MC Tools &
NLO Monte Carlos

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Contents

- Short Introduction:
  - Automatic NLO+PS has been solved
  - Understanding the merging of multiplicities is underway
  - Even first steps for NNLO+PS have been taken
- Spin-correlations in ttbarHiggs
- Higgs Characterization framework
- VBF comparisons between aMC@NLO and POWHEG
- Open questions in H+2j vs. VBF
- Mass effects in gg->H and the Higgs pT distribution
  --> see H. Sargsyan's talk tomorrow afternoon

NLO predictions

- The most accurate predictions for fully exclusive event generation are based on NLO matrix elements. What does it give us?
  - 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; smaller uncertainties in interpolation from calibration regions to regions of interest
- 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 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 (+simple BSM extensions)

Available NLO+PS codes

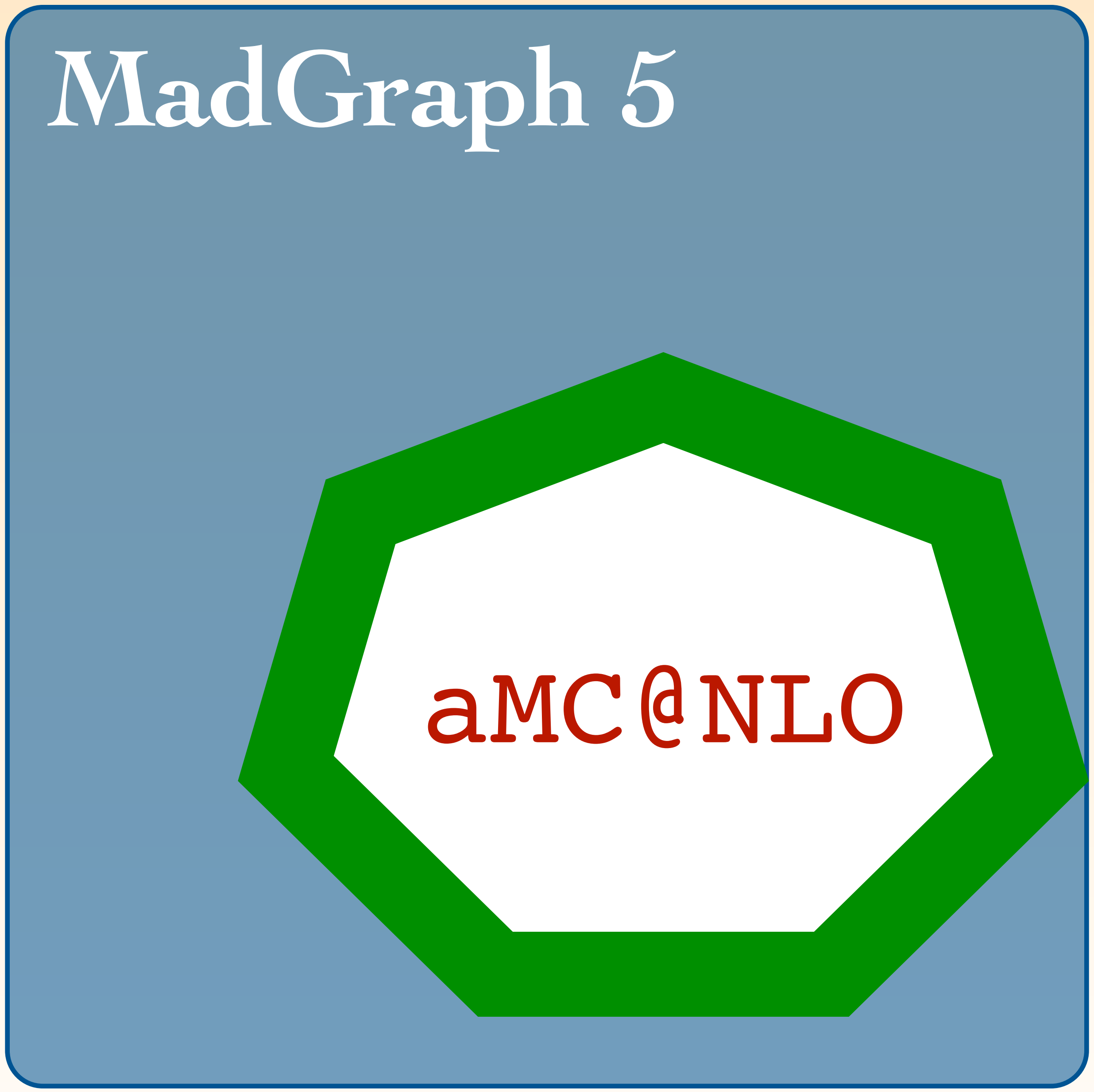
	NLO + PS	Parton Shower	Processes	Merging multiplicities at NLO
MC@NLO	Yes	Herwig 6 and Herwig++	Library for key SM processes	No
aMC@NLO	Yes	Herwig6, Herwig++, Pythia6 and Pythia8*	Code generation allows for any SM process, including simple BSM extensions	Yes, FxFx merging
POWHEG BOX	Yes	All*	Large library of processes; implementing new processes is relatively easy	Yes, MiNLO (without merging scale for simple processes)
SHERPA	Yes	Sherpa	Needs virtual corrections from external code	Yes, MEPS@NLO

