Experimental and theoretical uncertainties in m_W measurements at hadron colliders

Caveats and credits

→ This talk in its contents would not have been possible without the help of my colleagues from ATLAS, CMS and LHCb
Many thanks to Josh, Maarten, Mika, Stefano and Will!

→ Nor would it have been possible without the time spent by Ashutosh in two of our LPCC precision EW meetings last year to discuss with us and answer the numerous questions raised by the new CDF result
Many thanks to Ashutosh and Chris!

→ As you have heard from Maarten in the previous talk, we (experimentalists and theorists working on hadron collider m_W measurements) are in a difficult situation:
a) we have a $\sim 4\sigma$ discrepancy between the average of previous m_W measurements (which are in reasonable agreement) and the new CDF result.
b) it seems very unlikely that any theoretical aspect can explain the large difference in the central values discussed in the combination group

Historical interlude: the 80's in UA1/UA2 at the SppS

From the beginning, with the observation of two-jet dominance and of 4 W → eν and 8 Z → e^+e^- decays

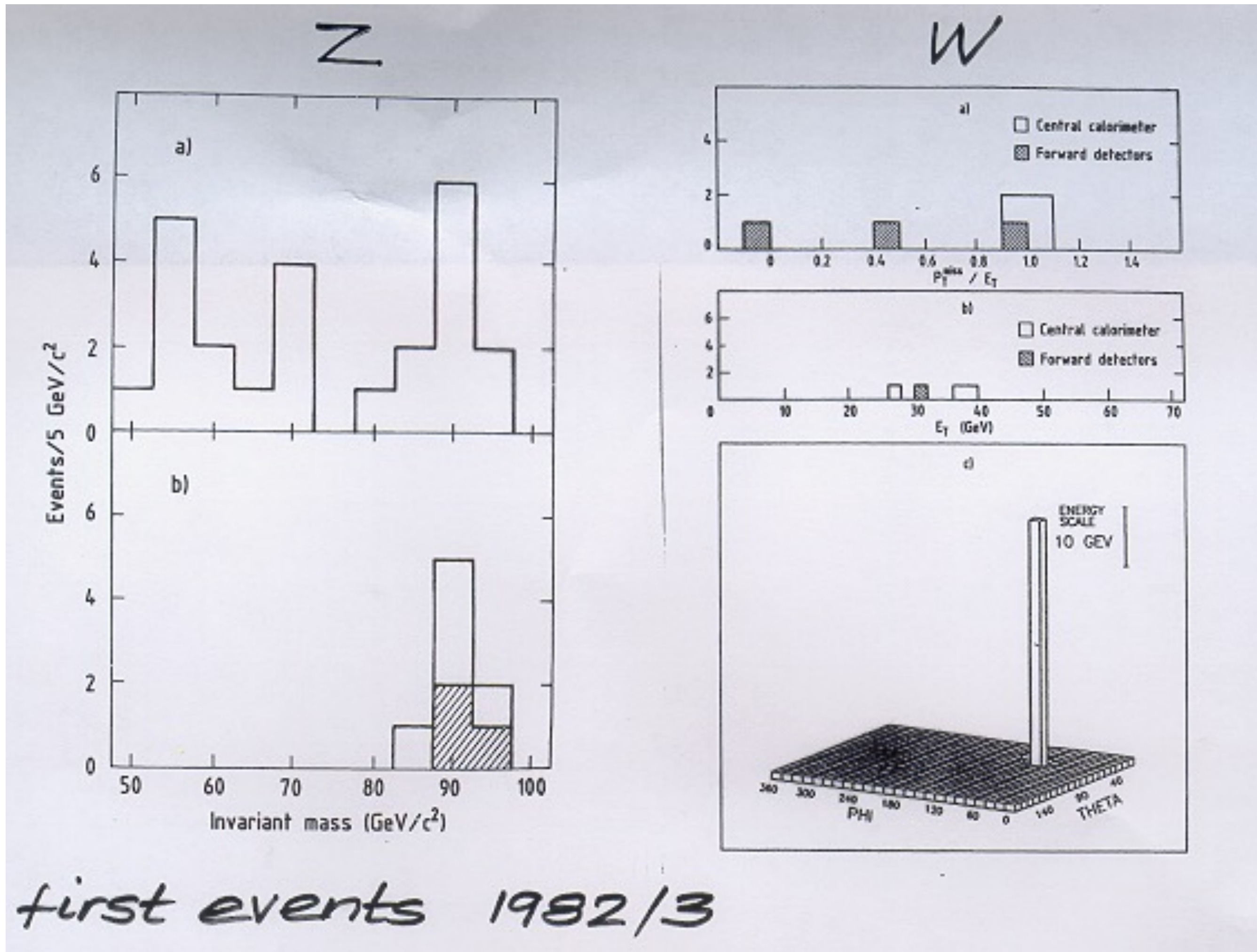
$\sqrt{s}$ = 546 GeV, L ~ 10^{29} cm^{-2}s^{-1}

UA2 was perceived as large at the time:

- 10-12 institutes
- from 50 to 100 authors
- cost ~ 10 MCHF
- duration 1980 to 1990

Physics analysis was organised in two groups:

1. Electrons → electroweak
2. Jets → QCD



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→ What the combination group explicitly decided not to discuss (except for PDFs) however were the uncertainties from the different sources for the various measurements.

→ For this talk, I have attempted something not possible with any scientific rigor such as that shown in the previous talk after many years of work: a comparison between the uncertainties assigned by CDF/ATLAS/LHCb (plus CMS to a certain extent) to such a measurement. This will be illustrative but hopefully interesting, don't shoot me down outright during the talk ☺

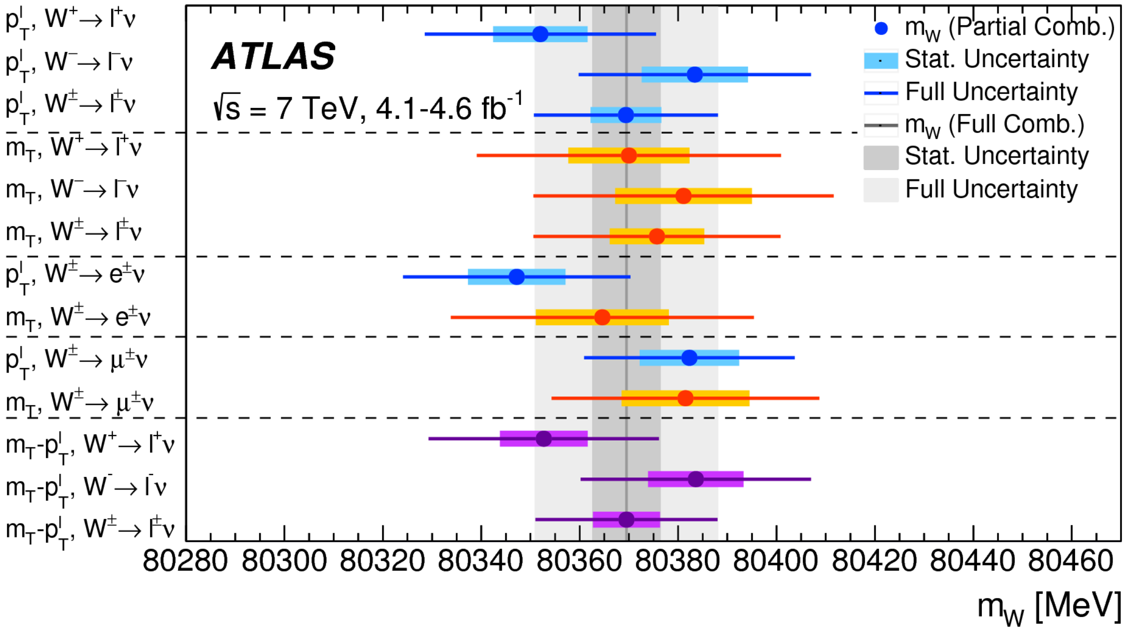
→ My main motivation to do this is to prolong in the future the work of the combination group by having a rigorous discussion of all these aspects between all the experiments, so that we may perhaps resolve this over a year or two rather than over decades with the much needed help of our theory colleagues working on precision DY predictions.

