Automated one-loop calculations with

GoSam 2.0

Gudrun Heinrich

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In collaboration with

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

Loops & Legs 2014

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

Particle physics after the Higgs discovery

- **the big question:** *is there something beyond the SM ?*
- *how to find out in the absence of "smoking gun" signals ?*

- *the key is* ***precision***

scrutinize Higgs properties/EWSB
(signal strengths, decay channels, couplings to gauge bosons and 3rd generation fermions, . . .)

- NN(N)LO QCD predictions
- NLO + parton shower matching
- impact of electroweak corrections
- reduction of PDF uncertainties
- quark mass effects
- resummation . . .

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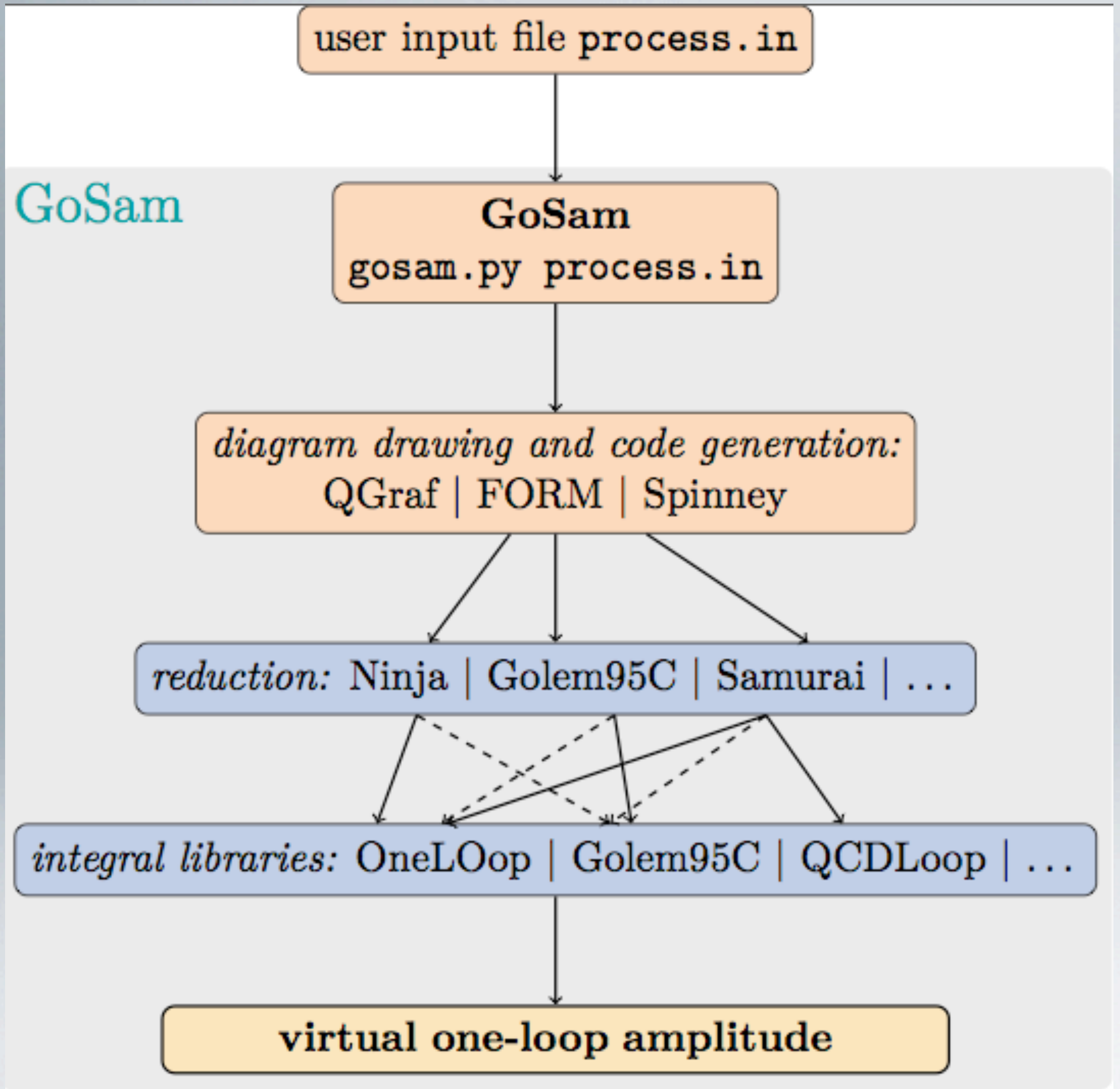
NLO automation

- "loops & legs number" is always increasing
- advanced techniques allow automation
- move from "proof of concept" multi-particle one-loop calculations towards automated tools with direct link to phenomenological analysis/experiment
- NLO matched to parton shower is new state of the art

many automated NLO tool, e.g.

FeynArts/FormCalc, BlackHat, Helac-NLO, aMC@NLO, NJet, OpenLoops, Recola, VBFNLO, MCFM, ... , **GoSam**

Structure of GoSam-2.0



arXiv:1404.7096

program available at

http://gosam.hepforge.org

very simple usage

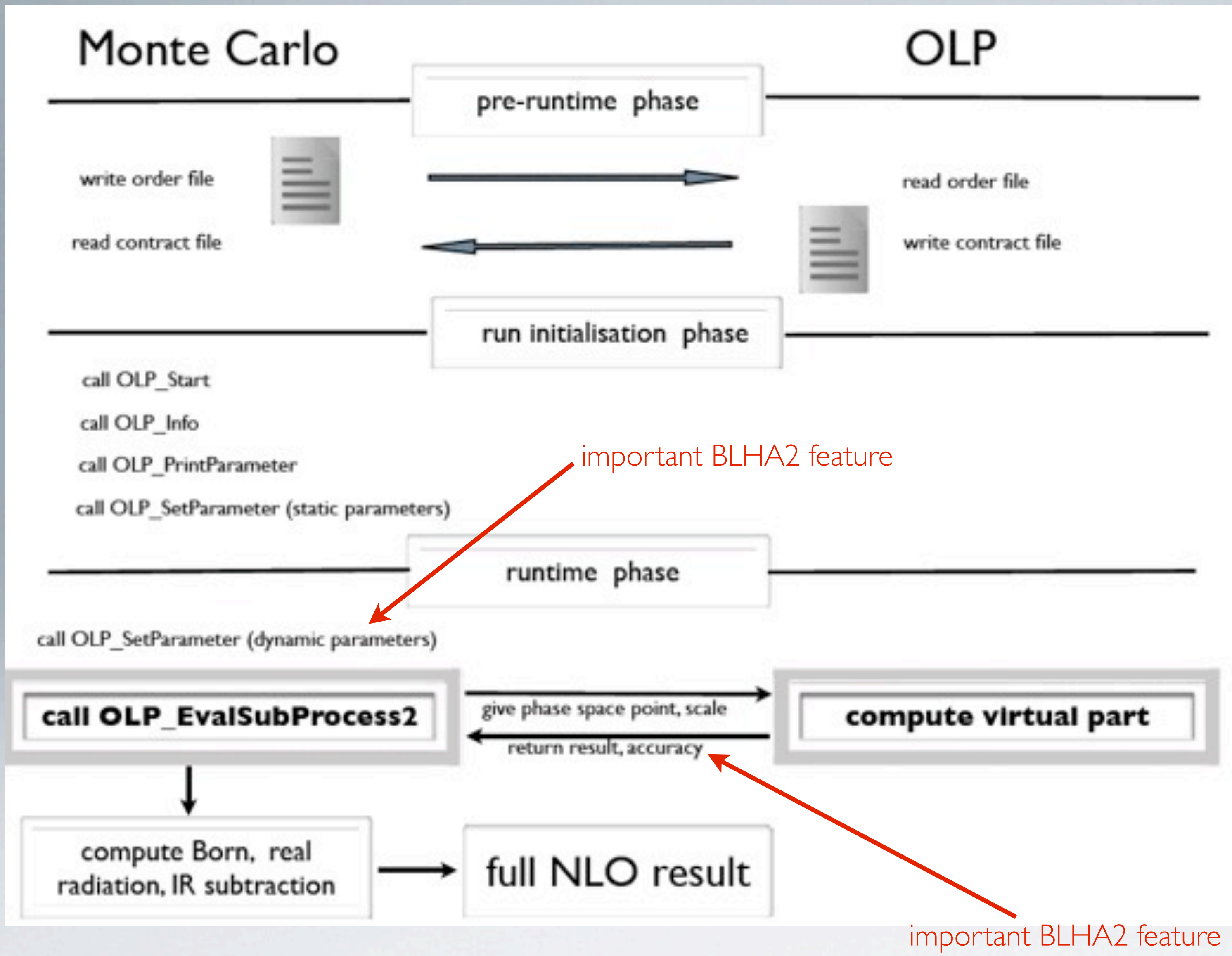
example input file for

$$e^+e^- \to t\,\bar{t}$$

```
process_path=eett
in=     e+, e-
out=    t, t~
order= gs, 0, 2
```

Interface to Monte Carlo programs

both original Binoth-Les-Houches-Accord
and extended standards are supported



allows combination with
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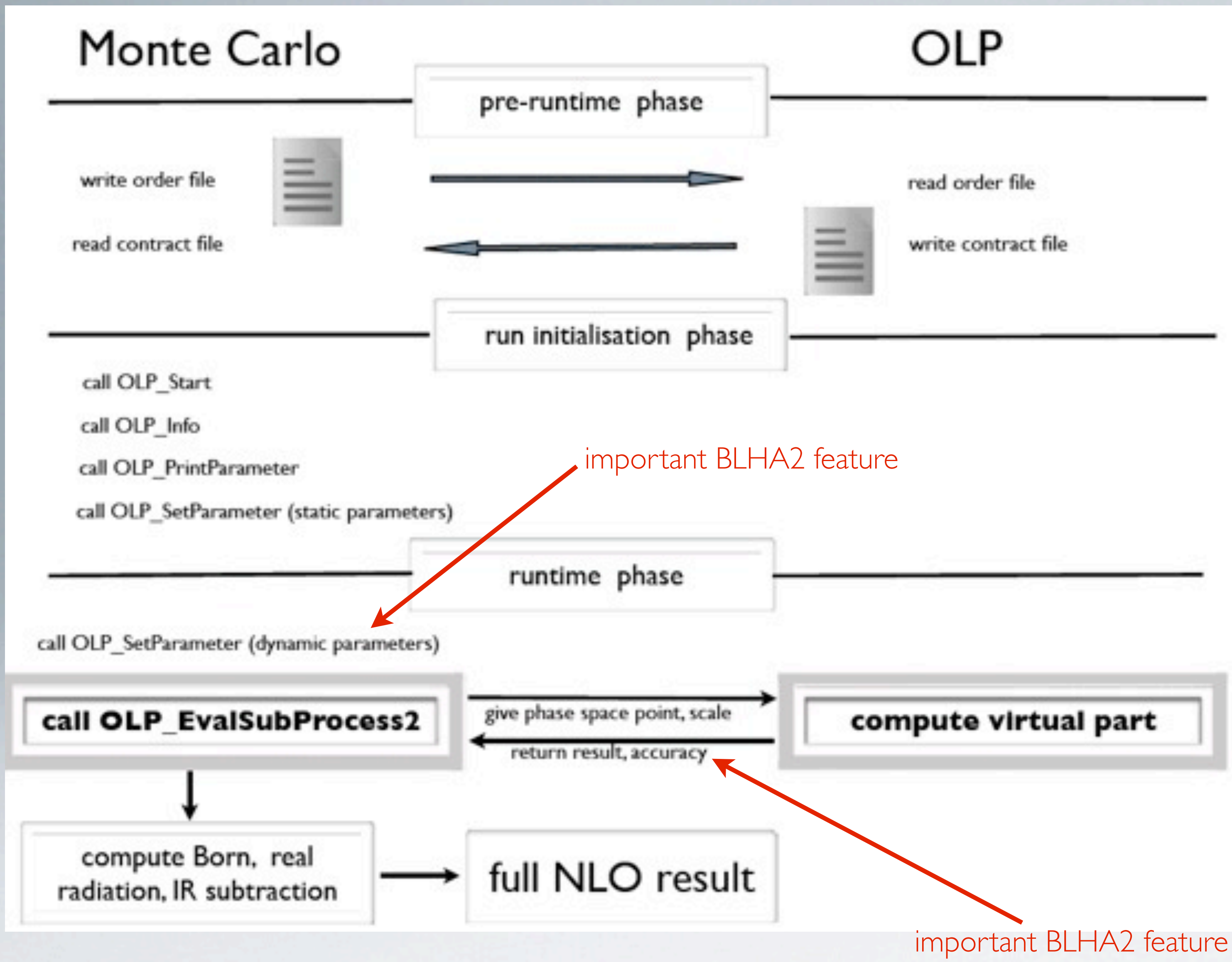

