W+3 jets at NLO using BlackHat and Sherpa

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in collaboration with

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Blackhat+Sherpa

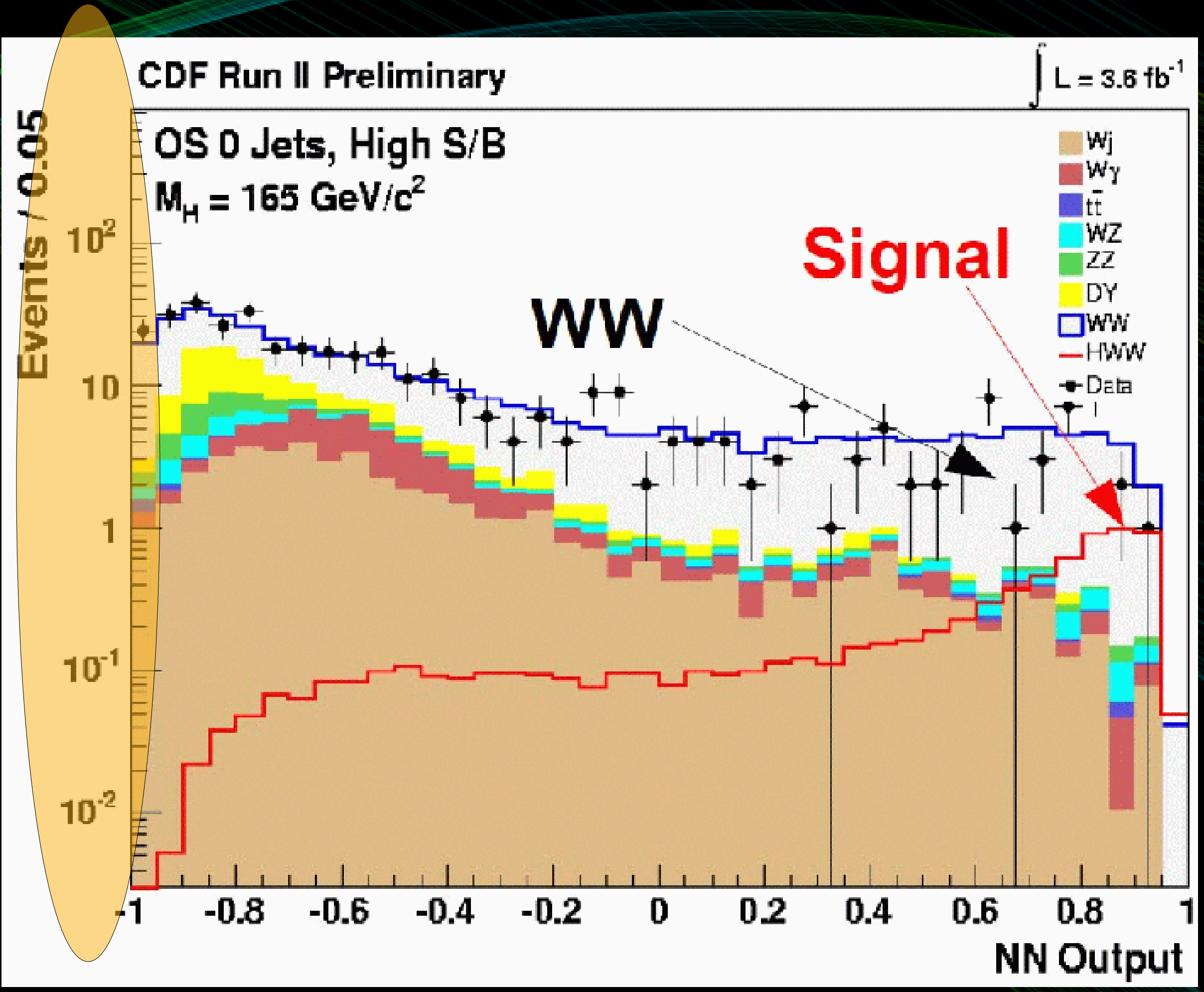
Motivation

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!

