Introduction to hadron collider physics

Theory challenges for LHC Physics

Dubna International Advanced School of Theoretical Physics

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Lecture 2

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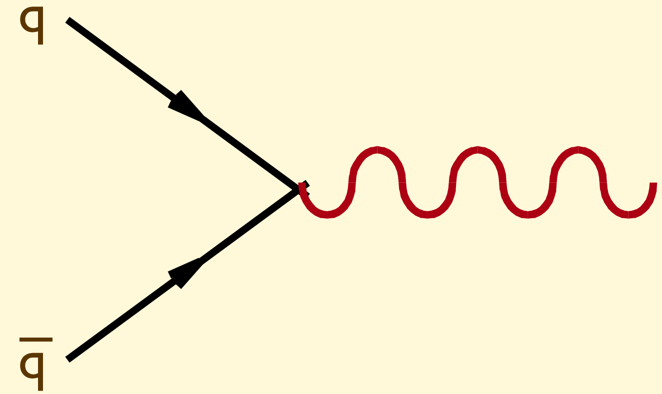
Example: Drell-Yan processes



$$W \to \ell\nu$$
$$Z \to \ell^+\ell^-$$

Properties/Goals of the measurement:

- Clean final state (no hadrons from the hard process)
- Tests of QCD: σ(W,Z) known up to NNLO (2-loops)
- Measure SM parameters: m(W), $\sin^2\theta_W$
- constrain PDFs (e.g. $f_{up}(x)/f_{down}(x)$)
- search for new gauge bosons: $q\bar{q} \to W', Z'$
- Probe contact interactions: $q\bar{q} \to e^+e^-$

Some useful relations and definitions

Rapidity: $y = \frac{1}{2} \log \frac{E_W + p_W^z}{E_W - p_W^z}$

Pseudorapidity: $\eta = -\log(\tan \frac{\theta}{2})$

where:

$\tan\theta = \frac{p_T}{p^z}$ and $p_T = \sqrt{p_x^2 + p_y^2}$

Exercise: prove that for a massless particle rapidity=pseudorapidity:

Exercise: using $\tau = \frac{\hat{s}}{S} = x_1 x_2$ and

$$\begin{cases} E_W = (x_1 + x_2)\, E_{\text{beam}} \\ p_W^z = (x_1 - x_2)\, E_{\text{beam}} \end{cases} \Rightarrow y = \frac{1}{2} \log \frac{x_1}{x_2}$$

prove the following relations:

$$x_{1,2} = \sqrt{\tau}\, e^{\pm y} \qquad dx_1\, dx_2 = dy\, d\tau$$

$$dy = \frac{dx_1}{x_1} \qquad d\tau\, \delta(\hat{s} - m_W^2) = \frac{1}{S}$$

LO Cross-section calculation

$$\sigma(pp \to W) = \sum_{q,q'} \int dx_1 dx_2\, f_q(x_1,Q)\, f_{\bar{q}'}(x_2,Q)\, \frac{1}{2\hat{s}} \int d[PS] \overline{\sum_{spin,col}} |M(q\bar{q}' \to W)|^2$$

where:

$$\overline{\sum_{spin,col}} |M(qq' \to W)|^2 = \frac{1}{3}\frac{1}{4} 8 g_W^2 |V_{qq'}|^2 \hat{s} = \frac{2}{3}\frac{G_F m_W^2}{\sqrt{2}} |V_{qq'}|^2 \hat{s}$$

$$d[PS] = \frac{d^3 p_W}{(2\pi)^3 2 p_W^0} (2\pi)^4 \delta^4(P_{in} - p_W)$$

$$= 2\pi\, d^4 p_W\, \delta(p_W^2 - m_W^2)\, \delta^4(P_{in} - p_W) = 2\pi\, \delta(\hat{s} - m_W^2)$$

leading to:

Partonic Luminosity

$$\sigma(pp \to W) = \sum_{ij} \frac{\pi A_{ij}}{m_W^2}\, \tau \int_\tau^1 \frac{dx}{x} f_i(x,Q)\, f_j(\frac{\tau}{x},Q) \equiv \sum_{ij} \frac{\pi A_{ij}}{m_W^2}\, \tau L_{ij}(\tau)$$

where:

$$\frac{\pi A_{ud}}{m_W^2} = 6.5\text{nb} \quad \text{and} \quad \tau = \frac{m_W^2}{S}$$

Exercise: Study the function τL(τ)

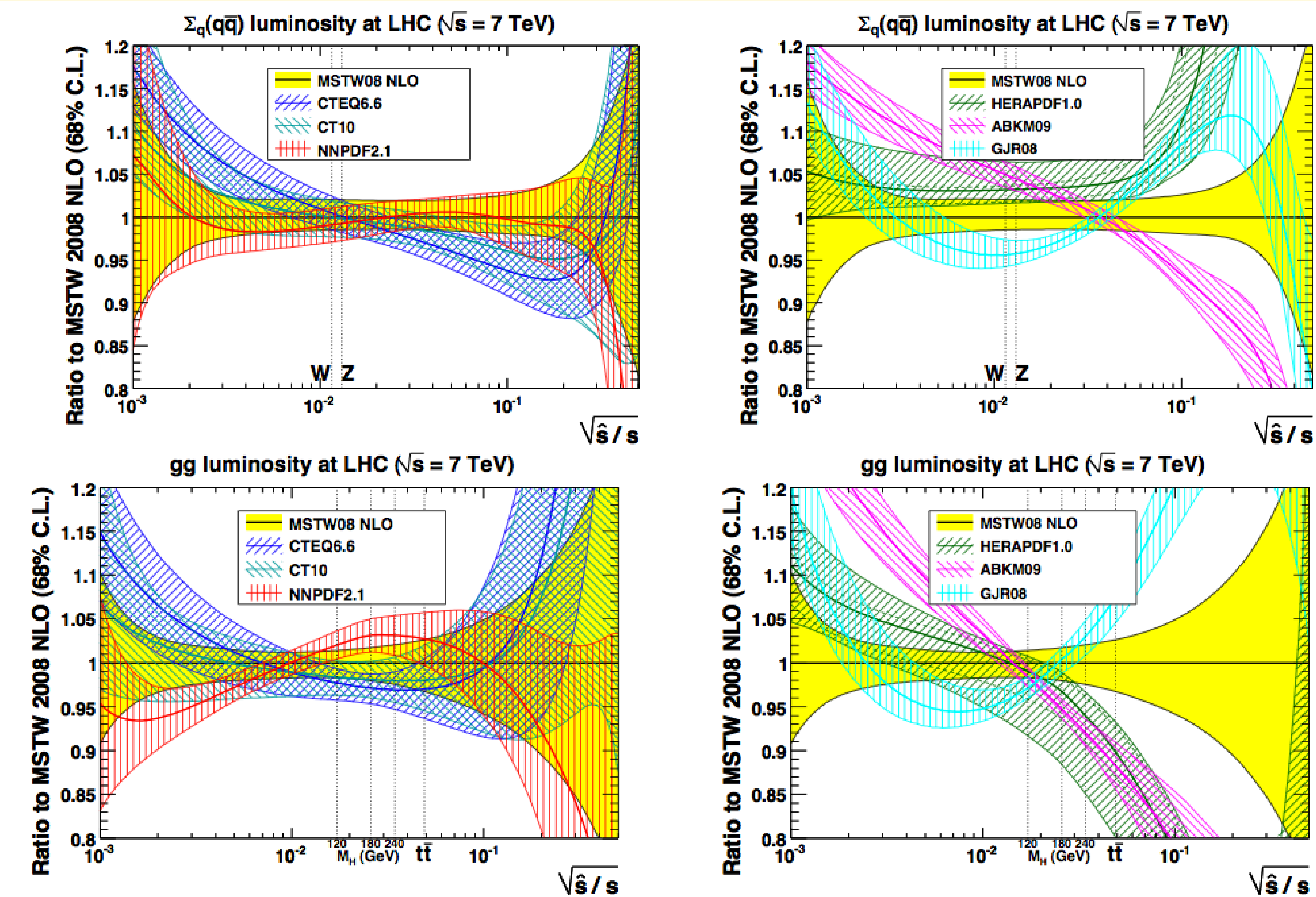
Assume, for example, that $$f(x) \sim \frac{1}{x^{1+\delta}}\,, \quad 0 < \delta < 1$$

Then: $$L(\tau) = \int_\tau^1 \frac{dx}{x} \frac{1}{x^{1+\delta}} (\frac{x}{\tau})^{1+\delta} = \frac{1}{\tau^{1+\delta}} \log(\frac{1}{\tau})$$

and: $$\sigma_W = \sigma_W^0 \left(\frac{S}{m_W^2}\right)^\delta \log\left(\frac{S}{m_W^2}\right)$$

Therefore the W cross-section grows at least logarithmically with the hadronic CM energy. This is a typical behavior of cross-sections for production of fixed-mass objects in hadronic collisions, contrary to the case of e+e- collisions, where cross-sections tend to decrease with CM energy.

