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

Historical perspective: 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

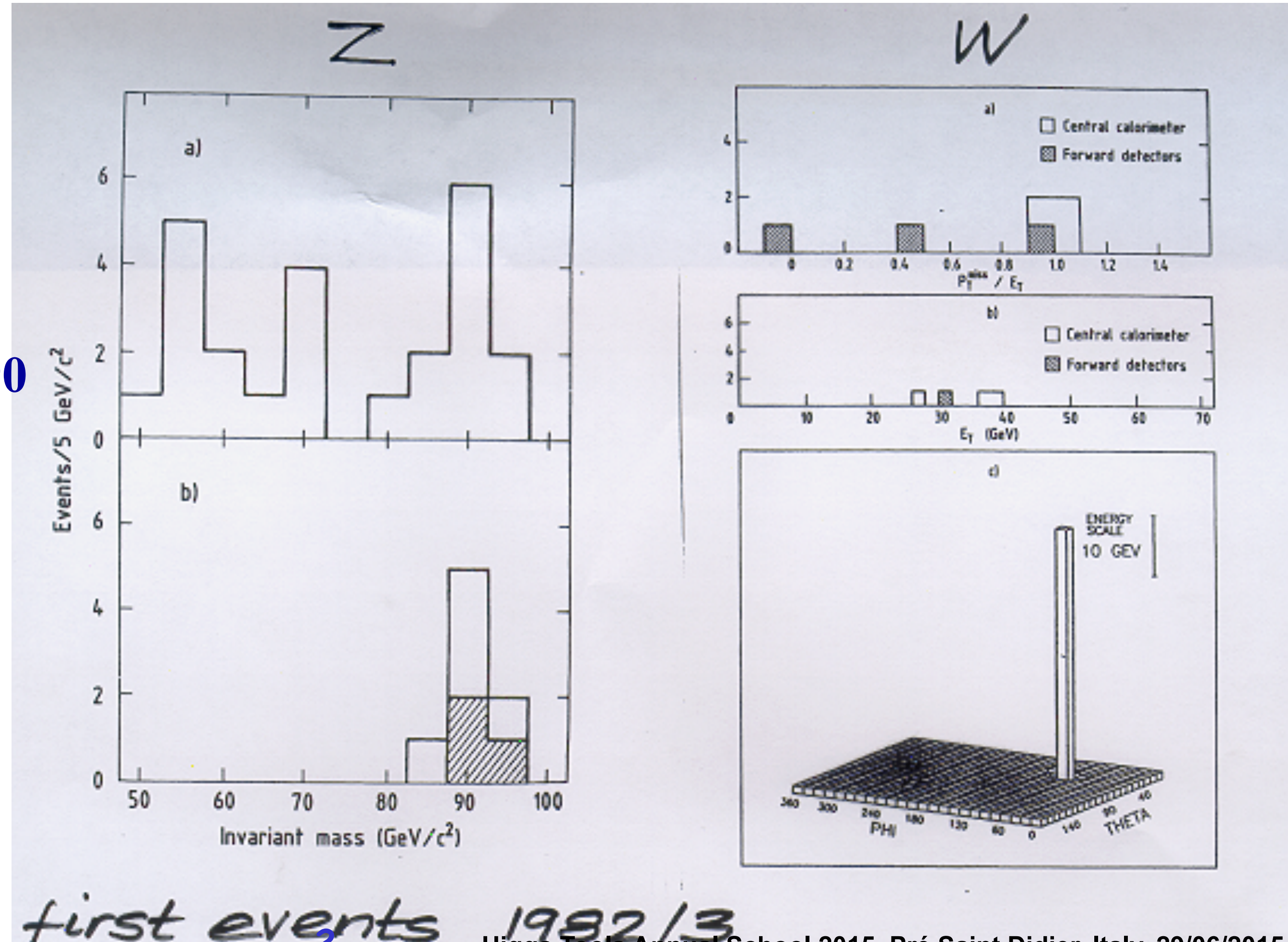
$\sqrt{s}$ = 546 GeV, L ~ 10^{29} cm^{-2}s^{-1}

UA2 was perceived as large at the time:

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

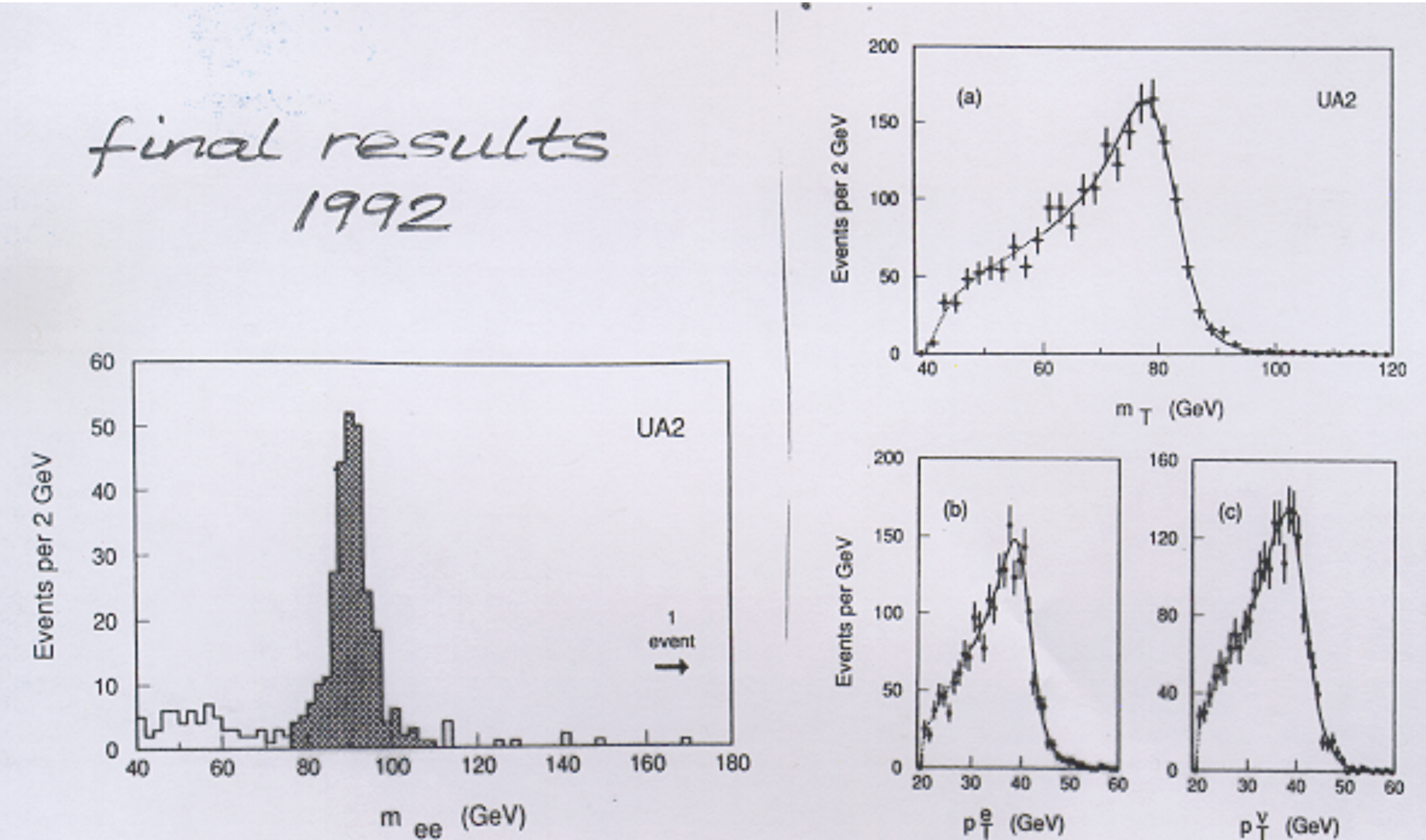
Physics analysis was organised in two groups:

