W/Z+3 jets at NLO for Hadron Colliders

Darren Forde (CERN)

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In collaboration with C. Berger, Z. Bern, L. Dixon, F. Febres Cordero,
H. Ita, D. Kosower, D. Maître, T. Gleisberg

Overview

- Automating NLO computations & BlackHat.
- Example: W+3 jets using BlackHat +Sherpa.
- Results.

NLO?

- Increased precision beyond Leading Order (LO).
- Gives better control of shapes and normalization's of distributions.
- Reduced scale dependance, e.g. for W+jets,

No. of Jets	LO	NLO
1	16%	7%
2	30%	10%
3	42%	12%

NLO Calculations

- Leading order requires only a single piece - Tree amplitudes. Many tools exist for this.
- Three pieces are needed for a complete NLO computation,
  - Real piece - Tree amplitudes with one extra leg. Re-use leading order tools.
  - Virtual piece - One-loop amplitudes with the same number of legs.

Virtual Term

- The virtual term has been considered the bottleneck in such computations up until now.

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

- Only recently has significant progress been made on automating the computation of one-loop amplitudes.

NLO Calculations

- Automated One-loop amplitude codes using new techniques-
  - BlackHat [Berger, Bern, Dixon, DF, Febres Cordero, Gleisberg, Ita, Kosower, Maître],
  - CutTools [van Harmeren, Bevilacqua, Czakon, Papadopoulos, Pittau, Worek],
  - Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi],
  - Others [Lazopoulos], [Giele, Kunszt, Winter].
- Feynman diagram approach : Golem [Binoth, Guillett, Heinrich, Pilon, Reiter]+[Guffanti, Karg, Kauer]

Automated IR Subtractions

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- Real and virtual terms are separately IR divergent. Numerically subtract IR singularities from real and add back to the virtual. Procedure now automated.
- Catani-Seymour Dipoles
  - Automation within Sherpa [Gleisberg, Krauss]
  - MadDipole (in MadGraph) [Frederix, Gehrmann, Greiner]
  - Others [Seymour, Tevlin], [Hasegawa, Moch, Uwer].
- Frixione, Kunzst and Signer subtraction, MadFKS [Frederix, Frixione, Maltoni, Stelzer]

Automated IR Subtractions

$$\sigma_n^{\mathrm{NLO}} = \int_n \sigma_n^{\mathrm{tree}} + \int_n \left(\sigma_{n+1}^{\mathrm{real}} - \sigma_{n+1}^{\mathrm{sub}}\right) + \int_n \left(\sigma_n^{\mathrm{virtual}} + \int_1 \sigma_{n+1}^{\mathrm{sub}}\right)$$

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The Goal

- Automation & Mass Production
- Many processes required at the LHC. Use computers to do the tedious work!
- **BlackHat** - an automated package for computing one-loop amplitudes.

Automation

- NLO computation Goal: pick an automatic tree-level code, a one-loop level code and a subtraction code, combine to get full NLO result.
- Great flexibility. Combine one-loop code with your other favorite tools.
  - Choose the best tool for each part.
  - Reduces the sources of potential error.

BlackHat+Sherpa

- How does this work in practice?
- Example : BlackHat + Sherpa.

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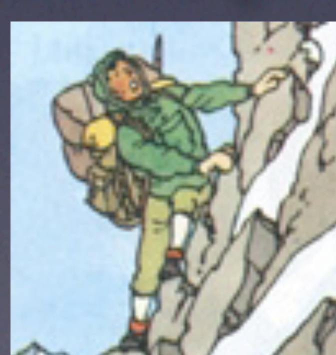
Sherpa

BlackHat



The Role of Sherpa

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

- We use this at the parton level only (AMEGIC++).
- Event generation.
- Efficient phase space integration of the real and virtual terms.
- Automated Dipole subtraction. [Catani, Seymour], [Gleisberg, Krauss]

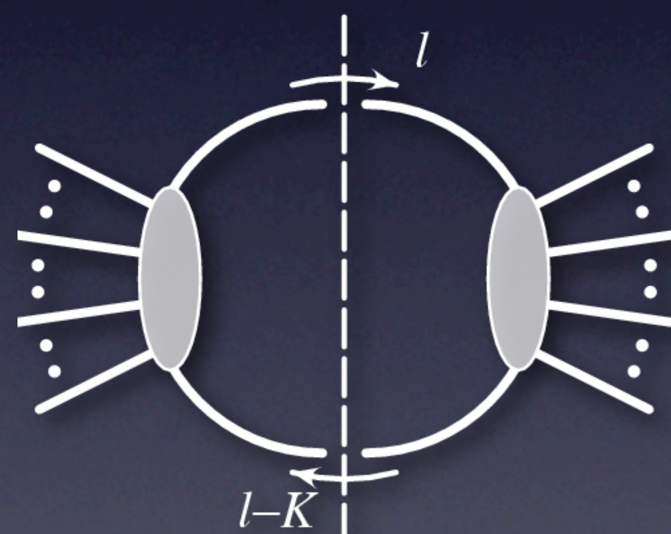
The Role of BlackHat

[Berger, Bern, Dixon, DF, Febres Cordero, Ita, Kosower, Maître, Gleisberg]

- Automated one-loop amplitude computation.
- Uses recent developments in unitarity & on-shell methods.
- Efficient computation of processes which would be much harder using Feynman diagram approaches.
- c++ framework.

Unitarity & On-shell methods

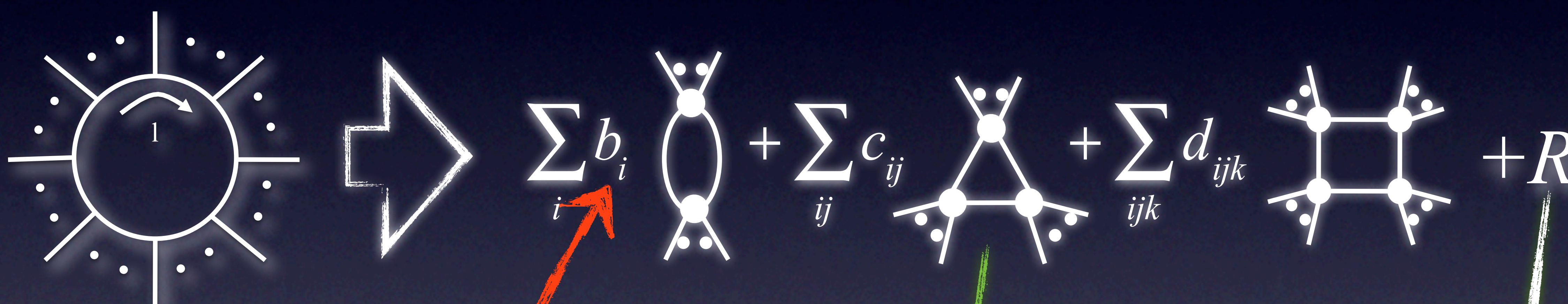
- Want to avoid using gauge dependent quantities, use only on-shell amplitudes.
- Unitarity: "Glue" together trees to produce loops.



- Efficient methods for computing trees lead to efficient computation of loops.

One-loop Basis

- Any one-loop amplitude can be decomposed into a standard basis of scalar integral functions,



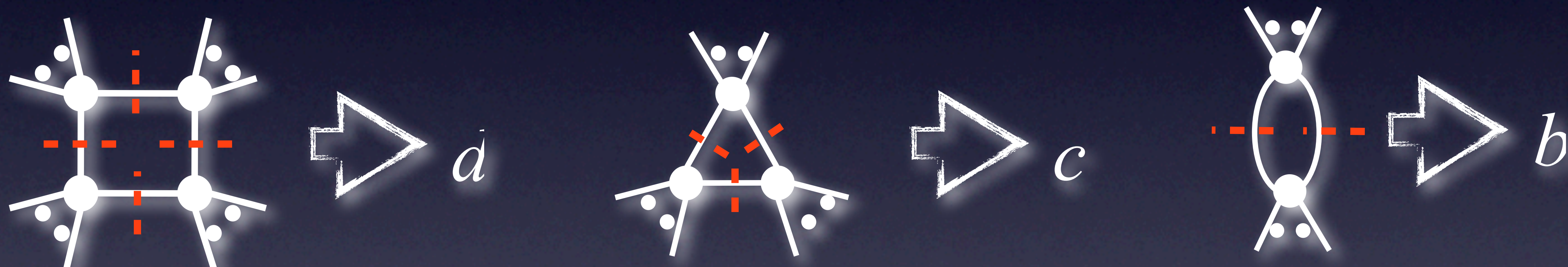
Scalar coefficients we want

All One-loop basis integrals known. (e.g. [Ellis, Zanderighi])

Use On-shell recursion or D-Dimensional unitarity.

Computing Coefficients

- Generalized unitarity, cut the loop more than two times, use to compute these coefficients. [Britto, Cachazo, Feng] [DF] [BlackHat]



- Similarly rational terms via D-Dimensional unitarity [Giele, Kunszt, Melnikov] [Badger] [BlackHat] or On-shell recursion [Berger, Bern, Dixon, DF, Kosower].
- Alternatively use OPP. [Ossola, Papadopoulos, Pittau]

BlackHat

- BlackHat is a numerical implementation of this.
- For massless particles and massive particles that do not enter the loop.
- Unitary approach completely general, will implement all massive particles in the future.
- Implements Binoth-Les Houches accord interface. Enables easy connection to external code.

