NLO calculations with **GoSam**

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In collaboration with:

G.Cullen, N. Greiner, G.Heinrich, P.Mastrolia, E.Mirabella, G.Ossola, F. Tramontano

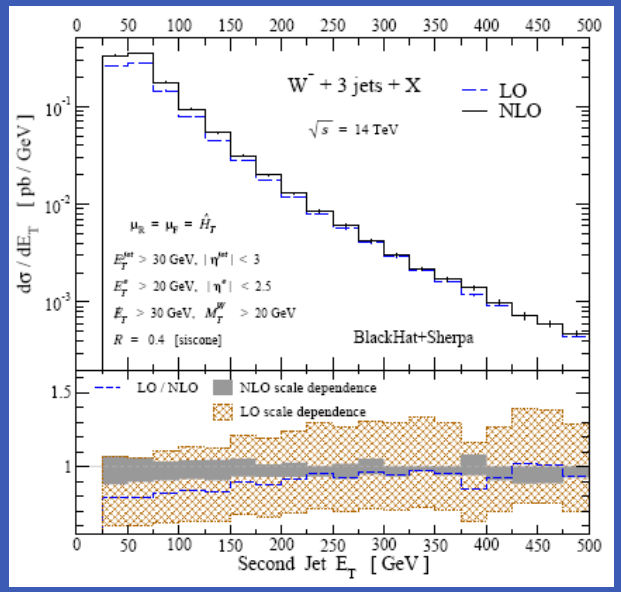
H. Van Deurzen, T.Peraro, J. Reichel , J. Schlenk, J.F.G. von Soden-Fraunhofen

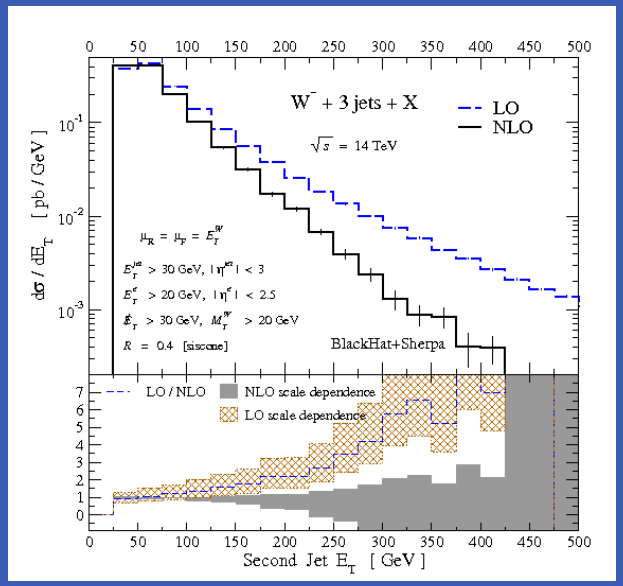
GoSam release: arXiv:1111.2034 [hep-ph] | http://gosam.hepforge.org/

Rencontres de Moriond 2013, La Thuile 11.03.2013

Motivation

- To control the theoretical uncertainties in the computation of LHC processes Next-to-Leading Order predictions are needed:
  - reduction of scale uncertainties
  - possibility to study the appropriate scale to be used
  - better description of jets: jets start to have structure
  - Better PDF fits





[Blackhat Collaboration]

NLO Calculation

- For a full NLO calculation several ingredients are needed:

Integrator / Event generator

One-loop amplitudes

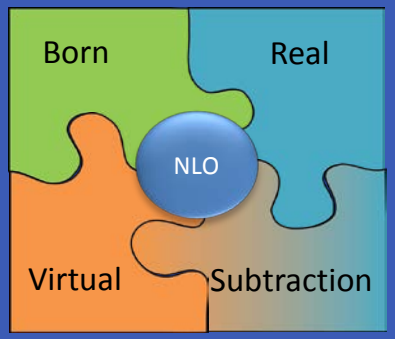
Virtual

Tree-level amplitudes

Born

Real

Subtraction



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

NLO Calculation

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AUTOMATION

Important :

