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(Werner-Heisenberg-Institut)

von Humboldt Stiftung/Found

NLO Higgs phenomenology with GoSam

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In collaboration with:

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Outline

- Introduction
- Calculation setup
  - GoSam-2.0: a quick overview
    - Generation
    - Reduction
    - NLO computations
- H+3 jets in gluon-gluon-fusion
- Conclusions

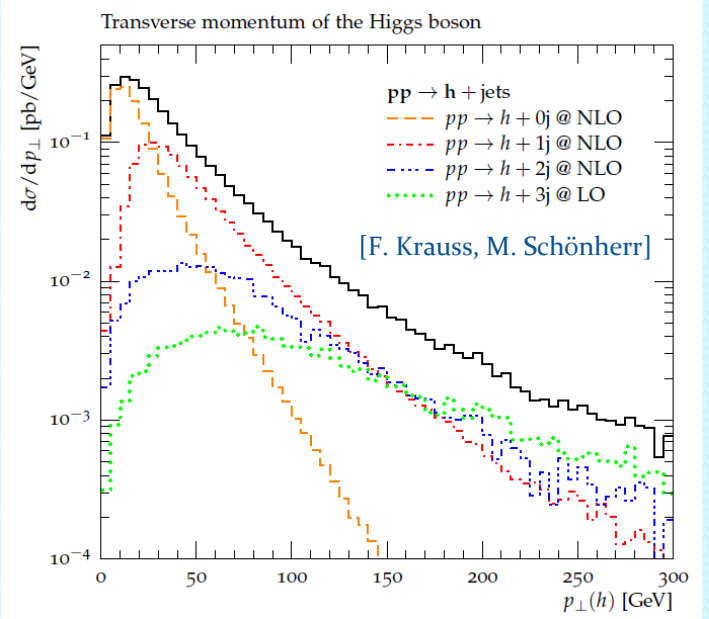
H+jets in gluon-gluon fusion

- Dominant channel of Higgs production
- Large background makes it a prohibitive channel to directly study the Higgs boson
- Nonetheless precise knowledge of ggf-channel is crucial:
  - When applying vetoes to jets

➔ H+jets cross section needed to estimate untertainties in efficiencies

  - When studying VBF production channel

➔ Estimate contamination in VBF sample of events coming from gluon-gluon fusion channel



H+jets in gluon-gluon fusion

H+3 jets

- Calculation setup:
  - B amplitudes: Sherpa
  - V amplitudes: GoSam

  } PS integration: Sherpa (BLHA)

  - IRS amplitudes: MG4/MadDipole

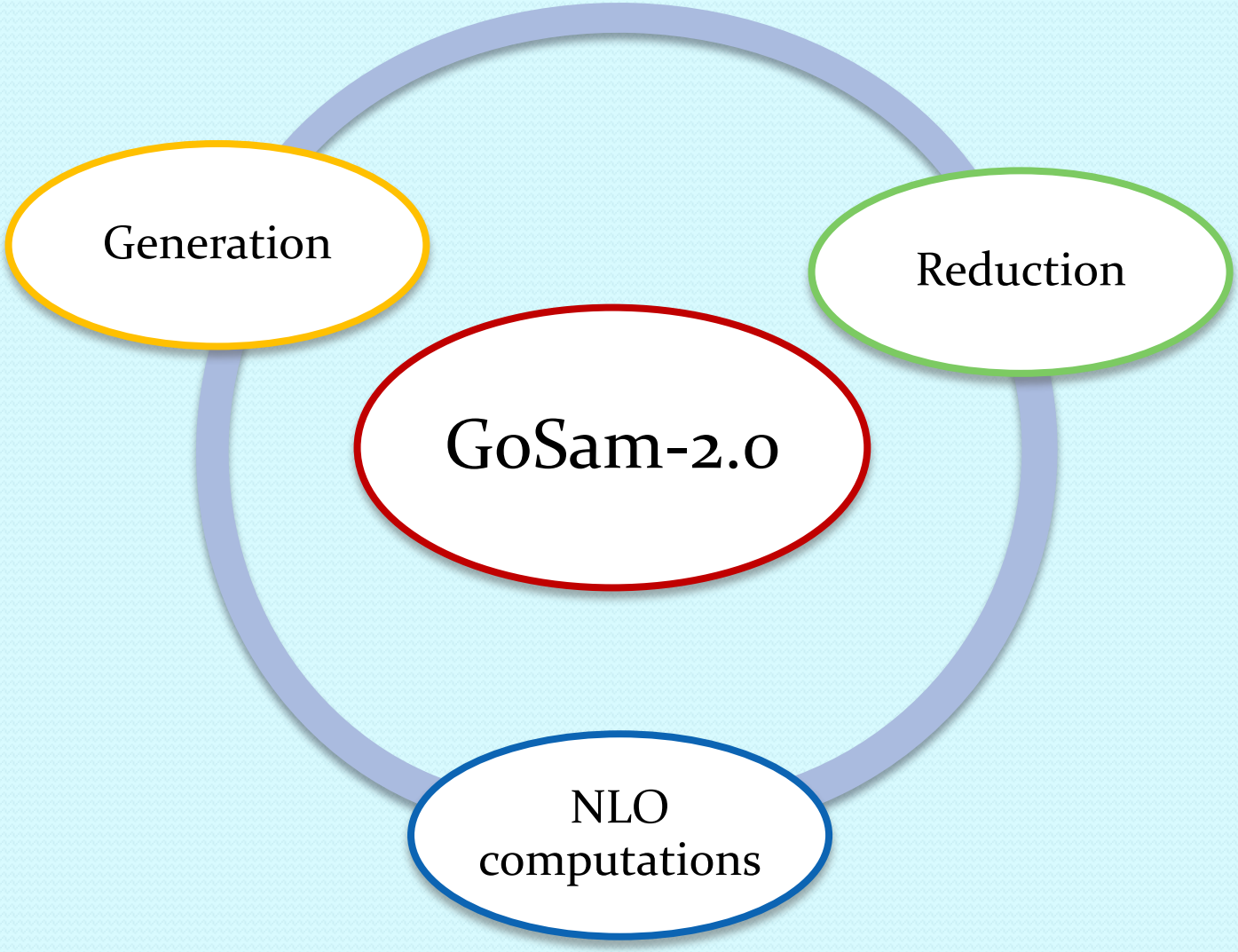
  } PS integration: MadEvent

  ↳ Full NLO

- Checks:
  - ✓ Gauge invariance of virtual amplitudes
  - ✓ α-independence of IRS contribution
  - ✓ H+2j comparison and B comparison for combination

GoSam-2.0: a quick overview

[G. Cullen, H. Van Deurzen, N. Greiner, G. Heinrich, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro, J. Reichel, J. Schlenk, J.F.G. von Soden-Fraunhofen, F. Tramontano]



