PDFs at the LHC – some issues, comments and questions

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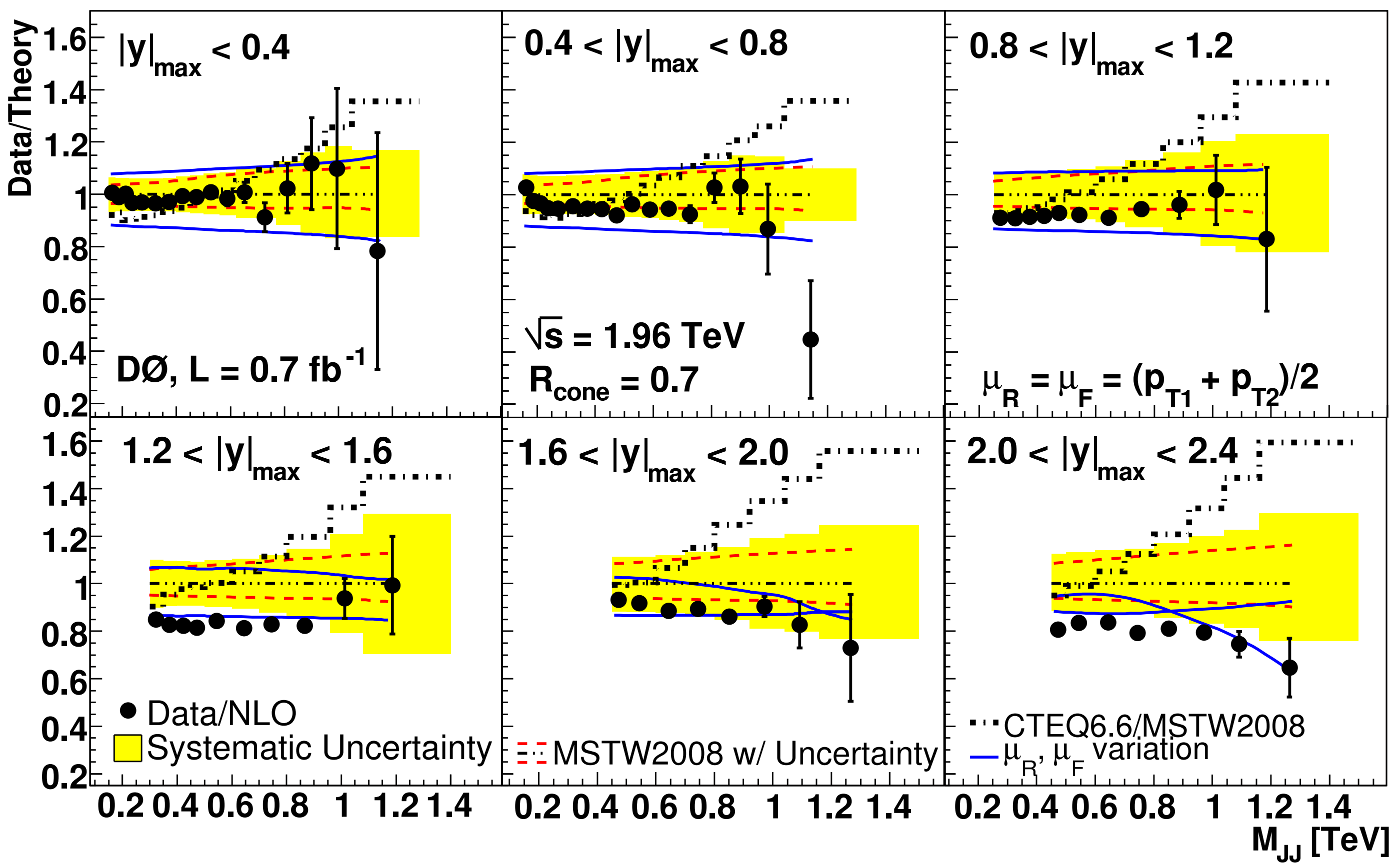
With thanks to Alan Martin, James Stirling and Graeme Watt

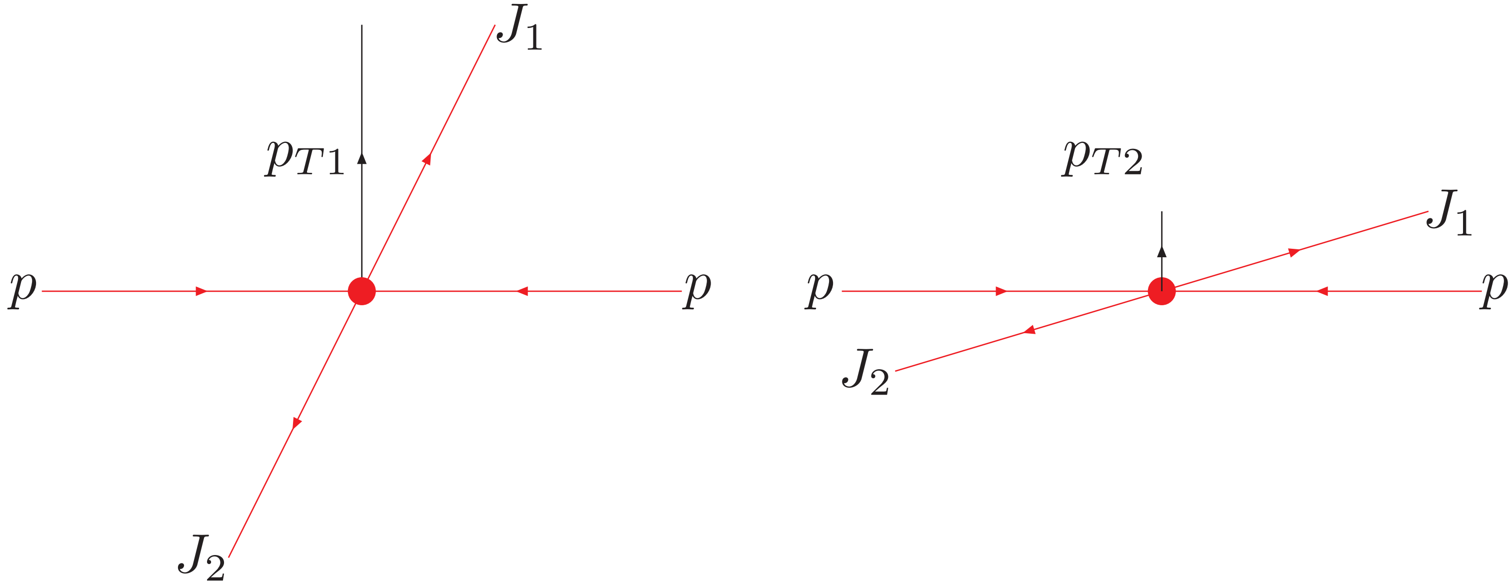
Jet production – particularly dijets.

Theoretical 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.



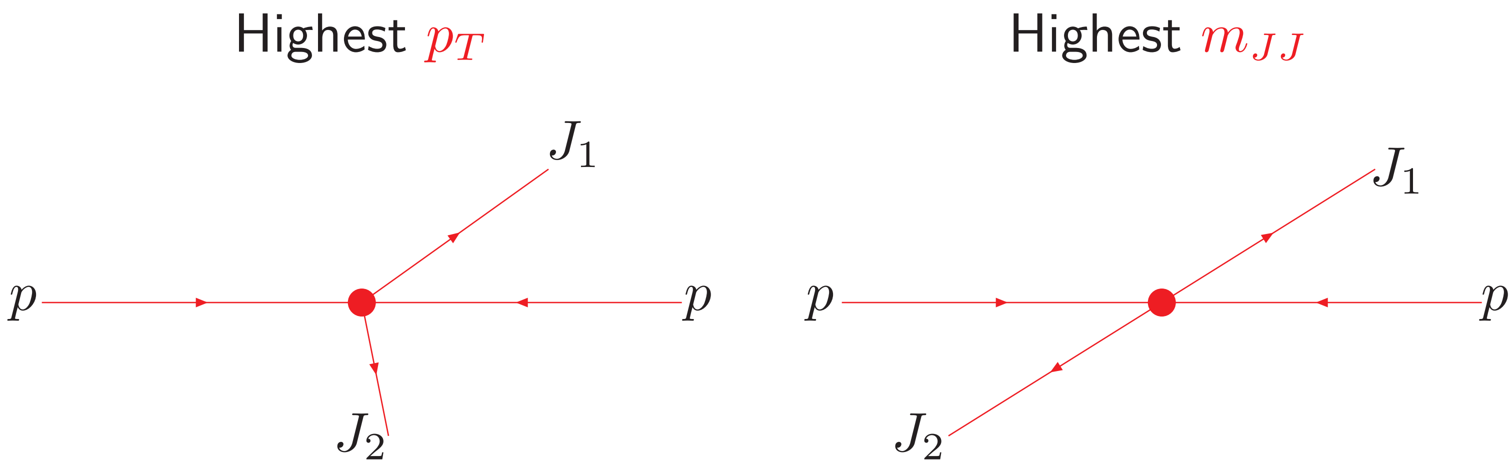
Generally use scale based entirely on p_T. Is the second event really that much less hard than the first?

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 wide range. Near p_T but some acknowledgement of hardness not associated with p_T. Qualitatively helps with 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.

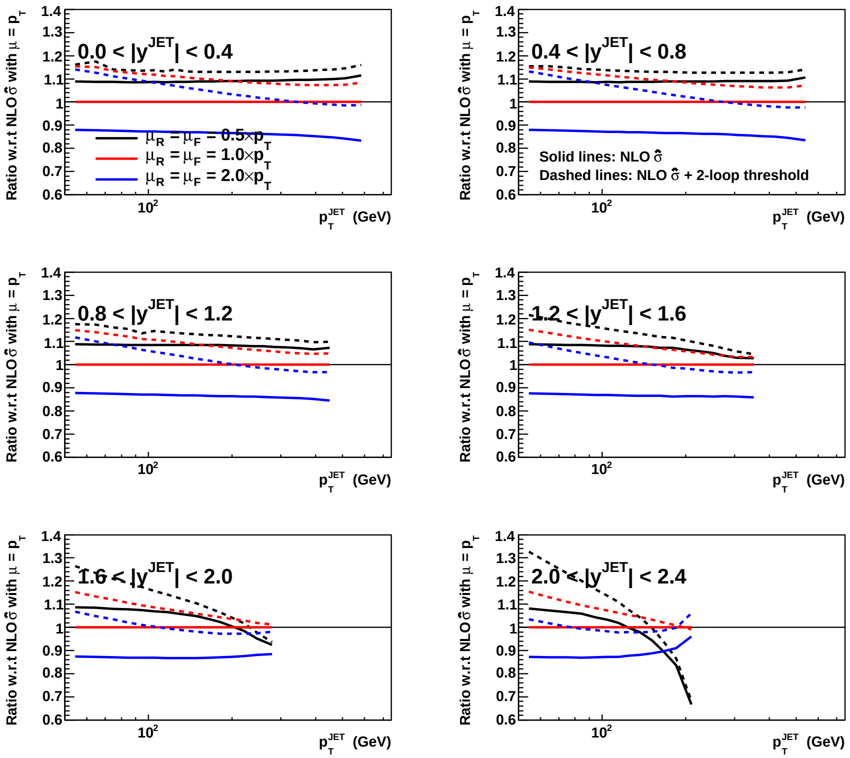
Small scale choice instead of $f(x_1, Q^2)$ get PDF and correction at NLO like

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

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.

