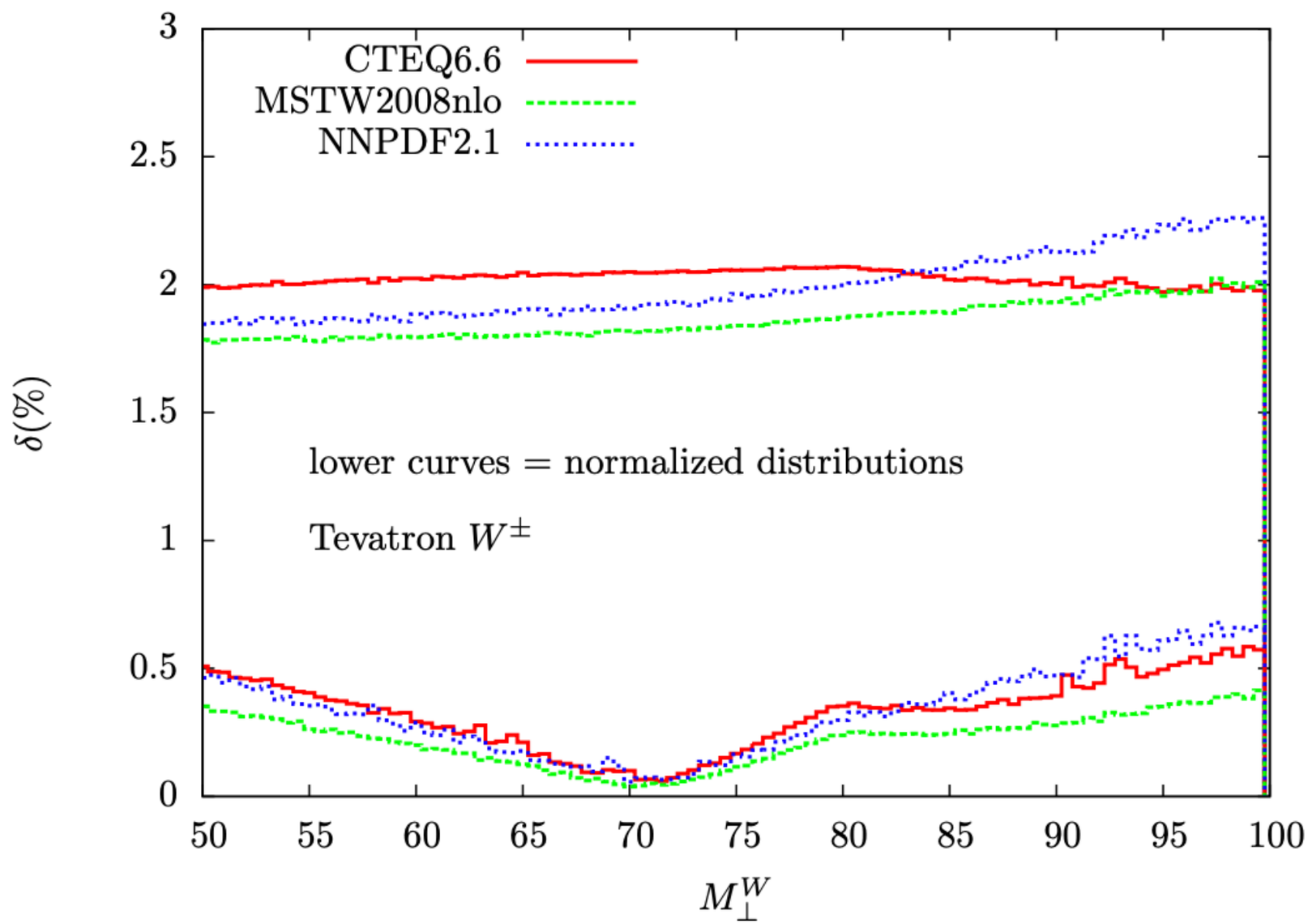
Template fits for the *W* mass

Two of the most frequently used distributions in M_W measurements are $\mathbf{p_T^l}$ and the **transverse mass** $\mathbf{M^W_T}$

$$M_T^W = \sqrt{2p_T^\ell p_T^\nu \left(1 - \cos(\phi^\ell - \phi^\nu)\right)}$$

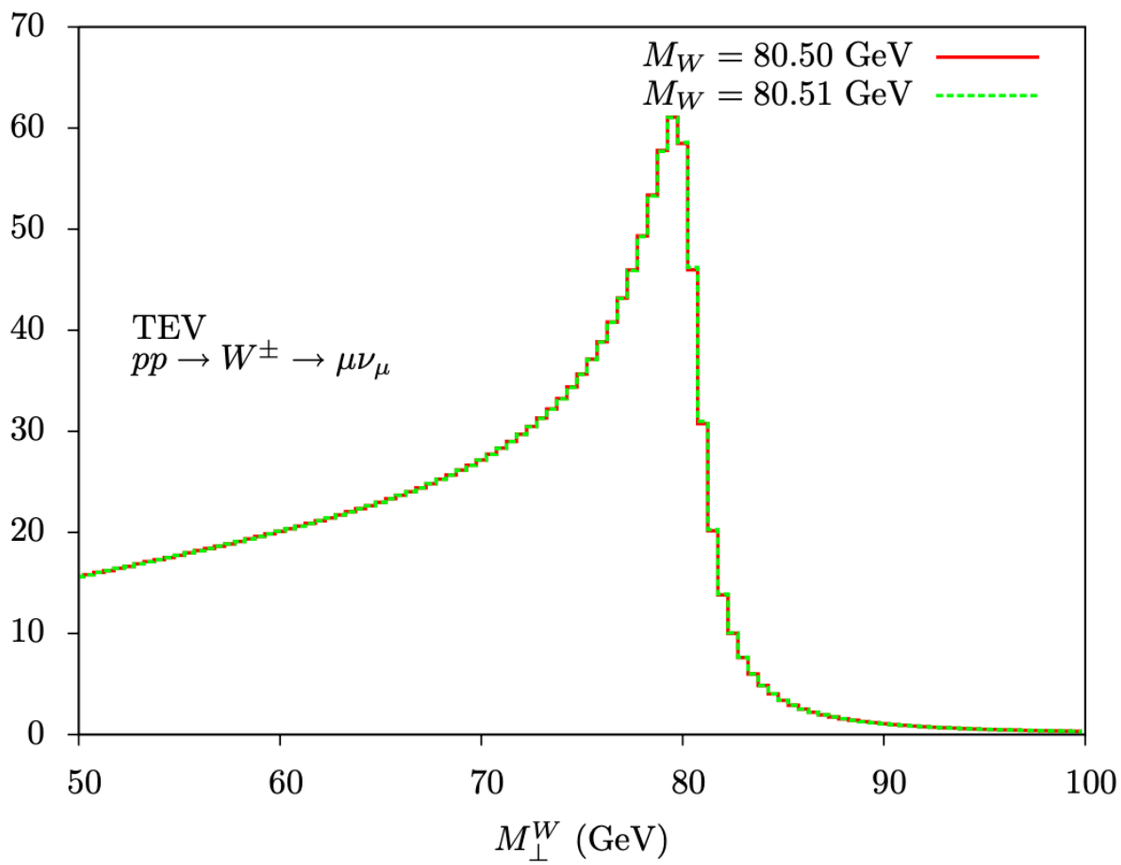
The M_W measurement is sensitive to the **shape** of the distribution: often normalised distributions are used

