W+3 jets at NLO using BlackHat and Sherpa

Daniel Maître, IPPP Durham

in collaboration with

C. Berger, Z. Bern, L. Dixon, F. Febres Cordero, D. Forde,
H. Ita, D. Kosower
T. Gleisberg

RADCOR 2009, Ascona, 26 October 2009

Blackhat+Sherpa

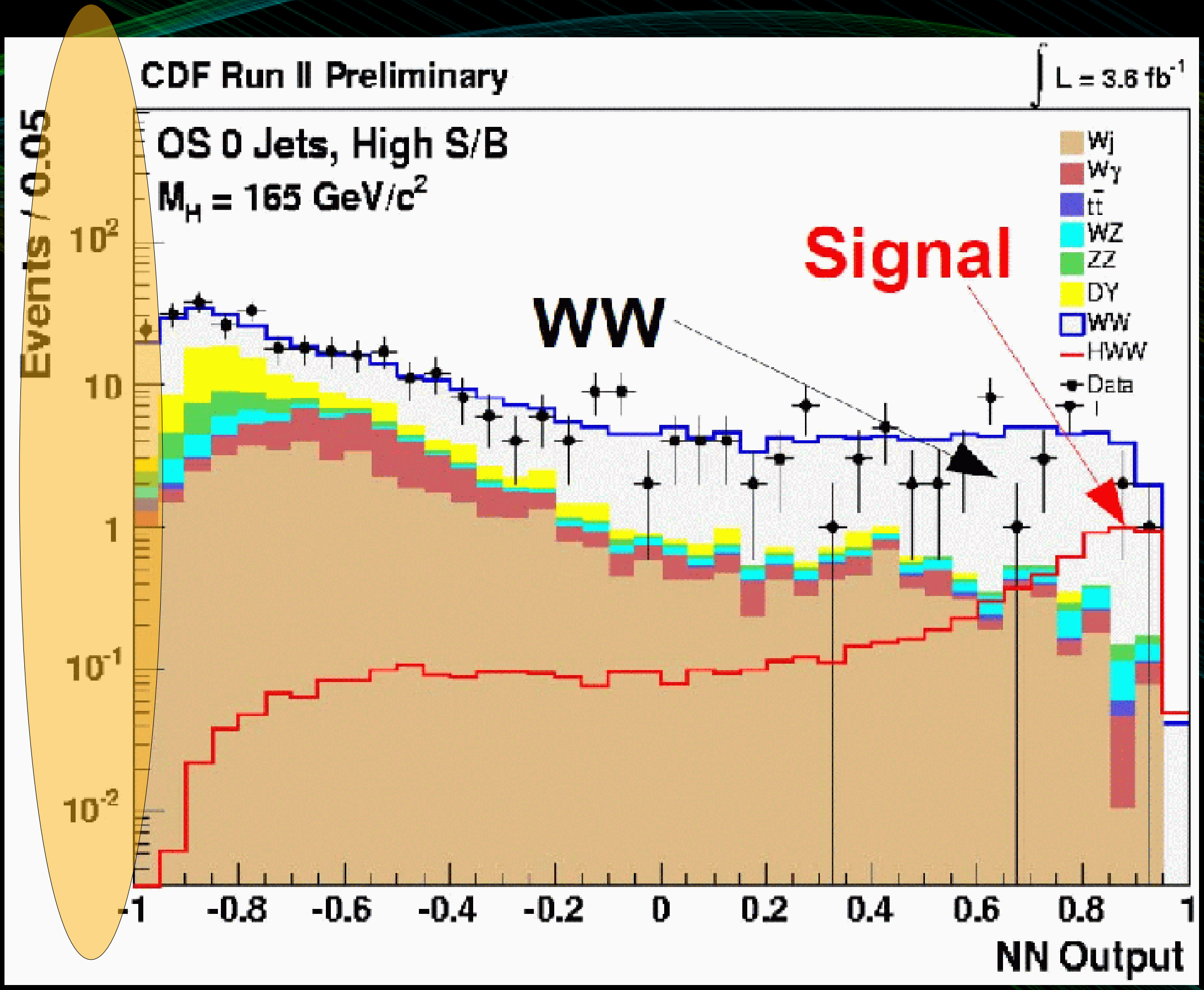
Motivation

Theoretical predictions for QCD processes are crucial for the physics program at a hadron collider

- Signal
- Background
- Many measurements are limited by theory
- Some (most) theory predictions need to be improved!

