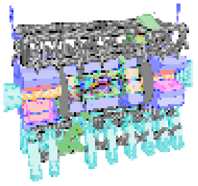


LHC Needs for PDF's (and other stuff)

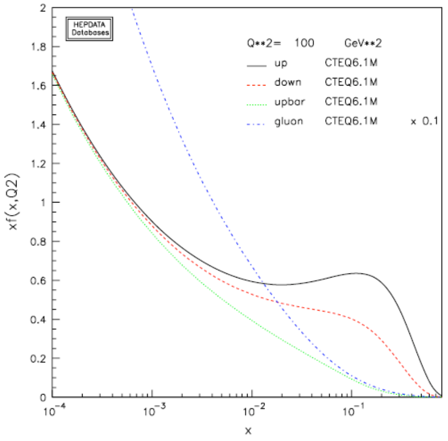
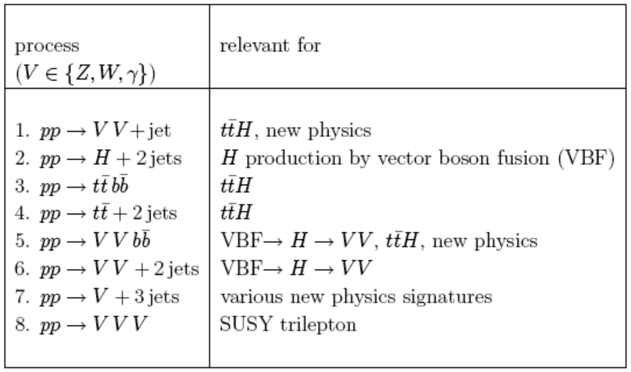


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.



process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$+jet	$t\bar{t}H$, new physics
2. $pp \to H + 2\,\text{jets}$	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2\,\text{jets}$	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2\,\text{jets}$	VBF$\to H \to VV$
7. $pp \to V + 3\,\text{jets}$	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

J. Huston

Michigan State University

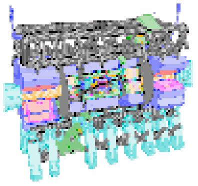
and

IPPP Durham

PDF4LHC meeting

CERN Feb. 21-22, 2008

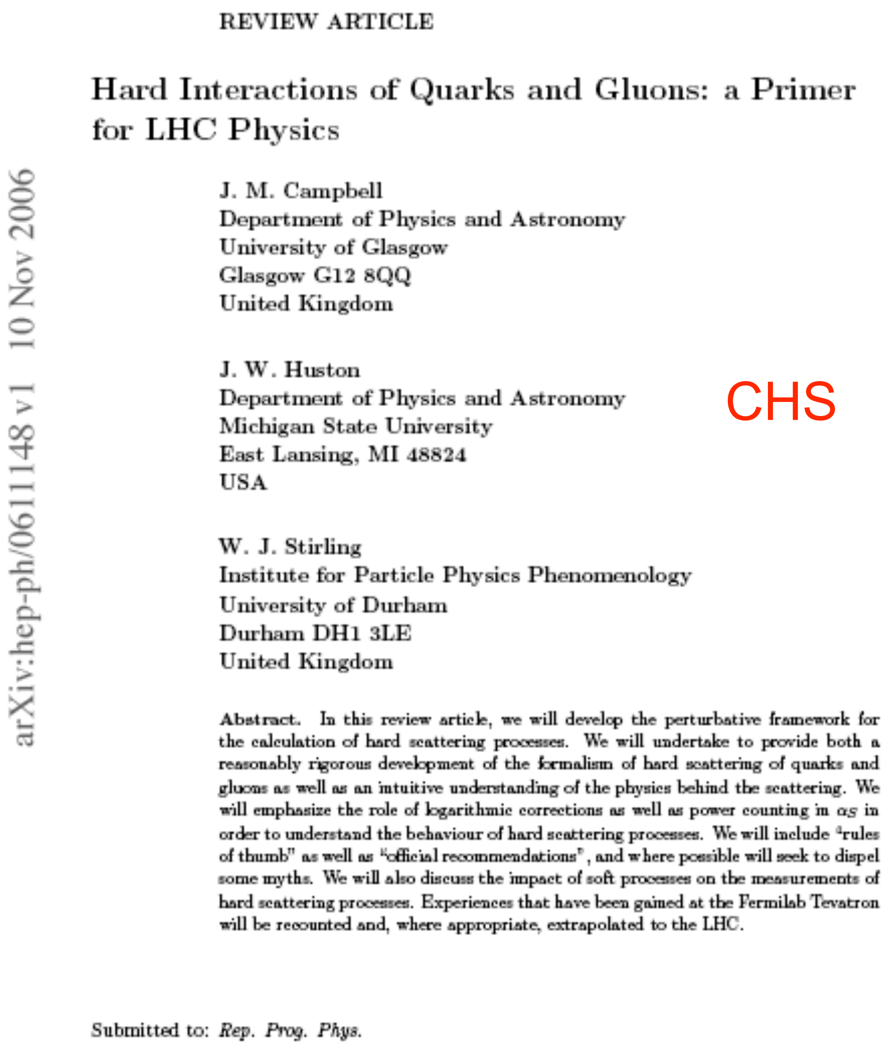
A reference for all of your LHC shopping needs



- online at ROP

http://stacks.iop.org/0034-4885/70/89

Some lecture notes based on review article can be found at www.pa.msu.edu/~huston/seignosse



arXiv:hep-ph/0611148 v1 10 Nov 2006

REVIEW ARTICLE

Hard Interactions of Quarks and Gluons: a Primer for LHC Physics

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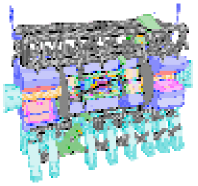
Abstract. In this review article, we will develop the perturbative framework for the calculation of hard scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard scattering of quarks and gluons as well as an intuitive understanding of the physics 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.

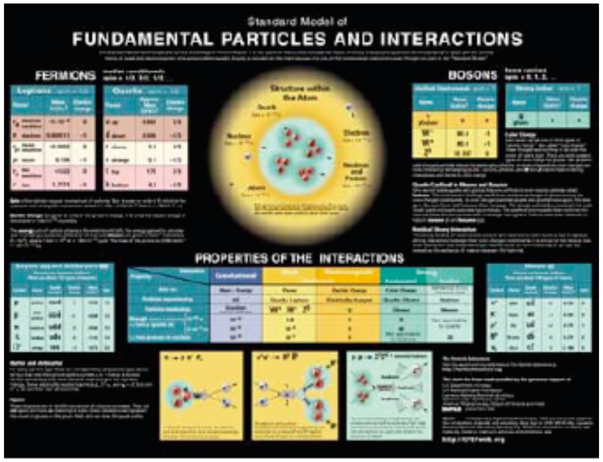
Submitted to: *Rep. Prog. Phys.*

CHS

(Re)Discovering the SM at the LHC



- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
  - PDF's and PDF uncertainties understood correctly

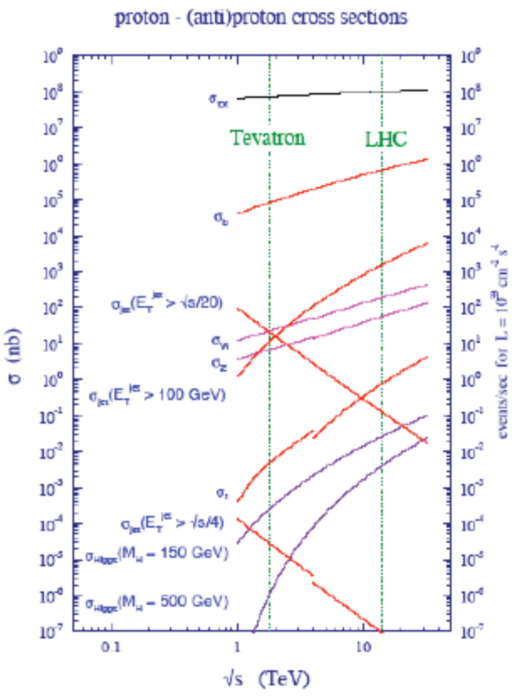


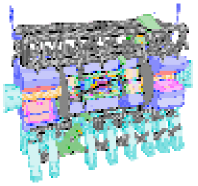
Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS

BOSONS

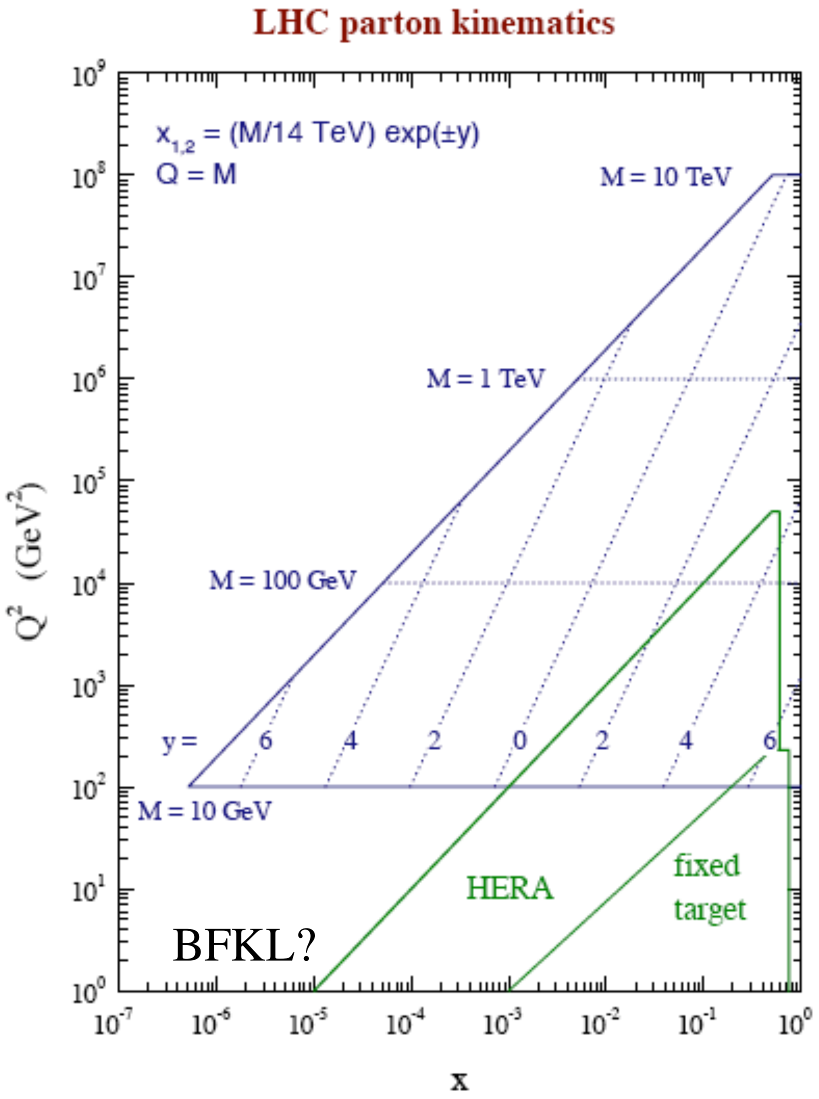
PROPERTIES OF THE INTERACTIONS

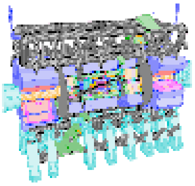




Cross sections at the LHC

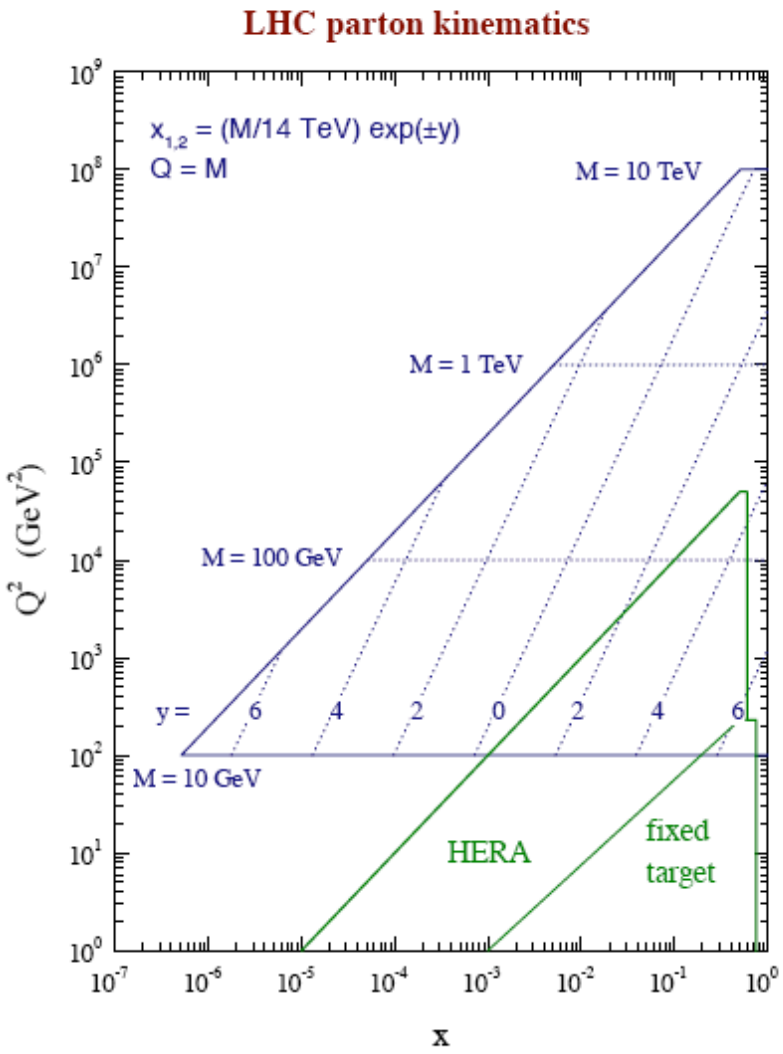
- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x (*Hera-like*) in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
- …and often a larger Q^2 than directly accessible at either HERA or the Tevatron





Parton distribution functions

- Calculation of production cross sections at the LHC relies upon knowledge of pdf’s in the relevant kinematic region
    - at the LHC that region extends down to $x<10^{-5}$ and up to $Q^2>10^7$ GeV^2
- Pdf’s are determined by global analyses of data from DIS, DY and jet production
    - from fixed target, Tevatron and HERA
    - in many cases at smaller Q^2 than needed for LHC calculations
        - so we rely on DGLAP evolution to go up; does NLO DGLAP work or do we need to go to NNLO? and/or add BFKL



ultimately the data will come from LHC as well, but not soon

Parton distribution functions

- Two major groups that provide semi-regular updates to parton distributions when new data/ theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004 ->MSTW
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5/6 *(->CTEQ7)*
- All global analyses use a generic form for the parametrization of both the quark and gluon distributions at some reference value Q_o, where Q_o is usually in the range of 1-2 GeV
- Pdf's are available at LO, NLO and NNLO
- …and *modified LO* pdf's for use with parton shower Monte Carlos; see Sat session