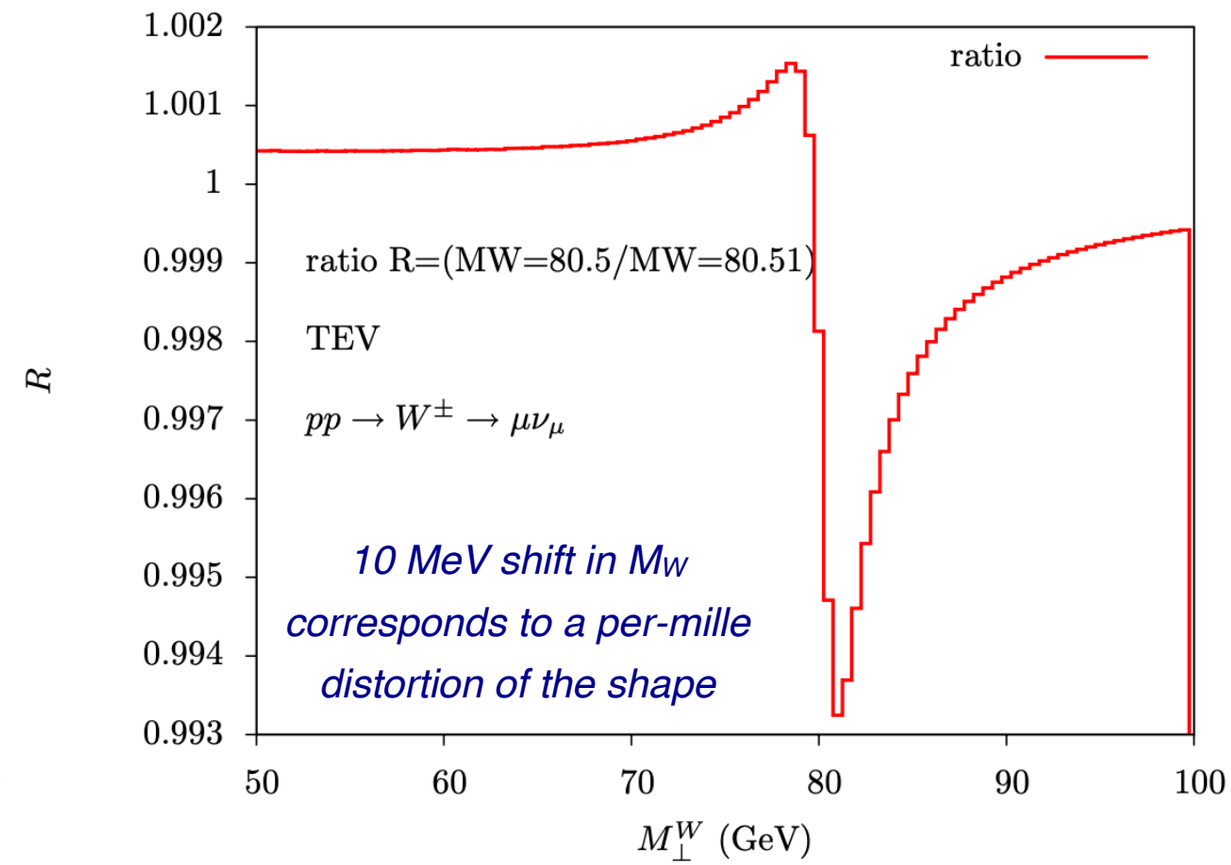
e.g. PDF uncertainties markedly reduced in normalised distributions



Template fits for the *W* mass

How sensitive is the measurement to variations in the theory modelling of the experimental distributions?



