Results from BLACKHAT

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on behalf of the BLACKHAT Collaboration,
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and
P. Hoffman (Freiburg) and Y. Li (FNAL)
[1412.4775, updated; 1512.07591; & in progress]

KITP Conference, *Stress-testing the Standard Model at the LHC*
May 23–27, 2016

Precision Calculations

- Test our understanding of the Standard Model in detail
  - that experimenters understand their detectors
  - and that theorists understand the theory
- Uncertainties in Standard Model measurements
  - precision measurements of M_W
- Backgrounds to Frontier Physics
  - precision measurements of Higgs branchings and couplings
- Backgrounds to New Physics
  - SUSY searches
  - candidate resonances

BlackHat

Bern, Dixon, Febres Cordero, Hoeche, Ita, Maitre, DAK, Lo Presti, Maitre

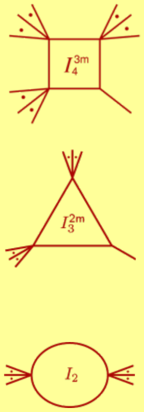
- Library for one-loop processes in automated form
- Specialty: High multiplicity
- Uses on-shell methods
- Uses multiple precision where needed for numerical stability term-by-term and point-by-point in phase space

- One of several libraries in current use: GoSAM, OpenLoops, Njets, MadLoop…

- SHERPA for real-emission matrix elements, Catani–Seymour dipoles, phase-space management, phase-space integration, and extra terms

On-Shell Methods

- Use only information from physical states
- Use properties of amplitudes as calculational tools
  - Factorization → on-shell recursion (Britto, Cachazo, Feng, Witten,…)
  - Unitarity → unitarity method (Bern, Dixon, Dunbar, DAK,…)
  - Underlying field theory → gedanken integral reduction



- Formalism at one loop, integral form

Rational function of spinors

Known integral basis:

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

D=4 Unitarity

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

- Suitable for direct numerical use
- Equivalent form at integrand level (Ossola–Papadopoulos–Pittau)

n-Tuples

- Matrix-element calculation is expensive
- Computation of observables is cheap

- Solution: recycle! Compute matrix elements once, save phase-space configurations with weights & coefficients needed to recompute for different μ_R, μ_F, PDFs; allows narrowing cuts

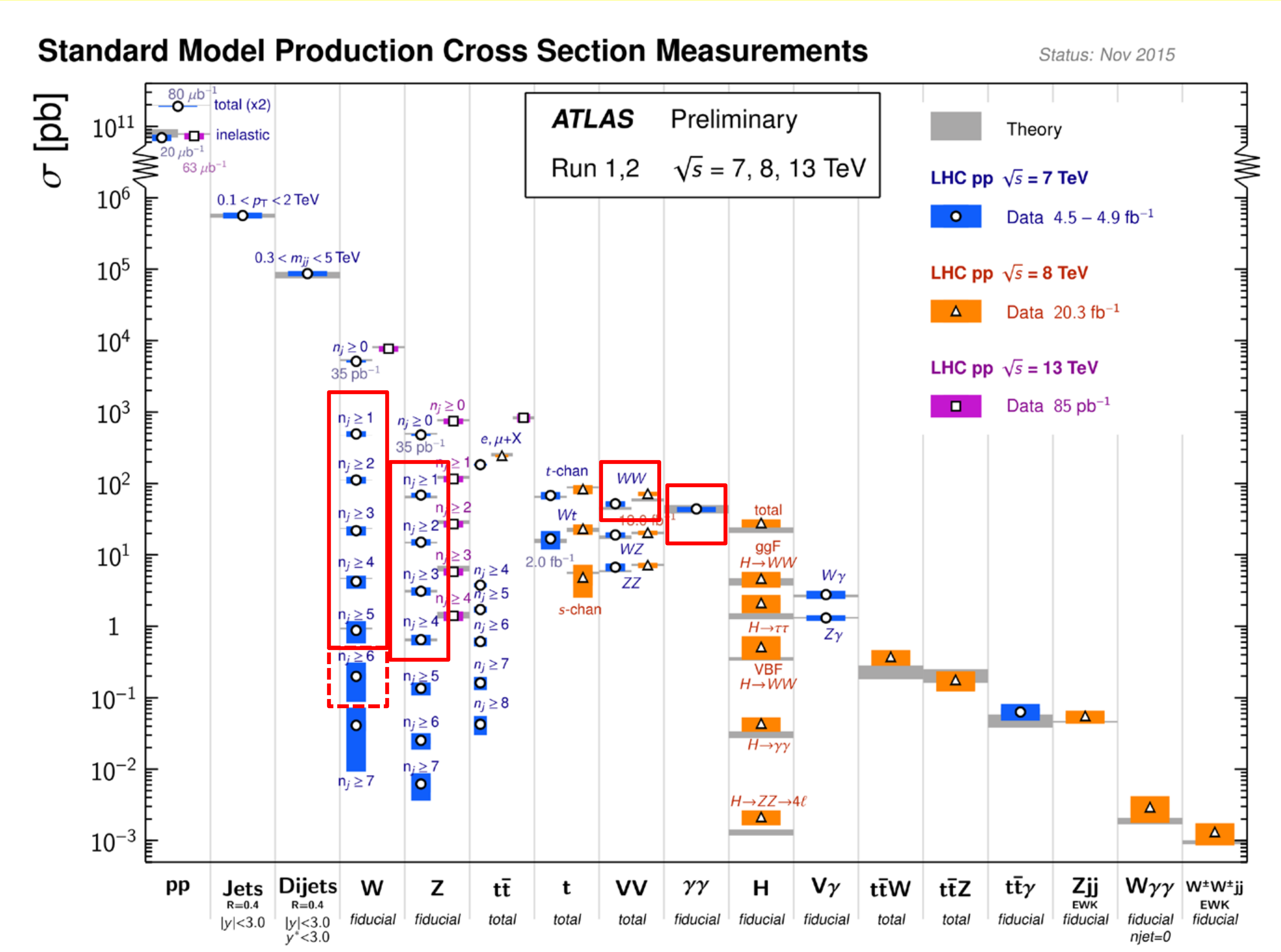
- Save these as ROOT *n*-tuple files
- Publicly available on the LHC Grid
  - Full support in SHERPA
  - C++ reader library available
  - RIVET support in beta

- Convenient for supplying predictions to experimenters
  - They can redo analyses without running or hacking code

n-Tuples

- Available processes at 7 & 13 TeV
  - W+0, 1, 2, 3, 4, 5 jets
  - Z+0, 1, 2, 3, 4 jets
  - 2, 3, 4 jets
  - $\gamma\gamma$+1, 2 jets
  - W^+W^-+0, 1, 2, 3 jets

[A subset also at 8 TeV: V+1,2,3 jets; W^+W^-+1, 2, 3 jets]

