FxFx merging with aMC@NLO

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CERN

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Need for NLO matched to Parton Shower

- NLO predictions predict rates much more precisely
- Reduced theoretical uncertainties due to meaningful scale dependence
- Shapes are better described
- Correct estimates for PDF uncertainties
- Parton shower matching ensures that we resum all collinear/soft emission at leading logarithmic accuracy and we can include effects from hadronization (and detector simulation, pile-up, underlying event, etc.)

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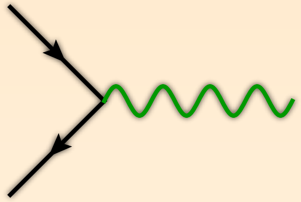
- Parton shower matching ensures that we resum all collinear/soft emission at leading logarithmic accuracy and we can include effects from hadronization (and detector simulation, pile-up, underlying event, etc.)
- These accurate theoretical predictions are particularly needed for
  - searches of signal events in large backgrounds samples and
  - precise extraction of parameters (couplings etc.) when new physics signals have been found

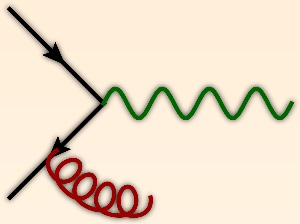
Sources of double counting

Parton shower

Born+Virtual:



Real emission:



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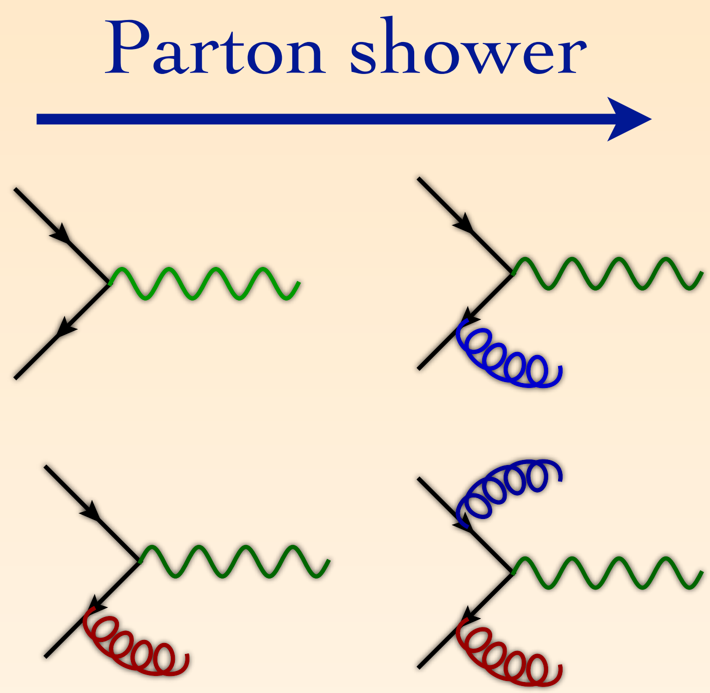

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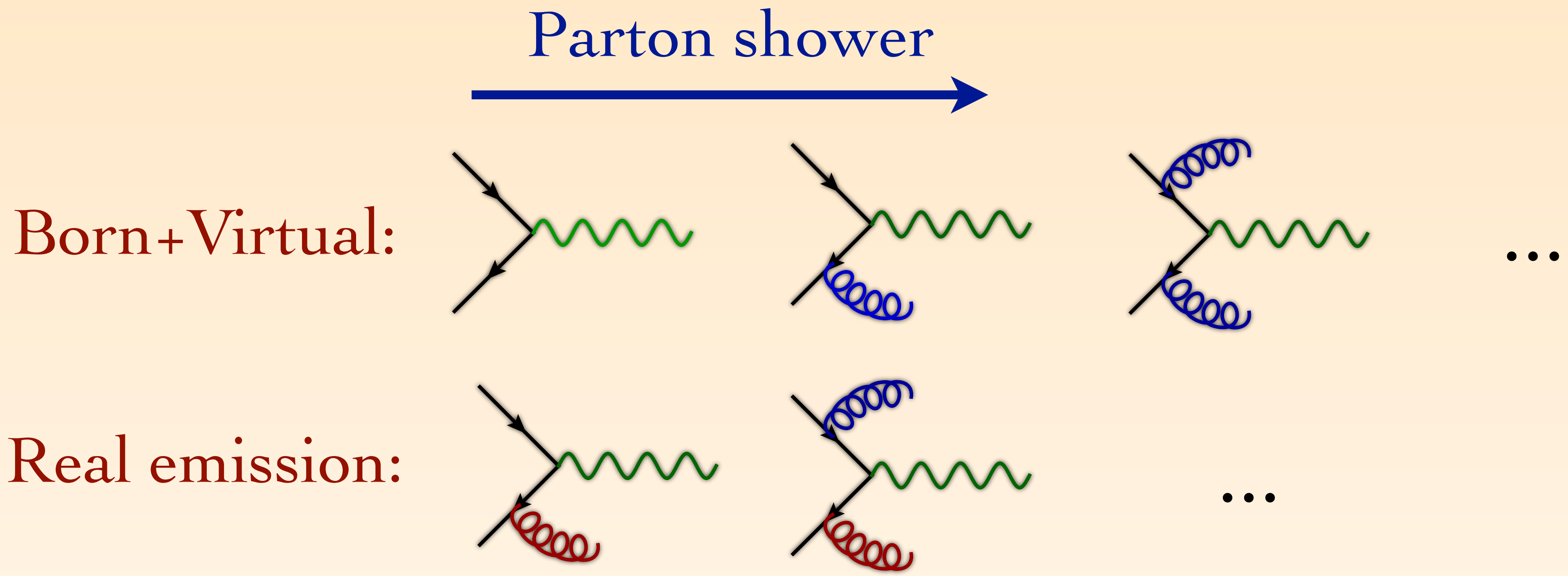

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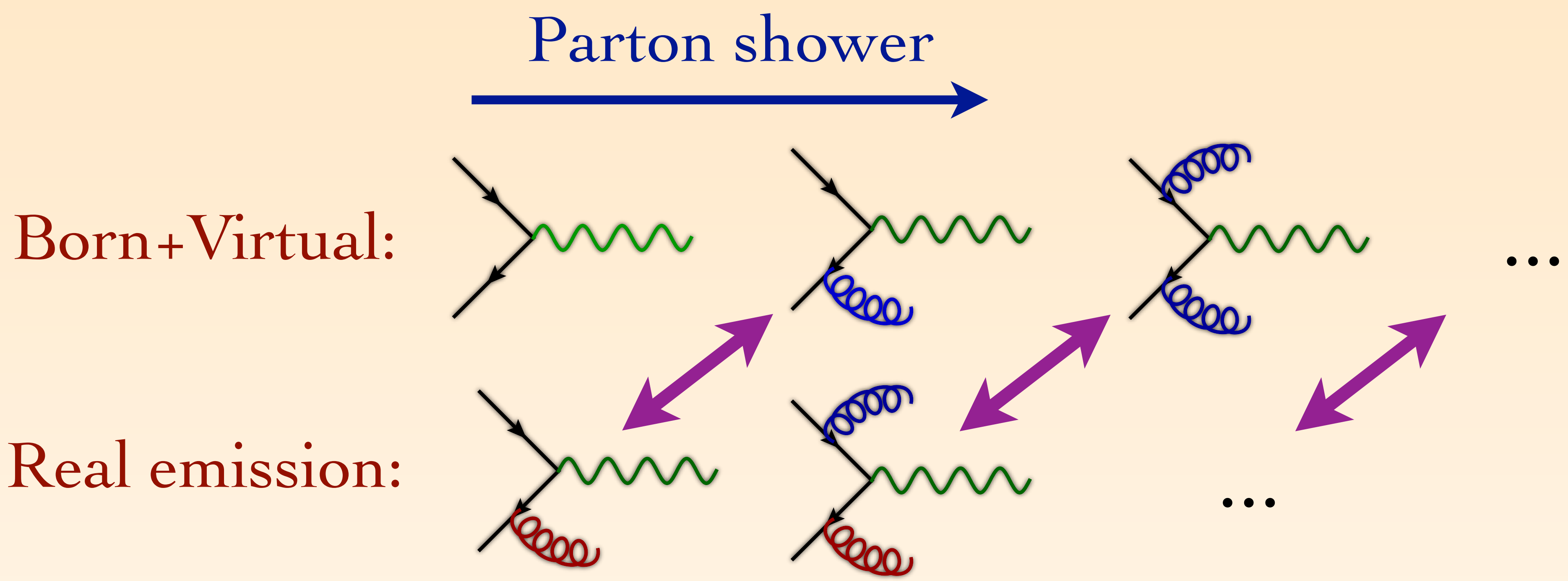

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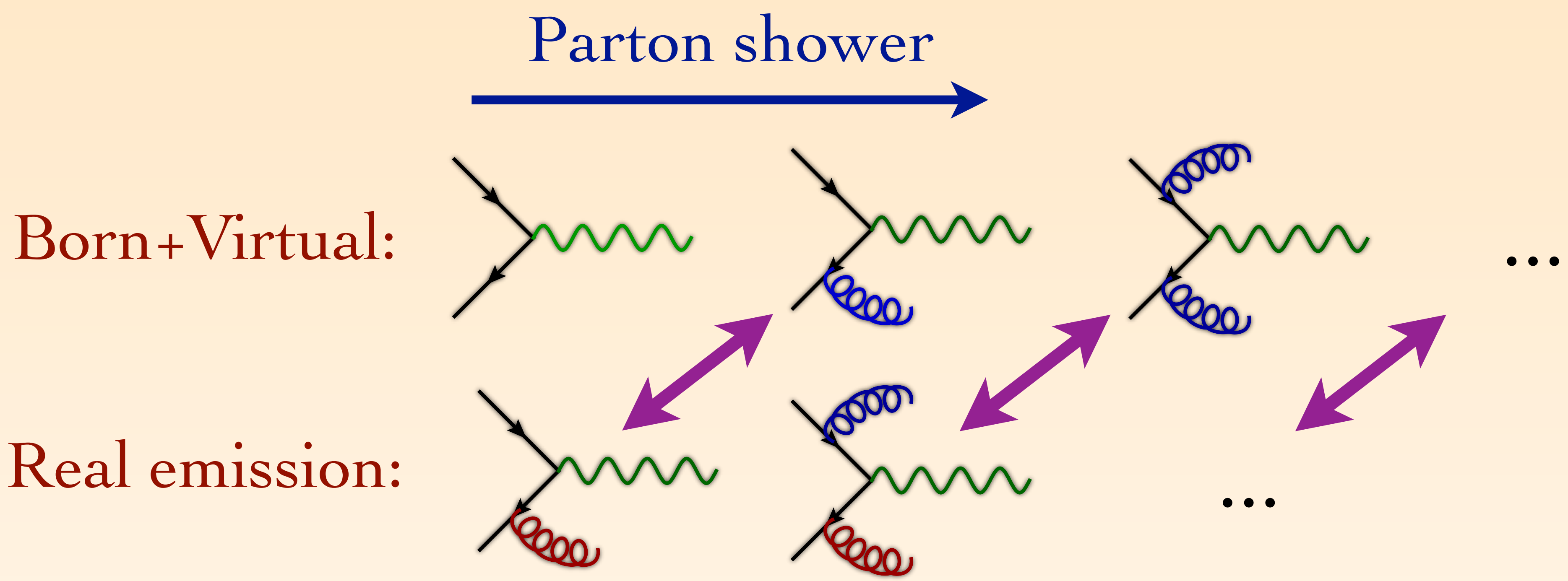
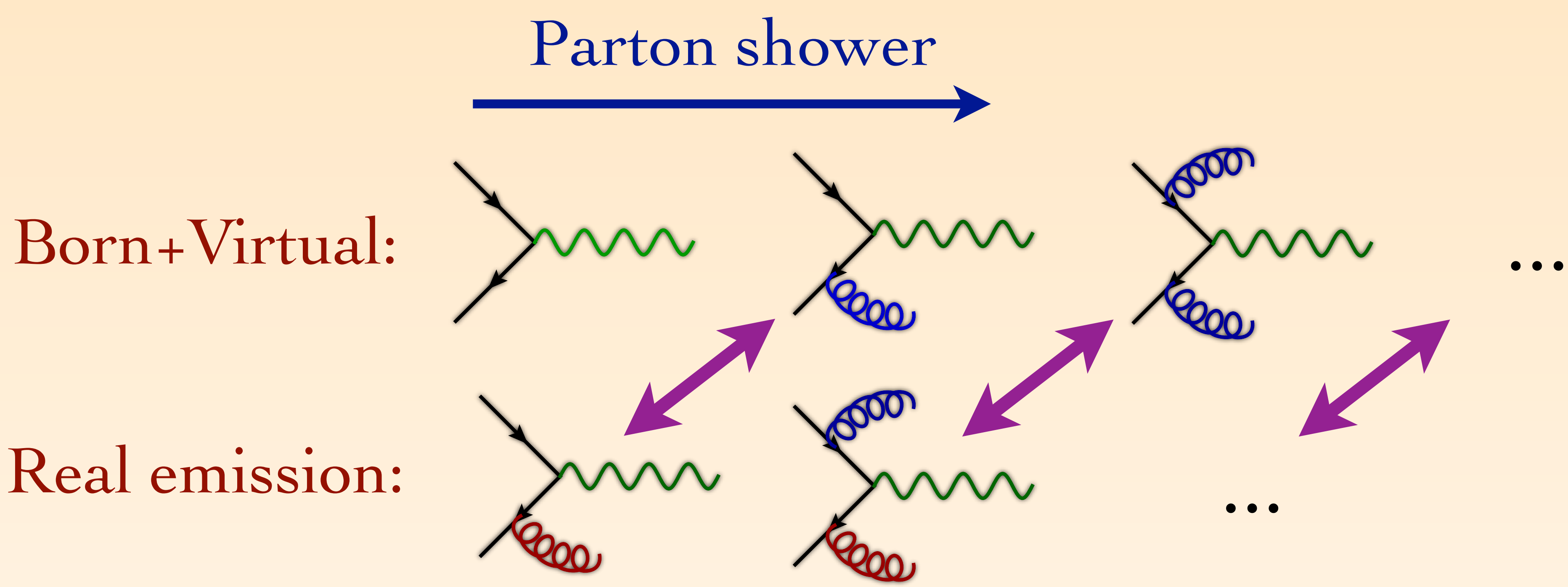


- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability

MC@NLO procedure

Frixione & Webber (2002)



$$\frac{d\sigma_{\mathrm{NLOwPS}}}{dO} = \left[d\Phi_m \left(B + \int_{\mathrm{loop}} V + \int d\Phi_1 MC \right) \right] I_{\mathrm{MC}}^{(m)}(O)$$

