LO/NLO, LO* and jet algorithms

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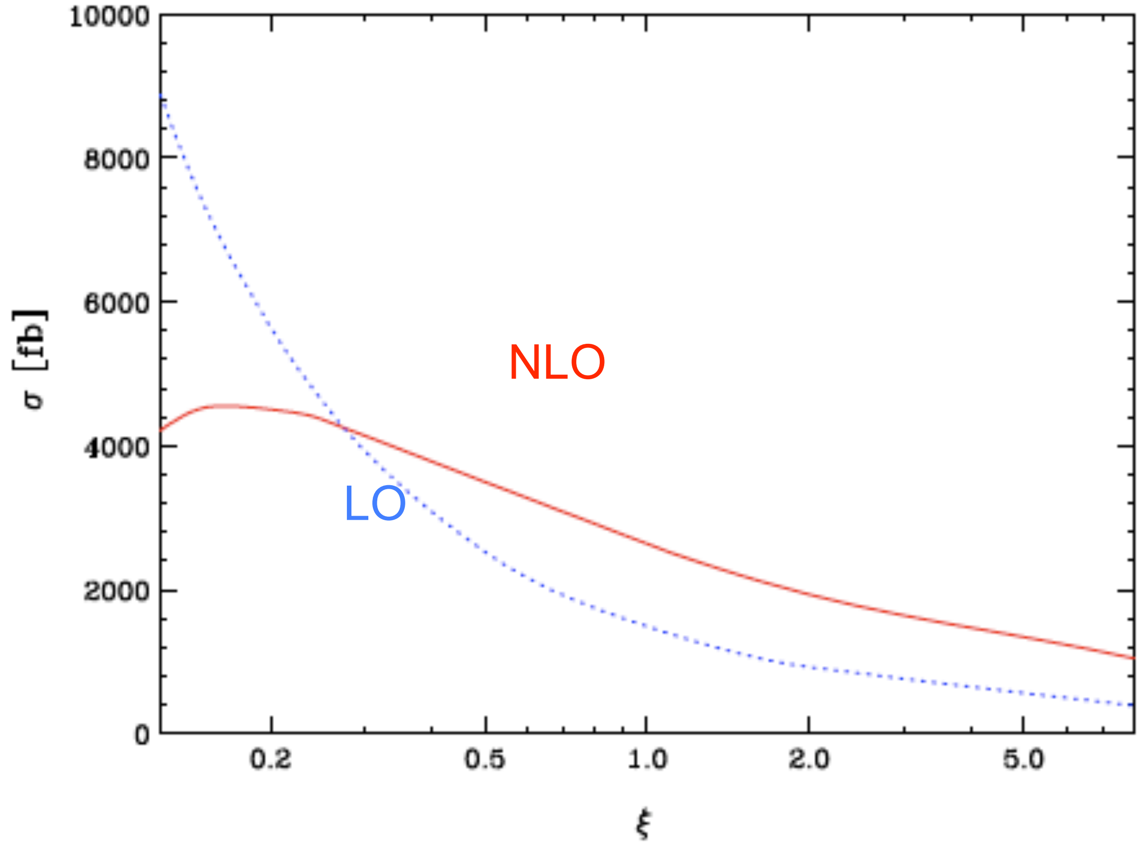
NLO and the Les Houches wishlist

- 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, I 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.

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

Consider tTbB (from wishlist)



scale dependence reduced at NLO; non-monotonic, i.e. there's a semi-parabolic shape

Figure 2: *Scale dependence of the total cross section for $pp \to t\bar{t}b\bar{b} + X$ at the LHC with $\mu_R = \mu_F = \xi m_t$. On the upper panel, the blue dashed curve corresponds to the leading order, whereas the red solid one to the next-to-leading order result. The lower panel shows the scale dependence of the*

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 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^{jet}	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	p_T^{jet}	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	p_T^{jet}	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	p_T^{jet}	1.07	0.97	1.07	1.23	1.34	0.85
Higgs+1jet	m_H	p_T^{jet}	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	p_T^{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 $p_T^{\text{jet}} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\text{jet}} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

CTEQ modified LO PDFs

- Discussed already in several PDF4LHC meetings
- Preprint available on the archive today (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

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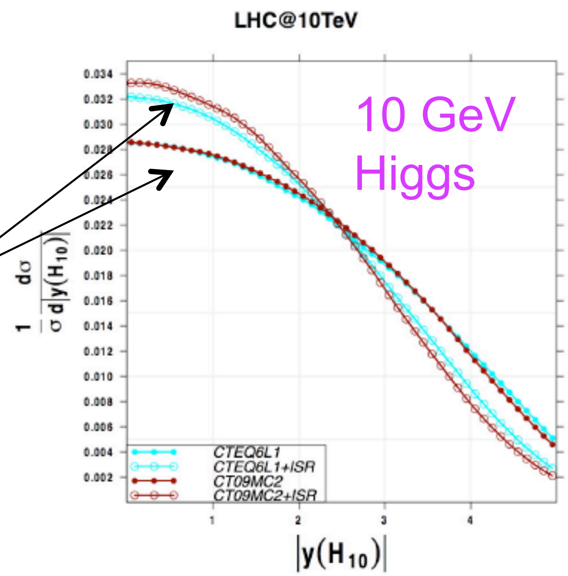
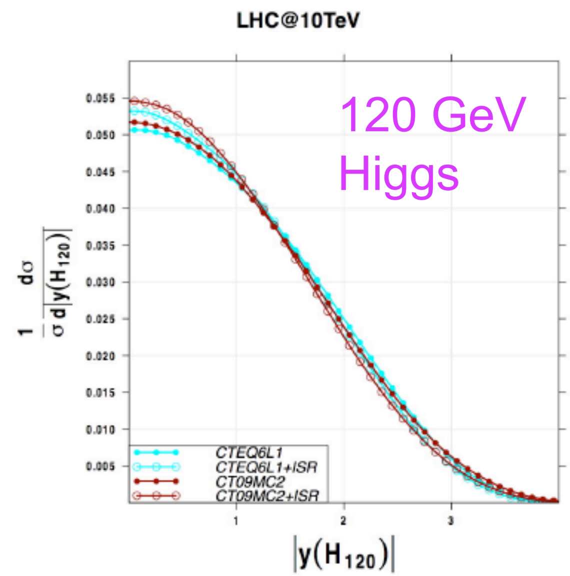
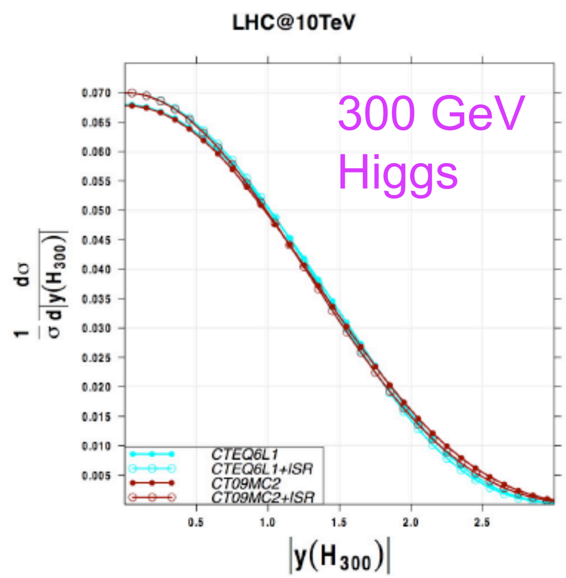
In this paper, conventional Global QCD analysis is generalized to produce parton distributions optimized for use with event generators at the LHC. This optimization is accomplished by combining the constraints due to existing hard-scattering experimental data with those from anticipated cross sections 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.

