Standard Model at the LHC – some issues, comments and questions

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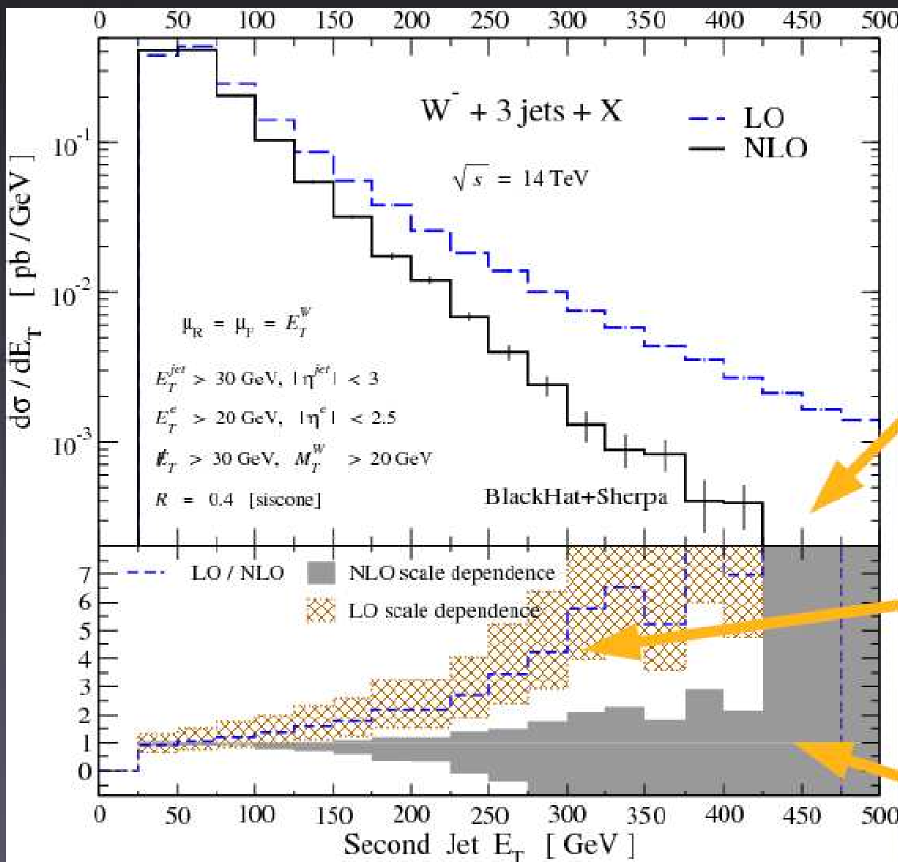
Scale choice

- Theory predictions depend on two unphysical scales
  - Renormalisation scale
  - Factorisation scale
- Due to the truncation of the perturbation series
- Want to choose a scale "typical" for the process
- Complicated processes have many scales

Scale choice



Differential cross section becomes negative

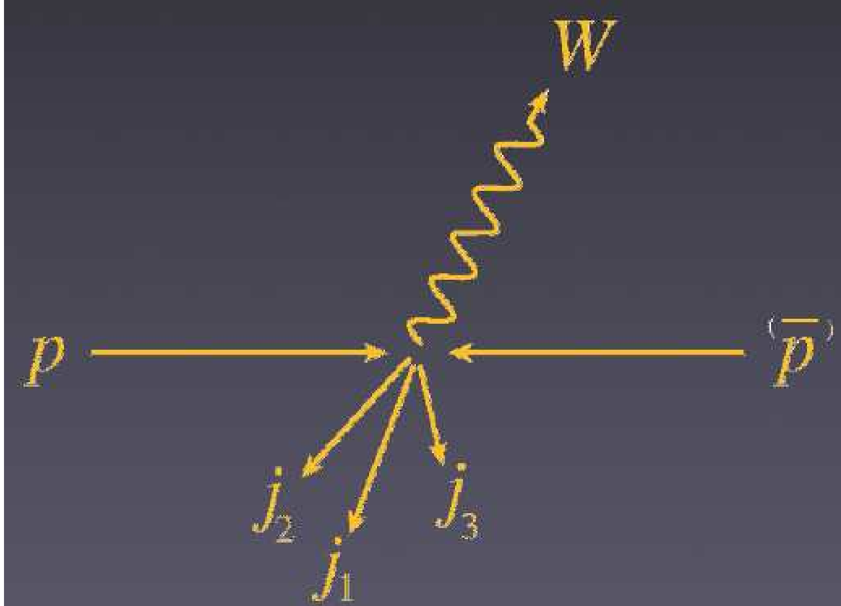
Large K factor and large dependence of the K factor

Large growth of the scale dependence of the NLO

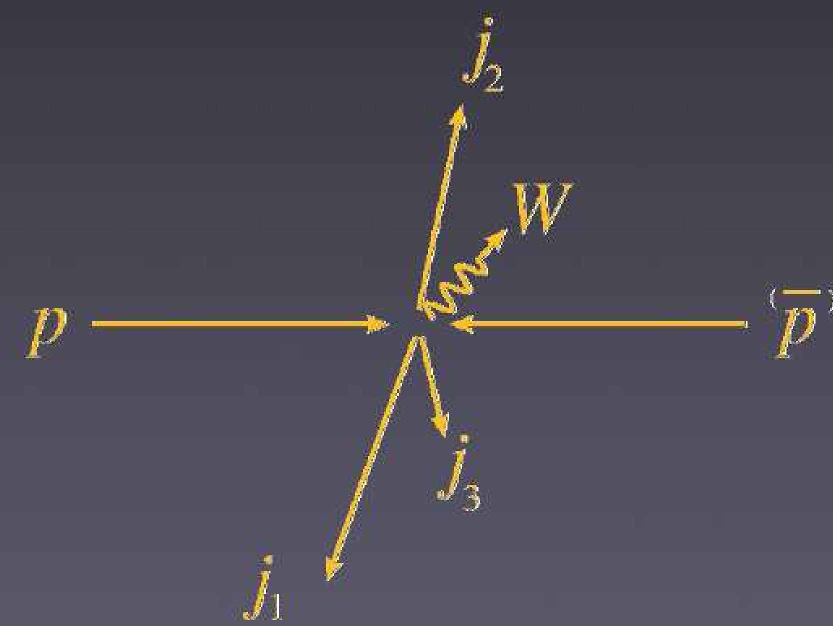
$$E_T^W = \sqrt{m_W^2 + p_T^2(W)}$$

Scale choice

$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\rm jet} + E_T^e + \not{E}_T$$