DØ Run II inclusive jet data (cone, R = 0.7)
(Ratio w.r.t. NLO $\hat{\sigma}$ with $\mu = p_T$ using MSTW08 NNLO PDFs)



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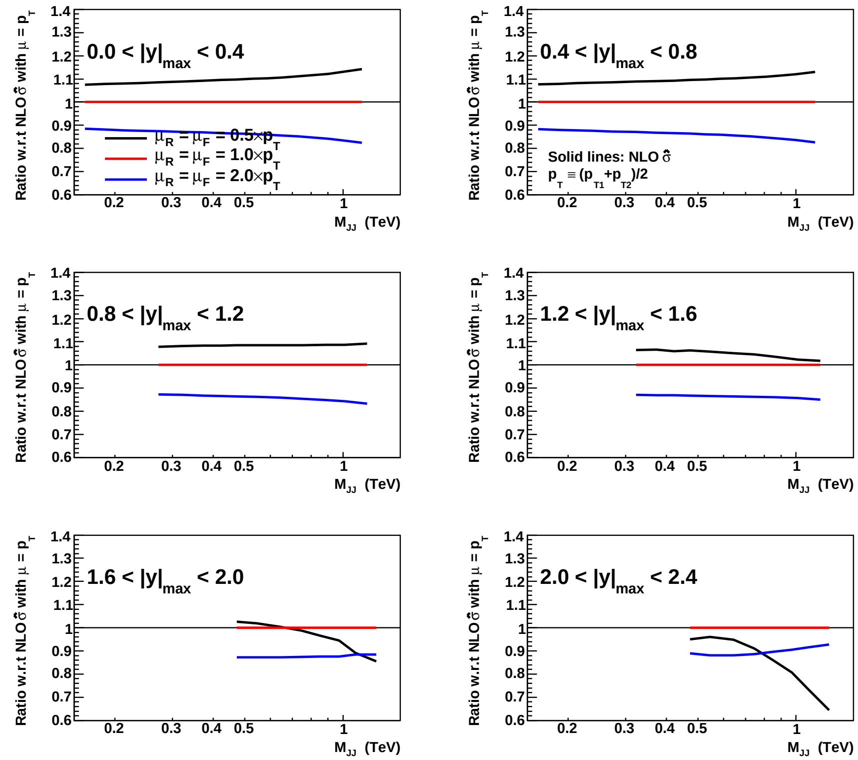
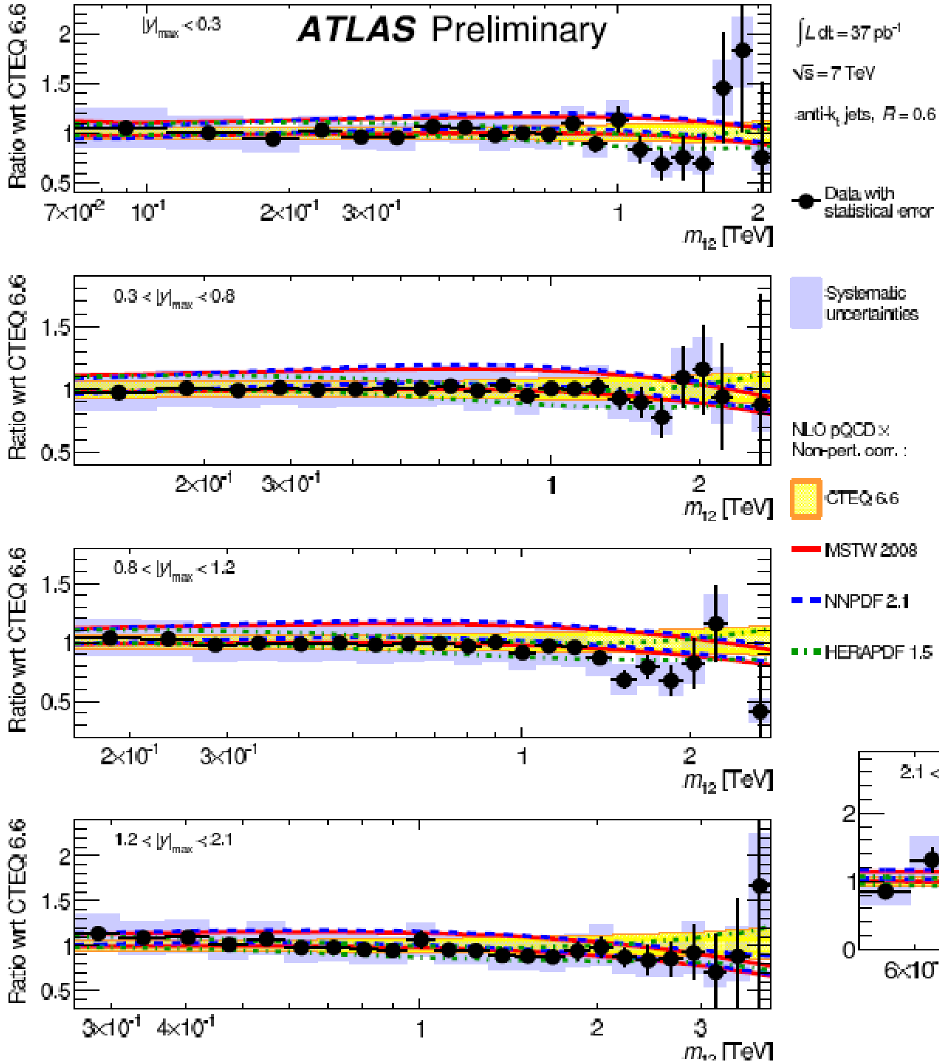


Shape of corrections as function of p_T at NLO and also at approx. NNLO in inclusive case. Problem at highest p_T and rapidity even for inclusive jets.

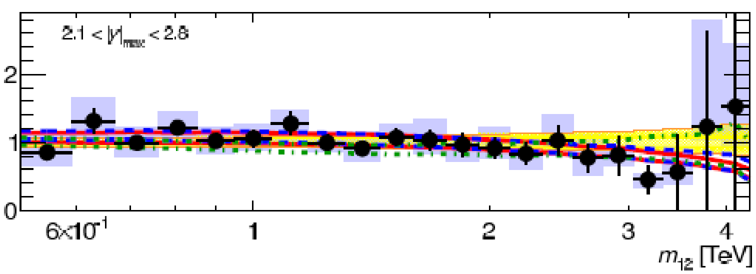
NNLO uses threshold (Kidonakis and Owens) approx. for Tevatron jets (see also de Florian and Vogelsang).

NNLO approximation aids stability – always worst at high-p_T i.e. high-x. Includes large $\ln(p_T/\mu)$ terms predicted by renormalisation group.

Dijets vs PDF



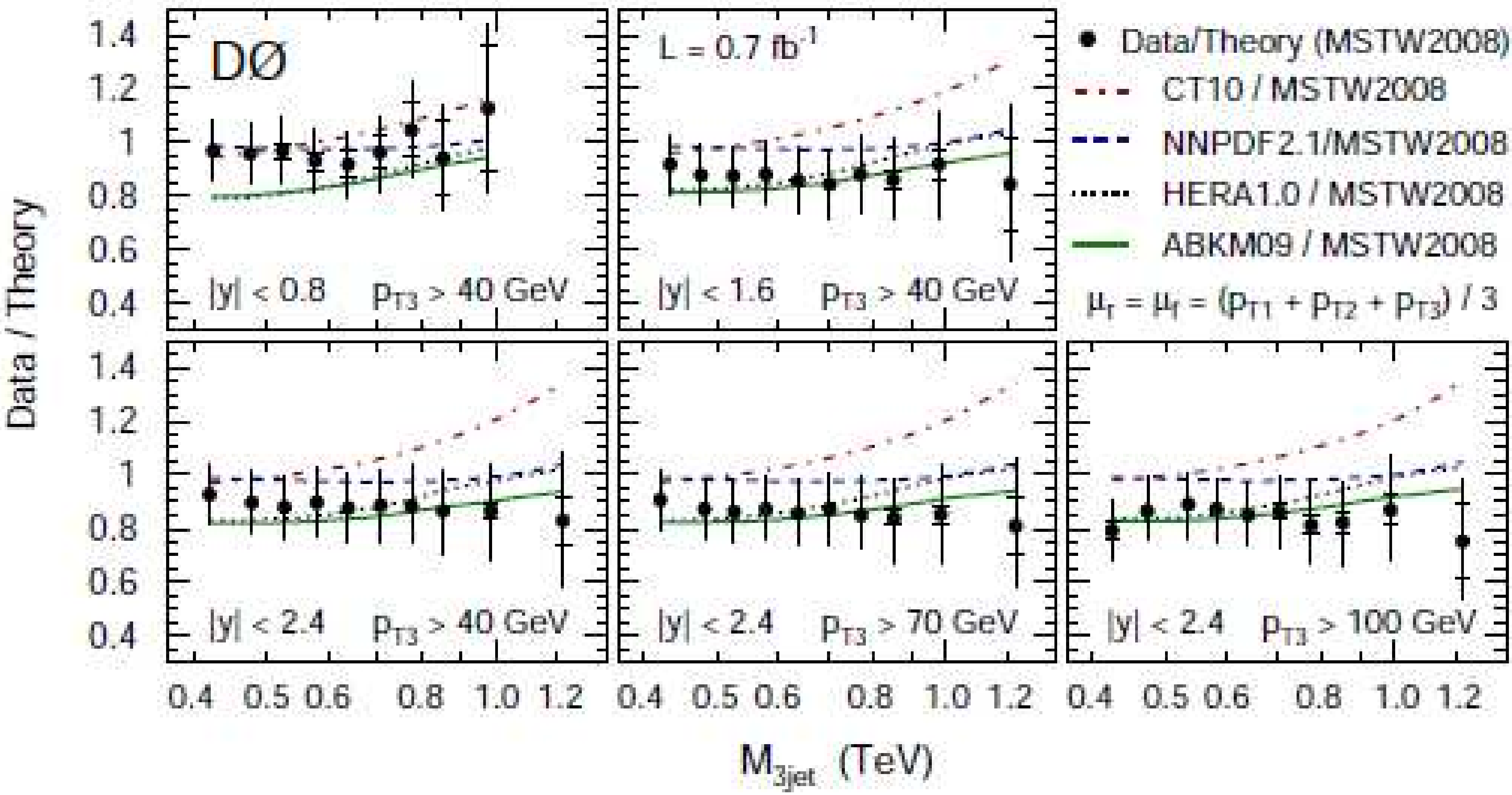
- boundaries of the theory uncertainty bands for various PDF sets are shown
- Predictions using HERAPDF 1.5 follow the data most closely



Dijets at LHC have slight tendency to trend. Higher M_{JJ}, p_T leads to higher scales, more convergent. However, get real problems with calculation at $|y|_{\rm max} \sim 4$.

Also size of correlated errors makes comparison the PDFs by eye very difficult.

Presentation and analysis of results.



Recent results from D0 (`arXiv 1104.1986`) on three jets cross sections.

Best fit by eye?