aMC@NLO joint venture

aMC@NLO joint venture

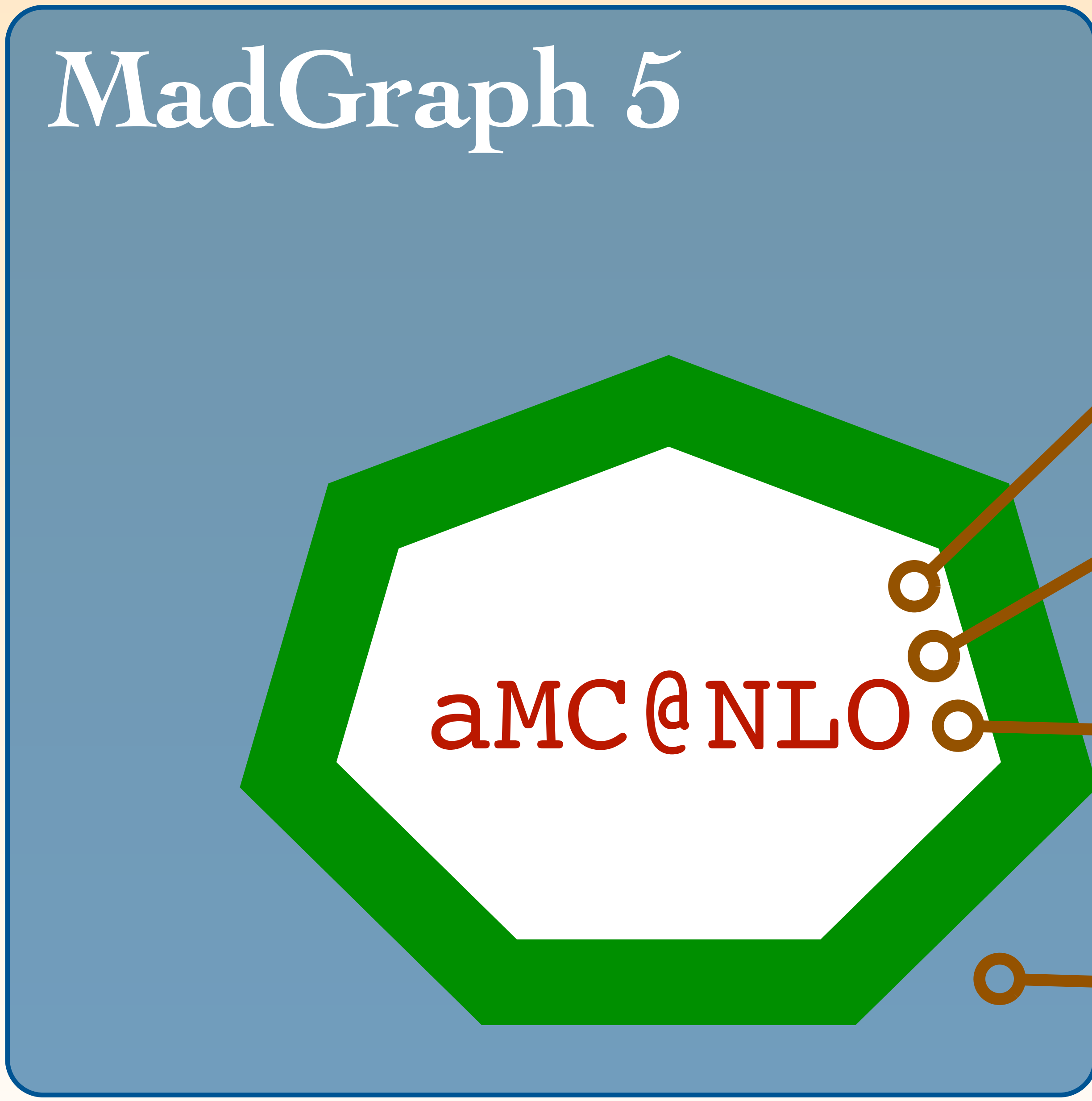
MadGraph 5

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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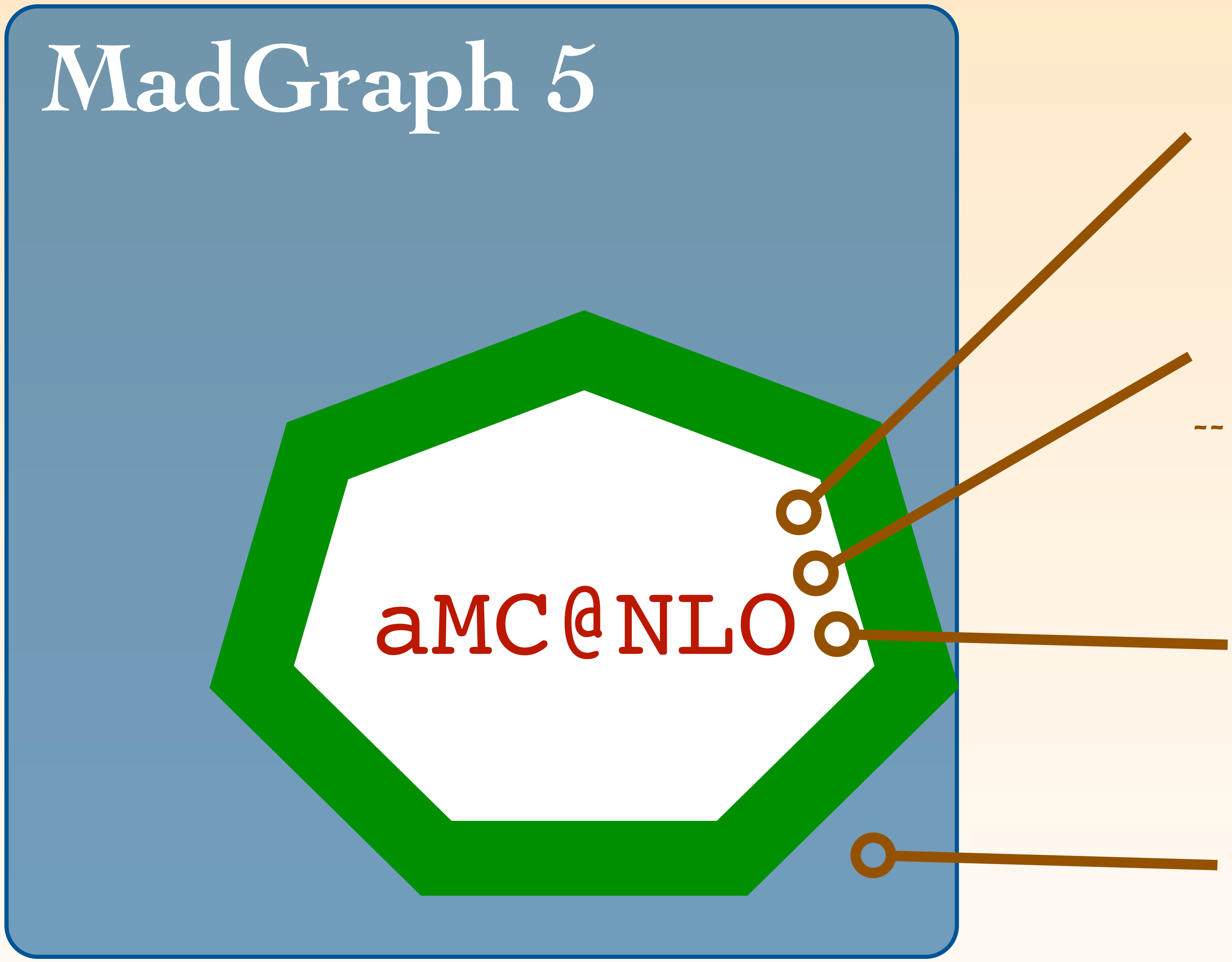

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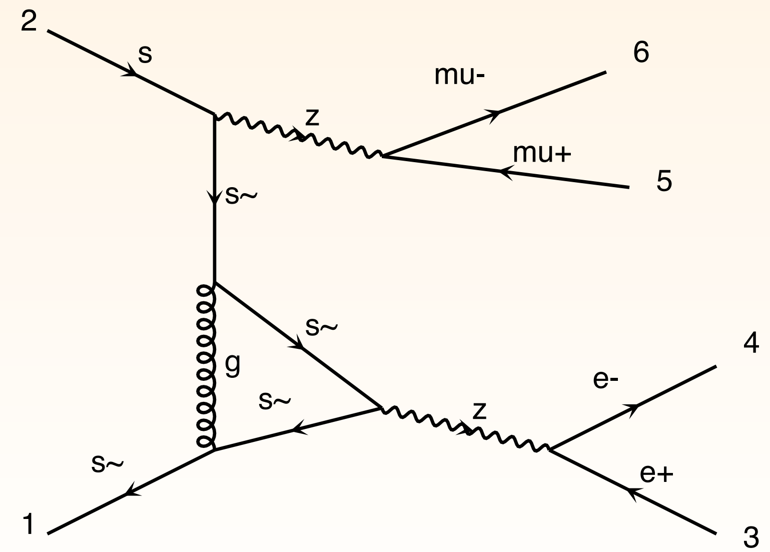
The code is publicly available since last November

