Top production at the LHC: a PDF perspective from the TEA group (Tung et al)

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Parton distribution functions and global fits

- Calculation of production cross sections at the LHC relies upon knowledge of pdf's in the relevant kinematic region
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- Two major groups that provide semi-regular updates to parton distributions when new data/theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004 ->MSTW2008
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5 ->CTEQ6.6->CT09
  - now also HERA and NNPDF

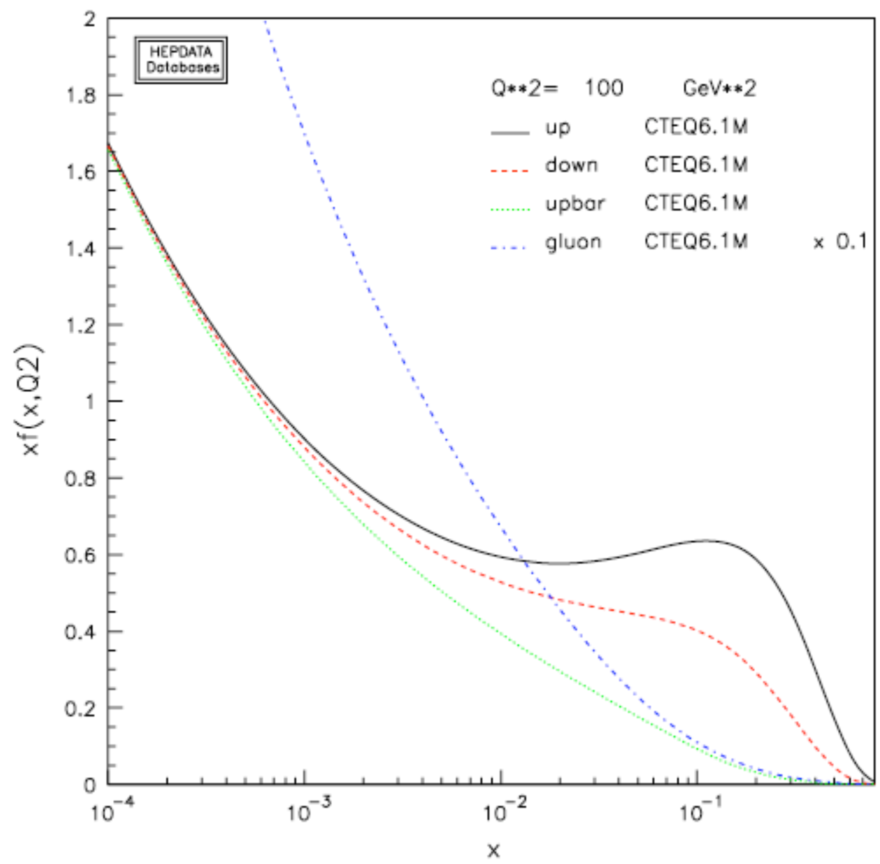
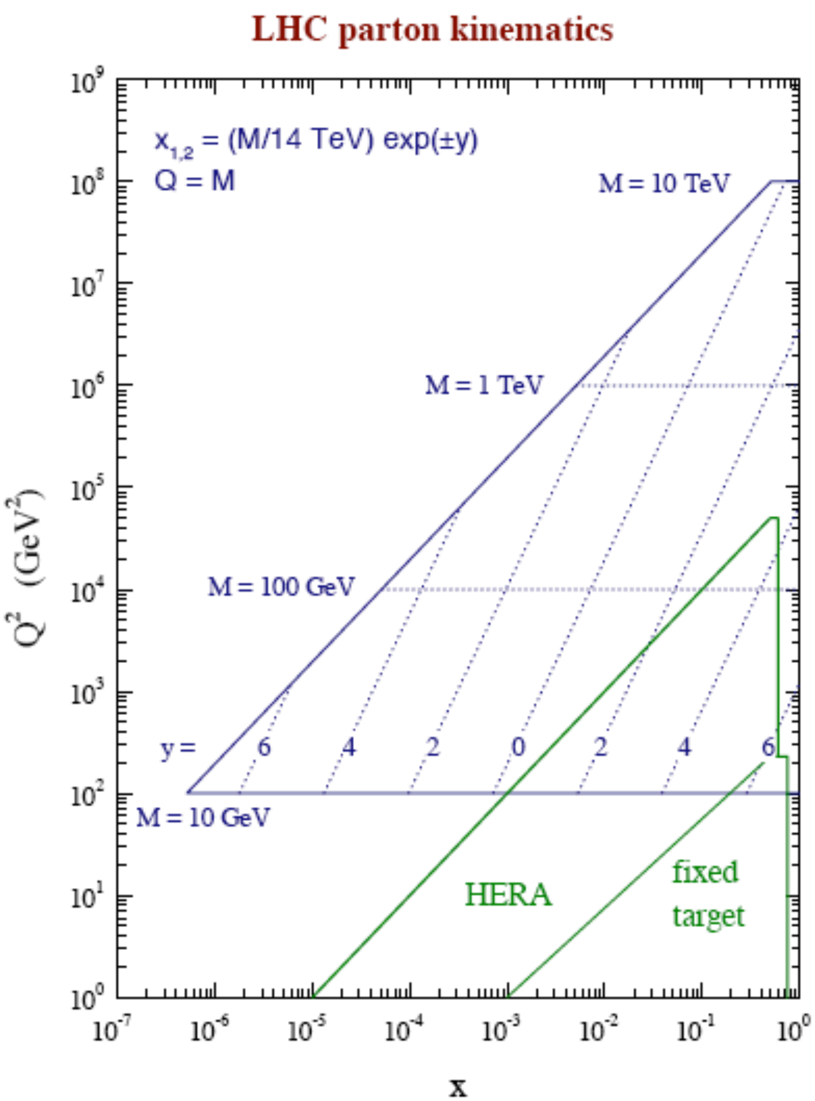


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

Cross sections at the LHC

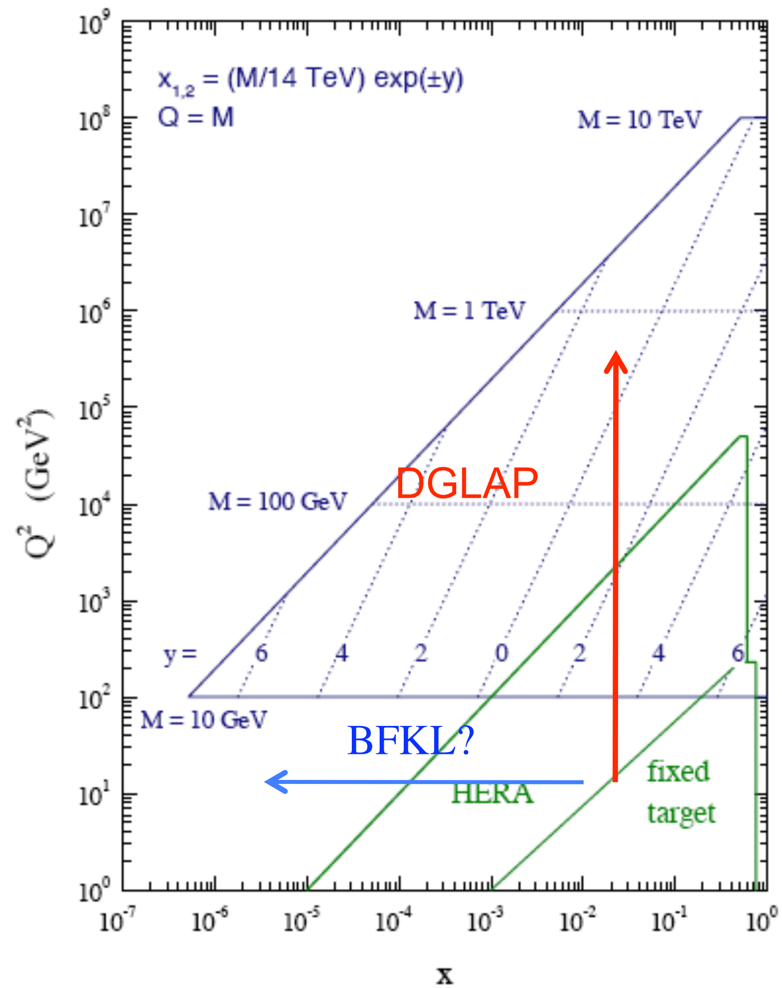
- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



Cross sections at the LHC

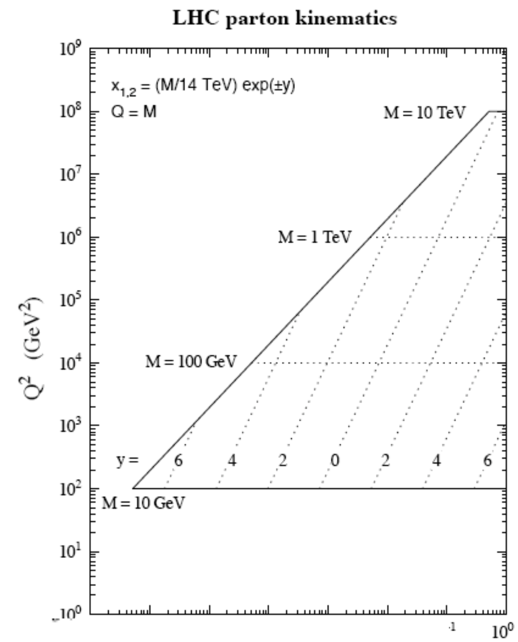
- Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC
- We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2
- We can use the DGLAP equations to evolve to the relevant x and Q^2 range, but…
  - we're somewhat blind in extrapolating to lower x values than present in the HERA data, so uncertainty may be larger than currently estimated
  - we're assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2 \left(q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2]\right)\right]$$



Parton kinematics at the LHC

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity (a la EHLQ)
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element



$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\,[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)]\ . \tag{1}$$

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

this is from the CHS review paper

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij} \tag{2}$$

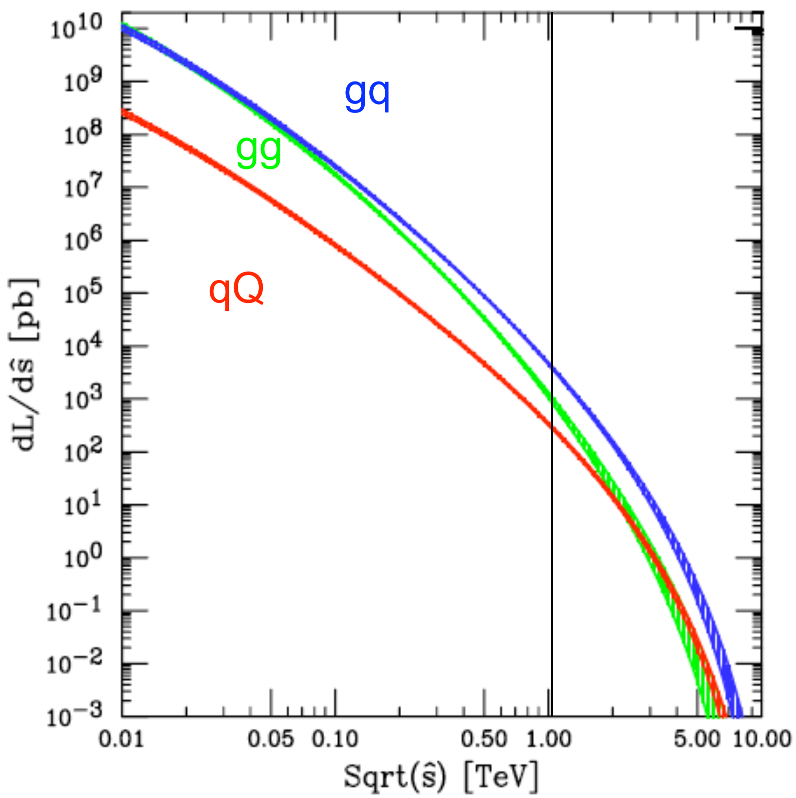
can then be written as

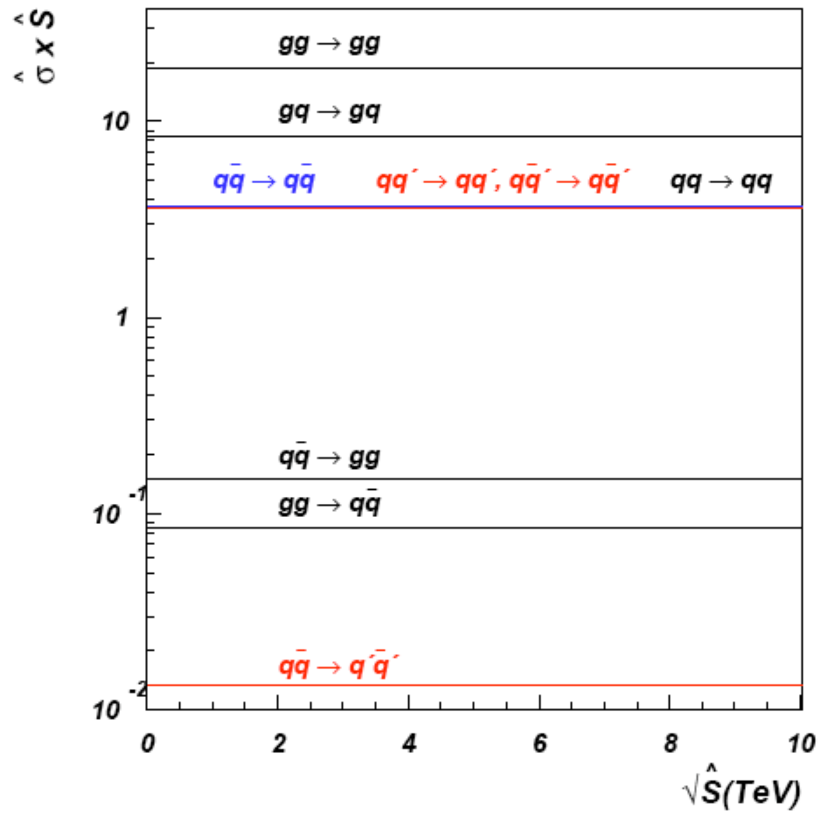
$$\sigma = \sum_{i,j} \int \left(\frac{d\hat{s}}{\hat{s}}\,dy\right) \left(\frac{dL_{ij}}{d\hat{s}\,dy}\right) (\hat{s}\,\hat{\sigma}_{ij})\ . \tag{3}$$

Cross section estimates

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$, we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb





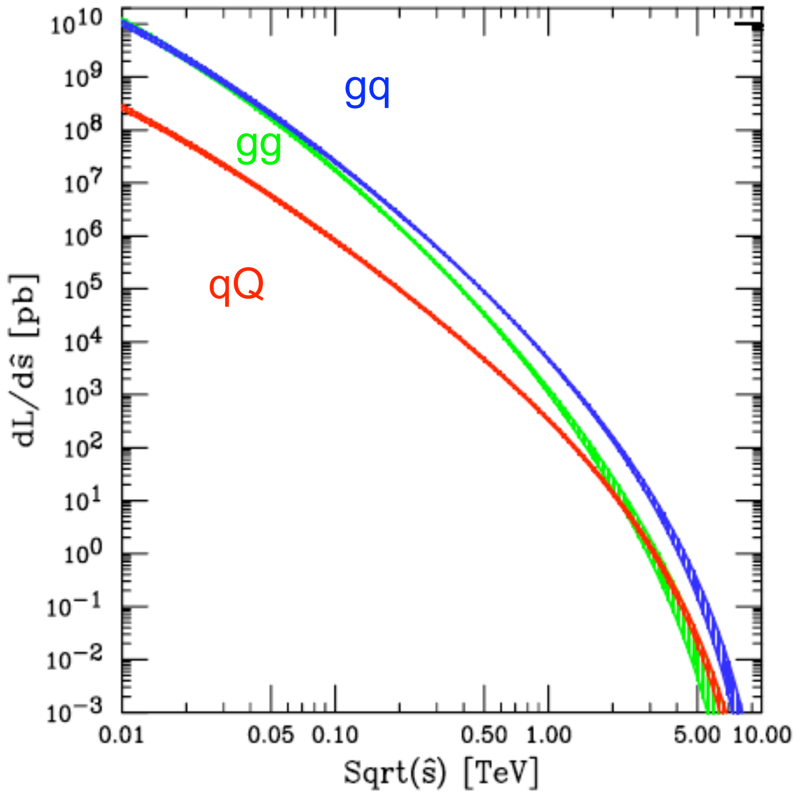
for p_T=0.1* sqrt(s-hat)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

Heavy quark production

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

threshold effects evident



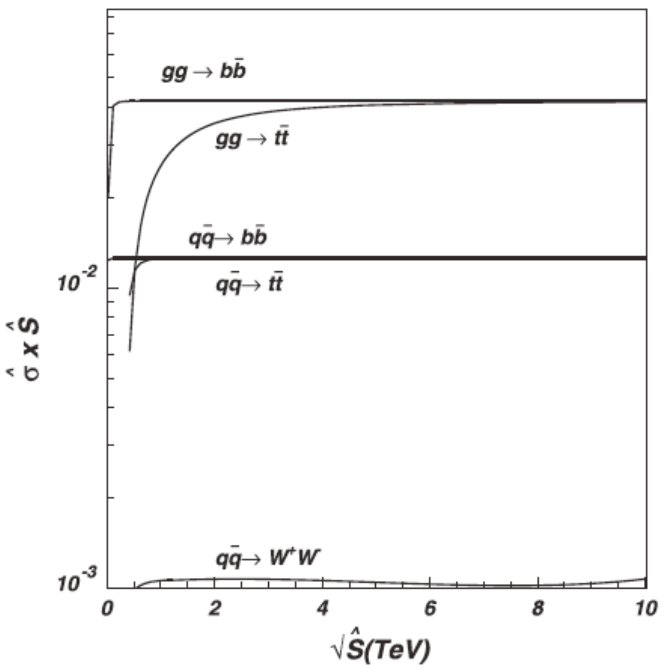
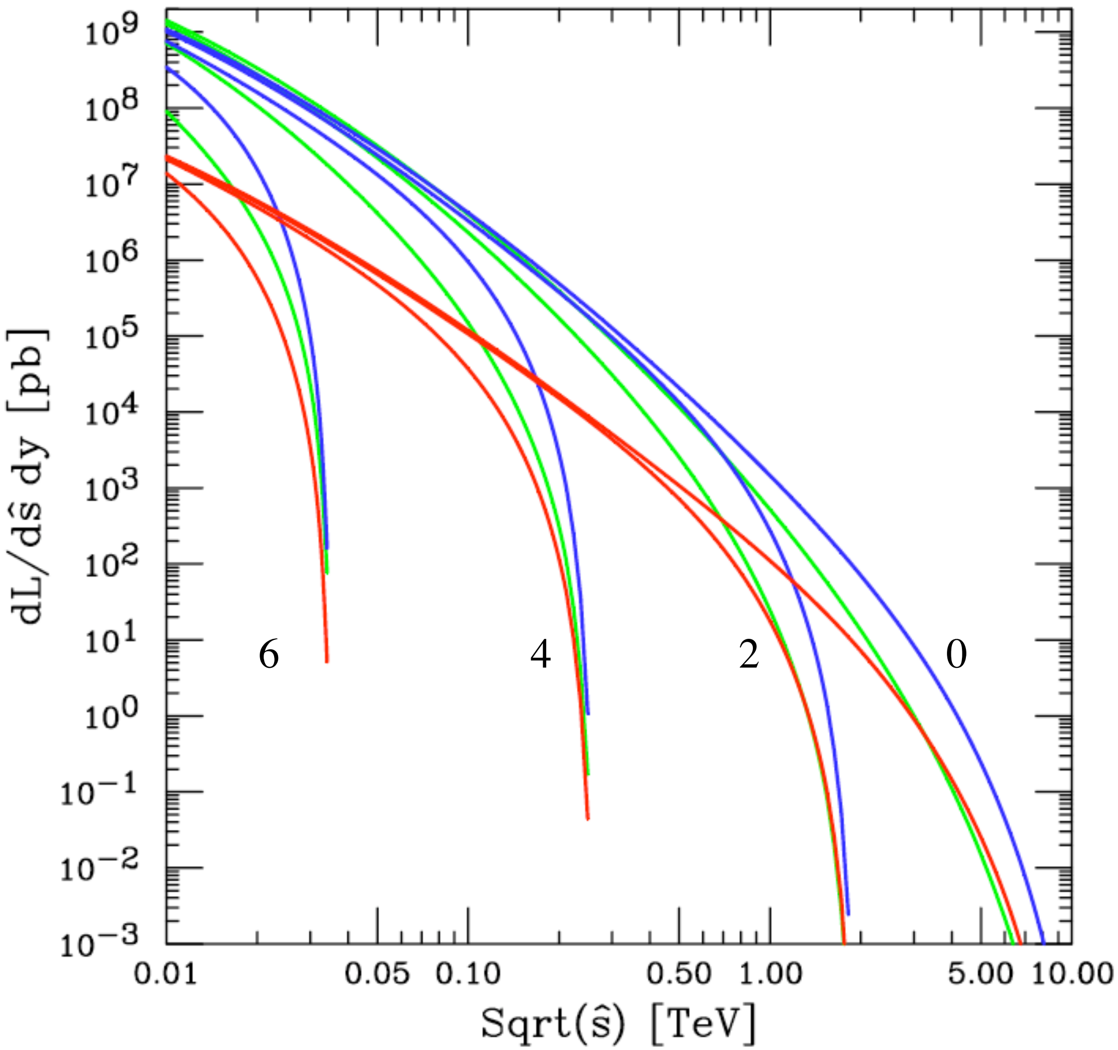


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

√S(TeV)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

PDF luminosities as a function of y



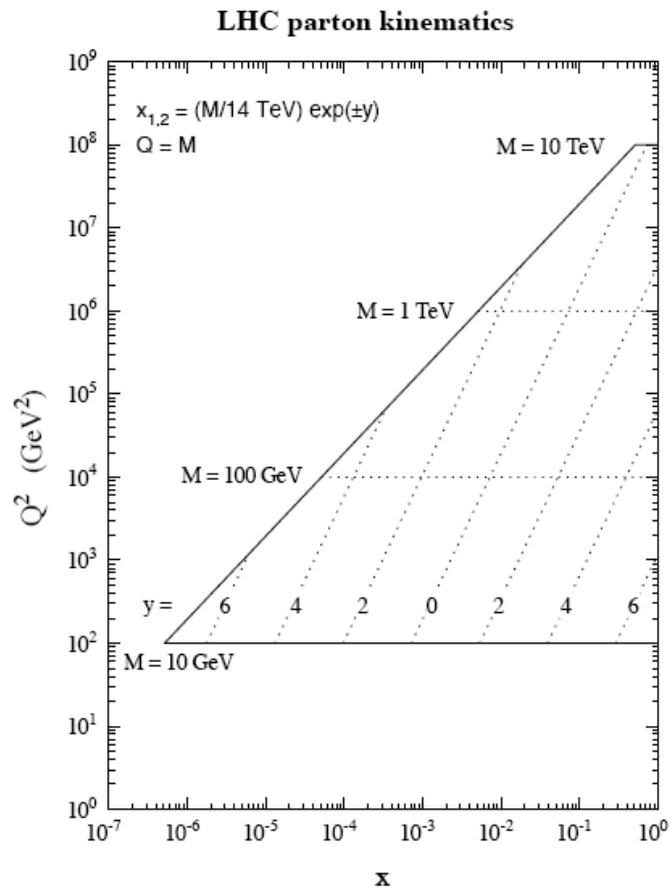


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

PDF uncertainties at the LHC

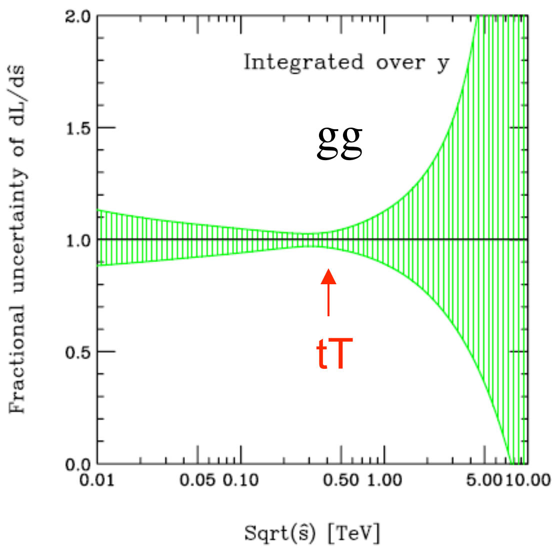


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small

Need similar level of precision in theory calculations

It will be a while, i.e. not in the first fb^{-1}, before the LHC data starts to constrain pdf's

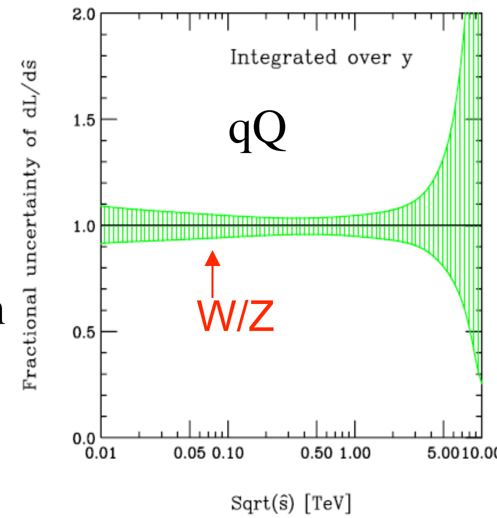


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

NBIII: tT uncertainty is of the same order as W/Z production

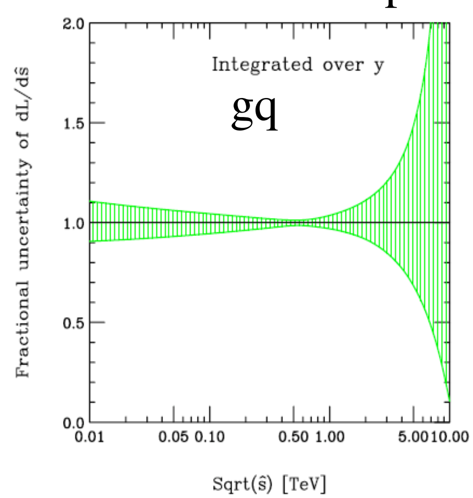


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NB I: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties,i.e. no theory uncertainties