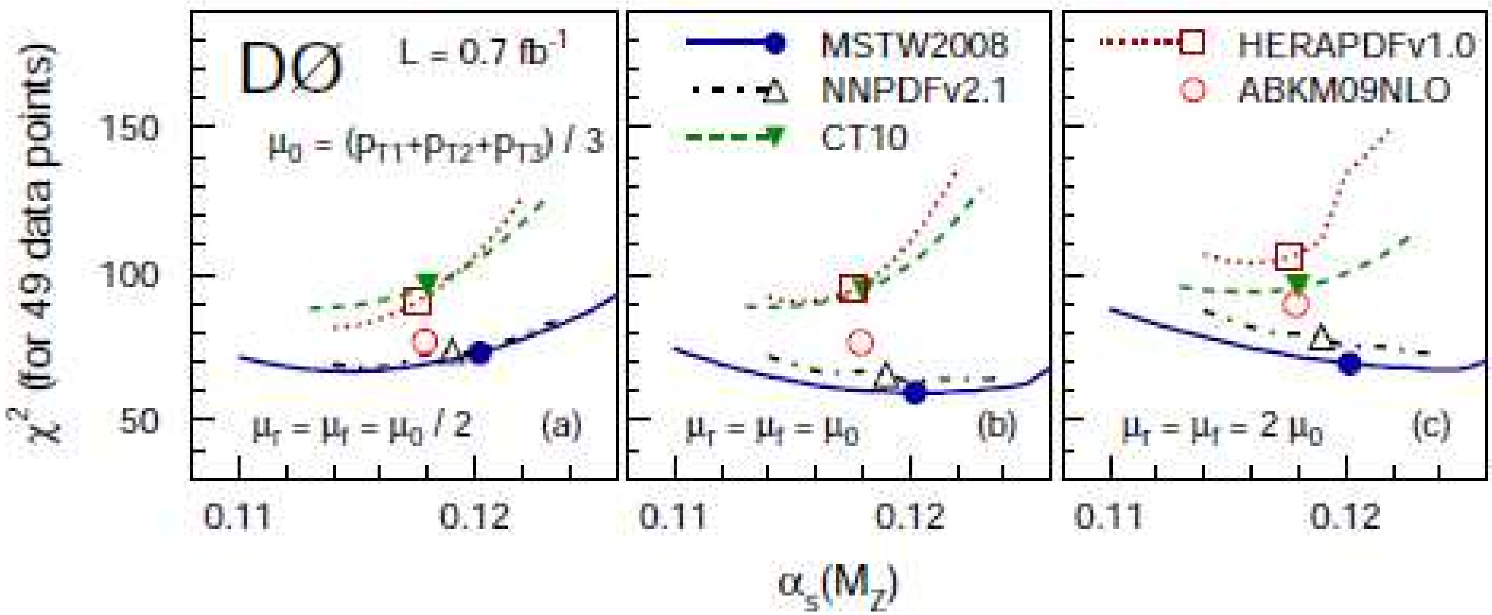


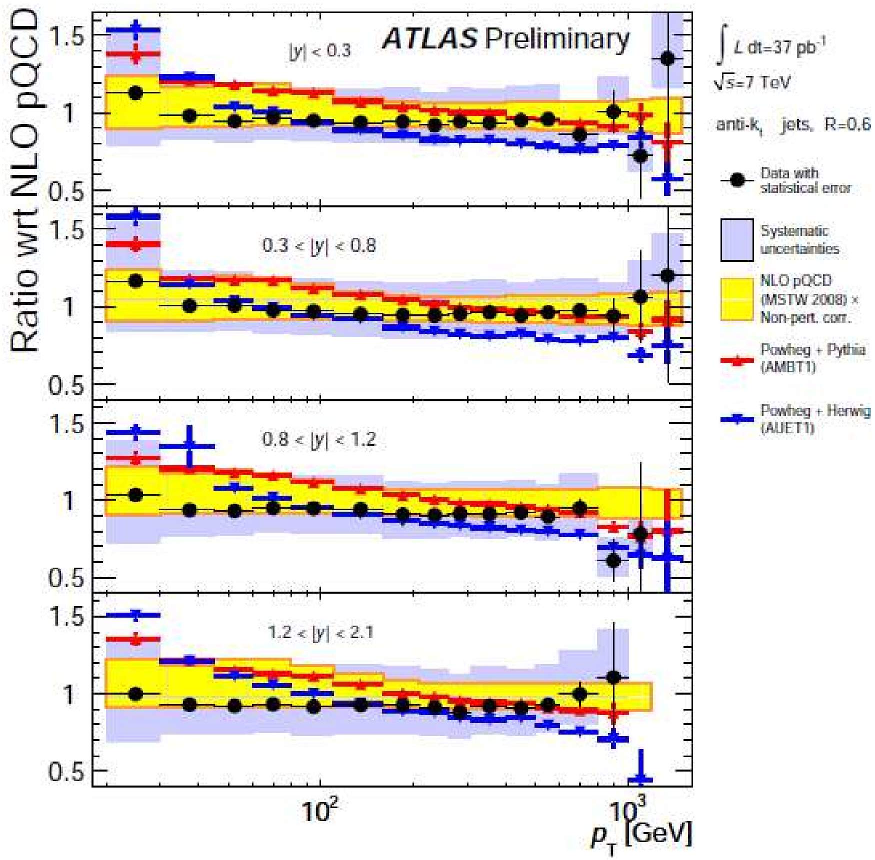
TABLE II: χ^2 values between data and theory for different PDF parametrizations in the order of decreasing χ^2, for all 49 data points.

PDF set	Default $\alpha_s(M_Z)$	χ^2 at $\mu_r = \mu_f = \mu_0$ for default $\alpha_s(M_Z)$	χ^2_{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.*.

Inclusive Jets: NLOJET++ vs. PowHeg

- A significant difference between NLOJET++, PowHeg+Pythia and PowHeg+Herwig was observed
- NLO Matrix Element in good agreement between NLOJET++ and PowHeg
- Indication of uncertainties due to non-perturbative effects?



However, use of POWHEG leads to a big variation compared to standard NLO, and a big variation depending on Monte Carlo tune.

Implications for PDFs.

Consideration of NNLO

One should clearly use NNLO if at all possible rather than NLO – many physical cross-sections, particularly $gg \to H$, not very convergent.

Fewer PDF sets available (rapidly changing), 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.

Converging on general agreement that the NNLO values of α_S are $0.0002 - 0.0003$ smaller than the NLO values of α_S?

MSTW08 – $\alpha_S(M_Z^2) = 0.1202 \rightarrow 0.1171$.

ABKM09 – $\alpha_S(M_Z^2) = 0.1179 \rightarrow 0.1135$.

GJR/JR – $\alpha_S(M_Z^2) = 0.1145 \rightarrow 0.1124$.

NNPDF2.1 – $\alpha_S(M_Z^2) = 0.1191 \rightarrow 0.1172$(prelim).

CT10.1 – $\alpha_S(M_Z^2) = 0.1196 \rightarrow 0.1180$(both prelim – PDF4LHC, DESY July).

HERAPDF1.6 – $\alpha_S(M_Z^2) = 0.1202$ at NLO and general preference for ~ 0.1176 at NNLO.

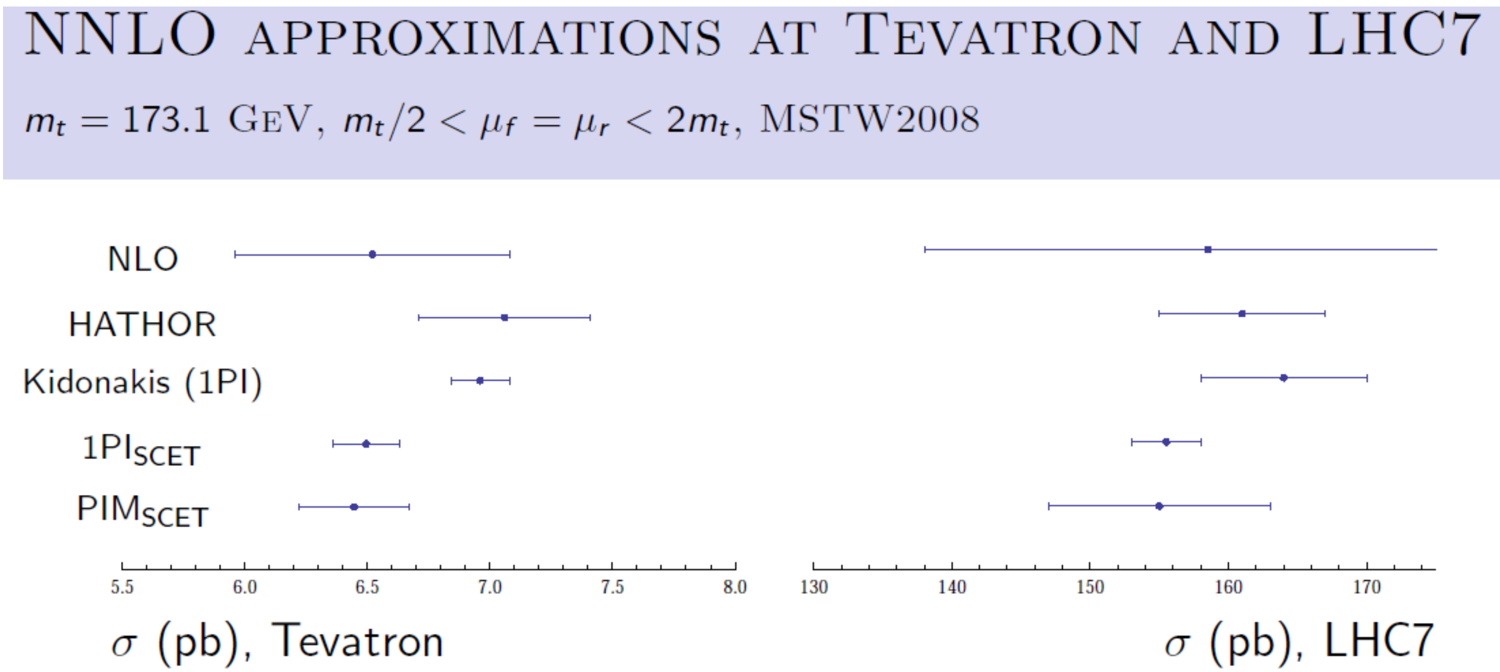
Central values differ far more than NLO $\rightarrow$ NNLO trend.