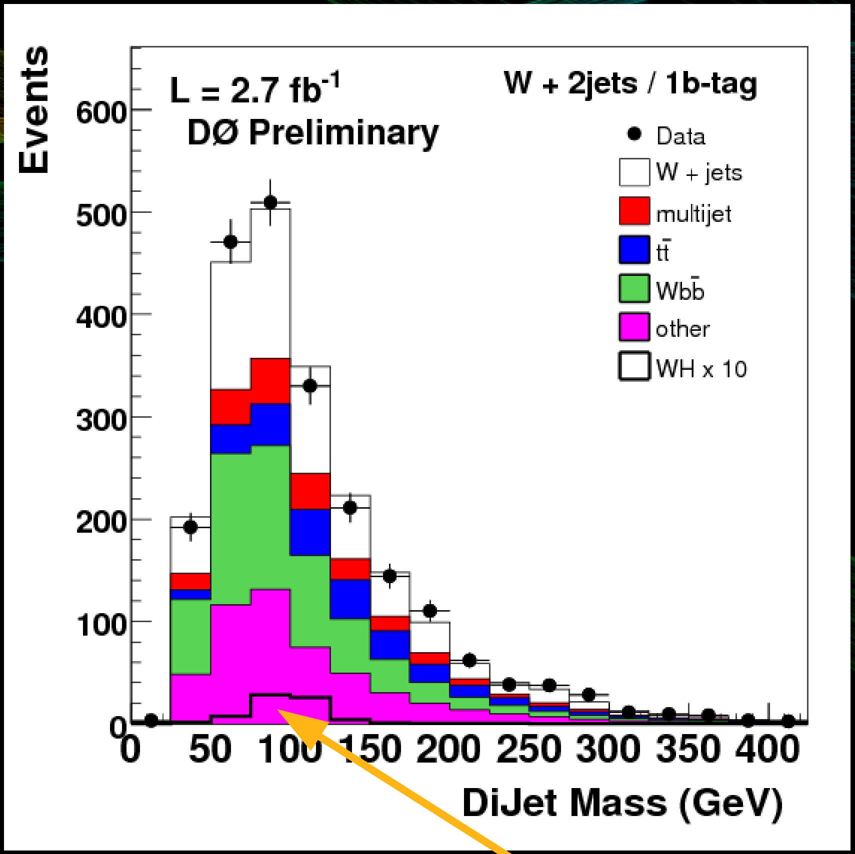
Motivation

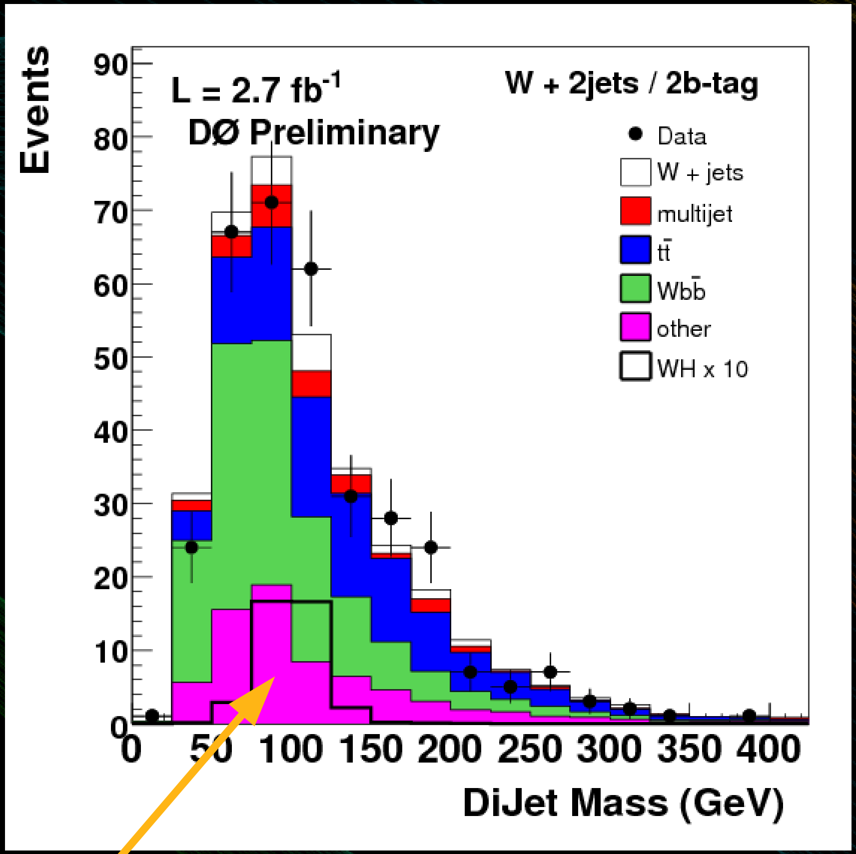
Higgs →WW search @ CDF



Motivation

Higgs associated production WH ($H \rightarrow b\bar{b}$)

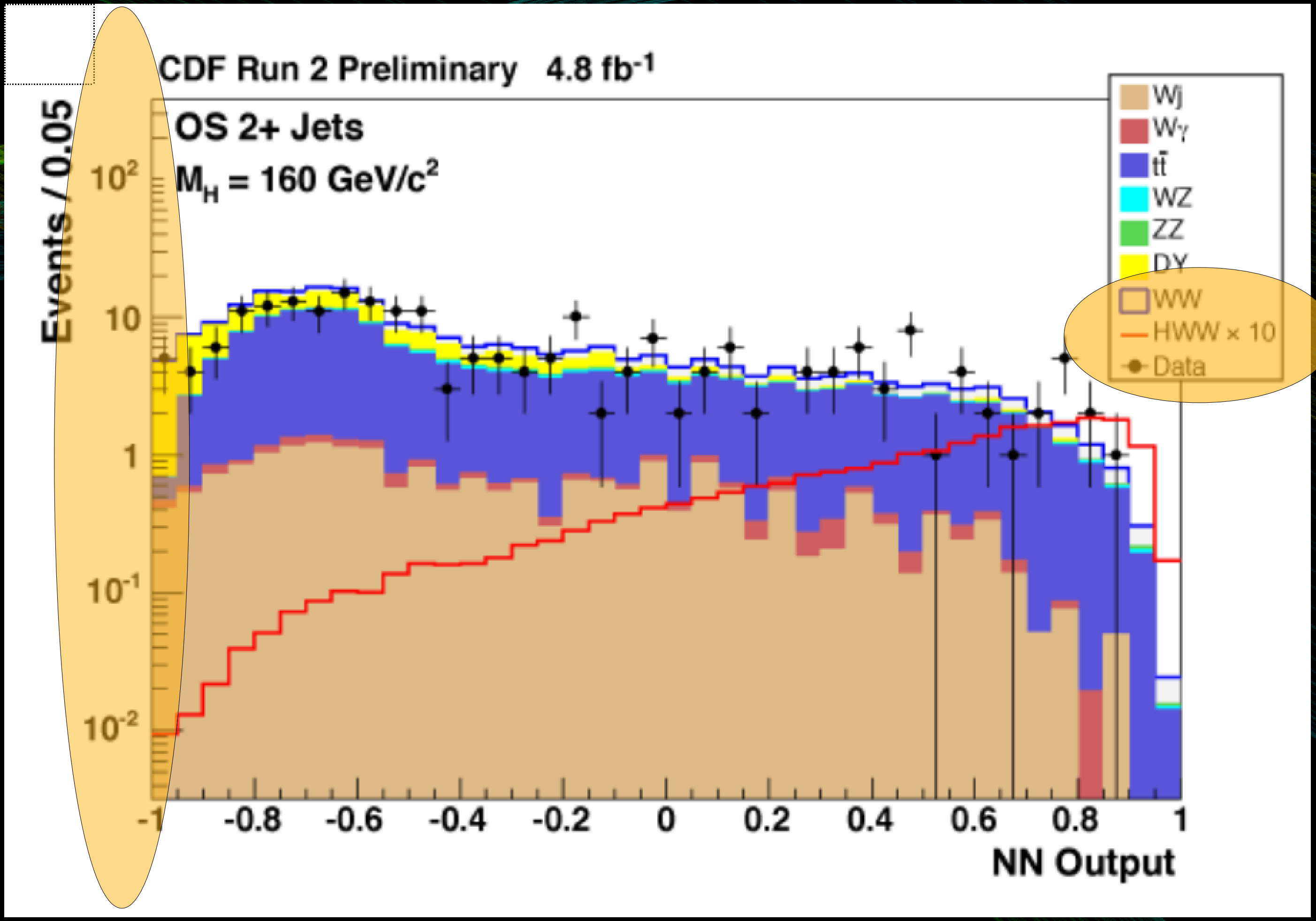




Signal x 10

Motivation

Higgs search HWW



NLO Corrections

NLO corrections are needed for a good theoretical understanding of QCD processes

Improve theory prediction for

- Absolute normalization
- Corrections can be very large
- Reduce renormalization scale dependency

Number of jets	LO	NLO
1	16%	7%
2	30%	10%
3	42%	12%

- Shape of distributions

NLO Corrections

NLO Cross section:

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \sigma_n^{virt} + \int_{n+1} \sigma_{n+1}^{real}$$

Real & virtual corrections have infrared divergences

- Combination is free of infrared divergences
- The cancellation is between objects living in two different phase spaces

NLO Subtraction

Introduce subtraction term σ_{n+1}^{sub}

- Same soft/collinear singularity structure as n+1 MEs

$$\int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right) \text{ is finite}$$

- Easy enough to be integrated over the singular PS

$$\int_{n+1} \sigma_{n+1}^{sub} = \int_{n} \int_{1} \sigma_{n+1}^{sub} = \int_{n} \Sigma_{n}^{sub}$$

- (numerical) NLO cross section

$$\sigma_{n}^{NLO} = \int_{n} \sigma_{n}^{tree} + \int_{n} \left(\sigma_{n}^{virt} + \Sigma_{n}^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

NLO with Blackhat+Sherpa

NLO cross section

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

BlackHat

Sherpa

Sherpa

[Gleisberg,Hoeche,Krauss,Schoenherr,Schumann,Siegert,Winter]