NB II: the pdf uncertainties for W/Z cross sections are not the smallest

Ratios:LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. chargino pair production) have small enchancements
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC
- W+4 jets is a background to tT production both at the Tevatron and at the LHC
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100
    - but increased W + jets background means that a higher jet cut is necessary at the LHC
    - known known: jet cuts have to be higher at LHC than at Tevatron

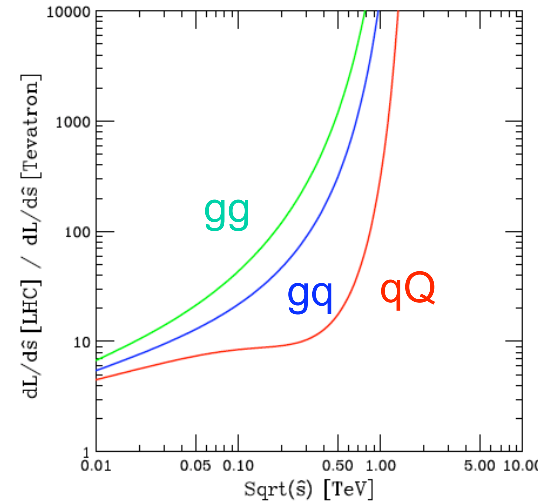


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

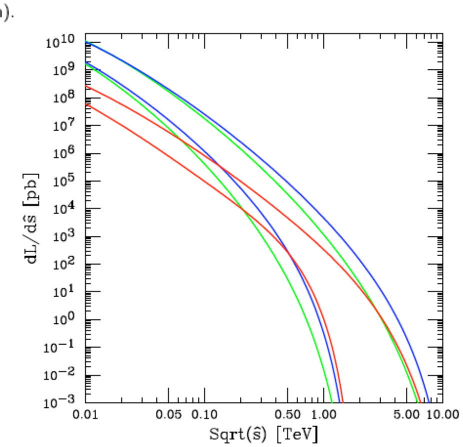


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

…but wait, we're not running at 14 TeV in 2009-2010

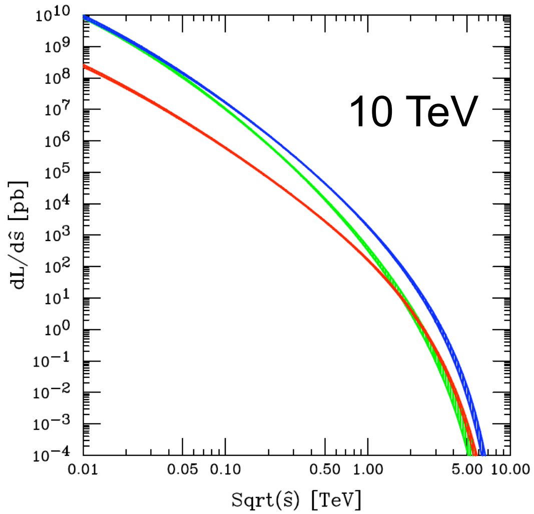


Figure 2: Luminosities integrated over y: LHC(pp) at $\sqrt{s} = 10\,\mathrm{TeV}$.
Green = gg, Blue = $gq + g\bar{q}$, Red = $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

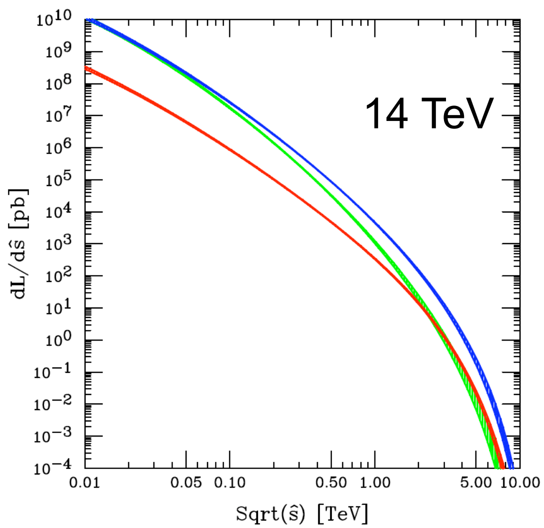


Figure 1: Luminosities integrated over y: LHC(pp) at $\sqrt{s} = 14\,\mathrm{TeV}$.
Green = $g\,g$, Blue = $gq + g\bar{q}$, Red = $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

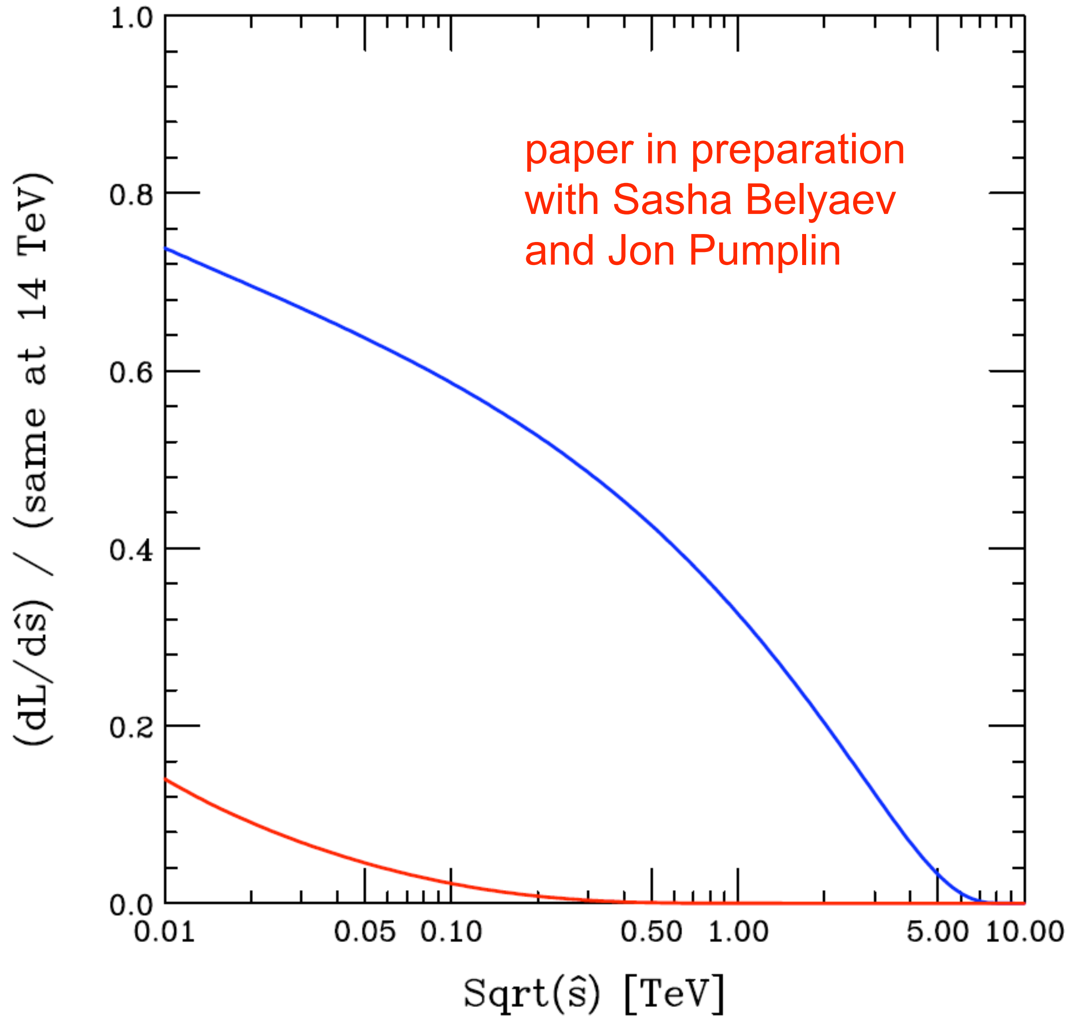


Figure 7: gg luminosity integrated over y:
Blue = (pp at 10 TeV) / (pp at 14 TeV);
Red = ($p\bar{p}$ at 1.96 TeV) / (pp at 14 TeV).

Look at ratios of pdf's at 1.96 and 10 TeV: from Tevatron perspective

- The plan is to run the LHC in 2009-2010 accumulating at least 200 pb^{-1}
- Take a discovery region (~1 TeV, say for squark pair production)
- The LHC is a factor of 50 more efficient at producing a 1 TeV object through a qQ initial state…so it would take 10 fb^{-1} at the Tevatron to equal the 200 pb^{-1} at the LHC
- …which the Tevatron will probably get (per expt)
- …with much better understood detectors and much lower backgrounds
- So don't count the Tevatron out just yet for discovery physics

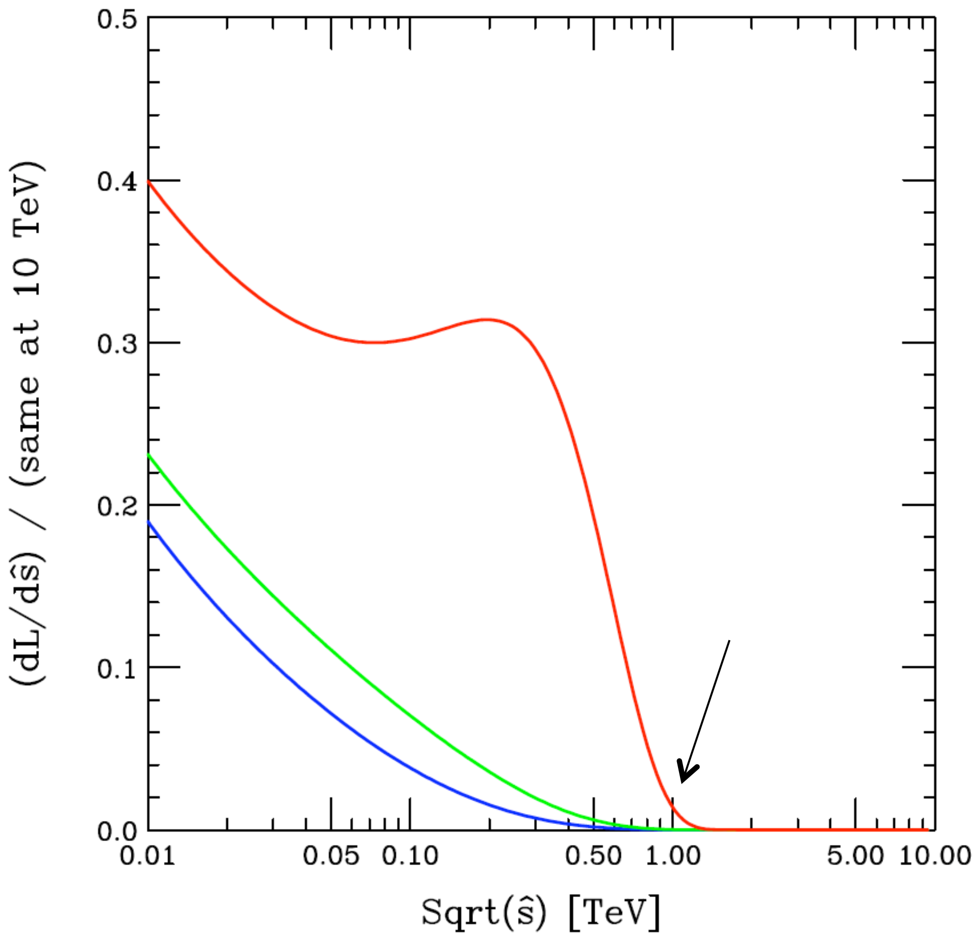


Figure 13: ($p\bar{p}$ at 1.96 TeV) / (pp at 10 TeV). luminosity integrated over y. Blue: gg; Green: $gq + g\bar{q}$; Red: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

Now from the LHC perspective

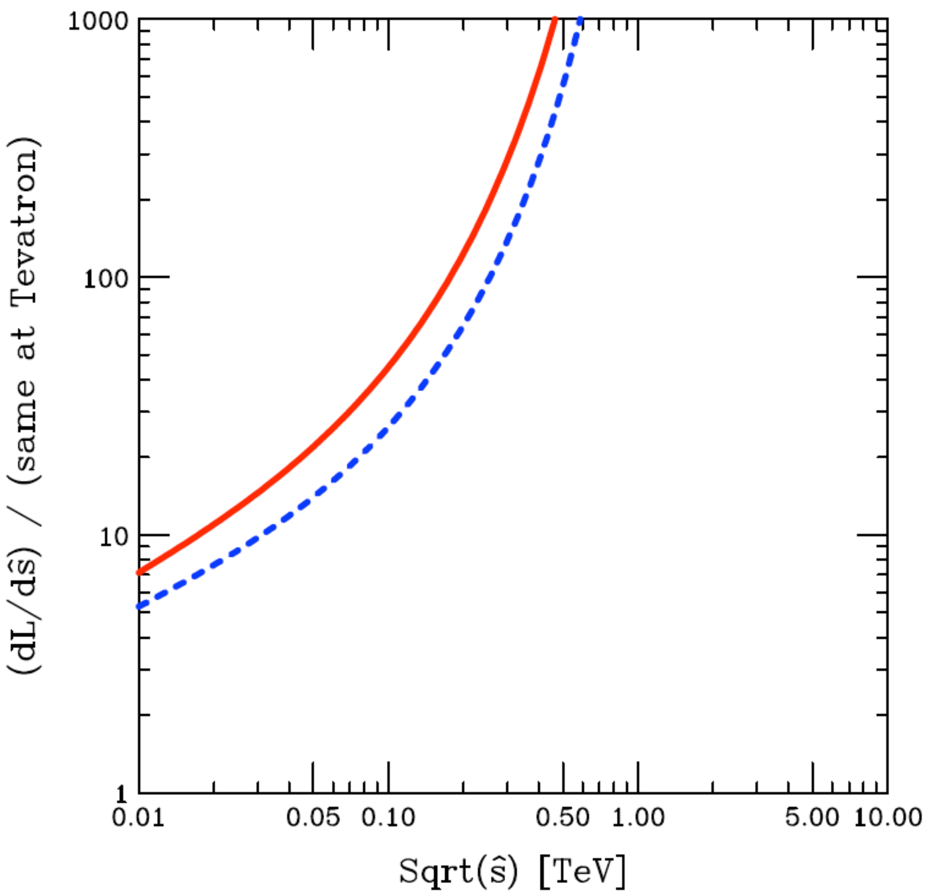


Figure 1: gg luminosity integrated over y:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

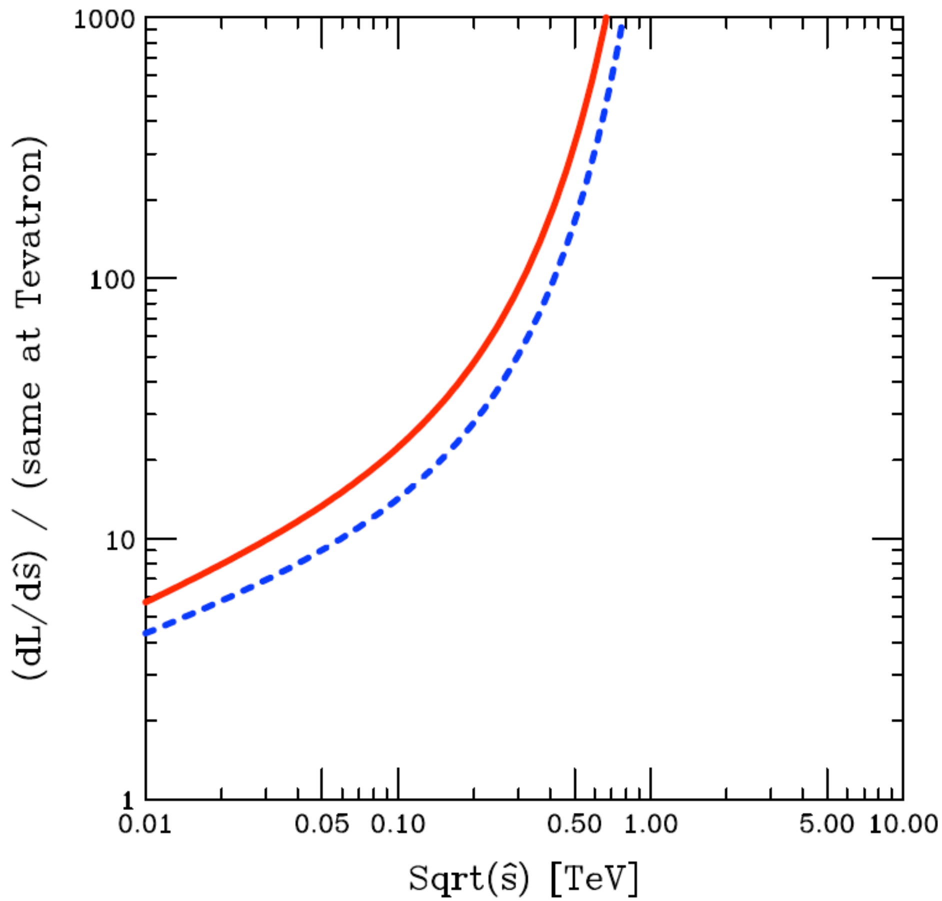


Figure 2: $gq + g\bar{q}$ luminosity integrated over y:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

LHC perspective, continued

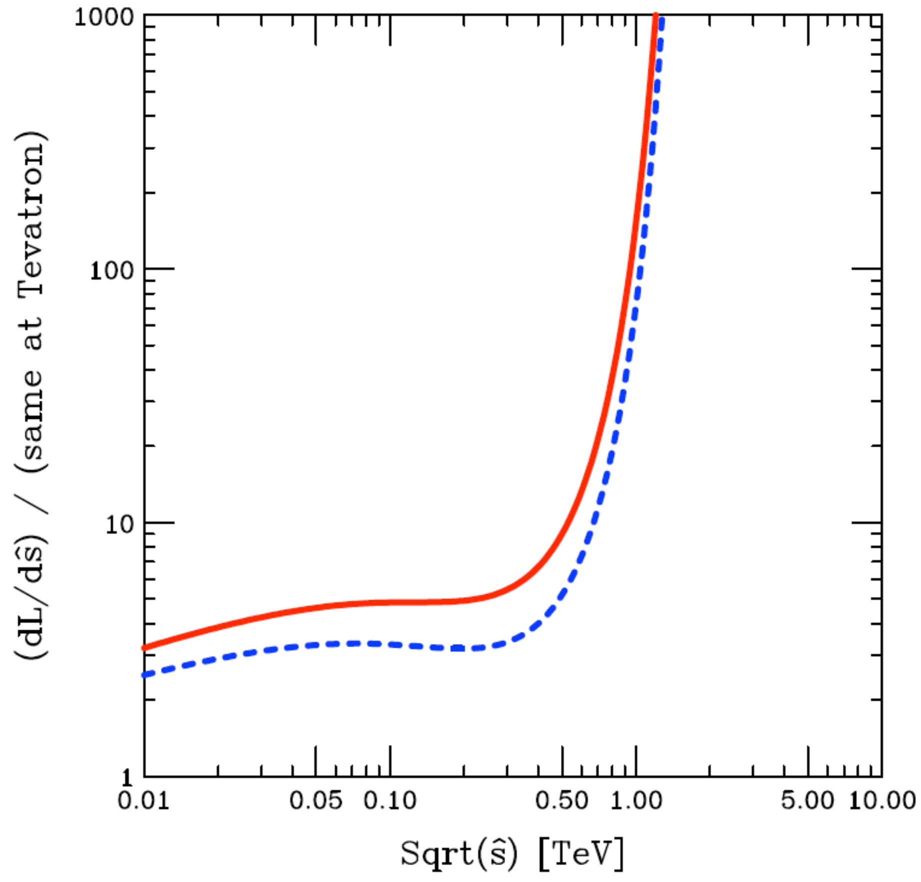


Figure 3: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

The LHC will be a very *jetty* place

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{W+3\ jets} > \sigma_{W+2\ jets}$

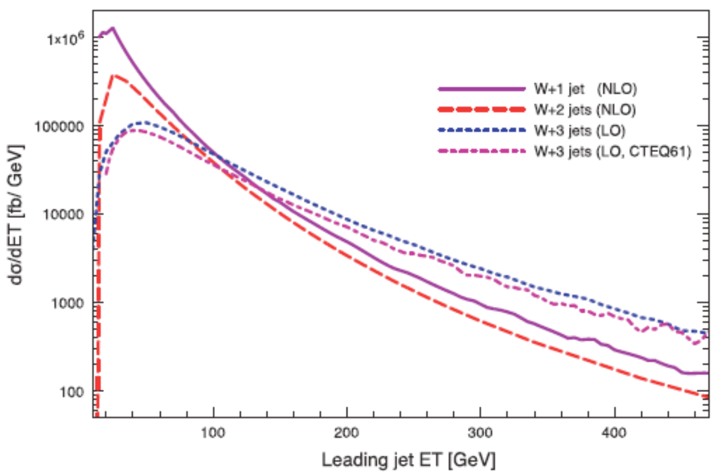


Figure 91. Predictions for the production of $W+\geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- also can be understood from point-of-view of Sudakov form factors

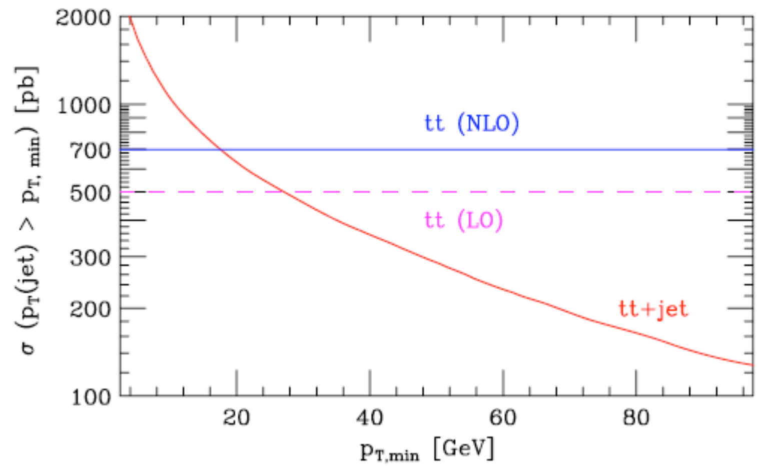


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

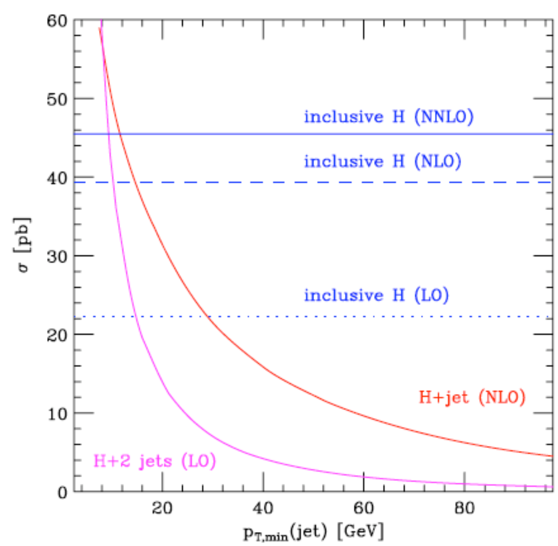


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

Aside: Sudakov form factors

- Sudakov form factors form the basis for both resummation and parton showering
- We can write an expression for the Sudakov form factor of an initial state parton in the form below, where *t* is the hard scale, to is the cutoff scale and *P(z)* is the splitting function

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int \frac{dz}{z} \frac{\alpha_S}{2\pi} P(z) \frac{f(x/z,t)}{f(x,t)}\right]$$

- Similar form for the final state but without the pdf weighting
- Sudakov form factor resums all effects of soft and collinear gluon emission, but does not include non-singular regions that are due to large energy, wide angle gluon emission
- Gives the probability **not** to radiate a gluon greater than some energy

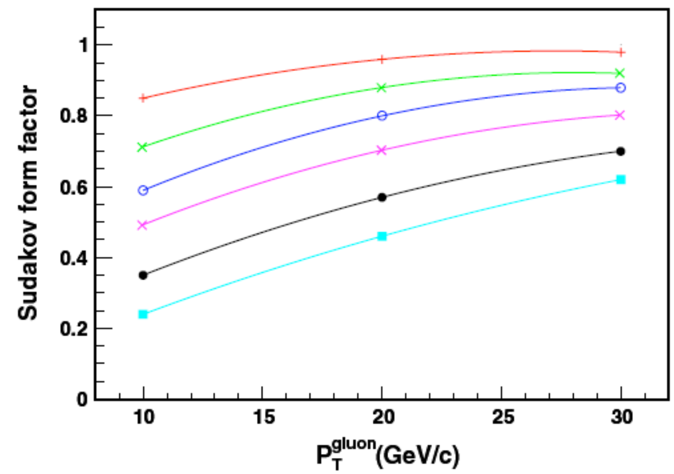


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

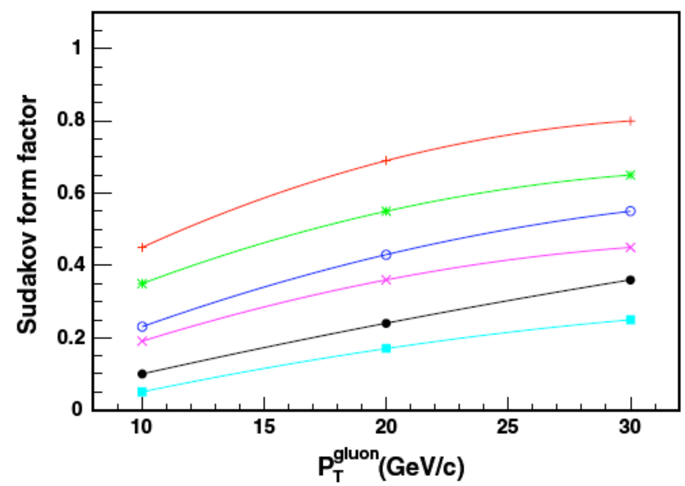
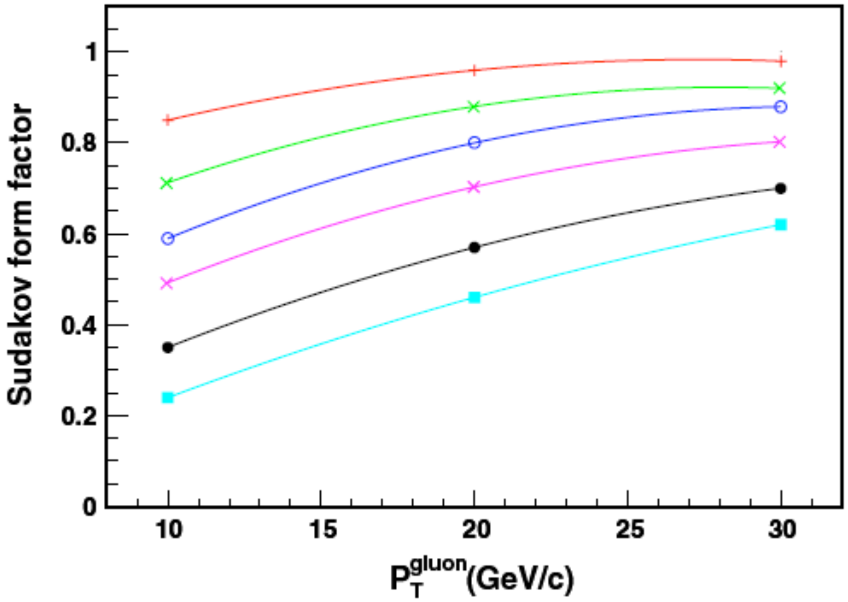


