Vector Bosons and Jets at NLO with BlackHat

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on behalf of the BlackHat Collaboration

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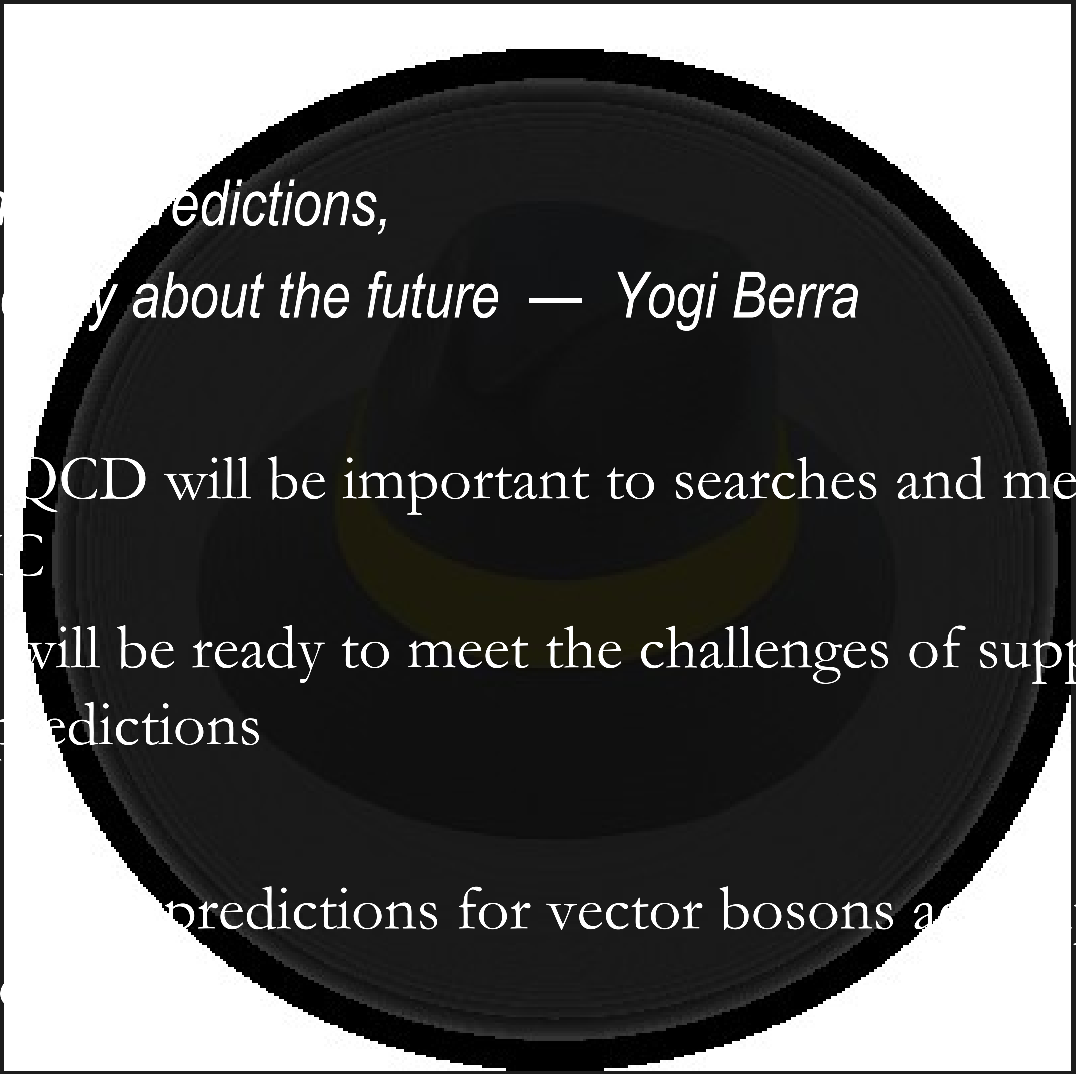
Winter Workshop on Recent QCD Advances at the LHC, Les Houches

February 13–18, 2011

It’s tough to m[illegible]edictions,

espe[illegible]y about the future — Yogi Berra

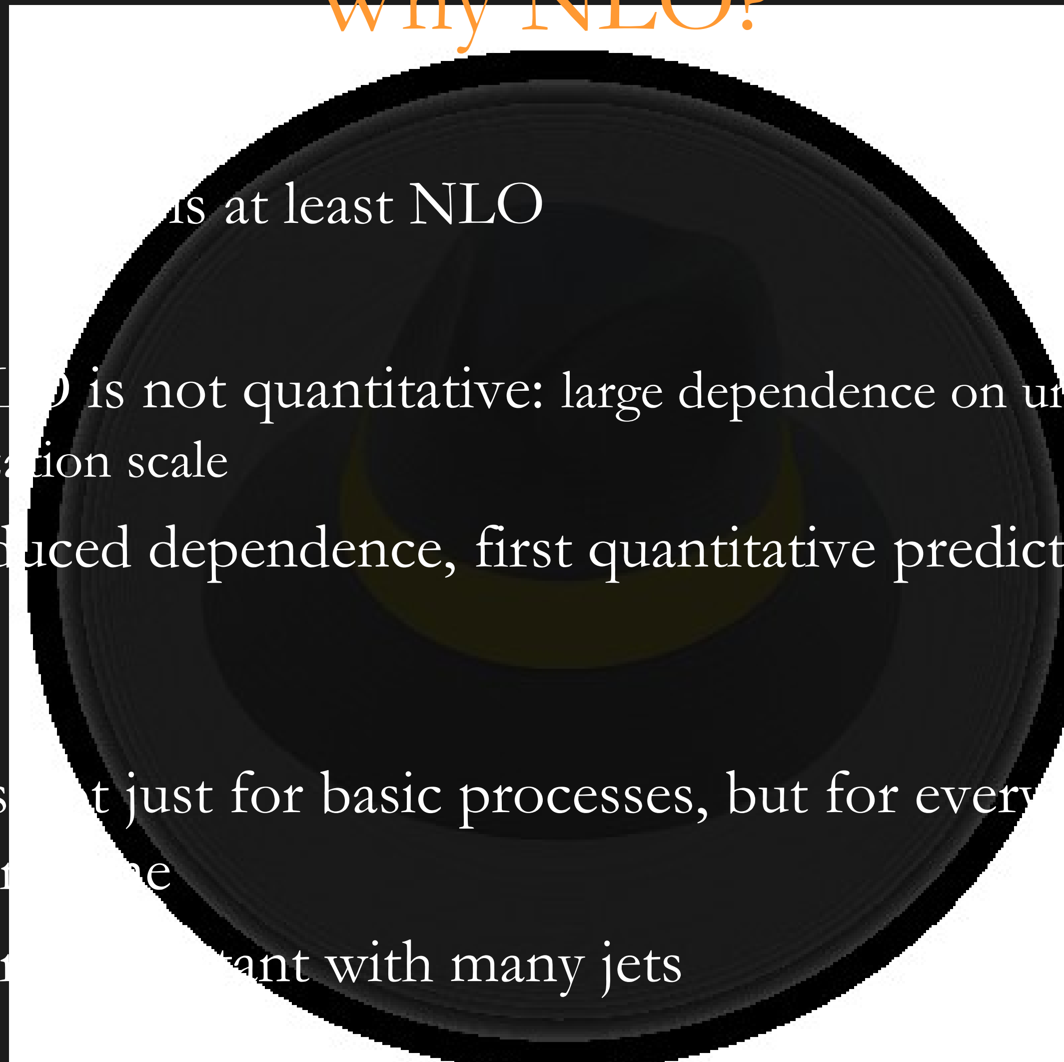


– Precision [illegible]QCD will be important to searches and measurements at the LH[illegible]C

– Theorists [illegible]will be ready to meet the challenges of supplying the required p[illegible]edictions

– Focus on [illegible]predictions for vector bosons a[illegible]panied by multiple j[illegible]

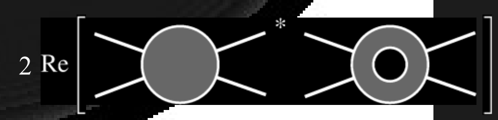
Why NLO?



