Multi-jet physics with BlackHat

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Work in collaboration with:

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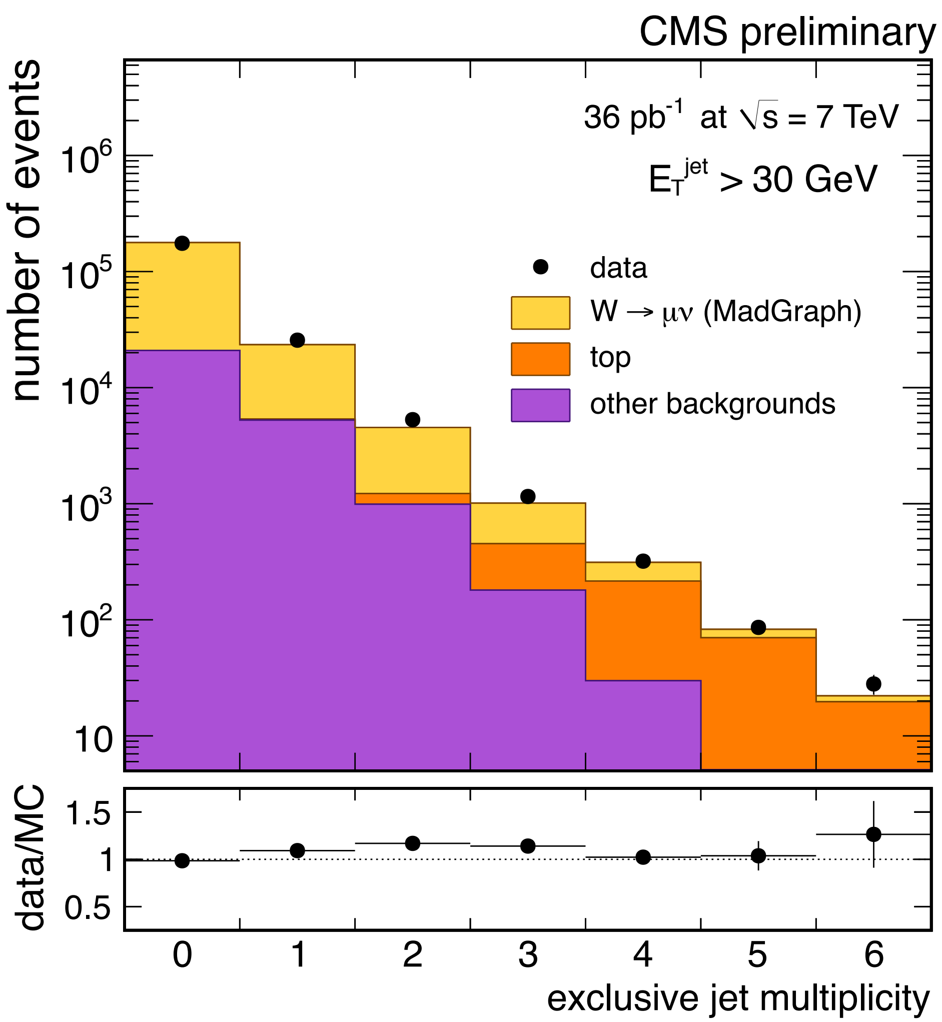
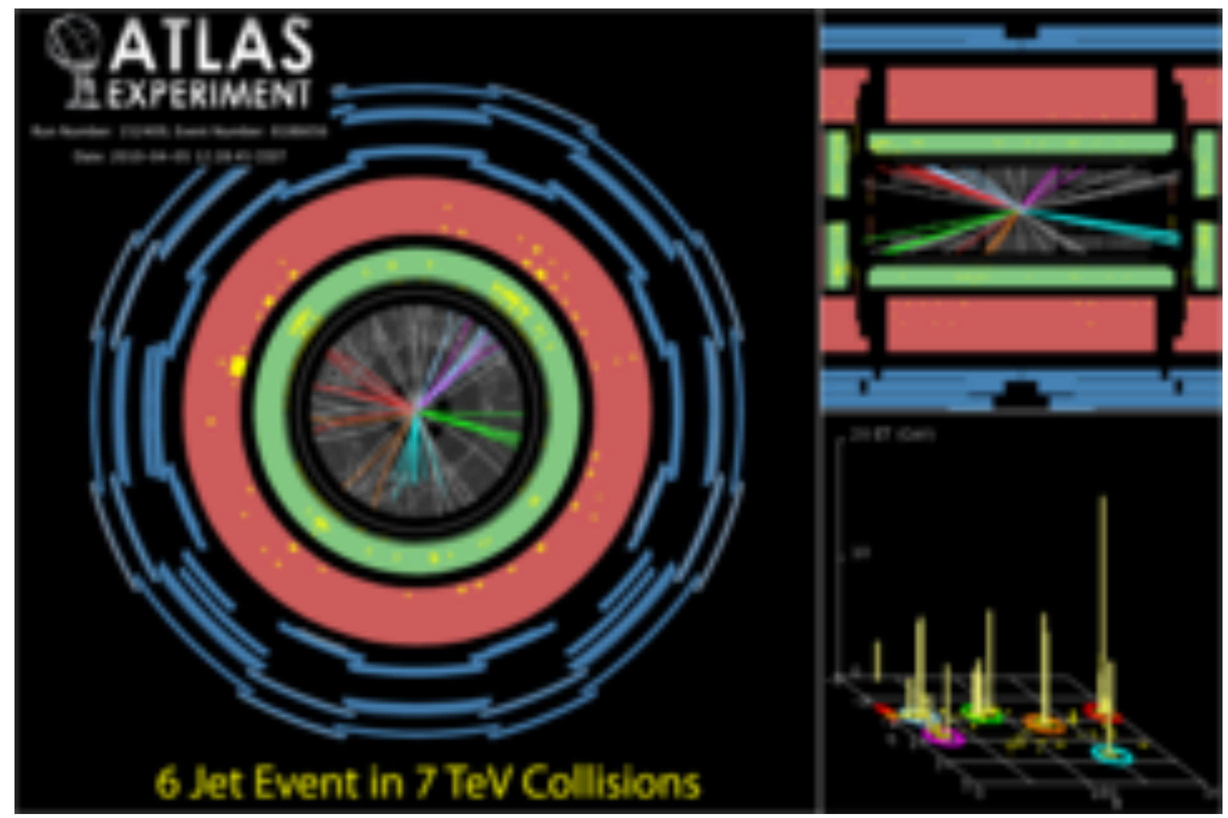
[1106.1423], [1112,3940], [1206.6064], [forthcoming]

Outline

- quest for precision: NLO and BlackHat
- Precision QCD used in CMS jets+MET search
- new result: W+5jets @ NLO
- distributing results: ROOT ntuples
- Fernando's talk: First NLO prediction of 4-jet production

Many hard jets...