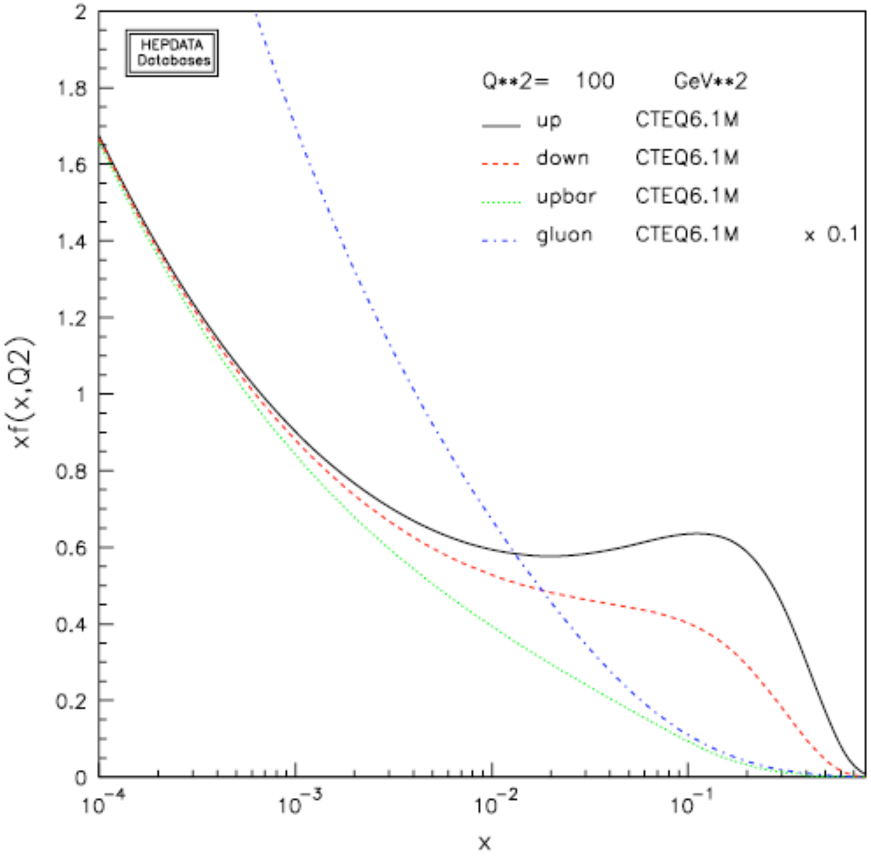
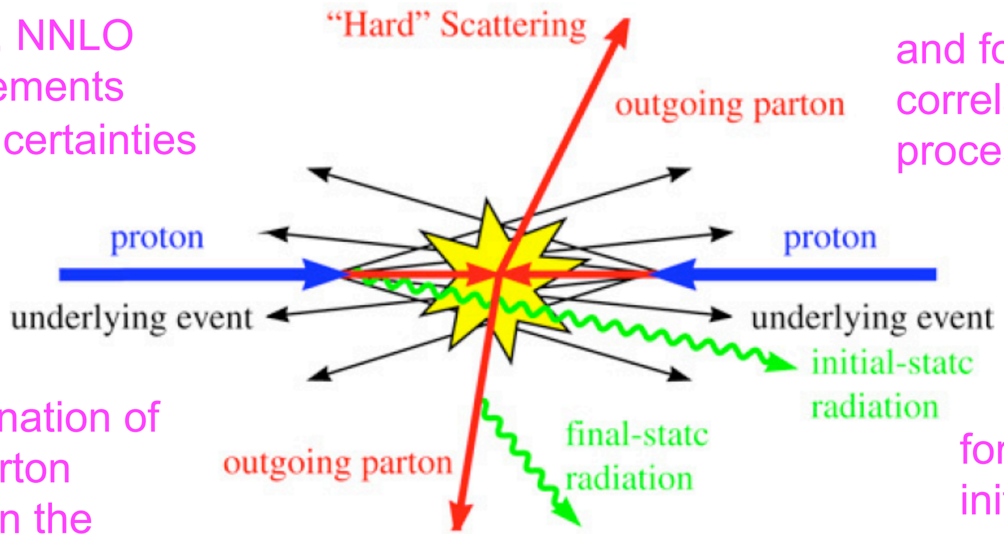


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

$$F(x,\,Q_0) = A_0 x^{A_1}(1-x)^{A_2} P(x;\,A_3,\ldots).$$

So what do we need pdf's for?

for calculation of:
LO, NLO, NNLO
matrix elements
+ their uncertainties



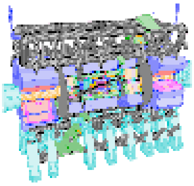
and for calculation of correlations between processes

for determination of multiple parton scattering in the underlying event

for determination of initial state Sudakov form factors, i.e. the parton showering

Most of existing machinery exists for NLO formalism, such as pdf uncertainties.
Most of experimental use is at LO.
Note to self: put plug in for MC@NLO here so Stefano stops bugging me.
NLO is the first order in which you believe the normalization, and in some cases, the shape of any cross section prediction. See later.

Errors in pdf's



- All of the pdf groups provide ways to estimate the error on the central pdf due to experimental uncertainties
  - Hessian methodology enables full characterization of parton parametrization space in neighborhood of global minimum

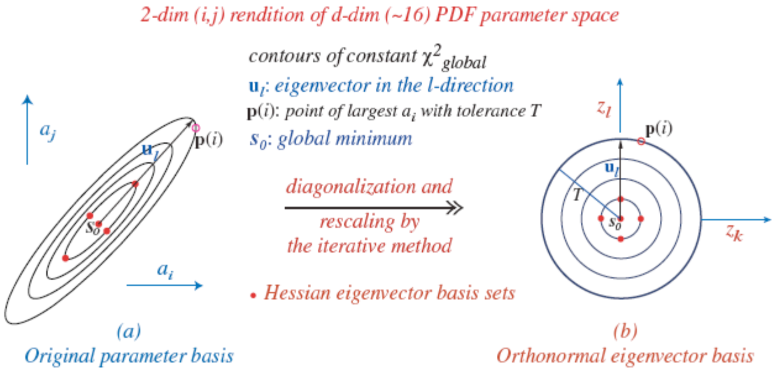


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

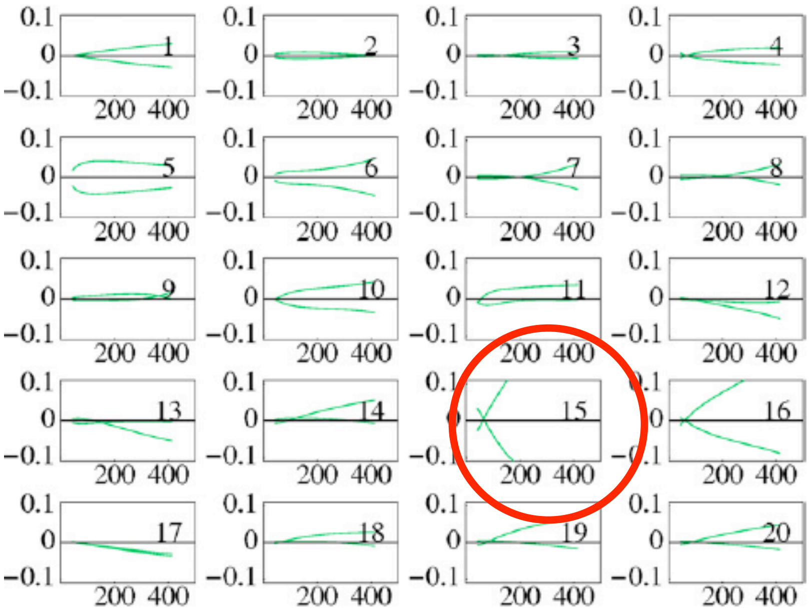
  - CTEQ6.1 has 20 free parameters so 20 directions in eigenvector space

40 error pdfs

$$\Delta X^{+}_{\max} = \sqrt{\sum_{i=1}^{N}[\max(X^{+}_{i} - X_0,\, X^{-}_{i} - X_0,\, 0)]^2},$$

$$\Delta X^{-}_{\max} = \sqrt{\sum_{i=1}^{N}[\max(X_0 - X^{+}_{i},\, X_0 - X^{-}_{i},\, 0)]^2}.$$

Inclusive jets at the Tevatron



eigen-vector 15

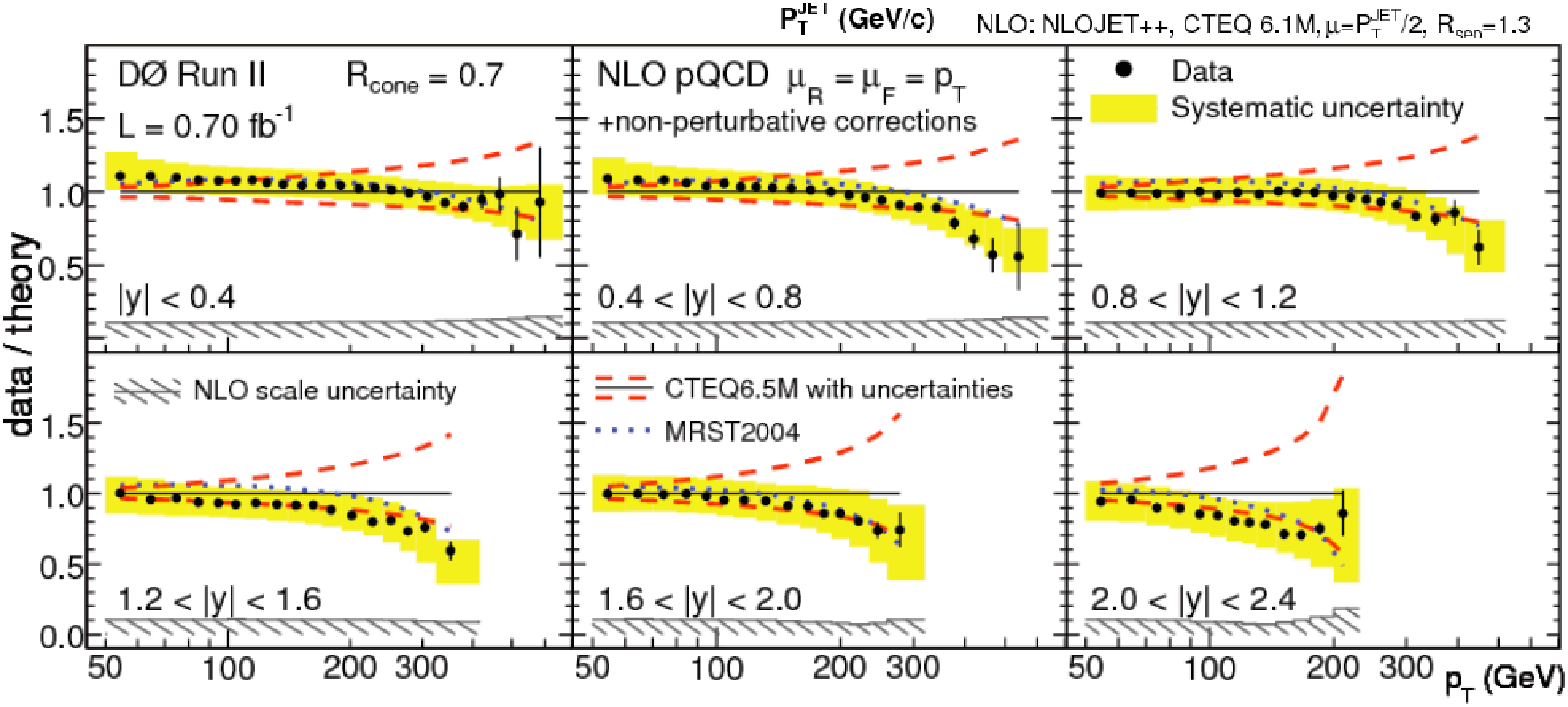
Figure 29. The pdf errors for the CDF inclusive jet cross section in Run 1 for the 20 different eigenvector directions. The vertical axes show the fractional deviation from the central prediction and the horizontal axes the jet transverse momentum in GeV.

▲ theory uncertainties
  ▲ higher twist/non-perturbative effects
    ▲ choose Q^2 and W cuts to avoid
  ▲ higher order effects (NNLO)
  ▲ **heavy quark mass effects (see later)**

Errors in data in (or soon to be in) global fits

Example: Inclusive jets at the Tevatron: M. Voutilainen Fermilab W&C Feb. 15

After years of work, D0 has JES error on order of 1%. Systematic error < pdf uncertainty. This data, along with the similar CDF data, should lead to a reduction of the pdf uncertainty in future fits and perhaps a change to the central pdf.

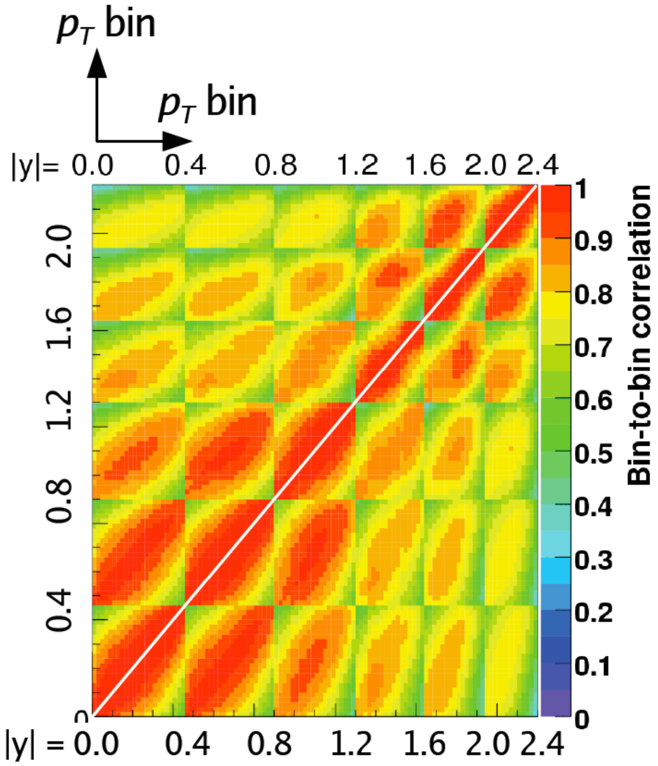


Systematic correlations

As important as the size of the systematic error is the knowledge of the bin-to-bin correlation. The systematic errors can be larger than the pdf uncertainty and still provide useful information that will further restrict the uncertainty, if the correlations are known.

