Standard Model physics at the LHC as seen by an experimentalist

I went to my first particle physics school in 1978 (or so) in Nafplion in Greece and after my PhD in 1981 I joined UA2 just in time for …

→ a historical perspective on early SM physics with a bit of top and Higgs somehow already in our consciousness as experimentalists

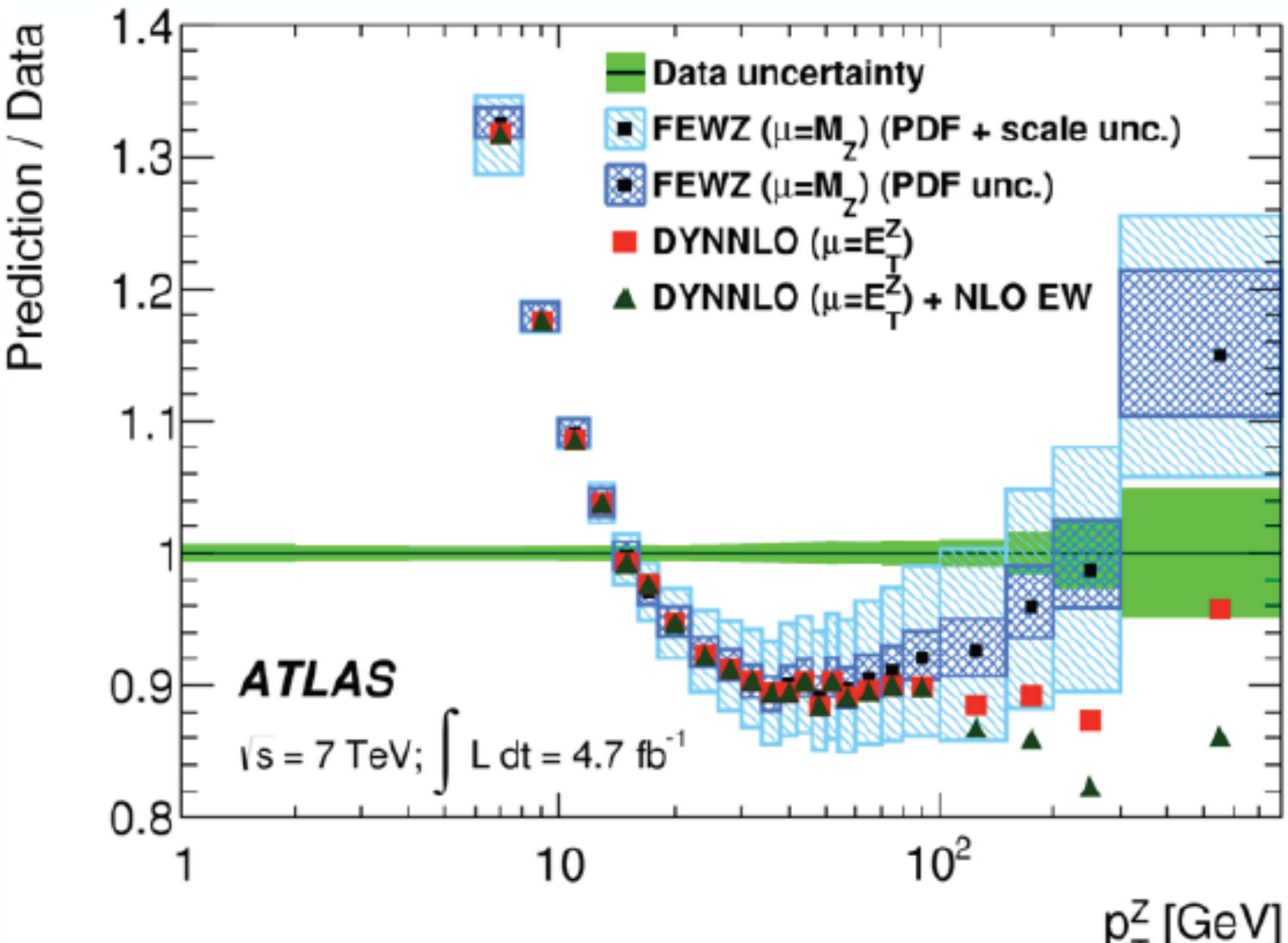
Precision SM measurements at the Tevatron and LHC:

→ measurements of W/Z production and comparisons to theory
→ measurement of A_{FB} and $\sin^2\theta_w$ by D0/CMS/ATLAS
→ measurements of m_W by CDF and D0 and prospects of such measurements for ATLAS and CMS

→ underlying thread in these lectures: how to improve links between theory and experiment

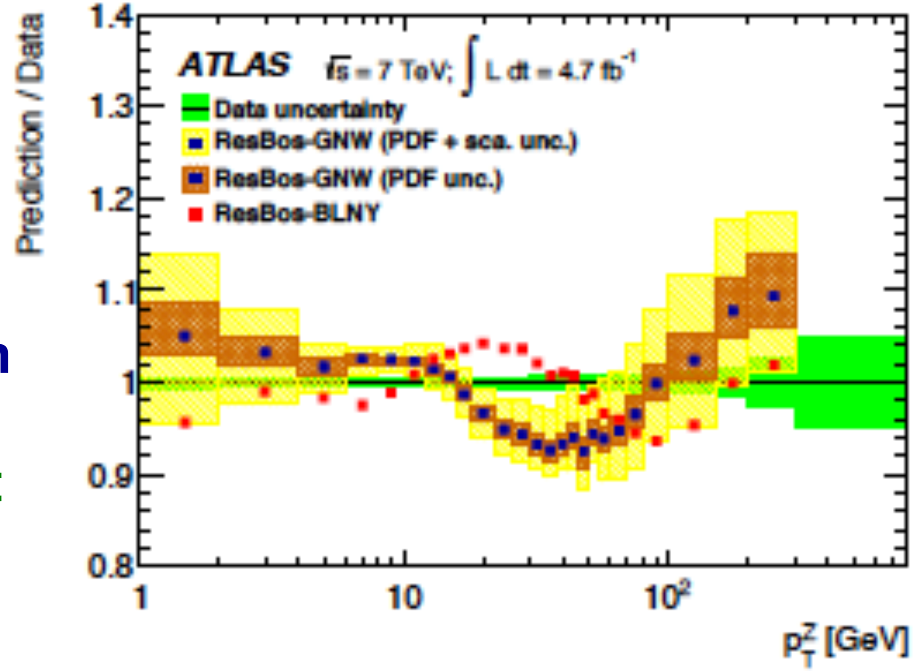
Very precise measurement of Z p_T poses problems to theory

ATLAS Z pT: NNLO / Data

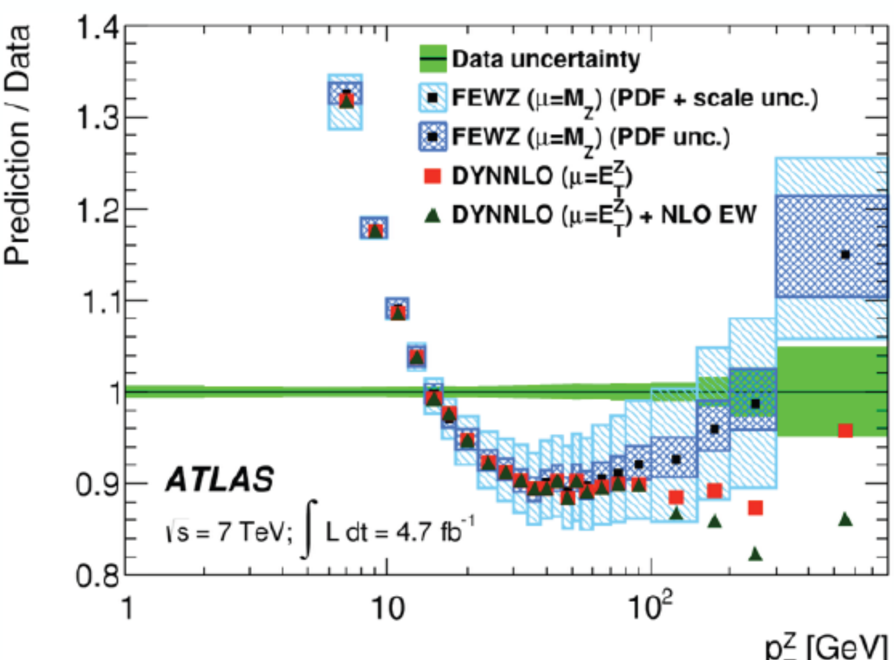


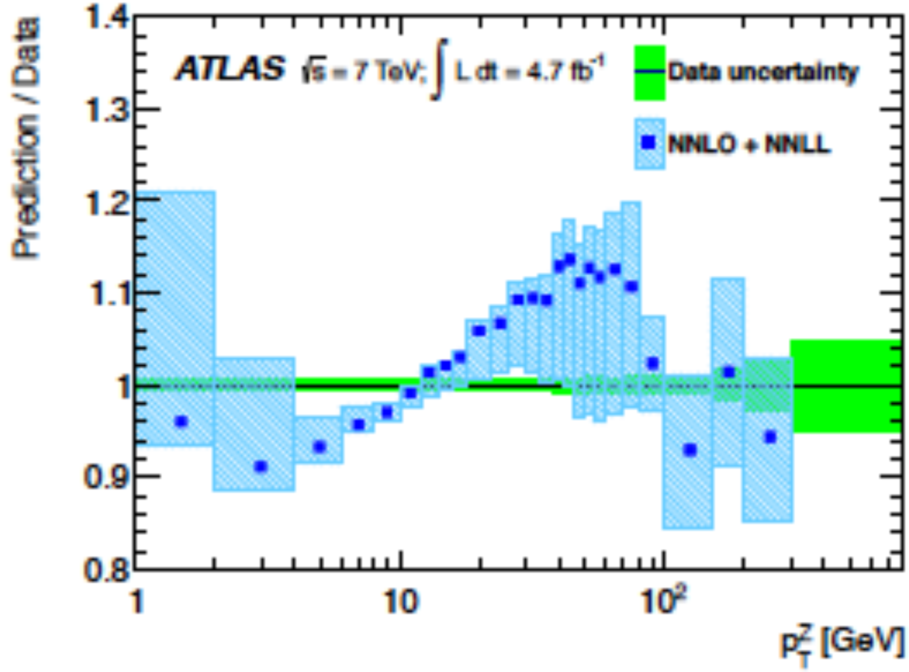
Very precise measurement of Z p_T poses problems to theory

- Shown also here are ResBos (top right) and resummation calculation by Banfi et al. (bottom right)
- Note: uncertainty on measurement at low p_T is ~ 0.5%, rising to 1.5% for p_T^Z ~ 150 GeV



ATLAS Z pT: NNLO / Data

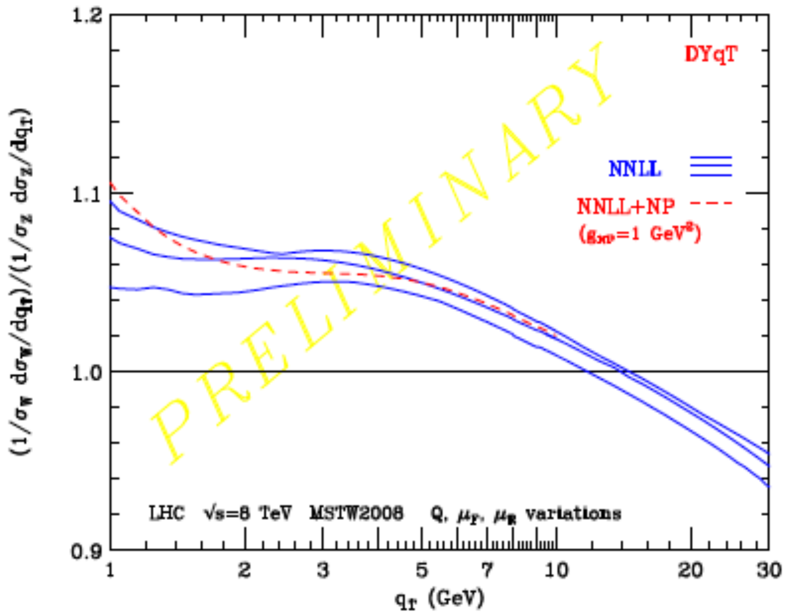




Cancellation of uncertainties in ratios (?)

Beware! Plot below assumes all three scales (renorm., fact. and resummation) are fully correlated between W and Z.

W/Z ratio of observables: the q_T spectrum



DYqT resummed predictions for the ratio of W/Z normalized q_T spectra.

- The use of the W/Z ratio observables substantially reduces both the experimental and theoretical systematic uncertainties [Giele,Keller('97)].
- Resummed perturbative prediction for

$$\frac{\frac{1}{\sigma_W}\frac{d\sigma_W}{dq_T}}{\frac{1}{\sigma_Z}\frac{d\sigma_Z}{dq_T}}(\mu_R, \mu_F, Q)$$

  with the customary scale variation.
- NNLL perturbative uncertainty band very small: 2-5% for $1 < q_T < 2$ GeV, 1.5-2% for $2 < q_T < 30$ GeV.
- Non perturbative effects within 1% for $1.5 < q_T < 5$ GeV and negligible for $q_T > 5$ GeV.

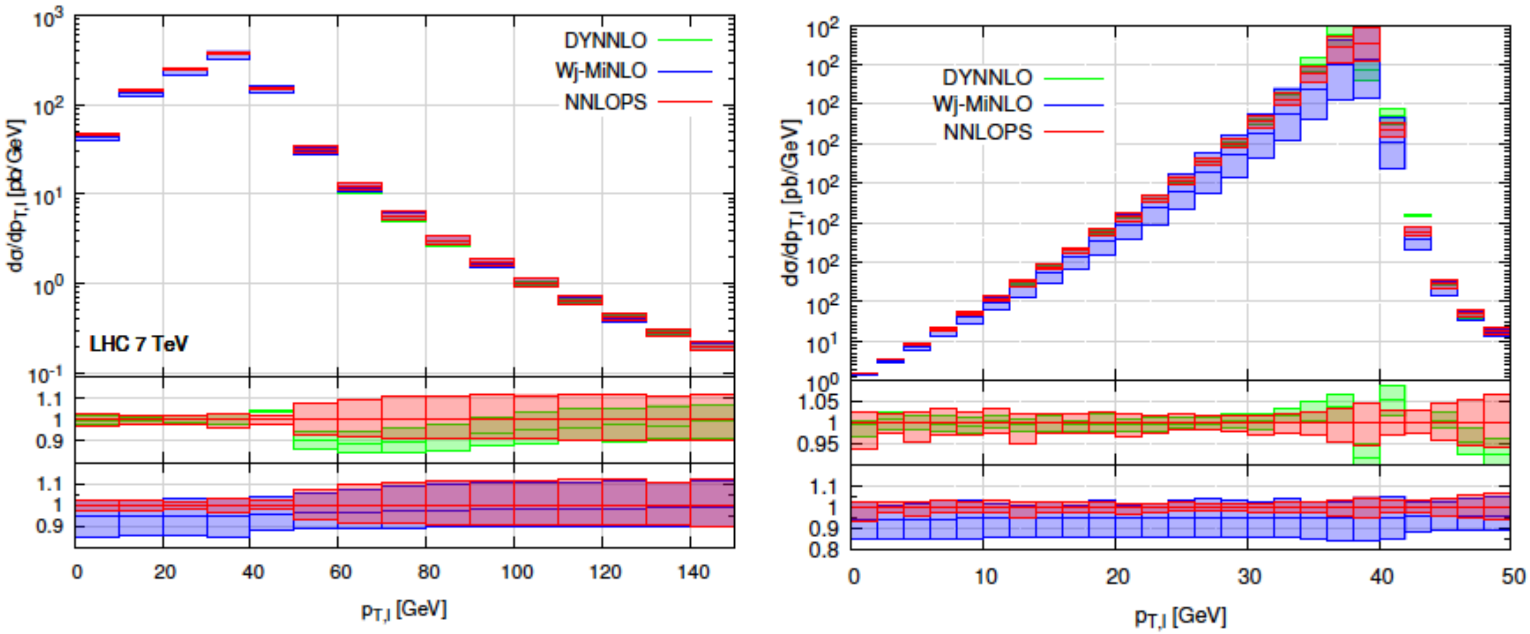
DYRES: a tool to be used at the LHC?

Is Powheg+MiNLO formally NNLO accuracy?

Powheg+Minlo also pays attention to polarisation now!

Thanks to Giulia and Elzbieta for discussing these issues.

W@NNLOPS, PS level

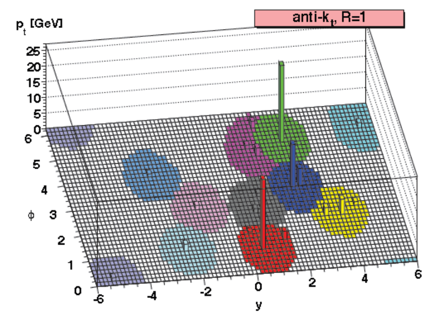


- not the observables we are using to do the NNLO reweighting
  - observe exactly what we expect:
    $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
  - smooth behaviour when close to Jacobian peak (also with small bins) (due to resummation of logs at small $p_{T,V}$)
- just above peak, DYNNLO uses $\mu = M_W$, WJ−MiNLO uses $\mu = p_{T,W}$
  - here $0 \lesssim p_{T,W} \lesssim M_W$ (so resummation region does contribute)

Analysis methodology for W/Z+jets

Measure absolute or normalised differential cross sections in fiducial phase spaces

- **event-based observables => N_{jets}, boson p_T, W M_T , H_T, event-shapes**
- **jet-based observables => n^{th}-jet p_T, y**
- **measure angular correlations (jet-jet, lepton-jet, Z-jet) => $\Delta\phi$, ΔR, Δy, m_{jj}**



- Variety of jet algorithms:
  - Tevatron: cone algorithms,
    - e.g Midpoint R=0.5
  - LHC: anti-k_T R=0.4 (ATLAS), 0.5 (CMS, LHCb)

Detector-Level Measurement → *unfolding* → Particle-Level Measurement/Prediction ← *non-pertur. corrections* ← Parton-Level Calculation

- MC simulations provide particle-level final states
- Parton-level calculations (BlackHat, MCFM) corrected for non-perturbative effects and for hadronisation and underlying event (3-4% corr.)
- Fixed order NLO uncertainties:
  - scales (renorm. and fact.): 4-13%
  - parton densities:1-3%, α_s: 1-3%

