# Automated NLO calculations with GoSam


Gudrun Heinrich

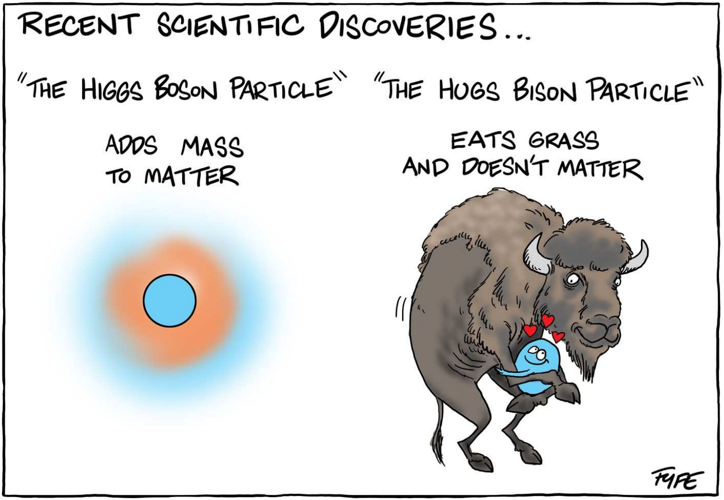
in collaboration with

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


ACAT Beijing, May 18, 2013

MAX-PLANCK-GESELLSCHAFT

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


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

# The post-discovery era

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

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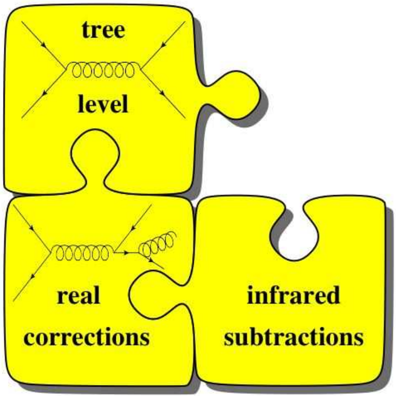
. . . the keyword is **precision** . . .

# 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
- non-perturbative effects
- . . .

# Ingredients of an NLO Calculation




NLO amplitude requires

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

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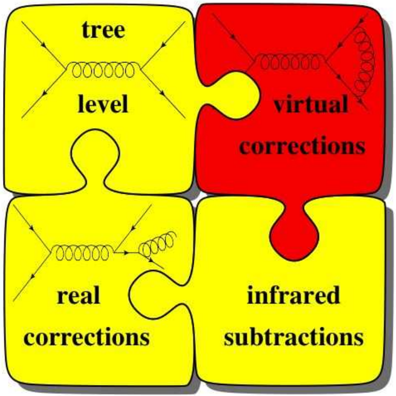


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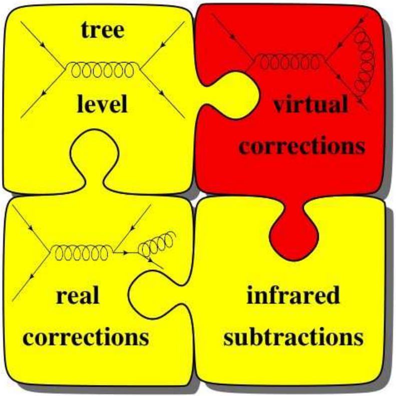


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- tree level amplitude,
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GoSam collaboration focuses on virtual corrections. Matching to other parts via BLHA interface

# Binoth Les Houches Accord (BLHA) interface

worked out at Les Houches 2009 workshop on TeV colliders, extension in preparation

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

initialisation:

process info
model parameters
fix scheme
...

order $\longrightarrow$ copy/confirm

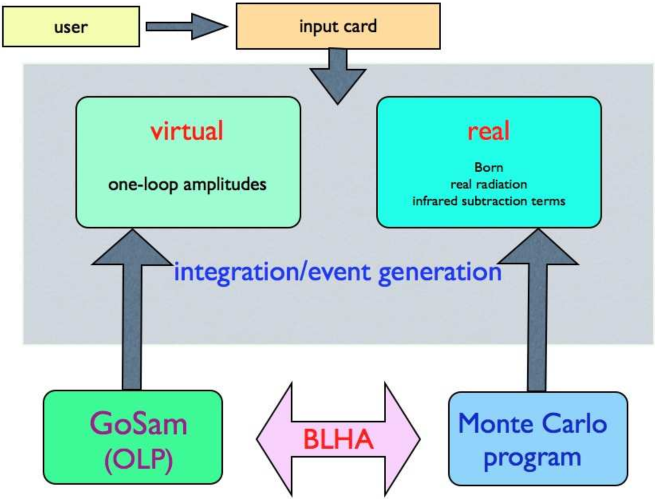
$\longleftarrow$ contract

runtime:

events $\rightleftarrows$ $A_2, A_1, A_0, |Born|^2$

standard interface

# OLP GoSam: NLO calculations made easy



# The GoSam collaboration

# 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

- user: fill out runcard
- code generation: algebraic generation of D-dimensional integrands based on Feynman diagrams, uses QGRAF [Nogueira], FORM [Vermaseren et al.], Spinney [Cullen et al]

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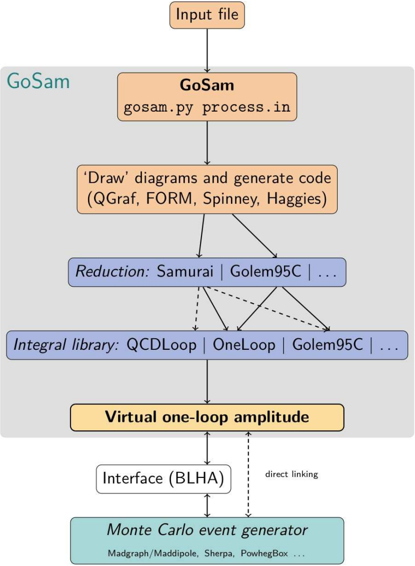
- at runtime: D-dimensional extension of OPP method: Samurai [Mastrolia, Ossola, Reiter, Tramontano] or, alternatively, tensor reduction with golem95 [Binoth et al.] tensor integral library
- can do QCD, EW, BSM

  (renormalisation fully automated for QCD case only)
- interface with existing tools for real radiation, e.g. Sherpa, MadGraph/MadEvent, Powheg, ...

# GoSam flowchart



# 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) |
| $gg \to gg$ | $pp \to t\bar{t}H$ |
| $pp \to \gamma\gamma$ | $pp \to t\bar{t}Z$ |
| $pp \to \gamma\gamma\, j$ | $pp \to t\bar{t}\, j$ |
| $pp \to t\bar{t}$ | $\gamma\gamma \to \gamma\gamma\gamma\gamma$ (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.) | $pp \to t\bar{t}b\bar{b}$ |
| $pp \to Z/\gamma^*\, j$ | $pp \to W^+W^- + 2\,\text{jets}$ |
| $pp \to W^\pm\, t$ | $pp \to H + 2j$ |
| $pp \to W^- + 3\,\text{jets}$ | $pp \to H + 3j$ |

# Interfacing GoSam

- GoSam + MadDipole [Frederix, Gehrmann,Greiner] +MadGraph/Madevent [Maltoni, Stelzer]
  - $pp \to b\bar{b}b\bar{b}$

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

    including massive top loops

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

    [Cullen, Greiner, GH '12]
  - QCD corrections to $\gamma\gamma$+jet production

    [Gehrmann, Greiner, GH '13]
- GoSam + Sherpa

  automated interface with Sherpa option –enable-lhole
  - $pp \to H$+2 jets (gluon fusion) [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]
  - $pp \to W^+W^-\, b\bar{b}$ [GH, Schlenk, Winter, to appear]
  - $pp \to W$+3 jets [unpublished]

# Precooked code ready to use

ready-made code for virtual amplitudes + Sherpa run cards

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

$$
\begin{aligned}
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) + 0,1,2\,\mathrm{jets} \\
pp/p\bar{p} &\to Z/\gamma^{*}(\to e^{+}e^{-}) + 0,1\,\mathrm{jets} \\
pp/p\bar{p} &\to W^{\pm}(\to e\nu_e) + b\bar{b}\ (\mathrm{massive\,b's}) \\
pp/p\bar{p} &\to W^{+}(\to \mu^{+}\nu_{\mu}) + W^{-}(\to e^{-}\bar{\nu}_e) \\
pp/p\bar{p} &\to W^{+}(\to \mu^{+}\nu_{\mu}) + W^{+}(\to e^{+}\nu_e) + 2\,\mathrm{jets}
\end{aligned}
$$

