High multiplicity processes with BlackHat and Sherpa

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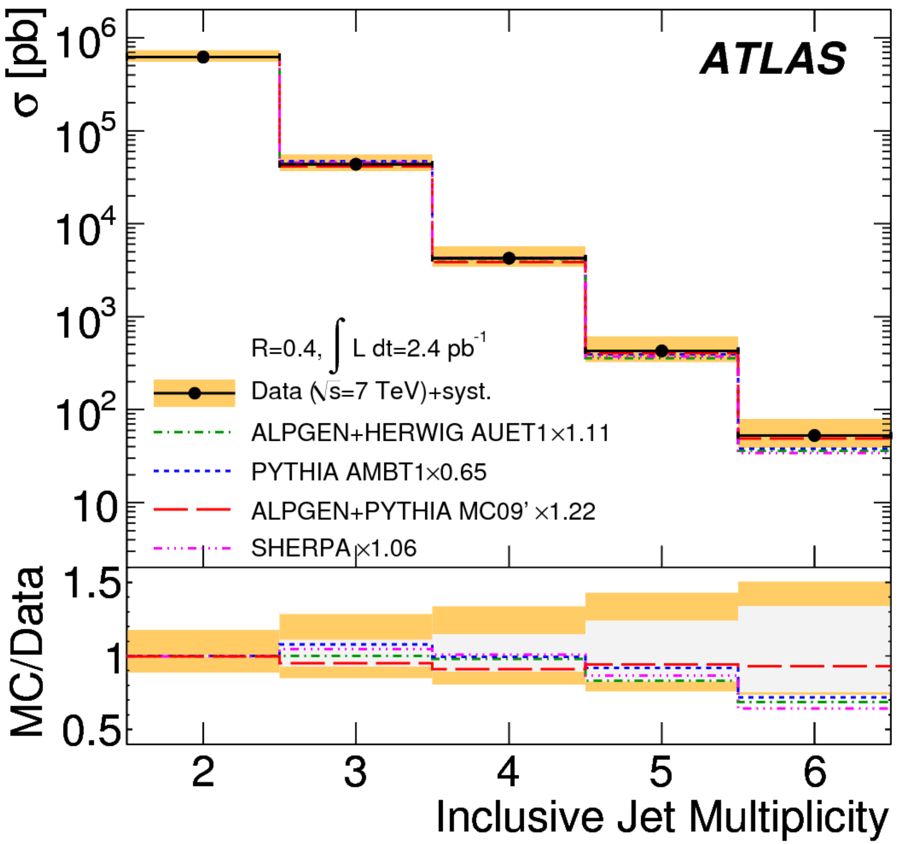
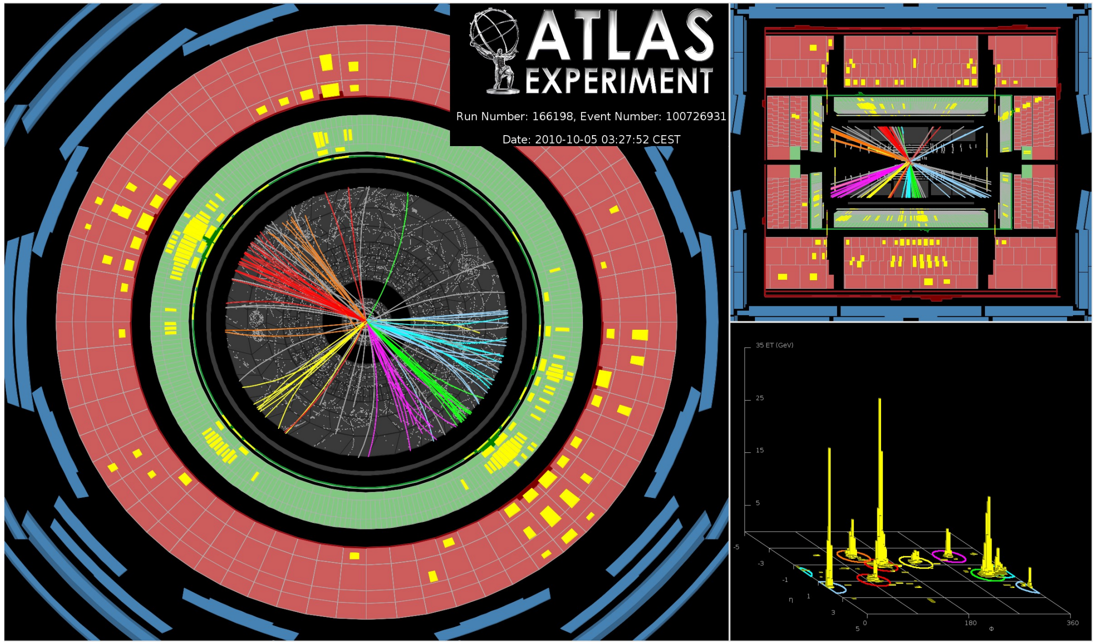
Outline

- BlackHat+Sherpa n-Tuple files and library
- Exclusive sums
- Universal behaviour in W+jets production

