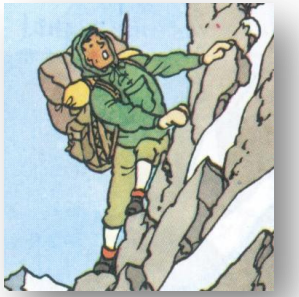
Towards automation of NLO calculations: W+3jet production at hadron colliders



Tanju Gleisberg, SLAC



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

IFIC seminar, 5/14/2009

Based on 0902.2760 [hep-ph]

Outline

- Motivation
- Calculation of cross sections
- Techniques & implementation
  - SHERPA
  - BlackHat
- Physics Results (W+3 jet)
  - Tevatron
  - LHC

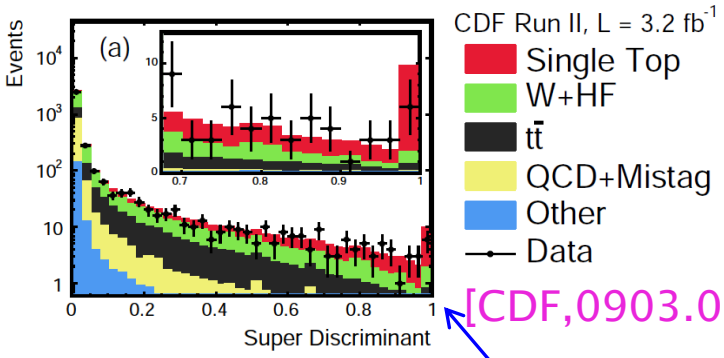
Motivation

- Many discoveries rely on precise theoretical predictions of signals and backgrounds

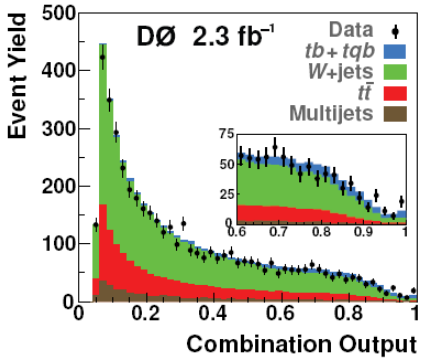
WW / WZ

[D0, 0810.3873]

Single Top

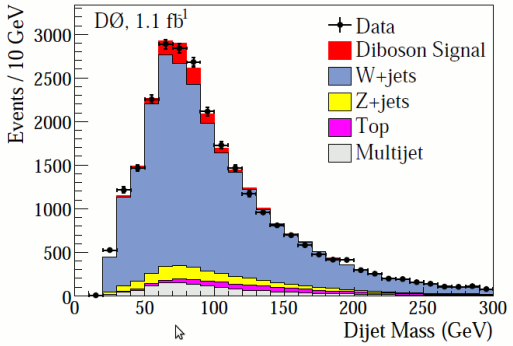


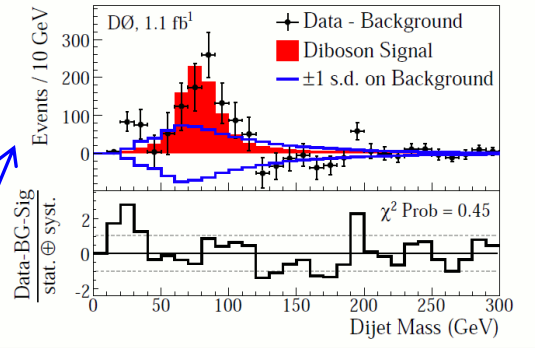
[CDF,0903.0885]



CDF & D0

5σ discovery





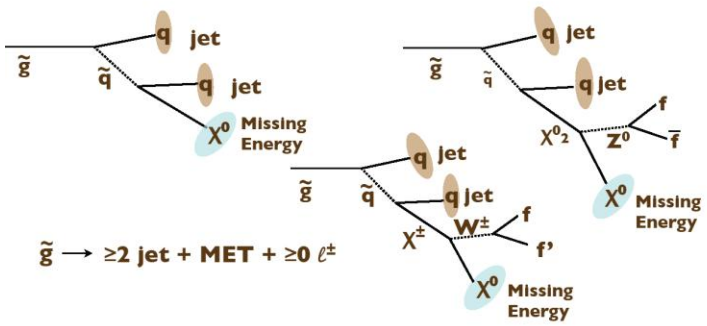
[D0,0903.0850]

D0, 4.4σ evidence

Motivation

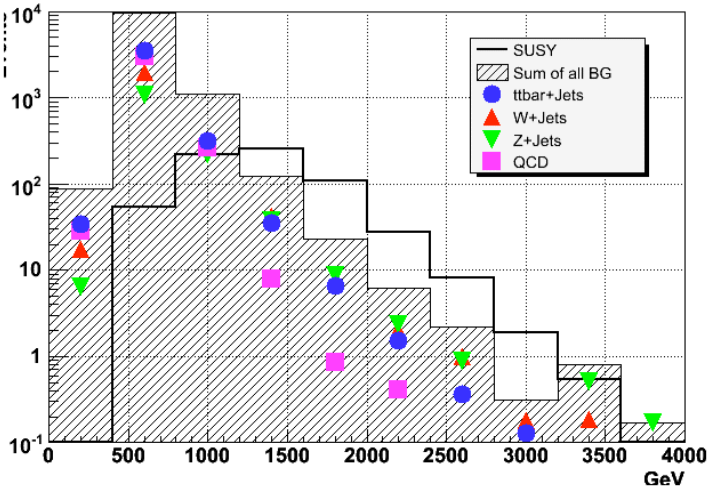
- Many discoveries rely on precise theoretical predictions of signals and backgrounds

Susy search at LHC



[M.L.Mangano, 2008]

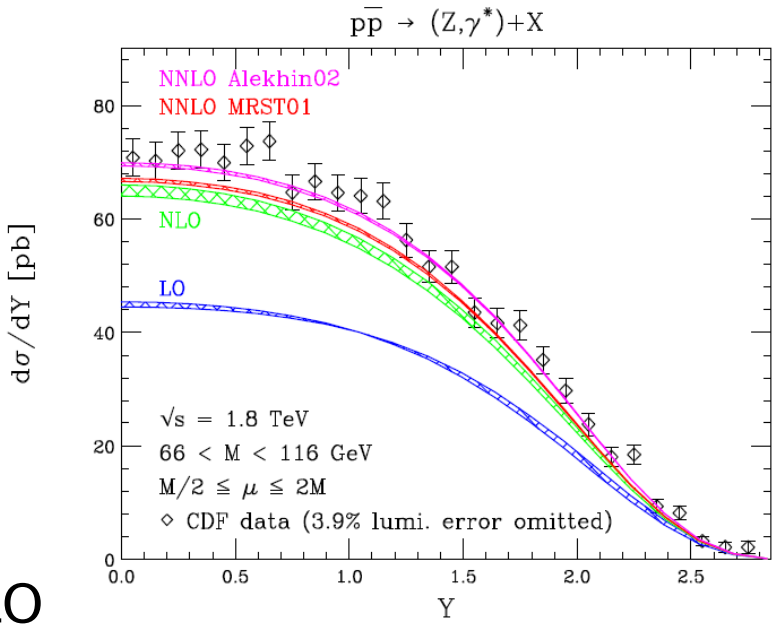
[Atlas Collaboration]



Multijet+missing ET final state

Motivation

[Anastasiou, Dixon, Melnikov, Petriello, 2004]



- Tree-level (LO) predictions only qualitative estimates due to poor convergence of expansion in strong coupling
- NLO corrections can be very large (30-100% of LO)
- Matching algorithms can improve shapes, but normalization in still LO
- Scale uncertainties: (W+ n jets)

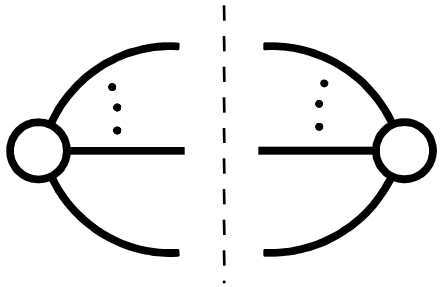
n	LO	NLO
1	16%	7%
2	30%	10%
3	42%	12%

- Need NLO for reliable predictions!