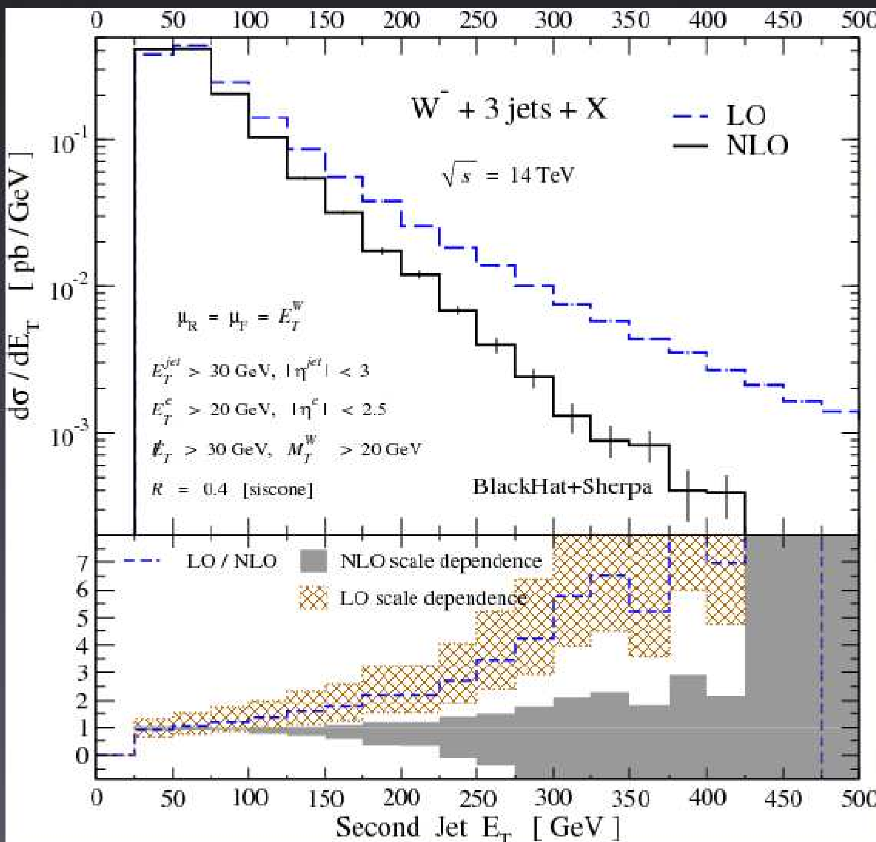


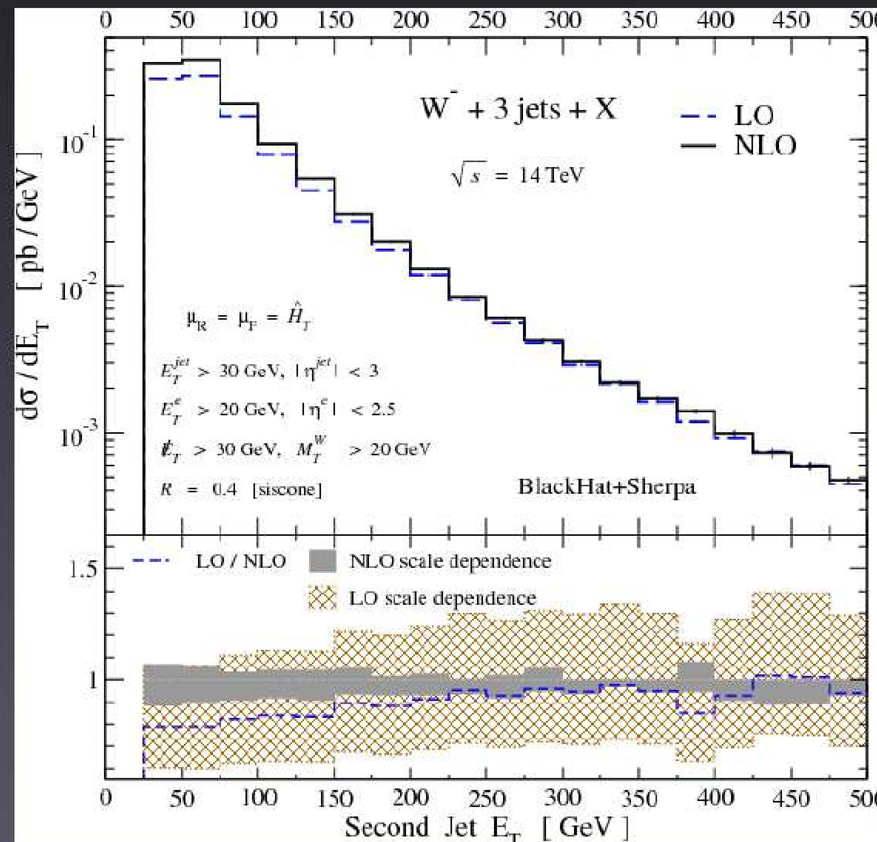
(a)



(b)

