Next-to-Leading Order Jet Physics with BlackHat

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on behalf of the BlackHat Collaboration
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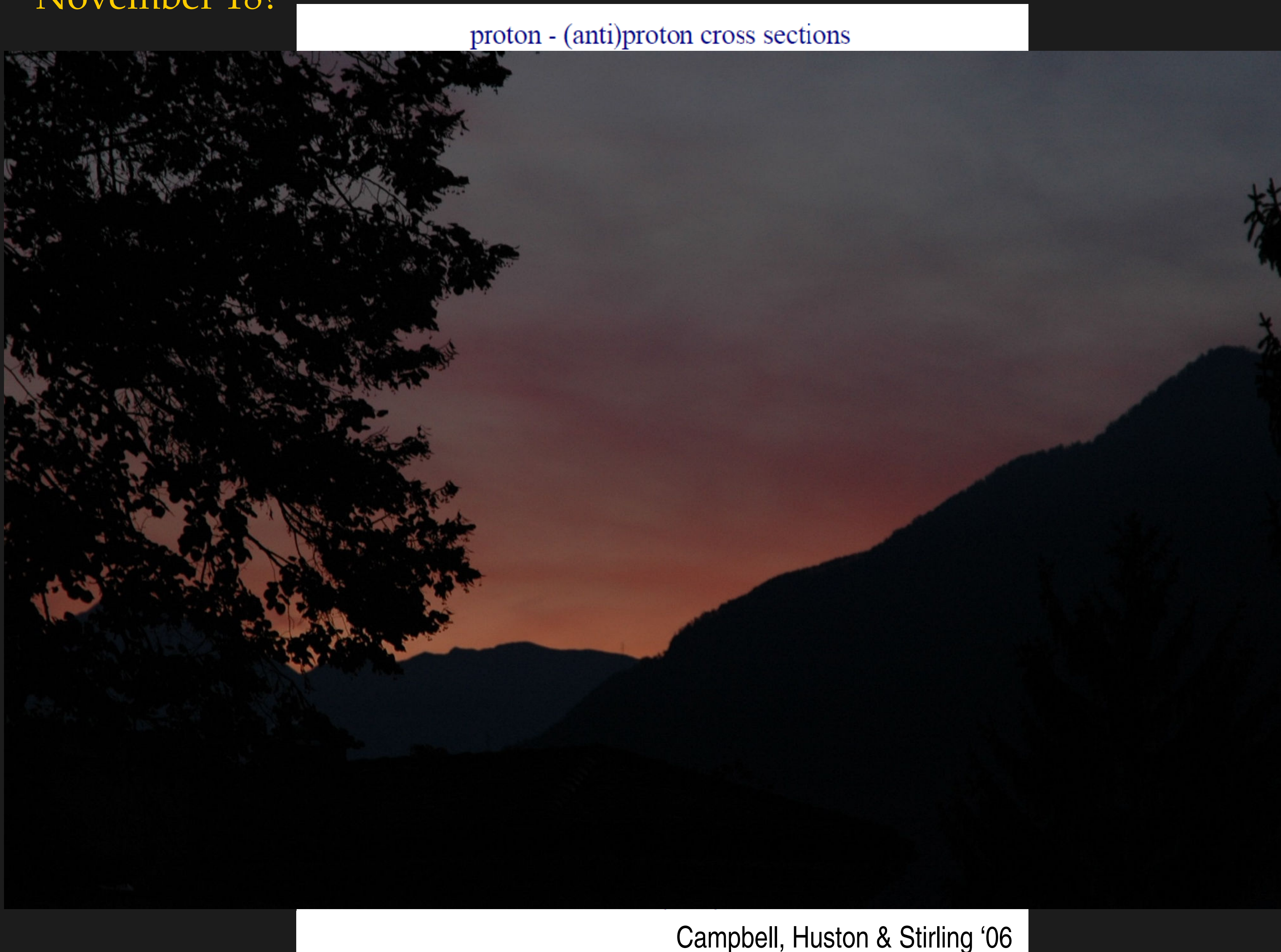
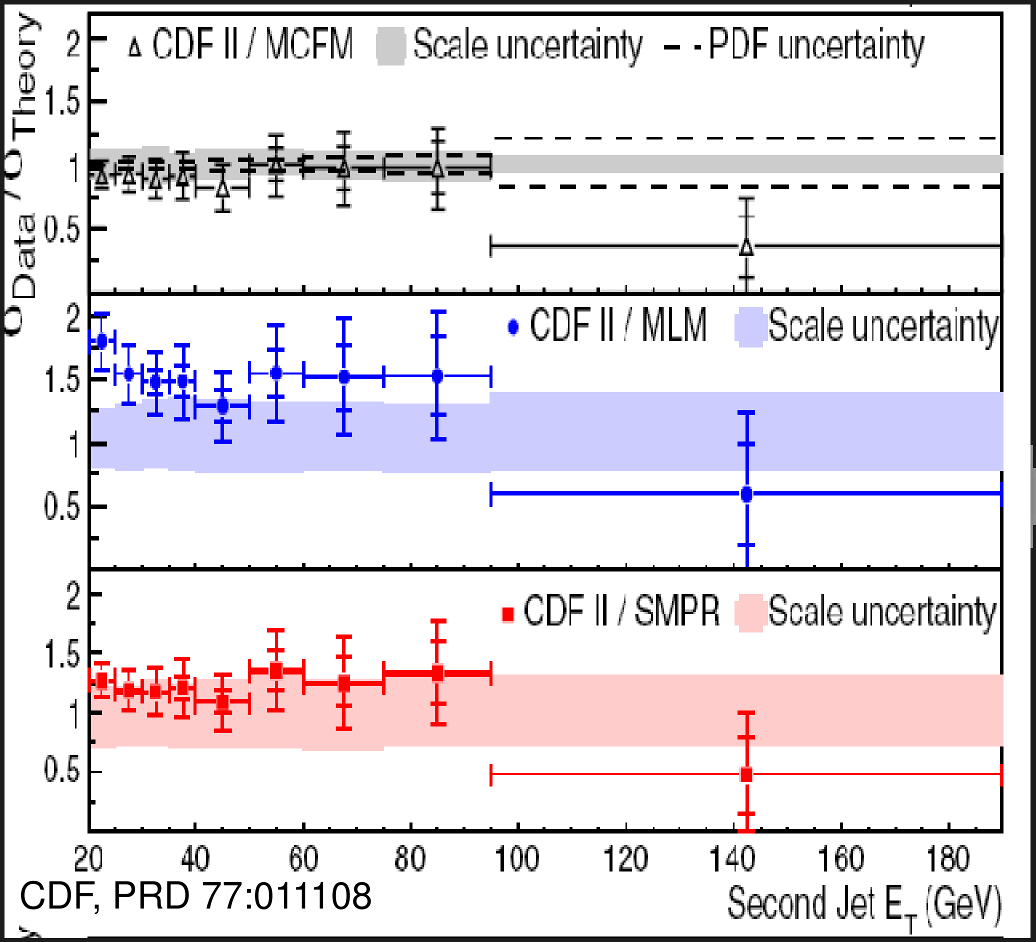
October 25–30, 2009