N_{jets}, jet p_T in W+jets at 7 TeV

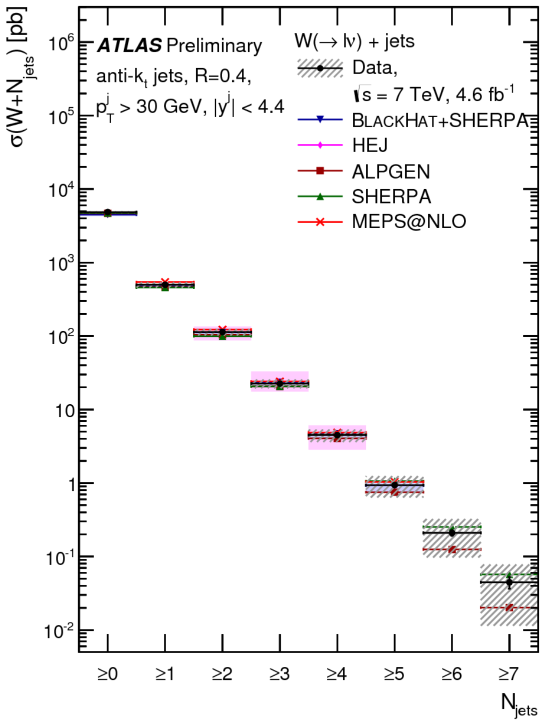
High-order pQCD corrections

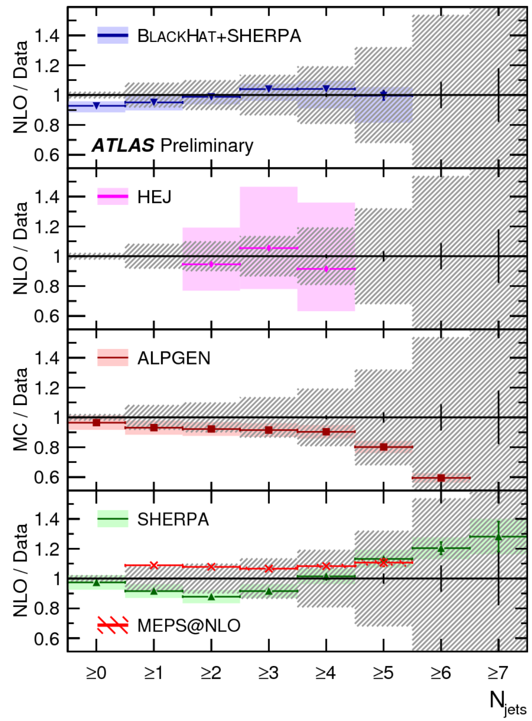
ATLAS-CONF-2014-035

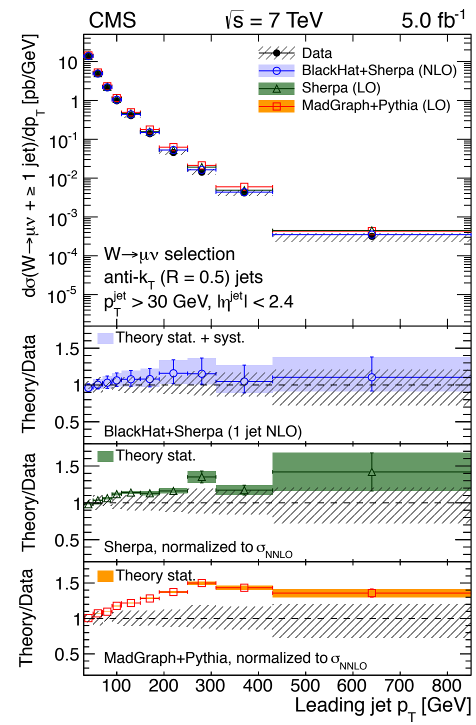
ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j)$ > 0.5
Missing E_T>25 GeV, M_T>40 GeV

arXiv.1406.7533

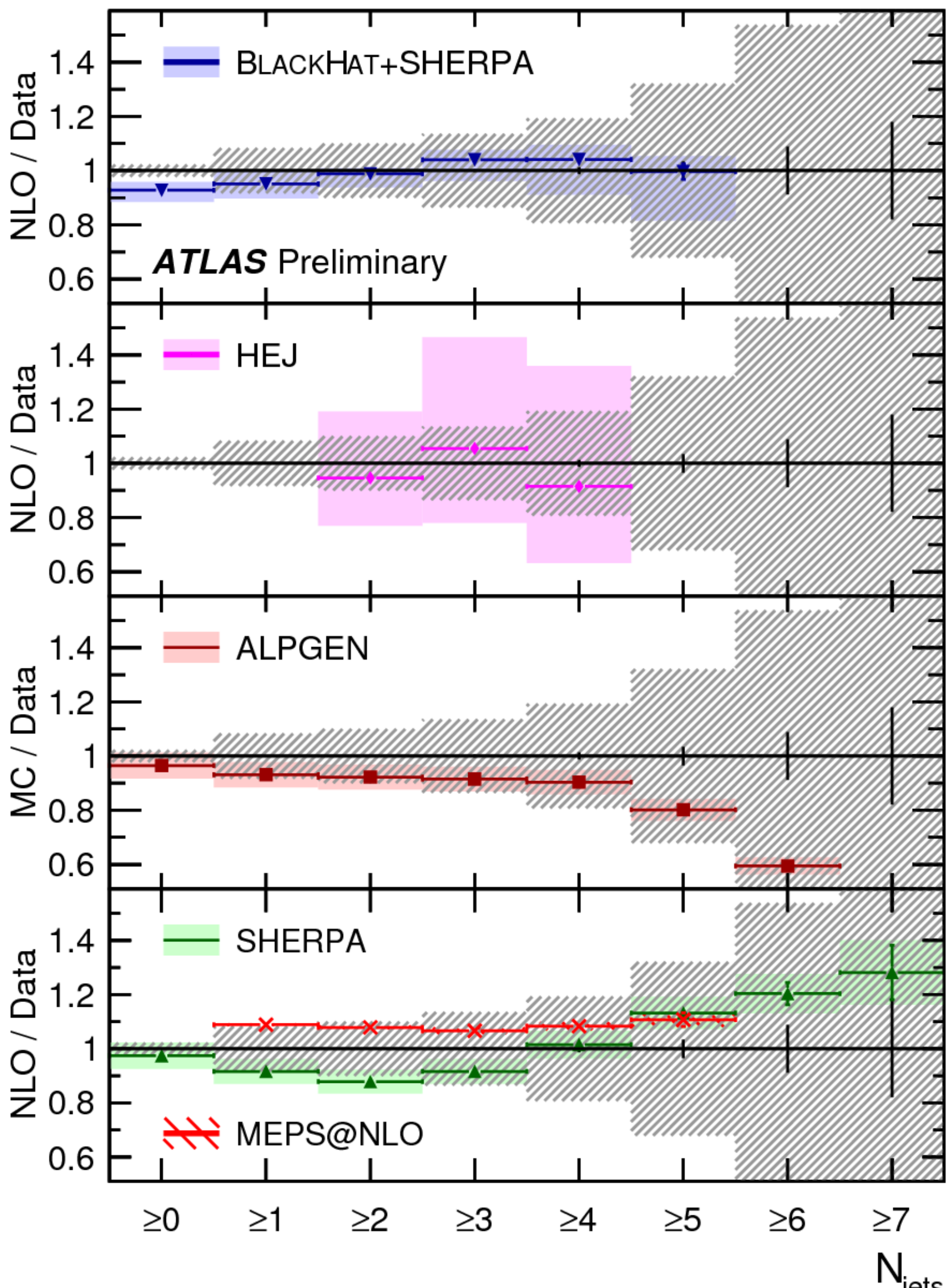
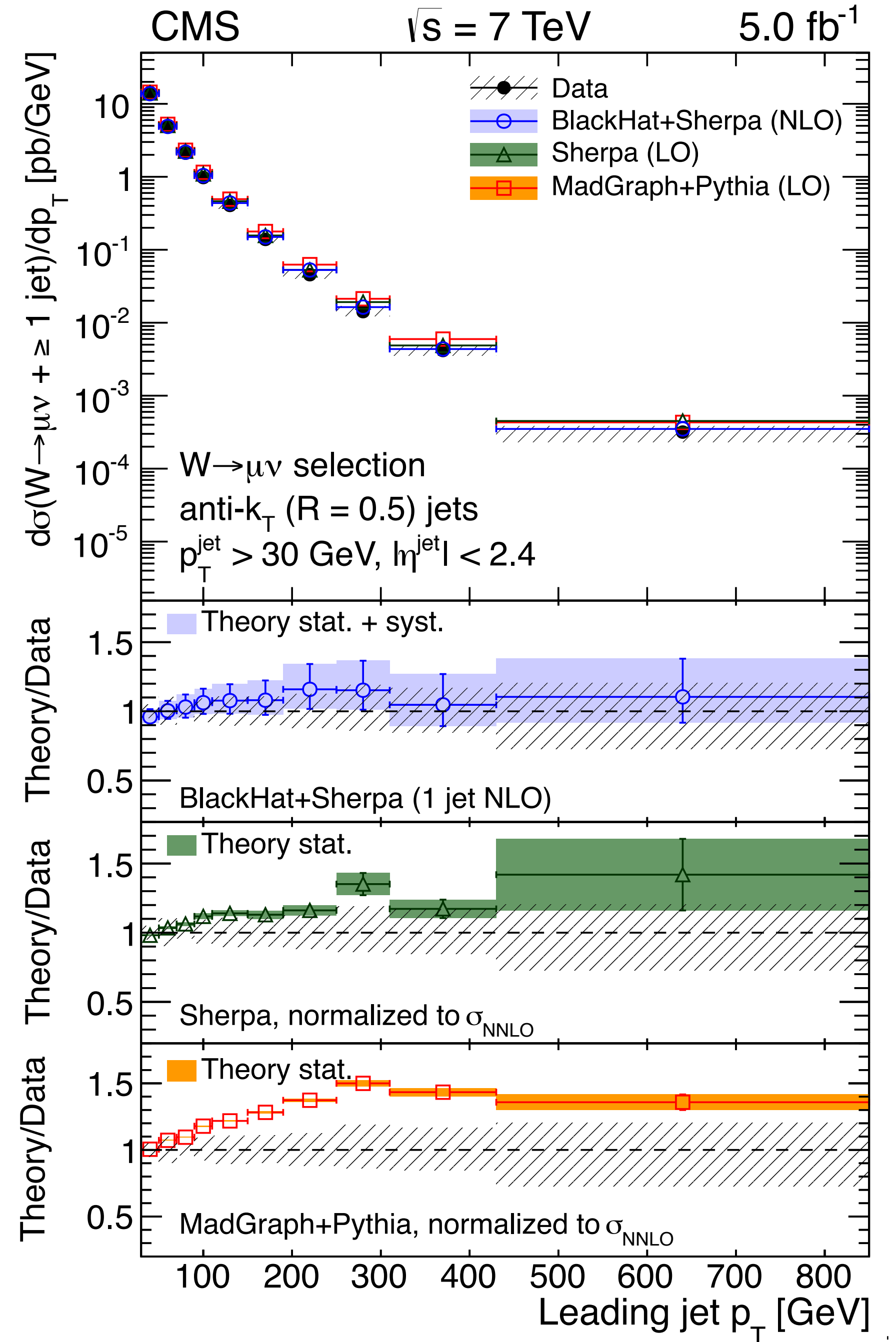
CMS:
Muon p_T>25 GeV, $|\eta|$<2.1
Anti-k_T jets R=0.5, p_T>30 GeV, $|\eta|$<2.4
$\Delta R(\mu,j)$ > 0.5
M_T>50 GeV





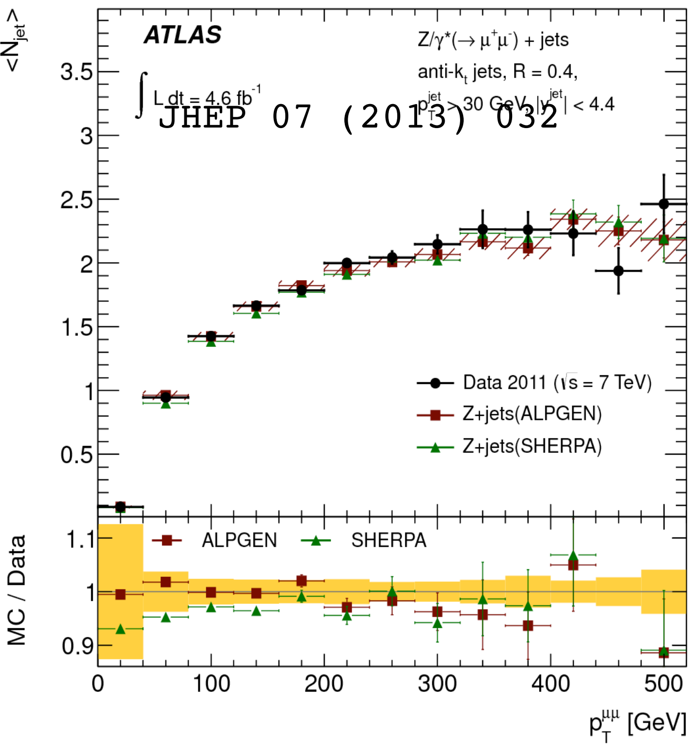


- **Extraordinary agreement between experiments and theory over 5 orders of magnitude in cross-sections**
- **High experimental accuracy exposes discrepancies with predictions**
  - **LO multileg+PS overestimate data at high jet scales (jet p_T)**

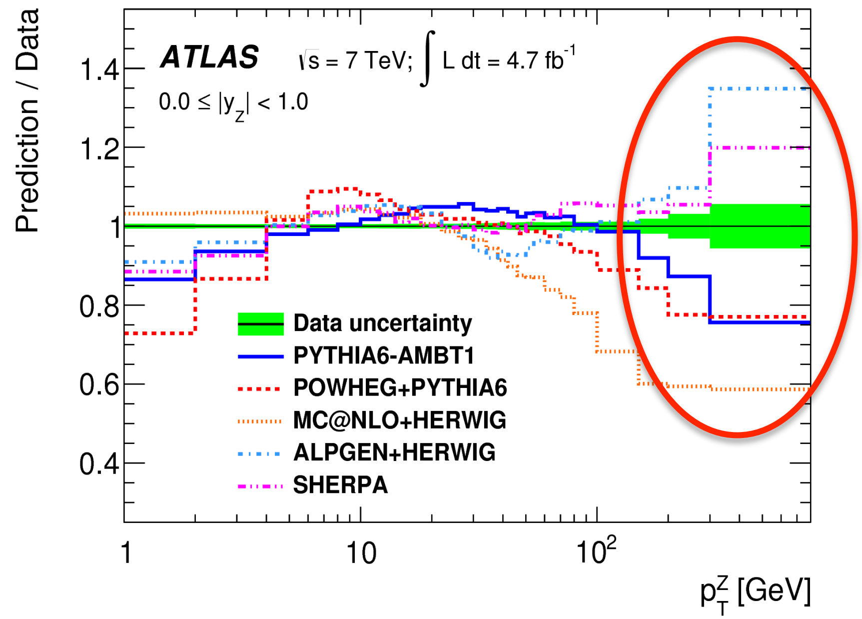

BLACKHAT+SHERPA
ATLAS Preliminary
HEJ
ALPGEN
SHERPA
MEPS@NLO
NLO / Data
MC / Data
1.4
1.2
1
0.8
0.6
≥0
≥1
≥2
≥3
≥4
≥5
≥6
≥7
N_jets

CMS
√s = 7 TeV
5.0 fb^-1
Data
BlackHat+Sherpa (NLO)
Sherpa (LO)
MadGraph+Pythia (LO)
dσ(W→μν + ≥ 1 jet)/dp_T [pb/GeV]
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
W→μν selection
anti-k_T (R = 0.5) jets
p_T^jet > 30 GeV, |η^jet| < 2.4
Theory/Data
Theory stat. + syst.
BlackHat+Sherpa (1 jet NLO)
Theory stat.
Sherpa, normalized to σ_NNLO
Theory stat.
MadGraph+Pythia, normalized to σ_NNLO
1.5
1
0.5
100
200
300
400
500
600
700
800
Leading jet p_T [GeV]

Lepton p_T>20 GeV, $|\eta|$<2.5
66 < m_{ll} < 116 GeV
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
ΔR(lept,jet) > 0.5

Z p_T in Z+jets at 7 TeV



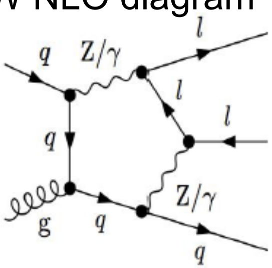
Prediction/data ratio of inclusive Z p_T distribution



Phys. Lett. B 722 (2013) 238–261

- At large p_T^Z multi-jet events contribute to inclusive Z + ≥ 1 jets
  - MC with NLO accuracy on inclusive Z production undershoot data
    - Multi-jet generator overpredict high Z p_T

EW NLO diagram



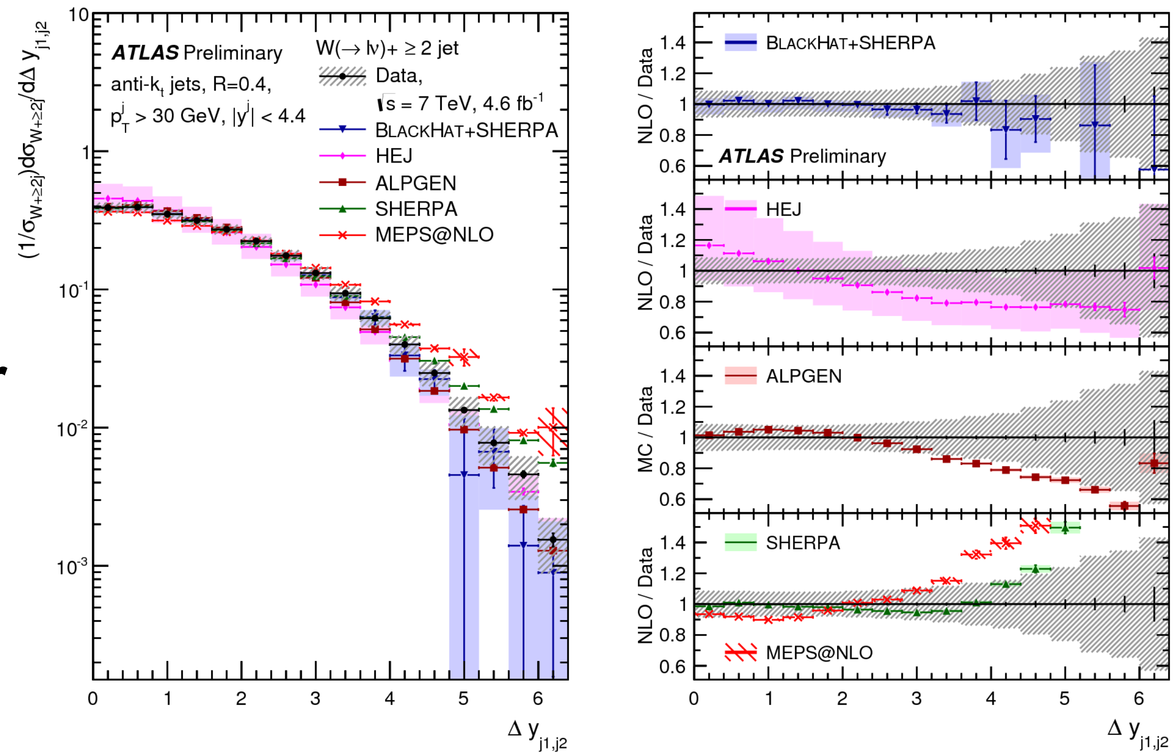
JHEP 1106 (2011) 069

- Higher-order EW corr. expected to reduce cross section by 5-20% at p_T^Z > 100 GeV (not included in main stream MC's)

Angular distributions in W+jets at 7 TeV

ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j) > 0.5$
Missing E_T>25 GeV, M_T>40 GeV

- **Angular distributions provide important test of QCD modeling:**
  - **Hard radiation at large angles**
    - **Modeled by M.E.**
  - **Unresolved soft/collinear radiation**
    - **Modeled by P.S.**
- **Important for Higgs selection and to study VBF/VBS mechanisms**



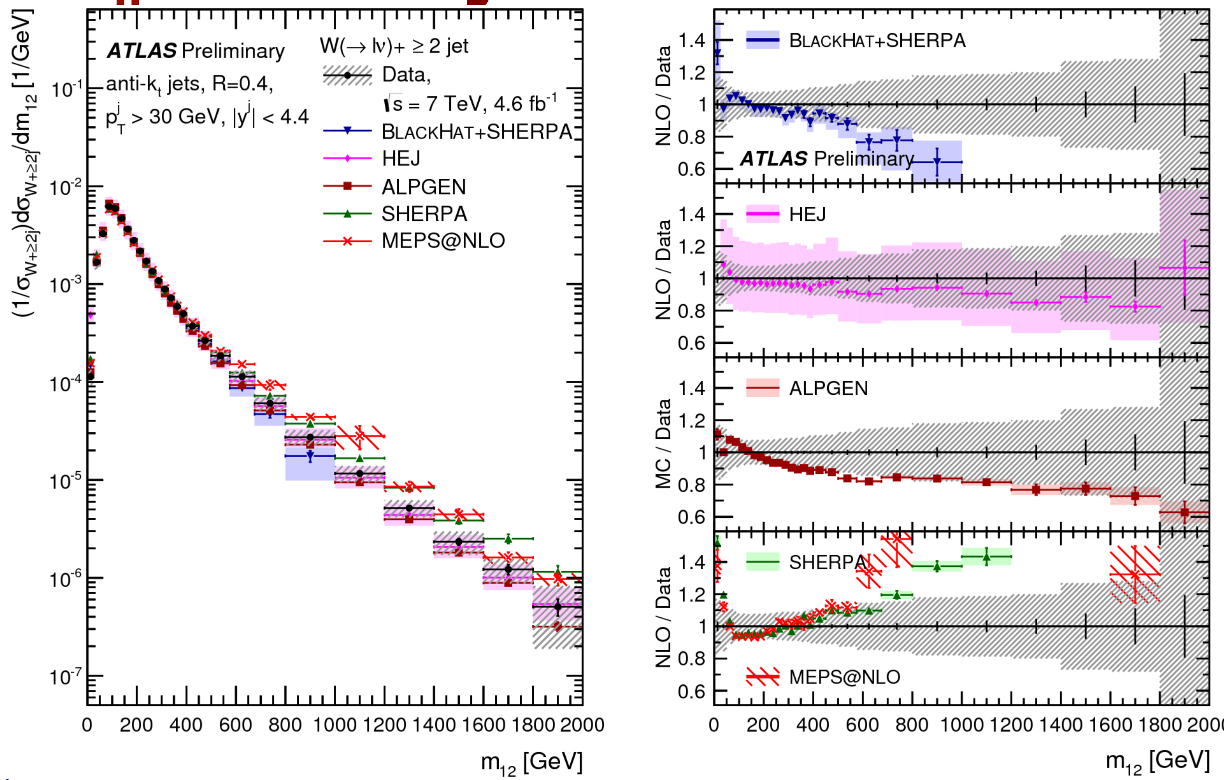
- ***BlackHat* in good agreement with data on $\Delta y(j,j)$**
- **Higher experimental precision exposes data-prediction discrepancies**