This will require open collaboration between us all, regardless of which experiment we are working in. And it will require work!

Comparison of systematics for m_W measurement

Uncertainties in MeV				
Measurement	**CDF_muon m_T**	**CDF_full**	**ATL_old/new p_T^l**	**LHCb p_T^μ**
Stat.	9.2	6.4	7.2/4.9	23
Momentum scale	2.1	3.0	8.4/6.8	7
Efficiency	0.5	0.4	5.0/4.0	7
Background	3.9	3.3	4.6/2.4	2
$p_T^{W/Z}$ model	1.1	1.8 + 1.3	5.9/3.5	11
Ai	0	0	5.8/3.5	10
QED	2.7	2.7	5.7/6.0	7
PDFs	3.9	3.9	9.0/7.7	9
Total syst.	7.4	6.9	17.2/15.5	22
Total unc.	11.8	9.4	18.7/16.3	32

Relative importance of different measurements



Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481

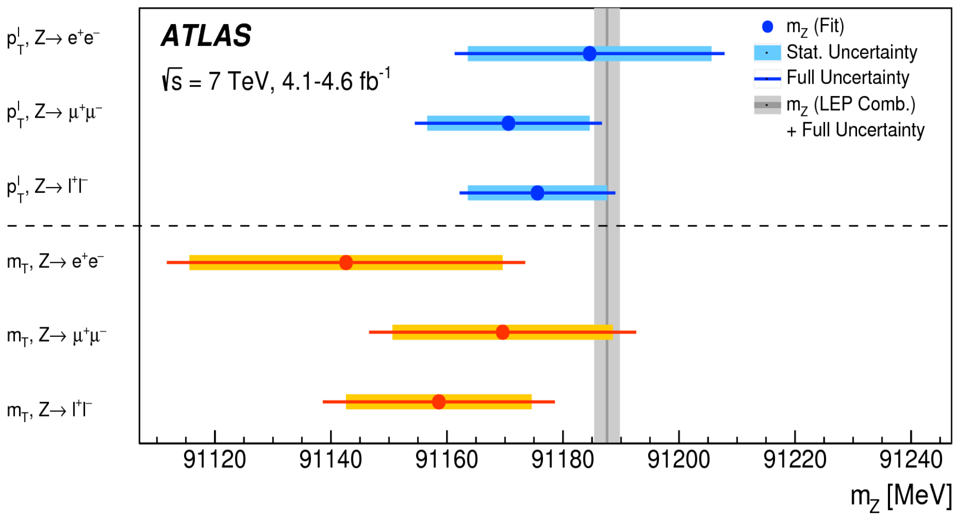
- **Measuring electrons AND muons provides a crucial set of closure constraints on the experimental systematic uncertainties. A number of experimental issues at the ~ 30-50 MeV level on m_W were resolved in both channels thanks to this.**

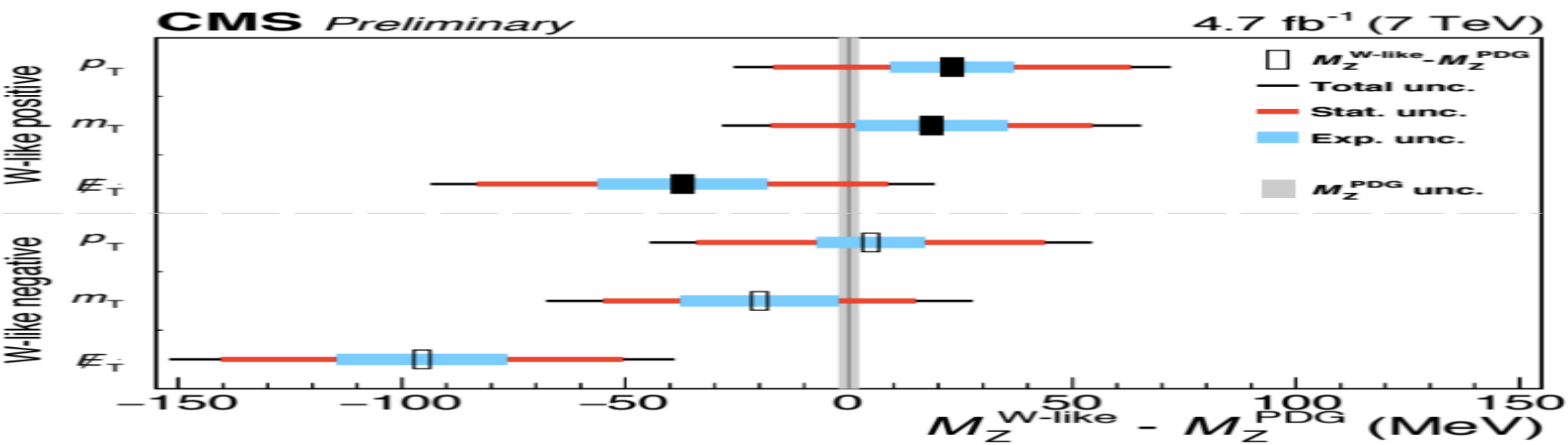
- **Even though the weight of the m_T measurement is much smaller than that of p_T^l, it plays an important role in the understanding of the theoretical modelling uncertainties on p_T^W**

Cross-checks with Z events (ATLAS and CMS 7 TeV):

remove one lepton from Z to ll decay to emulate neutrino

→ verify exp. syst. for recoil measurement within limits of Z stats





https://cds.cern.ch/record/2139655?ln=en

Cross-checks with Z events (ATLAS and CMS 7 TeV)

Source of uncertainty (values in MeV for m_T meas.)	CMS muons	ATLAS muons	ATLAS electrons
Lepton efficiencies	1	3.9	8.2
Lepton calibration	14	8.9	11.6
Recoil calibration	9	12.0	12.0
Statistics	35	28	38

Remarks

1. The CMS measurement is less precise statistically than the ATLAS one for muons for several reasons (only muons with $|\eta| < 0.9$ used in CMS, half of the sample used for the recoil calibration and the other half for the measurement)
2. The lepton calibration in ATLAS is more precise because it is based on the full run-1 dataset (7 and 8 TeV)
3. The recoil calibration in CMS appears more precise than the ATLAS one (particle flow versus 3D topological clusters) but the response of the recoil in CMS is ~30%, to be compared to ~70% in ATLAS
4. The efficiency systematics for CMS are much smaller (stats insufficient?)

Experimental issues : internal consistency of results

→ **All publications discuss the consistency and robustness of the results**

→ **This can be studied in many ways by slicing up data sample as a function of time or of "hidden" variables such as the amount of pile-up**

→ **At this point, one has to mention the poor agreement of the previous CDF result with the new one, of which it is a subset.**

> Upon incorporating the improved understanding of PDFs and track reconstruction, our previous measurement is increased by 13.5 MeV to 80,400.5 MeV; the consistency of the latter with the new measurement is at the percent probability level.

