MC tools and NLO Monte Carlos

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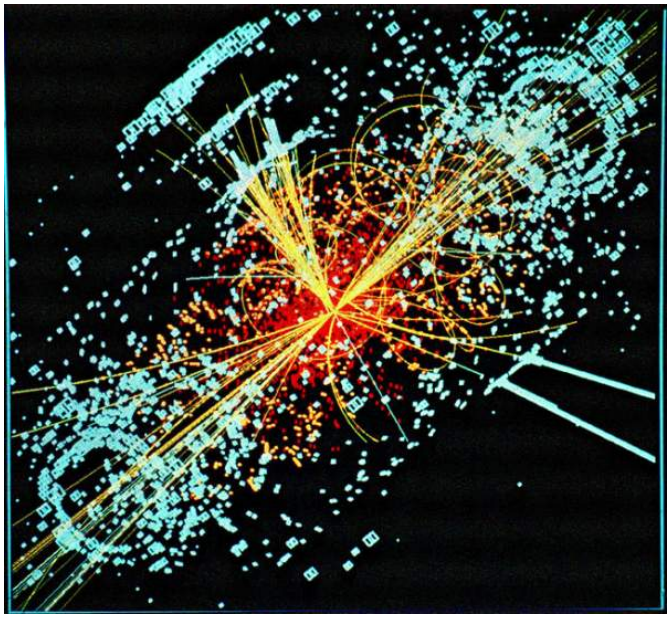
Introduction

1. status of Monte Carlo simulation tools
   - NLO+PS matching & pheno applications
   - automation
2. current developments
   - NLO+PS merging
   - NNLO+PS matching
   - BSM searches in Higgs sector
3. conclusion and outlook



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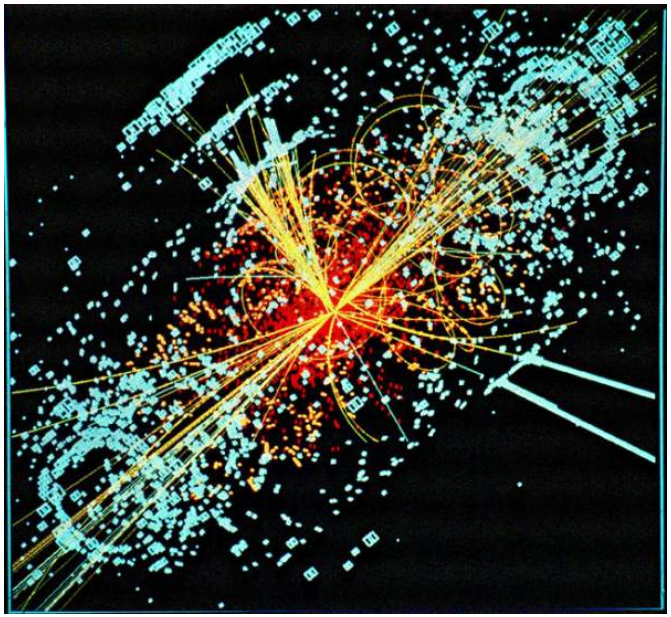

- discussion restricted to methods and tools relevant for Higgs studies (signal/backgrounds) in Run II. Not included the developments of other tools that as of today are not yet ready for LHC phenomenology
- surely I've missed something - apologies for omissions
- for more details: talks at "Higgs Cross Section WG" and "NLO MC & Tools Workshop for Run II"

NLO+PS matching

- **MC@NLO** [Frixione,Webber '02] and **POWHEG** [Nason '04] are by now well established: method of choice when available

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- if a QCD NLO computation for $pp \to X$ exists, it can be (was) matched to a PS
  - inclusive observables at NLO [much better than LO+PS ✓]
    - cross-section normalisation starts to stabilise
    - K-factors included
    - meaningful assessment of theoretical uncertainties (*e.g.* compensation in scale dependence)
  - (N)LL Sudakov resummation where relevant [much better than NLO ✓]
  - large-p_T hardest associated jet at LO [better than LO+PS ✓]
  - extra jets at LL [better than NLO ✓]
  - fully exclusive events
- X can contain jets
  (but if it contains N-jets, not possible to describe observables with $n < N$ jets)

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☞ when precision is an issue, then using a NLO+PS tool is very important, especially because it allows to attach a meaningful theoretical uncertainty to a prediction

☞ a NLO+PS prediction also allows for smaller uncertainties on backgrounds when interpolating from control region to signal region

NLO+PS: public codes

code	shower	processes	automation
MG5_aMC@NLO	Pythia, Herwig	all (including BSM)	FULL
POWHEG BOX	Pythia, Herwig	"all" (some BSM)	large library; easy to add new processes
Sherpa-MC@NLO	Sherpa	"all"	external 1-loop provider (BLHA)
PowHel	Pythia, Herwig	heavy pair$+X$	public events; code partially available
Matchbox [Herwig++]	Herwig (ang. ordered, dipole)	work in progress	external 1-loop provider (BLHA)

"Recent" activities

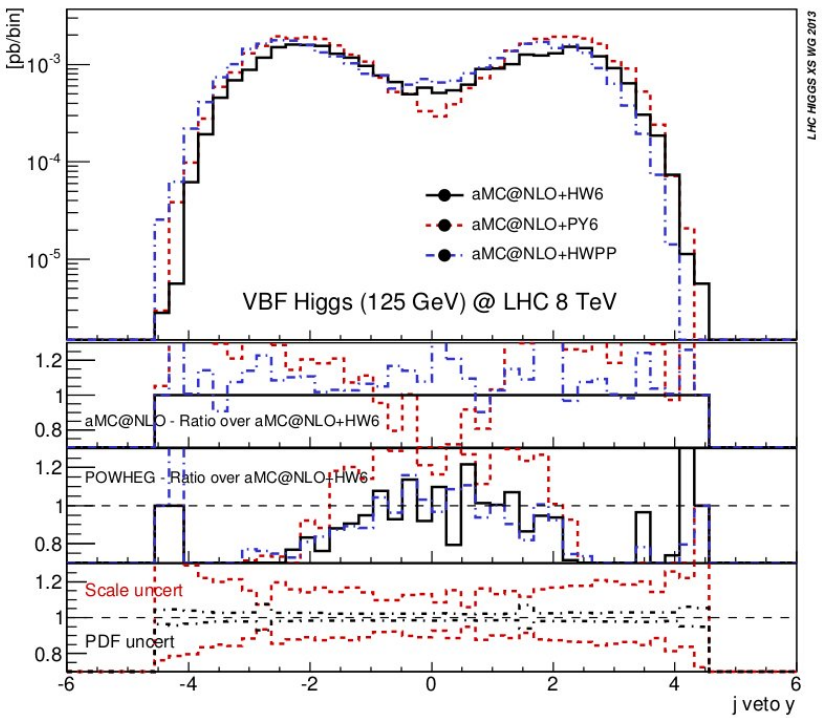
- automation (including NLO EW corrections)
- fast estimation of uncertainties (scales and PDFs)
- phenomenological studies of multijet processes
- theoretical developments: NLO+PS multijet merging and NNLO+PS matching

POWHEG

- `POWHEG BOX` [Alioli,Nason,Oleari,ER,Hamilton,Zanderighi+...]
- `PowHel` [Garzelli,Kardos,Papadopoulos,Trócsányi]

★ VBF: Higgs boson couplings and CP-properties ($\sigma_{\text{VBF cuts}}, \Delta\phi_{j_1 j_2}$,...)

- little jet activity in central rapidity ⇒ "Central Jet Veto": theoretical control on the 3rd jet



$pp \to Hjj$ [HXSWG YR3 '13]

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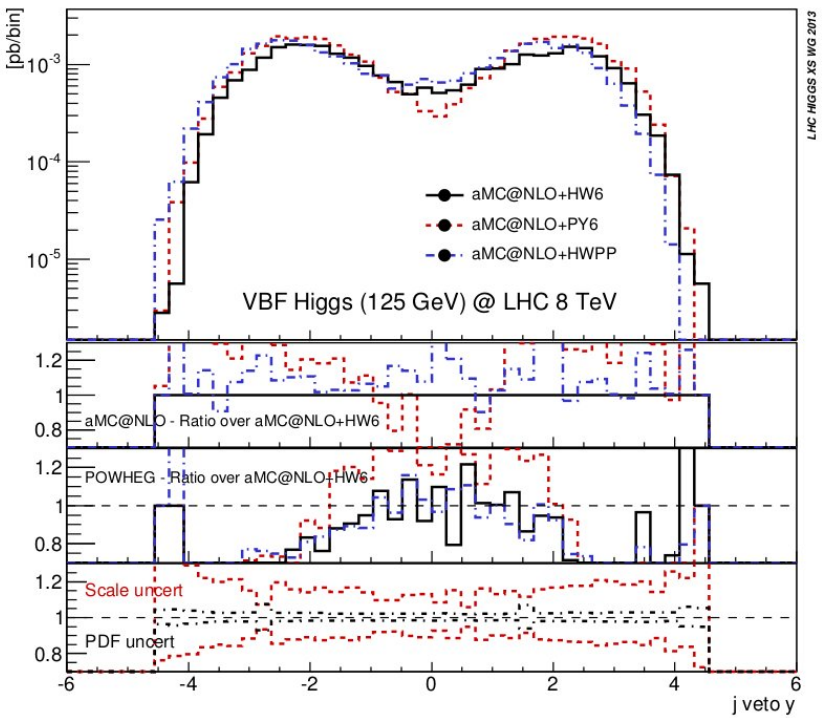