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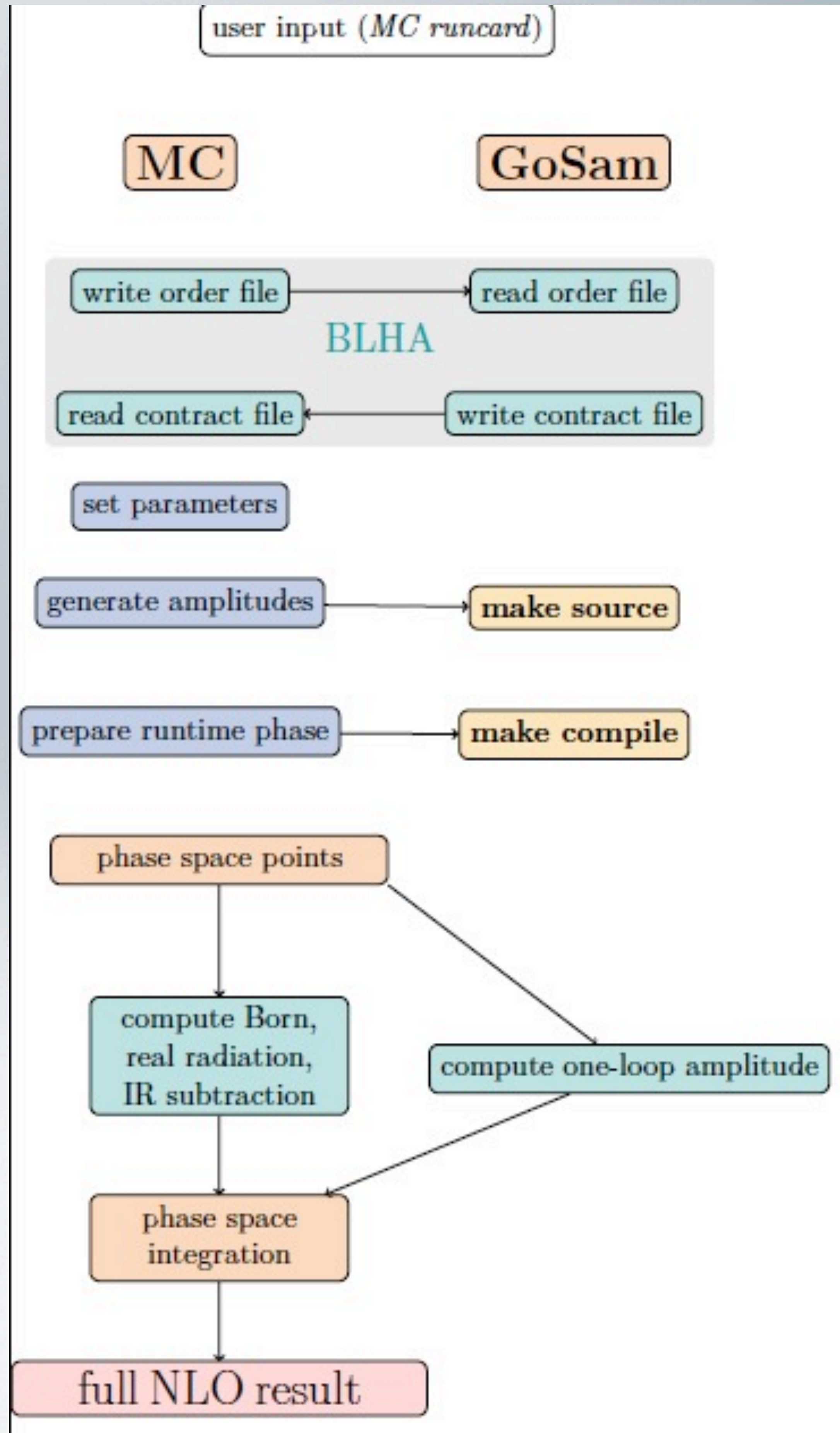

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Examples of processes calculated with GoSam

- GoSam + MadDipole/MadGraph/MadEvent

$pp \to W^+W^- + 2\,jets$ [Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]

$pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 + jet$ [Cullen, Greiner, GH '12]

$pp \to (G \to \gamma\gamma) + 1\,jet$ [Greiner, GH, Reichel, von Soden-Fraunhofen '13]

$pp \to \gamma\gamma + 1, 2\,jets$ [Gehrmann, Greiner, GH '13]

$pp \to HH + 2\,jets$ [Dolan, Englert, Greiner, Spannowsky '13]

- GoSam + Sherpa

$pp \to W^+W^+ + 2\,jets$ [Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano '12]

$pp \to H + 2\,jets$ [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]

$pp \to W^+W^-\,b\bar{b}$ [GH, Maier, Nisius, Schlenk, Winter '13]

$pp \to t\bar{t} + 0, 1\,jet$ (includes shower) [Höche, Huang, Luisoni, Schönherr, Winter '13]

$pp \to H\,t\bar{t} + 0, 1\,jet$ [van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]

- GoSam + Powheg (includes shower)

$pp \to HW/HZ + 0, 1\,jet$ [Luisoni, Nason, Oleari, Tramontano '13]

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- GoSam + MadDipole/MadGraph/MadEvent + Sherpa

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- GoSam + MadDipole/MadGraph/MadEvent + Sherpa **see also talk by F.Tramontano**

$pp \to H + 3\,jets$ [Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13]

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  more compact code, faster evaluation

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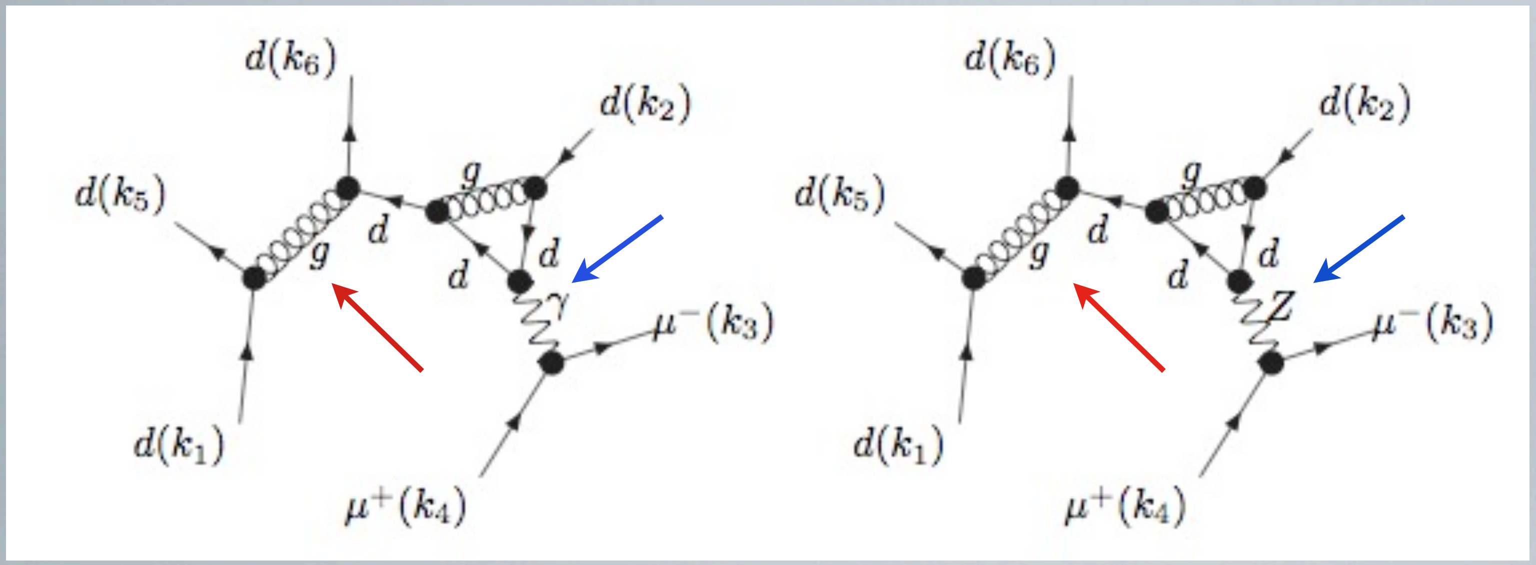
- Easy installation

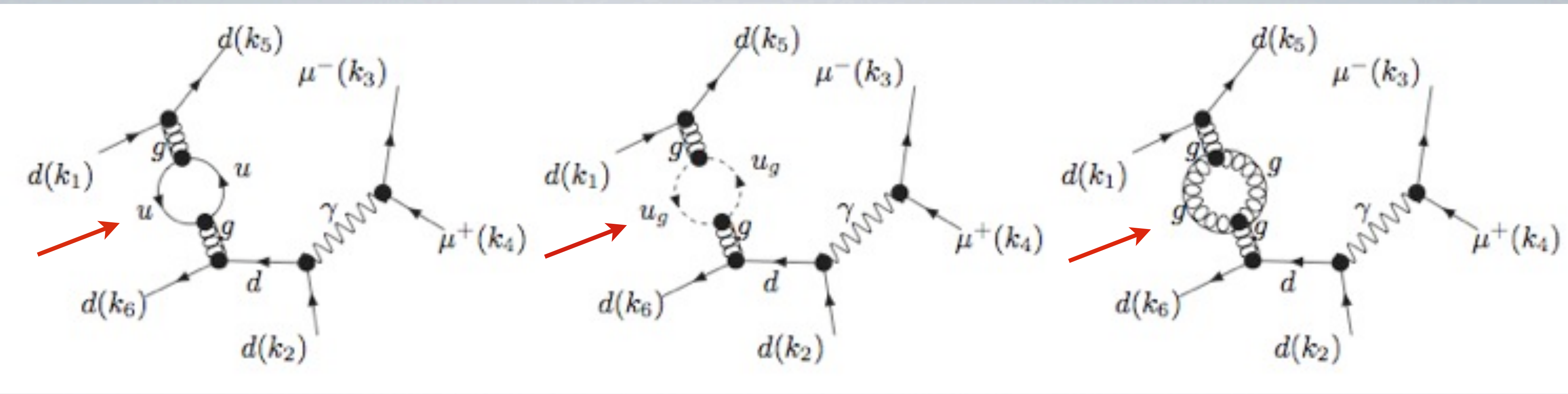
  installation script installs and builds the code and all libraries