November 18?


proton - (anti)proton cross sections
Campbell, Huston & Stirling '06

Why NLO?

W+2 jets



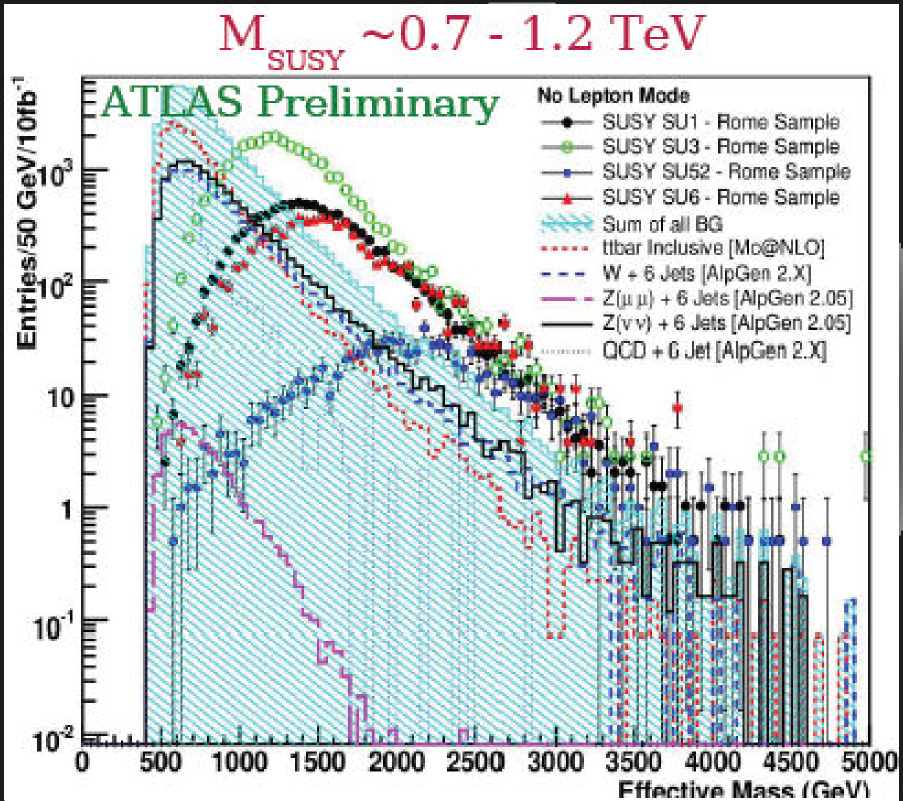
← NLO (MCFM)

← PS+LO matching

← PS+LO matching

- …need quantitative predictions; for *W*+more jets too

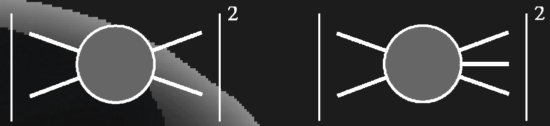
Backgrounds to New Physics



Ströhmer, WIN '07

Ingredients for NLO Calculations

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



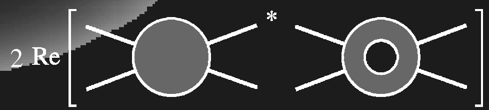
- Singular (soft & collinear) behavior of tree-level amplitudes, integrals, initial-state collinear behavior *known since '90s* ✓
- NLO parton distributions *known since '90s* ✓
- General framework for numerical programs *known since '90s* ✓