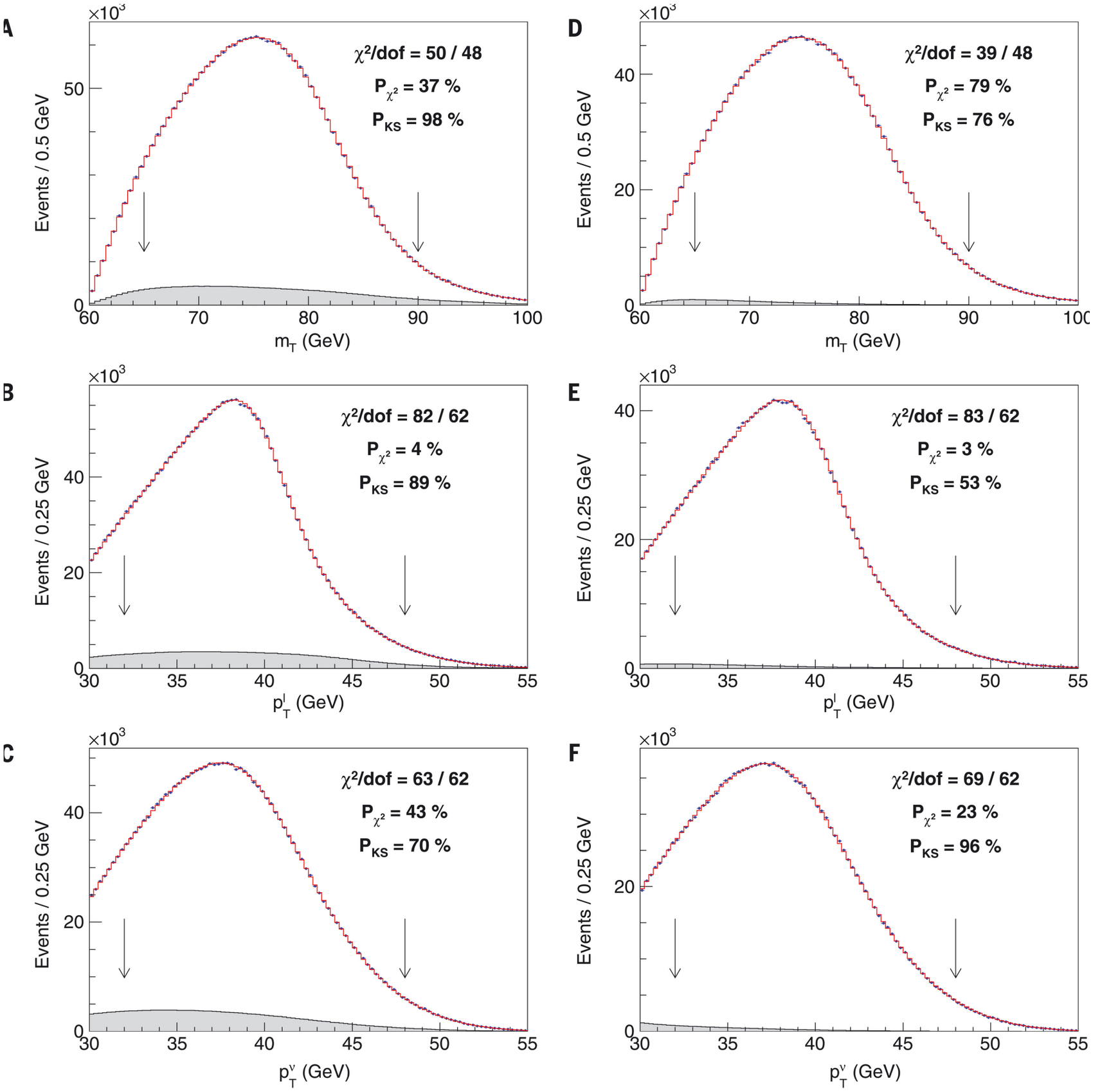


$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{PS}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^l	M_T	p_T^l
1	NLO-QCD+(QCD+QED)$_{PS}$	PYTHIA	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{PS}$	PHOTOS	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	PYTHIA	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	PHOTOS	-88.6±0.6	-370±3	-39.2±0.6	-159±2

Shifts induced by the inclusion of QED radiation and EW corrections

Many small effects can affect the measurement!

Template fits for the *W* mass



- ☑ left: electrons, right: muons
- ☑ arrows indicate fitting ranges
- ☑ shaded area indicates backgrounds
- ☑ These are the distributions for which theory templates need to be generated

CDF-II, *Science* (2022)

The CDF measurement

m_T on the muon channel has the lowest uncertainty (and highest central value …)

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80,429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^{\ell}(e)$	$80,411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^{\nu}(e)$	$80,426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80,446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^{\ell}(\mu)$	$80,428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^{\nu}(\mu)$	$80,428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80,433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

Note that in this categorisation one cannot easily separate theory from experimental systematics, since these are **intertwined** (e.g. modelling p_T^{ν})

dominated by statistics

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

PDFs are the dominant source of systematic error

Where QCD errors are classified?

Template fits for the *W* mass

From a theoretical point of view, which components of the modelling should we pay attention to?

- ☑ Parton Distribution Functions (PDFs) and the associated uncertainties
- ☑ Hard-scattering matrix element (fixed-order) and the associated uncertainties

$$\sigma_{W^\pm}(M,s) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\; \underbrace{\mathscr{L}_{ij}(\hat{s},s)}_{\text{partonic luminosities}}\; \underbrace{\widetilde{\sigma}_{ij}(\hat{s},\alpha_s(M))}_{\text{partonic cross-section}}\,, \quad i,j = u,d,s,g,\ldots$$

$$\widetilde{\sigma}(\alpha_s,\alpha) = \widetilde{\sigma}^{(0)}(\alpha_s,\alpha)\big(1 + c_{1,0}\alpha_s + c_{0,1}\alpha + c_{2,0}\alpha_s^2 + c_{3,0}\alpha_s^3 + c_{1,1}\alpha_s\alpha + c_{0,2}\alpha^2\big)$$

Born (tree-level)	***NLO QCD correction***	***NLO EW correction***	***NNLO QCD correction***	***N3LO QCD correction***	***NNLO mixed correction***	***NNLO EW correction***

- ☑ Hard-scattering matrix element (transverse momentum resummation)
- ☑ QCD and QED parton showers and extra radiation
- ☑ Electroweak corrections
- ☑ …..