Provides

- Efficient phase space integration
- Event generation
- Analysis framework
- Automated dipole subtraction for the real part [Catani,Seymour] [Gleisberg,Krauss]
- (and much more)
- Is written in C++

BlackHat

[Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, DM]

- Goal : automate computation of virtual 1-loop amplitudes for QCD processes
- C++ framework
- Uses new progress in the unitarity techniques, spinor formalism, complex momenta
  [Ossola,Papadopoulos,Pittau;Forde]
- Separate one-loop Amplitude into cut-containing part and rational part
- Cut containing part: 4 Dim, using Forde's method
- Use higher precision package to deal with numerical instabilities automatically [QD: Bailey,Hida,Li]

Rational Term

- Many different techniques
  - Using Specialized Feynman Diagrams
    [Xiao,Yang, Zhu; Draggiotis, Garzelli, van Hameren, Ossola, Papadopoulos, Pittau]
  - Computing the cuts in D dimensions
    - Analytic using Spinor integration
      [Anastasiou, Britto, Feng, Kunszt, Mastrolia]
    - Numerical method [Ellis,Giele,Kunszt,Mellnikov,Zanderighi]
      implemented in Rocket.
  - D-dimensionality can be seen as a mass [Badger]
    - numerical adaptation in BlackHat
- On-shell recursive approach [Berger,Bern,Dixon,Forde,Kosower]
  - implemented in BlackHat

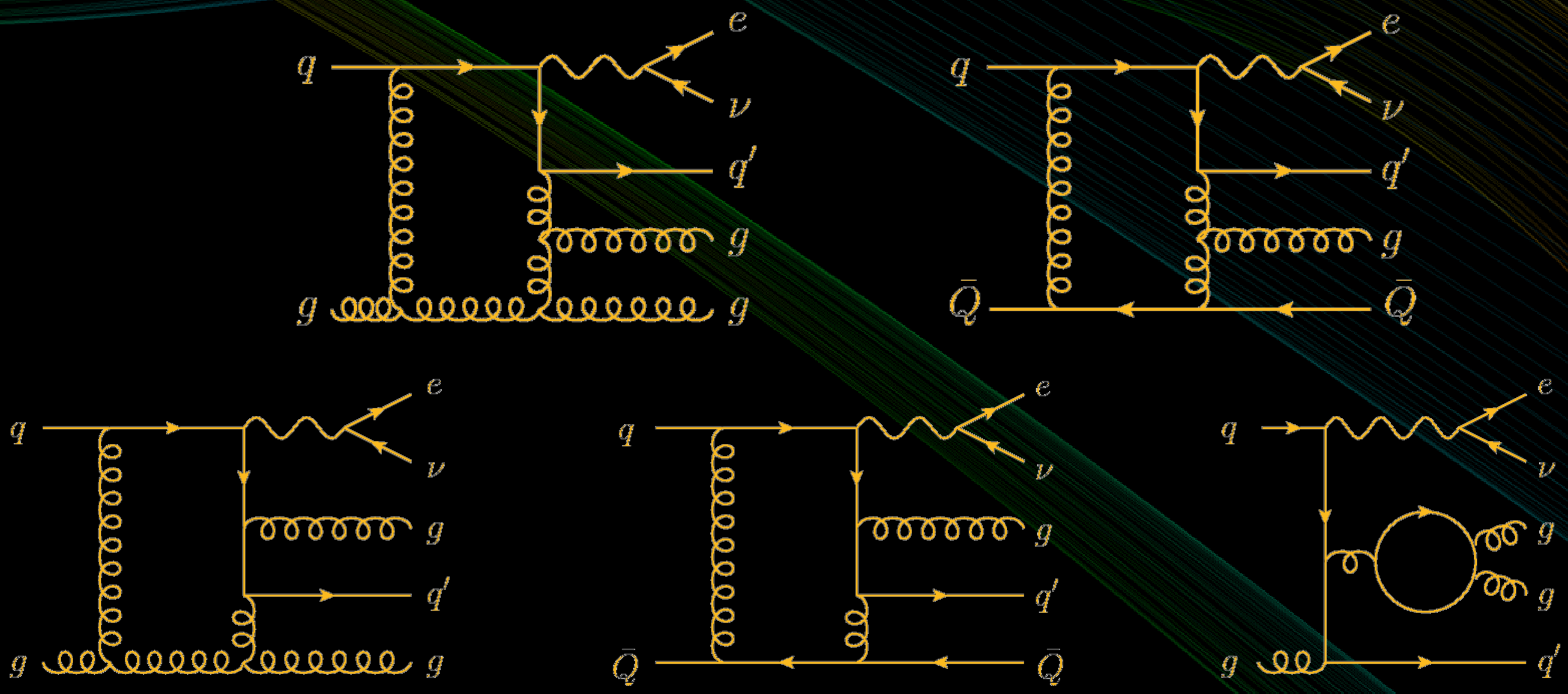
Application:

W + jets

W + jets

W/Z+jets processes are important

- For SM physics (Higgs, $t\bar{t}$, single top)
- Background to new physics
- Luminosity determination



So far

- MCFM [John Campbell, Keith Ellis]
  - NLO W+1 jet (Feynman diagrams)
  - NLO W+2 jets (amplitudes from unitarity methods)
- Amplitudes
  - Leading color primitive amplitudes (2q3gW) [BlackHat]
  - All primitive amplitudes [Ellis,Giele,Kunszt,Melnikov,Zanderighi; van Hameren,Papadopoulos,Pittau]
- Cross section
  - Leading color W+3 jets (2q3gW) [Ellis,Melnikov,Zanderighi]
  - Leading color W+3 jets (all subprocesses) [BlackHat]
  - Leading color W+3 jets (with rescaling to account for subleading color) [Ellis,Melnikov,Zanderighi]
  - Full color W+3 jets (all subprocesses) [BlackHat]

