Parton **D**istribution **F**unctions for the **L**arge **H**adron **C**ollider

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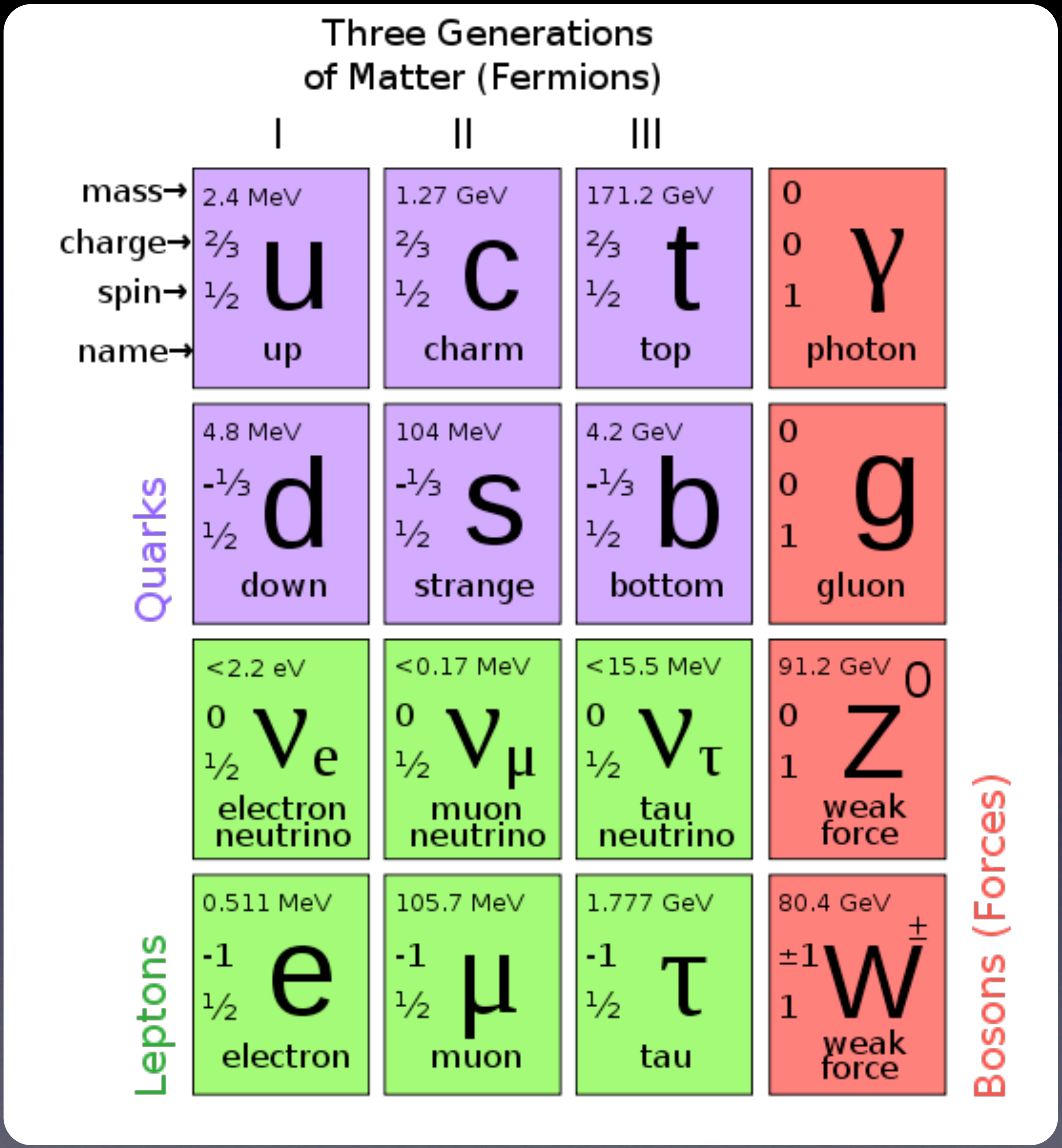
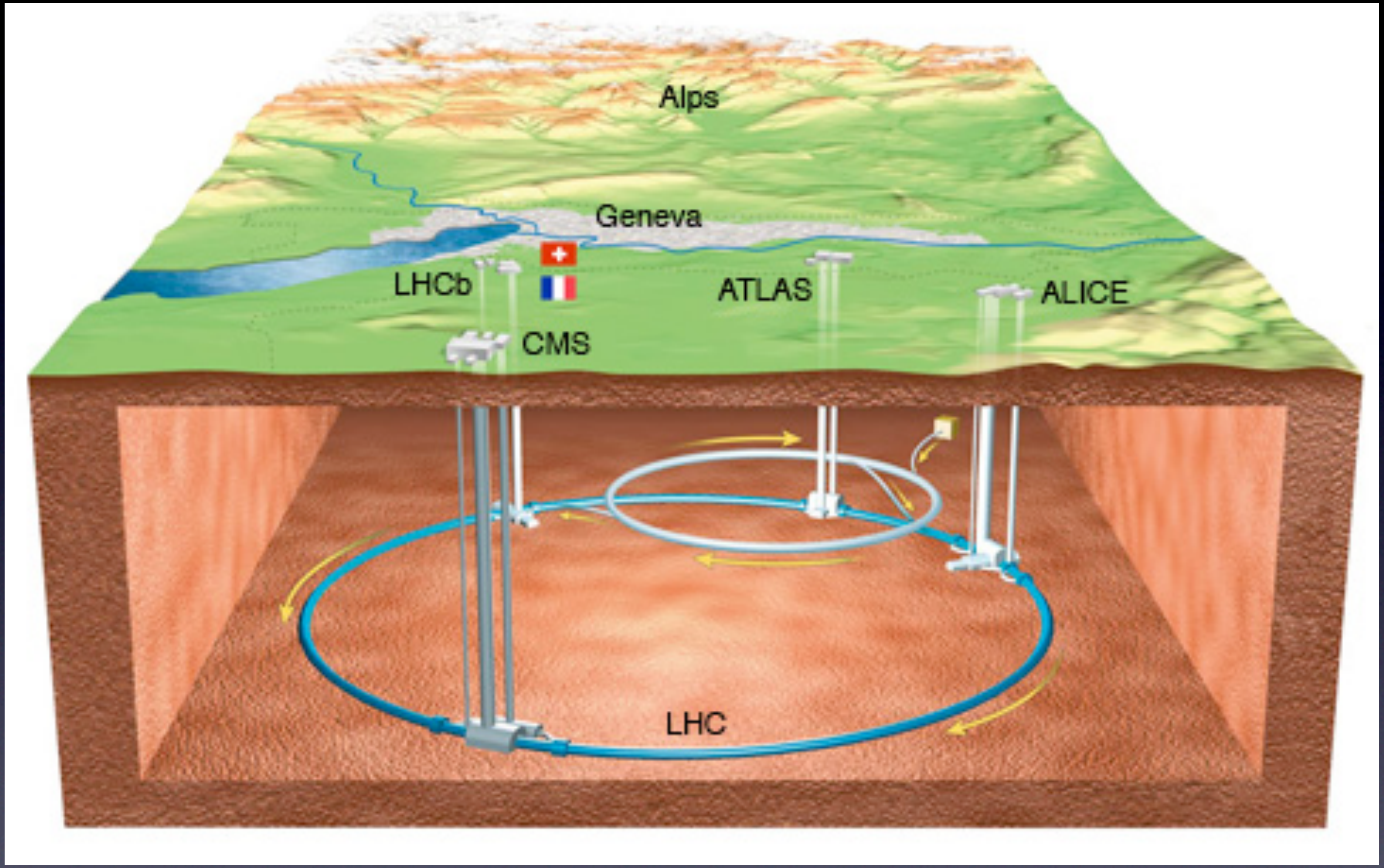
THEORETICAL PHYSICS

Standard Model of Particle Physics



- ... is very successful.
- Missing ingredient: Higgs boson.
- What lies beyond the Standard Model?
- SUperSYmmetry?
- Nature of Dark Matter?
- Extra Dimensions?

Large **H**adron **C**ollider (**LHC**)

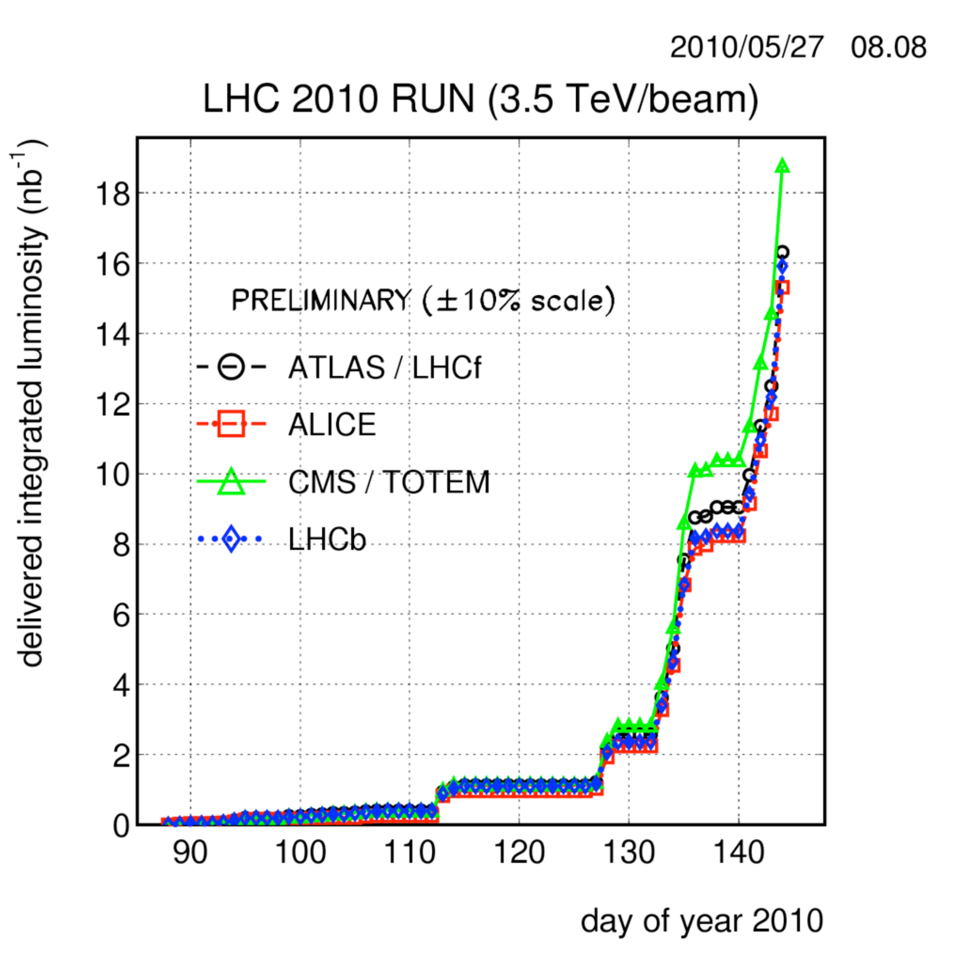


- 27 km circumference, *pp* collisions at 7 TeV.
- 4 experiments (ATLAS, CMS, LHCb, ALICE).

Status of the LHC

- False start in September 2008 (electrical fault)
  $\Rightarrow$ ~1 year to repair damage to magnets.

- 2.36 TeV collisions on 30 November 2009
  $\Rightarrow$ surpasses Tevatron $p\bar{p}$ collider (1.96 TeV).



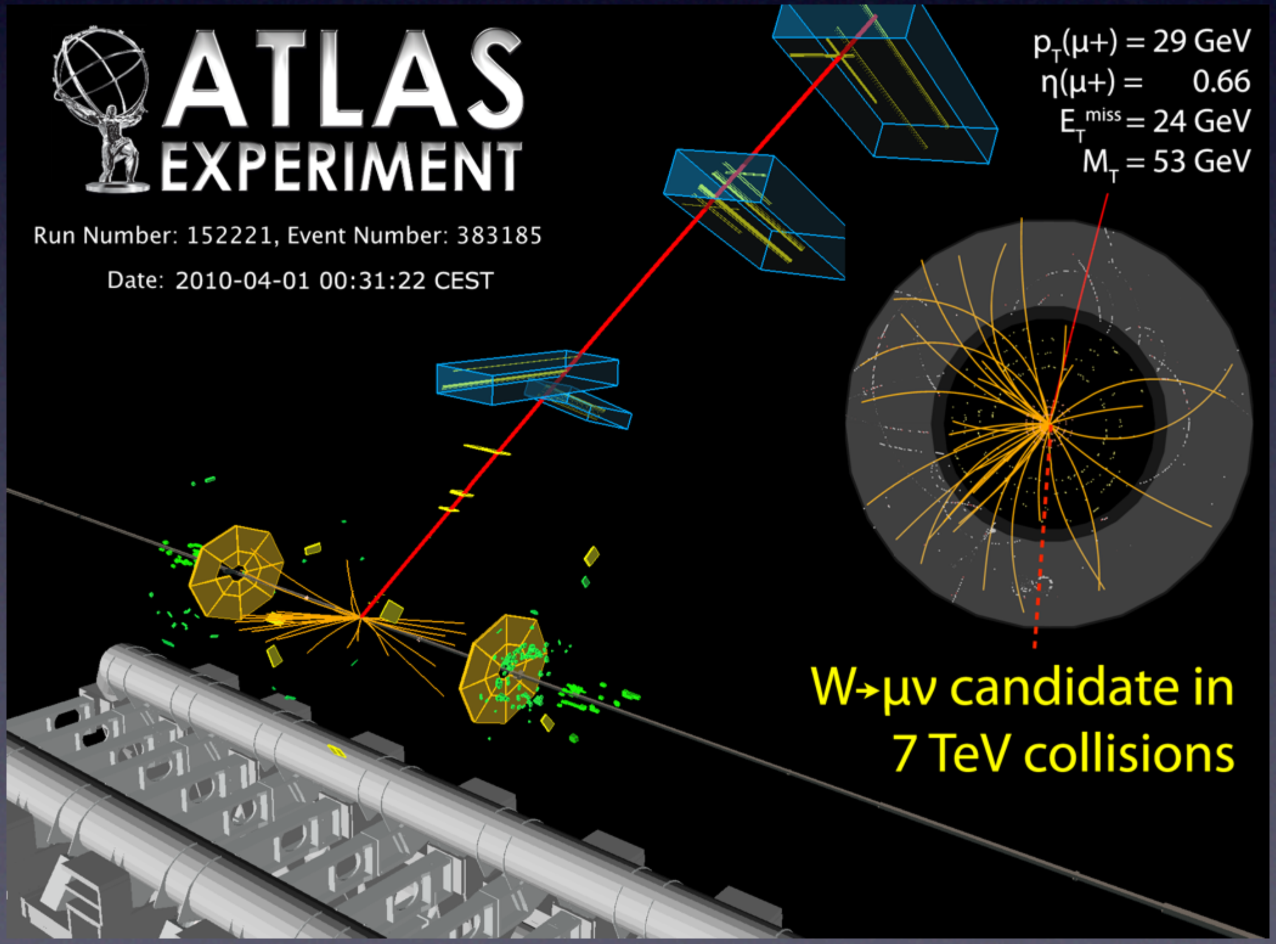
- 7 TeV collisions on 30 March.

- Peak luminosity: 10^{27} cm^{-2} s^{-1} (30 March), $2 \cdot 10^{29}$ (22 May), aim for 10^{32} by end 2010.

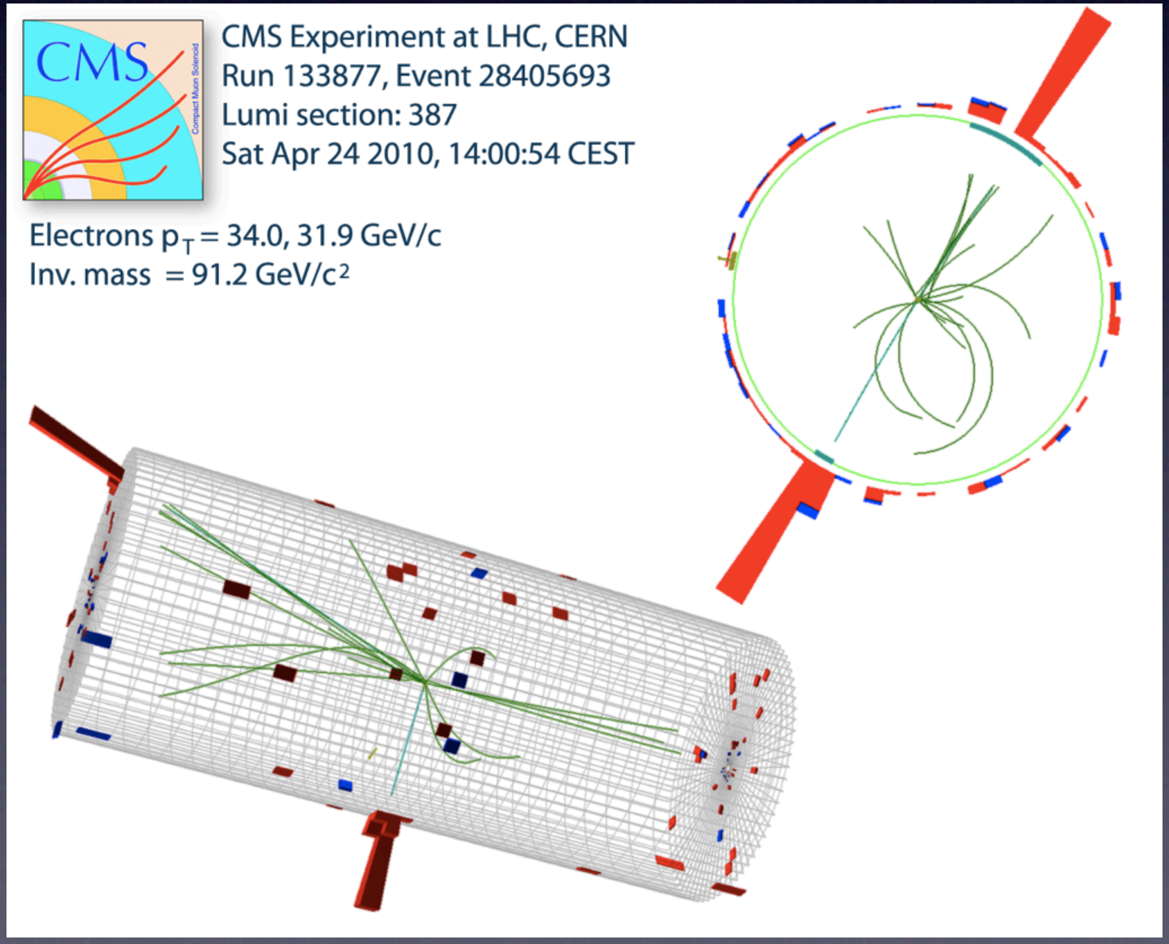
- Goal is integrated luminosity of 1 fb^{-1} by end of 2011, then prepare for 14 TeV collisions.

First W and Z candidate events

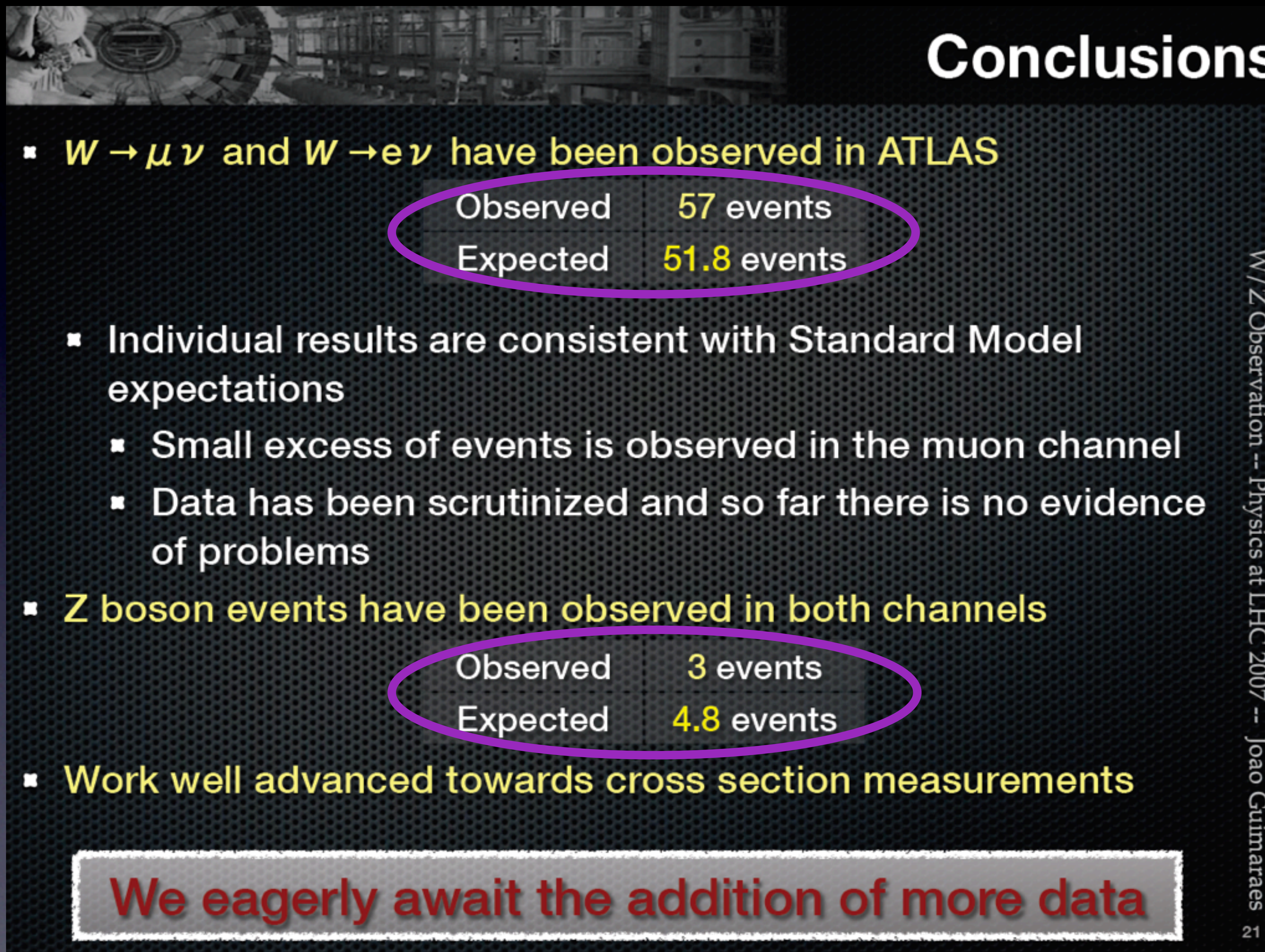
First W (→μν) candidate event from ATLAS:



First Z (→ee) candidate event from CMS:

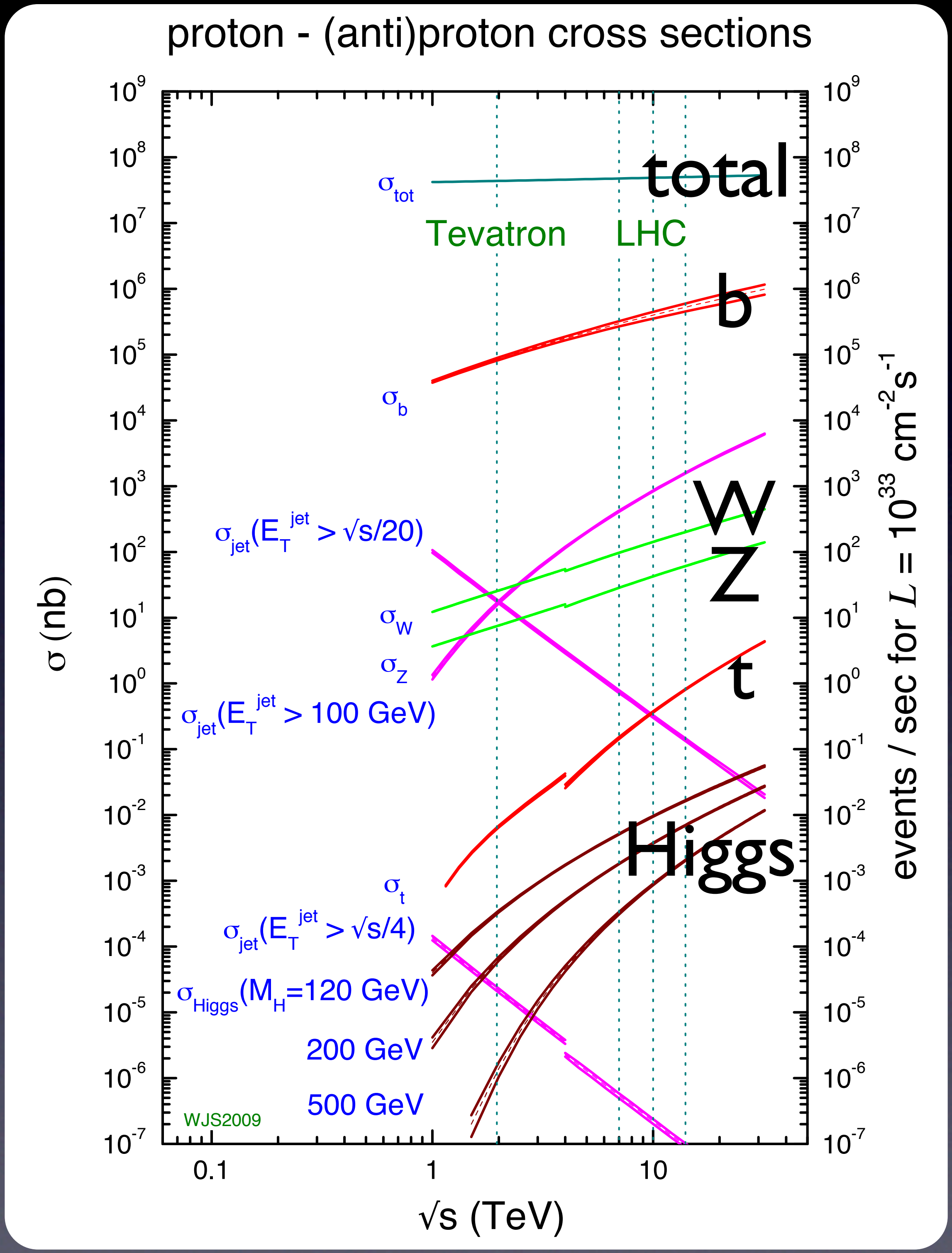


W and Z events in ATLAS



J. Guimaraes (ATLAS), "Physics at LHC 2010",
10th June 2010, DESY, Hamburg

Event rate = Cross section (σ) × Luminosity (*L*)



$$\sigma_W \cdot \mathrm{Br}(W \to \ell\nu) \approx 10\,\mathrm{nb}$$

$$\sigma_Z \cdot \mathrm{Br}(Z \to \ell\ell) \approx 1\,\mathrm{nb}$$

Theory ⟷ Cross sections ⟷ Experiment

- Theoretical calculations: Feynman diagrams have initial quarks and gluons.
- **Problem:** the LHC collides protons. Need to know density of quarks and gluons (partons) inside the proton.