New code generation methods

- code optimisation with FORM version 4 [Vermaseren, Kuipers, Ueda, Vollinga]
- construction of "meta-diagrams" from diagrams sharing common substructures



share a tree sub-diagram



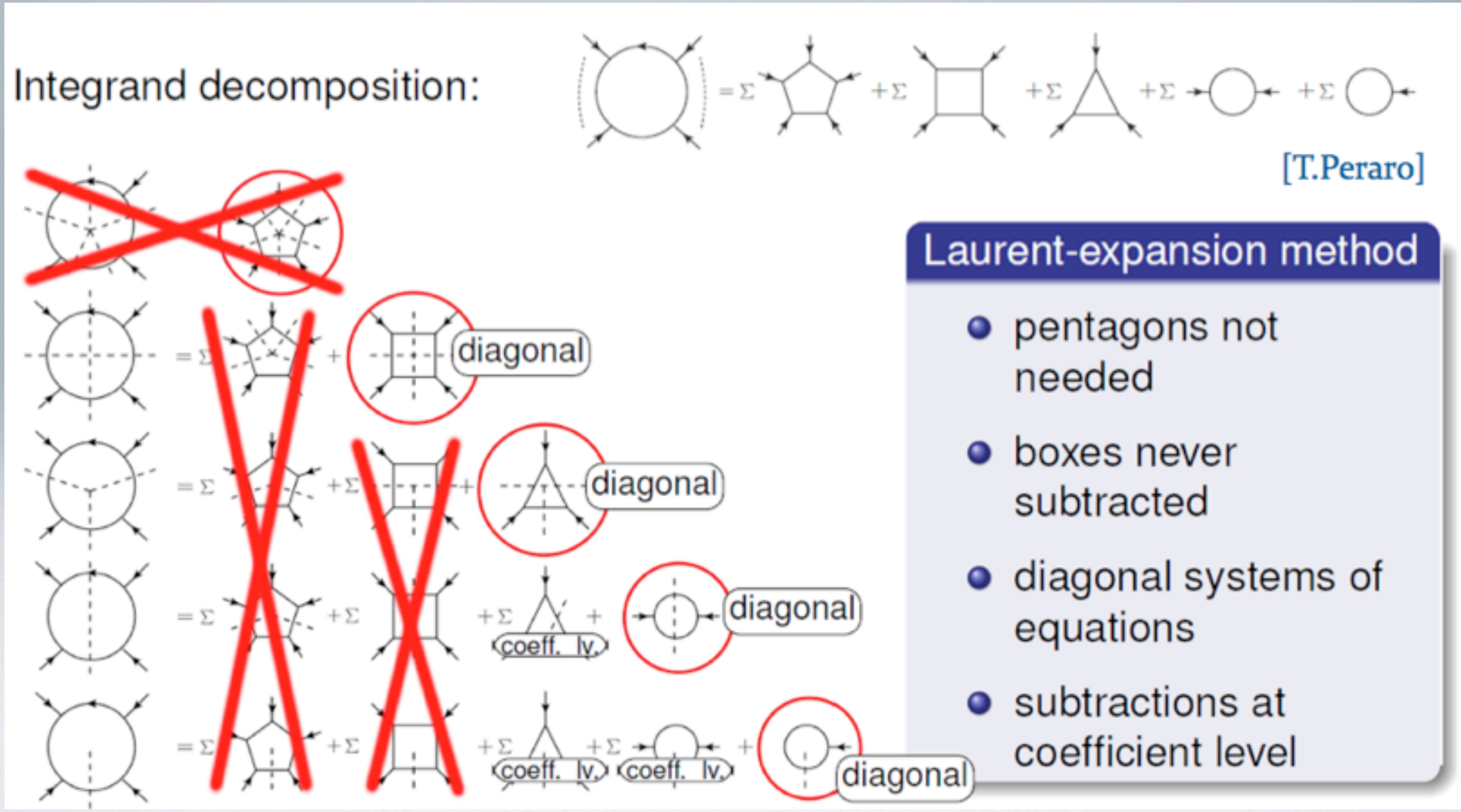
share a loop sub-diagram

New reduction methods

basic idea: extract the coefficients of the residues of a loop integral by performing a Laurent expansion of the integrand

[Mastrolia, Mirabella, Peraro '12]

implemented in the code **Ninja** [T. Peraro '14]



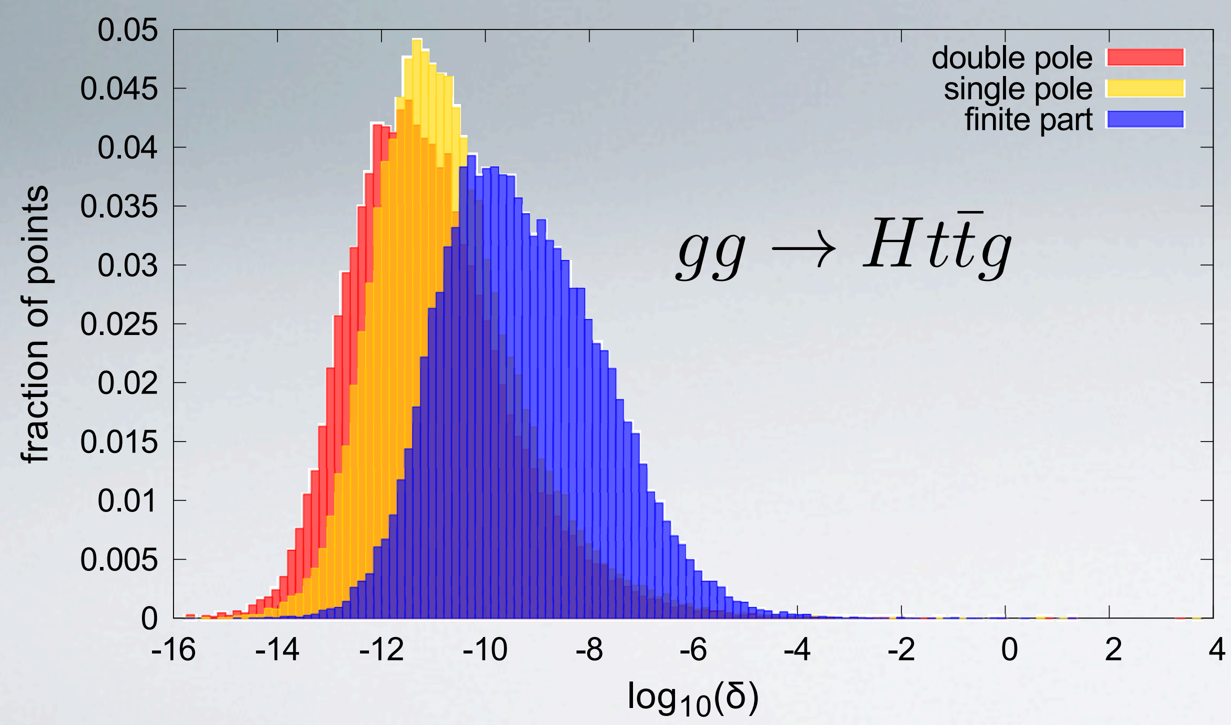
New reduction methods

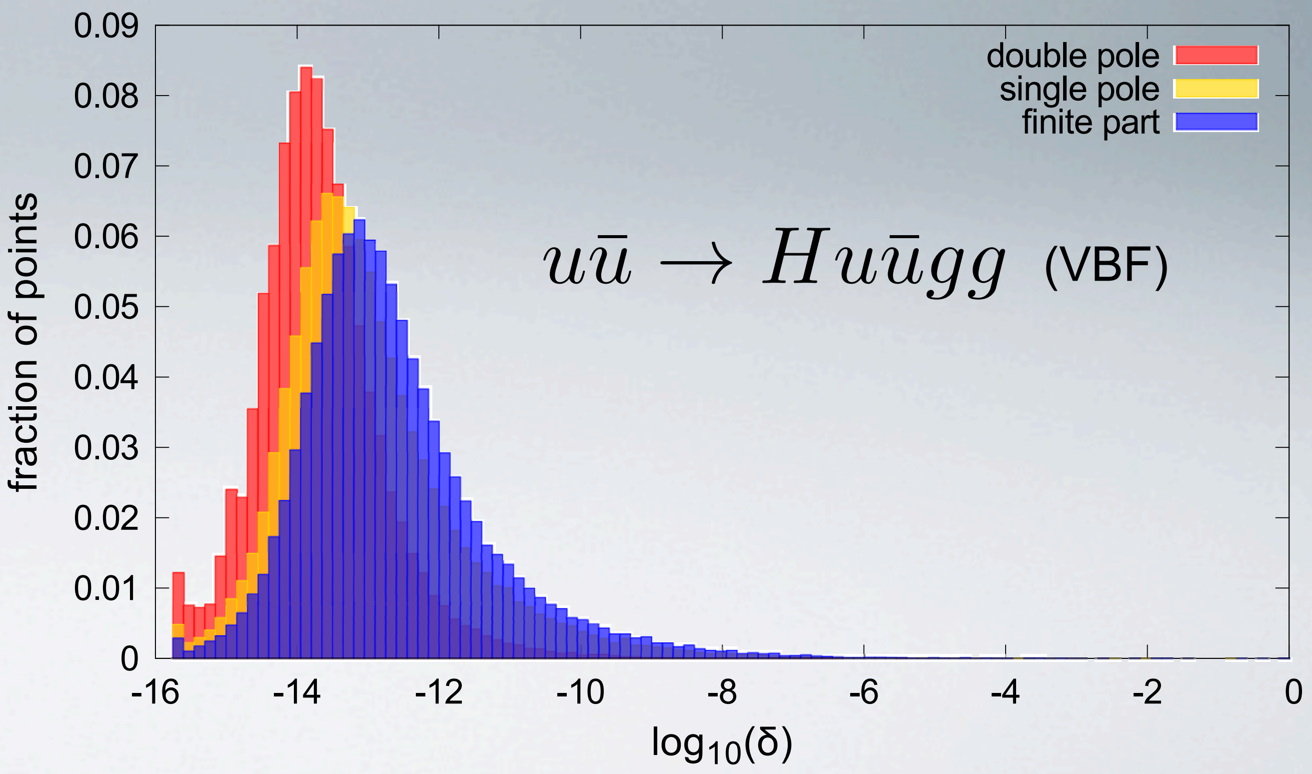
- in GoSam-2.0 several reduction libraries available:

  Ninja, Golem95C, Samurai

- switch between different reduction algorithms "on the fly" $\Rightarrow$ flexible rescue system for problematic points

- Ninja performs particularly well for massive particles in the loops





[van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]

$$\delta = \left| \frac{A_{\text{"}exact\text{"}} - A}{A_{\text{"}exact\text{"}}} \right|$$

new range of applicability

- electroweak scheme choice

ewchoice	input parameters	derived parameters
1	G_F, m_W, m_Z	e, $\sin\theta_w$
2	α, m_W, m_Z	e, $\sin\theta_w$
3	α, $\sin\theta_w$, m_Z	e, m_W
4	α, $\sin\theta_w$, G_F	e, m_W
5	α, G_F, m_Z	e, m_W, $\sin\theta_w$
6	e, m_W, m_Z	$\sin\theta_w$
7	e, $\sin\theta_w$, m_Z	m_W
8	e, $\sin\theta_w$, G_F	m_W, m_Z

