GoSam Beyond

Gavin Cullen, DESY Zeuthen

In collaboration with: N. Greiner, G. Heinrich, P. Mastrolia, E. Mirabella, H. Van Deurzen, G. Luisoni, J.F. von Soden-Fraunhofen, T. Peraro, J. Reichel, J. Schlenk, G. Ossola, F. Tramontano

MC4BSM: 19th April 2013

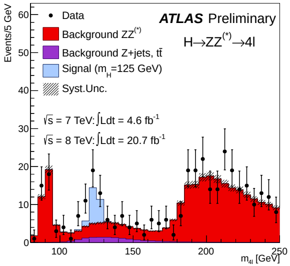
Outline

- Why NLO? Why automatic?
- Introduce GoSam
- Applications of GoSam in NLO calculations in (B)SM

Problem

We want to go from point A to point B while minimizing work:

- $\mathcal{L} \rightarrow$



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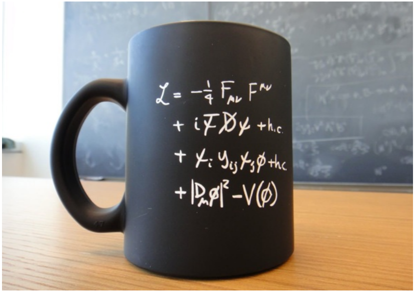
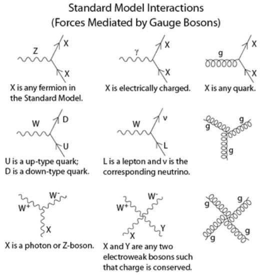
- $\mathcal{L}$



Problem

We want to go from point A to point B while minimizing work:

- $\mathcal{L}$
- $\to$ Feynman rules

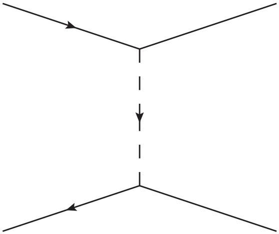


[Old Approach] : all good textbooks

[Modern Approach] : FeynRules [Fuks, Duhr, Degrande, Christensen] , $\cdots$

Problem

We want to go from point A to point B while minimizing work:



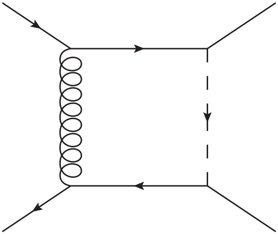
- $\mathcal{L}$
- $\rightarrow$ Feynman rules
- $\rightarrow$ Leading Order

[Old Approach] : find a diploma student
[Modern Approach] : MadGraph/MadEvent, Alpgen, Amegic, Comix, Helac, Whizhard, $\cdots$

Problem

We want to go from point A to point B while minimizing work:

- $\mathcal{L}$
- $\rightarrow$ Feynman rules
- $\rightarrow$ Next to Leading Order



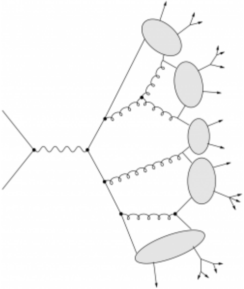
[Old Approach] : find a PhD student (and wait 2-3 years)

[Modern Approach] : This talk

Problem

We want to go from point A to point B while minimizing work:

- $\mathcal{L}$
- $\rightarrow$ Feynman rules
- $\rightarrow$ (Next to Leading Order)
- $\rightarrow$ parton shower (+matching)

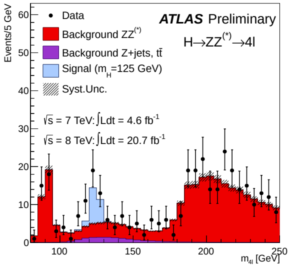


[Old Approach] : all good textbooks
[Modern Approach] : Sherpa, Alpgen, Whizard (Matrix element generators); Pythia, Herwig (parton shower + hadronisation),$\cdots$

Problem

We want to go from point A to point B while minimizing work:

- $\mathcal{L}$
- $\rightarrow$ Feynman rules
- $\rightarrow$ Next to Leading Order
- $\rightarrow$ parton shower (+matching)
- $\rightarrow$ full detector simulation



[Old Approach] : find an experimentalist
[Modern Approach] : find an experimentalist

Why NLO?

Common answers :

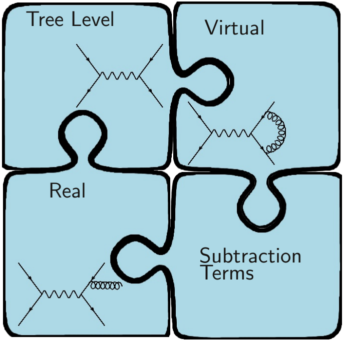
- scale uncertainty reduced (more precise)
- better PDF fits (more precise)
- jet start to have structure (more realistic)
- shape of distribution can change (more serious)

Why Automatic?

