MadGolem & aMC@NLO: further on the road of automation

David López-Val

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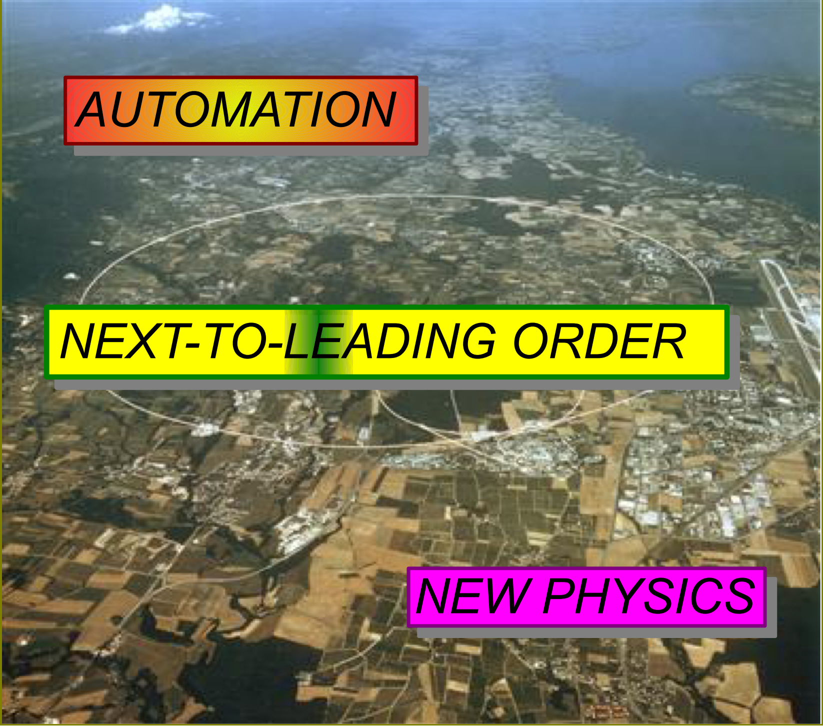
CP3 - Université catholique de Louvain

UCL Université catholique de Louvain

SUSY 2014, Manchester (UK) - **July 21st 2014**

Outline

Outline


AUTOMATION
NEXT-TO-LEADING ORDER
NEW PHYSICS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+PS
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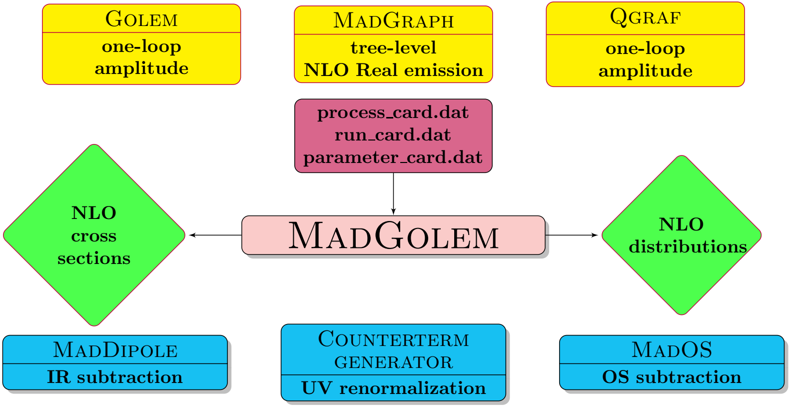
Modules & flowchart



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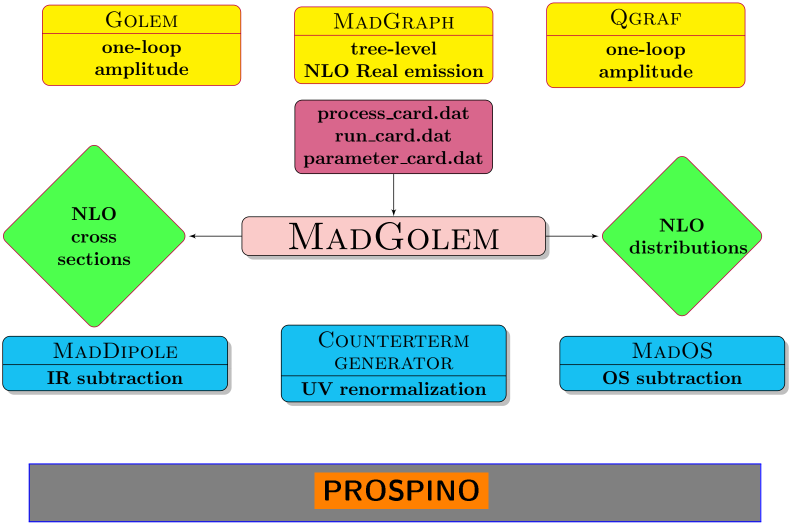

