

MadGolem: automated NLO predictions for BSM searches

David López-Val

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ITP - Universität Heidelberg

[arXiv:1108.1250](https://arxiv.org/abs/1108.1250)



[arXiv:1203.6358](https://arxiv.org/abs/1203.6358)



[arXiv:1209.2797](https://arxiv.org/abs/1209.2797)



Charged Higgs 2012 @ Uppsala, Sweden - October 10th 2012

Outline

1 Motivations and overview

2 MadGolem – the tool

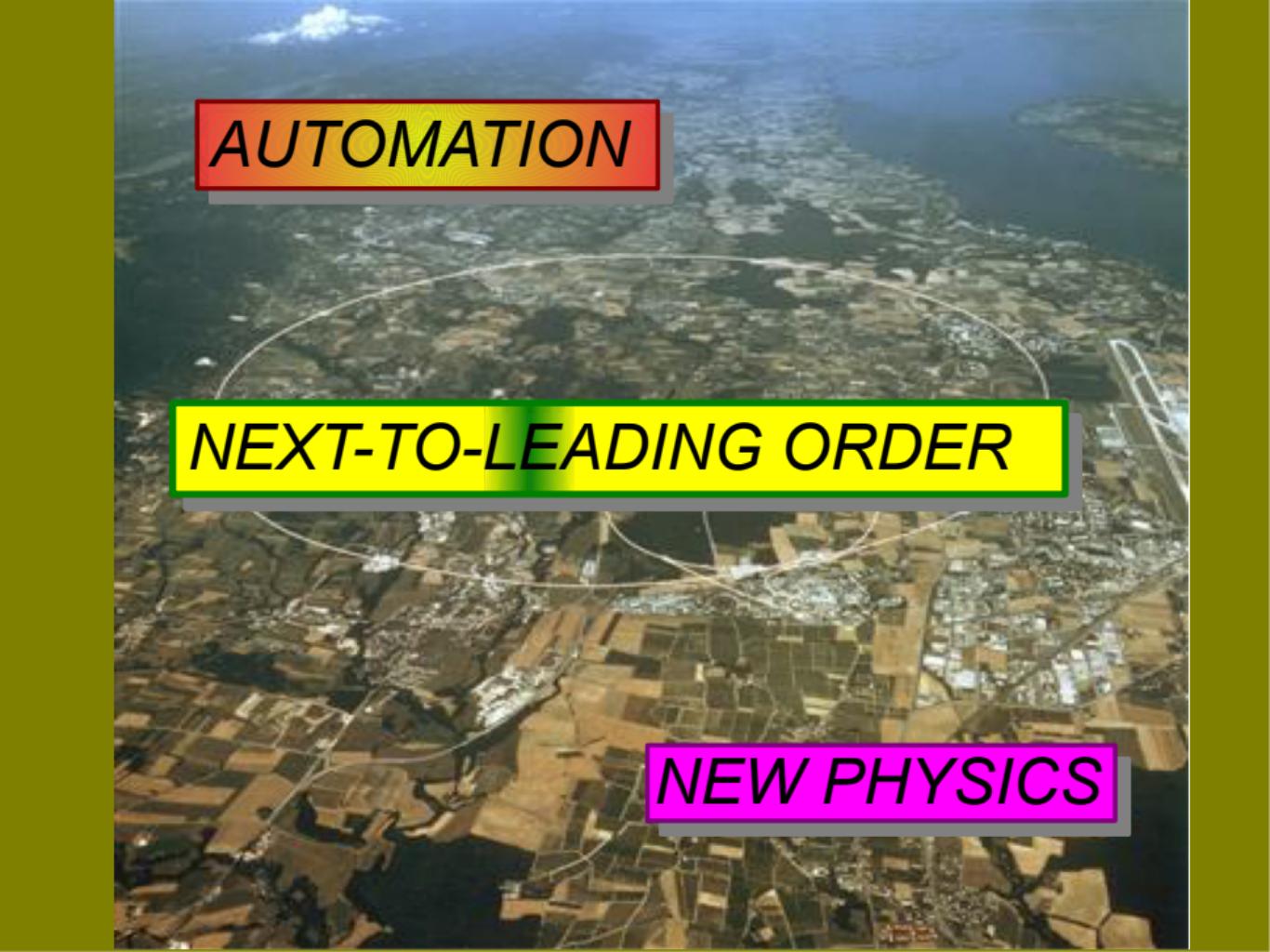
- MadGolem's structure
- MadGolem in use

3 Applications to BSM phenomenology

4 Summary & outlook

What ?





AUTOMATION

NEXT-TO-LEADING ORDER

NEW PHYSICS

Why ?



