Automated one-loop calculations with GoSam

Gudrun Heinrich

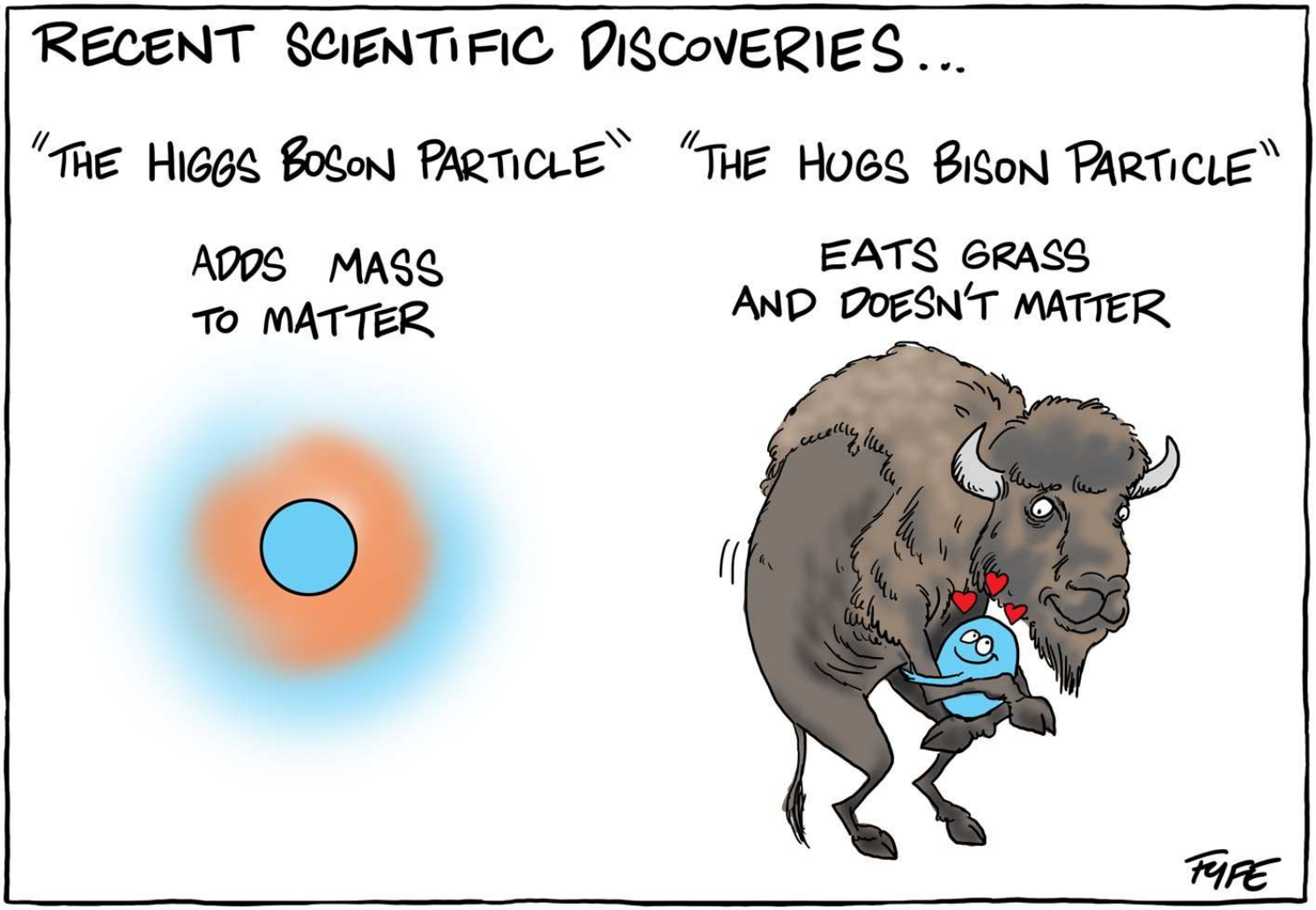
in collaboration with

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

Zurich Phenomenology Workshop, January 8, 2013

MAX-PLANCK-GESELLSCHAFT

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


RECENT SCIENTIFIC DISCOVERIES...
"THE HIGGS BOSON PARTICLE"
ADDS MASS TO MATTER
"THE HUGS BISON PARTICLE"
EATS GRASS AND DOESN'T MATTER
FOYFE

The post-discovery era

- nature was kind, but not too generous:
  we found a (?) resonance

The post-discovery era

- nature was kind, but not too generous:
  we found a (?) resonance
- is it really the Standard Model Higgs boson?

Wikipedia	Higgs-Boson (H)
	Klassifikation
Elementarteilchen Boson	
Eigenschaften	
Ladung	neutral
Masse	ca. $2{,}25 \cdot 10^{-25}$ kg ca. 125–127 GeV/c^2
Spin	0
mittlere Lebensdauer	ca. 10^{-22} s

The post-discovery era

- nature was kind, but not too generous:
  we found a (?) resonance
- is it really the Standard Model Higgs boson?
- How can we make the best out of the 2010-2012 data?

Higgs boson Wiki in local dialect

Higgs-Boson

S **Higgs-Boson** oder **Higgs-Däili**, wo noch em britische Füsiker Peter Higgs benennt isch, isch s äinzige Elimentaardäili im Standardmodäll vo dr Elimentaardäilifüsik, wo bis jetzt experimentell nonig het chönne noochgwiise wärde. Theoretisch wird d Existänz vom Higgs-Boson vom Higgs-Mechanismus, eme Däil vom Standardmodäll, vorusgsäit, wo d Erkläärig für d Masse vo de Äichbosone liiferet, de Z- und W-Bosone, wo experimentell noochgwiise si. Wil mindestens äi Sorte vo Higgs-Bosone muess existiere, für dass dr Higgs-Mechanismus funkzioniert, gältet dr Noochwiis vom ene Higgs-Boson as e wichdige Bewiis drfür, ass s Standardmodäll richdig isch.

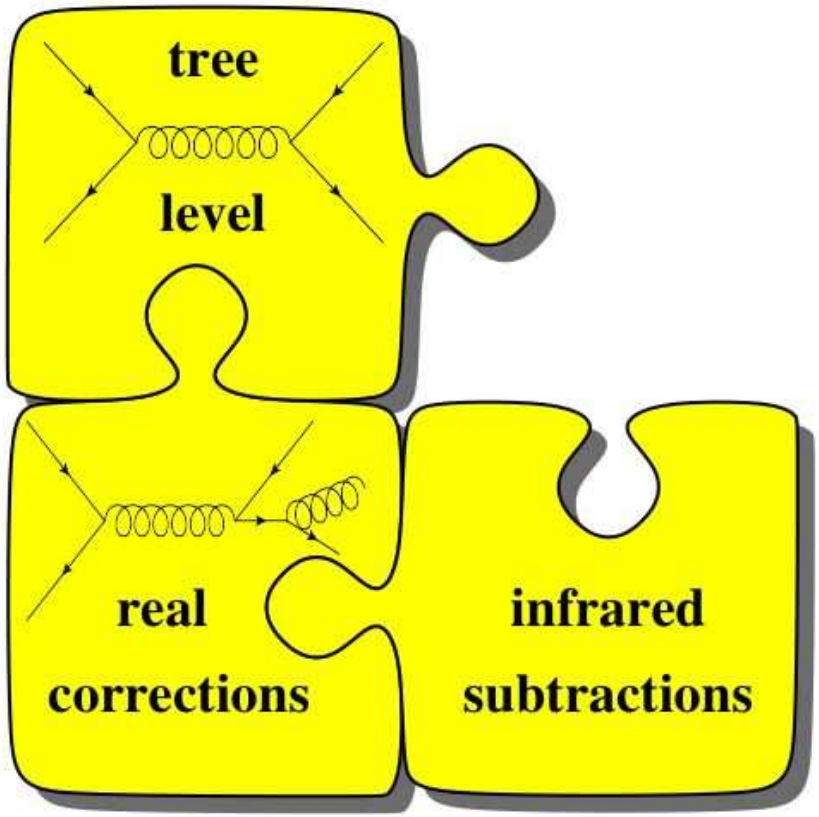
Aktuell macht mä Experimänt, ATLAS und CMS, am Large Hadron Collider (LHC) vom CERN-Institut z Gämf, zum s Higgs-Boson noochzwiise.

Precise predictions

to interpret "anomalies" in the data correctly, we need to understand the effects of

- higher order QCD corrections
  (N(N)LO, resummation, parton shower, matching, ...)
- electroweak effects at high energies
- quark mass effects
- PDF uncertainties
- phase space restrictions
- non-perturbative effects
- ...

