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von Humboldt Stiftung/Found

Recent Developments in GoSam

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In collaboration with:

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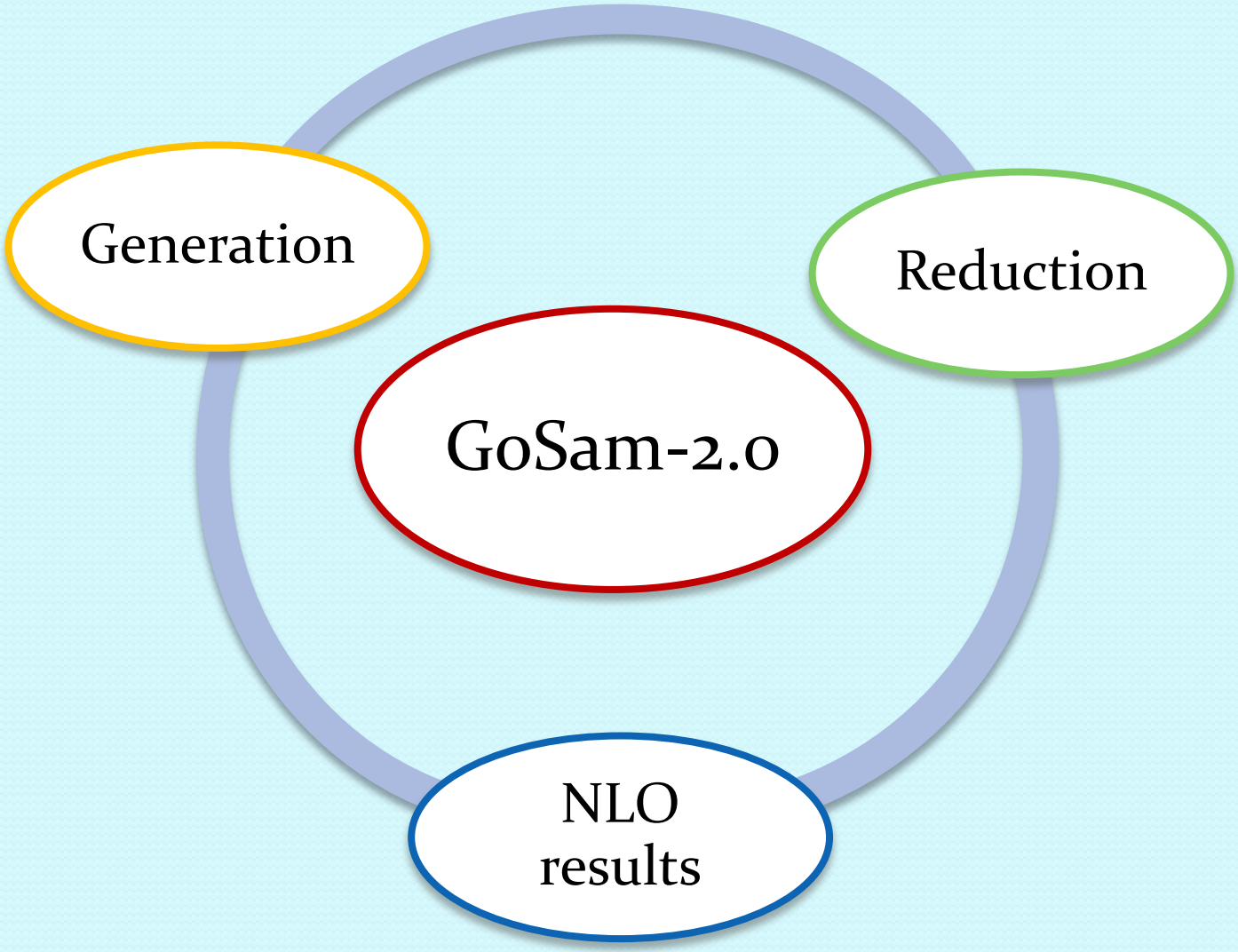
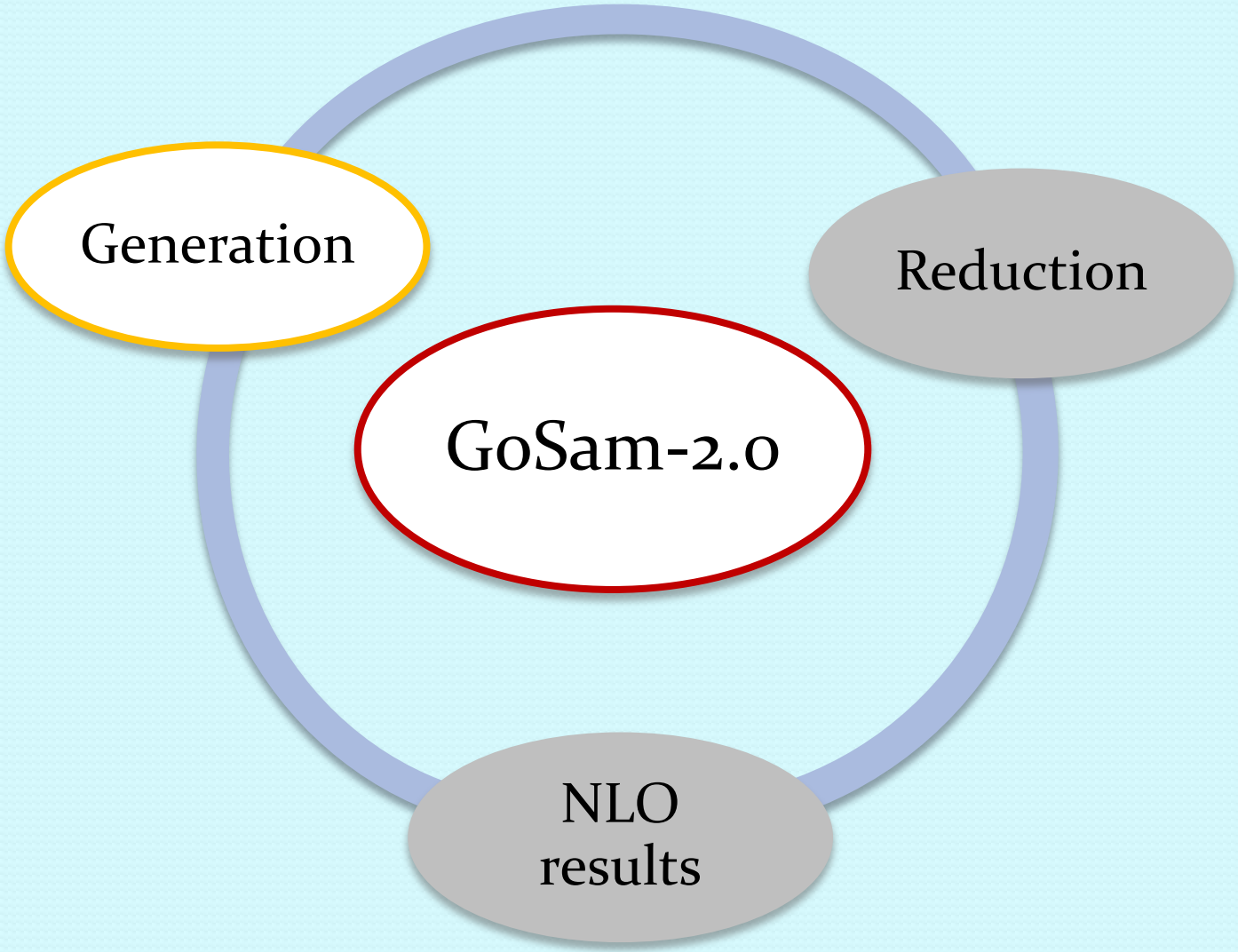
Outline

- The GoSam framework:
  - Generation
  - Reduction
  - NLO results
- Phenomenology:
  - Process packages
  - H+2 and H+3 jets in gluon-gluon-fusion
  - H $t\bar{t}$ + 1 jet
- Sherpa as a user
- Conclusions