- Precision ns at least NLO
- QCD at L D is not quantitative: large dependence on u physical renormaliz tion scale
- NLO: red ced dependence, first quantitative prediction
- Want this t just for basic processes, but for every signal and backgrou e
- Even mo ant with many jets

Ingredients for NLO Calculations

- Automating it for general processes
  Gleisberg, Krauss; Seymour, Tevlin; Hasegawa, Moch, Uwer; Frederix, Gehrmann, Greiner (2008); Frederix, Frixione, Maltoni, Stelzer (2009)

- Bottleneck: p amplitudes 

- W+2 jets (MCFM) → W+3 jets → W+4 jets → →

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

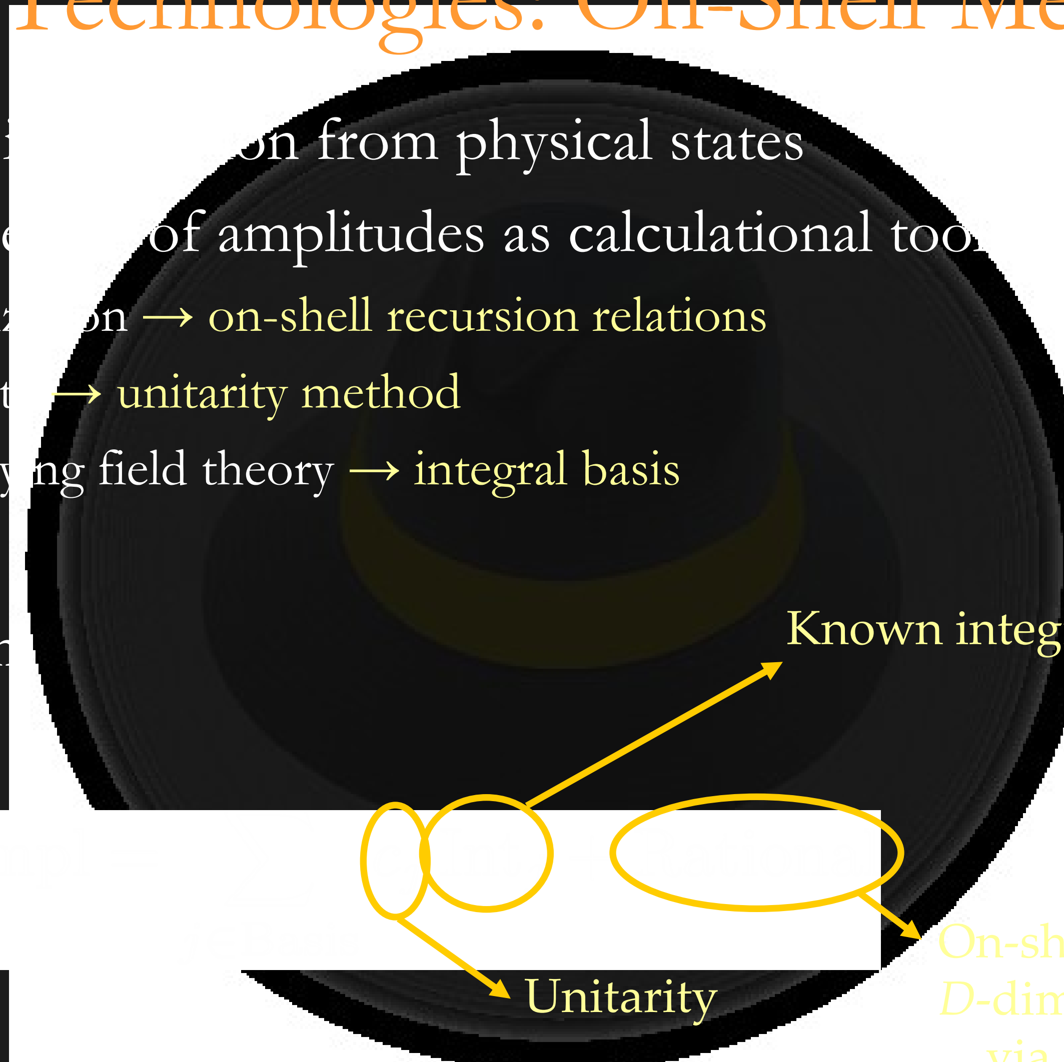
BlackHat

- New techno one-loop computation cal implementa on-shell methods
- Automated lementation ⇒ industrialization

- SHERPA f r real subtraction, real emission, phase-space integration, and analysis
- Other groups sing on-shell methods numerically:
  CUTTOOLS[+ HELAC](Ossola, Papadopoulos, Pittau, Actis, Bevilacqua, Czakon, Draggiotis, Garzelli, van Hameren, Mas olia, Worek);
  ROCKET (Ell iele, Kunszt, Lazopoulos, Melnikov, Zander i);
  GKW (Giele, t, Winter);
  SAMURAI (M Ossola, Reiter, Tramontano);
- On-going ana ons
  Anastasiou, Britto, Feng, Mastrolia; Almeida, Britto, Feng, Mirabella

New Technologies: On-Shell Methods

- Use only i[…]on from physical states
- Use prop[…] of amplitudes as calculational too[…]
  - Factori[…]on → on-shell recursion relations
  - Unitarit[…] → unitarity method
  - Underly[…]ng field theory → integral basis
- Formalism[…]

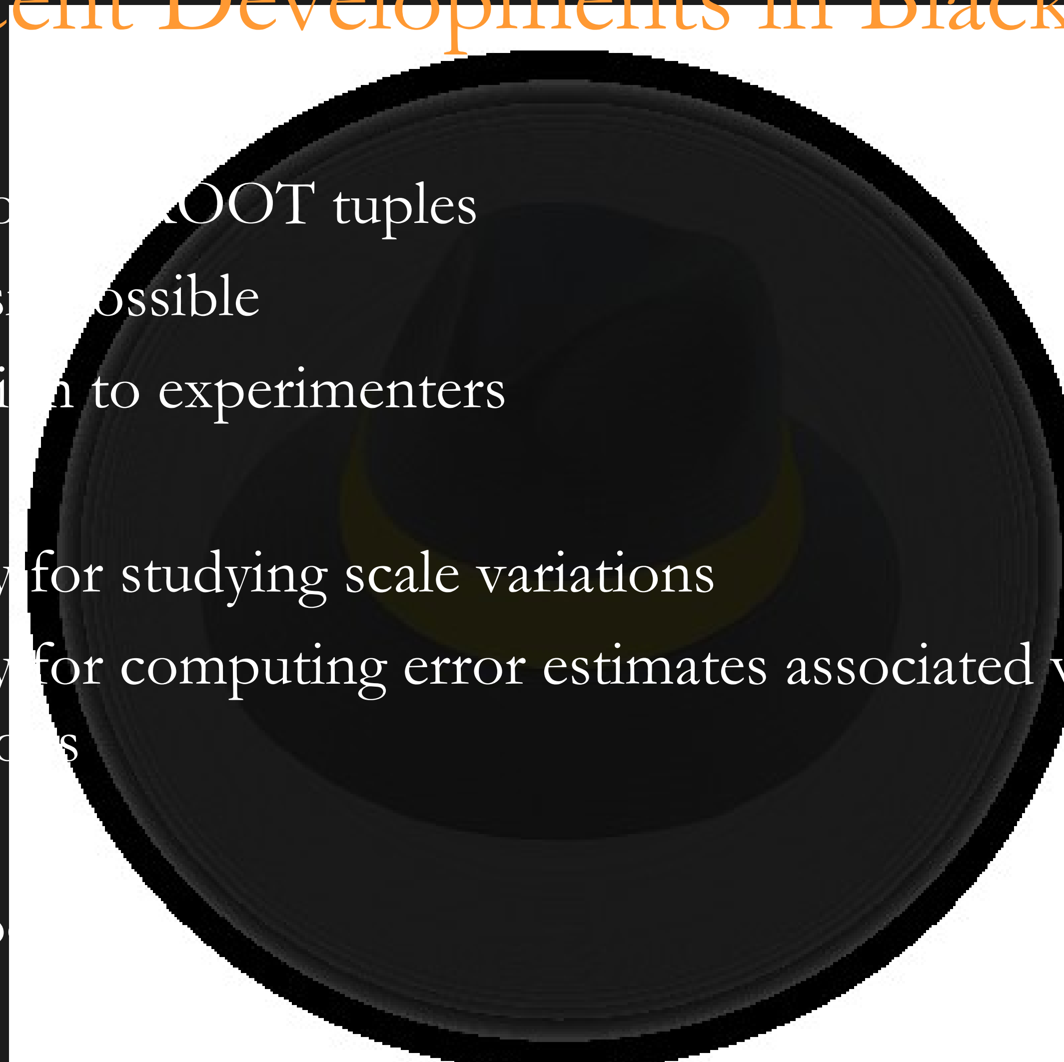


Known integral basis:

Unitarity

On-shell Recursion;
D-dimensional unitarity
via ∫ mass

Recent Developments in BlackHat



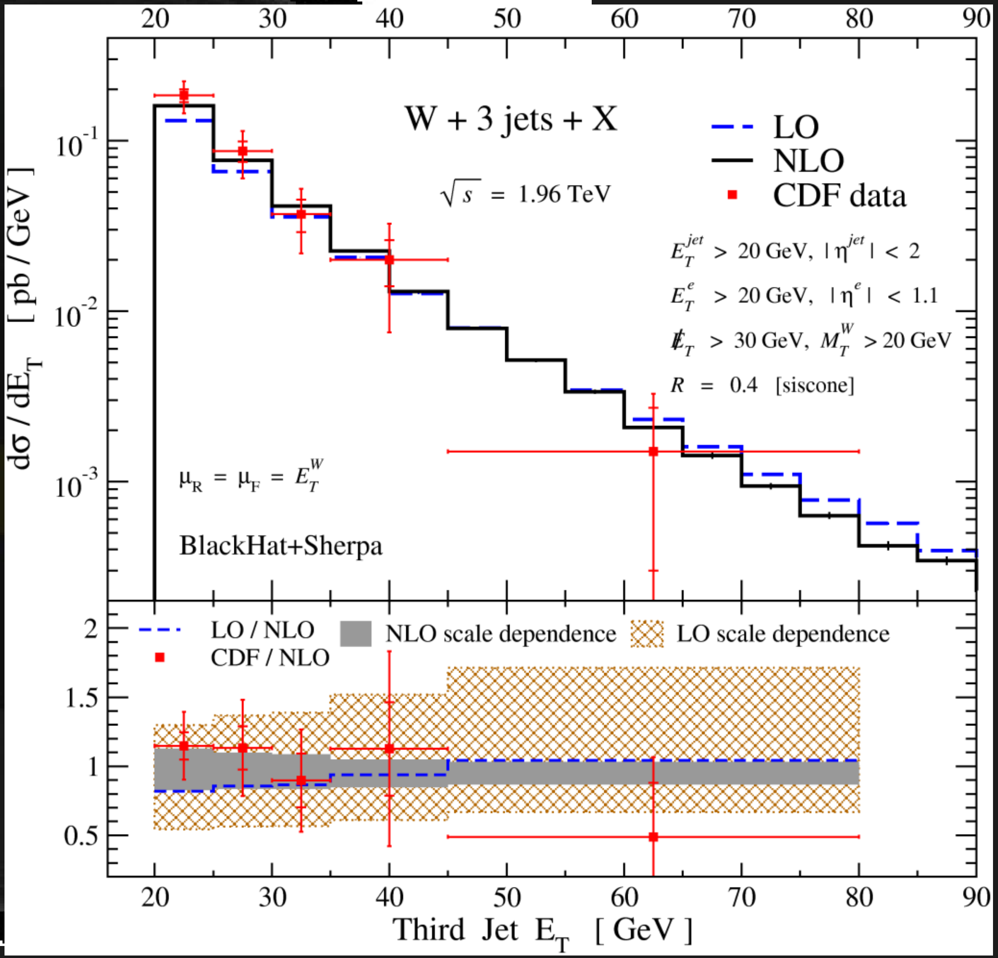
- Generatio[illegible]OOT tuples
- Re-analys[illegible]ossible
- Distributi[illegible]n to experimenters

- Flexibility for studying scale variations
- Flexibility for computing error estimates associated with parton distributi[illegible]s

- More pro[illegible]

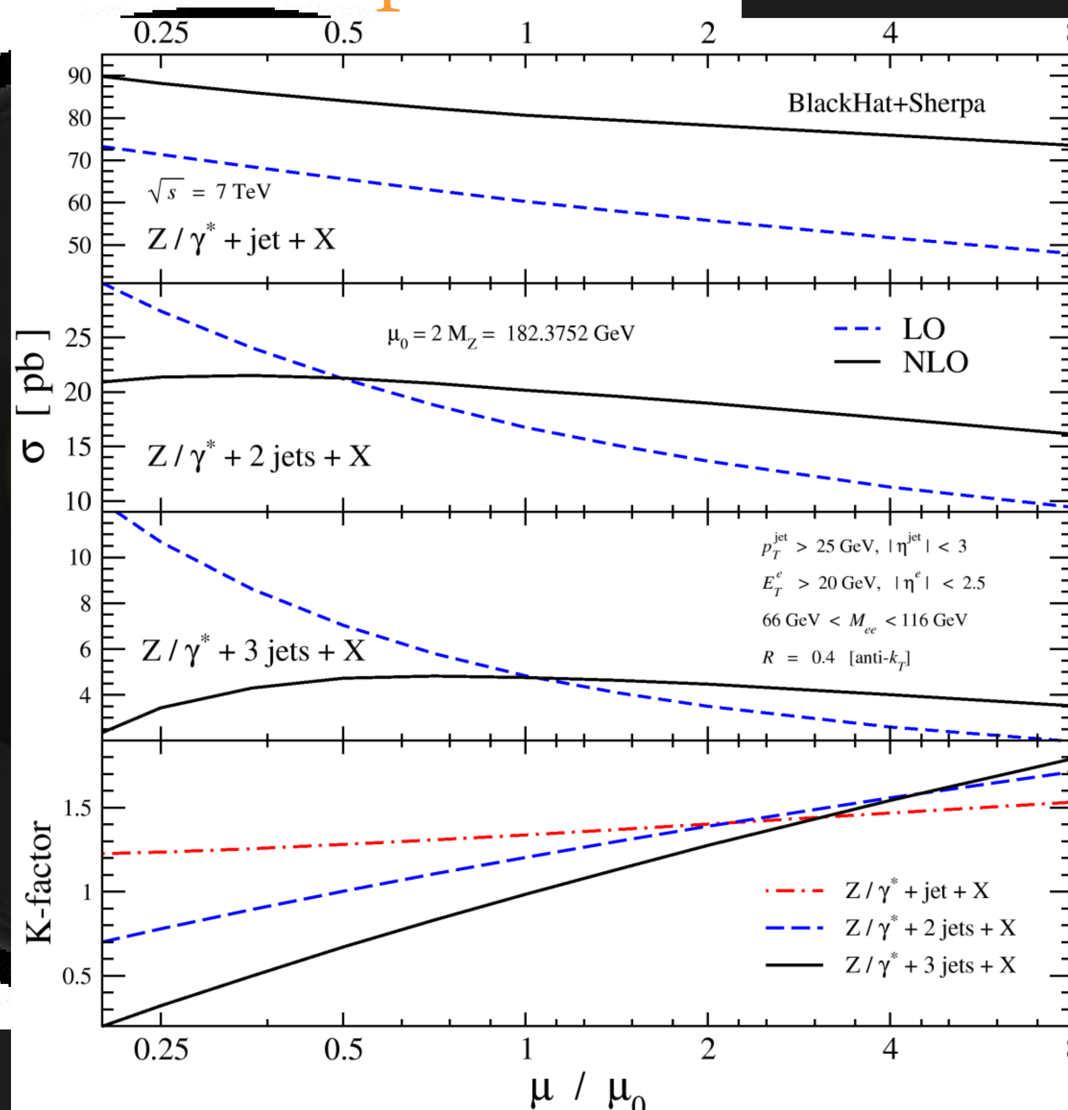
The Tevatron is Still Producing Ws…

- Third jet in W+3 jets [0907.1984]
- Reduced sca dependence at NLO
- Good agreement with CDF data [0711.4 44]
- Shape chang small compared to LO scale iation
- SISCone (Salam & Soyez) vs JETCLU — I eriments will use anti-

