Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

von Humboldt Stiftung/Found

Recent Developments in GoSam

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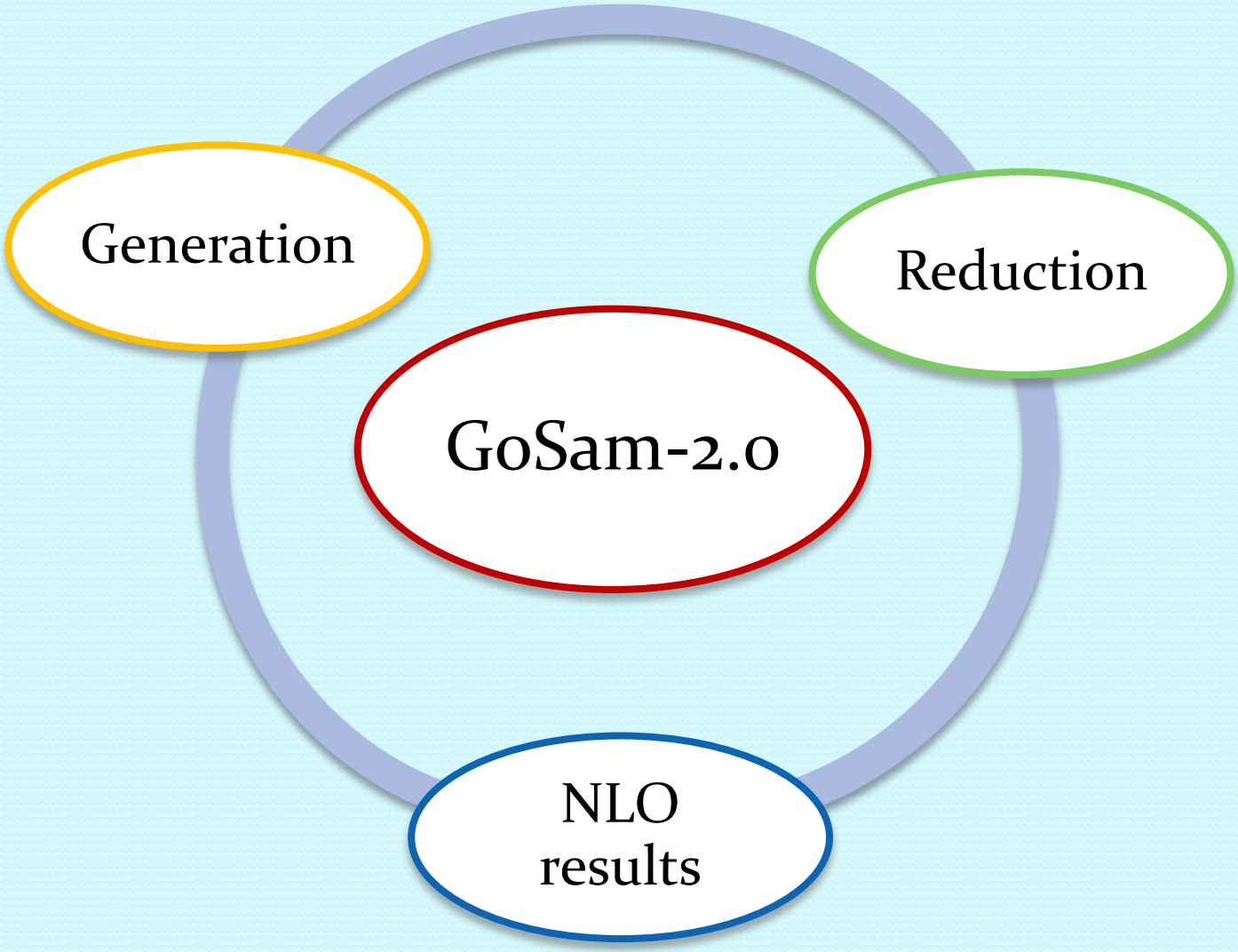
In collaboration with:

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, V. Yundin

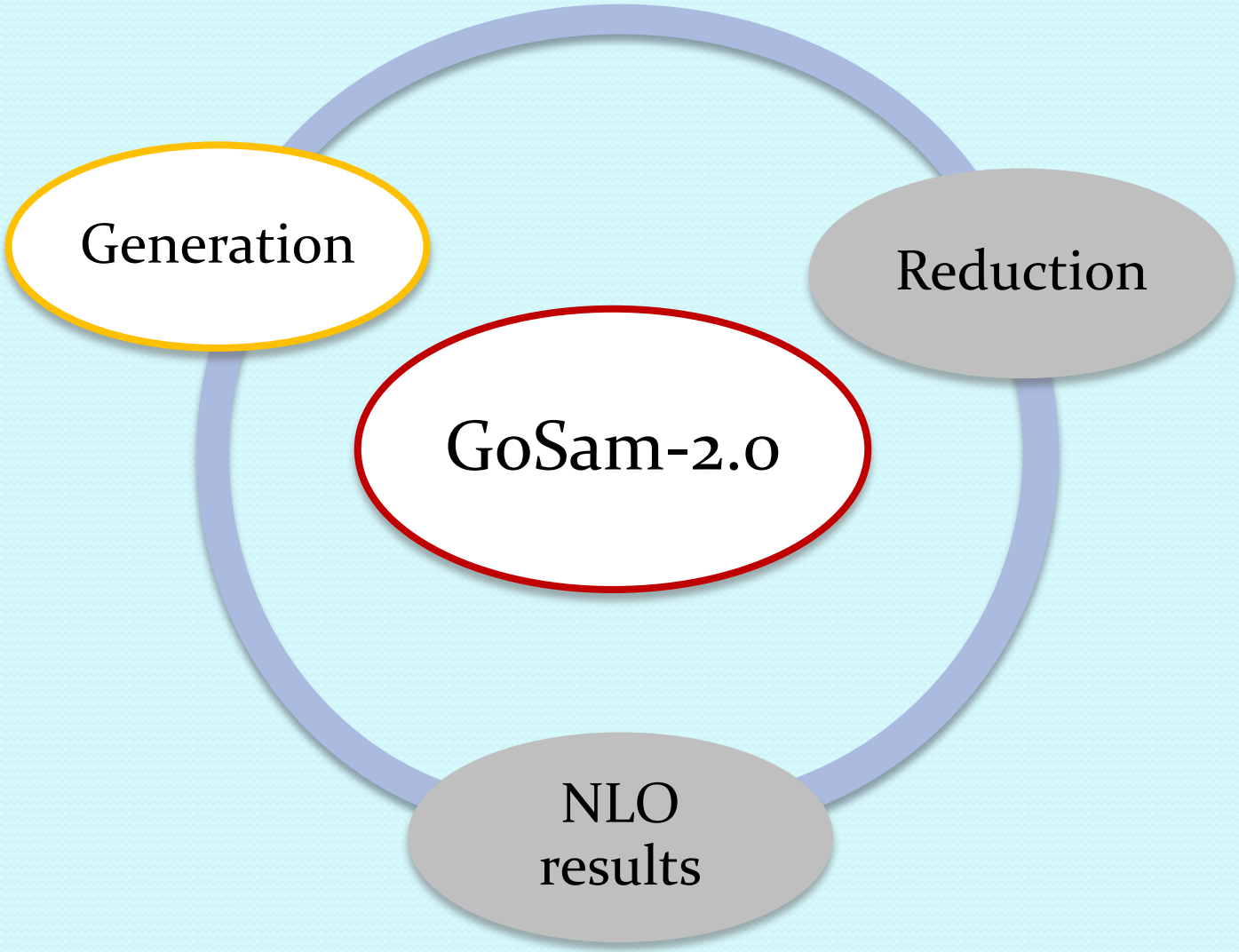
Outline

- The GoSam framework:
  - Generation
  - Reduction
  - NLO results
- Phenomenology:
  - HV + 1 jet with Powheg+GoSam
  - H+2 and H+3 jets in gluon-gluon-fusion
  - H $t\bar{t}$ + 1 jet
  - BSM physics
- Conclusions

