QCD at the LHC

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- introduction and overview
- HO corrections
- PDFs
- LHC benchmarks
- (double parton scattering)
- summary

apologies for omitting many topics of interest!

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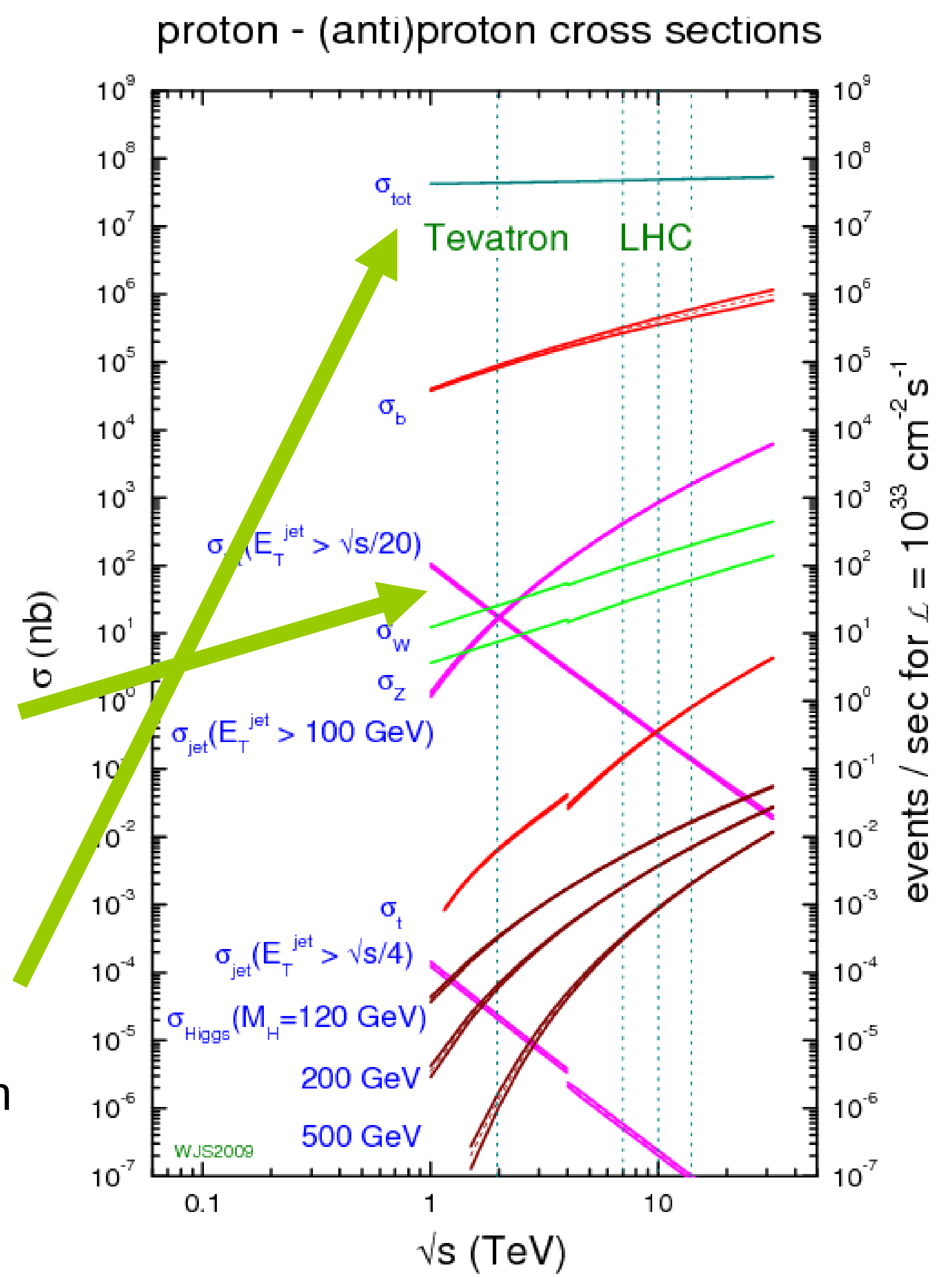
introduction and overview

Scattering processes at high energy hadron colliders can be classified as either **HARD** or **SOFT**

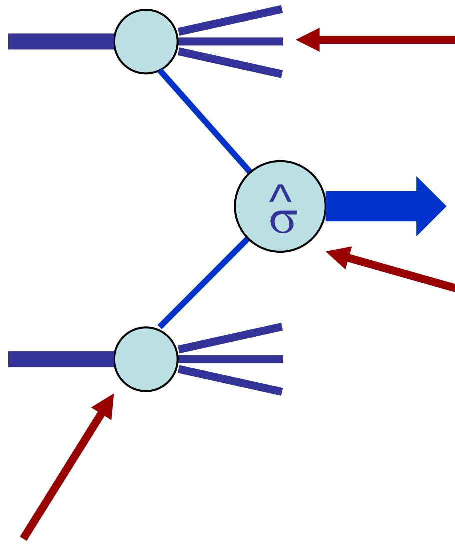
Quantum Chromodynamics (QCD) is the underlying theory for **all** such processes, but the approach (and the level of understanding) is very different for the two cases

For **HARD** processes, e.g. W or high-E_T jet production, the rates and event properties can be predicted with some precision using perturbation theory

For **SOFT** processes, e.g. the total cross section or diffractive processes, the rates and properties are dominated by non-perturbative QCD effects, which are much less well understood



precision pQCD in the LHC era



tuned event simulation (parton showers + UE) MCs, interfaced with LO or NLO hard scattering MEs

LO, NLO, NNLO, … supplemented by resummed N^{n}LL improvements, EW corrections, …

parton distribution functions

the QCD **factorization theorem** for hard-scattering (short-distance) inclusive processes

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2)$$

$$\times \; \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

precision phenomenology

- *Benchmarking*
  - inclusive SM quantities (V, jets, top,…), calculated to the highest precision available (e.g. NNLO)
  - tools needed: robust jet algorithms, decays included, PDFs, …

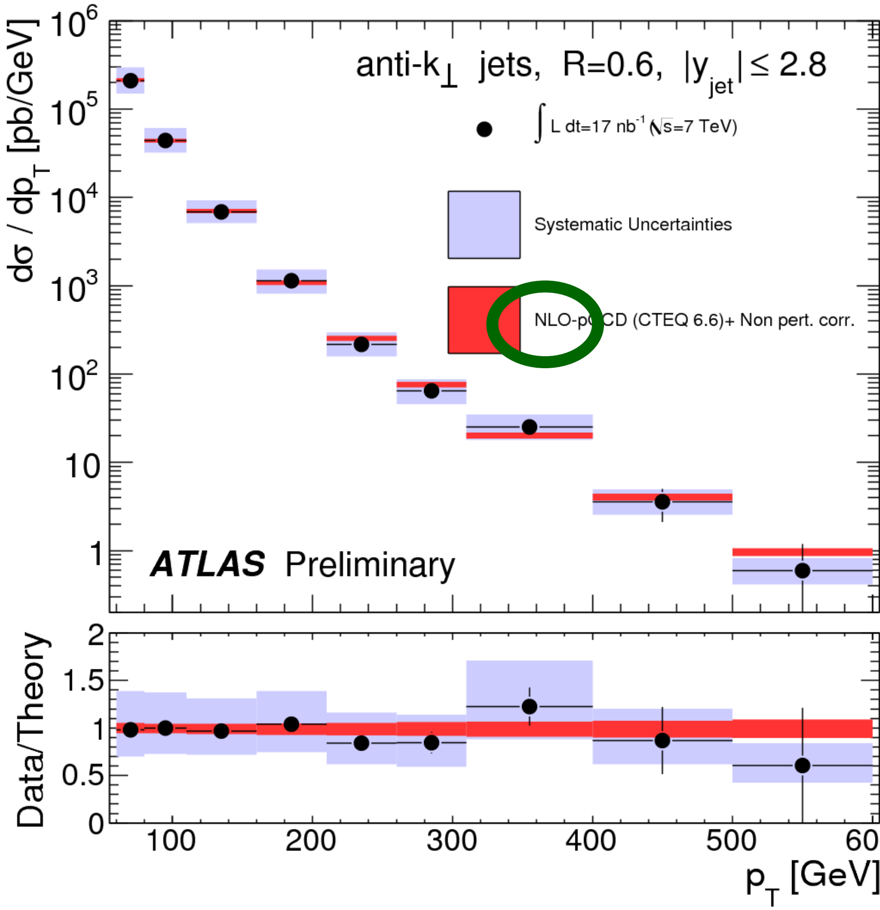
e.g. anti-k_T (Cacciari, Salam, Soyez)

- *Backgrounds*
  - new physics generally results in some combination of multijets, multileptons, missing E_T
  - therefore, we need to know SM cross sections {V,VV,bb,tt,H,…} + jets to high precision → \`wish lists'
  - ratios can be useful

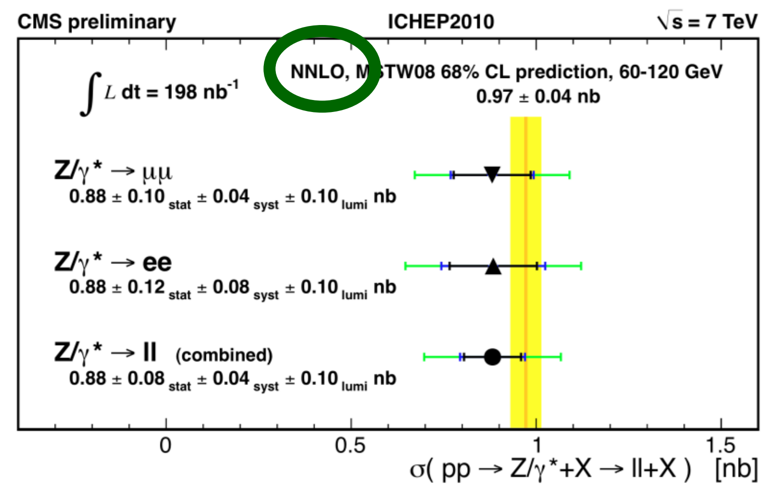
Note: V = γ^*,Z,$W^{\pm}$

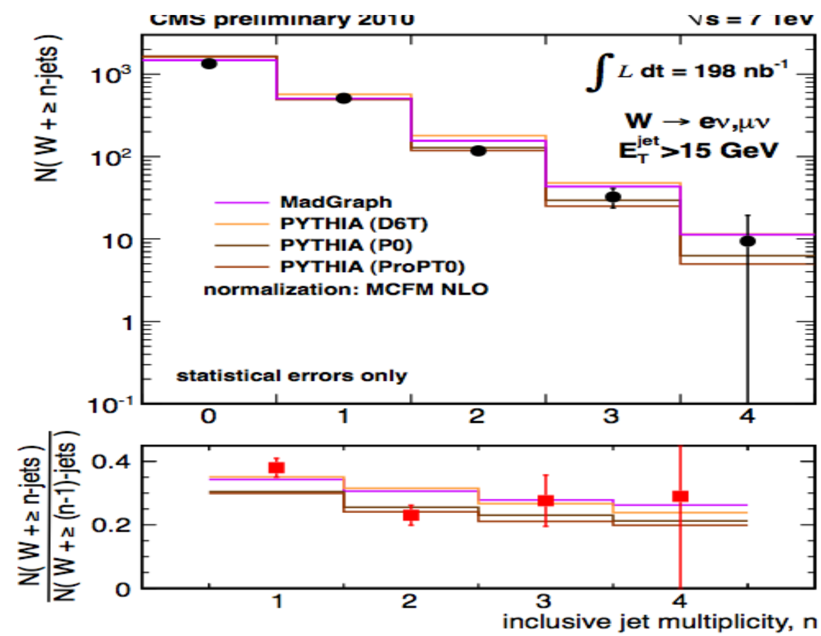
emerging ‘precision’ phenomenology at LHC

jet production



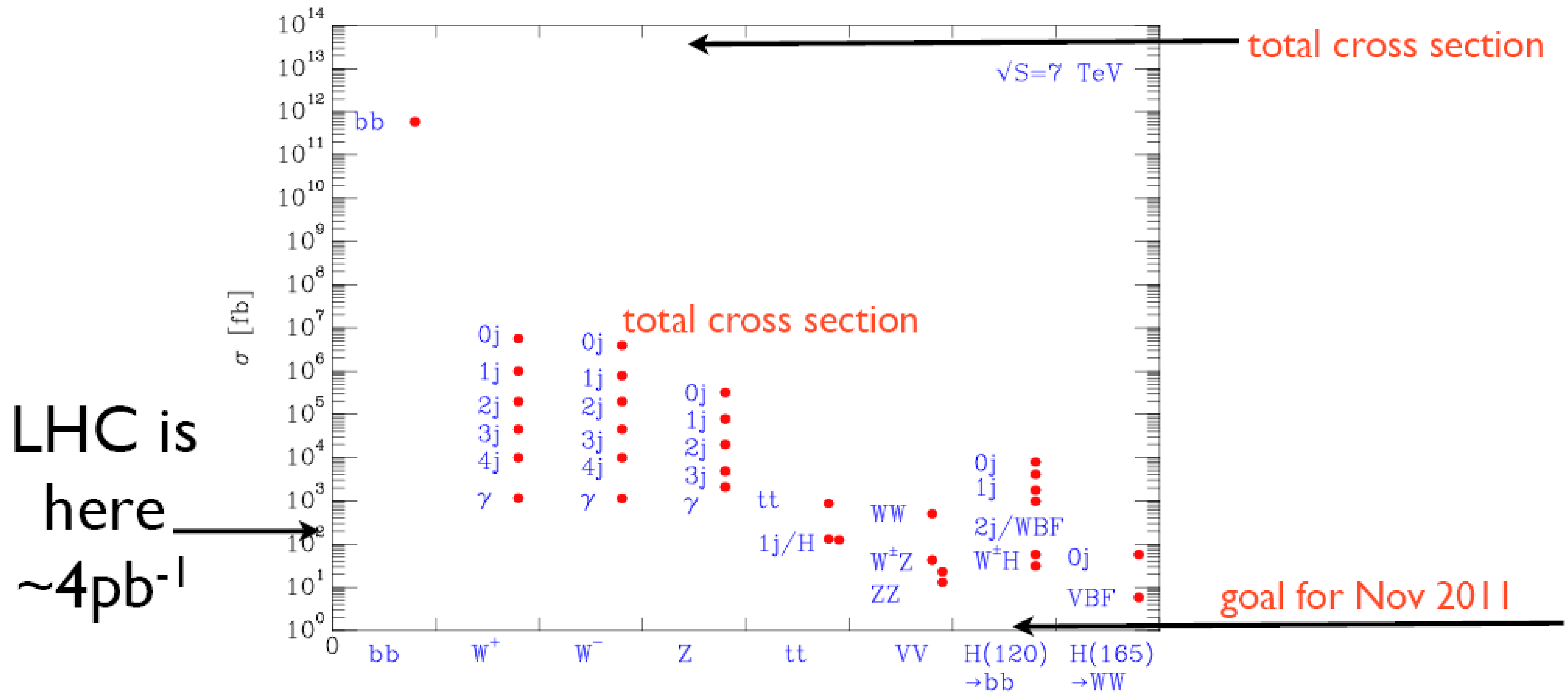
W, Z production





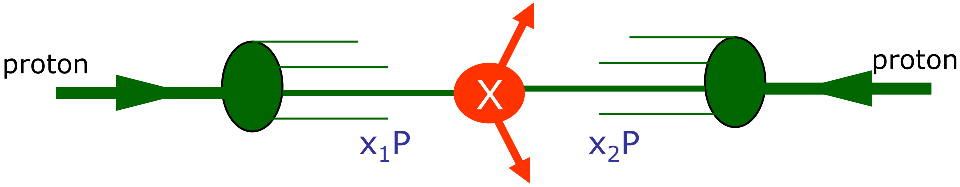
the SM Ladder at 7 TeV

Keith Ellis, MCFM



Includes decay of W/Z to one species of charged lepton and semi-leptonic decay of top (t → b l ν) (where applicable) and jets, Et> 25 GeV.

Parton Distribution Functions



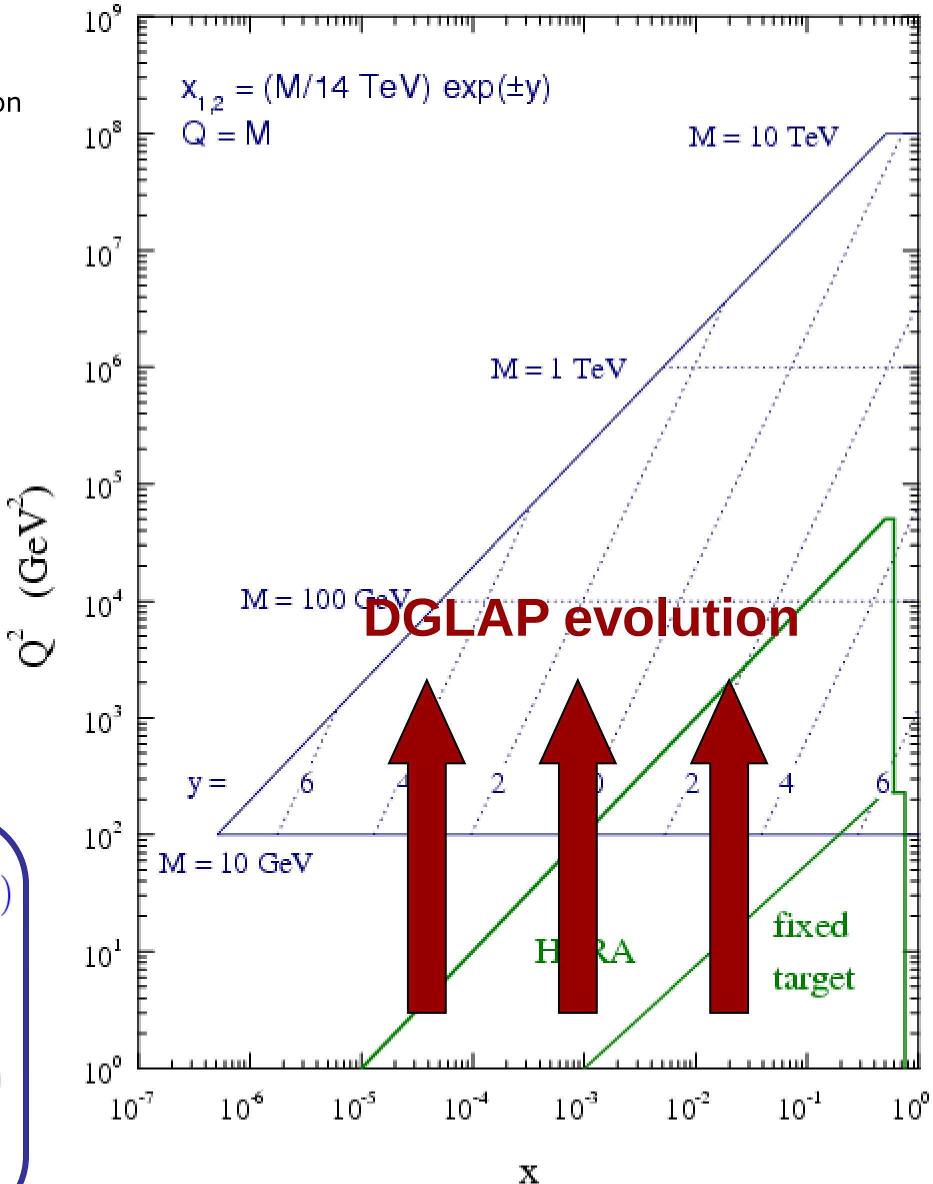
momentum fractions x_1 and x_2 determined by mass and rapidity of **X**

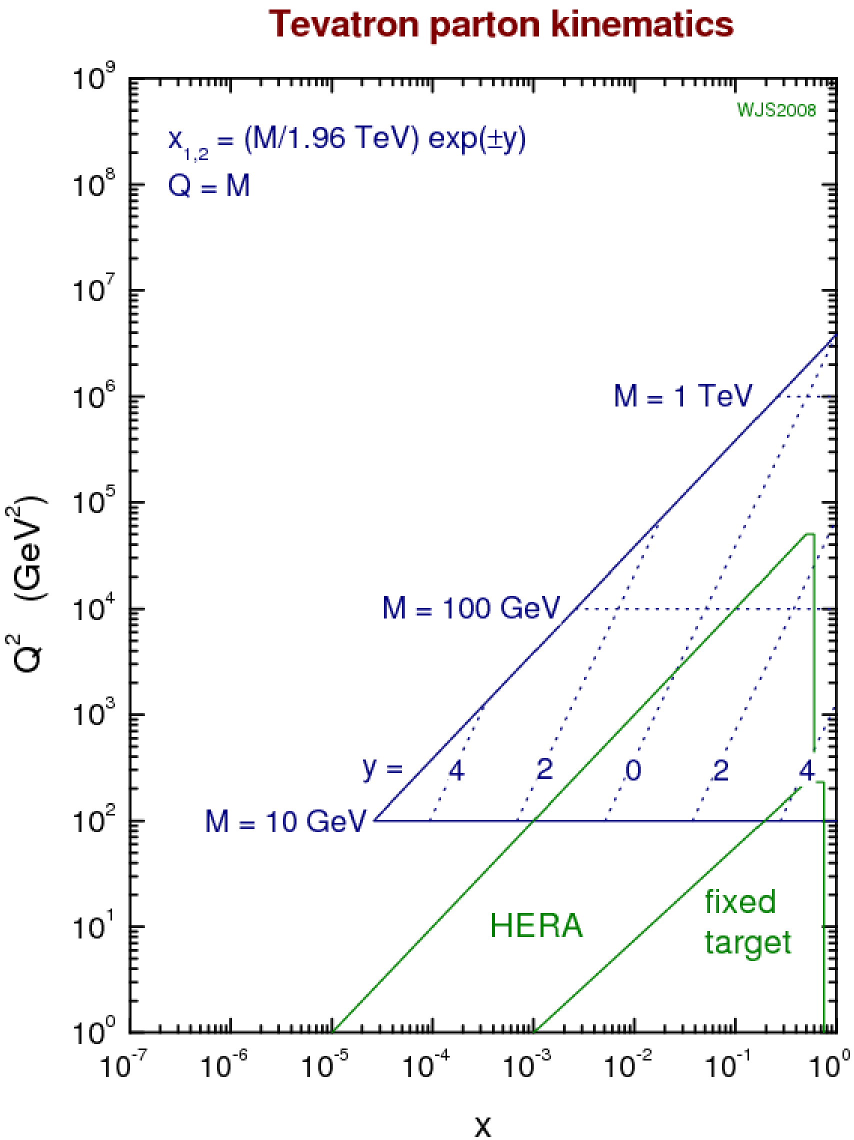
x dependence of $f_i(x,Q^2)$ determined by ‘global fit’ to deep inelastic scattering and other data, Q^2 dependence determined by **DGLAP** equations:

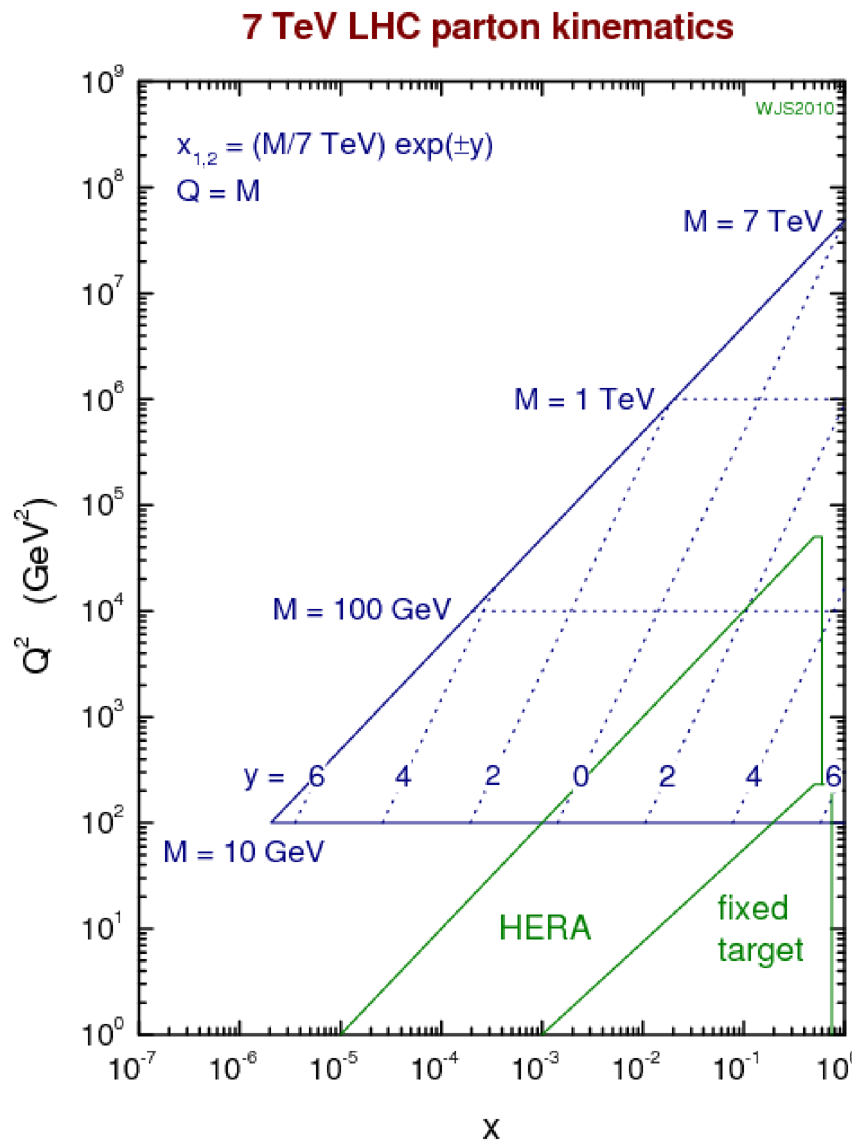
$$\frac{\partial q_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{q_iq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) + P_{q_ig}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\Big\}$$

$$\frac{\partial g(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\Big\{P_{gq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2) + P_{gg}(y,\alpha_S)\, g(\frac{x}{y},Q^2)\Big\}$$

LHC parton kinematics

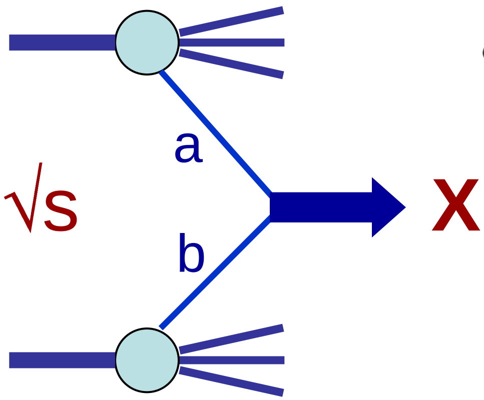



Tevatron parton kinematics
WJS2008
x1,2 = (M/1.96 TeV) exp(±y)
Q = M
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 4 2 0 2 4
HERA
fixed target
Q2 (GeV2)
x


7 TeV LHC parton kinematics
WJS2010
x1,2 = (M/7 TeV) exp(±y)
Q = M
M = 7 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
HERA
fixed target
Q2 (GeV2)
x

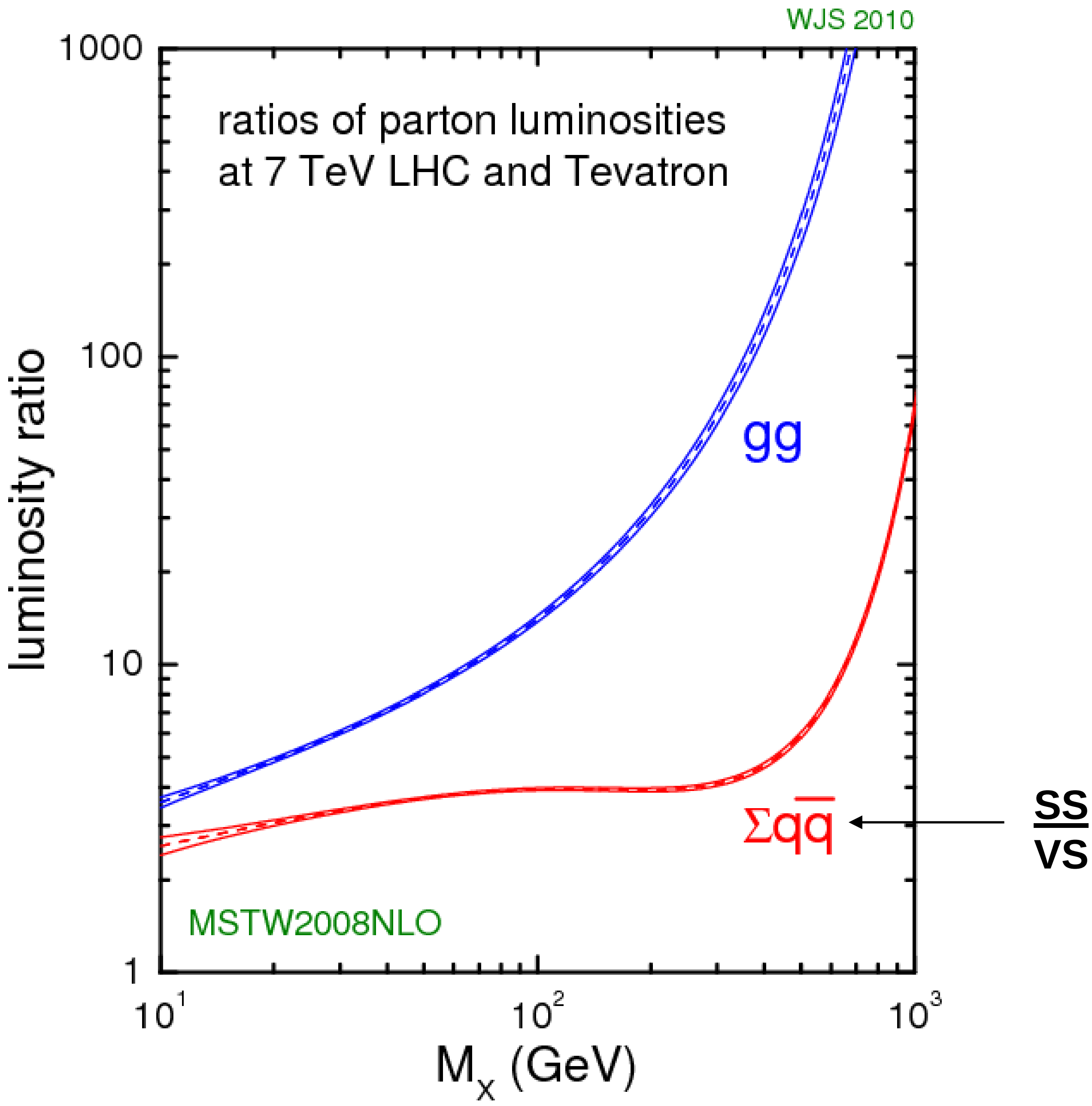
parton luminosity functions

- a quick and easy way to assess the mass, collider energy and pdf dependence of production cross sections

