BlackHat

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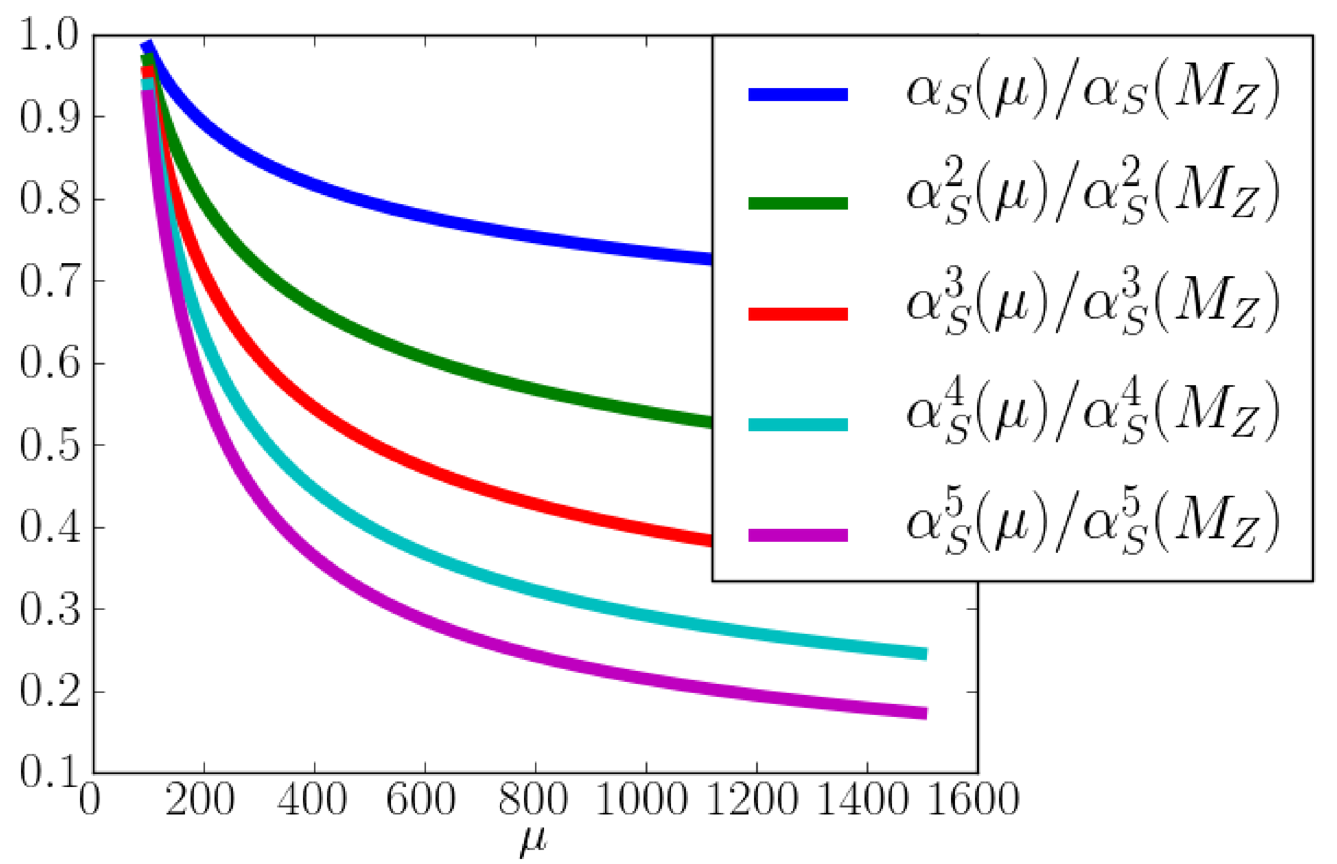
Precise predictions

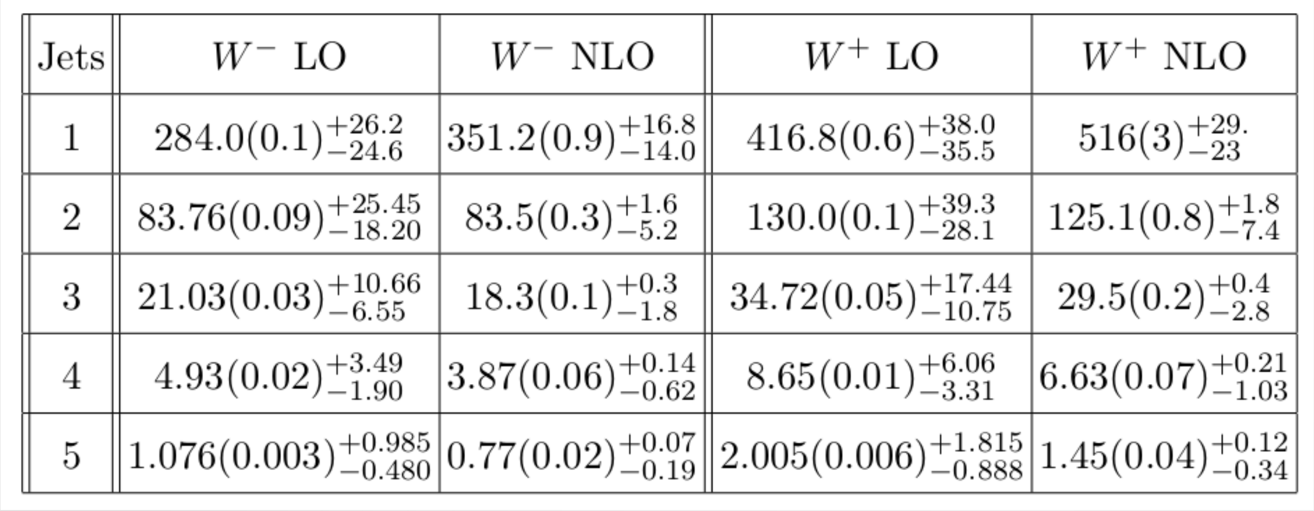
- Precise predictions are needed
  - Signal
  - Background
  - Also for data-driven methods
    - Extrapolation from control to signal region
    - Transfer of information from one process to another
- NLO improves
  - Absolute normalisation
  - Shapes of distributions
  - Scale dependence