Common answers :

- human error is reduced (less frustrating)
- human time of computation is reduced (more efficient)
- process independent (more flexibility)
- confidence in results (more sleep)
- tools can be used by “non-experts” (open to debate)

What goes into an NLO calculation?



- a NLO calculation is a complicated project
- Exploit modular structure
  - Tree level
  - Virtual corrections
  - Real emissions
  - Subtraction terms for soft and collinear singularities

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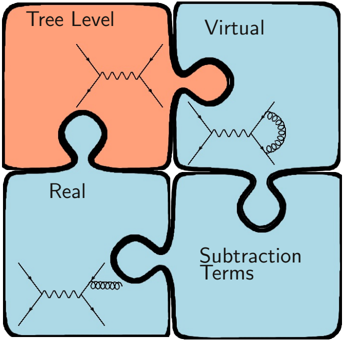

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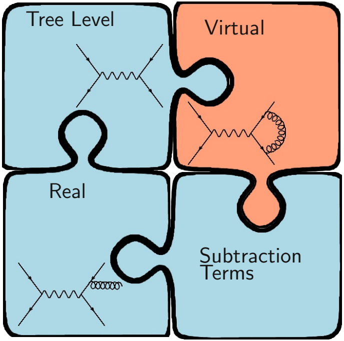

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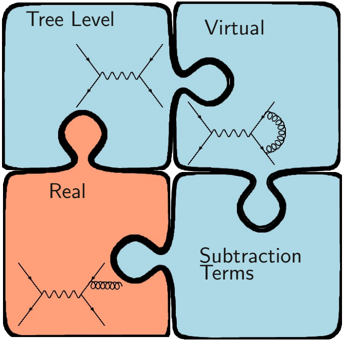

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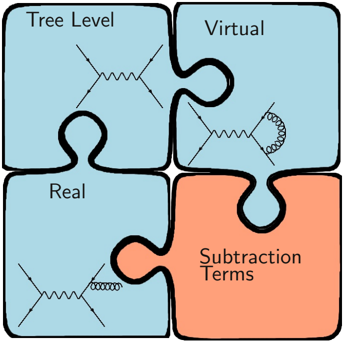

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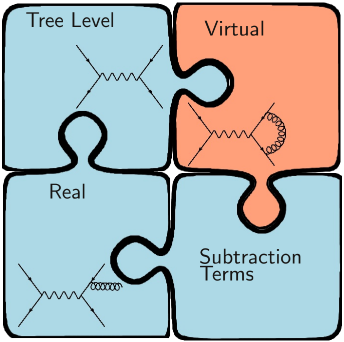

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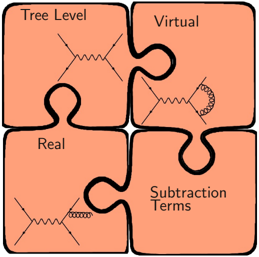
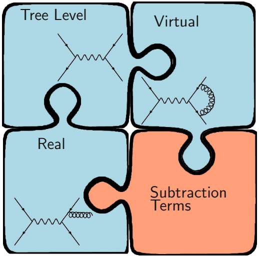
Automated NLO tools



- Hard coded processes:
  - POWHEG-Box [Alioli, Nason, Oleari, Re et al]
  - MCFM/Rocket [Campbell, Ellis, Williams, Melnikov, Zanderighi et al]
  - VBFNLO [Zeppenfeld et al] , . . .

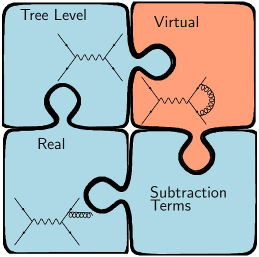
Automated NLO tools



Automation of subtraction terms for IR divergent real radiation

- MadDipole [Frederix, Greiner, Gehrmann]
- Dipole subtraction in Sherpa [Gleisberg, Krauss]
- TevJet [Seymour, Tevlin]
- AutoDipole [Hasegawa, Moch, Uwer]
- Helac-Phegas [Czakon, Papadopoulos, Worek]
- MadFKS [Frederix, Frixione, Maltoni, Stelzer]

Automated NLO tools



And at one-loop

- FeynArts/FormCalc/LoopTools [T. Hahn et al]
- MadGolem [Wigmore 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
- NJet [Badger, Biedermann, Uwer, Yundin]
- OpenLoops [Pozzorini, Maierhöfer, Cascioli]
- Recola [Actis, Denner, Hofer, Scharf, Uccirati]
- GoSam

GoSam

GoSam is a joining of two collaborations Golem and Samurai:

- Golem: General One Loop Evaluator of Matrix Elements
- Samurai : Scattering Amplitudes from Unitarity based Reduction At Integrand level
- Now with added PhD/Diploma Students!

GoSam

Aim: to have a general tool that can compute the **one-loop amplitude** for any process in and beyond the SM.