↓

Parton **D**istribution **F**unctions (PDFs)

QCD factorisation

QCD = Quantum Chromodynamics

(describes interactions between quarks and gluons)

- $f_{a/A}(x, Q^2)$ gives *number density* of partons a in hadron A with momentum fraction x at a hard scale $Q^2 \gg \Lambda^2_{\rm QCD}$.

$$\sigma_{AB} = \sum_{a,b=q,g} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a/A}(x_a, Q^2) \, f_{b/B}(x_b, Q^2) \, \hat{\sigma}_{ab}$$

Perturbative expansion: $\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{\rm LO} + \alpha_S \, \hat{\sigma}_{ab}^{\rm NLO} + \alpha_S^2 \, \hat{\sigma}_{ab}^{\rm NNLO} + \ldots$

PDF evolution:
(DGLAP equation)

$$\frac{\partial f_{a/A}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} [P_{aa'}^{\rm LO} + \alpha_S P_{aa'}^{\rm NLO} + \ldots] \otimes f_{a'/A}$$

α_S evolution:

$$\frac{\partial \alpha_S}{\partial \ln Q^2} = -\beta^{\rm LO} \alpha_S^2 - \beta^{\rm NLO} \alpha_S^3 - \ldots$$

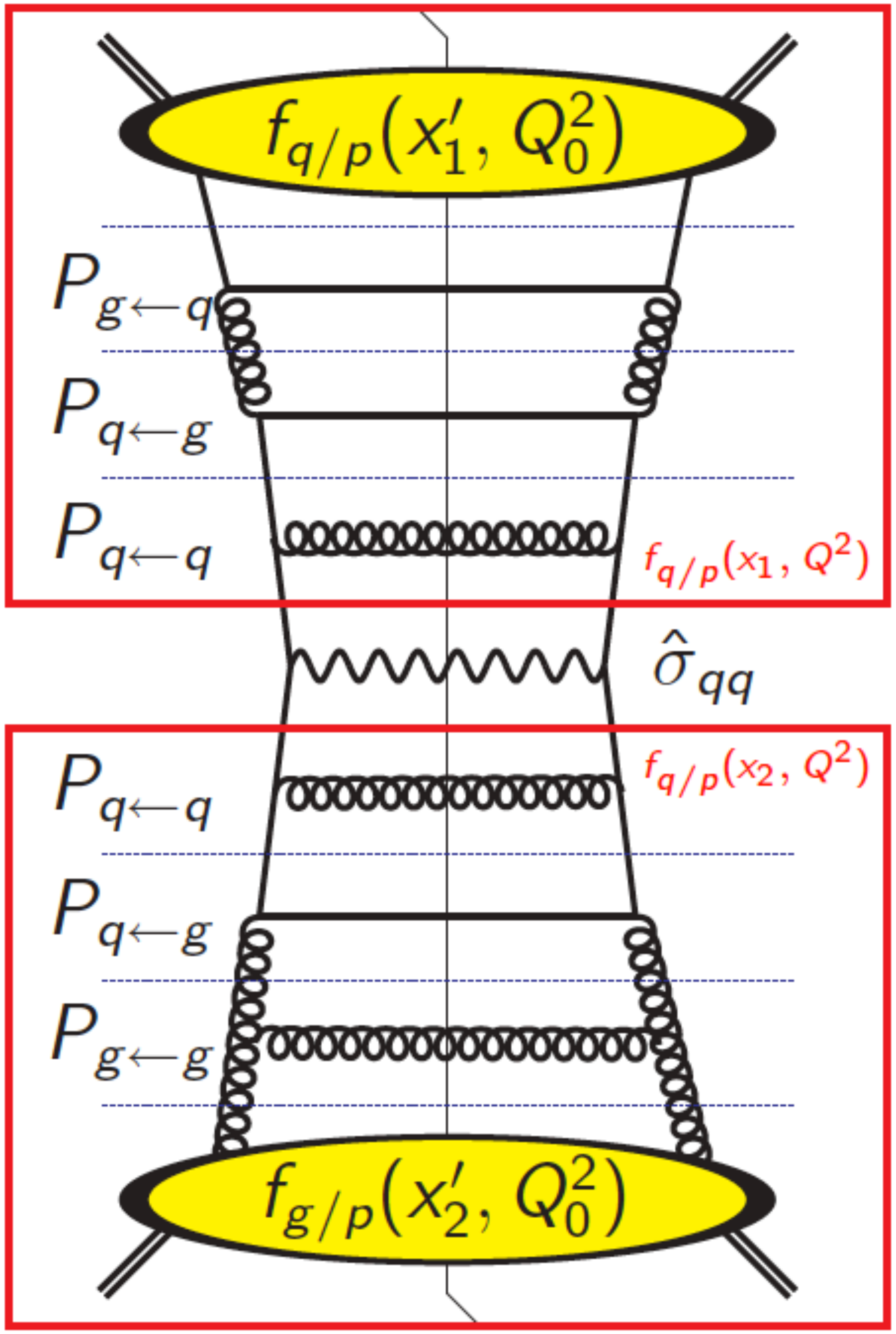
- Need to extract input values $f_{a/A}(x, Q_0^2)$ and $\alpha_S(M_Z^2)$ from data.

NLO is standard.

NNLO $P_{aa'}$ (2004) and 2→1.

Lattice QCD?

Diagrammatic interpretation

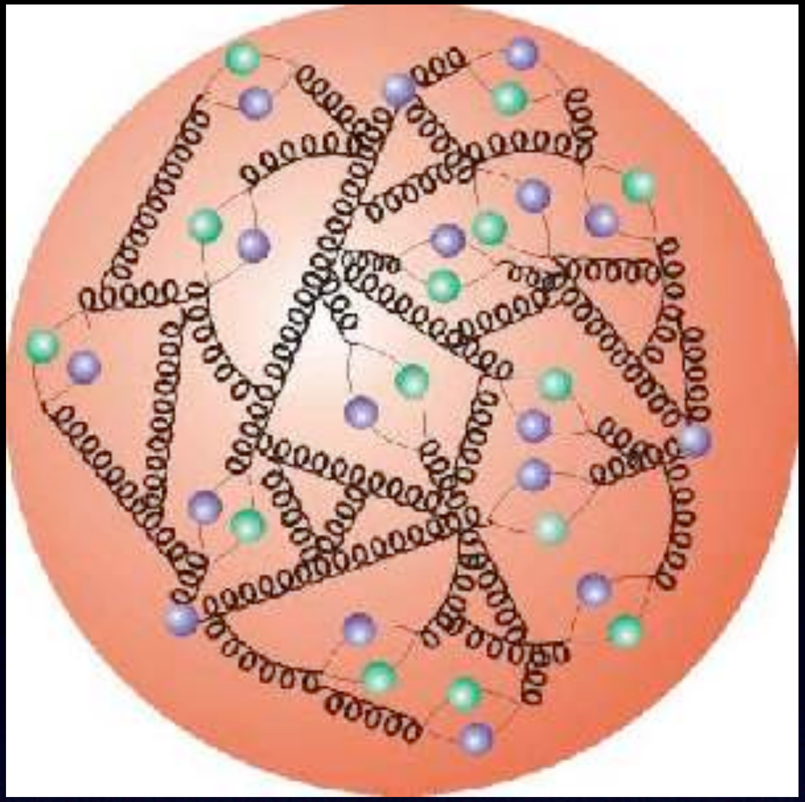


- Drell–Yan production at LO: $q\bar{q} \to V = W/Z/\gamma^*$
- Cut diagram: $|\mathcal{M}|^2 = \mathcal{M}\mathcal{M}^*$
- Large logarithm from collinear gluon emission: $\int_{k_0^2}^{Q^2} (\mathrm{d}k_T^2/k_T^2)\, \frac{\alpha_S}{2\pi}\, P_{q\leftarrow q}(z)$
- Similar collinear logs from other parton splittings.
- DGLAP evolution equation:

$$\frac{\partial f_{a/p}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} P_{a\leftarrow a'} \otimes f_{a'/p}$$

- $f_{a/p}(x, Q_0^2) \Rightarrow f_{a/p}(x, Q^2)$

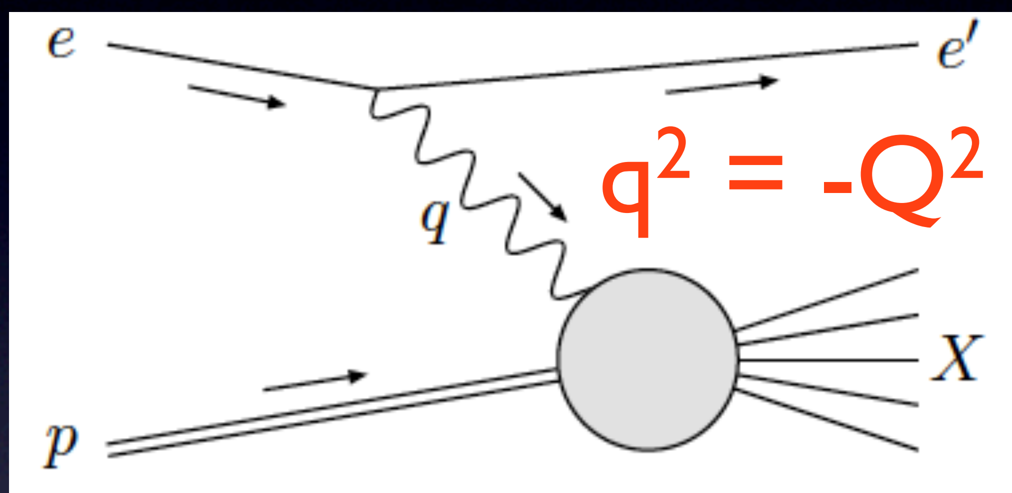
HERA *ep* collider



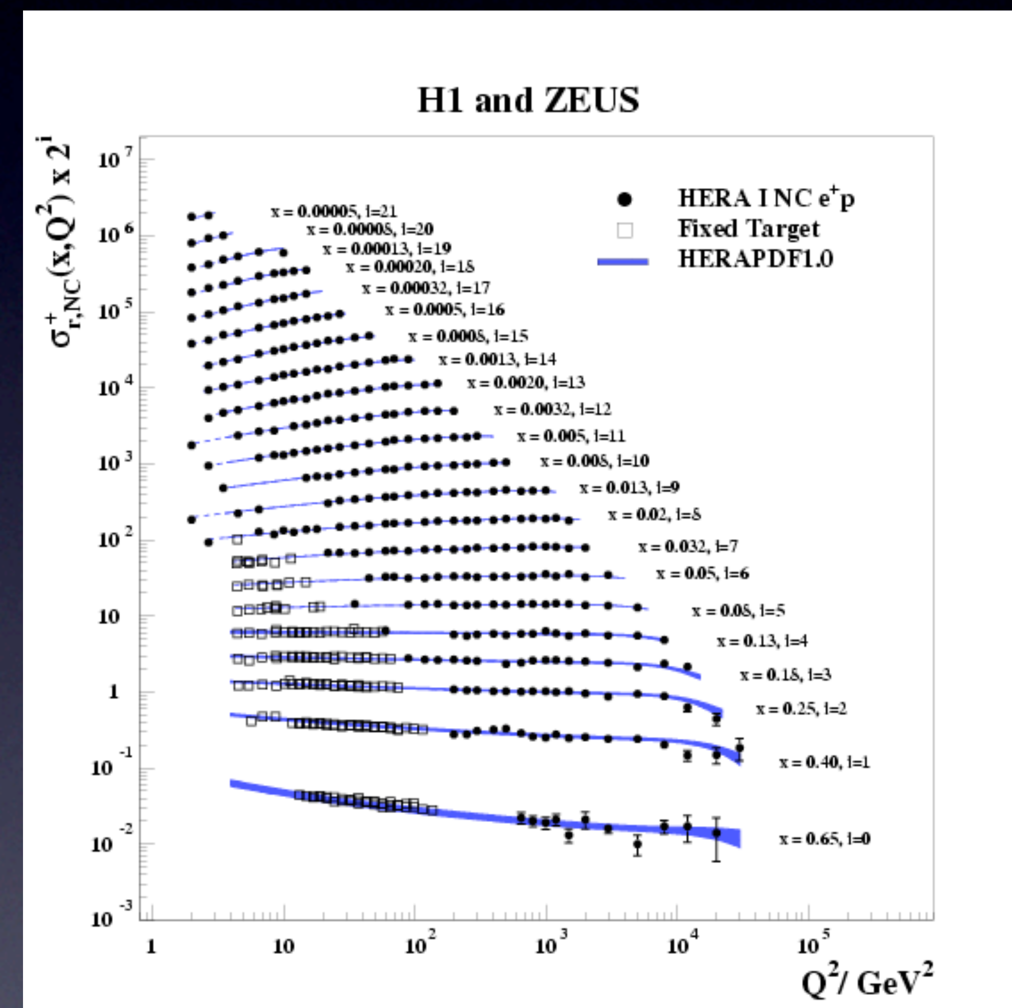
- Located at DESY, Hamburg.
- Operated from 1992-2007.
- *ep* collisions at 318 GeV.
- 6.3 km circumference.
- Experiments: H1, ZEUS.

Deep-inelastic scattering (DIS)

$$F_i\left(x,Q^2\right) = \sum_{a=q,g} C_{i,a} \otimes f_{a/A}, \quad C_{i,a} = C_{i,a}^{\rm LO} + \alpha_S C_{i,a}^{\rm NLO} + \ldots$$



$$F_2^{\rm LO}(x,Q^2) = \sum_q e_q^2\, x f_{q/p}$$



Deep-inelastic scattering (DIS)

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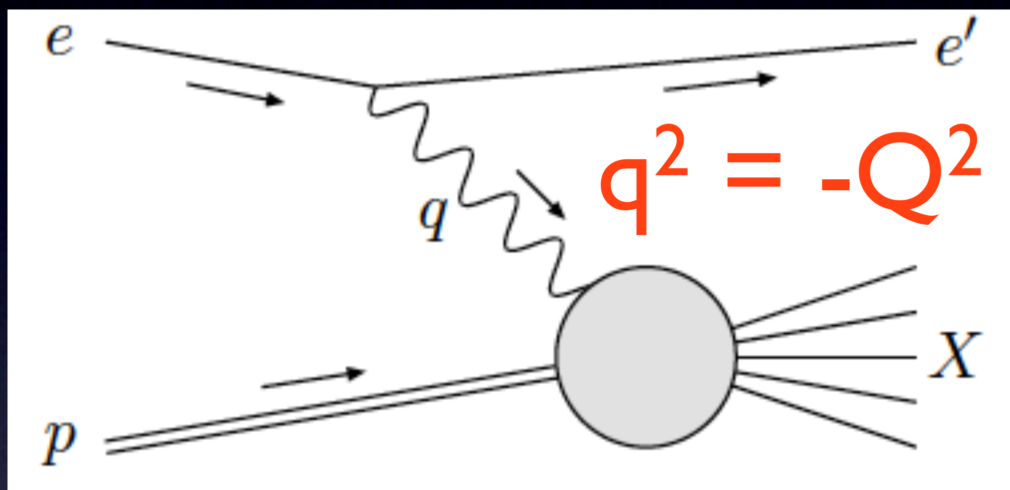
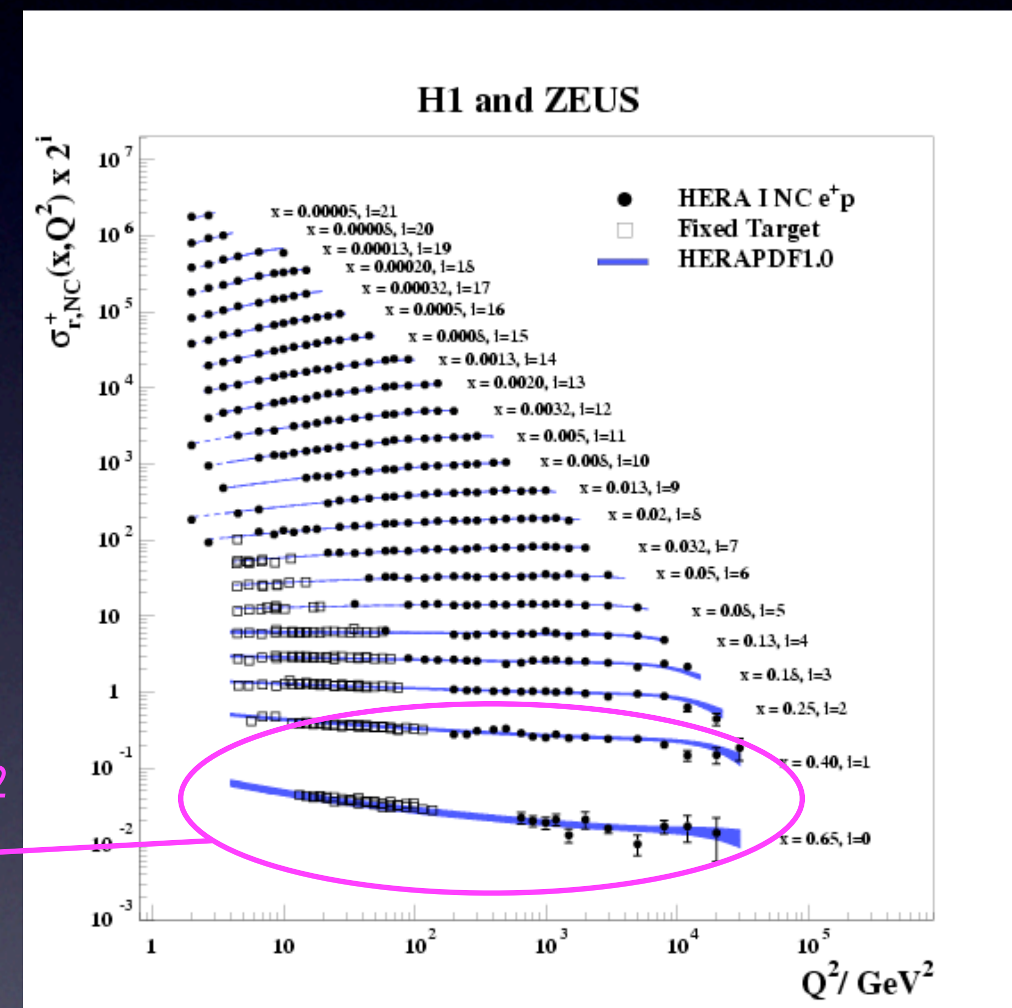




$$F_2^{\mathrm{LO}}(x,Q^2) = \sum_q e_q^2\, x f_{q/p}$$

↓ At large x,
F_2 falls with Q^2

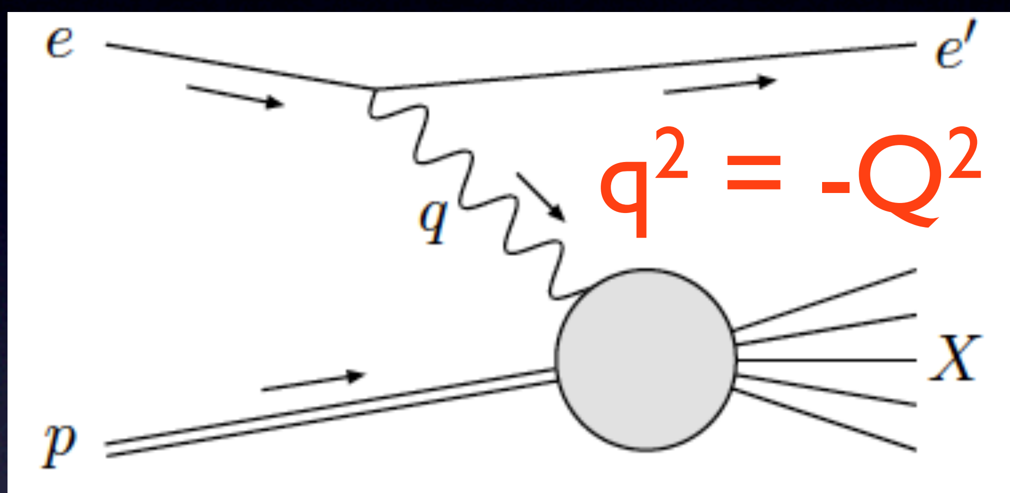
QCD scaling violations

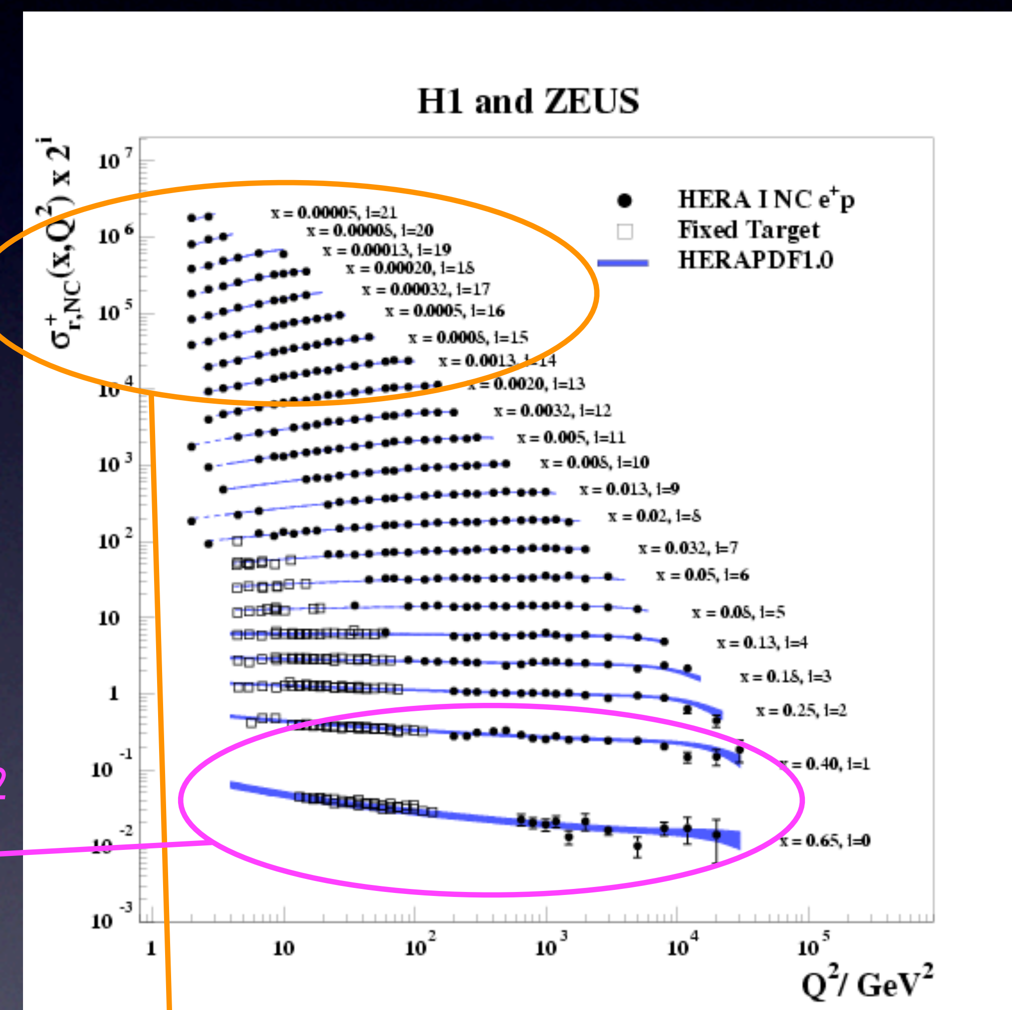
DGLAP

$$\frac{\partial F_2^{\mathrm{LO}}(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi}\left[P_{q\leftarrow q}^{\mathrm{LO}} \otimes F_2^{\mathrm{LO}} + \sum_q e_q^2\, P_{q\leftarrow g}^{\mathrm{LO}} \otimes f_{g/p}\right]$$

Deep-inelastic scattering (DIS)

$$F_i\left(x, Q^2\right) = \sum_{a=q,g} C_{i,a} \otimes f_{a/A}, \quad C_{i,a} = C_{i,a}^{\mathrm{LO}} + \alpha_S C_{i,a}^{\mathrm{NLO}} + \ldots$$





$$F_2^{\mathrm{LO}}(x, Q^2) = \sum_q e_q^2 \, x f_{q/p}$$

↓ At large *x*, F_2 falls with Q^2

QCD scaling violations

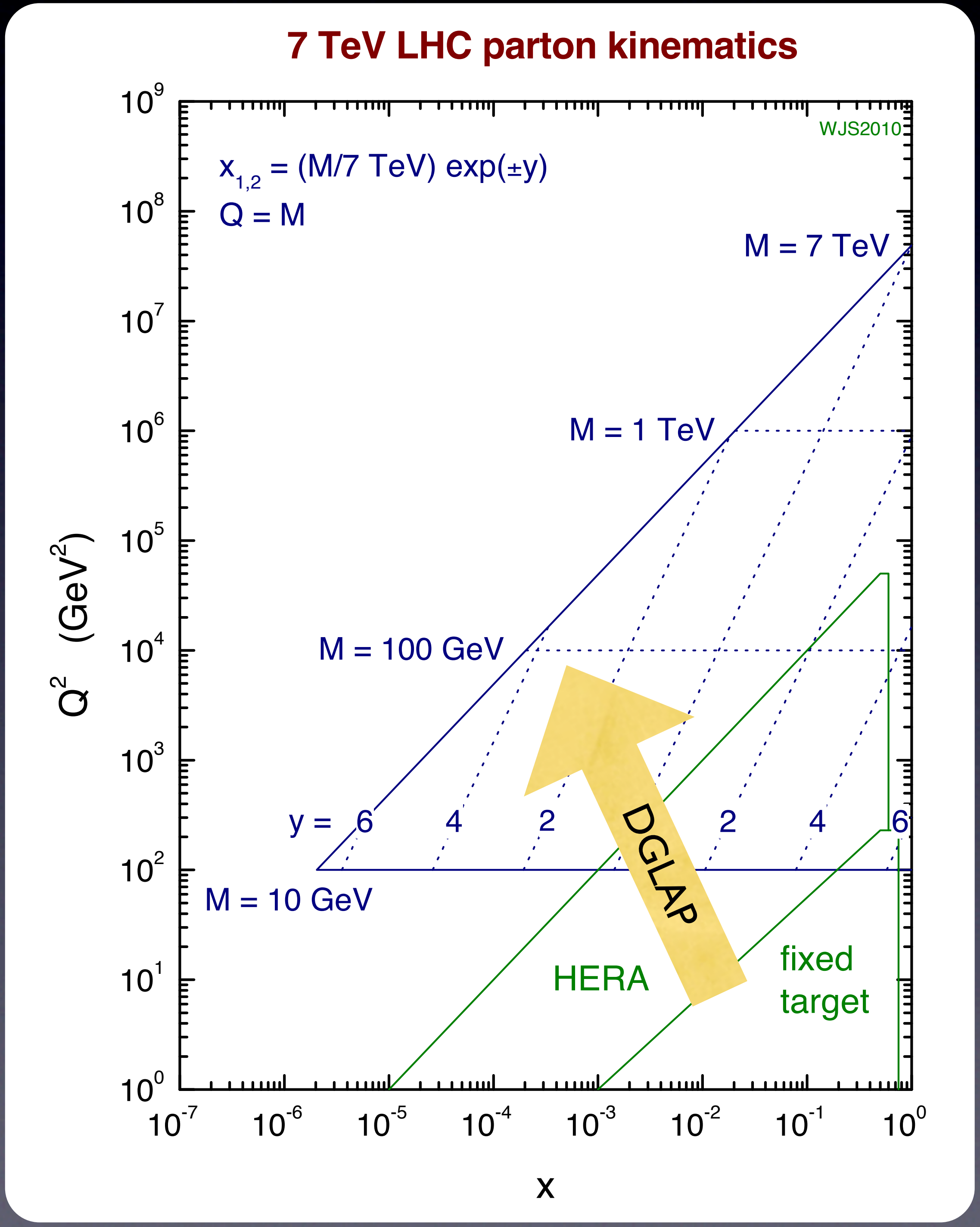
DGLAP

$$\frac{\partial F_2^{\mathrm{LO}}(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi}\left[P_{q\leftarrow q}^{\mathrm{LO}} \otimes F_2^{\mathrm{LO}} + \sum_q e_q^2 \, P_{q\leftarrow g}^{\mathrm{LO}} \otimes f_{g/p}\right]$$

↑ At small *x*, F_2 rises with Q^2

LHC kinematic plane

Produce a final state of mass $M = \sqrt{(x_1 x_2 s)}$ and rapidity $y = 0.5 \log(x_1/x_2)$ at LHC ($\sqrt{s}$ = 7 TeV) from two partons with momentum fractions x_1 and x_2.