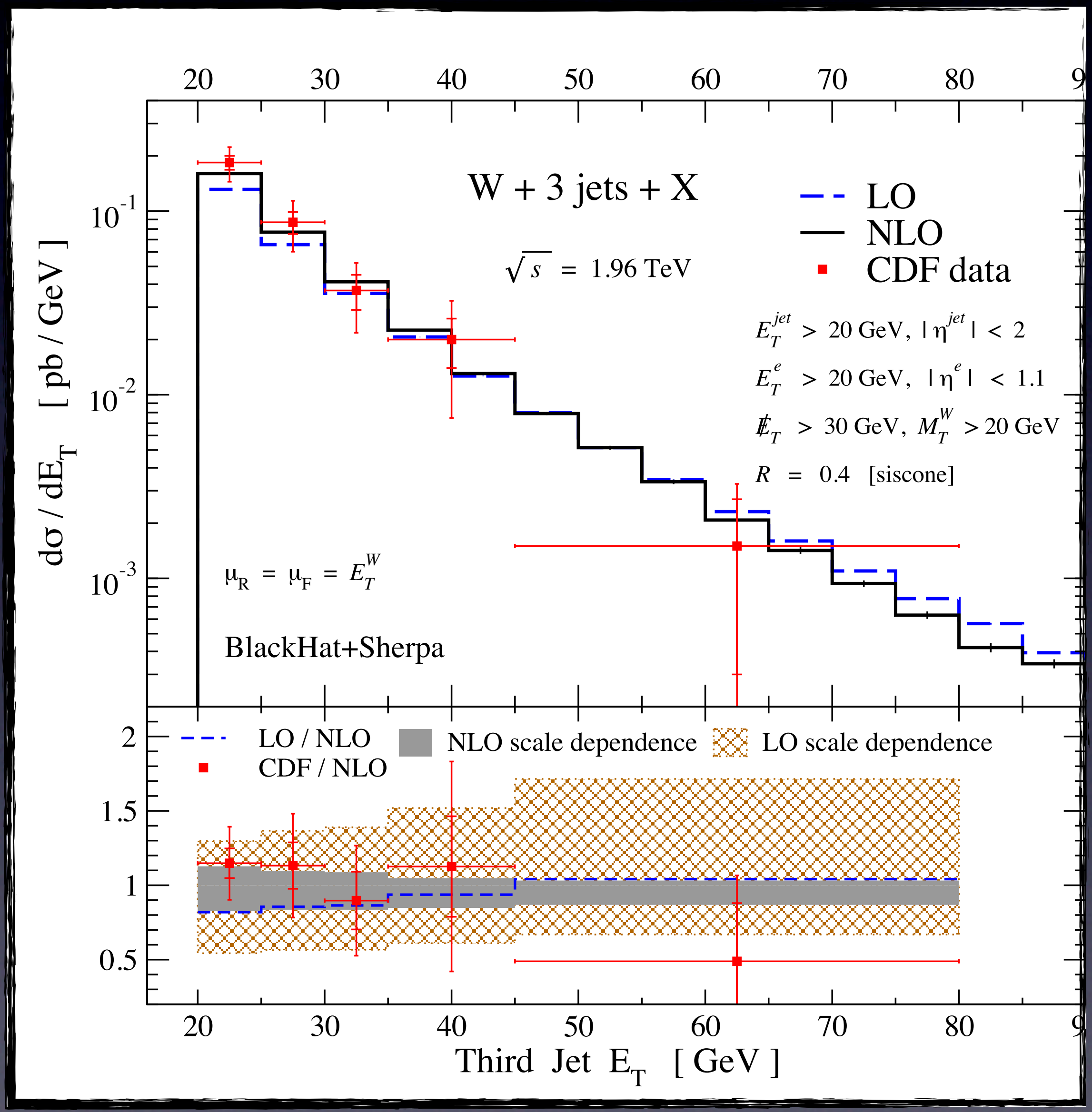
Results

W/Z+jets

- The W/Z+jets processes are important for
  - SM physics (e.g. Higgs, tt and single top)
  - Backgrounds to new physics.
  - Luminosity determination.
- Much recent work,
  - Full W+3 jets and Z+3 jets. [BlackHat]
  - Leading colour W+3 jets rescaled to account for sub-leading colour. [Ellis,Melnikov,Zanderighi], [Melnikov,Zanderighi]

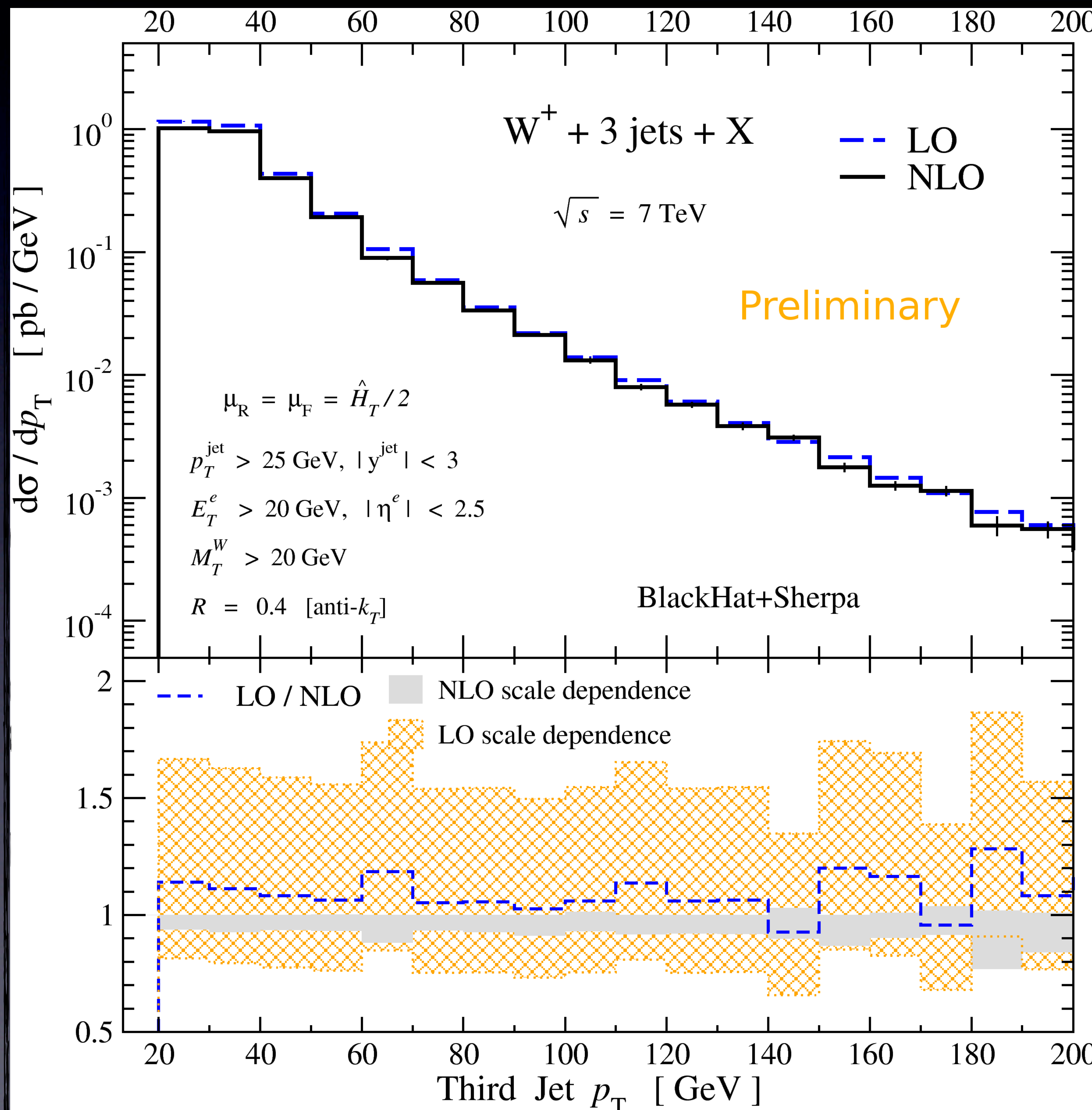
W+3 jets at the Tevatron

[Berger, Bern, Dixon, DF, Febres Cordero, Ita, Kosower, Maître, Gleisberg]