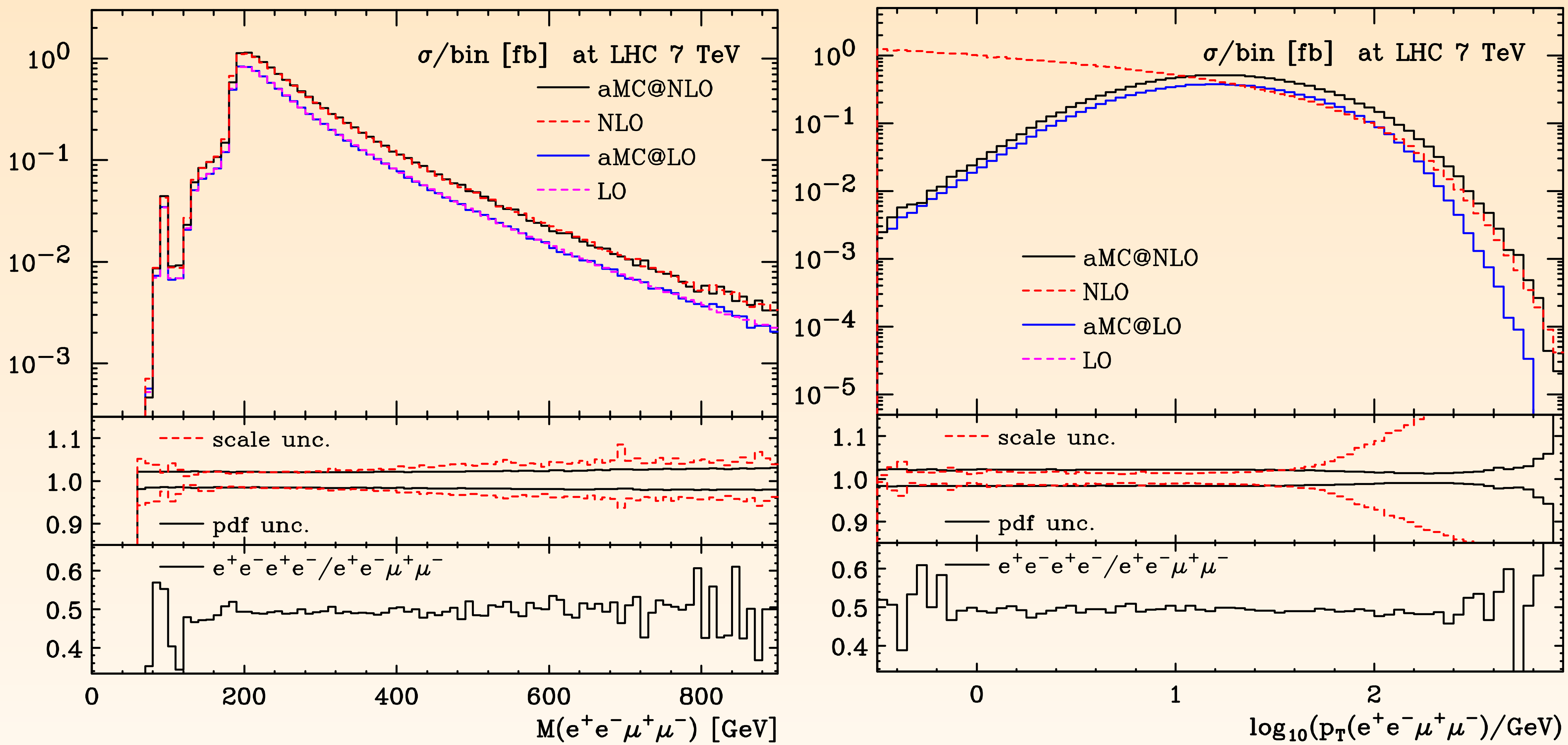
AMC@NLO: QUICK GUIDE

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



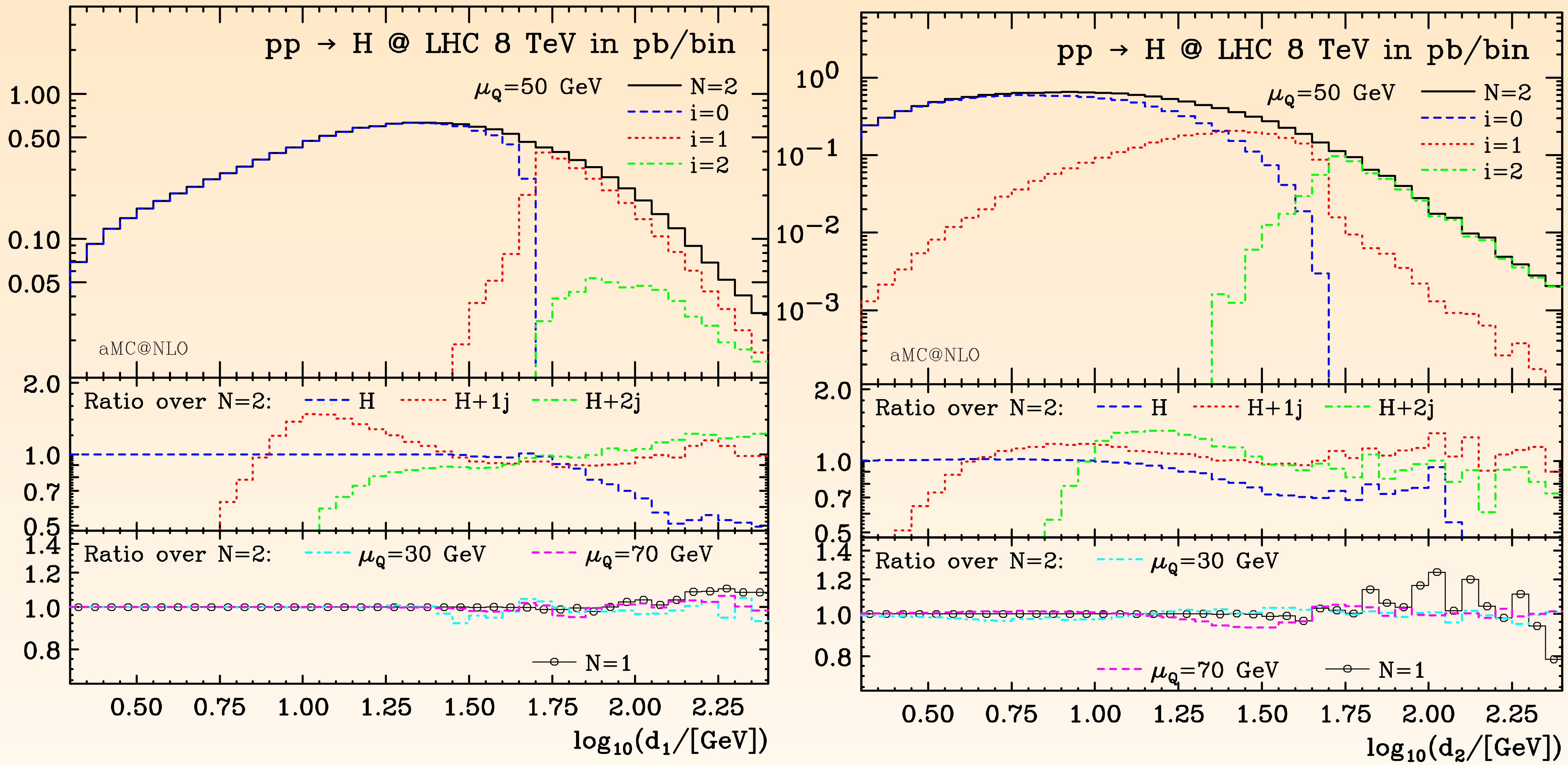
- 4-lepton invariant mass is almost insensitive to parton shower effects. 4-lepton transverse momentum is extremely sensitive
- Including scale uncertainties

Merging jet multiplicities at NLO

- Recent development in combining samples of various jet multiplicities (e.g. H+0j @NLO + H+1j @NLO + H+2j @NLO + ...) into one consistent event sample (also known as "CKKW" or "MLM" at NLO)
- Works very similar to their LO counterparts: (except the one implemented in POWHEG BOX)
  - Introduce a merging scale: use NLO matrix elements with jets harder than that scale, and the shower below the scale
  - Solve the extra sources of double counting compared to LO:
    explicit virtual corrections $\Longleftrightarrow$ Sudakov in shower
    real emission (below merging scale) $\Longleftrightarrow$ shower emissions
  - Also imposing "unitarity" (as defined by the "unlops" procedure) helps
- Merging scale cannot be chosen very small, because that formally hampers NLO precision of inclusive observables (e.g. Higgs rapidity)