The GoSam framework



The GoSam framework: Generation

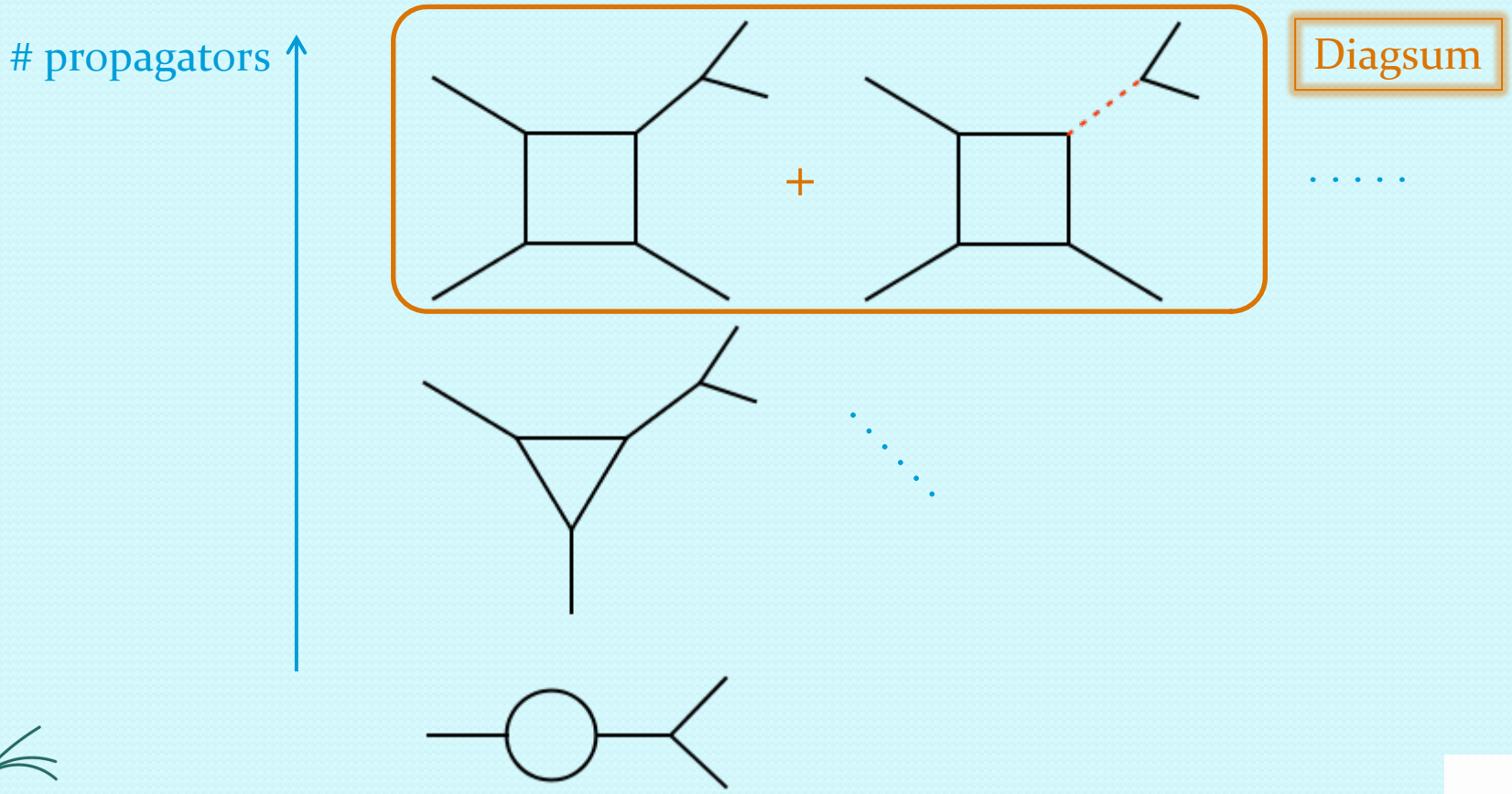


Generation

- 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 analytically

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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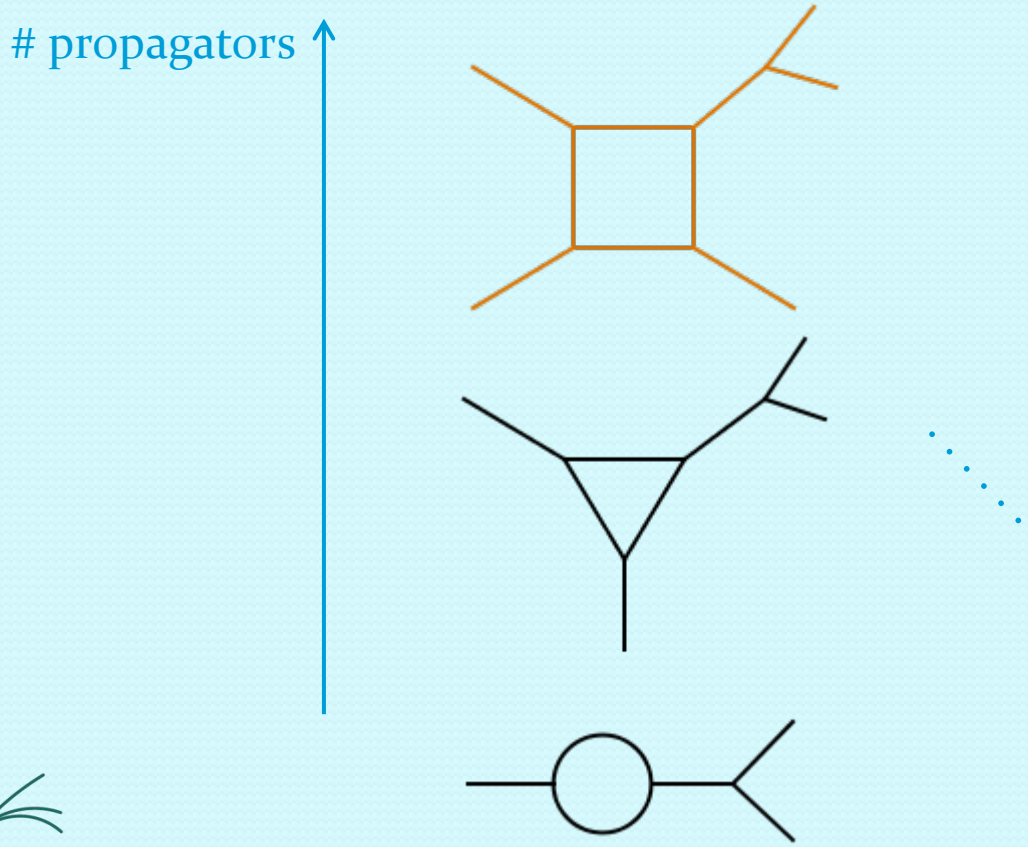

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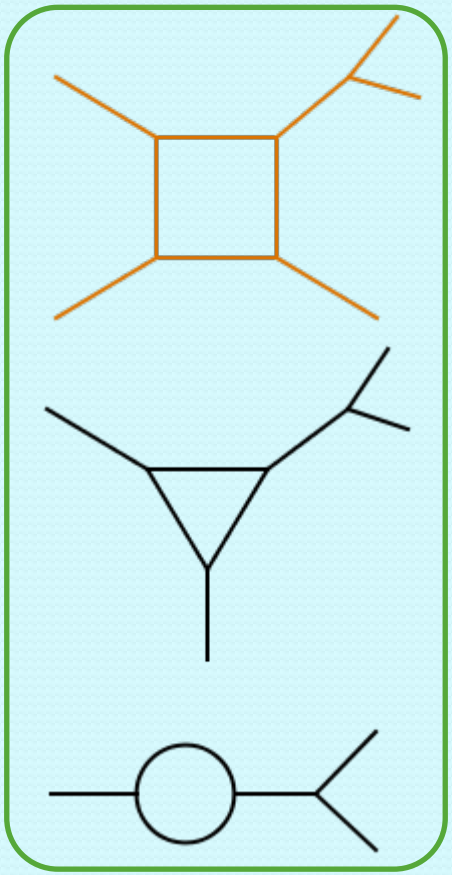
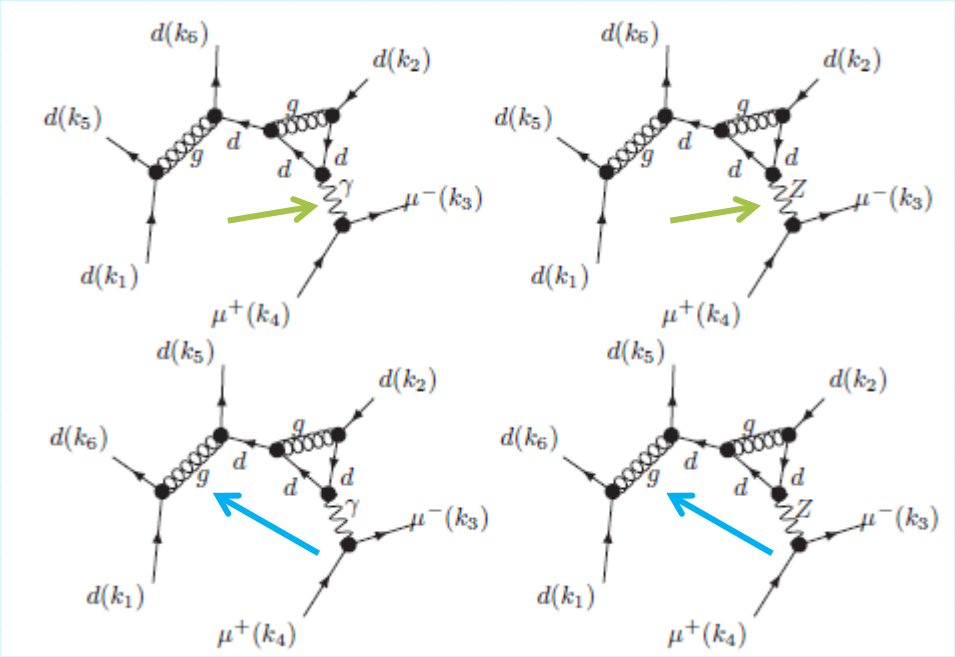
propagators