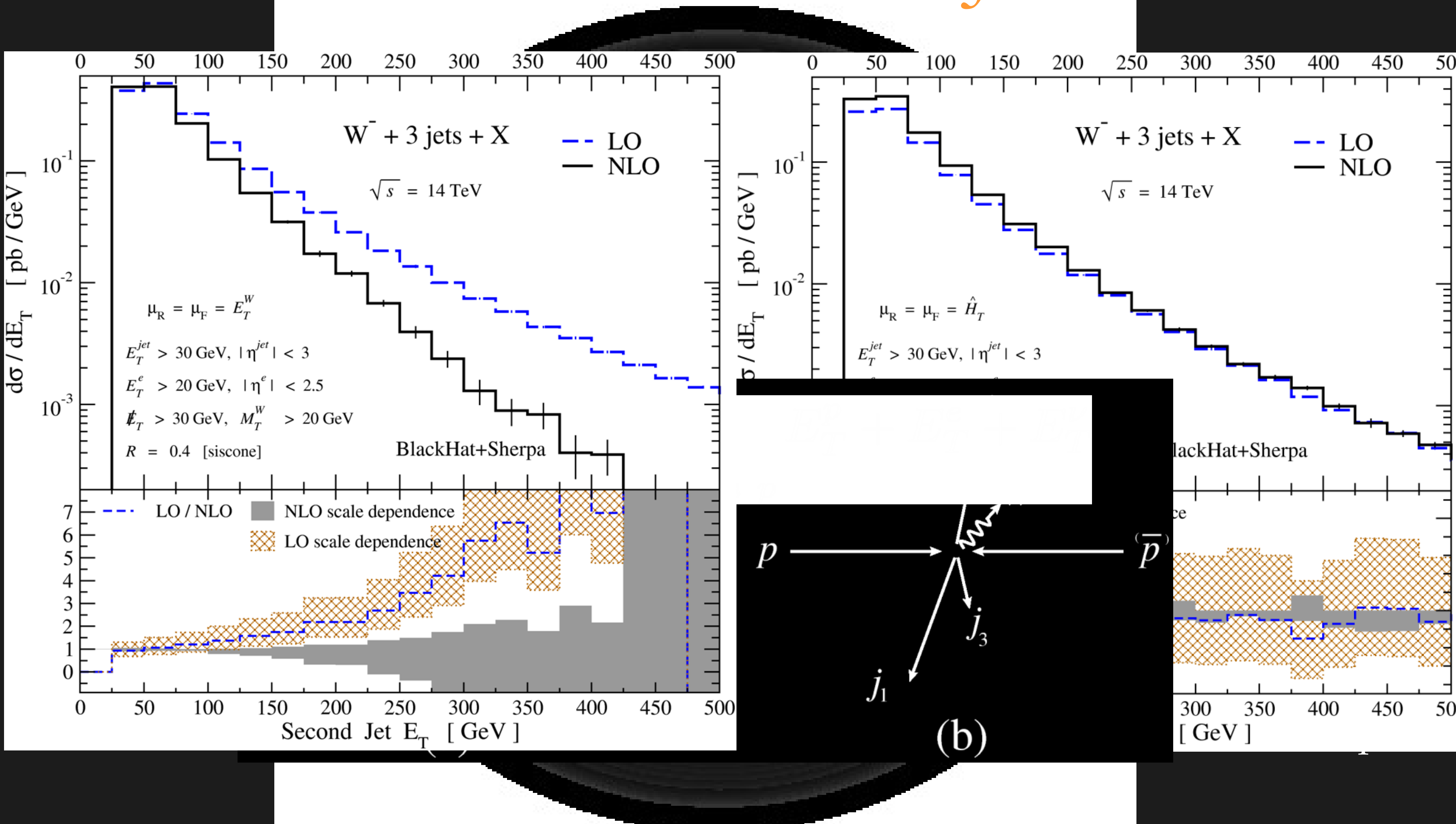


Reduced Scale Dependence

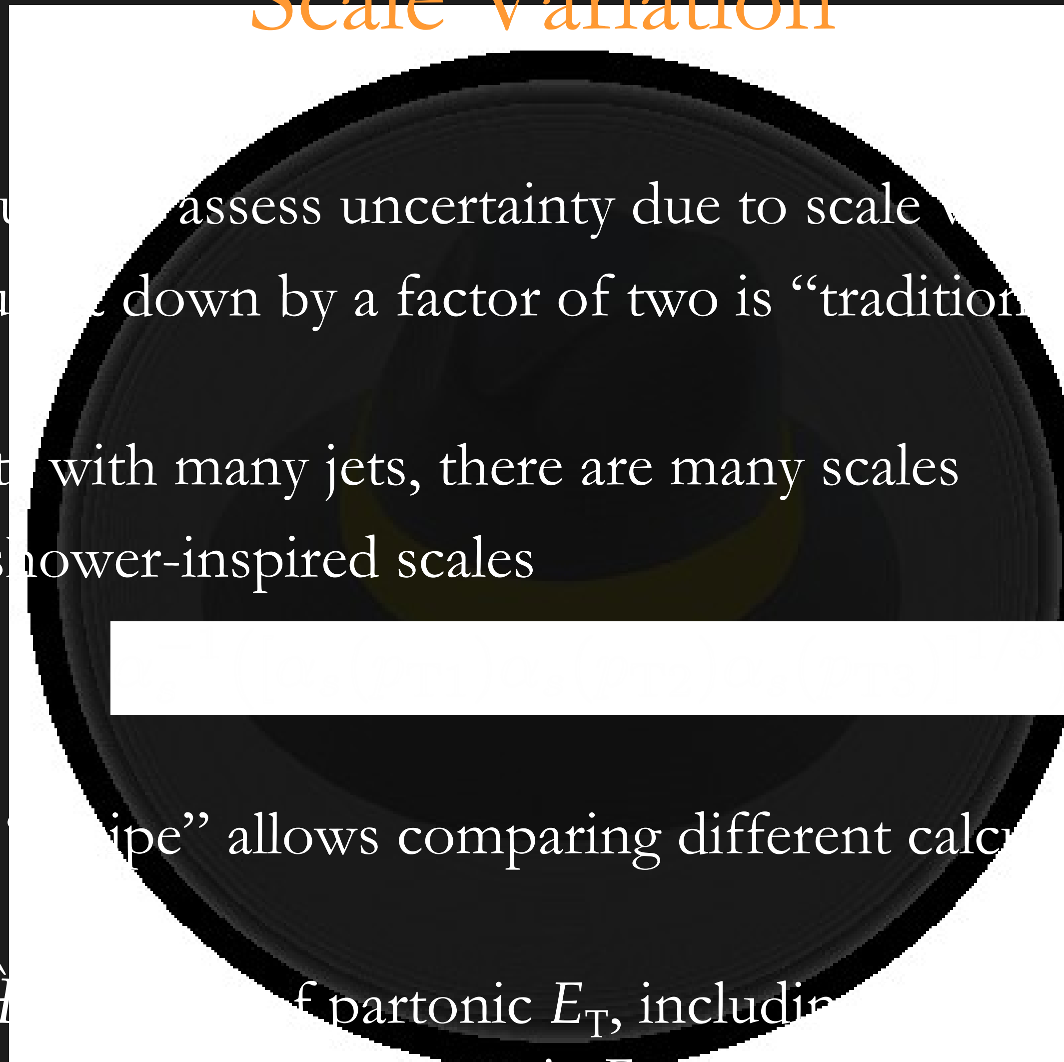
- Anti-k_T @ L TeV
- Reduction o ale dependence
- NLO impor ance grows with i creasing number of je ts