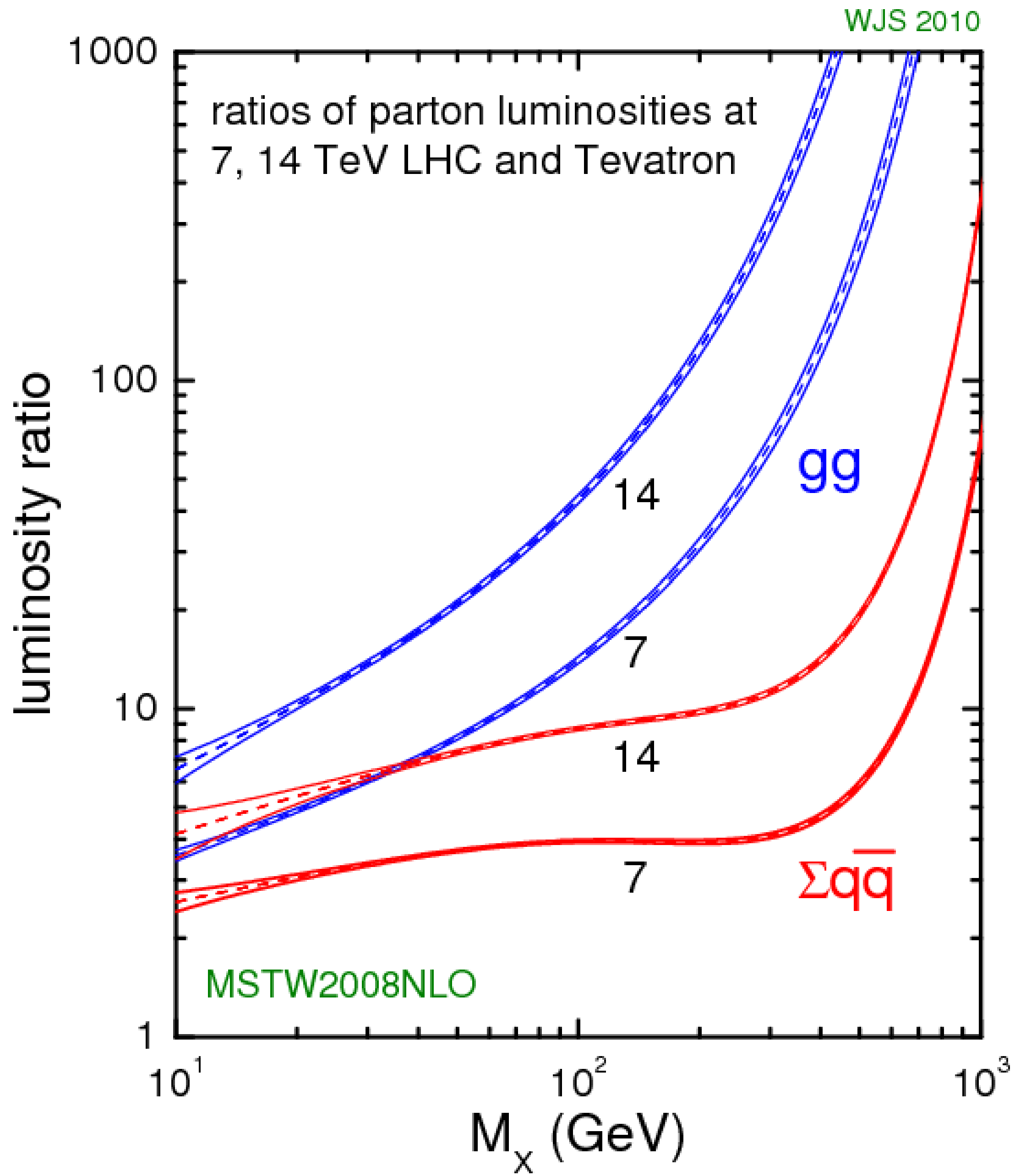


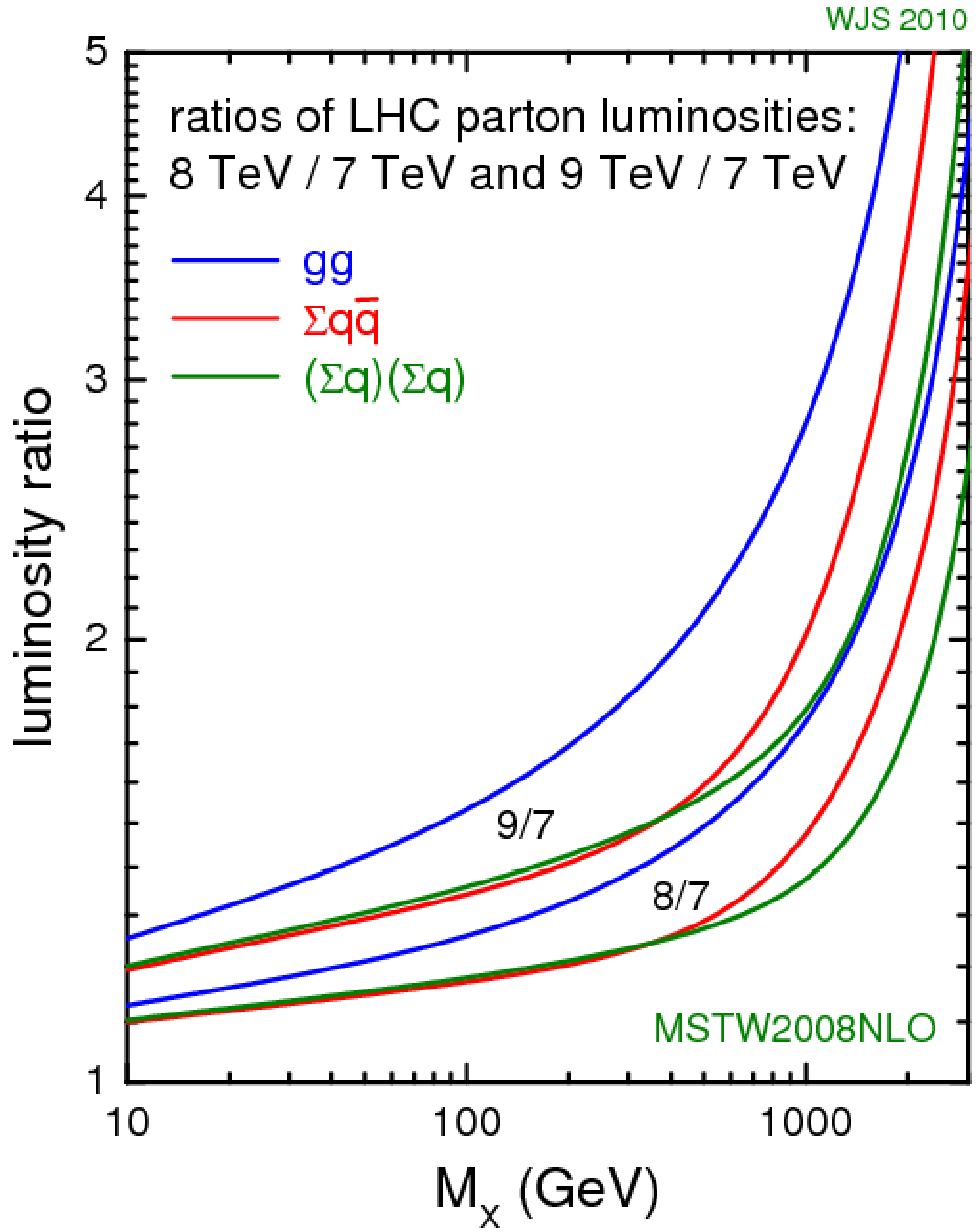
$$
\begin{aligned}
\hat{\sigma}_{ab\to X} &= C_X \delta(\hat{s} - M_X^2) \\
\sigma_X &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, C_X\, \delta(x_a x_b - \tau) \\
&\equiv C_X \left[\frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau} \right] \qquad\qquad (\tau = M_X^2/s) \\
\frac{\partial \mathcal{L}_{ab}}{\partial \tau} &= \int_0^1 dx_a dx_b\, f_a(x_a, M_X^2) f_b(x_b, M_X^2)\, \delta(x_a x_b - \tau)
\end{aligned}
$$

- i.e. all the mass and energy dependence is contained in the **X**-independent parton luminosity function in [ ]
- useful combinations are $ab = gg, \sum_q q\bar{q}, \ldots$
- and also useful for assessing the uncertainty on cross sections due to uncertainties in the pdfs (see later)



more such luminosity plots available at www.hep.phy.cam.ac.uk/~wjs/plots/plots.html


WJS 2010
ratios of parton luminosities at
7, 14 TeV LHC and Tevatron
1000
100
10
1
luminosity ratio
14
7
gg
14
7
Σq$\bar{q}$
MSTW2008NLO
10^1
10^2
10^3
M_X (GeV)



e.g.
gg→H
qq̄→VH
qq→qqH

2

higher-order perturbative QCD corrections

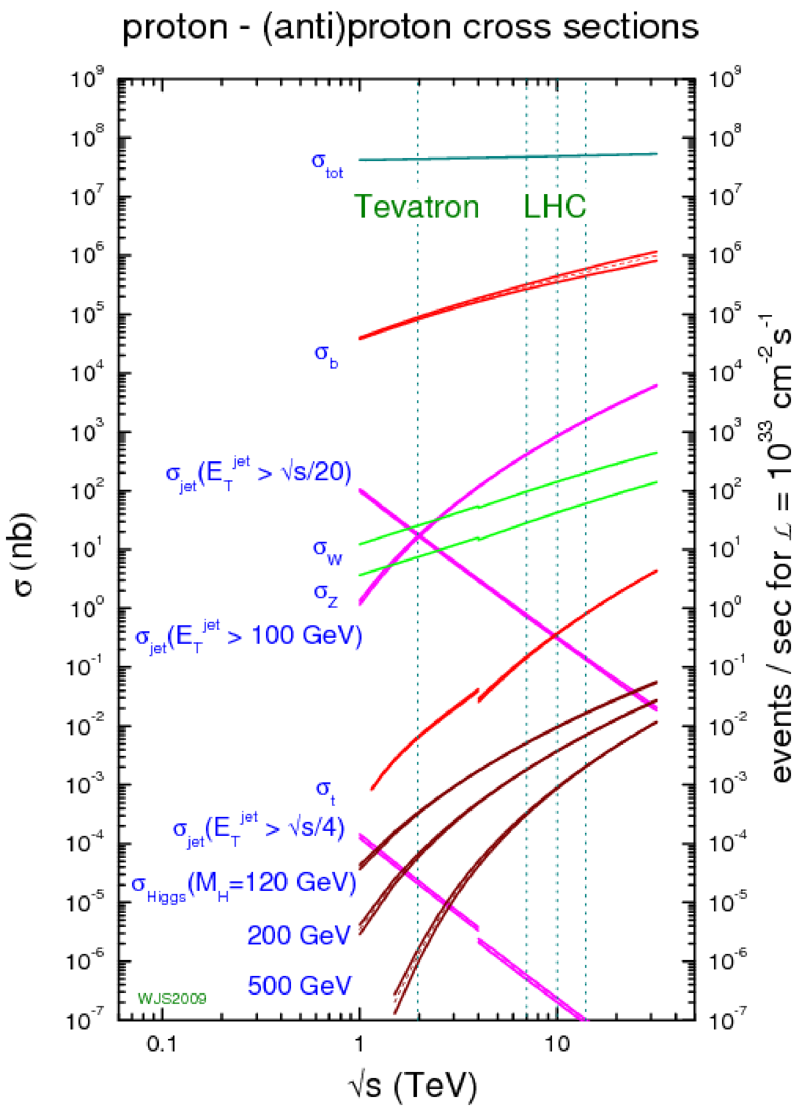
how precise?

- LO for generic PS Monte Carlos, tree-level MEs

- NLO for NLO-MCs and many parton-level signal and background processes
  - in principle, less sensitivity to unphysical renormalisation and factorisation scales, μ_R and μ_F
  - parton merging to give structure in jets
  - more types of incoming partons
  - more reliable pdfs
  - better description of final state kinematics

- NNLO for a limited number of 'precision observables' (W, Z, DY, H, …)

\+ E/W corrections, resummed HO terms etc…



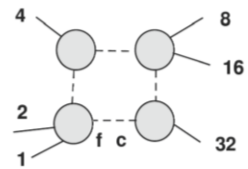
$$\delta\sigma_{th} = \delta\sigma_{UHO} \oplus \delta\sigma_{pdf} \oplus \delta\sigma_{param} \oplus \ldots$$

what does this mean?!

recent developments at NLO

- traditional methods based on Feynman diagrams, then reduction to known (scalar box, triangle, bubble and tadpole) integrals

- … and new methods based on unitarity and on-shell recursion: assemble loop-diagrams from individual tree-level diagrams
  - basic idea: Bern, Dixon, Kosower 1993
  - cuts with respect to on-shell complex loop momenta: Cachazo, Britto, Feng 2004
  - tensor reduction scheme: Ossola, Pittau, Papadopoulos 2006
  - integrating the OPP procedure with unitarity: Ellis, Giele, Kunszt 2008
  - D-dimensional unitarity: Giele, Kunszt, Melnikov 2008
  - …



- … and the appearance of automated programmes for one-loop, multi-leg amplitudes, either based on
  - traditional or numerical Feynman approaches (Golem, …)
  - unitarity/recursion (BlackHat, CutTools, Rocket, …)

➡ see talk by Lance Dixon

recent NLO results…*

• pp → W+3j	[Rocket: Ellis, Melnikov & Zanderighi]	[unitarity]
• pp → W+3j	[BlackHat: Berger et al]	[unitarity]
• pp → tt bb	[Bredenstein et al]	[traditional]
• pp → tt bb	[HELAC-NLO: Bevilacqua et al]	[unitarity]
• pp → qq → 4b	[Golem: Binoth et al]	[traditional]
• pp → tt+2j	[HELAC-NLO: Bevilacqua et al]	[unitarity]
• pp → Z+3j	[BlackHat: Berger et al]	[unitarity]
• pp → W+4j	[BlackHat: Berger et al, partial]	[unitarity]
• …		

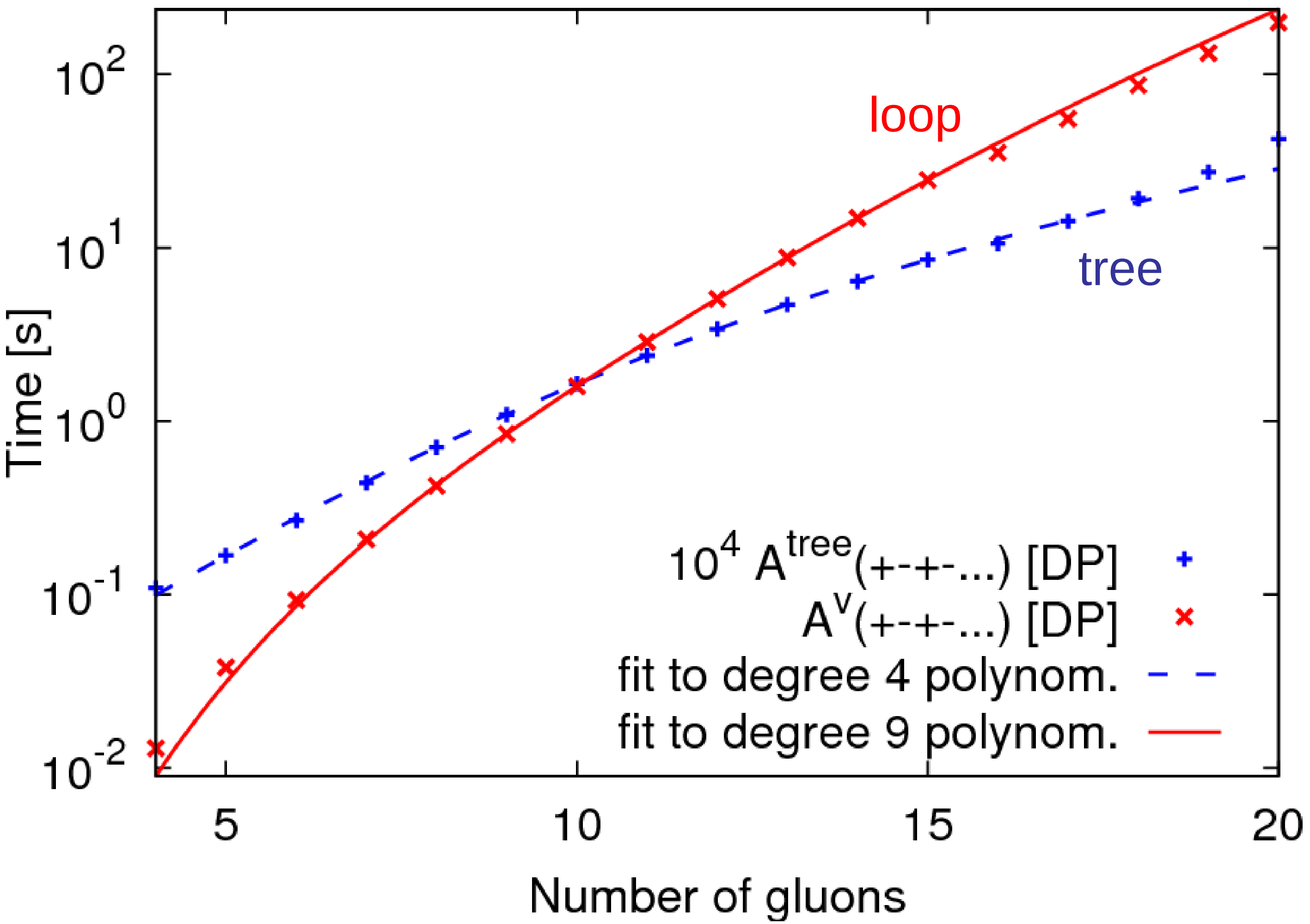
with earlier results on V,H + 2 jets, VV,tt + 1 jet, VVV, ttH, ttZ, …

In contrast, for NNLO we still only have inclusive γ^*,W,Z,H with rapidity distributions and decays (although much progress on top, single jet, …)

*relevant for LHC

calculation time: one-loop pure gluon amplitudes

Giele and Zanderighi, 2008



general structure of a QCD perturbation series

- choose a renormalisation scheme (e.g. MSbar)
- calculate cross section to some order (e.g. NLO)

$$\sigma(P) \;=\; A\,\alpha_S^N(\mu) + \alpha_S^{N+1}(\mu)\;\left[B + \frac{NAb}{2\pi}\ln\frac{\mu}{P}\right] + \ldots$$

physical variable(s)

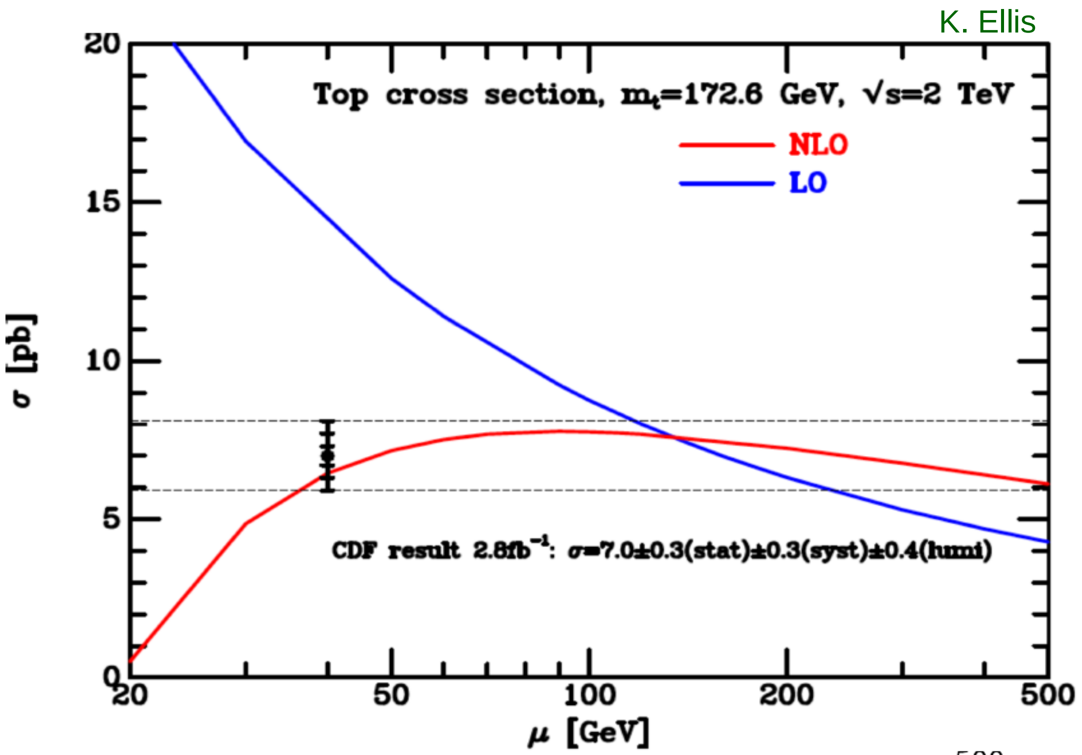
process dependent coefficients depending on *P*

renormalisation scale

- note $d\sigma/d\mu=0$ "to all orders", but in practice
  $d\sigma^{(N+n)}/d\mu = O((N+n)\,\alpha_S^{N+n+1})$

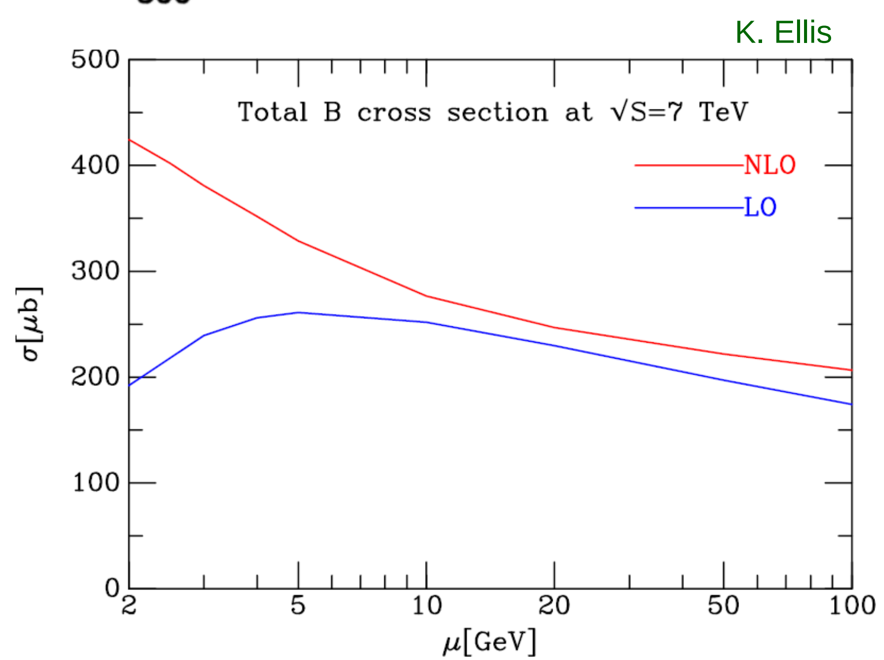
- can try to help convergence by using a "physical scale choice", $\mu \sim P$, e.g. $\mu = M_Z$ or $\mu = E_T^{jet}$

- what if there is a wide range of *P*'s in the process, e.g. W + n jets?



Top at Tevatron

Bottom at LHC

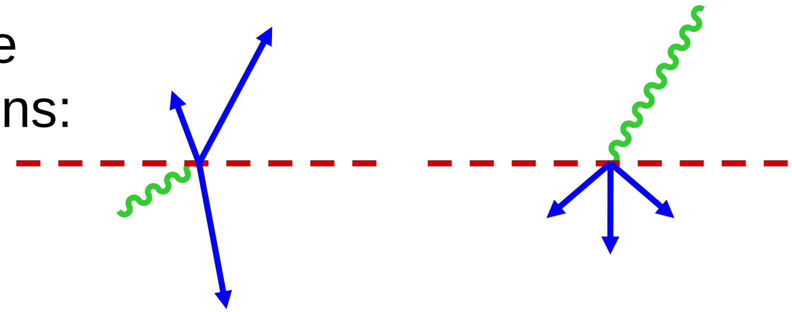


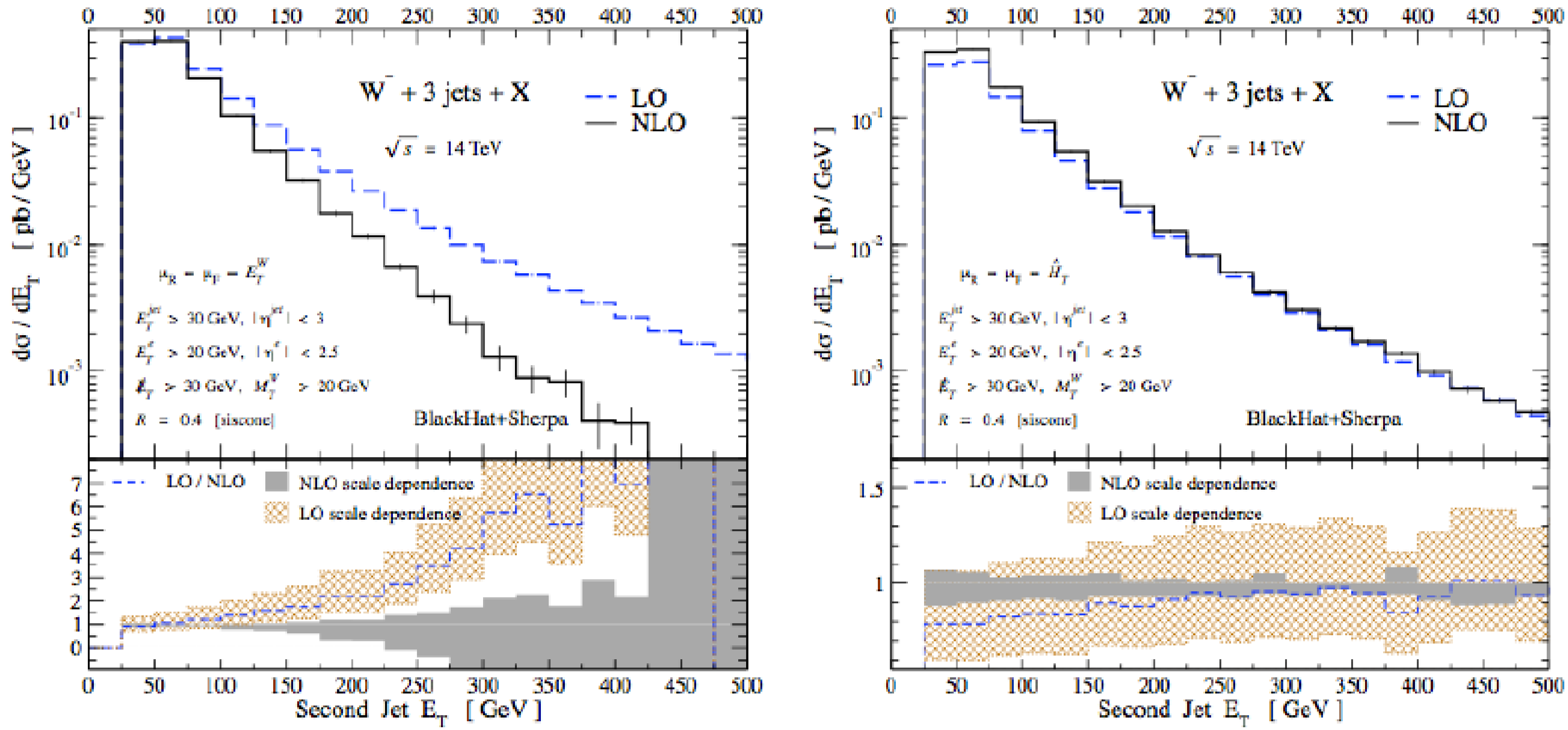
reason: new processes open up at NLO!

in complicated processes like W + n jets, there are often many ‘reasonable’ choices of scales: $\mu = M_W,\ E_{TW},\ \langle E_{T\text{jet}}\rangle,\ H_T,\ \ldots$

‘blended’ scales like H_T can seamlessly take account of different kinematical configurations:

$$H_T = \sum_{\text{i=partons}} E_{Ti} + E_{Te} + E_{T\text{miss}}$$





Berger et al., arXiv:0907.1984

using the W^{+-} charge asymmetry at the LHC

- at the Tevatron $\sigma(W^+) = \sigma(W^-)$, whereas at LHC $\sigma(W^+) \sim (1.4 - 1.3)\, \sigma(W^-)$

- can use this asymmetry to calibrate backgrounds to new physics, since typically $\sigma_{NP}(X \rightarrow W^+ + \ldots) = \sigma_{NP}(X \rightarrow W^- + \ldots)$