- support of complex masses

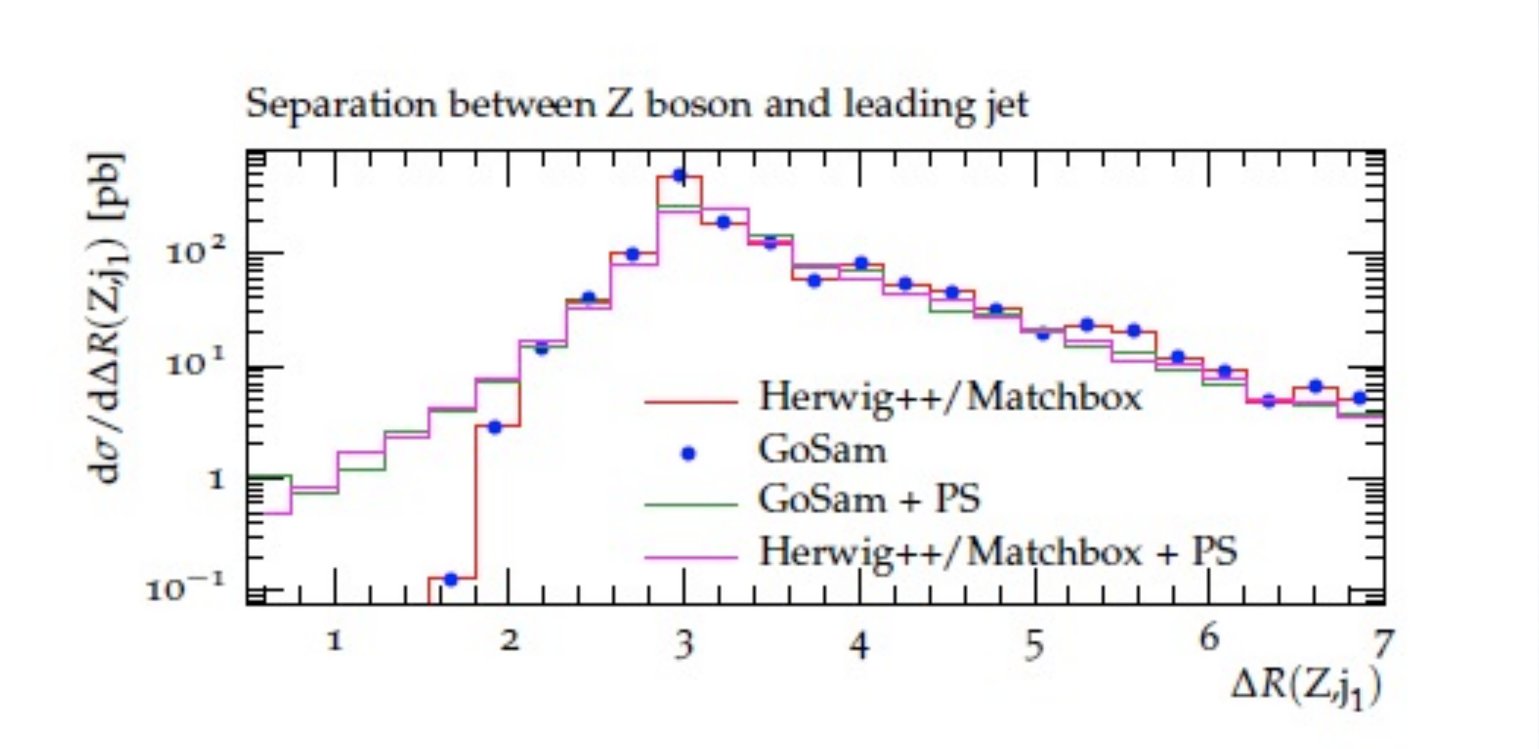
complex masses/parameters in generated code and in loop integrals supported

$$m_V^2 \to \mu_V^2 = m_V^2 - i m_V \Gamma_V, \quad V = W, Z$$

$$\cos^2\theta_W = \mu_W^2/\mu_Z^2$$

- colour- and spin-correlated tree amplitudes

can be used e.g. to build subtraction terms for NLO real radiation



[Bellm, Gieseke, Greiner, GH, Plätzer, Reuschle, von Soden-Fraunhofen '13]

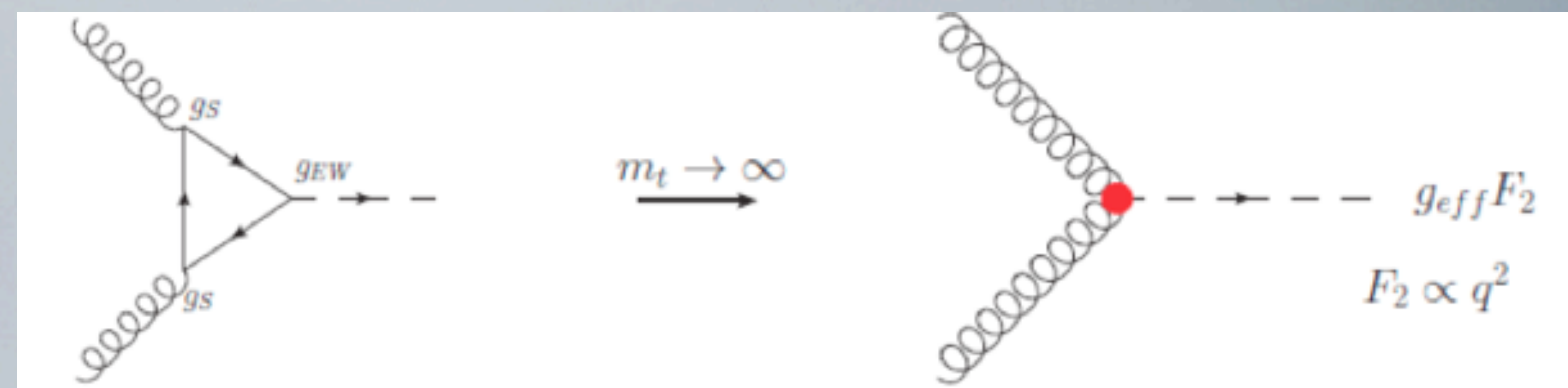
higher rank tensor integrals

$$I_N^{n,\mu_1\ldots\mu_r}(S) = \int \mathrm{d}^n k \frac{k^{\mu_1}\ldots k^{\mu_r}}{\prod_{i=1}^N \left((k+r_i)^2 - m_i^2 + i\delta\right)}$$

with $r \geq N+1$

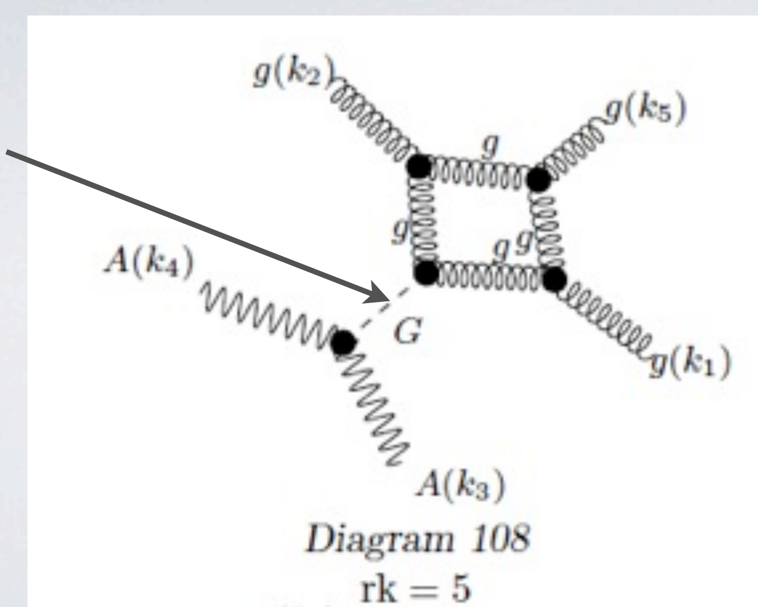
- needed for example in

- effective theories



- BSM models involving spin-2 particles

graviton



all reduction programs,
Ninja, Golem95C, Samurai
have been extended to support higher rank integrals

Ninja, Samurai:
van Deurzen, Mastrolia, Mirabella, Peraro '13, '14

Golem95C: Guillet, GH, von Soden-Fraunhofen '13

BSM applications of GoSam

$pp \to (\text{graviton} \to \gamma\gamma) + 1\,\text{jet}$ [Greiner, GH, Reichel, von Soden-Fraunhofen '13]

within ADD models of large extra dimensions

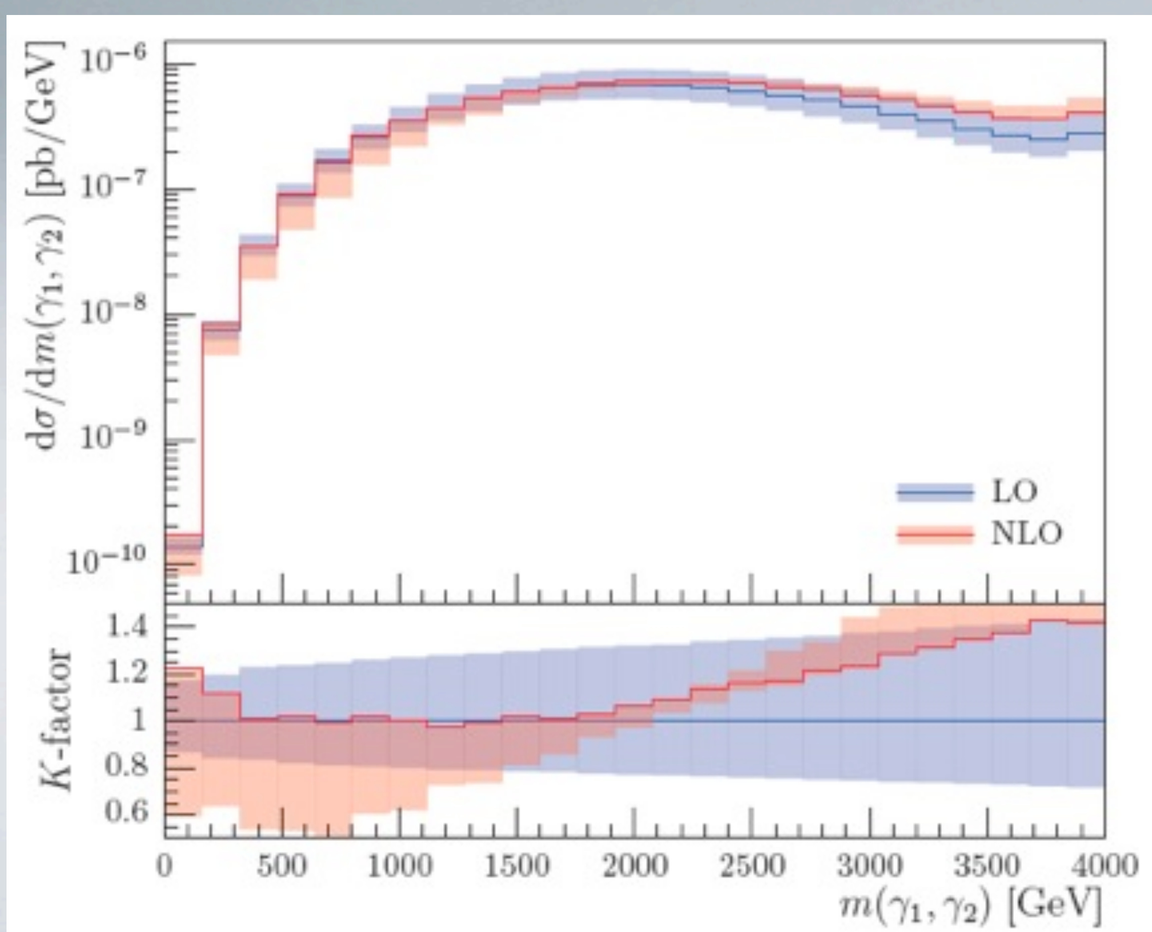
non-standard propagator for gravitons $\Rightarrow$ `customspin2prop` in GoSam