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

- Automating it for general processes ⇒ Frederix's talk

  Gleisberg, Krauss; Seymour, Tevlin; Hasegawa, Moch, Uwer; Frederix, Gehrmann, Greiner (2008)

- Bottleneck: one-loop amplitudes



- W+2 jets (MCFM) → W+3 jets

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

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

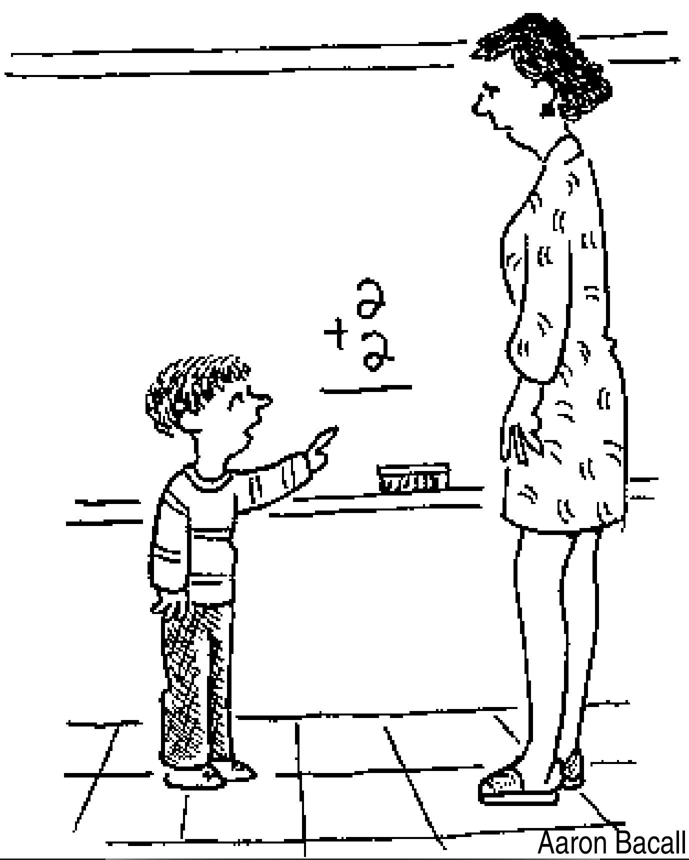
Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Campbell

Traditional Approach

- Pick a process
- Grab a graduate student
- Lock him or her in a room
- Supply caffeine, a modicum of nourishment, and occasional instructions
- Provide a computer, a copy of *Mathematica* & a C++ compiler



"Rather than learning how to solve that, shouldn't I be learning how to write software that can solve that?"

Industrialization

- Moving from bespoke calculations to mass production is more than just automation
- Need a technology which scales
- Likely to be dominantly numerical (more direct, fewer pieces)
- Gain insight by thinking about computational complexity
  Don't get hung up about prefactors or nitpick about precise values of n

- Polynomial complexity scales well (example: Berends–Giele recursion relations with caching ⇒ Giele's talk)
- Numerical evaluation critical to obtaining this scaling

- Extend polynomial complexity to loops: use numerical implementation of on-shell methods

- For the future:
  - Identical contributions: remove by symmetry (phase space)
  - Correlated contributions: sum via Monte Carlo (helicities?)
  - Anticorrelated contributions: sum explicitly
  - Expansion in color orders: $O(1)$ at leading color, $O(n^4)$ at next-to-leading color

Intelligent Automation

- BLACKHAT Carola Berger, Z. Bern, L. Dixon, Fernando Febres Cordero, Darren Forde, Harald Ita, DAK, Daniel Maître, Tanju Gleisberg
  - On-shell Methods
  - Do analysis analytically
  - Do algebra numerically
  - C++ framework for automated one-loo… …ions: organization, integral basis, spinor products, residue… …tree ingredients, caching
  - Thus far: gluon amplitudes; V + one/two quark pairs + gluon amplitudes
  - Tevatron and LHC phenomenology results

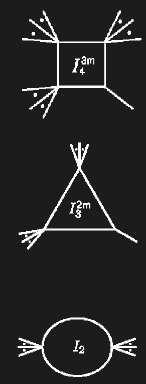
  ⇒ Daniel Maître's talk

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:

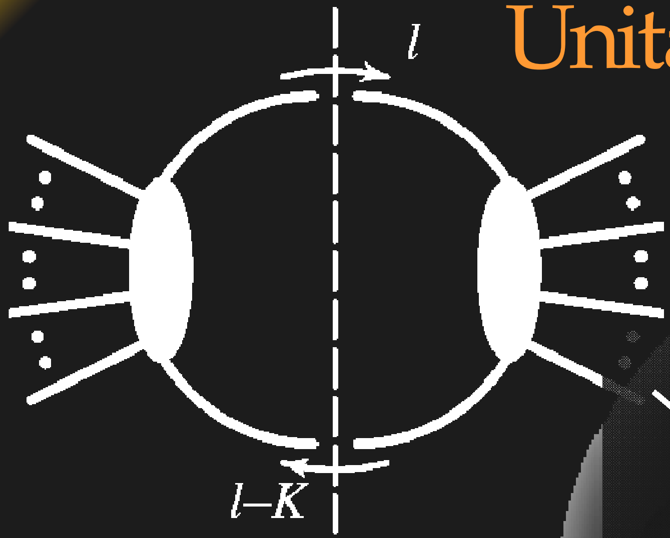


$$\text{Ampl} = \sum_{j\in\text{Basis}} c_j\,\text{Int}_j + \text{Rational}$$

Unitarity

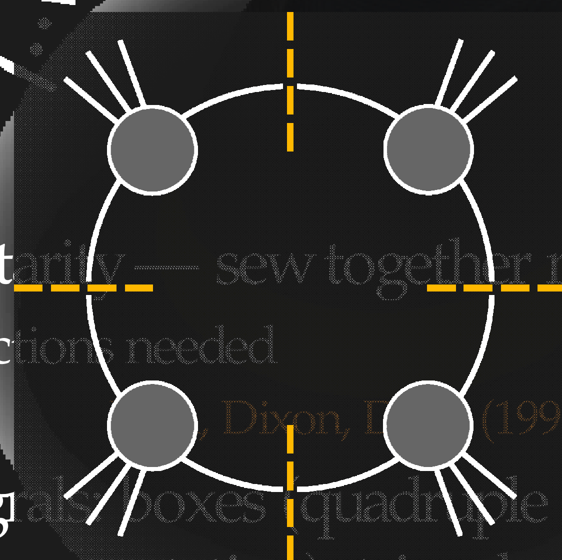
On-shell Recursion;
D-dimensional unitarity
via ∫ mass

Unitarity as a Practical Tool



Bern, Dixon, Dunbar, & DAK (1994)

Sew together tree amplitudes to form loop amplitudes



- Generalized Unitarity — sew together more than two amplitudes
  - No tensor reductions needed

Dixon, D (1997); Britto, Cachazo, & Feng (2004)

- Basis set of integrals: boxes (quadruple cuts: coefficient given by purely algebraic computation); triangles; bubbles
  - No higher-point integrals needed
- Rational terms from *D*-dimensional unitarity Bern & Morgan (1996); Bern, Dixon, Dunbar, & DAK (1997); Anastasiou, Britto, Feng, Kunszt & Mastrolia (2007); Giele, Kunszt, & Melnikov (2008)

Triangle and Bubble Integrals

- Triangle coefficients can be extracted from triple cuts
- But boxes have triple cuts too $\Rightarrow$ need to isolate triangle from them
  - Subtract box integrands (Ossola, Papadopoulos, Pittau)
  - Compute using contour integral at ∞ (Forde)
  - Spinor residue extraction (Britto, Feng, Mastrolia)

- Other groups pursuing complementary lines of attack for numerical calculations within the unitarity framework:
  Ossola, Papadopoulos, Pittau, Actis, Bevilacqua, Czakon, Draggiotis, Garzelli, van Hameren, Mastrolia, Worek;
  Ellis, Giele, Kunszt, Lazopoulos, Melnikov, Zanderighi;
  Giele, Winter;
- New developments for analytic calculations of internal masses: Anastasiou, Britto, Feng, Mastrolia; Badger

- To compute a physical cross-section, also need
  - real-emission contributions
  - subtraction terms
  - Integration over phase space
  - Analysis package

  Use SHERPA for these

- Standard CDF jet cuts

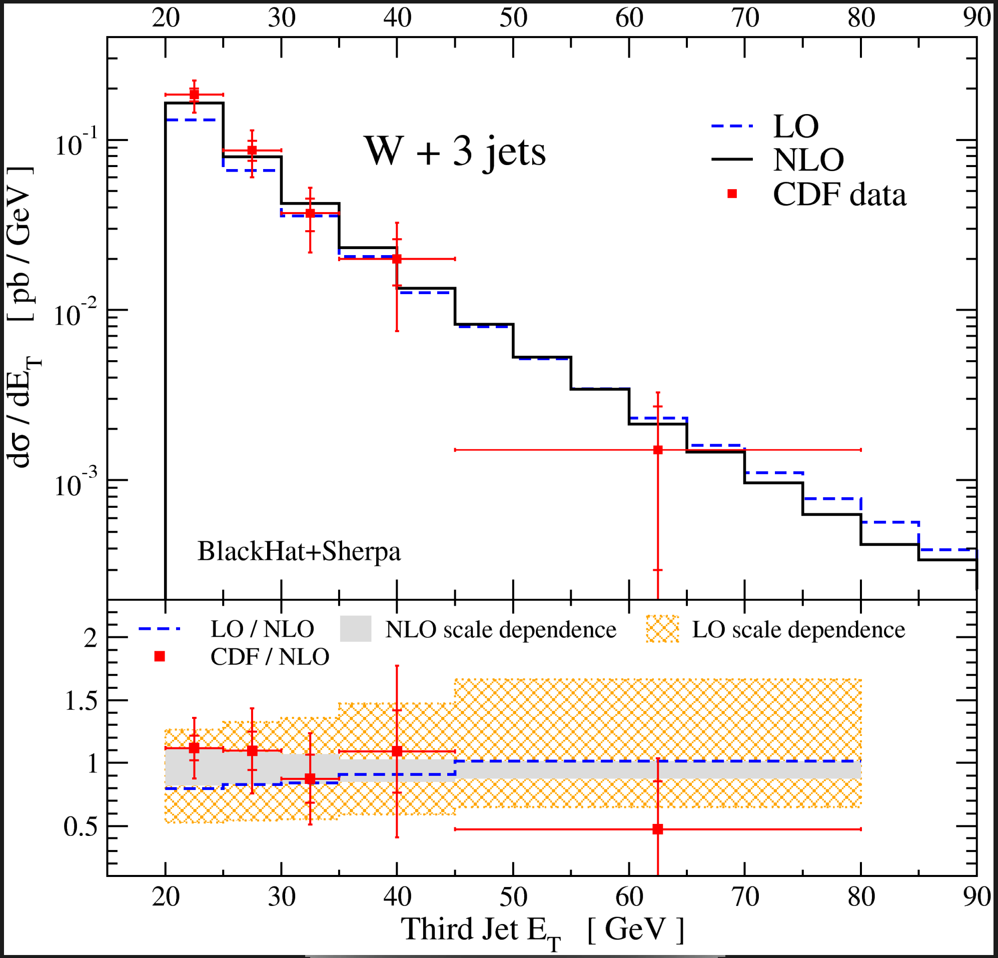
$$E_T^e > 20 \text{ GeV};\ |\eta^e| < 1.1$$

