Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

Highlights from the Saclay workshop “Ultimate precision at hadron colliders”

Alessandro Vicini
University of Milano, INFN Milano

Pisa, February 7th 2020

Schedule of the workshop

first week: PDF
EW precision measurements
low-energy observables

second week: Higgs and high-energy probes
global interpretation

Wednesday, 27 November

9:00 → 11:00 **Measurements of EW precision observables**
Conveners: Alessandro Vicini (Università degli Studi e INFN Milano (IT)), Mika Anton Vesterinen (University of Warwick (London (GB))

- 10:00 **Measurement of m_W : experimental and theoretical requirements**
  Speaker: Stefano Camarda (CERN)
  wmass.pdf

1:00 → 11:30 **Break**

1:30 → 12:30 **Measurements of EW precision observables**
Conveners: Alessandro Vicini (Università degli Studi e INFN Milano (IT)), Mika Anton Vesterinen (University of Warwick (GB)), Ulla Blumenschein (University of London (GB))

- 11:30 **Measurement of $\sin^2\theta$: experimental and theoretical requirements**
  Speaker: Arie Bodek (University of Rochester (US))
  Mixing_angle-Bode...

2:30 → 14:00 **Lunch**

4:00 → 18:00 **Informal discussions: 2**

Thursday, 28 November

09:00 → 12:30 **Measurements of EW precision observables: QCD issues in the high-precision determination of EW parameters**
Conveners: Alessandro Vicini (Università degli Studi e INFN Milano (IT)), Mika Anton Vesterinen (University of Warwick (GB)), Ulla Blumenschein (University of London (GB))

- 09:15 **Experimental challenges: high- vs low-pileup measurements** (35m)
  Speaker: Josh Bendavid (CERN)
  expChallengesEWK...
- 09:50 **Revisiting the estimate of PDF uncertainties** (35m)
  Speaker: Emanuele Angelo Bagnaschi (Paul Scherrer Institut)
  OrsayWorkshop-Ba...
- 10:25 **Coffee Break** (40m)
- 11:05 **Ultimate QCD tools** (35m)
  Speaker: Thomas Gehrmann
  Ultimate_Gehrman...
- 11:40 **Discussion** (20m)

14:00 → 17:30 **Measurements of EW precision observables: Towards a global EW fit**
Conveners: Alessandro Vicini (Università degli Studi e INFN Milano (IT)), Mika Anton Vesterinen (University of Warwick (GB)), Ulla Blumenschein (University of London (GB))

- 14:00 **Combination of MW / sin2theta final values obtained at different colliders/experiments** (35m)
  Speaker: Nansi Andari (Université Paris-Saclay (FR))
  presentation_andar...
- 14:35 **Global EW fits: experimental and theoretical issues** (35m)
  Speaker: Matthias Schott (CERN / University of Mainz)
  LHC_Ultimate_Prec...
- 15:10 **Discussion** (20m)
- 15:30 **Coffee break** (30m)
- 16:00 **O(alpha^2) initial state QED corrections in e+e- -> f fbar**
  Speaker: Kay Schönwald (DESY)
  talk-schoenwald.pdf
- 16:35 **Towards fully NLO-EW analyses**
  Speaker: Mauro Chiesa (University of Würzburg)
  chiesa_orsay.pdf
- 17:10 **Discussion**

Different open problems and challenges

Theory

role of higher-order corrections in the description of differential observables (Gehrmann)
impact of the QCDxEW interplay in the MW determination (Chiesa)
role the input scheme in the $\sin^2\theta_{eff}$ determination (Chiesa)
relevance of the PDF correlations in the MW determination (Bagnaschi)

Global fits and interpretation

prospects for the GFitter results in view of new improved experimental inputs (Schott)

Experiments

relevance of low- and high-pile-up data (Camarda, Bendavid)
bayesian reweighing and PDF uncertainty in the $\sin^2\theta_{eff}$ determination (Bodek)
methodologies to combine the MW results of different experiments/channels/energies (Andari)

Triple-differential Drell-Yan cross section

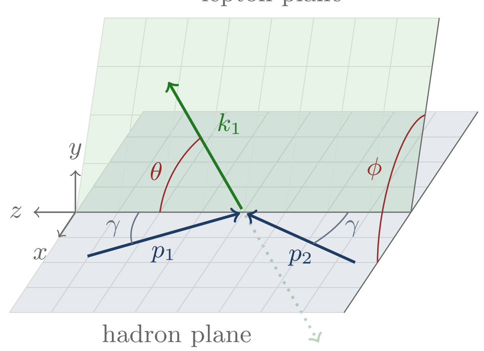
T. Gehrmann

- Lepton pair production: EW precision observable

$$\frac{d^3\sigma}{dm_{ll}dy_{ll}d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{ll}s}\sum_q P_q(\cos\theta^*)\left[f_q(x_1,Q^2)f_{\bar{q}}(x_2,Q^2)+(q\leftrightarrow\bar{q})\right]$$

- ATLAS 8 TeV measurement [1710.05167]

Observable	Central-Central	Central-Forward
m_{ll} [GeV]	[46,66,80,91,102,116,150,200]	[66,80,91,102,116,150]
$\lvert y_{ll}\rvert$	[0,0.2,0.4,0.6,0.8,1,1.2, 1.4,1.6,1.8,2,2.2,2.4]	[1.2,1.6,2,2.4,2.8,3.6]
$\cos\theta^*$	[-1,-0.7,-0.4,0,0.4,0.7,1]	[-1,-0.7,-0.4,0,0.4,0.7,1]
Total Bin Count:	504	150



Triple-differential Drell-Yan cross section

- Measured with fiducial event selection cuts (on single leptons)

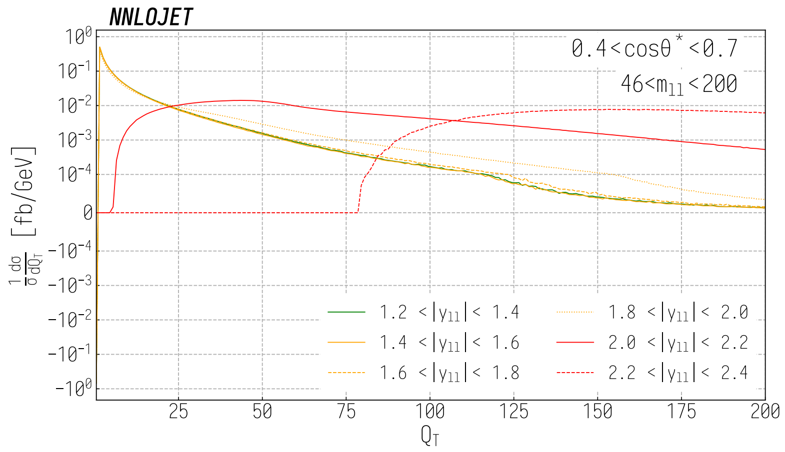
Central-Central	Central-Forward	
$p_T^l > 20$ GeV	$p_{T,F}^l > 20$ GeV	$p_{T,C}^l > 25$ GeV
$\lvert y^l\rvert < 2.4$	$2.5 < \lvert y_F^l\rvert < 4.9$	$\lvert y_C^l\rvert < 2.4$
46 GeV $< m_{ll} <$ 200 GeV	66 GeV $< m_{ll} <$ 150 GeV	

