MadGolem: Automated NLO predictions for SUSY and beyond

David López-Val

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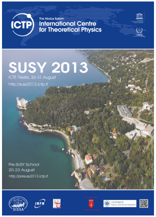
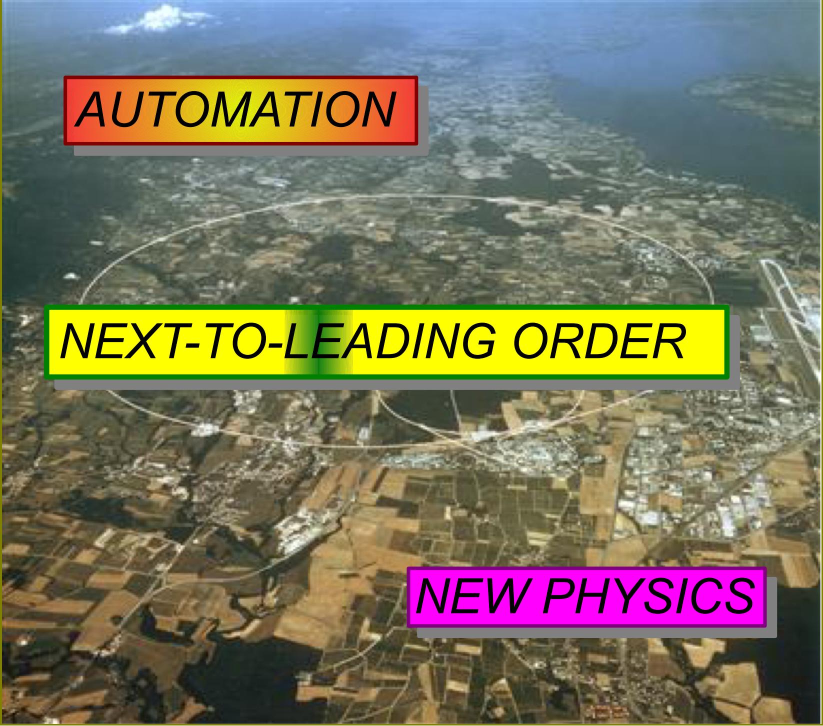
ITP - Universität Heidelberg



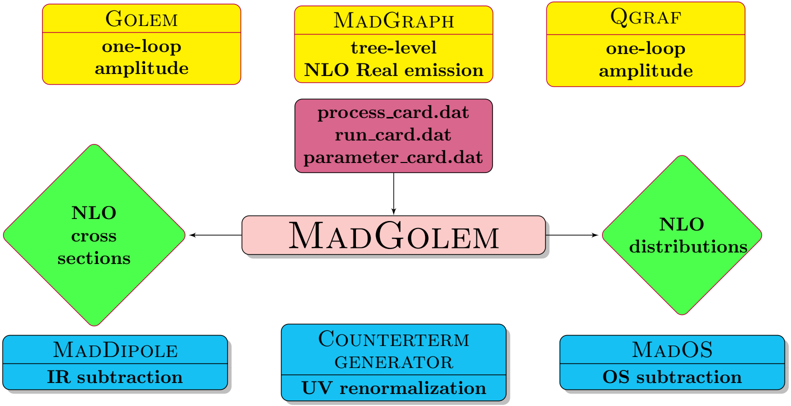
SUSY 2013, Trieste (Italy) - **August 29th 2013**