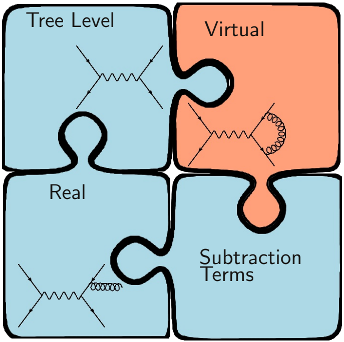
- Public and open source: download at
  http://projects.hepforge.org/gosam/
  [arXiv: 1111.6534 [hep-ph]]

- GoSam is a Python program that automatically generates Fortran 95 library for the virtual piece of a NLO calculation

GoSam current status

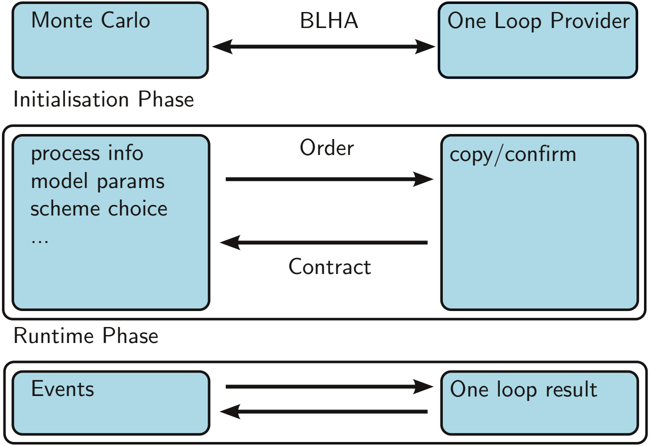
- Pheno Projects
  - SM:
    - $W^+W^- + 2$ jets [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
    - $b\bar{b}b\bar{b}$ production [Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '10, '11]
    - $H + 2$ jets [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]
    - $H + 3$ gluon fusion [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Schoenherr, Tramontano, work in progress]
    - $\gamma\gamma + j$ [T. Gehrmann, Greiner, Heinrich '13]
  - BSM:
    - $\chi_1^0\chi_1^0 + 1$ jet [GC, Greiner, Heinrich, '12]
    - Graviton + 1 jet (ADD model) [Greiner, Heinrich, Reichel, von Soden-Fraunhofen (in preparation)]
- Code Development
  - BLHA interface to Sherpa, POWHEG
  - UFO interface for BSM models
  - Higher rank integrals supported
  - New optimisation strategy

What goes into an NLO calculation?



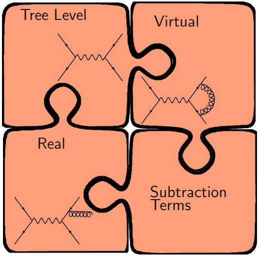
- a NLO calculation is a complicated project
- Exploit modular structure
  - Tree level
  - Virtual corrections
  - Real emissions
  - Subtraction terms for soft and collinear singularities
- GoSam focuses on the virtual piece, the matching to the other pieces is through the BLHA interface

Binoth Les Houches Accord (2009) [Les Houches 2009]



- Update to basic accord to come this year

GoSam Pheno Projects



- GoSam + MadGraph4
  - $W^+W^- + 2$ jets
  - $\chi_1^0\chi_1^0 + 1$ jet
  - $b\bar{b}b\bar{b}$ production
- GoSam + POWHEG [Luisoni, Nason, Oleari, Tramontano]
  Working interface (to BLHA Standard), [coming soon]
- GoSam + Sherpa automated interface with Sherpa option -enable-lhole
  - $H + 2$ jets
  - $H + 3$ jets [in progress]
  - $\gamma\gamma + j$
  - Graviton + 1 jet (ADD model) [in progress]

GoSam: Quick Tutorial

Process: $u\bar{d} \rightarrow W^+W^+\bar{c}s \rightarrow e^+\nu_e\mu^+\nu_\mu\bar{c}s$

- Prepare input card

```
in=u,d~
out=c~,s,e+,ne,mu+,nmu
model=smdiag
order=QCD,2,4
zero=mU,mD,mC,mS,mB,me,mmu,wB
one=gs,e
helicities=-++-+-+-
extensions=dred,samurai
```

- and run..

```
gosam.py process.in
```

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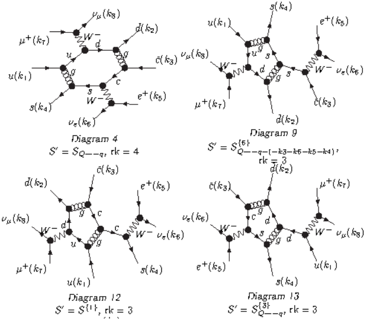
Process: $u\overline{d} \to W^+W^+\overline{c}s \to e^+\nu_e\mu^+\nu_\mu\overline{c}s$

- Draw diagrams
  make doc
- Write source files
  make source
- Compile source files
  make compile