PDF luminosity uncertainties -- NLO -- 2011



G. Watt, http://arXiv.org/pdf/1106.5788

Example: gg->H cross section

G.Watt, http://arXiv.org/pdf/1106.5788

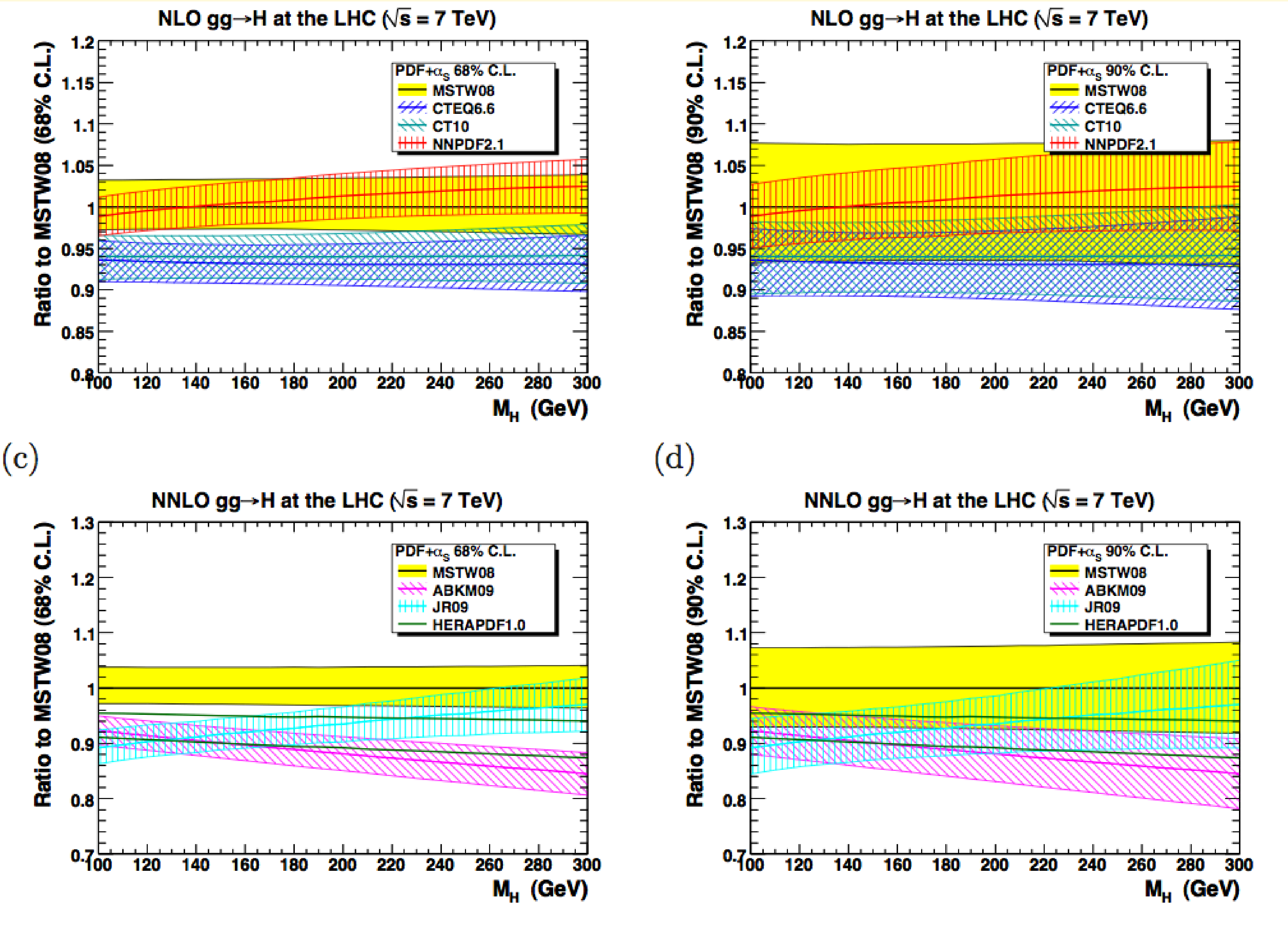
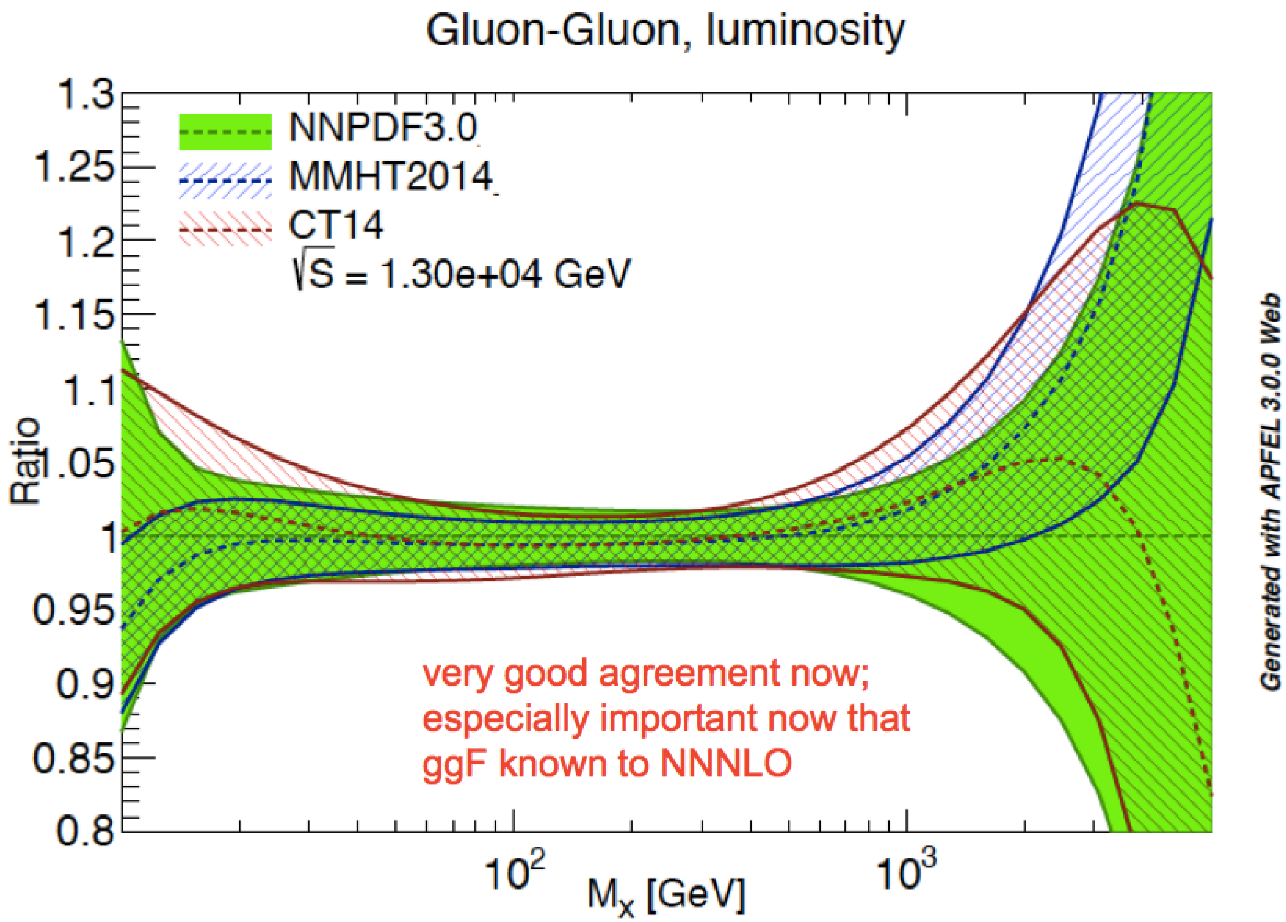


Figure 15. Ratio to the MSTW08 prediction for $gg \to H$ with PDF+α_S uncertainties for (a) NLO at 68% C.L., (b) NLO at 90% C.L., (c) NNLO at 68% C.L., (d) NNLO at 90% C.L.