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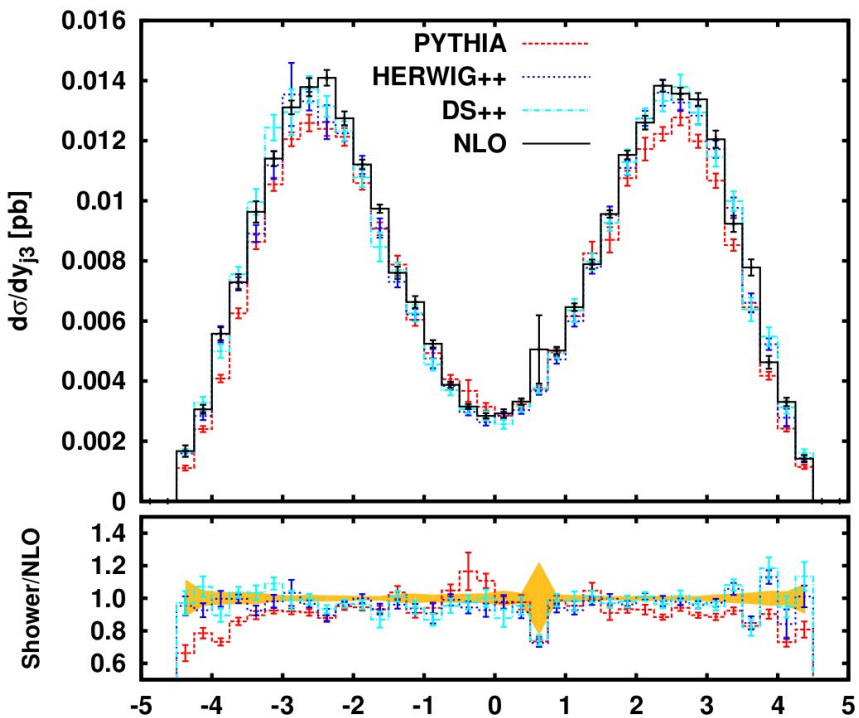

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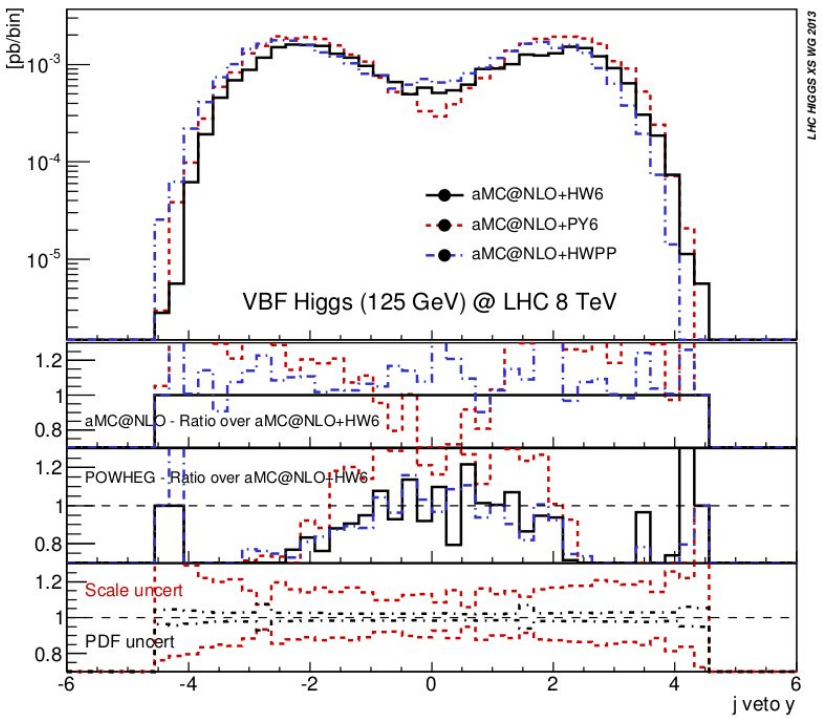

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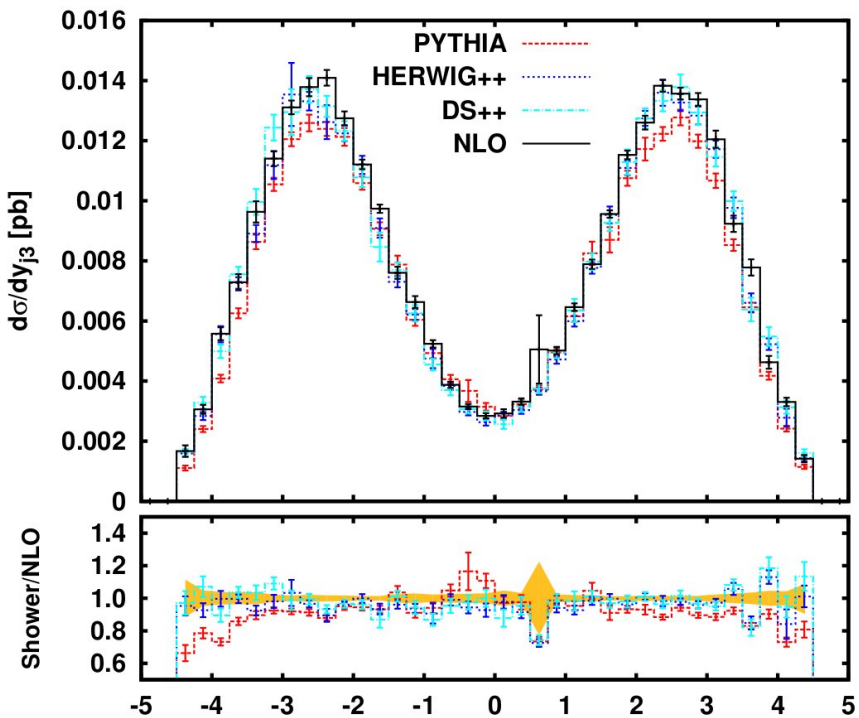

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- challenge: have VBF Hjj and $Hjjj$ at NLO+PS simultaneously

MadGraph5_aMC@NLO

- fully automated! [Alwall,Frederix,Frixione,Hirschi,Maltoni,Mattelaer,Shao,Stelzer,Torrielli,Zaro]
- many pheno studies previously prohibitive now possible ($HH(+XX)$, tH, $b\bar{b}H$,...)

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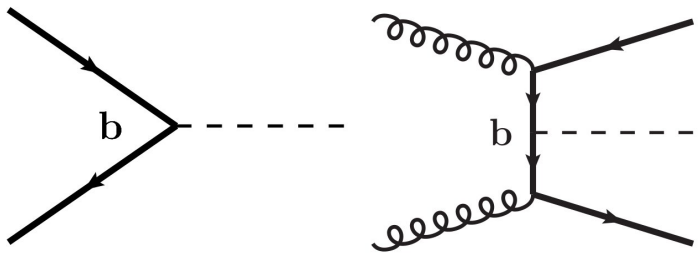

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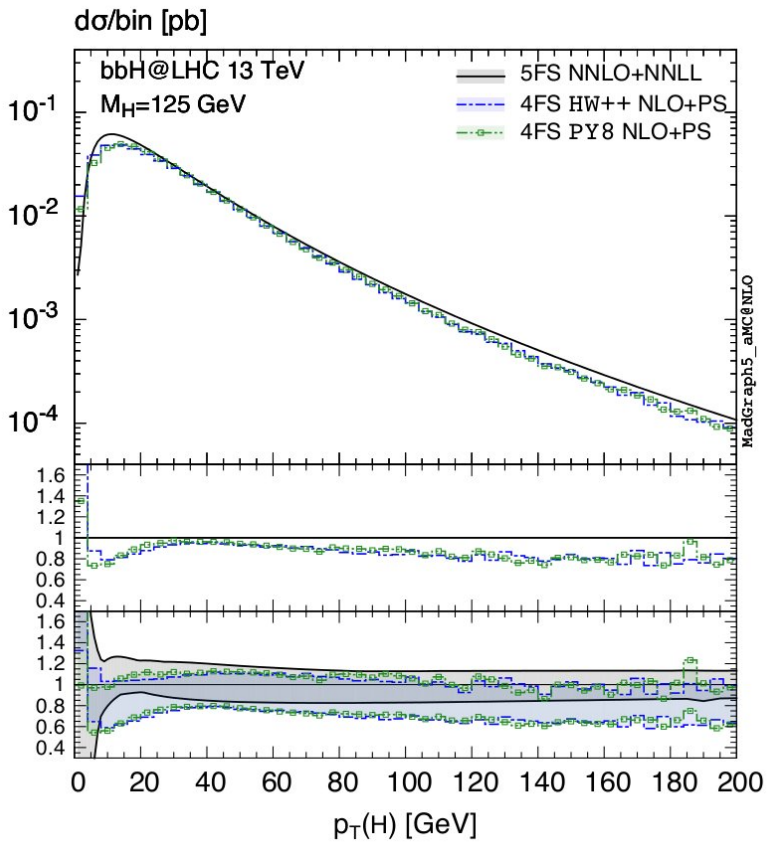

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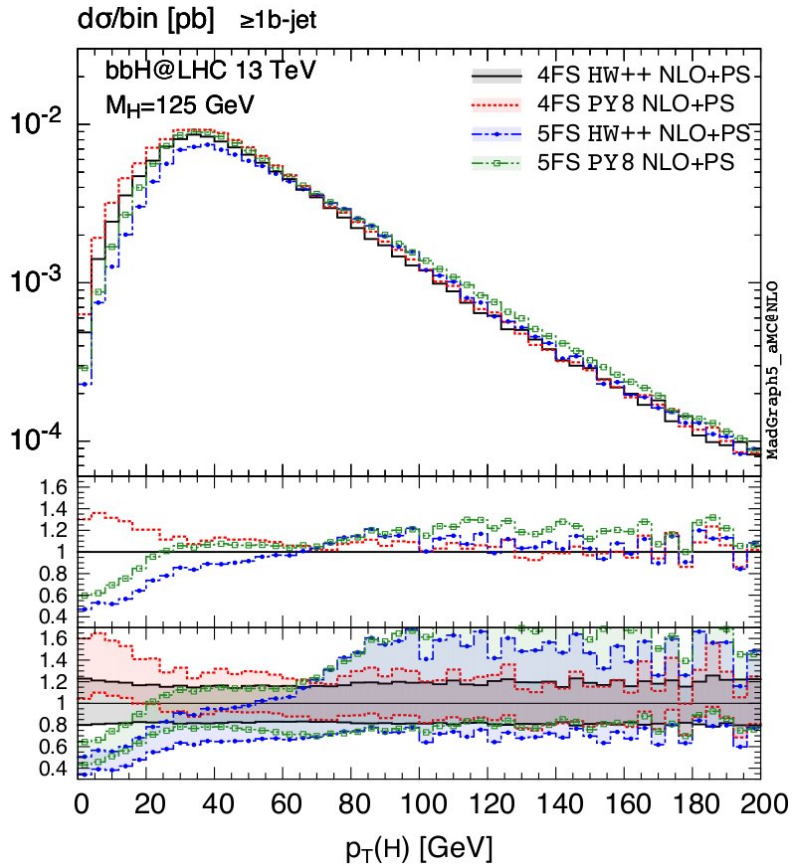

- computation in 4FS vs 5FS
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- 4FS: x-section with b-tagging at NLO (needed to distinguish from ggH!)