High multiplicities

- At the LHC events with many jets are common place



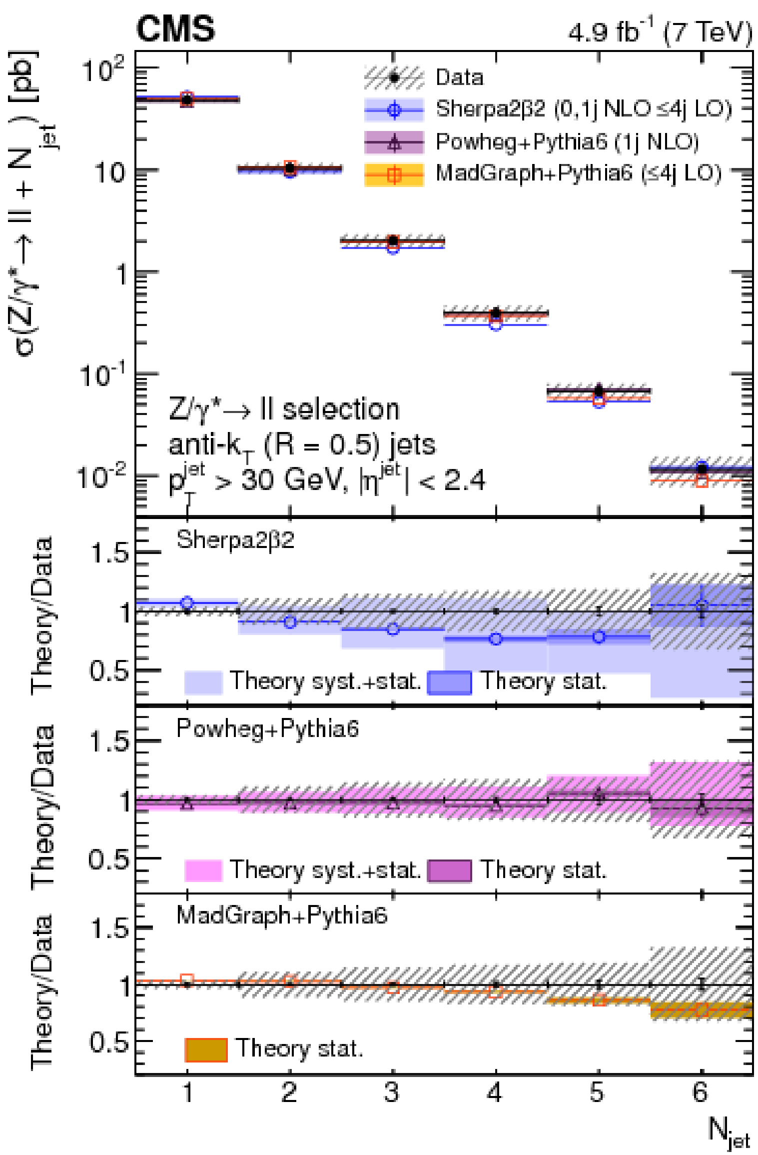


8-jets event at ATLAS

ArXiv:1202.3548

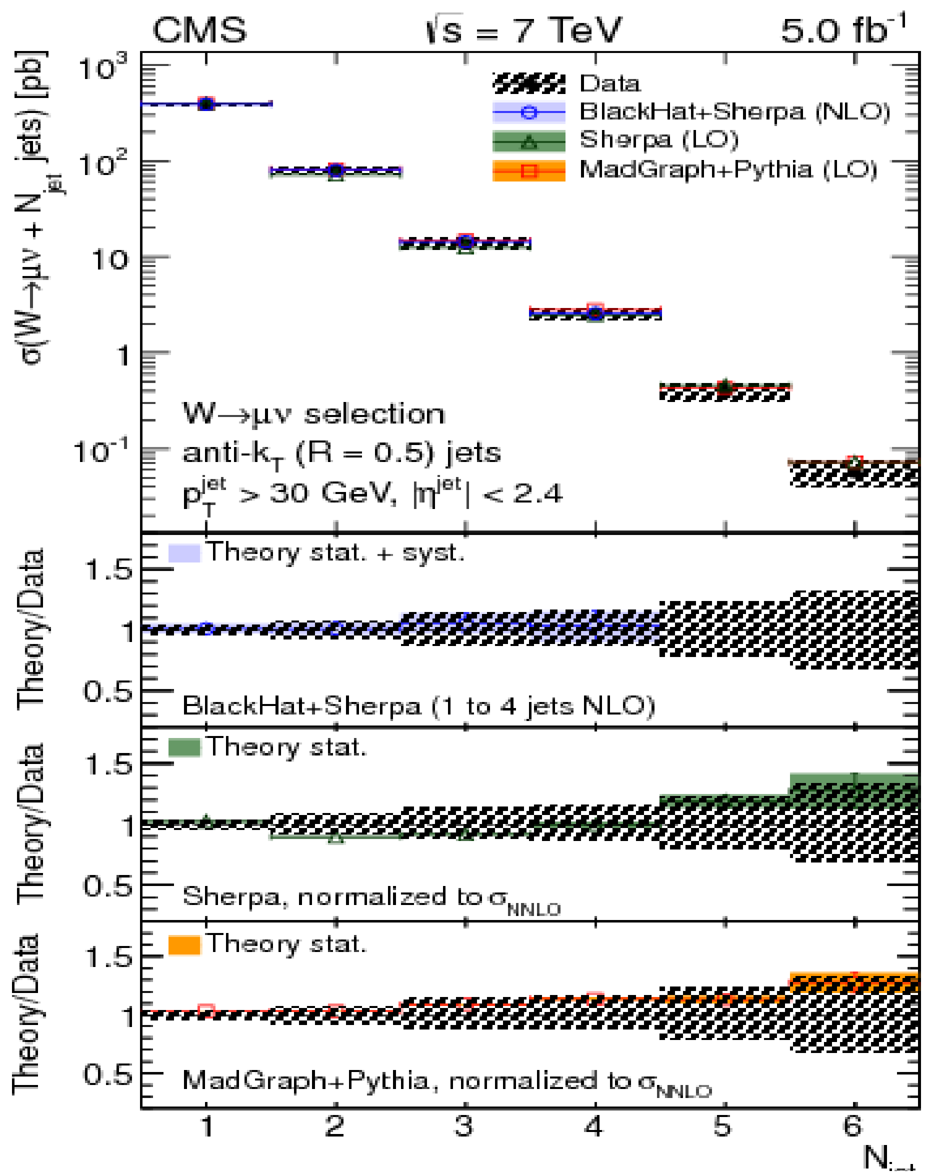
High multiplicities

- Z+jets



arXiv:1408.3104

- W+jets



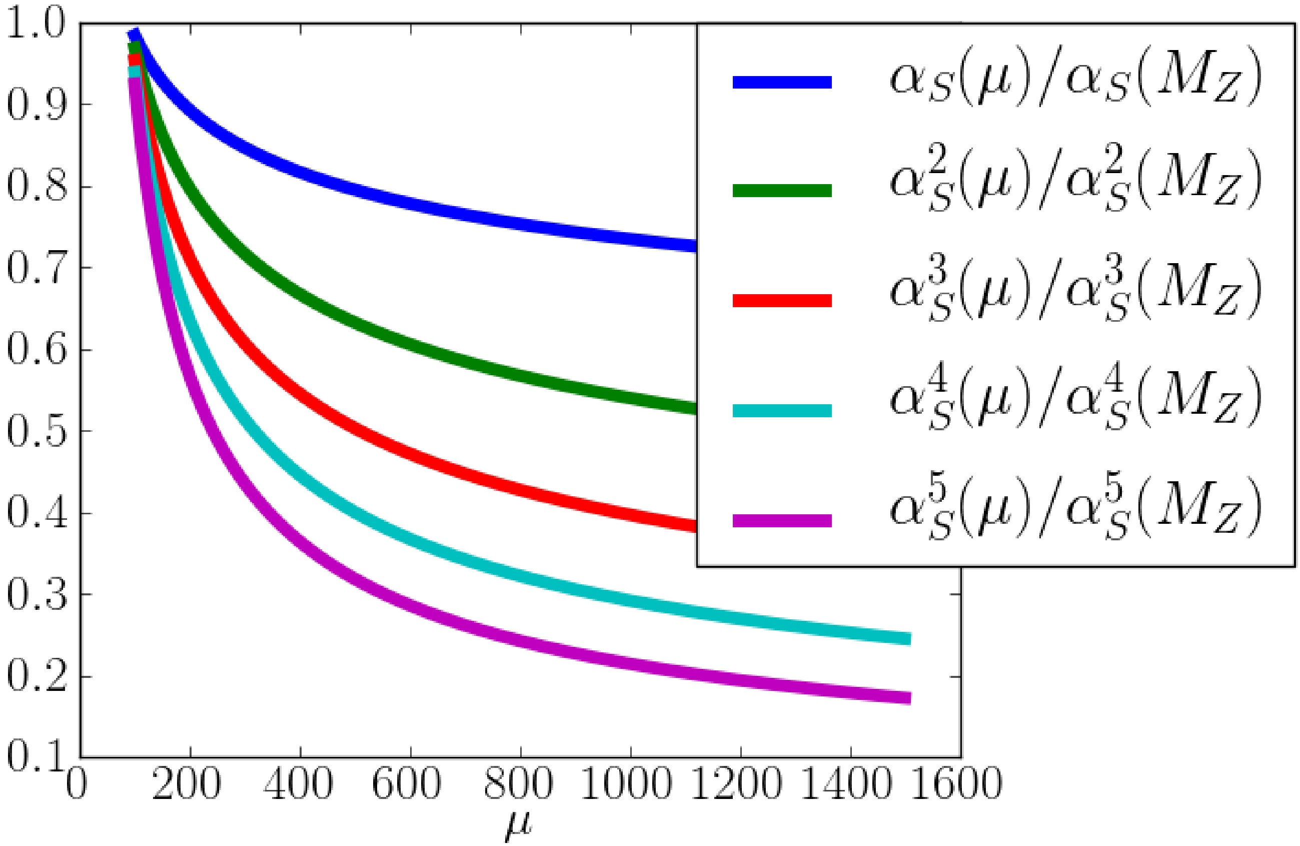
arXiv:1406.7533

Precise predictions

- Precise predictions are needed
  - Signal
  - Background
  - Also for data-driven methods
    - Extrapolation from control to signal region
    - Transfer of information from one process to another
- NLO improves
  - Absolute normalisation
  - Shapes of distributions
  - Scale dependence

NLO scale dependence

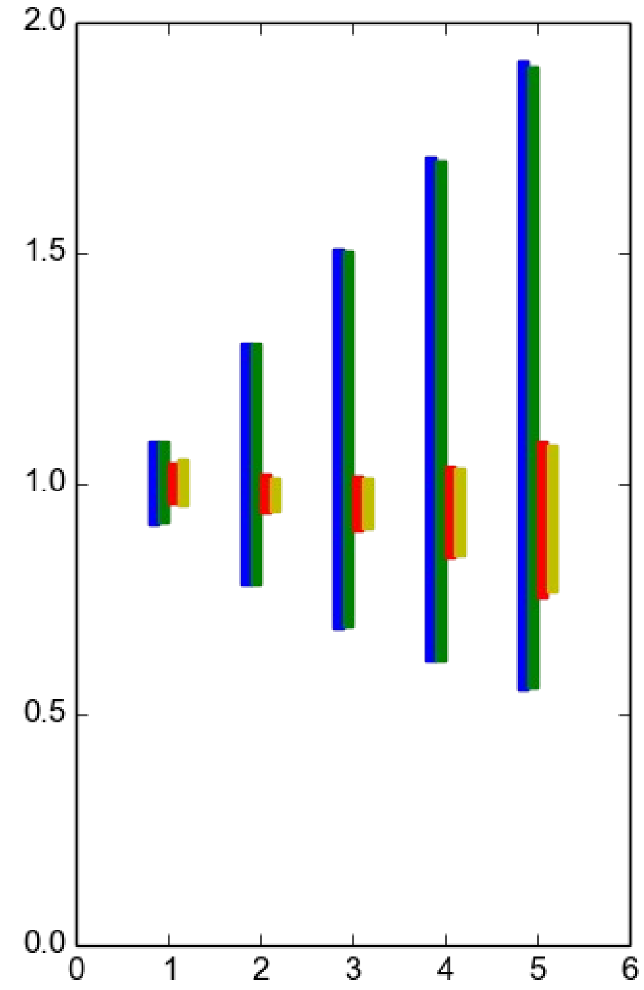
- The theory prediction depends on two unphysical scales, the renormalisation and factorisation scale
- The strong coupling constant is a function of the renormalisation scale



Scale variation

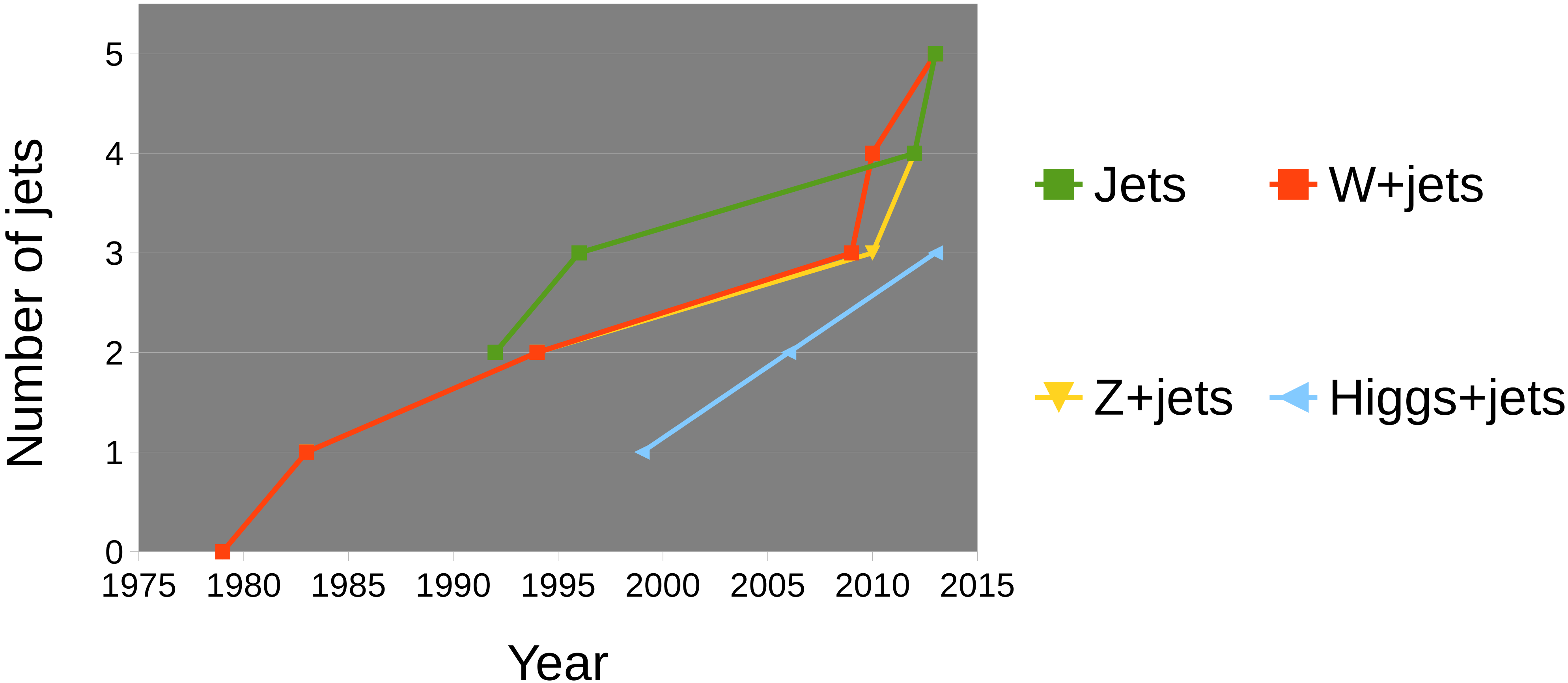
- Scale variation is largely reduced at NLO
- More and more important as multiplicity increases
- W+n jets cross sections:

Jets	W^- LO	W^- NLO	W^+ LO	W^+ NLO
1	$284.0(0.1)^{+26.2}_{-24.6}$	$351.2(0.9)^{+16.8}_{-14.0}$	$416.8(0.6)^{+38.0}_{-35.5}$	$516(3)^{+29.}_{-23}$
2	$83.76(0.09)^{+25.45}_{-18.20}$	$83.5(0.3)^{+1.6}_{-5.2}$	$130.0(0.1)^{+39.3}_{-28.1}$	$125.1(0.8)^{+1.8}_{-7.4}$
3	$21.03(0.03)^{+10.66}_{-6.55}$	$18.3(0.1)^{+0.3}_{-1.8}$	$34.72(0.05)^{+17.44}_{-10.75}$	$29.5(0.2)^{+0.4}_{-2.8}$
4	$4.93(0.02)^{+3.49}_{-1.90}$	$3.87(0.06)^{+0.14}_{-0.62}$	$8.65(0.01)^{+6.06}_{-3.31}$	$6.63(0.07)^{+0.21}_{-1.03}$
5	$1.076(0.003)^{+0.985}_{-0.480}$	$0.77(0.02)^{+0.07}_{-0.19}$	$2.005(0.006)^{+1.815}_{-0.888}$	$1.45(0.04)^{+0.12}_{-0.34}$



Recent progress

- Number of jets in addition to the vector boson



- Has been called 'NLO revolution'

BlackHat+Sherpa

- BlackHat is a C++ library for virtual one-loop matrix elements
- Recent calculations with Sherpa:
  - W/Z+4 jets
  - 2,3,4 jets
  - Z/gamma ratios with up to 3 jets
  - W+5 jets
  - diphoton+2 jets

n-Tuple files [arXiv:1310.7439]

- High multiplicity NLO calculations are computationally intensive
- It would not be possible to rerun a high multiplicity W+jet calculation every time a new interesting observable comes up
- Matrix elements are expensive, while
  - Jet clustering
  - Observables
  - PDF evaluation

  are relatively cheap
- Store each matrix element, PS point and the information necessary to change the factorisation and renormalisation scales in large files we call n-Tuple files
- We use ROOT file as storage

n-Tuple files

- Goodies
  - One can change the analysis cuts, add observables
  - Scale variation
  - PDF errors (otherwise extremely expensive)
  - Easy communication between theorists and experimenters
  - No need for specific know-how of the tool which produced the NLO calculation
  - Easier to “endorse” an event file than a program
- Price to pay
  - Large files
  - Generation cuts need to be loose enough to accommodate many analysis → efficiency cost

n-Tuple availability

- The n-Tuple files are available
  - On the grid
  - On castor at CERN
- For a range of processes

Process	Pathname	Energy	Jet cut
W+ + 1,2,3,4 jets	Wp<n>j	7TeV	25GeV
W+ + 1,2,3 jets	Wp<n>j	8TeV	20GeV
W- + 1,2,3,4 jets	Wm<n>j	7TeV	25GeV
W- + 1,2,3 jets	Wm<n>j	8TeV	20GeV
Z/gamma* + 1,2 jets	Zee<n>j	7TeV	25GeV
Z/gamma* + 3,4 jets	Zee<n>j	7TeV	20GeV
Z/gamma* + 1,2,3 jets	Zee<n>j	8TeV	20GeV
2,3,4 jets	PureQCD<n>j	7TeV,8TeV	40GeV

From http://blackhat.hepforge.org/trac/wiki/Availability

nTupleReader library

- We provide a C++ library to facilitate the use of the n-Tuple files
- Allows:
  - Change of factorisation and renormalisation scales
  - Change of pdf (from LHAPDF set), including error sets
- Has a Python interface
- Template for a customised implementation
- Available on hepforge

nTupleReader library

- Example

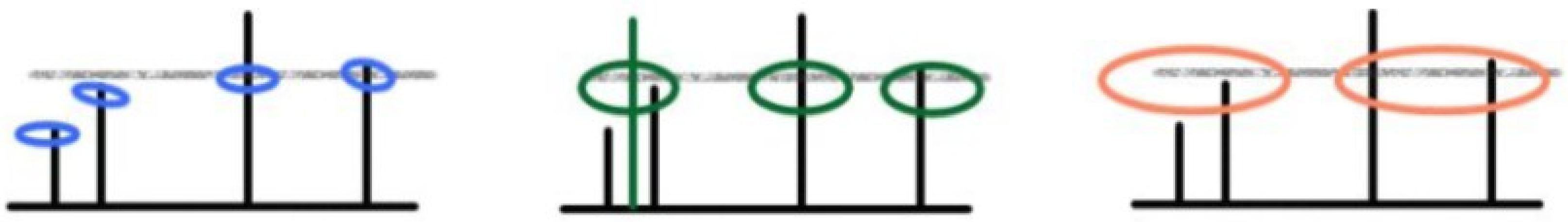
```
import nTupleReader as NR
r=NR.nTupleReader()
r.addFile('sample.root')

r.setPDF("CT10nlo.LHgrid")
r.setPDFmember(12)

while r.nextEntry():
    # compute new scales
    RenScale = ....
    FacScale = ....
    newWeight=r.computeWeight(FacScale,RenScale)
    // use this weight in the analysis
    ...
```

Pitfalls

- There can be negative weights
- For the real part the matrix elements and the subtraction terms are highly anti-correlated (by construction)
- Some common operations have to be modified to take this into account:
  - statistical error calculation
  - Rebinning, cumulative distributions

NLO event files

- Issues with NLO event files
  - Only fixed number of radii are supported



  - Negative weights
  - Highly anti-correlated weights (by construction!) affect
    - Integration error estimate
    - Rebining and cumulative distributions

NLO events

- Standard formula for integration error:

$$\sigma^2 = \langle(\omega - \langle\omega\rangle)^2\rangle = \langle\omega^2\rangle - (\langle\omega\rangle)^2$$
$$\simeq \frac{\sum \omega_i^2}{N} - \left(\frac{\sum \omega_i}{N}\right)^2 = \frac{1}{N}\left(\sum \omega_i^2 - \frac{\left(\sum \omega_i\right)^2}{N}\right)$$

- If we have only pairs of large anti-correlated weights

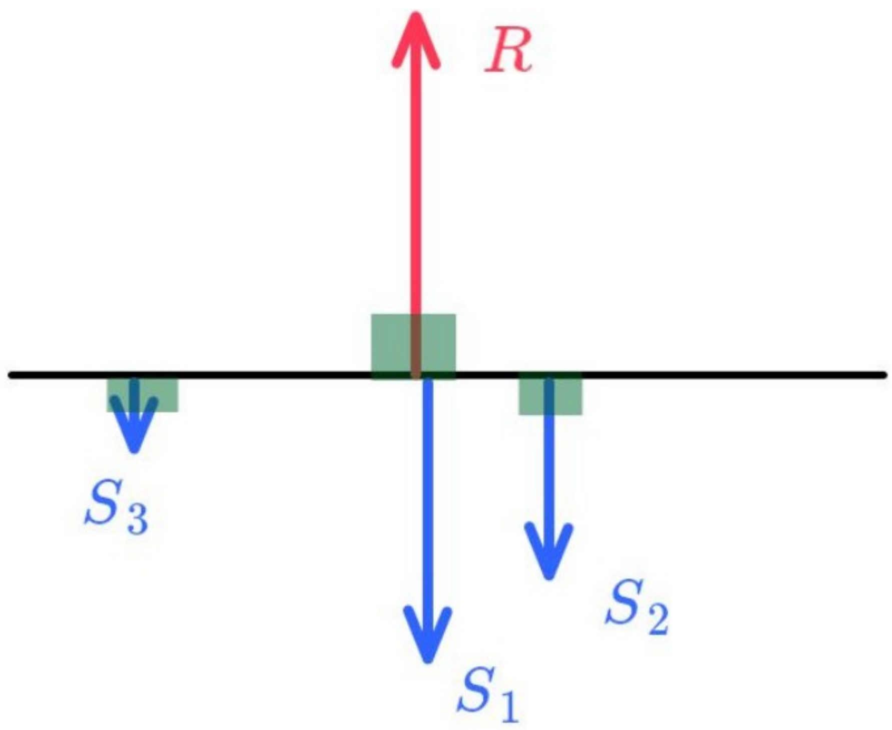
$$\omega_+ \simeq L\ ,\ \omega_- \simeq -L\ , \qquad \omega_+ - \omega_- \simeq s$$
$$\sigma^2 \simeq \frac{1}{N}\left(NL^2 + \frac{(Ns)^2}{N}\right) = L^2 - s^2 \simeq L^2$$