PDF luminosity uncertainties -- NLO -- 2015

See PDF4LHC mtg, Apr 13 2015

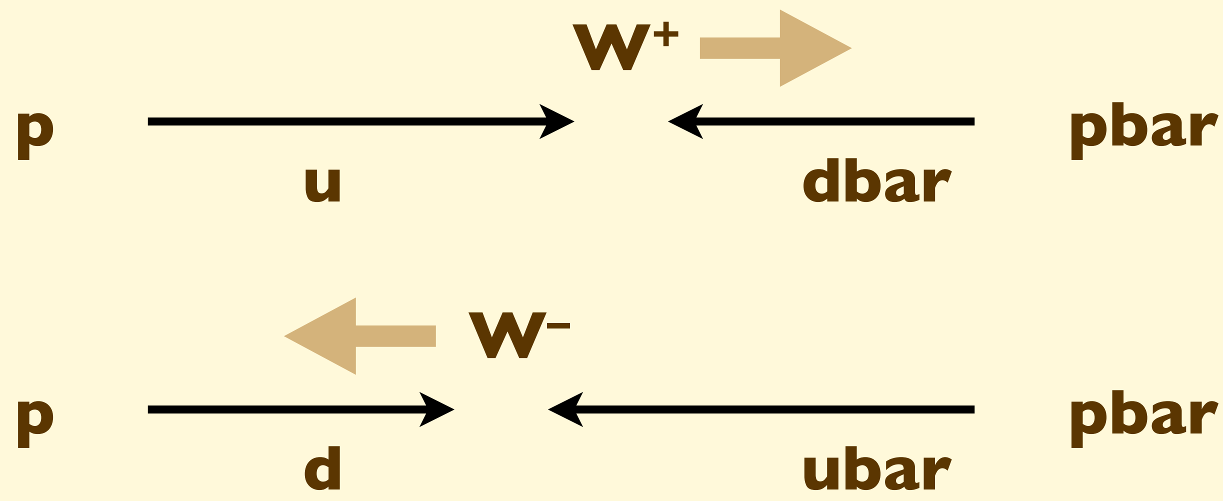


Systematics for Higgs cross section

	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

Drell-Yan observables to improve the knowledge of PDFs

W rapidity asymmetry in p-pbar



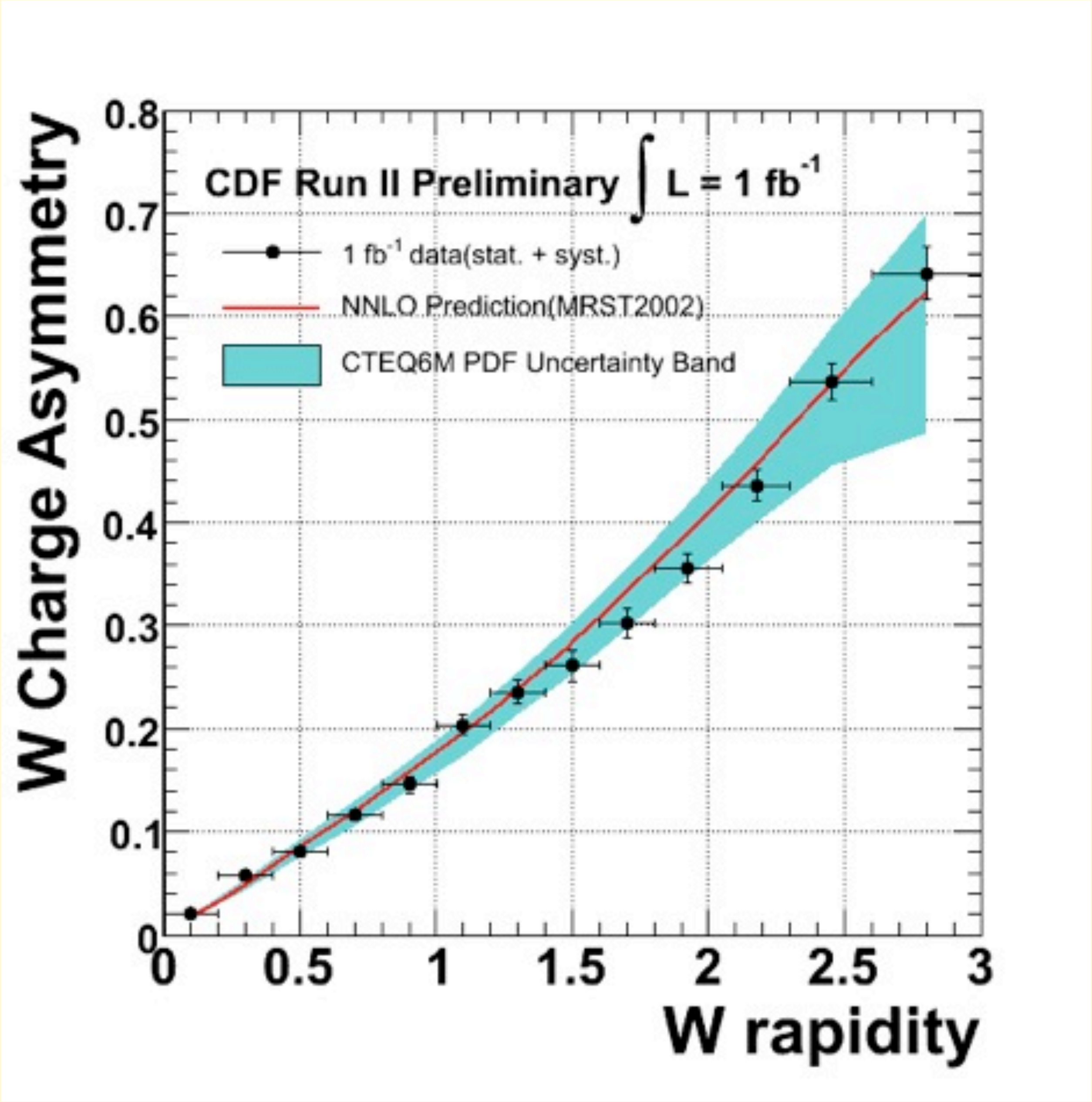
$$\frac{d\sigma_{W^+}}{dy} \propto f_u^p(x_1)\ f_{\bar{d}}^{\bar{p}}(x_2) + f_{\bar{d}}^p(x_1) f_u^{\bar{p}}(x_2)$$

$$\frac{d\sigma_{W^-}}{dy} \propto f_{\bar{u}}^p(x_1)\ f_d^{\bar{p}}(x_2) + f_d^p(x_1) f_{\bar{u}}^{\bar{p}}(x_2)$$

(Assuming dominance of valence contributions)

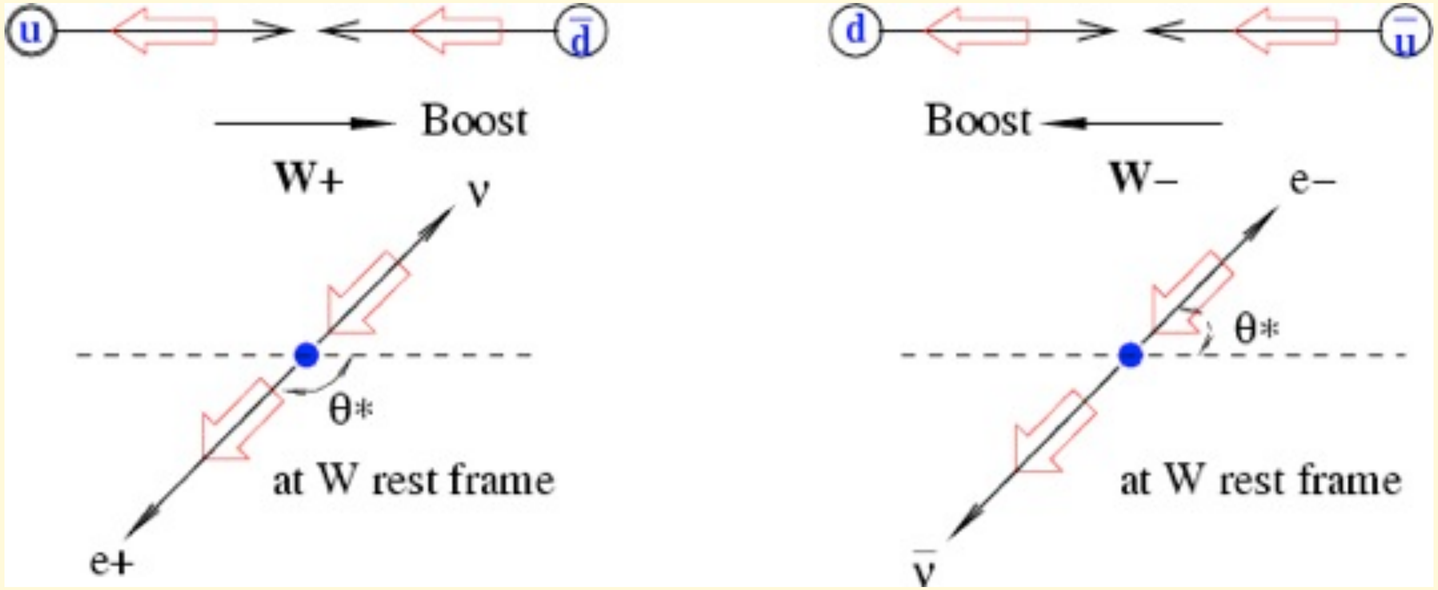
$$f_d(x) = f_u(x)\ R(x)$$

$$A(y) = \frac{\frac{d\sigma_{W^+}}{dy} - \frac{d\sigma_{W^-}}{dy}}{\frac{d\sigma_{W^+}}{dy} + \frac{d\sigma_{W^-}}{dy}} = \frac{f_u^p(x_1)\ f_d^p(x_2) - f_d^p(x_1)\ f_u^p(x_2)}{f_u^p(x_1)\ f_d^p(x_2) + f_d^p(x_1)\ f_u^p(x_2)} = \frac{R(x_2) - R(x_1)}{R(x_2) + R(x_1)}$$