Scale choice

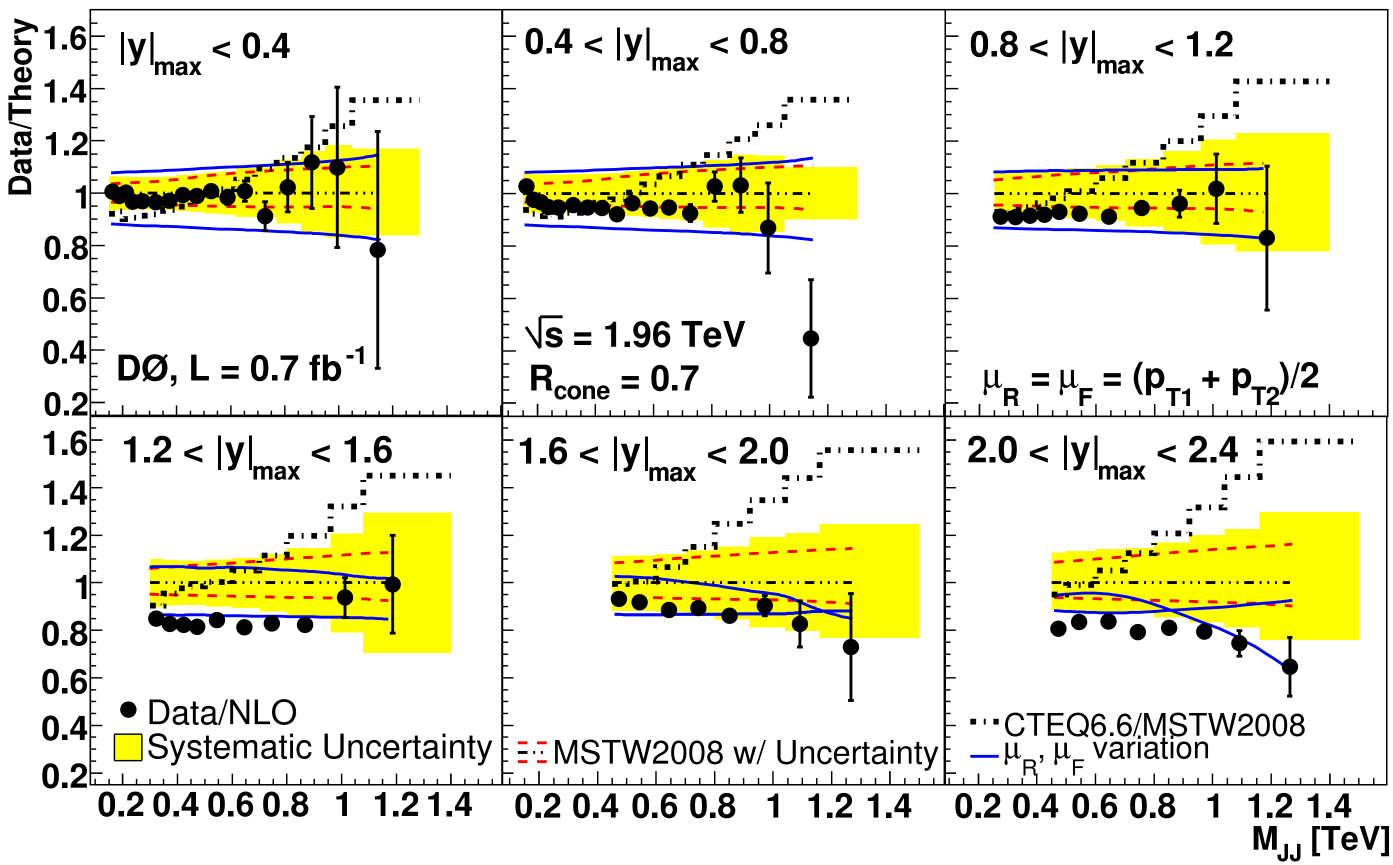




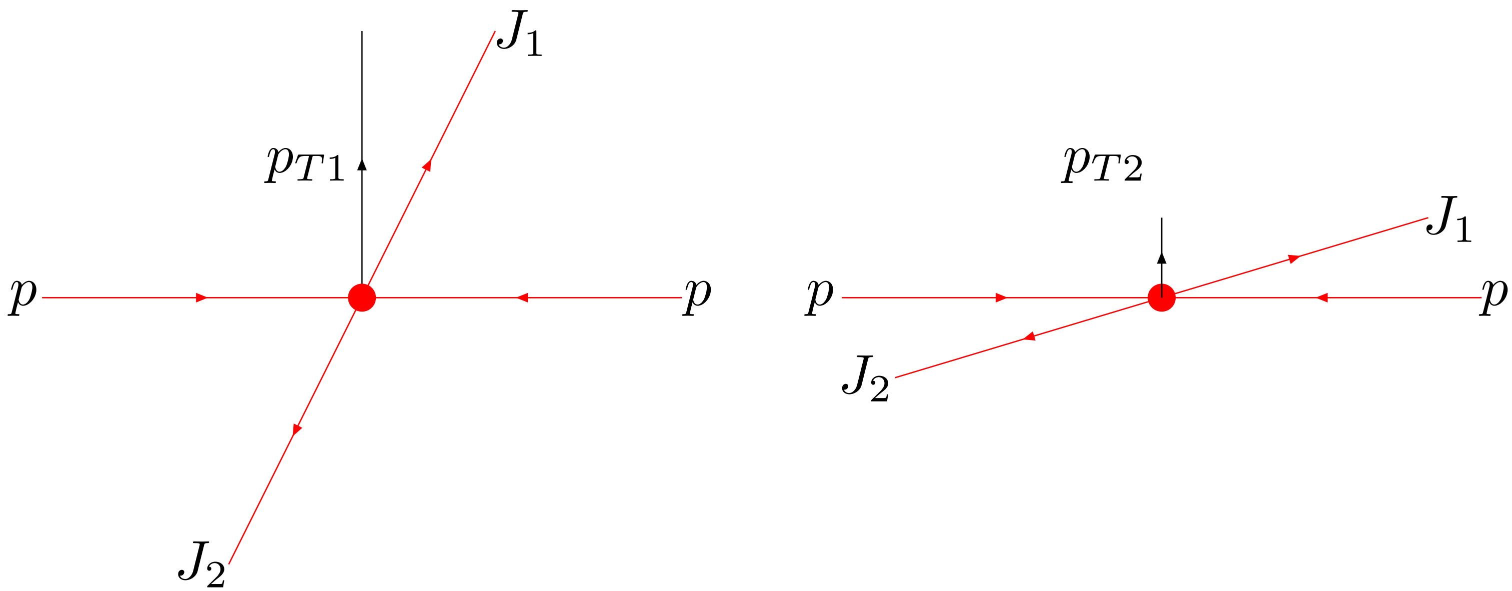
$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$$

Issue in dijet production. Scale for high-rapidity jets.

For jet production probed at the Tevatron scale and PDF uncertainty similar (and both similar to data *systematic* uncertainty)



Consider two dijet processes with similar energy jets, but with one at much smaller angle to beam.



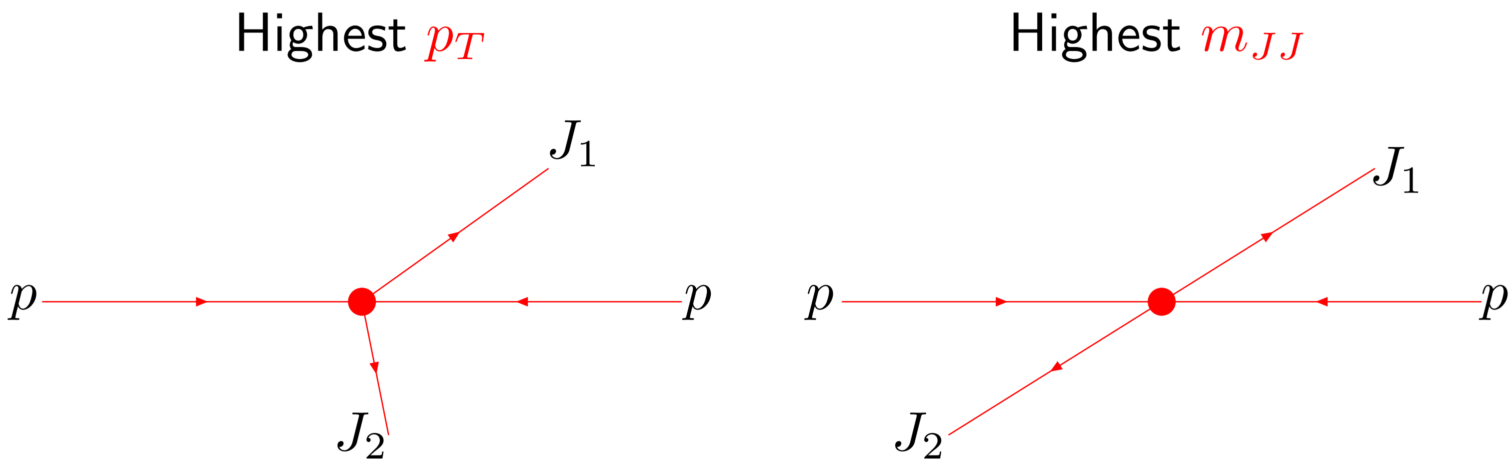
Generally use scale based entirely on p_T. Is the second event really that much less hard than the first?

1983 paper from S. Ellis, Kunszt and Soper suggests

$$\mu \sim M_{JJ}/(4\cosh 0.7y^*) \approx p_T/2\exp(0.3y^*)$$

as stable choice over full range. Mainly p_T but some acknowledgement of hardness not associated with p_T. Qualitatively what seems to solve problems. Seems sensible to me. Personally would prefer $p_T\exp(0.3y^*)$ (avoiding small scales), but same idea.

Why is highest p_T and particularly highest M_{JJ} at high y a problem for stability in scale variation, i.e. why can $p_T/4$ or even $p_T/2$ give negative results.



In first case one x very large other quite small, in second both x values very large. In both cases p_T not too large.

Possibility – at large x values PDFs fall quickly and roughly exponentially with scale.

Small scale choice instead of $f(x_1, Q^2)$ get PDF and correction at NLO like

$$f(x_1, \mu_F^2) + \alpha_S(\mu_R^2) \ln(Q^2/\mu_F^2) P_{qq}^0 \otimes f(\mu_F^2)$$

where second term large and negative, and in dijet a term from each PDF.

Like writing $\exp(-2x) \approx \exp(-x) * (1-x)$ when x not that small – unstable.

Of course, NNLO corrections (Grazzini) would be useful in quantifying these issues.

Does it mean that NNLO calculations are essential for every process ?

Well, we can say that NNLO predictions are desirable at least in the following cases:

- For those processes whose NLO corrections are comparable to the LO contributions
  - → e.g. Higgs production at hadron colliders
- For those benchmark processes measured with high experimental accuracy
  - α_S measurements from e^+e^- event shape variables
  - → - W,Z hadroproduction
  - heavy quark hadroproduction
  - ....
- For some important background processes
  - → e.g. vector boson pair production

Use NNLO PDFs.Would ideally like NNLO calculations for the important data sets in fits, e.g jets.

Consideration of NNLO

Very good evidence that one should use NNLO if at all possible rather than NLO – many physical cross-sections, particularly $gg \to H$, not very convergent.

Fewer PDF sets available (soon to change?), can study differences between them better at NLO, but for central prediction need NNLO.