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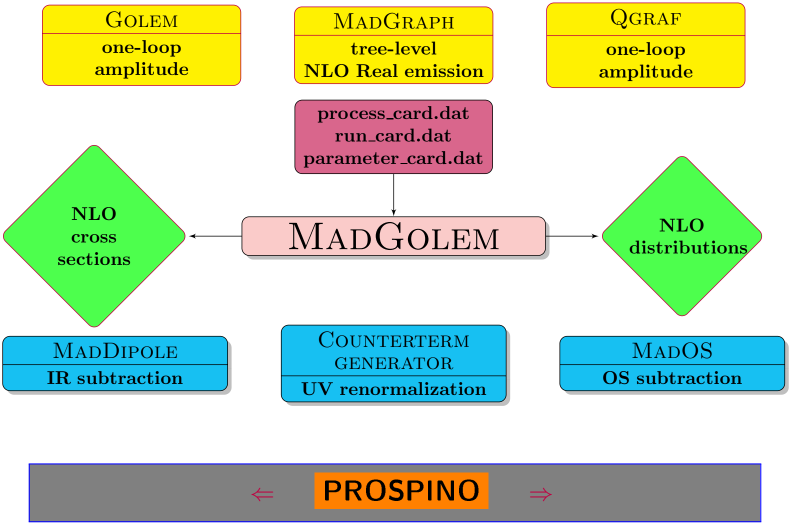

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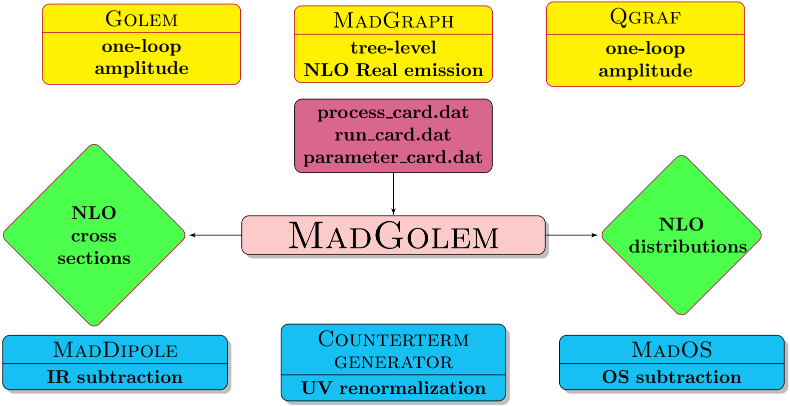

Automating ⇐ **PROSPINO** ⇒ *Generalizing*

Outline

The MadGolem program

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

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$pp \to \tilde{q}\tilde{\chi}_0$	$pp \to GG^*$	$pp \to \tilde{t}_1\tilde{t}_1^*, \tilde{b}_1\tilde{b}_1^*, \tilde{t}_1\chi_1^-$
arXiv:1108.1250	arXiv:1203.6358	arXiv:1407.4302
$pp \to [\tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}]$	$pp \to l_8\bar{l}_8$	Overview
arXiv:1211.0311	arXiv:1303.0845	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** – (topologies, subchannels)
- **Analytical expression for the one-loop amplitudes**
- **Scale dependence – theory uncertainties**
- **NLO distributions**
- **Latest updates:** MSSM@NLO with finite quark mass & squark mixing