- This is far too large, one should use

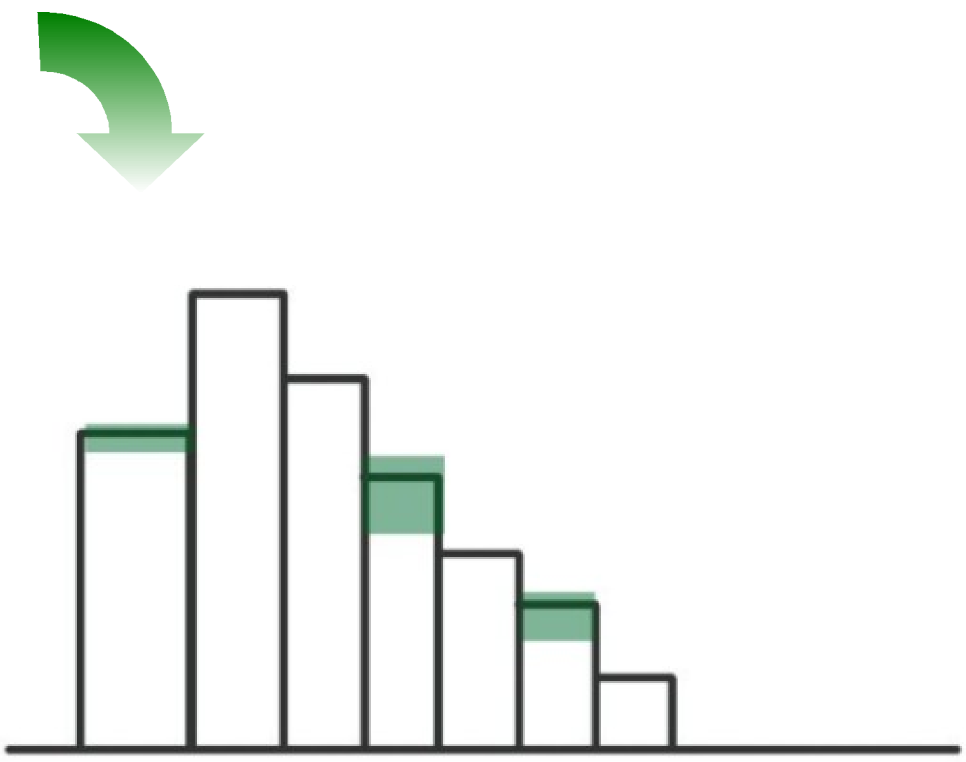
instead $$\sigma^2 \simeq \frac{1}{N}\left(\sum(\omega_{i,+} + \omega_{i,-})^2 - \frac{\left(\sum \omega_i\right)^2}{N}\right)$$

NLO events

- First bin all contribution from the event in auxiliary histogram



- Then transfer to the true histogram



fastNLO

- A direct analysis using n-Tuple files can still be too slow for some applications
  - PDF4LHC-type error require several PDF sets with errors
  - alphas determination
  - PDF fitting
- We can use the n-Tuple files to create fastNLO tables for very quick evaluation
  - Very fast
  - Need one table for each measured distribution
- Similar to the APPLgrid and other projects

fastNLO

- Replace PDF functions with

  where the the extrapolation kernels *E(x)* have the properties

$$f_a(x) \simeq \sum_i f_a(x_i) E(x)$$

- The cross section can be written as

$$\sum_i E_i(x) = 1 \ , \qquad E_i(x_j) = \begin{cases} 1 & \text{if} \quad i = j \\ 0 & \text{otherwise} \end{cases}$$

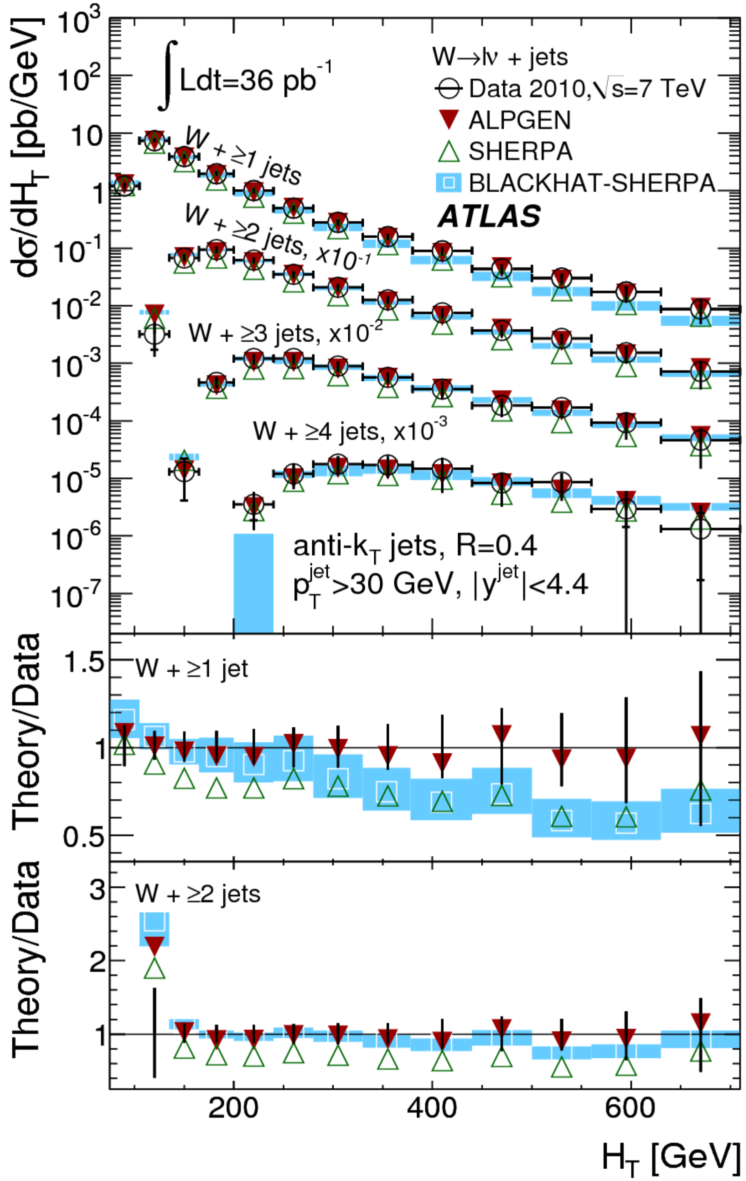
$$\sigma = \sum_{a,b,i,j} f_a(x_i) f_b(x_j) \underbrace{\int dx_1\, dx_2\, E_i(x_1) E_j(x_2) \int d\phi\, \hat{\sigma}(x_1, x_2; \phi)}_{c_{a,b;i,j}}$$

Can compute this with n-Tuples!

