CTEQ

Higgs Physics at the Tevatron and LHC: the QCD issues

J. Huston Michigan State University

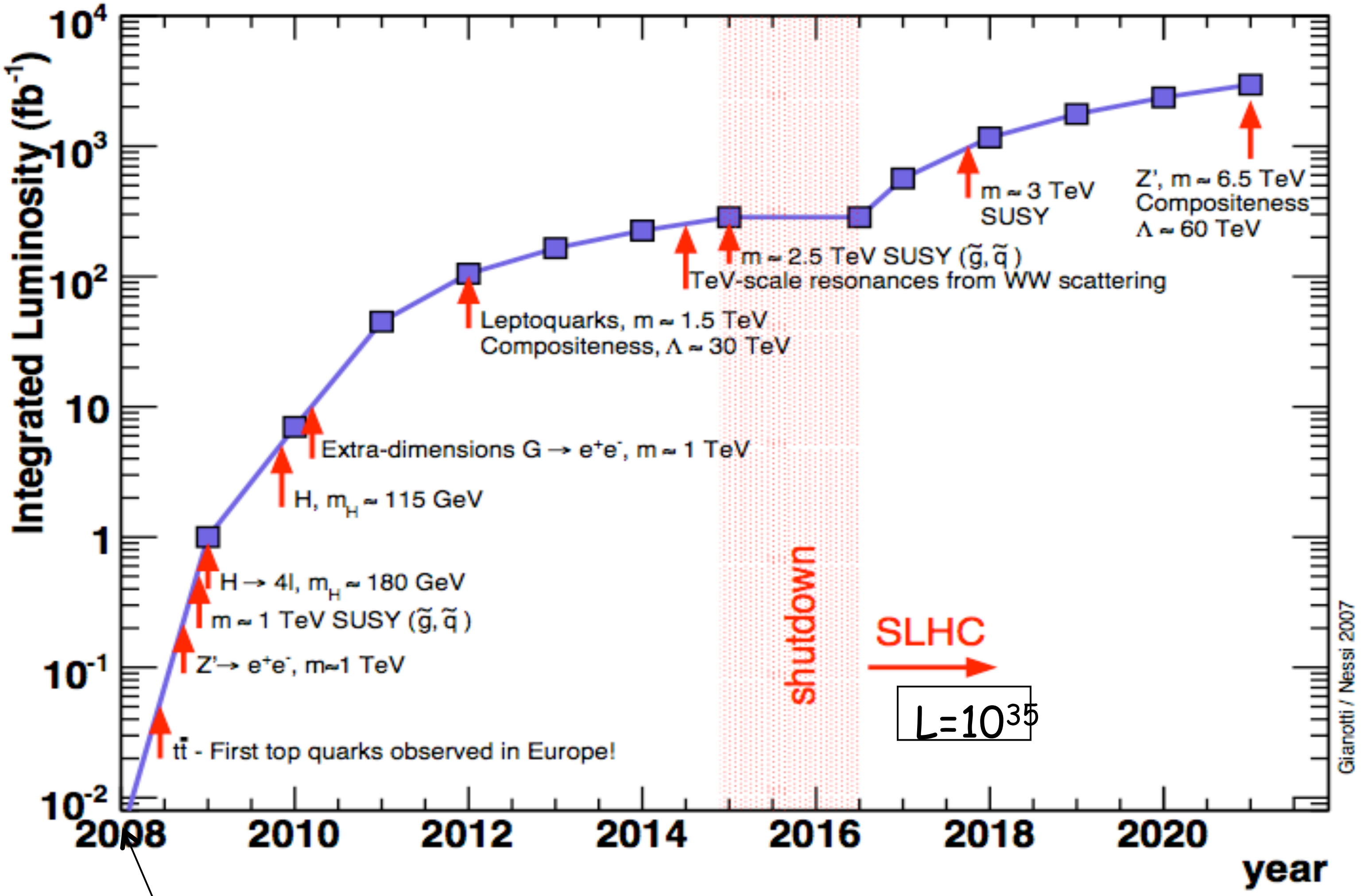
Using the data & experience from the Tevatron to prepare for the LHC

+ maybe discovering the Higgs while we're at it

We'll look back on early LHC trouble in 15 years and laugh

C T E Q

LHC vs time: a wild guess ...



L=10^{35}

you are here (even though it's now 2009)

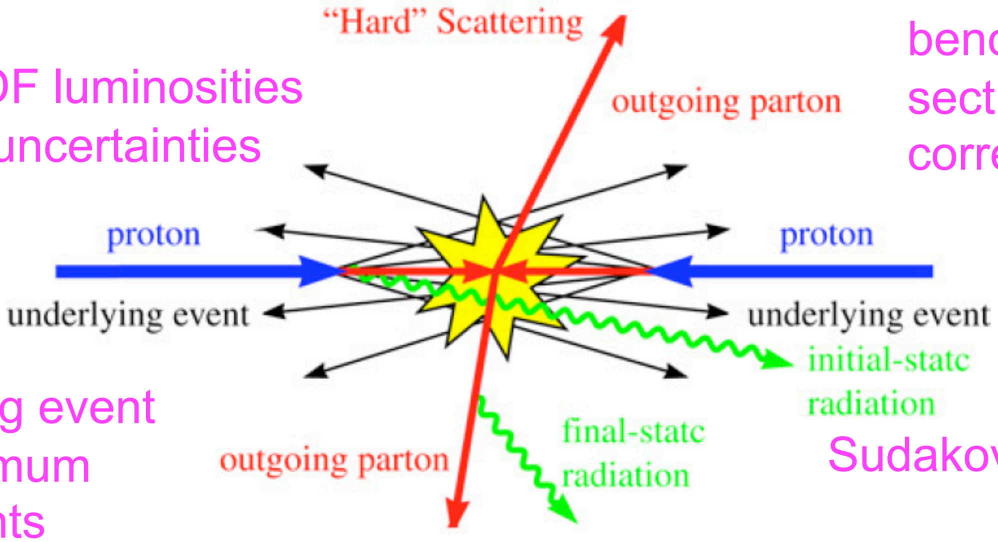
Understanding cross sections at the LHC

C T E Q

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

Sudakov form factors

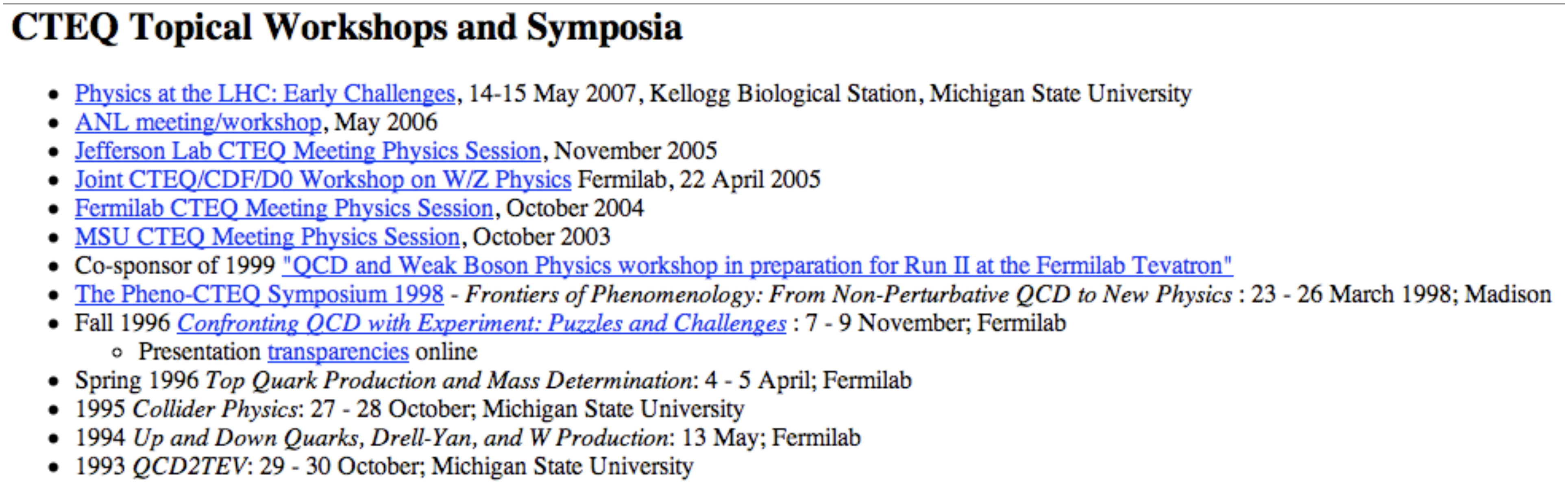
jet algorithms and jet reconstruction

…but before we can laugh, and count the Higgs bosons,
we have to understand QCD (at the LHC)

CTEQ workshops

CTEQ

- CTEQ has organized a series of workshops in the past, dealing with both Tevatron and LHC physics
- Given the importance of Higgs physics, at both the Tevatron and LHC, and the QCD-related questions that have arisen recently, we thought it would be useful to collaborate with the Fermilab LPC (thanks for the coffee and cookies, by the way) to bring about this workshop



CTEQ Topical Workshops and Symposia

- Physics at the LHC: Early Challenges, 14-15 May 2007, Kellogg Biological Station, Michigan State University
- ANL meeting/workshop, May 2006
- Jefferson Lab CTEQ Meeting Physics Session, November 2005
- Joint CTEQ/CDF/D0 Workshop on W/Z Physics Fermilab, 22 April 2005
- Fermilab CTEQ Meeting Physics Session, October 2004
- MSU CTEQ Meeting Physics Session, October 2003
- Co-sponsor of 1999 "QCD and Weak Boson Physics workshop in preparation for Run II at the Fermilab Tevatron"
- The Pheno-CTEQ Symposium 1998 - *Frontiers of Phenomenology: From Non-Perturbative QCD to New Physics* : 23 - 26 March 1998; Madison
- Fall 1996 *Confronting QCD with Experiment: Puzzles and Challenges* : 7 - 9 November; Fermilab
  - Presentation transparencies online
- Spring 1996 *Top Quark Production and Mass Determination*: 4 - 5 April; Fermilab
- 1995 *Collider Physics*: 27 - 28 October; Michigan State University
- 1994 *Up and Down Quarks, Drell-Yan, and W Production*: 13 May; Fermilab
- 1993 *QCD2TEV*: 29 - 30 October; Michigan State University

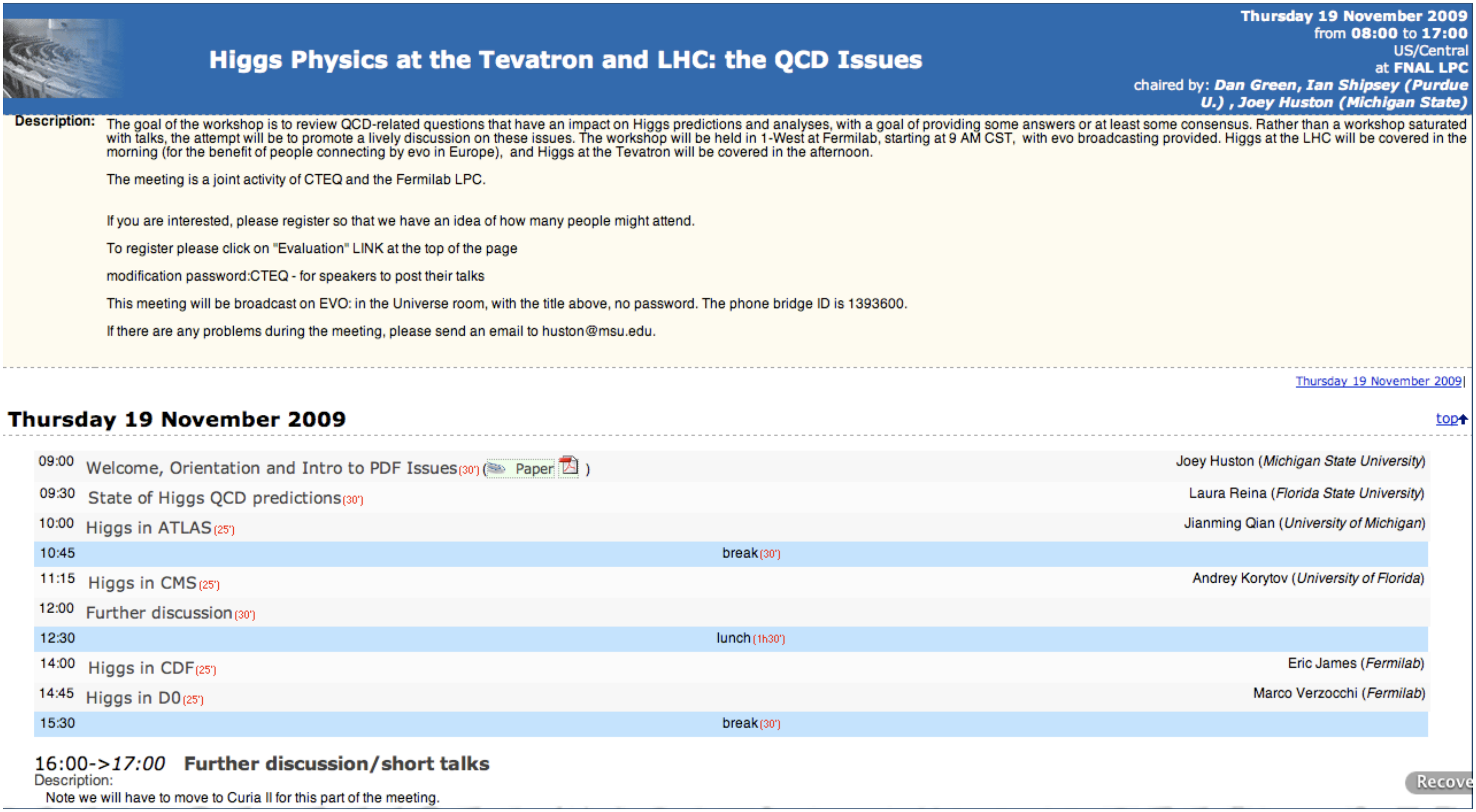
CTEQ

Wu Ki

- This is in keeping with the goal that Wu Ki had in mind when he formed CTEQ almost two decades ago

The agenda

C T E Q



Higgs Physics at the Tevatron and LHC: the QCD Issues

Thursday 19 November 2009
from **08:00** to **17:00**
US/Central
at **FNAL LPC**
chaired by: ***Dan Green, Ian Shipsey (Purdue U.) , Joey Huston (Michigan State)***

Description: The goal of the workshop is to review QCD-related questions that have an impact on Higgs predictions and analyses, with a goal of providing some answers or at least some consensus. Rather than a workshop saturated with talks, the attempt will be to promote a lively discussion on these issues. The workshop will be held in 1-West at Fermilab, starting at 9 AM CST, with evo broadcasting provided. Higgs at the LHC will be covered in the morning (for the benefit of people connecting by evo in Europe), and Higgs at the Tevatron will be covered in the afternoon.

The meeting is a joint activity of CTEQ and the Fermilab LPC.

If you are interested, please register so that we have an idea of how many people might attend.

To register please click on "Evaluation" LINK at the top of the page

modification password:CTEQ - for speakers to post their talks

This meeting will be broadcast on EVO: in the Universe room, with the title above, no password. The phone bridge ID is 1393600.

If there are any problems during the meeting, please send an email to huston@msu.edu.

Thursday 19 November 2009|

Thursday 19 November 2009

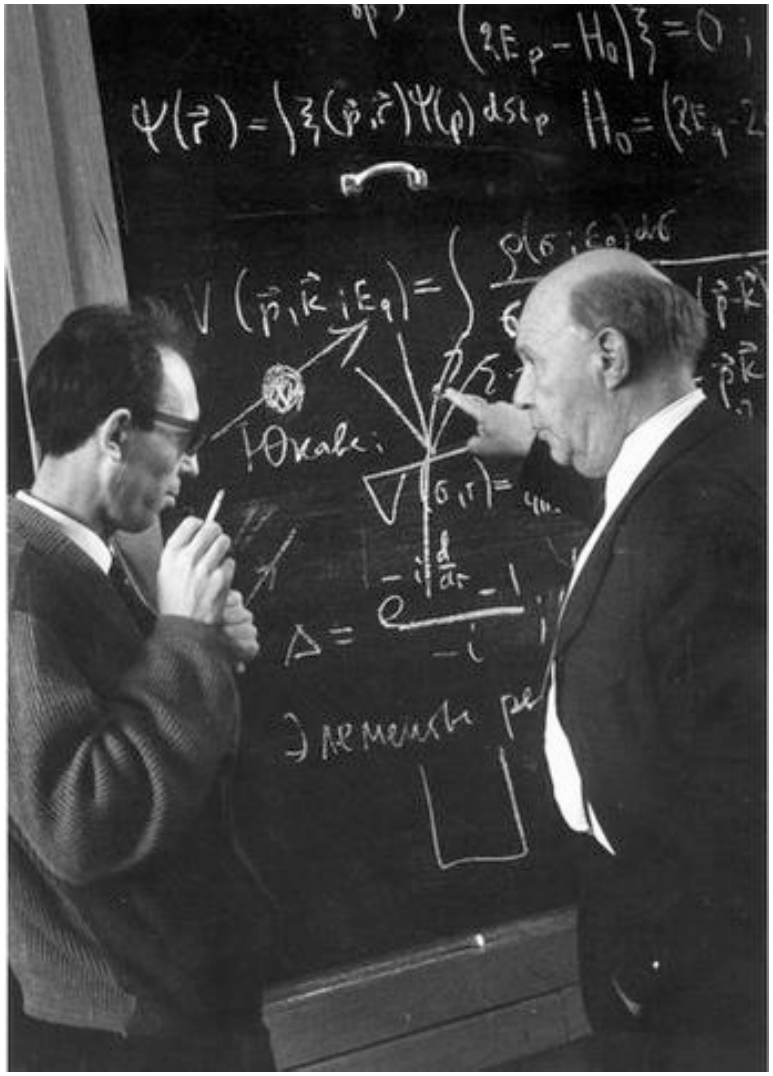
top↑

09:00	Welcome, Orientation and Intro to PDF Issues (30') (Paper)	Joey Huston (*Michigan State University*)
09:30	State of Higgs QCD predictions (30')	Laura Reina (*Florida State University*)
10:00	Higgs in ATLAS (25')	Jianming Qian (*University of Michigan*)
10:45	break (30')	
11:15	Higgs in CMS (25')	Andrey Korytov (*University of Florida*)
12:00	Further discussion (30')	
12:30	lunch (1h30')	
14:00	Higgs in CDF (25')	Eric James (*Fermilab*)
14:45	Higgs in D0 (25')	Marco Verzocchi (*Fermilab*)
15:30	break (30')	

16:00->*17:00* **Further discussion/short talks**
Description:
Note we will have to move to Curia II for this part of the meeting.

Russian seminar

- …relatively small number of talks, focused on QCD issues, with lots of time for discussion;
- the goal is to be like a “Russian seminar”
- If the speaker is the one who is doing the most talking, it’s not a success
    - but no smoking



Questions

1) Theory predictions for Higgs + backgrounds to Higgs
    a. can we have a dynamic collection of cross sections (detailing methods and parameters used to calculate these cross sections) for all Higgs production processes and main backgrounds?
    b. understanding consistency and best use of predictions at LO, NLO, NNLO,NLO+NLL, NNLO+NNLL
        i. how consistent are the predictions from CTEQ, MSTW, NNPDF?
        ii. how to properly include the cross section/PDF uncertainty due to the uncertainty on α_s?
        iii. what is the best way of adding PDF and scale uncertainties?
        iv. should the factorization and renormalization scales be varied separately or together?
        v. can we assume similar scales for related processes?
        vi. how best to treat the PDF correlations between cross sections?
        vii. can we improve the PDF and scale uncertainties by normalizing to the W/Z cross section?
        viii. how do we relate these higher order predictions to the LO event generators that we most often use?
        ix. how to deal with higher order information for differential distributions ; for example, for the Higgs pT distribution or for n-jet distributions?
        x. what theory uncertainties do we have to include as acceptance uncertainties when setting a limit on a cross section, such as gg->H+X*BR(H->WW)?
        xi. is there a concensus on how to deal with calculations of MSSM Higgs and their uncertainties in 4- and 5-flavor schemes?

I'll start the discussion

Questions

in extra slides, for discussion

c. using knowledge of NLO calculations to provide best LO estimates for multi-parton final state calculations for Higgs + backgrounds
    i. best scale choices
    ii. impact of jet choices
    iii. dynamic K-factors for re-weighting of LO distributions

d. using NNLO/NNLL calculations to provide best estimates for NLO
    i. best scale choices
    ii. dynamical K-factors for reweighting

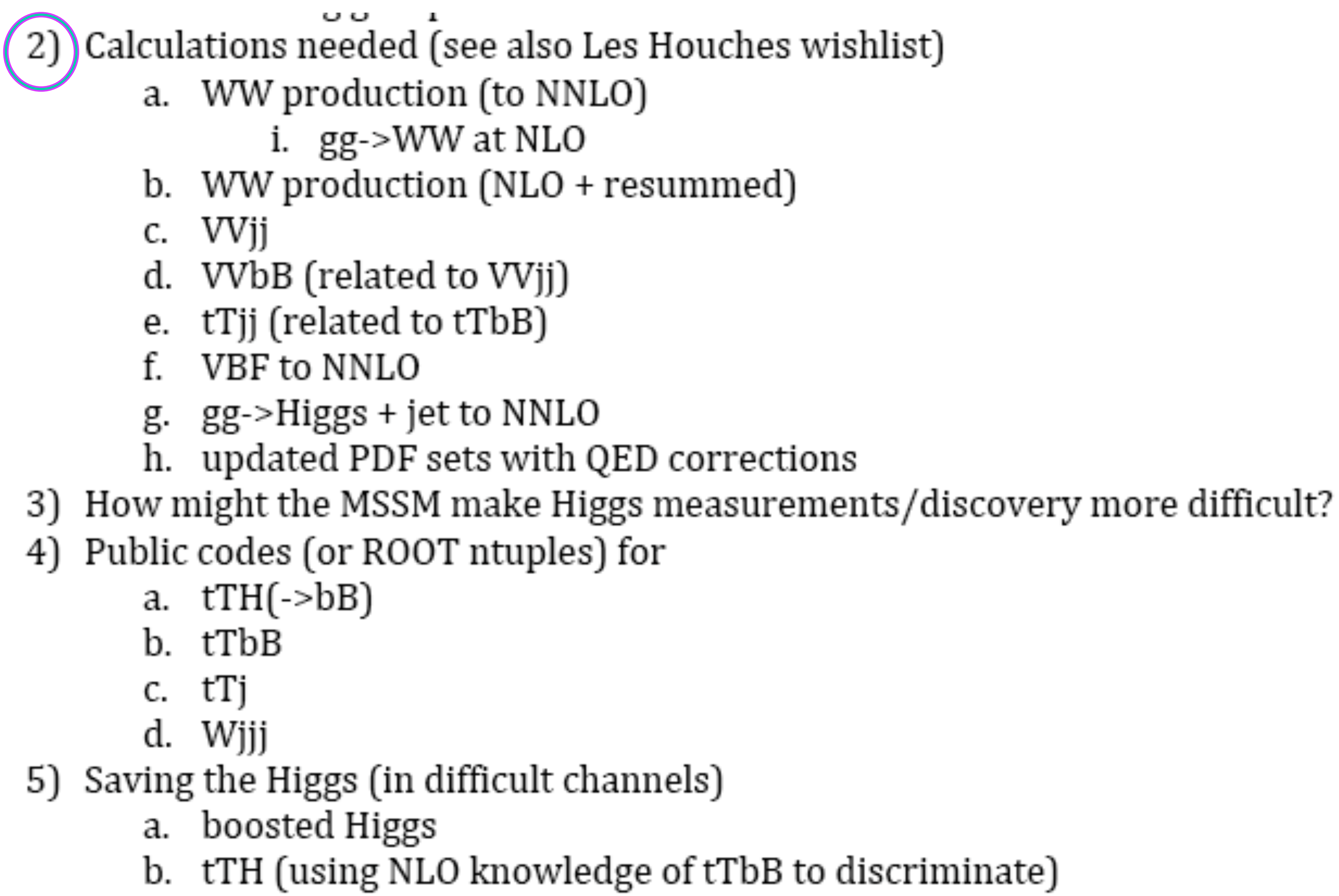
e. what is the impact of jet vetoing on the theoretical uncertainty for a signal cross section; for a background cross section? How do we evaluate the efficiency uncertainties for the central jet veto for the classical VBF Higgs signature? What are the experimental benchmarks that allow us to choose between the different predictions?

f. how do we tie the theoretical predictions into data-driven background predictions?

g. how do we properly split the Higgs signal into 0-jet , 1-jet samples? How do we evaluate the theoretical uncertainties?