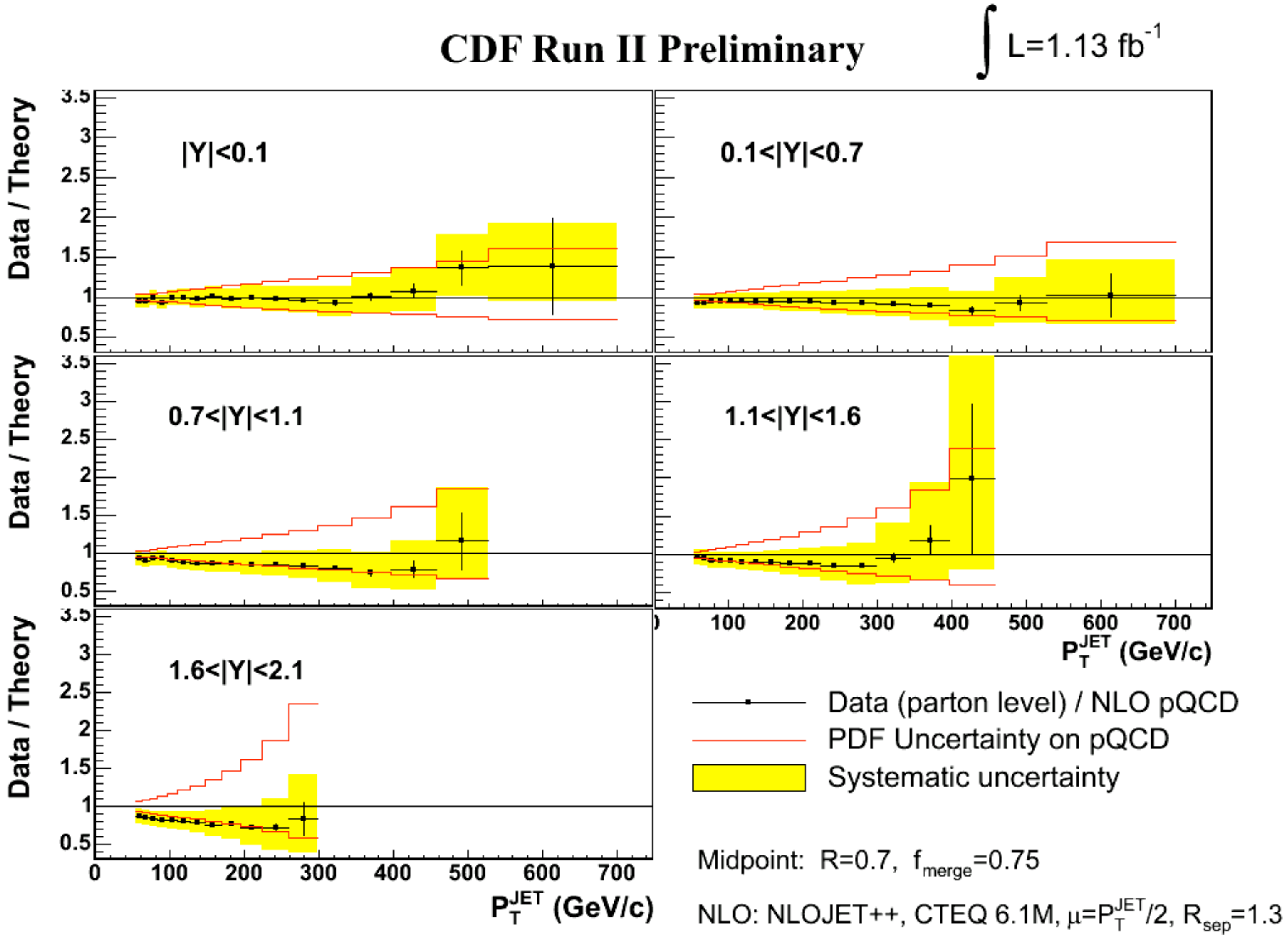
- The uncertainty correlations are provided in the format CTEQ uses: set of independent variations (sources) describing how points move together
- Average bin-to-bin correlation of about **80% with RMS of 10%**
- Using the correlation information in the global PDF fit should **further reduce the effective uncertainty** in the measurement

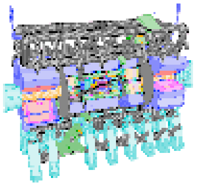
M. Voutilainen Fermilab W&C Feb. 15



Note to LHC: data should be provided in a fully corrected form (hadron level, with hadron to parton corrections if possible) with full information about correlated systematic errors to be of maximal use in global pdf fitting

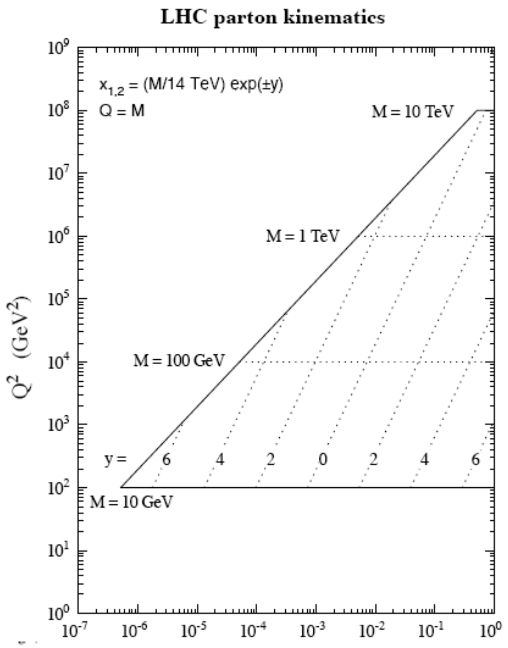
CDF Run 2 midpoint results





Aside: parton kinematics

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity
  - this is from the review paper (CHS) and the Les Houches 2005 writeup
- 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



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

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

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

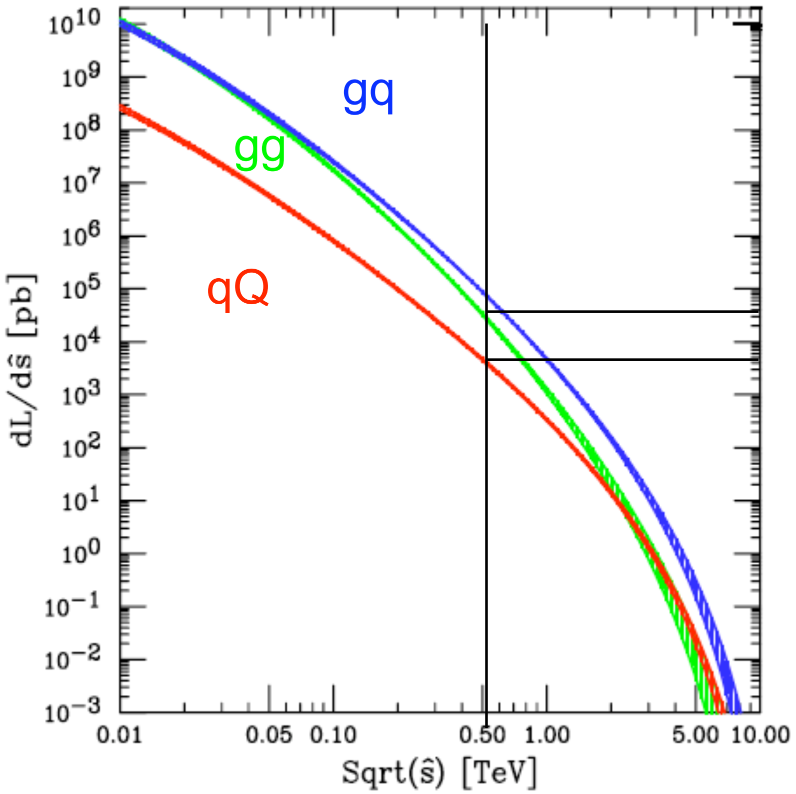
can then be written as

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

Cross section estimates

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

@500 GeV tT mass, gg factor of 10 larger than qQ; σxs factors ~ same;
~1 * 4E4 pb * 0.012 = order of 500 pb (LO)



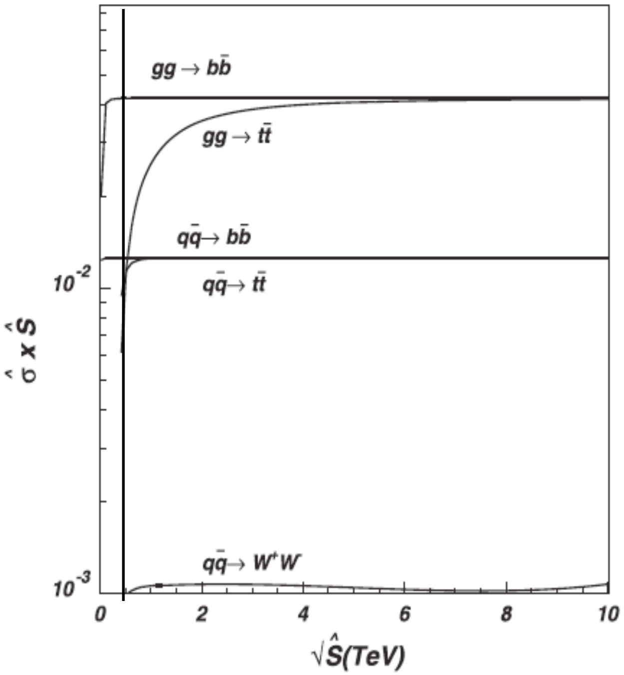
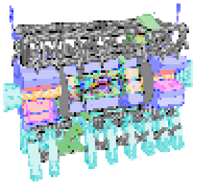


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

Note threshold behavior for gg more complex than for qQ

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 uncertainties at the LHC

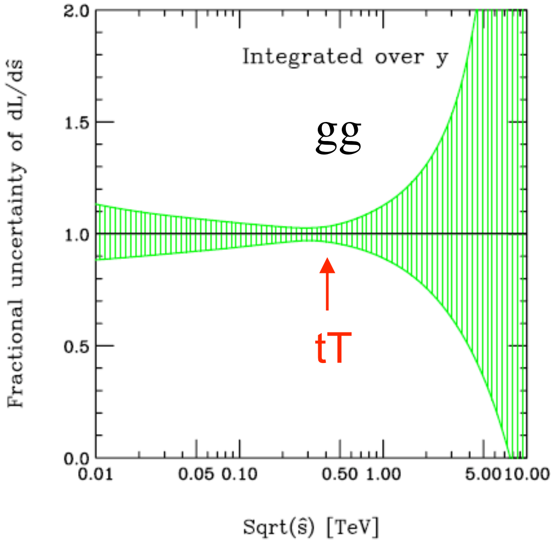


Fig. 4: Fractional uncertainty of gg luminosity integrated

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

Need similar level of precision in theory calculations. i.e. NLO and NNLO

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

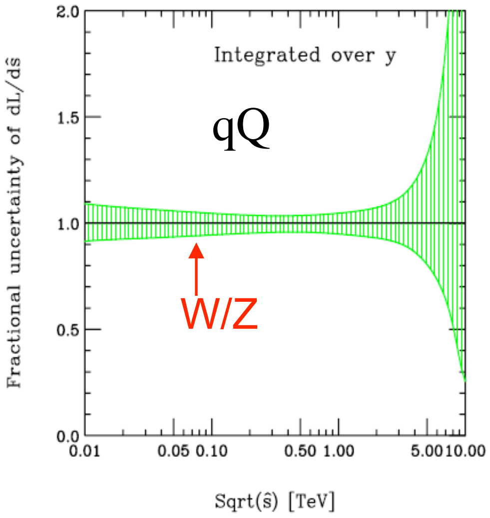


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

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

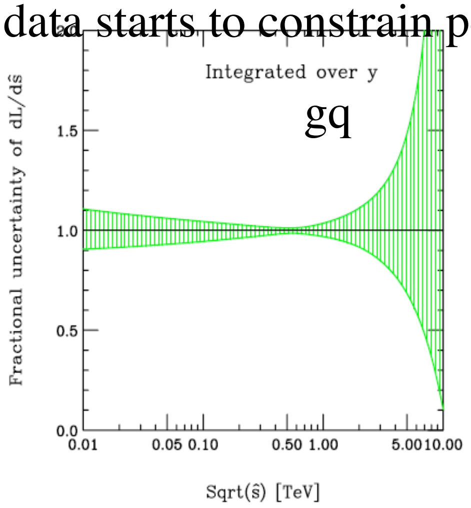
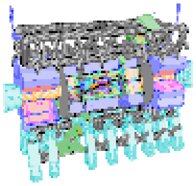


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

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

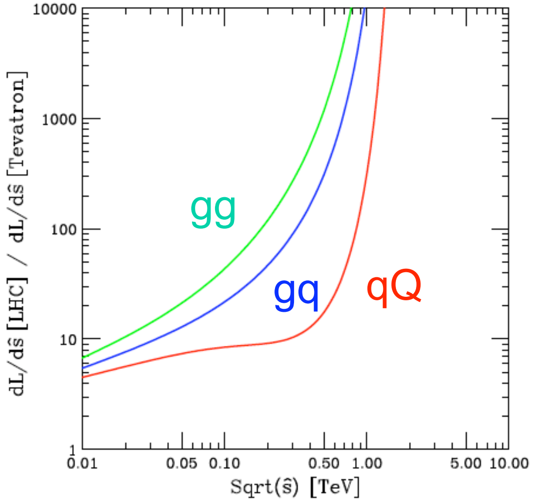


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

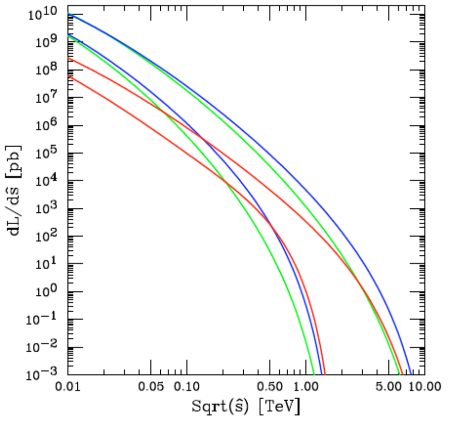


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

NLO corrections

- NLO is the first order for which the normalization, and sometimes the shape, is believable
- NLO is necessary for precision comparisons of data to theory
- Sometimes backgrounds to new physics can be extrapolated from non-signal regions, but this is difficult to do for low cross section final states and/or final states where a clear separation of a signal and background region is difficult

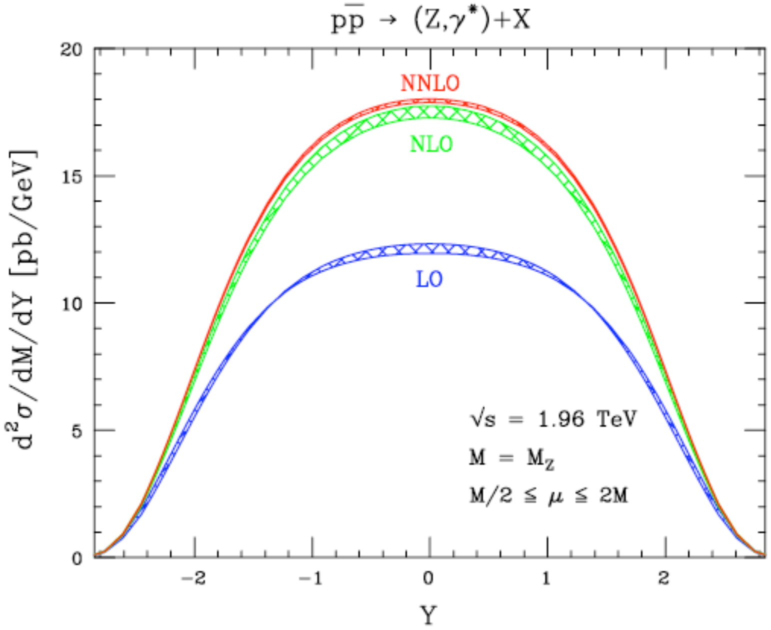


Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

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.