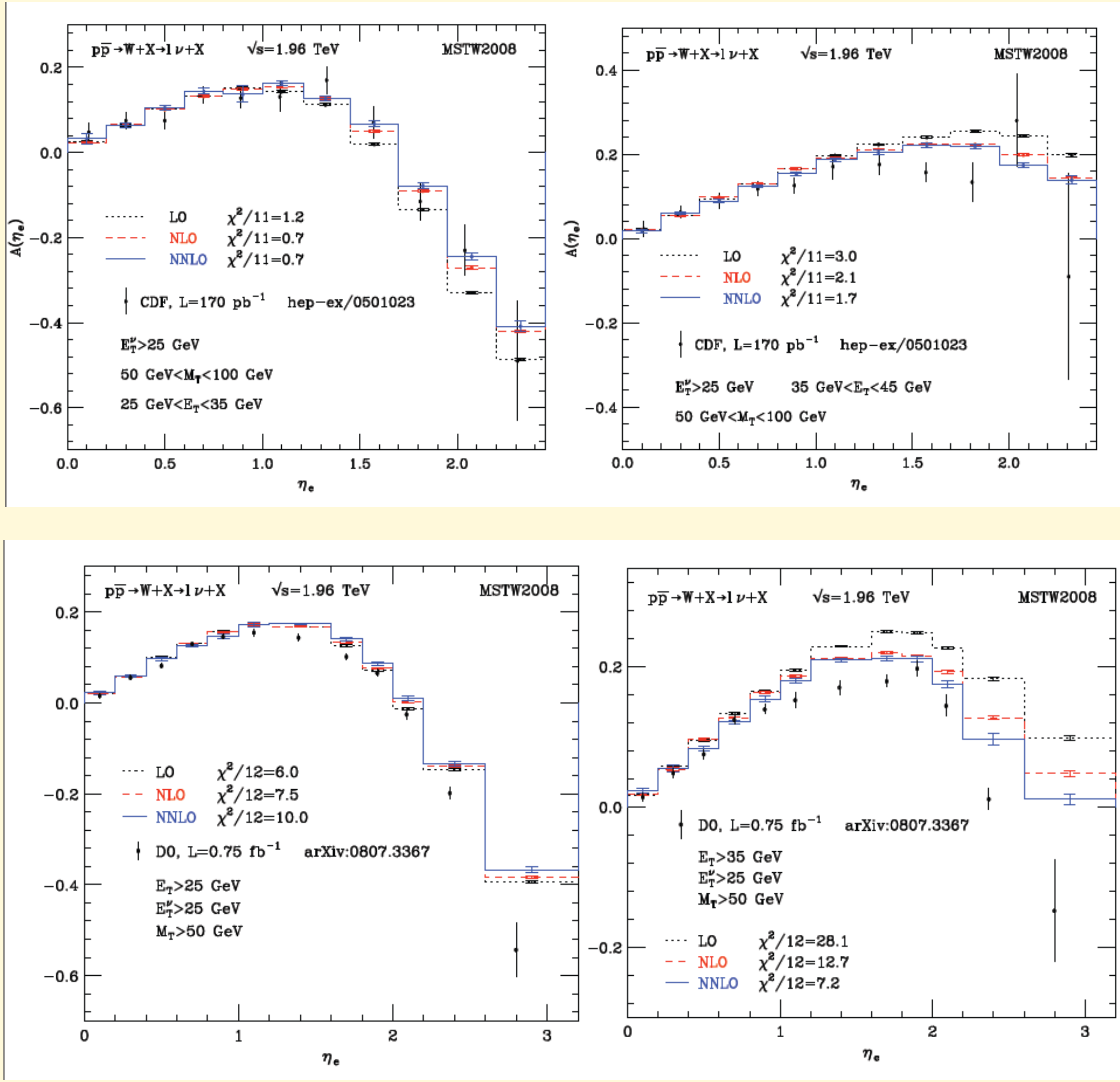
Run II comparison of W charge asymmetry with PDF parameterizations at the time (~2005)

Lepton charge asymmetry in W production

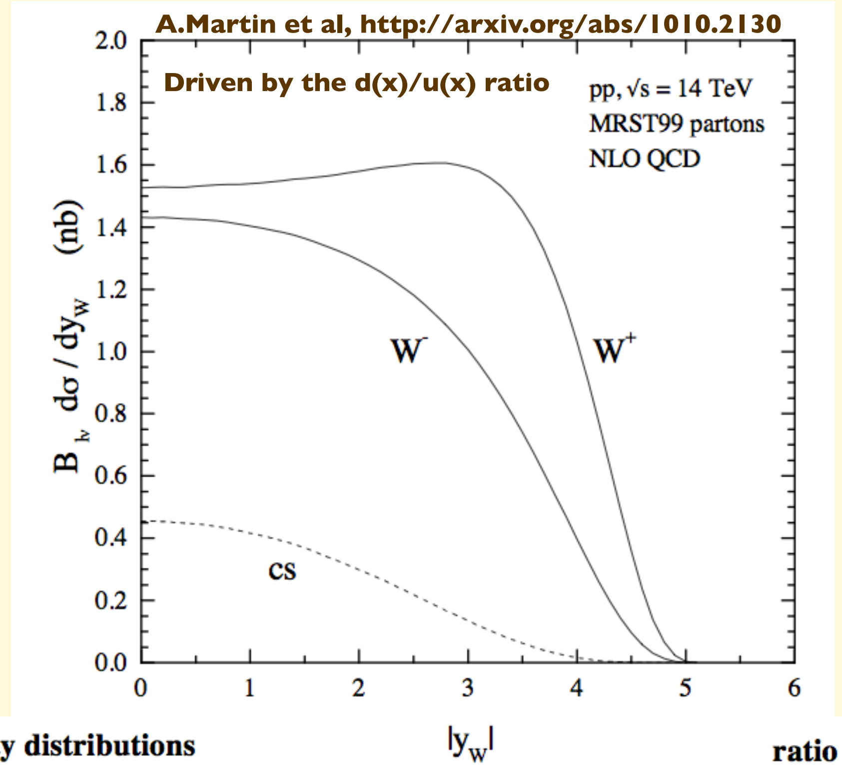


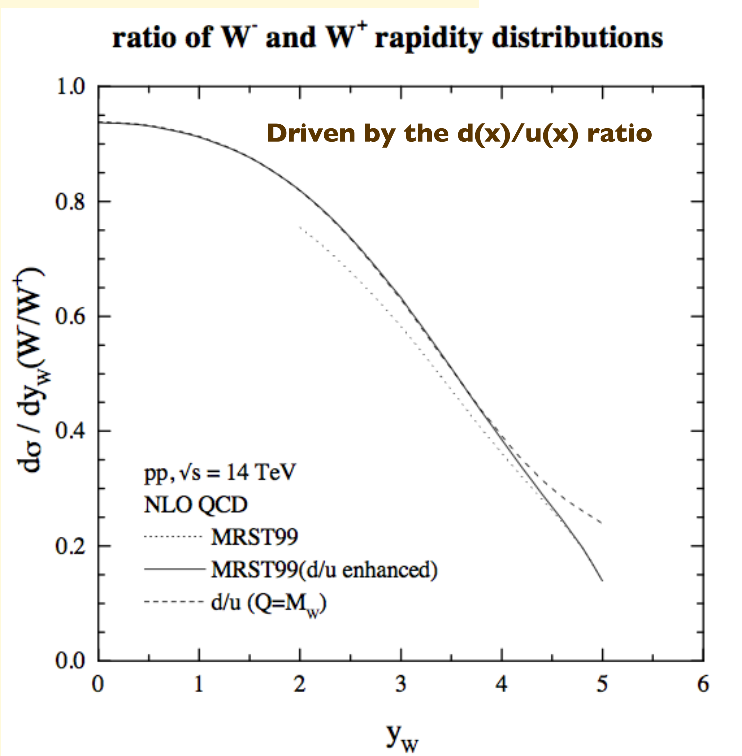
While the W+ prefers to go in the u-quark direction, the emerging e^+ prefers to go backward. The competition between these two effects leads to a non-trivial structure in the lepton charge asymmetry distribution!

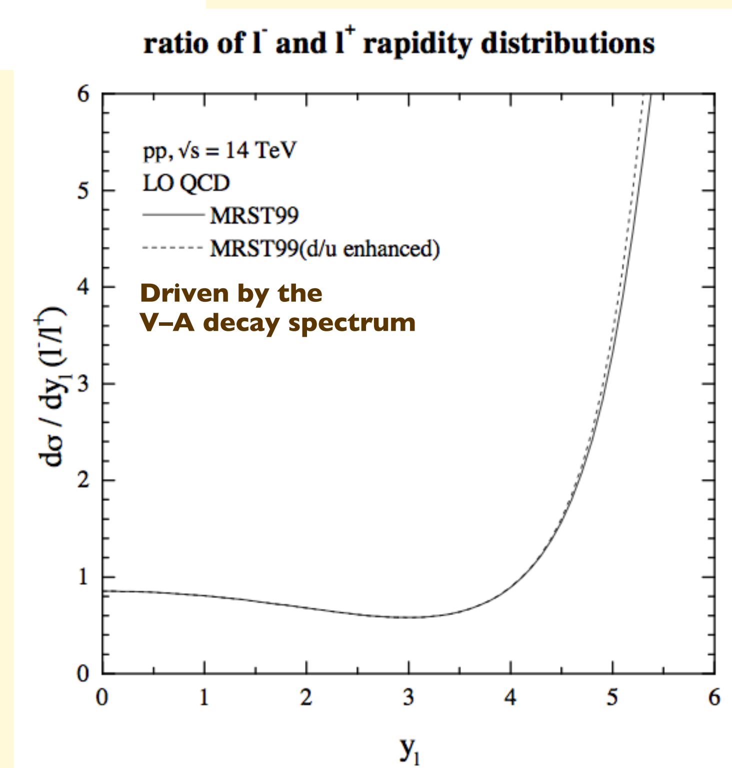
Lepton rapidity charge-asymmetry in W production at the Tevatron