- Electrons → electroweak
- Jets → QCD

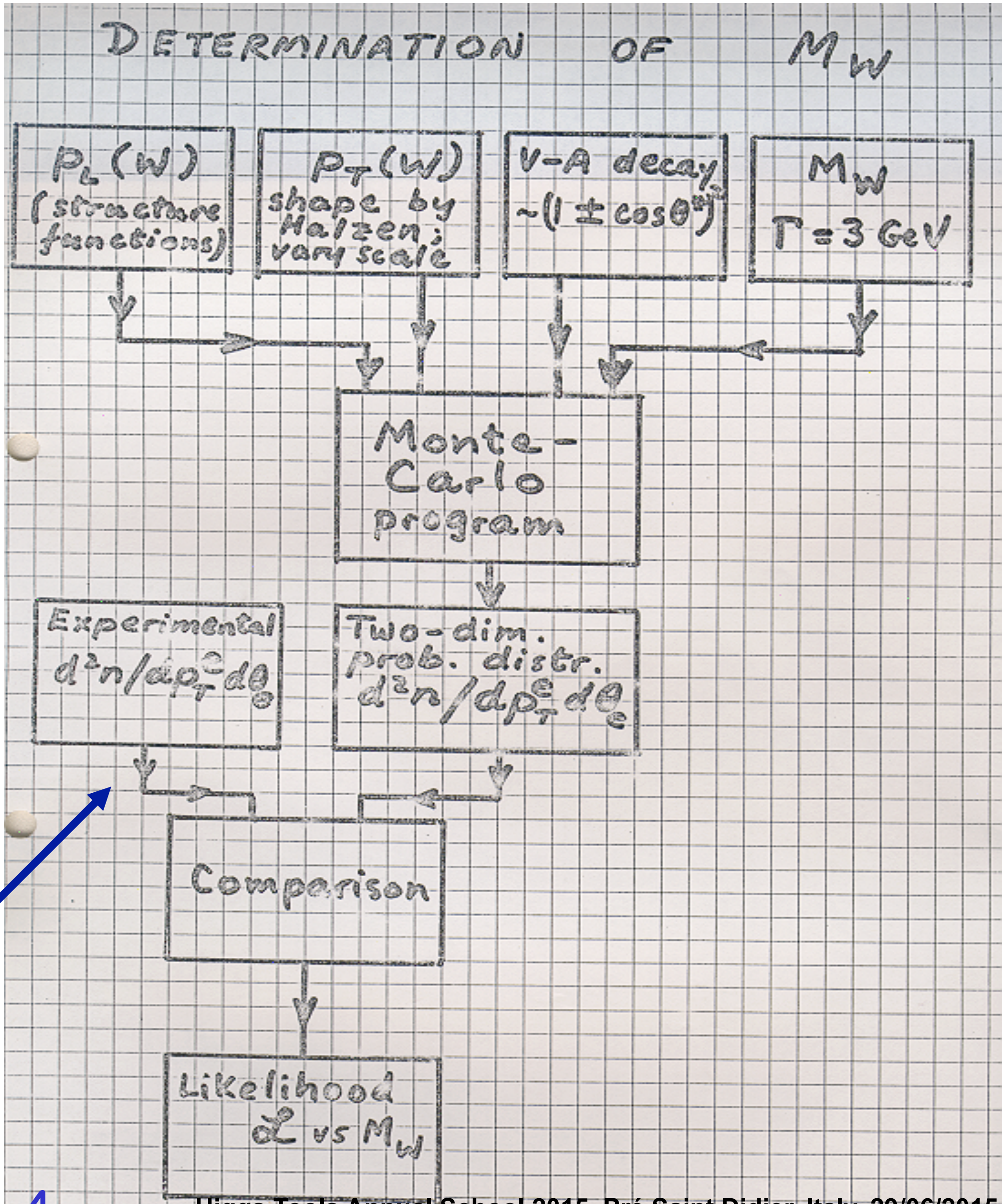


Historical perspective: the 80's in UA1/UA2 at the SppS

To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry

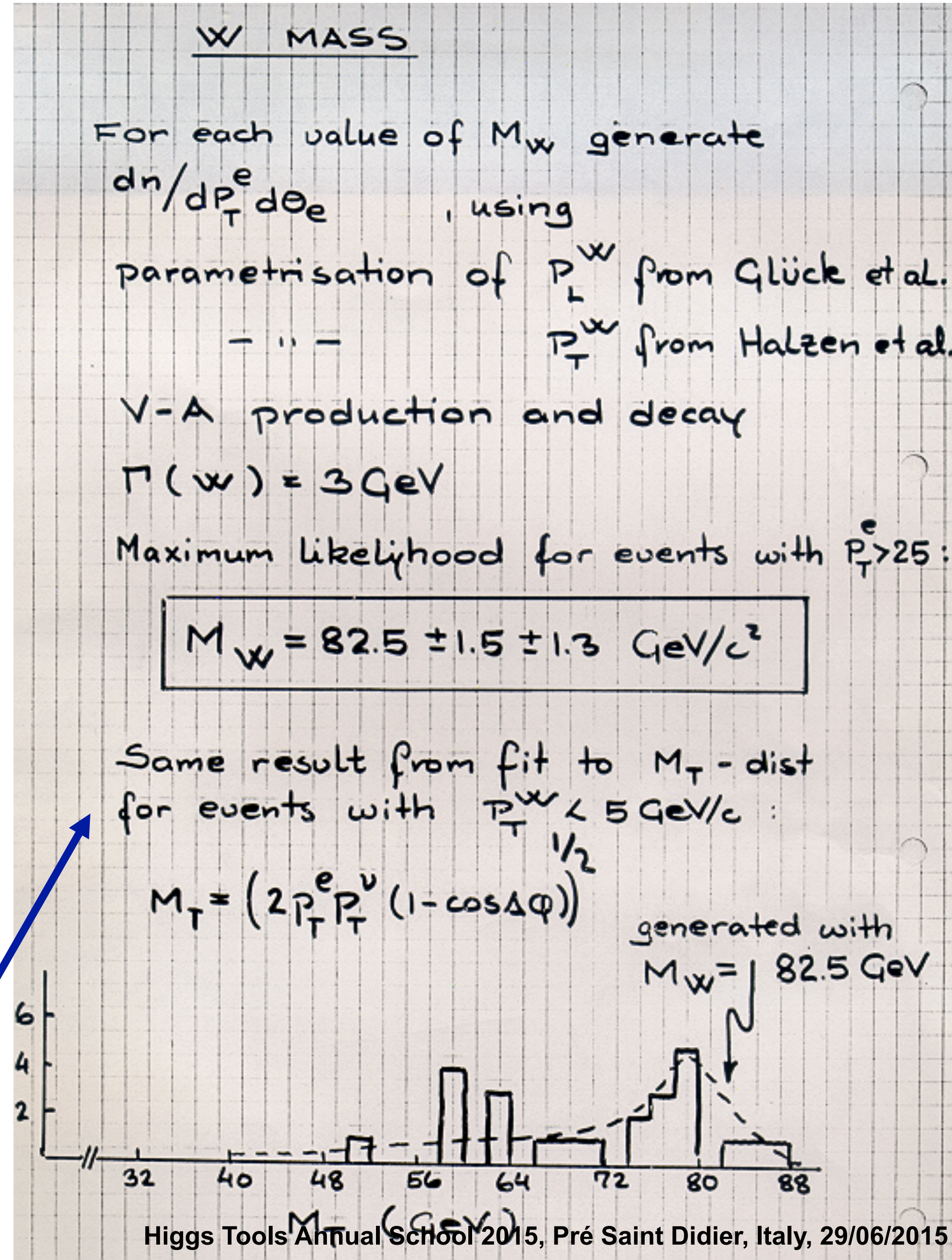


Historical perspective: the 80's in UA1/UA2 at the SppS



Software design in UA2

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


W MASS

For each value of M_W generate $dn/dP_T^e d\theta_e$, using

parametrisation of P_L^W from Glück et al.

— " — P_T^W from Halzen et al.

V-A production and decay

$\Gamma(W) = 3$ GeV

Maximum likelihood for events with $P_T^e > 25$:

$$M_W = 82.5 \pm 1.5 \pm 1.3 \text{ GeV}/c^2$$

Same result from fit to M_T - dist for events with $P_T^W < 5$ GeV/c :

$$M_T = \left(2 P_T^e P_T^\nu (1 - \cos\Delta\varphi)\right)^{1/2}$$

Software documentation in UA2

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

1984-1985 were exciting (and confusing) times!
Beware false positive signals!!

Over-abundance of $Z \rightarrow ee\gamma$ events

Monojets

Dijets with missing E_T

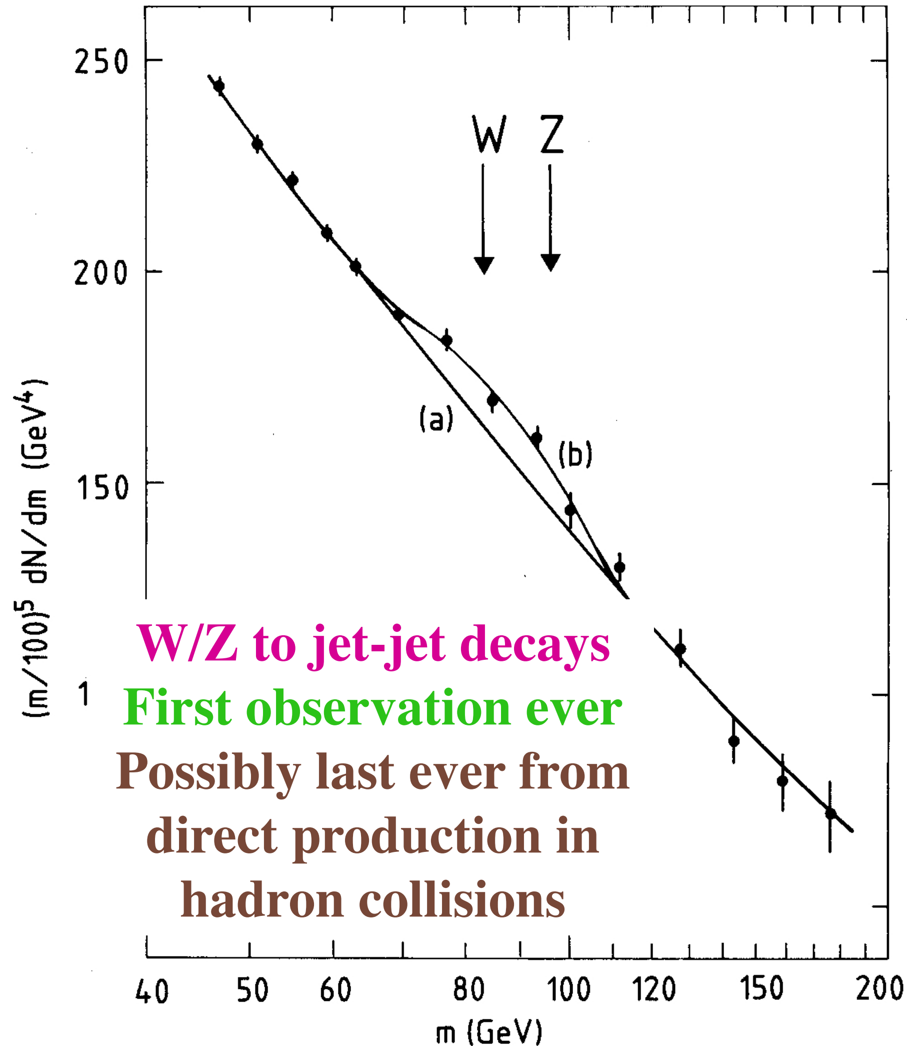
High-p_T electrons with jets and missing E_T

Top quark "discovery"

Bumps in distributions
(jet-jet mass in UA2,
W decay electron spectrum in UA1)

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

We have presented evidence for a signal, at the level of ≃ 3 standard deviations above the copious and steeply falling strong interaction background, in agreement with Standard Model expectations for W and Z bosons decaying into two quark jets. It contains 632 ± 190 events, 1.4 standard deviations above the expectation of 340 ± 80 events. Stronger evidence for the signal and a significant quantitative measurement of the $W,Z \rightarrow q\bar{q}$ branching fractions will require the collection of a significantly larger data sample [18].



W/Z to jet-jet decays

First observation ever

Possibly last ever from direct production in hadron collisions

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

First ever EW fits in UA2 before LEP turned on

From these events we measure the mass of the Z^o boson to be :

$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV}/c^2 \qquad (2)$$

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

The rms of this distribution is 2.6 GeV/c^2, consistent with the expected Z^o width[14] and with our experimental resolution of ∿ 3%.

Under the hypothesis of Breit-Wigner distribution we can place an upper limit on its full width

$$\Gamma < 11 \text{ GeV}/c^2 \quad (90\% \text{ CL}) \qquad (3)$$

corresponding to a maximum of ∿ 50 different neutrino types in the universe[15]

The standard SU(2) × U(1) electroweak model makes definite predictions on the Z^o mass. Taking into account radiative corrections to 0 (α) one finds[14]

$$M_Z = 77\ \rho^{-\frac{1}{2}}\ (\sin 2\ \theta_W)^{-1} \text{ GeV}/c^2 \qquad (4)$$

where θ_W is the renormalised weak mixing angle defined by modified minimal subtraction, and ρ is a parameter which is unity in the minimal model.

Assuming ρ = 1 we find

$$\sin^2\theta_W = 0.227 \pm 0.009 \qquad (5)$$

However, we can also use the preliminary value of the W mass found in this experiment[16]

$$M_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV}/c^2.$$

Using the formula[14]

$$M_W = 38.5\ (\sin\ \theta_W)^{-1} \text{ GeV}/c^2 \qquad (6)$$

we find $\sin^2\theta_W = 0.226 \pm 0.014$, and using also Eq. (4) and our experimental value of M_Z we obtain

$$\rho = 1.004 \pm 0.052 \qquad (7)$$

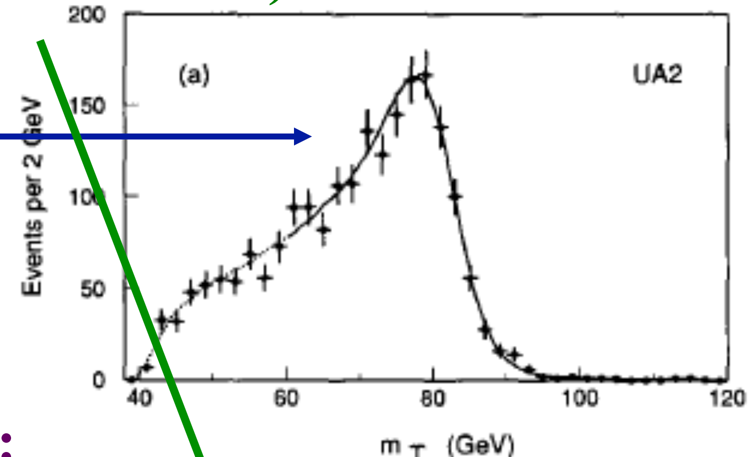
Historical perspective: the 80's in UA1/UA2 at the SppS

Most important results from 1987-1990 campaign with UA2:

precise measurement of m_W/m_Z

and direct limit on top-quark mass (m_{top} < 60 GeV)

Transverse mass distribution for electron-neutrino pairs



$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

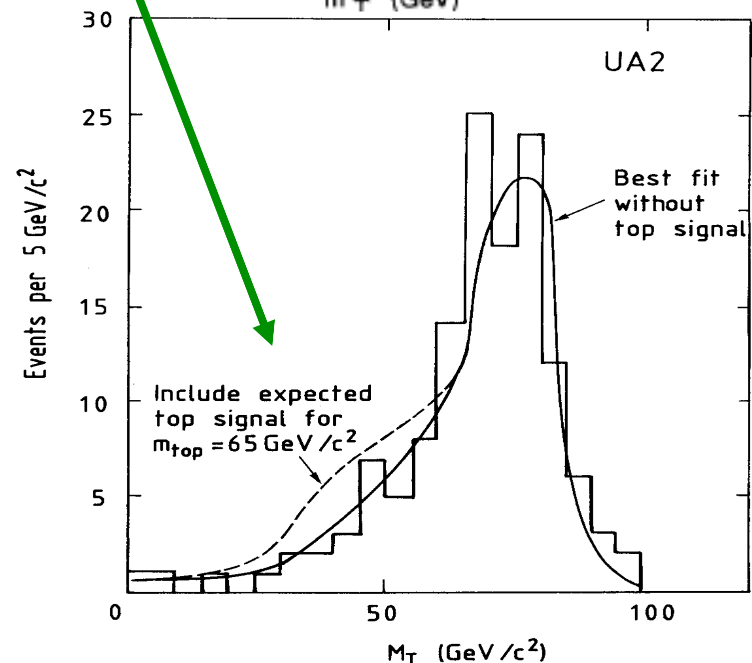
Using the precise measurement of m_Z (LEP):

$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

Indirect limits on top-quark mass in the context of the Standard Model:

$$m_{top} = 160^{+50}_{-60} \text{ GeV}$$

(four years before the discovery of the top quark at Fermilab)



Historical perspective: the Higgs boson

Doing these first measurements in EW physics based on radiative corrections to the W/Z masses, the top mass appeared quadratically at a time when we had just found out to our dismay that most likely $m_{top} > m_W$ and when nothing much was known about m_H!

1964

Five pages that changed the course of the Standard Theory of particles...