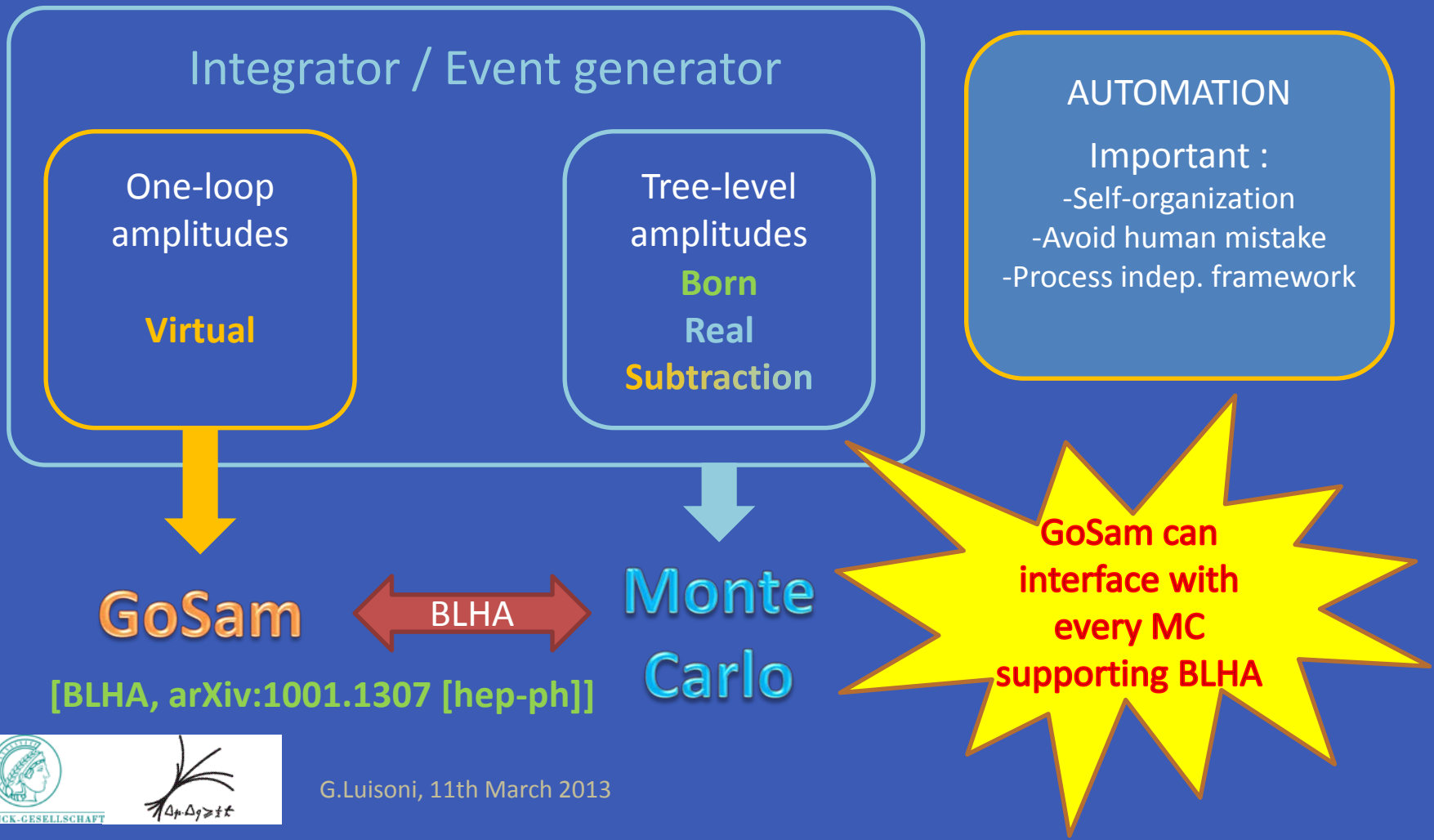
-Self-organization

-Avoid human mistake

-Process indep. framework

NLO Calculation

- For a full NLO calculation other ingredients are needed:



The GoSam Project: the codes

GoSam Project

GoSam: Python package to write code (fortran95)

Code generation

- Diagram generation:
  - QGRAF [Nogueira 92]
- Algebra:
  - FORM [Vermaseren 91]
  - SPINNEY [Cullen, Koch-Janusz, Reiter 10]
- Code generator:
  - HAGGIES [Reiter 09]

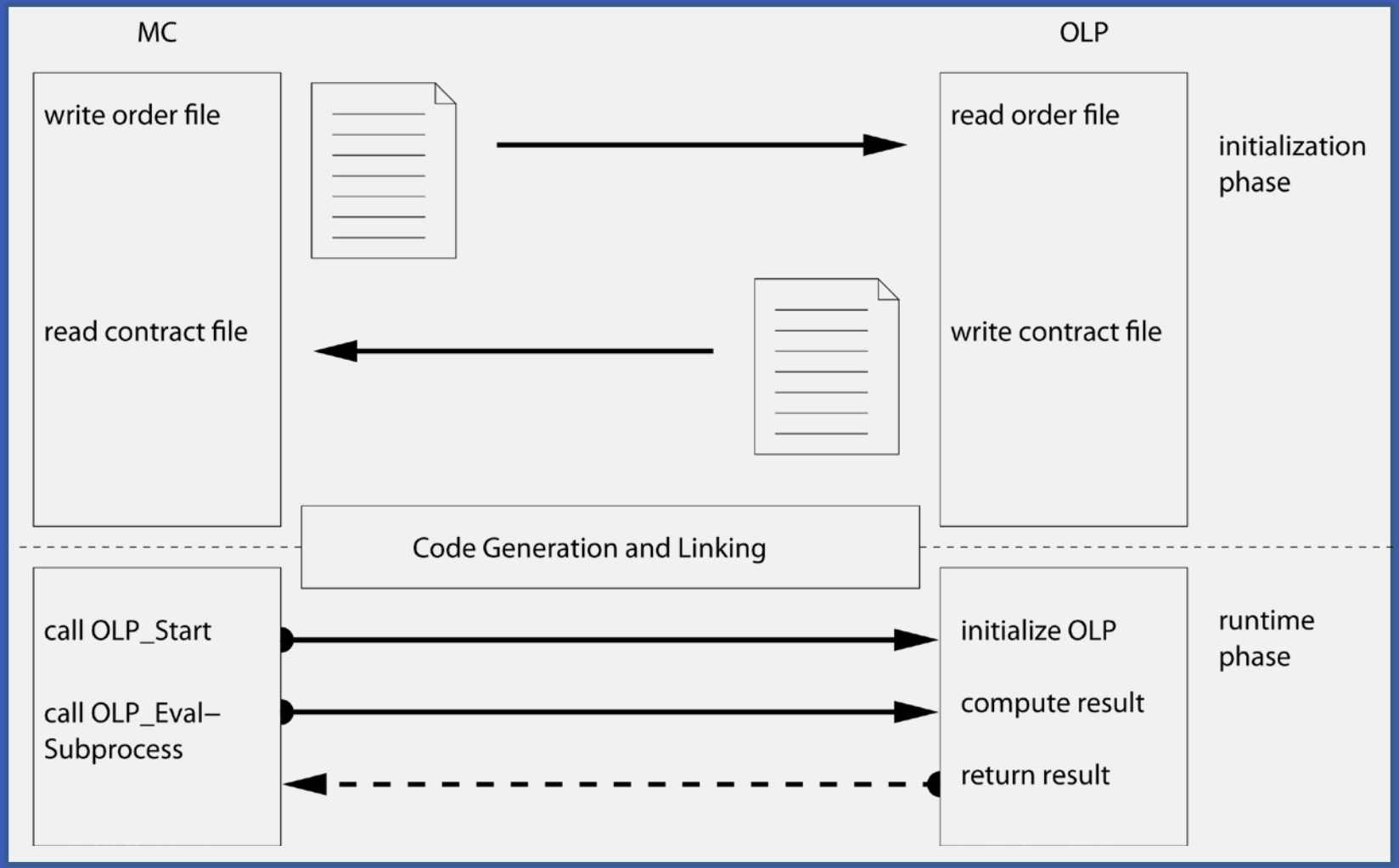
Yellow codes distributed separately

Generated code execution

- Loop integral reduction:
  - SAMURAI [Mastrolia, Ossola, Reiter, Tramontano 10]
  - GOLEM95 [Binoth, Cullen, Guillet, Heinrich, Pilon, Reiter 08]
- Scalar integral evaluation:
  - AVHOLO [van Hameren]
  - QCDLOOP [Ellis, Zanderighi]
  - GOLEM95C [Cullen, Guillet, Heinrich, Kleinschmidt, Pilon, Reiter, Rodgers 11]