- PDFs are **universal**.
- Fit existing data from HERA and fixed-target experiments, together with Tevatron data.
- HERA *ep* (H1, ZEUS).
- Fixed-target experiments:
  ℓp, *ℓd*
  (BCDMS, NMC, E665, SLAC),
  νN
  (CCFR, NuTeV, CHORUS),
  pp, *pd* (E866/NuSea).
- Tevatron $p\bar{p}$ (CDF, DØ).
- DGLAP evolution gives PDFs at higher Q^2 for LHC.

Which processes constrain different PDFs?

Process	Subprocess	Partons	x range
$\ell^\pm \{p, n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+ \{d, s\} \to \{u, c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$	$\gamma^* c \to c$, $\gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm \nu) X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-) X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

Need many processes from different experiments
⇒ **global** analysis needed for flavour separation.

Paradigm for PDF determination

1. **Parameterise** the x dependence for each flavour $a = q, g$ at the input scale $Q_0^2 \sim 1\ \text{GeV}^2$ in some flexible form, e.g.

$$xf_{a/p}(x, Q_0^2) = A_a\, x^{\Delta_a}\, (1-x)^{\eta_a}\, (1 + \epsilon_a \sqrt{x} + \gamma_a\, x),$$

   subject to number- and momentum-sum rule constraints.

2. **Evolve** the PDFs to higher scales $Q^2 > Q_0^2$ using the DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) evolution equations.

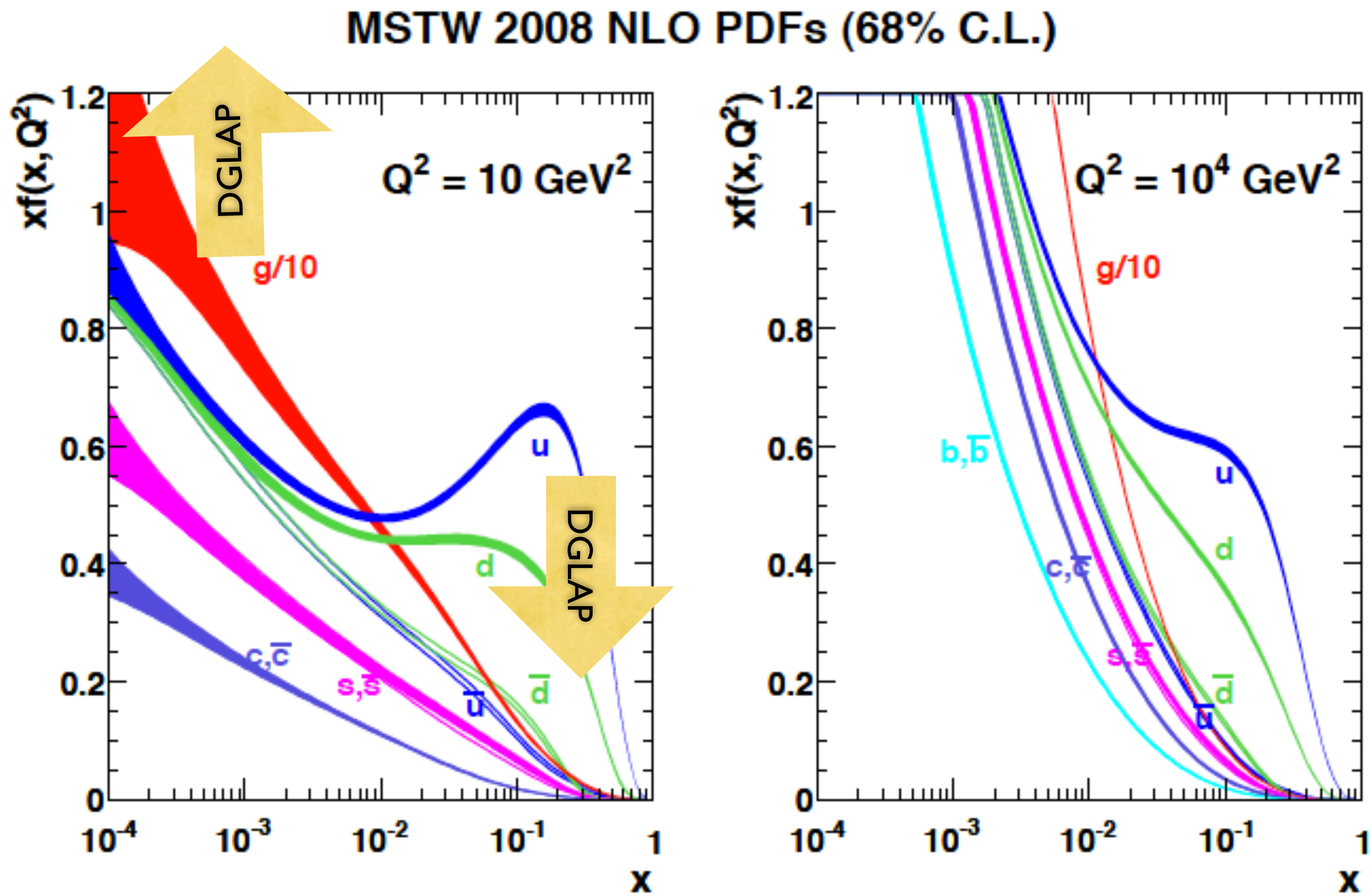
3. **Convolute** the evolved PDFs with $C_{i,a}$ and $\hat{\sigma}_{ab}$ to calculate theory predictions corresponding to a wide variety of data.

4. **Vary** the input parameters $\{A_a, \Delta_a, \eta_a, \epsilon_a, \gamma_a, \ldots\}$ to minimise

$$\chi^2 = \sum_{i=1}^{N_{\text{pts.}}} \left(\frac{\text{Data}_i - \text{Theory}_i}{\text{Error}_i} \right)^2$$

   or generalisations to account for *correlated* systematic errors.

Example of PDFs from global analysis



- **Error bands** shown are obtained from propagation of experimental uncertainties on the fitted data points.

$$\int_0^1 \mathrm{d}x\ \left[f_{q/p}(x,Q^2) - f_{\bar{q}/p}(x,Q^2)\right] = n_q \qquad (n_u = 2, n_d = 1, n_s = 0),$$

Quark number sum rules

$$\sum_{a=q,\bar{q},g} \int_0^1 \mathrm{d}x\ x f_{a/p}(x,Q^2) = 1$$

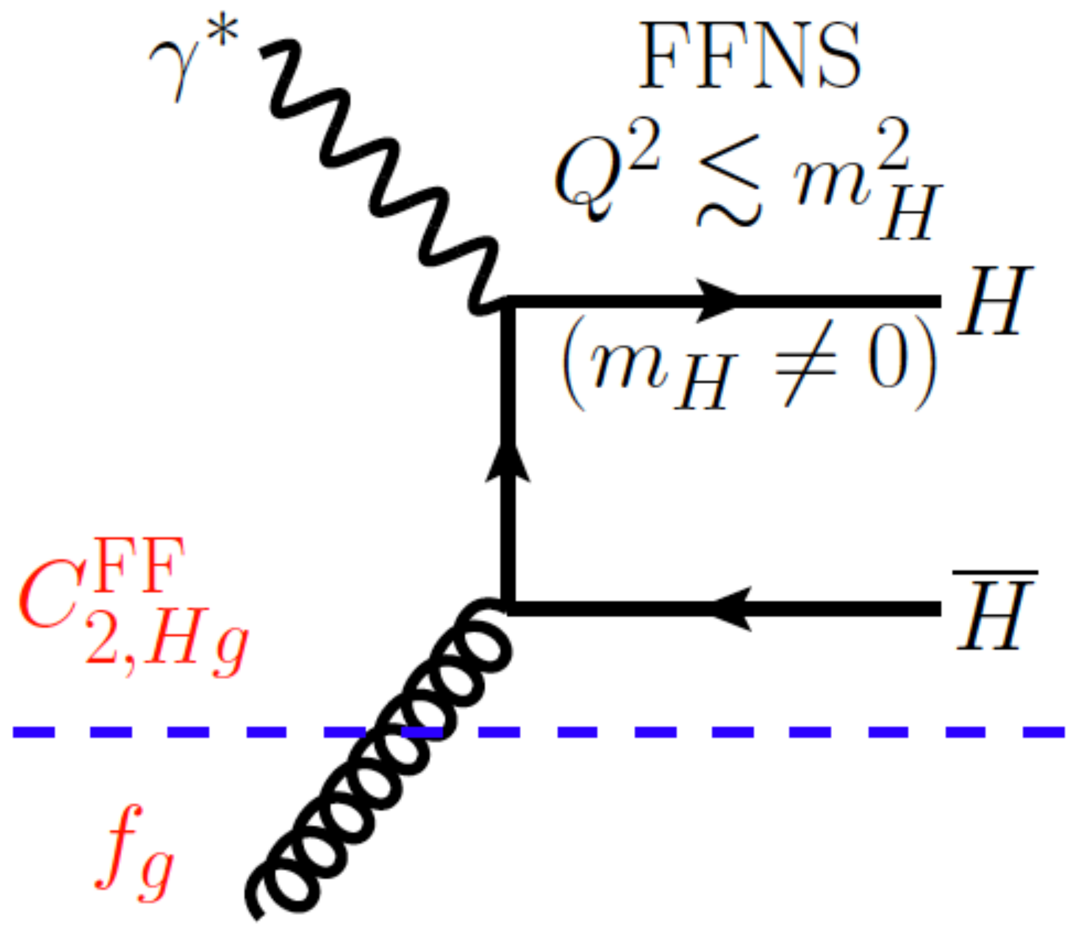
Momentum sum rule

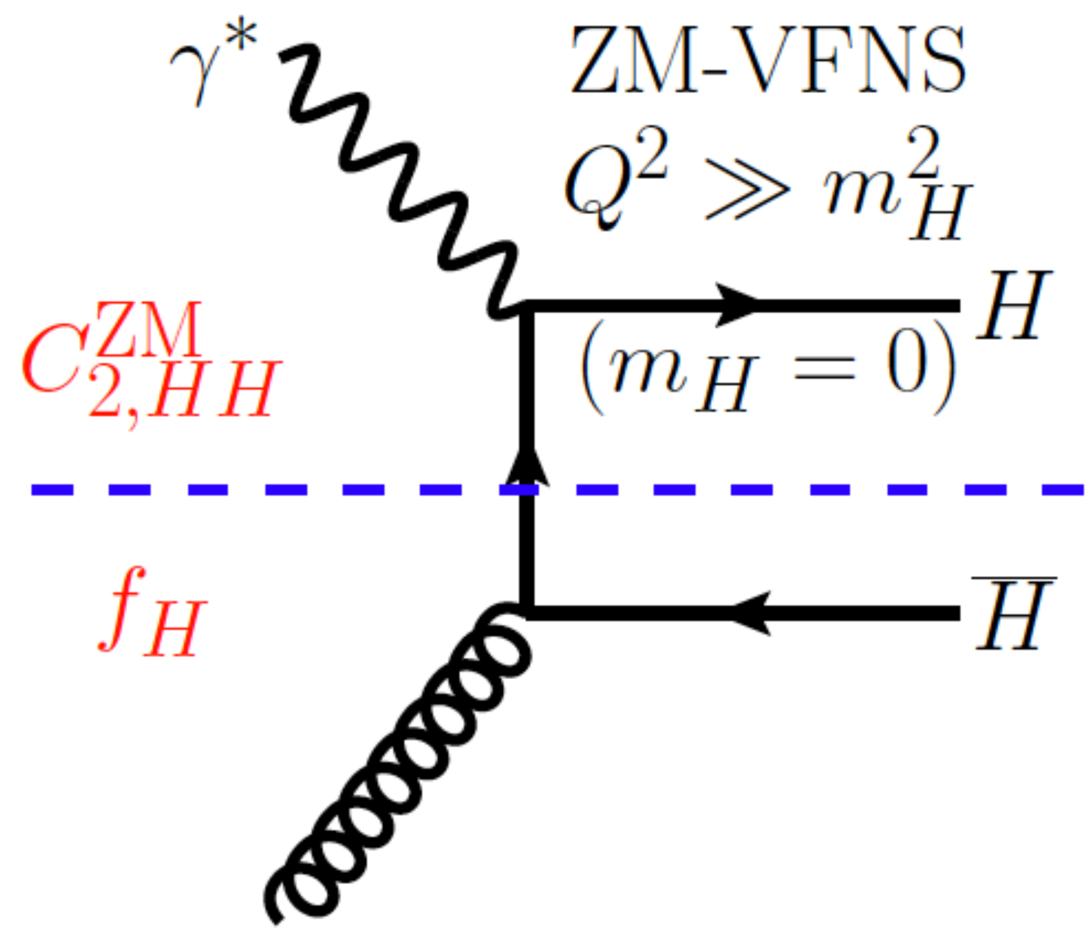
Who does PDF fits?

Name of group	Who?	Global?
MSTW (MRST) [arXiv:0901.0002]	A. D. **M**artin (1987-), R. G. **R**oberts (1987-2004), W. J. **S**tirling (1987-), R. S. **T**horne (1998-), G. **W**. (2006-)	✔
CTEQ (Coordinated Theoretical-Experimental Project on QCD)	J. Huston, H.-L. Lai, P. Nadolsky, J. Pumplin, D. Stump, C.-P. Yuan (W.-K. Tung), and others	✔
NNPDF	R. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. Latorre, J. Rojo, M. Ubiali, and others	✔
HERAPDF (H1, ZEUS)	H1 and ZEUS Collaborations	✘
ABKM (Alekhin)	S. Alekhin, J. Blümlein, S. Klein, S. Moch, and others	✘
GJR (GRV)	M. Glück, P. Jimenez-Delgado, E. Reya (A. Vogt)	✘

- **NN**PDF: parameterise input PDFs by a **N**eural **N**etwork. Error propagation using Monte Carlo methods.

Heavy quarks in DIS





Fixed flavour number scheme

- No heavy quark PDF.
- Includes $\mathcal{O}(m_H^2/Q^2)$ terms.
- No resummation of $\alpha_S \ln(Q^2/m_H^2)$ terms.

Zero-mass variable flavour number scheme

- Use heavy quark PDF.
- Mass dependence neglected.
- Resums $\alpha_S \ln(Q^2/m_H^2)$ terms similar to light quarks.

General-mass variable flavour number scheme (GM-VFNS)

- Interpolate between two well-defined regions.
- FFNS for $Q^2 \leq m_H^2$, ZM-VFNS for $Q^2 \gg m_H^2$.
- Details of interpolation are ambiguous ($\Rightarrow$ **uncertainty**).

CTEQ6.1 (ZM-VFNS) $\rightarrow$ CTEQ6.5 (GM-VFNS)

- 8% increase in W and Z cross sections at LHC (14 TeV).

MRST 1998–2006 and MSTW 2008

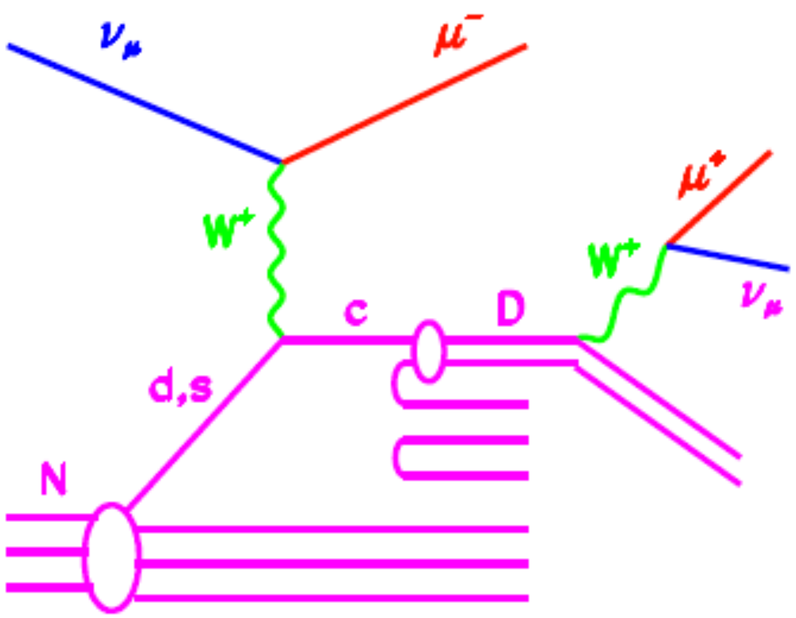
- MRST/MSTW group have used a GM-VFNS since 1998.

NNPDF 1.0–2.0

- Fits still use ZM-VFNS ($\rightarrow$ GM-VFNS [arXiv:1002.4407]).

Recent comparison between GM-VFN schemes used by different PDF groups:
J. Rojo, S. Forte, J. Huston, P. Nadolsky, P. Nason, F. Olness, **R. Thorne and G. W.**
"*The Les Houches benchmarks for GM-VFN heavy quark schemes in DIS*", arXiv:1003.1241

NuTeV/CCFR dimuon cross sections and strangeness



$$\frac{d\sigma}{dxdy}(\nu_\mu N \to \mu^+\mu^- X) \propto \frac{d\sigma}{dxdy}(\nu_\mu N \to \mu^- c\, X)$$

- ν_μ and $\bar{\nu}_\mu$ cross sections constrain s and $\bar{s}$, respectively, for $0.01 \lesssim x \lesssim 0.2$.

- Can **relax assumption** made in previous fits that

$$s(x, Q_0^2) = \bar{s}(x, Q_0^2) = \frac{\kappa}{2}\left[\bar{u}(x, Q_0^2) + \bar{d}(x, Q_0^2)\right], \text{ with } \kappa \approx 0.5.$$

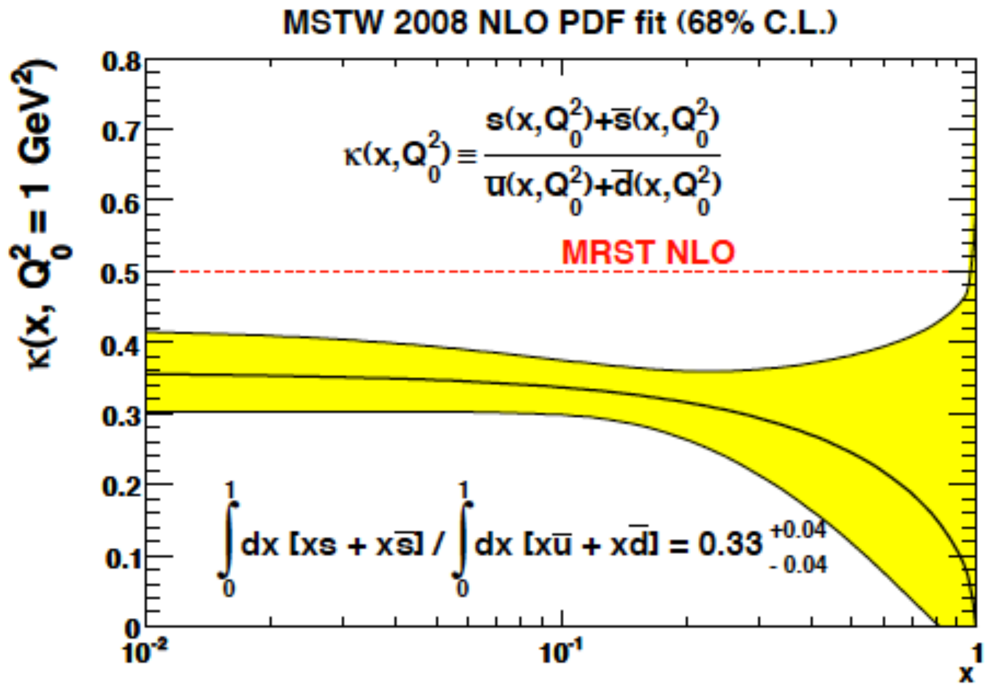
- MSTW **parameterise** at input scale of $Q_0^2 = 1$ GeV^2 in the form:

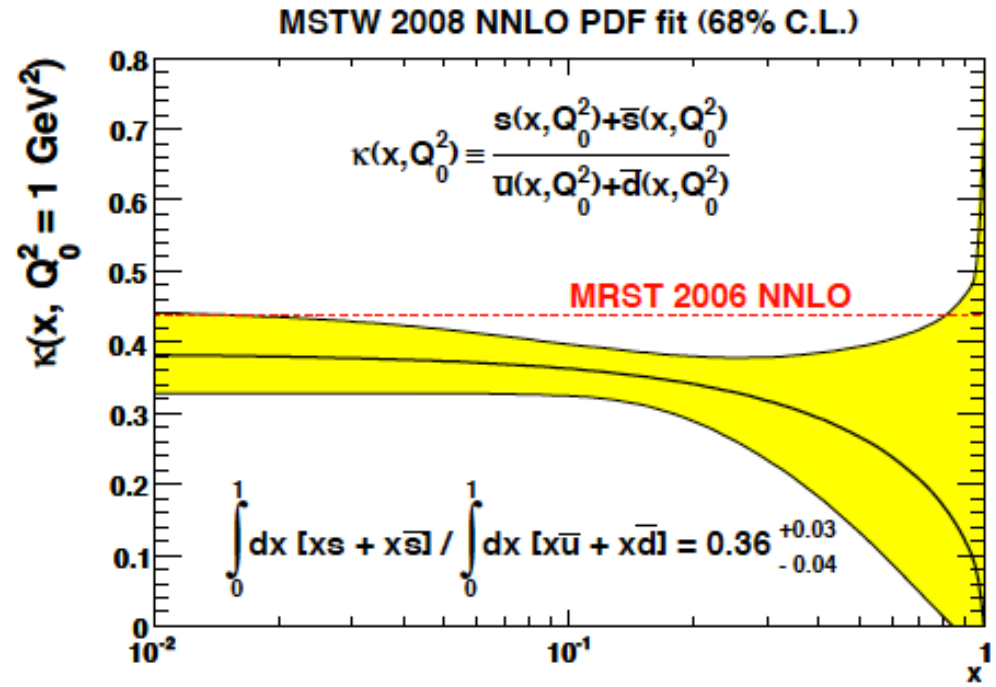
$$xs^+(x, Q_0^2) \equiv xs(x, Q_0^2) + x\bar{s}(x, Q_0^2) = A_+\,(1-x)^{\eta_+}\,xS(x, Q_0^2),$$
$$xs^-(x, Q_0^2) \equiv xs(x, Q_0^2) - x\bar{s}(x, Q_0^2) = A_-\,x^{0.2}(1-x)^{\eta_-}(1 - x/x_0).$$

- x_0 fixed by zero strangeness: $\int_0^1 dx\,\left[s(x, Q_0^2) - \bar{s}(x, Q_0^2)\right] = 0.$

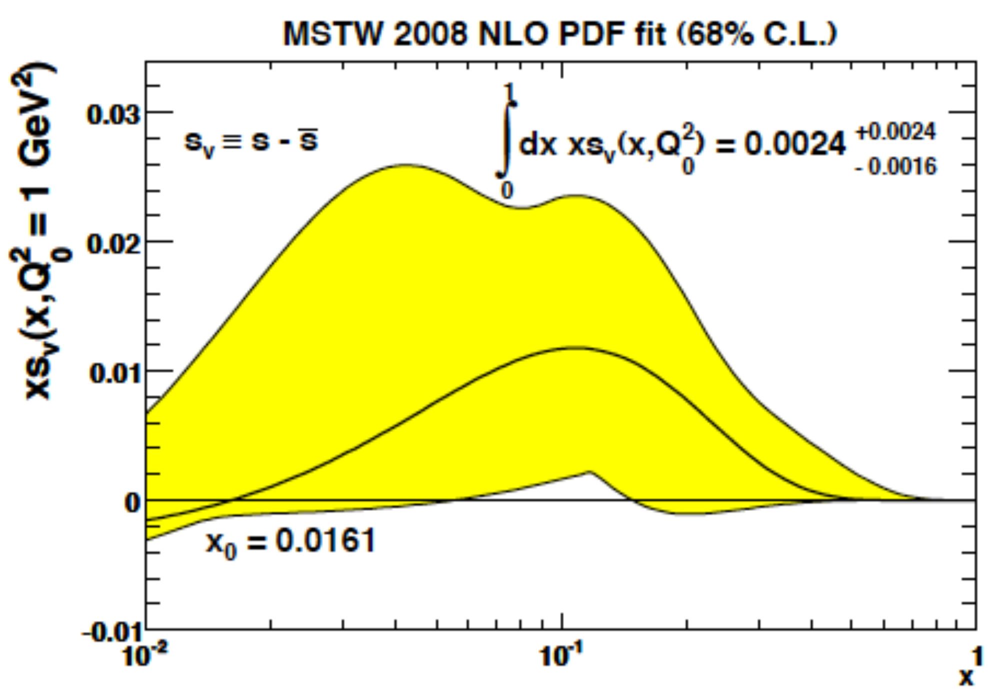
Strange quark and antiquark distributions

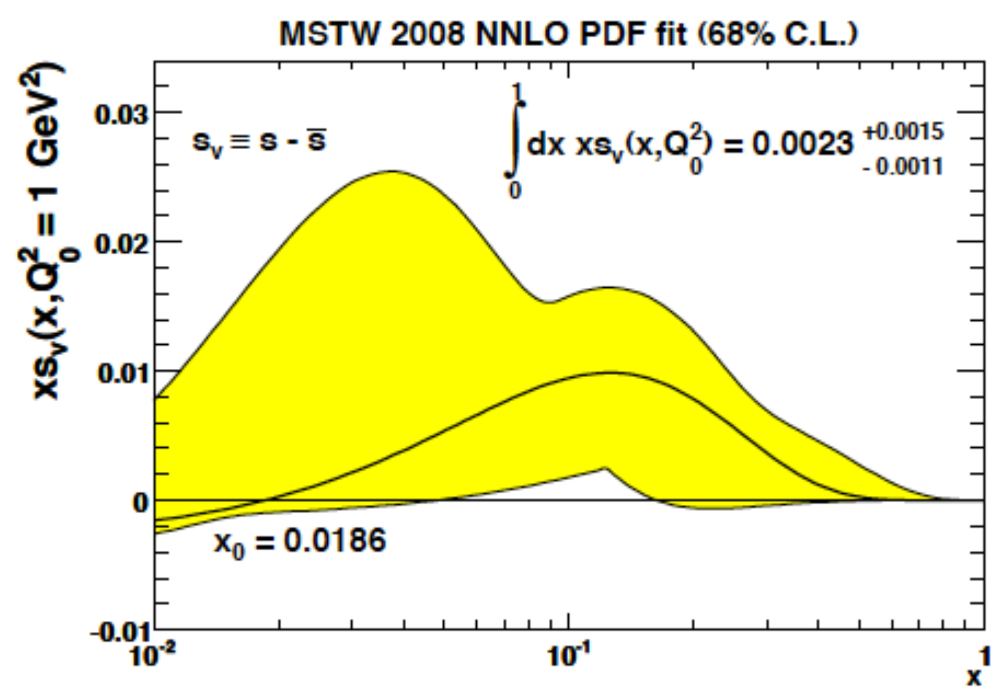
- Ratio of strange sea to non-strange sea: $(s+\bar{s})/(\bar{u}+\bar{d})$.