Scale Choices in *V*+Jets



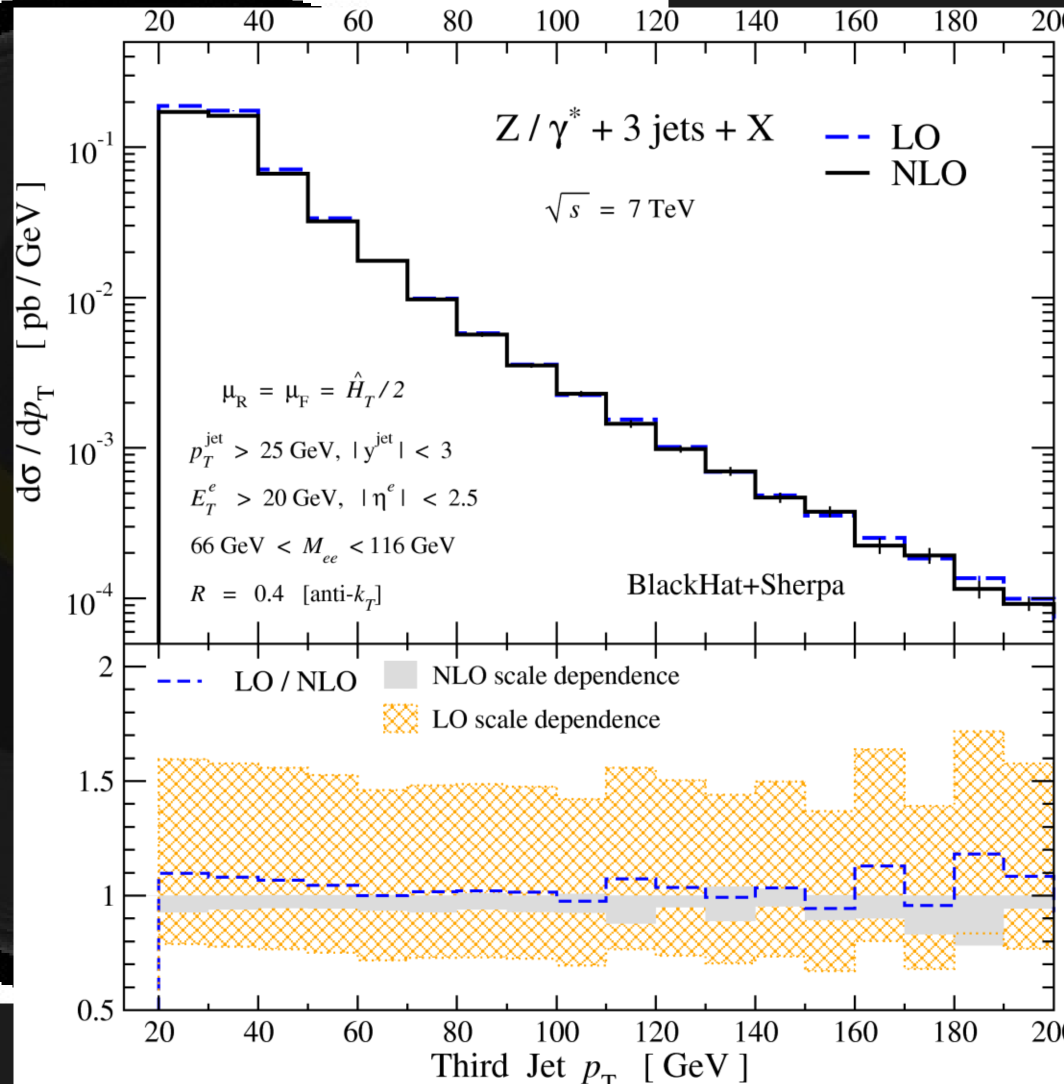
Scale Variation



- How shou … assess uncertainty due to scale … ion?
- Varying u … down by a factor of two is "tradition…" but arbitrary
- For event … with many jets, there are many scales
- Can use s … hower-inspired scales
- Standard "… ipe" allows comparing different calc … tions across time
- We use $\hat{H}$ … f partonic E_T, includi …
  or $\hat{H}'_T/2$ (sum of QCD partonic E_T & E_T^{ν})

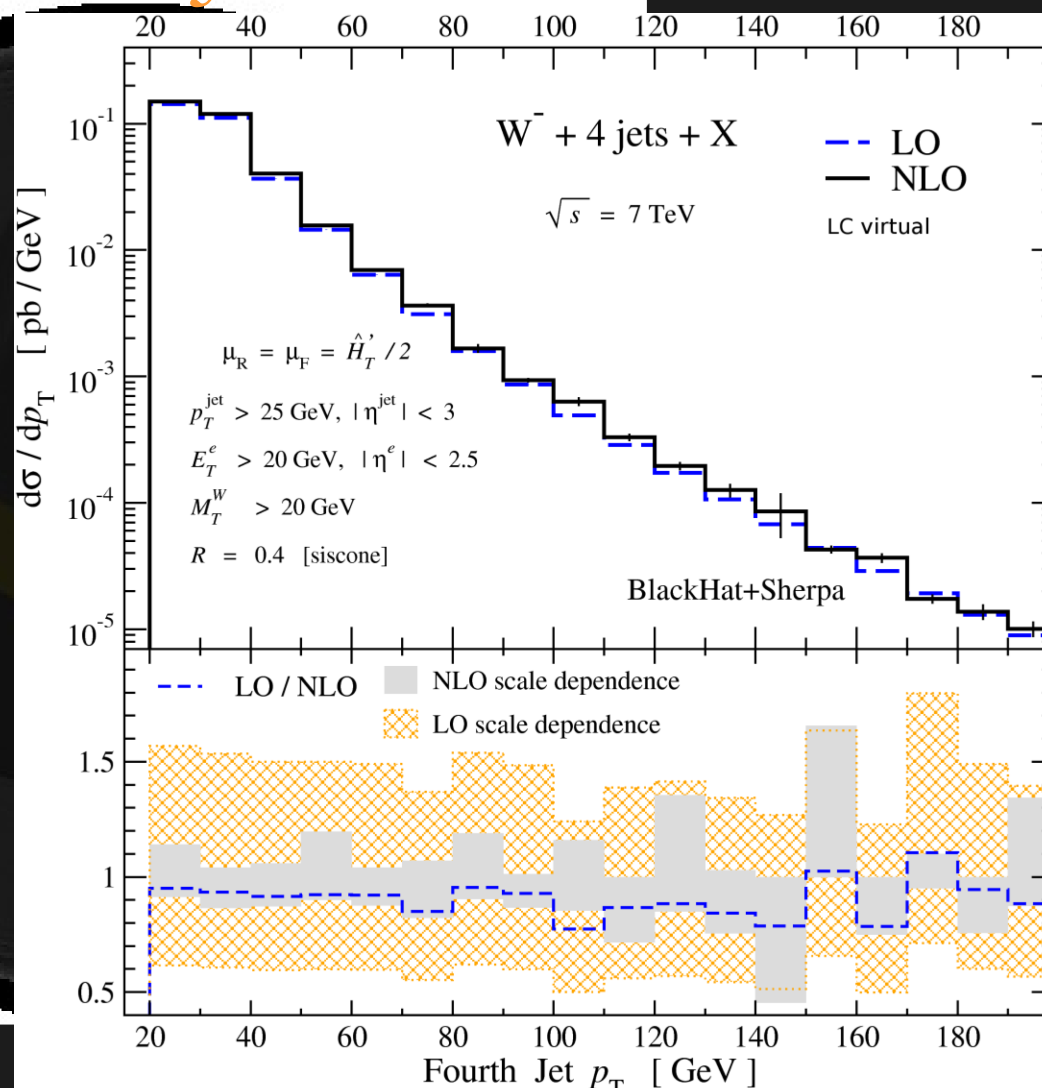
Z+3 Jets at the LHC

- NLO scale un ity smaller than L band accidentally narr given central choice — but wo ld in any case be much improved)
- Shape change mild
- Scale choice $\hat{H}_T/2$ (half total partonic E_T)
- Anti-k_T jets

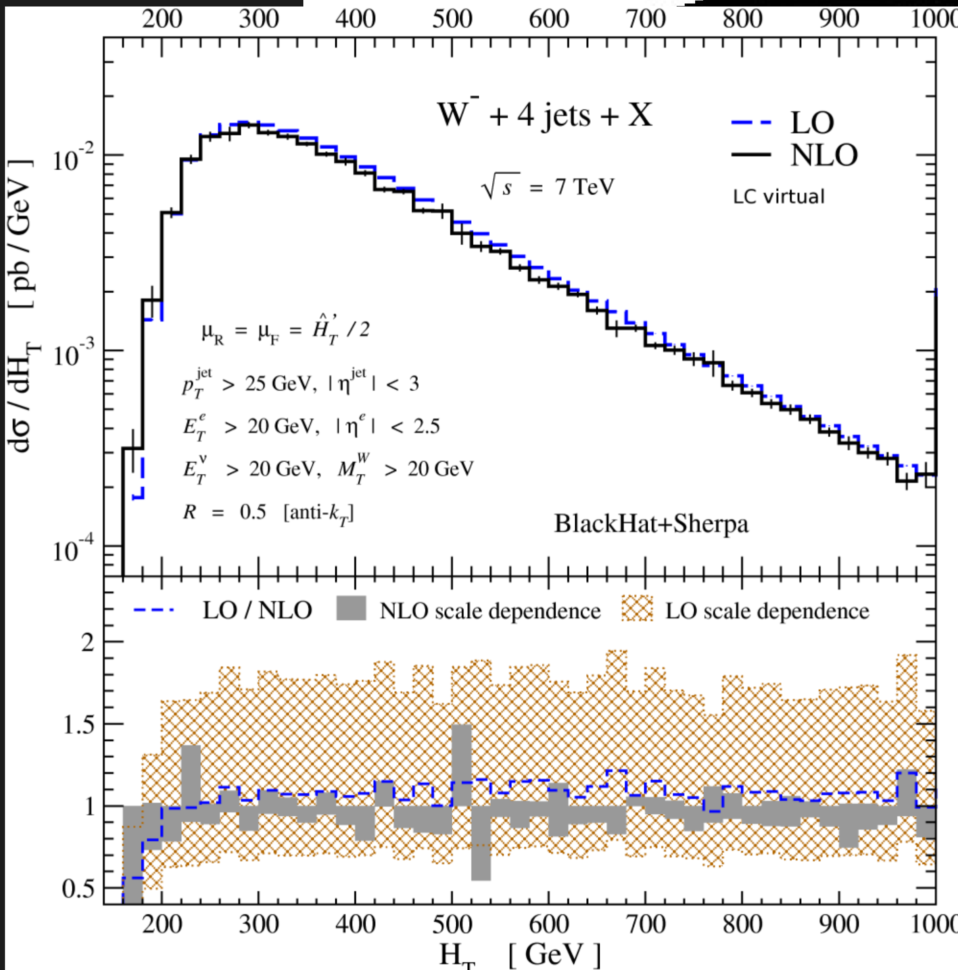


W^{-} + 4 Jets

- Background [illegible] quark studies
- Background [illegible] new physics searches
- High-multipl[illegible]city frontier
- SISCone, R = [illegible] 0.4