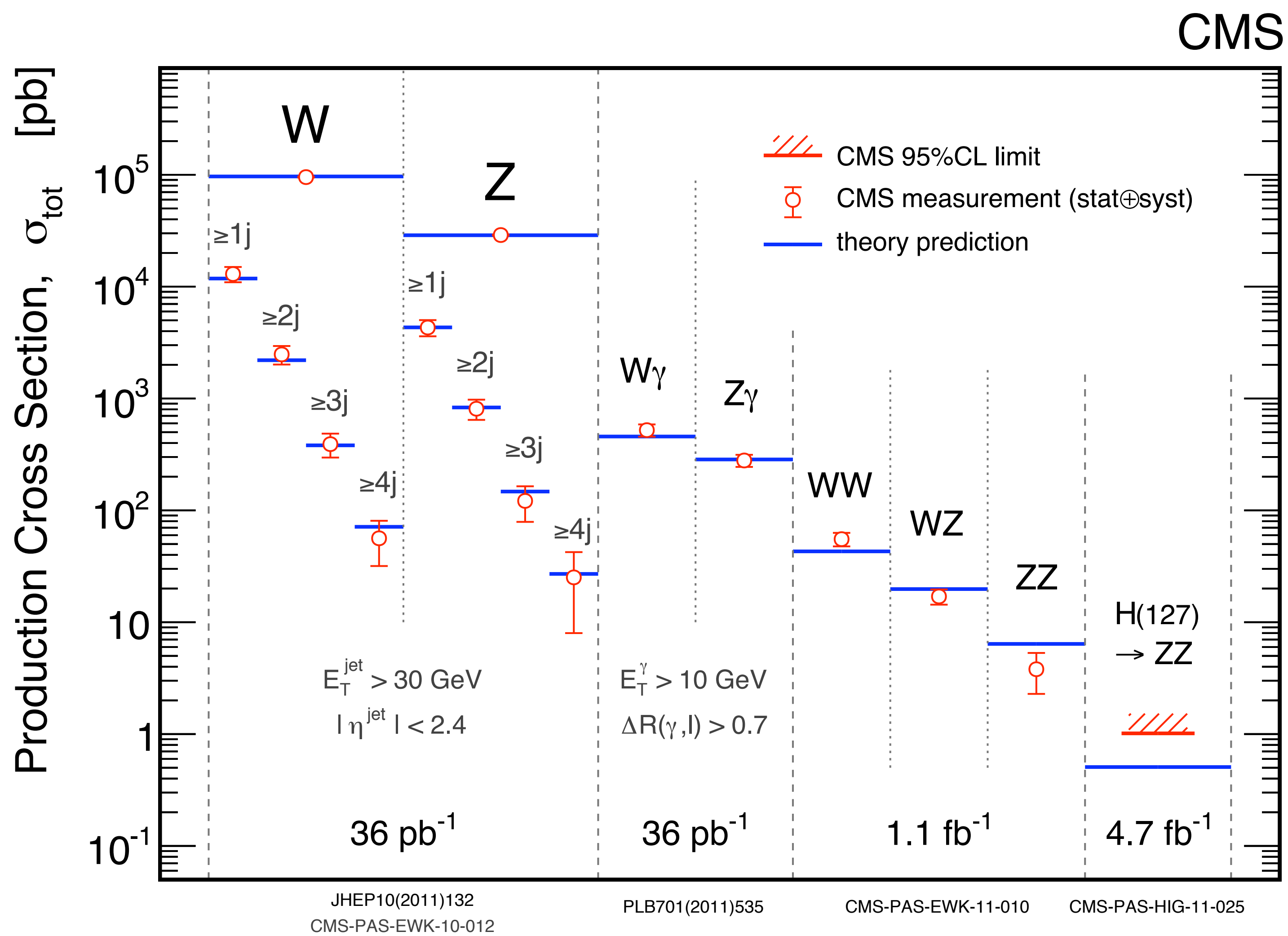




To get the most from the LHC, we need to understand multi-jet final states

A few words on QCD Predictions

- LHC workhorses for full event simulation: Herwig, Sherpa, Pythia
- ME+PS matching when there are many hard jets - big improvement
- But need NLO for reliable first principles QCD prediction, including correct normalization



- Recent exciting progress in matching NLO/PS
  MC@NLO [Frixione, Webber; Sherpa]
  POWHEG [Nason; Frixione, Nason, Oleari]
- These tools still require the one-loop amplitude as input...

BlackHat

- Efficient evaluation of one-loop QCD amplitudes

  (traditionally the hardest aspect of NLO predictions)

- Implementation of modern generalized unitarity method
- Evaluates coefficients of integrals

$$A = \quad R + \sum_i d_i + \sum_i c_i + \sum_i b_i$$

- Tree amplitudes in → one-loop amplitudes out
- Opens the door to precise predictions for multi-jets, used in conjunction with SHERPA
- Well tested and battle-hardened:

W+1,2,3,4,(5) jets, Z+1,2,3,4

- similar codes available: GoSam, HELAC-NLO, Madloop, NGluon, Rocket ...

Jets+MET at CMS

Data-Driven Background Estimation

- New physics search in jets + MET channel
- CMS estimates Z + 3 jets background by measuring photon + 3 jets events

$$\sigma(pp \to Z(\to \nu\bar{\nu})) = \sigma(pp \to \gamma) \times R_{Z/\gamma}$$

background to NP

measure this

theory input

So what is R ? Let's *calculate* it at NLO QCD...

Photon Isolation: theory vs experiment

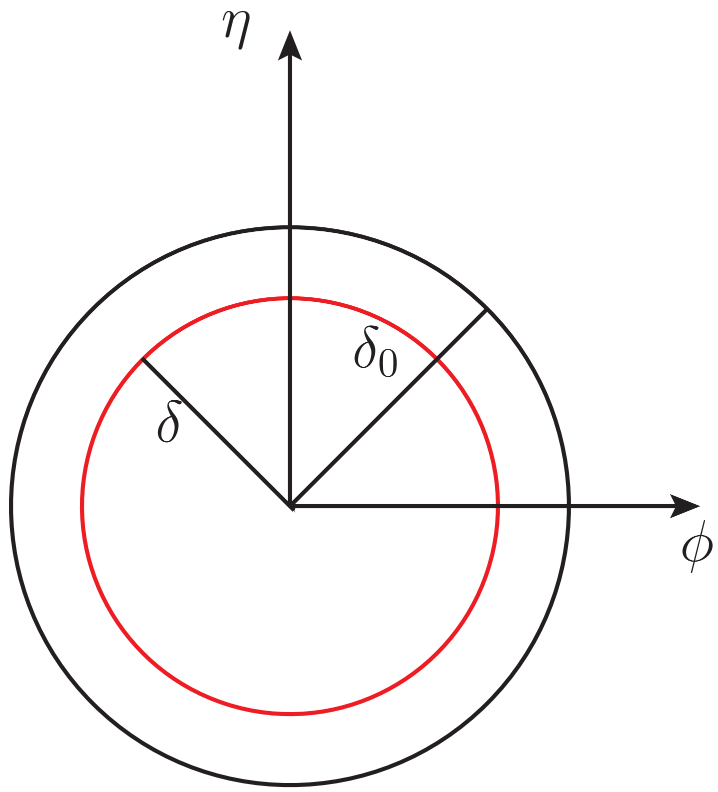
- We are interested in isolated photons
- "Fixed cone" used by experiments is not IR-safe. Described using fragmentation functions on the theory side.
- We employ Frixione isolation [Frixione arxiv:9801442]