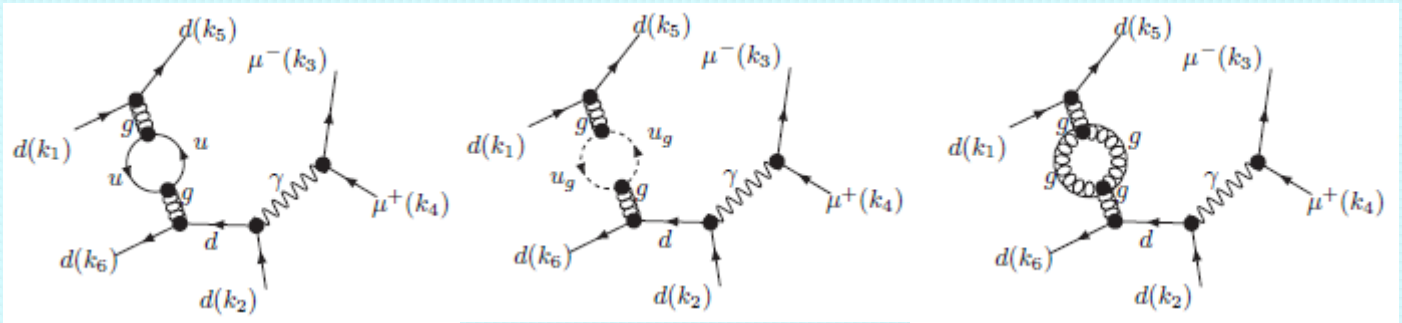
Grouping

Diagsum

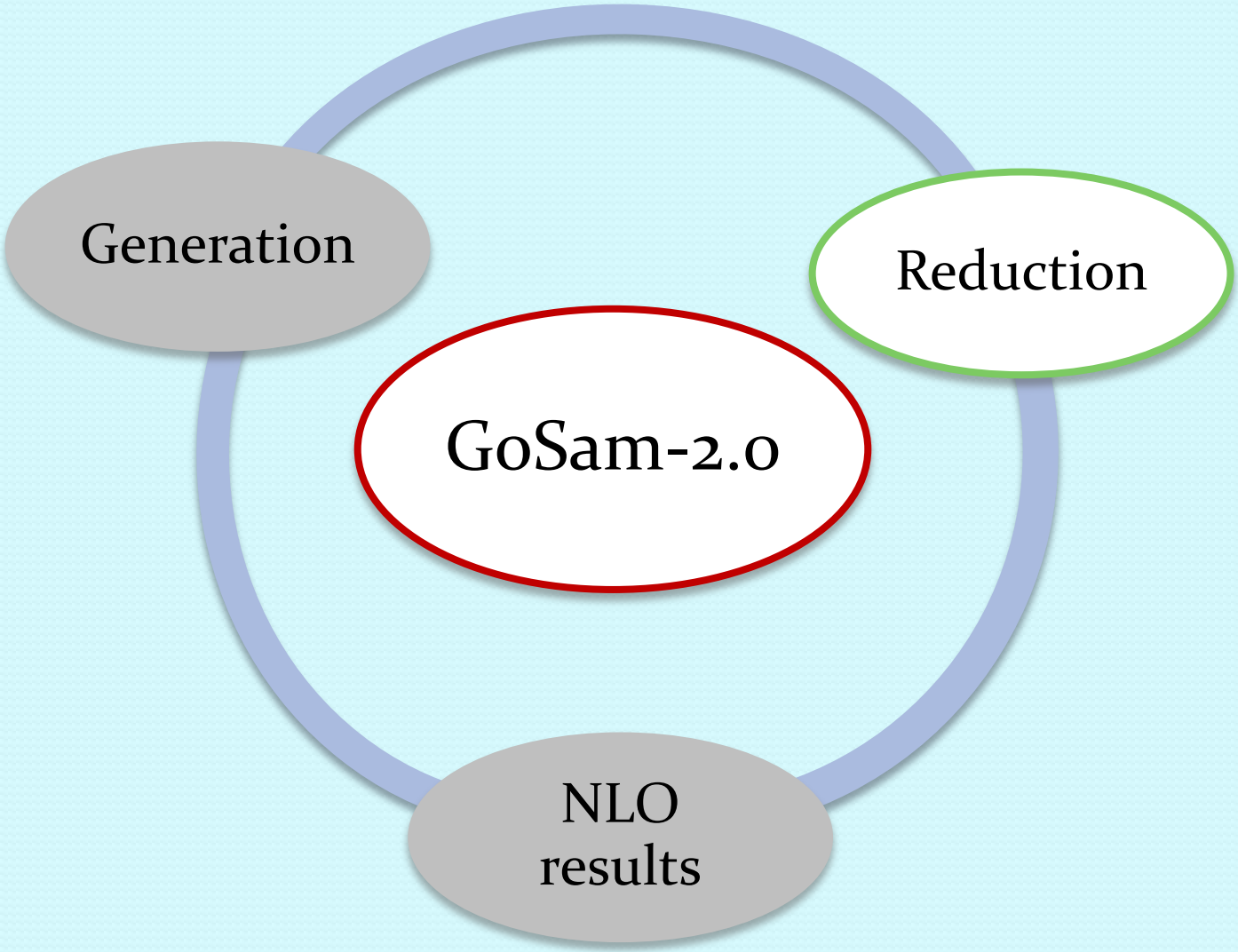
- Sum diagrams which have different tree-part:



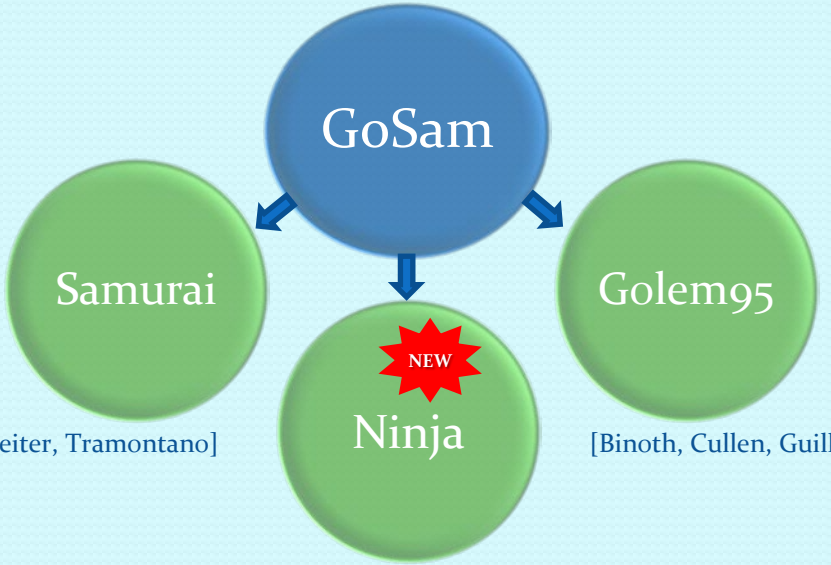
- Sum diagrams with same loop but different particles in loop



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:

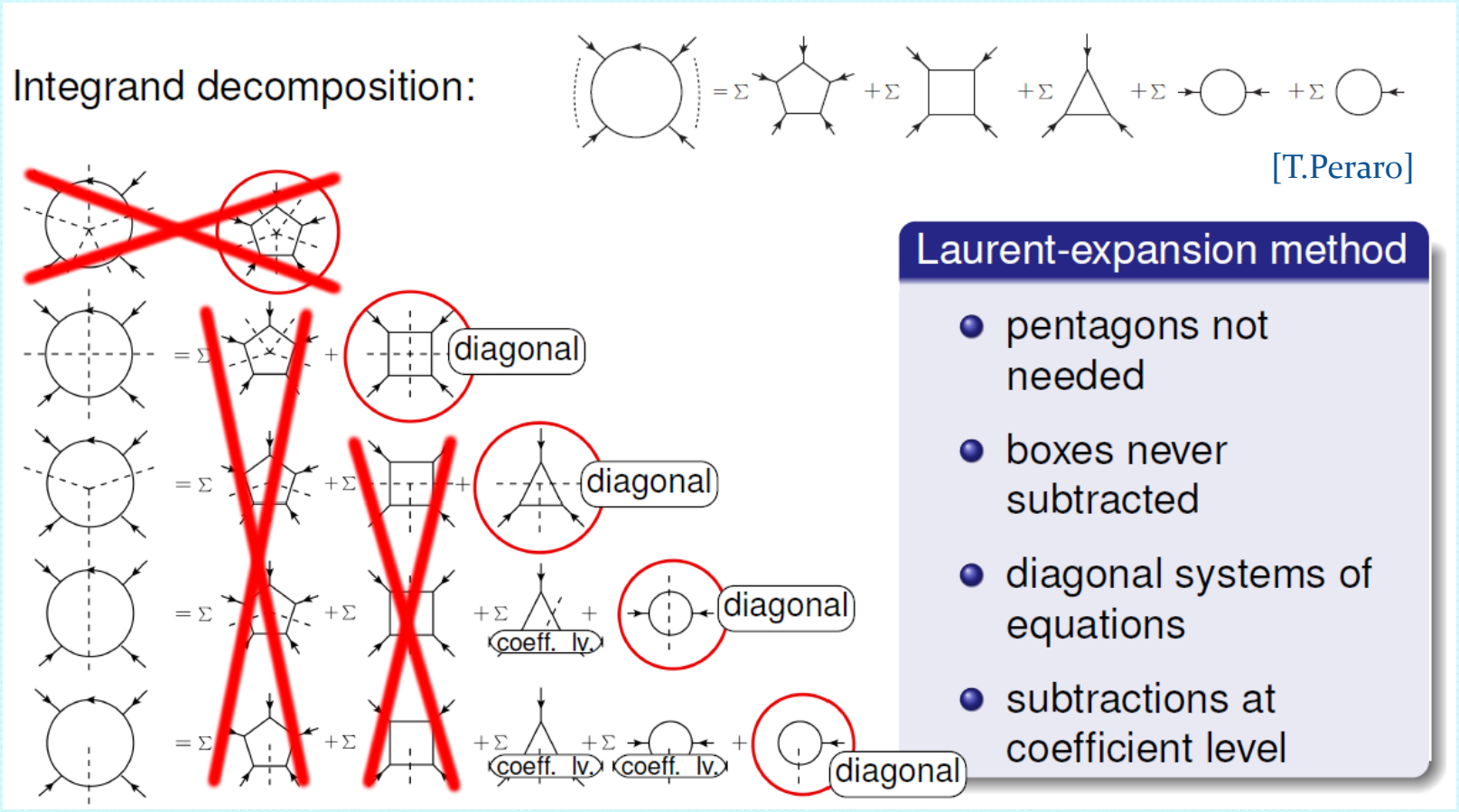
Ninja

Higher Rank Support

Ninja

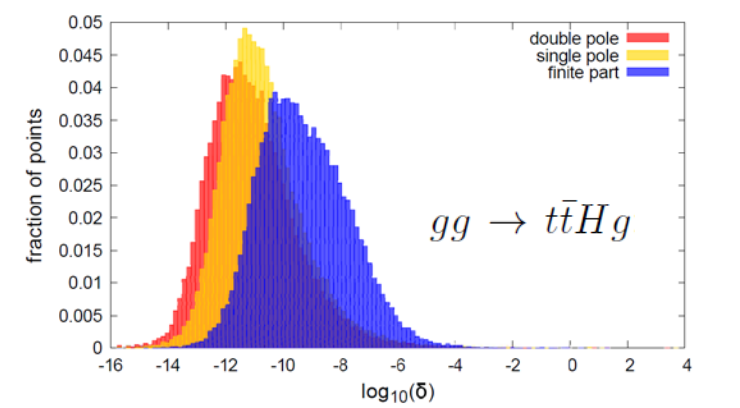
- Key Idea: extract the coefficients of the residues of a loop integral by performing a Laurent expansion of the integrand

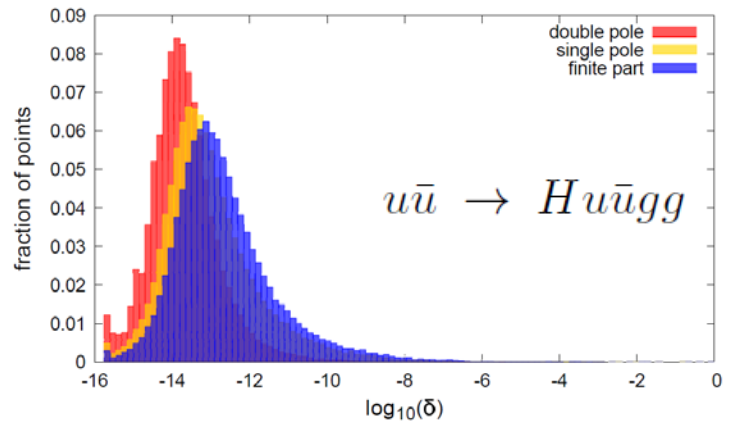
[Mastrolia, Mirabella, Peraro]



Ninja

- Tested recently on several processes: [Van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro]
  - Reduced timing
  - Increased stability