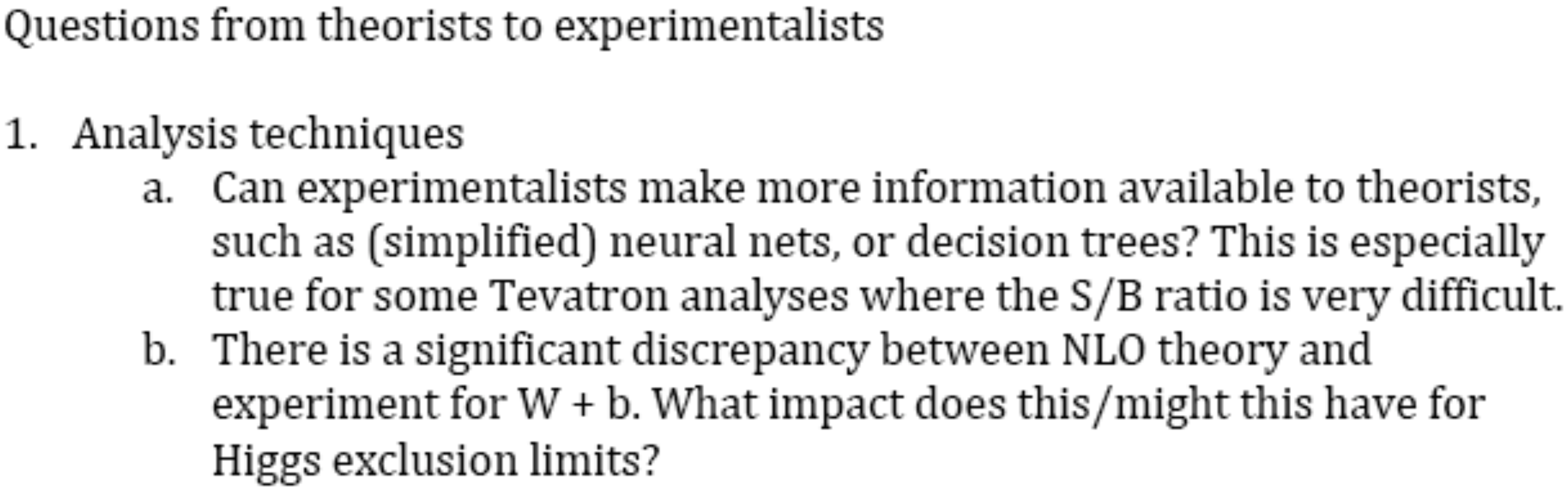
h. photon isolation; can a meaningful definition of isolation that works for both theory and experiment be adopted a la the Les Houches working group?

Questions



2) Calculations needed (see also Les Houches wishlist)
    a. WW production (to NNLO)
        i. gg->WW at NLO
    b. WW production (NLO + resummed)
    c. VVjj
    d. VVbB (related to VVjj)
    e. tTjj (related to tTbB)
    f. VBF to NNLO
    g. gg->Higgs + jet to NNLO
    h. updated PDF sets with QED corrections
3) How might the MSSM make Higgs measurements/discovery more difficult?
4) Public codes (or ROOT ntuples) for
    a. tTH(->bB)
    b. tTbB
    c. tTj
    d. Wjjj
5) Saving the Higgs (in difficult channels)
    a. boosted Higgs
    b. tTH (using NLO knowledge of tTbB to discriminate)

Questions



Questions from theorists to experimentalists

1. Analysis techniques
    a. Can experimentalists make more information available to theorists, such as (simplified) neural nets, or decision trees? This is especially true for some Tevatron analyses where the S/B ratio is very difficult.
    b. There is a significant discrepancy between NLO theory and experiment for W + b. What impact does this/might this have for Higgs exclusion limits?

Parton distribution functions and global fits

C T E Q

- Calculation of production cross sections at the Tevatron and LHC relies upon knowledge of pdf's in the relevant kinematic region
- Higgs (gg channel) at the LHC sensitive to gluons in range 0.001 to 0.1; at Tevatron ~0.01 to 0.3
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- ~~Two~~ Three major groups that provide semi-regular updates to parton distributions when new data/ theory becomes available
  - MRS>MRST98>MRST99>MRST 2001->MRST2002 ->MRST2003 ->MRST2004->MSTW2008
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5 ->CTEQ6.6->CT09->CT09.1
  - NNPDF1.0->NNPDF1.1 ->NNPDF1.2

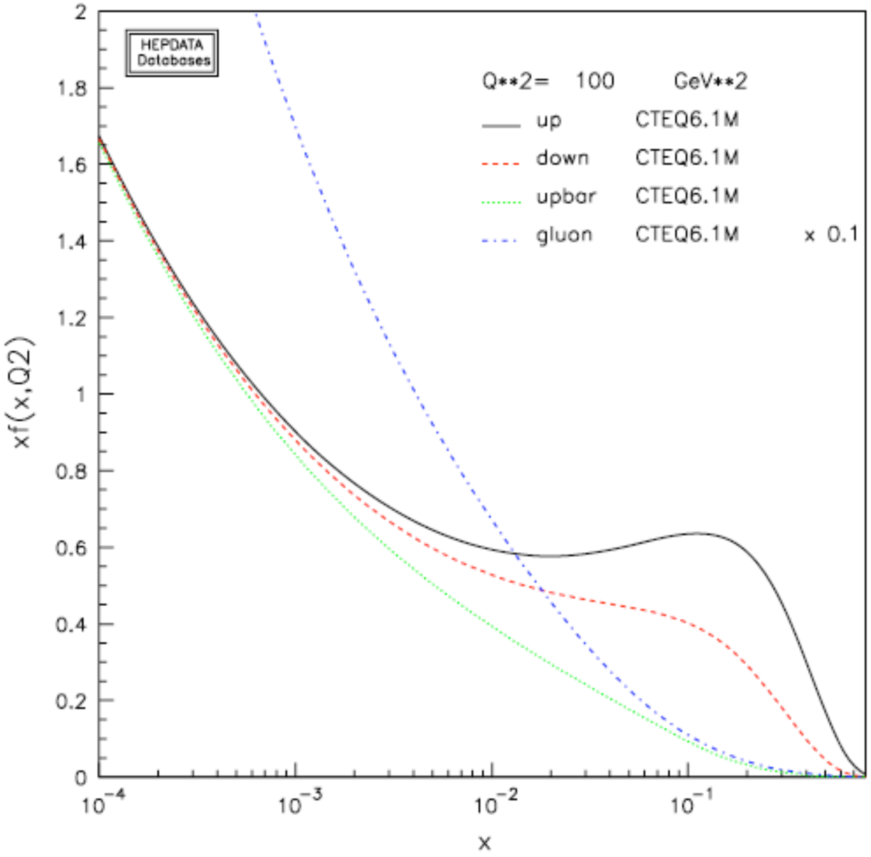
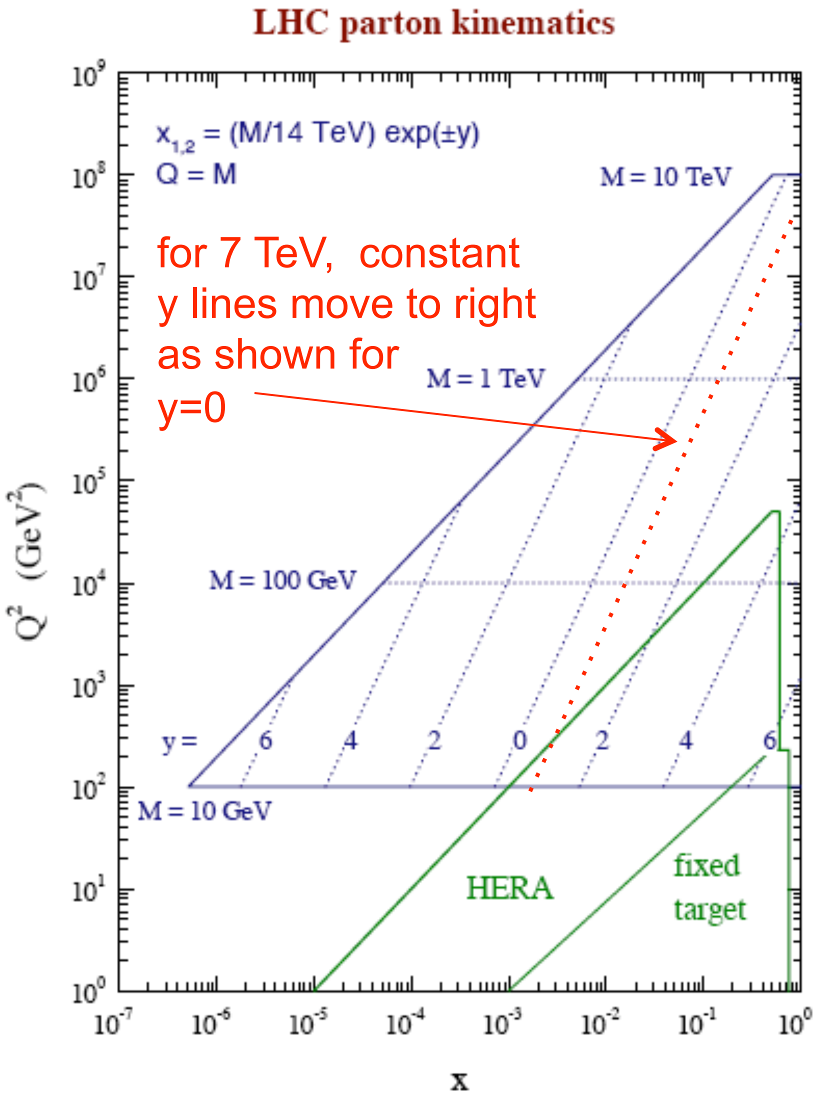


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

Use only modern versions of PDFs; older versions can lead to surprises

Cross sections at the LHC

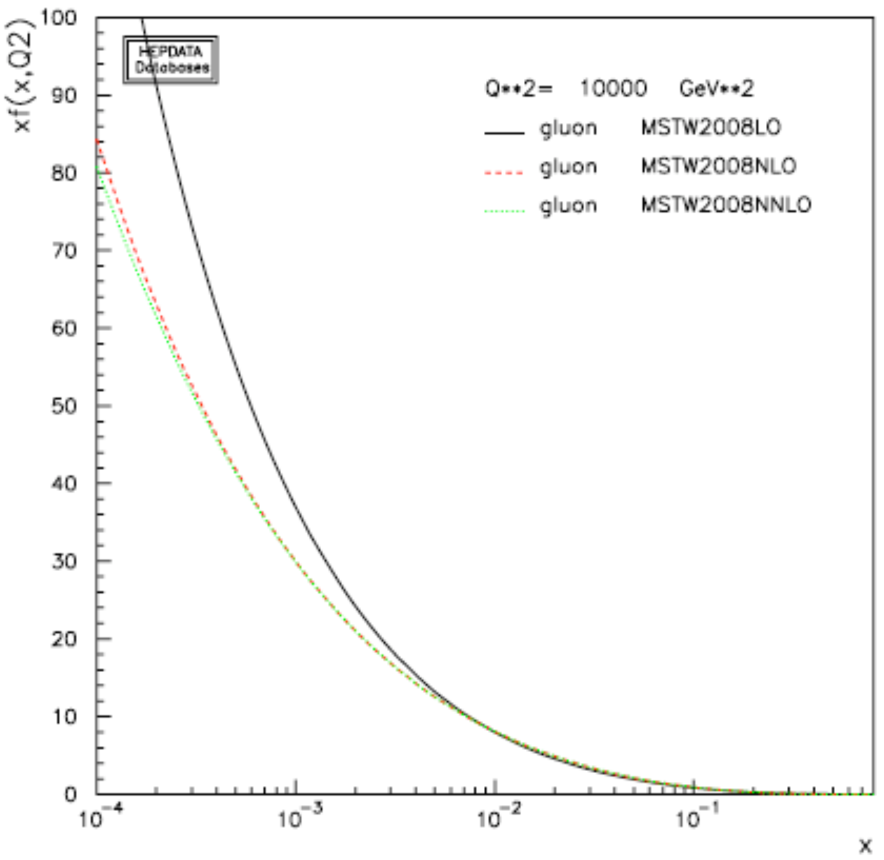
- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x for the quarks and gluons in many key searches
    - dominance of gluon and sea quark scattering
    - large phase space for gluon 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

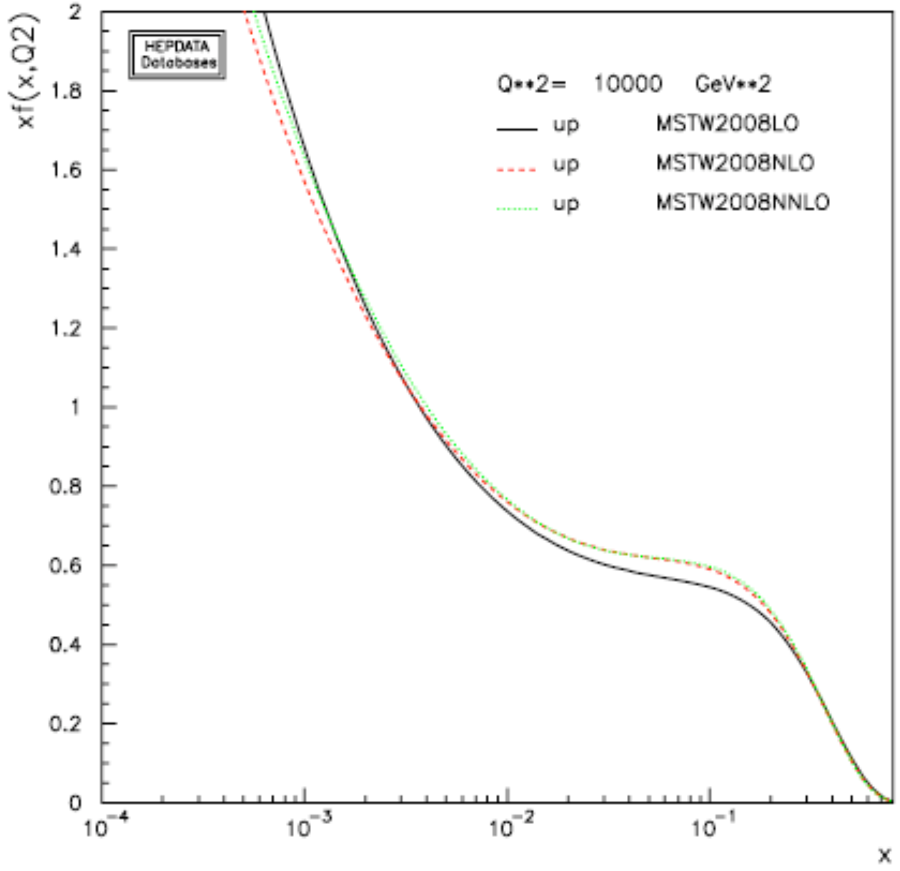


for 7 TeV, constant y lines move to right as shown for y=0

LO->NLO->NNLO

- There is a big change in general for PDFs in going from LO to NLO, but not from NLO to NNLO





W/Z agreement

CTEQ

- 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 good agreement
- NNPDF still low by 5% or so since still working with zero mass approximation
  - but error estimates will still be very useful
- …but, MSTW2008 tT,Higgs predictions larger than that for CTEQ6.6
  - primarily due to the different value of α_s used

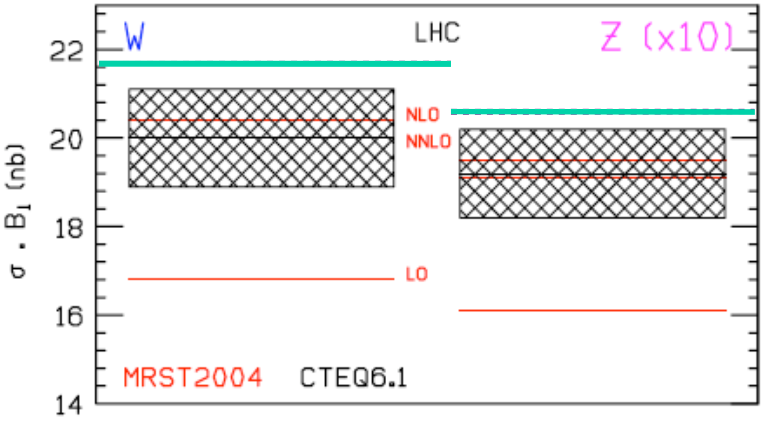


Figure 80. Predicted cross sections for *W* and *Z* production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

CTEQ6.5(6)

MSTW08

PDF Errors

- So we have optimal values (minimum χ^2) for the d=20 (22,24) free pdf parameters in the global fit
  - $\{a_\mu\}, \mu=1,\ldots d$
- Varying any of the free parameters from its optimal value will increase the χ^2
- It's much easier to work in an orthonormal eigenvector space determined by diagonalizing the Hessian matrix, determined in the fitting process

$$H_{uv} = \frac{1}{2}\frac{\partial\chi^2}{\partial a_\mu \partial a_\nu}$$

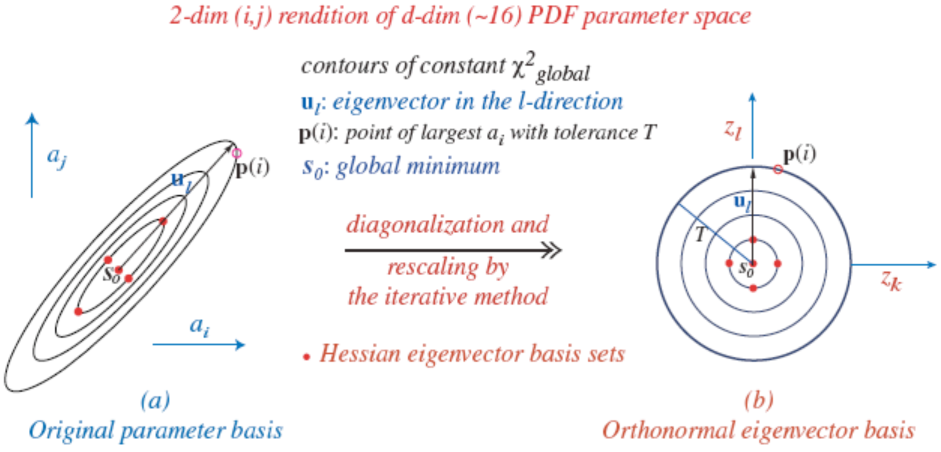


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

To estimate the error on an observable X(a), due to the experimental uncertainties of the data used in the fit, we use the *Master Formula*

$$(\Delta X)^2 = \Delta\chi^2 \sum_{\mu,\nu} \frac{\partial X}{\partial a_\mu}\left(H^{-1}\right)_{\mu\nu}\frac{\partial X}{\partial a_\nu}$$

PDF Errors

C T E Q

- 20 (22,24) eigenvectors with the eigenvalues having a range of >1E6
- Largest eigenvalues (low number eigenvectors) correspond to best determined directions; smallest eigenvalues (high number eigenvectors) correspond to worst determined directions
- Easiest to use Master Formula in eigenvector basis

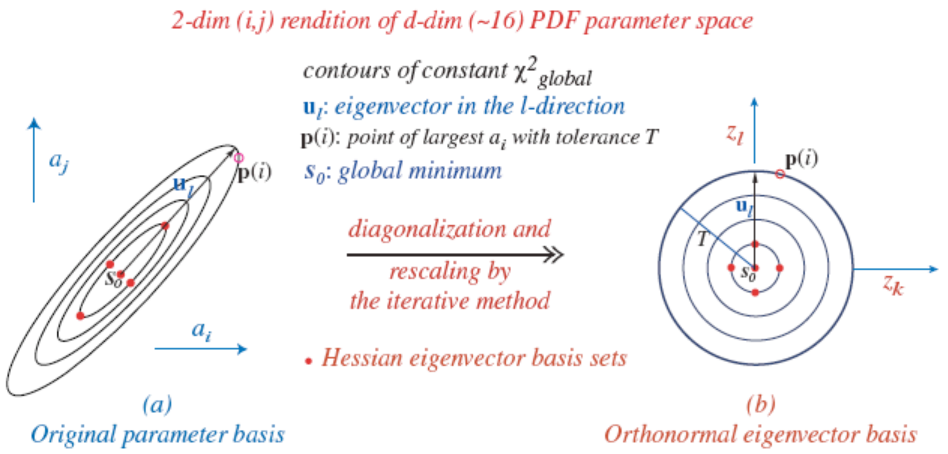


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

To estimate the error on an observable X(a), from the experimental errors, we use the *Master Formula*

$$(\Delta X)^2 = \Delta\chi^2 \sum_{\mu,\nu} \frac{\partial X}{\partial a_\mu}\left(H^{-1}\right)_{\mu\nu} \frac{\partial X}{\partial a_\nu}$$

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

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

where X_i^+ and X_i^- are the values for the observable X when traversing a distance corresponding to the tolerance T(=sqrt($\Delta\chi^2$)) along the ith direction

PDF uncertainties

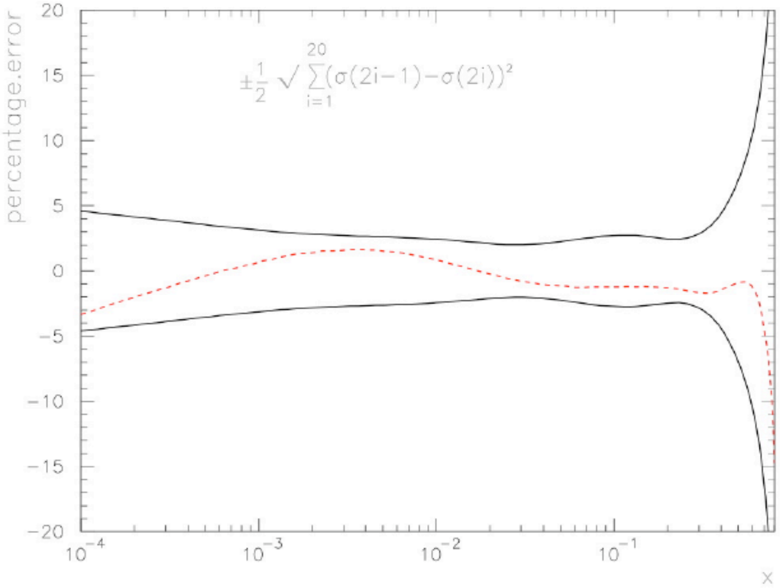
- Use master formula to construct PDF uncertainties

