# Vector-Boson + Multi-Jet Production with BlackHat

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*on behalf of the* BlackHat Collaboration
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High Precision for Hard Processes (HP2.3), Florence
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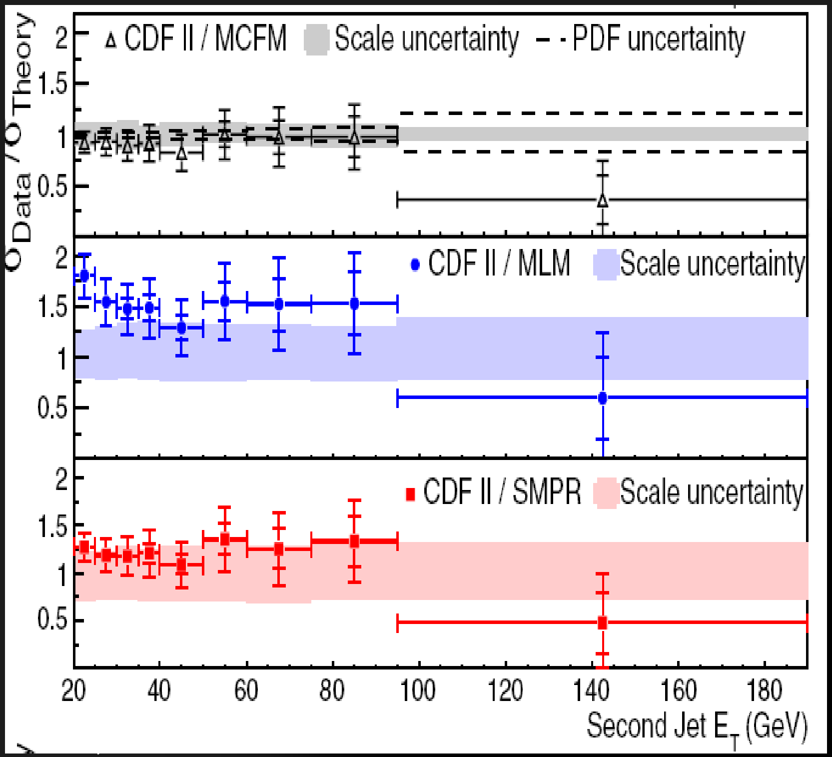
# Why NLO?

W+2 jets




- NLO (MCFM Campbell & Ellis 2002)
- PS+LO matching
- PS+LO matching

QCD at LO is not quantitative: large dependence on unphysical renormalization scale

NLO: reduced dependence, first quantitative prediction

…want this for *W*+more jets too

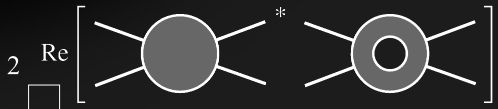
# Ingredients for NLO Calculations

- Tree-level matrix elements for LO and real-emission terms
  *known since '80s* □


- Singular (soft & collinear) behavior of tree-level amplitudes, integrals, initial-state collinear behavior *known since '90s* □
- NLO parton distributions *known since '90s* □
- General framework for numerical programs *known since '90s* □

  Catani, Seymour (1996); Giele, Glover, DAK (1993); Frixione, Kunszt, Signer (1995)

- Automating it for general processes
  Gleisberg, Krauss; Seymour, Tevlin; Hasegawa, Moch, Uwer; Frederix, Gehrmann, Greiner (2008); Frederix, Frixione, Maltoni, Stelzer (2009)
- Bottleneck: one-loop amplitudes
- *W*+2 jets (MCFM) □ *W*+3 jets □ □ □




Bern, Dixon, DAK, Weinzierl (1997–8); Campbell, Glover, Miller (1997)

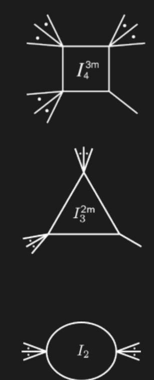
# BlackHat

- New technologies for one-loop computations: numerical implementation of on-shell methods
- Automated implementation  industrialization

- SHERPA for real subtraction, real emission, phase-space integration, and analysis
- Other groups using on-shell methods numerically:
  CUTTOOLS[+HELAC ](Ossola, Papadopoulos, Pittau, Actis, Bevilacqua, Czakon, Draggiotis, Garzelli, van Hameren, Mastrolia, Worek);
  ROCKET (Ellis, Giele, Kunszt, Lazopoulos, Melnikov, Zanderighi);
  GKW (Giele, Kunszt, Winter);
  SAMURAI (Mastrolia, Ossola, Reiter, Tramontano);
- On-going analytic computations
  Anastasiou, Britto, Feng, Mastrolia; Britto, Feng, Mirabella

# New Technologies: On-Shell Methods

- Use only information from physical states
- Use properties of amplitudes as calculational tools
  - Factorization → on-shell recursion relations
  - Unitarity → unitarity method
  - Underlying field theory → integral basis



- Formalism

Known integral basis:

$$\text{Ampl} = \sum_{j \in \text{Basis}} c_j \, \text{Int}_j + \text{Rational}$$

$c_j$ → Unitarity

$\text{Int}_j$ → Known integral basis

Rational → On-shell Recursion; *D*-dimensional unitarity via ∫ mass

# Recent Developments in BlackHat

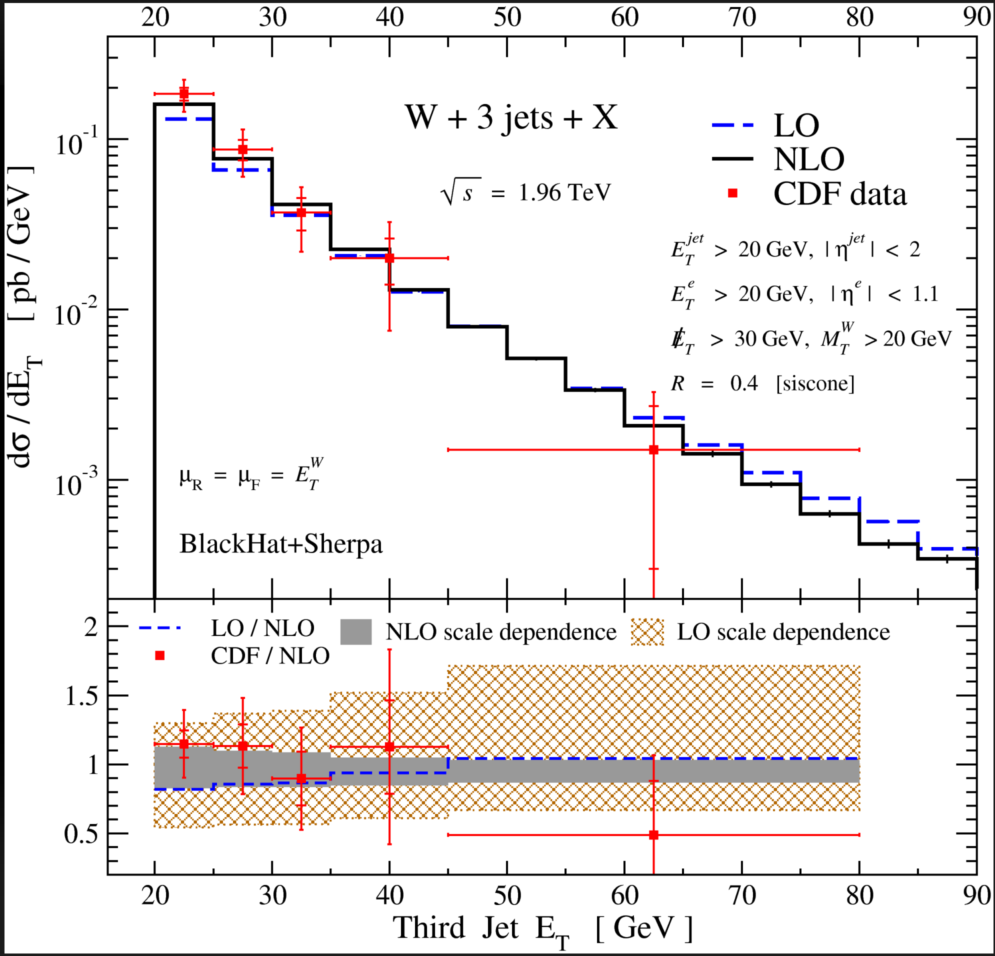
- Generation of ROOT tuples
- Re-analysis possible
- Distribution to experimenters