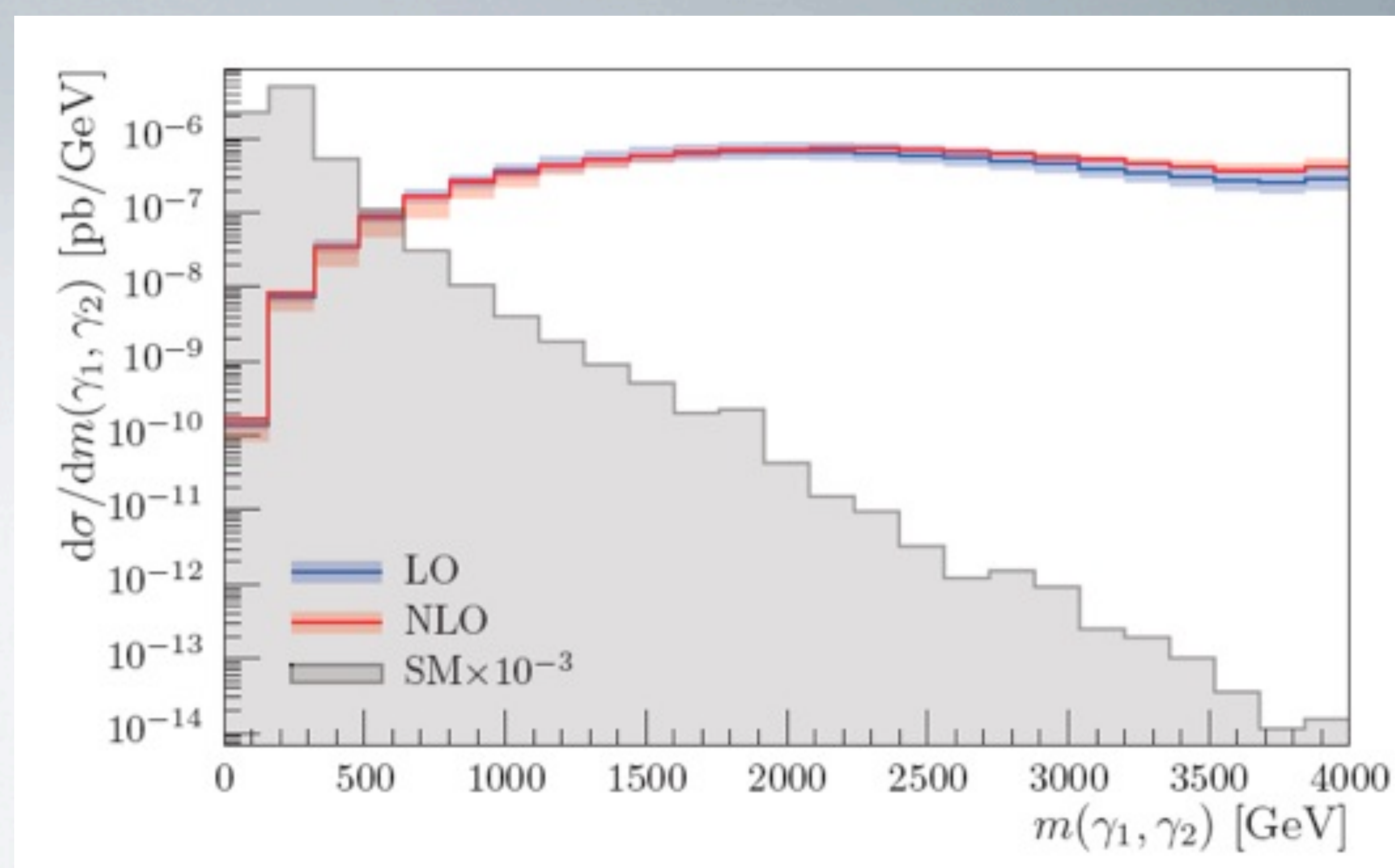
involves rank 5 box integrals

import of model file in **UFO** (Universal Feynrules Output [Degrande, Duhr et al.]) format

only task for the user: specify format and path to model file in input card, e.g.

```
model=FeynRules,[gosampath]/examples/model/LED_UFO
```





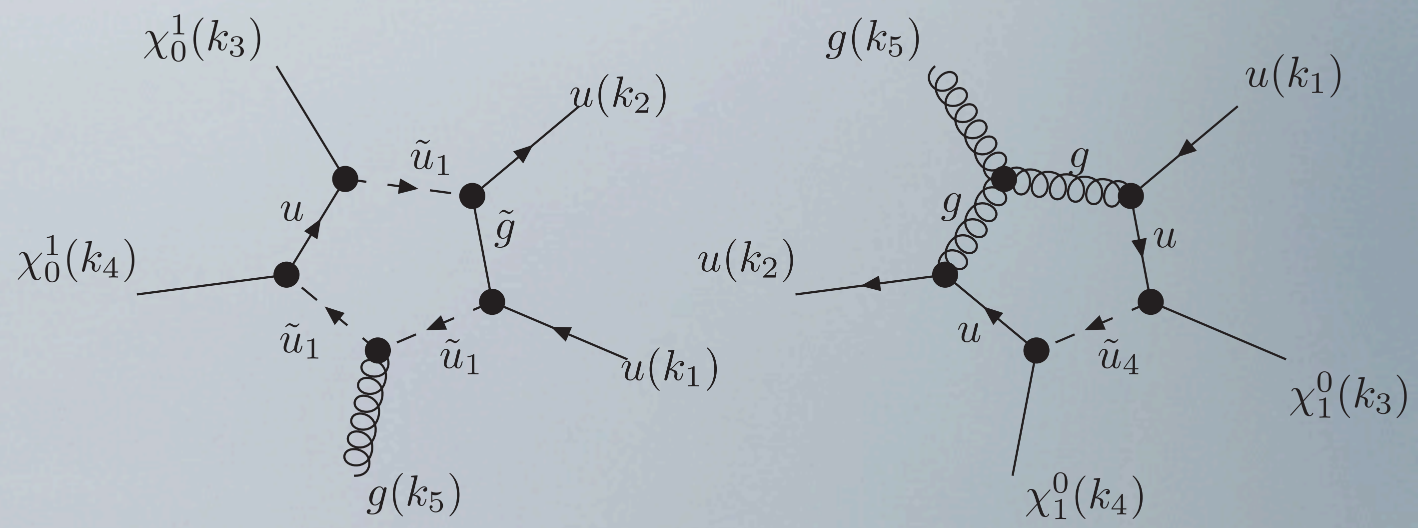
BSM applications of GoSam

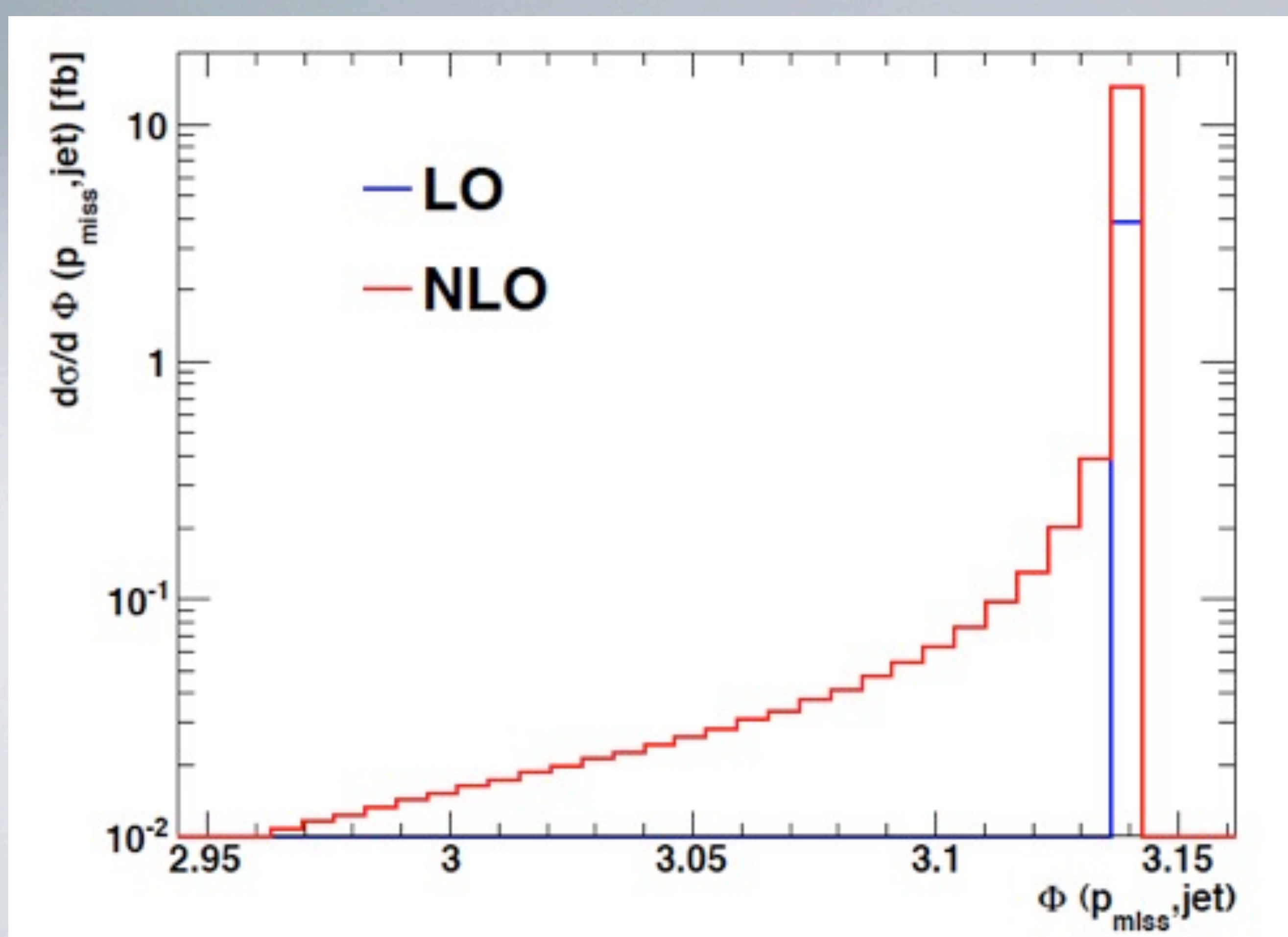
$$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + jet$$ [Cullen, Greiner, GH '13]

(SUSY QCD corrections)

signature monojet + missing ET

- full off-shell effects included
- complex masses
- UFO model file import, renormalisation done separately