FxFx merging: Higgs boson production

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

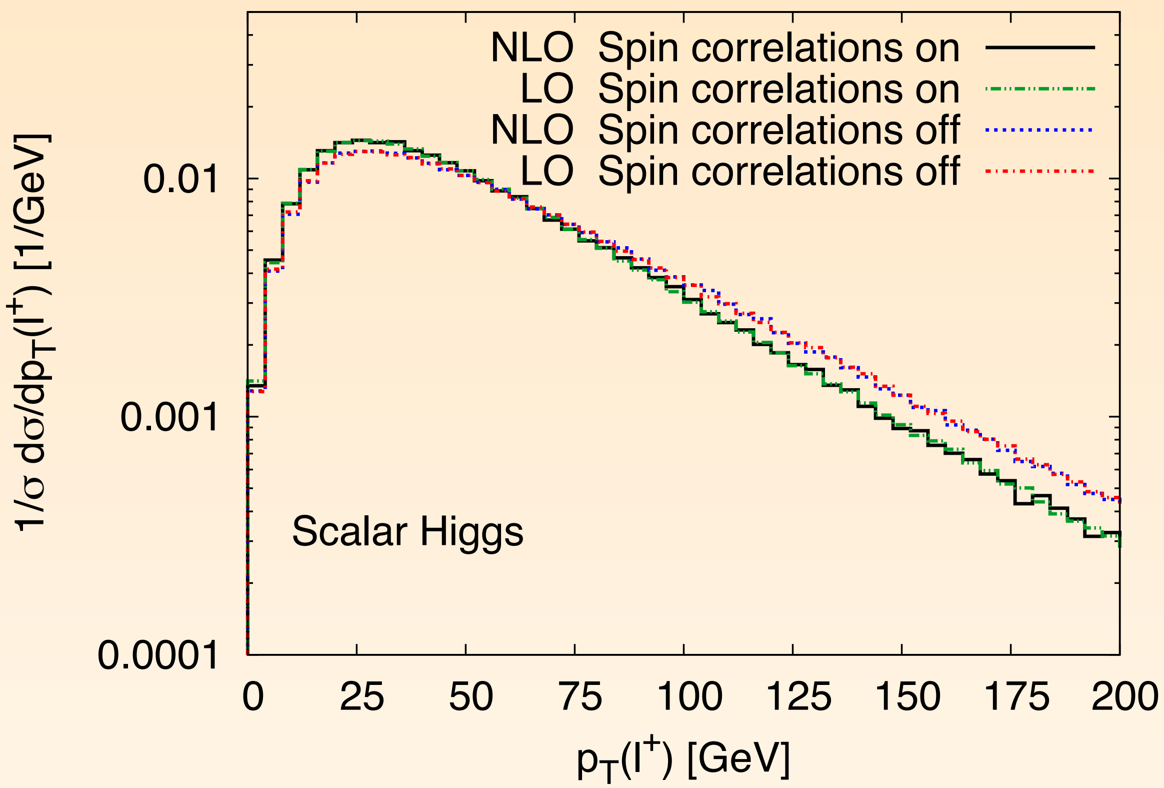
MiNLO: merging without a merging scale

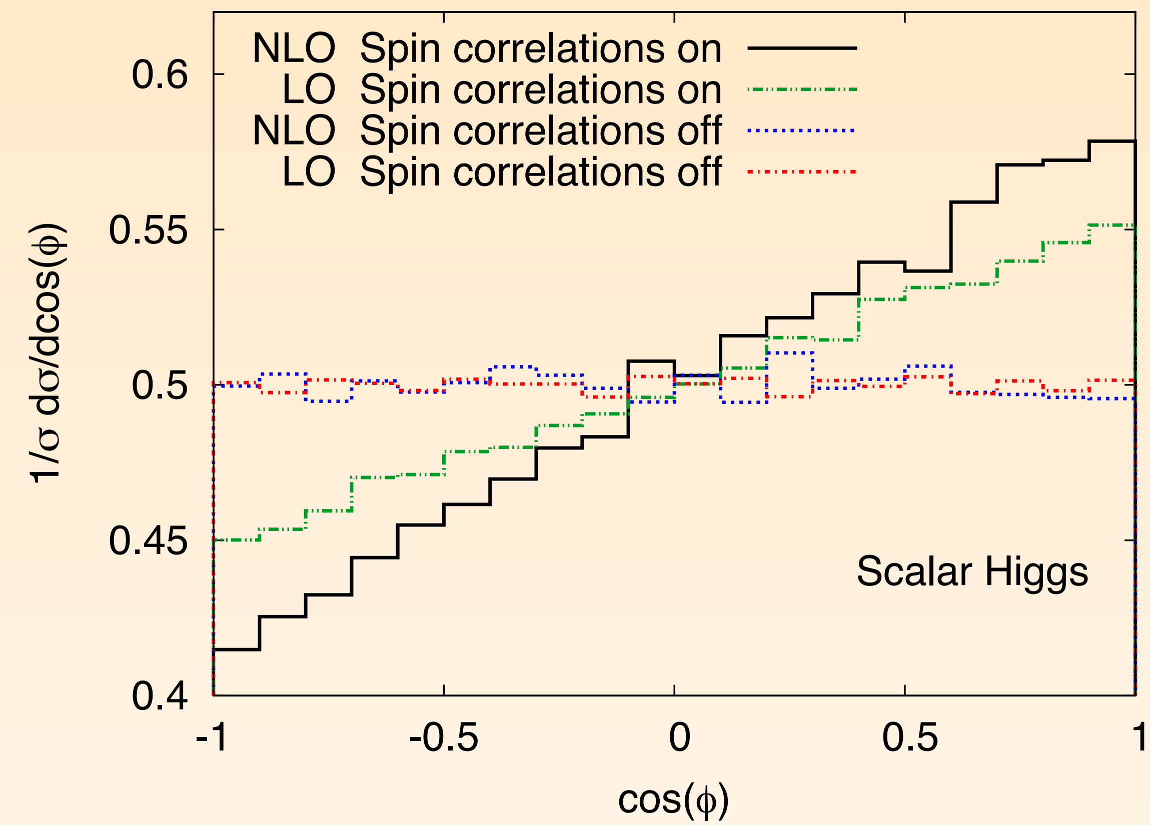
Hamilton, Nason, Oleari, Zanderighi, 2013

- By changing the Sudakov factor, the merging scale can be taken very small, without hampering the precision of inclusive observables (like the Higgs rapidity distribution)
- This effectively resums some higher order logarithmic effects
- However, this change in the Sudakov factor is process dependent and not so straight-forward to compute
- In fact, it is only known for S+0,1jets, where S is a general color-singlet state (H, H+W, Z, etc) and implemented in the POWHEG BOX for these kind of processes
- This opens a road to NNLO+PS by reweighting the events to the NNLO rapidity distribution. The technical details and validation of this method are currently on-going

Spin correlations in ttbarH production

Artoisenet, RF, Mattelaer, Rietkerk arXiv:1212.3460





- Using MadSpin, spin correlations can be included for LO as well as NLO events
- Only tree-level matrix elements are used (i.e. only NLO spin correlations in the virtual corrections that do not factor over the Born are lost)
- For some observables, spin correlations are much more important than higher order effects

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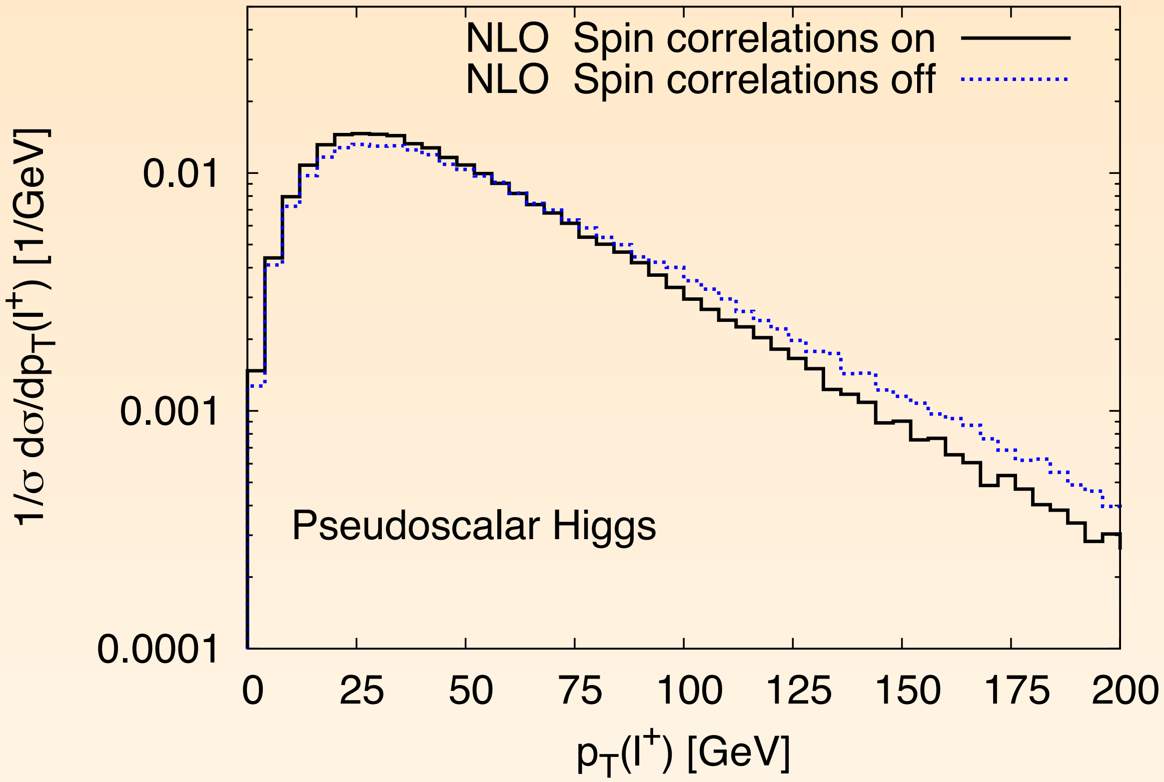