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

2 pages

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

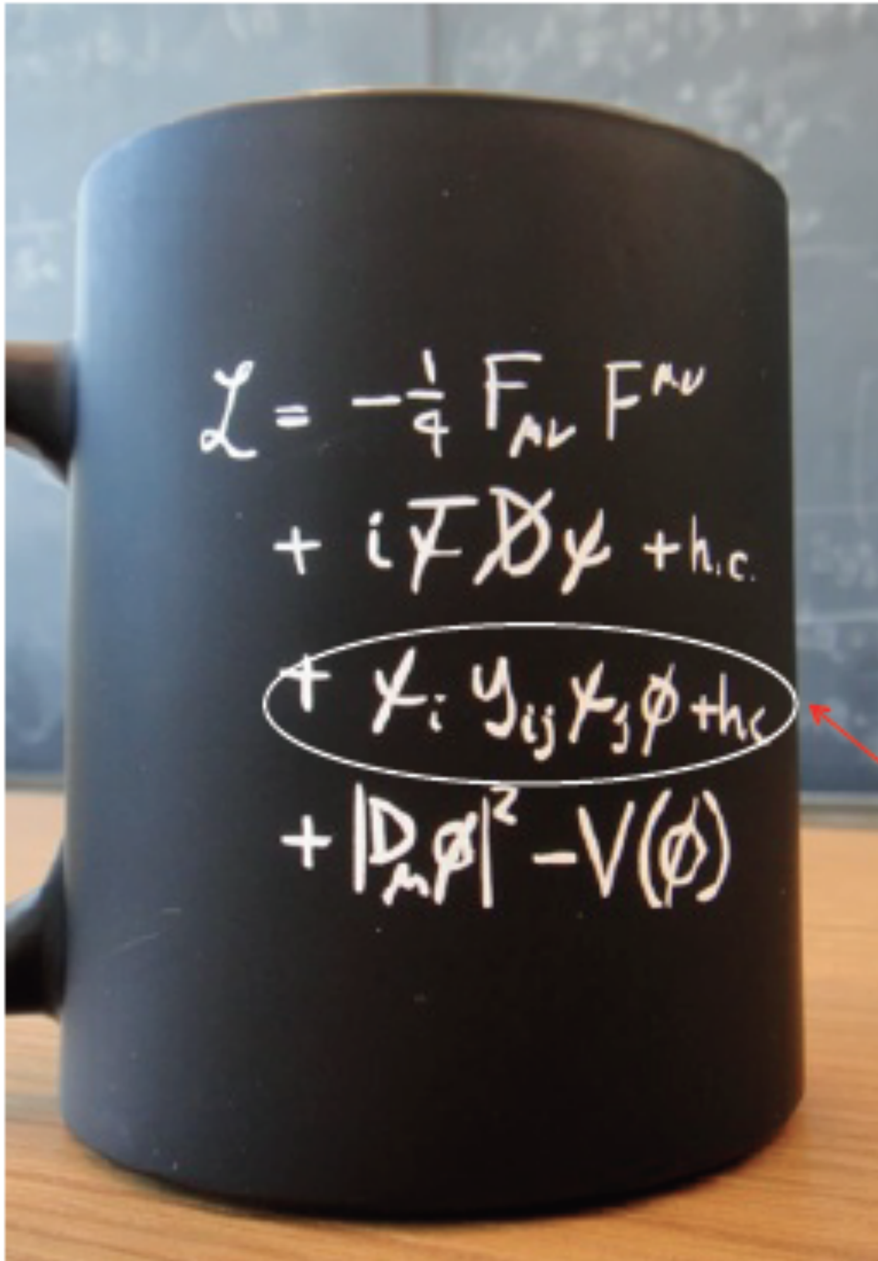
1 page

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

2 pages

Historical perspective: the Higgs boson

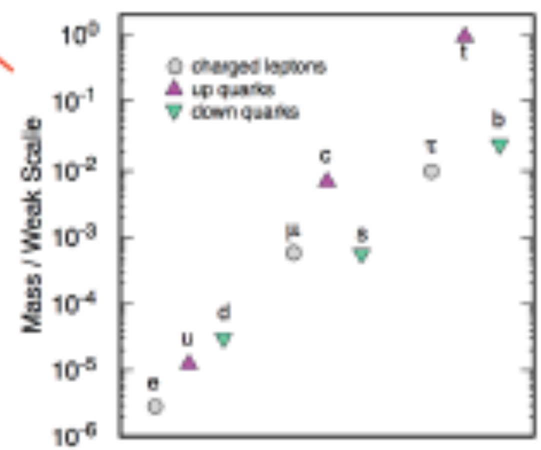


The BEH mechanism allows:

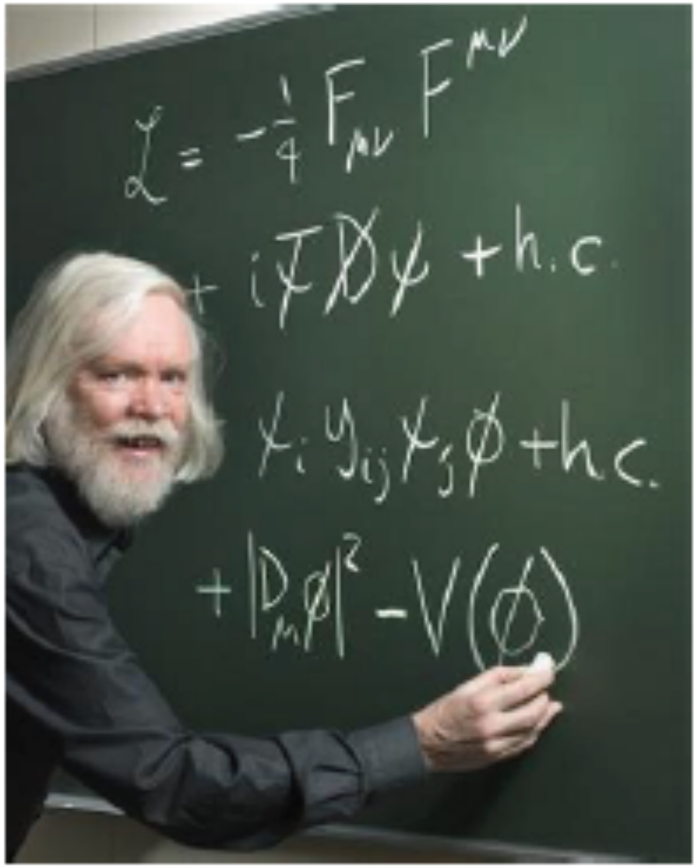
- Massive gauge bosons
- Massive fermions
- Renormalizability
- Unitarity

Splendid… but yet the least elegant part of the Standard Model

- No gauge principle
- Accounts for most free param.



Historical perspective: the Higgs boson



1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

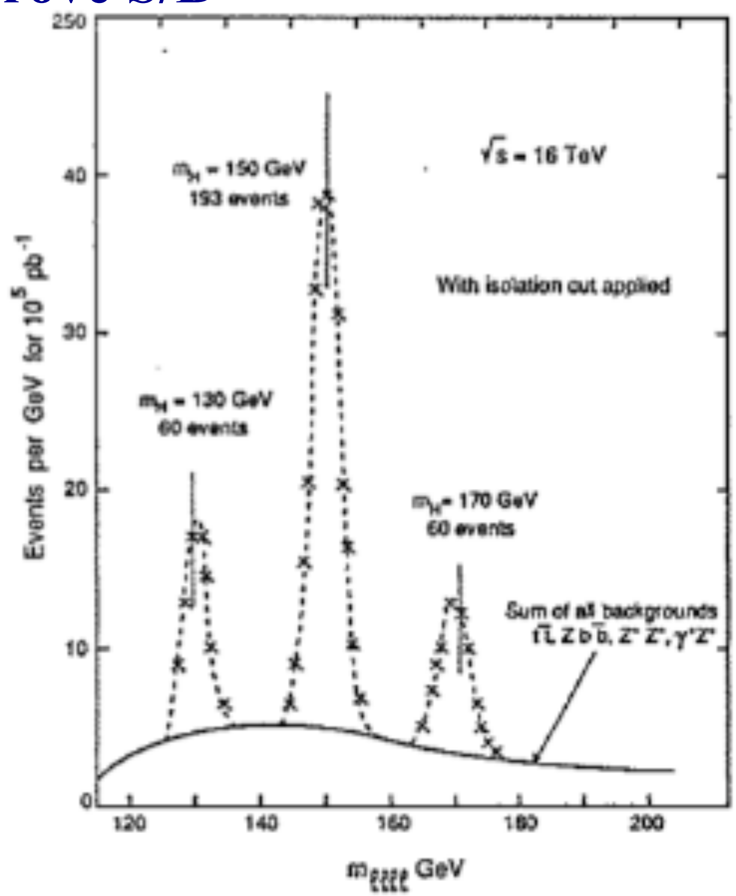
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Historical perspective: the Higgs boson

The two channels which are at the basis of the Higgs boson discovery had been already quite well studied for the La Thuile (1988-1989) and Aachen (1990) workshops.

This includes VBF, H to ττ mass measurements, but not H to WW (a counting experiment), H to bb (very difficult!), nor boosted topologies as a way to improve S/B

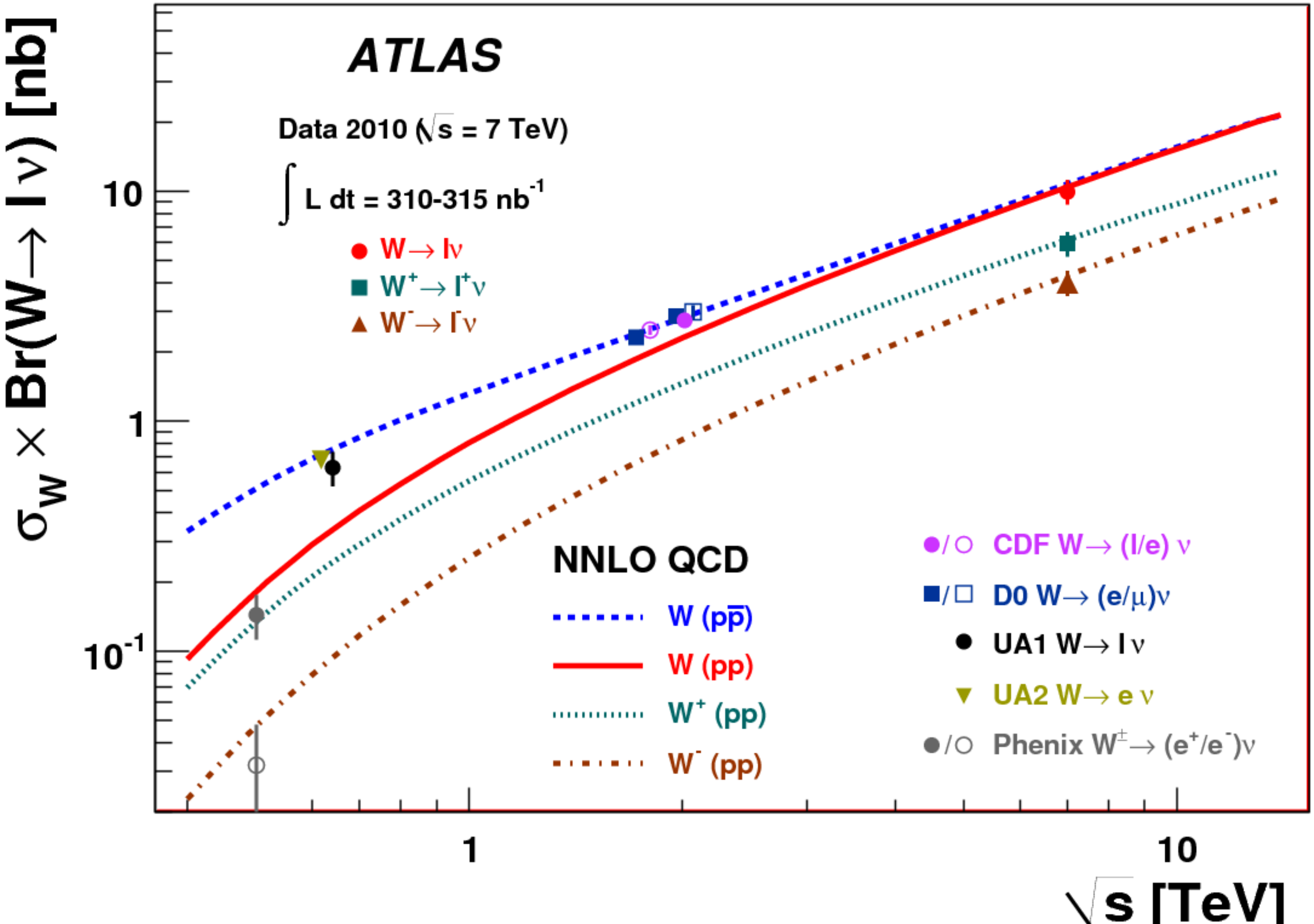


1990

Proceedings of LHC Workshop (Aachen, 1990): $\sqrt{s}$ = 16 TeV, 100 fb^{-1}

Historical perspective: first run at 7 TeV in 2010

First W/Z events seen in April-May 2010 were very exciting!