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```
Form is processing loop diagram 1 @ Helicity 0
  1.36 sec out of 1.36 sec
Haggies is processing abbreviations for loop diagram 1
Form is processing loop diagram 2 @ Helicity 0
  1.54 sec out of 1.55 sec
Haggies is processing abbreviations for loop diagram 2
Form is processing loop diagram 3 @ Helicity 0
  0.84 sec out of 0.85 sec
Haggies is processing abbreviations for loop diagram 3
Form is processing loop diagram 4 @ Helicity 0
  0.92 sec out of 0.93 sec
Haggies is processing abbreviations for loop diagram 4
Form is processing loop diagram 5 @ Helicity 0
  0.98 sec out of 0.99 sec
```

GoSam: Quick Tutorial

Process: $u\overline{d} \to W^+W^+\overline{c}s \to e^+\nu_e\mu^+\nu_\mu\overline{c}s$

- Draw diagrams
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GoSam: Quick Tutorial

Process: $u\bar{d} \to W^+W^+\bar{c}s \to e^+\nu_e\mu^+\nu_\mu\bar{c}s$

- We compare to MMRZ
  [Melia, Melnikov, Rontsch, Zanderighi (1104.2327)]

```
+--------------------------------------------------------------------------+
|                                                  GoSam                   |
|   __   __   ___   __   __ __                An Automated One-Loop       |
|  / _) /  \ / __) (  ) (  \/  )            Matrix Element Generator       |
| ( (/\( () )\__ \ /__\  )    (                  Version 1.0               |
|  \__/ \__/ (___/(_)(_)(_/\/\_)                                           |
|                                                                          |
|                                    (c) The GoSam Collaboration 2011      |
+--------------------------------------------------------------------------+

LO:          1.143226406875312E-017
NLO/LO, finite part:    23.3596454824712
NLO/LO, single pole:    13.6255429253600
NLO/LO  double pole:   -5.33333333333331