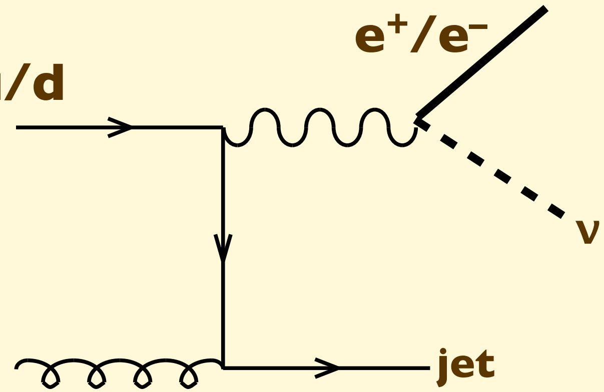
W+ / W– production asymmetries in pp collisions

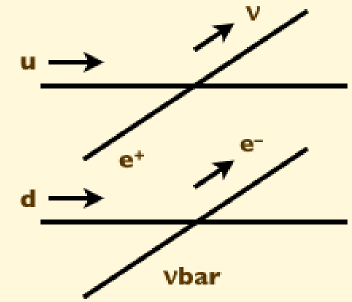




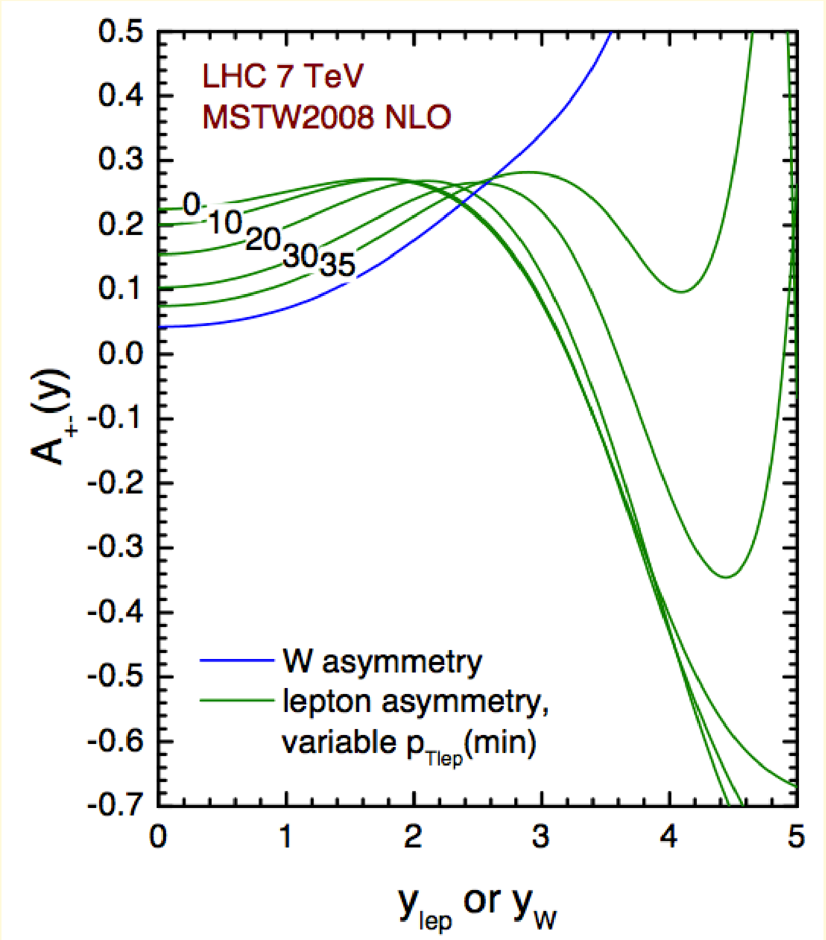


W charge asymmetry at large lepton pt





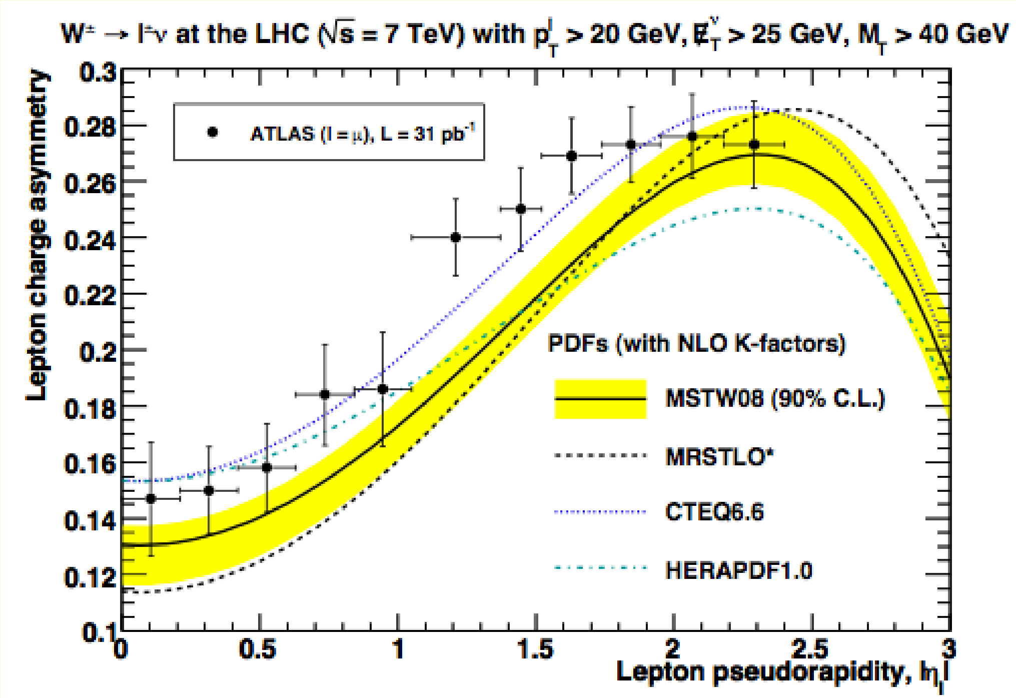
At large pt this diagram dominates.
V–A does not align the lepton with the IS quark, so u/d asymmetry dominates over V–A effects, which cause the bend over of the asymmetry at small ptW