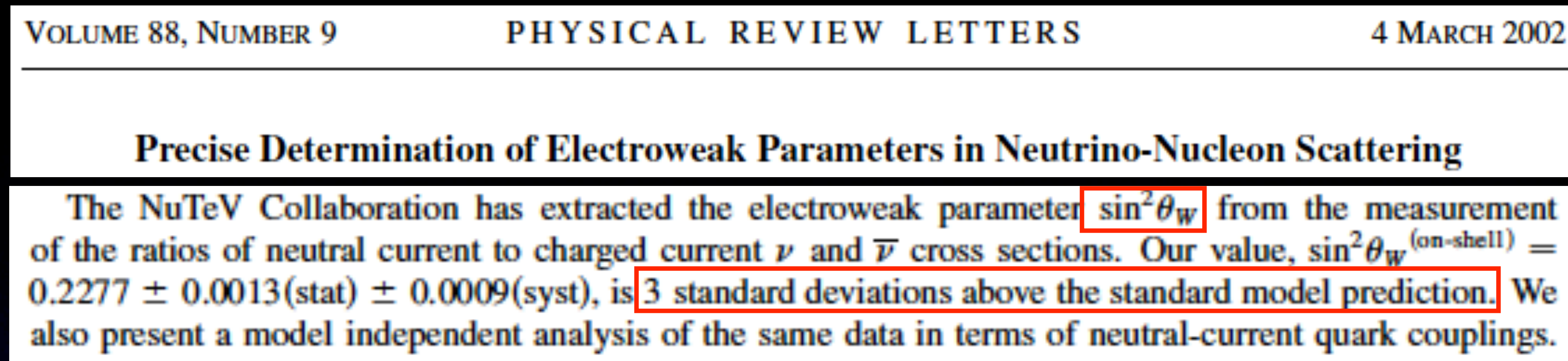


- Strange sea asymmetry: $xs - x\bar{s}$.





Importance of PDFs: NuTeV "anomaly"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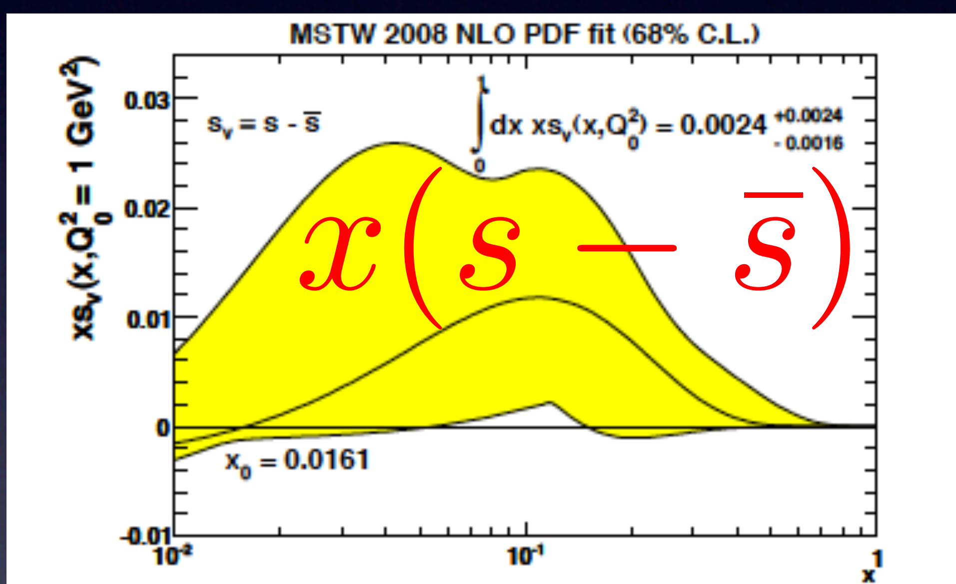
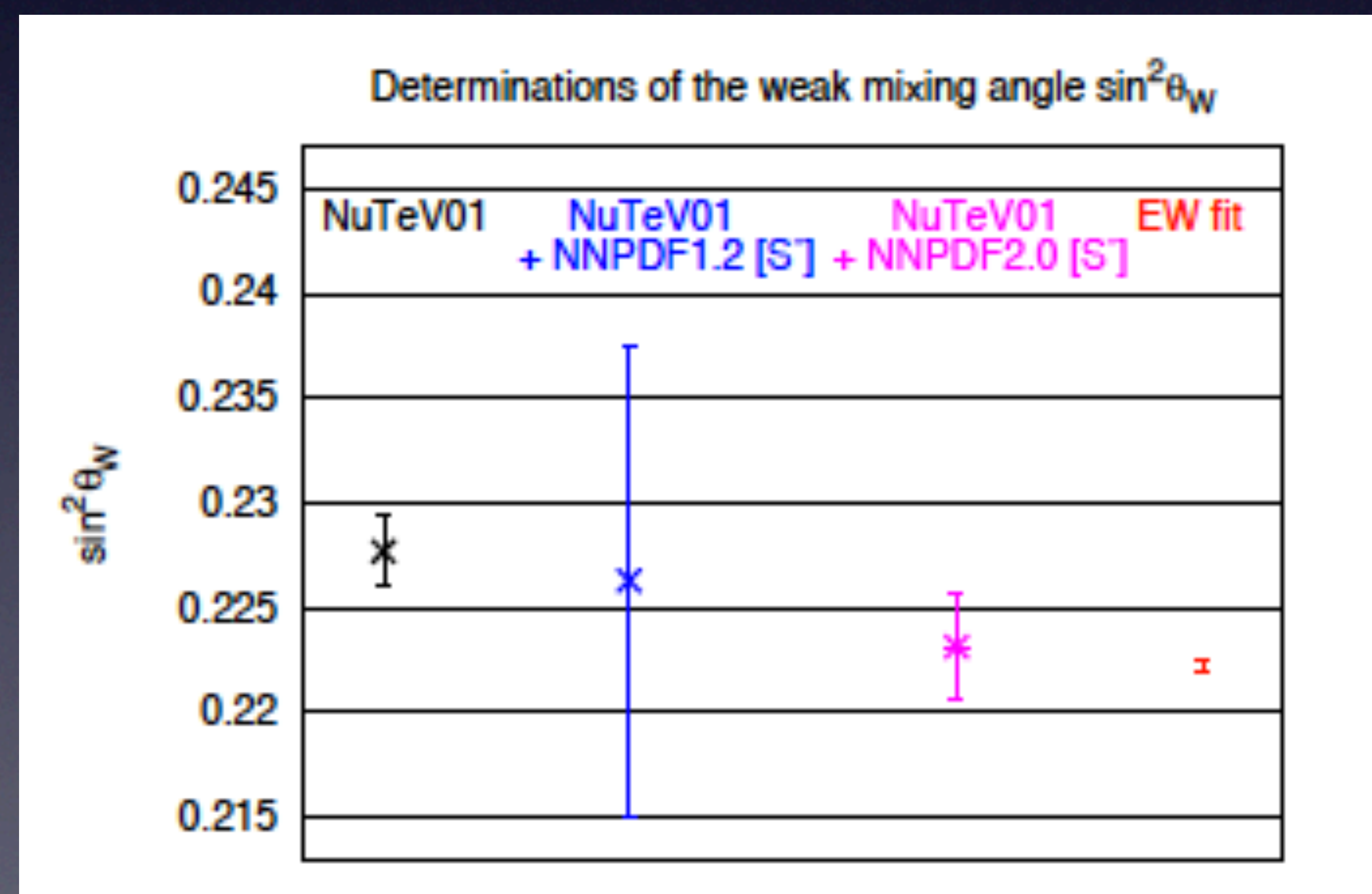
Precise Determination of Electroweak Parameters in Neutrino-Nucleon Scattering

The NuTeV Collaboration has extracted the electroweak parameter $\sin^2\theta_W$ from the measurement of the ratios of neutral current to charged current ν and $\overline{\nu}$ cross sections. Our value, $\sin^2\theta_W^{\text{(on-shell)}} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, is 3 standard deviations above the standard model prediction. We also present a model independent analysis of the same data in terms of neutral-current quark couplings.

But corrections from strange sea asymmetry and isospin violation.



NNPDF: isospin symmetry, unbiased parameterisation

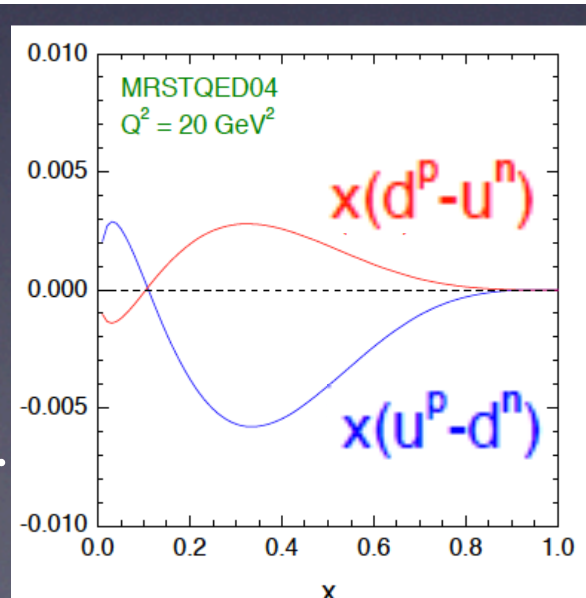


Isospin violation:

$$u^p \neq d^n,$$

$$d^p \neq u^n,$$

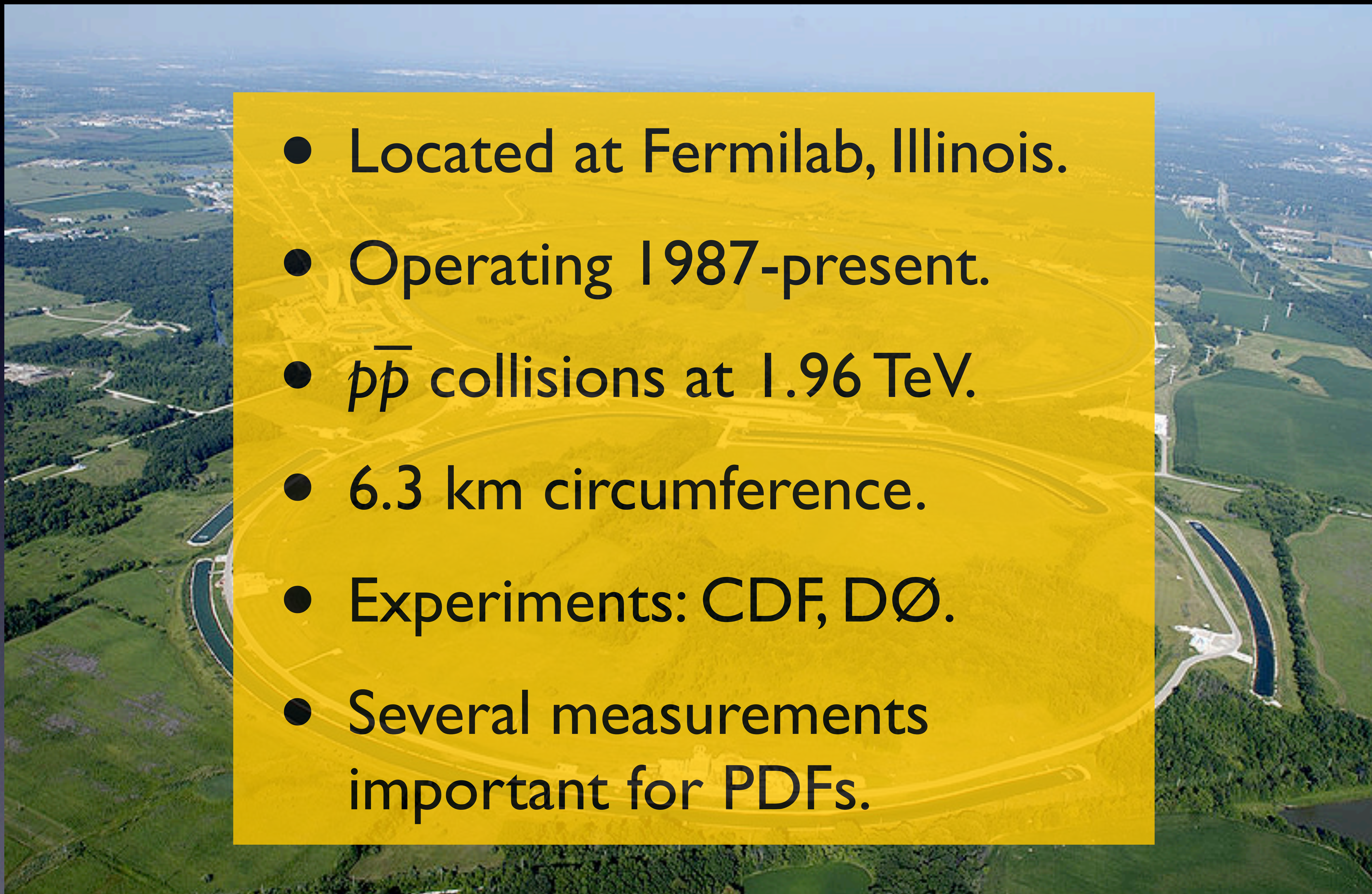
naturally from QED corrections.



[arXiv:1002.4407]

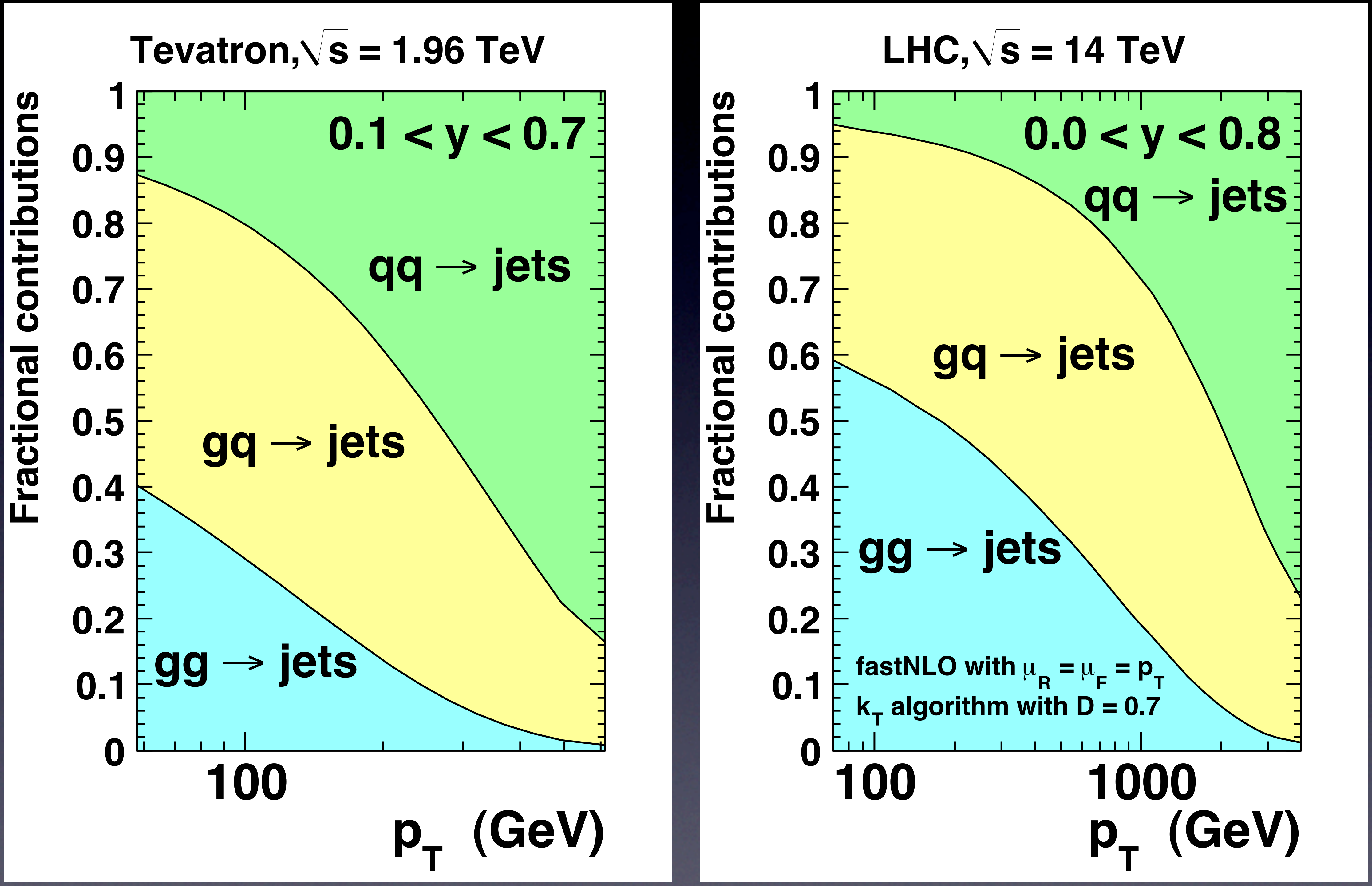
Tevatron $p\bar{p}$ collider

Tevatron $p\bar{p}$ collider



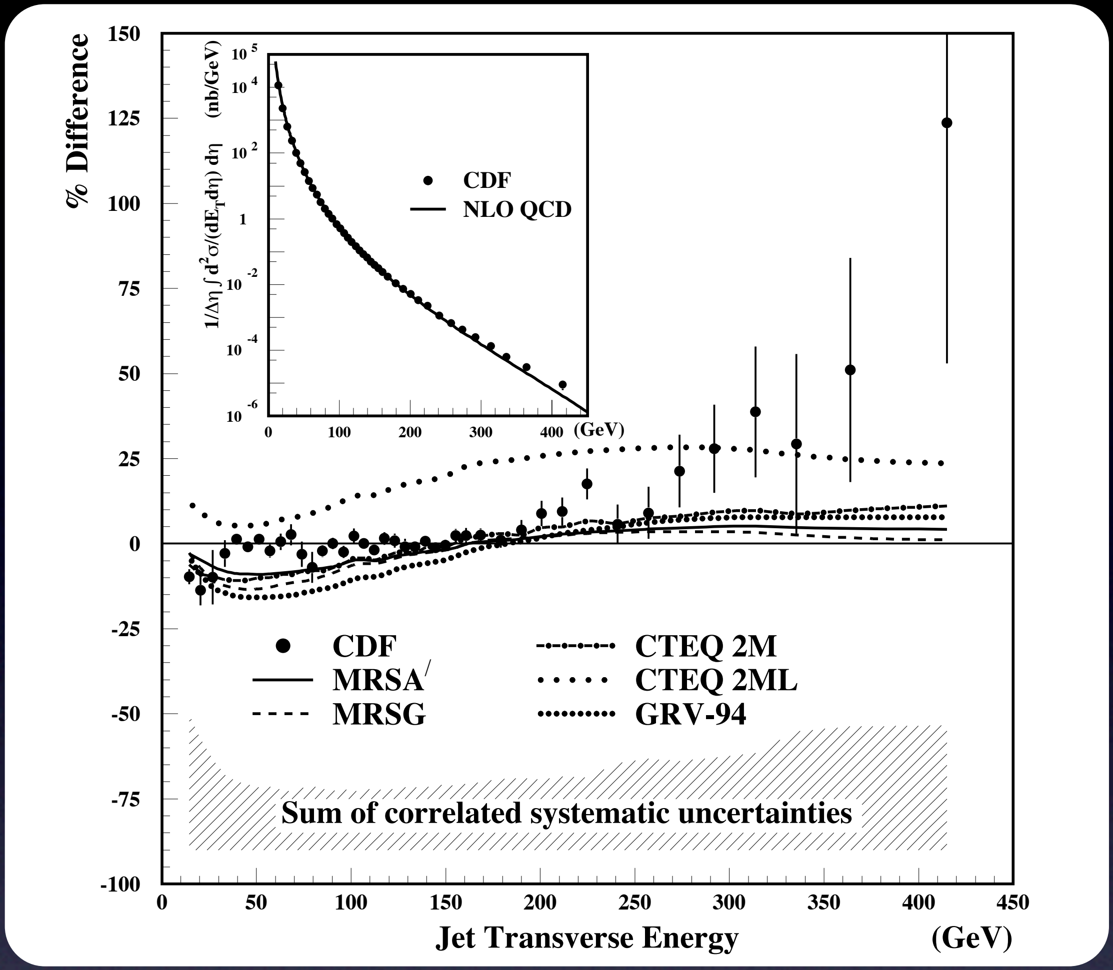
- Located at Fermilab, Illinois.
- Operating 1987-present.
- $p\bar{p}$ collisions at 1.96 TeV.
- 6.3 km circumference.
- Experiments: CDF, DØ.
- Several measurements important for PDFs.

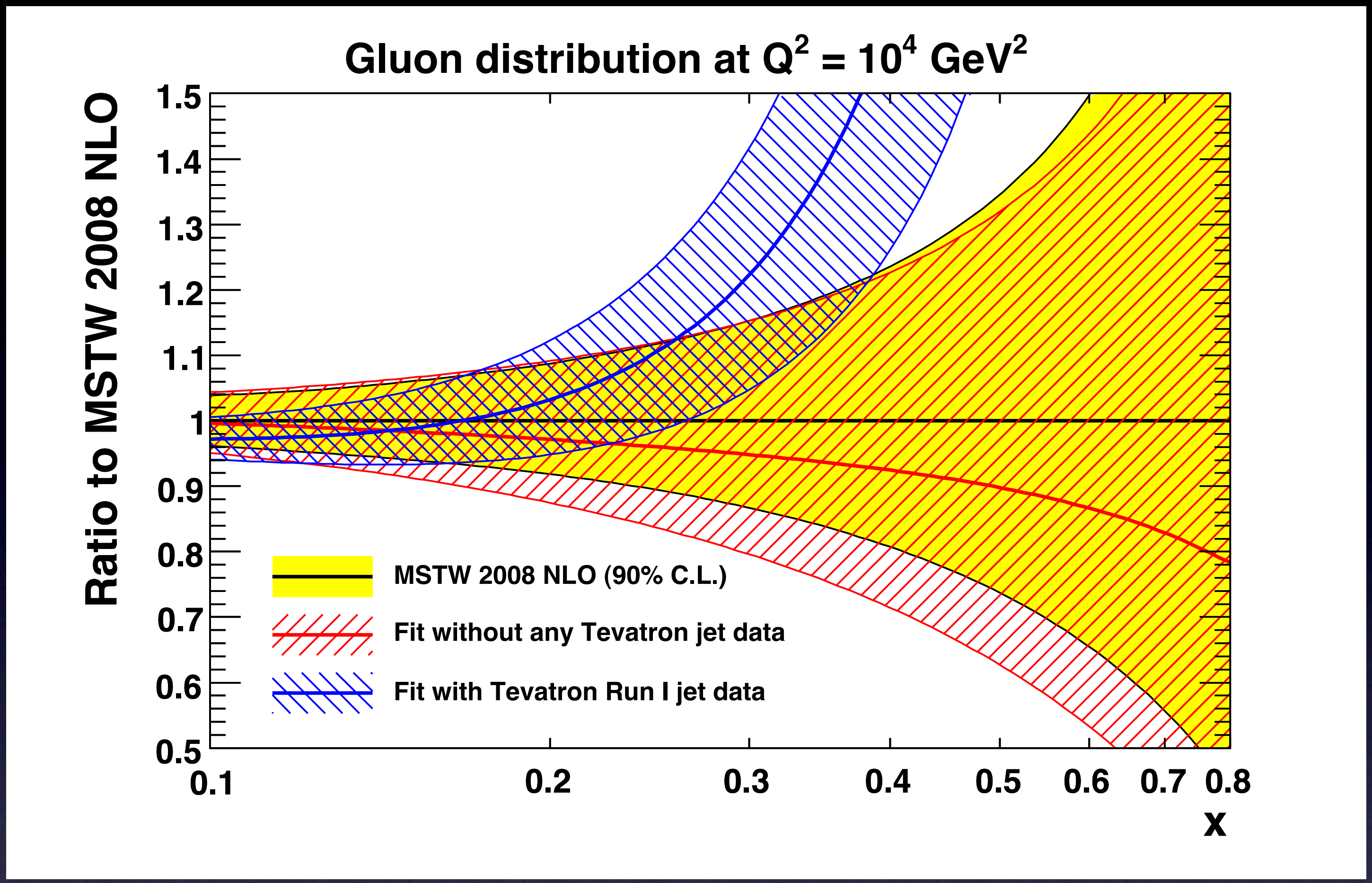
Inclusive jet production



Sensitive to high-x gluon distribution.

