Tools for LHC Pheno

the road from postdictions to predictions

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POSTDICTIVE APPROACH

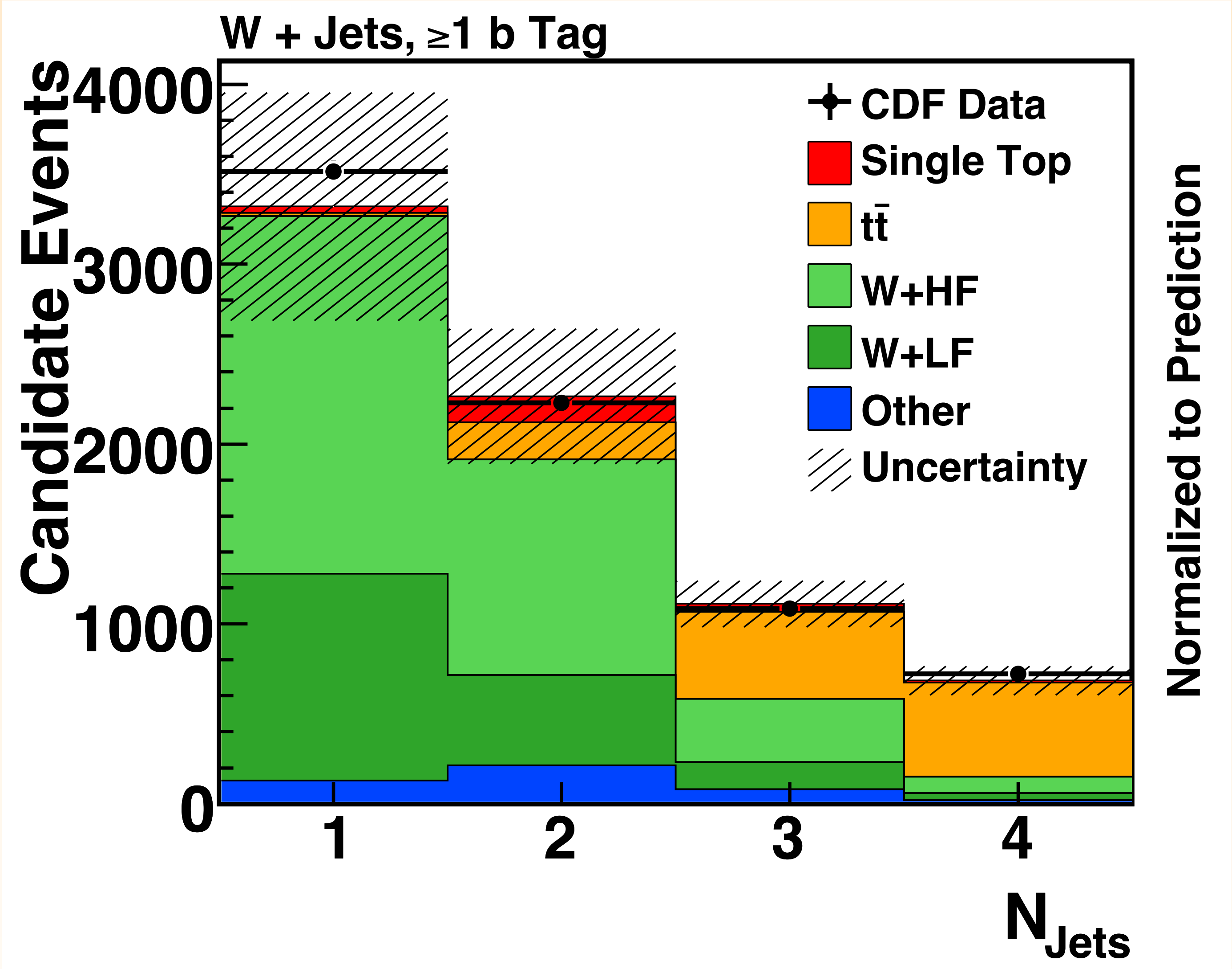
- Tune (i.e. calibrate) the MC tools on the data: this will give a control sample
- Apply the calibrated data to regions on interest, i.e. where we want to make the measurement/discovery/set limits
- When the control region and the region of interest do not overlap, we need to trust the MC tool outside the region where we tuned it. A leap of faith is needed

PREDICTIVE APPROACH

- A prediction can be wrong... Accept the risk associated with it
- Or better: not only the central value needs to be predicted
  ---> a reliable estimate of uncertainties is as important
- Namely, predict and compare to data
  - If there is a discrepancy (larger than the uncertainties) ---> discovery
  - else ---> another SM success

Can we still make discoveries?

- Prime example: single top production at the Tevatron
- Theory uncertainty is much larger than the single-top signal process. Still, this is the data that was used to get 5 std.dev. significance for the single top process
- Indeed, by measuring the data in control regions, uncertainties on backgrounds can be reduced



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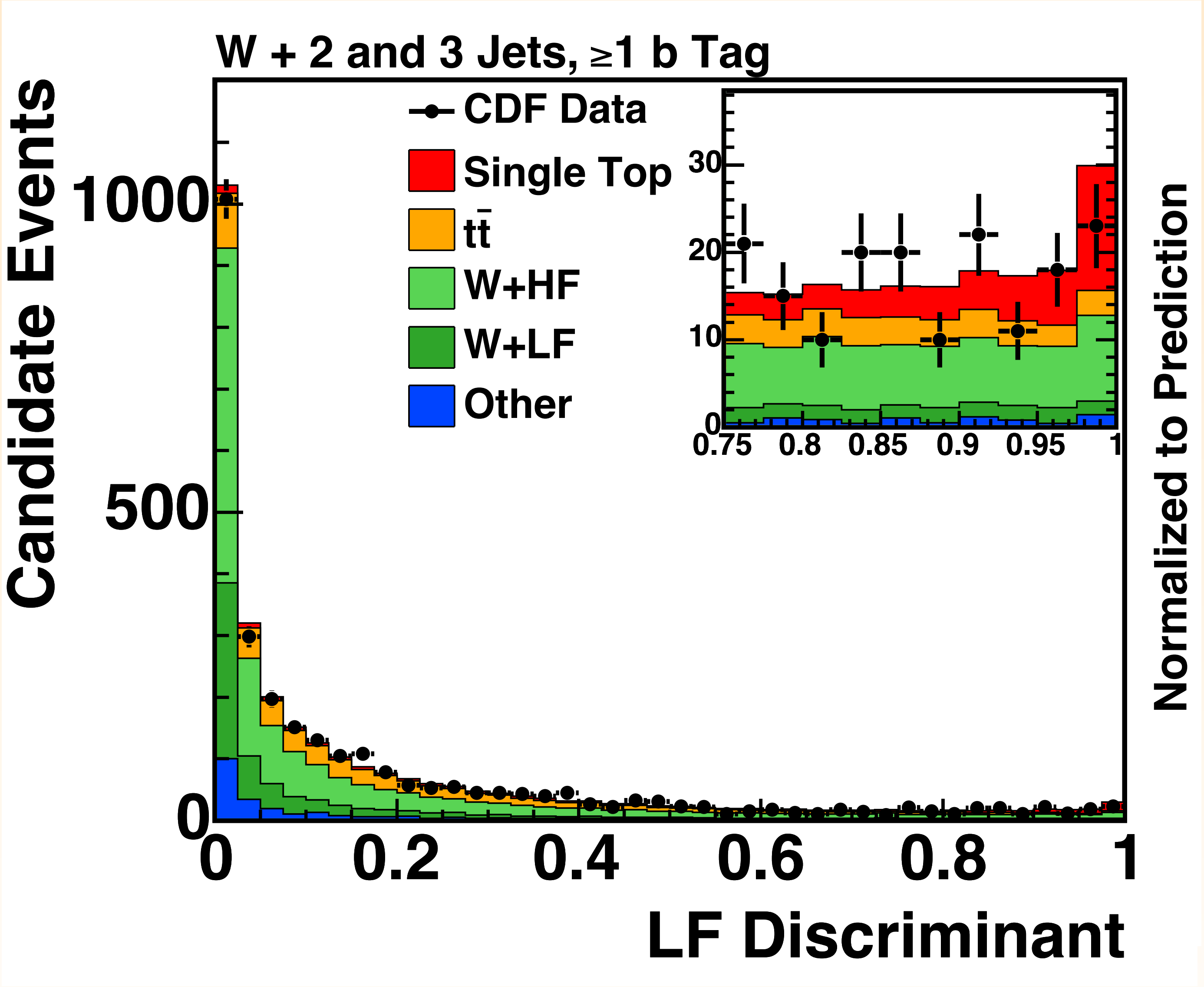


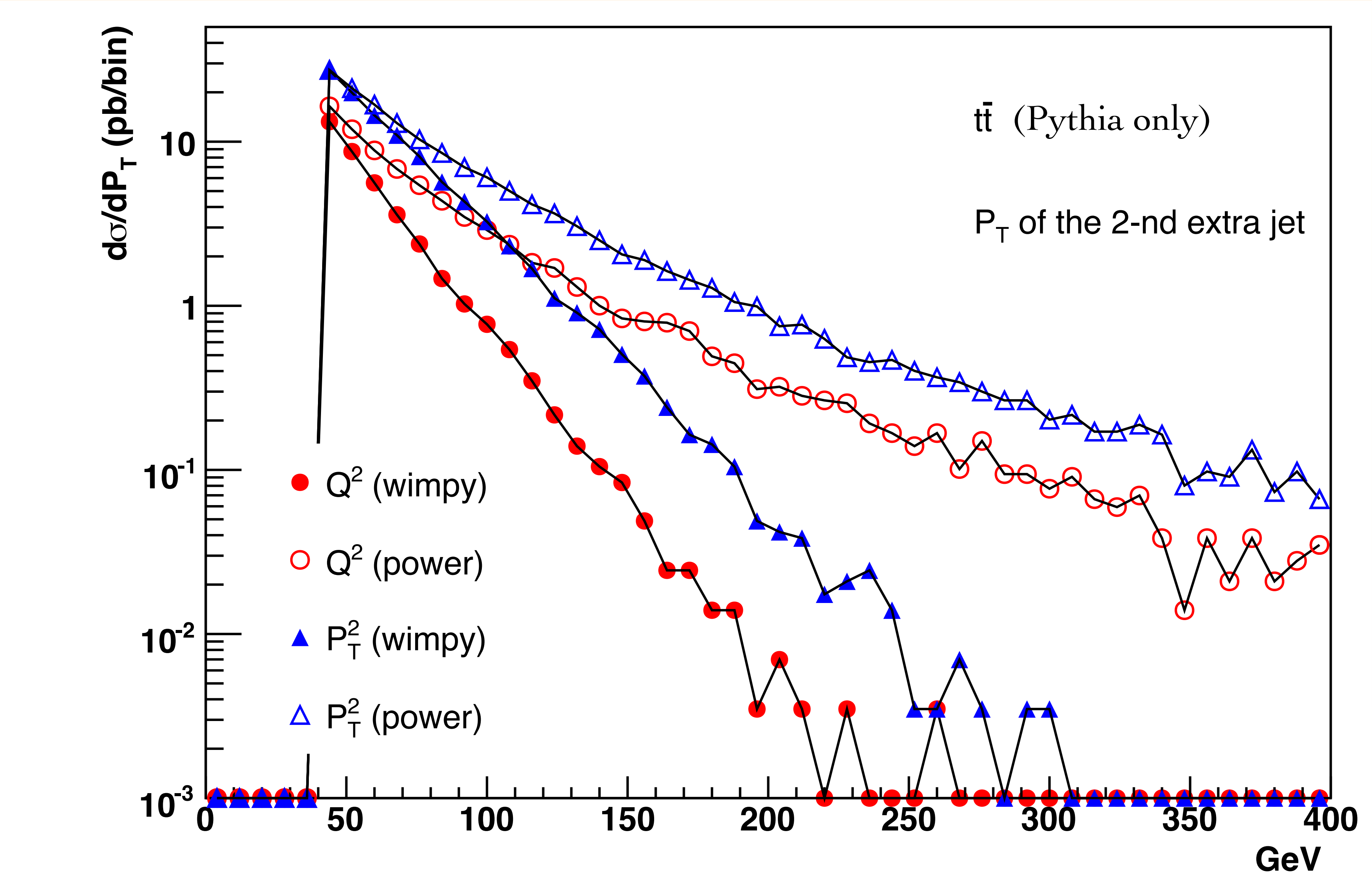
Real life

- In practice, there is always a mixture of postdictions and predictions
- There is no way out. There are (e.g. non-perturbative) effects that have to be tuned to data and/or cannot be computed
  - hadronization effects, underlying event etc.
- **The question is only to know when to stop: what can be tuned and what shouldn't be tuned. This depends on how accurate the theory is**

Parton shower tuning

The soft-collinear approximation of Parton Shower MCs used outside of the range of validity; parameters can be used to tune the result

⇒ Ideal for postdictions

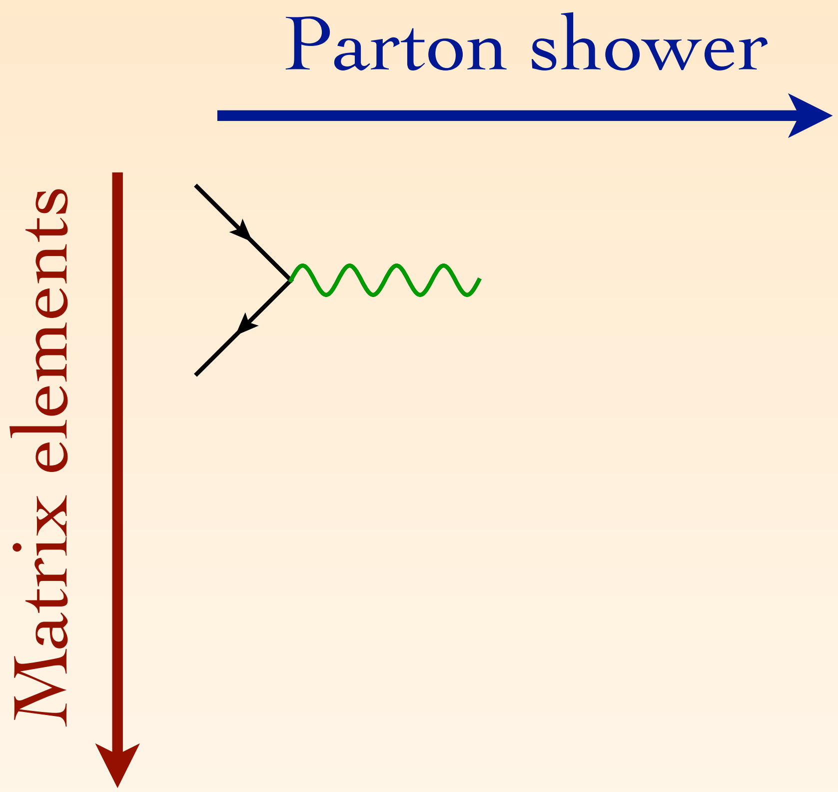


More accurate theory

- Tuning this just loses predictive power and is not needed at all. We do have a much more accurate theory description
  - Instead of generating the extra radiation by the parton shower, it should be described by higher multiplicity matrix elements.
  - However, we do want to keep the parton shower to be able to get fully exclusive events
- Need to merge parton shower with matrix element descriptions, making sure to prevent double counting: radiation can either be described by the matrix elements, or by the parton shower.