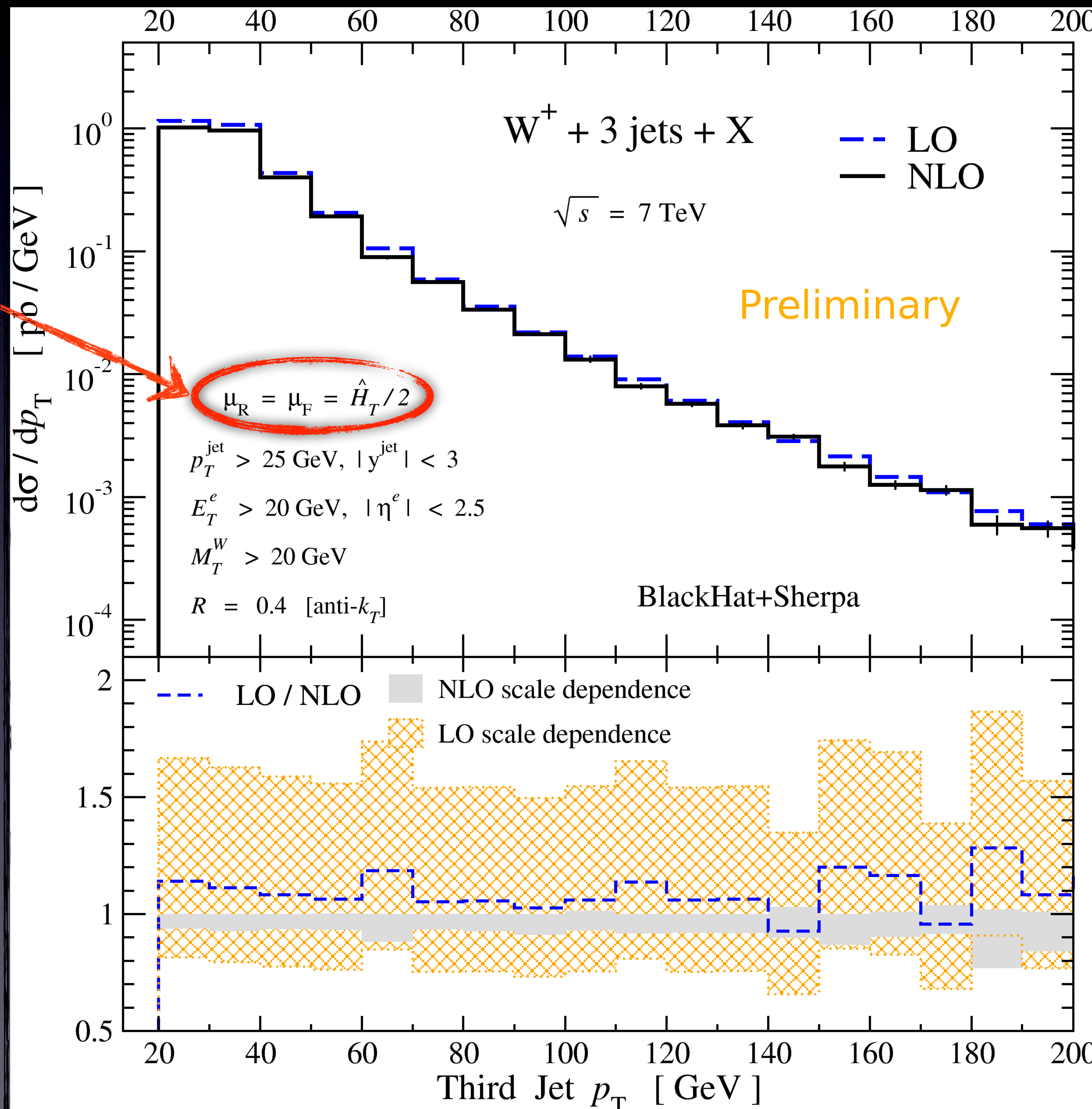
- Good agreement with Tevatron data. (arXiv:0711.4044)
- Reduced scale dependance at NLO.

W+3 jets at the 7 TeV LHC



W+3 jets at the 7 TeV LHC

Scale Choice is Important



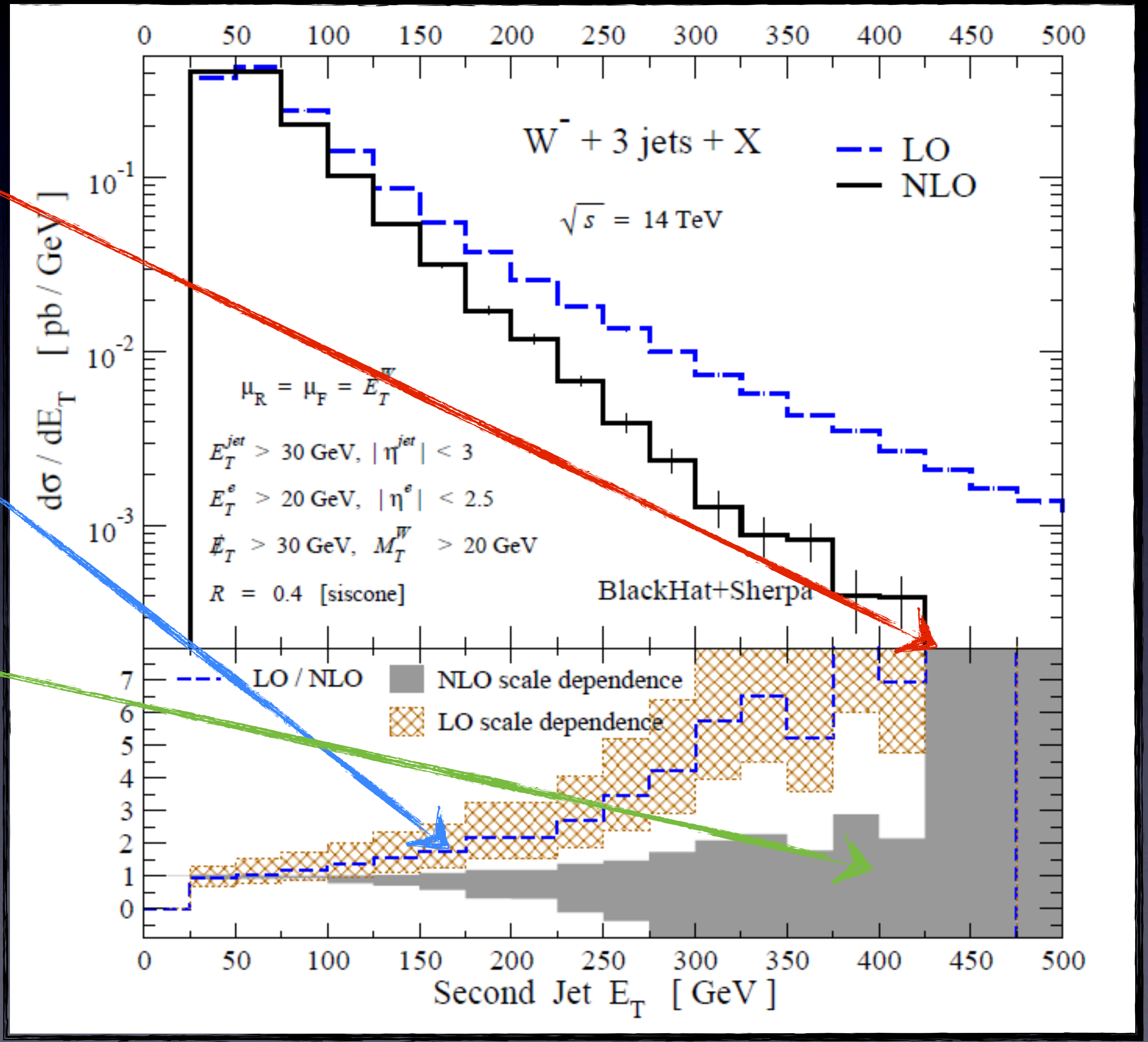
Scale choices

- A perturbative computation contains a dependance upon unphysical renormalisation and factorization scales.
- Careful choice of scale to minimize large corrections due to dropping terms in the perturbative calculation.
- Gets complicated when we have many scales in the problem.
- Choose scale event by event, what should the functional form of this be?
- Why differ from the usual choice for Tevatron W studies?

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

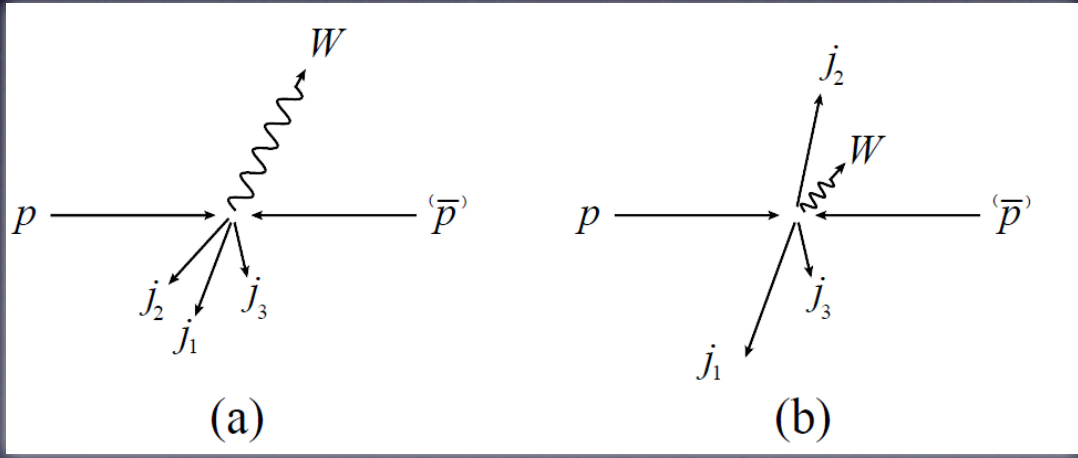
Difficulties with scale choice

- Negative Differential Cross section.
- Large deviation between LO and NLO.
- Rapid growth of scale bands with E_T.
- So this is a bad choice for NLO LHC studies.