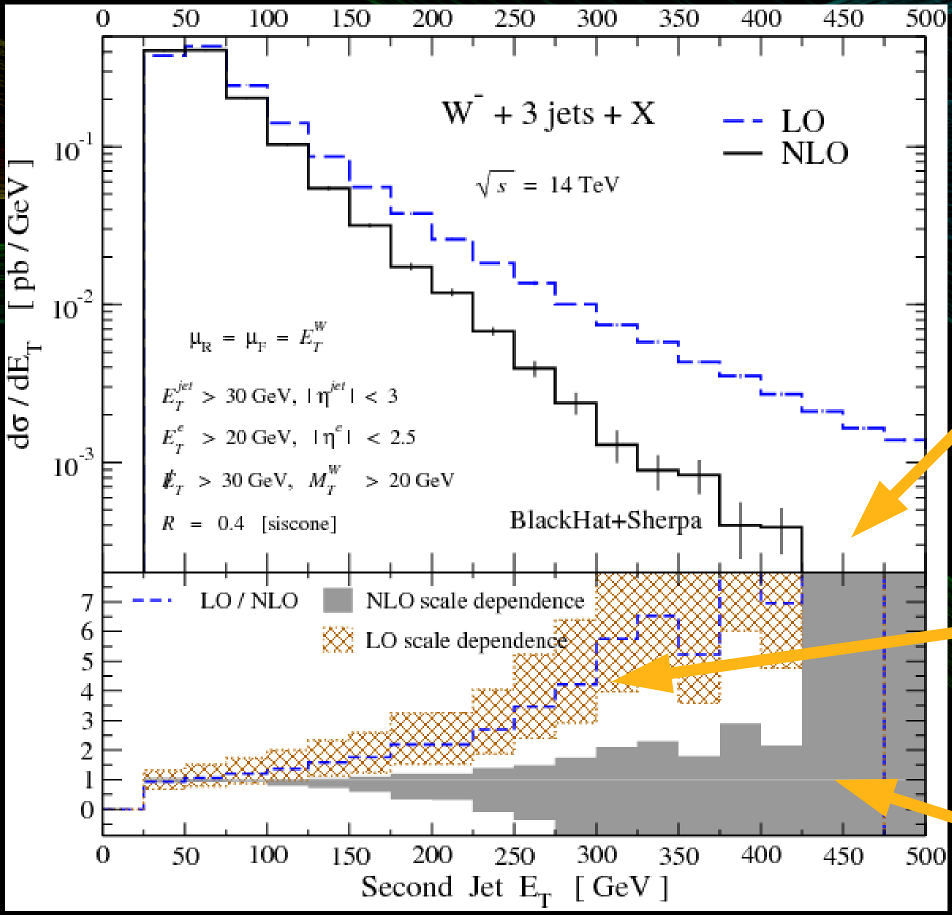
W+3 jets at the LHC

Scale choice

- Theory predictions depend on two unphysical scales
  - Renormalization scale
  - Factorization scale
- Due to the truncation of the perturbation series
- Want to choose a scale “typical” for the process
- Complicated processes have many scales
- Good choice of scale
  - Cross sections and distributions should be positive
  - LO has a shape close to the NLO one

Scale choice

Poorly chosen scale has consequences



Differential cross section becomes negative

Large K factor and large dependence of the K factor

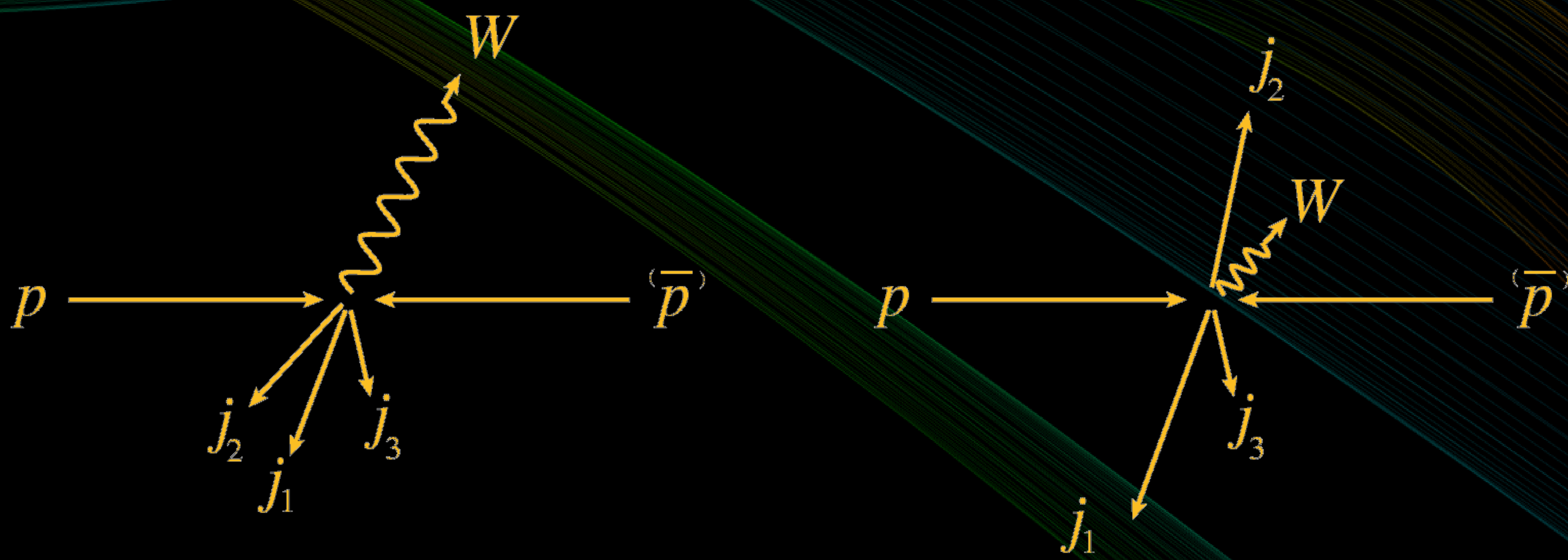
Large growth of the scale dependence of the NLO

$$E_T^W = \sqrt{m_W^2 + p_T^2(W)}$$

Scale choice

Possible scale choice

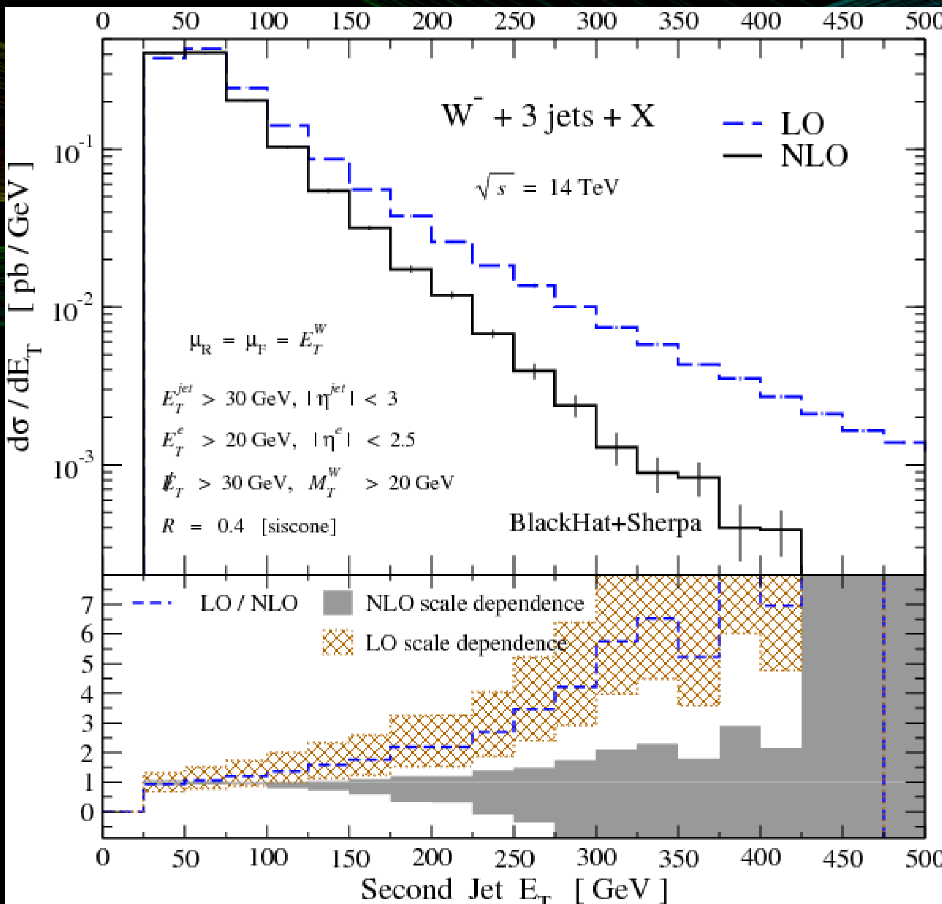
$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\mathrm{jet}} + E_T^e + \not{E}_T$$