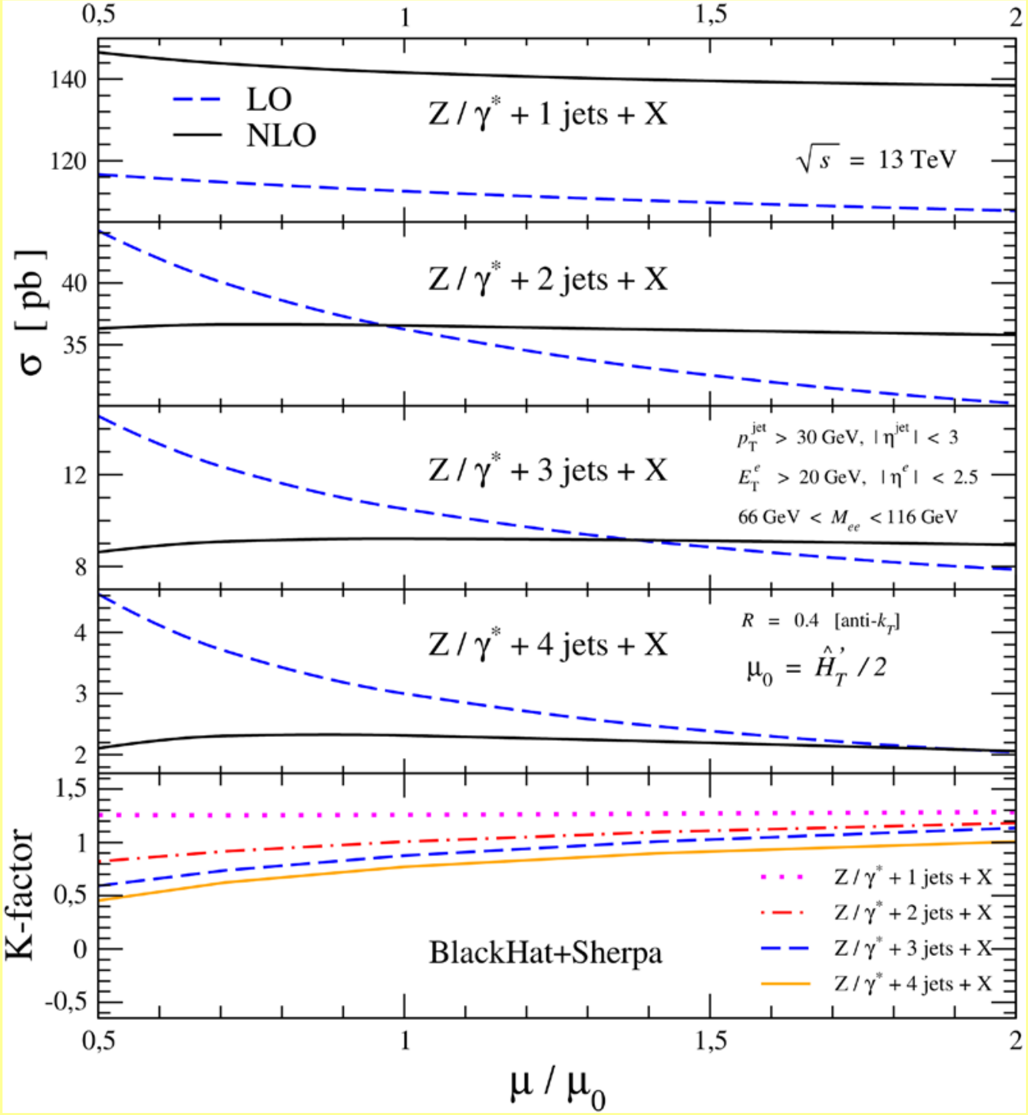

Standard Model Production Cross Section Measurements
Status: Nov 2015
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 85 pb⁻¹
σ [pb]
80 μb⁻¹
total (x2)
inelastic
20 μb⁻¹
63 μb⁻¹
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
nj ≥ 0
35 pb⁻¹
nj ≥ 1
nj ≥ 2
nj ≥ 3
nj ≥ 4
nj ≥ 5
nj ≥ 6
nj ≥ 7
nj ≥ 8
e, μ+X
t-chan
Wt
2.0 fb⁻¹
s-chan
WW
WZ
ZZ
total
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
pp
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ total
t total
VV total
γγ fiducial
H fiducial
Vγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial

V+Jets

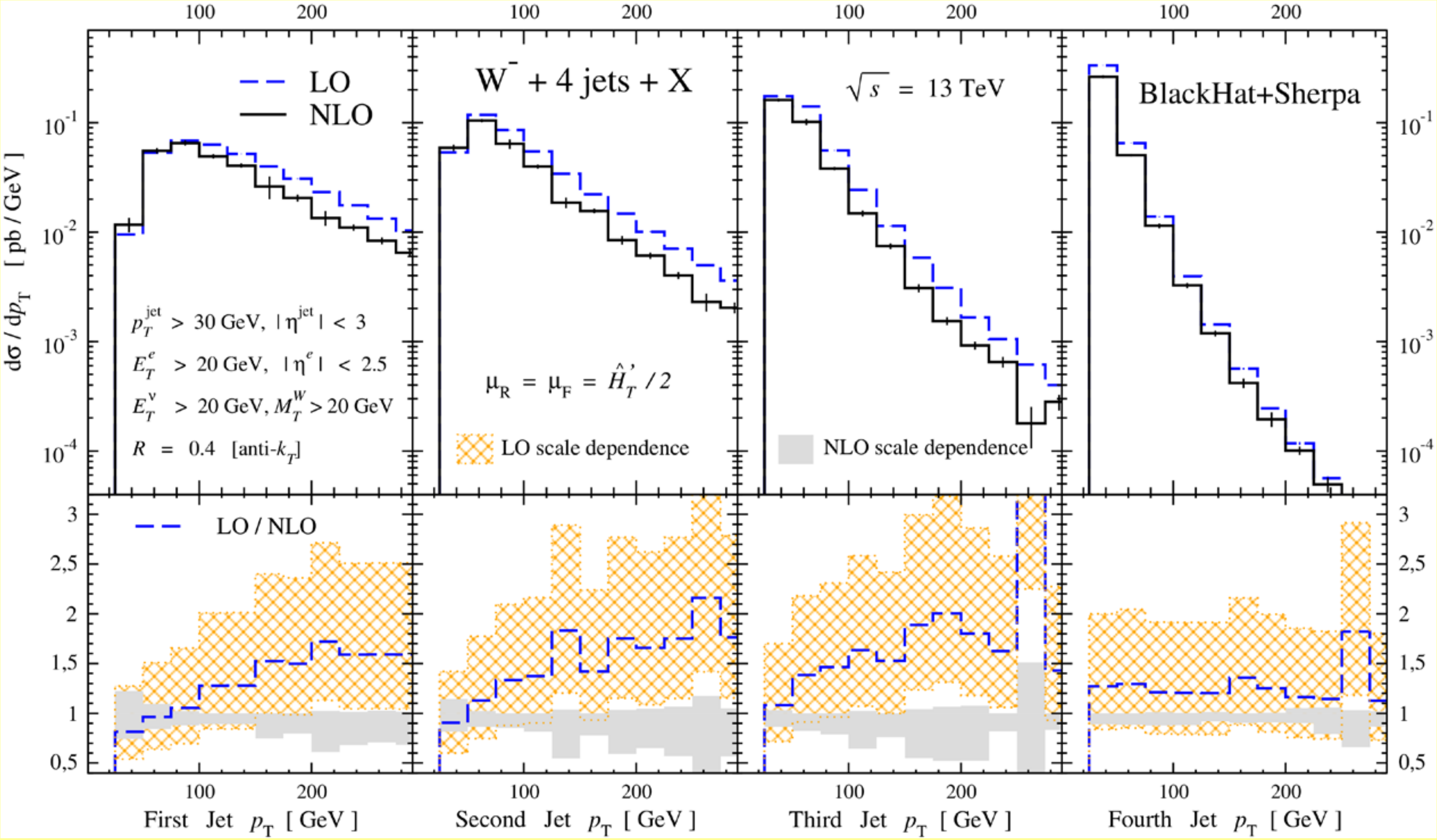
- Detailed study of known physics in complicated final states with many scales
- Edges of distributions host searches for new physics in cascade decays (SUSY)
- EW corrections and Sudakovs will be important in the future ⇒ Freitas's and Hollik's talks
- Indications of universality for 3 or more jets
- Studied extensively at 7 TeV, now updated to 13 TeV

Scale Sensitivity

- Reduced scale dependence at NLO as expected
- NLO importance grows with increasing number of jets
- Trend flattens out at ~3 jets thanks to use of a dynamical scale