Whys and wherefores: physical & technical

Why NLO ?

- Heavy colored states as a **BSM hallmark**:
 - ♠ SUSY \Rightarrow squarks&gluinos ;
 - ♠ Compositeness \Rightarrow sgluons&colorons ;
 - ♠ Extra dim. \Rightarrow KK gluons ;
- QCD corrections quantitatively relevant : $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, kinematics. . .

Whys and wherefores: physical & technical

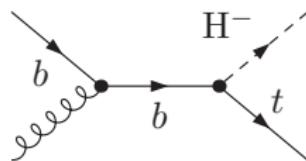
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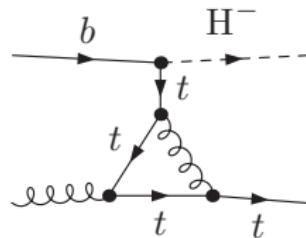
Why Automation ?

- Many models & processes \leftrightarrow analogue technical challenges
- Cost & time saving, robustness, accessibility, validation, EXP-TH interchange:
MadGolem; MadGraph5 [Hirsch et al., arXiv:1103.0621]; GoSam [Cullen et al., arXiv:1111.2034]; HELAC-NLO [Bevilacqua et al., arXiv:1007.4918]; aMC@NLO [Frederix et al. arXiv:1104.5613]

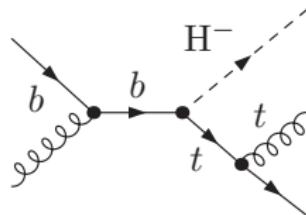
Seeking for new physics with MadGolem



tree-level



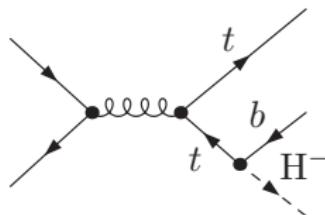
virtual corrections $\mathcal{O}(\alpha_{ew} \alpha_s^2)$



real corrections $\mathcal{O}(\alpha_{ew} \alpha_s^2)$



ii , fi & if dipoles



OS divergent real corrections $\mathcal{O}(\alpha_{ew} \alpha_s^2)$



OS subtraction

How ?