Effects of parton showering

- Parton showering induces suppression for Higgs production at forward regions
  - compare for example the two red curves
- Tends to make production more central
- Effect is large for 10 GeV Higgs
- Decreases for more realistic values/ higher Q^2 processes

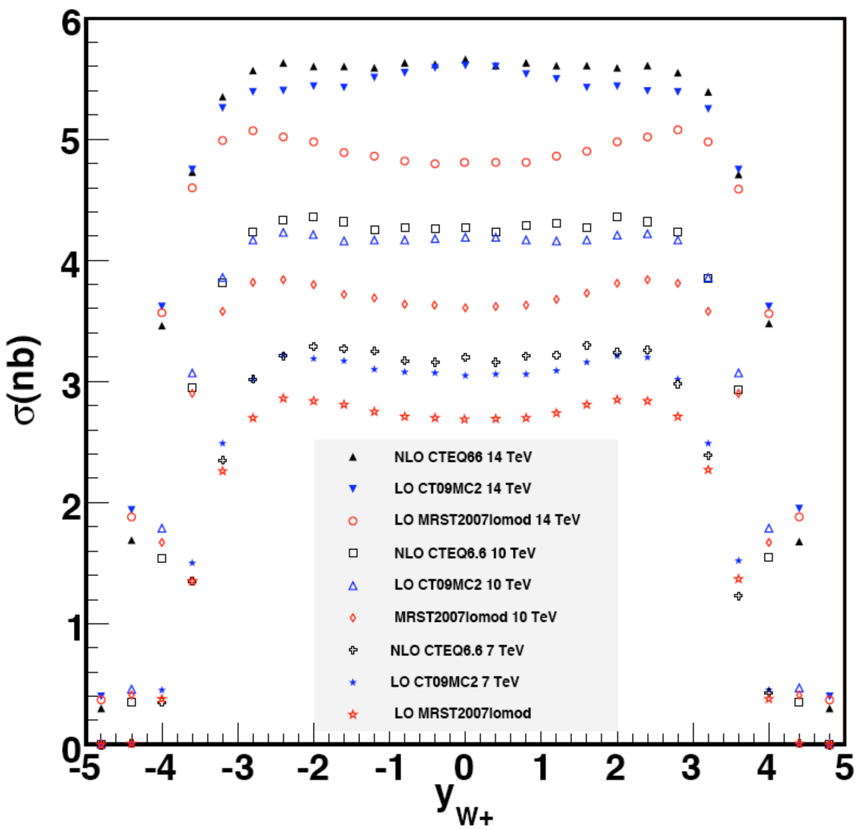




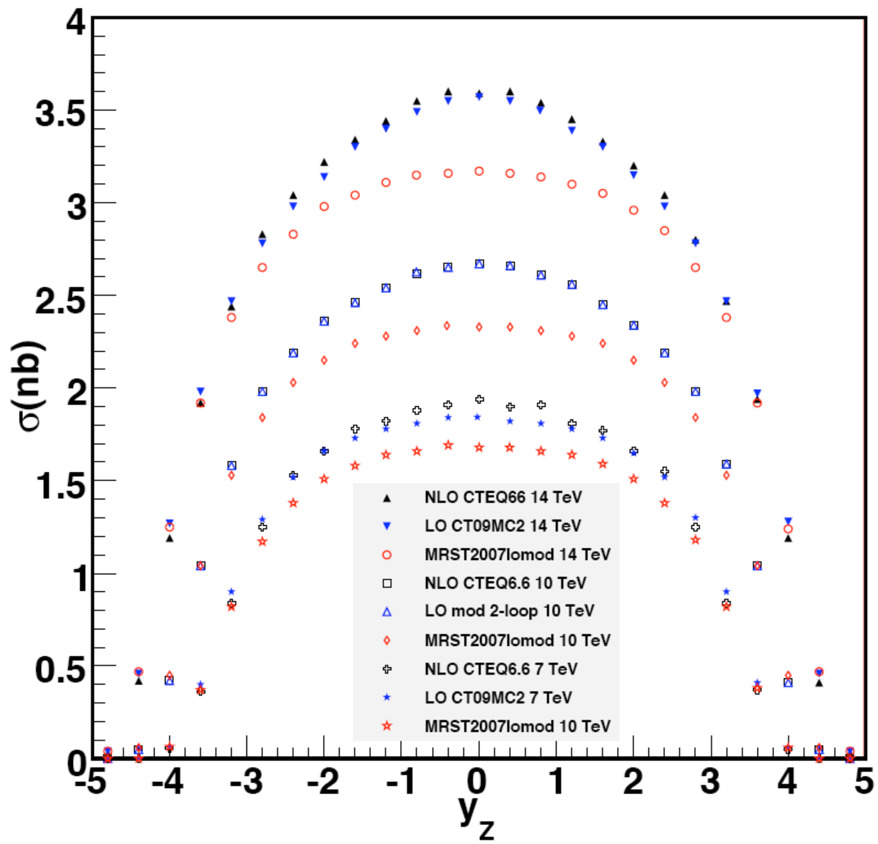


Comparison of W/Z rapidity distributions

W+ rapidity distribution



Z rapidity distribution



Lepton rapidity distributions

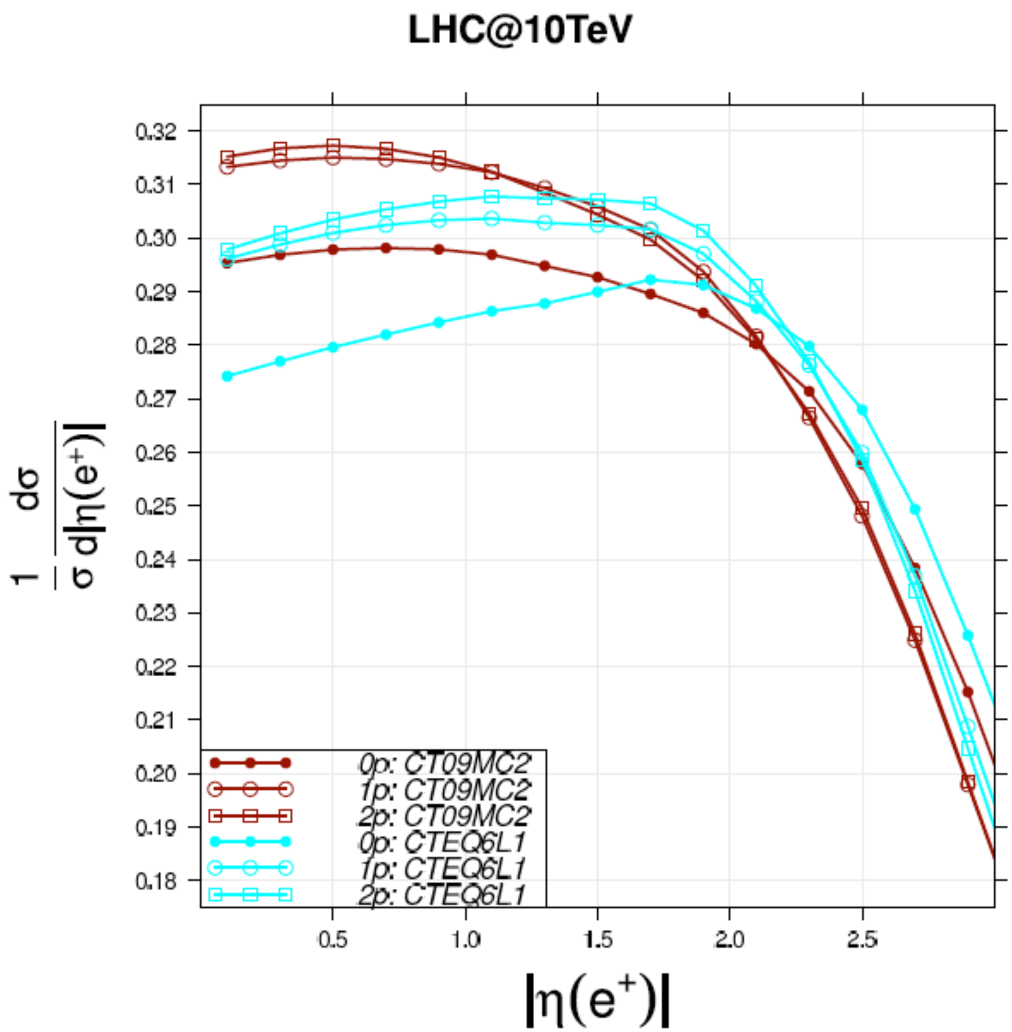


Figure 19: Distribution of positron pseudo-rapidity $|\eta(e^+)|$ for various partonic p multiplicities in the case of $W^+ + np$ ($n = 0, 1, 2$) production at the LHC (with a center of mass energy of 10 TeV) and for CTEQ6L1 and CT09MC2 PDF sets. The partonic jets are defined with $k_T \geq 10$ GeV.