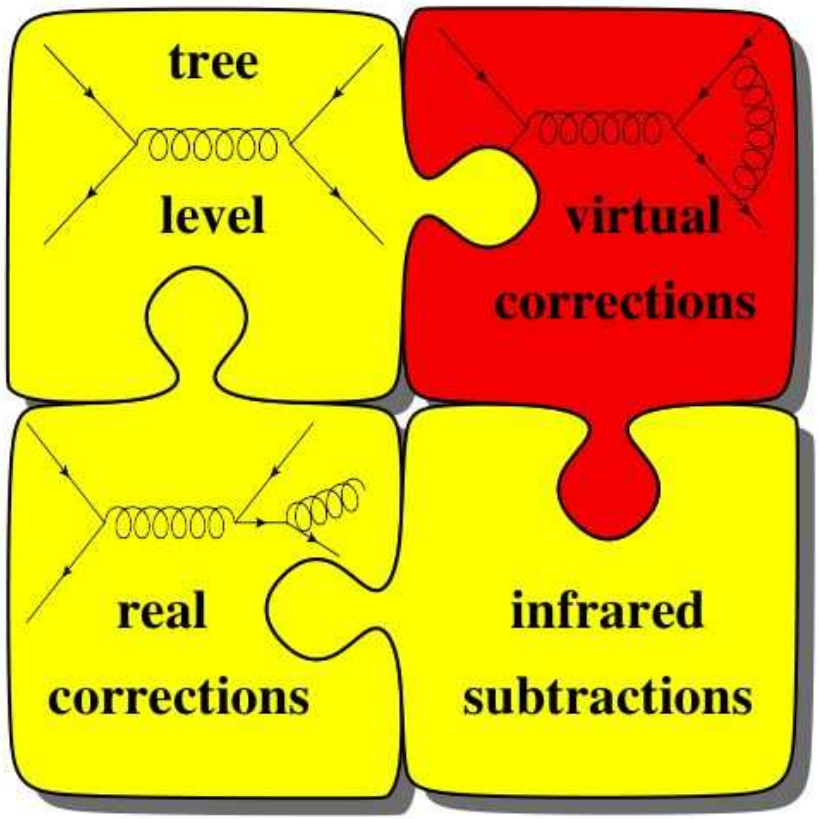
Ingredients of an NLO Calculation



NLO amplitude requires

- tree level amplitude,
- real emission,
- infrared subtraction terms

Ingredients of an NLO Calculation



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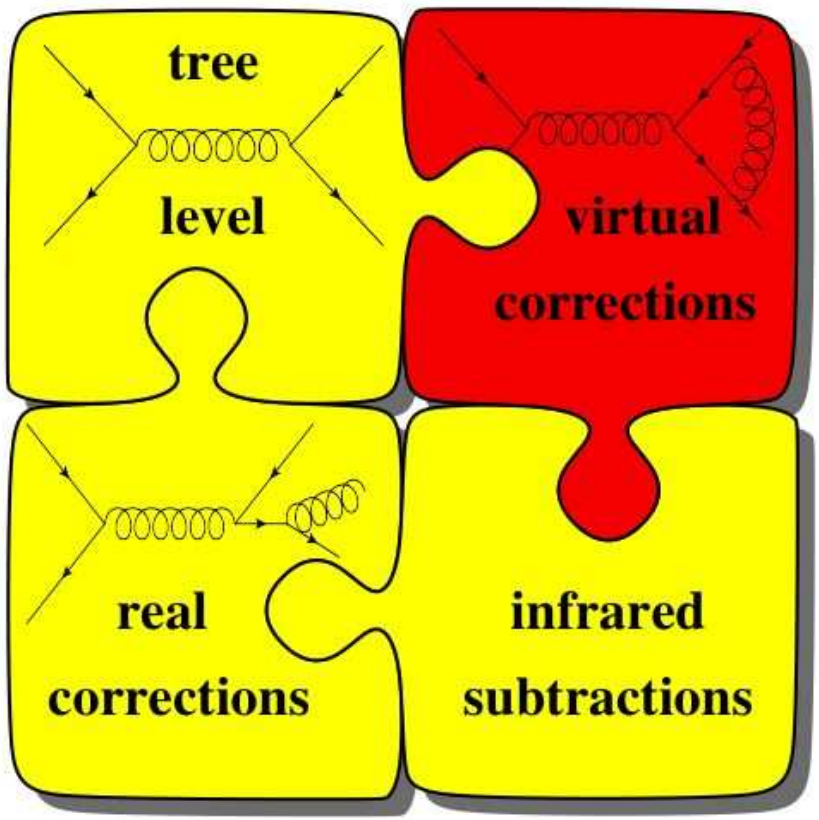


NLO amplitude requires

- tree level amplitude,
- real emission,
- infrared subtraction terms
- virtual corrections

GoSam collaboration focuses on virtual corrections. Matching to other parts via BLHA interface

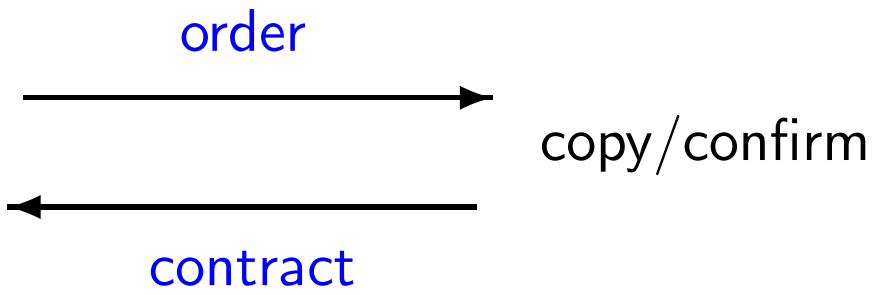
Binoth Les Houches Accord (BLHA) interface

(worked out at Les Houches 2009 workshop on TeV colliders)

Monte Carlo program (MC) | One-Loop-Provider (OLP)

initialisation:

process info
model parameters
fix scheme
...



runtime:

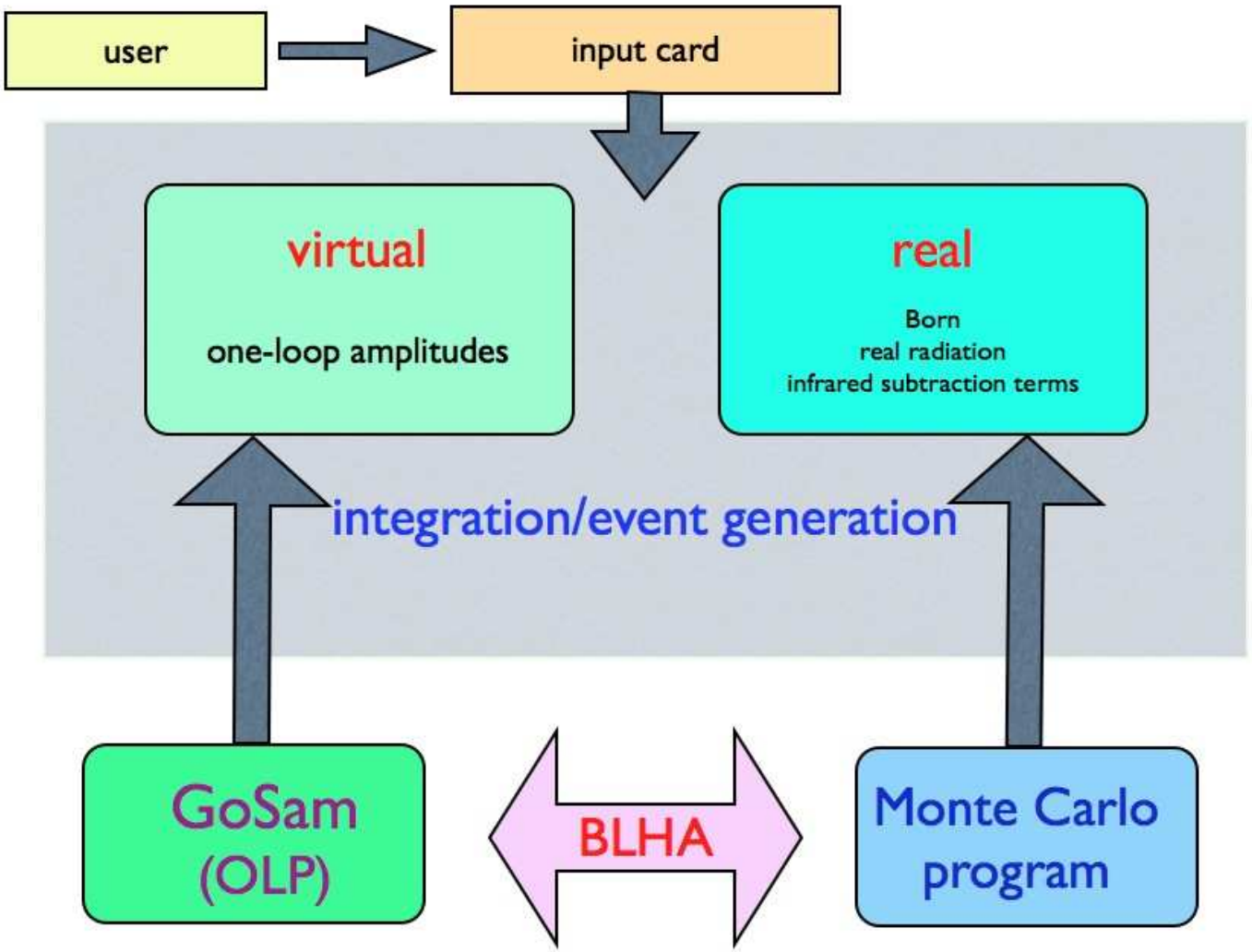
events

$A_2, A_1, A_0, |Born|^2$

standard interface

(extension in preparation)

GoSam: NLO calculations made easy



Golem-Samurai (GoSam)

General One-Loop Evaluator of Matrix elements &

Scattering Amplitudes from Unitarity based Reduction At Integrand level

G. Cullen, N. Greiner, G.H., G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Reiter, F. Tramontano,

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

arXiv: 1111.2034 [hep-ph] (EPJC 72, 2012)