n.b. naive power counting often poor predictor of the size of HOs

$$\alpha_s \sim 0.1, \quad \alpha \sim 0.01$$

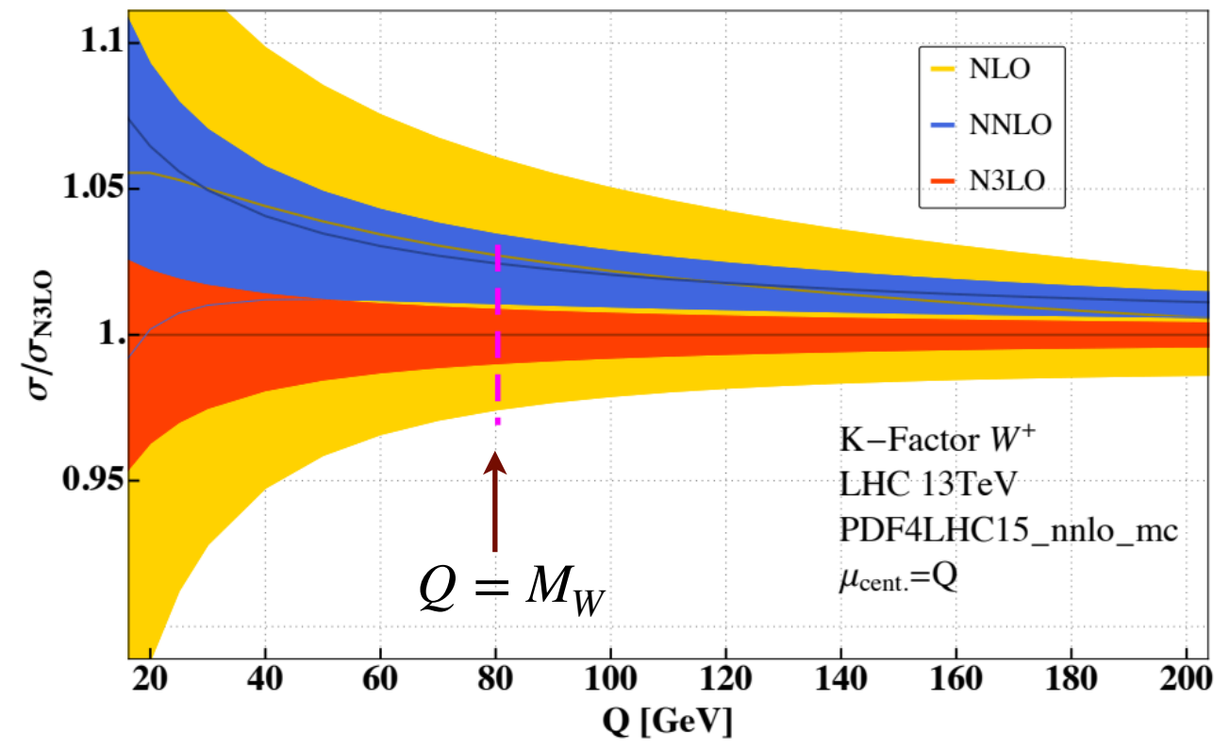
Drell-Yan at N3LO QCD

Several key LHC processes are now available with **N³LO QCD corrections** (inclusive and/or differential)

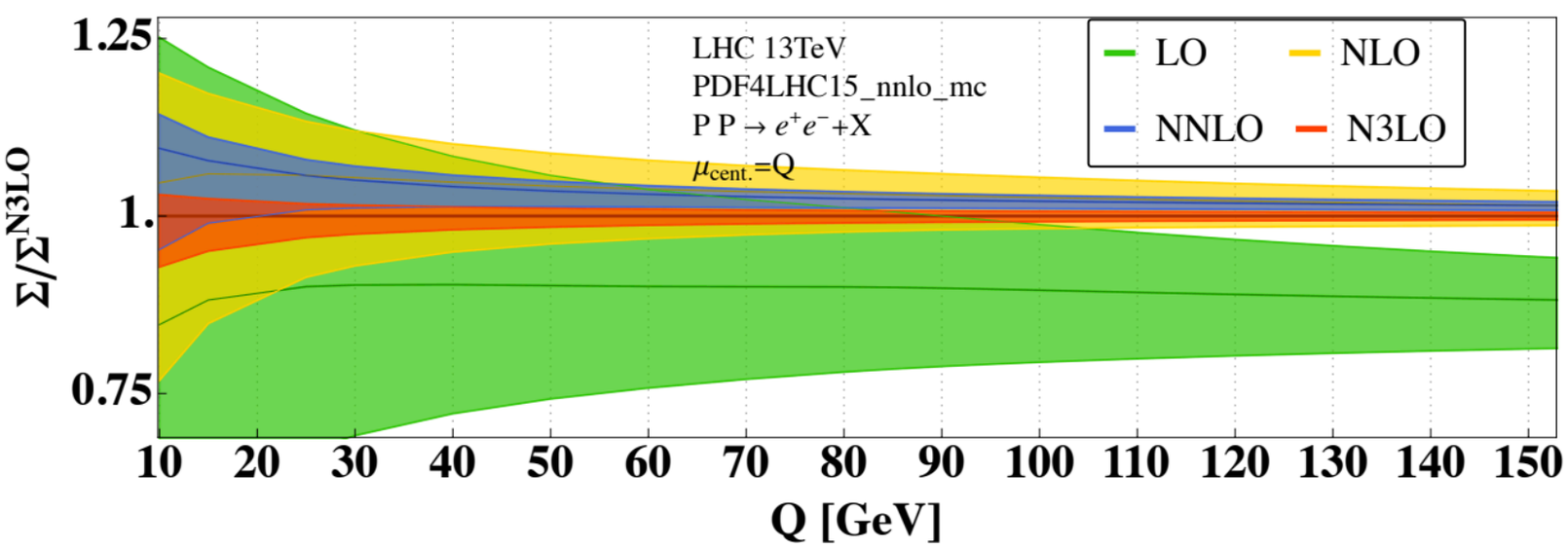
e.g. inclusive charged and neural-current **Drell-Yan**

Perturbative convergence not ideal: for both ***W*** and ***Z/γ****** production the NNLO and N³LO bands do not overlap

nb all ``N3LO" calculations rely on NNLO PDFs, hence one cannot claim **N3LO accuracy** yet