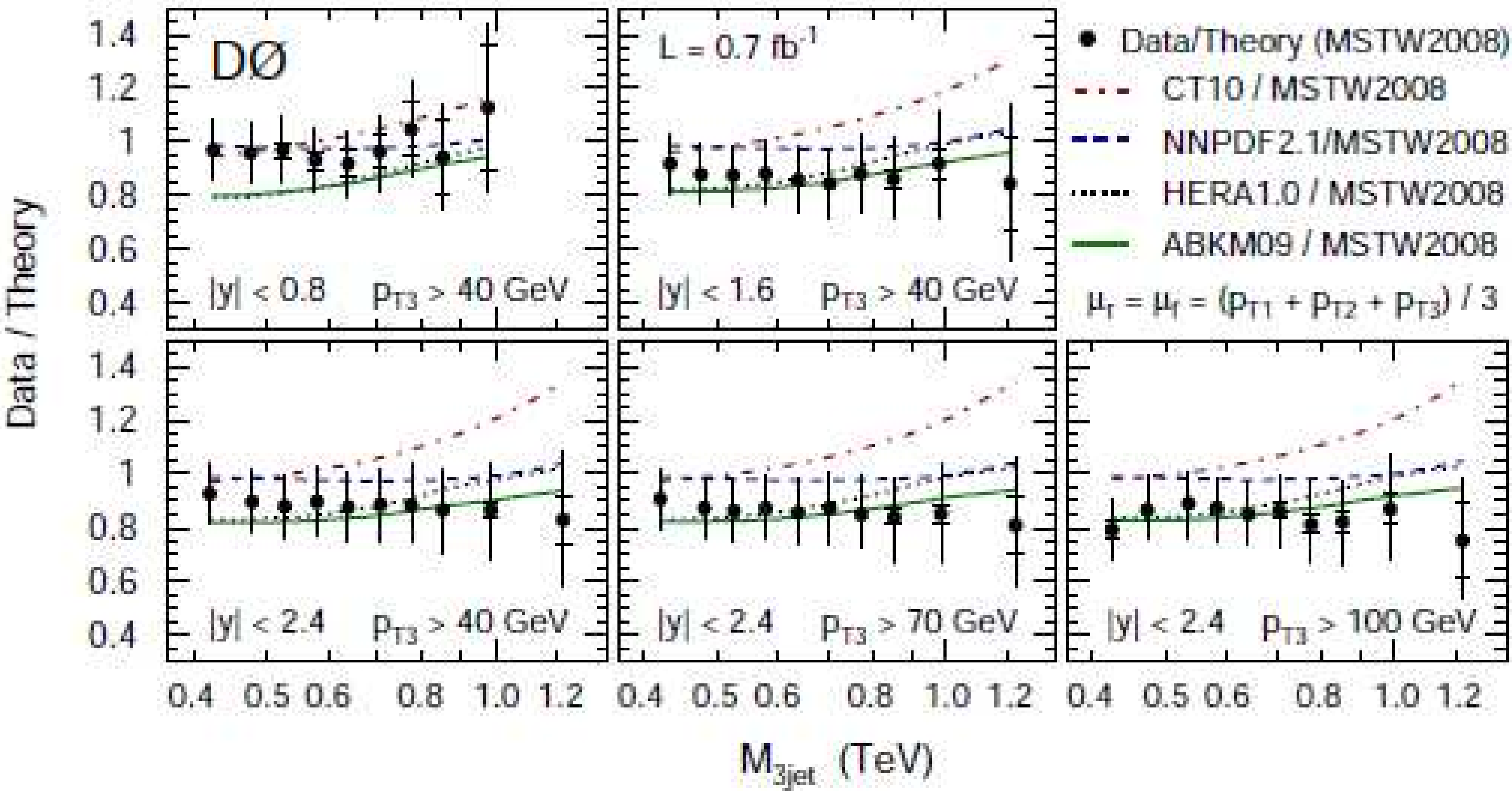
Related to issue of use and uncertainty of $\alpha_S(M_Z^2)$. Noted systematic change in value from fit as one goes from NLO to NNLO. Seen in (most) other extractions. Also highlighted in stability of predictions.

Consider percentage change from NLO to NNLO in MSTW08 predictions for best fit α_S compared to fixed $\alpha_S(M_Z^2) = 0.119$.

	$\sigma_{W(Z)}$ 7TeV	$\sigma_{W(Z)}$ 14TeV	σ_H 7TeV	σ_H 7TeV
MSTW08 best fit α_S	3.0	2.6	25	24
MSTW08 $\alpha_S = 0.119$	5.3	5.0	32	30

$\alpha_S(M_Z^2)$ is not a physical quantity. In (nearly) all PDF related quantities (and many others) shows tendency to decrease from order to order. Noticeable if one has fit at NNLO. Any settling on, or near common $\alpha_S(M_Z^2)$ **has** to take this into account.

Living with NLO. Presentation and analysis of results.



Very new results from D0 (`arXiv 1104.1986`) - i.e. this Tuesday.

Best fit by eye?

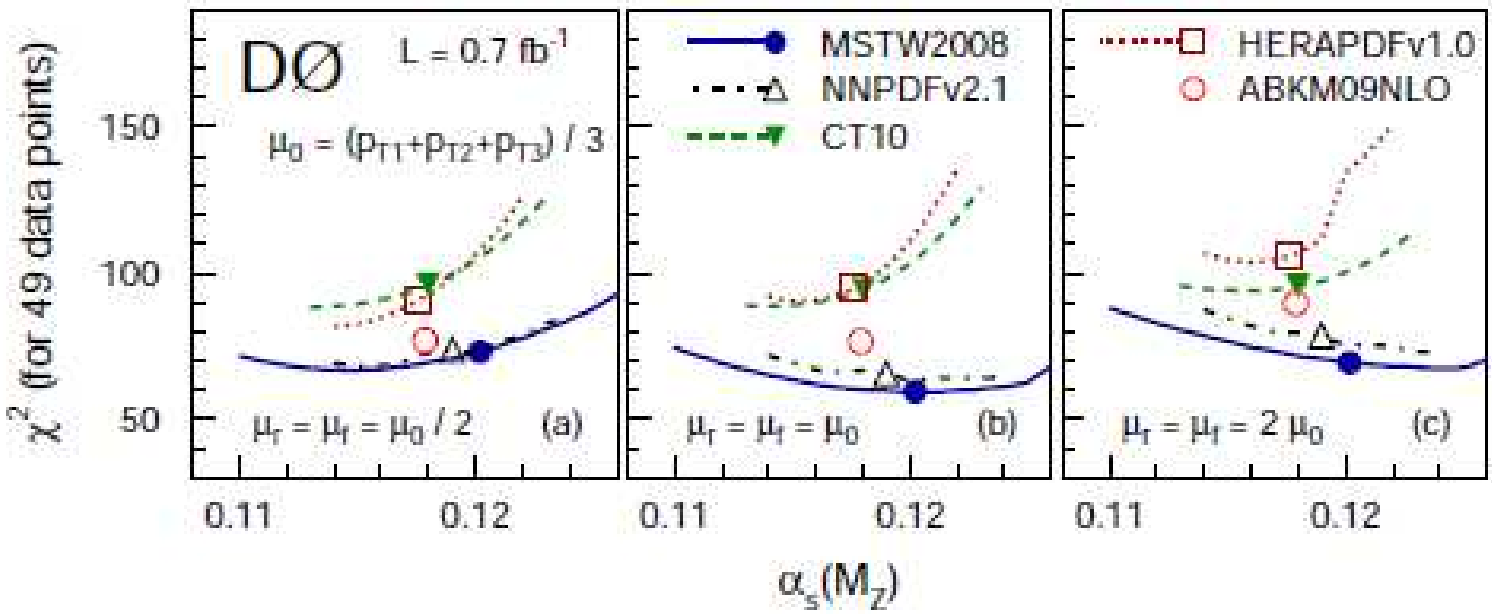


TABLE II: χ^2 values between data and theory for different PDF parametrizations in the order of decreasing χ^2, for all 49 data points.

PDF set	Default $\alpha_s(M_Z)$	χ^2 at $\mu_r = \mu_f = \mu_0$ for default $\alpha_s(M_Z)$	$\chi^2_{\rm minimum}$
HERAPDFv1.0	0.1176	95.1	81.7
CT10	0.1180	94.5	88.2
ABKM09NLO	0.1179	76.5	76.5
NNPDFv2.1	0.1190	65.9	63.3
MSTW2008NLO	0.1202	59.5	59.5

Seems like an excellent way to present significance of results. Groups can then study effects on central values uncertainties (consistency) *etc.*.