"Standard events"

$$+ \left[d\Phi_{m+1} (R - MC) \right] I_{\mathrm{MC}}^{(m+1)}(O)$$

"Hard events"

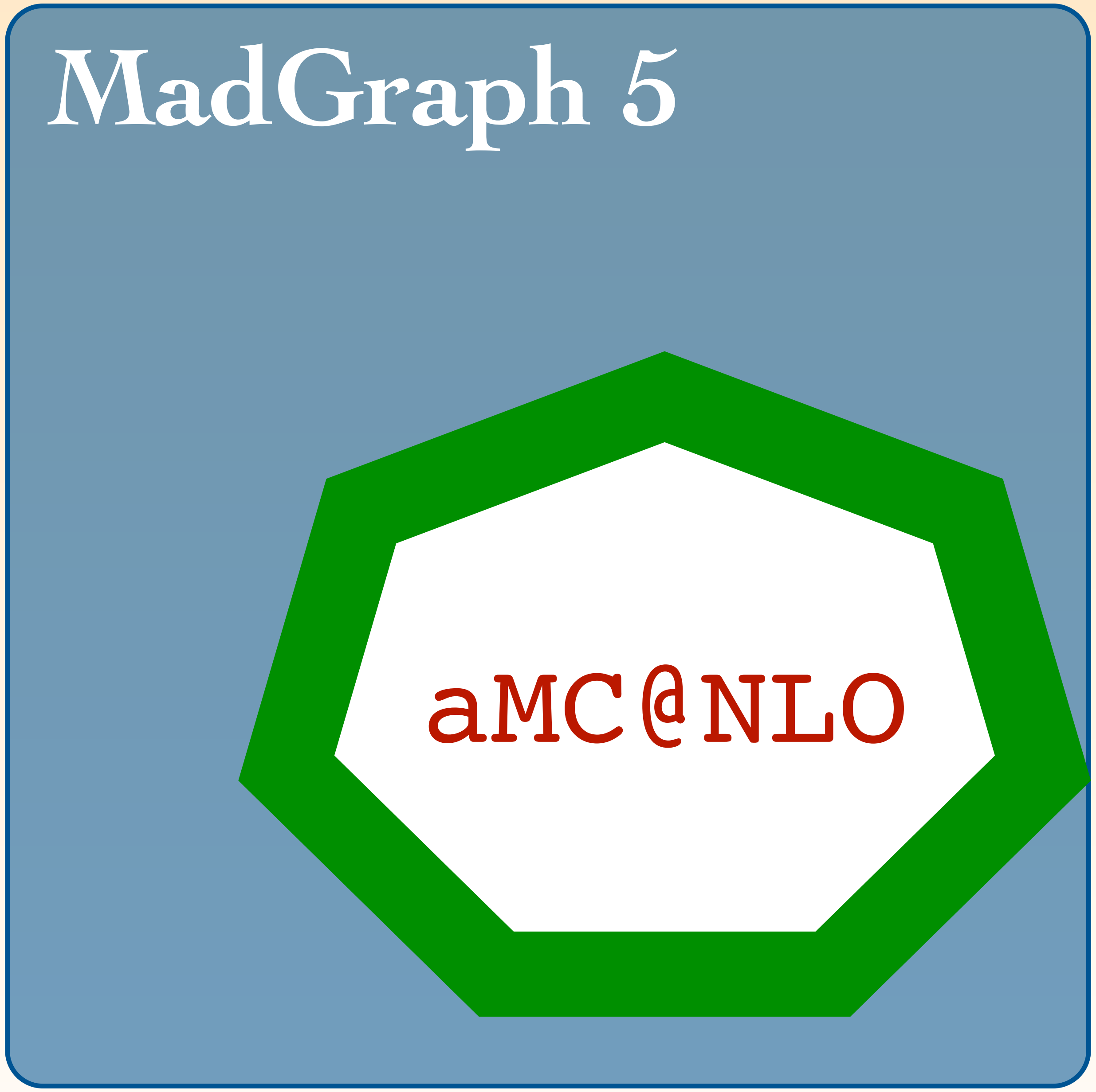
- Double counting is explicitly removed by including the "shower subtraction terms"
- MC@NLO code is a library of simple processes

aMC@NLO joint venture

aMC@NLO joint venture

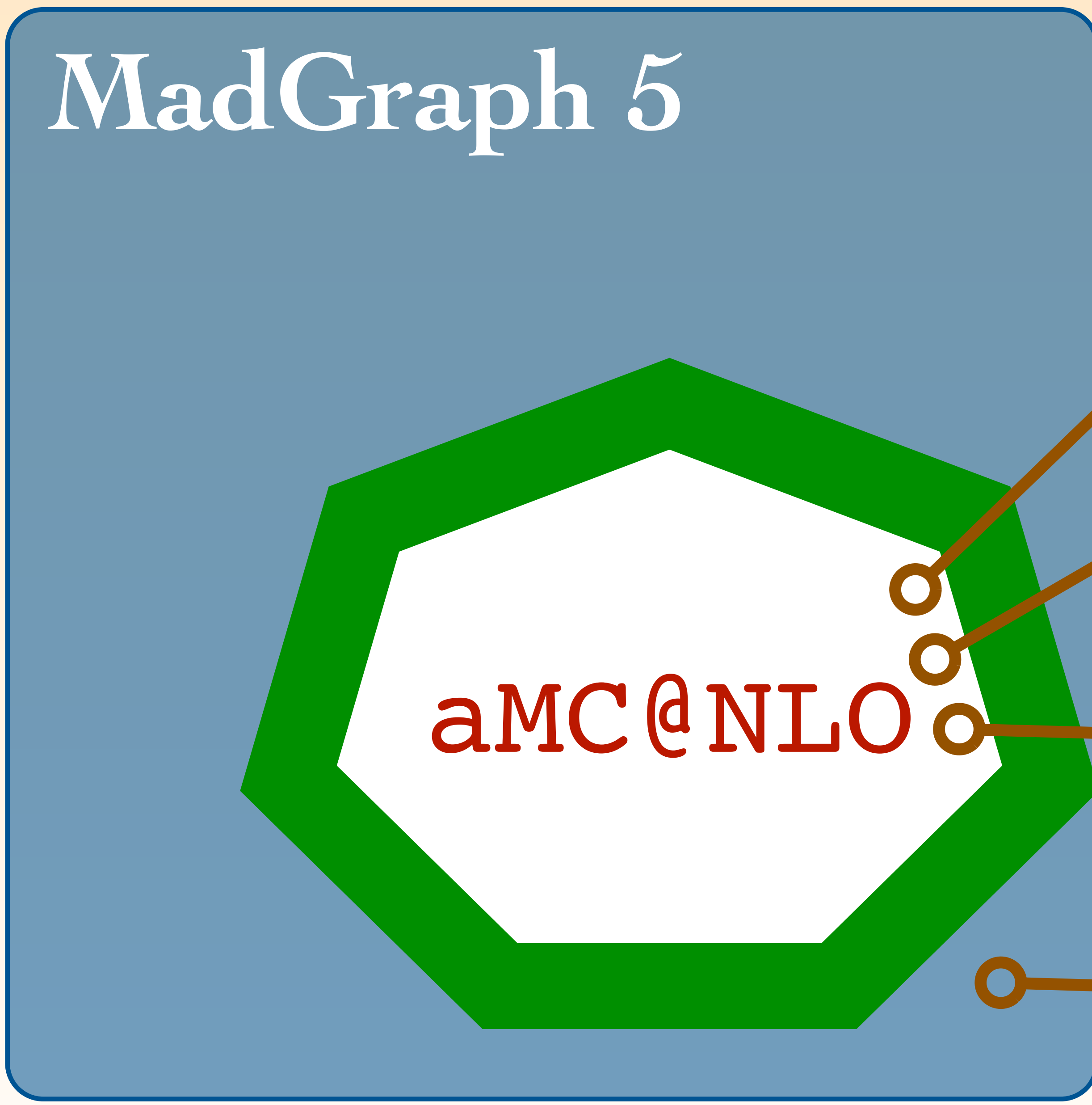
MadGraph 5

aMC@NLO joint venture



aMC@NLO JOINT VENTURE

Hirschi, Zaro, Alwall, RF, Mattelaer, Torrielli, Frixione, Maltoni, Pittau + Artoisenet, Rietkerk; + Collaborators



MC@NLO method

to match NLO to parton shower (Herwig(++) & Pythia6/8)

MadLoop (+CutTools)

for the one-loop virtual corrections -- also possible to use external tools via Binoth-LHA

MadFKS

to factor out IR divergences in phase-space integrals

MadSpin

to keep spin-correlations in particle decays

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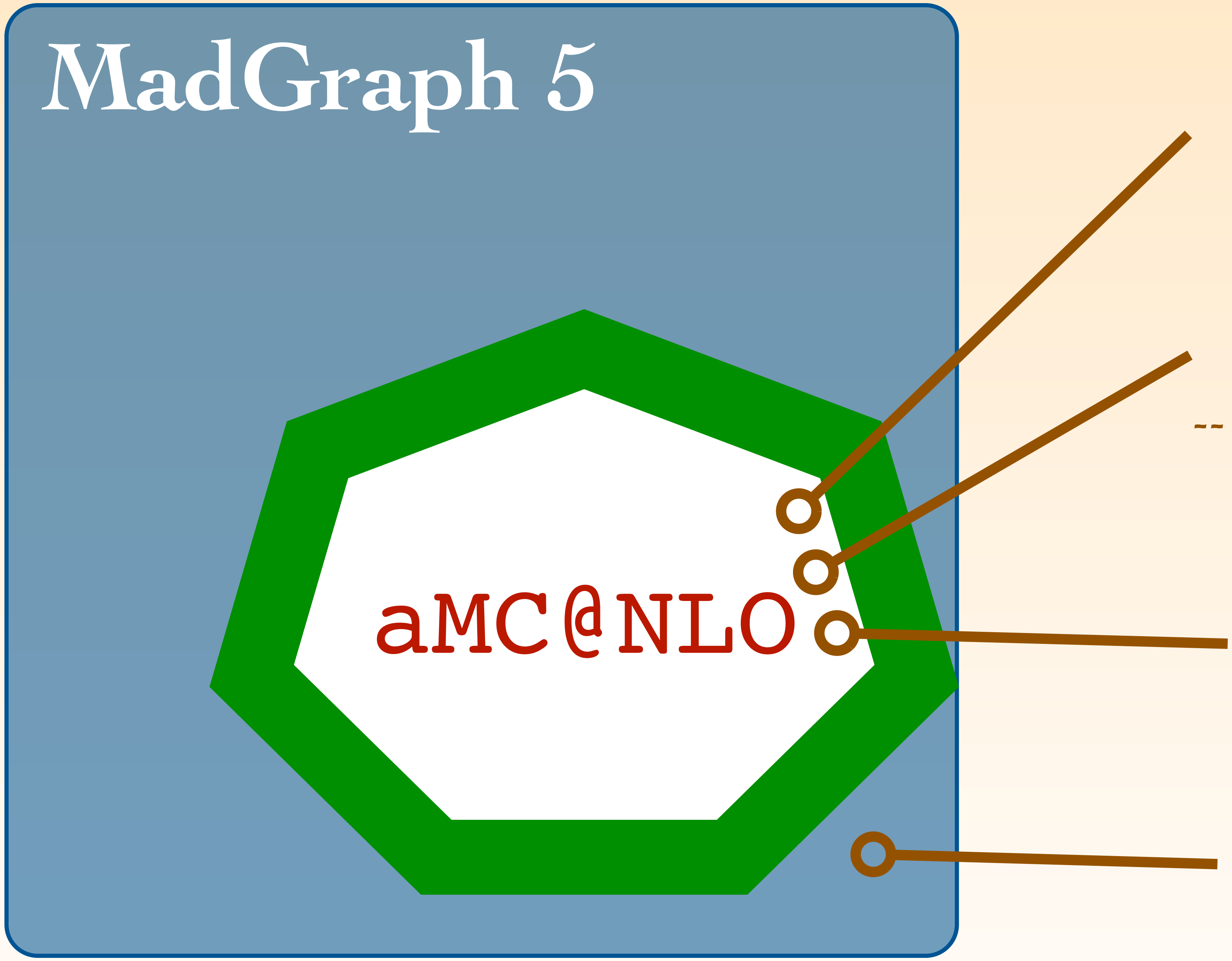

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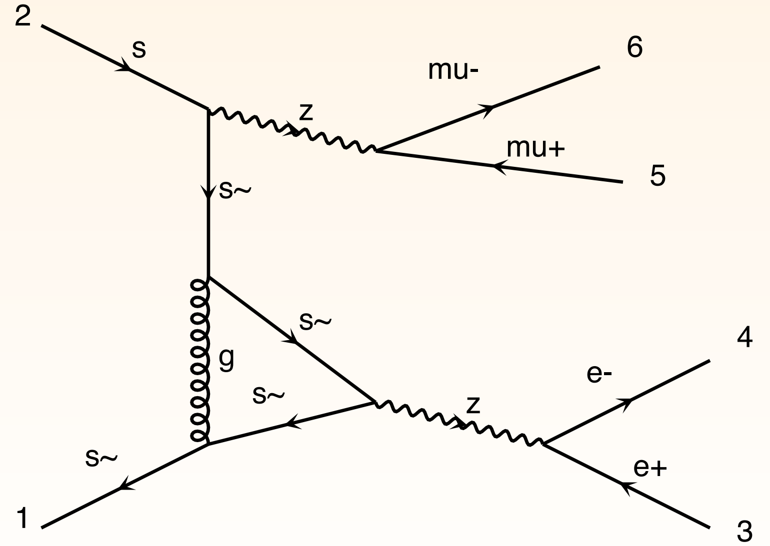
The code is publicly available since last November