Top-antitop Cross-section

Inclusive cross-section known approximately to NNLO

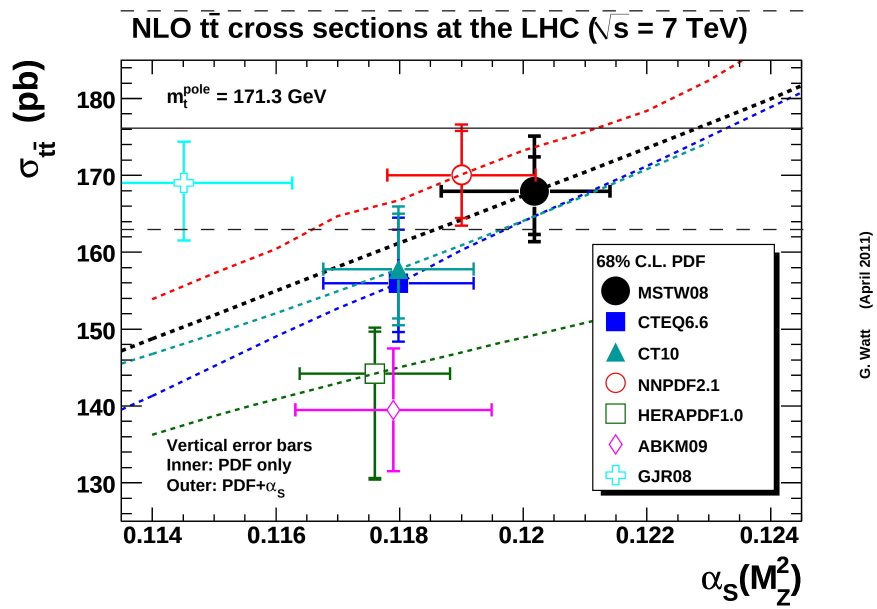
Intrinsic theory uncertainty not very large – see. e.g. talk by Pecjak at EPS 2011.

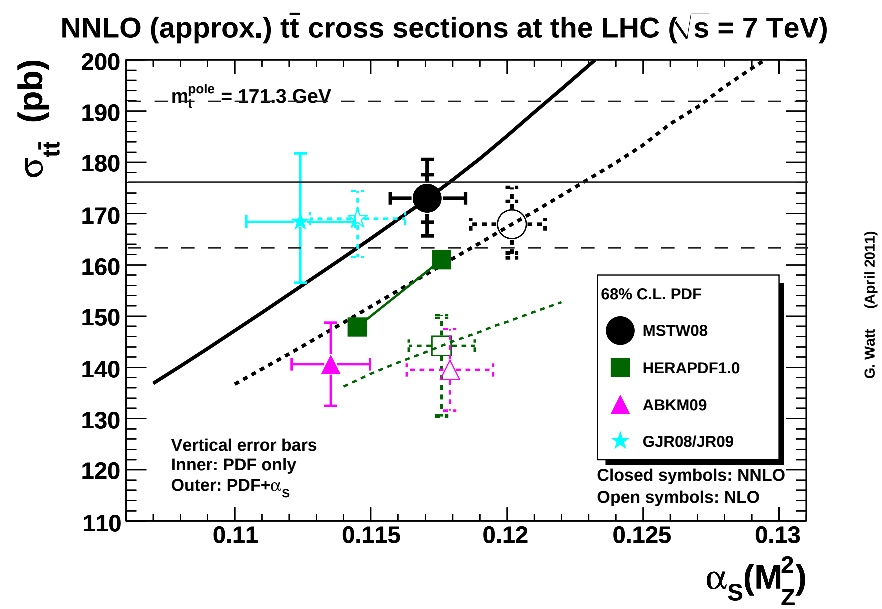
Error bars contain scale dependence and PDF uncertainty at 90%CL.



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

Plots by G. Watt – modified by RST



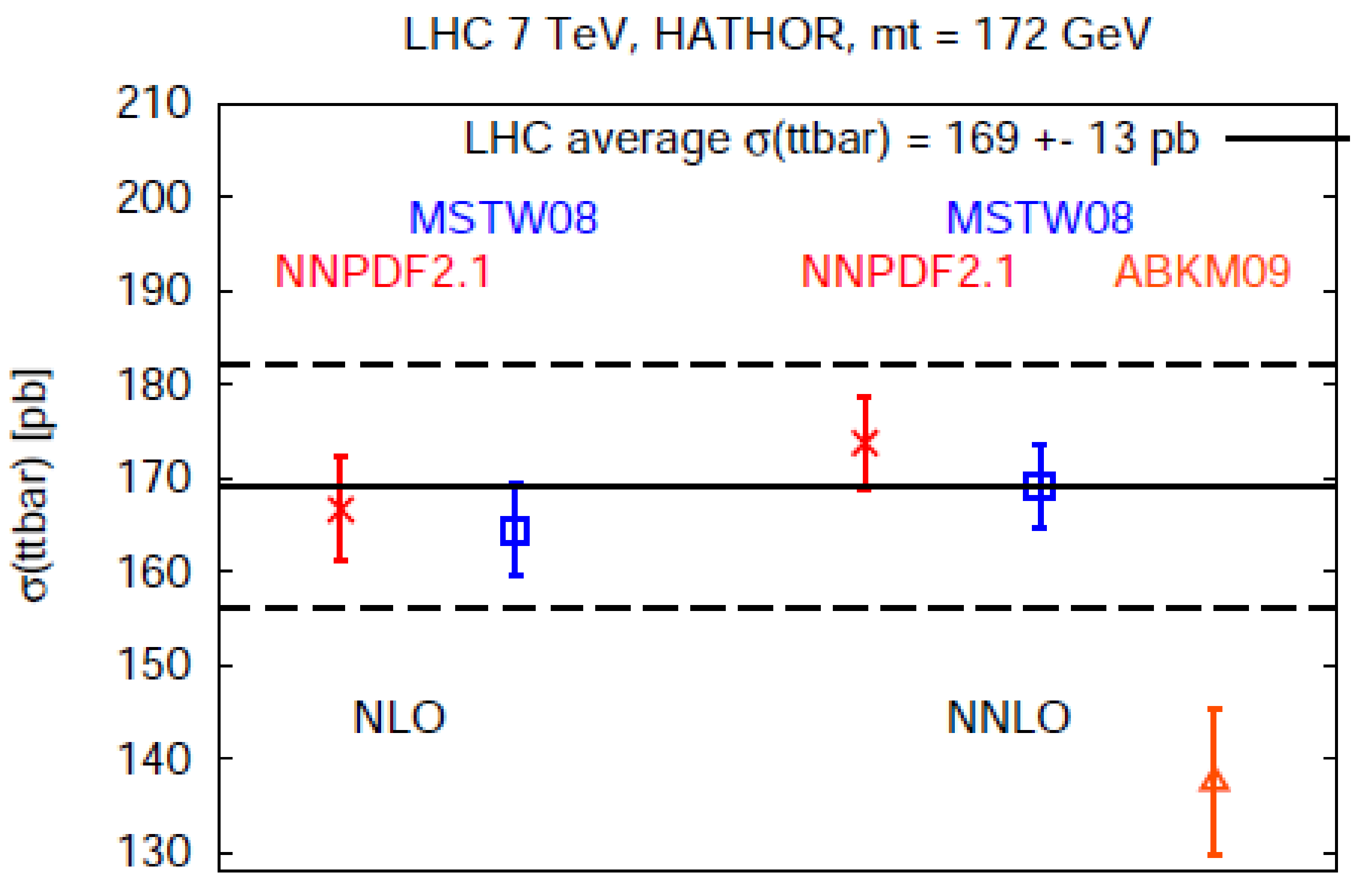


Differences between groups significant at NLO, and at NNLO.

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.

m_t settled at about 172-3GeV? Lowers these predictions by $5-10$pb.

Top cross-section measurement potential discriminator of PDF sets, and correlated to Higgs predictions. For example, ATLAS preliminary combined $\sigma_{t\bar{t}} = 176^{+16}_{-13}$pb.



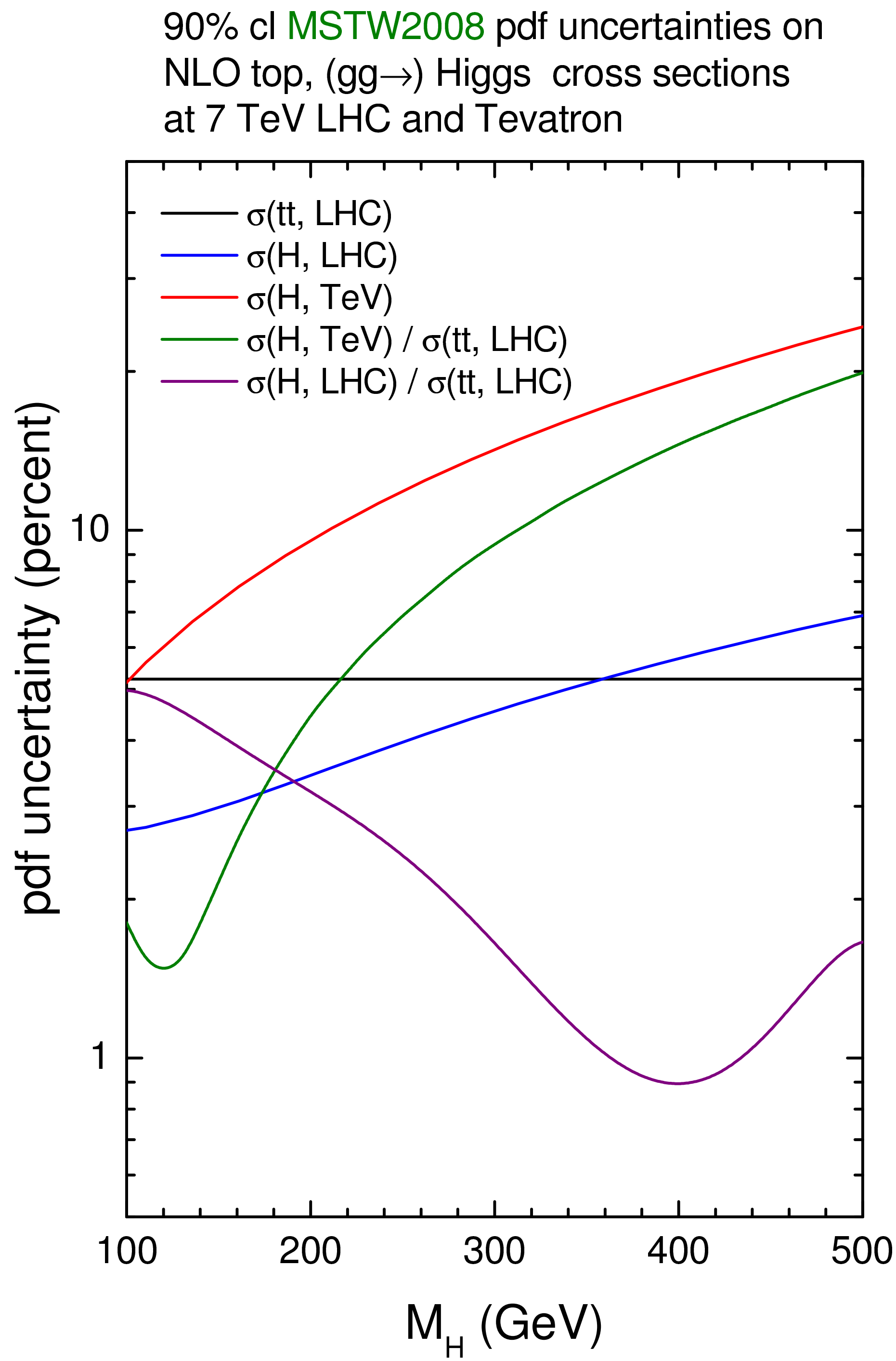
NNPDF NNLO prediction slightly bigger than MSTW, but use $\alpha_S = 0.119$ – not preferred value? General very good agreement

Uncertainty in $t\bar{t}$, Higgs via gluon fusion and ratios. PDF only uncertainty, but α_S uncertainty cancels in ratios.