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

RWTH

EW corrections

generic size:

- expect percent level corrections
- naive comparison with QCD: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$
  $\Rightarrow$ needed for high precision observables (like Drell-Yan)
- choose α appropriately (G_μ scheme for Drell-Yan)

This scheme is not always the default, so be careful.

In particular "official" PDF4LHC benchmark does not use this, so σ_Z a bit low.

Photons

How to deal with photon radiation from bare leptons?

- keep physical lepton mass in the amplitudes

  $\Rightarrow$ numerical integration of large logarithms necessary
- subtraction formalism also for non-collinear safe observables

  $\Rightarrow$ muon-mass logarithms extracted analytically

Need consistent, and clear, presentation of results on W and Z results regarding this. Particularly interested in effect on effect on cuts on p_T in lepton asymmetries. Results very sensitive indeed to this.

At present PDF fits are not including any allowance for the photon radiation, assuming all effects accounted for in data.

What about photons in the proton?

- initial state photon emission ⇒ collinear singularity
- absorb singularity into PDF ↔ include QED effects in PDF fit
- include QED in DGLAP evolution
  ⇒ photon density inside the proton: MRSTQED2004 PDF
  Martin, Roberts, Stirling, Thorne [hep-ph/0411040]
- other PDF sets are in principle inconsistent at NLO EW
  ⇒ but numerical effect expected to be small

Is there an urgent need for an update of PDFs including QED evolution?

Change in quark and gluon PDFs very small, rather smaller than many other effects, particularly change in MSTW2008 compared to MRST2004. (Unless you are interested in charge symmetry violation.)

If $\gamma(x, Q^2)$ distribution needed, this will be similar to that in MRST2004. Uncertainty dominated by model assumptions, e.g. effective light quark masses.

QCD $\otimes$ EW corrections

Theory status:

- QCD: NNLO, resummation, parton shower matching
- EW: NLO, leading higher order contributions
- combined EW and QCD corrections?

full (2-loop) $\mathcal{O}(\alpha\alpha_s)$ corrections not known

$\rightarrow$ different possible choices for the combination:

Balossini et al. [arXiv:0907.0276]

additive:

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{QCD+EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\mathrm{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{LO}}\right\}_{\mathrm{HERWIG\ PS}}$$

factorized:

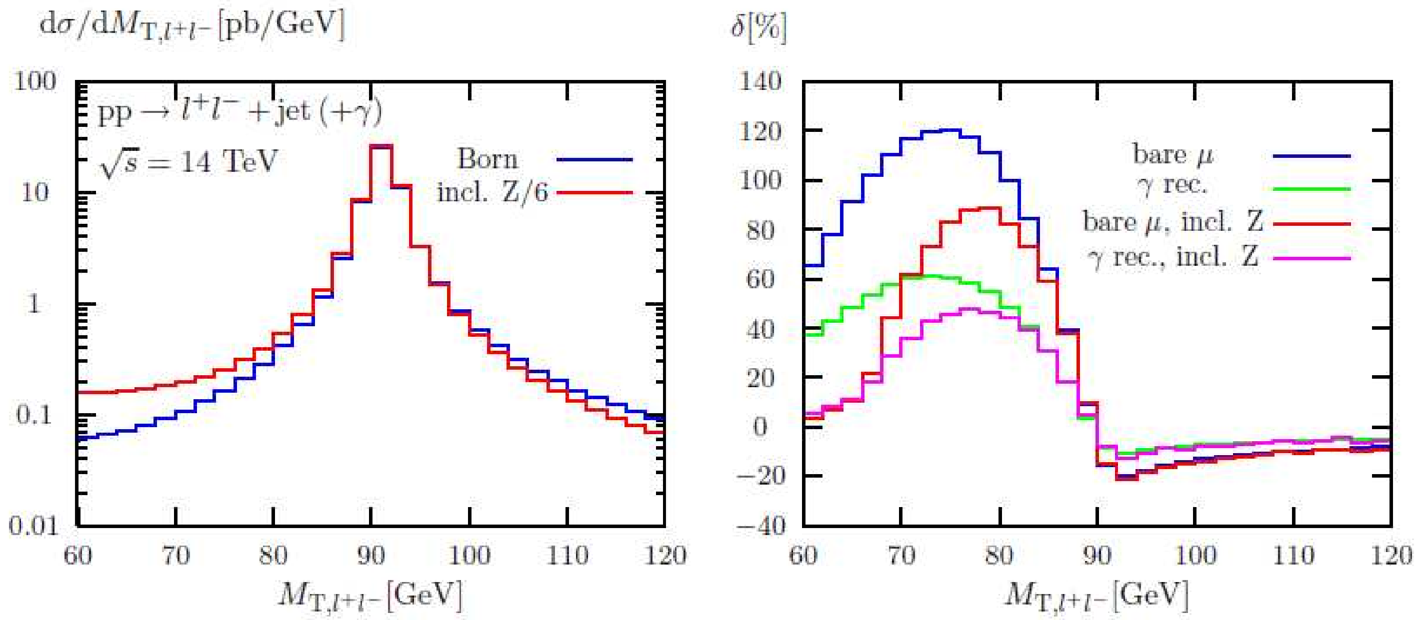
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{QCDxEW}} = \left(1 + \frac{[d\sigma/d\mathcal{O}]_{\mathrm{MC@NLO}} - [d\sigma/d\mathcal{O}]_{\mathrm{HERWIG\ PS}}}{[d\sigma/d\mathcal{O}]_{\mathrm{LO/NLO}}}\right) \times \left\{\frac{d\sigma}{d\mathcal{O}_{\mathrm{EW}}}\right\}_{\mathrm{HERWIG\ PS}}$$

⇐ | ⟷ | ⇒ Electroweak Precision Physics at the LHC – Alexander Mück – p.14/ 25

CDF m_W determination trying building EW effects on top of RESBOS and alternatively p_T resummation on top of HORACE. Not sure of results.

selected W/Z+jet results

comparison with inclusive Z production:



lineshape (and corrections) depends on $p_{\mathrm{T,Z}}$ in the tail

How significant is the breaking of factorisation likely to be? Is the assumption good enough?

PDFs – Forte.

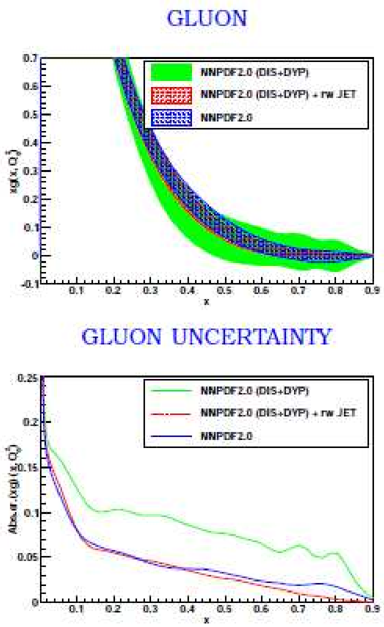
DO PDF UNCERTAINTIES
HAVE A STATISTICAL MEANING?