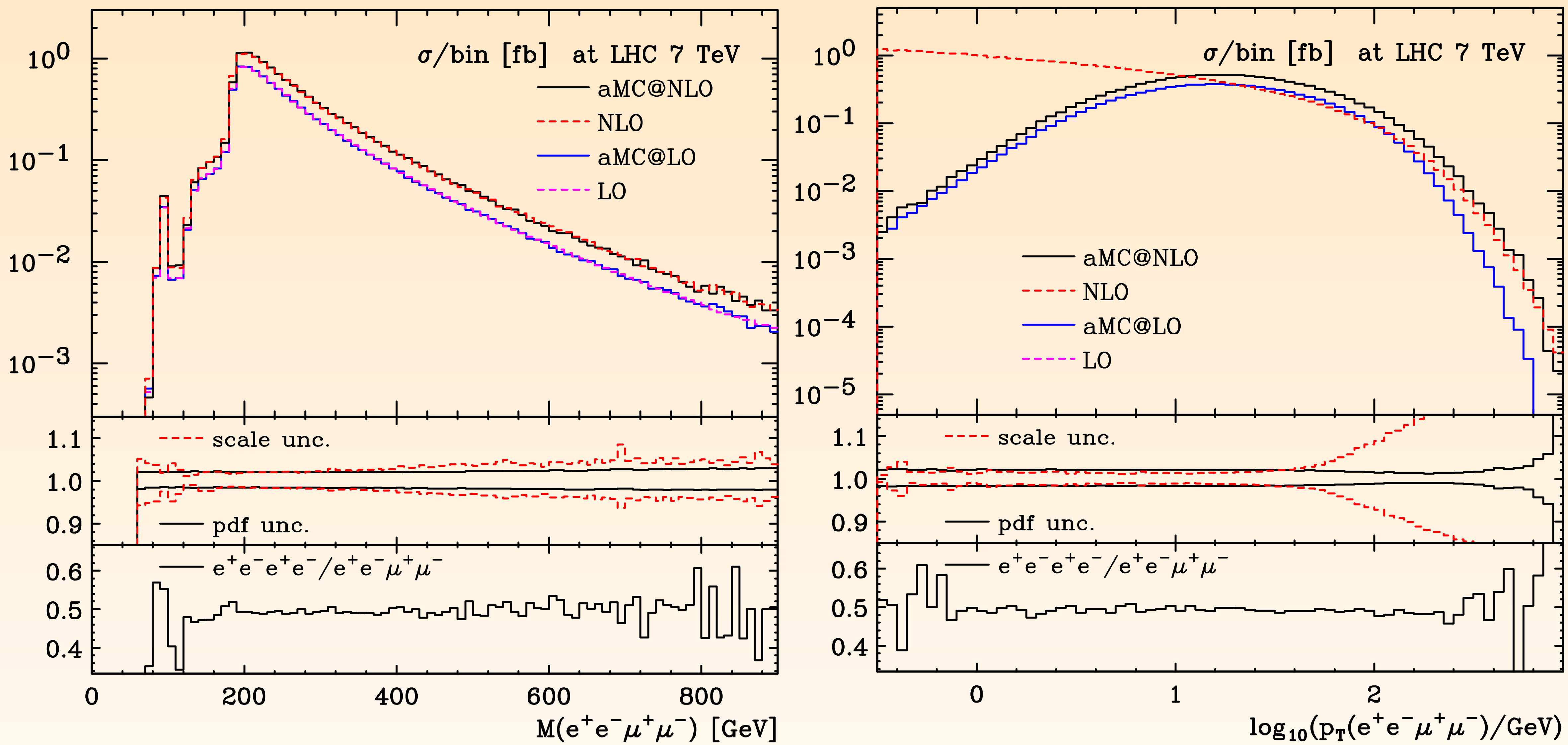
aMC@NLO: QUICK GUIDE

- Open the madgraph python shell:
  `$ ./bin/mg5`
- From the shell generate the requested process:
  `> generate p p > e+ e- mu+ mu- [QCD]`
  (the tag "`[QCD]`" means: do NLO QCD corrections). This generates the process internally in the code
- Output the process and write it to disk:
  `> output my_NLO_eemumu_process`
- And launch the event generation:
  `> launch`
- And the code will generate the events at NLO accuracy



Four-lepton production

RF, Frixione, Hirschi, maltoni, Pittau & Torrielli (2011)



- 4-lepton invariant mass is almost insensitive to parton shower effects. 4-lepton transverse momentum is extremely sensitive
- Including scale uncertainties

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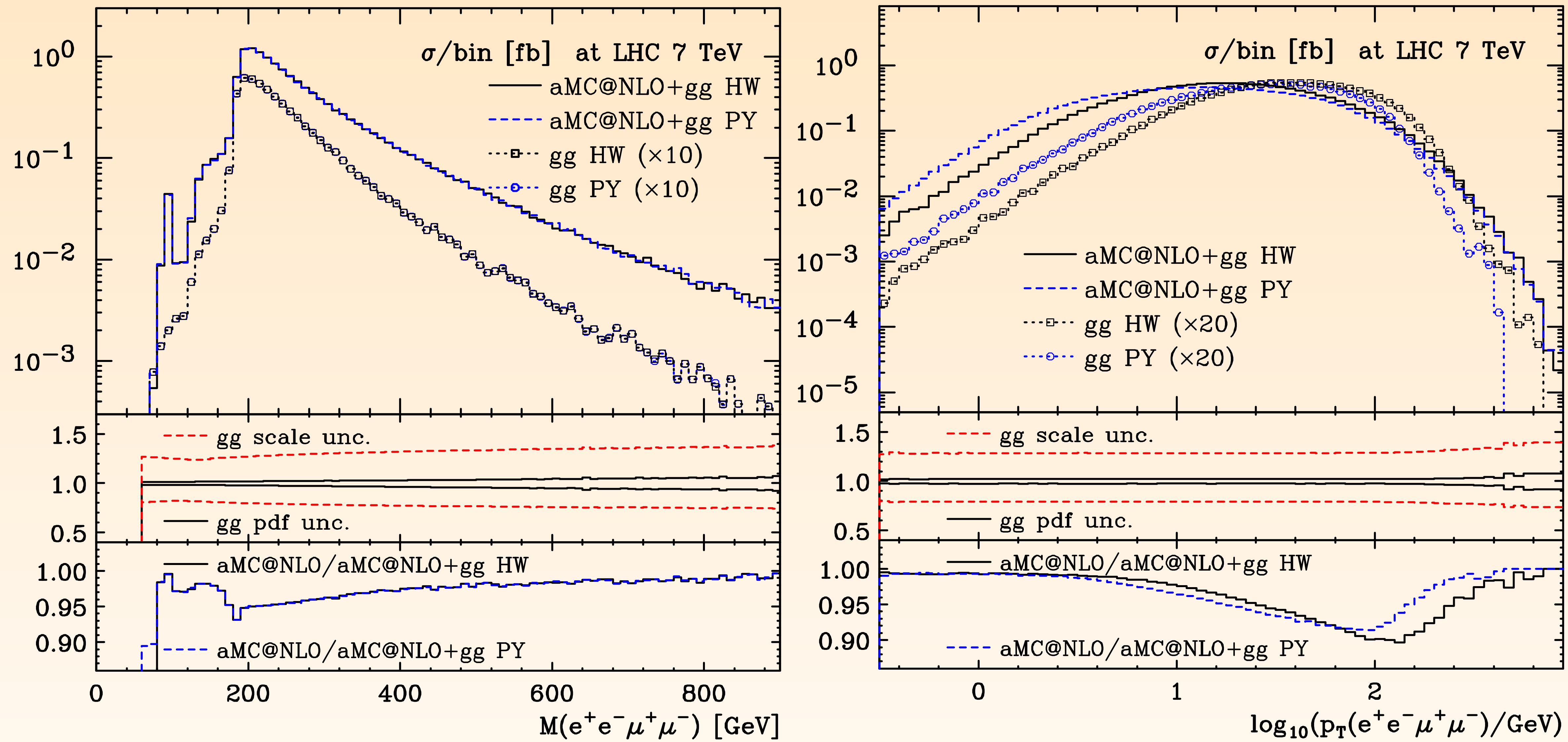

- Differences between Herwig (black) and Pythia (blue) showers large in the Sudakov suppressed region (much larger than the scale uncertainties)
- Contributions from gg initial state (formally NNLO) are of 5-10%

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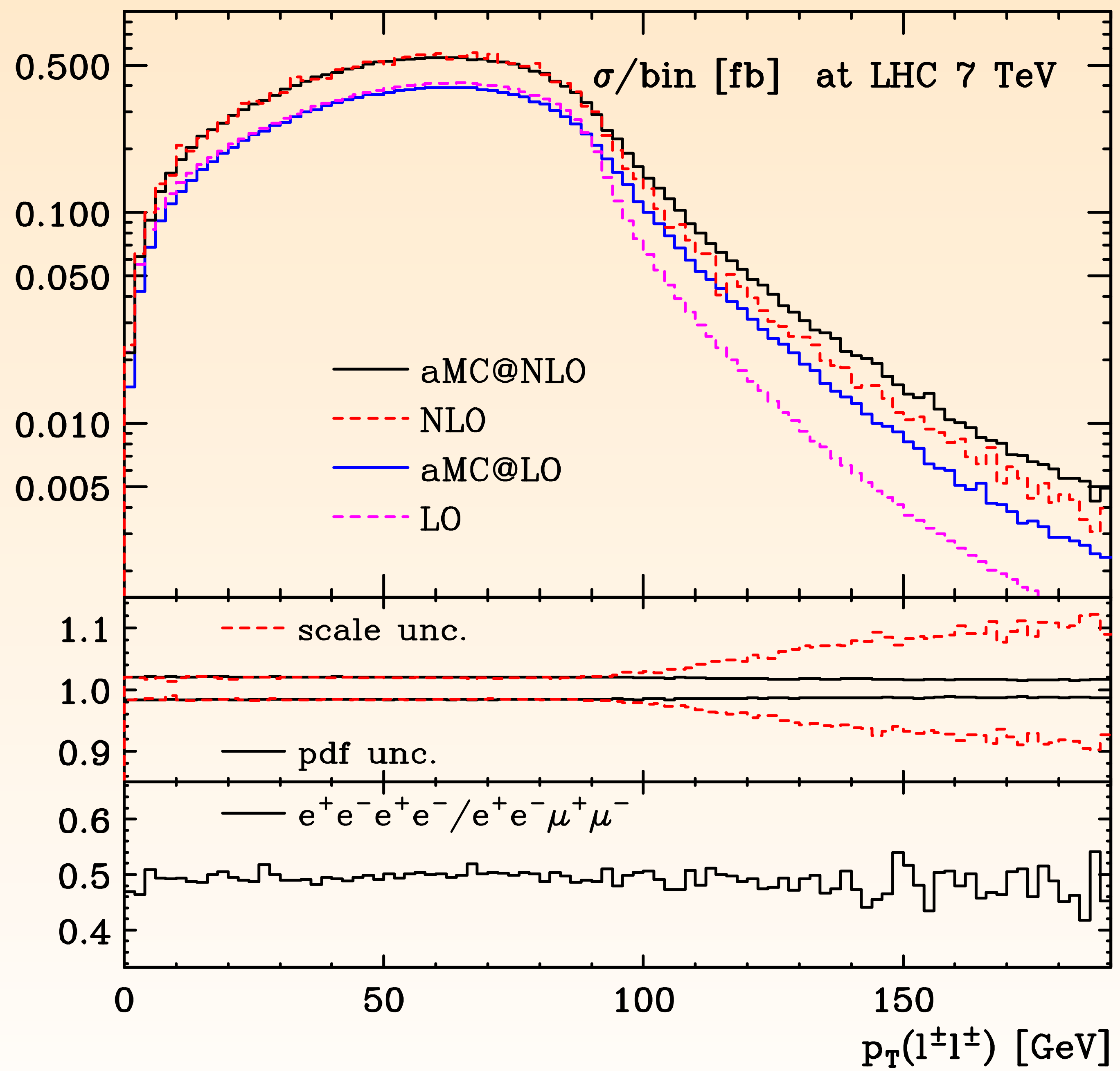
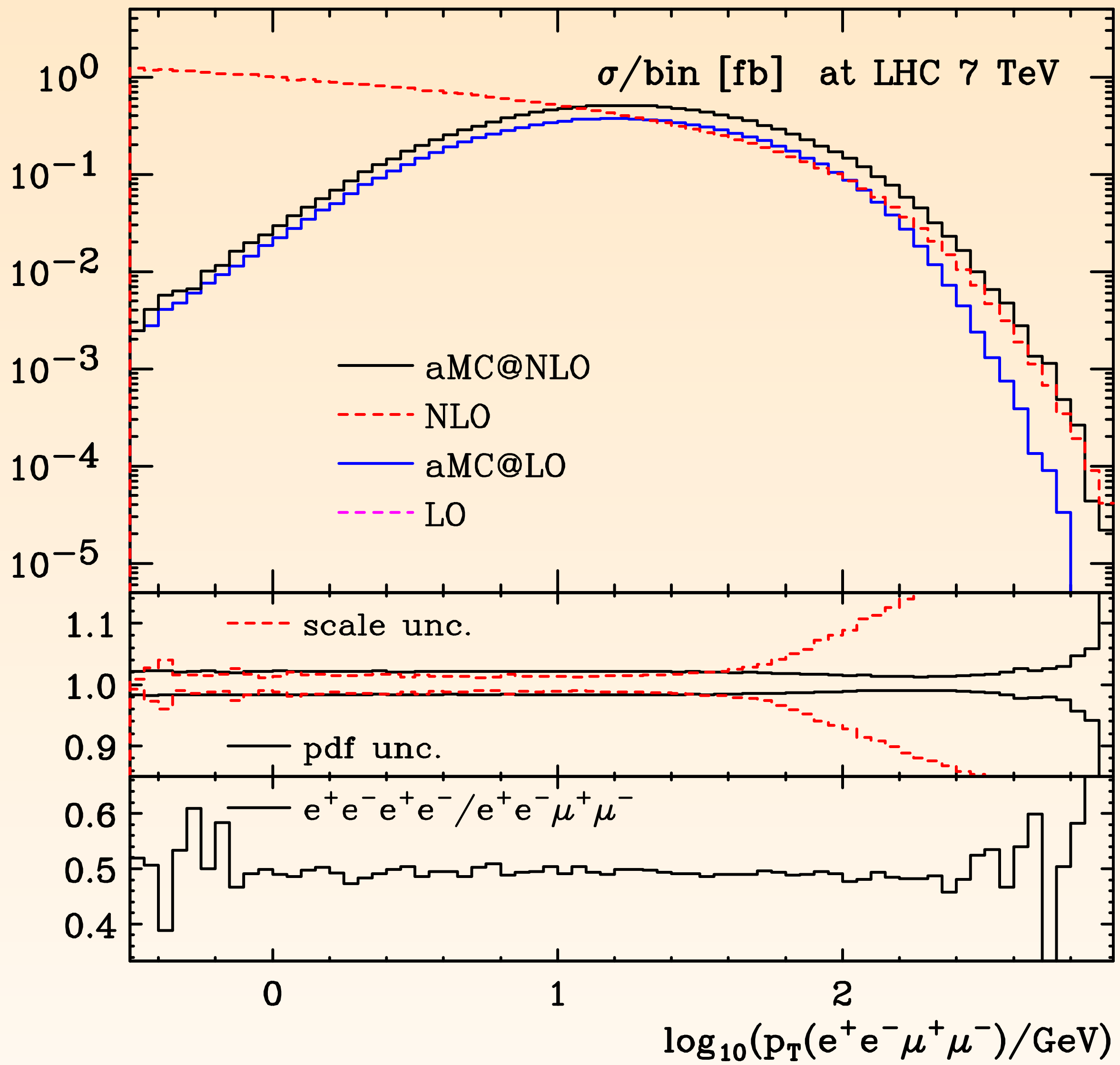