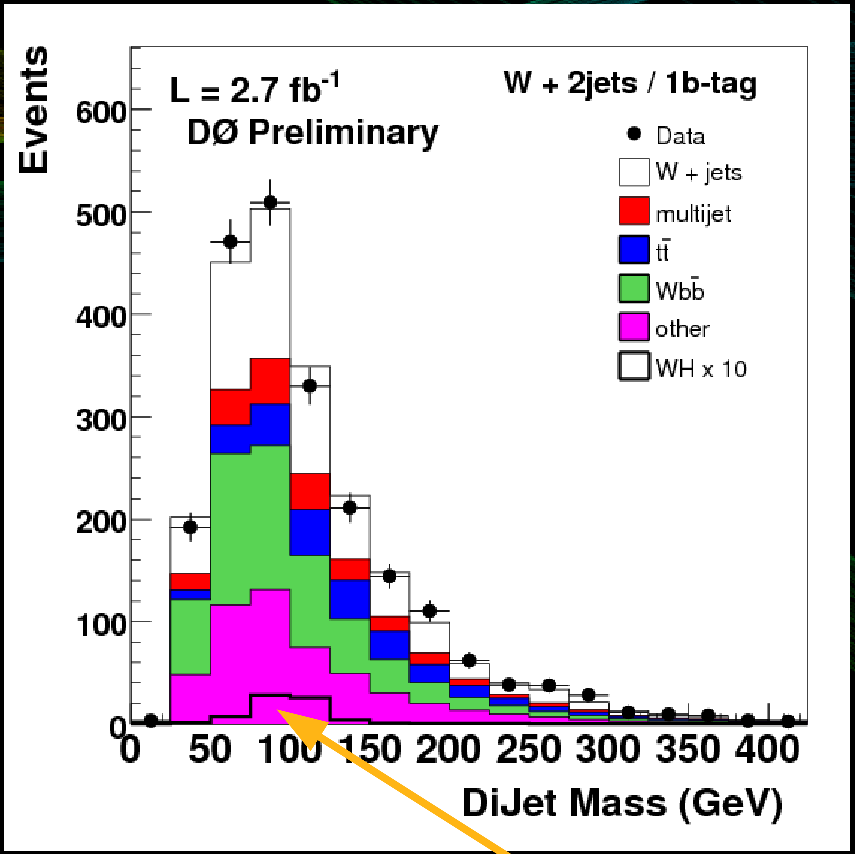
Motivation

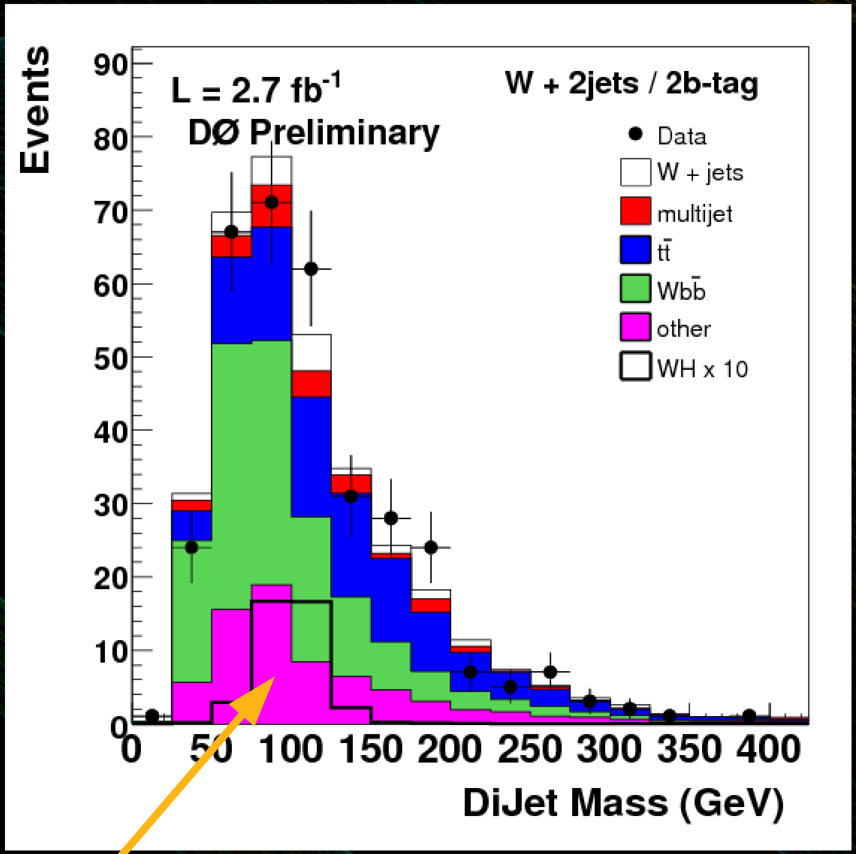
Higgs →WW search @ CDF



Motivation

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

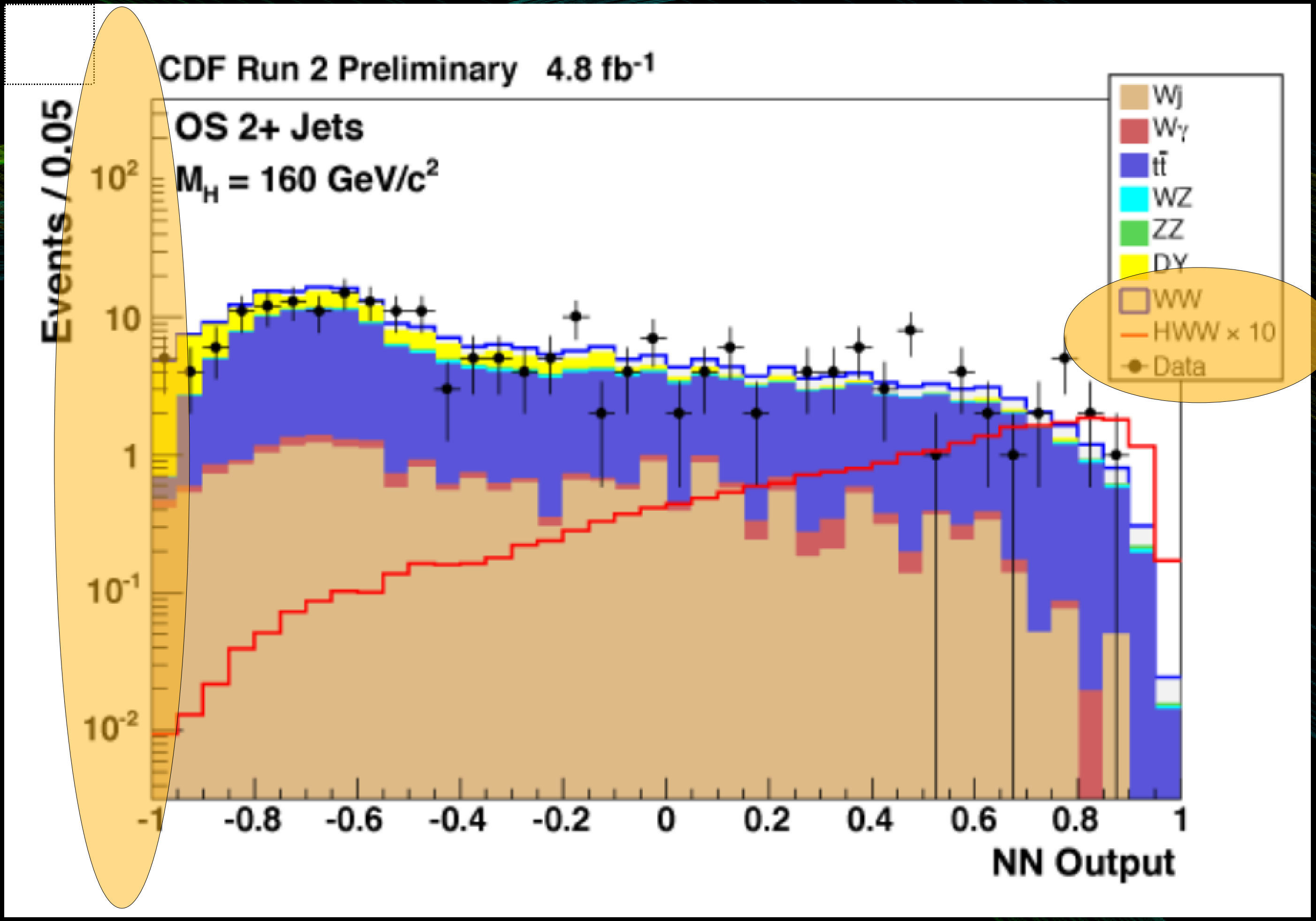




Signal x 10

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

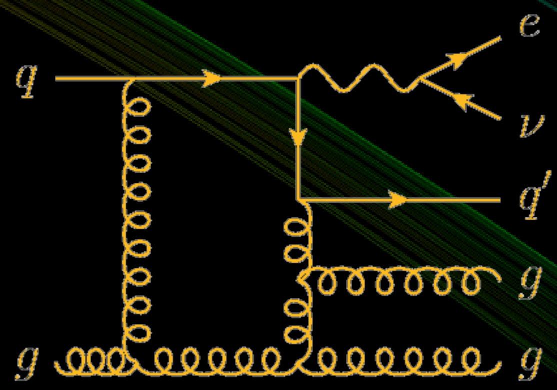
Application:

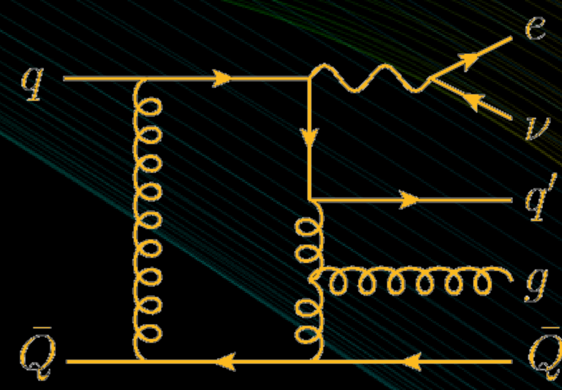
W + jets

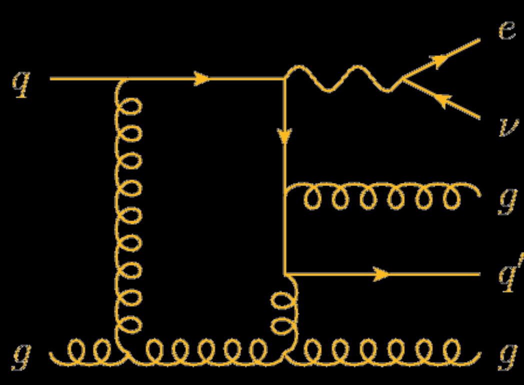
W + jets

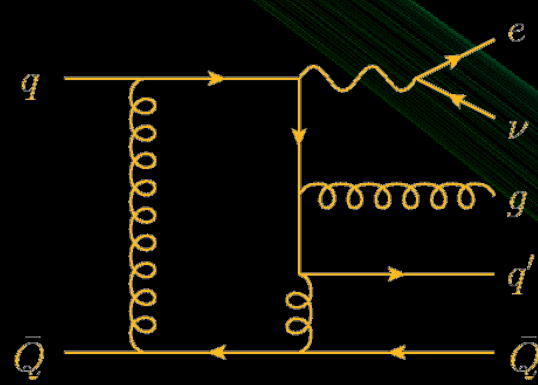
W/Z+jets processes are important

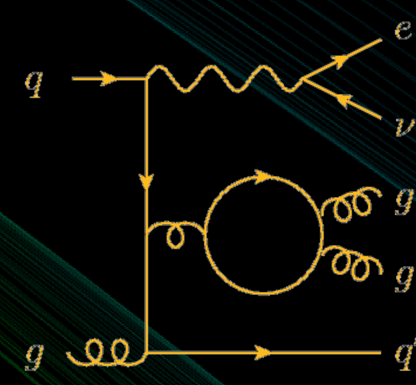
- For SM physics (Higgs, $t\bar{t}$, single top)
- Background to new physics
- Luminosity determination











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]