$$E_T^\nu > 20 \text{ GeV};\ m_T^W > 20 \text{ GeV}$$

$$E_T^{\text{jet}} > 20 \text{ GeV};\ |\eta^{\text{jet}}| < 2$$

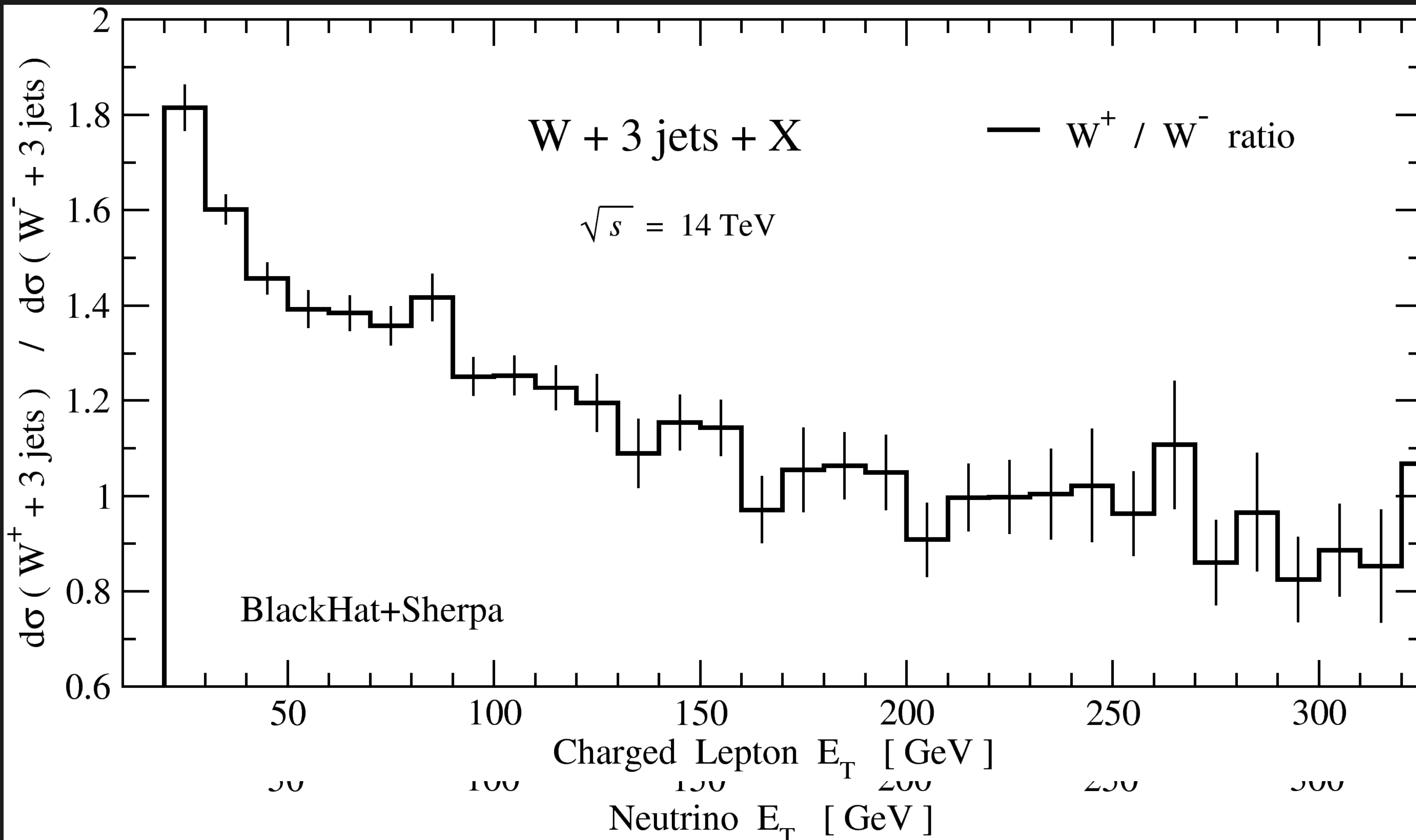
- SIScone (Salam & Soyez), with $R = 0.4$

