MadGOLEM: Automatizing NLO Calculations for New Physics

David López-Val

in collaboration with D. Gonçalves Netto, F. Gross, T. Plehn (Heidelberg U.), I. Wigmore (Edinburgh U.), K. Mawatari (Vrije U.)

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Ruprecht-Karls Universität Heidelberg

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Northwestern University, Illinois

Outline

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Tools for New Physics Searches at Hadron Colliders

The pathway towards Automatization

Why Automatization ?

- Many models & processes $\leftrightarrow$ analogue technical challenges
- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange

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Recent highlights

- Automated SM @ NLO : MadNLO [Hirsch et al.], arXiv:1103.0621
- Automated SM @ NLO + parton-shower : aMC@NLO [Frederix et al.] arXiv:1104.5613
- Automated BSM @ NLO : MadGOLEM [Gonçalves Netto, DLV, Mawatari, Plehn, Wigmore]

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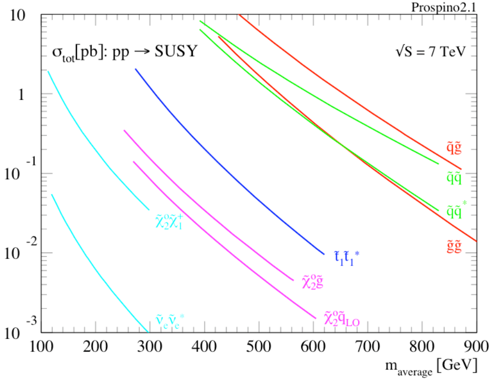
PROSPINO

Benakker, Höper, Krämer, Plehn, Spira, Zerwas



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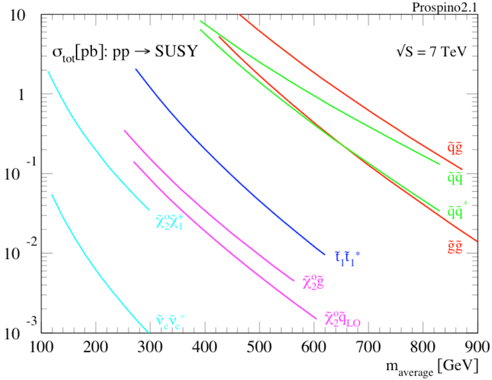
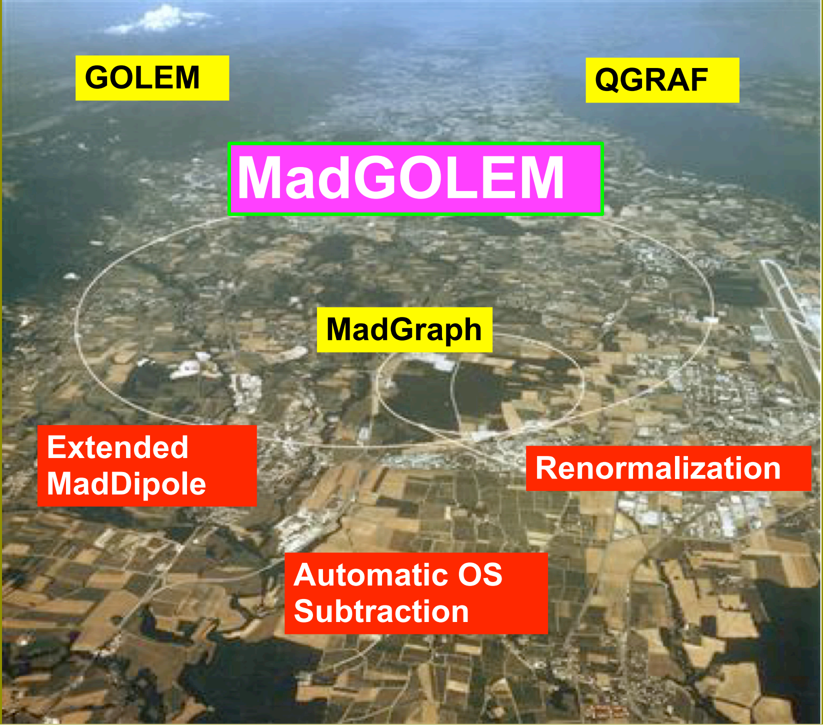