The GoSam framework



The GoSam framework: Generation

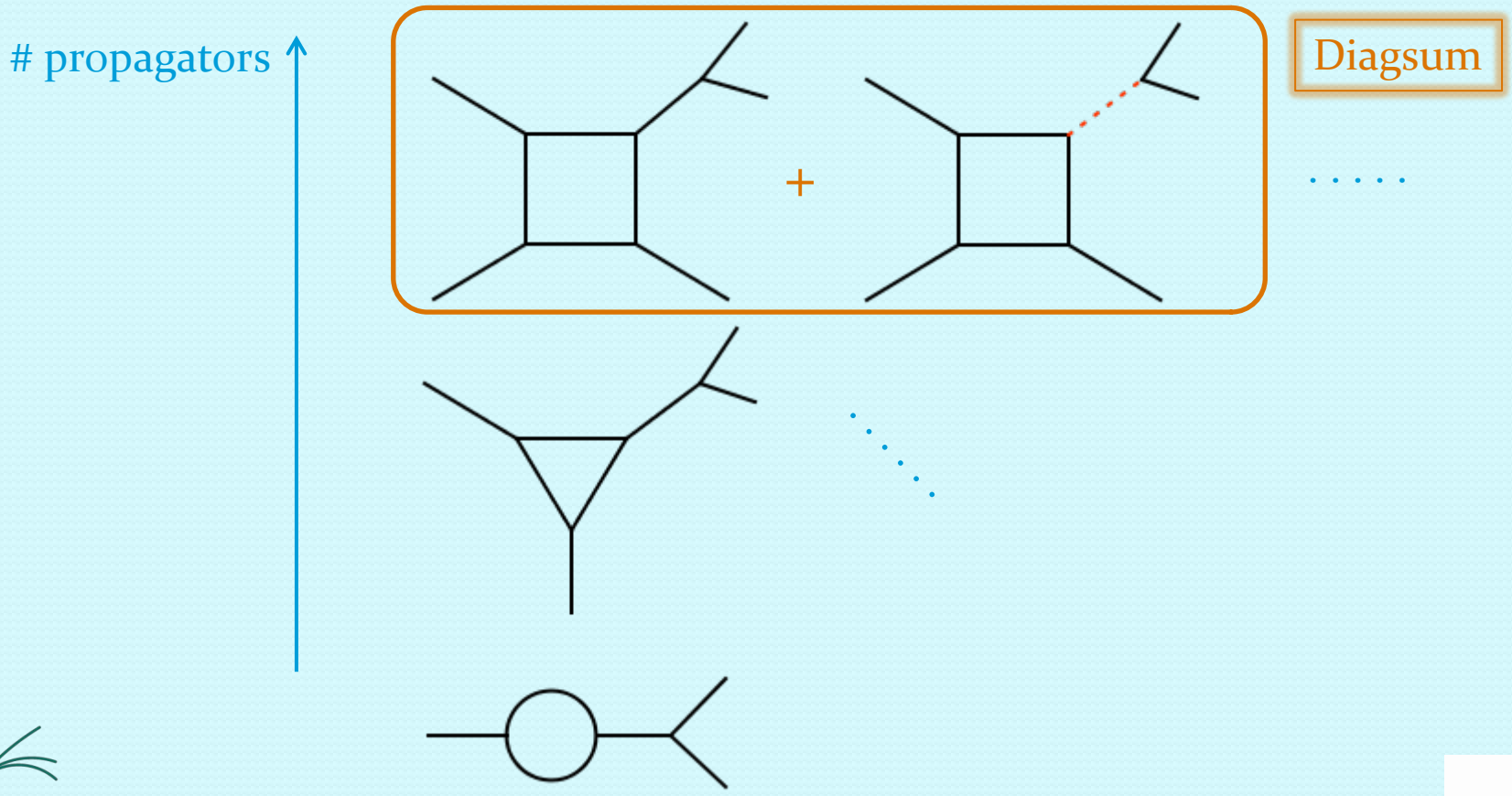


Generation

- 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: cashing/grouping/summing
    - ➔ GoSam
  - Generation on the fly of the full rational term
    - Implicit: retaining full μ-dependent part for reduction
    - Explicit: computing μ-dependent integral analitically

Summing/Grouping

- To reduce the number of calls to the reduction program, diagrams are collected both "horizontally" and "vertically" in the number of propagators:



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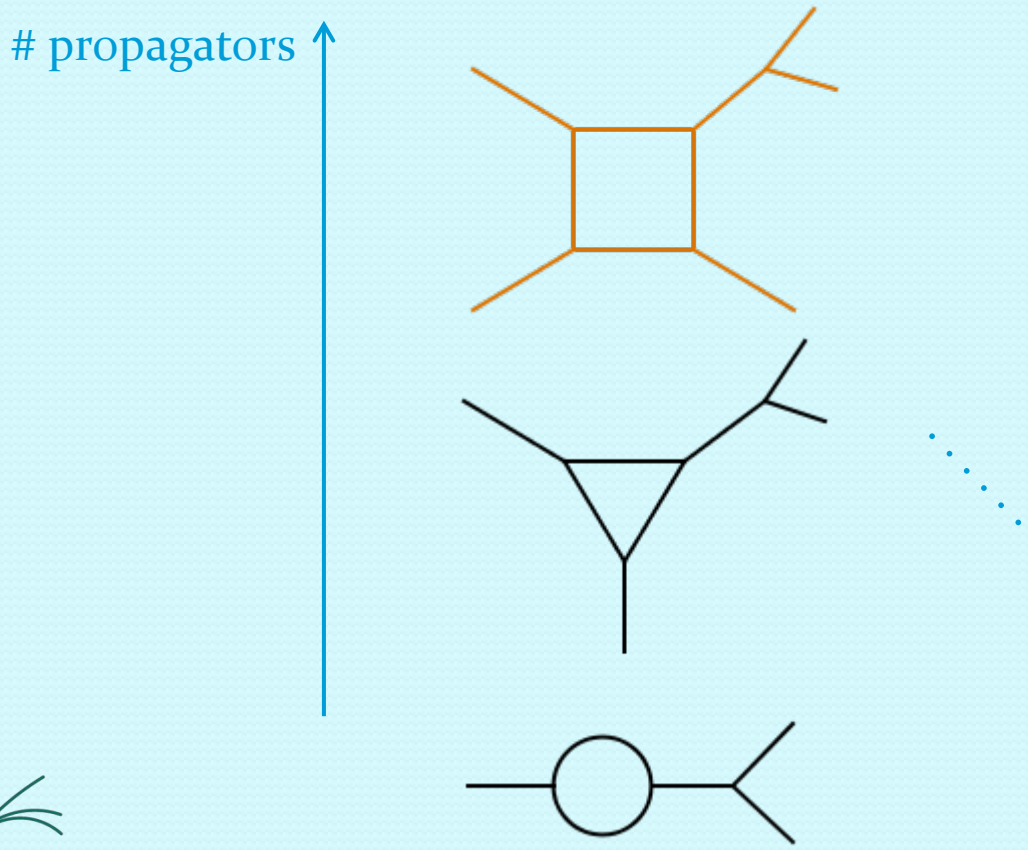

