Controlling large K-factors in processes with jets

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in collaboration with Gavin Salam and Mathieu Rubin [1]

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[1] M.Rubin, G.P.Salam and SS, JHEP 1009 (2010) 084

Example search at LHC: SUSY with data-driven method

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$$E_T^{\text{miss}} + \geq 4\text{jets } (+ \text{ leptons})$$

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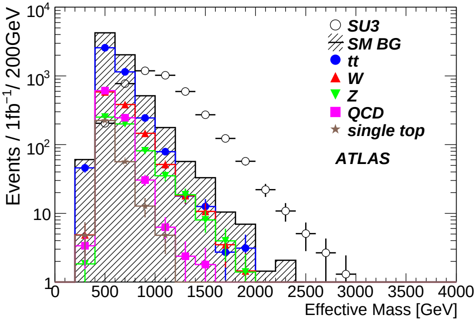
Example: no-lepton search mode

[ATLAS NOTE '08, CERN-OPEN-2008-020]

Cuts:

- $p_T^{\text{lepton}} < 20$ GeV
- 4 jets with $|\eta| < 2.5$ and $p_T > 50$ GeV
- hardest jet $p_T > 100$ GeV
- $E_T^{\text{miss}} > 100$ GeV



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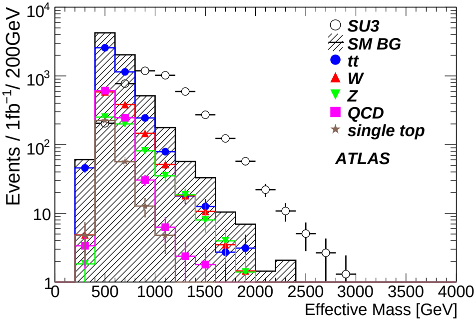
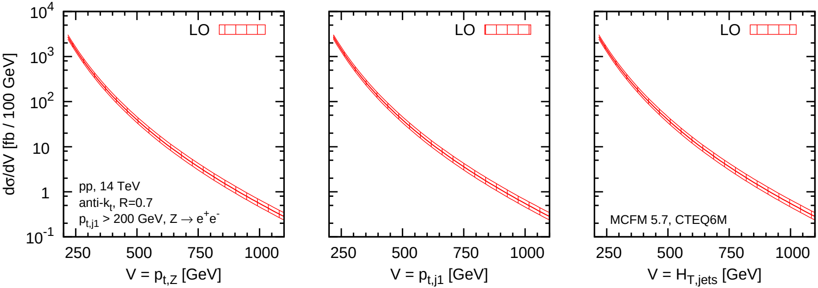


Is it really safe? Let us look at a simpler process...

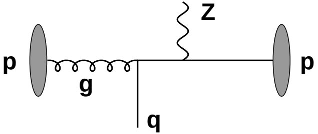
The problem of giant K factors

- Z+j at the LHC $\left[\mu_{R,0} = \mu_{F,0} = \sqrt{m_Z^2 + p_{t,\text{hardest jet}}^2}\right]$

$p_{t,Z}$ | **$p_{t,\text{hardest jet}}$** | $H_{T,\text{jets}} = \sum_{\text{all jets}} p_{t,j}$



LO:



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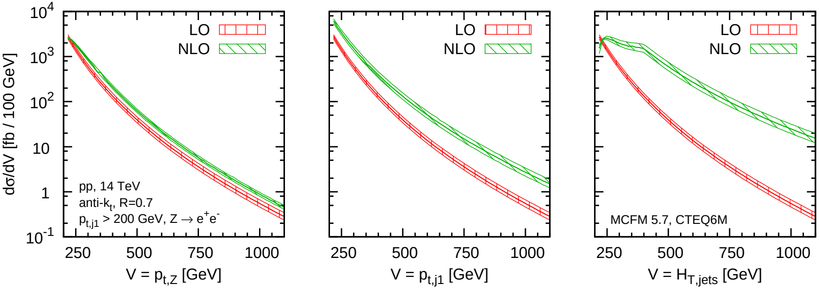
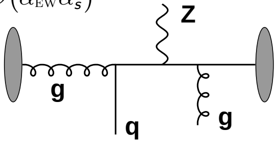
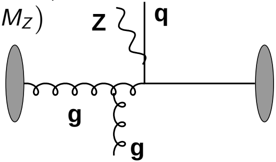