Comparison of PDFs

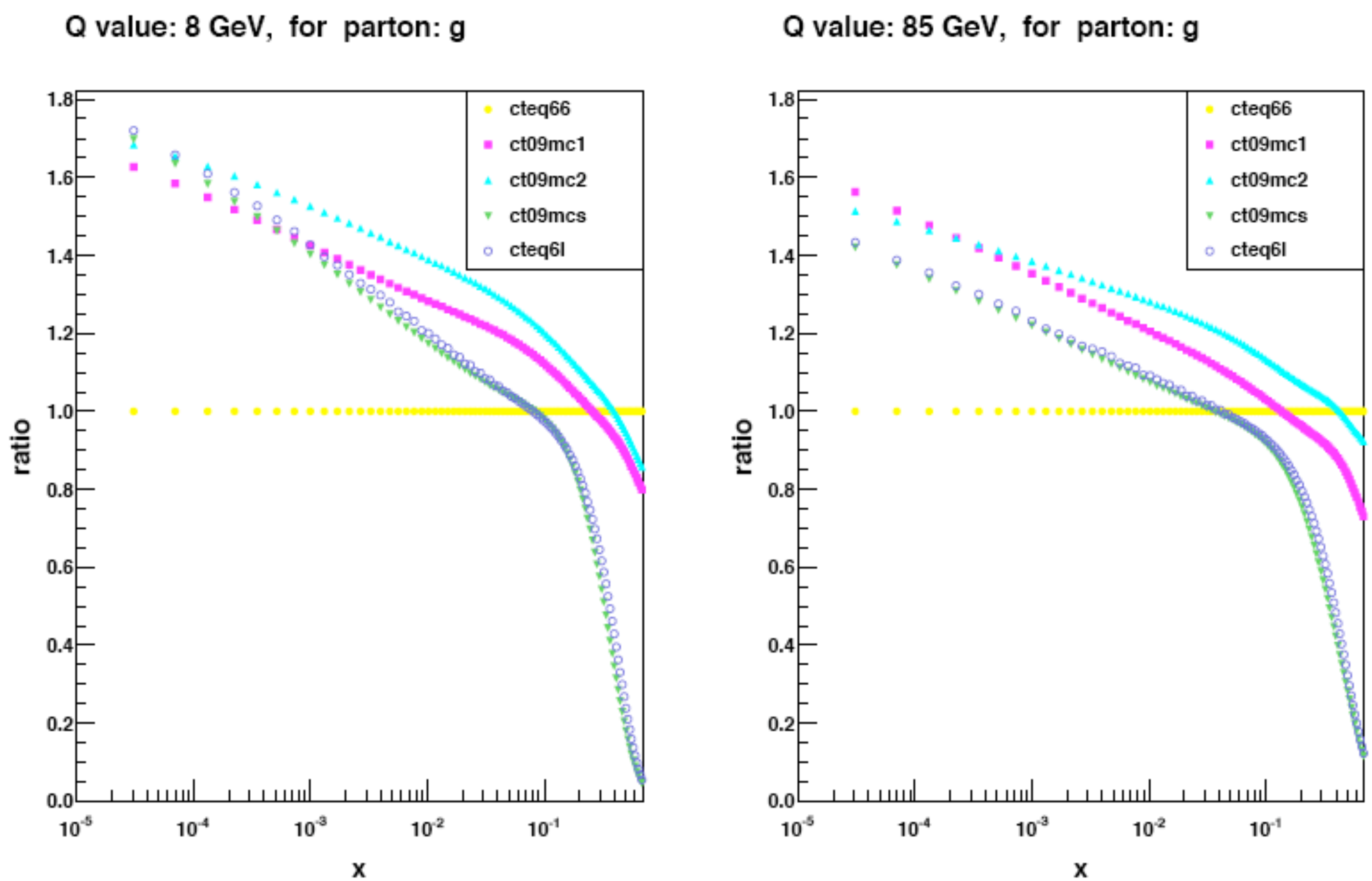


Figure 12: The ratio of the gluon distributions from various LO PDFs to the gluon distribution from CTEQ6.6 at Q values of 8 and 85 GeV.

Comparison of PDFs

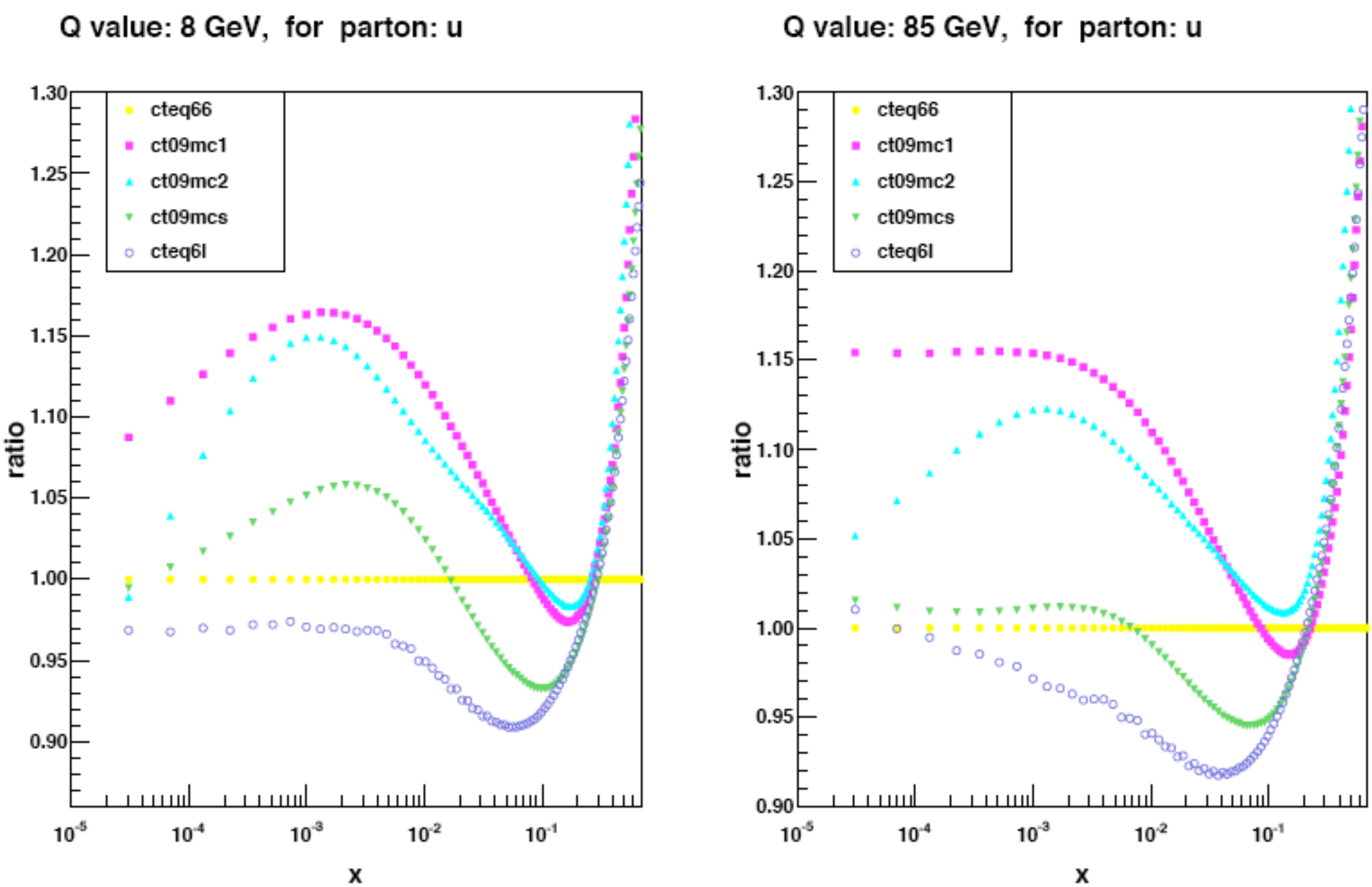


Figure 13: The ratio of the up quark distributions from various LO PDFs to the up quark distribution from CTEQ6.6 at Q values of 8 and 85 GeV.