Importance of PDFs: Tevatron jets

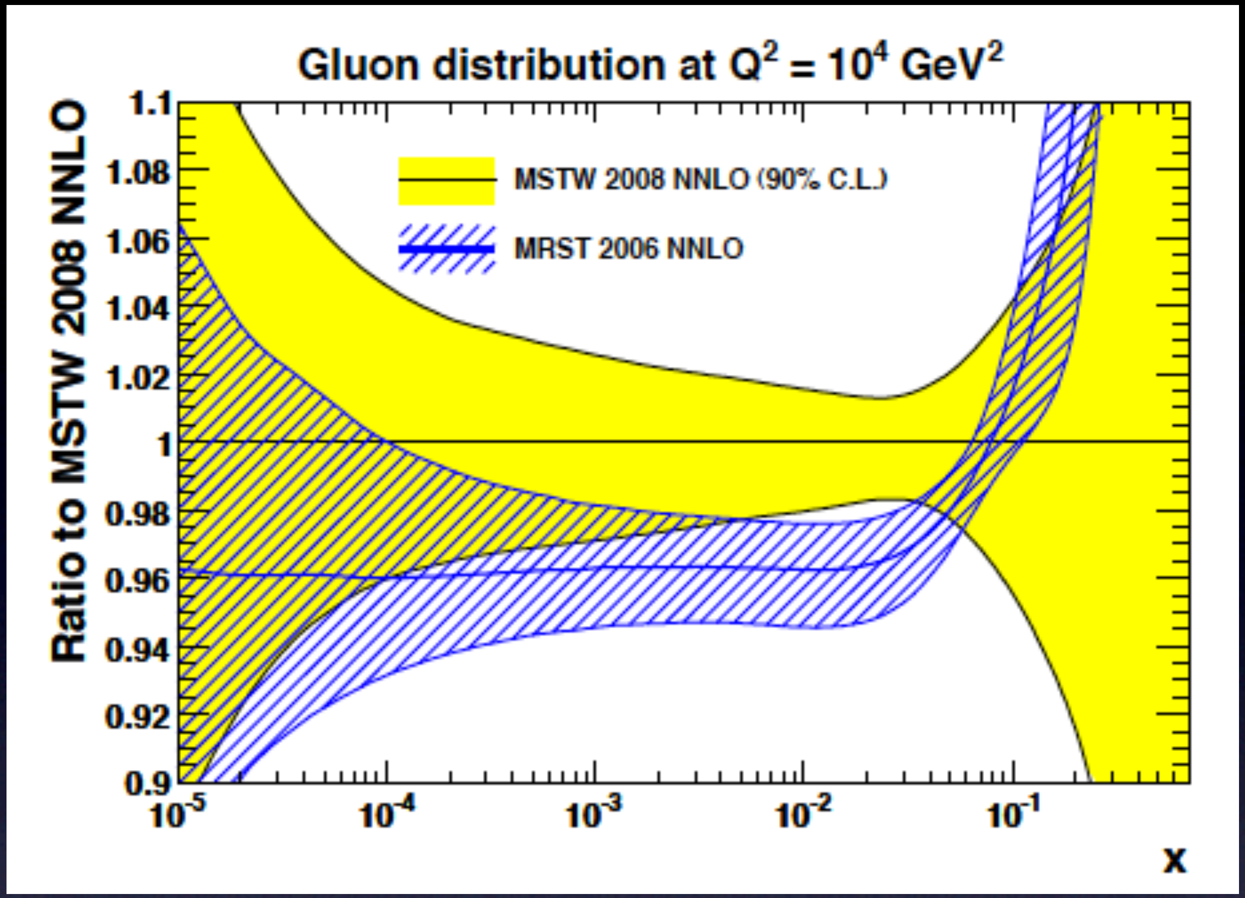


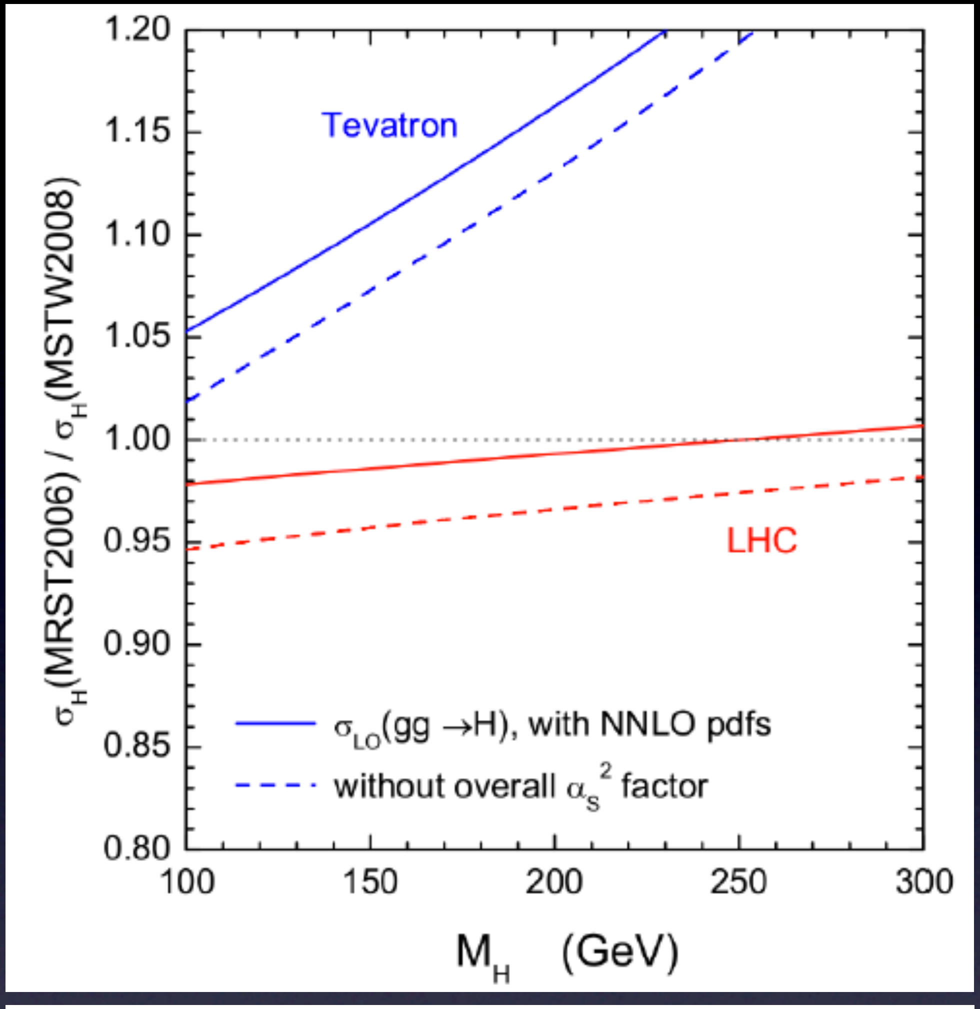


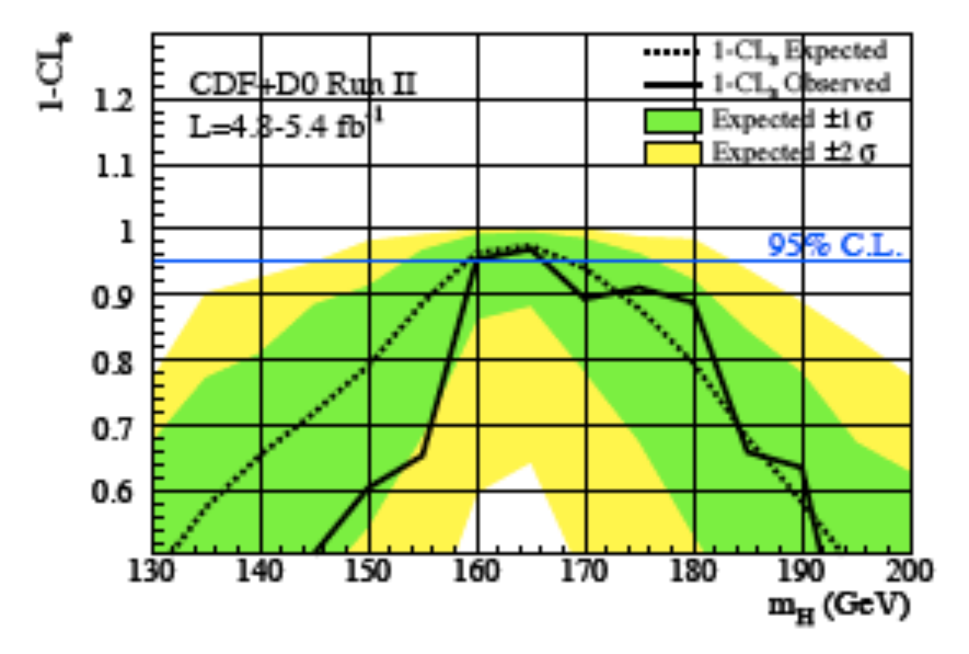
- Early Tevatron Run I jet data showed an **excess** at high E_T (sign of quark compositeness?), but later **accommodated** by refitting gluon distribution (⇒ PDF uncertainties needed).

- MSTW 2008 was **first** PDF fit to include Run II data: preference for **smaller** gluon distribution at high x.

Implications for Higgs cross sections



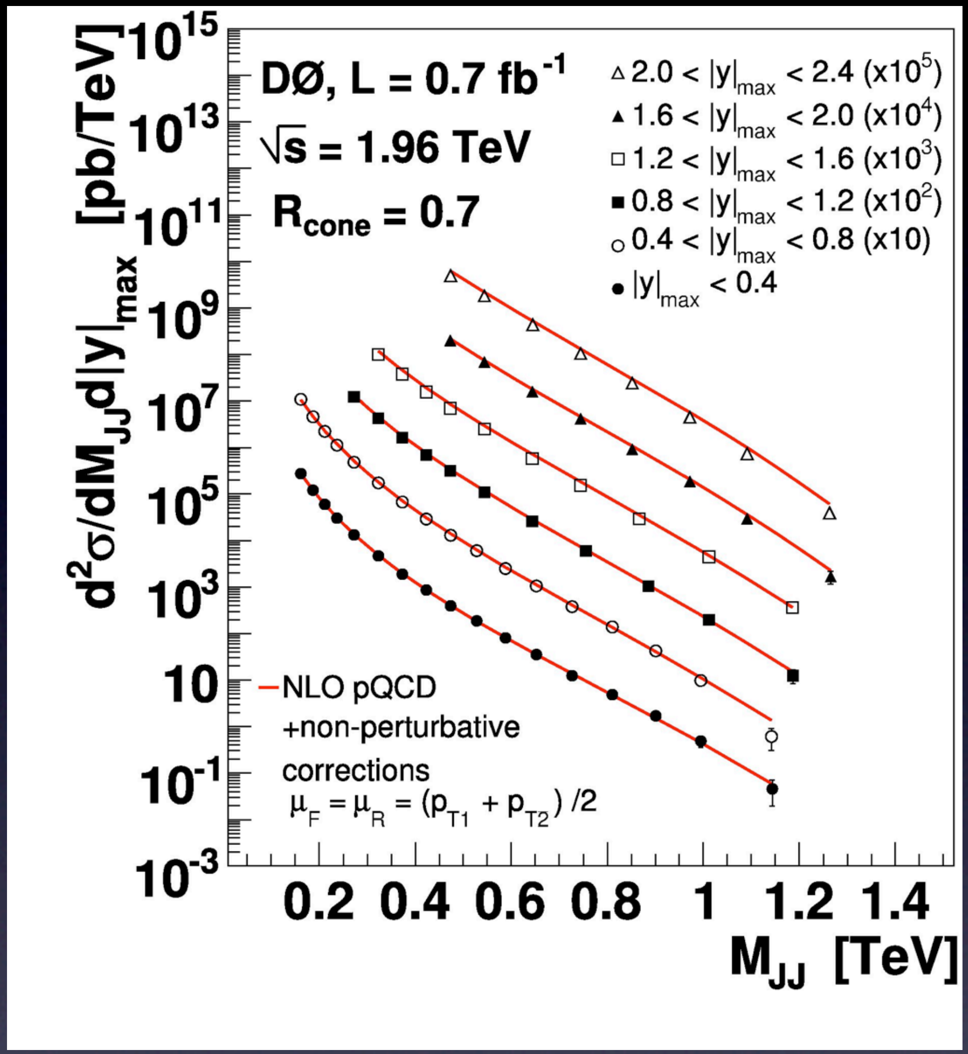




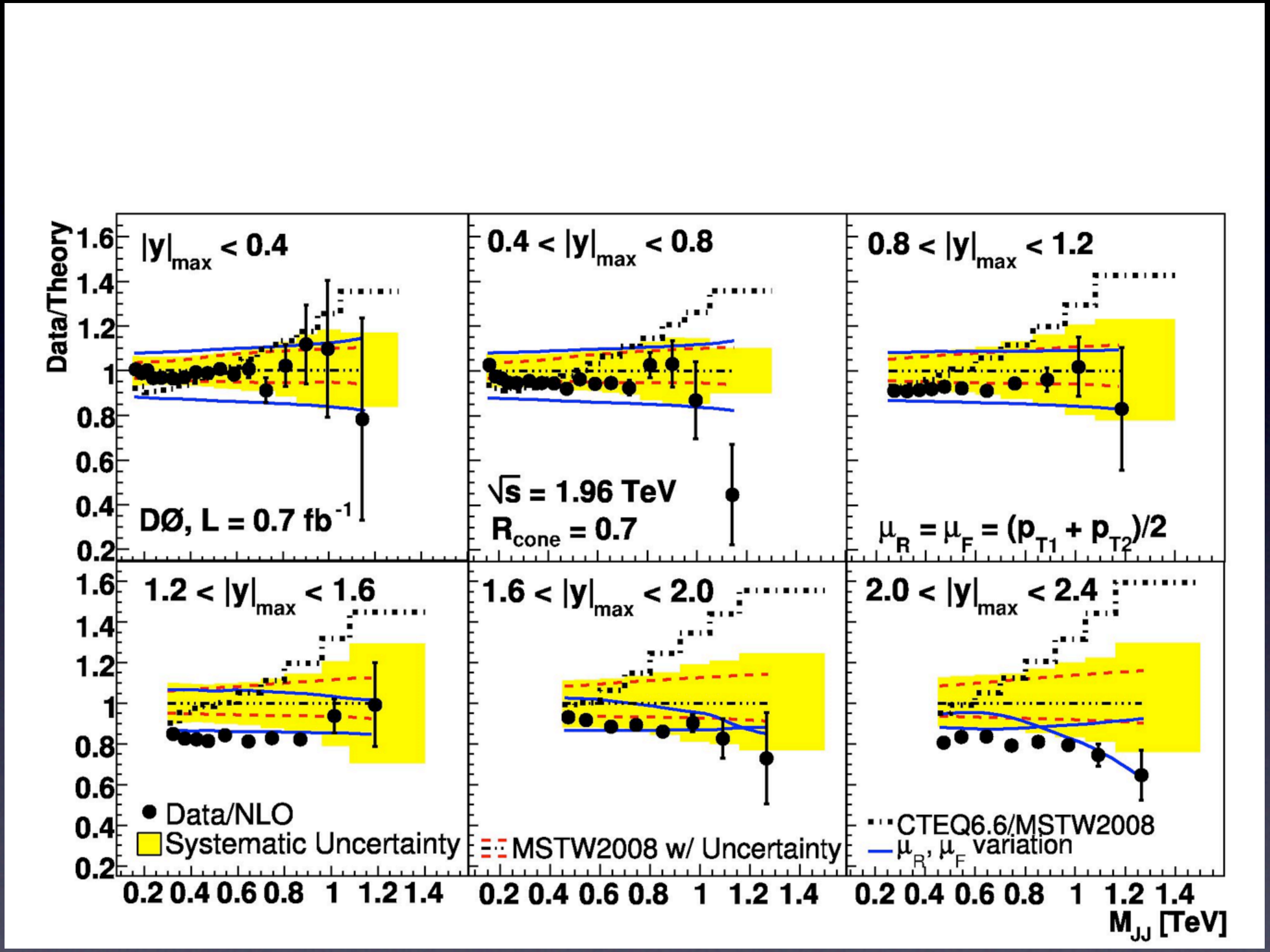
- Dominant $gg \rightarrow H$ via t-loop.
- Higgs cross sections smaller at Tevatron with 2008 PDFs.
- Used in Tevatron exclusion.

arXiv:1001.4162

Description of DØ dijet mass spectrum

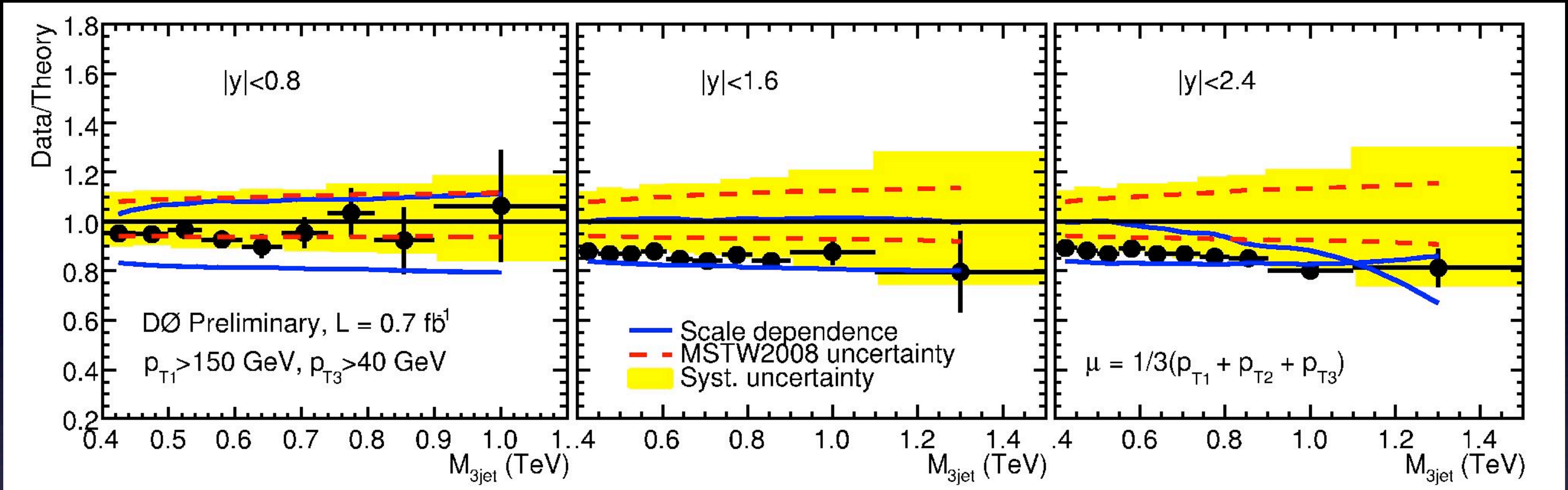


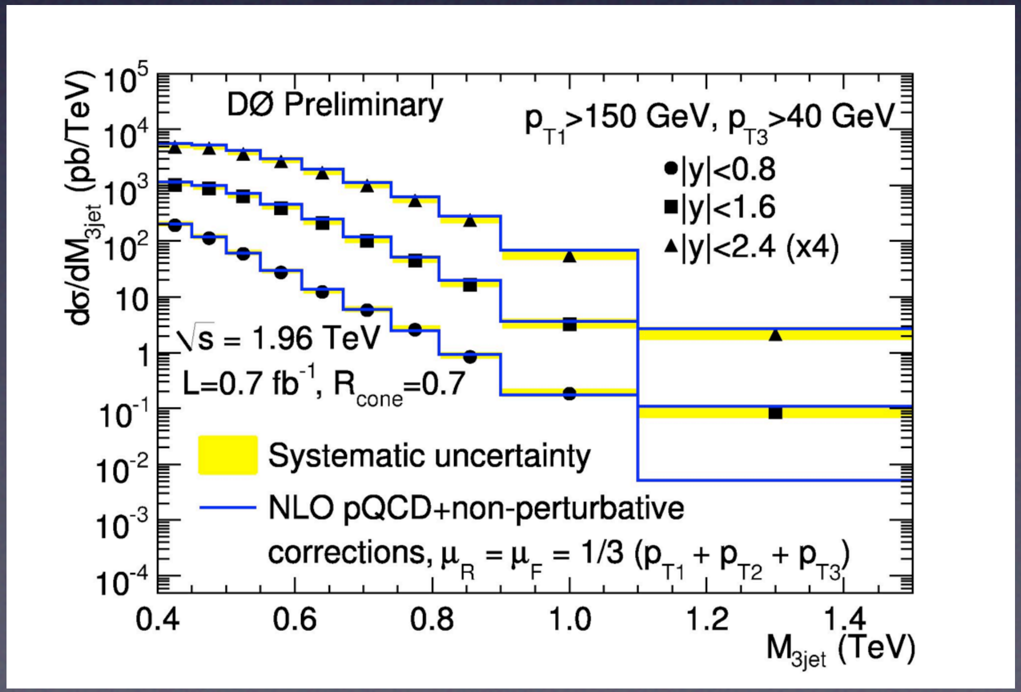
arXiv:1002.4594



- Data favour less gluon at high x (MSTW 2008 over CTEQ6.6).

Three-jet mass cross section

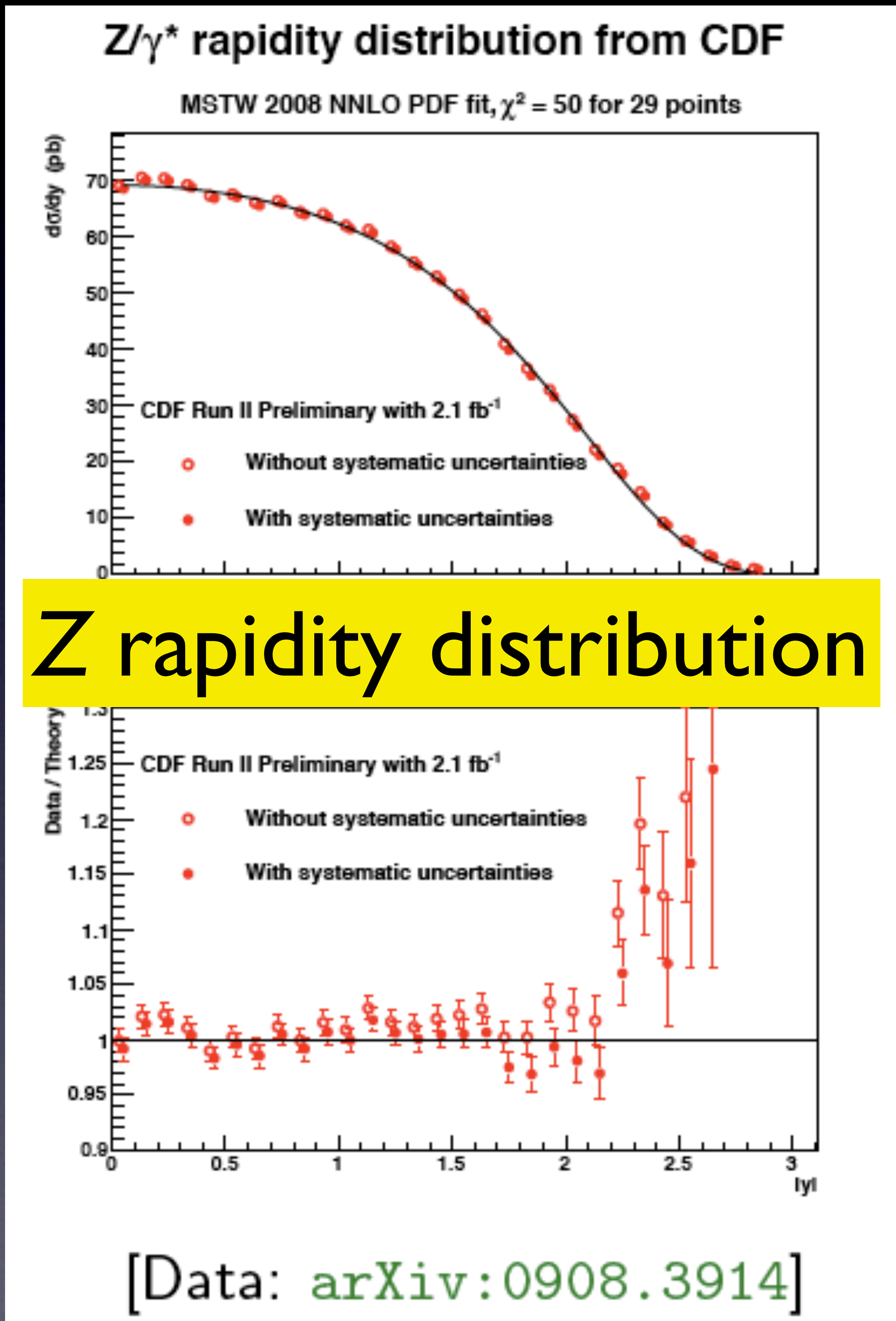


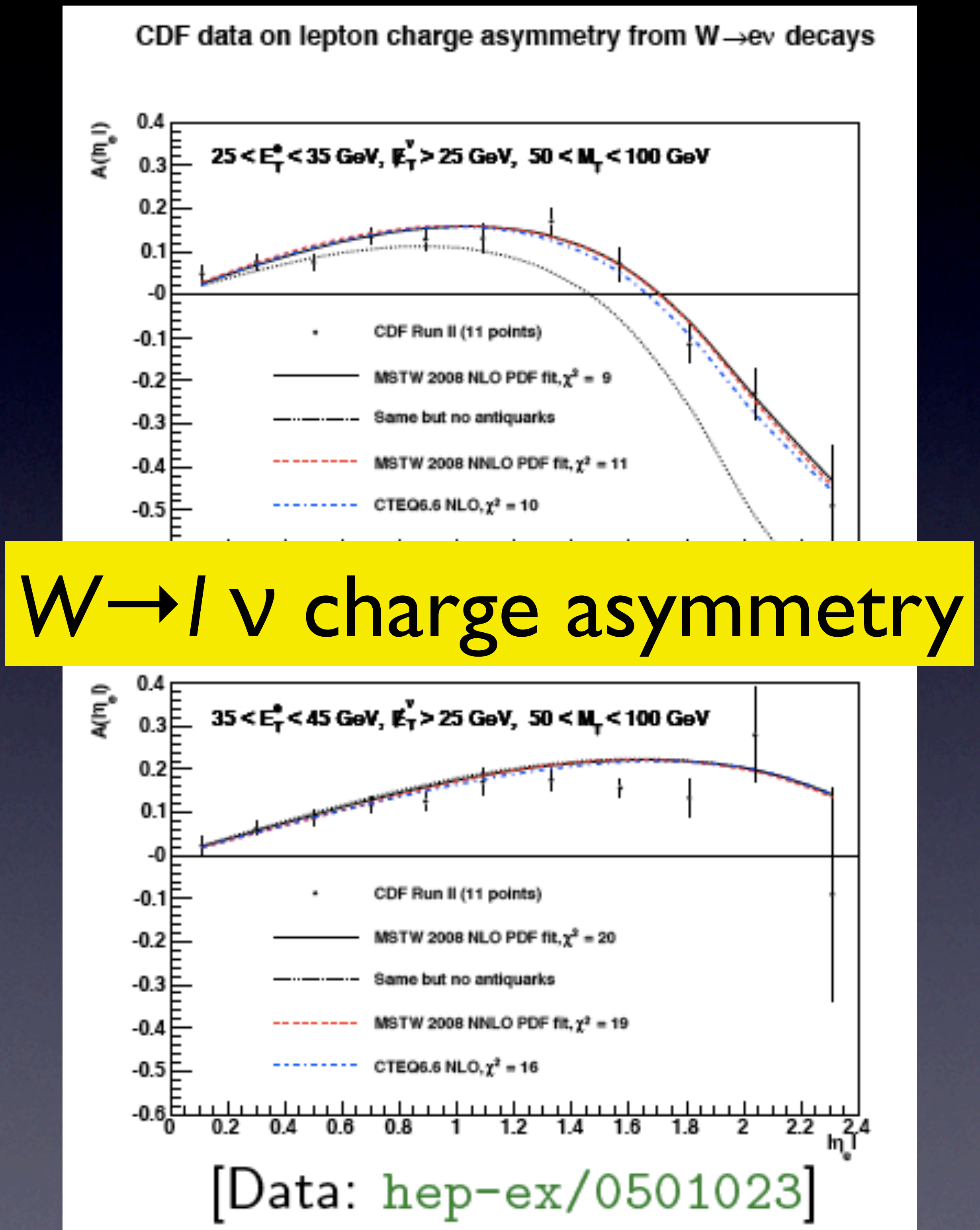


D0 Note 6043-CONF

- Reasonably well described by MSTW 2008 PDFs.