$\mathcal{O}\left(\alpha_{\text{EW}}\alpha_s^2\right)$

$\mathcal{O}\left(\alpha_{\text{EW}}\alpha_s^2 \ln^2 p_{t,j1}/M_Z\right)$

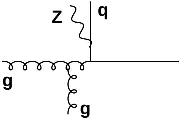
NLO:

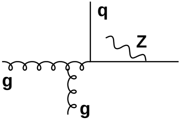




What do we have and what is missing?

- The large K factor for the Z+jet comes from the new "dijet type" topologies that appear at NLO





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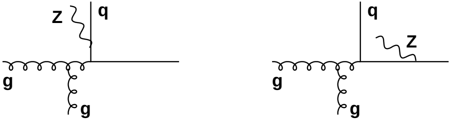

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- this raises doubts about the accuracy of these predictions
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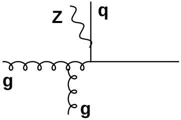

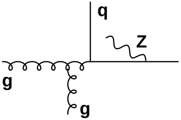

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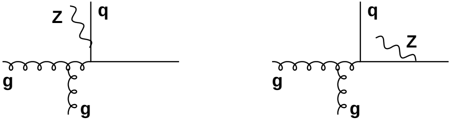

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- **2-loop part**
  - we need it to cancel IR and collinear divergences from Z+2j at NLO result
  - it will have the topology of Z+j at LO so it will not contribute much to the cross sections with giant K-factor

The basic idea

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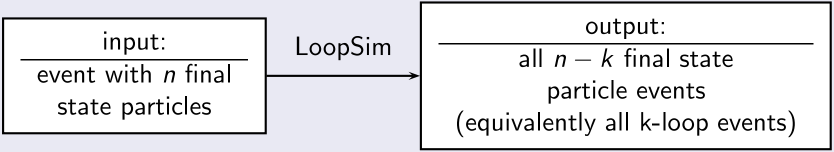
LoopSim procedure



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input: event with n final state particles → LoopSim → output: all $n-k$ final state particle events (equivalently all k-loop events)

- notation:

$\bar{n}$**LO**	–	simulated 1-loop
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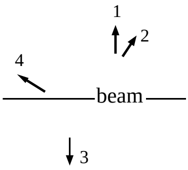
- this will work very well for the processes with large K factors e.g.

$$\sigma_{\bar{n}\text{NLO}} = \sigma_{\text{NNLO}} \left(1 + \mathcal{O}\left(\frac{\alpha_s^2}{K_{\text{NNLO}}}\right)\right) , \quad K_{\text{NNLO}} \gtrsim K_{\text{NLO}} \gg 1$$

The LoopSim method: $\bar{n}$LO, $\bar{n}\bar{n}$LO etc.

Input event



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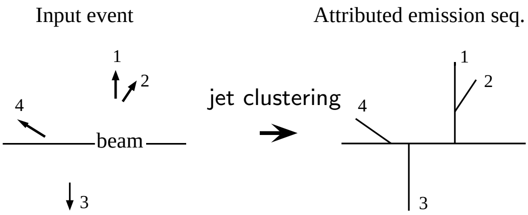

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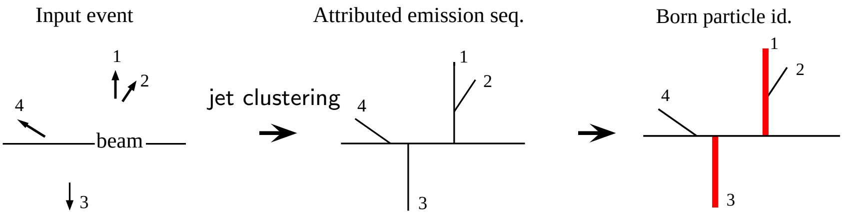