Benchmarks: GoSam + Ninja			
Process		# NLO diagrams	ms/event
$W+3j$	$d\bar{u} \to \bar{\nu}_e e^- ggg$	1 411	226
$Z+3j$	$d\bar{d} \to e^+e^- ggg$	2 928	1 911
$ZZZ+1j$	$u\bar{u} \to ZZZg$	1 305	*12 000
$WWZ+1j$	$u\bar{u} \to W^+W^-Zg$	972	*7 050
$WZZ+1j$	$u\bar{d} \to W^+ZZg$	836	*3 300
$WWW+1j$	$u\bar{d} \to W^+W^-W^+g$	729	*1 800
$ZZZZ$	$u\bar{u} \to ZZZZ$	741	*1 070
$t\bar{t}b\bar{b}\,(m_b \neq 0)$	$d\bar{d} \to t\bar{t}b\bar{b}$	275	178
	$gg \to t\bar{t}b\bar{b}$	1 530	5 685
$t\bar{t}+2j$	$gg \to t\bar{t}gg$	4 700	13 827
$Zb\bar{b}+1j\,(m_b \neq 0)$	$dug \to ue^+e^-b\bar{b}$	708	*1 070
$Wb\bar{b}+1j\,(m_b \neq 0)$	$u\bar{d} \to e^+\nu_e b\bar{b}g$	312	67
$Wb\bar{b}+2j\,(m_b \neq 0)$	$u\bar{d} \to e^+\nu_e b\bar{b}s\bar{s}$	648	181
	$u\bar{d} \to e^+\nu_e b\bar{b}d\bar{d}$	1 220	895
	$u\bar{d} \to e^+\nu_e b\bar{b}gg$	3 923	5387
$WWb\bar{b}\,(m_b \neq 0)$	$d\bar{d} \to \nu_e e^+ \bar{\nu}_\mu \mu^- b\bar{b}$	292	115
	$gg \to \nu_e e^+ \bar{\nu}_\mu \mu^- b\bar{b}$	1 068	*5 300
$WWb\bar{b}+1j\,(m_b = 0)$	$u\bar{u} \to \nu_e e^+ \bar{\nu}_\mu \mu^- b\bar{b}g$	3 612	*2 000
$H+3j$ in GF	$gg \to Hggg$	9 325	8 961
$t\bar{t}H+1j$	$gg \to t\bar{t}Hg$	1 517	1 505
$H+3j$ in VBF	$u\bar{u} \to Hgu\bar{u}$	432	101
$H+4j$ in VBF	$u\bar{u} \to Hggu\bar{u}$	1 176	669
$H+5j$ in VBF	$u\bar{u} \to Hgggu\bar{u}$	15 036	29 200

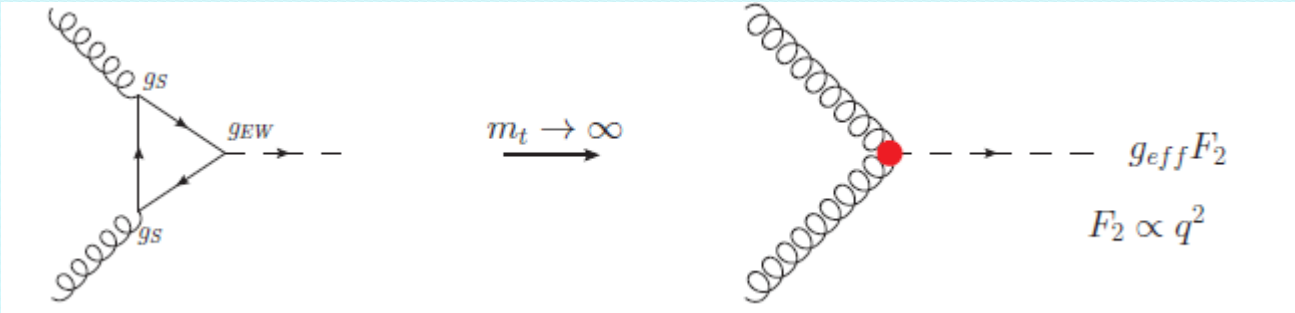
* Different CPU.

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



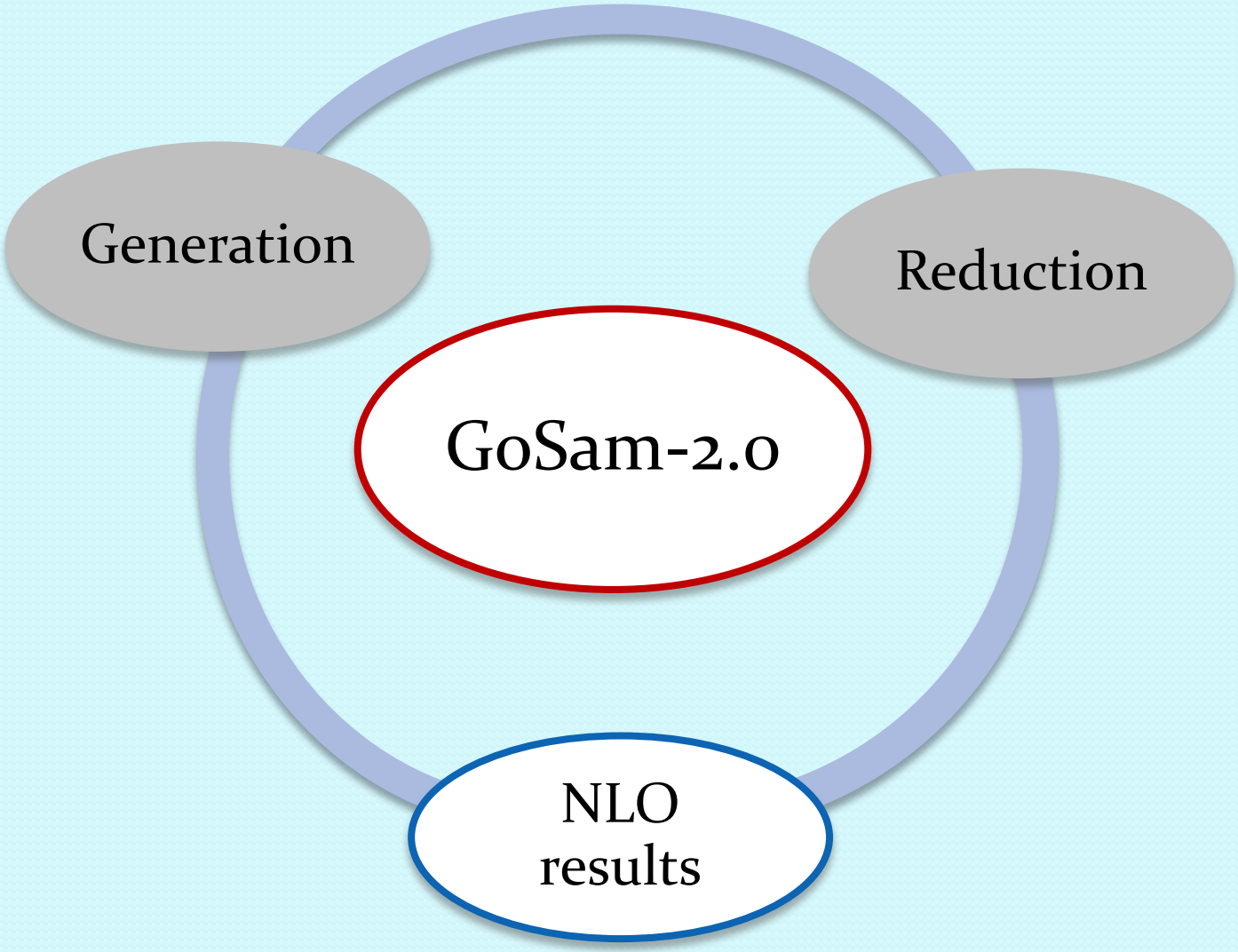
Adapt reduction programs Samurai, Ninja and Golem95C to deal with higher rank loop integrals

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

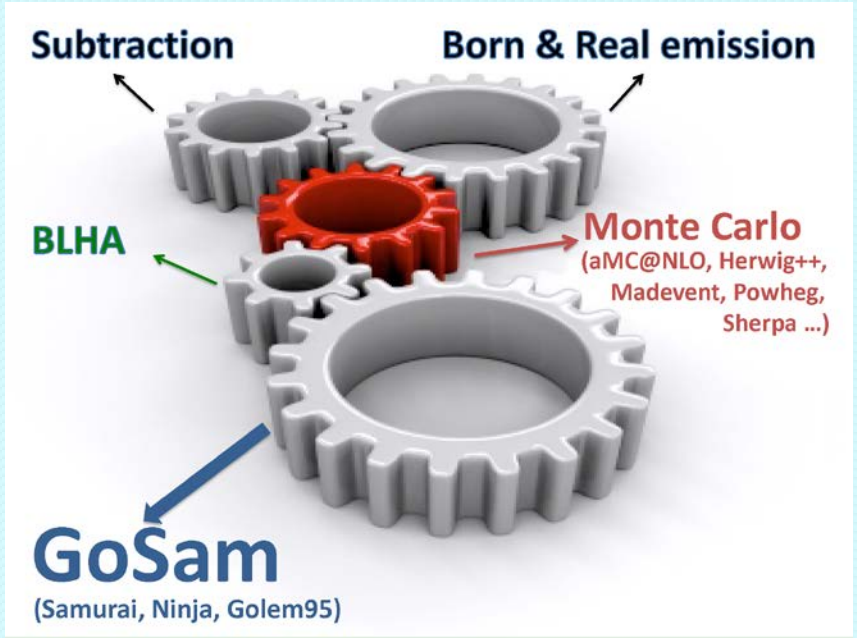
One Loop Program

BLHA

Tree amplitude

Monte Carlo

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

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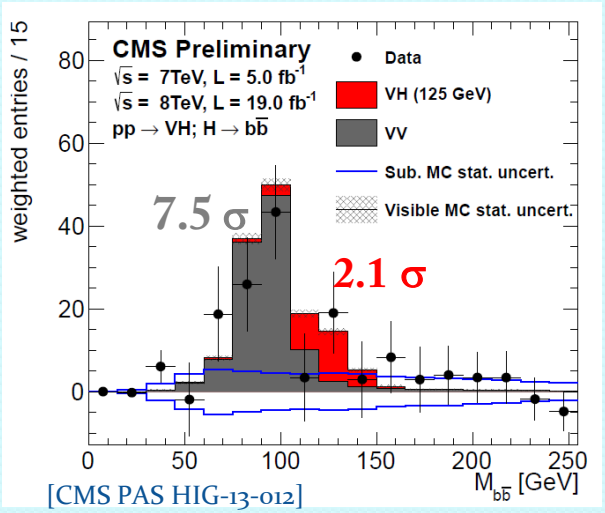
Phenomenology

HV / HV+1j with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- Allow to measure **H→ bb** or set limit to **invisible** decay
  - Tevatron: ~3σ significance
  - ATLAS: no significant excess
  - CMS: 2.1σ excess over 7.5 σ significance for VZ signal

[Status at EPS 2013]



[CMS PAS HIG-13-012]