Calculation of cross sections

- LO:

$$\sigma^{LO} = \int_m d\sigma^B$$



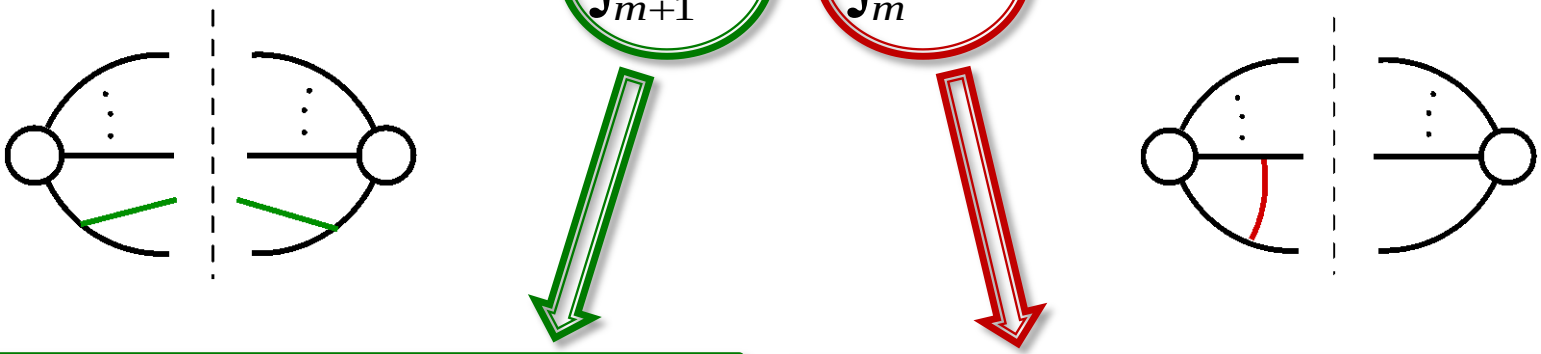
- Finite within the whole phase space (by definition)
- Straightforward to calculate, highly automated tools available:
  - Alpgen
  - Helac/Phegas
  - MadGraph
  - O'Mega/Wizard
  - AMEGIC++
  - Comix
- Typically up to 6-10 final state particles feasible

Calculation of cross sections

- NLO:

$$\sigma = \sigma^{LO} + \sigma^{NLO}$$

$$\sigma^{NLO} = \int_{m+1} d\sigma^{R} + \int_{m} d\sigma^{V}$$



Real correction:
- Radiation of additional parton
- Divergent in soft and collinear limits

Virtual correction:
- Loop amplitudes
- Infrared poles after integration over loop momentum

- Sum is free of divergencies, but cancelation only after integration over phase space!

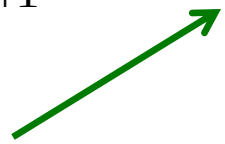
Calculation of cross sections

Construct finite integrands: **Subtraction method**

- Introduce subtraction term $d\sigma^A$

$$\sigma^{NLO} = \int_{m+1} d\sigma^R - \int_{m+1} d\sigma^A + \int_m d\sigma^V + \int_{m+1} d\sigma^A$$

$$= \int_{m+1} (d\sigma^R - d\sigma^A) + \int_m (d\sigma^V + \int_1 d\sigma^A)$$





Cancels soft/collinear singularities of the real correction

Simple enough to be integrated analytically over one-parton emission in dimensional regularization:

$$\int_1 d\sigma_\varepsilon^A = \varepsilon^{-2} d\sigma^{(A,2)} + \varepsilon^{-1} d\sigma^{(A,1)} + d\sigma^{(A,0)} + O(\varepsilon)$$

Poles cancel with virtual correction

Calculation of cross sections

Construct finite integrands: Subtraction method

- Introduce subtraction term $d\sigma^A$

$$\sigma^{NLO} = \int_{m+1} d\sigma^R - \int_{m+1} d\sigma^A + \int_m d\sigma^V + \int_{m+1} d\sigma^A$$

$$= \int_{m+1} \underbrace{(d\sigma^R - d\sigma^A)} + \int_m \underbrace{(d\sigma^V + \int_1 d\sigma^A)}$$

Integrands are finite and suitable for numerical integration over phase space

- Main bottleneck for NLO: virtual amplitudes
- Physics results available for hadron colliders: 2->2 and most 2->3 processes:

  (+ decays of weak bosons and NWA decays of top-quarks)

  pp $\longrightarrow$ 3 jets / V+2 jets / VV+jet / VVV
  Higgs+2jets / Higgs+$t\bar{t}$ / $t\bar{t}$+jet / ...
- Many processes publicly available in codes like MCFM and NLOJET

NLO with BlackHat & Sherpa

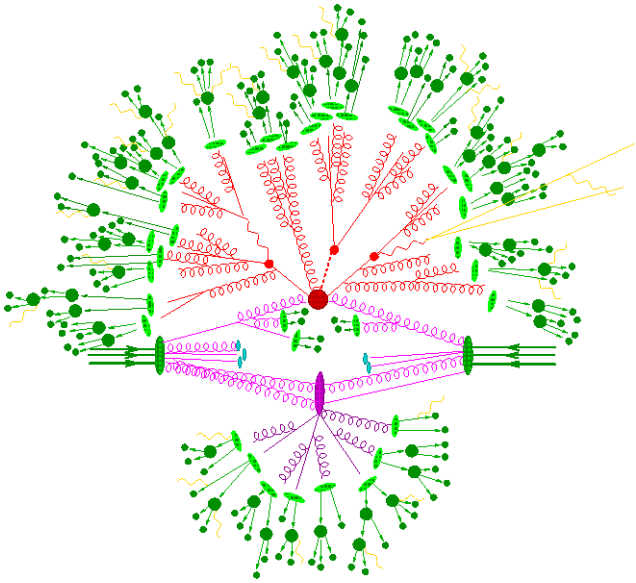
$$\sigma = \int_m d\sigma^B + \int_{m+1} (d\sigma^R - d\sigma^A) + \int_m (d\sigma^V + \int_1 d\sigma^A)$$







SHERPA



- SHERPA is a full event generator, combining a number of perturbative and non-perturbative approaches to simulate high energy collisions

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

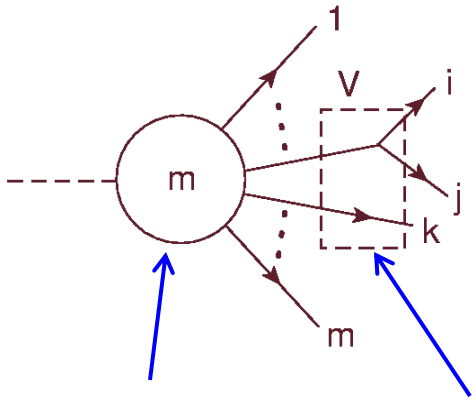
- Here just parts of the framework are used:
  - The automated tree-level matrix element generator AMEGIC++, includes automated dipole subtraction

    [TG, Krauss]
  - Phase space integration techniques
  - The event generation framework and the ANALYSIS package to evaluate generated events

Automated dipole subtraction

[S. Catani, M.H. Seymour,1997]
[TG, F. Krauss, 2007]

Subtraction term: $d\sigma^A = \sum_{i \neq j \neq k} d\sigma^A_{ij,k}$ (for m+1-parton real correction)



m-parton LO-ME Splitting operator

Momentum map: $p_i, p_j, p_k \to \tilde{p}_{ij}, \tilde{p}_k$

$$d\sigma^A_{ij,k} = d\sigma^{LO}_{\tilde{ij},\tilde{k}} \otimes dV_{ij,k}$$

$$dV_{ij,k} \sim \frac{1}{p_i p_j} \mathbf{T}_{ij} \cdot \mathbf{T}_k \; \mathbf{V}_{ij,k} \; d\Phi^{(1)}$$

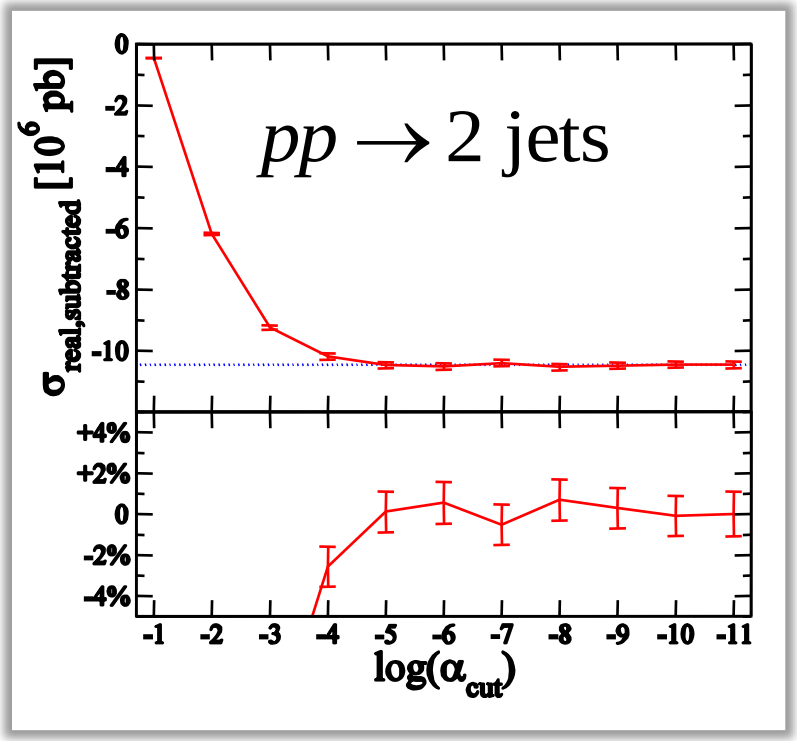
Integrated subtraction term: $\int_{m+1} d\sigma^A_{ab}(p_a, p_b) = \int_m \left[d\sigma^B_{ab}(p_a, p_b) \otimes \mathbf{I}(\varepsilon) \right]$