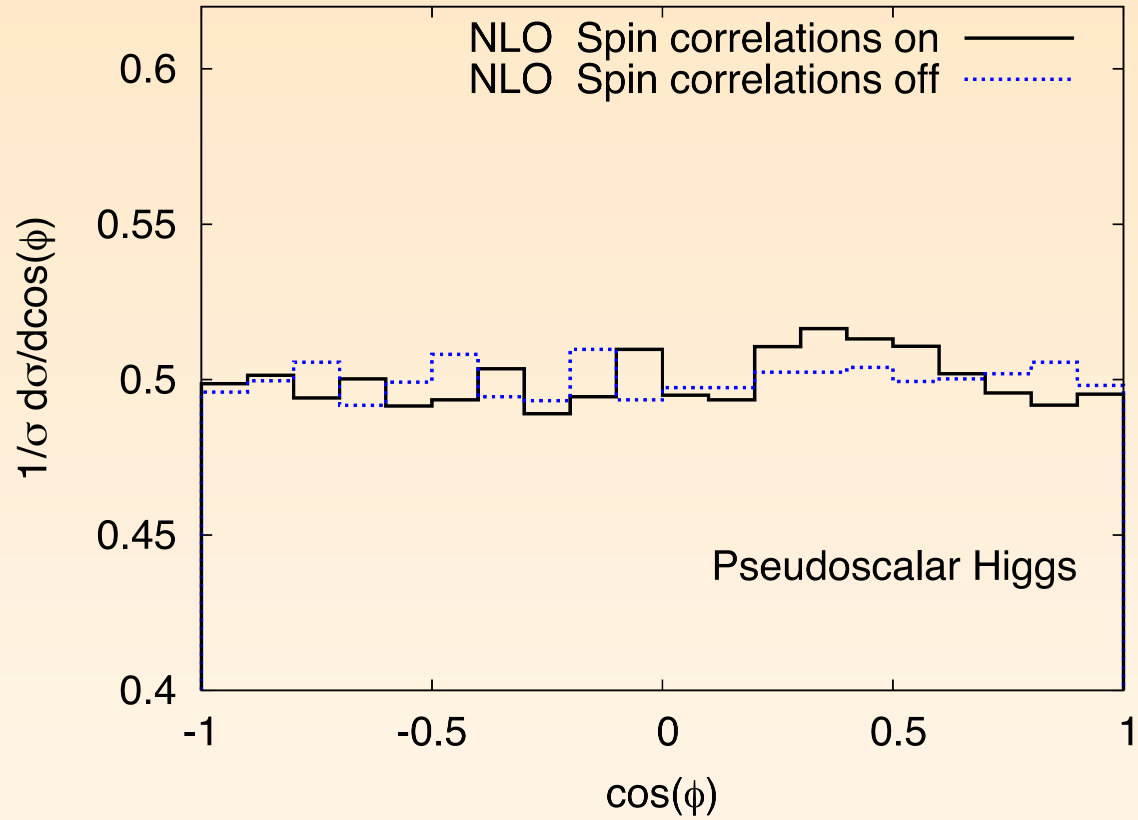

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Higgs characterization: spin-0

[P. Artoisenet et al. 2013]

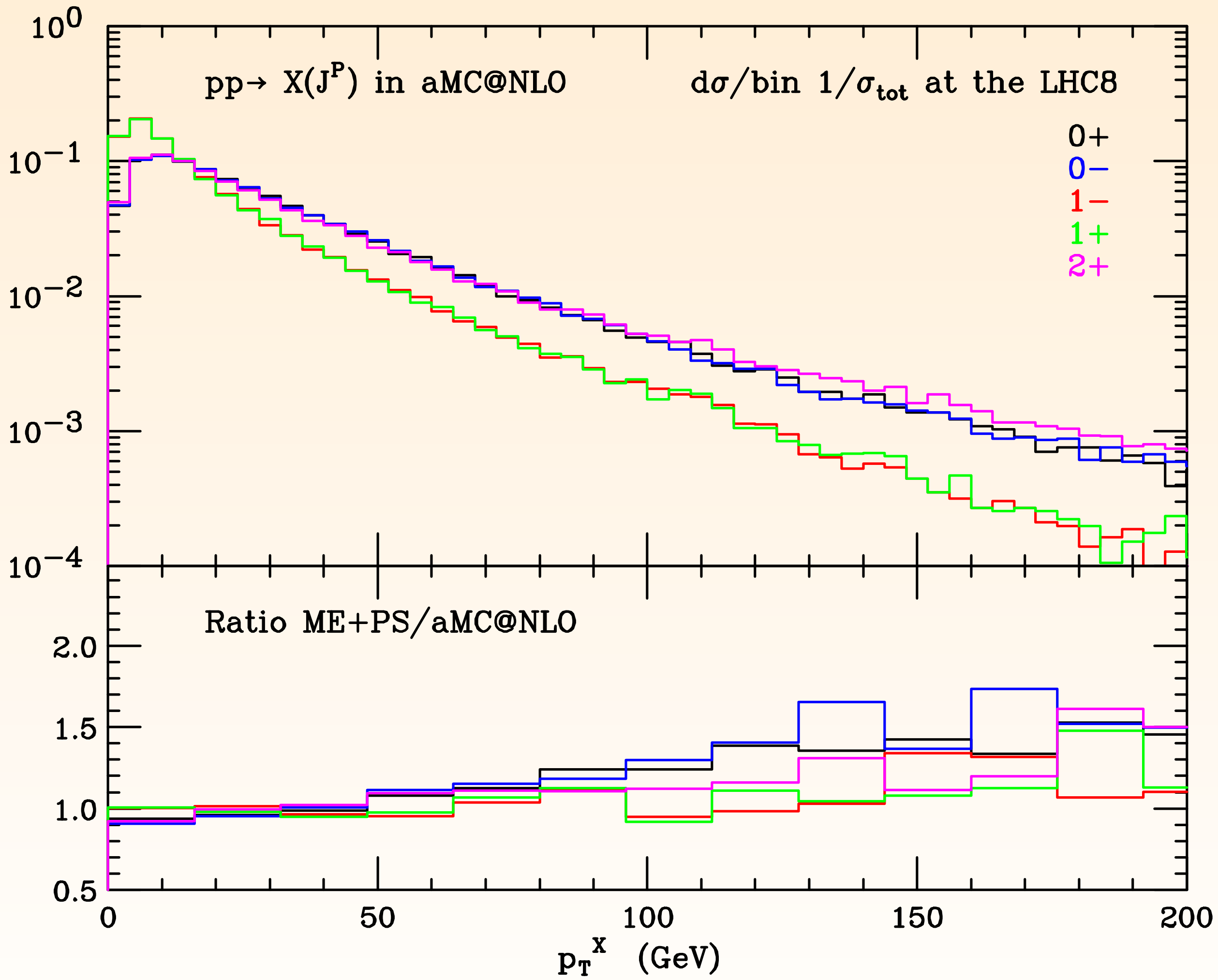
- Completely general spin-0, spin-1 and spin-2 "Higgs" with couplings up to dimension 6 are available as the FeynRules model "Higgs Characterization"
- This allows for automatic ME+PS event generation, but also NLO+PS (if the one-loop matrix elements are provided) within the MG5 framework
- For example: general Lagrangian for spin-0 "Higgs"

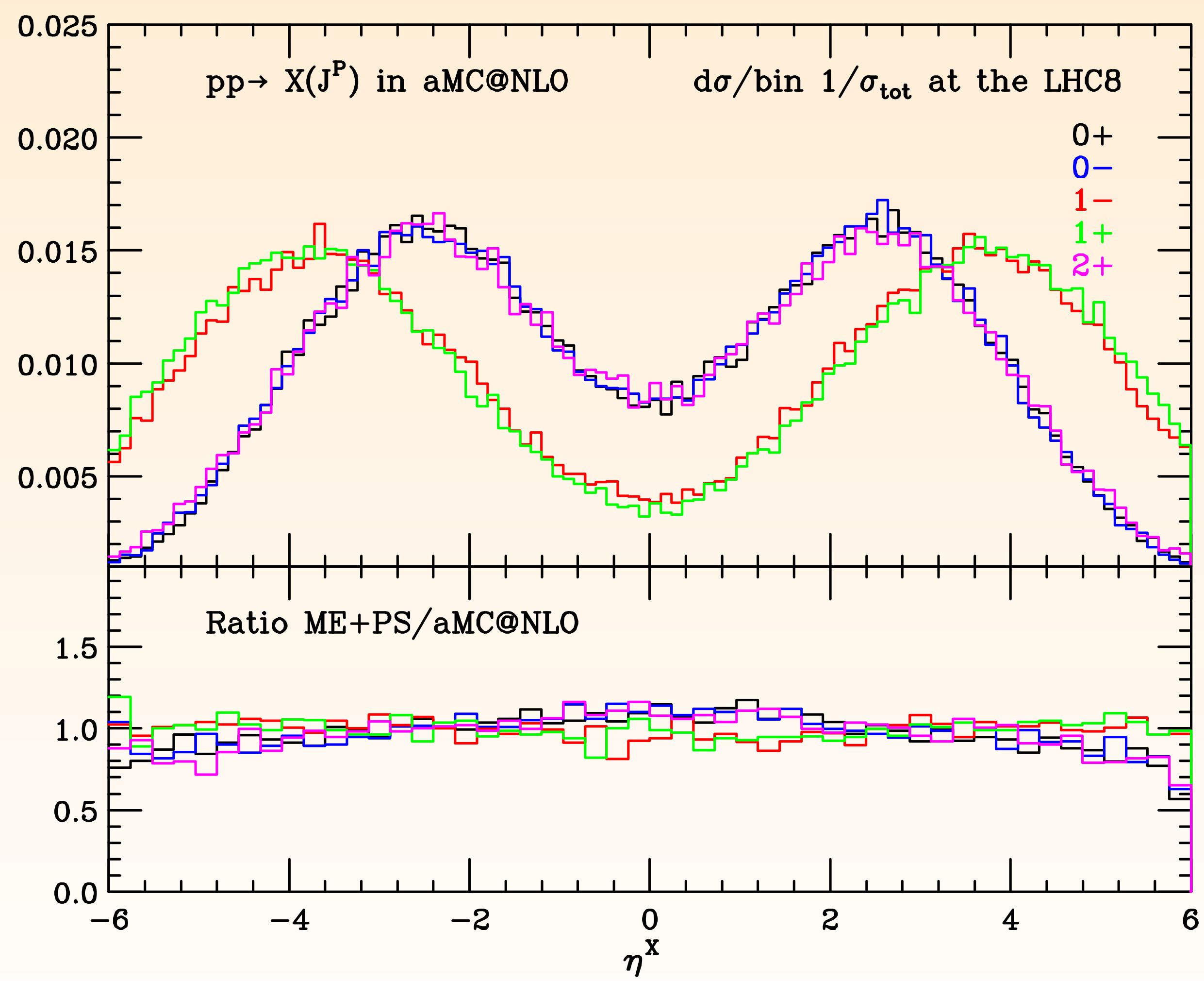
$$
\begin{aligned}
\mathcal{L}_0^f &= -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\, \gamma_5\big) \psi_f X_0 \\
\mathcal{L}_0^V &= \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\
&\quad - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
&\quad - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
&\quad - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] \\
&\quad - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
&\quad - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big] \\
&\quad - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W}\, \big(W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \Big\} X_0
\end{aligned}
$$