All codes in gosam-contrib package

BLHA-interface



GoSam with external MC

- GoSam + MadGraph4 + MadDipole + MadEvent
  - Interfaced via add-hoc interface
  - Succesfully used to compute:
    - W^+W^- + 2 jets [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano 12] [Melia et al. 11]
    - $b\bar{b}b\bar{b}$ production [Greiner, Guffanti, Reiter, Reuter 11] [Binoth Guillet 10, 11]
    - $X^0_1 + X^0_1$ + 1 jet [Cullen, Greiner, Heinrich 12]
    - $\gamma + \gamma$ + 1 jet [Gehrmann, Greiner, Heinrich 13]
- GoSam + POWHEG [Nason, Oleari, Tramontano, G.L. in preparation]
  - Development phase completed
  - Finalizing test phase
- GoSam + SHERPA [Schönherr, Tramontano, G.L. in preparation]
  - Possible since Sherpa 1.4.0 (March 2012) : [--enable-lhole]
  - Little additional patch needed for parameter communication
  - Packages publicly available at: http://gosam.hepforge.org/proc/
  - Succesfully used to compute
    - H+2 jets in gluon-gluon fusion [van Deurzen, Greiner, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano, G.L. 13]
    - Graviton + 1 jet in ADD model [Greiner, Heinrich, Reichel, von Soden-Fraunhofen in preparation]

Via BLHA Interface

GoSam+Sherpa Process Packages

Available on: http://gosam.hepforge.org/proc/

- Single process packages with pre-generated virtual code for the calculation of NLO QCD corrections to selected LHC processes.
- Available online for the current stable version of Sherpa-1.4.X. (version for Sherpa-2.0.X in preparation)

  - Completely stand-alone
    - No need to install further code other than Sherpa
  - Only 3 steps for NLO:
    - Download / un-tar package / run ‘makecode‘ script
    - Script for plots is also attached
    - Packages come with example Run card for LO/NLO/NLO+Rivet

GoSam+Sherpa Process Packages

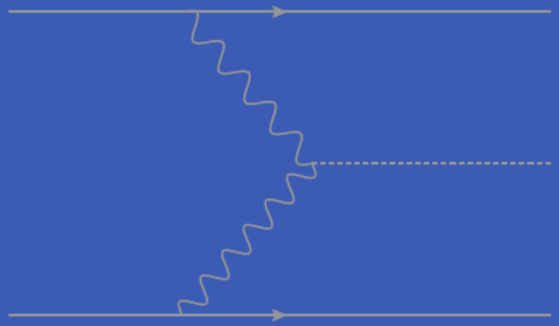
- Actual status of freely available processes:

Process	Number of extra jets	COMING SOON
W	0,1,2	3
Z	0,1	2
W+ b $\bar{b}$ (massive b's)	0	1
γ	-	0,1,2
H	-	0,1,2
W^+W^-	0	1,2 + 0 loop-induced
W^+W^+	2	-
W^+W^- b b	-	0
t $\bar{t}$	-	0,1
H t $\bar{t}$	-	0

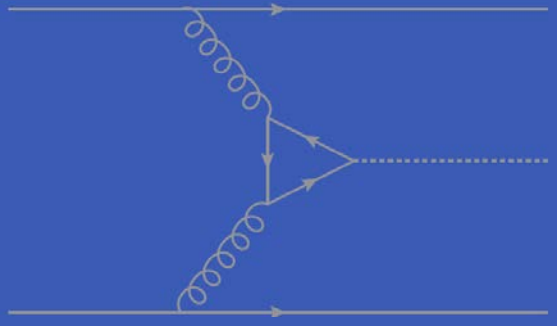
Available on: http://gosam.hepforge.org/proc/

Higgs+jets: Motivation

- Higgs-like boson discovered last July: is it the Higgs?
- Need to determine properties by studying all possible production/decay channels and background processes
- Many precise studies ongoing
  - e.g contamination of vbf sample by ggf events [Gangal, Tackmann 13; NLO MC in YR3; …]



Vector boson fusion



Gluon-gluon fusion

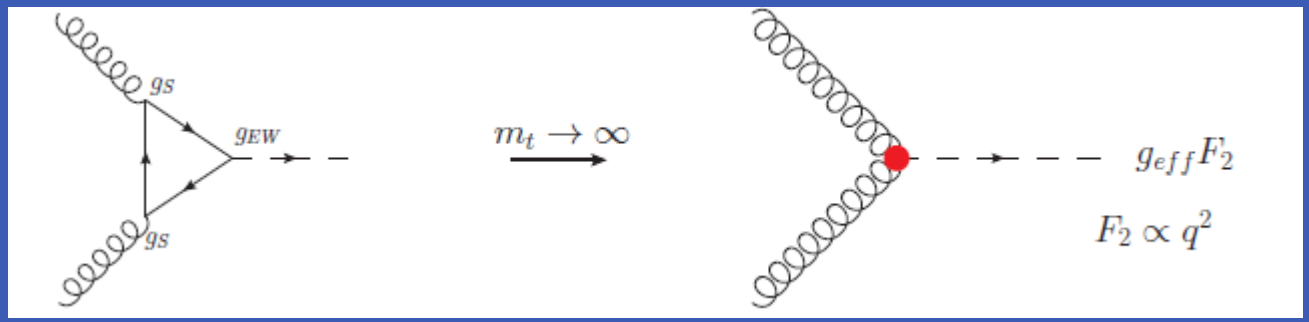
→ Started systematic computation of QCD corrections to H+jets using GoSam