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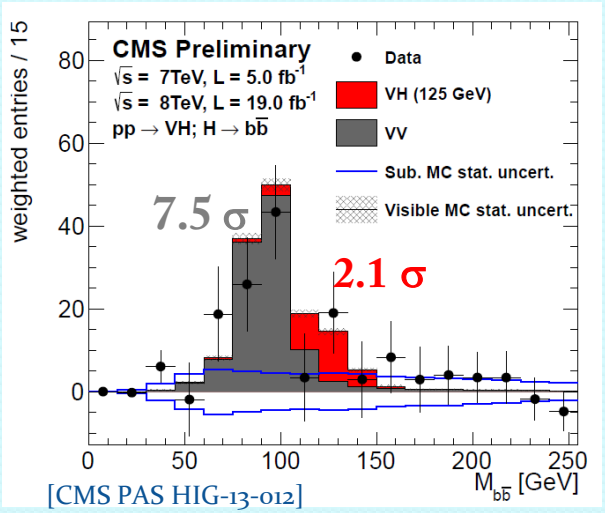
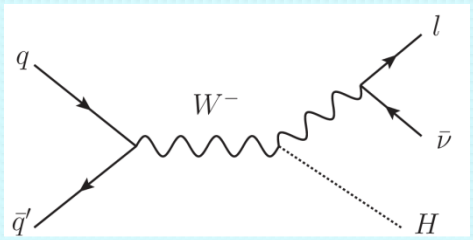
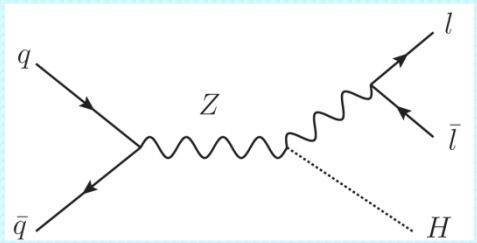
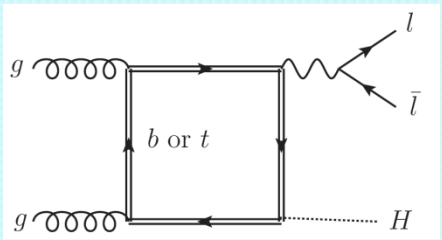


[CMS PAS HIG-13-012]

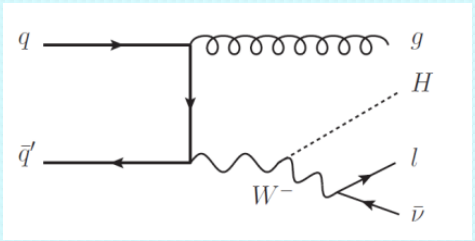
- HV production:

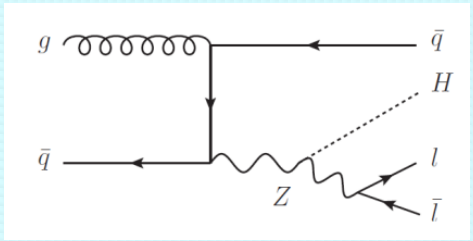






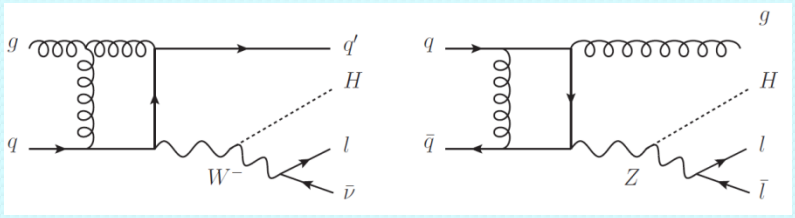
- HVJ production:

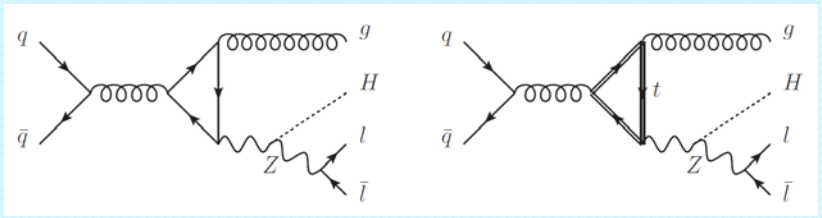


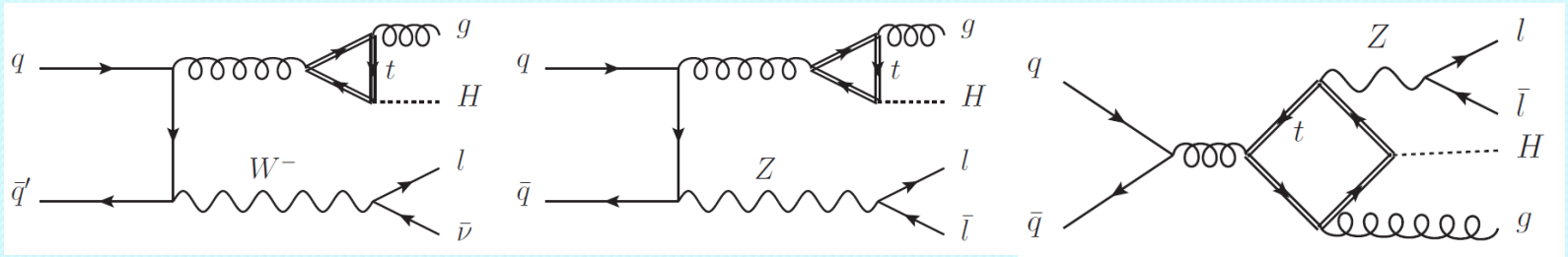


HV+1j with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- 3 classes of loop diagrams:
  - 1. 

    Higgs-strahlung type with no closed fermion loops
  - 2. 

    Higgs-strahlung type with closed fermion loops (only axial current contribution from top and bottom)
  - 3. 

    Higgs coupled directly to massive top in the loop
  - Diagrams from class 2 and 3 are finite.

HV+1j with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- MiNLO: Multi-scale Improved NLO [Hamilton, Nason, Zanderighi]
  - Inspired by the CKKW method

    (most likely branching history / Sudakov to external & intermediate lines / α_s at nodal values)
  - Improved MiNLO applied to production of colorless system (B) plus 1 jet,

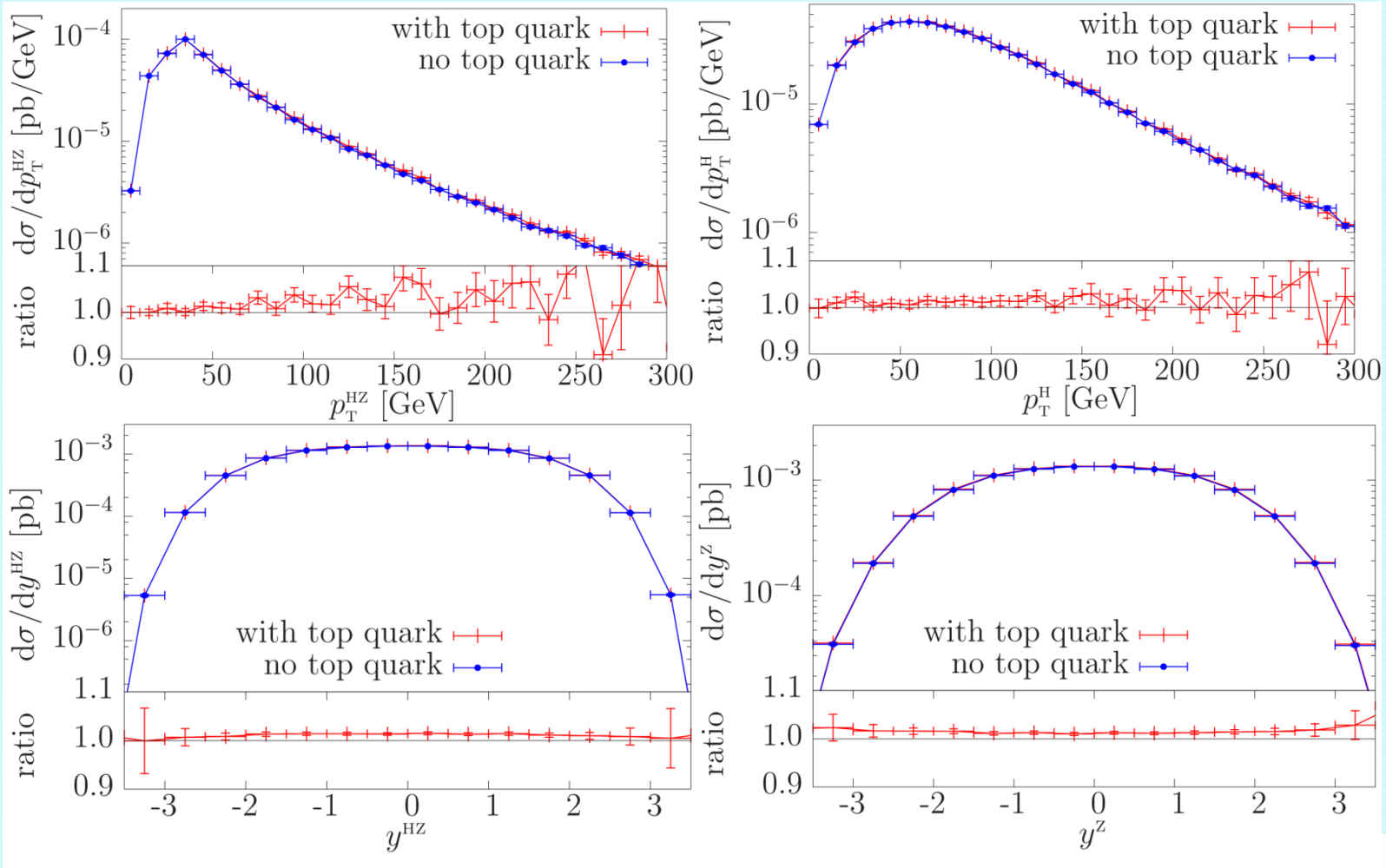
  ➔ single sample of events can be produced which
    - is NLO accurate in distributions inclusive in B,
    - is NLO accurate in distributions inclusive in B + 1 jet.