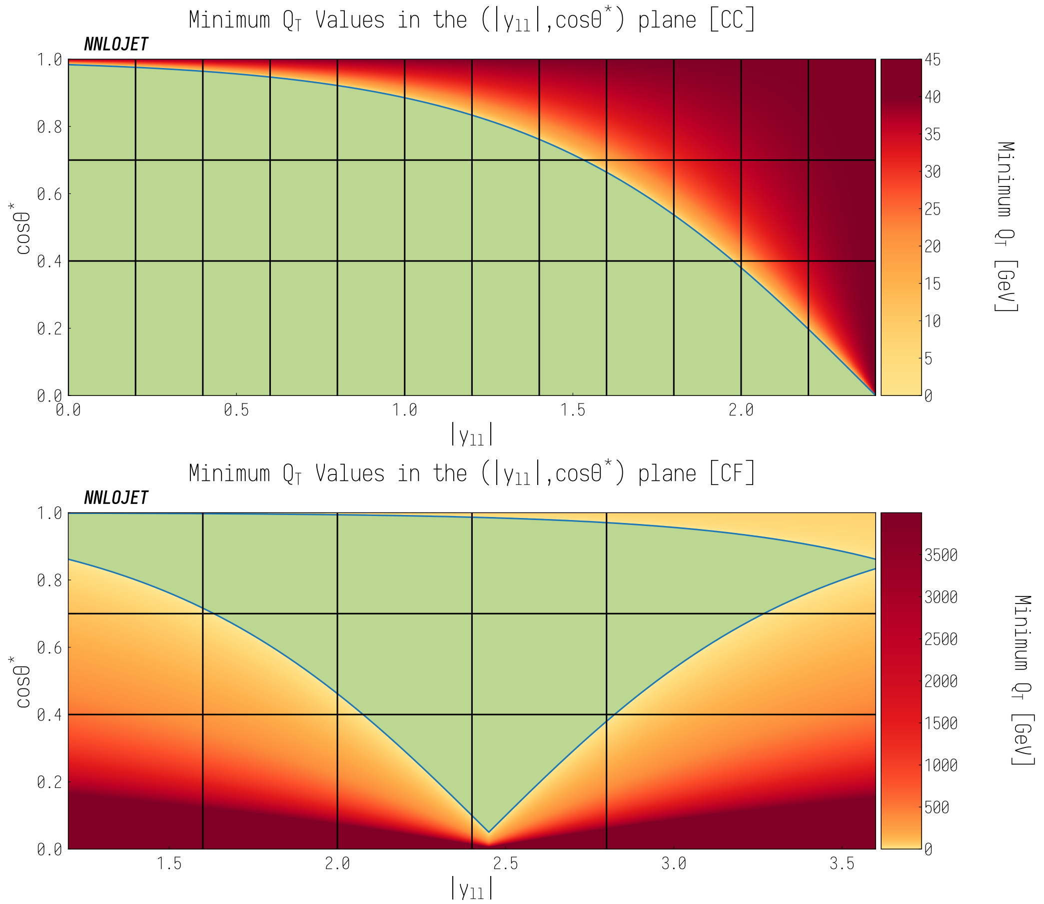
- Fiducial cuts influence acceptances in triple-differential bins
[D.Walker, Durham 2019 PhD thesis]

Triple-differential Drell-Yan cross section

- Leading-order forbidden bins
  - require finite Q_T of lepton pair
  - shown here: symmetric lepton pair

→ prediction starts only at NLO
  - lower accuracy
  - potential perturbative instabilities



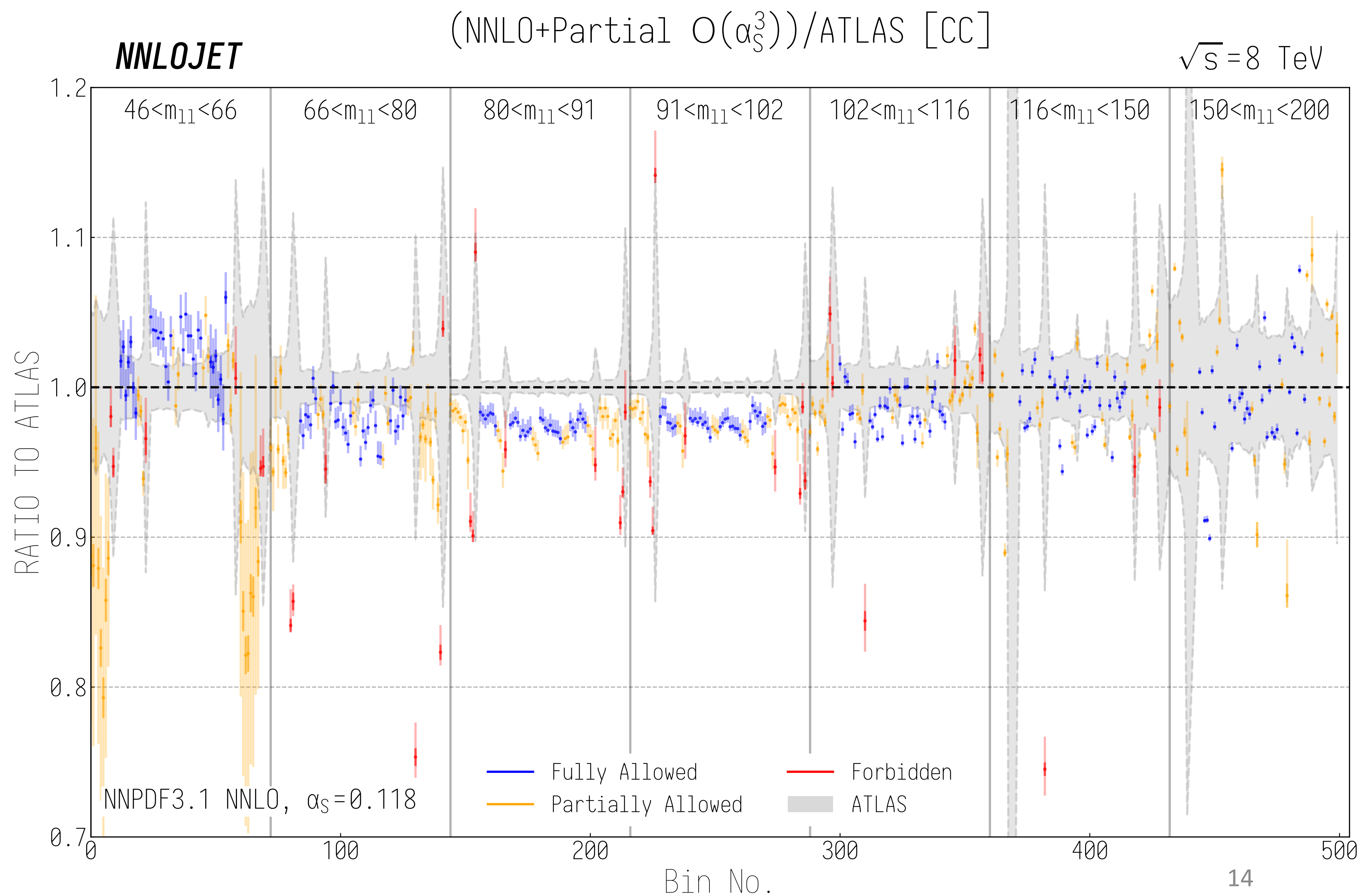


T. Gehrmann

Triple-differential Drell-Yan cross section

Including $O(\alpha_s^3)$ in forbidden bins

- improve theory uncertainty
- better agreement with data
- sizable deviations in bins around M_Z
- require NLO EW



Thomas Gehrmann

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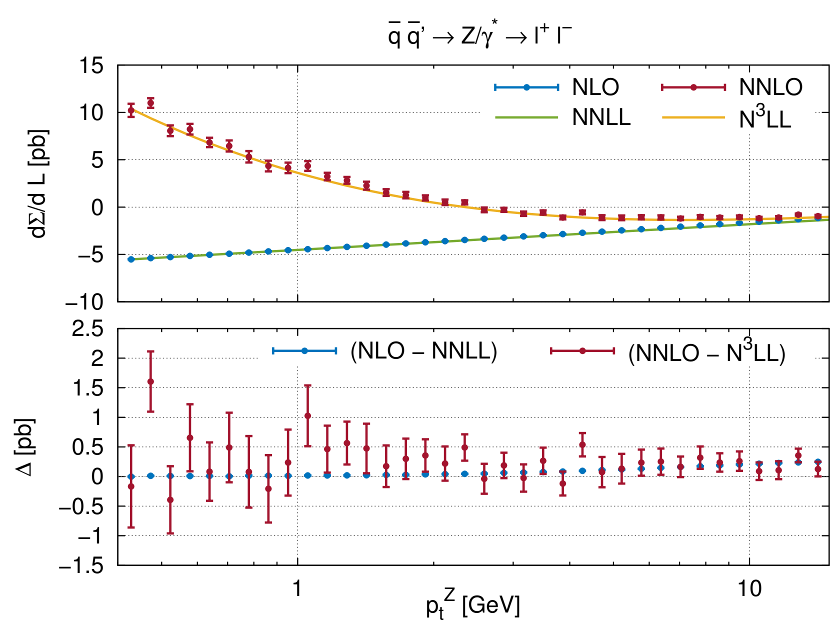
Triple-differential Drell-Yan cross section