MC@NLO in Sherpa

- `Sherpa-MC@NLO` [Hoeche,Krauss,Schoenherr,Siegert]
- well-established interfaces (*e.g.* with `OpenLoops`), used for several applications

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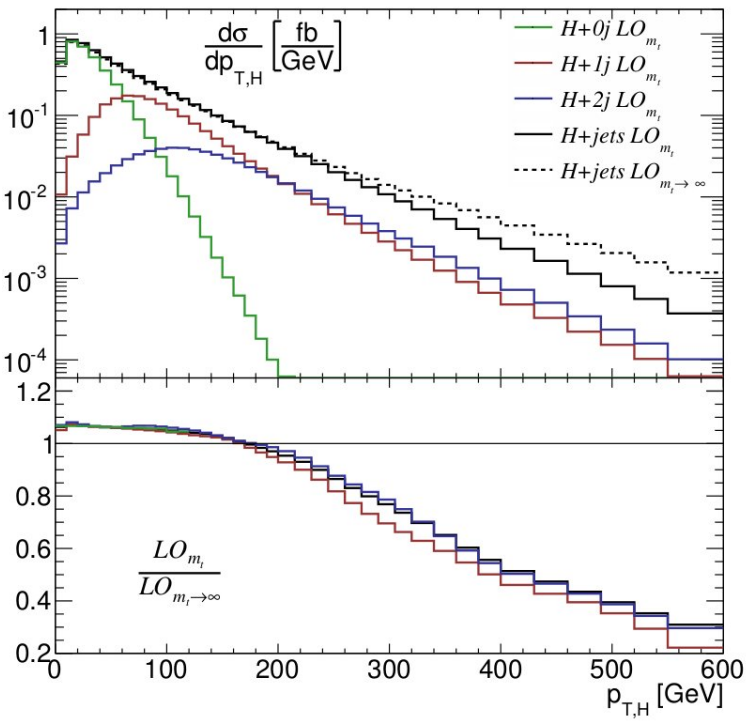
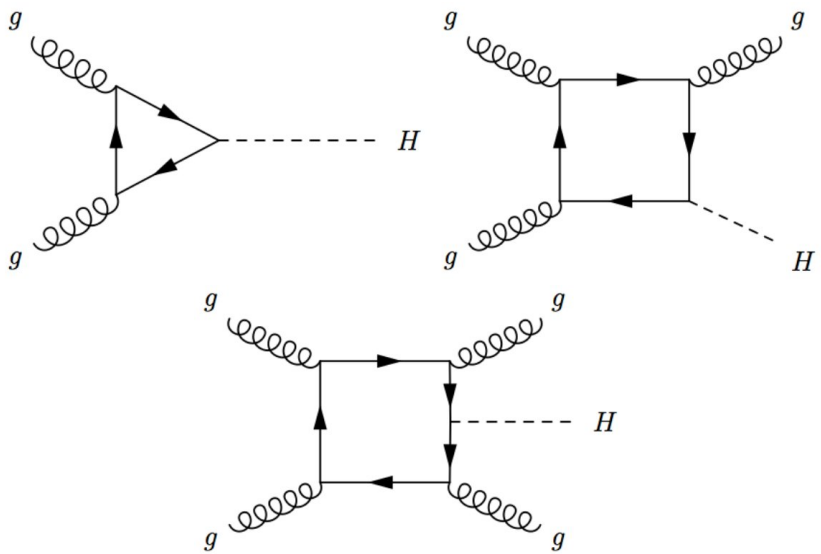
★ boosted Higgs and finite mass effects [Buschmann,Goncalves,Kuttimalai,Schoenherr,Krauss,Plehn '14]

- loop effects from heavy BSM particles can be resolved by boosted Higgs kinematics
- but need to know finite mass effects from SM !





- top mass effects similar for all "jet bins" at LO

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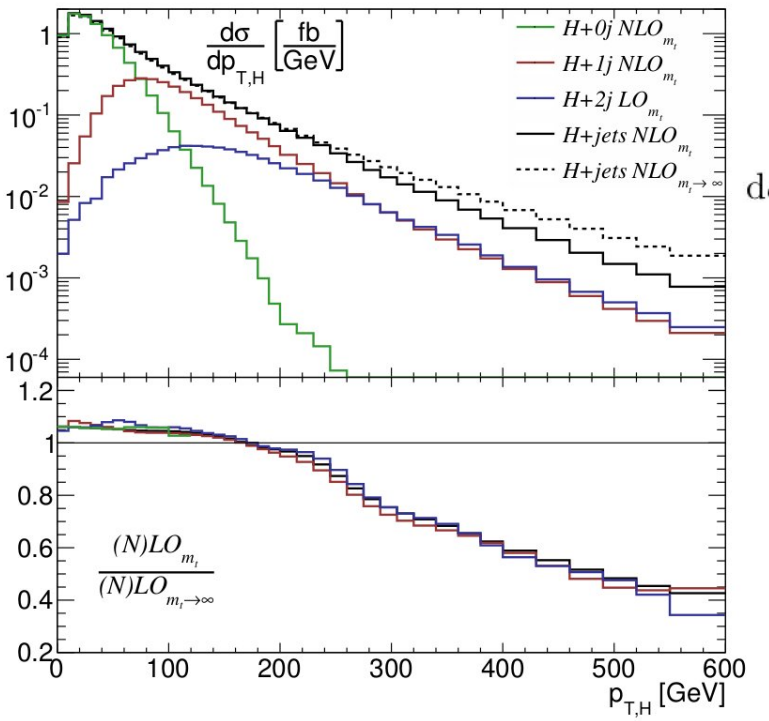

- use this observation to upgrade NLO corrections in the EFT limit

$$\mathrm{d}\sigma^{\text{S-MC@NLO}} = \mathrm{d}\Phi_n\, r_t^{(n)} \left[\mathcal{B} + \mathcal{V} + \int \mathrm{d}\Phi_1\, \mathcal{D}\right] \left(\Delta(t_0) + \int \mathrm{d}\Phi_1\, \frac{\mathcal{D}}{\mathcal{B}}\, \Delta(t)\right) + \mathrm{d}\Phi_{n+1} \left[r_t^{(n+1)}\mathcal{R} - r_t^{(n)}\mathcal{D}\right]$$

with $$r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \to \infty)|^2}$$

- caveat: "*Eventually, it needs to be tested once the two-loop multi-scale diagrams can be evaluated over the full phase space.*"

NLO+PS merging

- significant fraction of interesting final states is accompanied by multiple jets (especially at 13-14 TeV and with large accumulated luminosity)
- important for experimental analysis (*e.g.* jet vetoes, jet activity in gg-fusion vs. VBF)
- sometime a single tool describing both soft and hard parts (via PS and exact ME, respectively) is needed
- CKKW-L and MLM-merging methods succesfully address this issue at LO: this accuracy will soon be a limiting factor for precision (if it is not already)

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- challenge: extend these methods to NLO ("NLOPS multijet merging"):
  - from one single event sample, have 1-, 2-,...,n-jet observables at NLO

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proposals:*

- MEPS@NLO [Sherpa]
- FxFx [MadGraph5_aMC@NLO]
- UNLOPS [Lonnbland,Prestel - Platzer]
- Geneva [Alioli,Bauer, et al]
- MiNLO [POWHEG]

*with published results, or where I'm aware of existing preliminary results for LHC Physics

NLO+PS merging

- multijet merging at NLO is more complicated than at LO, and more subtle: the matrix element "$pp \to S + (n+1)$ partons" enters in
  - real emission for "$pp \to S + n$ partons" @ NLO
  - Born contribution for "$pp \to S + (n+1)$ partons" @ NLO

- similarly to LO, many of these methods use a merging scale ($Q_{\rm MS}$): a bad choice of merging scale can spoil the formal accuracy
  - typically this can happen if $\alpha_{\rm S} \log^2 (Q_{\rm MS}/Q) \simeq 1$: when $L \simeq 1/\sqrt{\alpha_{\rm S}}$, uncontrolled NNLL logs $\alpha_{\rm S}^2 L$ scale as $\alpha_{\rm S}^{1.5}$ (and not as $\alpha_{\rm S}^2$).
  - to avoid any formal issue, one needs either to not have $Q_{\rm MS}$ at all, or have a very precise control of logarithmic structure (beyond the PS accuracy), so that even if $\alpha_{\rm S} \log^2 (Q_{\rm MS}/Q) \simeq 1$, the formal NLO accuracy of each jet bin is not spoiled. Alternatively, avoid $\alpha_{\rm S} \log^2 (Q_{\rm MS}/Q) \simeq 1$.
  - not having $Q_{\rm MS}$ requires control of NNLL terms (or at least part thereof)
  - if $Q_{\rm MS}$ is present, include the uncertainty due to its choice