Outline

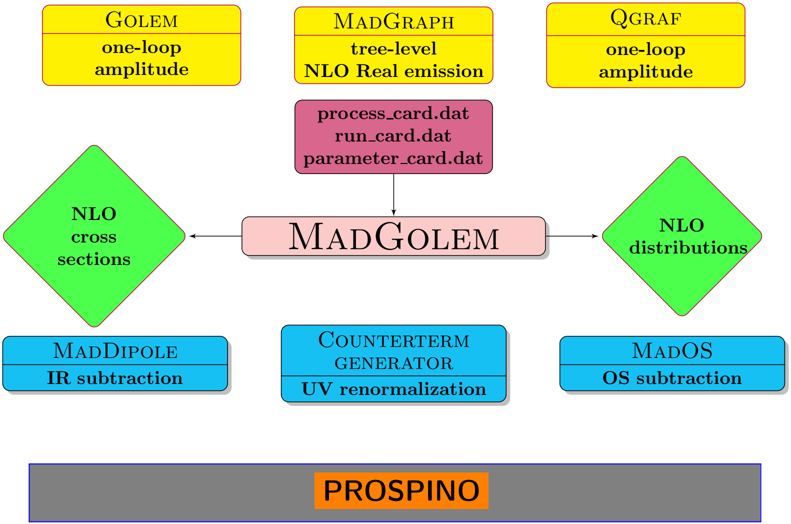
Outline


AUTOMATION
NEXT-TO-LEADING ORDER
NEW PHYSICS

Modules & flowchart



Modules & flowchart



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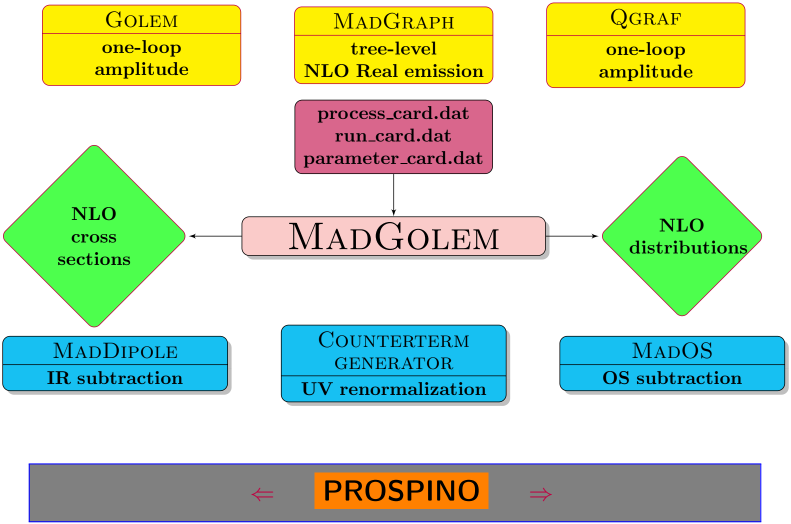

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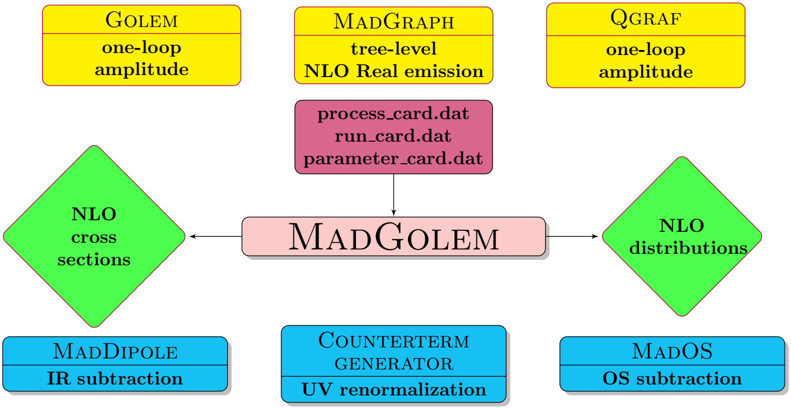

Automating ⇐ **PROSPINO** ⇒ *Generalizing*

Outline

Automating NLO – the major hurdles

Loops

Divergences

One-loop amplitude

The lo ♠ GENERATION $\longleftrightarrow$ Qgraph [Nogueira]

Model files $\xrightarrow{\text{FORTRAN}}$ Feynman diagrams

One-loop amplitude

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♠ TRANSLATION ⟷ Qgraf-Golem

Feynman diagrams $\xrightarrow{\text{BASH,PERL,FORM}}$ Amplitude

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vertices propagators color Lorentz structures rel. signs sym. factors

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vertices propagators color Lorentz structures rel. signs sym. factors

♠ CALCULATION ⟷ Golem [Binoth et al.]