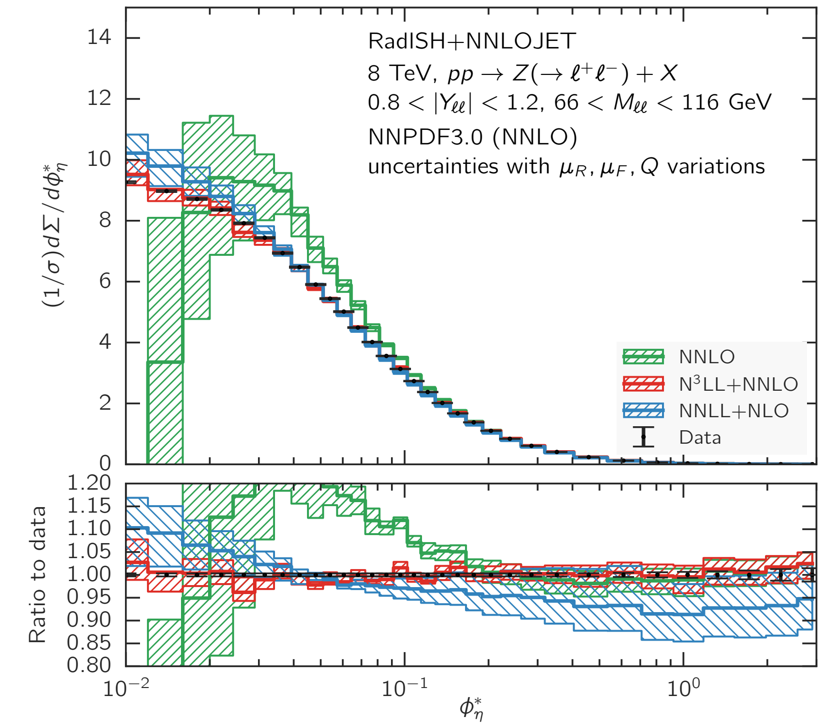
Forbidden bins at leading order

- similar kinematics to Q_T or ϕ^* distribution of lepton pairs
- $O(\alpha_s^3)$ corrections (Drell-Yan N^{3}LO) obtained from V+jet at NNLO

[R.Boughezal, X.Liu, F.Petriello; NNLOJET: A.Gehrmann-De Ridder, N.Glover, A.Huss, T.Morgan, D.Walker, TG]

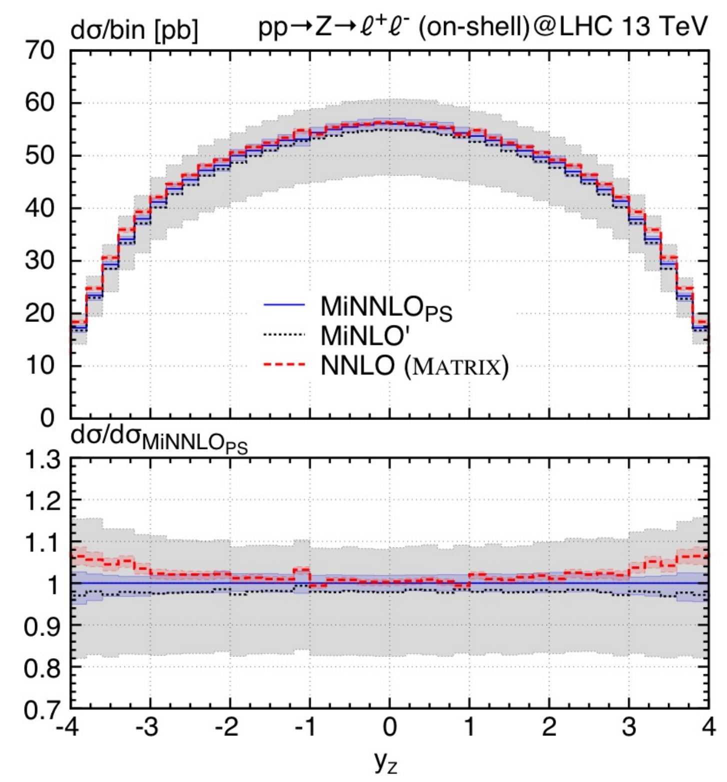
- replace jet requirement by (small) Q_T cut
- NNLOJET: small QT region validated expanding N3LL resummation [W.Bizon, P.F.Monni, E.Re, L.Rottoli, P.Torrielli + NNLOJET]
- in future: can be matched to N3LL resummation





Directions in precision QCD

- NNLO for higher multiplicities (beyond 2 $\longrightarrow$ 2)
  - virtual two-loop amplitudes and integrals largely unknown
  - methods for handling infrared singularities becoming unpractical
  - much room for conceptual and technical progress
- Matching NNLO and parton showers
  - Higgs and Drell-Yan production [S.Höche, Y.Li, S.Prestel; P.Monni, P.Nason, E.Re, M.Wiesemann, G.Zanderighi]
- Matching NNLO and analytic resummation
  - Higgs and Drell-Yan q_T distribution [HX.Zhu et al., P.Monni et al.]
- N3LO for benchmark processes



Combination of EW and QCD corrections

M. Chiesa

Templates accuracy: LO		M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	Pseudodata accuracy	M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

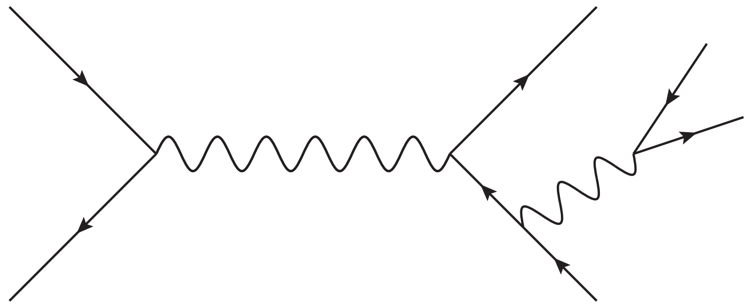
$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\rm PS}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\rm PS}$	PYTHIA	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\rm PS}$	PHOTOS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

convolution with QCD can change a lot the impact of EW corrections

the bulk of the QCDxQED effects is included in the analyses
but
an estimate of the uncertainty on the size of these corrections is not available

Uncertainties from higher order effects: pair radiation

same order as 2 γ radiation (NNLO)



$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$ M_T	 p_T^ℓ
1 HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
2 HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1

$\Delta M_W(\mu^+\nu) \sim 5 \pm 1$ MeV (from μ) and $\sim 3 \pm 2$ MeV (from e)

An electroweak scheme with (Gmu, MZ, $\sin^2\theta_{eff}$) as inputs

M.Chiesa, F.Piccinini, AV, arXiv:1906.11569

The weak mixing angle is related to the left- and right-handed (vector and axial-vector) couplings of the Z boson to fermions

$$\sin^2\theta^l_{eff} = \frac{I^l_3}{2Q_l}\left(1-\frac{g^l_V}{g^l_A}\right) = \frac{I^l_3}{Q_l}\left(\frac{-g^l_R}{g^l_L-g^l_R}\right)$$

The request that the tree-level relation holds to all orders fixes the counterterm for $\sin^2\theta_{eff}$ on-shell definition

$$\delta\sin^2\theta^\ell_{eff} = -\frac{1}{2}\frac{g^\ell_L g^\ell_R}{(g^\ell_L-g^\ell_R)^2}\,\mathrm{Re}\left(\frac{\delta g^\ell_L}{g^\ell_L}-\frac{\delta g^\ell_R}{g^\ell_R}\right)$$

The renormalised angle is identified with the LEP leptonic effective weak mixing angle

The Z mass is defined in the complex mass scheme.