ATLAS-CONF-2014-035

ATLAS:
Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j) > 0.5$
Missing E_T>25 GeV, M_T>40 GeV

High-order pQCD corrections
Matrix Element – Parton Shower

m_{jj} in W+jets at 7 TeV



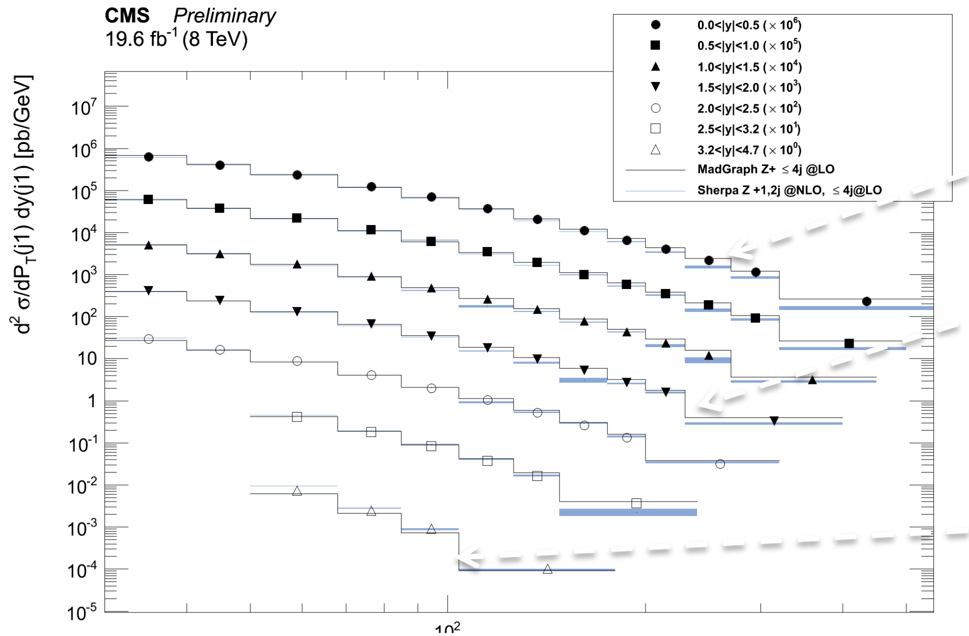
- ❑ **Fixed-order NLO calculation (BlakHat) underestimates the high m_{jj} region**
- ❑ **BFKL-like resummation (*HEJ*) is in agreement with data on m_{jj}**
- ❑ **Discrepancies of LO and NLO multi-leg MC predictions**
  - ➢ **Room for MC tuning, e.g. P.S, M.E.- P.S matching**

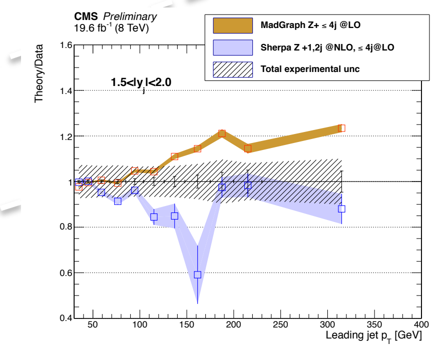
Matrix Element – Parton Shower
Parton densities

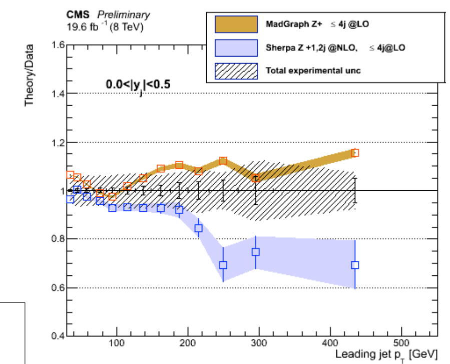
Double differential cross sections in Z+jets at 8 TeV

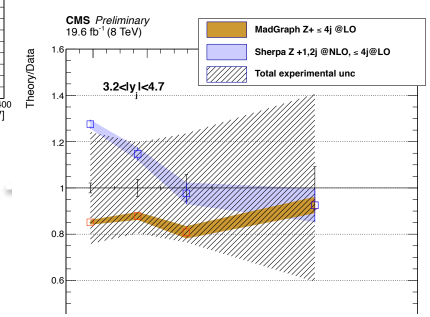
CMS:
Muon p_T>20 GeV, $|\eta|$<2.4
Anti-k_T jets R=0.5, p_T>30(50) GeV, $|\eta|$<2.5 (>2.5)
$\Delta R(\mu,j)$ > 0.5
M_T>50 GeV

- **First double differential measurement: leading jet p_T and rapidity (like in jet measurements)**
  - **also suitable for PDF fitting**
- **Extended jet rapidity range, up to $|\eta|$ = 4.7**





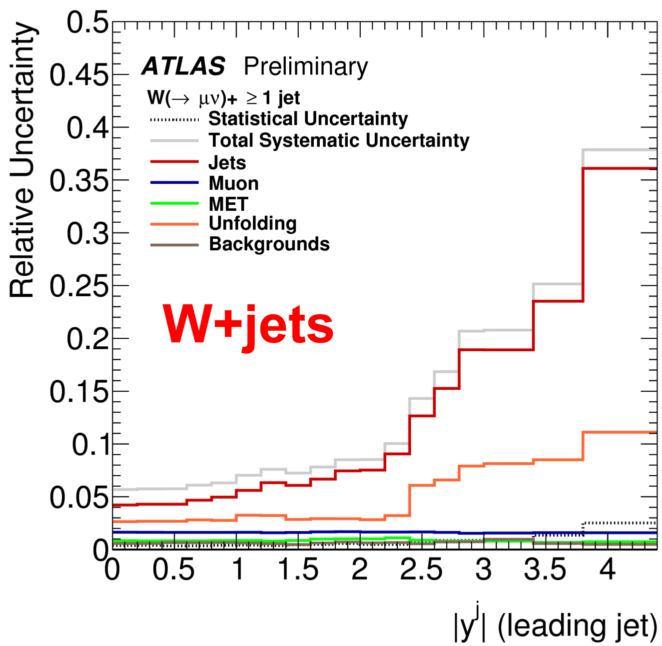


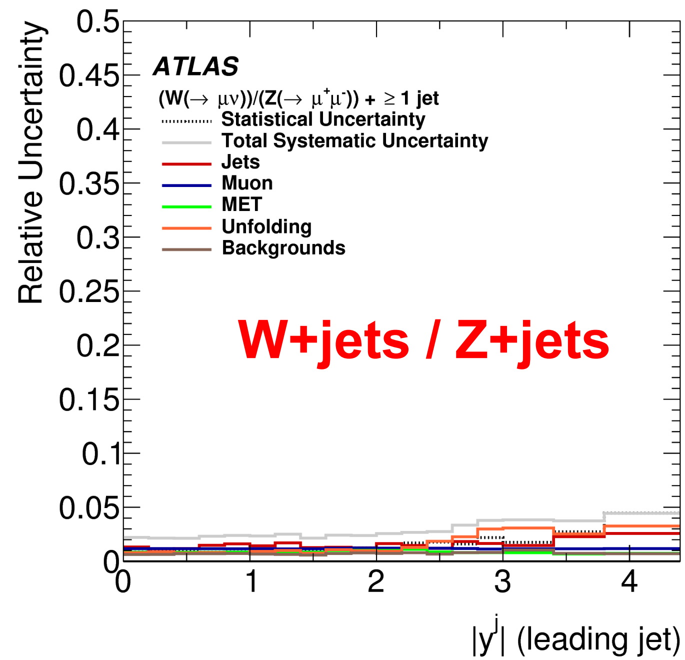


- **For central jets, the precision of experimental measurements is higher than prediction-to-prediction differences**
- **up to ±20% data-theory discrepancies (Madgraph, Sherpa MEPS@NLO) in high p_T tails of 1st jet**

Cancellation of uncertainties in ratios (?)

- ❑ **Ratio measurements allow for cancellations of uncertainties (exp. and theory)**
  - **Experimental: jet calibration uncertainties, lumi etc.**





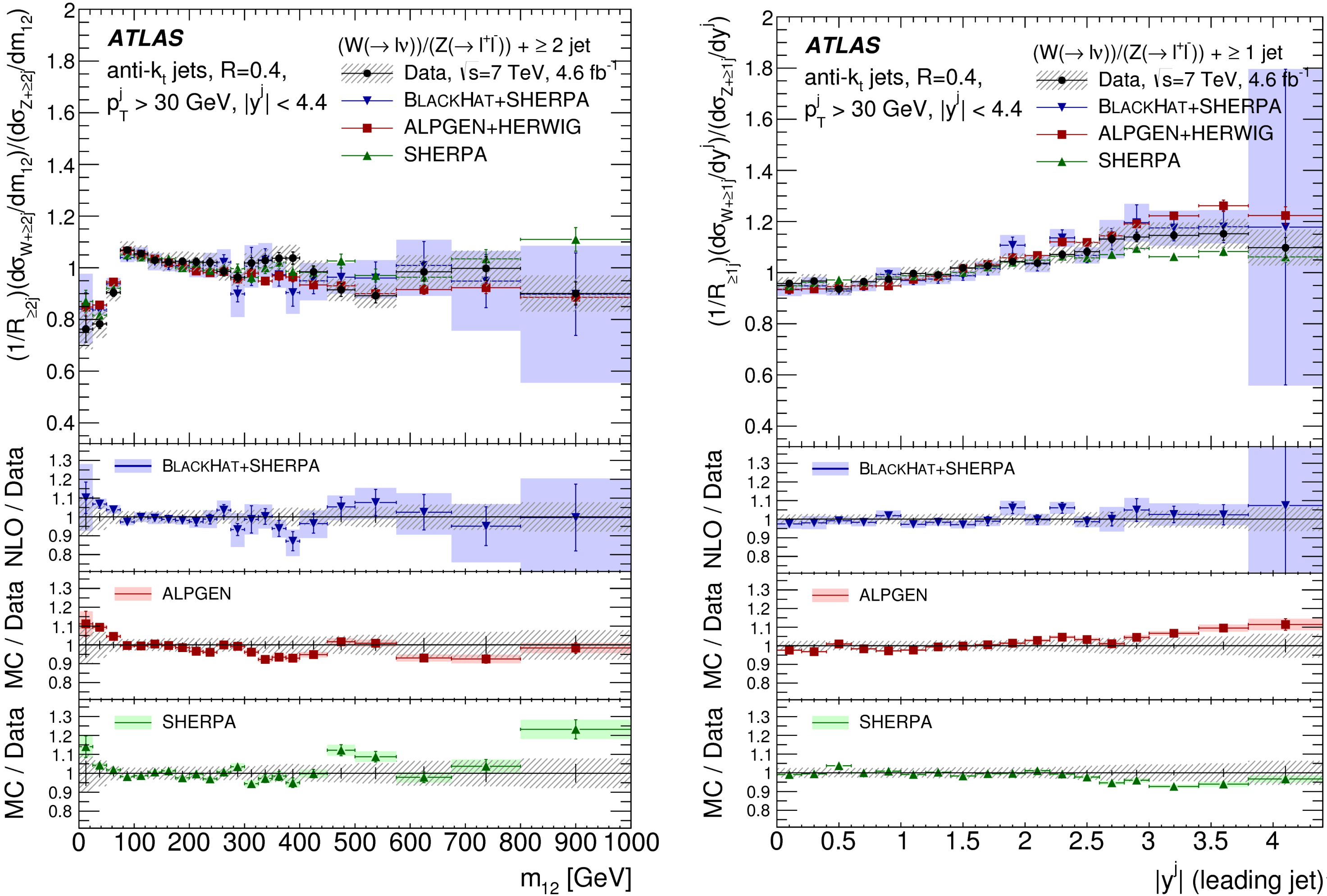
Theory: (if treated as correlated between numerator and denominator)

- ❑ **scale+PDF uncertainties: *20%* (W+1j) -> *2-4%* on W+1j/Z+1j at jet p_T=800 GeV**
- ❑ **Accurate test of SM predictions**
- ❑ **Important for Z(νν)+jets background estimation in searches**
- ❑ **Model-independent searches for new physics**

R_{jets} = W+jets / Z+jets

Lepton p_T>25 GeV, $|\eta|$<2.5
Anti-k_T jets R=0.4, p_T>30 GeV, $|y|$<4.4
$\Delta R(l,j)$ > 0.5
W: Missing E_T>25 GeV, M_T>40 GeV
Z: 66<m_{ll}<116 GeV

- **Significant discrepancies with theory in some regions of phase space**
  - **e.g. high leading-jet rapidity**
- **Mismodeling seen in W+jets and Z+jets separately mostly cancel in R_{jets}**

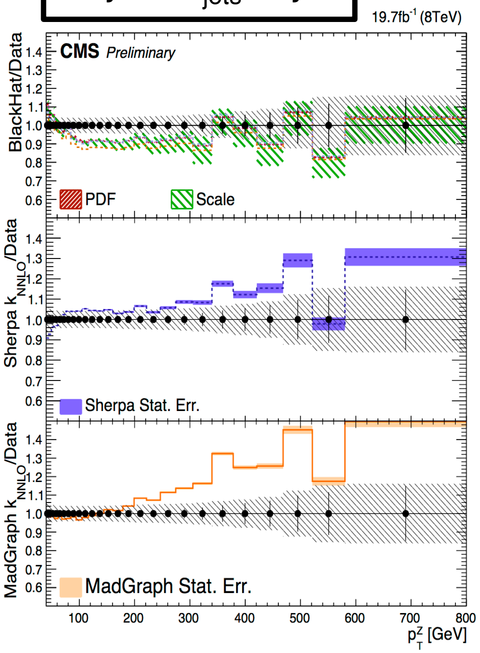


Z+jets / γ+jets ratio

Lepton p_T>20 GeV |η|<2.4
V-boson p_T>100 GeV
V-boson |y| < 1.4
Anti-Kt R=0.5 jet p_T>30 GeV, |η|<2.4
ΔR(l,j) > 0.5

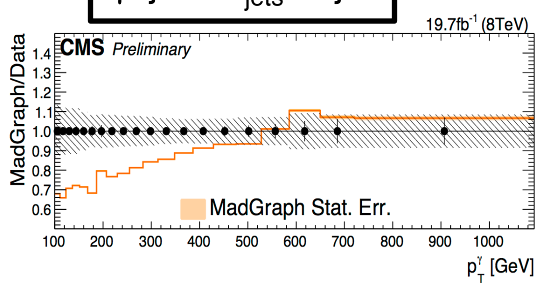
- **At large V-boson p_T QCD and EW introduce large high-order corr.**
  - **NLO (BlakHat) underestimate data at Z p_T≥100 GeV by ~10%**
  - **LO multileg MC (Madgraph, Sherpa) overestimate high Z p_T**
    - **scaled to NNLO inclusive Z cross-section**

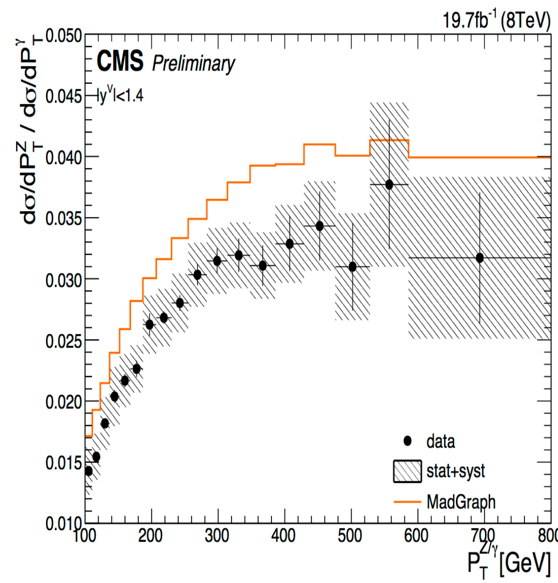
Z+jets N_{jets}≥ 1jet

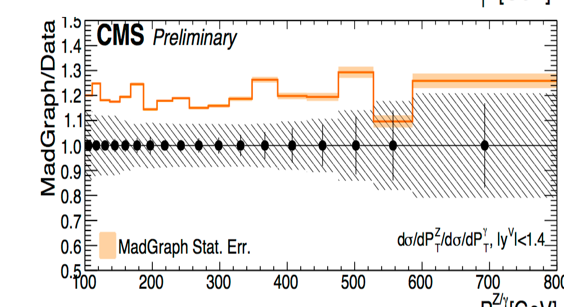


Cancellation of JES, JER and lumi in ratio

γ+jets N_{jets}≥ 1jet







Ratios in Z+jets

CMS-PAS-SMP-14-005

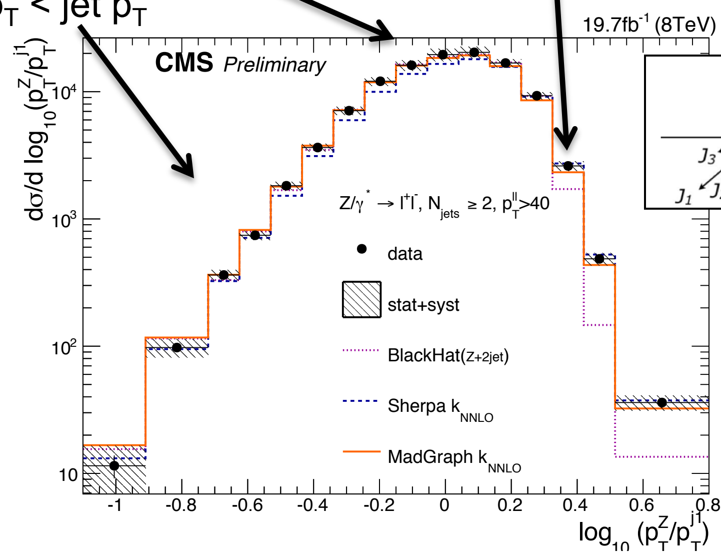
Lepton p_T>20 geV $|\eta|$<2.4
Z p_T>100 GeV
antiKt5 jet p_T>30 GeV, $|\eta|$<2.4
$\Delta R(l,j) > 0.5$

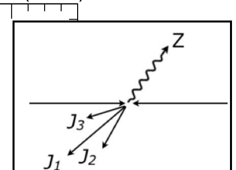
- ❑ **Test limit of validity of NLO pQCD calculation (where large logs are expected or missing higher orders)**
- ❑ **Fixed-order NLO fails at large $p_T^Z/p_T^{\text{1st jet}}$ due to missing higher-order predictions**
  - ▪ **3-jet emission only at LO in BlackHat**
- ❑ **Parton shower adds soft jets and provides better description of high tails**

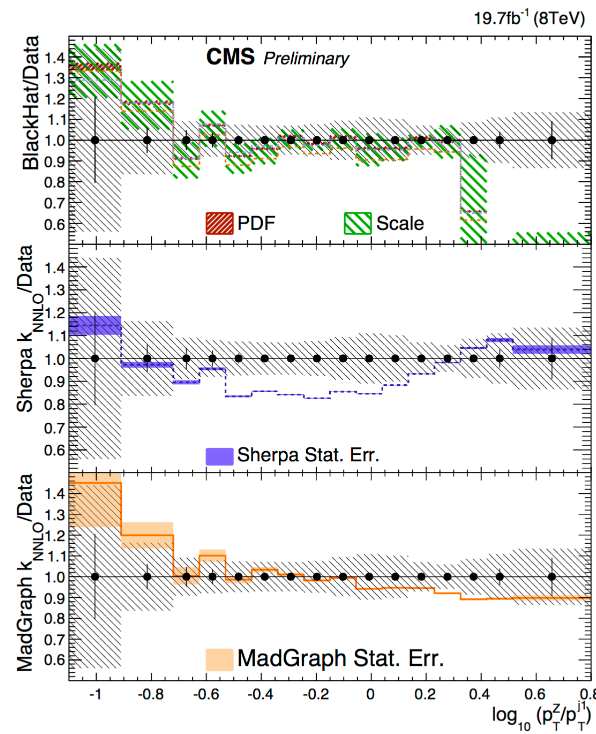
Z-jet are back-to-back

Z p_T < jet p_T

3rd jet is relevant (NLO becomes LO)