- all is still quite new: a thorough comparison among different approaches and validation against data (*e.g.* in V+jets) will be extremely useful

- the development of these techniques lead to match PS with NNLO computations (for simple processes)

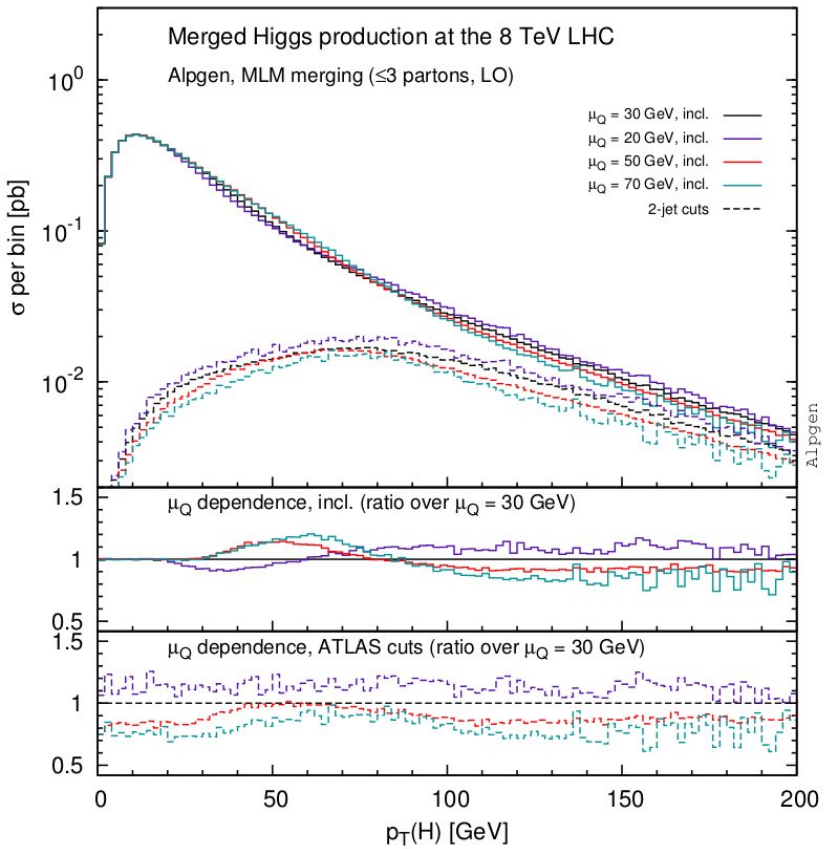
“FxFx” merging

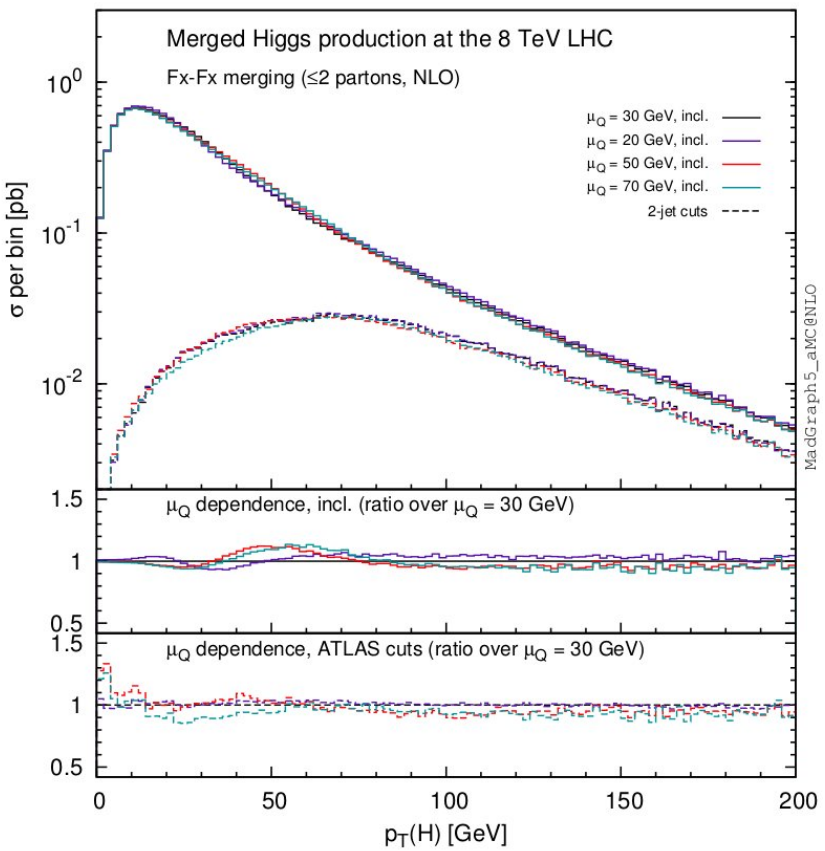
[Frederix,Frixione ’12]

- now automated in MadGraph5_aMC@NLO

★ H + 0,1,2 jets

[MG5_aMC@NLO paper ’14]





MEPS@NLO

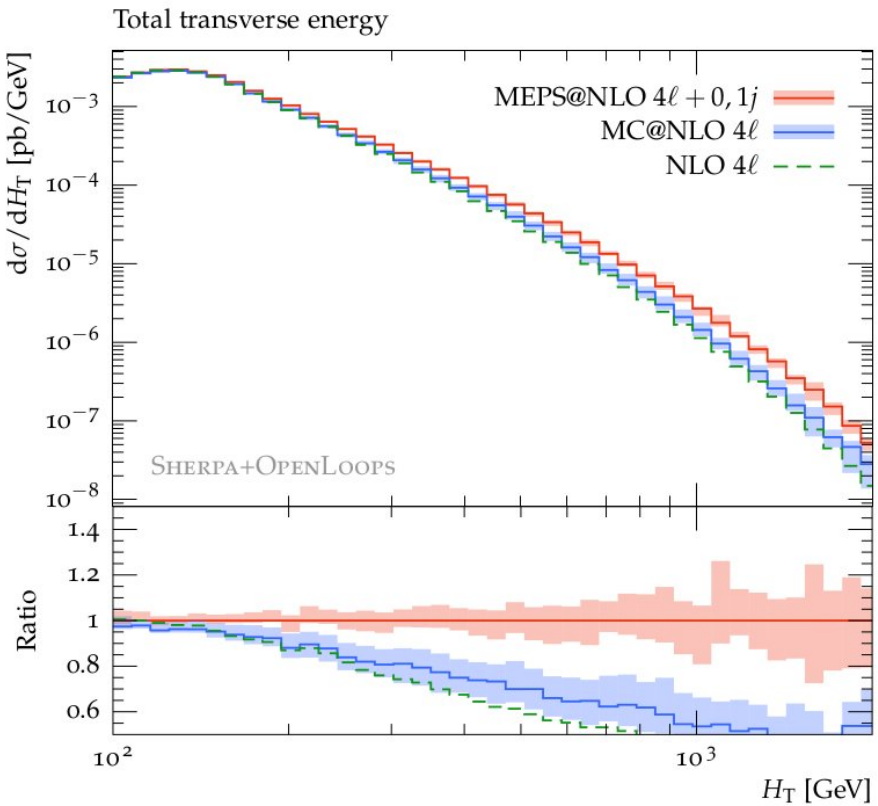
[Hoeche,Krauss,Schoenherr,Siegert + Gehrmann '12]

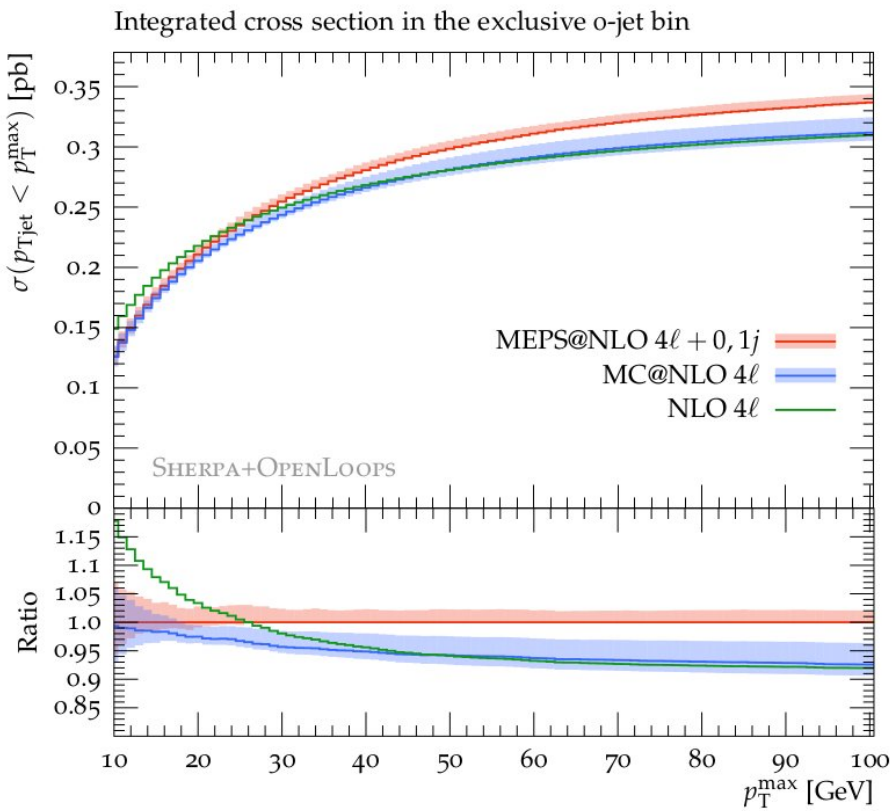
- proof of concept in e^+e^- and $W+$ jets, applied in several other processes
- share some similarities with "FxFx"