MERGING MATRIX ELEMENT MULTIPLICITIES

CKKW & MLM



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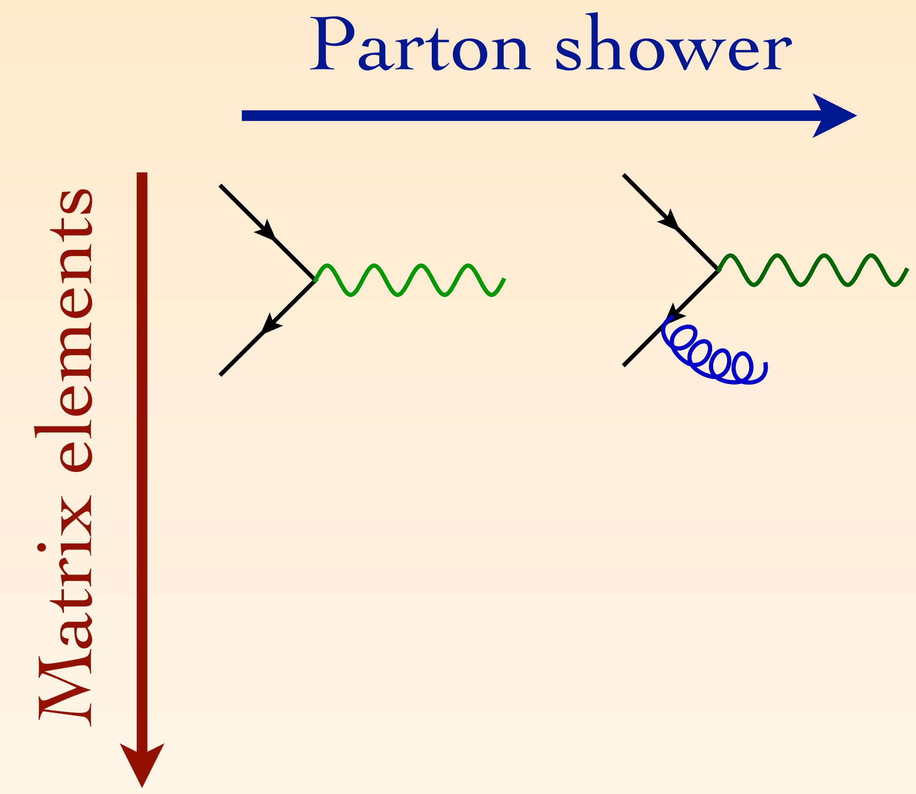

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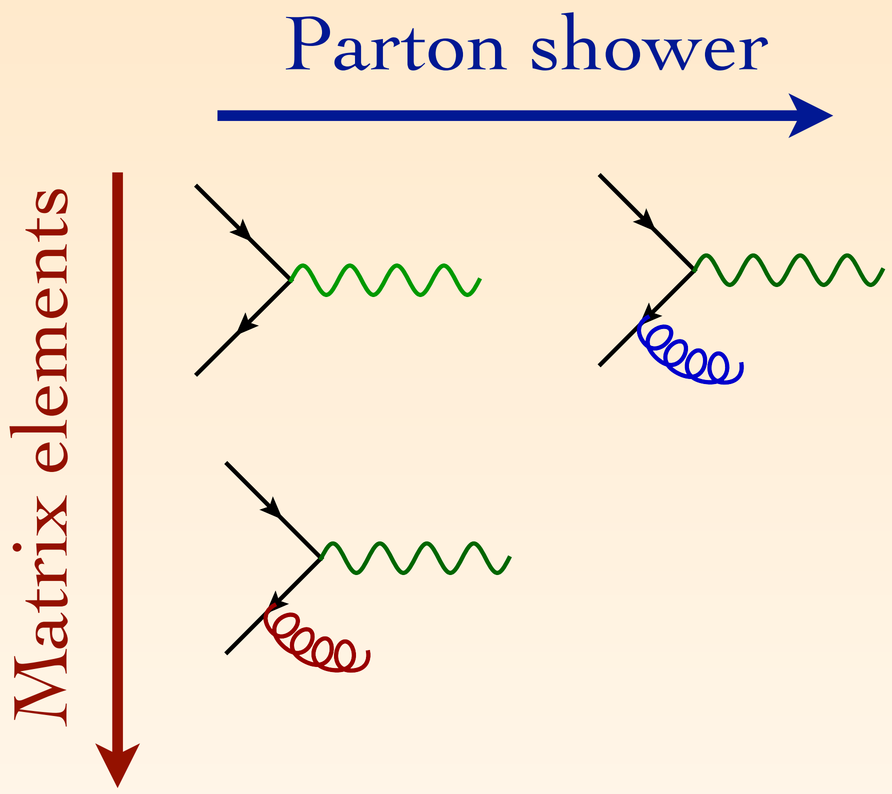

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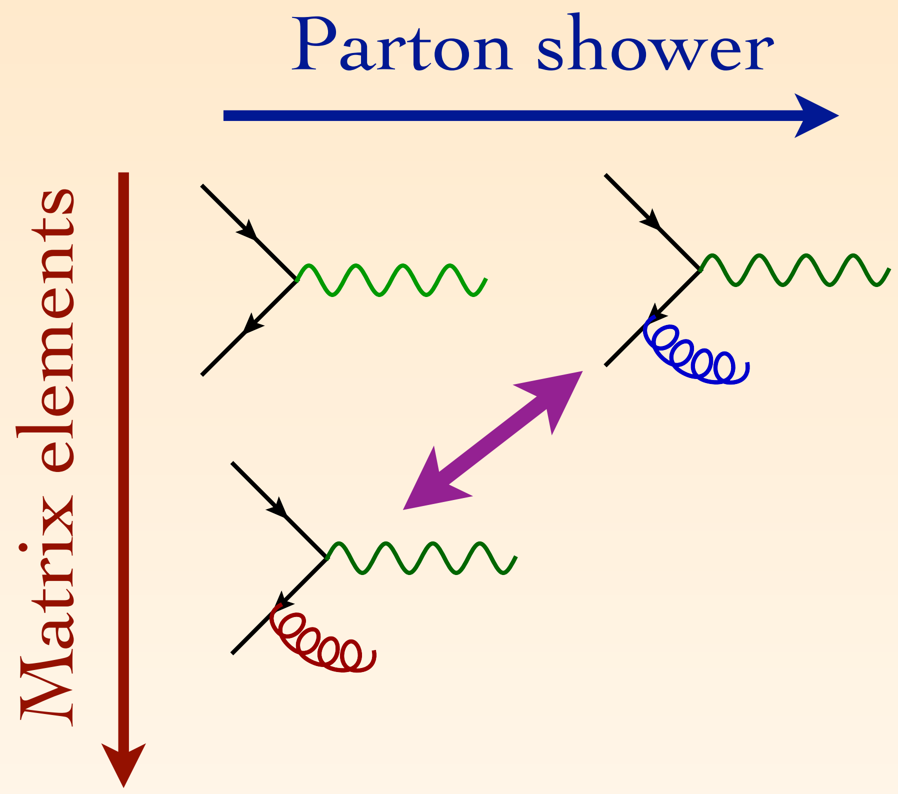

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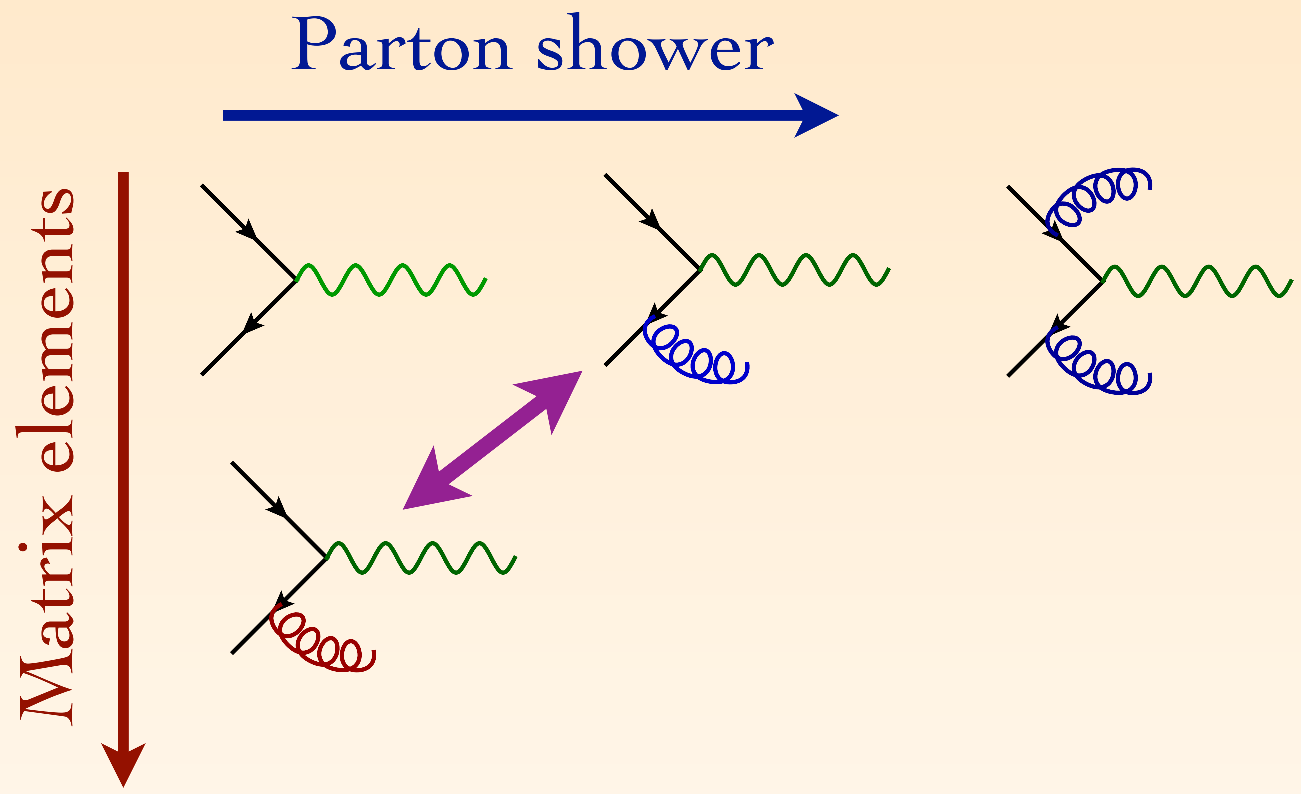

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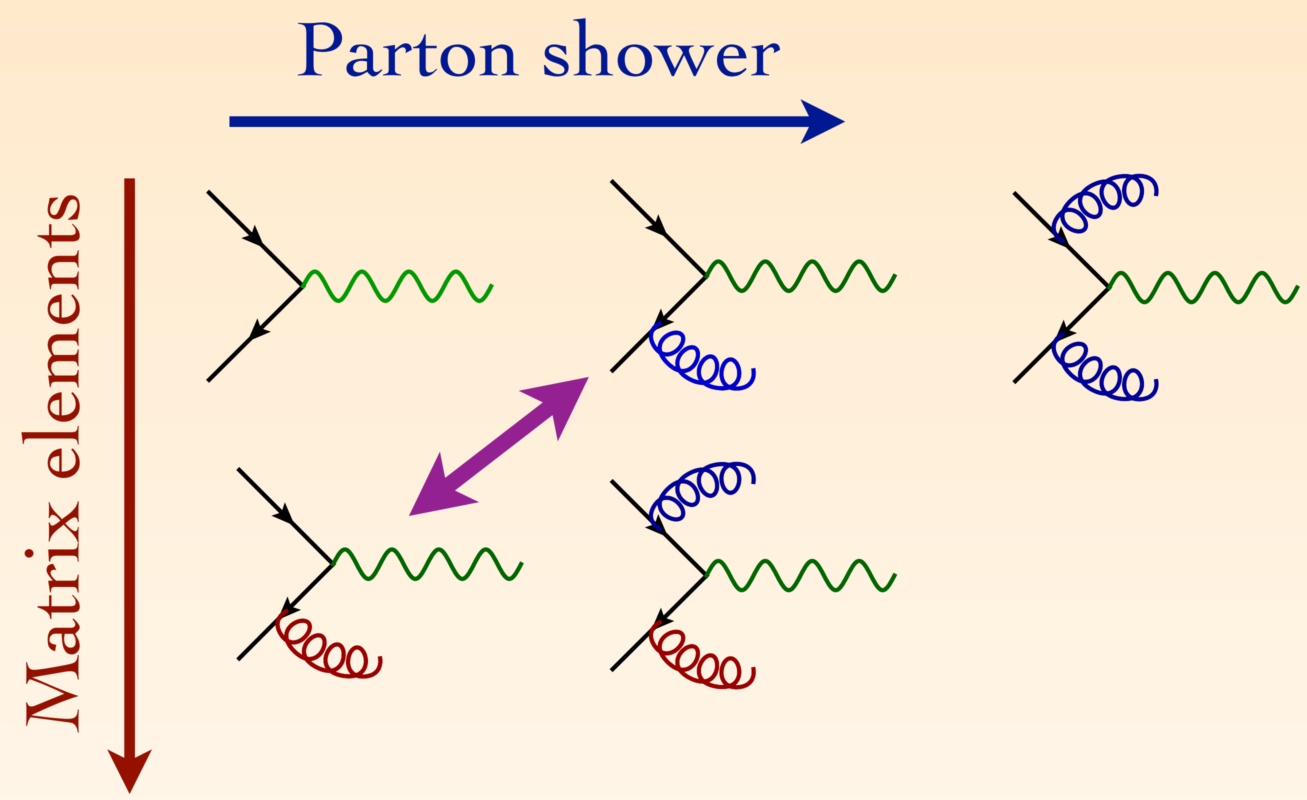

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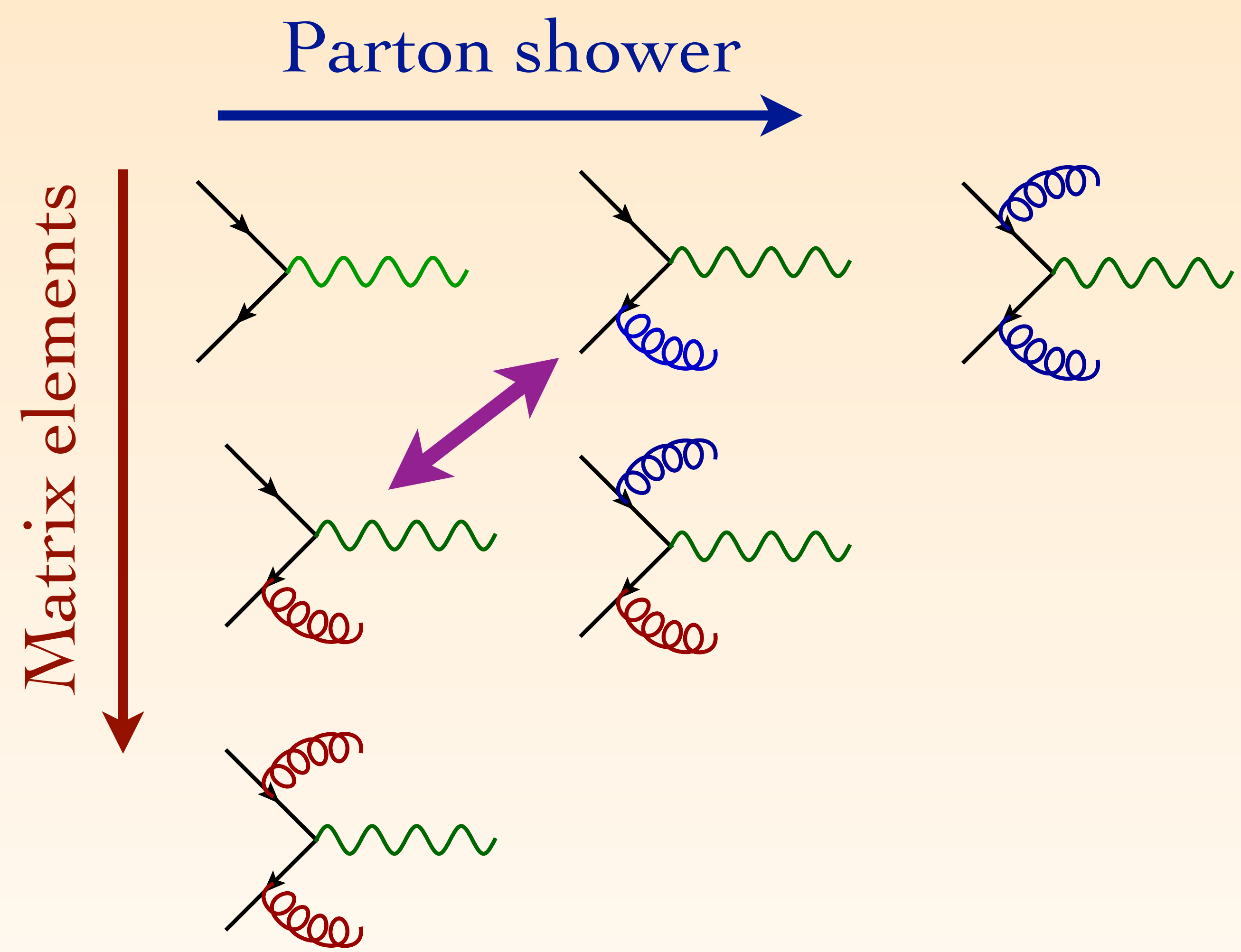