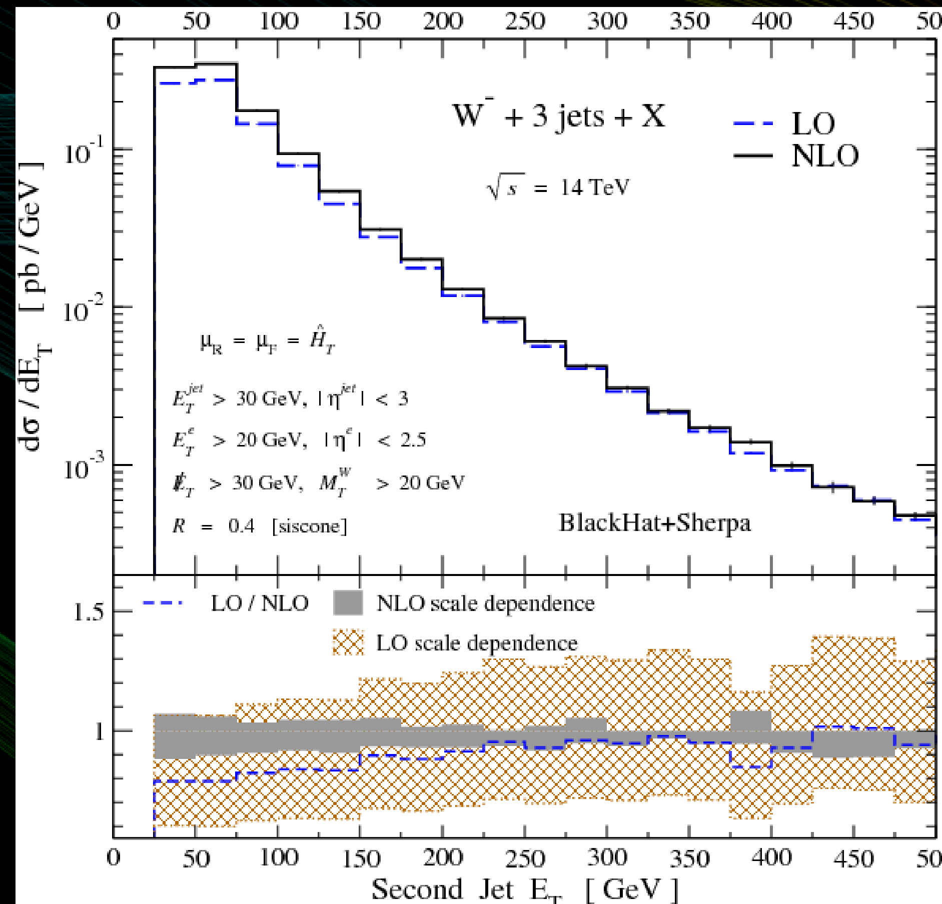


(a) (b)

Scale choice

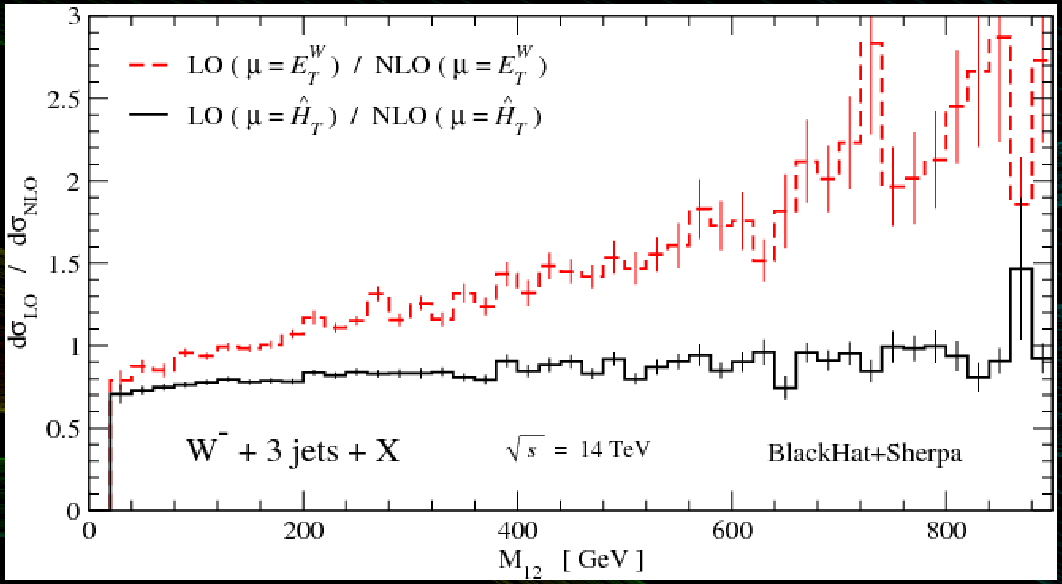
Two different scale choices



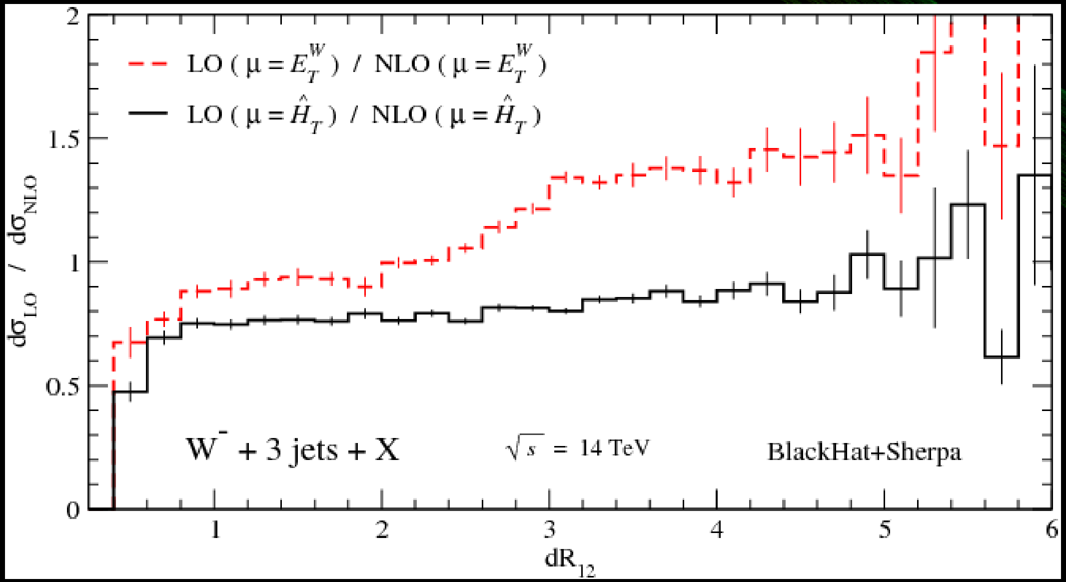


$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\rm jet} + E_T^e + \not{E}_T$$