Choosing the "Typical" Scale

- Compared to the Tevatron there is a much larger dynamic scale at the LHC, have jet E_T's much higher than M_W.
- Consider "scale" of the W in different configurations,

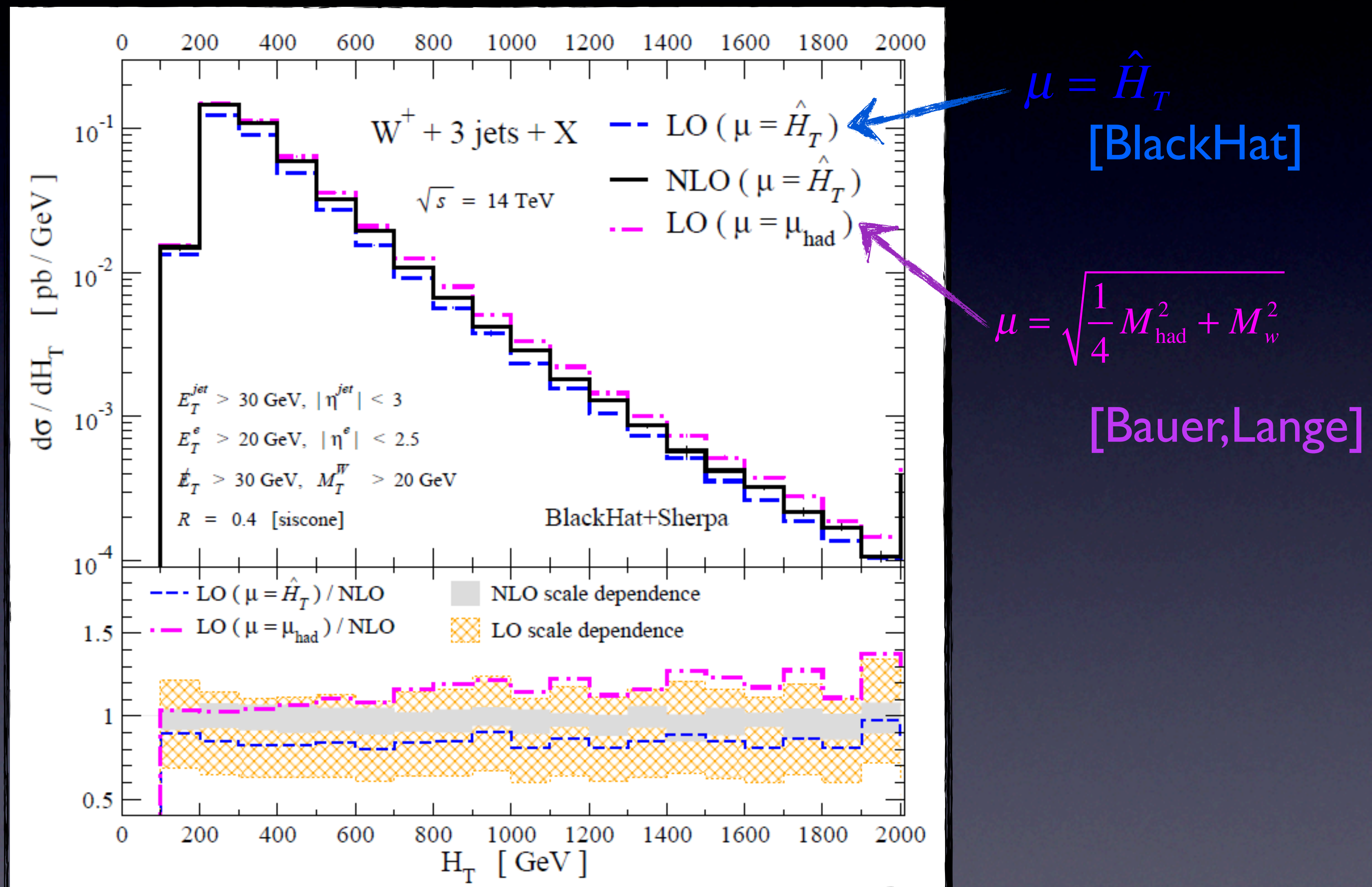


(b) is more favorable in the high E_T region of the second jet

- In (a) the W has a large p_T and so E_T is a good choice, but in (b) the W can have a low p_T, so not a good choice.
- Total (partonic) transverse energy is a better choice here as it gets large in both regions. (Or invariant mass of the n jets [Bauer,Lange])

$$\hat{H}_T = \sum_{j=1,2,3} E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$$

Alternative Scale Choices

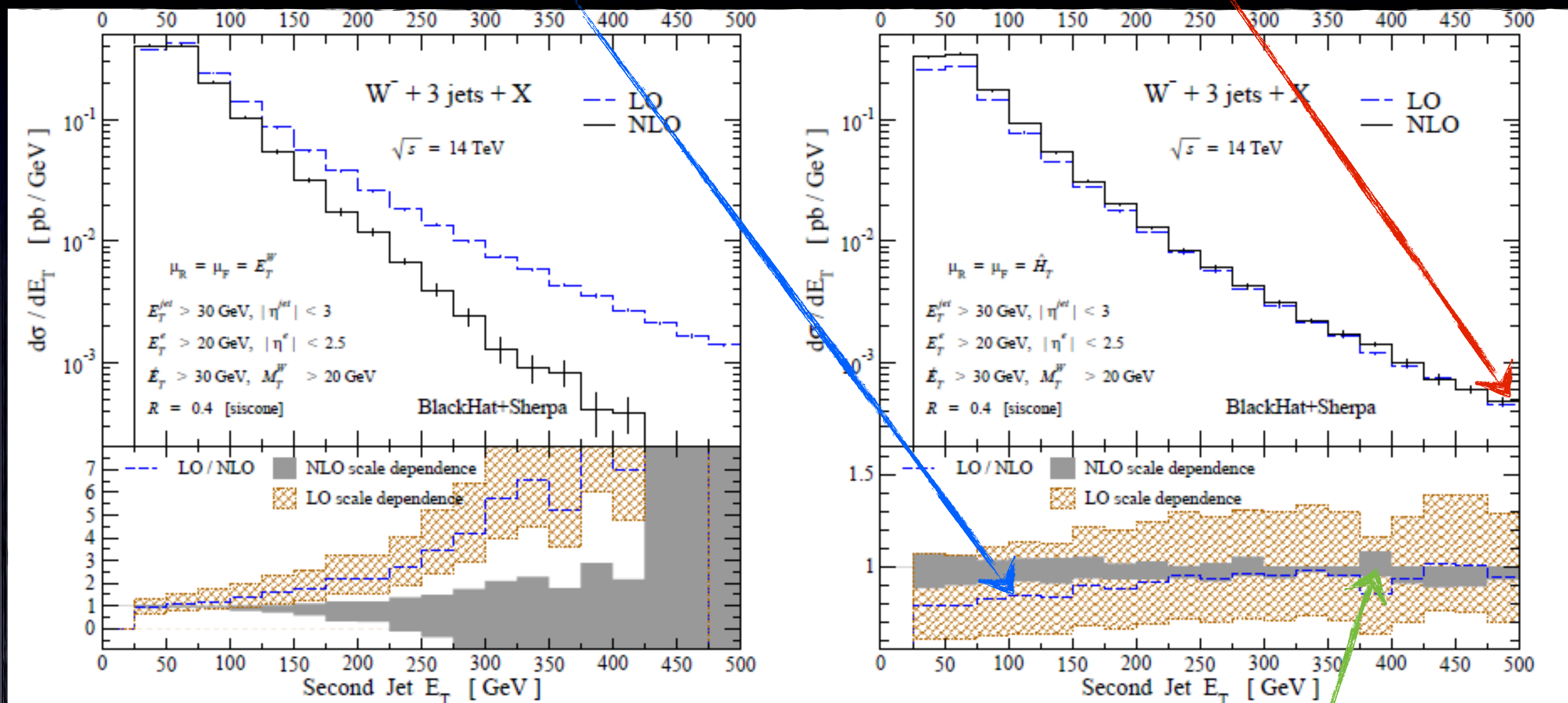


- Reasonable scale choices give similar results for the shape.

Comparing scale choices

NLO and LO much closer

Positive Differential Cross section.



Reduced scale variation between $\mu_{F/R}/2 \leftrightarrow 2\ \mu_{F/R}$

(accidentally narrower than "expected")

Lesson, need to be careful with how we handle scale choice.