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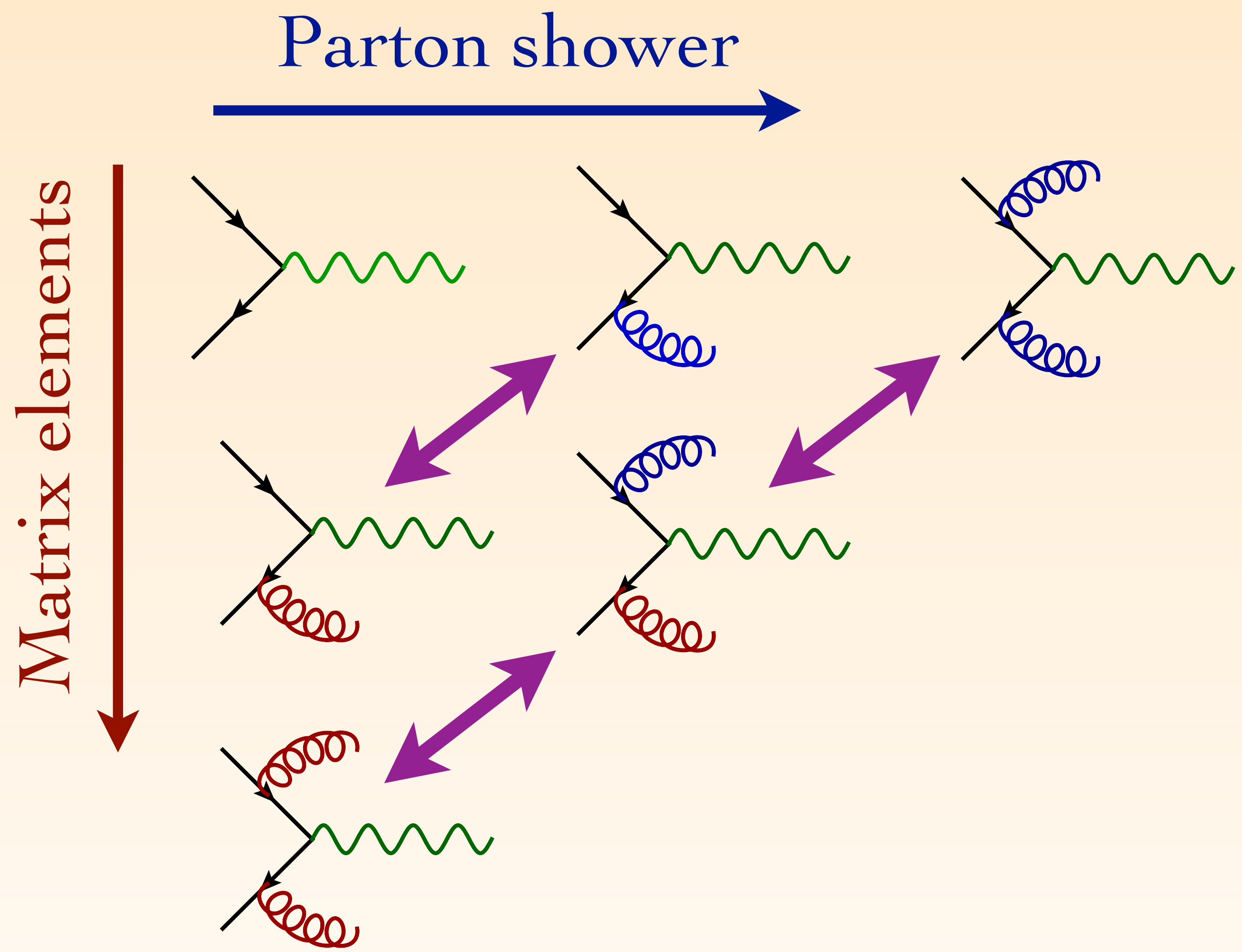

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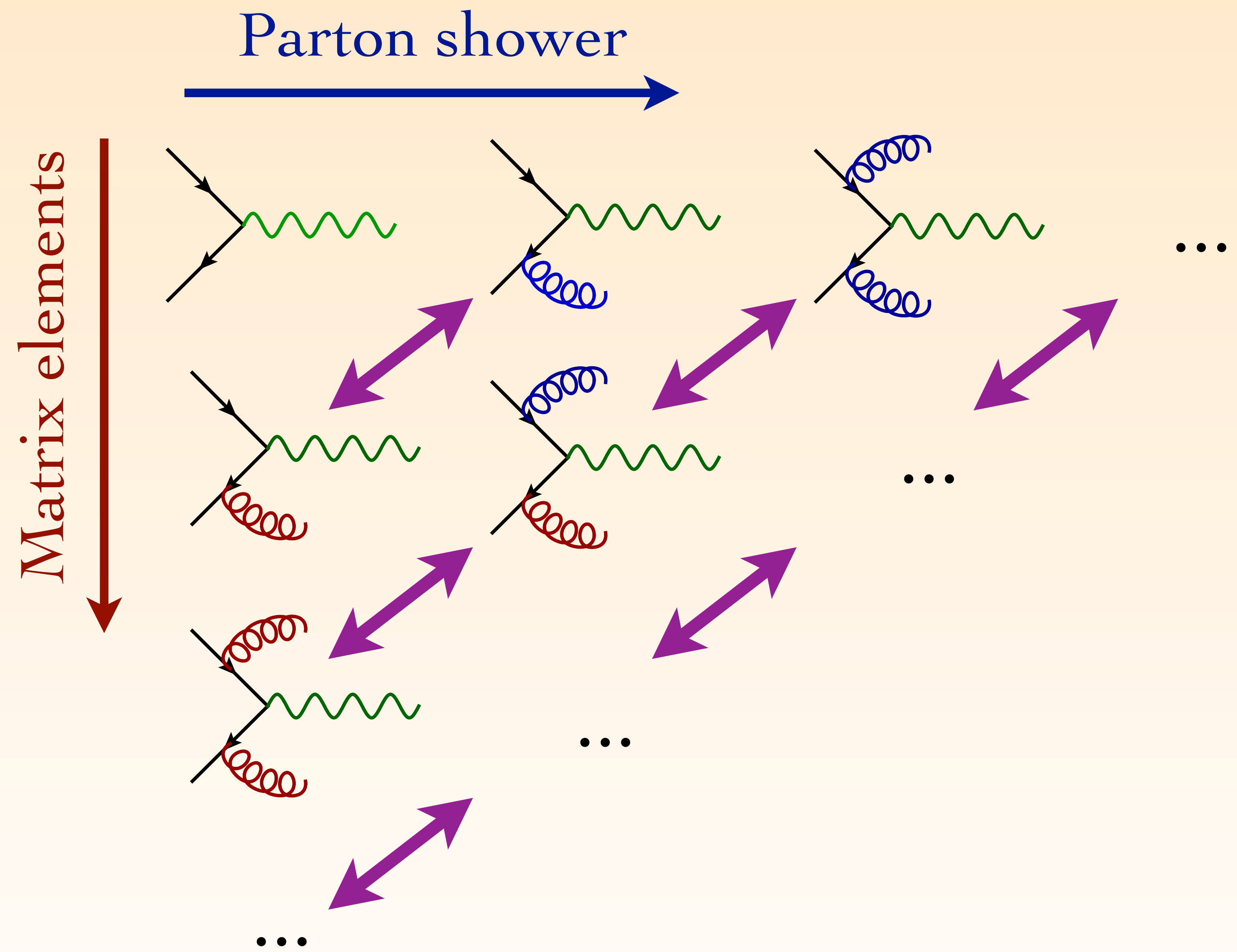

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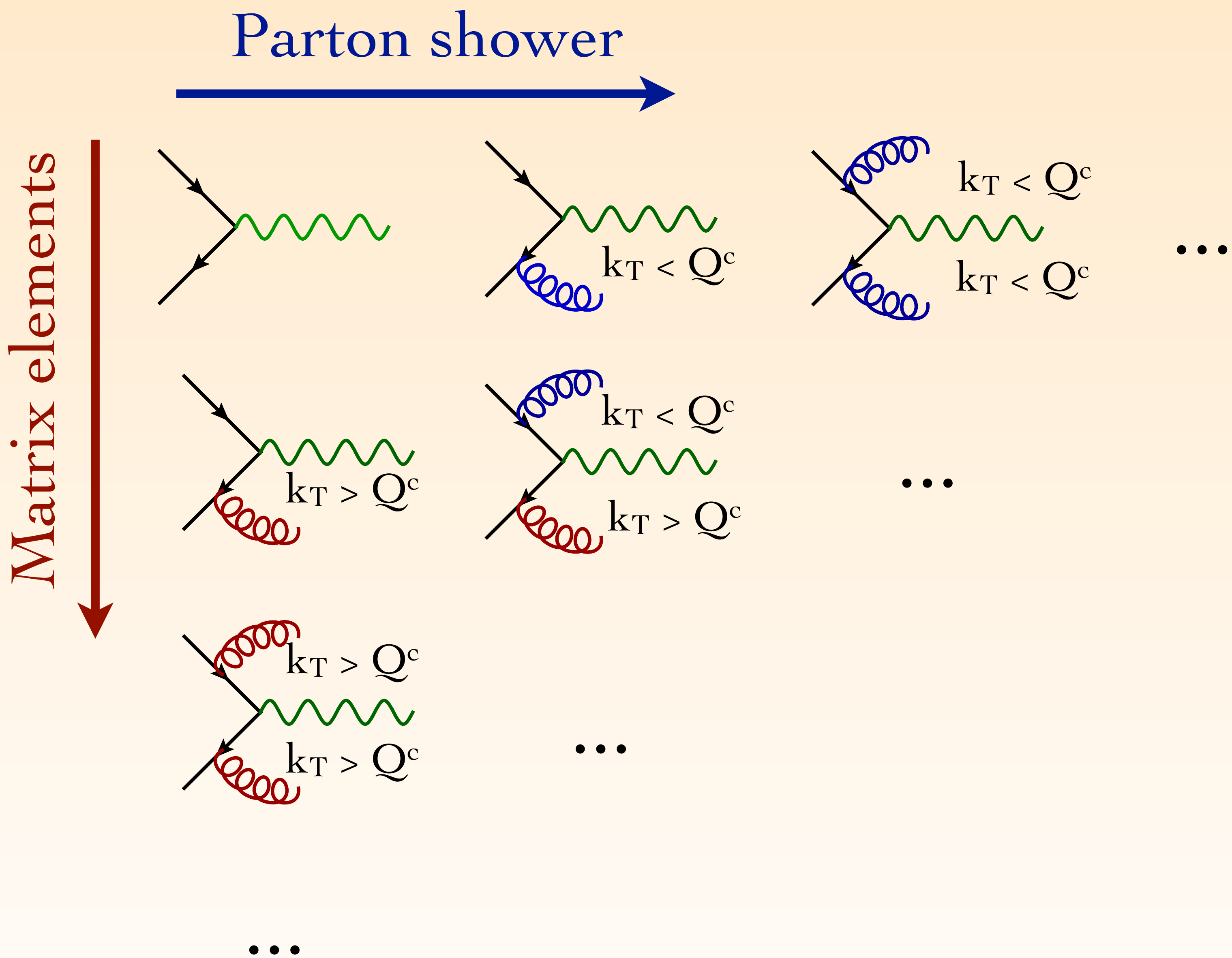
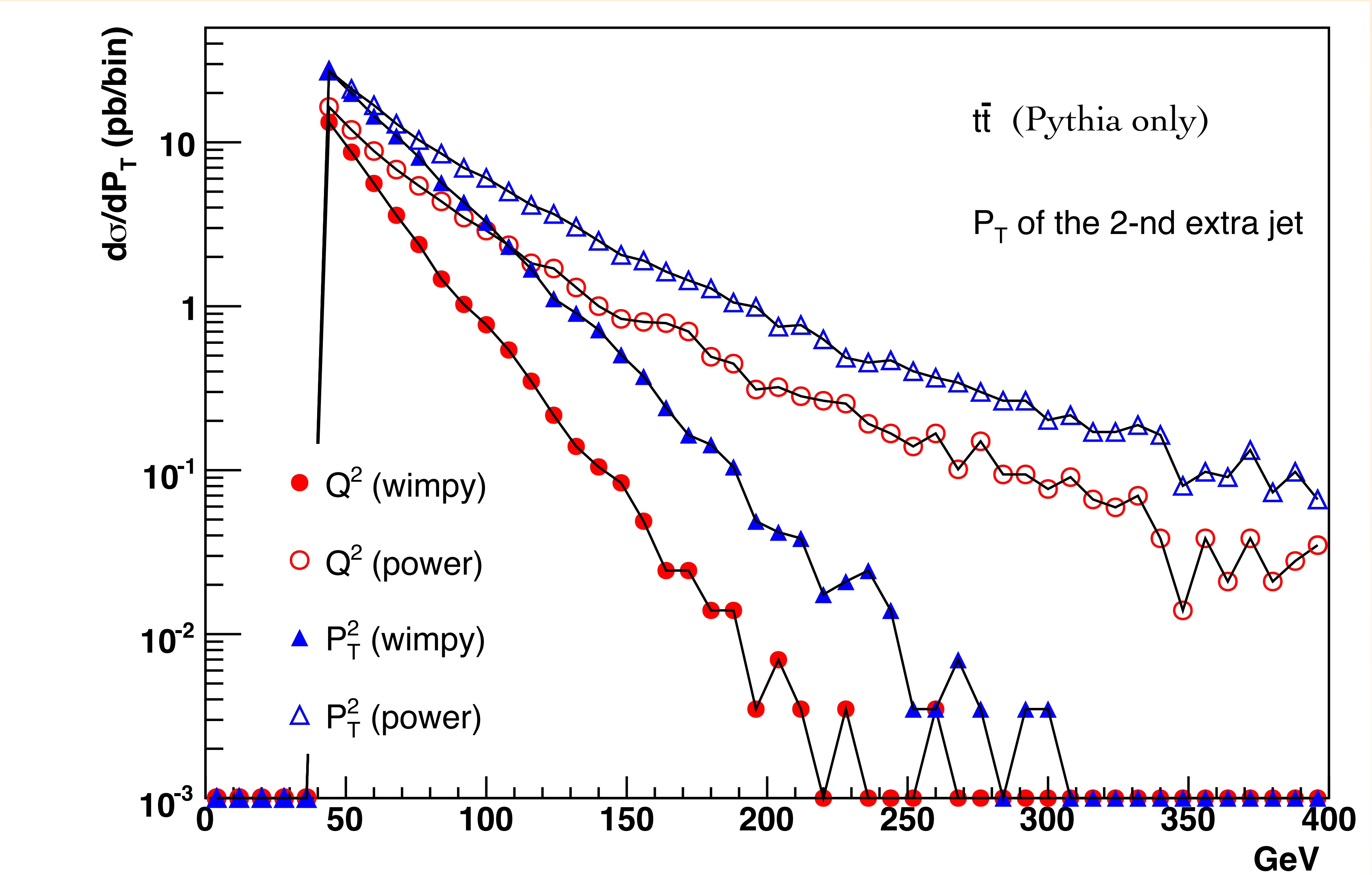