Δr is evaluated with $\sin^2\theta_{eff}$ as input and differs from the usual (α,MW,MZ) expression

See also D.C.Kennedy, B.W.Lynn,Nucl.Phys.B322, 1; F.M.Renard, C.Verzegnassi, Phys.Rev.D52,1369; A.Ferroglia, G.Ossola, A.Sirlin,Phys.Lett.B507,147; A.Ferroglia, G.Ossola, M.Passera, A.Sirlin,Phys.Rev.D65 (2002) 113002

This scheme allows to express any observable as $\mathcal{O} = \mathcal{O}(G_\mu, m_Z, \sin^2\theta^{lep}_{eff})$

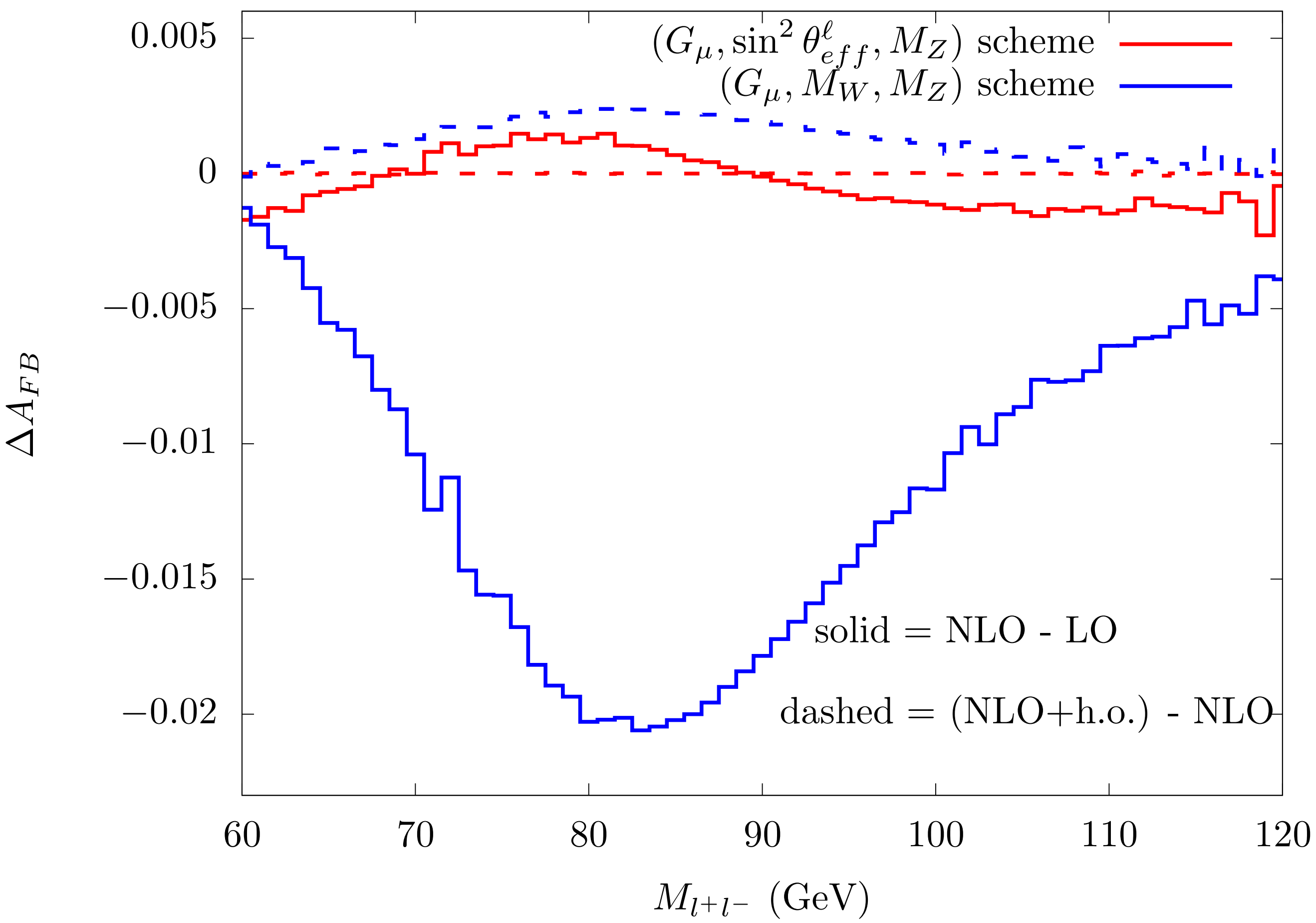
so that templates as a function of $\sin^2\theta_{eff}$ can be easily generated

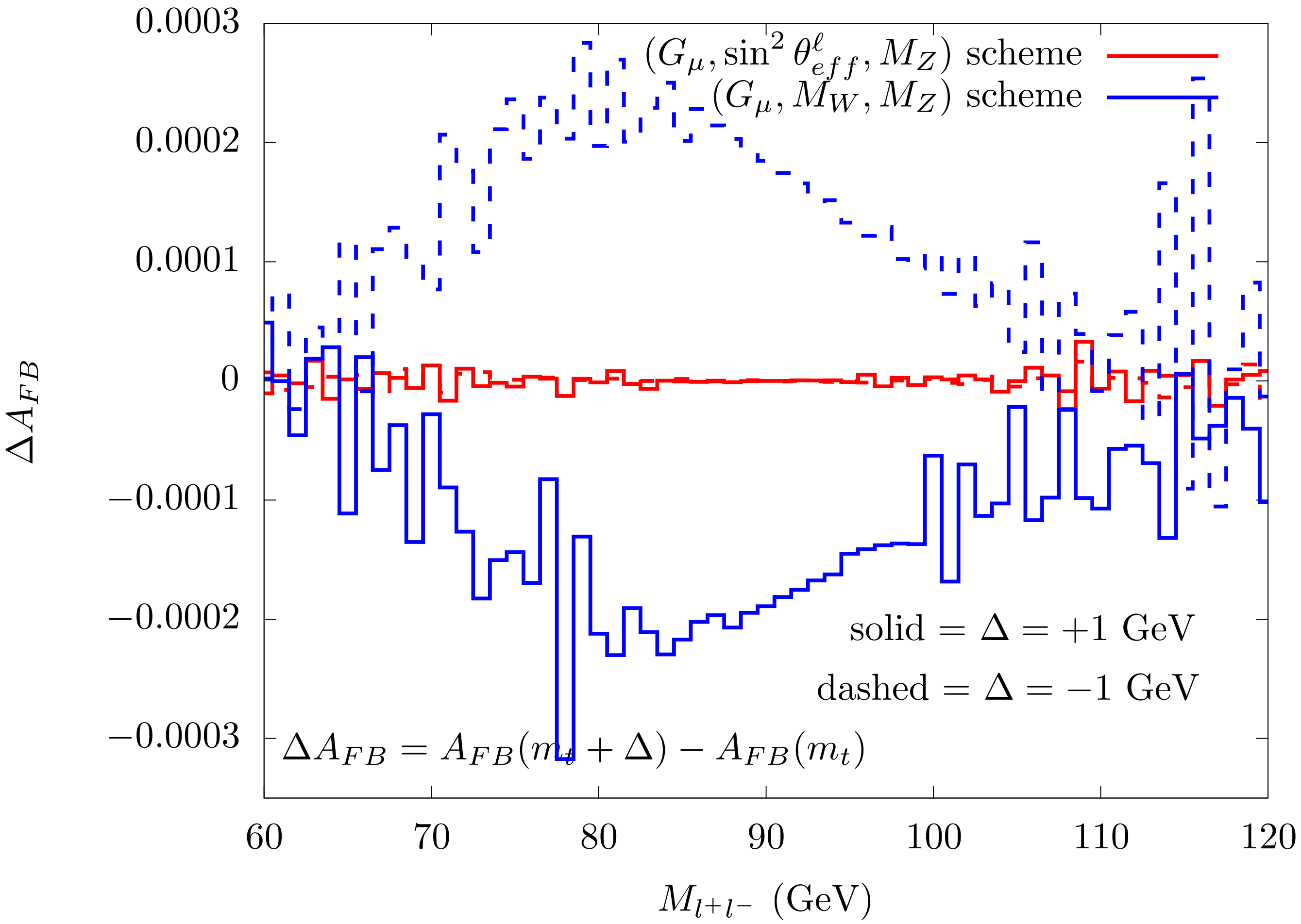
- → direct relation between the data and the parameter of interest
- → simple estimate of all the systematic effects, theoretical and experimental