Duhr et al, 2007.13313

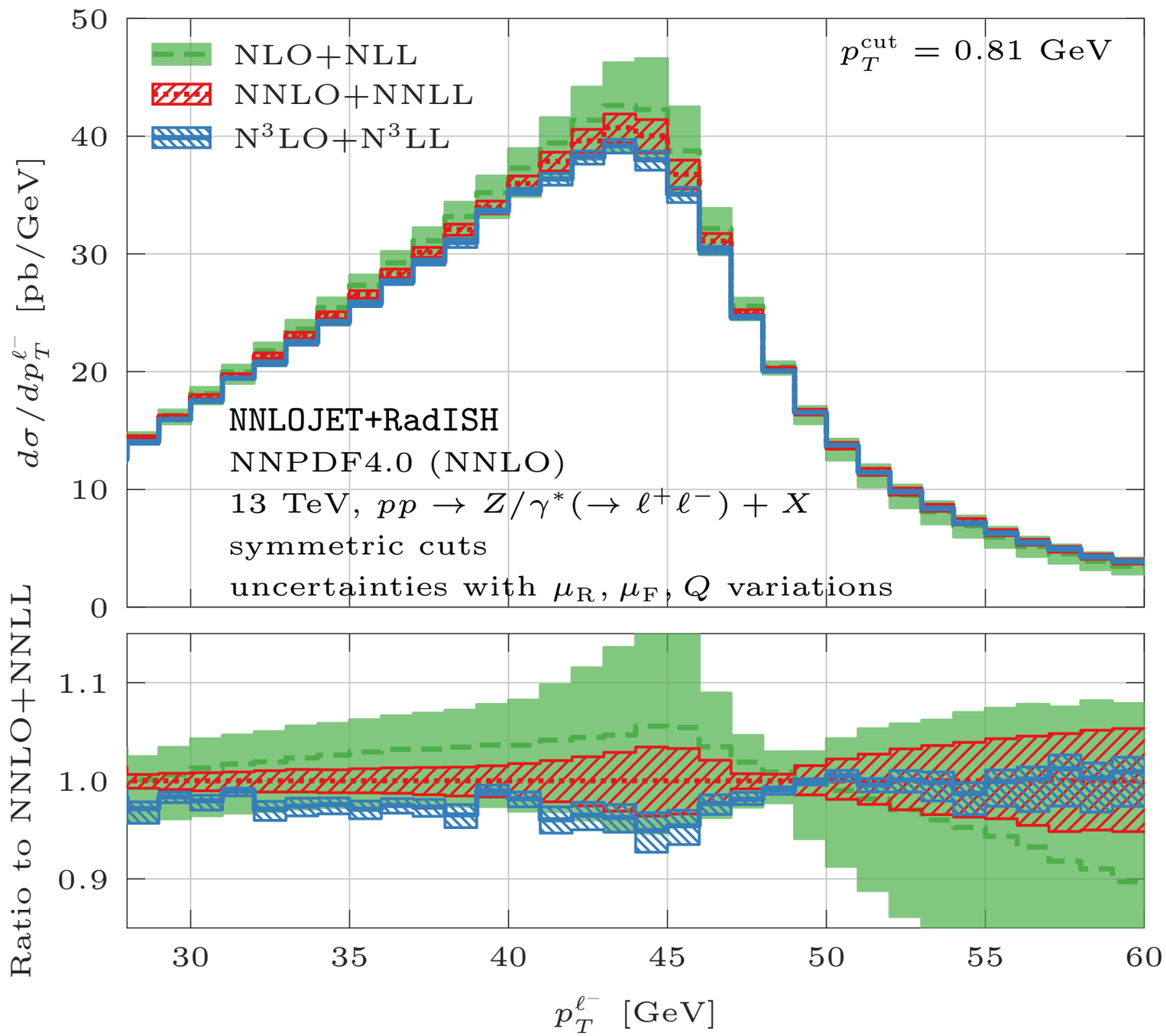


Duhr et al, 2111.10379

Impact for *W* mass measurement?

Drell-Yan at N3LO QCD

Drell-Yan is also available at N3LO at the **fiducial level**, where **realistic kinematic cuts** can be applied



Chen at al, 2203.01565

Impact for *W* mass determinations!

perturbative stability can be optimised with tailored ***kinematic cuts***

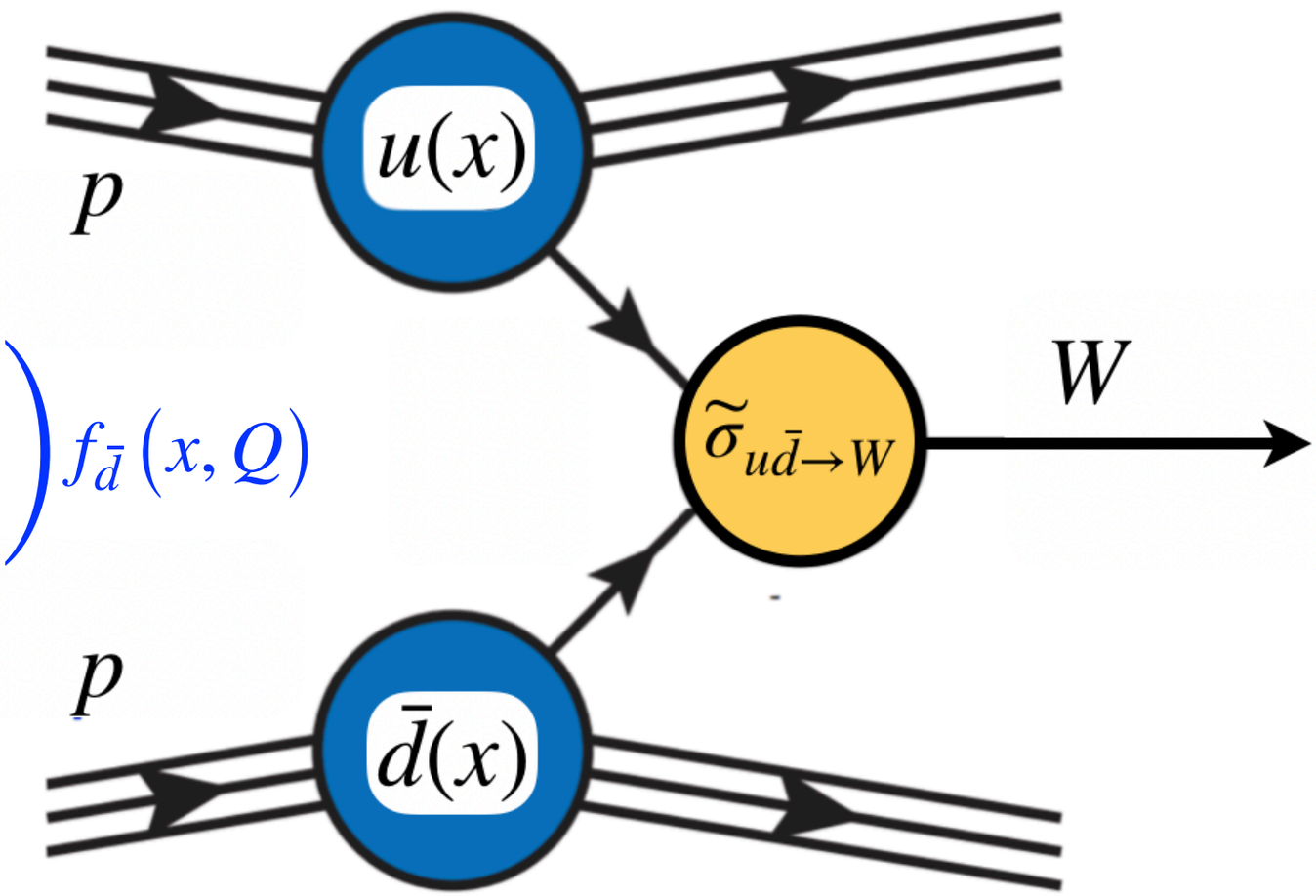
precision *does not necessarily improve at N³LO ….*

