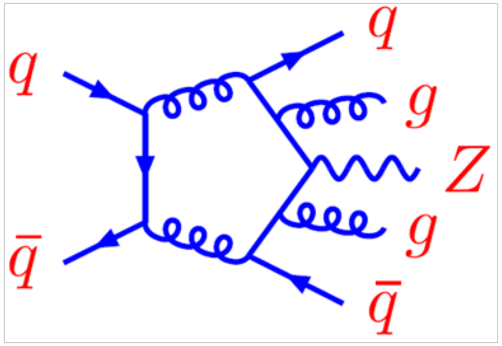
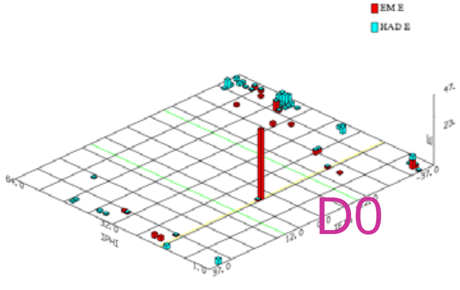
Vector Bosons and Jets Early On



Lance Dixon (SLAC)

**Berkeley Workshop on
Physics Opportunities
with Early LHC Data
May 6-8, 2009**

What is a vector boson?



At a hadron collider, it's

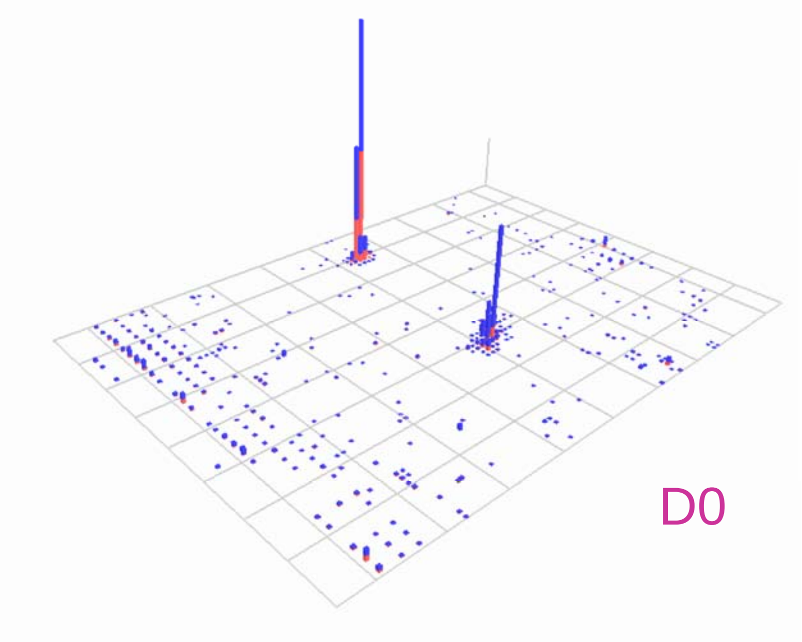
- **a charged lepton + missing E_T**
  $W^+ \rightarrow l^+ \nu$
- **an opposite sign charged lepton pair ($M_{l+l-} \sim M_Z$)**
  $Z^0 \rightarrow l^+ l^-$ **[or maybe** $\gamma^* \rightarrow l^+ l^-$ **]**

Of course most of the time W's and Z's decay to hadrons, but that signal is almost* invisible at a hadron collider

*0801.3906 $p\bar{p} \rightarrow Z \rightarrow b\bar{b}$ with dedicated trigger at CDF
*D0, 0811.3873 4.4σ evidence for $p\bar{p} \rightarrow$ ***WW*** **or** ***WZ***
with one ***W/Z*** → di-jets **– not easy!**
(not for first 200pb^{-1} unless in $t\bar{t}$ events?)

What is a jet?

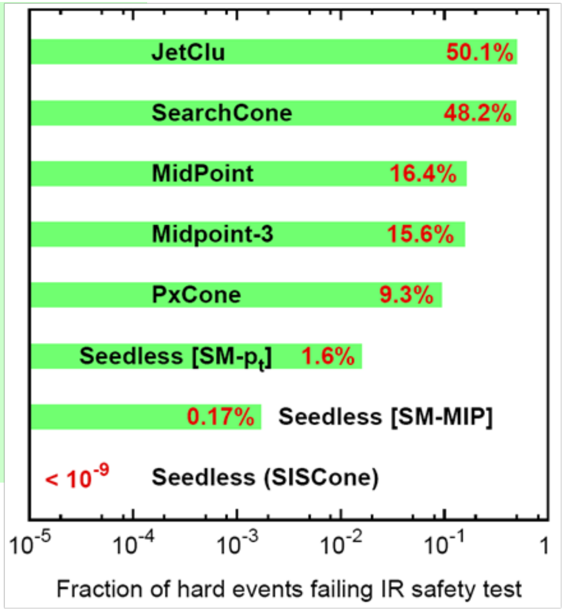
- As Dave Soper emphasized, intuitively it is clear: a spray of hadrons moving in roughly the same direction.
- But to be quantitative, precise definition required – there are (many) different possible definitions, or jet algorithms.
- Two basic types:
  - cone
  - cluster
- One basic requirement (if you ever want to compare to NLO theory): Infrared safety – insensitivity to collinear splitting and soft gluon emission

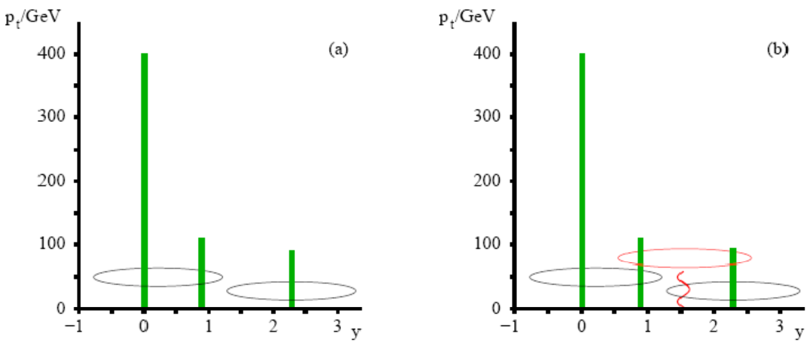


Cone Jets & Infrared Safety

- Conventional hadron collider algorithms use **cones**
- However, for **seeded iterative cones** there is a danger of **infrared unsafety**: jet configuration can depend on arbitrarily soft gluons
- Practical (fast) IR safe seedless cone (**SIScone**) now available

Salam, Soyez (2007)



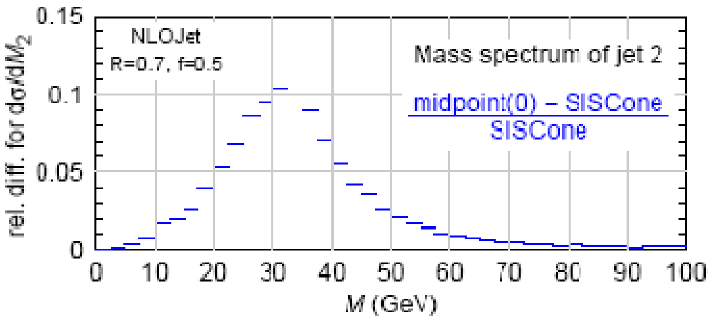


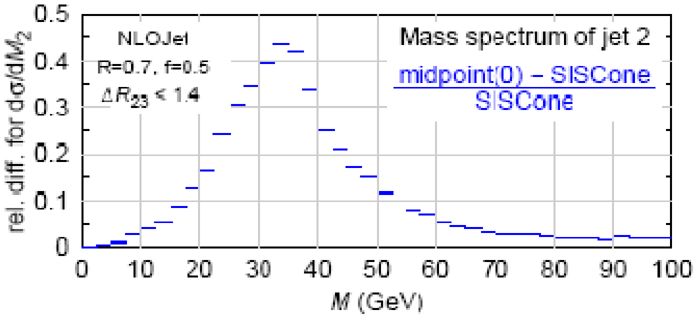
Arbitrarily soft particle can lead to different jet configuration (midpoint algorithm).
→ NLO calculation impossible

Does seeding make a big difference?