coming soon:

$$
\begin{gathered}
W^{+}W^{-}\,b\bar{b}\,,\ W^{+}W^{-} + 1,2\,\mathrm{jets}, \\
W^{\pm} + 3\,\mathrm{jets}\,,\ Z + 2\,\mathrm{jets}\,,\ \gamma + 0,1,2,\mathrm{jets} \\
H + 0,1,2\,\mathrm{jets}\,,\ t\bar{t} + 0,1\,\mathrm{jets}\,,\ t\bar{t}\,H + 0,1\,\mathrm{jets}
\end{gathered}
$$

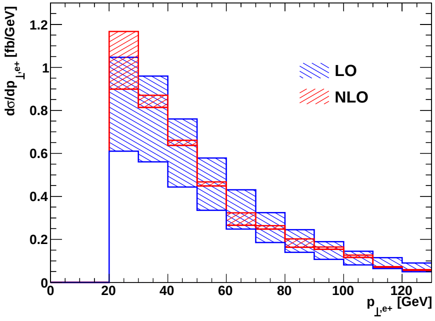
## GoSam + MadDipole + MadGraph4

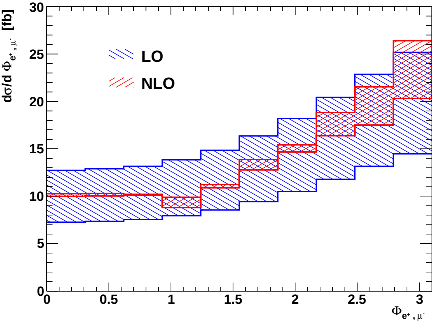
[Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12, massive top loops included]

[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 results: $W^+W^- b\bar{b}$

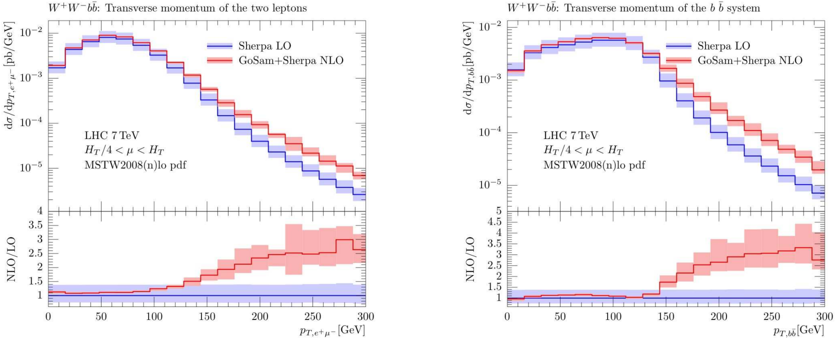
## GoSam + Sherpa [GH, J. Schlenk, J. Winter]

see also [Denner, Dittmaier, Kallweit, Pozzorini '11, '12],

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

$\sqrt{s} = 7$ TeV, $\mu_0 = H_T/2\,,\ H_T = \sum_j p_T^j$,

$p_T^b \geq 30\,\text{GeV}$ , $p_T^{miss} \geq 20\,\text{GeV}$ , $p_T^l \geq 20\,\text{GeV}$ , $|\eta_b| \leq 2.5$, $\Delta R_{jj} \geq 0.5$, $|\eta_l| \leq 2.5$




figures by Johannes Schlenk

# Diphotons + jet

$pp \to \gamma\gamma$+jet: background to H ($\to \gamma\gamma$)+jet
$\Rightarrow$ NLO QCD corrections important

hard photons can have several origins:

- direct production in hard subprocess
- fragmentation of large-$p_T$ partons into a photon and hadrons: non-perturbative, described by fragmentation function

need isolation from hadronic background

standard cone isolation:

$$E_{\rm had} \leq \epsilon_{\rm cone}\, p_T^{\gamma}$$

$$z_c = \frac{|\vec{p}_{T,\rm cone}^{\,\rm had}|}{|\vec{p}_T^{\,\gamma} + \vec{p}_{T,\rm cone}^{\,\rm had}|} \leq z_{\rm cut}$$

smooth isolation (Frixione):

$$E_{\rm had,max}(r_\gamma) = \epsilon\, p_T^{\gamma} \left( \frac{1 - \cos r_\gamma}{1 - \cos R} \right)^n$$