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

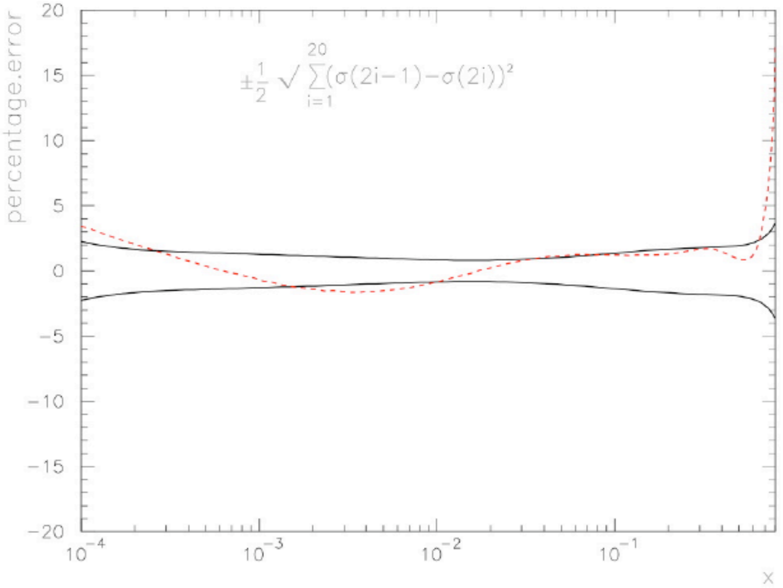
$$\Delta X^{-}_{max} = \sqrt{\sum_{i=1}^{N}[max(X_0 - X_i^{+}, X_0 - X_i^{-}, 0)]^2}$$

tolerance larger for CTEQ
than for MSTW (by design)

up quark: MSTW2008 in CTEQ6.6 error bands



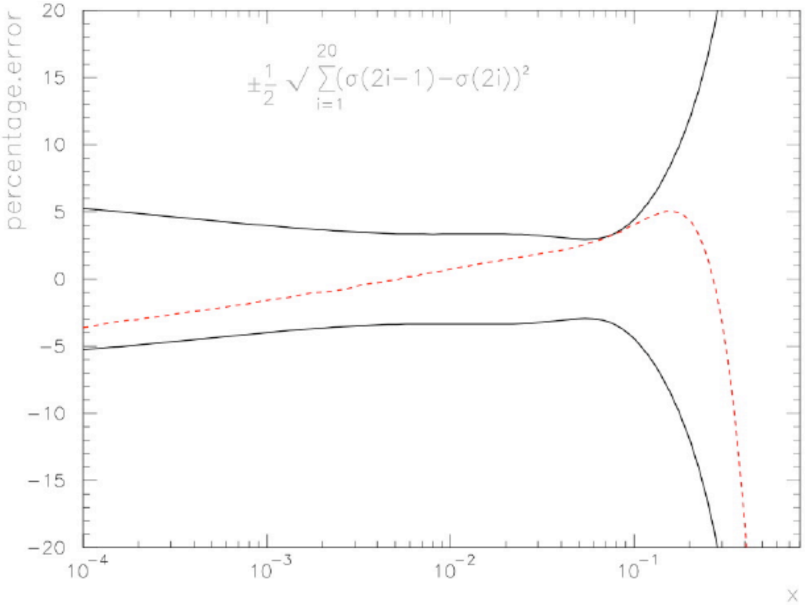
CTEQ6.6 in MSTW2008 error bands



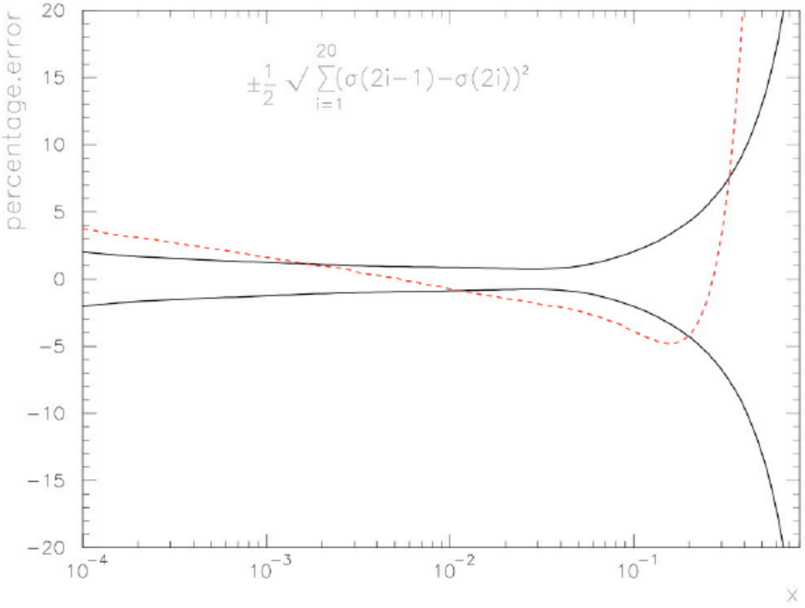
PDF uncertainties

- Necessary condition for PDF uncertainties: central fits for other PDF should be inside error band
- Not always the case for MSTW

gluon distribution: MSTW compared to CTEQ6.6 error band



CTEQ6.6 compared to MSTW error band



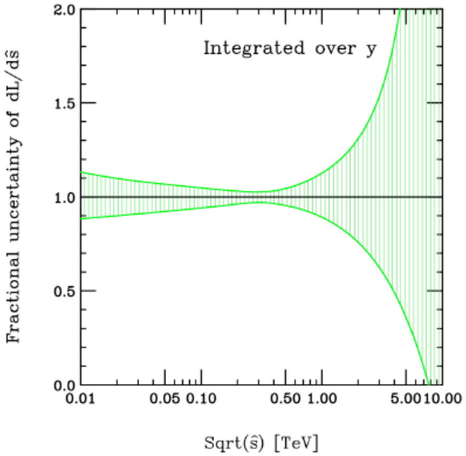
Higgs and eigenvectors

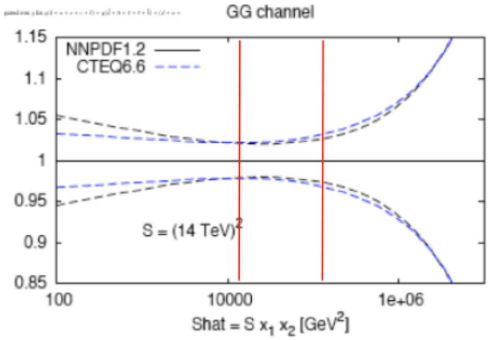
- 20 eigenvectors for CTEQ6.1 and MSTW2008
  - 22 eigenvectors for CTEQ6.6
    - Higgs cross section at LHC sensitive to eigenvectors 4, 6, 11 and 16 (for Higgs masses of 120 and 200 GeV, joined by eigenvectors 5 and 7 at 300 GeV
    - a new technique has been developed by CTEQ called data set diagonalization, which makes it possible to create a new eigenvector sensitive to a cross section/distribution of choice, i.e. one could create an eigenvector that probes the Higgs cross section uncertainty
  - 24 eigenvectors for CT09

PDF luminosities

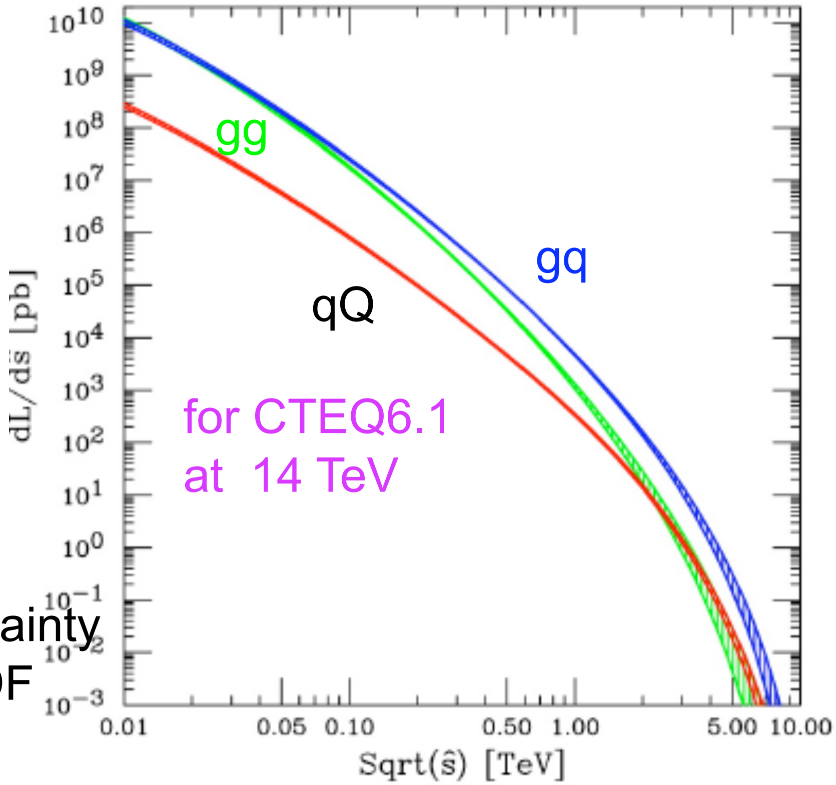
C T E Q

- Define pdf parton-parton luminosity





CTEQ6.6 PDF uncertainty close to that of NNPDF



for CTEQ6.1 at 14 TeV

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

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

$$\sigma = \sum_{i,j}\int_0^1 dx_1\,dx_2\,f_i(x_1,\mu)\,f_j(x_2,\mu)\,\hat{\sigma}_{ij} \tag{3}$$

Ratios:LHC to Tevatron pdf luminosities

C T E Q

- 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

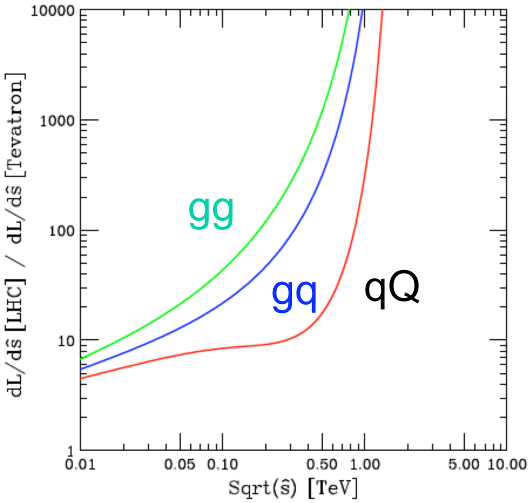


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

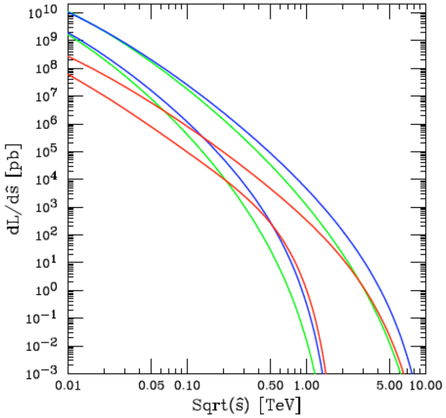


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

Ratios:LHC to Tevatron pdf luminosities

- But wait, we're not running at 14 TeV, but at 7->10 TeV
- Ratios proportionally smaller
- You get the picture for 7 TeV

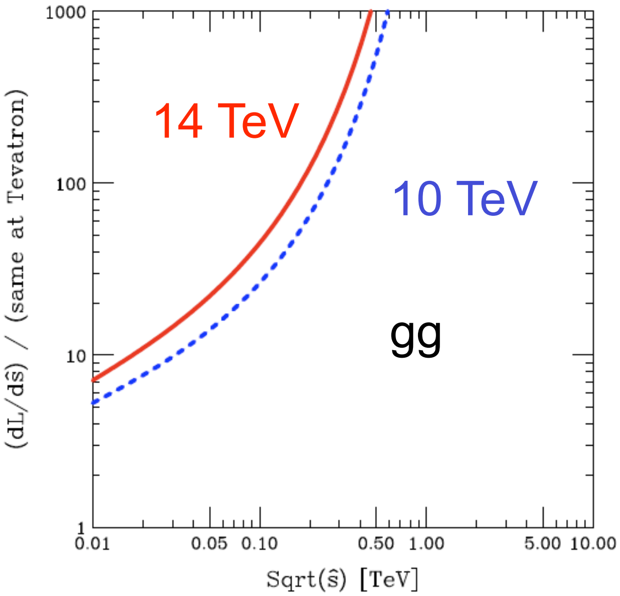


Figure 1: gg luminosity integrated over y:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

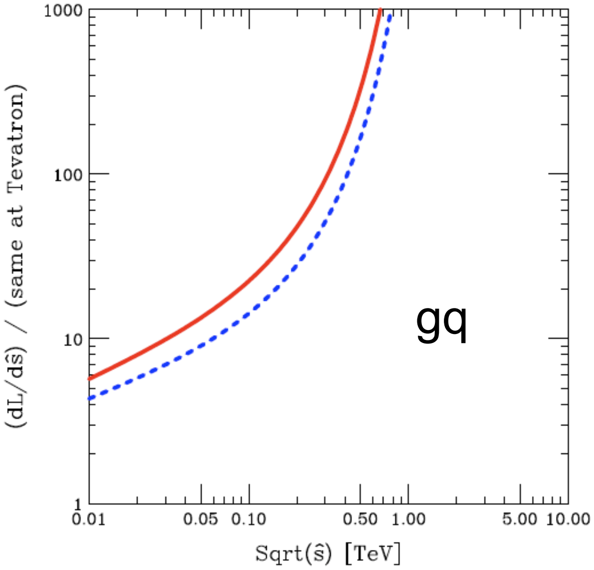


Figure 2: $gq + g\bar{q}$ luminosity integrated over y:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

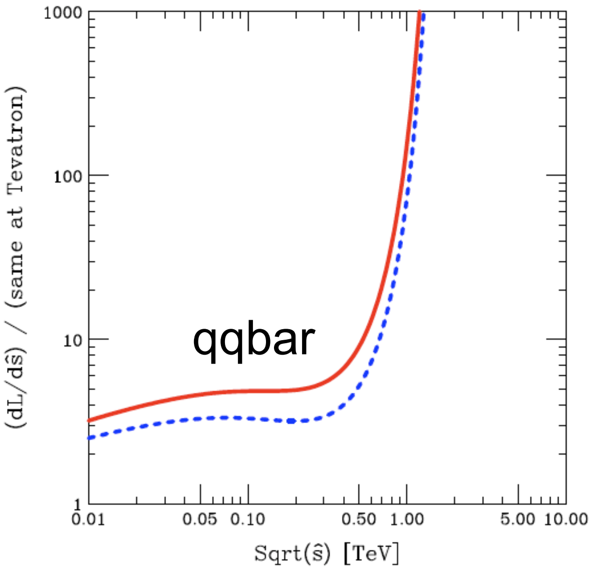
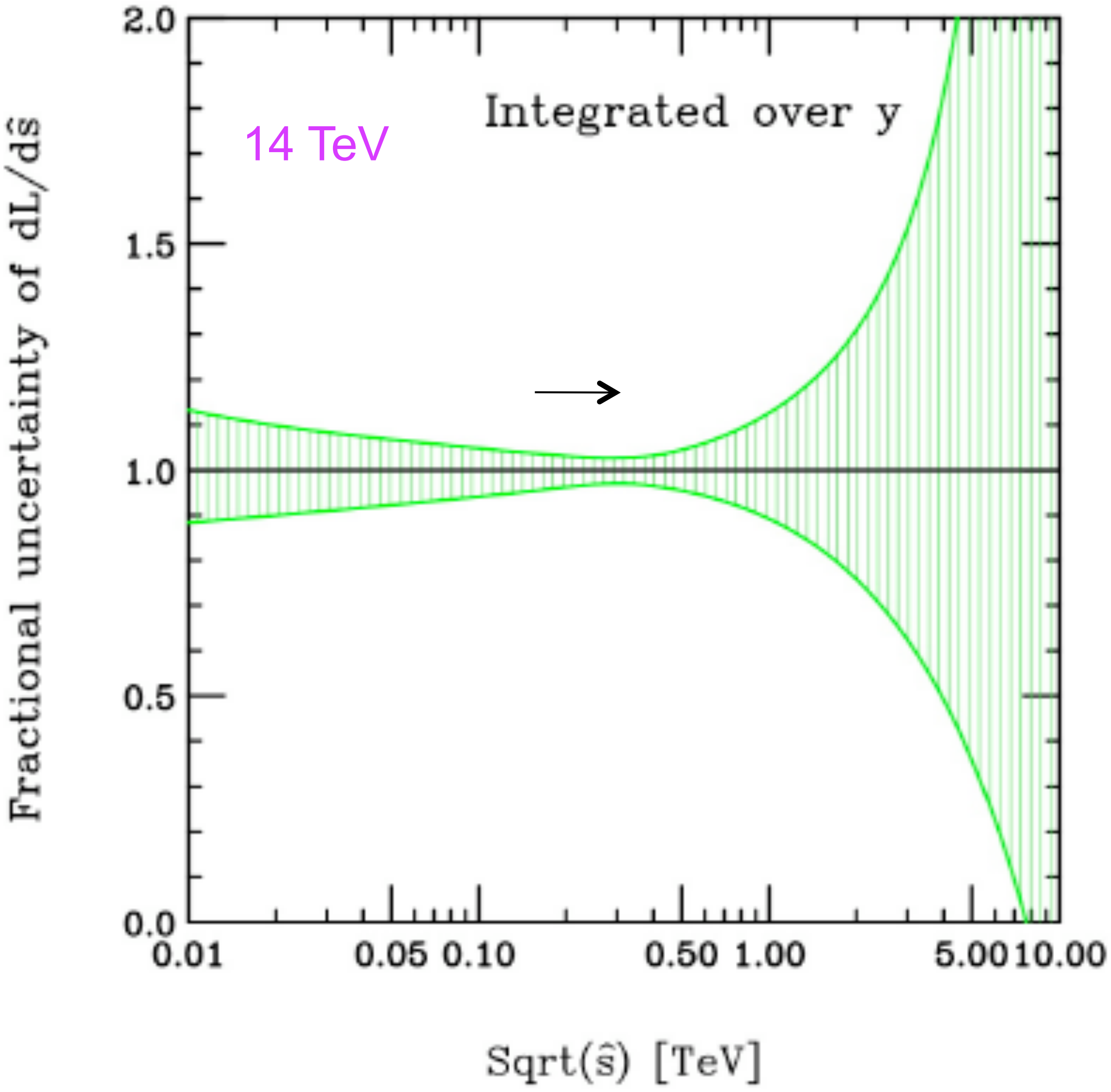


Figure 3: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$:
Blue = (pp at 10 TeV)/($p\bar{p}$ at 1.96 TeV);
Red = (pp at 14 TeV)/($p\bar{p}$ at 1.96 TeV).

gg uncertainties for lower energies

CTEQ

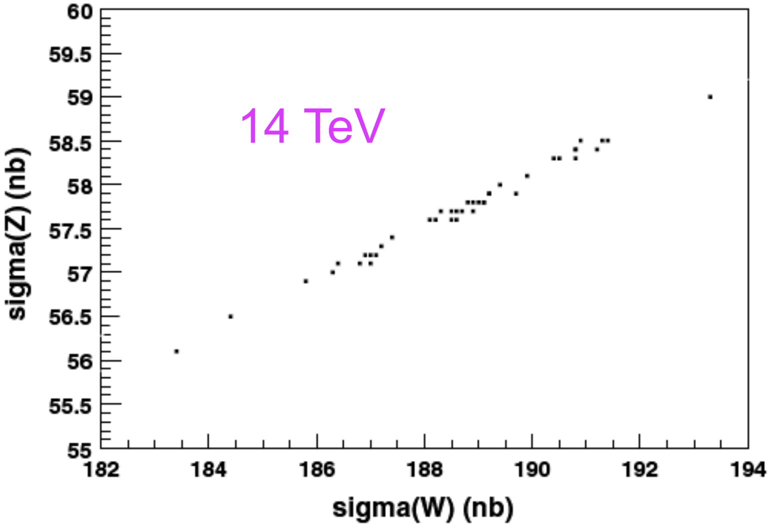
- Impact of lower energies is that you slide to the right along the uncertainty curve (for fixed Higgs mass)
- Consider a Higgs of mass 120 GeV; at 7 TeV, the gg pdf luminosity uncertainty is similar to that of 240 GeV Higgs at 14 TeV
- In this case, a good thing



C T E Q

Correlations

- 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 H and W cross sections



14 TeV

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.

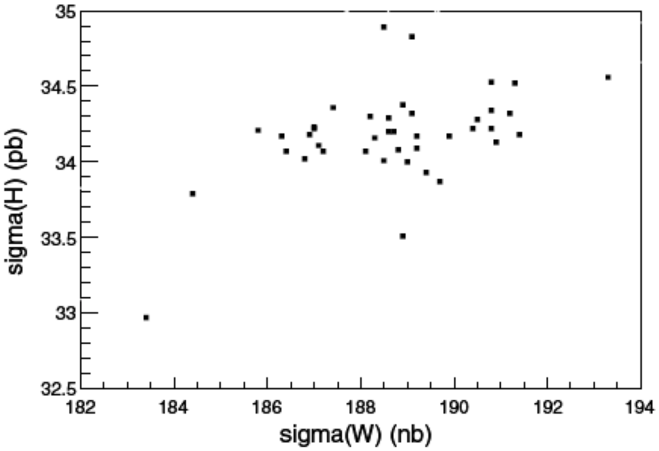


Figure 99. The cross section predictions for Higgs production versus the cross section predictions for *W* production at the LHC plotted using the 41 CTEQ6.1 pdfs.

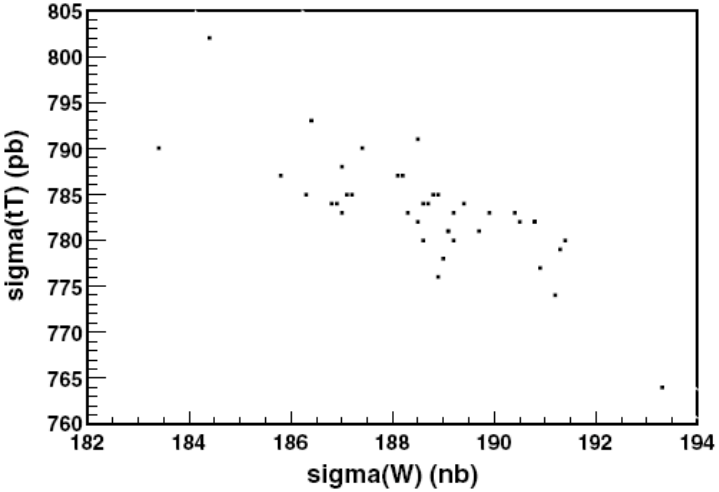


Figure 93. The cross section predictions for $t\bar{t}$ production versus the cross section predictions for *W* production at the LHC plotted using the 41 CTEQ6.1 pdfs.