(no fragmentation piece)

$$\sum_i E_{iT}\theta(\delta - R_{i\gamma}) \leq H(\delta)$$

Transverse Energy in Cone

vanishes as $\delta \rightarrow 0$



- This is ideal for theorists, problematic for experiments

(detector is granular, but isolation condition is continuous)

Z/gamma ratio for CMS

- We calculate Z+3j and γ+3j to NLO using BlackHat +Sherpa
- Critical variables:

$$H_T = \sum_{\text{jets}} E_T^{jet} \qquad \overrightarrow{\text{MET}} = -\sum_{\text{jets}} \vec{p}_{T,\text{jet}}$$

Set 1: $H_T^{\text{jet}} > 300$ GeV, $|\text{MET}| > 250$ GeV;

Set 2: $H_T^{\text{jet}} > 500$ GeV, $|\text{MET}| > 150$ GeV;

Set 3: $H_T^{\text{jet}} > 300$ GeV, $|\text{MET}| > 150$ GeV;

Set 4: $H_T^{\text{jet}} > 350$ GeV, $|\text{MET}| > 200$ GeV;

Set 5: $H_T^{\text{jet}} > 500$ GeV, $|\text{MET}| > 350$ GeV;

Set 6: $H_T^{\text{jet}} > 800$ GeV, $|\text{MET}| > 200$ GeV;

Set 7: $H_T^{\text{jet}} > 800$ GeV, $|\text{MET}| > 500$ GeV.

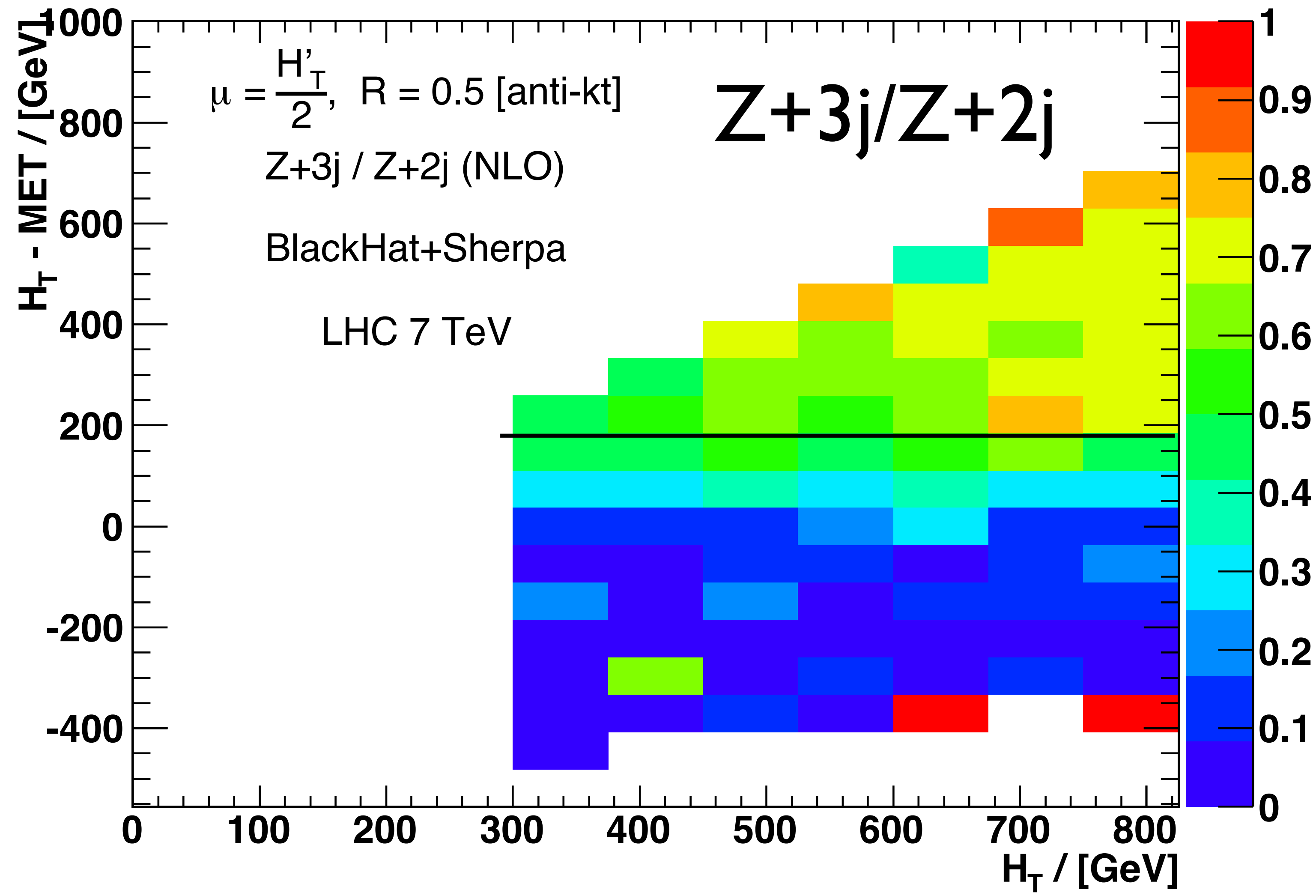
- Jet cut: 50 GeV
- Many different regions of interest: study them all [1106.1423], [1206.6064]

Z/gamma ratio for CMS

How to estimate the error on a ratio?

- Correlated scale variation leads to tiny errors. Should we trust this?
- We study NLO - MEPS and take this as a guide to the uncertainty, finding around 5-10% error
- Other issues: large QCD logs, large EW logs [0508253]. What is their impact?