For jet E_T and η distributions seeding probably does not matter much, but if you "look inside the jets" (e.g. jet masses), effects can be ~ 30% (e.g. between midpoint and SISCone)

Salam, Soyez (2007)

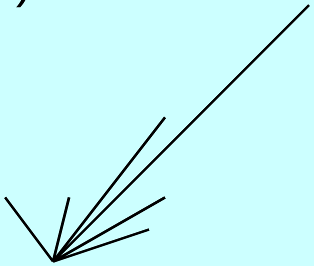




jets that are close to merging

Cluster Algorithms & Underlying Event

- Typical e^+e^- jet algorithm **clusters** particles/towers (bottom up)
- Inherently IR safe.
- However, danger at a hadron collider of picking up too much (or unknown amount) of unwanted soft energy from:
  - underlying event
  - pileup events



- First cluster algorithm tried at hadron colliders (k_T) clusters i and j which have minimum value of

$$d_{ij} = \mathrm{min}(E_{T,i}^2, E_{T,j}^2)\,[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2]/R^2$$

Catani, Dokshitzer, Seymour, Webber; Ellis, Soper (1993)

Recently realized that changing to "anti-k_T"

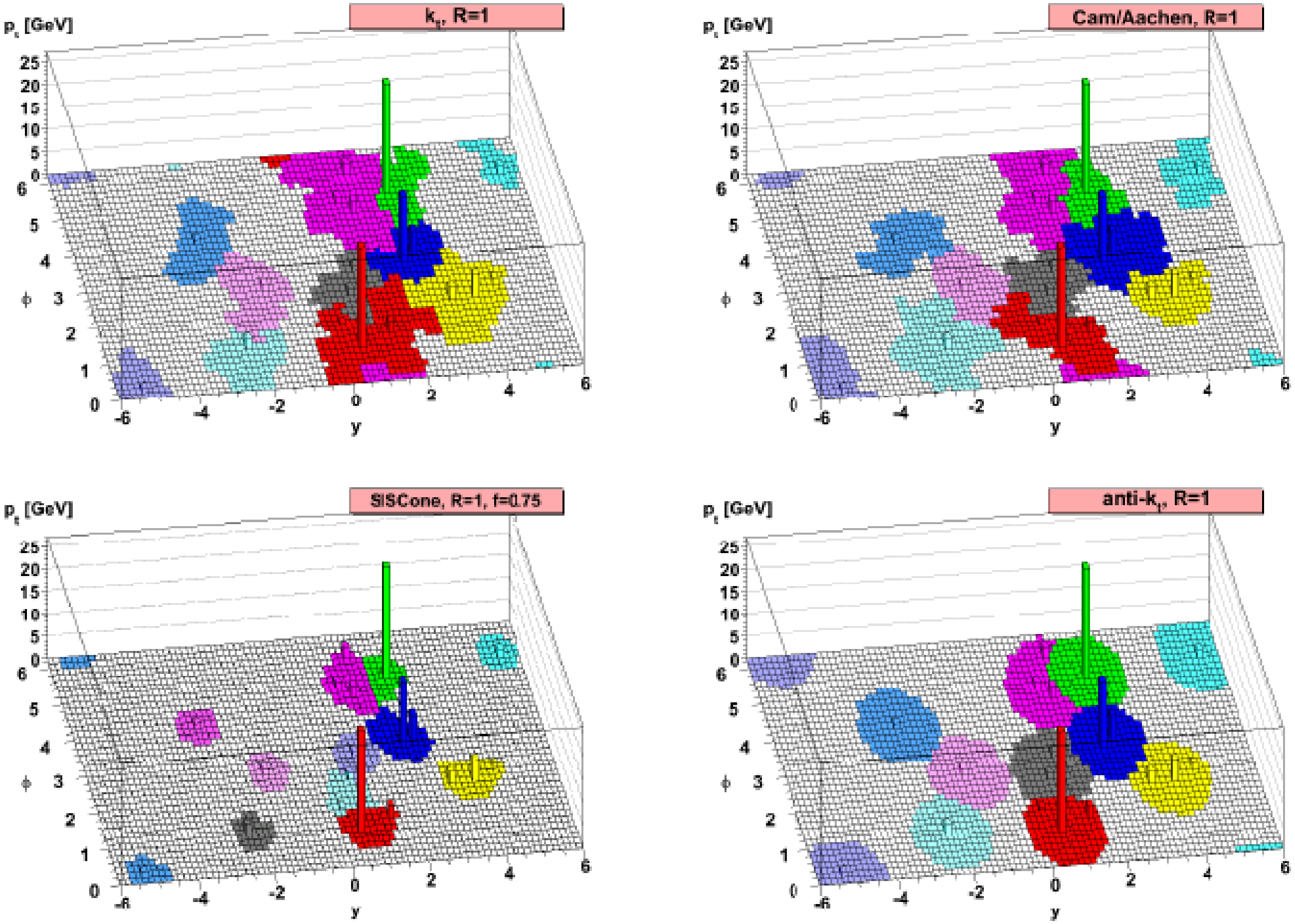
$$d_{ij} = \mathrm{min}(E_{T,i}^{-2}, E_{T,j}^{-2})\,[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2]/R^2$$

Cacciari, Salam, Soyez, 0802.1189

is still IR safe, gives priority to high E_T towers, makes jets very conical, should minimize above problems

“Catchment areas” of different algorithms

Cacciari, Salam, Soyez, 0802.1189



Jet Sociology

- Jets are complicated, yet at the heart of almost every measurement at a hadron collider. Require a lot of effort to calibrate.

→ Natural desire to settle on a very few default algorithms & parameters

- Please make them IR safe algorithms!
- “For searches for e.g. SUSY we don't care much about the algorithm being IR safe and we are lazy” -- Anonymous Experimentalist
- That’s fine if the signal is way above the SM background, or if you can quantify the background experimentally without reference to NLO QCD.
- But if you are background dominated and want/need to fall back on theory, it’s much better if you have an IR safe algorithm in place.
- Early data is the time to find IR safe algorithms that also work well experimentally.

Tools are available

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

a package giving the user flexibility to reconstruct jets with a variety of algorithms/parameters and do comparisons. In use in CDF, ATLAS and CMS.

Also FastJet package http://www.lpthe.jussieu.fr/~salam/fastjet/

Another Plea

- Don’t publish only data that is “corrected back to parton level”, without also supplying data corrected back to particle (hadron) level.

- Corrections often depend heavily on the Monte Carlo version and obscure parameter values, and these are sometimes not well enough documented to be reproduced.

Why use NLO theory?

$$\hat{\sigma}(\alpha_s,\mu_F,\mu_R) \;=\; [\alpha_s(\mu_R)]^{n_\alpha}\left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{(1)}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F,\mu_R) + \cdots\right]$$

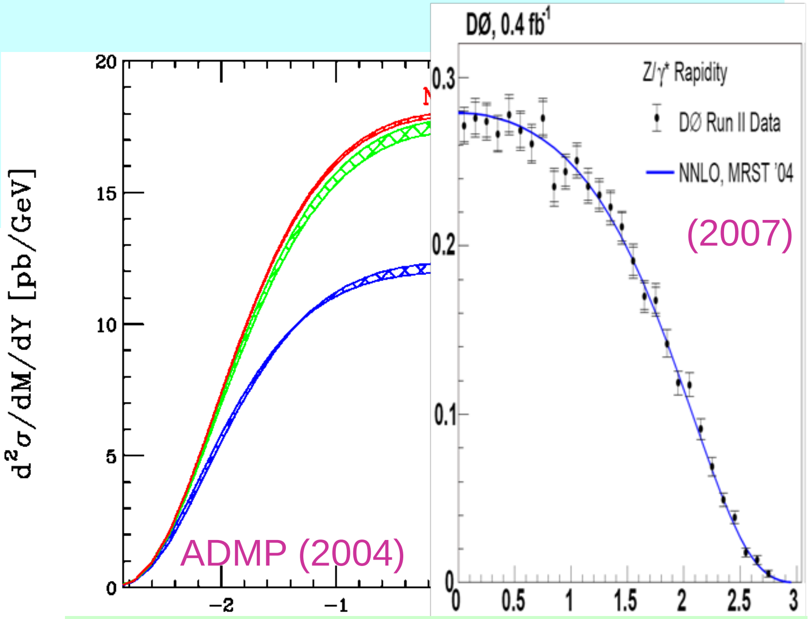
LO NLO NNLO

Because leading order (LO) predictions are only qualitative in normalization, due to **poor convergence** of expansion in $\alpha_s(\mu)$

Example: *Z* production at Tevatron
Distribution in rapidity *Y*

$$Y \;=\; \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$\frac{d\sigma}{dY}$ has $n_\alpha = 0$



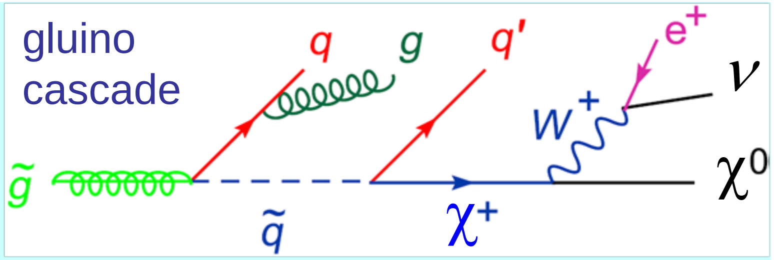
(2007)

ADMP (2004)

still ~50% corrections, LO → NLO

by NNLO, a precision observable

Why *W* (or *Z*) + n jets?