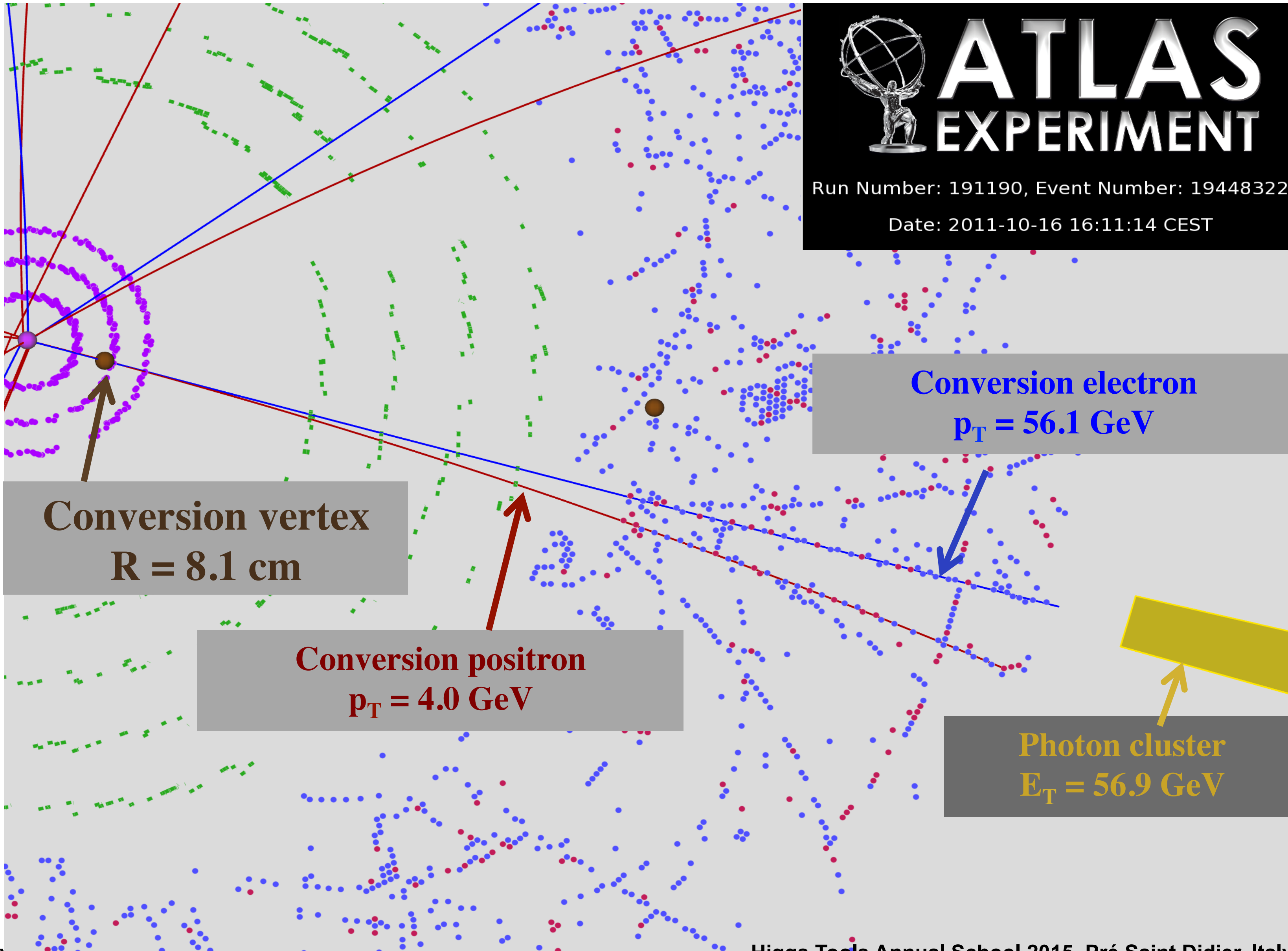




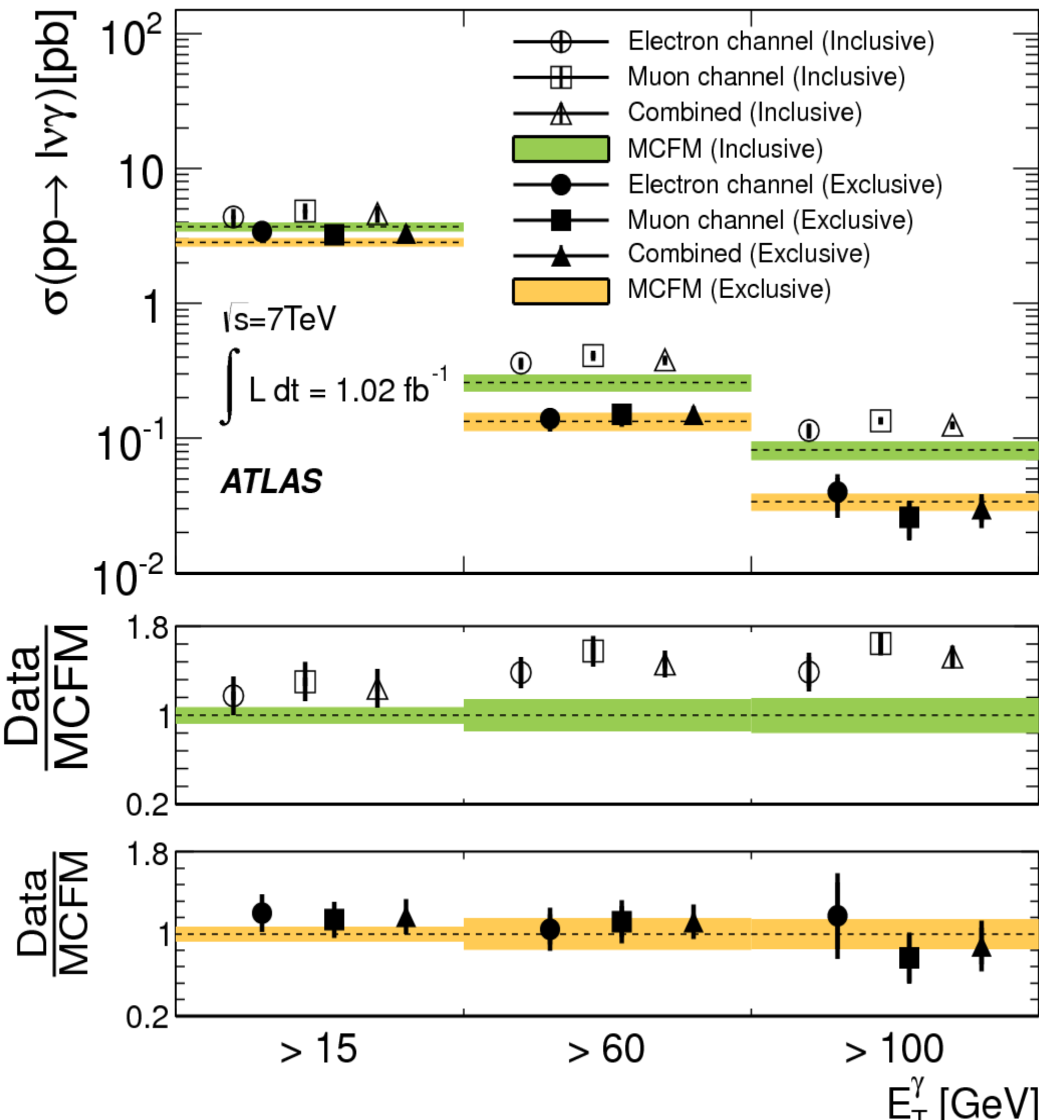


Diboson measurements: Wγ and Zγ

- **Need to efficiently reconstruct converted photons in high pile-up environment**

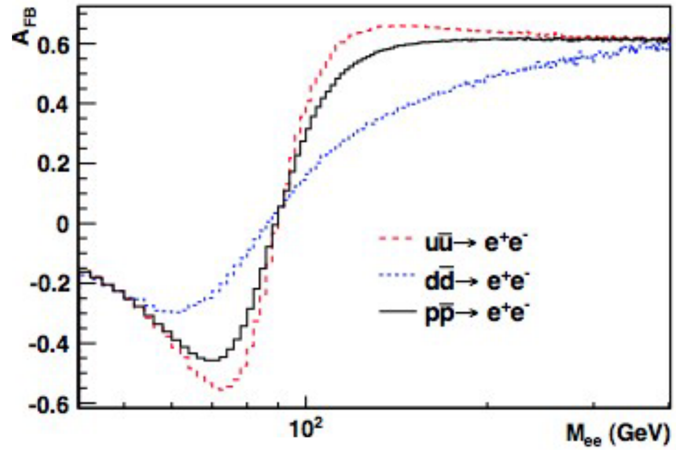


Diboson measurements: Wγ comparison to MCFM



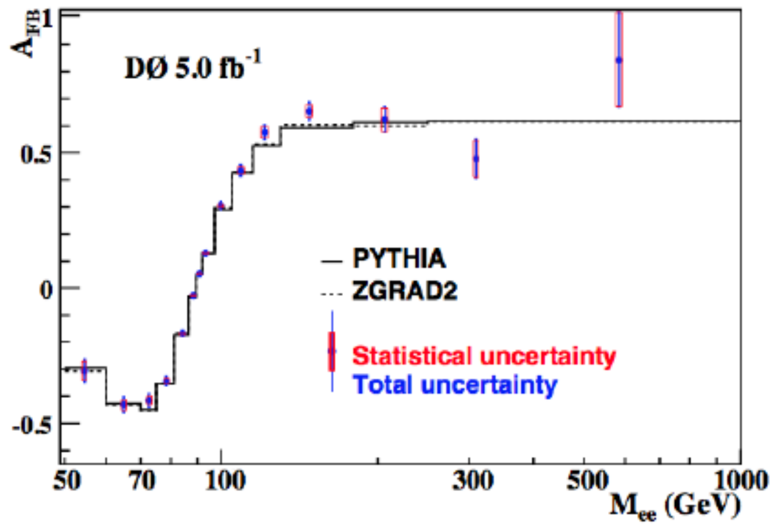
- Disagreement between data and MCFM for inclusive selection
- Increases as p_T^γ increases, from data/MC = 1.24 ± 0.20 for p_T^γ > 15 GeV to data/MC = 1.52 ± 0.31 for p_T^γ > 100 GeV
- MCFM exclusive calc. ~ NLO but error band not quite correct
- Need improved theoretical tools:
- NNLO calculations?
- NLO predictions at particle level for dibosons plus one or two jets will eventually be needed
- improved QCD tools now available to and higher-stat measurements also
•- eventually will need the same for WWjj

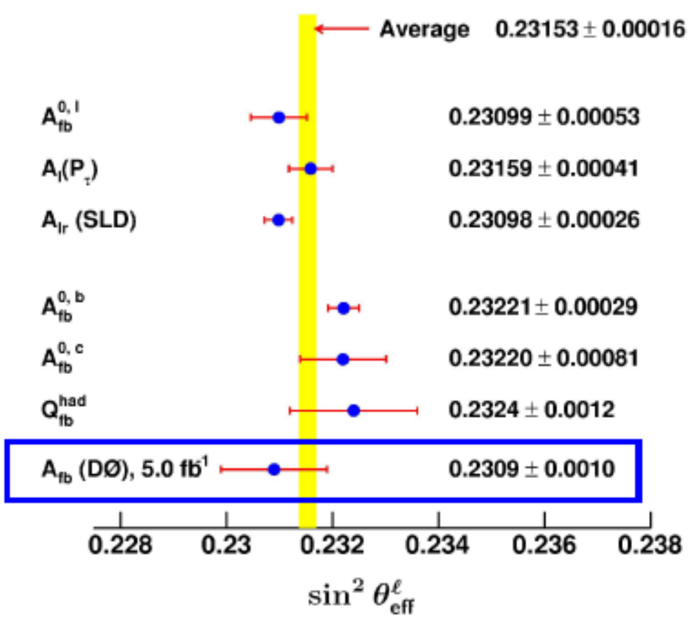
Measurement of Z forward-backward asymmetry: beyond the legacy of LEP and Tevatron?



- Unfolded AFB agrees well with theoretical prediction
- No evidence for new physics at high mass
- Extracted $\sin^2\theta^{l}_{eff}$

= 0.2309 ± 0.0008 (stat.) ± 0.0006 (syst.)



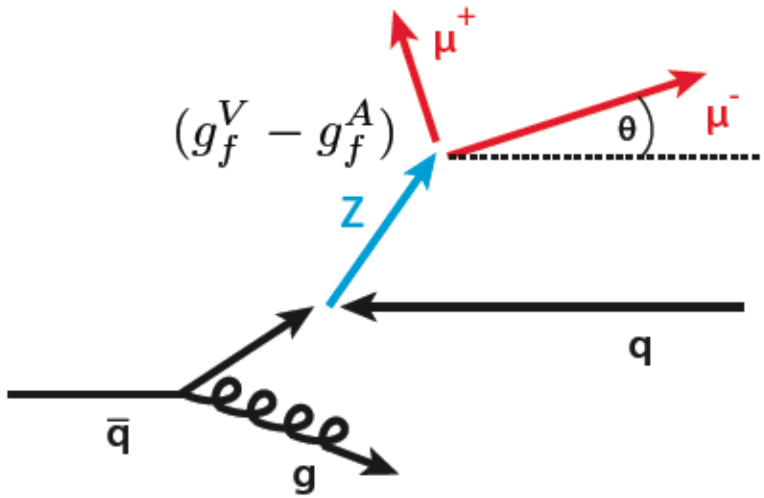


- Statistical uncertainty is still dominant
- PDF uncertainty (0.00048) is dominant in systematic uncertainty
- Most precise measurement based on Z to light quark couplings

Published: Phys. Rev. D 84, 012007 (2011)

Measurement of Z forward-backward asymmetry at the LHC

Weak interaction dominates this reaction



Parity violation in weak interactions:

- Z Boson polarized (wrt. q)
- μ⁻ has preferred direction wrt. Z pol.
- asymmetric θ distribution (wrt. q)
- actually: Z/γ* interference responsible for mass dependent asymmetry

Weinberg angle ↔ Vector coupling:

$$g_f^V = T_3^f - 2Q_f \sin^2\theta_w$$

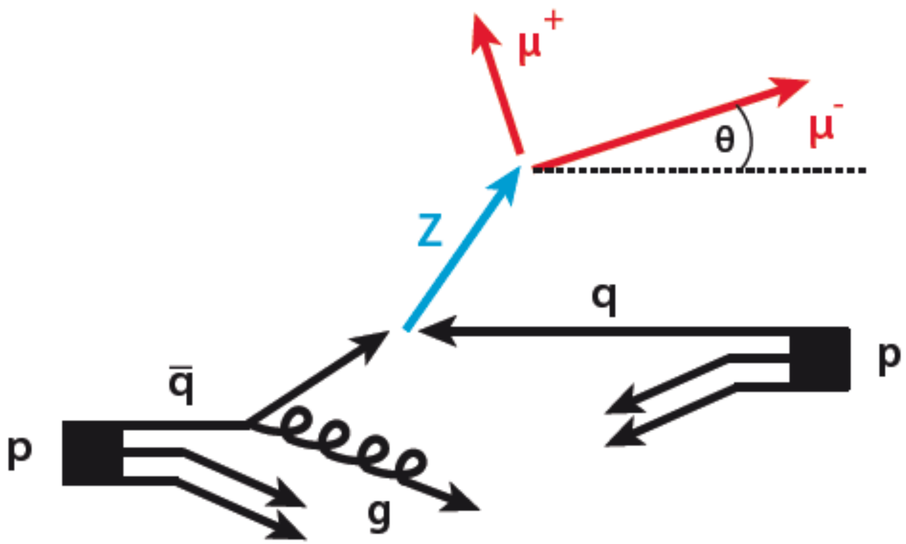
weak Isospin — Charge — Weinbergwinkel

Forward events: $\cos\theta > 0$
Backward events: $\cos\theta < 0$

$$A_{fb} = \frac{N^{\cos\theta>0} - N^{\cos\theta<0}}{N^{\cos\theta>0} + N^{\cos\theta<0}}$$

Measurement of Z forward-backward asymmetry in ATLAS

From which Proton originates Quark?



Sensitivity to **sign** of cos θ only on **statistical basis**:

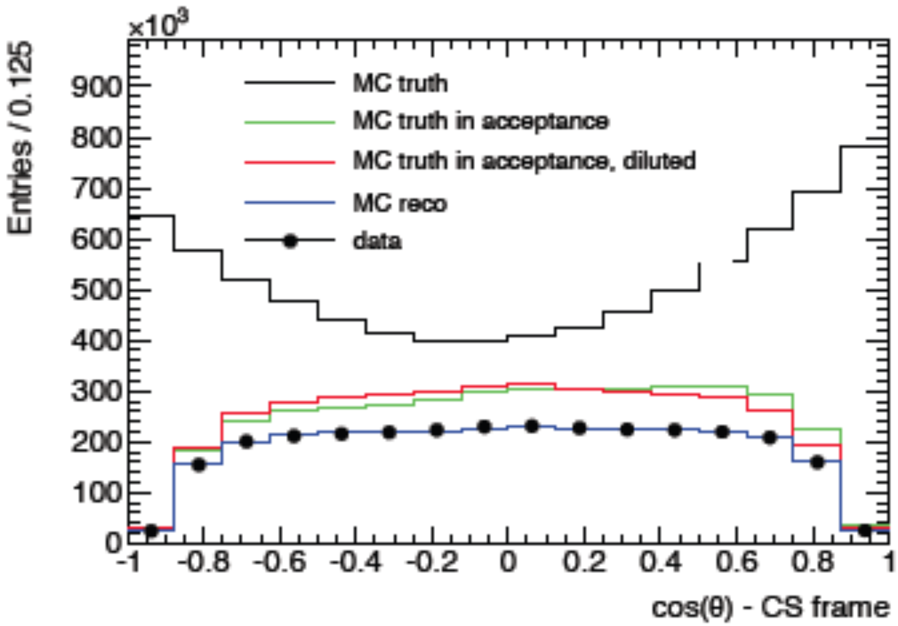
- quarks carry larger momentum fraction of the proton than anti-quarks (PDFs)
- sign estimated from longitudinal boost
- dilution of A_{fb}

Dilution has huge impact:

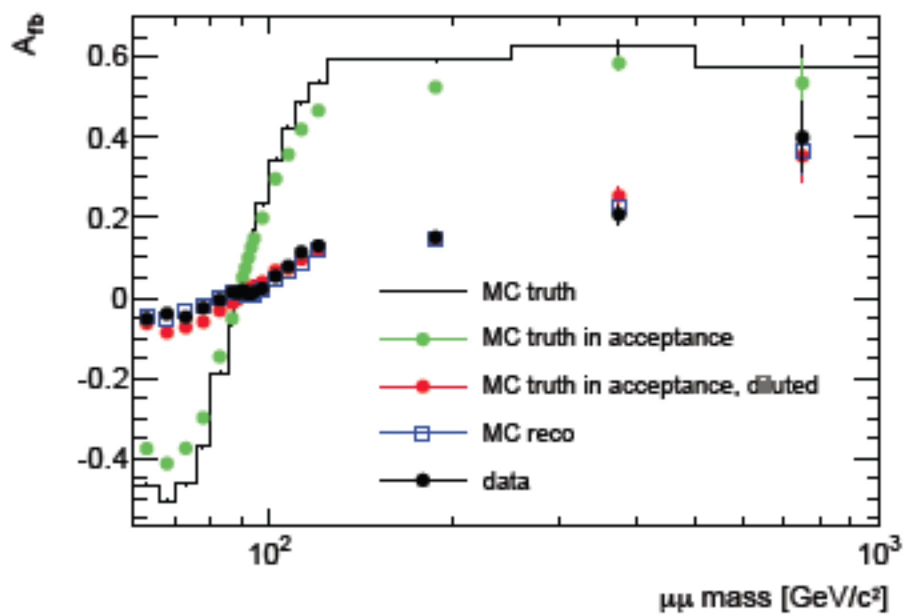
Asymmetry reduced by a factor of ~5

Measurement of Z forward-backward asymmetry in ATLAS

- Shape of angular distribution distorted due to finite detector acceptance



- Dilution of asymmetry
- Shape preserved



Measurement of Z forward-backward asymmetry in ATLAS

Electrons CC

Systematic uncertainty	Deviation [10^{-5}]
PDF (CT10/ATLAS-epWZ12)	91/ 102
Energy Scale	35
Energy Smearing	42
Electron ID	1
Pile-up	8
Background	3
MC statistics	48
EWK NLO corrections	6
QCD NLO corrections	32
Total (CT10/ATLAS-epWZ12)	121/130

Breakdown of systematic uncertainties in each channel

2 largest contributions are highlighted

Electrons CF

Systematic uncertainty	Deviation [10^{-5}]
PDF (CT10/ATLAS-epWZ12)	46/97
Energy Scale	57
Energy Smearing	45
Electron ID	4
Pile-up	5
Background	8
MC statistics	23
EWK NLO corrections	6
QCD NLO corrections	10
Total (CT10/ATLAS-epWZ12)	90/ 124

Muons

Systematic uncertainty	Deviation [10^{-5}]
PDF (CT10/ATLAS-epWZ12)	89/86
Smearing correction	3
Scale correction (charge indep.)	14
Scale correction (charge dep.)	53
Misalignment	18
Background	3
MC statistics	48
EWK NLO corrections	6
QCD NLO corrections	32
Total (CT10/ATLAS-epWZ12)	121/119