- Flexibility for studying scale variations
- Flexibility for computing error estimates associated with parton distributions

- More processes

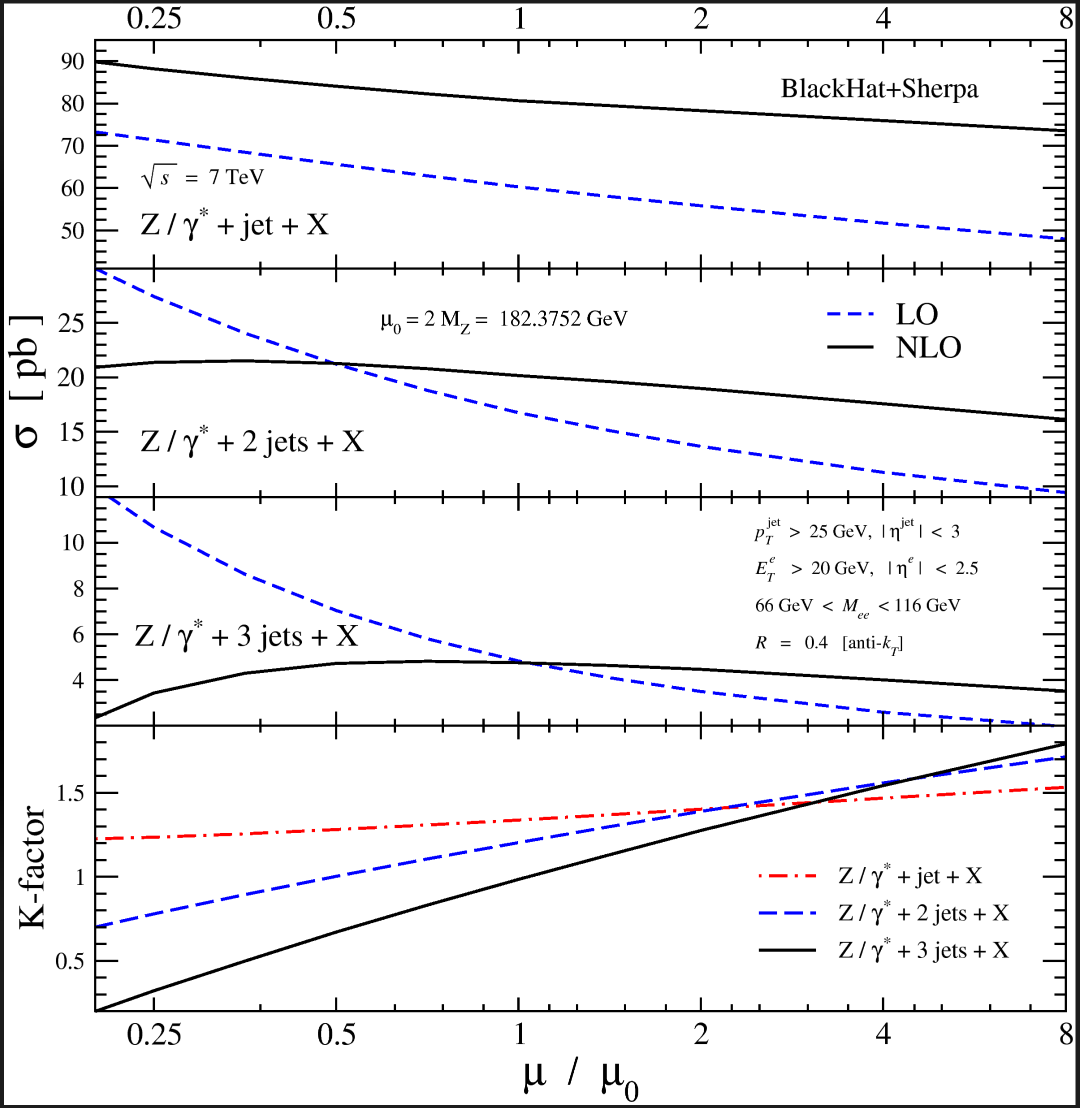
# The Tevatron is Still Producing *W*s…

- Third jet in W+3 jets [0907.1984]
- Reduced scale dependence at NLO
- Good agreement with CDF data [0711.4044]
- Shape change small compared to LO scale variation
- SISCone (Salam & Soyez) vs JETCLU — LHC experiments will use anti-*k*T

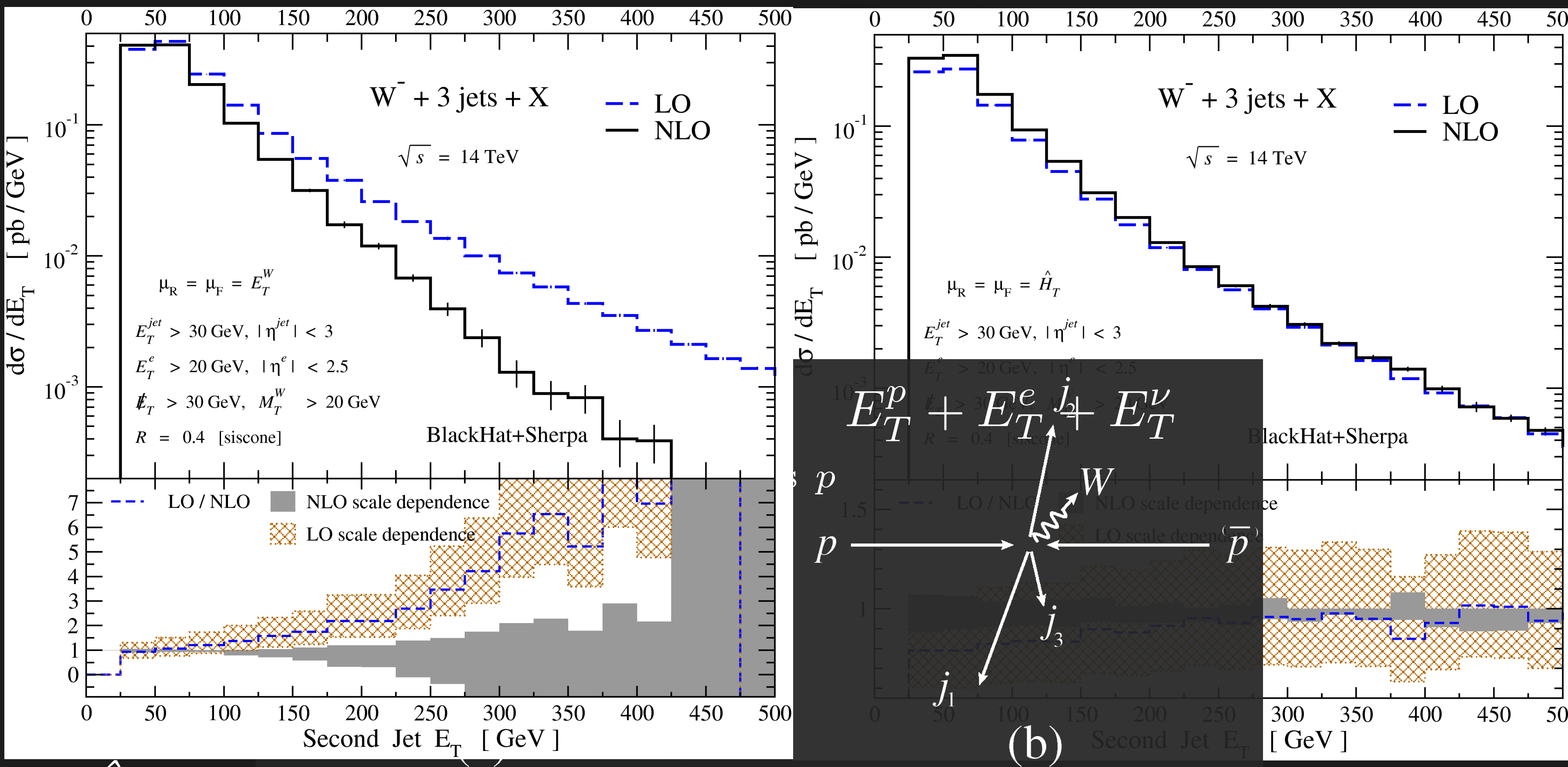


# Reduced Scale Dependence

- Anti-*k*T @ LHC 7 TeV
- Reduction of scale dependence
- NLO importance grows with increasing number of jets