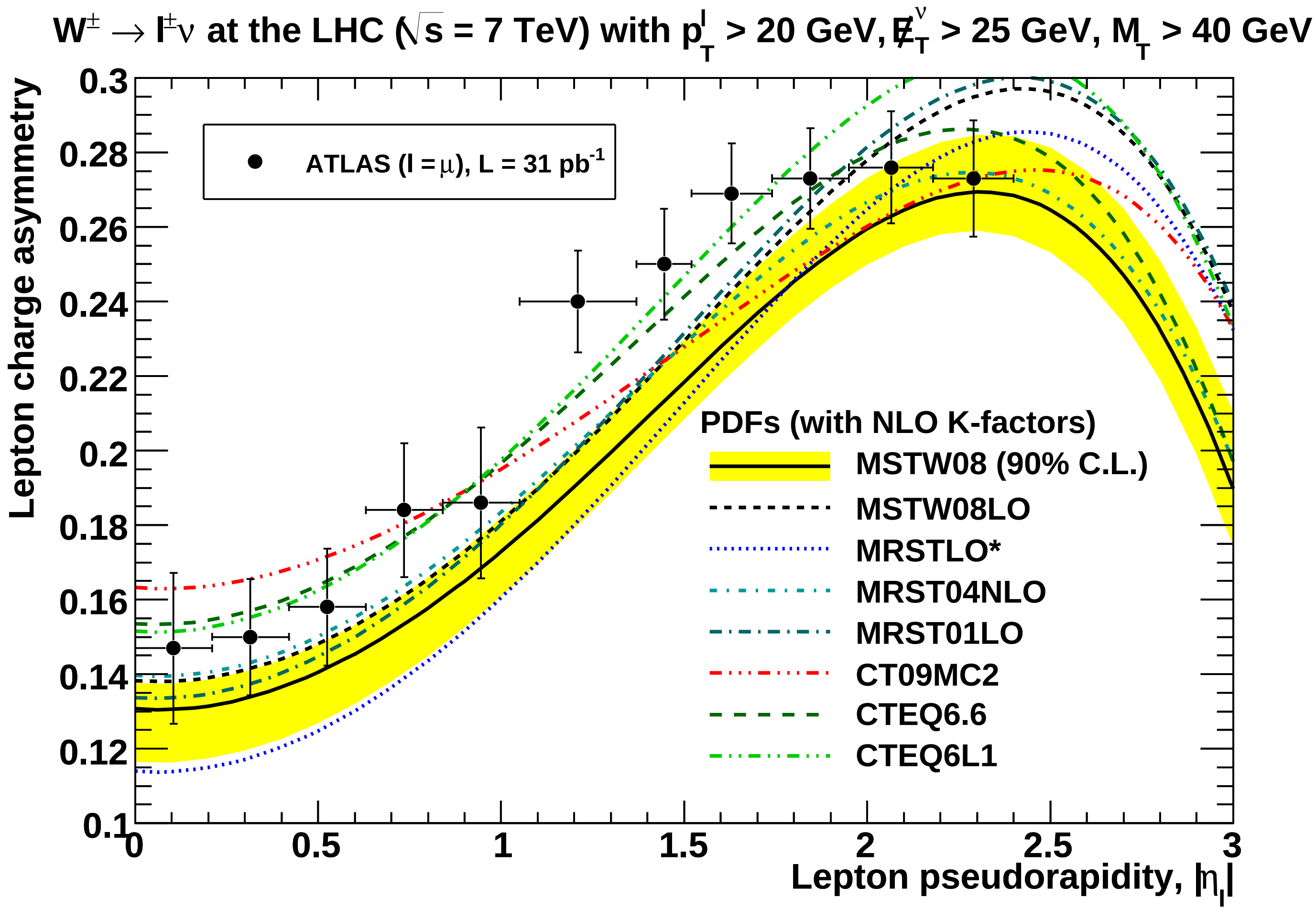
Very strong correlation of top with Higgs production for $m_H \sim 400\text{GeV}$ at the LHC.

Similar correlation for $m_H \sim 400 \times 1.96/7 \sim 130\text{GeV}$ at the Tevatron.

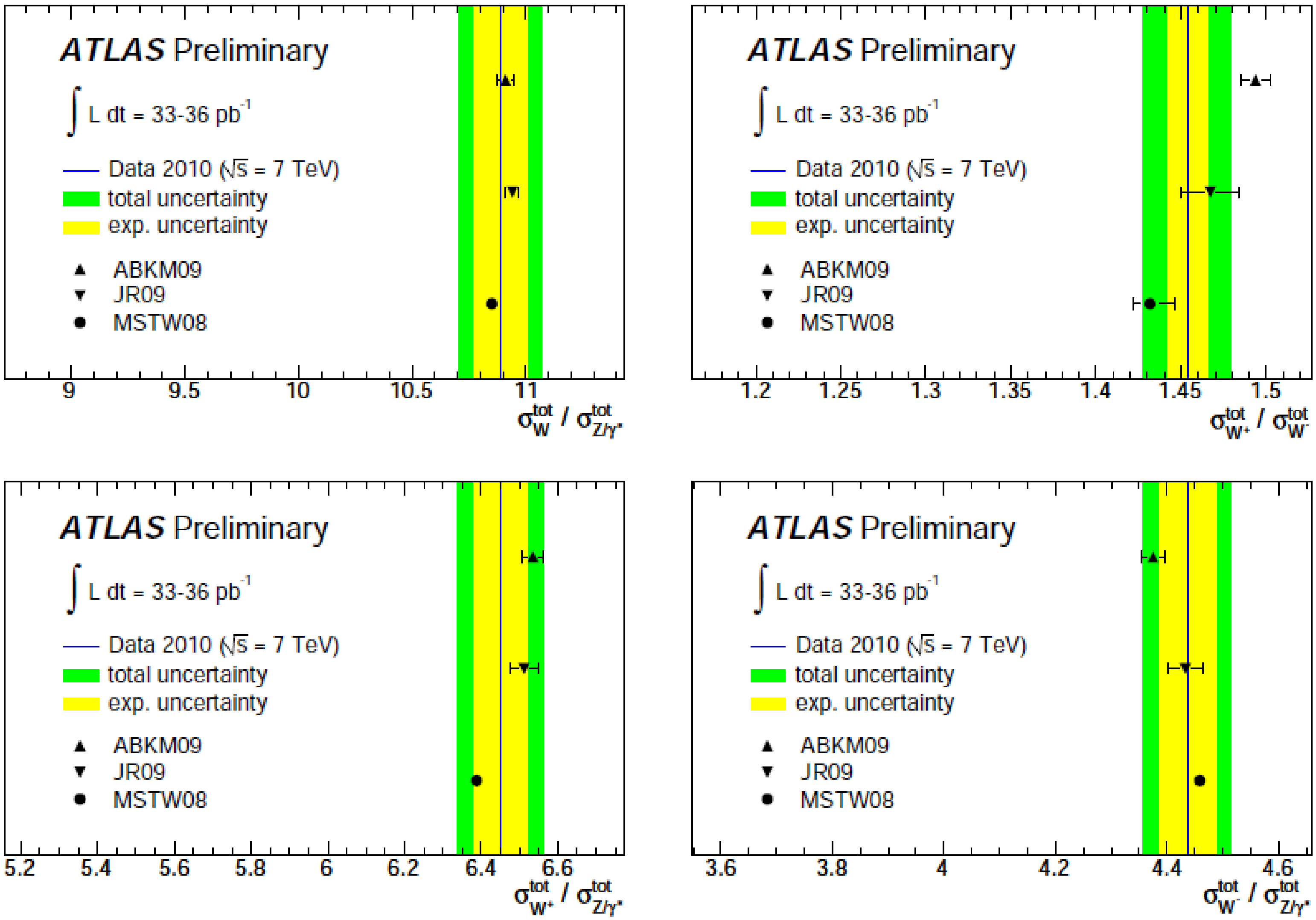
Particularly important at the moment.