VBF Higgs production

- LO predictions from CT09MC2 and CT09MCS bracket NLO prediction

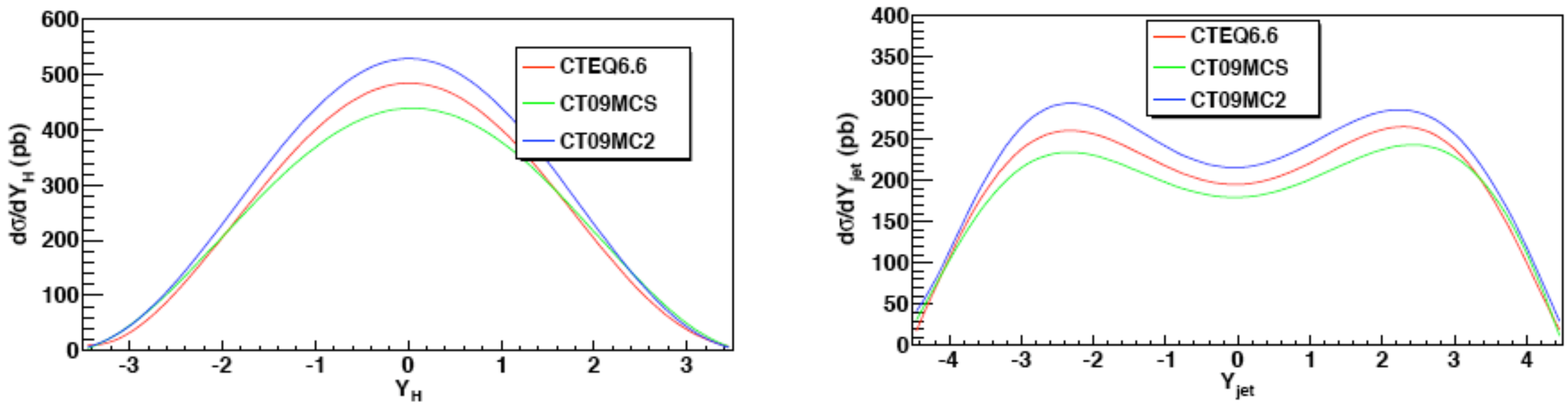


Figure 16: The rapidity distribution for the production of a 120 GeV Higgs through vector boson fusion at 14 TeV (left). Also shown (right) is the rapidity distribution of the leading jet. NLO predictions are shown using the CTEQ6.6 PDFs, and LO predictions are shown using the CT09MC2 and CT09MC1 PDFs.

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 $\mathcal{K}$-factor			LHC $\mathcal{K}$-factor			
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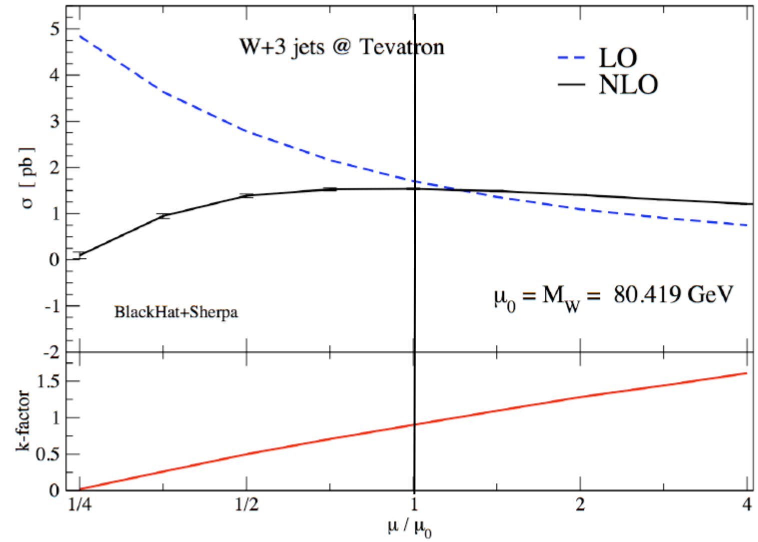
Table 3: $\mathcal{K}$-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ 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

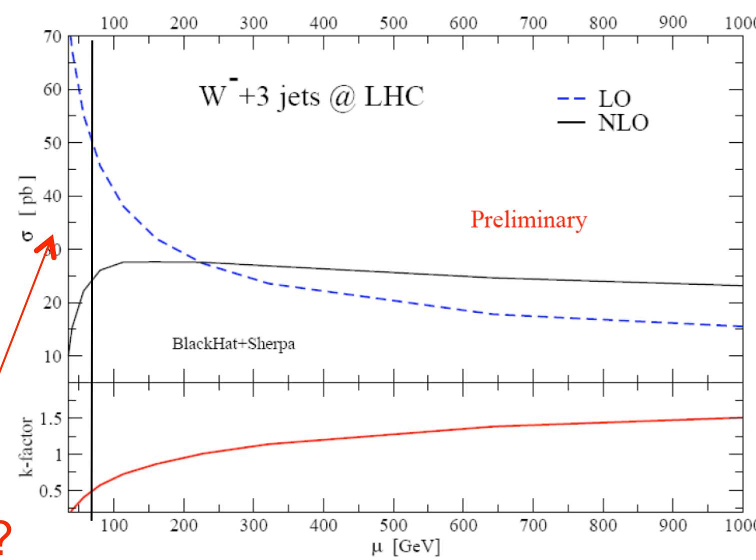
Note K-factor for W < 1.0, since for this table the comparison is to CTEQ6.1 and not to CTEQ6.6, i.e. corrections to low x PDFs due to treatment of heavy quarks in CTEQ6.6 "built-in" to mod LO PDFs

Now consider W + 3 jets

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.