Comparing scale choices

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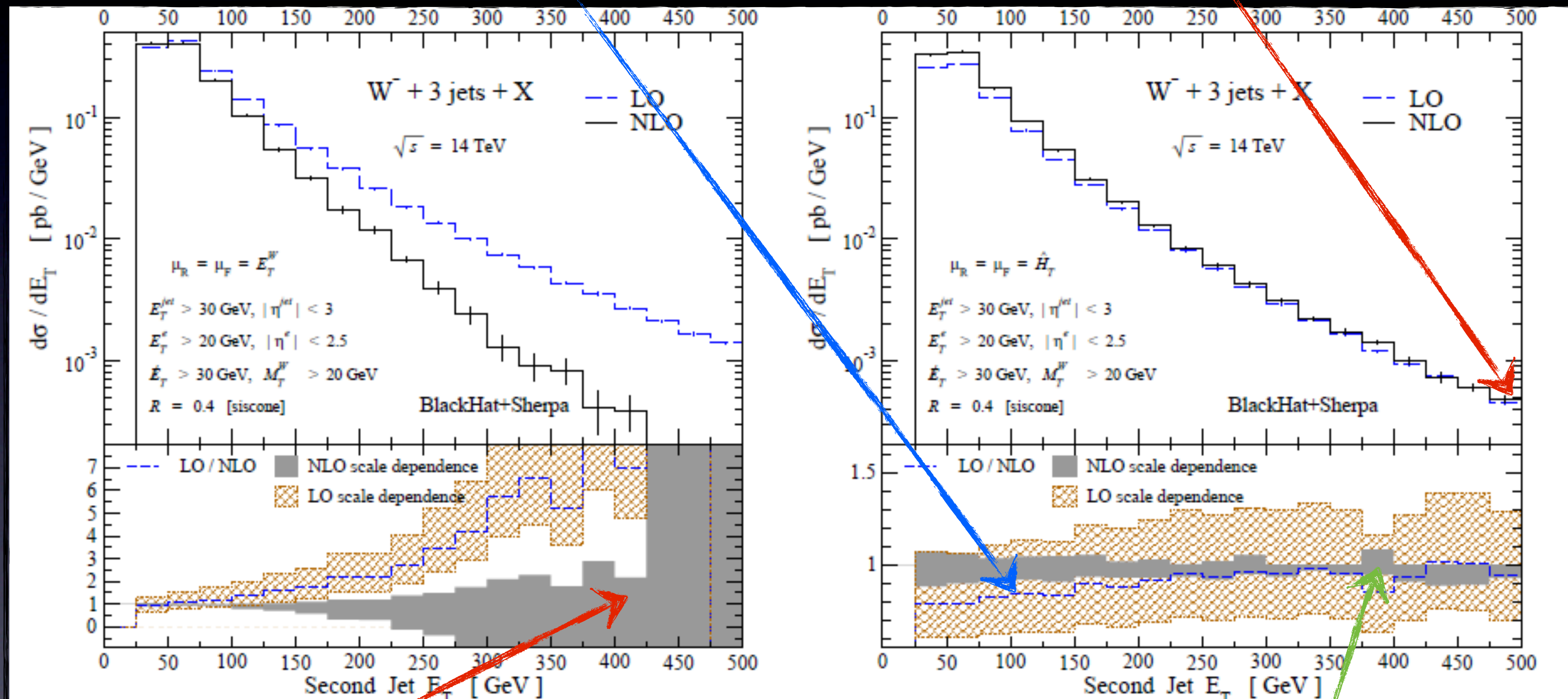

Relationship to "theoretical error"?

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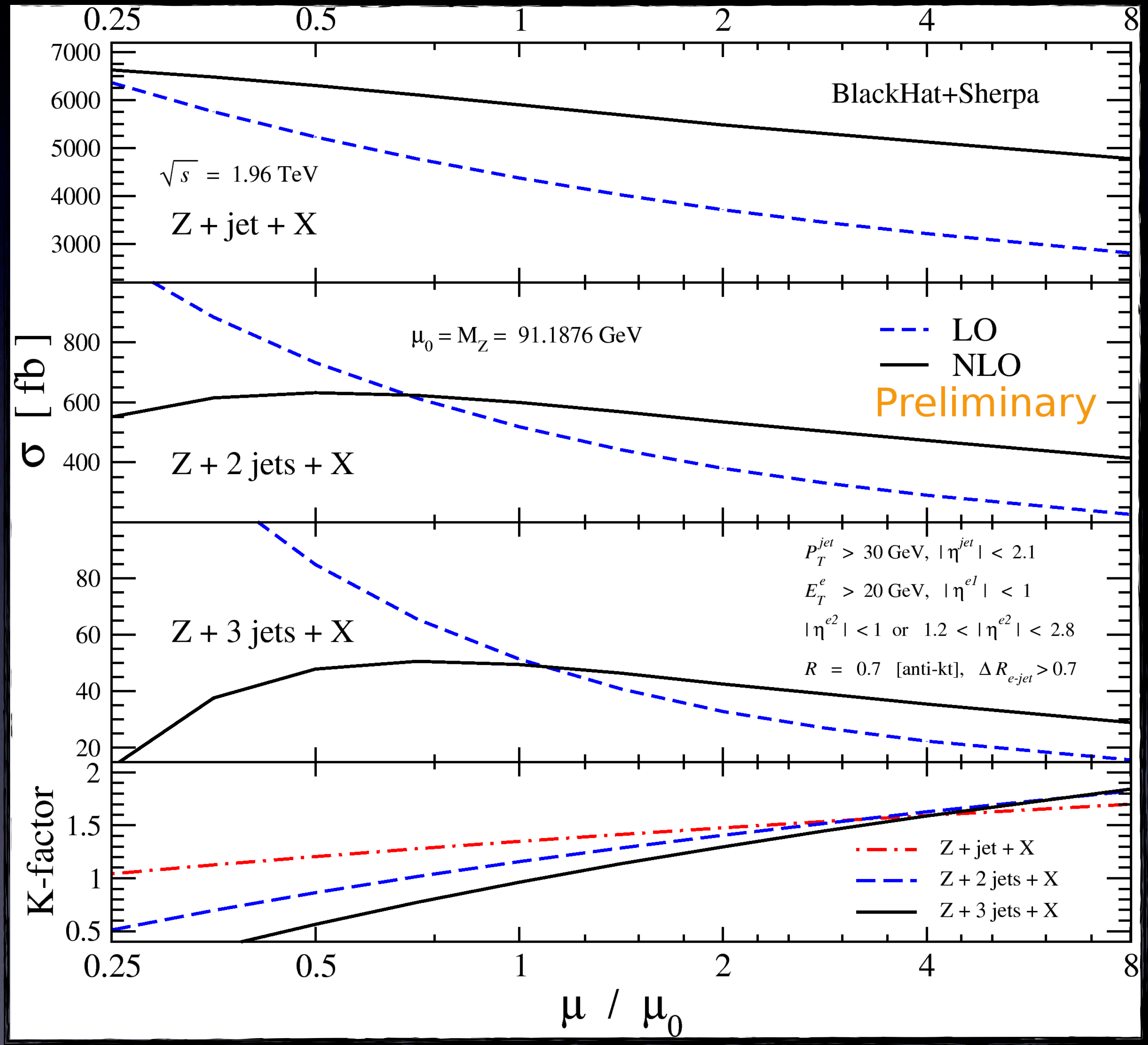
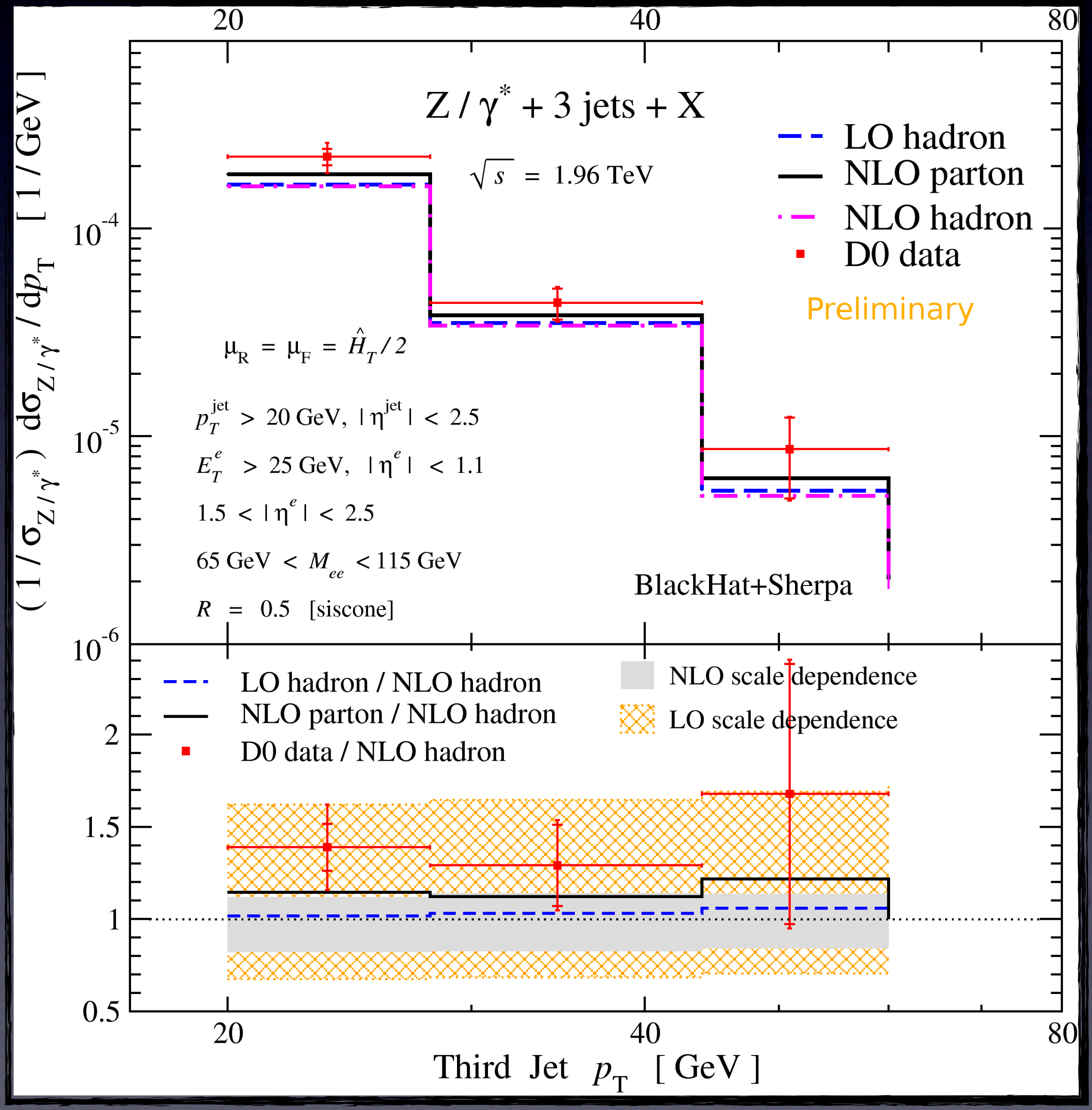
Z+3 Jets Scale dependence