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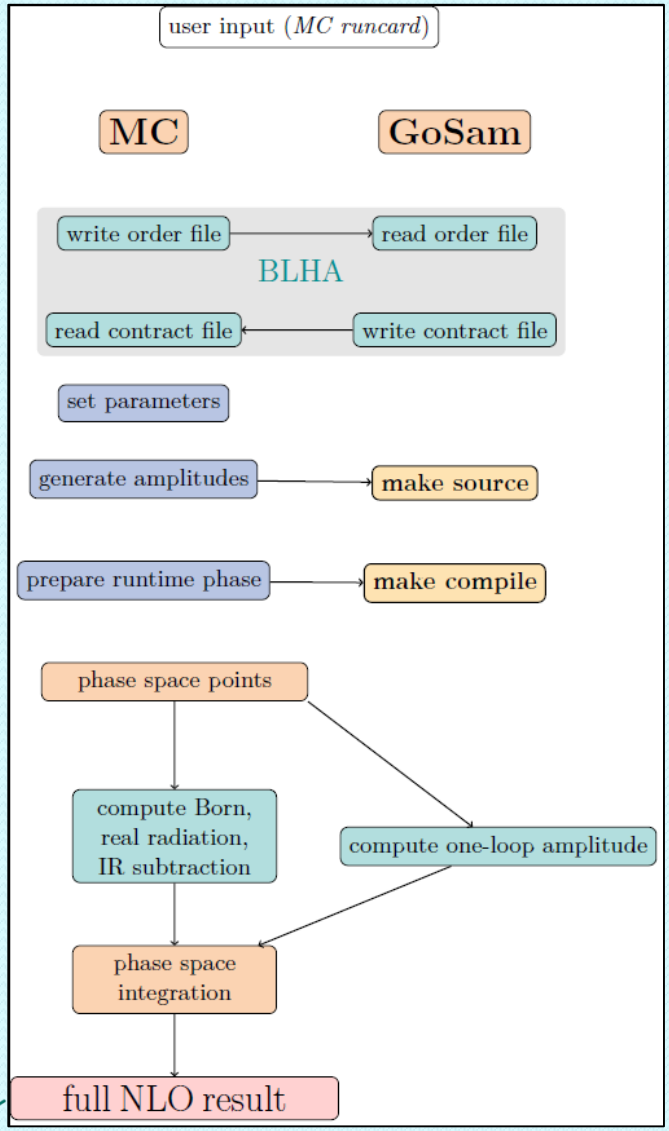

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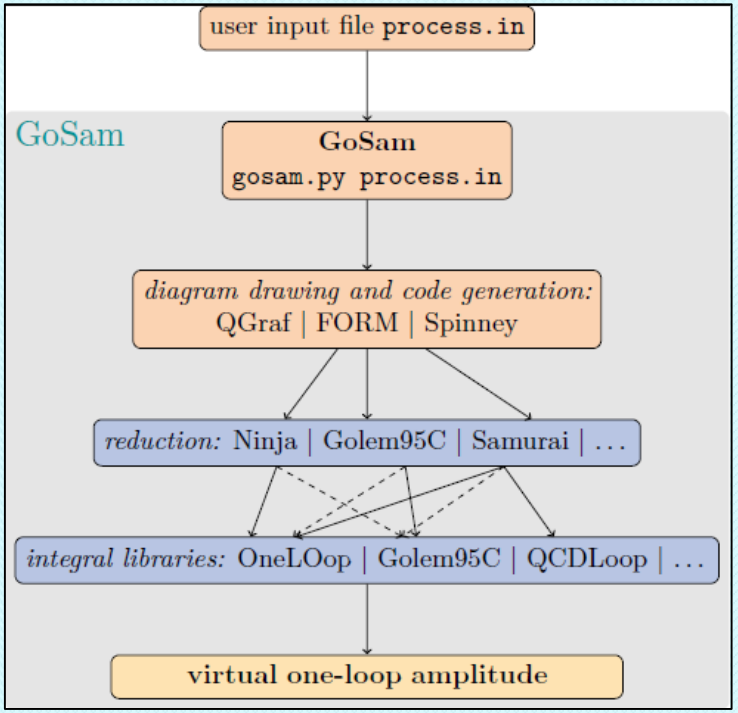

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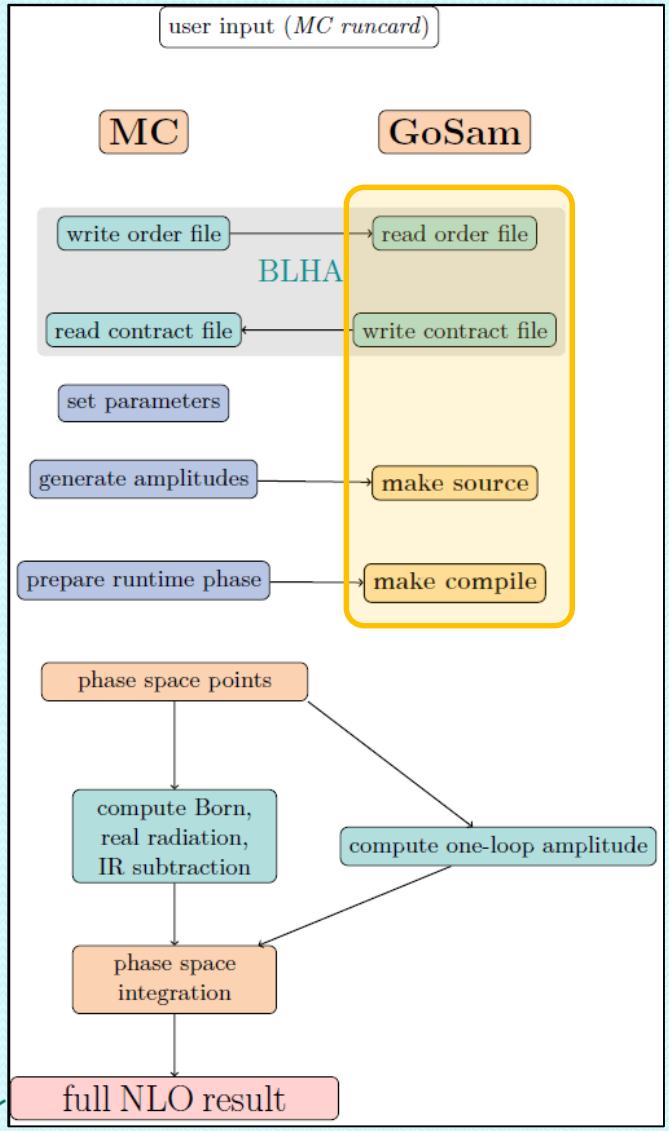