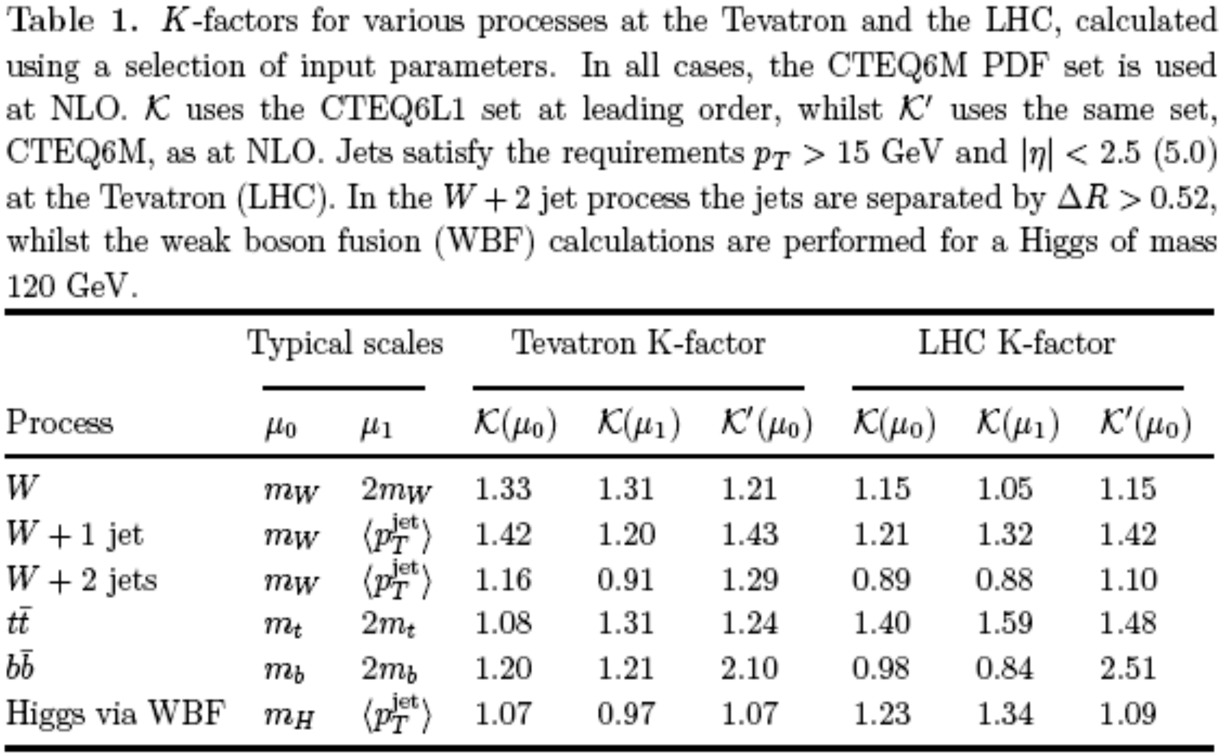
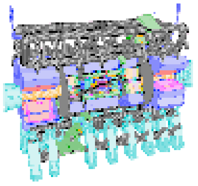


Table 1. K-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15$ 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.

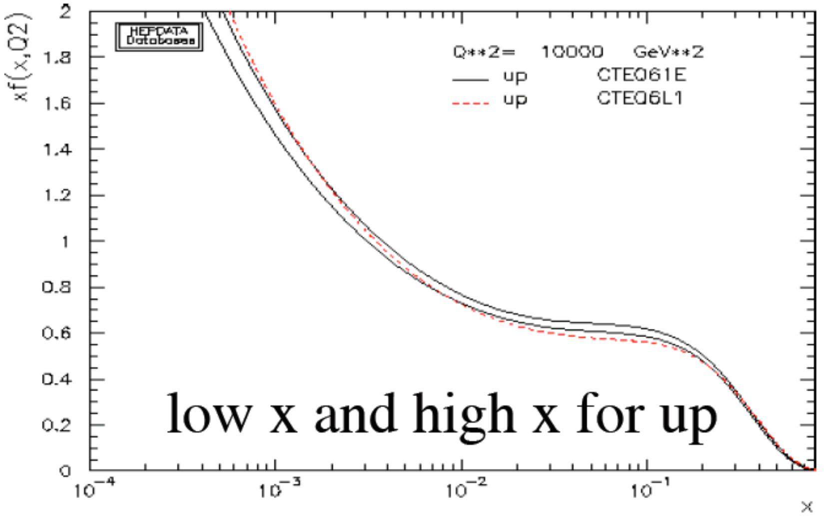
	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W + 1$ jet	m_W	$\langle p_T^{\text{jet}} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W + 2$ jets	m_W	$\langle p_T^{\text{jet}} \rangle$	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	$\langle p_T^{\text{jet}} \rangle$	1.07	0.97	1.07	1.23	1.34	1.09
Higgs + 1 jet						1.42		
Higgs + 2 jets						1.15		
tT + 1 jet			1.19	1.37	1.26	0.97	1.29	1.10

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

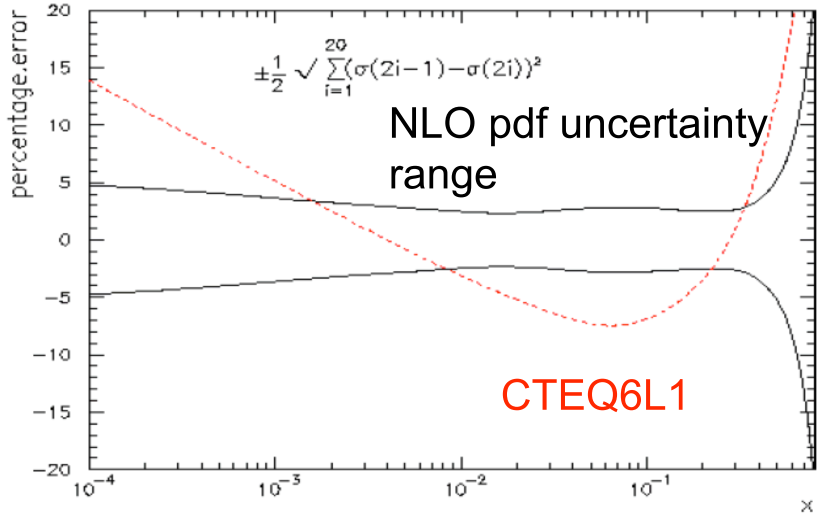
What pdf's to use in parton shower Monte Carlos?



- No question in MC@NLO: NLO pdf's
- Traditional answer for LO MC's has been LO pdf's,BUT…
    - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
    - DIS data in global fits affect LO pdf's in ways that may not directly transfer to LO hadron collider predictions
    - LO pdf's for the most part are outside the NLO pdf error band
    - experimenters use the NLO error pdf's in combination with the central LO pdf even with this mis-match
    - LO matrix elements for many of the processes that we want to calculate are not so different from NLO matrix elements
    - by adding parton showers, we are partway towards NLO anyway



low x and high x for up

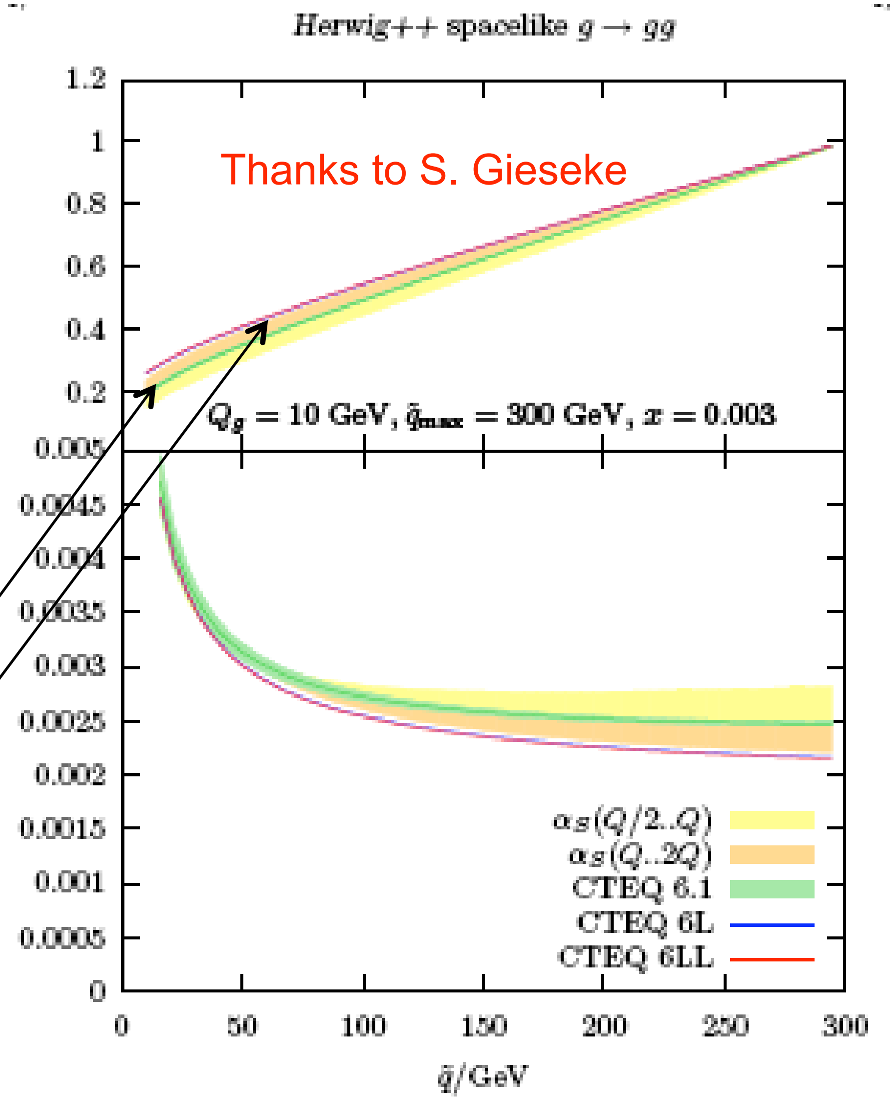


NLO pdf uncertainty range

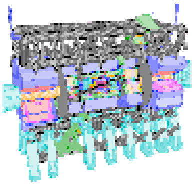
CTEQ6L1

Sudakov’s and LO/NLO pdf’s

- Sudakov form factors form the basis for parton showers
- Typically at both the Tevatron and LHC, MC events are generated with a LO pdf and then pdf uncertainty is evaluated by performing a pdf re-weighting using the NLO error pdf’s
- Works if Sudakov is the same for the LO pdf and the NLO error pdf’s
- NLO pdf error band very small
- LO Sudakov outside this error band, so ISR not correct for re-weighted events generated using LO pdf
- Need to generate MC events and to evaluate pdf’s with same order



Thanks to S. Gieseke



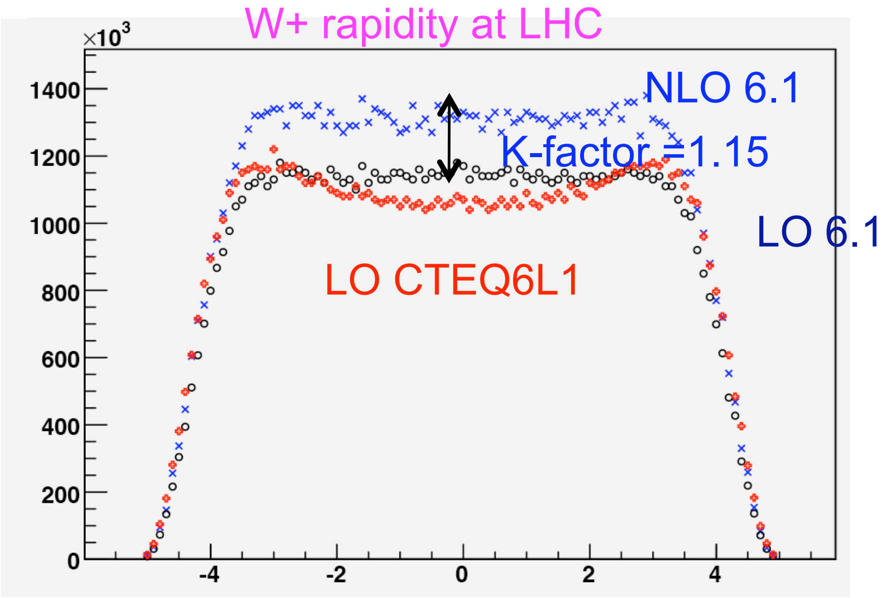
Modified LO pdf's

- LO pdf's result in bad behavior for many important physics distributions at the LHC
  - see W+ rapidity distribution
- But NLO pdf's would cause some bad behavior in other regions
  - see bB distributions for low mass
- …and UE models tied to existing behavior of low x gluon of LO pdf's
  - and Torbjorn doesn't like the idea of using NLO pdf's

Solution: modified LO pdf's which try to mimic the best behaviors of LO and NLO pdf's in the relevant kinematic regions

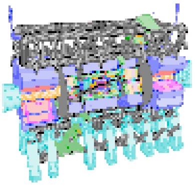
..maybe at the expense of the momentum sum rule, but who's counting (at LO)

need also rational error pdf structure to accompany modified LO pdf's



This has been a hot topic, especially since Les Houches. See session Saturday afternoon.

NLO calculation priority list from Les Houches 2005: theory benchmarks



G. Heinrich and J. Huston

process ($V \in \{Z, W, \gamma\}$)	relevant for	
1. $pp \to V\,V$+jet	$t\bar{t}H$, new physics	*
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)	*
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$	+
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics	
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$	
7. $pp \to V + 3$ jets	various new physics signatures	+
8. $pp \to V\,V\,V$	SUSY trilepton	*

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

pp->bBbB
pp->4 jets
gg->W*W*
pp->W/Z NNLO QCD and NLO EW

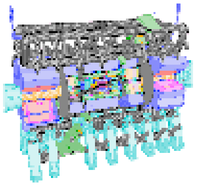
added in 2007

*completed since list
+people are working

- $pp \to$ VV + jet: One of the most promising channels for Higgs production in the low mass range is through the $H \to WW^*$ channel, with the W's decaying semi-leptonically. It is useful to look both in the $H \to WW$ exclusive channel, along with the $H \to WW$+jet channel. The calculation of $pp \to WW$+jet will be especially important in understanding the background to the latter.
- $pp \to H$+2 jets: A measurement of vector boson fusion (VBF) production of the Higgs boson will allow the determination of the Higgs coupling to vector bosons. One of the key signatures for this process is the presence of forward-backward tagging jets. Thus, QCD production of H + 2 jets must be understood, especially as the rates for the two are comparable in the kinematic regions of interest.
- $pp \to t\bar{t}b\bar{b}$ and $pp \to t\bar{t}$ + 2 jets: Both of these processes serve as background to $t\bar{t}H$, where the Higgs decays into a $b\bar{b}$ pair. The rate for $t\bar{t}jj$ is much greater than that for $t\bar{t}b\bar{b}$ and thus, even if 3 b-tags are required, there may be a significant chance for the heavy flavour mistag of a $t\bar{t}jj$ event to contribute to the background.
- $pp \to VVb\bar{b}$: Such a signature serves as non-resonant background to $t\bar{t}$ production as well as to possible new physics.
- $pp \to$ VV + 2 jets: The process serves as a background to VBF production of Higgs.
- $pp \to$ V + 3 jets: The process serves as background for $t\bar{t}$ production where one of the jets may not be reconstructed, as well as for various new physics signatures involving leptons, jets and missing transverse momentum.
- $pp \to VVV$: The process serves as a background for various new physics subprocesses such as SUSY tri-lepton production.