Parton Distributions and M_W

Drell-Yan measurements are mostly sensitive to the quark and antiquark PDFs at intermediate *x*

$$\sigma_{W^+}(M,s) \propto \int_{M^2}^{s} d\hat{s}\ \mathscr{L}_{u\bar{d}}(\hat{s},s)\,\widetilde{\sigma}_{u\bar{d}}(\hat{s},\alpha_s(M)) + \ldots$$

$$\mathscr{L}_{u\bar{d}}(Q,s) = \frac{1}{s}\int_{Q^2/s}^{1} \frac{dx}{x} f_u\left(\frac{Q^2}{sx},Q\right) f_{\bar{d}}\left(x,Q\right)$$



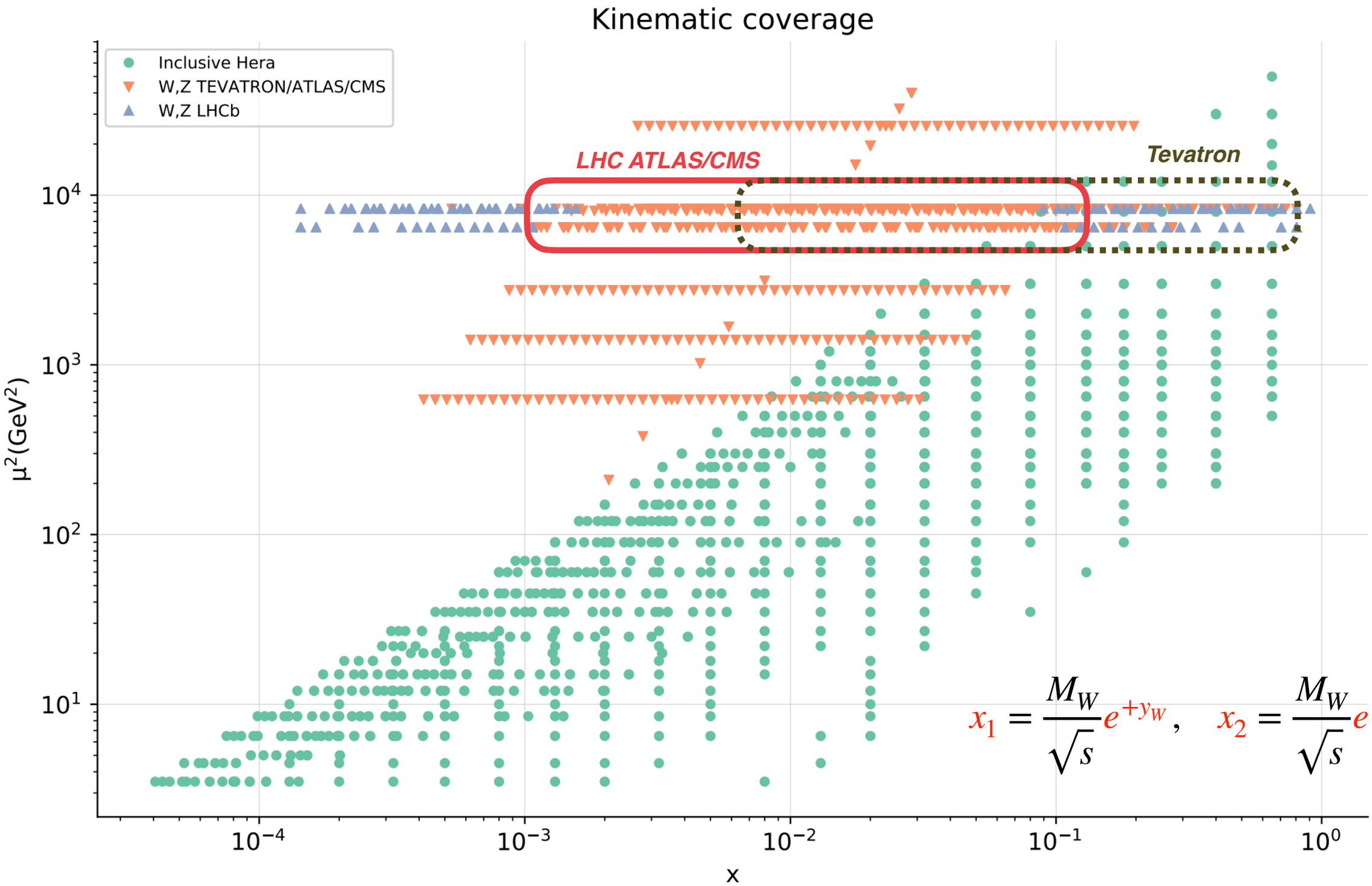
large contributions from subleading partonic channels

$$x_1 = \frac{M_W}{\sqrt{s}} e^{+y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

Parton Distributions and M_W

Drell-Yan measurements are mostly sensitive to the quark and antiquark PDFs at intermediate x