$$\text{Amplitude} \xrightarrow{\text{BASH,PERL,FORM,MAPLE}} \text{Reduced amplitude}$$

One-loop amplitude

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$$\mathcal{M}^{\text{NLO}} = \underbrace{\mathcal{M}^{\text{NLO}}_{[\text{color}/\text{helicity}/\text{1l}-\text{function}]}}_{\text{partial amplitudes}} \times \underbrace{\mathcal{B}_{\text{color}} \otimes \mathcal{B}_{\text{hel}} \otimes \mathcal{B}_{\text{1Lfunction}}}_{\text{basis}}$$

One-loop amplitude

♠ ***Analytical results accessible at any time***

♠ ***Dedicated coding**: efficient generation & numerical evaluation*

- Loop filtering
- Grouping of topologically equivalent one-loop diagrams
- Amplitude coefficients as split dynamic libraries loaded at runtime

♠ ***Genuine New Physics structures treatable***

- Majorana fermions (clashing arrows !)
- complex color & spin structures
- MSSM renormalization – including heavy flavor squarks & SUSY restoration.

♠ ***Most easily interfaced with MG tools*** : FeynRules, MadAnalysis, . . .

Outline

Running MadGolem

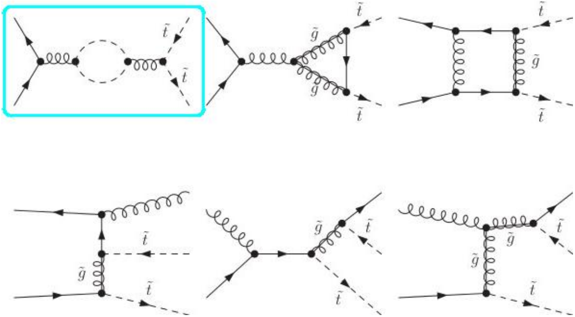
3-stage procedure – 3 interfaces ↔ 3 executables

Stage 1: PROCESS GENERATION

process_card ↔ ./newprocess_snlo

Feynman diagrams @NLO

- Virtual corrections – $\mathcal{O}(\alpha_s)$ virtual gluon/gluino/squark exchange
- Real corrections: quark and gluon emission off the initial partons and the final-state squark



i) **self-energy insertions**; ii) vertex corrections; iii) box diagrams; iv) real emission

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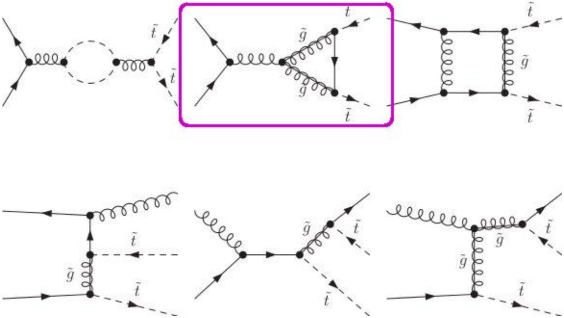

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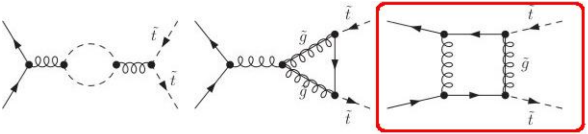

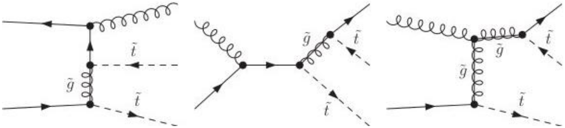

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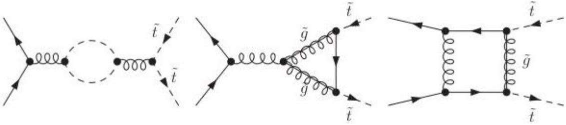
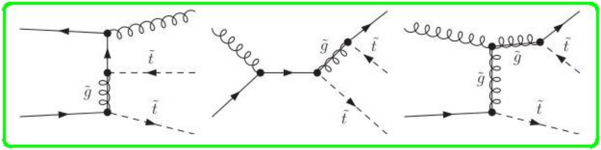
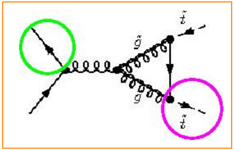




i) self-energy insertions; ii) vertex corrections; iii) box diagrams; iv) **real emission**