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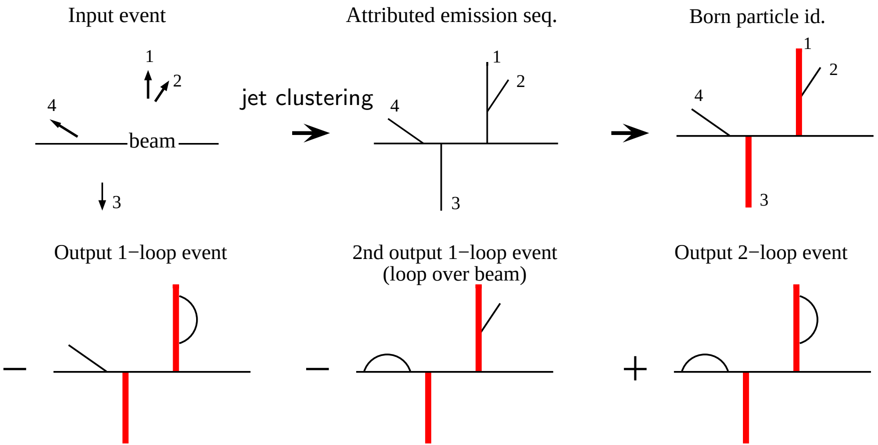

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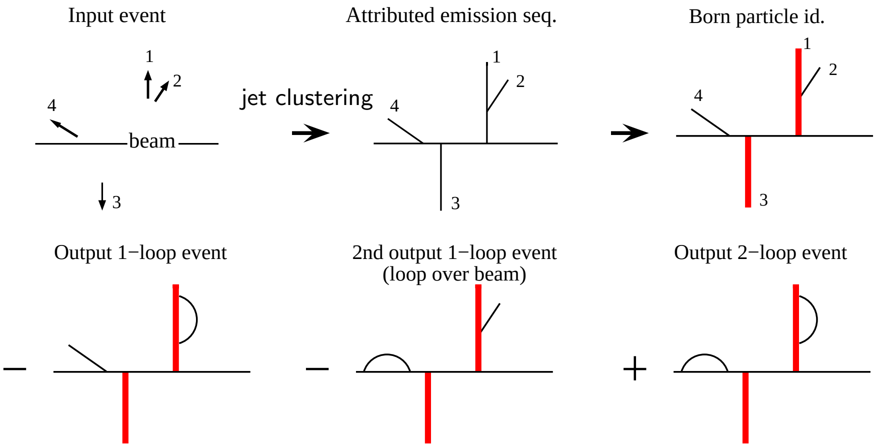

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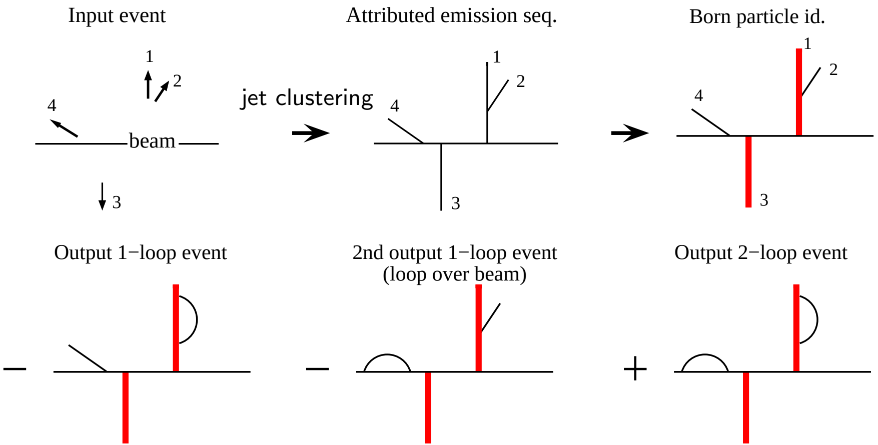

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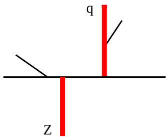
- beware: the loops above are just a shortcut notation!