# Diphotons + jet

public codes:

- NLOJET++ [DelDuca,Maltoni,Nagy,Trocsanyi '03]
  Frixione isolation only
- GoSam+MadDipole/MadGraph/MadEvent
  [Gehrmann, Greiner, GH '13]
  fragmentation part included (frag functions $\mathcal{O}(\alpha)$) $\Rightarrow$ allows comparison of standard cone isolation and Frixione isolation

  available at

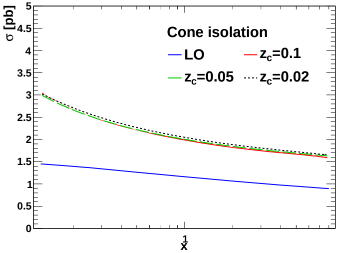
http://gosam.hepforge.org/diphoton

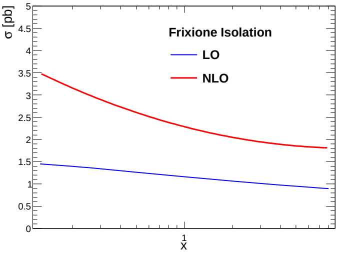
# Diphotons + jet

scale variations: $\mu_0^2 = \frac{1}{4}\left(m_{\gamma\gamma}^2 + \sum_j p_{T,j}^2\right)$ ; $\mu = \mu_r = \mu_F$ ; $x = \mu/\mu_0$

cuts: $p_T^{\rm jet} > 40\,\text{GeV},\ p_T^{\gamma} > 20,\ |\eta^{j,\gamma}| \leq 2.5,\ R_{\gamma j} > 0.4,\ R_{\gamma\gamma} > 0.8\,,\ 100\,\text{GeV} \leq m_{\gamma\gamma} \leq 140\,\text{GeV}$

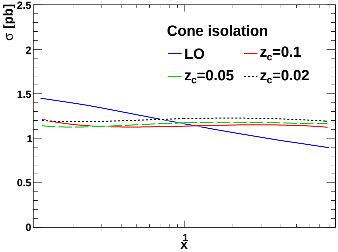
1-jet inclusive:

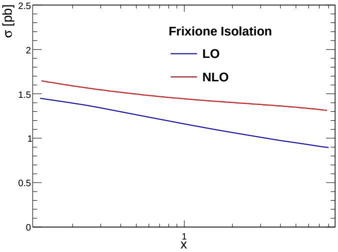


# Diphotons + jet

exclusive cuts: veto on second jet $p_{T,j2} \leq 30\,\text{GeV}$



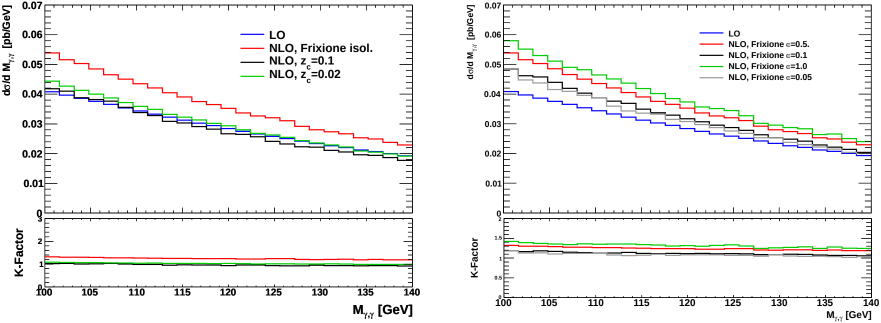




- strong reduction of K-factor compared to inclusive cuts
- scale uncertainty smaller with cone isolation