SUSY Parameters	
$M_{\tilde{\chi}_1^0} = 299.5$	$\Gamma_{\tilde{\chi}_1^0} = 0$
$M_{\tilde{g}} = 415.9$	$\Gamma_{\tilde{g}} = 4.801$
$M_{\tilde{u}_L} = 339.8$	$\Gamma_{\tilde{u}_L} = 0.002562$
$M_{\tilde{u}_R} = 396.1$	$\Gamma_{\tilde{u}_R} = 0.1696$
$M_{\tilde{d}_L} = 348.3$	$\Gamma_{\tilde{d}_L} = 0.003556$
$M_{\tilde{d}_R} = 392.5$	$\Gamma_{\tilde{d}_R} = 0.04004$
$M_{\tilde{b}_L} = 2518.0$	$\Gamma_{\tilde{b}_L} = 158.1$
$M_{\tilde{b}_R} = 2541.8$	$\Gamma_{\tilde{b}_R} = 161.0$
$M_{\tilde{t}_L} = 2403.7$	$\Gamma_{\tilde{t}_L} = 148.5$
$M_{\tilde{t}_R} = 2668.6$	$\Gamma_{\tilde{t}_R} = 182.9$

angle between leading jet and missing momentum

SM applications of GoSam

$$pp \to W^+W^-\,b\bar{b}$$

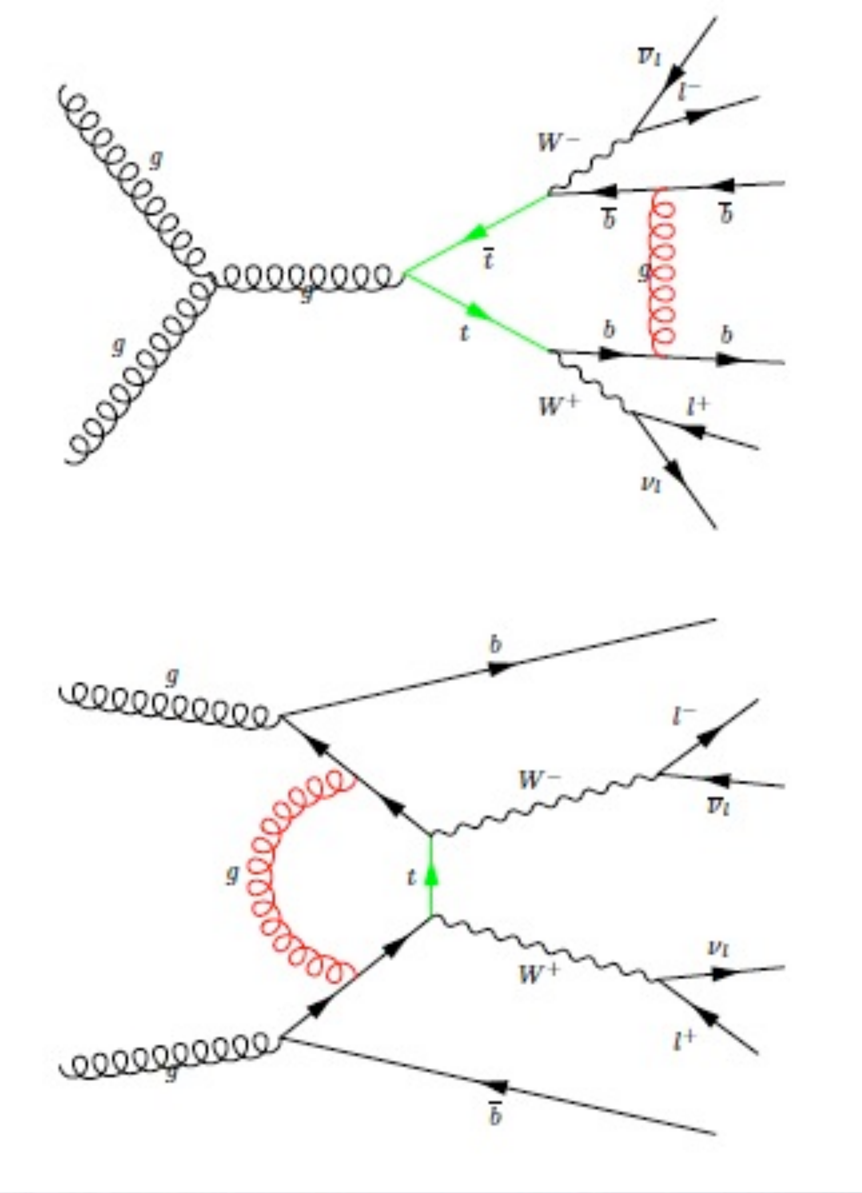
[GH, Maier, Nisius, Schlenk, Winter '13]

[Denner, Dittmaier, Kallweit, Pozzorini '11]

[Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11]

investigate influence of NLO decays and non-resonant contributions on

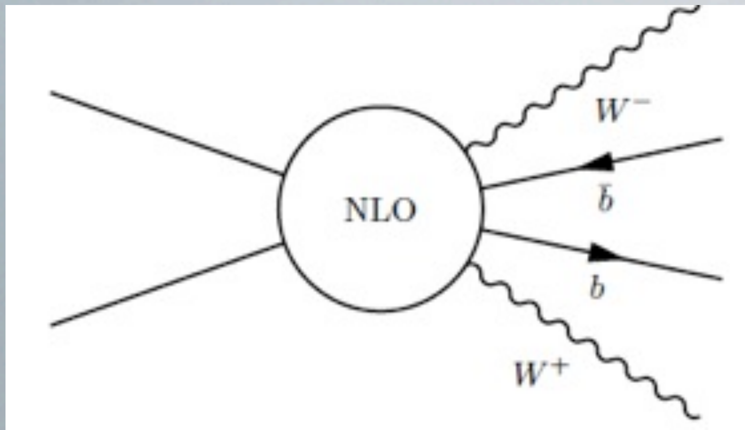
top mass determination

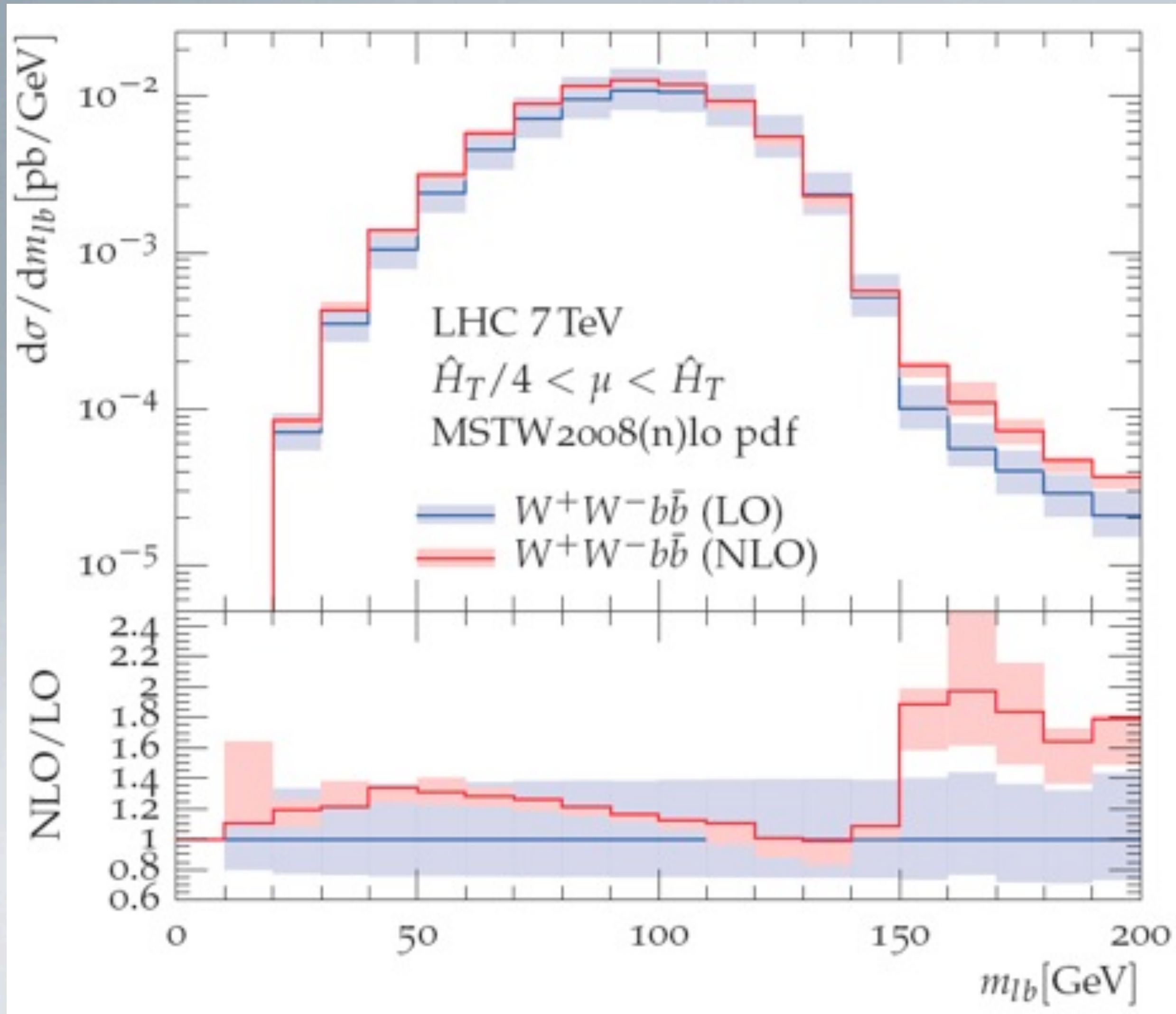


- leptonic W-decays
- use $m_{lb}^2 = (p_{\text{b-jet}} + p_l)^2$ for mass measurement, following ATLAS-CONF-2013-77
- analysis is sensitive to the shape of the distribution, independent of the rate

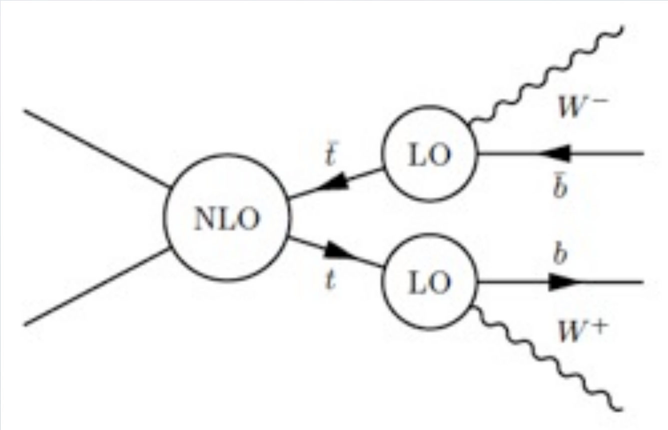
- compare full versus factorized calculation for observable m_{lb}

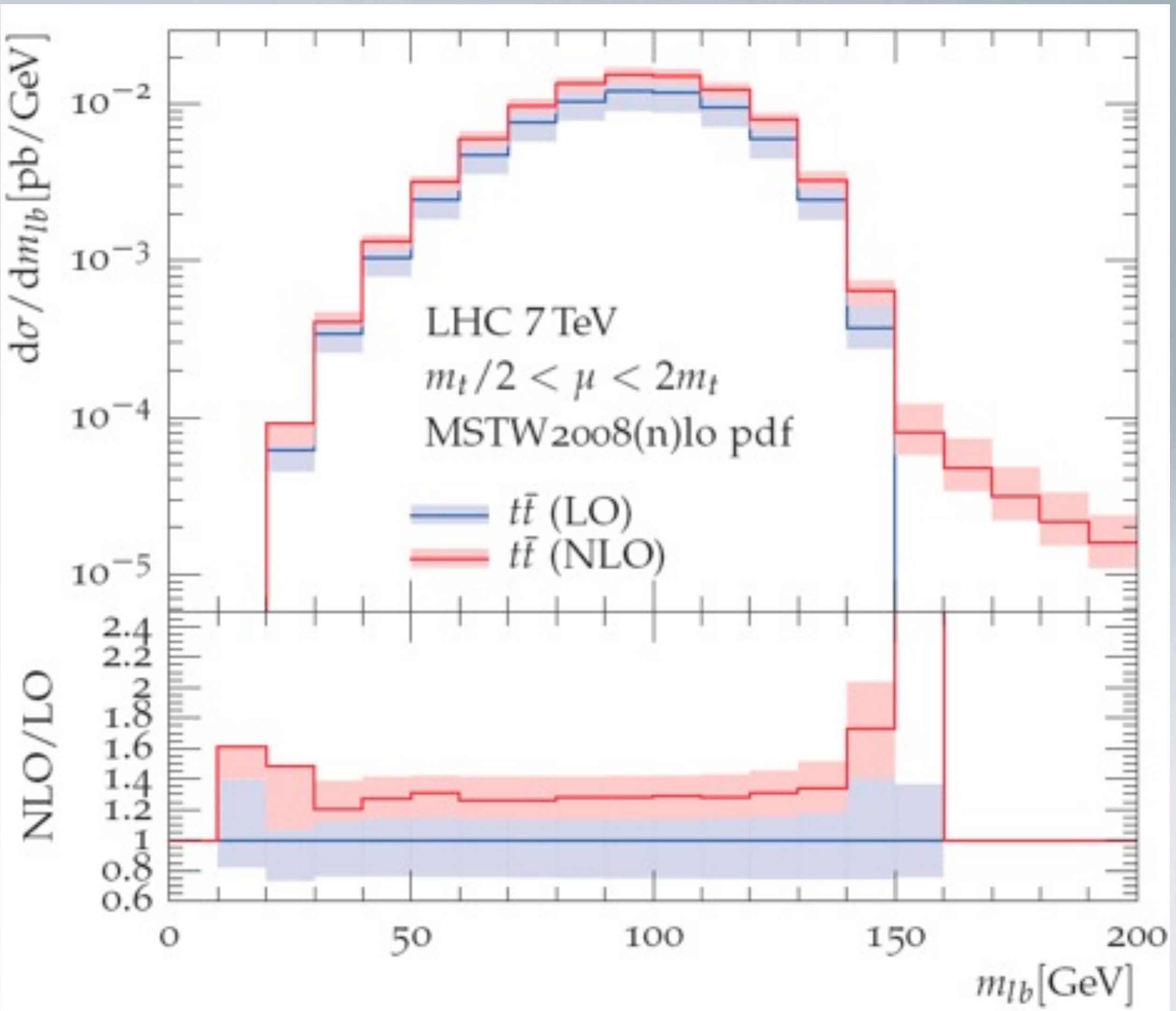
full (WWbb)





factorized ($t\bar{t}$)





shape differences in full calculation, amplified by scale variations, have important consequences on uncertainties on m_top