- New particles – whether from
  - supersymmetry
  - extra dimensions
  - ...

typically decay into old particles:

quarks, gluons, charged leptons, neutrinos, photons, *W*s & *Z*s (which in turn decay to leptons, …)

- Kinematic signatures not always that clean (*e.g.* mass bumps) if neutrinos, or other escaping particles (dark matter) present

- Most important irreducible Standard Model backgrounds often from *W*/*Z* + jets, with $W \rightarrow l\nu$, $Z \rightarrow \nu\nu$

(Also pure jets, with jets faking leptons and missing E_T)

W (or *Z*) + n jets predictions

Very early studies, using pure parton shower Monte Carlos, underestimated hard jet radiation by factor of 10.

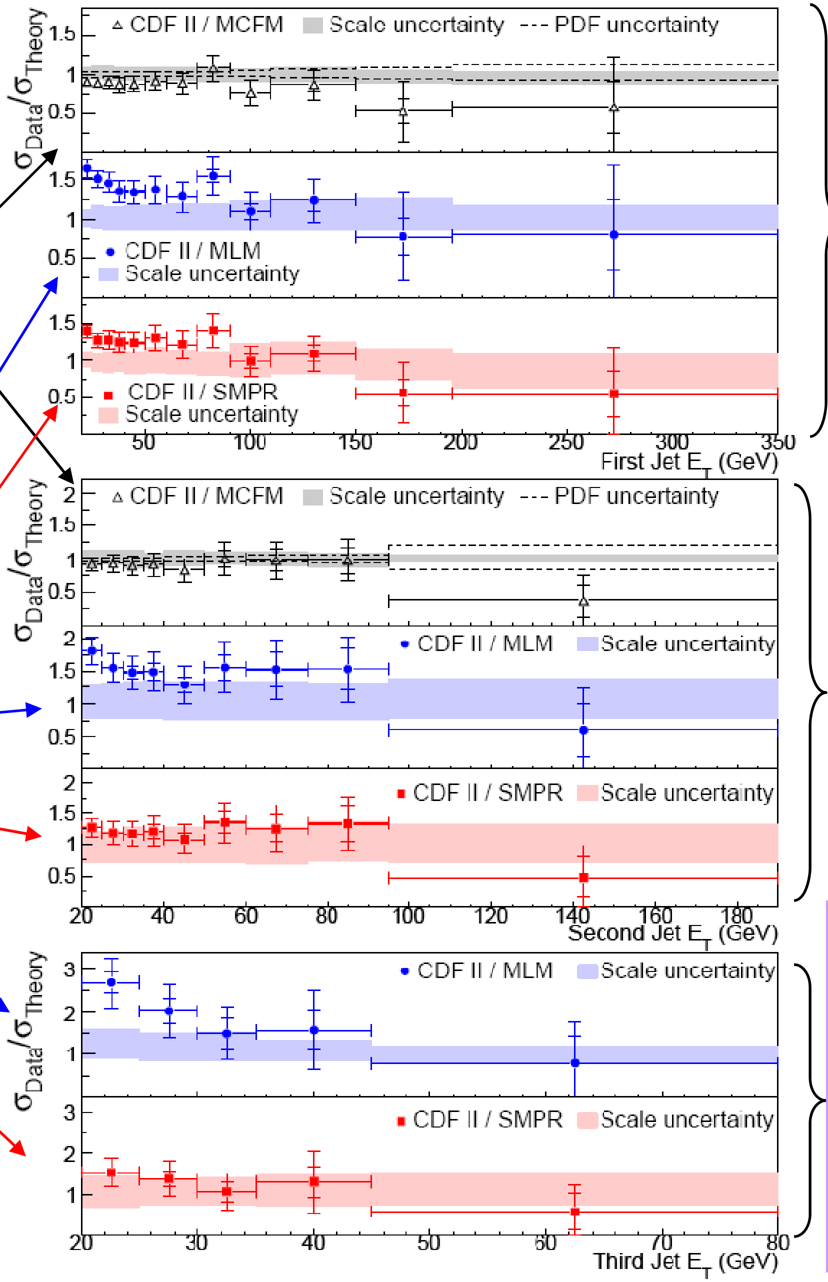
- State-of-art tool for the most complex events ($n_{jet} > 3$) is "exact leading order matrix elements matched to (or merged with) a parton shower" also known as "enhanced leading order" (ELO).
- Represented, for example, by
  - ALPGEN (PYTHIA or HERWIG shower, MLM matching)
  - SHERPA (HERWIG or PYTHIA shower, CKKW matching)
  - MadGraph/MadEvent (either shower(?), matching)
- Provides complete hadronic final states
- But, because it is based on LO (**tree** amplitudes), the overall normalization can be uncertain by nearly a factor of 2, especially as n_{jet} increases
- Need NLO cross sections to improve this
- NNLO for a very few high precision measurements

Tevatron
W + n jets Data

NLO (MCFM)

CDF, 0711.4044 [hep-ex]

ELO with different matching schemes



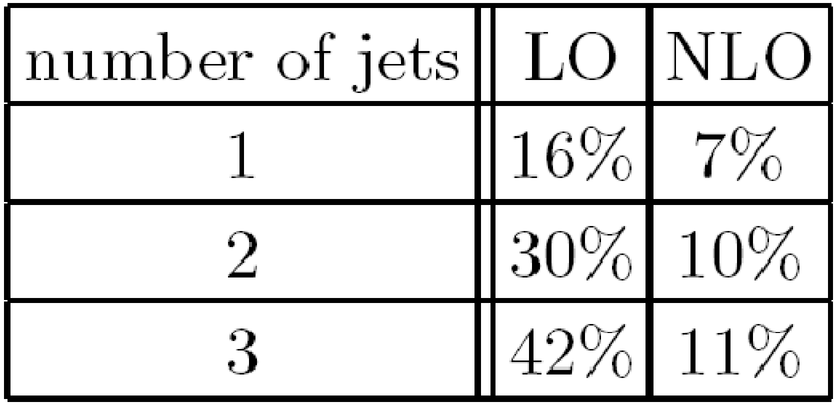
n = 1

n = 2

n = 3: only LO was available until this year

Reduction in Uncertainty

In going from LO to NLO for "total cross section" for *W* + n jets at Tevatron (will be similar for LHC):