(in $4-2\varepsilon$ dimensions)

$$+ \sum_{a'} \int_0^1 dx \int_m \left[\left(\mathbf{K}^{a,a'}(x) + \mathbf{P}^{a,a'}(xp_a, x, \mu_F) \right) \otimes d\sigma^B_{a'b}(xp_a, p_b) \right] + \langle a \leftrightarrow b \rangle$$

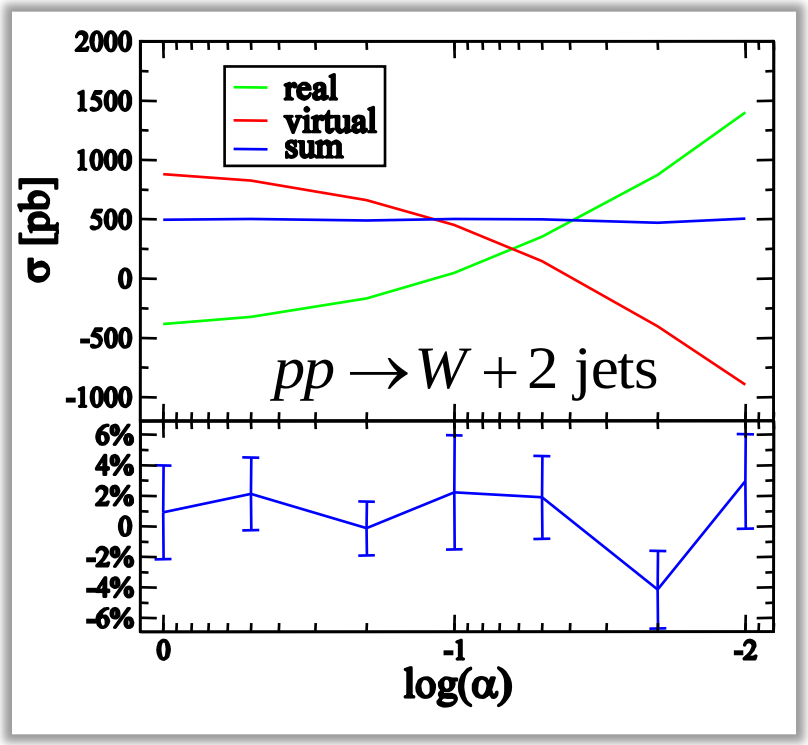
Convergence and consistency checks

Cutoff dependence of subtracted real correction:



Consistency check with modified dipole terms:

$$d\sigma_{ij,k}^{A'} = d\sigma_{ij,k}^{A}\theta(\alpha - y_{ij,k})$$



BlackHat



[Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maître]

- Goal: Automating computation of QCD one-loop amplitudes
- Use of unitarity techniques

[Bern, Dixon, Dunbar, Kosower, 1994]
[Berger, Bern, Dixon, Forde, Kosower, 2006]
[Ossola, Papadopolous, Pittau; Forde, 2007]

  - ➢Work with gauge invariant on-shell objects
  - ➢Allows recursive calculation
  - ➢Better scaling with increasing number of external legs

  (compared to traditional Feynman diagramatic approach)

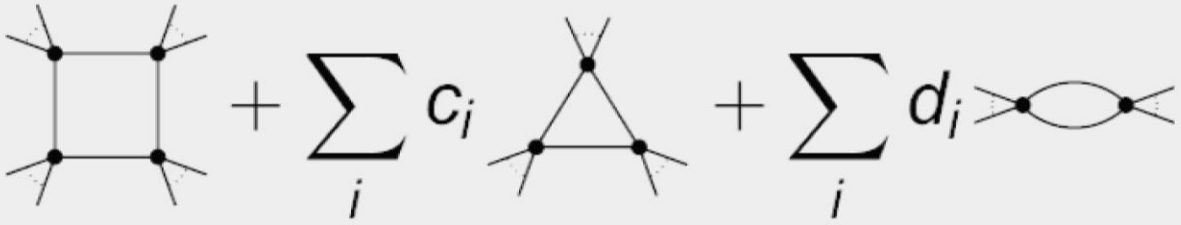
- C++ framework

Main technique: unitarity bootstrap

Decomposition of one-loop amplitudes into coefficients of scalar integrals and rational terms:

$$A = R + C$$

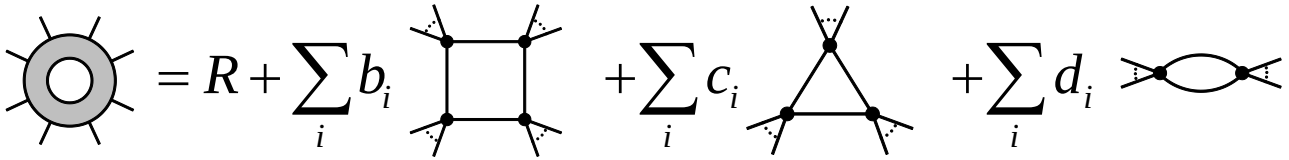
$$C = \sum_i b_i \; + \sum_i c_i \; + \sum_i d_i$$



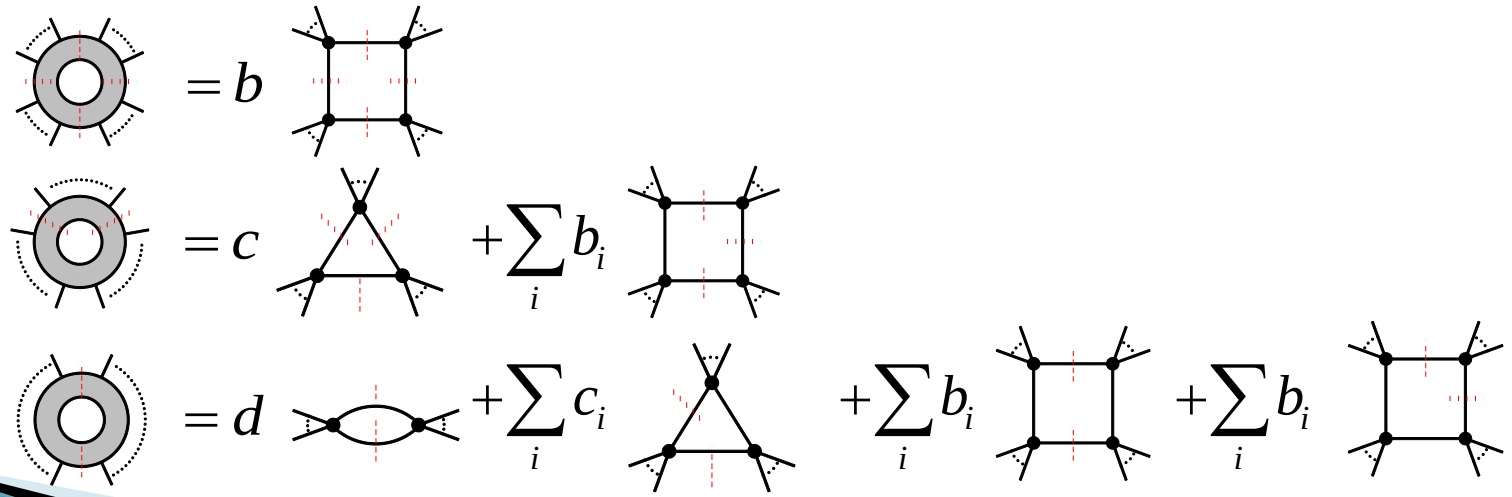
- The coefficients b_i, c_i, d_i can be computed in d=4 dimensions using generalized unitarity
- The rational term is computed separately using on-shell recurrence relations

Integral coefficients from unitarity

- Unitarity cut: $\frac{1}{p^2 - m^2 + i0} \to 2\pi\delta(p^2 - m^2)$

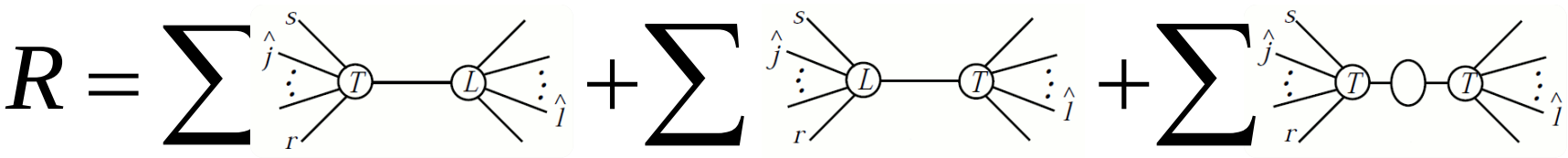


- Apply cuts on both side of the equation



On-shell recursions for rational terms

- Construct rational part recursively from on-shell tree-amplitudes (T) and rational pieces of one-loop amplitudes (L)