W/Z differential measurements

- Fiducial measurements provide already now a more precise test of QCD predictions, at least in terms of pdfs, than when they are corrected back to the total cross-sections

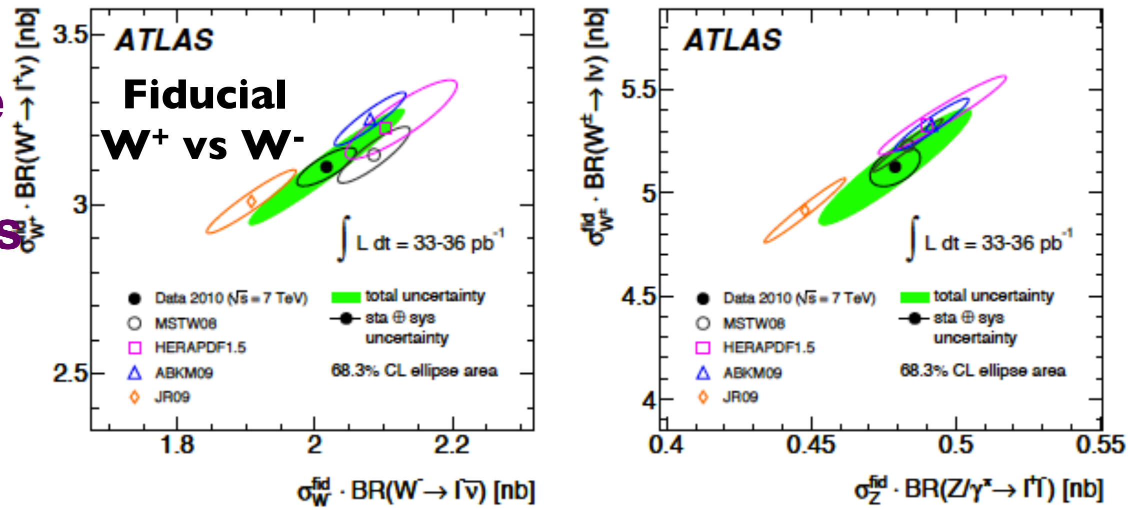


FIG. 15. *Measured and predicted fiducial cross sections times leptonic branching ratios, σ_{W^+} vs. σ_{W^-} (left) and $(\sigma_{W^+} + \sigma_{W^-})$ vs. σ_{Z/γ^*} (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

- Reducing the size of the error bars on the major axes of these ellipses is the challenge ATLAS/CMS have worked on very hard!

Note that the green ellipse is dominated by the uncertainty on the luminosity measurement which was 3.4%.
For 2011 data, down to 1.8%

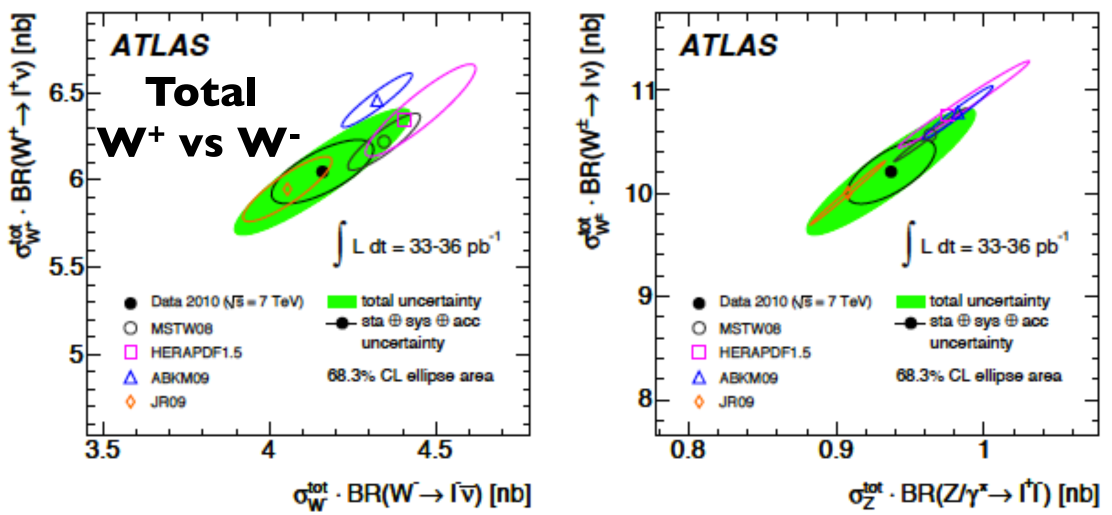


FIG. 16. *Measured and predicted total cross sections times leptonic branching ratios: σ_{W^+} vs. σ_{W^-} (left) and $(\sigma_{W^+} + \sigma_{W^-})$ vs. σ_{Z/γ^*} (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

W/Z differential measurements

- Finally, the differential ratios of W to Z fiducial cross-sections have perhaps the highest potential for precision measurements in the future

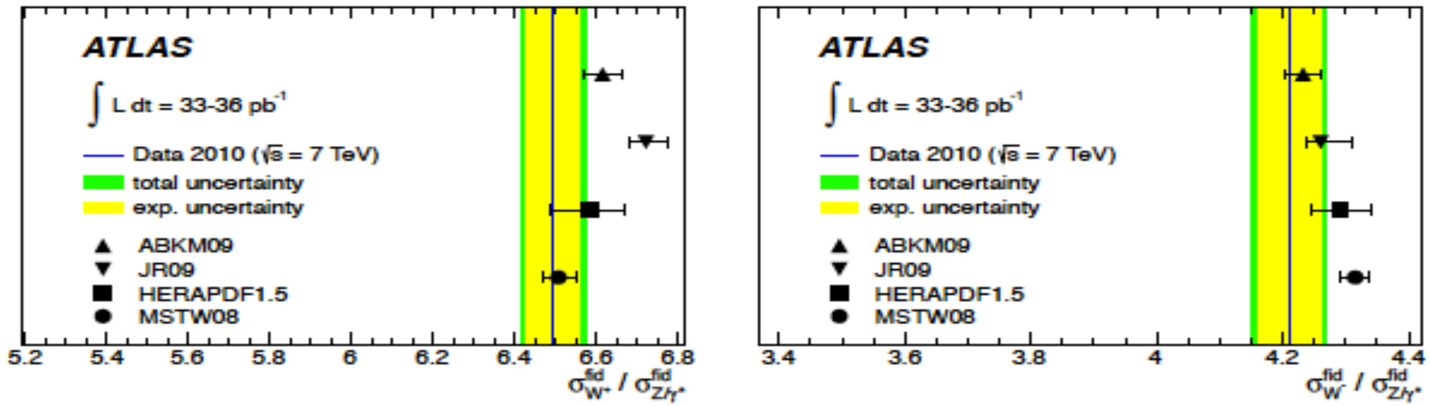
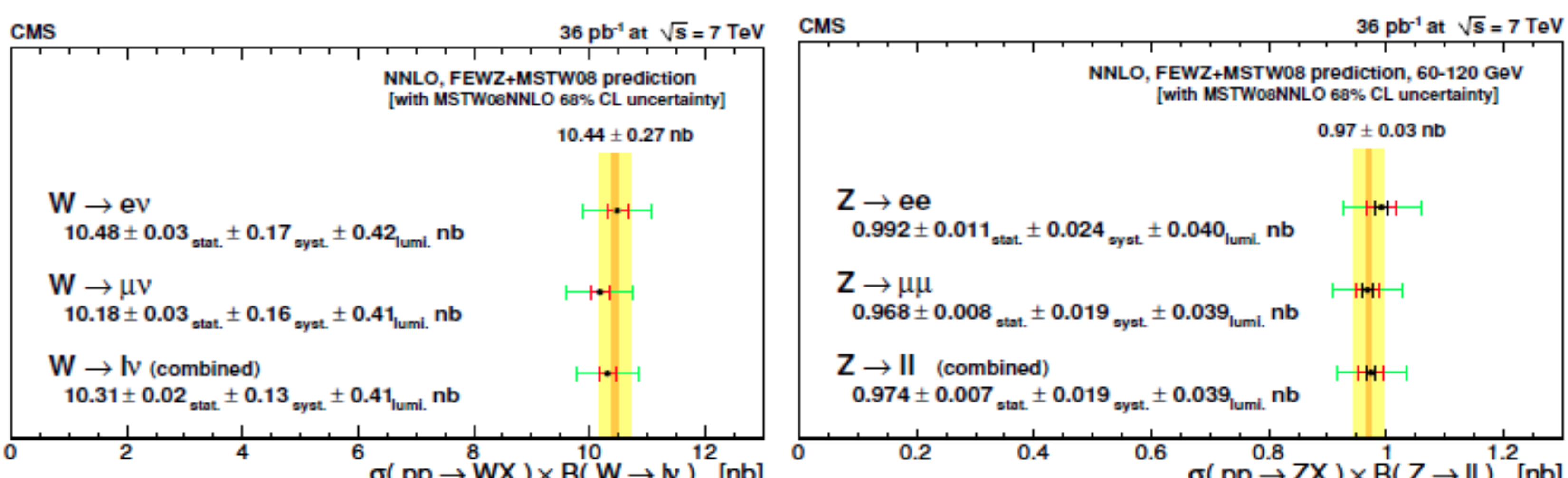
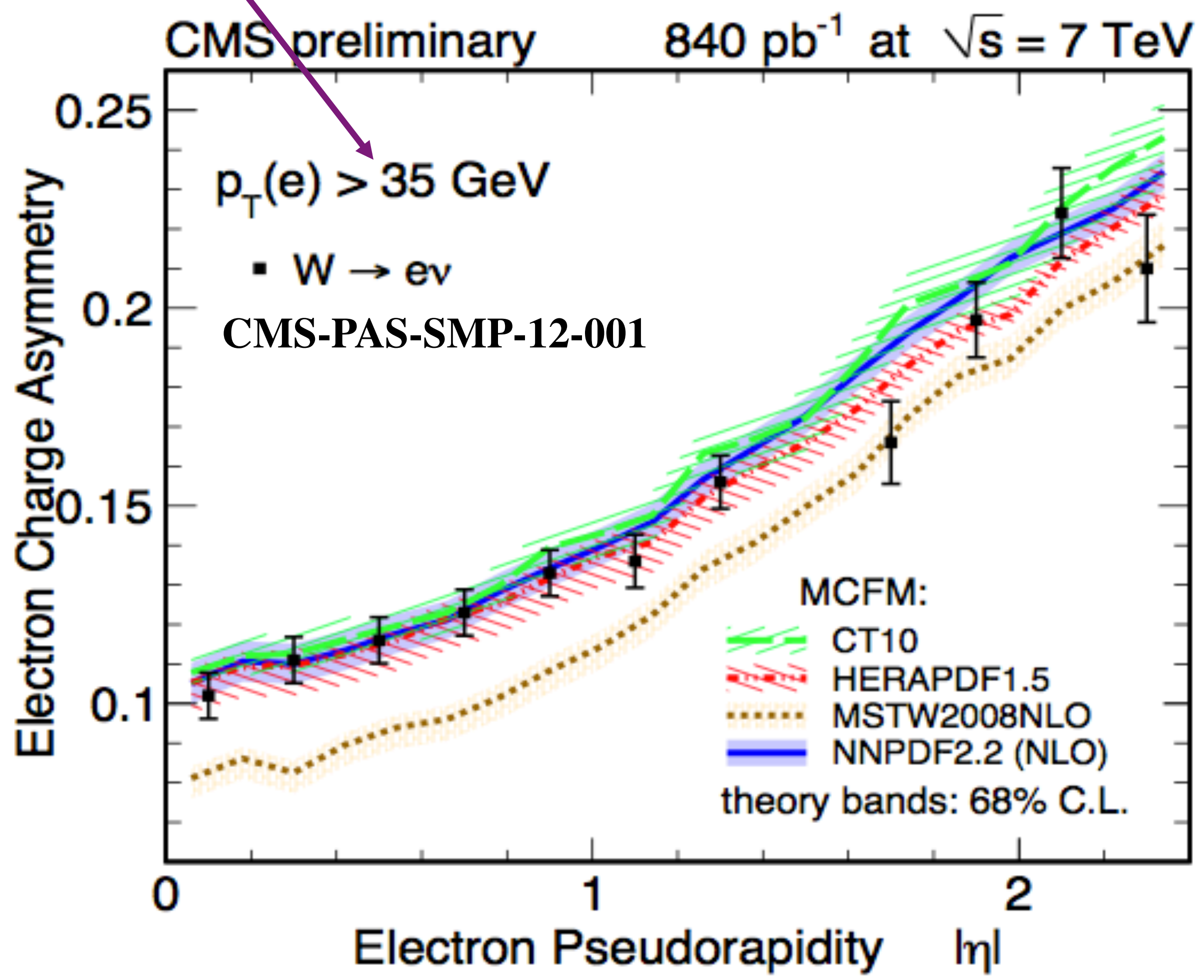


FIG. 19. *Measured and predicted fiducial cross section ratios, $\sigma_{W+}/\sigma_{Z/\gamma^*}$ (left) and $\sigma_{W-}/\sigma_{Z/\gamma^*}$ (right). The experimental uncertainty (inner yellow band) of the measurement includes the experimental systematic errors. The total uncertainty (outer green band) includes the statistical uncertainty and the small contribution from the acceptance correction. The uncertainties of the ABKM, JR and MSTW predictions are given by the PDF uncertainties considered to correspond to 68 % CL and their correlations are derived from the eigenvector sets. The results for HERAPDF comprise all three sources of uncertainty of that set.*



Measurement of lepton charge asymmetry in W decays

- **Lepton charge asymmetry in the lab is one of the sensitive 1D distributions to PDFs and was the first used to produce LHC combined plot with 2010 data**
- **High-statistics results from 2011 data by CMS already disfavoured certain PDF sets but trigger threshold was very high (thereby diluting the measurement)**
- **PDF4LHC workshops show that interaction between PDF fitters and LHC experiments is developing rapidly**