NLO scale dependence

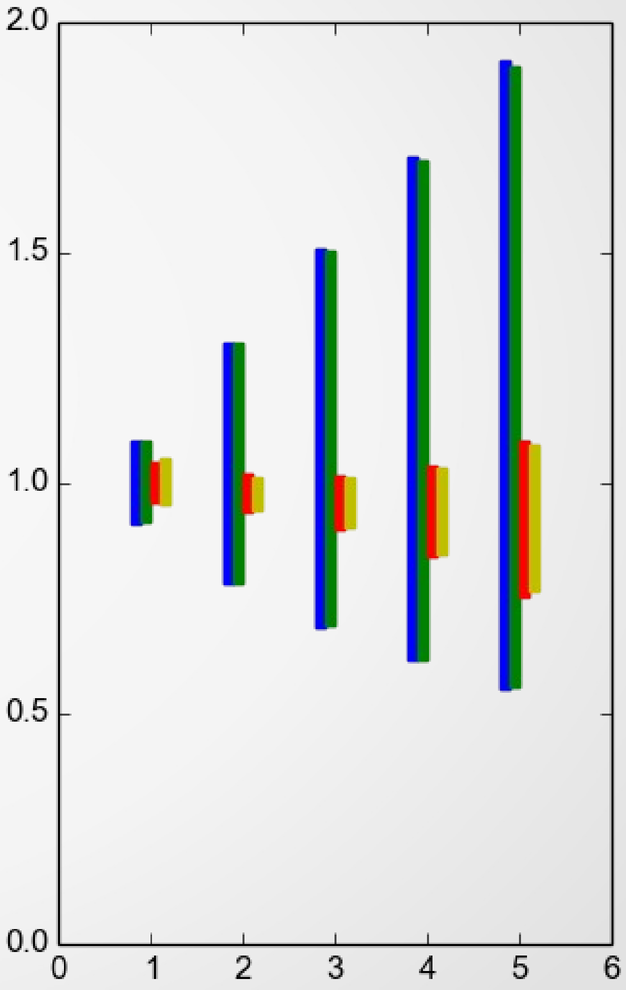


Scale variation

- 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	$1.076(0.003)^{+0.985}_{-0.480}$	$0.77(0.02)^{+0.07}_{-0.19}$	$2.005(0.006)^{+1.815}_{-0.888}$	$1.45(0.04)^{+0.12}_{-0.34}$



BlackHat

- BlackHat is a C++ library for virtual one-loop matrix elements
- It uses unitarity techniques
- 'Run-time' library, not a 'code generating engine'

BlackHat+Sherpa

- NOT NLO+parton shower, only parton level although Sherpa can provide some NLO+parton shower results
- Recent calculations:
  - W/Z+4 jets
  - 2,3,4 jets
  - Z/gamma ratios with up to 3 jets
  - W+5 jets
  - Soon: diphoton+2 jets

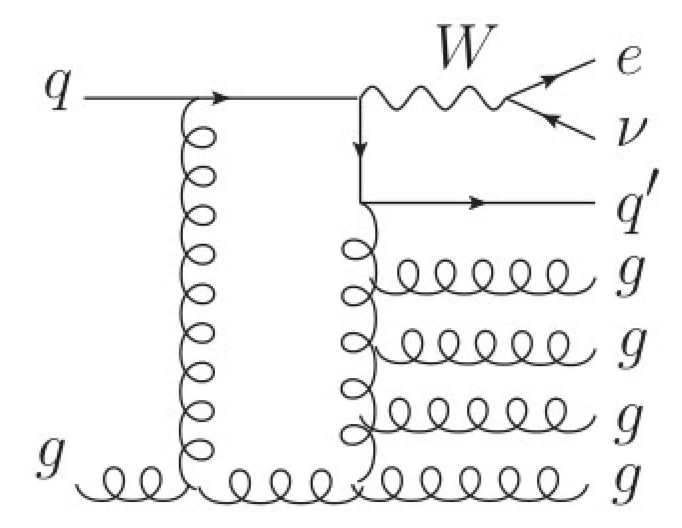
W/Z+jets with BlackHat and Sherpa

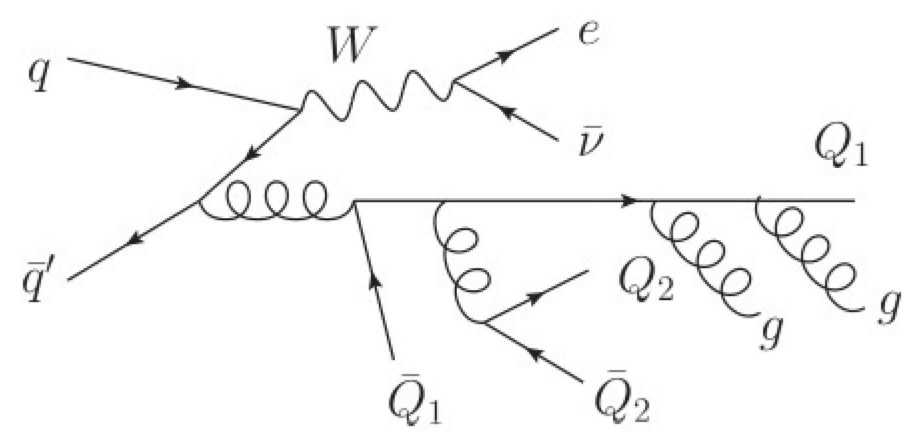
- Use Sherpa for the subprocess organisation and the phase-space integration
- Use BlackHat for the virtual part
- The real part and subtraction is also very challenging, we use COMIX [Gleisberg, Hoeche [0808.3674]]