MadGOLEM

AUTOMATIZING $\Longrightarrow$ Prospino $\Longleftarrow$ *GENERALIZING*


GOLEM
QGRAF
MadGOLEM
MadGraph
Extended MadDipole
Renormalization
Automatic OS Subtraction

Outline

MadGOLEM from inside: an automatic NLO calculator

$2 \rightarrow 2(+j)$ cross-section at a hadron collider

$$\sigma^{NLO}_{\mathsf{pp}(p_1,p_2)\to X} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_a(x_1,\mu_F^2)\, f_b(x_2,\mu_F^2) \times \underbrace{\sigma^{NLO}_{p_1 p_2 \to X}\left(x_1, x_2, \alpha_s(\mu_R^2), Q^2/\mu_F^2, Q^2/\mu_R^2\right)}$$

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$$d\sigma^{NLO} = \left[\mathcal{B}(\Phi_{p1p2}) + \alpha_s \, \mathcal{V}(\Phi_{p1p2})\right] \, d\,\Phi_{p1p2} + \alpha_s \, \mathcal{R}(\Phi_{p1p2j}) d\,\Phi_{p1p2j}$$

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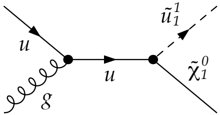
♠ (modified) MadGraph 4.5 [Alwall et al.]



Surveying the tools

Step	Tool	features
Multileg ME generation	Modified MadGraph	LO + real emission input from QGRAF/GOLEM output for QGRAF/GOLEM
One-loop ME generation	QGRAF	one-loop amplitudes
Analytical processing of the 1-loop ME	QGRAF-GOLEM interface	fermionic & color structures
Reduction of 1-loop integrals	GOLEM	tensor reduction Gram determinants avoided
Renormalization of UV divergences	own routines	OS / $\overline{\mathrm{MS}}$ schemes SUSY restoration
Subtraction of IR divergences	Modified MadGraph/MadDipole	I_{SUSY} α-dependence
Subtraction of OS divergences	own routines	based on [Beenakker et al]

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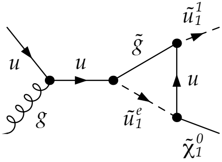
- QGRAF [Nogueira]
- GOLEM [Binoth et al.]
- QGRAF-GOLEM interface
- CT generator& library



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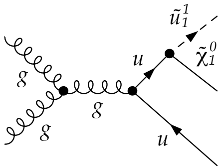
- ♠ (extended) MadDipole [Frederix, Gehrmann, Greiner]
- ♠ Automatic OS subtraction based on [Beenakker et al.]



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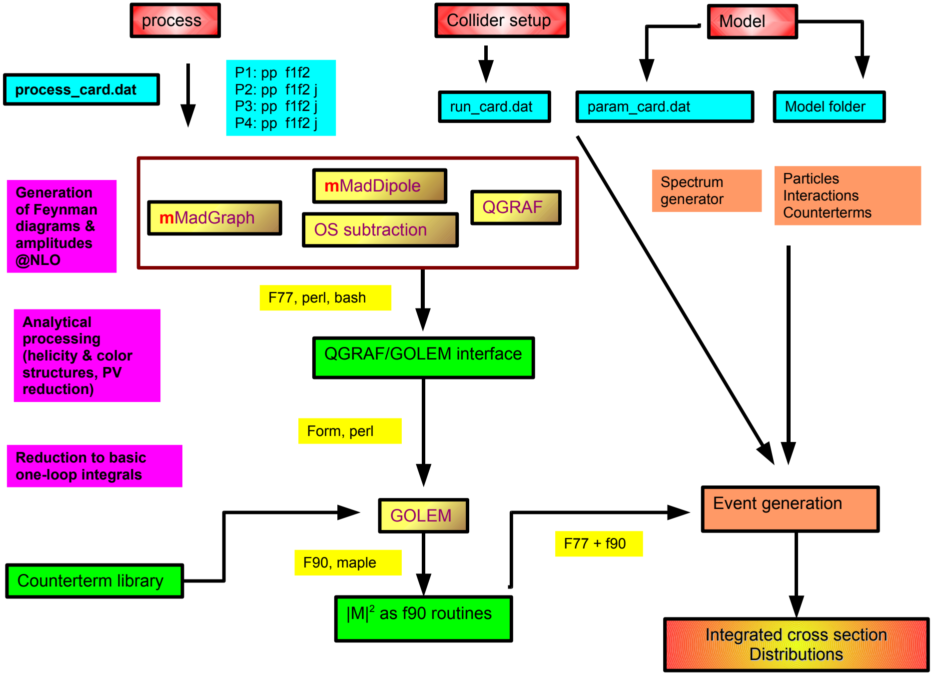