# Diphotons+jet

comparison of isolation parameters for $\gamma\gamma$ invariant mass $M_{\gamma,\gamma}$

exclusive cuts



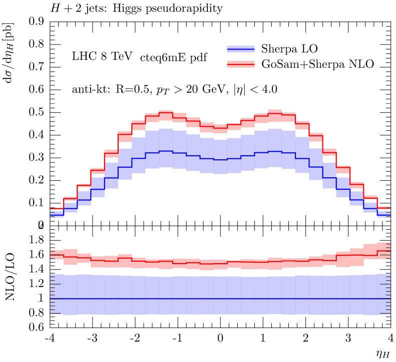

differences between standard cone isolation and Frixione isolation decrease for decreasing $z_c$ resp. $\epsilon$

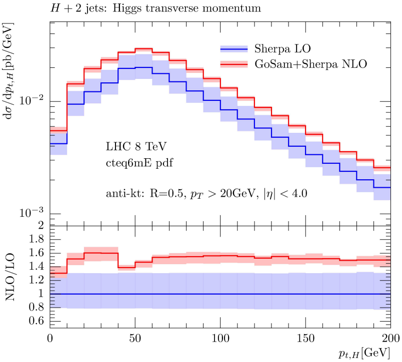
# GoSam & effective vertices: H+2 jets

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

## GoSam + Sherpa

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



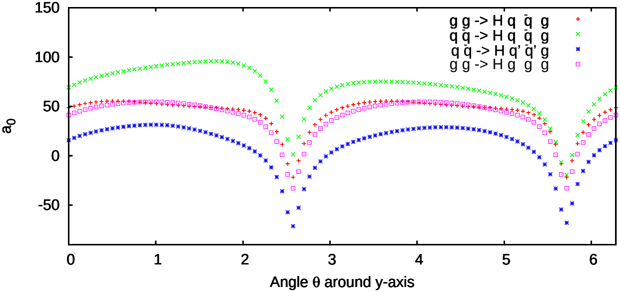



# Towards pp $\to$ H+3 jets

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

finite parts of virtual matrix elements for

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




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

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

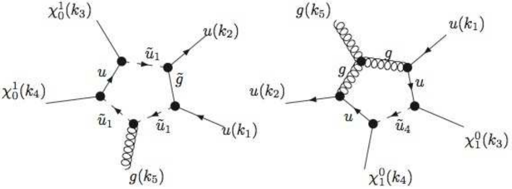
# GoSam goes BSM

- import model file from FeynRules [Alloul, Christensen, Degrande, Duhr, Fuks]
  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 + MadGraph4

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

signature: monojet plus missing $E_T$




example pentagon diagrams

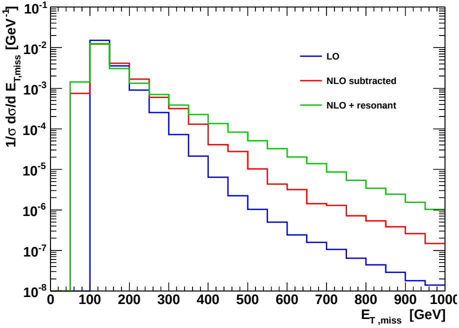
# GoSam & Susy

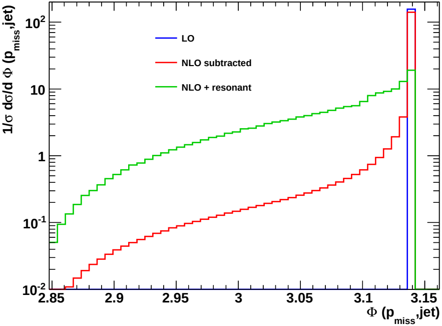
$\sqrt{s} = 8$ TeV, NNPDF2.3 set

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



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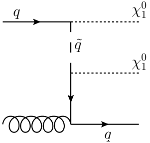
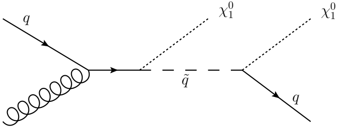
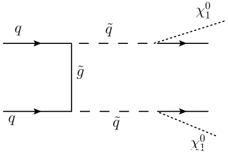



t-channel squark exchange




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]

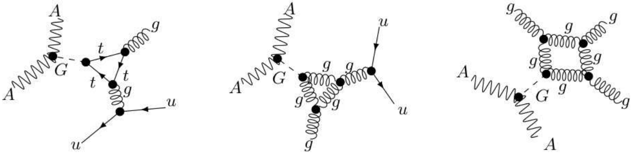
$$Dim = 4 + \delta\,,\; M^2_{\rm Planck} = 8\pi R^\delta\, M_S^{\delta+2}$$