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Aside: Sudakov form factors



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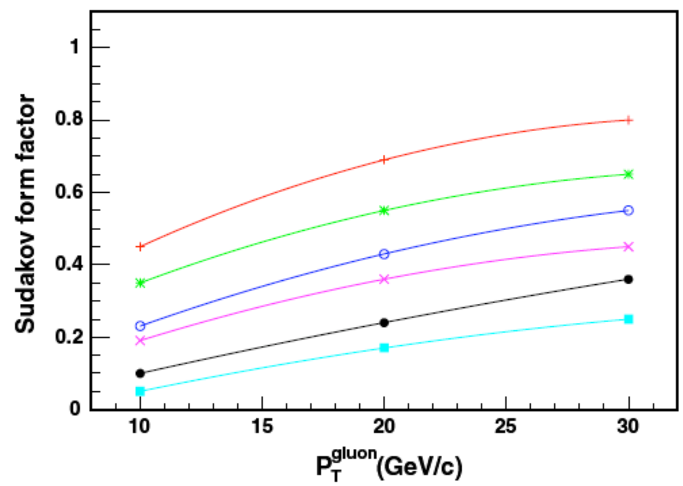


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Sudakov form factors for tT

- tT production at the LHC dominated by gg at x values factor of 7 lower than Tevatron
- So dominant Sudakov form factor goes from
- to

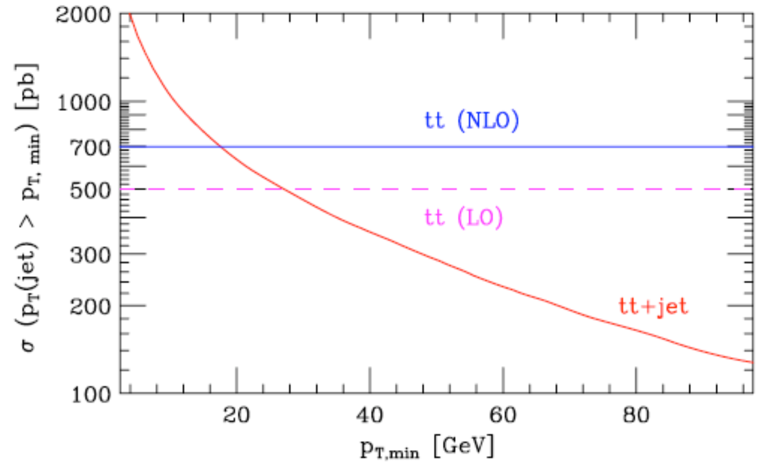


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

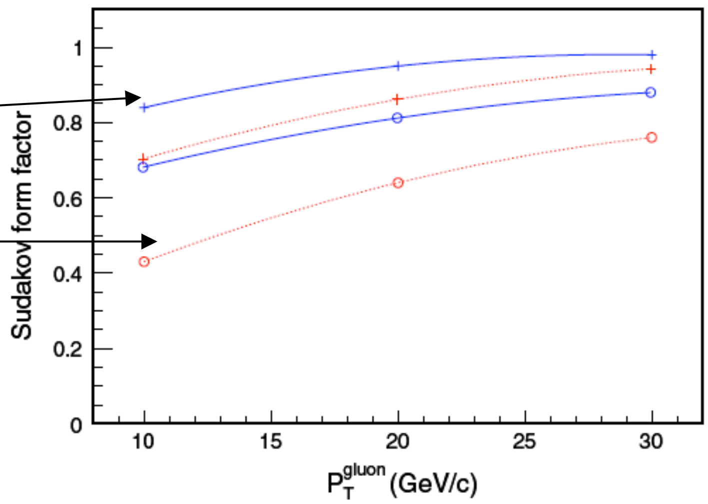


Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton x values of 0.3 (crosses) and 0.03 (open circles).

Sudakov form factors: quarks and gluons

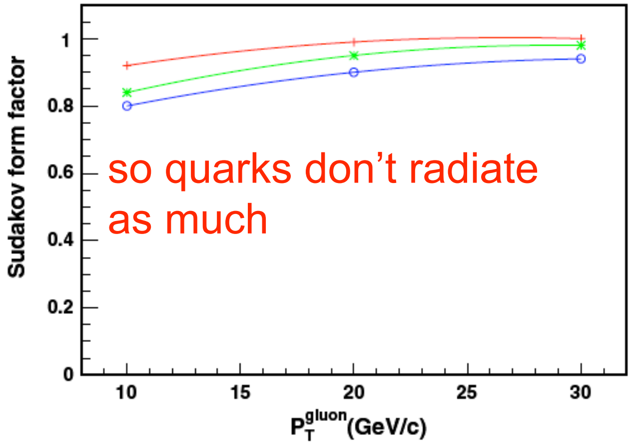


Figure 23. The Sudakov form factors for initial-state quarks at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

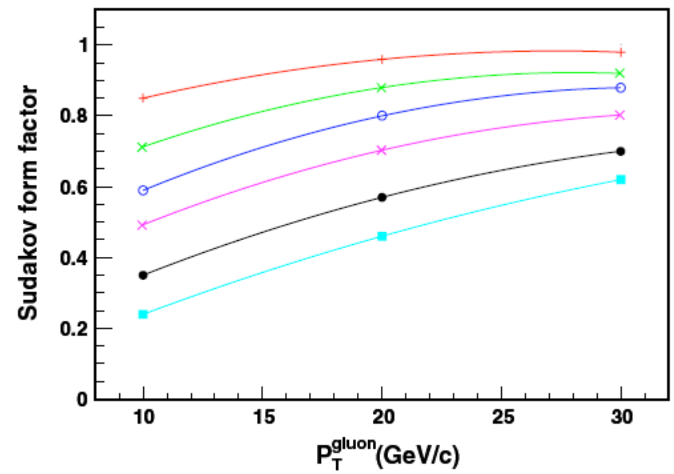


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

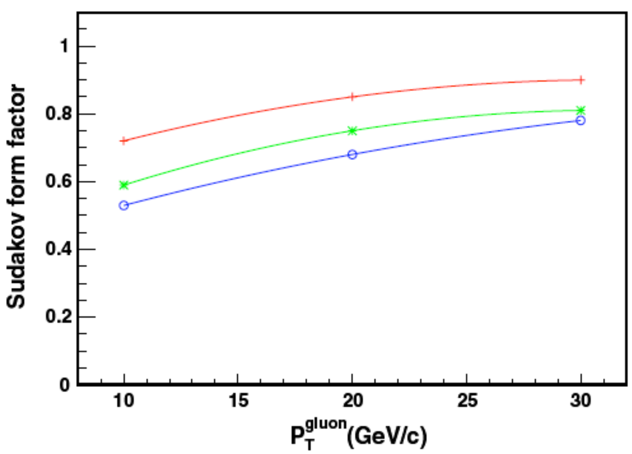


Figure 24. The Sudakov form factors for initial-state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

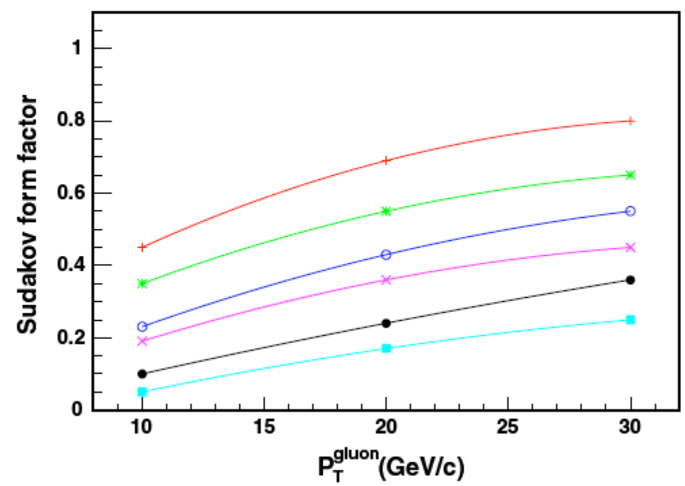


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Sudakov form factors: quarks and gluons

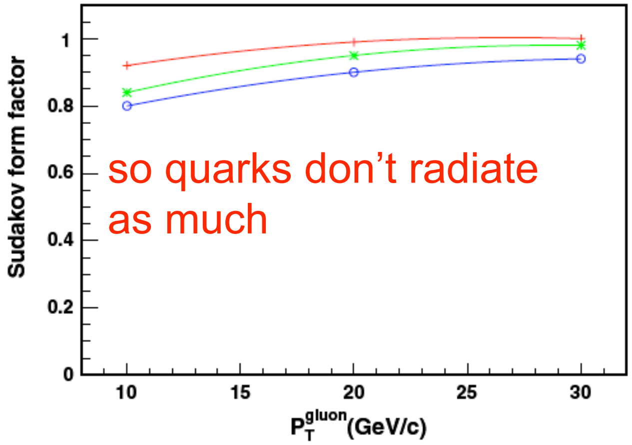


Figure 23. The Sudakov form factors for initial-state quarks at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

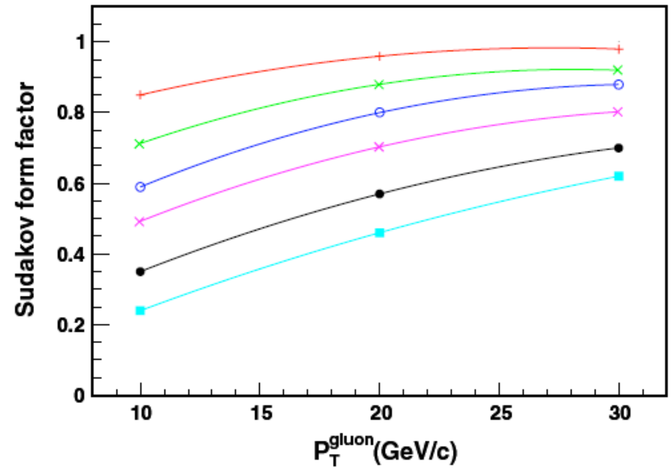


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

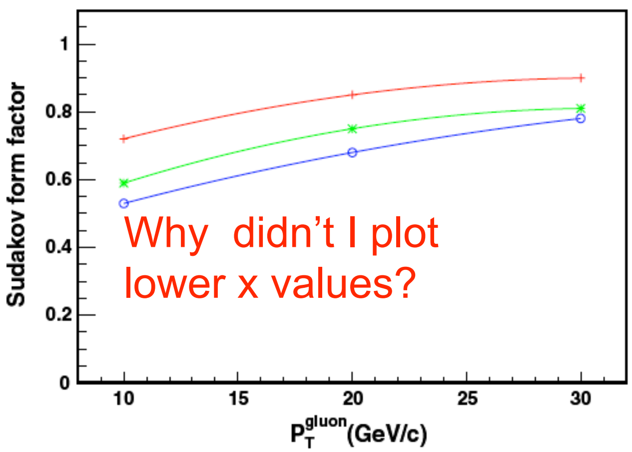


Figure 24. The Sudakov form factors for initial-state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

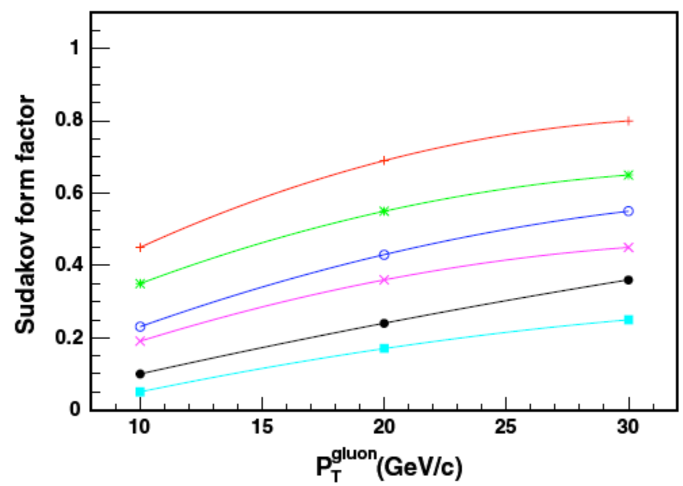


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Precision benchmarks:
W/Z cross sections at the LHC

- CTEQ6.1 and MRST NLO predictions in good agreement with each other
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

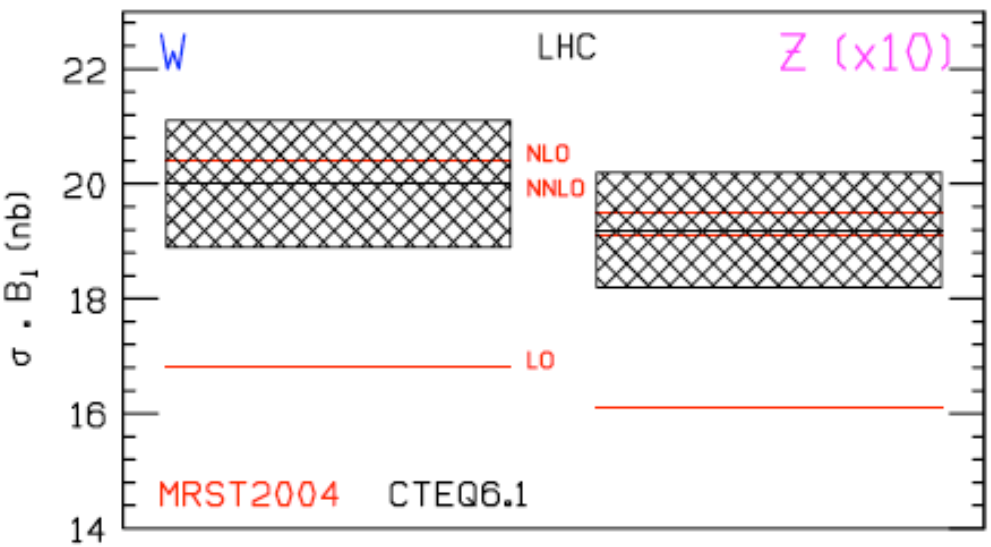


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

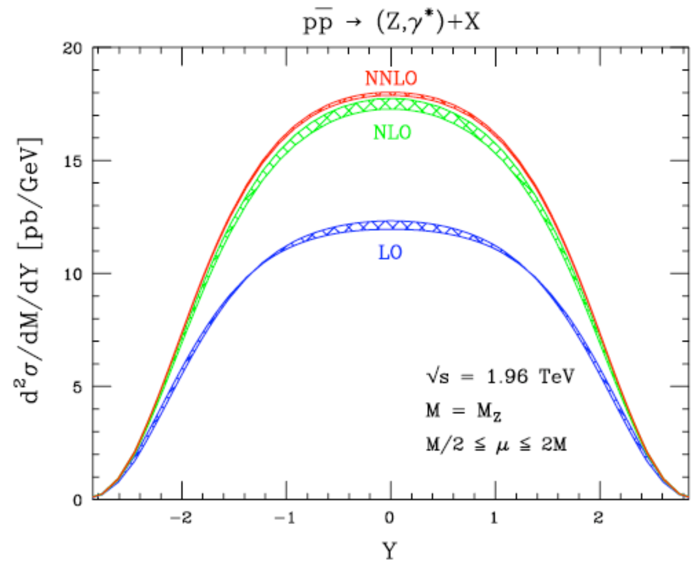
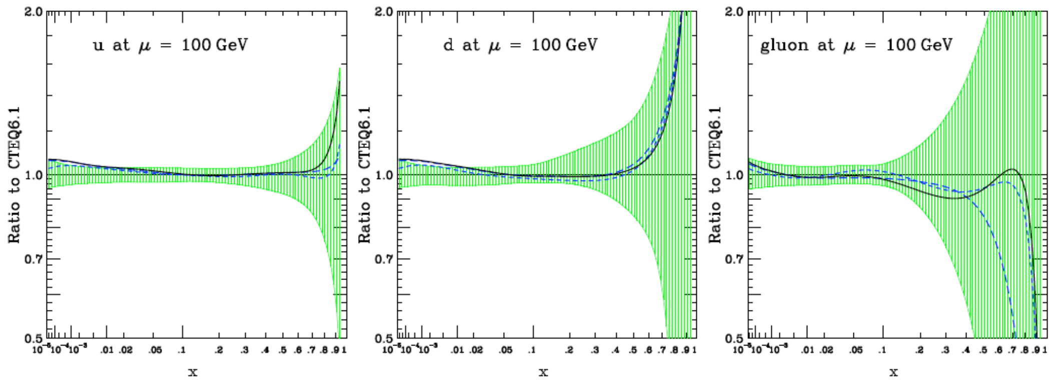


Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

Heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With newer sets of pdf's (>=CTEQ6.5), heavy quark mass effects consistently taken into account in global fitting cross sections and in pdf evolution
- In most cases, resulting pdf's are within CTEQ6.1 pdf error bands
- But not at low x (in range of W and Z production at LHC)
- Heavy quark mass effects only appreciable near threshold
    - ex: prediction for F_2 at low x,Q at HERA smaller if mass of c,b quarks taken into account
    - thus, quark pdf's have to be bigger in this region to have an equivalent fit to the HERA data



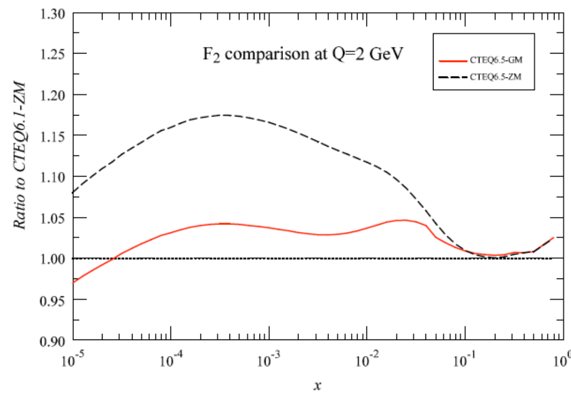
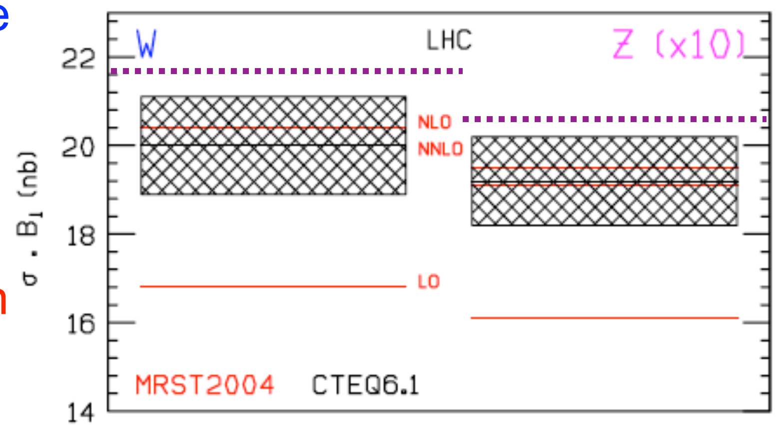


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

implications for LHC phenomenology

CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- Cross sections for W/Z increase by 7-8%
  - now CTEQ and MRST2004 in disagreement, not a good sign for an important LHC benchmark
  - and relative uncertainties of W/Z increase
  - although individual uncertainties of W and Z decrease somewhat
- Two new free parameters in fit dealing with strangeness degrees of freedom so now have 44 error pdf's rather than 40



CTEQ6.5(6)

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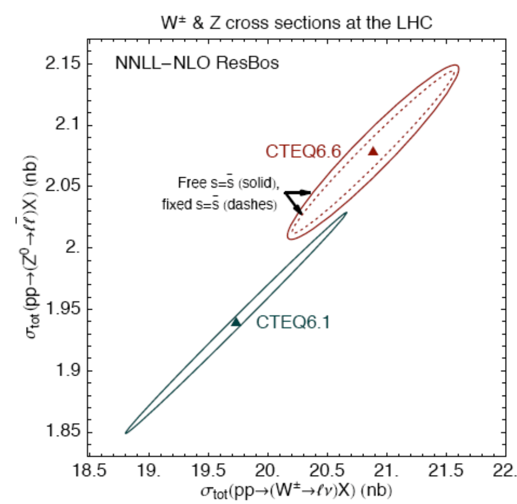
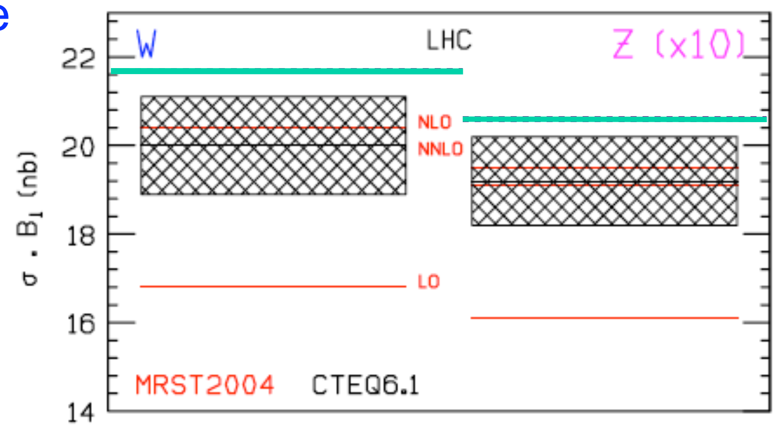


Note importance of strange quark uncertainty for ratio

Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

…but

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- …but MSTW2008 also has increased W/Z cross sections at the LHC
  - now CTEQ6.6 and MSTW2008 in better agreement



CTEQ6.5(6)

MSTW08

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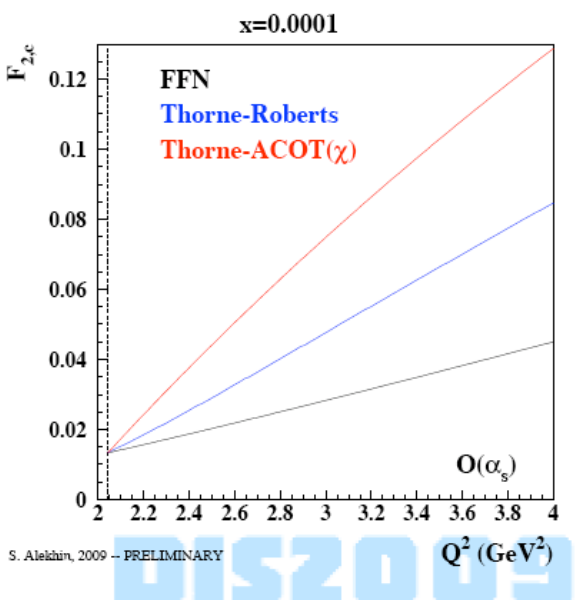


Alekhin and Blumlein

PDF correlations

- Consider a cross section X(a), a function of the Hessian eigenvectors
- i^{th} component of gradient of X is

$$\frac{\partial X}{\partial a_i} \equiv \partial_i X = \frac{1}{2}(X_i^{(+)} - X_i^{(-)})$$

- Now take 2 cross sections X and Y
  - or one or both can be pdf's
- Consider the projection of gradients of X and Y onto a circle of radius 1 in the plane of the gradients in the parton parameter space
- The circle maps onto an ellipse in the XY plane
- The angle ϕ between the gradients of X and Y is given by

$$\cos\varphi = \frac{\vec{\nabla}X \cdot \vec{\nabla}Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

- The ellipse itself is given by

$$\left(\frac{\delta X}{\Delta X}\right)^2 + \left(\frac{\delta Y}{\Delta Y}\right)^2 - 2\left(\frac{\delta X}{\Delta X}\right)\left(\frac{\delta Y}{\Delta Y}\right)\cos\varphi = \sin^2\varphi$$

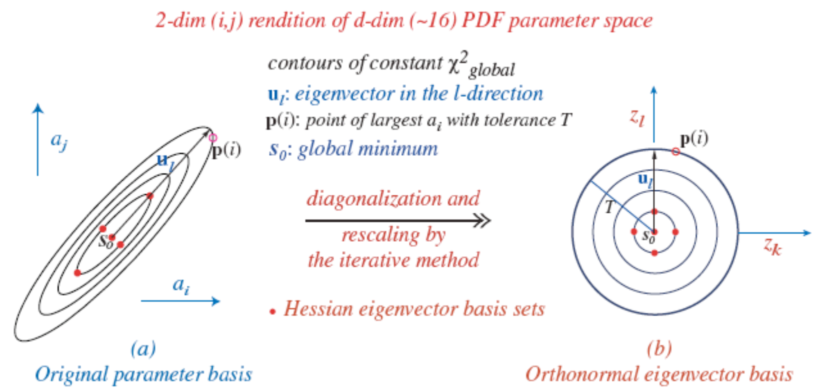


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1

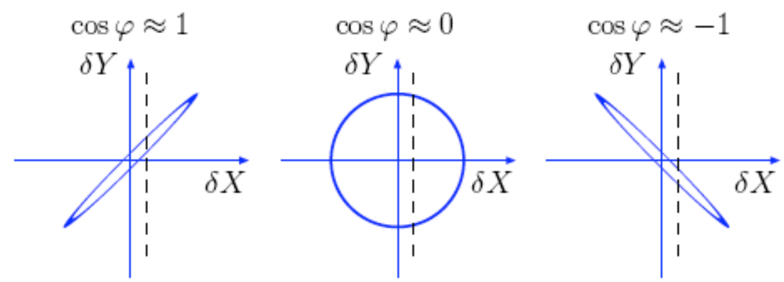
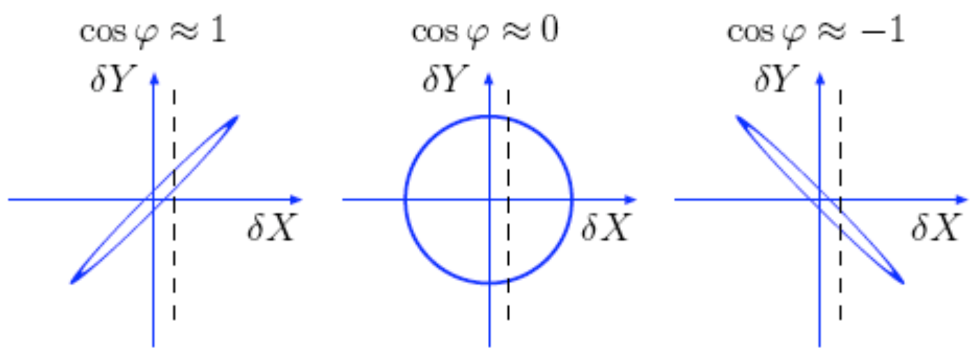