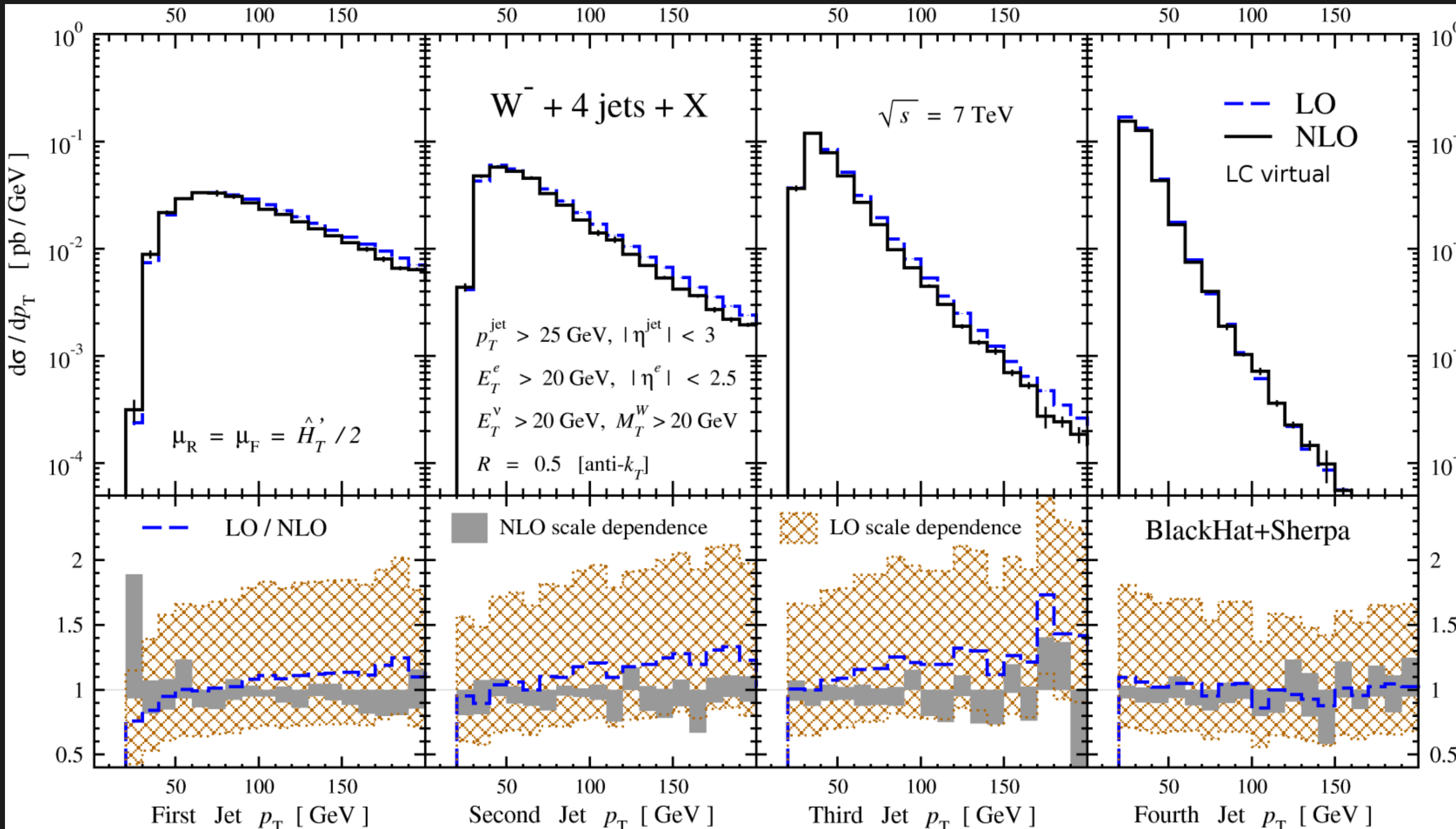


Total Transverse Energy

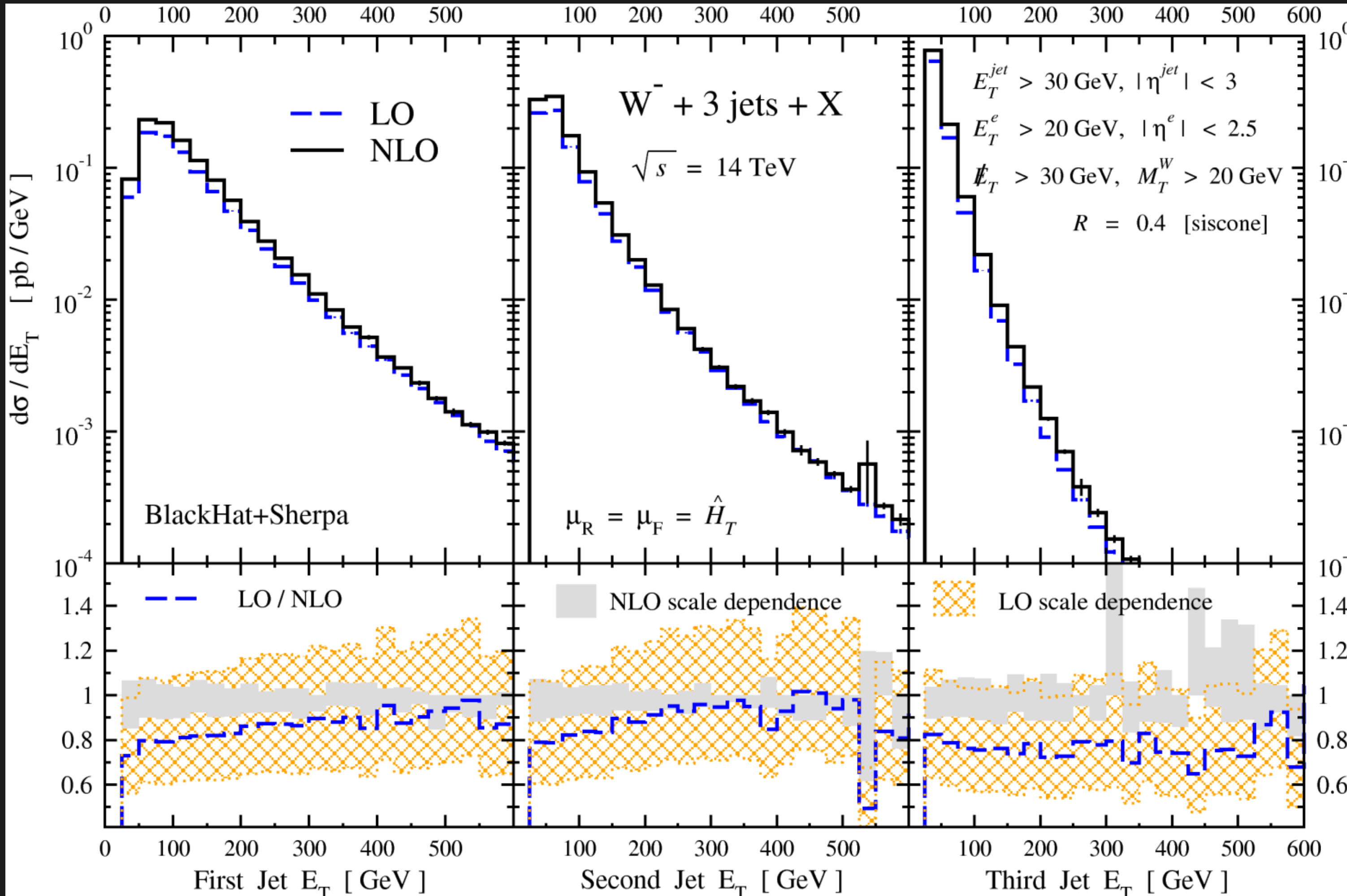


$$H_T = \sum_{\text{jets } j} E_T^j + E_T^e + E_T^\nu$$

- Useful distribution in new-physics searches
- Normalization corrected but shape is stable at NLO
- Anti-k_T jets $R = 0.5$