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

W+5 jets at NLO

- First NLO corrections for a 2→6 hadron collider process calculated

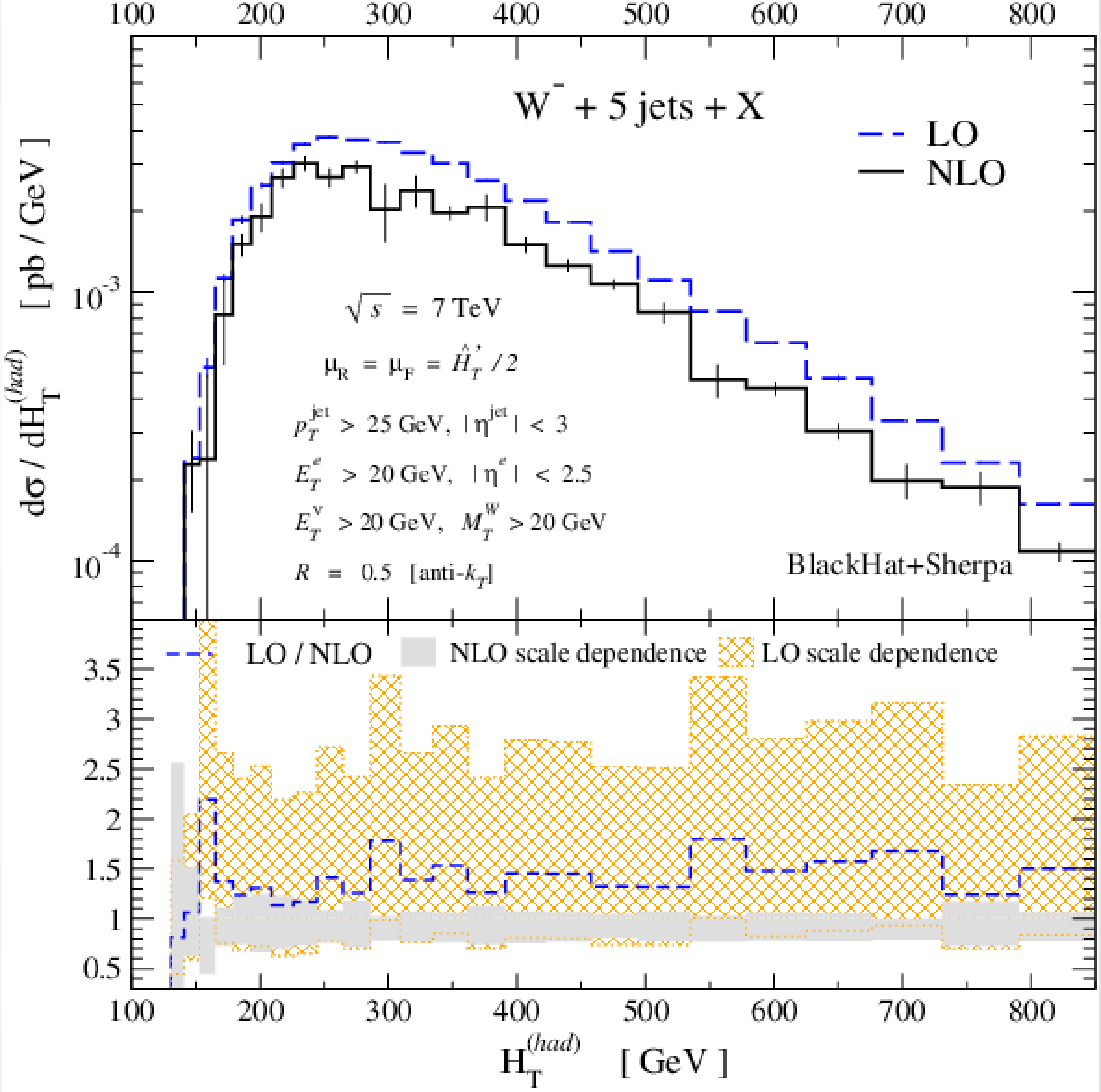




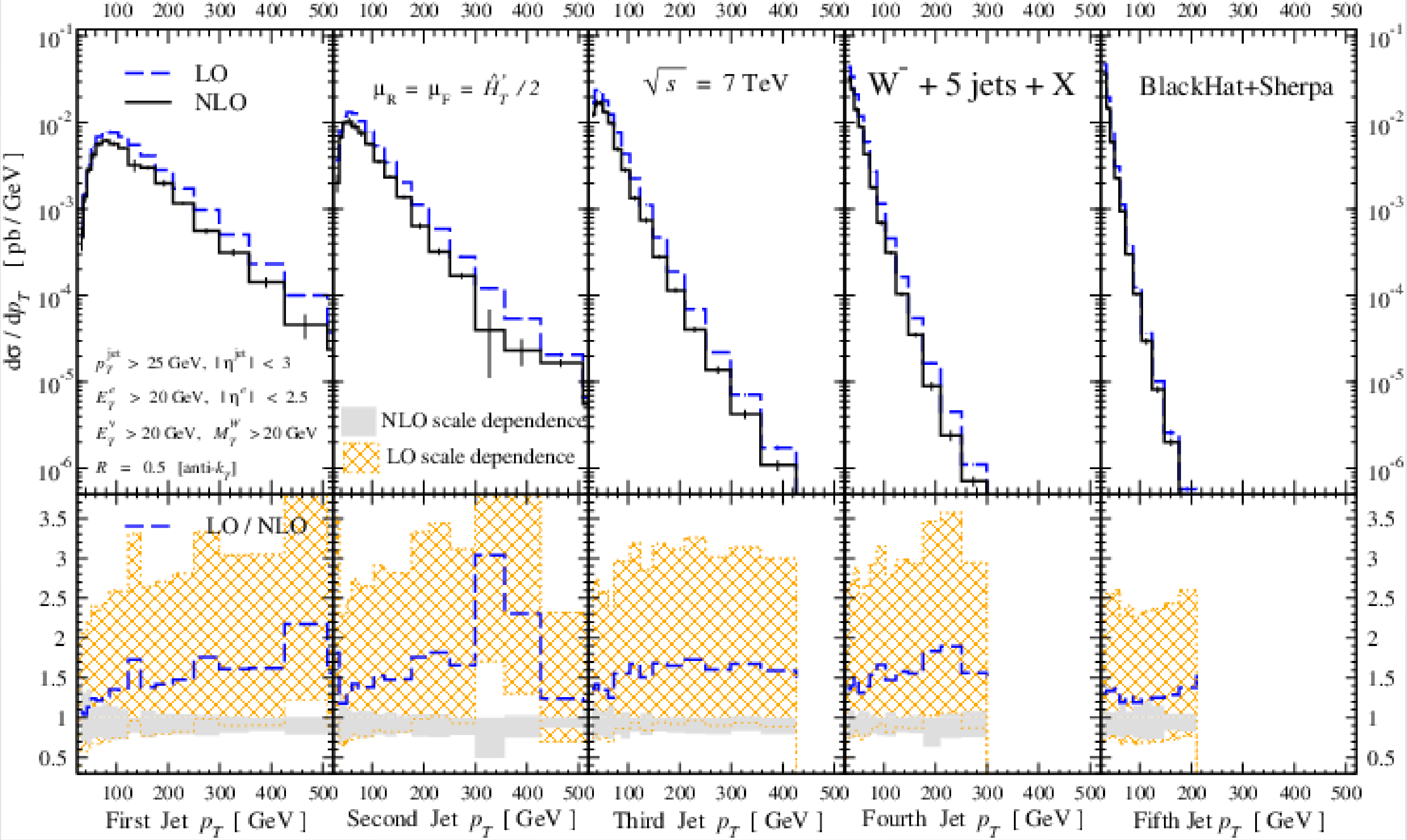
W+5 jets at NLO

- Leading color approximation for loop part (good to 3%)
- Scale $\hat{H}'_T$
- $\hat{H}'_T \equiv \sum_m p_T^m + E_T^W$