number of jets	LO	NLO
1	16%	7%
2	30%	10%
3	42%	11%

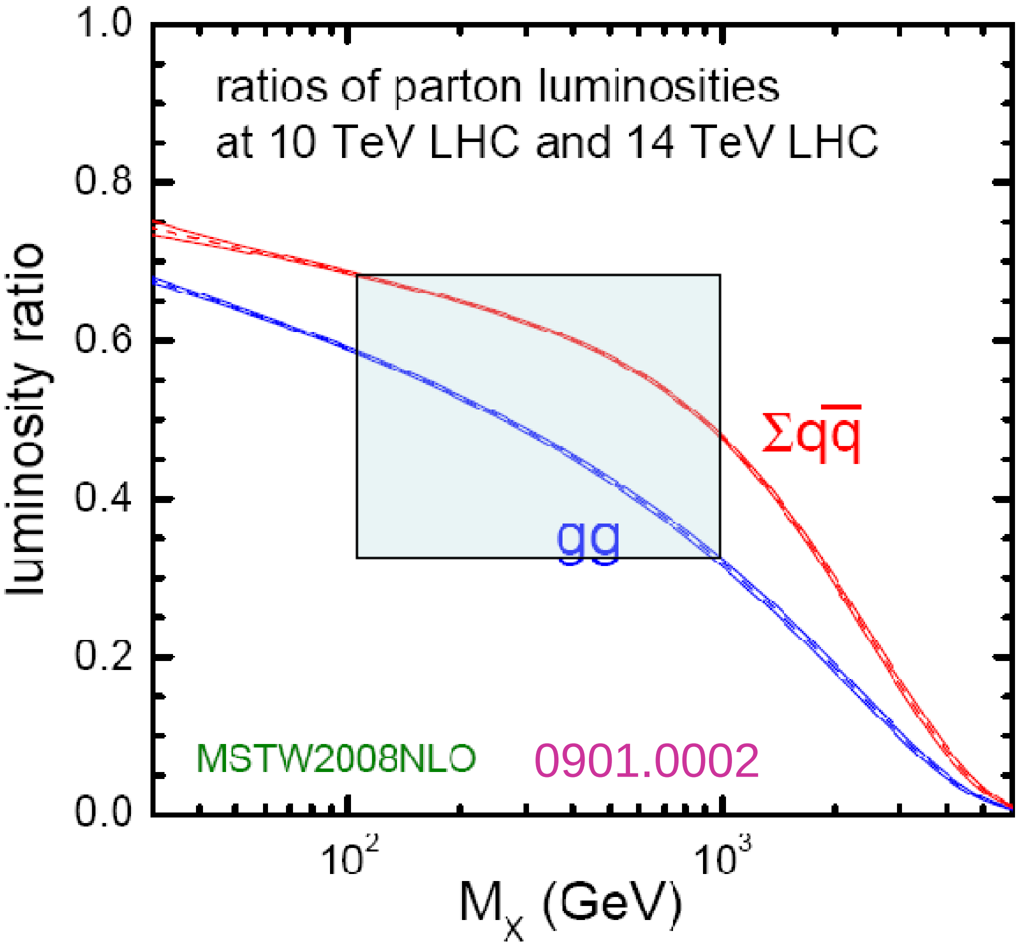
NNLO
2-3%?

does not include pdf uncertainty

"shapes" (distributions within total event sample) can be affected as well as normalizations

How many events?

14 → 10 TeV: reduction in parton luminosity ~ 1/2



Rough numbers of events

$E_{CM} = 10\ \text{TeV}$ $\qquad$ $E_T^{\text{n}^{\text{th}}\text{jet}} > 30\ \text{GeV}$

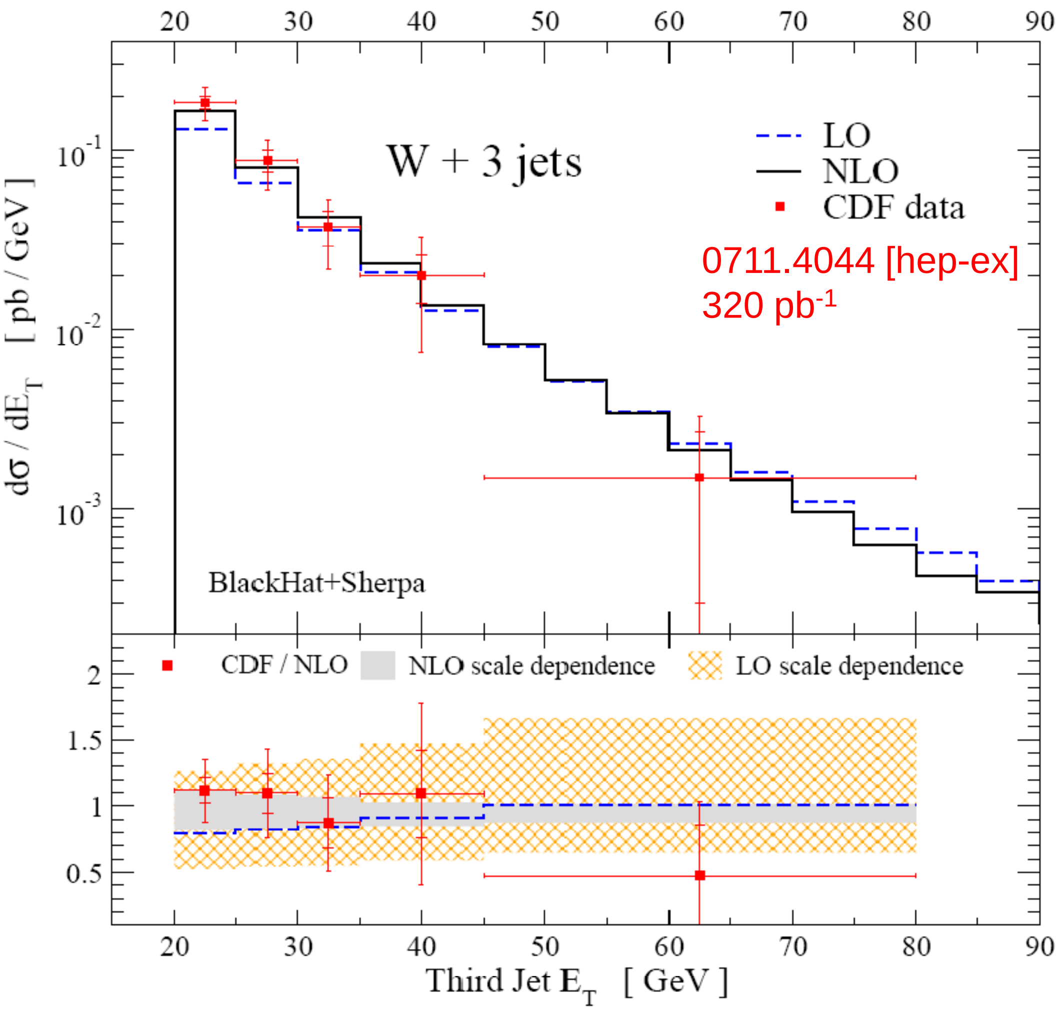
plus standard jet, rapidity, lepton, missing E_T cuts

$W^\pm \to e^\pm\nu$ or $\mu^\pm\nu$ $\qquad$ $Z^0 \to e^+e^-$ or $\mu^+\mu^-$

$\int \mathcal{L}\,dt =$	$10\ \text{pb}^{-1}$	$200\ \text{pb}^{-1}$
$\sigma(W^\pm j) \approx 1,500\ \text{pb}$	15,000	300,000
$\sigma(W^\pm jj) \approx 300\ \text{pb}$	3,000	60,000
$\sigma(W^\pm jjj) \approx 70\ \text{pb}$	700	15,000
$\sigma(Zj) \approx 125\ \text{pb}$	1,250	25,000
$\sigma(Zjj) \approx 25\ \text{pb}$	250	5,000
$\sigma(Zjjj) \approx 5\ \text{pb}$	50	1,250

At these small E_T's, roughly comparable to Tevatron @ few fb^{-1}

NLO works for *W* + 3 jets at Tevatron



0711.4044 [hep-ex]
320 pb^{-1}

NLO:
BlackHat+SHERPA
0902.2760 [hep-ph]

Cuts:

$E_T^e > 20$ GeV $\quad E_T^{\text{jets}} > 20$ GeV

$|\eta^e| < 1.1 \quad \not{E}_T > 30$ GeV

$|\eta^{\text{jets}}| < 2 \quad M_T^W > 20$ GeV

Central Scale:

$$\mu_0 \equiv \mu_F = \mu_R = \sqrt{M_W^2 + p_T^2(W)}$$

Range $\mu_0/2 < \mu < 2\mu_0$

see also Ellis, Melnikov, Zanderighi, 0901.4101

$W^\pm$ + 3 jets at LHC

SISCone

$$E_{CM} = 14 \text{ TeV}$$

Cuts:

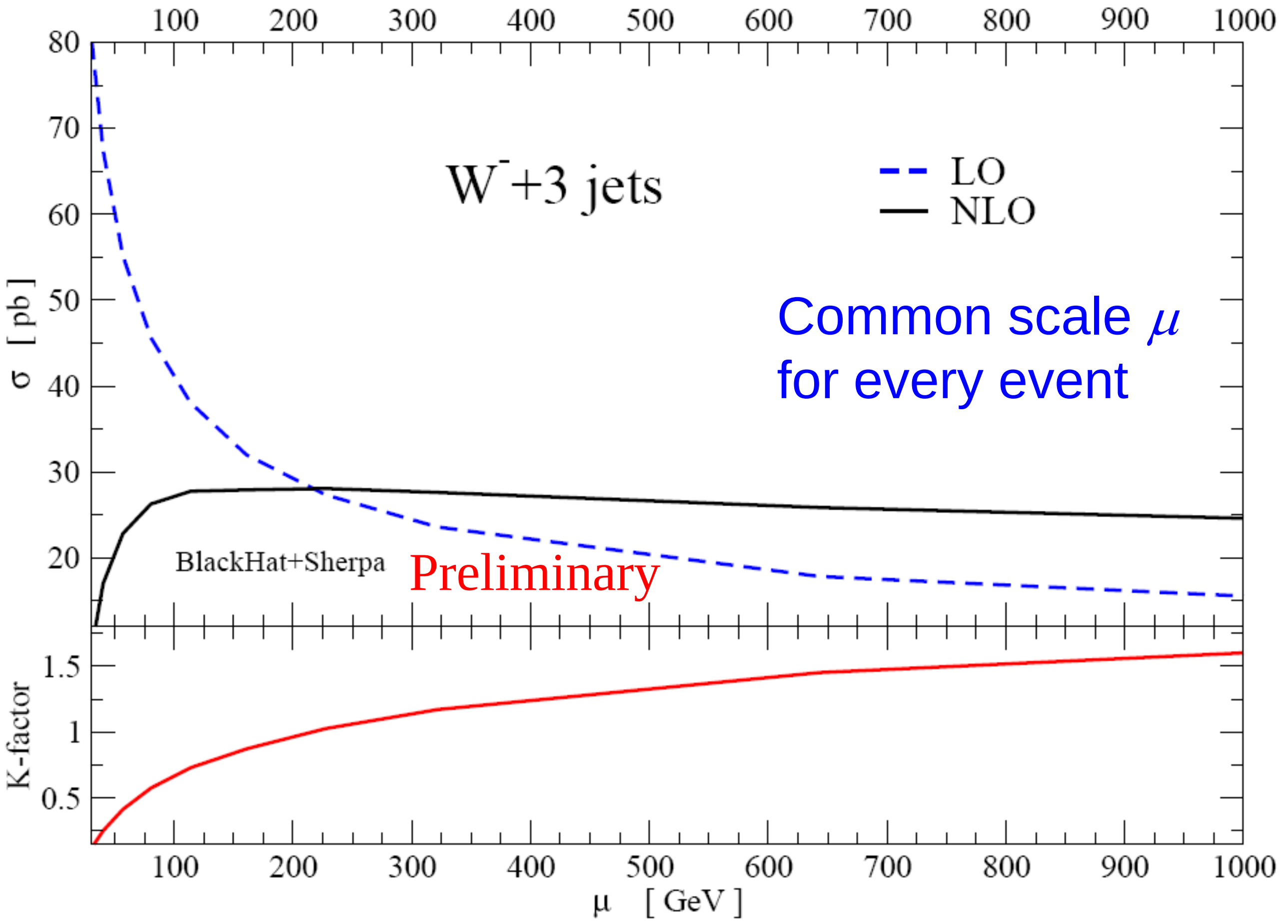
$E_T^e > 20$ GeV $\qquad E_T^{\text{jets}} > 30$ GeV

$|\eta^e| < 2.5 \qquad \not{E}_T > 30$ GeV

$|\eta^{\text{jets}}| < 3 \qquad M_T^W > 20$ GeV

NLO study by C. Berger, Z. Bern, L.D., F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. Kosower, D. Maître, to appear

LHC total cross section



Common scale μ
for every event

W+3 jet K factor: Tevatron to LHC

- K factor at $\mu = M_W$ drops from 1 to ½.
- Much of this can probably be attributed to a shift from quark to gluon initial states as the average x drops:

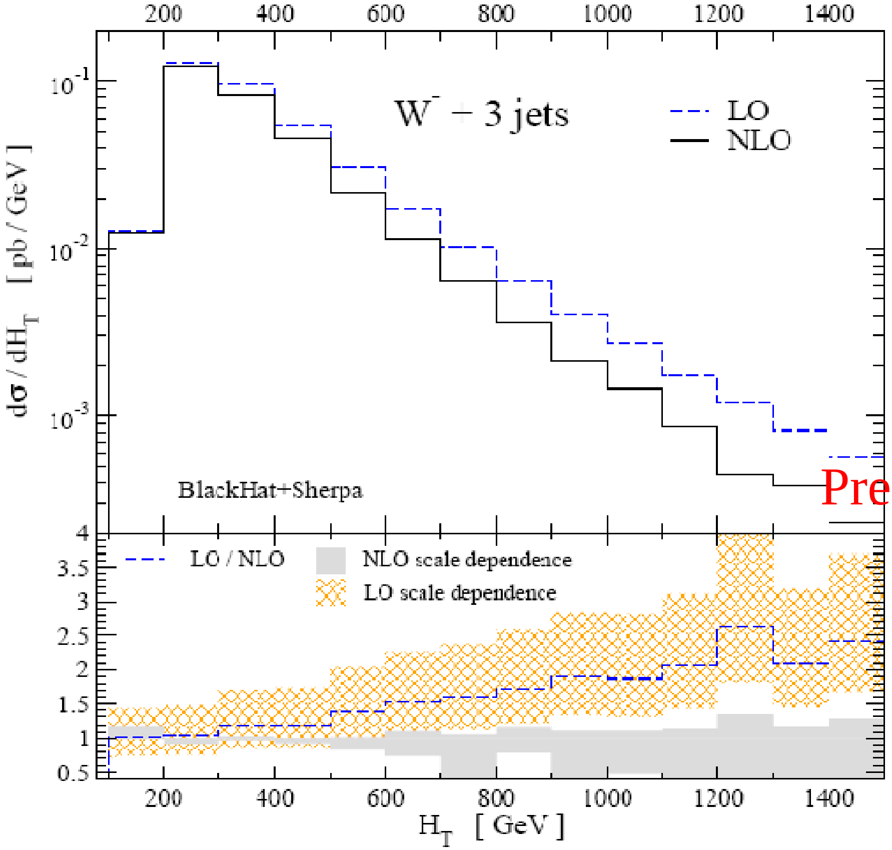
  in going from LO to NLO

  for $0.01 < x < 0.1$

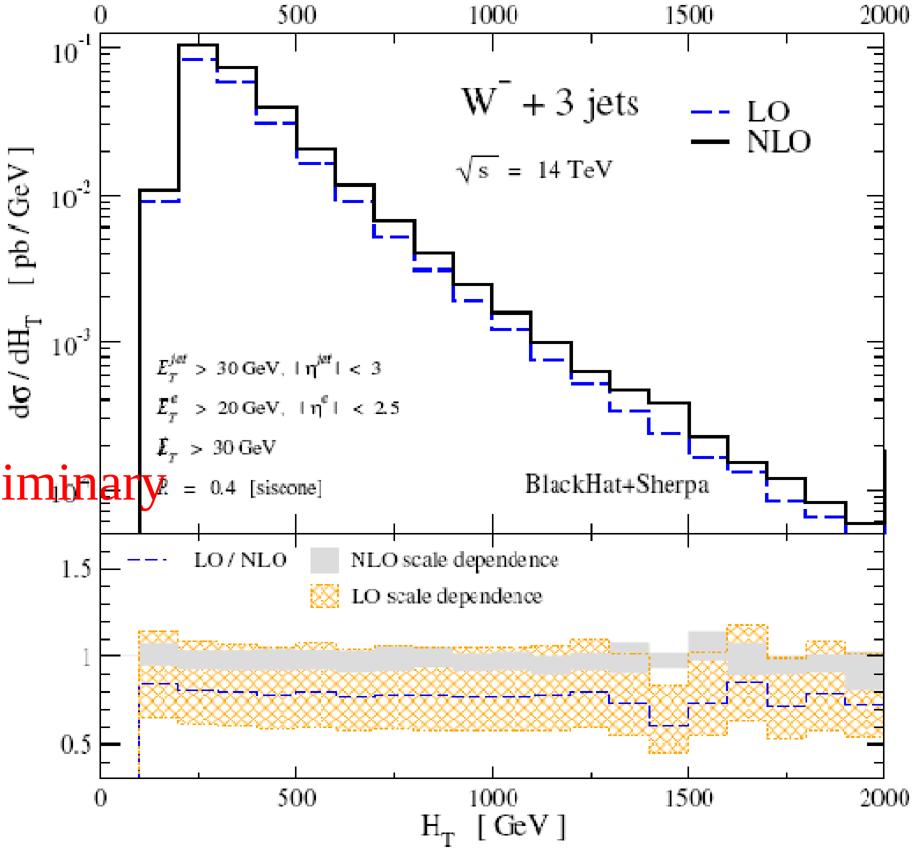
  $g(x)$ decreases while $q(x)$ increases