Make it more concrete example: Z+j at $\bar{n}\bar{n}$LO



weight = 1	p_x	p_y	p_z	E
particle 0: Z	-21.01	7.90	-1561.72	1564.54
particle 1: q	19.40	-10.65	1006.92	1007.16
particle 2: q	-5.75	-0.15	-150.64	150.75
particle 3: q	7.36	2.90	418.96	419.03
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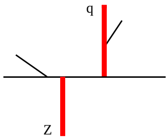

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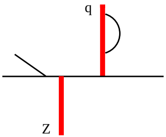

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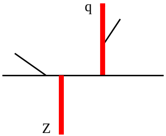

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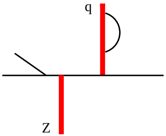

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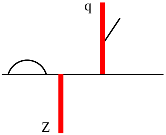

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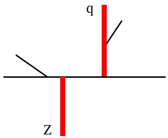

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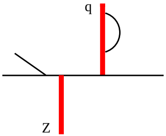

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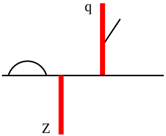

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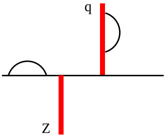

weight = 1	p_x	p_y	p_z	E
particle 0: Z	-24.03	7.82	-1573.56	1576.4
particle 1: q	24.03	-7.82	1196.14	1196.4
total momentum :	0	0	-377.42	2772.8

The LoopSim method: some more details

The principle of the method is simple. There is, however, a number of issues that need to be addressed to fully specify the procedure and make it usable:

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The principle of the method is simple. There is, however, a number of issues that need to be addressed to fully specify the procedure and make it usable:

- infrared and collinear safety
- conservation of four-momentum
- choice of jet definition (algorithm, value of R)
  - in what follows: Cambridge/Aachen with $R = 1$
- treatment of flavour (e.g. for processes with vector bosons)
  - Z boson can be emitted only from quarks and never itself emits
- extension to input events with exact loops

Including exact loops

$E_{n,l}$	–	input event with n final state particles and l loops
U_l^b	–	operator producing event with b Born particles and l loops
$U_\forall^b$	–	operator generating all necessary loop diagrams at given order

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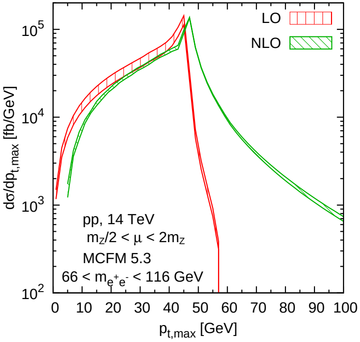
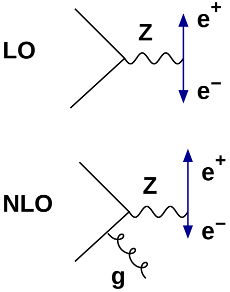
- inclusion of exact loops helps reducing scale uncertainties
- straightforward generalization to arbitrary number of exact loops

Validation

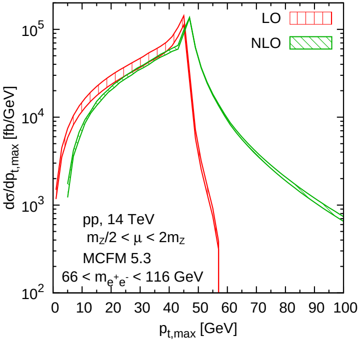
Drell-Yan at NNLO: spectrum of harder lepton

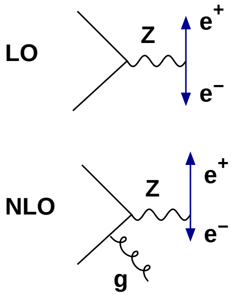




- giant K factor due to a boost caused by initial state radiation

Drell-Yan at NNLO: spectrum of harder lepton





- giant K factor due to a boost caused by initial state radiation
- the agreement between NLO and $\bar{n}$LO may serve as a indication whether the method works for a given observable, $Z@\bar{n}\text{LO} = Z@\text{LO}+\text{LoopSim} \circ (Z+j@\text{LO})$

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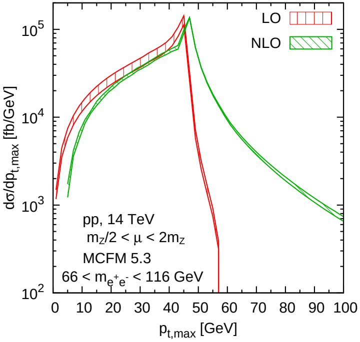