Tevatron is sensitive to larger-x PDFs than LHC

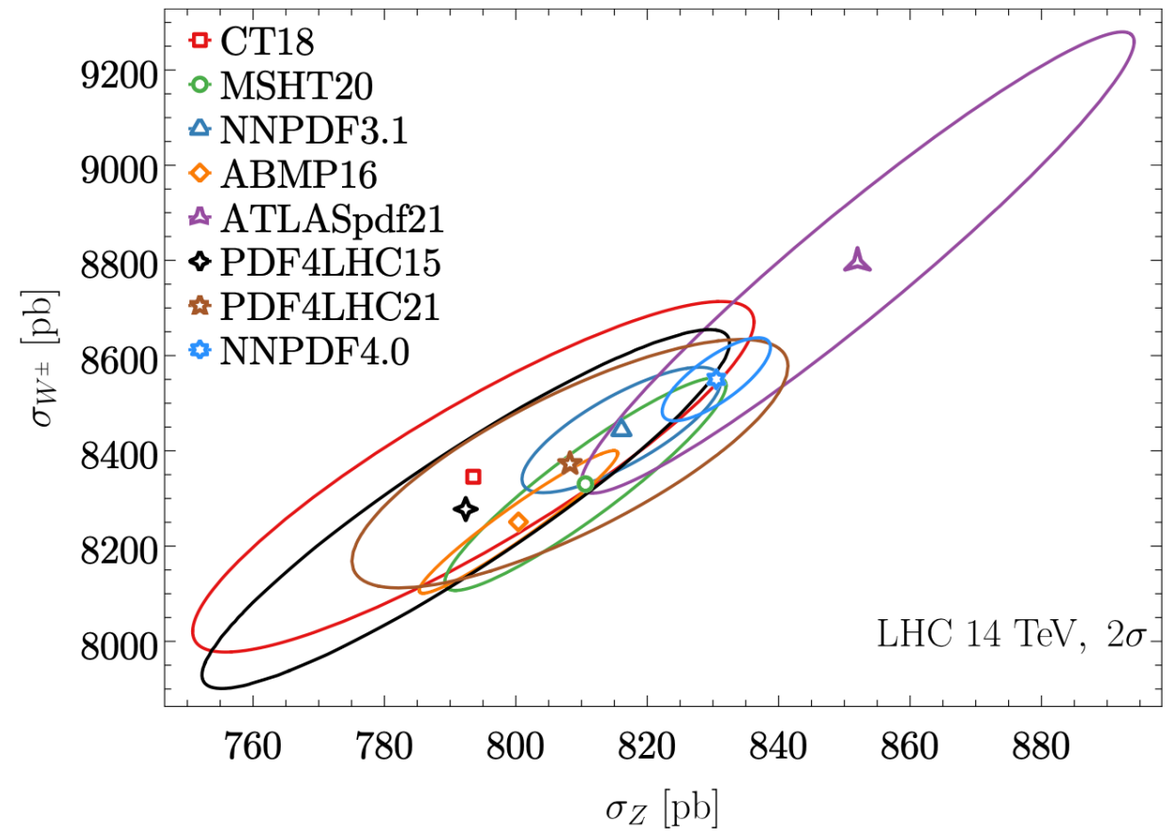


$$x_1 = \frac{M_W}{\sqrt{s}} e^{+y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

Parton Distributions and M_W

program (58, 59). We use the NNPDF3.1 (60) parton distribution functions (PDFs) of the (anti)proton, as they incorporate the most complete relevant datasets of the available next-to-next-to-leading order (NNLO) PDFs. Using 25 symmetric eigenvectors of the NNPDF3.1 set, we estimate a PDF uncertainty of 3.9 MeV. We find that the CT18 (61), MMHT2014 (62), and NNPDF3.1 NNLO PDF sets produce consistent results for the W boson mass, within ±2.1 MeV of the midpoint of the interval spanning the range of values. The model-dependent nature of the analysis implies that future improvements or corrections in any relevant theoretical modeling can be used to update our measurement quantifiably [see section IV of (63)].

CDF-II, *Science* (2022)



The CDF measurements quotes **4 MeV as PDF error**

- not enough info to reproduce their extraction
- Spread in size of PDF errors accounted for?
- Specific selection of PDF sets?
- PDF correlations accounted for?

δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT14	NNPDF4.0	MSHT20	CTEQ6M
$\langle M_T \rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$	$-7.3^{+8.4}_{-12.0}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$	$-7.3^{+5.6}_{-9.3}$
$\langle M_T \rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$	$-14.0^{+9.0}_{-11.9}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$	$-14.6^{+5.8}_{-5.4}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–	-3.3