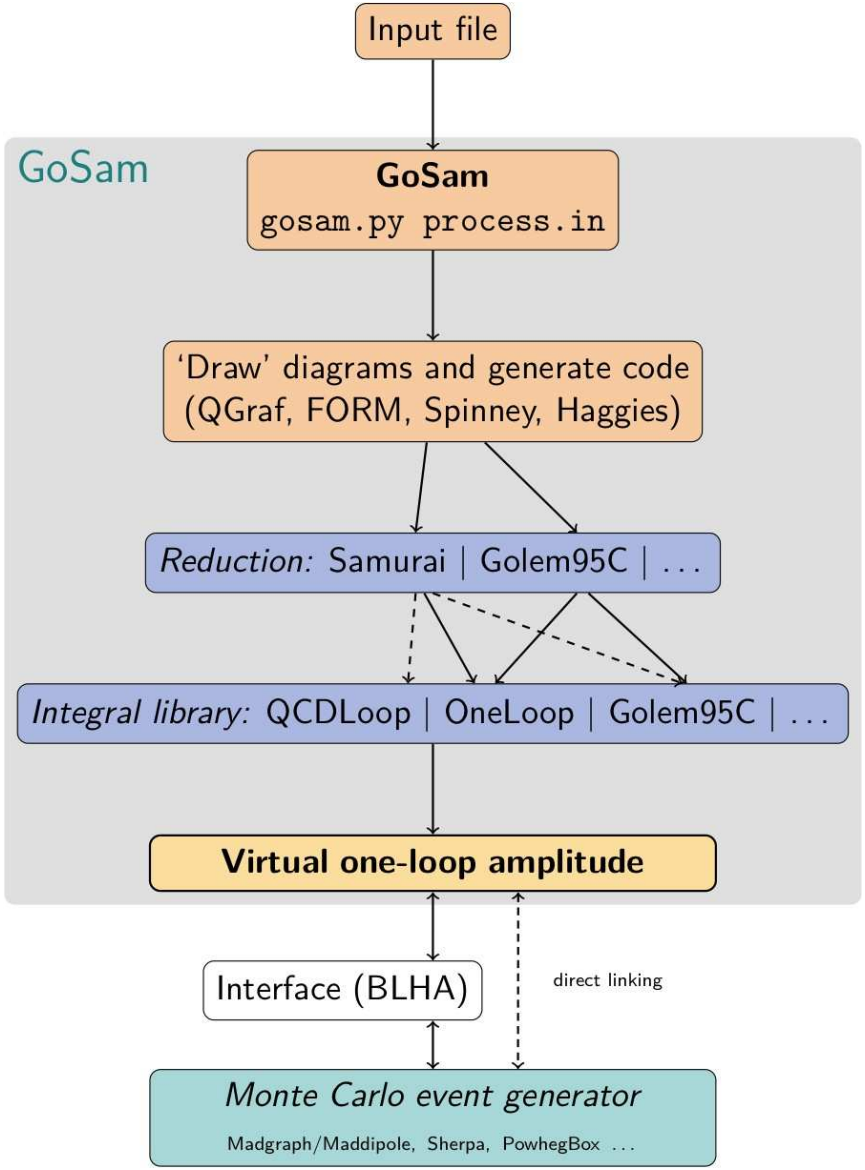
http://gosam.hepforge.org

Golem-Samurai (GoSam)

GoSam method

- algebraic generation of D-dimensional integrands based on Feynman diagrams
- reduction by
  - D-dimensional extension of OPP method (Samurai), or, alternatively
  - tensor reduction with golem95 tensor integral library
- can do QCD, EW, BSM
- interface with existing tools for real radiation, e.g. Sherpa, MadGraph/MadEvent, Powheg, ...

GoSam flowchart



List of other (more or less) automated NLO Tools

generate one-loop amplitude "on the fly": (red means "public")

- FeynArts/FormCalc/LoopTools Thomas Hahn et al
- GRACE Fujimoto et al.
- BlackHat Bern, Dixon, FebresCordero, Hoeche, Ita, Kosower, Maitre, Ozeren
- Helac-NLO Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek
- MadLoop/ aMC@NLO Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau
  uses CutTools [Ossola, Papadopoulos, Pittau] and MadFKS
- GoSam Cullen, Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano, uses
  Samurai [Mastrolia, Ossola, Reiter, Tramontano], golem95 [Binoth et al]
- NJET Badger, Biedermann, Uwer, Yundin
- OpenLoops Pozzorini, Maierhöfer, Cascioli
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hard coded (library of) processes (also involve high level of automation)

- POWHEG-Box Alioli, Nason, Oleari, Re et al
- MCFM/Rocket Campbell, Ellis, Williams, Melnikov, Zanderighi et al
- VBFNLO Zeppenfeld et al , ...

GoSam validation

some examples of amplitudes produced by GoSam

process	process
$e^+e^- \to u\bar{u}$	$pp \to W^\pm jj$
$e^+e^- \to t\bar{t}$	$pp \to W^\pm b\bar{b}$ (massive b's)
$u\bar{u} \to d\bar{d}$	$e^+e^- \to e^+e^-\gamma$ (QED)
$gg \to gg$	$pp \to t\bar{t}H$
$gg \to gZ$	$pp \to t\bar{t}Z$
$pp \to t\bar{t}$	$\gamma\gamma \to \gamma\gamma\gamma\gamma$ (fermion loop)
$bg \to H\,b$	$pp \to W^+W^+jj$
$\gamma\gamma \to \gamma\gamma$ (f and W loop)	$pp \to b\bar{b}b\bar{b}$
$pp \to W^\pm j$ (QCD corr.)	$pp \to W^+W^-b\bar{b}$
$pp \to W^\pm j$ (EW corr.)	$pp \to t\bar{t}b\bar{b}$
$pp \to Z/\gamma^* j$	$pp \to W^+W^- + 2\,\text{jets}$
$pp \to W^\pm t$	$pp \to W^- + 3\,\text{jets}$

Interfacing GoSam

- GoSam + MadGraph4
  - $pp \to b\bar{b}b\bar{b}$

    [Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '10, '11]
  - NLO QCD corrections to $pp \to W^+W^-$+2 jets

    including massive top loops

    [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
  - SUSY QCD corrections to $\tilde{\chi}_1^0\tilde{\chi}_1^0$+jet production

    [Cullen, Greiner, Heinrich '12]
- GoSam + Powheg [Luisoni, Nason, Oleari, Tramontano]
  working interface (BLHA standards), coming soon
- GoSam + Sherpa
  automated interface with Sherpa option –enable-lhole
  - $pp \to H$+2 jets [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]
  - $pp \to W$+3 jets [unpublished]
  - ready-made process packages publicly available at http://gosam.hepforge.org/proc/

Precooked code ready to use

ready-made code for virtual amplitudes + Sherpa run cards, scripts for interface and plotting available at

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

$$
\begin{aligned}
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) \\
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) + jet \\
pp/p\bar{p} &\to Z/\gamma^*(\to e^+e^-) \\
pp/p\bar{p} &\to Z/\gamma^*(\to e^+e^-) + jet \\
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) + 2\,jets \\
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) + b\bar{b} \\
pp/p\bar{p} &\to W^{+}(\to \mu^+\nu_\mu) + W^{-}(\to e^-\bar{\nu}_e) \\
pp/p\bar{p} &\to W^{+}(\to \mu^+\nu_\mu) + W^{+}(\to e^+\nu_e) + 2\,jets
\end{aligned}
$$

process packages

more process packages in preparation

e.g. $t\bar{t}$, $t\bar{t}$ jet, H+jets, W^-+3 jets, ...

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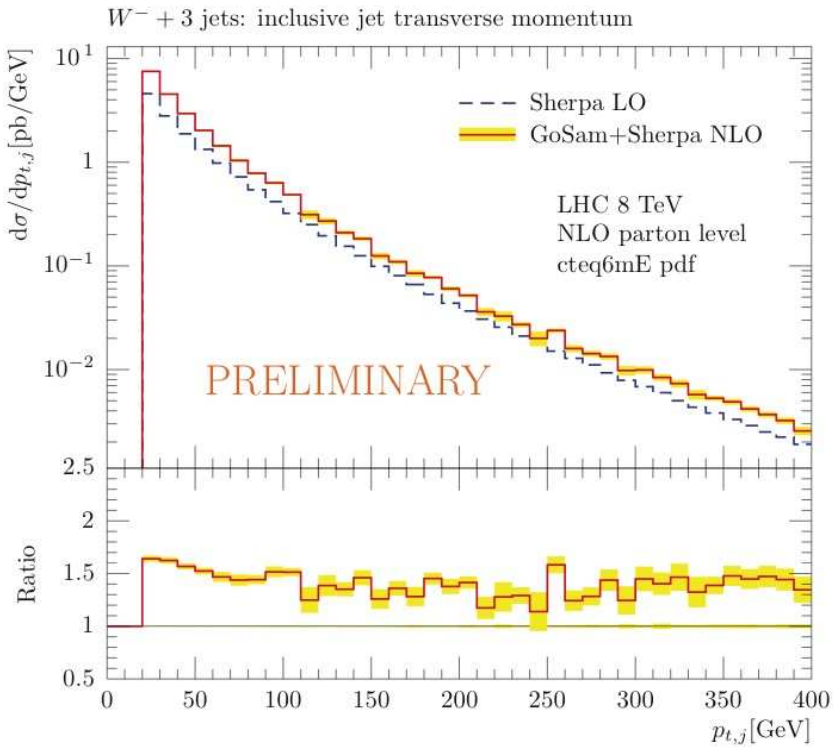
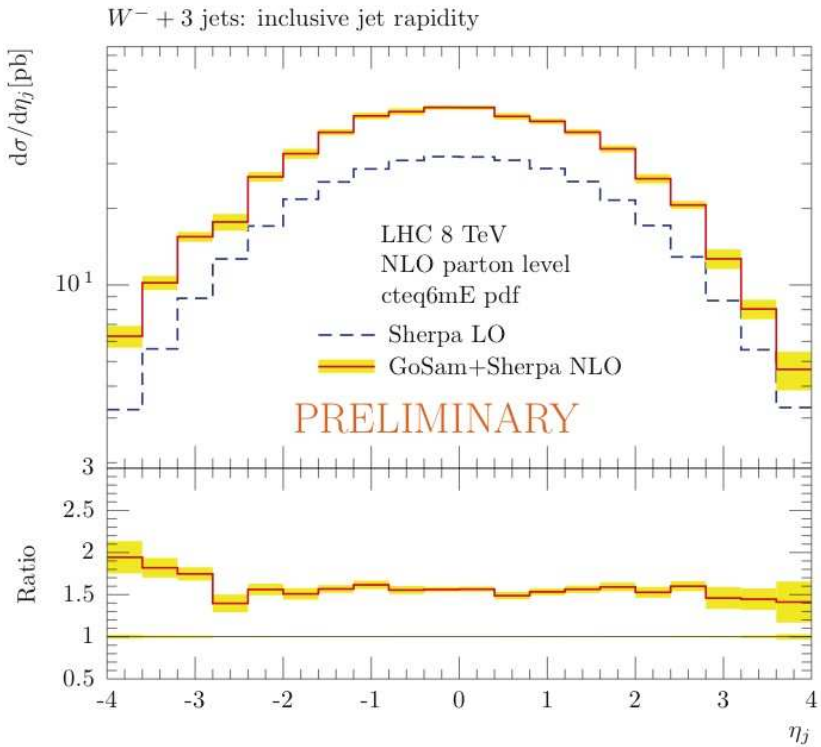