$$E_T^W \equiv \sqrt{M_W^2 + (p_T^W)^2}$$



W+5 jets at NLO

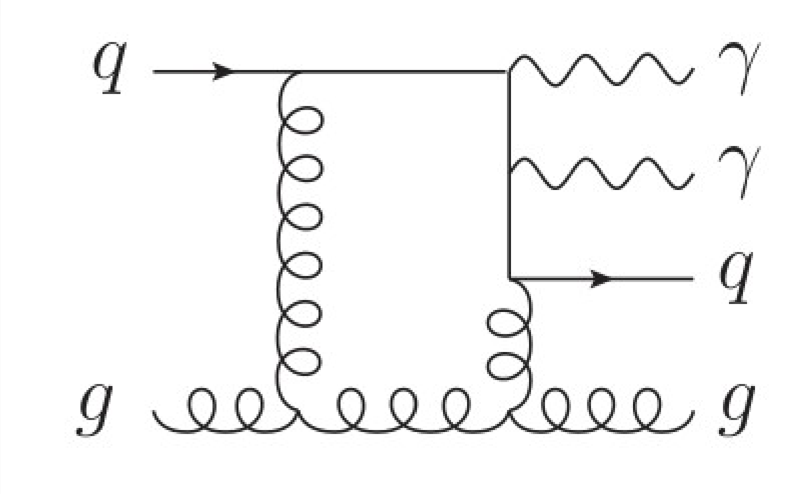


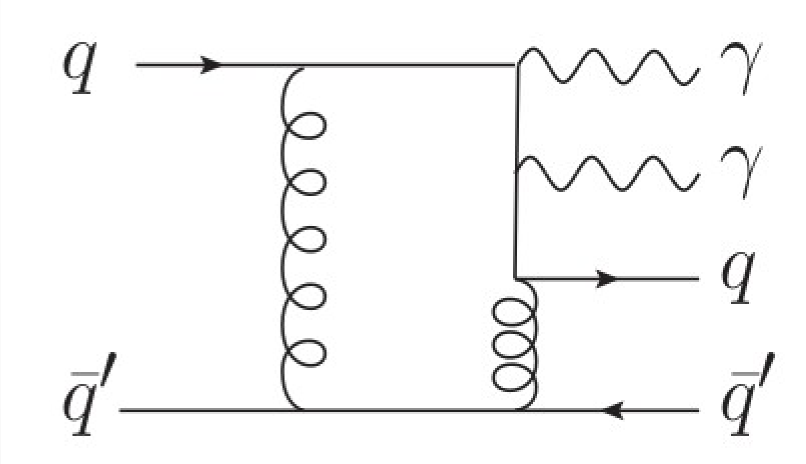
Di-photon + 2 jets

- Important background for VBF Higgs boson production
- History
  - Inclusive NLO di-photon know since a long time [Binoth,Guillet,Pilon,Werlen [hep-ph/9911340], Bern,Dixon,Schmidt [hep-ph/0206194], Campbell,Ellis,Williams [1105.0020]]
  - Inclusive NNLO [Catani, Cieri, de Florian, Ferrera and Grazzini [1110.2375]]
  - NLO di-photon + 1 jet [Del Duca,Maltoni,Nagy,Trocsanyi [hep-ph/0303012] Gehrmann,Greiner,Heinrich [1303.0824]]
  - NLO di-photon + 2 jets [Gehrmann, Greiner,Heinrich [1308.3660,1311.4754]]

Di-photon + 2 jets

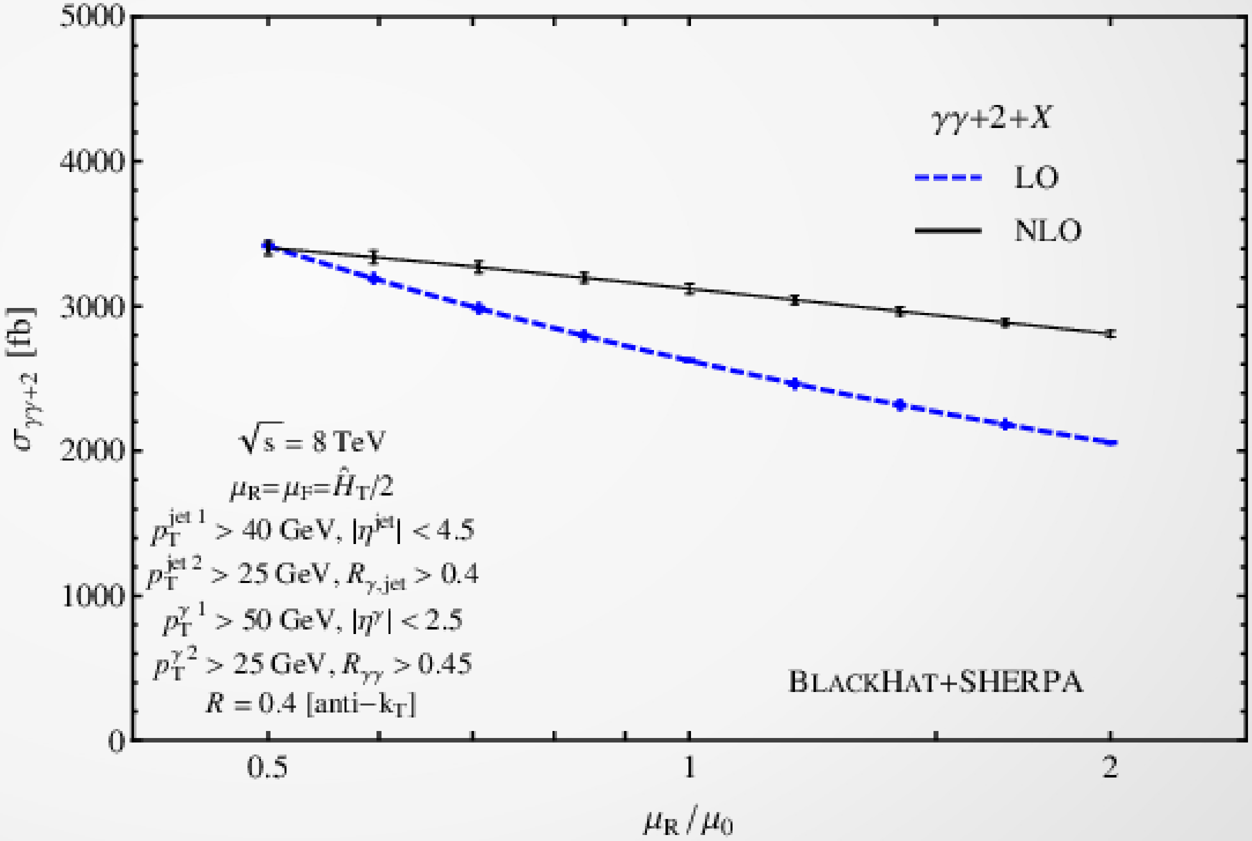
- Include the loop-induced $gg \to gg\gamma\gamma$ because of the potentially large gluon partonic luminosity
- No real or virtual top quarks





Di-photon scale dependence

$$\begin{aligned}
p_T^{\gamma_1} &> 50\ \mathrm{GeV}\,,\\
p_T^{\gamma_2} &> 25\ \mathrm{GeV}\,,\\
|\eta_\gamma| &< 2.5\,,\\
R_{\gamma\gamma} &> 0.45\,,\\
p_T^{j_1} &> 40\ \mathrm{GeV}\,,\\
p_T^{j_2} &> 25\ \mathrm{GeV}\,,\\
|\eta_j| &< 4.5\,,\\
R_{\gamma,} &> 0.4\,.
\end{aligned}$$