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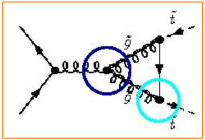
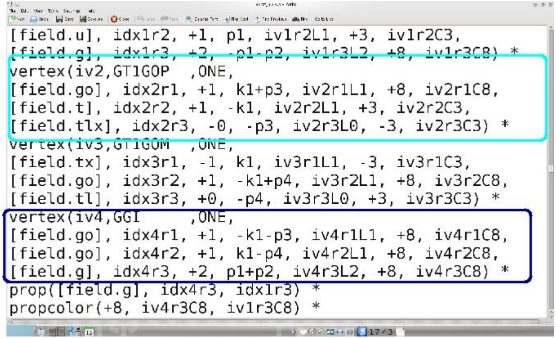
Architecture

From Feynman diagrams . . .





```
[field.u], idx1r2, +1, p1, iv1r2L1, +3, iv1r2C3,
[field.g], idx1r3, +2, -p1-p2, iv1r3L2, +8, iv1r3C8) *
vertex(iv2,GT1GOP   ,ONE,
[field.go], idx2r1, +1, k1+p3, iv2r1L1, +8, iv2r1C8,
[field.t], idx2r2, +1, -k1, iv2r2L1, +3, iv2r2C3,
[field.tlx], idx2r3, -0, -p3, iv2r3L0, -3, iv2r3C3) *
vertex(iv3,GT1GOM   ,ONE,
[field.tx], idx3r1, -1, k1, iv3r1L1, -3, iv3r1C3,
[field.go], idx3r2, +1, -k1+p4, iv3r2L1, +8, iv3r2C8,
[field.tl], idx3r3, +0, -p4, iv3r3L0, +3, iv3r3C3) *
vertex(iv4,GGI      ,ONE,
[field.go], idx4r1, +1, -k1-p3, iv4r1L1, +8, iv4r1C8,
[field.go], idx4r2, +1, k1-p4, iv4r2L1, +8, iv4r2C8,
[field.g], idx4r3, +2, p1+p2, iv4r3L2, +8, iv4r3C8) *
prop([field.g], idx4r3, idx1r3) *
propcolor(+8, iv4r3C8, iv1r3C8) *
```

Architecture

. . . to analytic amplitudes . . .

```
FUN[  4] :=  BUBd4(S12,MGO2,MGO2):
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,MGO2,MGO2):
FUN[ 10] :=  TRId4(MT12,S12,MT12,MT12,MT12,0):
FUN[ 11] :=  TRId4(MT12,S12,MT12,TMASS2,TMASS2,MGO2):
#
#   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*GT1GOP2*GT1GOM1+MT1
GRAPH_COEFF[  4,  2,  2,  1,  2] := 3/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(MT12*GT1GOP2*GT1GOM1+MT12
GRAPH_COEFF[  4,  2,  1,  1,  4] := 1/32*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-2*MT12*GT1GOP1*GT1GOM2-2
GRAPH_COEFF[  4,  2,  2,  1,  4] := -3/32*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-2*MT12*GT1GOP1*GT1GOM2-
GRAPH_COEFF[  4,  2,  1,  1,  9] := -1/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-MGO^2*MT12*GT1GOP1*GT1G
GRAPH_COEFF[  4,  2,  2,  1,  9] := 3/16*GG2*GGI2*(S23^2-2*MT12*S23+MT12^2+S23*S12)*(-MGO^2*MT12*GT1GOP1*GT1GO
SPINOR_FAC[  4,  2] := InvSpaa(k2,k3)*InvSpbb(k1,k3):
```

Architecture

In 3 steps – through 3 interfaces ↔ with 3 executables

Step 1: PROCESS GENERATION

process_card ↔ ./newprocess_snlo

Step 2: AMPLITUDE CALCULATION

./run_golem_pl

Step 3: NUMERICAL EVALUATION

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

3gen@NLO – the physics case

Light 3rd generation squarks are motivated

- Naturalness – little hierarchy $\Longleftrightarrow$ Natural SUSY
- RG effects, squark mixing, non–universal soft–breaking
- Implications for Higgs physics, Astrophysics & Cosmology
- 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 $m_{\tilde{t}_1} - m_{\chi_1^0}$ spectra)
  - **associated production with $\chi^{\pm}$**