W+3 Jet Production

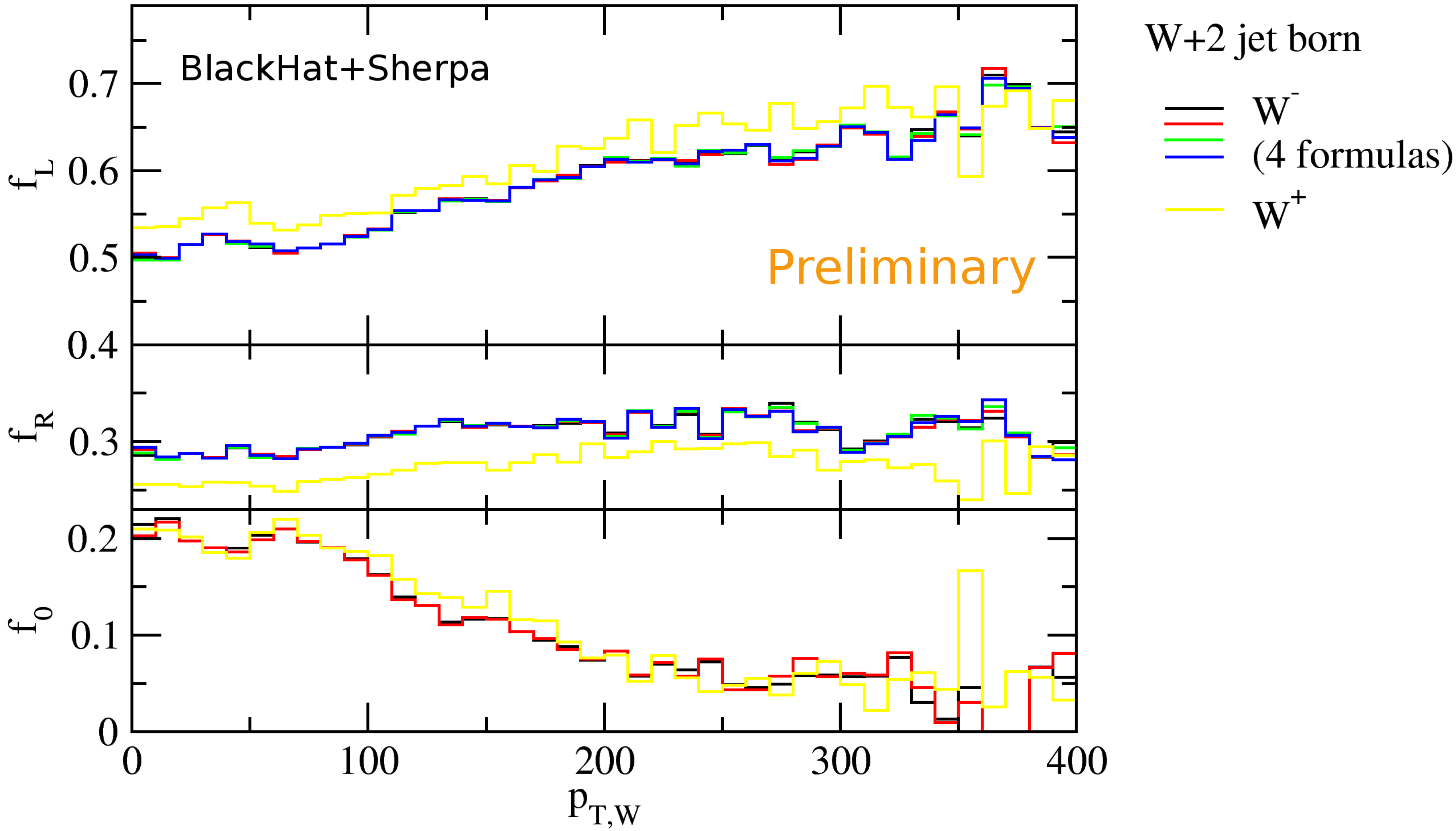


- Reduced scale dependence at NLO
- Good agreement with CDF data (arXiv:0711.4044)