The result of the fit in this scheme can be directly combined with LEP results

AFB mtop parametric uncertainties and perturbative convergence

M.Chiesa, F.Piccinini, AV, arXiv:1906.11569





prediction for AFB at the LHC in the (Gmu, MZ, $\sin^2\theta_{eff}$) input scheme (red),
comparison with (Gmu,MW,MZ)   (blue)

faster perturbative convergence
very weak parametric mtop dependence
→ good control over the systematic uncertainties of the templates used to fit the data

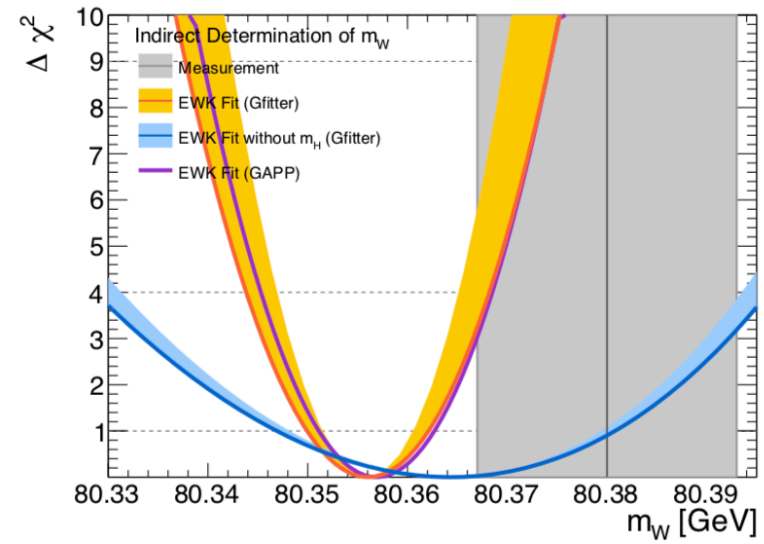
The combination (Gmu, MZ, $\sin^2\theta_{eff}$) offers a very effective parameterisation of the Z resonance in terms of normalisation, position, shape

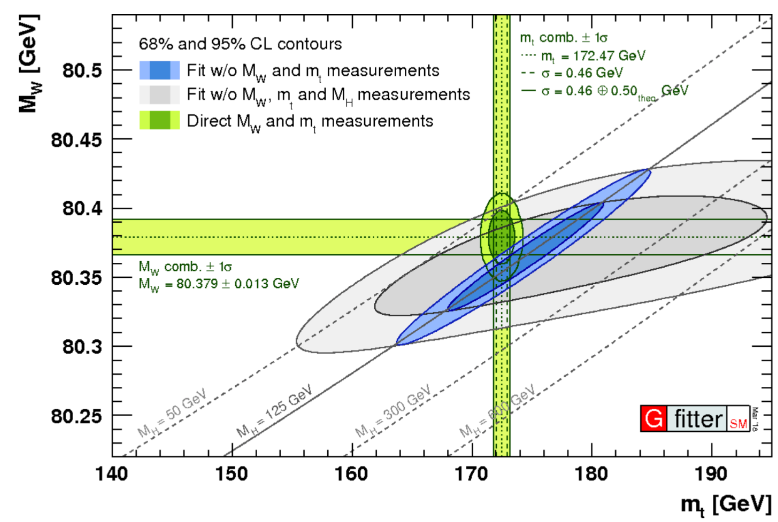
M. Schott

Interpretation in the context of the Electroweak Fit

- Unofficial combination yields a value of
  - M_W = 80380±13 MeV, with a p-value of 0.74
  - Several PDF correlation scenarios tested and results are stable

- Predicted value of the electroweak fit
  - M_W = 80356±6 MeV
  - 1.6σ "tension" with the SM prediction
  - Dominated by m_{top} and m_Z uncertainty, contributing 2.6 and 2.5 MeV
  - Without m_H: M_W=80364±17MeV





The estimate of the residual theoretical error on the MW prediction (3 MeV)
is not supported by the comparison of calculations in different renormalisation schemes (OS vs MSbar)
and might have a role in the significance of the fit
→ 3-loop EW results would be needed to solve this issue

Prospects and challenges

Two paths for future measurements at ATLAS and CMS

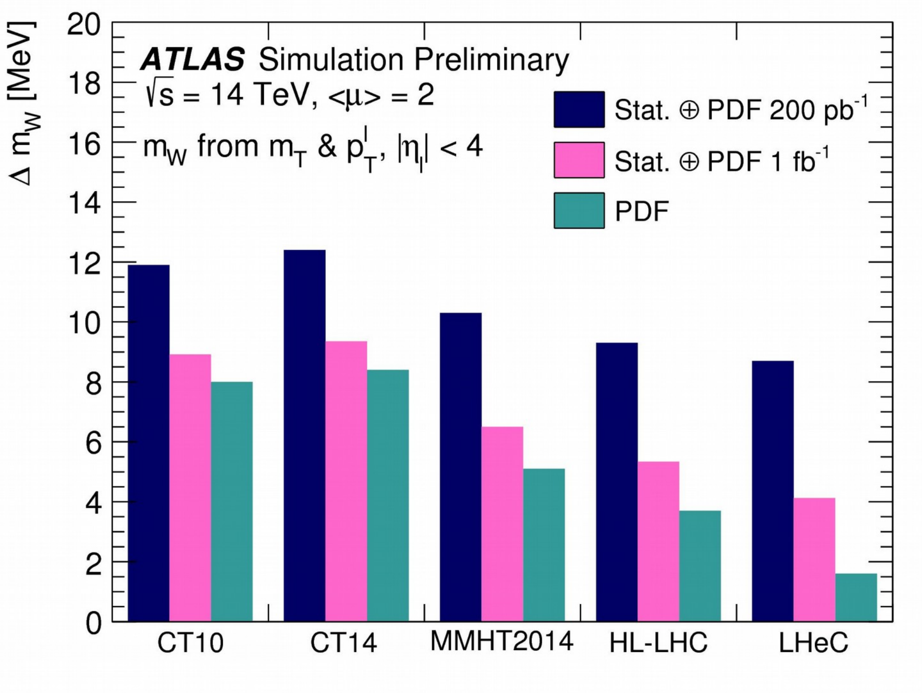
	High pileup	Low pileup
Most sensitive observable	p_T lepton	m_T
Theory challenge	W/Z p_T ratio, PDFs	PDFs
Experimental challenge	p_T lepton calibration	Recoil calibration
Dominant uncertainties	Physics modelling, PDFs	Recoil, stat, PDFs

High pileup:
- Only option at LHCb
- Can benefit from very high stat of the HL-LHC program

Low pileup:
- Requires dedicated runs
- Provides measurement and data-driven modelling of p_T W

- Orthogonal approaches with different dominant uncertainties
- Should be both pursued, will benefit from the combination

Prospects for m_W at the HL-LHC with low pileup data



ATL-PHYS-PUB-2018-026

- Increased acceptance provided by the new inner detector in ATLAS, (ITk) extends the coverage up to $|\eta| < 4$
- Allows further in-situ constraints on PDFs from pseudorapidity bins
- With $1 fb^{-1}$ of low pileup data ($<\mu>\sim 2$) likely to reach ~ 6 MeV of stat+PDF uncertainty
- LHeC ep collisions would largely reduce PDF uncertainties (< 2 MeV)