3gen@NLO – Benchmarks

3rd generation phenomenology

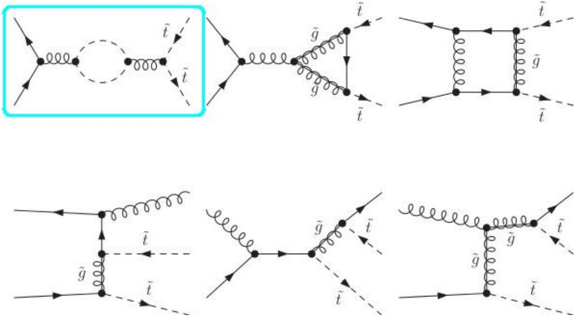
- **NSUSY** Dine, Dimopoulos, Espinosa, Giudice, Weiler ['93 – '13] Buchmuller ['13]; Baer, List ['13] light soft-masses for strong Yukawas ; light μ term ; sub–TeV 3gen, heavy gluinos, higgsino–like inos.
- **Natural–like CMSSM** **non–universal GUT–scale squark soft–breaking masses**
- **Light SUSY** non–decoupling SUSY Higgs sector Han et al. ['13]

	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$	$m_{\chi_1^0}$	$m_{\chi_1^-}$	$m_{\tilde{g}}$
NSUSY1	434.93	990.31	891.56	1356.94	216.79	222.60	3202.64
NSCMSSM-10.2.2	398.43	682.54	572.4	684.6	231.32	425.38	1354.71
Light1	374.43	2022.88	387.88	2011.63	301.30	498.87	1102.32

Gonçalves Netto, DLV, Mawatari, Plehn [arXiv:1407.4302]

3gen@NLO – squark pairs

- **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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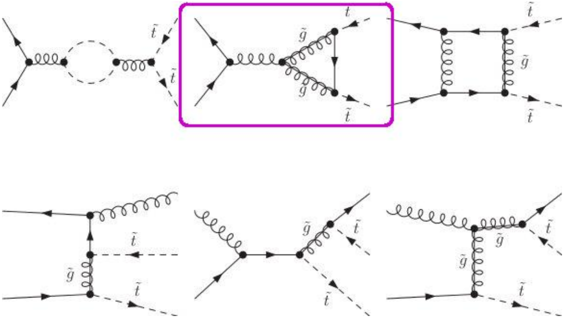

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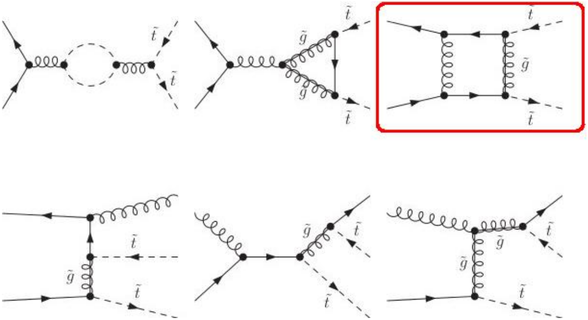

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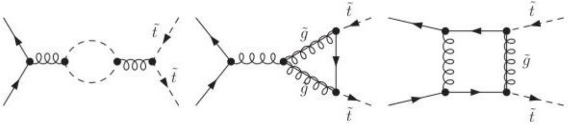

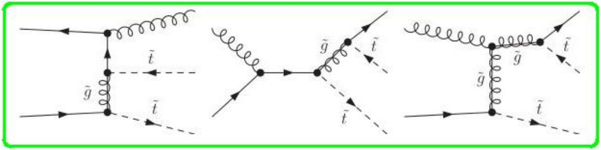

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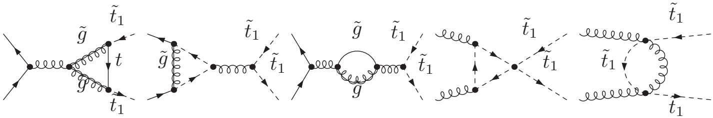

	$pp \to \tilde{t}_1\tilde{t}_1$			$pp \to \tilde{b}_1\tilde{b}_1$		
	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K
NSUSY1	881.0	1380.0	1.57	10.8	18.0	1.70
NSUSY2	12.1	20.4	1.69	0.11	0.23	1.87
NSCMSSM-10.2.2	1430.0	2210	1.54	180	290	1.61
NSCMSSM-40.2.2	14800.0	21800	1.47	558.0	882.0	1.58
NSCMSSM-40.3.2	4680.0	7010.0	1.50	28900	46200	1.60
Light1	2010	3080	1.53	1660.0	2550.0	1.53