Estimated shifts in M_W from modern PDF sets, arXiv:2205.03942

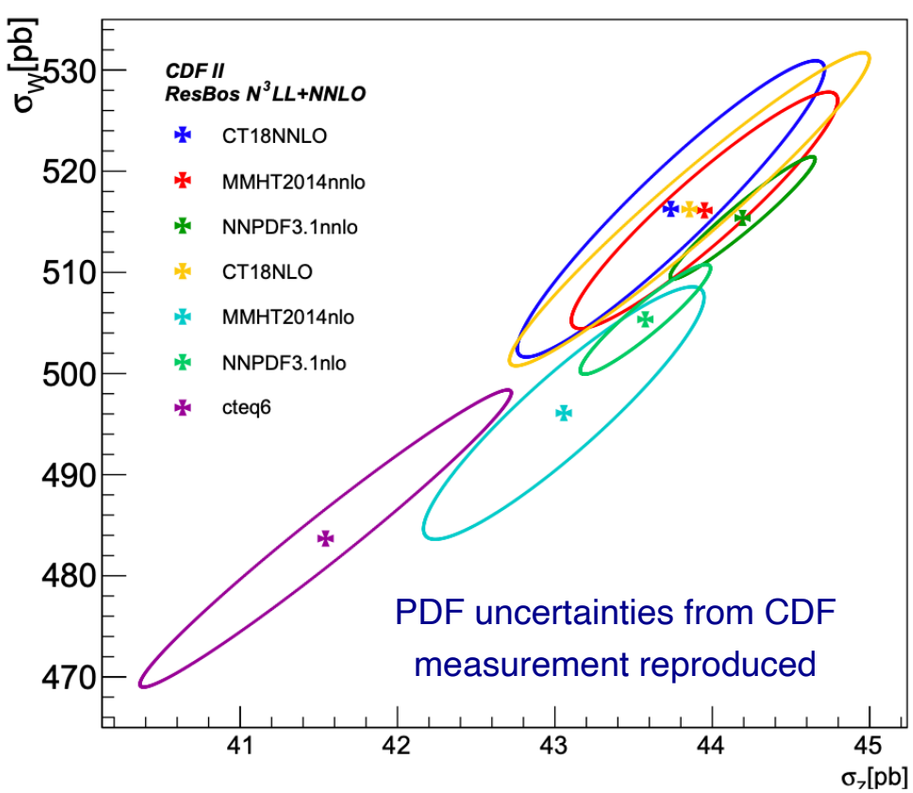
Modelling differential distributions

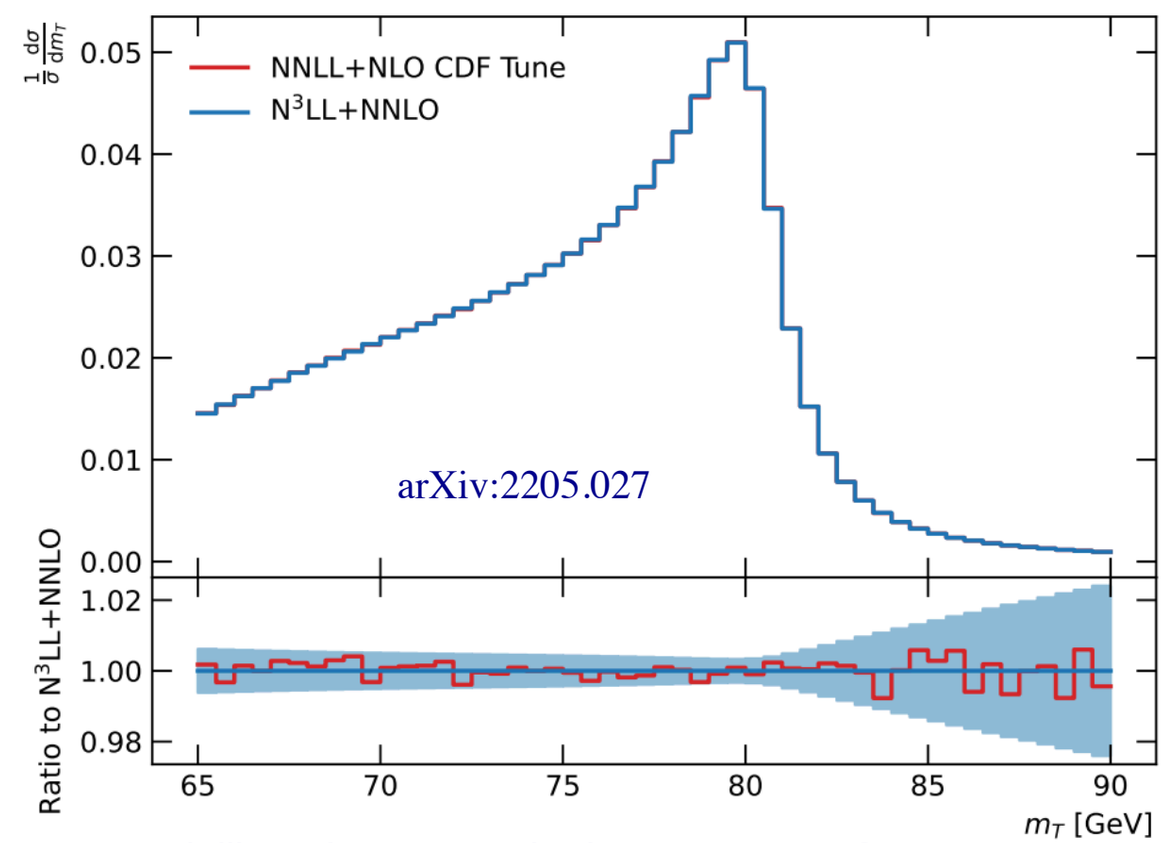
The data distributions of m_T, p_T^ℓ, and p_T^ν are compared with corresponding simulated line shapes ("templates") as functions of M_W from a custom Monte Carlo simulation that has been designed and written for this analysis. A binned likelihood is maximized to obtain the mass and its statistical uncertainty. The kinematic properties of W and Z boson production and decay are simulated using the RESBOS program (54–56), which calculates the differential cross section with respect to boson mass, transverse momentum, and rapidity for boson production and decay. The calculation is performed at next-to-leading order in perturbative quantum chromodynamics (QCD), along with next-to-next-to-leading logarithm resummation of higher-order radiative quantum amplitudes. RESBOS offers one of the most accurate theoretical calculations available for these processes. The nonperturbative model parameters in RESBOS and the QCD interaction coupling strength α_s are external inputs needed to complete the description of the boson p_T spectrum and are constrained from the high-resolution dilepton $p_T^{\ell\ell}$ spectrum of the Z boson data and the p_T^W data spectrum. EM radiation from the leptons is modeled with the PHOTOS program (57), which is calibrated to the more accurate HORACE program (58, 59). We use the NNPDF3.1 (60) parton distribution functions (PDFs) of the

Templates for the differential distributions are produced with **ResBos** at NLO+NNLL, complemented with a data-driven determination of input parameters

A similar extraction of M_W with pseudo-data and **ResBos2 (NNLO+N³LL)** finds at most a **downward shift of 10 MeV**, unable to explain the discrepancy with the SM

CDF-II, *Science* (2022)





modelling of non-perturbative parameters?

CDF vs ATLAS/LHCb

CDF-II

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

ATLAS

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
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

LHCb

Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

PDF errors halved in CDF compared to ATLAS/LHCb

Statistical error the same in ATLAS and CDF

Theory (excl. PDF) errors is 11 MeV and 17 MeV in ATLAS/LHCb, what about CDF?

explained by different kinematics? Data-driven theory calibration? Different definition of uncertainties?

Some points for discussion

From a theoretical perspective, a measurement of M_W at hadron colliders with **O(few MeV) precision** is extremely challenging. Some points for the discussion

How to define the PDF systematic error? Which PDF sets to include? How to combine them?

Treatment of missing higher-order uncertainties and resummation parameters? Dependence with the generator? Impact of N3LO?

Modelling of the correlations between the **p_T^Z and p_T^W distributions?**

Impact of higher order electroweak and mixed QED/QCD corrections?

Why the CDF-II measurement is more precise than ATLAS/LHCb? What about CMS?

What would have happened if different MC generators other than ResBos had been used?

What is the most appropriate definition of theory uncertainties in this measurement?