Feynman diagrams @NLO

The Feynman diagrams get generated . . .



```
+ 1   *
inp([field.u], idx1r2, p1) *
inplorentz(+1, iv1r2L1, p1, ZERO   ) *
inpcolor(1, iv1r2C3) *
inp([field.ux], idx1r1, p2) *
inplorentz(-1, iv1r1L1, p2, ZERO   ) *
inpcolor(2, iv1r1C3) *
out([field.tl], idx2r3, p3) *
outlorentz(+0, iv2r3L0, p3, MT1    ) *
outcolor(1, iv2r3C3) *
out([field.tlx], idx3r3, p4) *
outlorentz(-0, iv3r3L0, p4, MT1    ) *
outcolor(2, iv3r3C3) *
vertex(iv1,GG       ,ONE,
[field.ux], idx1r1, -1, p2, iv1r1L1, -3, iv1r1C3,
[field.u], idx1r2, +1, p1, iv1r2L1, +3, iv1r2C3,
```

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♠ At this point the user is able to:

- Select diagram topologies ⇒ detailed analysis of the virtual corrections
- Access the **analytical output** in several stages ⇒ very useful for cross-checking (and to dig out some physics!)

Feynman diagrams @NLO

The scattering amplitudes are further translated . . .

GRAPHS_MGGOLEM_LOOP.h – KWrite

File Edit View Tools Settings Help

New Open Save Save As Close Undo Redo Enlarge Font Find Next Find Previous Find Go to Line

```
G diagram4 =  + Den( - k1 - k2,0)*intM(Den(q1,TMASS2),Den(k3 + q1,MGO2)
      ,Den( - k4 + q1,MGO2))*SUNF(Glu19,Glu17,Glu18)*SUNSum(Col10,3)*
      SUNSum(Glu17,8)*SUNSum(Glu18,8)*SUNSum(Glu19,8)*SUNT(Glu17,Col3,
      Col10)*SUNT(Glu18,Col10,Col4)*SUNT(Glu19,Col2,Col1)*GG2*scalar3*
      scalar4*Pi^(-2) * ( 1/64*Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,
         0,1)*g_(2,7_,k4,Lor5,k3,q1)*i_*GT1GOP1*GT1GOM2*GGI2 + 1/64*
         Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,1)*g_(2,7_,k4,Lor5,
         k3)*i_*TMASS*GT1GOP2*GT1GOM2*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,
         7_,Lor5)*Spinor(k2,0,1)*g_(2,7_,k4,Lor5,k3)*i_*TMASS*GT1GOP1*
         GT1GOM2*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,
         1)*g_(2,7_,k4,Lor5,q1,q1)*i_*GT1GOP1*GT1GOM2*GGI2 + 1/64*
         Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,1)*g_(2,7_,k4,Lor5,
         q1)*i_*TMASS*GT1GOP2*GT1GOM2*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,
         7_,Lor5)*Spinor(k2,0,1)*g_(2,7_,k4,Lor5,q1)*i_*TMASS*GT1GOP1*
         GT1GOM2*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,
         1)*g_(2,7_,k4,Lor5)*i_*MGO*TMASS*GT1GOP2*GT1GOM2*GGI2 + 1/64*
         Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,1)*g_(2,7_,q1,k4,
         Lor5,k3)*i_*GT1GOP2*GT1GOM1*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,
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         GT1GOM1*GGI2 + 1/64*Spinor(k1,0,-1)*g_(2,7_,Lor5)*Spinor(k2,0,
         1)*g_(2,7_,q1,k4,Lor5)*i_*MGO*GT1GOP2*GT1GOM1*GGI2 - 1/64*
```