G. Luisoni, F. Tramontano

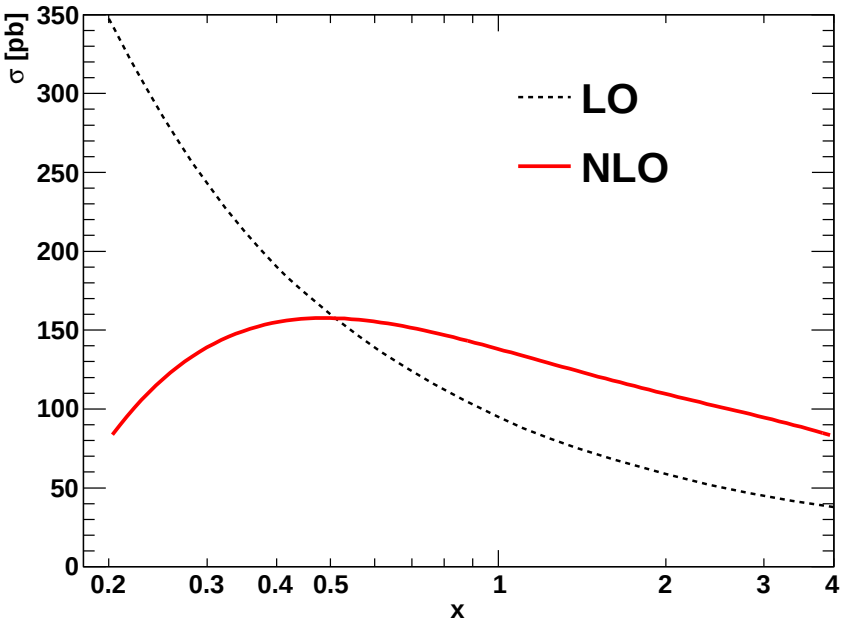
GoSam results: $pp \to b\bar{b}b\bar{b}$

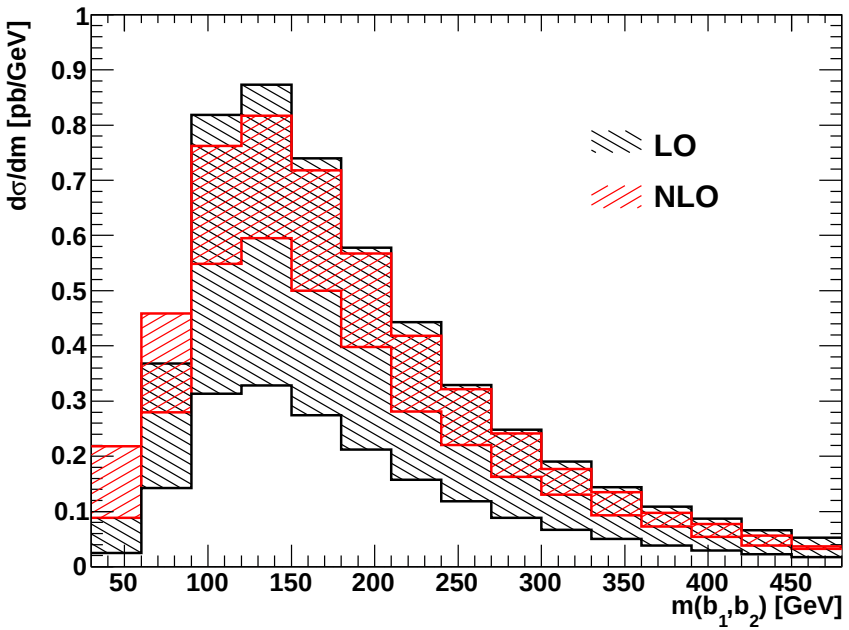
GoSam + MadGraph4 (+Whizard)

[Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '10, '11]

$\sqrt{s} = 14\,\mathrm{TeV}$, $p_T(b_j) > 30\,\mathrm{GeV}$, $\Delta R(b_i, b_j) > 0.8$

$\mu_0 = \frac{1}{4}\sqrt{\sum_i p_{T,i}^2}$, $\mu = \mu_r = \mu_F = x \cdot \mu_0$





GoSam results: W^+W^-+2 jets

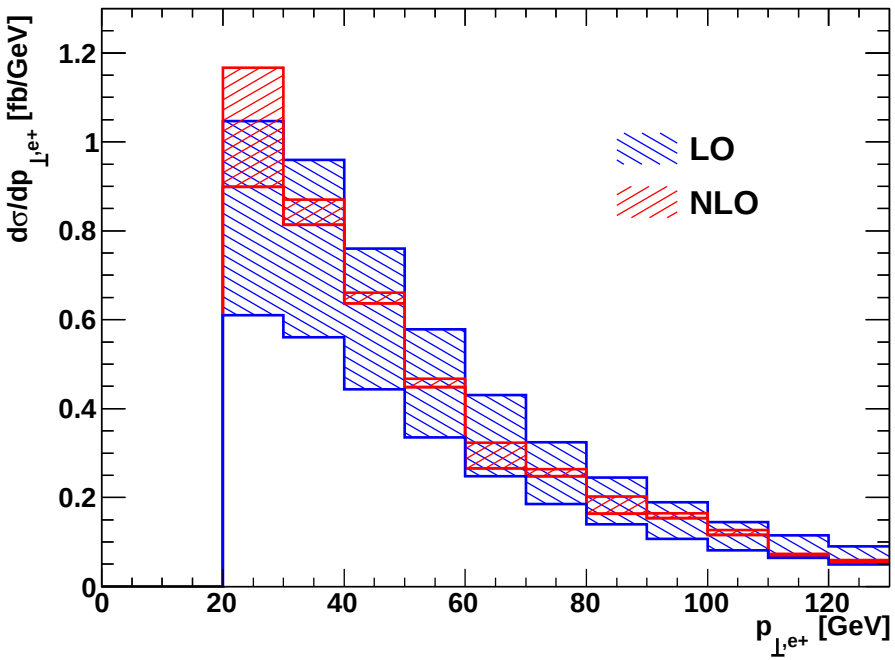
GoSam + MadGraph4

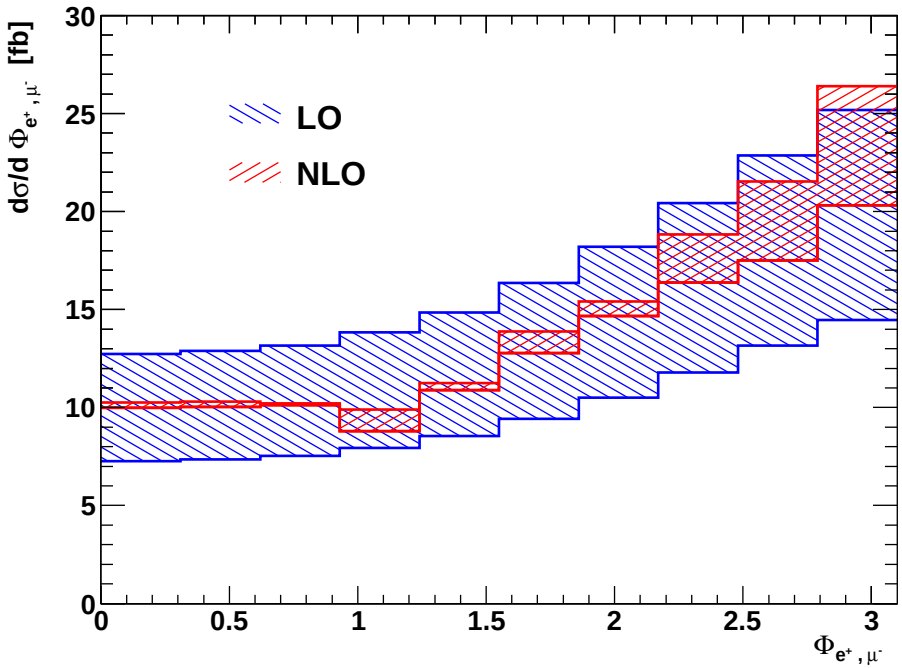
[Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12, massive top loops included]

[see also Melia, Melnikov, Rontsch, Zanderighi '11]

$\sqrt{s} = 7$ TeV, $M_W \leq \mu \leq 4M_W$, $E_{T,miss} \geq 30$ GeV

$p_{T,j} \geq 20$ GeV , $|\eta_j| \leq 3.2$, $\Delta R_{jj} \geq 0.4$, $p_{T,l} \geq 20$ GeV , $|\eta_j| \leq 2.4$