- example:

$$gg \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow W^\pm(\rightarrow l^\pm + \nu) + \text{4jets}$$

in this case

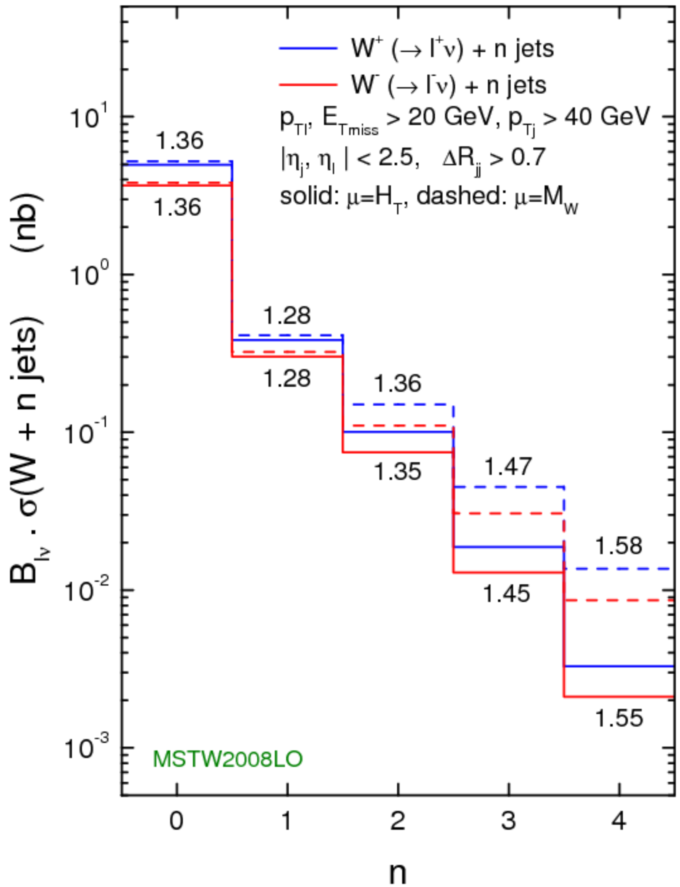
$$\sigma_{\text{signal}}(W^+ + \text{4jets}) = \sigma_{\text{signal}}(W^- + \text{4jets})$$

whereas…

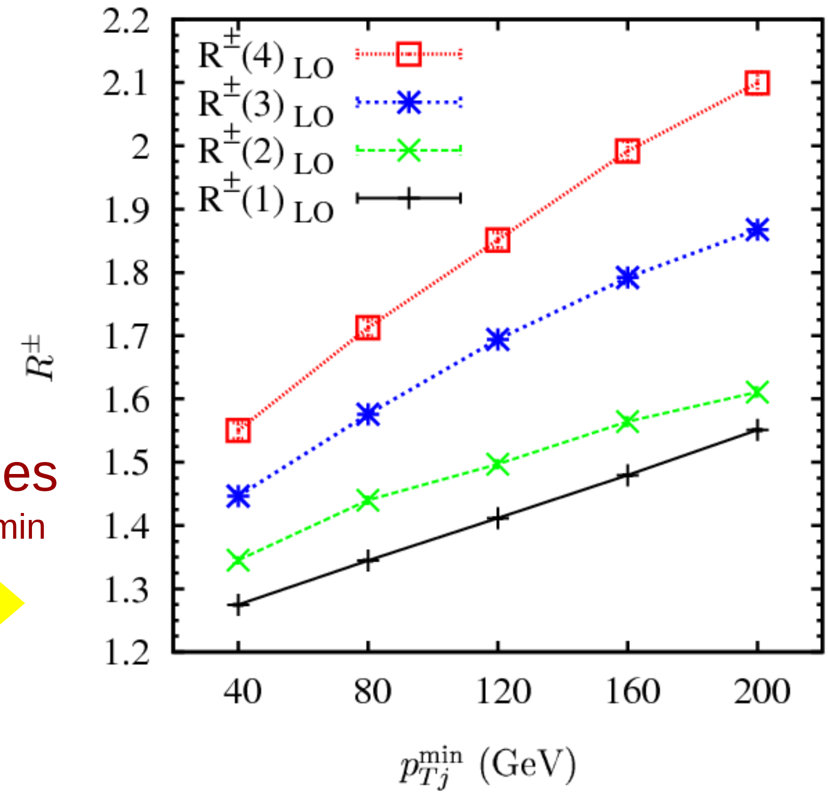
$$\sigma_{\text{QCDbkgd}}(W^+ + \text{4jets}) \neq \sigma_{\text{QCDbkgd}}(W^- + \text{4jets})$$

which can in principle help distinguish signal and background

C.H. Kom & WJS, arXiv:1004.3404



$R^{\pm}$ increases with jet p_T^{min}



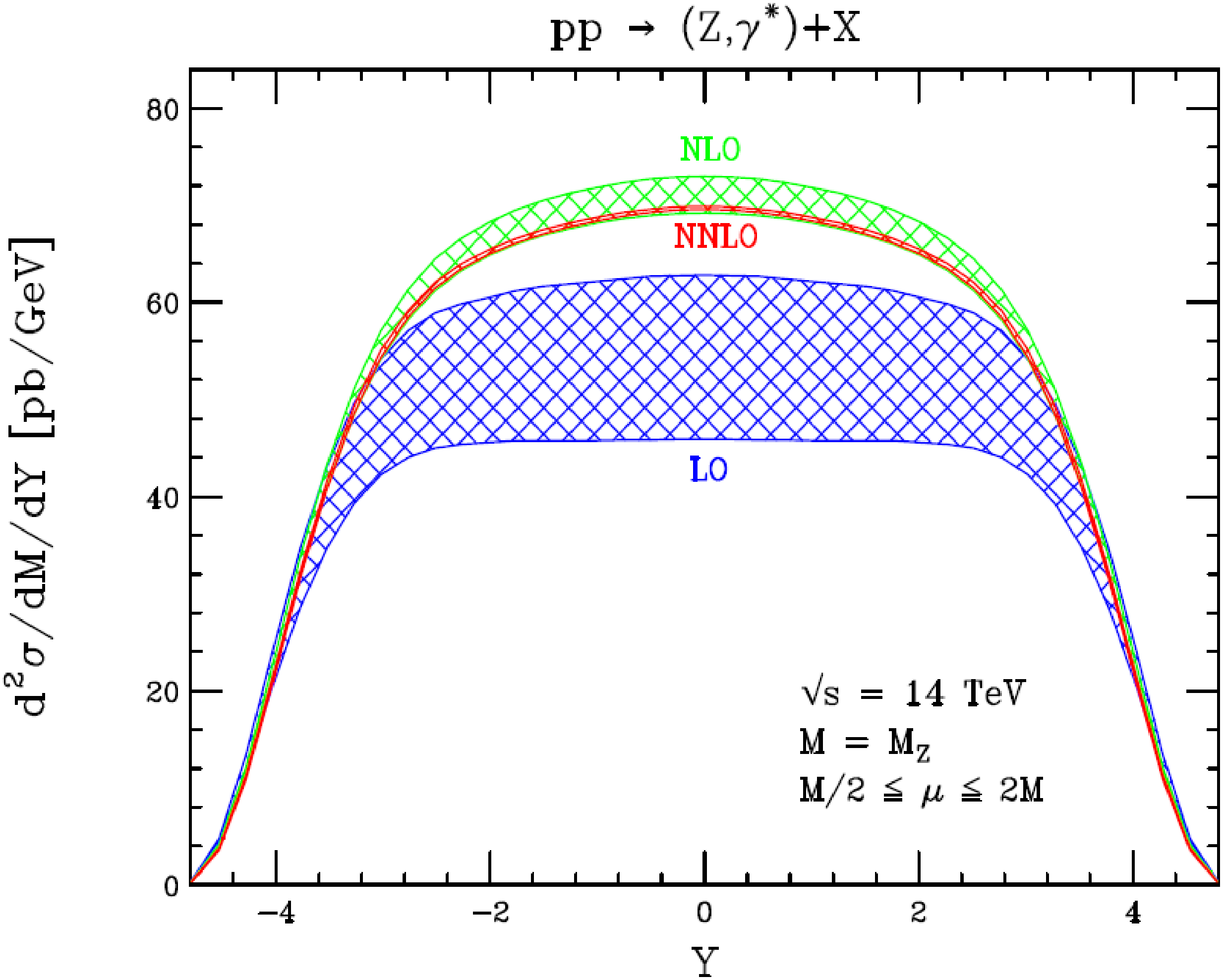
$R^{\pm}$ larger at 7 TeV LHC

n	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 14$ TeV
0	1.52 ± 0.01 (scl) ± 0.02 (pdf)	1.31 ± 0.01 (scl) ± 0.01 (pdf)
1	1.45 ± 0.01 (scl) ± 0.01 (pdf)	1.27 ± 0.01 (scl) ± 0.01 (pdf)
2	1.56 ± 0.02 (scl) ± 0.02 (pdf)	1.33 ± 0.02 (scl) ± 0.01 (pdf)
3	1.72 ± 0.03 (scl) ± 0.03 (pdf)	1.45 ± 0.03 (scl) ± 0.02 (pdf)
4	1.87 ± 0.04 (scl) ± 0.03 (pdf)	1.55 ± 0.04 (scl) ± 0.02 (pdf)

Berger et al (arXiv:1009.2338)
- 7 TeV, slightly different cuts

W^+/W^- LO	W^+/W^- NLO
1.656(0.001)	1.580(0.004)
1.507(0.002)	1.498(0.009)
1.596(0.003)	1.57(0.02)
1.694(0.005)	1.66(0.02)
1.817(0.003)	—

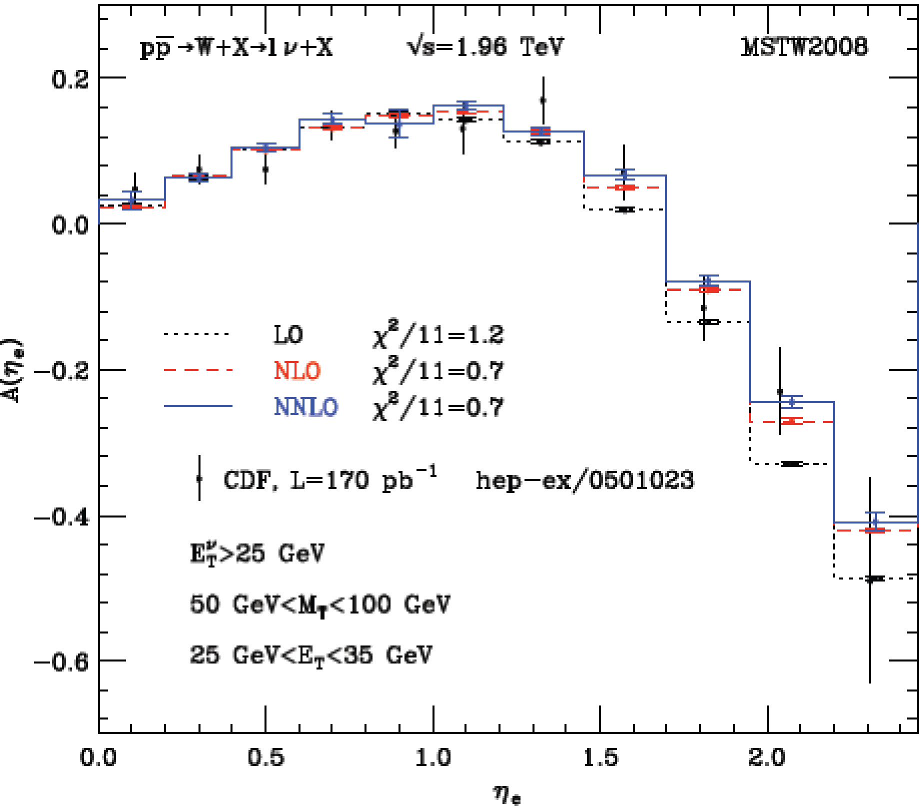
the impact of NNLO: W,Z

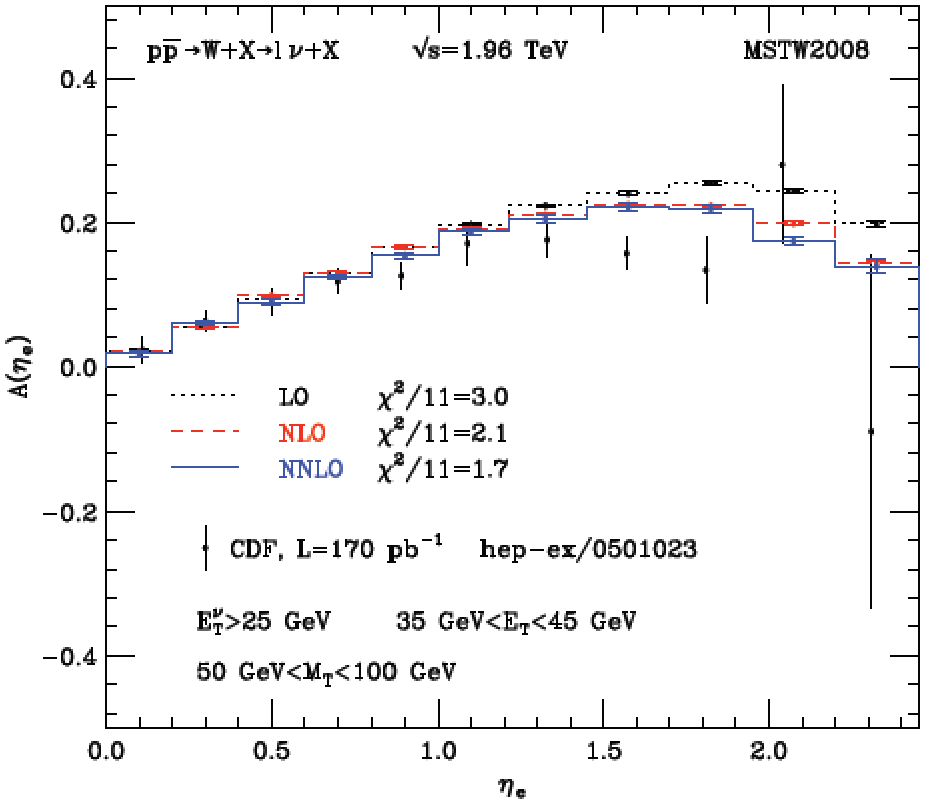


Anastasiou, Dixon, Melnikov, Petriello, 2004

- only scale variation uncertainty shown
- central values calculated for a *fixed* set pdfs with a *fixed* value of $\alpha_S(M_Z^2)$

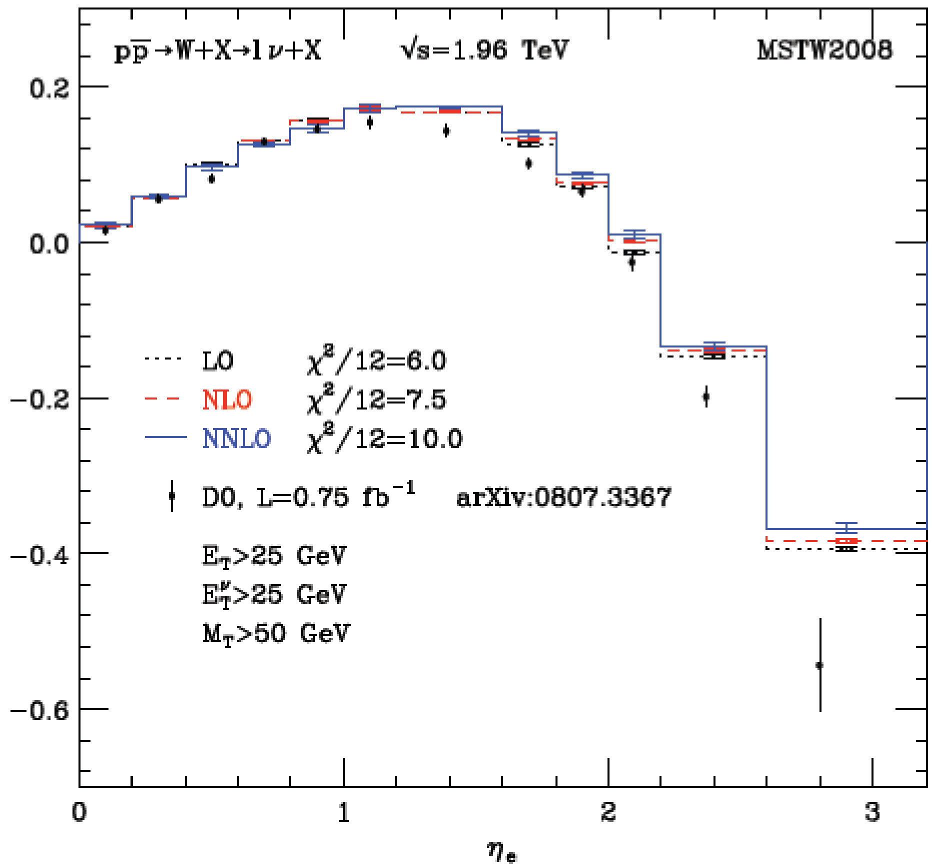
Lepton asymmetry at NNLO and CDF data

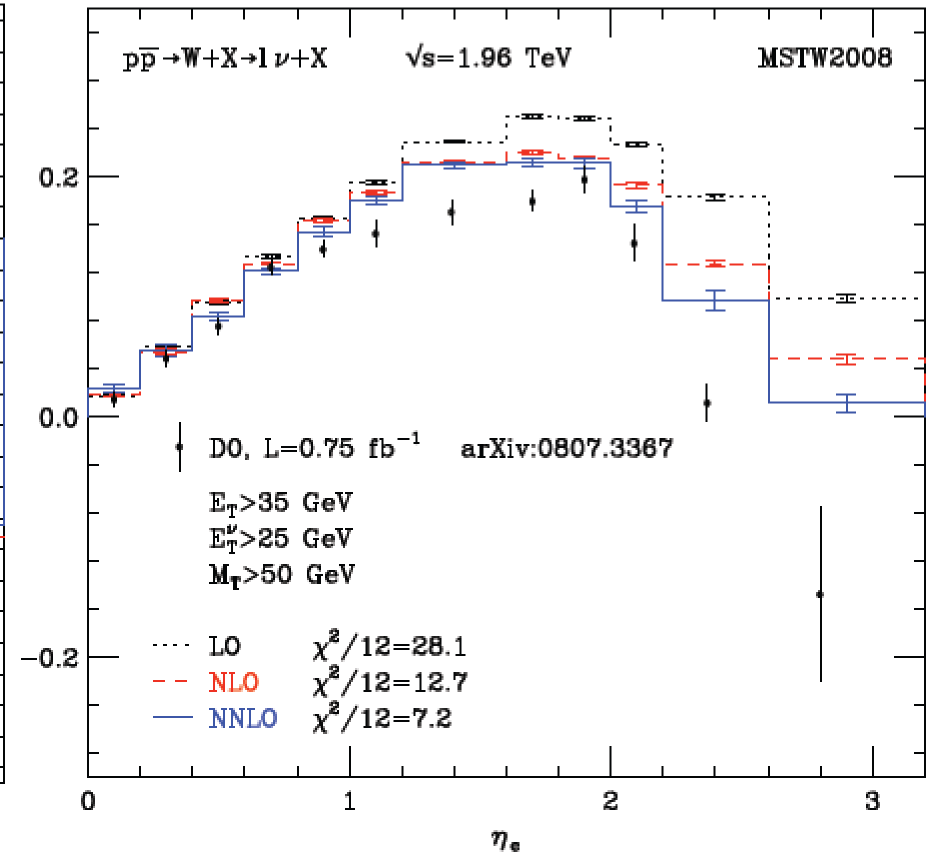




Catani, Ferrara, Grazzini, arXiv:1002.3115

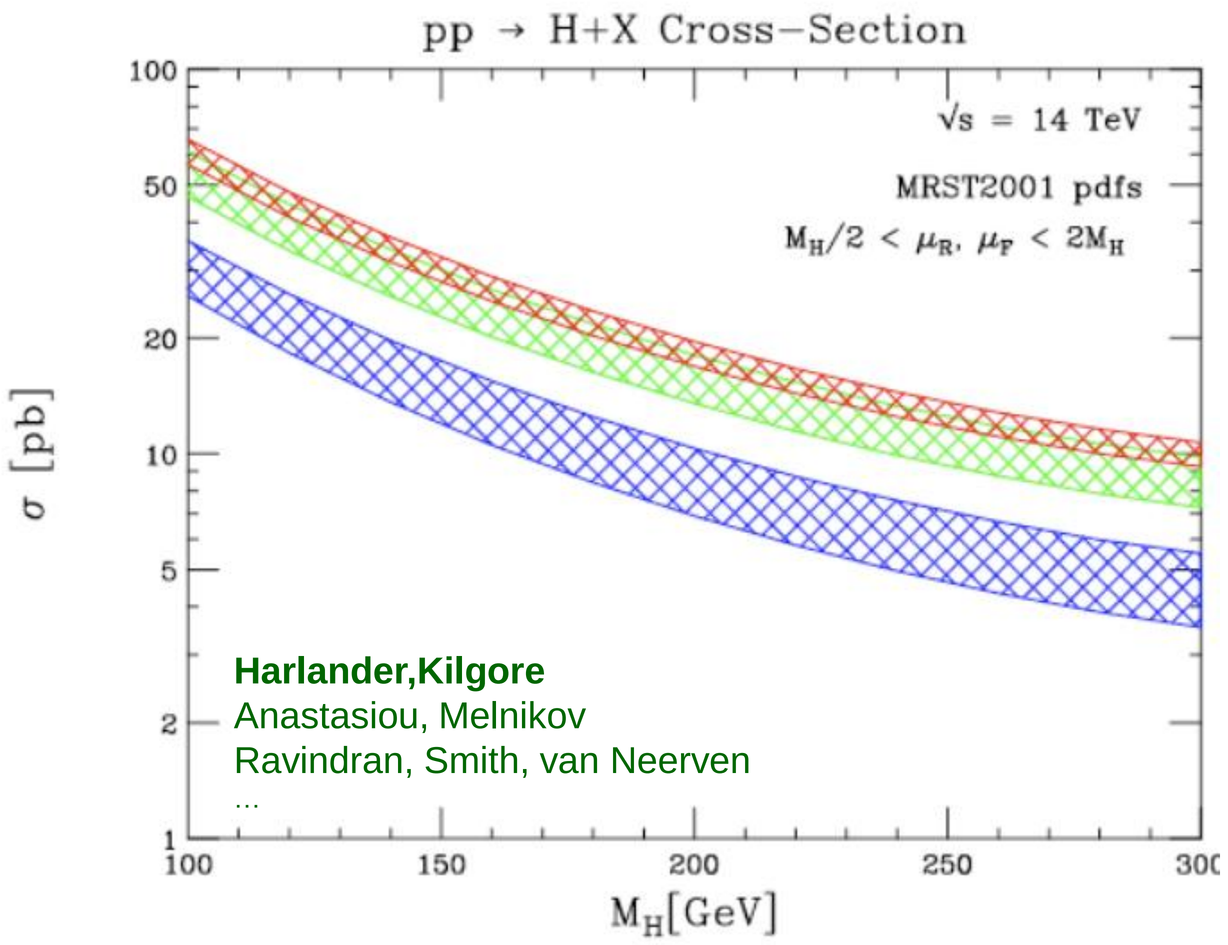
Lepton asymmetry at NNLO and D0 data





Catani, Ferrara, Grazzini, arXiv:1002.3115

the impact of NNLO: H



- the NNLO band is about ±10%, or ±15% if μ_R and μ_F varied independently

scale variation in gg→ H?

- 'conventional' approach (NNLO):

$$\mu_R = \mu_F = \mu, \quad \frac{\mu_0}{2} \le \mu \le 2\mu_0, \quad \mu_0 = M_H$$

+10%
- 10%

- 'conservative' approach (Baglio and Djouadi) , NNLO normalised to NNLL

$$\mu_R = \mu_F = \mu, \quad \frac{\mu_0}{3} \le \mu \le 3\mu_0, \quad \mu_0 = \frac{1}{2} M_H$$

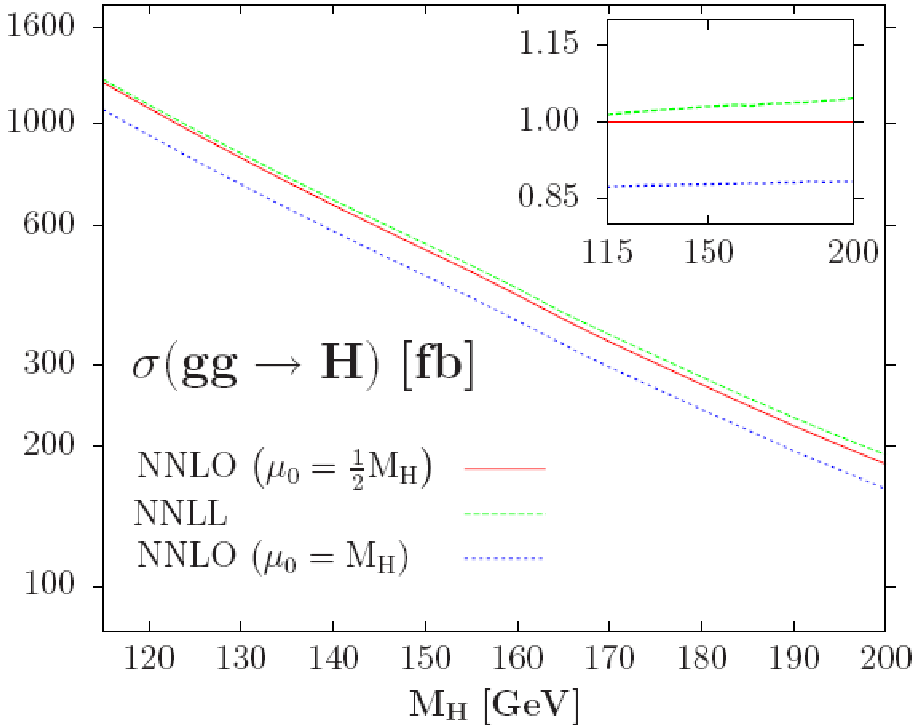
+15%
- 20%

- 'radical approach': N^3LL (Ahrens, Becher, Neubert, Yang, 1008.3162)

$$\mu_R = \mu_F = \mu, \quad \frac{\mu_0}{2} \le \mu \le 2\mu_0, \quad \mu_0 = M_H$$

+3%
- 3%

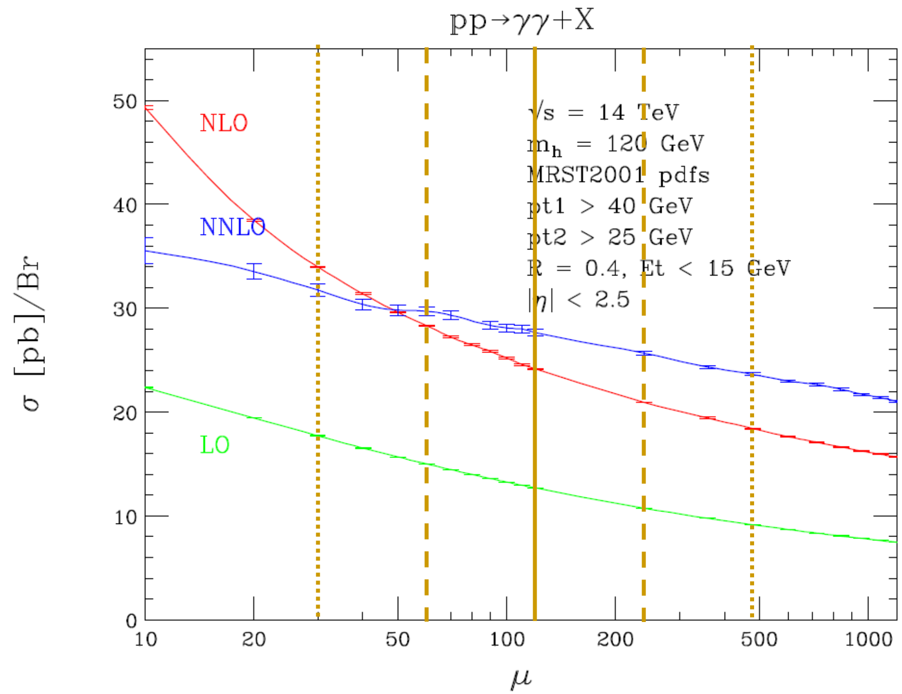
→ **choice of scale and range – flat prior?**



Baglio and Djouadi, arXiv:1009.1363

NNLO: Anastasiou, Boughezal, Petriello (2009)

NNLL: de Florian and Grazzini (2009)



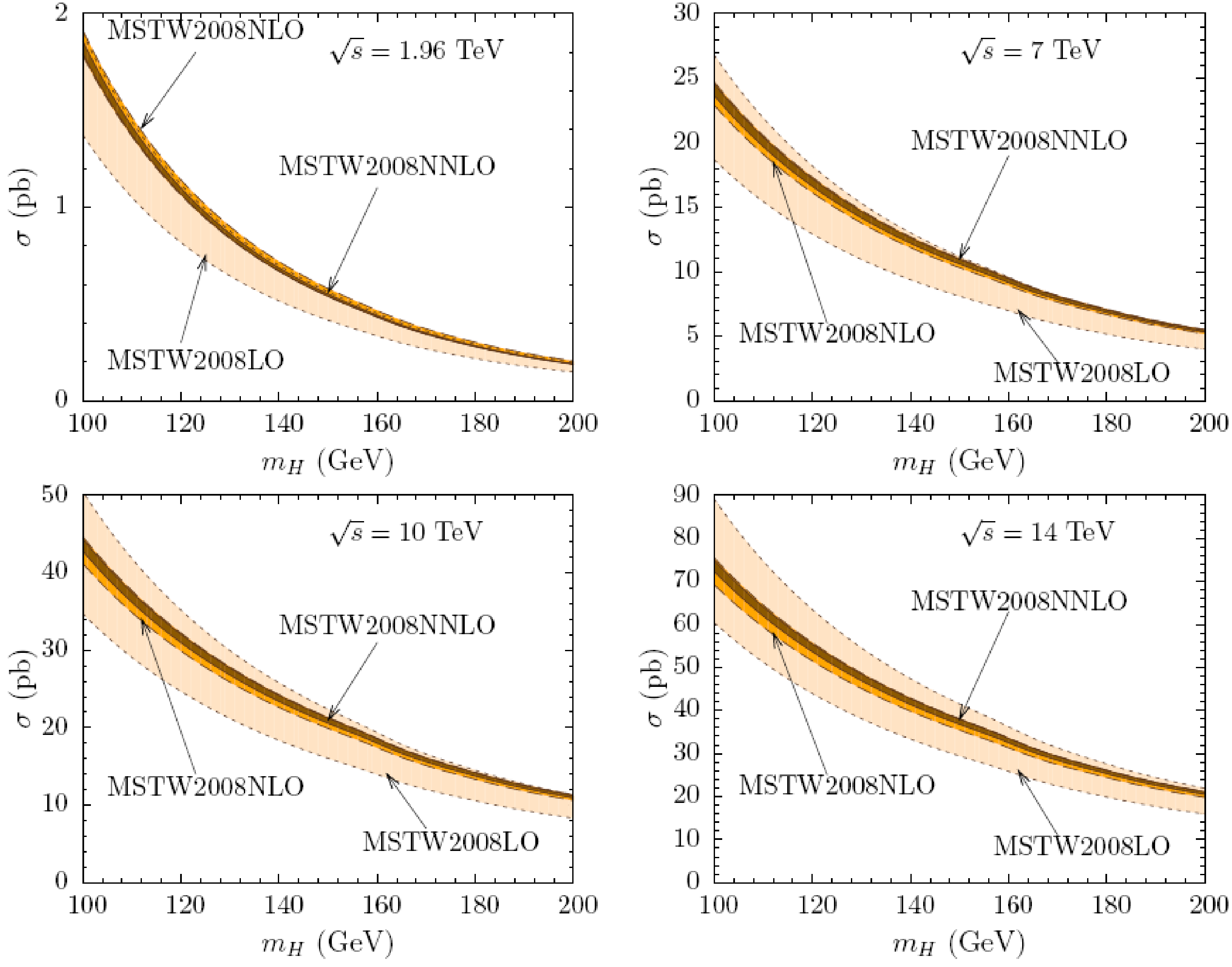
Anastasiou, Melnikov, Petriello (2005)