Feynman diagrams @NLO

and analytically reduced

```
FUN[  4] :=  BUBd4(S12,MG02,MG02):
FUN[  5] :=  BUBd4(S12,MT12,MT12):
FUN[  6] :=  BUBd4(S12,TMASS2,TMASS2):
FUN[  7] :=  TADd4(MT12):
FUN[  8] :=  TRId4(MT12,MT12,S12,MT12,0,0):
FUN[  9] :=  TRId4(MT12,MT12,S12,TMASS2,MG02,MG02):
FUN[ 10] :=  TRId4(MT12,S12,MT12,MT12,MT12,0):
FUN[ 11] :=  TRId4(MT12,S12,MT12,TMASS2,TMASS2,MG02):
#
#   2 non-zero out of   4 helicity amplitudes found
#   1 unique helicity amplitudes found
#
NUM_HELIS :=   4:
base_helis := [2, 3]:
unique_helis := [2]:
symmetry_helis := [[2, 3]]:
HELI[  2]:=[1, -1, 5, 5]:
HELI[  3]:=[-1, 1, 5, 5]:
#
ReferenceVector  := [k3b, k3b, k1, k1]:
FINAL_GRAPH_LIST := [2, 3, 4, 5, 6, 7]:
#
GRAPH_COEFF[  4,  2,  1,  1,  2] := -1/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(MT12*GT1G0P2*GT1G0M1+MT1
GRAPH_COEFF[  4,  2,  2,  1,  2] := 3/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(MT12*GT1G0P2*GT1G0M1+MT12
GRAPH_COEFF[  4,  2,  1,  1,  4] := 1/32*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-2*MT12*GT1G0P1*GT1G0M2-2
GRAPH_COEFF[  4,  2,  2,  1,  4] := -3/32*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-2*MT12*GT1G0P1*GT1G0M2-
GRAPH_COEFF[  4,  2,  1,  1,  9] := -1/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-MG0^2*MT12*GT1G0P1*GT1G
GRAPH_COEFF[  4,  2,  2,  1,  9] := 3/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-MG0^2*MT12*GT1G0P1*GT1G0
SPINOR_FAC[  4,  2] := InvSpaa(k2,k3)*InvSpbb(k1,k3):
```

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  - Access the **analytical output** in several stages ⇒ very useful for cross-checking (and to dig out some physics!)

Stage 3: NUMERICAL EVALUATION

param_card.dat, run_card.dat ↔ ./generate_events_nlo 2 2 myrun

Running MadGolem

MadGolem results

K-factor=(P1+P2+P3)/P1= 1.647

Total LO cross section 204.221

Total NLO cross section 336.318

Graph	Cross Sect(fb)	Error(fb)	Events (K)	Eff	Unwgt	Luminosity
NLO CONTRIBUTION: TREE-LEVEL SQUARED						
P1_gg_tltlx	187.220	0.438	0	0.0		0.00
P1_uux_tltlx	22.421	0.029	0	0.0		0.00
P1_uxu_tltlx	22.411	0.029	0	0.0		0.00
total NLO (tree-level squared) = 232.05199999999999						
LEADING ORDER						
P0_gg_tltlx	150.570	0.348	0	0.0		0.00
P0_uux_tltlx	26.833	0.035	0	0.0		0.00
P0_uxu_tltlx	26.818	0.035	0	0.0		0.00
total LO = 204.22100000000003						
NLO CONTRIBUTION: Virtual part						
P2_gg_tltlxg	104.190	0.448	0	0.0		0.00
P2_uux_tltlxg	2.366	0.013	0	0.1		0.00
P2_uxu_tltlxg	2.119	0.012	0	0.1		0.00
P2_gux_tltlxux	-0.293	0.003	0	0.0		0.00
P2_uxg_tltlxux	-0.298	0.003	0	0.0		0.00
P2_gu_tltlxu	-1.195	0.043	0	0.0		0.00
P2_ug_tltlxu	-1.312	0.044	0	0.0		0.00
total NLO (virtual part)= 105.57695000000001						
NLO CONTRIBUTION: Real part						
P3_gg_tltlxg	1.523	0.024	0	0.2		0.00
P3_uux_tltlxg	0.689	0.003	0	0.0		0.00
P3_uxu_tltlxg	0.688	0.003	0	0.0		0.00
P3_gux_tltlxux	-0.111	0.001	0	0.0		0.00
P3_uxg_tltlxux	-0.112	0.001	0	0.0		0.00
P3_ug_tltlxu	-1.986	0.014	0	0.0		0.00

♠ And the user retrieves the results !