[23] Process 2 has been calculated since the first version of this list was formulated [138].

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available? See e.g. H + 2 jets. Other processes are going to be just as complex. What about other processes for which we are theorist/time-limited?



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

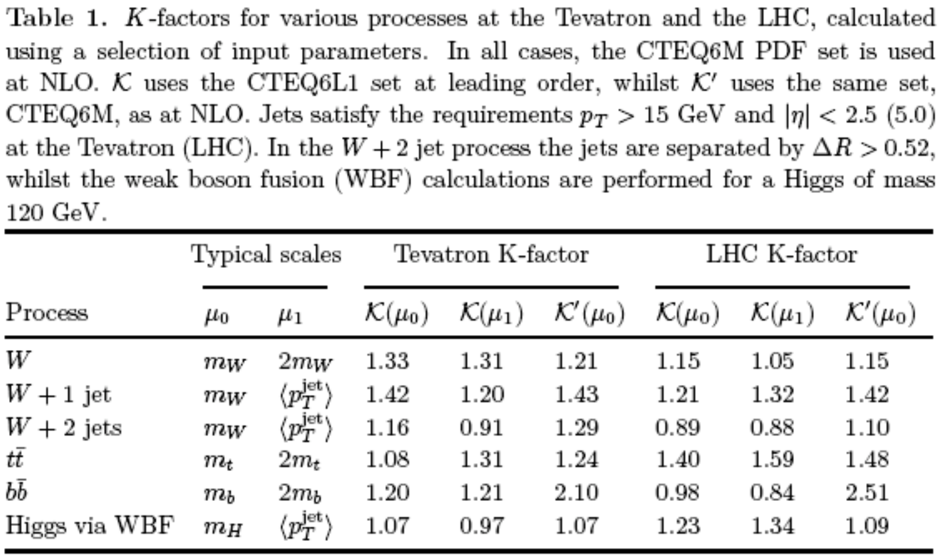


Table 1. K-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15$ 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.

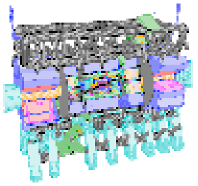
	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W+1$ jet	m_W	$\langle p_T^{\text{jet}} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W+2$ jets	m_W	$\langle p_T^{\text{jet}} \rangle$	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	$\langle p_T^{\text{jet}} \rangle$	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



Don’t forget

- NNLO: we need to know some processes (such as inclusive jet production) at NNLO
    - for inclusion of inclusive jet data in global pdf fits, from Tevatron for now, but ultimately from LHC as well
- Resummation effects: affect important physics signatures
    - has not been taken into account in global fits so far
    - CTEQ project: combined p_T and x global fit

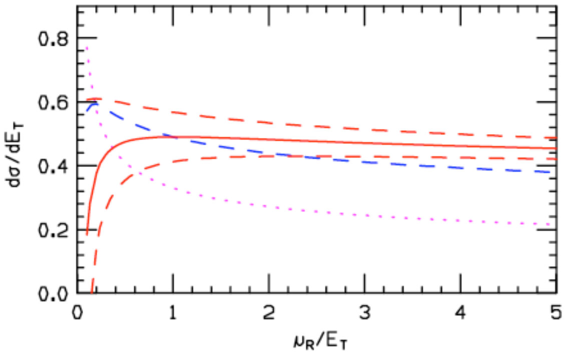


Figure 16. The single jet inclusive distribution at $E_T = 100$ GeV, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

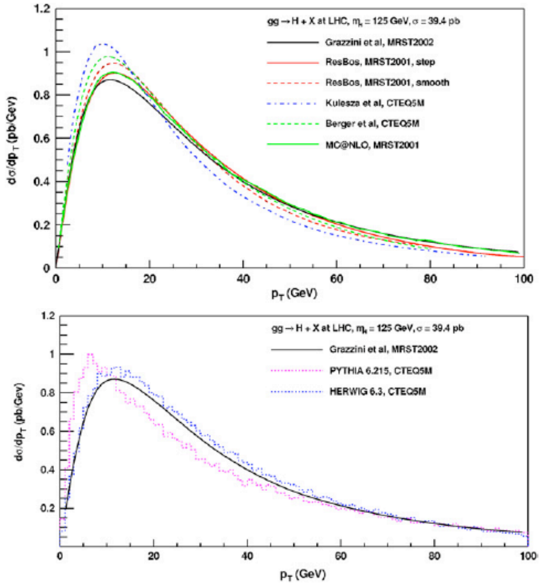


Figure 102. The predictions for the transverse momentum distribution for a 125 GeV mass Higgs boson at the LHC from a number of theoretical predictions. The predictions have all been normalized to the same cross section for shape comparisons. This figure can also be viewed in colour on the benchmark website.

…and

- BFKL logs: will we finally see them at the LHC? Will evolution formalism have to be modified to take them into account?
- EW logs: $\alpha_W \log^2(p_T^2/m_W^2)$ can be a big number at the LHC

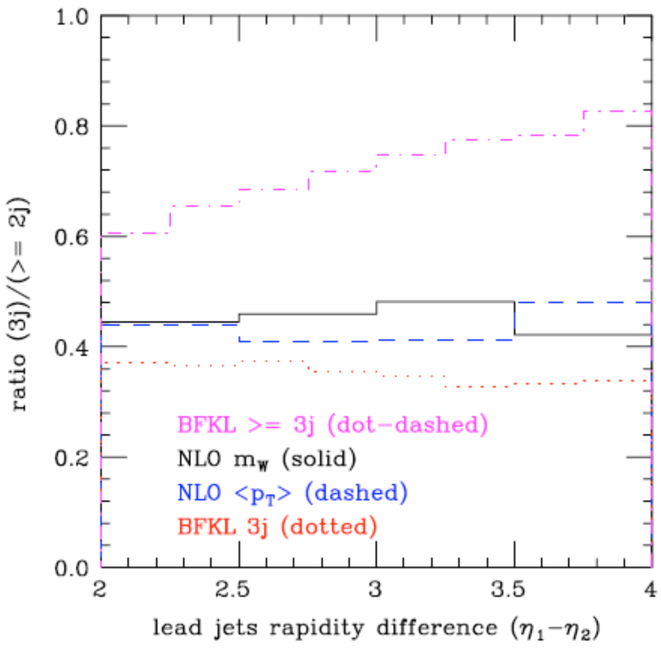
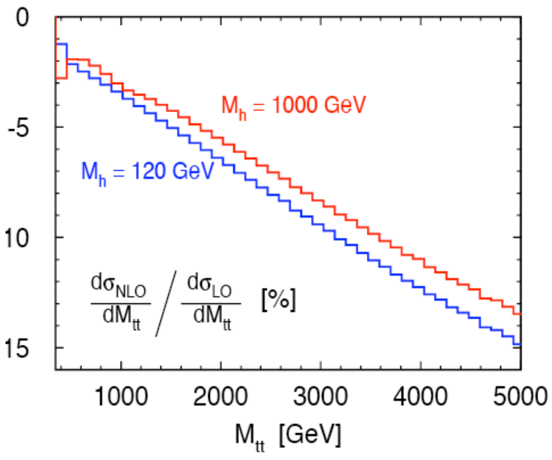


Figure 92. The rate for production of a third (or more) jet in $W+\geqslant 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale, and using the BFKL formalism, requiring either that there be exactly 3 jets or 3 or more jets.



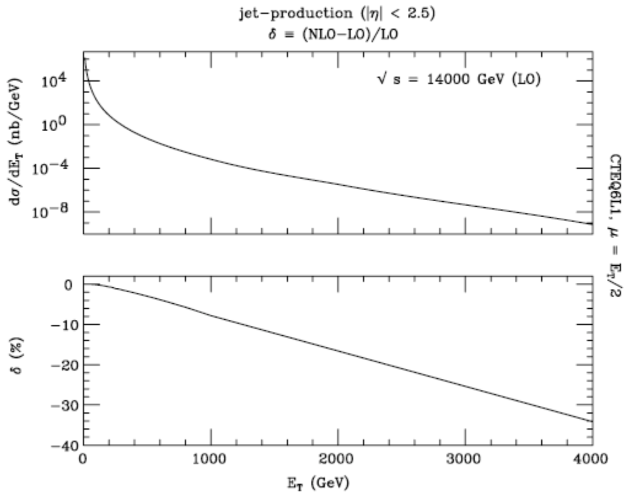
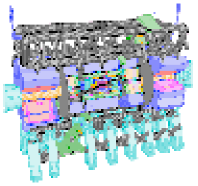


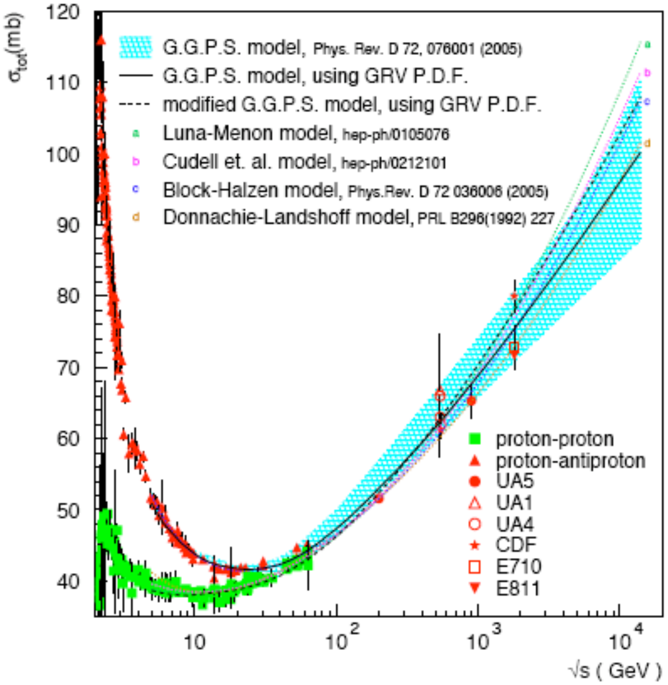
Figure 107. The effect of electroweak logarithms on jet cross sections at the LHC.



Cross section determinations at the LHC

$$\sigma = \frac{\#\,\text{events} * \text{acceptance}}{L}$$

- L depends on a knowledge of the total inelastic cross section and of the fraction of the cross section accessed by the trigger
- Fair amount of uncertainty on extrapolation to LHC
  - ln(s) or $\ln^2(s)$ behavior
  - rely on Roman pot measurements
    - not right away
  - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)



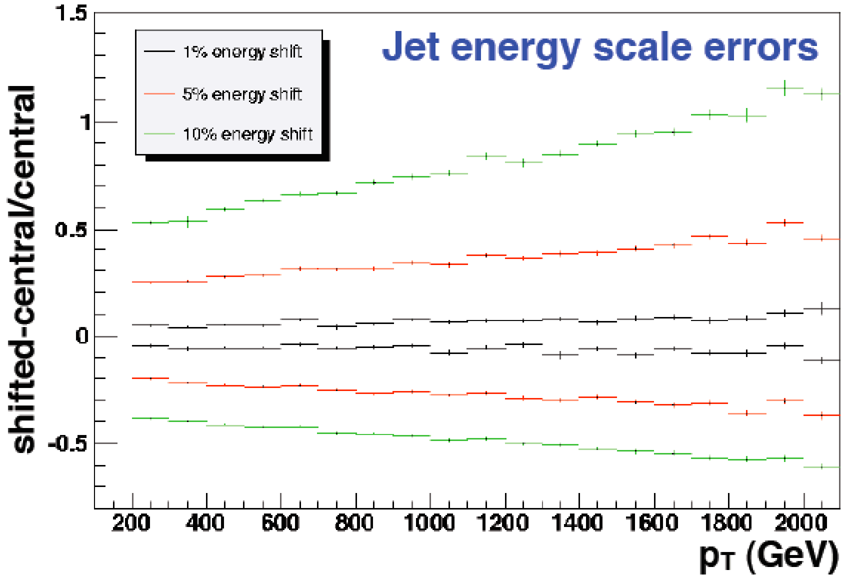
don't expect better than a 15-20% uncertainty on any cross section during first year of running; (ultimately maybe 5%)

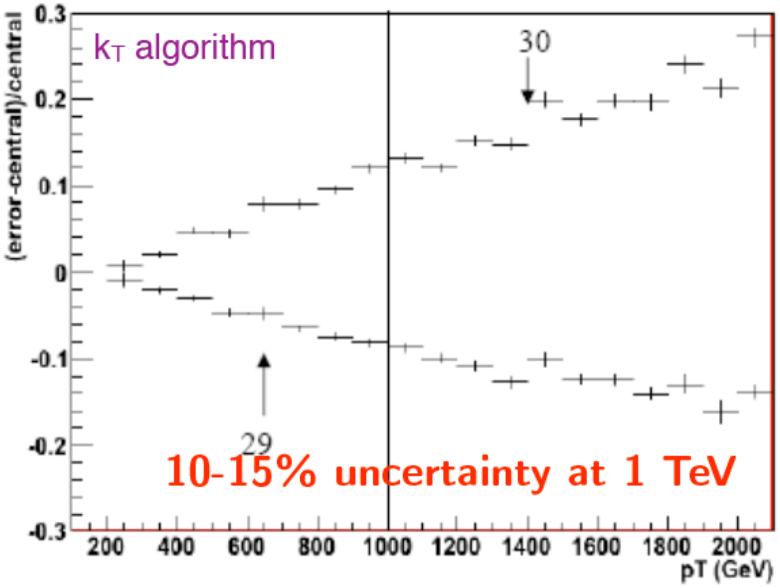
>>pdf uncertainties

we need precision cross sections to normalize to, at first and maybe always

(Early) Cross sections at LHC

- We are not going to know L to better than 15-20%
- We are going to have large systematic errors (JES ~>5%)
- Global pdf fits are precision physics; LHC data may not be in that category at first
- …with some possible exceptions