Correlation cosines

- Define angle ϕ between gradients for two cross sections X and Y (for example Higgs and Z cross section)

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

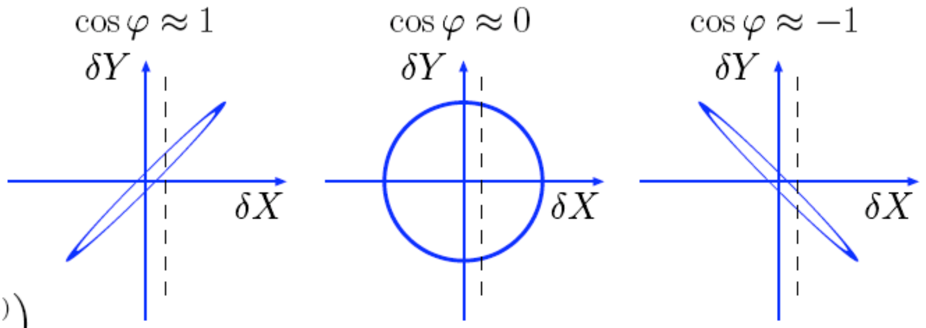
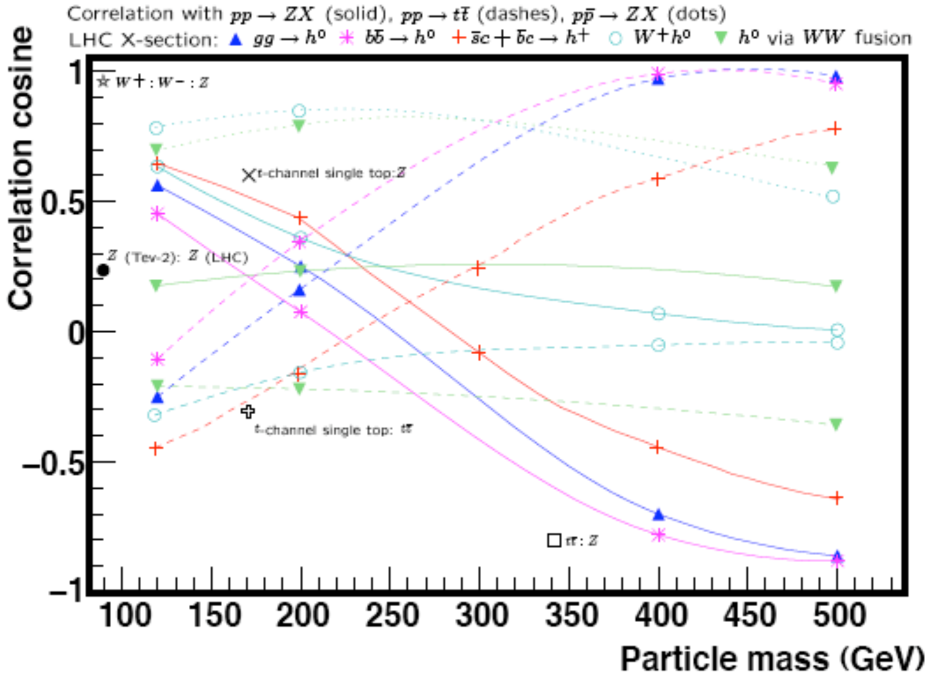


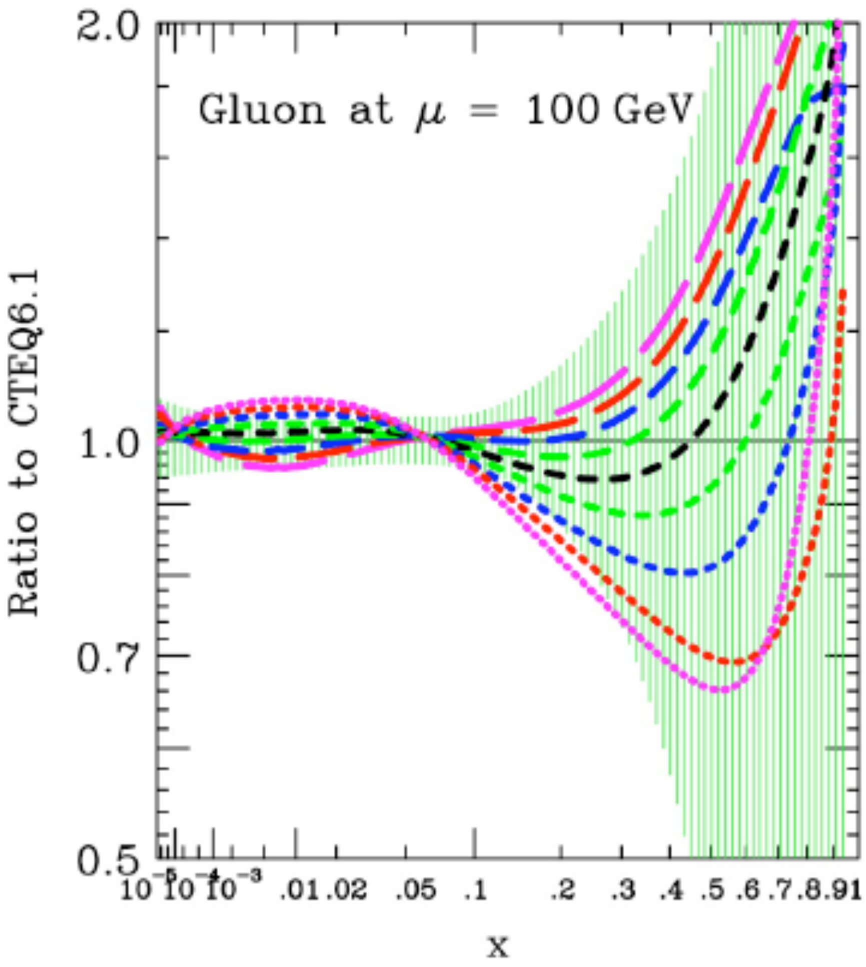
Figure 10. Dependence on the correlation ellipse formed in the $\delta X - \delta Y$ plane on the value of $\cos\varphi$.

- Higgs cross section (through gg fusion) goes from being correlated with W/Z at low mass to being highly anti-correlated for high mass
- Has impact on normalizing to W/Z cross section
  - if two cross sections are correlated, then relative PDF uncertainty cancels
- This is for 14 TeV; will re-do for 7 and 10 TeV



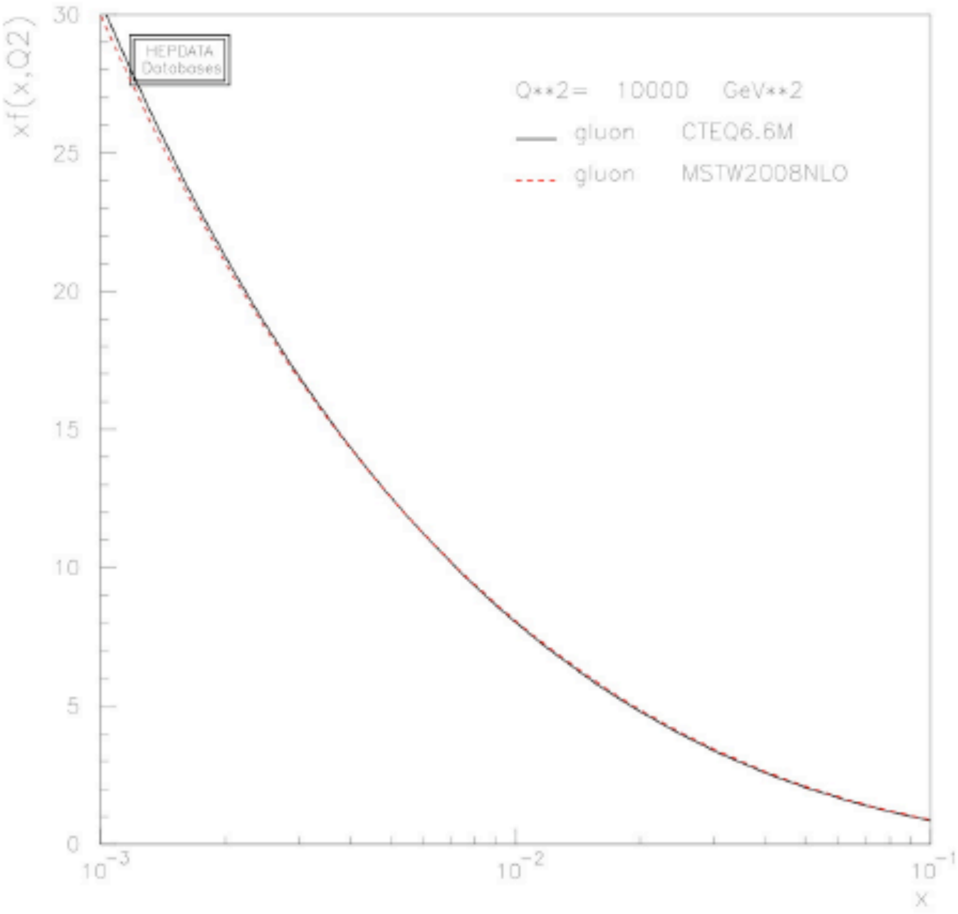
α_s

- In x range relevant for Higgs production, the gluon distribution is correlated with the value of α_s, i.e. the larger the value of α_s, the larger the gluon
- This means that there is an especially large sensitivity to the value of α_s
- Two different philosophies
  - CTEQ and NNPDF use the world average value of $\alpha_s(m_Z)$(=0.118)
  - MSTW uses the value obtained in their fit (0.120 for MSTW2008)
  - large impact on cross sections such as Higgs which have large α_s^3 and α_s^4 contributions



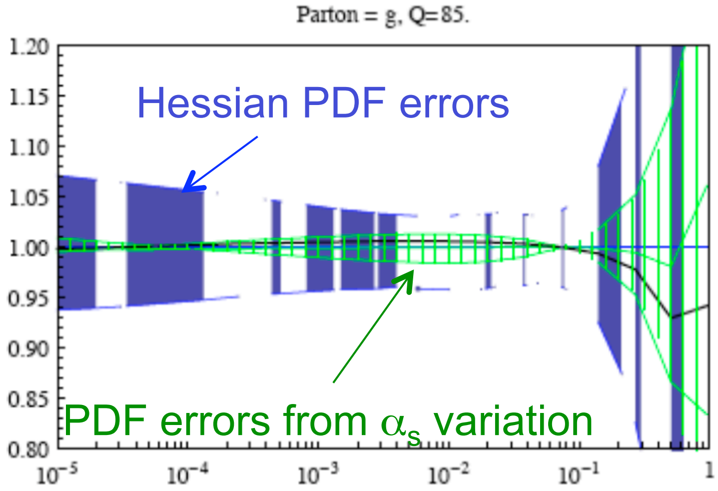
Higgs and gluon

- Gluon distribution for CTEQ6.6 and MSTW2008 almost indistinguishable in relevant x range at LHC
- But MSTW Higgs (and tT) cross sections are larger because of the larger value of α_s



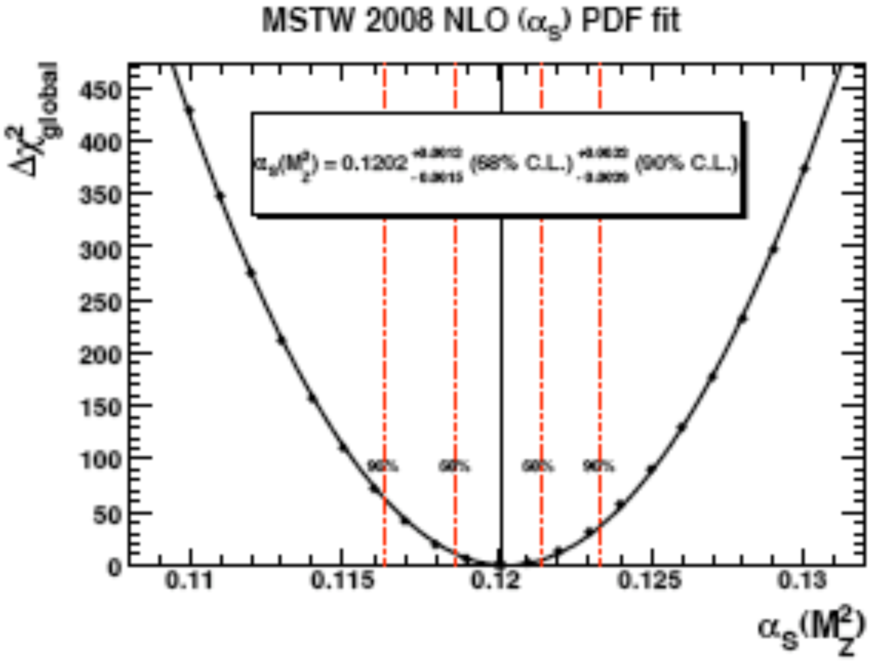
α_s errors

- CTEQ has produced PDF sets with different α_s values in the past
  - we have new α_s sets from CTEQ6.6 corresponding to α_s=0.116,0.117,0.119,0.120
- MSTW has come out with a new prescription for calculating α_s errors
- The key is
  - what is the uncertainty on α_s
  - if it is +/-0.002, the impact is relatively small
  - talking with Siggi Bethke; in his latest fit ($\alpha_s(m_Z)$=0.1184), the uncertainty is +/-0.0007 (which he considers to be >1 sigma)
  - take 0.0014 as 90%CL errors
  - then α_s varies between 0.117 and 0.1198; maybe call it 0.118+/-0.002
  - MSTW starts from a higher central value and has a larger error



Hessian PDF errors

PDF errors from α_s variation



MSTW α_s error prescription

- Since the prescription for dealing with the varied α_s values is a bit complicated, they give examples

PDF uncertainties given by [1]

$$(\Delta F^{\alpha_S}_{\rm PDF})_+ = \sqrt{\sum_{k=1}^{n}\left\{\max\left[\,F^{\alpha_S}(S_k^+) - F^{\alpha_S}(S_0),\; F^{\alpha_S}(S_k^-) - F^{\alpha_S}(S_0),\; 0\right]\right\}^2}, \qquad (7)$$

$$(\Delta F^{\alpha_S}_{\rm PDF})_- = \sqrt{\sum_{k=1}^{n}\left\{\max\left[\,F^{\alpha_S}(S_0) - F^{\alpha_S}(S_k^+),\; F^{\alpha_S}(S_0) - F^{\alpha_S}(S_k^-),\; 0\right]\right\}^2}, \qquad (8)$$

for each of the five fixed values of α_S. Then the overall best-fit prediction is $F^{\alpha_S^0}(S_0)$, where α_S^0 is the best-fit α_S value, and the overall "PDF+α_S" uncertainties are given by

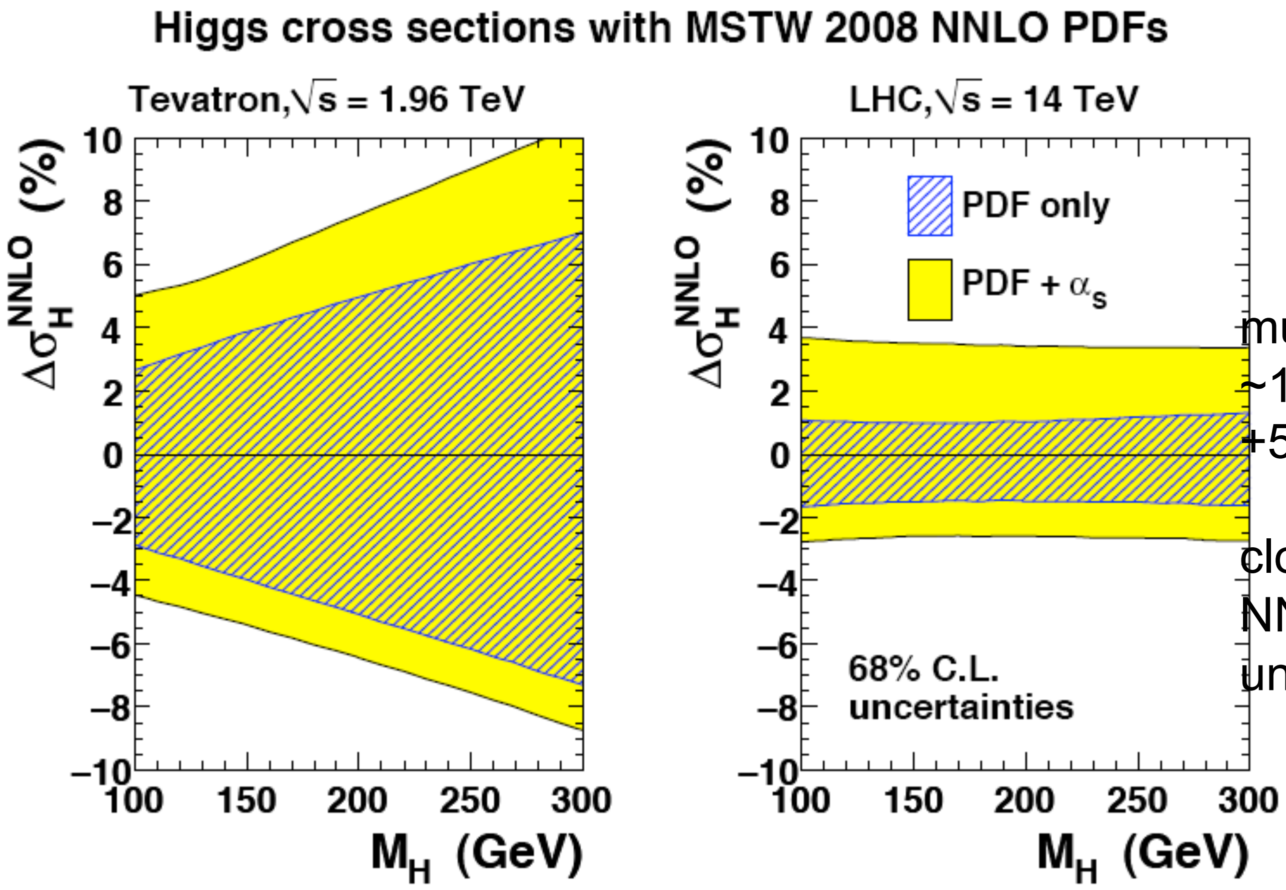
$$(\Delta F_{{\rm PDF}+\alpha_S})_+ = \max_{\alpha_S}\left(\{F^{\alpha_S}(S_0) + (\Delta F^{\alpha_S}_{\rm PDF})_+\}\right) - F^{\alpha_S^0}(S_0), \qquad (9)$$

$$(\Delta F_{{\rm PDF}+\alpha_S})_- = F^{\alpha_S^0}(S_0) - \min_{\alpha_S}\left(\{F^{\alpha_S}(S_0) - (\Delta F^{\alpha_S}_{\rm PDF})_-\}\right). \qquad (10)$$

Since this prescription might look quite complicated at first sight, we will give a few concrete examples of its application and consequences in the following subsections.[3]

Significant change to Higgs uncertainty

(b)



multiply by ~1.6 for 90%CL; +5.8%,-4.5%

closer to CTEQ/ NNPDF uncertainties

Figure 15: (a) Higgs total cross sections as a function of the Higgs mass at the Tevatron and LHC. (b) Percentage uncertainty in the Higgs total cross sections when accounting simultaneously for PDF and α_S uncertainties (outer error bands) as compared to that due to the PDF uncertainty alone (inner error bands).

Some quick answers

C T E Q

1) Theory predictions for Higgs + backgrounds to Higgs
   a. can we have a dynamic collection of cross sections (detailing methods and parameters used to calculate these cross sections) for all Higgs production processes and main backgrounds?

      yes, see for example CTEQ4LHC/ATLAS

   b. understanding consistency and best use of predictions at LO, NLO, NNLO,NLO+NLL, NNLO+NNLL
      i. how consistent are the predictions from CTEQ, MSTW, NNPDF?

         ~ok

      ii. how to properly include the cross section/PDF uncertainty due to the uncertainty on α_s?

         use world average

      iii. what is the best way of adding PDF and scale uncertainties?

         add in quadrature

      iv. should the factorization and renormalization scales be varied separately or together?
      v. can we assume similar scales for related processes?
      vi. how best to treat the PDF correlations between cross sections?

         correlation cosines

      vii. can we improve the PDF and scale uncertainties by normalizing to the W/Z cross section?

         yes (in many cases)

EXTRA

CTEQ4LHC/FROOT

CTEQ

- 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

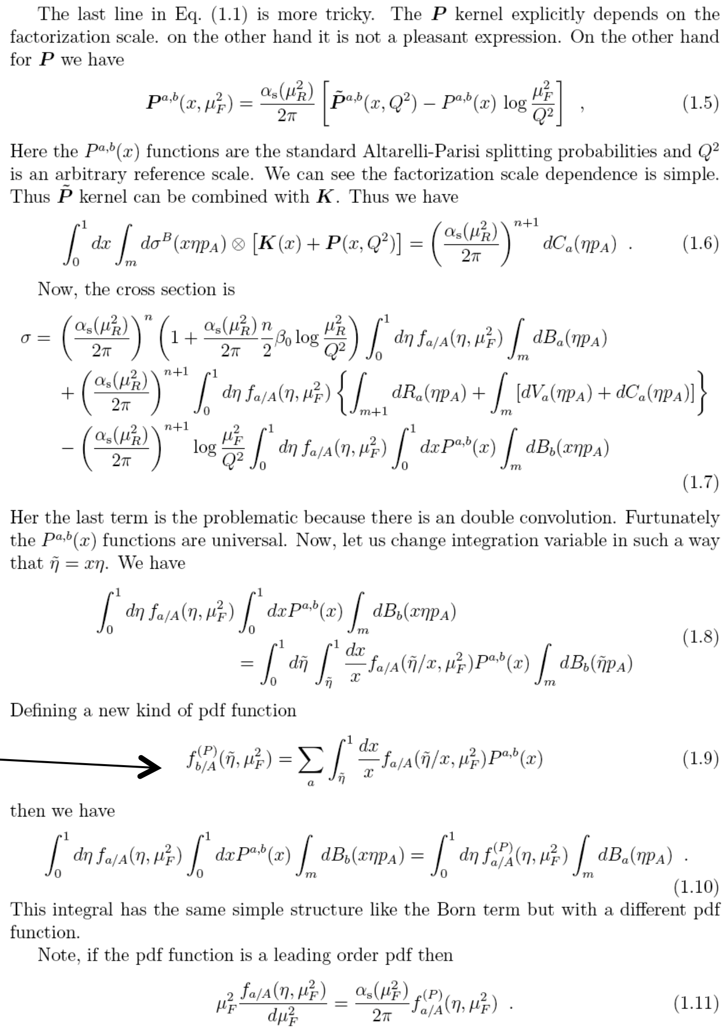
<u>Primary goal</u>: have all theorists (**including you**) write out parton level output into ROOT ntuples
<u>Secondary goal</u>: make libraries of prediction ntuples available

- 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

CTEQ

- Zoltan Nagy has some ideas for making the calculation of the factorization scale uncertainty somewhat easier, by simplifying the pdf convolutions



The last line in Eq. (1.1) is more tricky. The $\boldsymbol{P}$ kernel explicitly depends on the factorization scale. on the other hand it is not a pleasant expression. On the other hand for $\boldsymbol{P}$ we have

$$\boldsymbol{P}^{a,b}(x, \mu_F^2) = \frac{\alpha_s(\mu_R^2)}{2\pi} \left[\tilde{\boldsymbol{P}}^{a,b}(x, Q^2) - P^{a,b}(x) \log \frac{\mu_F^2}{Q^2} \right] \quad , \tag{1.5}$$

Here the $P^{a,b}(x)$ functions are the standard Altarelli-Parisi splitting probabilities and Q^2 is an arbitrary reference scale. We can see the factorization scale dependence is simple. Thus $\tilde{\boldsymbol{P}}$ kernel can be combined with $\boldsymbol{K}$. Thus we have

$$\int_0^1 dx \int_m d\sigma^B(x\eta p_A) \otimes [\boldsymbol{K}(x) + \boldsymbol{P}(x, Q^2)] = \left(\frac{\alpha_s(\mu_R^2)}{2\pi} \right)^{n+1} dC_a(\eta p_A) \quad . \tag{1.6}$$

Now, the cross section is

$$\begin{aligned} \sigma = & \left(\frac{\alpha_s(\mu_R^2)}{2\pi} \right)^n \left(1 + \frac{\alpha_s(\mu_R^2)}{2\pi} \frac{n}{2} \beta_0 \log \frac{\mu_R^2}{Q^2} \right) \int_0^1 d\eta \, f_{a/A}(\eta, \mu_F^2) \int_m dB_a(\eta p_A) \\ & + \left(\frac{\alpha_s(\mu_R^2)}{2\pi} \right)^{n+1} \int_0^1 d\eta \, f_{a/A}(\eta, \mu_F^2) \left\{ \int_{m+1} dR_a(\eta p_A) + \int_m [dV_a(\eta p_A) + dC_a(\eta p_A)] \right\} \\ & - \left(\frac{\alpha_s(\mu_R^2)}{2\pi} \right)^{n+1} \log \frac{\mu_F^2}{Q^2} \int_0^1 d\eta \, f_{a/A}(\eta, \mu_F^2) \int_0^1 dx P^{a,b}(x) \int_m dB_b(x\eta p_A) \end{aligned} \tag{1.7}$$

Her the last term is the problematic because there is an double convolution. Furtunately the $P^{a,b}(x)$ functions are universal. Now, let us change integration variable in such a way that $\tilde{\eta} = x\eta$. We have

$$\begin{aligned} & \int_0^1 d\eta \, f_{a/A}(\eta, \mu_F^2) \int_0^1 dx P^{a,b}(x) \int_m dB_b(x\eta p_A) \\ & \qquad = \int_0^1 d\tilde{\eta} \int_{\tilde{\eta}}^1 \frac{dx}{x} f_{a/A}(\tilde{\eta}/x, \mu_F^2) P^{a,b}(x) \int_m dB_b(\tilde{\eta} p_A) \end{aligned} \tag{1.8}$$

Defining a new kind of pdf function

$$f_{b/A}^{(P)}(\tilde{\eta}, \mu_F^2) = \sum_a \int_{\tilde{\eta}}^1 \frac{dx}{x} f_{a/A}(\tilde{\eta}/x, \mu_F^2) P^{a,b}(x) \tag{1.9}$$

then we have

$$\int_0^1 d\eta \, f_{a/A}(\eta, \mu_F^2) \int_0^1 dx P^{a,b}(x) \int_m dB_b(x\eta p_A) = \int_0^1 d\eta \, f_{a/A}^{(P)}(\eta, \mu_F^2) \int_m dB_a(\eta p_A) \quad . \tag{1.10}$$

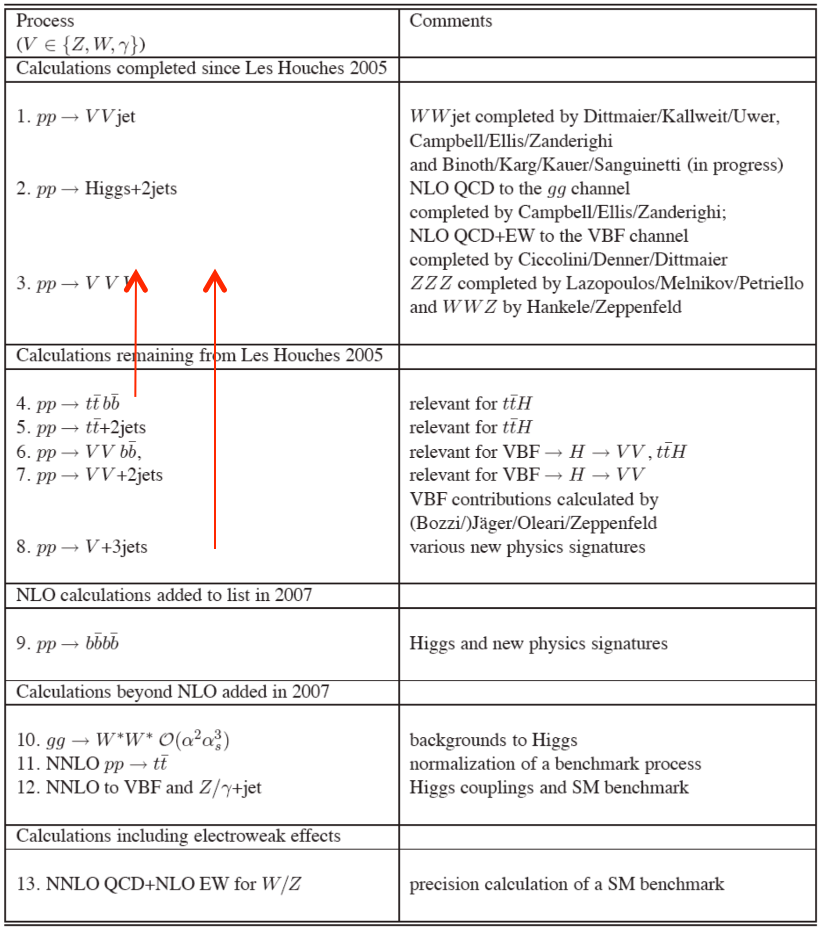
This integral has the same simple structure like the Born term but with a different pdf function.