Automated NLO BSM phenomenology

First complete fully automated NLO calculations of BSM $2 \to 2$

Automated NLO BSM phenomenology

First complete fully automated NLO calculations of BSM $2 \to 2$

$pp \to \tilde{q}\tilde{\chi}_0$

arXiv:1108.1250

$pp \to GG^*$

arXiv:1203.6358

$pp \to [\tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}]$

arXiv:1211.0311

$pp \to l_8 \bar{l}_8$

arXiv:1303.0845

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BSM phenomenology @ NLO

- **Total NLO rates and K factors**
- unconstrained **Parameter space surveys**
- **Anatomy of the NLO quantum effects** – separated contributions for each one-loop topology & partonic sub-channel
- **Analytical expression for the one-loop amplitudes**
- **Scale dependences**
- **NLO distributions** & comparison to jet merging

Outline

Phenomenological case

Light 3rd generation squarks are motivated

- Naturalness – little hierarchy $\Longleftrightarrow$ Natural SUSY
- Unconstrained MSSM – no high-scale relations
- Higgs physics – a viable non-decoupling SUSY Higgs sector Han et al. ['13]
- Astrophysics & Cosmology – EW phase transition & baryogenesis
- Experimentally:
  - **Compelling decay patterns** – eventually rich in t/b
  - **t/b-rich final-states from $\tilde{g}$ decays**
  - **Loose mass constraints** – (e.g. for compressed $m_{\tilde{t}_1} - m_{\chi^0_1}$ spectra)

Benchmarks

3rd generation phenomenology

- pMSSM Berger et al ['08]; Cahill-Rowley ['13]:
  no high-scale relations R-parity; MFV;
  degenerated 1st & 2nd generations;
  suppressed Yukawas & trilinears for 1st & 2nd generations
  Light 3rd generation & Higgs physics Han ['13]

- NSUSY Dine, Dimopoulos, Espinosa, Giudice, Weiler ['93 – '13]
  light soft-masses for strong Yukawas; light μ term
  Specific benchmarks as laid out in Buchmuller ['13]; Baer, List ['13]

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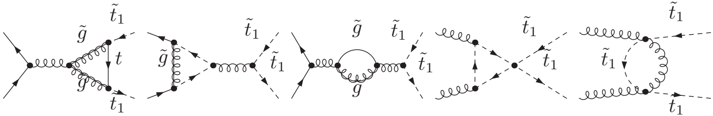
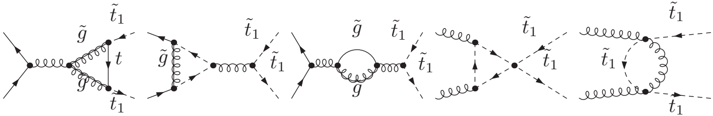
	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$	$m_{\chi_1^0}$	$m_{\chi_1^-}$	$m_{\tilde{g}}$
NSUSY1	434.93	990.31	891.56	1356.94	216.79	222.60	3202.64
NSCMSSM-10.2.2	398.43	682.54	155.16	303.00	231.32	425.38	1354.71
Light1	374.43	2022.88	387.88	2011.63	301.30	498.87	1102.32

$\tilde{t}\tilde{t}^*$ & $\tilde{b}\tilde{b}^*$ @ NLO: rates [preliminary]



(all rates in fb)

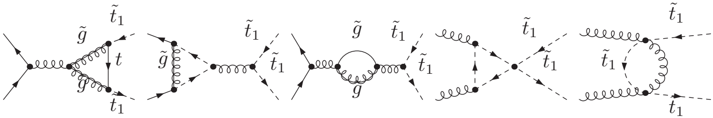
$\tilde{t}\tilde{t}^*$ & $\tilde{b}\tilde{b}^*$ @ NLO: rates [preliminary]