Parton shower tuning

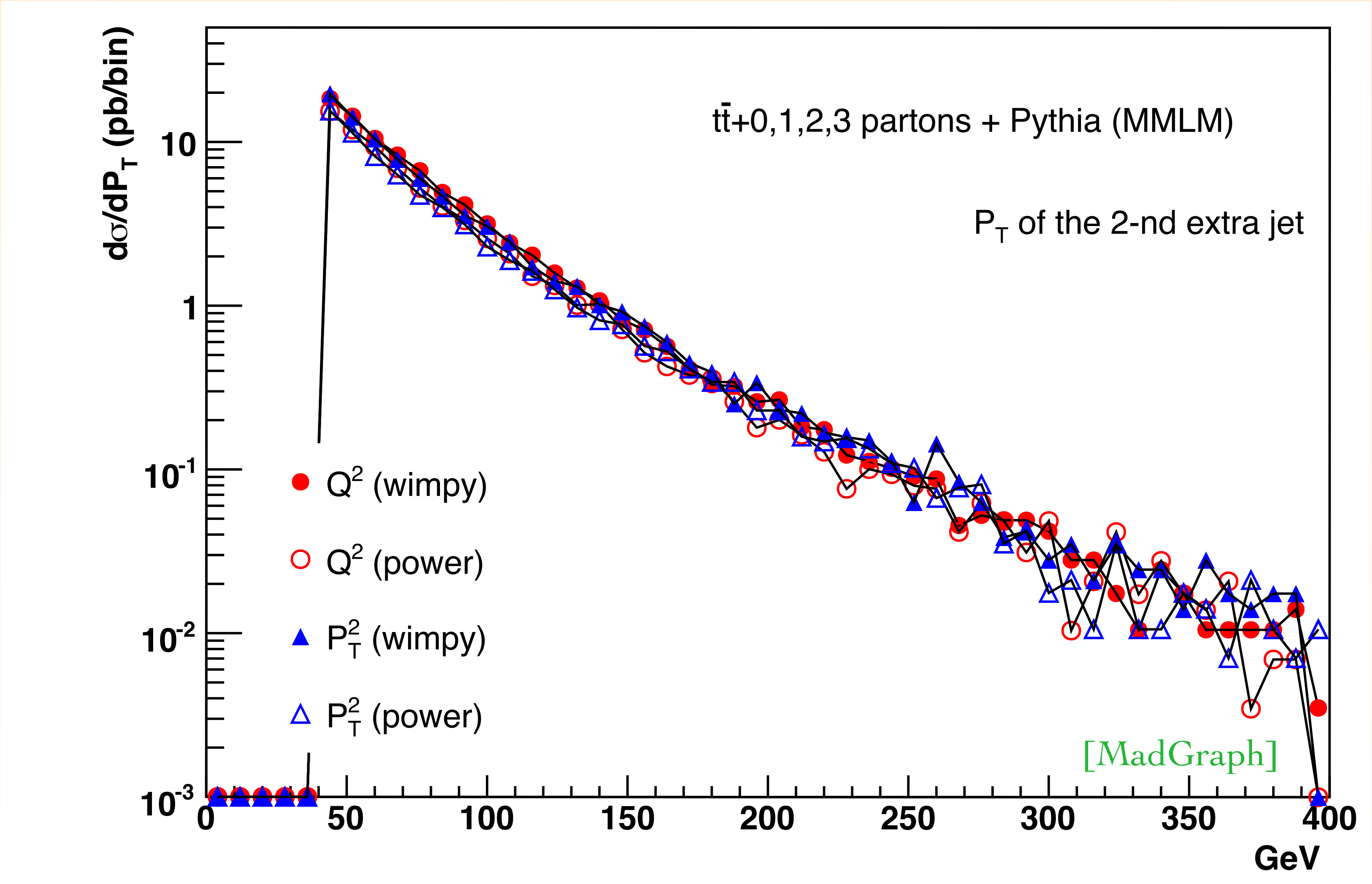
The soft-collinear approximation of Parton Shower MCs used outside of the range of validity; parameters can be used to tune the result

$\Rightarrow$ Ideal for postdictions



Tree-level ME+PS merging

In a matched sample these differences are irrelevant since the behavior at high pt is dominated by the matrix element.



QCD and MC progress

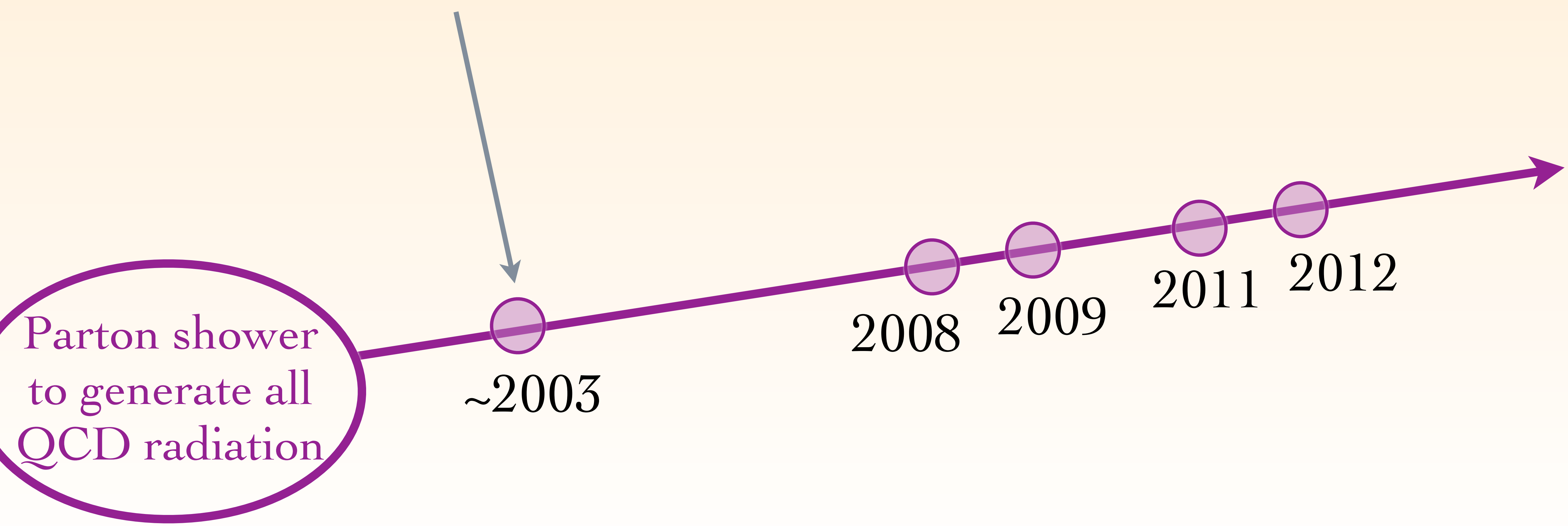
Merging & matching:

ME+PS

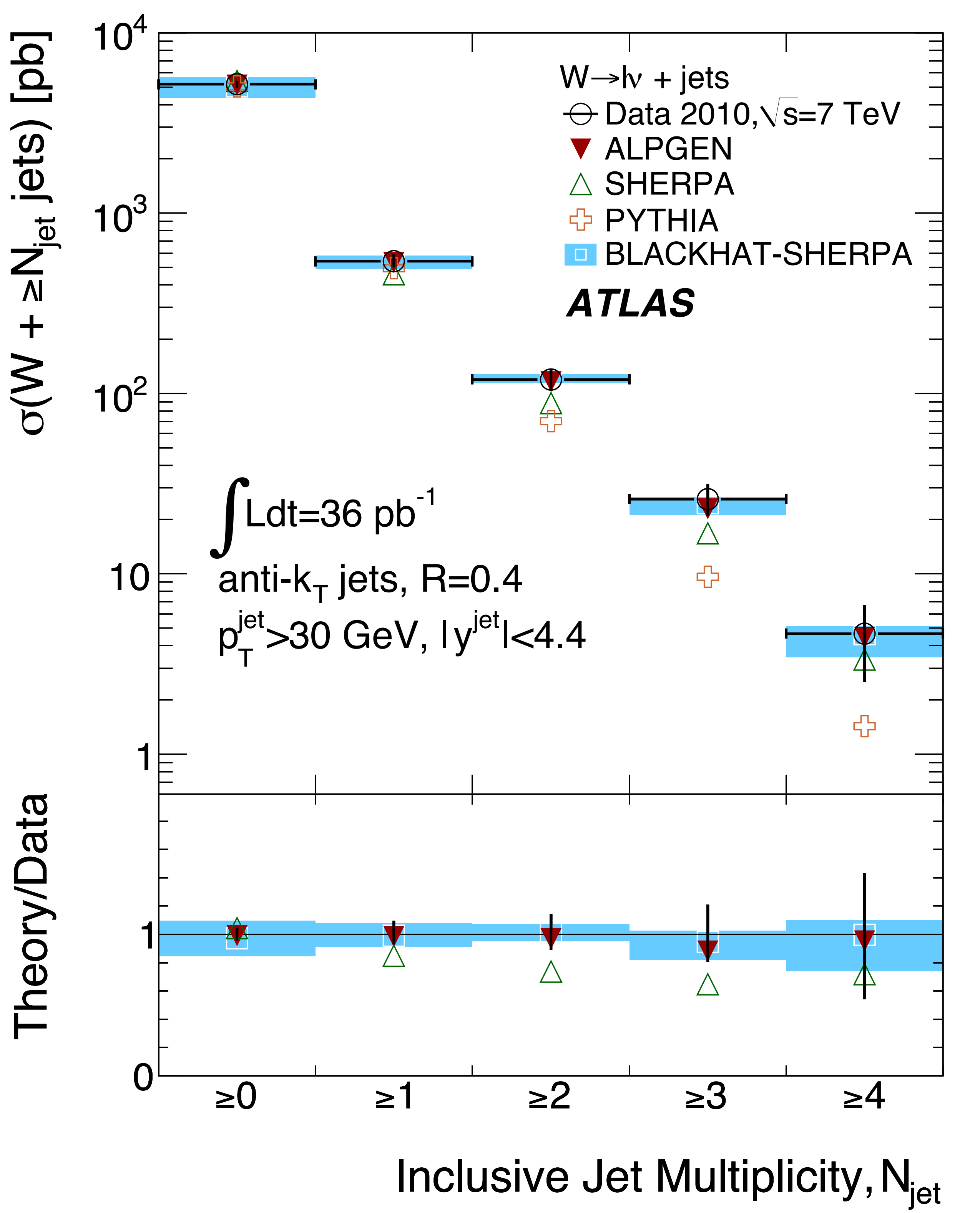
(CKKW, MLM)

NLO+PS

(MC@NLO, POWHEG)



Comparing to data



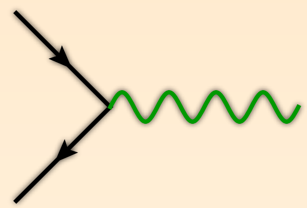
- ATLAS compared to
  - parton shower only (Pythia)
  - ME+PS LO predictions (Alpgen (MLM) & Sherpa (CKKW))
  - NLO (BlackHat+Sherpa)
- Only NLO shows uncertainties

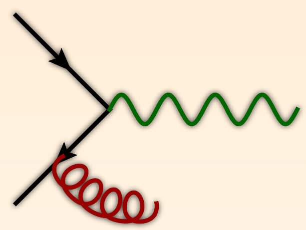
NLO predictions

- Why is it needed?
  - Predictions are much more reliable
  - compensation in the scale dependences make for a reliable estimate of the uncertainties
  - PDF uncertainties can be trusted
- It improves the theory accuracy: less need for tuning; more predictive power; better understanding of the data; less uncertainties in interpolation from calibration regions to interesting regions
  - Note that we should keep the fully exclusive event generation: matching with parton shower a requirement
- However, does the advantage of NLO overcome the enormously steep increase in complexity one faces (in particular for higher multiplicities)? This is not obvious

NLO+PS: sources of double counting

Parton shower

Born+Virtual: 

Real emission: 

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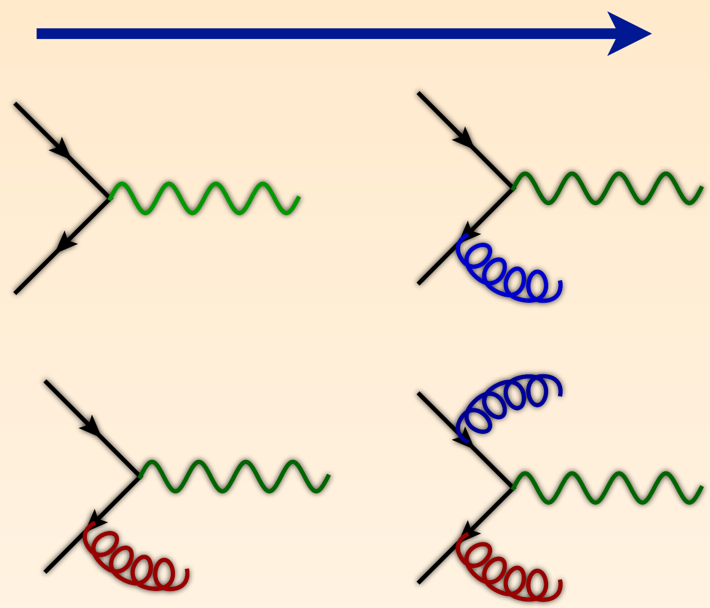

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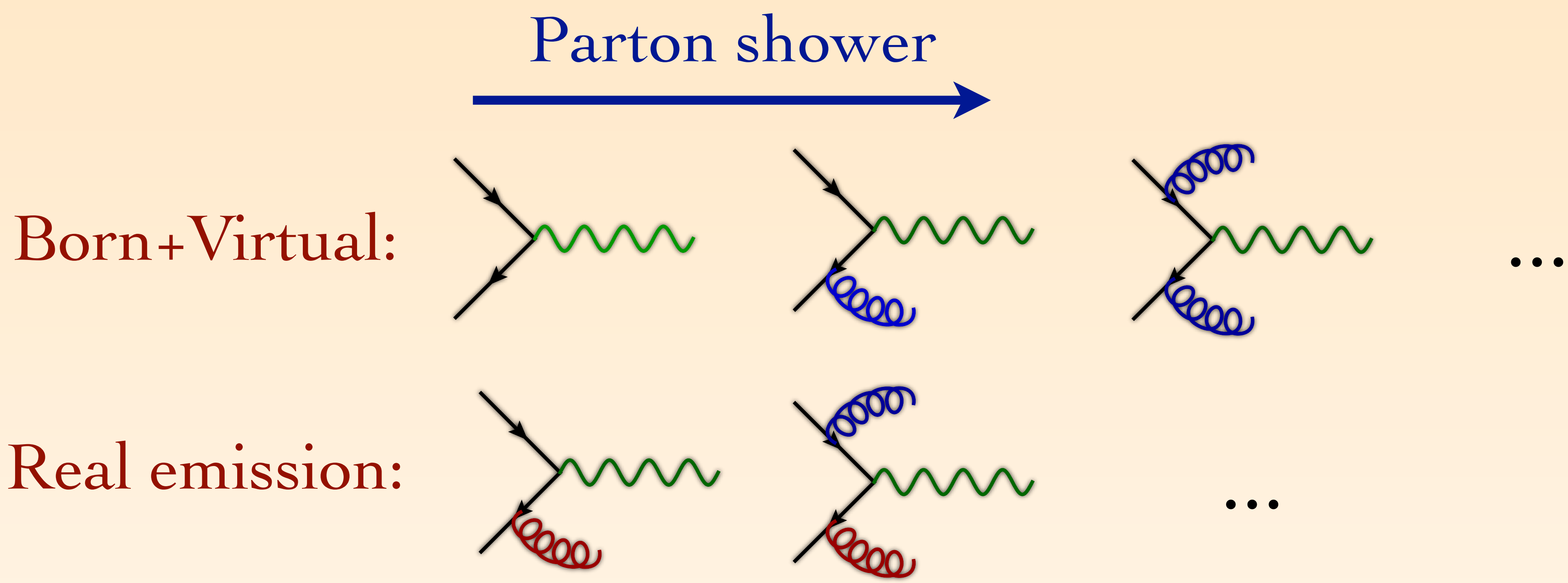