→ **In short: 20% of data with lowest amount of pile-up are more than 2σ away from 80% of data with significantly larger pile-up. What do control plots look like for these new data? What are the results of the fit for these new data?**

→ **Stability of results as a function of instantaneous luminosity could perhaps be checked? We are not sure from discussions with Ashutosh whether this might be impossible technically or whether it is a person-power issue.**

Experimental issues

Magnetic field, alignment and momentum scales

- **It is quite interesting and somewhat distressing to see that significant offsets are observed in some experiments between observed mass scale for known particles and expected mass scale. One can try to compare here all four experiments.**
- **Observed offsets :**
  CDF: -1.4 per mil
  ATLAS: -0.85 per mil
  CMS: -0.80 per mil in situ for field, not known yet what is size of residual offset but should be ok if at the ~ 0.2 per mil level?
  LHCb: ~ 0.5 per mil from Y

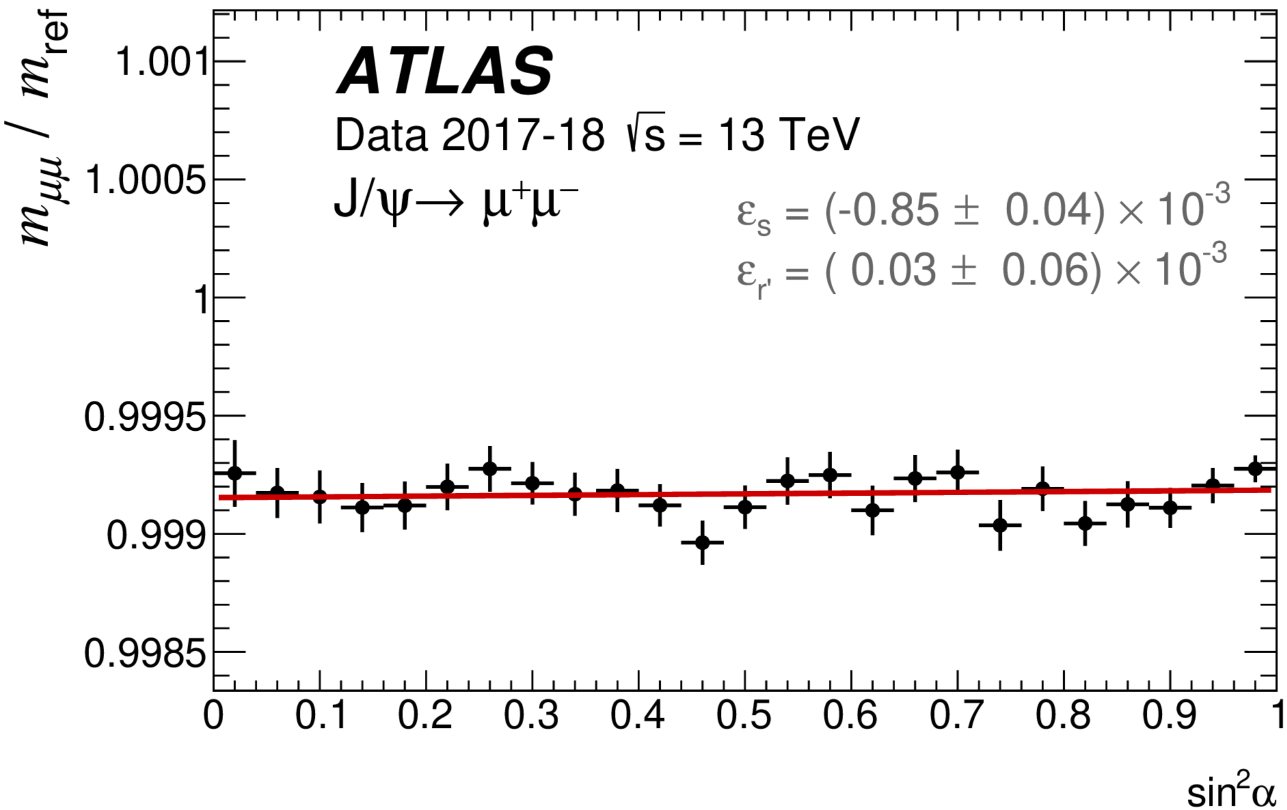
- **Even though this can be calibrated away using data (large J/ψ,Y and Z to ll statistics available in all experiments), it is hard to be easily convinced that a large offset is not an issue at the few MeV level.**

- **ATLAS solenoid field map known to 0.2 per mil in central region (measured in situ but without the tracker)** https://iopscience.iop.org/article/10.1088/1748-0221/3/04/P04003/pdf

- **CMS solenoid measured on the surface without any detector with very high accuracy. It is much longer than the tracker itself, so the field could be remeasured in situ with the tracker installed just outside its volume.**

ATLAS momentum scale discussion

- **Observed offset is stable versus particle mass (and hence lepton p_T) and also versus particle rapidity**
- **Could be due to weak modes, but these are now excluded, see below**
- **So we are left with a ~ 4σ deviation from our magnetic field measurement (overall syst. unc. increases from 0.2 to 1.0 per mil from z = 0 to z = z_{max})**



ATLAS momentum scale discussion

ATLAS scale is off by 0.00085 or 80 MeV at m_Z:

Alignment systematics

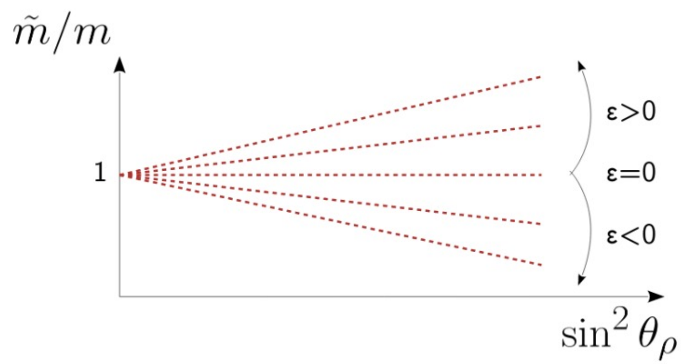
- Misalignment of the ID could be responsible for biases in the propagation of the p_T scale from the Jpsi to the Z mass

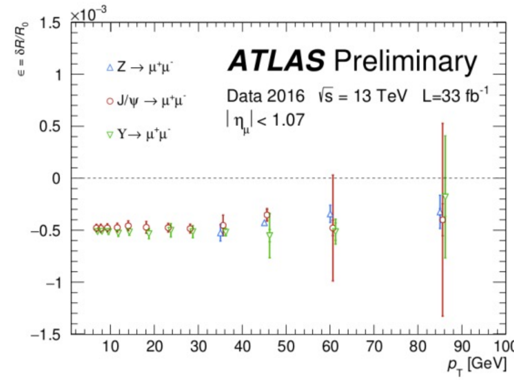
Magnetic field bias

$$\begin{aligned} \tilde{p}_T &= p_T(1+\delta) \\ \cot\tilde{\theta} &= \cot\theta \\ \tilde{p}_Z &= p_Z(1+\delta) \end{aligned}$$

Radial distortion alignment weak mode

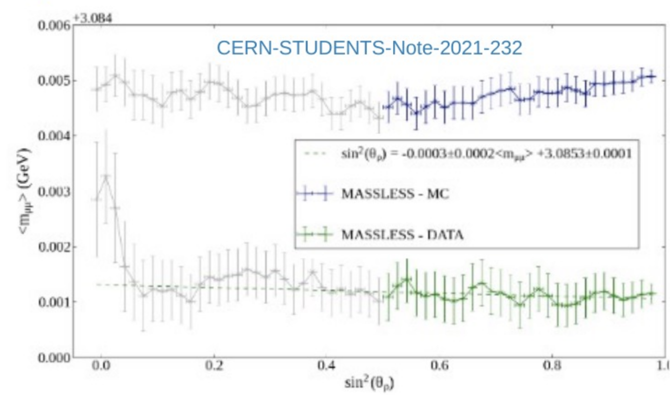
$$\begin{aligned} \tilde{p}_T &= p_T(1+\epsilon) \\ \cot\tilde{\theta} &= \cot\theta(1+\epsilon)^{-1} \\ \tilde{p}_Z &= p_Z \end{aligned}$$





$$\sin^2\theta_\rho = \frac{\frac{E_k}{E_p}p_T^2 + \frac{E_p}{E_k}k_T^2 - 2\vec{p_T}\cdot\vec{k_T}}{m^2}$$

$$\tilde{m}/m = (1+\delta)(1+\epsilon\sin^2\theta_\rho)$$



$$\epsilon = -0.0001 \pm 0.0001$$

LHCb momentum scale discussion

LHCb does a sophisticated simultaneous fit of the known resonances, and uses m_Z as a constraint.