Note, if the pdf function is a leading order pdf then

$$\mu_F^2 \frac{f_{a/A}(\eta, \mu_F^2)}{d\mu_F^2} = \frac{\alpha_s(\mu_F^2)}{2\pi} f_{a/A}^{(P)}(\eta, \mu_F^2) \quad . \tag{1.11}$$

NLO and the Les Houches wishlist

- NLO is the first order at which the normalization, and sometimes the shape, can be taken seriously
- A great deal of effort has gone into calculations of 2->3 processes, and now we even have a formalism(s) for tackling 2->4
- The Les Houches wishlist from 2005/2007 is filling up slowly but progressively. The effort in 2009 will result in an updated Les Houches list. For the Les Houches 2009 writeup, we would like to specify not only the new calculations needed, but the level of accuracy to which we need to know them. This would tell us, for example, whether EW corrections are needed as well
- Public code/ntuples will make the contributions to this wishlist the most useful/widely cited
  - not many of the calculated processes are available to the public



Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer, Campbell/Ellis/Zanderighi and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello and WWZ by Hankele/Zeppenfeld
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Table 1: The updated experimenter's wishlist for LHC processes

It's also imperative that decays be included to allow better matching to experimental cuts.

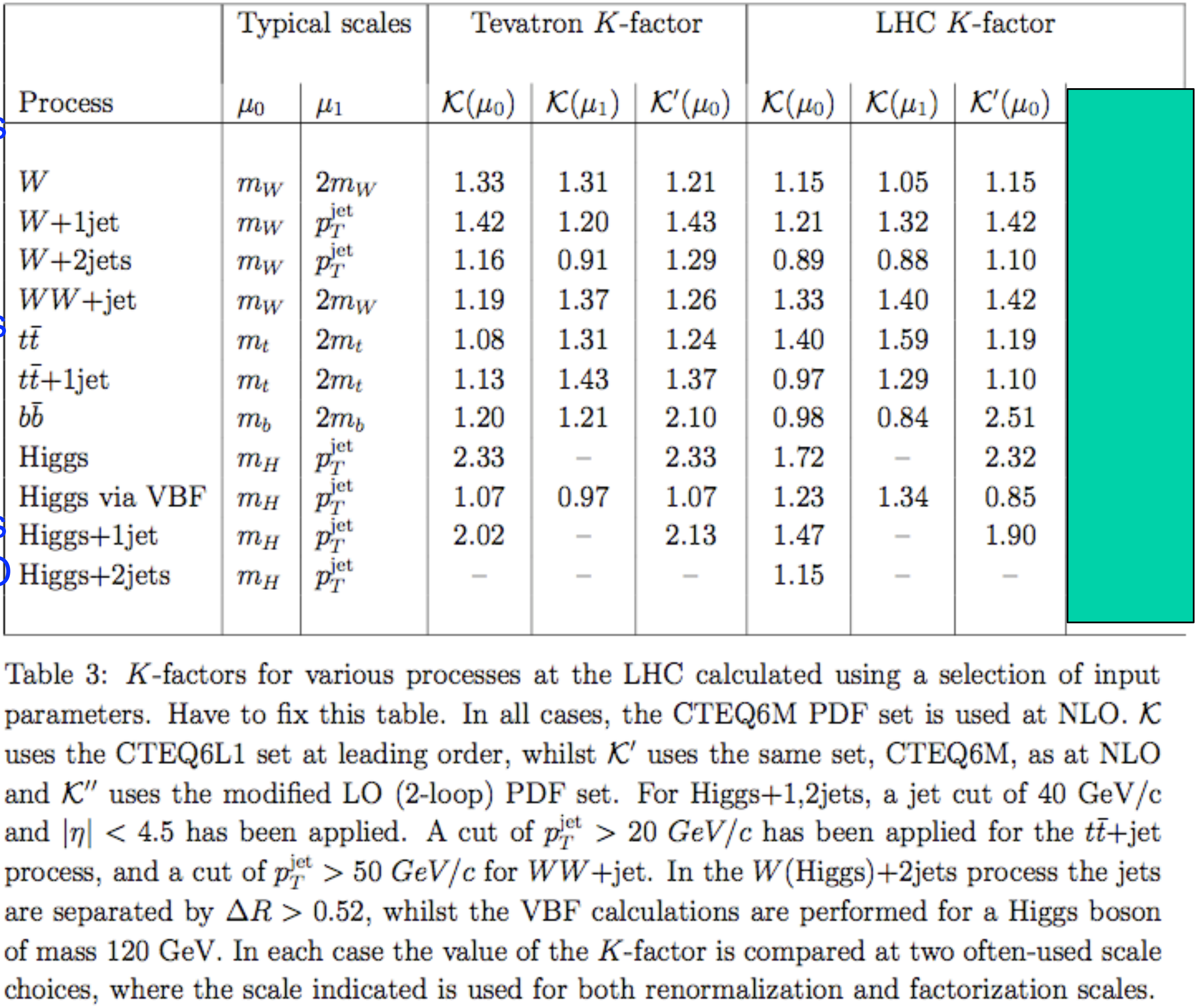
K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections

K-factor table from CHS paper

K-factors for LHC slightly less K-factors at Tevatron

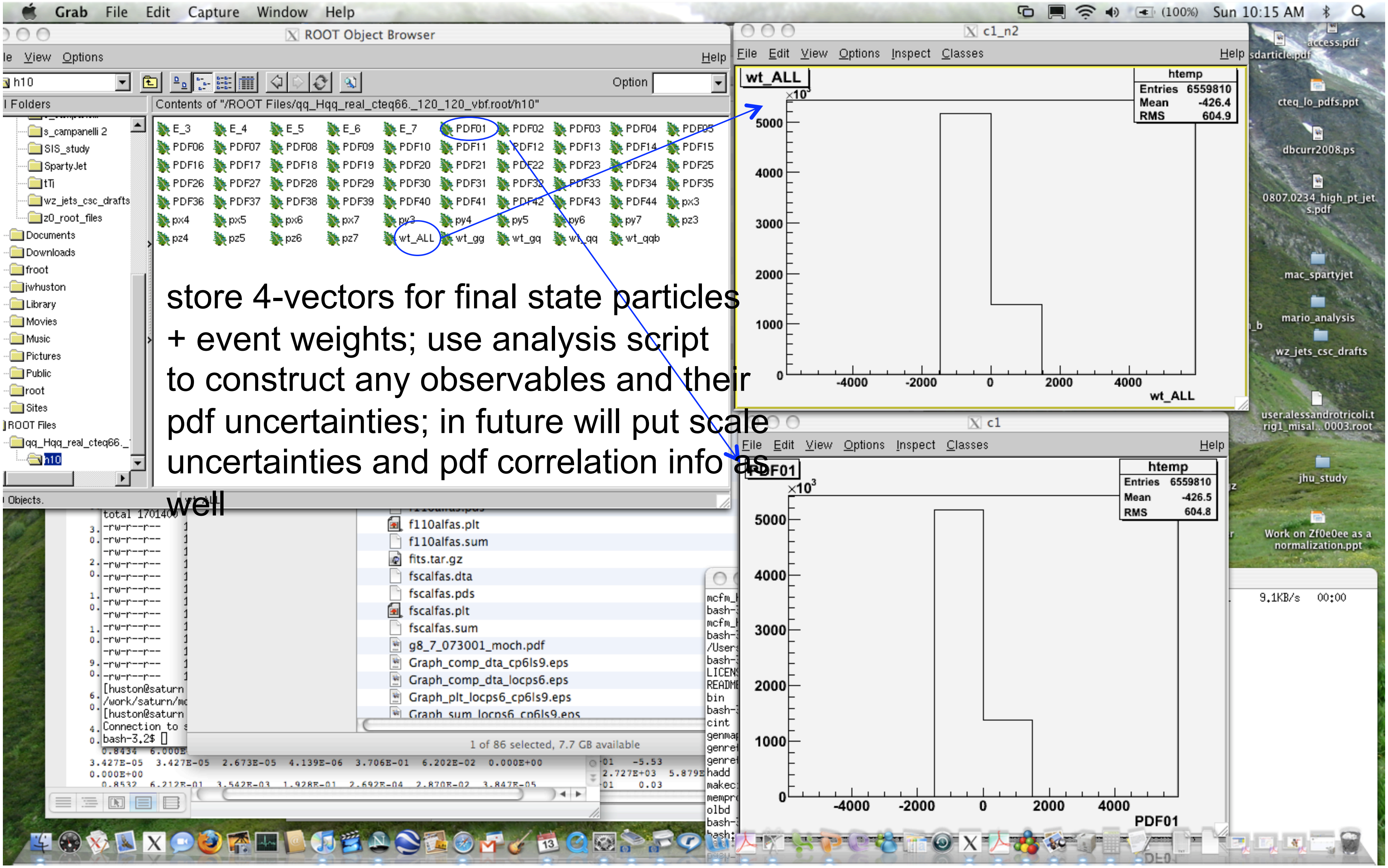
K-factors with NLO PDFs at LO are more often closer to unity



Process	Typical scales		Tevatron K-factor			LHC K-factor		
	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	1.19
$t\bar{t}$+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	0.85
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 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 $p_T^{\rm jet} > 20\ GeV/c$ 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.

MCFM has ROOT output built in; standard Les Houches format will be developed



wt_ALL — htemp: Entries 6559810, Mean -426.4, RMS 604.9

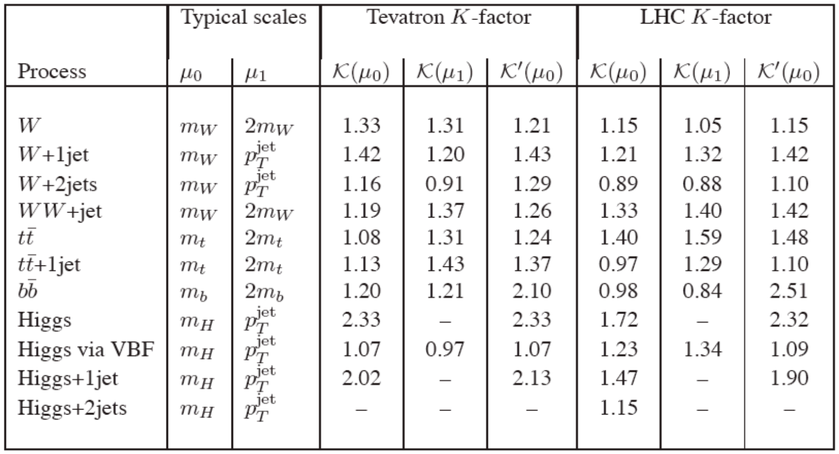
PDF01 — htemp: Entries 6559810, Mean -426.5, RMS 604.8

```
total 170140
-rw-r--r--
[huston@saturn
/work/saturn/m
[huston@saturn
Connection to s
bash-3.2$
3.427E-05  3.427E-05  2.673E-05  4.139E-06  3.706E-01  6.202E-02  0.000E+00
0.000E+00
```

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

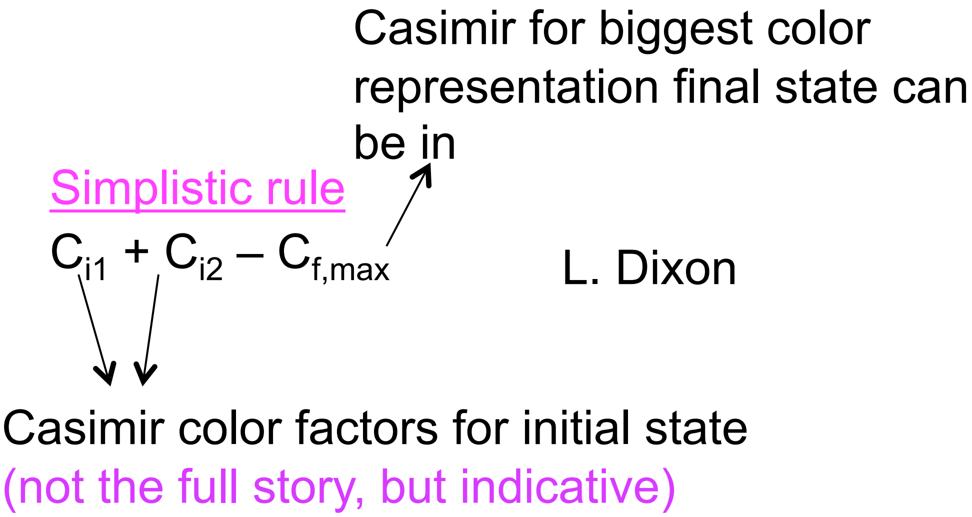
Go back to K-factor table

- 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)
    - these gg initial states want to radiate like crazy (see Sudakovs)
- 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?
- What about effect of jet vetoes on K-factors? Signal processes compared to background. Of current interest.



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 $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
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.



Casimir for biggest color representation final state can be in

Simplistic rule

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

L. Dixon

Casimir color factors for initial state

(not the full story, but indicative)

CTEQ modified LO PDFs

CTEQ

- Discussed already in several PDF4LHC meetings
- Preprint available on the archive last Friday (0910.4183)
- Three different flavors of PDFs
  - CT09MCS: momentum sum rule kept; fit to NLO pseudo-data
  - CT09MC1: 1-loop α_s; momentum sum rule violated (by ~10%); fit to NLO pseudo-data;
  - CT09MC2: 2-loop α_s; momentum sum rule violated (by ~14%); fit to NLO pseudo-data

Parton Distributions for Event Generators

Hung-Liang Lai,[1] Joey Huston,[2] Stephen Mrenna,[3] Pavel Nadolsky,[4]
Daniel Stump,[2] Wu-Ki Tung,[2,5,†] C.-P. Yuan[2]

[1]Taipei Municipal University of Education, Taipei, Taiwan
[2]Department of Physics and Astronomy, Michigan State University,
East Lansing, MI 48824-1116, U.S.A.
[3]Fermilab, Batavia, IL 60510 U.S.A.
[4]Department of Physics, Southern Methodist University, Dallas, TX
[5]Department of Physics, University of Washington, Seattle, WA 98105, U.S.A.
† Deceased

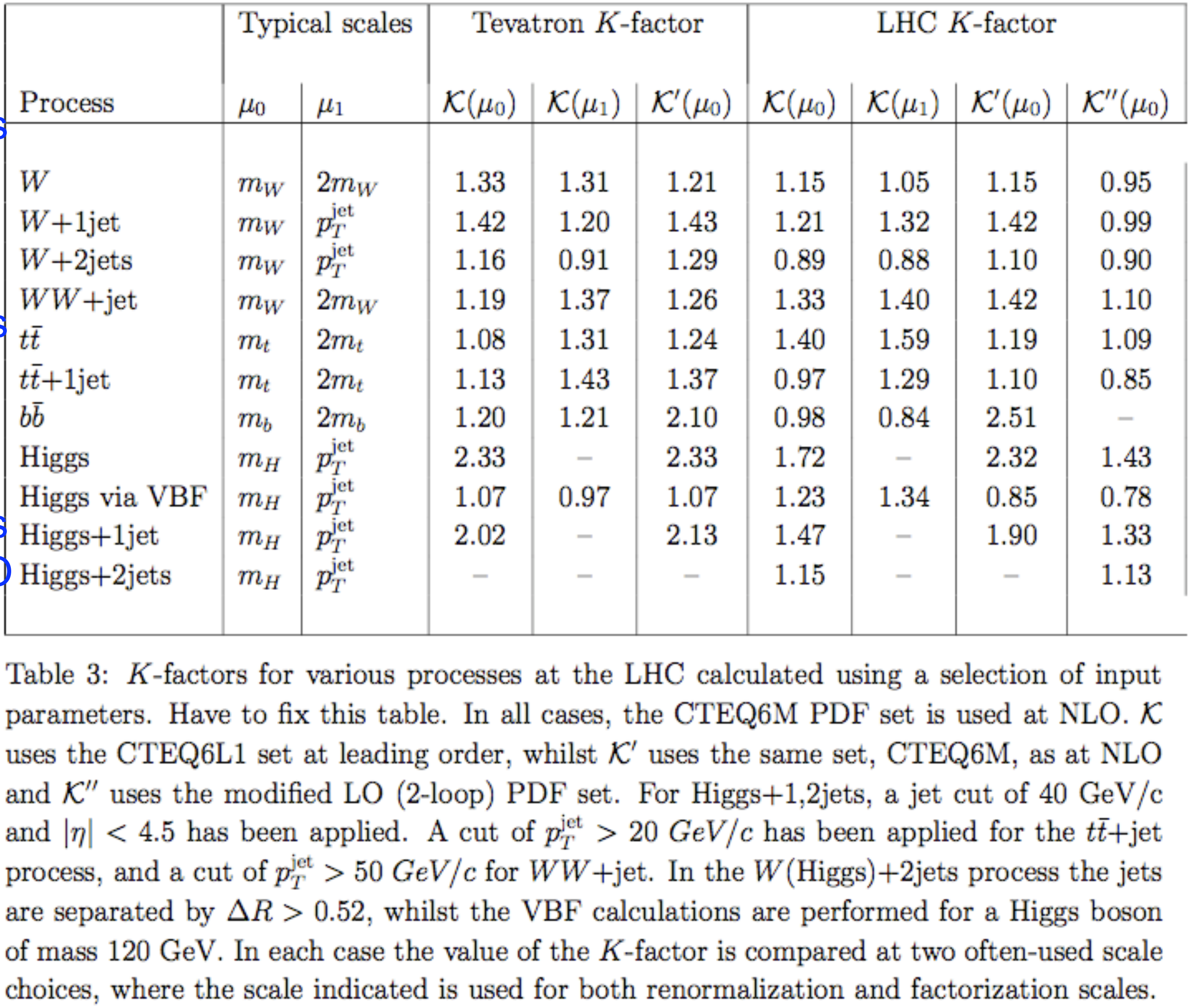
In this paper, conventional Global QCD analysis is generalized to produce parton distributions optimized for use with event generators at the LHC. This optimization is accomplished by combining the constraints due to existing hard-scattering experimental data with those from anticipated cross sections for key representative SM processes at LHC (by the best available theory) as joint input to the global analyses. The PDFs obtained in these new type of global analyses using matrix elements calculated in any given order will be best suited to work with event generators of that order, for predictions at the LHC. This is most useful for LO event generators at present. Results obtained from a few candidate PDF sets (labeled as CT09MCS, CT09MC1 and CT09MC2) for LO event generators produced in this way are compared with those from other approaches.

K-factor table with the modified LO PDFs

CTEQ

K-factors for LHC slightly less K-factors at Tevatron

K-factors with NLO PDFs at LO are more often closer to unity



	Typical scales		Tevatron K-factor			LHC K-factor			
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10	0.90
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	1.10
$t\bar{t}$	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	0.85
$b\bar{b}$	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	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	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 $p_T^{\rm jet} > 20\ GeV/c$ 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.

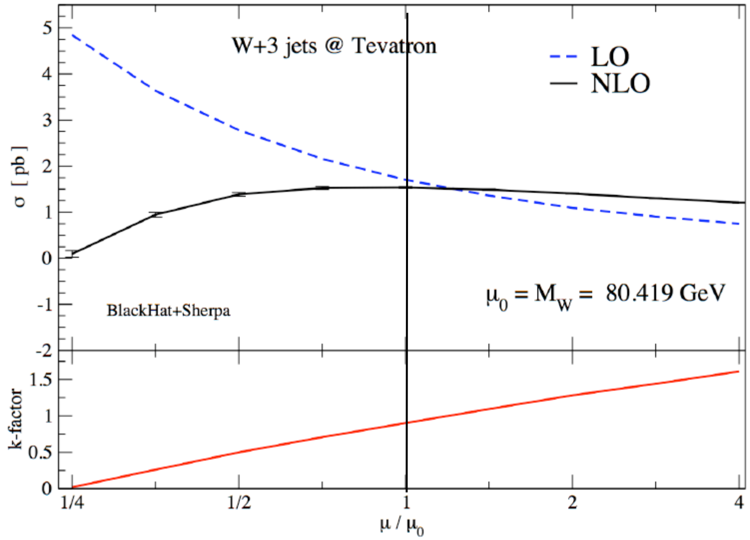
mod LO PDF

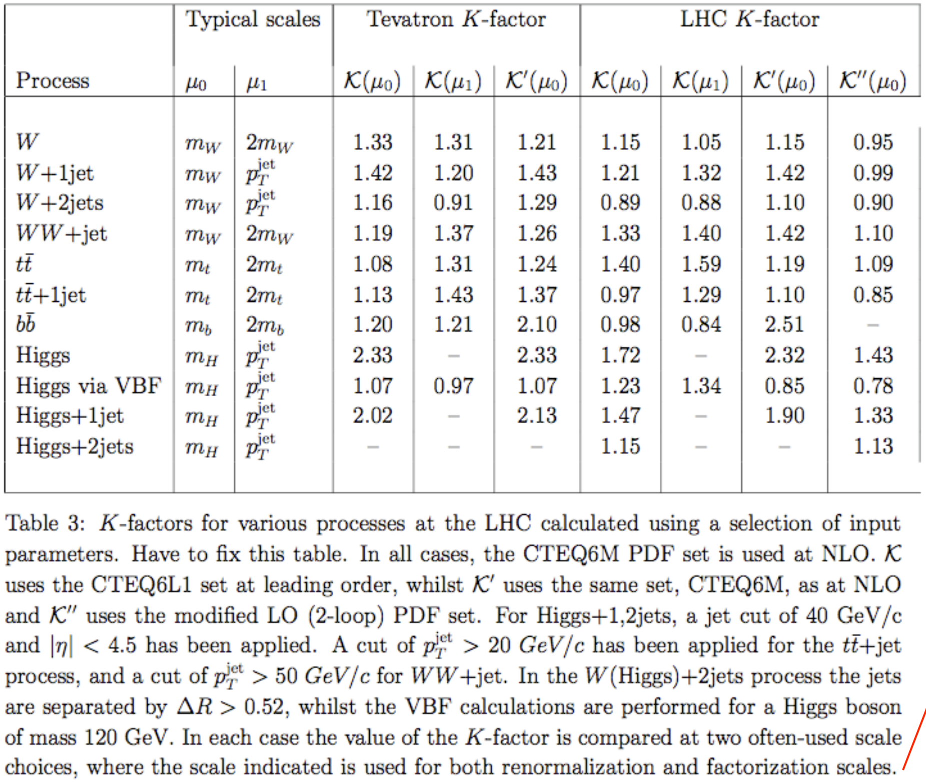
Note K-factor for W < 1.0, since for this table the comparison is to CTEQ6.1 and not to CTEQ6.6, i.e. corrections to low x PDFs due to treatment of heavy quarks in CTEQ6.6 "built-in" to mod LO PDFs

Now consider W + 3 jets

CTEQ

Consider a scale of m_W for W + 1,2,3 jets. We see the K-factors for W + 1,2 jets in the table below, and recently the NLO corrections for W + 3 jets have been calculated, allowing us to estimate the K-factors for that process.