W mass at the LHC with high pileup data

- The statistical uncertainty is expected to be reduced by factors of 2 to 7 by analysing 8 and 13 TeV datasets

sqrt(s)	7 TeV	8 TeV	13 TeV
Lumi	~4.5 fb^{-1}	~20 fb^{-1}	~100 fb^{-1}
Events	$15x10^{-6}$	$80x10^{-6}$	$600x10^{-6}$
Stat Unc.[MeV]	7	3	1
	Measured	Expected	Expected

- The muon momentum calibration uncertainty in the ATLAS 7 TeV m_W result is ~9 MeV in the p_T lepton category and ~6 MeV in the combined result

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8

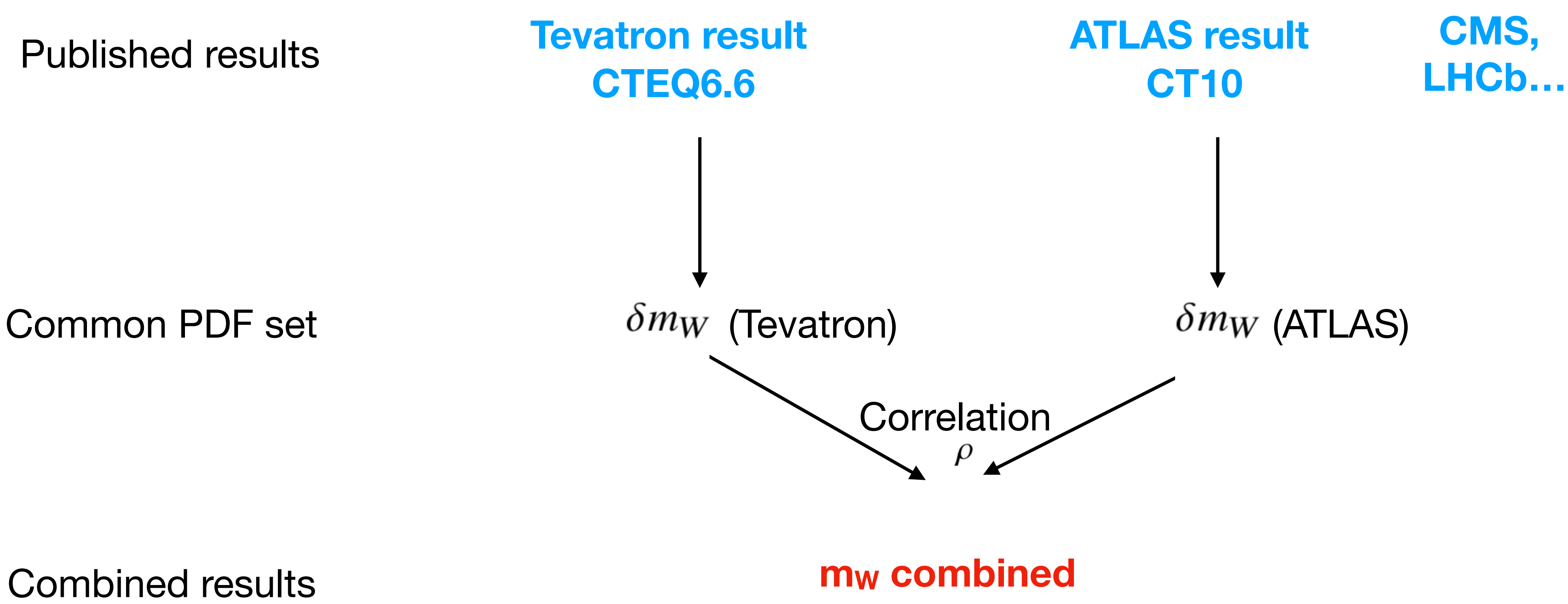
- This is likely to be the dominant experimental uncertainty in high pileup measurements

Uncertainty correlation

	ATLAS	Tevatron
pT	Pythia8	RESBOS
Ai, y	DYNNLO	RESBOS
PDF	CT10nnlo	CTEQ6.6
EW	Photos	Photos

- All experimental : uncorrelated
  - Small caveat : m Z, the primary reference for calibration in ATLAS and D0 (CDF uses J/psi)
- Physics modelling
  - Boson pT : can be assumed uncorrelated
    - Model purely based on Z data at the Tevatron
    - Combination of Z data and Z $\rightarrow$ W extrapolation at ATLAS
  - QED / EW corrections : under discussion
    - Photon radiation uncertainties
    - Radiation of pairs
    - Weak corrections
  - PDFs are the main source of correlations

Correlation between PDF uncertainties to be evaluated



- PDFs are the main source of correlations:
  - Re-create analyses on "smeared" truth-level samples (Powheg) with variety of weights corresponding to different PDFs
  - Evaluate shifts in m_W from use of different PDF sets and PDF uncertainties from EV
  - Evaluate correlations and perform combinations

PDF uncertainties and correlations

PDF variations are applied as event weights on the generator level, calculated internally in Powheg as the ratio of the event cross sections predicted by CT10 and alternative PDF sets:

- CT10 nnlo, CTEQ6.6, CTEQ6.1, MSTW2008 used in publications
- *CT10*, *CT14, MMHT2014, NNPDF31, CT18:* other PDF sets

Different energies 2, 7 TeV (pp-bar for 2 TeV)

$$\delta m^{+}_{W\alpha} = \left[\sum_i \left(\delta m^{i}_{W\alpha}\right)^2\right]^{1/2} \text{ if } \delta m^{i}_{W\alpha} > 0, \qquad \delta m^{-}_{W\alpha} = \left[\sum_i \left(\delta m^{i}_{W\alpha}\right)^2\right]^{1/2} \text{ if } \delta m^{i}_{W\alpha} < 0,$$

Where i runs for the uncertainty sets

$$\rho_{\alpha\beta} = \frac{\sum_i \delta m^{i}_{W\alpha} \delta m^{i}_{W\beta}}{\delta m_{W\alpha} \delta m_{W\beta}}$$

Correlation of PDF uncertainties between different categories alpha and beta

PDF correlations (preliminary; to be redone with latest inputs...)

CT10	1.	2.	3.	4.
1. W^+ 2 TeV	1	0.99	0.26	0.51
2. W^- 2 TeV	0.99	1	0.31	0.52
3. W^+ 7 TeV	0.26	0.31	1	-0.23
4. W^- 7 TeV	0.51	0.52	-0.23	1

CTEQ6.6	1.	2.	3.	4.
1. W^+ 2 TeV	1	1	0.37	0.45
2. W^- 2 TeV	1	1	0.36	0.46
3. W^+ 7 TeV	0.37	0.36	1	-0.42
4. W^- 7 TeV	0.45	0.46	-0.42	1