Can use jet ratios as a diagnostic for large logs



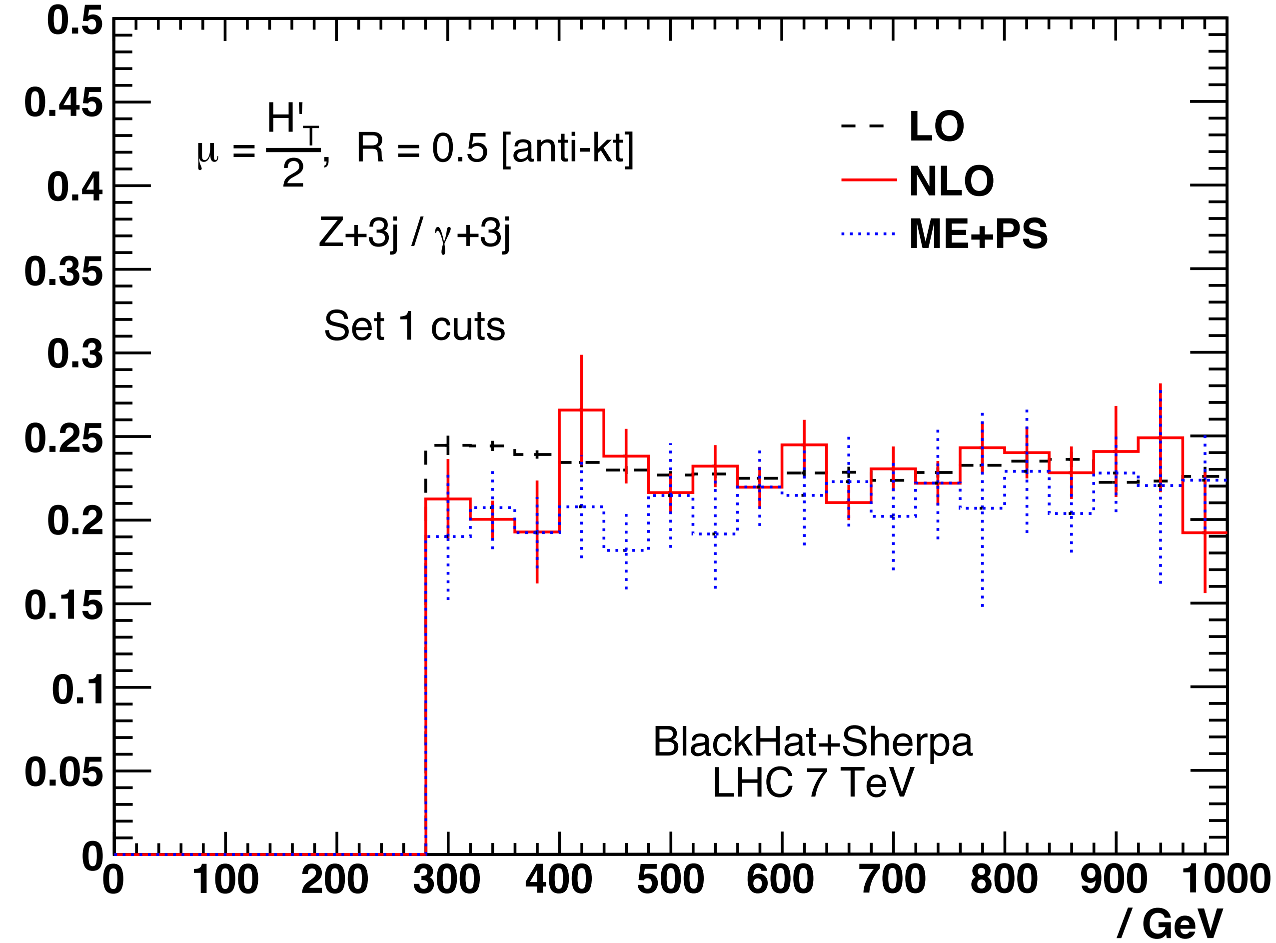
Outcome

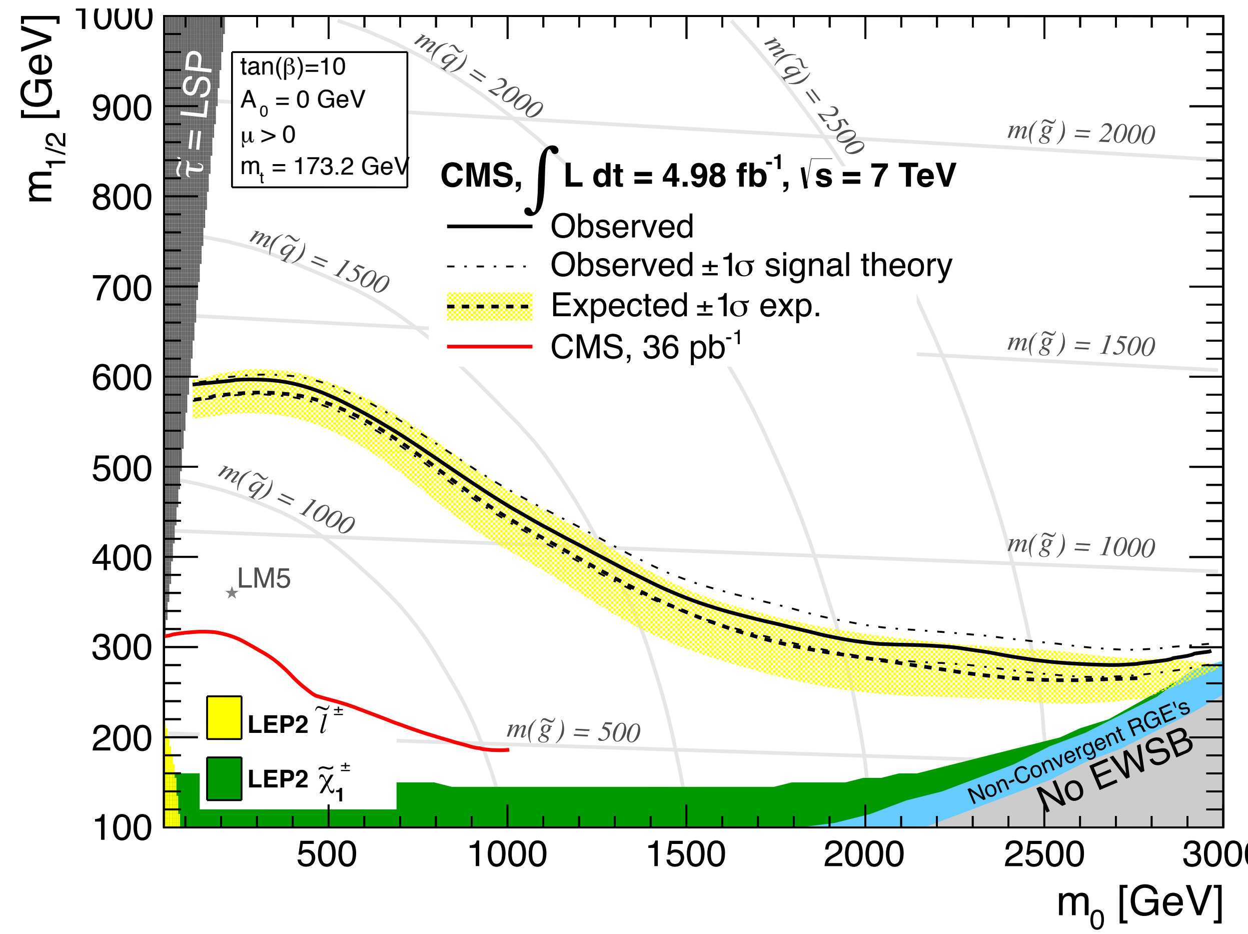
- We worked closely with groups from CMS
- Fruitful cross-talk between theory and experiment
- This search was very constraining...