- Transverse momentum of the same-charge lepton pairs
- Sensitive to both NLO and shower effects in the tail
- Theory uncertainty due to scale dependence grows in the tail of the distribution

Four-lepton production



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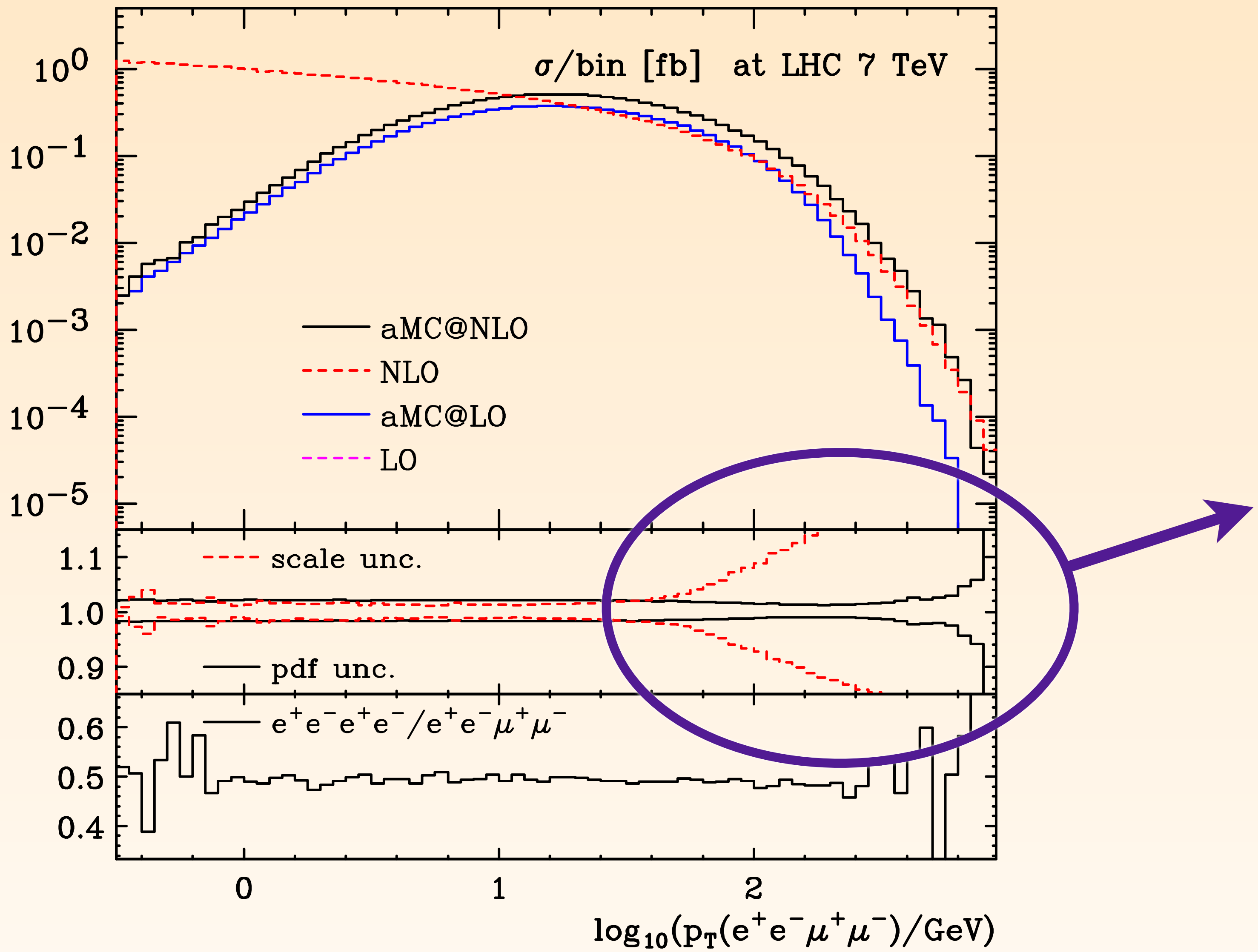
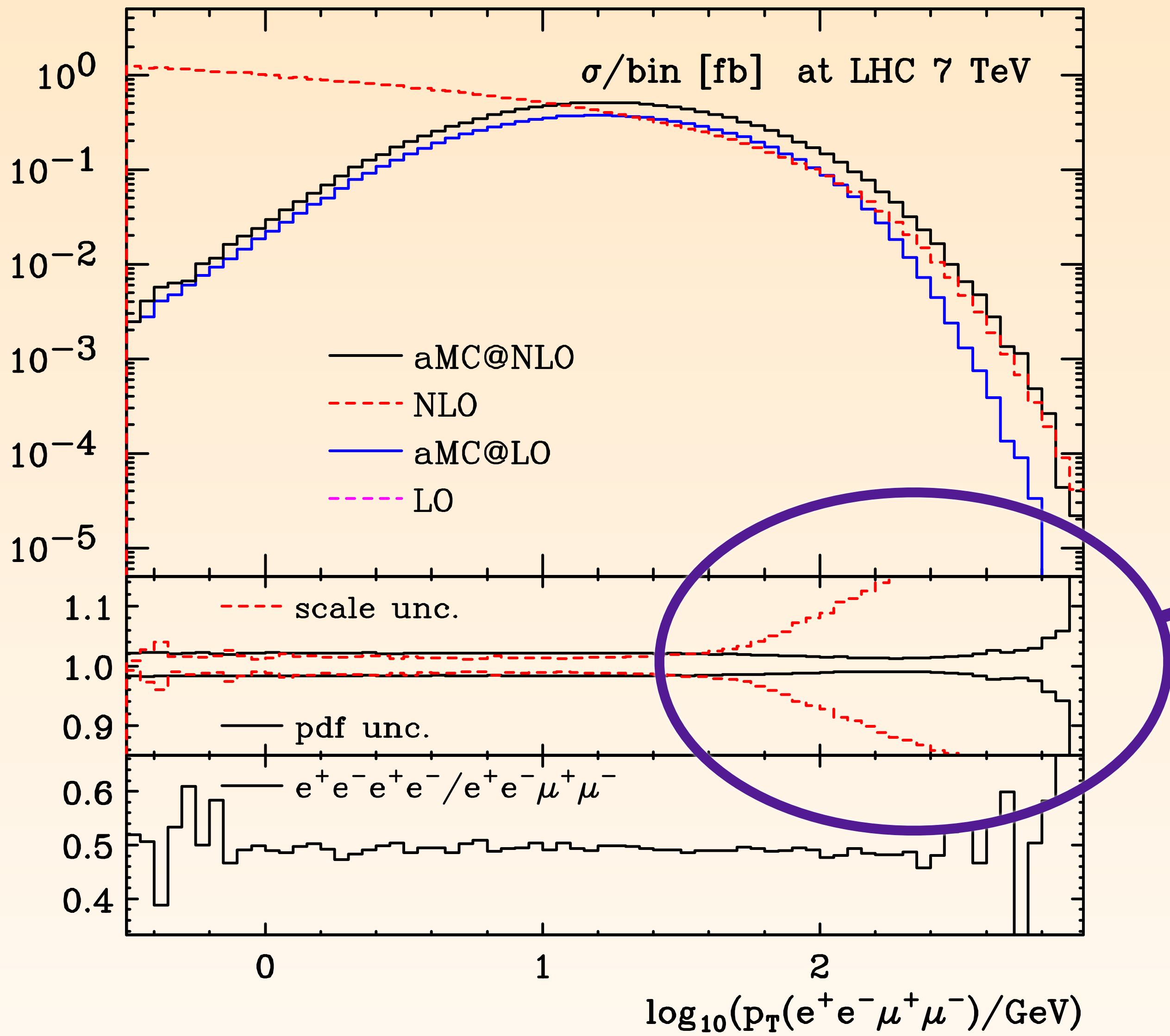


In the tail of the pT spectrum, there are large theoretical uncertainties. This is no surprise! Here the NLO calculation has actually only LO accuracy, because there must be a hard parton/jet recoiling against the 4-lepton system.

Four-lepton production



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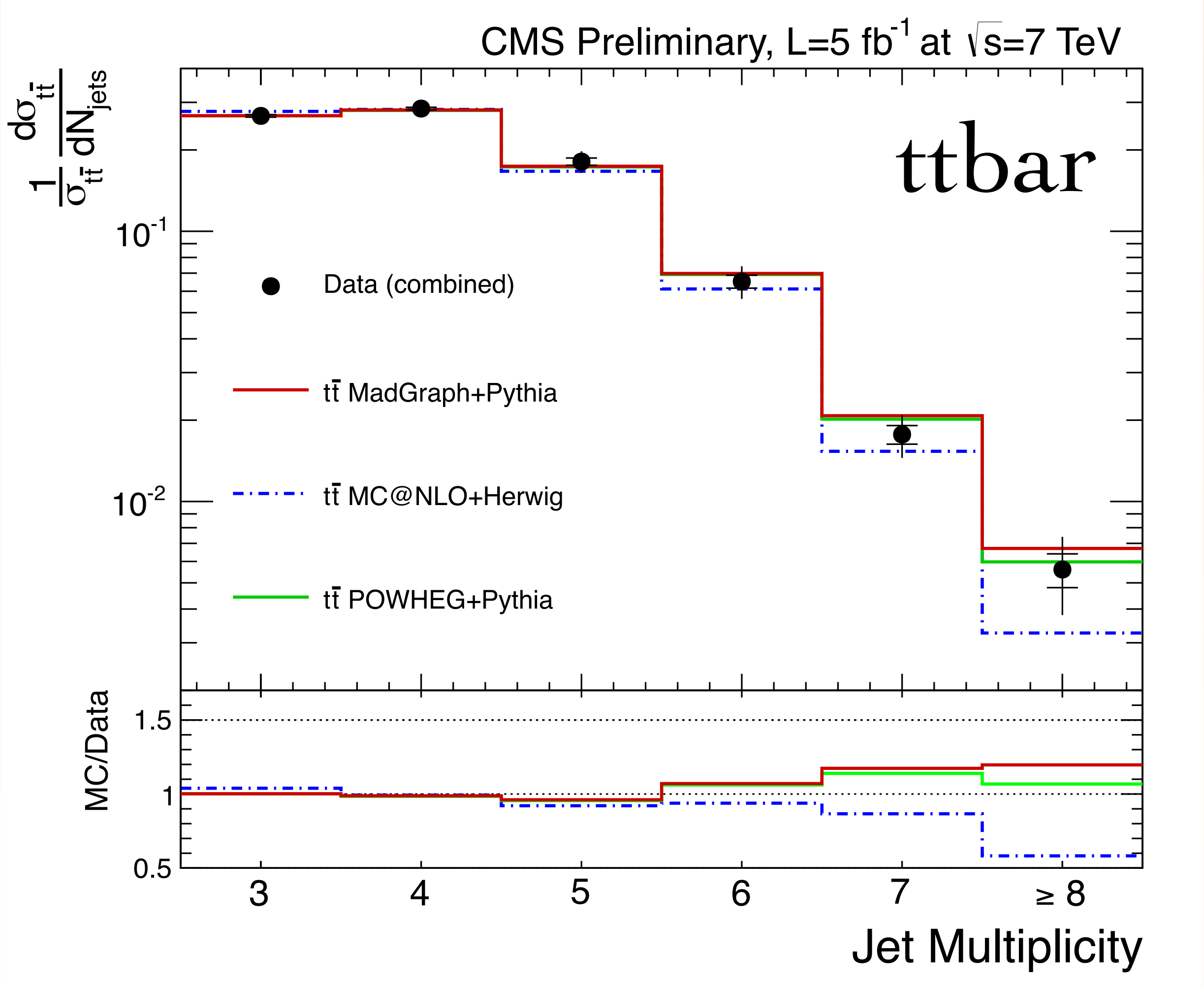
Can we include the NLO corrections to 4 leptons + 1 (hard) jet here?

Limitations

There are more observables very sensitive to theory uncertainties -- all related to **hard emissions** in the real-emission matrix elements and even stronger if they are emitted by the shower.