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

Correlations with Z, tT

Define a correlation cosine between two quantities (see extra slides for more detail)



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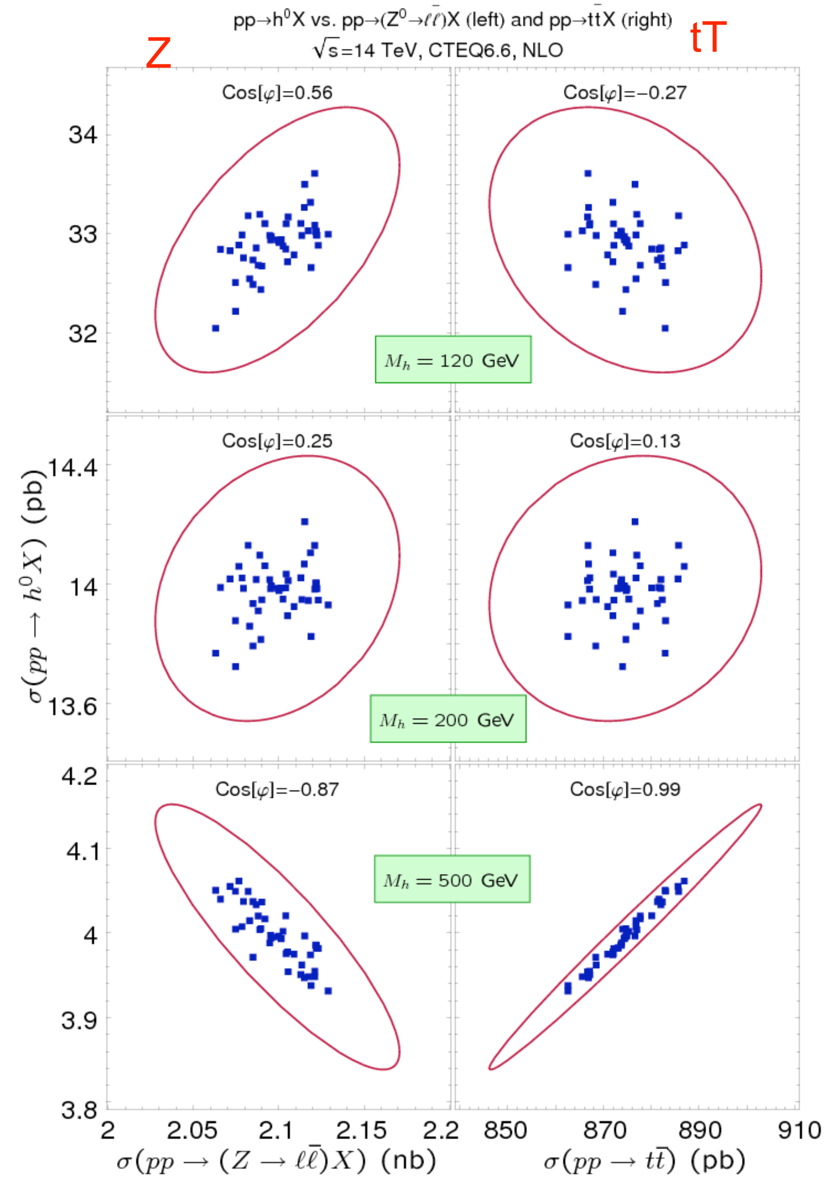

Correlations with Z, tT

Define a correlation cosine between two quantities

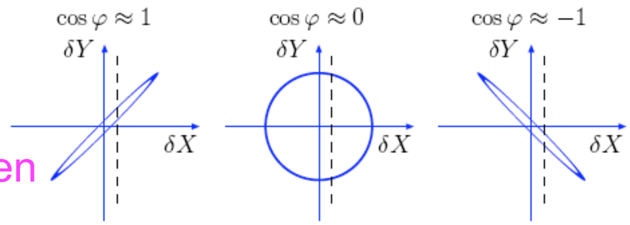

Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

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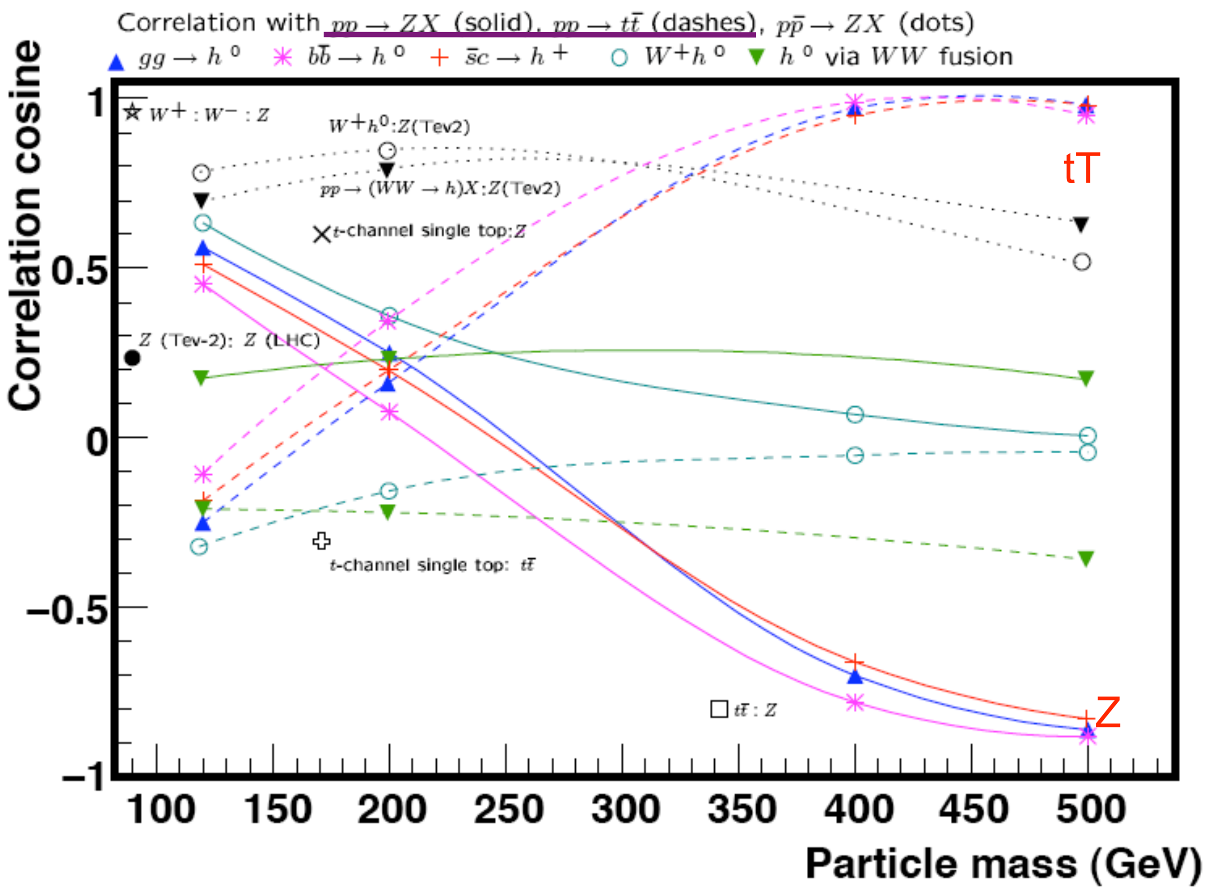


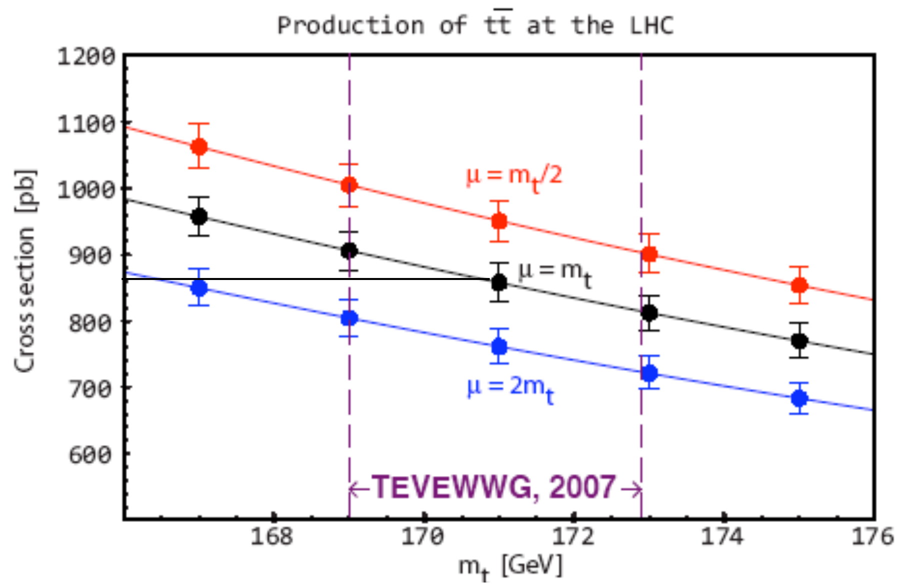
- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W^+}/\sigma_Z)$~1%
- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

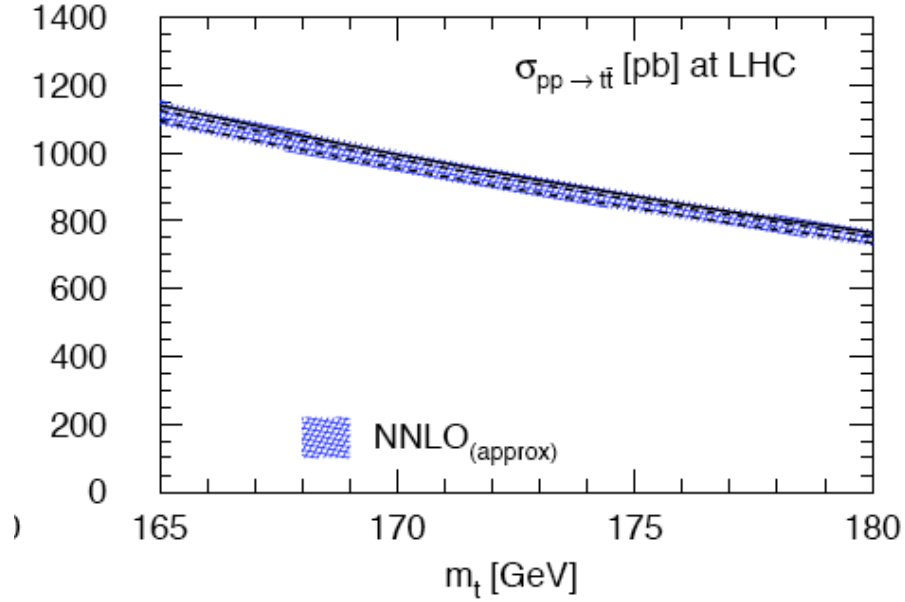
W/Z summary so far

- We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
  - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
- The pdf uncertainty for the ratio of a cross section that proceeds with a qQ initial state to the W/Z cross section is significantly reduced
- The pdf uncertainty for the ratio of a cross section that proceeds with a gg initial state to the W/Z cross section is significantly increased
- Would it be reasonable to use tT production as an *additional* benchmark?
  - yeah, yeah I know it's difficult, and it won't happen early, but just keep it in mind

Theory uncertainties for tT at LHC

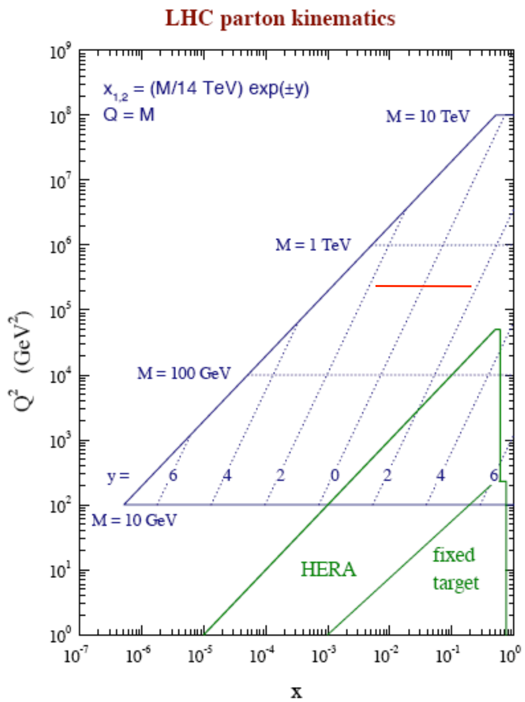
- Note that at NLO with CTEQ6.6 pdf's the central prediction for the tT cross section for $\mu=m_t$ is ~850 pb for 171 GeV (not 800 pb, which it would be if the top mass were 175 GeV); ~880 pb if use effect of threshold resummation
- The scale dependence is around +/-11% and mass dependence is around +/-6%
- Tevatron plans to measure top mass to 1 GeV
  - mass dependence goes to ~+/-3%
- NNLO tT cross section will be finished in (hopefully) near future
  - scale dependence will drop
  - threshold resummation reduces scale dependence to perhaps 3% (Moch and Uwer)
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller

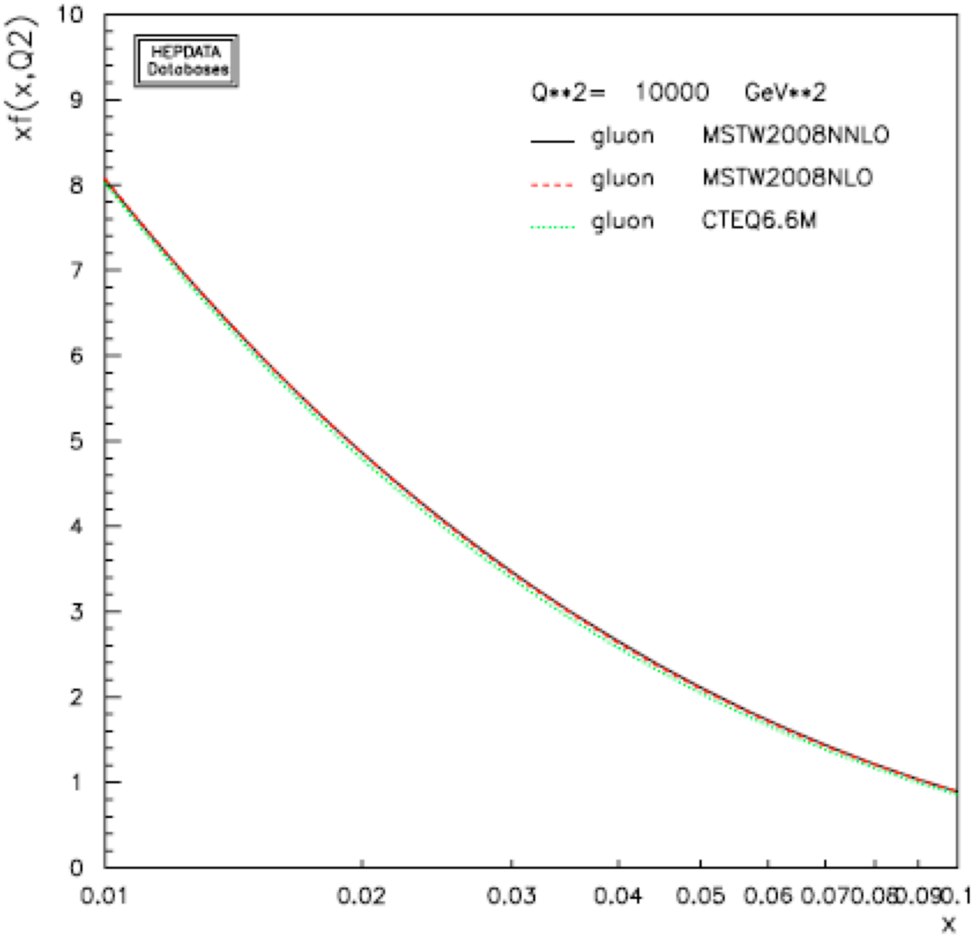




NLO->NNLO gluon

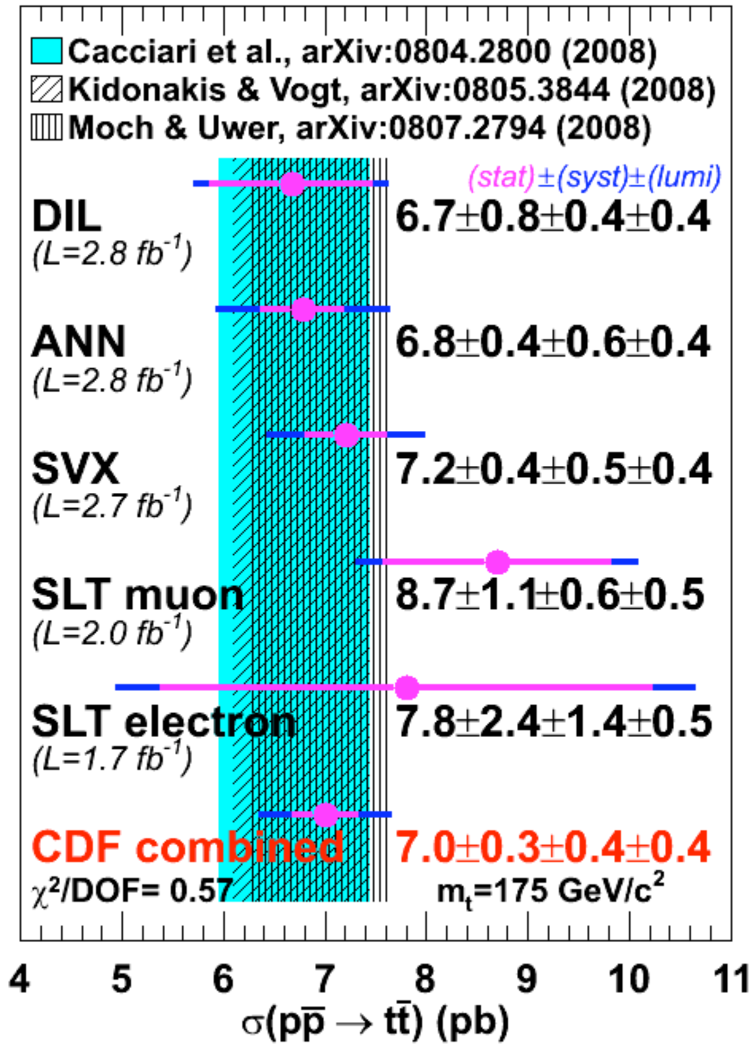
- MSTW2008NNLO gluon close to MSTW2008NNLO and to CTEQ6.6 NLO
  - note this was not the case for 2002 versions of MRST NLO and NNLO; related to large changes noted for Higgs cross sections at NNLO





What about experimental uncertainties?

- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lum)



NLO corrections

Sometimes it is useful to define a K-factor (NLO/LO). Note the value of the K-factor depends critically on its definition. K-factors at LHC (mostly) similar to those at Tevatron.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	1.09
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–

Table 2: K-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. For most of the processes listed, jets satisfy the requirements $p_T > 15$ GeV/c and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

K-factors may differ from unity because of new subprocesses/ contributions at higher order **and/or differences between LO and NLO pdf's**

Les Houches 2007

Shape dependence of a K-factor

- Inclusive jet production probes very wide x,Q^2 range along with varying mixture of gg,gq,and qq subprocesses
- PDF uncertainties are significant at high p_T
- Over limited range of p_T and y, can approximate effect of NLO corrections by K-factor but not in general
  - in particular note that for forward rapidities, K-factor <<1
  - LO predictions will be large overestimates
  - see CHS paper for discussion on why

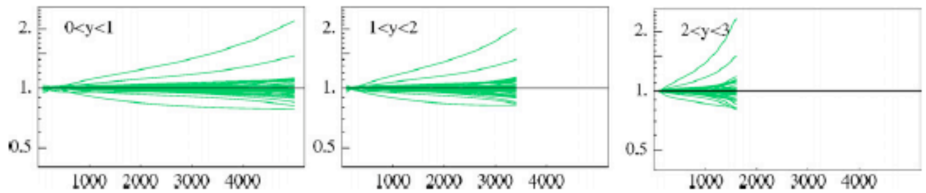


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

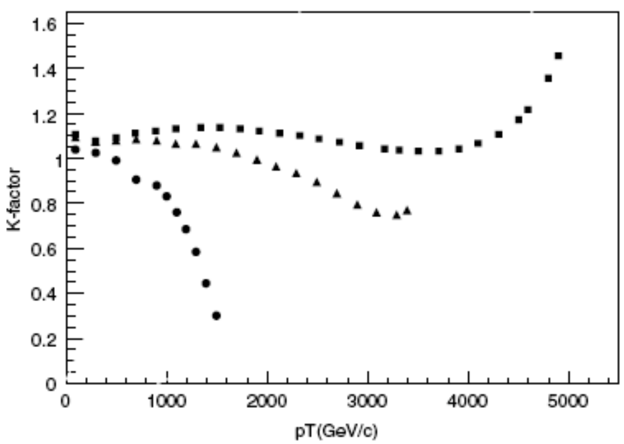
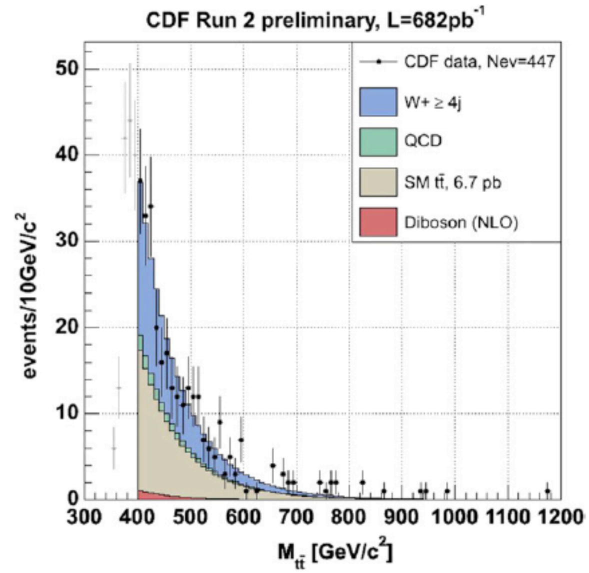


Figure 106. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdfs for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

Another example, from the Tevatron

- Suppose you measure the high m_{tT} region looking for new physics
- Suppose that your measurement agrees well with Pythia
- Have you missed something?
- Yes, because NLO prediction at high mass is about half of LO prediction
  - partially pdf's
  - partially matrix elements
- Why not just use MC@NLO?



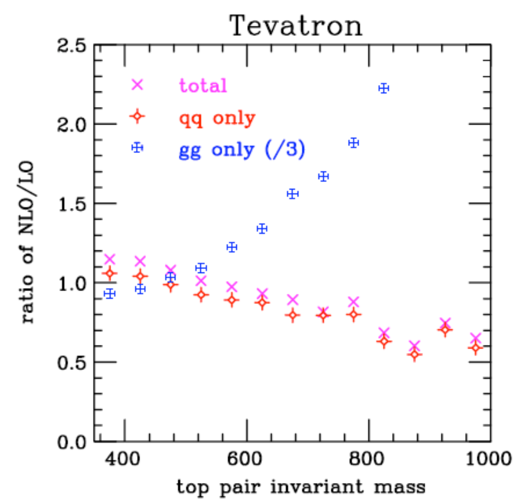
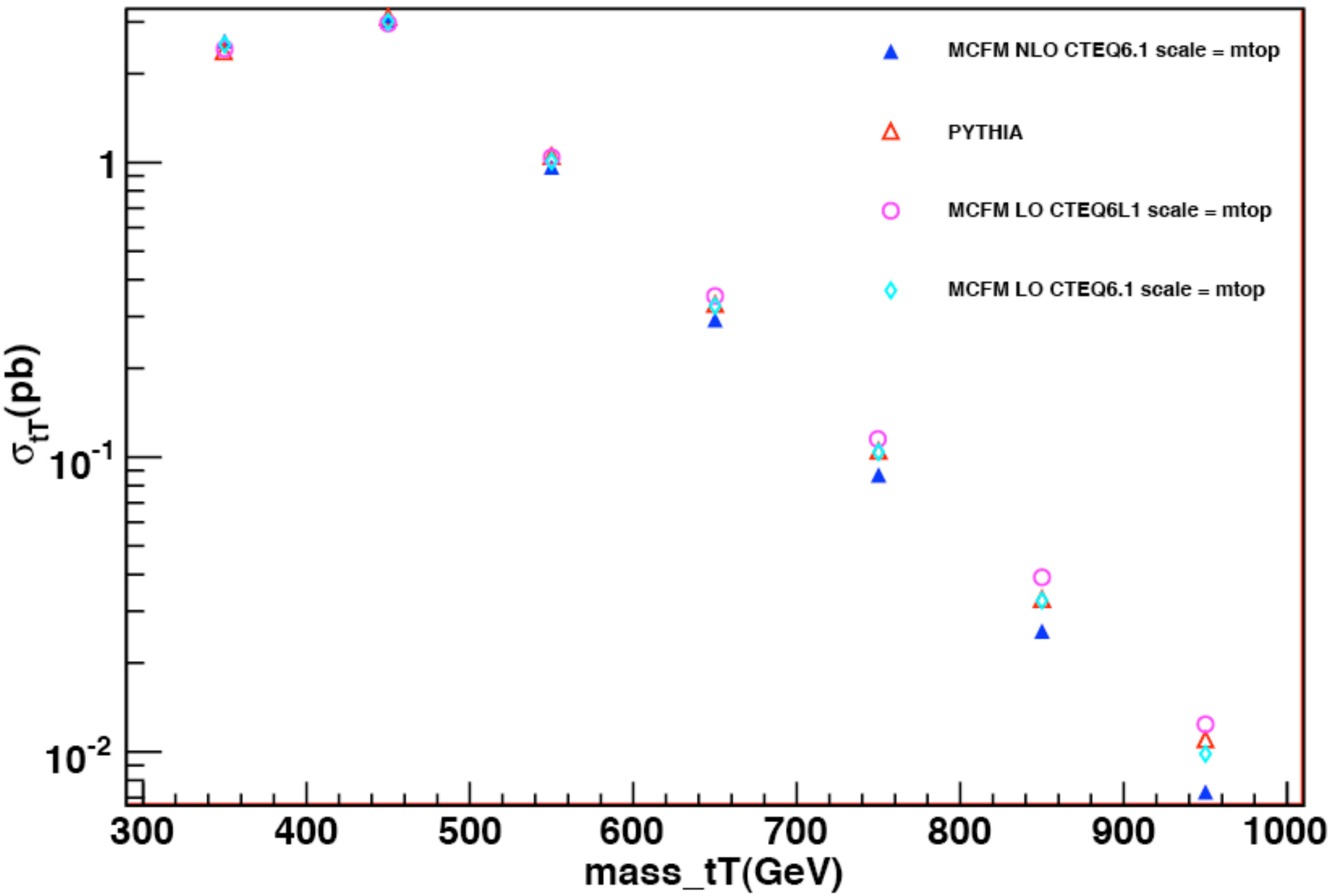


Figure 68. The ratio of the NLO to LO predictions for the $t\bar{t}$ mass at the Tevatron. The predictions include the ratio for the total cross section and for the specific $q\bar{q}$ and gg initial-states. Note that the total also includes a gq contribution (not present at LO) and that the gg ratio is divided by a factor of 3.