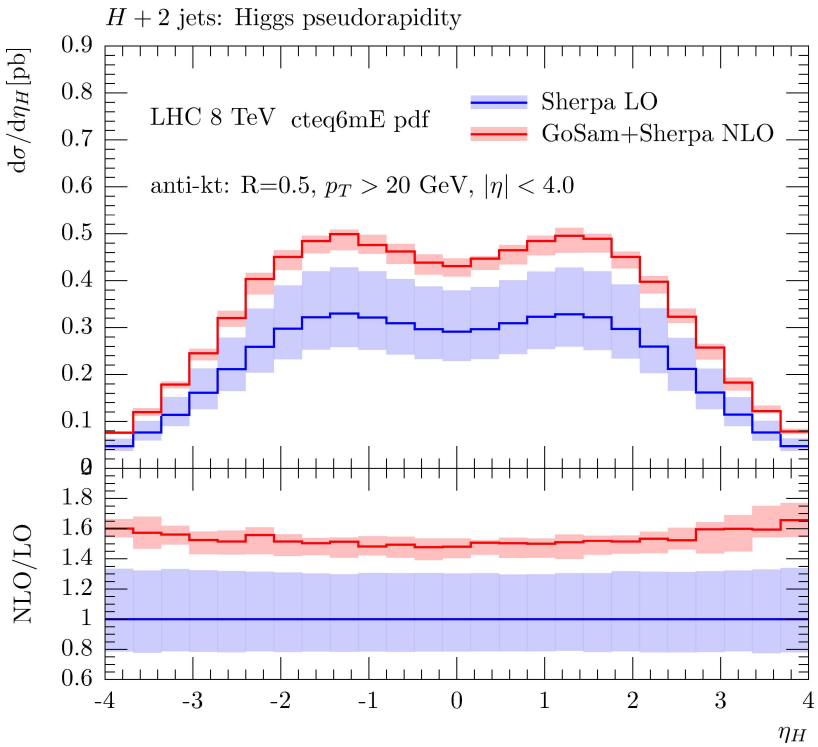


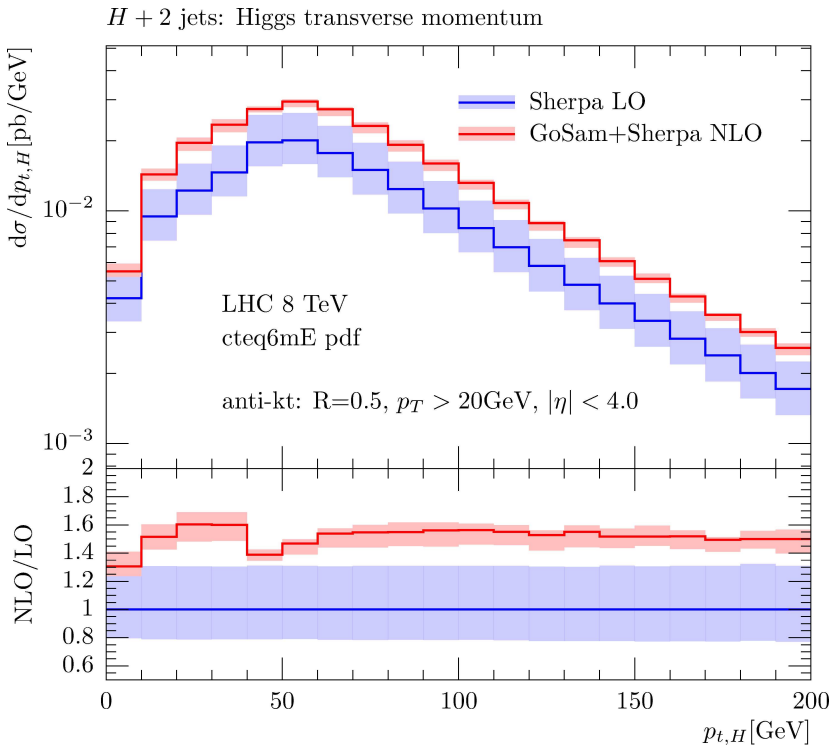
GoSam & effective vertices: H+2 jets

$$\mathcal{L} = -\frac{g_{\text{eff}}}{4} H \,\text{tr}\left(G_{\mu\nu} G^{\mu\nu}\right) \quad (m_t \to \infty \text{ limit})$$

GoSam + Sherpa

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



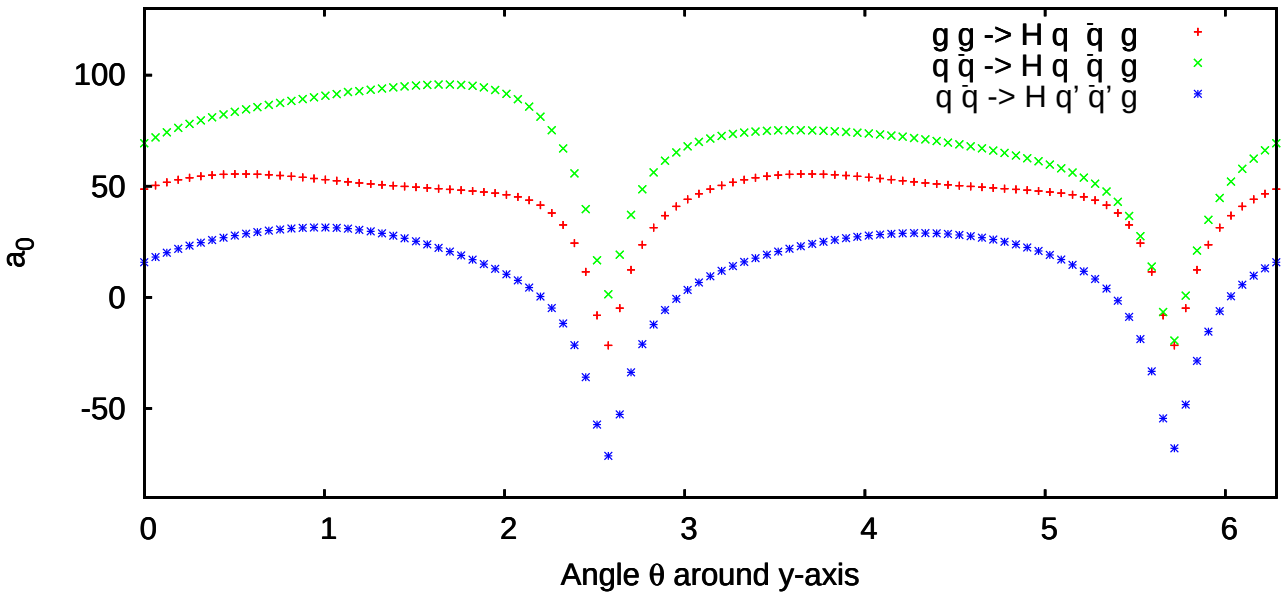


Towards pp → H+3 jets

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

finite parts of virtual matrix elements for

$gg \to Hq\bar{q}g$, $q\bar{q} \to Hq\bar{q}g$, $q\bar{q} \to Hq'\bar{q}'g$



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

final state momenta rotated from $\theta = 0$ to $\theta = 2\pi$

GoSam goes BSM

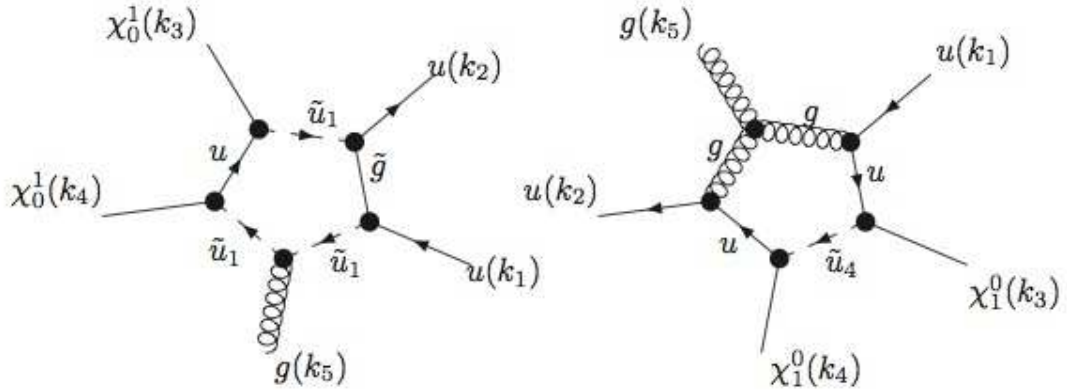
- import model file from FeynRules [Christensen, Duhr, Fuks et al.] in UFO (Universal FeynRules Output) format or LANHEP [Semenov et al] format (input in SLHA format also supported)
- make sure renormalization is done correctly
- apart from renormalization: fully automated, in particular no need for additional Feynman rules for rational part
- support for effective vertices/high tensor ranks/spin-two particles