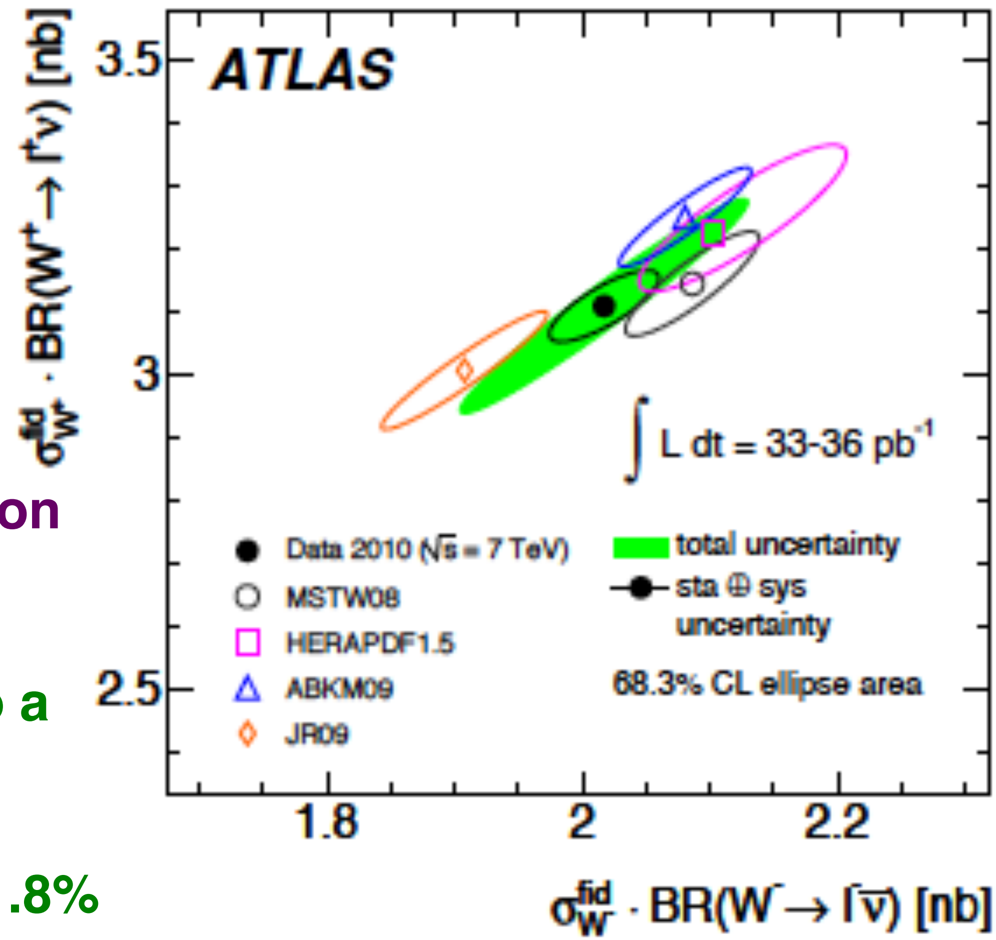
W/Z differential measurements

- What is theory in this plot of integrated fiducial cross sections?

FEWZ (NNLO QCD differential MC, at parton level) with different NNLO PDF sets. Uncertainties on the theory ellipses are therefore purely QCD scale uncertainties i.e. they supposedly cover our lack of knowledge of higher-order corrections.

Can these be improved?

This is highly unlikely



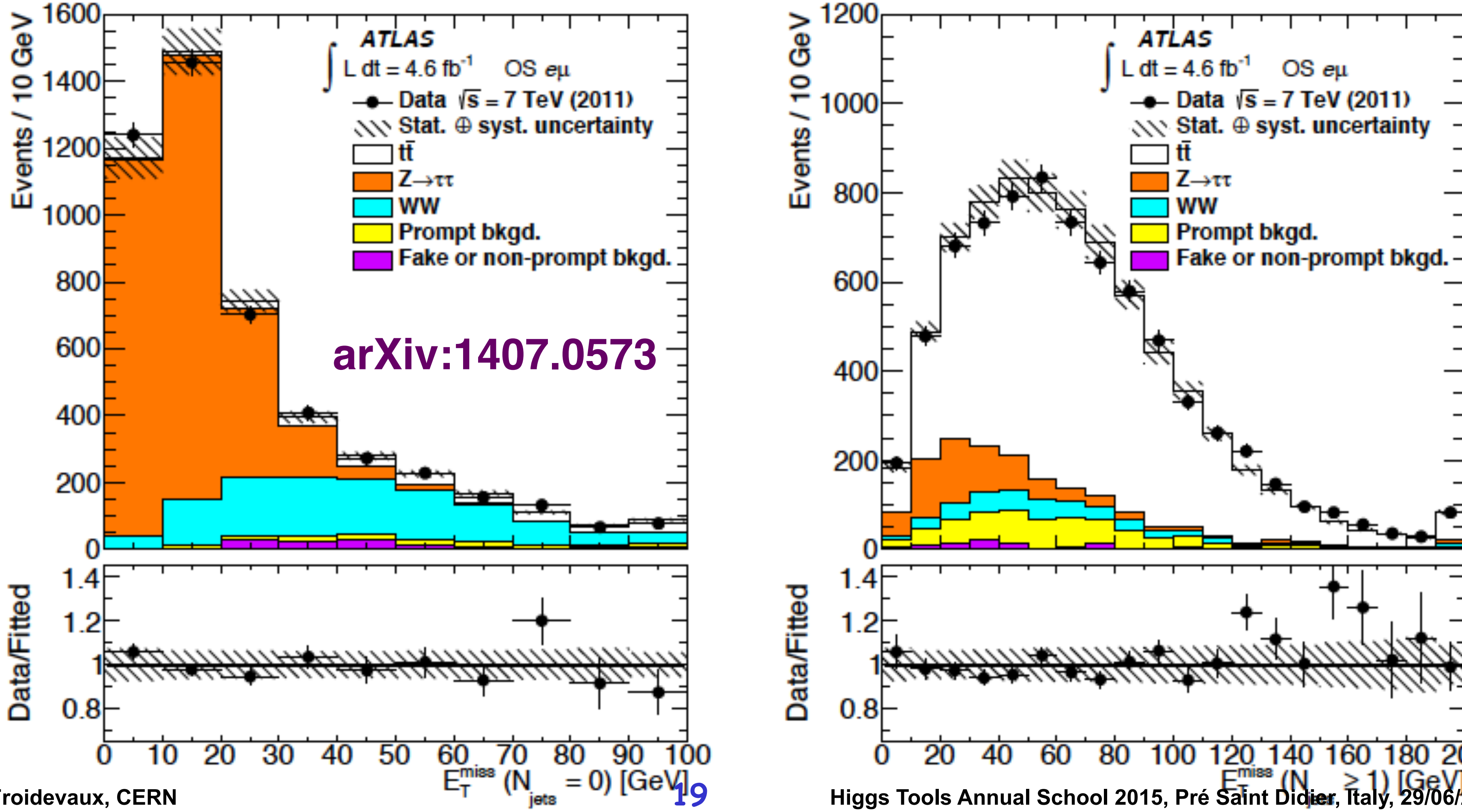
- How to reach even better precision experimentally?

- Improve exp. syst. from few % to a total of ~ 0.5%

- Improve lumi syst from 3.4% to 1.8%

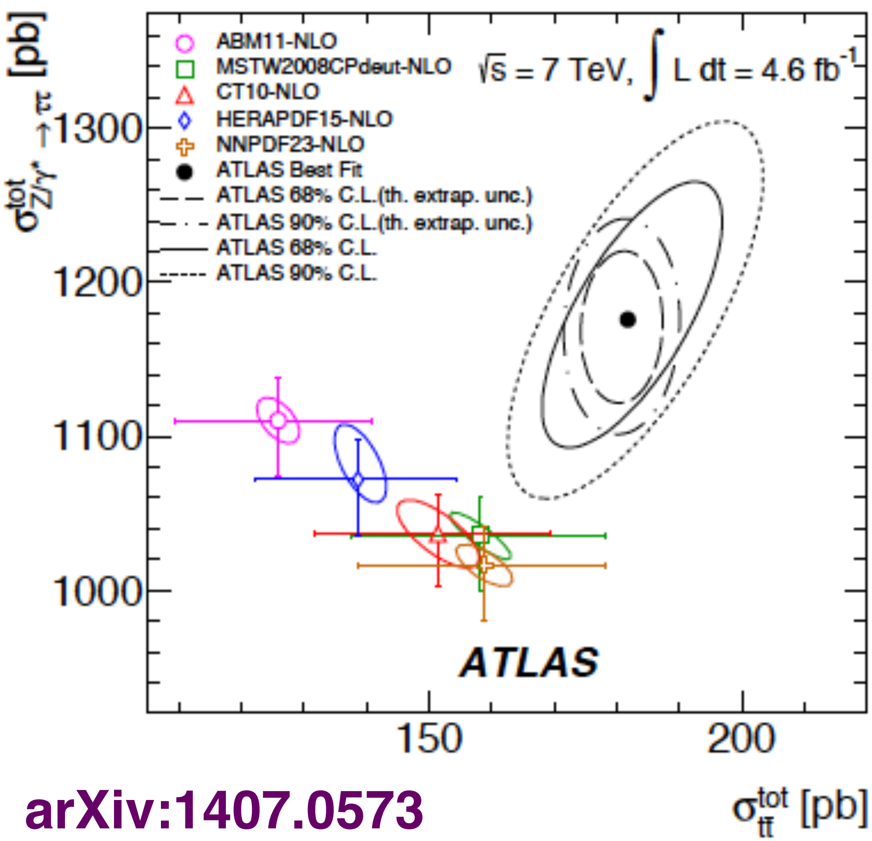
NLO QCD is clearly insufficiently precise for SM, top (and even Higgs) measurements

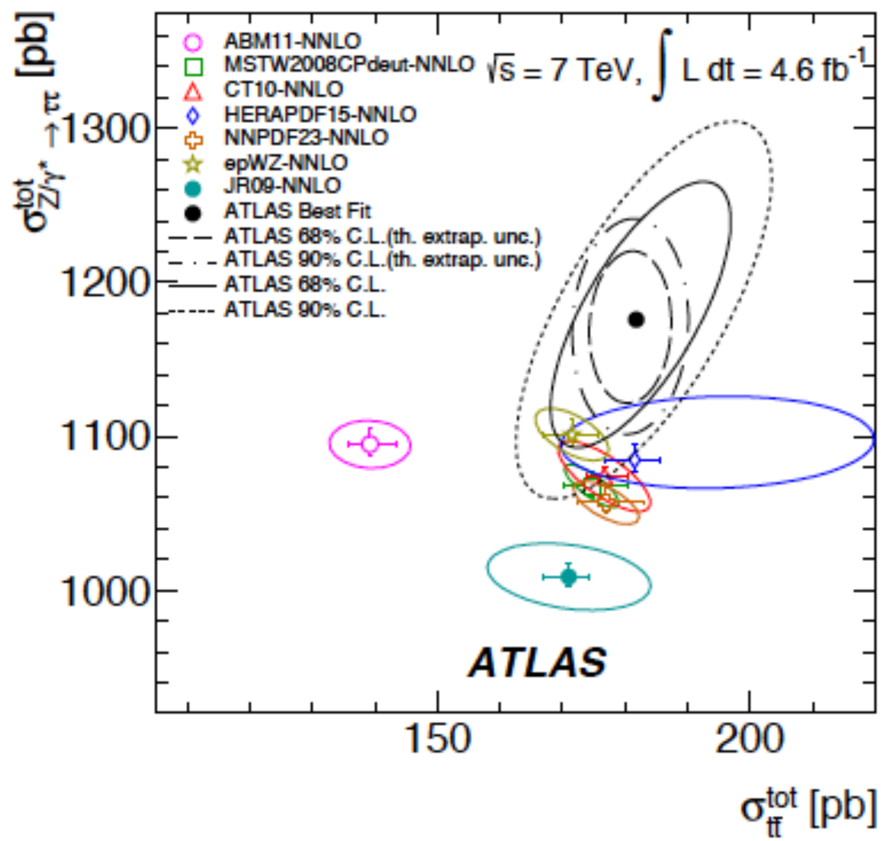
Simultaneous measurements of the $t\bar{t}$, W^+W^-, and $Z/\gamma^* \to \tau\tau$ production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector



NLO QCD is clearly insufficiently precise for SM, top (and even Higgs) measurements

- **Fiducial cross sections can only be compared at NLO**
- **Until recently, total cross sections could be compared only between Z Drell-Yan and top pair production**
- **Note that ttbar NNLO calculation is > 3 years old now, still no NNLO differential MC available. Note also that Z to $\tau\tau$ to eμ is not ok in MCFM**