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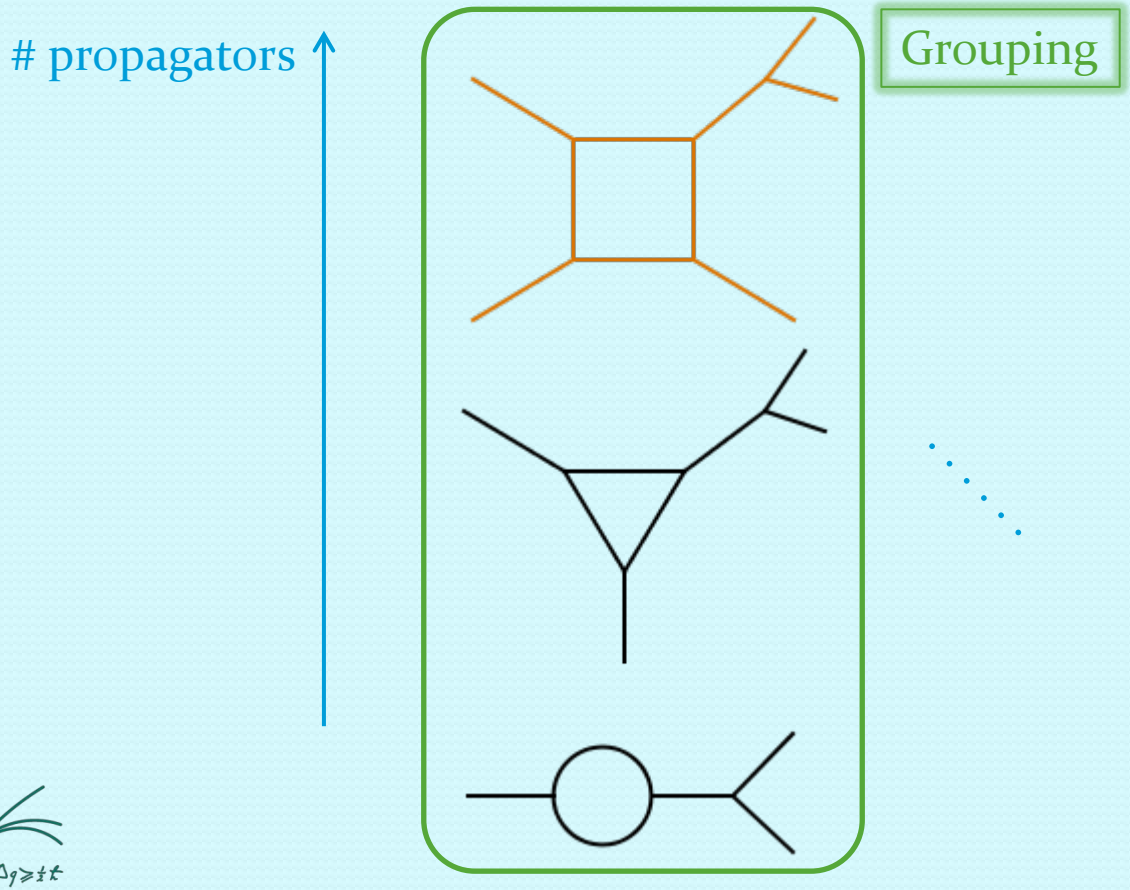
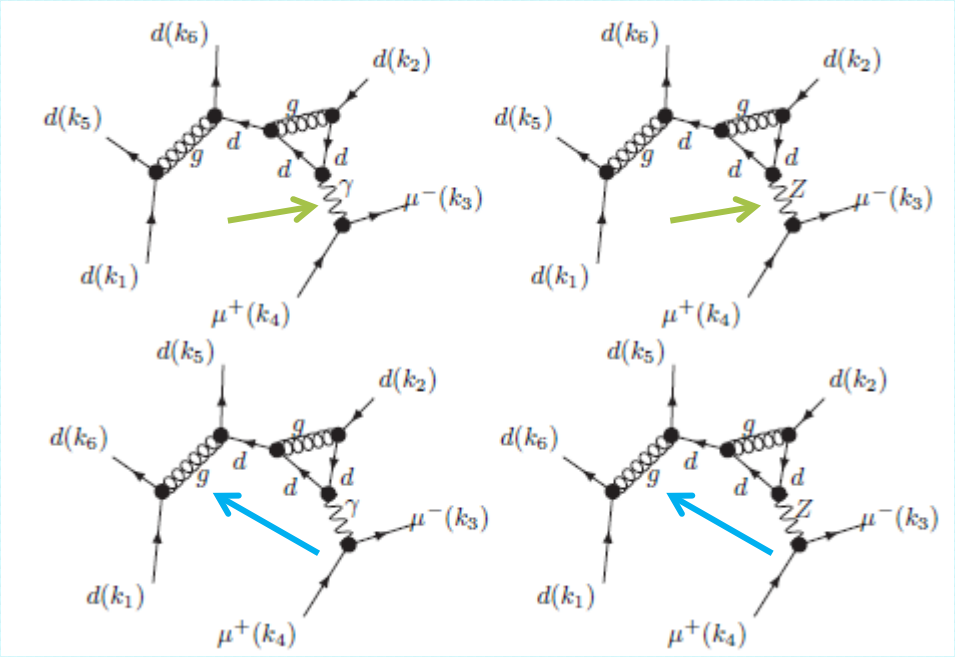
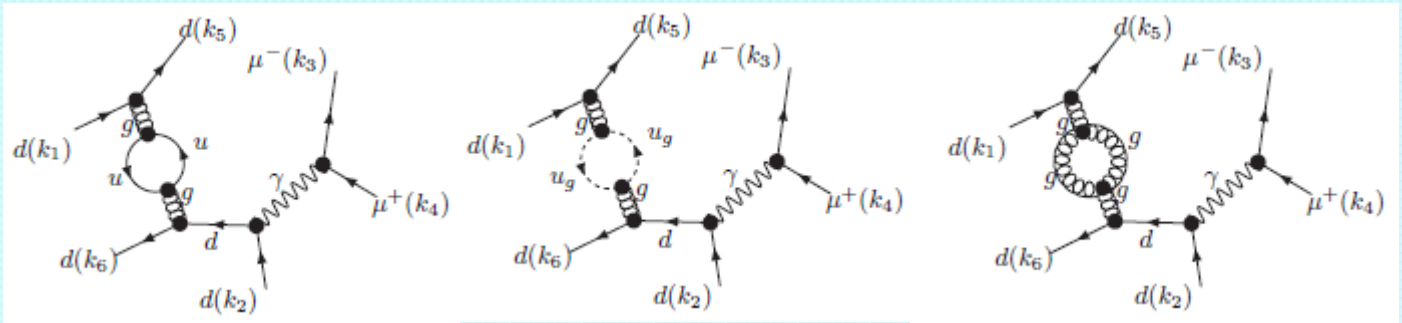


Diagsum

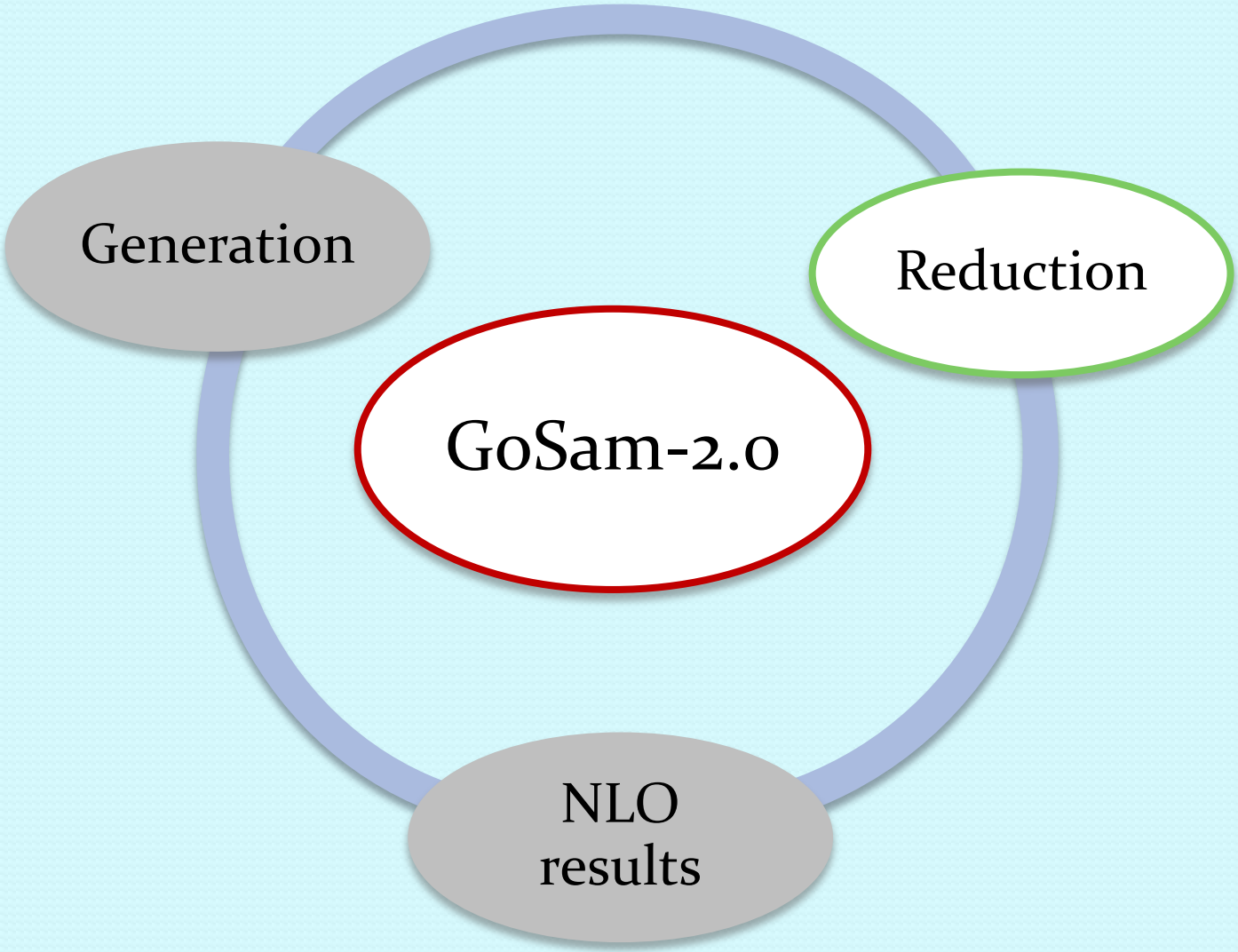
- Sum diagrams which have different tree-part:



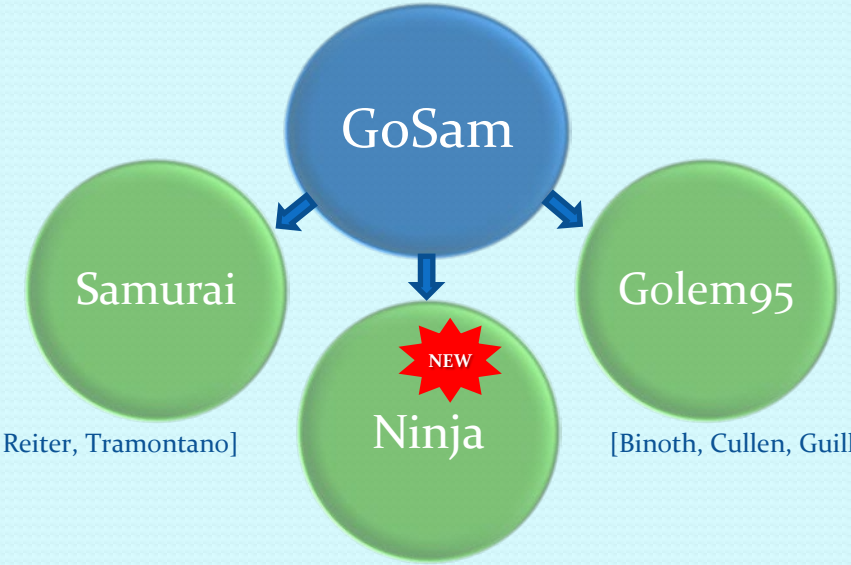
- Sum diagrams with same loop but different particles in loop



The GoSam framework: Reduction



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

→ See talk by T. Peraro

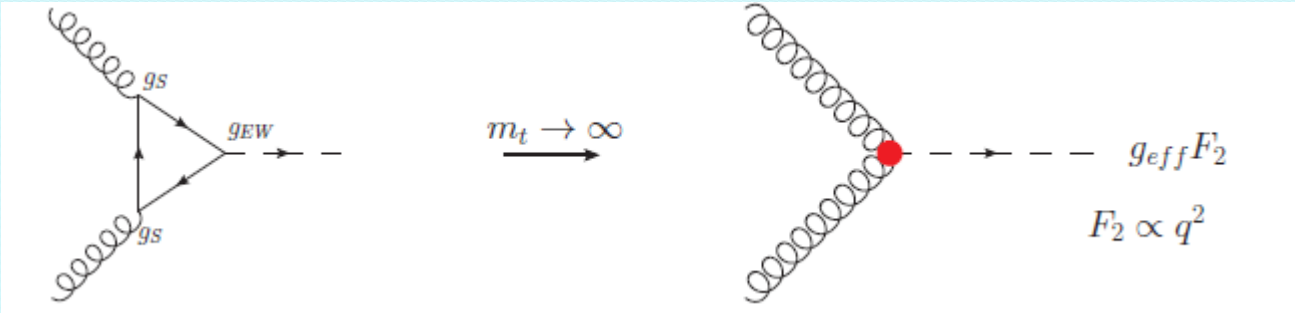
Higher Rank Support

Higher rank extension

- 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: $r_{\mathcal{N}} \leq n+1$



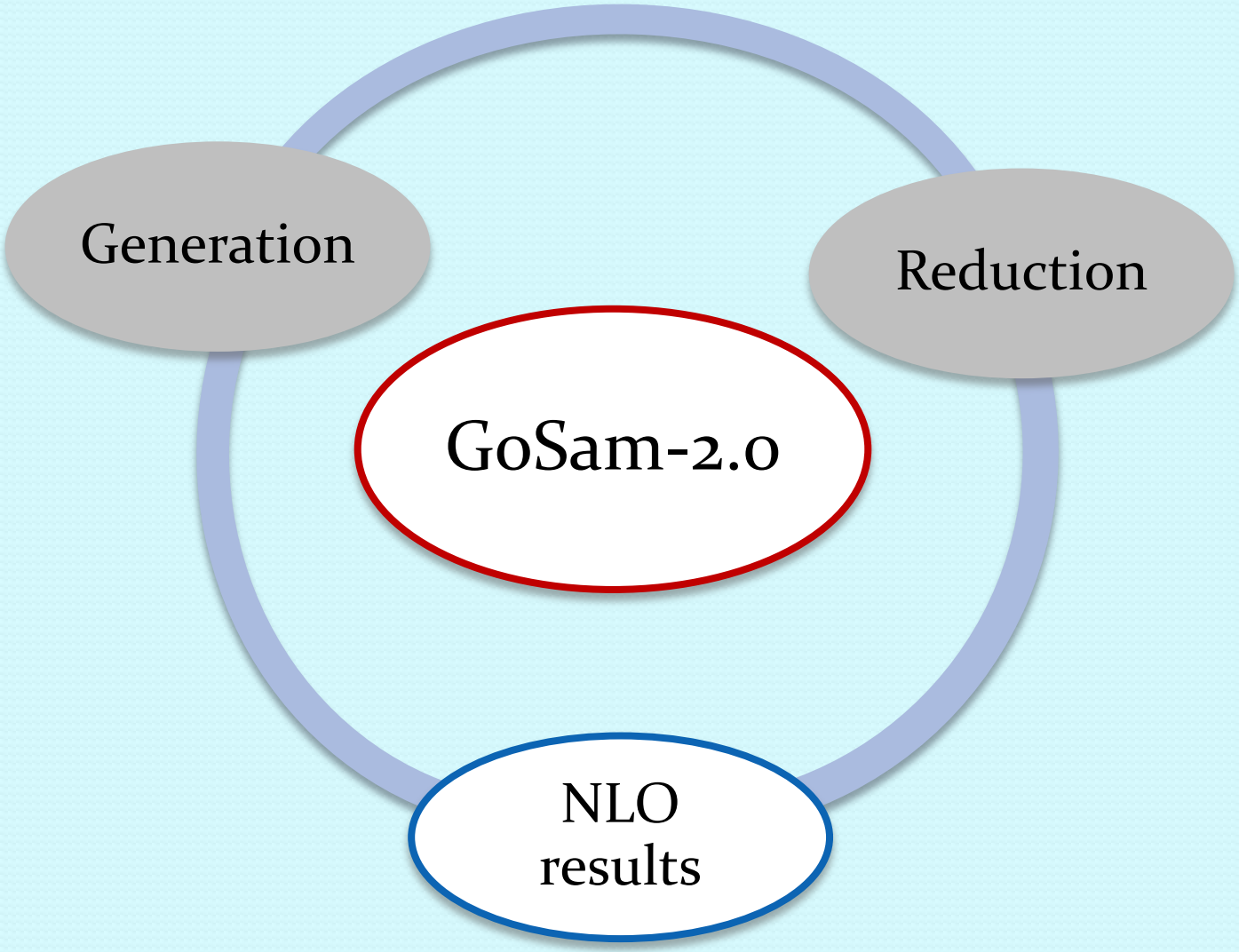
Adapt reduction programs Samurai, Ninja and Golem95C to deal with higher rank loop integrals

NEW

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

[Guillet, Heinrich, von Soden-Fraunhofen]