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

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

GoSam + MadDipole+MadGraph4 and GoSam+ Sherpa

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




example diagrams

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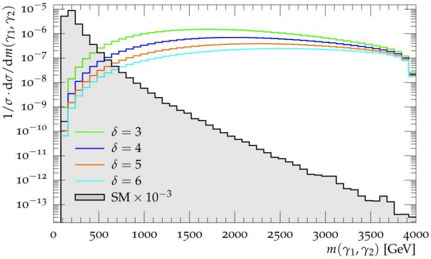



$\mu^2 = \frac{1}{4}\left(m^2_{\gamma\gamma} + \sum_{jets} p^2_{T,jet}\right)$

CT10 pdf set

cuts:

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

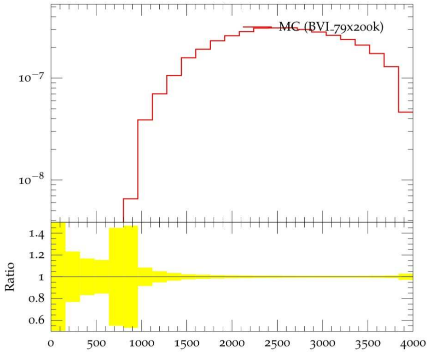
$p_T^\gamma > 25$ GeV, $p_T^{jet} > 30$ GeV

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

leading order

figure by Joscha Reichel

# GoSam & extra dimensions

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

$\delta = 4$ extra dims

BVI: Born+Virtual+Integrated subtraction terms

figure by Joscha Reichel

# Towards GoSam 2.0

- code generation
  - new strategy to produce optimized `fortran95` code based on new features in `FORM` version 4 [Vermaseren, Ueda et al.]
    $\Rightarrow$ faster code generation, more compact code
  - parallelization at diagram level possible
    $\Rightarrow$ enormous gain in code generation time
  - option to have numerical polarisation vectors
    $\Rightarrow$ reduces code size
  - option to sum diagrams sharing the same propagators algebraically at `FORM` level

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  - implementation of integrals where rank exceeds number of propagators in Samurai [van Deurzen, Mastrolia] and golem95 [Guillet, GH, von Soden-Fraunhofen]
  - alternative reduction with Ninja [Mastrolia, Mirabella, Peraro]
    (C++ code, based on Laurent expansion of numerator)

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will be public as GoSam 2.0 later this year

# Summary and Outlook

- automation is necessary to have NLO predictions as a standard at LHC

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- GoSam is a powerful and flexible automated tool for one-loop multi-leg amplitudes

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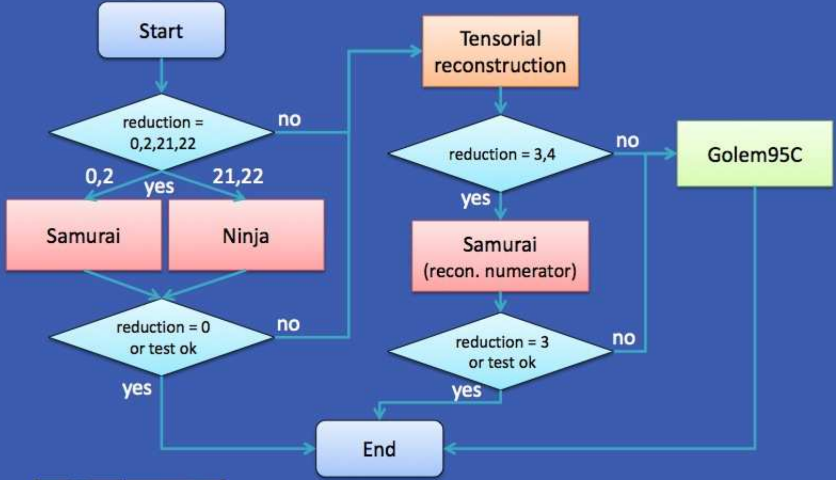
- GoSam is publicly available at http://projects.hepforge.org/gosam/