process
Collider setup
Model
process_card.dat
P1: pp f1f2
P2: pp f1f2 j
P3: pp f1f2 j
P4: pp f1f2 j
run_card.dat
param_card.dat
Model folder
Generation of Feynman diagrams & amplitudes @NLO
mMadDipole
mMadGraph
OS subtraction
QGRAF
Spectrum generator
Particles Interactions Counterterms
F77, perl, bash
Analytical processing (helicity & color structures, PV reduction)
QGRAF/GOLEM interface
Form, perl
Reduction to basic one-loop integrals
GOLEM
Event generation
F77 + f90
F90, maple
Counterterm library
|M|2 as f90 routines
Integrated cross section Distributions

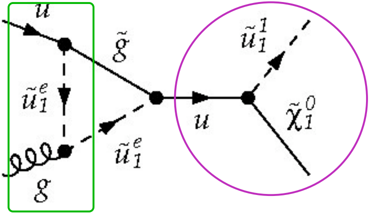
The MadGOLEM one-loop Calculator

Step	Command	Tools	languages
Generation	newprocess_nlo	QGRAF	`bash, Fortran`
Translation	perl run_golem.pl	QGRAF-GOLEM	`bash, perl, FORM`
Calculation	perl run_golem.pl	GOLEM	`bash, perl` `FORM, Maple`

Step 1: Generation of the one-loop amplitude

One-loop amplitude from QGRAF: qgraf_nlo.dat

```
+ 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.n1], idx1r1, p4) *
outlorentz(+1, iv1r1L1, p4, MN1   ) *
outcolor(2, iv1r1C1) *
vertex(iv1,GULN1P  ,ONE,
[field.n1], 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) *
```



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outcolor(2, iv1r1C1) *
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[field.u], idx1r2, +1, p3+p4, iv1r2L1, +3, iv1r2C3,
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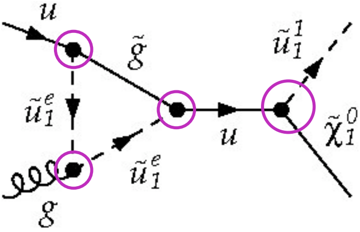
[field.ul], idx3r2, +0, k1, iv3r2L0, +3, iv3r2C3,
[field.ulx], idx3r3, -0, -k1-p2, iv3r3L0, -3, iv3r3C3) *
```



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vertex(iv4,GQLGOM  ,ONE,
[field.ux], idx4r1, -1, -p3-p4, iv4r1L1, -3, iv4r1C3,
[field.go], idx4r2, +1, -k1+p1, iv4r2L1, +8, iv4r2C8,
[field.ul], idx4r3, +0, k1+p2, iv4r3L0, +3, iv4r3C3) *
prop([field.u], idx4r1, idx1r2) *
propcolor(+3, iv4r1C3, iv1r2C3) *
proplorentz(+1, p3+p4, ZERO  , iv4r1L1, iv1r2L1) *
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proplorentz(+0, k1, MUL   , iv2r3L0, iv3r2L0) *
prop([field.go], idx4r2, idx2r1) *
propcolor(+8, iv4r2C8, iv2r1C8) *
proplorentz(+1, k1-p1, MGO   , iv4r2L1, iv2r1L1) *
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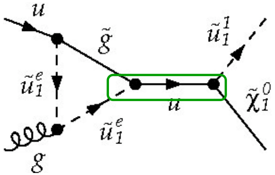

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vertices.h | propagators.h | color.h | stitch.h | dirac.h | sign

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Particular care devoted to handle Majorana fermions consistently [Denner et al.]

Step 2: Translation of the one-loop amplitude

One-loop amplitude upon translation: GRAPH_MGOLEM_LOOP.h