Scale choice



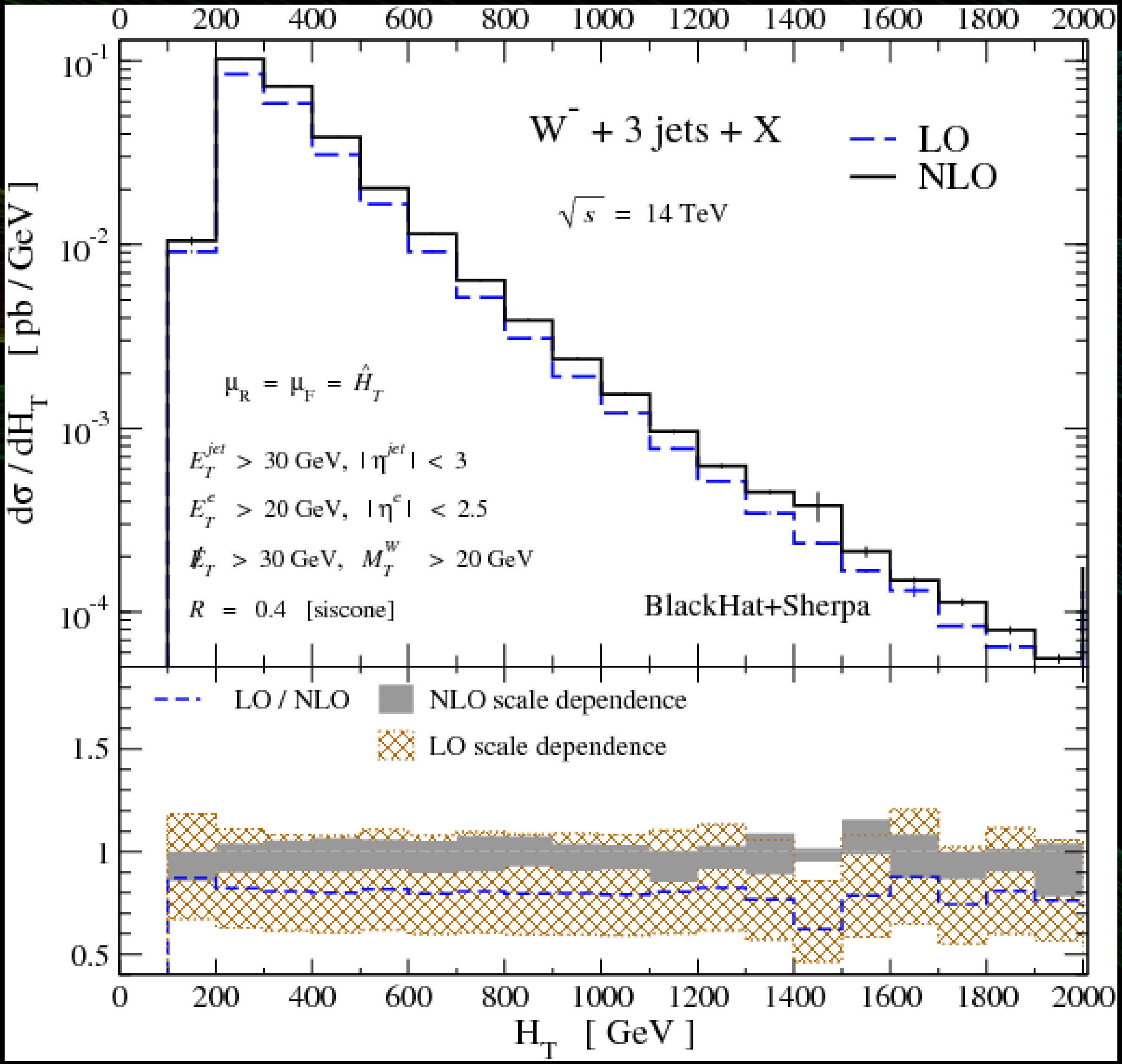
$$M_{ij}^2 = (p_i^{\text{jet}} + p_j^{\text{jet}})^2$$



- Does not work for all distributions!
- Distributions that are specifically sensitive to the W
- Choice of scale has more effect at LHC, but visible at Tevatron

$$\Delta R_{12} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

W+3 jets @ LHC



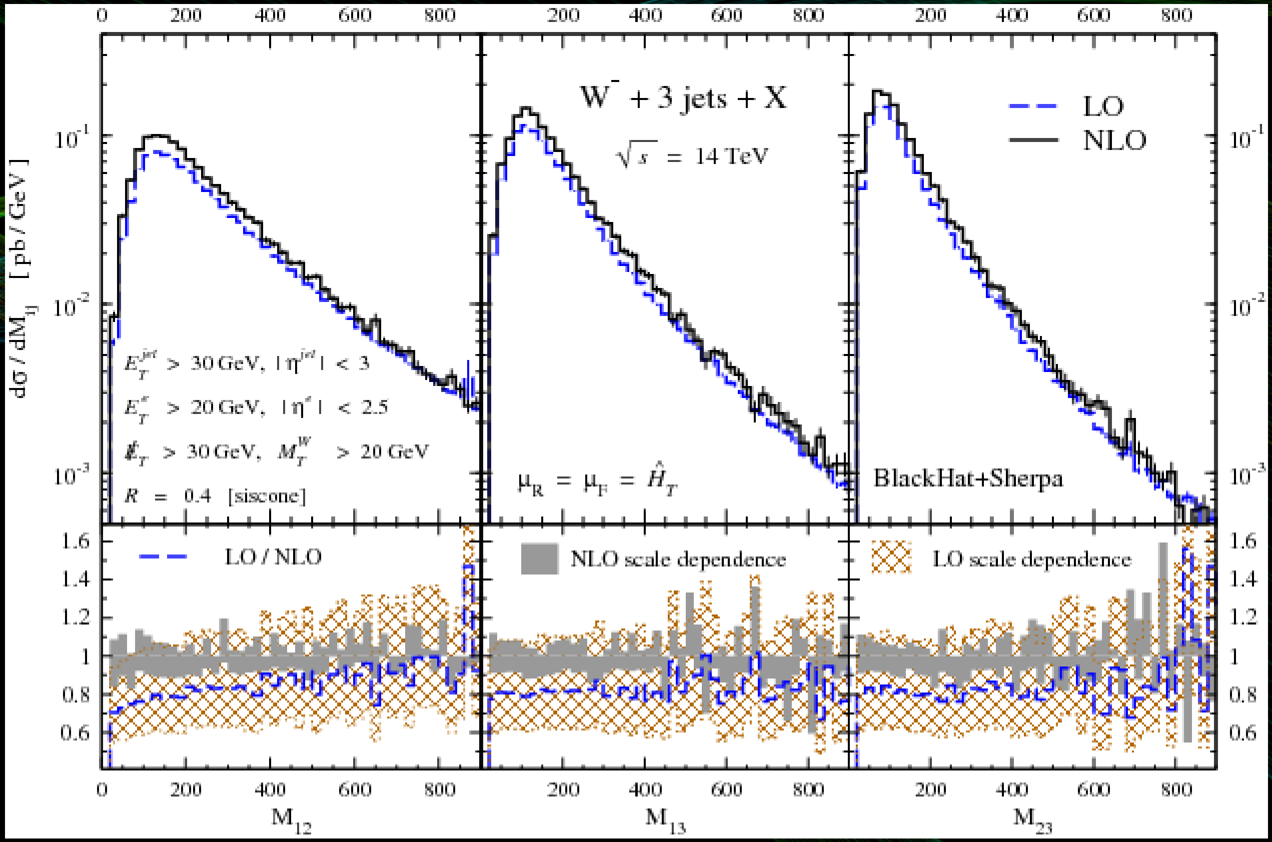
$\mu = H_T$

PDF: CTEQ6M

Jet algorithm: SISCone [Salam,Soyez]