# Scale Choices in $V$+Jets




$\hat{H}$T

# Scale Variation

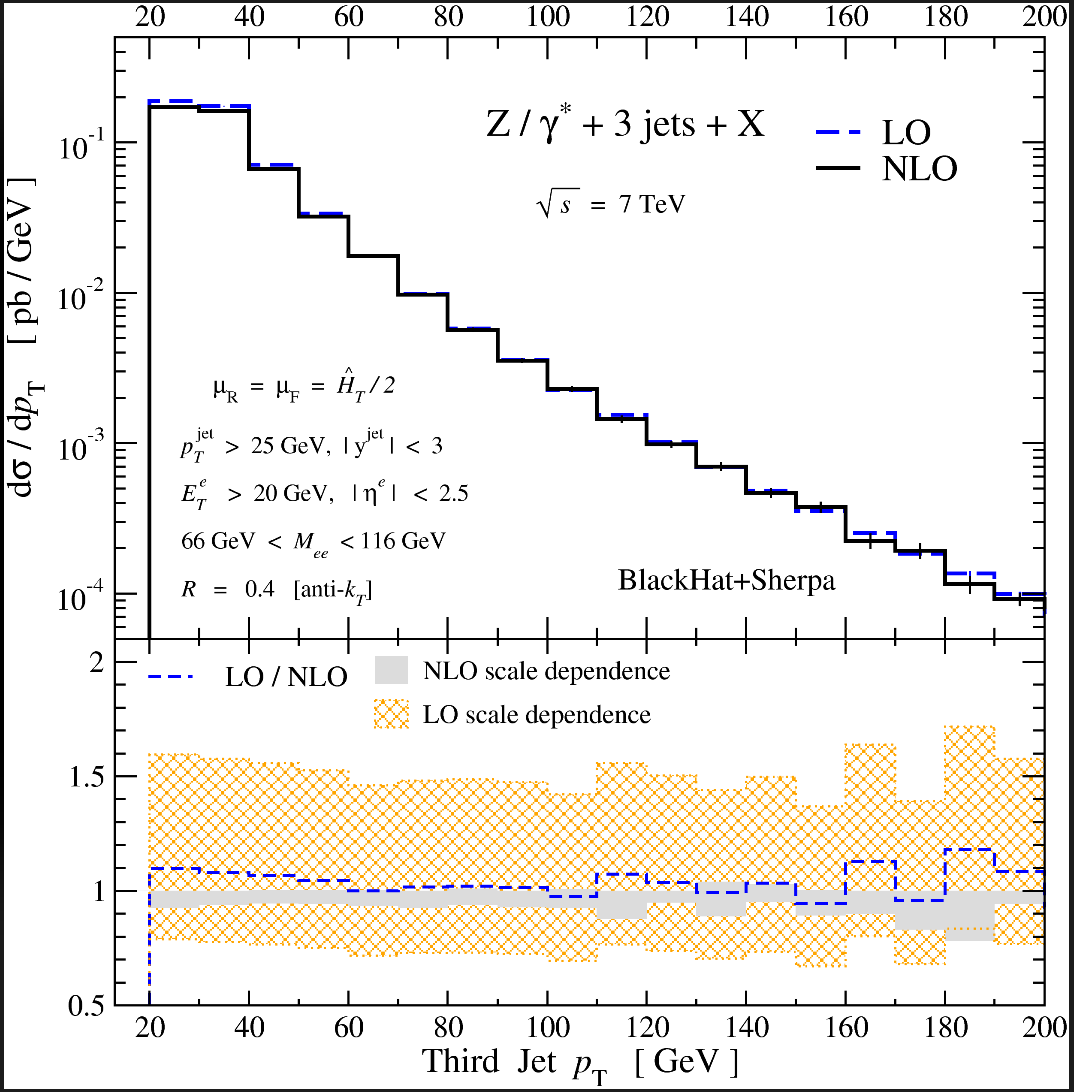
- How should we assess uncertainty due to scale variation?
- Varying up & down by a factor of two is “traditional” but arbitrary
- For events with many jets, there are many scales
- Can use shower-inspired scales

$$\alpha_s^{-1}\left([\alpha_s(p_{\mathrm{T}1})\alpha_s(p_{\mathrm{T}2})\alpha_s(p_{\mathrm{T}3})]^{1/3}\right)$$

- Standard “recipe” allows comparing different calculations across time
- We use $\hat{H}\mathrm{T}/2$ (sum of partonic $E$T, including leptons) or $\hat{H}'\mathrm{T}/2$ (sum of QCD partonic $E$T & $E$TW)

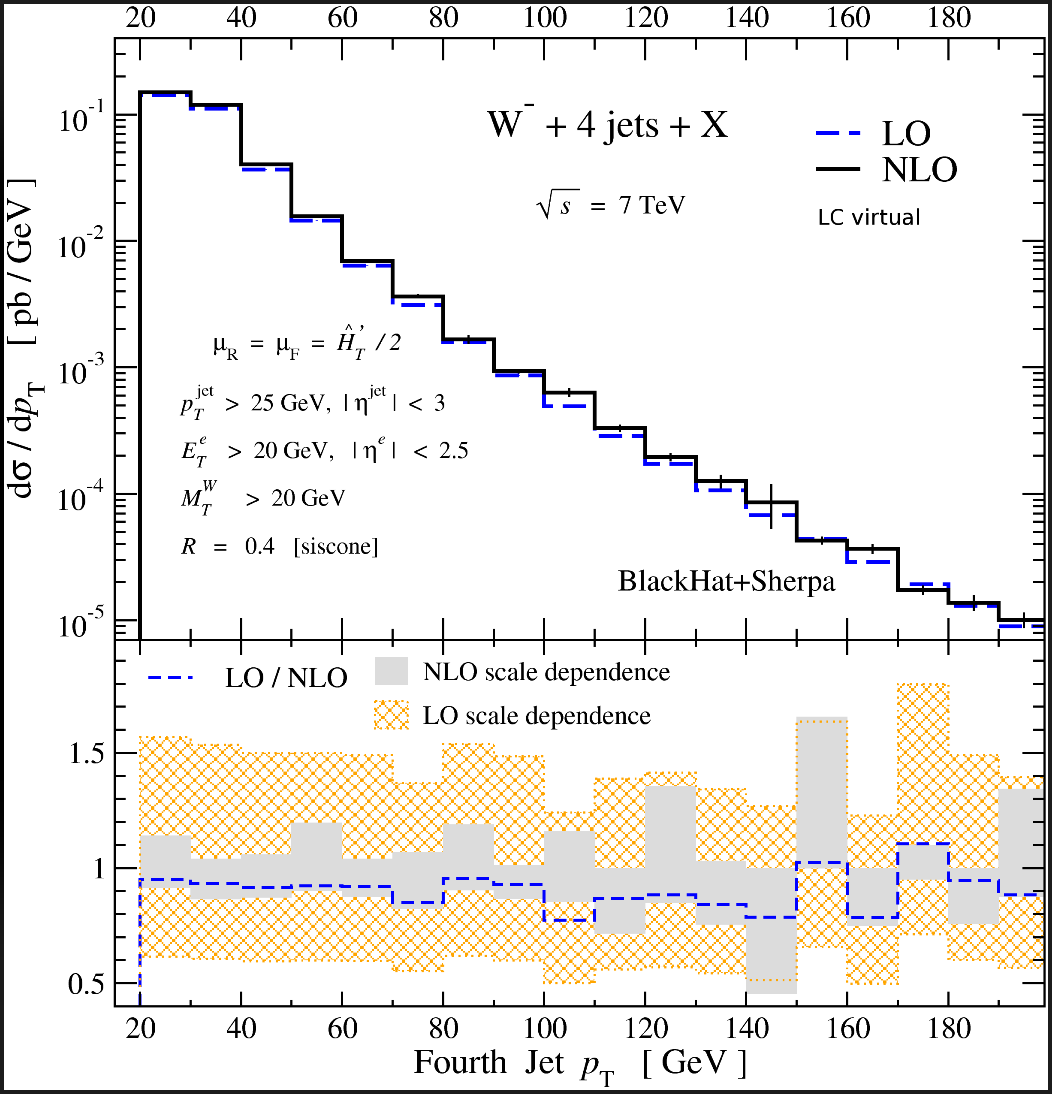
# Z+3 Jets at the LHC

- Z+3 jets: new
- NLO scale uncertainty smaller than LO (band accidentally narrow given central choice — but would in any case be much improved)
- Shape change mild
- Scale choice $\hat{H}T/2$ (half total partonic $ET$)
- Anti-$k$T