…with scale variation factor 1/2,1/4,2,4

$\delta\sigma_{PDF}$ (see below) attempts to be a genuine $\pm 1\sigma$ uncertainty related to global fit data

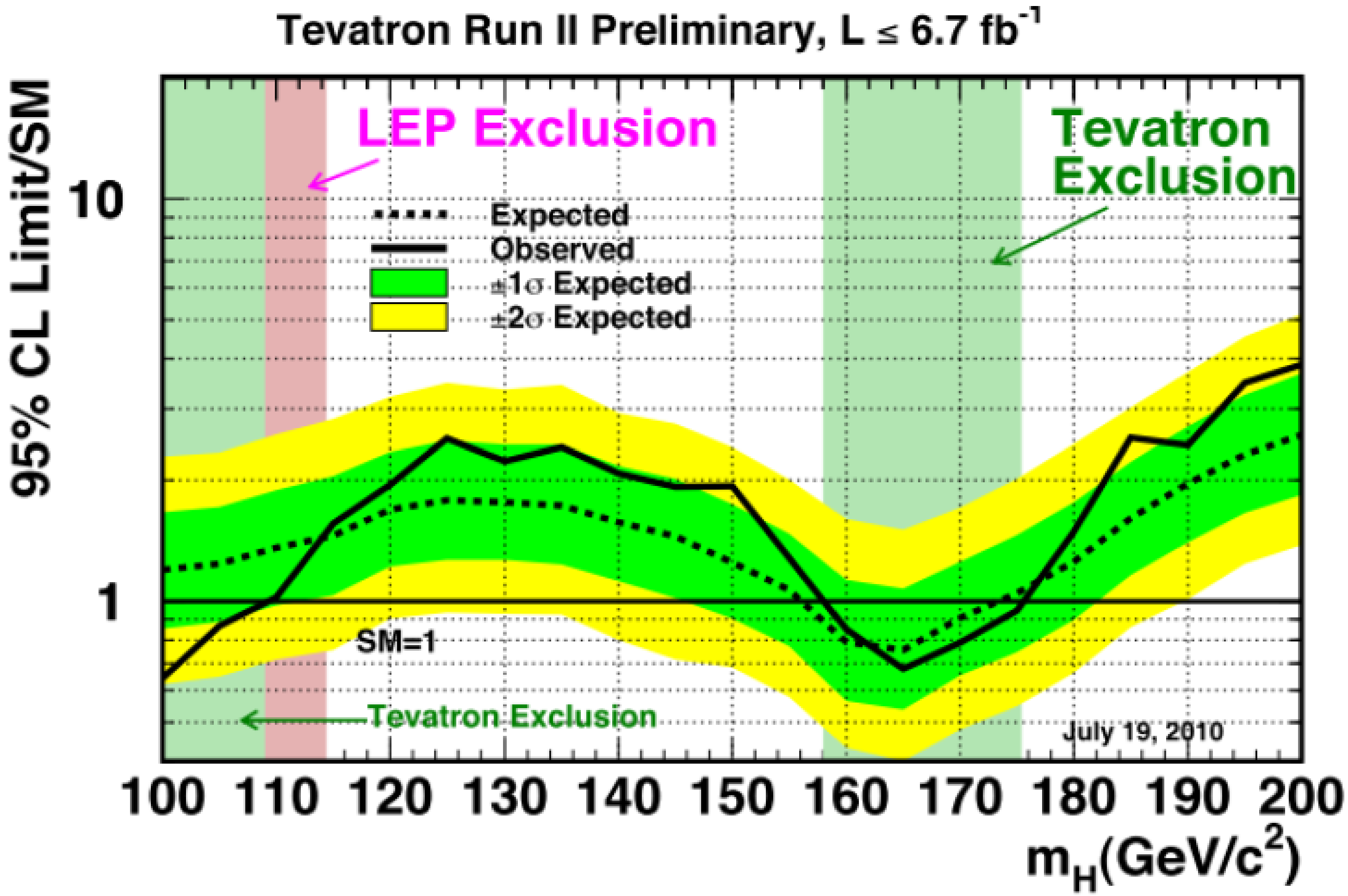
$\delta\sigma_{SCL}$ is an estimate of the impact of the unknown higher-order pQCD corrections

— there is no unique prescription for combining them!



Ahrens, Becher, Neubert, Yang (2010)

SM Higgs: Tevatron exclusion limits



3

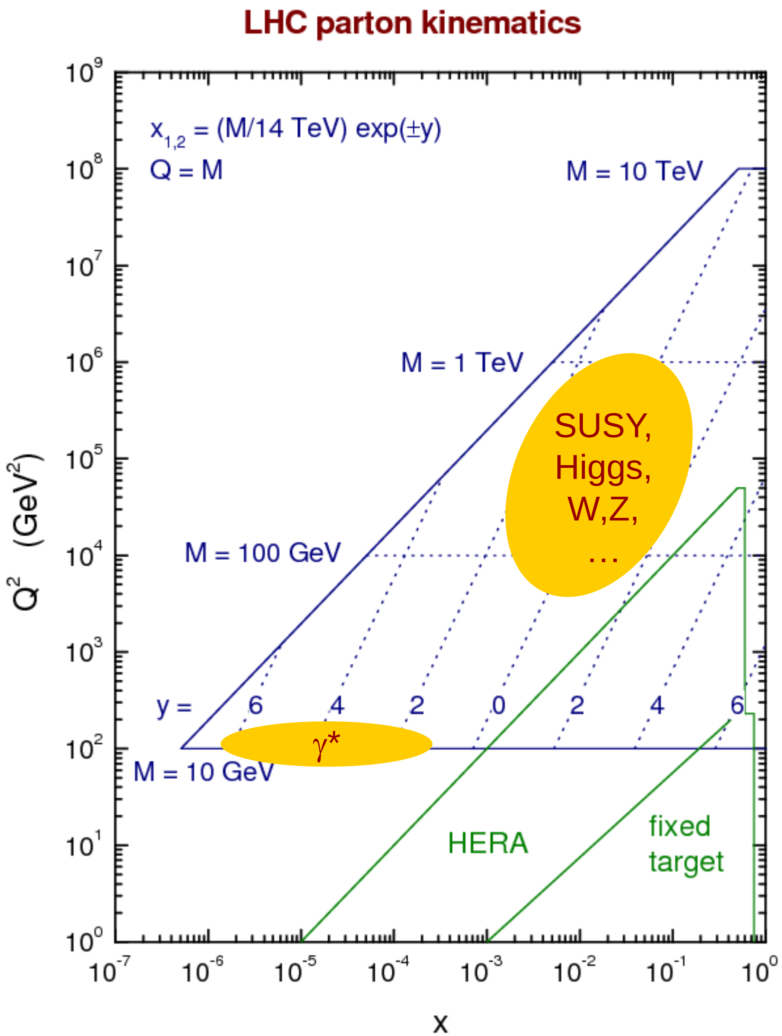
parton distribution functions

pdfs @ LHC

- most SM and new physics sample pdfs in a region of x where they are already well known

- current pdf uncertainties provide the benchmark for whether LHC can add new information

- low-mass forward production (e.g. b quarks, Drell-Yan) might provide new information on small-x partons



how pdfs are obtained*

- choose a factorisation scheme (e.g. $\overline{\text{MS}}$), an order in perturbation theory (LO, NLO, NNLO) and a ‘starting scale’ Q_0 where pQCD applies (e.g. 1-2 GeV)
- parametrise the quark and gluon distributions at Q_0, e.g.

$$f_i(x, Q_0^2) = A_i x^{a_i}[1 + b_i\sqrt{x} + c_i x](1-x)^{d_i}$$

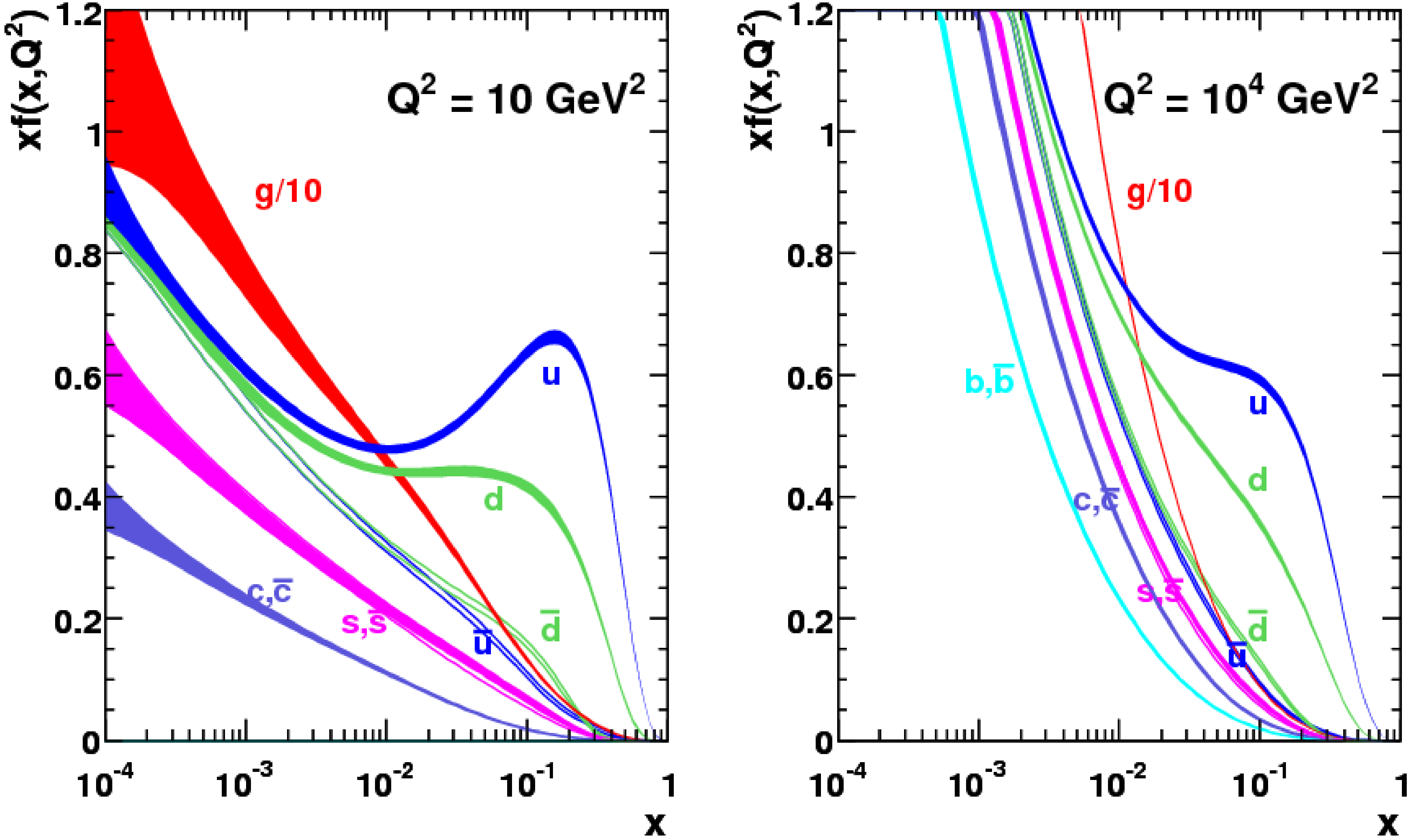
- solve DGLAP equations to obtain the pdfs at any x and scale $Q > Q_0$; fit data for parameters $\{A_i, a_i, \ldots \alpha_S\}$
- approximate the exact solutions (e.g. interpolation grids, expansions in polynomials etc) for ease of use; thus the output ‘global fits’ are available ‘off the shelf”, e.g.

```
SUBROUTINE PDF(X,Q,U,UBAR,D,DBAR,…,BBAR,GLU)
```

input | output

*traditional method

MSTW 2008 NLO PDFs (68% C.L.)



MSTW = Martin, S, Thorne, Watt

the pdf industry

- many groups now extracting pdfs from 'global' data analyses (MSTW, CTEQ, NNPDF, …)

- broad agreement, but differences due to
  - choice of data sets (including cuts and corrections)
  - treatment of data errors
  - treatment of heavy quarks (s,c,b)
  - order of perturbation theory
  - parameterisation at Q_0
  - theoretical assumptions (if any) about:
    - flavour symmetries
    - $x \rightarrow 0,1$ behaviour
    - …

HERA-DIS
FT-DIS
Drell-Yan
Tevatron jets
Tevatron W,Z
other

recent global or quasi-global pdf fits

pdfs	authors	arXiv
ABKM	S. Alekhin, J. Blümlein, S. Klein, S. Moch, and others	1007.3657, 0908.3128, 0908.2766, …
CTEQ	H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, C.-P. Yuan, and others	1007.2241, 1004.4624, 0910.4183, 0904.2424, 0802.0007, …
GJR	M. Glück, P. Jimenez-Delgado, E. Reya, and others	0909.1711, 0810.4274, …
HERAPDF	H1 and ZEUS collaborations	1006.4471, 0906.1108, …
MSTW	A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt	1006.2753, 0905.3531, 0901.0002, …
NNPDF	R. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. Latorre, J. Rojo, M. Ubiali, and others	1005.0397, 1002.4407, 0912.2276, 0906.1958, …

	MSTW08	CTEQ6.6[X]	NNPDF2.0	HERAPDF1.0	ABKM09[X]	GJR08
HERA DIS	✓	✓	✓*	✓*	✓	✓
F-T DIS	✓	✓	✓	✘	✓	✓
F-T DY	✓	✓	✓	✘	✓	✓
TEV W,Z	✓	✓+	✓	✘	✘	✘
TEV jets	✓	✓+	✓	✘	✘	✓
GM-VFNS	✓	✓	✘	✓	✓	✘
NNLO	✓	✘	✘	✘	✓	✓

+ Run 1 only

* includes new combined H1-ZEUS data → few% increase in quarks at low x

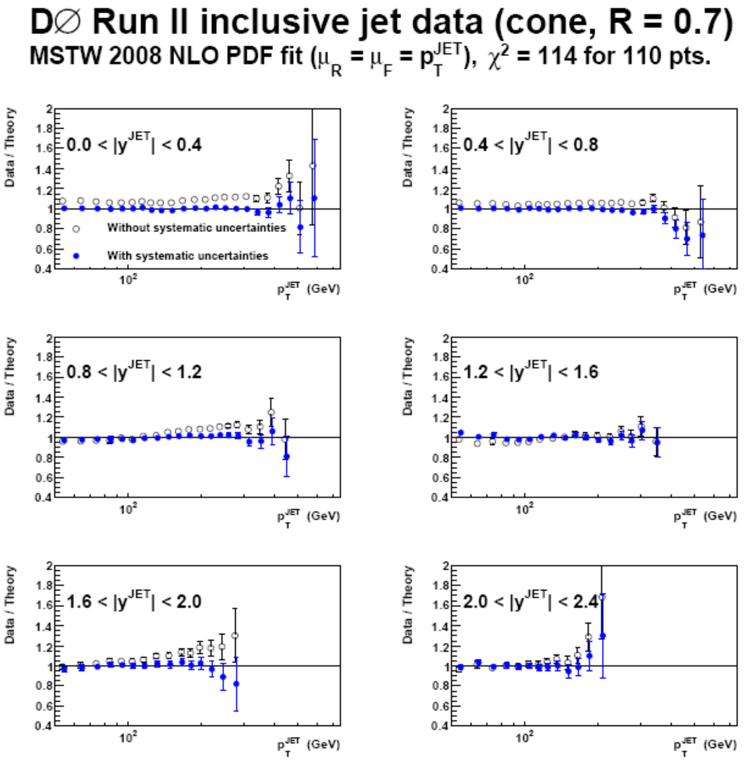
X new (July 2010) ABKM and CTEQ updates: ABKM includes new combined H1-ZEUS data + new small-x parametrisation + partial NNLO HQ corrections; CT10 includes new combined H1-ZEUS data + Run 2 jet data + extended gluon parametrisation + … → more like MSTW08

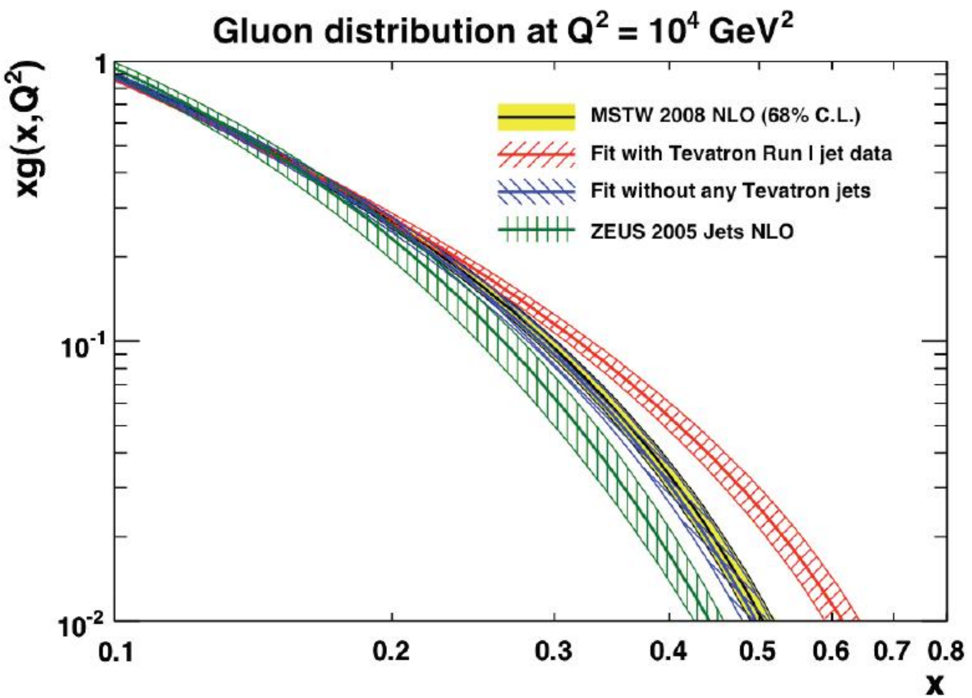
impact of Tevatron jet data on fits

- a distinguishing feature of pdf sets is whether they use (MRST/MSTW, CTEQ, NNPDF, GJR,…) or do not use (HERAPDF, ABKM, …) Tevatron jet data in the fit: the impact is on the *high-x gluon*

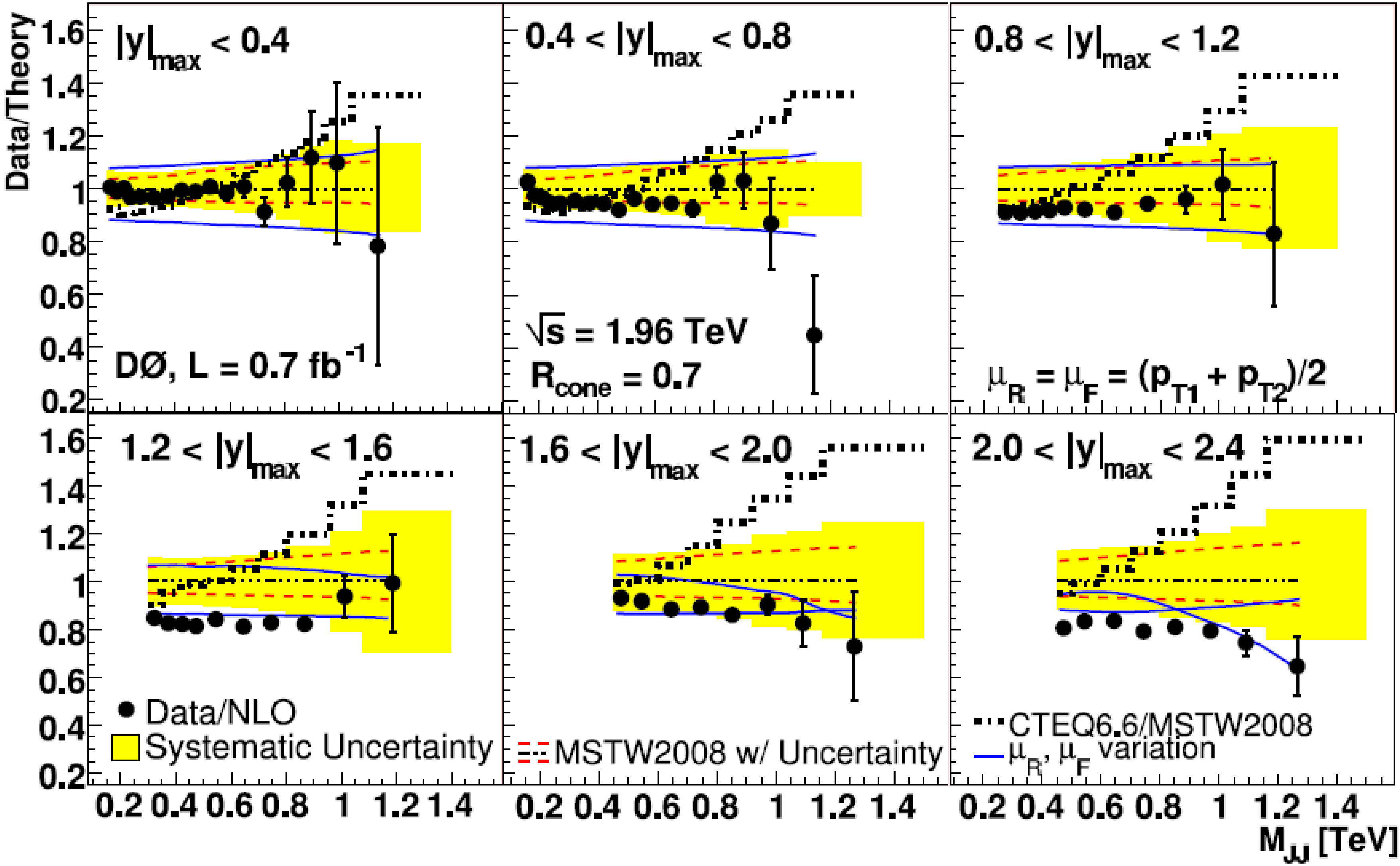
  (Note: Run II data requires slightly softer gluon than Run I data)

- the (still) missing ingredient is the full NNLO pQCD correction to the cross section, but not expected to have much impact in practice [Kidonakis, Owens (2001)]





dijet mass distribution from D0



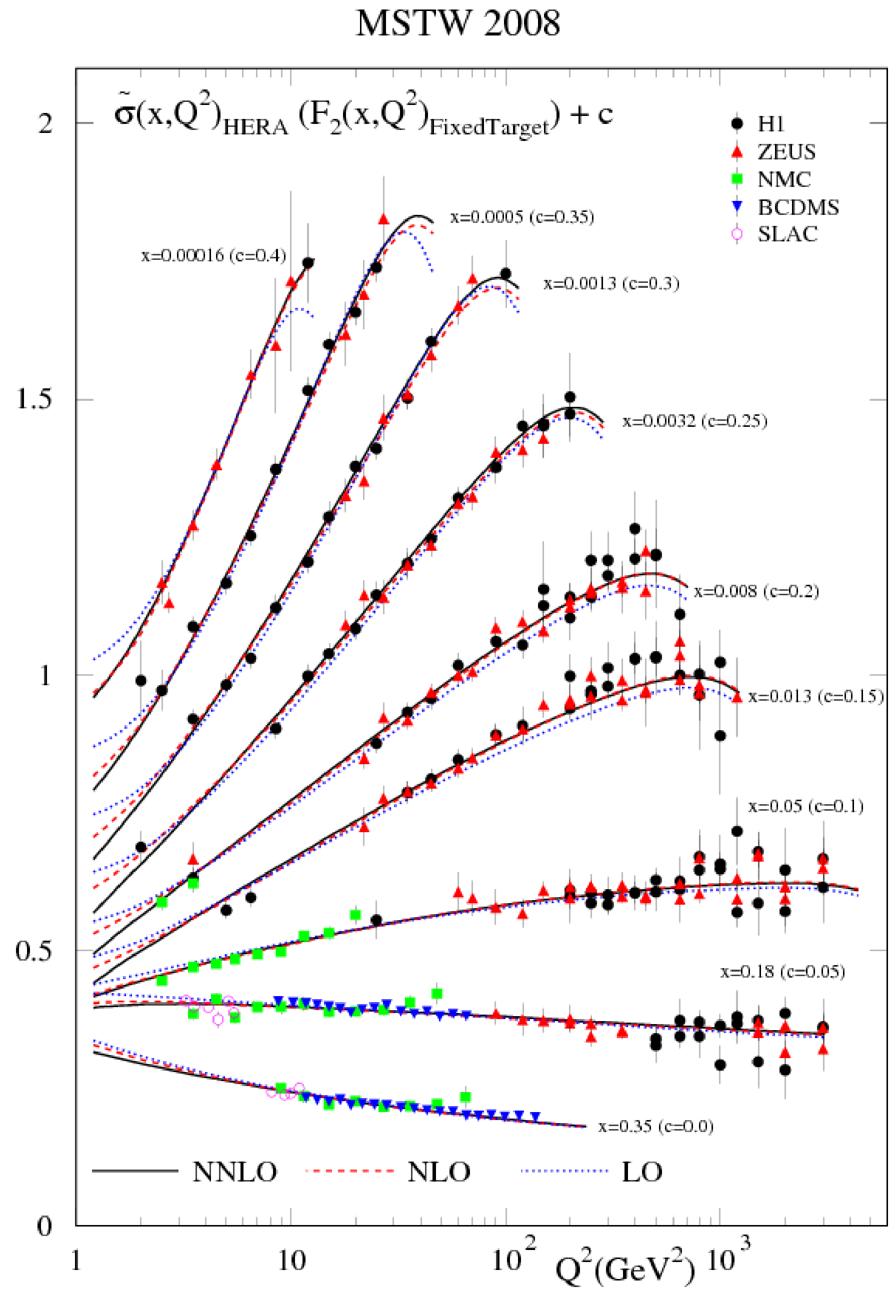
D0 collaboration: arXiv:1002.4594

LO *vs* NLO *vs* NNLO?

in the MSTW2008 fit

χ^2_{global} /dof = 3066/2598 (LO)
2543/2699 (NLO)
2480/2615 (NNLO)

LO evolution too slow at small x;
NNLO fit marginally better than NLO



Note:
- an important ingredient missing in the full NNLO global pdf fit is the NNLO correction to the Tevatron high E_T jet cross section
- LO can be improved (e.g. LO*) for MCs by adding K-factors, relaxing momentum conservation, etc.

pdf uncertainties

- all groups produce 'pdfs with errors'

- typically, 20-40 'error' sets based on a 'best fit' set to reflect 1σ variation of all the parameters* $\{A_i, a_i, \ldots, \alpha_S\}$ inherent in the fit

- these reflect the uncertainties on the data used in the global fit (e.g. $\delta F_2 \approx 3\% \rightarrow \delta u \approx 3\%$)

- however, there are also systematic pdf uncertainties reflecting theoretical assumptions/prejudices in the way the global fit is set up and performed (see earlier slide)

* e.g. $f_i(x, Q_0^2) = A_i x^{a_i}[1 + b_i\sqrt{x} + c_i x](1-x)^{d_i}$

pdf uncertainties (contd.)

- NNPDF create many replicas of data and obtain PDF replicas in each case by fitting to training set and comparing to validation set → uncertainty determined by spread of replicas. Direct relationship to χ^2 in global fit not trivial.