GoSam & Susy

GoSam + MadGraph4

SUSY QCD corrections to $\tilde{\chi}_1^0\,\tilde{\chi}_1^0 + \text{jet}$ (p19MSSM)
[Cullen, Greiner, Heinrich '12]

signature: monojet plus missing E_T



example pentagon diagrams

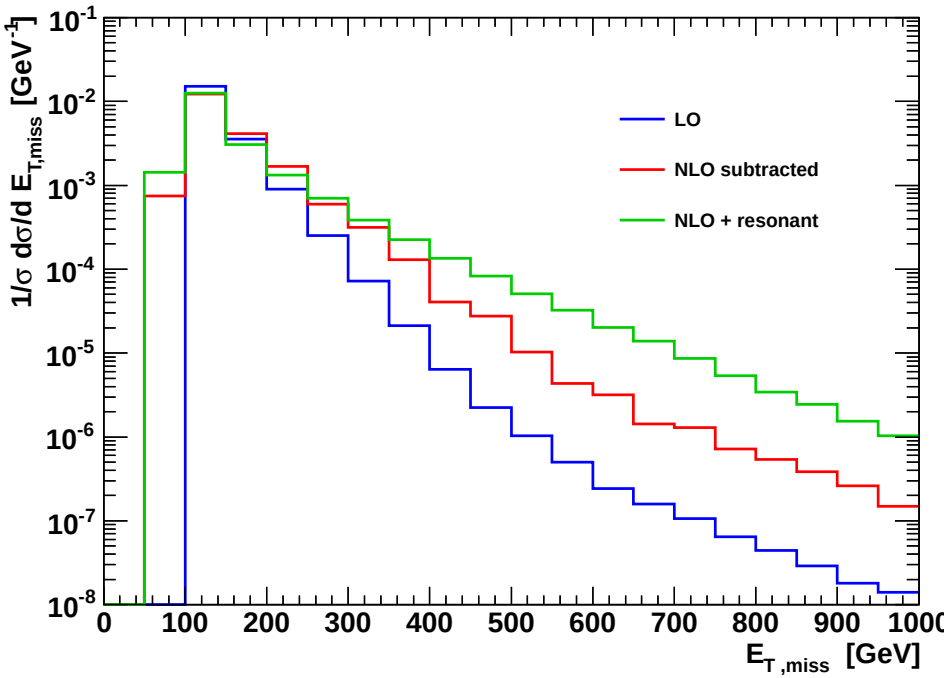
GoSam & Susy

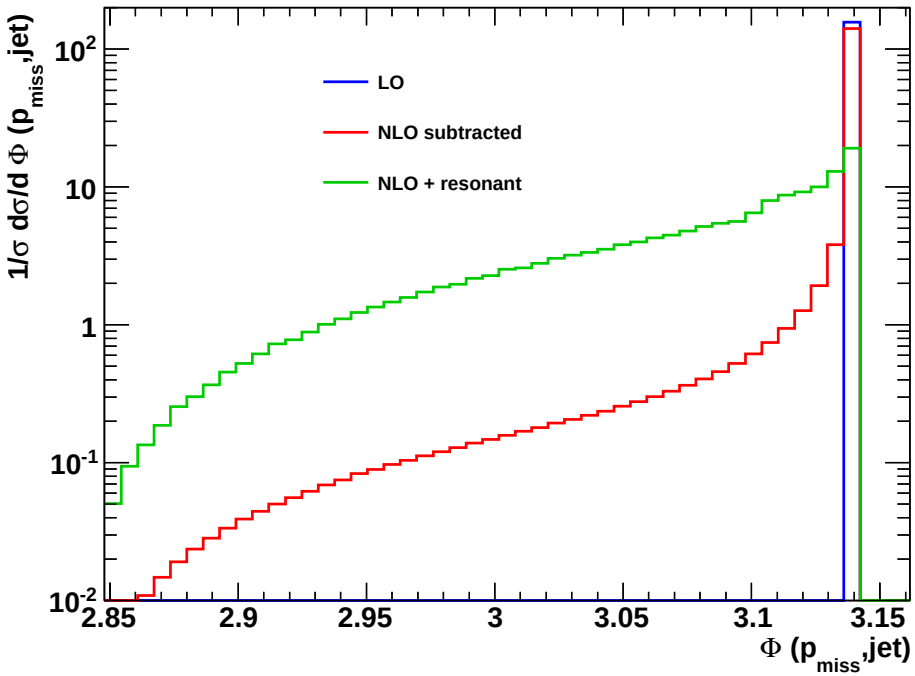
$\sqrt{s} = 8$ TeV, NNPDF2.3 set

$H_T/4 \leq \mu \leq 2\,H_T$, $H_T = \sum_i E_{T\,i}$, $E_{T\,miss} \geq 85$ GeV

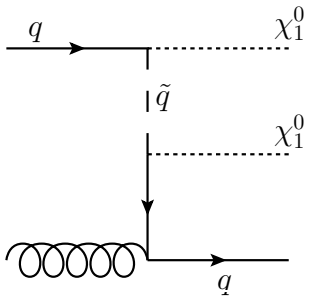
$p_T(\text{leading jet}) \geq 100$ GeV, $p_T(\text{2nd jet}) \leq 30$ GeV, $|\eta_j| \leq 4.5$

full off-shell effects included

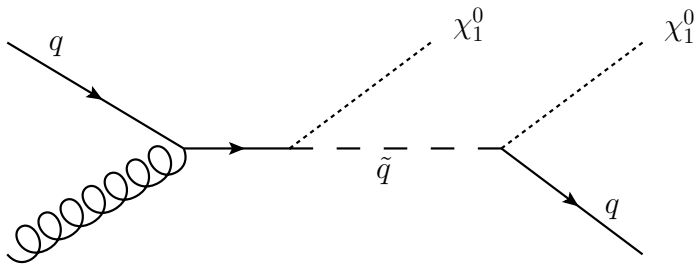




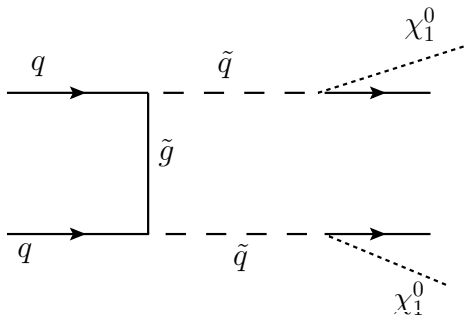
GoSam & Susy



t-channel squark exchange



s-channel squark exchange



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

$\Rightarrow$ huge contribution

GoSam & extra dimensions

NLO QCD corrections to diphoton + jet production through graviton exchange within the ADD model [Arkani-Hamed, Dimopoulos, Dvali]

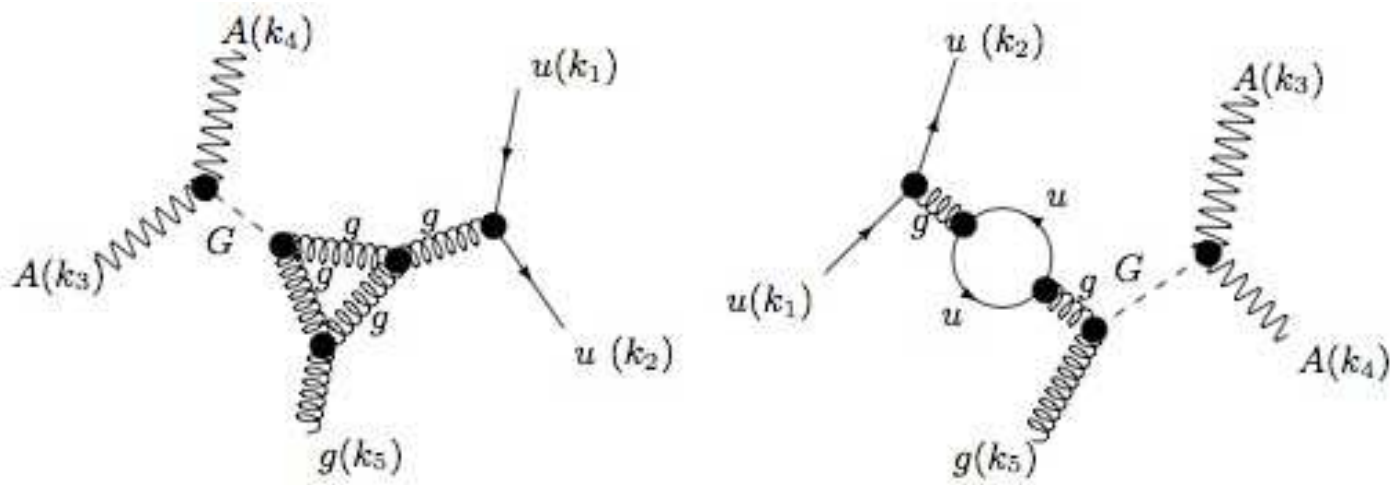
$Dim = 4 + \delta\,,\ M^2_{\rm Planck} = 8\pi R^\delta\, M_S^{\delta+2}$

for large compactification radius R: $M_S \sim$ TeV

summation over Kaluza-Klein modes replaced by integral over a mass density

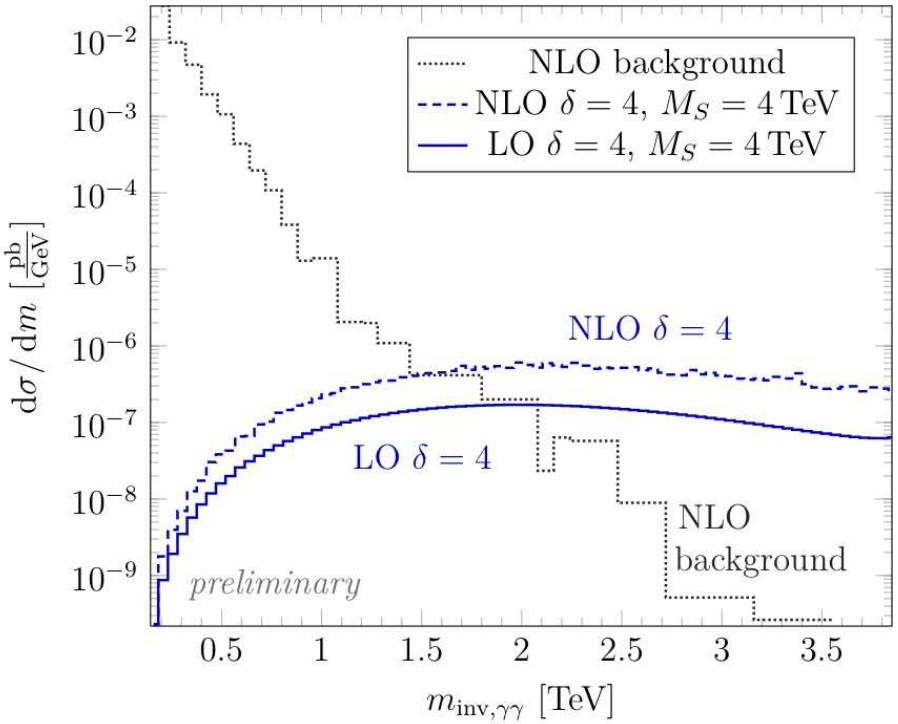
GoSam+ MadGraph4

[Greiner, Heinrich, Reichel, von Soden-Fraunhofen, to appear]



example diagrams

GoSam & extra dimensions



J.F. von Soden-Fraunhofen

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

CT10 pdf set

cuts:

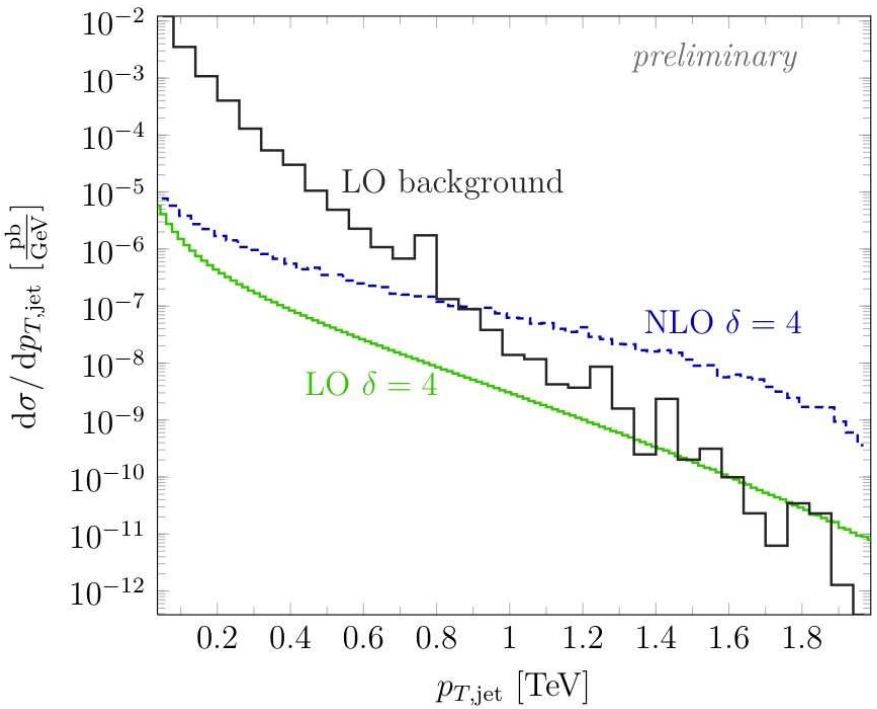
$140\,\text{GeV} \leq m_{\gamma\gamma} < M_S = 4\,\text{TeV}$

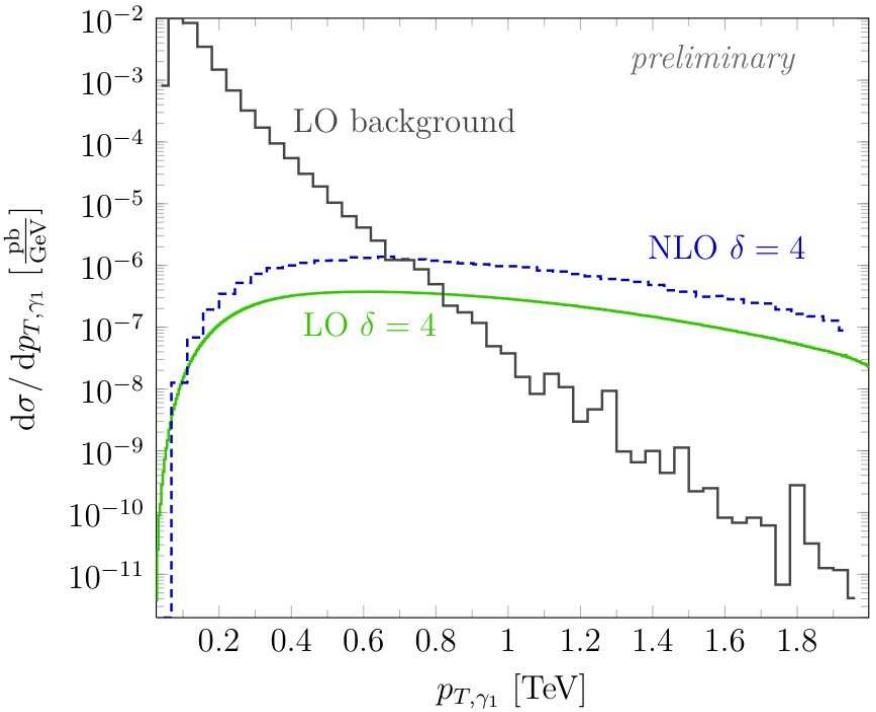
$p_T^{\gamma} > 25\,\text{GeV},\ p_T^{jet} > 30\,\text{GeV}$

$\Delta R_{\gamma\gamma} \geq 0.4, \Delta R_{\gamma\,\text{jet}} \geq 0.4$

GoSam & extra dimensions

$pp \to \text{graviton} + jet \to \gamma\gamma + jet$





J.F. von Soden-Fraunhofen

Summary and Outlook

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- not limited to Standard Model
- standard interface to real radiation programs (BLHA)
- has been used to calculate various NLO QCD $2 \to 4$ processes, also $2 \to 3$ BSM processes

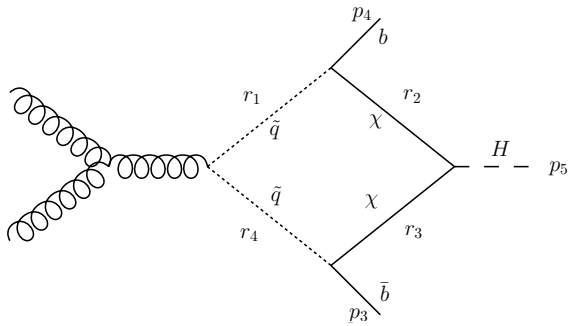
Summary and Outlook

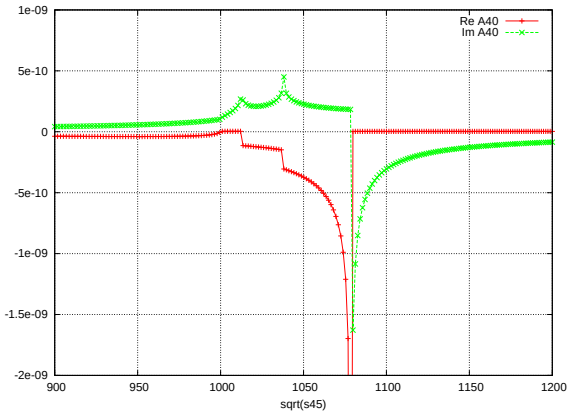
- automation is necessary to have NLO predictions as a standard at LHC
- Golem/Samurai (GoSam) is a powerful and flexible automated tool for one-loop multi-leg amplitudes
- not limited to Standard Model
- standard interface to real radiation programs (BLHA)
- has been used to calculate various NLO QCD $2 \to 4$ processes, also $2 \to 3$ BSM processes
- GoSam is publicly available at http://projects.hepforge.org/gosam/

additional slides

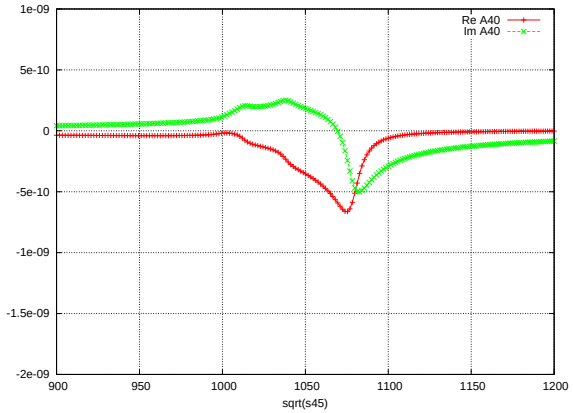
golem95C integral library

Example: production of a heavy neutral MSSM Higgs and a $b\bar{b}$ pair with unstable particles (squarks, neutralinos) in the loop





real masses



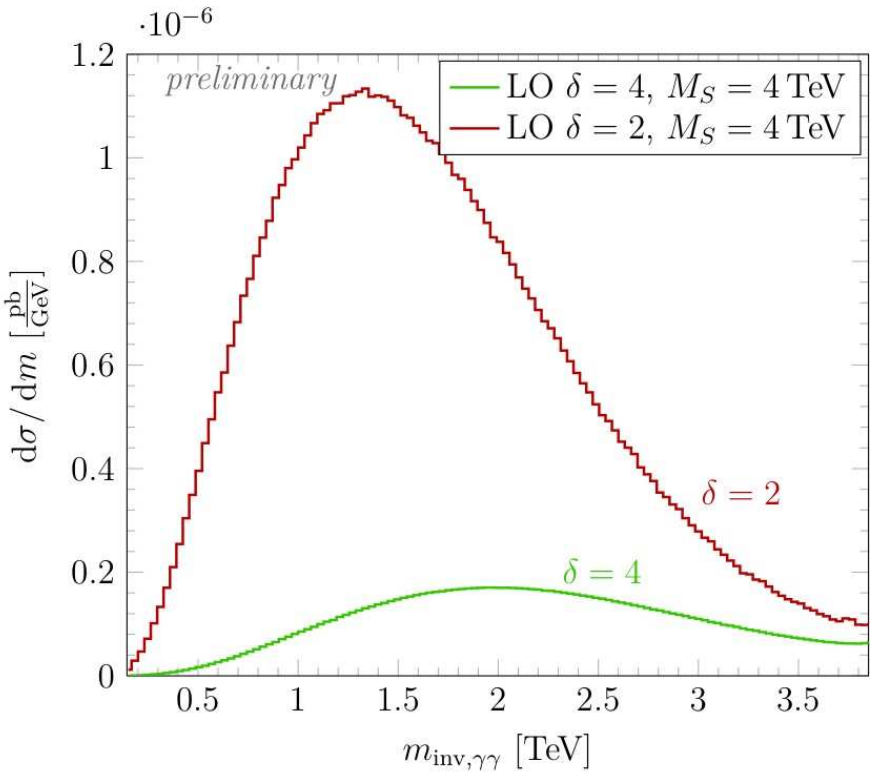
complex masses

contained in golem95C library: 1101.5595 [hep-ph]