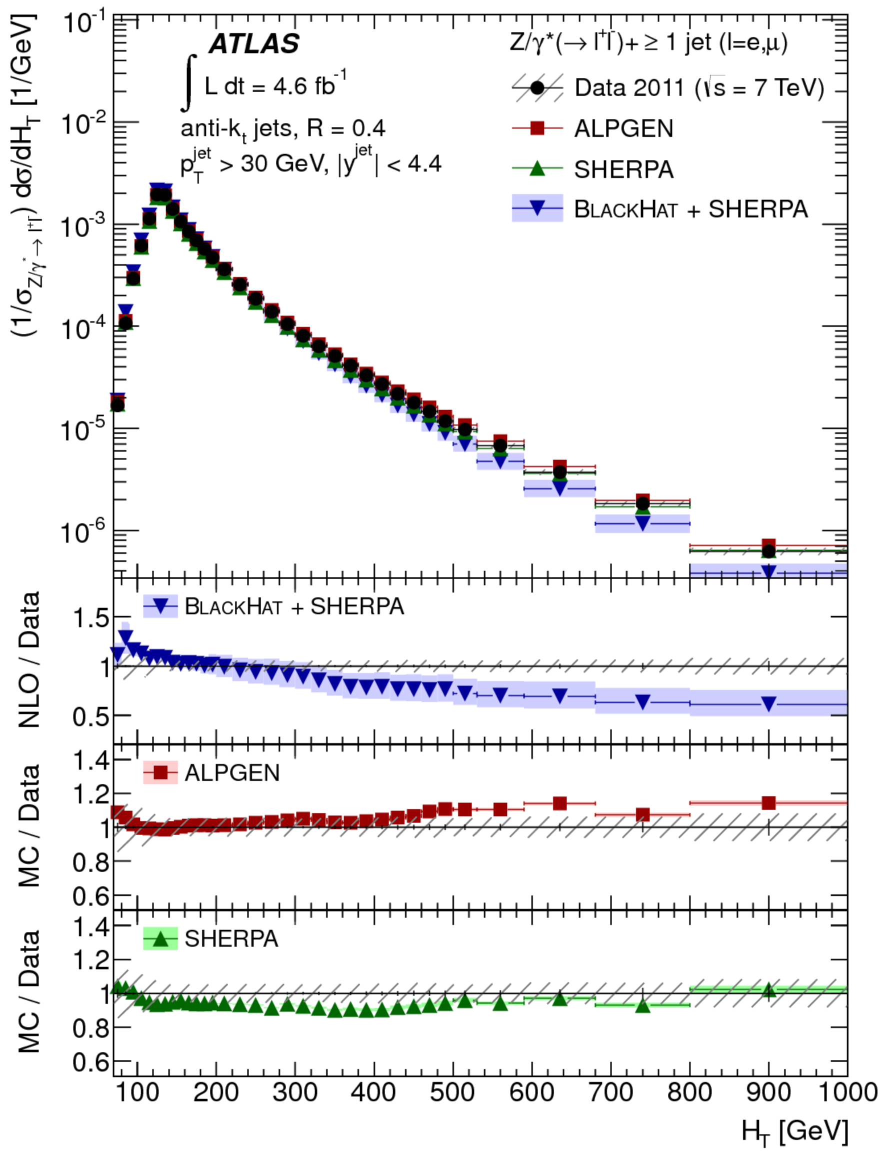
Speed vs Generality

HT distribution

- W+jet



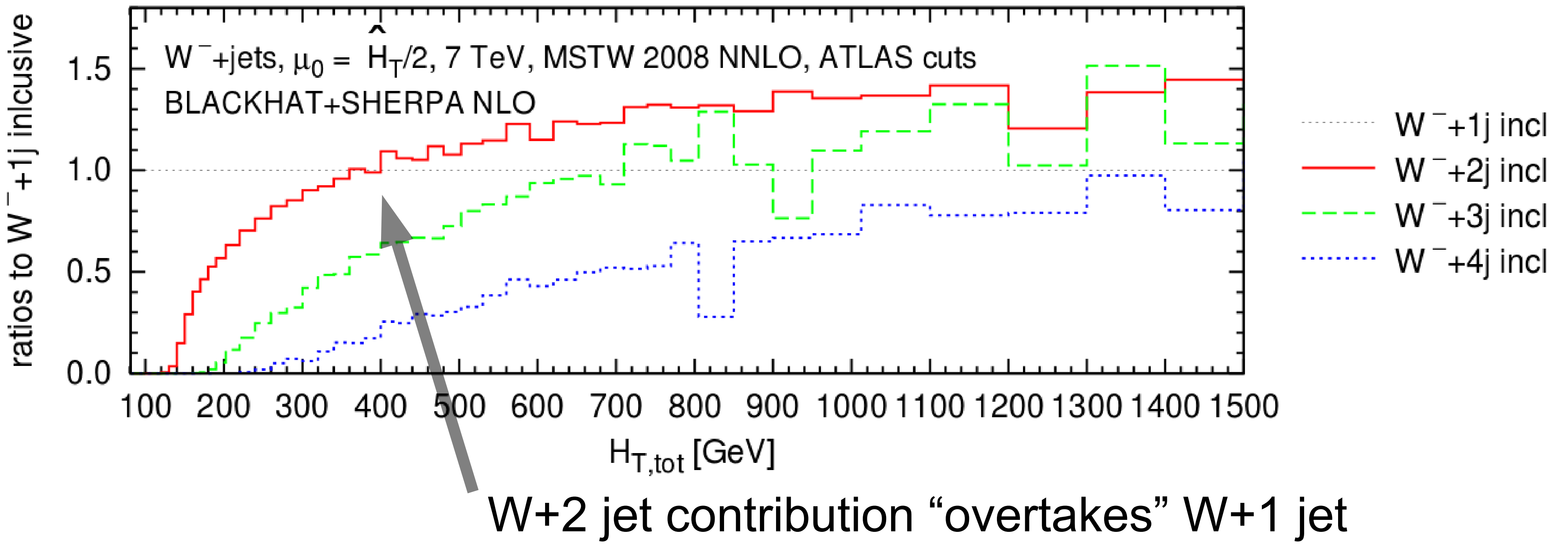
- Z+jets



*HT is basically the sum of all transverse energies of the particles in the event

HT distribution

- Already at quite moderate HT the higher multiplicity samples have sizeable contributions

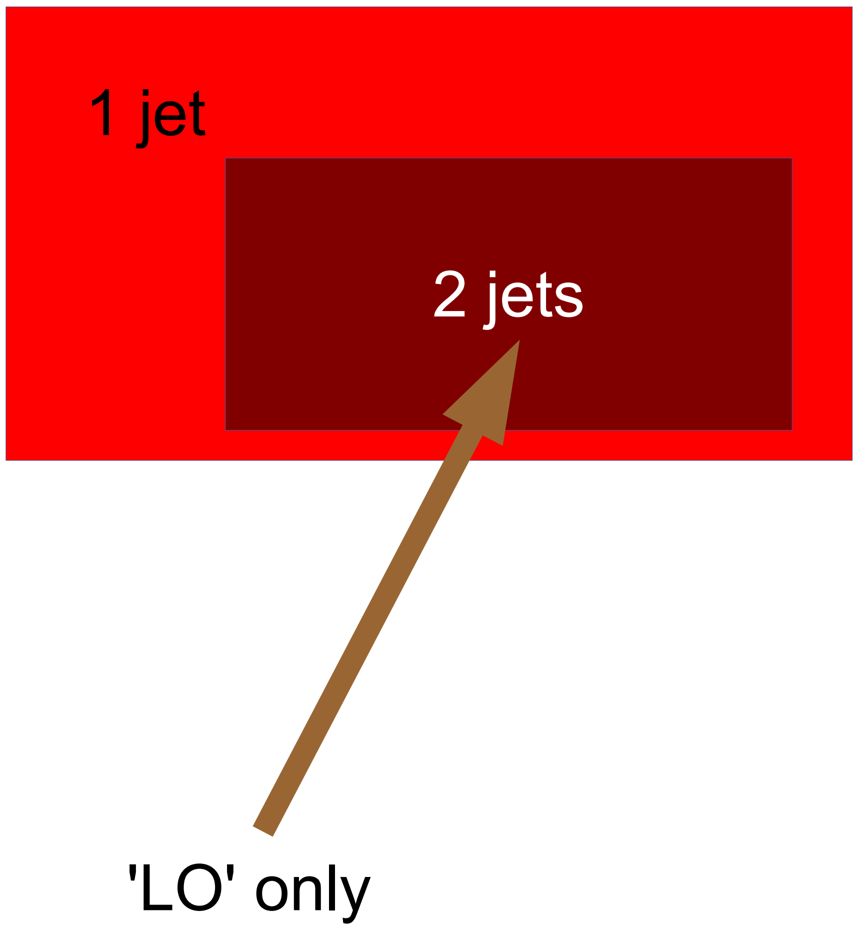


Exclusive sums

- Combine NLO event samples of different multiplicity
- Justified (if at all) for observables where higher multiplicities are important
- Avoid double counting by restricting the samples to a fixed multiplicity
- Formally not better than a NLO calculation
- No systematic study of uncertainties/stability
- Very crude method