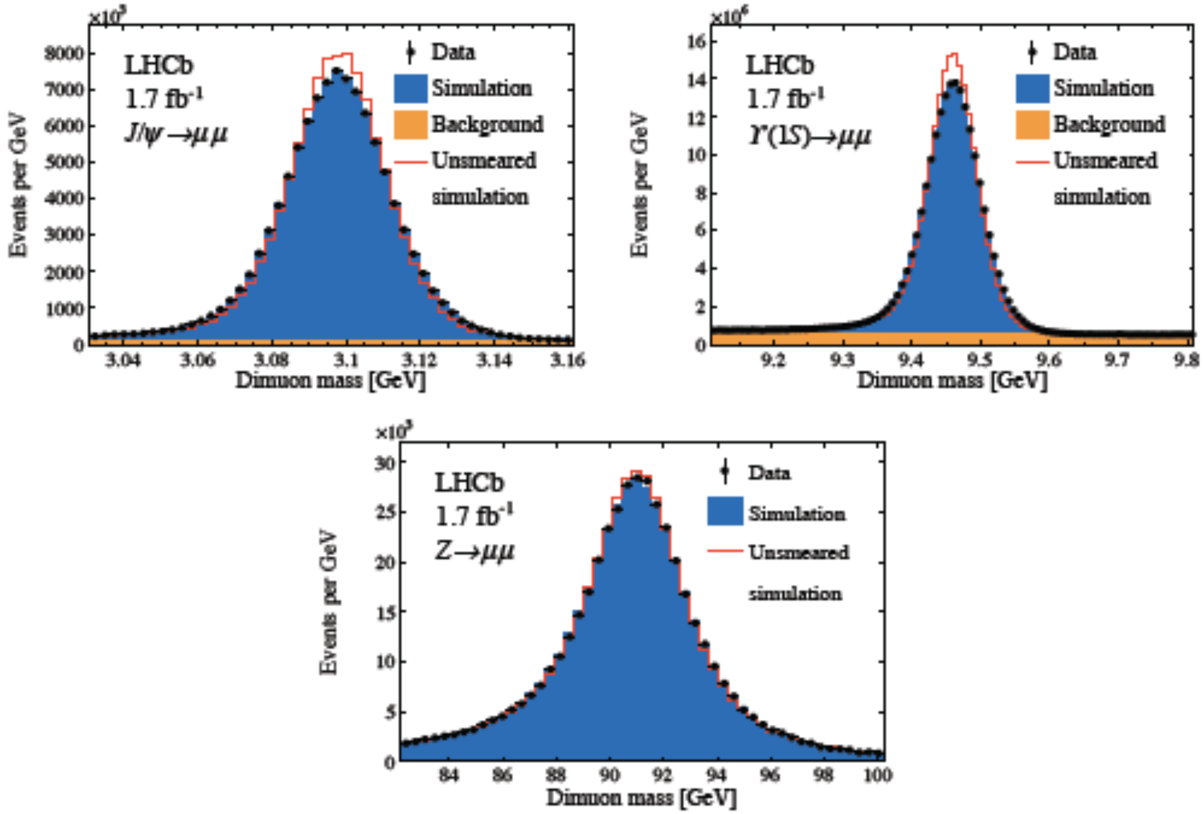


Figure 3: Dimuon mass distributions for selected J/ψ, $\Upsilon(1S)$ and Z boson candidates. All categories with both muons in the $2.2 < \eta < 4.4$ region are combined. The data are compared with the fit model. The red histogram delineates the model before the application of the smearing.

LHCb momentum scale discussion

LHCb scale is at m_Z is fully compatible with Y scale

After the curvature corrections are applied to the data and simulation, the momenta of the simulated muons are smeared to match those in the data, as described below, according to

$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh \eta}\right), \tag{5}$$

Table 1: Parameters in the momentum smearing model where the uncertainties quoted are statistical.

Parameter	Fit value
α ($\eta < 2.2$)	$(0.58 \pm 0.10) \times 10^{-3}$
α ($2.2 < \eta < 4.4$)	$(-0.0054 \pm 0.0025) \times 10^{-3}$
δ	$(-0.48 \pm 0.37) \times 10^{-6}$ GeV^{-1}
σ_δ ($\eta < 2.2$)	(17.7 ± 1.2) keV^{-1}
σ_δ ($2.2 < \eta < 4.4$)	(14.9 ± 0.9) keV^{-1}
σ_{MS}	$(2.015 \pm 0.019) \times 10^{-3}$