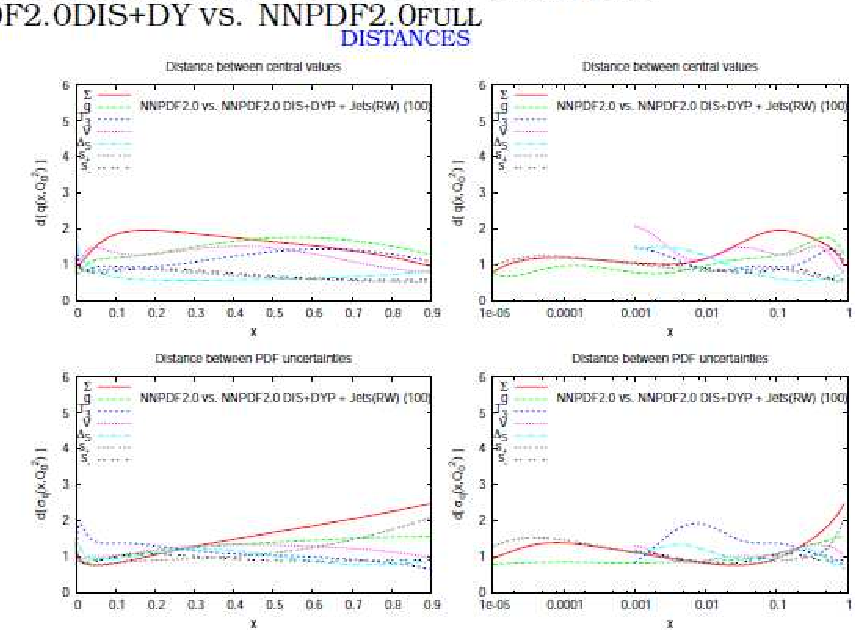
SOMETIMES STATED THAT "PDF UNCERTAINTIES ARE THEORETICAL UNCERTAINTIES" (THUS DEVOID OF STATISTICAL MEANING) IS IT TRUE?

RUNNING THE TEST

INCLUSION OF JET DATA: REWEIGHTING VS. REFITTING

NNPDF2.0DIS+DY VS. NNPDF2.0FULL





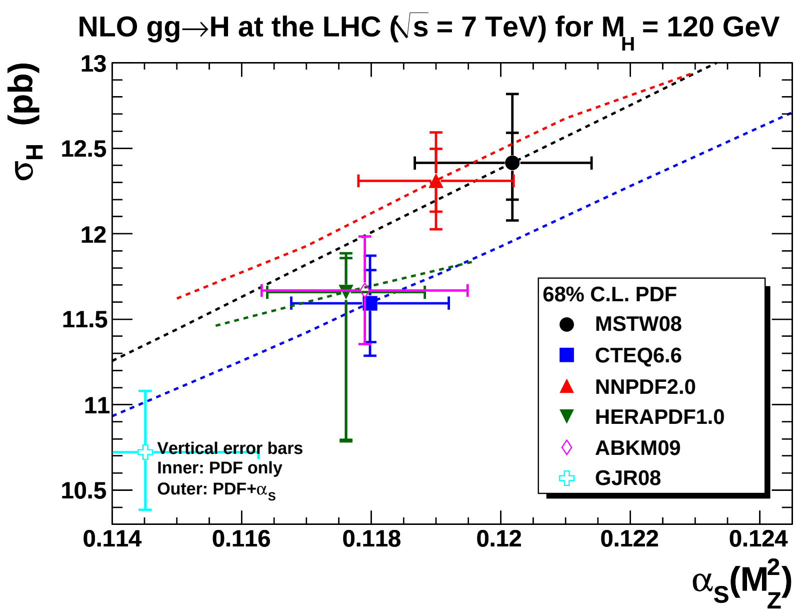
$d \sim 1 \Rightarrow$ STATISTICAL EQUIVALENCE

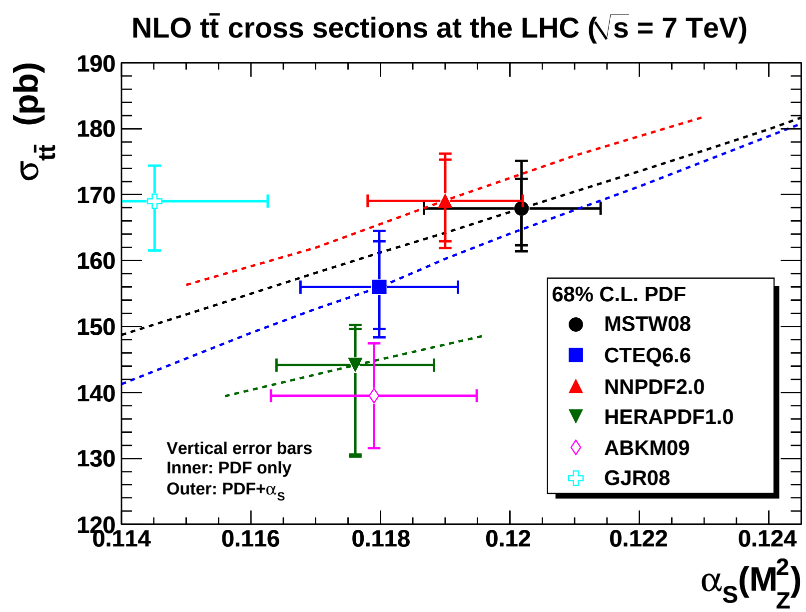
IT LOOKS LIKE WE DO KNOW WHAT WE ARE DOING....

Indeed PDF uncertainties are statistical. PDF fits very strongly correlated. naively should largely agree but some have greater uncertainties than others.

Variations in Cross-Section Predictions – NLO

Is this what happens.

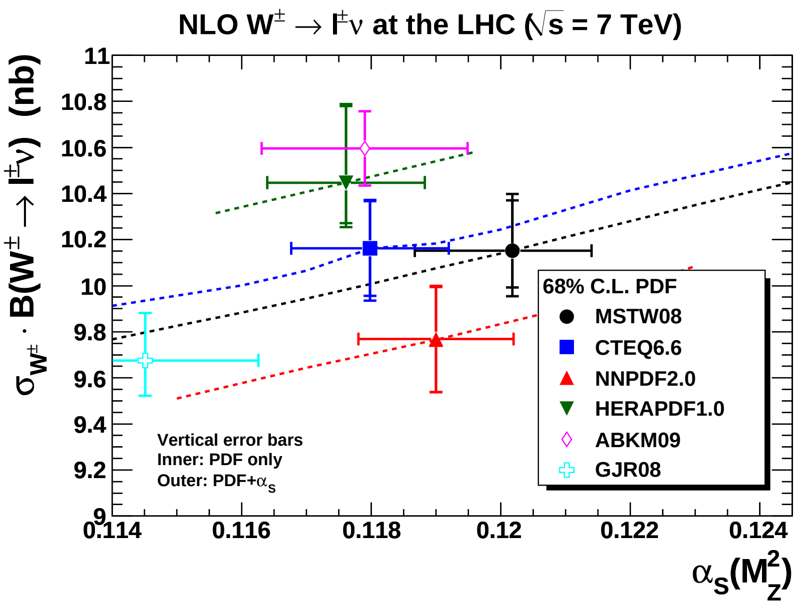


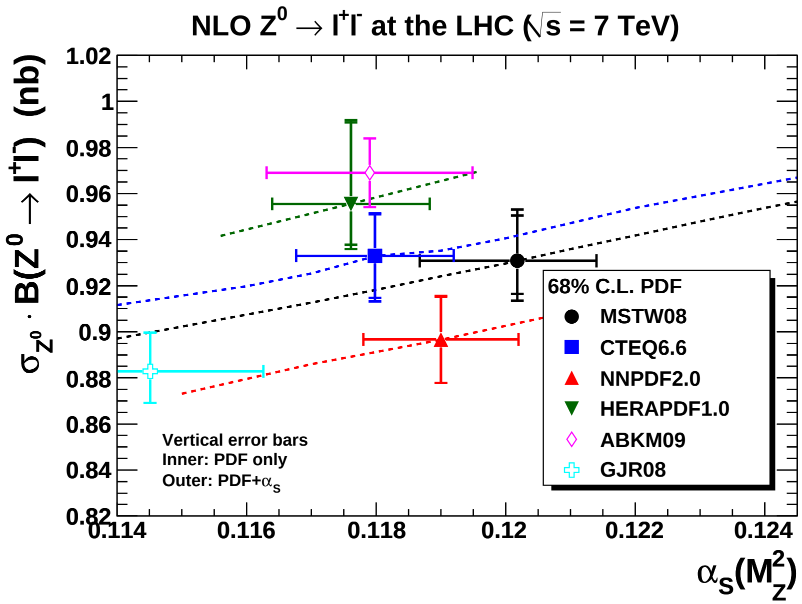


Unfortunately not. Dotted lines show how central PDF predictions vary with $\alpha_S(M_Z^2)$.