```
diagram1 =  + Den(k1 + k2,0)*Den( - k3 - k4,0)*intM(Den(q1,0),Den(k1
     + k2 + q1,0))*SUNSum(Col14,3)*SUNSum(Glu15,8)*SUNSum(Col18,3)*
    SUNT(Glu2,Col14,Col1)*SUNT(Glu15,Col3,Col18)*SUNT(Glu15,Col18,
    Col14)*GG1^3*scalar3*Pi^(-2) * ( 1/32*Spinor(k4,MN1,-1)*g_(2,7_,
       k3,Lor5,k1,Lor5,k1,Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2
        + 1/32*Spinor(k4,MN1,-1)*g_(2,7_,k3,Lor5,k1,Lor5,k2,Lorhx2)*
       Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(
       2,7_,k3,Lor5,k2,Lor5,k1,Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*
       GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(2,7_,k3,Lor5,k2,Lor5,k2,
       Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1
       ,-1)*g_(2,7_,k3,Lor5,q1,Lor5,k1,Lorhx2)*Spinor(k1,0,1)*
       e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(2,7_,k3,Lor5,q1
       ,Lor5,k2,Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*
       Spinor(k4,MN1,-1)*g_(2,7_,k4,Lor5,k1,Lor5,k1,Lorhx2)*Spinor(k1
       ,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(2,7_,k4,
       Lor5,k1,Lor5,k2,Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/
       32*Spinor(k4,MN1,-1)*g_(2,7_,k4,Lor5,k2,Lor5,k1,Lorhx2)*
       Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(
       2,7_,k4,Lor5,k2,Lor5,k2,Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*
       GULN1P2 + 1/32*Spinor(k4,MN1,-1)*g_(2,7_,k4,Lor5,q1,Lor5,k1,
       Lorhx2)*Spinor(k1,0,1)*e2(Lorhx2)*GULN1P2 + 1/32*Spinor(k4,MN1
       ,-1)*g_(2,7_,k4,Lor5,q1,Lor5,k2,Lorhx2)*Spinor(k1,0,1)*
```

The MadGOLEM one-loop Calculator

Step	Command	Tools	languages
Generation	newprocess_nlo	QGRAF	`bash, Fortran`
Translation	perl run_golem.pl	QGRAF-GOLEM	`bash, perl, FORM`
Calculation	perl run_golem.pl	GOLEM	`bash, perl` `FORM, Maple`

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

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

- **color structure** $\Rightarrow$ color decomposition & saturation
- **helicity structure** $\Rightarrow$ spinor-helicity formalism
- **loop functions** $\Rightarrow$ GOLEM reduction algorithm

Step 3: Calculation of the one-loop amplitude

One-loop amplitude upon translation: GRAPH_MGOLEM_LOOP.h

```
# Colour basis has   2 elements.
#
NCOLS :=   2:
COL[  1] :=  dd(Col022,Col021)*dd(Col1,Col3):
COL[  2] :=  dd(Col022,Col3)*dd(Col1,Col021):
NC := 3:
TR := 1/2:
NF := 5:
#
# epsilon_tensor basis has   1 elements.
#
NEPS :=   1:
EPSTEN[  1] :=  1:
#
# Function basis has  4 elements.
#
NUM_LOC_FUNS :=  4:
FUN[  1] :=  BUBd4(S12,0,0):
FUN[  2] :=  BUBd4(S12,MUL2,MG02):
FUN[  3] :=  BUBd4EPS(S12,0,0):
FUN[  4] :=  BUBd4EPS(S12,MUL2,MG02):
#
#  12 helicity amplitudes found
#
NUM_HELIS :=  12:
HELI[  1]:=[1, 1, 5, 1]:
HELI[  2]:=[1, 1, 5, -1]:
HELI[  3]:=[1, -1, 5, 1]:
```

Step 3: Calculation of the one-loop amplitude

One-loop amplitude upon translation: GRAPH_MGOLEM_LOOP.h