The GoSam framework: NLO Results



NLO Results

- For a full NLO calculation other ingredients are needed:

$$\sigma_{\rm NLO} = \int_{\rm d\Phi_m} {\rm d}\sigma_{\rm Born} + \int_{\rm d\Phi_{m+1}} ({\rm d}\sigma^{\rm R}_{\rm NLO} - {\rm d}\sigma^{\rm S}_{\rm NLO}) + \int_{\rm d\Phi_m} \left[\int_{\rm d\Phi_1} {\rm d}\sigma^{\rm S}_{\rm NLO} + {\rm d}\sigma^{V}_{\rm NLO} \right]$$

- Virtual corrections

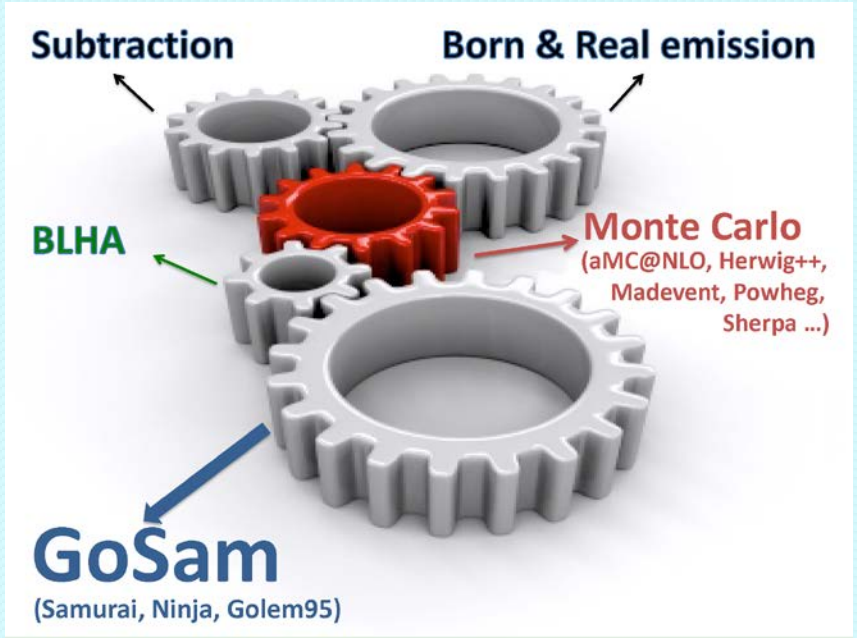
One Loop Program

BLHA

Monte Carlo

Tree amplitude

- Subtraction scheme
- Phase space integral



Recent NLO results using GoSam

- **GoSam + MadGraph/MadDipole/MadEvent**
  - pp - > $b\bar{b}b\bar{b}$ [Greiner, Guffanti, Reiter, Reuter]
  - pp - > $W^+ W^-$ j j [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]
  - pp - > $\tilde{\chi}^0\tilde{\chi}^0$ j [Cullen, Greiner, Heinrich]
  - pp - > $\gamma\gamma$ j / $\gamma\gamma$ j j [Gehrmann, Greiner, Heinrich] **http://gosam.hepforge.org/diphoton**
  - pp - > G (-> $\gamma\gamma$) j [Greiner, Heinrich, Reichel, v. Soden-Fraunhofer]
- **GoSam + Powheg**
  - pp - > HW j / HZ j [G.L., Nason, Oleari, Tramontano]
- **GoSam + Sherpa**
  - pp - > H j j [in ggf] [v. Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, v. Soden-Fraunhofer, Tramontano]
  - pp - > $t\bar{t}$ (j) [Höche, Huang, G.L., Schönherr, Winter]
  - pp - > H $t\bar{t}$ (j) [v.Deurzen, G.L., Mastrolia, Mirabella, Ossola, Peraro]
  - pp - > $W^+ W^- b\bar{b}$ [Heinrich, Schlenk, Winter]

Other process packages available at:
http://gosam.hepforge.org/proc/

- **GoSam + MadGraph/MadDipole/MadEvent +Sherpa**
  - pp - > H j j j [in ggf] [Cullen, v. Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro, Tramontano]

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Phenomenology

Process packages for Sherpa

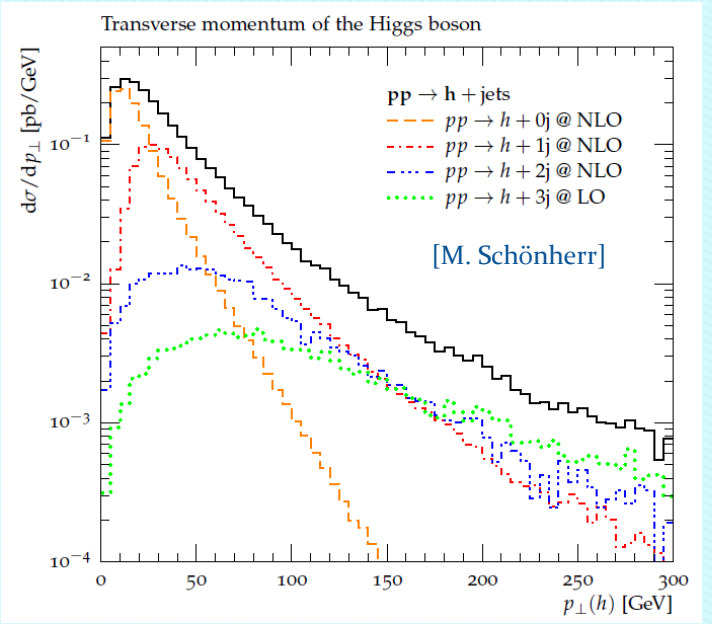
- Ready-to-use process packages for Sherpa-1.4.x:

pp -> W + 0,1,2 jets
pp -> Z/g* + 0,1 jets
pp -> W b $\bar{b}$
pp -> W^+W^-
pp -> W^+W^+ + 2 jets
…

  - Plan to update to Sherpa-2.0.0
  - Add more packages

H+jets in gluon-gluon fusion

- Dominant channel of Higgs production
- Large background makes it a prohibitive channel to directly study the Higgs



- 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: virtual corrections

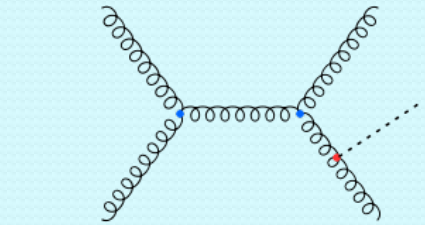
	Processes	# Diagrams	# Helicities	# Groups	Timing (col.+hel. summed)
H+0 jets	$g+g \longrightarrow H$	1	1	1	< 1 ms
H+1 jets	$q+\bar{q} \longrightarrow H+g$	14	4	3	~ 3 ms
	$g+g \longrightarrow H+g$	48	8	3	~ 7 ms
		62			
H+2 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'$	32	4	6	~ 9 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}$	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: $\mu_F = \mu_R = \hat{H}_T = \left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$