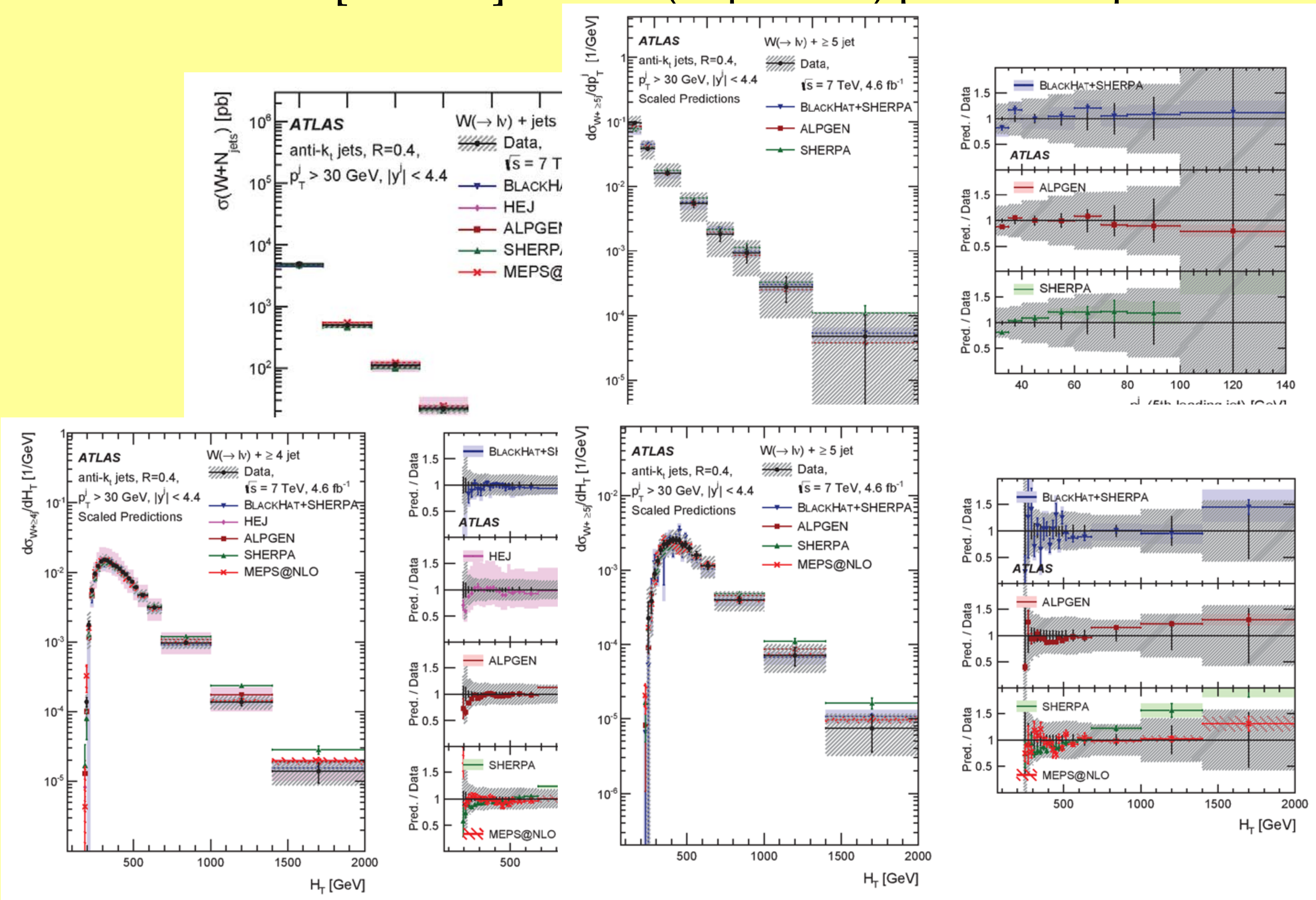


p_T Spectra



- Much narrower uncertainties at NLO
- Shape changes for leading jets

ATLAS 7 TeV [4.6 fb^{-1}] results (Sept 2014) [1409.8639]