cpu time (secs) :  5.299200000000000E-002
```

NLO/LO	GoSam	MMRZ
$1/\epsilon^2$	-5.33333333	-5.33333
$1/\epsilon$	13.62554293	13.62554
finite	23.35964548	23.35965

GoSam tests

Processes tested at release:

- $u\bar{d} \to W^+ s\bar{s} \to e^+ \nu_e s\bar{s}$
- $u\bar{d} \to W^+ gg \to e^+ \nu_e gg$
- $d\bar{d} \to Zgg \to e^+ e^- gg$
- $u\bar{d} \to W^+ gg \to e^+ \nu_e b\bar{b}$ (massive b)
- $u\bar{d} \to W^+ g \to e^+ \nu_e g$ (EW)
- $e^+ e^- \to Z \to d\bar{d}g$
- $\gamma\gamma \to \gamma\gamma\gamma\gamma$
- $q\bar{q} \to b\bar{b}b\bar{b}$
- $gg \to b\bar{b}b\bar{b}$
- $u\bar{d} \to W^+ W^+ s\bar{c} \to e^+ \nu_e \mu^+ \nu_\mu s\bar{c}$
- $u\bar{u} \to W^+ W^+ c\bar{c} \to e^- \bar{\nu}_e \mu^+ \nu_\mu c\bar{c}$
- $u\bar{d} \to W^+ W^- s\bar{c} \to e^- \bar{\nu}_e \mu^+ \nu_\mu \bar{s}c$
- Plus many $2 \to 2$ processes

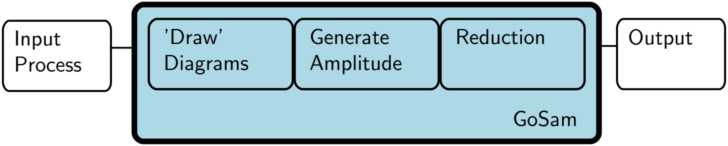
GoSam tests

Updated table:

$\gamma\gamma \to \gamma\gamma$ (W and fermion loop)	$pp \to t\bar{t}\,H$
$\gamma\gamma \to \gamma\gamma\gamma\gamma$ (fermion loop)	$pp \to t\bar{t}\,Z$
$e^+e^- \to e^+e^-\gamma$ (QED)	$pp \to t\bar{t}\,j$
$pp \to W^\pm\,j$ (QCD corr.)	$pp \to W^+W^+jj$
$pp \to W^\pm\,j$ (EW corr.)	$pp \to W^+W^-jj$
$pp \to W^\pm\,t$	$pp \to W^+W^-b\bar{b}$
$pp \to W^\pm\,jj$	$pp \to b\bar{b}b\bar{b}$
$pp \to W^\pm b\bar{b}$ (massive b's)	$pp \to t\bar{t}b\bar{b}$
$pp \to W^+jjj$	$pp \to Hjj$
$pp \to \tilde{\chi}^0_1\tilde{\chi}^0_1$	$pp \to Hjjj$
$pp \to \tilde{\chi}^0_1\tilde{\chi}^0_1\,j$	$pp \to \gamma\gamma\,j$

Table: Examples of one-loop amplitudes computed with GoSam.

GoSam: An Overview



- **Diagrams drawn** by QGRAF [Nogueira] (one can provide their own model files in the UFO format [Duhr et al])
- **Algebraic generation** of D-dimensional integrands based on Feynman diagrams using the Spinney [GC et al] library (written in Form [Vermaseren])
- **Options for reduction:**
  - Samurai: D-Dimensional integrand reduction [Ossola Papadopoulos, Pittau, Ellis, Giele, Kunszt and Melnikov, Mastrolia, Reiter, Tramontano]
  - "traditional" tensor reduction using golem95 [Binoth et al]
  - tensorial reduction at the integrand level [Heinrich, Ossola, Reiter, Tramontano]
  - Different integral libraries available at runtime: Golem95C , OneLoop [A. van Hameren]
- **Output** is an optimized fortran code (currently using Haggies [Reiter] : soon using new features of Form [Vermaseren et al])

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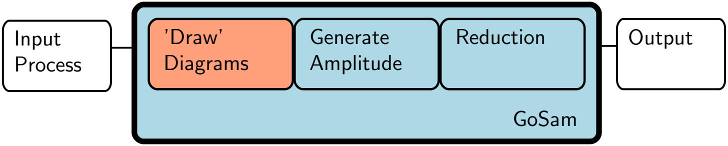

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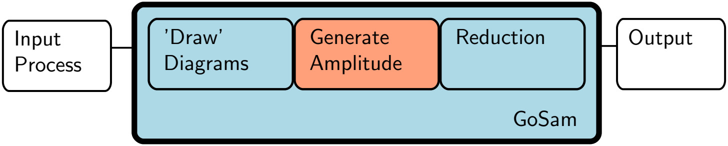

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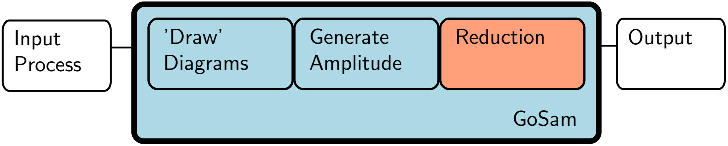

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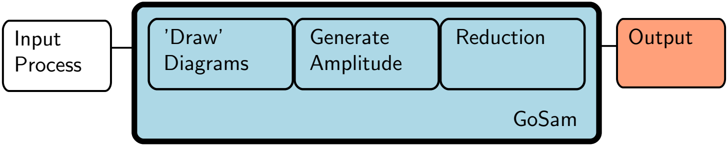