Even though our NLO computation is "inclusive in all extra radiation" (which is made explicit by the parton shower), the shower is only correct in the strict collinear approximation. It cannot generate hard extra jets correctly (i.e. jets beyond the first, which is included in the real emission corrections of the NLO computation and therefore already has a large uncertainty associated with it)



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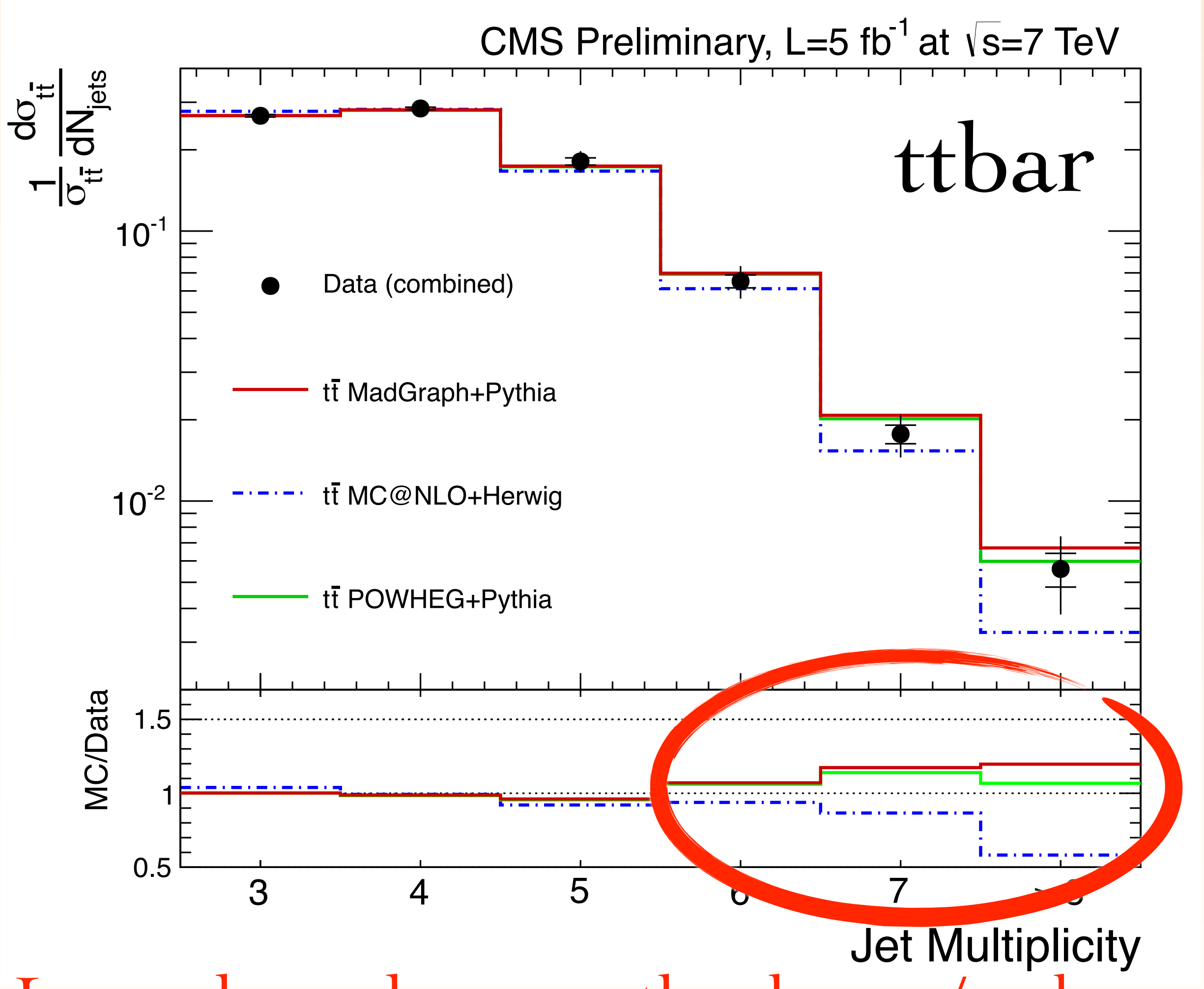
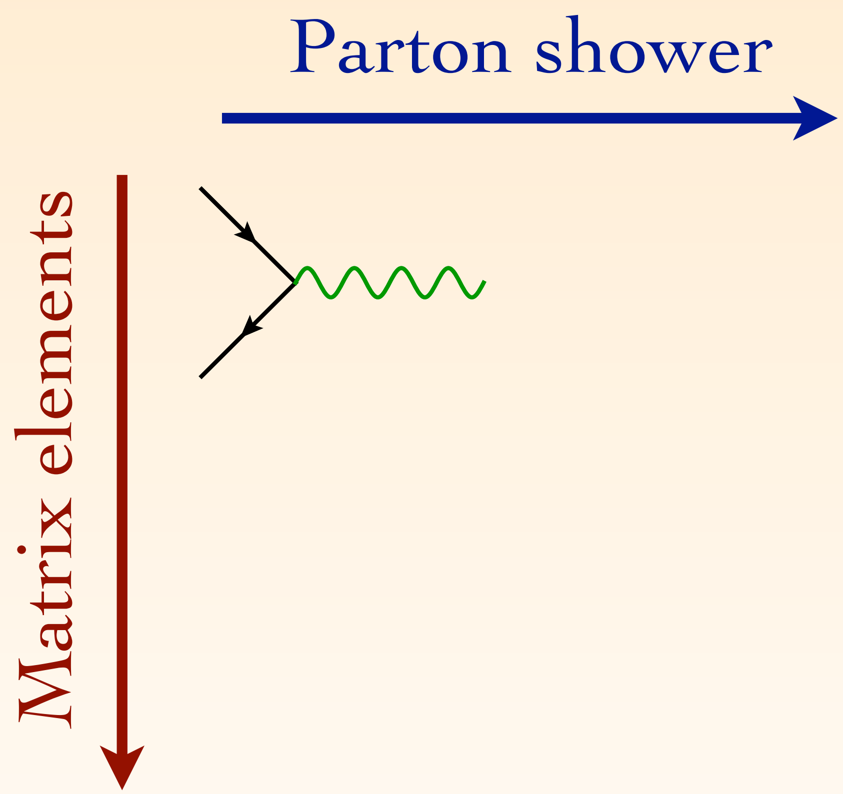


Large dependence on the shower/scales

At LO: merging various multiplicities

- At LO this problem is solved: it is possible to use LO matrix elements of various multiplicities and correctly merge them with help of the parton shower to get also the multi-jets correctly described at LO. The idea is simple:



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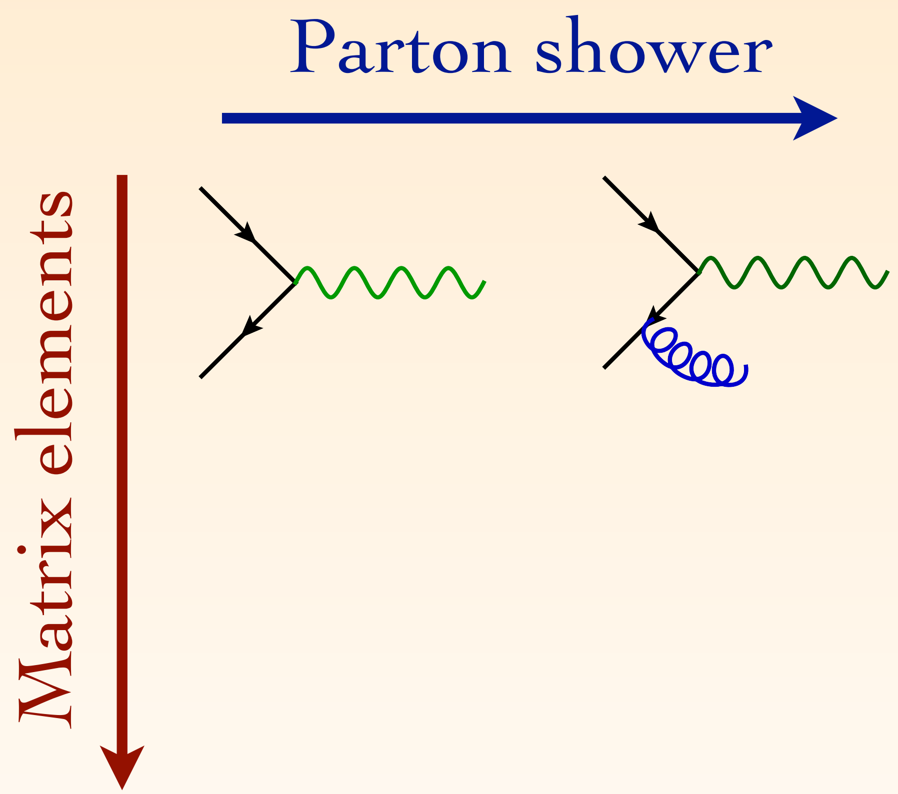

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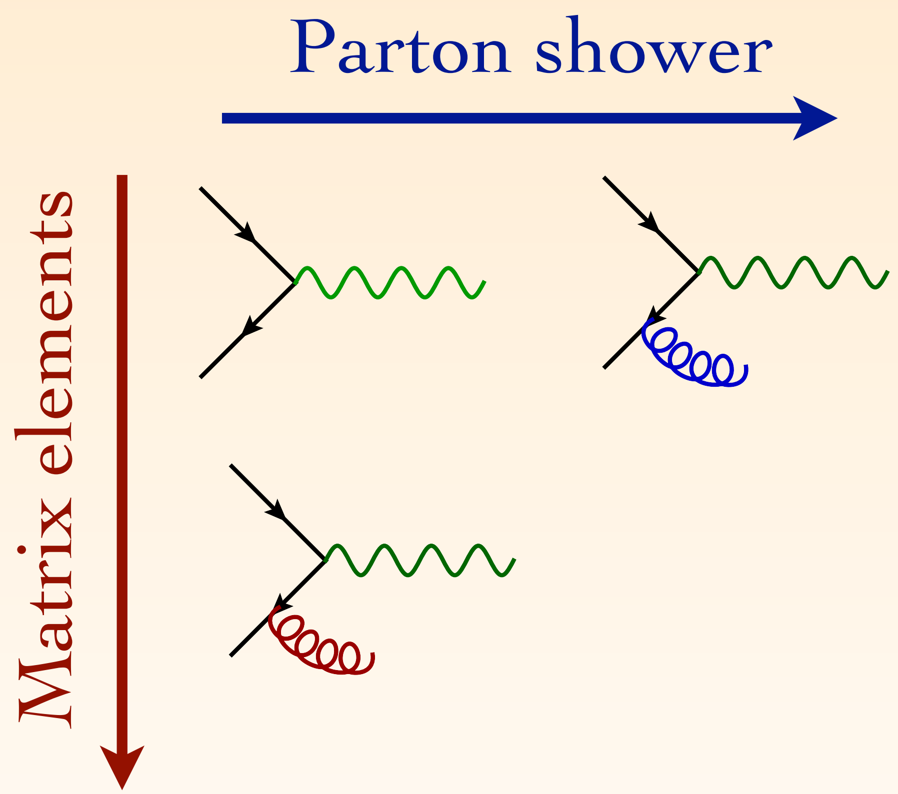

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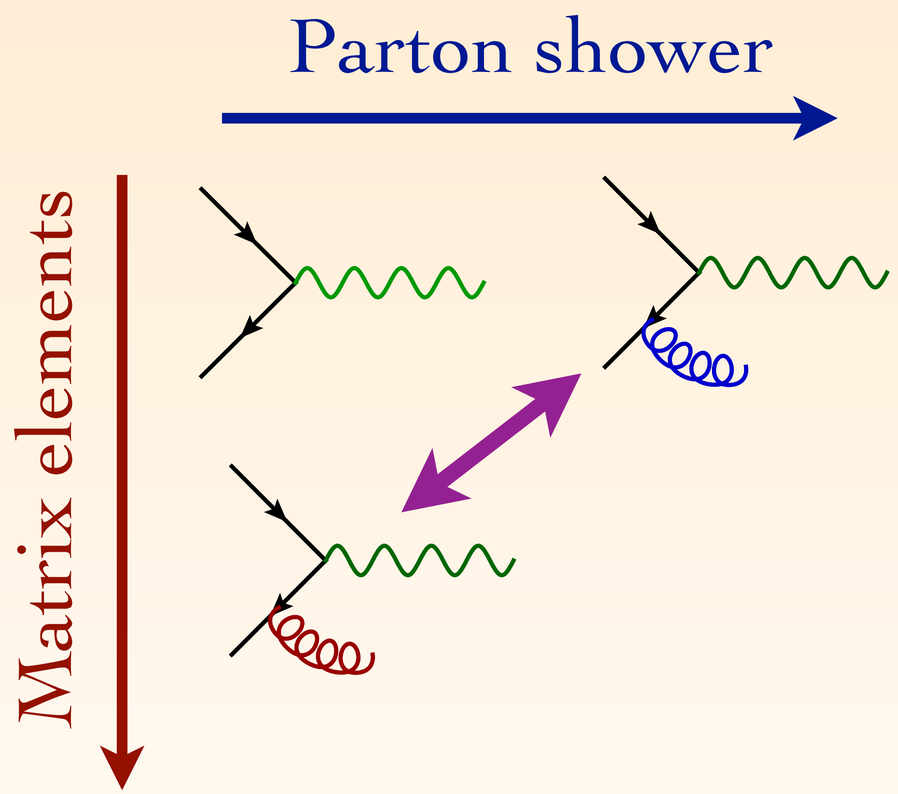

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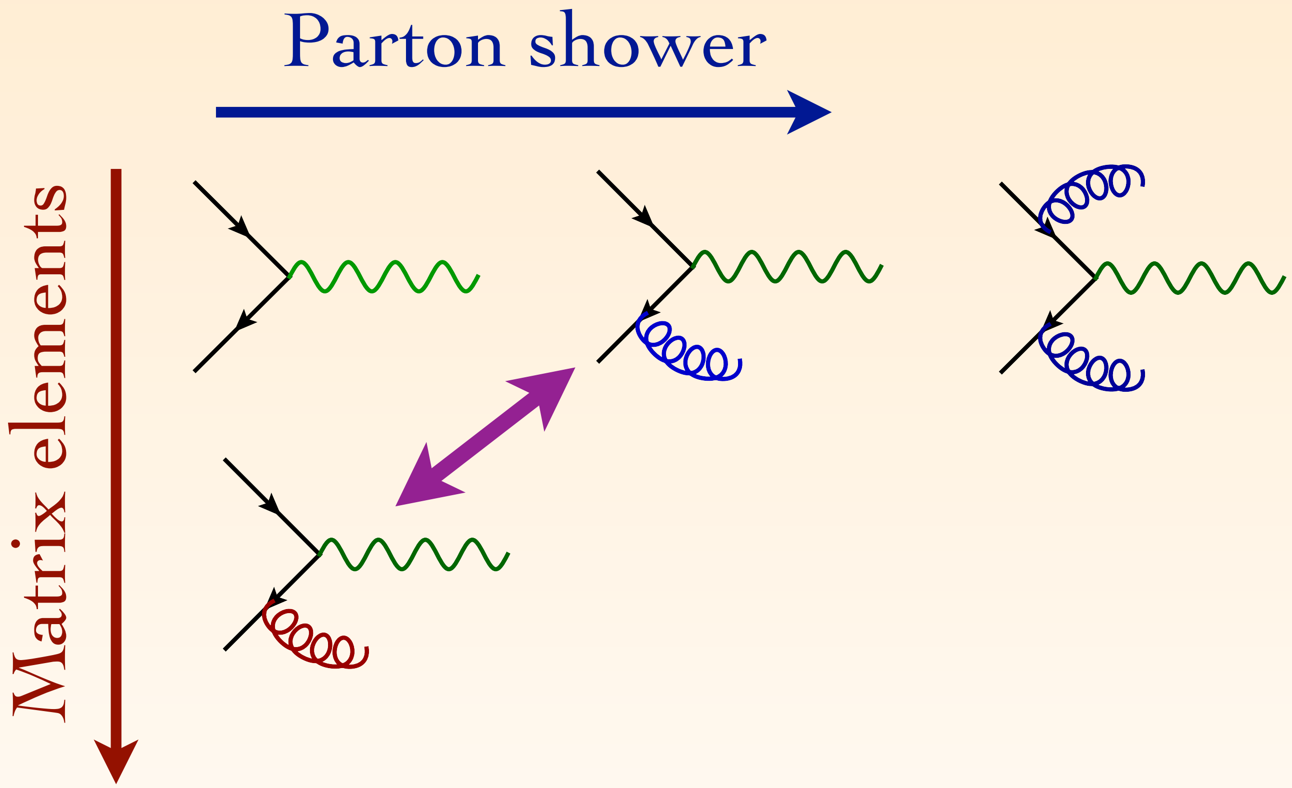