At the Tevatron



What about tT at the LHC?

- The cross section is dominated by the gg subprocess so the K-factor is approximately constant and > 1
  - unlike the Tevatron

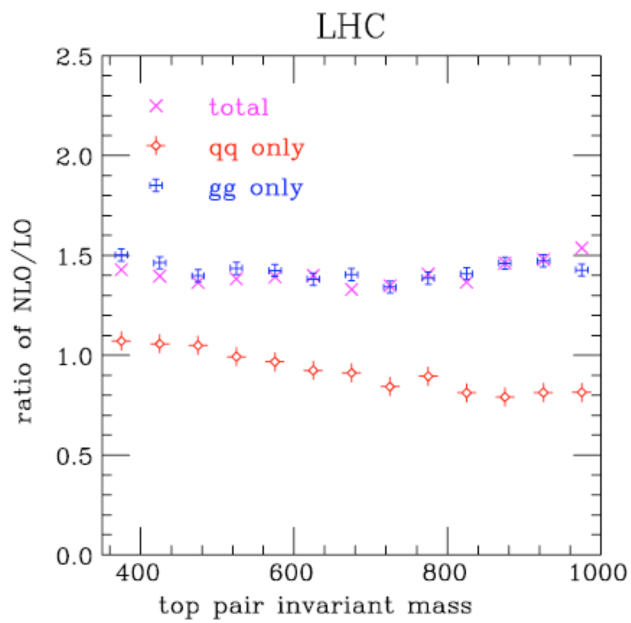


Figure 94. The ratio of the NLO to LO predictions for the $t\bar{t}$ mass at the LHC. The predictions include the ratio for the total cross section and for the specific $q\bar{q}$ and gg initial-states. Note that the total also includes a gq contribution (not present at LO).

PDF progress from CTEQ

- NLO updates (CT09)
  - using new Tevatron Run 2 data, concentrating on jets
  - see Jon’s talk at PDF4LHC workshop last week
- Combined fits (q_T+x)
  - useful for precision physics such as W mass determination
- Mod LO pdf’s
  - for use in parton shower Monte Carlos at the LHC
- NNLO pdf’s
  - precision physics at the LHC
  - HOPPET used for evolution

NLO fits

- 37 data sets with 2898 data points
  - chisquare=2756
  - full correlated experimental errors used for all data sets that report such errors
- Gluon parametrization

$$g(x,\mu_0) = a_0\, x^{a_1}\,(1-x)^{a_2}\,\exp(a_3 x + a_4 x^2 + a_5\sqrt{x})$$

  - more general than what was used in CTEQ66
  - crucial to have flexible parametrization to correctly calculate uncertainties
  - have to control instabilities caused by numerical evaluation of second deriviatives of the Hessian
  - now 24 free parameters

- Have added a penalty to chisquare that rises as the 4th power to prevent large contributions from any particular experiment
  - this will be more crucial for eigenvector sets
- CTEQ66 pdf's known to describe Run 2 data reasonably well, so don't expect too much change with their inclusion in the fit
  - chisquare decreases to 2740, a reduction of 16
  - only significant change is in the gluon sector

New pdf's (CT09G)

- Somewhat of a reduction in gluon uncertainty for low Q, but very similar to CTEQ6.6 at high Q
- At large scales, the gluon distributions are very similar

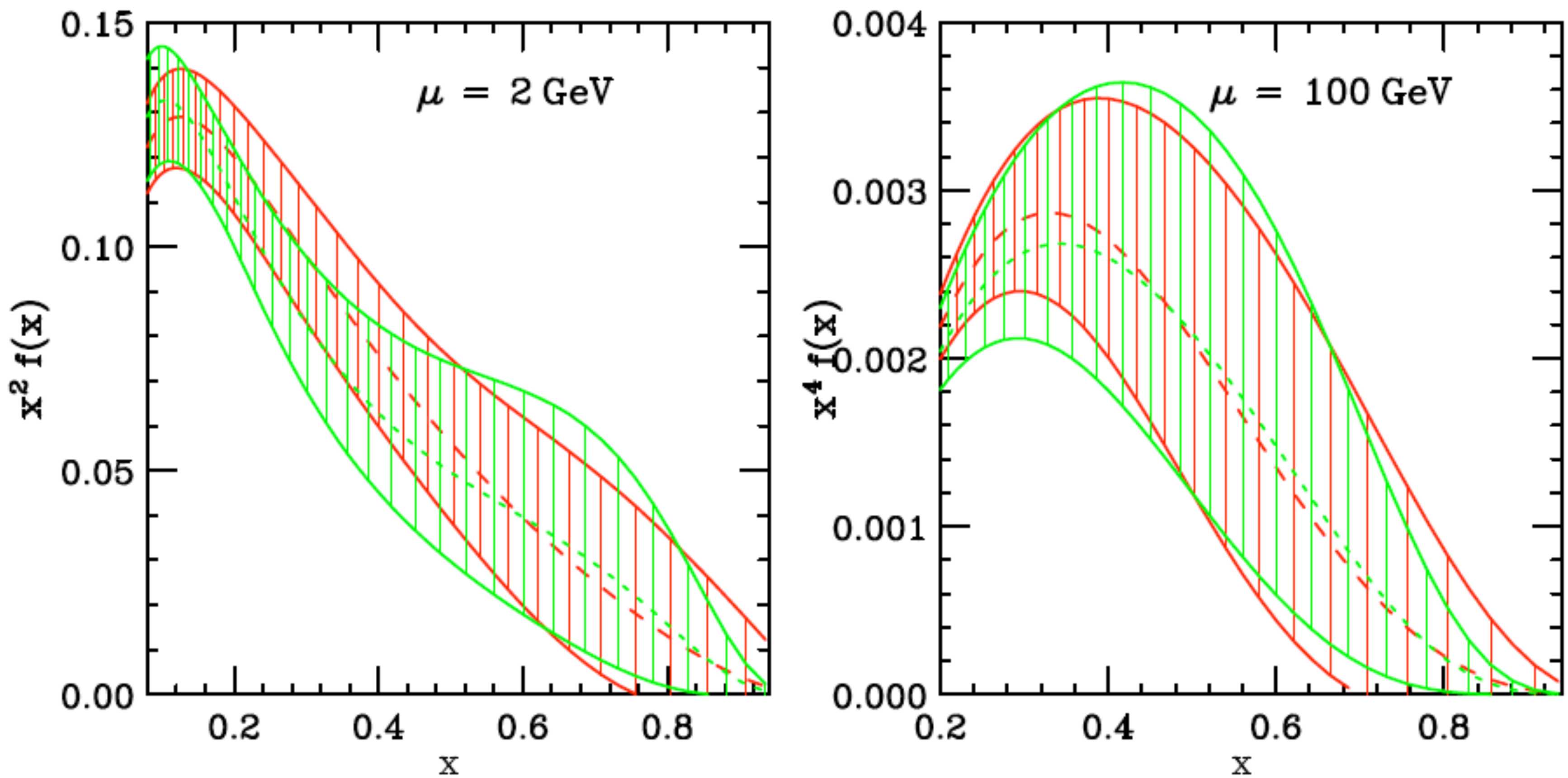
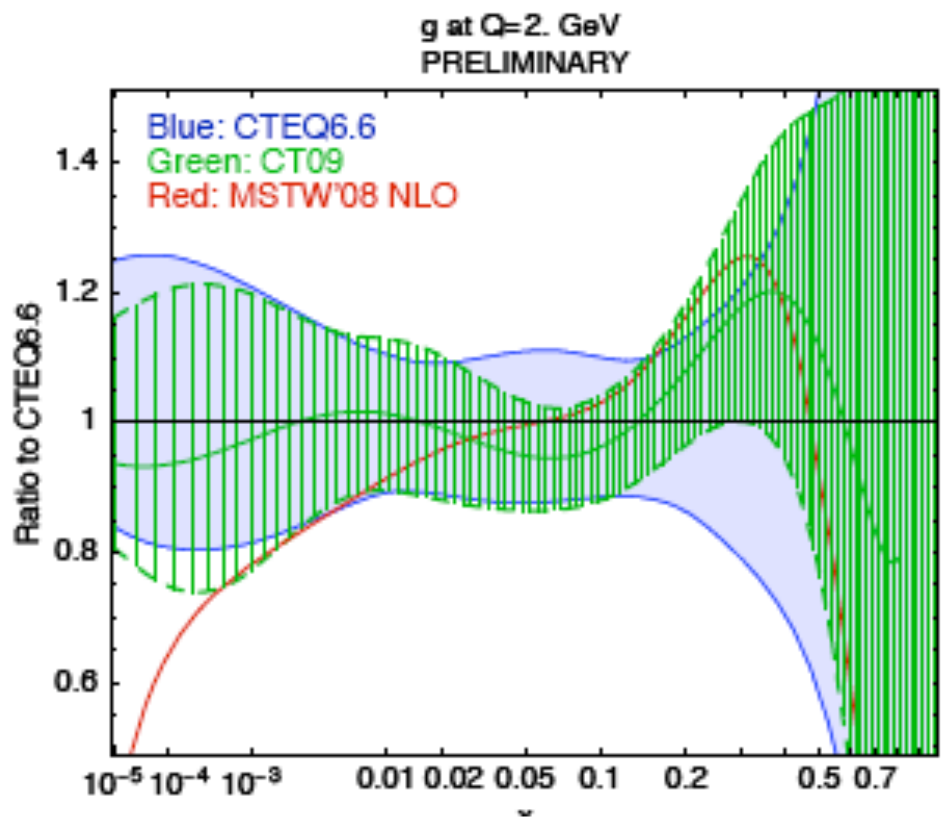


Figure 8: Gluon distributions and uncertainties in CT09G (red) and CTEQ6.6 (green).

Comparison to MSTW08

- MSTW08 gluon much weaker at high x
- …but still within CT09 error bands
- Note converse is not true, i.e. CT09 not within MSTW08 error bands
  - MSTW08 not within MRST2004 error bands



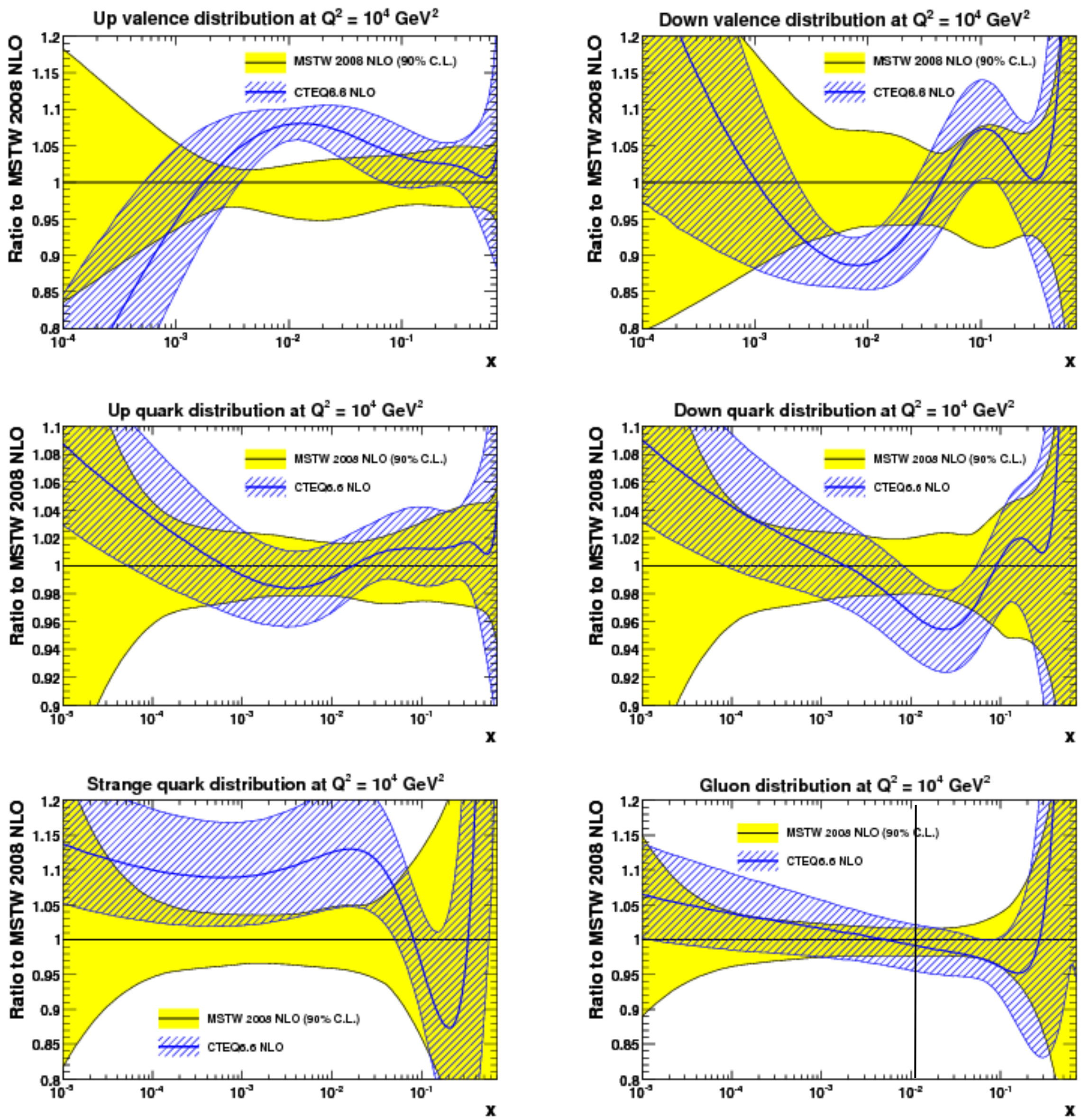
Some tT cross section comparisons (m_{top}=172 GeV)

- NLO
  - 14 TeV
  - CTEQ6.6: 829 pb
  - CTEQ6M: 852 pb
  - MSTW2008: 902 pb
  - 10 TeV
  - CTEQ6.6: 375 pb
  - CT09: 382 pb
  - MSTW2008: 408 pb
- LO
  - 14 TeV
  - CTEQ6L1: 617 pb
  - CTEQ6L: 533 pb
  - CTQE6.6: 569 pb
  - CT09MC1: 804 pb
  - CT09MC2: 780 pb
  - 10 TeV
  - CTEQ6L1: 267 pb
  - CTEQ6L: 229 pb
  - CTE09MC2: 342 pb

Comparisons of CTEQ and MSTW2008 at NLO

Note that CTEQ (sea) quark and gluon distributions tend to be larger at small x

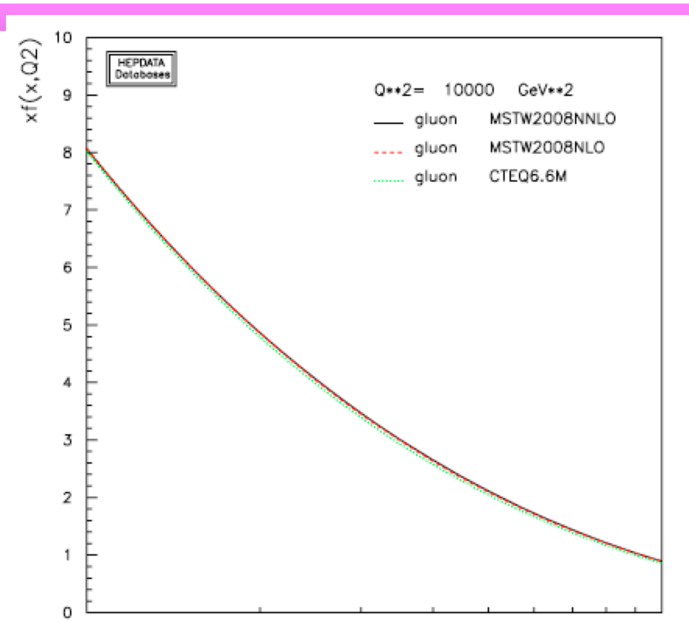
Perhaps due to positive nature of gluon in CTEQ framework

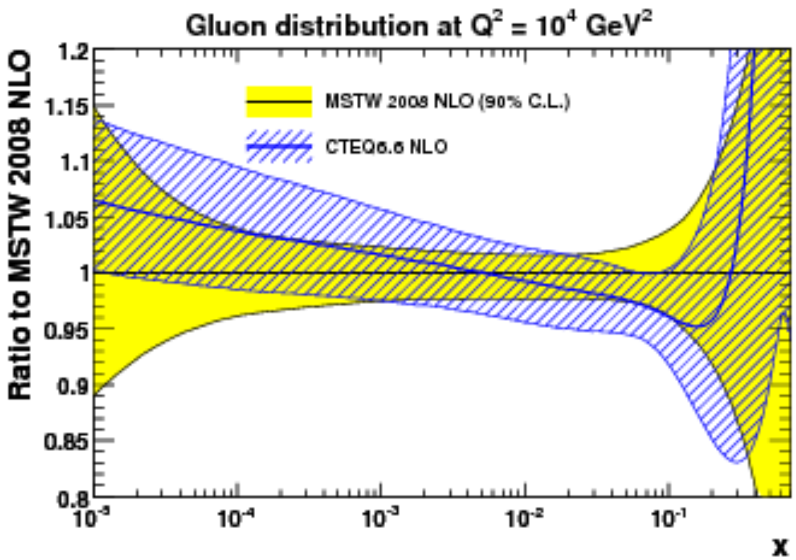


CTEQ and MSTW gluon fairly close in x range at NLO for tT production at LHC

Compare gluons

- The MSTW2008 NNLO gluon is close to the NLO gluon which is close to that of CTEQ6.6
- Why the difference in cross sections then?
  - partially gluon
  - partially α_s
  - CTEQ uses world average value of as in global fits ($\alpha_s^{2loop}(m_Z)$=0.118)
  - MSTW leaves it as a a free parameter in fit
    - 0.120 for MSTW08

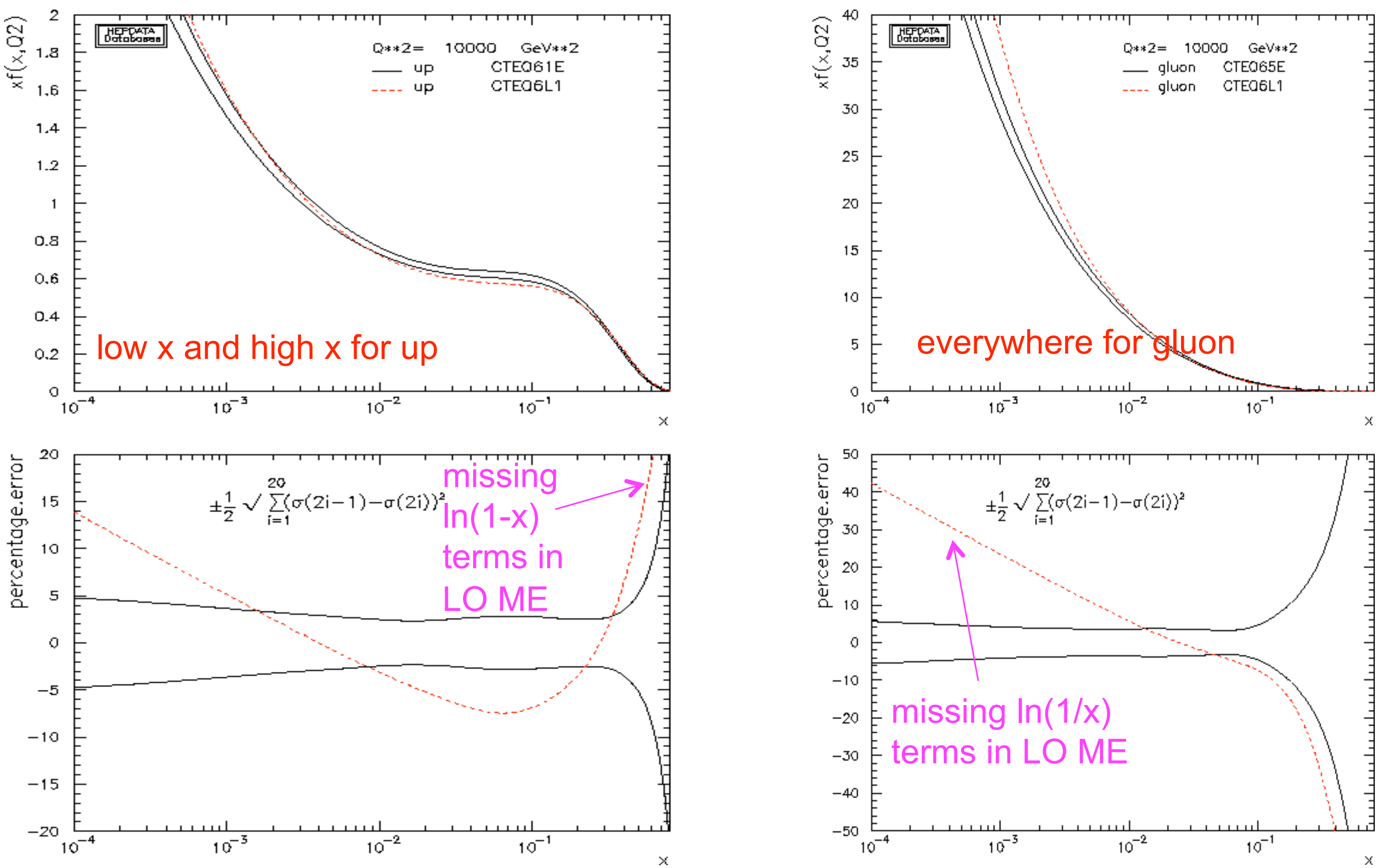




CTEQ modified LO PDFs

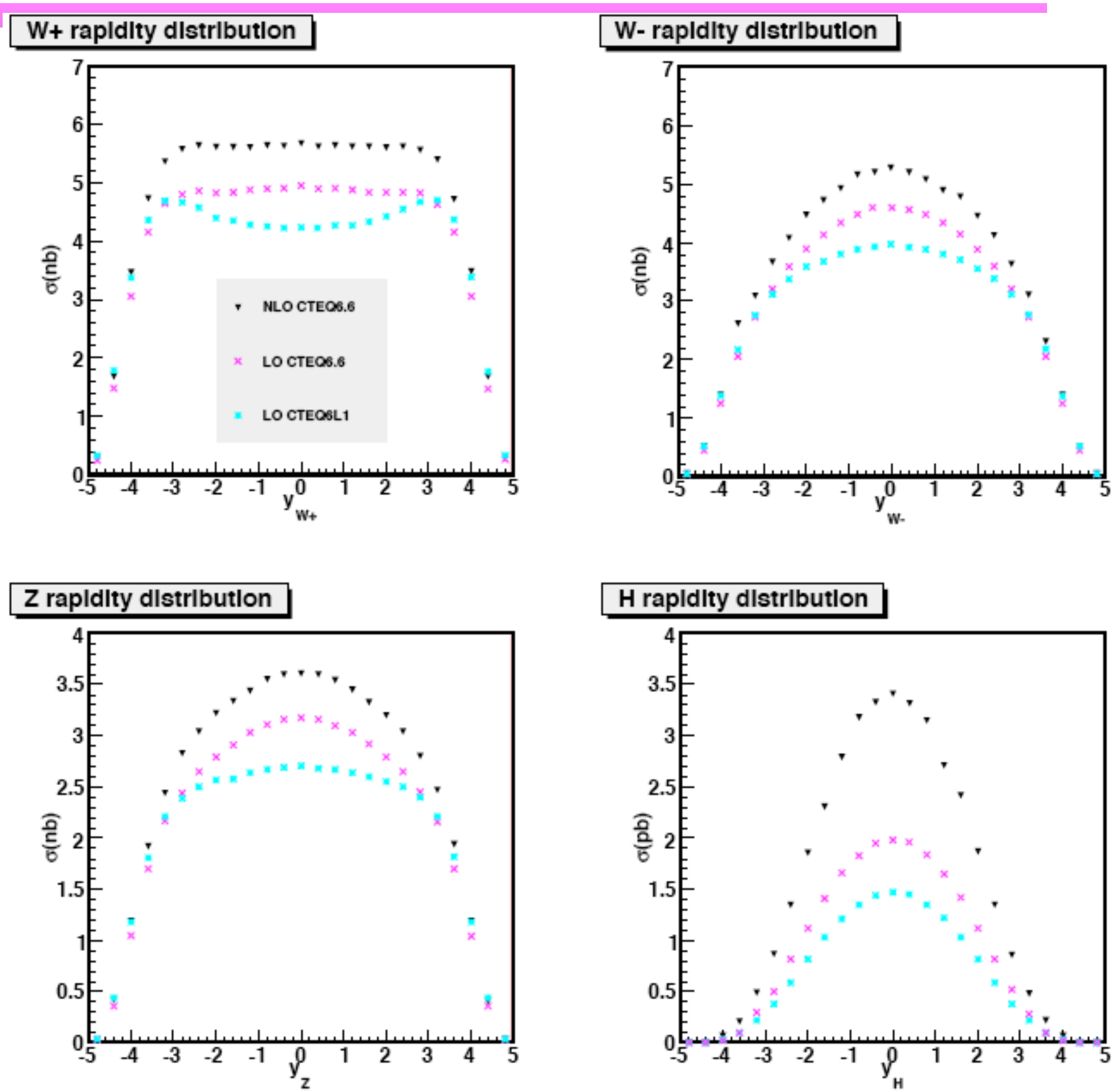
- Skip the detailed motivation since we've all seen it before…
- Basically,we want the LO* pdf's to behave as LO as x->0; as close to NLO as possible as x->1
- In this way, we can
  - maintain the connection to the underlying event tunes already in use (dependent on the low x behavior of the gluon)
  - better describe the shapes (and normalizations) of hard cross sections at the LHC (dependent on the high x behavior of the PDFs)

Where are the differences between LO and NLO partons?