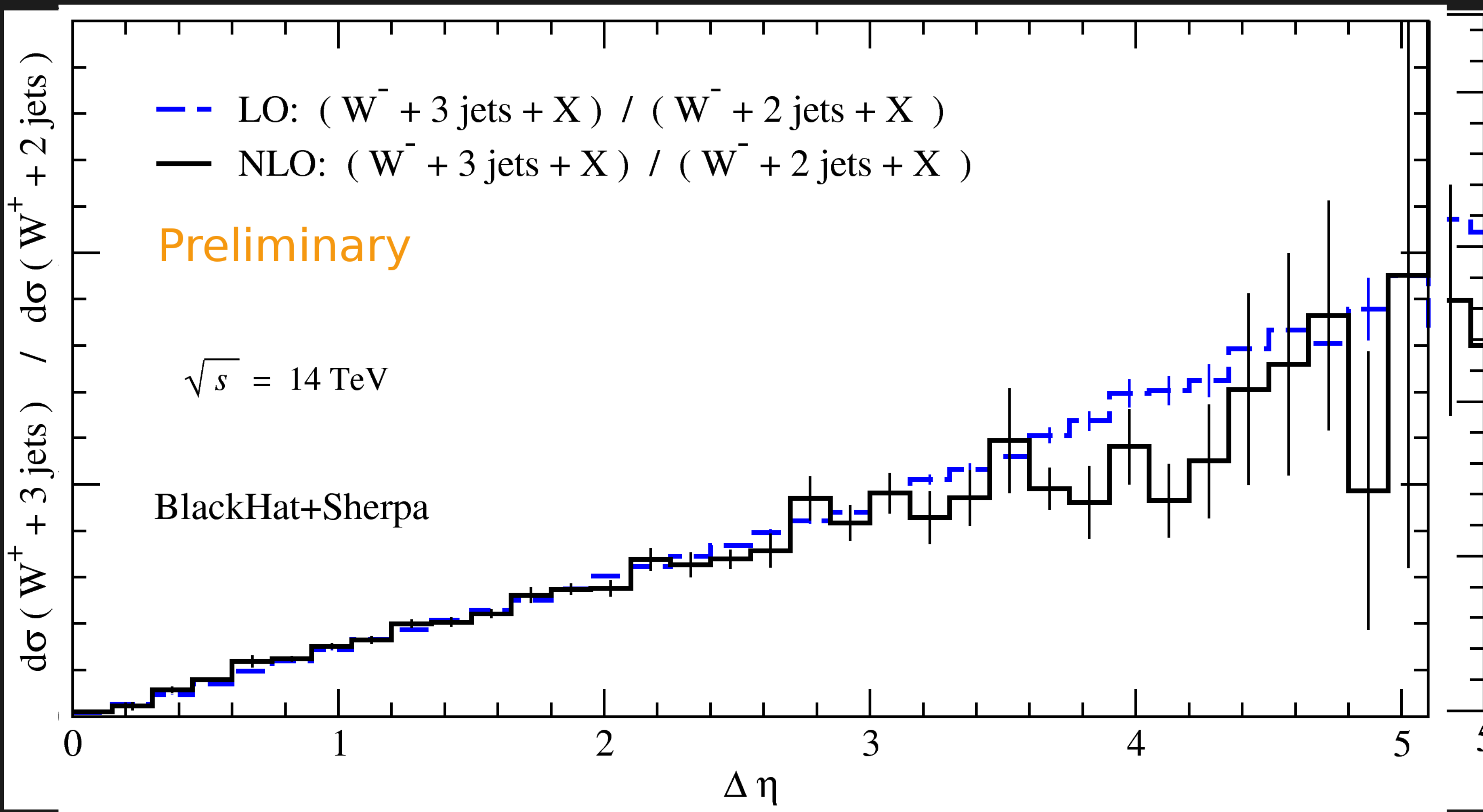
W+3 jets at the LHC: W^+/W^- Ratio



W Polarization

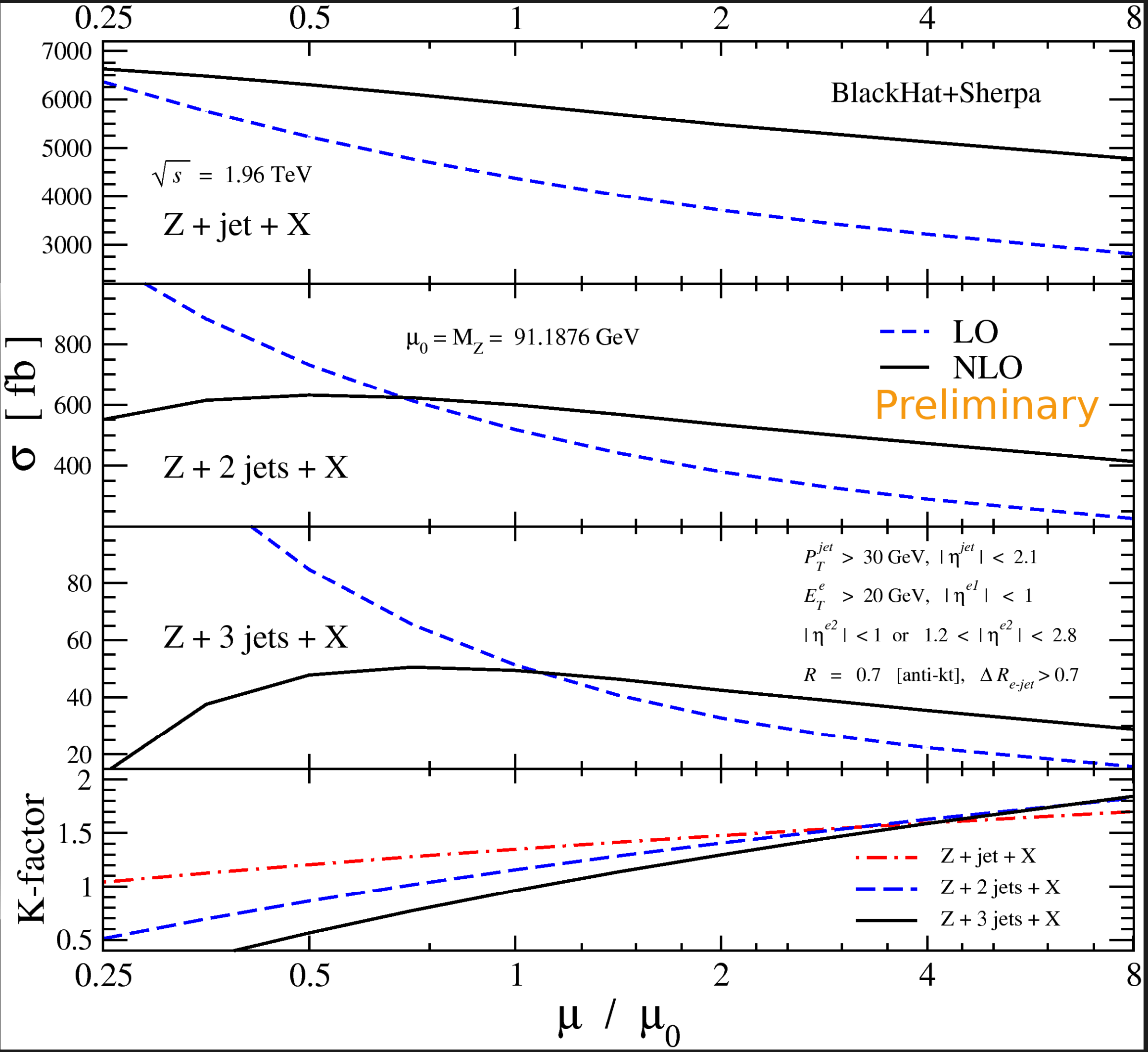


Radiation Between Jets: W+3/W+2-Jet Ratio

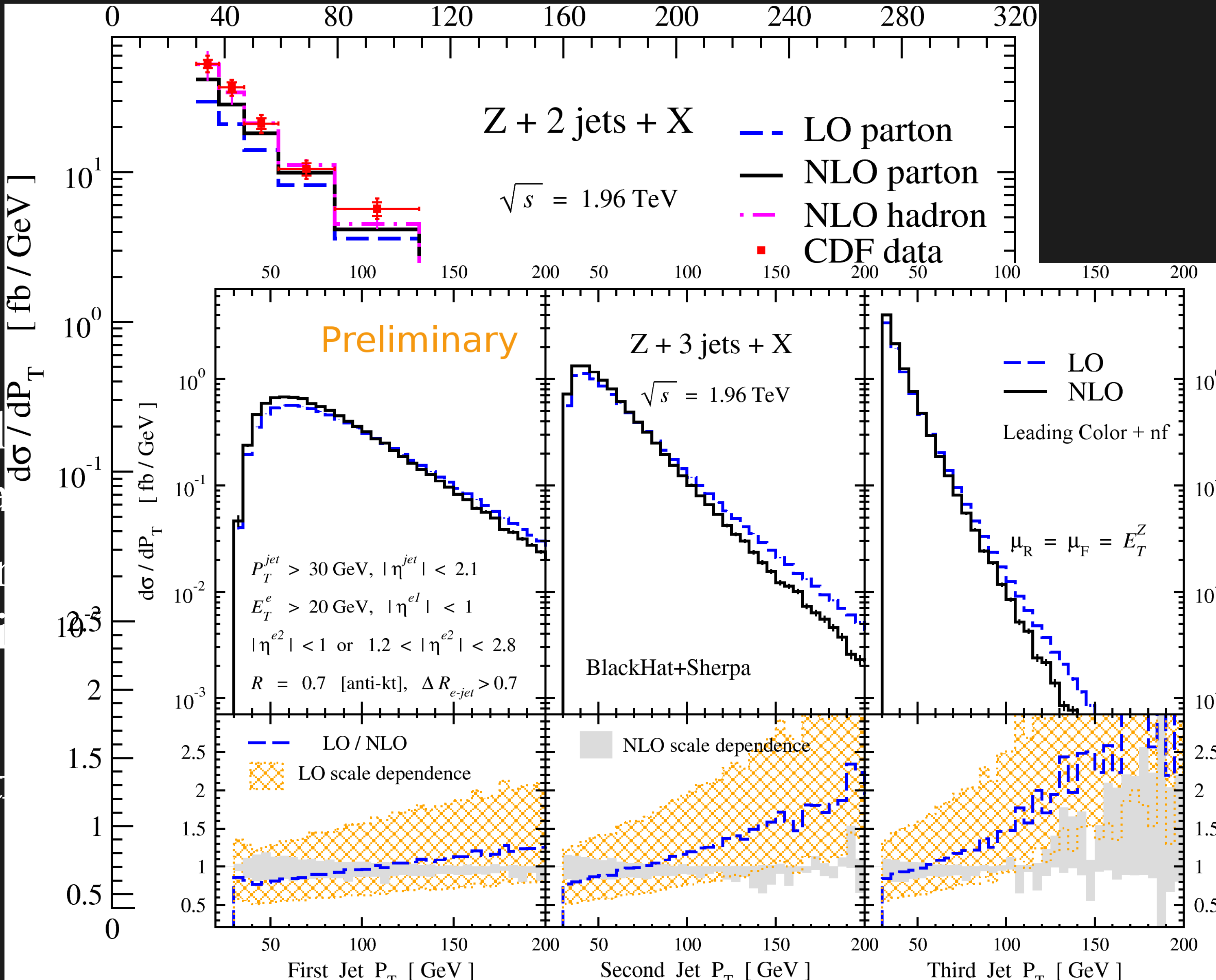


Z + Jets at Tevatron

- Reduced scale dependence
- NLO importance grows with number of jets



Z+3 Jets at Tevatron



- Good
  with a
- Parton
  experi
- Await

Summary

- On-shell methods are method of choice for QCD calculations for colliders
- 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