LOOPS
GOLEM

LOOPS
QGRAF

MadGOLEM

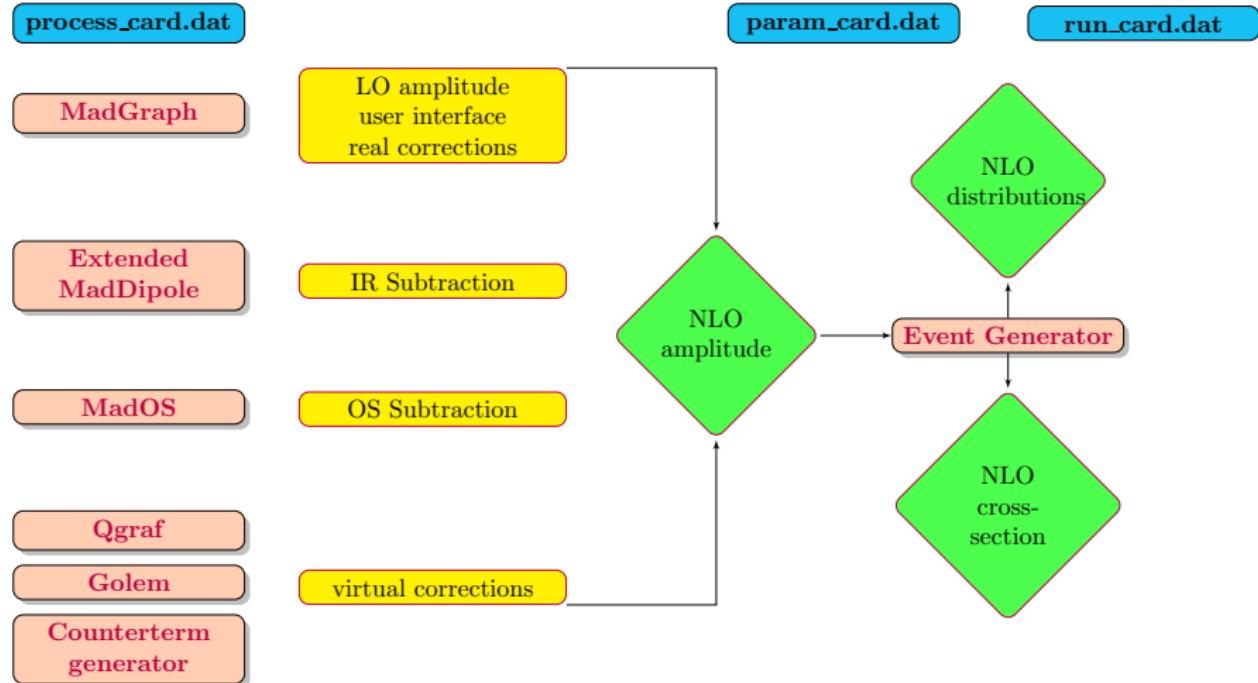
TREE
MadGraph

IR divergences
**Extended
MadDipole**

UV divergences
Renormalization

OS divergences
MadOS

MadGolem's architecture: modules and flowchart



Handling the virtual parts



GENERATION



Qgraph [Nogueira]

Model files FORTRAN Feynman diagrams

Handling the virtual parts



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Model files

FORTRAN

Feynman diagrams



TRANSLATION



Qgraf-Golem

Feynman diagrams

BASH,PERL,FORM

Amplitude

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vertices

propagators

color

Lorentz structures

rel. signs

sym. factors

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**CALCULATION****Golem [Binoth et al.]**

Amplitude

BASH,PERL,FORM,MAPLE

Reduced amplitude

Handling the virtual parts

♠ GENERATION \longleftrightarrow Qgraph [Nogueira]

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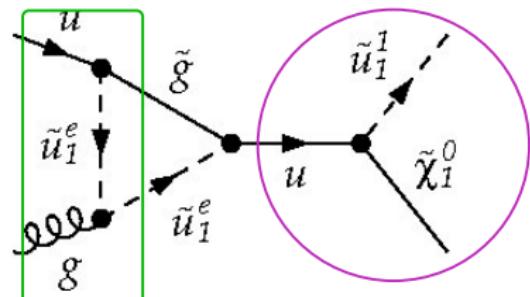
Amplitude $\xrightarrow{\text{BASH,PERL,FORM,MAPLE}}$ Reduced amplitude

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

Handling the loops

The Feynman diagrams get generated ...

```
+ 1 *
inp([field.u], idx2r2, p1) *
inplorentz(+1, iv2r2L1, p1, ZERO ) *
inpcolor(1, iv2r2C3) *
inp([field.g], idx3r1, p2) *
inplorentz(+2, iv3r1L2, p2, ZERO ) *
inpcolor(2, iv3r1C8) *
out([field.ul], idx1r3, p3) *
outlorentz(+0, iv1r3L0, p3, MUL ) *
outcolor(1, iv1r3C3) *
out([field.nl], idx1r1, p4) *
outlorentz(+1, iv1r1L1, p4, MN1 ) *
outcolor(2, iv1r1C1) *
vertex(iv1,GULNIP ,ONE,
[field.nl], idx1r1, +1, -p4, iv1r1L1, +1, iv1r1C1,
[field.u], idx1r2, +1, p3+p4, iv1r2L1, +3, iv1r2C3,
[field.ulx], idx1r3, -0, -p3, iv1r3L0, -3, iv1r3C3) *
vertex(iv2,GQLGOP ,ONE,
[field.go], idx2r1, +1, k1-p1, iv2r1L1, +8, iv2r1C8,
[field.u], idx2r2, +1, p1, iv2r2L1, +3, iv2r2C3,
[field.ulx], idx2r3, -0, -k1, iv2r3L0, -3, iv2r3C3) *
vertex(iv3,GC ,ONE,
[field.g], idx3r1, +2, p2, iv3r1L2, +8, iv3r1C8,
[field.ul], idx3r2, +0, k1, iv3r2L0, +3, iv3r2C3,
[field.ulx], idx3r3, -0, -k1-p2, iv3r3L0, -3, iv3r3C3) *
```



Handling the loops

and analytically reduced

`GRAPH_COEFF` has indices: `NGRAPH,NHELI,NCOL,NEPSTEN,NFUN`

```

GRAPH_COEFF[ 1, 8, 1, 1, 1]:= -1/36*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/P
GRAPH_COEFF[ 1, 8, 2, 1, 1]:= 1/12*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/P
GRAPH_COEFF[ 1, 8, 1, 1, 2]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 2]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 3]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 3]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 4]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 4]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 5]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 5]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 6]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 6]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 7]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 7]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 8]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 8]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 9]:= 1/36*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/P
GRAPH_COEFF[ 1, 8, 2, 1, 9]:= 1/12*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/P
GRAPH_COEFF[ 1, 8, 1, 1, 10]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 10]:= 0:
GRAPH_COEFF[ 1, 8, 1, 1, 11]:= 0:
GRAPH_COEFF[ 1, 8, 2, 1, 11]:= 0:
SPINOR_FAC[ 1, 8 ]:= InvSpaa(k1,k2)*InvSpaa(k1,k4)*InvSpaa(k2,k3)*InvSpbb(k1,k3):