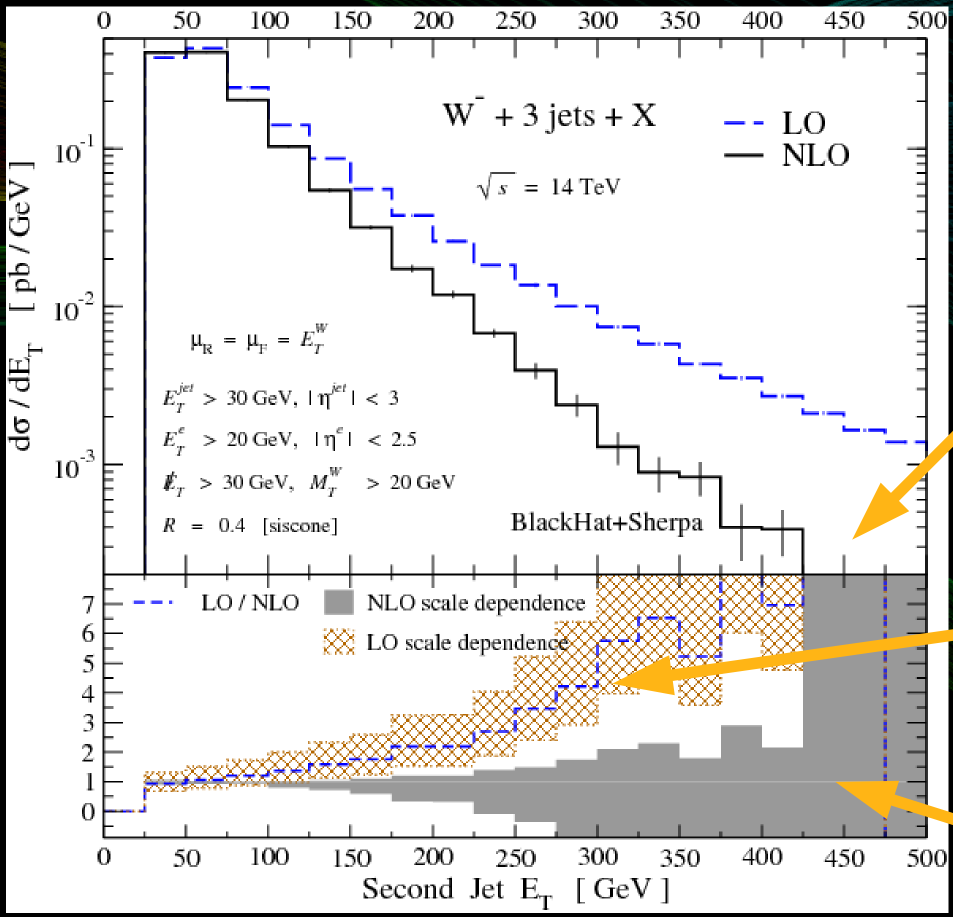
W+3 jets at the LHC

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



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

Differential cross section becomes negative

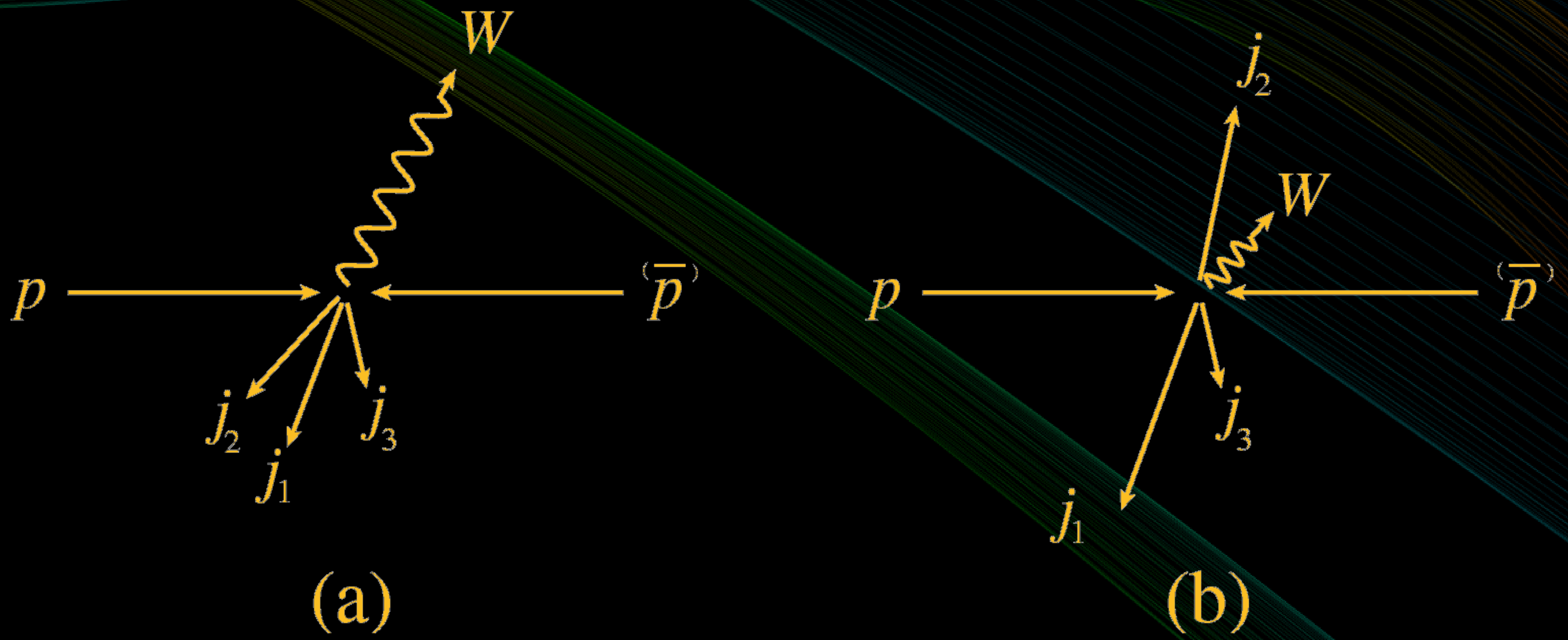
Large K factor and large dependence of the K factor