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

Traditional SUSY search variable – but also an excellent characterization of “the right scale” for LO – note uniformity of “K factor”

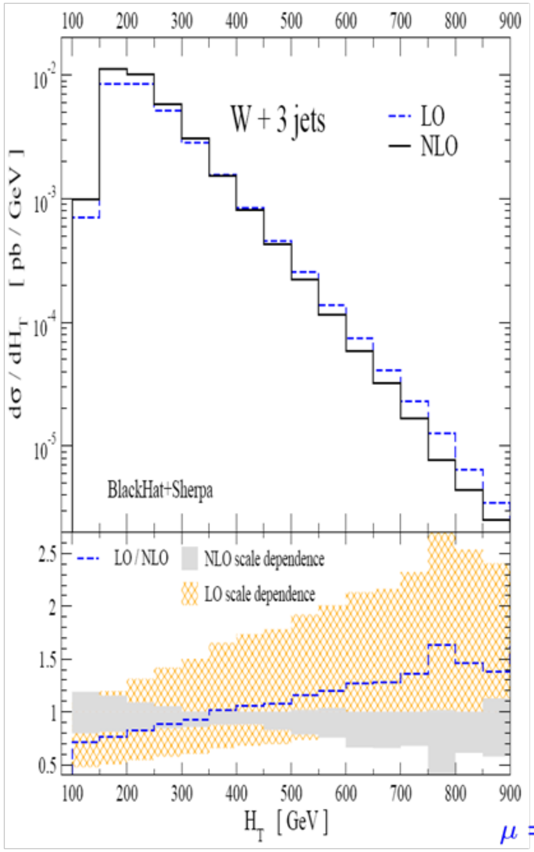


$\mu = \sqrt{M_W^2 + p_T^2(W)}$

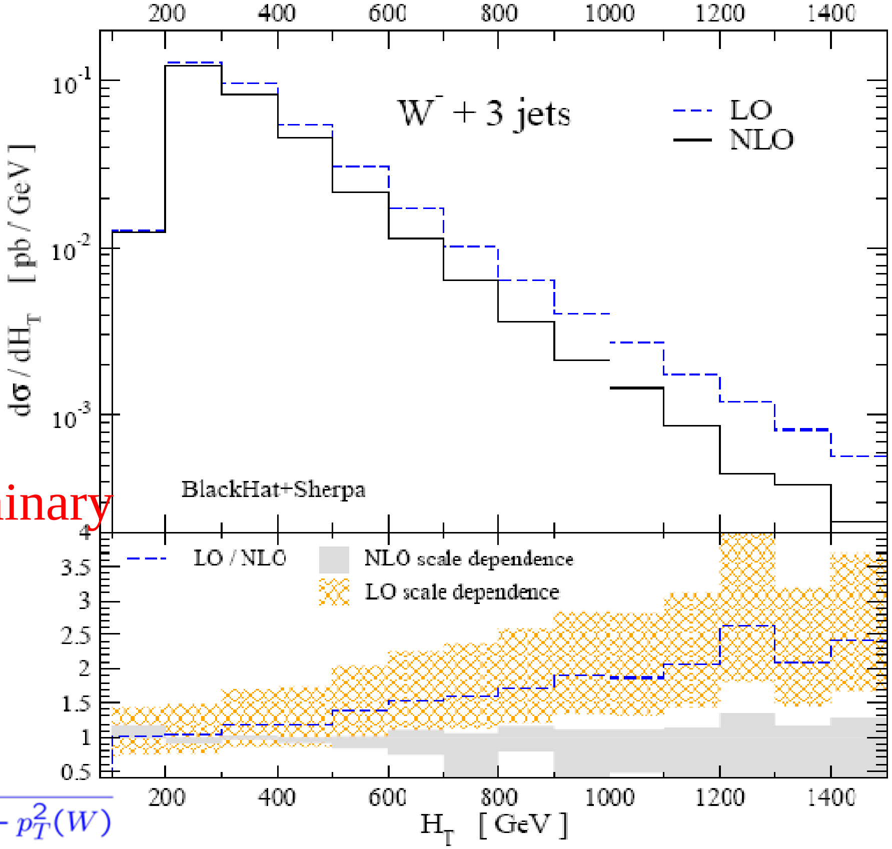


$\mu = H_T$

Compare H_T distributions



Preliminary

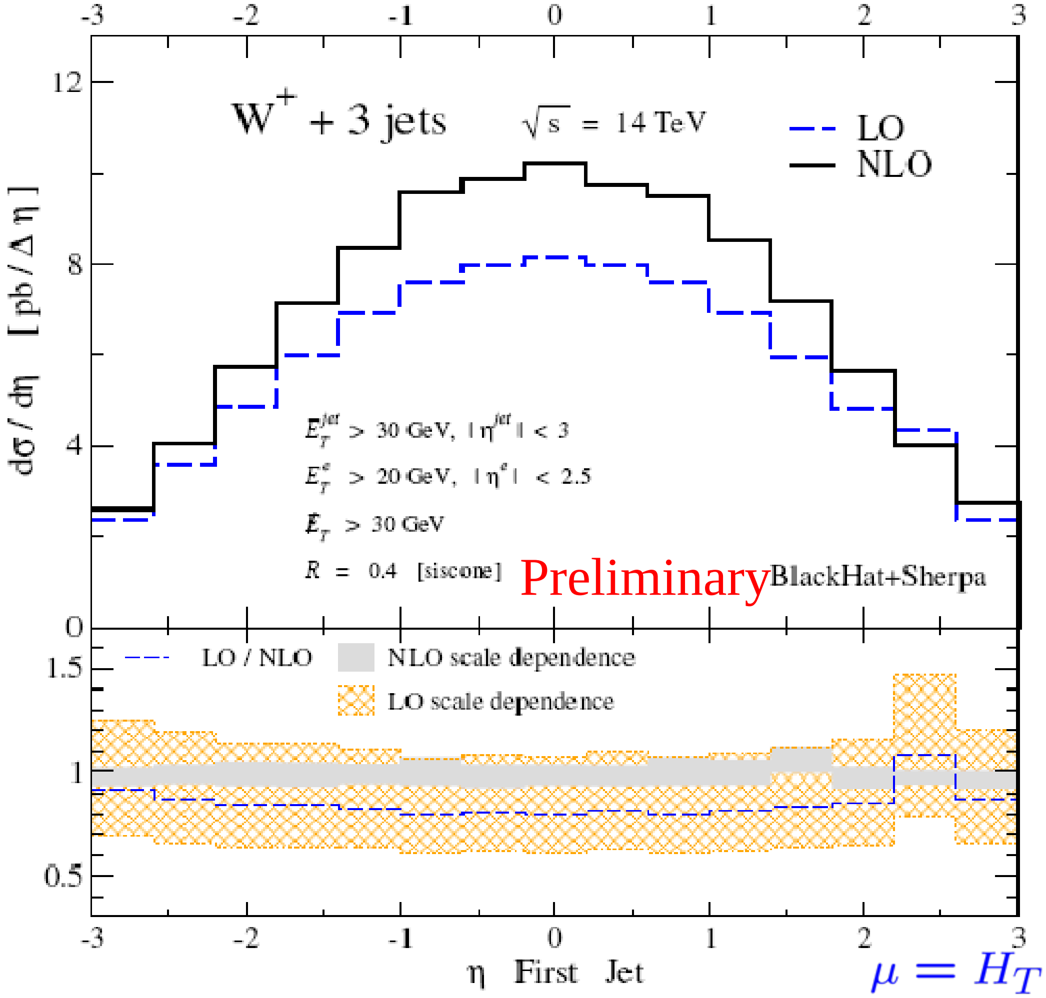


$\mu = \sqrt{M_W^2 + p_T^2(W)}$

Tevatron with few fb^{-1} $\sim$ $\sqrt{s} = 10$ TeV LHC with 200 pb^{-1}

events similar but distribution is ~ 50% broader at LHC

Pseudorapidity of first jet



$\mu = H_T$

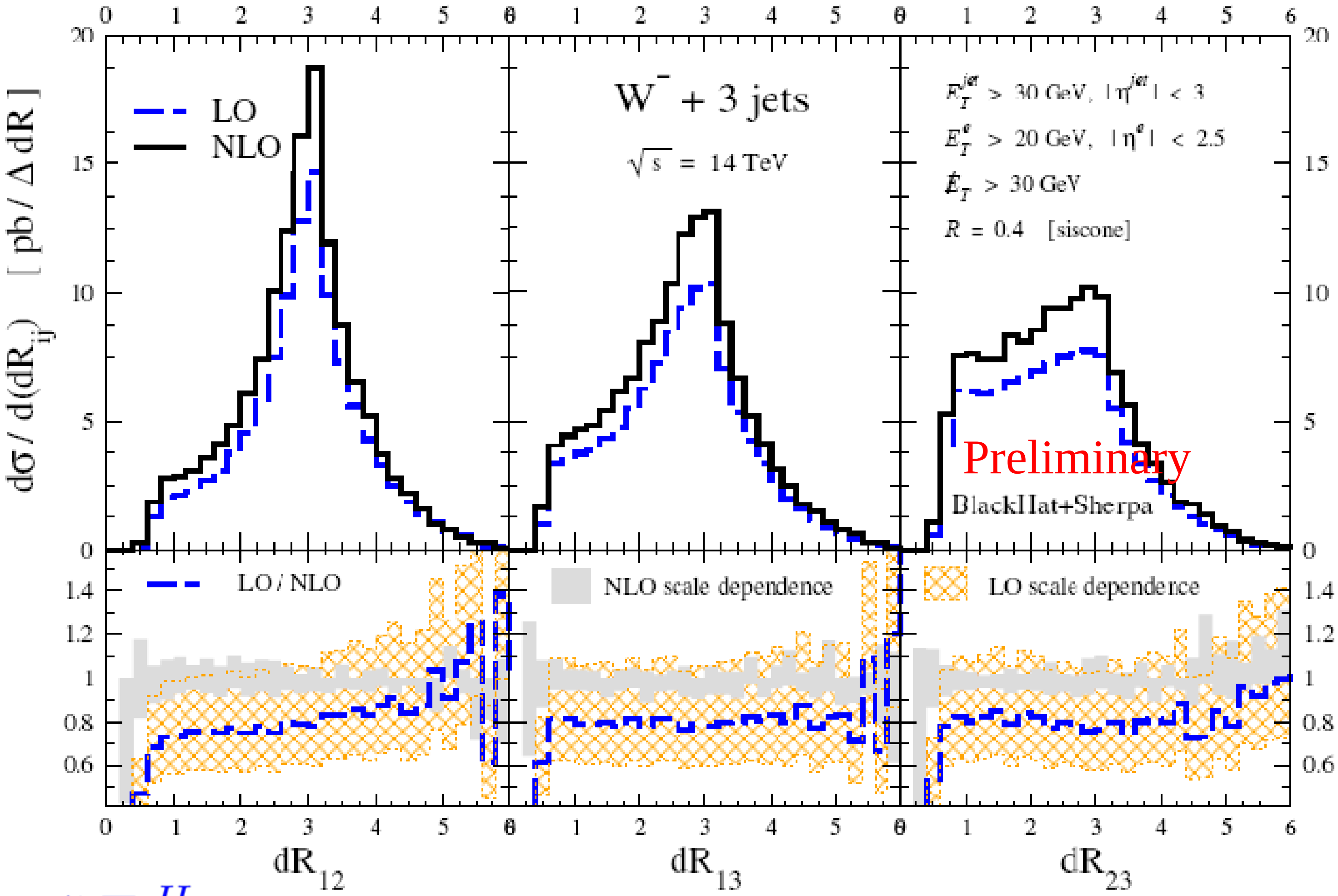
essentially
no change
in shape from
LO to NLO

Distance between jets

Significant change in shape for dR_{12} from LO to NLO.