```

Handling the divergences

UV divergences & Renormalization



Counter terms \Rightarrow tree-level diagrams + $\mathcal{O}(\alpha_s)$ 2-point functions

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Handling the divergences

UV divergences & Renormalization

- ♠ Counter terms \Rightarrow tree-level diagrams + $\underbrace{\mathcal{O}(\alpha_s) \text{ 2-point functions}}_{\delta Z_{g_s}, \delta Z_\psi \sim \Sigma_\psi}$
- ♠ Renormalization scheme : masses @ OS, $g_s @ \overline{\text{MS}}$ with decoupled heavy colored-states [Beenakker et al, Berge et al]
- ♠ SUSY restoration (if applicable) automatically included [Martin, Vaughn; Beenakker et al].



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IR divergences

- ♠ Dipole Subtraction:
[Catani, Seymour; Catani, Dittmaier, Seymour, Trocsanyi]
- ♠ New dipole structures for novel heavy colored particles – including α -dependence
- ♠ Extended MadDipole module [Frederix, Gehrmann, Greiner '07]

Handling the OS Divergences

Automatized Prospino OS Subtraction [Beenakker, Höpker, Spira, Zerwas]

$$\begin{aligned} d\sigma^R &\longrightarrow d\sigma^R \Big]_{\text{regular}} + d\sigma^{R*} \Big]_{\mathcal{O}(1/(p^2 - m^2))} \\ bg \rightarrow tH^- j &+ qq \rightarrow t\bar{t} \rightarrow tH^- + 1 b\text{jet} \end{aligned}$$

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$$\sigma = \int_{m+1}^R d\sigma^R$$

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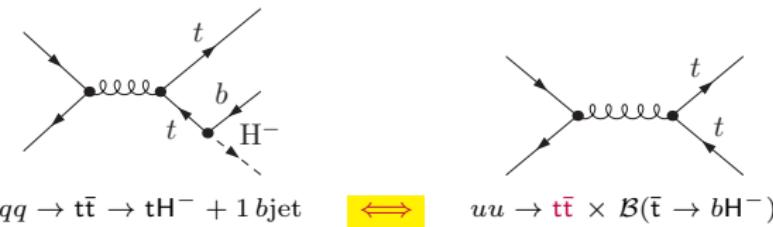
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$$d\sigma^{\text{OS}} = \sigma^{\text{LO}} \frac{m_t \Gamma_t / \pi}{(s_{tH}^2 - m_t^2) + m^2 \Gamma_t^2} + \mathcal{O}\left(\frac{1}{(s_{tH}^2 - m_t^2)}\right)$$

- Pointwise subtraction of the OS poles – analogue to CS dipoles
- Avoids double-counting & preserves gauge invariance & spin correlations
- Γ_t as regulator \Rightarrow dependence cancels in the final results

From the user's viewpoint ...

3-stage procedure – 3 interfaces ↔ 3 executables

Stage 1: DEFINING THE PROCESS

process_card ↔ ./newprocess_nlo

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Stage 2: COMPUTING THE AMPLITUDE

./run_golem_pl

- ♣ 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!)

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Stage 3: EVALUATING THE CROSS-SECTIONS

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

From the user's viewpoint ...

♠ And the user retrieves the results !

MadGolem results

$$s = 8533.480 \pm 0.793(\text{ab})$$

$$\text{K-factor} = (P1 + P2 + P3)/P1 = 1.119$$

Graph	Cross Sect(ab)	Error(ab)	Events (K)	Eff	Unwgt	Luminosity
Sum	8533.480	0.793		0	0.0	
LEADING ORDER						
P1_e-e+_ululx	7625.900	0.506	0	0.0		0.00
total LO = 7625.899999999996						
NLO CONTRIBUTION: Virtual part						
P2_e-e+_ululxg	578.990	0.068	0	0.0		0.00
total NLO (virtual part) = 578.99000000000001						
NLO CONTRIBUTION: Real part						
P3_e-e+_ululxg	328.590	0.219	0	0.0		0.00
total NLO (real part) = 328.59000000000003						

Seeking for new physics with MadGolem

First **complete fully automated NLO calculations of BSM $2 \rightarrow 2$**

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$$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$$