- Improved scale dependence at NLO (more important at higher multiplicity)

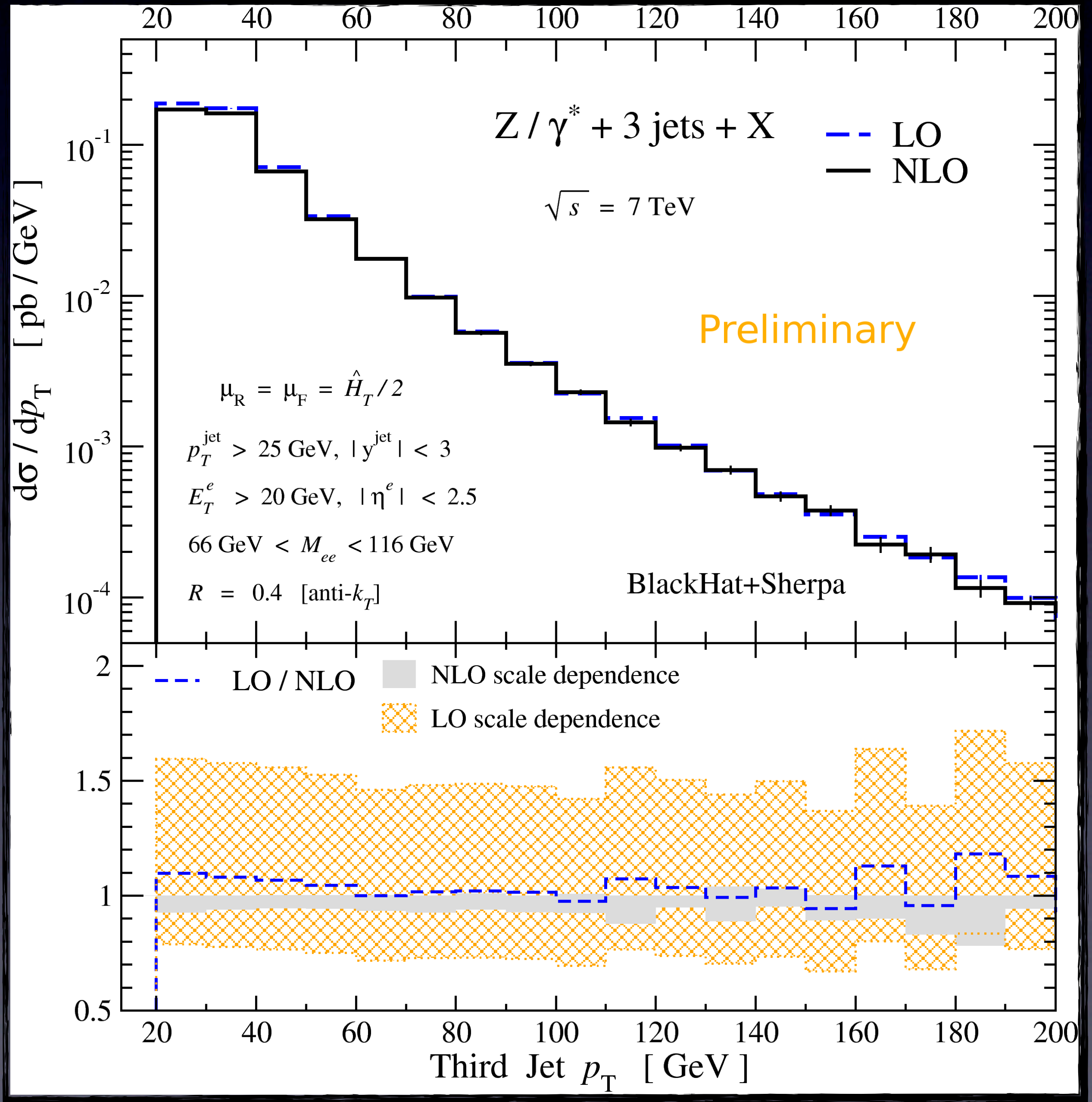
Z+3 Jets at the Tevatron

- Reasonable agreement with D0 data [0903.1748].
- SISCone [Salam, Soyez] rather than D0 midpoint.
- Parton calculation corrected to Hadron level using experiment-provided table.
- Reduced scale dependence.



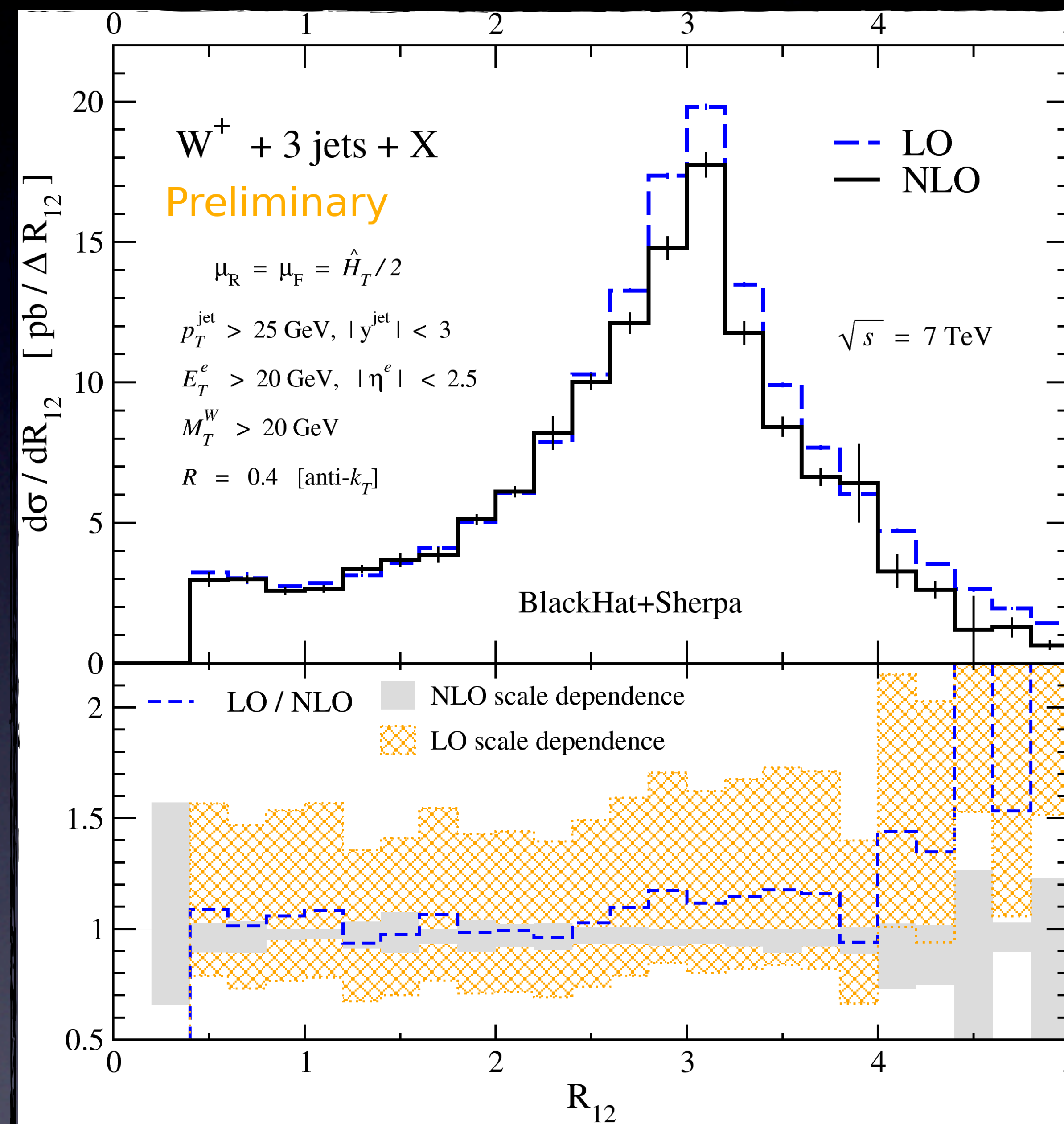
Z+3 Jets at the 7 TeV LHC

- Reduced artificially narrow scale variation band.
- Scale choice $H_T/2$.
- Mild change of shape.
- Can use W+3/Z+3 ratios to analyze missing E_T+3 jets.



Shape changes at NLO

- Distributions can change at NLO e.g. ΔR_{12}
  - Additional radiation allows jets to move closer together at NLO.
  - Alternatively to pure LO, use matrix element matching & showering (ME&TS) in SHERPA [Hoche, Huston, Maitre, Winter, Zanderighi]
- Need guidance from NLO.