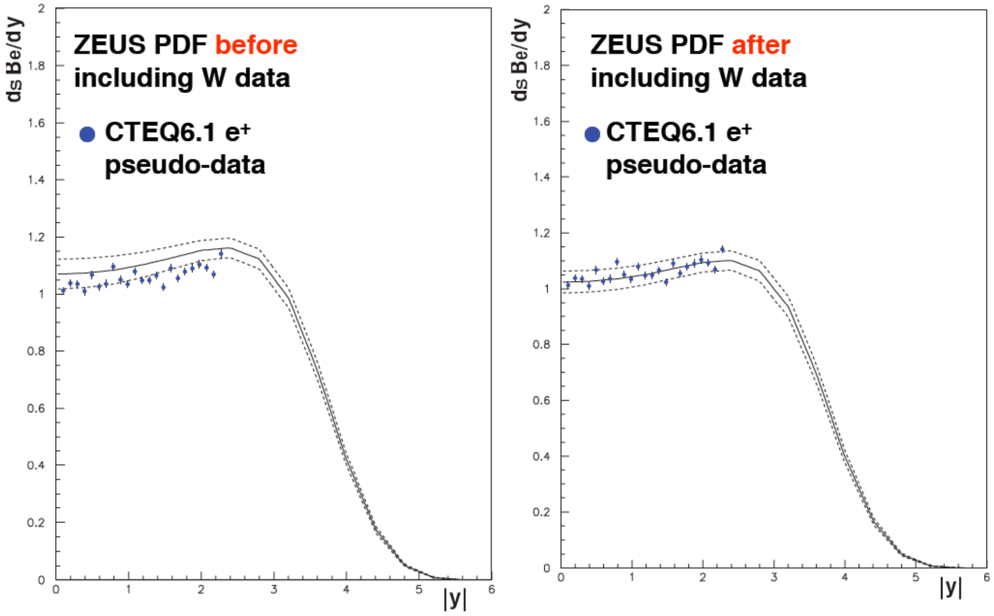




10-15% uncertainty at 1 TeV

Rapidity distributions

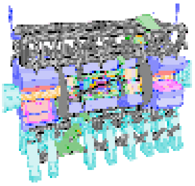
- Rapidity distributions may offer precise early information to be fed back into global pdf fits, independent of normalization



- ◉ low-x gluon distribution determined by shape parameter λ, $xg(x) \sim x^{-\lambda}$
  - ★ BEFORE **$\lambda = -0.199 \pm 0.046$**
  - ★ AFTER **$\lambda = -0.186 \pm 0.027$**
- ◉ **41% error reduction with 100 pb^{-1} of data**

Normalization free ⇒ luminosity independent

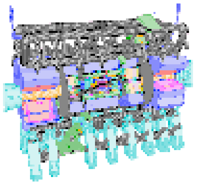
Mandy Cooper-Sarkar
Clare Gwenlan



Ultimately…

- We will use as much LHC data as possible in the global fits
  - Drell-Yan
    - particularly W and Z cross sections
  - Inclusive jets
  - W/Z + jets
  - tT
  - …

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 (CTEQ)

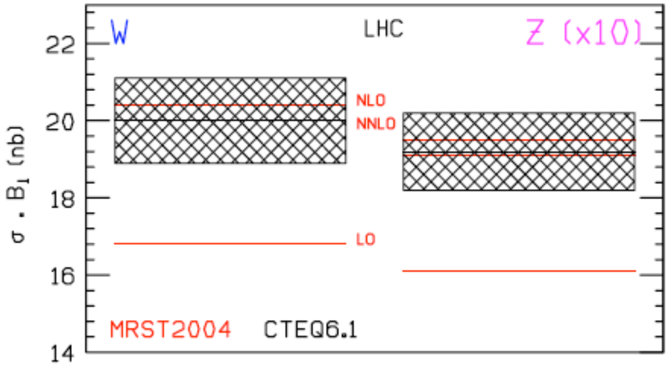


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

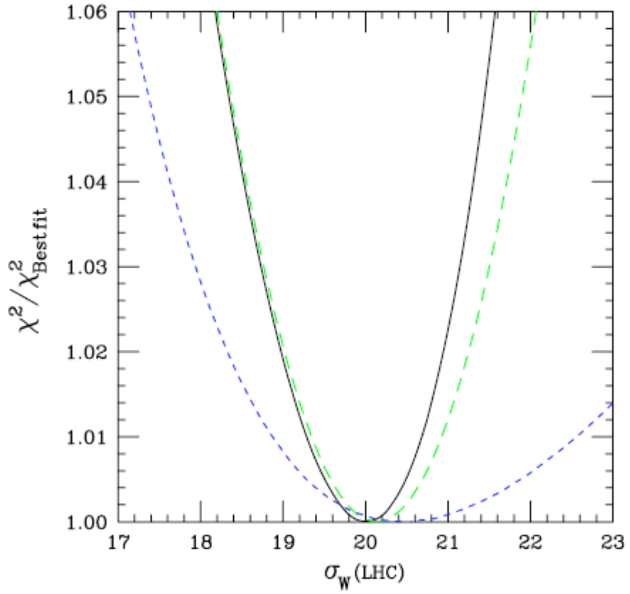


Figure 82. Lagrange multiplier results for the W cross section (in nb) at the LHC using a positive–definite gluon. The three curves, in order of decreasing steepness, correspond to three sets of kinematic cuts, standard/intermediate/strong.

removing low x data from global fits increases uncertainty but does not significantly move central answer

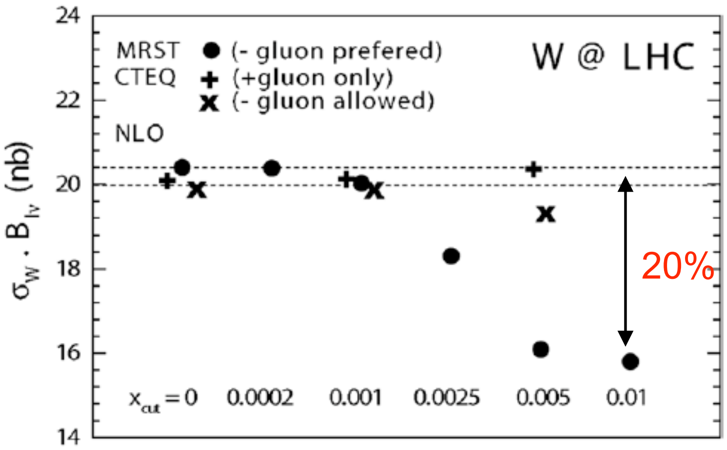
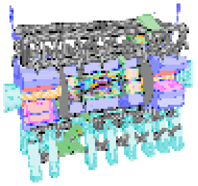


Figure 81. Predicted total cross section of $W^+ + W^-$ production at the LHC for the fits obtained in the CTEQ stability study, compared with the MRST results. The overall pdf uncertainty of the prediction is ∼5%, as observed in figure 77.

MRST found a tension between low x and high x data; not present in CTEQ analysis



Rapidity distributions and NNLO

- Effect of NNLO just a small normalization factor over the full rapidity range
- NNLO predictions using NLO pdf's are close to full NNLO results, but outside of (very small) NNLO error band

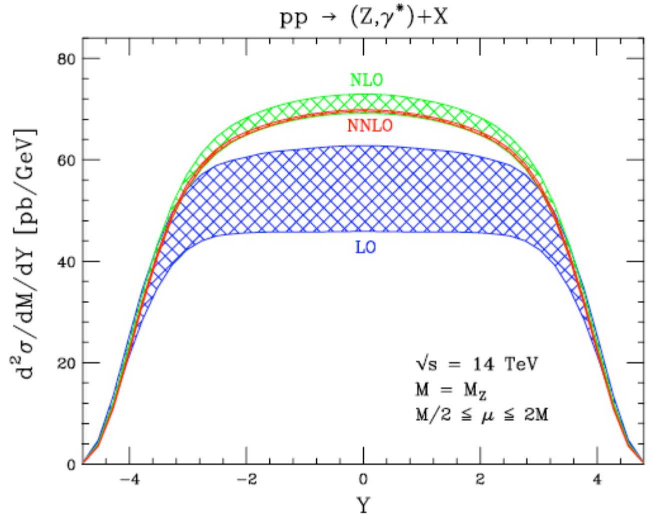


Figure 87. The rapidity distributions for *Z* production at the LHC at LO, NLO and NNLO.

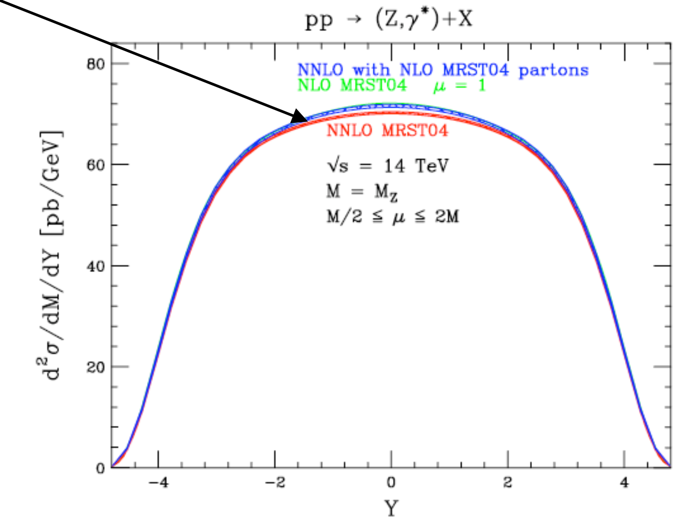
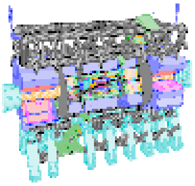
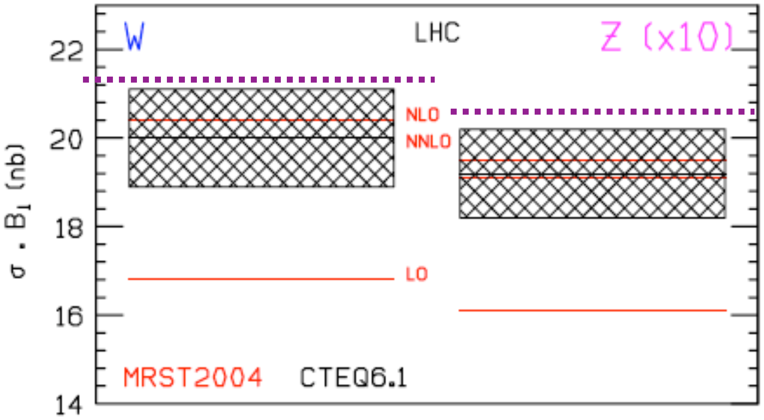


Figure 88. The rapidity distributions for *Z* production at the LHC at NNLO calculated with NNLO and with NLO pdfs.



CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC (see Pavel’s talk)
- Cross sections for W/Z increase by ~6%
    - now CTEQ and MRST2004 in disagreement
    - and relative uncertainties of W/Z increase
    - although individual uncertainties of W and Z decrease



CTEQ6.5(6)

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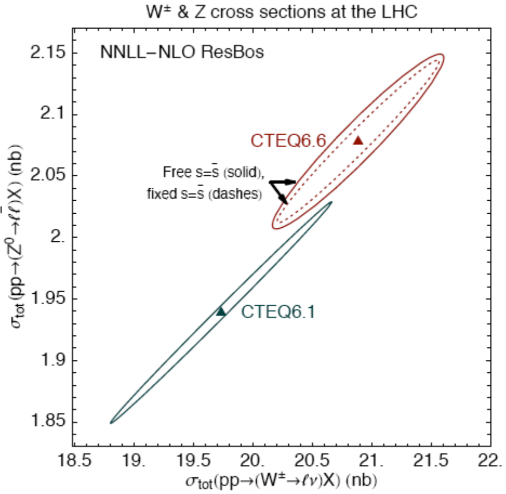
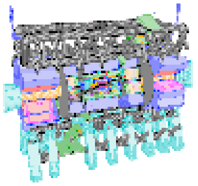


Note importance of strange quark uncertainty for ratio

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



Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

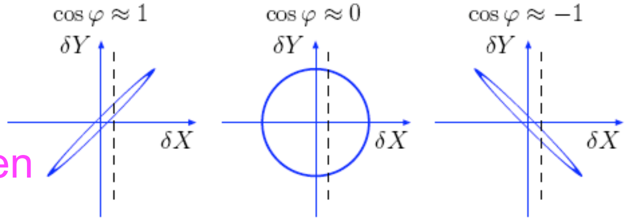
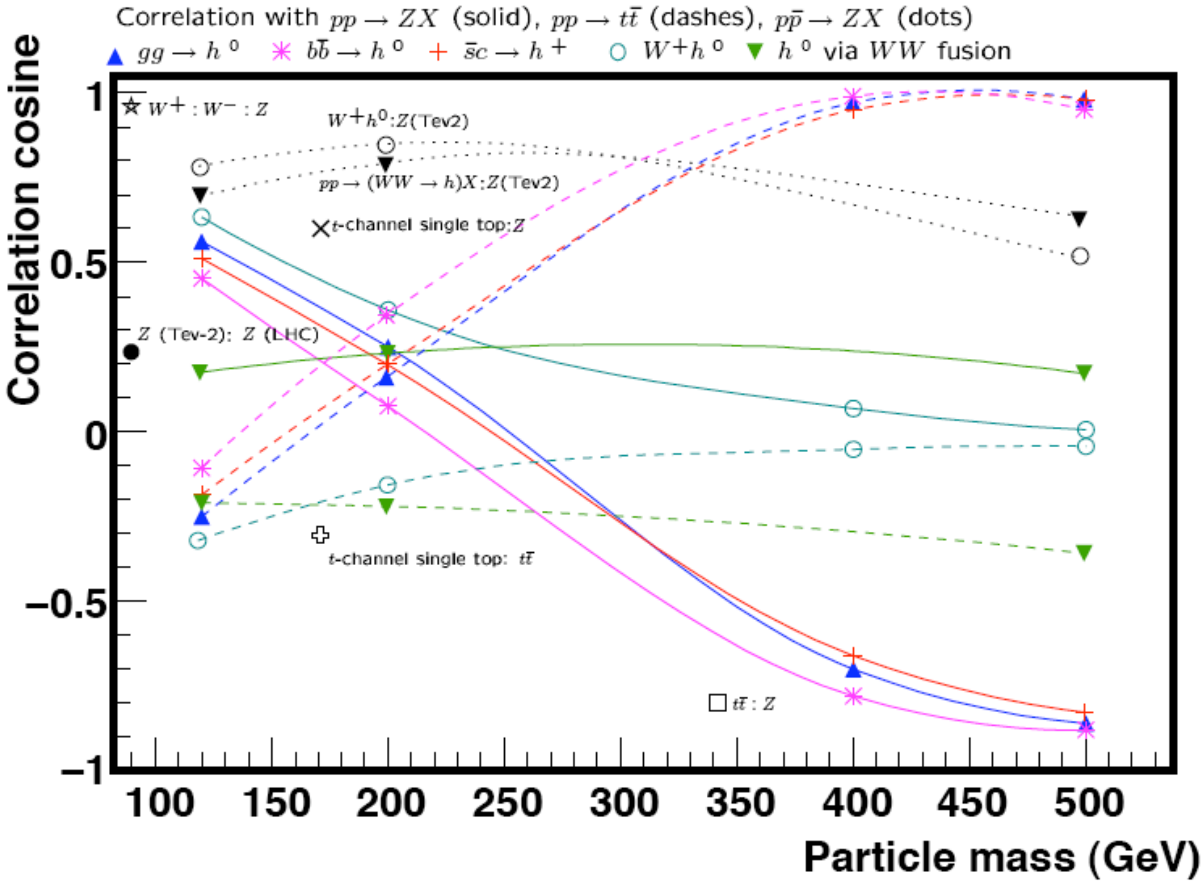
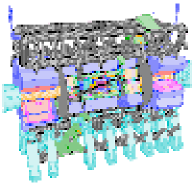