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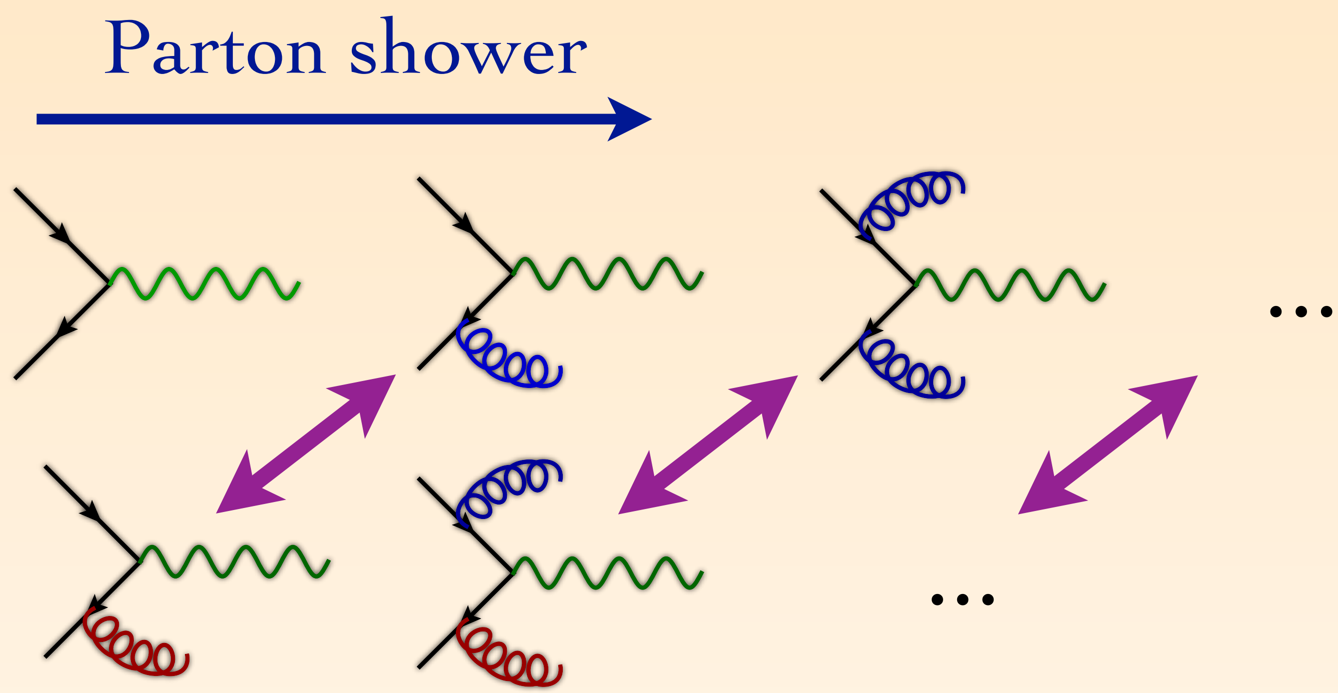

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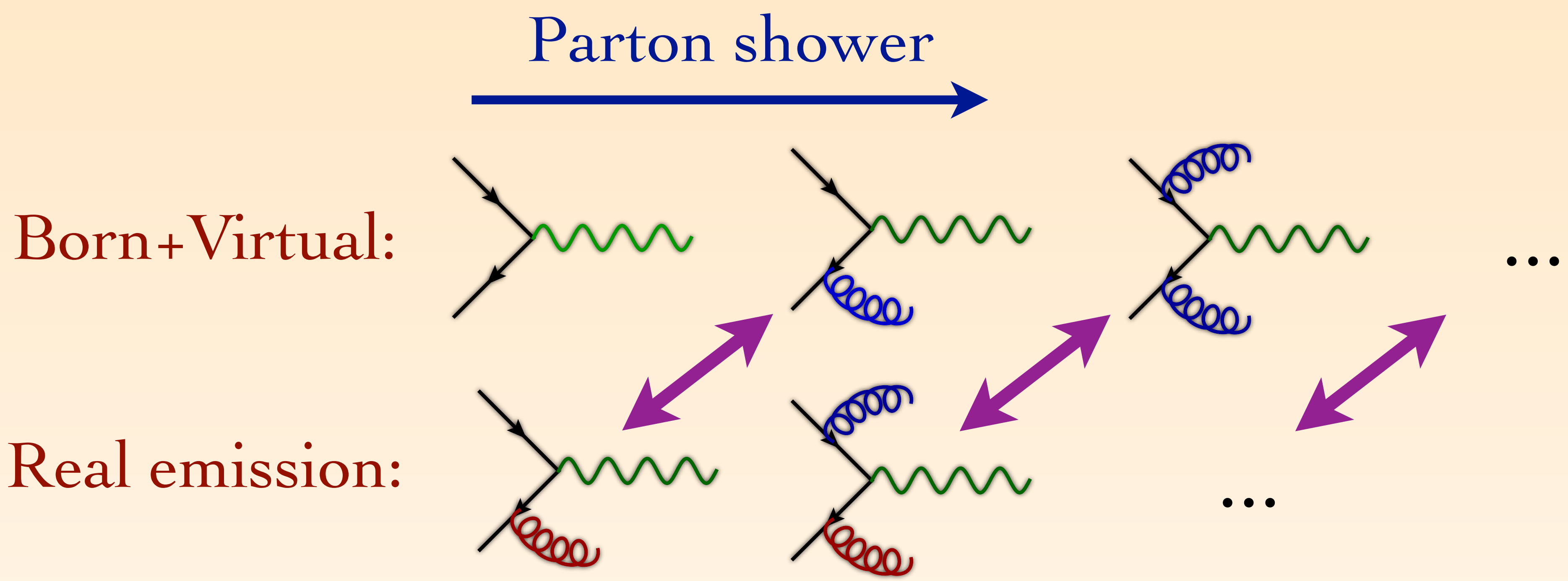
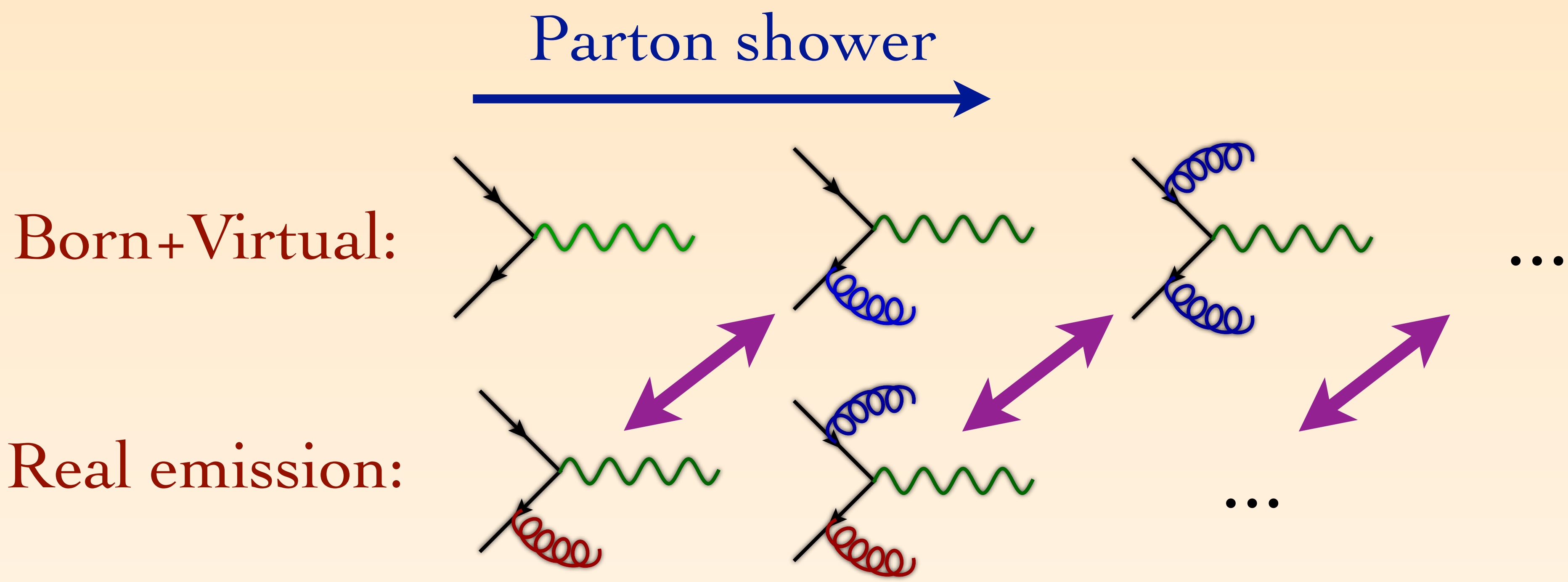


- There is double counting between the real emission matrix elements and the parton shower: the extra radiation can come from the matrix elements or the parton shower
- There is also an overlap between the virtual corrections and the Sudakov suppression in the zero-emission probability

NLO+PS

- Remove the double counting by
  - explicitly subtracting it: “MC@NLO approach”
    [Frixione & Webber]
  - modifying the first emission of the parton shower accompanied by an inclusive NLO corrections to each given event: “POWHEG approach”
    [Nason]

NLO+PS: SCHEMATICALLY



$$d\sigma_{\text{MC@NLO}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} MC + d\Phi_{(+1)}(R - MC) \right]$$

$$d\sigma_{\text{POWHEG}} = d\Phi_B \left[B + V + \int d\Phi_{(+1)} R \right] \left[\tilde{\Delta}(Q^2, Q_0^2) + \tilde{\Delta}(Q^2, t)\ d\Phi_{(+1)} \frac{R}{B} \right]$$

NLO predictions

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The answer is obviously 'yes', if we let the computer do the hard work. The increased complexity just means longer CPU computing time

Full automation also builds trust in the calculation. Separate pieces can be checked independently

This has now been achieved for NLO corrections in any SM process

QCD and MC progress

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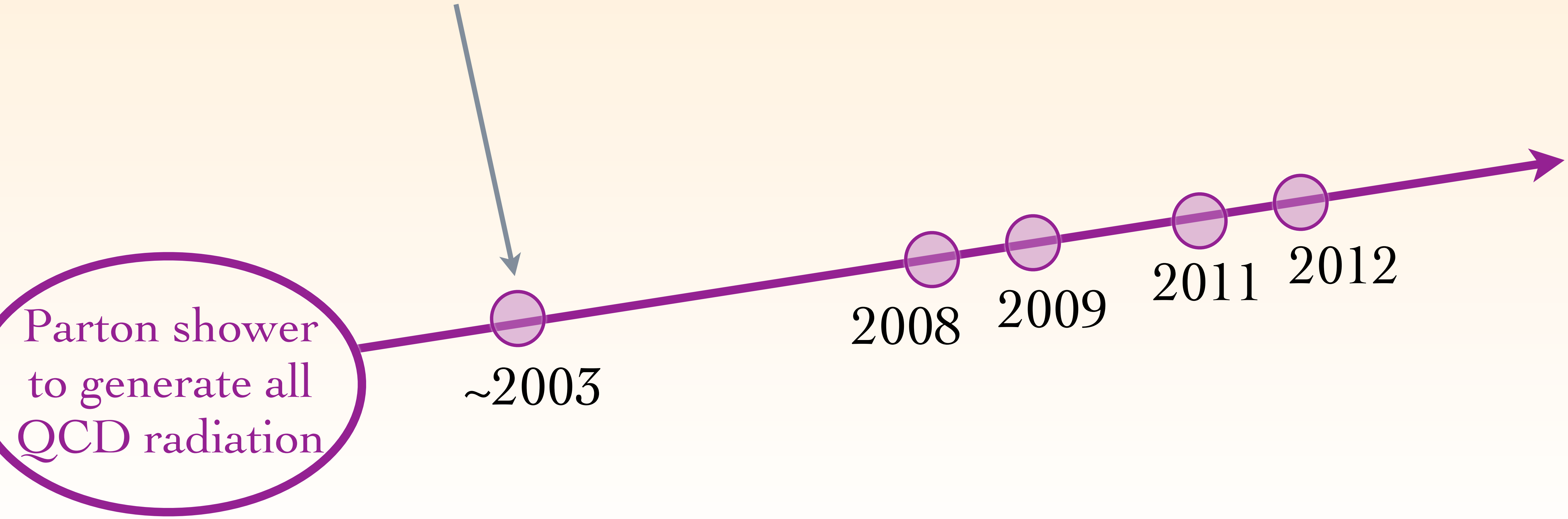

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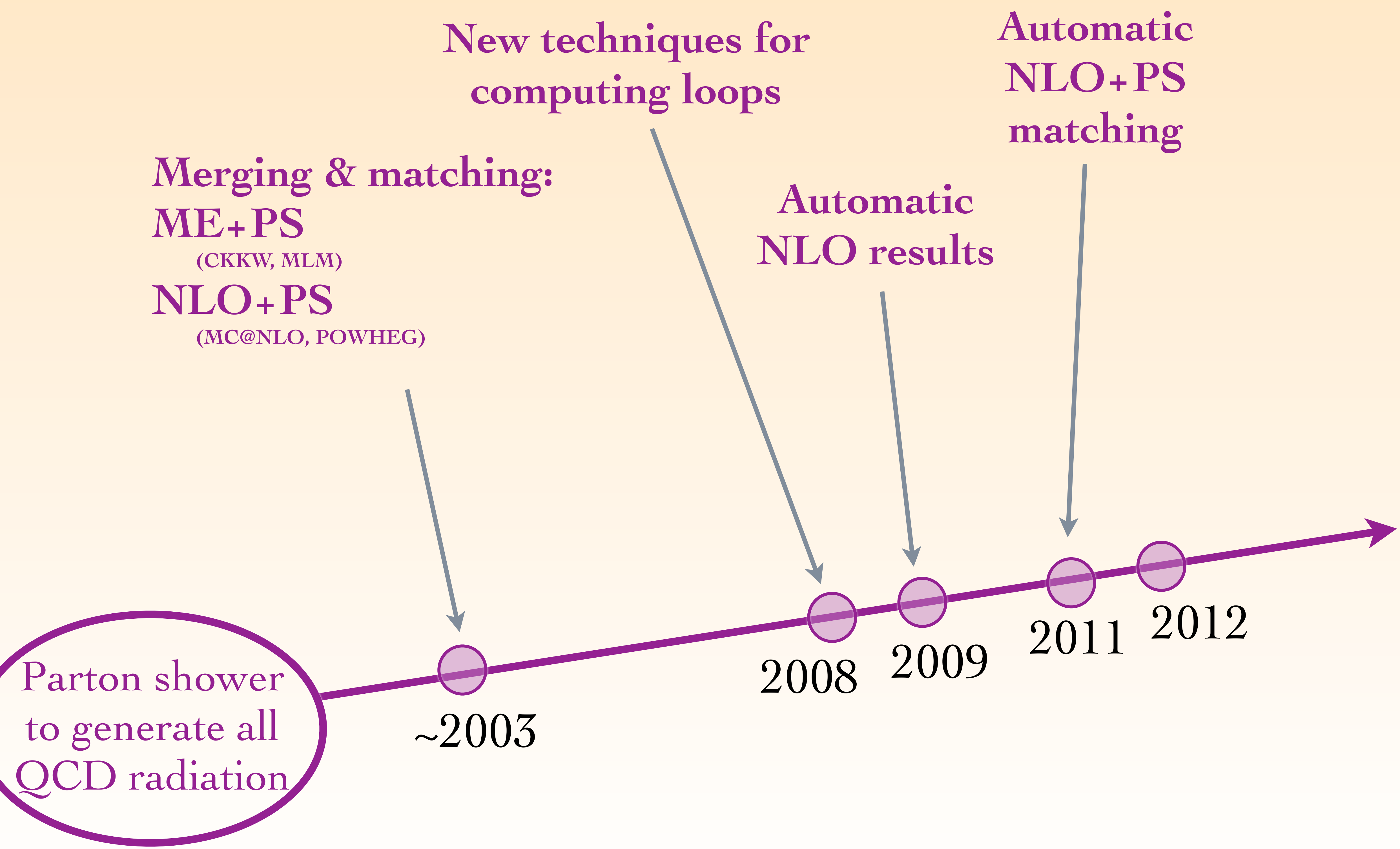