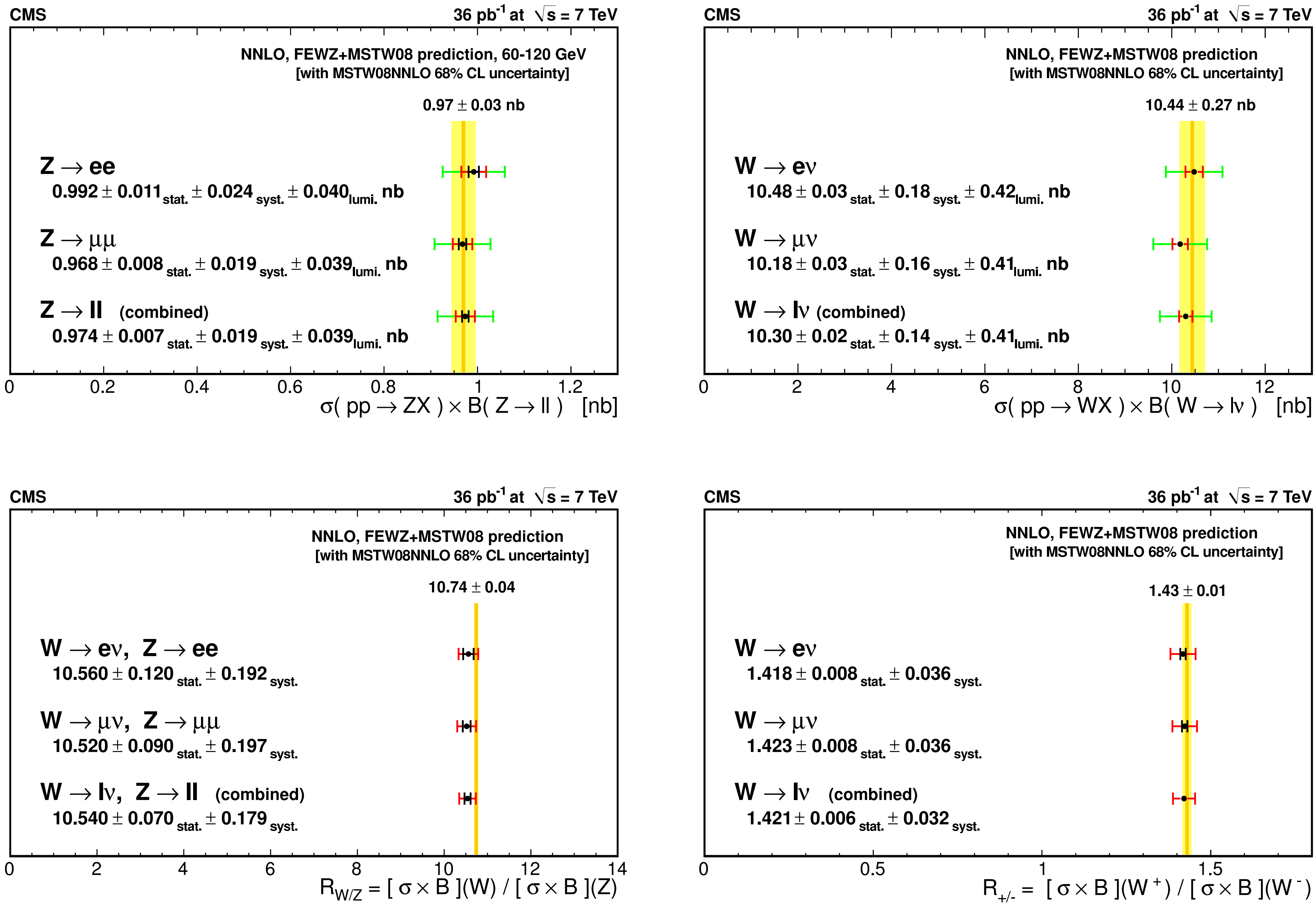
Acceptance Corrections – Watt



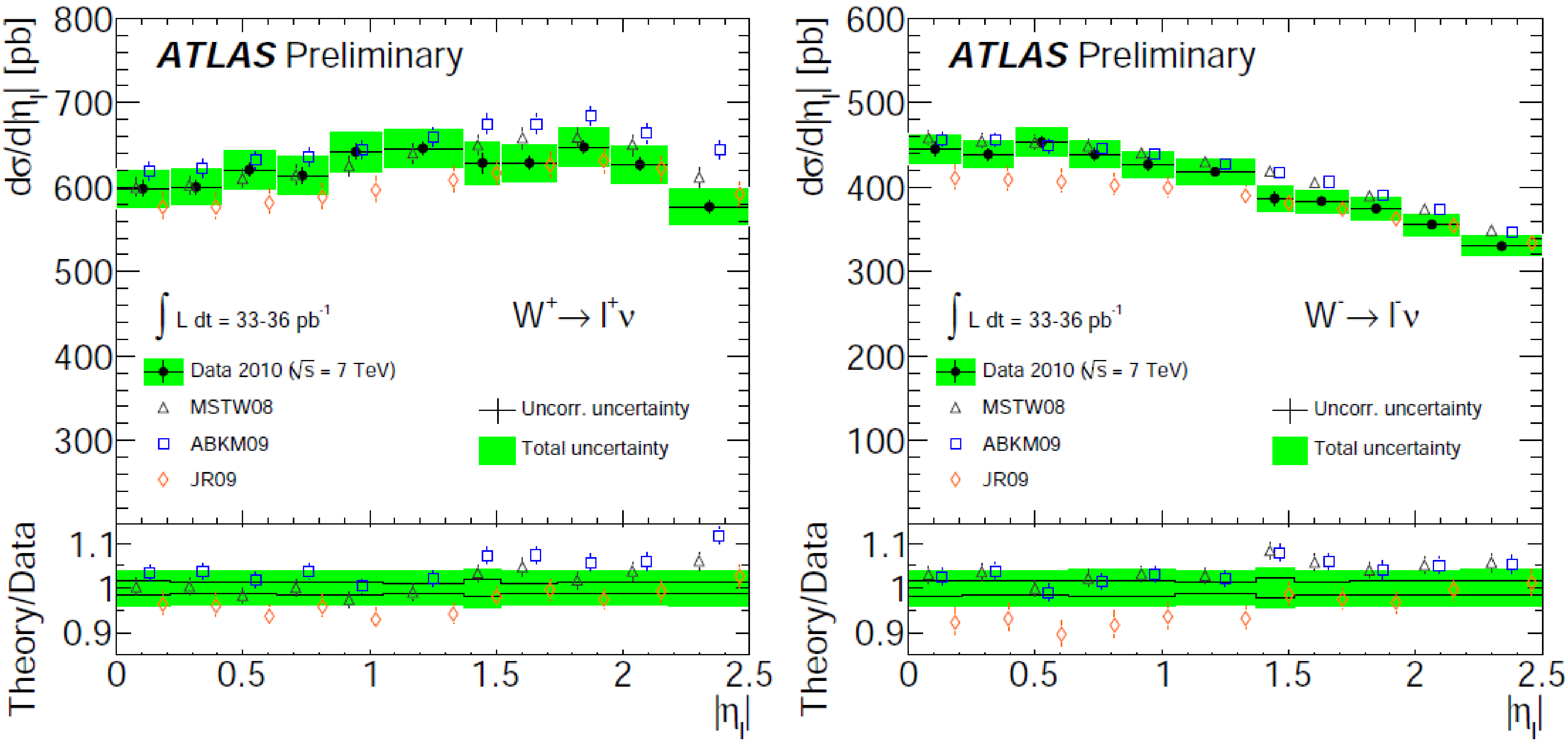
Need to be careful with precision quantities relying on flavour decomposition (Watt), especially if NLO corrections are available.



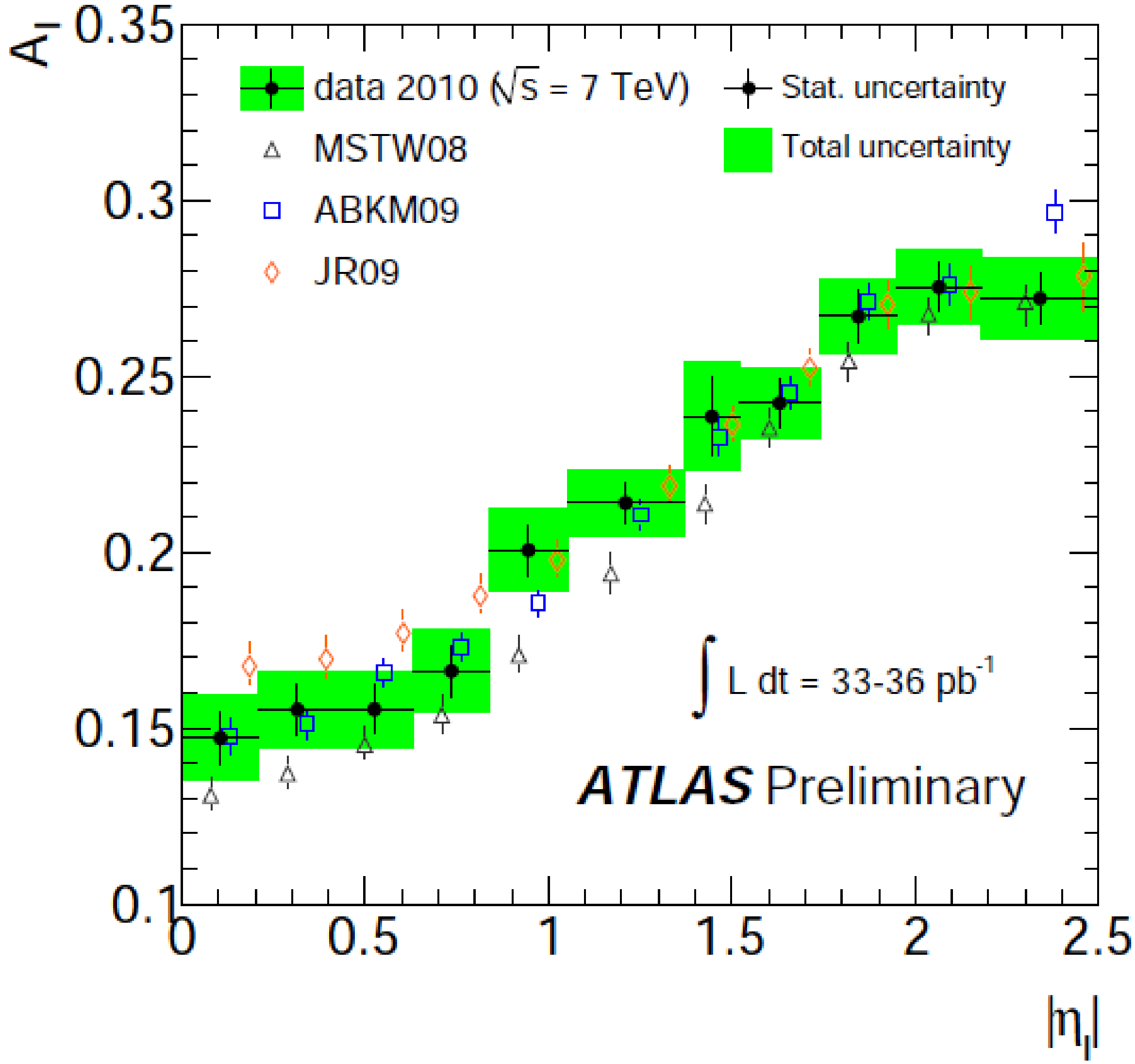
Example, earlier versions of ATLAS results implied some slightly different in ratios.



CMS results very similar.



Differential data on rapidity is becoming very constraining – on both shapes and on normalisations of predictions.



Clearly some of this information lost in ratios and asymmetries.

Ideally want individual distributions, with full correlations.

Details from single charged-lepton cross sections and asymmetries – Stirling

Asymmetries can however, be very useful in relating features to PDFs.

$$A_W(y_W) = \frac{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W - \mathrm{d}\sigma(W^-)/\mathrm{d}y_W}{\mathrm{d}\sigma(W^+)/\mathrm{d}y_W + \mathrm{d}\sigma(W^-)/\mathrm{d}y_W}$$

$$A_W(y_W) \approx \frac{u_V(x_1)S(x_2) + S(x_1)u_V(x_2) - d_V(x_1)S(x_2) - S(x_1)d_V(x_2)}{u_V(x_1)S(x_2) + S(x_1)u_V(x_2) + d_V(x_1)S(x_2) + S(x_1)d_V(x_2) + 4S(x_1)S(x_2)}$$

where $x_{1,2} = (M_W/\sqrt{s})\exp(\pm y_W)$ and $S(x) \approx \bar{u}(x) \approx \bar{d}(x)$.In particular at $y = 0$, where $x_0 = (M_W/\sqrt{s})$,

$$A_W(0) \approx \frac{u_V(x_0) - d_V(x_0)}{u_V(x_0) + d_V(x_0) + 2S(x_0)} \approx \frac{u_V(x_0) - d_V(x_0)}{u(x_0) + d(x_0)},$$

i.e. direct probe of valence quark difference (Cooper-Sarkar), the total quark distributions $u(x_0), d(x_0)$ being well-constrained by (mainly) HERA data.