Plots based on PDF4LHC benchmark criteria, but from extensive independent study by G. Watt.

Clearly much more variation in predictions than uncertainties claimed by individual groups.





$W^+ + W^-$ cross-section. $\alpha_S(M_Z^2)$ dependence now more due to PDF variation with $\alpha_S(M_Z^2)$.

Again variations somewhat bigger than individual uncertainties.

Roughly similar variation for $\hat{s}$ up to a few times higher.

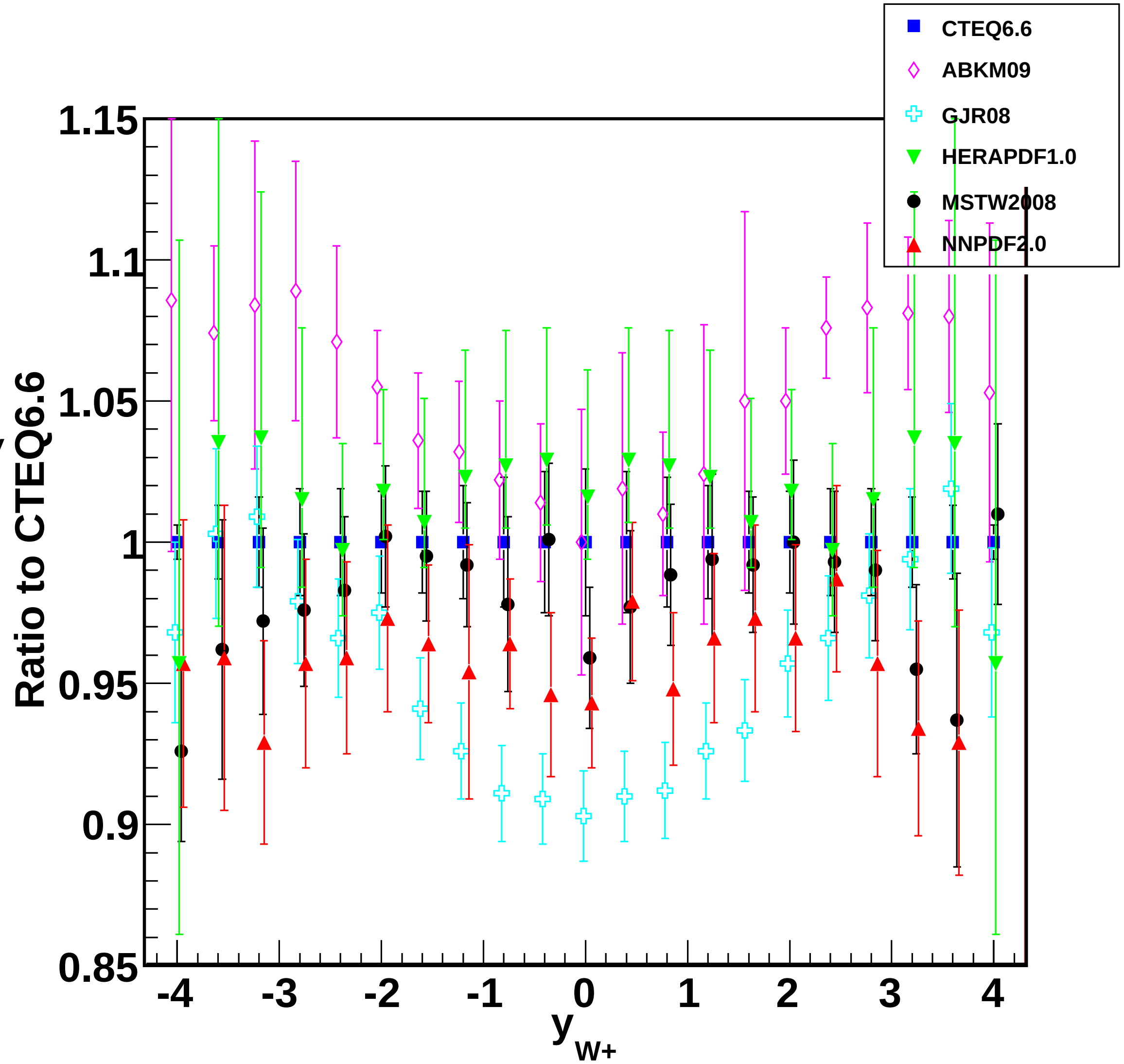
All plots and more at http://projects.hepforge.org/mstwpdf/pdf4lhc

Differences also clear in rapidity distributions.

Plot from PDF4LHC Interim Report.

Shape discriminating and improved normalisation uncertainty is important.

Would prefer absolute cross-section to normalised cross-section if possible.



Deviations In predictions clearly much more than uncertainty claimed by each.

In some cases clear reason why central values differ, e.g. lack of some constraining data, though uncertainties then do not reflect true uncertainty.

Sometimes no good understanding, or due to difference in procedure which is simply a matter of disagreement, e.g. gluon parameterisation at small x affects predicted Higgs cross-section.

What is true uncertainty. PDF4LHC interim recommendation take envelope of $global$ sets, MSTW, CTEQ NNPDF (check other sets) and take central point as uncertainty.

Not very satisfactory, but not clear what would be an improvement, especially as a general rule.

Usually a factor of 2, or less, expansion of MSTW uncertainty.

Only to b used to make calculations when necessary to have some conservative (but $not\ too\ conservative$) estimate of uncertainties from PDFs, e.g. exclusion limits, acceptance corrections (if necessary).

For measurement testing PDFs compare to different PDFs (whichever you like – as many as possible), e.g. like D0 3-jet measurement.

Top-antitop Cross-section – Signer

Inclusive cross-section known approximately to NNLO

SM top quark pair production

- fully exclusive known at $\sim$ one-loop

  electroweak corrections known [Bernreuther et.al., Kuhn et.al.]
  spin correlations included [Bernreuther et.al., Melnikov et.al.]
  non-factorizable corrections computed [Denner et.al., Bevilacqua et.al.]
  included in MC@NLO and POWHEG [Frixione, Nason, Webber . . . . . .]
  two-loop corrections on their way . . .