(all rates in fb for the LHC@14 TeV)

Gonçalves Netto, DLV, Mawatari, Plehn [arXiv:1407.4302]

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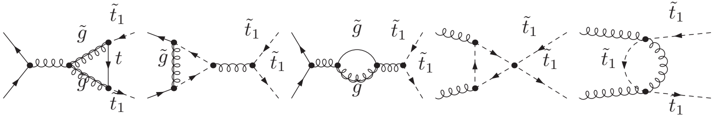

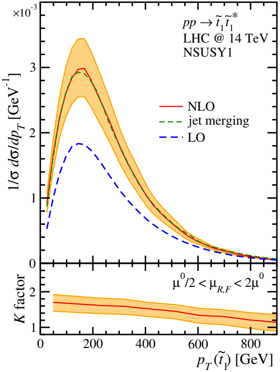

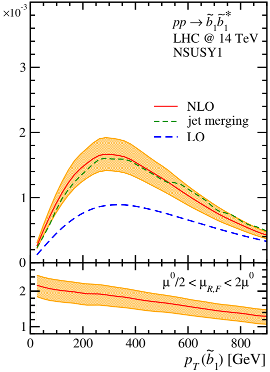

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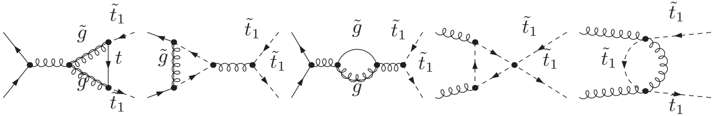

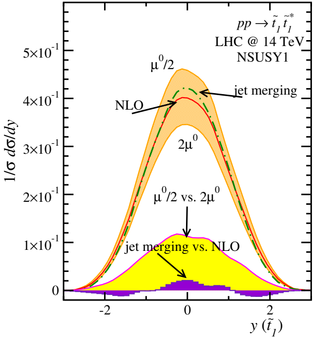

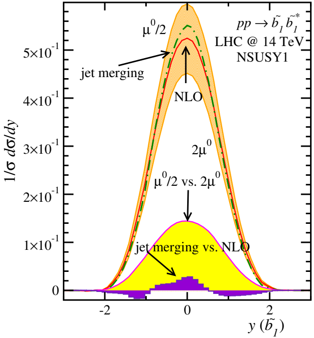

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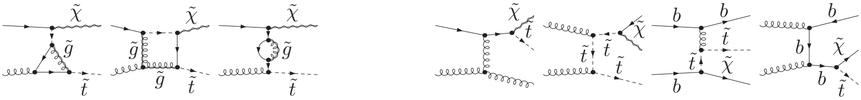
3gen@NLO – associated stop–chargino



	$pp \to \tilde{t}_1 \chi_1^-$		
	σ^{LO}	σ^{NLO}	K
NSUSY1	40.97	49.98	1.22
NSUSY2	1.94	2.51	1.29
NSCMSSM-10.2.2	13.40	20.14	1.50
NSCMSSM-40.2.2	47.83	71.21	1.48
NSCMSSM-40.3.2	53.39	78.94	1.48
Light1	9.96	10.51	1.05

(all rates in fb for the LHC@14 TeV)

Gonçalves Netto, DLV, Mawatari, Plehn [arXiv:1407.4302]

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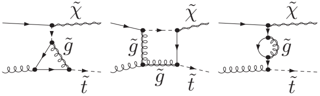

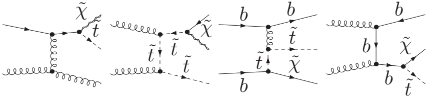

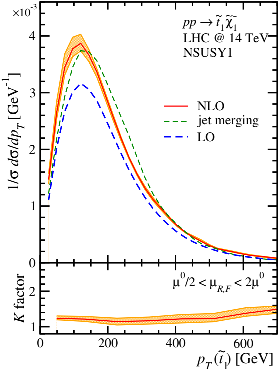

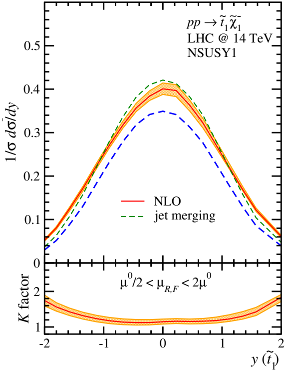

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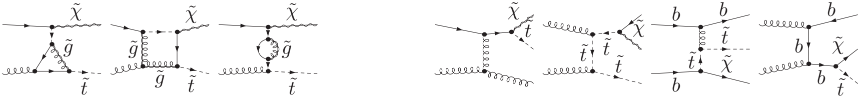