However, really measure

$$A(y_\ell) = \frac{\mathrm{d}\sigma(\ell^+)/\mathrm{d}y_\ell - \mathrm{d}\sigma(\ell^-)/\mathrm{d}y_\ell}{\mathrm{d}\sigma(\ell^+)/\mathrm{d}y_\ell + \mathrm{d}\sigma(\ell^-)/\mathrm{d}y_\ell},$$

If θ^* is angle of lepton to proton beam $\cos^2\theta^* = 1 - 4p_T^2/M_W^2$ and

$$y_\ell = y_W + y^*, \quad y^* = \frac{1}{2}\ln\left(\frac{1+\cos\theta^*}{1-\cos\theta^*}\right)$$

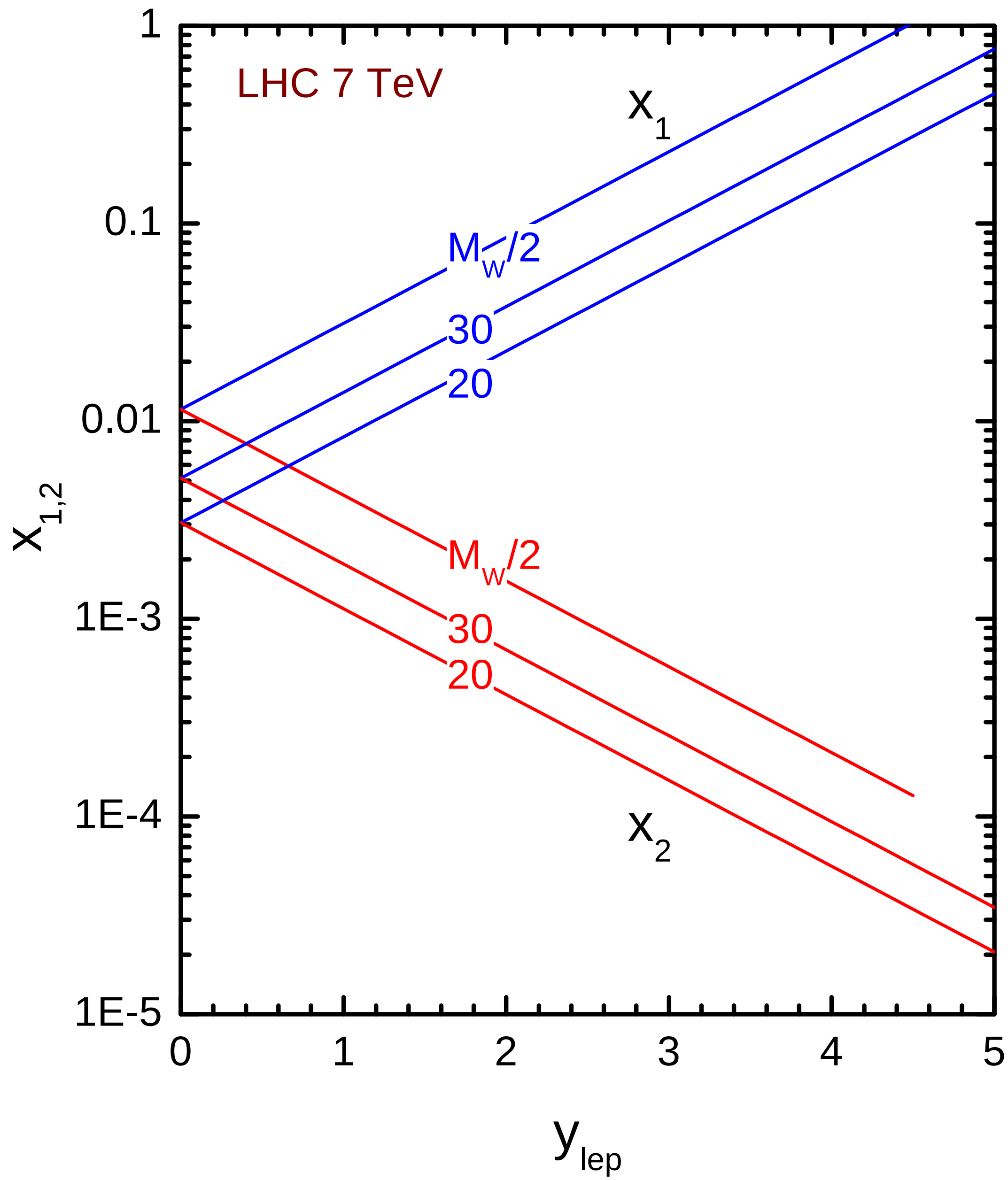
$$x_{1,2} = x_0 \exp(\pm y_W) = x_0 \exp(\pm y_\ell)\kappa^{\pm 1}, \quad \kappa = \left(\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}\right)^{1/2}$$

$$x_1^+ = x_0 \exp(+y_\ell)\kappa > x_1^- = x_0 \exp(+y_\ell)\kappa^{-1} \quad x_2^+ = x_0 \exp(-y_\ell)\kappa > x_2^- = x_0 \exp(-y_\ell)\kappa^{-1}.$$

Since all PDFs decrease with increasing x, the $x_{1,2}^-$ contributions are numerically dominant, particularly as we go away from central rapidity.

Values of generally dominant x^- values probed shown opposite.

For $p_T = 20\mathrm{GeV}$ a factor of 3 from naive estimate.



Ignoring sea-sea contributions

$$\frac{\mathrm{d}\sigma(\ell^+)}{\mathrm{d}y_\ell} \propto \left(u_V(x_1^+)S(x_2^+) + u_V(x_1^-)S(x_2^-)\right)(1-\cos\theta^*)^2$$
$$+ \left(S(x_1^+)u_V(x_2^+) + S(x_1^-)u_V(x_2^-)\right)(1+\cos\theta^*)^2$$

$$\frac{\mathrm{d}\sigma(\ell^-)}{\mathrm{d}y_\ell} \propto \left(S(x_1^+)d_V(x_2^+) + S(x_1^-)d_V(x_2^-)\right)(1-\cos\theta^*)^2$$
$$+ \left(d_V(x_1^+)S(x_2^+) + d_V(x_1^-)S(x_2^-)\right)(1+\cos\theta^*)^2$$

As p_T deviates further from $M_W/2$, $(1+\cos\theta^*)^2$ dominates.

For large y_ℓ, $x_1^- \gg x_2^-$ and the asymmetry becomes more and more dominated by the $d_V(x_1^-)S(x_2^-)$ contribution to l^- and $A_\ell(y_\ell) \to -1$.

$d_V(x)$ decreases faster at large x than $u_V(x)$, and so at some point at large y_ℓ the approximation

$$d_V(x_1^-)S(x_2^-)(1+\cos\theta^*)^2 \gg u_V(x_1^-)S(x_2^-)(1-\cos\theta^*)^2$$

breaks down, i.e. the $V \pm A$ unfavoured forward $u\bar{d} \to \ell^+\nu_\ell$ scattering process will eventually dominate, and $A_\ell(y_\ell) \to +1$

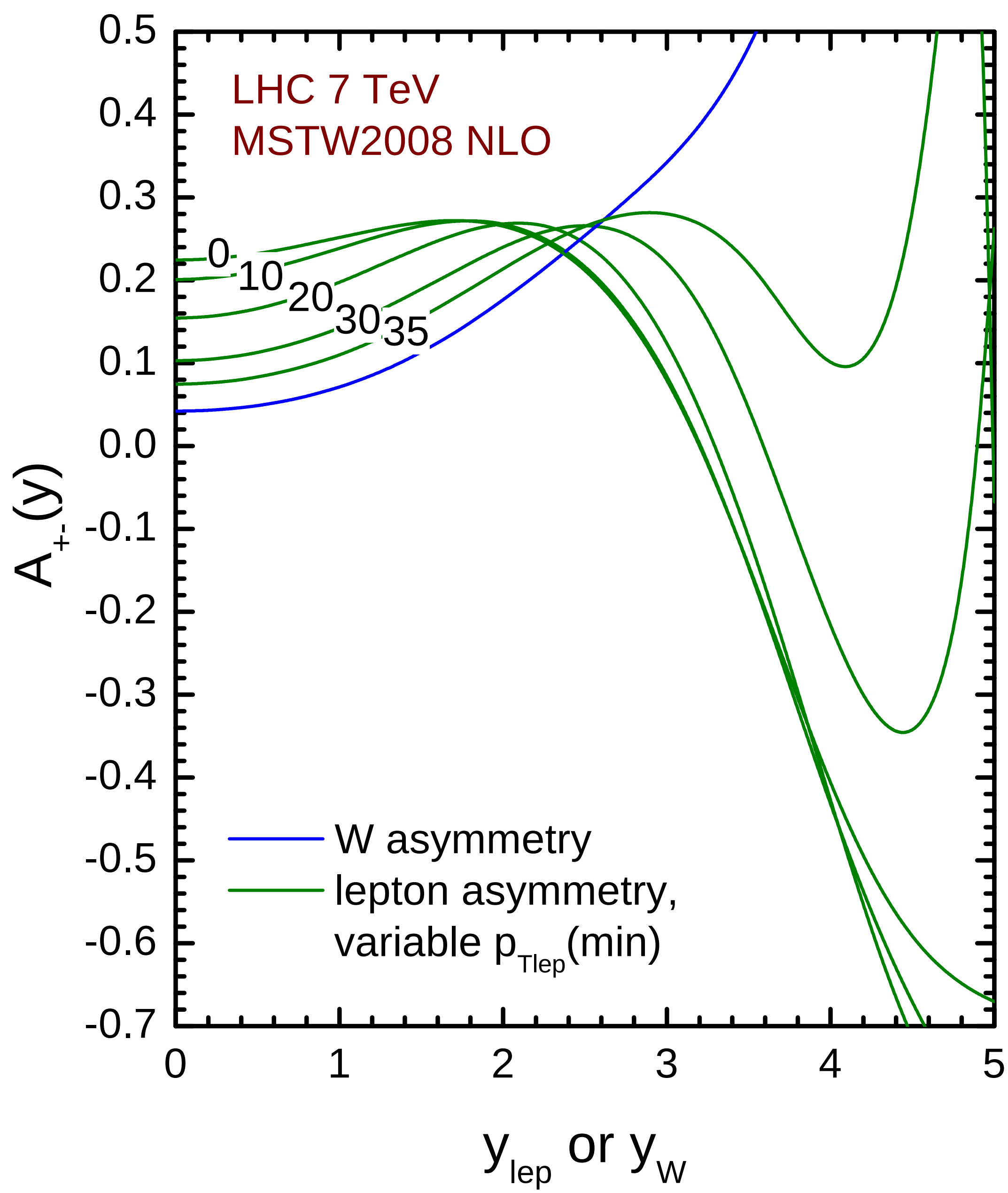
This will happen at the y_ℓ value for which