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

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



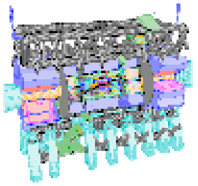
- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W}+/\sigma_{Z})$~1%
- If cos ϕ < 0, pdf uncertainty for one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



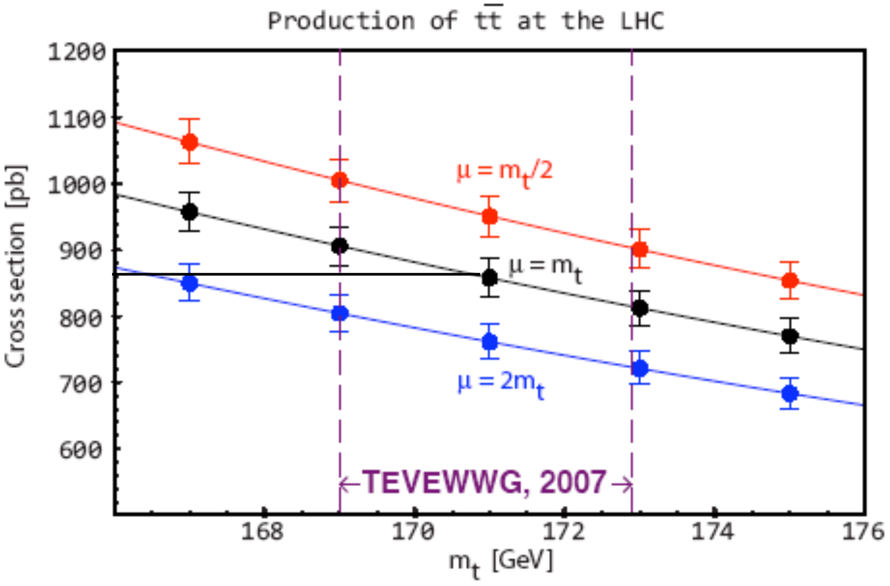
W/Z summary so far

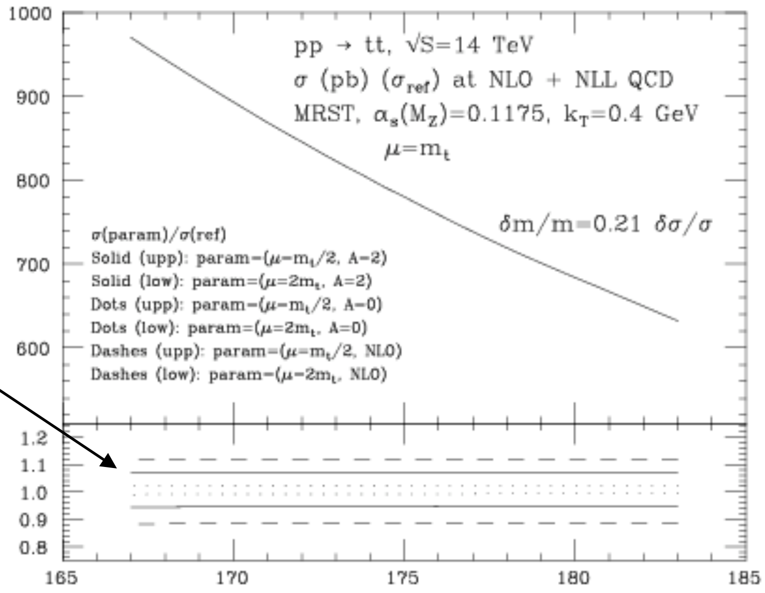
- We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
    - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
- The pdf uncertainty for the ratio of a cross section that proceeds with 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 normalization tool?

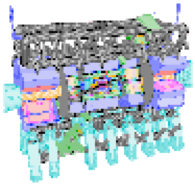
Theory uncertainties for tT at LHC



- Note that at NLO with CTEQ6.6 pdf's the central prediction for the tT cross section for $\mu=m_t$ is ~850 pb (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 this year (Czakon et al)
  - scale dependence will drop (how far?)
  - threshold resummation reduces scale dependence to <6%; may hope for 3% with full NNLO
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller







New pdf tool from John: MCFM with pdf errors

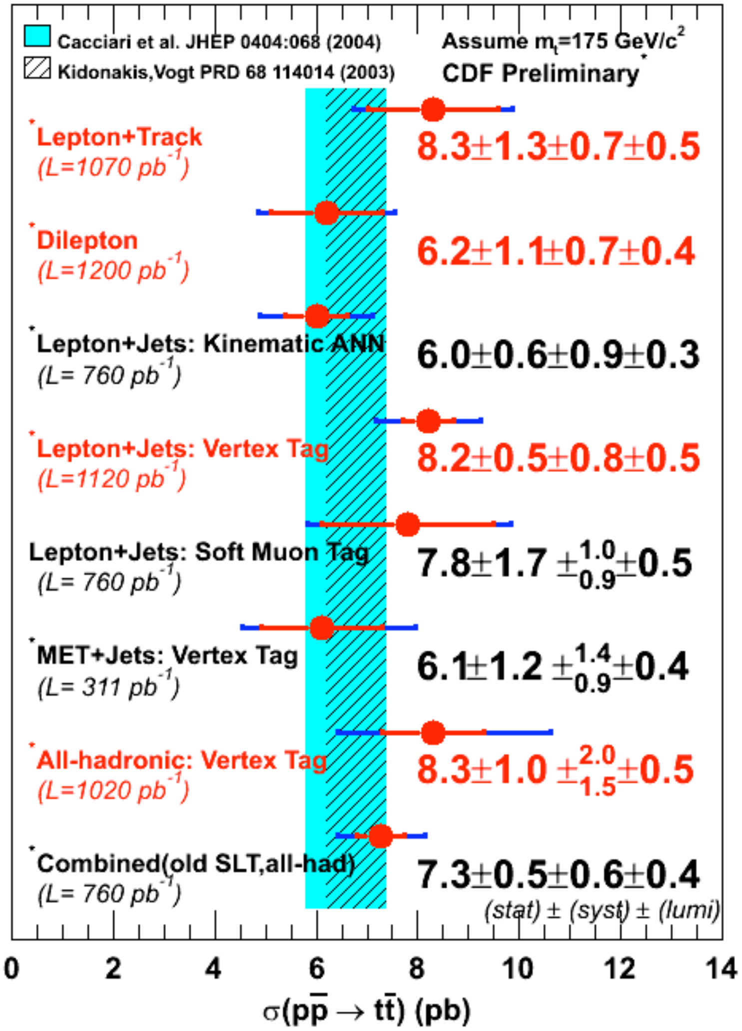
- Error pdf parton luminosities stored along with other event information; tremendous time-saving for MCFM
- Example output below from tT at LHC with CTEQ6.1(virtual diagrams only)

```
PDF error set   0  --->   922503.705 fb
PDF error set   1  --->   924901.729 fb
PDF error set   2  --->   920106.561 fb
PDF error set   3  --->   926873.142 fb
PDF error set   4  --->   918314.821 fb
PDF error set   5  --->   924319.039 fb
PDF error set   6  --->   920737.988 fb
PDF error set   7  --->   930912.022 fb
PDF error set   8  --->   914120.978 fb
PDF error set   9  --->   944892.019 fb
PDF error set  10  --->   899134.509 fb
PDF error set  11  --->   910661.311 fb
PDF error set  12  --->   933849.973 fb
PDF error set  13  --->   918037.641 fb
PDF error set  14  --->   926658.411 fb
PDF error set  15  --->   929544.061 fb
PDF error set  16  --->   916165.078 fb
PDF error set  17  --->   926807.189 fb
PDF error set  18  --->   918520.852 fb
PDF error set  19  --->   914185.317 fb
PDF error set  20  --->   928791.454 fb
PDF error set  21  --->   916124.098 fb
PDF error set  22  --->   919646.351 fb
PDF error set  23  --->   922102.562 fb
PDF error set  24  --->   920512.494 fb
PDF error set  25  --->   923791.211 fb
PDF error set  26  --->   919567.536 fb
PDF error set  27  --->   924333.235 fb
PDF error set  28  --->   922540.280 fb
PDF error set  29  --->   917348.784 fb
PDF error set  30  --->   933489.451 fb
PDF error set  31  --->   921711.144 fb
PDF error set  32  --->   920739.212 fb
PDF error set  33  --->   919592.767 fb
PDF error set  34  --->   923451.843 fb
PDF error set  35  --->   923859.904 fb
PDF error set  36  --->   923632.556 fb
PDF error set  37  --->   923740.945 fb
PDF error set  38  --->   921204.429 fb
PDF error set  39  --->   922465.341 fb
PDF error set  40  --->   922560.436 fb
* --------------- SUMMARY -------------
*      Minimum value    899134.509 fb
*      Central value    922503.705 fb
*      Maximum value    944892.019 fb
*      Err estimate +/- 31131.272 fb
*      +ve direction    31383.680 fb
*      -ve direction    32098.504 fb
****************************************
```

real diagrams contribute -70000 fb, so
central NLO is ~850 pb; threshold resum->880 pb

What about experimental uncertainties?

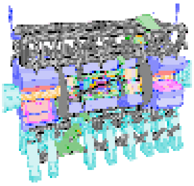
- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lum)



Summary

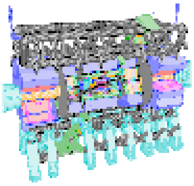
- Physics will come flying hot and heavy when LHC turns on at full energy in 2008
- Important to establish both the SM benchmarks and the tools, particularly with regards to pdf's, that we will need to properly understand this flood of data

- "We fit pdf's with the data we have, not with the data we want."



New CTEQ project

- 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)
    - combined NNLO W/Z +NLO EW W/Z production
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- Using programs such as:
  - MCFM
  - ResBos
  - EKS
  - Pythia/Herwig/Sherpa
  - …numerous private codes with CTEQ
- First on webpage and later as a report
- Feedback on utility of project would be helpful



Extra slides

Sudakov form factors

- Sudakov form factor gives the probability for a gluon **not** to be emitted; basis of parton shower Monte Carlos
- Consider tT production
- In going from the Tevatron to the LHC, you are moving from primarily qQ initial states to gg initial states
- …and to smaller values of parton x
  - so there's more phase space for gluon emission
- So significantly more *extra* jets associated with the tT final state

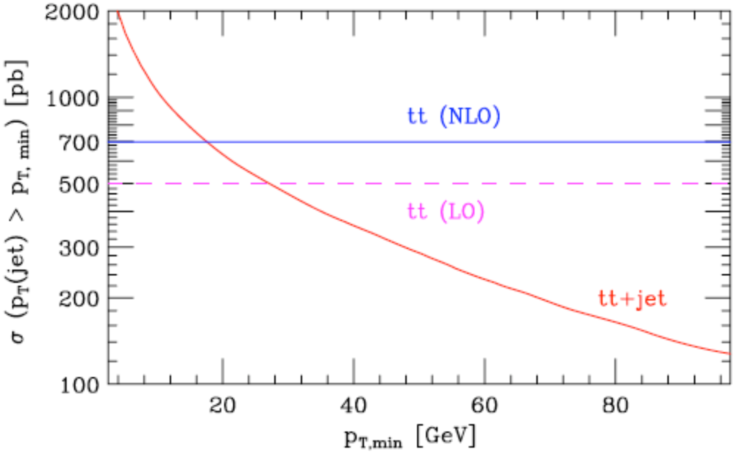


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

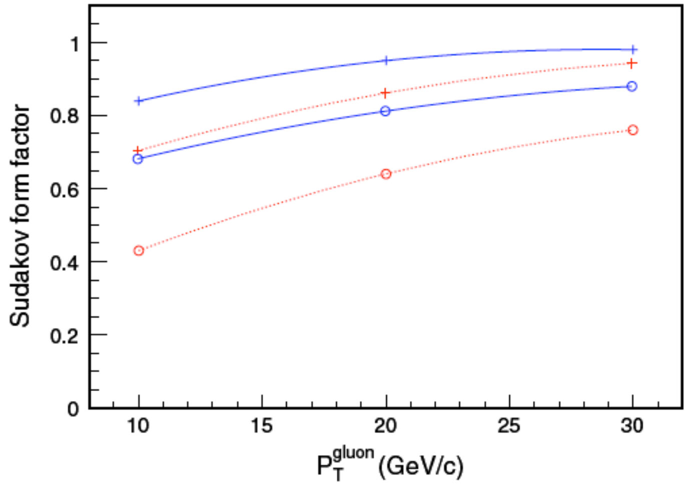


Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton x values of 0.3 (crosses) and 0.03 (open circles).