LO and NLO distributions

- The shapes for the cross sections shown to the right are well-described by LO matrix elements using NLO PDFs, but there are distortions that are evident when LO PDFs are used
- Normalizations are not fully described using LO matrix elements (K-factor)



CTEQ mod LO PDFs

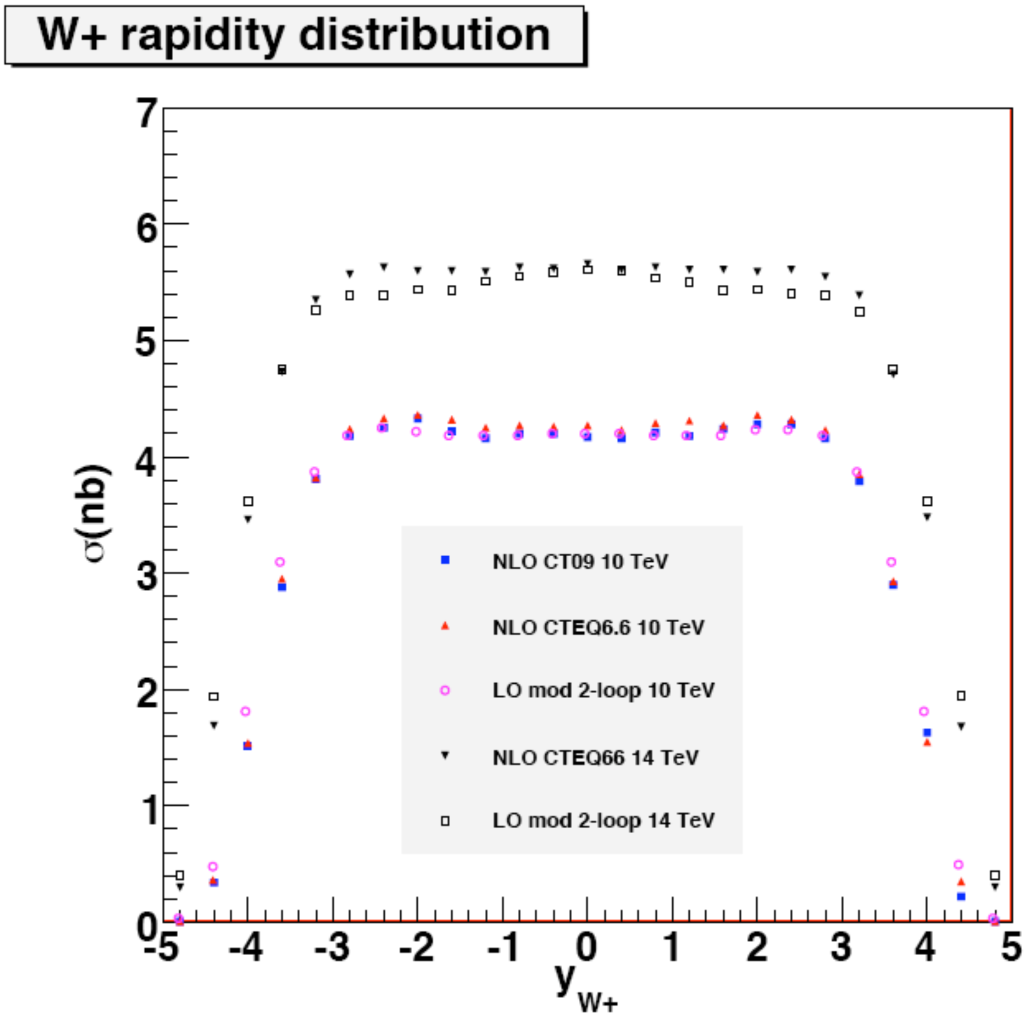
- Include in LO* fit (weighted) pseudo-data for characteristic LHC processes produced using CTEQ6.6 NLO pdf's with NLO matrix elements (using MCFM), along with full CTEQ6.6 dataset (2885 points)
  - low mass bB
    - fix low x gluon for UE
  - tT over full mass range
    - higher x gluon
  - W^+, W^-, Z^0 rapidity distributions
    - quark distributions
  - gg->H (120 GeV) rapidity distribution
- Allow total momentum in proton to exceed 1.00 if needed to fit the real and pseudo-data
  - other sum rules intact
- Use 1-loop or 2-loop α_s
  - two different fits and thus 2 different PDFs
  - will concentrate on 2-loop results here
  - keep $\alpha_s(m_Z)$ fixed on 1-loop (2-loop) world averages, for better connection to other CTEQ PDFs
- Also, another technique involving use of scales

Some observations

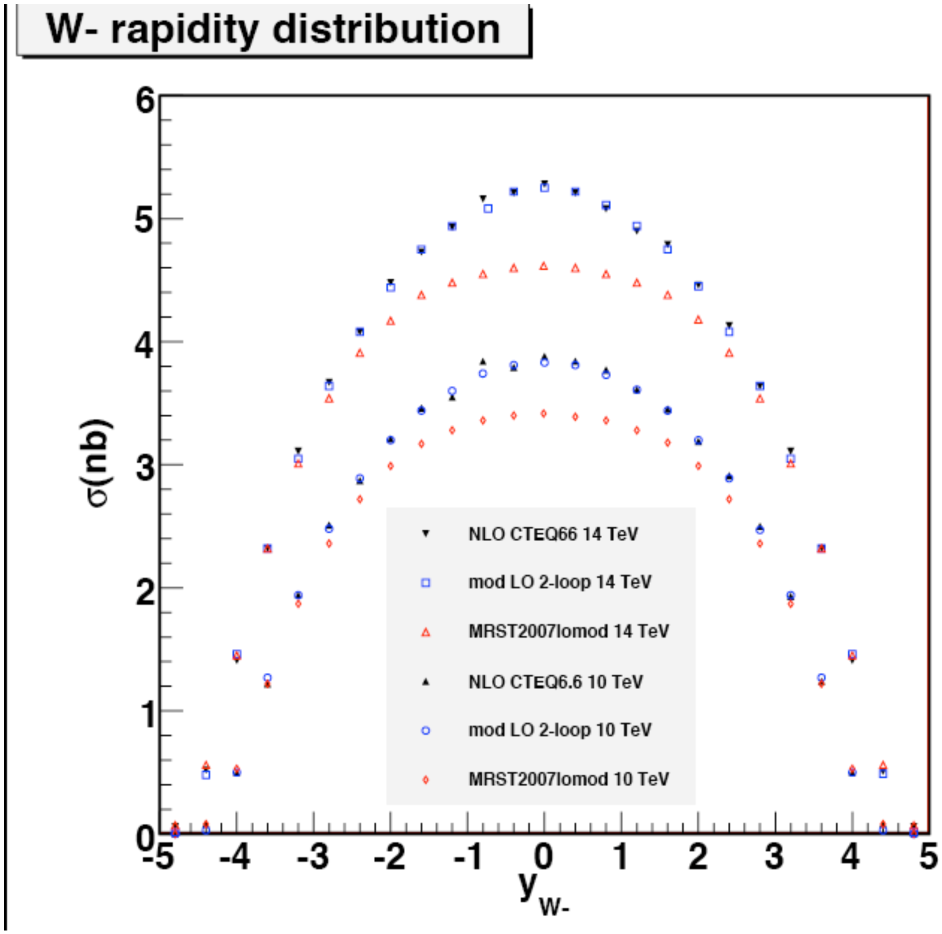
- χ^2 improves with momentum sum rule free
  - without pseudo-data in fit, the momentum sum increases by ~3-4%
- Pseudo-data has conflicts with global data set
  - that's the motivation of the modified pdf's
- Requiring better fit to pseudo-data increases chisquare of LO fit to global data set by about 10-20% (although this is not the primary concern; the fit to the pseudo-data is)
  - prefers more momentum (1.10 for 1-loop and 1.14 for 2-loop); mostly goes into the gluon distribution
- No strong preference for 1-loop or 2-loop α_s that I can see, with fits containing weighted pseudo-data; without pseudo-data, prefers 2-loop
- Normalization of pseudo-data (needed K-factor) gets closer to 1
  - 1.00 for W production (instead of 1.15)
  - ~1.1 for tT production (instead of 1.4)
  - ~1.4 for Higgs (120 GeV) (instead of 1.7)

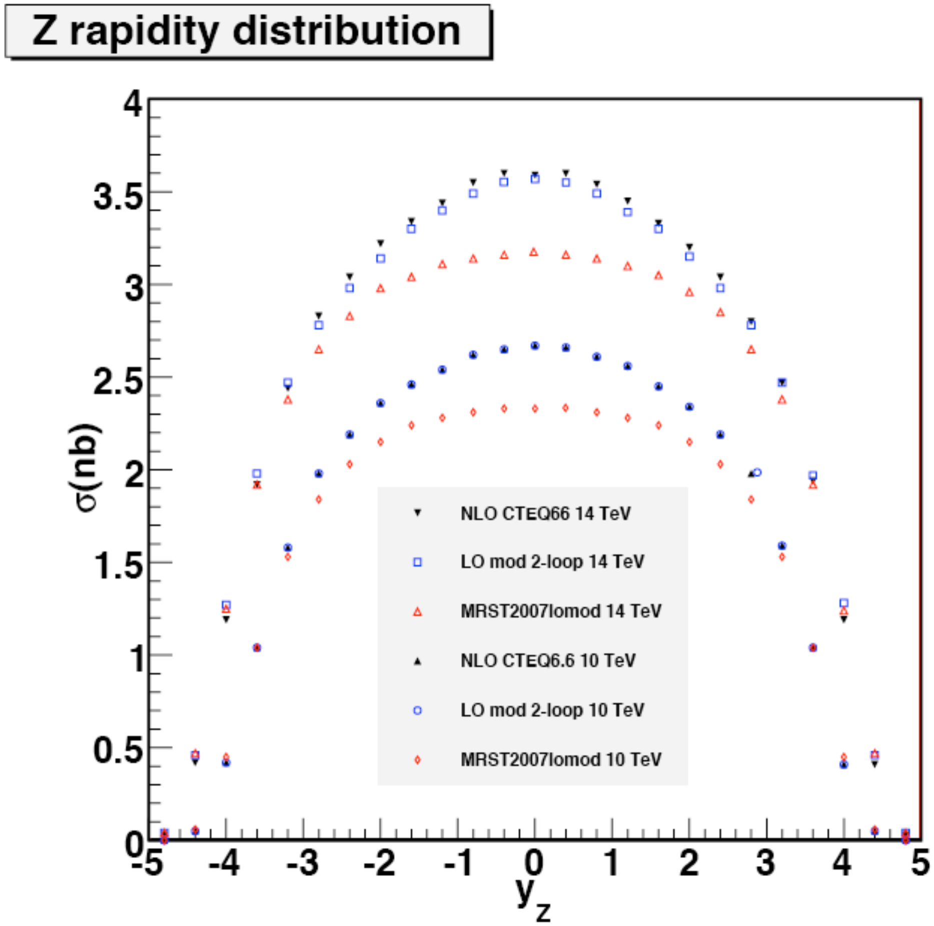
Results

- Mod LO W^+ rapidity distribution agrees better with NLO prediction in both magnitude and shape
- Agreement at 10 TeV (not in fit) even better



Results

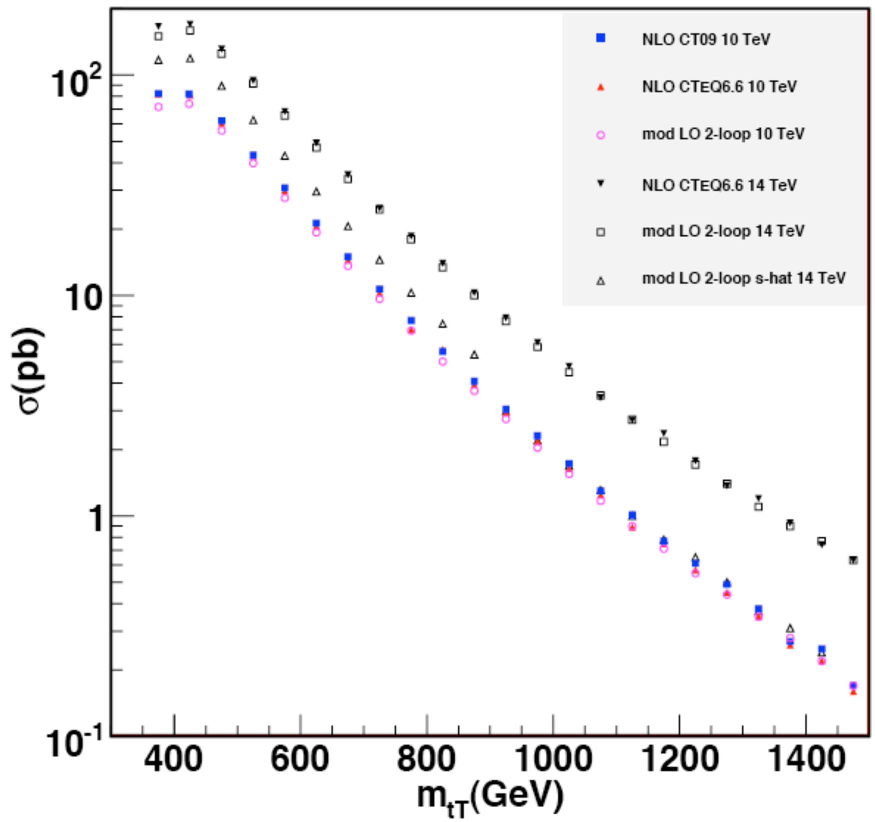

W- rapidity distribution
σ(nb)
y_{W-}
NLO CTEQ66 14 TeV
mod LO 2-loop 14 TeV
MRST2007lomod 14 TeV
NLO CTEQ6.6 10 TeV
mod LO 2-loop 10 TeV
MRST2007lomod 10 TeV


Z rapidity distribution
σ(nb)
y_Z
NLO CTEQ66 14 TeV
LO mod 2-loop 14 TeV
MRST2007lomod 14 TeV
NLO CTEQ6.6 10 TeV
LO mod 2-loop 10 TeV
MRST2007lomod 10 TeV

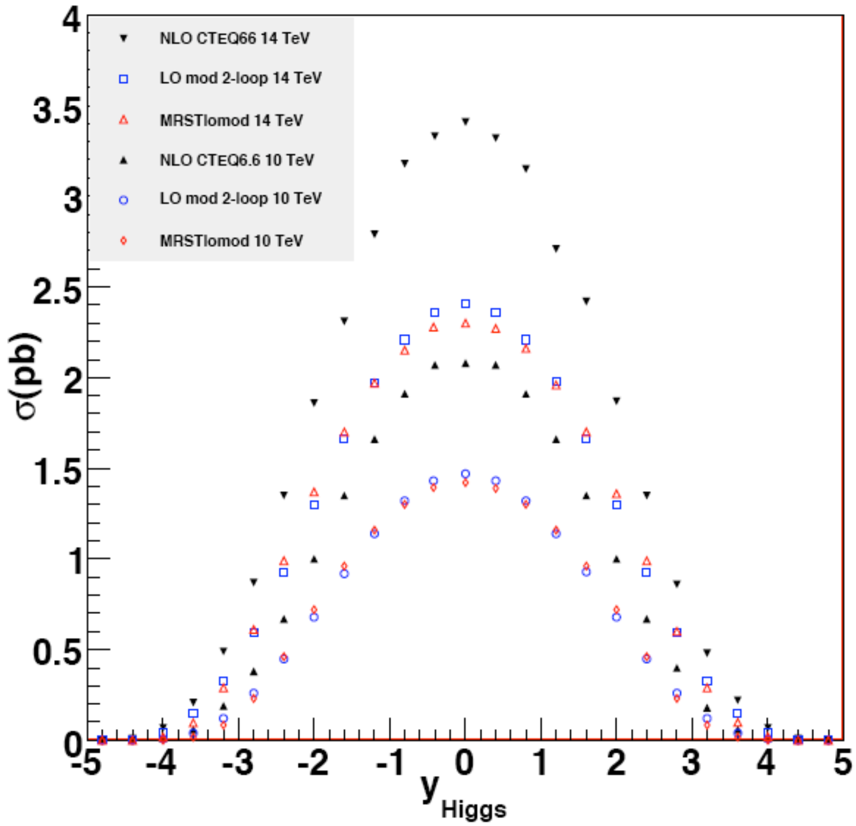
Results

- Can get a normalization (for scale m_T much closer to NLO)
- Virtual corrections very large; better normalization but mod LO still < NLO

tT mass distribution



Higgs(120 GeV) rapidity distribution



K-factor table from CHS paper

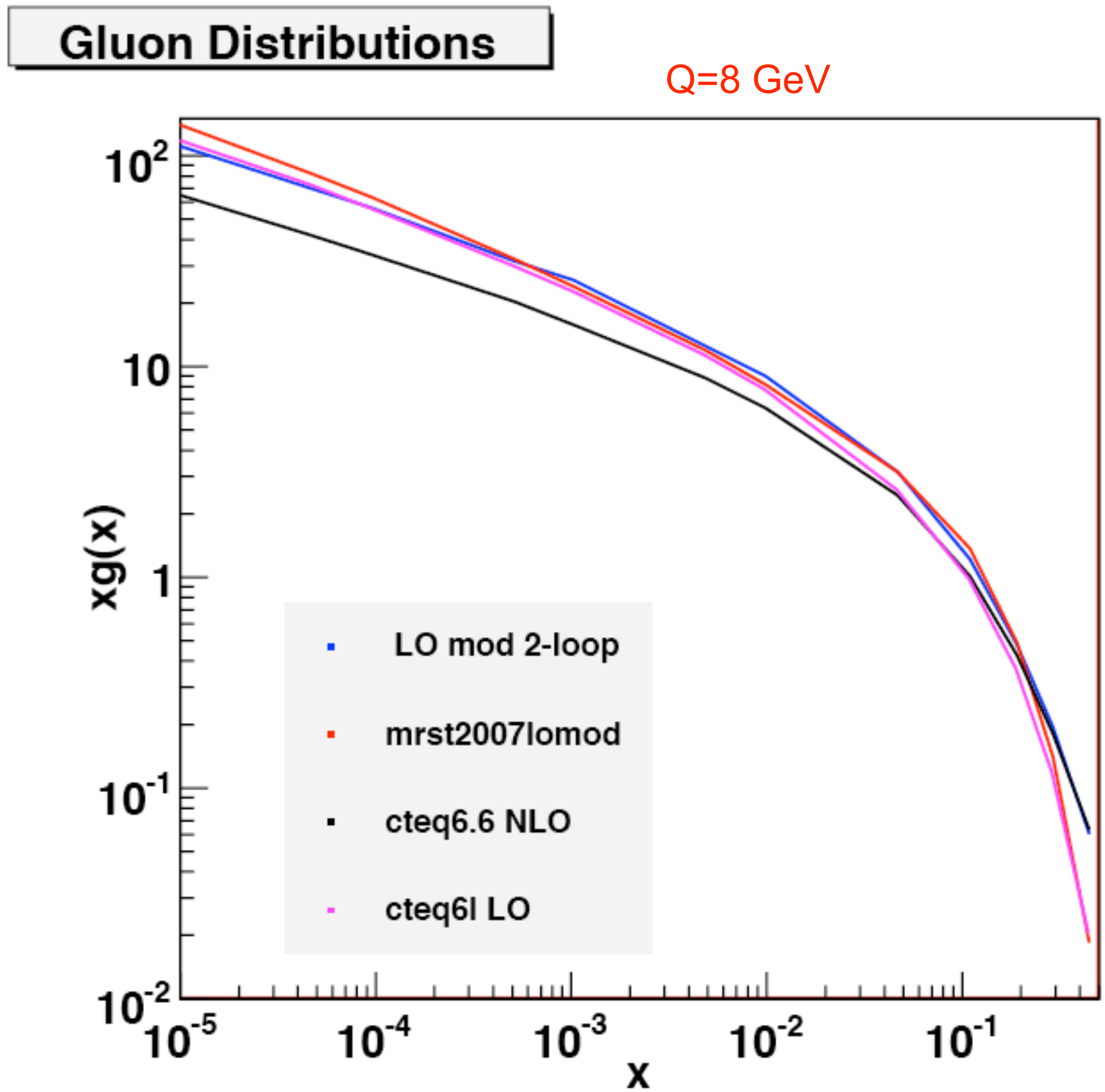
Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	p_T^{jet}	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	p_T^{jet}	1.16	0.91	1.29	0.89	0.88	1.10	–
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	–
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19	1.09
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10	
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51	–
Higgs	m_H	p_T^{jet}	2.33	–	2.33	1.72	–	2.32	1.43
Higgs via VBF	m_H	p_T^{jet}	1.07	0.97	1.07	1.23	1.34	0.85	0.75
Higgs+1jet	m_H	p_T^{jet}	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	p_T^{jet}	–	–	–	1.15	–	–	1.13

Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\text{jet}} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\text{jet}} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

Note K-factor for W < 1.0, since for this table the comparison is to CTEQ6.1 and not to CTEQ6.6, i.e. corrections to low x PDFs due to treatment of heavy quarks in CTEQ6.6 "built-in" to mod LO PDFs

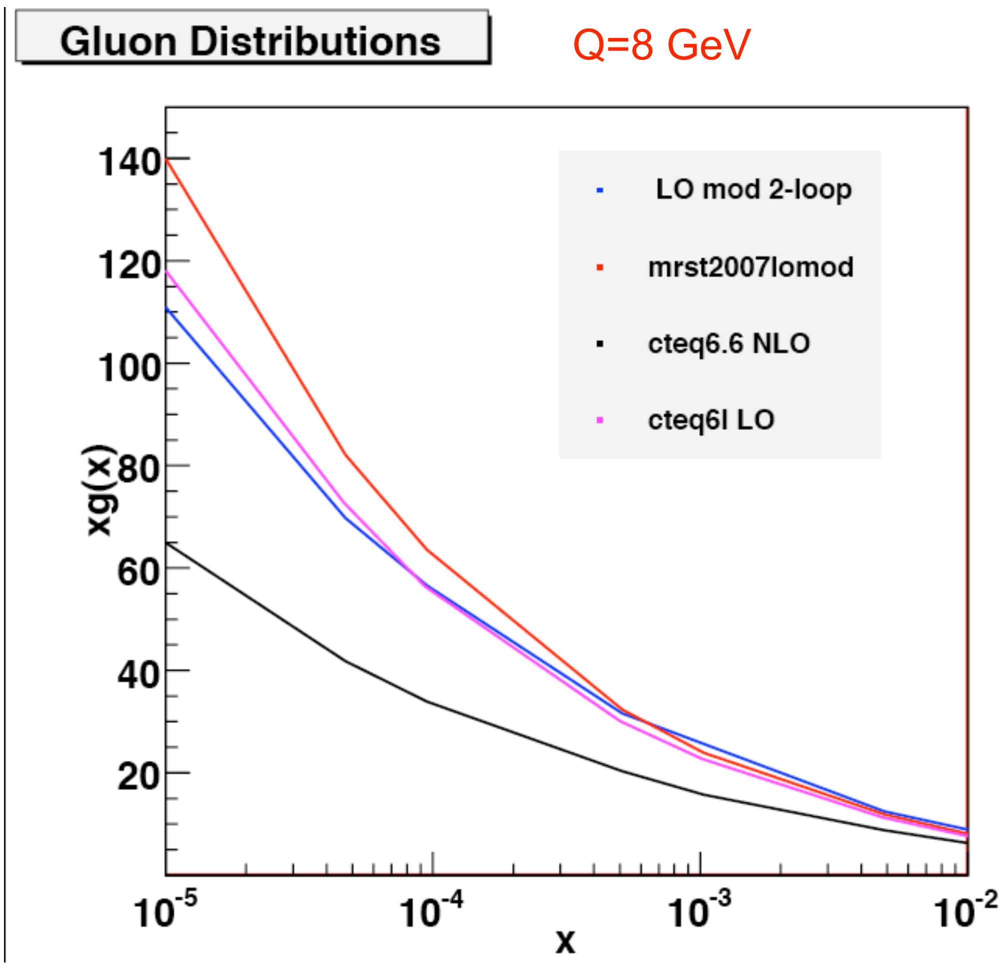
Some PDF comparisons

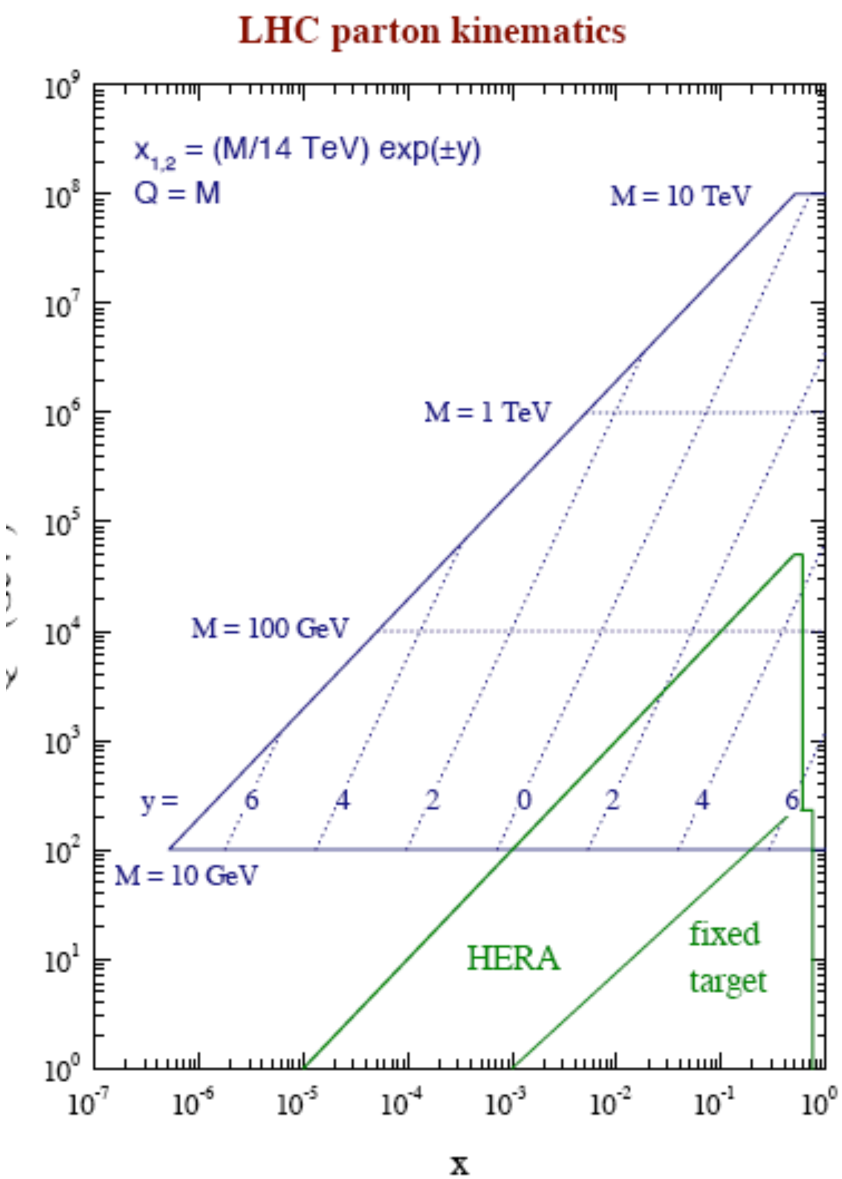
- The 2-loop modified LO PDF is similar to CTEQ6L at low x and to CTEQ6.6 at high x, as designed
- Also shown for comparison is the mrst2007lomod gluon PDF