    [Hamilton, Oleari, Nason, Zanderighi]
- Procedure can be applied to HV/HV + 1 jet if only Higgs-Strahlung diagrams are kept (no top):

$$pp \text{ - > } V^*(\text{-> } H\ l_1\ l_2)\ j$$

HV+1j with Powheg+GoSam

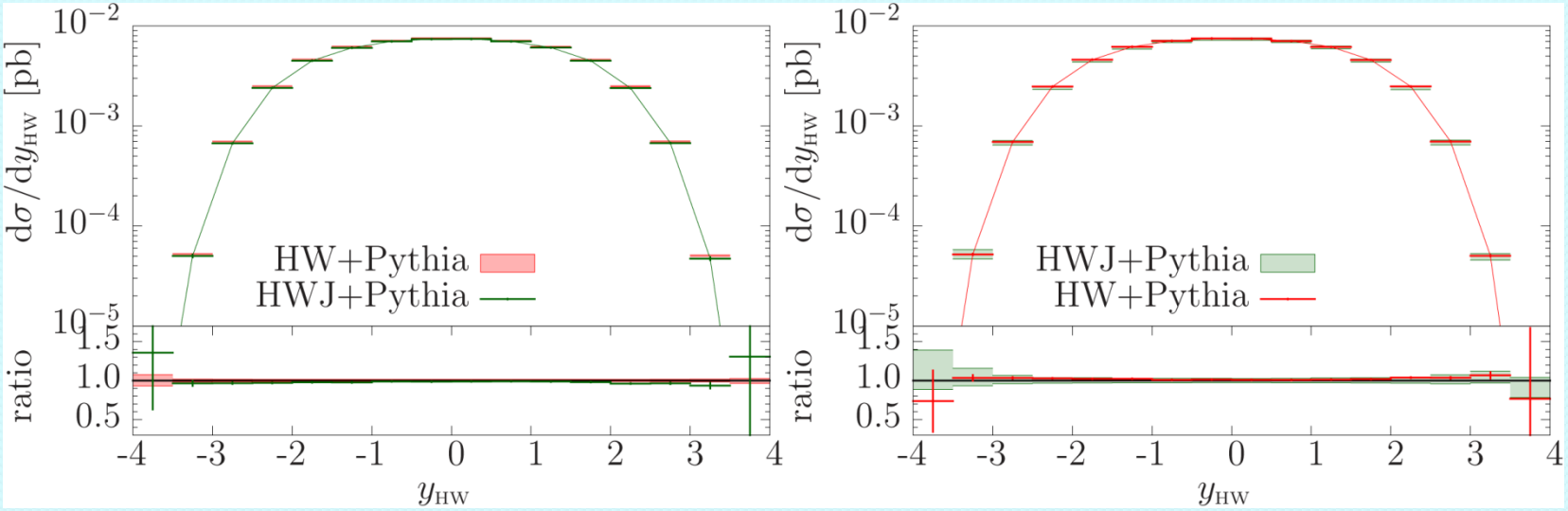
- Effect of inclusion of top-quark 1-loop diagrams:



HV+1j with Powheg+GoSam

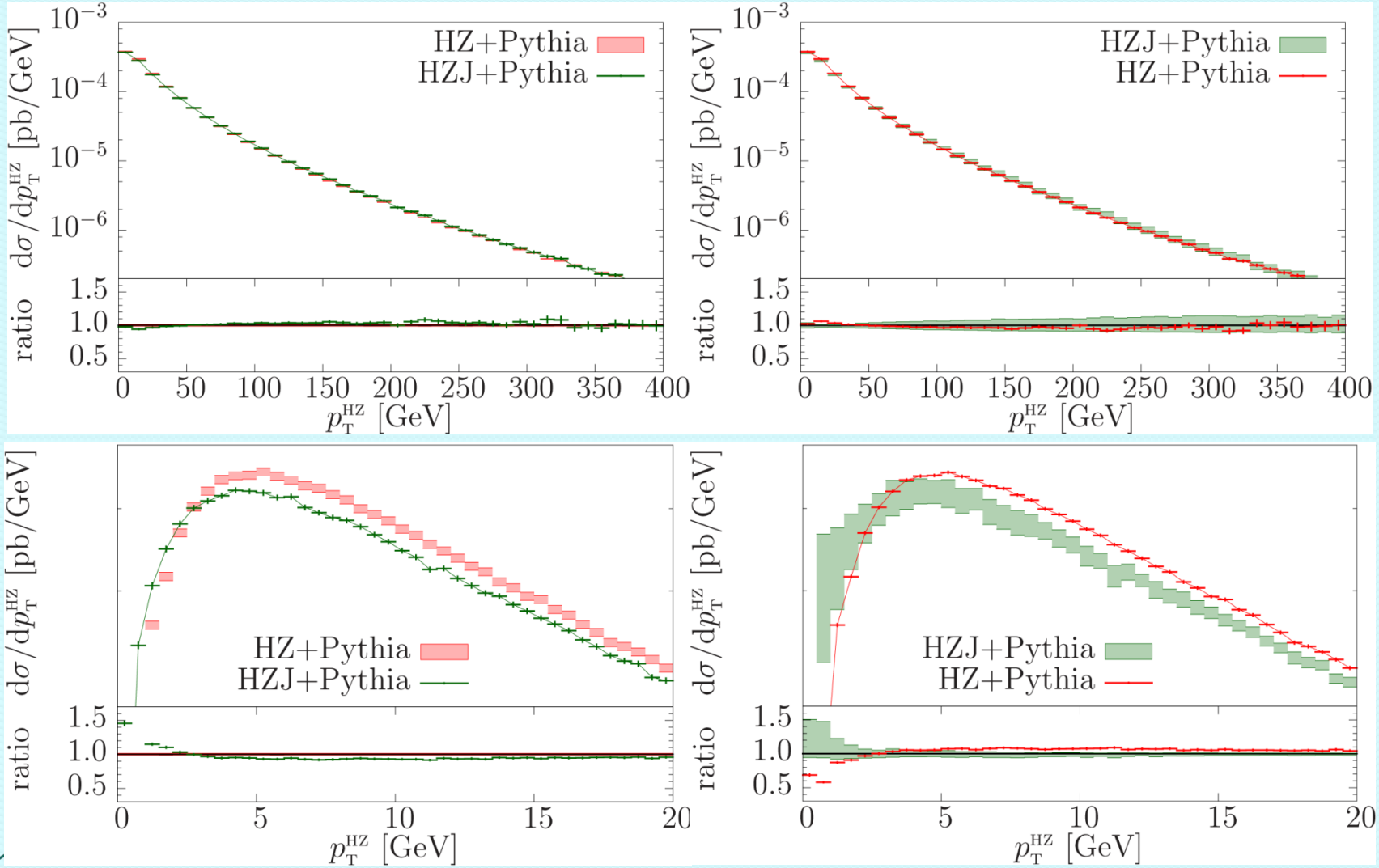
[Luisoni, Nason, Oleari, Tramontano]

- Results for LHC @ 8 TeV:
  - uncertainty band by varying independently K_R,K_F by factors of **0.5** and **2**.



HV+1j with Powheg+GoSam

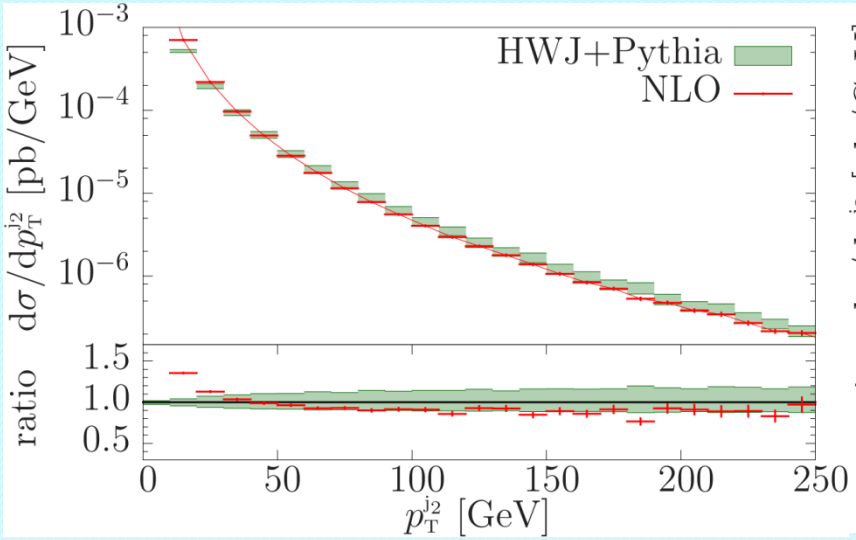
[Luisoni, Nason, Oleari, Tramontano]

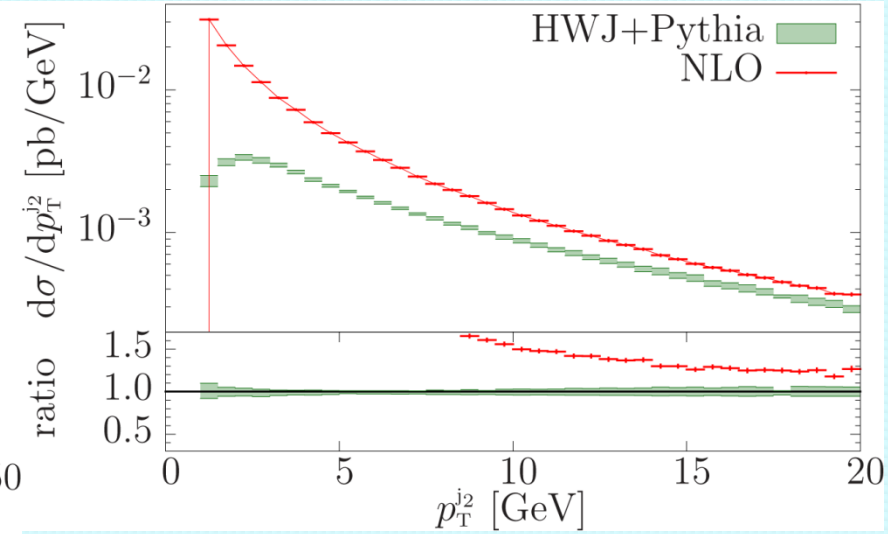


HV+1j with Powheg+GoSam

[Luisoni, Nason, Oleari, Tramontano]

- Effect of the Powheg formalism visible on the 2. jet:



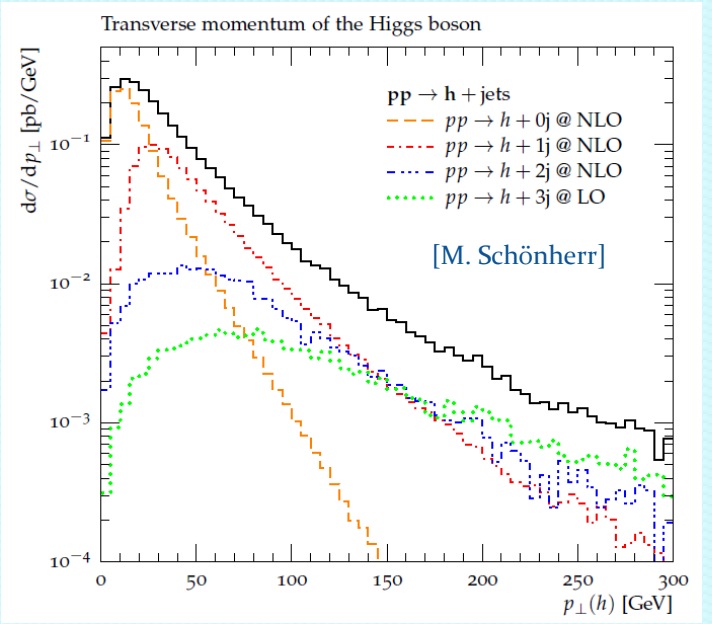


- Possibility to construct an NNLO+PS generator by reweighting with NNLO results.