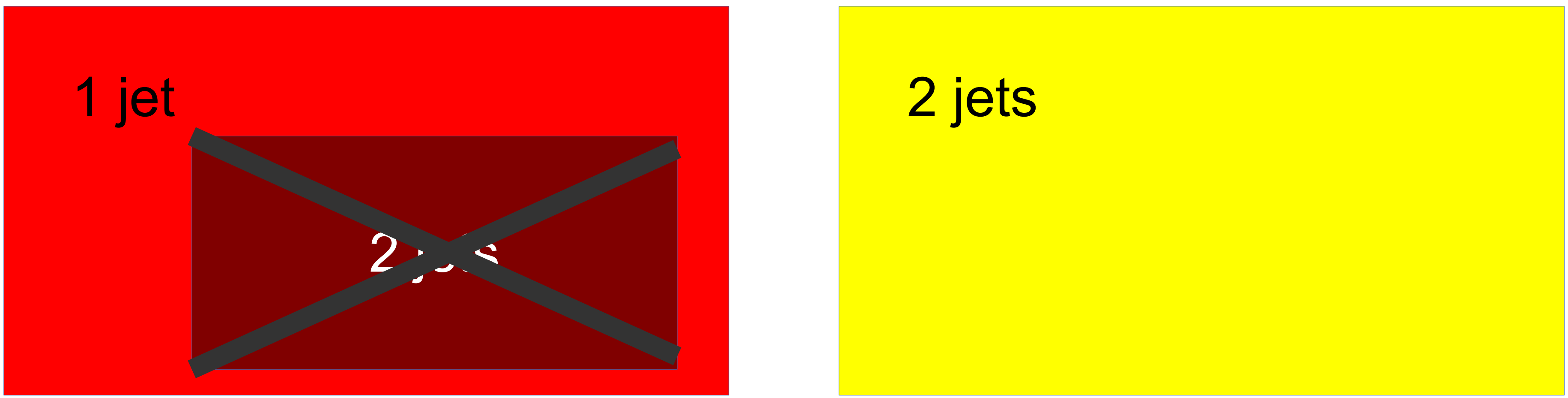
Exclusive sums

- W+1 jet at NLO

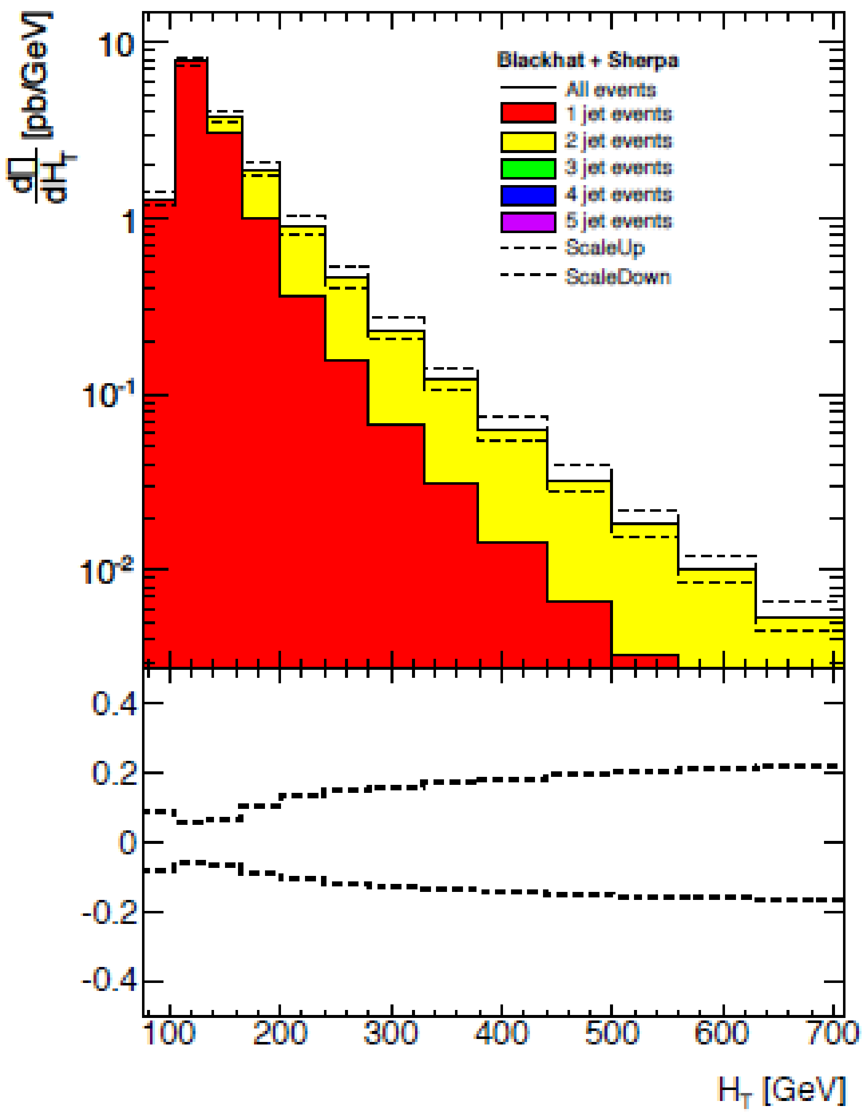


Exclusive sums

- W+1 jet at NLO W+2 jets at NLO



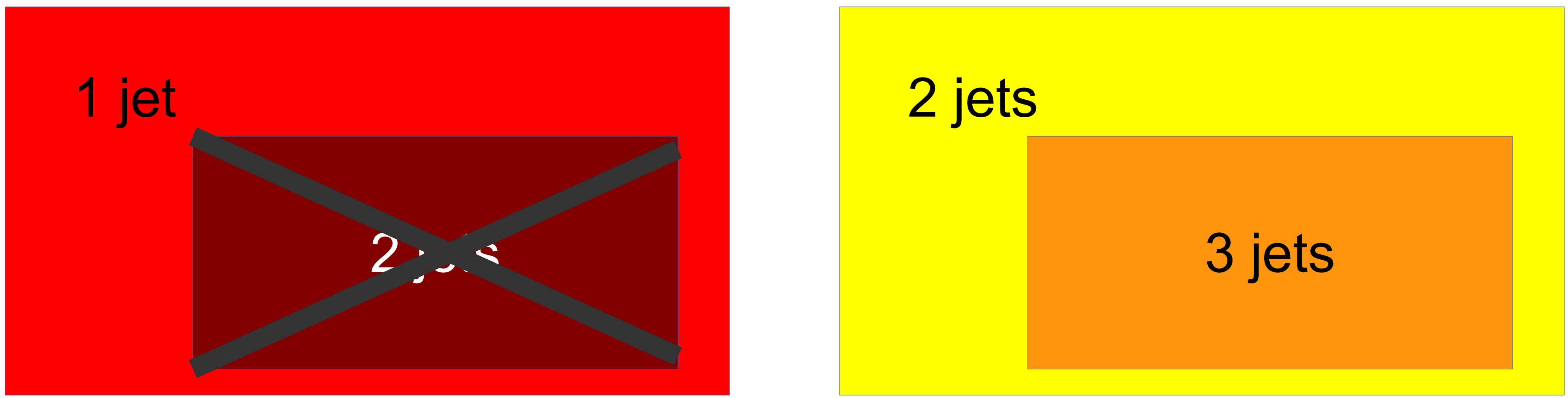
W+1 jet



Blackhat + Sherpa
All events
1 jet events
2 jet events
3 jet events
4 jet events
5 jet events
ScaleUp
ScaleDown
$\frac{d\Pi}{dH_T}$ [pb/GeV]
10
1
10^{-1}
10^{-2}
0.4
0.2
0
-0.2
-0.4
100
200
300
400
500
600
700
H_T [GeV]

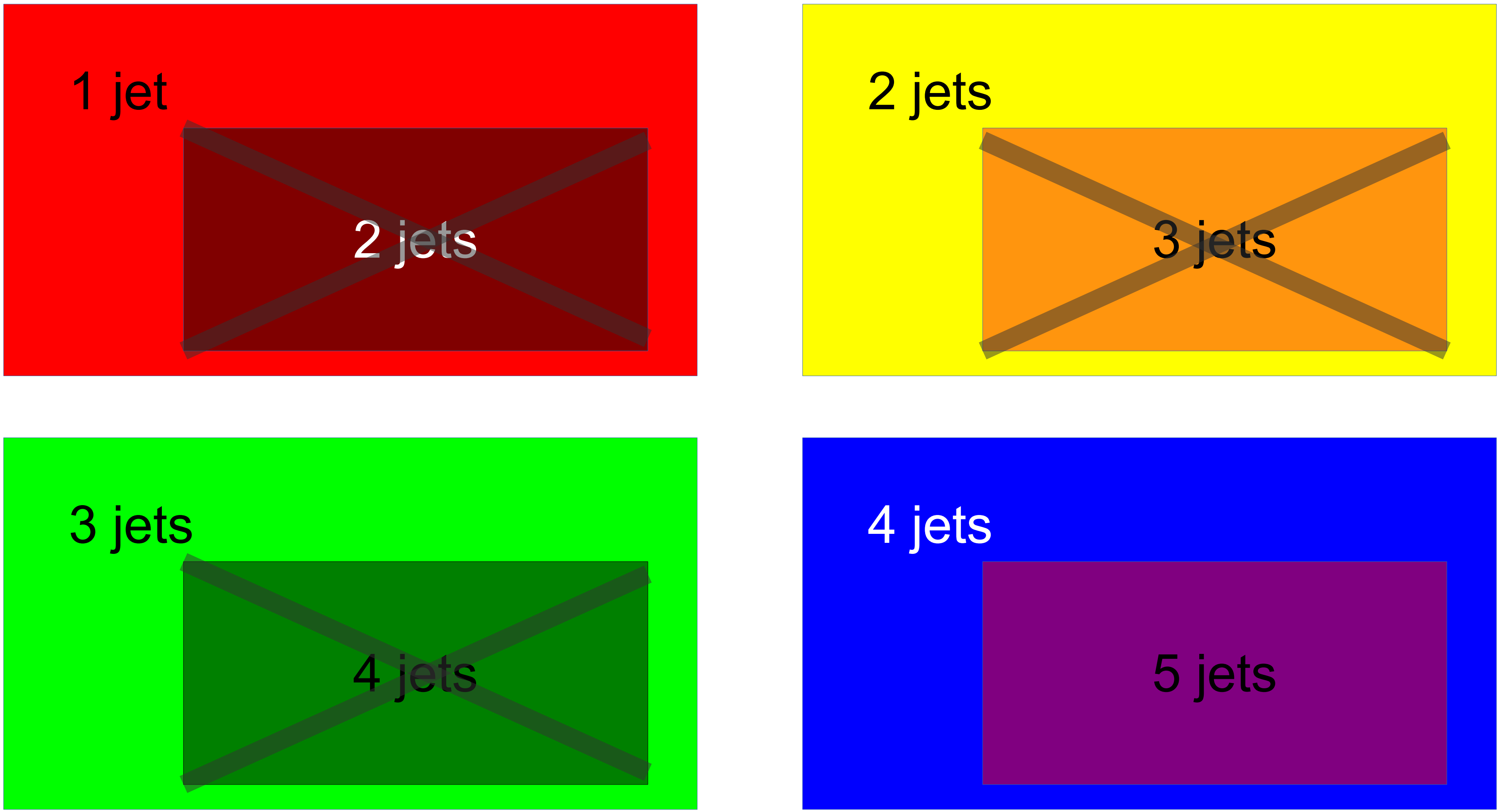
Exclusive sums

- W+1 jet at NLO W+2 jets at NLO



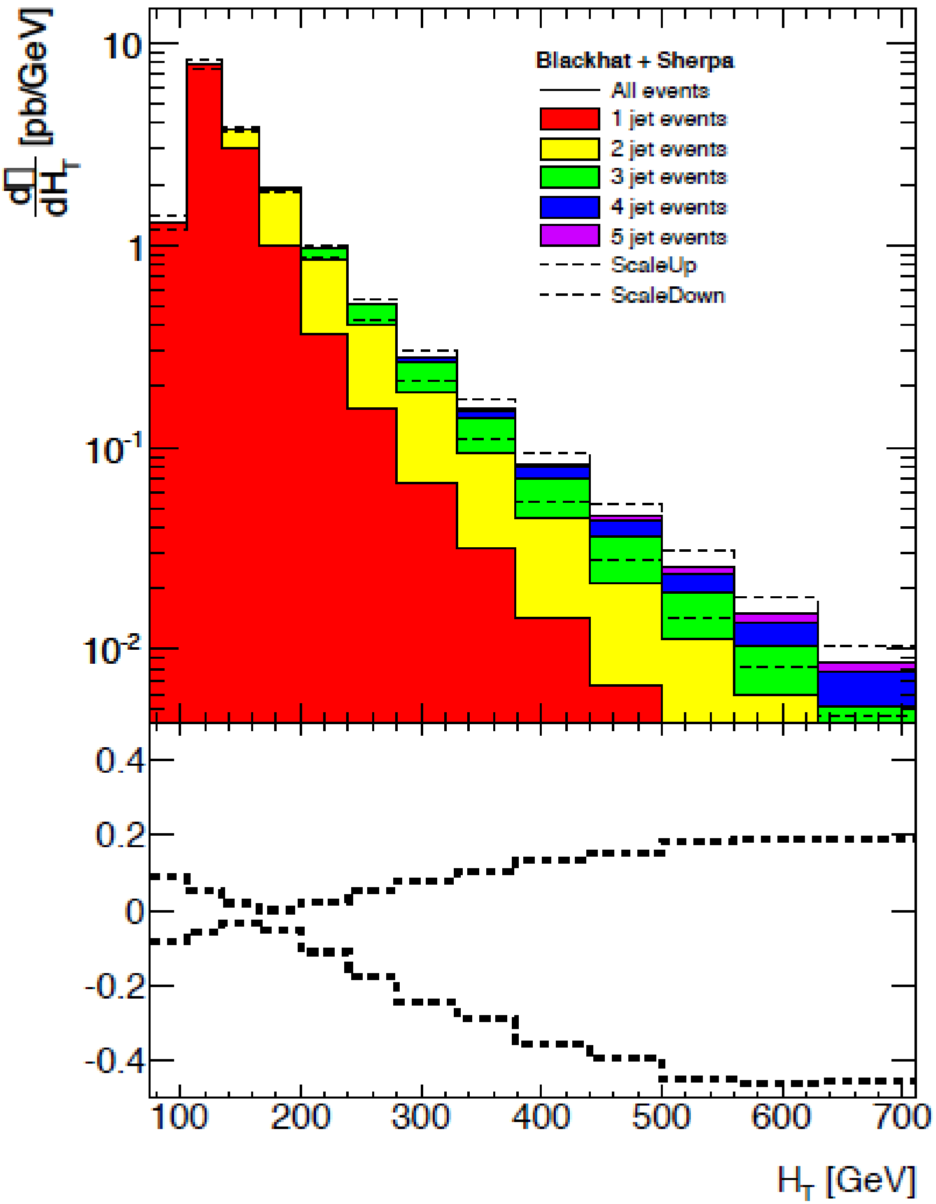
Exclusive sums

- W+1 jet at NLO W+2 jets at NLO



Exclusive sums

- Scale variation much larger than at NLO
- Need to be investigated more precisely
- Combination can be made 'official' using LoopSim [Rubin,Salam,Sapeta] (under investigation)
- Better : 'ME+PS'-type merging