W+3 jets @ LHC

$$M_{ij}^2 = (p_i^{\text{jet}} + p_j^{\text{jet}})^2$$



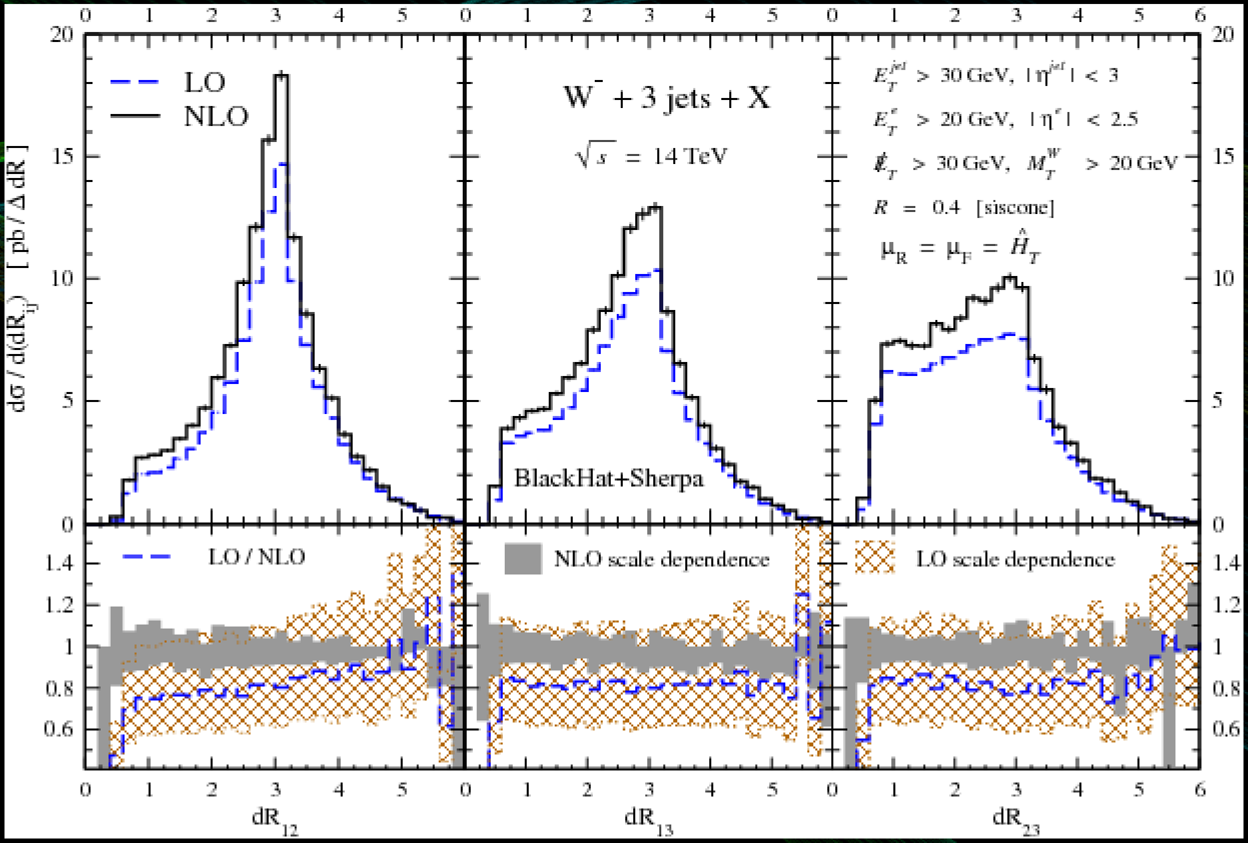
$$\mu = H_T$$

PDF: CTEQ6M

Jet algorithm: SISCone [Salam,Soyez]

W+3 jets @ LHC

$$\Delta R_{ij} = \sqrt{(\Delta\phi_{ij})^2 + (\Delta\eta_{ij})^2}$$



$\mu = H_T$

PDF: CTEQ6M

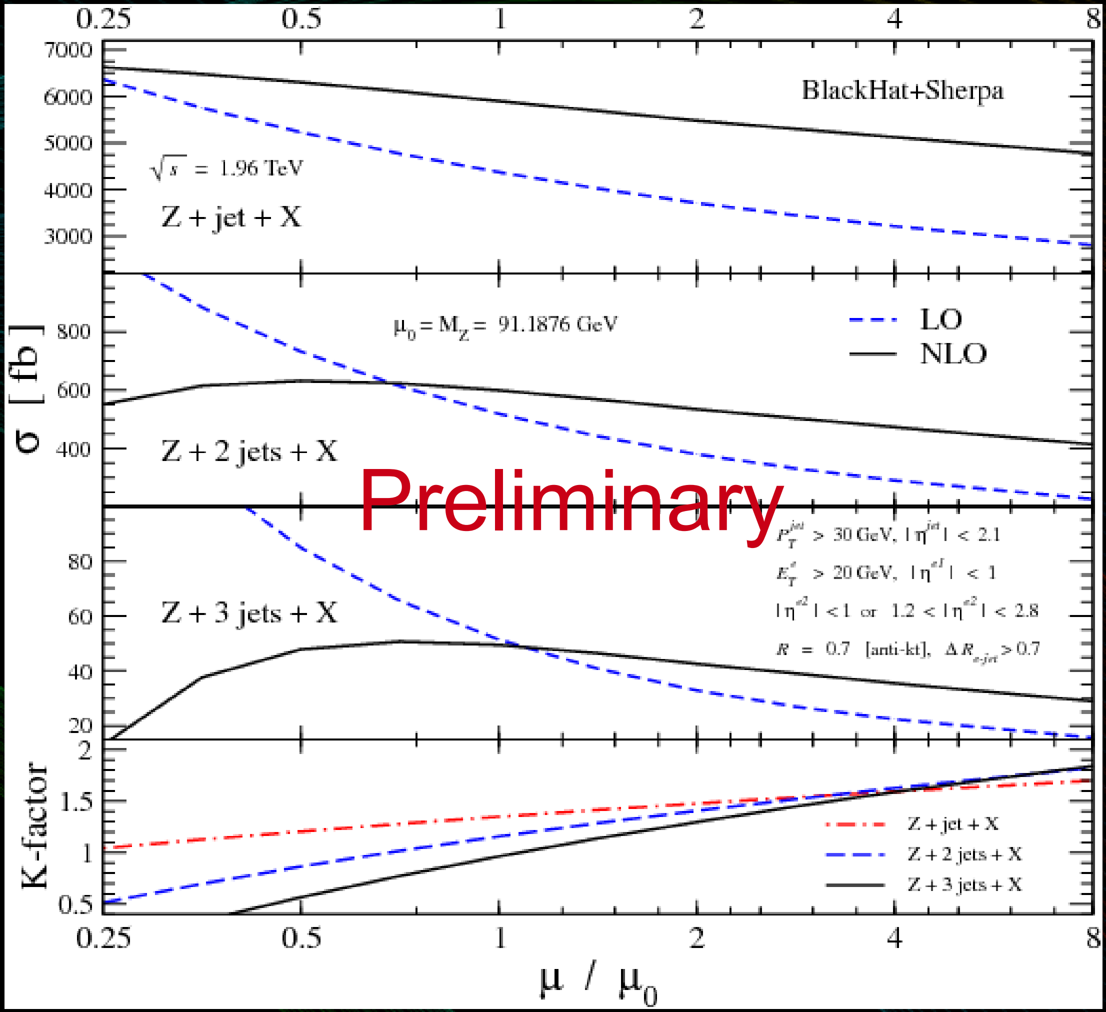
Jet algorithm: SISCone [Salam,Soyez]