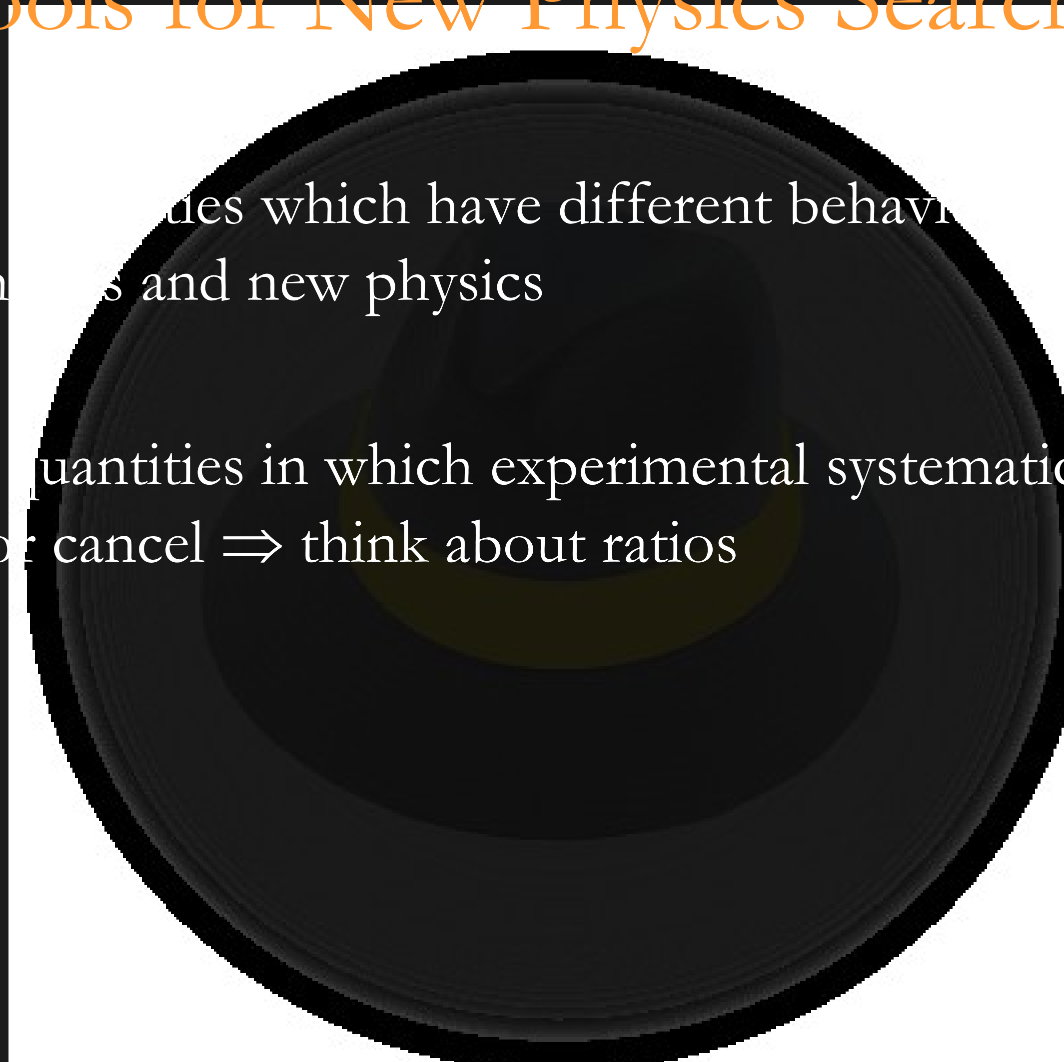


- All four jets … leading three show shape changes fr… LO to NLO
- Anti-k_T jets, … 5



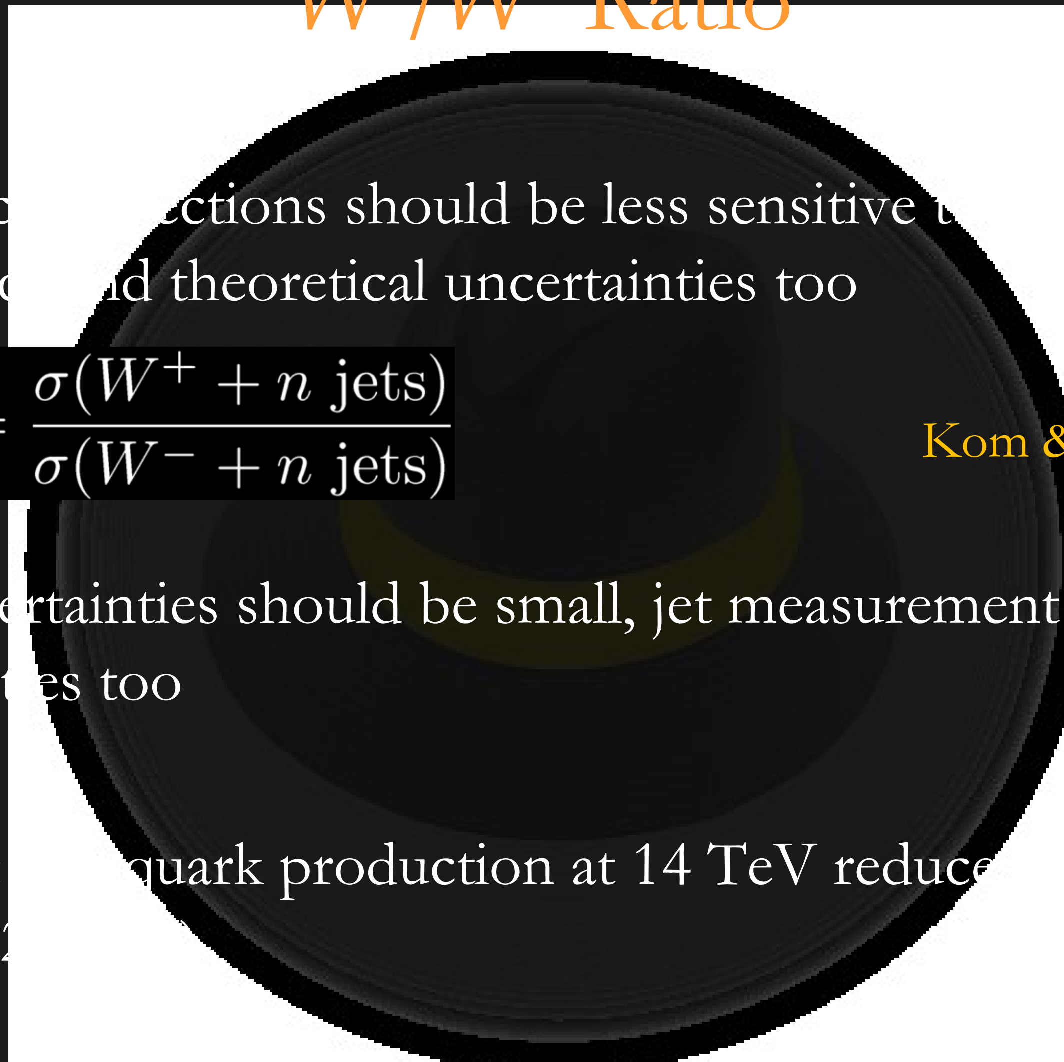
- Also seen … +3 jet production at 14 TeV (SIS…e): leading two jets h… corrections to E_T distrib…
- Cannot always choose scales to make all LO/NLO ratios flat simultaneously!

Tools for New Physics Searches



- Look for [illegible]ties which have different behavi[illegible]r Standard-Model ph[illegible]s and new physics
- Look for quantities in which experimental systematics are reduced or cancel ⇒ think about ratios

W^+/W^- Ratio



- Ratio of c… …ctions should be less sensitive t… …perimental systemati… …d theoretical uncertainties too