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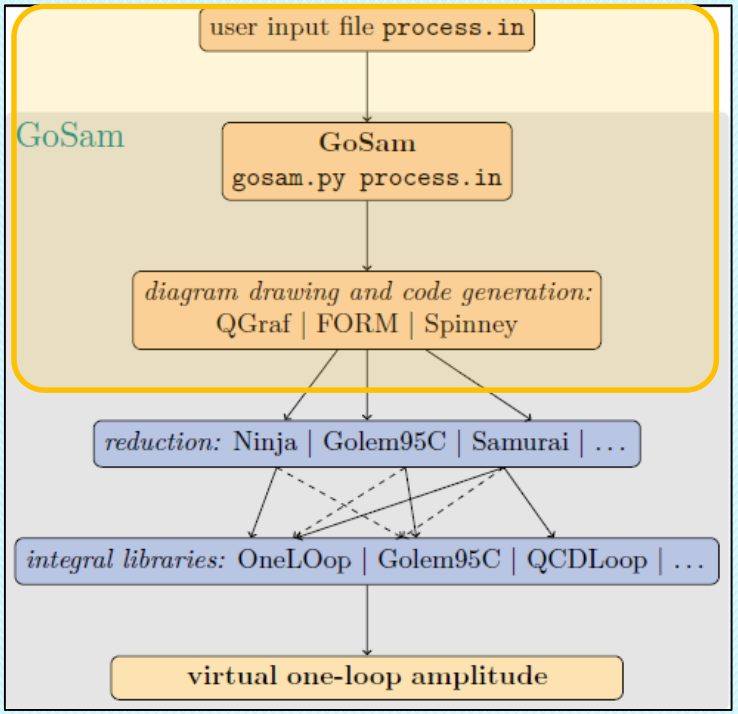
Generation



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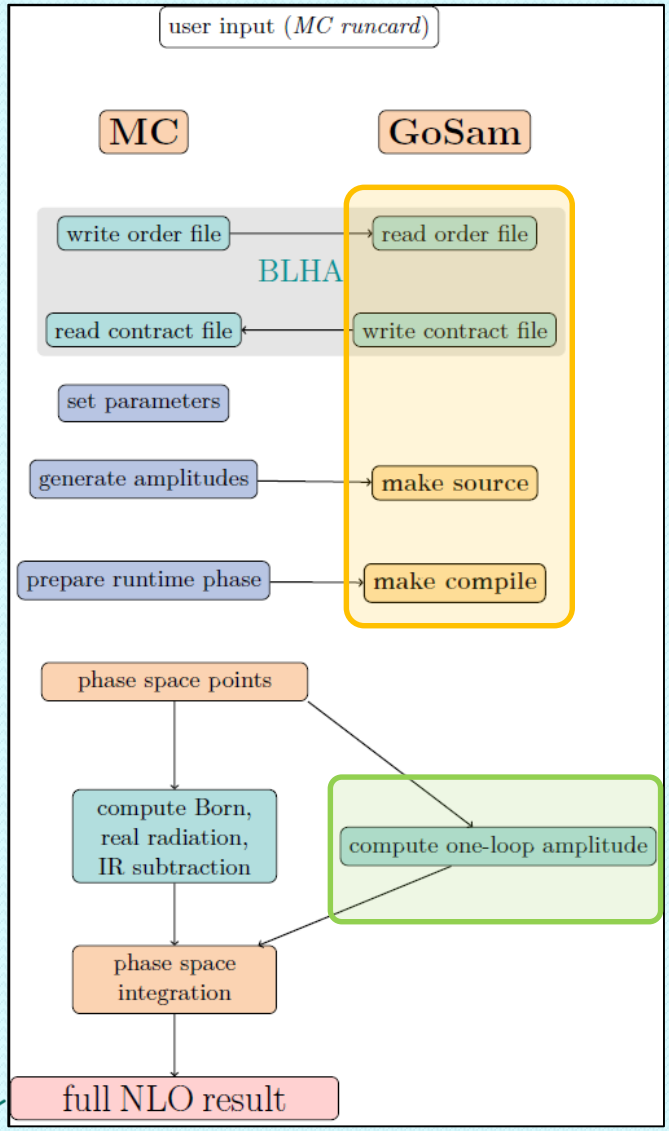

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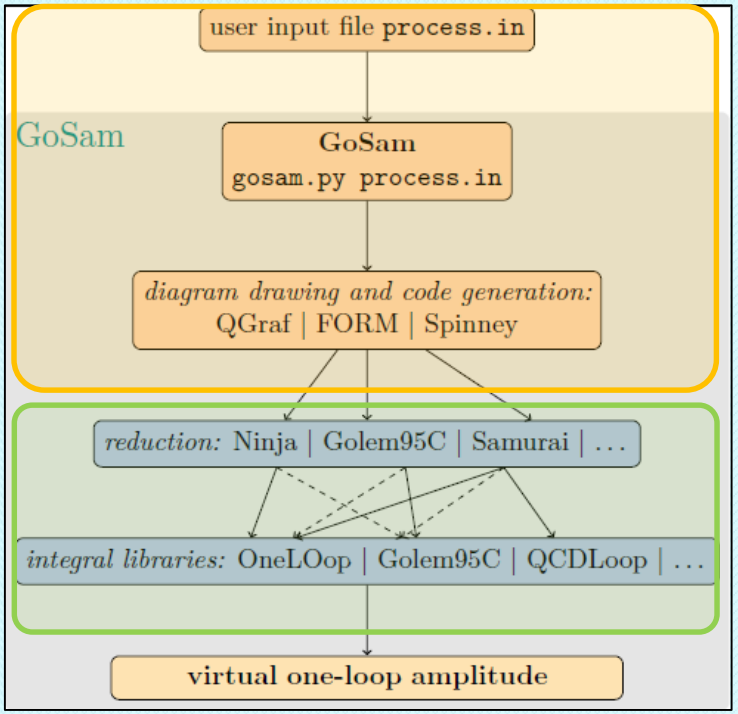
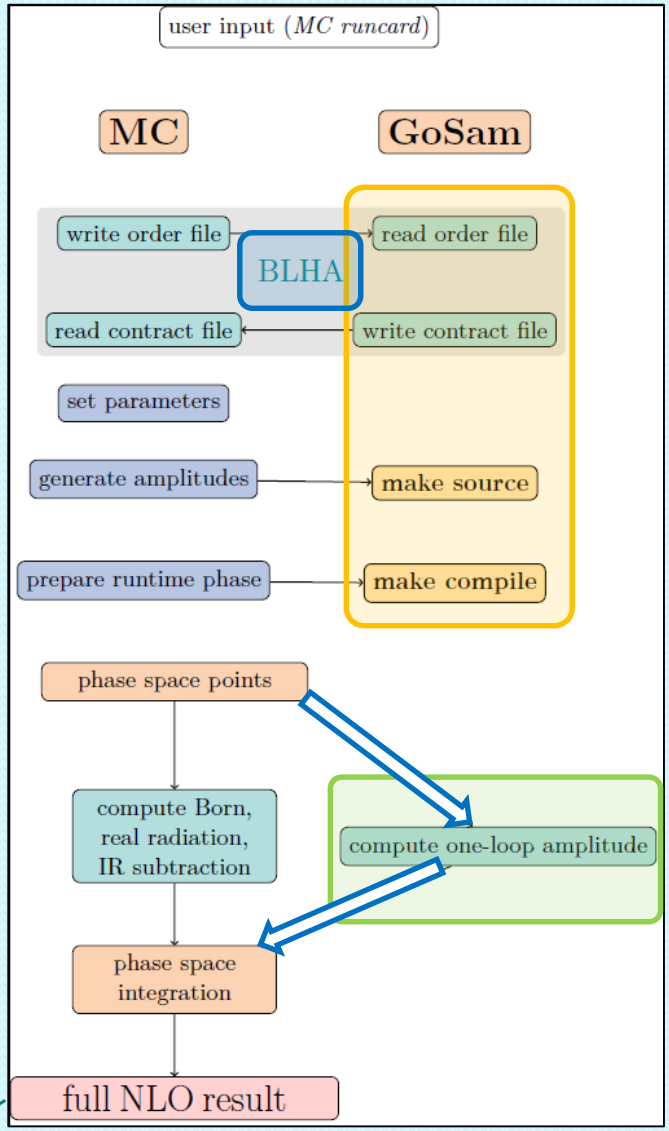
Generation