Measurement of Z forward-backward asymmetry in ATLAS

- The most relevant renormalization scheme for A_{fb} measurements is the ***Effective*** one, since it is directly related to the coupling of Z to fermions

Scheme	Notation	Value
On-shell	s_W^2	0.2233
NOV	$s_{M_Z}^2$	0.2311
$\overline{\text{MS}}$	$\hat{s}_Z^2$	0.2313
$\overline{\text{MS}}$ ND	$\hat{s}_{\text{ND}}^2$	0.2315
$\boxed{\text{Effective angle}}$	$\bar{s}_f^2$	0.2316

- EW corrections have been absorbed into corrections $\rho_f - 1$ and $\kappa_f - 1$
  - ρ & κ depend on underlying normalization scheme, in our case MSbar

- One then defines an effective weak mixing angle in such a way that the new couplings are proportional to the tree-level ones

  - The predictions for the asymmetries stay formally identical to the tree-level expressions, modulo using the effective angle instead of the "bare" one

Measurement of Z forward-backward asymmetry in ATLAS

	$\sin^2\theta_W^{eff}$	Δ/σ (wrt LEP+SLC)	Δ/σ (wrt ATLAS *ATLAS-epWZ12*)
ATLAS, CC electrons	0.2279 ± 0.0016	-2.3	–
ATLAS, CF electrons	0.2295 ± 0.0011	-1.8	–
ATLAS, muons	0.2293 ± 0.0015	-1.5	–
ATLAS, combined	0.2291 ± 0.0010	-2.4	–
ATLAS, combined, *ATLAS-epWZ12*	0.2311 ± 0.0012	-0.4	–
CMS [45]	0.2287 ± 0.0032	-0.9	-0.7
D0 [46]	0.2309 ± 0.0010	-0.6	-0.1
CDF [47]	0.2328 ± 0.0011	1.1	1.1
LEP, $A_{FB}^{0,b}$ [4]	0.23221 ± 0.00029	–	1.0
LEP, $A_{FB}^{0,l}$ [4]	0.23099 ± 0.00053	–	-0.1
SLD, A_l [4]	0.23098 ± 0.00026	–	-0.1
LEP+SLD [4]	0.23153 ± 0.00016	–	0.4
PDG global fit [44]	0.23146 ± 0.00012	-0.4	0.3

Still a long way to go to reach SLD/LEP individual experiment sensitivity:

- **Stat: expect ~ 20 10^{-5} for full 2012 dataset**
- **Experimental syst: improve to 10 10^{-5}?**
- **QCD theory syst: reduce to small contribution with polarisation measurements?**
- **EW theory syst: seems to be below 10 10^{-5}**
- **PDF syst: the real challenge. Need to use ATLAS/CMS DY data to reduce it from the current 70 10^{-5} estimate to below 10-20 10^{-5}.**

DY precision measurements: Z polarisation

Angular coefficients A_i are functions of lepton-pair kinematics: p_T^{ll}, y_{ll}, m_{ll}. They contain information about the underlying QCD dynamics, and are subject to modifications from higher-order perturbative and non-perturbative corrections, structure functions, renormalisation/ factorisation scale uncertainties, the underlying event, etc...

They depend on the sub-process type: annihilation, Compton scattering,

$$\frac{d\sigma}{dp_T^2\ dy\ d\cos\theta\ d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^2 dy}$$
$$\{\underbrace{\boxed{(1+\cos^2\theta)}}_{\text{LO term}} + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + \underbrace{\boxed{A_4\cos\theta}}_{\text{AFB term}}$$
$$+A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\}$$

This decomposition is valid in the limit of massless leptons -> 2-body phase-space and helicity conservation in the decay.

A_0, A_1, A_2 – parity conserving

A_3, A_4, A_5, A_6, A_7 – parity violating

A_4 – related to A_{FB}

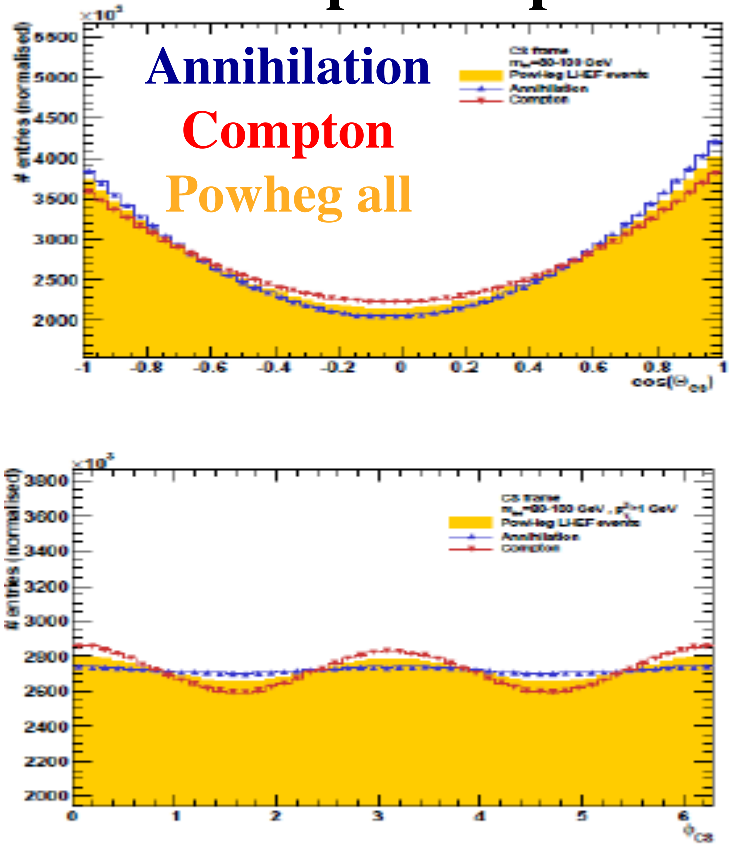
A_5, A_6, A_7 – T-violating, set to 0 in most generators?

Unfolded fiducial measurements

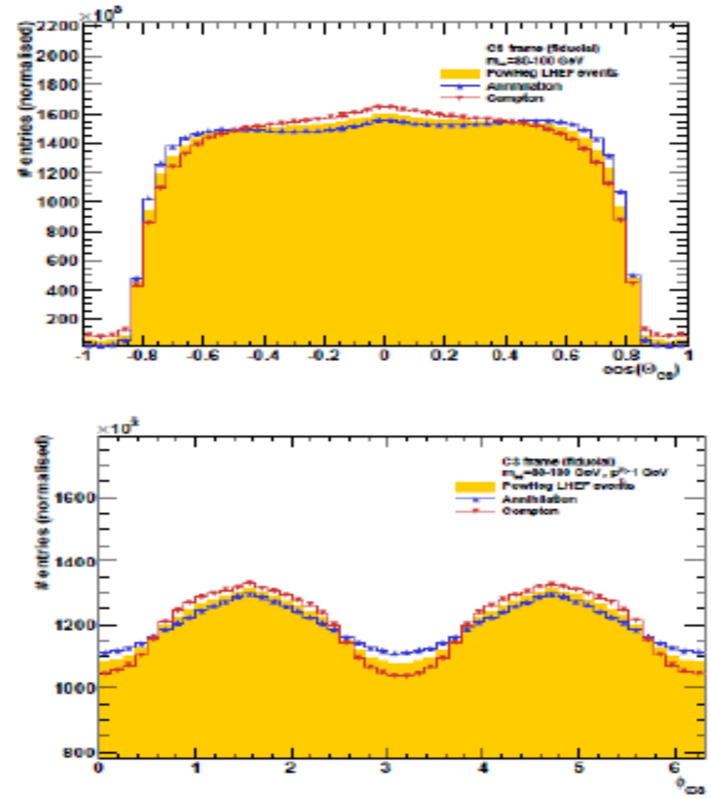
Distributions are sensitive to the production sub-process, and the shapes change rapidly with p_T^Z

In fiducial volume, the shapes are dominated by kinematic effects, as shown below for $\cos\theta_{CS}$ and ϕ_{CS} (integrated over p_T^Z).

Full phase-space



Fiducial phase-space



Angular coefficients in W production

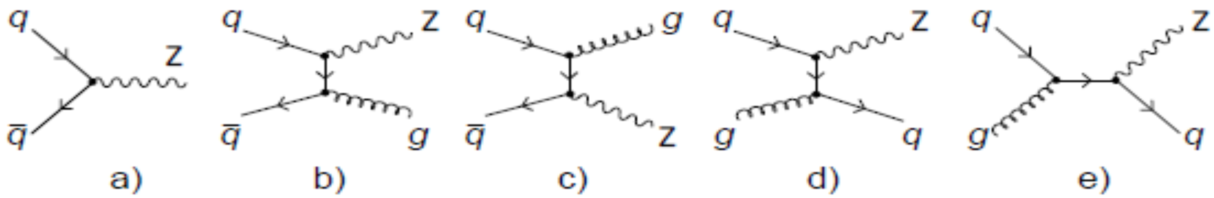
Same decomposition as in the case of Z boson

How to define Collins-Soper frame?

- use hadronic recoil for p_T of the W
- use m_W constraints for resolving kinematics -> longitudinal component of neutrino momenta with twofold ambiguity (ambiguity in the sign of $\cos\theta$)
  - Measurement of A_1, A_4 not possible directly
  - A_3 most interesting for measuring gluon structure functions.

Important ingredient also for precision m_W measurement (such issues have not really been considered by m_W measurements at Tevatron, at least not explicitly)

Frame-dependence of results?



P. Faccioli et al., arXiv:1010.1552

FIG. 1. $O(\alpha_s^0)$ and $O(\alpha_s^1)$ processes for Z/γ^* and W production, giving rise to transverse dilepton polarizations along different quantization axes: Collins–Soper (a), Gottfried–Jackson (b, c, d) and helicity (e).

The lowest-order diagramme for DY production (W, Z, γ^*) is annihilation process qq->V in the s-channel. At higher order, Compton scattering process appears, becoming dominant with increasing transverse momentum of the V produced.

As a consequence, transverse polarisation of the vector boson is along different quantisation axes: Collins-Soper (a), Gottfried-Jackson (b,c,d) and helicity (e).

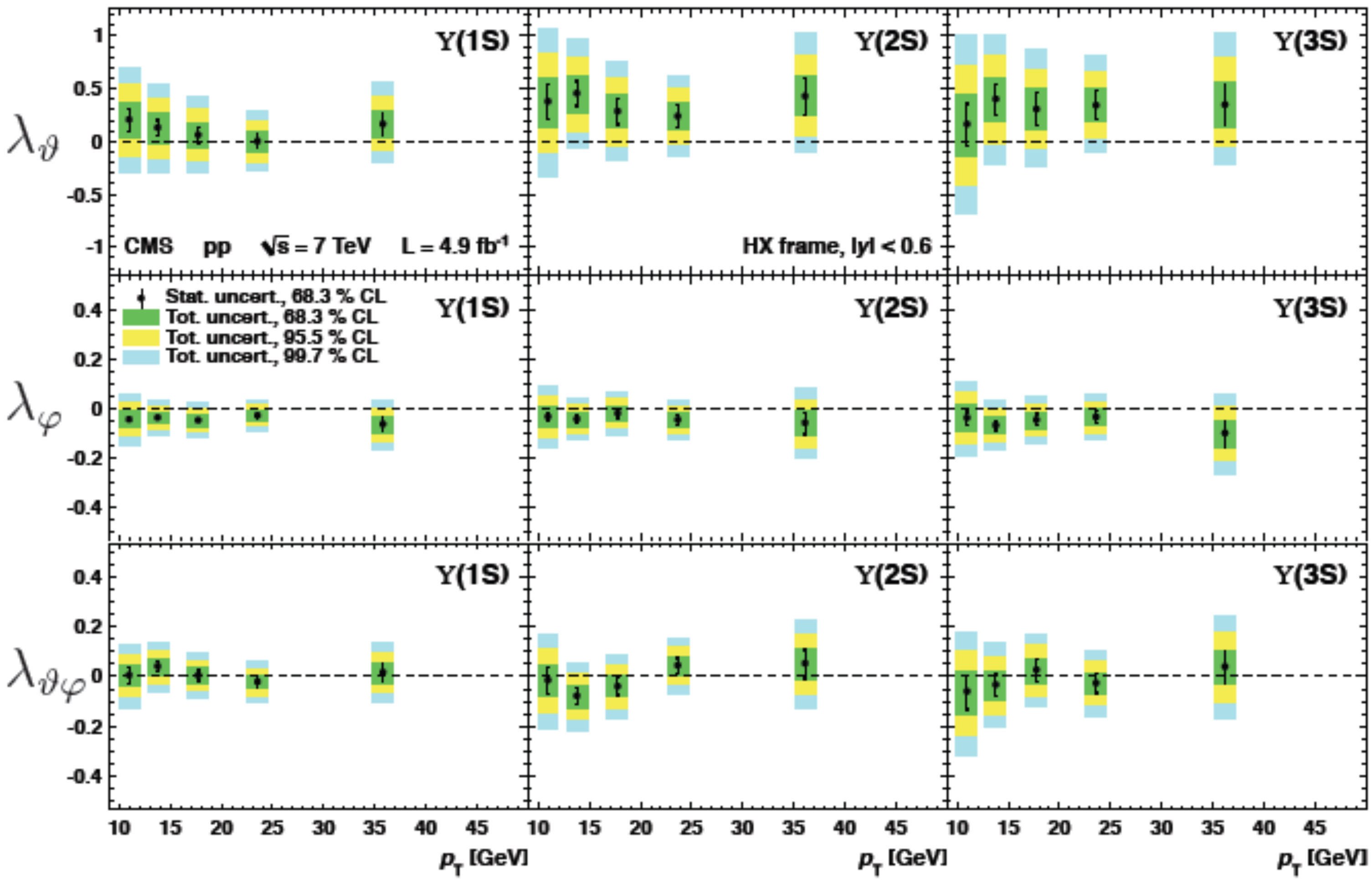
Transformation between different frames is a simple rotation characterised by one parameter:

- **in case of presence of n processes each contributing with weight f_i, the resulting observable has a general expression which is formally analogous → same polynomials.**
- **A_i coefficients depend on the choice of the quantisation frame used and effectively represent weighted averages of the ones of the corresponding sub-processes.**

Frame-dependence of results?

CMS have made a *superb* measurement of ϒ production...

All three angles, cross checked with λ_t , for each ϒ state, in three frames...



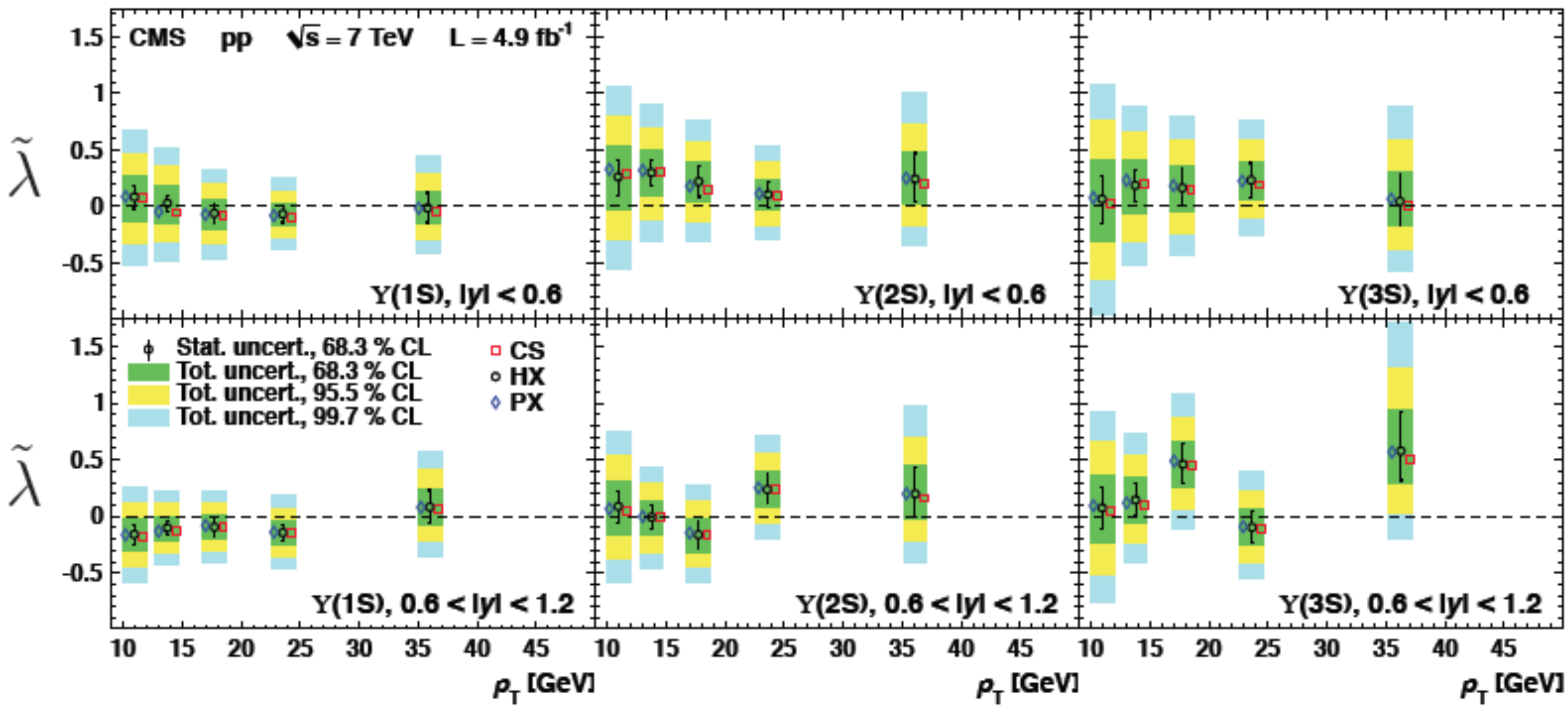
They see no evidence for strong spin alignment...

Frame-dependence of results?

Will need to perform similar closure for Z (and probably also W) polarisation measurements

CMS Υ cross check

CS, HX and PX completely consistent as they should be
→ high degree of confidence in the results



Modelling of QCD dynamics

A_i coefficients depend on the di-lepton quantities and encode a lot of EW and QCD effect.