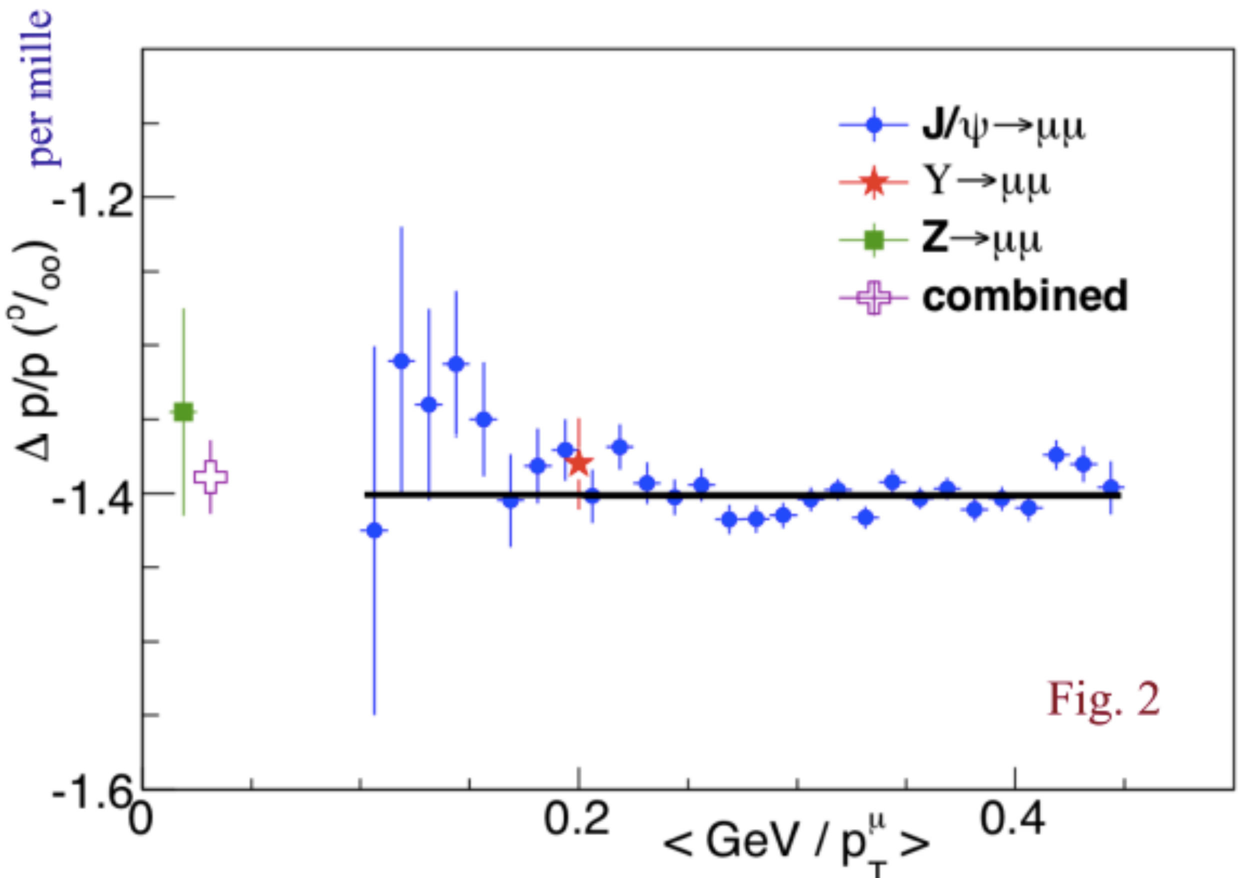
Discussion of CDF measurement

- Final calibration using the J/ψ, ϒ and Z bosons for calibration
- Combined momentum scale correction :

$$\Delta p/p = (-1389 \pm 25_{syst}) \text{ parts per million}$$

– Z mass consistent with PDG value (91188 MeV) (0.7σ statistical)

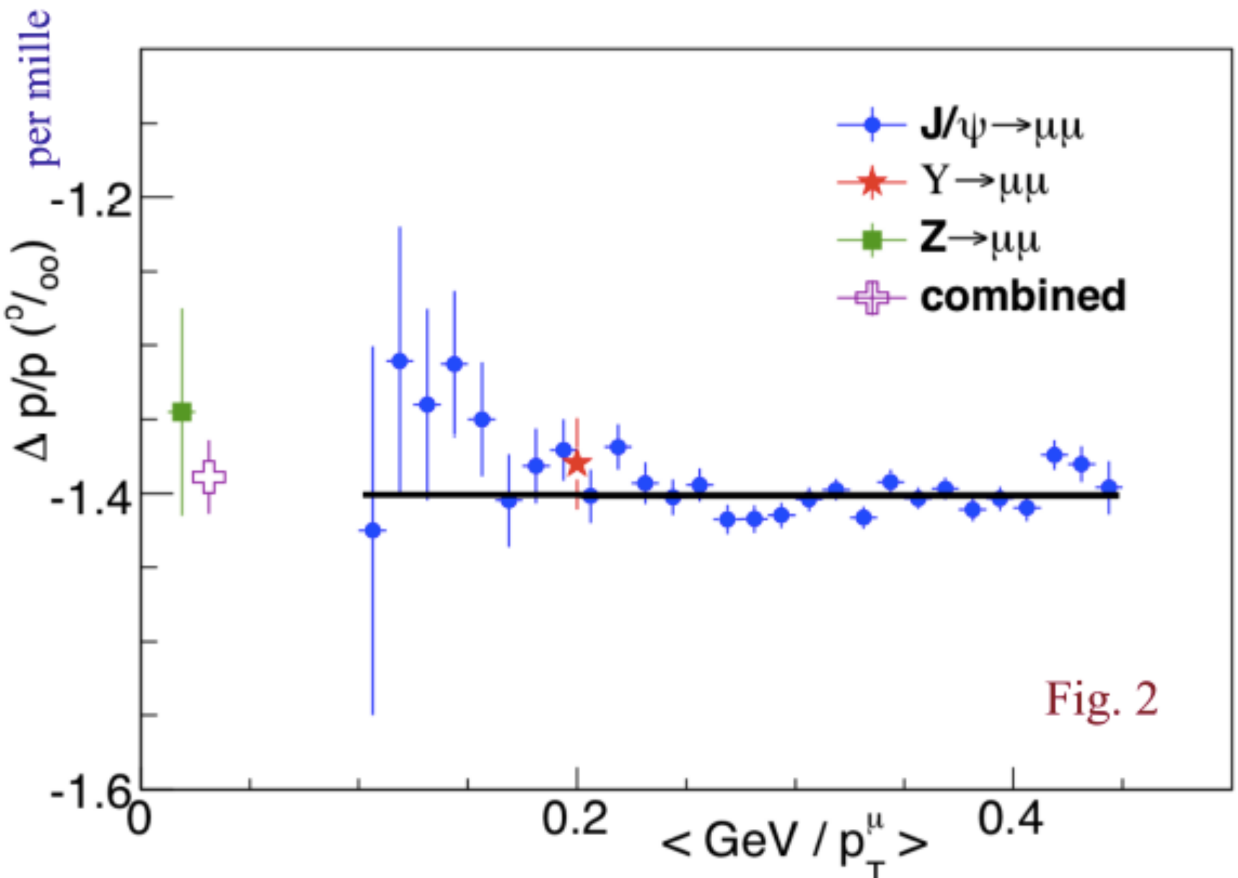
– $M_Z = 91192.0 \pm 6.4_{stat} \pm 2.3_{momentum} \pm 3.1_{QED} \pm 1_{alignment}$ MeV