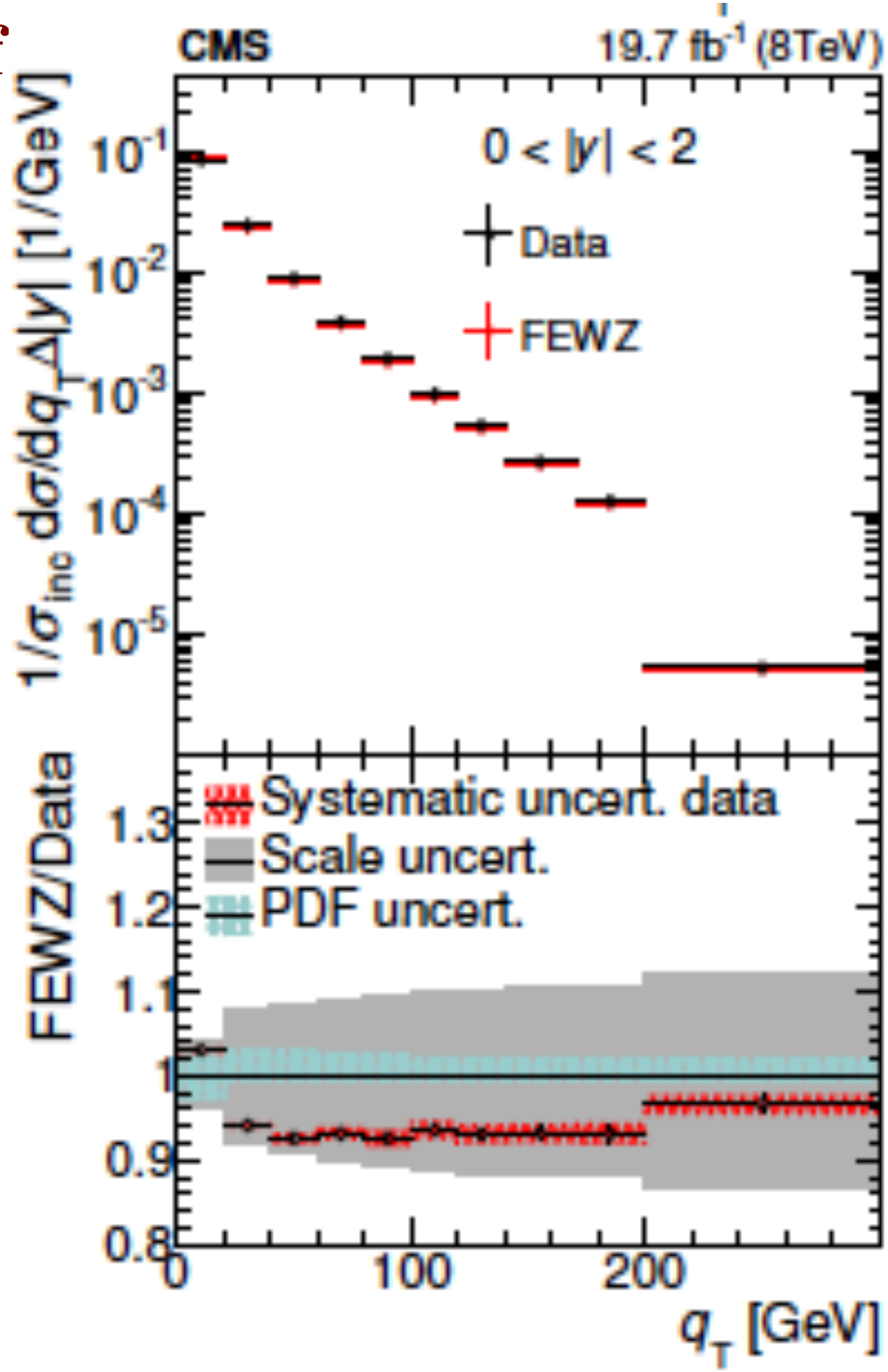


arXiv:1407.0573

Very precise measurement of p_T^Z in terms of shape!

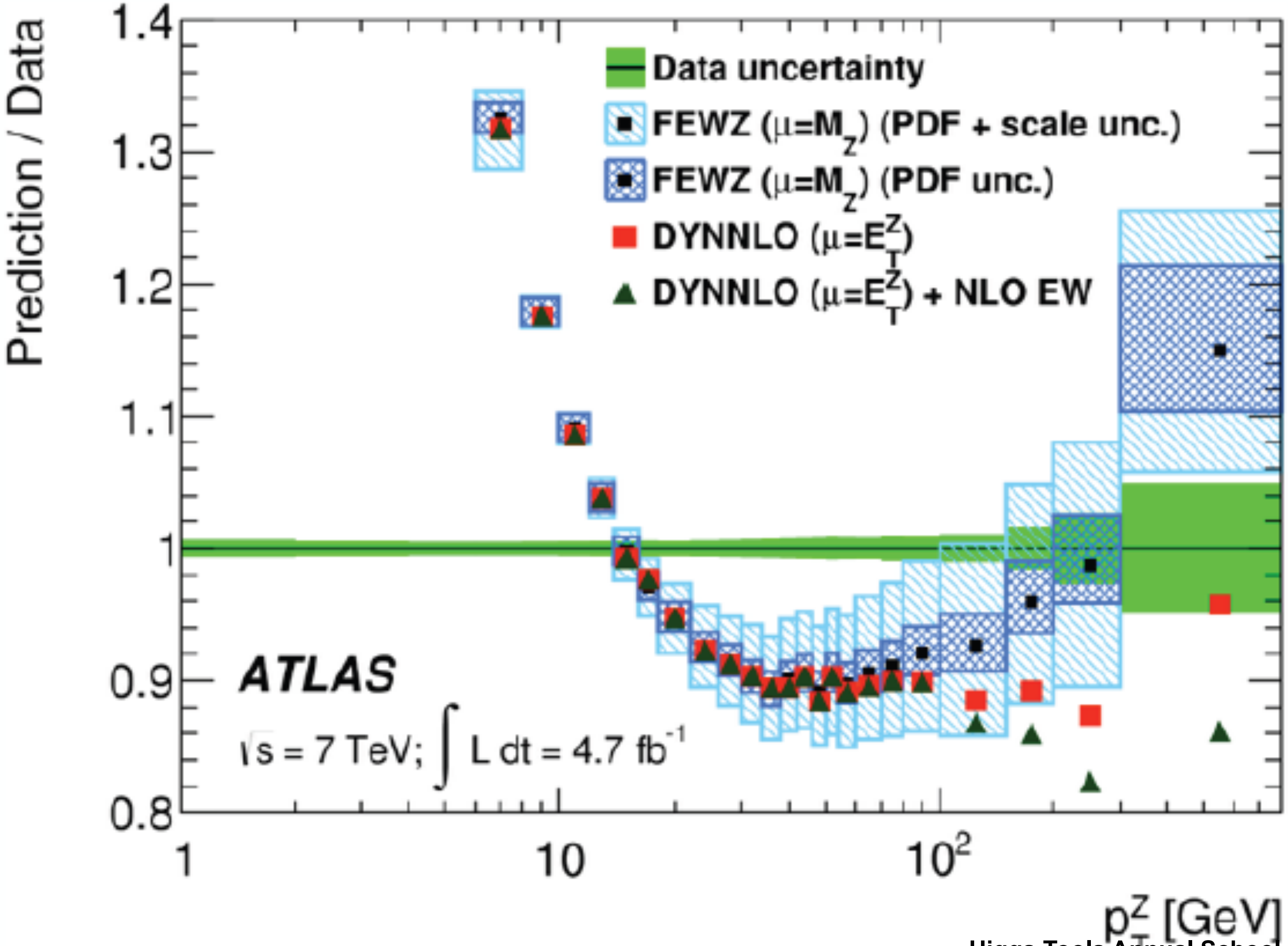
- Recent measurement published by CMS seems to indicate reasonable agreement between fixed-order calculations by FEWZ (NNLO) and measurements
- Measurements are much more precise than theory (σ_{meas}~1.5%)
- This measurement is very important for many reasons, one of them being m_W measurement

- But what does NNLO mean here?
- Actually, it means NNLO differential for any distribution which is defined for $p_T^Z = 0$ but only NLO for the others
- Non-trivial examples: $\cos\theta_{CS}$ is NNLO but ϕ_{CS} is only NLO



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 (and experiments)!

- **ATLAS and CMS both have uncertainties which are far smaller than the theoretical ones and agree with each other to < 1%.**
- **However, ATLAS theory uncertainty estimates for FEWZ are smaller than those estimated by CMS, by a factor ~ 2. Why?? MC stats??**

- **Key point however is that PDF uncertainties are far smaller than the difference between data and theory at pT ~ 40 GeV which is well in perturbative regime**
- **This means that the data cannot be included in PDF fits because they will come out wrong.**
- **Why? Because PDF fits do not include theory scale uncertainties, they are not designed for this (yet). This has been a problem for jet physics results since a while and now it appears also for p_T^Z**

- **There are other more “hidden” uncertainties in PDF fits, related to assumptions such as that proven somewhat mistaken for the strange sea. PDF fit results can then suddenly move “out of their uncertainties”.**

Very precise measurement of Z p_T poses problems to theory (and experiments)!

G. Salam

Z p_T mystery needs solving

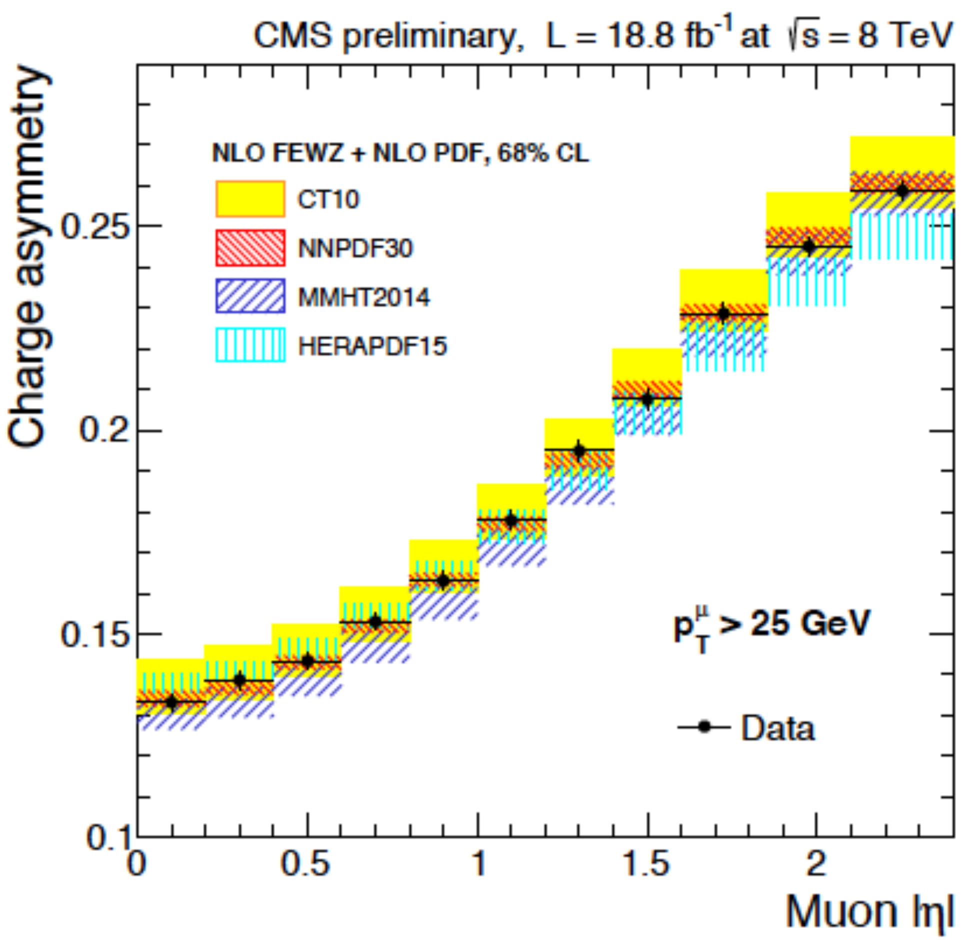
The discrepancy feeds into other observables (e.g. jet dist^n in Z+jet events).