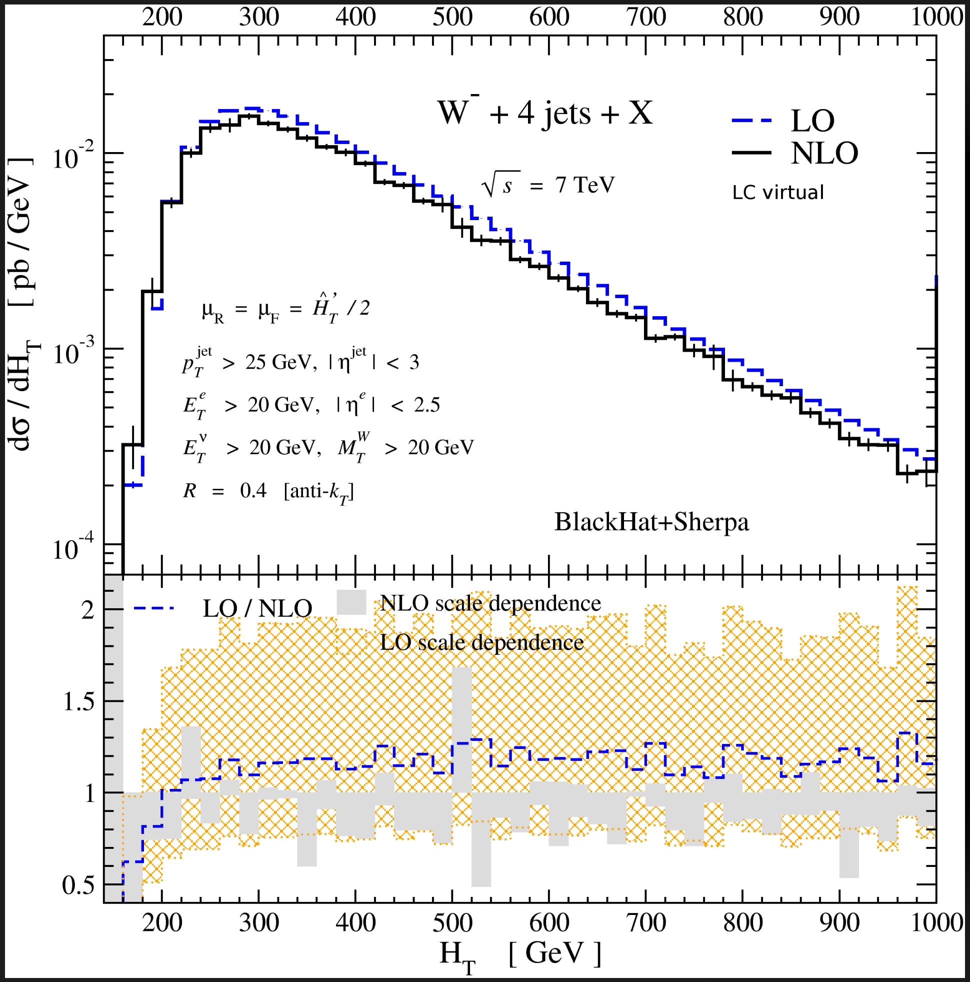


# W– + 4 Jets

- Background to top quark studies
- Background to new physics searches
- High-multiplicity frontier
- SISCone, R = 0.4