More chance for hardest jets to be closer if extra radiation.

Large η separation → costs more in terms of parton luminosity if extra radiation.



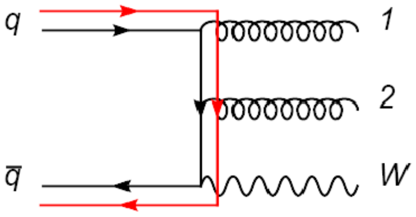
$\mu = H_T$

$$dR_{ij} \equiv \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2}$$

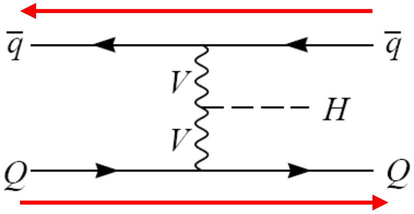
Tag W + 2 jets
then look for additional jet in “gap”

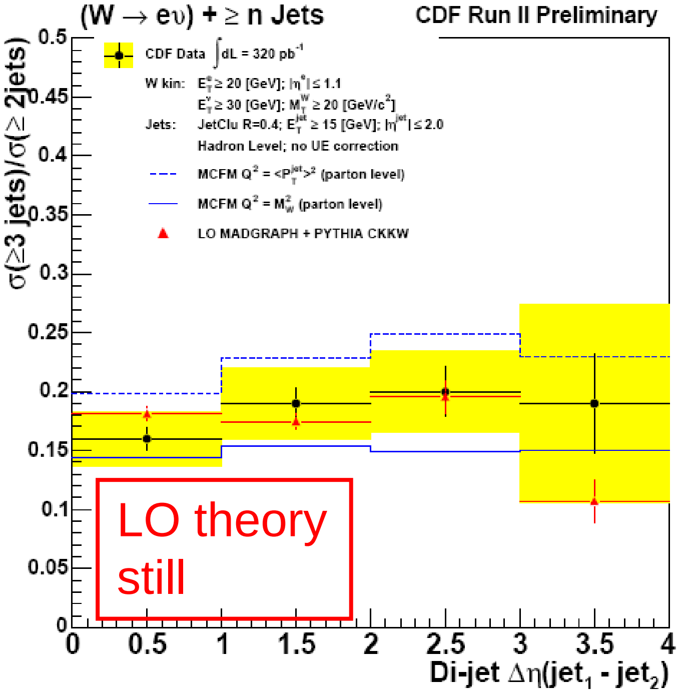
Hard Interactions of Quarks and Gluons: a Primer for LHC Physics 75

Campbell, Huston, Stirling, hep-ph/0611148



vs.





LO theory still

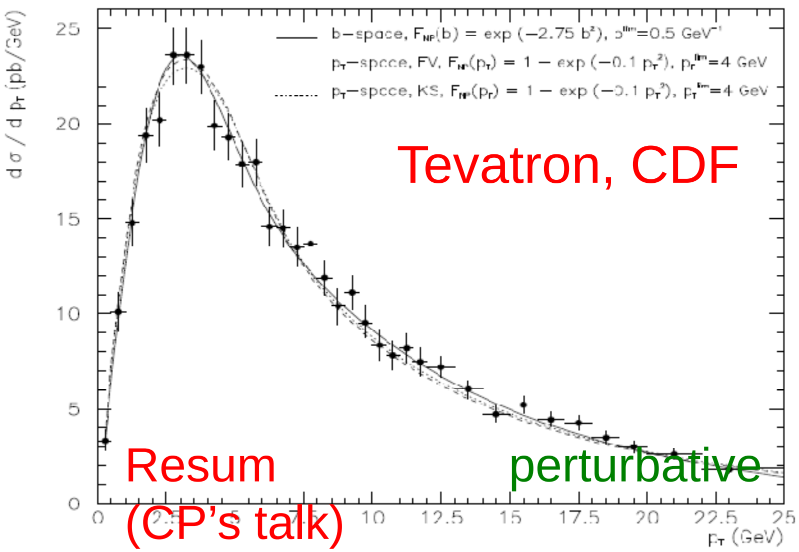
Want this fraction to remain sizable for non-color-singlet exchange at large $\Delta\eta$, in order for central jet veto to be effective in studies of Higgs production via vector boson fusion.