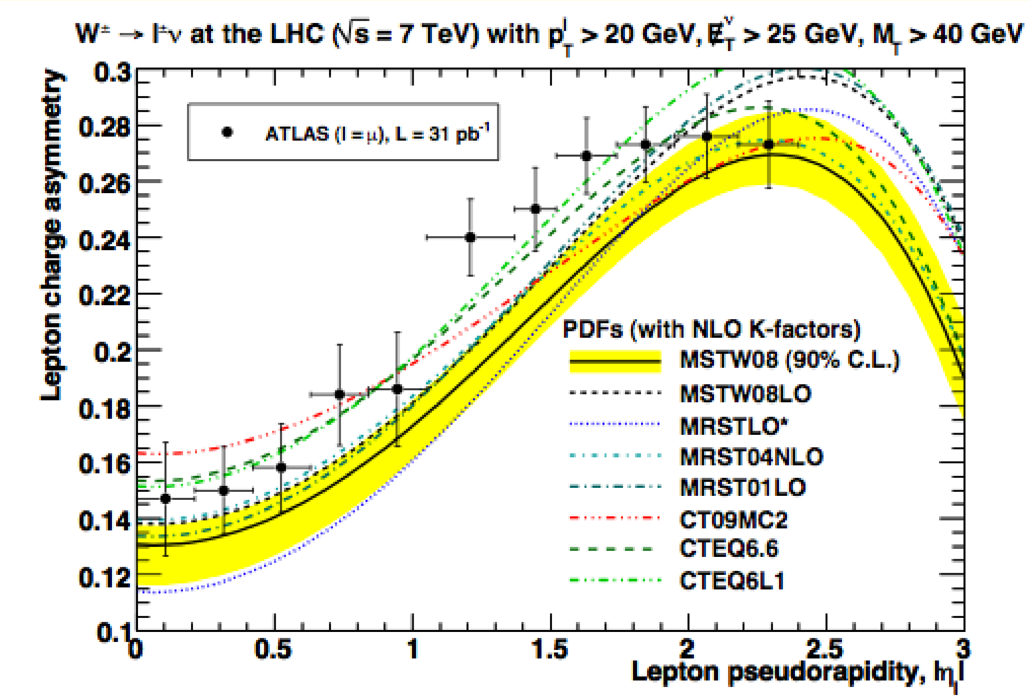


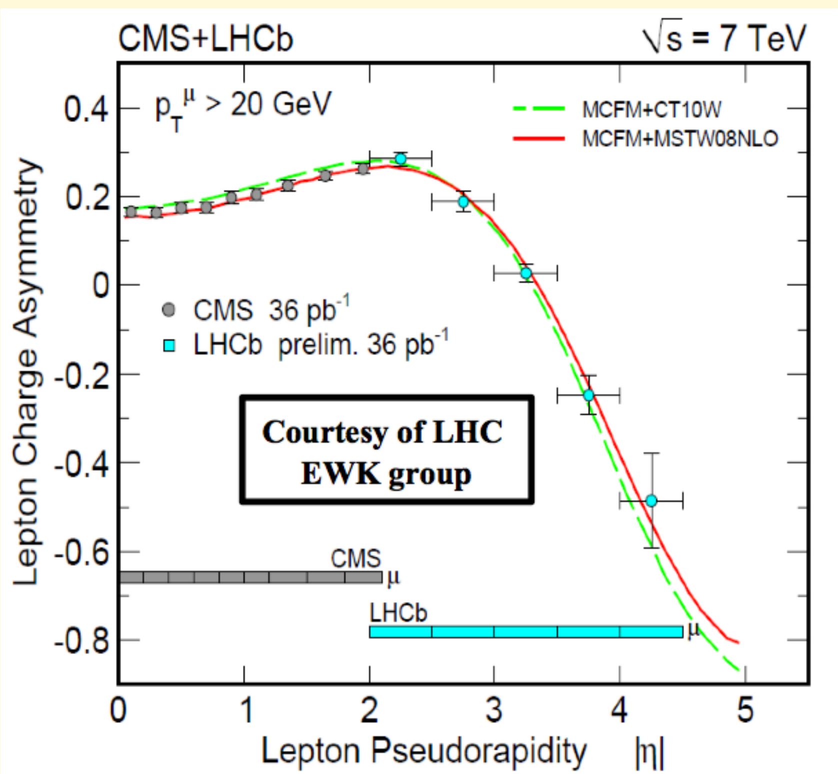
⇒ push the measurement to large pt
⇒ also consider large-pt and large-MET, to probe large x values

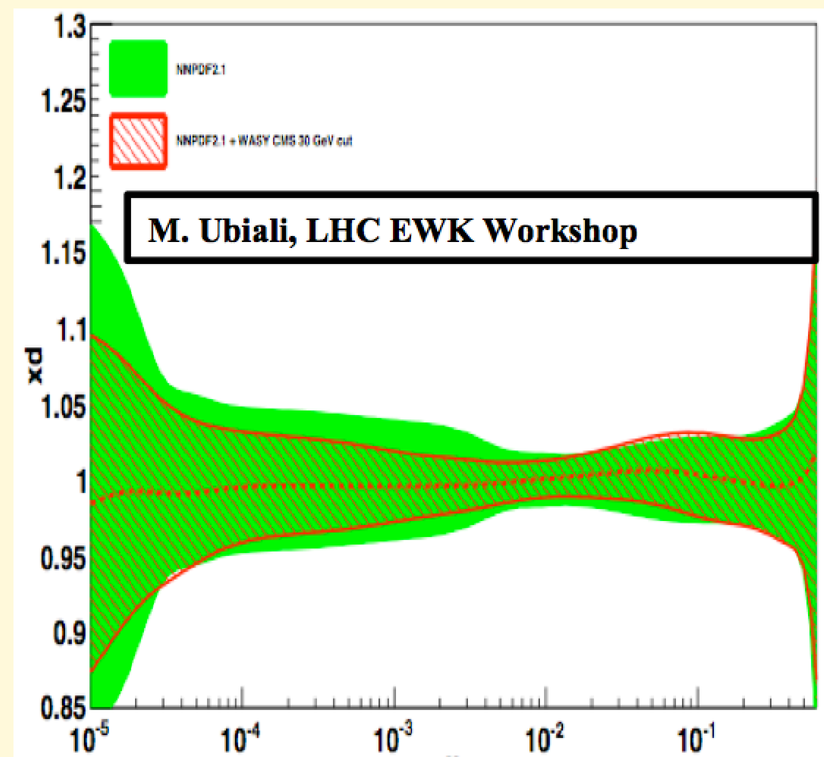
Lepton charge asymmetry in W production

G. Watt, http://arXiv.org/pdf/1106.5788



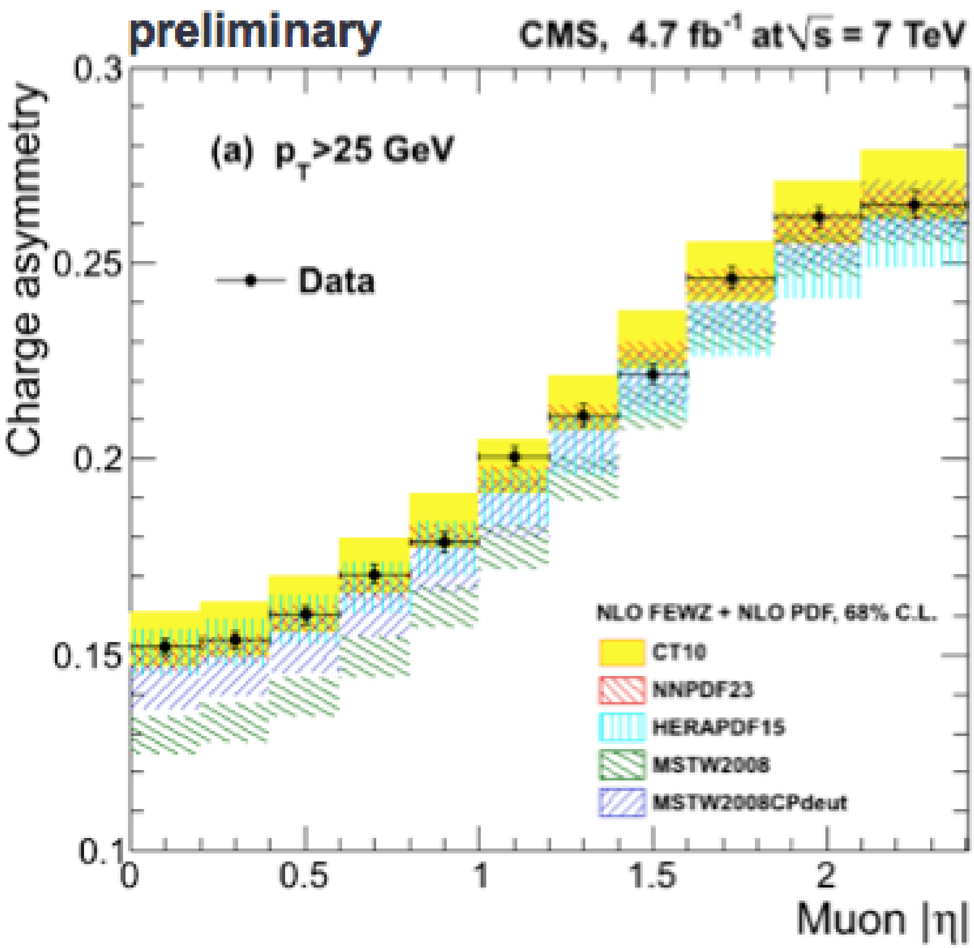


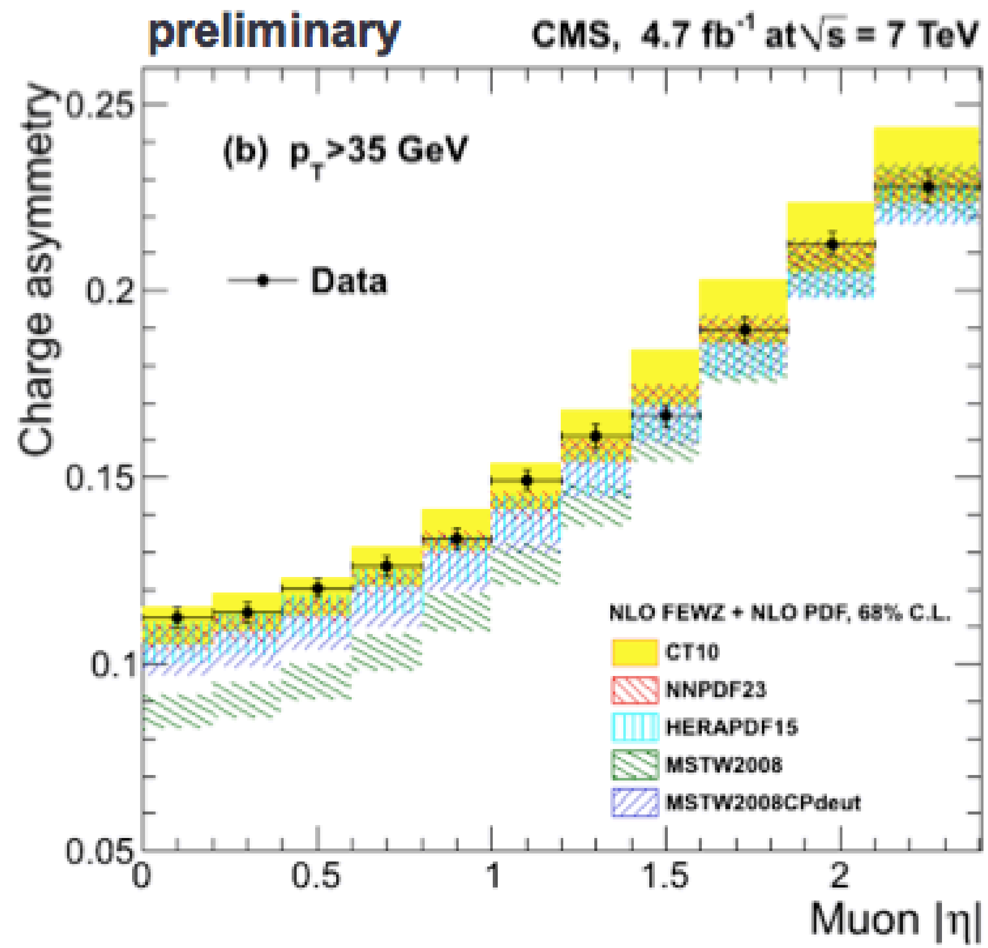




There is still room to further constrain PDF distributions relevant for W/Z production properties.