CMS [1207.1898]

Good example of utility of high-precision theory: ratio = input to data-driven method

See [1106.1423] and [1206.6064] for many plots and numerical results





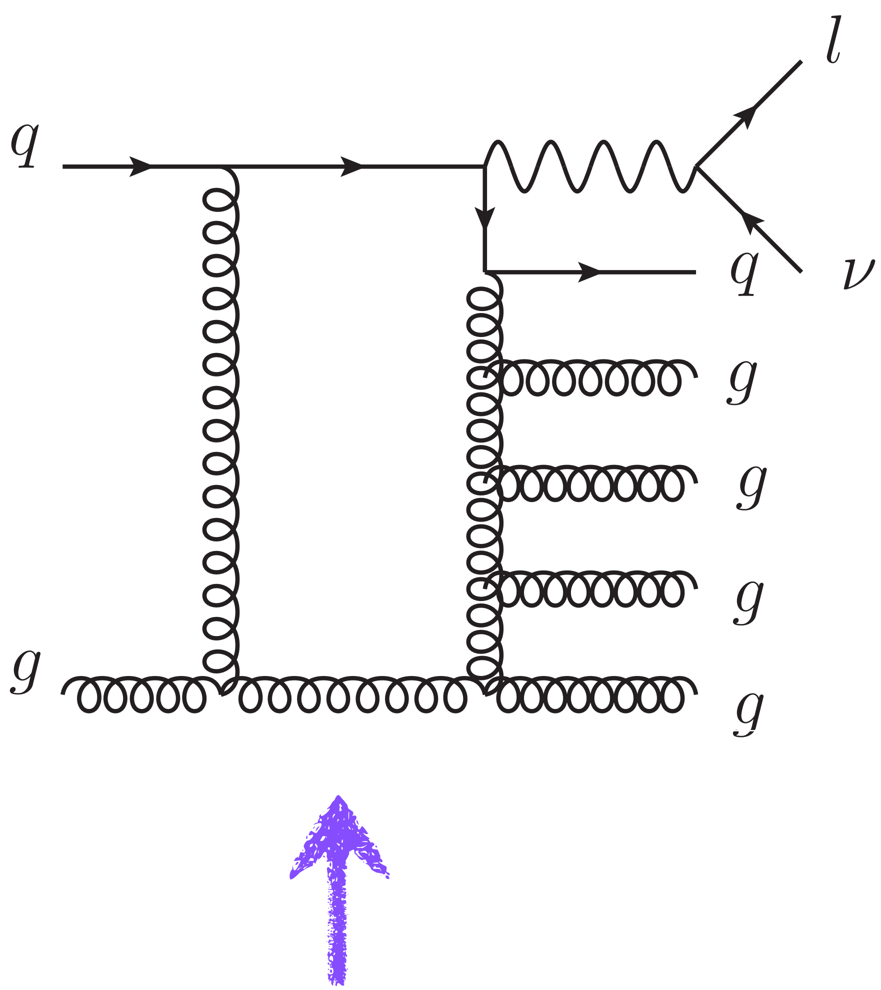
W+5j Production at NLO

this talk: preliminary results

W + 5jets Production at the LHC

Preliminary

First 2→6 NLO **calculation at a hadron collider**



sample Feynman diagram
(octogon!)

$$\text{p p} \to \overbrace{\text{lepton} + \text{MET}}^{\text{W boson}} + 5\text{j}$$

For searches: background for various NP signatures (also to top pair production)

For measurements: check theory vs experiment

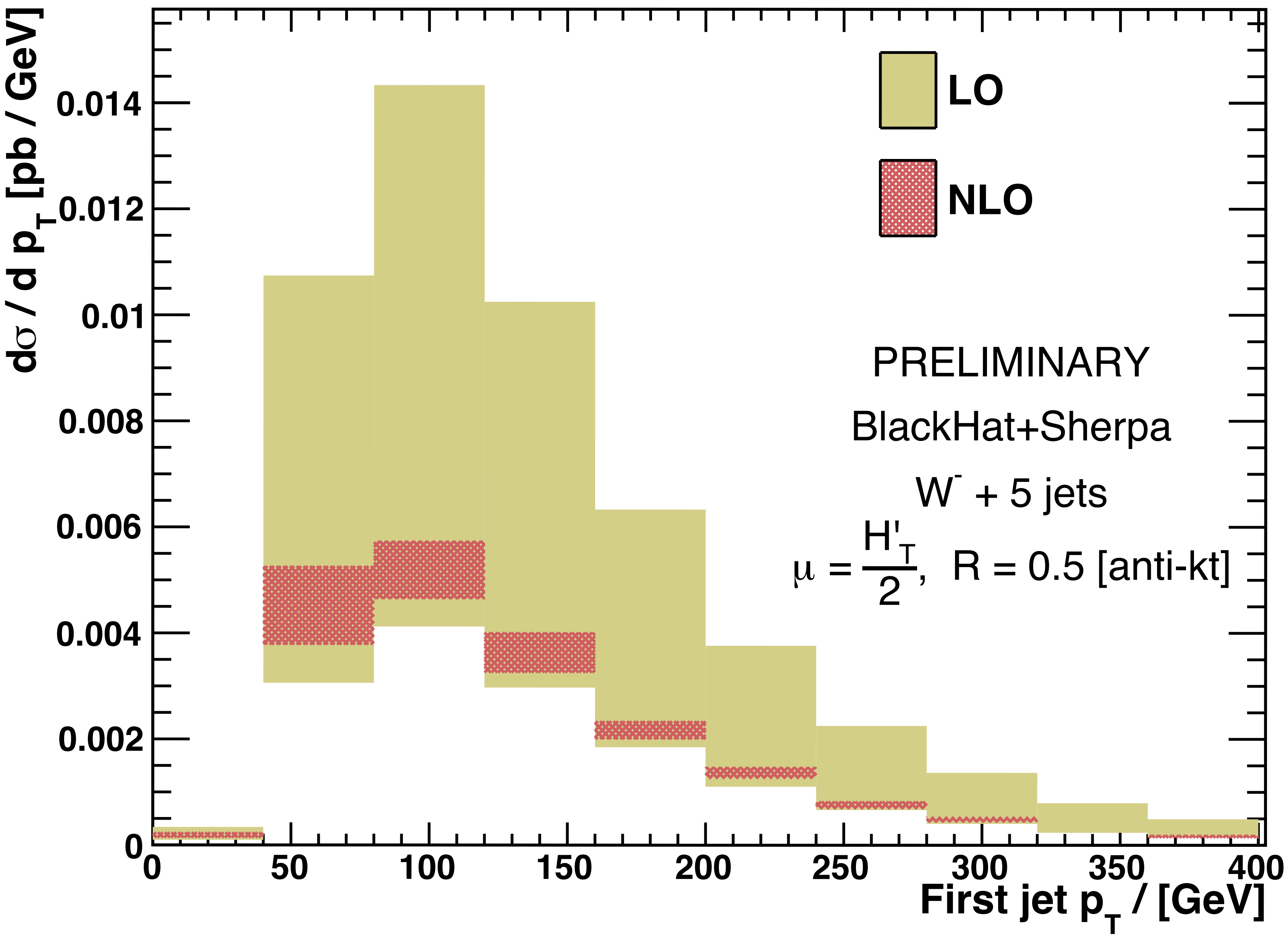
leading colour approx. in the virtual part only: expect 2-3%