Installation and usage of GoSam

installation: installation script downloads GoSam and reduction libraries and installs everything

wget **http://gosam.hepforge.org/gosam-installer/gosam_installer.py**

chmod +x **gosam_installer.py**

./gosam_installer.py **[**--prefix=installation_path**]**

installation script will also install FORM [J.Vermaseren et al.] and QGraf [P. Nogueira] if not present already

usage: create template for input file process.in:

gosam.py --template process.in

edit input file process.in

to generate amplitude (standalone):

gosam.py process.in

within BLHA:

gosam.py --olp order.lh

example input file:

```
process_name=eett
process_path=eett
in=     e+, e-
out=    t, t~
model= smdiag
model.options=ewchoose
order= gs, 0, 2
zero=me
one=gs,e
regularisation_scheme=dred
```

many more options available, will take defaults if not set

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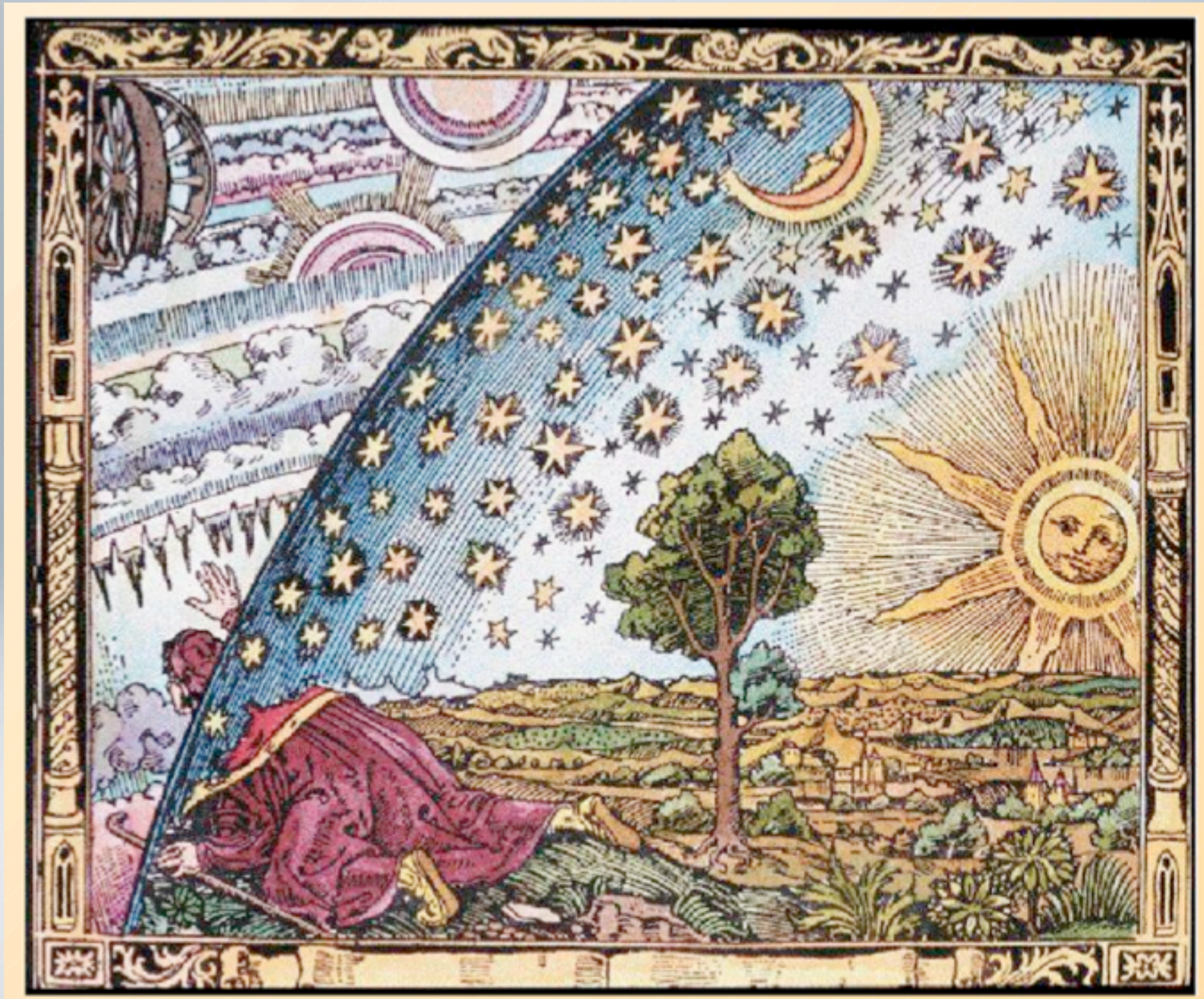
looking forward to a multitude of phenomenological applications !

Additional Slides

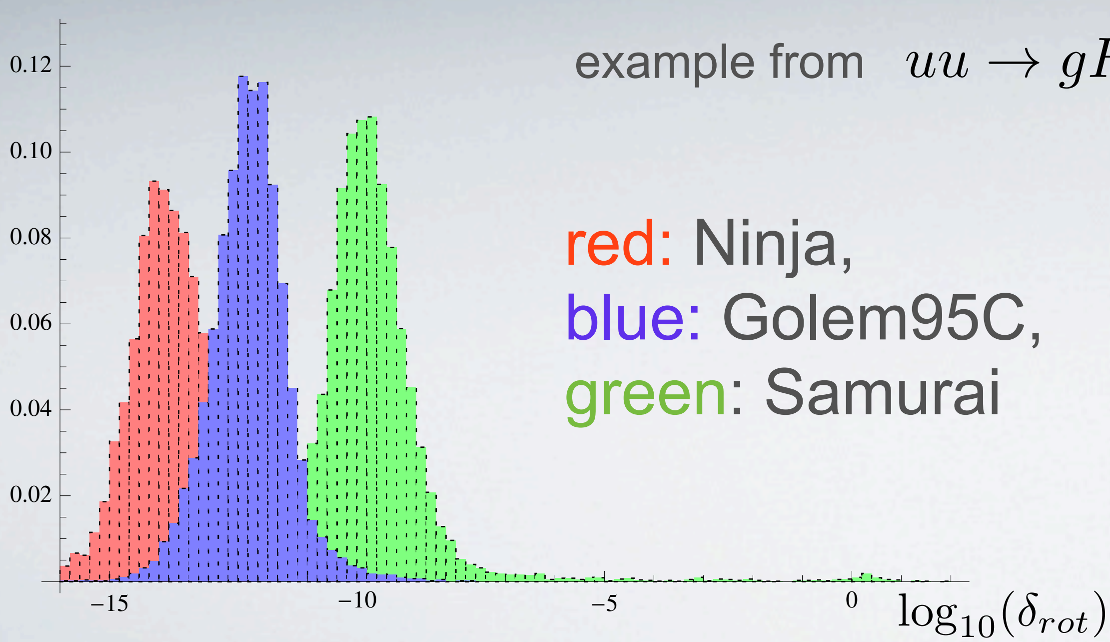


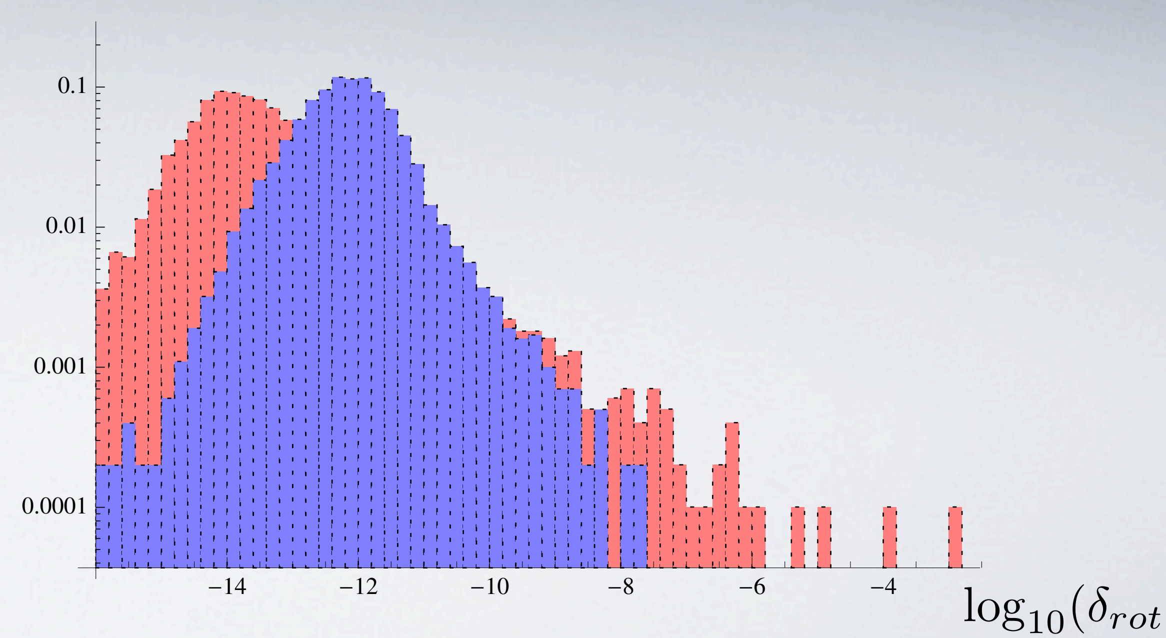
stability tests and rescue system

- pole test : $\delta_{pole} = \left| \frac{\mathcal{S}_{IR} - \mathcal{S}}{\mathcal{S}_{IR}} \right|$ $P_{pole} = -\log_{10}(\delta_{pole})$

- rotation test: $\delta_{rot} = 2 \left| \frac{A^{\text{fin}}_{rot} - A^{\text{fin}}}{A^{\text{fin}}_{rot} + A^{\text{fin}}} \right|$