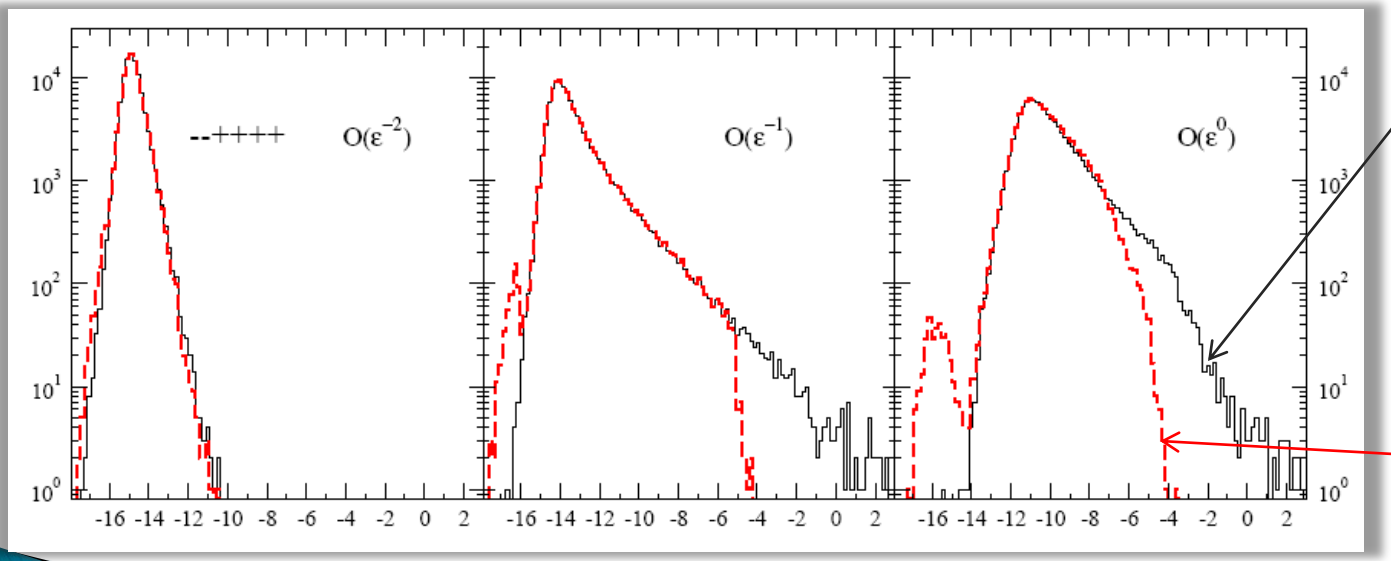


- "spurious poles" to cancel with unphysical poles in the cut part
  - Extracted numerically from the cut part (somewhat tricky and possible source for numerical inaccuracies, but works…)

Amplitudes and numerical stability

- Quantify numerical precision: $x = \log_{10}\left(\frac{|A^{\text{num}} - A^{\text{target}}|}{A^{\text{target}}}\right)$
- Improvement:
  - Perform tests to identify problematic phase space points
  - Recalculate those point with higher precision

  → Increases average computation time only by few %



W + jets physics…

W + jets

- Important background process to
  - SM physics: Higgs, single top, diboson, …
  - New physics
- NLO at cross section level
  - MCFM: W+0/1/2 jets [Campbell, Ellis, 2002]
  - Leading color 2q3gW [Ellis, Melnikov, Zanderighi, 2009]
  - Leading color, all subprocesses [0902.2760]
    (very recently also subleading color…)

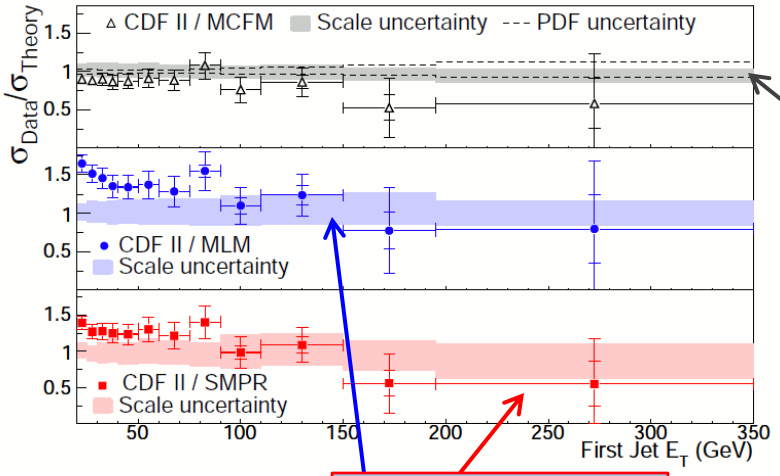
Leading color approximation

- "LC NLO" neglects subleading-color terms $\sim 1/N_C^2$ and contributions from closed fermion loops $\sim N_f/N_C$ in the finite part of one-loop amplitudes
- Contribution to W+1/2/3 jets is just about 3-5%, but they are much more expensive to compute

W + n jets @ Tevatron

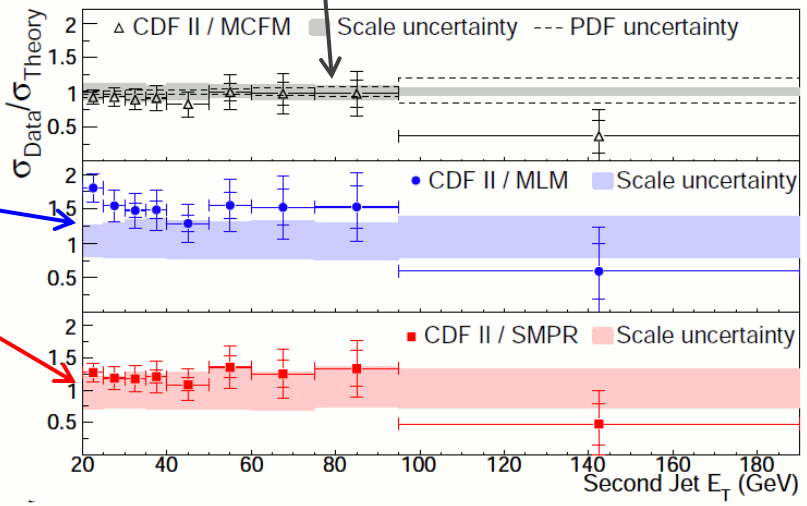
[CDF: PRD 77 011108, arXiv:0711.4044]

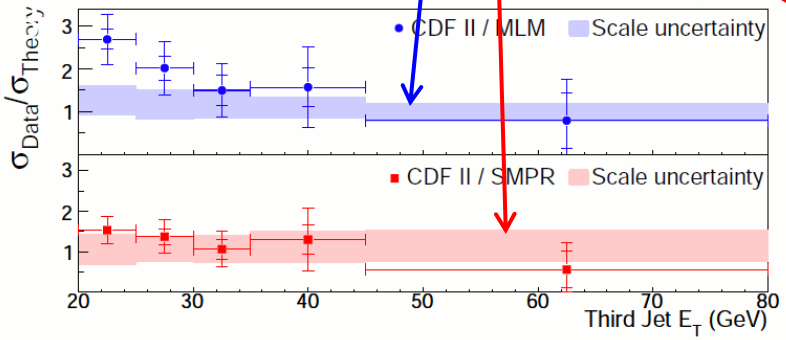
integrated luminosity: 320 pb^{-1}



NLO predictions with MCFM

Matched LO predictions





W + n jet @ Tevatron

Total Rates: [CDF: PRD 77 011108, arXiv:0711.4044]

number of jets	CDF	LC NLO	NLO
1	53.5 ± 5.6	$58.3^{+4.6}_{-4.6}$	$57.8^{+4.4}_{-4.0}$
2	6.8 ± 1.1	$7.81^{+0.54}_{-0.91}$	$7.62^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.908^{+0.044}_{-0.142}$	$0.882^{+0.057}_{-0.138}$

Preliminary

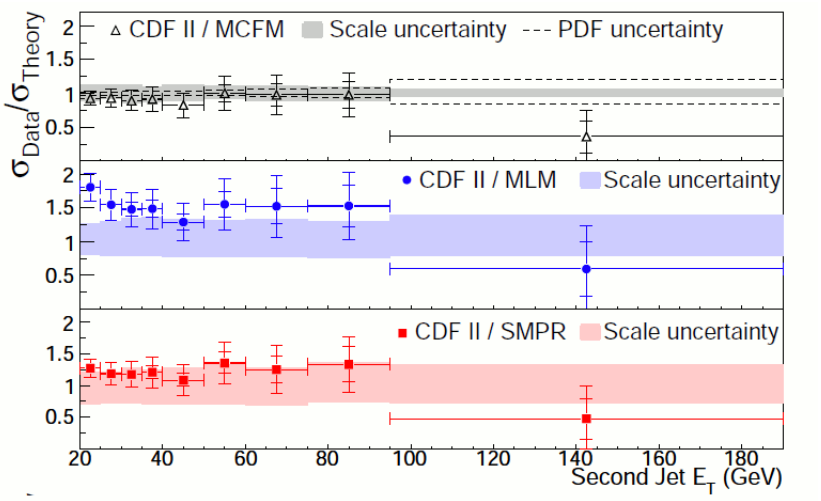
$E_T^{jet} > 25GeV$ $\quad |\eta^{jet}| < 2$