Theoretical Tools

- BlackHat for virtual part [Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, KJO]
- COMIX (part of Sherpa) for real emission [Hoeche]
- Sherpa - organizational framework [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Winter]
- LHAPDF for parton distributions [Whalley, Bourilkov, Group]
- FASTJET for jet clustering [Cacciari, Salam, Soyez]
- ROOT for analysis and storing events [see later]

W+5jets: reduced scale variation at NLO

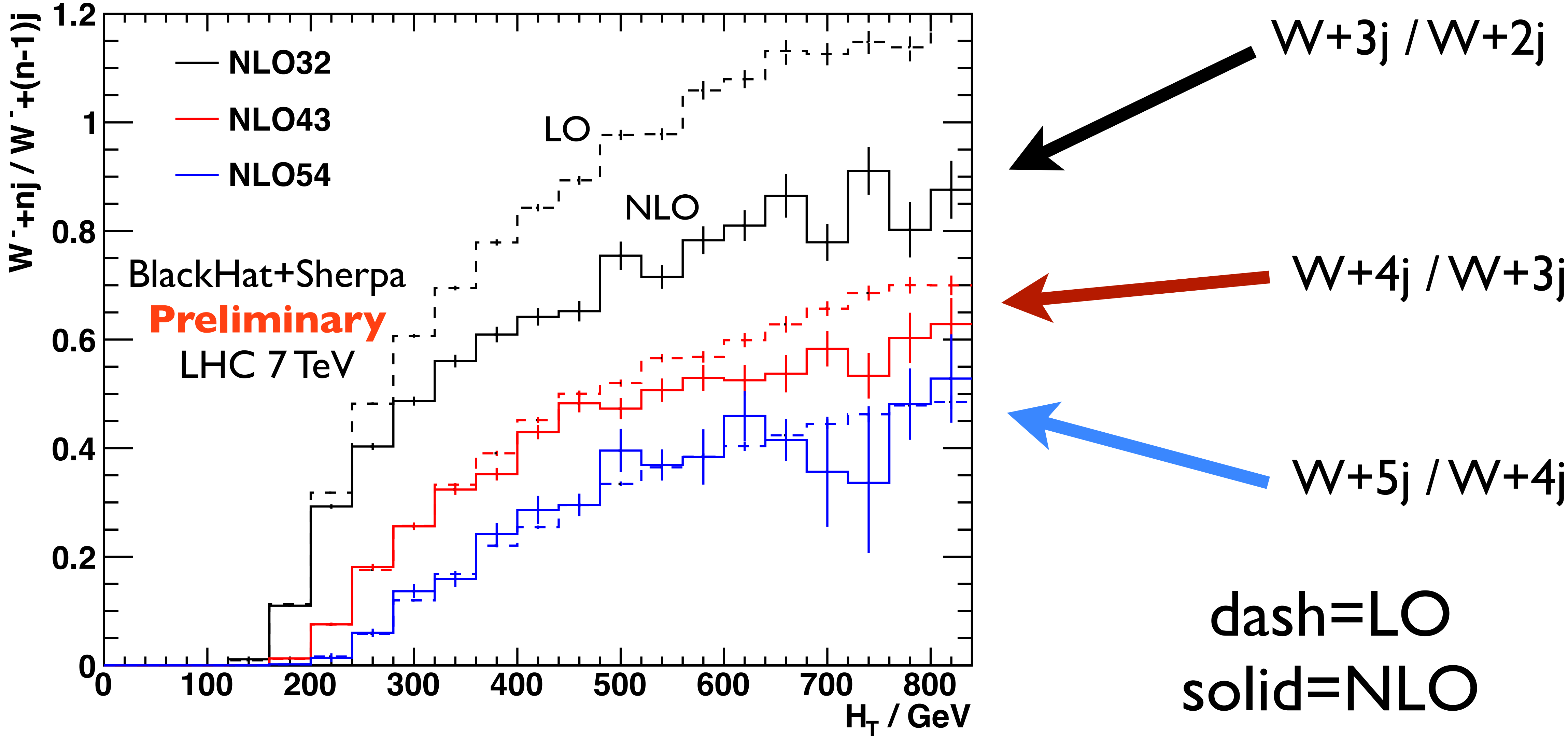


Strong reduction in scale uncertainty

$$\mu_F = \mu_R$$