Higgs+jets: the higher rank issue

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

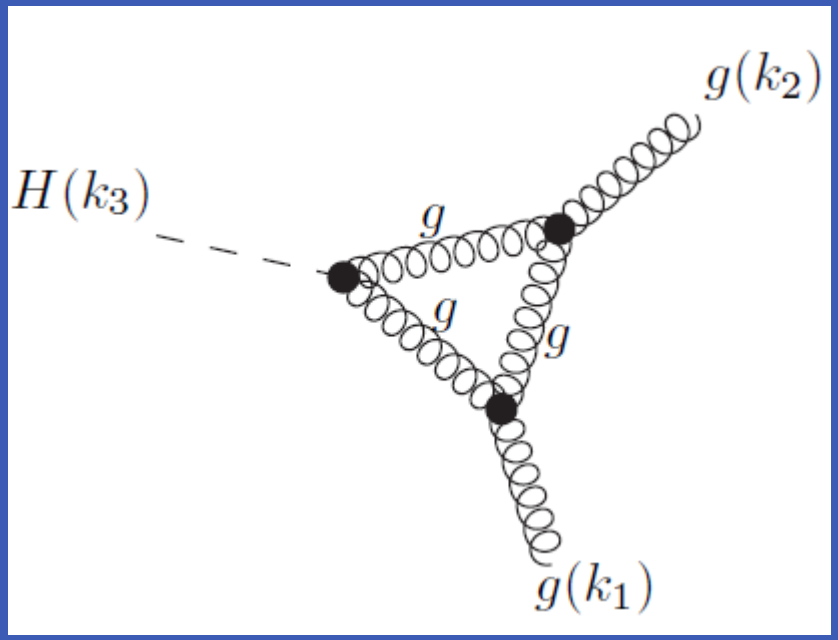


Adapt reduction programs Samurai and Golem95 to deal with higher rank loop integrals

[Mastrolia, Mirabella, Peraro 12; van Deurzen, Mastrolia 12]
[Guillet, Heinrich, von Soden-Fraunhofen ongoing]

Higgs+jets: NLO virtual corrections

	Processes	# Diagrams	# Groups	Timing (per PS point)
H+0 jets	$g + g \longrightarrow H$	1	1	< 1 ms



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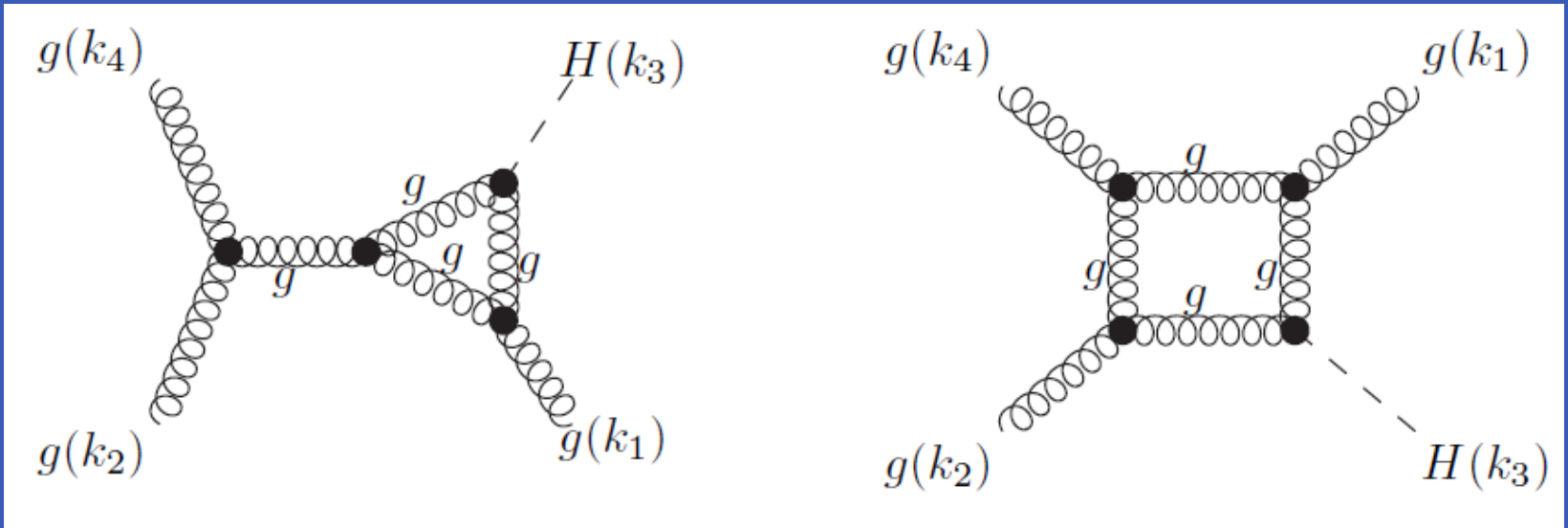
H+1 jets	$q+\bar{q} \longrightarrow H+g$	14	3	~ 3 ms
	$g+g \longrightarrow H+g$	48	3	~ 7 ms
		62		