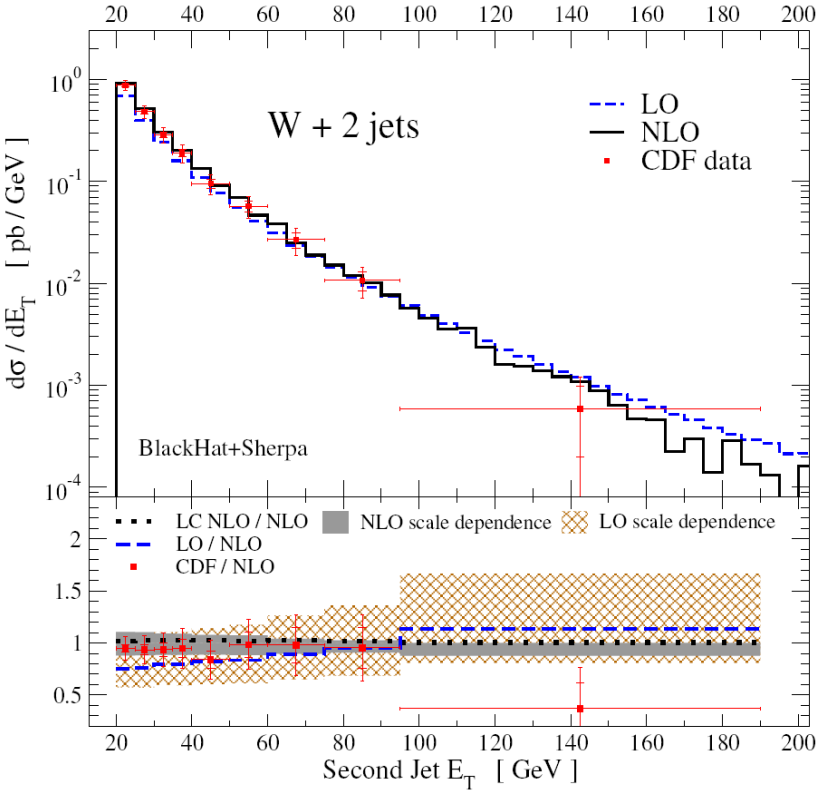
$E_T^{e} > 20GeV$ $\quad |\eta^{e}| < 1.1$

$E_T^{miss} > 30GeV$ $\quad M_T^W > 20GeV$

SISCone
[G. Salam, G. Soyez]

Warmup: W + 2 jets @ Tevatron

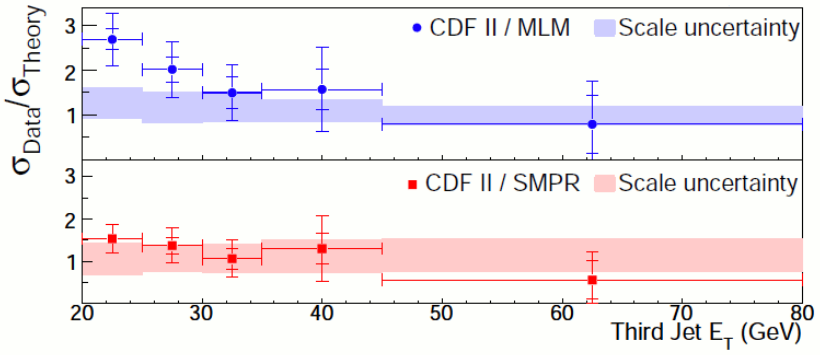




$$\mu_r = \mu_f = \sqrt{M_W^2 + p_{T,W}^2}$$

$$\mu/2 \ldots 2\mu$$

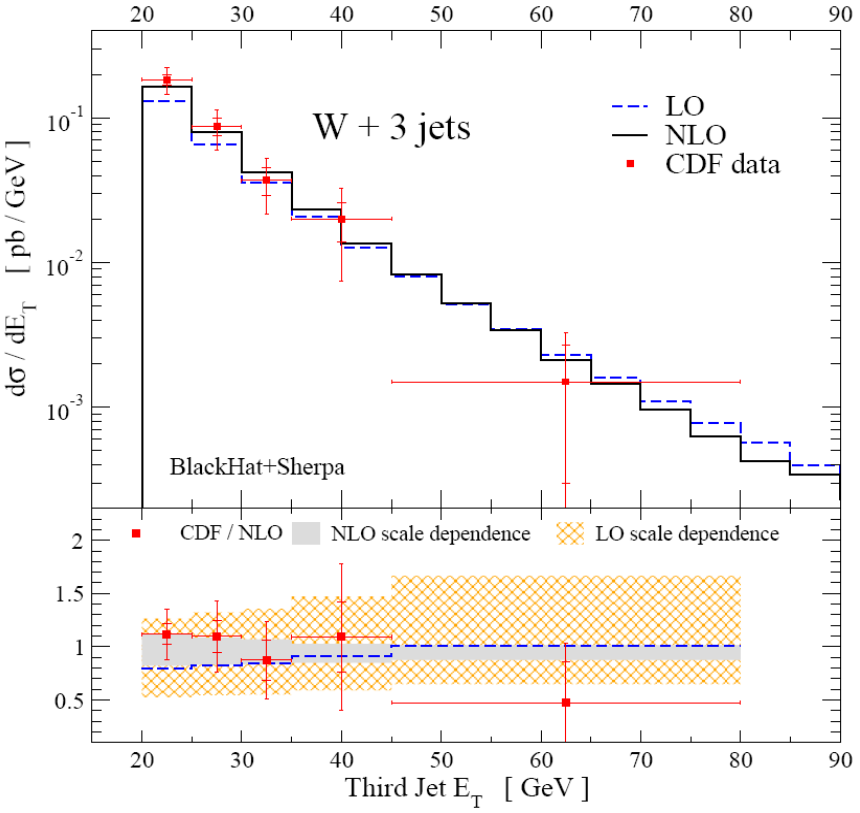
W + 3 jets @ Tevatron



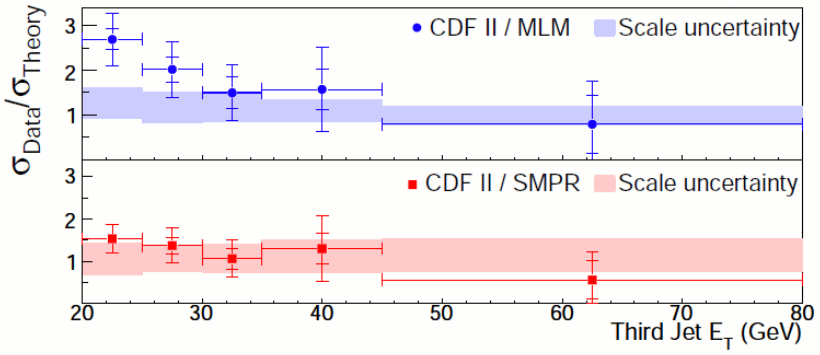
$$\mu_r = \mu_f = \sqrt{M_W^2 + p_{T,W}^2}$$

$$\mu/2 \ldots 2\mu$$

Leading Color:

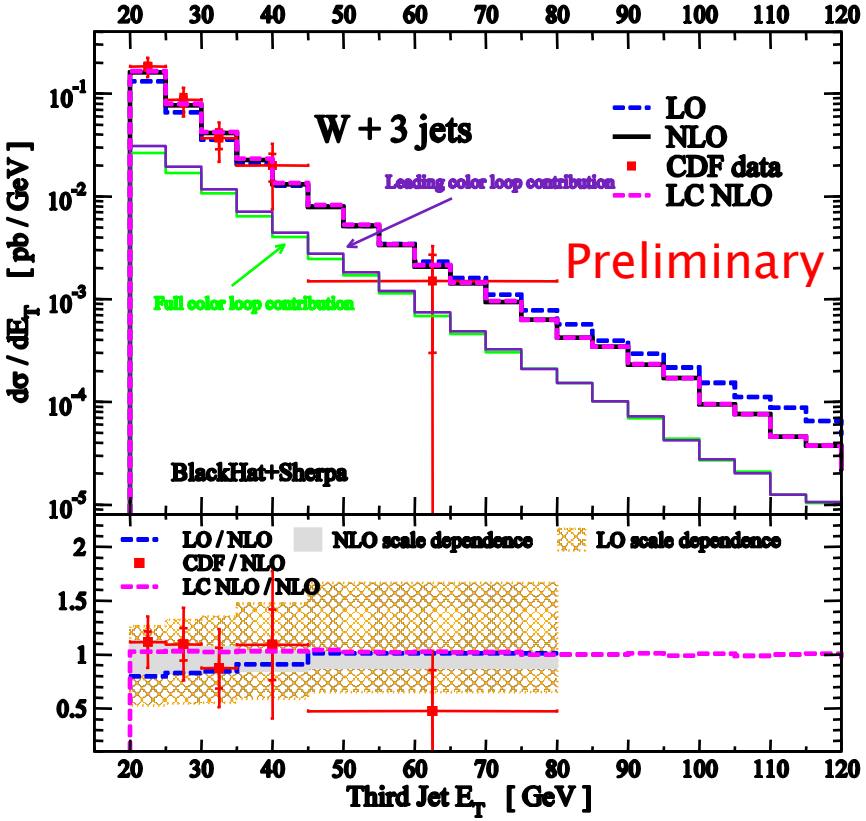


W + 3 jets @ Tevatron

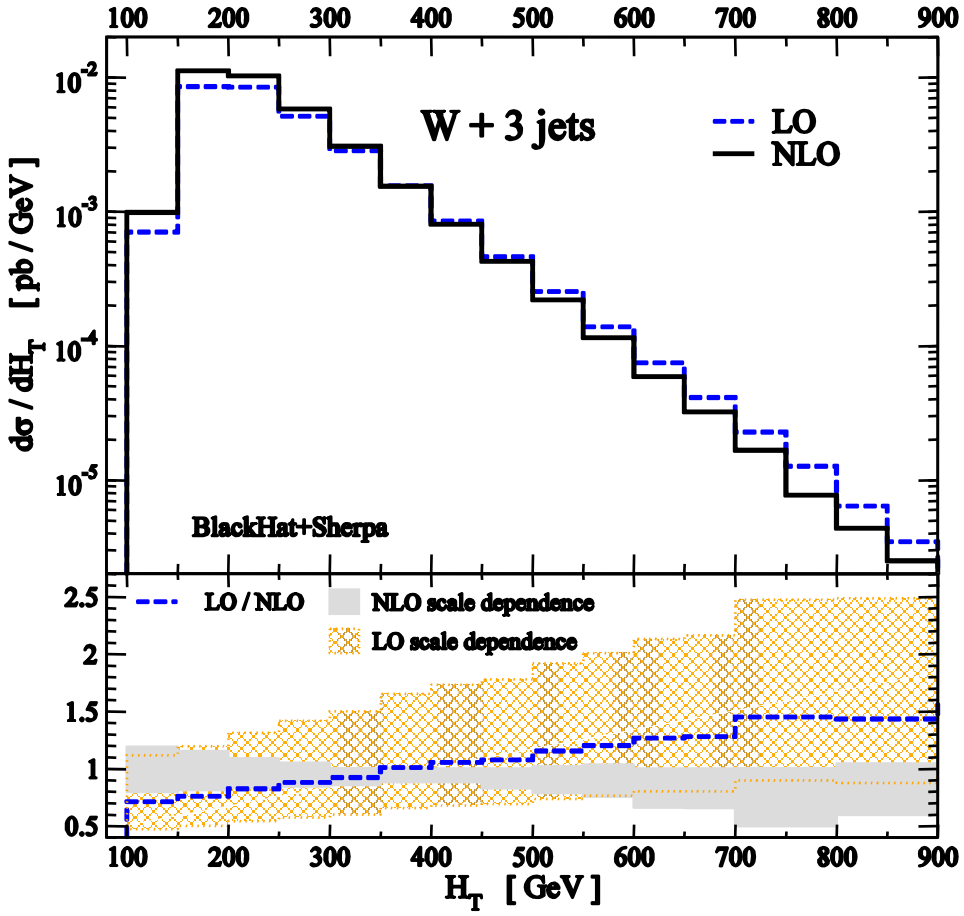


$$\mu_r = \mu_f = \sqrt{M_W^2 + p_{T,W}^2}$$

$$\mu/2 \ldots 2\mu$$

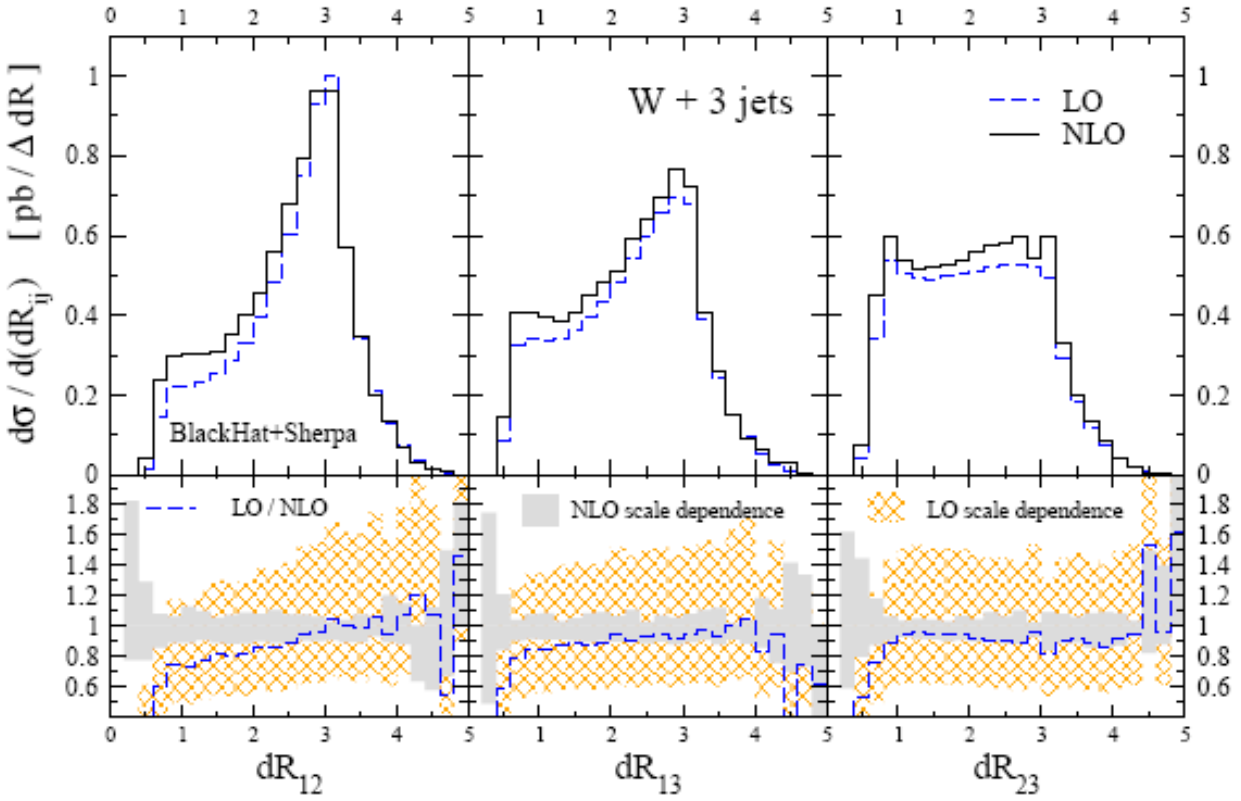


W + 3 jets @ Tevatron



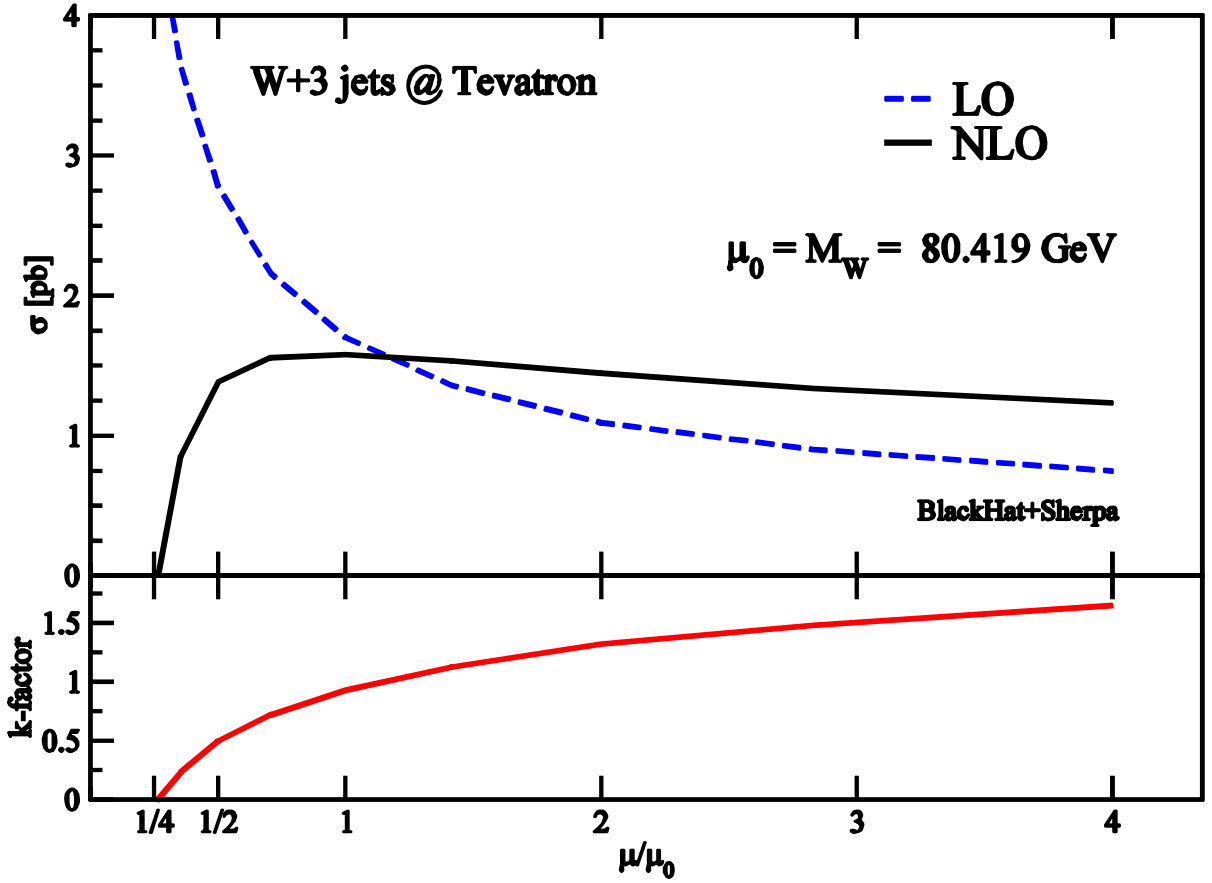
$$H_T = \sum_j E_{T,j}^{jet} + E_T^e + E_T^{miss}$$