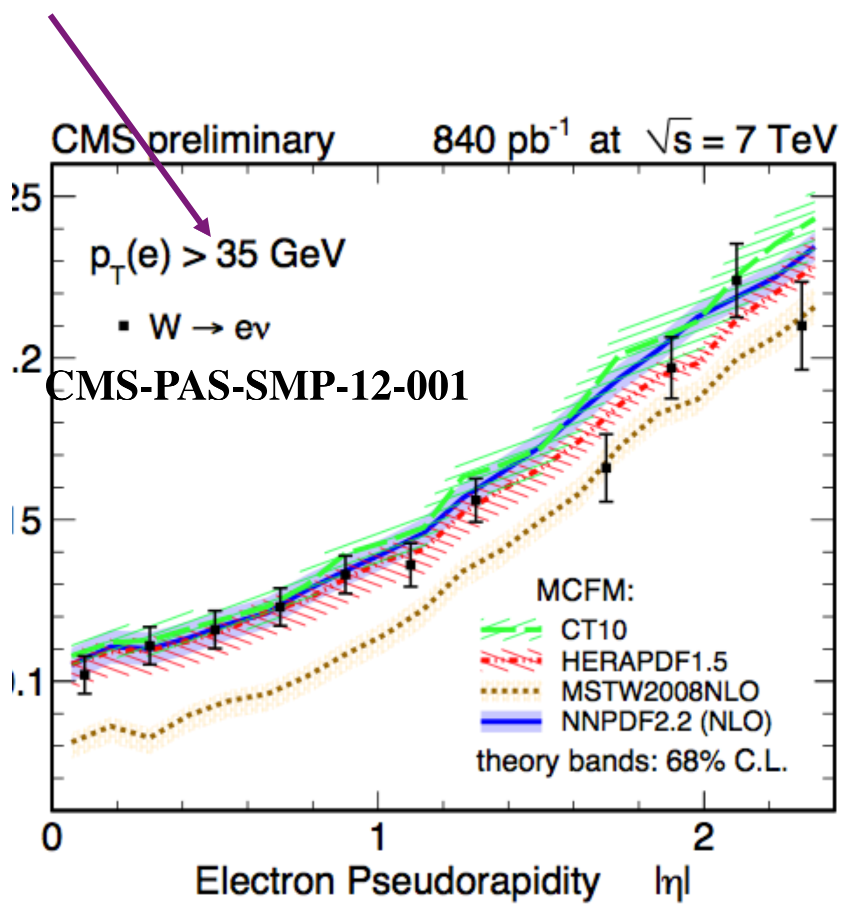
Is theory uncertainty badly underestimated? Will NNLO solve the problem? What's the real scope for resummation to modify distribution for p_T > 40 GeV?

Or are PDFs substantially wrong? (Z p_T is never an input; while much less precise incl. jets are an input — why?)

Measurement of lepton charge asymmetry in W decays

- Lepton charge asymmetry in the lab is one of the sensitive 1D distributions to PDFs and was the first used to produce LHC combined plot with 2010 data
- High-statistics results from 2011 data by CMS already disfavoured certain PDF sets but trigger threshold was very high (thereby diluting the measurement)
- From MSTW2008NLO to MMHT2014, one specific PDF set has "adapted" to the data from LHC. What is the meaning of the error bands from the PDF fits??



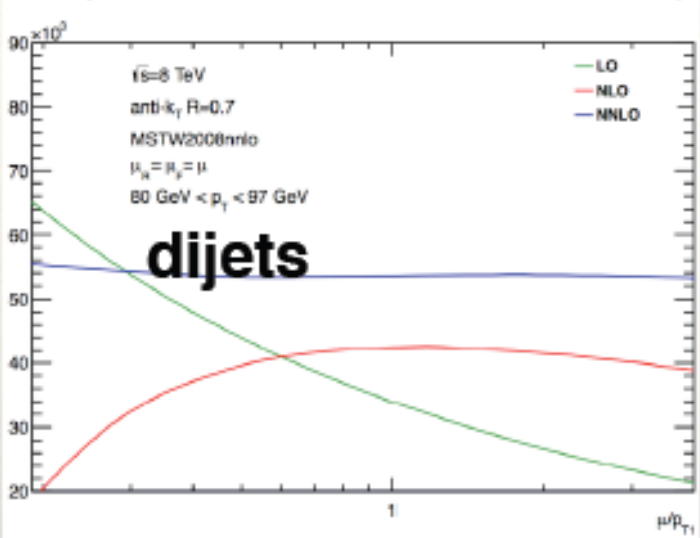


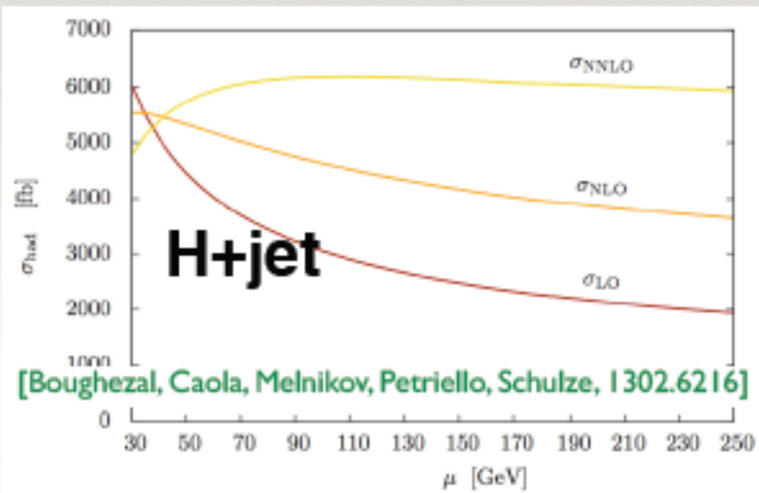
QCD scale variations

G. Salam

How reliable is scale variation?

[Gehrmann-De Ridder, Gehrmann, Glover, Pires, 1301.7310]





[Boughezal, Caola, Melnikov, Petriello, Schulze, 1302.6216]

There's no shortage of cases where (sometimes partial) NNLO is at or beyond edge of NLO scale variation

[Czakon, Fiedler & Mitov 1303.6254]

$t\bar{t}$ @ LHC8

LO: 145^{+49}_{-34} pb

NLO: 213^{+25}_{-27} pb

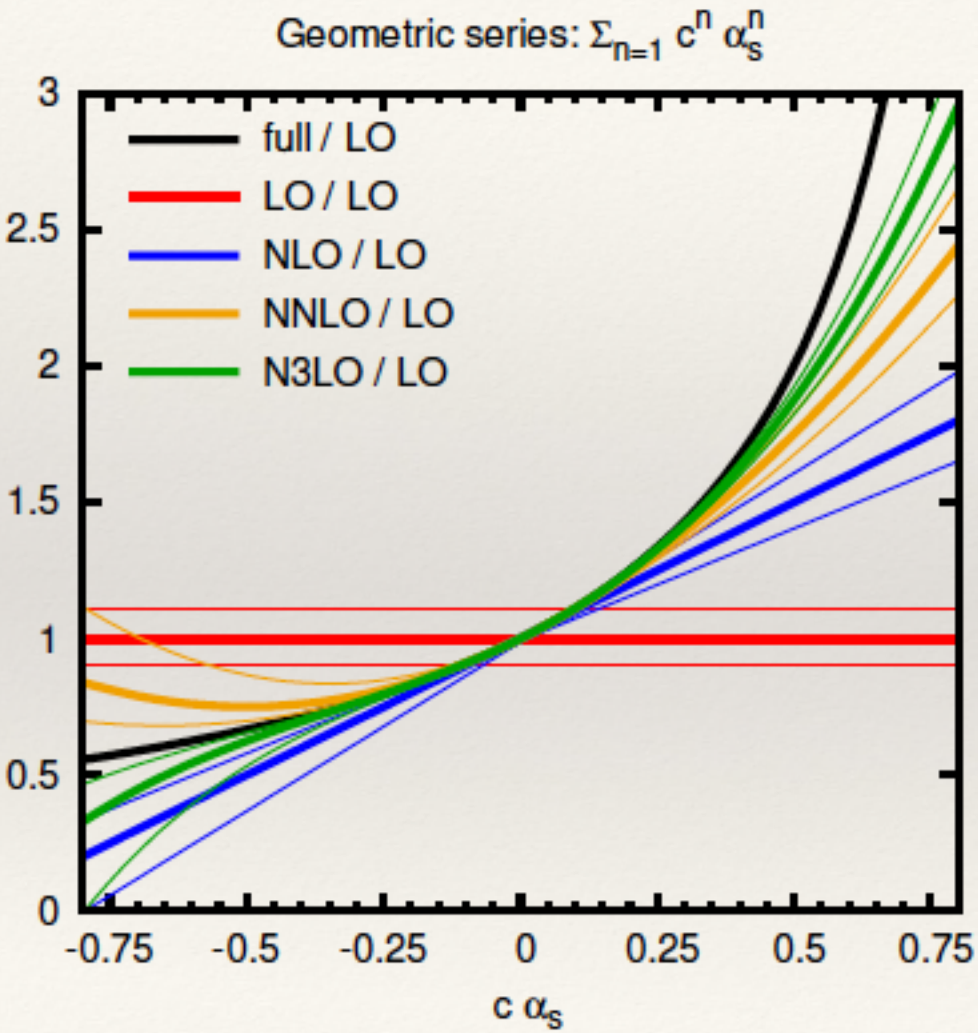
NNLO: 239^{+9}_{-15} pb

top++, MSTW2008NNLO, $\mu = m_t$

QCD scale variations

Now examine truncations of series, as a function of c for $\alpha_s = 0.12$

G. Salam



LO: scale variation mostly useless.

NLO: it's usefulness extends further, but at some point breaks down.

NNLO: ditto
NNNLO: ditto

QCD scale variations

G. Salam

$$\sigma = \sum_{n=1} (c\,\alpha_s)^n$$

Higgs $(\mu = m_H)$

$$\mathcal{N} \times (\alpha_s^2 + 11\alpha_s^3 + 62\alpha_s^4)$$

Normalised to LO, what's missing from N^{p}LO is:

$$\sim c^{p+1}\alpha_s^{p+1}$$

Scale var^n ($c \gg 1$) gives:

$$\sim (p+1) \cdot c^p \alpha_s^{p+1} \quad *$$

Ratio scale uncertainty/ true missing higher orders:

$$\sim \frac{p+1}{c}$$

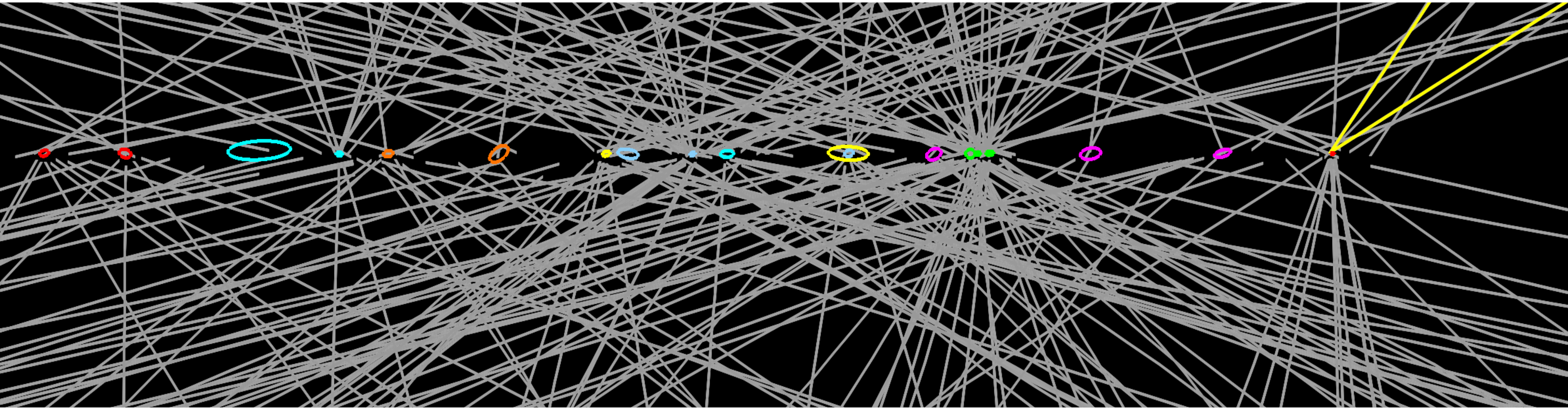
For poorly converging series ($c \gg 1$), scale variation **parametrically** underestimates the uncertainty.

At higher orders ($\equiv$ for larger p) scale variation works further, but for large enough c inevitably breaks down

*coefficient is $\frac{23}{6\pi} \ln 2 \simeq 0.85$

Precision meas. in the SM: pile-up and underlying event

- Pile-up (and underlying event) not glamorous physics topics, but these do turn out to be important aspects of modelling systematics
- 2011: achieved $L_{max} \sim 3.4\ 10^{33}$, $L_{tot} \sim 5\ fb^{-1}$ at 7 TeV
- 2012: achieved $L_{max} \sim 6.7\ 10^{33}$, $L_{tot} \sim 20\ fb^{-1}$ at 8 TeV
- Very high average number of interactions excellent for discovery reach, but not so good for precision SM physics!



Example of Z → μμ decay in ATLAS with 20 reconstructed vertices.
Total scale along z is ~ ± 15 cm, p_T threshold for track reco is 0.4 GeV
(ellipses have size of 20σ for visibility).

In 2012, reached maximum of ~ 40 interactions per BX at $L \sim 6\ 10^{33}$!