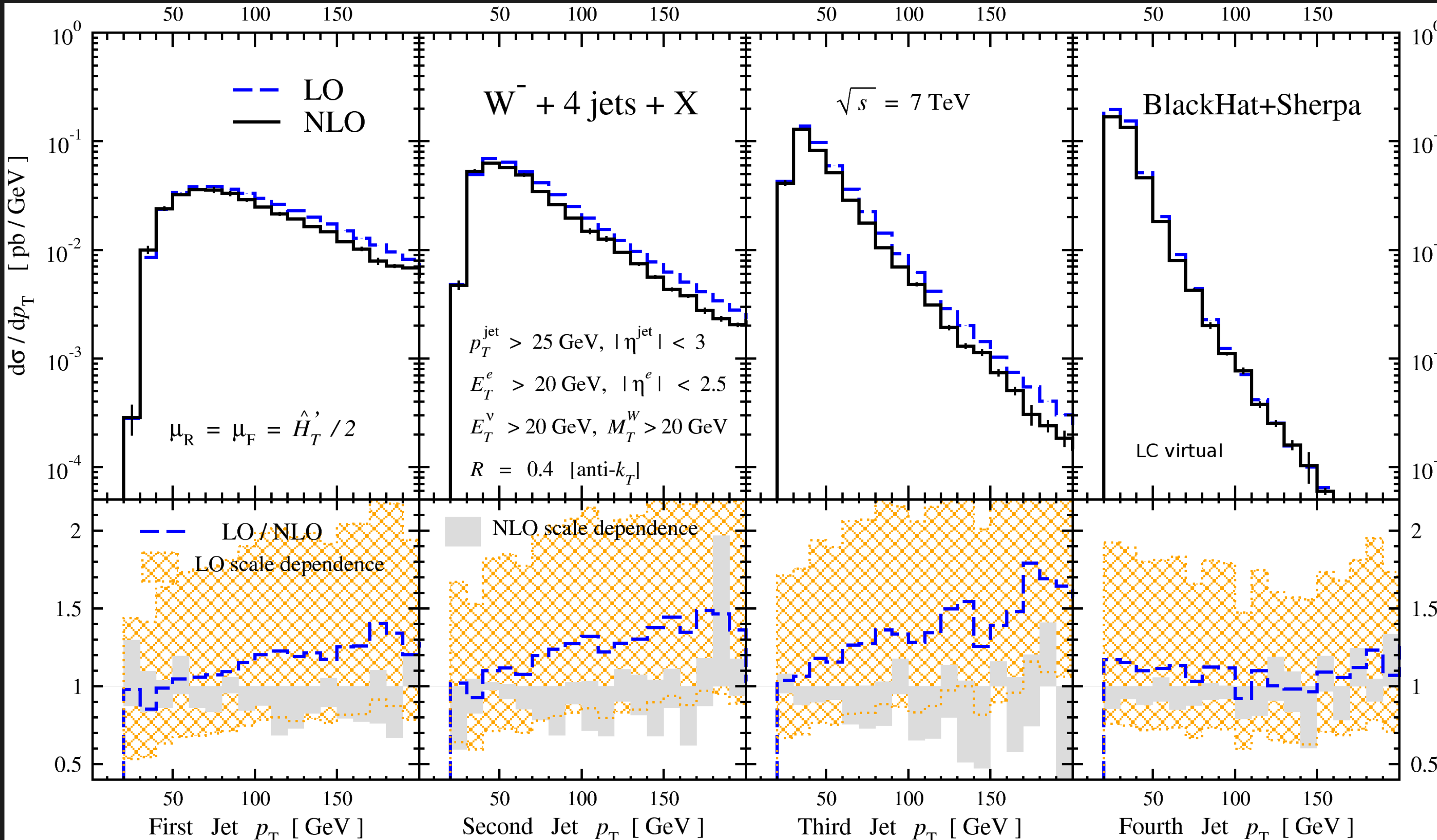


# Total Transverse Energy

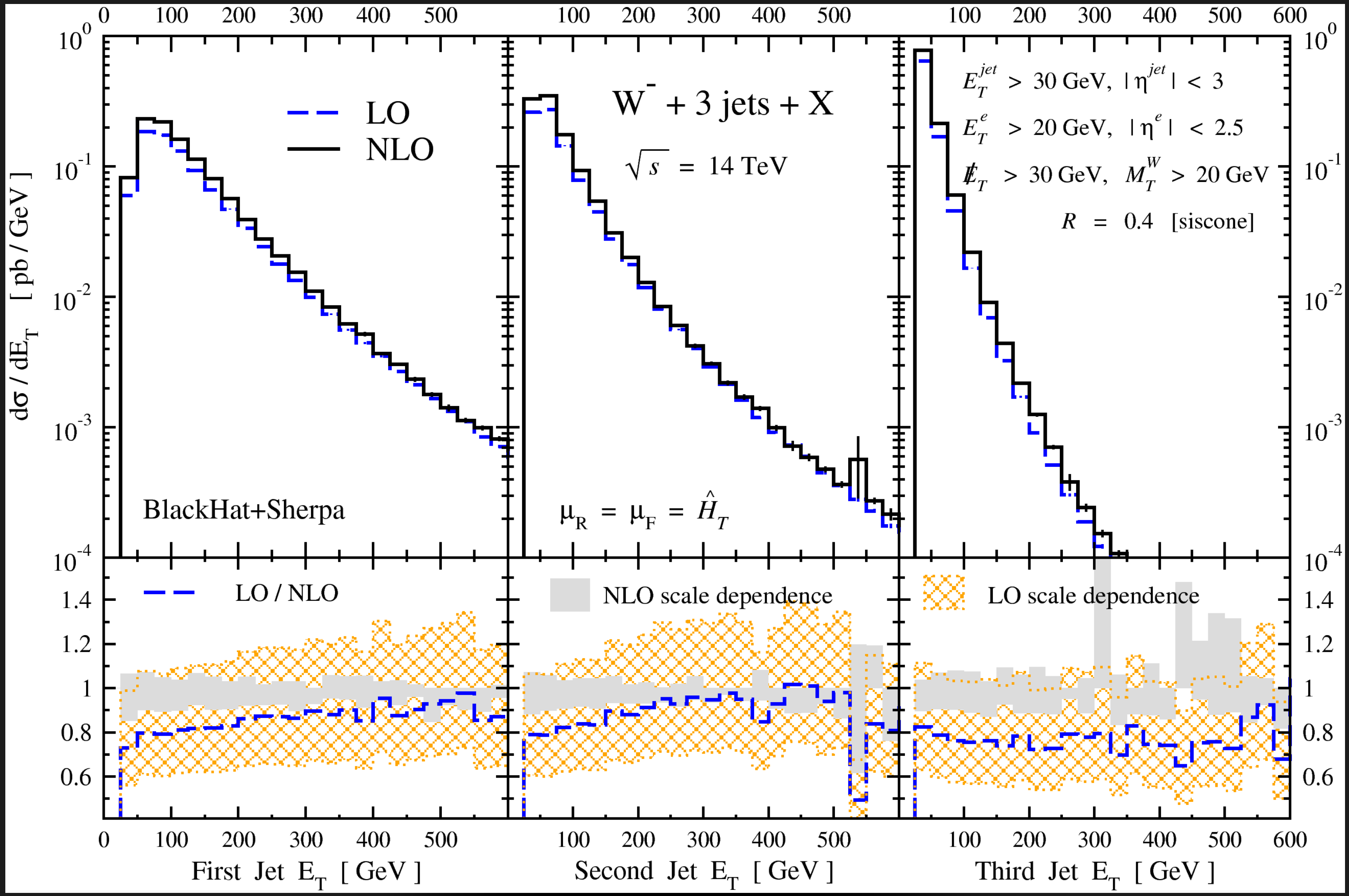



$$H_T = \sum_{\text{jets } j} E_T^j + E_T^e + E_T^\nu$$

- Useful distribution in new-physics searches
- Normalization corrected but shape is stable at NLO

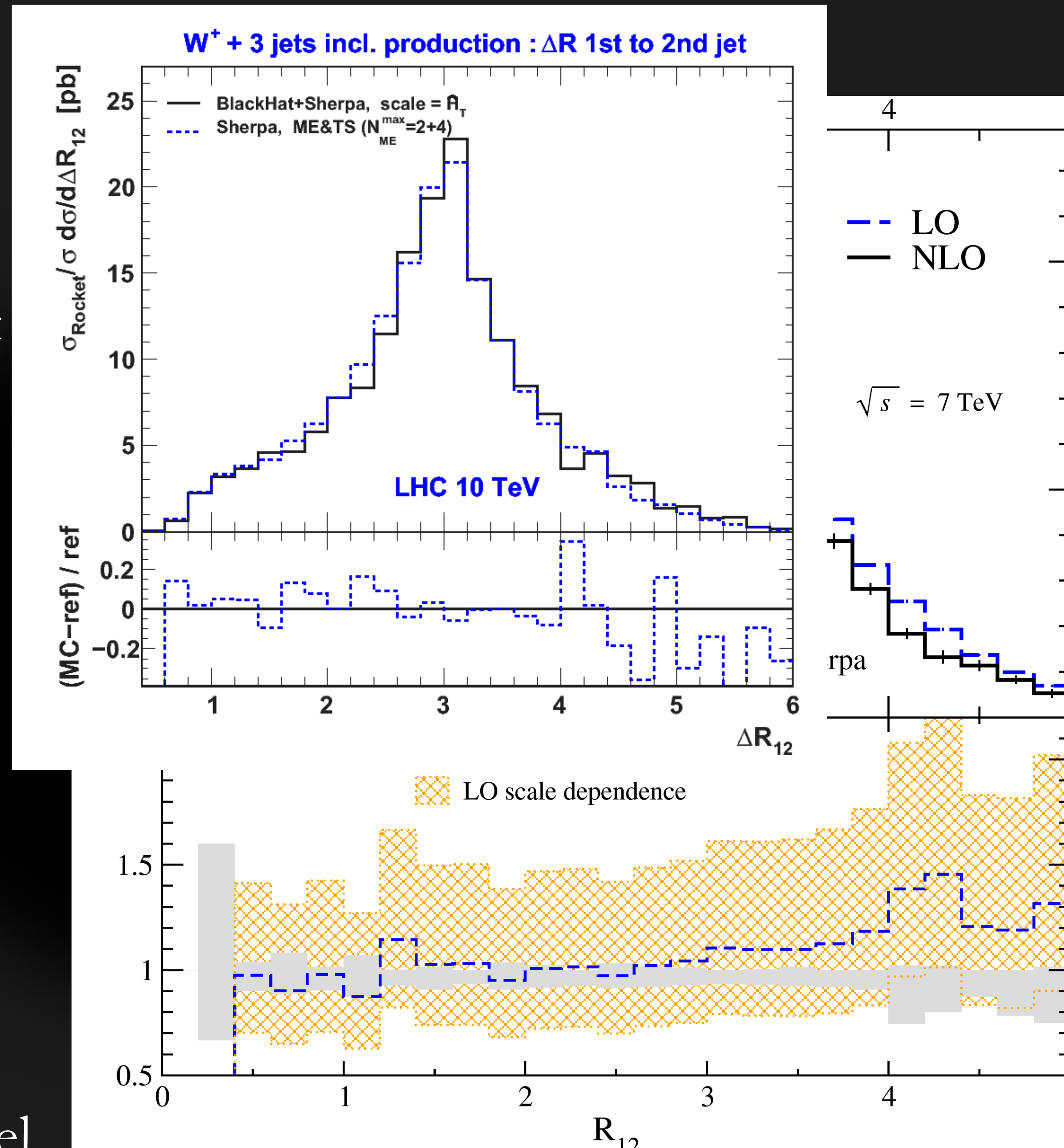



- All four jets — leading three show shape changes from LO to NLO




- Also seen in W+3 jet production at 14 TeV (SISCone): leading two jets have shape corrections to *E*T distributions
- Cannot always choose scales to make all LO/NLO ratios flat simultaneously!