LHC total cross section



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

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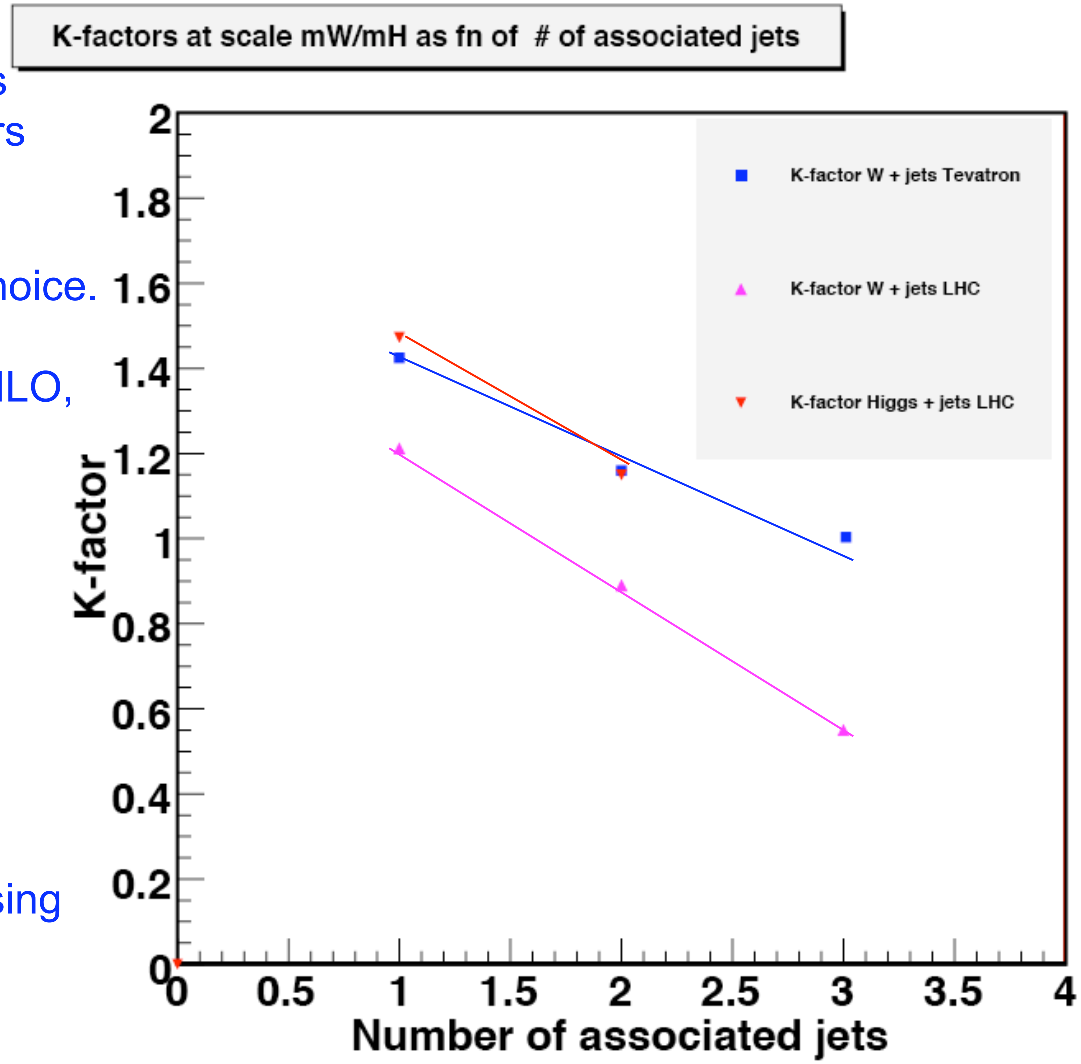
The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

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



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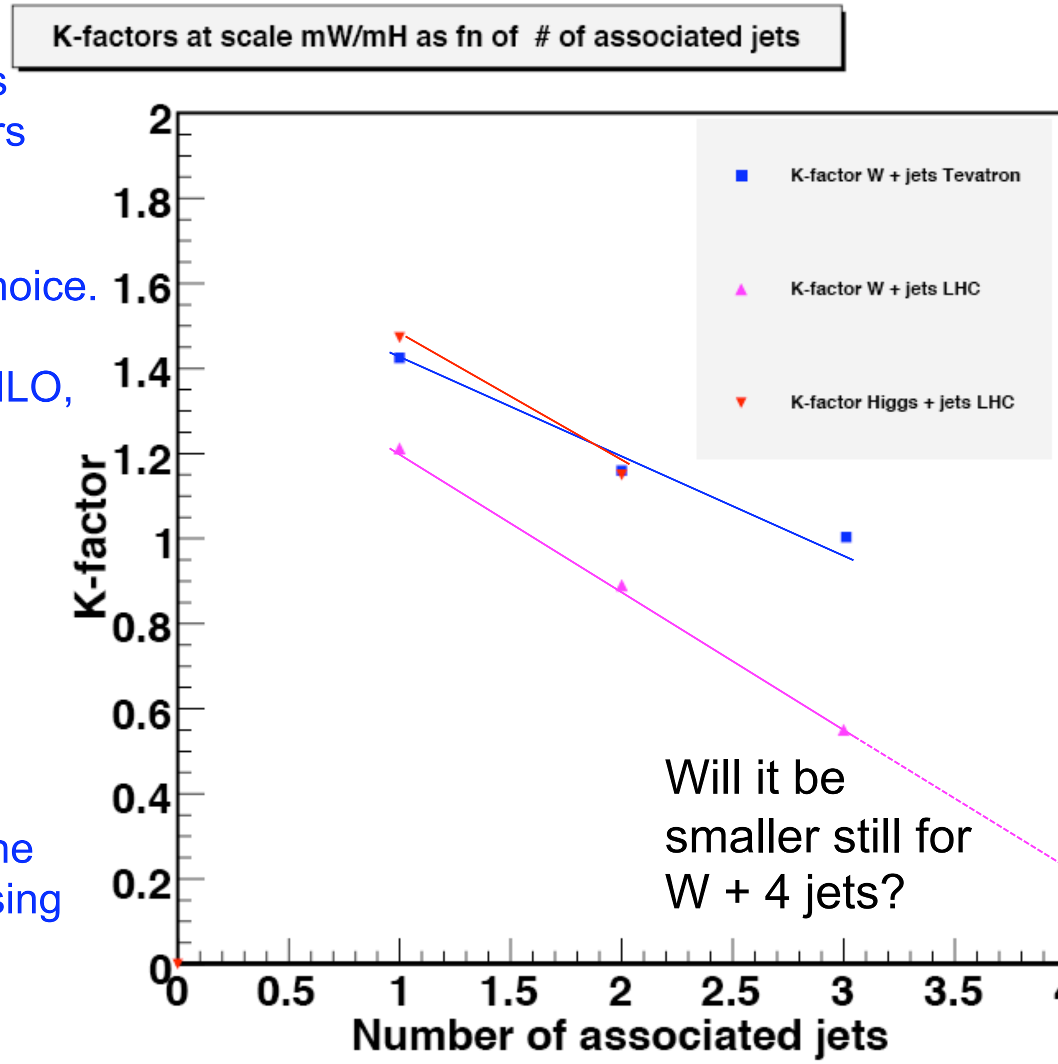
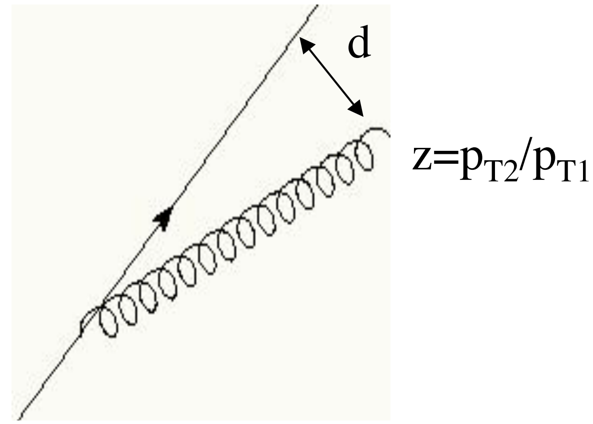


Jet algorithms at LO/NLO

- 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 $1/\Delta R$ 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



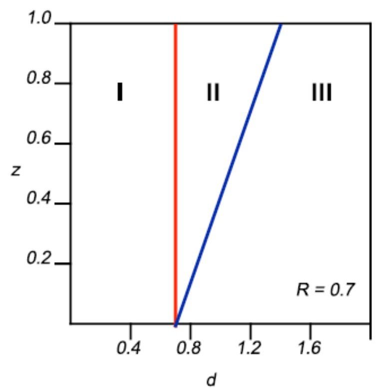
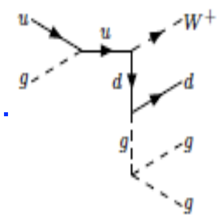


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

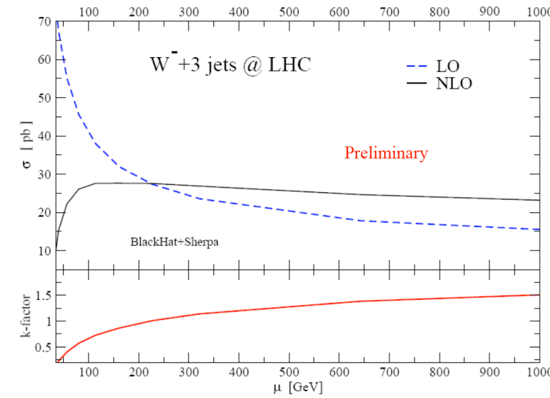
For $D=R_{cone}$, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

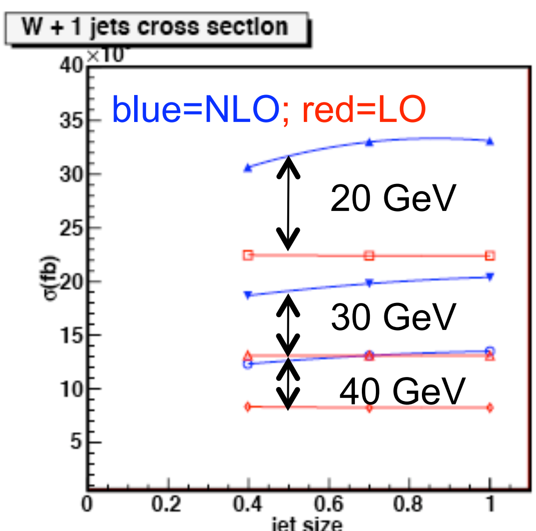
Is the K-factor (at m_W) at the LHC surprising?