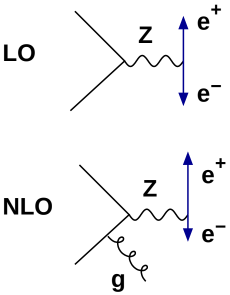

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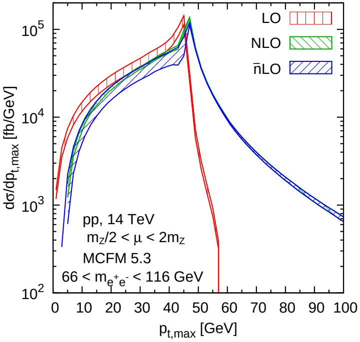

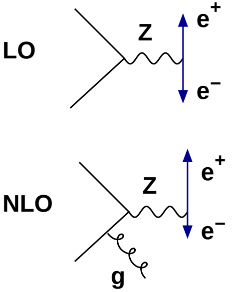

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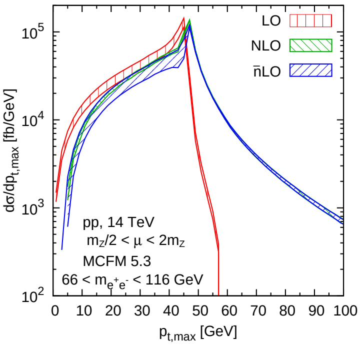

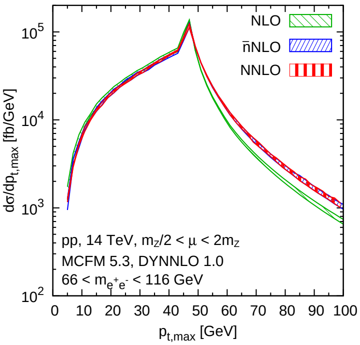

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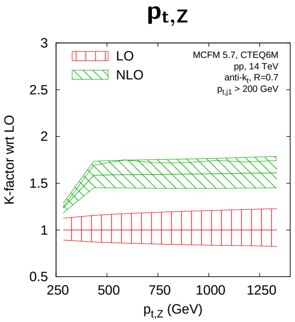
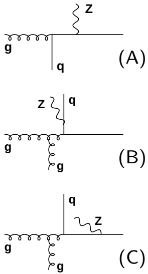
$\bar{n}$NLO predictions for LHC

Z+jet at $\bar{n}$NLO

$$\mu = \sqrt{m_Z^2 + p_{t,\text{hardest jet}}^2}$$





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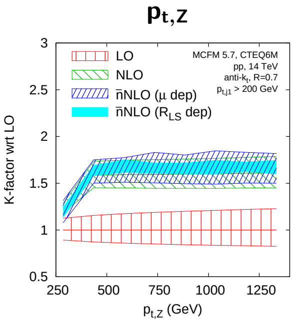

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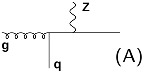

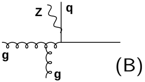

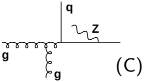

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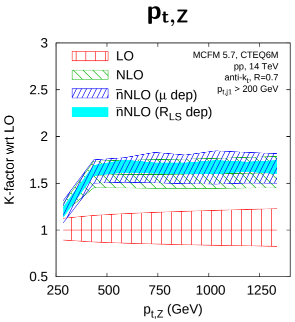

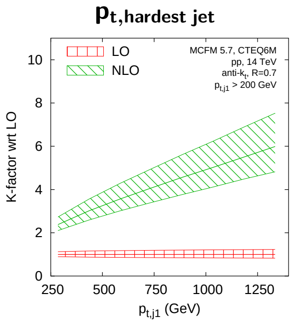

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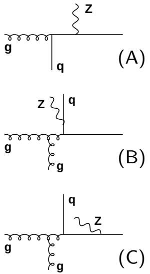