[Hamilton, Nason, Oleari, Re, Zanderighi]

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]

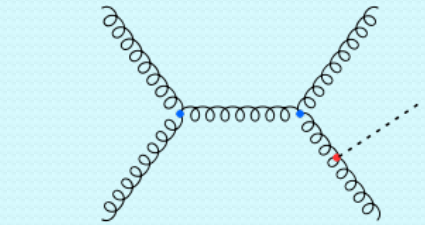
- Computed using GoSam + Sherpa
- Possibility to test the framework by comparing to existing results/codes
  --> agreement with MCFM (v6.4) [Campbell, Ellis, Williams]

  - Physical setup: LHC 8 TeV

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

    PDFs: cteq6L1 @ LO cteq6mE @ NLO

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

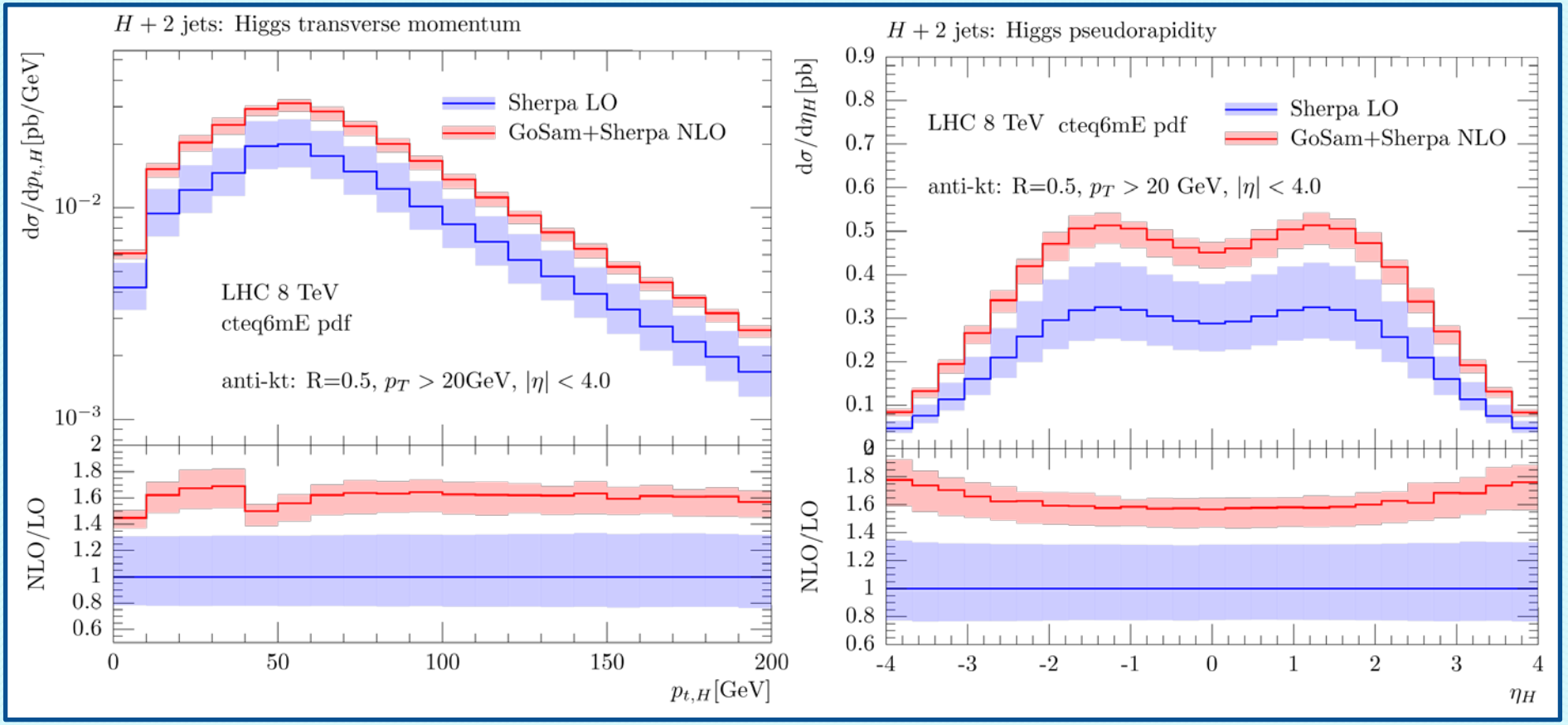


$$\alpha_s^4 \longrightarrow \alpha_s^2(m_H)\alpha_s^2(H_T)$$

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

H+2 jets

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



- Reduction of scale uncertainty
- Large K-factor
- Important impact of scale choice in effective vertex

- Next steps
  - Include Higgs decays
  - Shower

H+3 jets

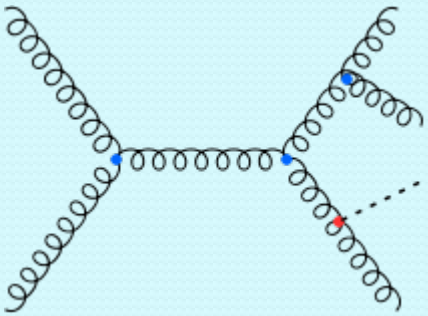
[Cullen, van Deurzen, Greiner, G.L., Mastrolia, Mirabella, Ossola, Peraro,Tramontano]

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

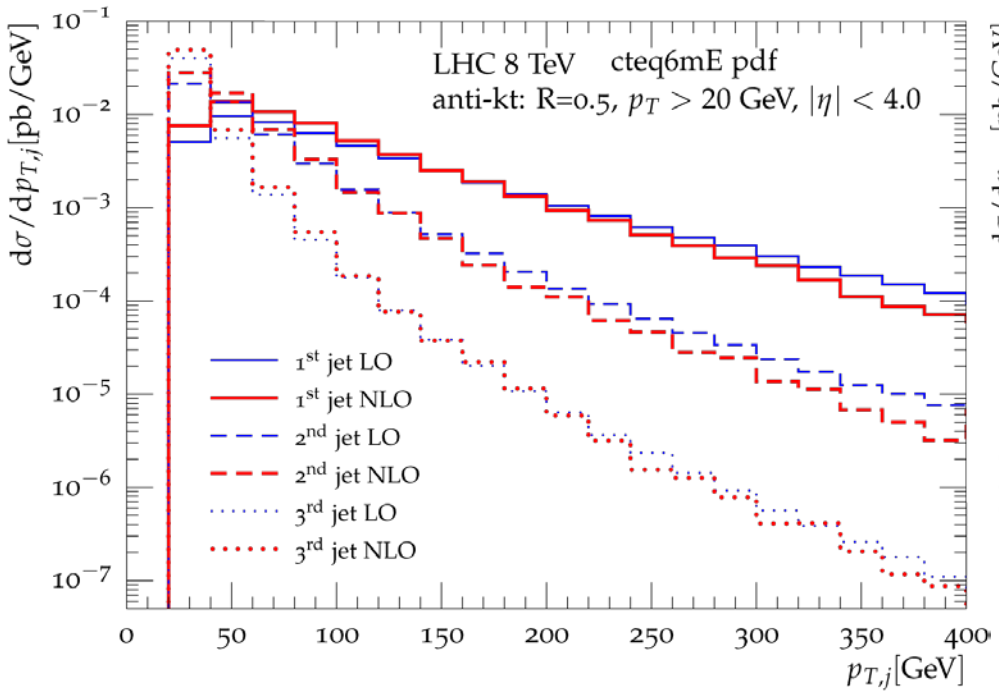


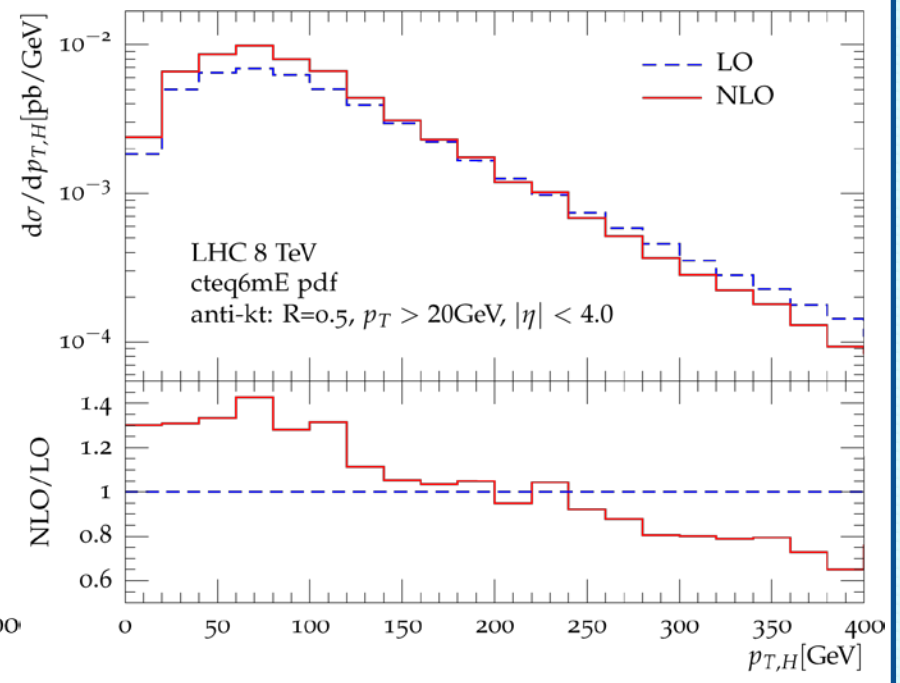
$$\alpha_s^5 \longrightarrow \alpha_s^2(m_H)\alpha_s^3(\hat{H}_T/2)$$

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

H+3 jets

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



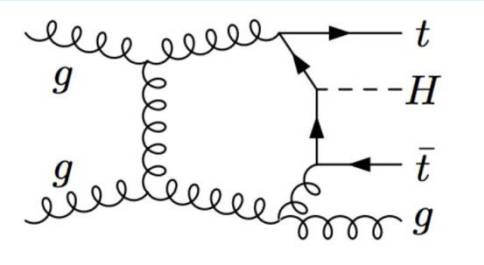


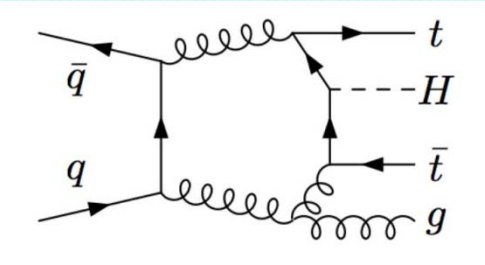
- Non constant K-factor
- Important change in shape from NLO corrections
- Work in progress..