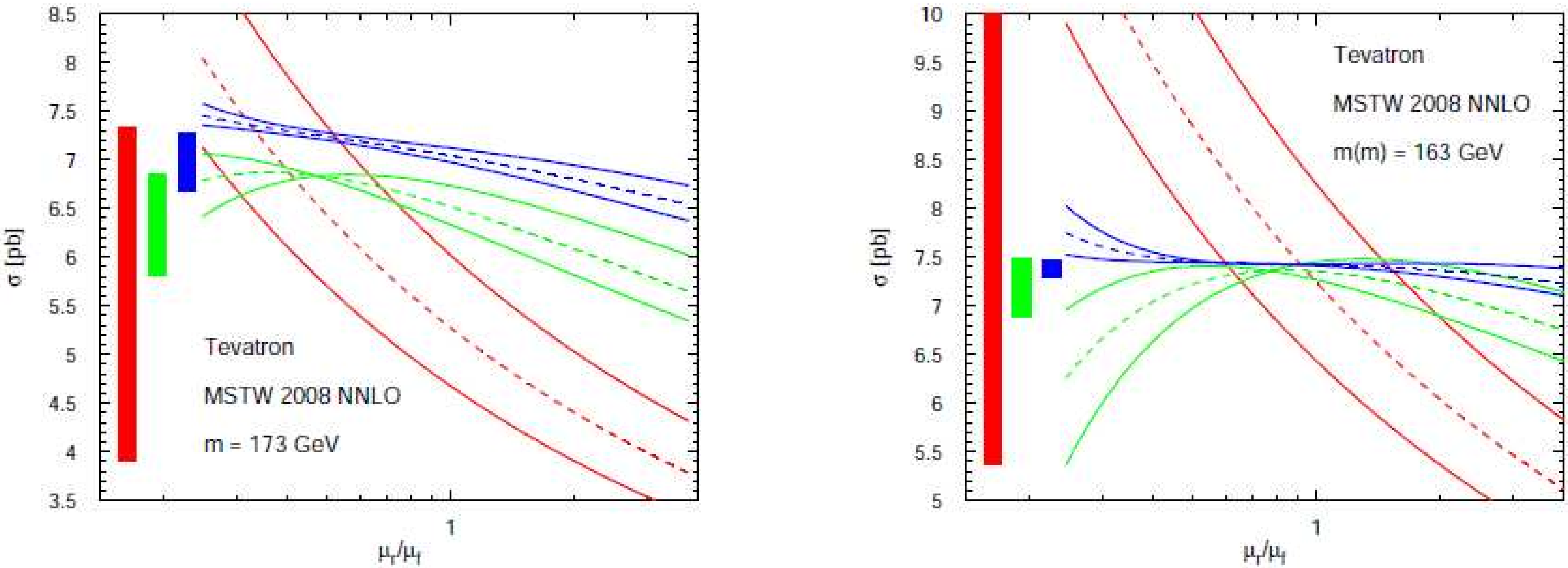
- inclusive cross section(s) known at $\sim$ two-loop

  two-loop nearly known [Czakon et.al, Moch et.al, . . .]
  bound-state effects computed [Hagiwara et.al., Kiyo et.al.]
  non-factorizable corrections computed [Beenakker et.al.]
  resummation of logs under control [Ahrens et.al, Beneke et.al . . .]

Intrinsic theory uncertainty not very large.

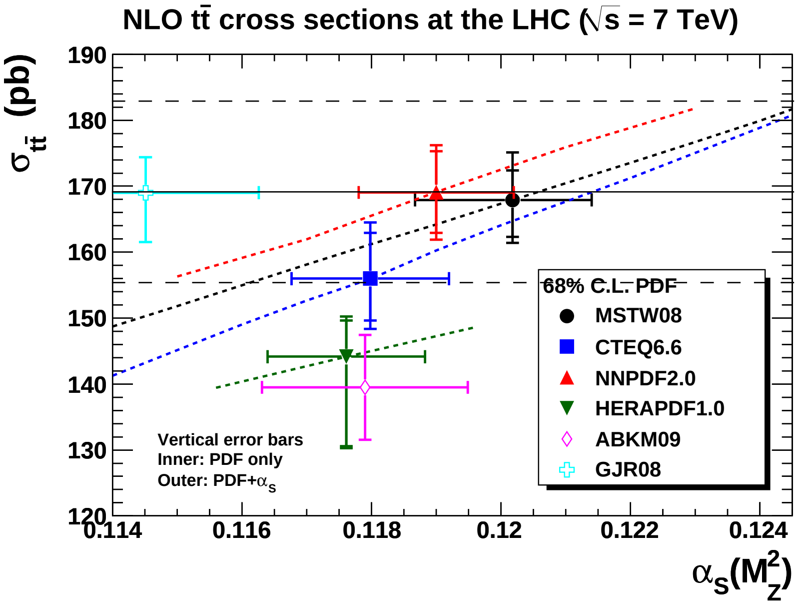
determination of $\overline{m}(\overline{m})$ through cross section [Langenfeld, Moch, Uwer]

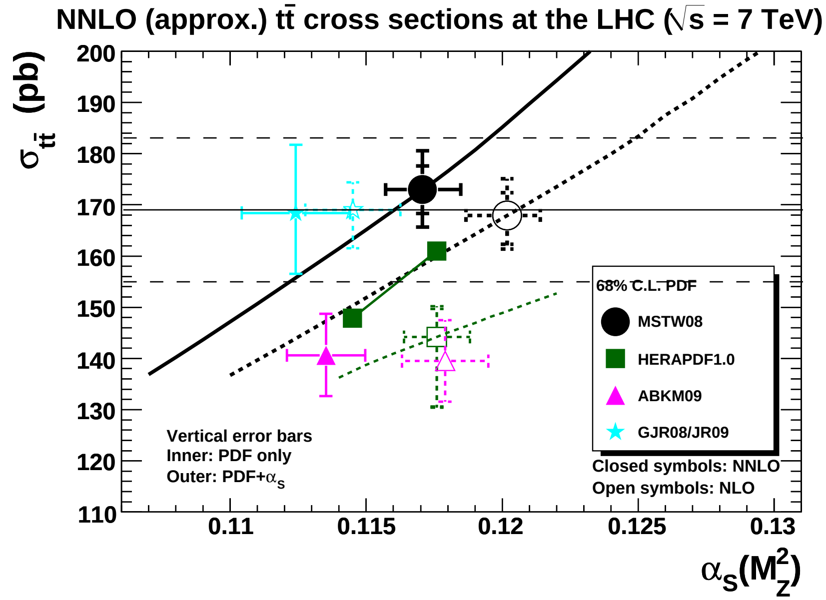
compare $\sigma_{\rm tot}$ expressed in terms of pole and $\overline{\rm MS}$ mass (for $\mu_F \in \{0.5, 1, 2\} \times m_t$)



Data getting precise. Main uncertainty in PDFs, not in individual uncertainty but choice of set.

Plots by G. Watt





Differences between groups significant at NLO, and at NNLO.

Approx NNLO using HATHOR - (Aliev *et al*), includes scale-dependent parts and large threshold corrections at NNLO. Hence some theoretical uncertainty, but NNLO corrections not large at LHC. See lower NNLO α_S improves stability.

Top cross-section measurement potential discriminator of PDF sets, and correlated to Higgs predictions. ATLAS and CMS preliminary combined very naively $\sigma_{t\bar{t}} = 0.169 \pm 0.14\mathrm{pb}$.

From PDF4LHC talk at CERN, March by Watt

Description of CDF II inclusive jet (k_T) data [hep-ex/0701051]

- Values of $\chi^2/N_{\rm pts.}$ with (without) accounting for correlations:

NLO PDF (with NLO $\hat{\sigma}$)	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	0.75 (0.30)	**0.68** (0.28)	0.91 (0.84)
CTEQ6.6	1.25 (0.14)	1.66 (0.20)	2.38 (0.84)
CT10	1.03 (0.13)	1.20 (0.19)	1.81 (0.84)
NNPDF2.1	0.74 (0.29)	0.82 (0.25)	1.23 (0.69)
HERAPDF1.0 ($\alpha_S = 0.1176$)	2.43 (0.39)	3.26 (0.66)	4.03 (1.67)
ABKM09	1.62 (0.52)	2.21 (0.85)	3.26 (2.10)
GJR08	1.36 (0.23)	0.94 (0.13)	0.79 (0.36)

NNLO PDF (with NLO+2-loop $\hat{\sigma}$)	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	1.39 (0.42)	**0.69** (0.44)	0.97 (0.48)
HERAPDF1.0 ($\alpha_S = 0.1145$)	2.64 (0.36)	2.15 (0.36)	2.20 (0.46)
HERAPDF1.0 ($\alpha_S = 0.1176$)	2.24 (0.35)	1.17 (0.32)	1.23 (0.31)
ABKM09	2.55 (0.82)	2.76 (0.89)	3.41 (1.17)
JR09	0.75 (0.37)	1.26 (0.41)	2.21 (0.49)

- $N_{\rm pts.} = 76$, $N_{\rm corr.} = 17$. 90% C.L. region for **MSTW08** ($\mu = p_T$) given by $\chi^2/N_{\rm pts.} < 0.83$ (NLO) or $\chi^2/N_{\rm pts.} < 0.85$ (NNLO).

G. Watt 24/37