- □ R(1st,2nd) jet
- Shapes can change!
- Physics of leading jets not modeled well at LO: additional radiation allows jets to move closer
- Cf Les Houches study [in 1003.1241] (Hoche, Huston, Maitre, Winter, Zanderighi) comparing to SHERPA w/ME matching & showering
- W+4 shows similar but milder effect at parton level



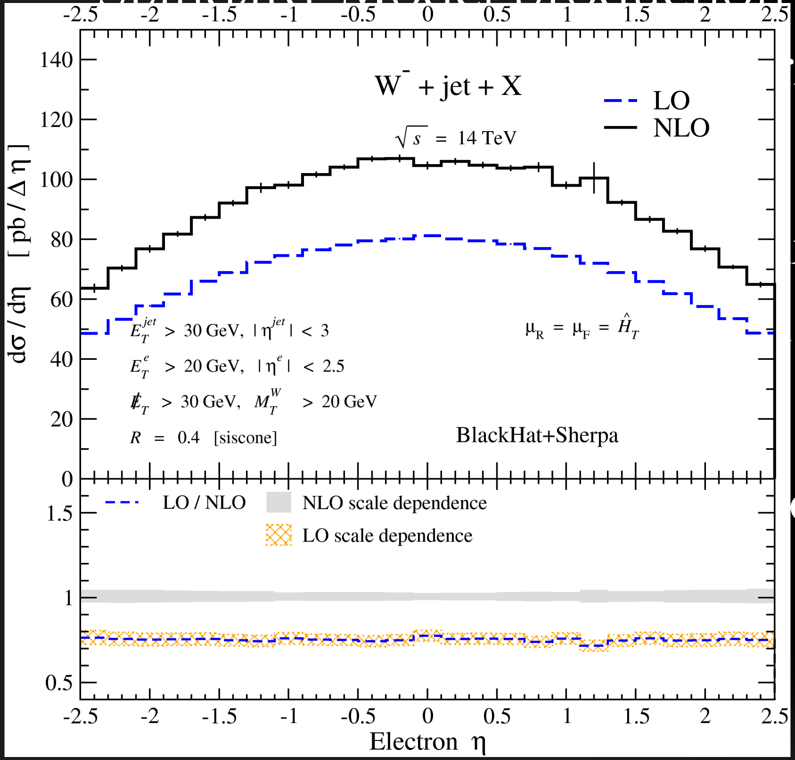
# Tools for New Physics Searches

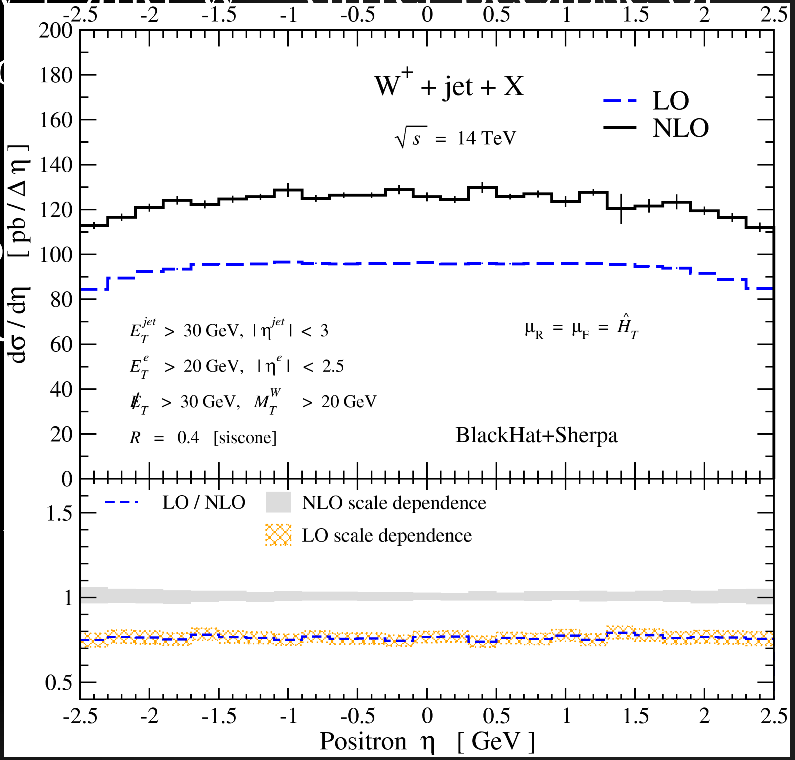
- Look for quantities which have different behavior for Standard-Model physics and new physics

- Look for quantities in which experimental systematics are reduced or cancel  think about ratios