★ 4 leptons + 0,1 jets

[Cascioli,Hoeche,Krauss,Maierhöfer,Pozzorini,Siegert '14]

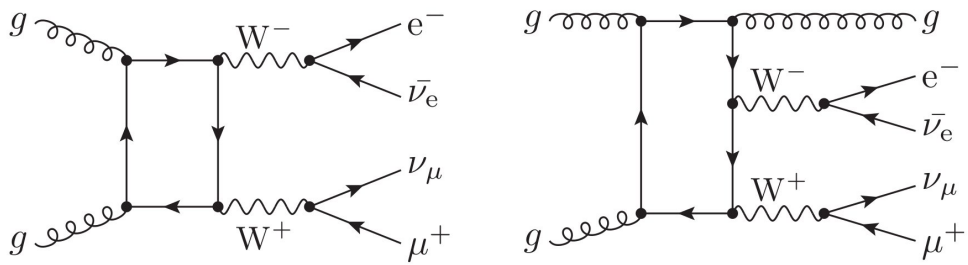
- important background in $H \to WW$, typically suppressed by jet-vetoing

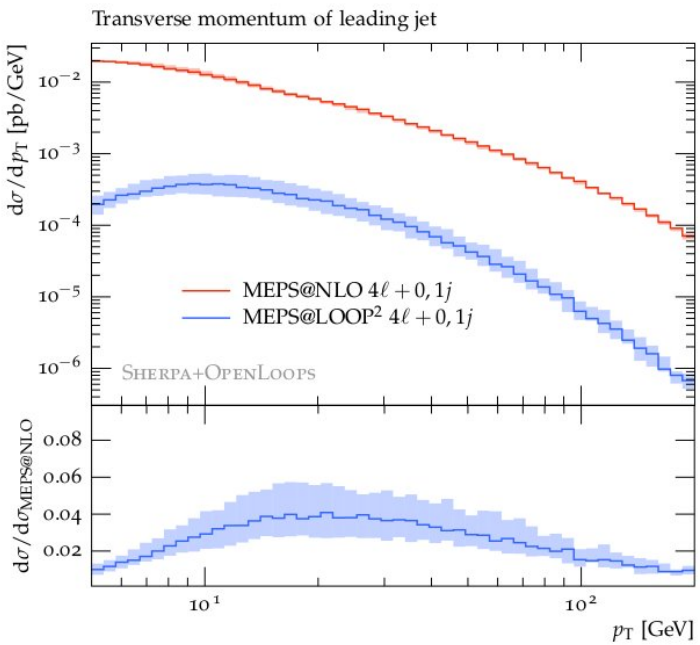


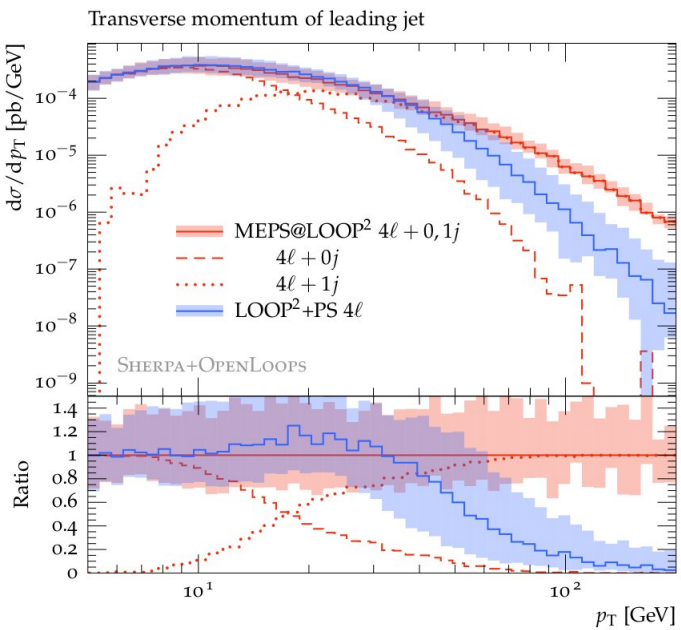


MEPS@NLO and loop-induced processes

- $gg \to VV$: finite subset of NNLO contribution
- numerically important, because of gluon flux
- first merging of 0-jet and 1-jet squared-loop contributions







Multiscale Improved NLO

[Hamilton,Nason,Oleari,Zanderighi '12 '12]

- original goal: method to a-priori choose scales in multijet NLO computation
  (in a multiscale process, this is not straightforward, in regions with widely-separated scales)
- idea: correct weights of different NLO terms with CKKW-inspired approach
  (without spoiling formal NLO accuracy)

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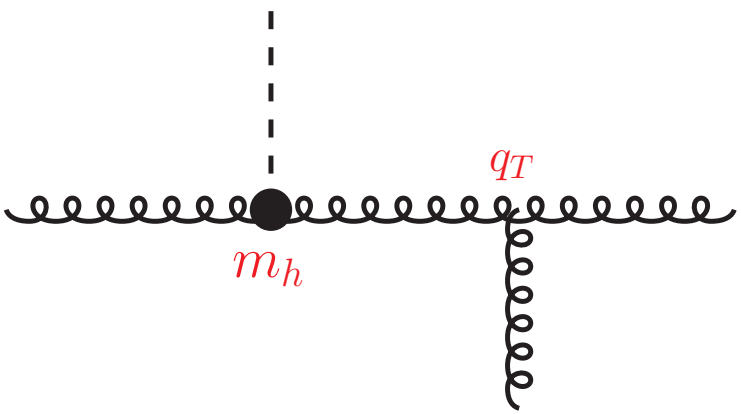

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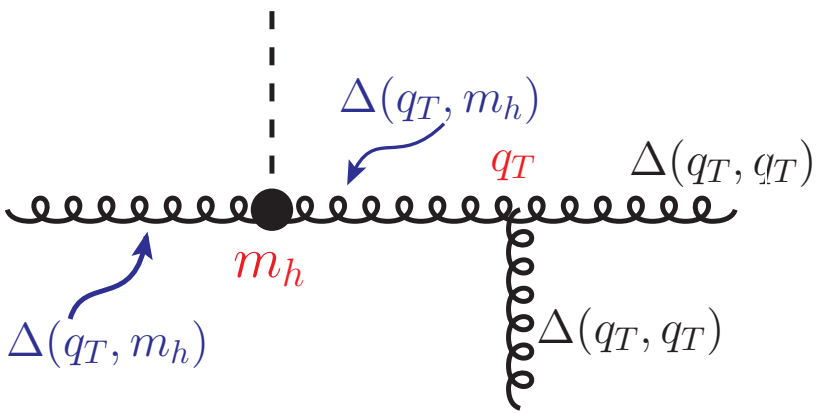

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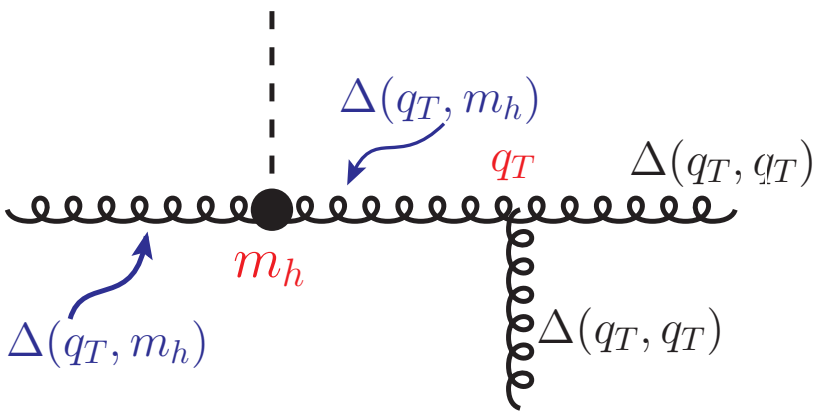


☞ Sudakov FF included on H+j Born kinematics

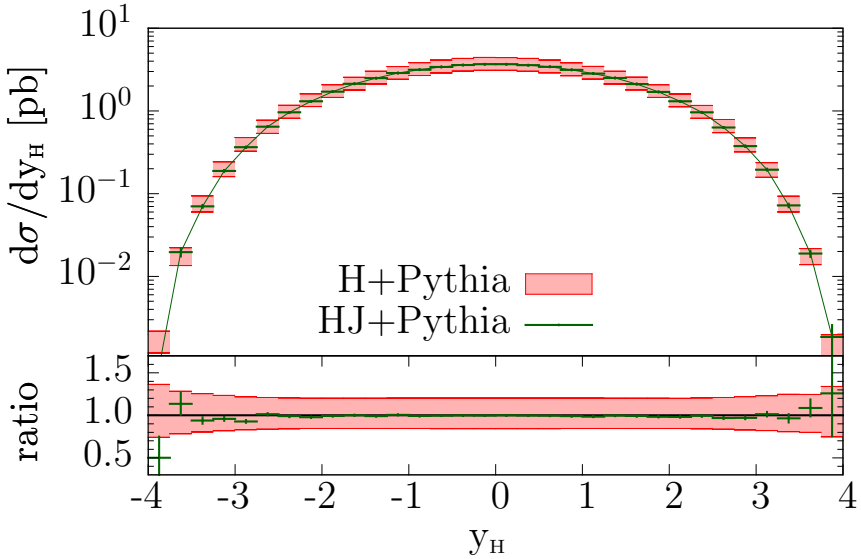
☞ finite results if first jet unresolved

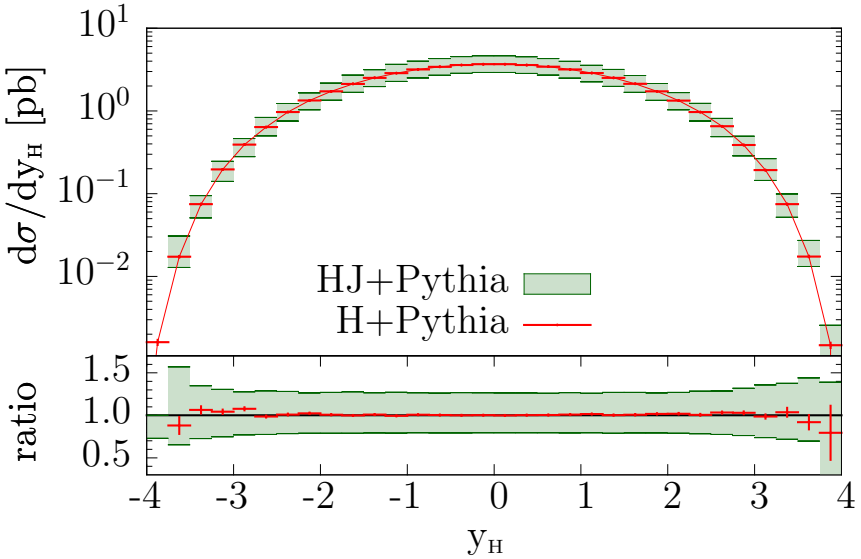
- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of H+j POWHEG
- including terms from NNLL resummation ⇒ NLO+PS merging without a merging scale
- limited to 0 and 1-jet: how to extend to higher multiplicity maintaning a formal claim not yet clear.