- NNPDF and MSTW (due to extra parameters) have more complicated shape for gluon at smaller x and bigger small-x uncertainty, ditto for CTEQ at large x

- different theory assumptions in strange quark pdf leads to vastly different uncertainties — e.g. MSTW small, NNPDF large; feeds into other ‘light’ quarks

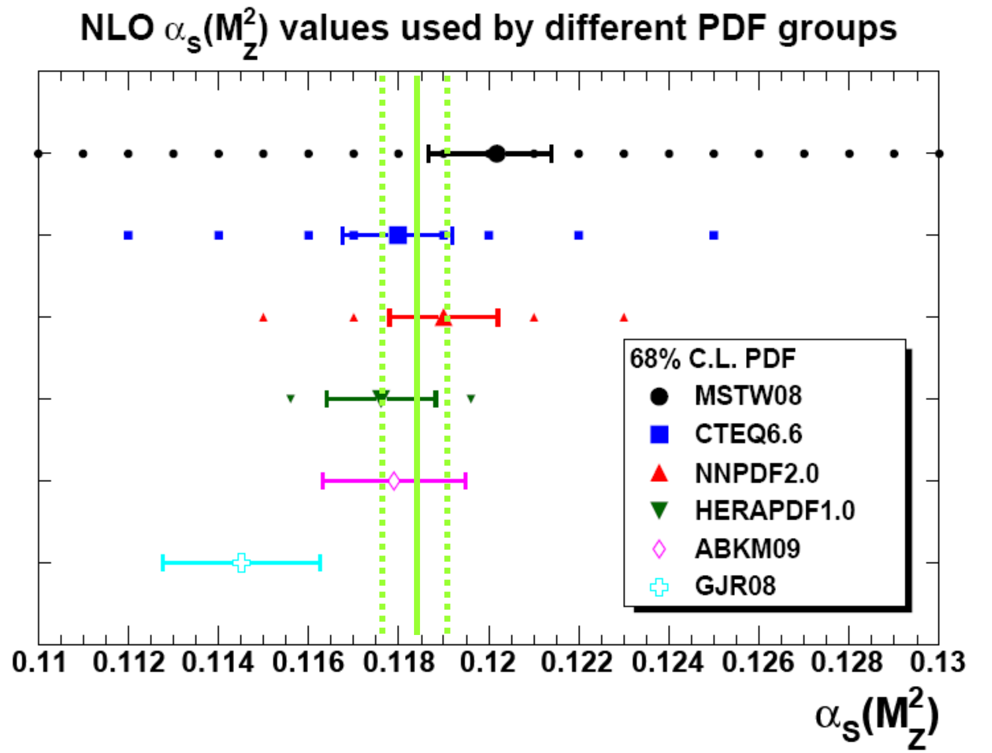
- perhaps surprisingly, all get rather similar uncertainties for pdfs and predicted cross sections — see later

pdfs and $\alpha_S(M_Z^2)$

- MSTW08, ABKM09 and GJR08: $\alpha_S(M_Z^2)$ values and uncertainty determined by global fit
- NNLO value about 0.003 – 0.004 lower than NLO value, e.g. for MSTW08

$$\alpha_S^{\overline{MS},NLO}(M_Z^2) = 0.1202^{+0.012}_{-0.015}$$

$$\alpha_S^{\overline{MS},NNLO}(M_Z^2) = 0.1171^{+0.014}_{-0.014}$$



- CTEQ, NNPDF, HERAPDF choose standard values and uncertainties
- world average (PDG 2009)

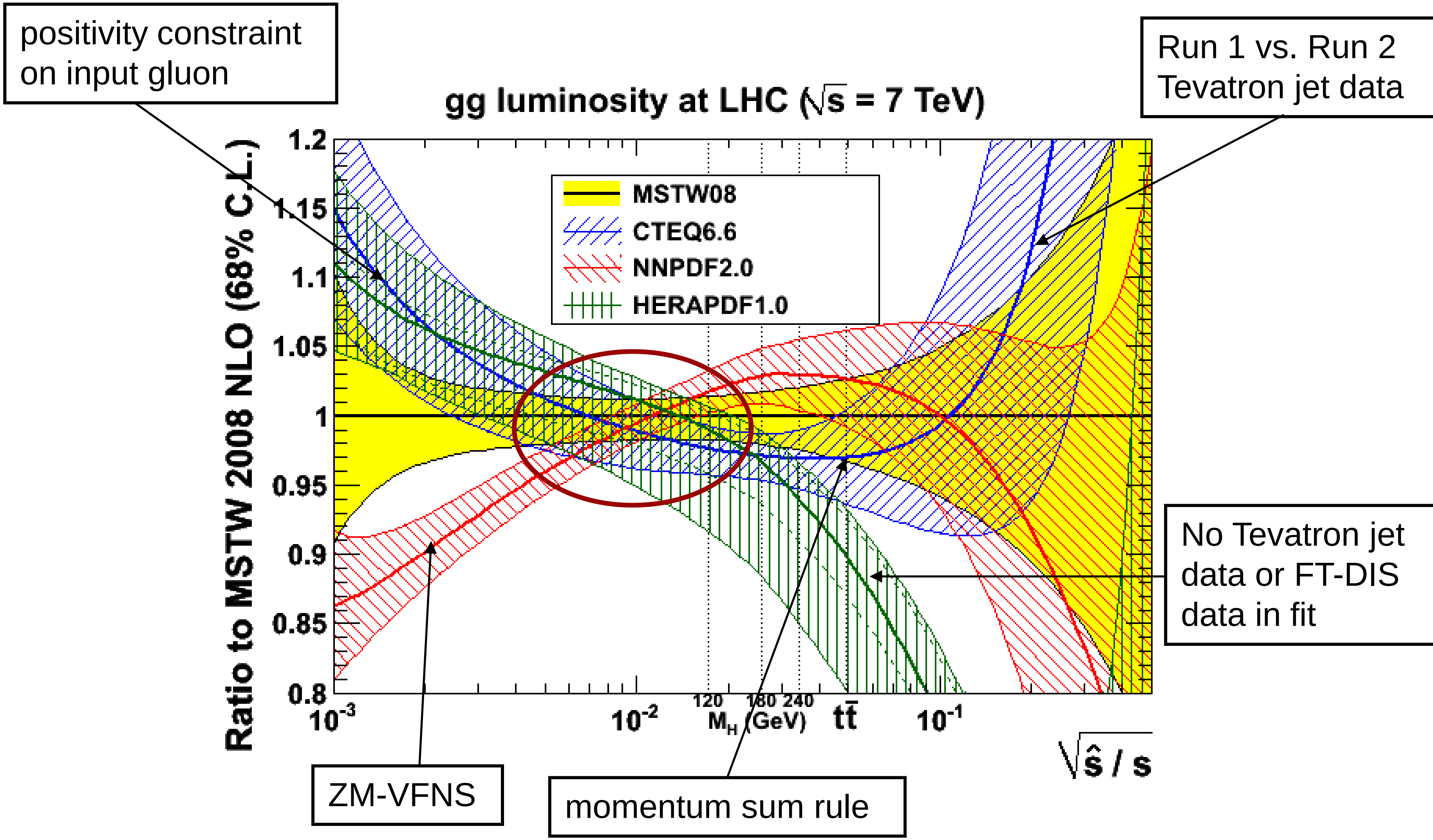
$$\alpha_S^{\overline{MS}}(M_Z^2) = 0.1184 \pm 0.0007$$

- note that the pdfs and α_S are correlated!
- e.g. gluon – α_S anticorrelation at small x and quark – α_S anticorrelation at large x

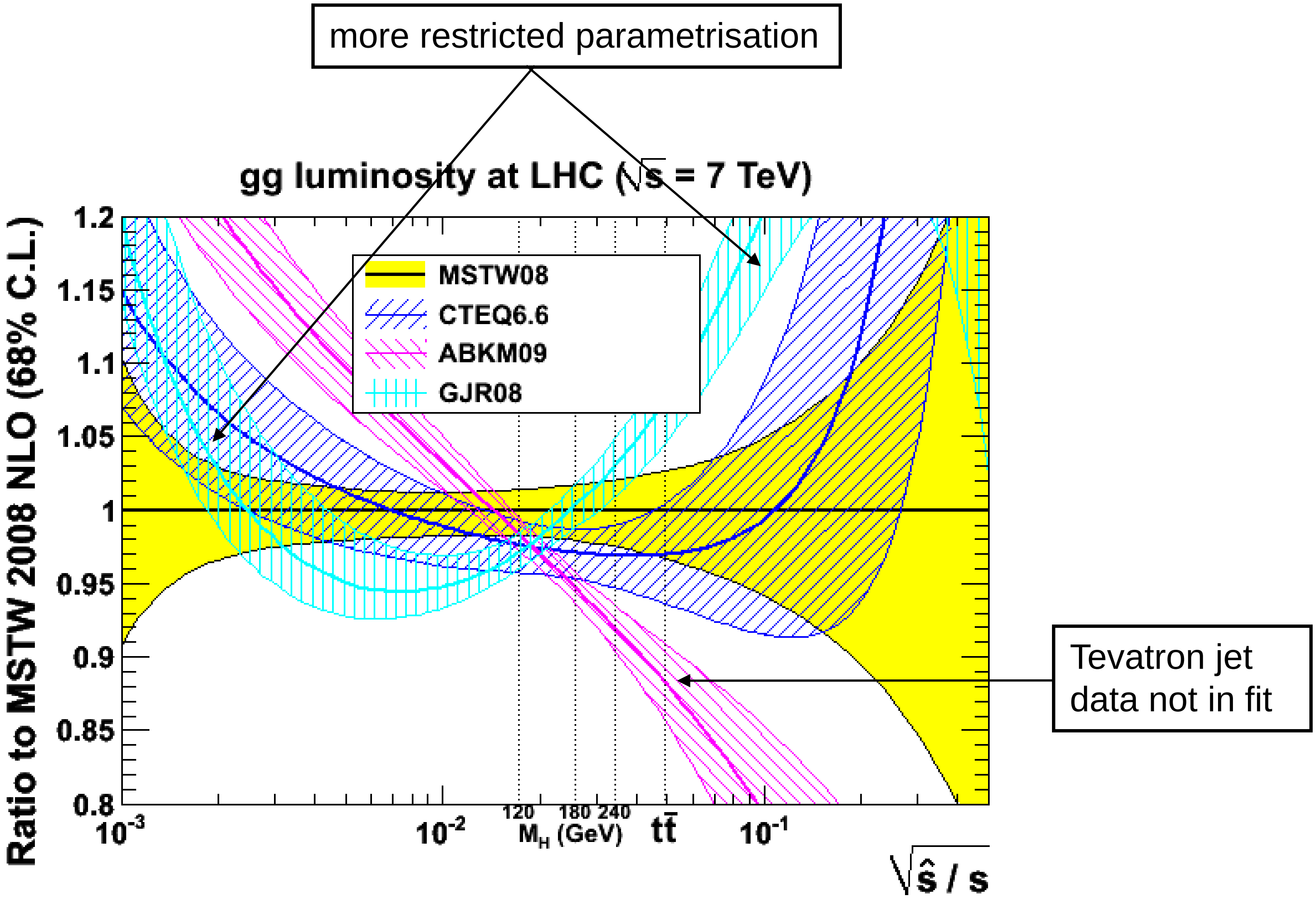
4

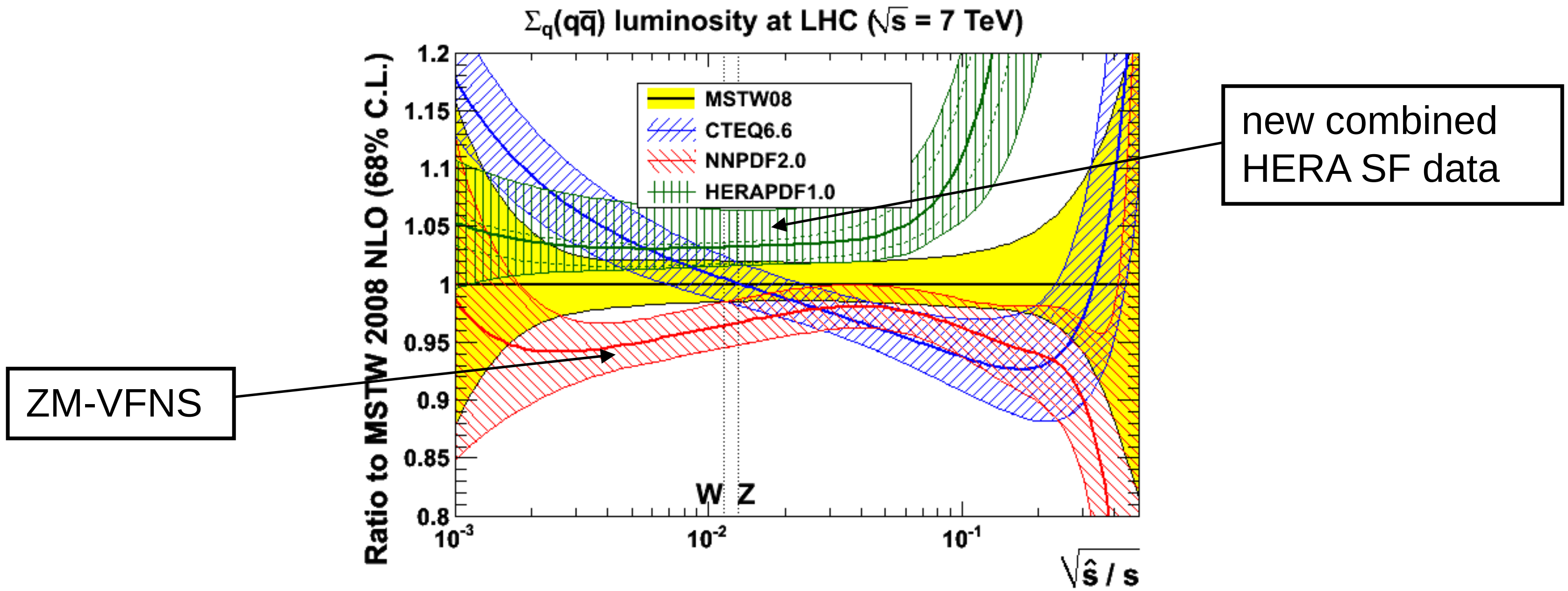
LHC benchmark cross sections

parton luminosity comparisons

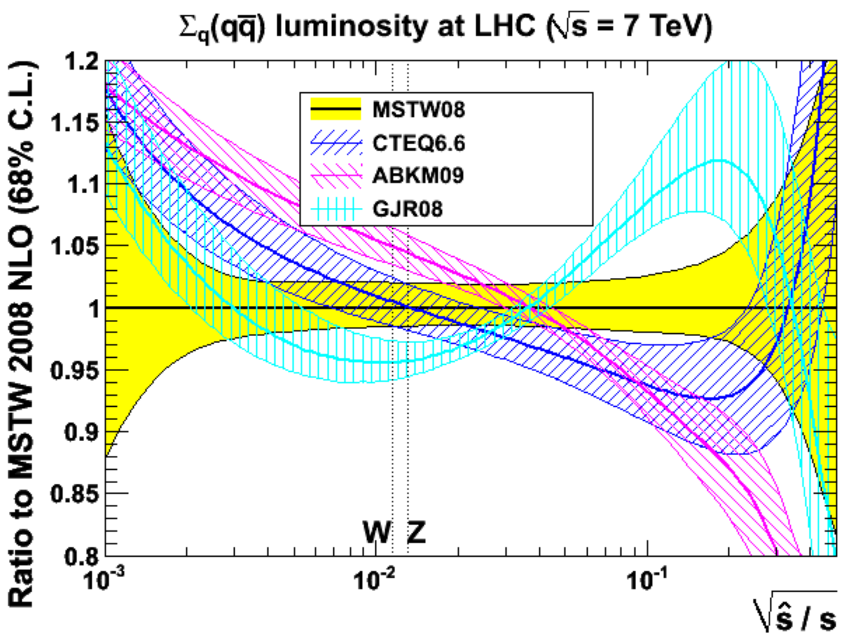


Luminosity and cross section plots from Graeme Watt (MSTW, in preparation), available at projects.hepforge.org/mstwpdf/pdf4lhc


more restricted parametrisation
gg luminosity at LHC (√s = 7 TeV)
MSTW08
CTEQ6.6
ABKM09
GJR08
Ratio to MSTW 2008 NLO (68% C.L.)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
10^-3
10^-2
120
180
240
M_H (GeV)
tt̄
10^-1
√(ŝ / s)
Tevatron jet data not in fit

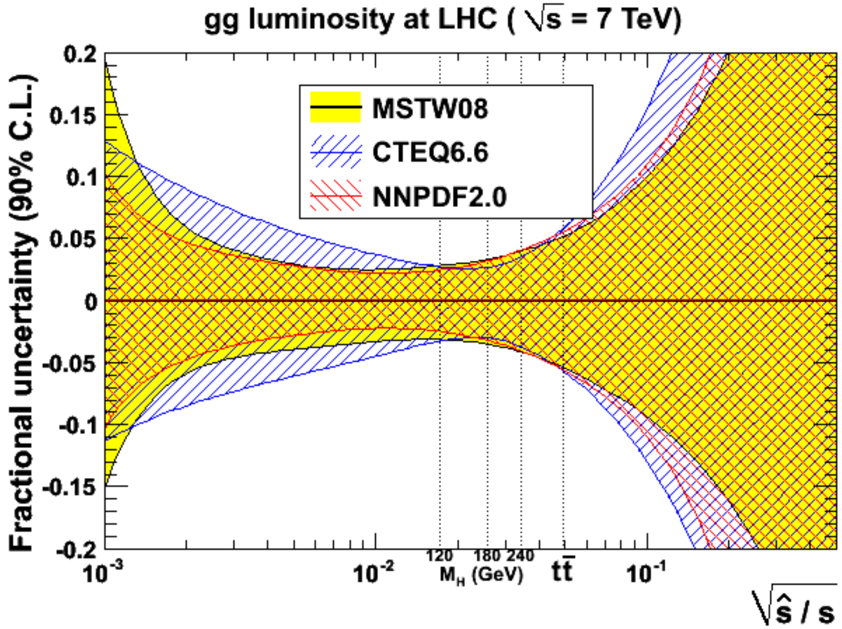


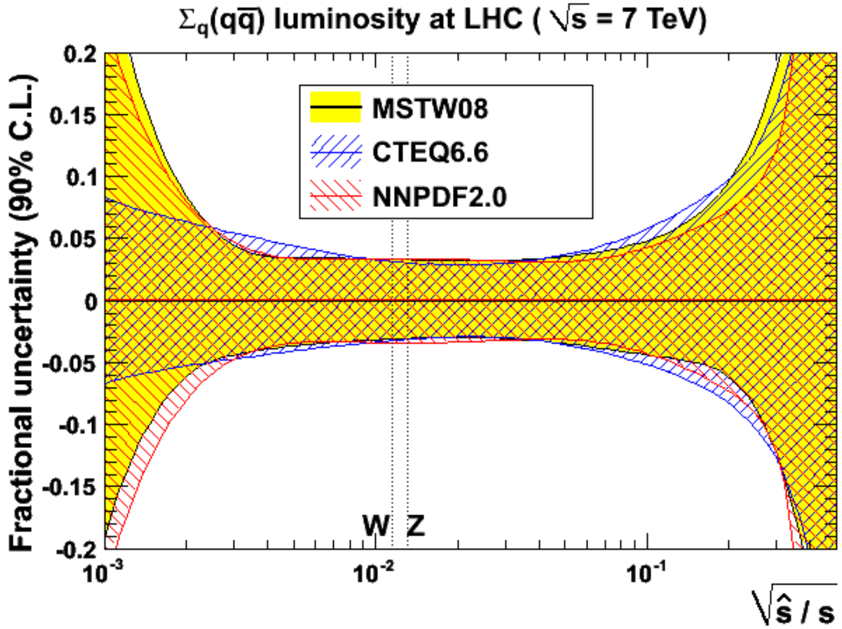
Σq(qq̄) luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
W Z
√ŝ / s
new combined
HERA SF data
ZM-VFNS



Σq(qq̄) luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
ABKM09
GJR08
W Z
√ŝ / s

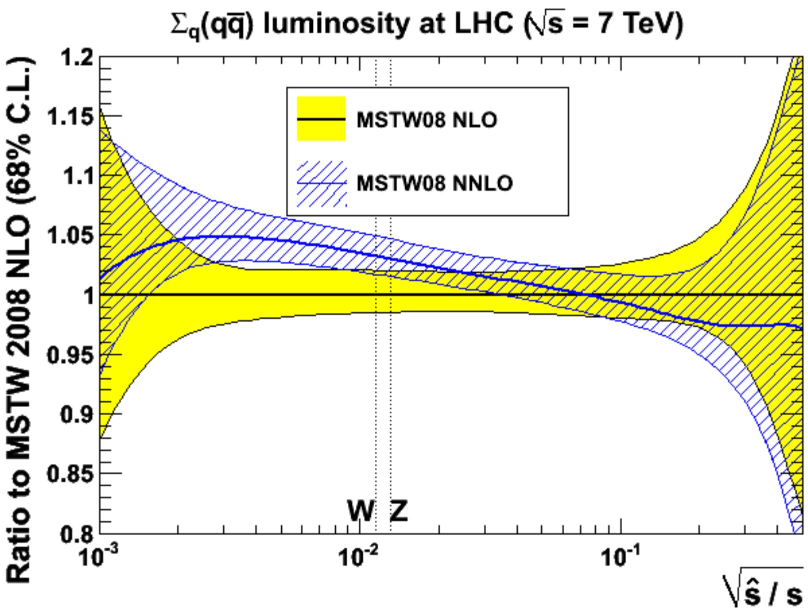
fractional uncertainty comparisons

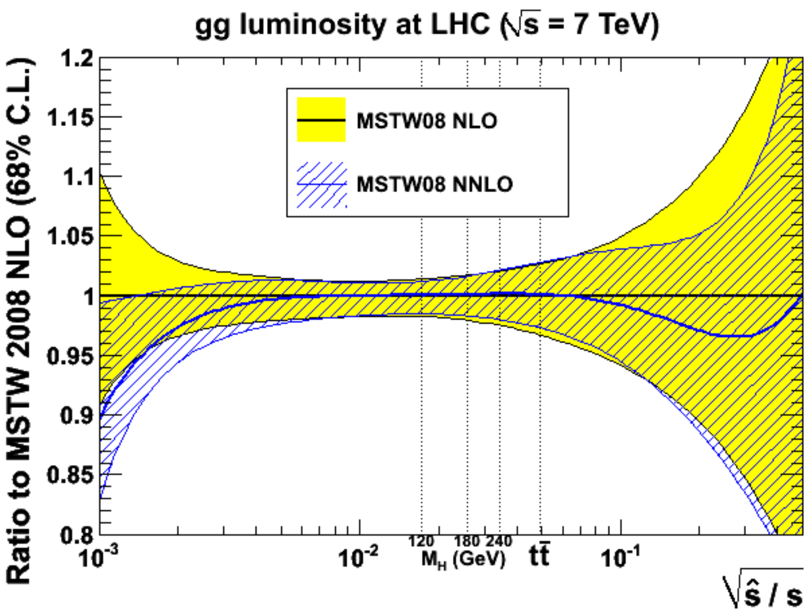




remarkably similar considering the different definitions of pdf uncertainties used by the 3 groups!

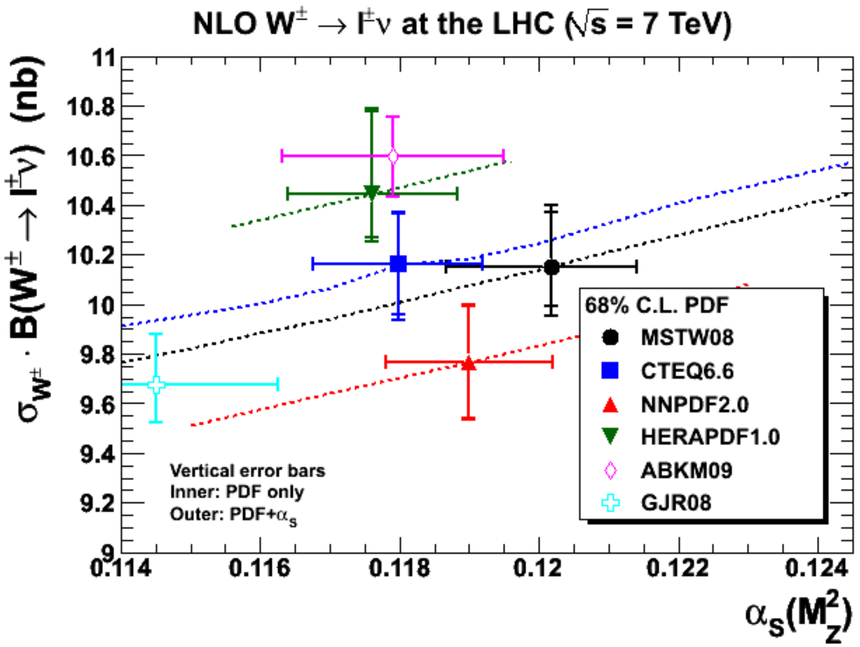
NLO and NNLO parton luminosity comparisons