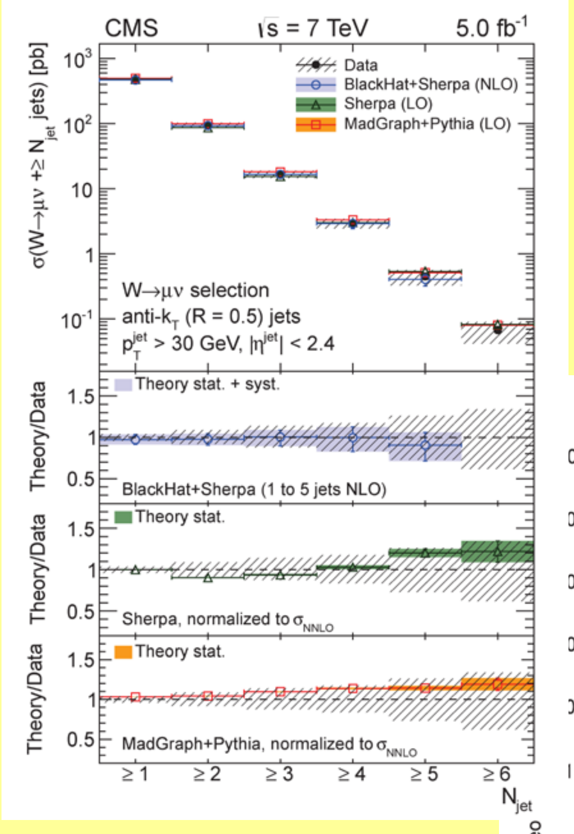


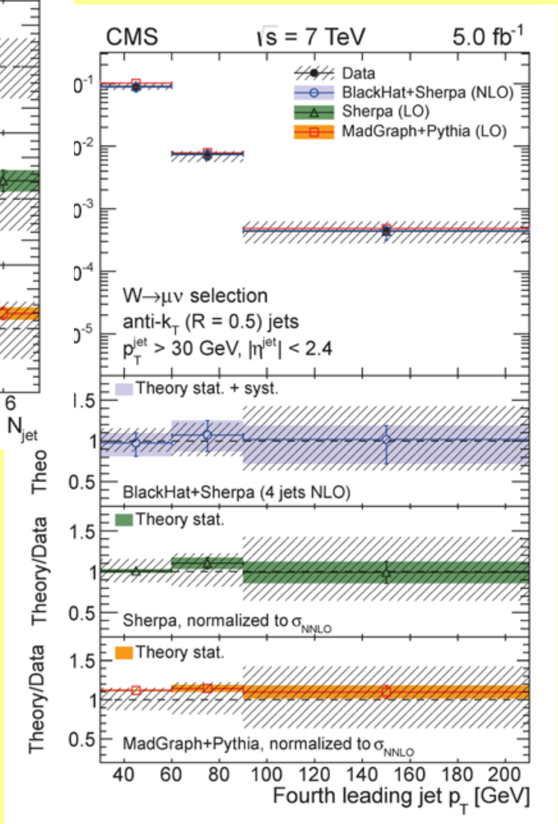
Comparisons with CMS

[1406.7533] Study of $W^\pm$ production in association with multiple jets

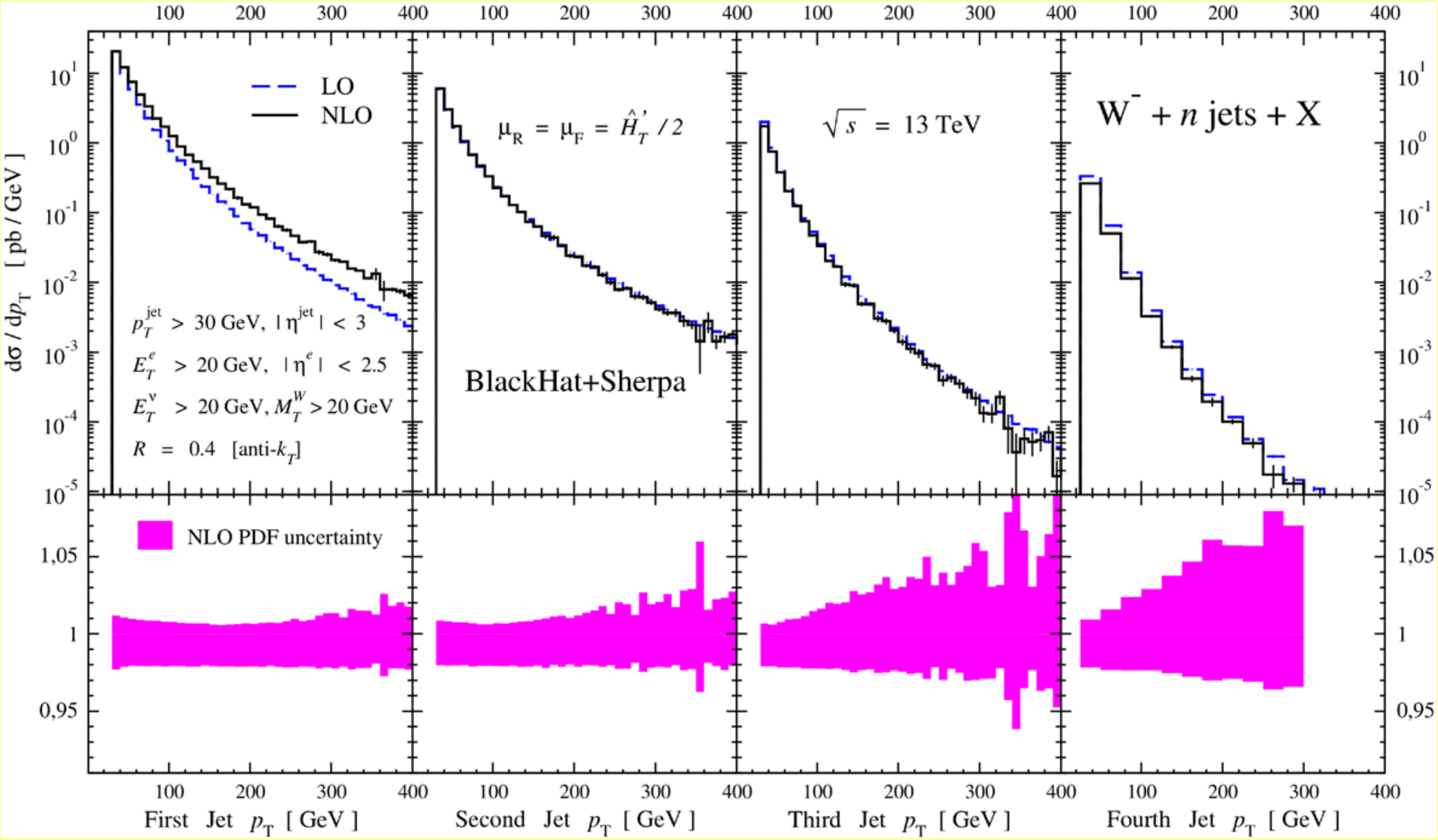
NLO QCD results from BLACKHAT n-tuples (with added nonperturbative corrections)

Similar studies for Z+jets





PDF Uncertainties



- Softest jet in W^-+jets
- n-Tuples make this straightforward
- Uncertainties small but growing with p_T

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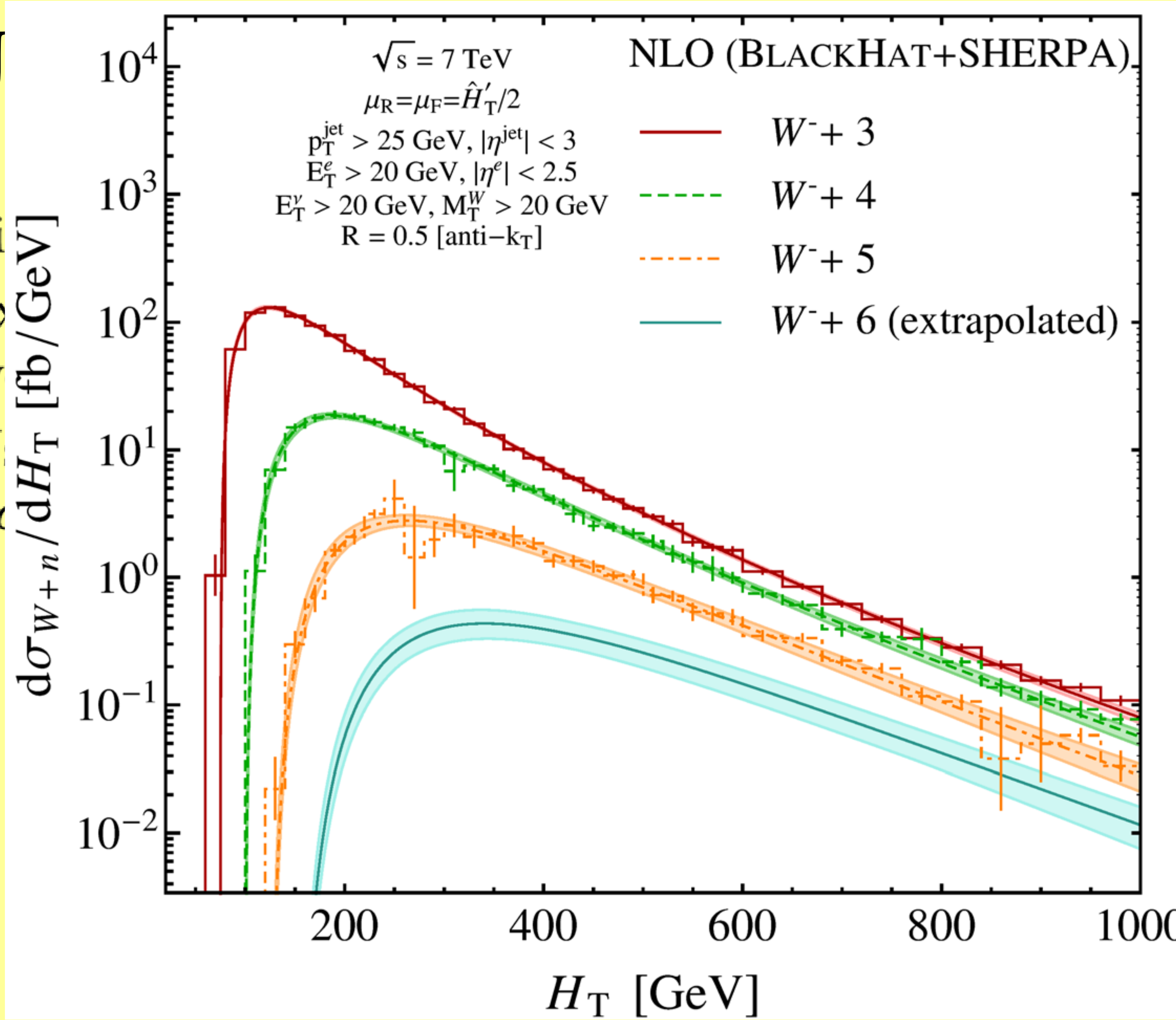
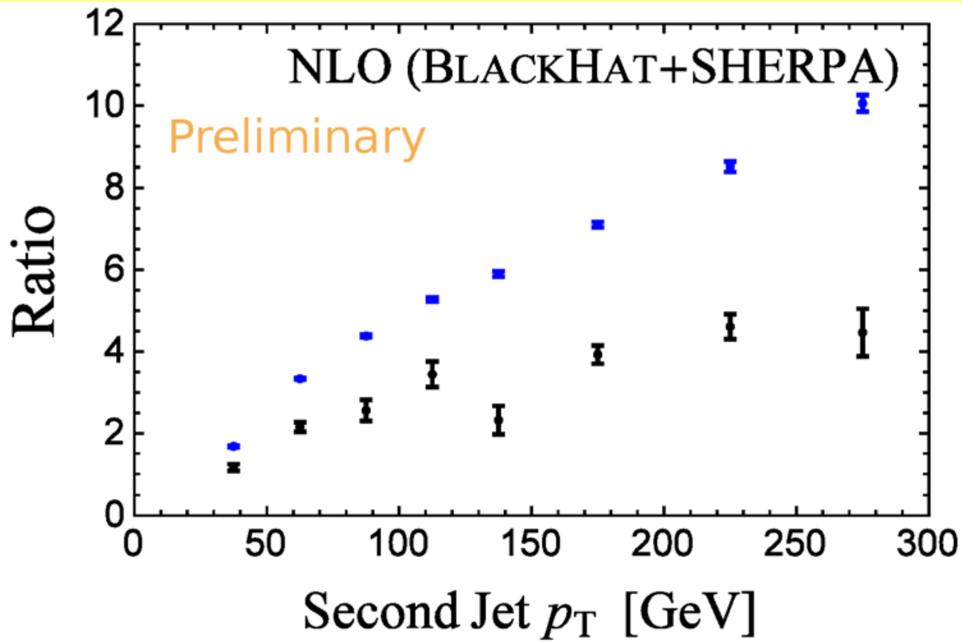
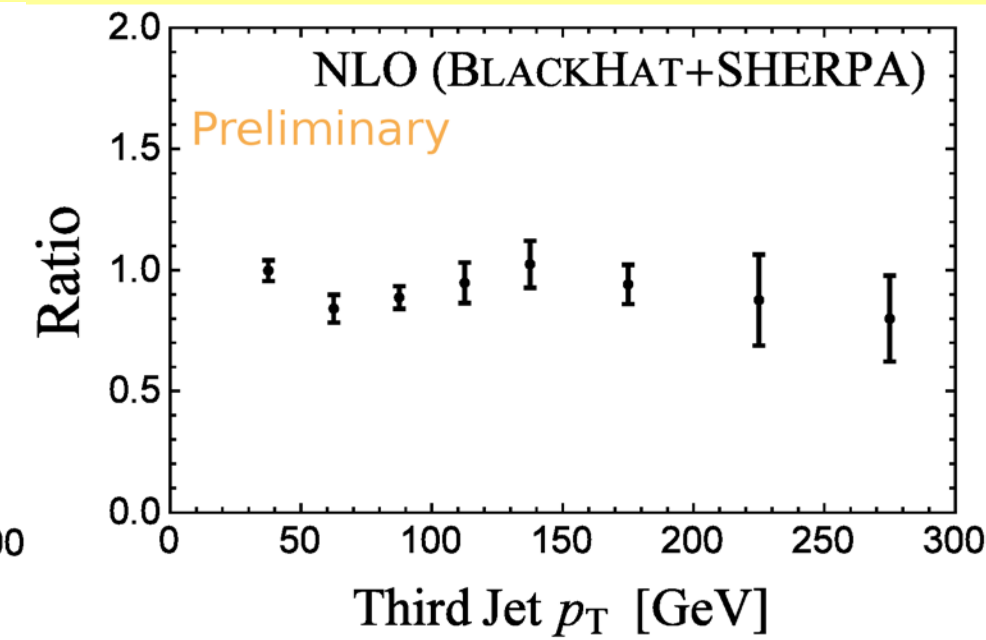