Large growth of the scale dependence of the NLO

Scale choice

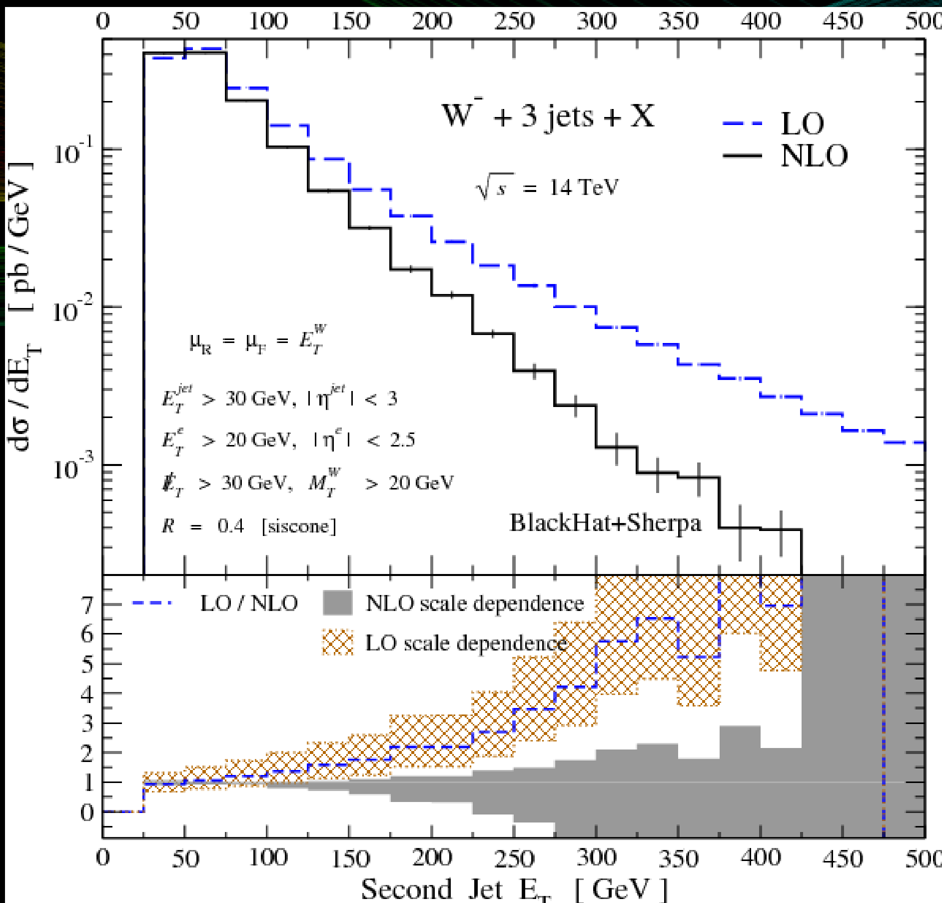
Possible scale choice

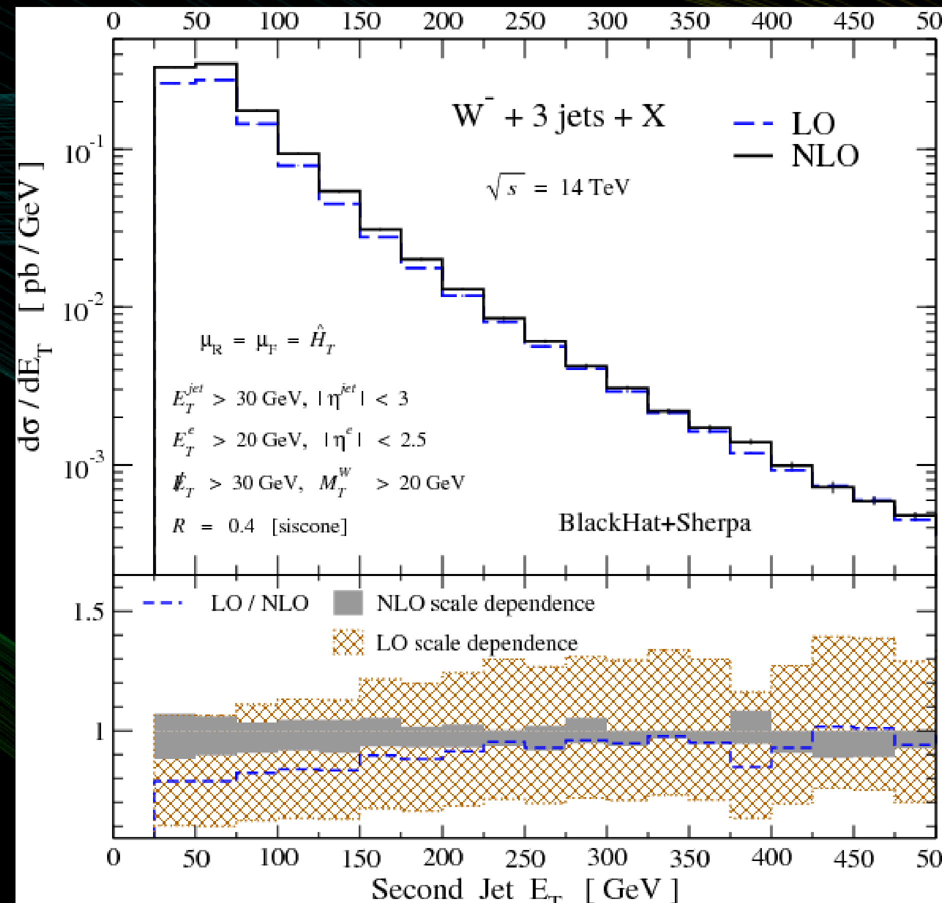
$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$$



Scale choice

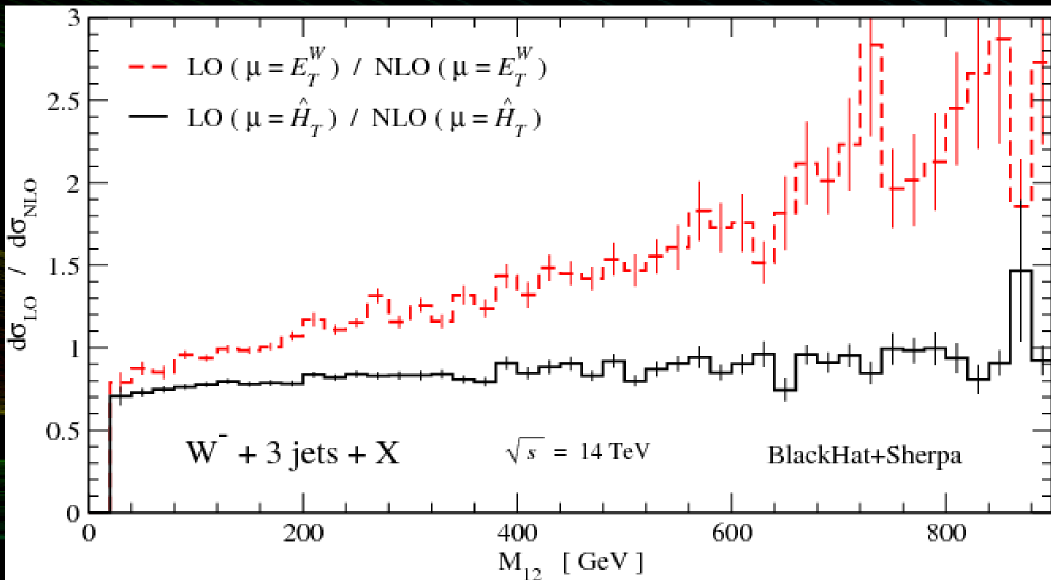
Two different scale choices



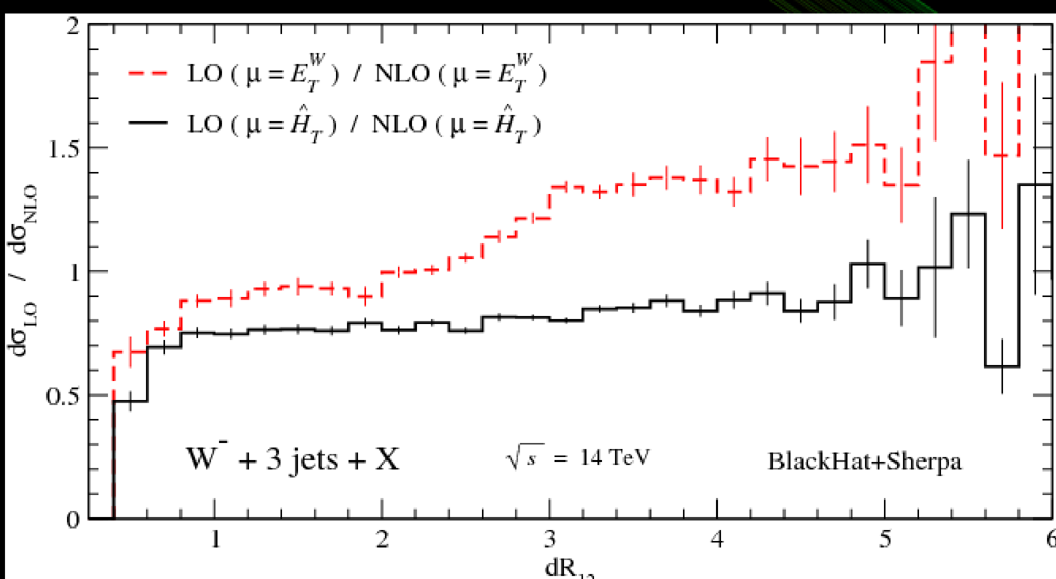


$$E_T^W = \sqrt{m_W^2 + p_T^2(W)} \qquad H_T = \sum_{j=1,2,3} E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$$