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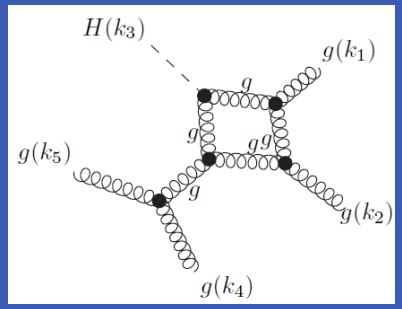
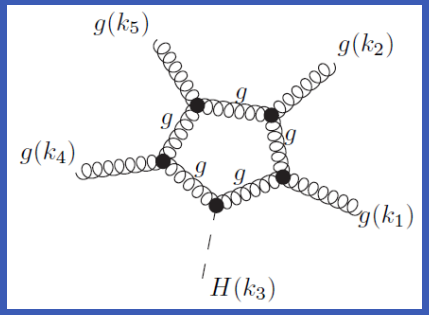
		62		
H+2 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'$	32	6	~ 9 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}$	64	8	~ 15 ms
	$q+\bar{q} \longrightarrow H+g+g$	179	12	~ 56 ms
	$g+g \longrightarrow H+g+g$	651	12	~ 316 ms
		926		



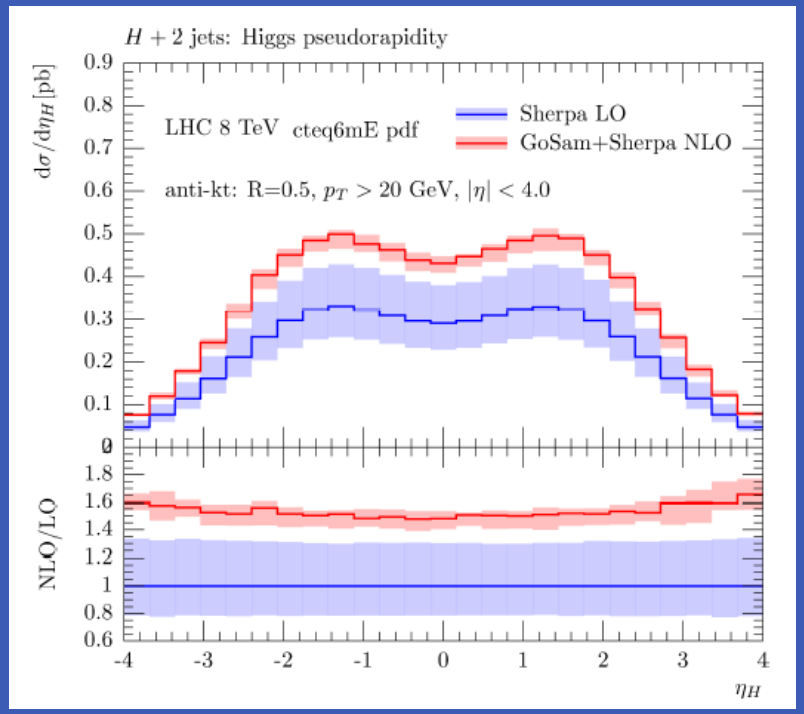


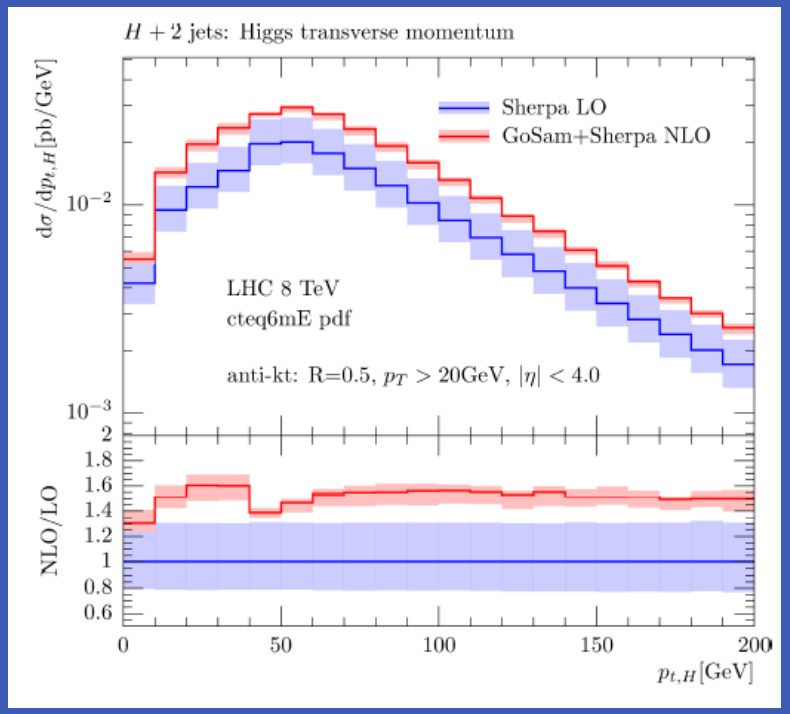
… 11 rank 6 pentagons

Higgs+2jets

[van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano 13]

- Using BLHA interface for GoSam+Sherpa
- Agreement with MCFM (v6.4) [Campbell, Ellis, Williams 10]