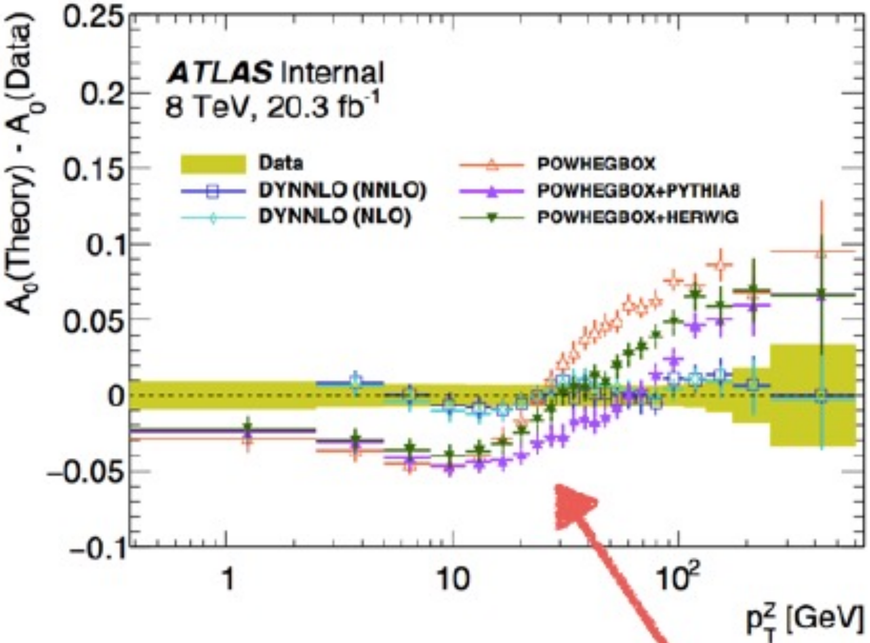
A. Kotwal

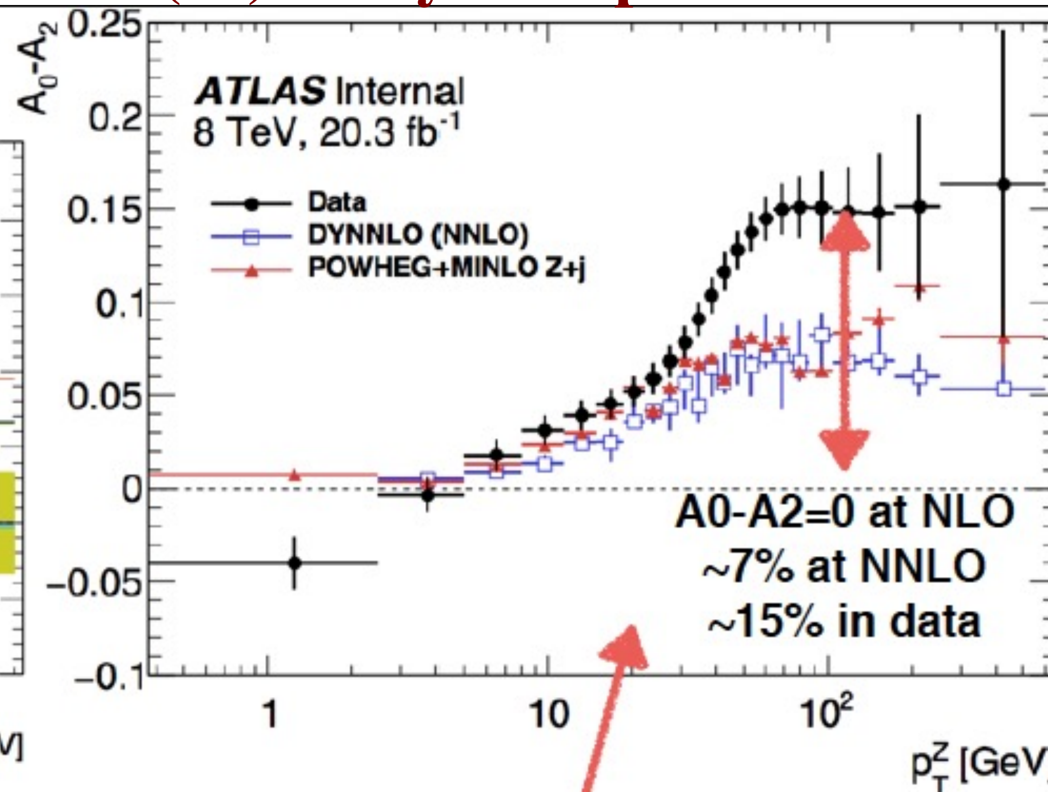
Discussion of CDF measurement

1) Very impressive work on muon momentum scale calibration
2) However overall shift of scale seen below, although compatible with being flat over whole spectrum corresponds to > 100 MeV
3) A bit difficult to believe the overall 2 MeV residual systematic assigned to m_W



Comparisons to theory





A_0, A_0-A_2

- Powheg completely mismodels A_0 (important for m_W discussion)
  - Related to implementation of Sudakov form factors and cutoffs in b-quark mass
  - Fixed in Powheg+MiNLO

A_0-A_2 (Lam-Tung) sensitive to higher order corrections

First ever observation of significant deviation from NNLO predictions

Measurement of angular coefficients in Z(W) decays to leptons

1) **NNLOJET authors claim that perhaps it makes more sense to decorrelate scale variations between polarized and unpolarized cross-section in Ai coefficient predictions, based on insufficient convergence of perturbation theory**

https://link.springer.com/article/10.1007/JHEP11(2017)003

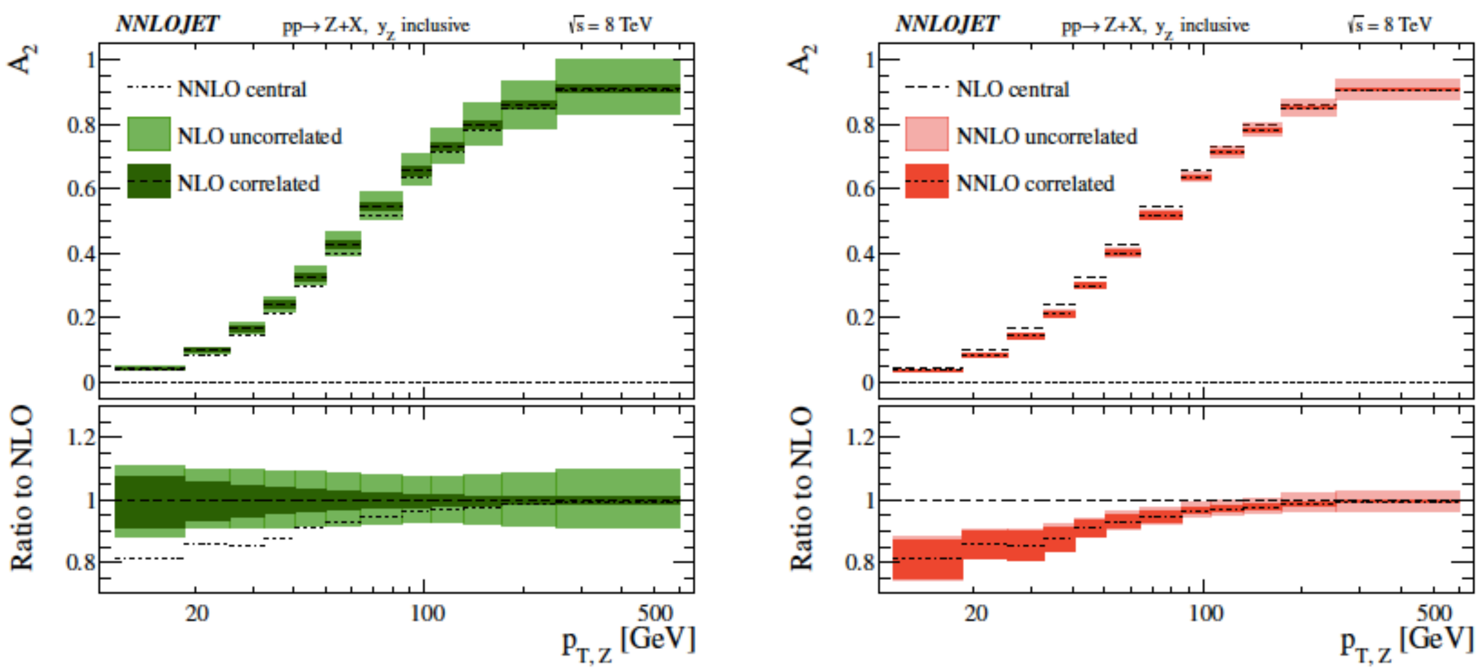


Figure 3. The $p_{T,Z}$ distribution for the angular coefficient A_2 in pp collisions at $\sqrt{s} = 8$ TeV. The uncertainty obtained when choosing to (un)correlate the scale choices in the extraction of A_2 is shown at NLO (left) and NNLO (right). In the lower panel, each distribution is shown normalised with respect to the central NLO prediction.