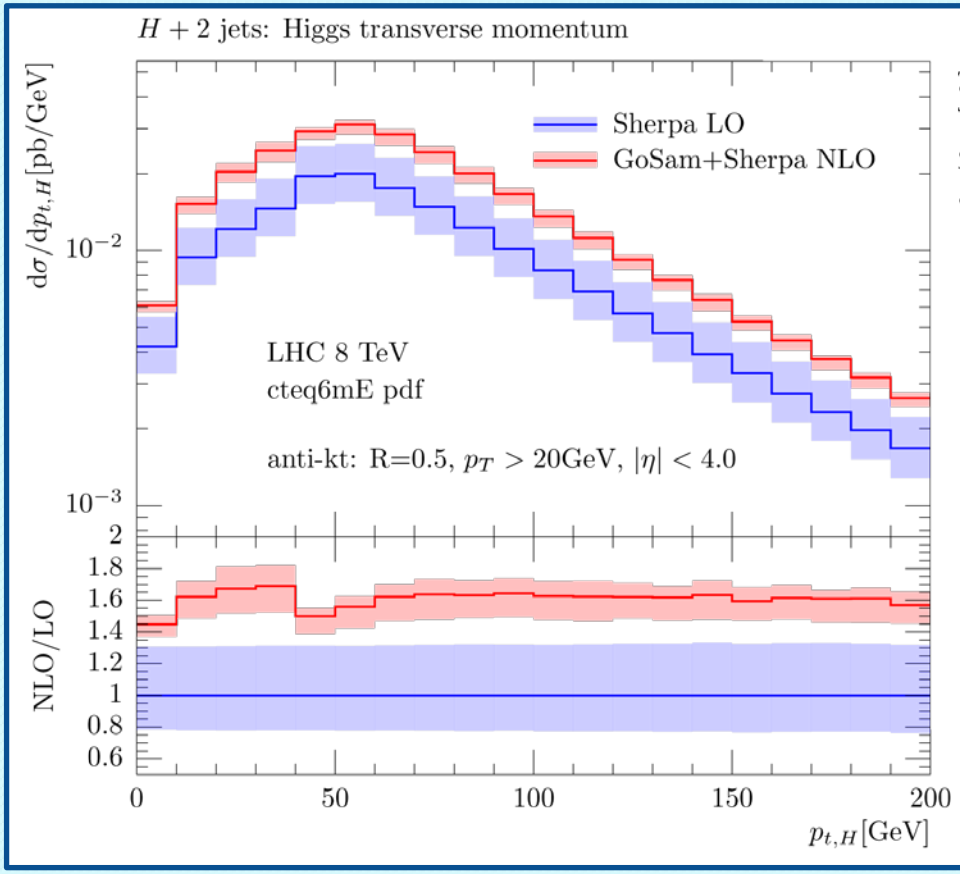


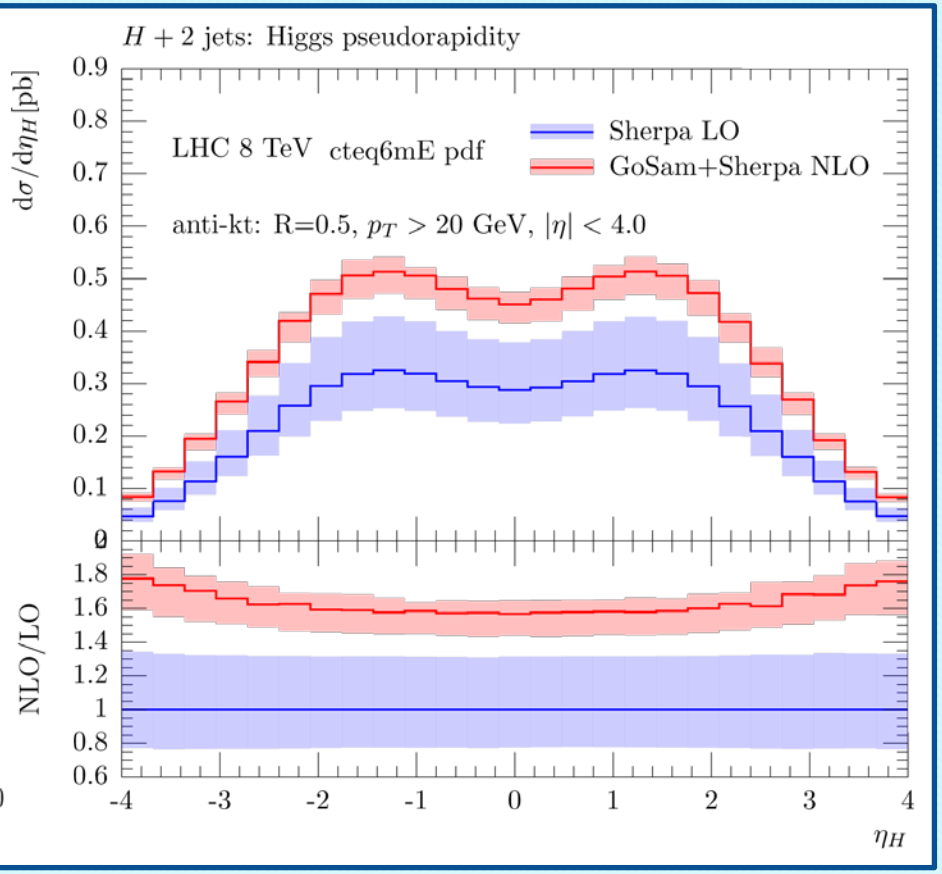
$$\alpha_s^4 \longrightarrow \alpha_s^2(m_H)\alpha_s^2(H_T)$$

$$\sigma_{LO}(\hat{H}_T) = 1.88^{+0.59}_{-0.43}\,[\text{pb}]$$
$$\sigma_{NLO}(\hat{H}_T) = 3.02^{+0.16}_{-0.27}\,[\text{pb}]$$

H+2 jets

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

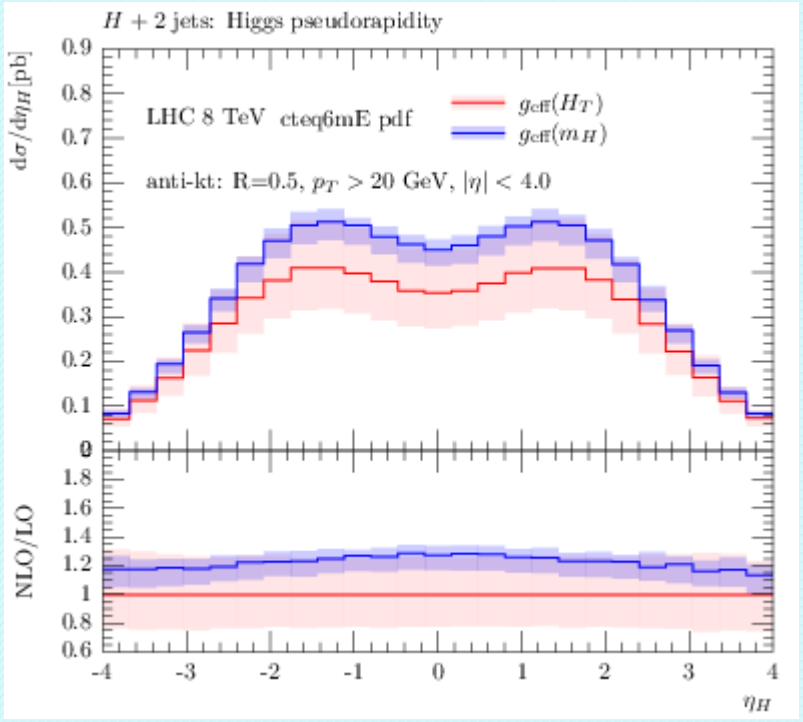


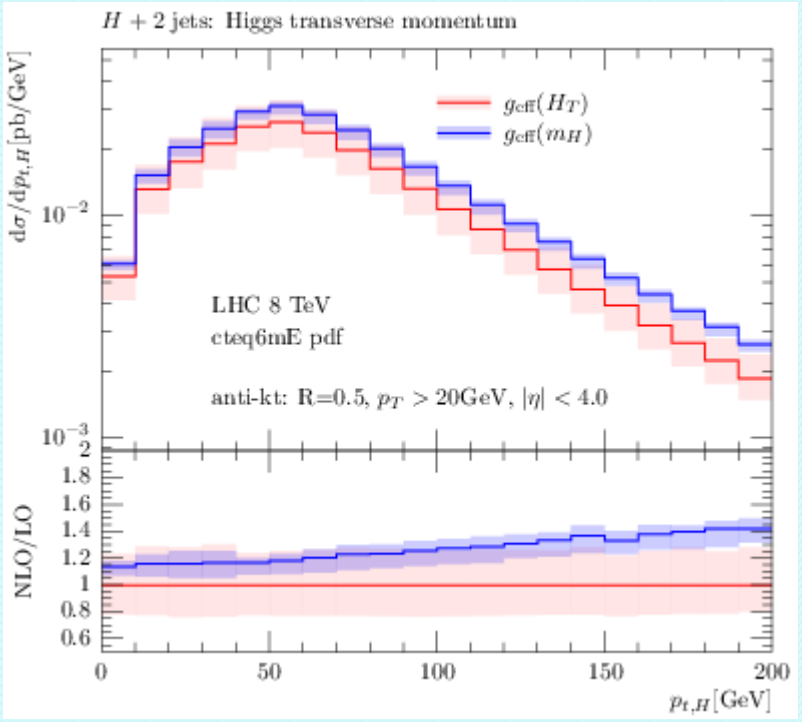


- Reduction of scale uncertainty
- Large K-factor

H+2 jets

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





- Important impact of scale choice in effective vertex

- Next steps
  - Include Higgs decays
  - Shower

H+3 jets

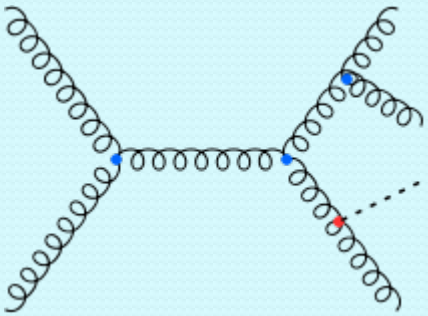
[Cullen, van Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano]