```
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/Pi^2:
GRAPH_COEFF[  1,  8,  2,  1,  1]:=1/12*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/Pi^2:
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/Pi^2:
GRAPH_COEFF[  1,  8,  2,  1,  9]:=-1/12*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/Pi^2:
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):
```

Step 3: Calculation of the one-loop amplitude

One-loop amplitude upon translation: GRAPH_MGOLEM_LOOP.h

```
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GRAPH_COEFF[  1,  8,  1,  1,  8]:=0:
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GRAPH_COEFF[  1,  8,  1,  1,  9]:=1/36*(-MUL2*S23+MUL2*MN12+S23^2+S12*S23-MN12*S23)*GULN1P2*GG1^3/Pi^2:
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GRAPH_COEFF[  1,  8,  1,  1, 10]:=0:
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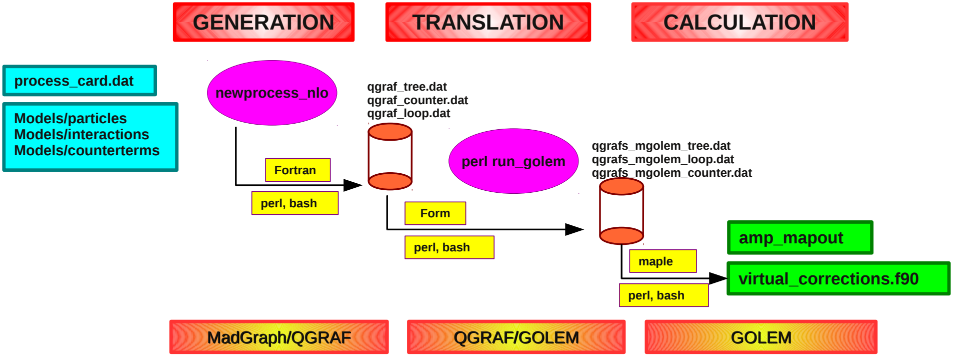
The MadGOLEM one-loop Calculator



Handling the UV divergences

Including the Counterterms

$$\mathcal{L}_0 \rightarrow \mathcal{L}(Z_\phi^{1/2}\,\phi, Z_g\, g) \quad = \quad \mathcal{L}(\phi, g) + \delta\,\mathcal{L}\,(\phi, g, \delta\, Z_\phi, \delta\, g)$$

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$$\underbrace{\delta\mathcal{L}(\delta\,Z_\phi, \delta\,g)}_{\text{Models/vertex\_ct.dat}} \qquad \Leftrightarrow \qquad \underbrace{\Sigma_q, \quad \Sigma_{\tilde{q}}, \quad \Sigma_g, \quad \Sigma_{\tilde{g}} \qquad @\mathcal{O}(\alpha_s)}_{\text{GOLEMproc/CT\_list.map}}$$

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Renormalization scheme

- $\overline{\mathrm{MS}}$, for the field-strength RCs of the massless particles
- OS, for the field-strength RCs of the massive particles
- $\overline{\mathrm{MS}}$/zero-momentum, for g_s [Beenakker et al, Berge et al]
- SUSY breaking from Dimensional Regularization restored through additional finite CTs [Martin, Vaughn; Beenakker et al].