Reduction



GoSam-2.0: a quick overview



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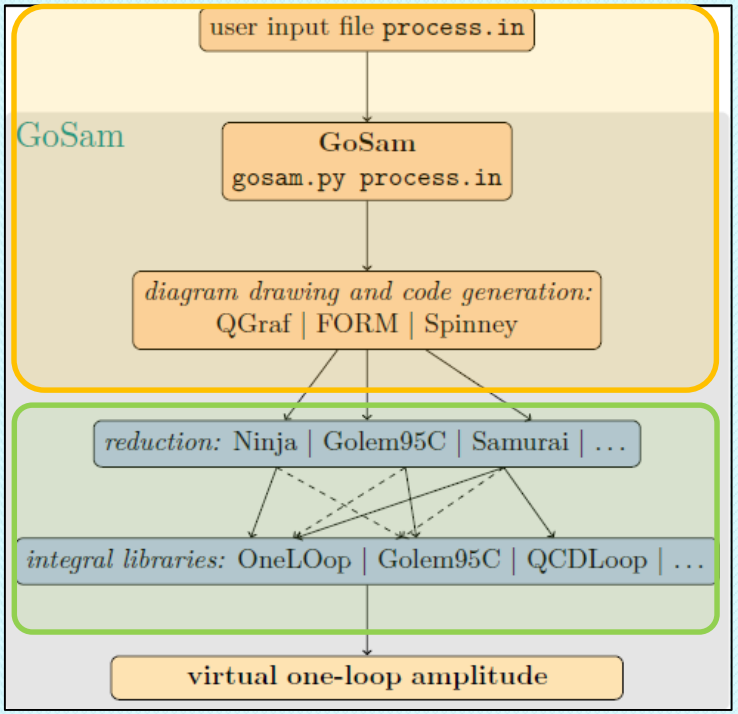
Generation

Reduction

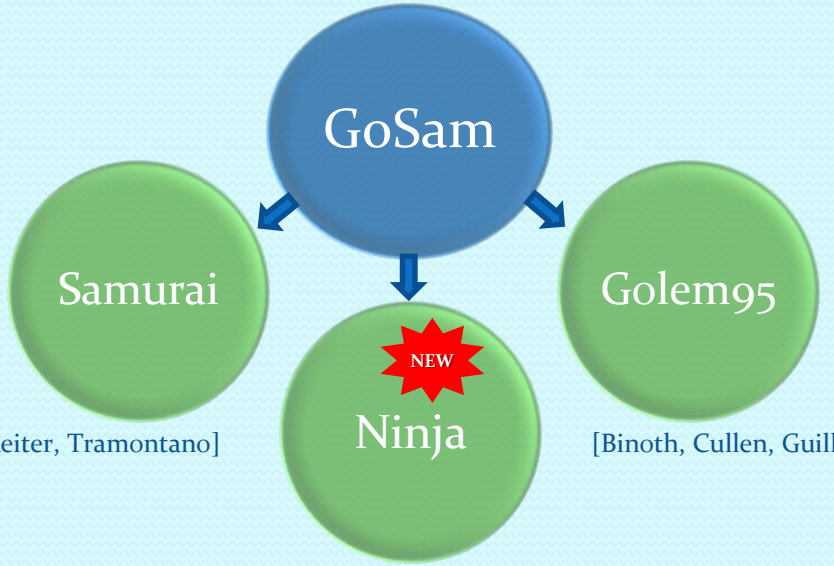
NLO computation



Generation

- GoSam: a tool to compute virtual 1-loop amplitudes:
  - Generation of numerators based on Feynman diagrams
    - ➔ QGRAF [Nogueira]
  - Algebraic manipulation in D-dimensions before reduction
    - ➔ FORM-4 [Kuipers, Ueda, Vermaseren] NEW
  - Optimization: caching/grouping/summing
    - ➔ GoSam
  - Generation on the fly of the full rational term
    - Implicit: retaining full μ^2-dependent part for reduction
    - Explicit: computing μ^2-dependent integral analytically

Reduction



[Mastrolia, Ossola, Reiter, Tramontano]

[Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter]

[Mastrolia, Mirabella, Peraro]
[Van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro]

NEW
All reduction programs support higher rank integrals

- Several reduction strategies/tools
- Switch among them on the fly at running time
  - Use tensorial reduction as rescue system when integrand reduction fails
- Recent developments:

Ninja

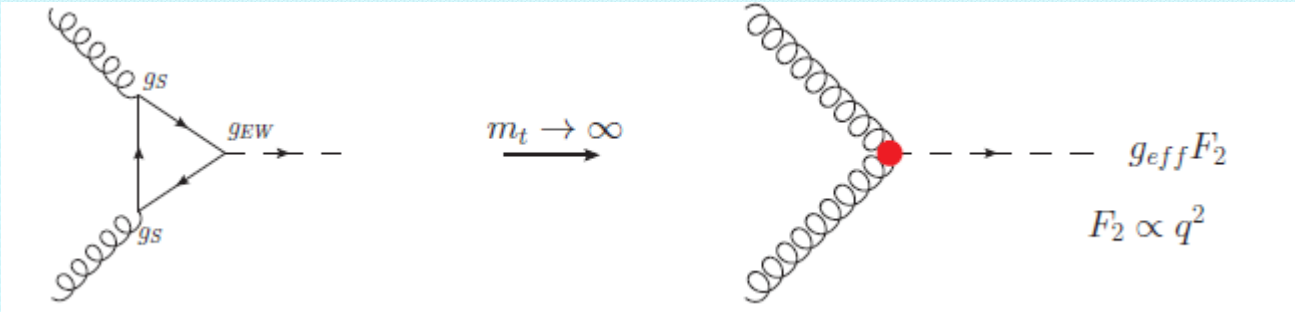
Higher Rank Support

Higher rank loop integrals

- For any 1-loop amplitude $\mathcal{A}_n = \int d^d\bar{q} \frac{\mathcal{N}(\bar{q},\epsilon)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{n-1}}$

Rank: $r_{\mathcal{N}}$ = # powers of loop momentum in numerator $\mathcal{N}(\bar{q})$

- in SM with renormalizable gauges: $r_{\mathcal{N}} \leq n$
- in SM with effective Hgg vertex or ADD models: $r_{\mathcal{N}} \leq n+1$



Adapt reduction programs Samurai, Ninja and Golem95C to deal with higher rank loop integrals

NEW

[Mastrolia, Mirabella, Peraro; van Deurzen, Mastrolia]

[Guillet, Heinrich, von Soden-Fraunhofen]

NLO Computation – BLHA2

[Binoth et al.]