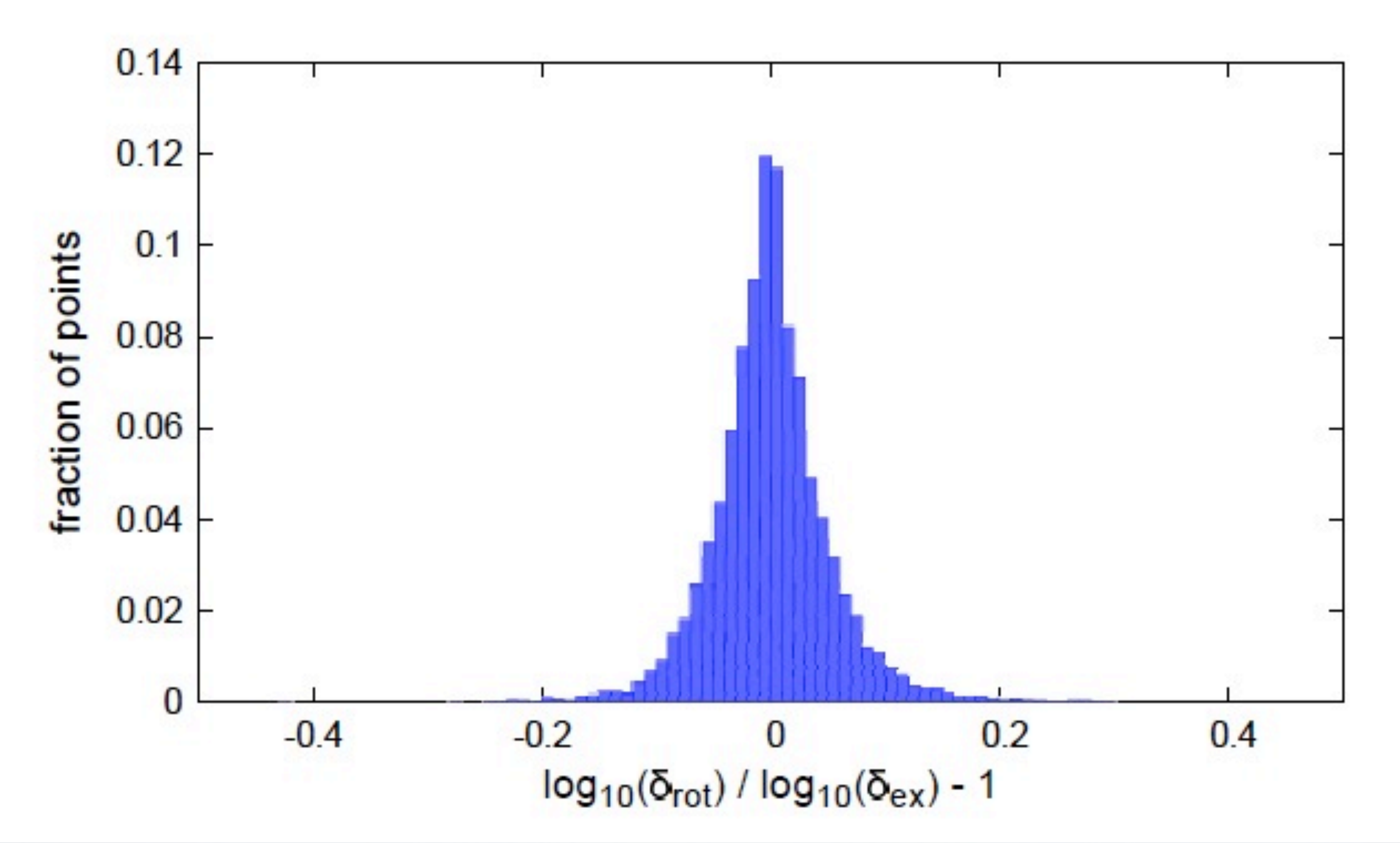
- three thresholds P_high (default 8), P_low (default 3), P_set (default 5)
    - if P_pole > P_high: accept
    - if P_pole < P_low: discard
    - if P_high > P_pole > P_low: do rotation test, discard if P_rot < P_set





- GoSam default: reduction with Ninja, rescue with golem95C

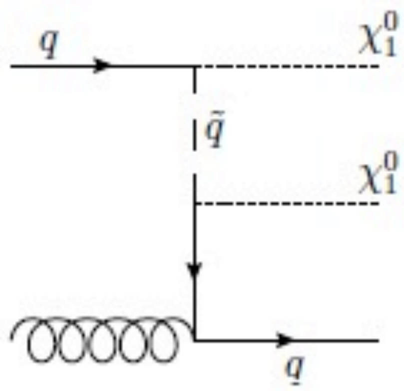
stability tests and rescue system



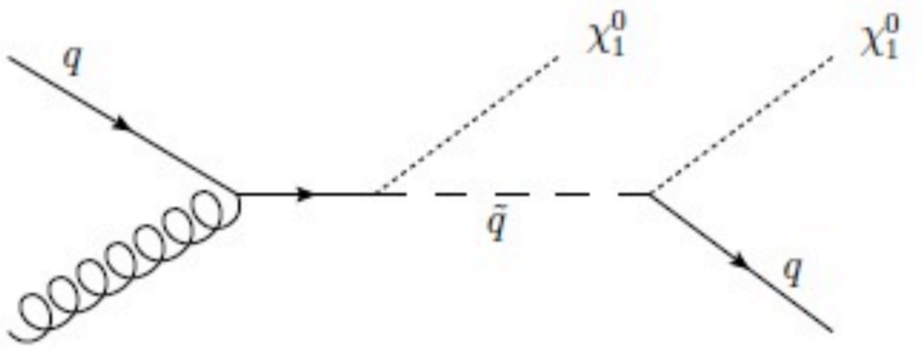
correlation plot based on 10^4 points between accuracy estimate based on “exact” and “rotated”

for $u\bar{d} \to W b\bar{b} g$ (massive b’s)

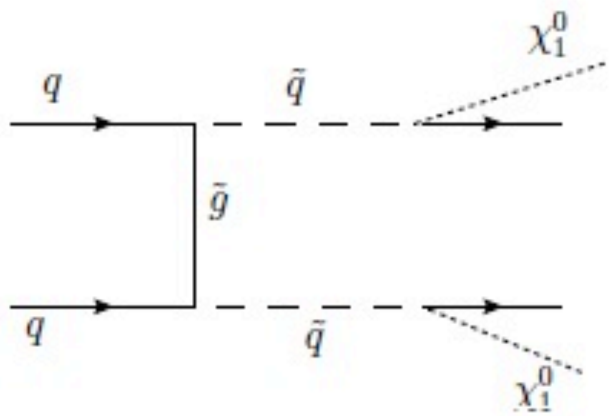
GoSam & Susy



t-channel squark exchange



s-channel squark exchange

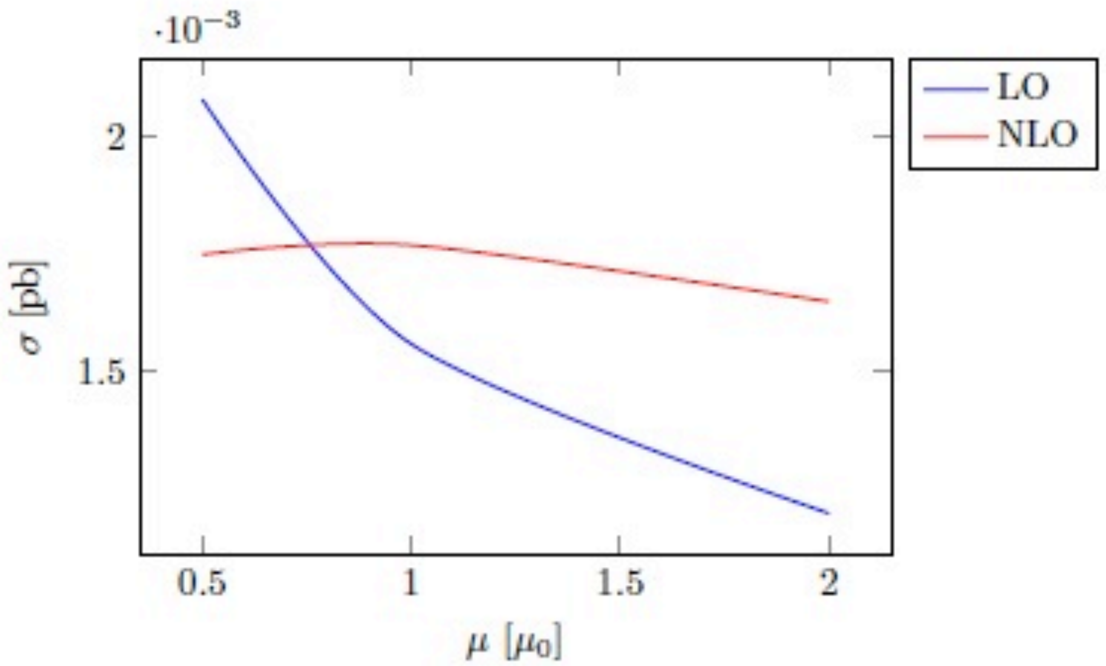


appears at NLO, can also be regarded as LO for squark pair production

$\Rightarrow$ huge contribution

$pp \to (\text{graviton} \to \gamma\gamma) + 1\,\text{jet}$

	cross section [fb]	MC error [fb]	scale uncertainty [fb]	
LO	1.561	$\pm 6.5 \times 10^{-4}$	0.522 −0.363	$\mu=\mu_0/2$ $\mu=2\mu_0$
NLO	1.767	$\pm 7.1 \times 10^{-3}$	−0.02 −0.11	$\mu=\mu_0/2$ $\mu=2\mu_0$



Cuts and parameters

$p_{T,\gamma} \geq 25$ GeV $\quad |\eta_\gamma| \leq 2.5 \quad 0.4 \leq \Delta R_{\gamma\gamma}$

$140 \text{ GeV} \leq m_{\gamma\gamma} < 3.99 \text{ TeV}$

$p_{T,\text{leading jet}} \geq 30$ GeV $\quad |\eta_{\text{jet}}| \leq 4 \quad 0.4 \leq \Delta R_{\text{jet},\gamma}$

$$\mu_0^2 = \mu_F^2 = \frac{1}{4}\left(m_{\gamma\gamma}^2 + p_{T,jet}^2\right)$$

4 (5 u. 6) extra dimensionens $\quad M_s = 4$ TeV

GoSam input card options

```
process_name=eett
process_path=eett
in=    e+, e-
out=   t, t~
model= smdiag
model.options=ewchoose
order= gs, 0, 2
zero=me
one=gs,e
regularisation_scheme=dred
helicities=
qgraf.options=onshell,notadpole,nosnail
qgraf.verbatim= True=iprop[Z, 0, 0];\n\
                true=iprop[H, 0, 0];
qgraf.verbatim.lo=
qgraf.verbatim.nlo=
polvec=numerical
diagsum=True
reduction_programs=ninja,golem95,samurai
extensions=shared
debug=nlo
select.lo=
select.nlo=
filter.lo=
filter.nlo=
filter.module=
renorm_beta=True
renorm_mqwf=True
renorm_decoupling=True
renorm_mqse=True
renorm_logs=True
renorm_gamma5=True
reduction_interoperation=-1
reduction_interoperation_rescue=-1
samurai_scalar=2
nlo_prefactors=0
PSP_check=True
PSP_rescue=True
PSP_verbosity=False
PSP_chk_th1=8
PSP_chk_th2=3
PSP_chk_th3=5
PSP_chk_kfactor=10000
reference-vectors=
abbrev.limit=0
templates=
qgraf.bin=qgraf
form.bin=form
form.threads=2
form.tempdir=/tmp
haggies.bin=
fc.bin=/usr/bin/gfortran
python.bin=python
ninja.fcflags=
ninja.ldflags=
samurai.fcflags=
samurai.ldflags=
golem95.fcflags=
golem95.ldflags=
r2=explicit
symmetries=family,generation
crossings=
```