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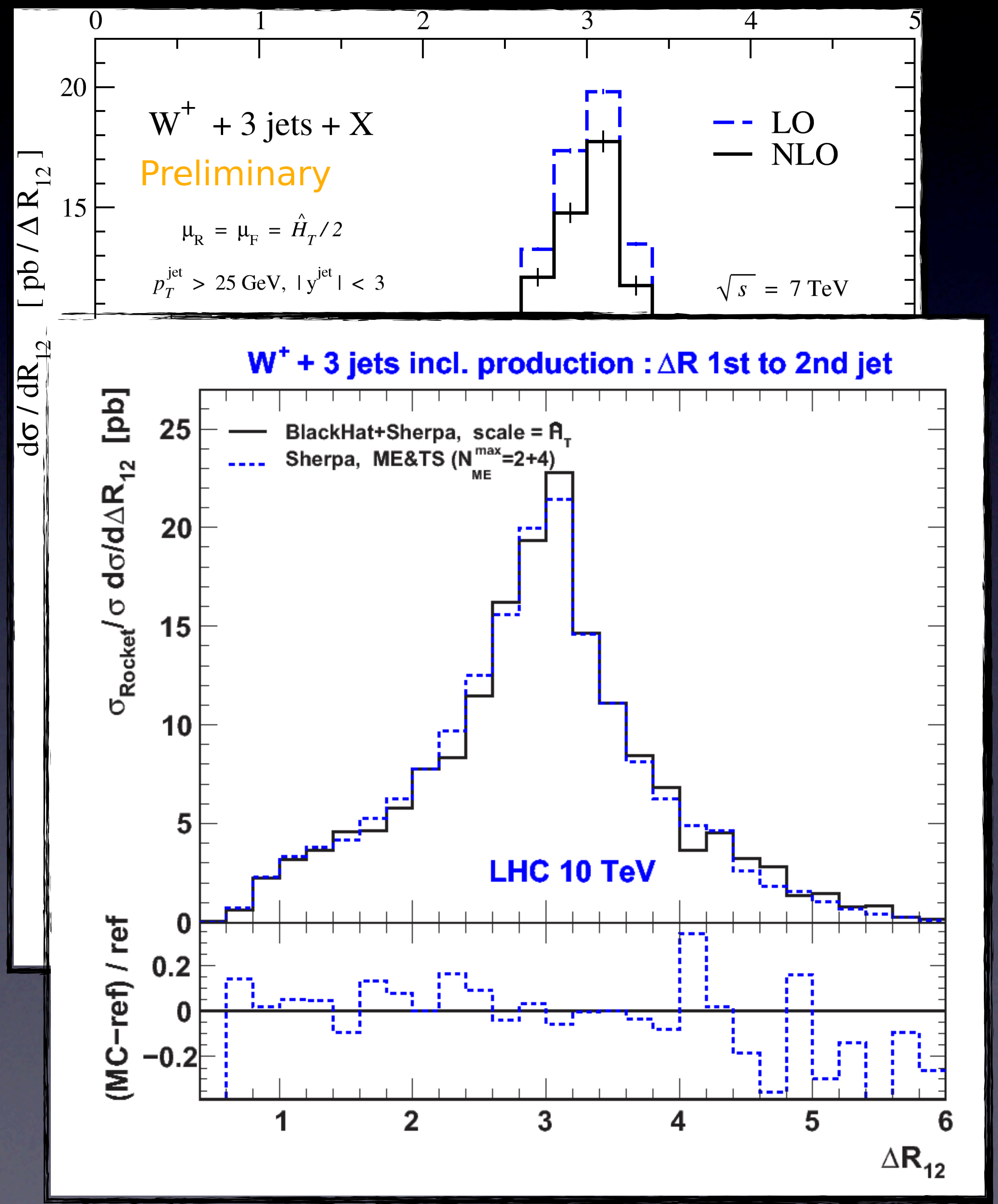
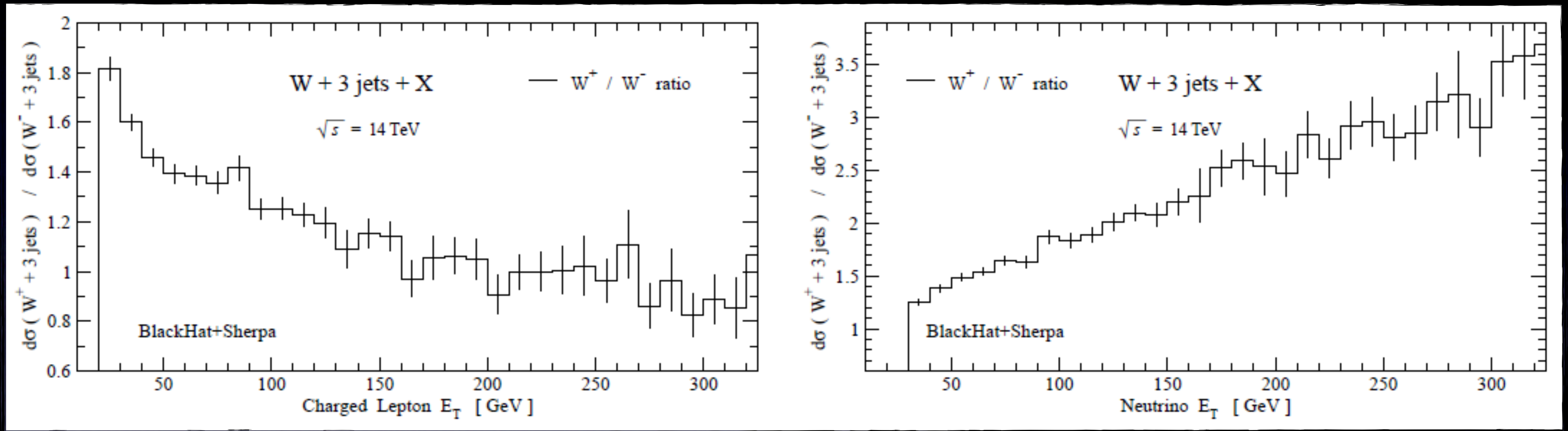


W^+/W^- Asymmetry



- There is a strong high p_T asymmetry in W^+/W^-, some asymmetry expected because of the dominant (at the LHC) qg initial state and $u(x)/d(x)$ pdf differences.
- Not the same as low p_T as seen at the Tevatron.
- Universal, seen at LO and in W+n jets n=1,2,3.
- Explained by predominantly left hand polarized W's at large $p_T(W)$.
- Top quark pair production does not have this asymmetry. Useful for separating W +n jets from top, possibly for new physics as well.

Jet production ratios in Z+jets

jet ratio	CDF	LO	NLO
2/1	0.099 ± 0.012	$0.093^{+0.015}_{-0.012}$	$0.093^{+0.004}_{-0.006}$
3/2	0.086 ± 0.021	$0.057^{+0.008}_{-0.006}$	$0.064^{+0.007}_{-0.006}$
4/3	—	$0.026^{+0.009}_{-0.012}$	—

jet ratio	D0	LO	NLO
2/1	0.150 ± 0.005	$0.153^{+0.026}_{-0.020}$	$0.147^{+0.003}_{-0.008}$
3/2	0.139 ± 0.012	$0.124^{+0.018}_{-0.013}$	$0.128^{+0.007}_{-0.010}$
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LHC 7 TeV Preliminary		
jet ratio	LO	NLO
2/1	$0.291(1)^{+0.052*}_{-0.038*}$	$0.246(4)^{+0.0009}_{-0.010}$
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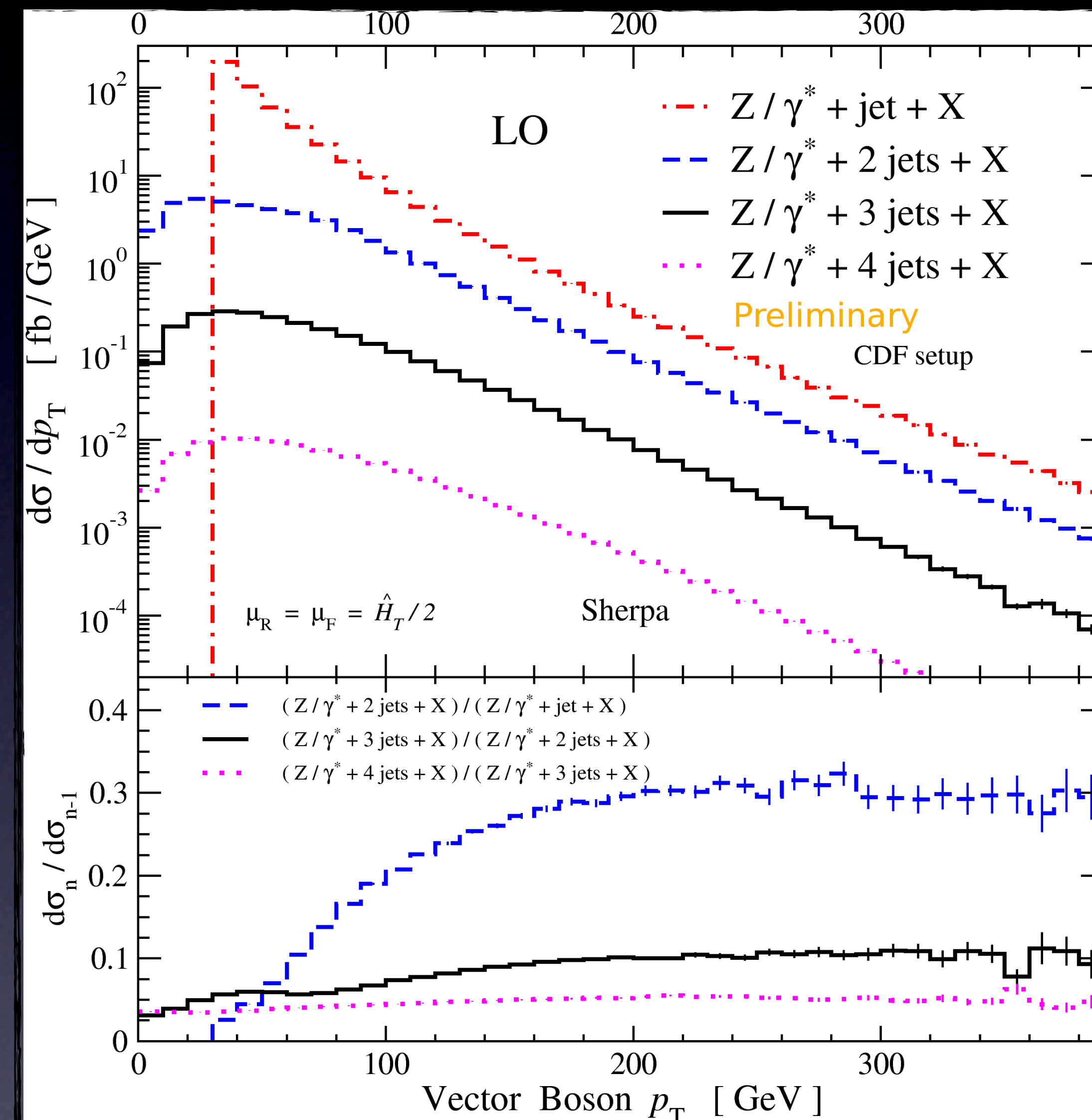