- Standards for comunication between **MC** and **OLP**
  - recently updated to increase automation and flexibility: NEW

    [Alioli et al.]
    - Support for dynamical parameters (coupling, masses, …)
    - Synchronization of EW schemes
    - Standards for treatment of unstable phase space points
    - Standards for merging different jet multiplicities
    - Extension to provide also colour correlated (CC) and helicity correlated (HC) tree amplitudes

Higgs+jets results

H+jets: virtual corrections

	Processes	# Diagrams	# Helicities	# Groups	Timing (col.+hel. summed)
H+0 jets	$g+g \longrightarrow H$	1	1	1	< 1 ms
H+1 jets	$q+\bar{q} \longrightarrow H+g$	14	4	3	~ 3 ms
	$g+g \longrightarrow H+g$	48	8	3	~ 7 ms
		62			
H+2 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'$	32	4	6	~ 9 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}$	64	6	8	~ 15 ms
	$q+\bar{q} \longrightarrow H+g+g$	179	8	12	~ 56 ms
	$g+g \longrightarrow H+g+g$	651	16	12	~ 309 ms
		926			
H+3 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$	467	8	32	~ 68 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}+g$	868	12	44	~ 157 ms
	$q+\bar{q} \longrightarrow H+g+g+g$	2519	16	60	~ 999 ms
	$g+g \longrightarrow H+g+g+g$	9325	32	60	~ 8'960 ms
		13179			

H+2 jets

[van Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano]

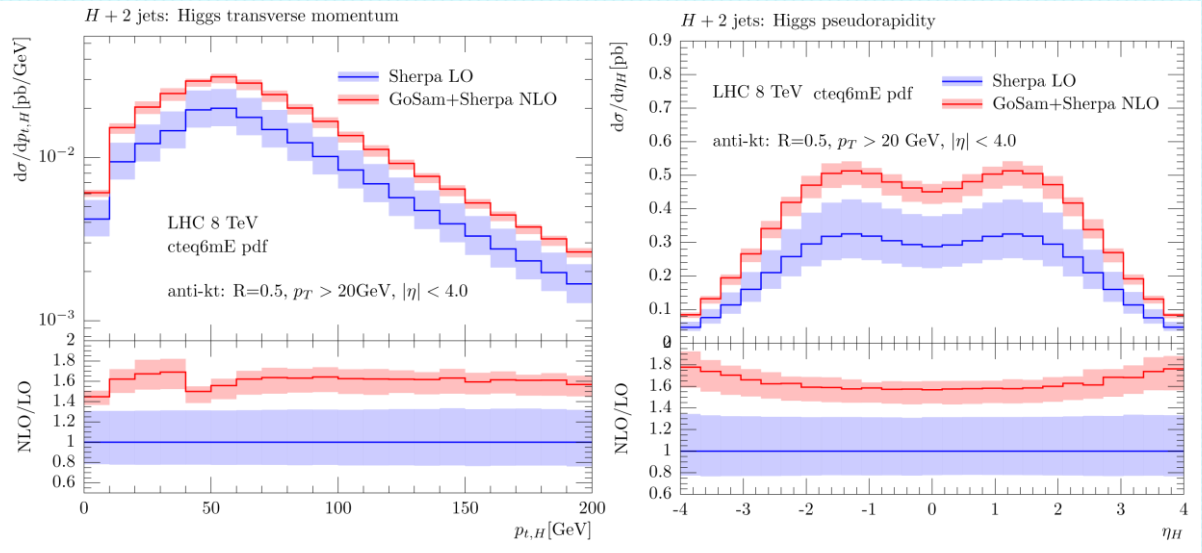
- Computed using GoSam + Sherpa
- Possibility to test the framework by comparing to existing results/codes
  --> agreement with MCFM (v6.4) [Campbell, Ellis, Williams]

  - Physical setup: LHC 8 TeV

    anti-kt: R=0.5 p_T>20 GeV $|\eta| < 4.0$

    PDFs: cteq6L1 @ LO cteq6mE @ NLO

    scales: $\mu_F = \mu_R = \hat{H}_T = \left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$



H+3 jets

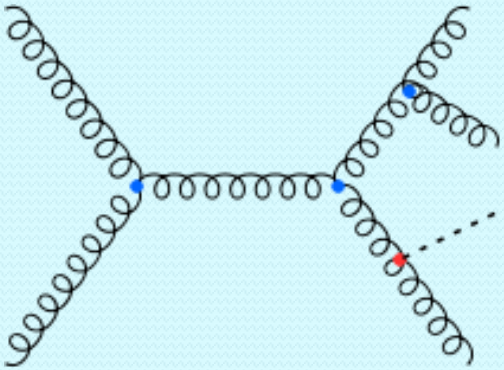
[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- Computed using GoSam + Sherpa + MadGraph4/MadDipole/MadEvent
  - Physical setup: LHC 8 TeV with ATLAS cuts

anti-kt: R=0.4 p_T>30 GeV $|\eta| < 4.4$

PDFs: cteq6L1 @ LO CT10nlo @ NLO

scales: $\mu_F = \mu_R = \frac{\hat{H}_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$



$$\alpha_s^5 \longrightarrow \alpha_s^2(m_H)\alpha_s^3(\hat{H}_T/2)$$

H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- Inclusive cross section:

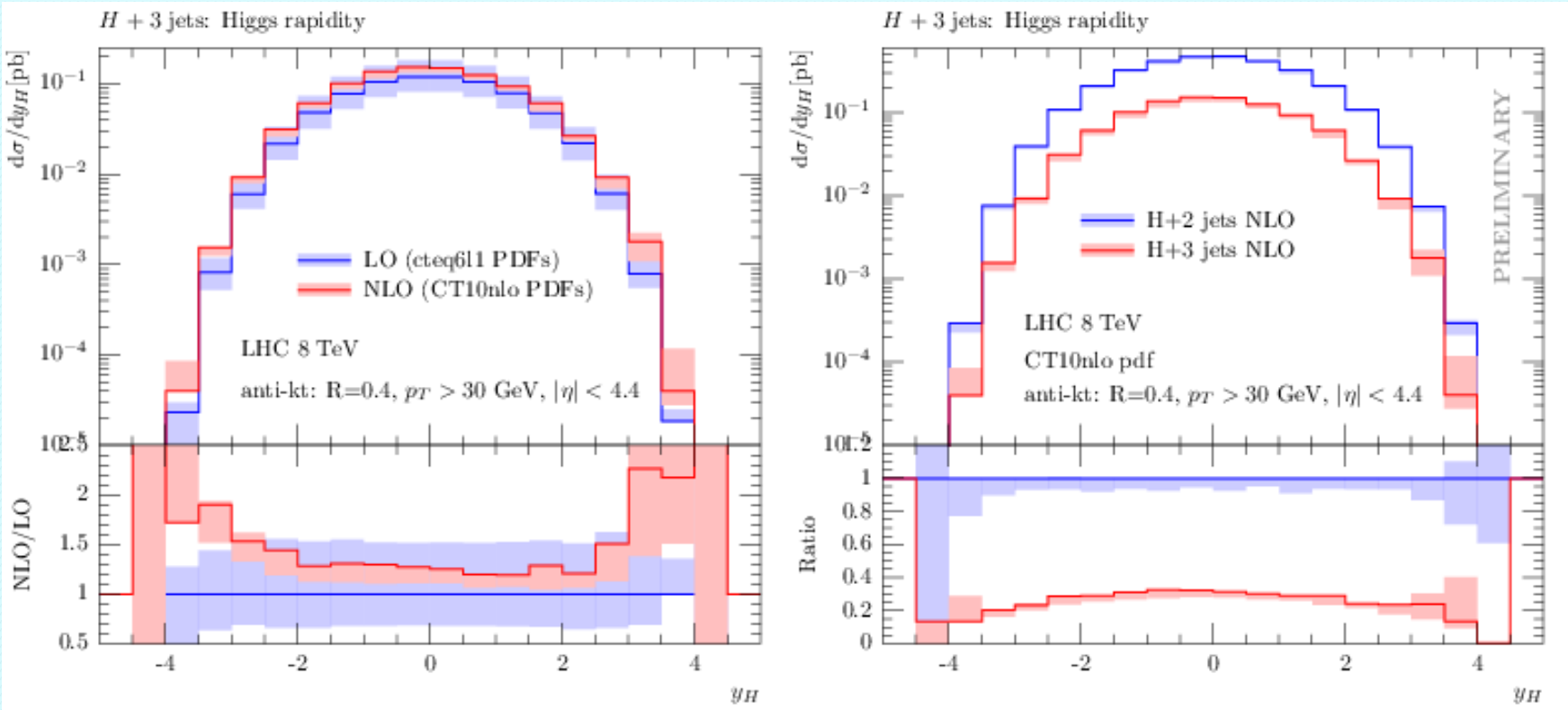
σ_n : inclusive cross section
f_3 : inclusive 3-jet fraction
$r_{(n+1)/n} = \sigma_{n+1}/\sigma_n$

Sample K-factor		Cross sections for Higgs boson plus ≥ 2 jets	f_3	≥ 3 jets	$r_{3/2}$
	LO	[pb]		[pb]	
H+2-jets (LO PDFs)		$1.23\ ^{+37\%}_{-24\%}$			
H+3-jets (LO PDFs)		(0.381)	1.0	$0.381\ ^{+53\%}_{-32\%}$	$0.310\ ^{0.347}_{0.278}$
	NLO				
H+2-jets		$1.590\ ^{-4\%}_{-7\%}$	0.182	$0.289\ ^{+49\%}_{-31\%}$	
H+3-jets		(0.485)	1.0	$0.485\ ^{-3\%}_{-13\%}$	$0.305\ ^{0.307}_{0.284}$
K_2, K_3 (LO PDFs for LO)		$1.29\ ^{0.911}_{1.59}$		$1.27\ ^{0.806}_{1.63}$	
K_2, K_3 (NLO PDFs for LO)		$1.64\ ^{1.19}_{1.98}$		$1.70\ ^{1.10}_{2.13}$	

H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

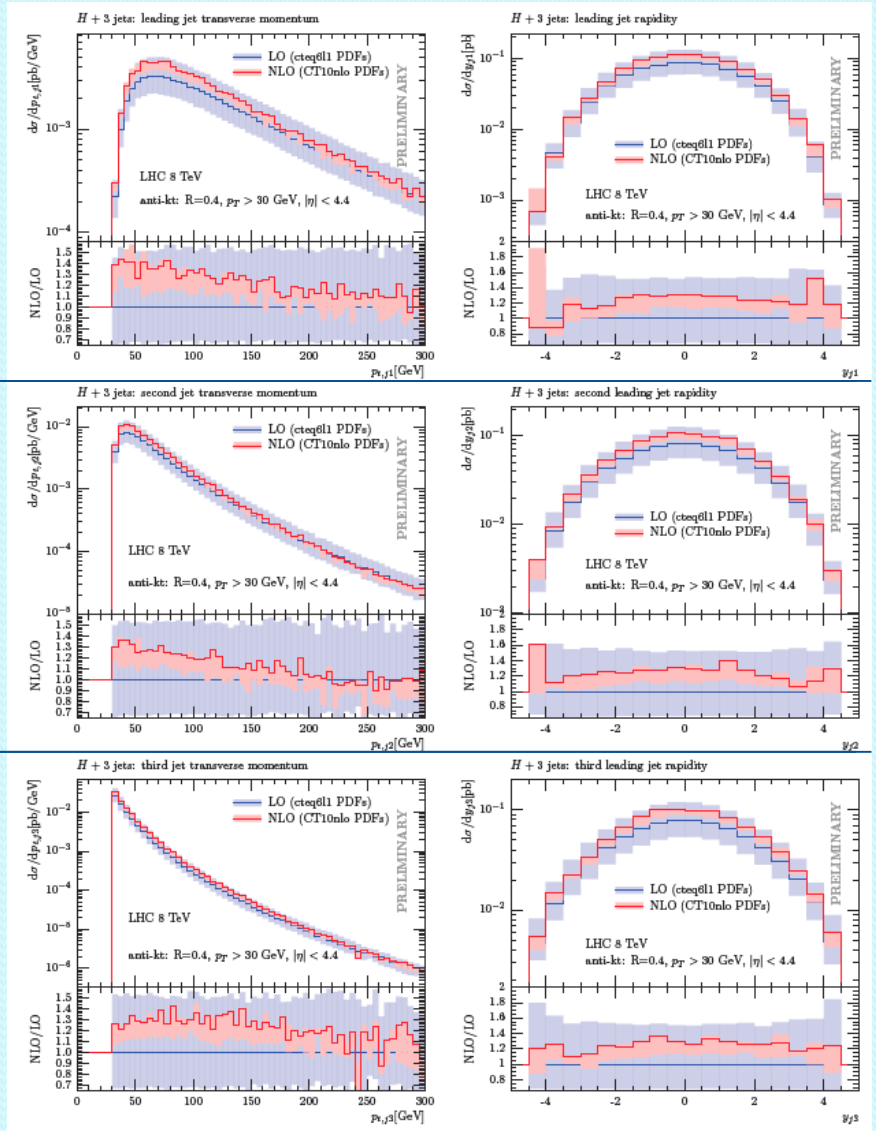
- Higgs rapidity distributions:



H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- 1st jet
- 2nd jet
- 3rd jet

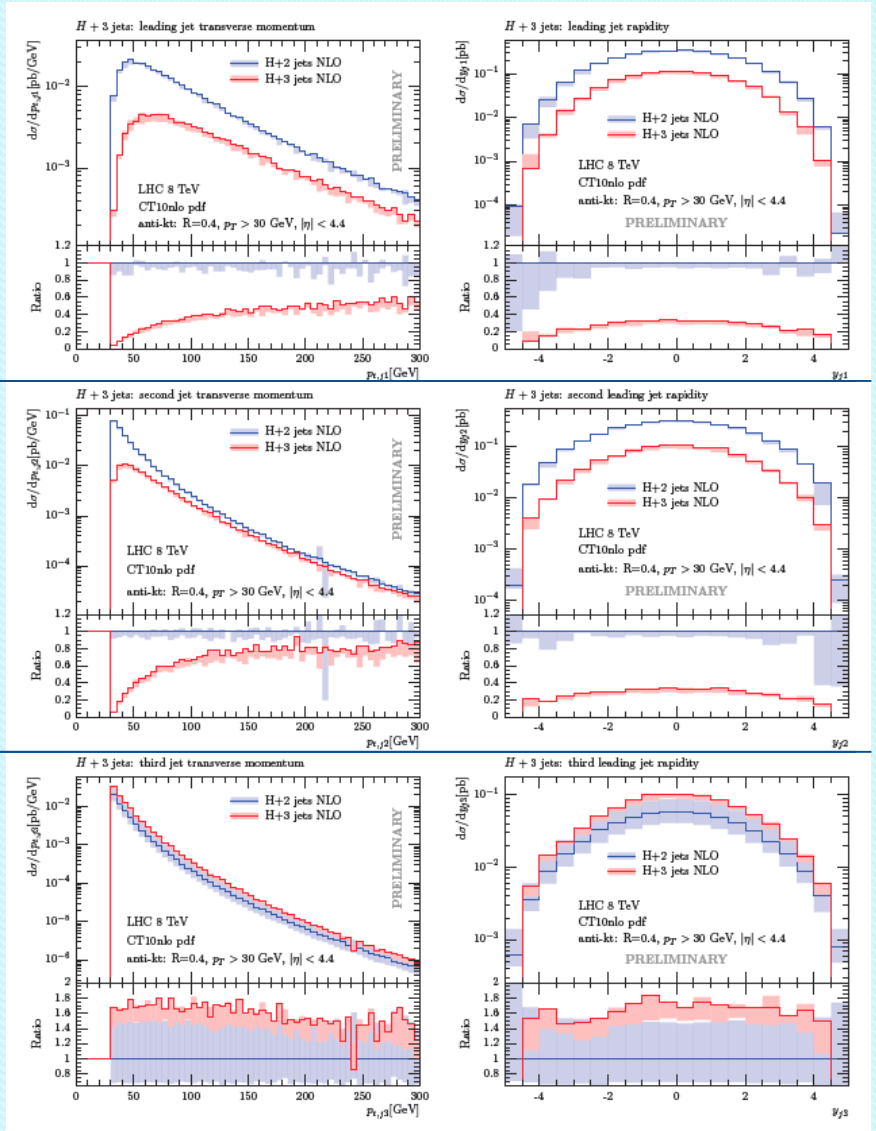


- Similar scale variations as Higgs rapidity
- y_j: +20% corrections from NLO
- Pt_j: important shape change due to NLO corrections

H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- 1st jet
- 2nd jet
- 3rd jet



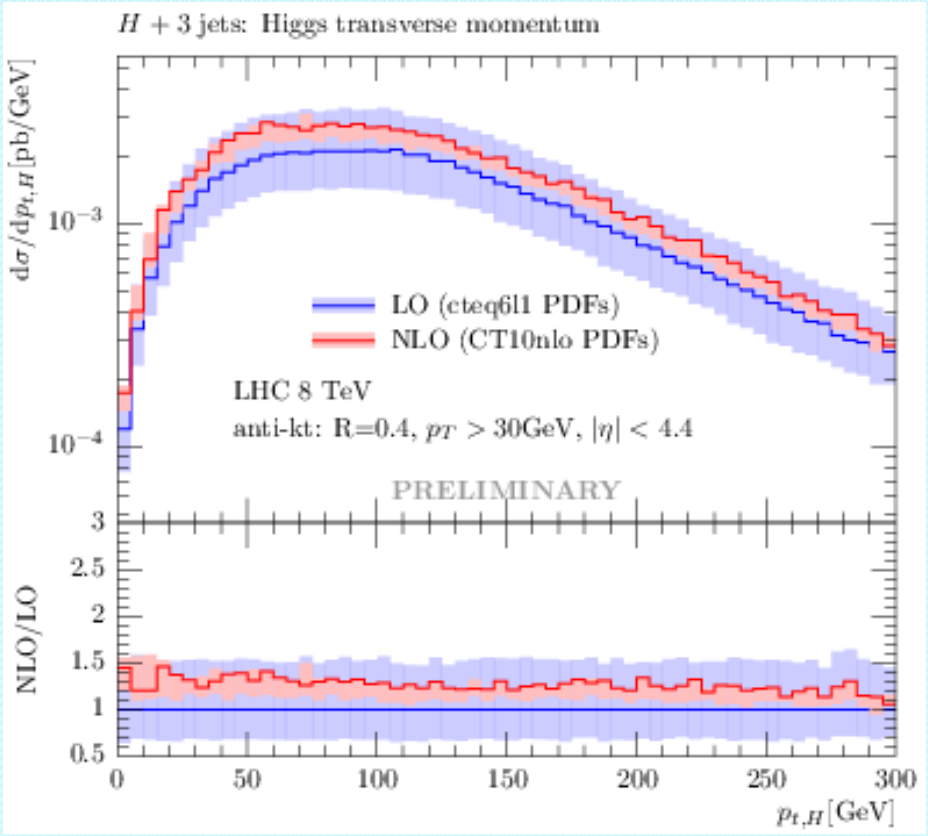
- $r_{3/2}$: different behaviour for hardest and 2nd hardest jet than for 3rd hardest one
- $r_{3/2}$: flat for y_j distributions
- $r_{3/2}$: strong dependence in Pt_j distributions (50% at 100 GeV)