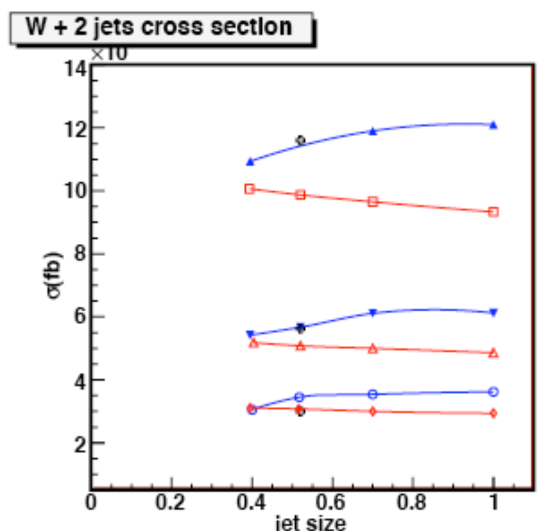
The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits ‘too-high’. The reason (one of them) for this is that we are ‘too-close’ to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~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).

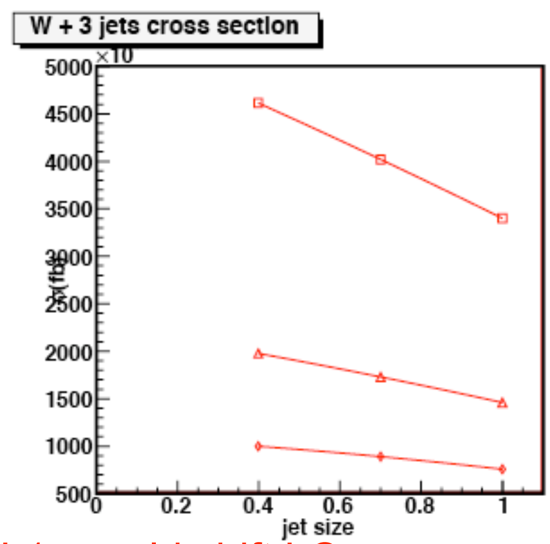


LHC total cross section







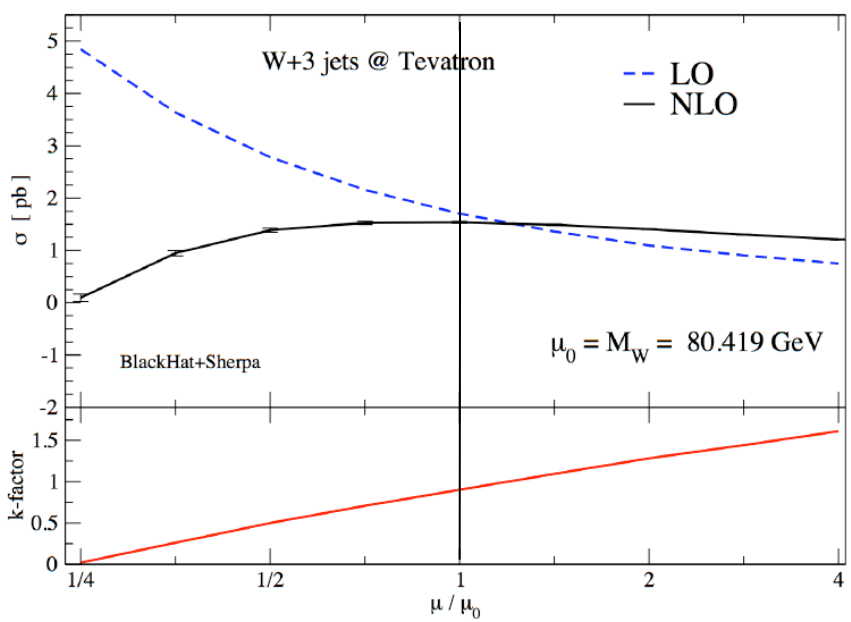


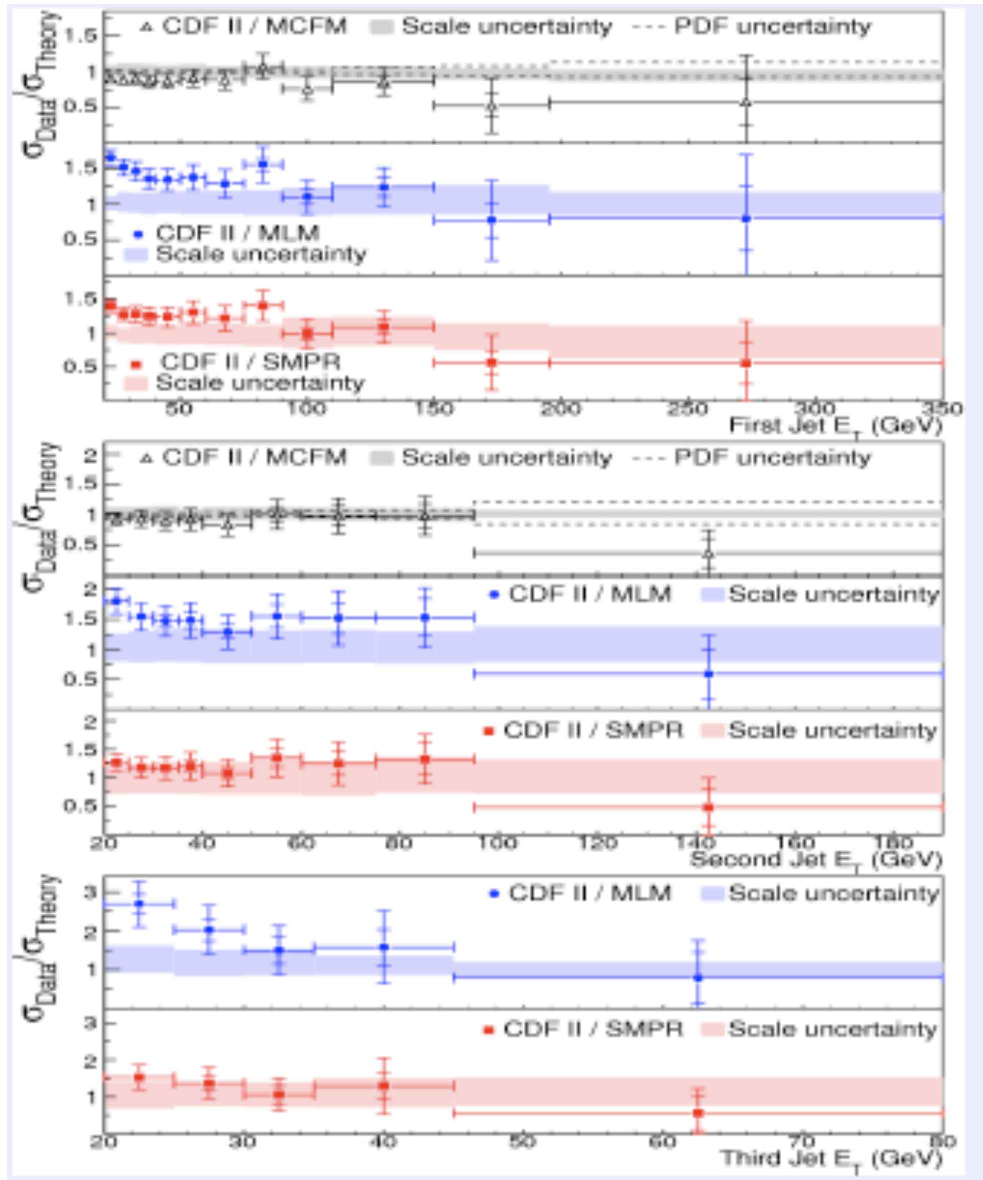
For 3 jets, the LO collinear singularity effects are even more pronounced.