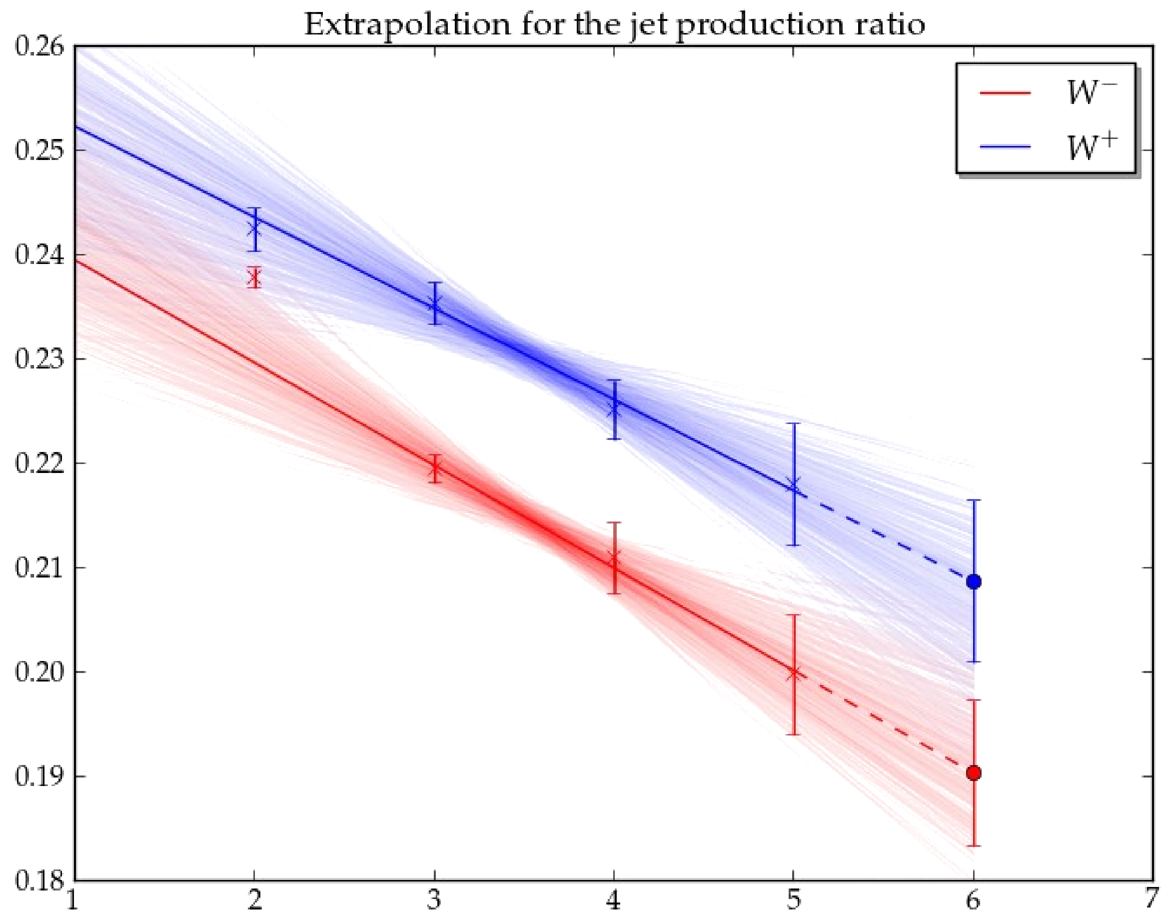


Towards higher multiplicities?

- We have a lot of prediction for high multiplicity processes at NLO
- We can try to find 'universal' properties/features
- Usually need to discard 0-jet and 1-jet because new partonic channels open
- Usually these features are more easily seen in ratios between multiplicities

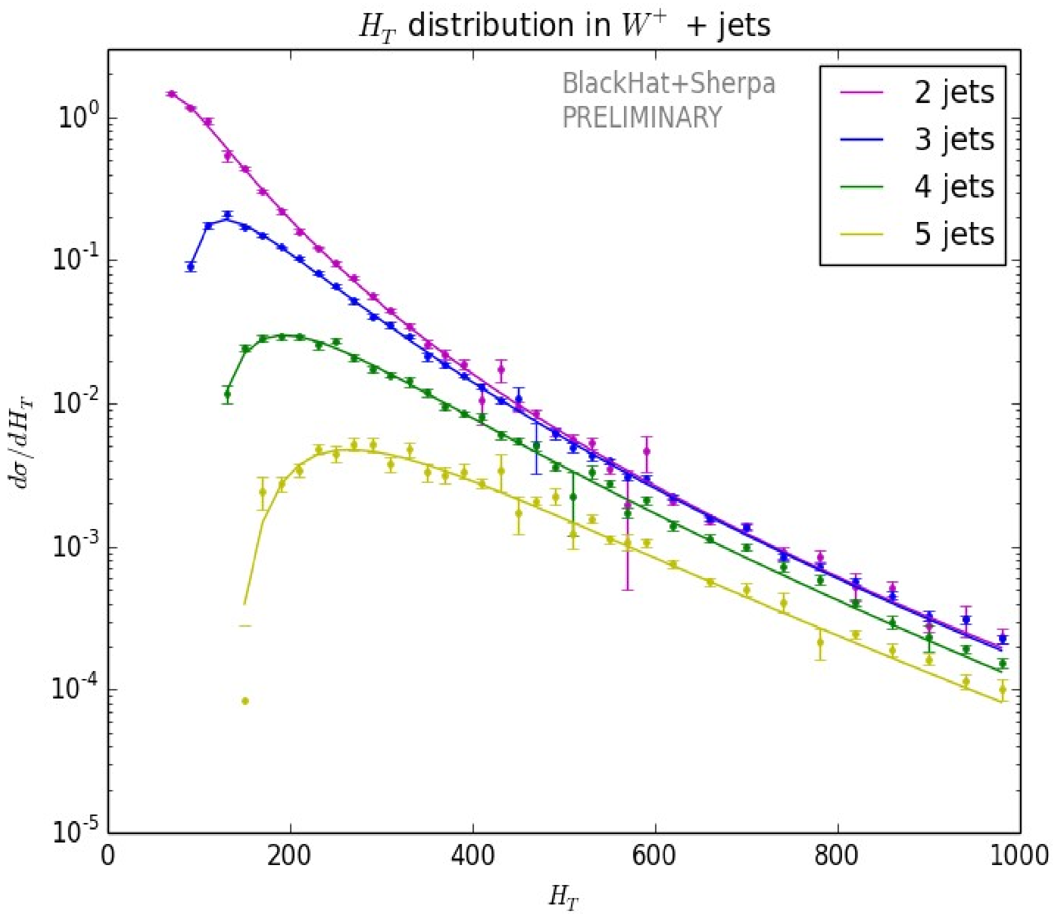
Extrapolation for ratios

- Ratio V+n jets/(V+n-1 jets)
- Consistent with straight line for n>2
- Use extrapolation for 6 jets:
- W^- : 0.15 ± 0.01 pb
- W^+ : 0.30 ± 0.03 pb
- Consistent with extrapolation of charge asymmetry
- Error estimates through Monte Carlo method



Distributions

- What about distributions?
- Look at sum of transverse energies of the jets (HT)
- Cannot extrapolate the value of each bin separately
  - Statistical errors are too large
  - Different thresholds
  - Different peak positions



Distributions

- Instead find a parametrisation and extrapolate the parameters of the parametrisation
- Ansatz for the HT distribution:

$$\frac{d\sigma_{V+n}}{d\,H_T} = \left(\frac{N_C \alpha_s}{2\pi}\right)^n f(H_T)\mathcal{N}_n \ln^{\tau_n} \rho_{H,n} \left(1 - H_T/H_T^{\max}\right)^{\gamma_n}$$

$$\rho_{H,n} = H_T/(np_T^{min})$$

HT Distribution

- Instead find a parametrisation and extrapolate the parameters of the parametrisation
- Ansatz for the HT distribution:

$$\frac{d\sigma_{V+n}}{d\,H_T} = \left(\frac{N_C \alpha_s}{2\pi}\right)^n f(H_T)\mathcal{N}_n \ln^{\tau_n} \rho_{H,n} \left(1 - H_T/H_T^{\max}\right)^{\gamma_n}$$