- Plot shows effect of varying μ up and down by a factor of 2

Jet Ratios: key observables



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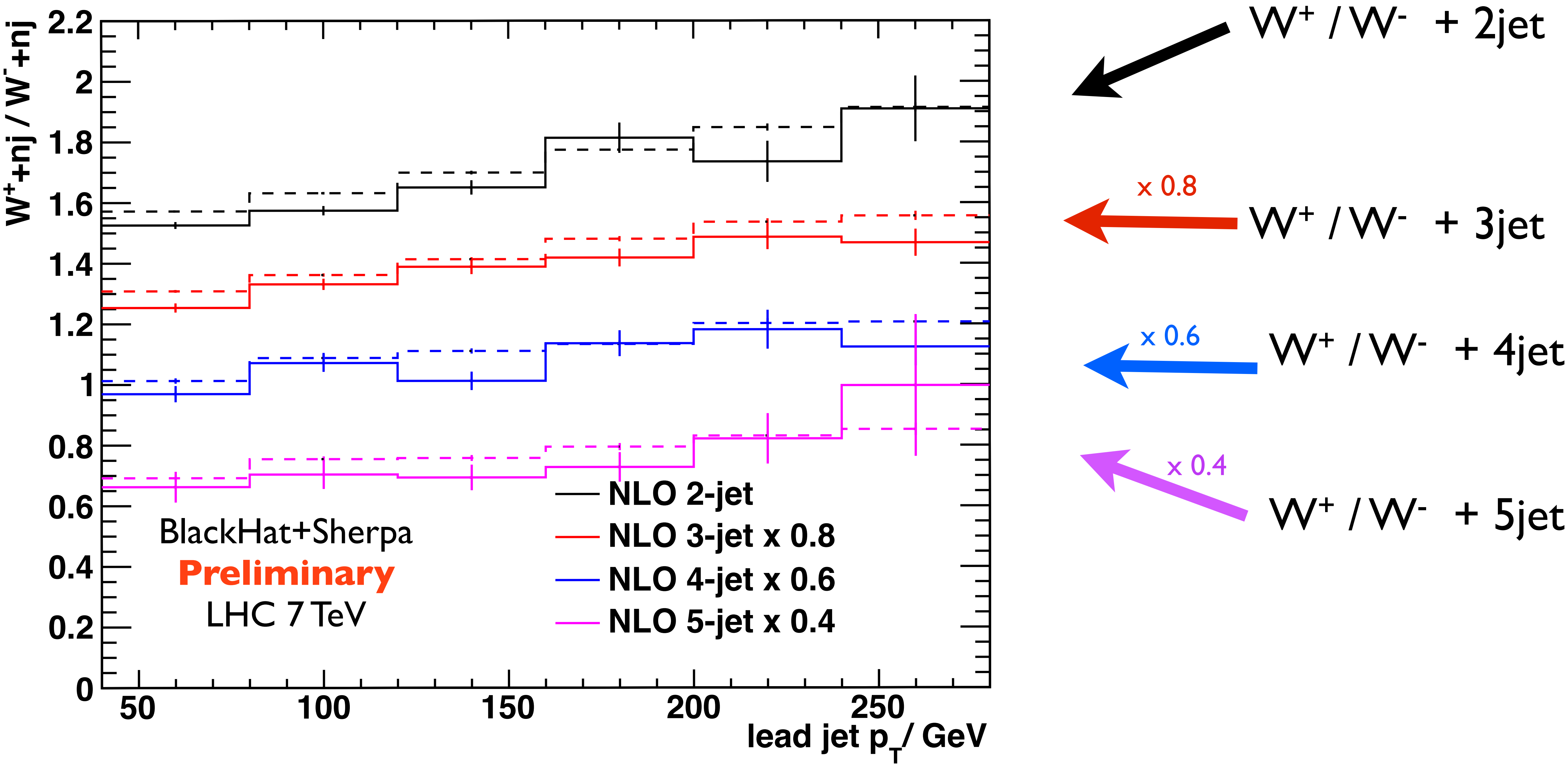
solid=NLO

- Note - they are not constant!
- Both theory and experimental errors are minimized in the ratio
- Can be important input to data-driven methods for backgrounds

(compare Z/γ + 3jets used in SUSY search)

More Ratios: W^+ / W^-



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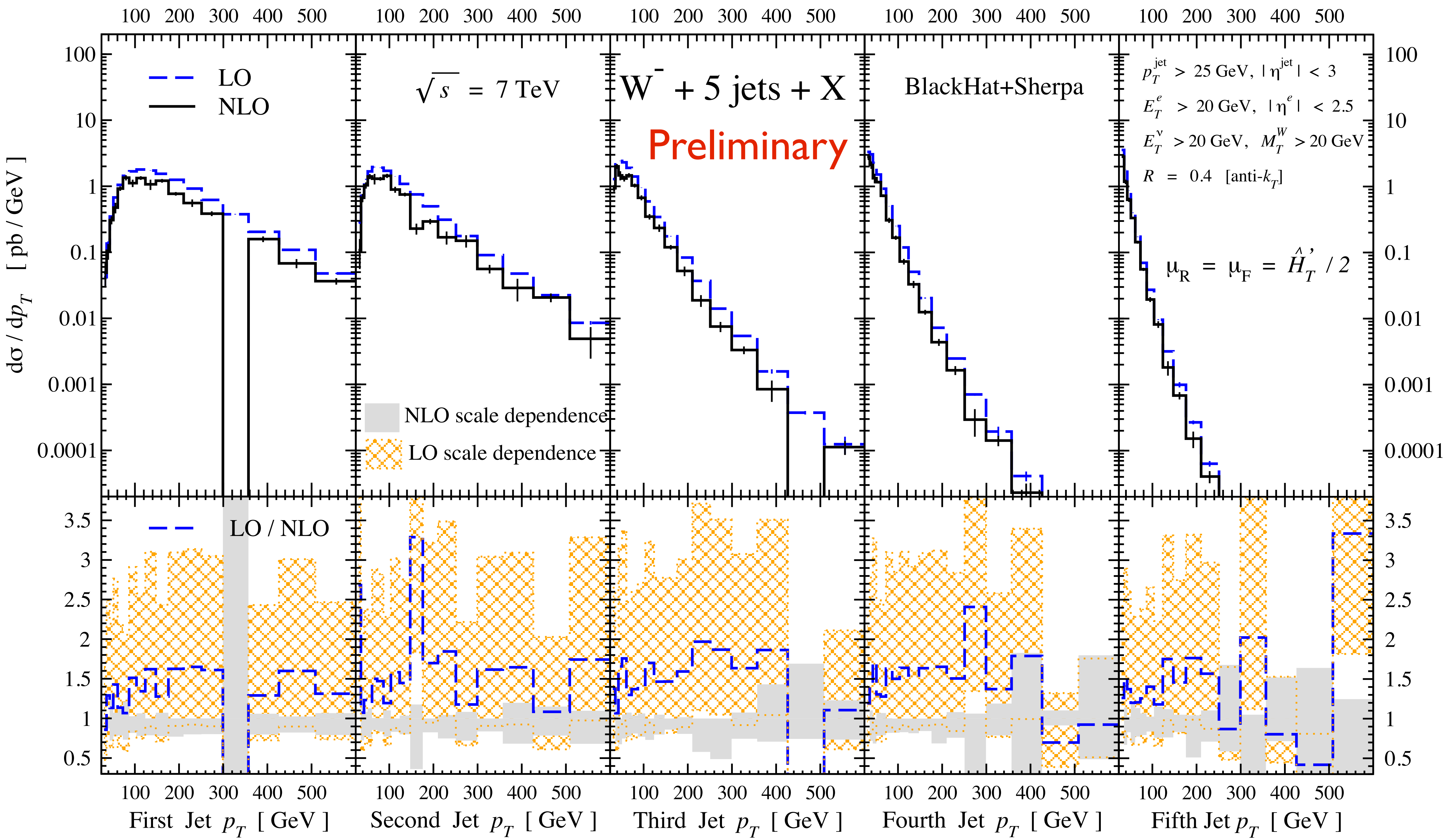
NOTE scalings for visual clarity