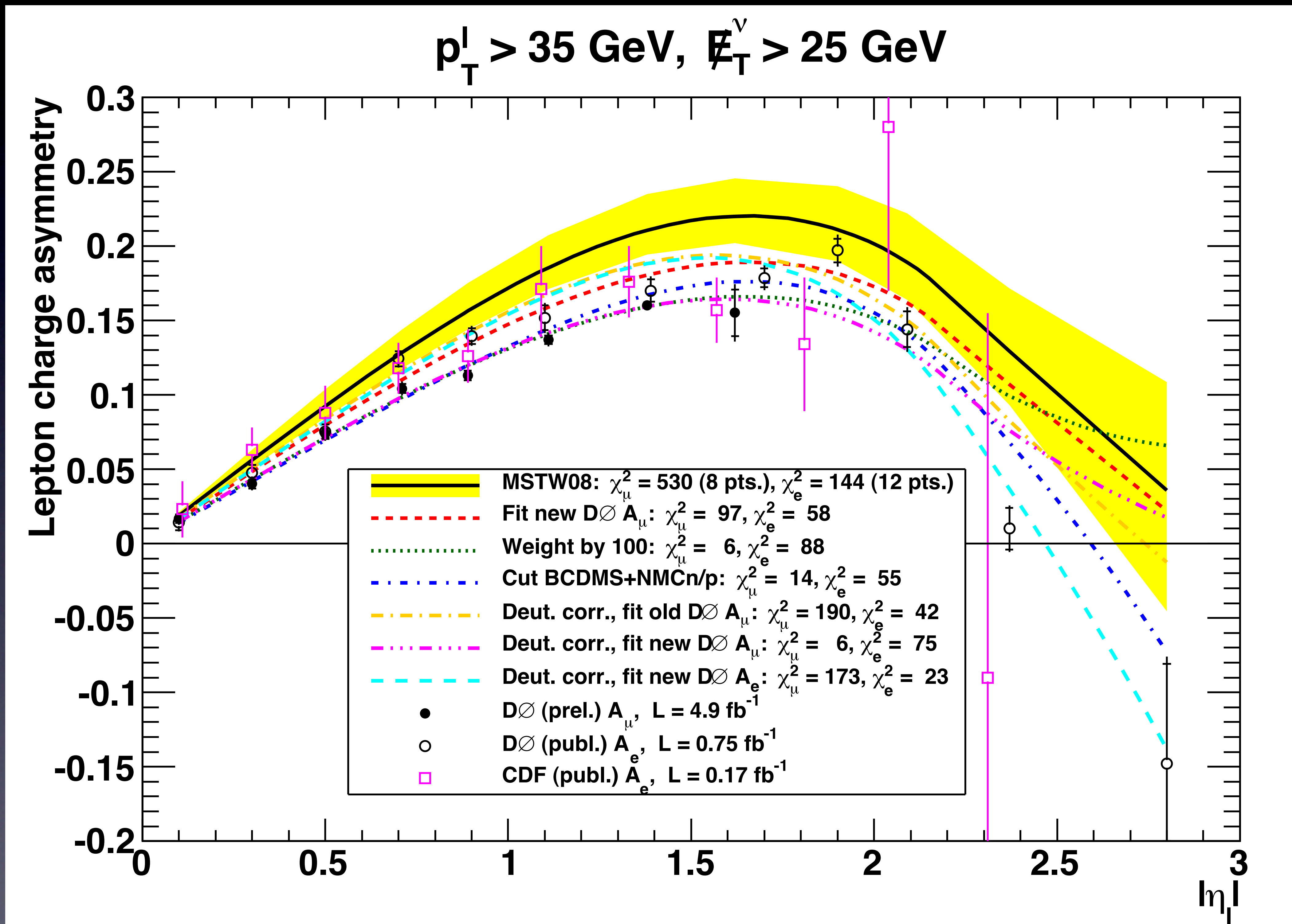
Tevatron W and Z data





Latest DØ data on $W \to l\,\nu$ charge asymmetry

A_e [arXiv:0807.3367] and A_μ [DØ Note 5976-CONF]



arXiv:1006.2753 (proceedings of DIS10)

PDF4LHC benchmark exercise

- Talk by **G.W.** at CERN on 26th March 2010.
- "PDF+α_S" uncertainties:

MSTW	arXiv:0905.3531 (May 2009)
CTEQ	arXiv:1004.4624 (April 2010)
NNPDF	arXiv:1004.0962 (April 2010) arXiv:1005.0397 (May 2010)

Eur. Phys. J. C (2009) 64: 653–680
DOI 10.1140/epjc/s10052-009-1164-2
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

Uncertainties on α_S in global PDF analyses and implications for predicted hadronic cross sections

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[2]Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK
[3]Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

- Use most recent public NLO PDFs from all fitting groups to calculate LHC benchmark processes at 7 TeV $(W^{\pm}, Z^0, t\bar{t}, gg \to H)$.

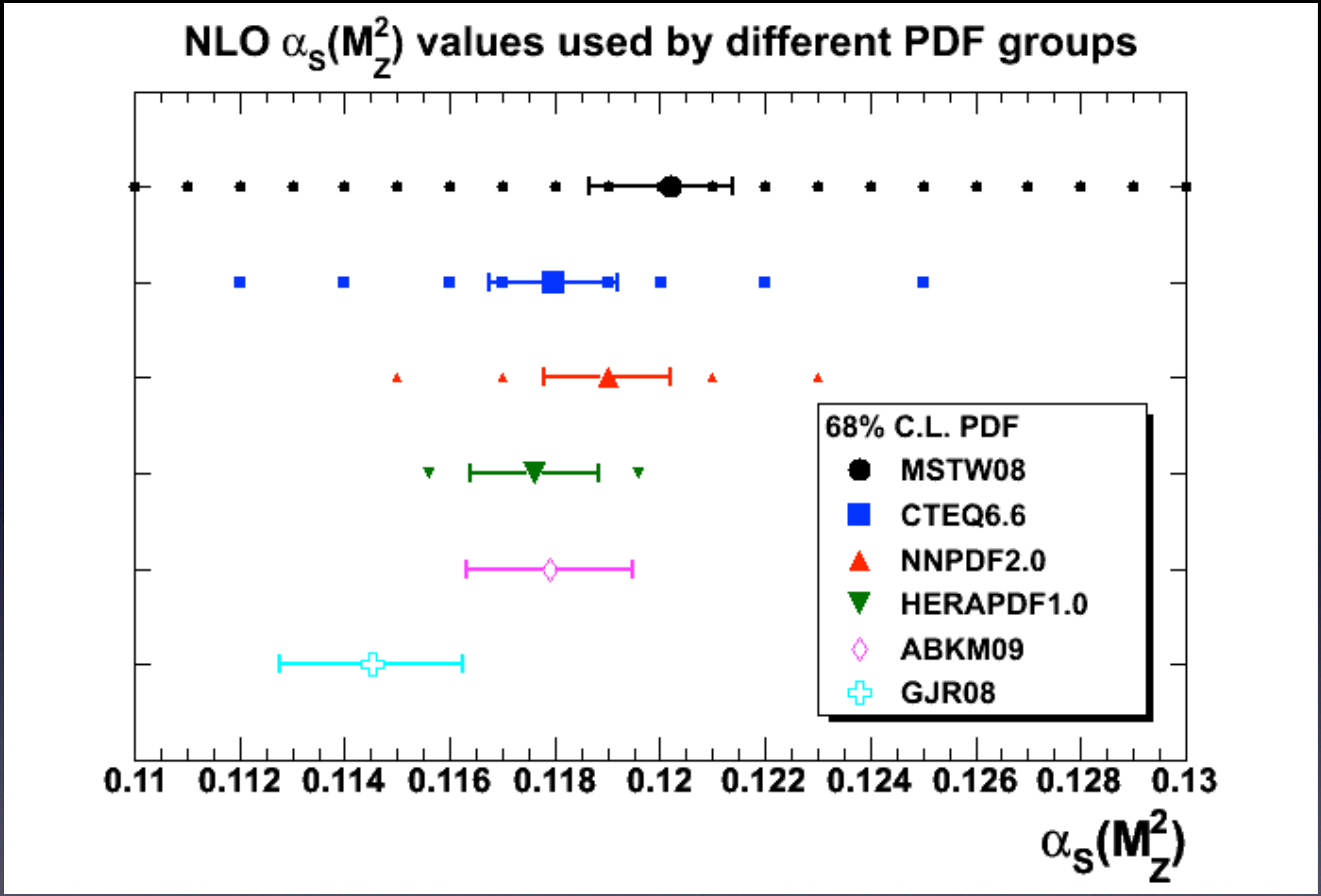
Aims:

1. Establish degree of compatibility and identify outliers.
2. Compare cross sections at **same** α_S values.
3. To what extent are differences in predictions due to different α_S values used by each group, rather than differences in PDFs?

Comparisons at NLO. (**MSTW** have NNLO PDFs, but CTEQ and NNPDF do not.)

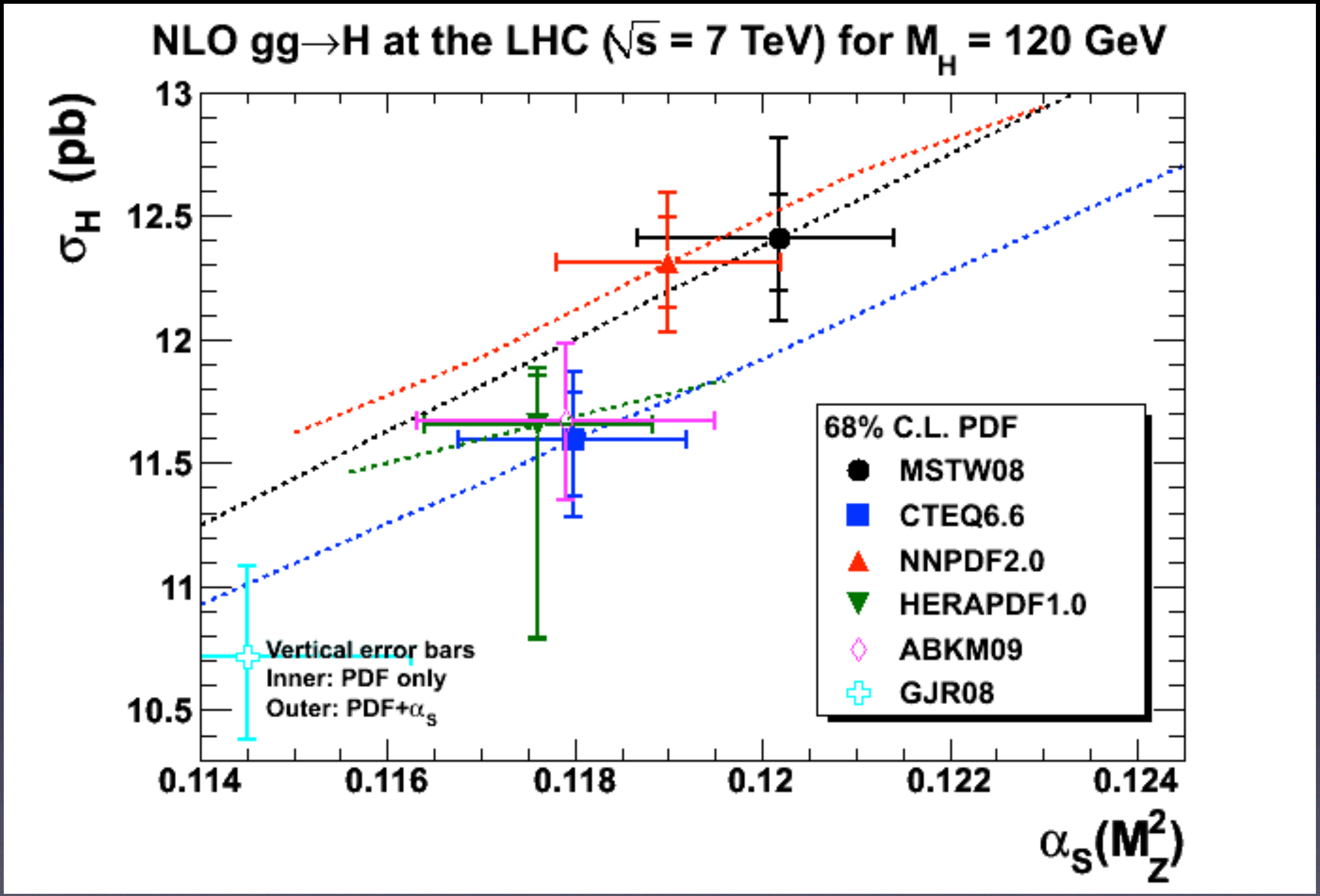
Plots: http://projects.hepforge.org/mstwpdf/pdf4lhc/

Values of $\alpha_S(M_Z)$ used by different fitting groups



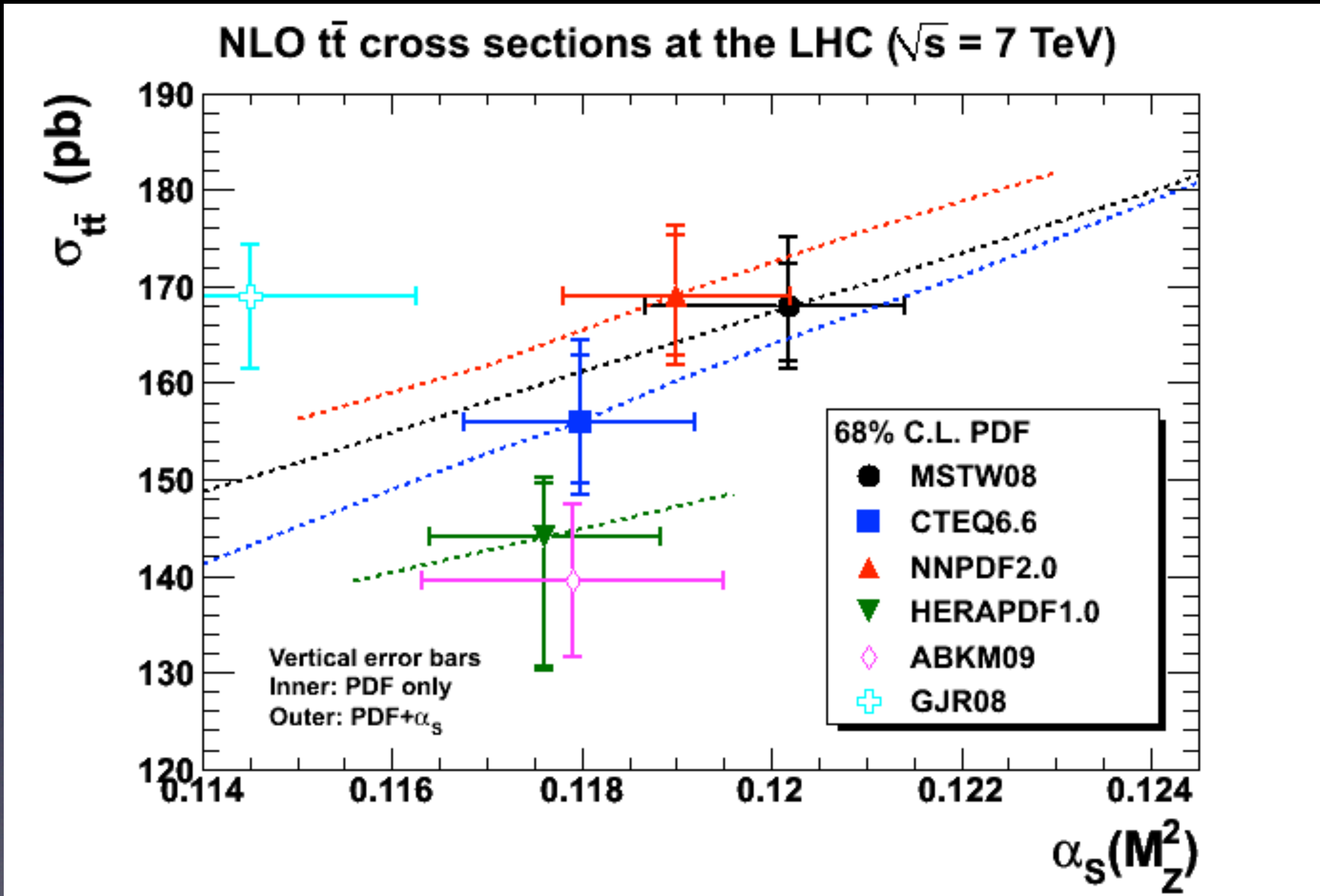
- $\alpha_S(M_Z)$ for **MSTW08**, ABKM09 and GJR08 obtained from fit.
- $\alpha_S(M_Z)$ for other groups applied as an external constraint.

Higgs total cross section



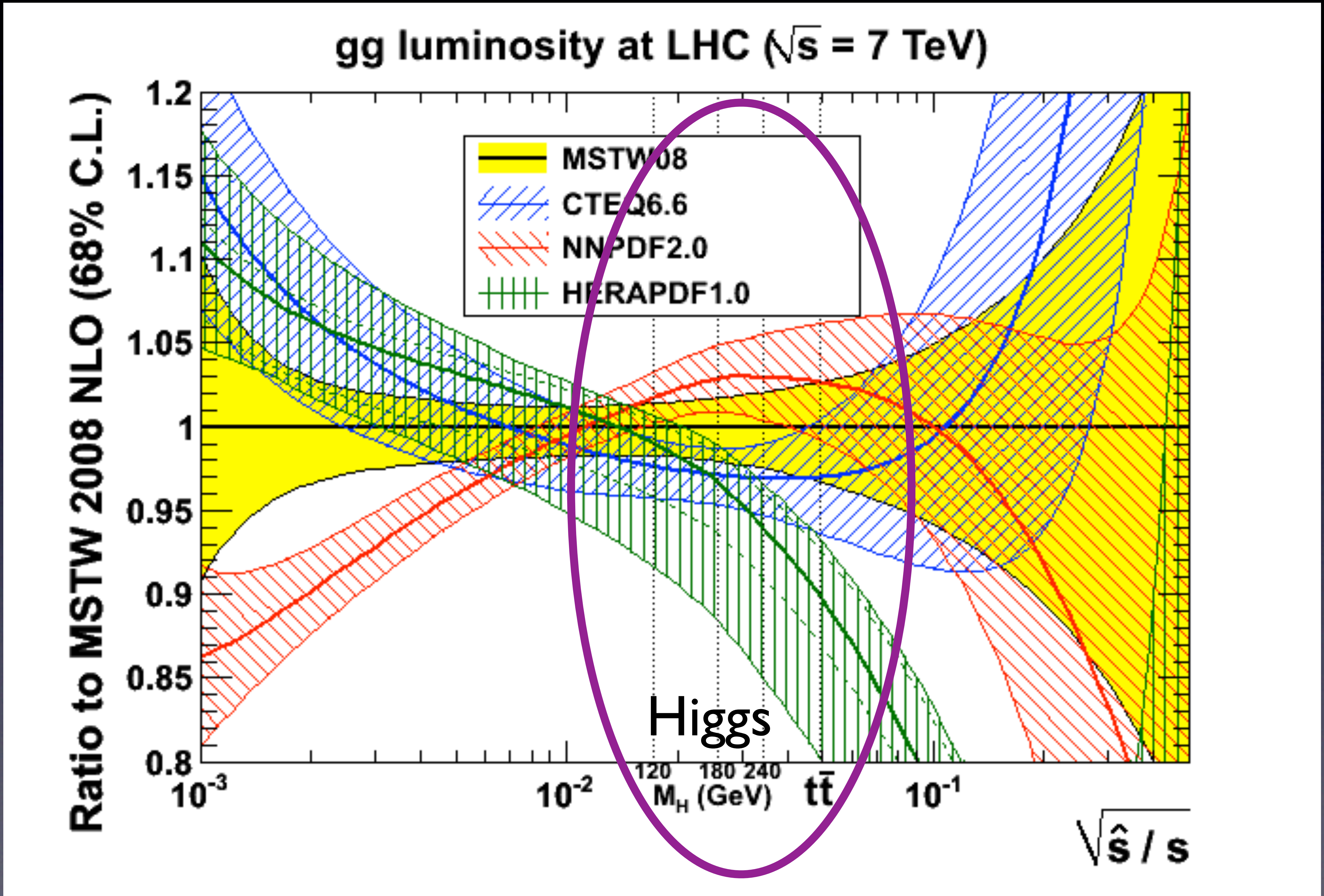
Higgs production via gluon-gluon fusion starts at $\mathcal{O}(\alpha_S^2)$

Top-quark pair production

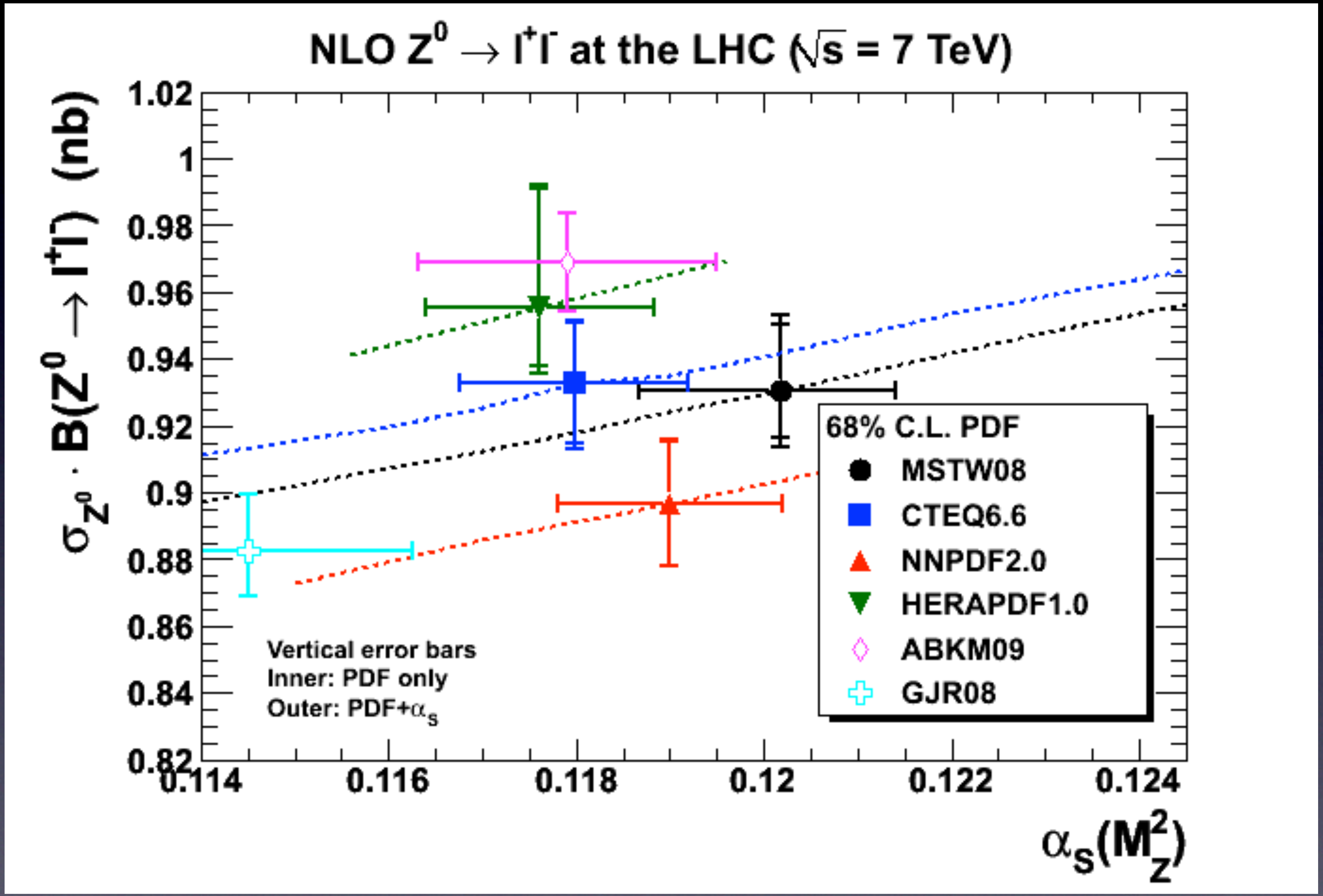


Predominantly via gluon-gluon fusion at the LHC.

$$\frac{\partial \mathcal{L}_{gg}}{\partial \hat{s}} = \frac{1}{s}\int_{\tau}^{1} \frac{\mathrm{d}x}{x}\, f_g(x,\hat{s})\, f_g(\tau/x,\hat{s}), \quad \tau \equiv \frac{\hat{s}}{s}$$