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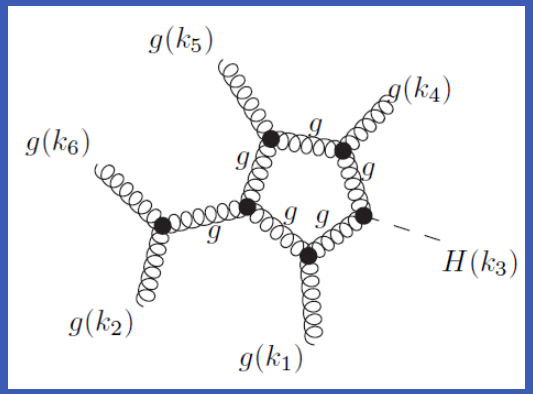
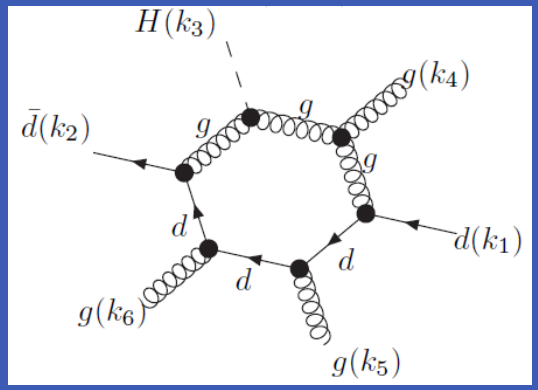
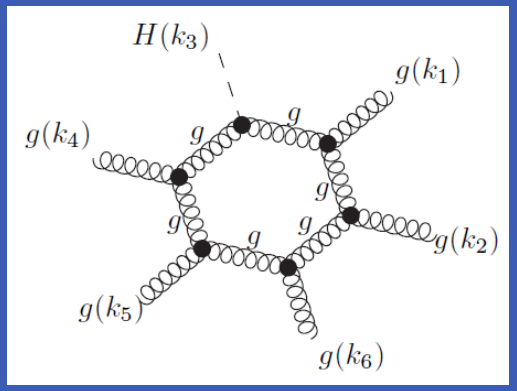
	$q+\bar{q} \longrightarrow H+g+g$	179	12	~ 56 ms
	$g+g \longrightarrow H+g+g$	651	12	~ 316 ms
		926		
H+3 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$	467	32	~ 290 ms
	$q+\bar{q} \longrightarrow H+q+\bar{q}+g$	868	24	~ 600 ms
	$q+\bar{q} \longrightarrow H+g+g+g$	2519	60	~ 3‘900 ms
	$g+g \longrightarrow H+g+g+g$	9325	60	~ 60‘100 ms
		13179		

Higgs+jets: NLO virtual corrections







… 60 rank 7 hexagons

	Processes	# Diagrams	# Groups	Timing (per PS point)
H+3 jets	$q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$	467	32	~ 290 ms
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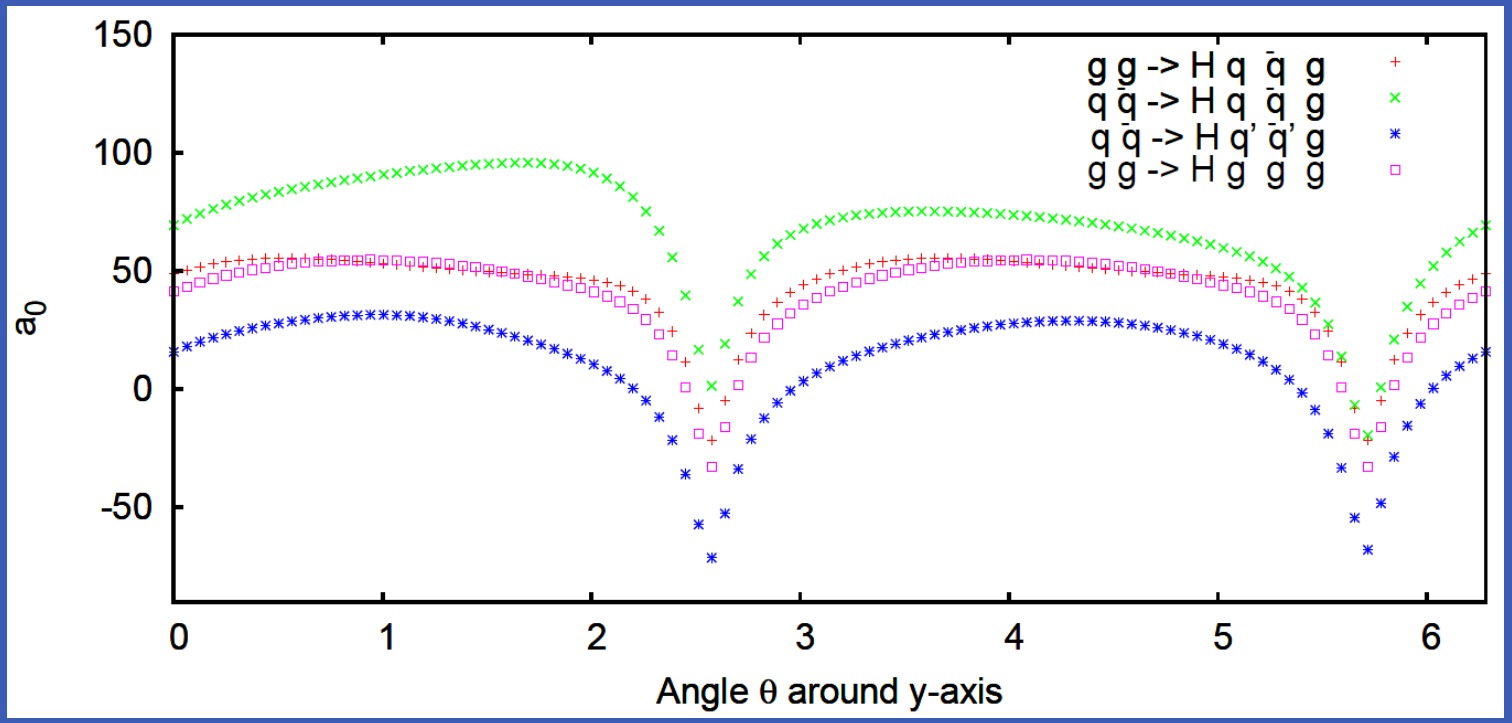
Higgs+3jets: virtual contribution