nth jet pT in events with at least 5 jets [preliminary]



1st jet 2nd 3rd 4th 5th

Distributing the Results - ROOT ntuples

- NLO calculations often very computationally intensive
- don't want to run again and again with different cuts etc.
- solution: store events and apply analysis cuts later
- ROOT ntuple files ideal for this purpose
- store coefficients of ln μ. For example, for the virtual piece:

$$M^{\text{loop}} = A + B \ln \mu + C \ln^2 \mu$$

- Major benefit 1: can change scales, PDF, add new observables...
- Major benefit 2: can hand over the ntuples to experimentalists

We are working towards release of ntuples, including a library of code for their analysis

Using the Ntuples

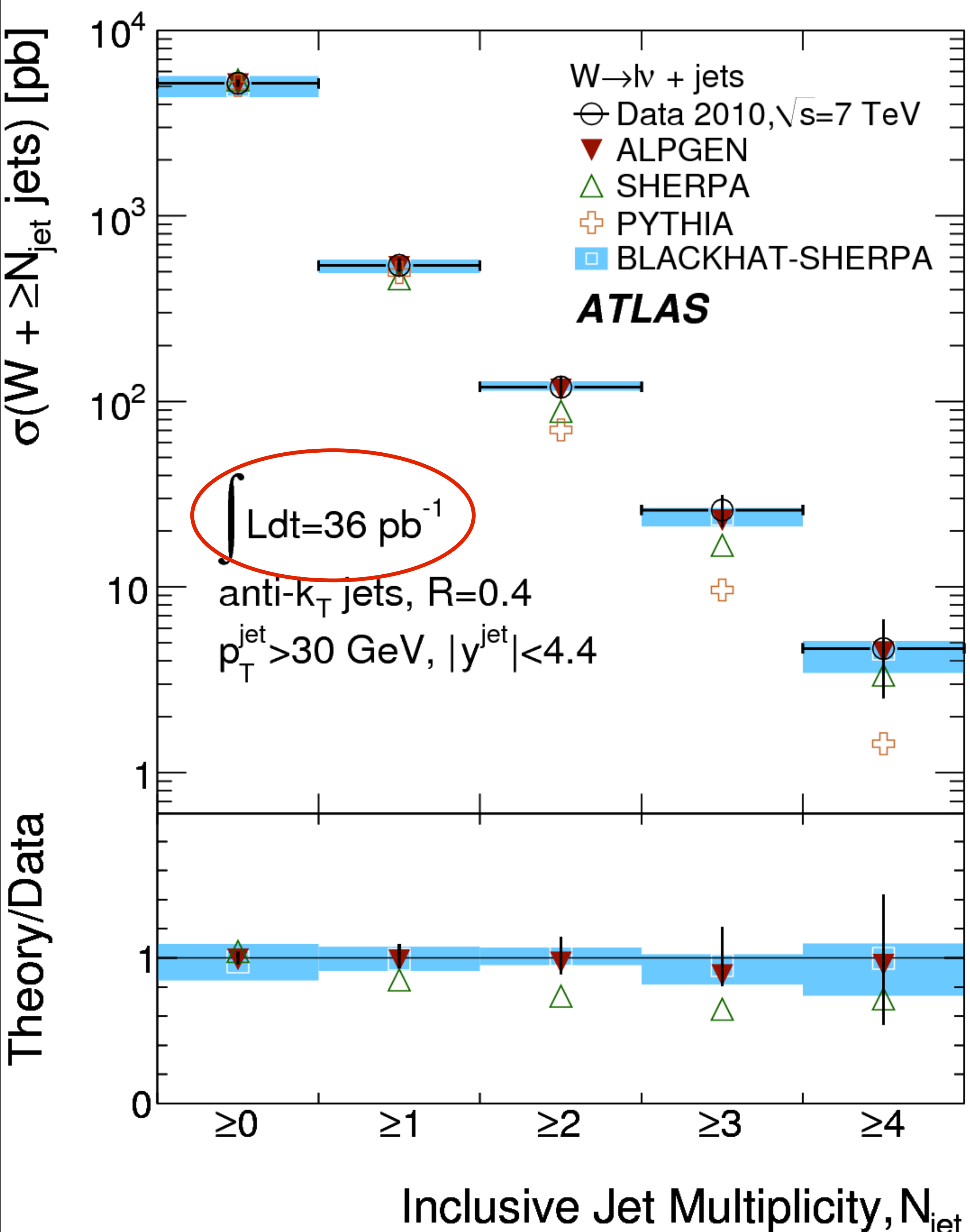
- events stored in ntuple are *parton level*
- user should perform clustering into jets [FASTJET]
- at generation level, event selection is such as to permit only certain jet algorithms (we choose siscone, kt, anti-kt R=0.4, 0.5, 0.6, 0.7)
- four parts to be added [c.f. Catani-Seymour subtraction]:

$$\underbrace{\text{Born} + \text{Virtual} + \text{Int Sub}}_{\text{n-parton events}} + \underbrace{\text{Real-Sub}}_{\text{(n+1) and n-parton events}}$$

- cancellations within RS piece - need to be careful when evaluating statistical error

ROOT ntuples in Action

ATLAS W+jets [1201.1276]



- ntuples created with BlackHat +Sherpa [1009.2338]
- experimenters perform their own analysis of the NLO results
- we are currently working also with CMS people

... we look forward to similar comparisons of our W+5jet NLO results with data!

Summary

- I stressed the importance of NLO precision in achieving our physics goals at the LHC

- Application of BlackHat+Sherpa to Jets+MET new physics search

- new result: W+5jets
  → highest multiplicity NLO calculation at a hadron collider

- described how our results are passed to experimenters and compared to data: ROOT ntuples