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

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

    PDFs: cteq6L1 @ LO cteq6mE @ NLO

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

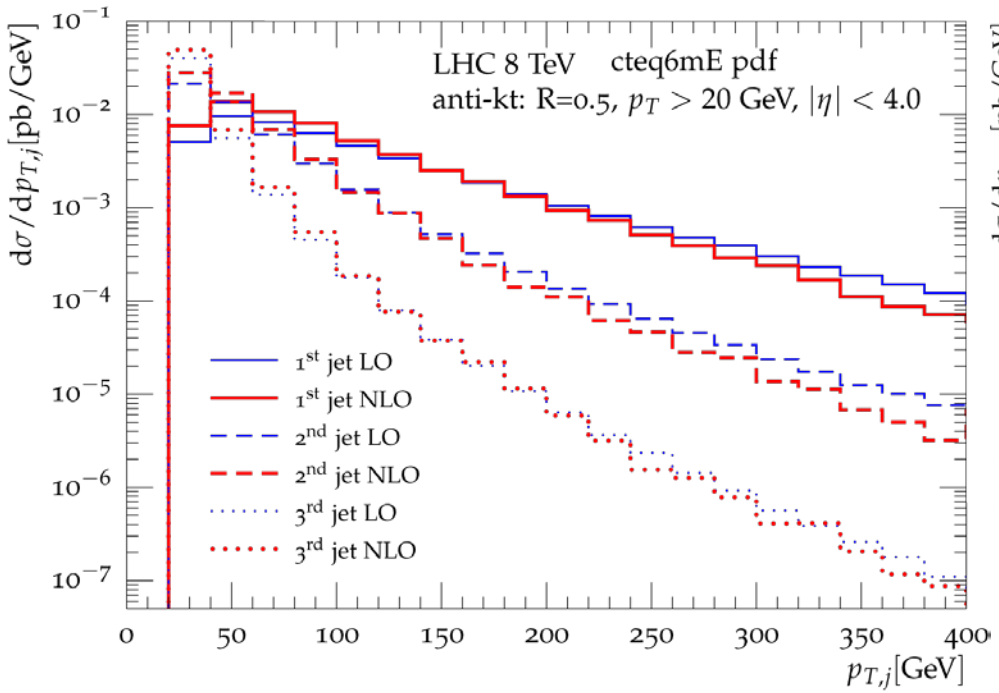


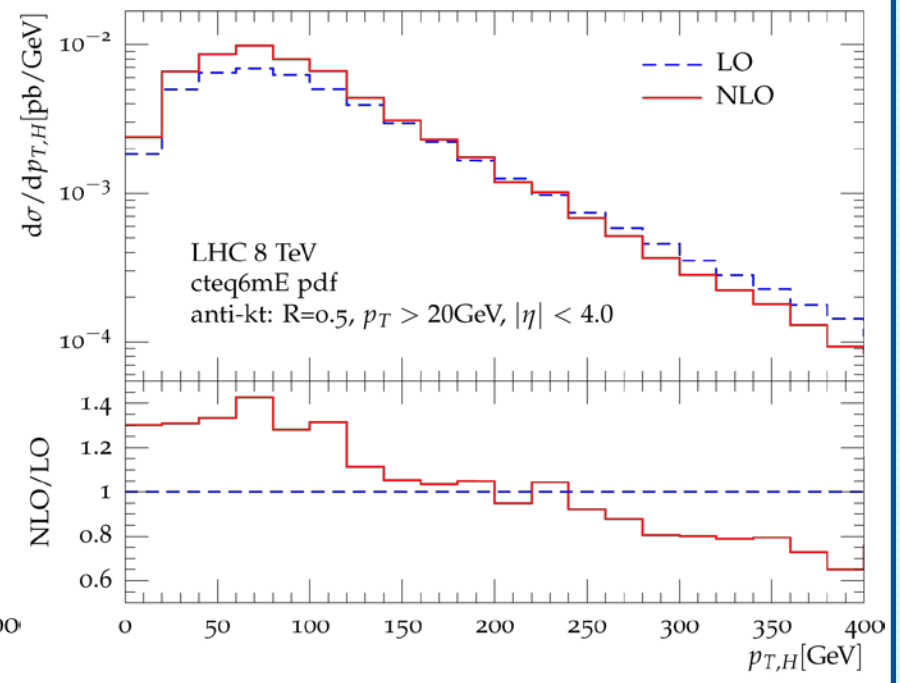
$$\alpha_s^5 \longrightarrow \alpha_s^2(m_H)\alpha_s^3(\hat{H}_T/2)$$

$$\sigma_{LO}(\hat{H}_T/2) = 0.96^{+0.51}_{-0.31}\,[\text{pb}]$$
$$\sigma_{NLO}(\hat{H}_T/2) = 1.18^{+0.01}_{-0.22}\,[\text{pb}]$$

H+3 jets

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



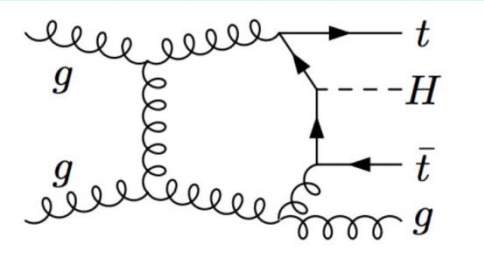


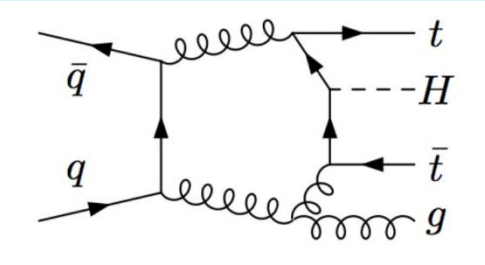
- Non constant K-factor
- Important change in shape from NLO corrections
- ➢ Plan to assemble into a single framework for phenomenology

$pp \longrightarrow H\,t\,\bar{t} + 1$ jet @ NLO

[van Deurzen, G.L., Mastrolia, Mirabella, Ossola, Peraro]

- Example using GoSam+Ninja with Sherpa:
  - $H\,t\,\bar{t}$ computed more than 10 years ago [Dittmaier et al.; Reina et al.]
  - Relevant for determination of Higgs-top Yukawa coupling
  - Two different masses: m_H, m_T





	Processes	#Diagrams	# Groups	# Hel.	Timing (col.+hel. summed)
$H\,t\,\bar{t} + 1$ jet	$q + \bar{q} \longrightarrow H + t + \bar{t} + g$	320	18	16	~ 223 ms
	$g + g \longrightarrow H + t + \bar{t} + g$	1575	3	32	~ 4160 ms
		1895			

$pp \longrightarrow H\, t\, \bar{t} + 1$ jet @ NLO

[van Deurzen, G.L., Mastrolia, Mirabella, Ossola, Peraro]

- Two different choices of scales:

$$\mu_R = \mu_F = \mu_0 \text{ with: } \quad \mu_0 = H_T \quad ; \quad H_T = \sum_i |p_{T,i}|$$

$$\mu_0 = 2 \times \mathrm{GA}_T \quad ; \quad \mathrm{GA}_T = \sqrt[3]{m_{T,H}\, m_{T,t}\, m_{T,\bar{t}}} + \sum_{\text{jets } j} |p_{T,j}|$$