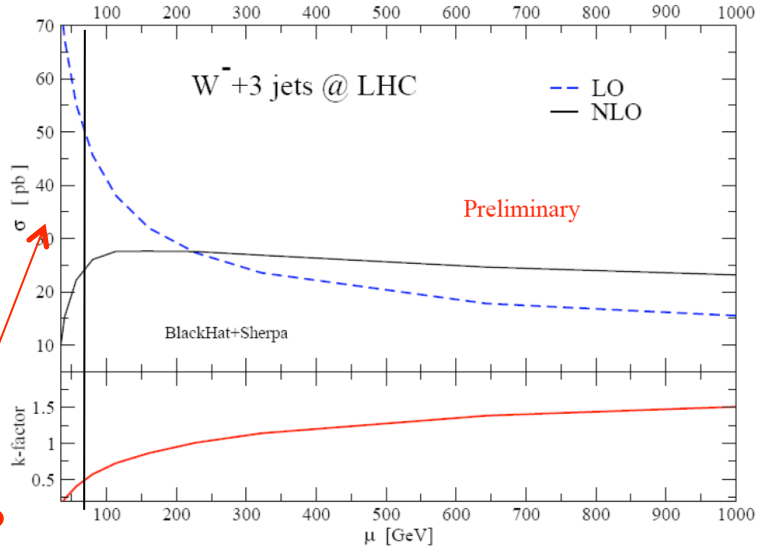




Process	Typical scales		Tevatron K-factor			LHC K-factor			
	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10	0.90
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	1.10
$t\bar{t}$	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	0.85
$b\bar{b}$	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	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	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 $p_T^{\rm jet} > 20$ 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.

LHC total cross section



Is the K-factor (at m_W) at the LHC surprising?

Is the K-factor (at m_W) at the LHC surprising?

C T E Q

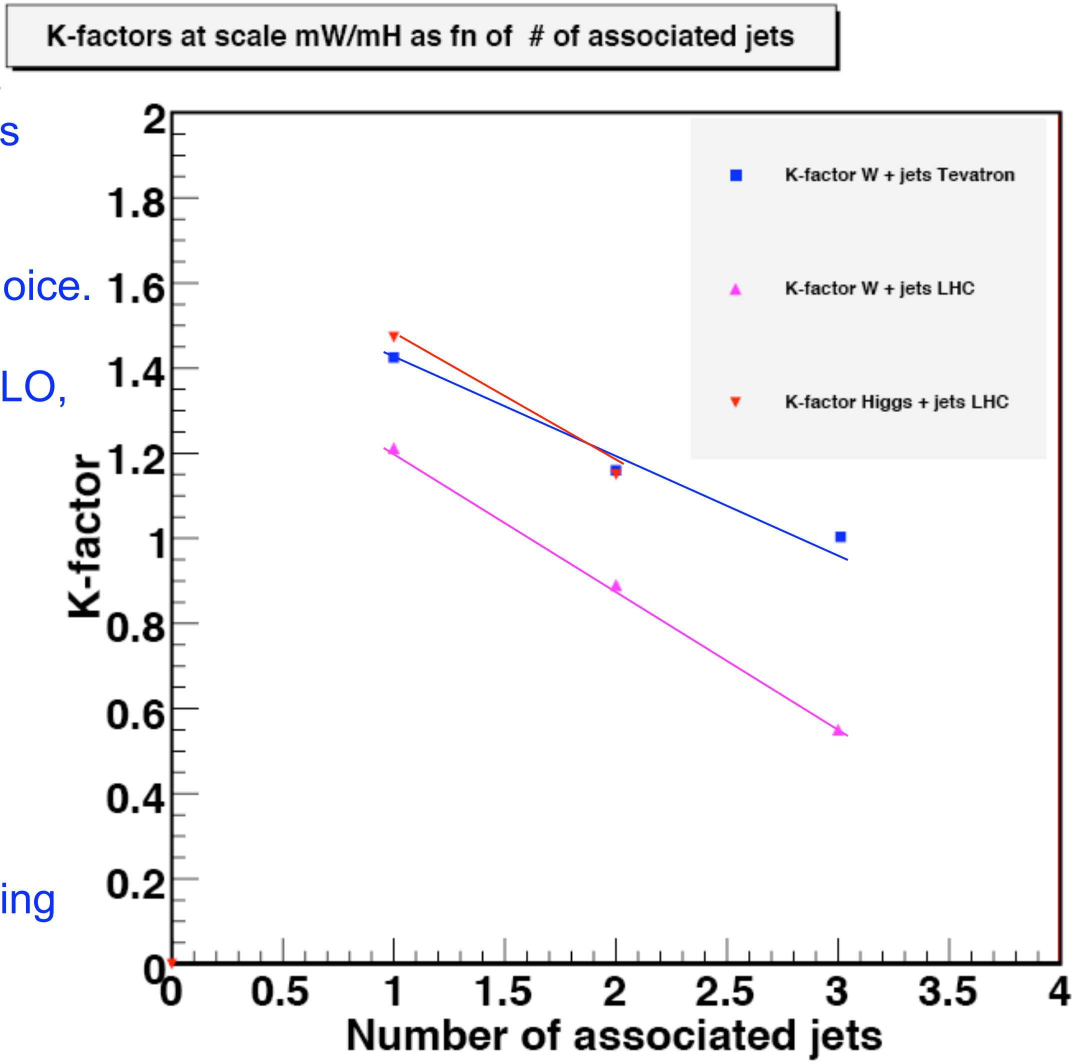
The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make some rules of thumb?

Related to this is:

- understanding the reduced scale dependences/pdf uncertainties for cross section ratios we have been discussing
-scale choices at LO for cross sections uncalculated at NLO



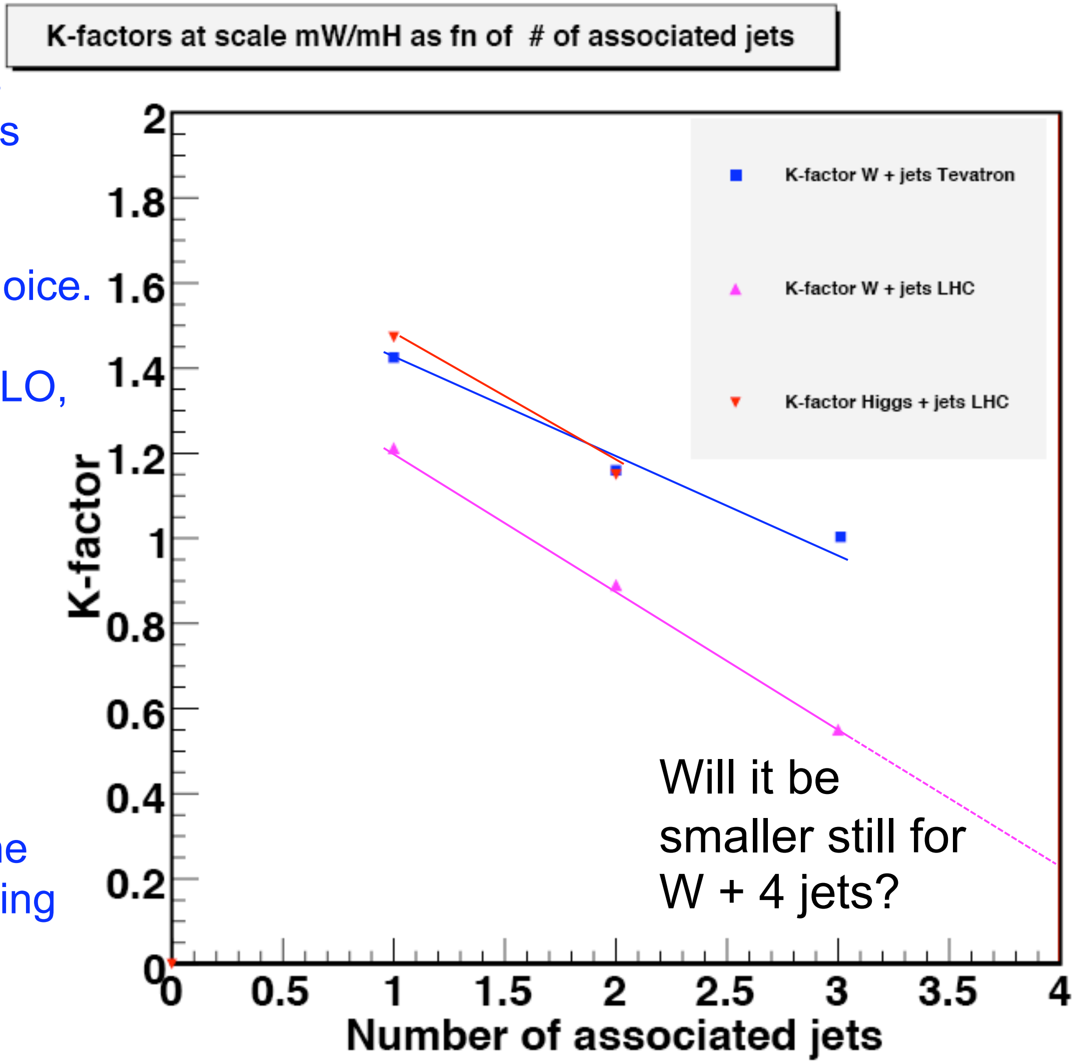
Is the K-factor (at m_W) at the LHC surprising?

The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make rules of thumb?

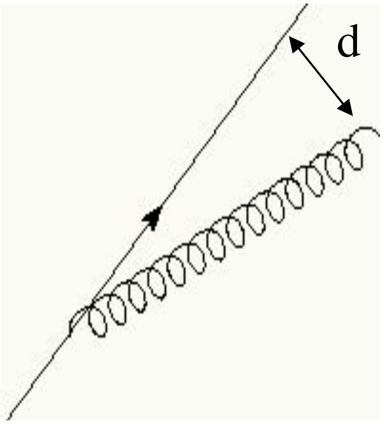
Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for the cross section ratios we have been discussing
-scale choices at LO for cross sections calculated at NLO
-scale choices at LO for cross sections uncalculated at NLO



Will it be smaller still for W + 4 jets?

Jet algorithms at LO/NLO

- Remember at LO, 1 parton = 1 jet
- By choosing a jet algorithm with size parameter D, we are requiring any two partons to be > D apart
- The matrix elements have 1/ΔR poles, so larger D means smaller cross sections
  - it's because of the poles that we have to make a ΔR cut
- At NLO, there can be two (or more) partons in a jet and jets for the first time can have some structure
  - we don't need a ΔR cut, since the virtual corrections cancel the collinear singularity from the gluon emission
  - **but there are residual logs that can become important if D is too small**
- Increasing the size parameter D increases the phase space for including an extra gluon in the jet, and thus increases the cross section at NLO (in most cases) → not true for WbB, for example



$z=p_{T2}/p_{T1}$

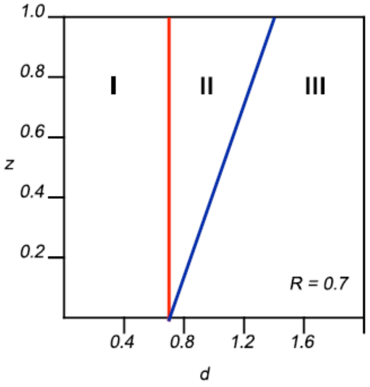


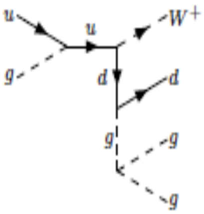
Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

For D=R_{cone}, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

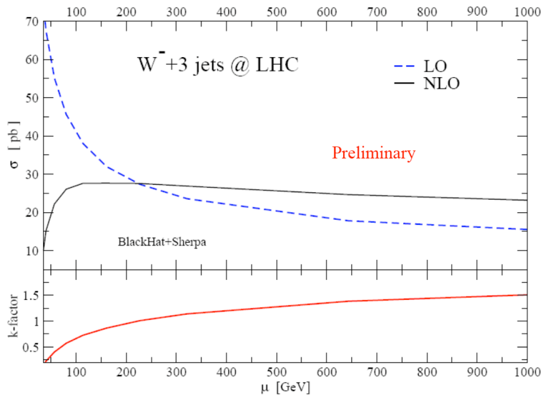
Is the K-factor (at m_W) at the LHC surprising?

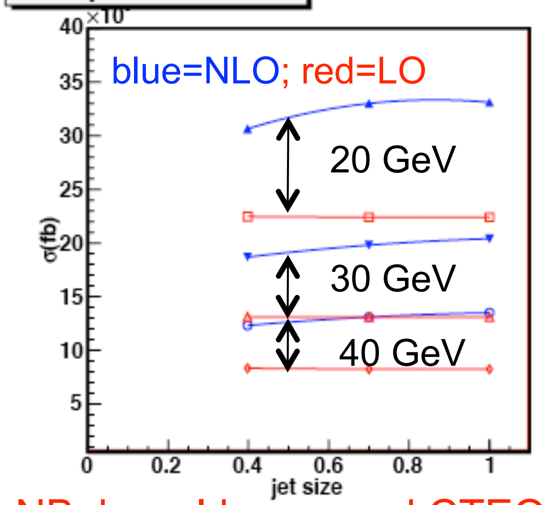
C T E Q

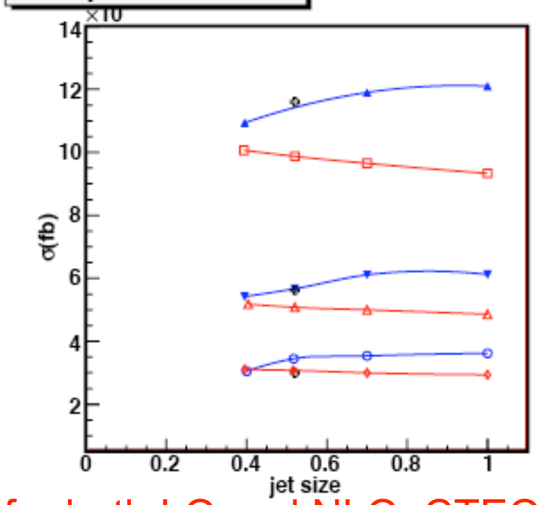
The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits ‘too-high’. The reason (one of them) for this is that we are ‘too-close’ to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~20 GeV/c)). Note that at LO, the cross section increases with decreasing R; at NLO it decreases.
The collinear dependence gets stronger as n_{jet} increases.
The K-factors for W + 3 jets would be more *normal* (>1) if a larger cone size and/or a larger jet p_T cutoff were used. But that’s a LO problem; the best approach is to use the appropriate jet sizes/jet p_T’s for the analysis and understand the best scales to use at LO (matrix element + parton shower) to approximate the NLO calculation (as well as comparing directly to the NLO calculation).

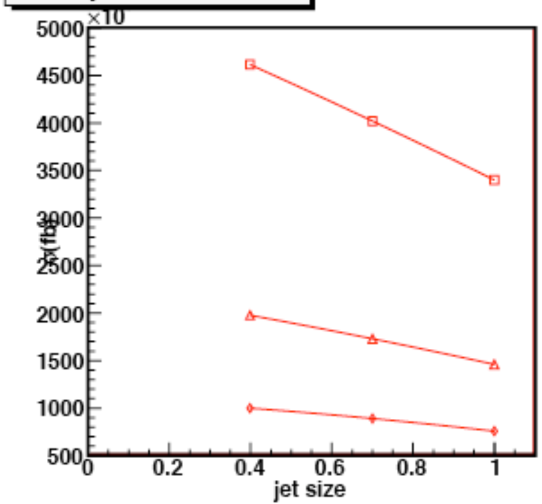


LHC total cross section




W + 1 jets cross section


W + 2 jets cross section

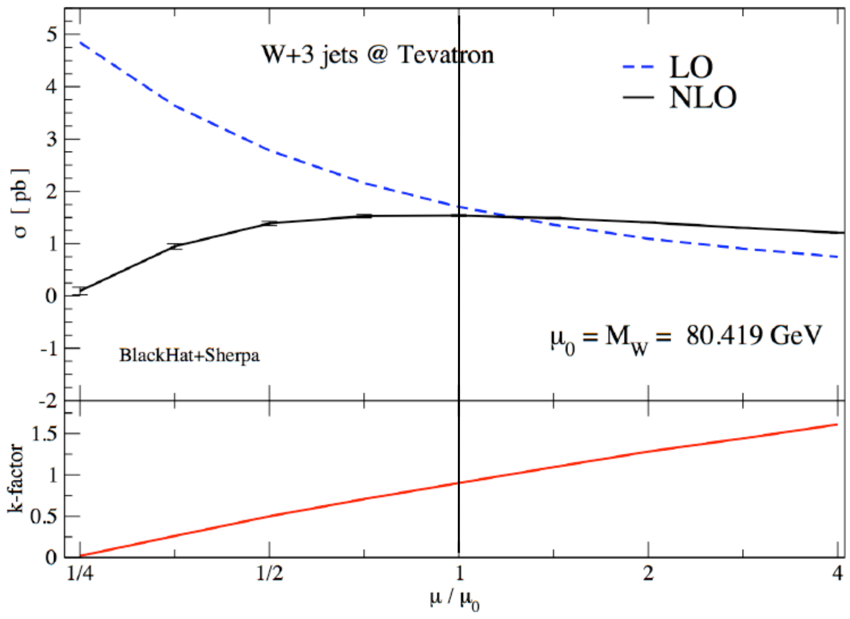

W + 3 jets cross section

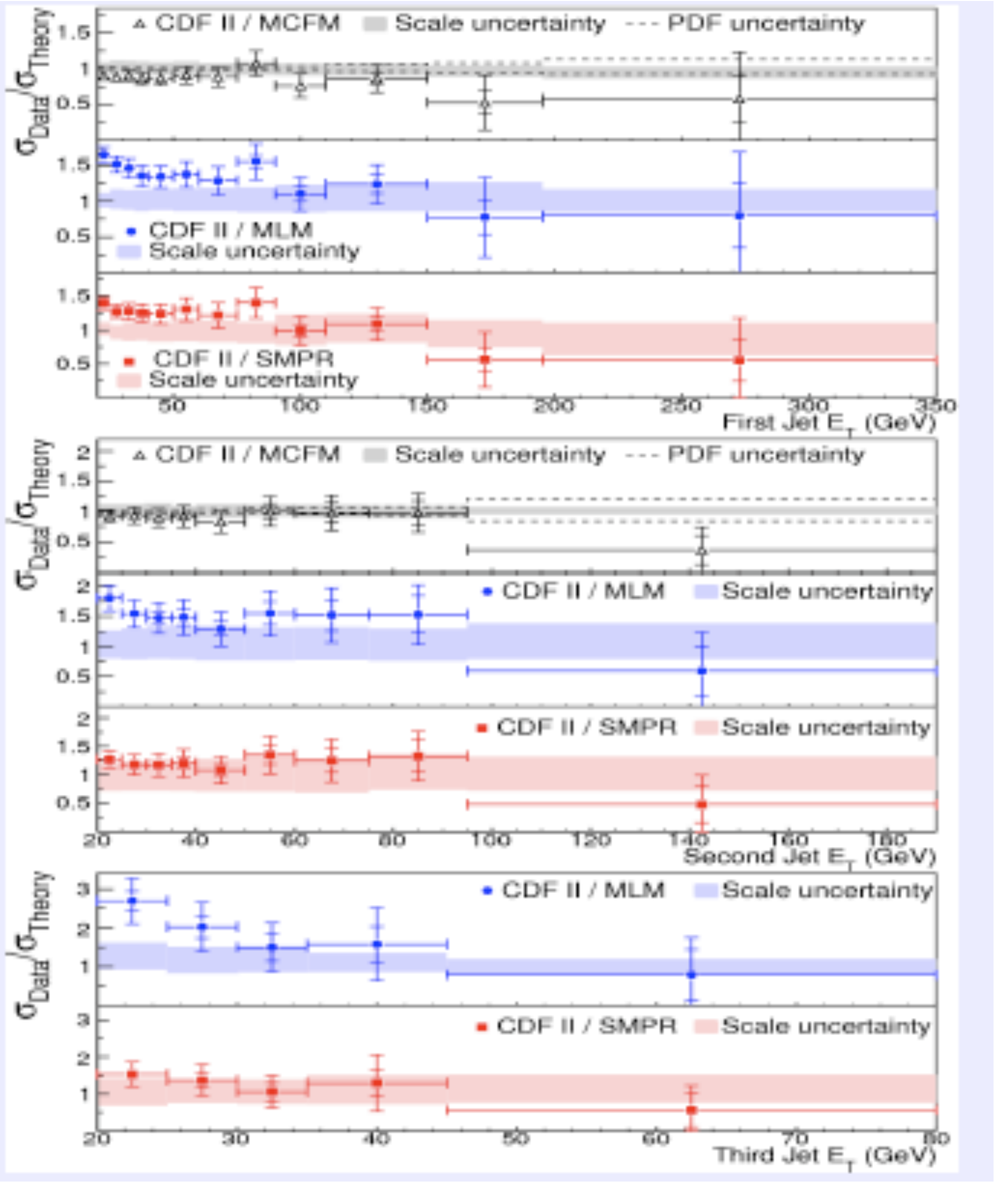
For 3 jets, the LO collinear singularity effects are even more pronounced.

NB: here I have used CTEQ6.6 for both LO and NLO; CTEQ6L1 would shift LO curves up

W + jets at the Tevatron

- At the Tevatron, m_W is a reasonable scale (in terms of K-factor~1)



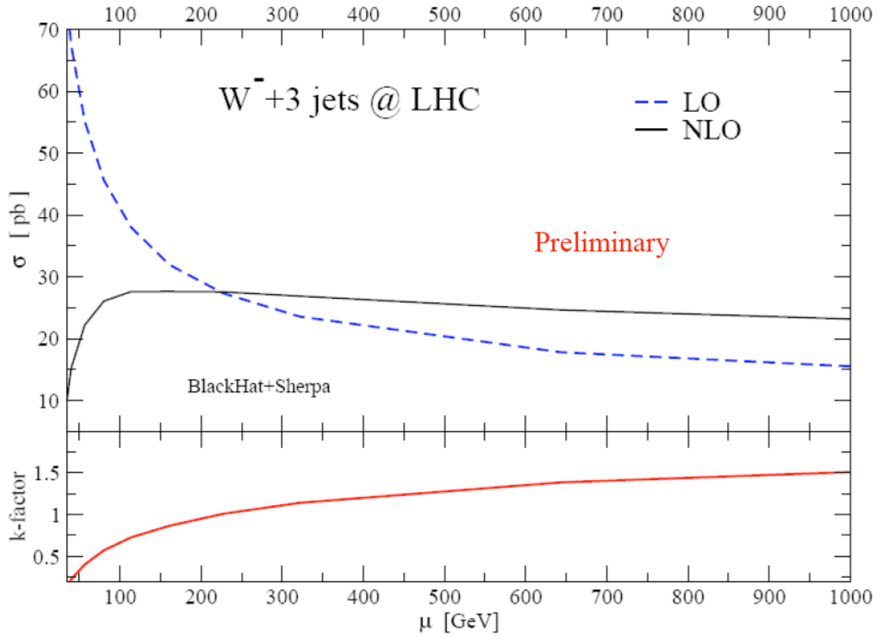


W + 3 jets at the LHC

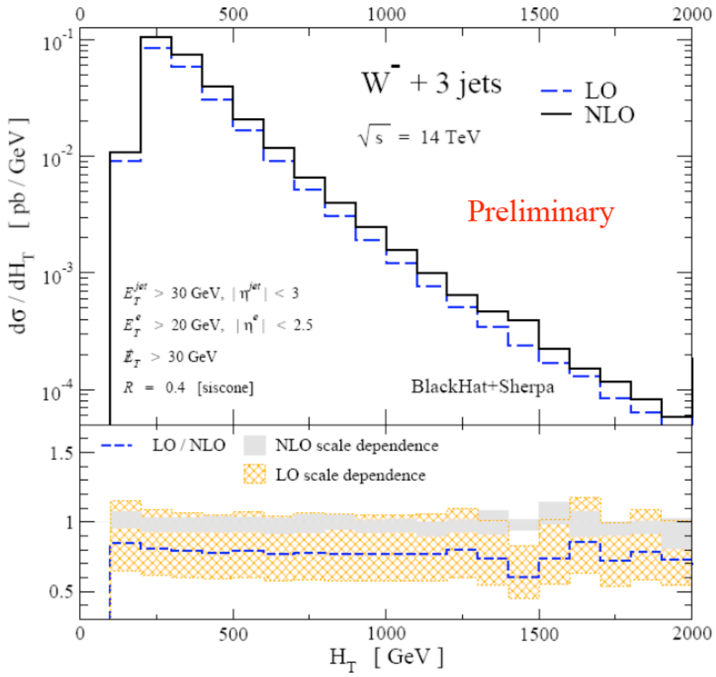
C T E Q

A scale choice of m_W would be in a region where LO >> NLO. In addition, such a scale choice (or related scale choice), leads to sizeable shape differences in the kinematic distributions. The Blackhat people found that a scale choice of H_T worked best to get a constant K-factor for all distributions that they looked at. Note that from the point-of-view of only NLO, all cross sections with scales above ~100 GeV seem reasonably stable.