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)

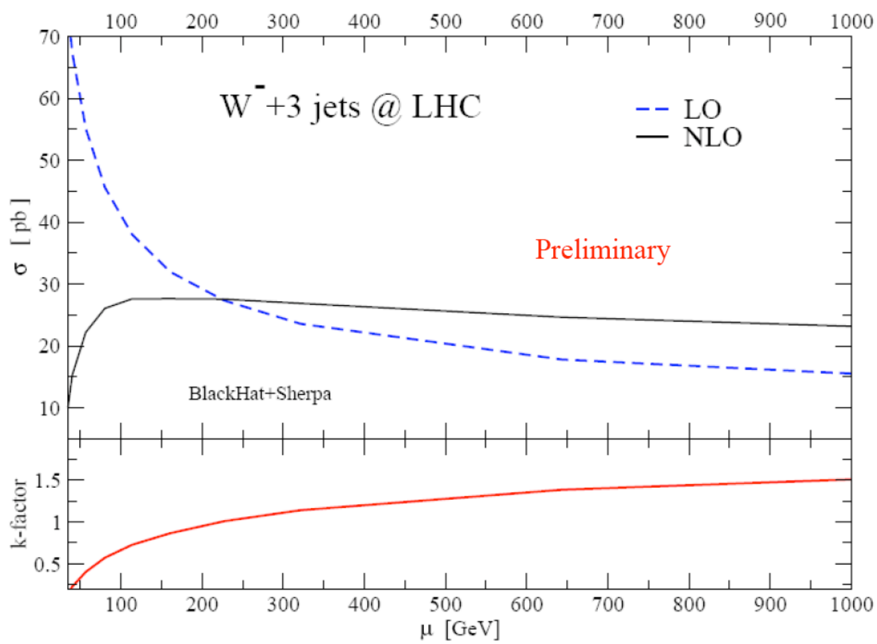




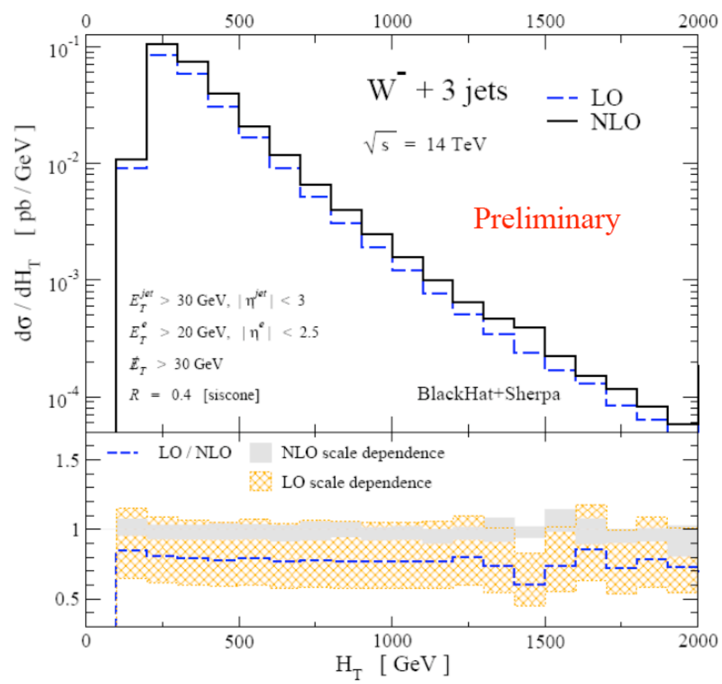
W + 3 jets at the LHC

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



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



mu = H_T

Some other observables

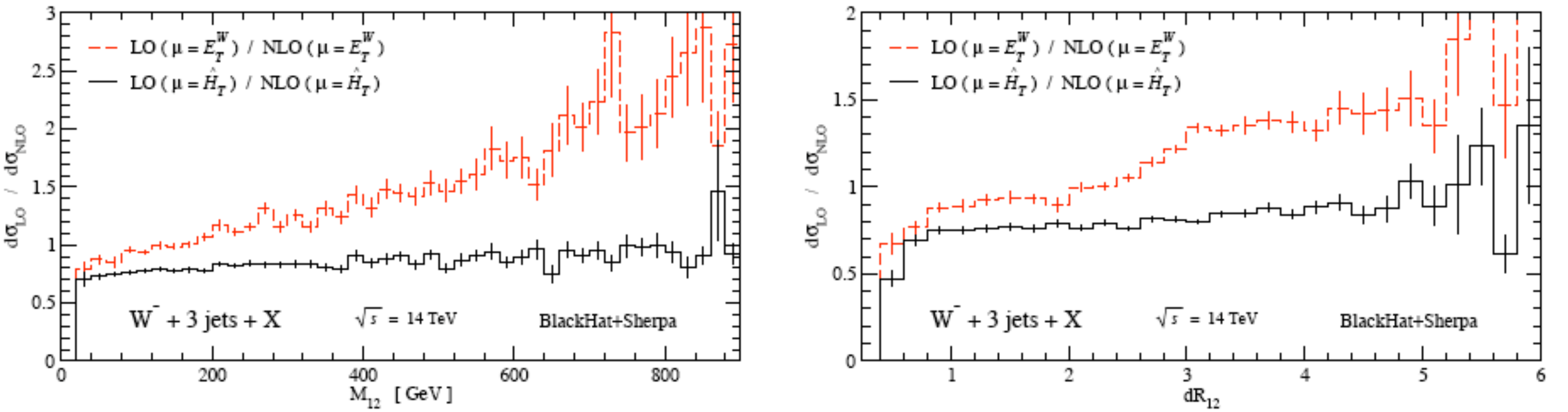


FIG. 12: Ratios of LO to NLO predictions for the distributions in the di-jet invariant mass (left panel) and ΔR separation (right panel) for the leading two jets in $W^- + $ 3-jet production at the LHC. In each panel, the dashed (red) line gives the scale choice $\mu = E_T^W$, while the solid (black)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

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.

The Goldilocks theorem may apply

- 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
  - now am trying to understand how to test the porridge in a general way for any NLO prediction

To do list for LHC

- We have done some comparisons of ALPGEN+PS/NLO for W + 1, 2 jet final states
- It would be useful to generalize them to different scale choices, jet sizes
  - do the current choices lead to any problems?
  - can we get better agreement in shape/size for kinematic distributions with particular scales and/or jet sizes?
- …as well as extending to W + 3 jets
- I'm going through an exercise now with the authors of one of the calculations for W + 3 jets, starting off with simple files, leading to files of W + 3 jets at NLO