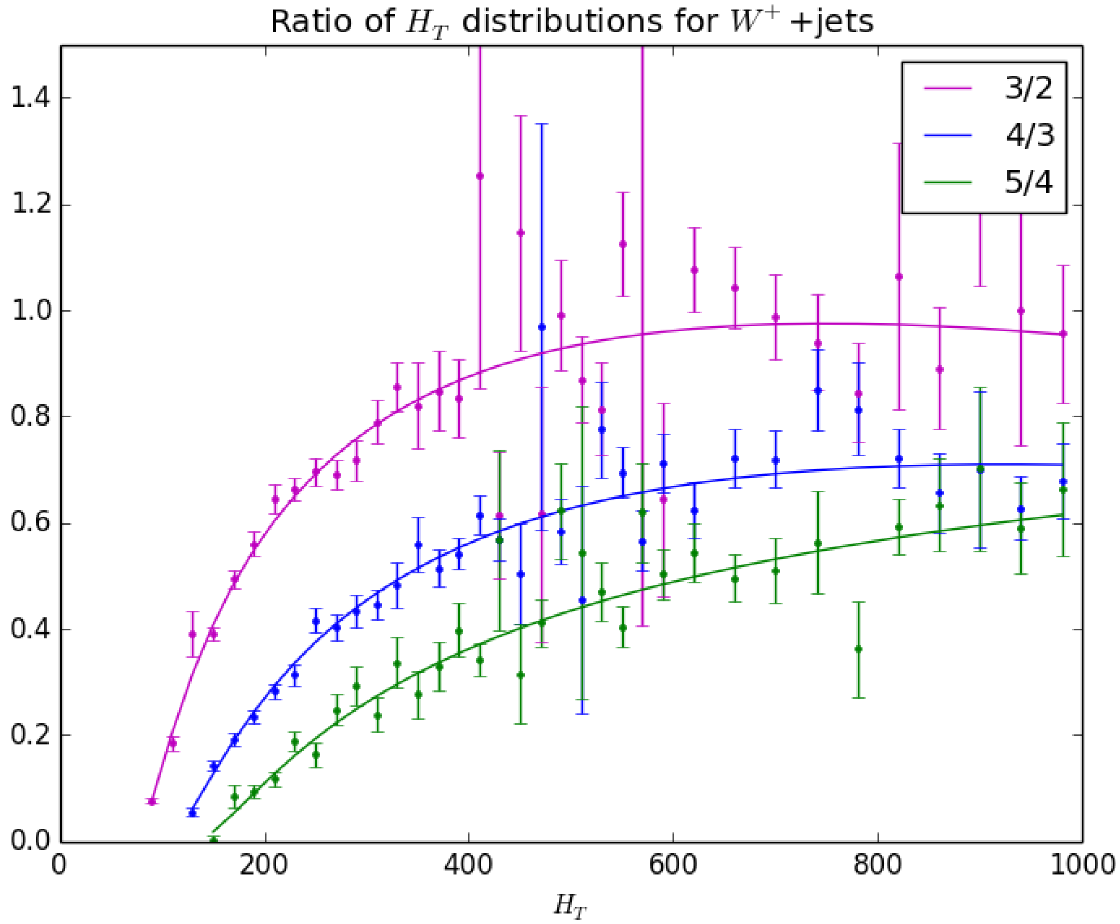
Independent of *n* ($f(H_T)$)

parameters ($\mathcal{N}_n$, τ_n, γ_n)

$$\rho_{H,n} = H_T/(np_T^{min})$$

HT distribution

- Fit ratios to get the parameters



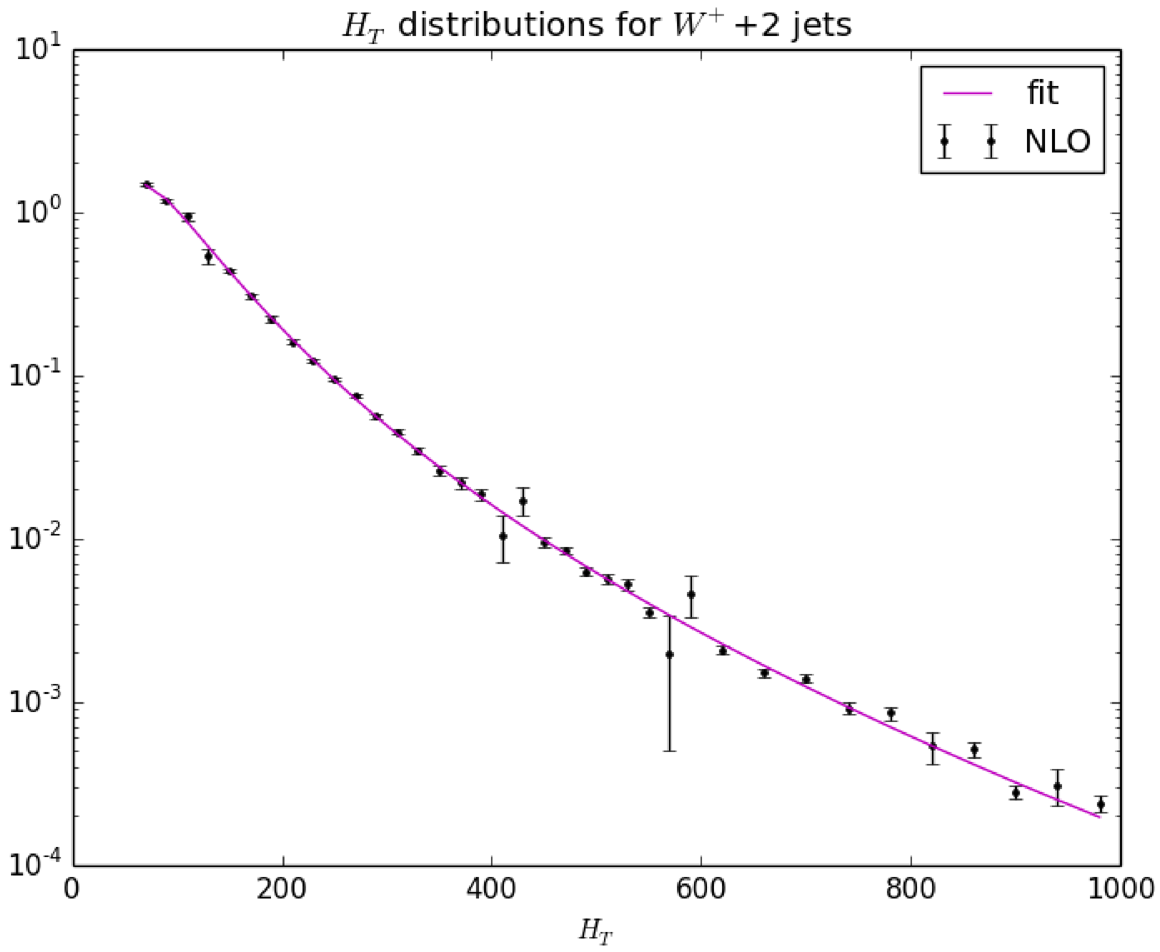
HT distribution

- With the parameters one can extract *f(H)* from a distribution
- But it is more convenient to have an analytical form for it
- We can use the following form

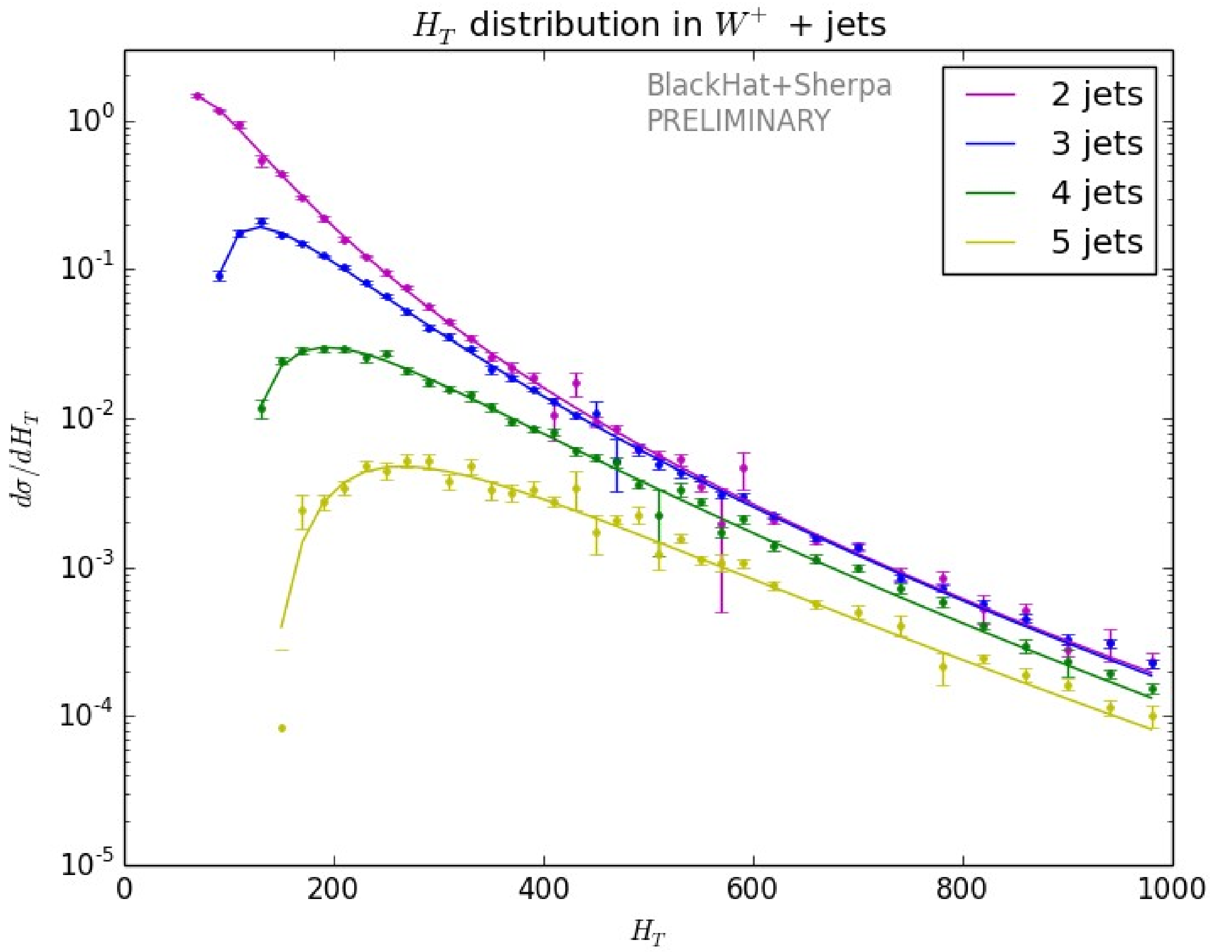
$$f(H) = c \ln^r(H/10) \left(\frac{H}{2p_T^{\min}} \right)^{\omega_2} e^{-h_* H},$$

and extract the parameters from the W+2 jets distribution

HT distribution



HT distribution



Distributions

- Extrapolated HT distribution
- Uncertainty bands are estimated using a MC method