aMC@NLO joint venture

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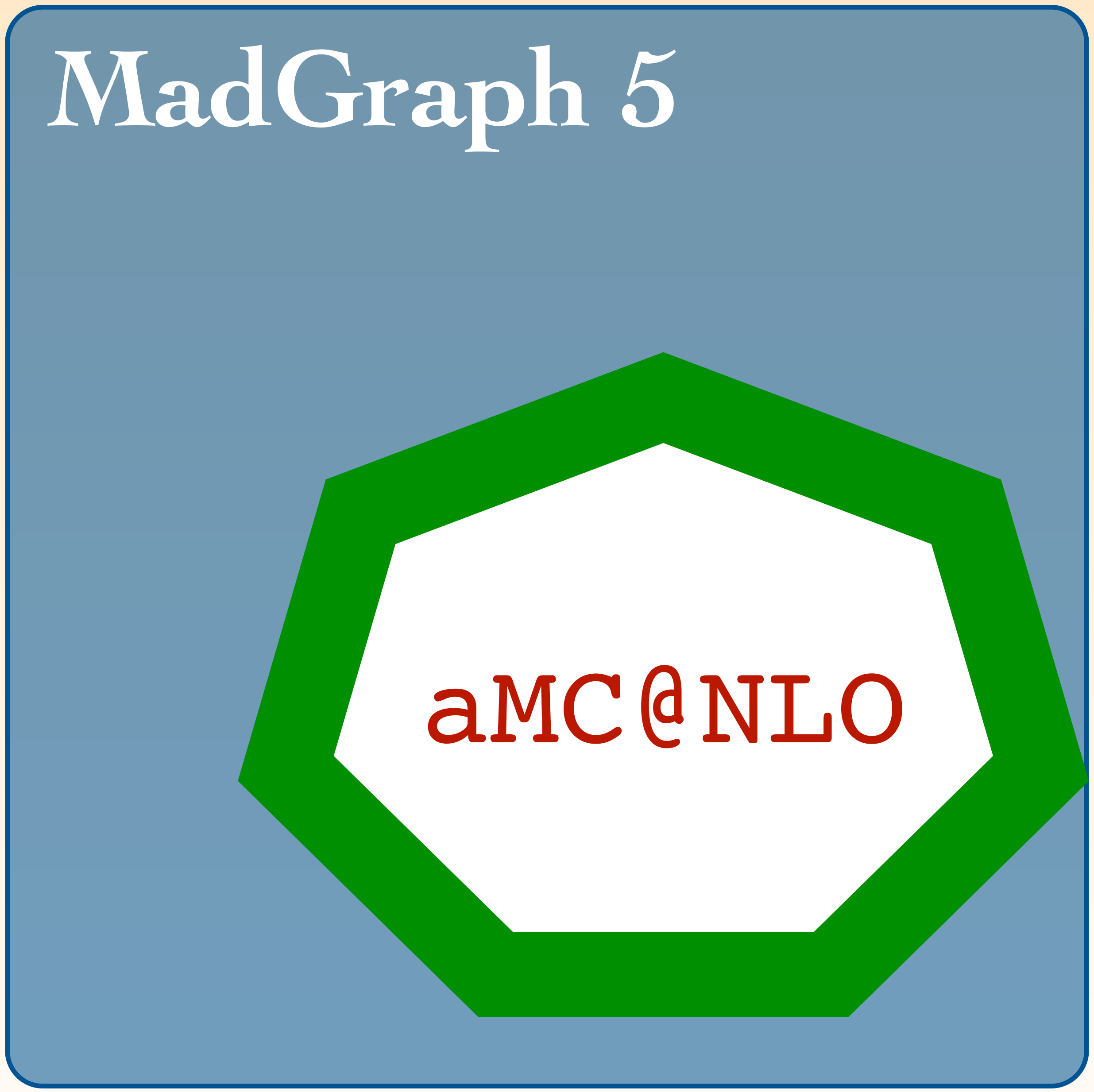
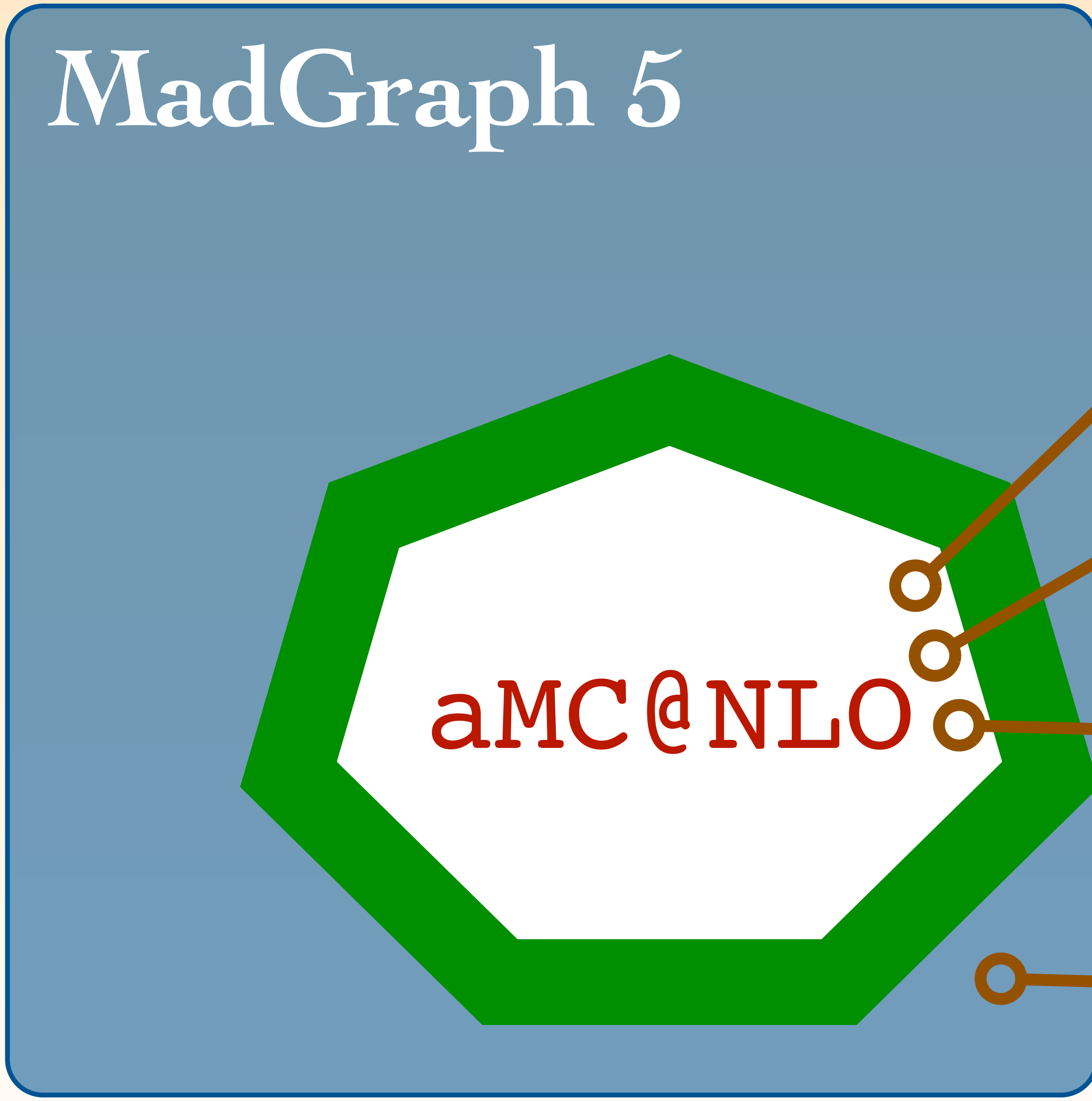
MadGraph 5

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

aMC@NLO JOINT VENTURE

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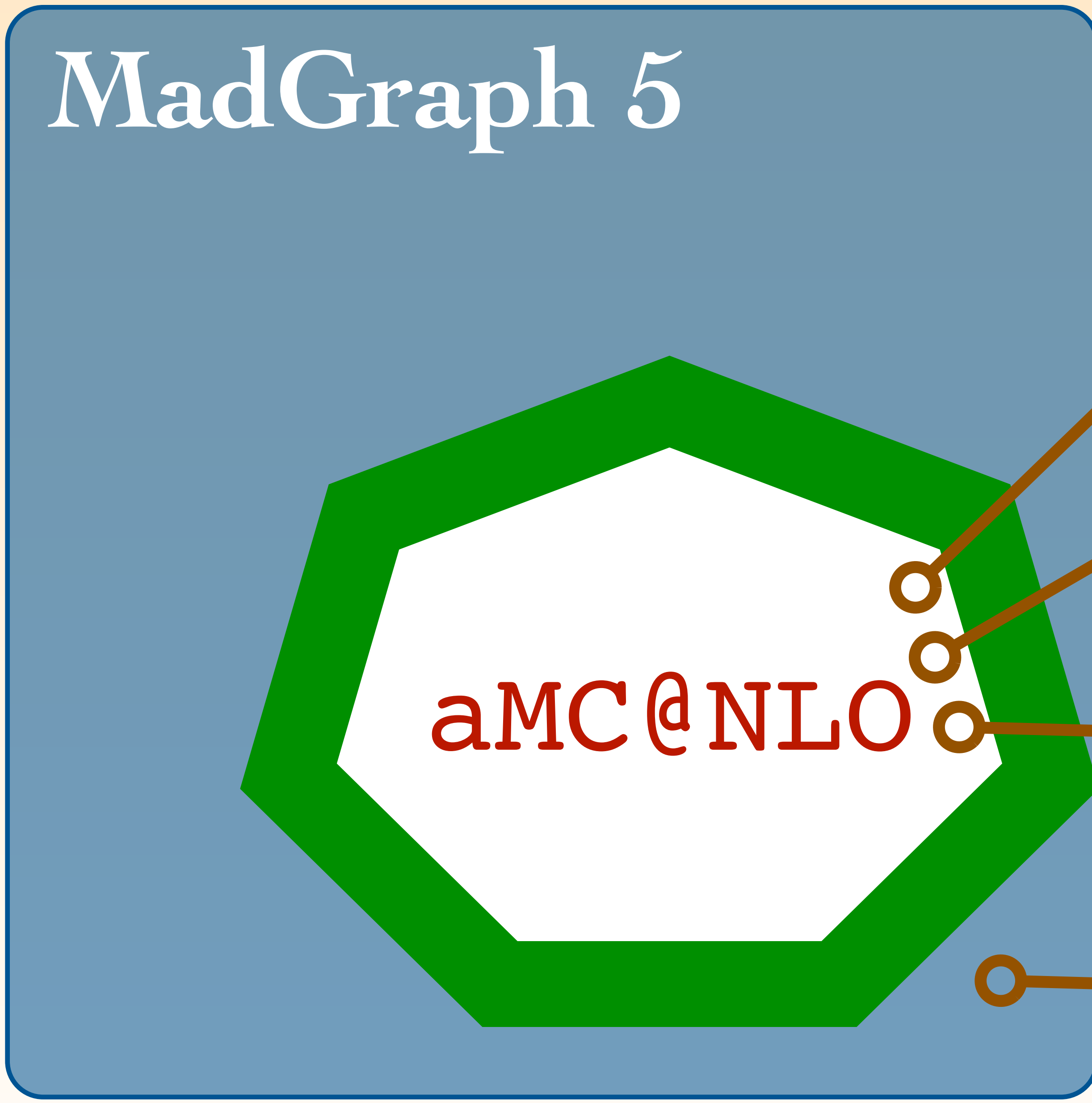

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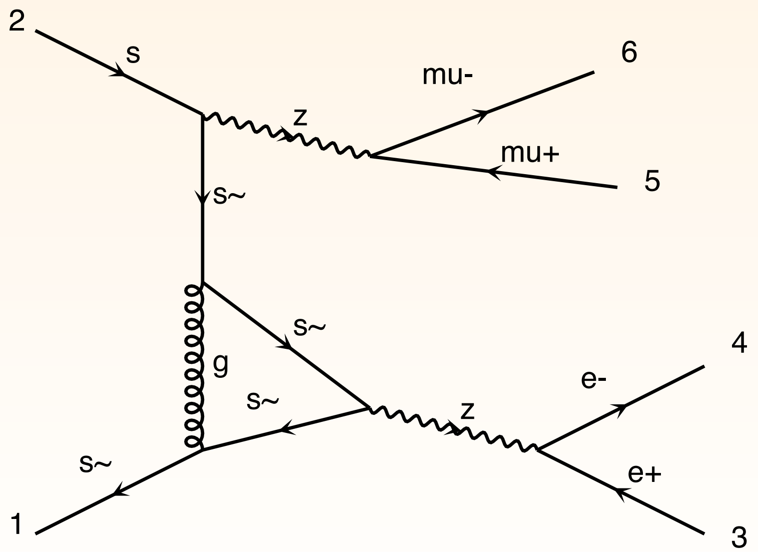
The code is publicly available since last November