POWHEG+MiNLO: Higgs production

★ H + 0,1 jets

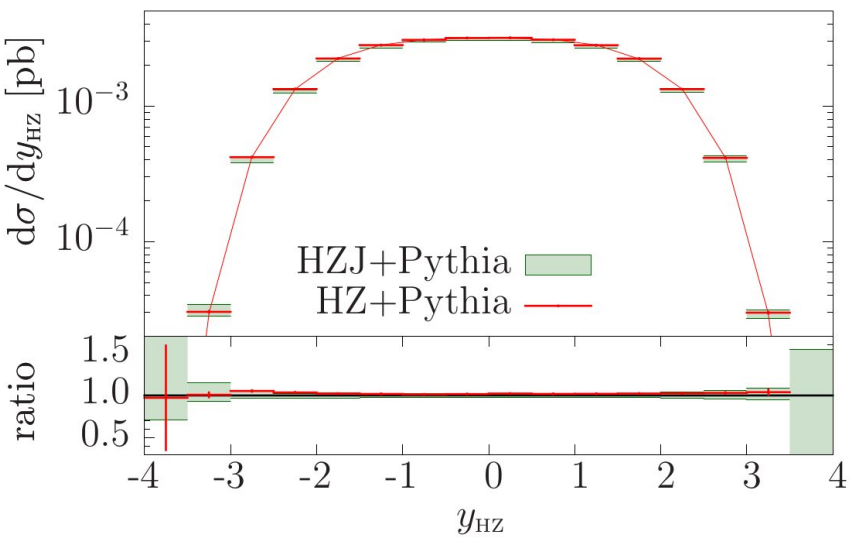
[Hamilton,Nason,Oleari,Zanderighi '12]

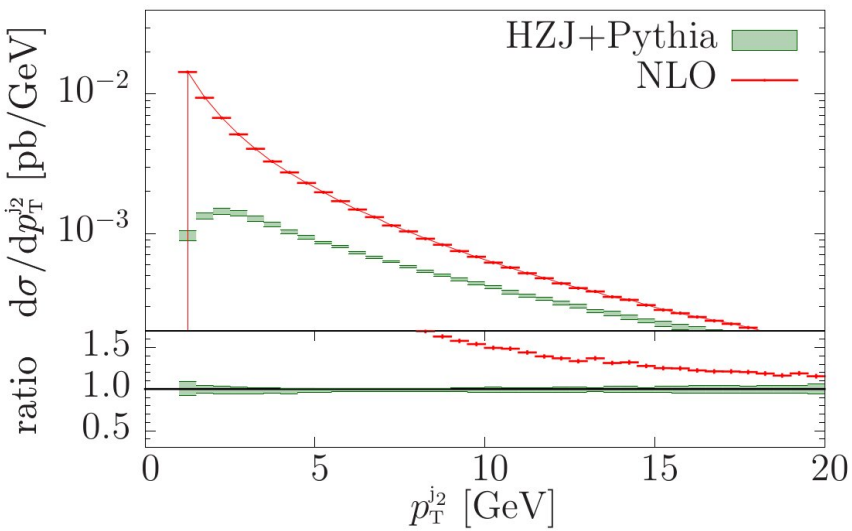




★ VH + 0,1 jets

[Luisoni,Nason,Oleari,Tramontano '13]





ggH at NNLO+PS (with MiNLO)

- `HJ-MiNLO+POWHEG` generator gives H-HJ @ NLOPS

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
✓ H-HJ @ NLOPS	NLO	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

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- reweighting (differential on Φ_B) of "`MiNLO`-generated" events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{HJ-MiNLO^*}}}$$

  - by construction NNLO accuracy on fully inclusive observables ($\sigma_{\mathrm{tot}}, y_H$) [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `HJ-MiNLO` in 1-jet region [ ]

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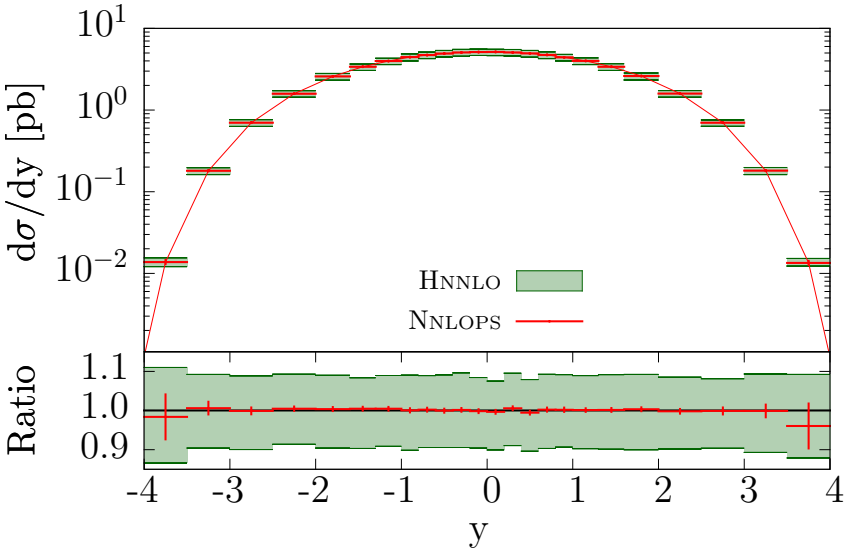
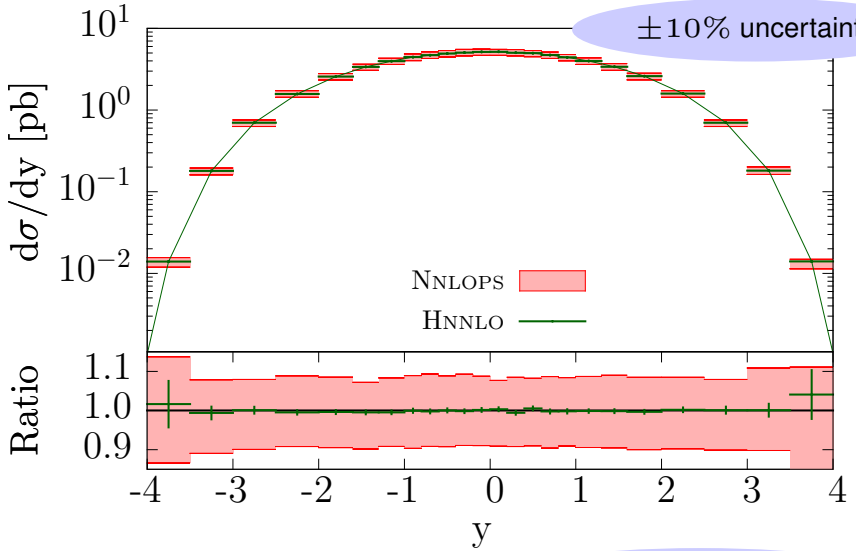
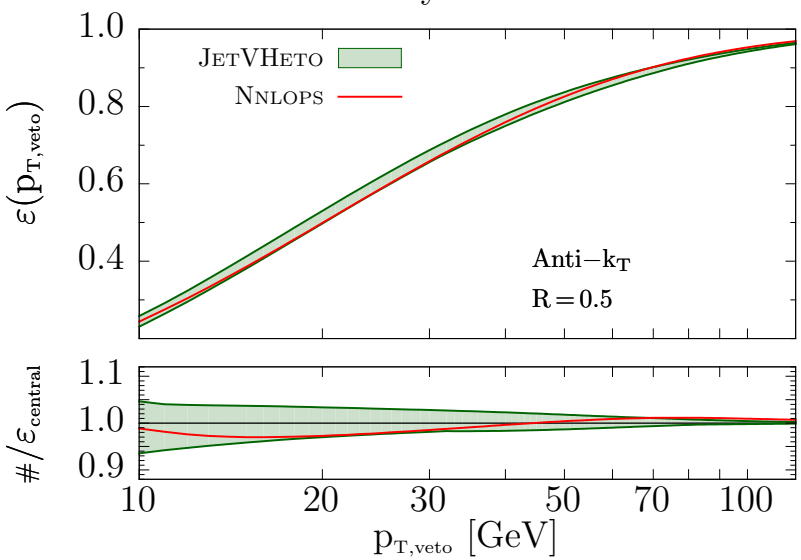
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `HJ-MiNLO` in 1-jet region [✓]
  - notice: formally works because no spurious $\mathcal{O}(\alpha_{\rm S}^{2+1.5})$ terms in H-HJ @ NLOPS