Mini-jet production

- …will be especially sensitive to gluons in x range of 1E-05 to 1E-02

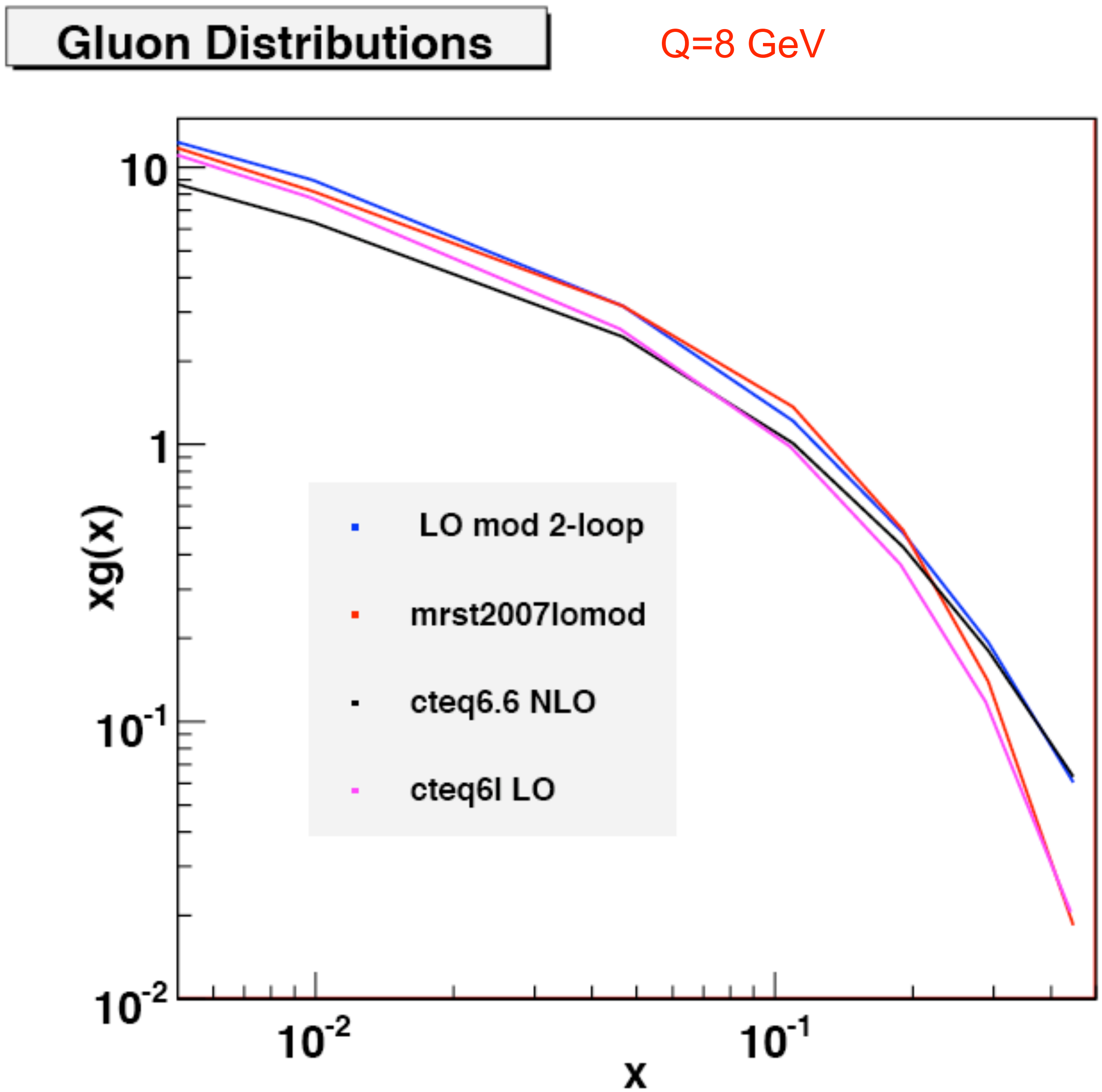




Some PDF comparisons

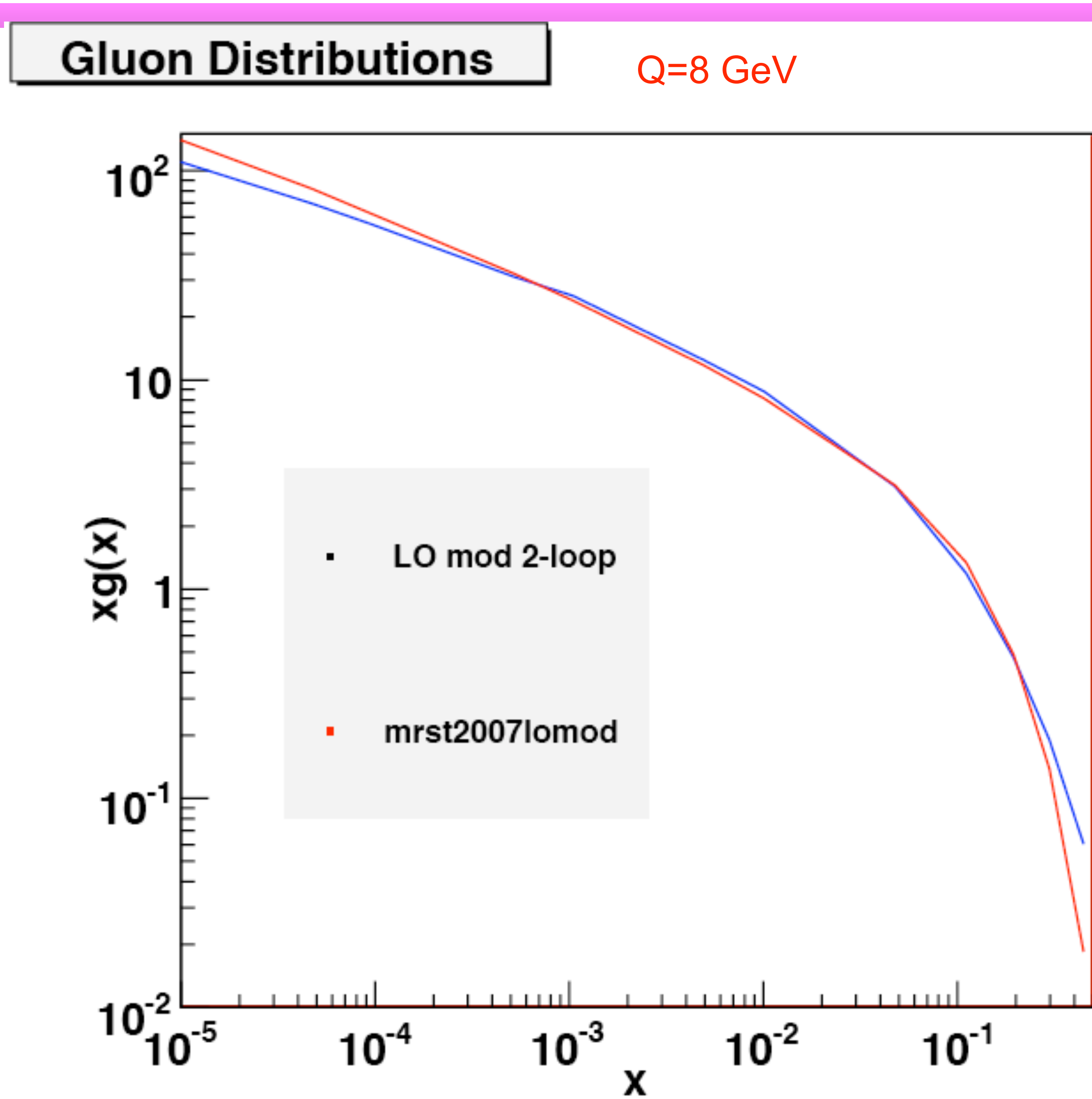
- high x region

Q=8 GeV



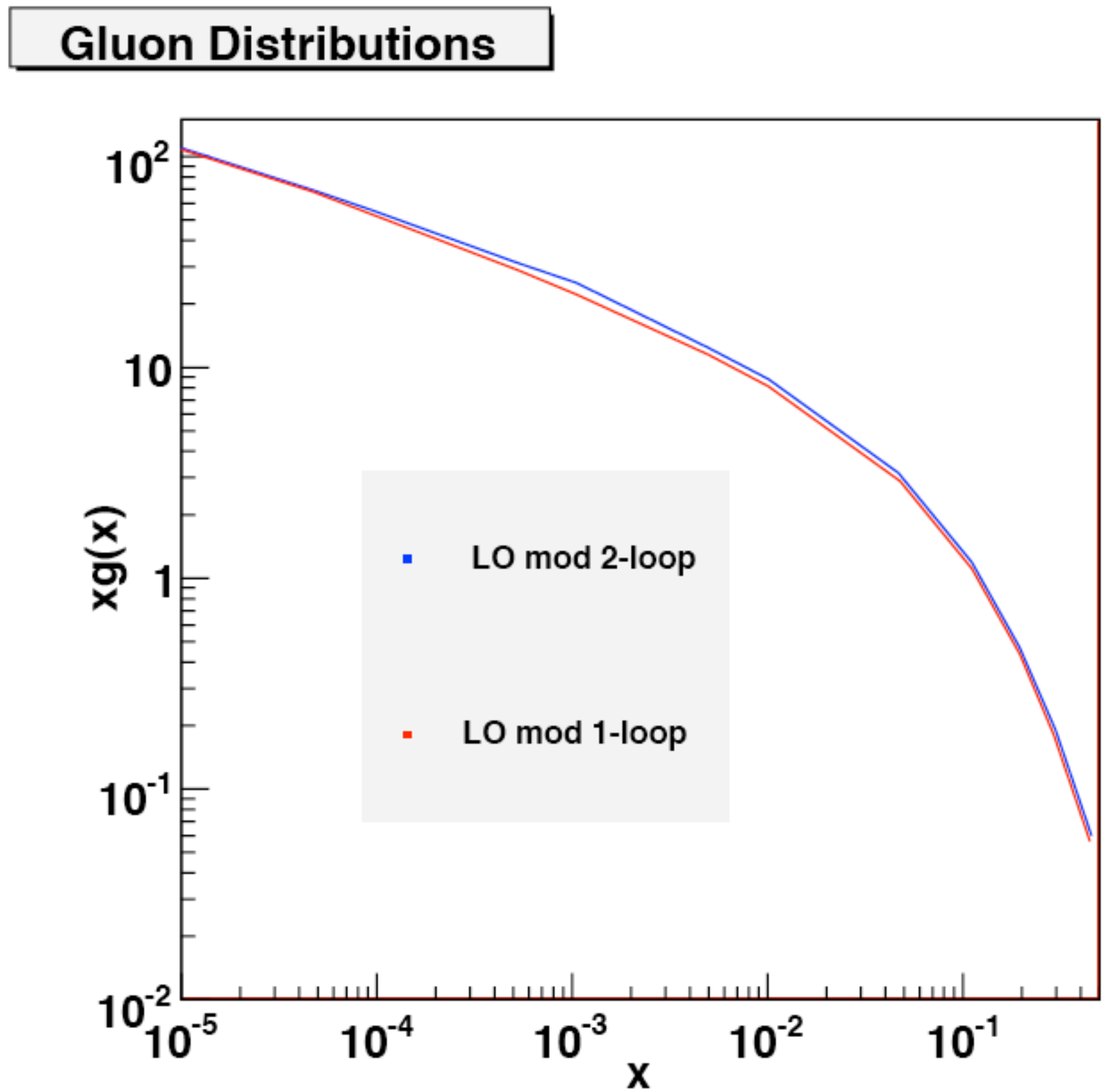
Only mod 2-loop and mrst

- similar over a wide x range
- mrst is larger at small x; CTEQ at high x



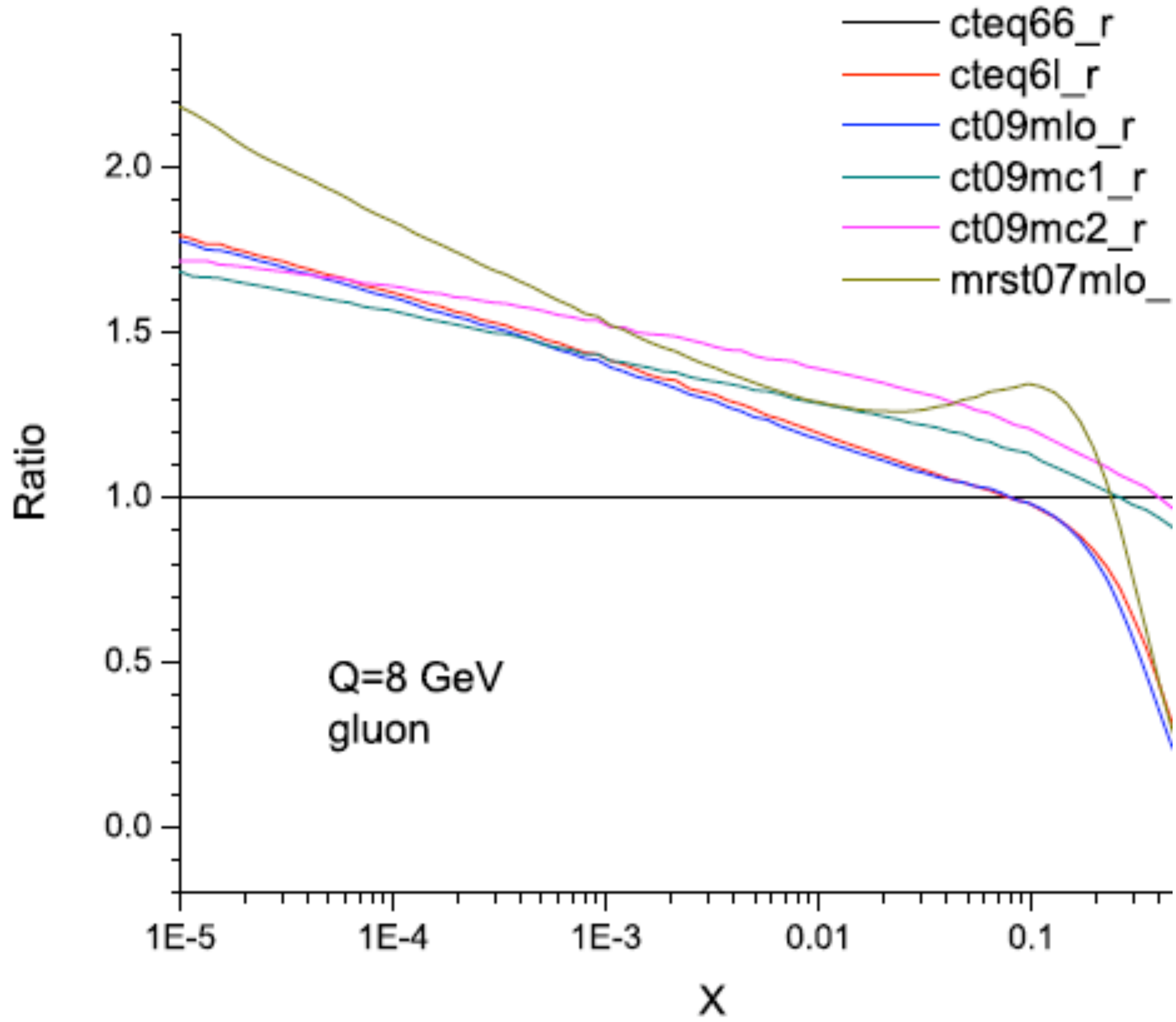
Compare 1-loop and 2-loop mod LO PDFs

- 2-loop slightly higher than 1-loop over most of x range
  - larger α_s for 1-loop version enables easier normalization for pseudo-data
- That's why the violation of the momentum sum rule is larger for the 2-loop



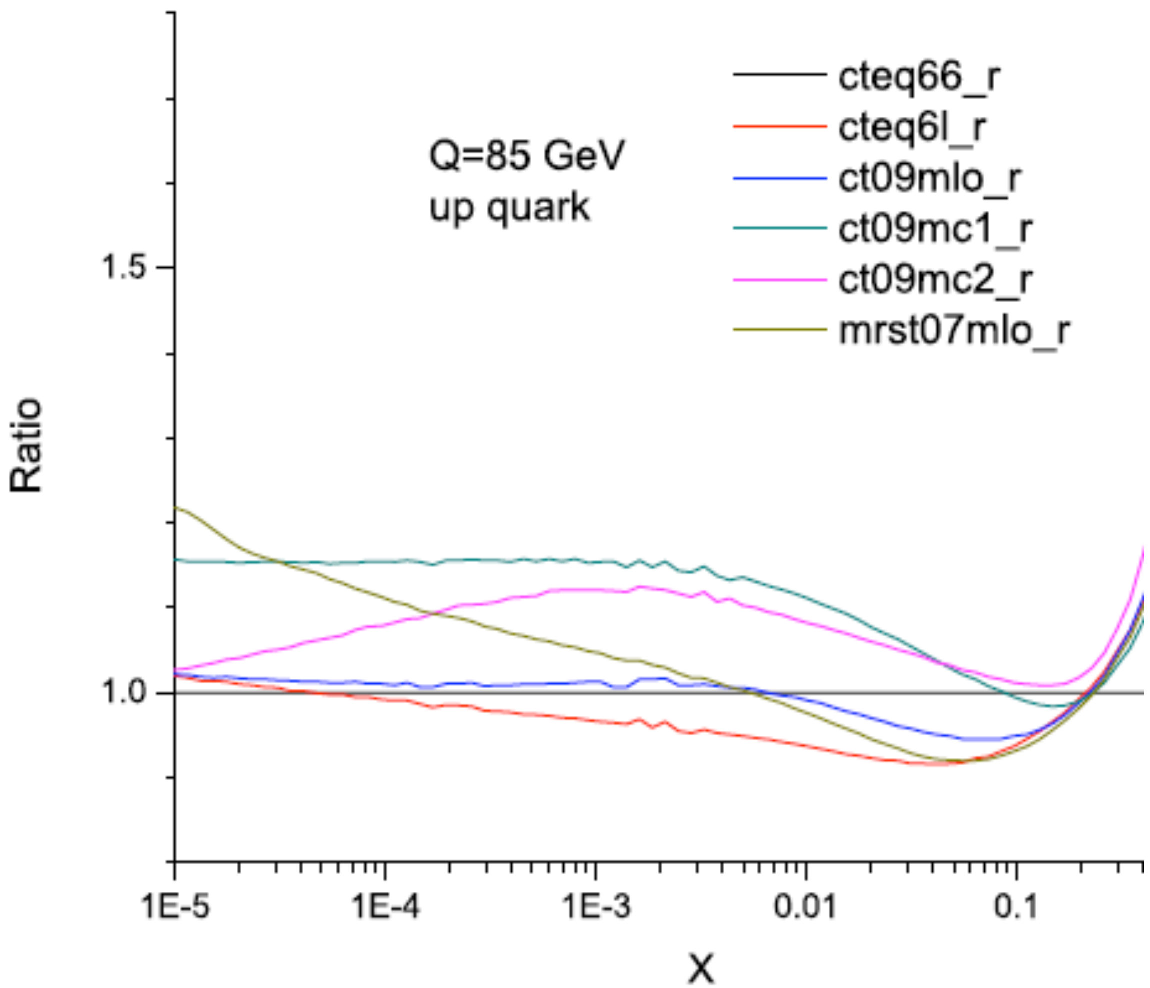
Ratio plot:comparison to CTEQ6.6

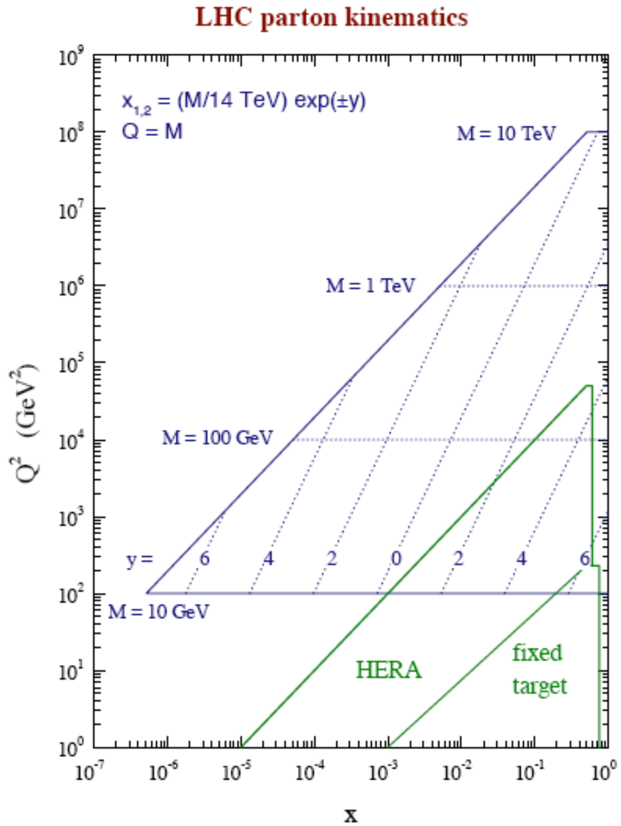
- CTEQ mod LO PDFs higher than CTEQ6.6 up to x ~0.3-0.4



Up quarks at Q=85 GeV

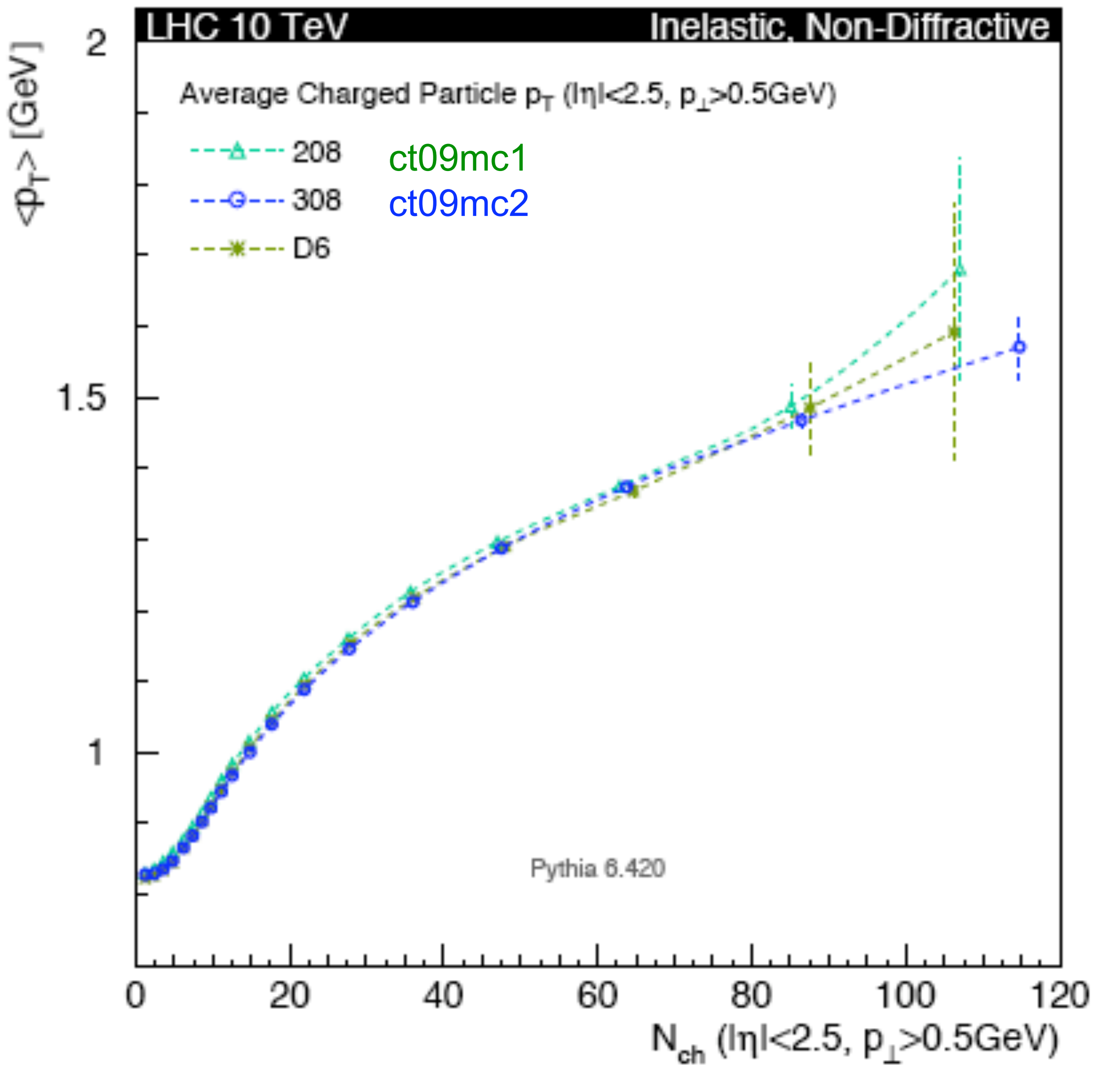
- Larger quark distributions in 1E-04 to 1E-01 lead to higher W/Z cross sections