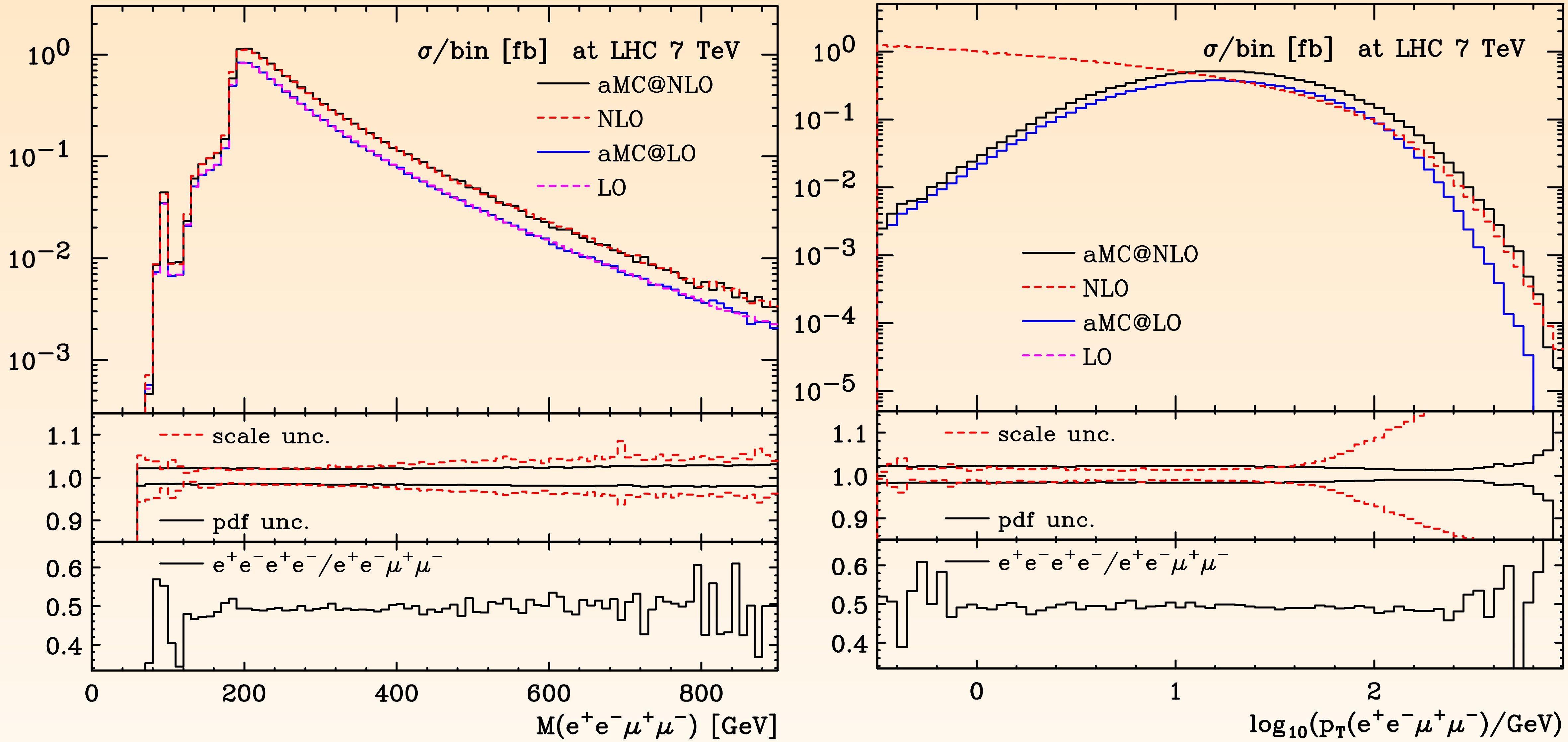
aMC@NLO: QUICK GUIDE

- Open the madgraph python shell:
```
$ ./bin/mg5
```
- From the shell generate the requested process, e.g.:
```
> 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



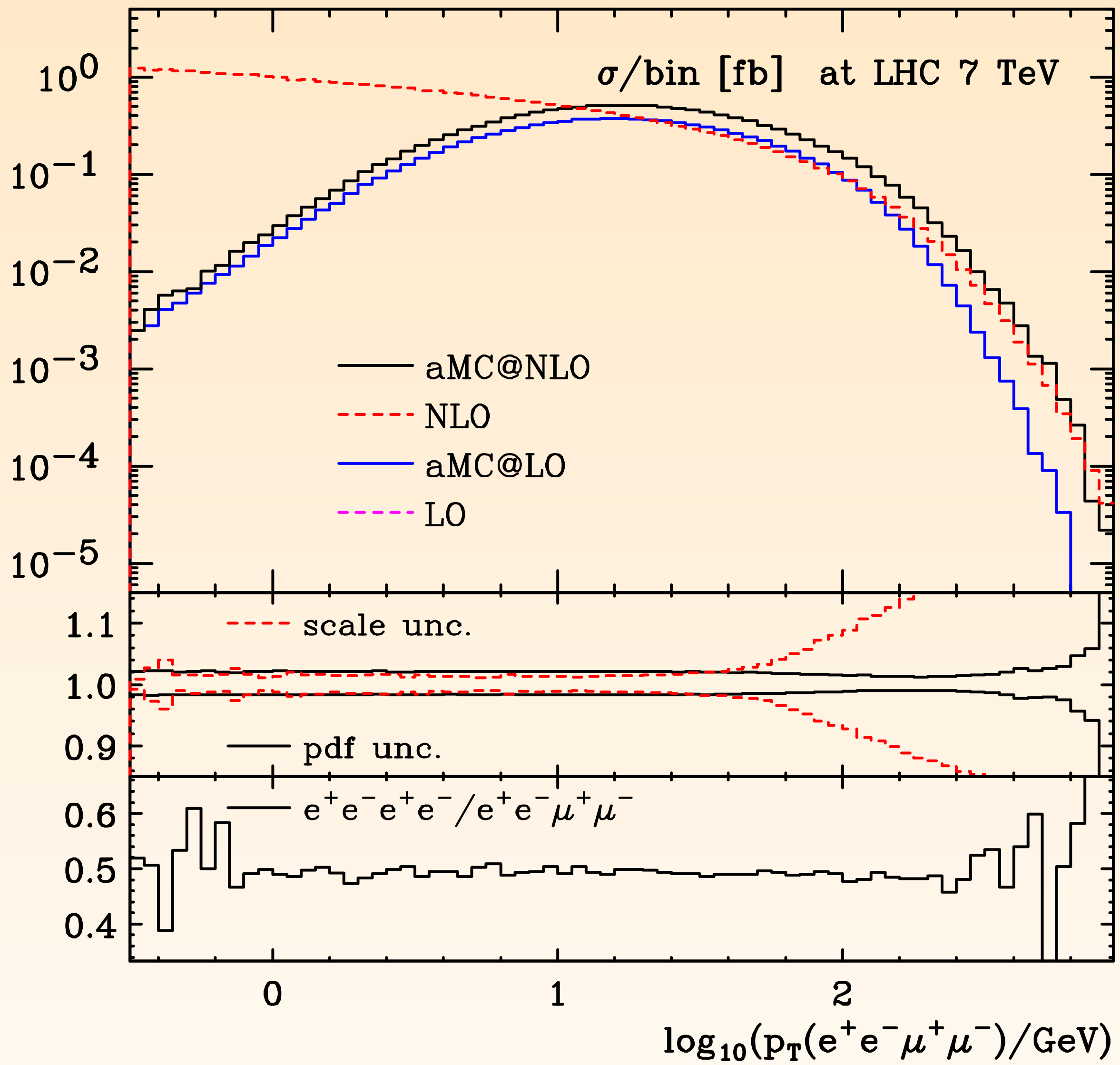
Four-lepton production

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

Four-lepton production



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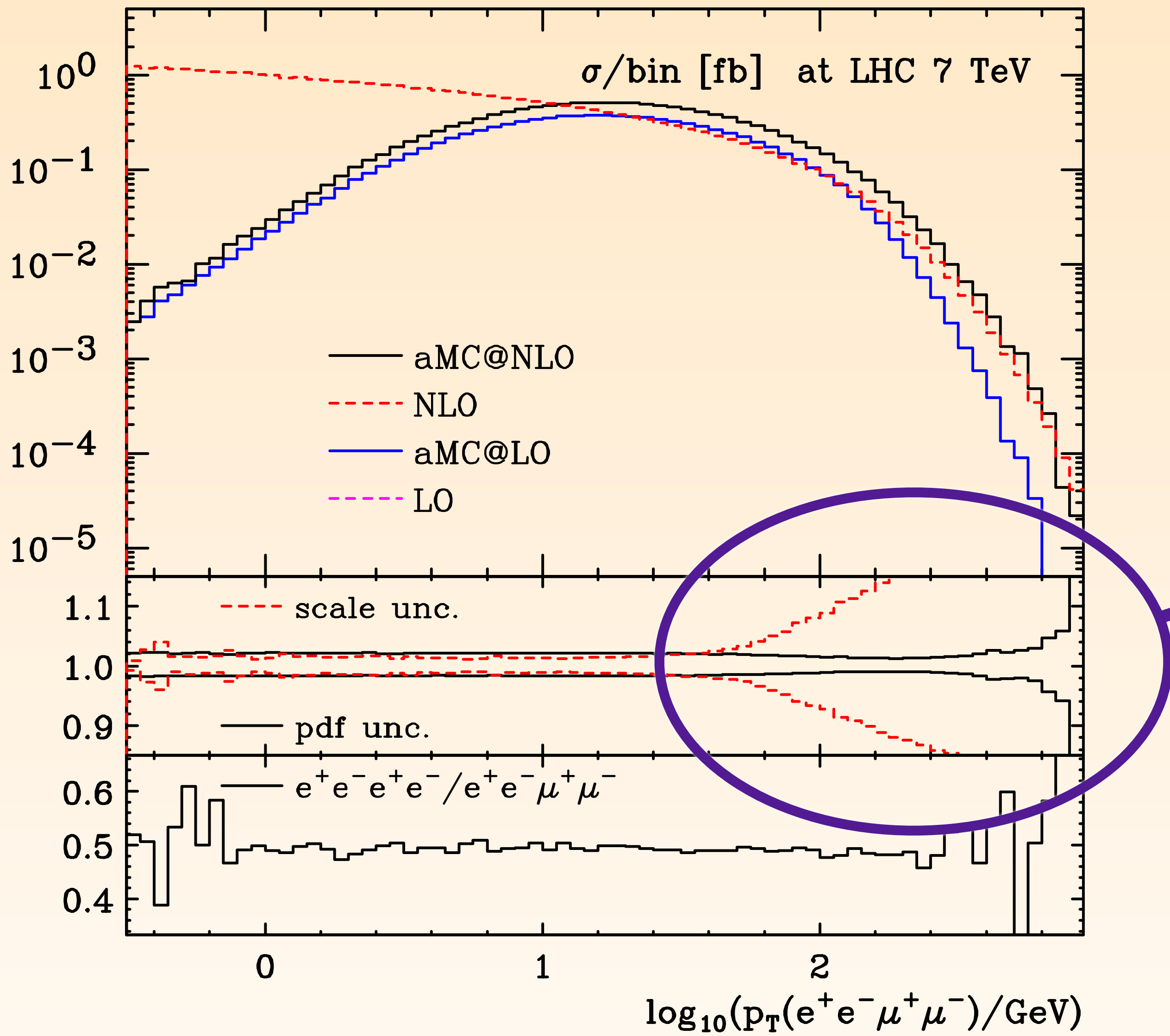
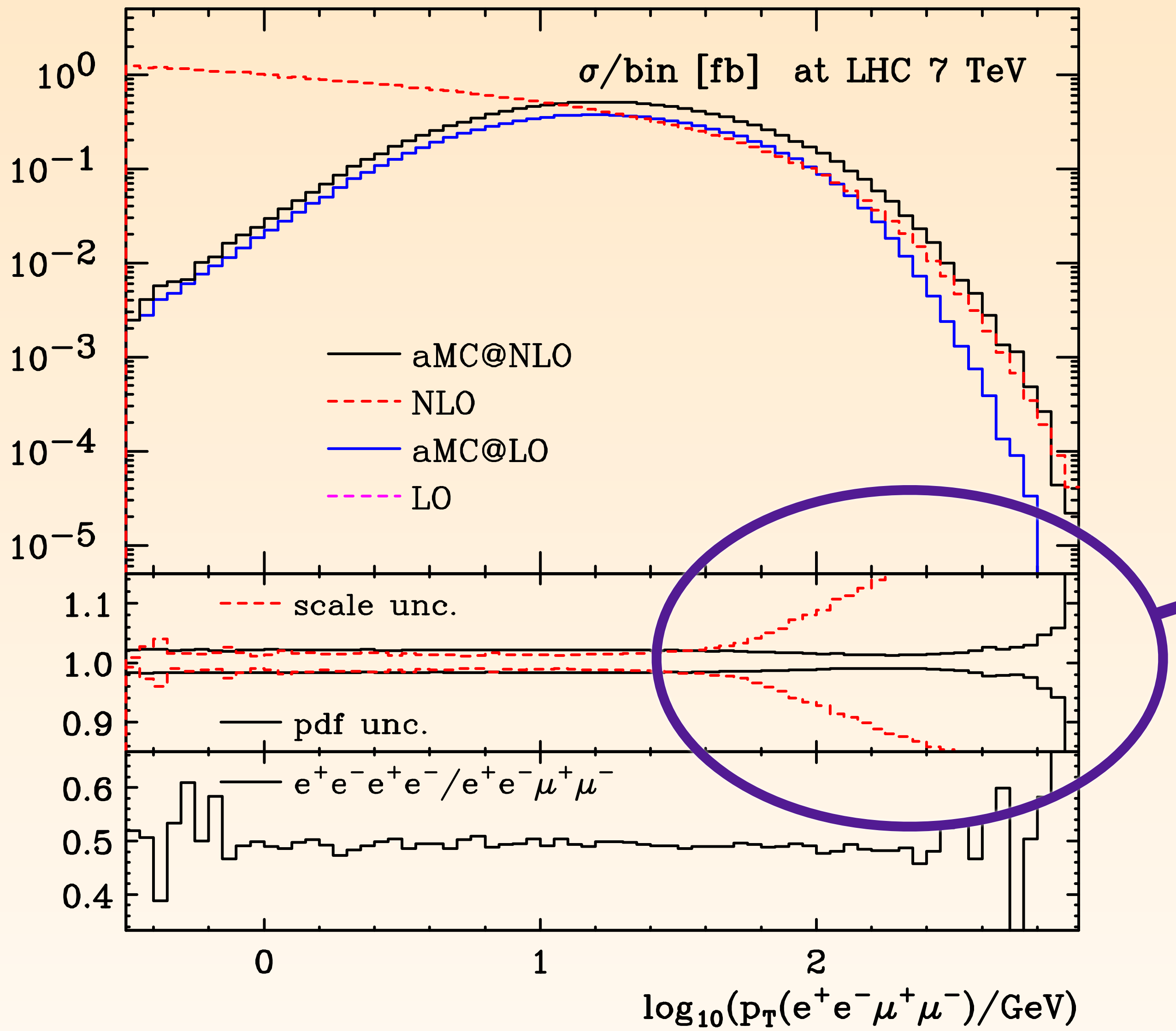


In the tail of the pT spectrum, there are large theoretical uncertainties. This is no surprise! Here the NLO calculation has actually only LO accuracy, because there must be a hard parton/jet recoiling against the 4-lepton system.

Four-lepton production



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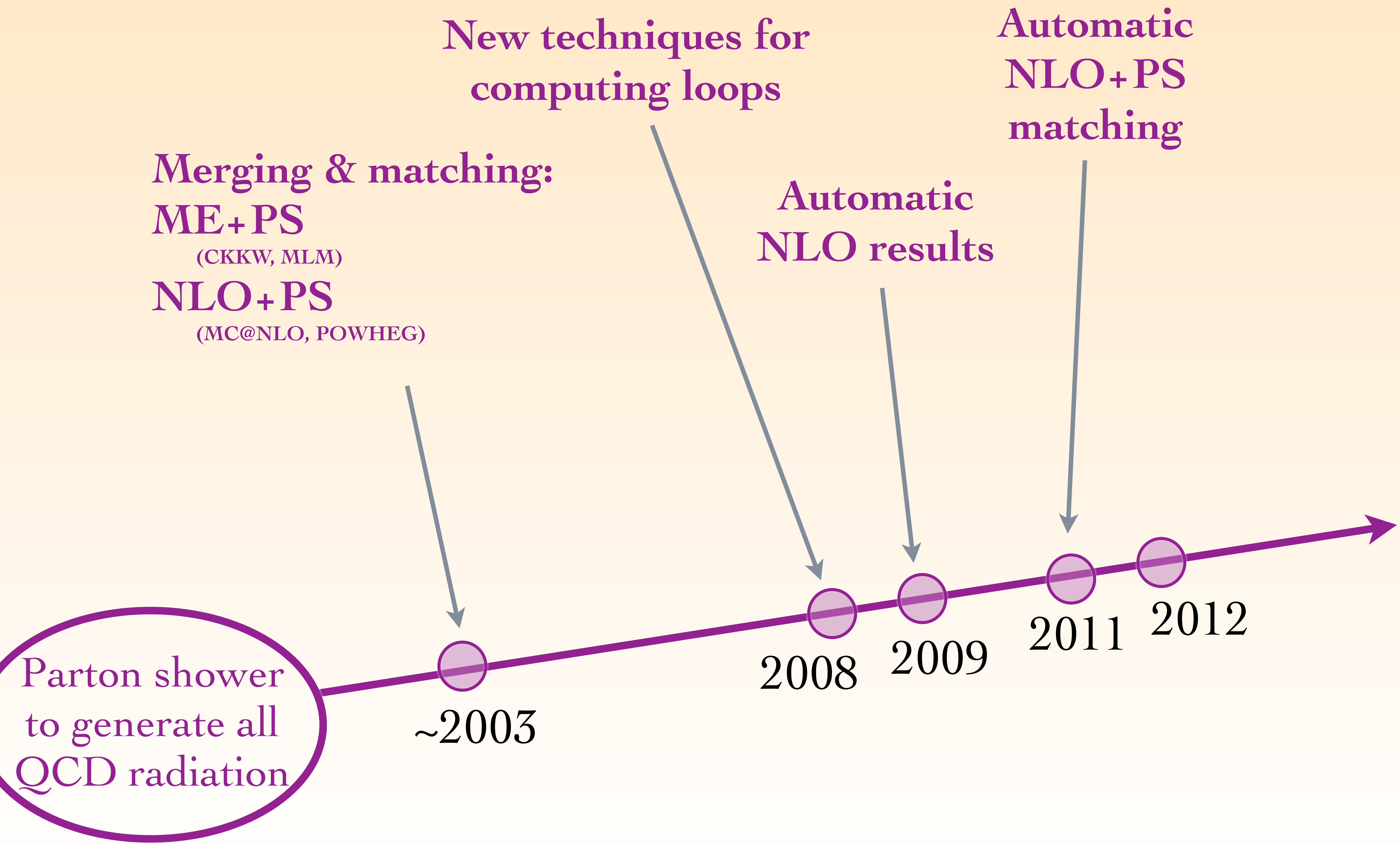
Can we include the NLO corrections to 4 leptons + 1 (hard) jet here?