# *W*+ vs *W*− Production

- Standard-Model production of W+ and W− differ because of

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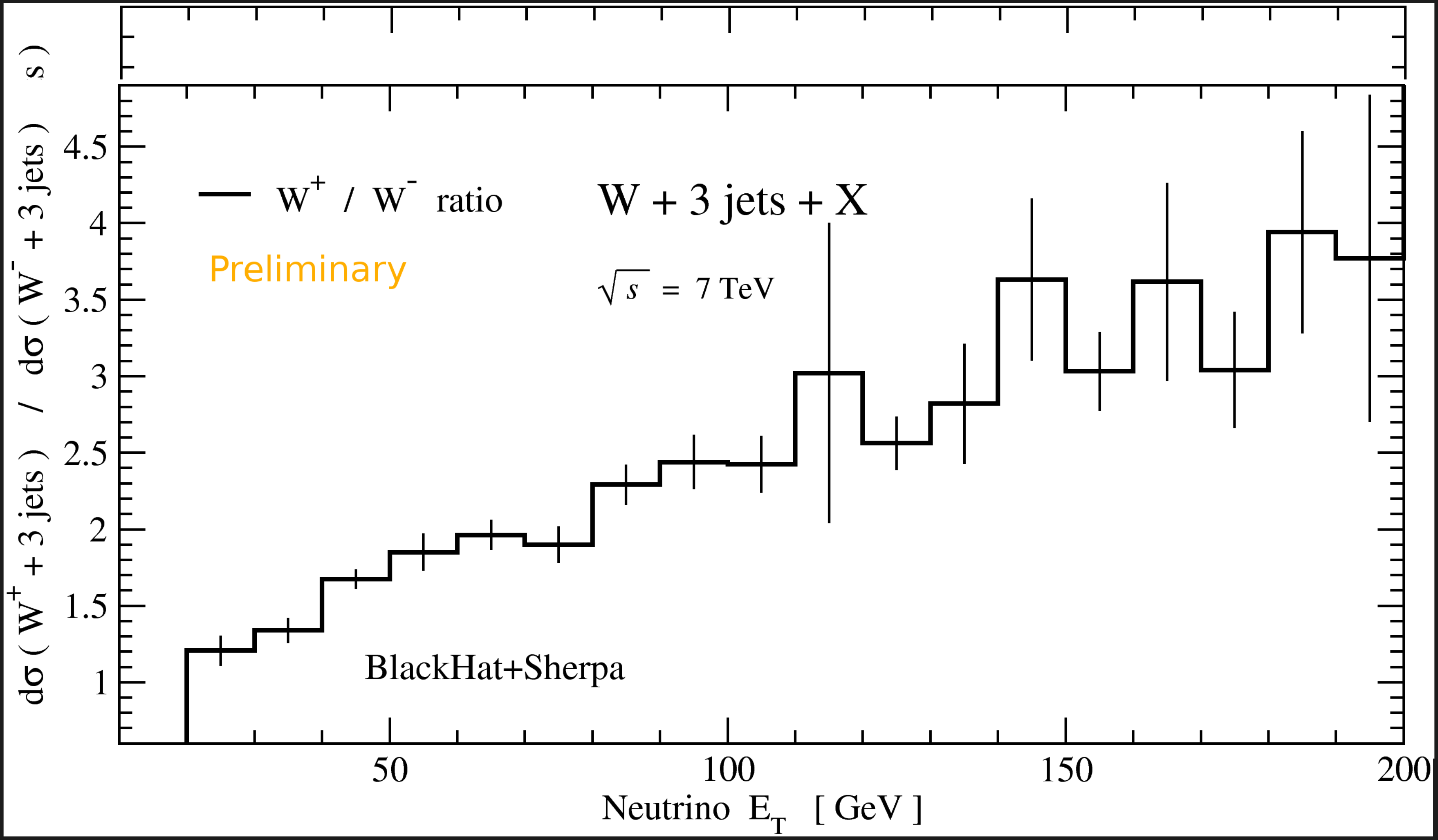
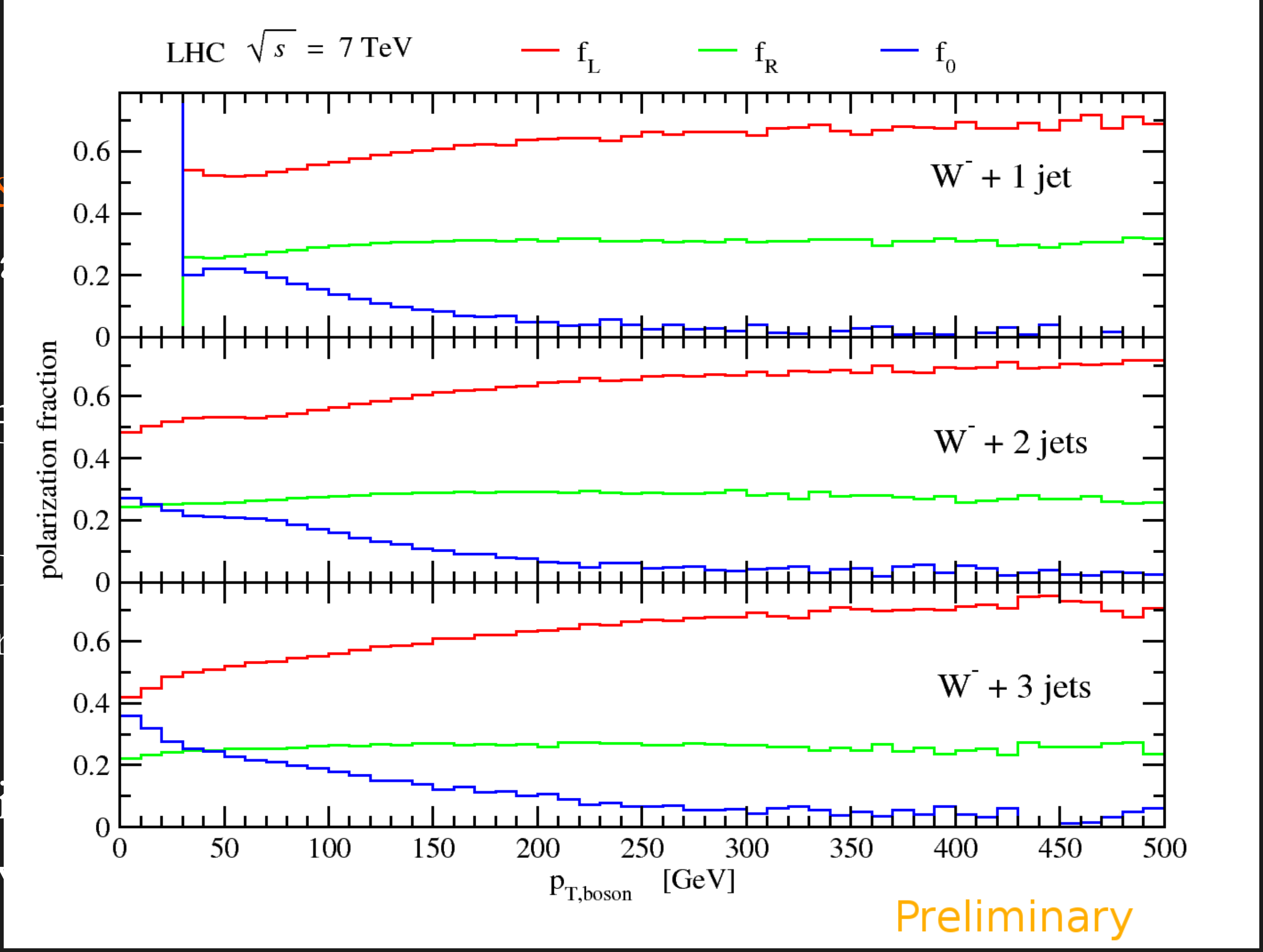
# W+3 jets at the LHC



# High-*ET* *W* Polarization

- Polarization
  (Ellis, Stirling &
  distribution
- This is a diff
  dependence
  - Present at
  - Present for
- Useful for di
  decay (or ne



# W+/W− Ratio

- Ratio of cross sections should be less sensitive to experimental systematics and theoretical uncertainties too

$$R^{\pm}(n) = \frac{\sigma(W^{+} + n \text{ jets})}{\sigma(W^{-} + n \text{ jets})}$$

Kom & Stirling (2010)

- PDF uncertainties should be small, jet measurement uncertainties too

- Example: top-quark production at 14 TeV reduces $R^{\pm}(4)$ from 1.44 to 1.22 (LO)

- Correlated scale variation cancels
- Ratio increases with $n$ as higher $x$ is probed

| Jets | $W^-$ LO | $W^-$ NLO | $W^+/W^-$ LO | $W^+/W^-$ NLO |
|---|---|---|---|---|
| 0 | $1614.0(0.5)^{+208.5}_{-235.2}$ | $2077(2)^{+40}_{-31}$ | — | — |
| 1 | $264.4(0.2)^{+22.6}_{-21.4}$ | $331(1)^{+15}_{-12}$ | 1.507(0.002) | 1.498(0.009) |
| 2 | $73.14(0.09)^{+20.81}_{-14.92}$ | $78.1(0.5)^{+1.5}_{-4.1}$ | 1.596(0.003) | 1.57(0.02) |
| 3 | $17.22(0.03)^{+8.07}_{-4.95}$ | $16.9(0.1)^{+0.2}_{-1.3}$ | 1.694(0.005) | 1.66(0.02) |
| 4 | $3.81(0.01)^{+2.44}_{-1.34}$ | $3.56(0.03)^{+0.08}_{-0.30}$ Watch this! | 1.817(0.003) | Watch this! Stay tuned! |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- LHC, 7 TeV, anti-$k$T ($R = 0.5$), $p$Tjet > 25 GeV