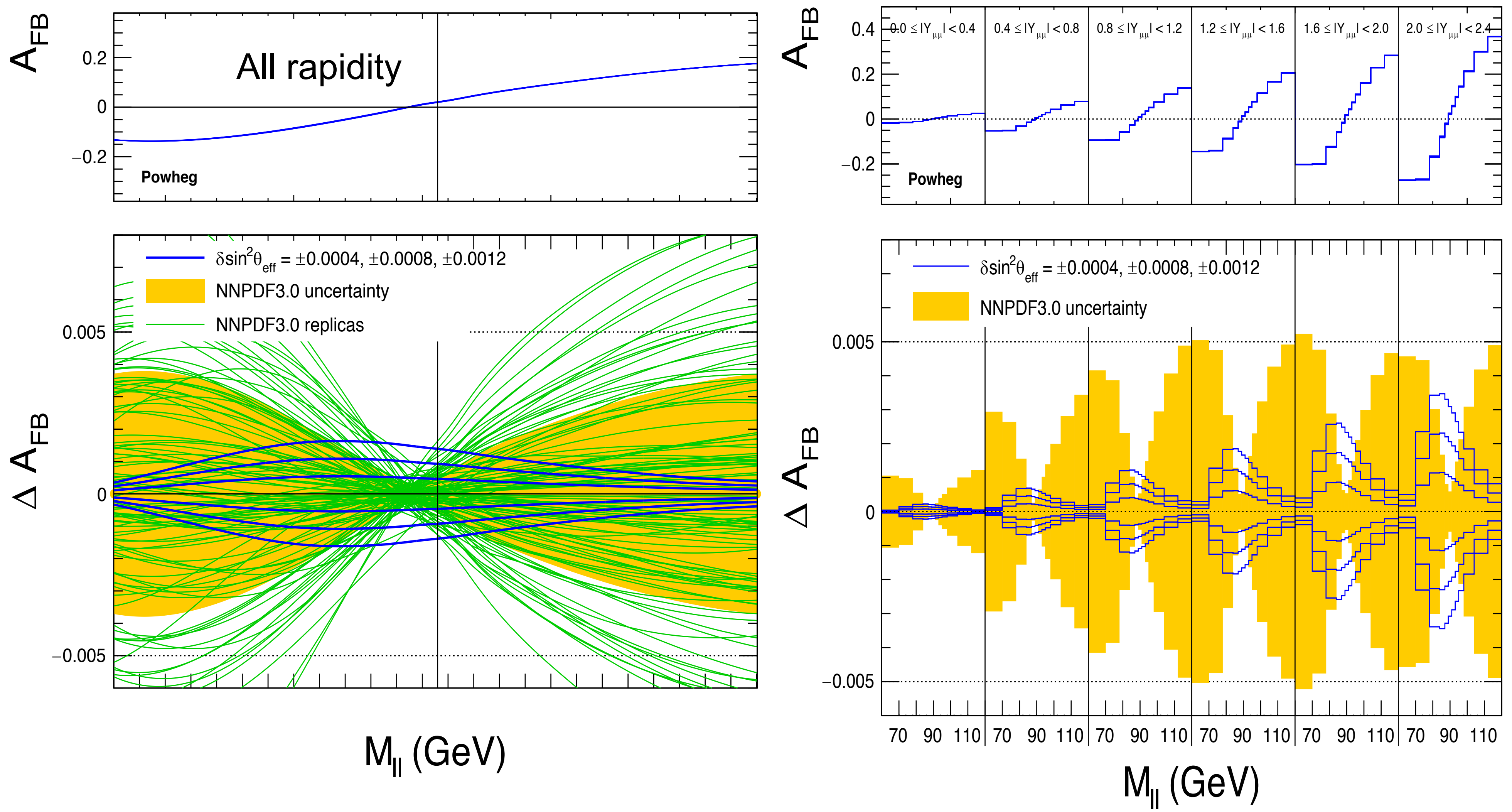
Few % stat uncertainties to be evaluated on the correlations

- Observed A_{FB} is very sensitive to PDFs
- Large in low and high masses, small near the peak (+ specific dependence on Y)

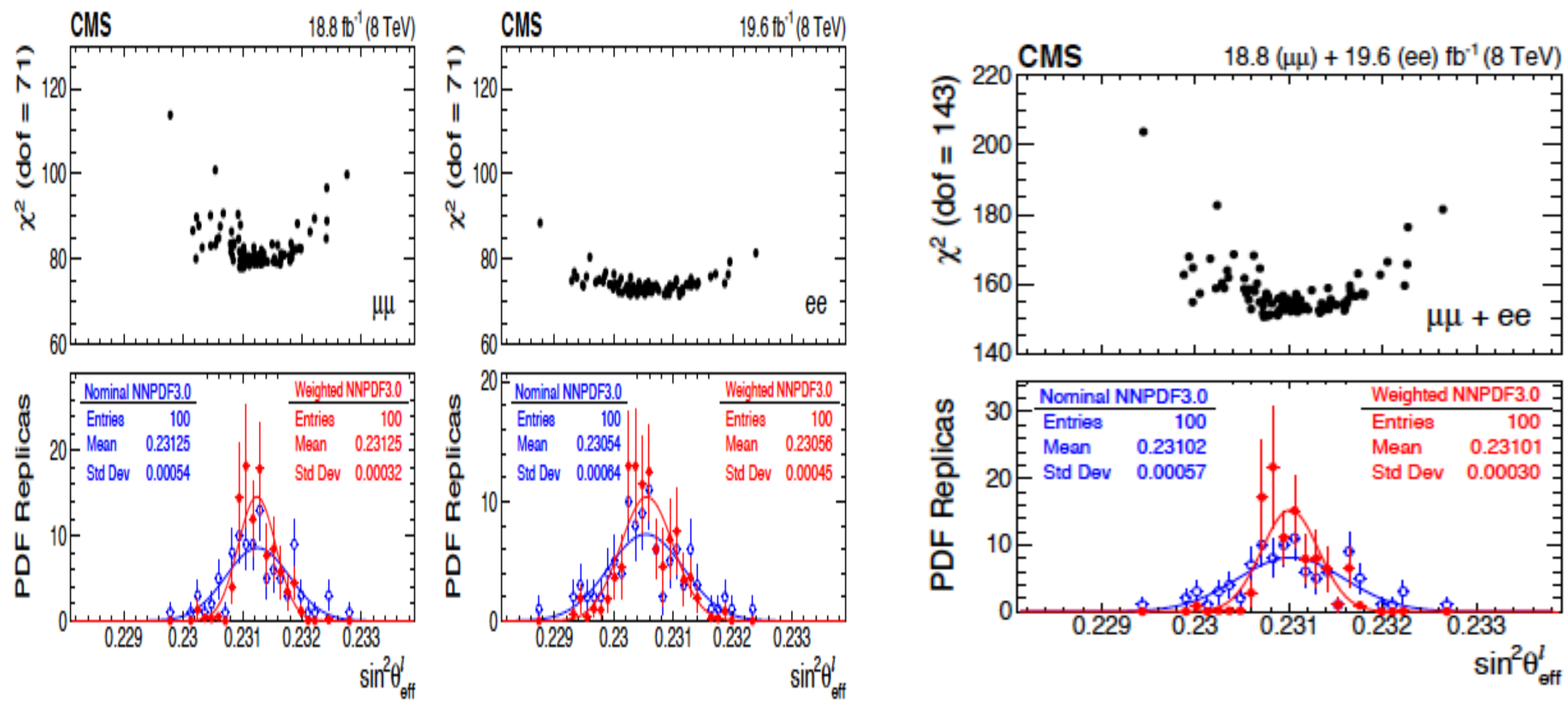
CMS

BLUE : Vary **$\sin^2\theta_{eff}$** for fixed PDF

ORANGE/green: Vary 100 NNPDF3.0 replicas for fixed **$\sin^2\theta_{eff}$**



muons **electrons** **combined** A.Bodek



Channel	without constraining PDF	with constraining PDFs
Muon	$0.23125 \pm 0.00048 \pm 0.00054$	$0.23125 \pm 0.00048 \pm 0.00032$
Electron	$0.23054 \pm 0.00069 \pm 0.00064$	$0.23056 \pm 0.00069 \pm 0.00054$
Combined	$0.23102 \pm 0.00040 \pm 0.00057$	$0.23101 \pm 0.00040 \pm 0.00030$

Precision Electroweak Physics

Arie Bodek, Aleko Khukhunaishvili , University of Rochester

Bayesian reweighting method
Factor of 2 reduction in errors

21

The Bayesian reweighing offers the most optimistic estimate of the uncertainty,
before a new global PDF fit includes the new data

The correlation between the PDFs and $\sin^2\theta_{eff}$ might be better handled in a simultaneous global fit