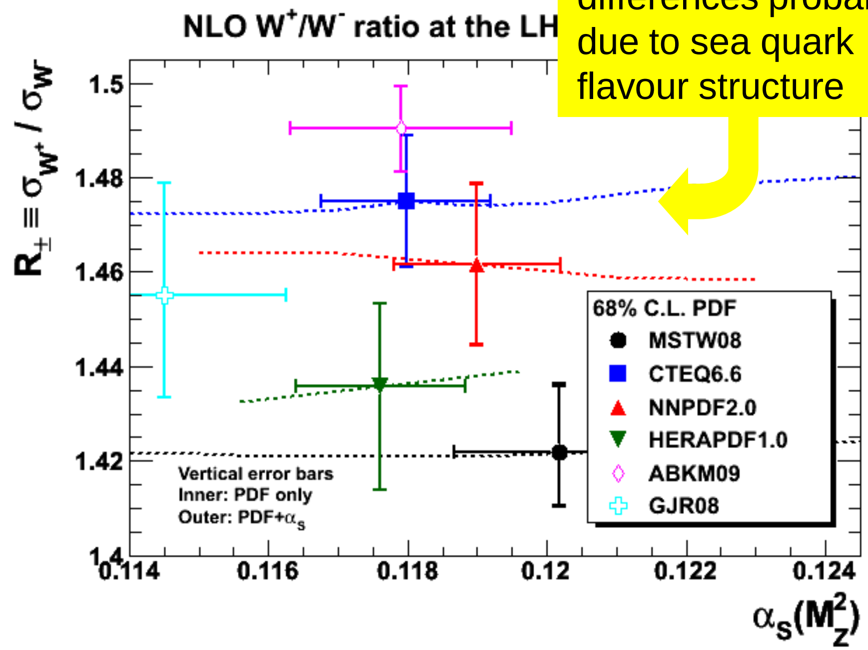


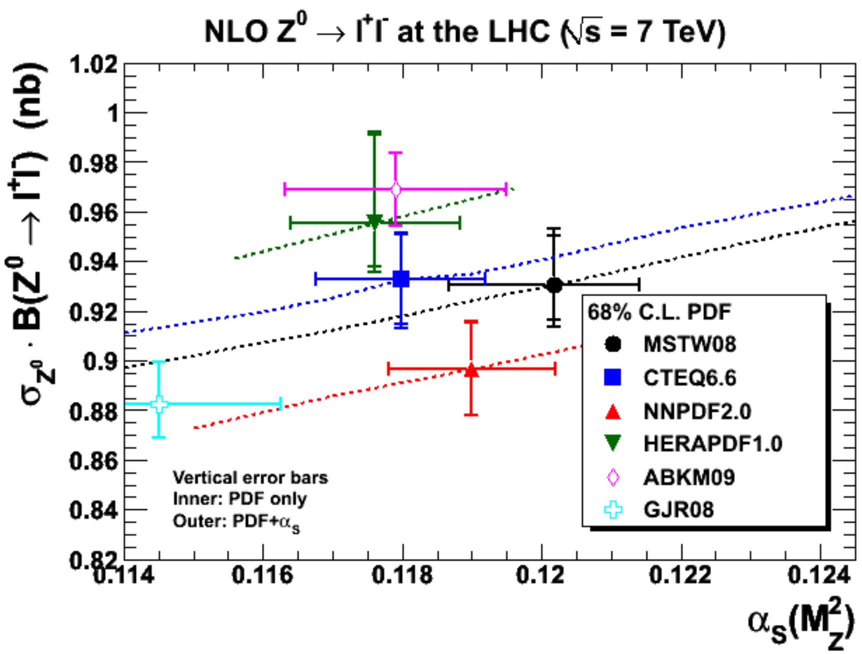


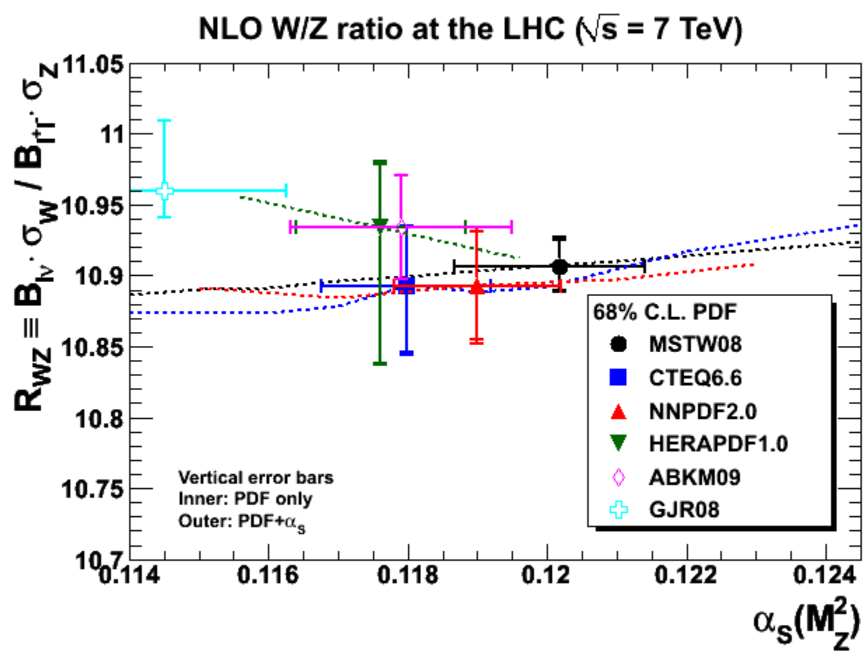
benchmark W,Z cross sections

differences probably due to sea quark flavour structure

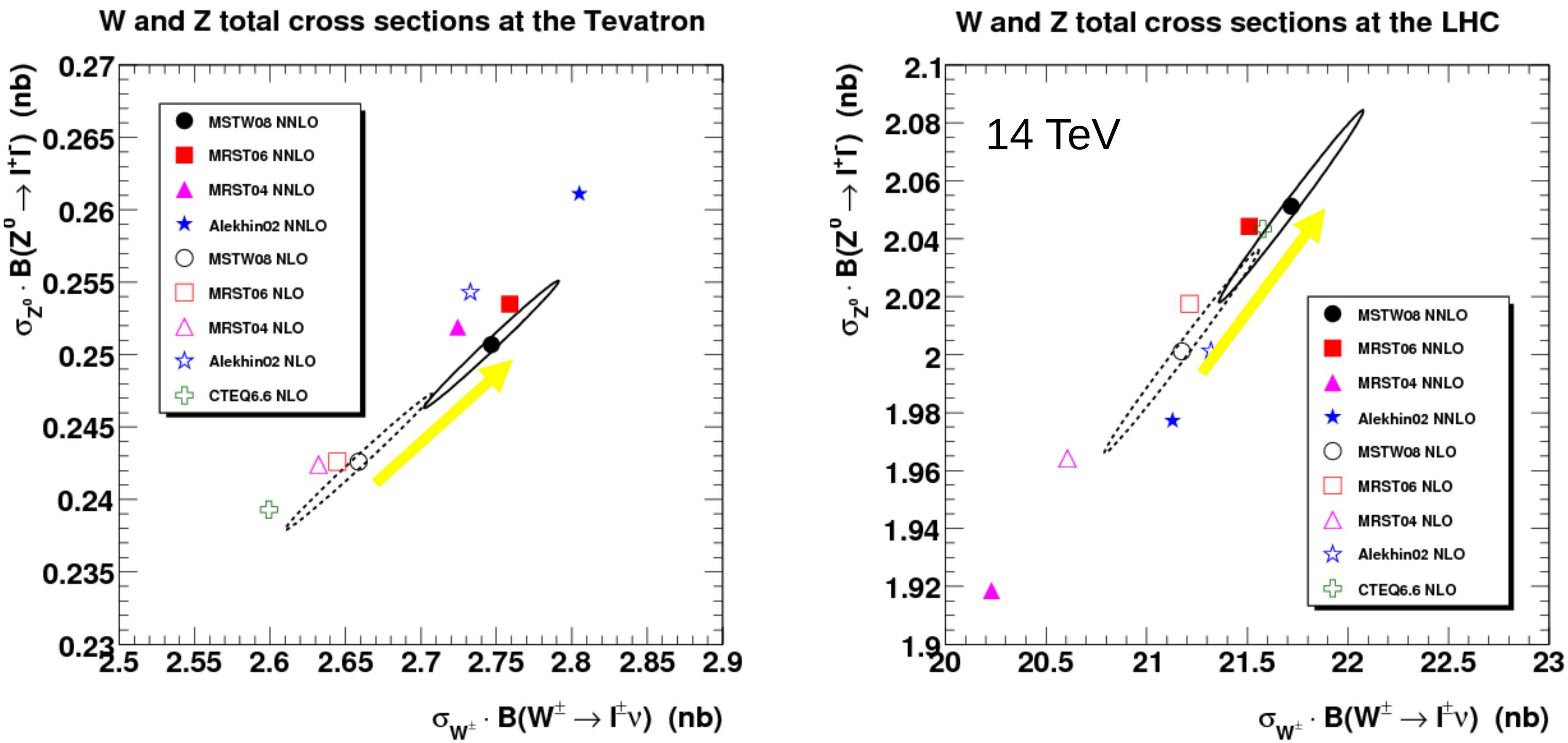




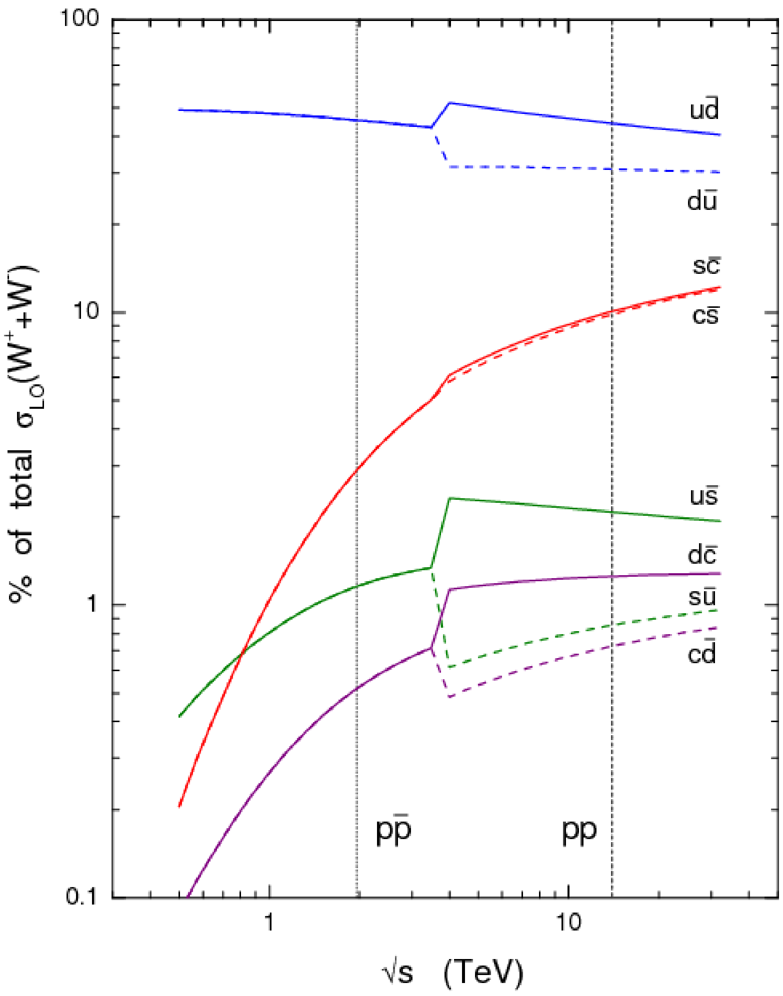




predictions for σ(W,Z) @ Tevatron, LHC: NLO *vs.* NNLO



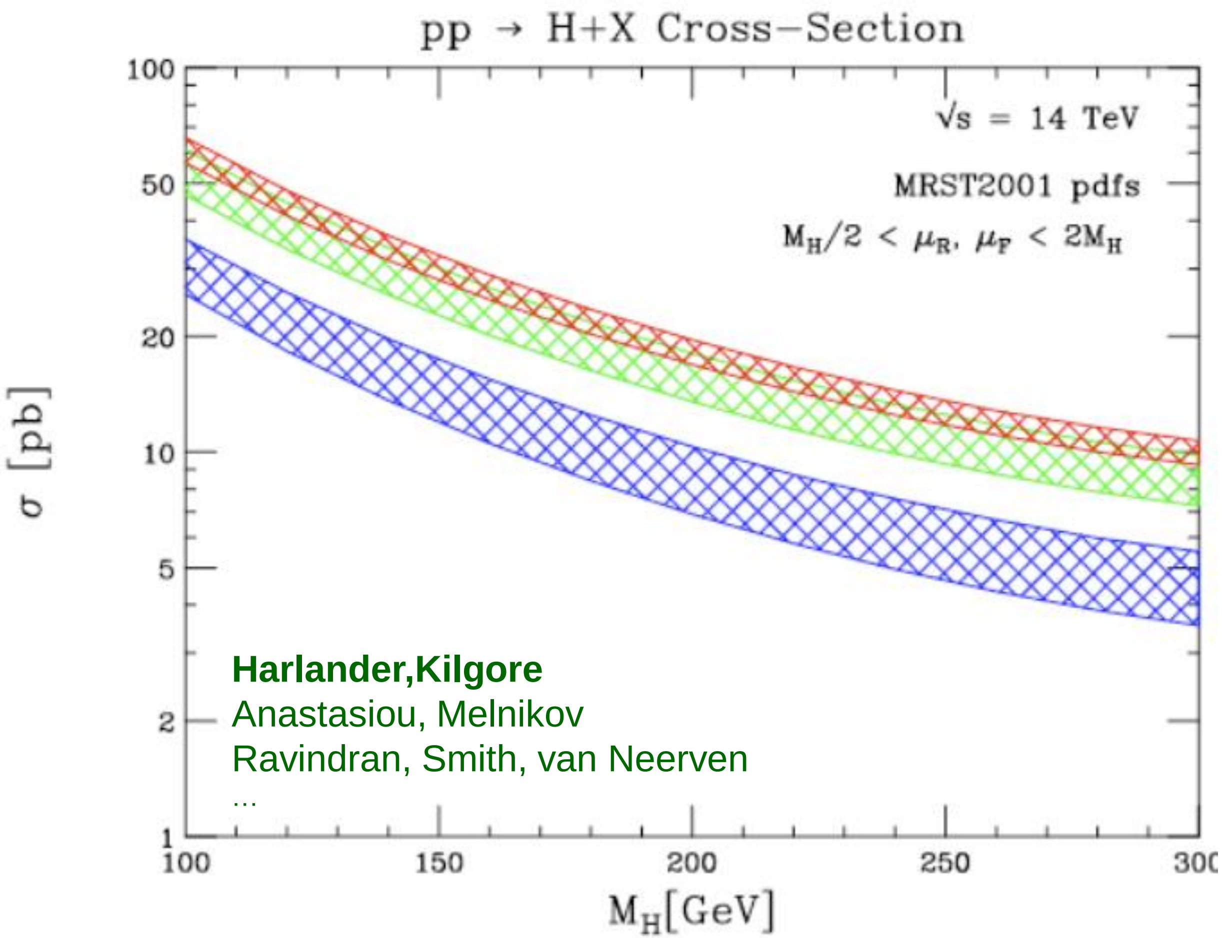
flavour decomposition of W cross sections



impact of sea quarks on the NLO W charge asymmetry ratio at 7 TeV:

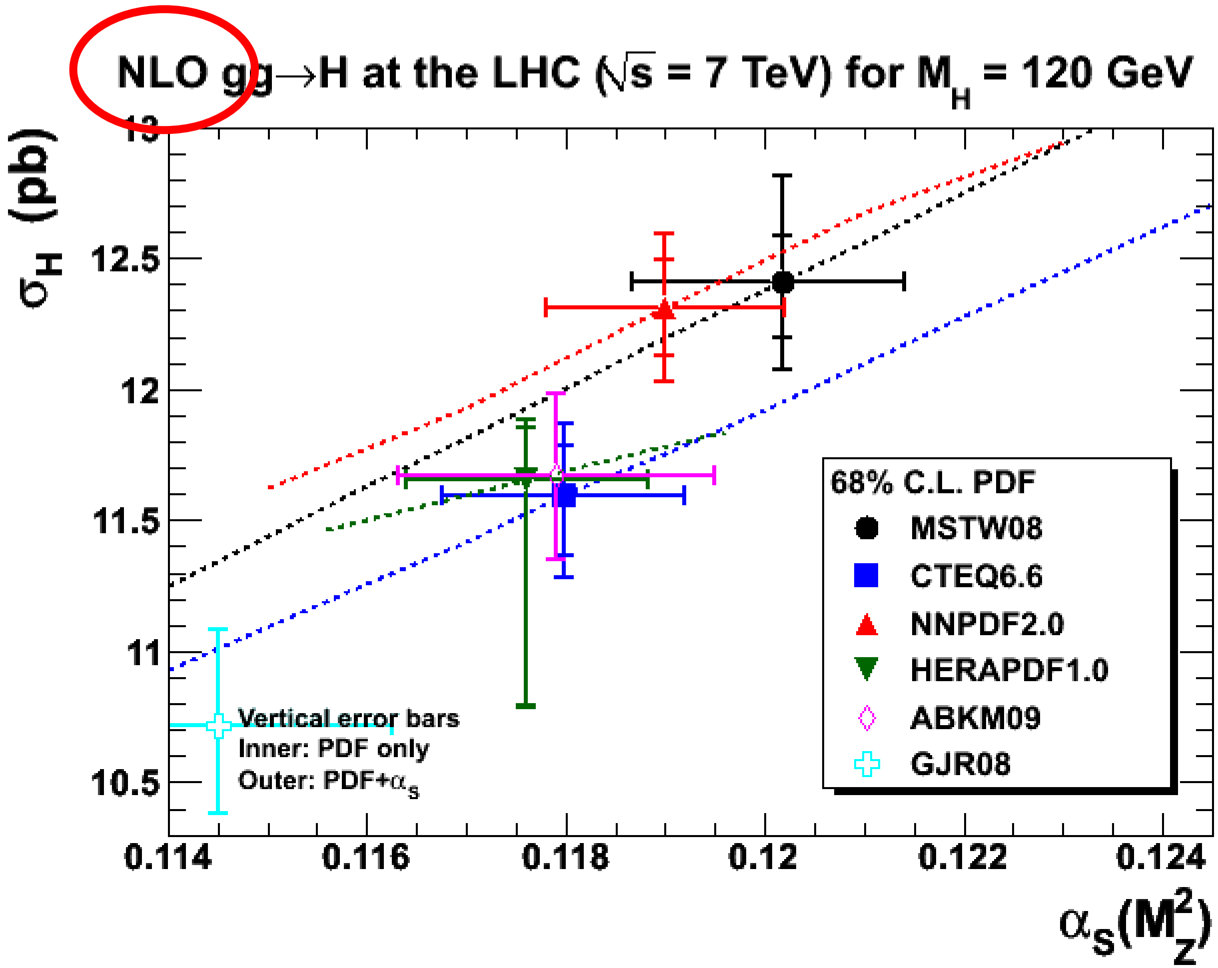
pdfs	$R(W^+/W^-)$
{udg} only	1.53
{udscbg} = MSTW08	1.42 ± 0.02
$\{udscbg\}_{sea}$ only	0.99
$\{udscbg\}_{sym.sea}$ only	1.00

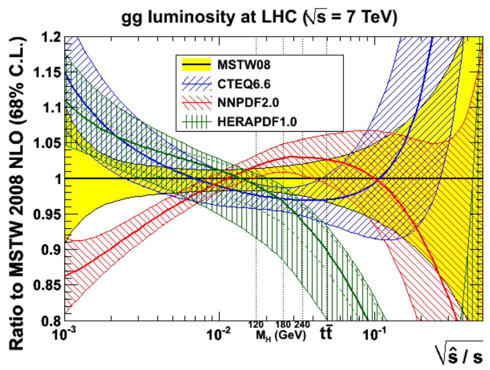
at LHC, ~30% of W and Z total cross sections involves s,c,b quarks

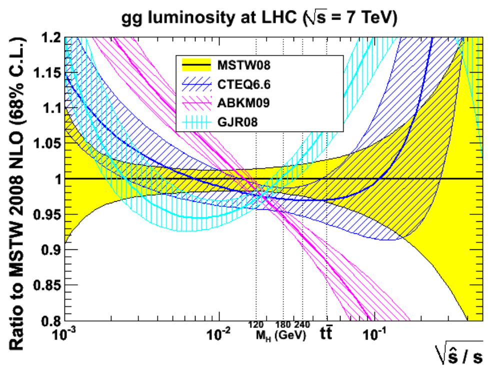


- only scale variation uncertainty shown
- central values calculated for a *fixed* set pdfs with a *fixed* value of $\alpha_S(M_Z)$

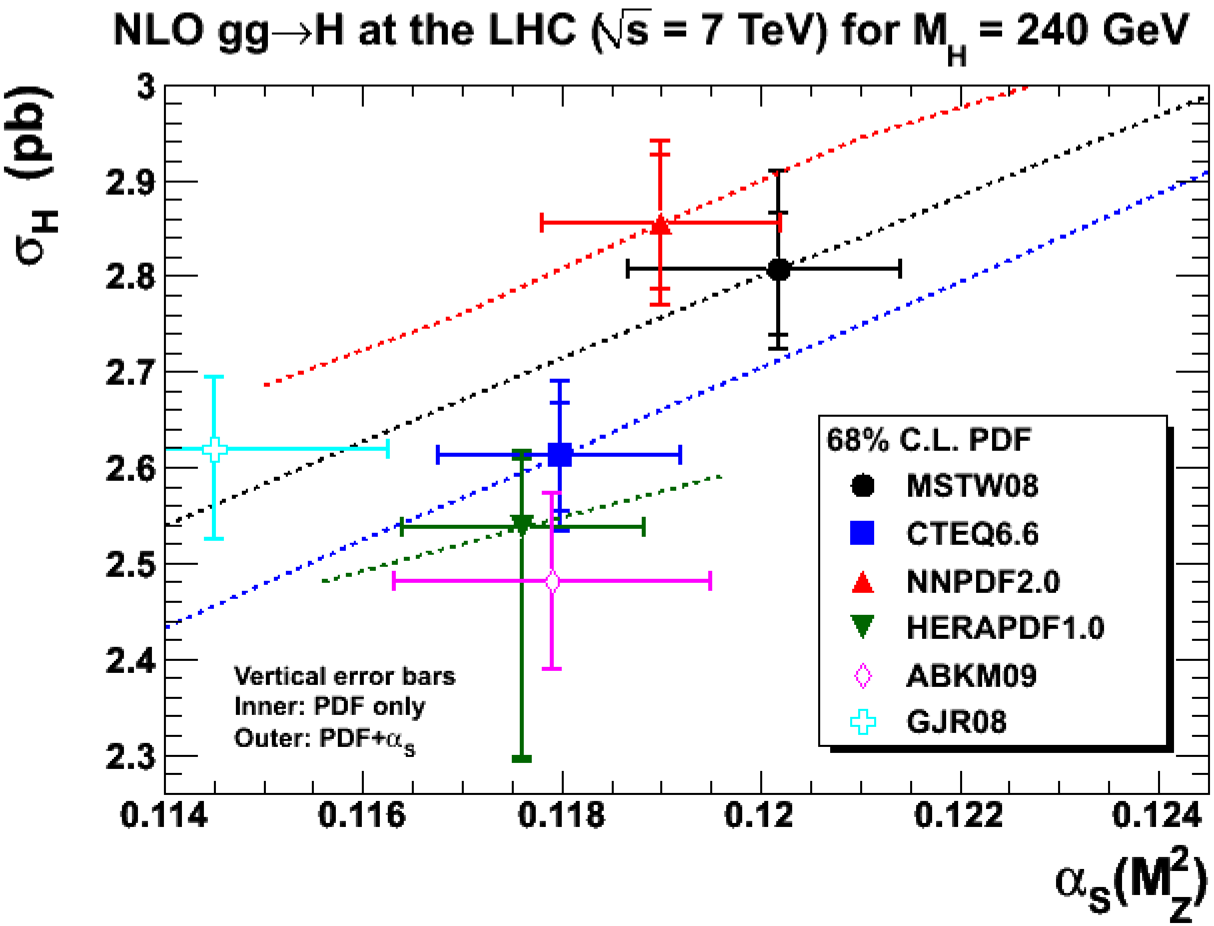
benchmark Higgs cross sections

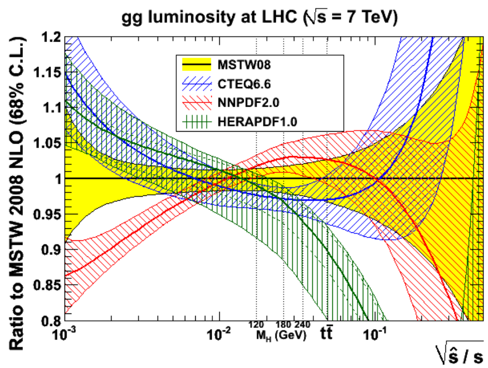


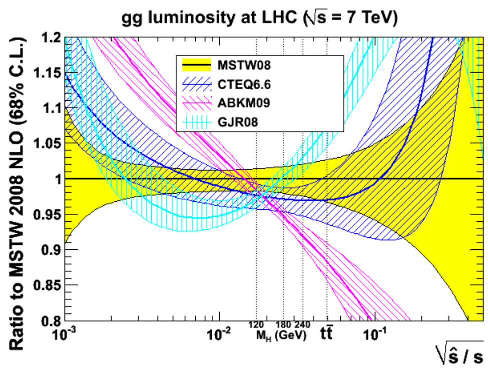


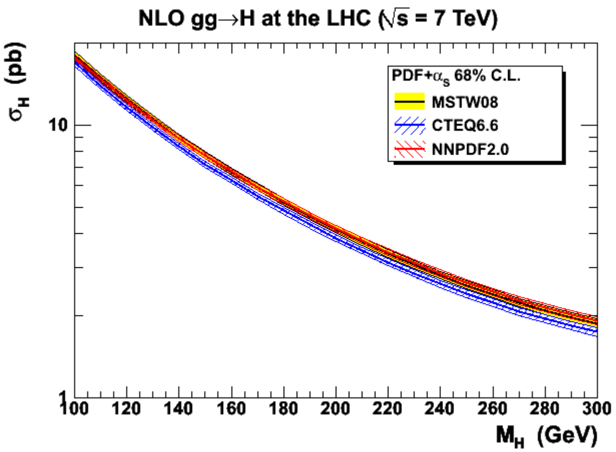


… differences from both pdfs AND α_S !


NLO gg→H at the LHC (√s = 7 TeV) for M_H = 240 GeV
σ_H (pb)
$\alpha_S(M_Z^2)$
68% C.L. PDF
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+α_S


gg luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
M_H (GeV)
tt̄
√ŝ / s

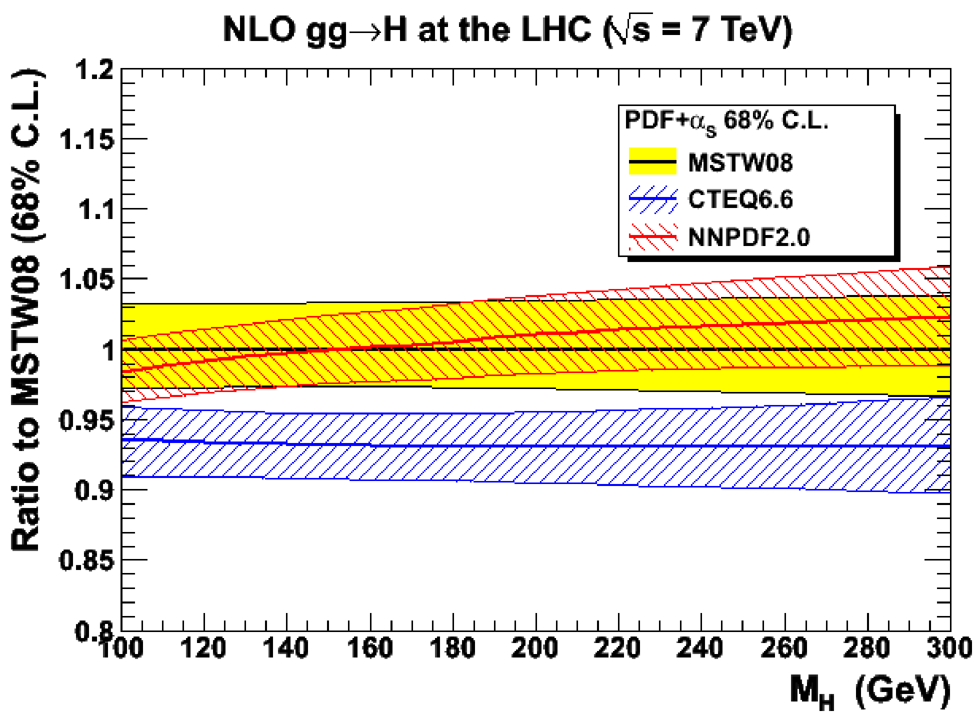

gg luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
ABKM09
GJR08
M_H (GeV)
tt̄
√ŝ / s



How to define an overall 'best theory prediction'?! See LHC Higgs Cross Section Working Group meeting, 5-6 July, higgs2010.to.infn.it

small print

Central predictions use the values of $\alpha_S(M_Z)$ favoured by each PDF group, i.e. 0.1202 for MSTW08, 0.1180 for CTEQ6.6 and 0.1190 for NNPDF2.0. For MSTW08, $\alpha_S(M_Z)$ was determined simultaneously with the PDFs in the global fit. The *experimental* uncertainties on $\alpha_S(M_Z)$ are +0.0012/-0.0015 at 68% C.L The uncertainties on $\alpha_S(M_Z)$ for CTEQ6.6 and NNPDF2.0 are taken to be ±0.0012 at 68% C.L. The combined PDF+α_S uncertainty is calculated following the prescription recommended by each group, i.e. α_S uncertainties are simply added in quadrature for CTEQ6.6, while for NNPDF2.0 the exact prescription is used as explained in arXiv:1004.0962.



Note: (i) for MSTW08, uncertainty band similar at NNLO
(ii) everything here is at fixed scale $\mu=M_H$!

summary

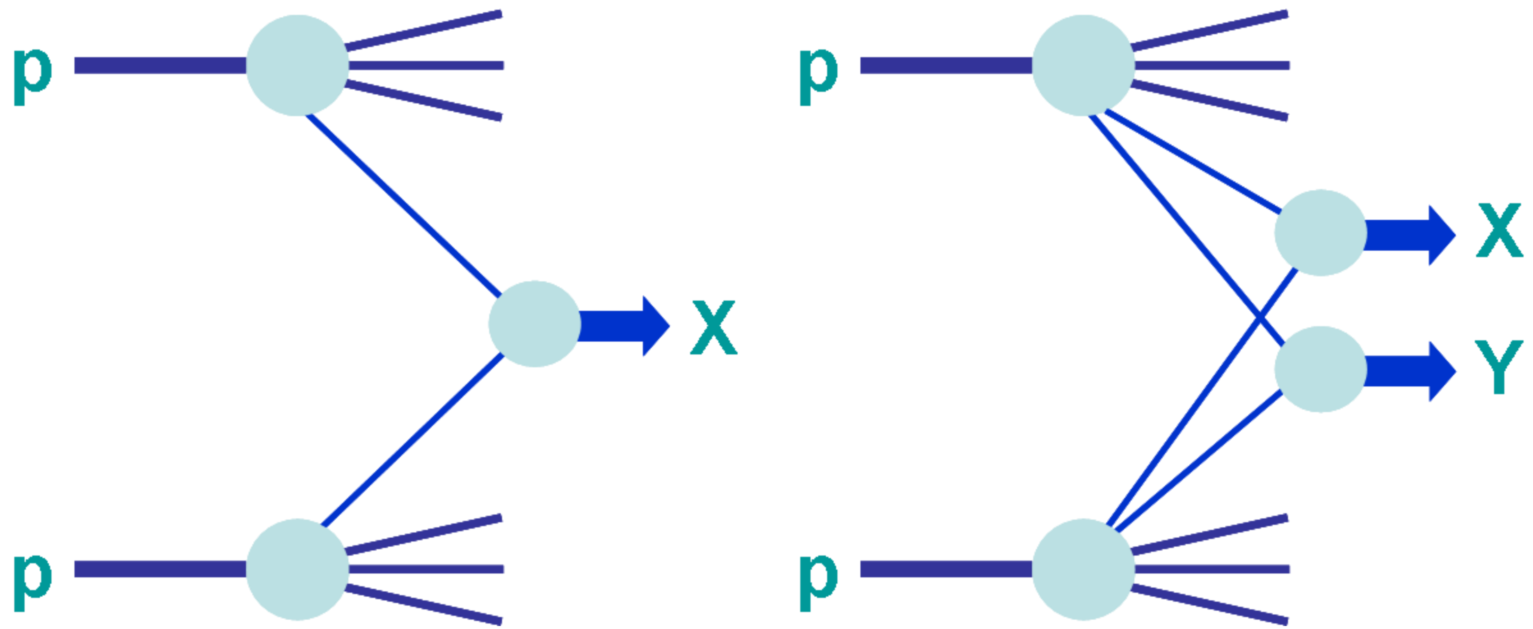
- two major advances in the past few years:
  - the NLO revolution – more and more SM background processes now known (see talks by Lance Dixon and others)
  - better understanding of and continuing convergence between the various pdf sets (see the PDF discussions this week)
    - inclusion of combined HERA data (not yet in all fits)
    - difficulty of reconciling Run II Tevatron W asymmetry data
    - proper assessment of uncertainties due to treatment of heavy quark flavours (GM-VFNS optimal but not uniquely defined)
    - beyond NNLO? e.g. influence of $[\alpha_S \ln(1/x)]^n$ contributions, higher twists, …
    - ‘QED pdfs’ (e.g. MRST 2004)
- other issues ‘solved’: PS-MCs at NLO, robust jet algorithms,…
- NNLO is the other major frontier: good for standard candles but no “+ jet” processes yet
- ‘scale variation uncertainty’ still a big issue: consensus needed
- eagerly awaiting *precision* cross sections at 7 TeV
- … and don’t forget other more novel applications of pQCD (hard diffraction, multiple parton interactions, etc.

5

double parton distributions

For a `state of the art' overview of Multiple Parton Interactions, see the talks at the recent DESY workshop:
indico.desy.de/conferenceDisplay.py?confId=3241

single and double hard parton scattering



$$f_{a/A}(x; Q^2)$$

$$f_{ab/A}(x_1, x_2; Q_X^2, Q_Y^2)$$

e.g. **X** = **Y** = W, $Q_X^2 \sim Q_Y^2 \sim M_W^2$

double parton scattering: rates and topologies

- if we assume that the dPDFs factorise, i.e.