Calculating „moments" of the cross-section one can efficiently extract the A_i of underlying QCD dynamics in a given MC

- MC generator can be probed by „measuring" effective coefficients using events generated in the full phase-space

E. Mirkes, Nucl. Phys. B387 (1992) 3

E. Mirkes, J. Ohnemus ,
Phys. Rev. D51 (1995) 4891
Phys. Rev. D50 (1994) 5692

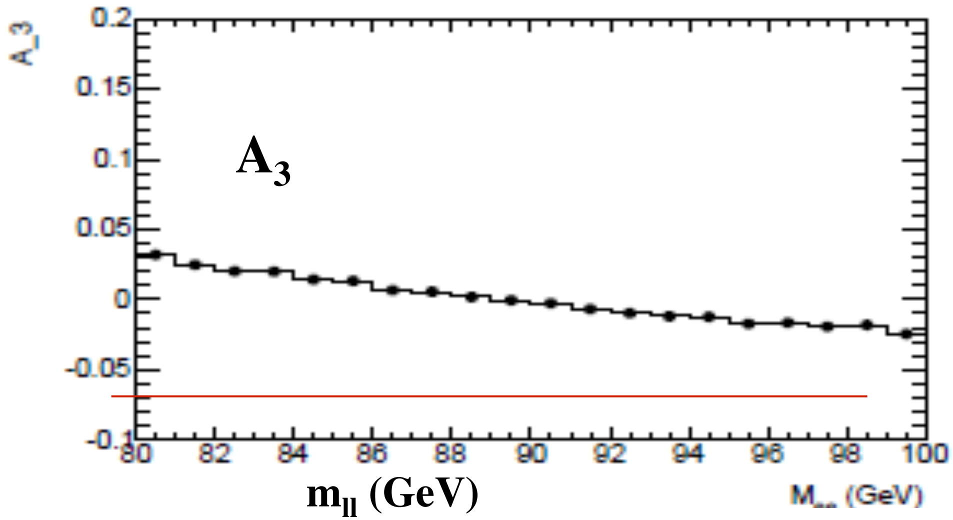
$$< m >= \frac{\int d\sigma(p_T, y, \theta, \phi) m \, d\cos\theta \, d\phi}{\int d\sigma(p_T, y, \theta, \phi) \, d\cos\theta \, d\phi}$$

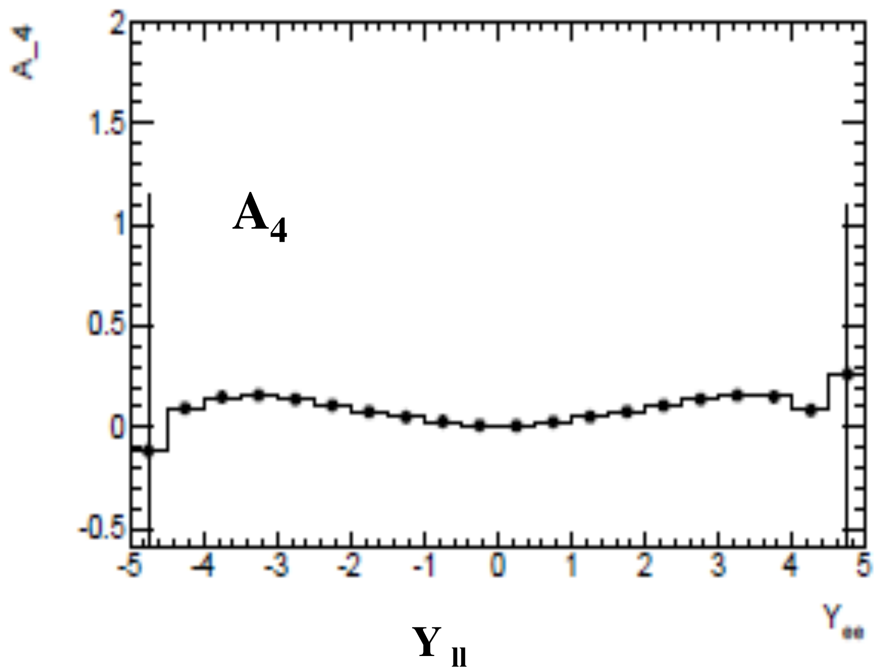
$$\begin{aligned}
< \frac{1}{2}(1 - 3\cos^2\theta) > &= \frac{3}{20}(A_0 - \frac{2}{3}) \\
< \sin 2\theta \cos\phi > &= \frac{1}{5} A_1 \\
< \sin^2\theta \cos 2\phi > &= \frac{1}{10} A_2 \\
< \sin\theta \cos\phi > &= \frac{1}{4} A_3 \\
< \cos\theta > &= \frac{1}{4} A_4 \\
< \sin^2\theta \sin 2\phi > &= \frac{1}{5} A_5 \\
< \sin 2\theta \sin\phi > &= \frac{1}{5} A_6 \\
< \sin\theta \sin\phi > &= \frac{1}{4} A_7
\end{aligned}$$

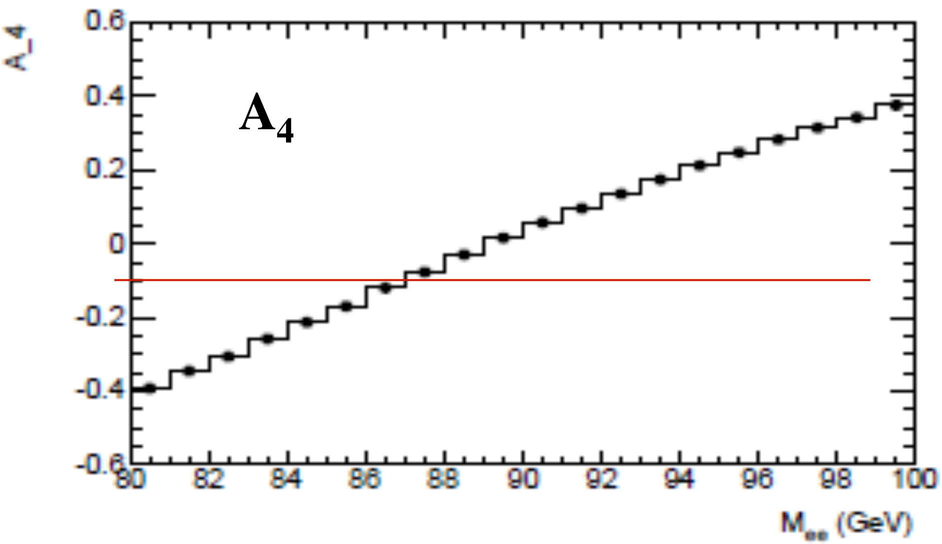
QCD modelling in Monte Carlo

Only A_3 and A_4 show some dependence on m_{ll} and Y_{ll}

In a first step, study how to extract A_i as a function of p_T^{ll}







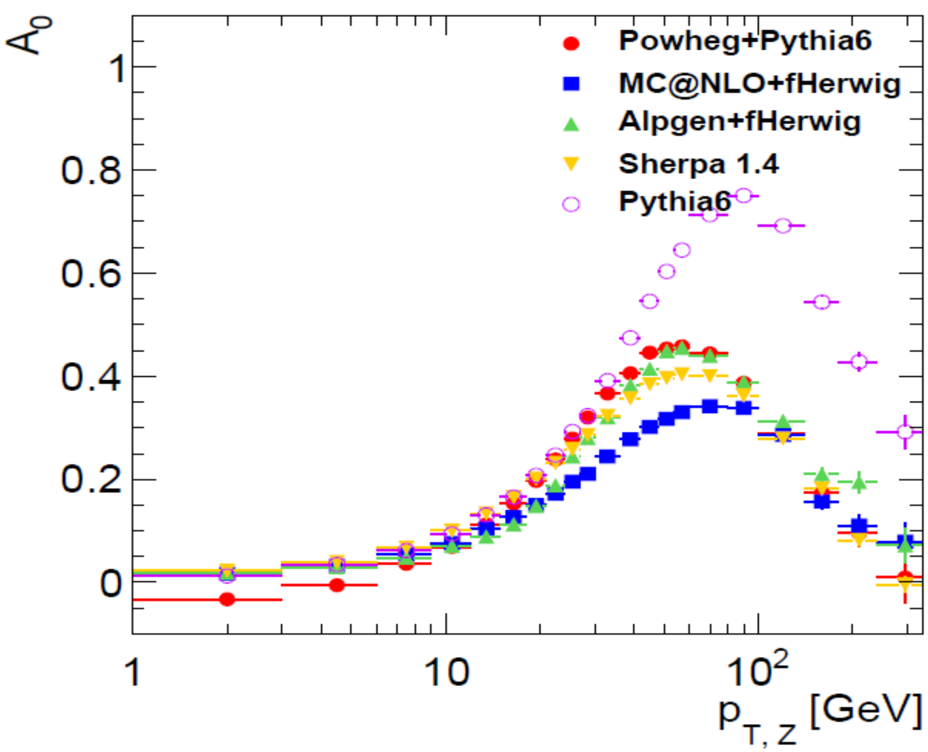
PowHeg LHEF events
MC12 production

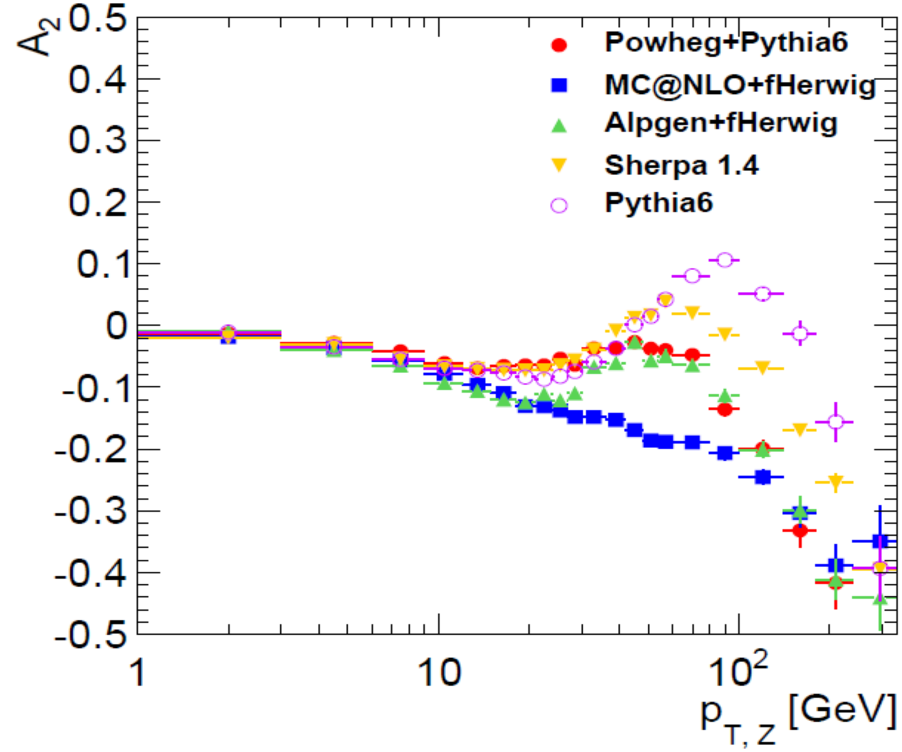
MC predictions: different generators

Impact of generators on shapes of Ai is quite large! This explains at least in part some not understood generator-dependent systematics, e.g. in W/Z differential measurements.

MC@NLO vs Powheg differences are most worrying!

Note different Z rest frame! HX axis, m_{ee} = 66 – 116 GeV



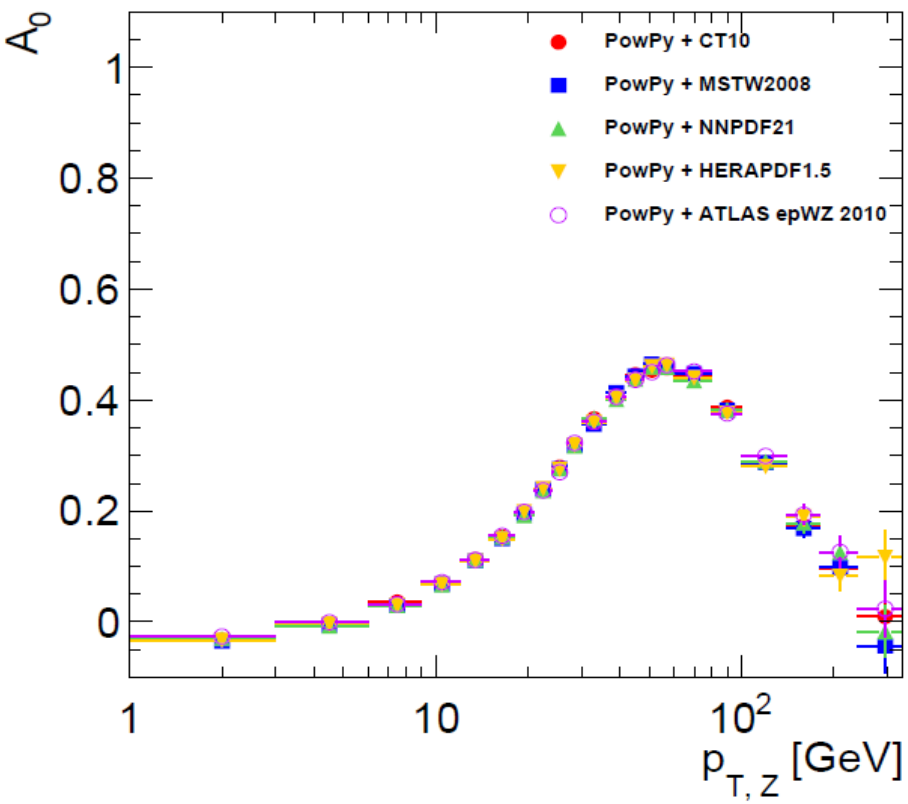


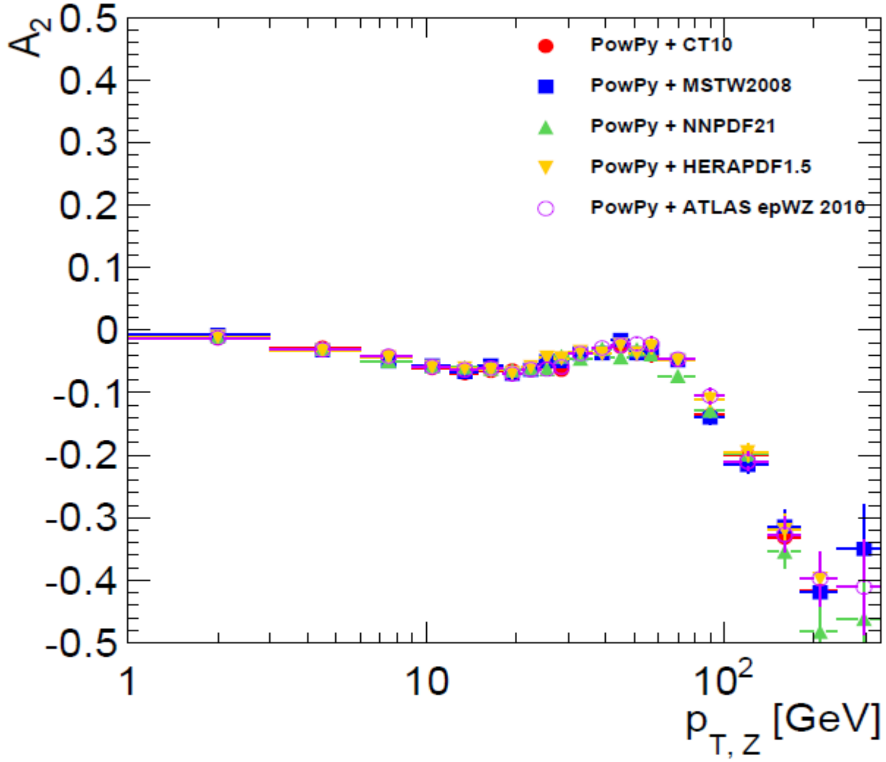
Largest differences are in the region 10 < p_T^Z < 100 GeV: the source of this is most likely in the matching between parton shower and matrix element!

MC predictions: different PDFs

Impact of PDFs on shapes of Ai is quite small vs p_T^Z: < 2%

Z rest frame, HX axis, m_{ee} = 66 – 116 GeV



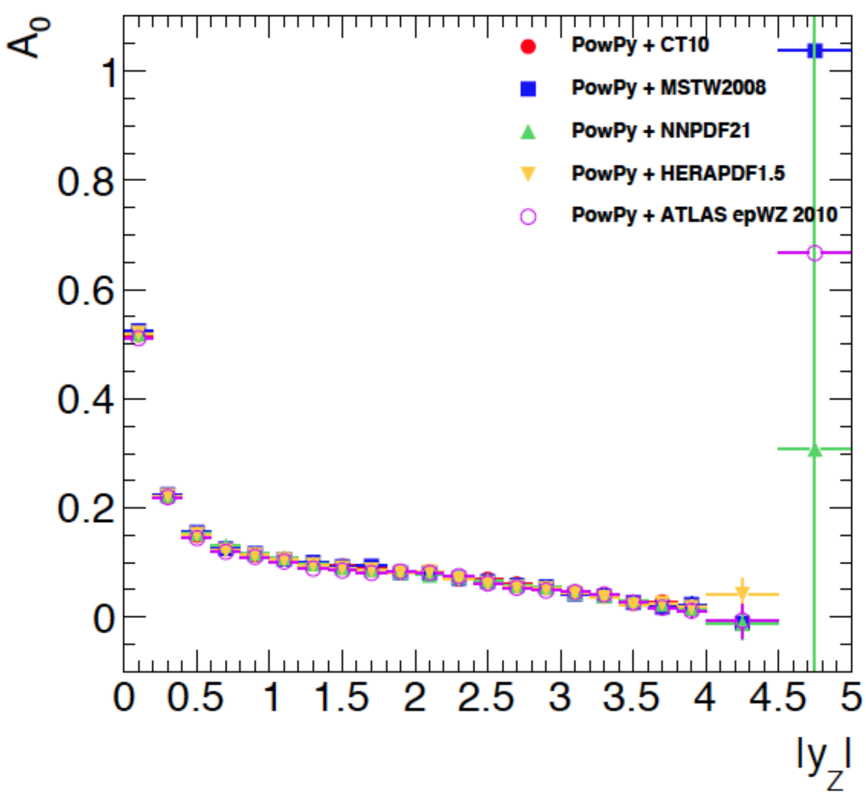


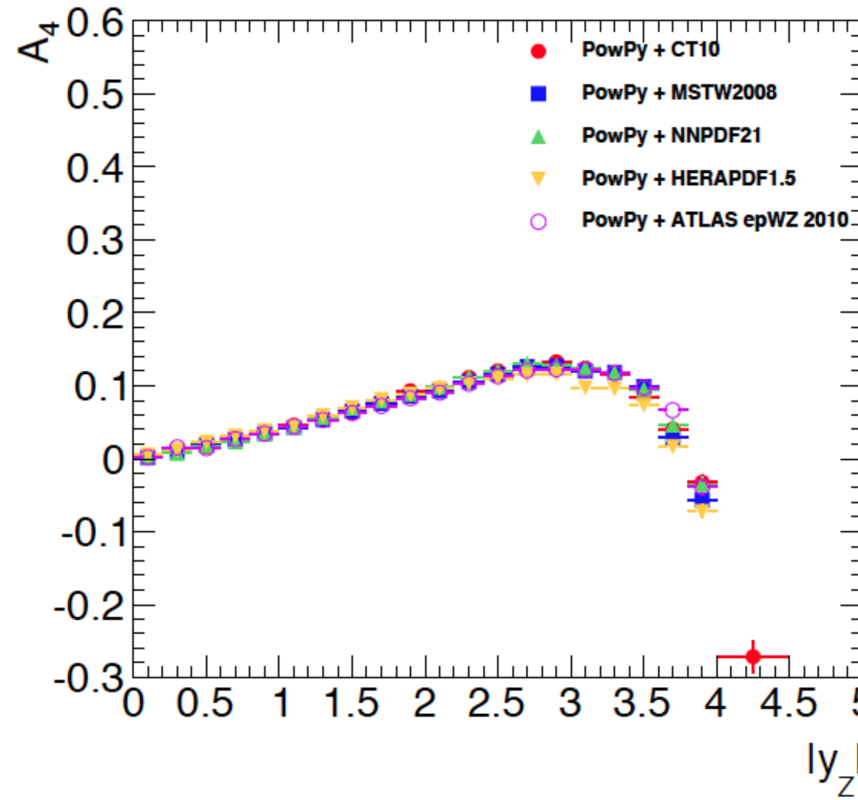
MC predictions: different PDFs

Needs to be quantified better but impact of PDFs seems quite small on shape of coefficients versus p_T^Z and also y_Z

Really promising: this could be a precise and unambiguous QCD measurement at the sub-percent level!