Photon isolation

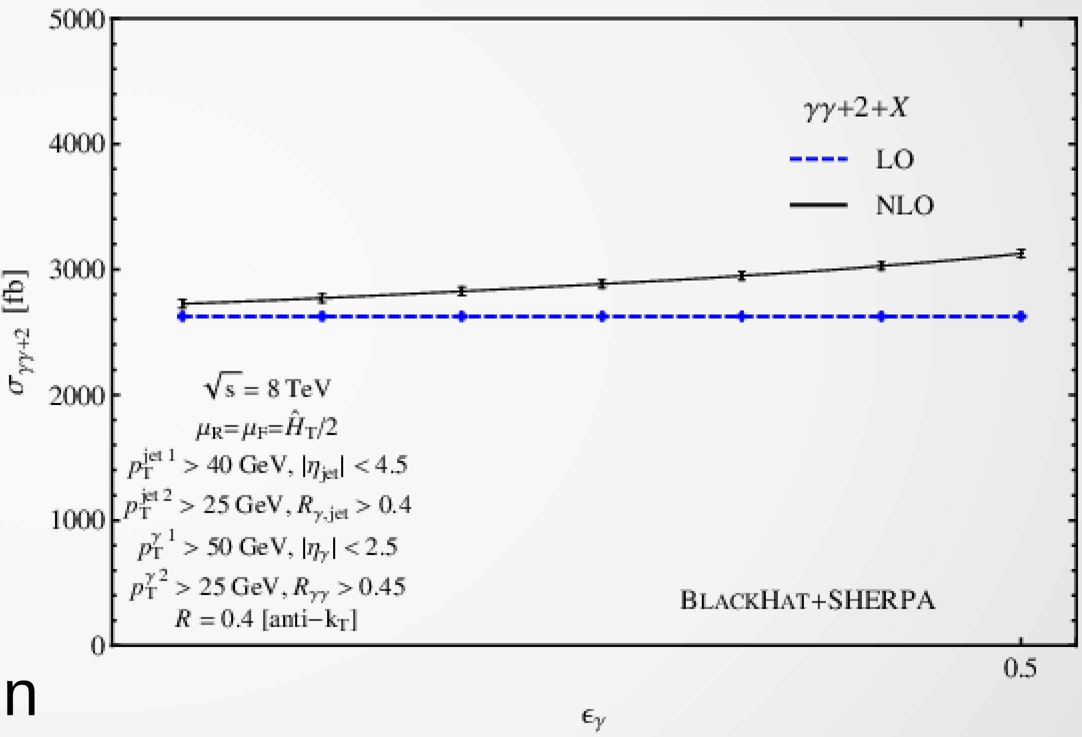
- We use Frixione isolation

$$\sum_i E_{\mathrm{T}i}\,\Theta\left(\delta - R_{i\gamma}\right) \leq E(\delta)$$

$$\delta = \sqrt{(\phi_\gamma - \phi)^2 + (\eta_\gamma - \eta)^2}$$

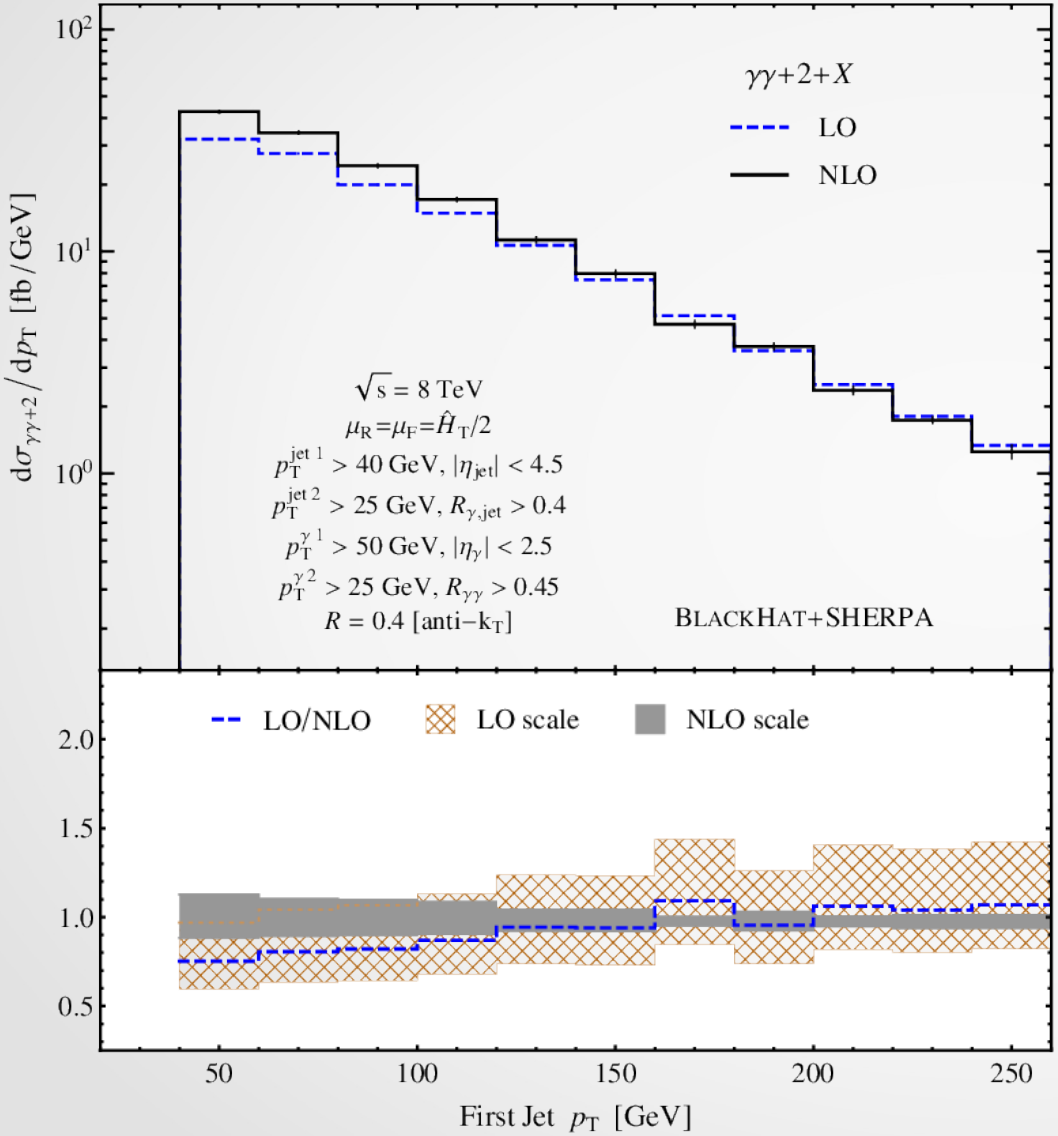
$$E(\delta) = E_T^\gamma\,\epsilon_\gamma \left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n$$