The Future for BlackHat

Imminent Future

Z(e+ e-) +1,2,3 jets

- Work in progress
- Real integration is more challenging due to the interference with photon
- Virtual part is essentially the same



→ See David Kosower's talk

Near future

- Development of a maintainable public version of BlackHat, still experimental
  - First stage: Lightweight fast for some easy processes
    - $e^+e^- \to 2, 3, 4\,\mathrm{jets}$
    - $j + j \to W/Z + 0, 1, 2\,\mathrm{jets}$
  - Second stage: All tested processes
  - Both can use the proposed Les Houches interface
    - Tested with both C++ and Fortran "client" programs

Future

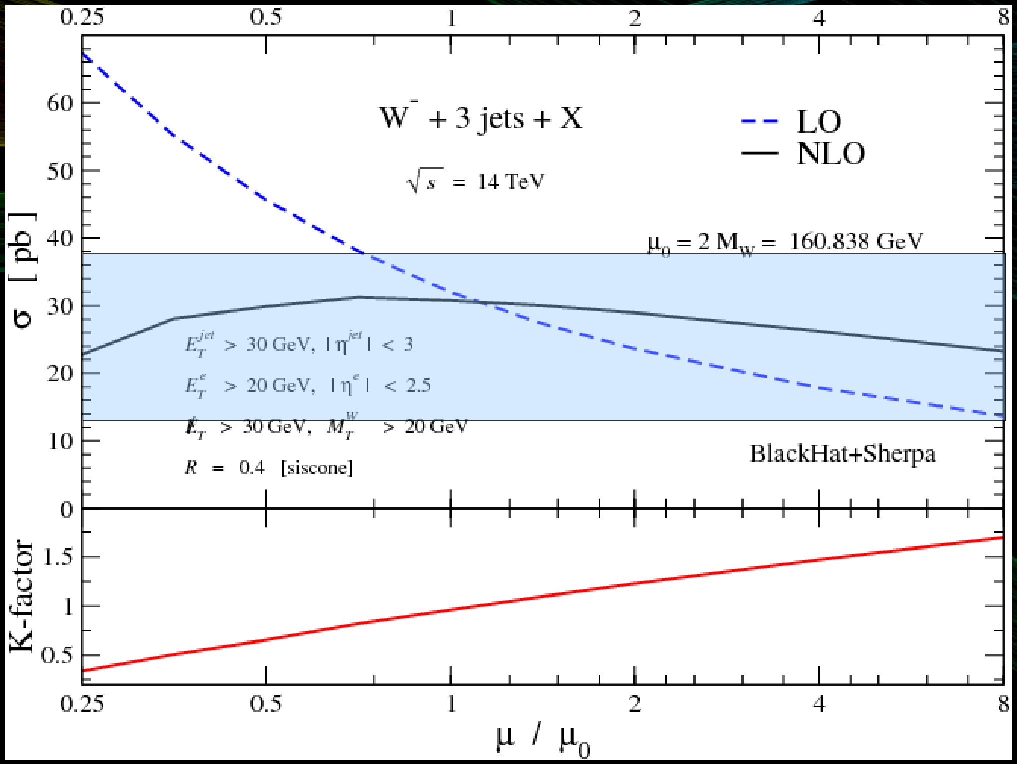
- W + 4 jets
  - Virtual part doable (but not necessarily easy...)
  - Real part more challenging
    - 8 (9) point real emission matrix elements are challenging
    - Many integration channels
    - Phase space integration very long
  - For this process, the virtual contribution is not the bottleneck anymore

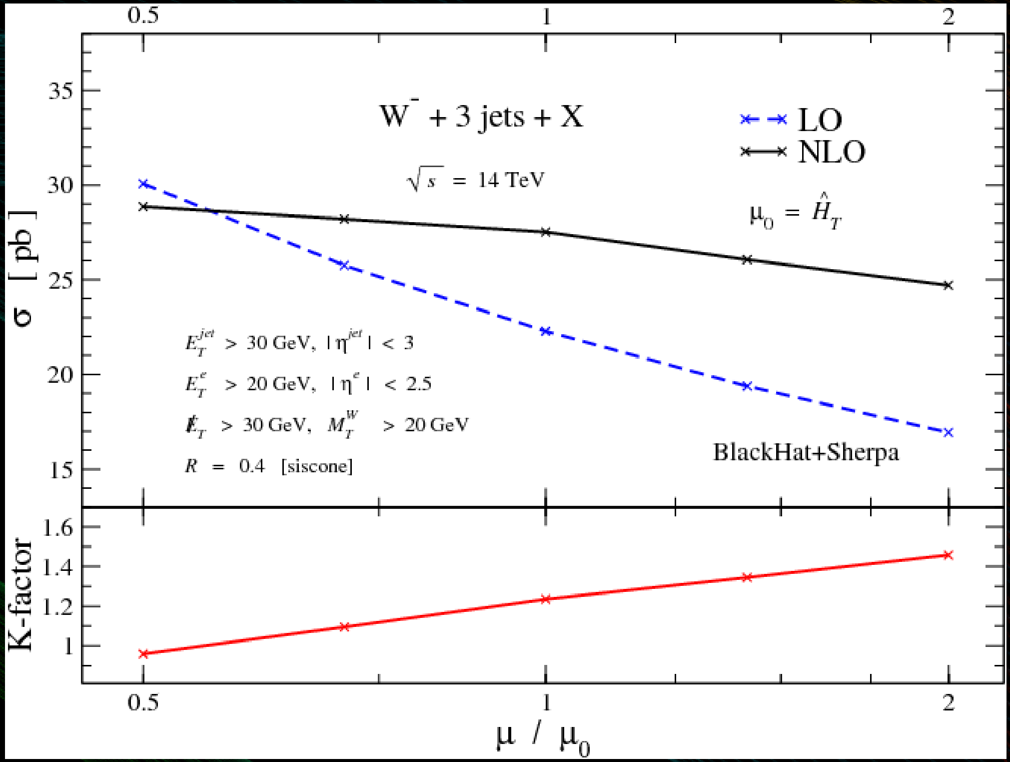
Conclusion

- Showed comparison of NLO W+3 jets and experimental data from the Tevatron
- Presented full color results for NLO W+3 jets at the Tevatron and the LHC
- Show potential of unitarity techniques for phenomenology

Scale dependence

Scale dependence of the NLO cross section is reduced compared the LO one.





Dynamic scale choice is flatter