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BSM phenomenology @ NLO

- **Total NLO rates and K factors**
- Parameter space surveys – with no constraints nor relations among couplings/masses assumed beforehand
- Anatomy of the NLO quantum effects – separated contributions for each one-loop topology & partonic subchannel
- Analytical expression for the one-loop amplitudes
- Scale dependencies
- NLO distributions – *easily compared to LO + jet merging with MadGraph5*

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Parameter space survey

$$pp \rightarrow \tilde{u}_L \tilde{u}_L$$

MSSM benchmark	$\tilde{u}_L \tilde{u}_L$			$\tilde{u}_L \tilde{u}_R$		
	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K
CMSSM 10.2.2	26.2	32.9	1.25	26.2	35.0	1.33
CMSSM 40.2.2	22.8	29.3	1.28	25.2	34.4	1.36
CMSSM 40.3.2	14.8	20.4	1.37	23.1	34.0	1.47
mGMSB 1.2	85.3	107.1	1.26	99.7	134.2	1.35
mGMSB 2.1.2	73.9	97.7	1.32	113.9	160.4	1.41
mAMSB 1.3	16.8	21.5	1.28	16.1	22.0	1.37

σ in fb, \sqrt{S} in TeV, m in GeV;

MSSM benchmarks from [\[Abdus Salam et al. arXiv:1109.3859\]](#)

Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore,to be submitted

Parameter space survey

$$pp \rightarrow \tilde{u}_L \tilde{u}_L$$

MSSM benchmark	$\tilde{u}_L \tilde{u}_L$			$\tilde{u}_L \tilde{u}_R$		
	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K
CMSSM 10.2.2	26.2	32.9	1.25	26.2	35.0	1.33
CMSSM 40.2.2	22.8	29.3	1.28	25.2	34.4	1.36
CMSSM 40.3.2	14.8	20.4	1.37	23.1	34.0	1.47
mGMSB 1.2	85.3	107.1	1.26	99.7	134.2	1.35
mGMSB 2.1.2	73.9	97.7	1.32	113.9	160.4	1.41
mAMSB 1.3	16.8	21.5	1.28	16.1	22.0	1.37

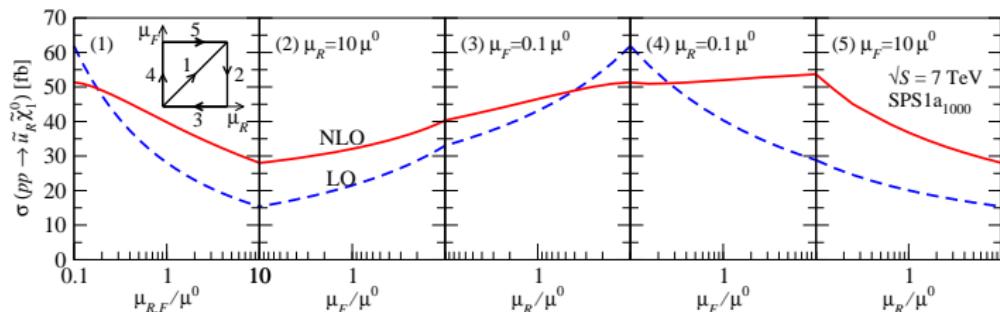
σ in fb, \sqrt{S} in TeV, m in GeV;

MSSM benchmarks from [\[Abdus Salam et al. arXiv:1109.3859\]](#)

Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore,to be submitted

Scale dependences

$$pp \rightarrow \tilde{u}_L \tilde{\chi}_1$$



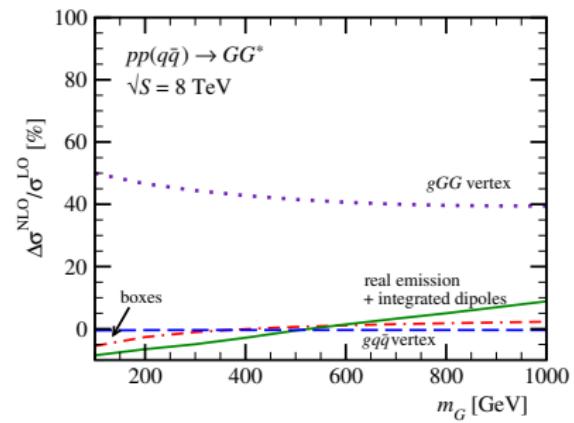
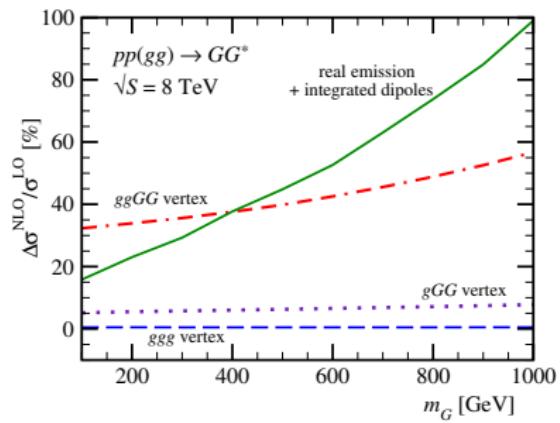
- Canonical estimate of the theory uncertainties: $\Delta\sigma^{\text{th}} = \sigma(\mu = \mu_0/2) - \sigma(\mu = 2\mu_0)$
- Remarkable scale stabilization