$$\epsilon_\gamma = 0.5\,,\ \delta_0 = 0.4\,,\ n = 1$$



- Dependence on the isolation parameter is weak

Di-photon+2 jets: first jet pt



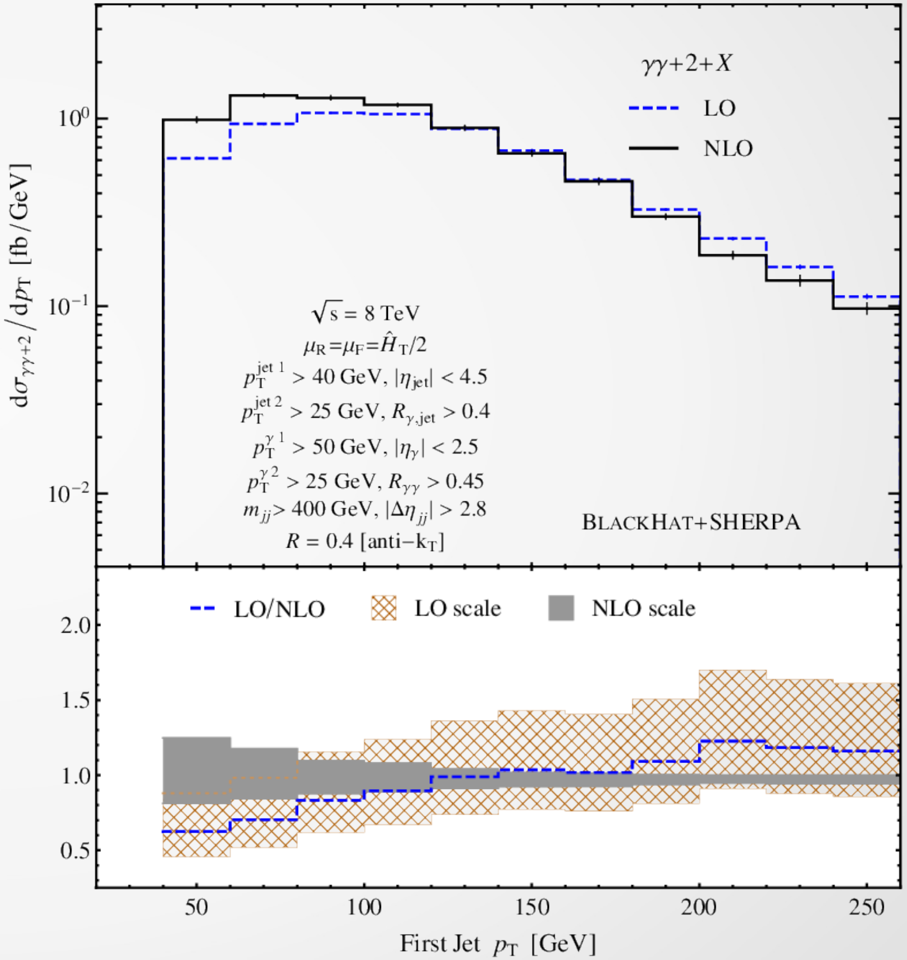
- Scale dependence reduced
- Shape changes
- NLO distribution falls off quicker

First jet pt with VBF cuts

- Additional cuts:

$$M_{jj} > 400\,\mathrm{GeV}$$

$$|\Delta\eta_{jj}| > 2.8$$

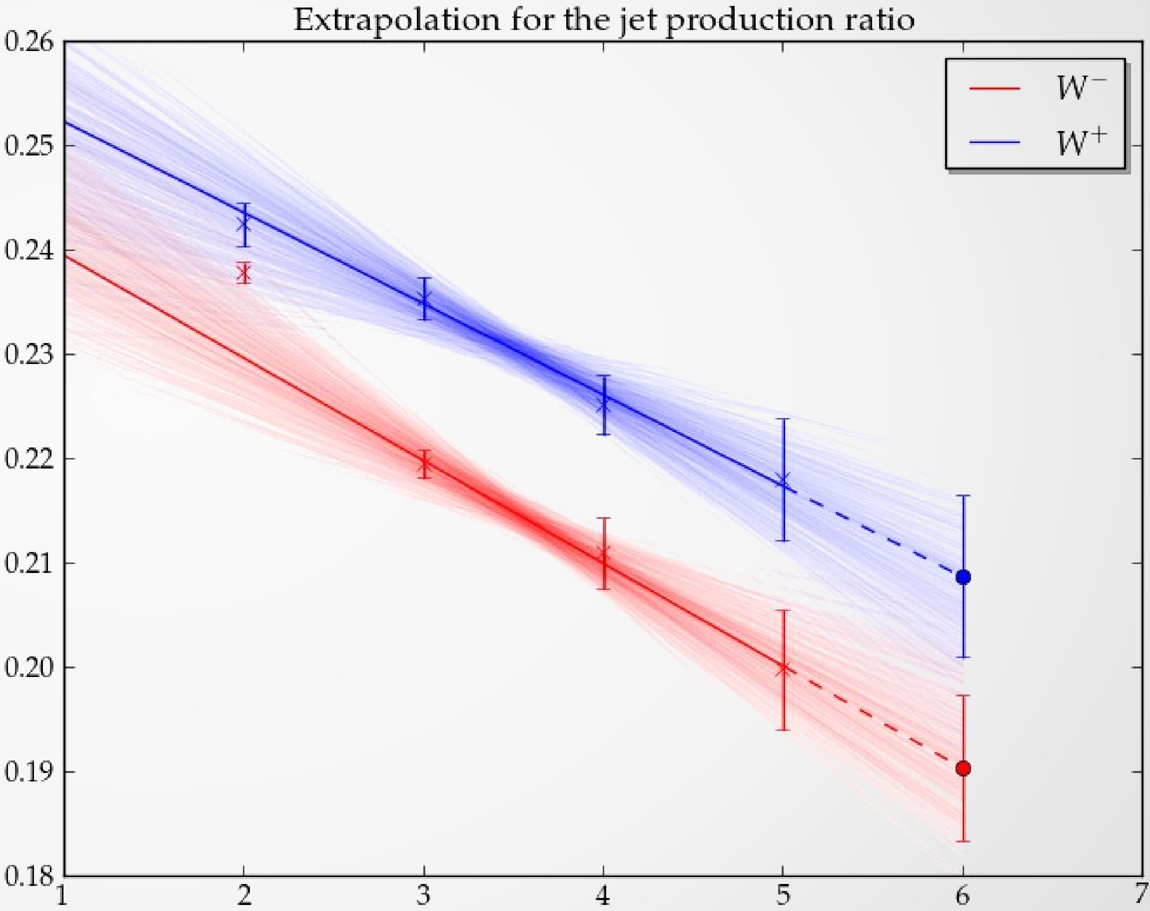


Towards higher multiplicities?