Binoth, Cullen, Guillet, GH, Kleinschmidt, Pilon, Reiter, Rodgers, v. Soden-Fraunhofen

http://golem.hepforge.org/95/

GoSam & extra dimensions



J.F. von Soden-Fraunhofen

W^+W^++2 jets

GoSam+Sherpa: W^+W^+ + 2 jets

Machine: Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz

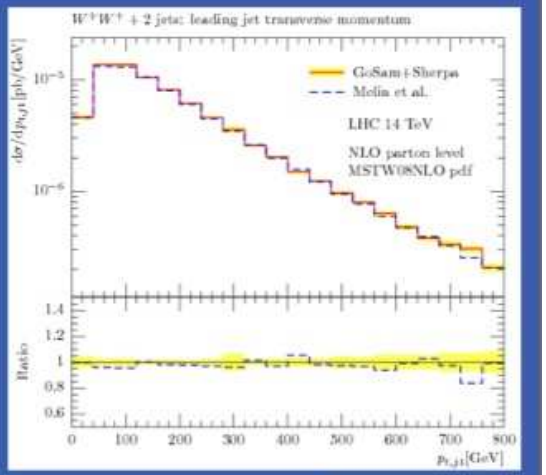
Timings:
Generation & Compilation
Virtual: ~ 5h 45 min

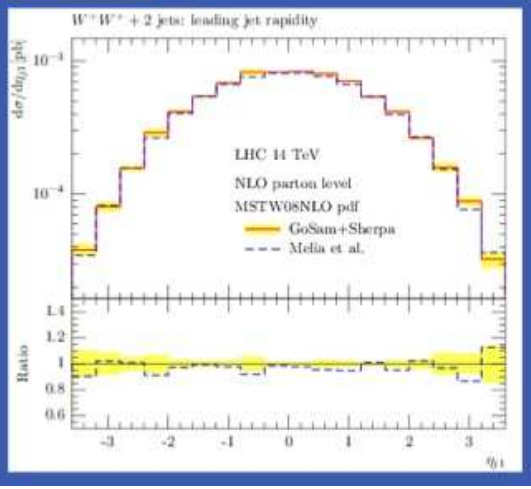
Running
Real : ~ 14h 15 min
Virtual: ~ 14h 40 min

NUMBER OF EVENTS:
Born : 1'000'000 x 5
Real : 50'000'000 x 5
Virtual: 1'000'000 x 5

Comparison with:
Melia, Melnikov,
Roentsch, Zanderighi;
JHEP 1012 (2010) 053;
[arXiv:1007.5313]

Rescue system:
Single Pole Threshold= 0.0001
Bad points: 1062 pts in grid
Bad points: 1409 pts in run



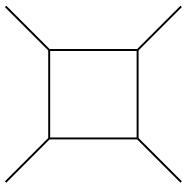
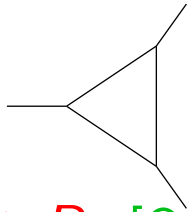
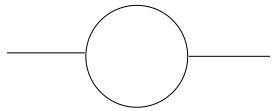
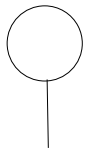


Plots for LHC at 14 TeV

Cuts	pt_lep > 20 GeV
	|eta_lep| < 2.4
	pt_miss > 30 GeV
	antikt_alg, R=0.4
Scale	150 GeV
PDF	MSTW2008nlo.LHgrid

G.Luisoni, 19th Novmber 2012

Rational Parts

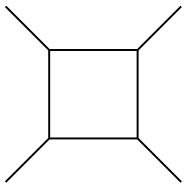
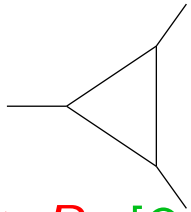
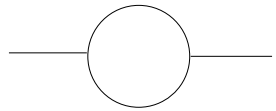
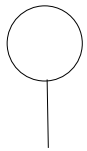
$\mathcal{A} = C_4$  $+ C_3$  $+ C_2$  $+ C_1$  $+ \mathcal{R}$

two categories: $\mathcal{R} = R_1 + R_2$ [Ossola, Papadopoulos, Pittau]

$$N(q) = \hat{N}(\hat{q}) + \tilde{N}(q, \mu^2, \epsilon)\ ,\ q^2 = \left(\hat{q}^{(4)}\right)^2 - \tilde{q}^2 = \hat{q}^2 - \mu^2$$

$$R_2 = \int \frac{d^D k}{(2\pi)^4} \frac{\tilde{N}(q, \mu^2, \epsilon)}{D_0 \dots D_{n-1}}$$

Rational Parts

$\mathcal{A} = C_4$  $+ C_3$  $+ C_2$  $+ C_1$  $+ \mathcal{R}$

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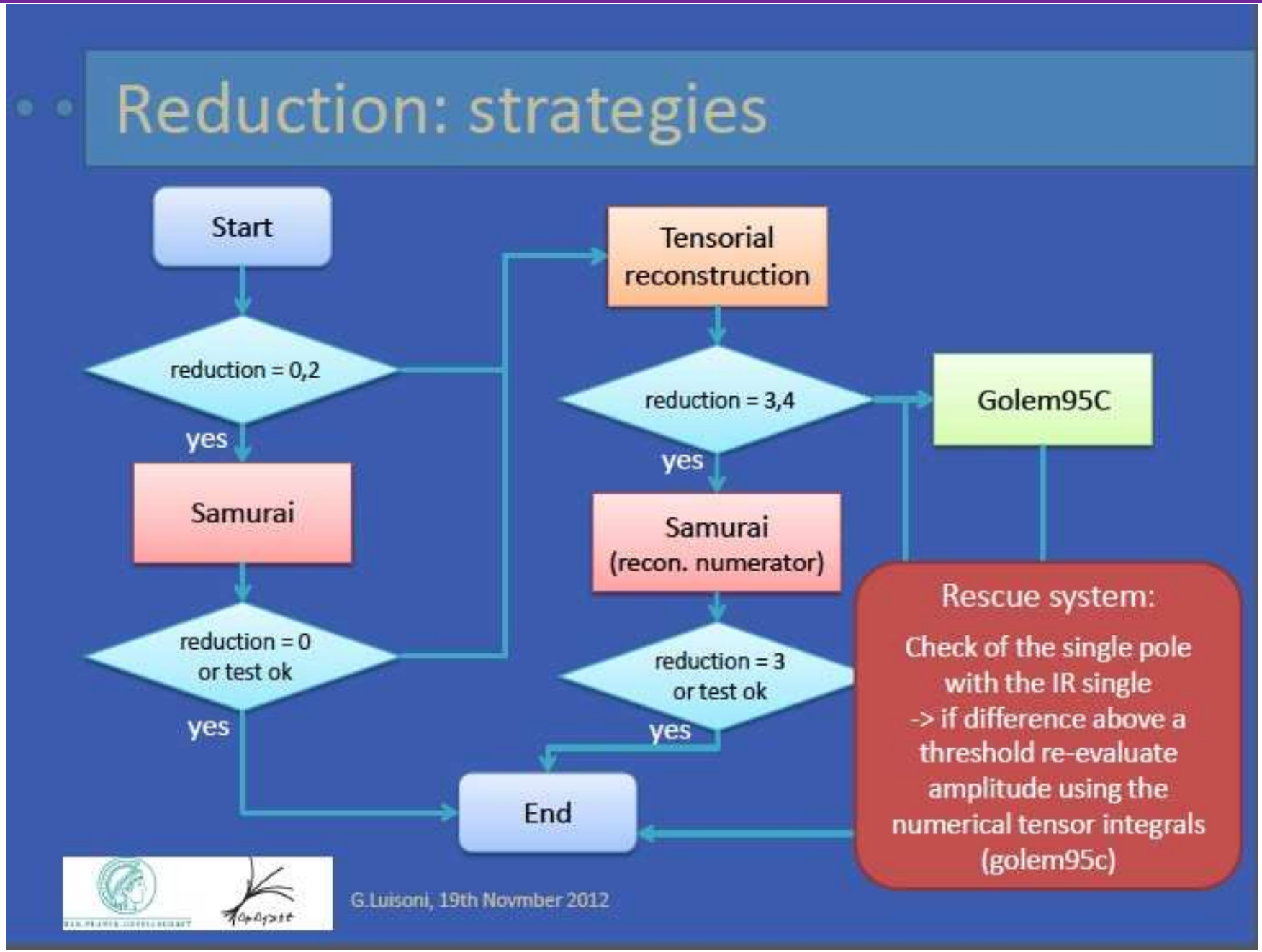
$$R_2 = \int \frac{d^D k}{(2\pi)^4} \frac{\tilde{N}(q, \mu^2, \epsilon)}{D_0 \dots D_{n-1}}$$

Golem-Samurai offers different options for calculation of R_2

- implicit: μ^2 terms kept in the numerator, reduced at runtime
- explicit: μ^2 terms are reduced analytically
- only: only the R_2 term is kept in the final result

  (does not require any additional libraries)
- off: all μ^2 terms are set to zero


Reduction: strategies
Start
reduction = 0,2
yes
Samurai
reduction = 0
or test ok
yes
Tensorial
reconstruction
reduction = 3,4
yes
Samurai
(recon. numerator)
reduction = 3
or test ok
yes
Golem95C
Rescue system:
Check of the single pole
with the IR single
-> if difference above a
threshold re-evaluate
amplitude using the
numerical tensor integrals
(golem95c)
End
G.Luisoni, 19th Novmber 2012