$$\Delta\sigma^{\text{LO}}/\sigma^{\text{LO}} \sim \mathcal{O}(80\%) \Rightarrow \Delta\sigma^{\text{NLO}}/\sigma^{\text{NLO}} \sim \mathcal{O}(30\%)$$
- Larger sensitivity to μ_R

Binoth, Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, PRD 84 (2011)
075005 arXiv:1108.1250 [hep-ph]

Anatomy of the virtual corrections

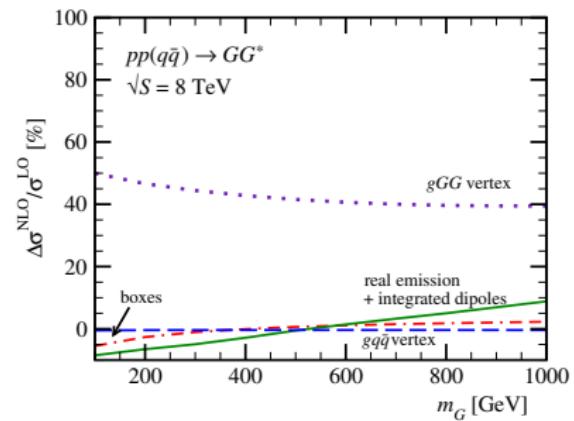
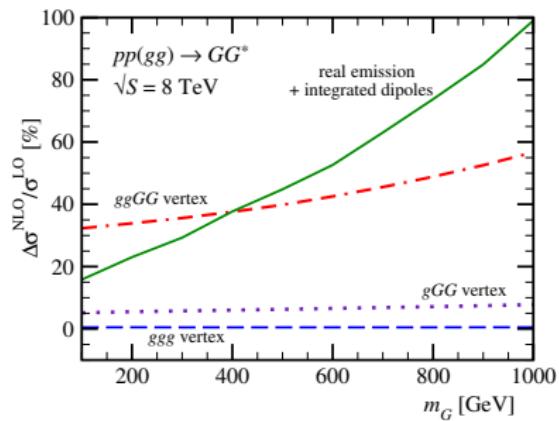
$pp \rightarrow GG^*$



♣ Dominance of the gGG & $ggGG$ vertex corrections and the real gluon emission

Anatomy of the virtual corrections

$pp \rightarrow GG^*$



♣ Dominance of the *gGG* & *ggGG* vertex corrections and the real gluon emission

♣ Sensitivity to threshold enhancements $\iff \beta = \sqrt{1 - \frac{4m^2}{s}}$

- Coulomb singularity $\sigma \sim \pi/\alpha_s \beta$ from long-range virtual gluon exchange

- Log-enhancement from gluon real emission $\sigma \sim [A \log^2(\beta) + B \log(8\beta^2)]$

Comparison with multi-jet merging

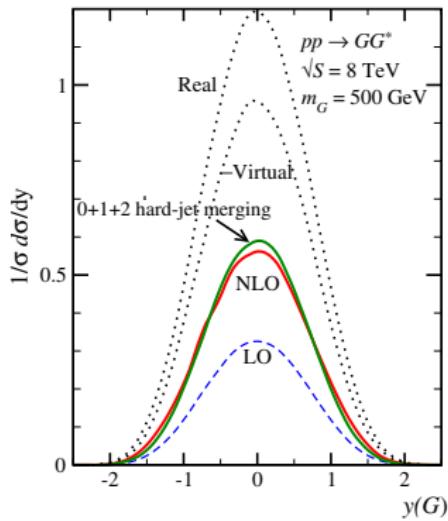
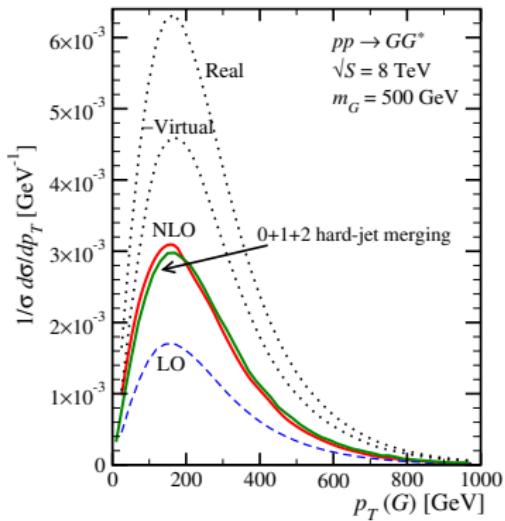