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

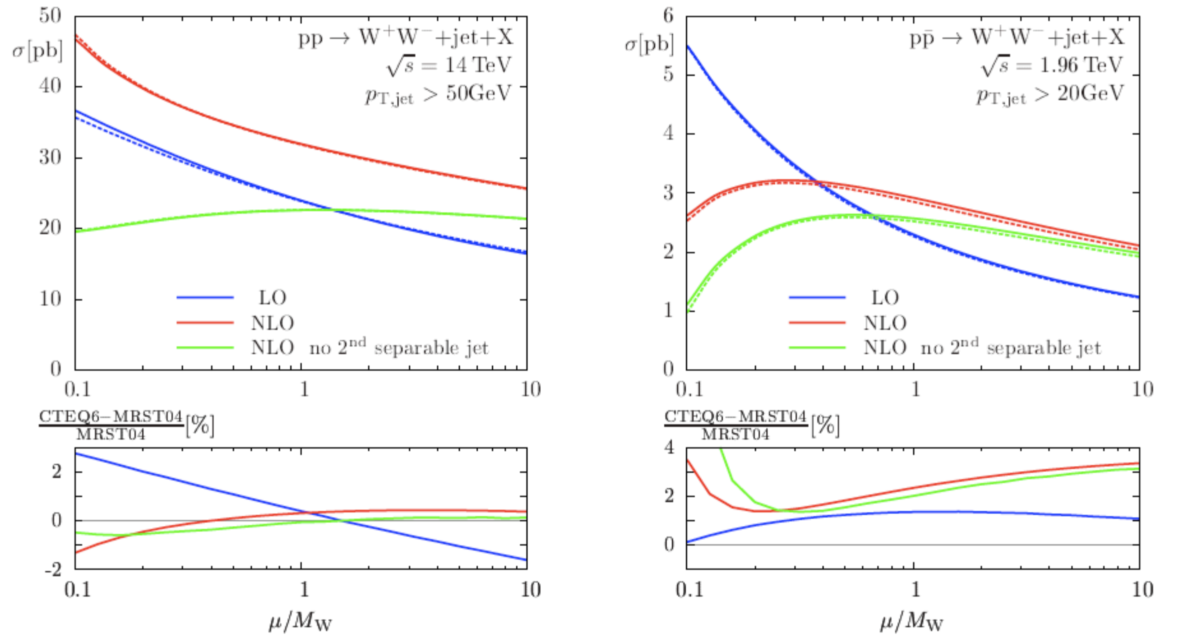
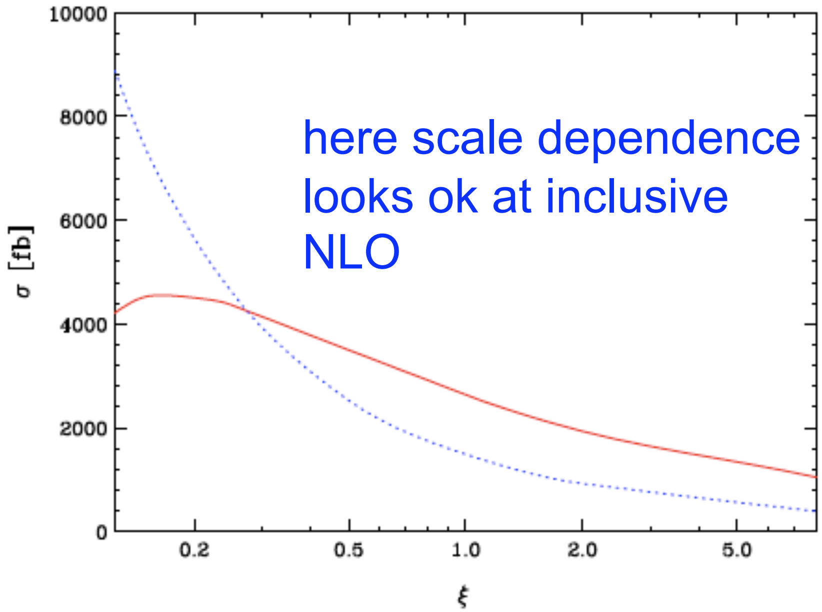


Figure 11: Comparison of WW+jet production cross sections in the LHC setup with $p_{T,jet} > 50$ GeV and for Tevatron with $p_{T,jet} > 20$ GeV: The straight lines show the results calculated with the five-flavour PDFs of CTEQ6, the dashed lines those calculated with the four-flavour PDFs of MRST2004F4.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

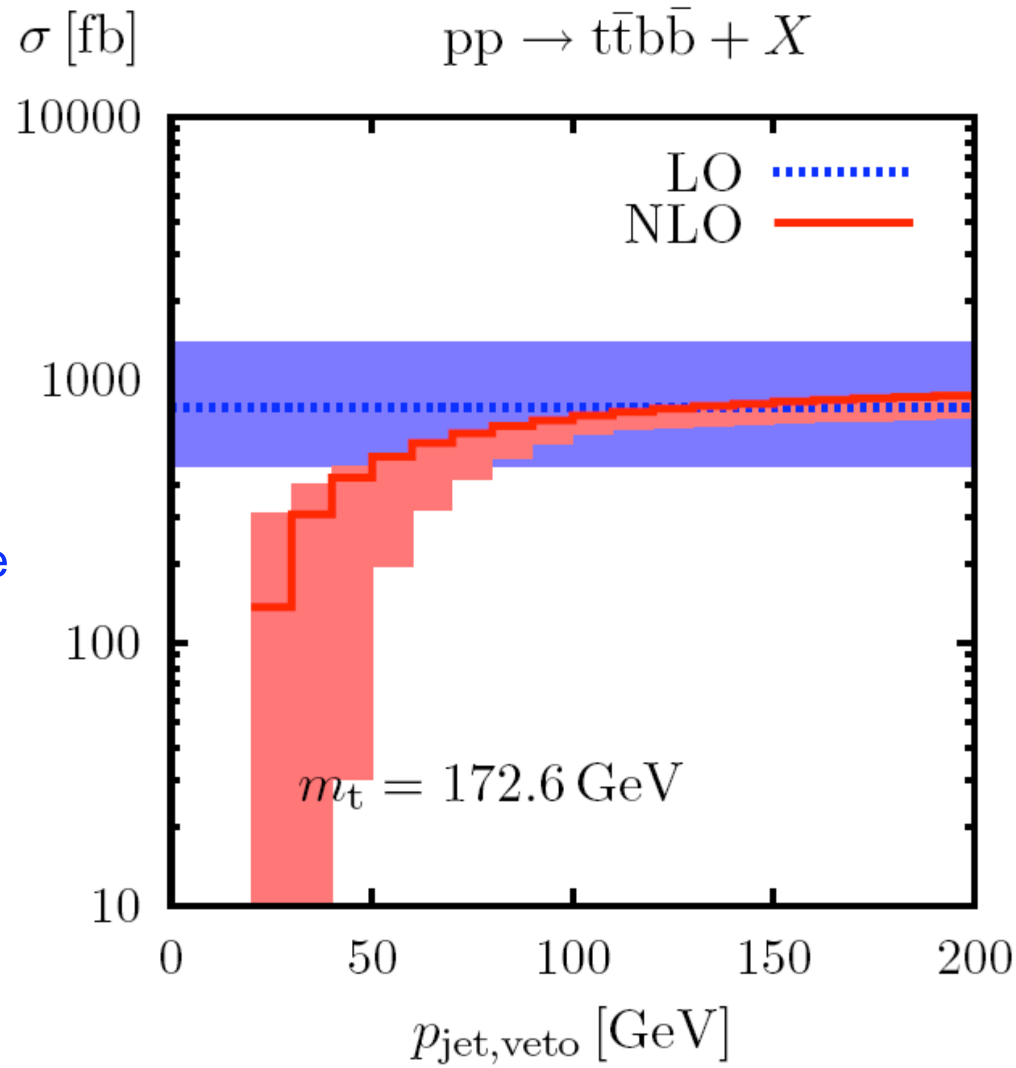
Project for Les Houches writeup: to categorize NLO calculations in terms of effect of jet veto

back to tTbB



here scale dependence looks ok at inclusive NLO

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

Summary

- CT09MC preprint now on the archive
- The choice of the jet size can/will have an impact on the relative size of the LO and NLO cross sections
  - relatively straightforward, but ignored up to this point
  - LO background rates for W + n jets may be too high with conventional scales; the relative ratios for n+1/n jets may also be wrong
- The choice of the jet size can/will have an impact on the *best* scale choice at LO/NLO
  - relatively straightforward, but ignored up to this point
  - W/Z + n-parton final states, with n large, will in general require larger scales at LO in order to agree in shape with NLO calculations
- The choice of the jet size can/will have an impact on the size of the scale uncertainty at NLO
  - relatively straightforward, but ignored up to this point
- The application of a jet veto will lead to a degradation on the true scale uncertainty of a cross section
  - even if it appears that the scale uncertainty is getting better!

Some references

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

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Abstract

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

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

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Review

Jets in hadron–hadron collisions

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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