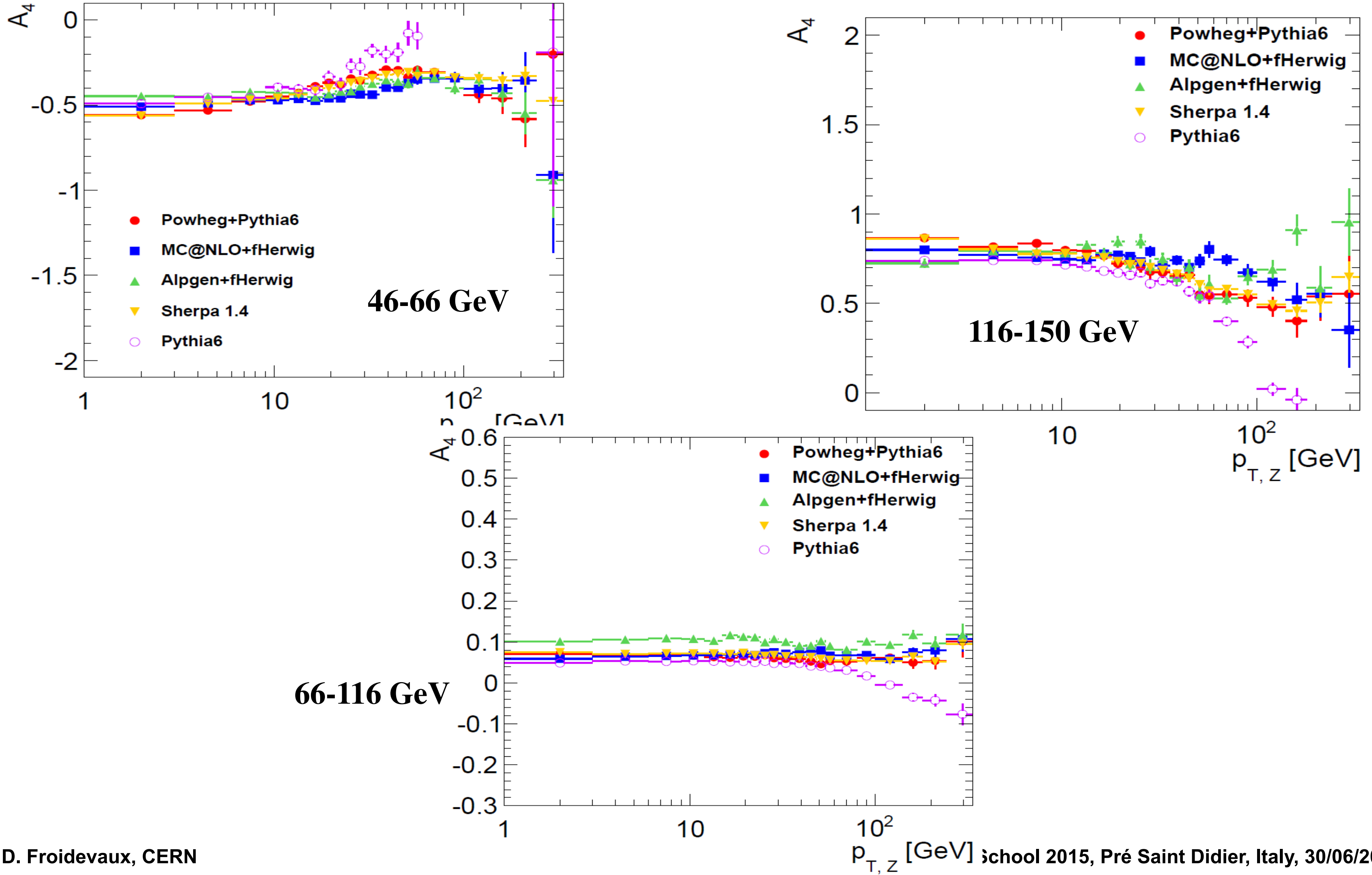
Z rest frame, HX axis, m_{ee} = 66 – 116 GeV





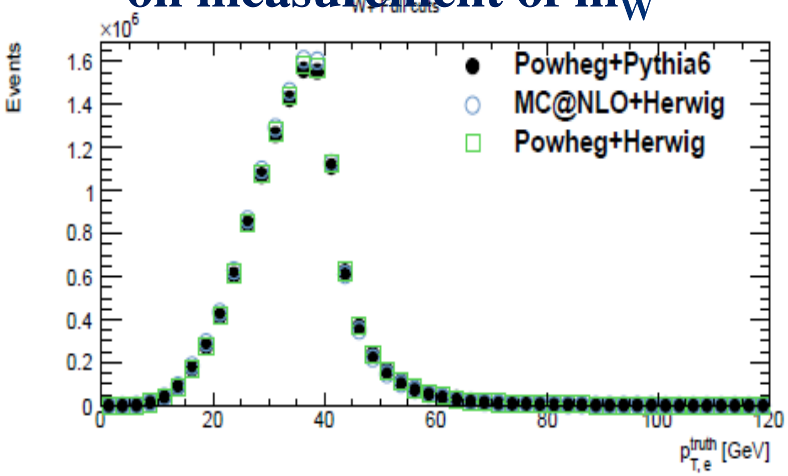
EW sensitivity: coefficient A_4

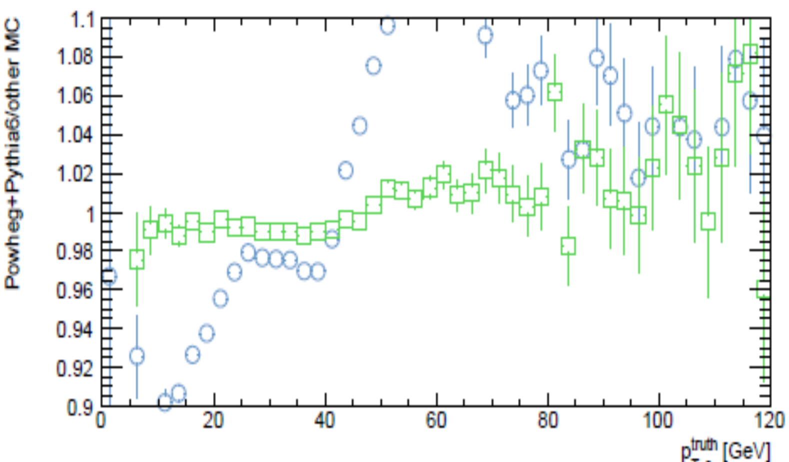
Note strong dependence of the plateau value on the mass window $\rightarrow$ forward-backward asymmetry, directly related to $\sin^2\theta_W$



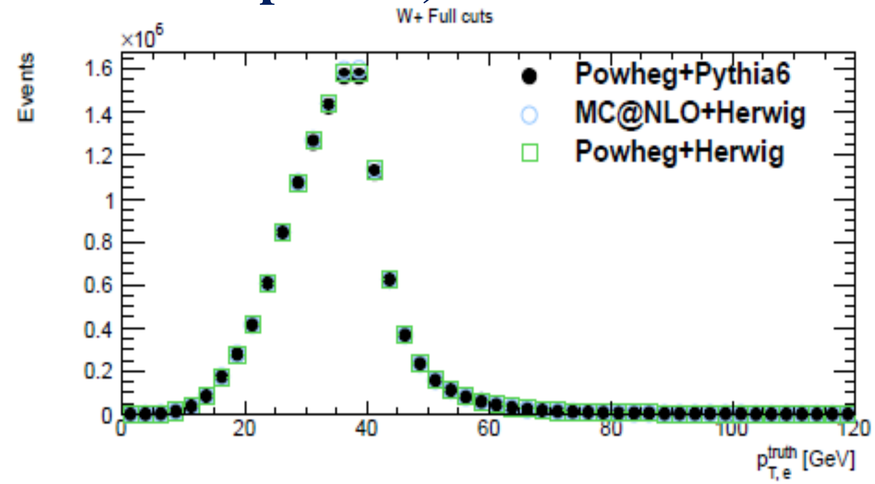
Similar differences observed for W

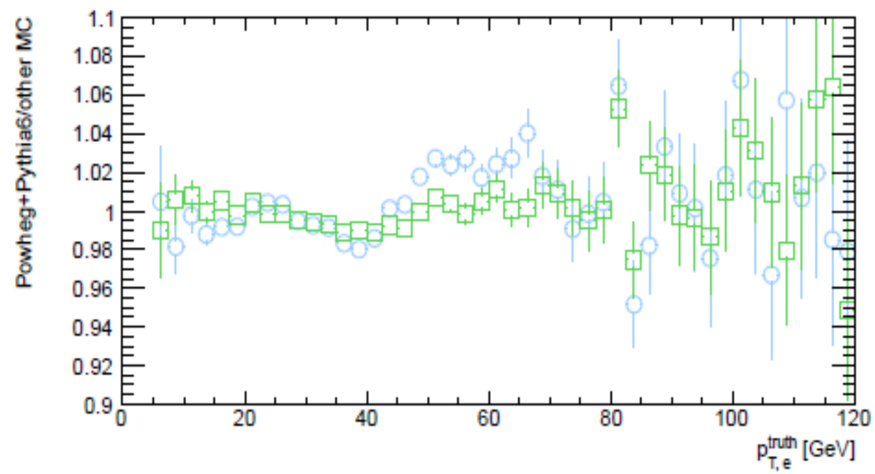
Before reweighting
Big differences of up to 10%!, especially for W^+ in MC@NLO: this may induce bias of ~50 MeV on measurement of m_W





After reweighting with A_i' s
Agreement to ~1%
Not perfect, but much better



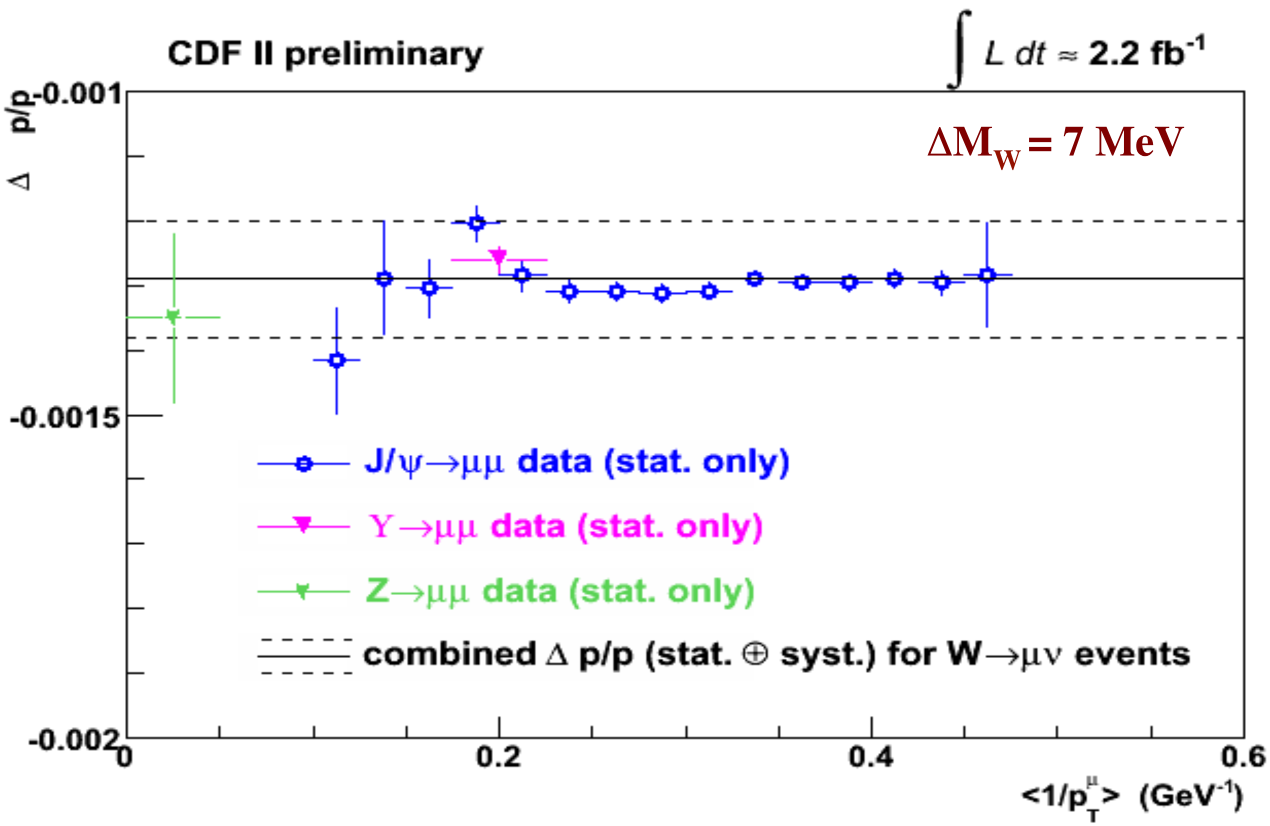


CDF: Tracker Linearity Cross-check & Combination

Final momentum calibration using the J/ψ, Υ and Z bosons

Combined momentum scale correction:

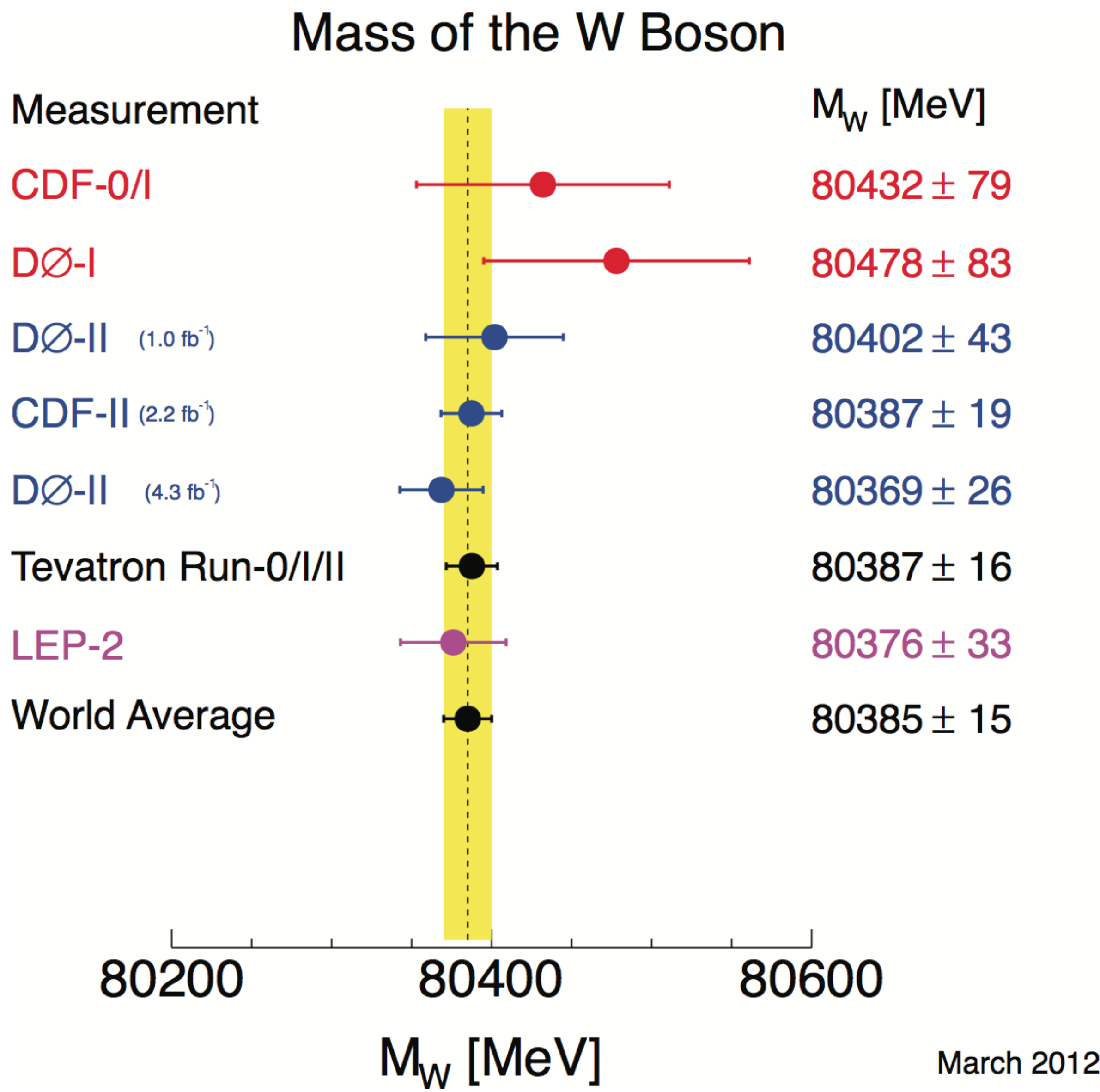
- $\Delta p/p = (-1.29 \pm 0.07_{\text{independent}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}}) \times 10^{-3}$



W-boson mass measurements: Tevatron versus LEP2

World average computed by TeVEWWG
ArXiv:0908.1374
FERMILAB-TM-2439-E

Previous world average:
80399 ± 23 MeV



Tevatron result is significantly more precise than LEP average

Measurement of m_W at the Tevatron: beyond the legacy of LEP!

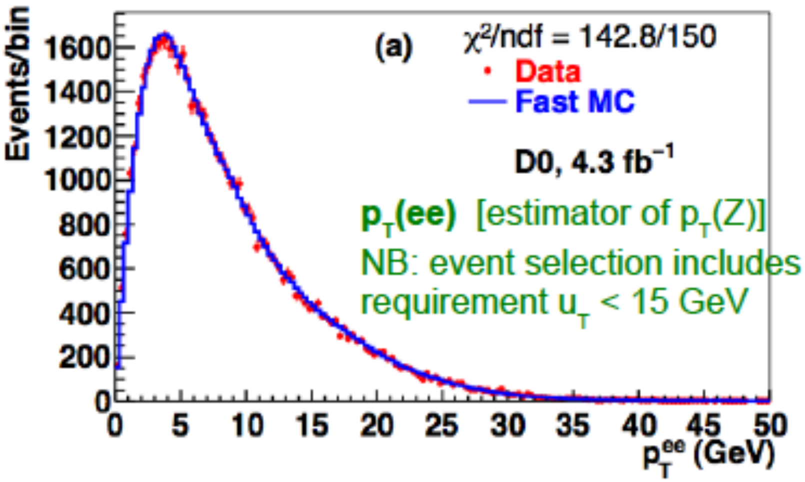
D0: W to $e\nu$ (4+1 fb^{-1})	CDF: W to $e\nu$ (2.2 fb^{-1})	CDF: W to $\mu\nu$ (2.2 fb^{-1})
55k Z to ee	16k Z to ee (!!)	60k Z to $\mu\mu$
1.7M W ($\lvert\eta\rvert$ < 1.05!!)	0.5M W	0.6M W
δm_W(stat) = 13 MeV	δm_W(stat) = 13 MeV	δm_W(stat) = 13 MeV
δm_W(syst) = 22 MeV	δm_W(syst) = 18 MeV	δm_W(stat) = 16 MeV
Combine with 1 fb^{-1} result	Combine J/ψ&Υ to $\mu\mu$ with m_Z from LEP!!	
δm_W(tot) = 23 MeV	δm_W(tot) = 19 MeV	

- Can more than double statistics with full runII dataset
- Current incompressible systematic is 10 MeV from PDFs (not worked on yet to reduce this using Tevatron data)
- Hope to reach 10-15 MeV ultimately per experiment

→ challenge for LHC will be at the 5 MeV level

Tevatron experience (D0)

We are interested in the events at low $p_T(Z)$ and $p_T(W)$ … this is where the bulk of the events is anyway, and we further suppress the high-p_T tail using a cut on the hadronic activity recoiling against the vector boson.



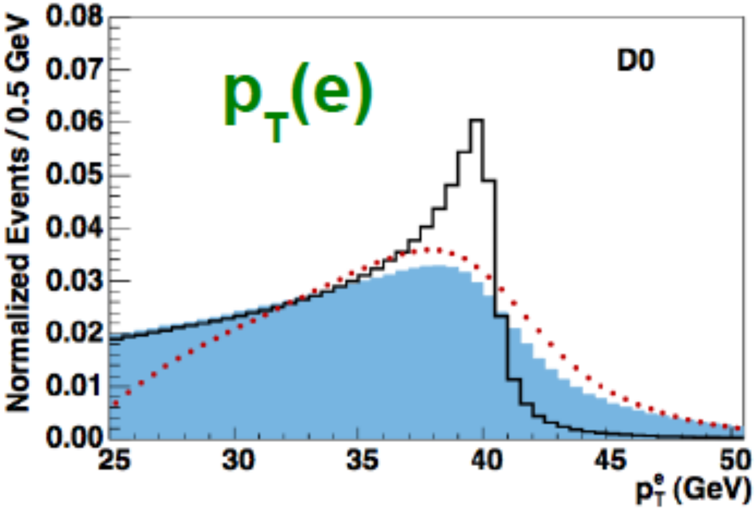
The "ideal generator" that does all this, including all QCD and EWK effects, does not exist.

Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons

Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

Tevatron experience (D0)

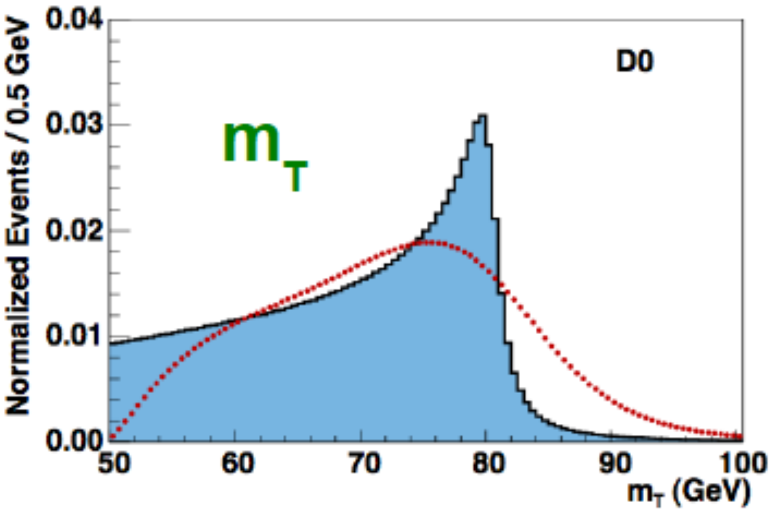
Single-most important QCD effect



Black histogram: no detector resolution and efficiencies, $p_T(W) = 0$.

Blue histogram: with realistic $p_T(W)$ distribution.

Red dots: after inclusion of detector resolutions and efficiencies.



For the purpose of the measurement of m(W), the single-most important QCD effect is the (low-p_T part) of the distribution $p_T(W)$ distribution.

This part of the distribution is driven by the emission of multiple soft gluons.