Higgs characterization: spin-0

[P. Artoisenet et al. 2013]

- Transverse momentum and rapidity of the "Higgs" boson
- Differences between ME+PS and aMC@NLO are small
- Difference between spin-0/2 and spin-1 are due to parton luminosities





aMC@NLO codes as "Special Codes"

http://amcatnlo.cern.ch

aMC@NLO web page

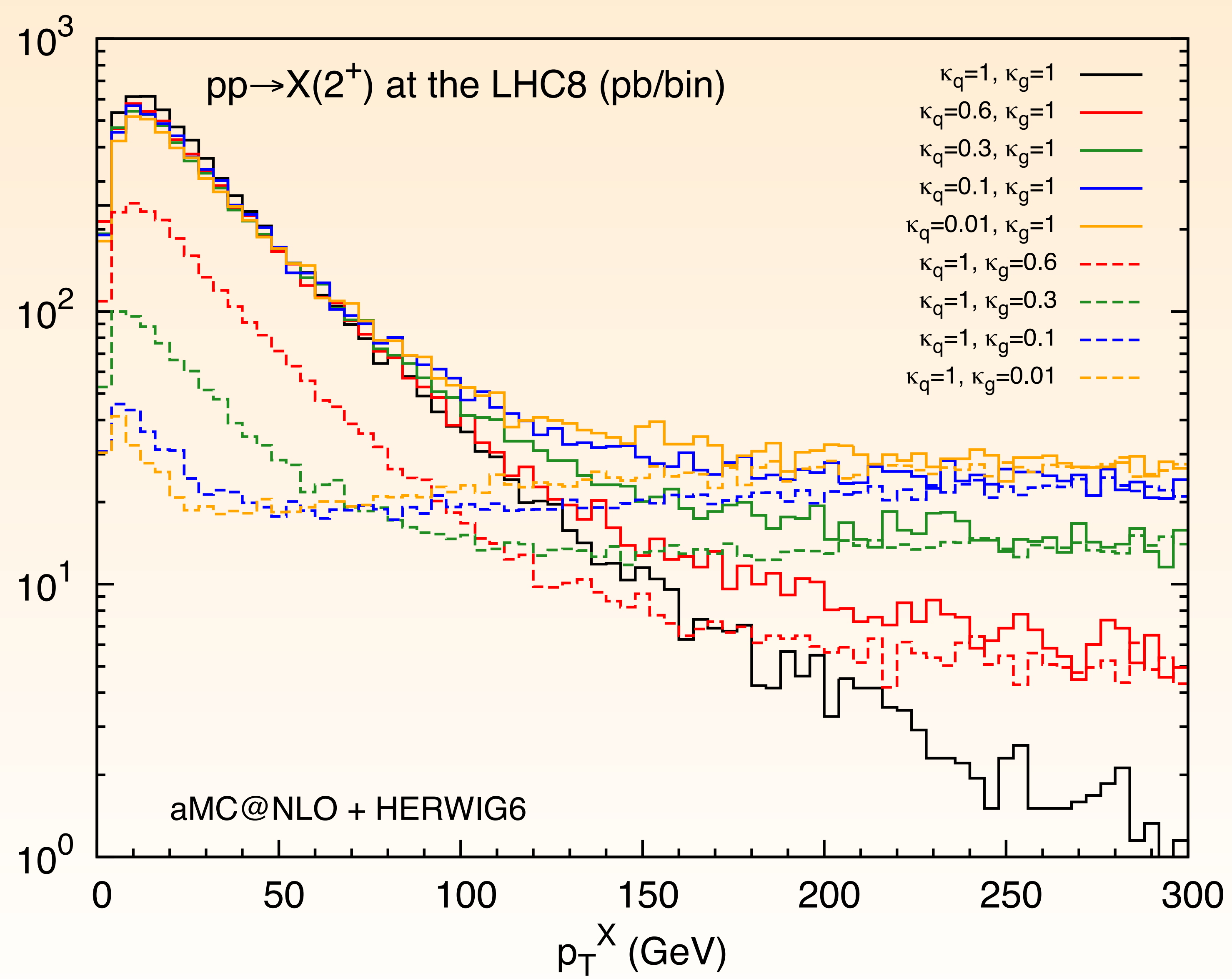
Process	Codes	Plots	Extra info
Higgs characterization. **Comparison plots:** pt of the "Higgs" rapidity of the "Higgs" jet rates			
New codes (version beta3): All codes use the Higgs Characterization 2.0 model (new since April 17, 2013) Please read the included README file.			
$pp \to 0^{\pm} + X$	Decay to 2 photons Decay to 2 Zs Decay to 2 Ws	Coming soon...	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. Setting the 'ca' parameter in the param_card.dat to 0 or 1 allows to obtain respectively a pseudoscalar or a scalar resonance. The mixed case is not allowed in aMCatNLO. Codes include the leptonic decay of vector bosons.
$pp \to 1^{\pm} + X$	Decay to 2 Zs Decay to 2 Ws	Coming soon...	Virtuals coded by hand by R. Frederix and M. Zaro from the known analytic results. The 1- (vector) case can be obtained setting the parameters $\kappa_{f_b} = \kappa_{V_4} = \kappa_{V_5} = 0$. For the 1+ (axial-vector) case: $\kappa_{f_a} = \kappa_{V_1} = \kappa_{V_2} = \kappa_{V_3} = 0$. Mixed cases are also possible. Codes include the leptonic decay of vector bosons.
$pp \to 2^{+} + X$	Decay to 2 photons Decay to 2 Zs Decay to 2 Ws	X Pt (varying kq, kg)	Virtuals from V. Ravindran et al. The 'kq', 'kg' parameters in the param_card.dat allow to change the relative strength of the spin-2 particle coupling to quarks and gluons. Codes include the leptonic decay of vector bosons.

HIGGS CHARACTERIZATION: SPIN-2 EXAMPLE

[P. Artoisenet et al. 2013]

$$\mathcal{L}_2^f = -\frac{1}{\Lambda}\sum_{f=q,\ell} \kappa_f\, T^f_{\mu\nu} X_2^{\mu\nu} \qquad \mathcal{L}_2^V = -\frac{1}{\Lambda}\sum_{V=Z,W,\gamma,g} \kappa_V\, T^V_{\mu\nu} X_2^{\mu\nu}$$

- Allow for non-standard RS scenarios with $\kappa_f \neq \kappa_V$
- Extra unitarity violating terms due to non-decoupling (when $\kappa_f \neq \kappa_V$) of the longitudinal parts of graviton polarization tensor
- Rather different shape between $\kappa_f \neq 0$ and $\kappa_V \neq 0$
- Need NLO or ME+PS to see these effects



JHU CHECK

- The well-known leading-order JHU code [Bolognesi et al.] covers only a subset of the allowed parameter space