Correlations using CTEQ6.1 error pdf's

- As expected, W and Z cross sections are highly correlated
- Anti-correlation between tT and W cross sections
  - more glue for tT production (at higher x) means fewer anti-quarks (at lower x) for W production
  - mostly no correlation for (low mass) H and W cross sections
  - see more later

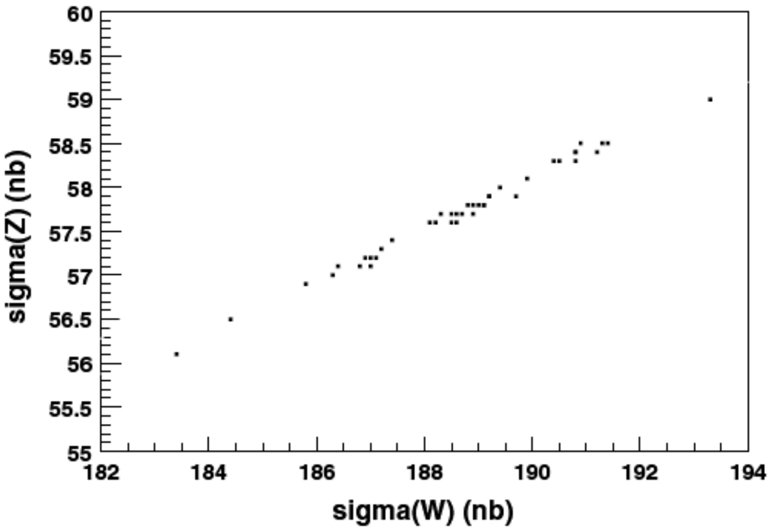


Figure 85. The cross section predictions for Z production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

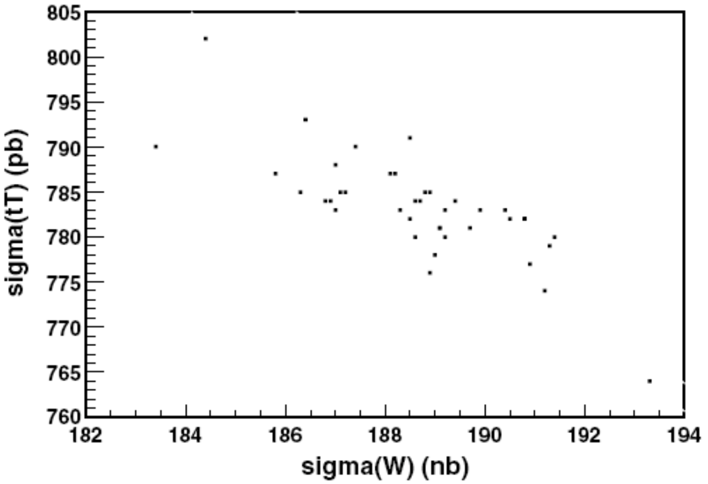


Figure 93. The cross section predictions for $t\bar{t}$ production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

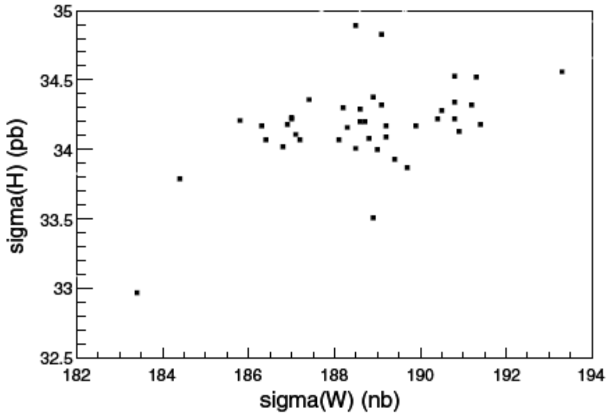
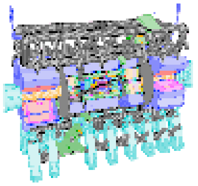
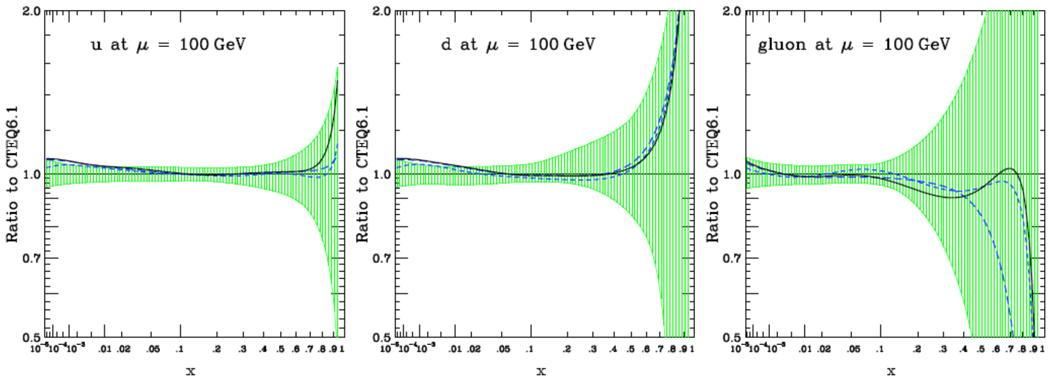


Figure 99. The cross section predictions for Higgs production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.



Heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With new sets of pdf’s (CTEQ6.5/6.6), 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



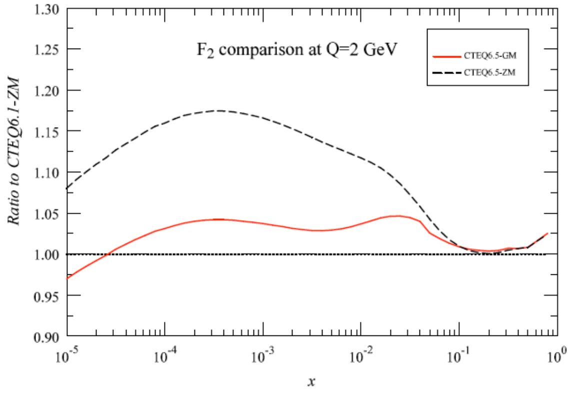
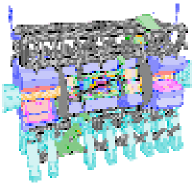


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

implications for LHC phenomenology



Now some technical stuff

- Consider a cross section X(a)
- 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

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

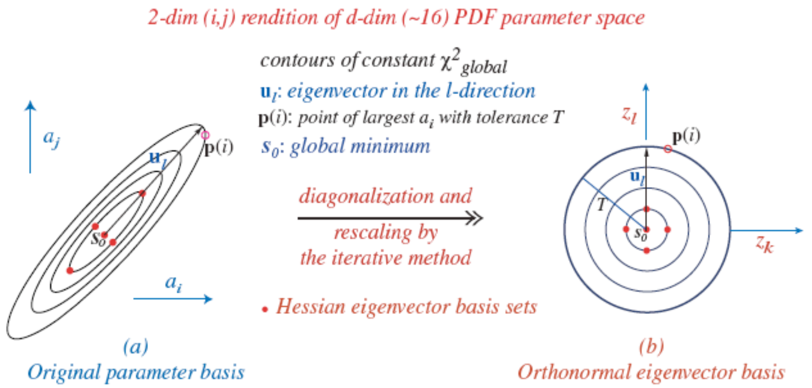


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

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

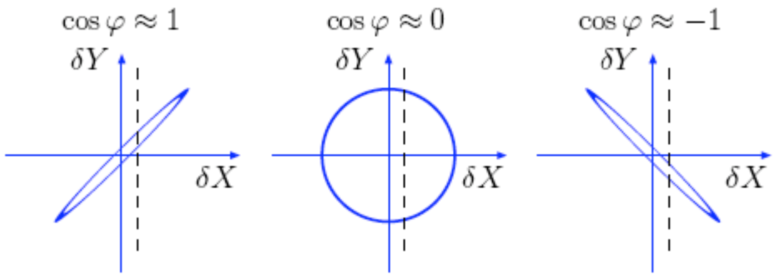
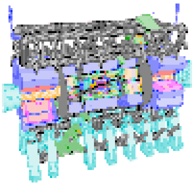


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

Correlations: W/Z and pdf’s

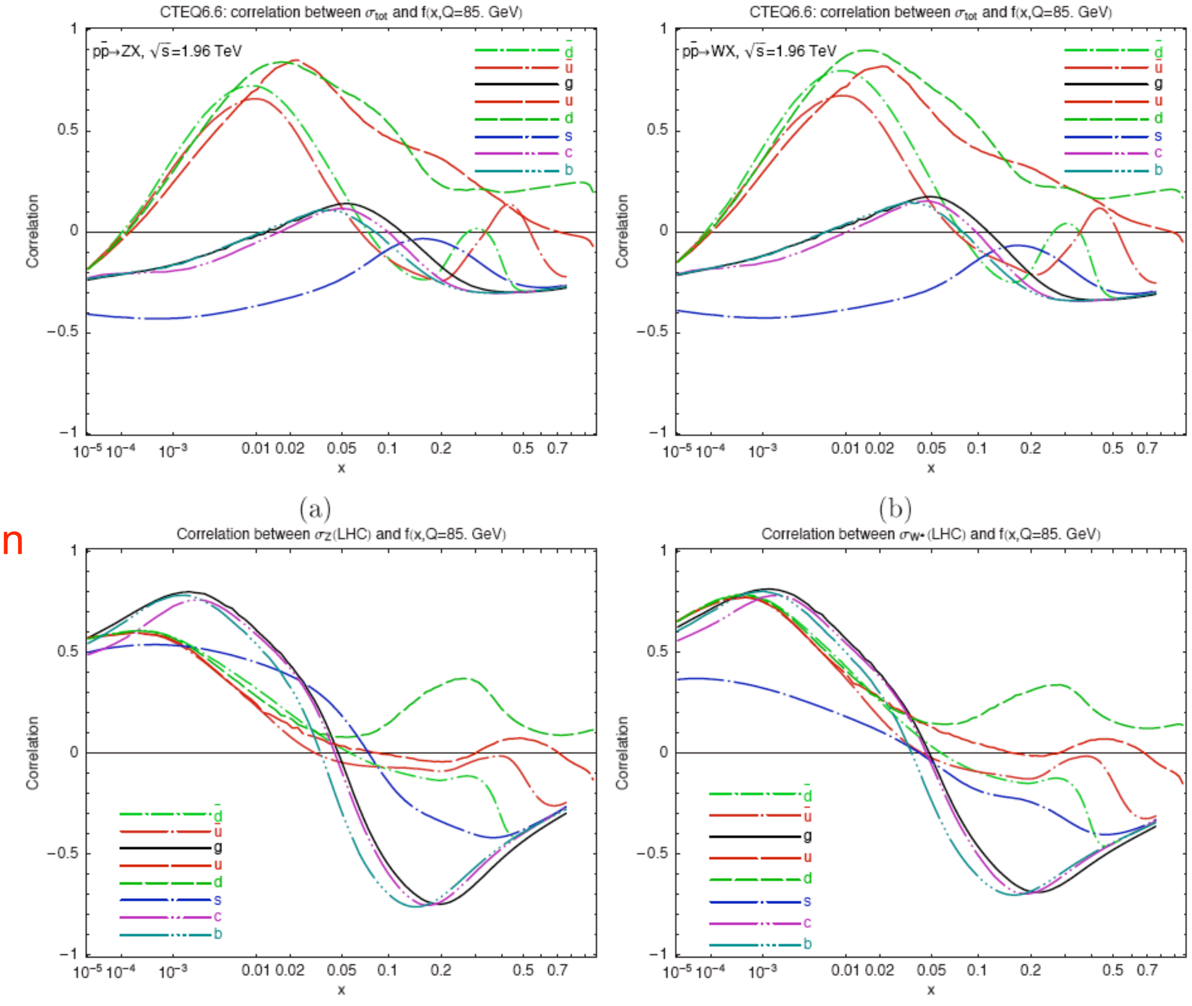


- At the Tevatron, W and Z cross sections most correlated with u,U,d,D pdf’s

- At the LHC, W and Z cross sections most correlated with charm, bottom and gluon distributions

- A large correlation with the gluon for x values ~0.005 is accompanied by a large anti-correlation with the gluon at larger x

- This implies a strong anti-correlation of W and Z with heavy states produced by gg



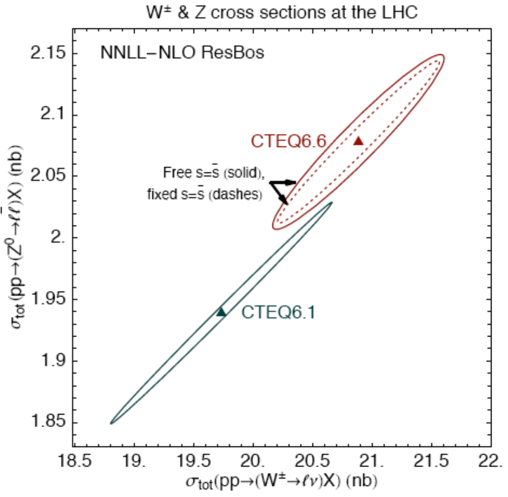
(a) (b)

(c) (d)

Figure 10: (a,b) Correlation between the total cross sections for Z^0 and $W^\pm$ production at the Tevatron and PDF’s of various flavors, plotted as a function of x for $Q = 85$ GeV; (c,d) the same for the LHC

Correlations: Z to W ratio

- The ratio of the Z to W cross section is most strongly correlated with the strange quark distribution



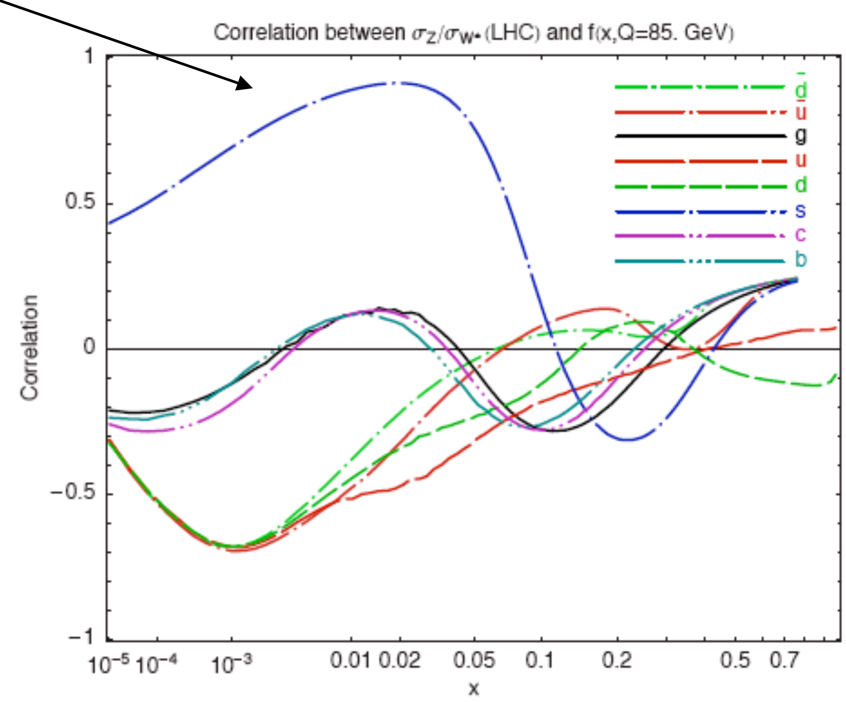


Figure 11: Correlation between the ratio σ_Z/σ_W of LHC total cross sections for Z^0 and $W^\pm$ production at PDF's of various flavors, plotted as a function of x for $Q = 85$ GeV.

Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

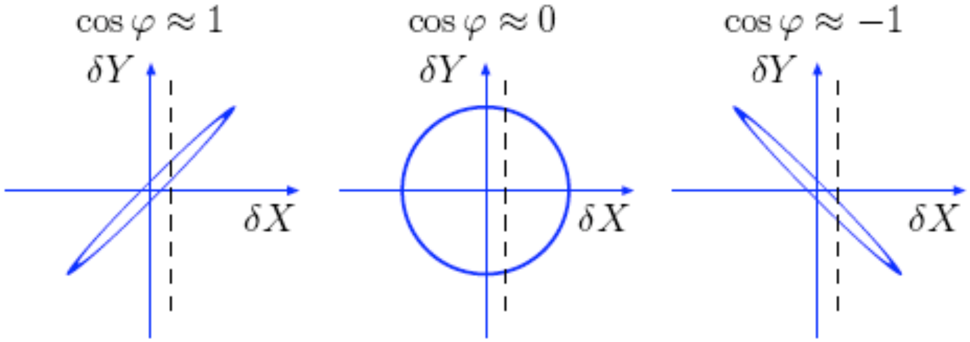


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

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