Ratios of 13 TeV to 7 TeV





- Third-jet distribution in W^{-}+3 jet production (p_T cut at 25 and 30 respectively)
- Third-jet distribution in double ratio of (W^{-}+4)/(W^{-}+3) production

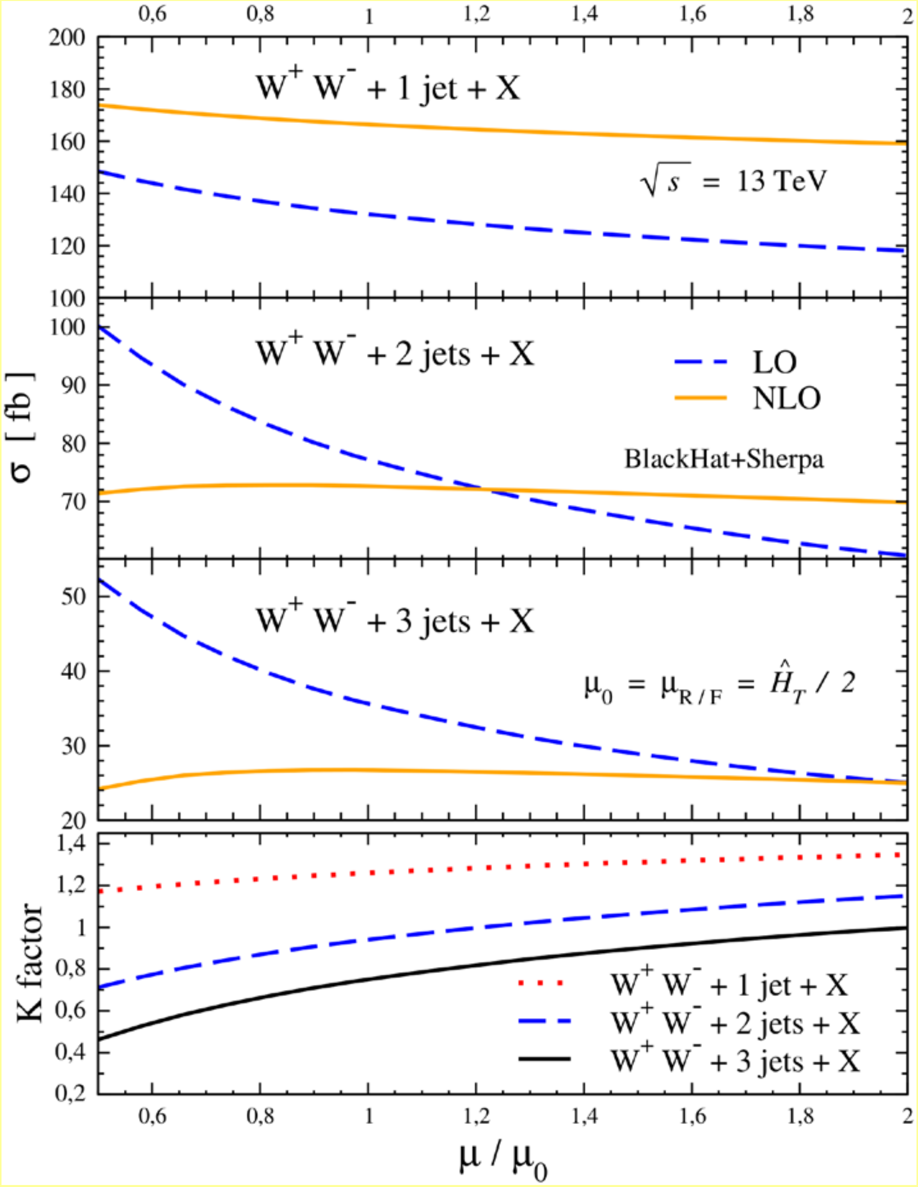
VV+Jets

Febres Cordero, Hoffman, & Ita [1512.07591]