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  - tensorial reduction at the integrand level [Heinrich, Ossola, Reiter, Tramontano]
  - Different integral libraries available at runtime: Golem95C , OneLoop [A. van Hameren]
- **Output** is an optimized fortran code (currently using Haggies [Reiter] : soon using new features of Form [Vermaseren et al])

GoSam goes Beyond (The Standard Model)

- We are interested in extending GoSam for Processes Beyond the Standard Model
- BSM Pheno projects:
  - $\chi_1^0 \chi_1^0 + 1$ jet [GC, Greiner, Heinrich]
  - Graviton + 1 jet (ADD model) [Greiner, Heinrich, Reichel, von Soden-Fraunhofen (in preparation)]
- BSM friendly code features:
  - GoSam can import model files in UFO [Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter] model format or Lanhep [Semenov et al] format
  - Majorana fermions
  - massive and complex loop integrals
  - effective vertices, higher rank tensor (development in Samurai and golem95), spin 2 particles

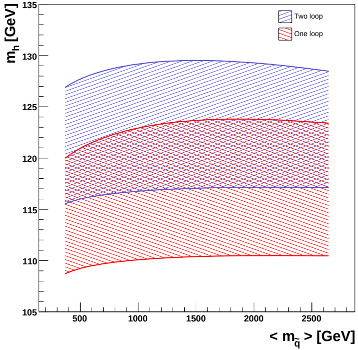
MonoJet Searches in SUSY

- A compressed SUSY spectrum can dramatically reduce SUSY search limits [Dreiner,Krämer,Tattersall]
- ATLAS relies on the following to untangle SUSY from the background: a hard jet, and a decent amount of missing energy
- But a compressed spectrum can lead to soft jets and so could be “hidden” at LHC
- We explore this scenario for the process $pp \to \chi_1^0 \chi_1^0 + j$

SUSY @ LHC

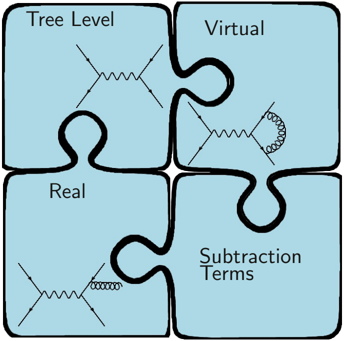
SUSY @ LHC : strong constraints on squark masses are weakened in "compressed" scenarios
For example : p19MSSM1A

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



At this point we get a signal that can be seen at LHC and is consistent with Higgs measurement

Neutralino Pair plus One Jet



Calculational setup:

- Virtual piece : GoSam
- Real piece: MadGraph
- Subtraction terms: MadDipole
- Phase space integration: MadEvent

Feynman rules provided by FeynRules in UFO format
Parameter point calculated in Softsusy [Allanach] and Susyhit [Djouadi, Mühlleitner, Spira]

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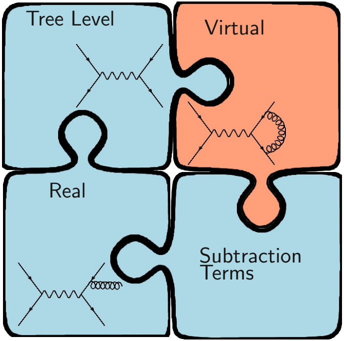

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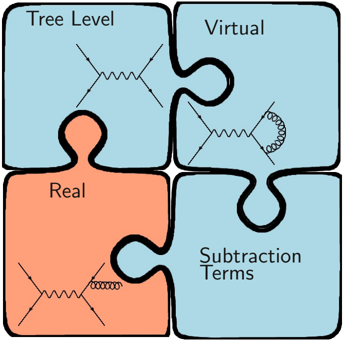

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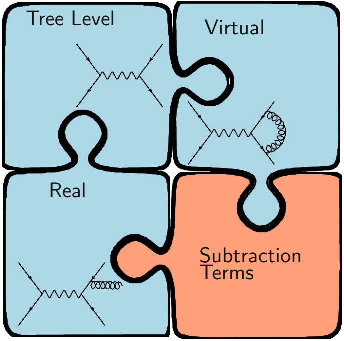

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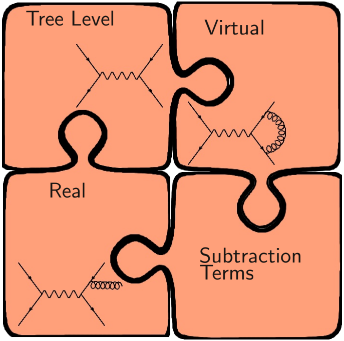

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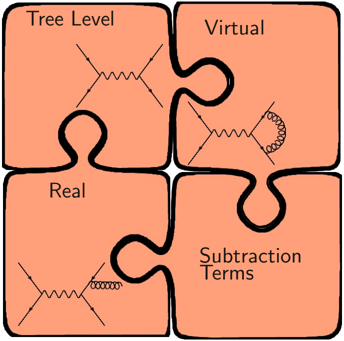

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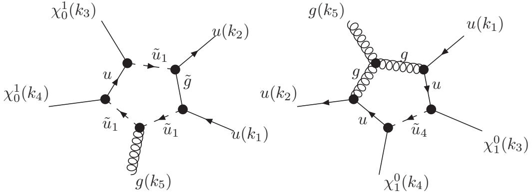
Neutralino Pair plus One Jet: The Virtual Piece

Contributing subprocess:

- $q\bar{q} \to \chi_1^0 \chi_1^0 g$
- $qg \to \chi_1^0 \chi_1^0 q$
- $g\bar{q} \to \chi_1^0 \chi_1^0 \bar{q}$

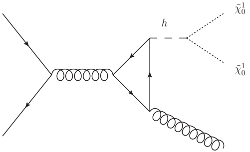
Challenge:

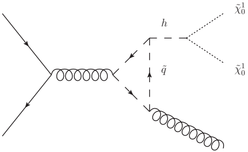