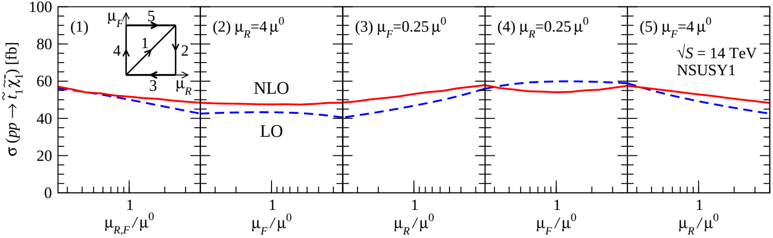

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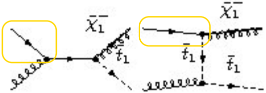
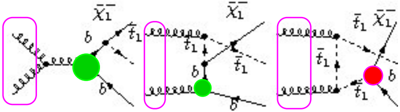
3gen@NLO: flavor schemes





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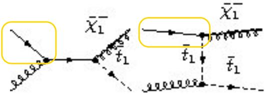
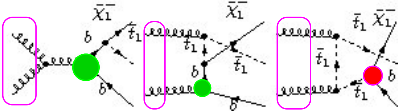


5FS

- $m_b = 0$
- $Q^2 \gg m_b^2$
- bottom PDF



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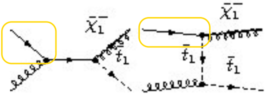

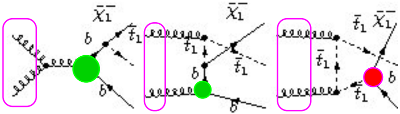

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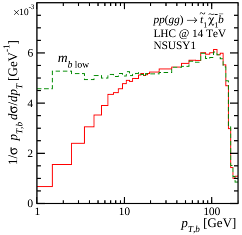
$$\frac{d\sigma[\tilde{t}_1 \tilde{\chi}_1^- \bar{b}]}{dp_{T,b}} \sim \frac{p_{T,b}}{p_{T,b}^2 + m_b^2}$$

$$\sigma[\tilde{t}_1 \tilde{\chi}_1^- \bar{b}] \sim \log \frac{p_{T,b}^{\mathrm{max}}}{m_b} \, .$$



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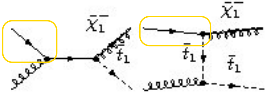

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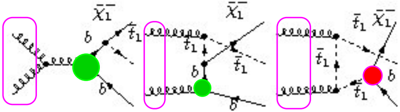

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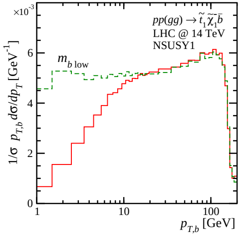
- gluon splitting $g \to b\bar{b}$

$$\frac{d\sigma[\tilde{t}_1\tilde{\chi}_1^-\bar{b}]}{dp_{T,b}} \sim \frac{p_{T,b}}{p_{T,b}^2 + m_b^2}$$

$$\sigma[\tilde{t}_1\tilde{\chi}_1^-\bar{b}] \sim \log \frac{p_{T,b}^{\text{max}}}{m_b} \; .$$



♠ 5FS validation with $\mu_F \lesssim (m_{\tilde{t}_1} + m_{\chi_1^-})/2$ – cf. e.g. Maltoni, Ridolfi, Ubiali ['12]

Outline

Beyond fixed–order predictions

Automating NLO+PS

♠ **Whys and wherefores**

- Improved accuracy in the distribution shapes
- Realistic description of final–states
- Better comparison to data