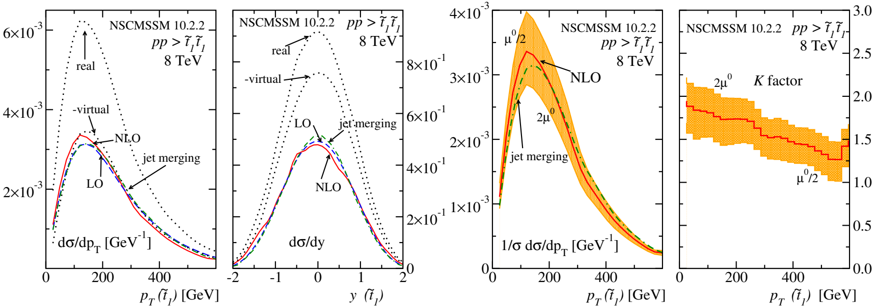


	$pp \to \tilde{t}_1\tilde{t}_1$			$pp \to \tilde{b}_1\tilde{b}_1$		
	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K
NSUSY1	11.56	224.40	1.88	2.62	7.01	2.67
NSUSY2	0.63	0.92	1.45	0.63	1.49	2.35
NSUSY3	214.91	281.91	1.32	2.62	9.03	3.45
NSCMSSM-10.2.2	2.11×10^2	3.38×10^2	1.60	4.17×10^4	6.12×10^4	1,47
NSCMSSM-40.2.2	2.69×10^3	4.61×10^3	1.64	47.32	80.95	1.71
NSCMSSM-40.3.2	7.86×10^2	1.25×10^4	1.59	0.16	0.31	1.93
Light1	3.00×10^3	4.95×10^2	1.65	1.93×10^3	3.02×10^3	1.57

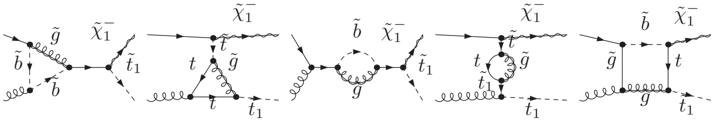
(all rates in fb)

$\tilde{t}\tilde{t}^*$ & $\tilde{b}\tilde{b}^*$ @ NLO: distributions [preliminary]

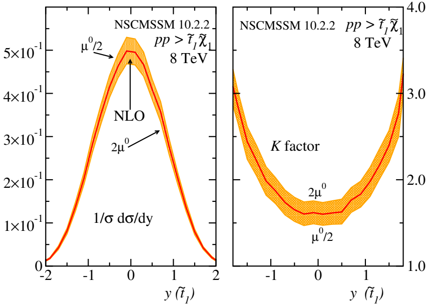




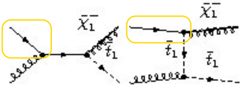
$\tilde{t}\tilde{\chi}^-$ @ NLO [preliminary]

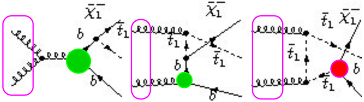


	$pp \to \tilde{t}_1 \chi_1^-$		
	σ^{LO}	σ^{NLO}	K
NSUSY1	5.60	7.73	1.38
NSUSY2	0.16	0.24	1.55
NSUSY3	8.56	10.93	1.28
NSCMSSM-10.2.2	1.47	2.58	1.76
NSCMSSM-40.2.2	6.57	10.89	1.66
NSCMSSM-40.3.2	8.46	12.86	1.52
Light1	0.10	0.12	1.17



4 versus 5 active flavors





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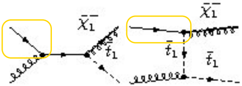
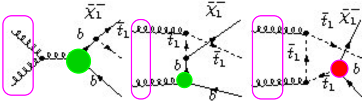


4FS

- $m_b \neq 0$
- $Q^2 \simeq m_b^2$
- initial-state b-quarks
- final-state b-quarks



5FS

- $m_b = 0$
- $Q^2 \gg m_b^2$
- b-quark PDF – $\log(Q^2/m_b^2)$
- Maltoni, Ridolfi, Ubiali ['12]

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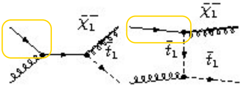