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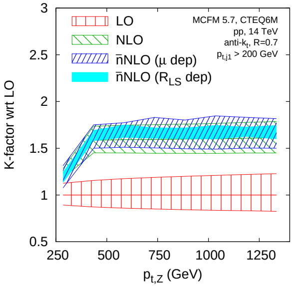
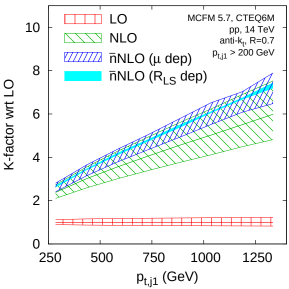


$p_{t,\text{hardest jet}}$



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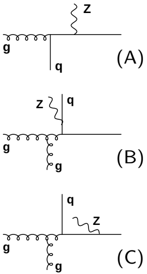

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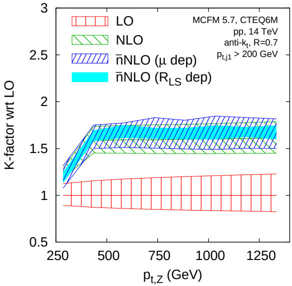

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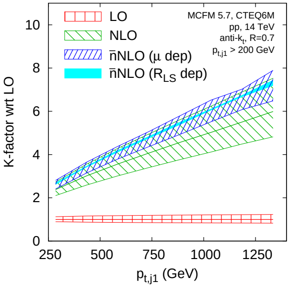
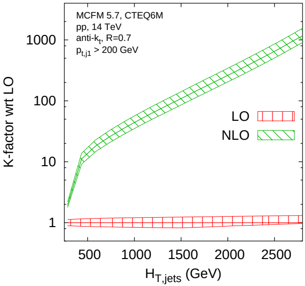


$H_{T,\text{jets}}$



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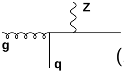
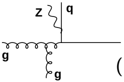
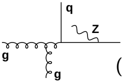


(A)



(B)



(C)

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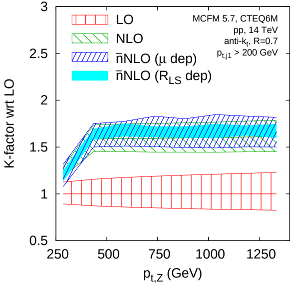

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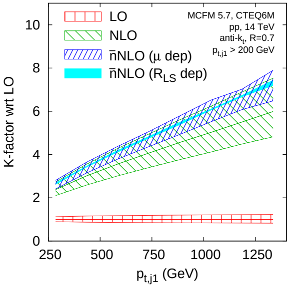
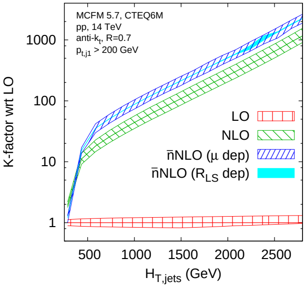


$H_{T,\text{jets}}$



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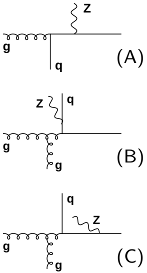
- $H_{T,\text{ jets}}$: significant correction; K factor ~ 2; given that it is more like going from LO to NLO this may happen sometimes, especially for nontrivial observables like H_T; can we understand it here?



H_T type observables at $\bar{n}$NLO for Z+jet and for dijets

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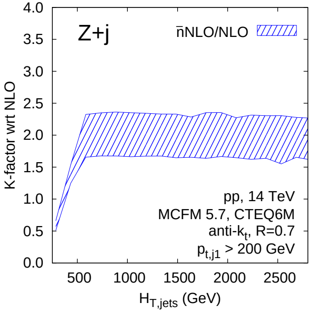

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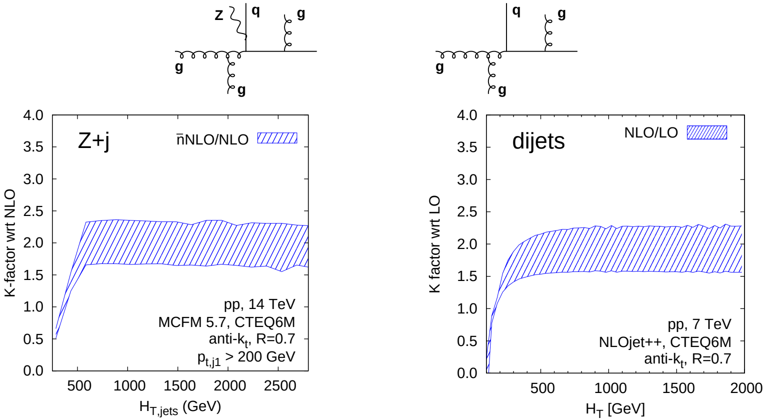
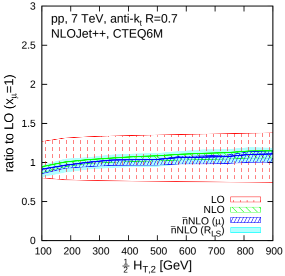