UE tuning for the LHC

- Working on UE tunes for the new PDFs (S. Mrenna)
- To the right is a comparison to Pythia reference tune D6



Modified LO PDF Summary

- Conventional ways of generating events with LO parton shower Monte Carlos have drawbacks from the point of view of parton distribution functions
- CTEQ mod LO PDFs reduce some of those drawbacks and can be considered as an additional tool for the LHC, leading to better shapes and normalizations with some LHC benchmark cross sections
  - I still also like the option in Pythia8 to be able to use a LO PDF for the UE and parton showering and a NLO PDF for the matrix element evaluation
- Paper almost complete; the two PDFs discussed here will be called
  - ct09mc1: 1-loop
  - ct09mc2: 2-loop
  - working on UE tune(s) and mini-jet implications for the LHC for these two PDFs

CTEQ4LHC/FROOT

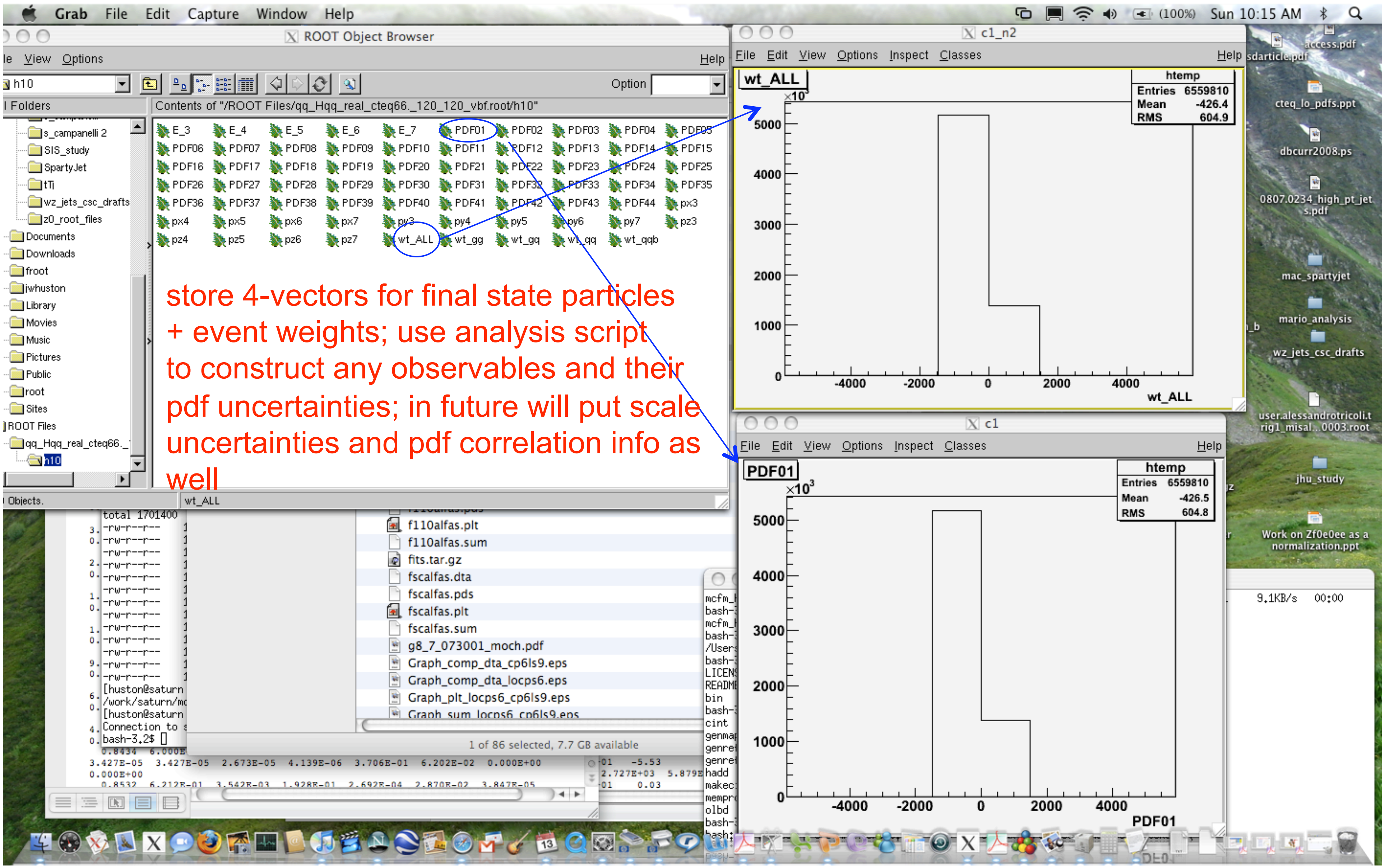
- Collate/create cross section predictions for LHC
  - processes such as W/Z/ Higgs(both SM and BSM)/ diboson/tT/single top/photons/ jets…
  - at LO, NLO, NNLO (where available)
    - new: W/Z production to NNLO QCD and NLO EW
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- As prelude towards comparison with actual data
- Using programs such as:
  - MCFM
  - ResBos
  - Pythia/Herwig/Sherpa
  - … private codes with CTEQ
- First on webpage and later as a report

Primary goal: have all theorists (**including you**) write out parton level output into ROOT ntuples
Secondary goal: make libraries of prediction ntuples available

- FROOT: a simple interface for writing Monte-Carlo events into a ROOT ntuple file
- Written by Pavel Nadolsky (nadolsky@physics.smu.edu)

- CONTENTS
- ========
- froot.c -- the C file with FROOT functions
- taste_froot.f -- a sample Fortran program writing 3 events into a ROOT ntuple
- taste_froot0.c -- an alternative top-level C wrapper (see the compilation notes below)
- Makefile

MCFM 5.3 has FROOT built in



store 4-vectors for final state particles + event weights; use analysis script to construct any observables and their pdf uncertainties; in future will put scale uncertainties and pdf correlation info as well prototype webpage

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

cteq4lhc_higgs

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

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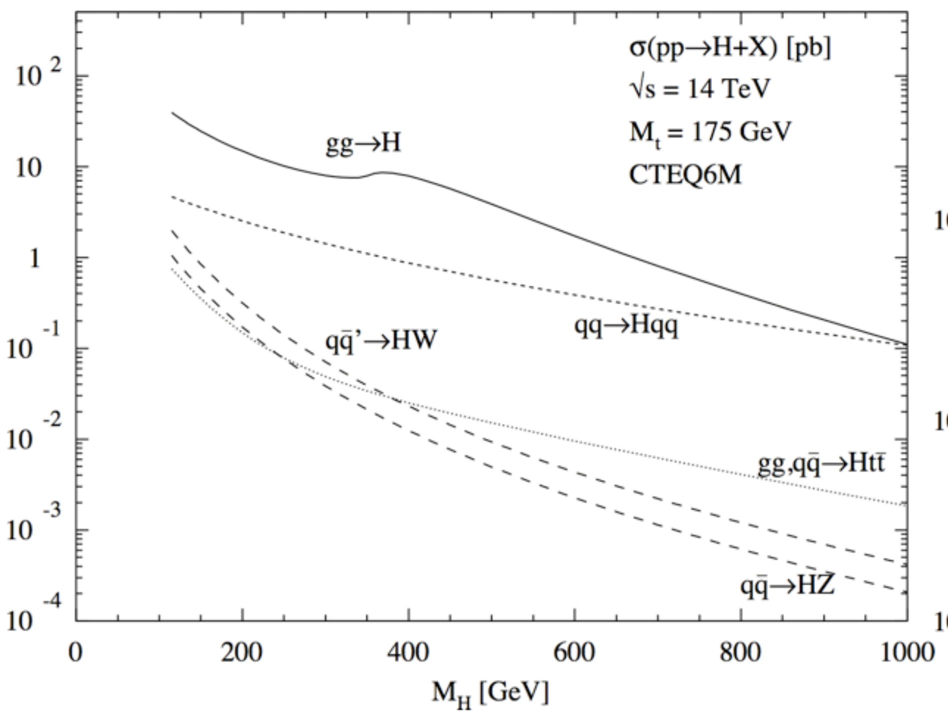
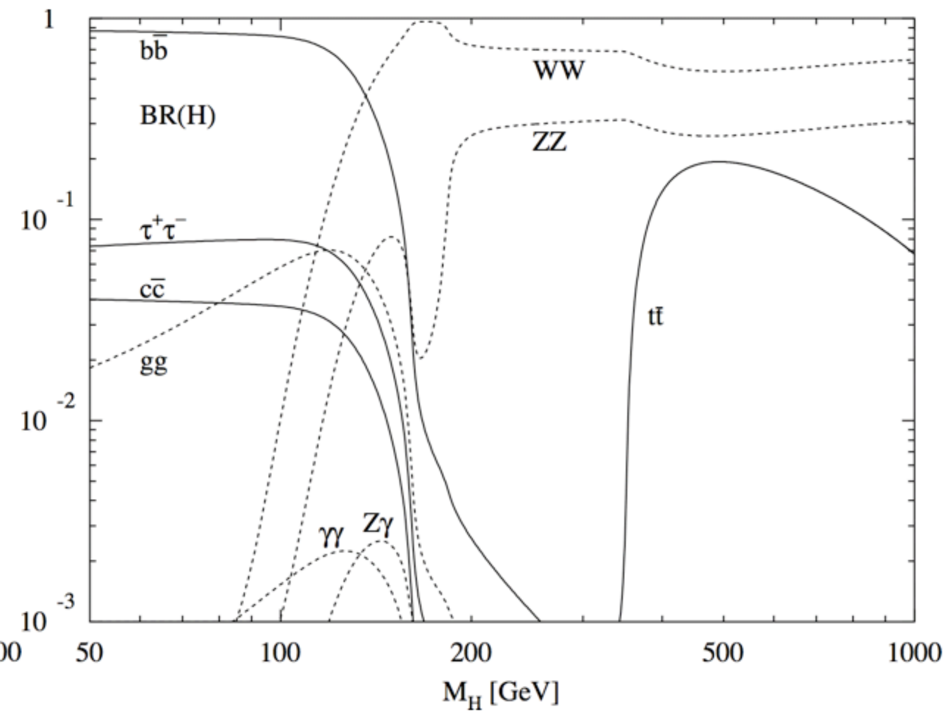
Standard Model Higgs Production at the LHC

The Standard Model inclusive Higgs cross section is known at LO, NLO and NNLO. The Higgs tranverse momentum distribution has been calculated to to NNLO+NNLL. The link to the discussion of Higgs production in CHS can be found here.

The cross section for Higgs production at NLO, using CTEQ6M pdfs, as a function of its mass is shown below. The largest production mechanism is gg fusion, through a top quark loop. The branching ratios for the Standard Model Higgs decay, as a function of its mass are also shown below.



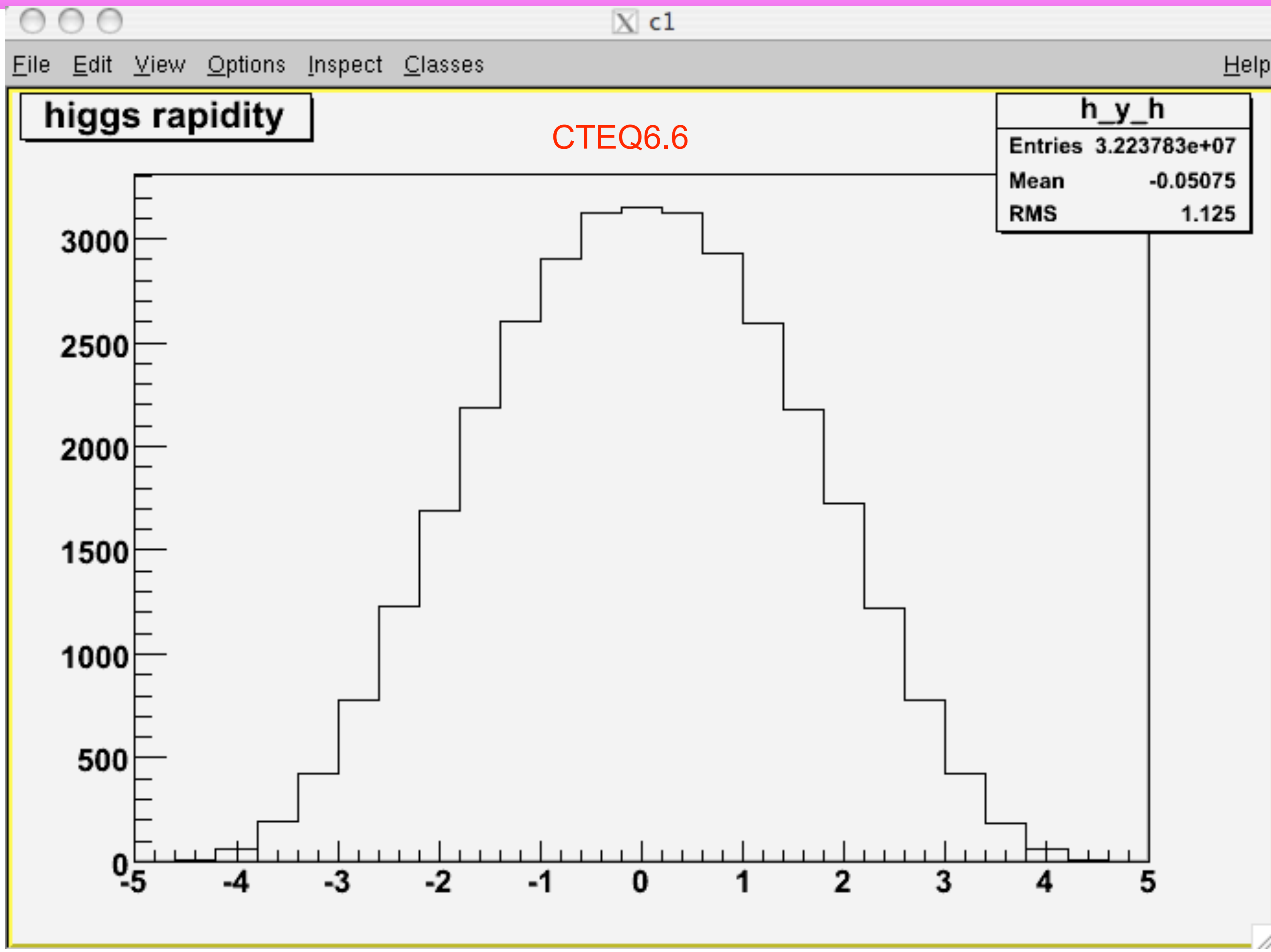


Example:gg->Higgs (125 GeV)

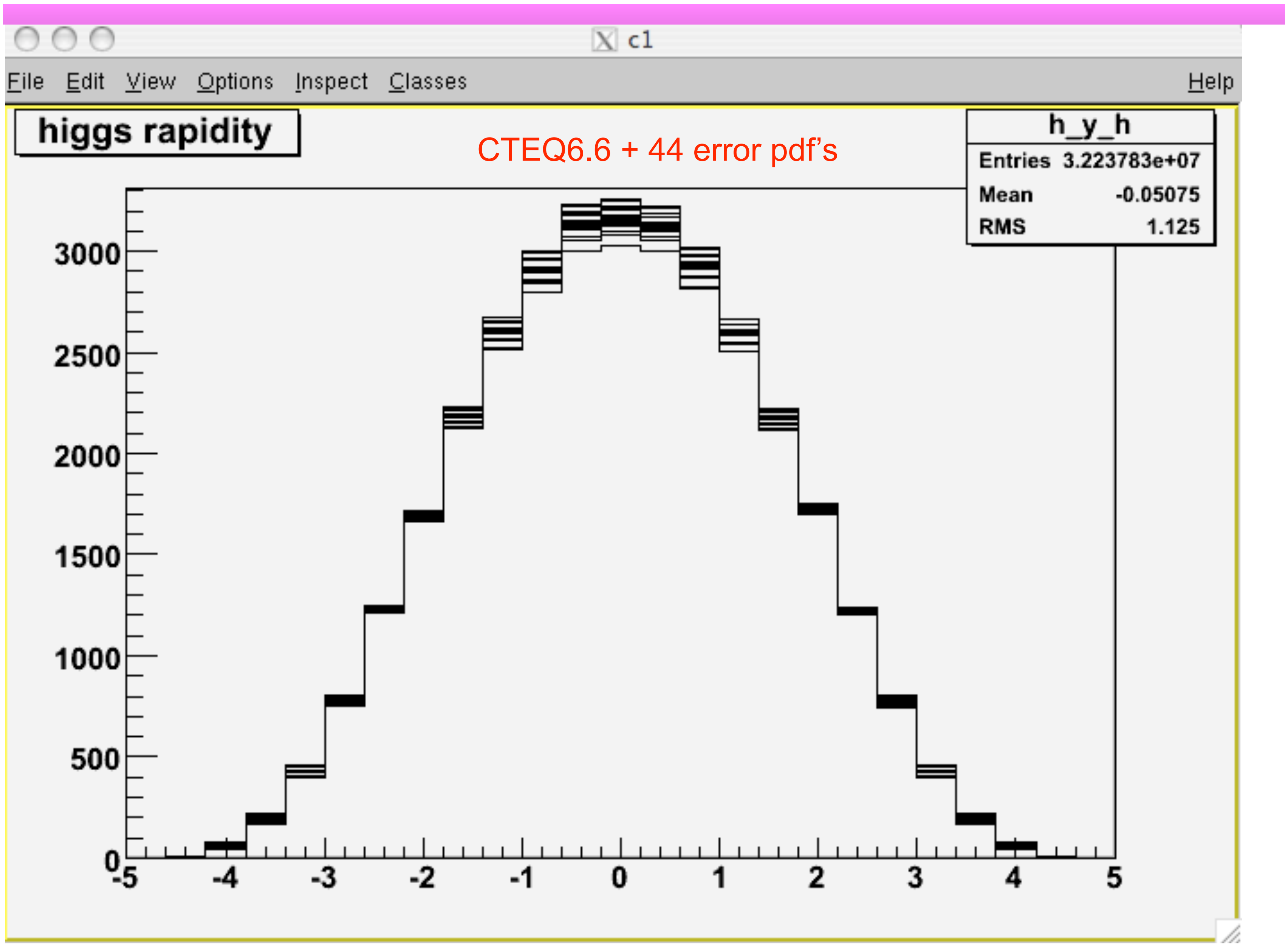
6.6 GB total for real+virtual

```
[huston@saturn 125_E6]$ ls -l
total 6474536
-rw-r--r--    1 huston    users    1900836256 Mar  9 16:00 ggfus0_real_cteq66._125_125_125_
lhc_1.root
-rw-r--r--    1 huston    users    1440740081 Mar  9 19:31 ggfus0_real_cteq66._125_125_125_
lhc_2.root
-rw-r--r--    1 huston    users         38165 Mar  9 19:31 ggfus0_real_cteq66._125_125_125_lh
c.dat
-rw-r--r--    1 huston    users        120912 Mar  9 19:31 ggfus0_real_cteq66._125_125_125_lh
c_error.top
-rw-r--r--    1 huston    users    1902099628 Mar  9 11:46 ggfus0_real_cteq66._125_125_125_
lhc.root
-rw-r--r--    1 huston    users         61186 Mar  9 19:31 ggfus0_real_cteq66._125_125_125_lh
c.top
-rw-r--r--    1 huston    users         27133 Mar 10 11:22 ggfus0_virt_cteq66._125_125_125_lh
c.dat
-rw-r--r--    1 huston    users         19768 Mar 10 11:22 ggfus0_virt_cteq66._125_125_125_lh
c_error.top
-rw-r--r--    1 huston    users    1379302499 Mar 10 11:23 ggfus0_virt_cteq66._125_125_125_
lhc.root
-rw-r--r--    1 huston    users         31156 Mar 10 11:22 ggfus0_virt_cteq66._125_125_125_lh
c.top
-rw-r--r--    1 huston    users         43399 Mar  9 19:31 higgs_125_1E6_real.log
-rw-r--r--    1 huston    users         41181 Mar 10 11:22 higgs_125_1E6_virt.log
-rw-r--r--    1 huston    users         26696 Mar 12 14:07 mcfm_histograms.root
-rw-r--r--    1 huston    users          9360 Mar 12 13:20 read.cc
[huston@saturn 125_E6]$
```

Output plots



Output plots



Summary

- Physics will come flying hot and heavy when LHC turns on in 2009
- Important to establish both the SM benchmarks and the tools we will need to properly understand this flood of data
- Having (only) 200 pb^{-1} of data at 10 TeV may be the best thing for us…understanding before discovery
- …but perhaps not the most exciting
- Much of the work discussed in this talk will continue at Les Houches
- June 8-26, 2009

- Plans for Les Houches
  - collecting results of completed higher order calculations
    - tables, plots and ntuples a la CTEQ4LHC
    - common format for storing parton level information in the ntuples
    - scale variations stored
  - special interest in higher order corrections of Higgs observables
  - missing processes for wishlist
  - standardization of NLO computations
    - minimal agreement on color and helicity management and on passing IR subtraction terms could lead to transportable modules for virtual corrections
  - new techniques for NLO computations
  - IR safe jet algorithms

http://www.lpthe.jussieu.fr/LesHouches09Wiki/index.php/Main_Page

Summary-2

- Update to NLO pdf's
  - recent Tevatron data
    - arXiv:0904.2424
  - eigenvector tools
    - arXiv:0904.2425
- In the near future, CTEQ will also have
  - modified LO pdf's
    - several types
  - combined (x and q_t) pdf fits
    - useful for precision measurements such as W mass
  - NNLO pdf's
    - will then make the relevant Higgs ntuples

- All of our work was made possible by the insight and inspiration of our late colleague Wu Ki Tung

Some references

INSTITUTE OF PHYSICS PUBLISHING REPORTS ON PROGRESS IN PHYSICS
Rep. Prog. Phys. **70** (2007) 89–193 doi:10.1088/0034-4885/70/1/R02

Hard interactions of quarks and gluons: a primer for LHC physics

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Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)

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www.elsevier.com/locate/ppnp

Review

Jets in hadron–hadron collisions

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[e] *Max Planck Institute fur Physics, Munich, Germany*

arXiv:07122447 Dec 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

Contents

New CTEQ technique

- With Hessian method, diagonalize the Hessian matrix to determine orthonormal eigenvector directions; 1 eigenvector for each free parameter in the fit
  - CTEQ6.6 has 22 free parameters, so 22 eigenvectors and 44 error pdf's
  - new NLO pdf's will have 24 free parameters
- Each eigenvector/error pdf has components from each of the free parameters
- Sum over all error pdf's to determine the error for any observable
- But,we are free to make an additional orthogonal transformation that diagonalizes one additional quantity *G*

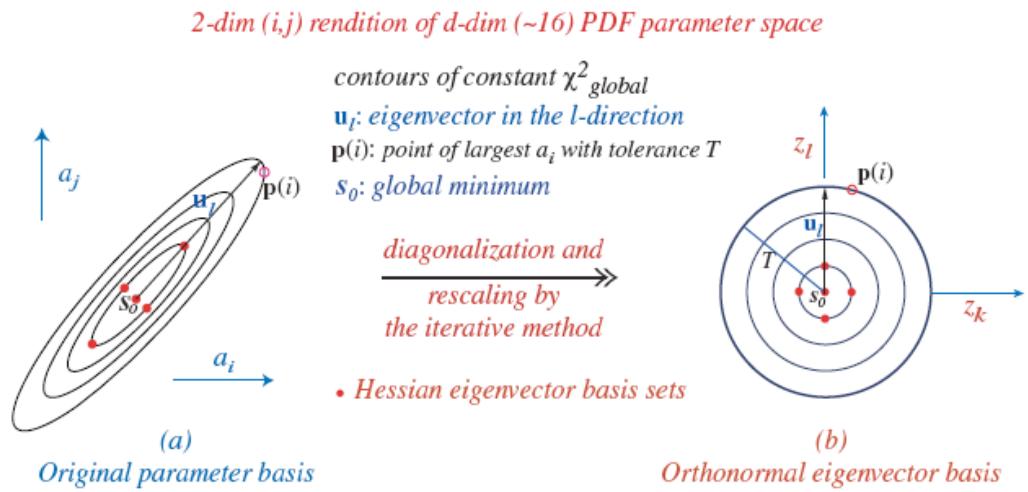

Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

- In these new coordinates, variation in a given quantity is now given by one or a few eigenvectors, rather than by all 44 (or however many)
- *G* may be the W cross section, or the W rapidity distribution or a tT cross section, depending on how clever one wants to be
- In principle these principal error pdf's could be provided as well, for example in CTEQ4LHC ntuples (see later)

Go back to K-factor table

- Some rules-of-thumb
- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - gg->Higgs
  - gg->γγ
  - *K*(gg->tT) > *K*(qQ -> tT)
- NLO corrections decrease as more final-state legs are added
  - *K*(gg->Higgs + 2 jets) < *K*(gg->Higgs + 1 jet) < *K*(gg->Higgs)
  - unless can access new initial state gluon channel
- Can we generalize for uncalculated HO processes?
  - so expect K factor for W + 3 jets or Higgs + 3 jets to be reasonably close to 1

Table 1. K-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15$ GeV and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). In the $W+2$ jet process the jets are separated by $\Delta R > 0.52$, whilst the weak boson fusion (WBF) calculations are performed for a Higgs of mass 120 GeV.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W+1$ jet	m_W	$\langle p_T^{\rm jet}\rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W+2$ jets	m_W	$\langle p_T^{\rm jet}\rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

Casimir color factors for initial state