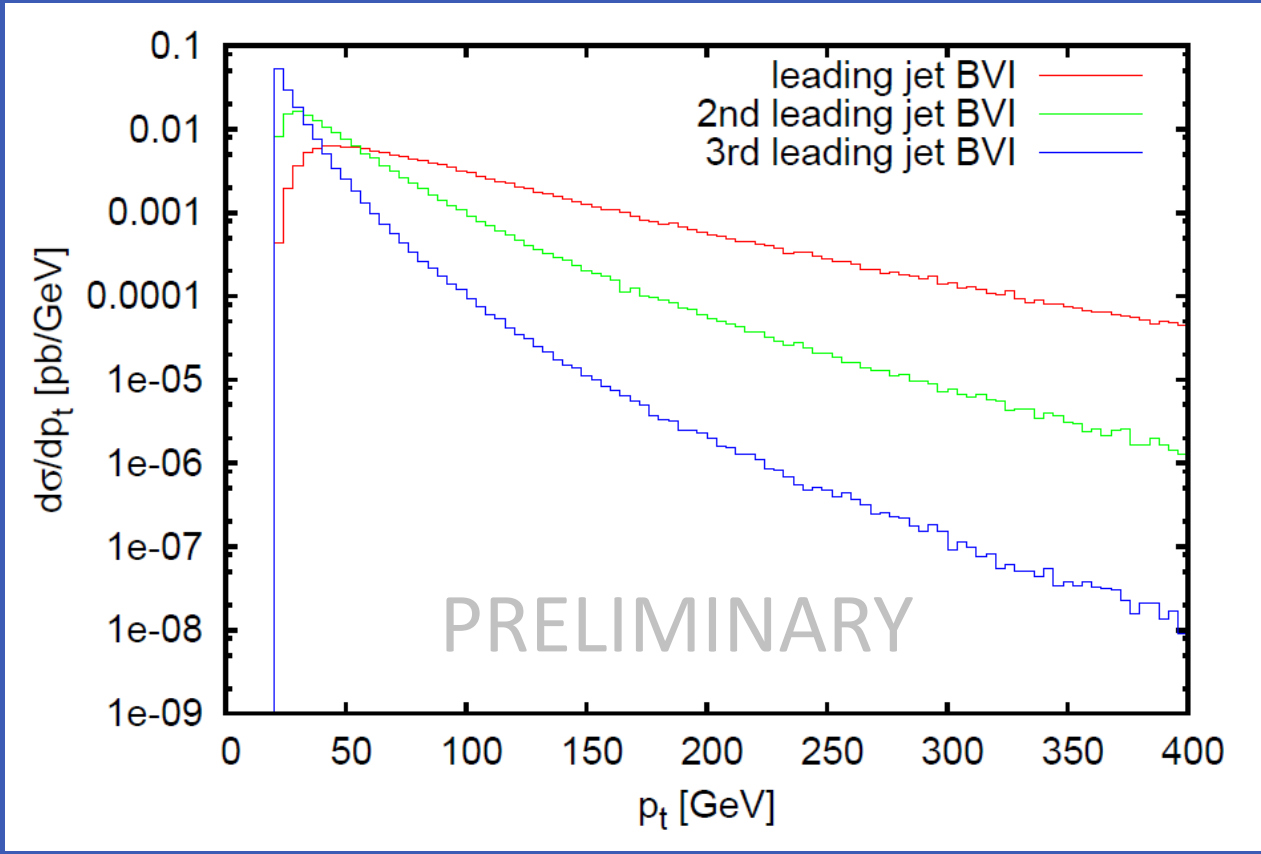
- Rotating a phase-space point around the y axis



$$\frac{2\Re\mathrm{e}\left\{\mathcal{M}^{\text{tree-level}*}\,\mathcal{M}^{\text{one-loop}}\right\}}{(4\pi\alpha_s)\left|\mathcal{M}^{\text{tree-level}}\right|^2} \equiv \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0 .$$

Towards Higgs+3jets @ NLO

- Transverse momentum distributions for Born + Virtual + Integrated dipoles



$$p_{t,j} \geq 20\text{Gev}, \qquad |\eta_j| \leq 4.0, \qquad R = 0.5$$

Conclusions & Outlook

http://gosam.hepforge.org/

- Successful use of GoSam interfaced with:

  MadGraph4 Powheg Sherpa

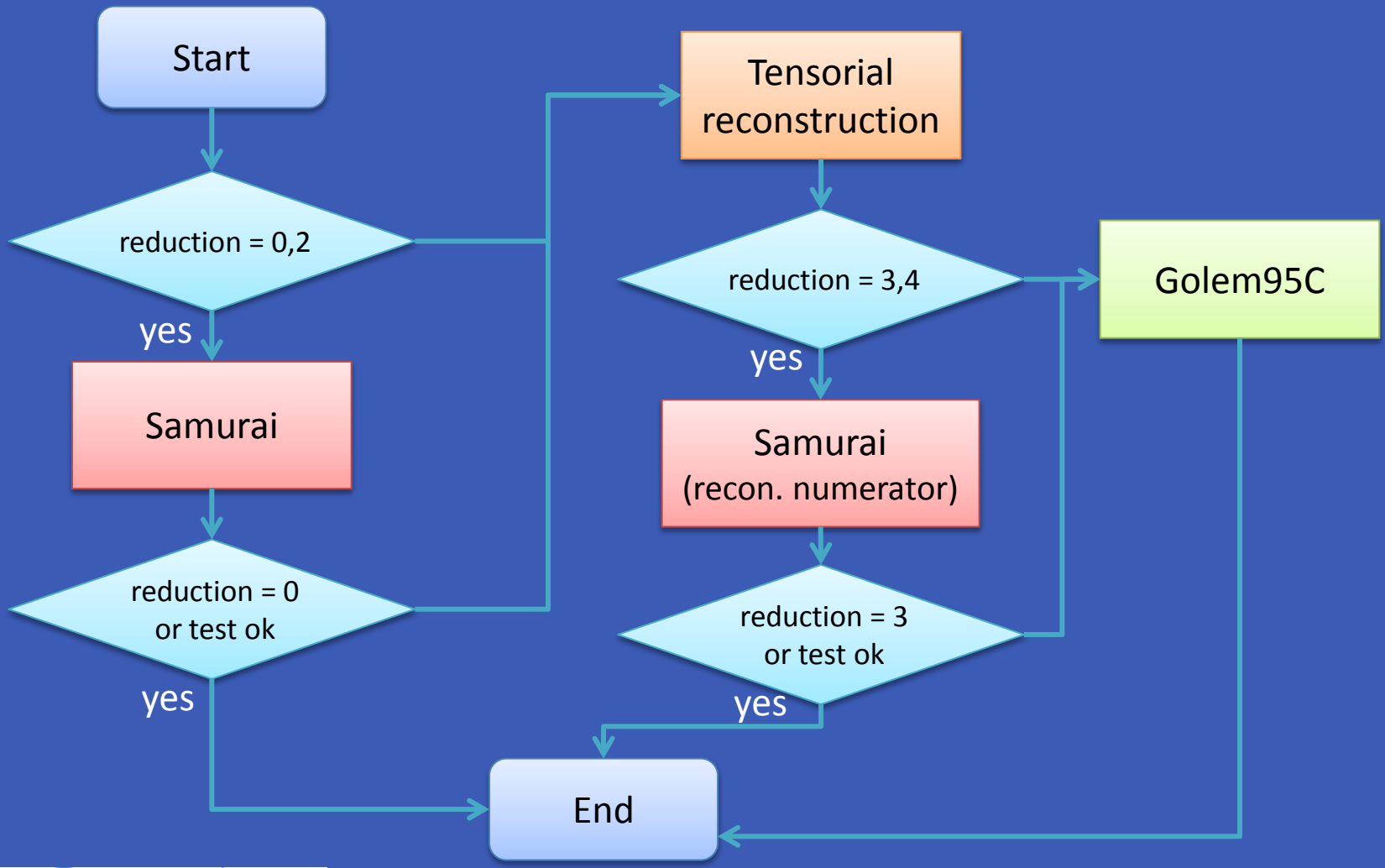
  for the computation of NLO corrections for a number of different processes.