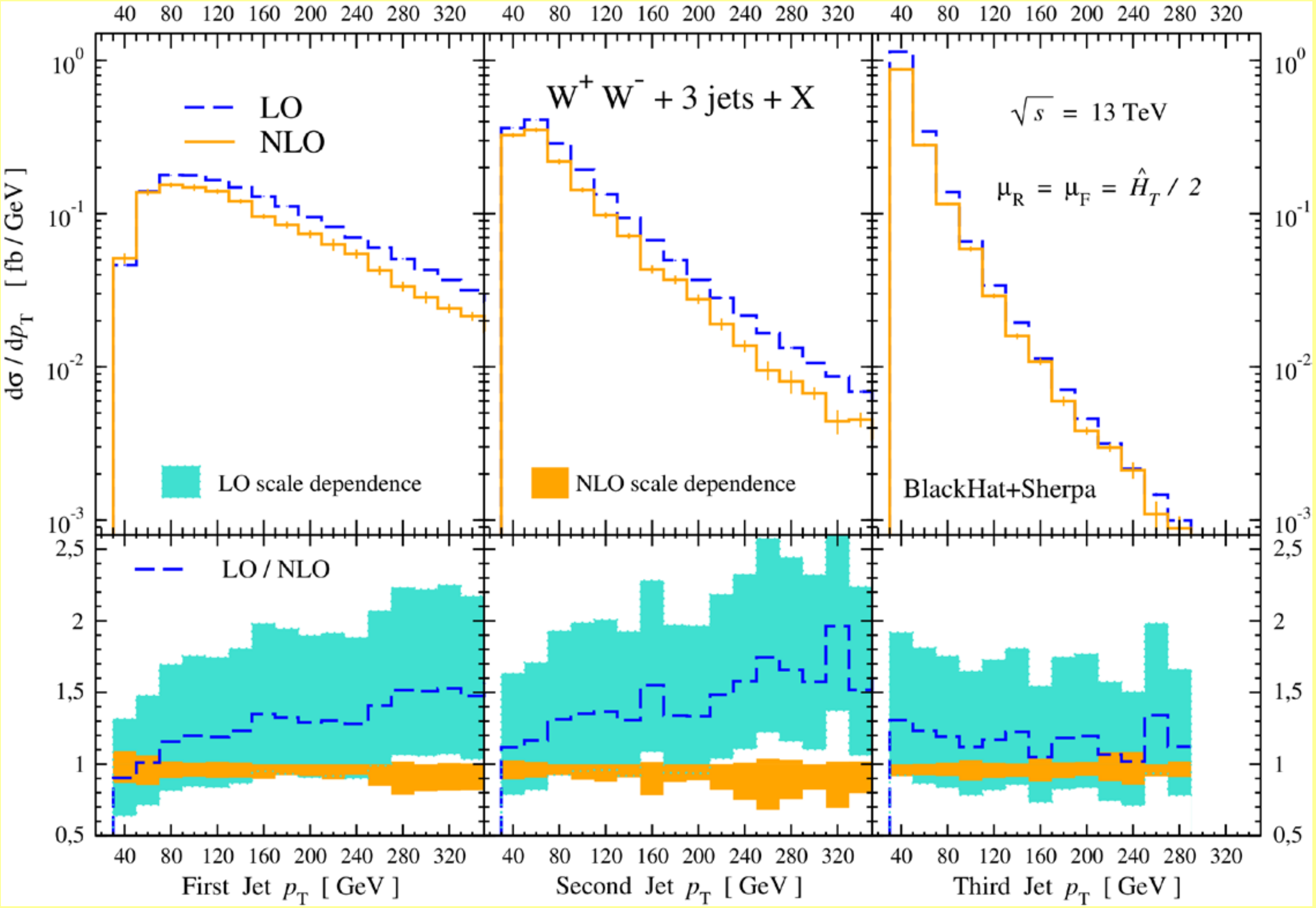
- Background to $t\bar{t}$ production
- Background to Higgs decay to W^+W^-
- Background to Higgs in vector-boson fusion (VBF)
- W^+W^-+3 jets relevant to radiation gap in VBF

Scale Sensitivity

- Similar pattern to V+jets
- Not yet clear at what multiplicity trend flattens out



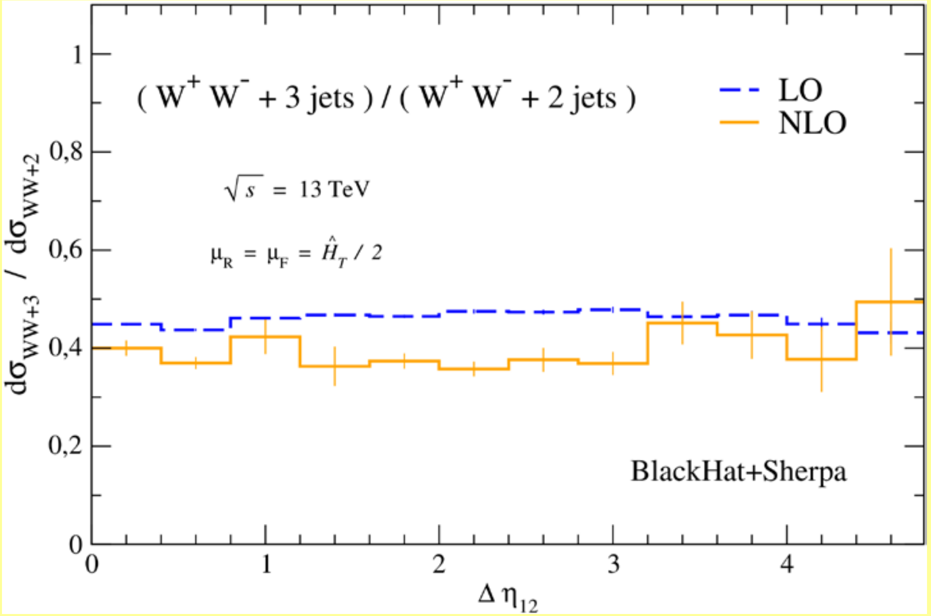
p_T Spectra

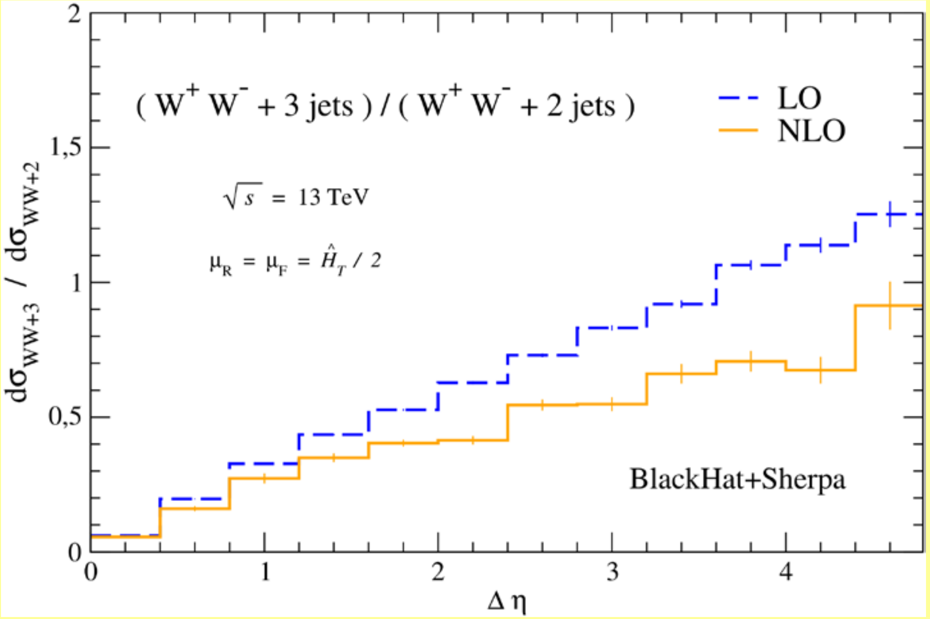


LO
NLO
$W^+ W^-$ + 3 jets + X
$\sqrt{s}$ = 13 TeV
$\mu_R = \mu_F = \hat{H}_T / 2$
LO scale dependence
NLO scale dependence
BlackHat+Sherpa
LO / NLO
dσ / dp_T [fb / GeV]
First Jet p_T [GeV]
Second Jet p_T [GeV]
Third Jet p_T [GeV]

Vector-Boson Fusion

- Study radiation into the gap (without mass cut)





Diphoton(+Jet)

with Ye Li (FNAL)

- Background to everyone's favorite candidate resonance at 750 GeV
- A first exploration of NNLO
  - Hybrid infrared-control scheme
  - Inclusive diphotons discussed earlier by Campbell