Precision meas. in the SM: pile-up and underlying event

- **Underlying event multiplicity in jet events and Z events precisely measured and hard to reproduce with MC models**

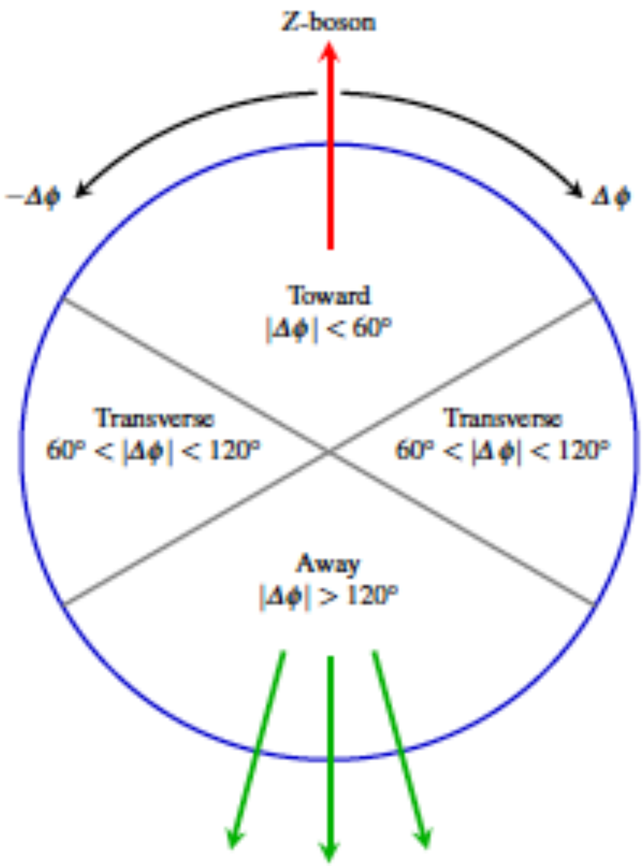
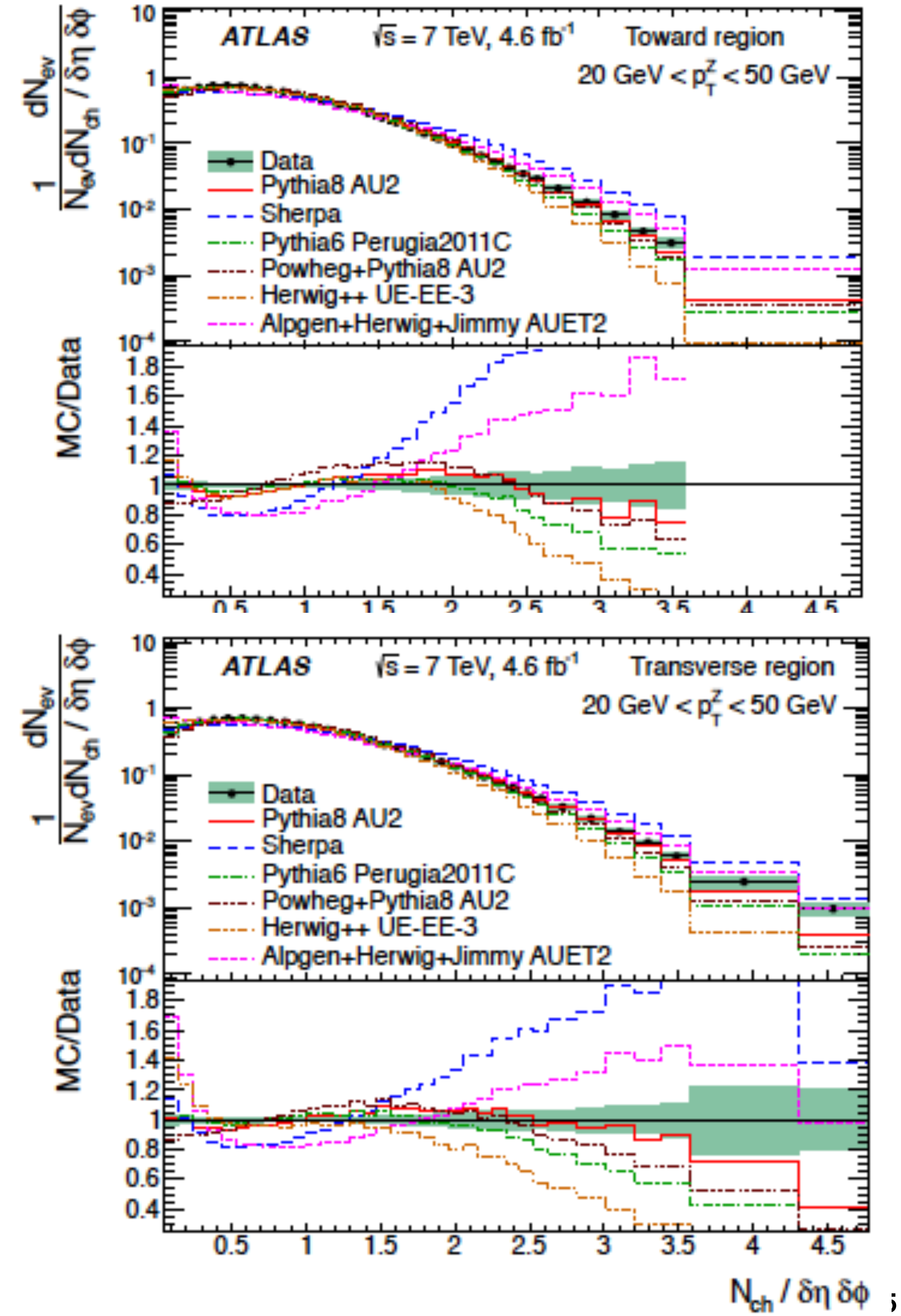


Fig. 1 Definition of UE regions as a function of the azimuthal angle with respect to the Z-boson.



Precision meas. in the SM: pile-up and underlying event

- **Underlying event multiplicity in jet events and Z events precisely measured and hard to reproduce with MC models.**
- **Same is true for $\langle p_T \rangle$ of ch. part.**

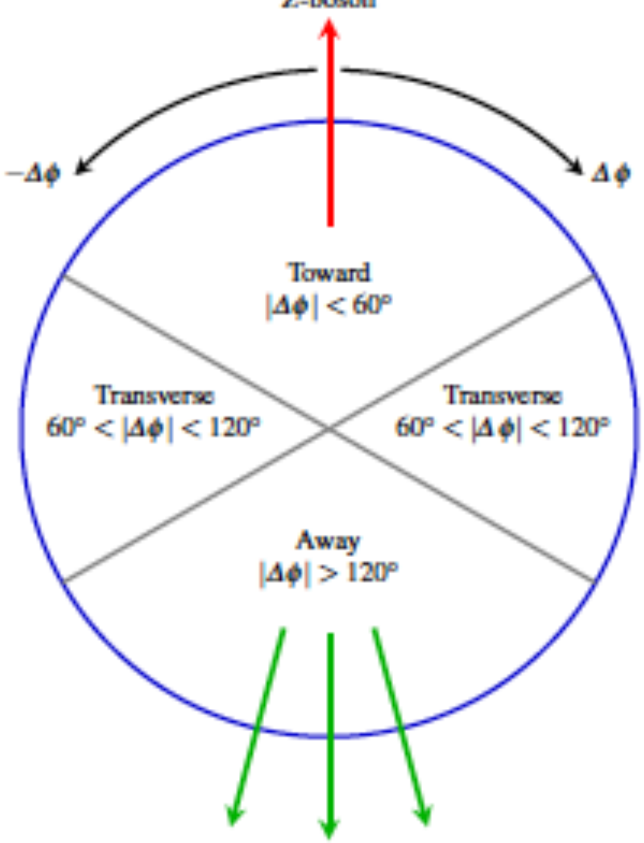
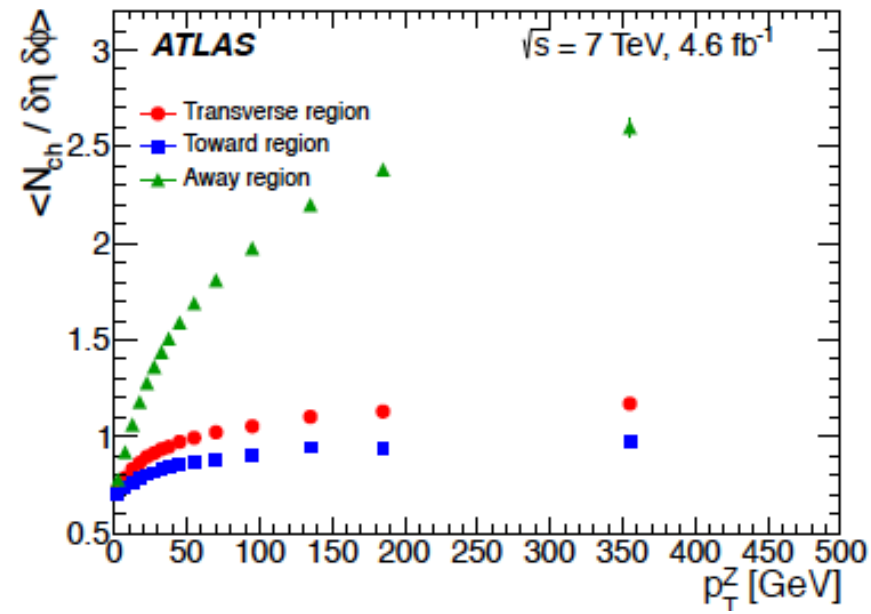
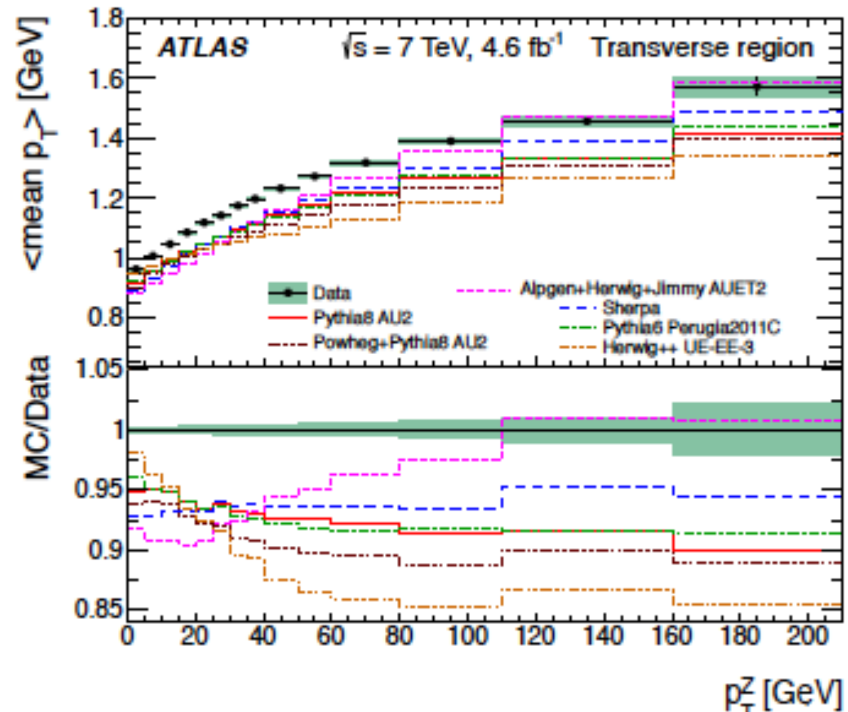


Fig. 1 Definition of UE regions as a function of the azimuthal angle with respect to the Z-boson.





Precision meas. in the SM: pile-up and underlying event

- **Underlying event multiplicity in jet events and Z events precisely measured but difficult to compare on the same footing**

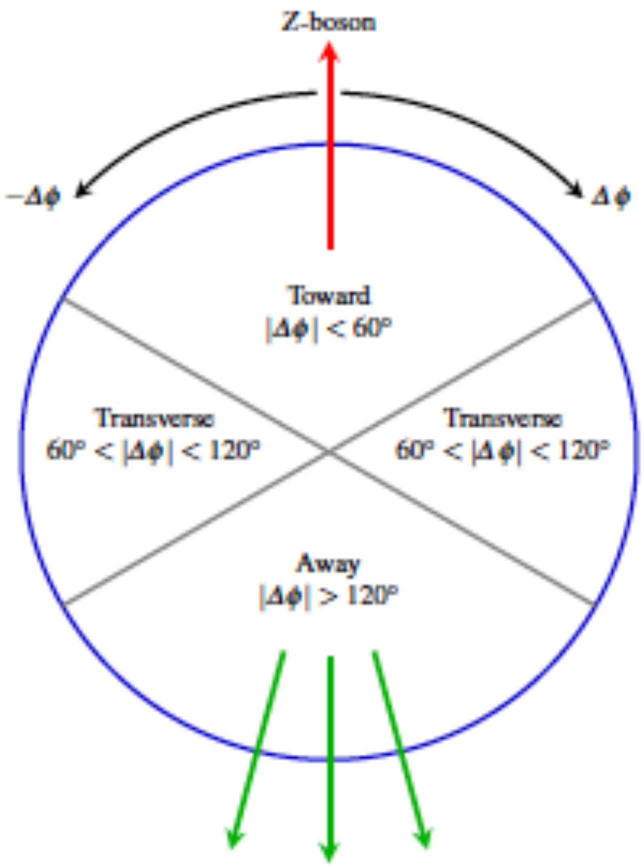


Fig. 1 Definition of UE regions as a function of the azimuthal angle with respect to the Z-boson.