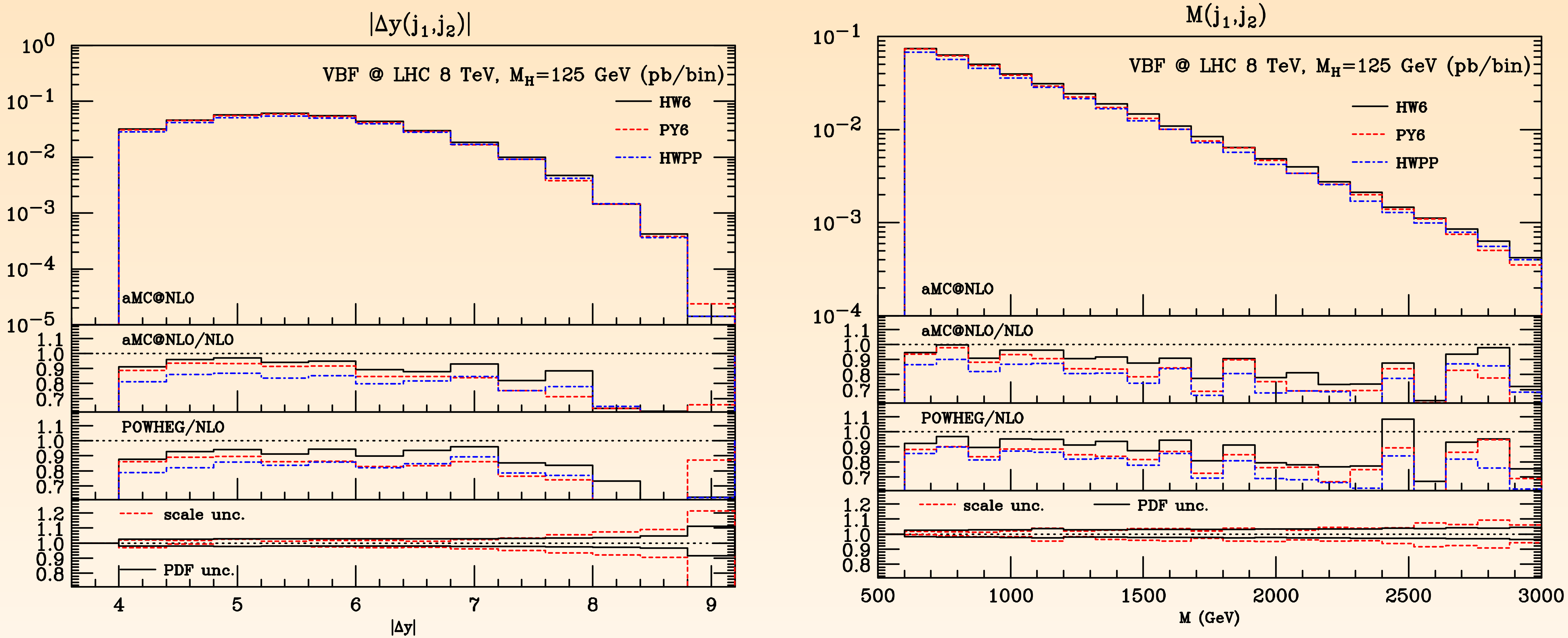
JHU scenario	HC parameter choice	
	X production	X decay
0^+_m	$\kappa_{Hgg} \neq 0$	$\kappa_{\rm SM} \neq 0$ $(c_\alpha = 1)$
0^+_h	$\kappa_{Hgg} \neq 0$	$\kappa_{H\gamma\gamma,HZZ,HWW} \neq 0$ $(c_\alpha = 1)$
0^-	$\kappa_{Agg} \neq 0$	$\kappa_{A\gamma\gamma,AZZ,AWW} \neq 0$ $(c_\alpha = 0)$
1^+	$\kappa_{f_a,f_b} \neq 0$	$\kappa_{Z_5,W_5} \neq 0$
1^-	$\kappa_{f_a,f_b} \neq 0$	$\kappa_{Z_3,W_3} \neq 0$
2^+_m	$\kappa_g \neq 0$	$\kappa_{\gamma,Z,W} \neq 0$

Couplings not explicitly mentioned are understood to be equal to zero

VBF with aMC@NLO and POWHEG

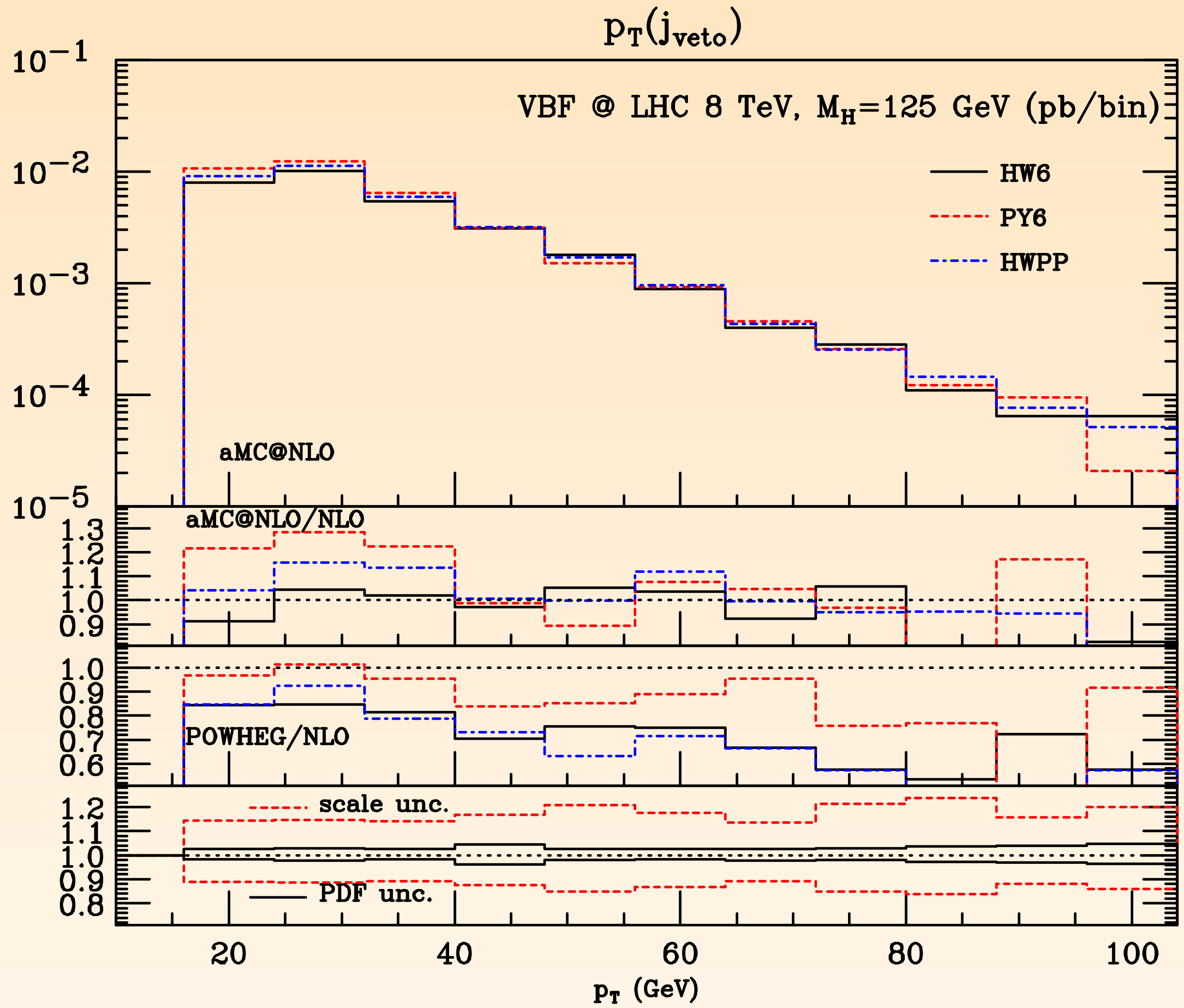
- Frixione, Torrielli and Zaro (arXiv:1304.7927) studied the differences between aMC@NLO and POWHEG as well as the dependence on the parton shower (Herwig6, Pythia6 and Herwig++) for key observables in Higgs production by VBF
- Very consistent picture:
  - Difference are ~5% for NLO accurate observables, which is the about the same as the scale uncertainty
  - Differences are 10-15% for LO accurate observables (related to a 3rd jet), which is again about the same as the scale uncertainty