Scale choice



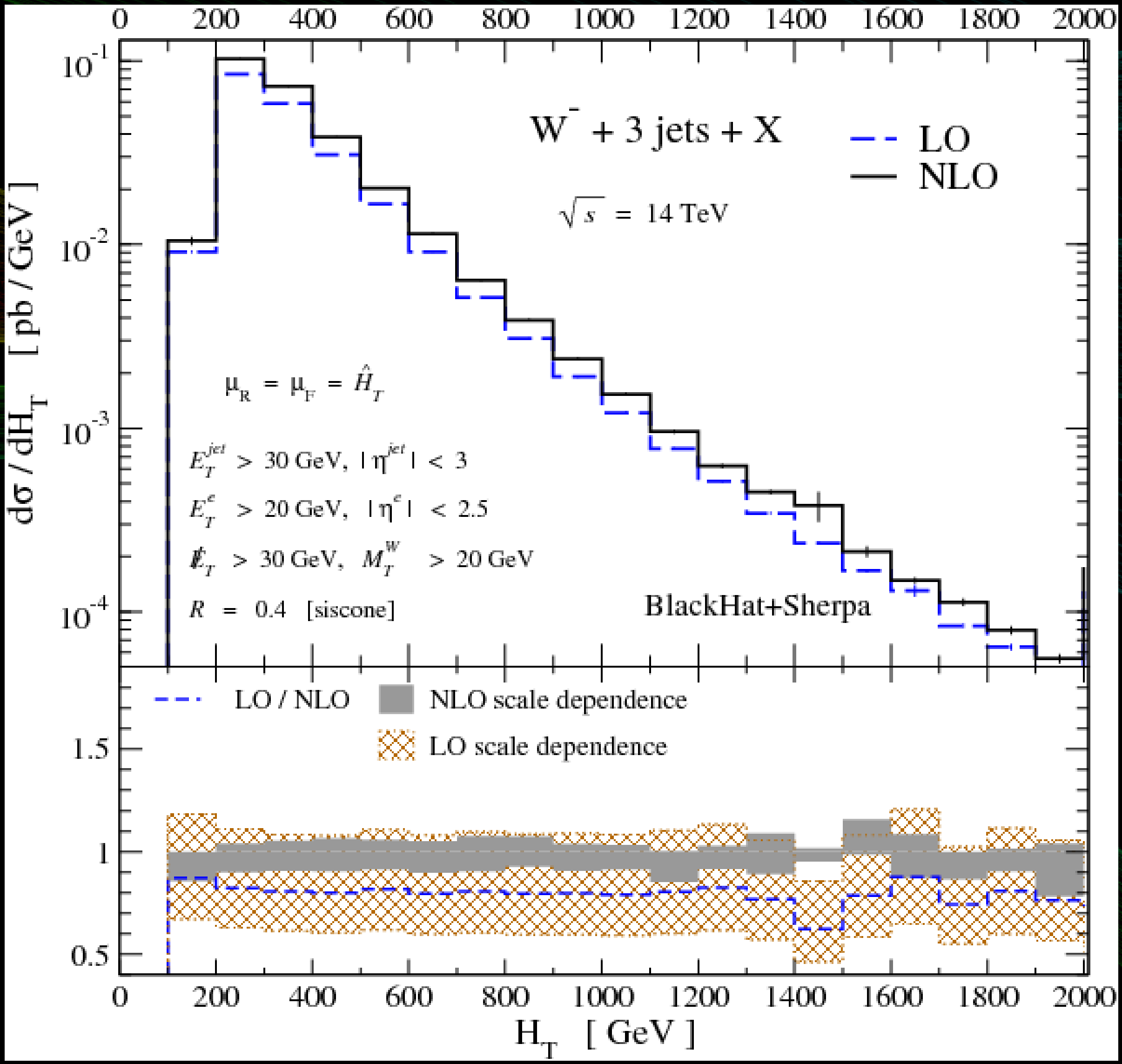
$$M_{ij}^2 = (p_i^{\text{jet}} + p_j^{\text{jet}})^2$$



- 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



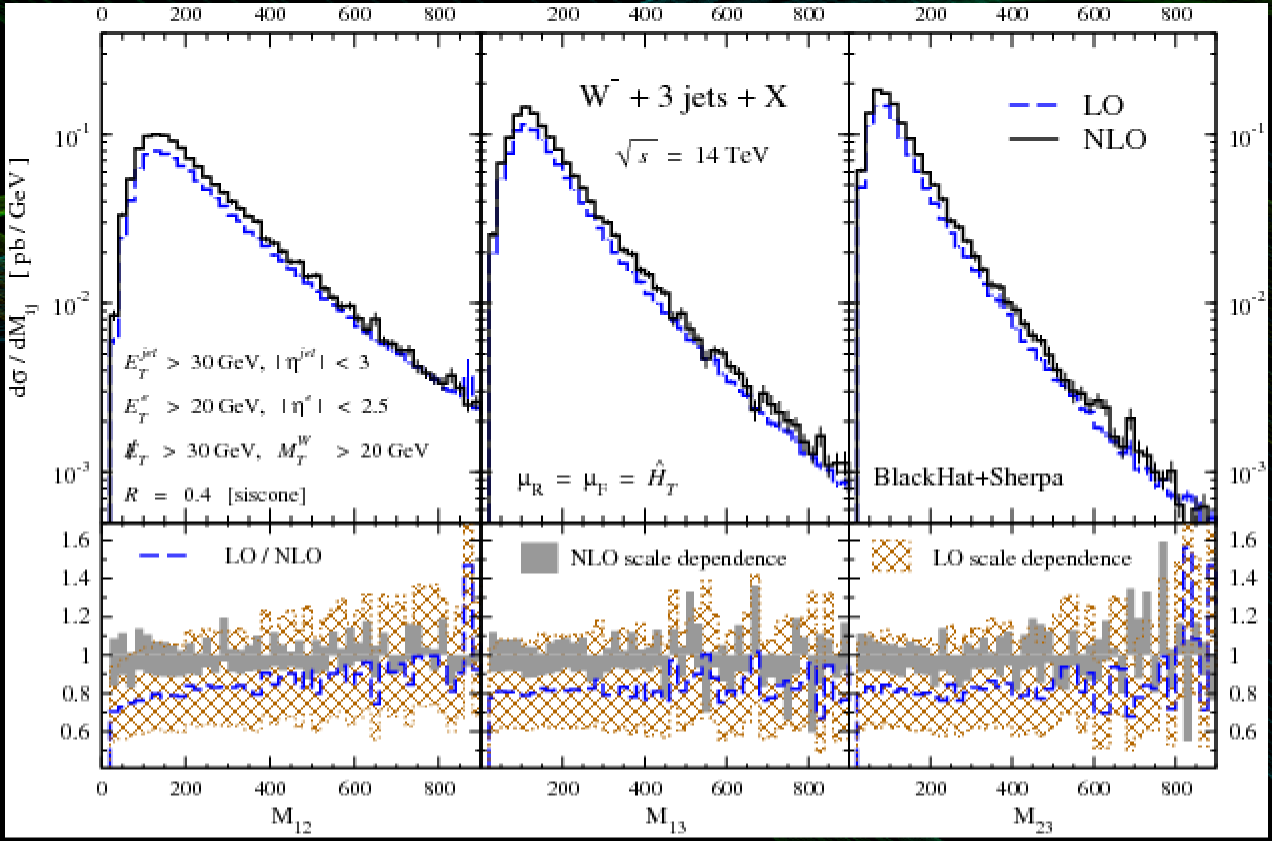
$\mu = H_T$

PDF: CTEQ6M

Jet algorithm: SISCone [Salam,Soyez]