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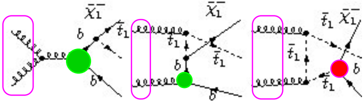

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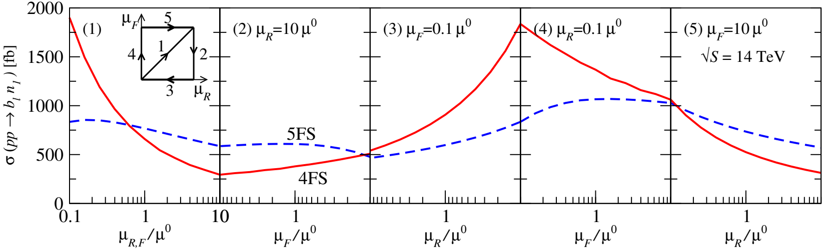
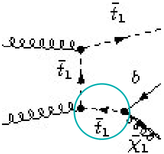
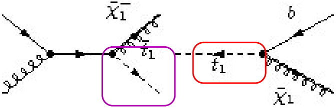


Automated on-shell subtraction



$gg \to \tilde{t}_1 \chi_1^- +$ b-jet



$gg \to \tilde{t}_1 \tilde{t}_1 \otimes \tilde{t}_1 \to \chi_1^- +$ b-jet

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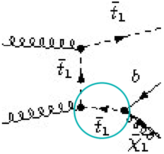
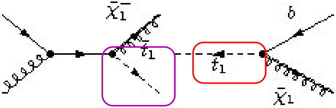


$gg \to \tilde{t}_1 \chi_1^- + \text{b-jet}$



$gg \to \tilde{t}_1 \tilde{t}_1 \otimes \tilde{t}_1 \to \chi_1^- + \text{b-jet}$

$$d\sigma^R \longrightarrow d\sigma^R\Big]_{\text{regular}} + d\sigma^{R*}\Big]_{\mathcal{O}(1/(p^2-m^2))}$$

$$\boxed{gg \to \tilde{t}_1 \chi_1^- + \text{b-jet}} + \boxed{gg \to \tilde{t}_1 \tilde{t}_1^*(\text{OS})} \otimes \boxed{\tilde{t}_1^*(\text{OS}) \to \chi_1^- + \text{b-jet}}$$

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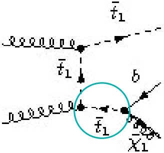
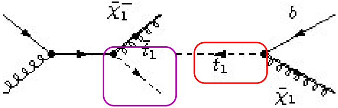


$gg \to \tilde{t}_1 \chi_1^- + \text{b-jet}$



$gg \to \tilde{t}_1 \tilde{t}_1 \otimes \tilde{t}_1 \to \chi_1^- + \text{b-jet}$

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$$gg \to \tilde{t}_1 \chi_1^- + \text{b-jet} \quad + \quad gg \to \tilde{t}_1 \tilde{t}_1^*(\text{OS}) \otimes \tilde{t}_1^*(\text{OS}) \to \chi_1^- + \text{b-jet}$$

$$\frac{d\sigma^{OS}}{dM^2} = \sigma^{Born}\, \frac{m_{\tilde{t}_1}\Gamma_{\tilde{t}_1}/\pi}{(M^2-m^2_{\tilde{t}_1})+m^2_{\tilde{t}_1}\Gamma^2_{\tilde{t}_1}} + \mathcal{O}\left(\frac{1}{(M^2-m^2_{\tilde{t}_1})}\right)$$

- ♠ phase-space singularity & double counting avoided
- ♠ gauge-invariance & spin correlations preserved

Beenakker, Höpker, Spira, Zerwas ['99]

Outline

Take-home ideas

MadGolem – THE TOOL

- Automated NLO cross-sections & distributions for $2 \to 2$ processes
- Highly modular, independent add-on to MadGraph/MadEvent
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Automated renormalization & subtraction
- Tailored for BSM & NLO studies

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MadGolem – ITS APPLICATION

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- NLO rates, K-factors, scale–dependences, distributions, theory uncertainties, flavor schemes

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♠ Standalones for numerical evaluation available upon request !