- We have a lot of 'data' 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

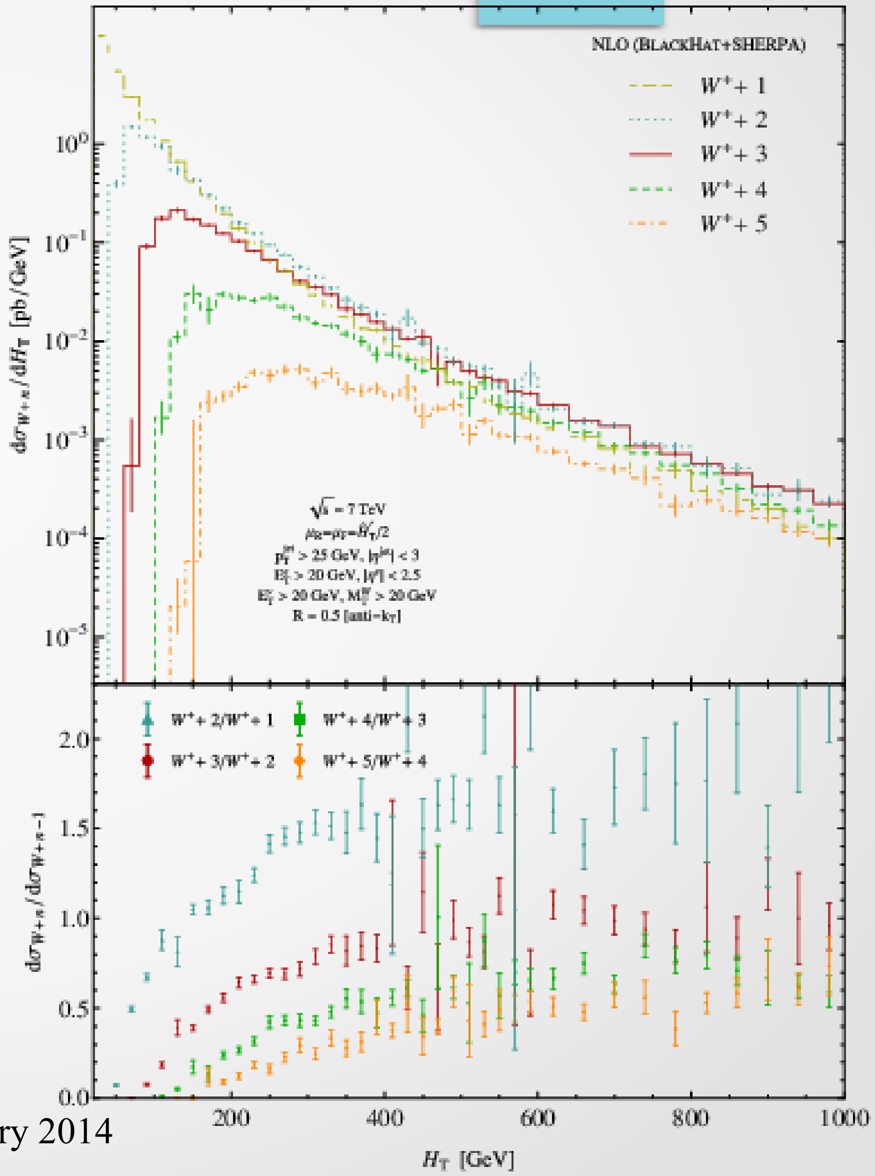
Extrapolation for ratios

- 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 too large
  - Different thresholds
  - Different peak positions



Distributions

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

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

$$\rho_{H,n} = \left(H_T/(n p_T^{min})\right)^2$$

HT Distribution

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

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

parameters

Independent of *n*

$$\rho_{H,n} = \left(H_T/(np_T^{min})\right)^2$$

HT distribution

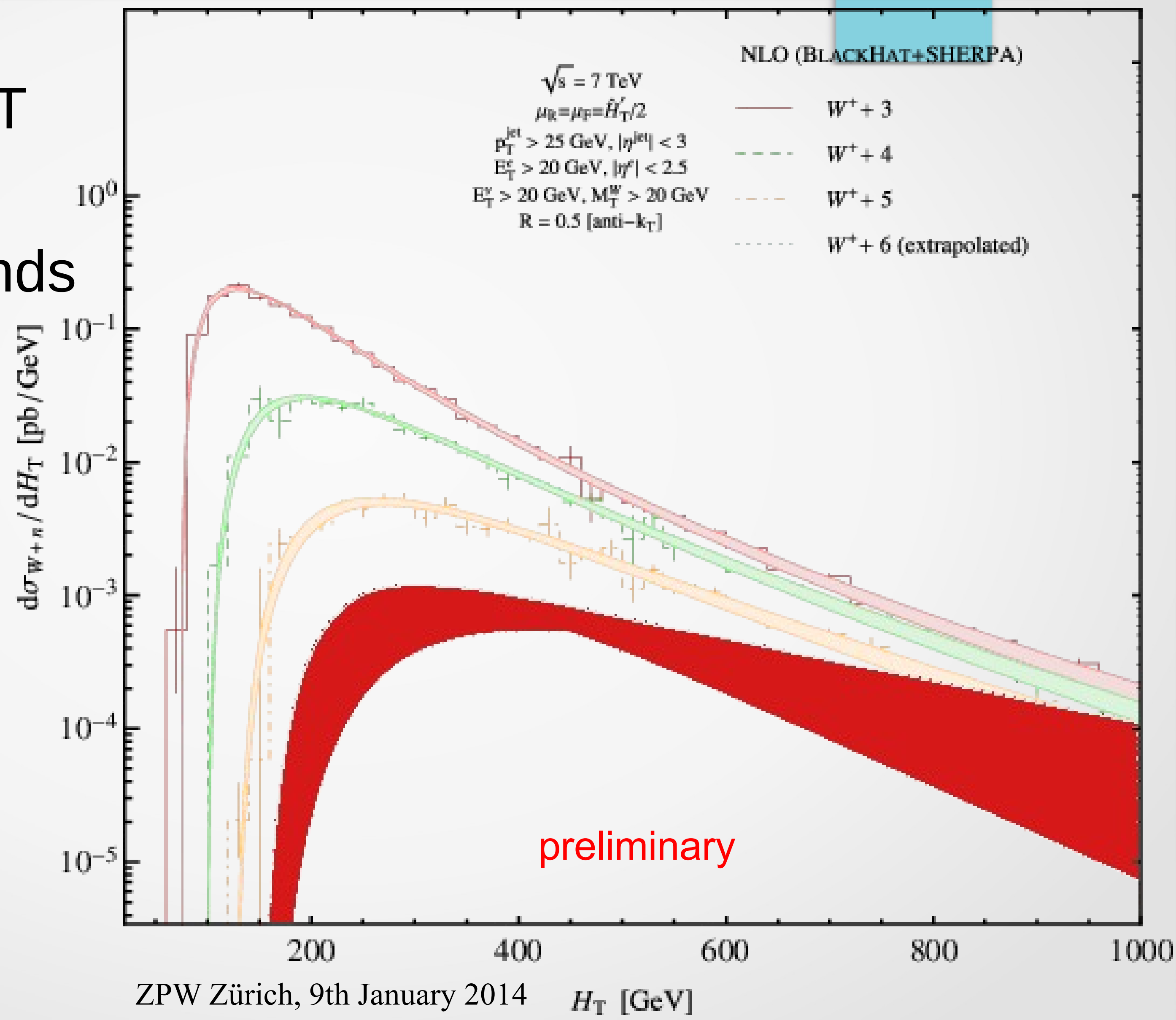
- Fit ratios to get the parameters
- With the parameters one can extract *f(H)* from a distribution
- But it is more convenient to have an analytical form for it
- We can use the following form

$$f(H) = c \ln^r(H/20) \left(\frac{H}{2}\right)^{\omega_2} e^{-h_* H} ,$$

for W+2 jets where the free parameters are fitted

Distributions

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



preliminary

nTuples [arXiv:1310.7439]

- High multiplicity NLO calculations are computing intensive
- Matrix elements are expensive, while
  - Jet clustering
  - Observables
  - Pdfs evaluation

  are relatively cheap
- Store each matrix element, PS point and the information necessary to change the factorisation and renormalisation scales
- We use ROOT file as storage