Handling the IR divergences

- **Dipole Subtraction:** [Catani, Seymour; Catani, Dittmaier, Seymour, Trocsanyi]

$$\sigma = \int_m d\,\sigma^B + \int_{m+1} d\,\sigma^R + \int_m \left[\int_1 d\,\sigma^V \right]$$

Handling the IR divergences

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$$\sigma = \int_m d\,\sigma^B + \underbrace{\int_{m+1} d\,\sigma^R}_{\int \frac{dk}{k^{1+\epsilon}} \sim \frac{1}{\epsilon_{IR}},\int \frac{d\theta}{\theta^{1+\epsilon}} \sim \frac{1}{\epsilon_{IR}}} + \int_m \left[\int_1 \underbrace{d\,\sigma^V}_{\int \frac{dk}{k^{1+\epsilon}} \sim \frac{1}{\epsilon_{IR}}} \right]$$

Handling the IR divergences

♠ Dipole Subtraction: [Catani, Seymour; Catani, Dittmaier, Seymour, Trocsanyi]

$$\sigma = \int_m d\sigma^B + \underbrace{\int_{m+1} d\sigma^R - d\sigma^A}_{\frac{1}{\epsilon_{IR}} - \frac{1}{\epsilon_{IR}}} + \int_m \left[\int_1 \underbrace{d\sigma^V + d\sigma^A}_{\frac{1}{\epsilon_{IR}} - \frac{1}{\epsilon_{IR}}} \right]$$

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Local (pointwise) subtraction of the IR poles

- Based on factorization of collinear&soft singularities
- Process-independent
- Analytically integrable over the single-parton phase-space containing the divergences

Handling the IR divergences

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Local (pointwise) subtraction of the IR poles

- Based on factorization of collinear&soft singularities
- Process-independent
- Analytically integrable over the single-parton phase-space containing the divergences

$$d\sigma^A = \sum_l f(\epsilon_{IR}) \times d\sigma_l^B \otimes V_l$$

$$\int_{m+1} d\,\sigma^A = \sum_l \int_m f(\epsilon_{IR}) \times d\,\sigma_l^B \otimes \int_1 V_l = f(\epsilon_{IR}) \times \int_m d\sigma_l^B \otimes I$$

I_{SUSY} (including α-dependence [Nagy, Trocsanyi]) available @ MadGOLEM

Handling the OS Divergences

Automatized OS Subtraction available @ MadGOLEM [Beenakker, Höpker, Spira, Zerwas]

$$d\sigma^R \quad \longrightarrow \quad d\sigma^R\Big]_{\text{regular}} \quad + \quad d\sigma^{R*}\Big]_{\mathcal{O}(1/(p^2-m^2))}$$
$$ug \to \tilde{u}_L\tilde{\chi}_1 j \quad + \quad uu \to \tilde{u}_L\tilde{u}_L^* \to \tilde{u}_L\tilde{\chi}_1 j$$

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$$ug \to \tilde{u}_L \tilde{\chi}_1 j \quad + \quad uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j$$

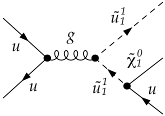
$$\sigma = \int_{m+1} d\,\sigma^R \longrightarrow \int_{m+1} \left[d\,\sigma^R + d\,\sigma^{R*}(\Gamma_{\tilde{u}_L}) - d\sigma^{OS}(\Gamma_{\tilde{u}_L}) \right]$$

Handling the OS Divergences

Automatized OS Subtraction available @ MadGOLEM [Beenakker, Höpker, Spira, Zerwas]

$$
\begin{array}{cccccc}
d\sigma^R & \longrightarrow & d\sigma^R\Big]_{\text{regular}} & + & d\sigma^{R*}\Big]_{\mathcal{O}(1/(p^2-m^2))} \\
 & & ug \to \tilde{u}_L \tilde{\chi}_1 j & + & uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j
\end{array}
$$

$$
\sigma = \int_{m+1} d\,\sigma^R \longrightarrow \int_{m+1} \left[d\,\sigma^R + d\,\sigma^{R*}(\Gamma_{\tilde{u}_L}) - d\sigma^{OS}(\Gamma_{\tilde{u}_L}) \right]
$$



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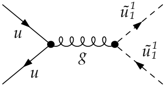

$uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j$ - $uu \to \tilde{u}_L \tilde{u}_L \times \mathcal{B}(\tilde{u}_L \to \tilde{\chi}_1 j)$