W+3 jets @ LHC

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



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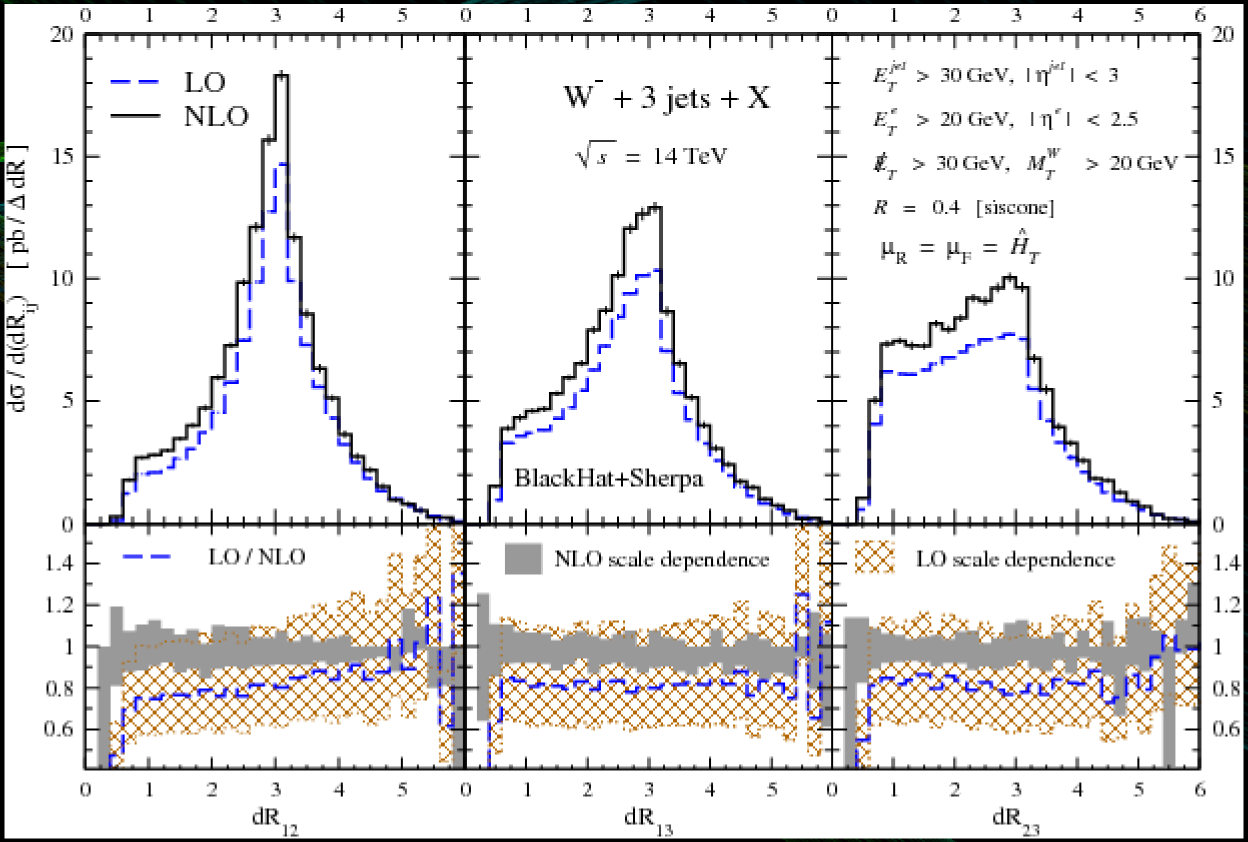
W+3 jets @ LHC

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



$$\mu = H_T$$

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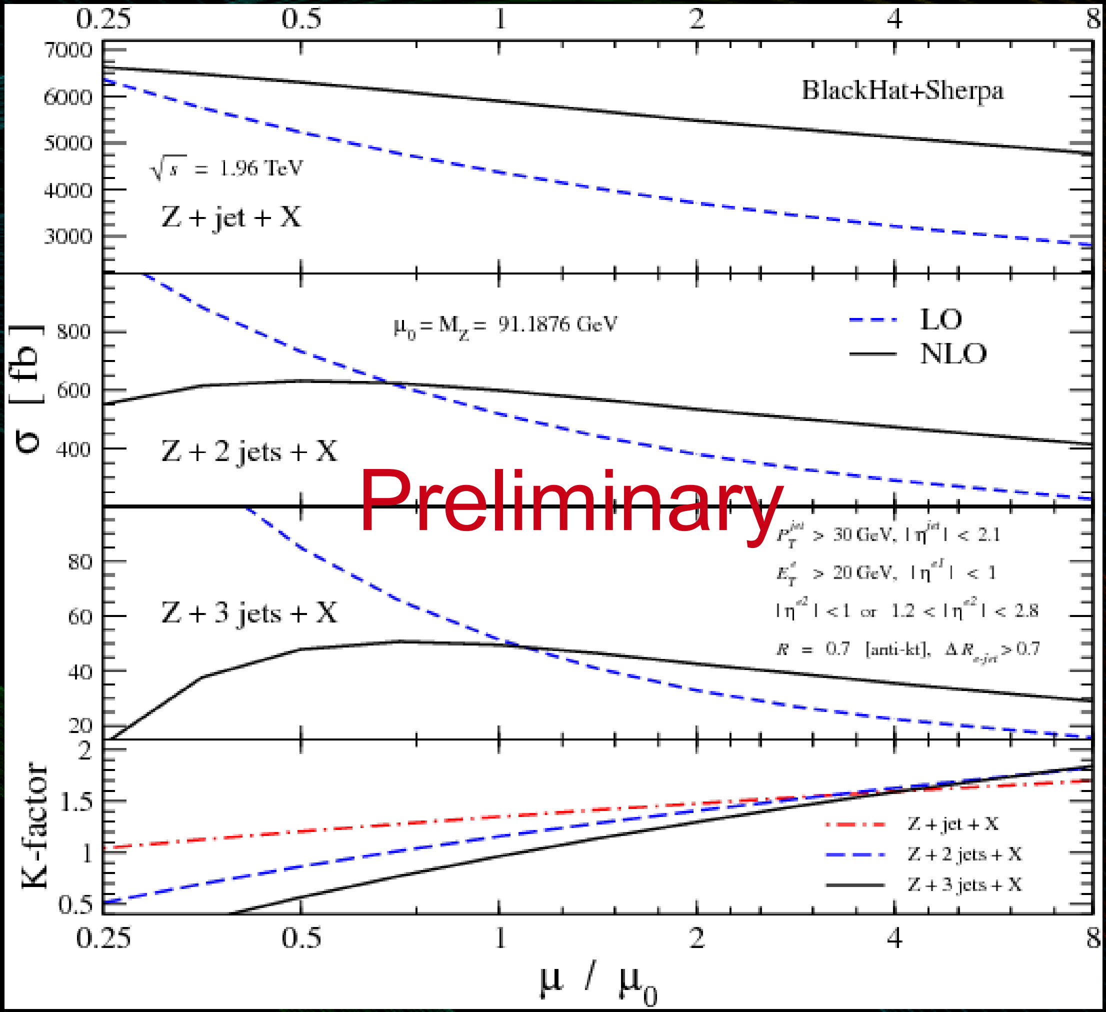
The Future for BlackHat