Figure 61. Predictions and a measurement from CDF Run 2 for the rate for the production of a third jet in $W+ \geq 2$ jet events, as a function of the rapidity separation of the two lead jets.

Z + 1 jet

- May be available at NNLO before too long.
- Can then also predict $p_T(Z)$ distribution at NNLO, to 2-3% at large $p_T(Z)$.
- Comparison of the two experimental distributions, $p_T(Z)$ [measured only with leptons] and $d\sigma/dE_T^{jet}$ is very sensitive to jet energy scale.

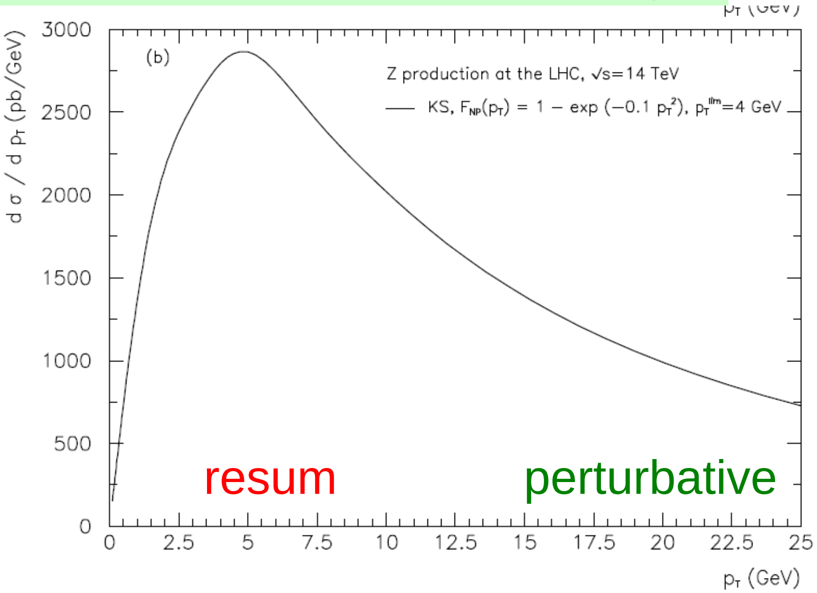
W + 1 jet similar (12x statistics!) but smeared by neutrino p_T



Tevatron, CDF

Resum (CP's talk)

perturbative



resum

perturbative

Kulesza, Stirling, hep-ph/0103089

Conclusions

- Vector bosons + jets very important for “validating Standard Model” at low E_T prior to searching for new physics excesses at higher E_T
- With 200 pb^{-1} small E_T rates similar to Tevatron but explore higher H_T, etc.
- New NLO results are becoming available for the LHC, in particular for *W* + 3 jets. *Z* + 3 jets also on the way.
- *W/Z* + 4 jets is probably also feasible before too long, as well as pure multi-jets if desired (n_{jet} = 3 already done, NLOJET++).
- Shapes as well as normalizations can be affected by NLO corrections, even for complex final states
- Important to use IR safe jet algorithms to take advantage of these results.
- Because the present NLO results are at parton level, and not yet matched to a parton shower (which may take quite a while), some thought should be given to how to make them most useful to experimenters
  - best distributions to study
  - best ratios of different processes to take: *W* → *Z*, etc.
- *Z* + 1 jet will probably be available at NNLO before too long. As a precision observable in jet physics at a hadron collider, it deserves experimental analysis; maybe possible with good precision with 200 pb^{-1}

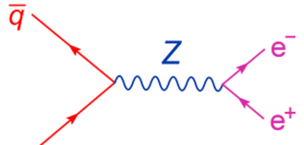
Extra Slides

Anatomy of an NLO computation

Need a “black box” for computing one-loop (virtual) corrections.
Also need to add **real radiative corrections**

Simple Example: *Z* production

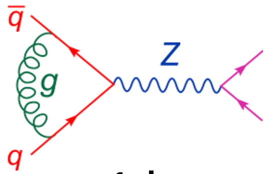
LO $\hat{\sigma}^{(0)}$



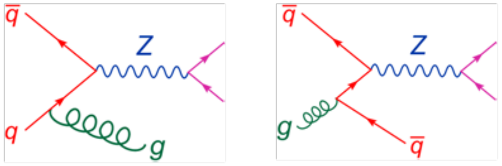
tree

convolute with pdfs
apply cuts

NLO $\hat{\sigma}^{(1)}$



1 loop



tree + 1 parton

dim. reg. $D = 4 - 2\epsilon$

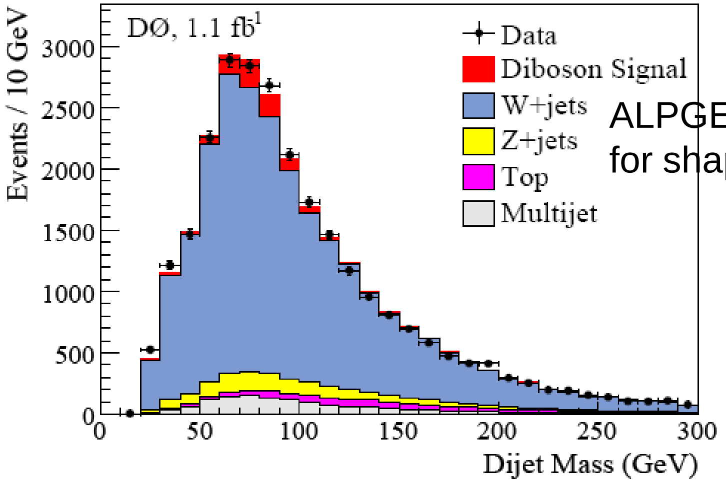
first, cancel infrared divergences ($1/\epsilon^2$) between virtual & real

BlackHat

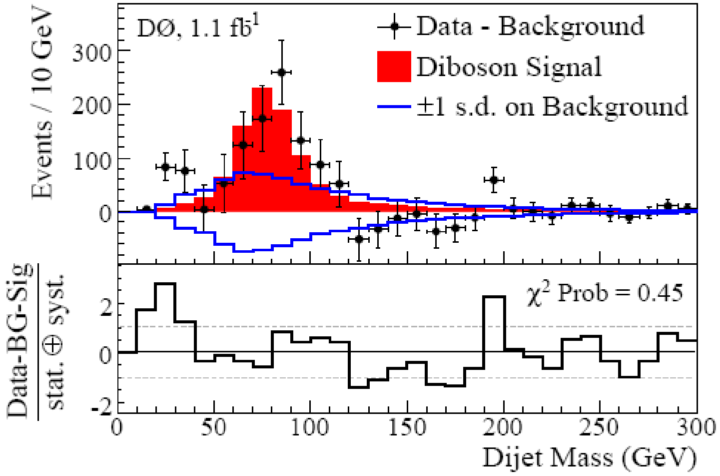
Catani-Seymour dipole subtraction, automated by Gleisberg, Krauss, 0709.2881, incorporated in **SHERPA**

W + 2 jets

D0, 0811.3873 4.4σ evidence



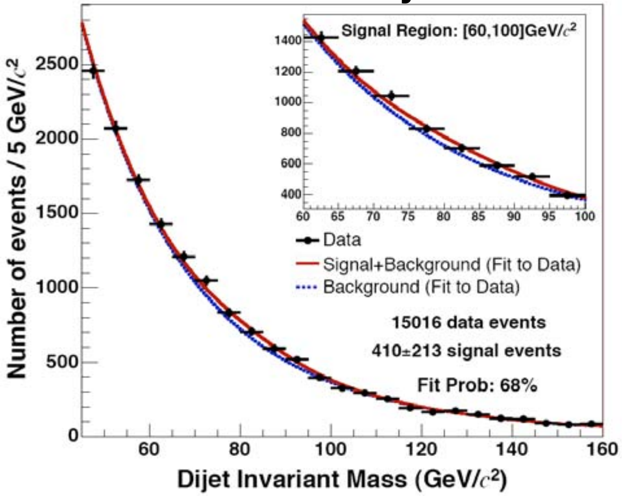
ALPGEN for shape



Background for current SM searches at the Tevatron:

- Single top (with a b tag)
- ***WW* or *WZ* with one *W/Z* → jets (warm-up for *WH* with *H* → $b\bar{b}$**

CDF, 0903.0814 “just missed”



“shape” – slope in dijet invariant mass very important