CMS-PAS-SMP-12-021





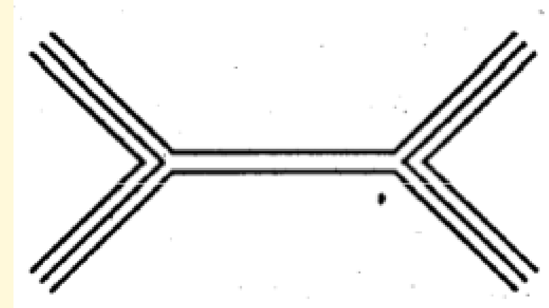
Questions:

- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements? Or perhaps fitting with PDFs some possible underlying new physics?

an example from the past ....

The presence of a quark substructure would manifest itself via contact interactions (as in Fermi's theory of weak interactions). On one side these new interactions would lead to an increase in cross-section, on the other they would affect the jets' angular distributions. In the dijet CMF, QCD implies Rutherford law, and extra point-like interactions can then be isolated using a fit.

Eichten, Lane, Peskin, Phys.Rev.Lett. 50 (1983) 811-814



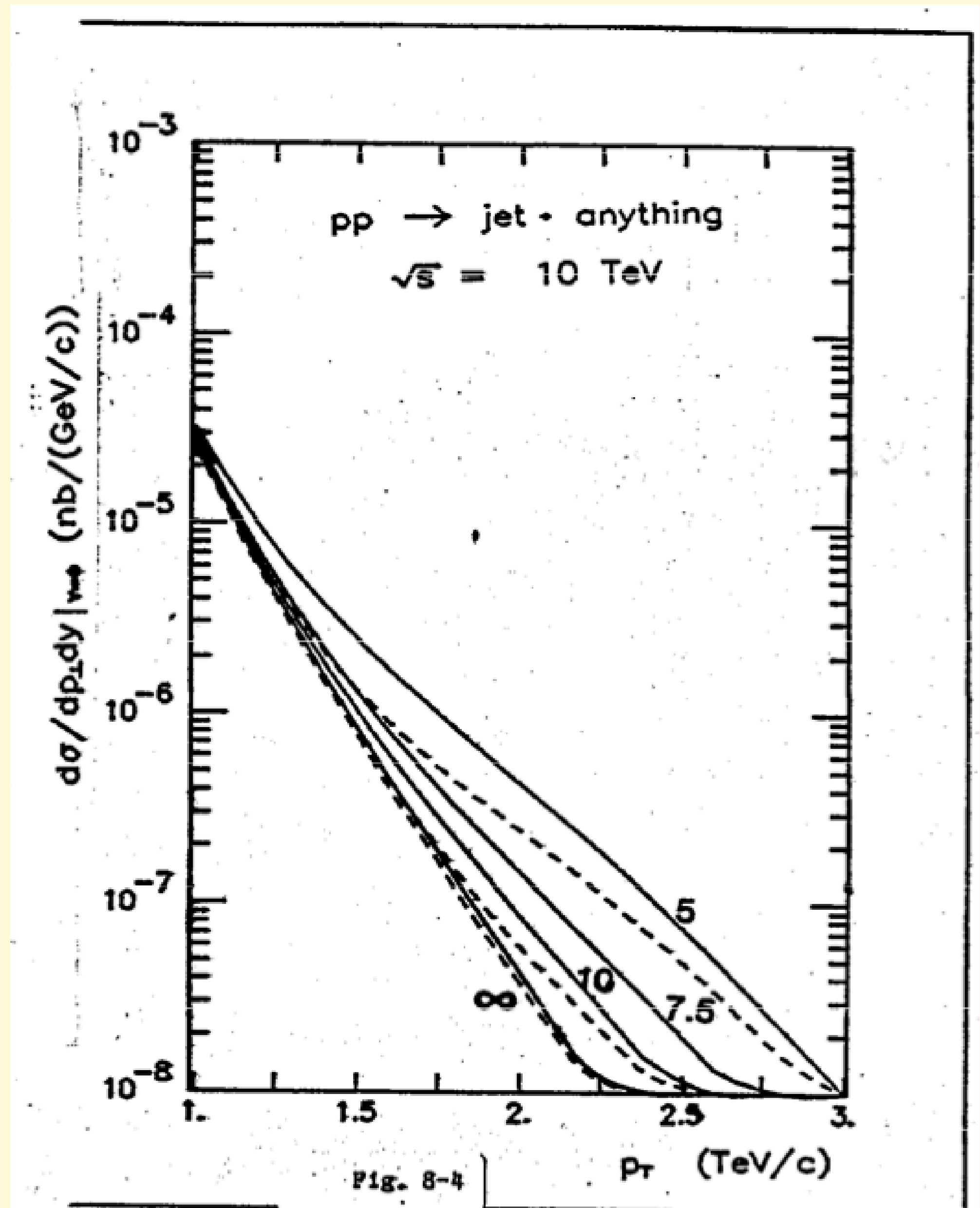
From the supercollider-bible of the 80's,

EHLQ (Eichten, Hinchliffe, Lane, Quigg): "Supercollider Physics", Rev.Mod.Phys. 56 (1984) 579-707

$$|A(u\bar{u}\to u\bar{u})|^2 = |A(d\bar{d}\to d\bar{d})|^2 =$$

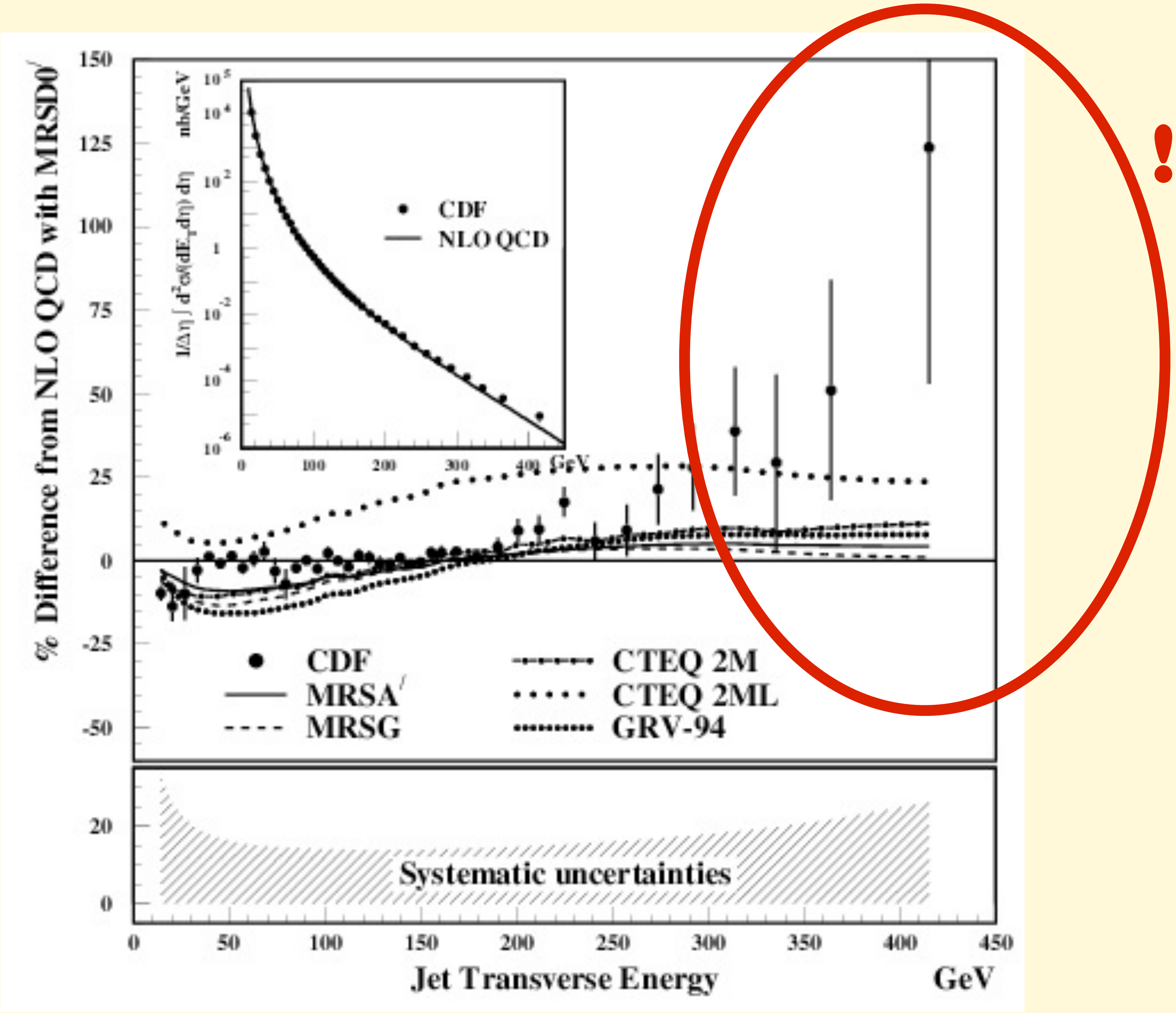
$$\frac{4}{9}\alpha_s^2(Q^2)\left[\frac{(\hat{u}^2+\hat{s}^2)}{\hat{t}^2} + \frac{(\hat{u}^2+\hat{t}^2)}{\hat{s}^2} - \frac{2}{3}\cdot\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$$