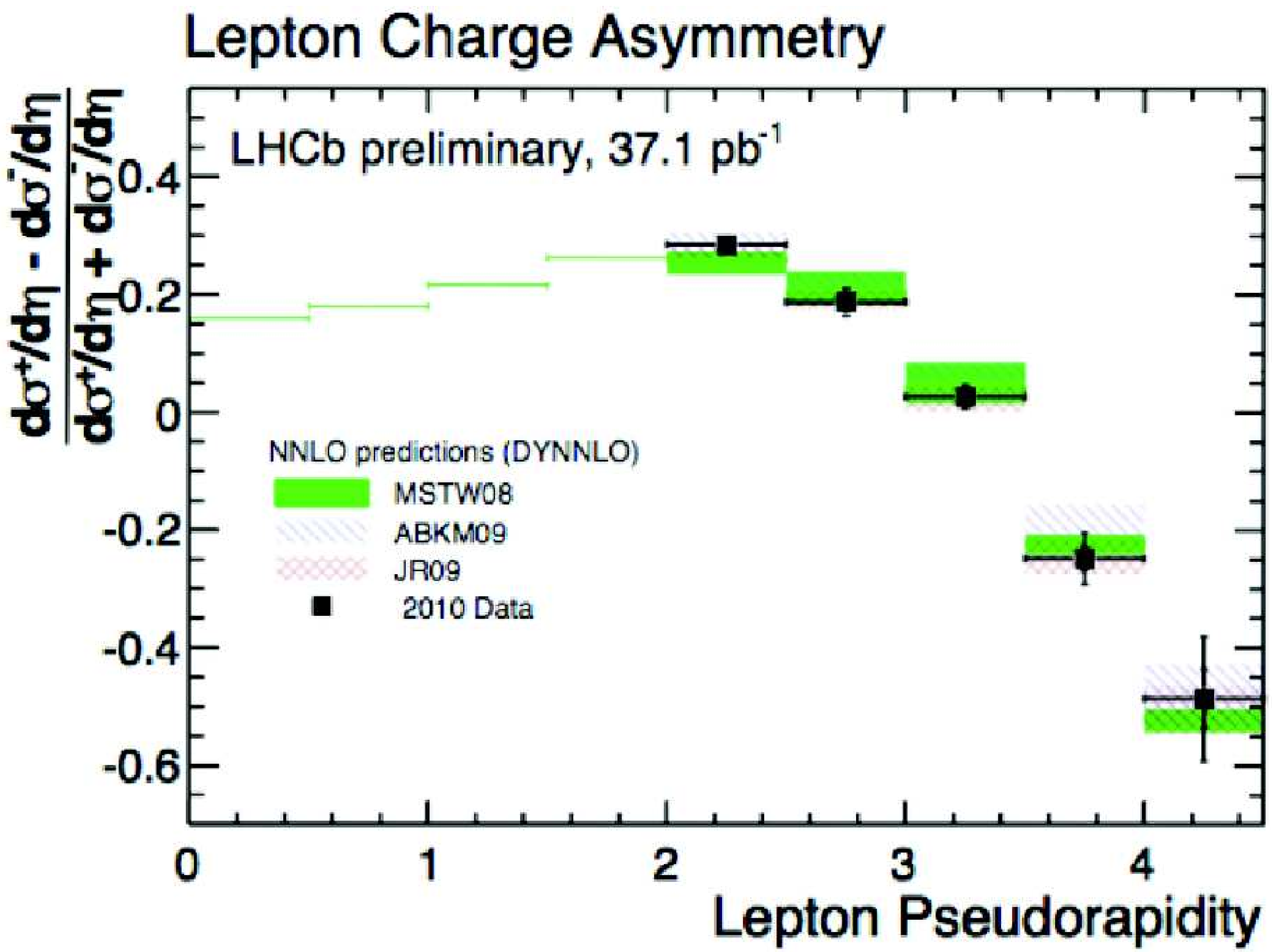
$$u_V(x_1^-)/d_V(x_1^-) \sim (1+\cos\theta^*)^2/(1-\cos\theta^*)^2 = \kappa^4.$$

The larger the lepton p_T the earlier (in terms of increasing y_ℓ) this will happen, and for $p_T \to m_W/2$ there is no $V \pm A$ dominance at all.

So asymmetry at large y_ℓ in terms of p_T tells us about d/u at large x.

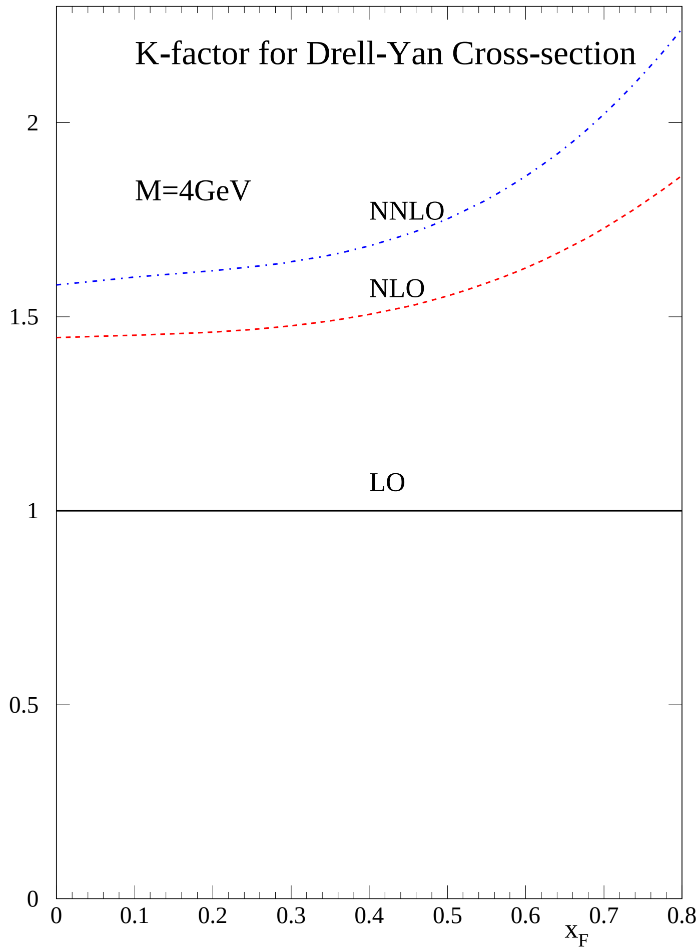
It also confirms that at high x, $S(x) \ll u_V(x)(d_V(x))$, since dip is diminished by (approximately) equal sea-sea contribution to ℓ^+ and ℓ^-.

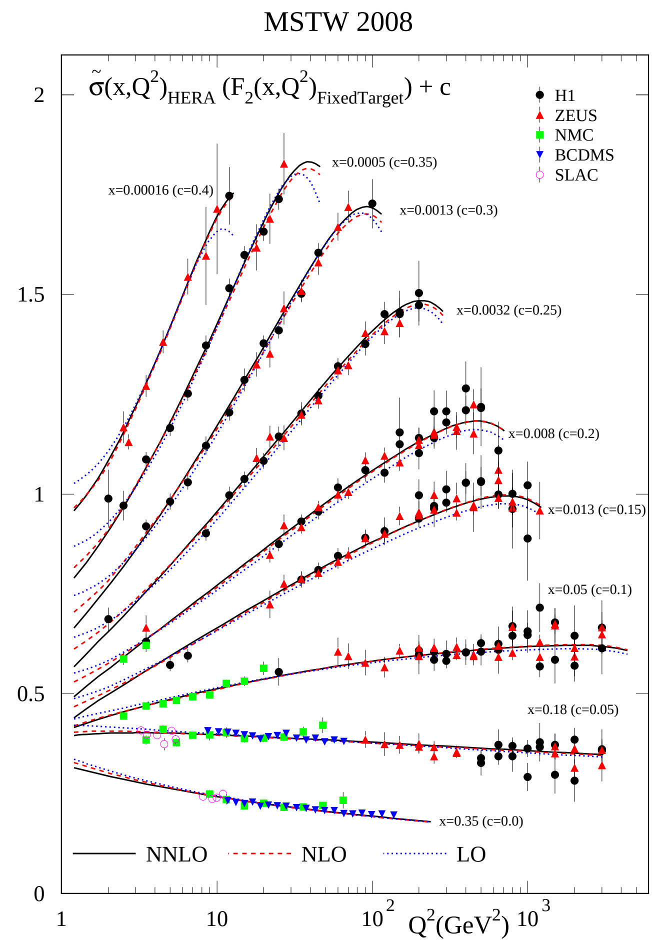




LHCb (with $p_T(\mathrm{min}) = 20\mathrm{GeV}$ already testing dip.

With higher $p_T(\mathrm{min})$ could potentially see upturn.





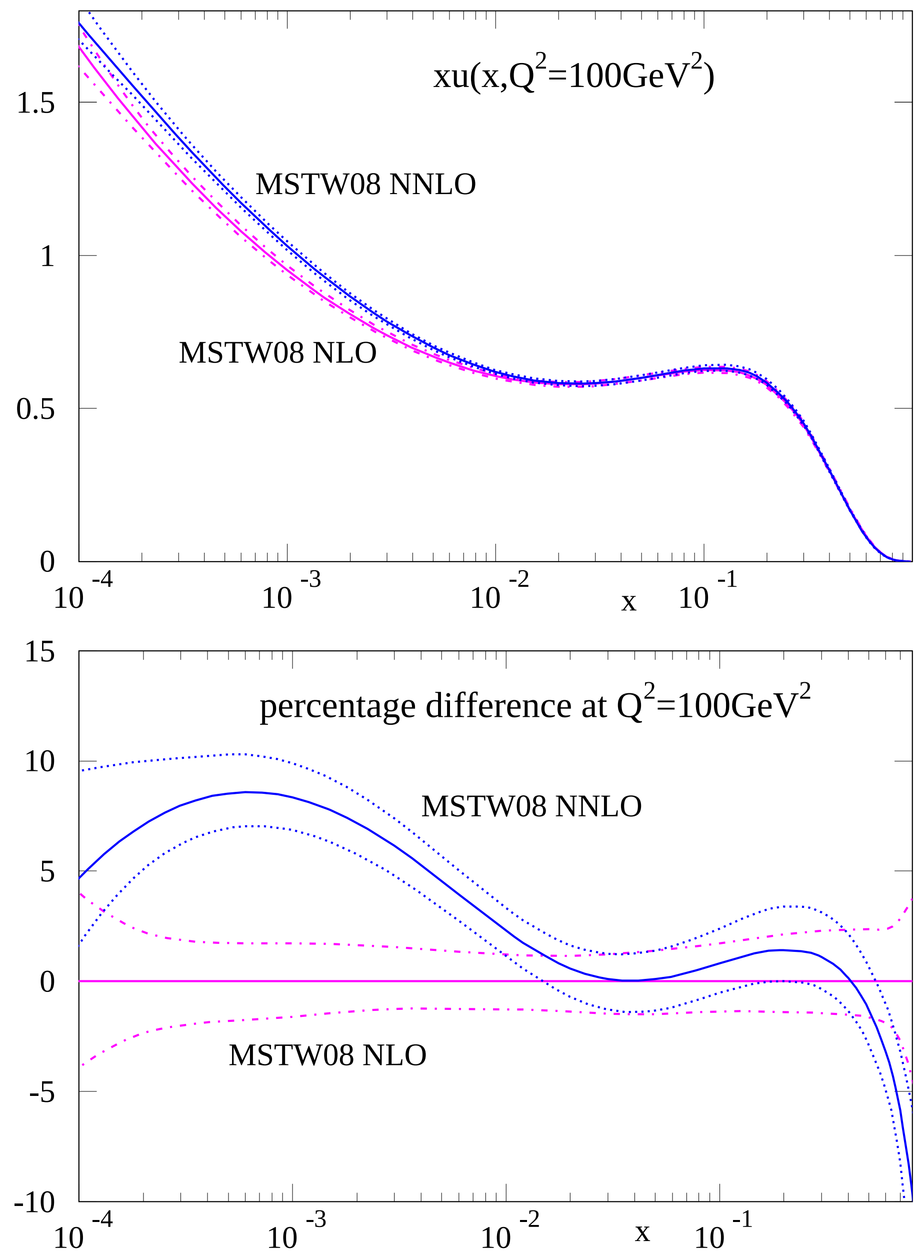
In general NNLO corrections either positive for cross sections, e.g. Drell Yan, or for evolution in structure functions.

Automatically leads to lower $\alpha_S(M_Z^2)$ at NNLO than at NLO, i.e. 0.1171 rather than 0.1202. Difference between two quite stable.

Sometimes vital to use NNLO PDFs if calculating at NNLO.

Systematic difference between PDF defined at NLO and at NNLO.

Due to large (negative) gluon coefficient function at not too small x.



de Florain and Vogelsang result for inclusive jet K-factor for $d\sigma/dp_T$ at order α_S^{2+n} compared to NLO.