- H_T for dijets receives large contributions at NLO!
  - caused by appearance of the third jet from initial state radiation

Dijets at $\bar{n}$NLO $H_{T,n} = \sum_{n \text{ hardest jets}} p_{t,\text{jet}}$



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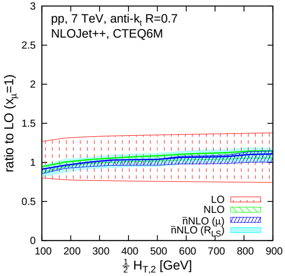

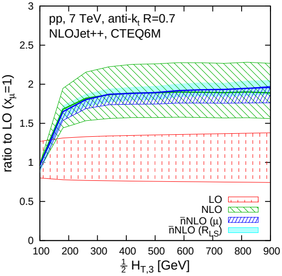

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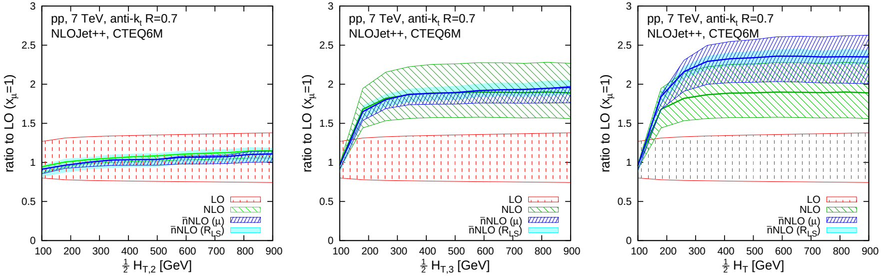

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- **H_T does not converge:** again caused by the initial state radiation, this time a second emission which shifts the distribution of H_T to higher values and causes no effect for the $H_{T,3}$ distribution

Summary

- several cases of observables with giant NLO K factor exist
- those large corrections arise due to appearance of new topologies at NLO
- we developed a method, called *LoopSim*, which allows one to obtain approximate NNLO corrections for such processes
- the method is based on unitarity and makes use of combining NLO results for different multiplicities
- we gave arguments why the method should produce meaningful results and we validated it against NNLO Drell-Yan and also NLO Z+j and NLO dijets
- we computed approximated NNLO corrections to Z+j and dijets at the LHC finding, depending on observable, either indication of convergence of the perturbative series or further corrections
- the latter has been understood and attributed to the initial state radiation

Outlook

- processes with W, multibosons, heavy quarks, ...

BACKUP SLIDES

What can we compute with LoopSim?

A few examples...

Drell–Yan

$$\begin{aligned} Z@\bar{n}LO &= Z@LO + \text{LoopSim} \circ (Z{+}j@LO) \\ Z@\bar{n}NLO &= Z@NLO + \text{LoopSim} \circ (Z{+}j@NLO_{\text{only}}) \end{aligned}$$