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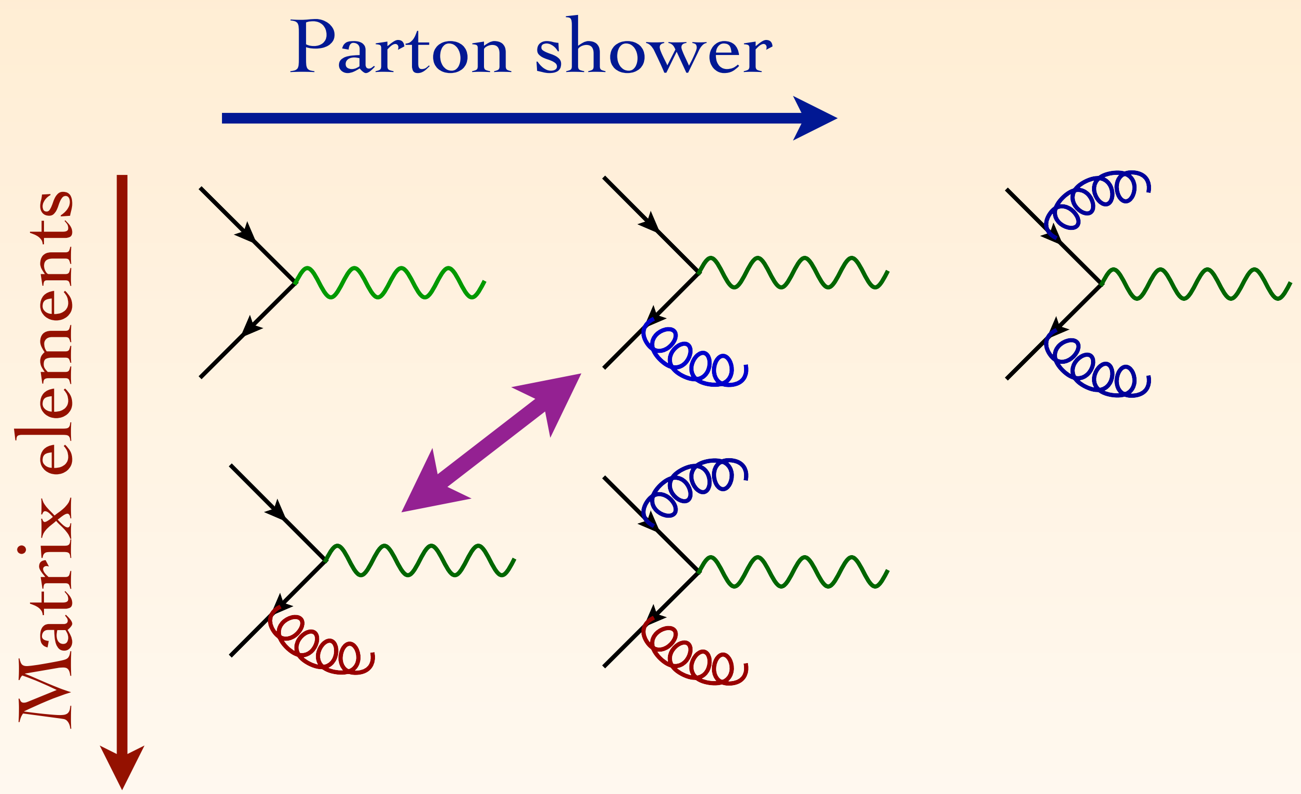

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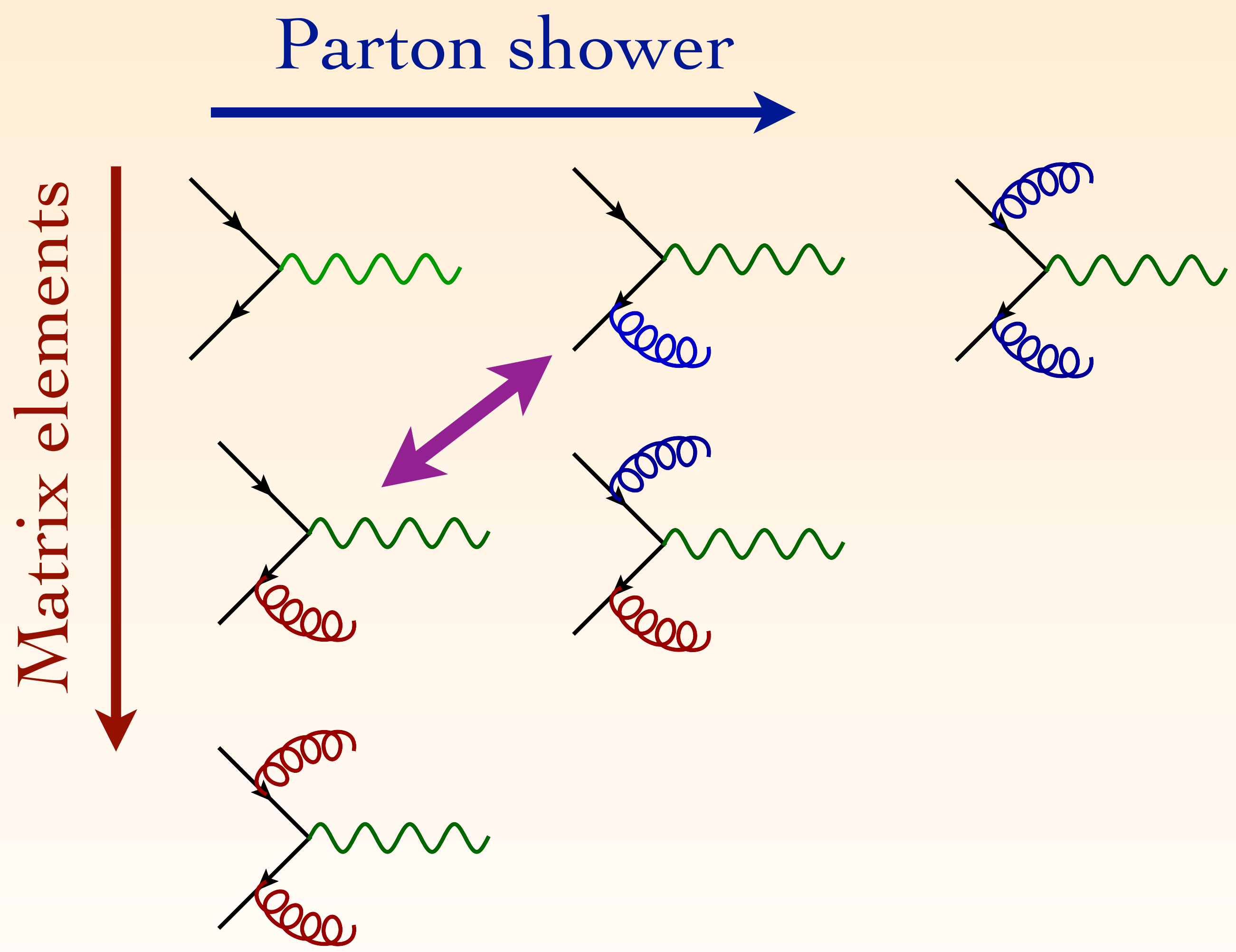

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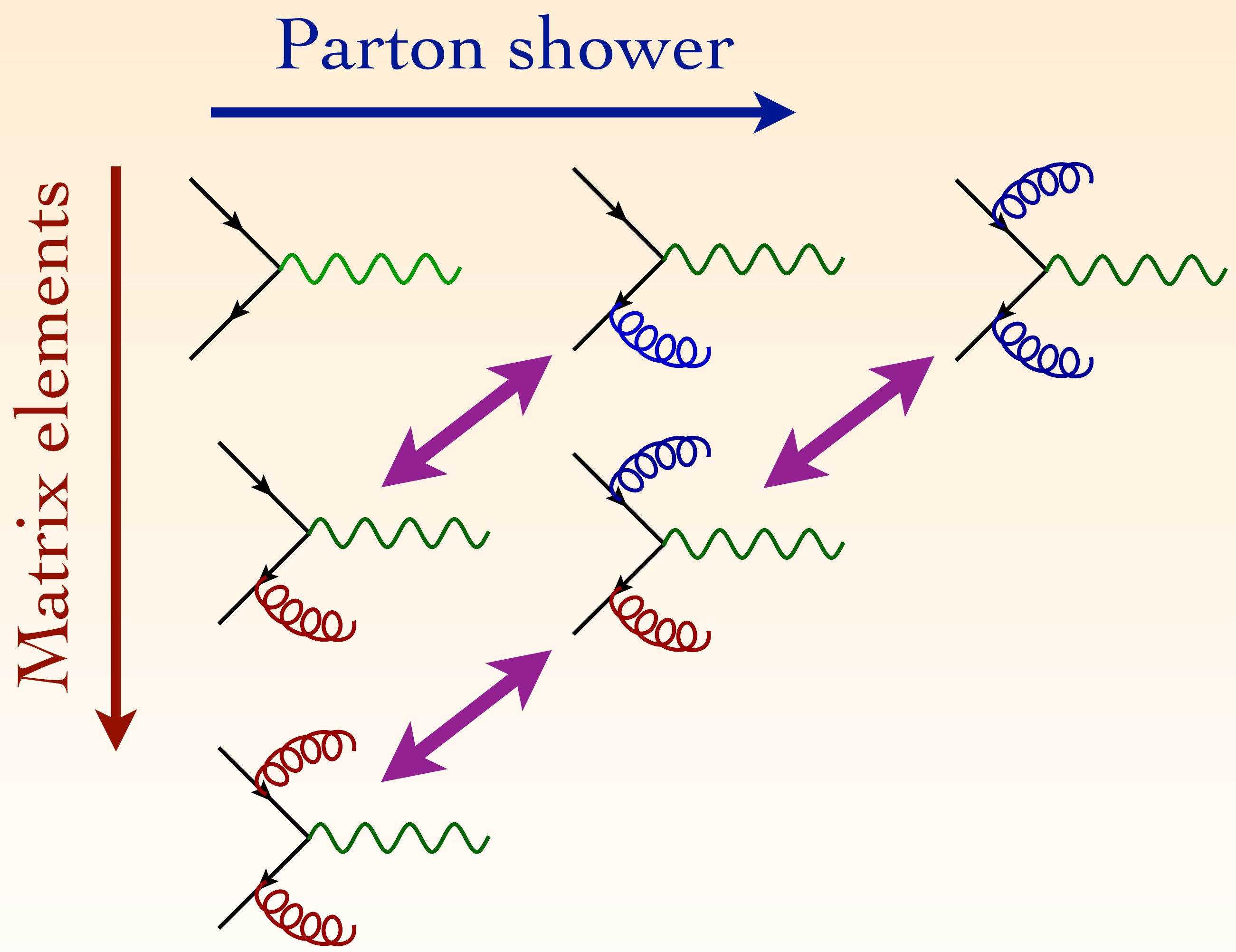

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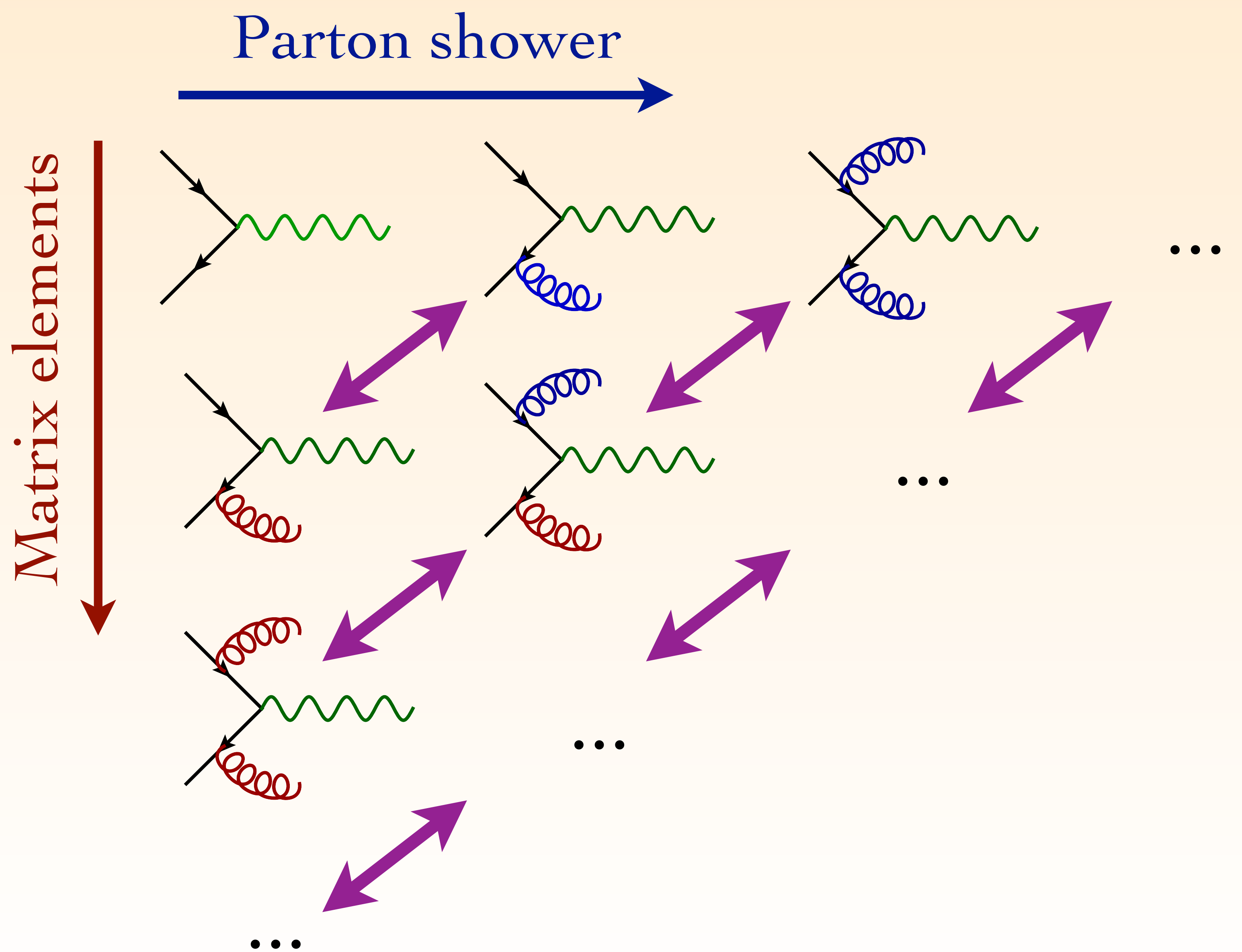