(fixed-order) NLO

VS

multi-jet merging

$$\frac{d\sigma}{dp_T} \Big|_{pp \rightarrow \bar{u}_R \bar{\chi}_1 \text{ @NLO}} \quad \text{VS} \quad \frac{d\sigma}{dp_T} \Big|_{pp \rightarrow \bar{u}_R \bar{\chi}_1 + 2j} \quad (\text{MLM}),$$



Comparison with multi-jet merging

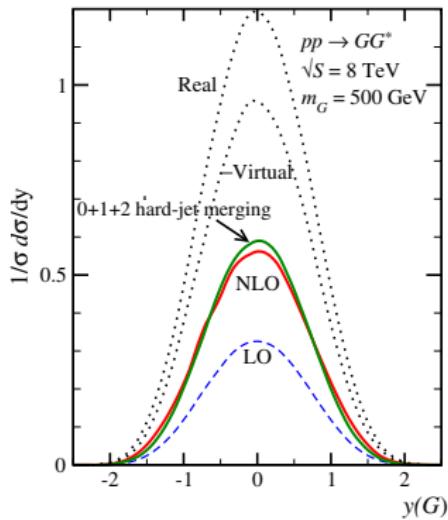
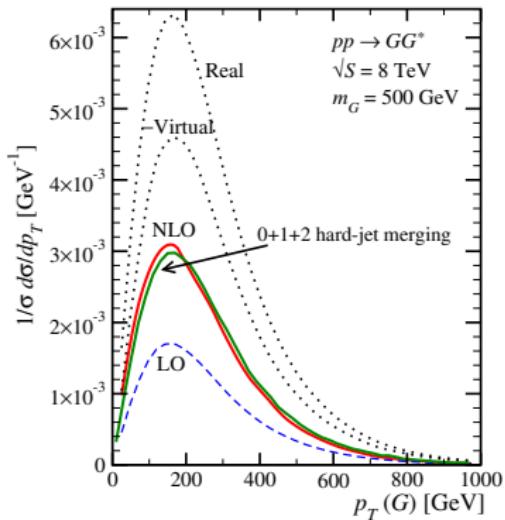


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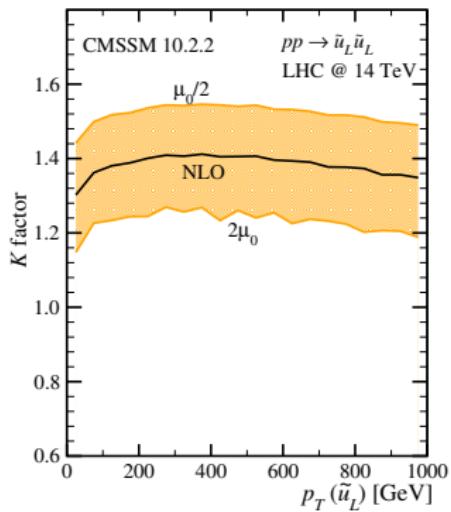
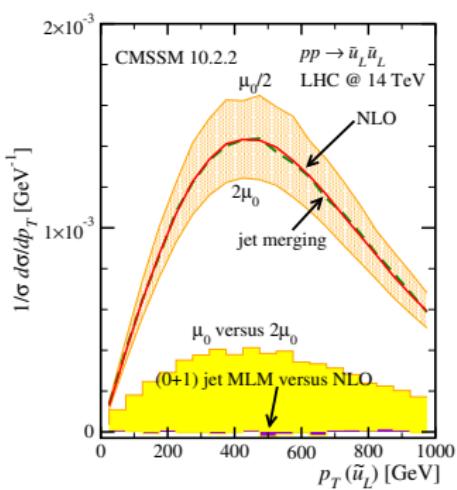


- Normalized distributions in **very good agreement**
- Common to **heavy particle** production – [Plehn, Rainwater, Skands '07], [Alwall, de Visscher, Maltoni '09]

Theoretical uncertainties

$$pp \rightarrow \tilde{u}_L \tilde{u}_L$$

- Scale dependence on a bin-by-bin basis - $\frac{d\sigma}{dp_T}|_{\mu=\mu_0/2} - \frac{d\sigma}{dp_T}|_{\mu=2\mu_0}$
- ⇒ Theoretical uncertainties from the distribution viewpoint



Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, to be submitted

2D distributions

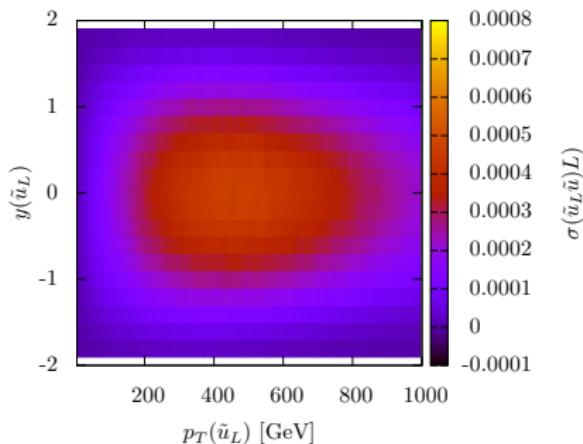
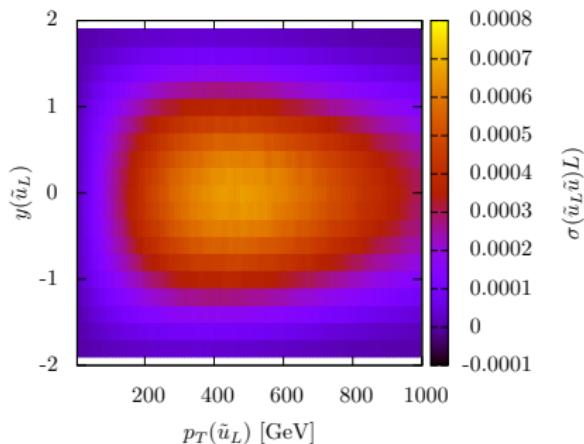
$$pp \rightarrow \tilde{u}_L \tilde{u}_L$$

Cross-section behavior across a p_T/y patch

$$- \frac{d\sigma}{dp_T dy}$$



Correlated observables at reach !



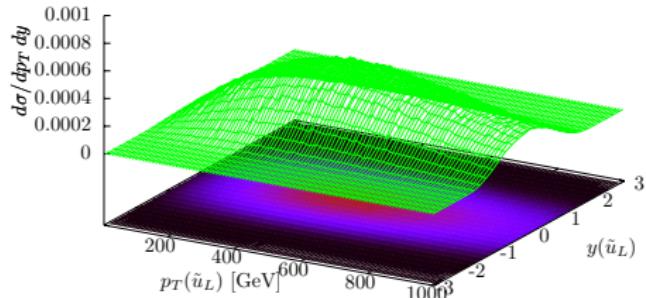
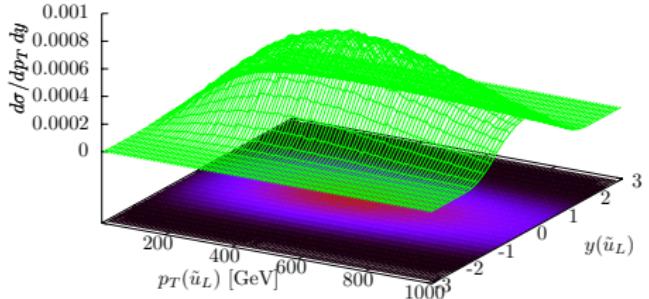
Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, to be submitted

2D distributions

$$pp \rightarrow \tilde{u}_L \tilde{u}_L$$

♠ Cross-section behavior across a p_T/y patch - $\frac{d\sigma}{dp_T dy}$

⇒ Correlated observables at reach !



Summing up ...



Take-home ideas

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MadGolem: the tool

- automates the calculation of **NLO cross-sections and distributions** for generic $2 \rightarrow 2$ new physics processes
- Highly **modular, independent** add-on to **MadGraph/MadEvent**
- **Analytical** one-loop calculation, based on **Feynman diagrams & Golem reduction**

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Heavy particle production at NLO: phenomenology

- **Large rates & K-factors**
- NLO $\mathcal{O}(\alpha_s)$ corrections **dominated** by pure QCD \iff gluon exchange/radiation
- Strongly **reduced** theoretical uncertainties
- **Excellent agreement** between NLO **VS** multi+jet merging

Take-home ideas

MadGolem contributes to extending bridges



Take-home ideas

MadGolem contributes to extending bridges



Theory

Experiment

Take-home ideas

MadGolem contributes to extending bridges



Theory

TACK SÅ MYCKET !!

Experiment