Tevatron experience (D0)

Single-most important EWK effect

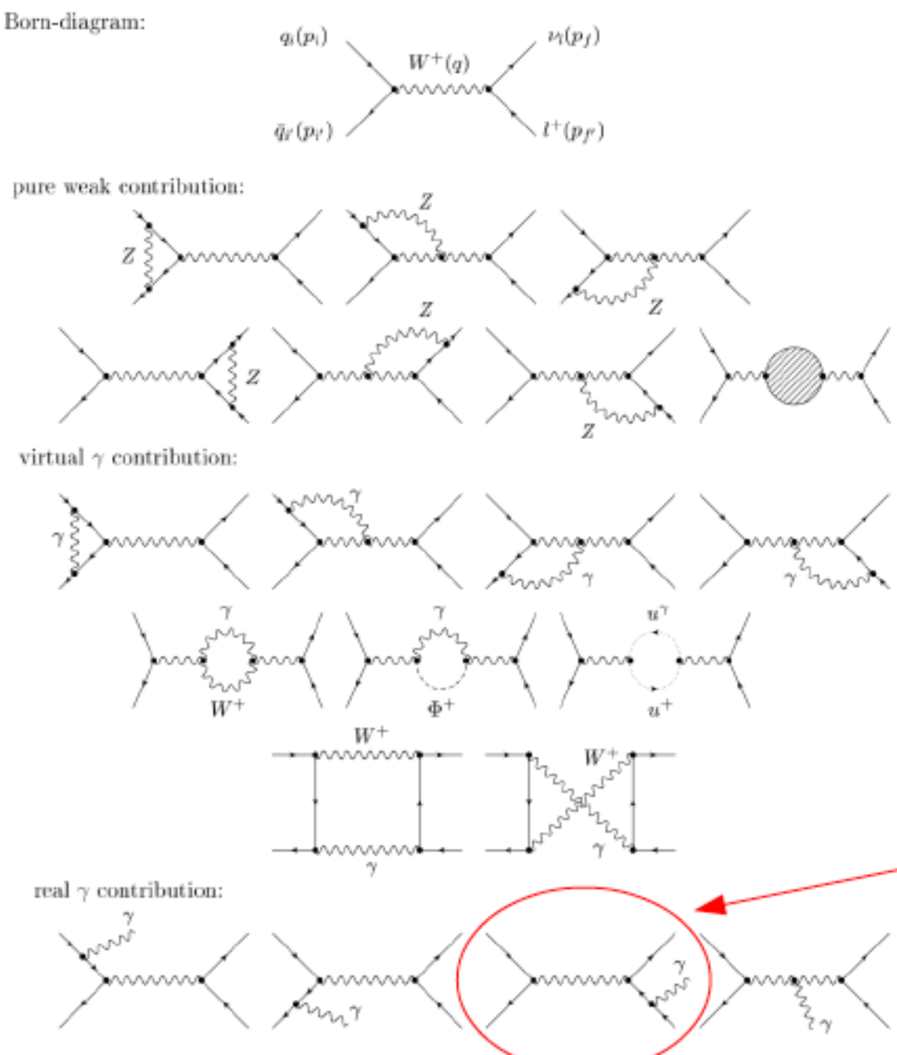


Figure from: Baur, Keller, Wackeroth, hep/ph-9807417.

Electroweak corrections have been studied (and these studies started a long time ago), by the authors of the W/ZGRAD and HORACE event generators and by many others.

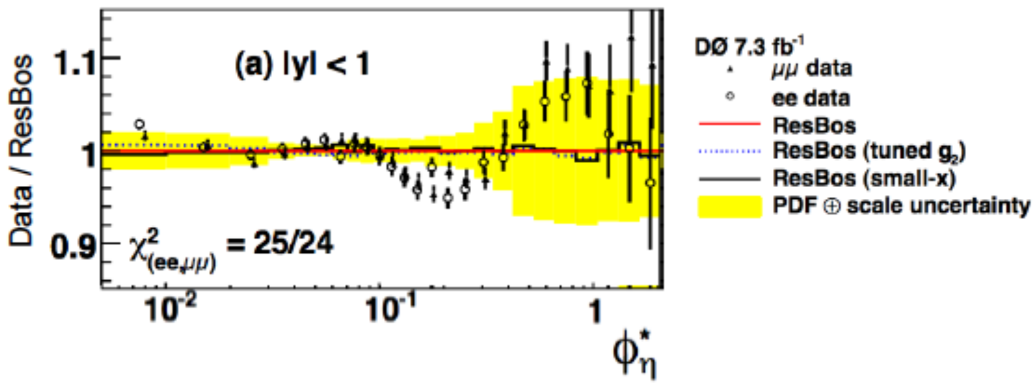
For the purpose of the measurement of m(W), the single-most important EWK effect (by far) is this one ("final-state radiation").

"These photons carry away energy that was part of the W boson mass".

Tevatron experience (D0)

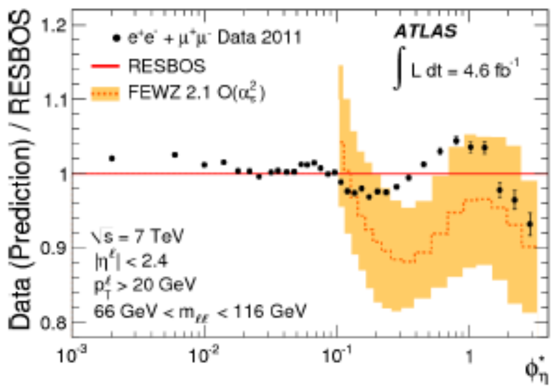
Z transverse momentum: ϕ^*_η

DØ (Phys. Rev. Lett. 106, 122001)

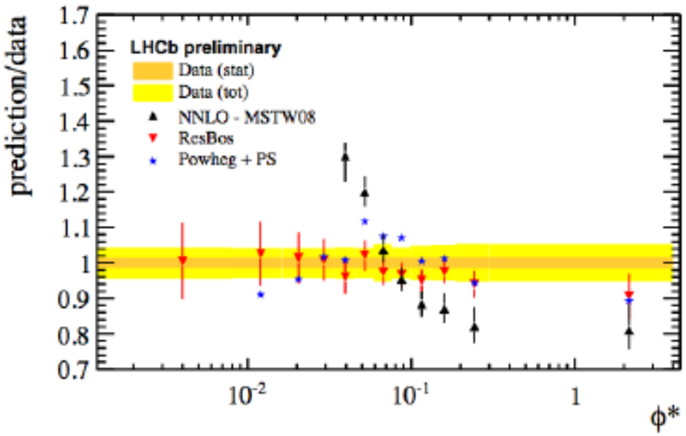


Available measurements more precise than the current best predictions.

ATLAS (Phys. Lett. B720, 32)



LHCb (LHCb-CONF-2013-007)



Yes, ancillary measurements are important!

Tevatron experience (D0)

In principle:
transverse observables (*e.g.* m_T) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDFs)

In practice:
the uncertainties are to some extent reintroduced via the limited η coverage of experiments,
which are not invariant under longitudinal boosts

How to reduce the impact of the PDF uncertainties in measurements of the W boson mass ?

- Reduce the uncertainties in the PDFs

  e.g. via measurements of the W charge asymmetry
  at the Tevatron and the LHC (complementarity of the two colliders)

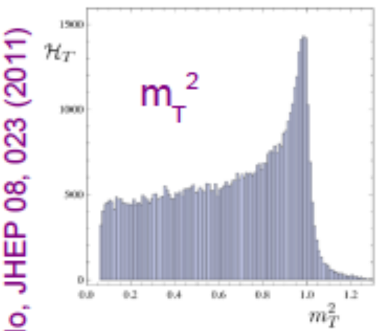
- Reduce the impact of the PDF uncertainties on W boson mass

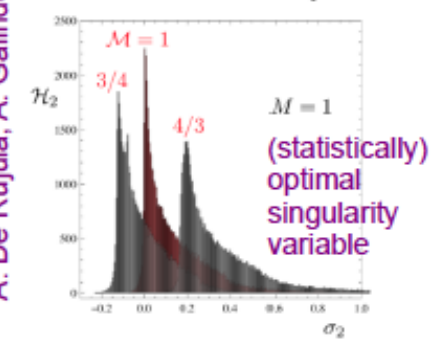
  by extending the η coverage as much as possible
  (challenging: understanding lepton energy scale and pile-up and backgrounds in the forward detectors)

- Possibly reduce the impact of the PDF uncertainties on W boson mass

  by exploring even more robust observables
  (“single out events with small longitudinal momentum”) to replace/complement m_T

A. De Rújula, A. Galindo, JHEP 08, 023 (2011)





These three approaches are not mutually exclusive, *i.e.* they can be pursued at the same time and gains should “add up”.

PDF uncertainties are not only dominant!

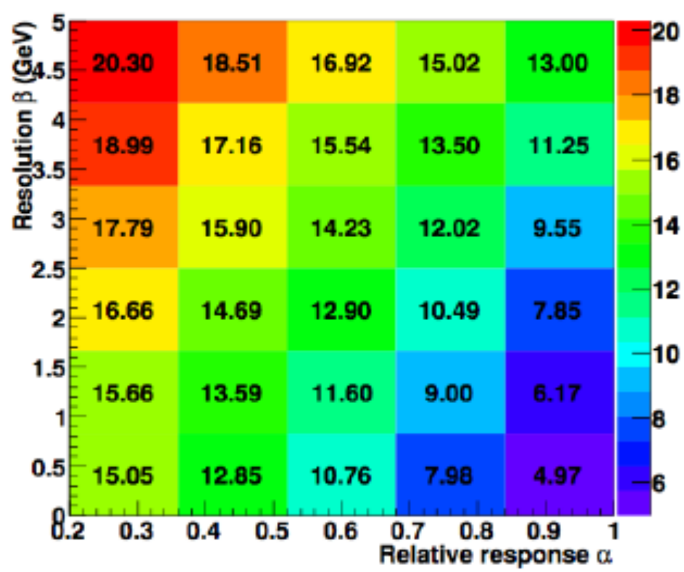
Tevatron experience (D0)

Another comment on PDF uncertainties: one has to keep in mind the interplay between the uncertainties in the PDFs and the detector effects that can make them more or less important in a given measurement.

The Table below shows the PDF uncertainty, using the m_T observable, for different values of

- the average the energy scale for the hadronic recoil,
- and resolution on the hadronic recoil (fluctuations around the average scale).

Ideal detection of the recoil:
$\alpha = 1$
$\beta = 0$ GeV



Huge effect !

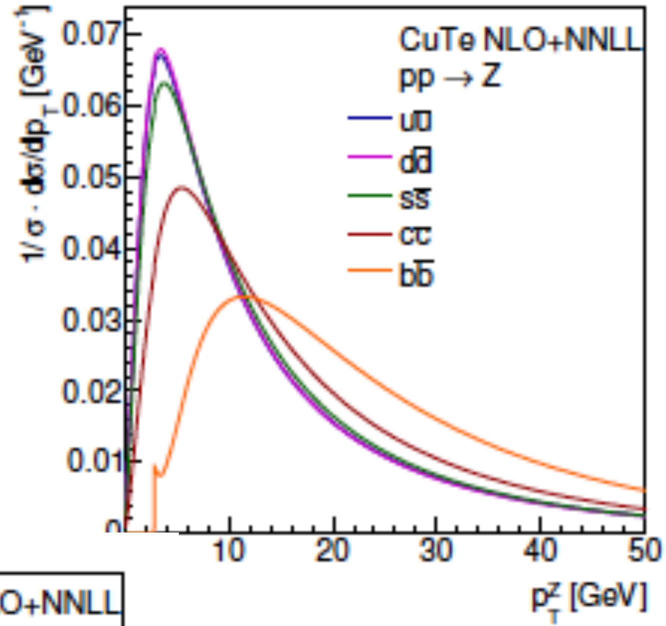
For "ideal detection" of the recoil, m_T is close to an invariant mass. For a realistic recoil reconstruction much less so.

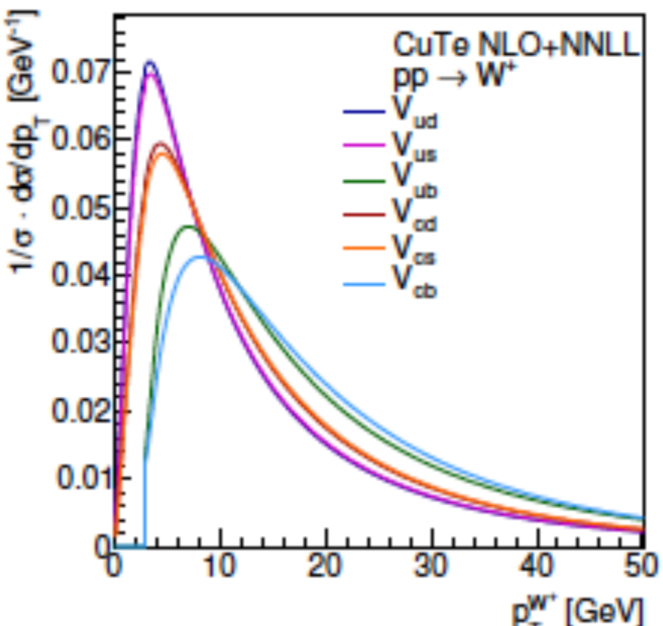
And an invariant mass is, well, invariant under certain things.

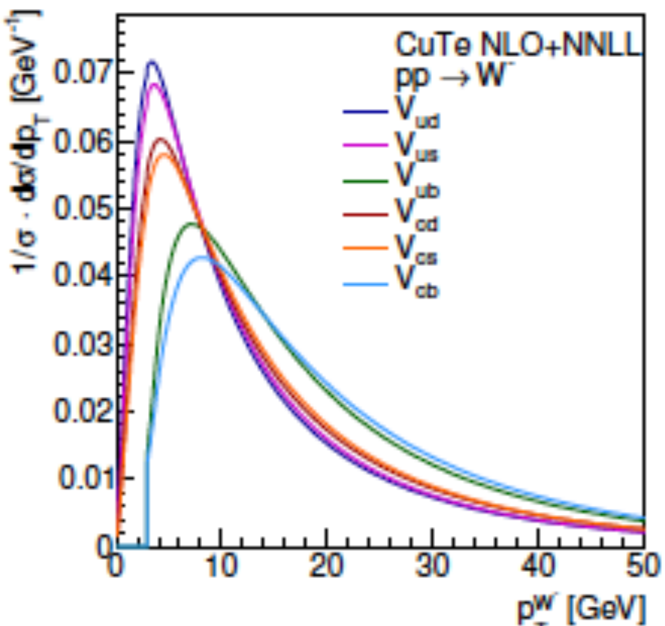
FIG. 9. Hadronic recoil dependence of the PDF uncertainty. m_T method, ResBos events, CTEQ6.6 PDF set.

PDF uncertainties are correlated to acceptance and to resolution

PDF uncertainties at the LHC







Treatment of PDF uncertainties at the LHC much more complex than at the TeVatron

Measurement of m_W at LHC: beyond the legacy of Tevatron?

• The ultimate event generator would somehow incorporate the impressive automatic QCD NLO tools available now in MG5 together with the mixed NLO QCD/EW recent POWHEG enhancements discussed by Alessandro Vicini in his talk.

• Even this would not be sufficient: we also need improved PDF tools, both in terms of the treatment of the uncertainties and of the PDF fitting itself. And we need to be very careful about mixed QCD and EW effects in this area too.

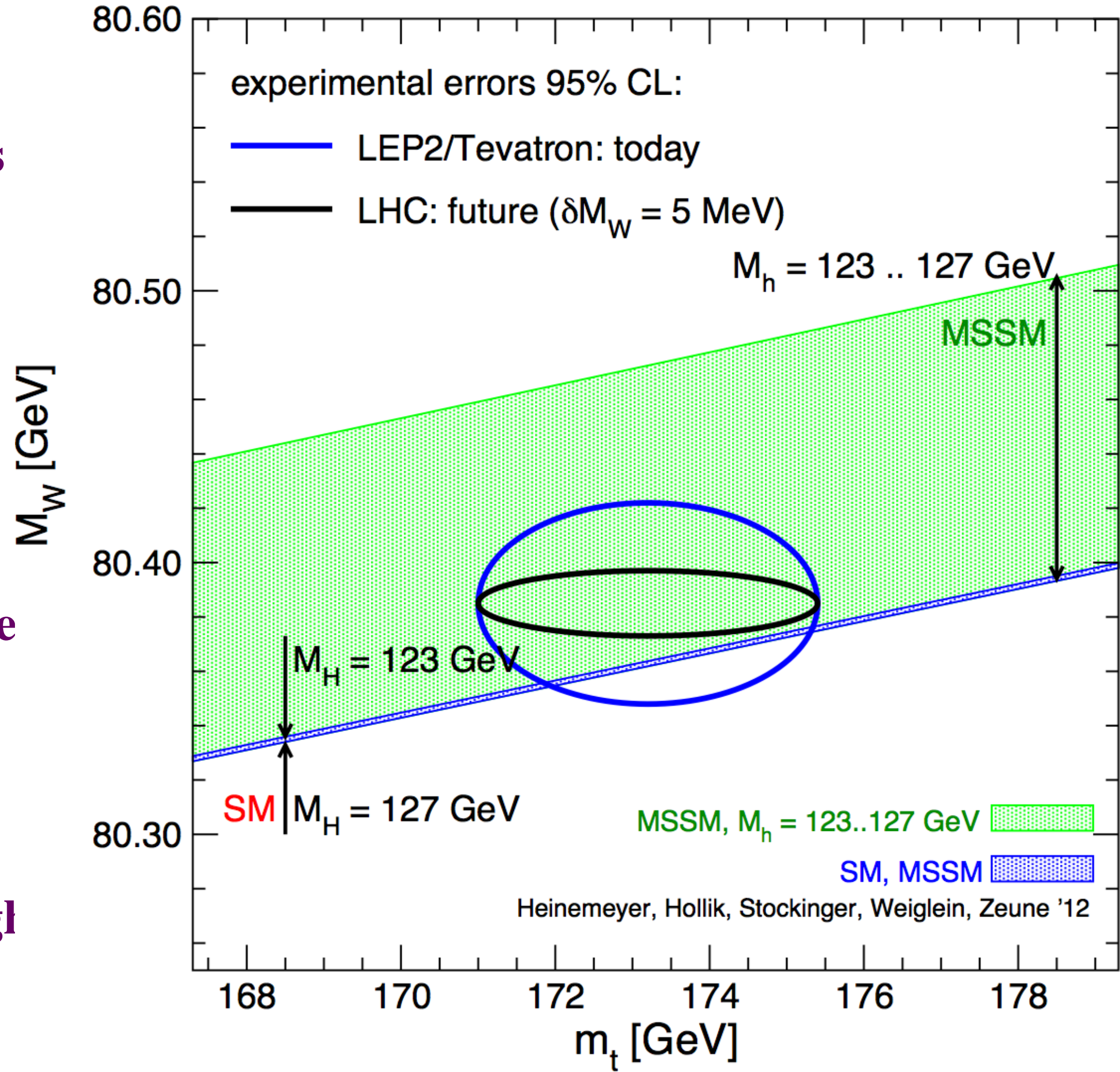
• Experimentally, the biggest challenges are the pile-up which is an enemy which cannot be fully neutralised and the experimental uncertainties related to efficiency dependences on kinematics and to scale uncertainties.
Basically, ATLAS and CMS need to follow the path laid out by CDF, namely demonstrate that based on the J/ψ to $\mu\mu$ samples adjusted to the PDF value for the J/ψ mass, the Z mass can be measured to better than 5-10 MeV. This is an enormous and exciting challenge!

Precision EW measurements: measure m_W to ~ 5 MeV: very difficult! What for?? It may be a real probe!!

- **Perhaps untangle whether possibly observed Higgs boson is SM or SUSY-like?**

- **From now to 2018 when LHC will take data at 13 TeV, our understanding of how well the SM describes fundamental interactions is quite likely to change**
- **The LHC community will continue the exploitation of the incredibly high quality data the machine and detectors have delivered**
- **The LHC community will probe much more deeply the nature of the Higgs boson nature has so kindly delivered to us**
- **And there might appear new riddles to solve such as a whole family of new particles (even thougl SUSY is feeling ill)…**

See eg http://arxiv.org/pdf/1112.3026.pdf



Outlook

♥ Today we are able to ask questions we were not able to formulate 25-30 years ago when I was a student. This together with what nature has in store for us over the next years of physics at the LHC is what is so exciting about our field, and probably any field in fundamental research

♥ The more we progress, the longer will be the gap between the reformulation of fundamental questions in our understanding of the universe and its complexity. This gap is already ~ equal to the useful professional lifetime of a human being. This poses real problems.

♥ But the first few years of LHC performance and physics studies have been an incredible reward to all those of us who have worked so long and so hard towards this goal.

It is even more rewarding to see that the LHC detectors have picked up rather quickly the challenge for precision measurements in the SM.

♥ In particular, it is a huge pleasure for me to be with all of you discussing physics again after so long without any data…

♥ Even though we have found the Higgs boson as early as summer 2012, only the third year of LHC operation, it will be a while before it is discussed in a SM EW overview talk although this is where eventually it will belong.