LHC total cross section



$H_T = \sum_j E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$ distribution



mu = H_T

Some other observables in Blackhat paper

CTEQ

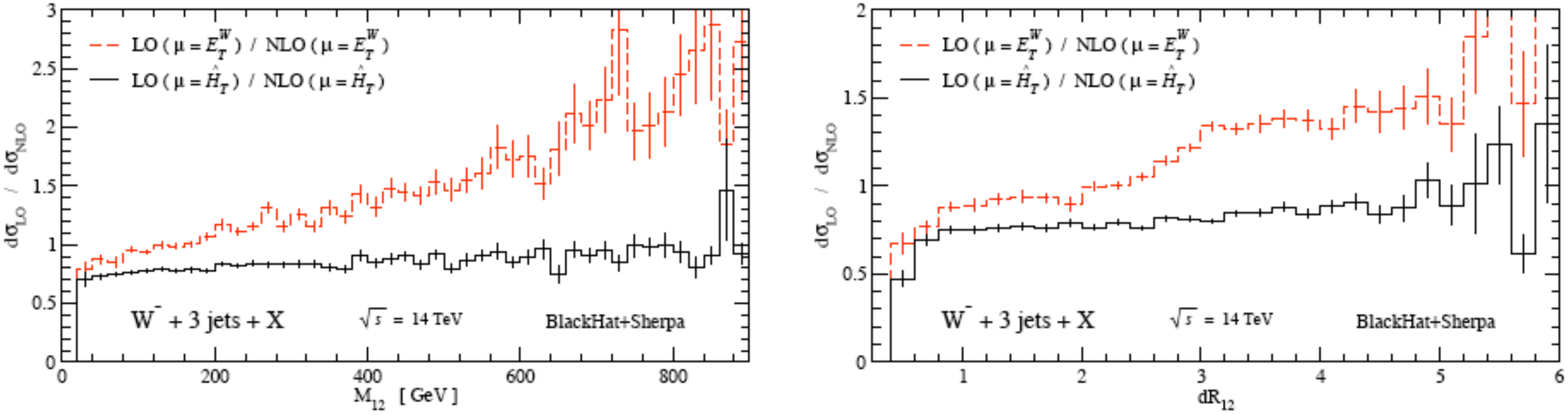


FIG. 12: Ratios of LO to NLO predictions for the distributions in the di-jet invariant mass (left panel) and ΔR separation (right panel) for the leading two jets in $W^- + 3$-jet production at the LHC. In each panel, the dashed (red) line gives the scale choice $\mu = E_T^W$, while the solid (black) line gives the (much flatter) ratio for $\mu = \hat{H}_T$.

Soft collinear effective theory (SCET) suggests scales on the order of $1/4M^2_{had} + M^2_W$, where M_{had} is the invariant mass of the jets

CKKW

- Applying a CKKW-like scale leads to better agreement for shapes of kinematic distributions

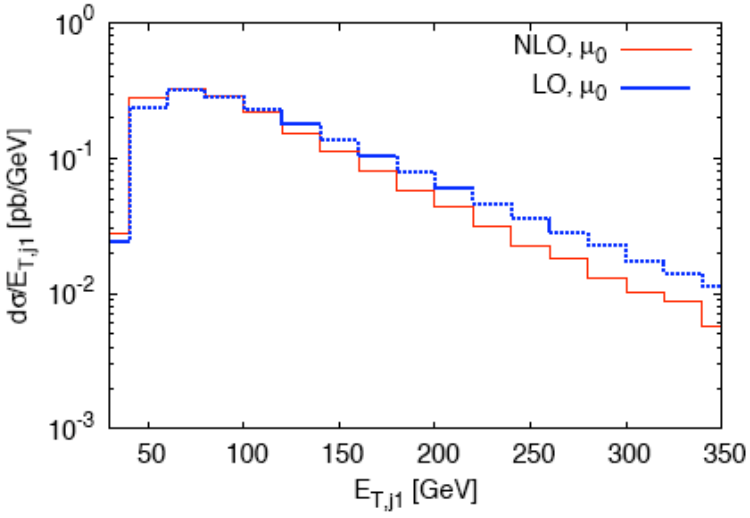


FIG. 3: The transverse momentum distribution of the leading jet for $W^+ + 3$ jet inclusive production cross section at the LHC. All cuts and parameters are described in the text. The leading color adjustment procedure is applied.

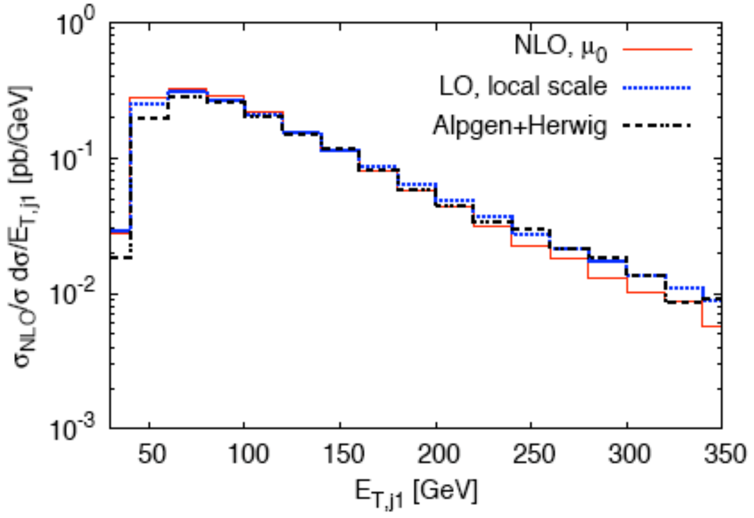


FIG. 4: The transverse momentum distribution of the leading jet for $W^+ + 3$ jet inclusive production cross section at the LHC. All cuts and parameters are described in the text. The leading color adjustment procedure is applied. All LO distributions are rescaled by constant factor, to ensure that the LO and NLO normalizations coincide.

0910.3671 Melnikov, Zanderighi

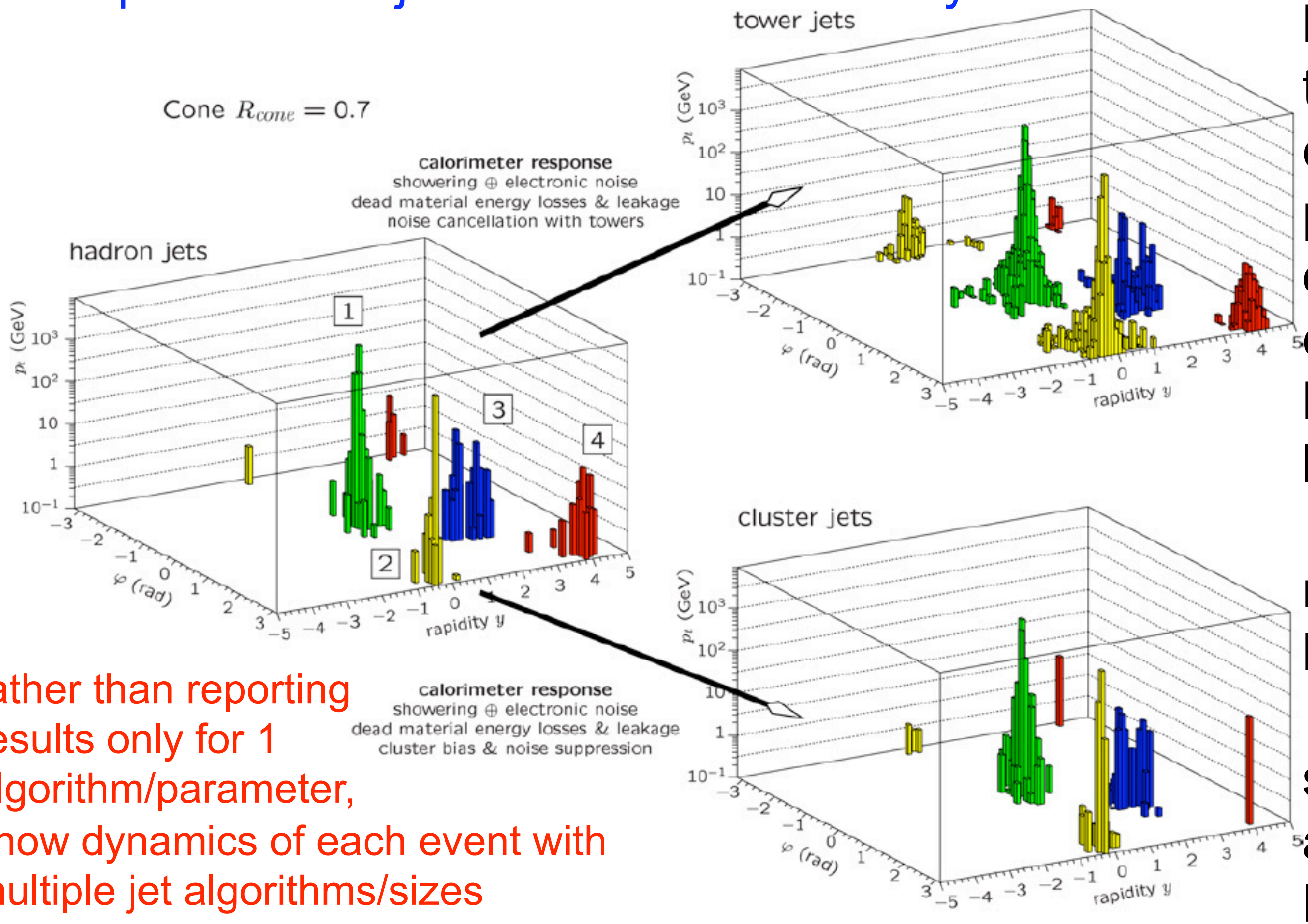
Choosing jet size

- Experimentally
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/ underlying event
- Theoretically
  - hadronization effects become larger as R decreases
  - for small R, the ln R perturbative terms referred to previously can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,
  - …under investigation

Another motivation for the use of multiple jet algorithms/parameters in LHC analyses.

ATLAS jet reconstruction

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/ parameters/jet substructure on every data set



blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos

rather than reporting results only for 1 algorithm/parameter, show dynamics of each event with multiple jet algorithms/sizes

SpartyJet

CTEQ

J. Huston, K. Geerlings,
Brian Martin
Michigan State University

P-A. Delsart, Grenoble

Sparty

http://www.pa.msu.edu/~huston/SpartyJet/SpartyJet.html/

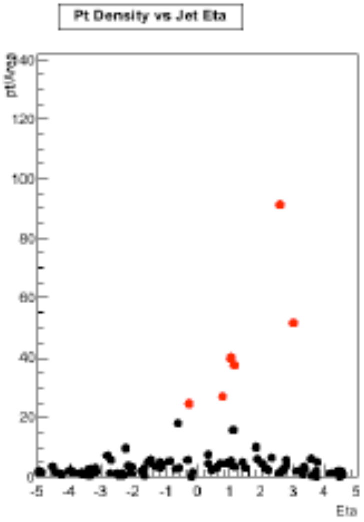
Provides the flexibility to perform the jet analyses with multiple algorithms/parameters

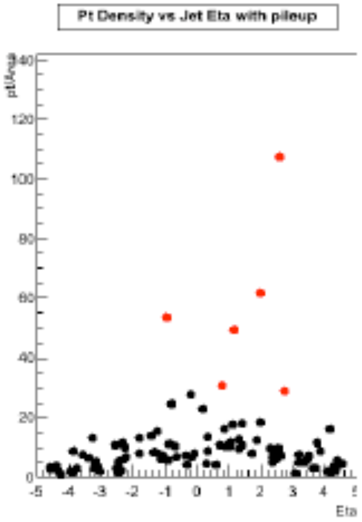
Area-based correction: Salam et al

CTEQ

1) Find low p_T jets in event. (< 10GeV) We use kT5jet.
2) From these, find average/median pT density of event ρ
3) Determine area A of signal jets
4) Subtract "pileup/UE"estimate

$$p_{Tcorr} = p_T - \rho A$$



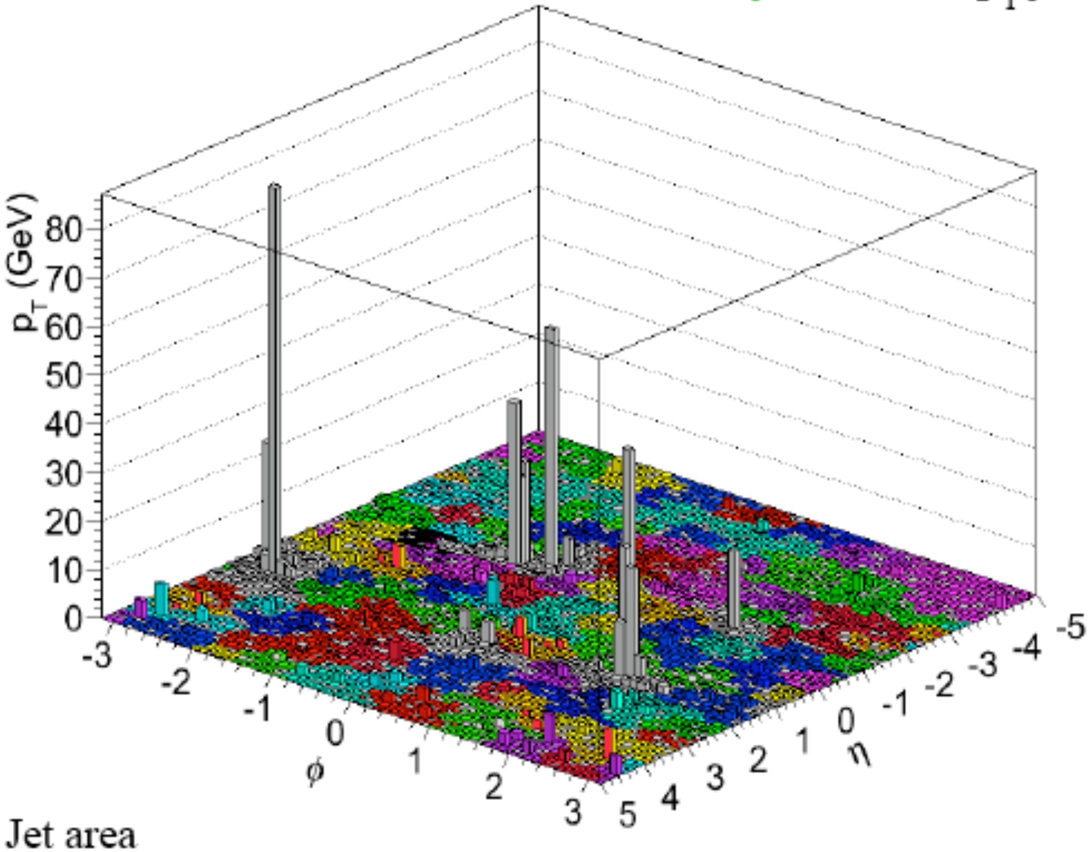


- Black points used to find pT density
- Red points are then corrected according to Jet area

W+5j event with kT5Jets

Gray jets = Signal Jets

Colored jets = Low p_T jets



See presentations of Brian Martin in ATLAS jet meetings.

arXiv:0712.3014

- Tried to come up with an optimal R value for jets, in terms of minimizing fluctuations
    - but, not taking into account the virtual terms present at NLO

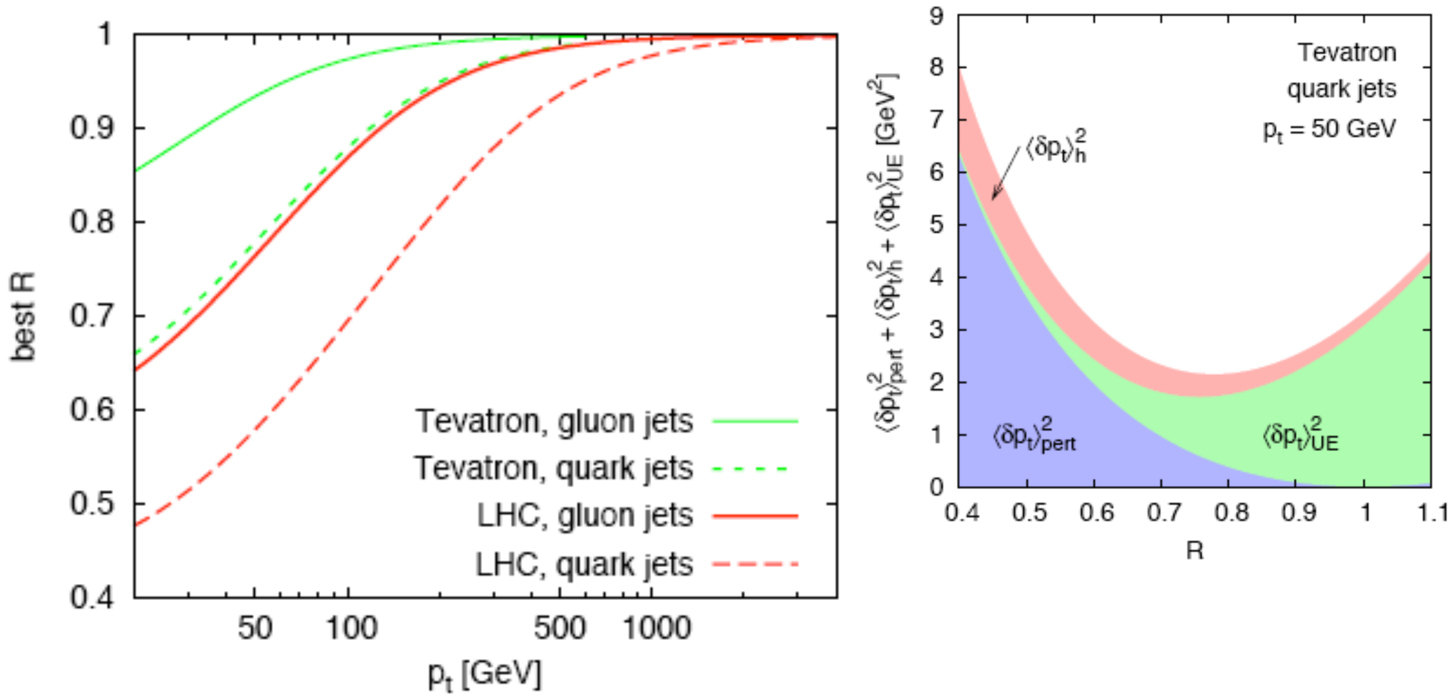


Figure 6: The R value that minimises the sum of squared average perturbative, hadronization and UE contributions, as a function of p_t. The approximations are the same as those in Fig. 5, except that for LHC we have used $\Lambda_{UE} = 10\,\mathrm{GeV}$.

Jet sizes and scale uncertainties: the Goldilocks theorm

CTEQ

- Take inclusive jet production at the LHC for transverse momenta of the order of 50 GeV
- Look at the theory uncertainty due to scale dependence as a function of jet size
- It appears to be a minimum for cone sizes of the order of 0.7
  - i.e. if you use a cone size of 0.4, there are residual un-cancelled virtual effects
  - if you use a cone size of 1.0, you are adding too much tree level information with its intrinsically larger scale uncertainty
- This effect becomes smaller for jet p_T values on the order of 100 GeV/c
  - how does it translate for multi-parton final states?

Jet vetos and scale dependence: WWjet

- Often, we cut on the presence of an extra jet
- This can have the impact of improving the signal to background ratio
  - …and it may appear that the scale dependence is improved
- However, in the cases I know about, the scale dependence was *anomalous* at NLO without the jet veto, indicating the presence of uncancelled logs
- The apparent improvement in scale dependence may be illusory

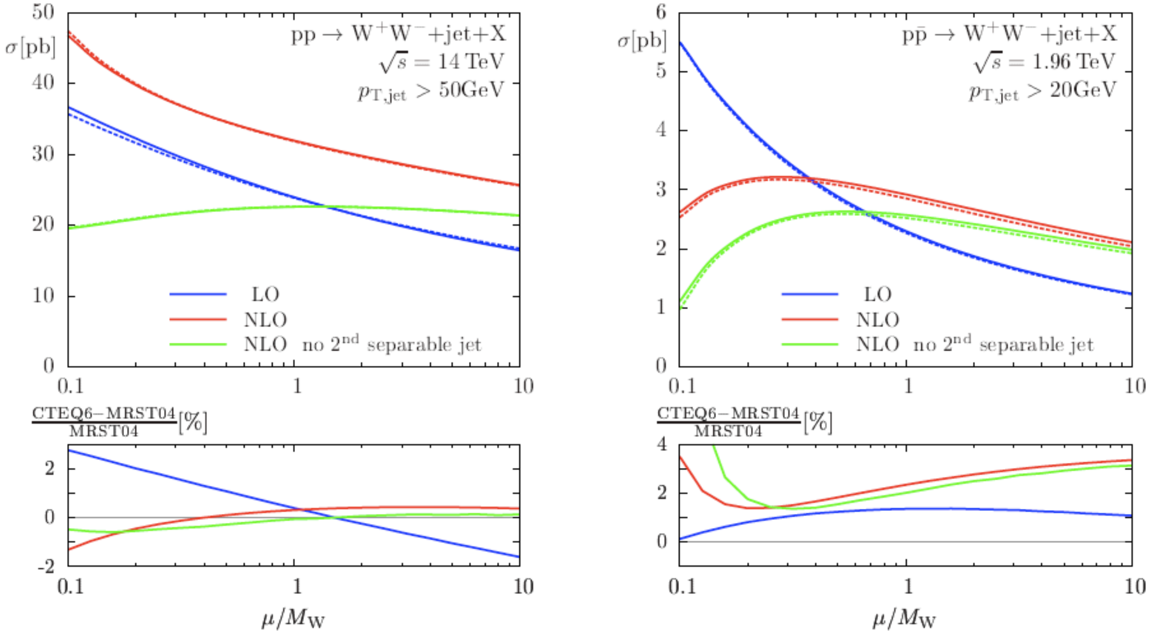
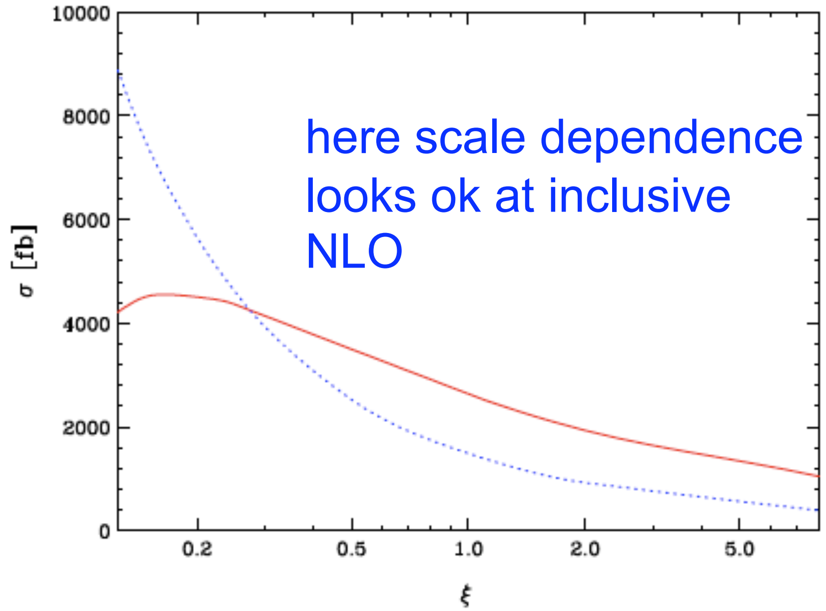


Figure 11: Comparison of WW+jet production cross sections in the LHC setup with $p_{T,\mathrm{jet}} > 50\,\mathrm{GeV}$ and for Tevatron with $p_{T,\mathrm{jet}} > 20\,\mathrm{GeV}$: The straight lines show the results calculated with the five-flavour PDFs of CTEQ6, the dashed lines those calculated with the four-flavour PDFs of MRST2004F4. Contributions from external bottom (anti-)quarks are omitted, as described in Section 2.2.