Z+j

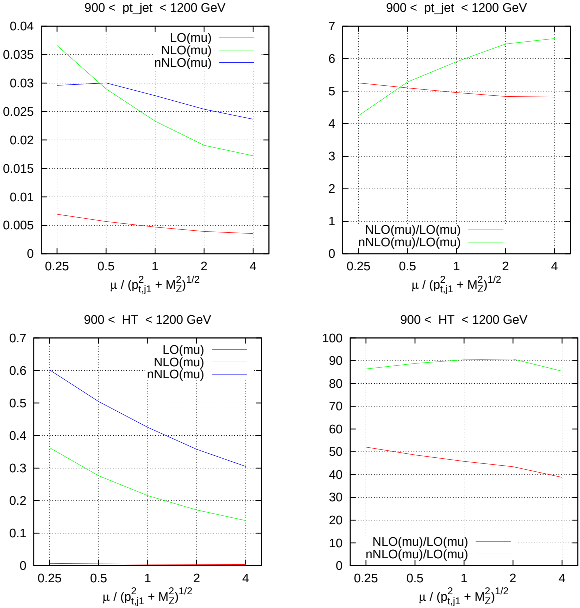
$$\begin{aligned} Z{+}j@\bar{n}\bar{n}LO &= Z{+}j@LO + \text{LoopSim} \circ (Z{+}2j@LO + Z{+}3j@LO) \\ Z{+}j@\bar{n}NLO &= Z{+}j@NLO + \text{LoopSim} \circ (Z{+}2j@NLO_{\text{only}}) \end{aligned}$$

dijets

$$2j@\bar{n}NLO = 2j@NLO + \text{LoopSim} \circ (3j@NLO_{\text{only}})$$

- $mZ{+}nj@NLO_{\text{only}}$ means only the highest order contribution

Scale dependence: Z + jet



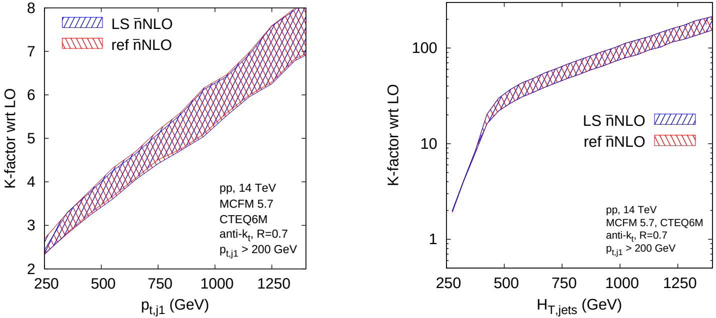
Reference-observable method

Take a reference observable identical at LO to the observable A

$$\sigma^{(A)}_{\text{Z+j@NNLO}} = \sigma^{(\text{ref})}_{\text{Z+j@NNLO}} + \left(\sigma^{(A)} - \sigma^{(\text{ref})}\right)_{\text{Z+j@NNLO}}$$
$$= \sigma^{(\text{ref})}_{\text{Z+j@NNLO}} + \left(\sigma^{(A)} - \sigma^{(\text{ref})}\right)_{\text{Z+2j@NLO}}$$

If the reference observable converges well

$$\sigma^{(A)}_{\text{Z+j@NNLO}} \simeq \sigma^{(\text{ref})}_{\text{Z+j@NLO}} + \left(\sigma^{(A)} - \sigma^{(\text{ref})}\right)_{\text{Z+2j@NLO}}$$



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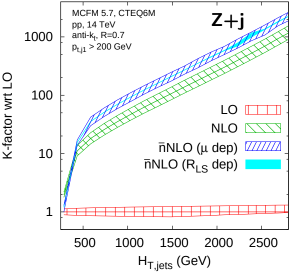

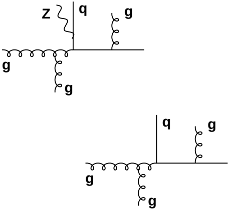

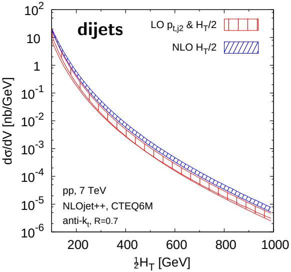

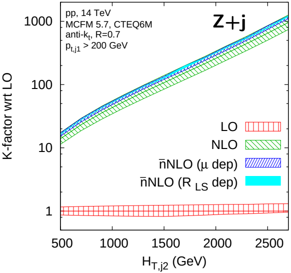

- H_T for dijets receives large contributions at NLO!
  - caused by appearance of the third jet from initial state radiation
- if the same is valid for $Z+j$ we should see only small correction for $H_{T,j2} = \sum_{i=1}^{2} p_{t,j_i}$
  - and indeed it is small!