- High multiplicity of loop diagrams $\mathcal{O}(1500)$ per subprocess
- Numerical stability of off-shell effects
- first $2 \to 3$ SUSY process including full off-shell effects and complex masses in loops



Neutralino Pair plus One Jet: The Virtual Piece

We also calculated the Higgs contribution to signal $h \in \{h, H, A\}$

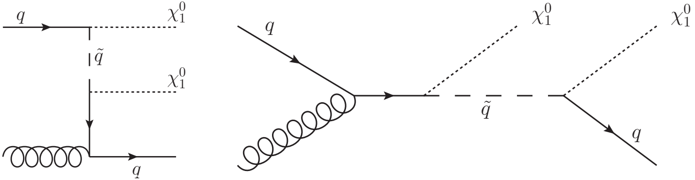




and found them to be negligible.

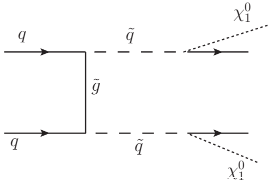
Neutralino Pair plus One Jet: The Real Problem

The real radiation is dominated by resonant contributions.
At leading order we have the following diagrams:



Neutralino Pair plus One Jet: The Real Problem

The "NLO" real contribution contains the following "doubly-resonant" diagrams



- Very sizeable contribution
- Ruins our perturbative expansion...

What has gone wrong?

- This is leading order "squark pair" production with subsequent decay

Neutralino Pair plus One Jet

Therefore we proceed using 2 approaches:

1. We include these diagrams
   - somewhere between LO and NLO.
   - One parton can become unresolved and this infrared singularity will be cancelled by the virtual contribution
   - More realistic but not a genuine NLO correction
2. We remove them:
   - We can get closer to a “K-factor” but unsure what it means physically

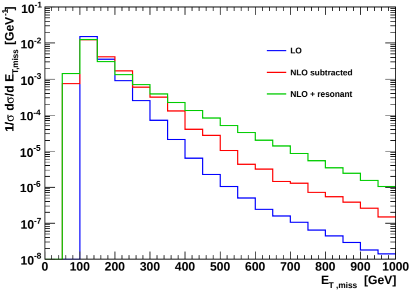
Neutralino Pair plus One Jet

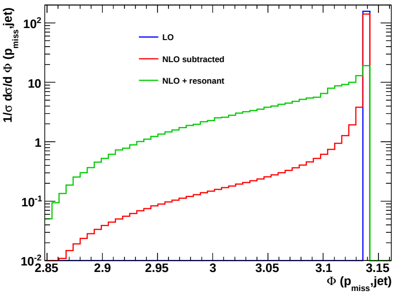
Checks on calculation:

- IR poles from virtual cancel with the poles from the real contribution
- Virtual matrix element agrees with FeynArts [T.Hahn et al]
- We check the small width limit

Neutralino Pair plus One Jet

- NLO pdf set NNPDF2.3
- Cuts: follow ATLAS monojet cuts
- $p_{T,1} \geq 100$ GeV, $p_{T,2} \leq 30$ GeV, $|\eta_j| \leq 4.5$
- $E_{T,\text{miss}} \geq 85$ GeV
- Scale choice: $\mu = H_T/2$ (where $H_T = \sum_i E_{T,i}$)





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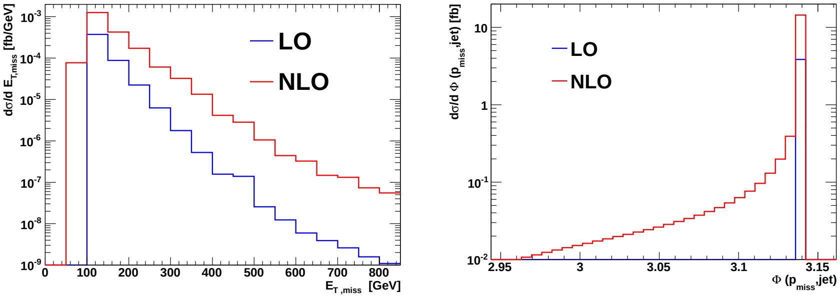


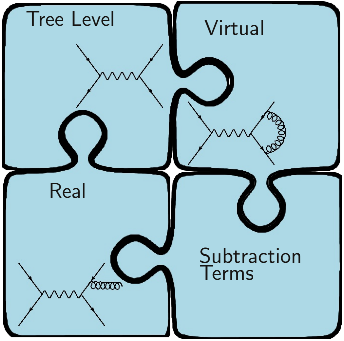
Neutralino Pair plus One Jet

Scale variation:

- "NLO" + resonant : no improvement (as expected)
- "NLO" subtracted: still dominated by new channels (gluon in the initial state) still no scale stabilisation (disappointing but true)
- We would expect to see a stabilization for the correction to neutralino pair plus two jets (no new surprises)
- Quite a striking demonstration that K-factors for NLO are not uniform across the distributions

Room for improvement

What did we learn?



Work flow:

- Virtual piece $\sim$ automatic
- Real piece $\sim$ automatic
- Subtraction terms $\sim$ automatic
- Matching : large cost of human time

Much progress has been made in the matching of the pieces using the Binoth Les Houches Interface

Room for improvement

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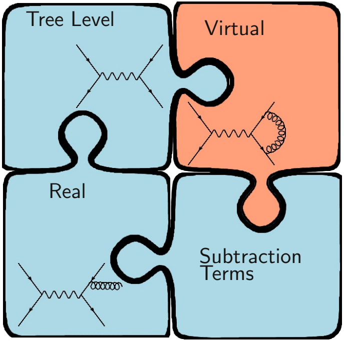