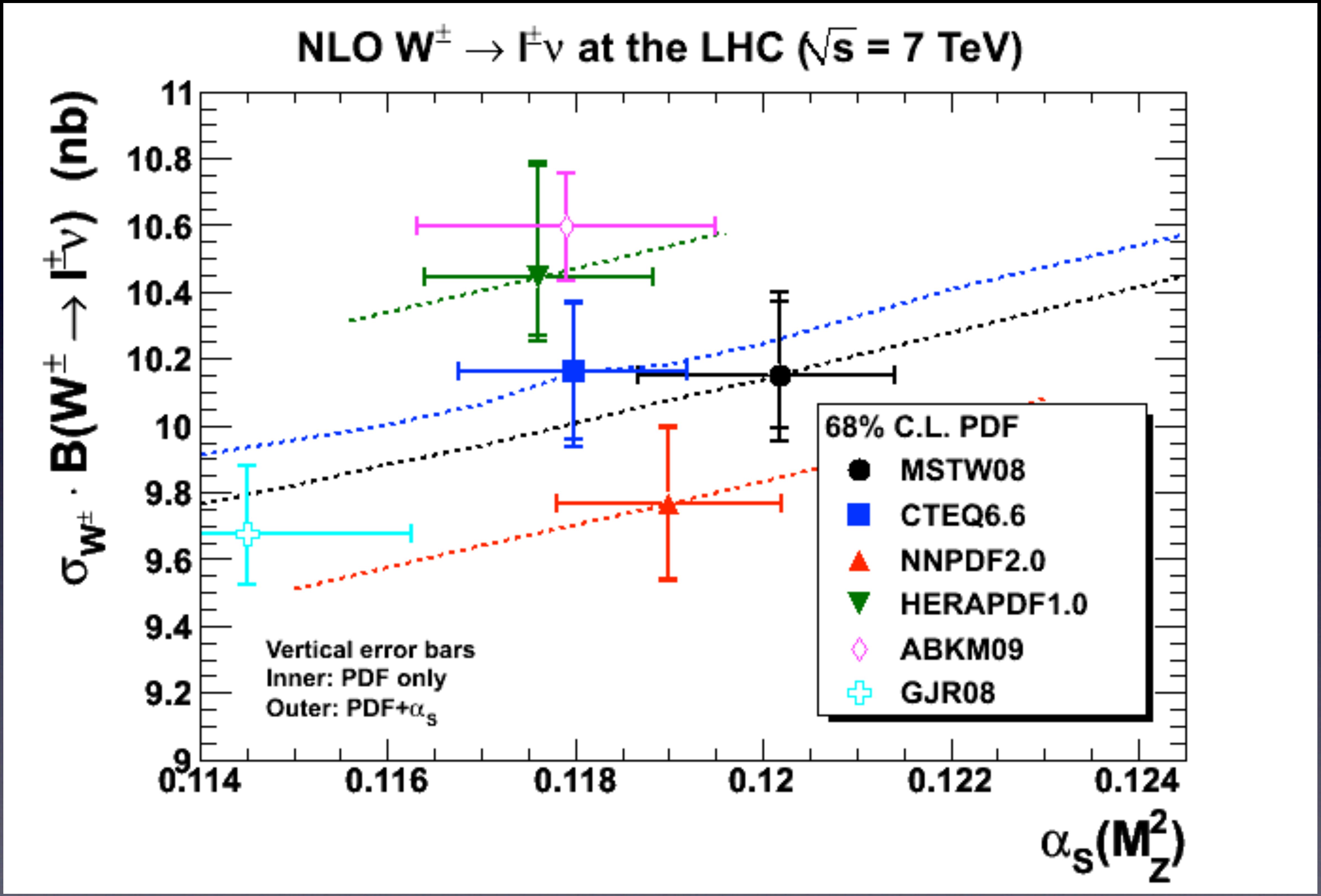


Z total cross section

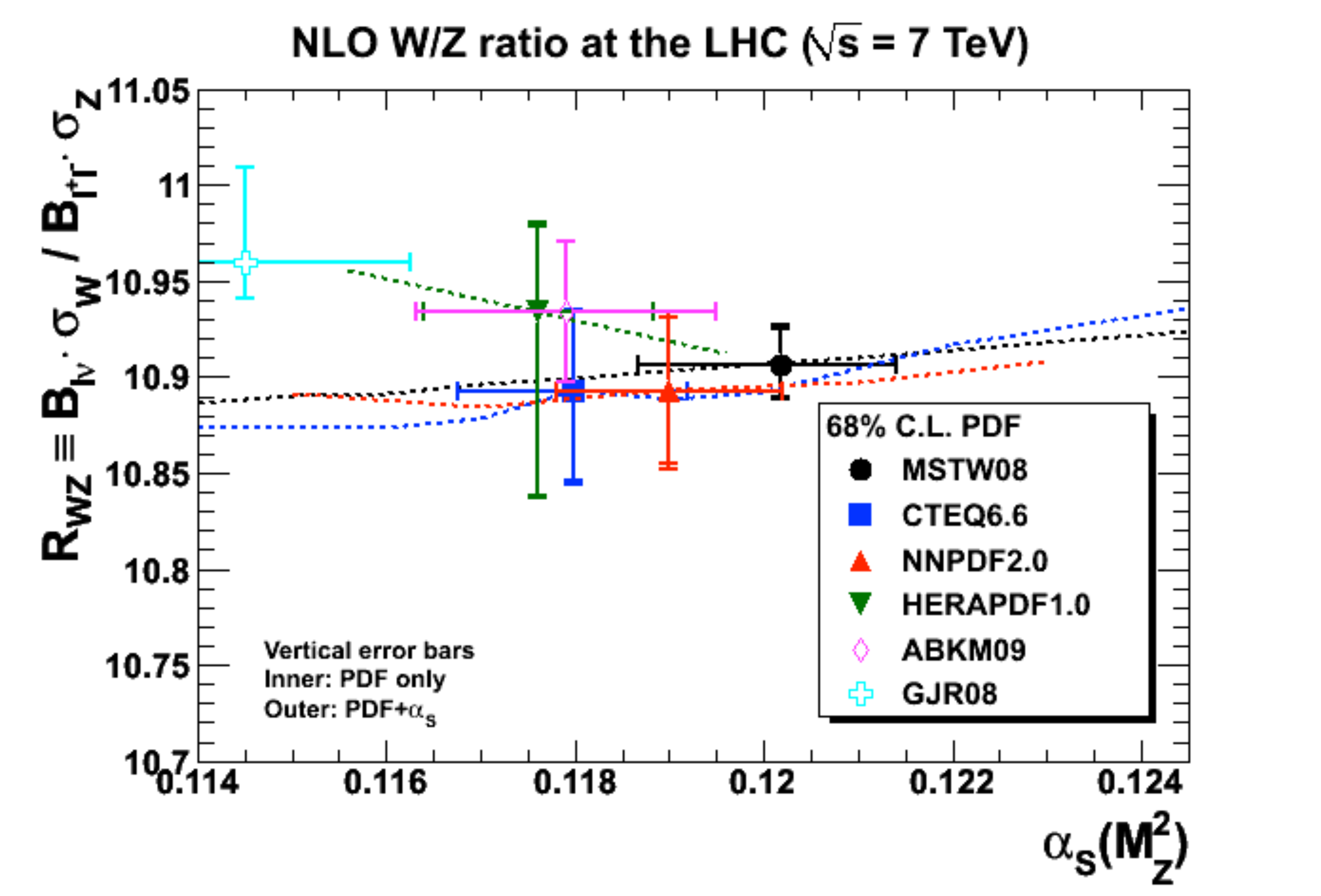


Potential "*standard candle*" to measure machine luminosity?

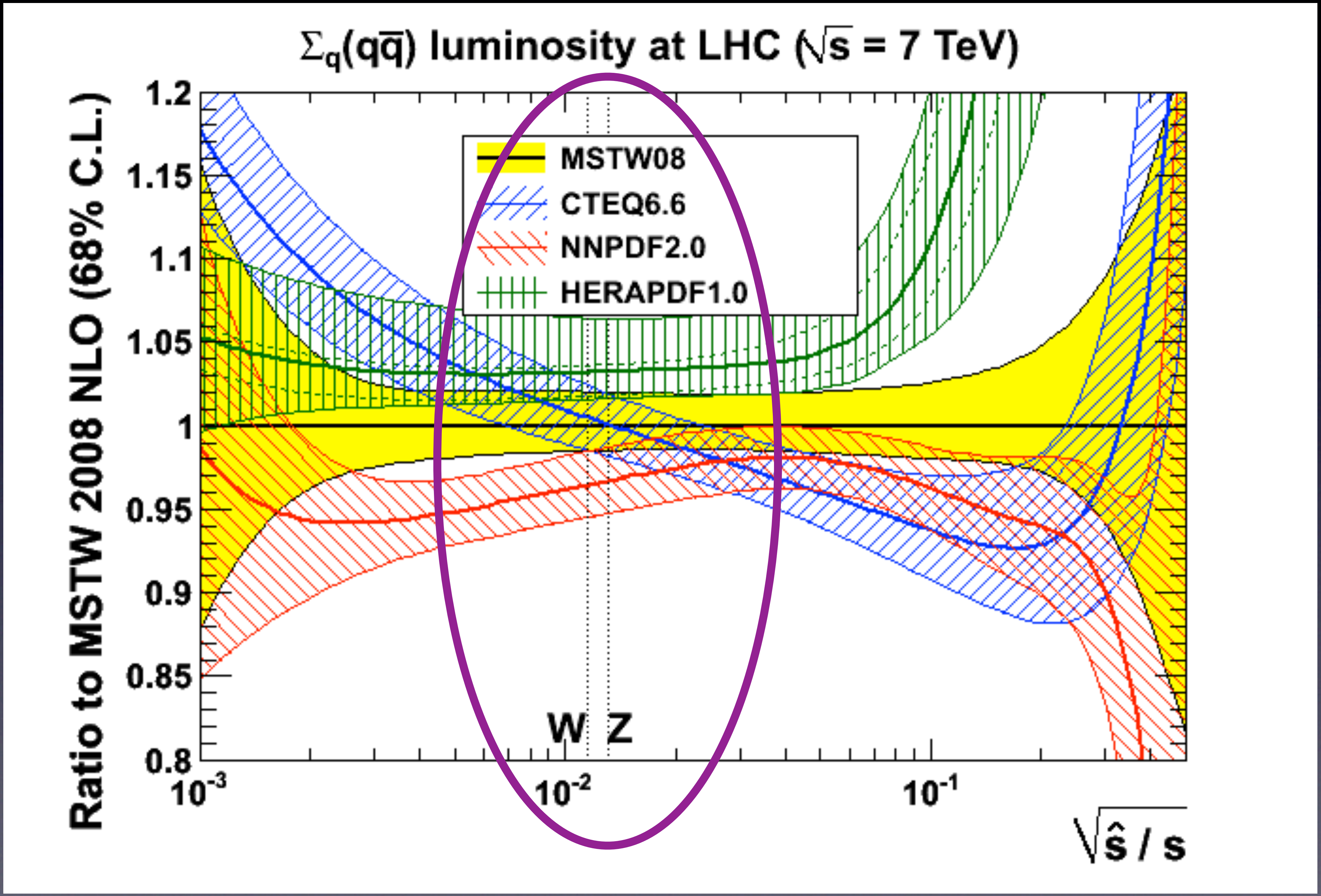
W total cross section



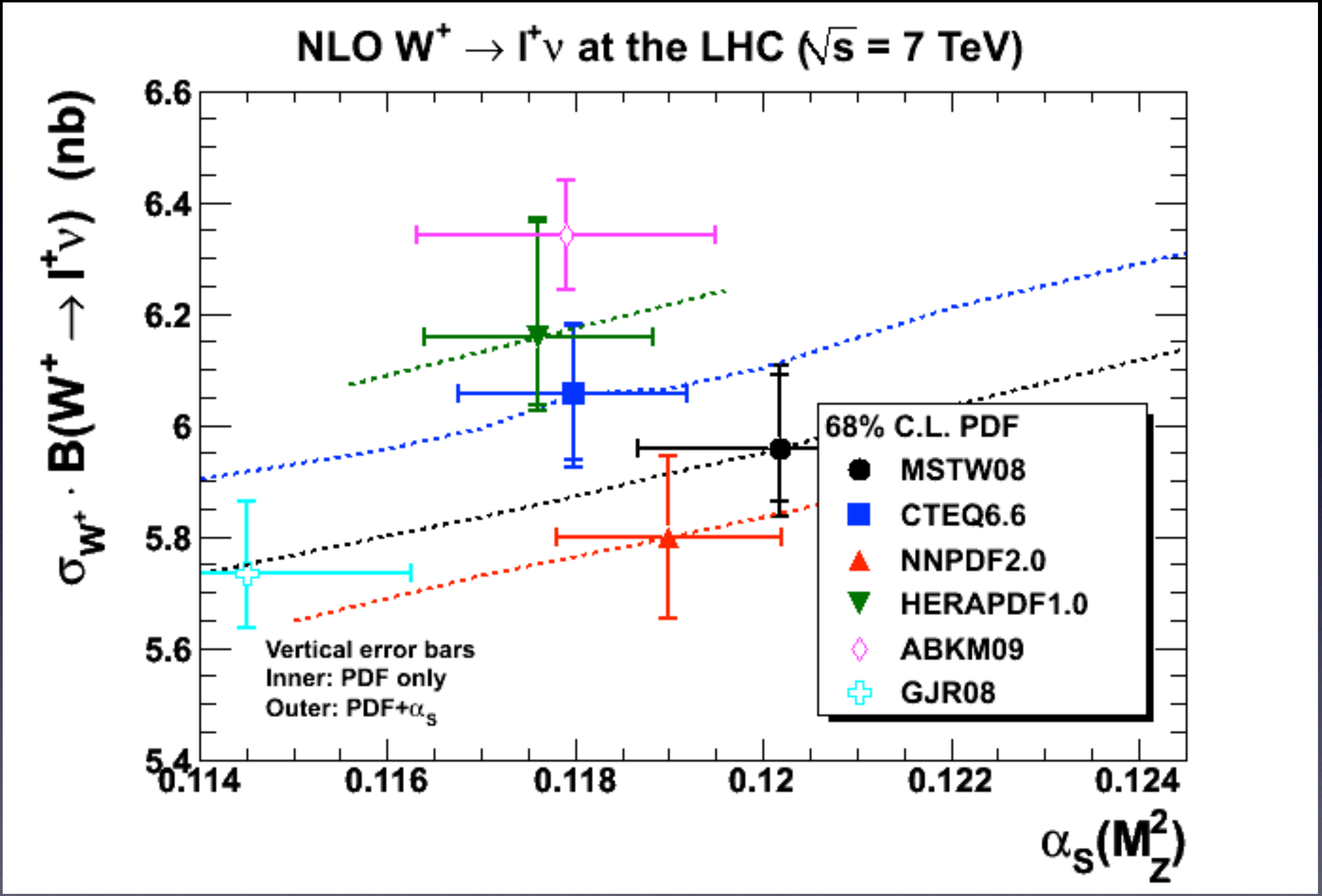
Ratio of W and Z



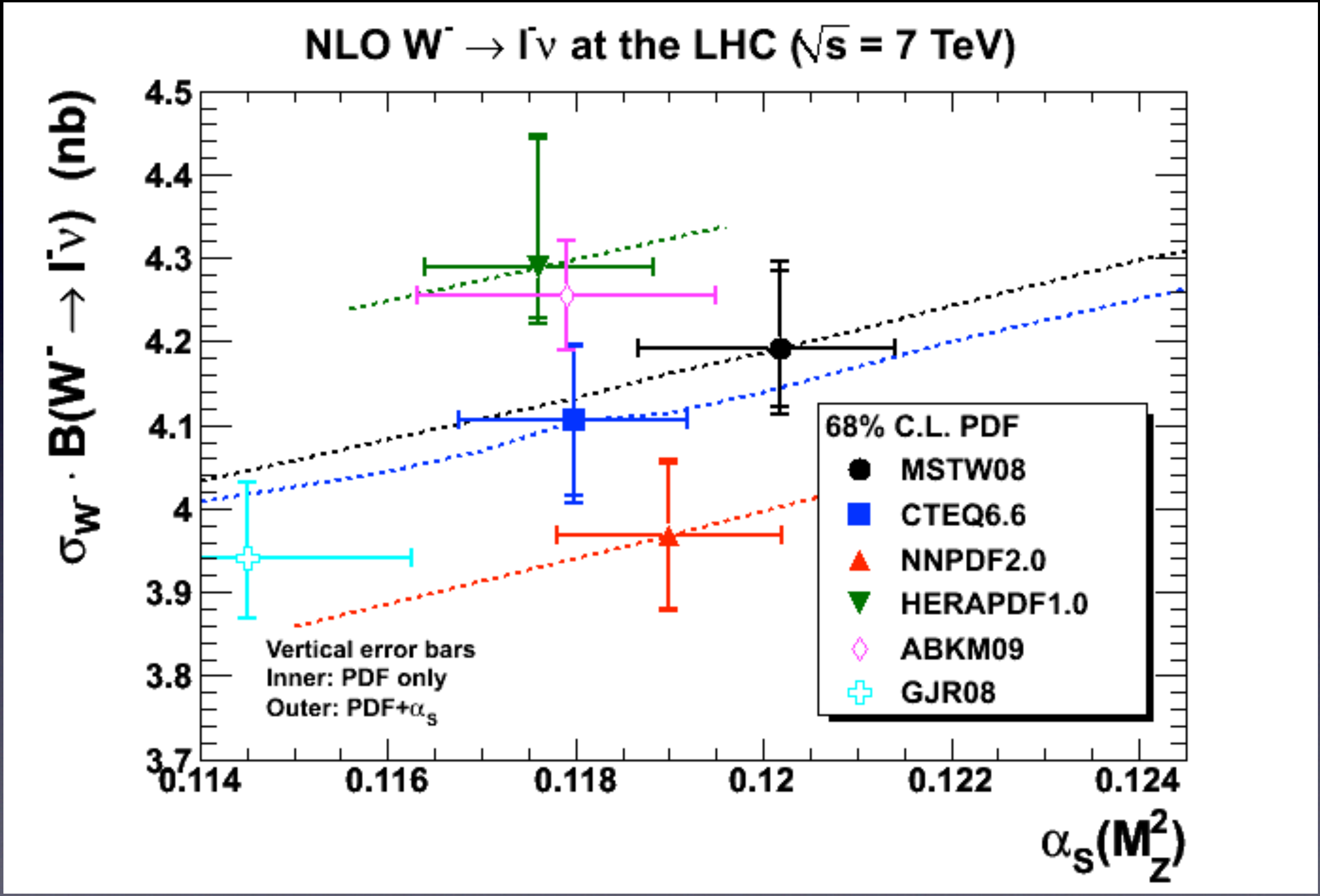
$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \hat{s}} = \frac{1}{s}\int_\tau^1 \frac{\mathrm{d}x}{x} \sum_q \left[f_q(x,\hat{s})f_{\bar{q}}(\tau/x,\hat{s}) + (q \leftrightarrow \bar{q})\right], \quad \tau \equiv \frac{\hat{s}}{s}$$



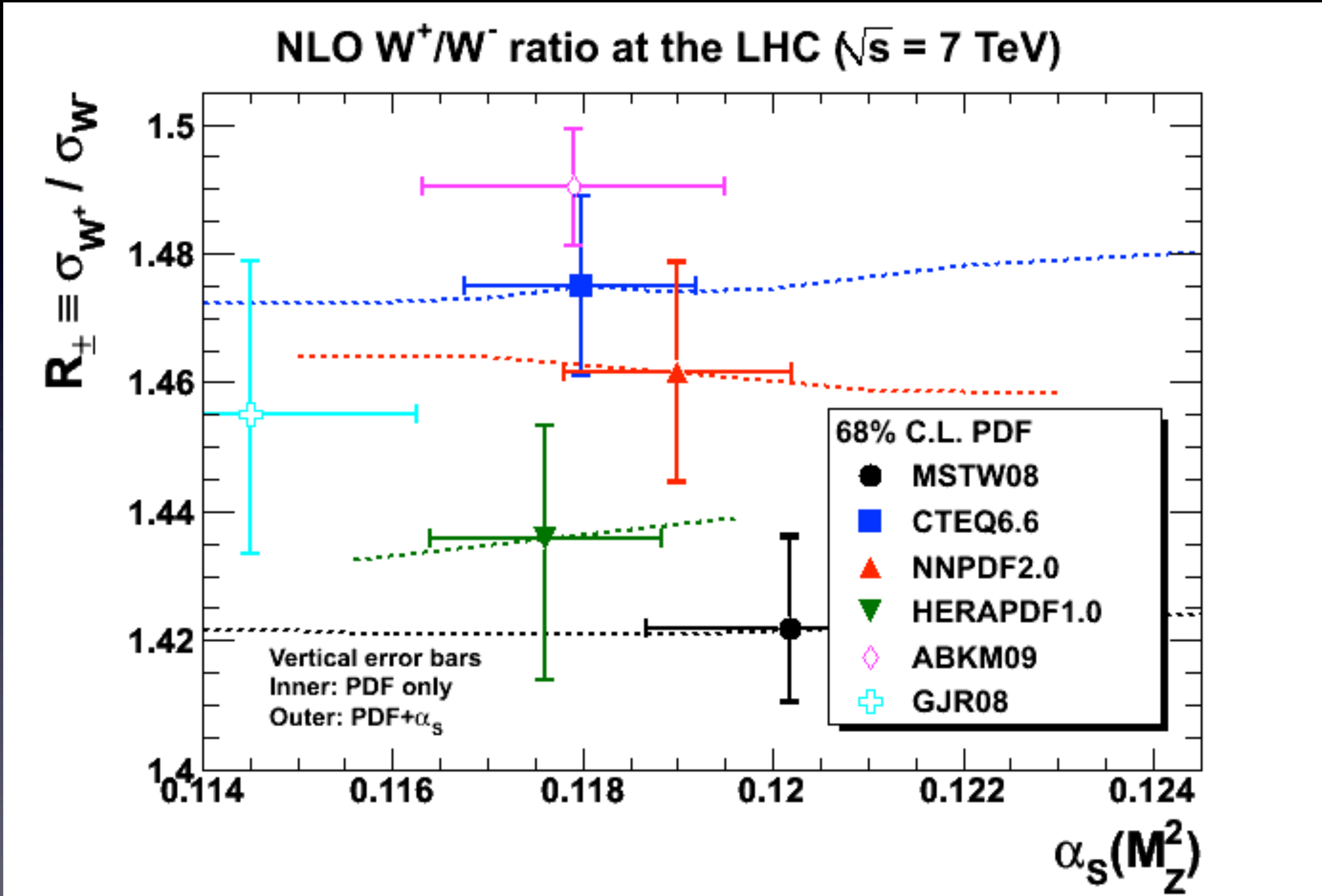
W^+ total cross section



W^- total cross section



Ratio of W^+ to W^-



Are all PDF sets equal?

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	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08

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	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔ (Run I)	✔	✘	✘	✘

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔ (Run I)	✔	✘	✘	✘
Tevatron jets	✔	✔ (Run I)	✔	✘	✘	✔

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔ (Run I)	✔	✘	✘	✘
Tevatron jets	✔	✔ (Run I)	✔	✘	✘	✔
GM-VFNS	✔	✔	✘	✔	✘	✘

Are all PDF sets equal?

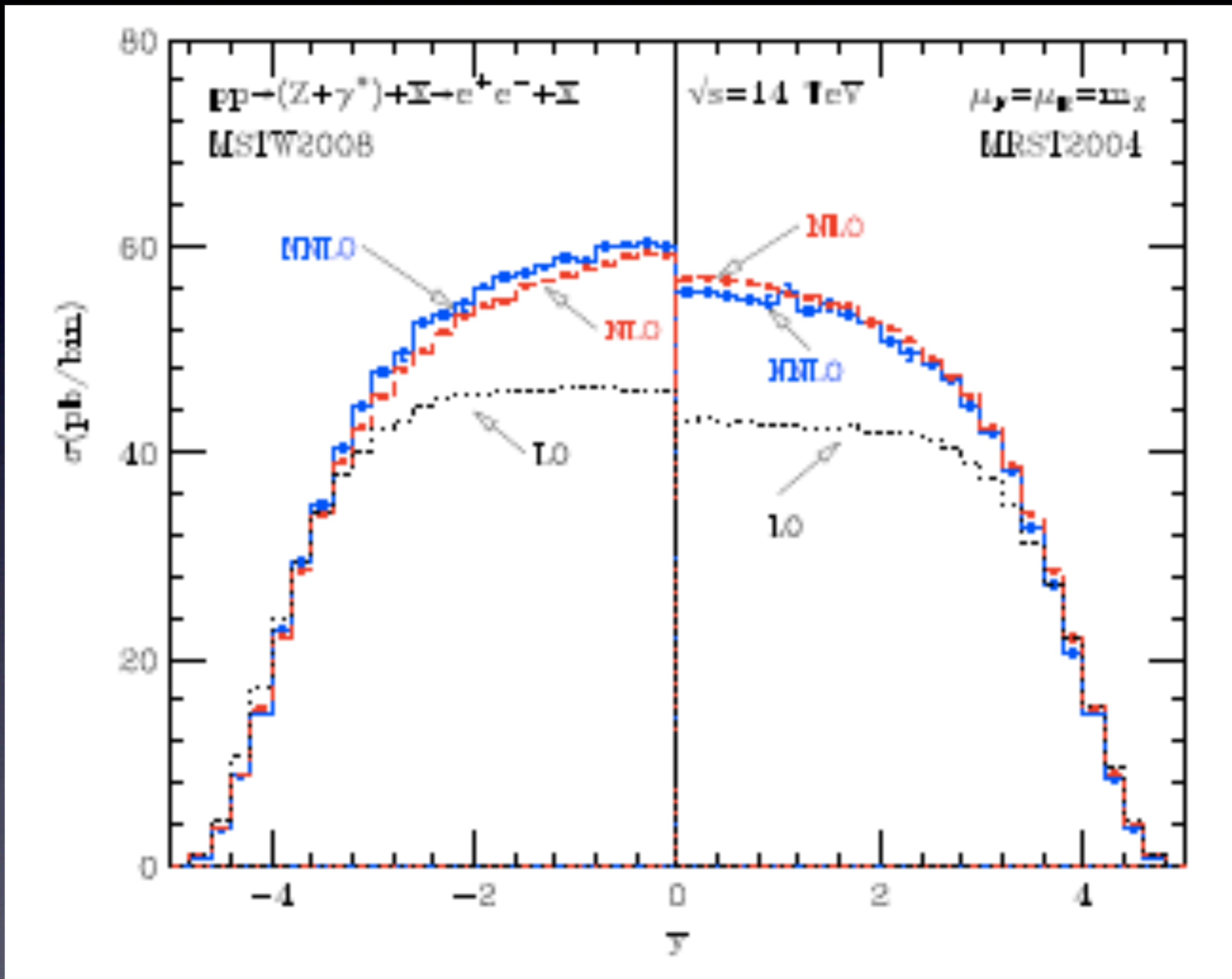
	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔ (Run I)	✔	✘	✘	✘
Tevatron jets	✔	✔ (Run I)	✔	✘	✘	✔
GM-VFNS	✔	✔	✘	✔	✘	✘
NNLO	✔	✘	✘	✘	✔	✔

Are all PDF sets equal?