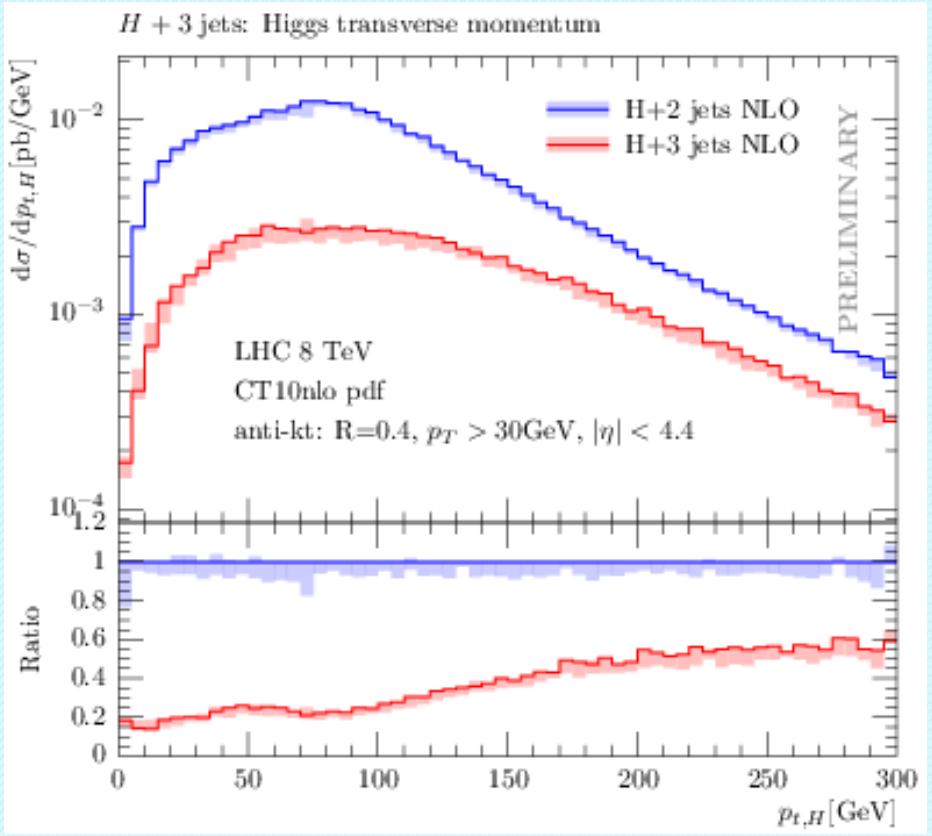
Higher jet multiplicity important

H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- Higgs transverse momentum distributions:

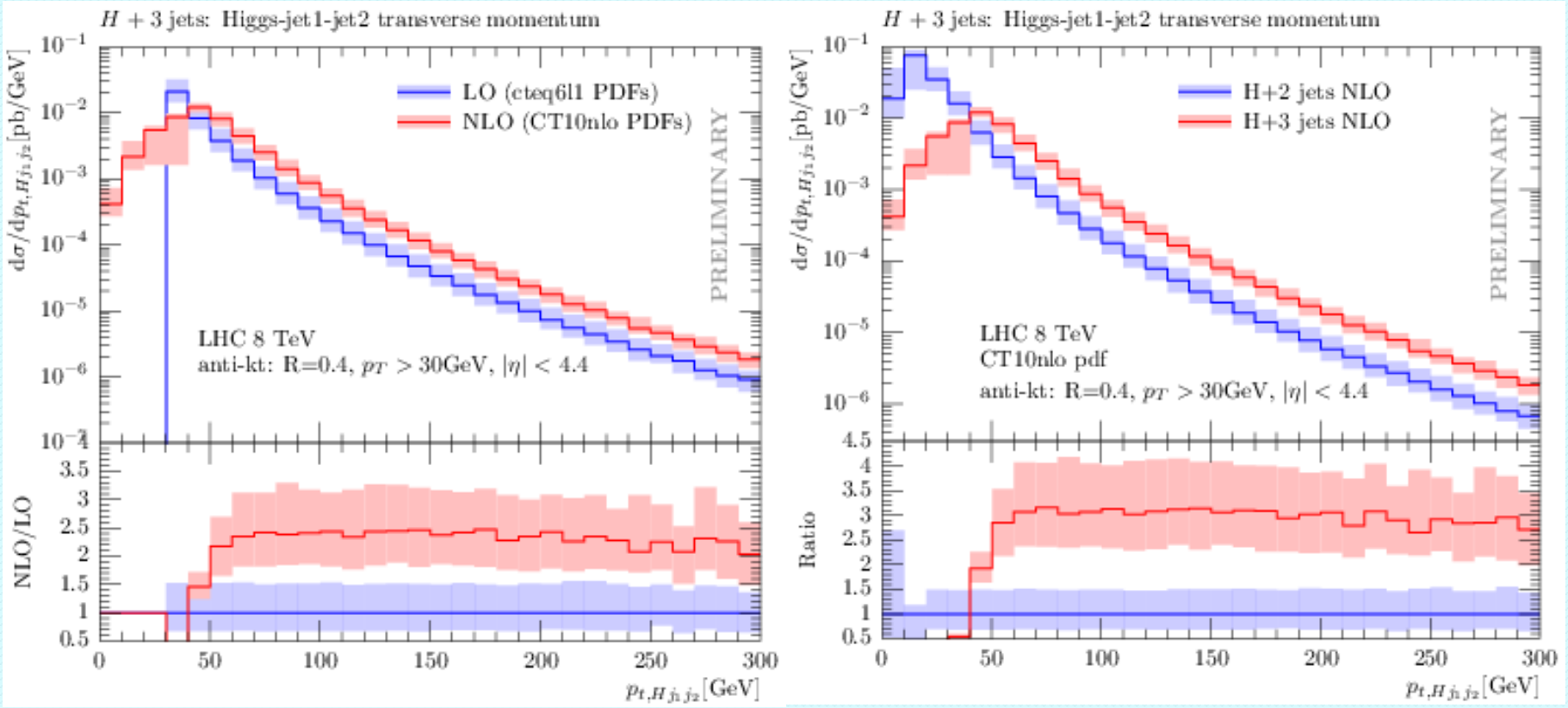




H+3 jets

[Cullen, van Deurzen, Greiner, Huston, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano, Yundin, Winter]

- Hj_1j_2 transverse momentum:



Conclusions & Outlook

- H+3 jets @ NLO in gluon-gluon fusion
  - GoSam+Sherpa+MadGraph/MadDipole/MadEvent
  - GoSam-2.0 released with many improvements:
    - New reduction algorithm / Higher rank support / Better optimization
    - Interfaced with several Monte Carlos/ BSM

    http://gosam.hepforge.org
  - Significant reduction of scale uncertainties
  - Important impact of NLO corrections on shapes
  - Pt of Hj_1j_2-system for the first time computed with NLO accuracy

- Work in progress
  - Impact of VBF-type cuts
  - Release code and ntuples generation
  - Merging with smaller multiplicities / matching with parton shower