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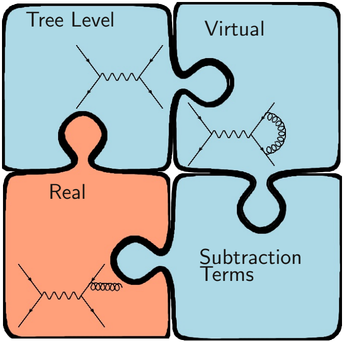

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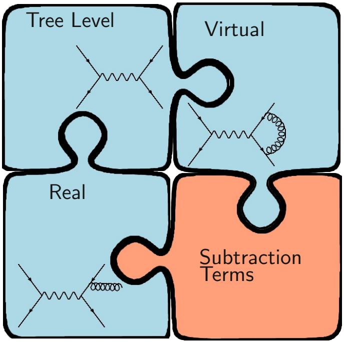

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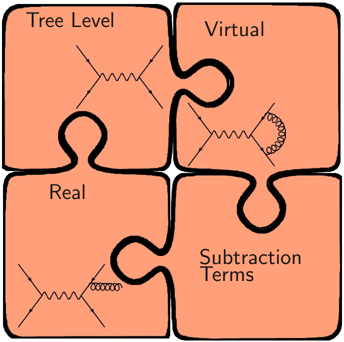

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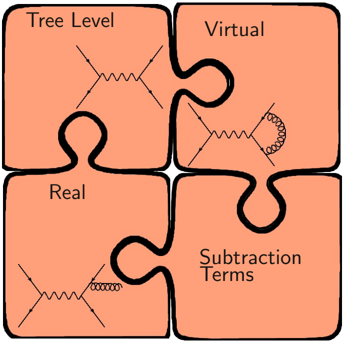

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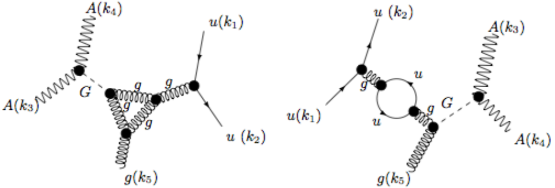
Graviton + 1 jet [Greiner, Heinrich, Reichel, von Soden-Fraunhofen (in preparation)]

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

- One-Loop : GoSam
- Real + Dipole + Phase Space integration : Sherpa
- Communication: Binoth Les Houches Accord
- Model : UFO format

Golem95C developed to treat up to boxes of rank 5 (will be extended in the future) and process checked with higher rank Samurai



More details and new results soon

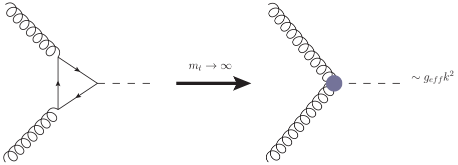
Moving towards full automated NLO in BSM

Towards Full NLO: Standard Model Example

GoSam + Sherpa: Higgs + 2 jets

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

- Effective theory in the limit $m_t \to \infty$
- One extra power of loop momentum in the numerator compared to renormalisable case $\to$ rank of integral can now be greater than the number of propagators
- Reduction libraries Samurai developed to treat higher rank multileg computation [Mastrolia, Mirabella, Peraro '12; van Deurzen, Mastrolia, Mirabella, Ossola, Tramontano '12]



Towards Full NLO: Standard Model Example

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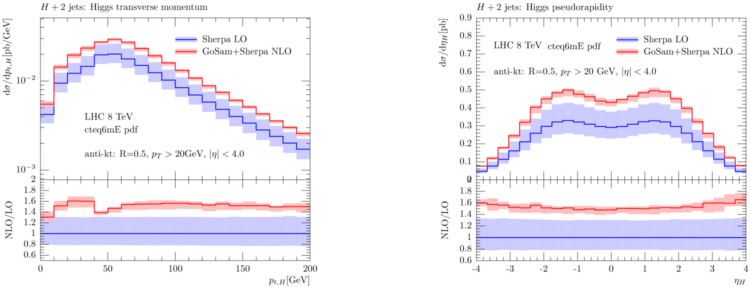
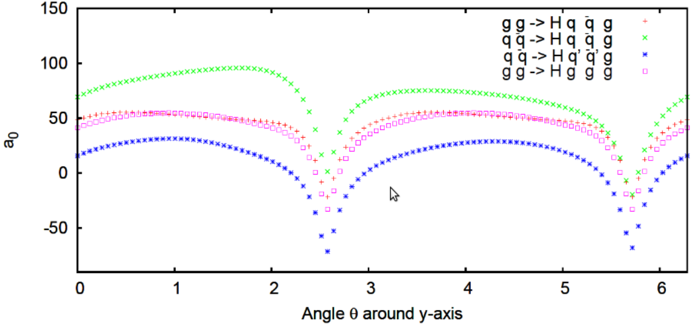


Towards Full NLO: Standard Model Example

GoSam + Sherpa: Higgs + 3 jets [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]

Rotation of phase space point around the y-axis



$$\frac{2Re(\mathcal{M}_B^* \mathcal{M}_V)}{(4\pi\alpha_s)|\mathcal{M}_B|^2} = \frac{a_{-2}}{\epsilon^2} + \frac{a_{-1}}{\epsilon} + a_0$$

Code Development Outlook

Further Code Optimisation:

- Challenge: How can we decrease the size of our generated code?
- Solution: Code optimised using new features of FORM (replacing Haggies) [FORM team, Nikhef]

Example:

- 1 loop piece of process : $gg \to t\bar{t}g$ ($\sim$ 500 diagrams, all helicities)
- Optimisations : Haggies $\to$ Form
- size of test.exe: 1.9 GB $\to$ 488 MB
- Executable is 1/4 of the size!

This and other code developments $\to$ GoSam-2.0 later this year

Summary and Outlook

- Interest in physics processes (and healthy competition) pushes code development and can lead to fruitful collaboration across groups
- GoSam in good shape for BSM physics: I presented a couple of examples Beyond the Standard Model
- Find it at http://projects.hepforge.org/gosam
- New release with significant optimizations expected v. soon