$$+\frac{8}{9}\alpha_s(Q^2)\frac{\eta_0}{\Lambda^{*2}}\left(\frac{\hat{u}^2}{\hat{t}} + \frac{\hat{u}^2}{\hat{s}}\right) + \frac{8}{3}\left(\frac{\eta_0\hat{u}}{\Lambda^{*2}}\right)^2;$$



At the LHC, with the anticipated statistics of 300 fb-1, limits on the scale of the new interactions in excess of 40 TeV should be reached (to increase to 60 TeV with 3000 fb-1)

Example, at the Tevatron, ~1995



!!!

Some kinematics

Prove as an **exercise** that

$$x_{1,2} = \frac{p_T}{E_{beam}} \cosh y^* \, e^{\pm y_b}$$

where

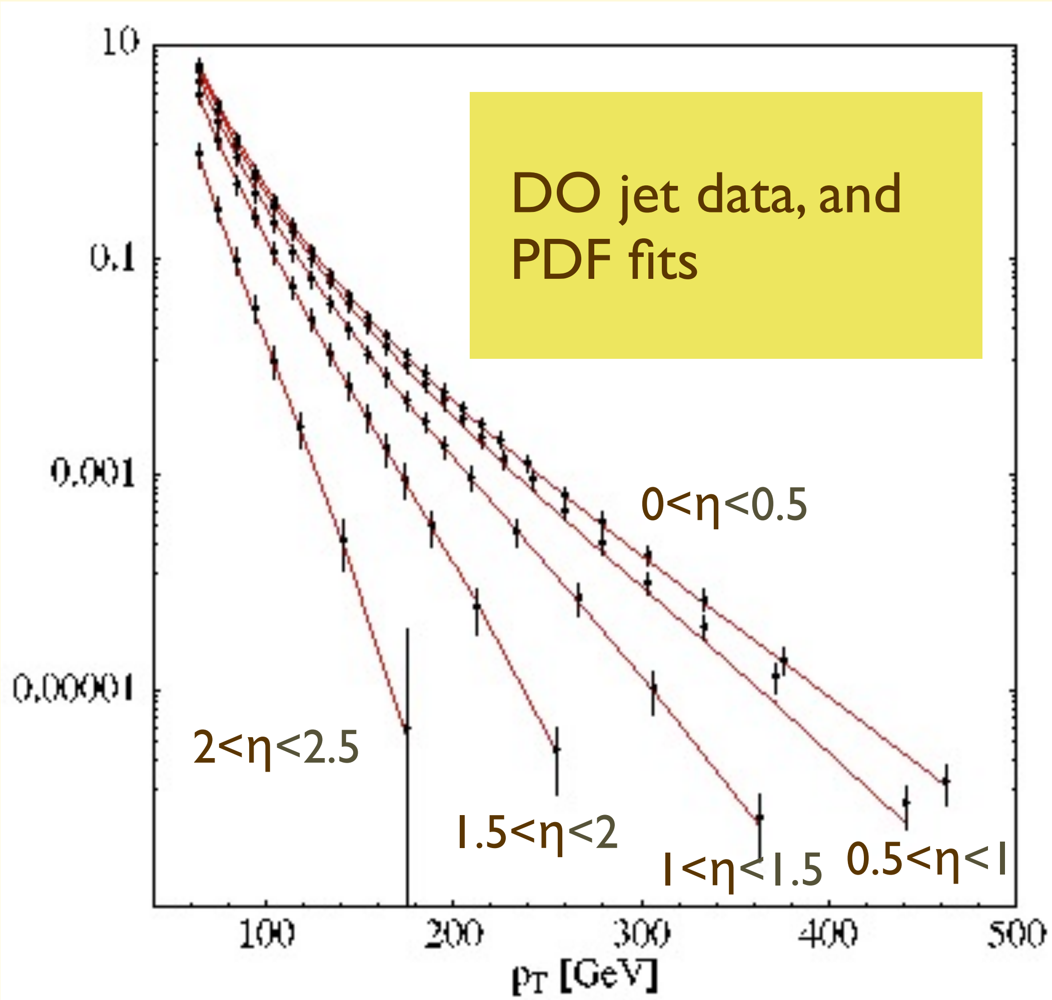
$$y^* = \frac{\eta_1 - \eta_2}{2}, \quad y_b = \frac{\eta_1 + \eta_2}{2}$$

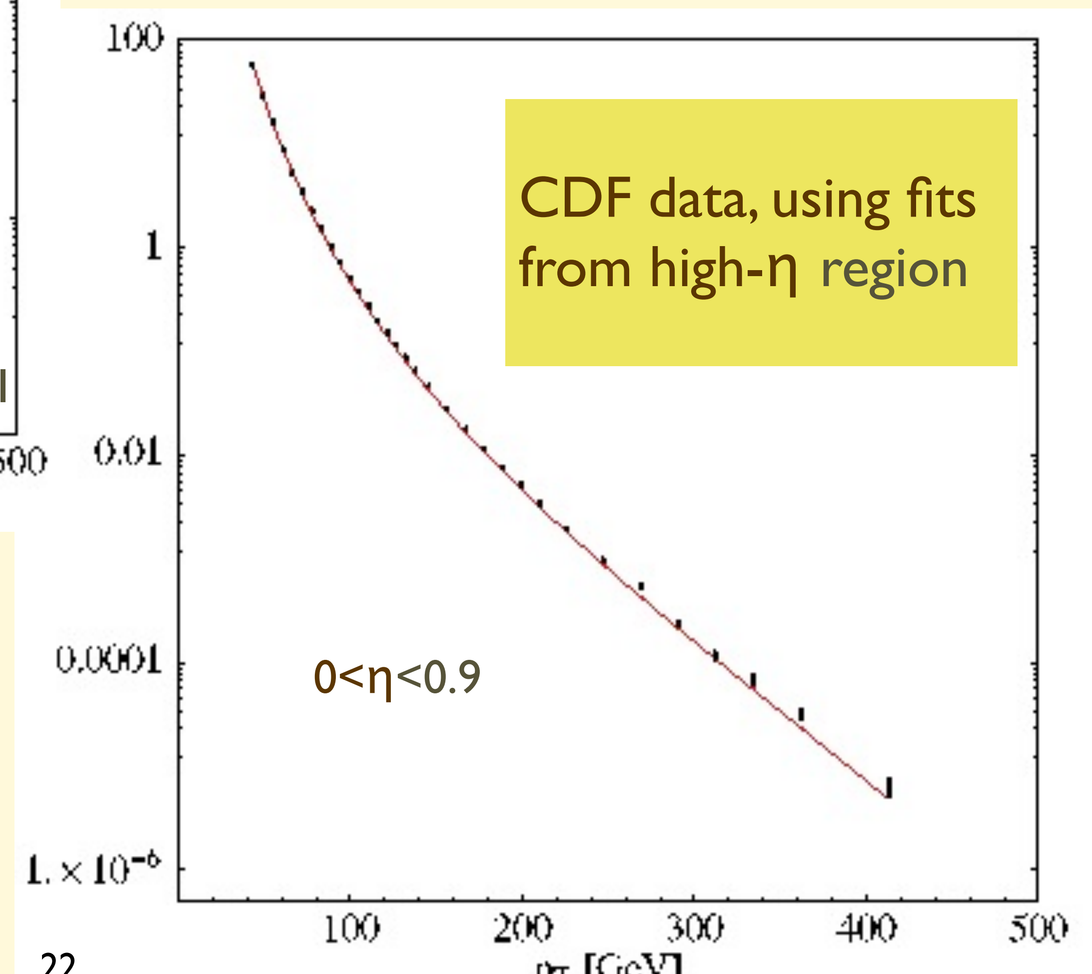
We can therefore reach large values of x either by selecting large invariant mass events:

$$\frac{p_T}{E_{beam}} \cosh y^* \equiv \sqrt{\tau} \to 1$$

or by selecting low-mass events, but with large boosts (y_b large) in either positive of negative directions. In this case, we probe large-x with events where possible new physics is absent, thus setting consistent constraints on the behaviour of the cross-section in the high-mass region, which could hide new phenomena.

Follow-up analyses, spectra vs eta, PDF refitting, ...





Tevatron, Run 2 results