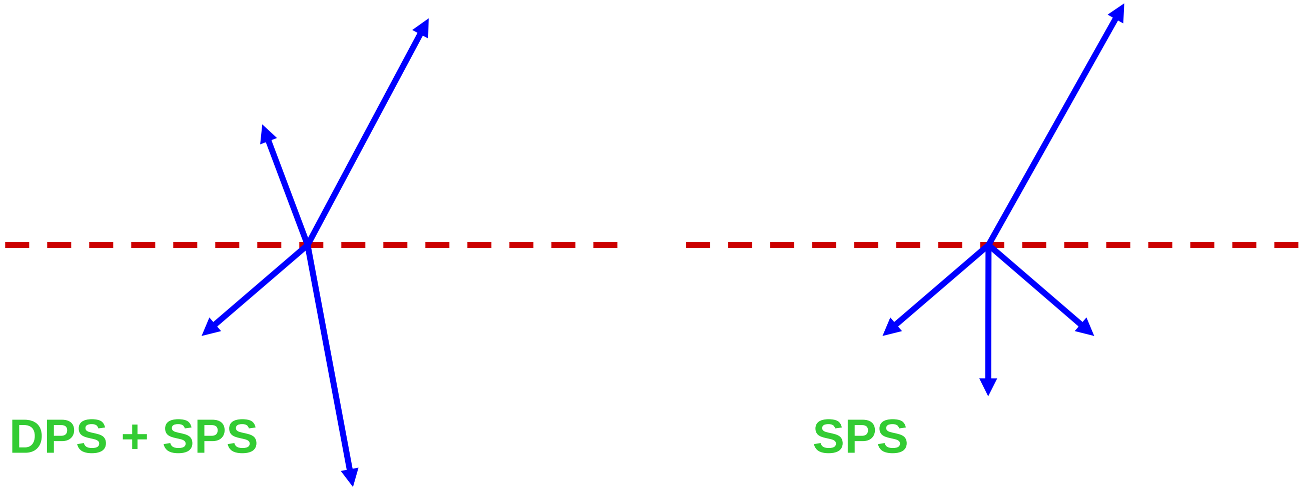
$$f_{ab/A}(x_1, x_2; Q_1^2, Q_2^2) = f_a(x_1, Q_1^2) f_b(x_2, Q_2^2)$$

- then we obtain

$$\sigma^{\mathrm{DPS}}(X,Y) = \frac{m}{2} \frac{\sigma_X \sigma_Y}{\sigma_{\mathrm{eff}}}$$

X,Y distinct: m=2
X,Y same: m=1

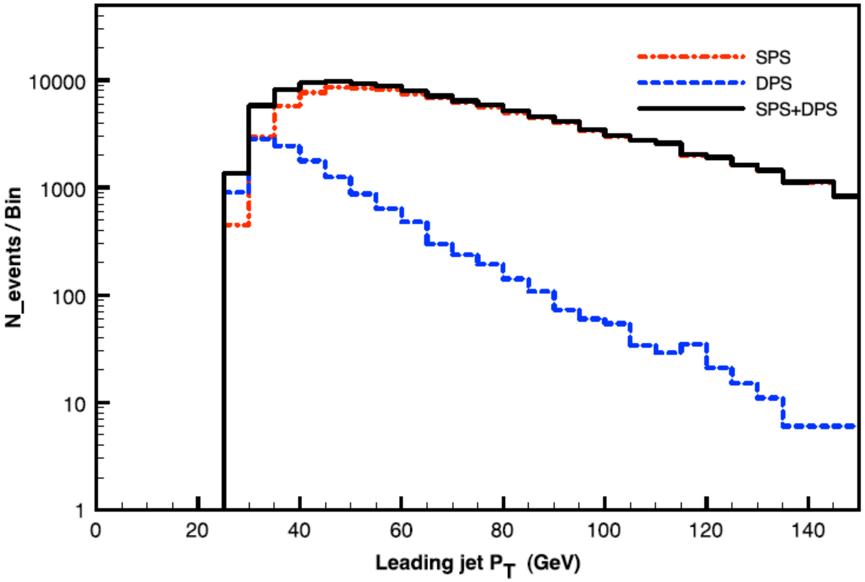
- studies of γ+3j production by CDF and D0 suggest $\sigma_{\mathrm{eff}} \approx 15$ mb
- but there is generally a SPS 'background', a+b → XY



- use `pairwise transverse momentum balance' (shape variable) as a signal for double parton scattering
- many final states have been studied*: X,Y = γj, 2j, W, bb, tt, H, …
- interesting example: same-sign W at LHC

*Del Fabbro, Treleani, Cattaruzza; Berger, Jackson, Shaughnessy; Maina; Hussein; Gaunt, Kom, Kulesza, S; …

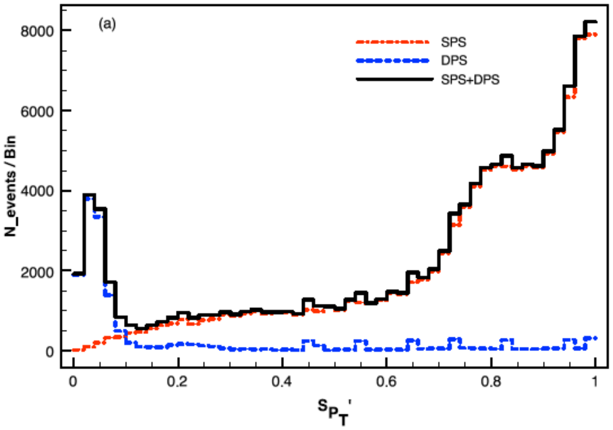
DPS in bbjj production at LHC



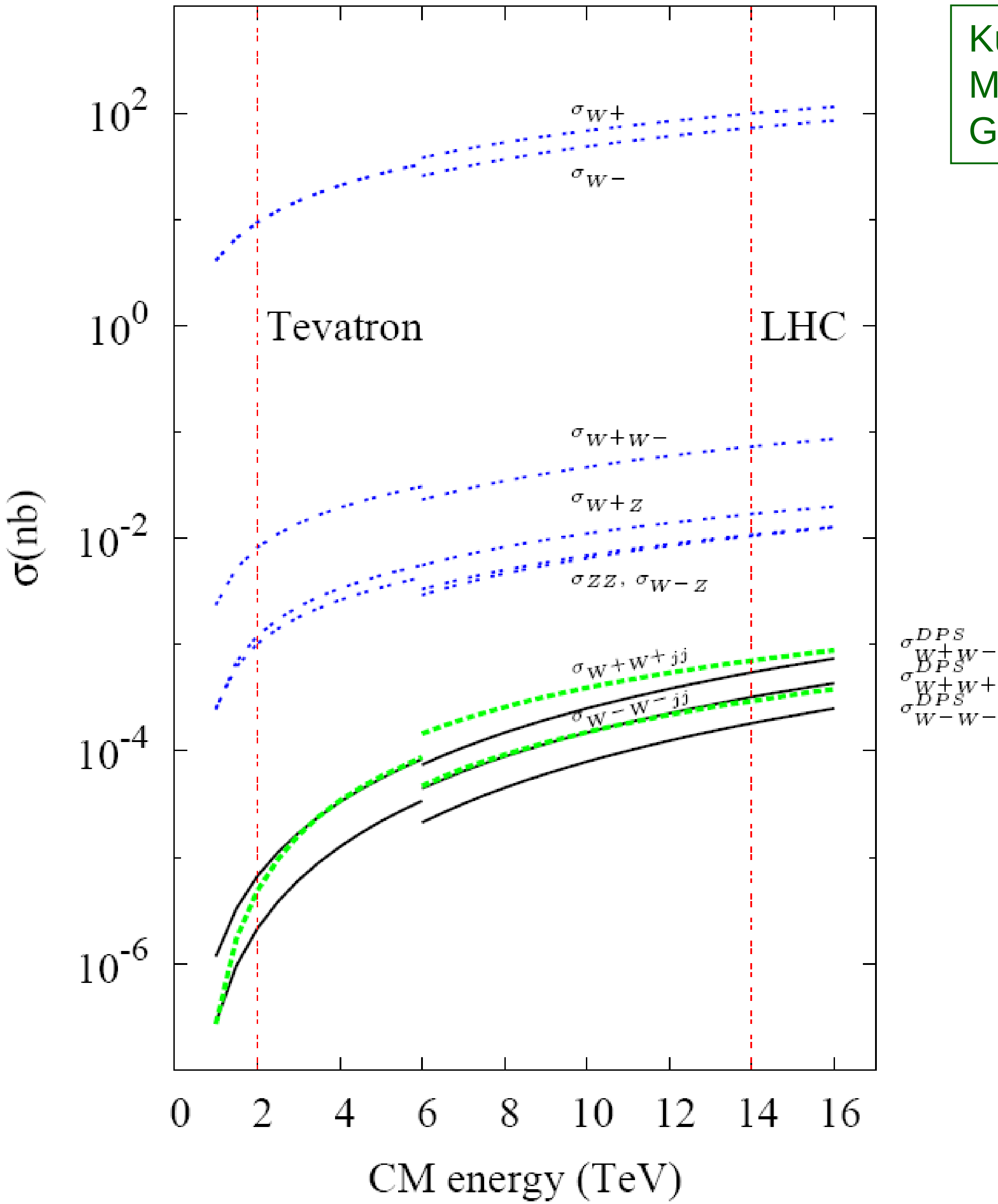
DPS dominates at low pT(jet)

$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(b_1,b_2)|}{|p_T(b_1)|+|p_T(b_2)|}\right)^2 + \left(\frac{|p_T(j_1,j_2)|}{|p_T(j_1)|+|p_T(j_2)|}\right)^2}$$

easy to separate DPS using shape (imbalance) variable



Berger, Jackson, Shaughnessy (2009)



Kulesza, S (1999)
Maina (2009)
Gaunt, Kom, Kulesza, S (2010)

Note:

a + b → W^+W^-

but

a + b ↛ W^+W^+

instead

q + q → W^+W^+ + q'q'

so same-sign W production could be a good place to look for DPS (with a lot of luminosity!)

dDGLAP

- the dPDFs satisfy a `double DGLAP' equation

$$\frac{dD_h^{j_1 j_2}(x_1,x_2;t)}{dt} = \frac{\alpha_s(t)}{2\pi}\Bigg[\sum_{j_1'}\int_{x_1}^{1-x_2}\frac{dx_1'}{x_1'}D_h^{j_1' j_2}(x_1',x_2;t)P_{j_1'\to j_1}\left(\frac{x_1}{x_1'}\right)$$
$$+\sum_{j_2'}\int_{x_2}^{1-x_1}\frac{dx_2'}{x_2'}D_h^{j_1 j_2'}(x_1,x_2';t)P_{j_2'\to j_2}\left(\frac{x_2}{x_2'}\right)$$
$$+\sum_{j'}D_h^{j'}(x_1+x_2;t)\frac{1}{x_1+x_2}P_{j'\to j_1 j_2}\left(\frac{x_1}{x_1+x_2}\right)\Bigg]$$

Kirschner 1979
Shelest, Snigirev, Zinovjev 1982
Snigirev 2003
Korotkikh, Snigirev 2004
Cattaruzza et al. 2005

- and note that $f_{ab}(x_1,x_2;Q_1^2,Q_2^2) = f_a(x_1,Q_1^2)f_b(x_2,Q_2^2)$
 is **not** a solution, i.e. factorisation is broken (in fact this must be true since must have $x_1+x_2 < 1$ for momentum conservation)

Snigirev 2003
Korotkikh, Snigirev 2004
Cattaruzza et al. 2005

- the dPDFs and sPDFS are related by sum rules, e.g.

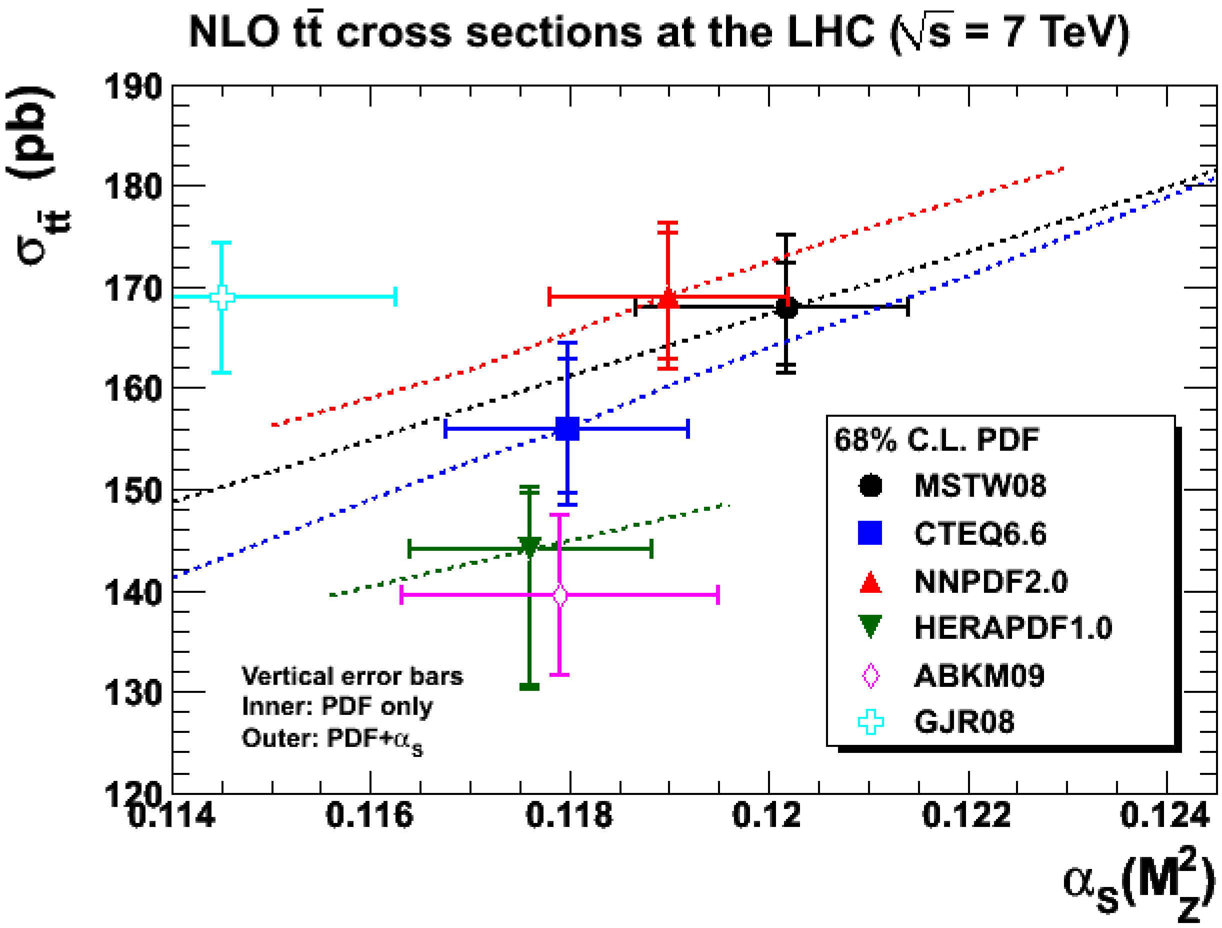
$$\sum_a \int_0^{1-x_2} dx_1 x_1 f_{ab}(x_1,x_2;Q^2) = (1-x_2)f_b(x_2,Q^2)$$

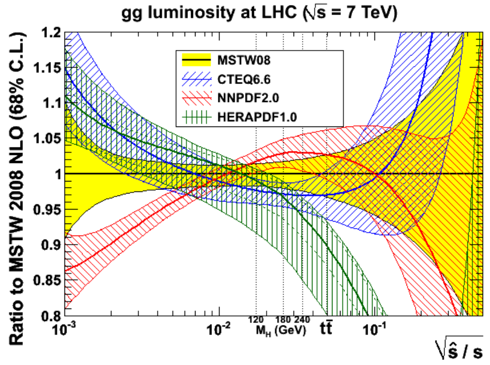
- a consistent LO package (GS09) is available

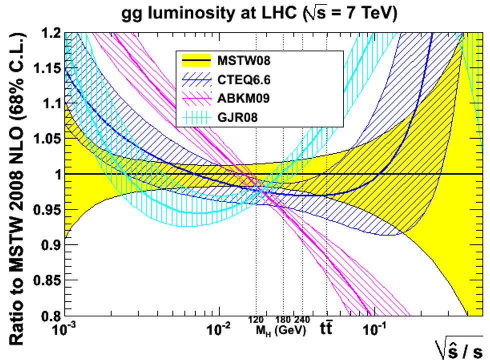
Gaunt, S 2009

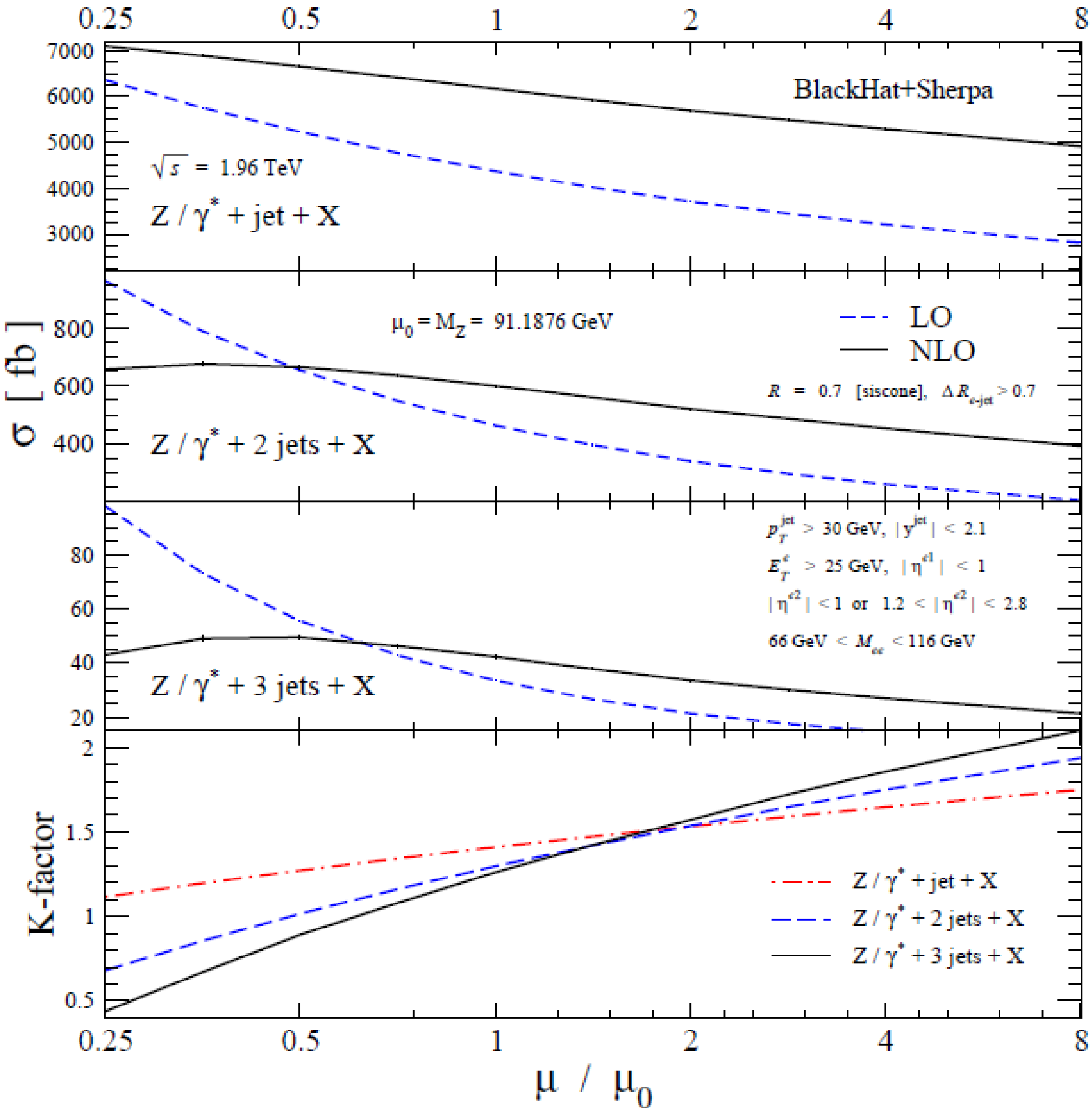
extra slides

benchmark top cross sections









Berger et al, arXiv:1004.1659

examples of data sets used in fits*

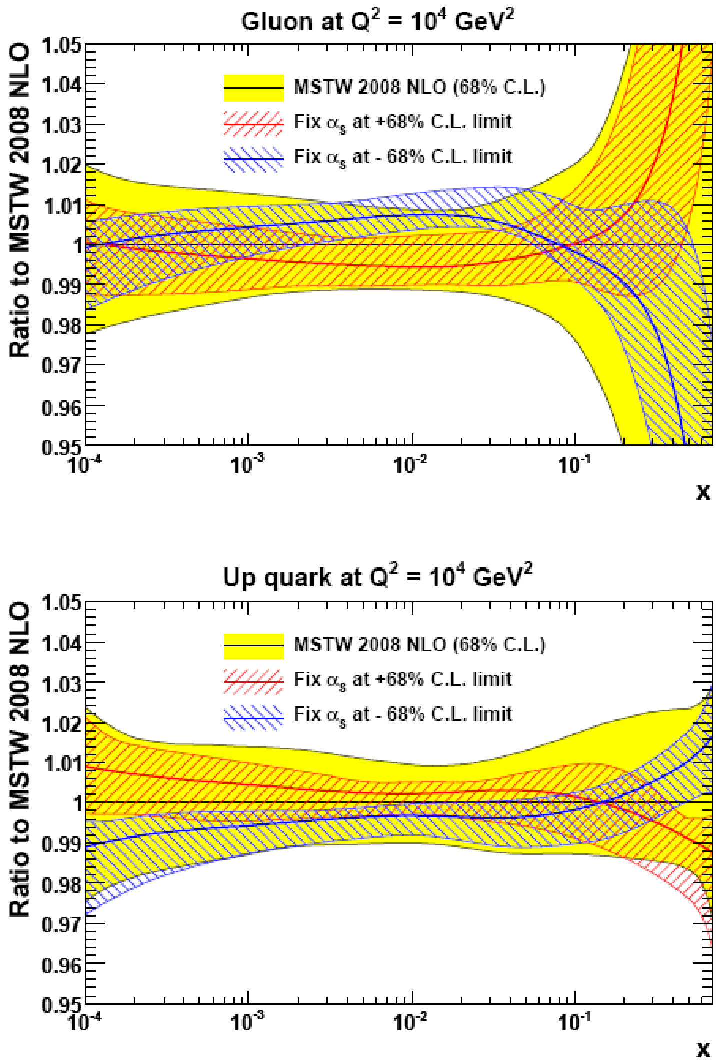
Data set	$N_{\text{pts.}}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
H1 low Q^2 96–97 e^+p NC	80
H1 high Q^2 98–99 e^-p NC	126
H1 high Q^2 99–00 e^+p NC	147
ZEUS SVX 95 e^+p NC	30
ZEUS 96–97 e^+p NC	144
ZEUS 98–99 e^-p NC	92
ZEUS 99–00 e^+p NC	90
H1 99–00 e^+p CC	28
ZEUS 99–00 e^+p CC	30
H1/ZEUS $e^\pm p$ F_2^{charm}	83
H1 99–00 e^+p incl. jets	24
ZEUS 96–97 e^+p incl. jets	30
ZEUS 98–00 $e^\pm p$ incl. jets	30
DØ II $p\bar{p}$ incl. jets	110
CDF II $p\bar{p}$ incl. jets	76
CDF II $W \to l\nu$ asym.	22
DØ II $W \to l\nu$ asym.	10
DØ II Z rap.	28
CDF II Z rap.	29

Data set	$N_{\text{pts.}}$
BCDMS μp F_2	163
BCDMS μd F_2	151
NMC μp F_2	123
NMC μd F_2	123
NMC $\mu n/\mu p$	148
E665 μp F_2	53
E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
E866/NuSea pp DY	184
E866/NuSea pd/pp DY	15
NuTeV νN F_2	53
CHORUS νN F_2	42
NuTeV νN xF_3	45
CHORUS νN xF_3	33
CCFR $\nu N \to \mu\mu X$	86
NuTeV $\nu N \to \mu\mu X$	84
All data sets	**2743**

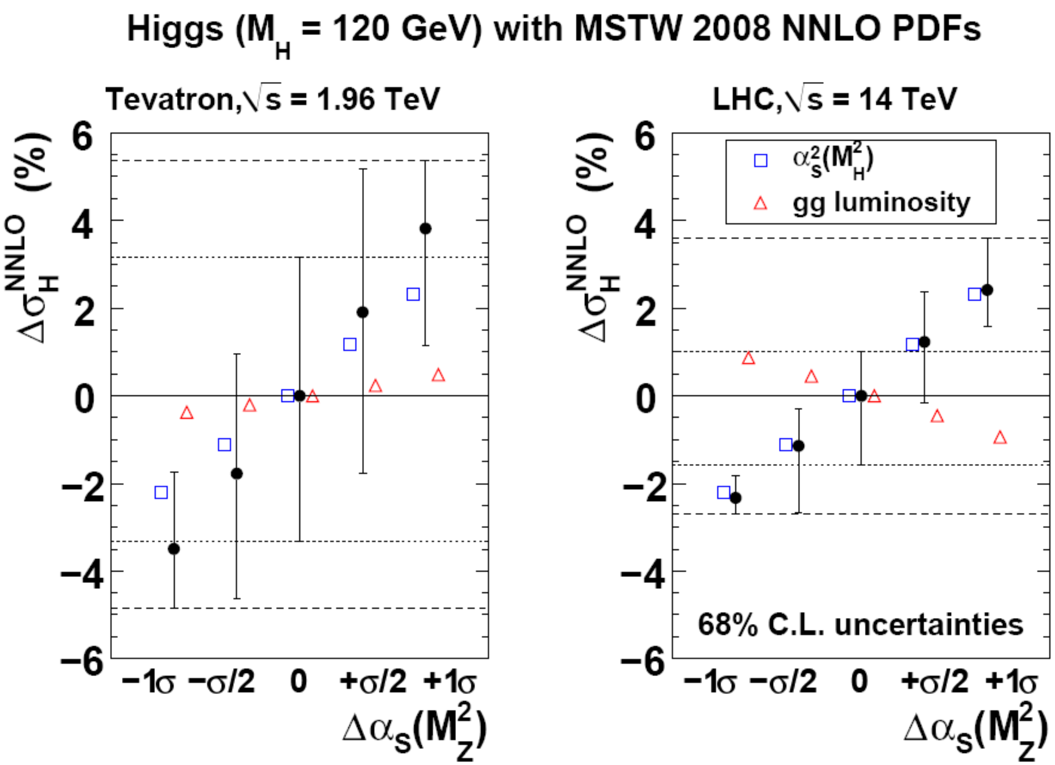
red font = new wrt MRST2006 fit

*MSTW2008

α_S - pdf correlations

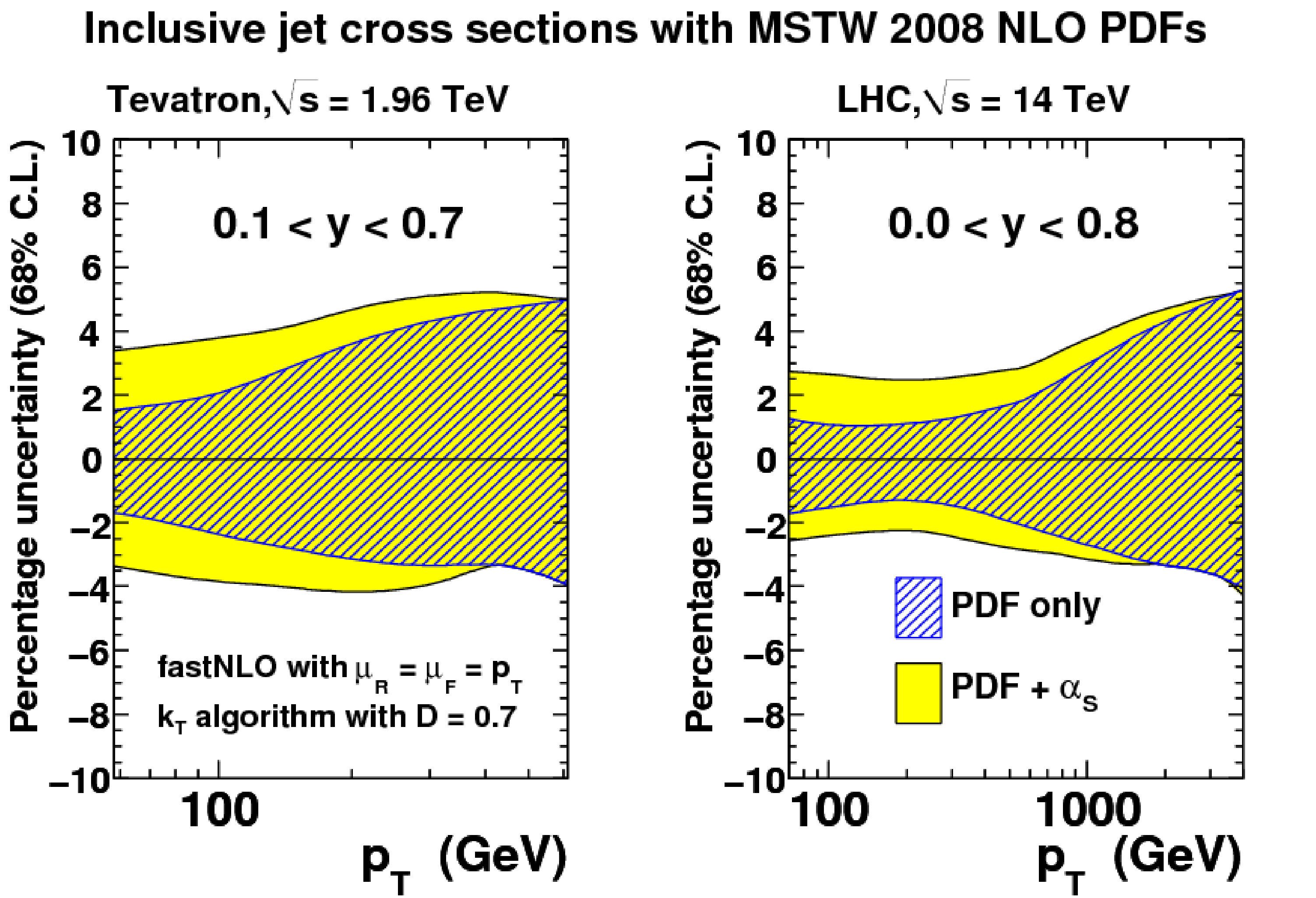


- care needed when assessing impact of varying α_S on cross sections $\sim (\alpha_S)^n$