  - Packages available online: http://gosam.hepforge.org/proc/
  - Computation of H+2 jets in gluon-gluon fusion
  - First preliminary results for H+3 jets in gluon-gluon fusion

- Outlook:
  - Use available packages for phenomenology
  - Preparation and optimization of packages for further processes
  - Phenomenology studies in H+jets with available codes
  - Code improvements to make computation faster and codes “lighter“

BACKUP SLIDES

Reduction: strategies



BLHA-interface: order & contract

- H+2 jets example:

```
# OLE_order.lh
# Created by Sherpa-2.0.beta
MatrixElementSquareType  Chsummed
CorrectionType           QCD
IRregularisation         DRED
AlphasPower              4
AlphaPower               1
OperationMode            CouplingsStrippedOff
ResonanceTreatment       ComplexMassScheme
EWRenormalisationScheme  alphaMZ
# process list
1 1 -> 25 1 1
1 -1 -> 25 1 -1
1 -1 -> 25 2 -2
1 -1 -> 25 21 21
1 2 -> 25 1 2
1 21 -> 25 21 1
-1 1 -> 25 1 -1
-1 2 -> 25 2 -1
21 1 -> 25 21 1
21 21 -> 25 1 -1
21 21 -> 25 21 21
```

```
# vim: syntax=olp
#@OLP GOLEM 1.0
#@IgnoreUnknown True
#@IgnoreCase False
#@SyntaxExtensions
IRregularisation DRED | OK
AlphaPower 1 | OK
MatrixElementSquareType CHsummed | OK
CorrectionType QCD | OK
AlphasPower 4 | OK
OperationMode CouplingsStrippedOff | OK
ResonanceTreatment ComplexMassScheme | OK # Ignored by OLP
EWRenormalisationScheme alphaMZ | OK # Ignored by OLP
1 1 -> 25 1 1 | 1 1
1 -1 -> 25 1 -1 | 1 2
1 -1 -> 25 2 -2 | 1 8
1 -1 -> 25 21 21 | 1 6
1 2 -> 25 1 2 | 1 9
1 21 -> 25 21 1 | 1 7
-1 1 -> 25 1 -1 | 1 3
-1 2 -> 25 2 -1 | 1 10
21 1 -> 25 21 1 | 1 4
21 21 -> 25 1 -1 | 1 5
21 21 -> 25 21 21 | 1 0
```

Higgs+3jets: virtual contribution

$$\frac{2\Re e\left\{\mathcal{M}^{\text{tree-level}*}\,\mathcal{M}^{\text{one-loop}}\right\}}{(4\pi\alpha_s)\left|\mathcal{M}^{\text{tree-level}}\right|^2} \equiv \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0 \,.$$

$gg \to Hq\bar{q}g$		
b_0	$0.6309159660038877 \cdot 10^{-4}$	
a_0	48.68424097859422	
a_{-1}	−36.08277727147958	−36.08277728199094
a_{-2}	−11.66666666667209	−11.66666666666667

$q\bar{q} \to Hq\bar{q}g$		
b_0	$0.3609139855530763 \cdot 10^{-4}$	
a_0	69.32351140490162	
a_{-1}	−29.98862932963380	−29.98862932963629
a_{-2}	−8.333333333333339	−8.333333333333334

$q\bar{q} \to Hq'\bar{q}'g$		
b_0	$0.2687990772405433 \cdot 10^{-5}$	
a_0	15.79262767177915	
a_{-1}	−32.35320587070861	−32.35320587073038
a_{-2}	−8.333333333333398	−8.333333333333332

$gg \to Hgg$		
c_0	$0.1507218951429643 \cdot 10^{-3}$	
a_0	59.8657965614009	
a_{-1}	−26.4694115468536	−26.46941154671207
a_{-2}	−12.00000000000001	−12.00000000000000

$gg \to Hq\bar{q}$		
c_0	$0.5677813961826772 \cdot 10^{-6}$	
a_0	66.6635142370683	
a_{-1}	−16.5816633315627	−16.58166333155405
a_{-2}	−8.666666666666669	−8.666666666666668

$q\bar{q} \to Hq\bar{q}$		
c_0	$0.1099527895267439 \cdot 10^{-5}$	
a_0	88.2959834057198	
a_{-1}	−10.9673755313443	−10.96737553134440
a_{-2}	−5.33333333333332	−5.333333333333334

$q\bar{q} \to Hq'\bar{q}'$		
c_0	$0.1011096724203529 \cdot 10^{-6}$	
a_0	33.9521626734153	
a_{-1}	−13.8649292834138	−13.86492928341388
a_{-2}	−5.33333333333334	−5.333333333333334