♠ **The challenge**

- Matching fixed–order to PS consistently

♠ **Our strategy**

- **MadGolem** – Gonçalves Netto, DLV, Mawatari, Plehn, Wigmore – arXiv:1303.0845
- MadGraph5_aMC@NLO – Alwall, Zaro, et al. – arXiv:1405.0301

MadGolem

Loop amplitudes
UV renormalization
OS subtraction

MadGraph5_AMC@NLO

User interfaces
Tree amplitudes
MadEvent
MadFKS
MC@NLO

Translation routines

Binoth LH accord

Beyond fixed–order predictions

♠ Automating NLO+PS Gonçalves Netto, DLV, Mawatari, Zaro [in progress]

Beyond fixed–order predictions

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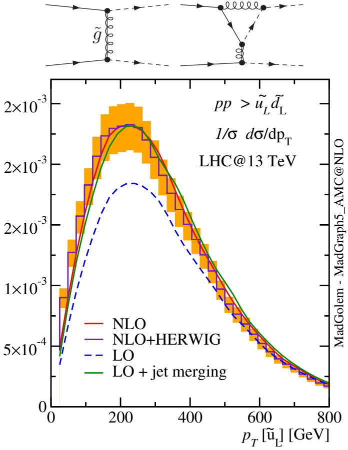
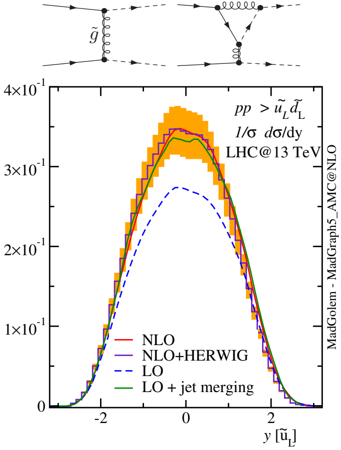
$pp \to \tilde{u}_L \tilde{d}_L$ $pp \to \tilde{u}_L \tilde{d}_L$





Outline

Take-home ideas

MadGolem carried to completion

- Automated NLO cross-sections & distributions for $2 \to 2$ processes
- Highly modular, independent add-on to MadGraph/MadEvent
- Analytical, Feynman-diagrammatic one-loop amplitudes – **tailored for BSM**
- Automated UV renormalization, SUSY dipole & OS subtraction
- Latest application: SUSY 3gen phenomenology

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Further on the road

- BSM @ NLO + PS
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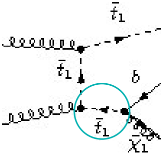
♠ Preliminary results for $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{\chi}$ at hand – **much more to come !**

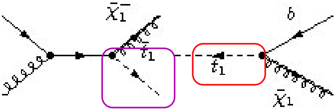
BACKUP

SLIDES

3gen@NLO – OS subtraction

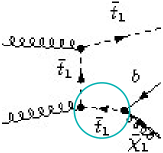


$gg \to \tilde{t}_1 \chi_1^- + \text{b-jet}$



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

3gen@NLO – OS subtraction



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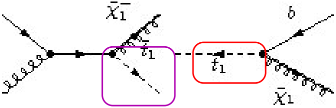
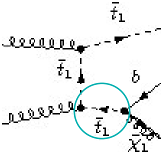


$gg \to \tilde{t}_1 \tilde{t}_1 \otimes \tilde{t}_1 \to \chi_1^- + \text{b-jet}$

♠ **A twofold caveat:** phase-space singularity & double counting

3gen@NLO – OS subtraction



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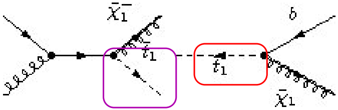

$gg \to \tilde{t}_1 \tilde{t}_1 \otimes \tilde{t}_1 \to \chi_1^- + \text{b-jet}$

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- Prospino scheme - Beenakker, Höpker, Spira, Zerwas ['99]

preserves **gauge invariance** & **spin correlations**

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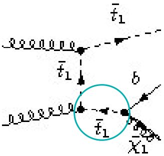
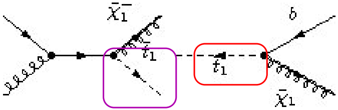


$gg \to \tilde{t}_1 \chi_1^- + \text{b-jet}$



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

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preserves **gauge invariance** & **spin correlations**

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

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