QCD and MC progress



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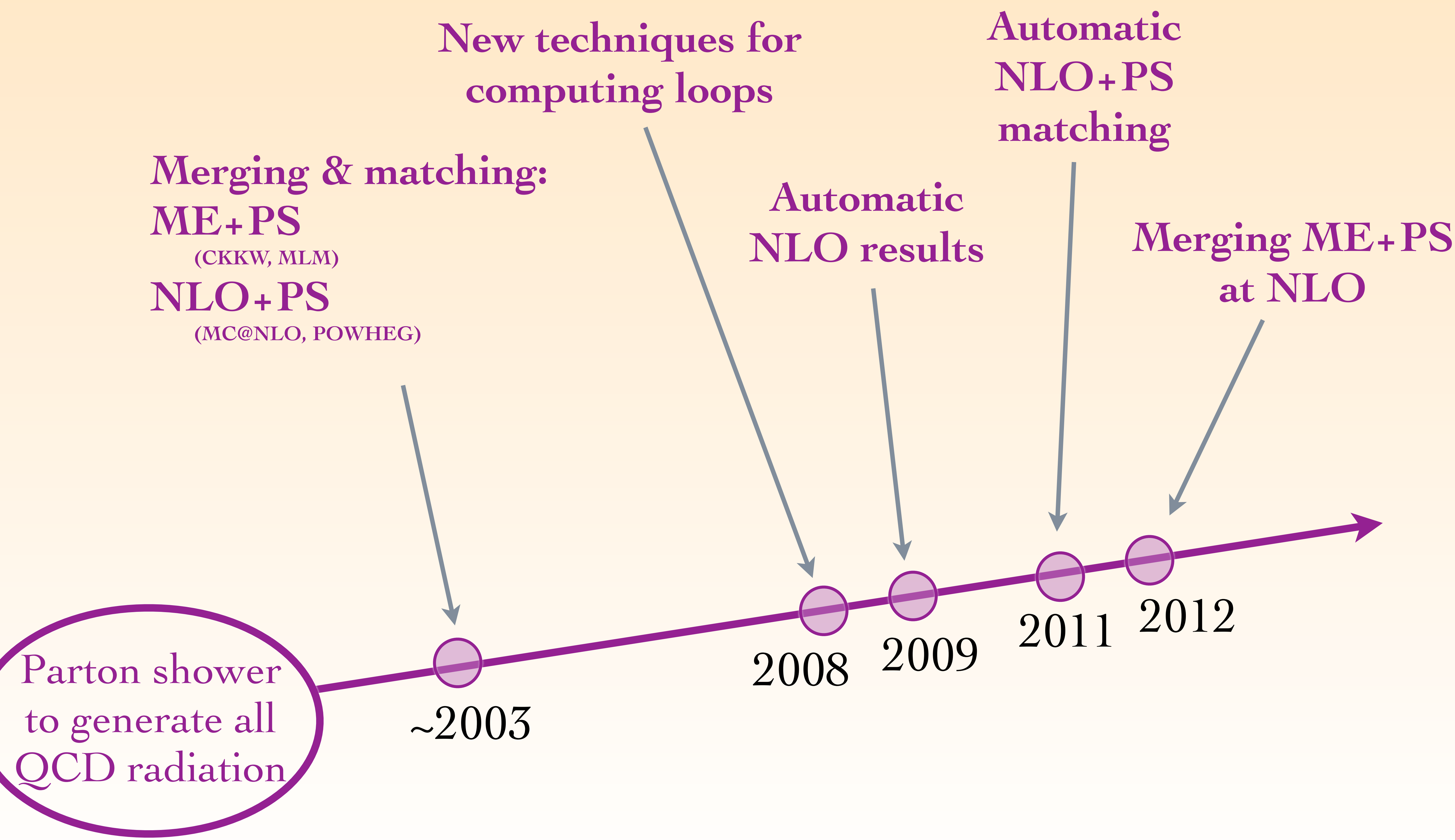
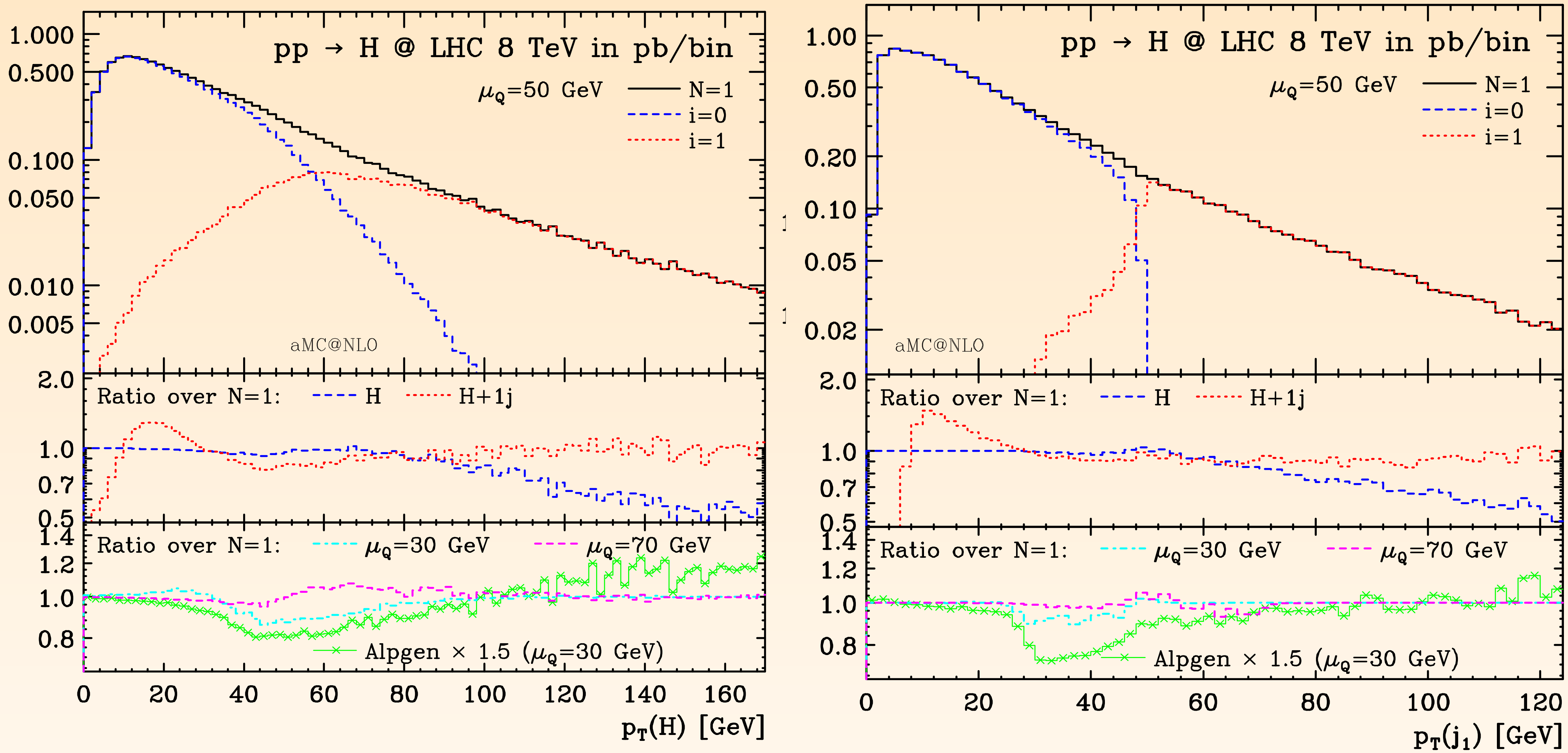


NLO merging: Higgs boson

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

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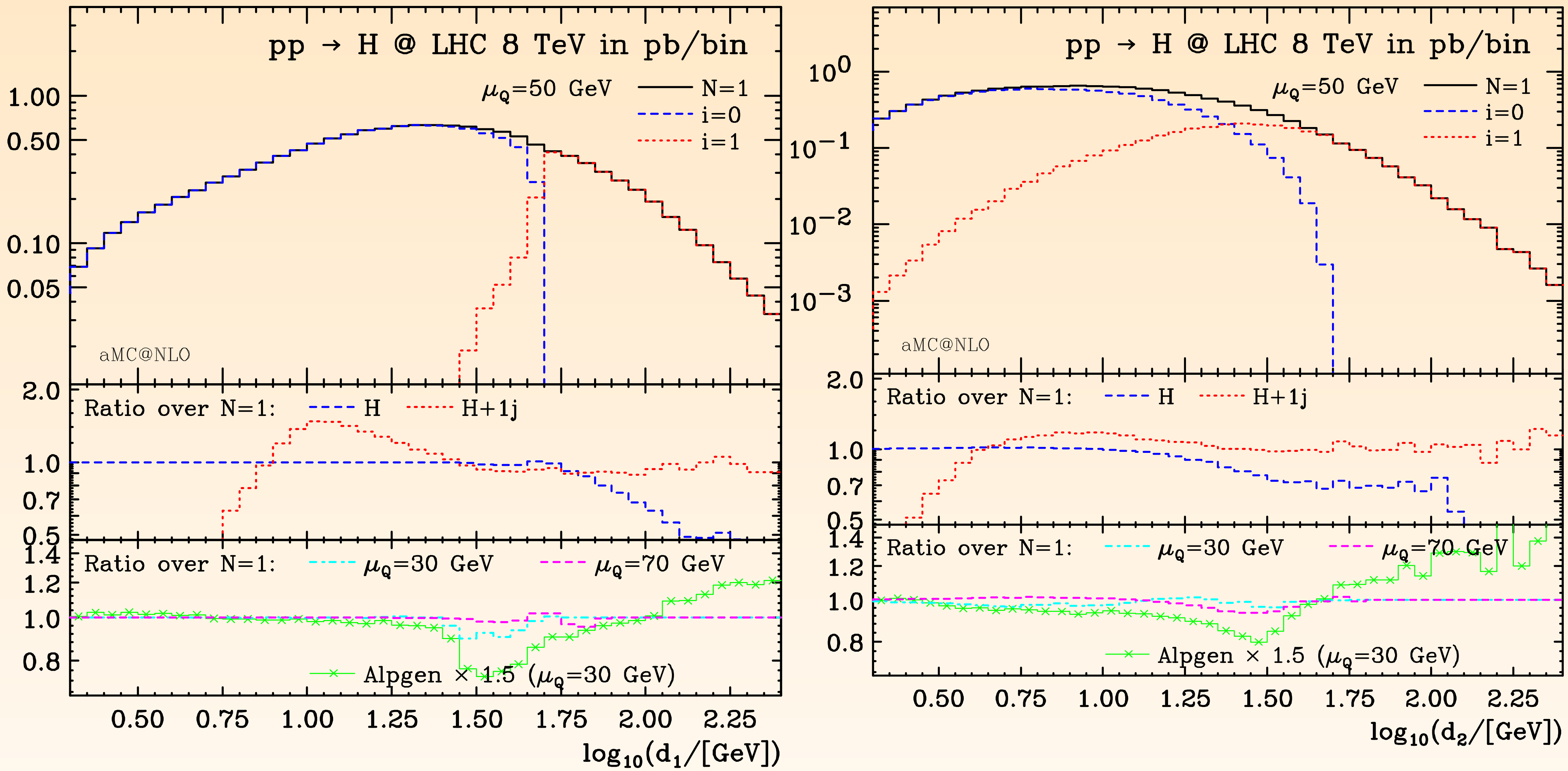
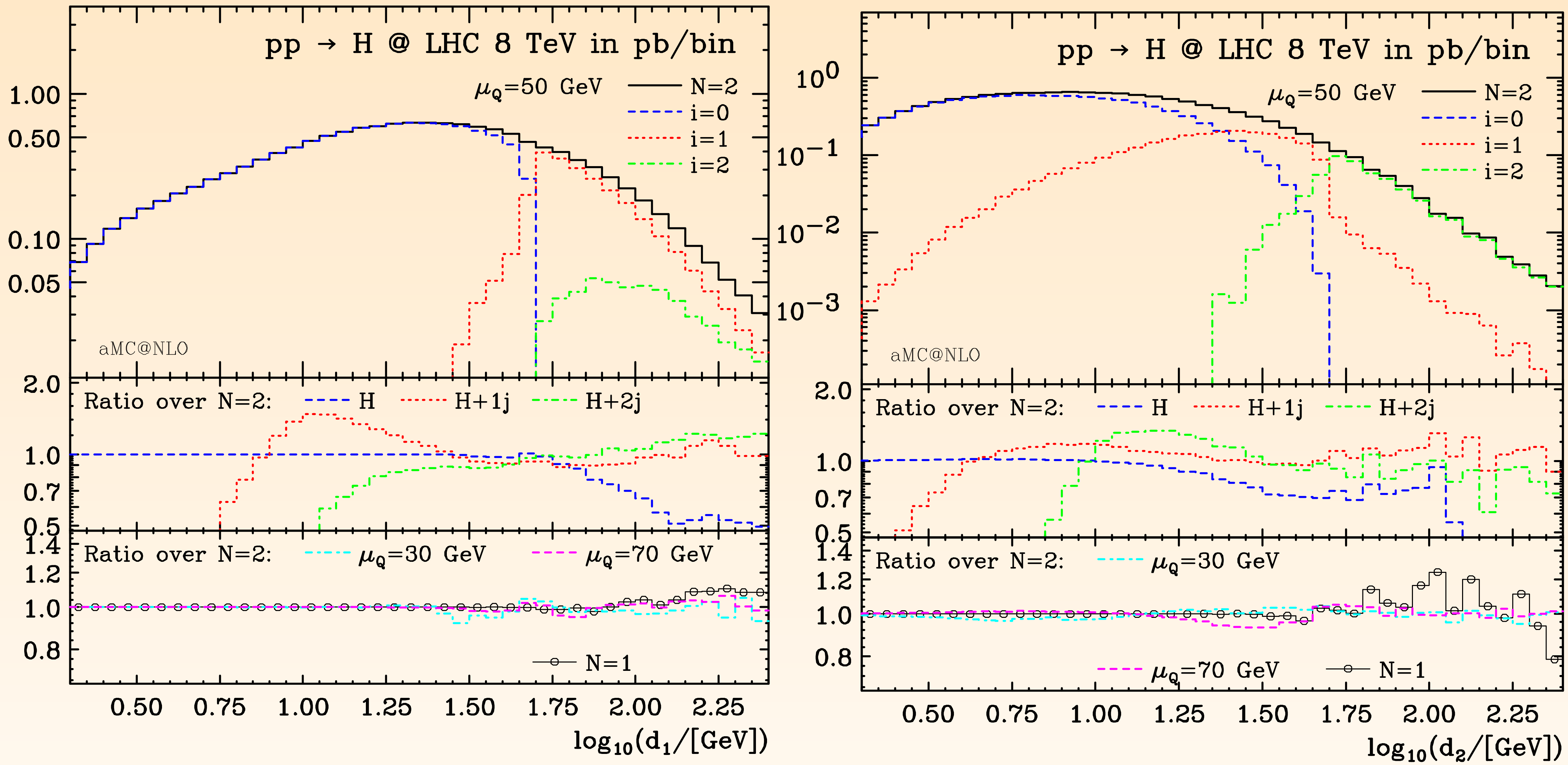


- Differential jet rates for 1->0 and 2->1

NLO merging: 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

Conclusions

- In the last ~10 years we've come a long way
- A lot of freedom in tuning has been replaced by accurate theory descriptions:
  - More predictive power
  - Better control on uncertainties
  - Greater trust in the measurements
- The only public tool that can generate events at NLO accuracy (in QCD) for any process in the SM (or simple extensions) is the `aMC@NLO` project. It is only limited in CPU time available