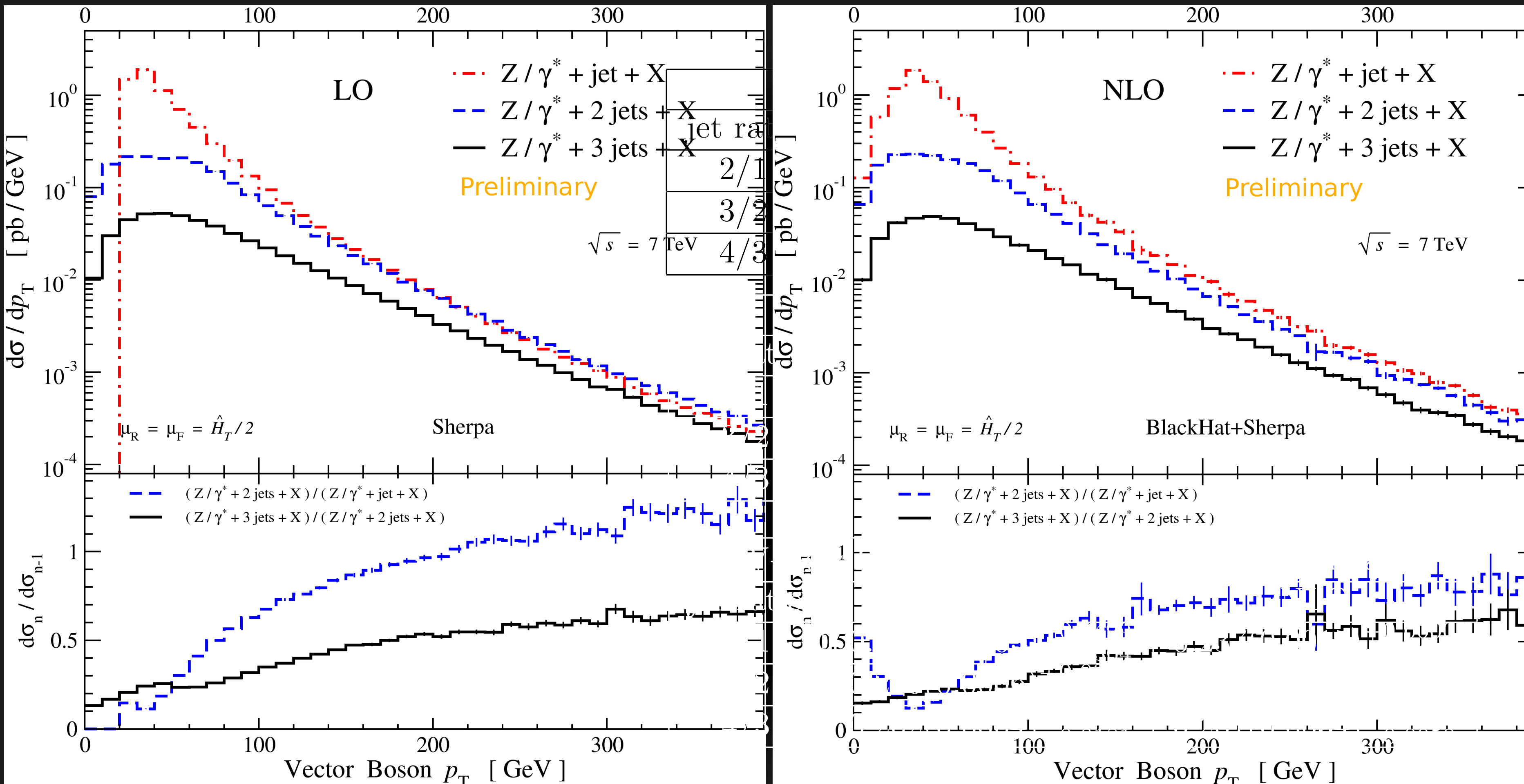
# Jet-Production Ratio in *W*+Jets

- Lore: ratio $\sigma(W{+}n)/\sigma(W{+}n{-}1)$ should be independent of $n$
- More dependence on jet systematics than $W+/W-$, but much less than $W+n$ jets

| Jets | $W^- n/(n-1)$ LO | $W^- n/(n-1)$ NLO |
|---|---|---|
| 1 | $0.1638(0.0001)^{+0.044}_{-0.031}$ | $0.159(0.001)$ |
| 2 | $0.2766(0.0004)^{+0.051}_{-0.037}$ | $0.236(0.002)$ |
| 3 | $0.2354(0.0005)^{+0.034}_{-0.025}$ | $0.216(0.002)$ |
| 4 | $0.2212(0.0004)^{+0.026}_{-0.020}$ | $0.211(0.003)$ |

- LHC, 7 TeV, anti-$k$T ($R$ = 0.5), $p$Tjet > 25 GeV

# Jet-Production Ratio in Z+Jets




suppression at higher pT

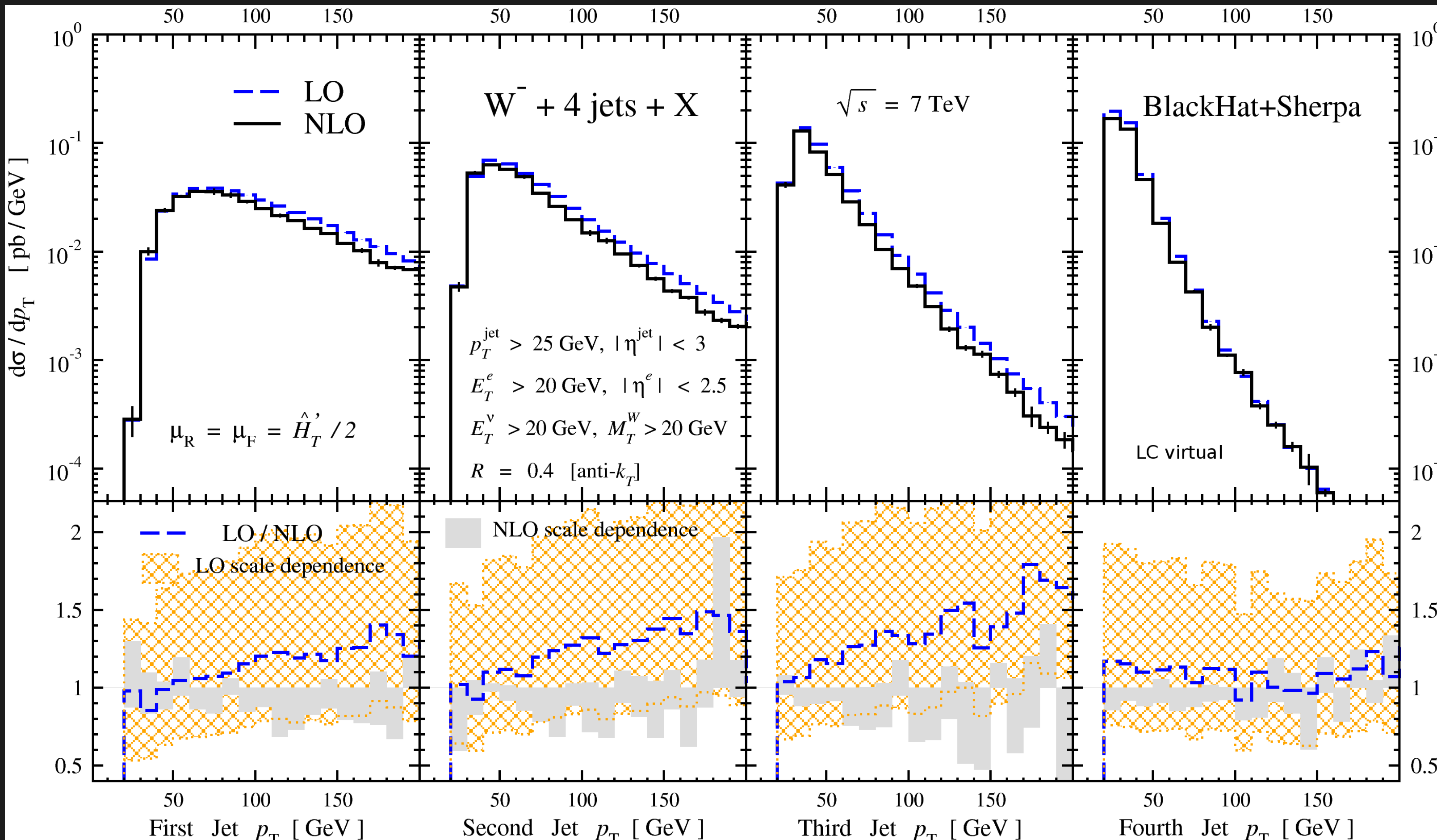
# More Ratios

- W/Z ratios should also be interesting to study
- Can now be done with up to three accompanying jets

# Summary

- NLO calculations required for reliable QCD predictions at the Tevatron and LHC
- On-shell methods are maturing into the method of choice for these QCD calculations

- BlackHat: automated seminumerical one-loop calculations
- Phenomenologically useful NLO parton-level calculations:
  - $W$+3 jets at Tevatron and LHC
  - $Z$+3 jets at Tevatron and LHC
  - First results for $W$+4 jets at LHC
  - Broad variety of kinematical configurations probed
- Detailed tools for new-physics searches


LO
NLO
W⁻ + 4 jets + X
$\sqrt{s}$ = 7 TeV
BlackHat+Sherpa
$d\sigma / dp_T$ [ pb / GeV ]
$\mu_R = \mu_F = \hat{H}_T' / 2$
$p_T^{jet}$ > 25 GeV, $|\eta^{jet}|$ < 3
$E_T^e$ > 20 GeV, $|\eta^e|$ < 2.5
$E_T^\nu$ > 20 GeV, $M_T^W$ > 20 GeV
$R$ = 0.4 [anti-$k_T$]
LC virtual
LO / NLO
LO scale dependence
NLO scale dependence
First Jet $p_T$ [ GeV ]
Second Jet $p_T$ [ GeV ]
Third Jet $p_T$ [ GeV ]
Fourth Jet $p_T$ [ GeV ]

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