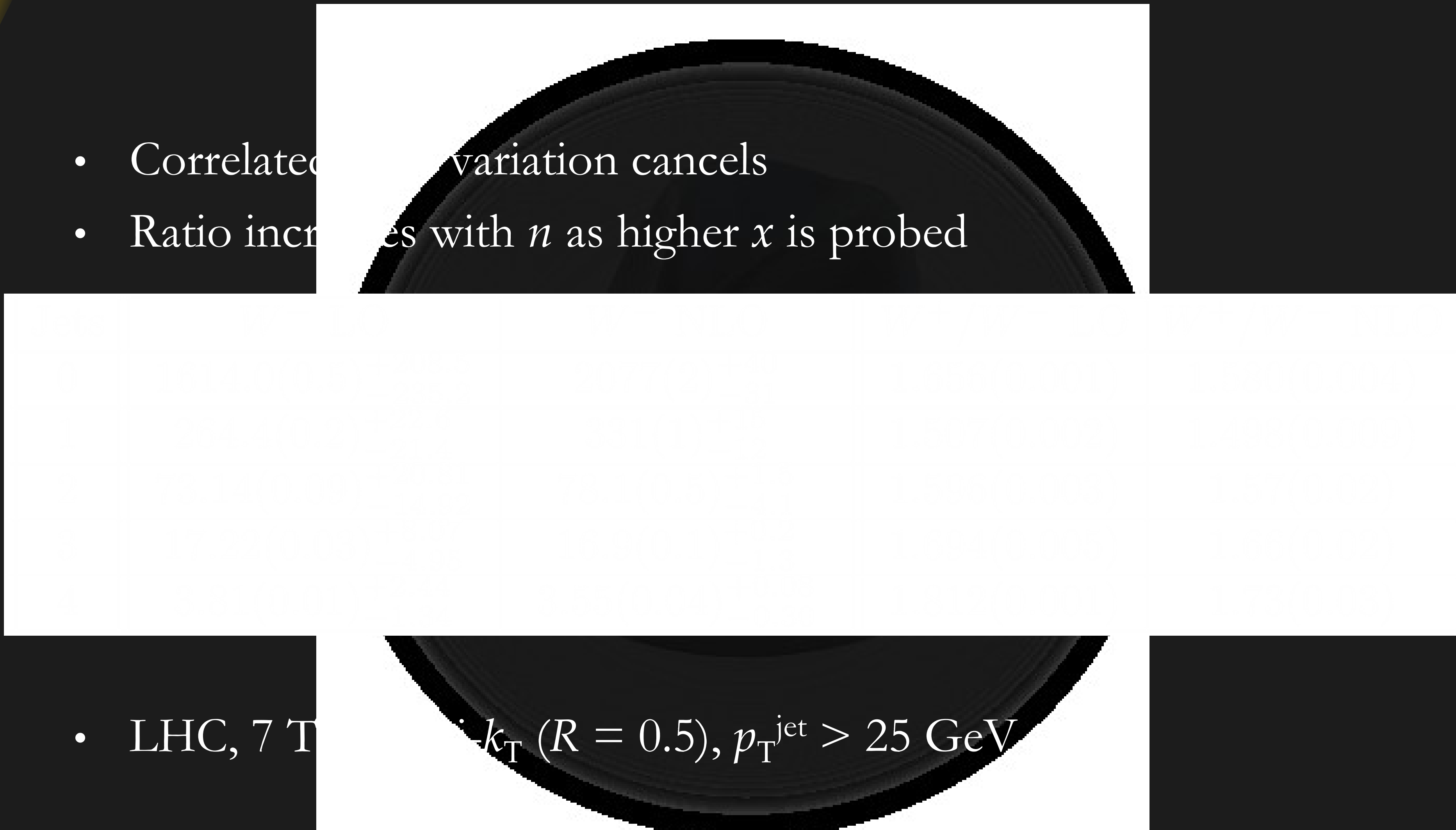
$$R^{\pm}(n) = \frac{\sigma(W^+ + n \text{ jets})}{\sigma(W^- + n \text{ jets})}$$

Kom & Stirling (2010)

- PDF unc…rtainties should be small, jet measurement uncertaint…es too

- Example: … …quark production at 14 TeV reduc… …$^{\pm}(4)$ from 1.44 to 1.…

- Correlate… variation cancels
- Ratio incr…es with n as higher x is probed



- LHC, 7 T… k_T ($R = 0.5$), $p_T^{jet} > 25$ GeV

Jet-Production Ratio in W+Jets

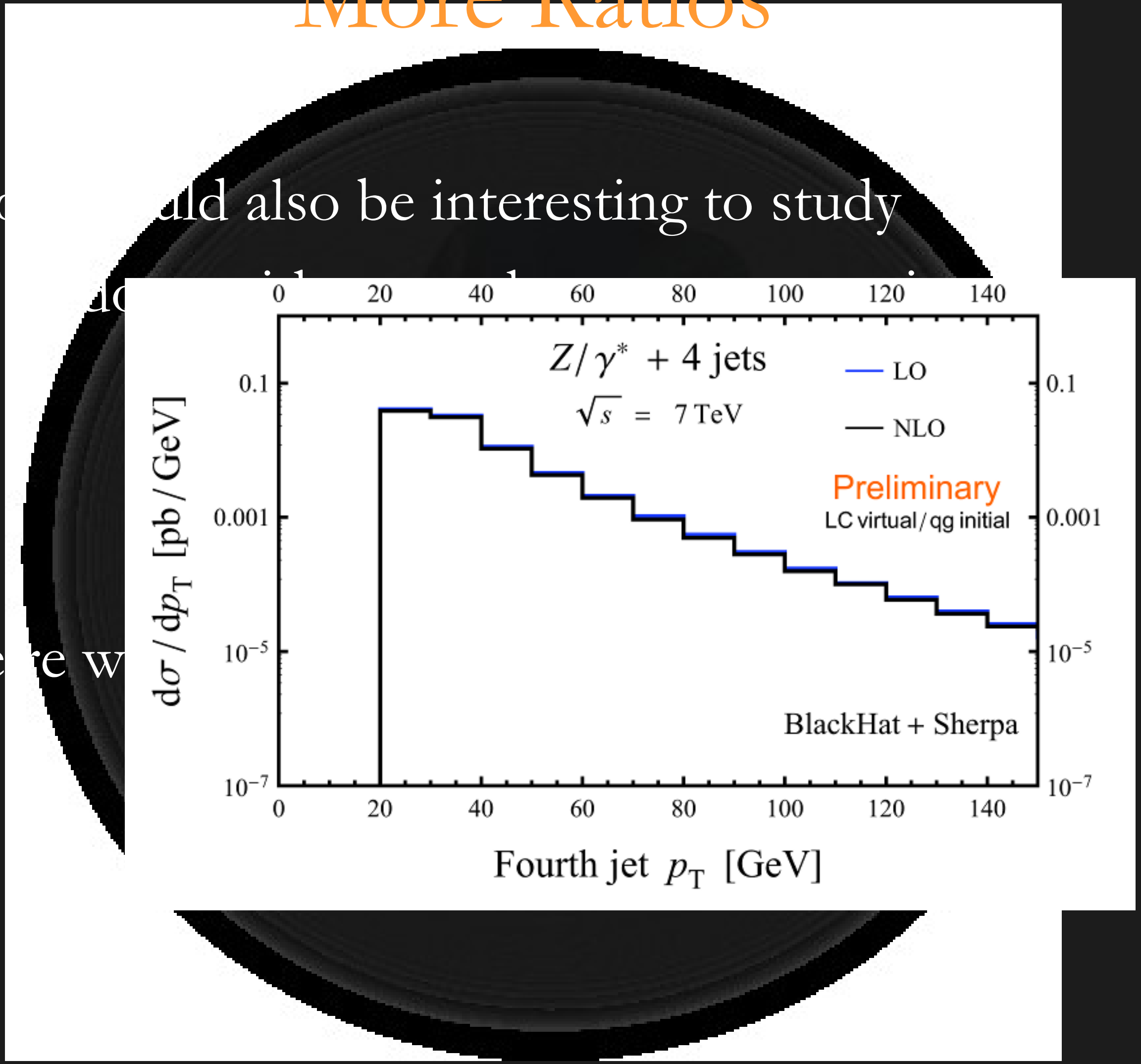
- Lore: ratio [illegible] $+n)/\sigma(W+n-1)$ should be indep[illegible]ent of n
- More dep[illegible]ence on jet systematics than W^+/W^-, [illegible]t much less than $W+n$ [illegible]ets

Jets	$W+n/(n-1)$ LO	$W+n/(n-1)$ NLO
1	0.1638(0.0001) [illegible]	0.159(0.00[illegible]
2	0.2766(0.0004) [illegible]	0.256(0.00[illegible]
3	0.2854(0.0005) [illegible]	0.26[illegible](0.00[illegible]
4	0.2812(0.0004) [illegible]	0.2[illegible]

- LHC, 7 T[illegible] [illegible]i-k_T ($R = 0.5$), $p_T^{jet} > 25$ GeV

More Ratios

- W/Z ratio[…]uld also be interesting to study
- Can now […]
- …and we[…]re w[…]



Summary

- NLO calc[illegible]equired for reliable QCD p[illegible]ons at the LHC
- On-shell m[illegible]ds are maturing into the method o[illegible]hoice for these QCD calc[illegible]ions

- BlackHat: [illegible]utomated seminumerical one-loop calculations
- Phenomen[illegible]logically useful NLO parton-level calculations:
  - *W*+3 jet[illegible] at Tevatron and LHC
  - *Z*+3 jets [illegible] Tevatron and LHC
  - First results for *W*+4 jets at LHC
  - Broad va[illegible]f kinematical configurations probed
- Detailed t[illegible]w-physics searches