$pp \longrightarrow H\,t\,\bar{t} + 1$ 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:

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

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

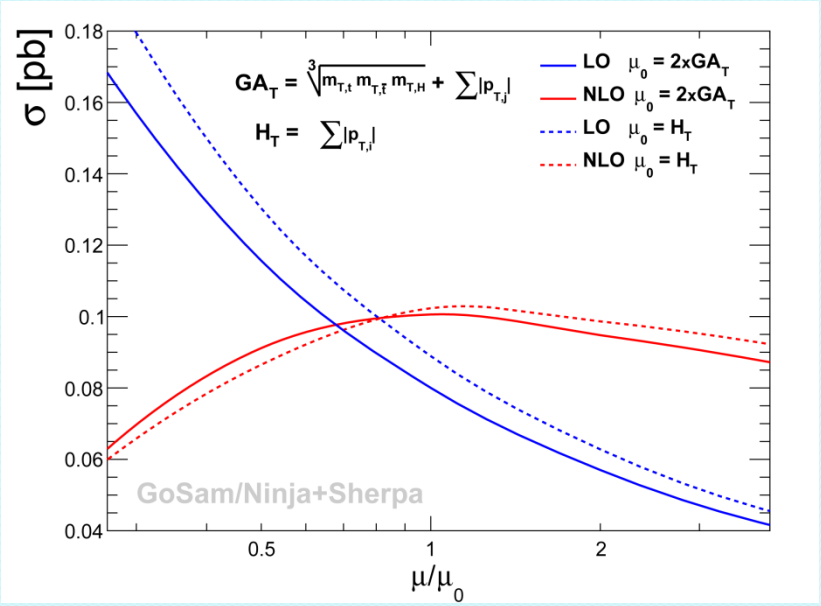
Physical setup: LHC 8 TeV

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

PDFs: cteq6L1 @ LO CT10 @ NLO

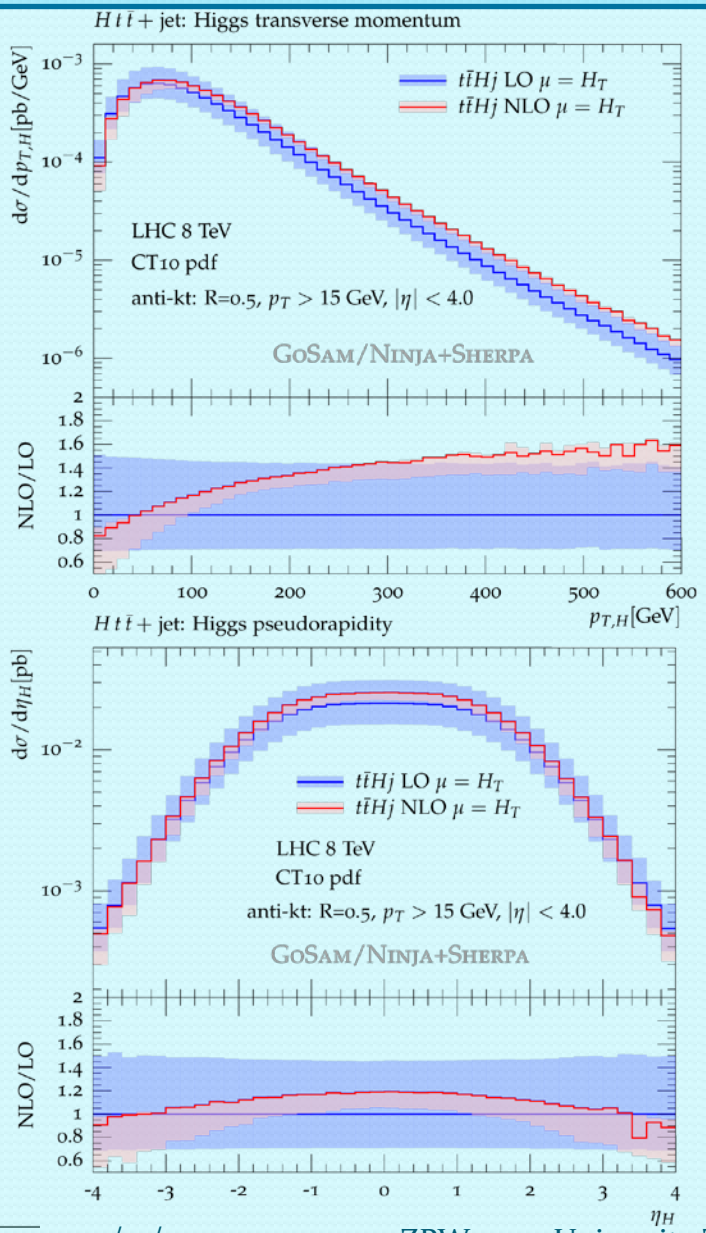
Central Scale	σ_{LO} [fb]	σ_{NLO} [fb]
$2\times\mathrm{GA}_T$	$80.03^{+35.64}_{-23.02}$	$100.6^{+0.00}_{-9.43}$
H_T	$88.93^{+41.41}_{-26.13}$	$102.3^{+0.00}_{-15.82}$

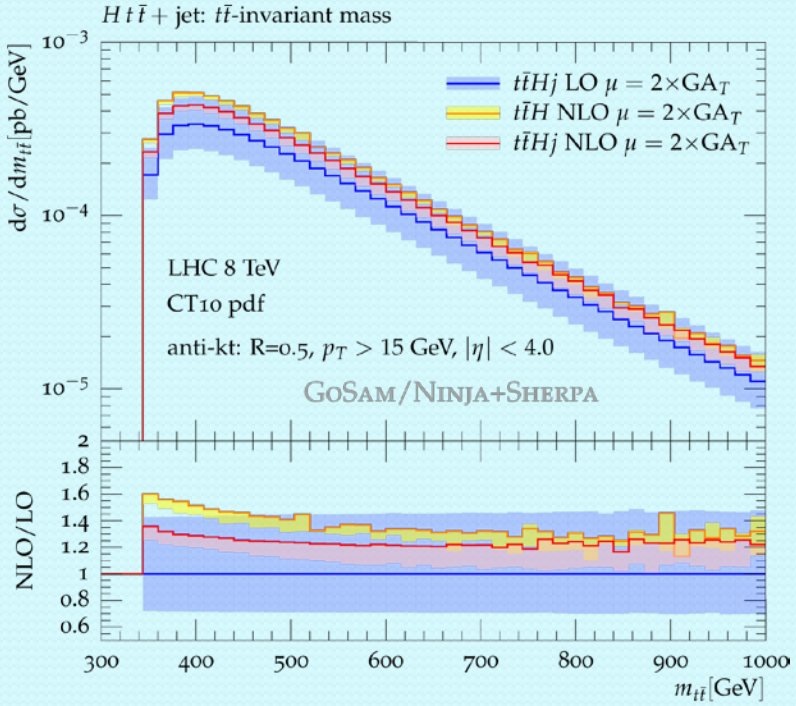
Very stable results with different scales!



pp ⟶ H t $\bar{t}$ + 1 jet @ NLO

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

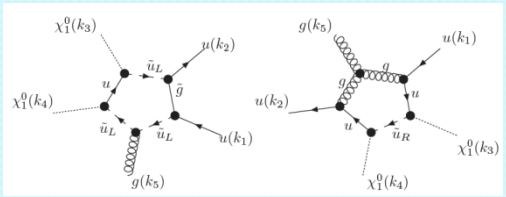


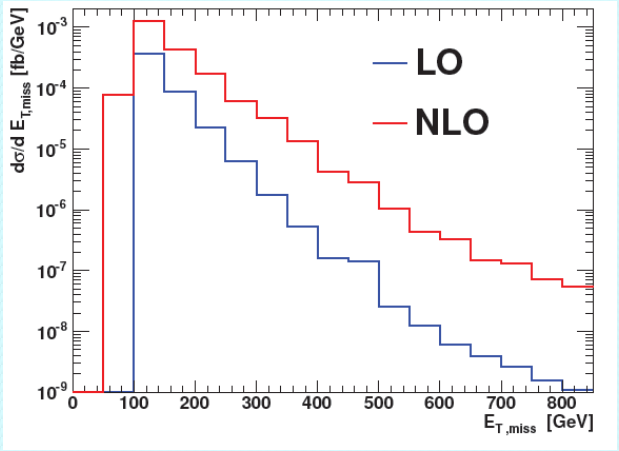


- Very similar results using the two scales
- Significant impact of NLO corrections on shapes of distributions

BSM physics with GoSam

- pp -> $\tilde{\chi}^0\tilde{\chi}^0$ j: [Cullen, Greiner, Heinrich]
  - Susy-QCD corrections
  - **FeynRules** → UFO model file → GoSam
  - **~1400** diag.: rank-3 pentagons, up to 4 internal masses
  - Full inclusion of all non-resonant diagrams

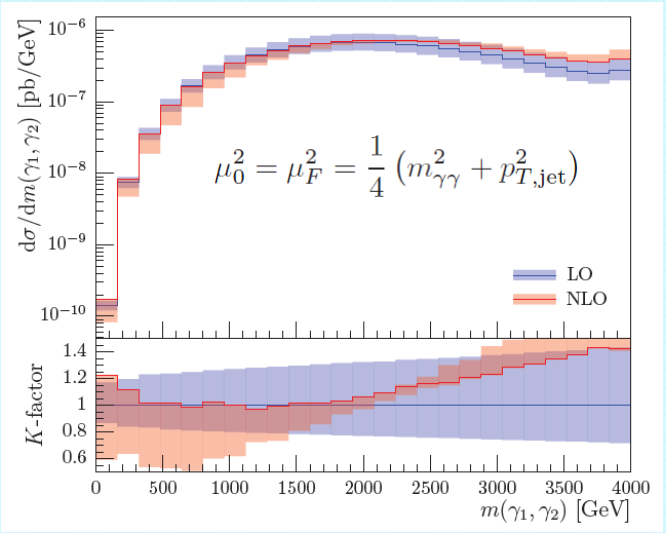




- pp -> G (-> γ γ) j: [Greiner, Heinrich, Reichel, v. Soden-Fraunhofer]
  - NLO QCD in ADD with δ=4 large extra dimensions
  - spin-2 particle / non-standard propagator of G due to sum over KK modes

$$D(s) = \sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\epsilon}$$

  - approx. spectrum with continuous density function



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 HV+1 jet, 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

➢ Release GoSam-2.0 / Further improvements and applications

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