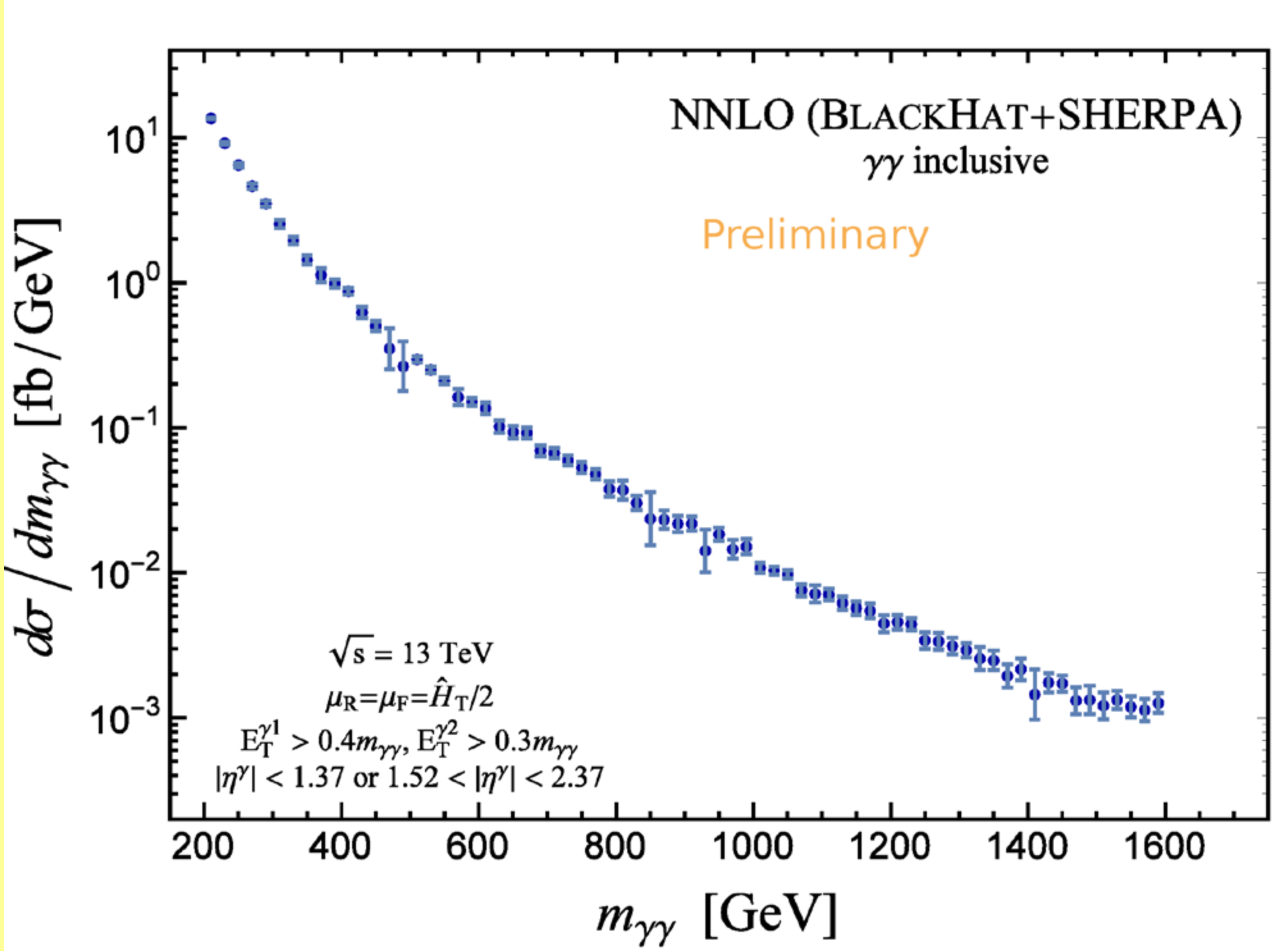
NNLO Ingredients

$\Rightarrow$ Giele's and Petriello's talks

- Two-loop 2 partons$\to\gamma\gamma$
- One-loop 2 partons$\to\gamma\gamma$+1 parton
- Tree-level 2 partons$\to\gamma\gamma$+2 partons
- Include *gg* initial state through two loops (its NLO)

- Tree-level: from SHERPA
- One-loop: from BlackHat
- Combined using Catani–Seymour subtraction, outside a q_T slicing region
- Two-loop, implemented directly along with small-q_T contribution
- Relative q_T cut

Invariant-Mass Distribution at NNLO



NLO and Fits

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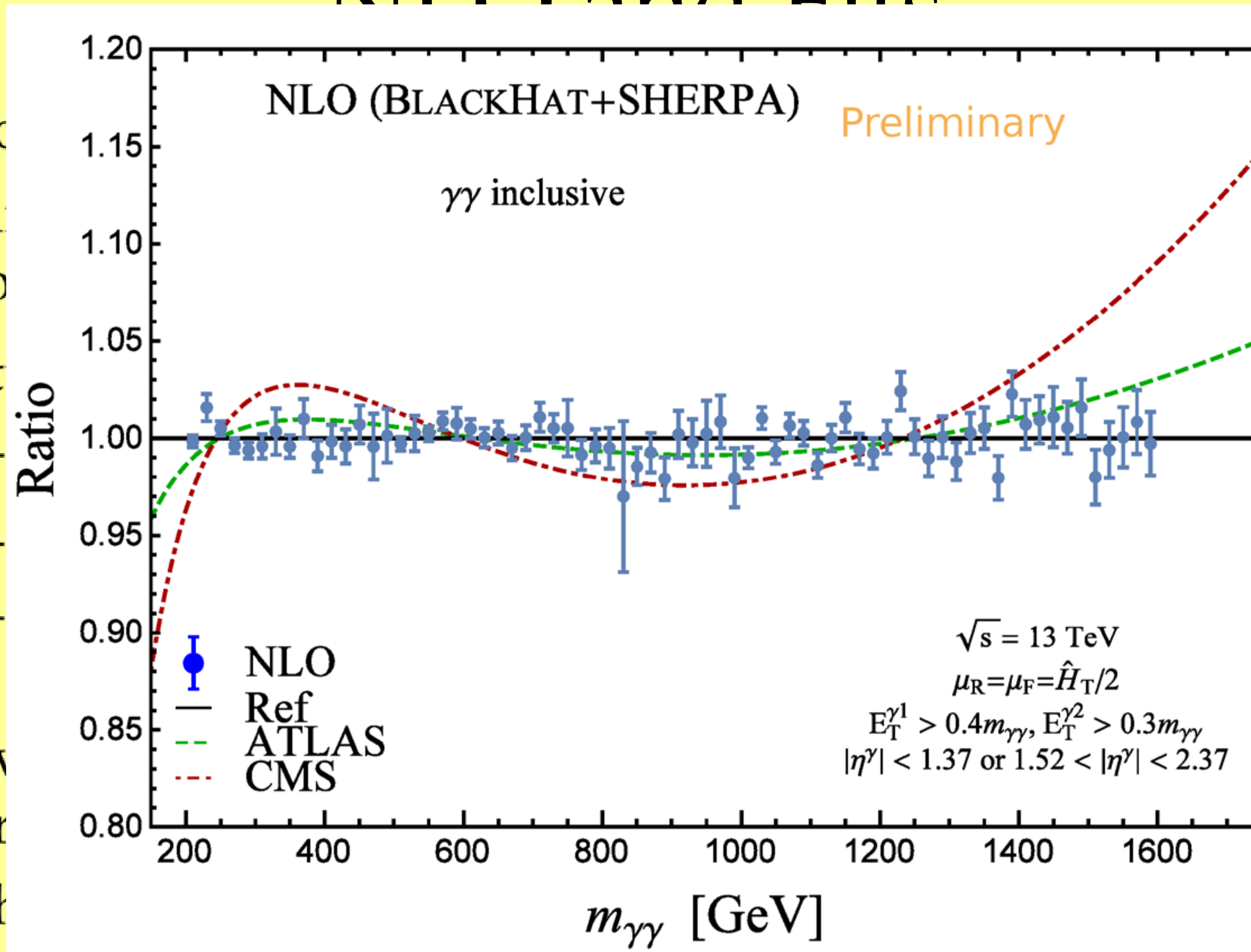
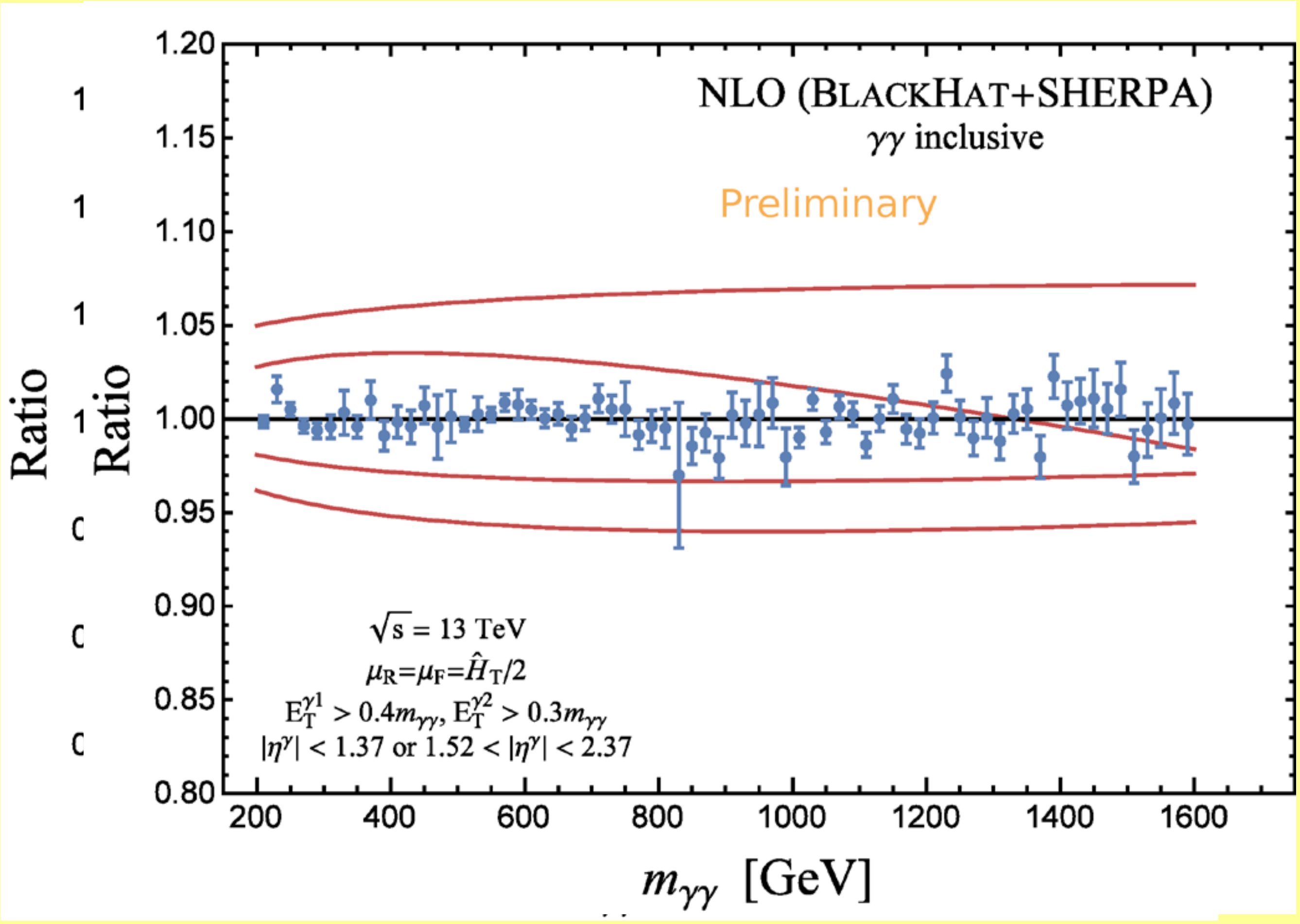
  –