W + 3 jets @ Tevatron



$$dR = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

W + 3 jets @ Tevatron: total cross section



Towards LHC

Collision energy: 14 TeV

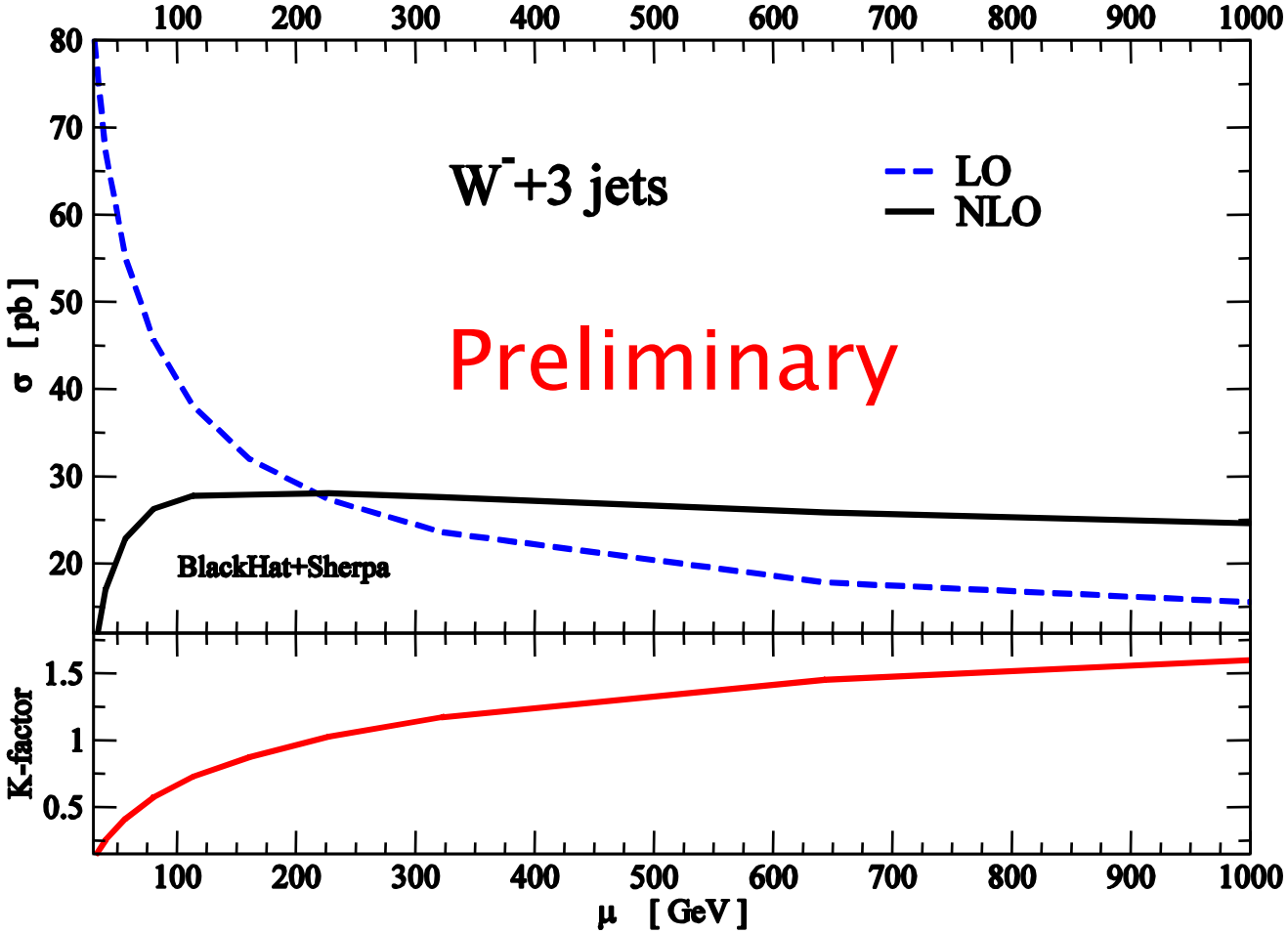
$$E_T^{jet} > 30GeV \qquad |\eta^{jet}| < 3$$

$$E_T^{e} > 20GeV \qquad |\eta^{e}| < 2.5$$

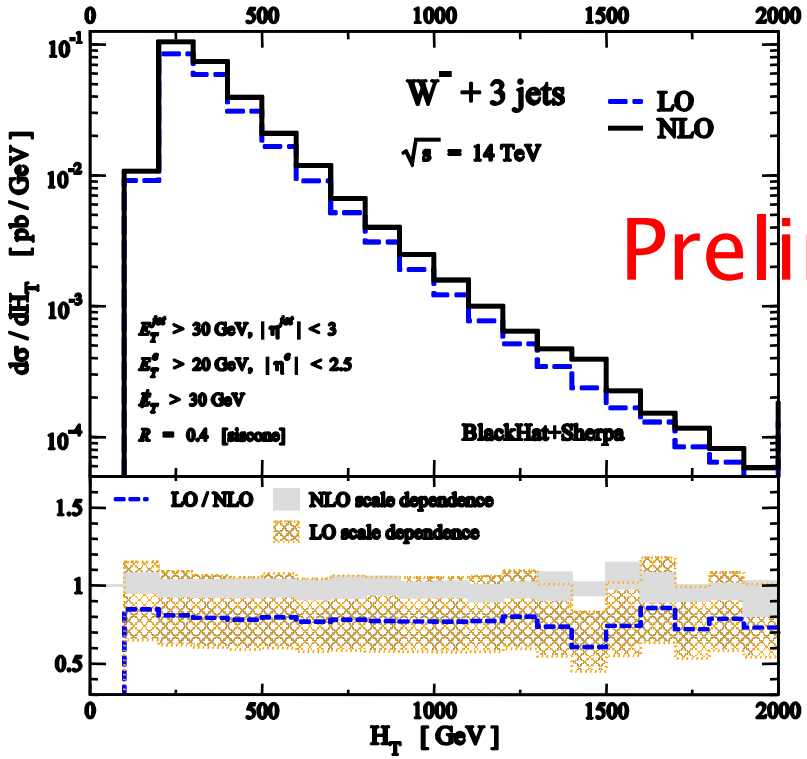
$$E_T^{miss} > 30GeV \qquad M_T^{W} > 20GeV$$

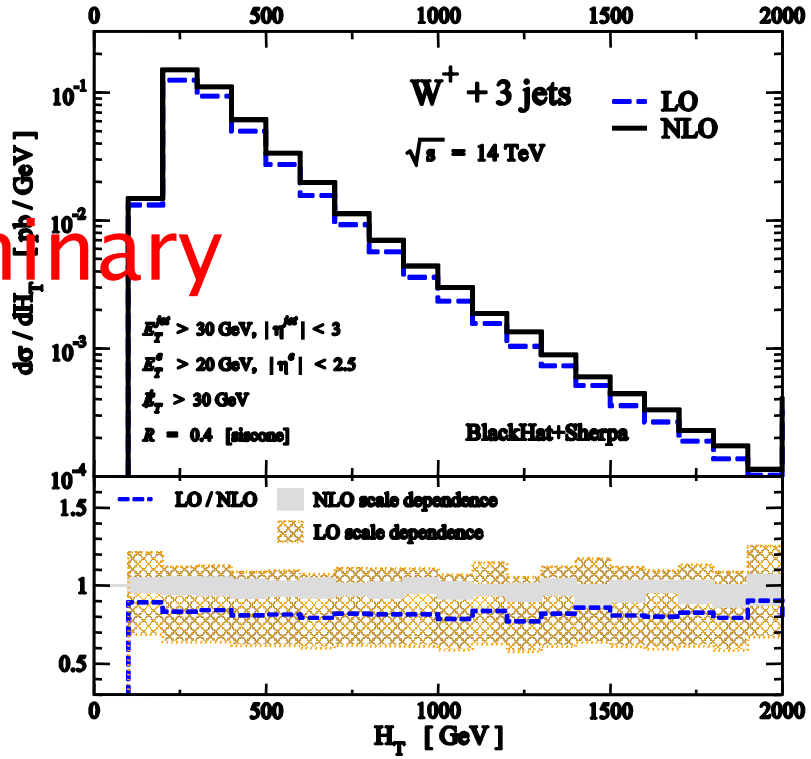
Jet algorithm: SISCone
[G. Salam, G. Soyez]