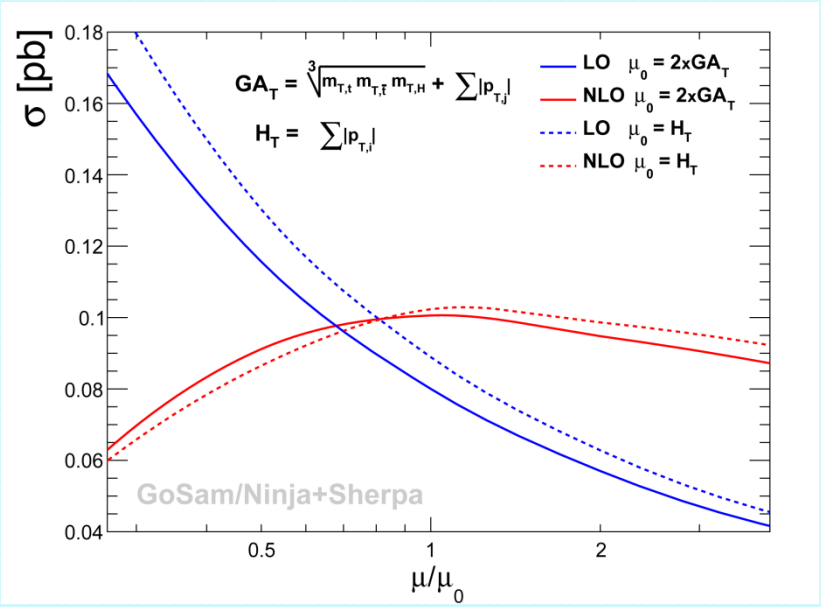
Physical setup: LHC 8 TeV

anti-kt: R=0.5 p_T>15 GeV $|\eta| < 4.0$

PDFs: cteq6L1 @ LO CT10 @ NLO

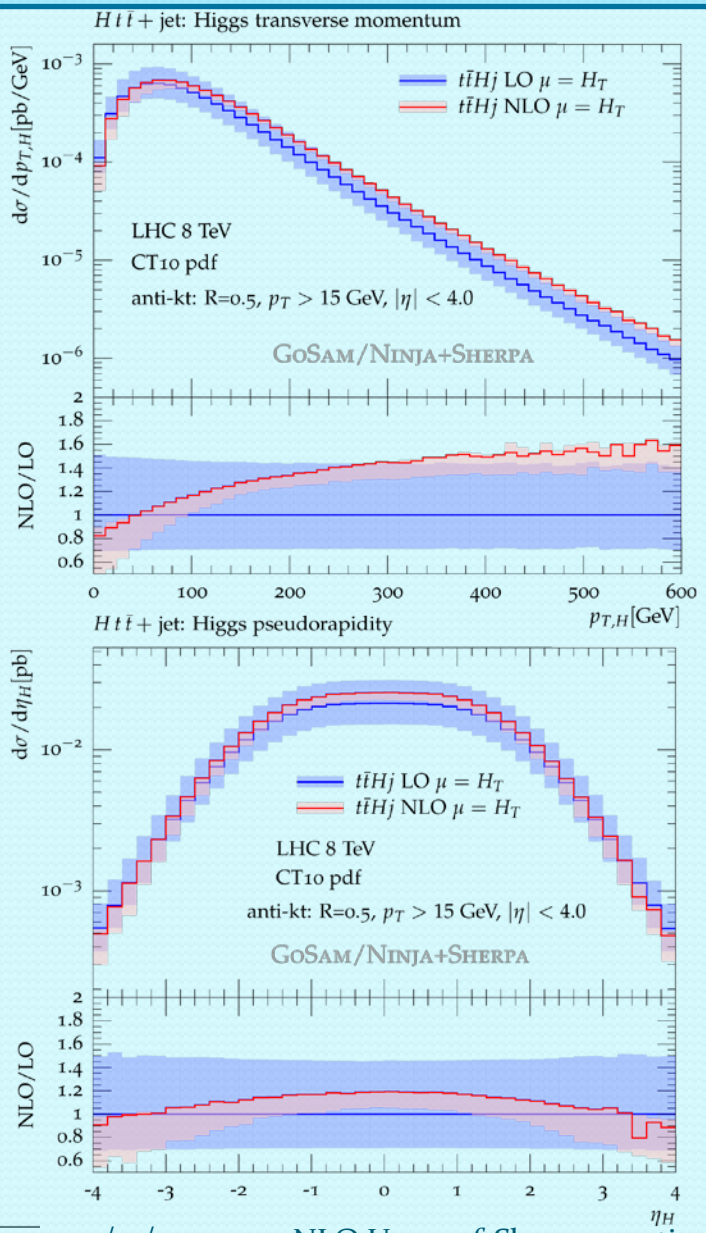
Central Scale	σ_{LO} [fb]	σ_{NLO} [fb]
$2\times\mathrm{GA}_T$	$80.03^{+35.64}_{-23.02}$	$100.6^{+0.00}_{-9.43}$
H_T	$88.93^{+41.41}_{-26.13}$	$102.3^{+0.00}_{-15.82}$

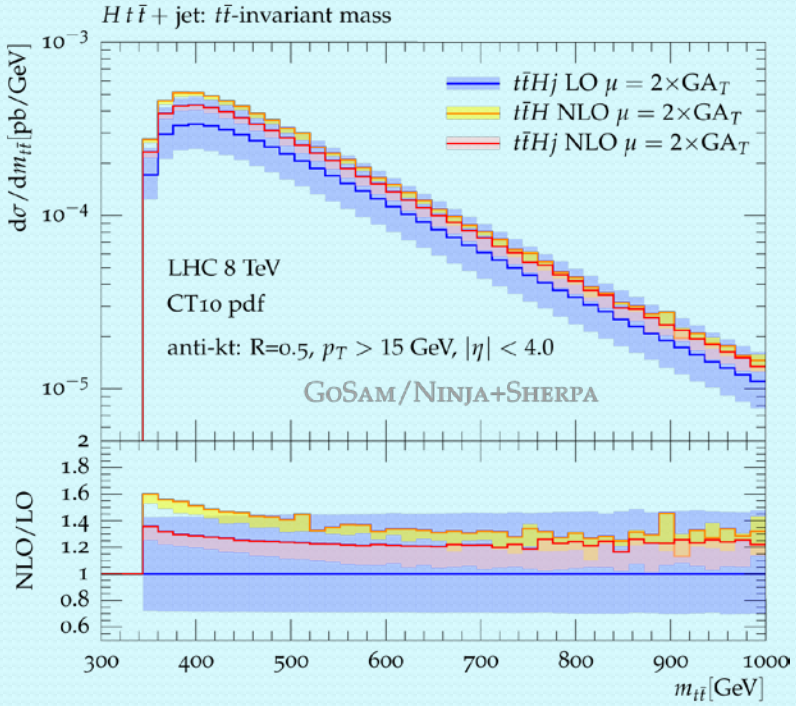
Very stable results with different scales!



pp ⟶ H t t̄ + 1 jet @ NLO

[van Deurzen, G.L., Mastrolia, Mirabella, Ossola, Peraro]





- Very similar results using the two scales
- Significant impact of NLO corrections on shapes of distributions

Sherpa as a user

- Why Sherpa?
  - User friendly – clear interface: 1 card is all I need
  - Get first results easily and in general fast
  - Flexible and versatile

- Open issues
  - H+3 jets → gluon-gluon fusion
  - H+3 jets → vector-boson fusion

Sherpa as a user

- Open questions / suggestions
  - is Sherpa doing what I would like?
  - weighted / unweighted events?
  - scale variations in one go?
  - …

Conclusions & Outlook

- GoSam: tool for automatic computation of 1-loop amplitudes
  - Flexible / fast / reliable / interfaced with several Monte Carlos
  - Release of a new version with many improvements:
    - New reduction algorithm / Higher rank support / Better optimization
- NLO results for H+2,3 jets in ggF and Htt̄+1 jet:
  - Important impact of NLO corrections on shapes
  - Significant reduction of scale uncertainties
  - Codes and libraries are publicly available

References: GoSam-2013

- H. van Deurzen, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro *"Multi-leg One-loop Massive Amplitudes from Integrand Reduction via Laurent Expansion"*, arXiv:1312.6678.
- G. Heinrich, A. Maier, R. Nisius, J. Schlenk, J. Winter, *"NLO QCD corrections to WWbb production with leptonic decays in the light of top quark mass and asymmetry measurements"*, arXiv:1312.6659.
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