	MSTW08	CTEQ6.6	NNPDF2.0	HERAPDF1.0	ABKM09	GJR08
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✘	✔	✔
Fixed-target Drell-Yan	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔ (Run I)	✔	✘	✘	✘
Tevatron jets	✔	✔ (Run I)	✔	✘	✘	✔
GM-VFNS	✔	✔	✘	✔	✘	✘
NNLO	✔	✘	✘	✘	✔	✔

Some PDF sets are ***more equal*** than others!

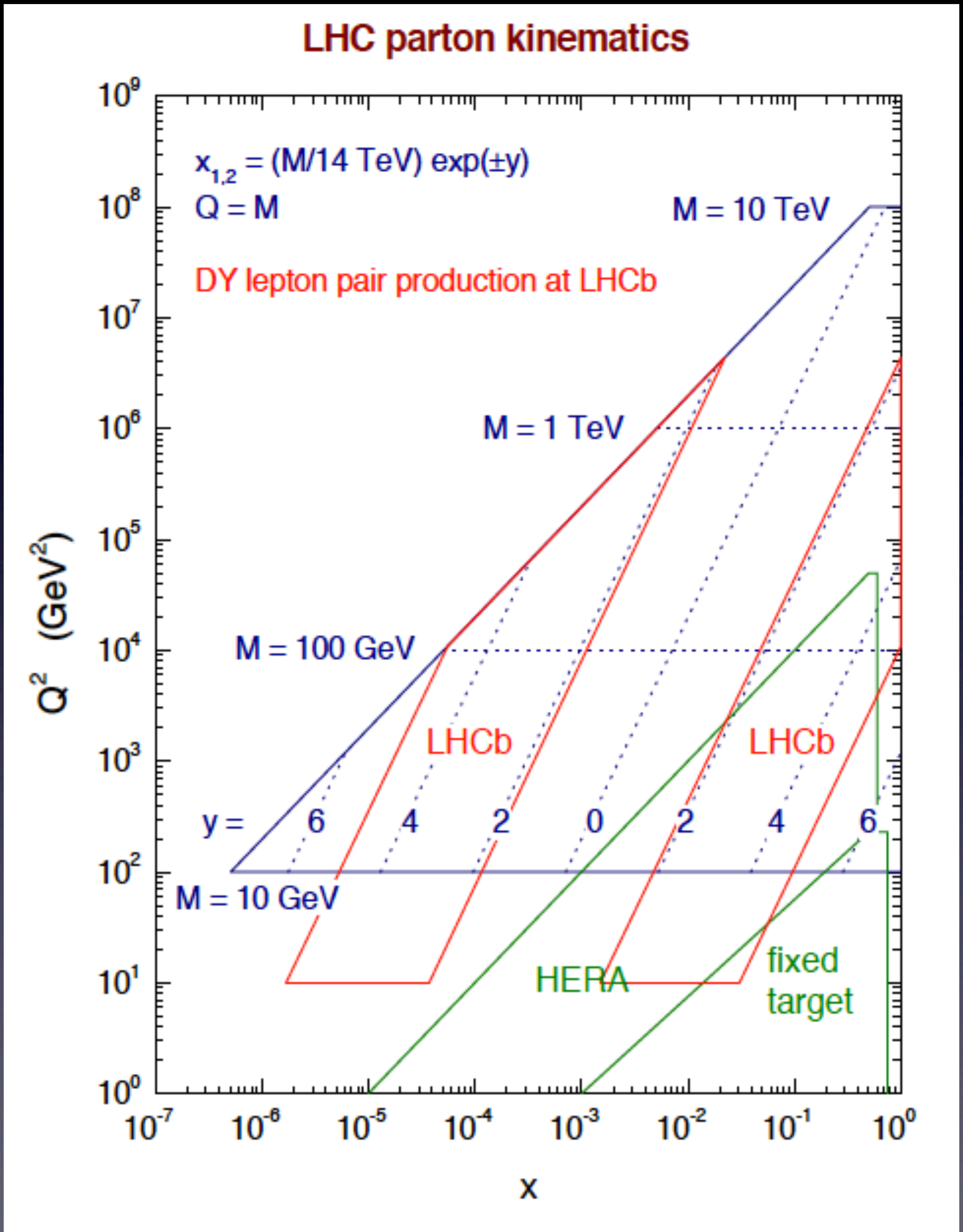
LHC constraints on PDFs



- Initial **jet** measurements subject to large uncertainty from *jet energy scale*.
- Use *W* and *Z* measurements: small uncertainty (< 1%) from higher-order QCD corrections.

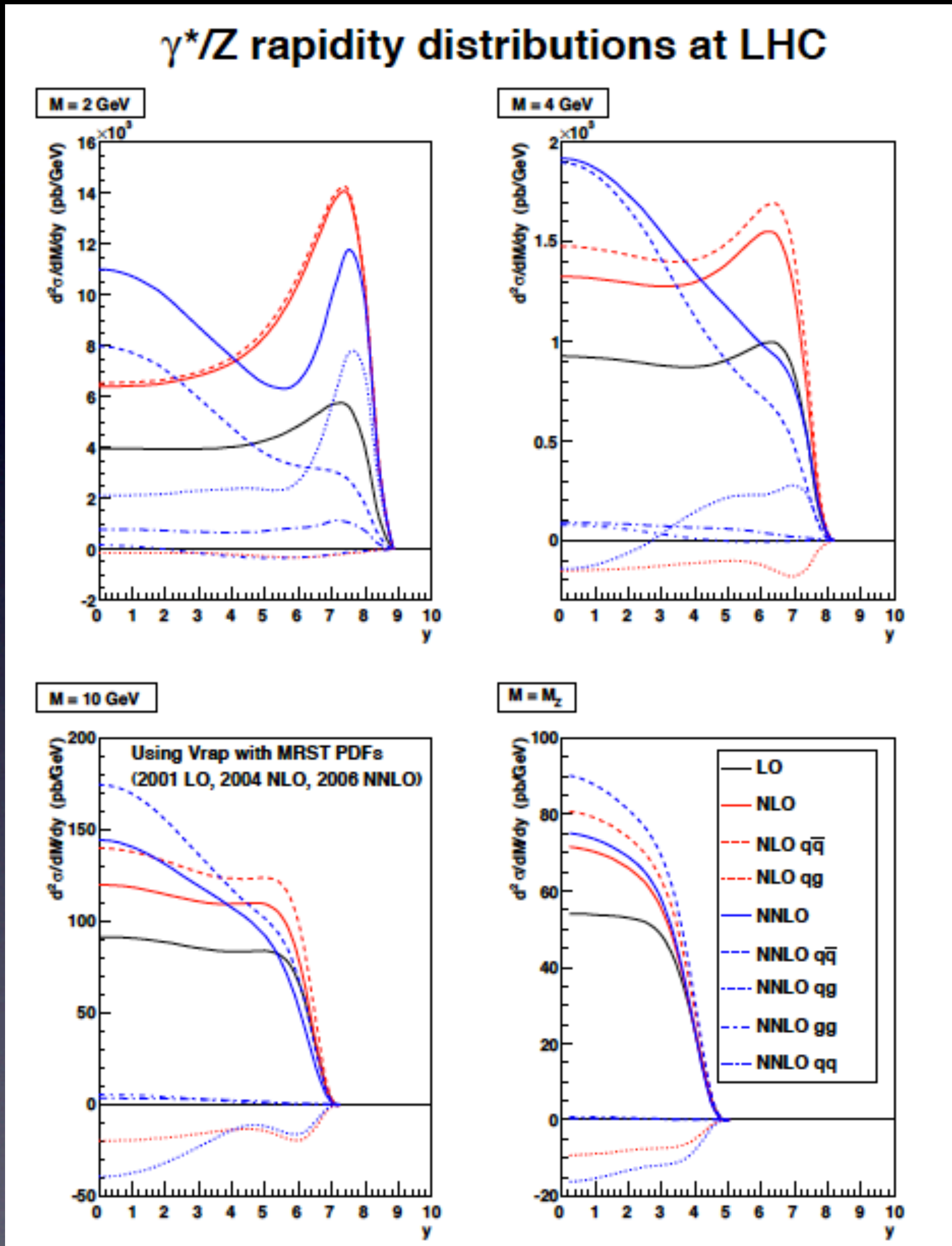
Catani, Cieri, Ferrera, de Florian, Grazzini [arXiv:0903.2120]

Potential of LHCb for PDFs



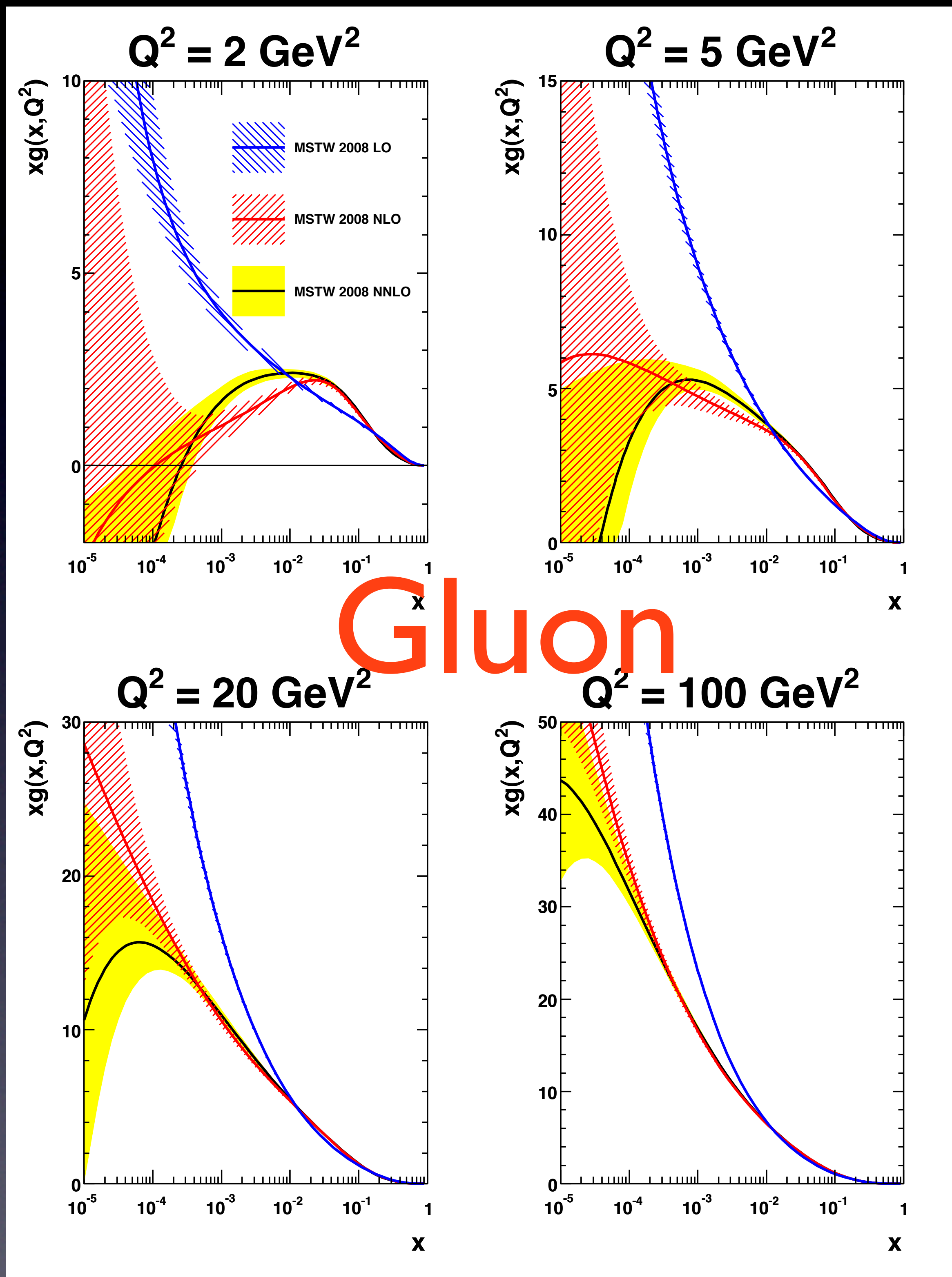
- Specialised *b*-physics experiment designed to study CP-violation.
- Forward spectrometer enables electroweak measurements at large (pseudo)rapidity
  ⇒ small-*x*!

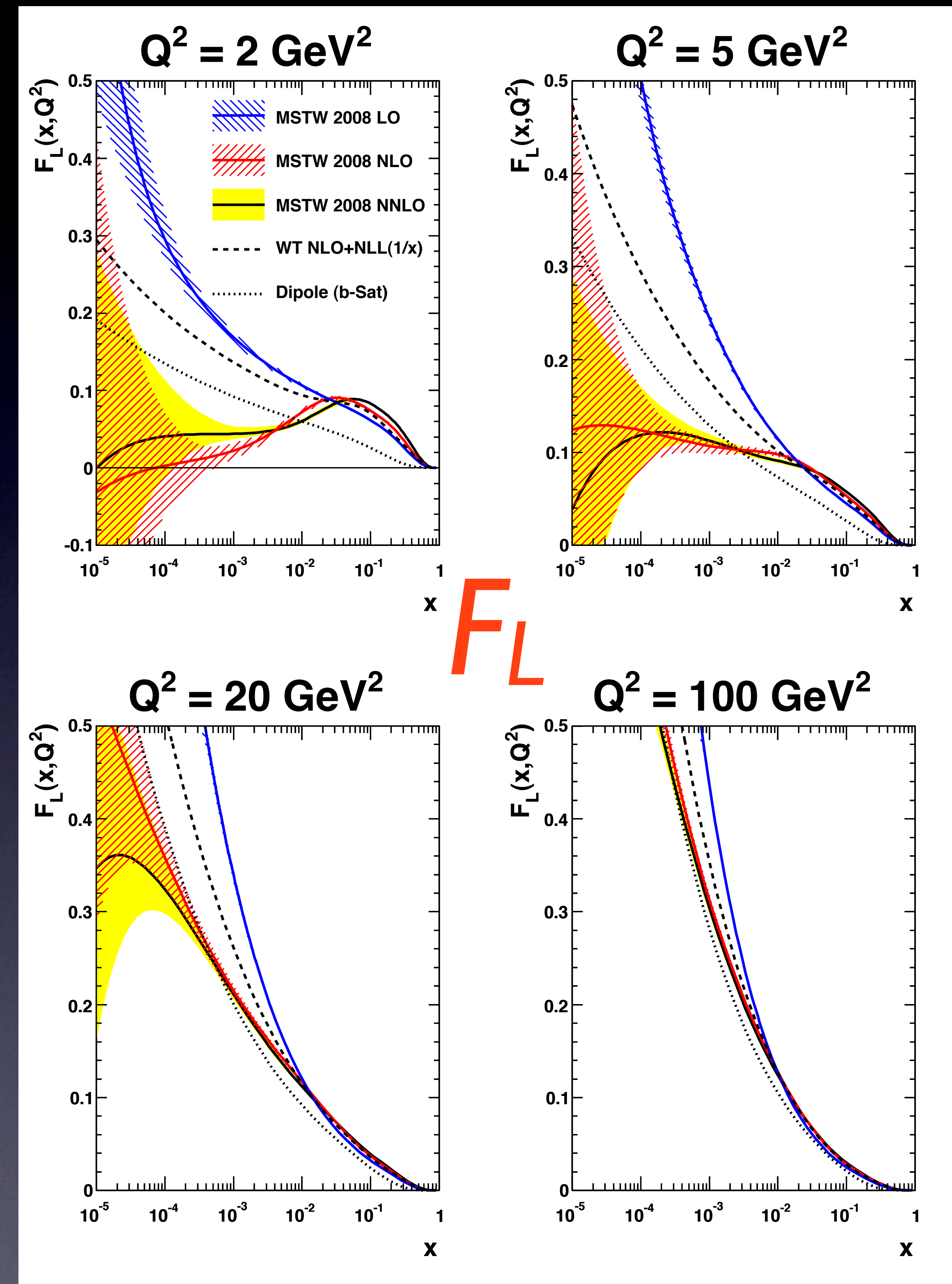
Drell-Yan rapidity distributions



- Rapidity distributions unstable for $M^2 << s$ $\Rightarrow$ small-x.
- Expect need to resum $\alpha_S \log(1/x)$ terms (BFKL) in addition to usual $\alpha_S \log(Q^2)$ terms (DGLAP).

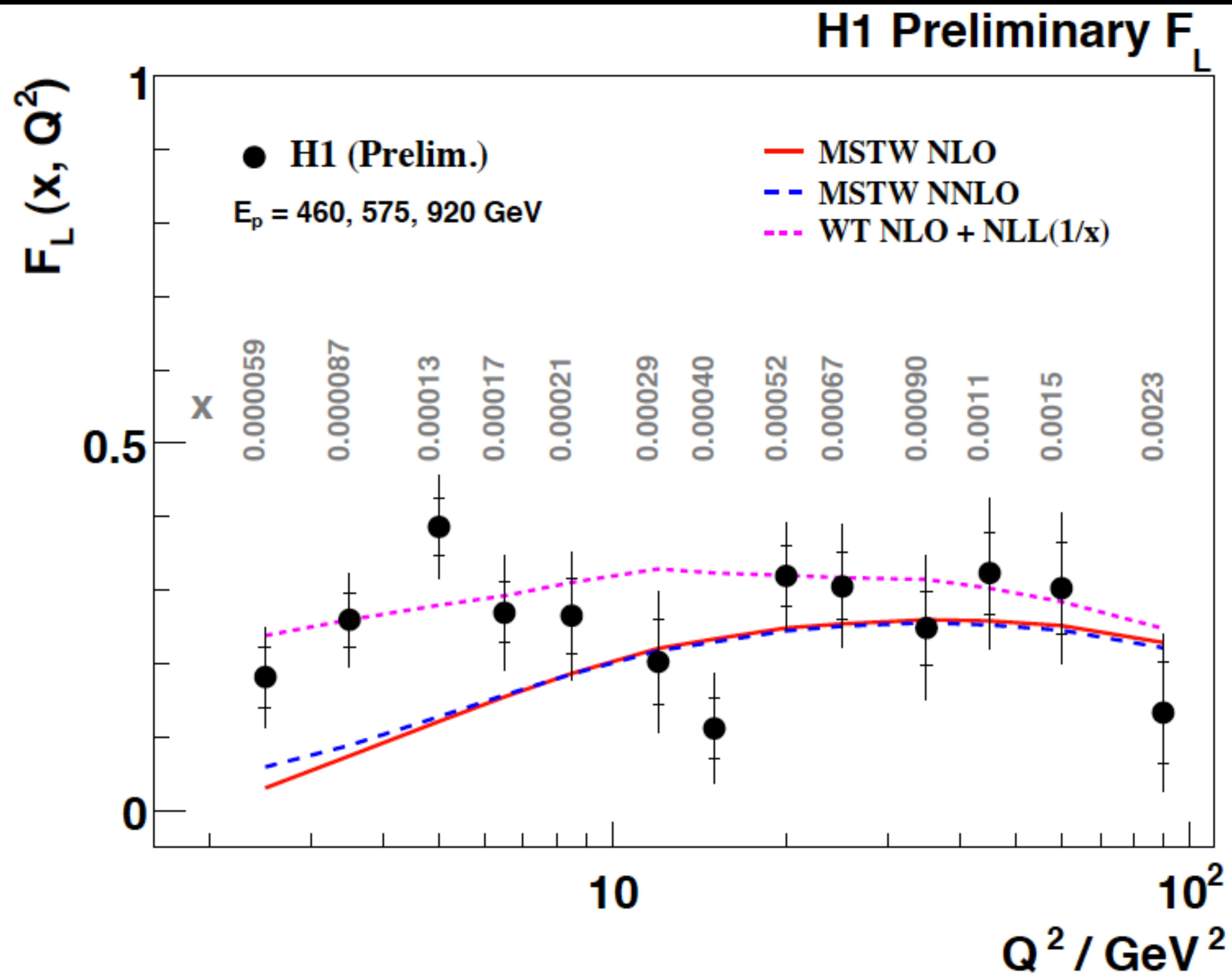
Gluon distribution and F_L





Perturbatively unstable as the hard scale Q^2 is lowered.

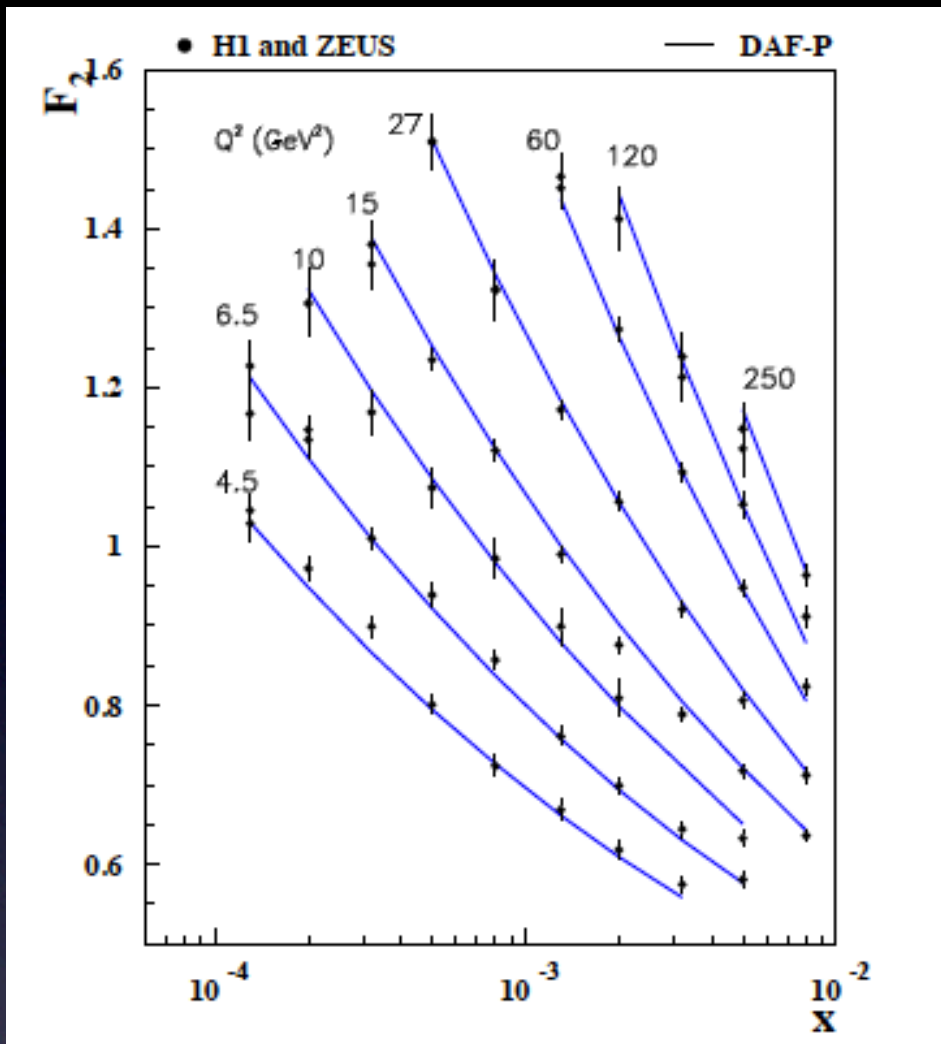
F_L compared to HERA data



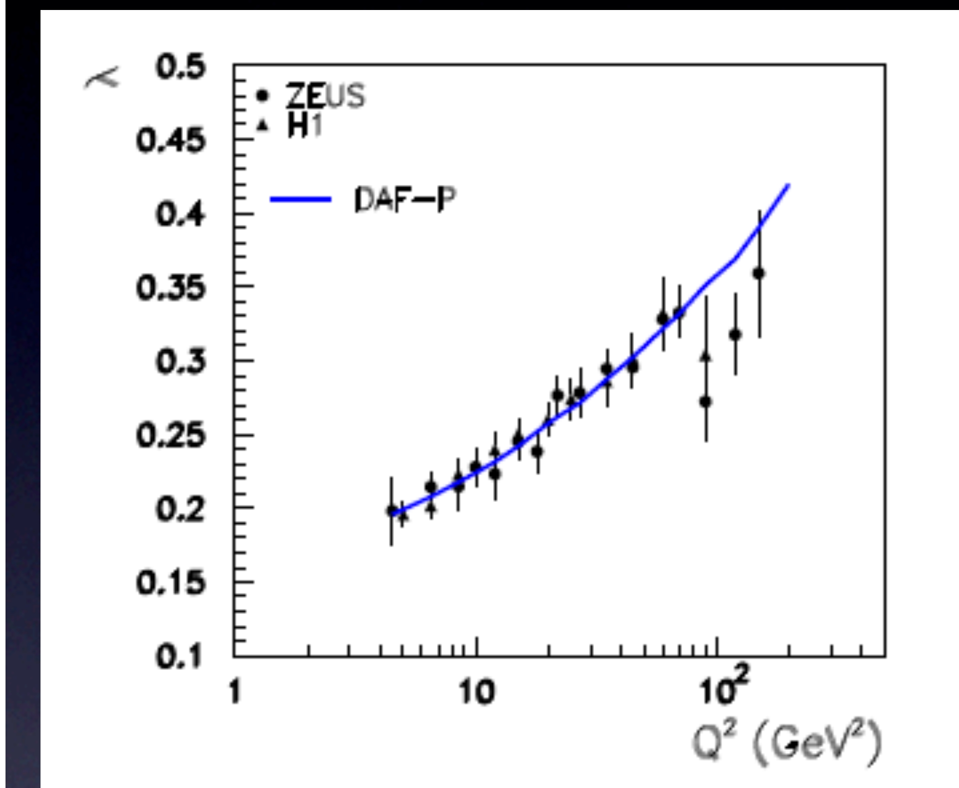
- NLO and NNLO calculations lower than data at low Q^2.
- Small-x resummation helps [White, Thorne, hep-ph/0611204].

Thorne-White approach is "BFKL-improved DGLAP".

DGLAP-improved BFKL



H. Kowalski, L.N. Lipatov, D.A. Ross, G.W.



arXiv:1005.0355

$$F_2(x,Q^2) \overset{x\to 0}{\longrightarrow} \left(\frac{1}{x}\right)^{\lambda(Q^2)}$$

- Successful BFKL description of HERA data.
- More work needed to unify with DGLAP approach and extend to hadronic processes.
- Electroweak data at LHC will provide a test.

Summary

- We are now firmly in the LHC era.
- **P**arton **D**istribution **F**unctions (**PDF**s) are a non-negotiable input to almost all theory predictions at the LHC.
- PDFs currently known fairly well, but still open issues for heavy-quarks and small-x.
- Early LHC **electroweak** data will play an important rôle in testing the PDFs.