- Ev … n
  pr
- Th … one
  isn't well-motivated
- Illustration of "uniform" treatment of data & theory

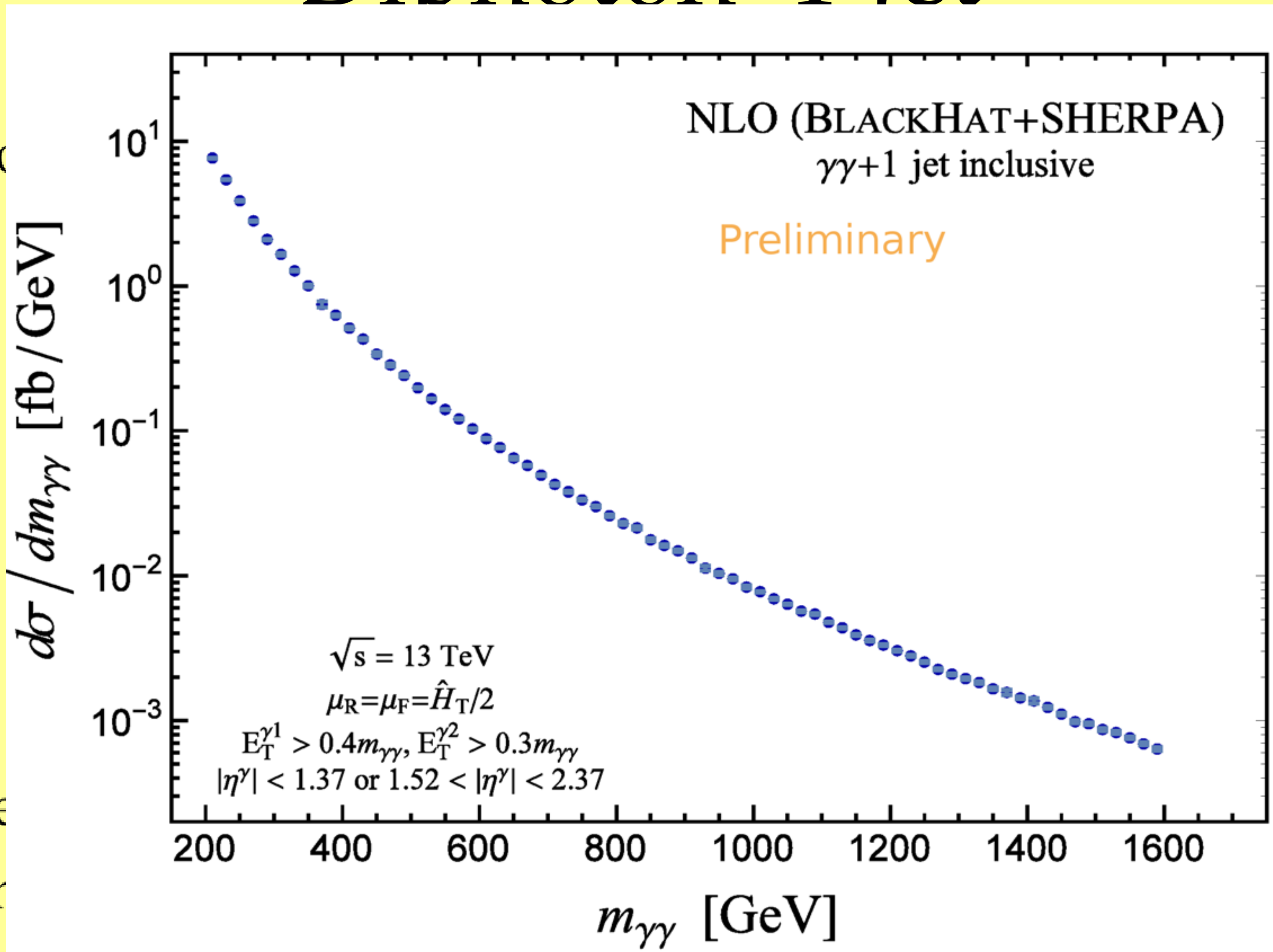
Assess PDF & Scale Uncertainties

- Straightforward & not computationally intensive, thanks to *n*-tuples



Diphoton+1 Jet

- Lo … O



- Pe …
- Sh … GeV

Summary

- NLO studies with multiple jets are becoming standard
- Good control of uncertainties in processes with many scales
- With slicing techniques, a smooth initial path to NNLO