# additional slides

# Running time reduction strategies




G.Luisoni, 2nd May 2013

# Higgs+jets: NLO virtual corrections

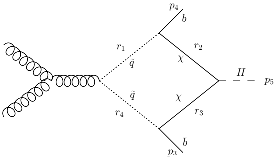
| | Processes | # Initial Diagrams | # Diagrams after sum | # Groups | Timing |
|---|---|---|---|---|---|
| H+0 jets | $g+g \longrightarrow H$ | 1 | 1 | 1 | < 1 ms |
| H+1 jets | $q+\bar{q} \longrightarrow H+g$ | 14 | 10 | 3 | ~ 3 ms |
| | $g+g \longrightarrow H+g$ | 48 | 25 | 3 | ~ 7 ms |
| | | 62 | 35 | | |
| H+2 jets | $q+\bar{q} \longrightarrow H+q'+\bar{q}'$ | 32 | 20 | 6 | ~ 9 ms |
| | $q+\bar{q} \longrightarrow H+q+\bar{q}$ | 64 | 35 | 8 | ~ 15 ms |
| | $q+\bar{q} \longrightarrow H+g+g$ | 179 | 85 | 12 | ~ 56 ms |
| | $g+g \longrightarrow H+g+g$ | 651 | 197 | 12 | ~ 316 ms |
| | | 926 | 337 | | |
| H+3 jets | $q+\bar{q} \longrightarrow H+q'+\bar{q}'+g$ | 467 | 202 | 32 | ~ 290 ms |
| | $q+\bar{q} \longrightarrow H+q+\bar{q}+g$ | 868 | 344 | 44 | ~ 600 ms |
| | $q+\bar{q} \longrightarrow H+g+g+g$ | 2519 | 645 | 60 | ~ 3'900 ms |
| | $g+g \longrightarrow H+g+g+g$ | 9325 | 1814 | 60 | ~ 20'100 ms |
| | | 13179 | 3005 | | |

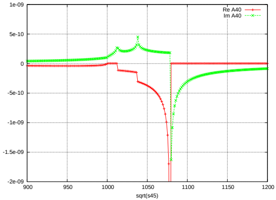
G.Luisoni, 2nd May 2013

Color & helicity summed

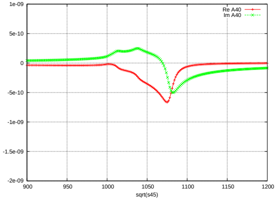
# golem95C integral library

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+Sherpa: $W^-$ + bb massive

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

**Timings:**

Generation & Compilation

Virtual: ~ 22 min

Running

Real : ~ 5h 20 min

Virtual: ~ 11h

MCFM:

ncalls 1: 100'000 pts

ncalls 2: 100'000 pts

itmx 1: 10

itmx 2: 10

time: ~ 7h 10 min

Rescue system:

Single Pole Threshold= 0.0001

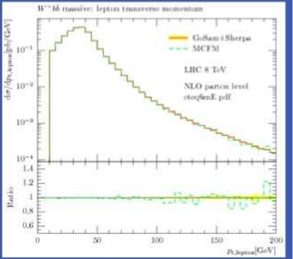
Bad points: none

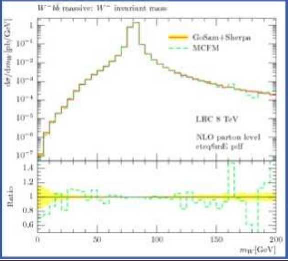
**NUMBER OF EVENTS:**

Born : 5'000'000 x 5

Real : 50'000'000 x 10

Virtual: 1'000'000 x 10

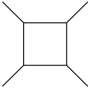
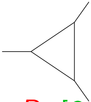
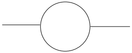
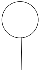



| | |
|---|---|
| Plots for LHC at 8 TeV | |
| Cuts | pt_miss > 20 GeV |
| | pt_lepton > 10 GeV |
| | inclusive in jets |
| Scale | H_T |
| PDFs | cteq6mE.LHgrid |

G.Luisoni, 3rd March 2013

# 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]

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

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

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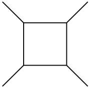
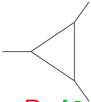
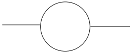
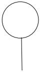
$\mathcal{A} = C_4$  $+ C_3$  $+ C_2$  $+ C_1$  $+ \mathcal{R}$

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**Golem-Samurai offers different options for calculation of $R_2$**

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

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