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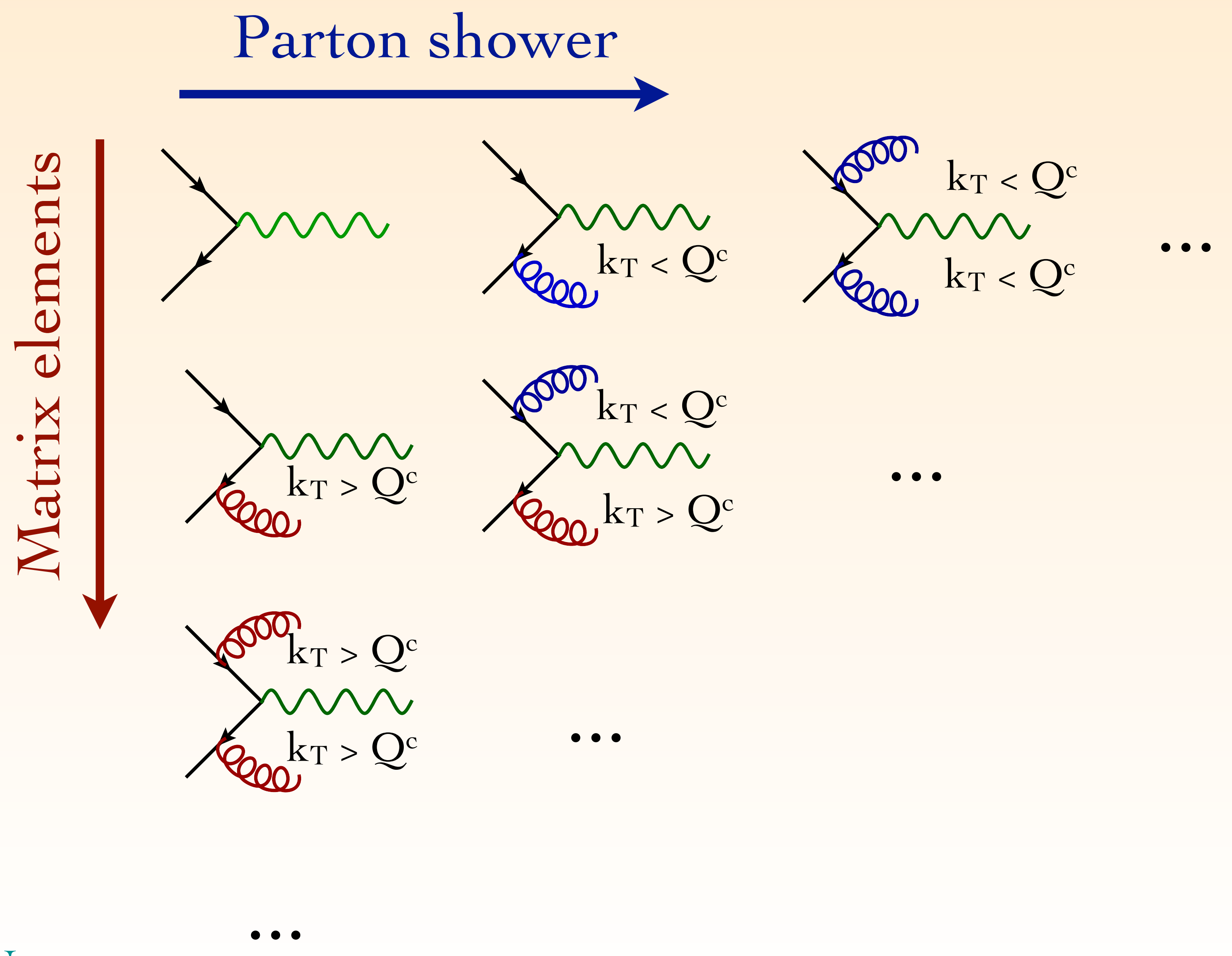
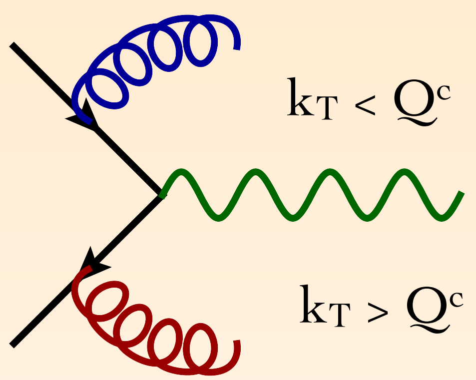


Merging ME with PS

CKKW (2004) and MLM (2004)

- Double counting no problem: we simply throw events away when the matrix-element partons are too soft, or when the parton shower generates too hard radiation
- Applying the matrix-element cut is easy: during phase-space integration, we only generate events with partons above the matching scale



- For the cut on the shower, there are two methods. Throwing events away after showering is not very efficient, although it is working ("MLM method")
- Instead we can also multiply the Born matrix elements by suitable product of Sudakov factors (i.e. the no-emission probabilities) $\Delta(Q^{max}, Q^c)$ and start the shower at the scale Q^c ("CKKW method"):
- For a given multiplicity we have $\sigma^{\rm LO}_{n,\rm excl} = B_n \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\rm max}, Q^c)$

Merging at NLO

- To make a LO prediction exclusive in the number of jets, we need to multiply it by a Sudakov damping factor; this is CKKW method:

$$\sigma^{\mathrm{LO}}_{n,\mathrm{excl}} = B_n \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\mathrm{max}}, Q^c)$$

  This makes the prediction exclusive at leading logarithmic accuracy

- Similarly we can make an NLO prediction exclusive at leading logarithm

$$\sigma^{\mathrm{NLO}}_{n,\mathrm{excl,\ LL}} = \left\{ B_n + V_n + \int d\Phi_1\, R_{n+1} \right\} \Theta(k_{T,n} - Q^c)\Delta_n(Q_{\mathrm{max}}, Q^c)$$

- We can improve here and use the real-emission matrix elements instead of just the Sudakov:

$$\sigma^{\mathrm{NLO}}_{n,\mathrm{excl,\ LL}} = \left\{ B_n + V_n + \int_0^{Q^c} d\Phi_1\, R_{n+1} - B_n \Delta^{(1)}_n(Q_{\mathrm{max}}, Q^c) \right\}$$
$$\Theta(k_{T,n} - Q^c)\Delta_n(Q_{\mathrm{max}}, Q^c)$$

Exclusive MC@NLO

RF & Frixione, 2012

- Converting the NLO exclusive predictions in the number of jets to the MC@NLO event generation is straight-forward:

$\mathbb{S}$-events: $$\left\{ B_n + V_n + \int_0^{Q^c} d\Phi_1 \,\mathrm{MC} - B_n \Delta_n^{(1)}(Q_{\mathrm{max}}, Q^c) \right\} \Theta(k_{T,n}^B - Q^c)\Delta_n(Q_{\mathrm{max}}^B, Q^c)$$

$\mathbb{H}$-events: $$\left\{ R_{n+1}\Theta(k_{T,n}^R - Q^c) - \mathrm{MC}\,\Theta(k_{T,n}^B - Q^c) \right\} \Theta(Q^c - k_{T,n+1}^R)\Delta_n(Q_{\mathrm{max}}^R, Q^c)$$

- Indeed, that doesn't look very hard...

  It's a straight-forward extension of the LO merging method, no?

The devil is in the details...

RF & Frixione, 2012

- What to choose for the renormalization scale (it does not only enter as argument of the strong coupling at NLO)?
- What to choose for the factorization scale (it does not only enter in the PDFs at NLO)?
- What to do for the PDF reweighting (NLO PDF counter terms)?
- What to choose for the starting scales of the parton shower?
- How to apply the Sudakov suppression (MLM or CKKW)?
- How to treat the extra parton in the real-emission? Do we need a Sudakov?
- What to do with the matching scale (fixed or a smooth function)?
- ...

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A lot of guidance from MINLO
(Hamilton, Nason & Zanderighi 2012)

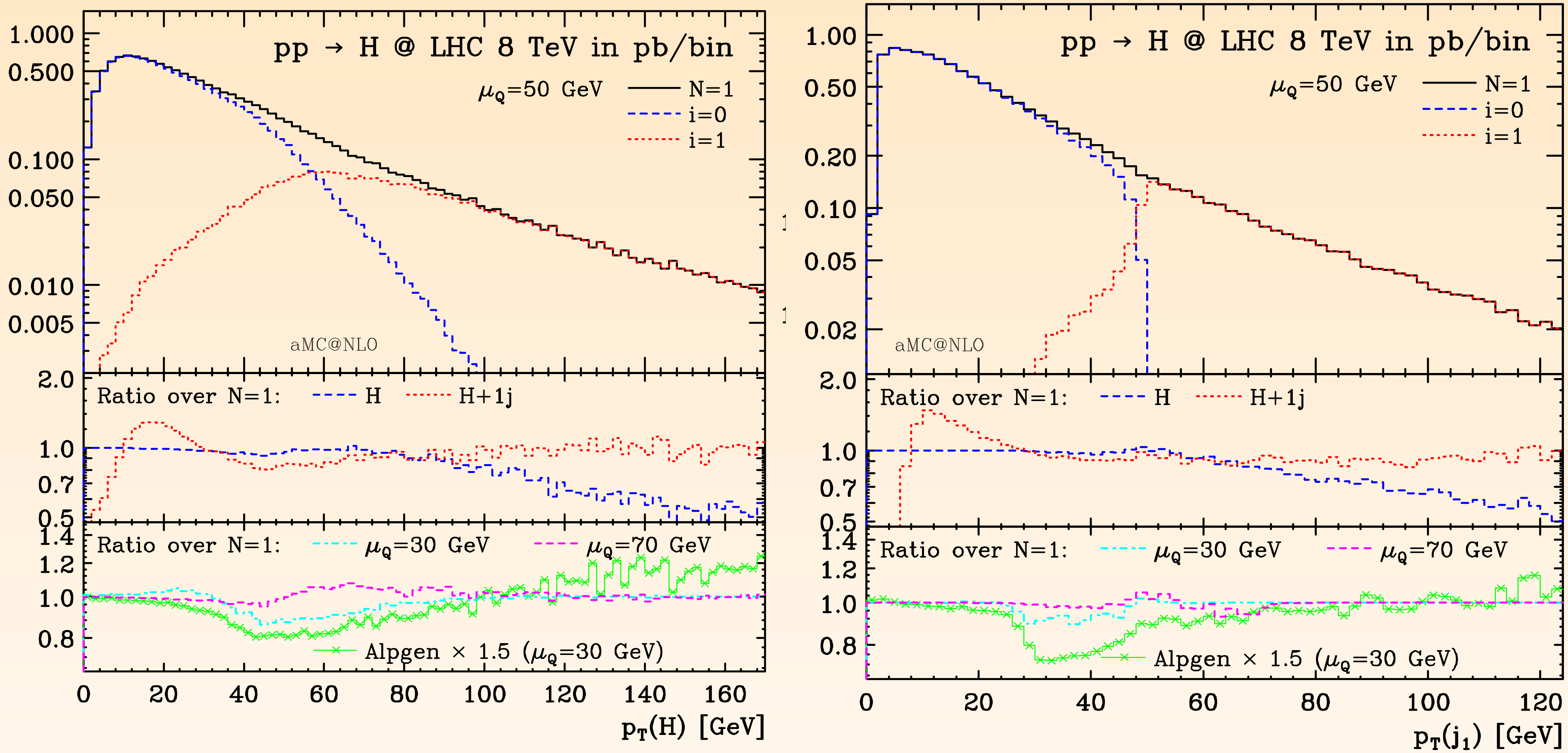
Validation

RF & Frixione, 2012

- Higgs boson production has large corrections and is very sensitive to extra radiation
  - Ideal testing ground for the merging method
- Start by merging H+0j and H+1j both at NLO
  - There will be a dependence on the merging scale --> it should be mild. Compare also to Alpgen to get a feeling what is happening at LO
  - Show that the merged results agree with the unmerged results in their respective regions of phase space
- Add the H+2j sample to the merging and show that results do not change, expect in the phase-space regions sensitive to having 2 additional hard jets
- Finally, make similar studies also for W-boson and ttbar production to make sure that the method works in general

Higgs boson

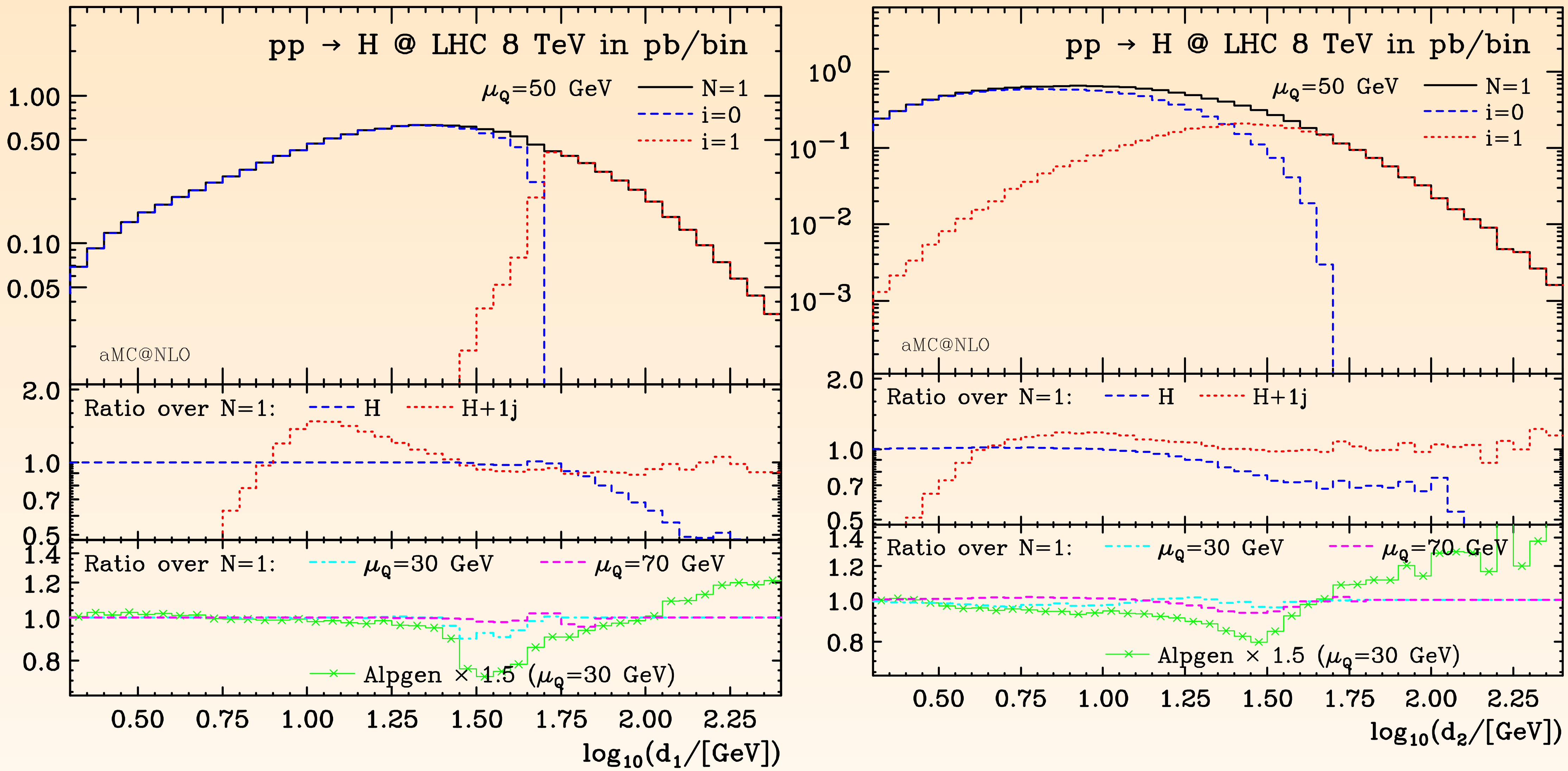
RF & Frixione, 2012



- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale
- Alpgen (LO matching) shows larger kinks