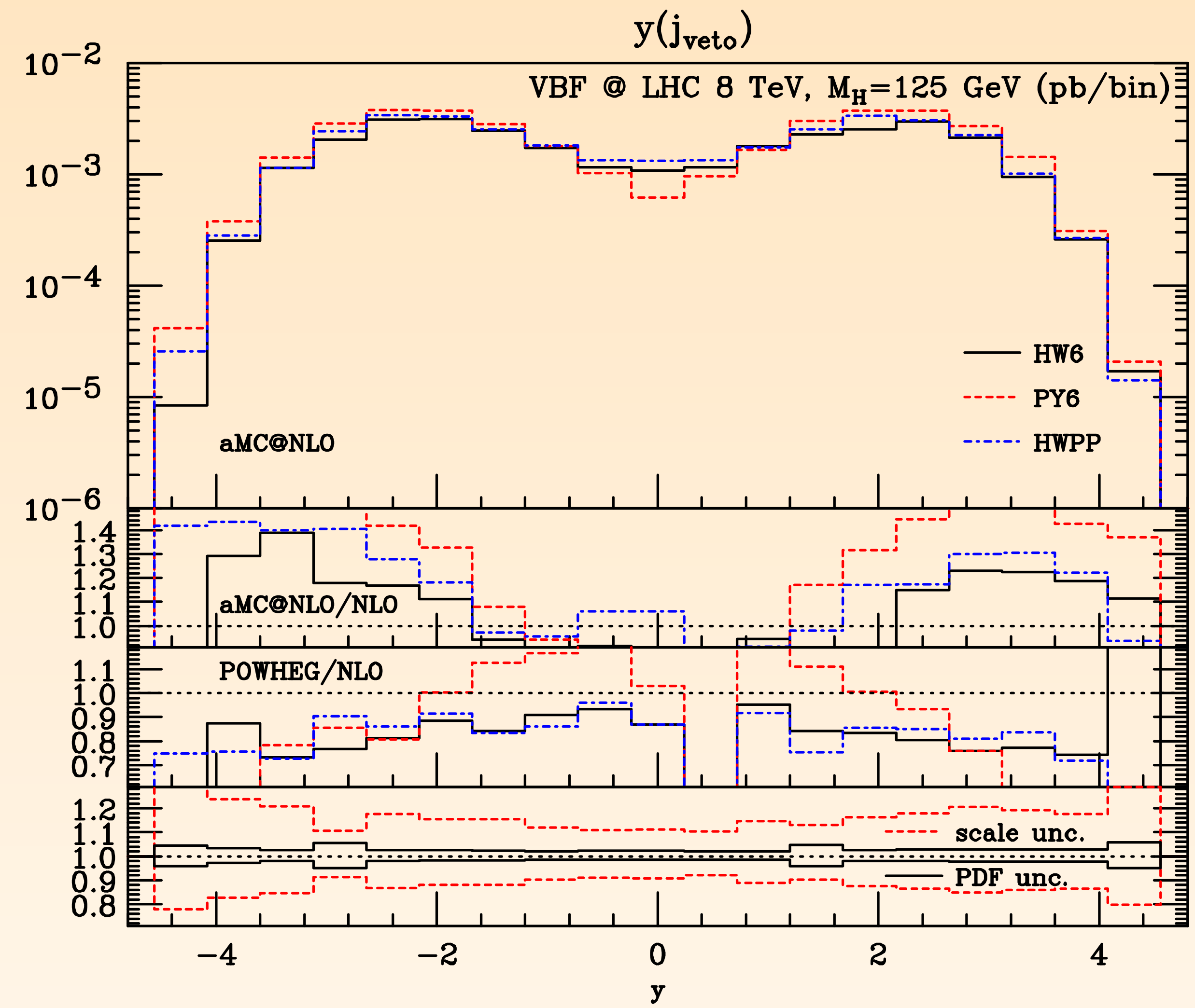
VBF WITH AMC@NLO AND POWHEG



- Rapidity difference (left) and invariant mass (right) of the two hardest jets, with VBF type cuts (without jet veto)
- Differences between the showers for the two matching methods are ~5%, which is of the same order as the scale uncertainty
- Difference with fixed order larger, in particular in the tails of the distributions

VBF with aMC@NLO and POWHEG





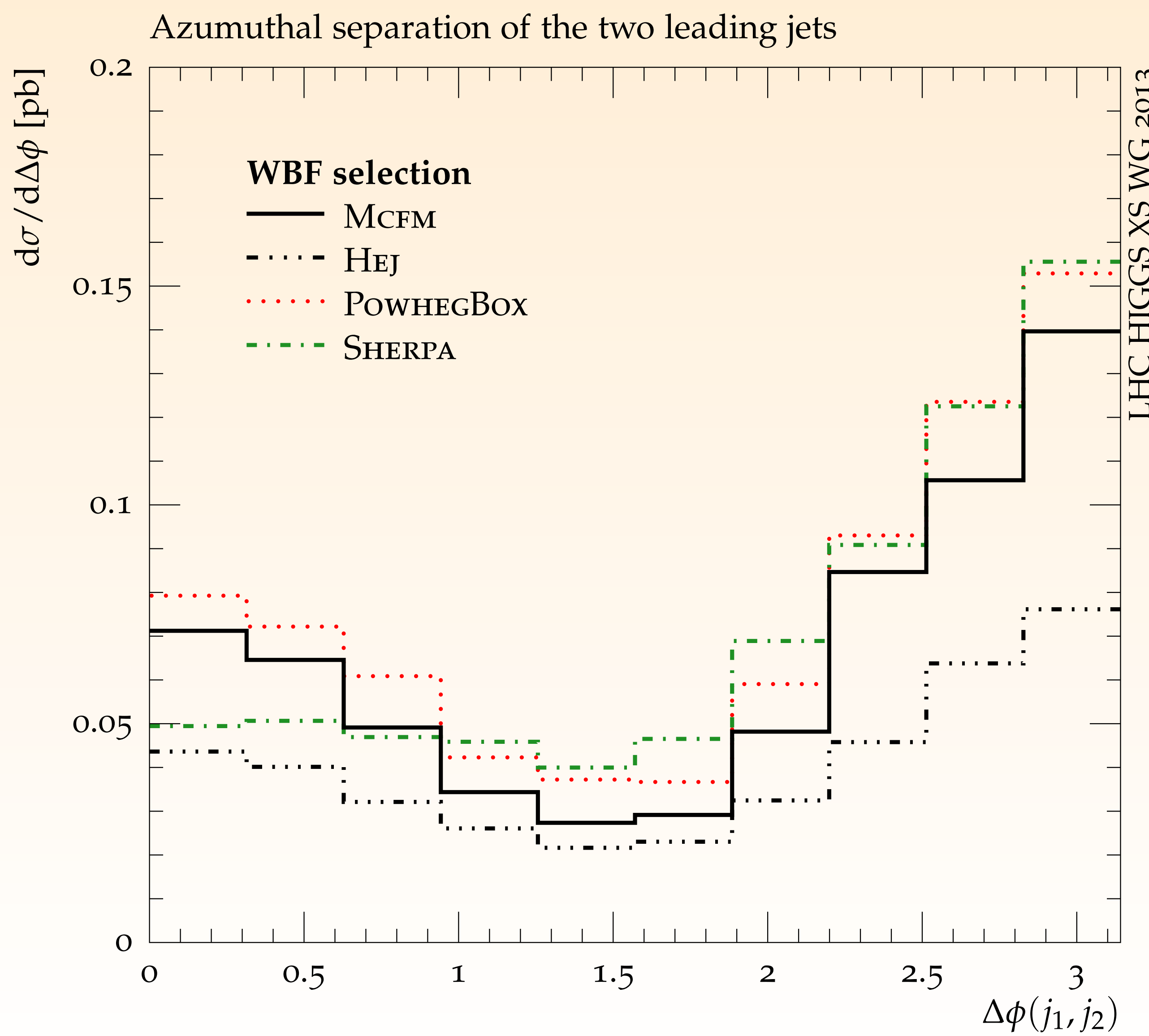
- pT and rapidity of the "veto-jet" (hardest jet between the two tagging jets)
- Differences between showers and between matching procedures are larger, but so is the scale uncertainty: these are LO observables, so no surprise
- If we want to reduce these uncertainties, need to do VBF+0,1Jet merging at NLO

GLUON FUSION AS BACKGROUND TO VBF

[From the Handbook of LHC Higgs Cross Sections: 3. Higgs properties]

	Dijet selection	WBF selection	Effect of WBF cut
MCFM	1.73 pb	0.192 pb	0.111
HEJ	2.20 pb	0.127 pb	0.058
POWHEGBOX	2.41 pb	0.237 pb	0.098
SHERPA	2.38 pb	0.225 pb	0.094

- Differences between approaches are non-negligible, and not understood
- In practice, this means large uncertainties
- There are on-going studies to try to get a consistent picture



Outlook and Conclusions

- Completely automatic NLO+PS is available. Merging event samples of various multiplicities mostly understood. For NNLO+PS first steps have been taken using MiNLO
- MiNLO method to merge without a merging scale looks like the correct way forward. However, can this be generalized to other processes with arbitrarily complicated color structures and/or also include S+2j@NLO ?
- Understand the systematics in gluon fusion with VBF-type cuts
- VBF+0,1j merged desirable? Yes, if we want to reduce uncertainty on jet-veto plot.
  Need to understand how to do the merging for processes that have jets already at the lowest order Born process
- Higgs Characterization framework available in MadGraph: completely general implementation of spin-0, spin-1 & spin-2 "Higgs" boson, including NLO+PS or ME+PS matching.