- “Berends ratio”.
- Ratios of jets should have reduced sensitivity to systematics.
- Differential distributions contain more structure.

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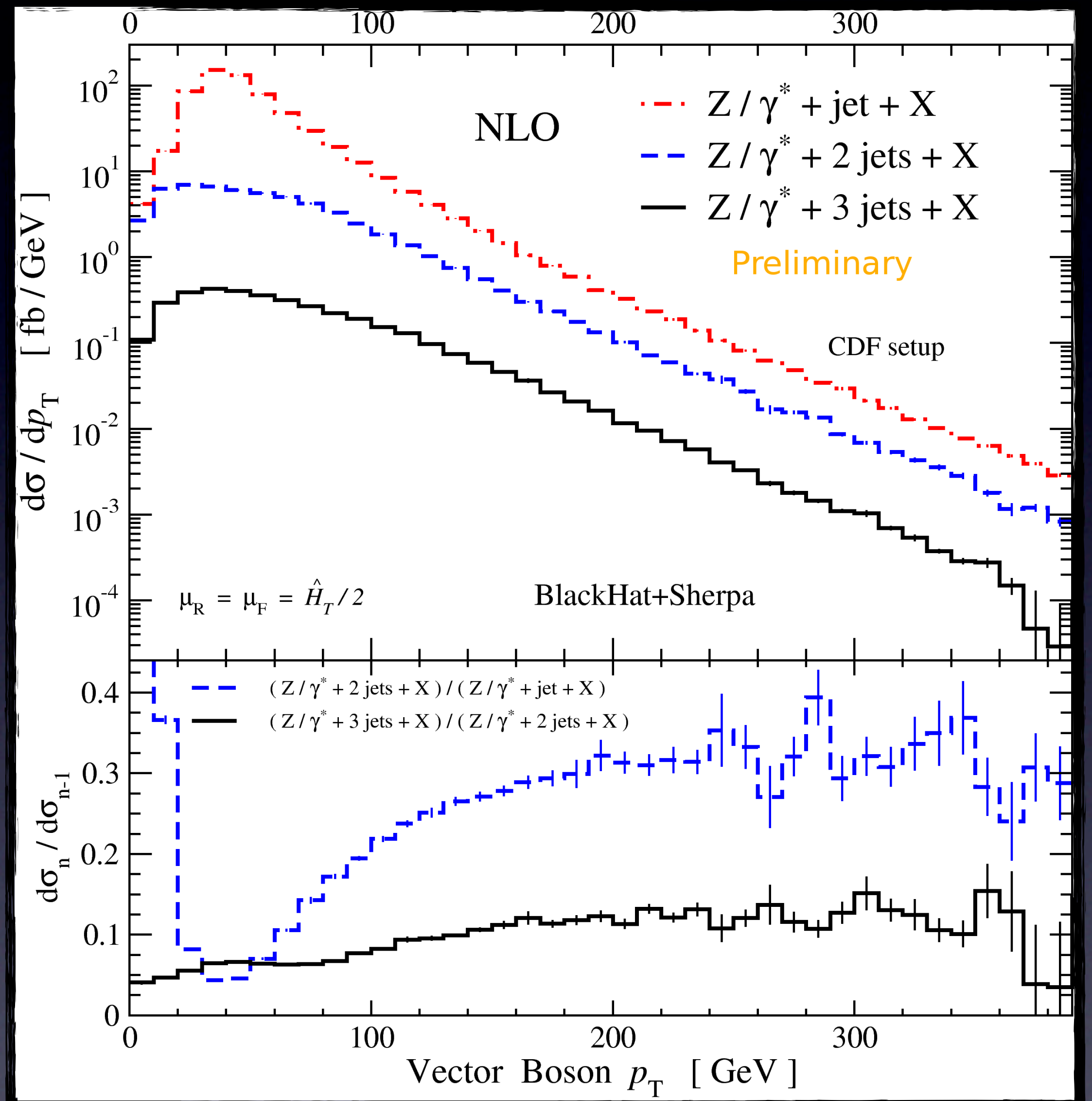

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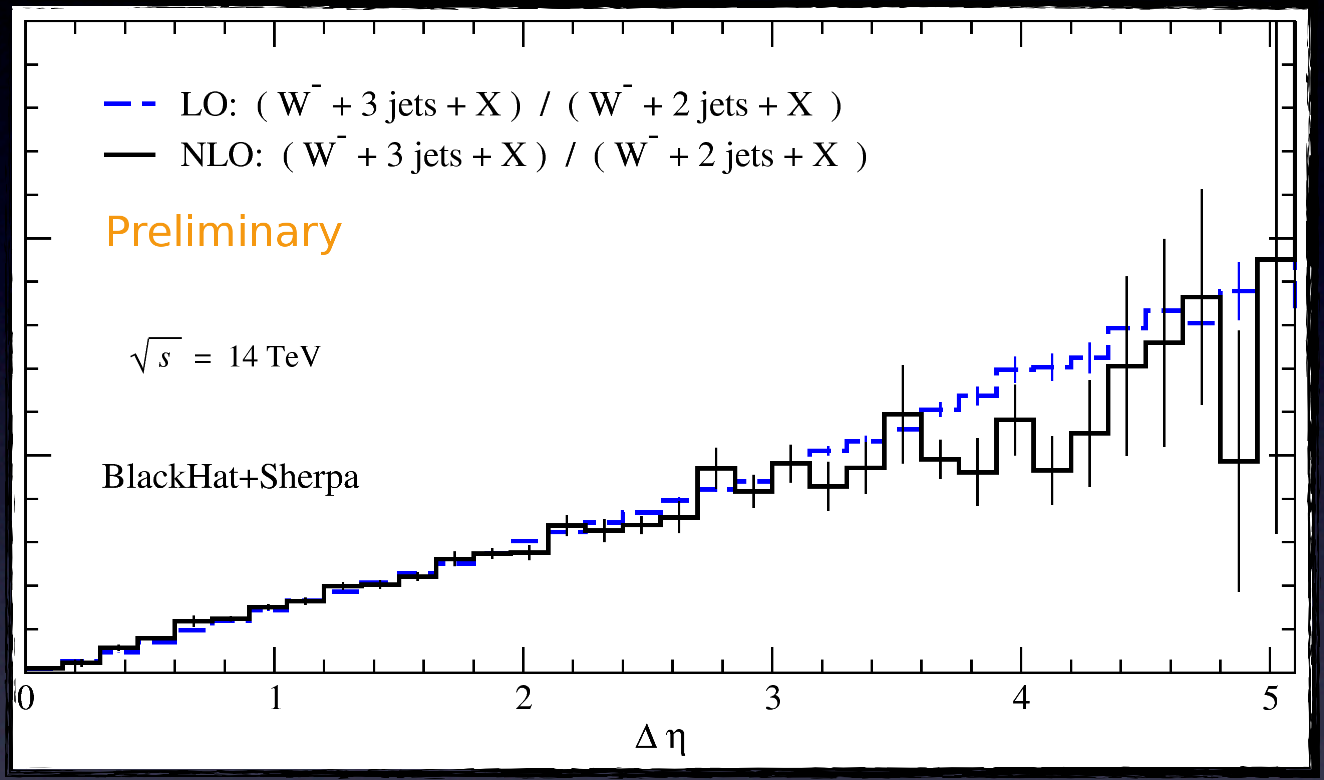
Radiation Between Jets



- NLO Study of emission between jets associated with colorless object production.
- Emission is approximately constant per unit of rapidity when tagged by largest η. (Similar result seen in [Anderson, Del Duca, White] [Anderson, Smillie])

Conclusion

- BlackHat - An automated one-loop computation package. Combine with Sherpa to produce NLO computations.
- Many new W+3 jet and Z+3 jet results.
  - Care needed with scale choices.
  - Improved understanding of Standard model processes, useful for new physics discovery.