Higgs boson

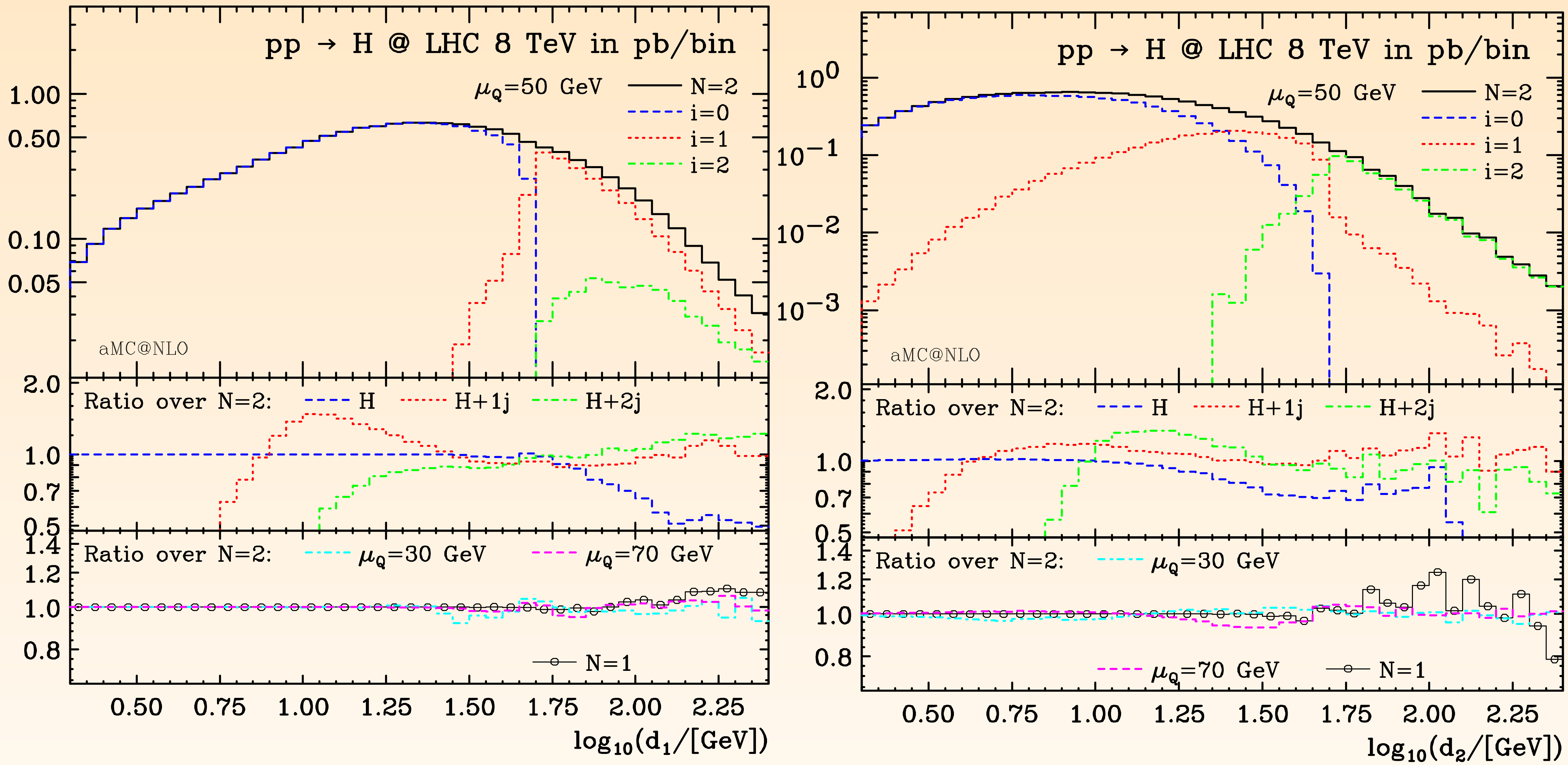
RF & Frixione, 2012



- Differential jet rates for 1->0 and 2->1

Higgs boson

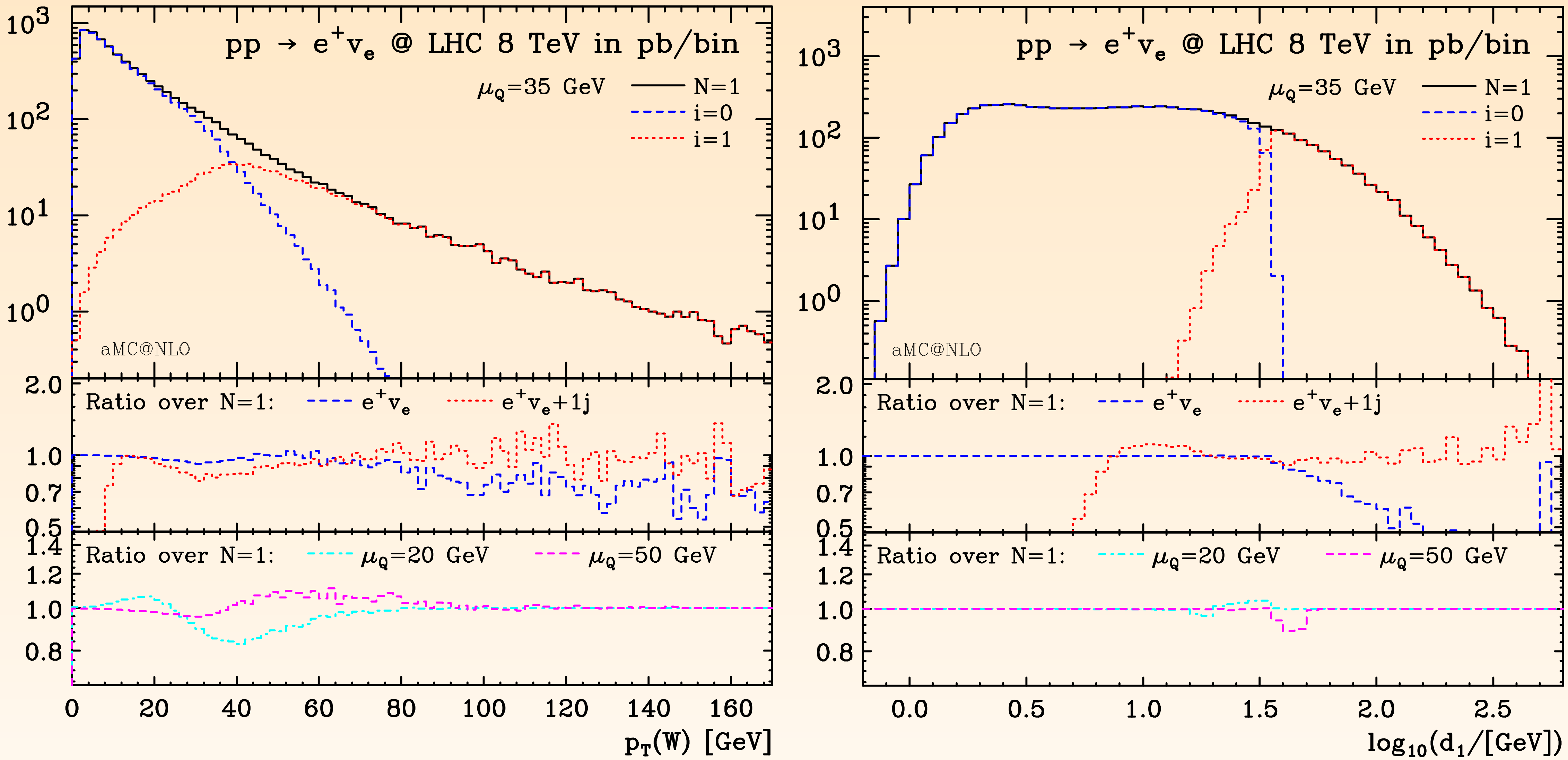
RF & Frixione, 2012



- Differential jet rates
- Matching up to 2 jets at NLO
- Results very much consistent with matching up to 1 jet at NLO

W boson

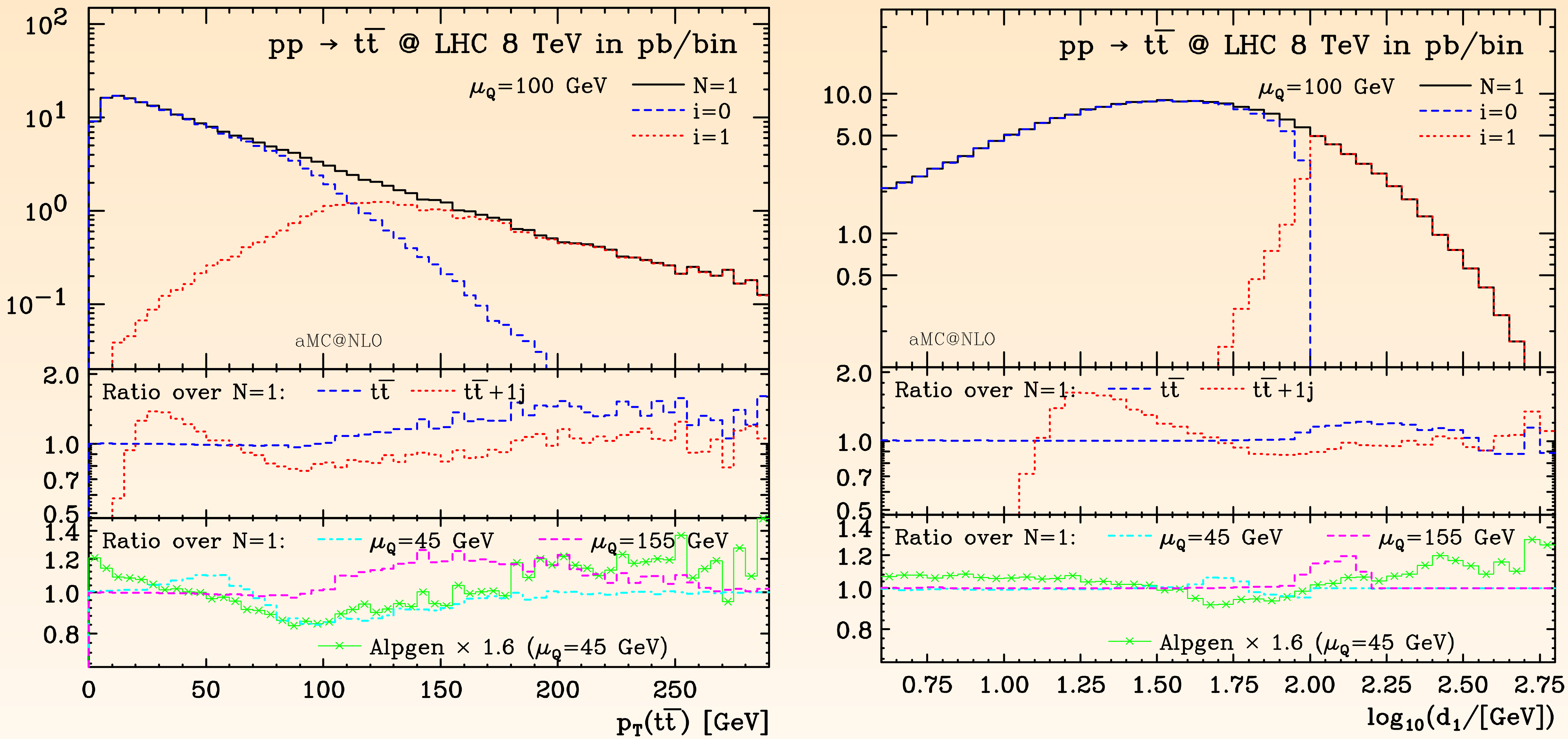
RF & Frixione, 2012



- Transverse momentum of the W-boson and of the 1st jet.
- Agreement with W+0j at MC@NLO and W+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale

TOP PAIR PRODUCTION

RF & Frixione, 2012



- and top pair production
- Only for VERY large scales tt+1j at MC@NLO is larger than than tt+0j at MC@NLO

Work in progress...

- Not easy to (analytically) proof what the accuracy of the NLO merged results actually is: how large is the left-over dependence on the merging scale formally?
  - From the plots it looks okay
  - What is a reasonable range to vary it?
- Not obvious how to estimate the theory uncertainties (scale dependence). Should the scale dependence in the Sudakov damping factors also be varied?
- Merging with b-jets (in the 4-flavor scheme) or processes that have already jets at the lowest-multiplicity Born level is probably non-trivial
- Automate the whole procedure and make it available within aMC@NLO --- event files to were used to make these plots are available upon request

Conclusions

- By offering NLO accuracy, improved by resummation of soft/collinear radiation (by the parton shower), results for high-precision collider phenomenology can be obtained
- aMC@NLO, a flexible, completely automatic event generator at NLO accuracy is publicly available for analyses for any process within the SM (or simple extensions)
- Merging NLO+PS samples of various jet multiplicities improves the predictions
  - However, systematics still need to be studied

aMC@NLO WEBSITE

aMC@NLO

http://amcatnlo.cern.ch

- On the aMC@NLO website you can find
  - Latest news on aMC@NLO
  - NLO event samples for some selected processes ready for showering and analysis
  - Download page for the code, FAQ and all that!