Measurement of angular coefficients in Z(W) decays to leptons

https://link.springer.com/article/10.1007/JHEP11(2017)003

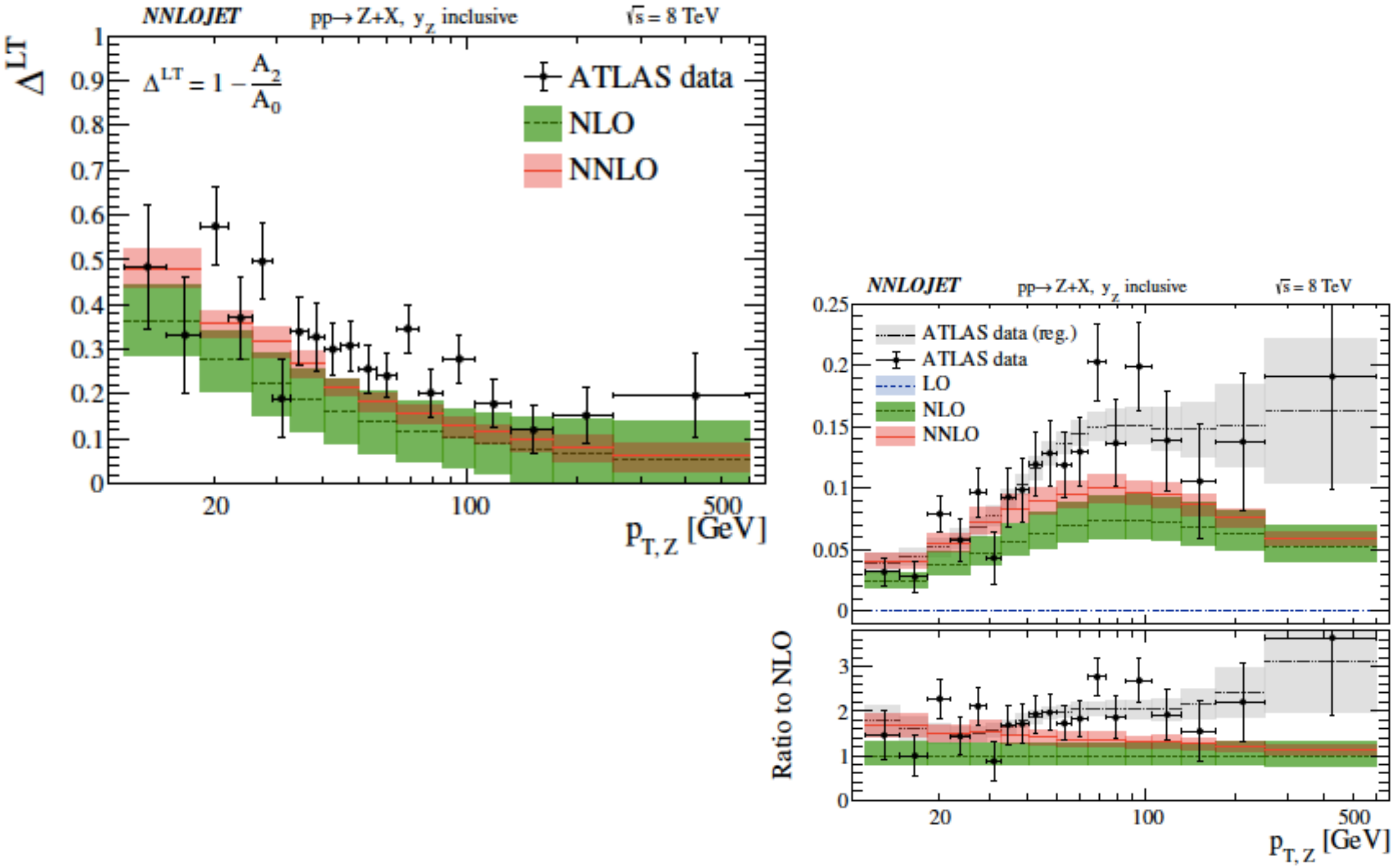


Figure 10. The $p_{\mathrm{T,Z}}$ distribution for the difference of angular coefficients $(A_0 - A_2)$ in pp collisions at $\sqrt{s} = 8$ TeV. The ATLAS data (black points) are compared to the LO (blue fill), NLO (green fill), and NNLO (red fill) theoretical predictions. In addition, the regularised ATLAS data is also included (grey fill). In the lower panel, each distribution is shown normalised with respect to the central NLO prediction.

Angular coefficients

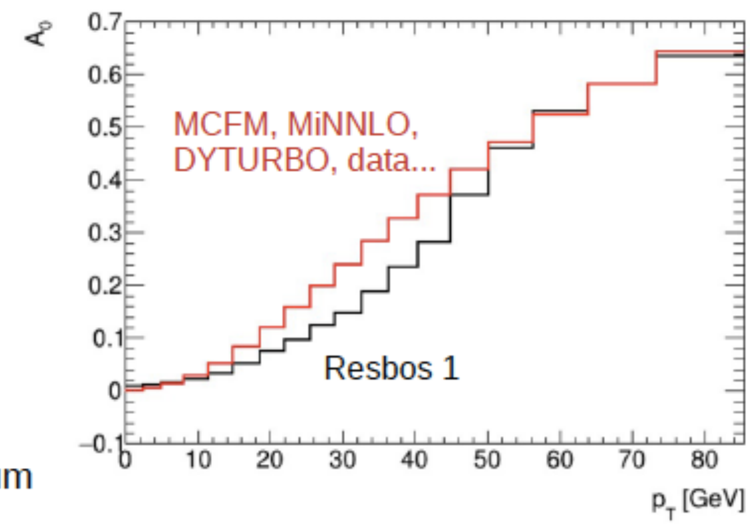
LHCb: 10 MeV based on eg correlated theory uncertainties from NNLOJET
ATLAS : 6 MeV uncertainty based on Z measurements of all Ai and on possible need for higher-order corrections relevant for A2-A0
CDF: 0 MeV (or negligible)

Effect below affects potentially central value but also uncertainty

Physics : QCD

- Scale variations found to have negligible impact (largely follows from fit procedure [normalized histograms] and tight uT cut)
- Spin correlations : problematic (and not mentioned)

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



biased A_0 → biased θ^* → biased p_T^l, m_T

Effect is typically to harden the predicted spectrum

Modelling of $p_T^{W/Z}$

CDF: use ResBos1 ~ $o(\alpha_s)$ + NLL
ATLAS: use Pythia8 parton shower ~ $o(\alpha_s)$ + NLL ?
LHCb: use Powheg/Pythia8 ~ $o(\alpha_s)$ + NLL
Today we have predictions at ~ $o(\alpha_s^3)$ + N4LL' !