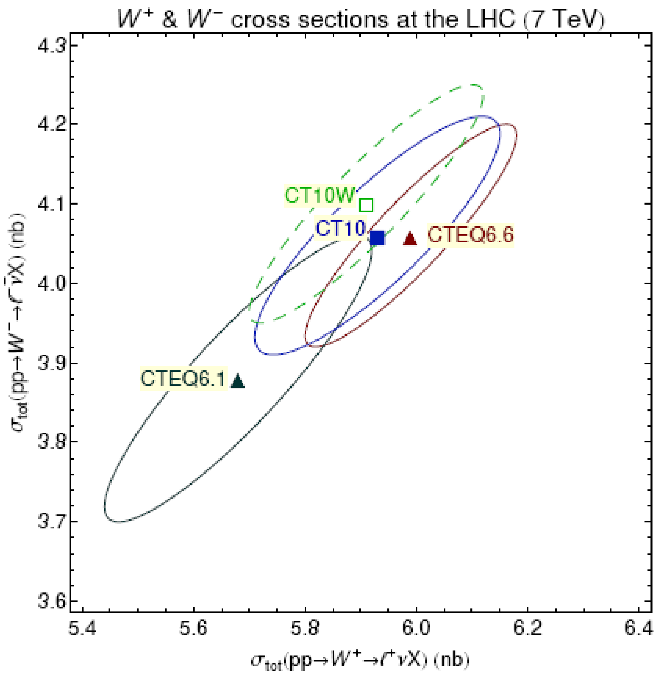


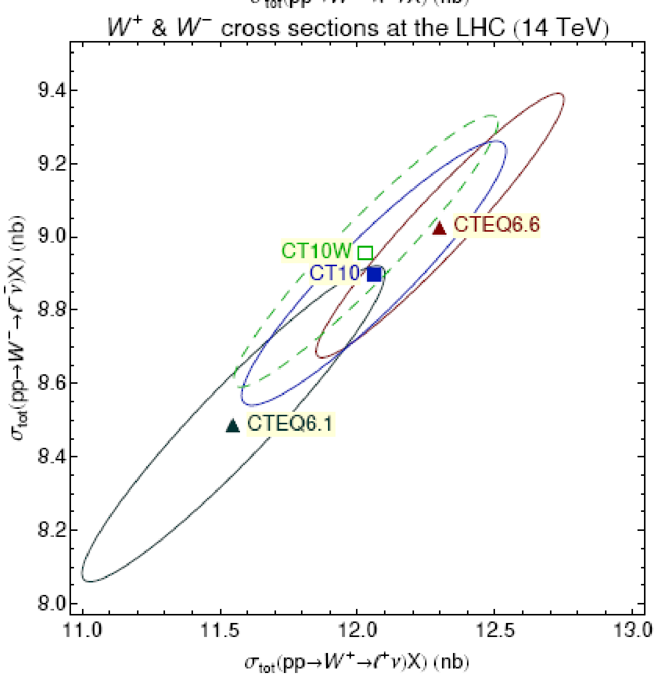
MSTW: arXiv:0905.3531

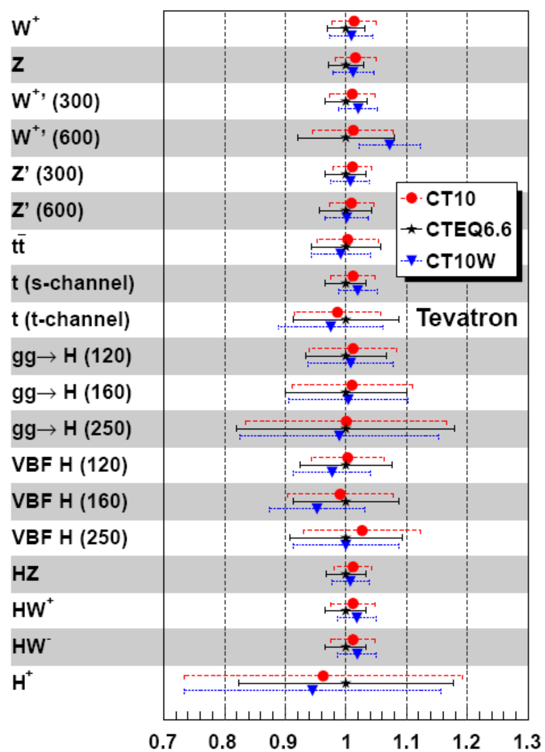
pdf + α_S uncertainties in jet cross sections

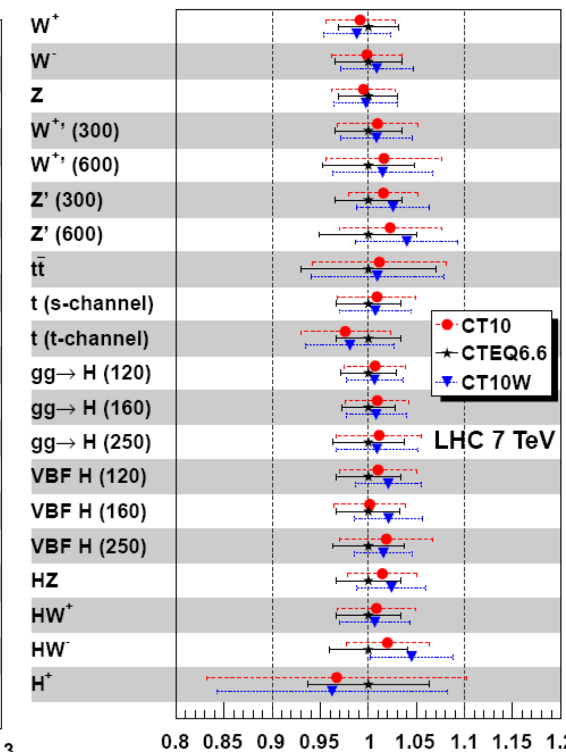


CTEQ6.6 vs. CT10, CT10W (NLO)









* CT10W: attempt to include recent D0 lepton asymmetry data in global fit
→ slightly different d/u

improved LO pdfs

- conventional wisdom is to match pQCD order of pdfs with that of MEs

- but, in practice,
  - σ_{LO} = PDFs(LO) $\otimes$ ME(LO) can be different from σ_{NLO} = PDFs(NLO) $\otimes$ ME(NLO), in both shape and normalisation
  - LO pdfs have very poor χ^2 in (LO) global fit (no surprise: NLO corrections at large and small x are significant and preferred by the data)

- momentum conservation limits how much additional glue can be added to LO partons to compensate for missing NLO pQCD corrections (e.g. to get correct evolution rate of small-x quarks)

- therefore relax momentum conservation and redo LO fit; study the impact of this on χ^2, partons and cross sections

- e.g. Thorne & Shertsnev 2007: LO* partons
  - χ^2: 3066/2235 → 2691/2235, momentum conservation: 100% → 113%

heavy quarks: charm, bottom, …

considered sufficiently massive to allow pQCD treatment: $g \to Q\overline{Q}$

distinguish two regimes:

(i) $Q^2 \sim m_H^2$ include full m_H dependence to get correct threshold behaviour

(ii) $Q^2 \gg m_H^2$ treat as ~massless partons to resum $\alpha_S^n \log^n(Q^2/m_H^2)$ via DGLAP

FFNS: OK for (i) only **ZM-VFNS:** OK for (ii) only

consistent **GM**(=general mass)-**VFNS** now available (e.g. ACOT(χ), RT, BMSN,…) which interpolates smoothly between the two regimes

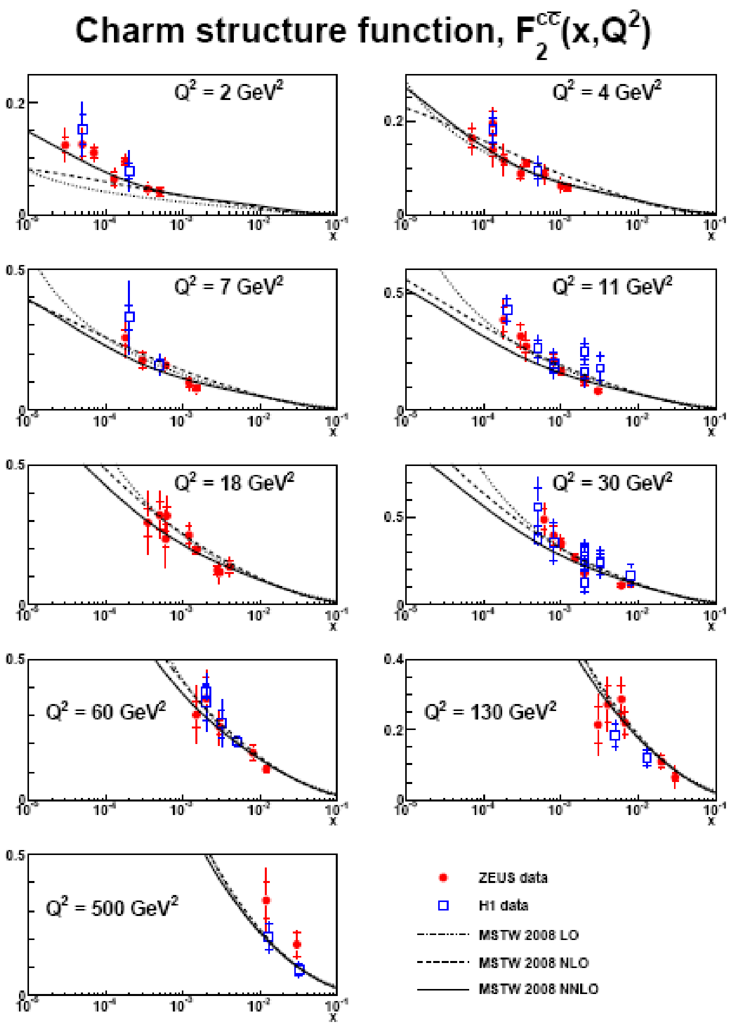
Aivazis, Collins, Olness,Tung; Roberts, Thorne; Buza, Matiounine, Smith, Migneron, van Neerven, …

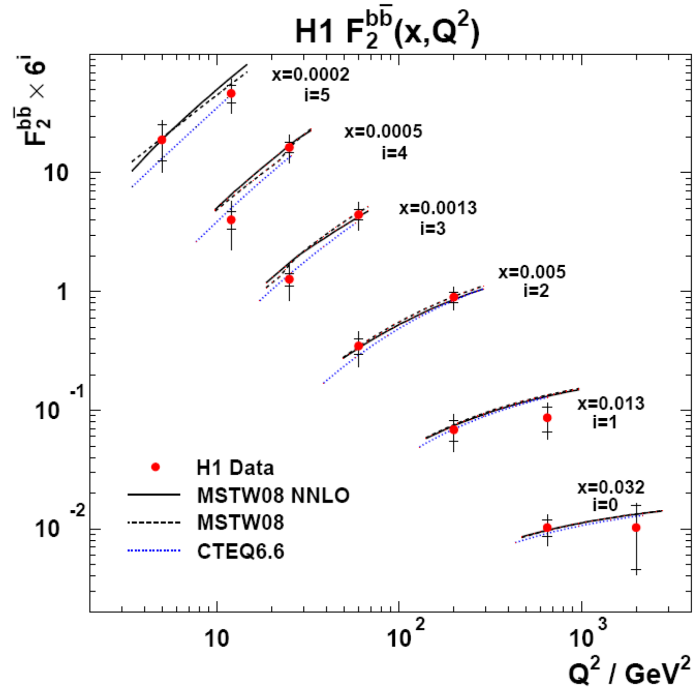
Note:

(i) the definition of these is tricky and non-unique (ambiguity in assignment of $O(m_H^2/Q^2)$ contributions), and the implementation of improved treatment (e.g. in going from MRST2004→MRST 2006 or CTEQ 6.1→6.5) can have a big effect on light partons

(ii) the *true* uncertainty on e.g. LHC predictions coming from ambiguities in the heavy quark treatment has yet to be quantified

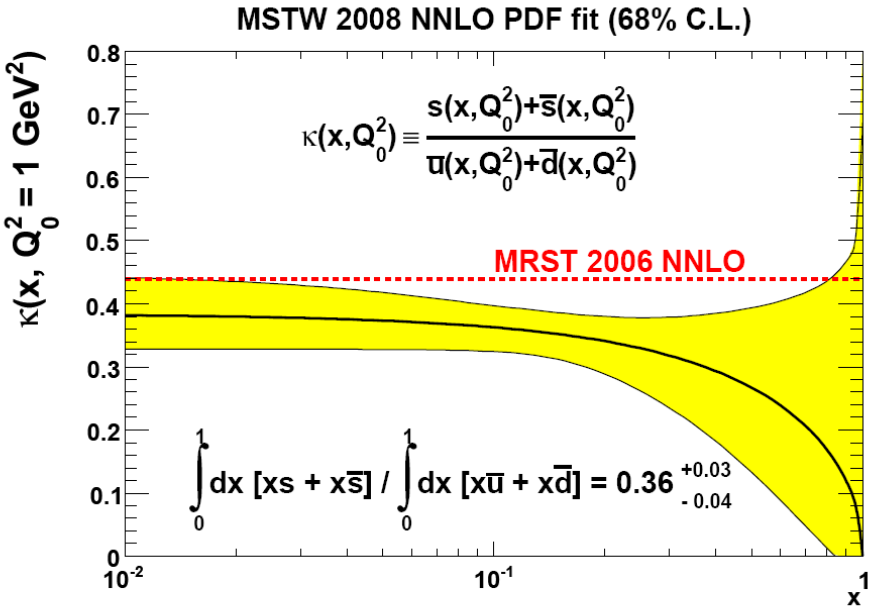
charm and bottom structure functions



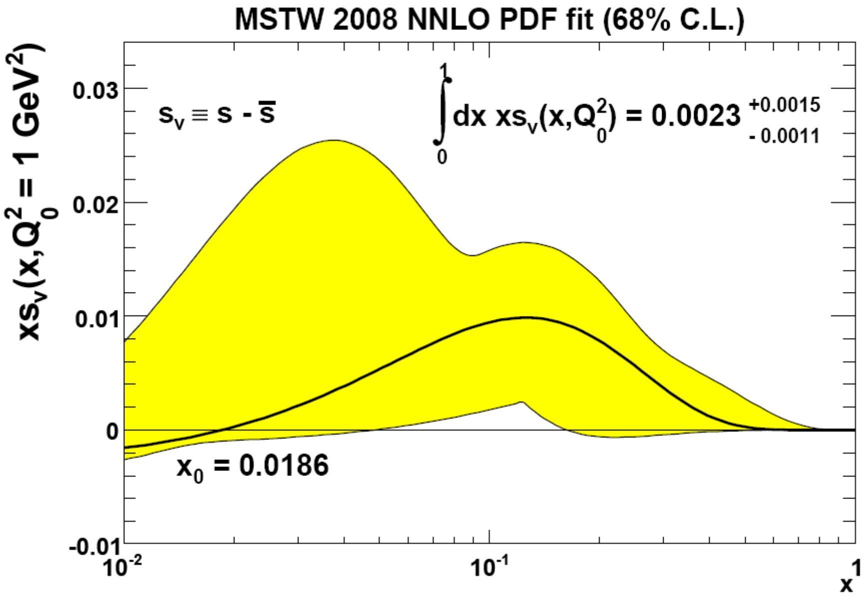


- MSTW 2008 uses *fixed* values of m_c = 1.4 GeV and m_b = 4.75 GeV in a GM-VFNS

- currently studying the sensitivity of the fit to these values, and impact on LHC cross sections



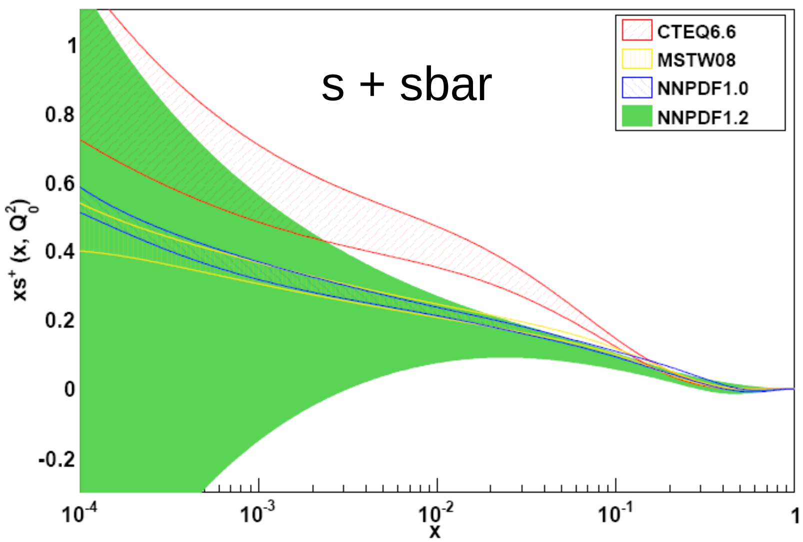
MSTW 2008 NNLO PDF fit (68% C.L.)
$\kappa(x, Q_0^2) \equiv \frac{s(x,Q_0^2)+\bar{s}(x,Q_0^2)}{\bar{u}(x,Q_0^2)+\bar{d}(x,Q_0^2)}$
MRST 2006 NNLO
$\int_0^1 dx\,[xs + x\bar{s}] \,/ \int_0^1 dx\,[x\bar{u} + x\bar{d}] = 0.36^{+0.03}_{-0.04}$
$\kappa(x,\ Q_0^2 = 1\ \mathrm{GeV}^2)$
x

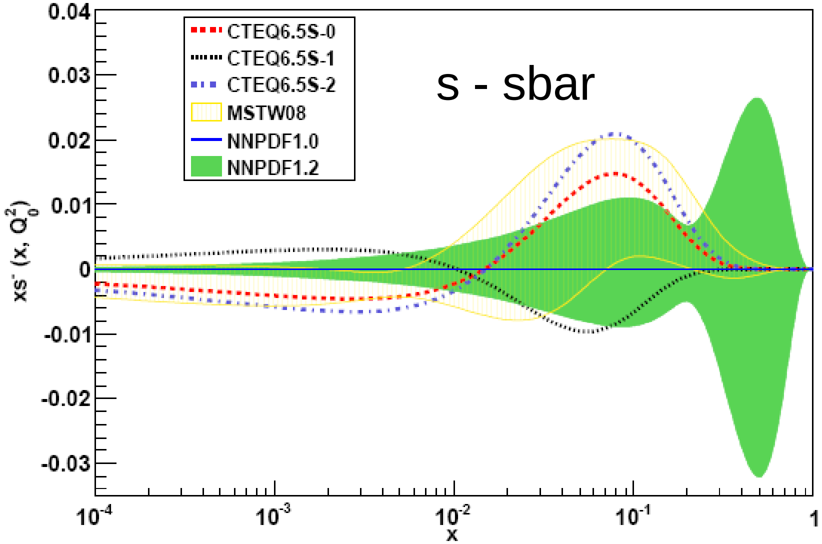


MSTW 2008 NNLO PDF fit (68% C.L.)
$s_v \equiv s - \bar{s}$
$\int_0^1 dx\ xs_v(x,Q_0^2) = 0.0023^{+0.0015}_{-0.0011}$
$x_0 = 0.0186$
$xs_v(x,Q_0^2 = 1\ \mathrm{GeV}^2)$
x

MSTW

strange quark in NNPDF





Note:

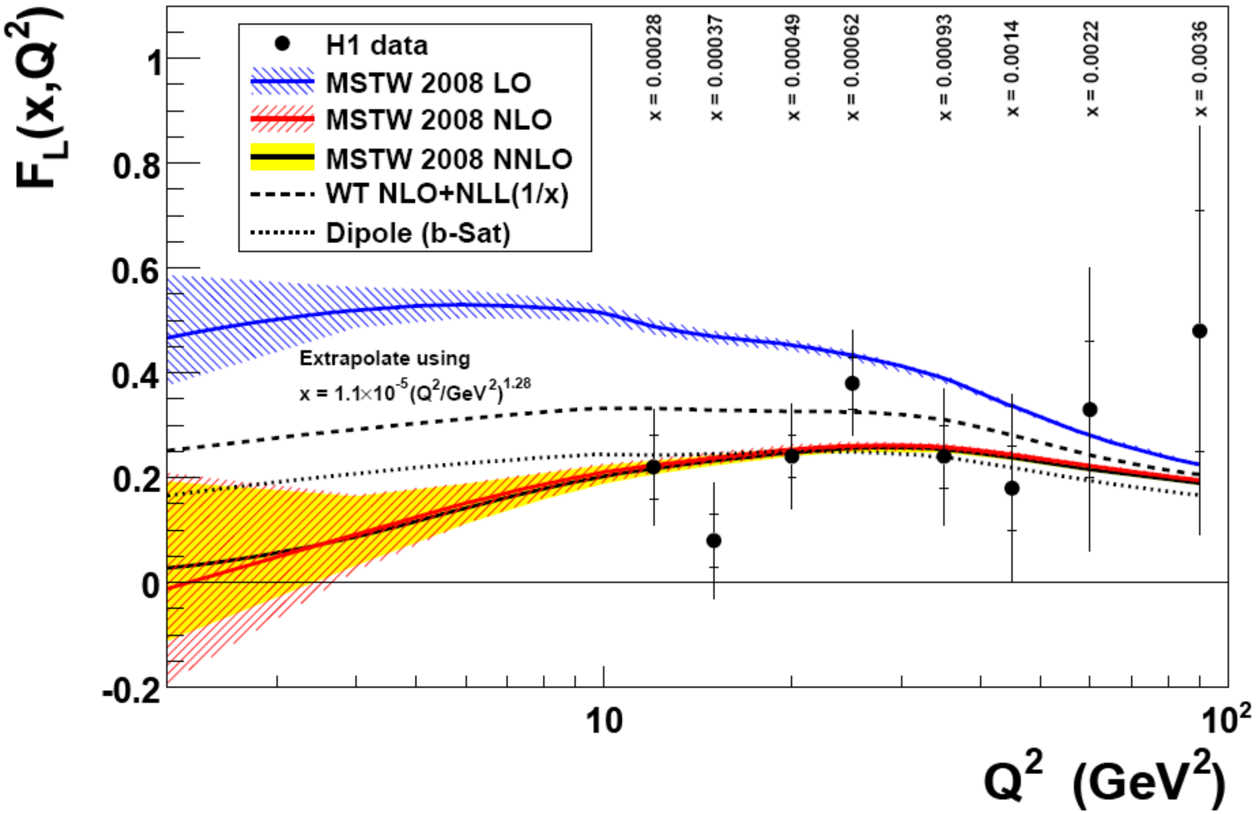
MSTW: assume u,d,s quarks have same x^δ behaviour as $x \to 0$

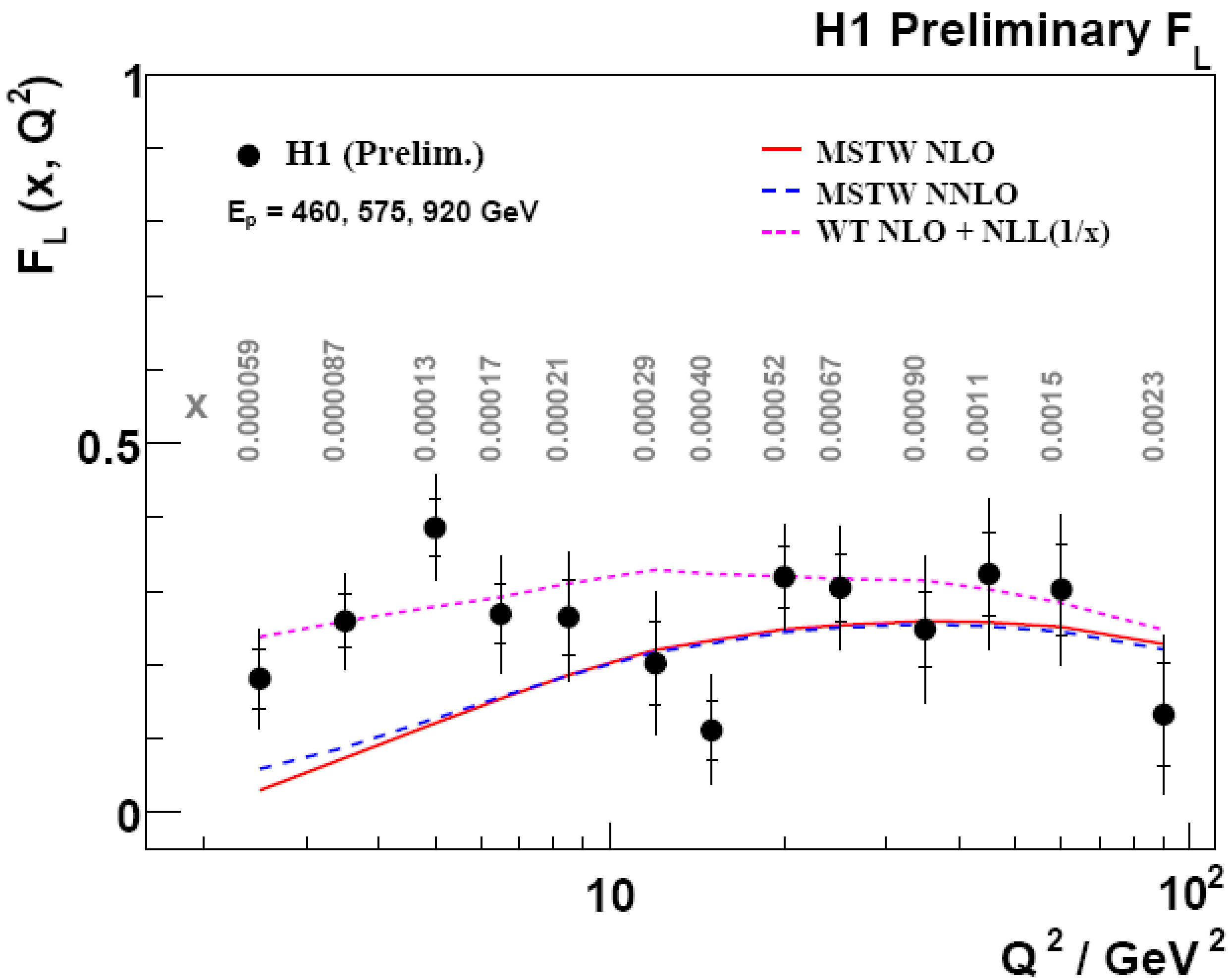
NuTeV $\sin^2\theta_W$ anomaly largely removed

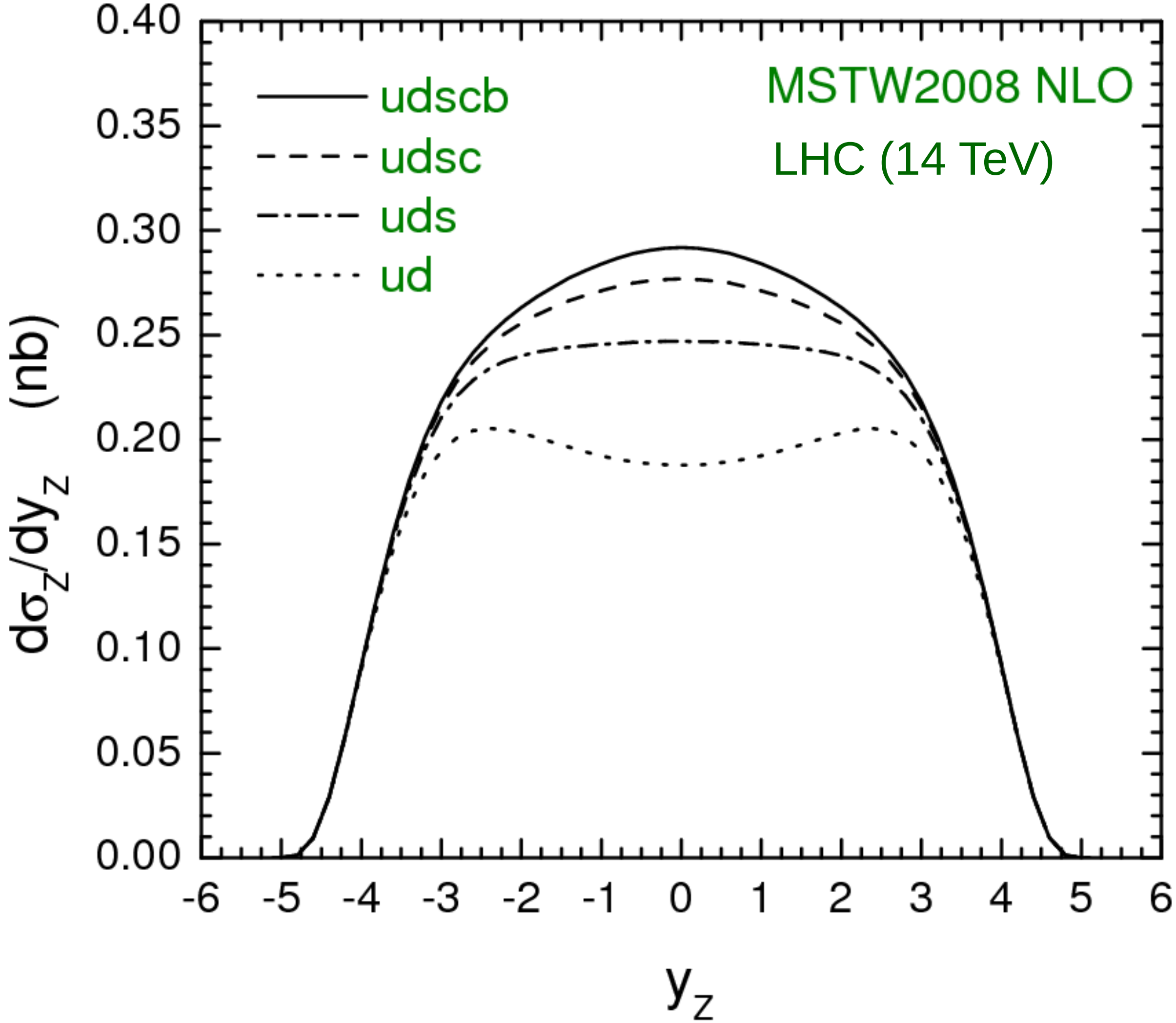
F_L

- an independent measurement of the small-x gluon
- a test of the assumptions in the DGLAP LT pQCD analysis of small-x F_2
- higher–order ln(1/x) and higher-twist contributions could be important

$$\frac{\partial F_2}{\partial \ln Q^2} \simeq \alpha_S P^{qg} \otimes g + \ldots$$
$$F_L \simeq \alpha_S C_{Lg} \otimes g + \ldots$$




H1 Preliminary F_L
F_L (x, Q^2)
1
0.5
0
H1 (Prelim.)
E_p = 460, 575, 920 GeV
MSTW NLO
MSTW NNLO
WT NLO + NLL(1/x)
x
0.000059
0.000087
0.00013
0.00017
0.00021
0.00029
0.00040
0.00052
0.00067
0.00090
0.0011
0.0015
0.0023
10
10^2
Q^2 / GeV^2



0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
udscb
udsc
uds
ud
MSTW2008 NLO
LHC (14 TeV)
dσZ/dyZ (nb)
yZ