Conclusions

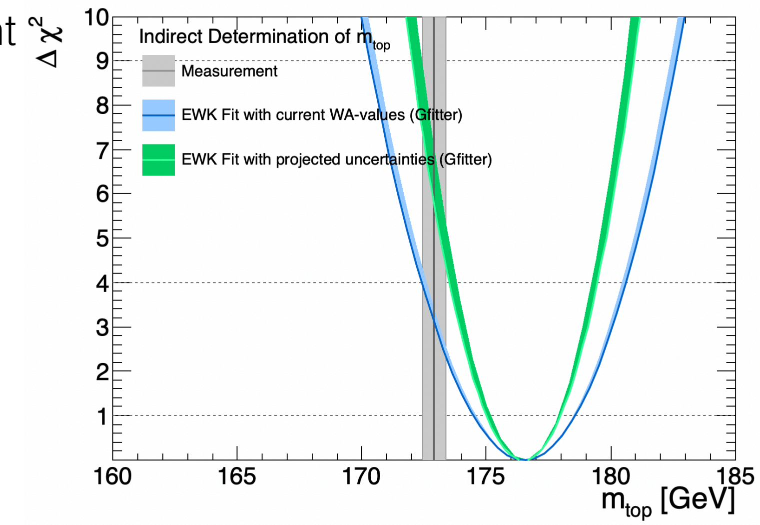
Many long and lively discussions during the Saclay workshop

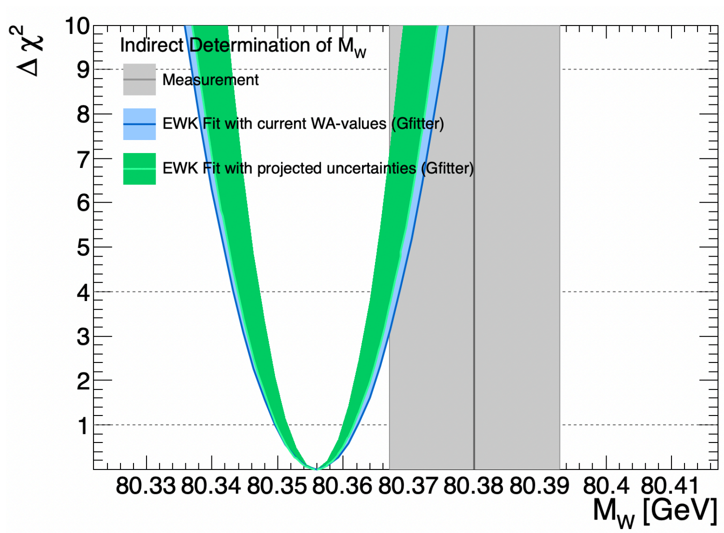
More work is needed from both th and exp sides

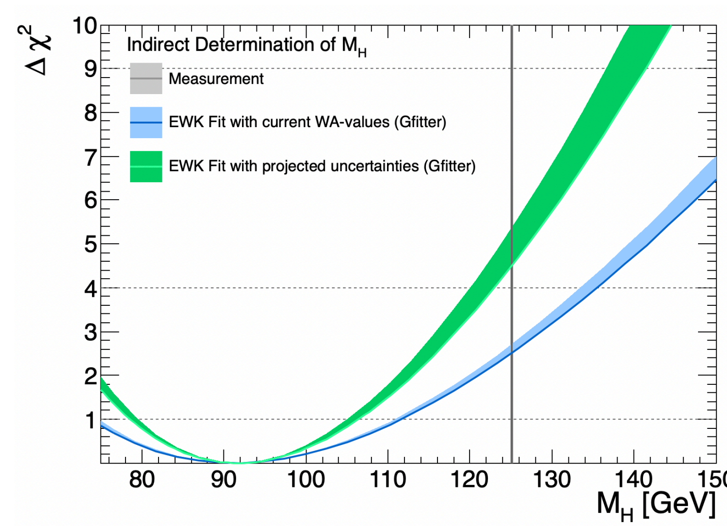
Optimistic but challenging perspectives

Where will we stand in 10 Years with an Ultimate Precision at the LHC?

- By the end of the LHC, we (being optimistic) might have
  - $\Delta m_W \approx 8$ MeV
  - $\Delta m_{Top} \approx 300$ MeV
  - $\Delta \sin^2\Theta_W \approx 0.00012$
- … results in indirect precisions of
  - $\Delta m_W \approx 4$ MeV, $\Delta m_{Top} \approx 1.3$ GeV, $\Delta m_H \approx 13$ GeV
  - See also a detailed studfy from Gfitter from 2014: https://arxiv.org/abs/1407.3792





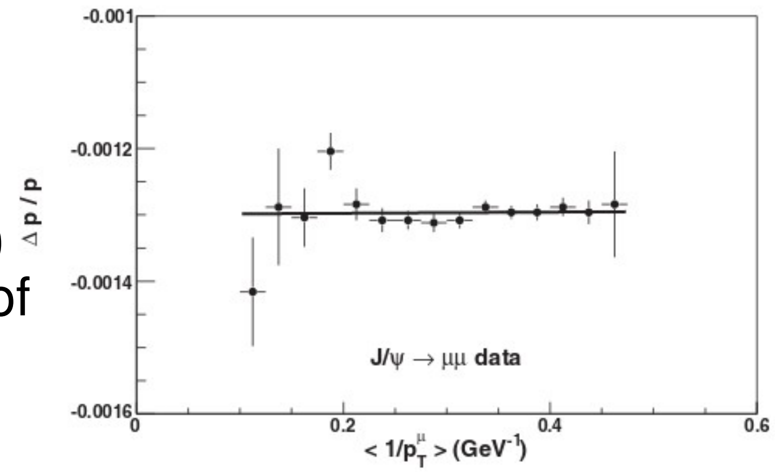


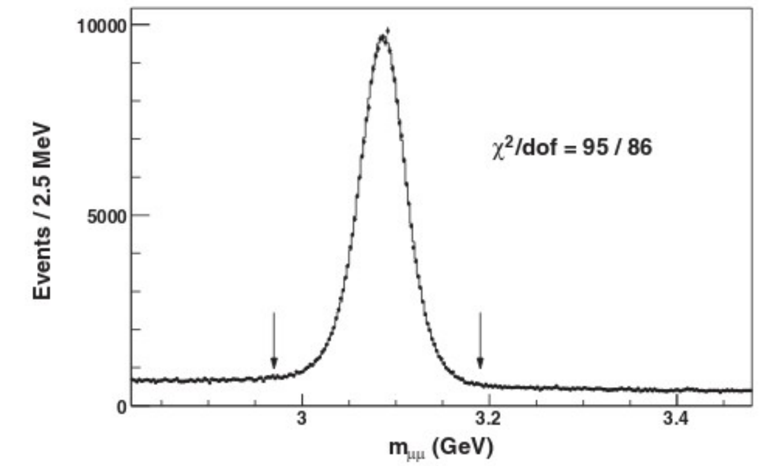
Momentum calibration

- Most measurements of m_W at hadron colliders (UA2, D0, ATLAS) lay the foundations of the energy and momentum calibration upon an external measurement of m_Z
- Drawbacks:
  - Effectively provide a measurement of m_W/m_Z, and suffer from an irreducible 2 MeV uncertainty from the LEP measurement of m_Z
  - Introduce correlation of momentum calibration uncertainites between different measurements

Muon momentum calibration with J/ψ

- One notable exception: CDF measurement of m_W based the muon momentum calibration on J/ψ (and Y)
- Electron energy and recoil momentum are cross-calibrated to the muon-momentum scale
- Propagation of the momentum scale from ~5 to ~80 GeV is a great challenges, requires perfect control of
  - Misalignments
  - Magnetic field nonuniformities
  - Material and energy loss





Source	J/ψ ($\times10^{-3}$)	Υ ($\times10^{-3}$)	Common ($\times10^{-3}$)
QED and energy-loss model	0.080	0.045	0.045
Magnetic field nonuniformities	0.032	0.034	0.032
Ionizing material correction	0.022	0.014	0.014
Resolution model	0.020	0.005	0.005
Background model	0.011	0.005	0.005
COT alignment corrections	0.009	0.018	0.009
Trigger efficiency	0.004	0.005	0.004
Fit range	0.004	0.005	0.004
$\Delta p/p$ step size	0.002	0.003	0
World-average mass value	0.004	0.027	0
Total systematic	0.092	0.068	0.058
Statistical	0.004	0.025	0
Total	0.092	0.072	0.058

- Benefit from larger sample than Z, and more precise mass measurement (10^{-6})