A great pity that RESBOS2 dropped out of the pTW/Z benchmarking

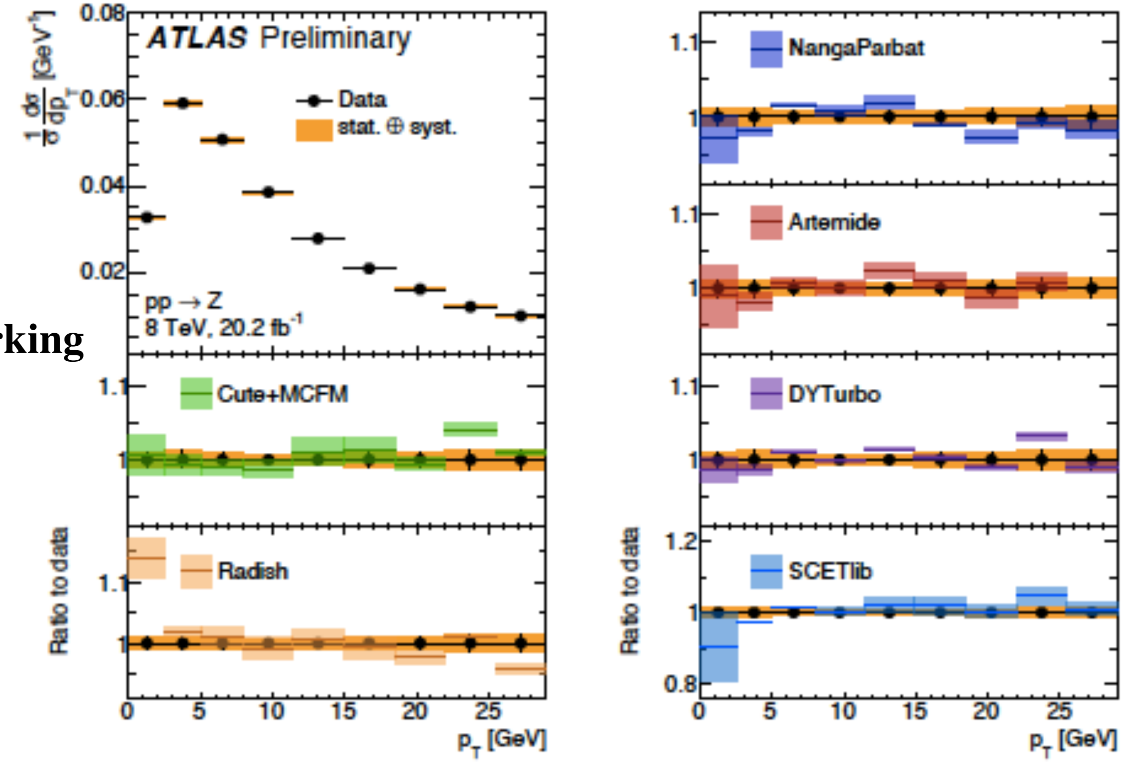


Figure 16: Comparison between the measured normalised differential $\frac{d\sigma}{dp_T}$ cross-sections, integrated over $|y| < 3.6$, with their total uncertainties and the predictions from the various resummation calculations. The top left panel shows the data, while the next panels show one by one the ratios between each prediction with its uncertainties as obtained from renormalisation/factorisation/resummation scale variations and the data. The predictions include approximate N^{4}LL resummation and, except for ARTEMIDE, fixed-order $O(\alpha_s^3)$ contributions from MCFM [47, 52].

Modelling of $p_T^{W/Z}$

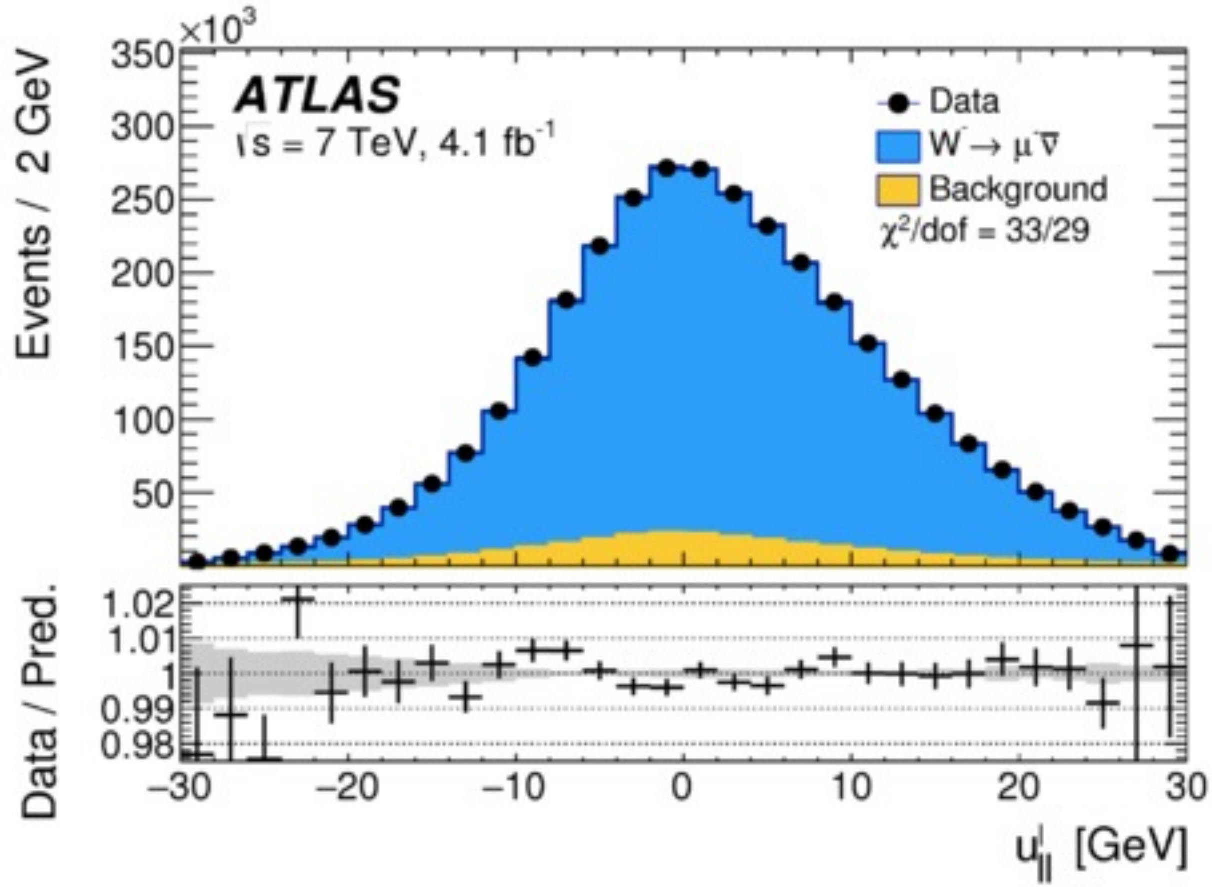
LHCb: 11 MeV (variations of α_s and tune parameters within nominal MC)
ATLAS: 6 MeV (PYTHIA8 vs HERWIG, tune unc., heavy flavour decorrelation between Z and W)
CDF: 1.8 Z + 1.3 W/Z (scale variations of DYqT constrained by u_T^W data)
Note: as mentioned already, reweighting $d\sigma/dp_T$ to state-of-the-art is ok for lepton p_T spectrum, but certainly not for hadronic recoil.

Is it kosher to constrain scale variation unc. on $p_T^{W/Z}$ through anti-correlation with hadron recoil response parameters (no full simulation performed) ?

Source of systematic	m_T fit			p_T^{ℓ} fit			p_T^{ν} fit		
uncertainty	Electrons	Muons	Common	Electrons	Muons	Common	Electrons	Muons	Common
Lepton energy scale	5.8	2.1	1.8	5.8	2.1	1.8	5.8	2.1	1.8
Lepton energy resolution	0.9	0.3	-0.3	0.9	0.3	-0.3	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8	3.5	3.5	3.5	0.7	0.7	0.7
Recoil energy resolution	1.8	1.8	1.8	3.6	3.6	3.6	5.2	5.2	5.2

The impact of this approach can be seen clearly in the table above from CDF suppl. material: as hadronic recoil becomes less and less relevant, from $p_T\nu$ to m_T to p_T^l, the recoil scale uncertainty increases!
In addition, the scale variations from DYqT are not allowed to change the central value of the fit result?

Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$



- **The region $u_{//}^l < -10$ GeV is sensitive to the physics modelling of the soft part of the p_T^W spectrum**
- **With a total of e.g. ~ 0.8M W to $\mu\nu$ decays, one can constrain modelling uncertainties to ~ 10 MeV**

Back-up slides

Discussion of CDF measurement

Information is scant: hard to assess very small numbers below

New CDF Result (8.8 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	10.3	9.2	0
Lepton energy scale	5.8	2.1	1.8
Lepton resolution	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8
Recoil energy resolution	1.8	1.8	1.8
Selection bias	0.5	0.5	0
Lepton removal	1	1.7	0
Backgrounds	2.6	3.9	0
pT(Z) & pT(W) model	1.1	1.1	1.1
Parton dist. Functions	3.9	3.9	3.9
QED rad. Corrections	2.7	2.7	2.7
Total systematic	8.7	7.4	5.8
Total	13.5	11.8	5.8