Project for Les Houches writeup: to categorize NLO calculations in terms of effect of jet veto

back to tTbB

CTEQ



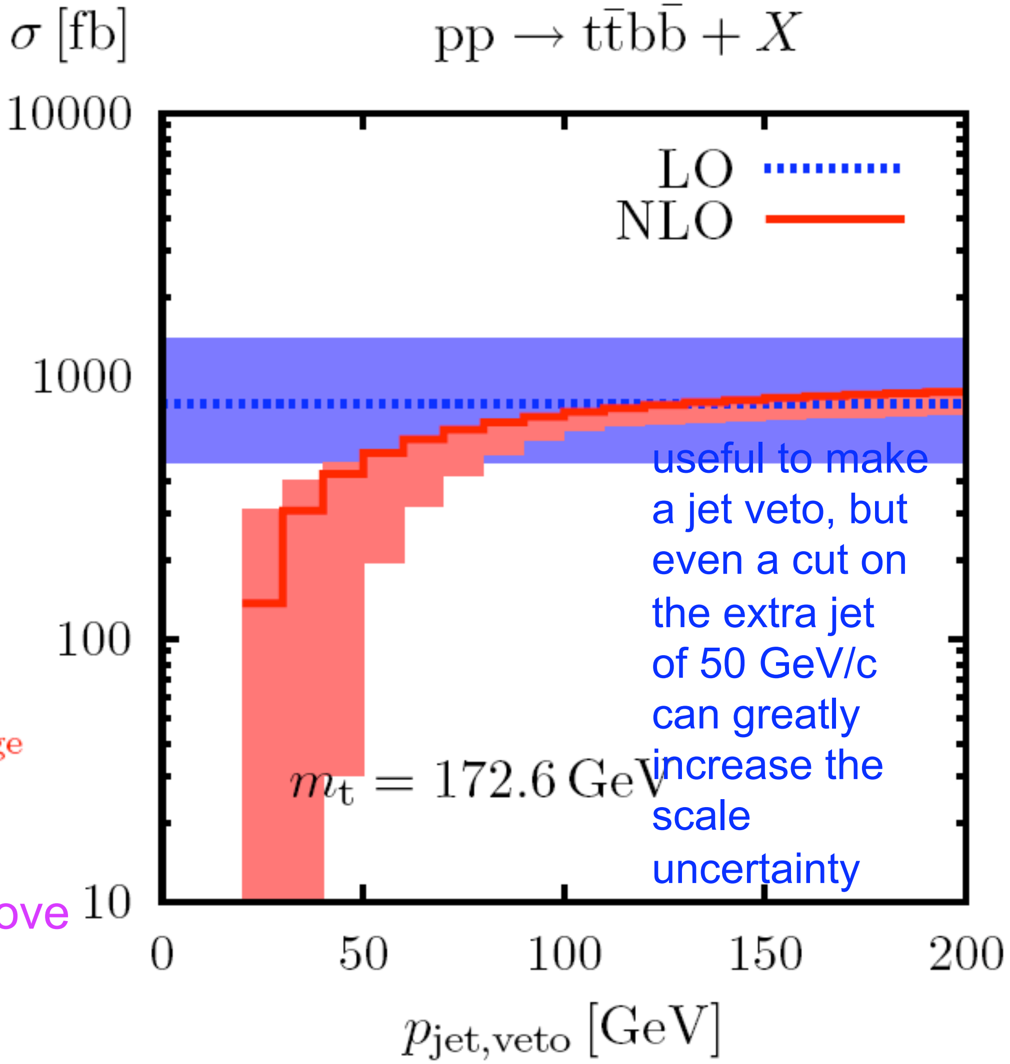
here scale dependence looks ok at inclusive NLO

Perturbative instability for small $p_{\mathrm{jet,veto}}$

- veto ⇒ negative contribution $-\alpha_s^5 \ln^2(Q_0/p_{\mathrm{jet,veto}})$
- IR log dramatically enhances NLO uncertainty
- $p_{\mathrm{jet,veto}} < 40\,\mathrm{GeV}$ ⇒ NLO-band enters $K < 0$ range
  NLO prediction completely unrealiable!

NB: a high p_T (100 GeV) jet veto can improve the scale dependence slightly; removing *extraneous* real radiation?

from Stefano Pozzorini



useful to make a jet veto, but even a cut on the extra jet of 50 GeV/c can greatly increase the scale uncertainty

Counter-example: W + 3 jets

- Here the NLO inclusive scale dependence looks ok
- Looks even better with exclusive cuts

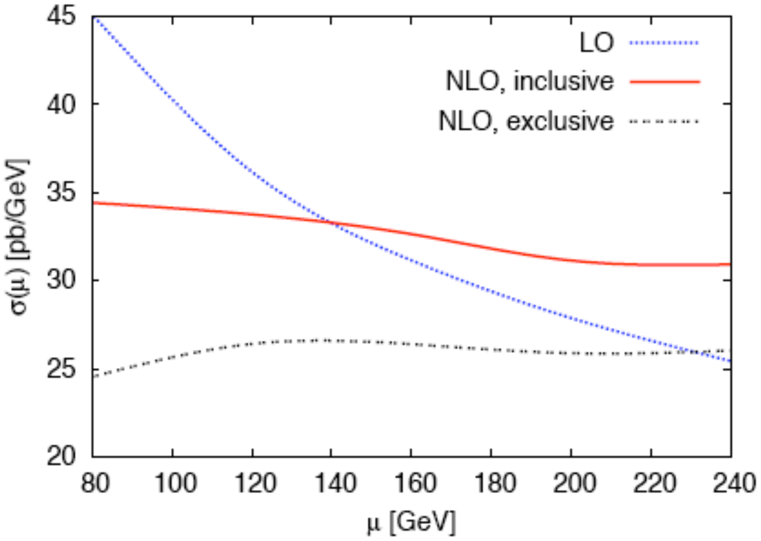


FIG. 1: The dependence of the $W^+ + 3$ jet inclusive production cross section at the LHC on the factorization and renormalization scale μ. All cuts and parameters are described in the text. The leading color adjustment procedure is applied.

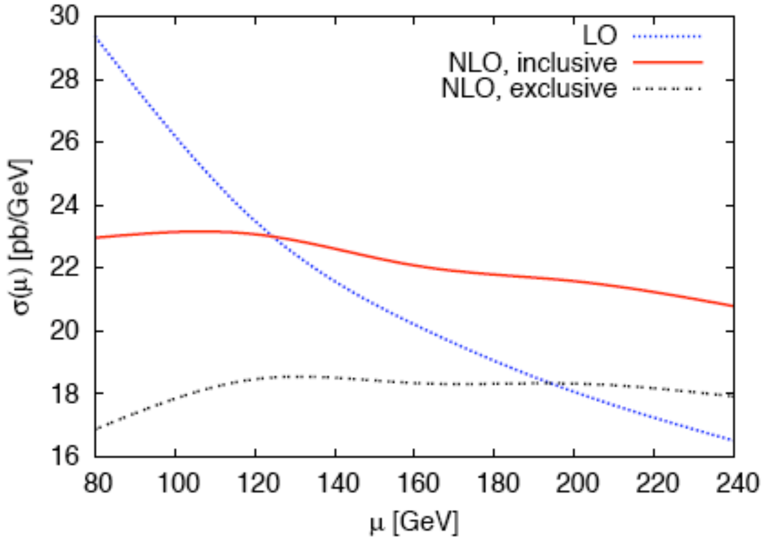


FIG. 2: The dependence of the $W^- + 3$ jet inclusive production cross section at the LHC on the factorization and renormalization scale μ. All cuts and parameters are described in the text. The leading color adjustment procedure is applied.

0910.3671 Melnikov, Zanderighi

C T E Q

Now consider jets in real life

- Jets don’t consist of 1 fermi partons but have a spatial distribution
- Can approximate this as a Gaussian smearing of the spatial distribution of the parton energy
    - the effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
    - the midpoint solution is (**almost always**) lost
        - thus region II is effectively truncated to the area shown on the right
    - the solution corresponding to the lower energy parton can also be lost
        - resulting in dark towers
        - clusters of energy not in jets

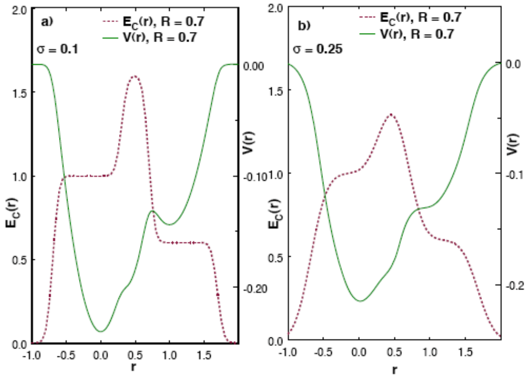


Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm

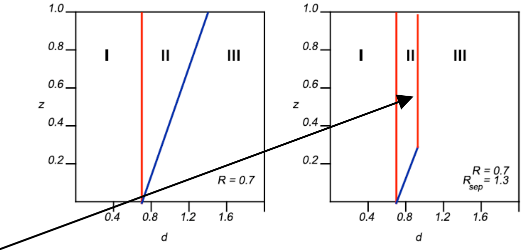


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

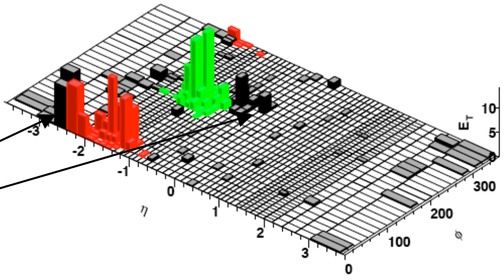


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II by including a parameter called R_{sep}
  - only merge two partons if they are within $R_{sep}*R_{cone}$ of each other
    - R_{sep}~1.3
  - ~4-5% effect on the theory cross section; effect is smaller with the use of p_T rather than E_T
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also on order of few (<5)% effect on the (experimental) cross section

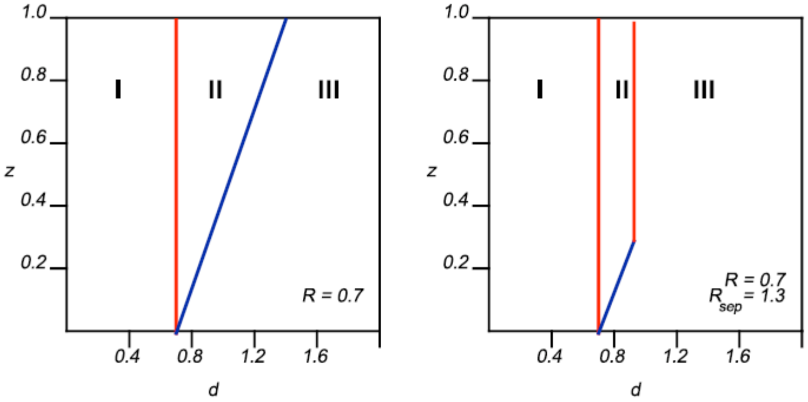
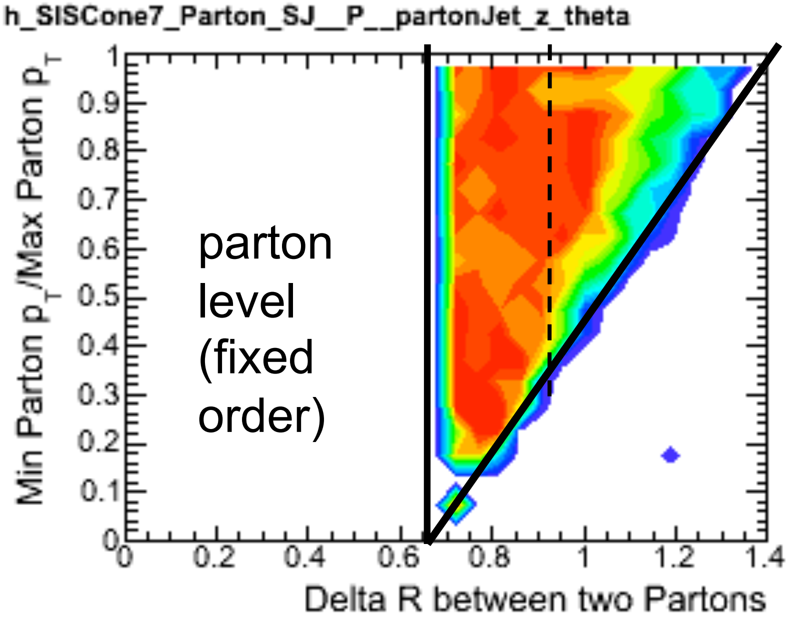


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

W + 2 partons at LHC: parton/hadron/detector levels

(Brian Martin)

C T E Q

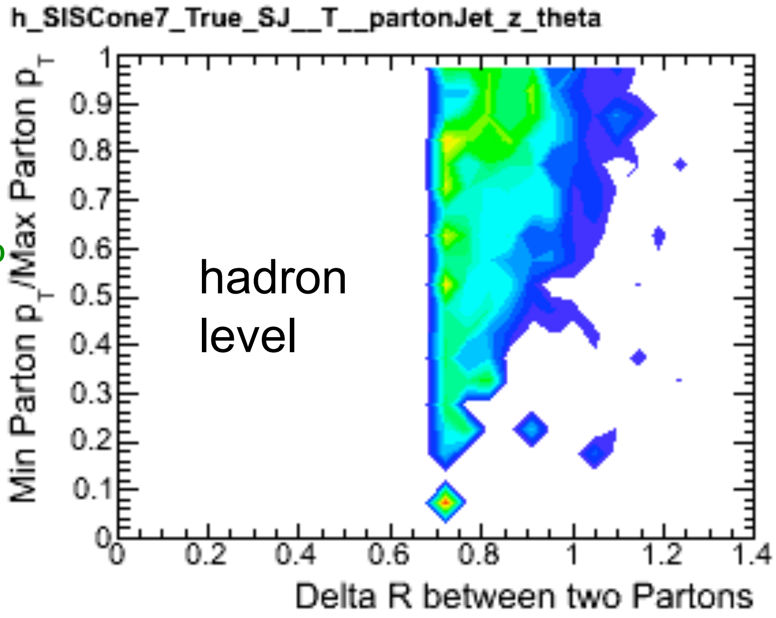


parton level (fixed order)

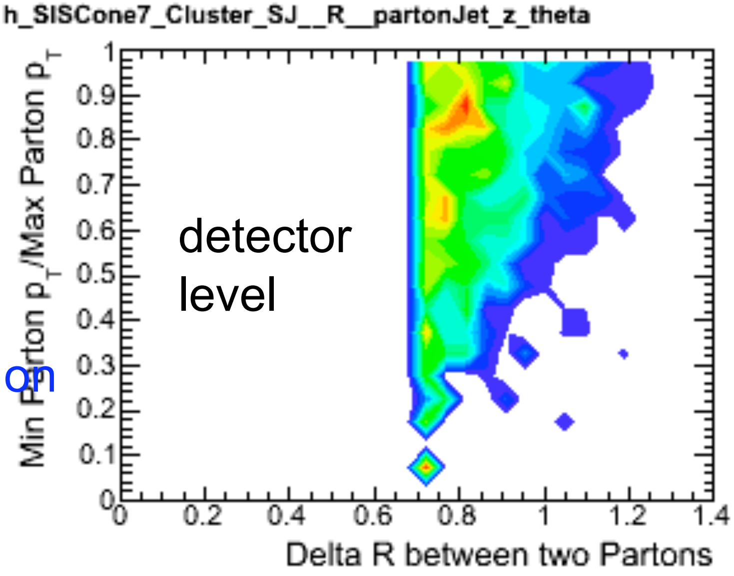
Red~100% merging

Green~50%

Blue~10%



hadron level



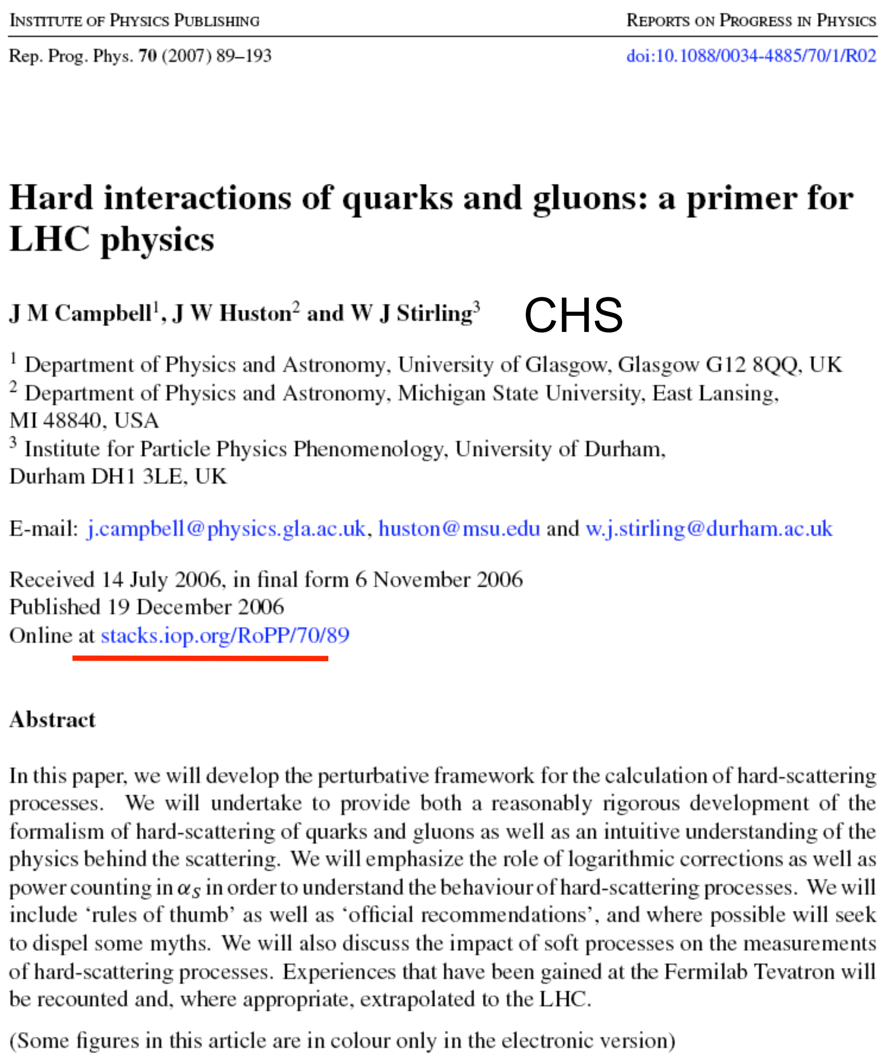
detector level

Simple parton level results not duplicated at either hadron level or detector level. Showers produced by widely separated partons tend to be reconstructed as separate jets. Same cause as *dark towers*.

Jet cores have a finite size, so this must depend on the jet parameters, i.e. as R_{cone}->inf, we should recover the simple parton level behavior.

Some references

CTEQ



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

J M Campbell[1], **J W Huston**[2] **and W J Stirling**[3]

[1] Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK
[2] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48840, USA
[3] Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK

E-mail: j.campbell@physics.gla.ac.uk, huston@msu.edu and w.j.stirling@durham.ac.uk

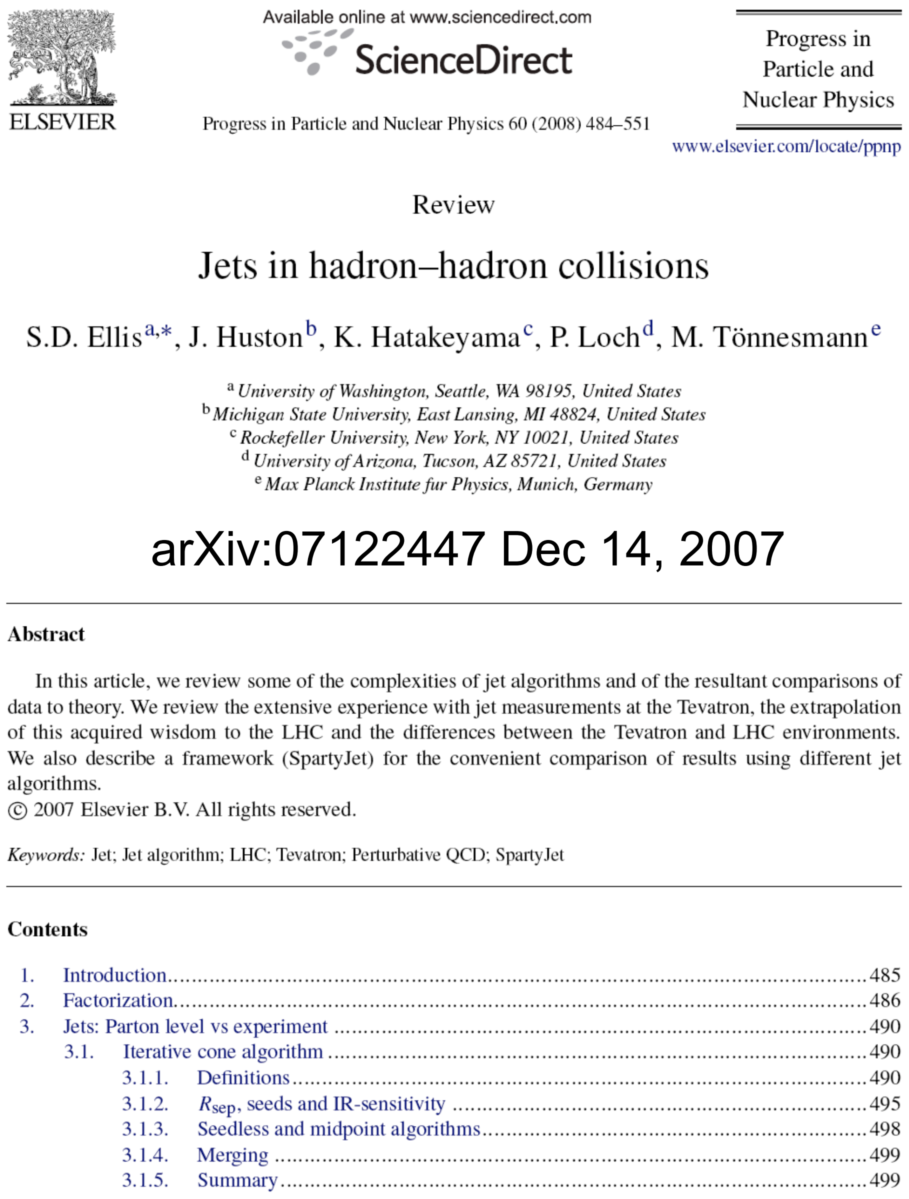
CHS

Received 14 July 2006, in final form 6 November 2006
Published 19 December 2006
Online at stacks.iop.org/RoPP/70/89

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)



ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Progress in Particle and Nuclear Physics 60 (2008) 484–551

Progress in Particle and Nuclear Physics

www.elsevier.com/locate/ppnp

Review

Jets in hadron–hadron collisions

S.D. Ellis[a,*], J. Huston[b], K. Hatakeyama[c], P. Loch[d], M. Tönnesmann[e]

[a] *University of Washington, Seattle, WA 98195, United States*
[b] *Michigan State University, East Lansing, MI 48824, United States*
[c] *Rockefeller University, New York, NY 10021, United States*
[d] *University of Arizona, Tucson, AZ 85721, United States*
[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