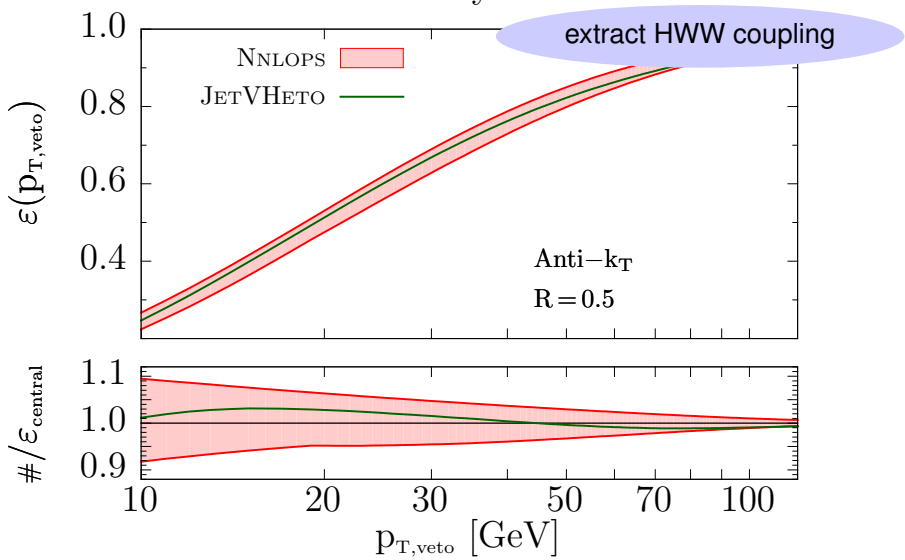
ggH at NNLO+PS (with MiNLO)

[Hamilton,Nason,ER,Zanderighi '13]









- approximate inclusion of t and b mass effects also studied
  [Hamilton,Nason,Zanderighi '15]

UNLOPS

[Lonnblad,Prestel '12 / (very similar approach by Plätzer '12)]

- keyword: "unitarity" (preserve NLO inclusive cross section)
- method: promote to NLO accuracy an "unitarized" CKKW approach, by carefully adding higher order contributions, and removing the pre-existing approximate α_S terms

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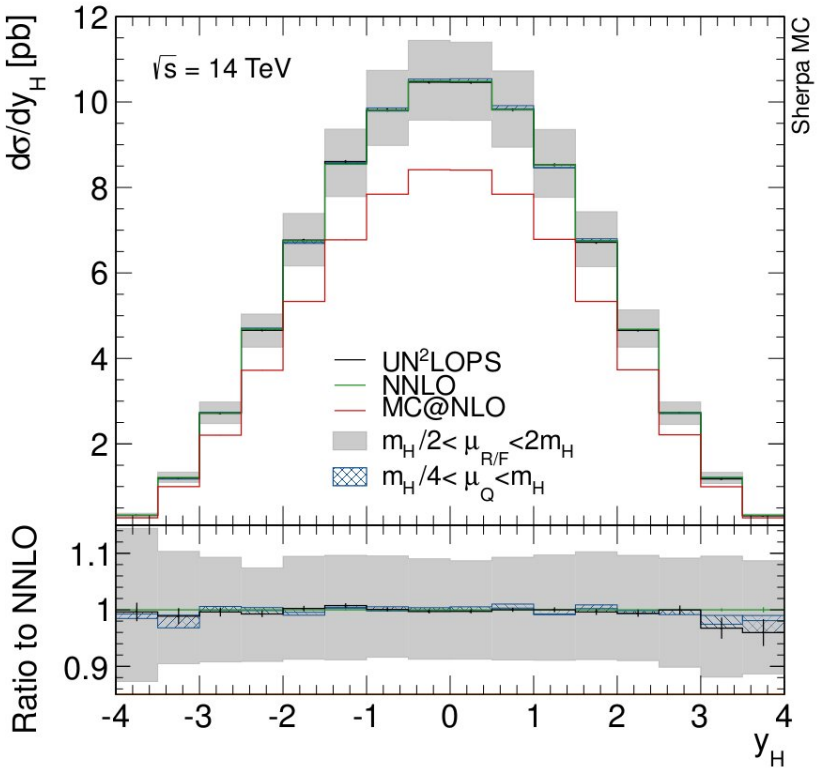
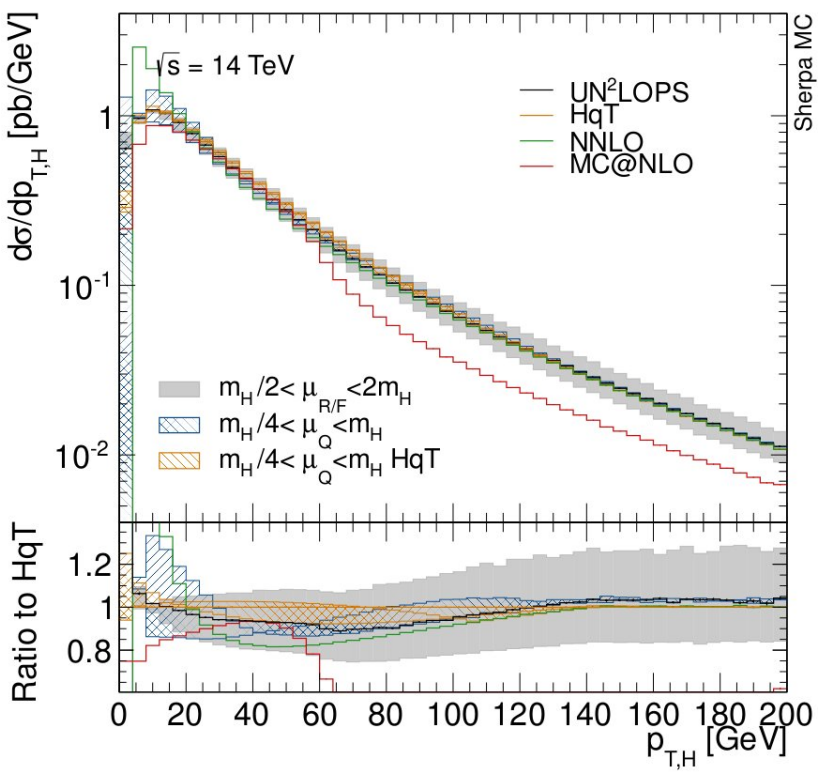
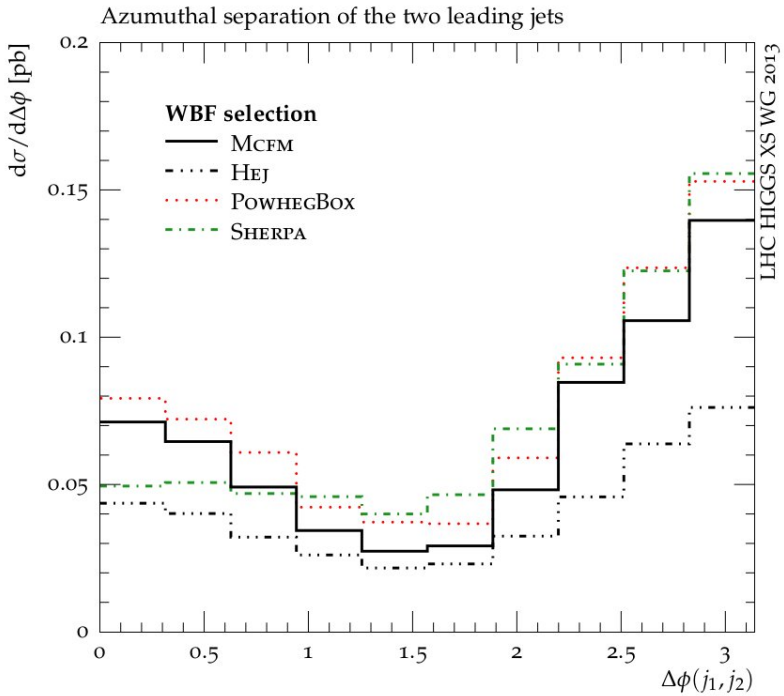
- pushed to NNLO (although treatment of "zero-jet" bin still under study) [Hoeche,Li,Prestel '14]





Higgs + multijets

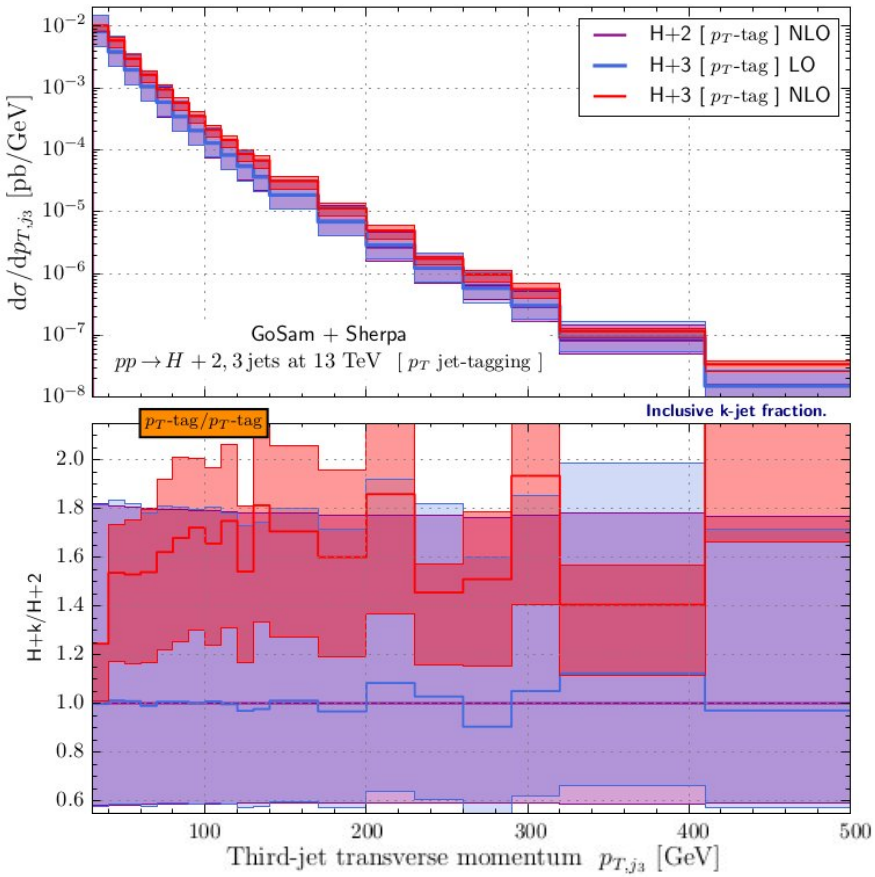
- measure VBF precisely is an important goal for Run II
- large contamination from gg-fusion (large energy available, gg luminosity)
- use central jet-veto, or BDT: more robust if higher-order corrections for fully differential observables are known
- very tough NLO computations, but doable thanks to automation



from [HXSWG YR3 '13]