nTuples

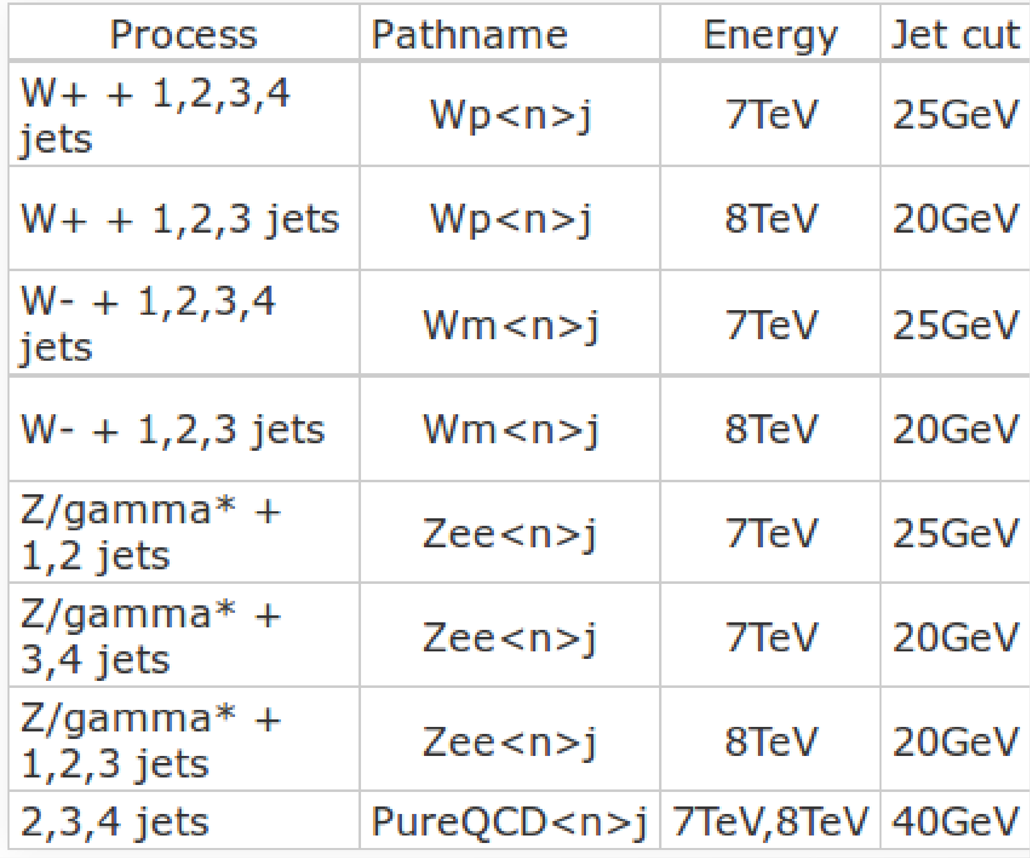
- At NLO for a fixed jet pt threshold the *n*-jet samples are not 'inclusive' in the sense that having *n* jets for a given cone radius doesn't guarantee that one has at least *n* jets for a smaller cone radius
- As a consequence a NLO sample cannot work for any jet parameters
- Several jet algorithms are supported:
  - Anti-kt, kt, Siscone (merging fraction 0.75)
  - R=0.4,0.5,0.6,0.7

nTuples

- Advantages
  - 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 them
- Disadvantages
  - Large files
  - Generation cuts need to be loose enough to accommodate many analysis --> often not very efficient

nTuples availability

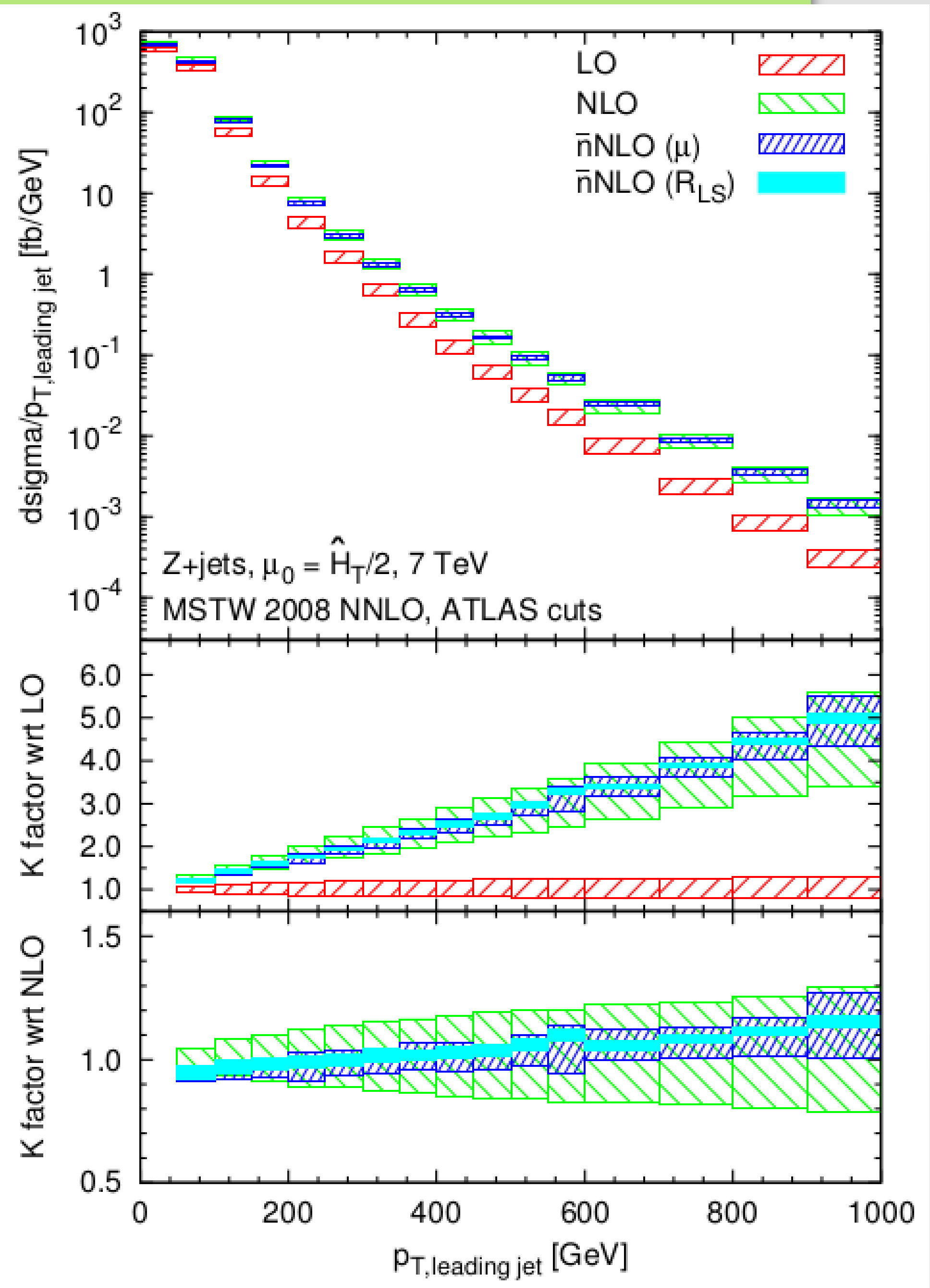
- The nTuple files are available
  - On the grid
  - On castor at CERN
- For a range of processes



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

nTuples

- Can be used to easily use NLO predictions in other frameworks
- For example with LoopSim [Maitre,Sapeta [1307.2252]]
- Merge Z+1,2 jets @ NLO



Pitfalls

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

nTupleReader library

- We provide a C++ library to facilitate the use of the nTuples 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’)

while r.nextEntry():
        for i in range(r.getParticleNumber()):
                print "p(%d)=(%f,%f,%f,%f)" % (
                 i,
                 r.getEnergy(i),
                 r.getX(i),
                 r.getY(i),
                 r.getZ(i)
                )
```

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
        ...
```

Future

- Public version in preparation
- Include more processes and provide nTuples
- Investigate extrapolation of distributions