LHC results: Total cross section



LHC results





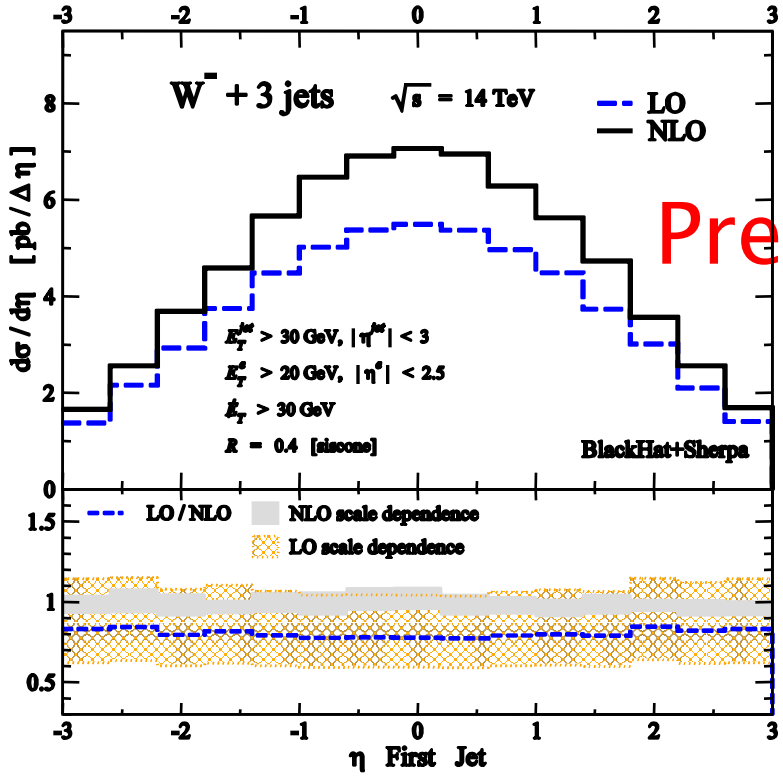
Preliminary

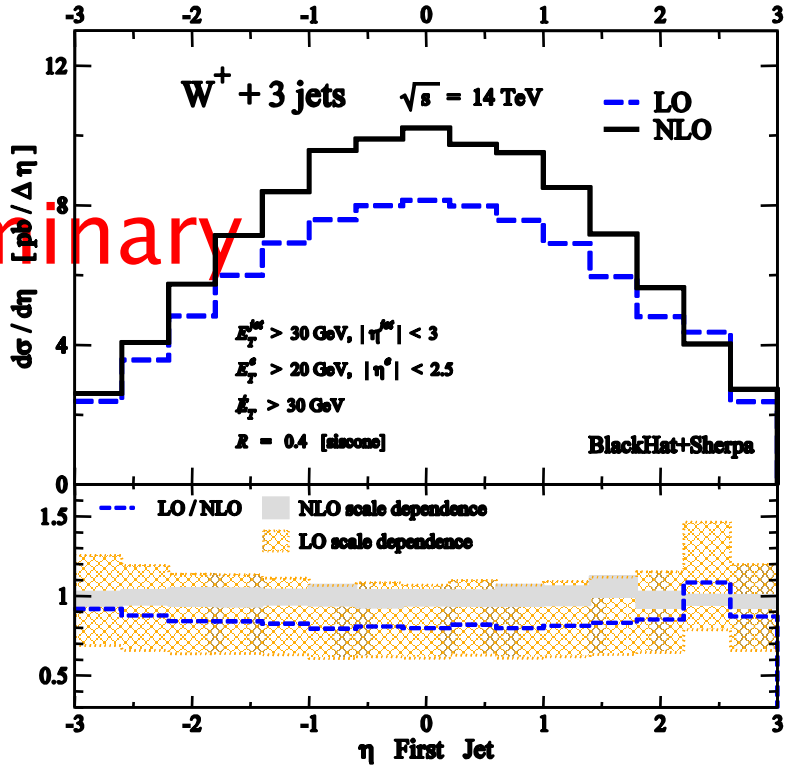
$$H_T = \sum_j E_{T,j}^{jet} + E_T^e + E_T^{miss}$$

$$\mu_r = \mu_f = H_T$$

Scale variation: $\mu/2 \ldots 2\mu$

LHC results



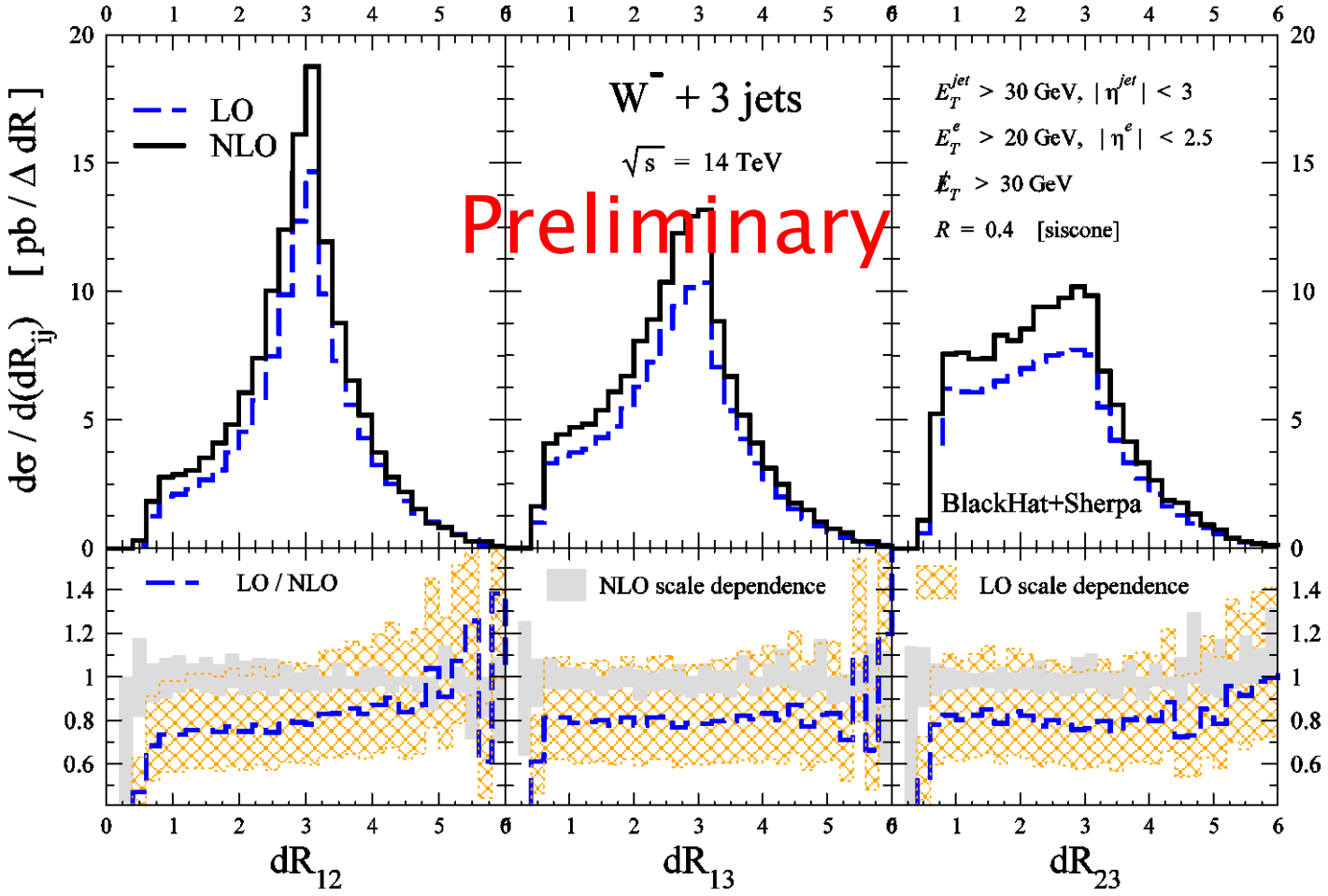


Preliminary

$$\mu_r = \mu_f = H_T$$

Scale variation: $\mu/2 \ldots 2\mu$

LHC results


LO
NLO
W⁻ + 3 jets
√s = 14 TeV
Preliminary
E_T^{jet} > 30 GeV, |η^jet| < 3
E_T^e > 20 GeV, |η^e| < 2.5
$\not{E}_T$ > 30 GeV
R = 0.4 [siscone]
BlackHat+Sherpa
dσ / d(dR_ij) [pb / Δ dR]
LO / NLO
NLO scale dependence
LO scale dependence
dR12
dR13
dR23

Summary and outlook

- NLO calculations with BlackHat & Sherpa
  - New efficient computational approach to one-loop QCD amplitudes
- First results for W+3 jet to compare to data
- LHC predictions
- Future:
  - More processes (Z+3 jets, …)
  - Improvements in speed
  - Automation