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
    - $e^+e^- \to 2, 3, 4\,\text{jets}$
    - $j + j \to W/Z + 0, 1, 2\,\text{jets}$
  - Second stage: All tested processes
  - Both can use the proposed Les Houches interface
    - Tested with both C++ and Fortran “client” programs

Future

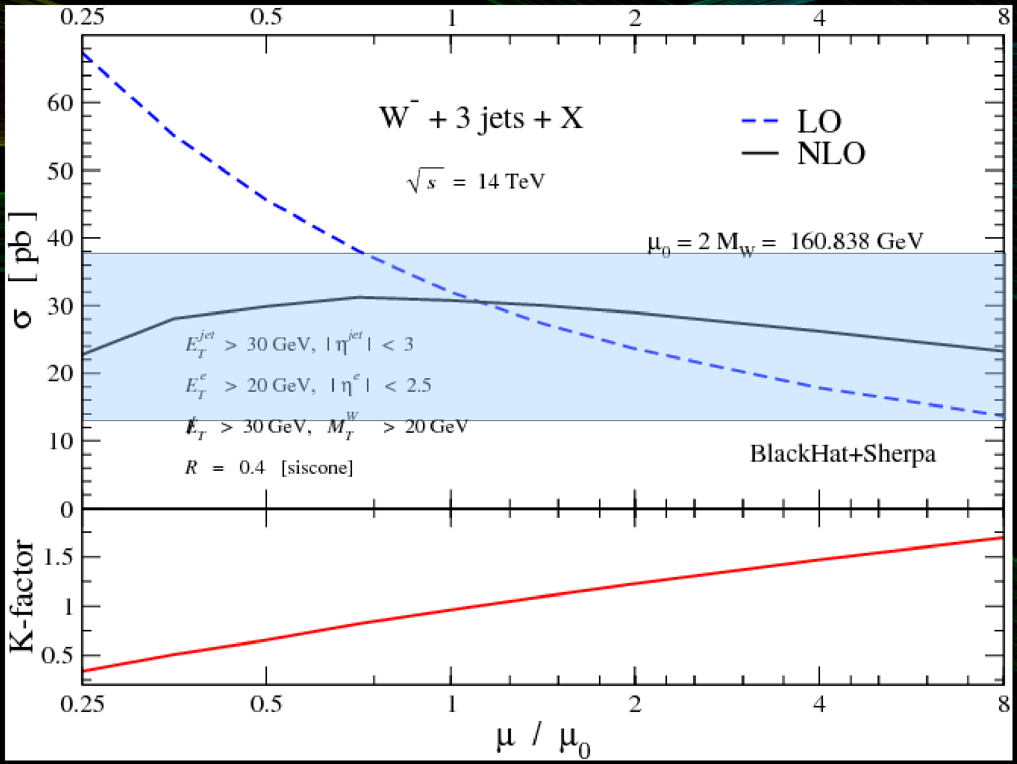
- W + 4 jets
  - Virtual part doable (but not necessarily easy...)
  - Real part more challenging
    - 8 (9) point real emission matrix elements are challenging
    - Many integration channels
    - Phase space integration very long
  - For this process, the virtual contribution is not the bottleneck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

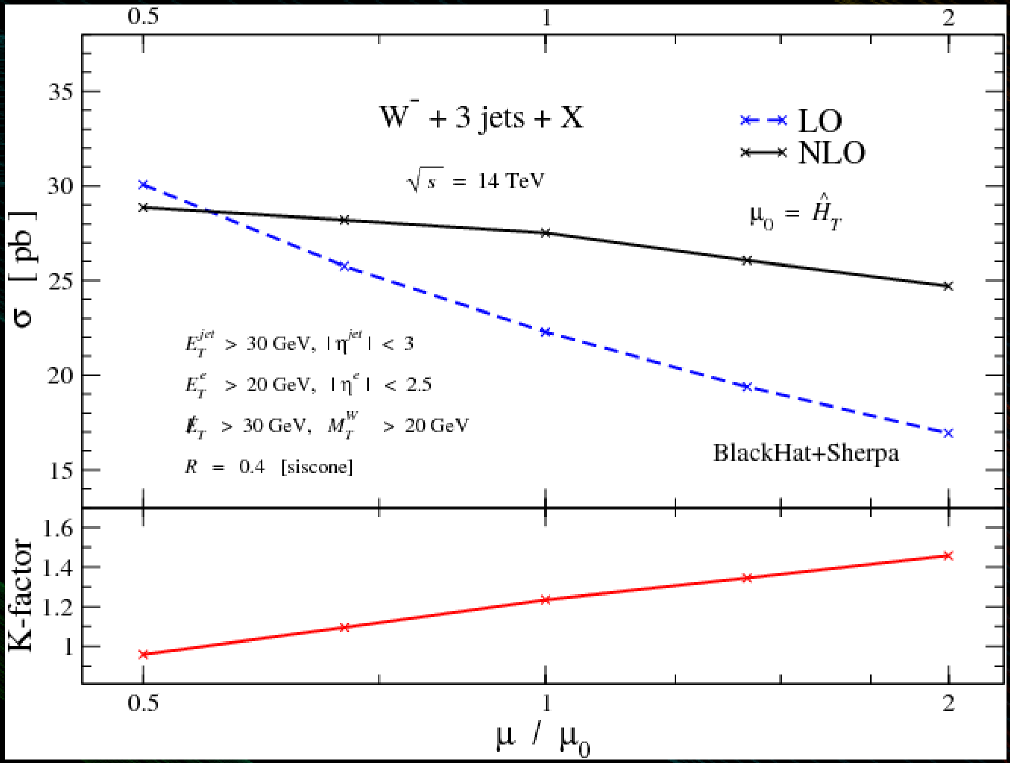
Conclusion

- Presented full color results for NLO W+3 jets at the LHC
- Show potential of unitarity techniques for phenomenology
- Future of BlackHat
  - Vector boson + jets
  - Public version

Scale dependence

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





Dynamic scale choice is flatter