Higgs + multijets

★ $pp \to Hjjj$ at NLO (gg-fusion) [Greiner,Hoeche,Luisoni,et al '15]

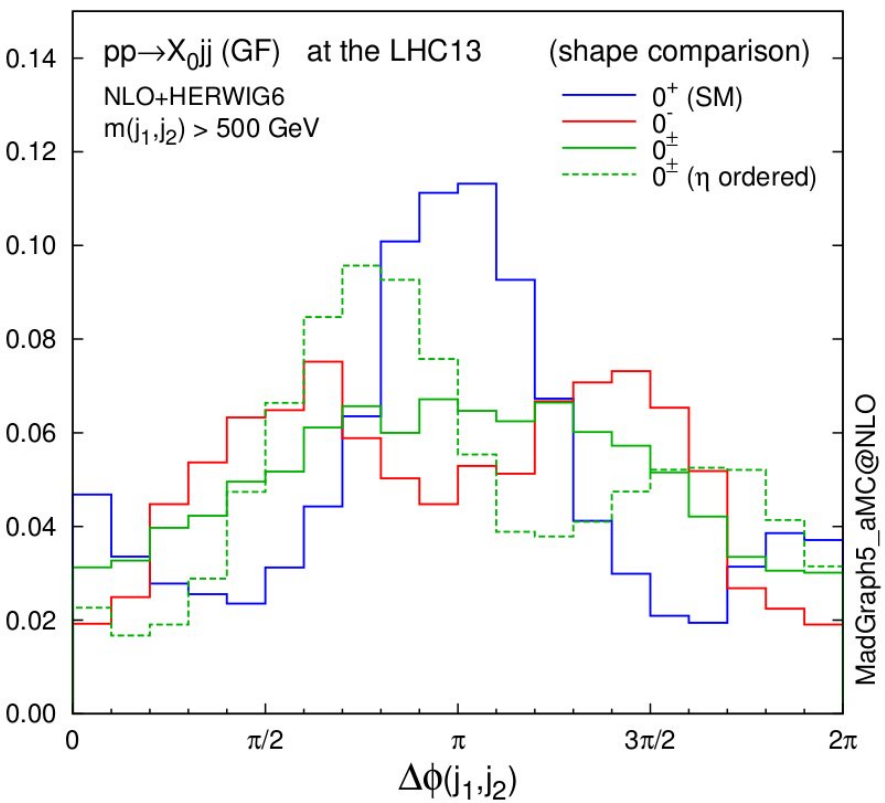


- VBF cuts:
  $m_{j_1 j_2} > 400$ GeV, $|\Delta y_{j_1 j_2}| > 2.8$
- non flat K-factor for p_T of non-tagging-jet
- differences also among different "tagging schemes"
- ntuples will be made public

- ultimate goal: include these effects in NLO+PS MC using multijet merging !
  Fully flexible tool to study cross sections (or train a BDT) for different jet bins (up to 3 at NLO) for the contamination of VBF from gg-fusion !

BSM

- POWHEG BOX: scalar and pseudoscalar in 2HDM and MSSM, $tH^{\pm}$ [Bagnaschi et al., Klasen et al.]
- MG5_aMC@NLO:
  - "Higgs Characterization" Lagrangian [Artoisenet et al. '13]
  - explicit BSM models: FeynRules and NLOCT [Degrande '14]



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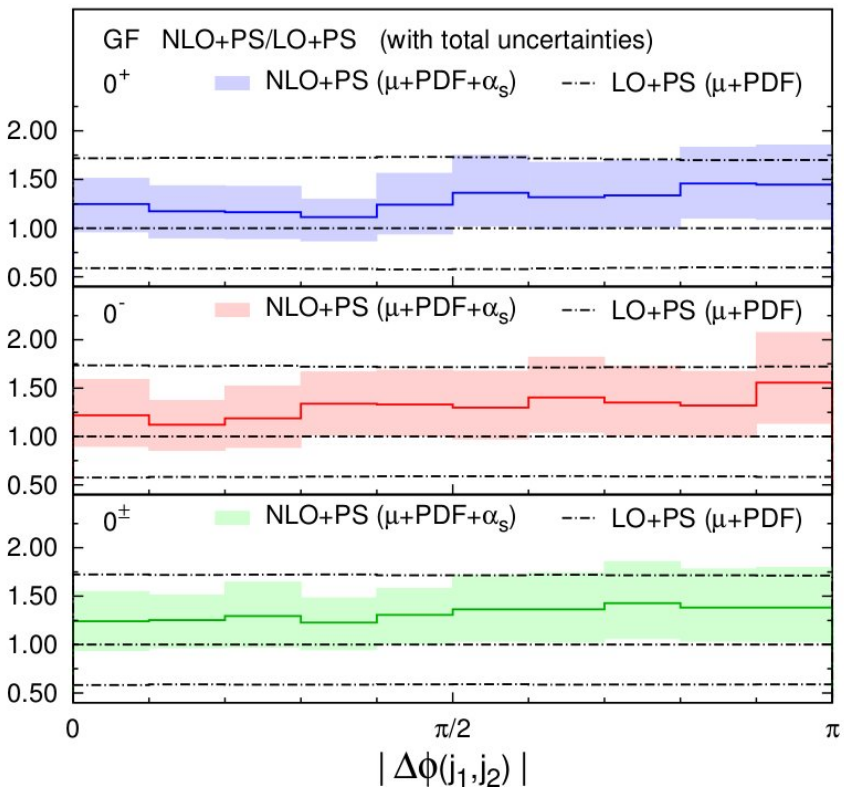

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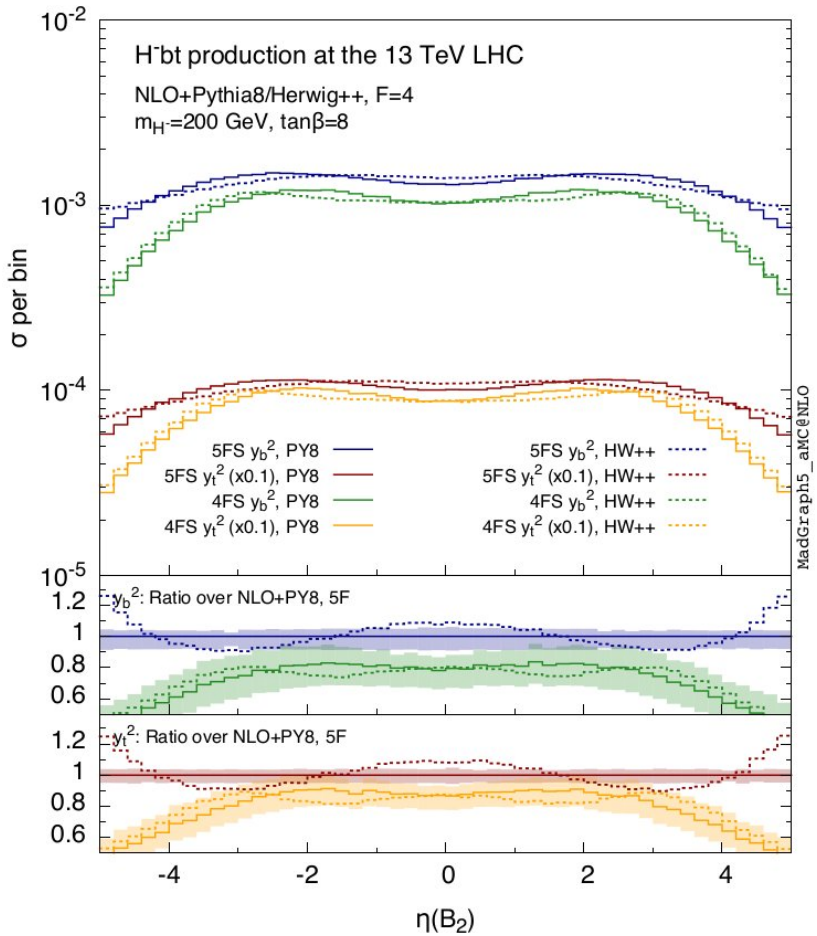

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  - well known azimuthal decorrelation
  - thorough assessement of uncertainties
- Heavy charged Higgs boson production: 4FS vs 5FS

  [Degrande,Ubiali,Wiesemann,Zaro '15]

Conclusion

- Monte Carlo tools play a major role for LHC searches, and Higgs Physics is no exception
- NLO+PS tools are by now well established and very mature:
  - started to see the profits due to huge progresses in QCD NLO community (automation): all is/will be available, for BSM signatures too
- major theoretical development in last 2 years: NLOPS multijet merging
  - in some cases, they could be *really* important (*e.g.* ggH vs VBF)
  - they are very new tools, not all we want/need is there yet
  - a lot of QCD effects go into them: accurate comparisons will take place, differences will be understood, as it was for NLO+PS programs
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Thank you for your attention!