Handling the OS Divergences

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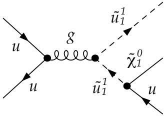
$$d\sigma^R \longrightarrow d\sigma^R\Big]_{\text{regular}} + d\sigma^{R*}\Big]_{\mathcal{O}(1/(p^2-m^2))}$$

$$ug \to \tilde{u}_L \tilde{\chi}_1 j \quad + \quad uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j$$

$$\sigma = \int_{m+1} d\,\sigma^R \longrightarrow \int_{m+1} \left[d\,\sigma^R + d\,\sigma^{R*}(\Gamma_{\tilde{u}_L}) - d\sigma^{OS}(\Gamma_{\tilde{u}_L})\right]$$



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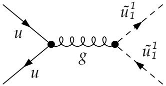

$$uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j \quad - \quad uu \to \tilde{u}_L \tilde{u}_L \times \mathcal{B}(\tilde{u}_L \to \tilde{\chi}_1 j)$$

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

- Pointwise subtraction of the OS poles – analogue to CS dipoles
- Avoids double-counting & preserves gauge invariance & spin correlations
- $\Gamma_{\tilde{u}_L}$ as regulator $\Rightarrow$ dependence cancels in the final results

Outline

The user's perspective: running MadGOLEM

3-stage procedure – 3 interfaces $\leftrightarrow$ 3 executables

Stage 1: DEFINING THE PROCESS

process_card $\leftrightarrow$ ./newprocess_nlo

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Stage 1: DEFINING THE PROCESS

process_card $\leftrightarrow$ ./newprocess_nlo

Stage 2: COMPUTING THE AMPLITUDE

./run_golem_pl

♠ At this point the user is able to:

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

The user's perspective: running MadGOLEM

3-stage procedure – 3 interfaces ↔ 3 executables

Stage 1: DEFINING THE PROCESS

process_card ↔ ./newprocess_nlo

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./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!)

Stage 3: EVALUATING THE CROSS-SECTIONS

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

Running a $2 \rightarrow 2$ process NLO

Running a $2 \rightarrow 2$ process NLO

Reading out the results for $2 \to 2$ NLO

Process results
s= 434.644± 0.860(ab)

Graph	Cross Sect(ab)	Error(ab)	Events (K)	Eff	Unwgt	Luminosity
Sum	434.644	0.860	1	0.1		
LO						
P1_gu_uln1	292.660	0.238	0	0.0		0.00
P1_ug_uln1	291.890	0.240	0	0.0		0.00
Total LO = 584.54999999999995						
NLO: REAL CORRECTIONS						
P3_gu_uln1g	0.600	0.002	0	0.0		0.00
P3_ug_uln1g	0.600	0.002	0	0.0		0.00
P3_gg_uln1ux	0.146	0.002	0	0.1		0.00
P3_uu_uln1u	0.079	0.230	0	29.1		0.00
P3_uux_uln1ux	0.027	0.007	0	2.5		0.00
P3_uxu_uln1ux	0.027	0.005	0	2.0		0.00
Total REAL = 1.4775809999999998						
NLO: VIRTUAL CORRECTIONS						
P2_ug_uln1g	0.000	0.000	0	0.0		**********
P2_gu_uln1g	0.000	0.000	0	0.0		**********
P2_gg_uln1ux	-2.965	0.002	0	0.0		**********
P2_uxu_uln1ux	-4.530	0.004	0	0.0		**********
P2_uux_uln1ux	-4.538	0.004	0	0.0		**********
P2_uu_uln1u	-139.350	0.122	0	0.0		**********
Total VIRTUAL = -151.38350000000000						

Outline

Validation strategies

♠ ONE-LOOP CORRECTIONS & COUNTERTERMS

- gauge invariance
- cancellation of UV/IR divergences (analytically & numerically)
- Finite parts – numerical comparison with FeynArts/FormCalc/LoopTools

[Hahn]

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♠ REAL EMISSION, DIPOLES AND OS SUBTRACTION

- $\alpha(\alpha_{OS})$ dependence & behavior in the soft and collinear limits, for all dipoles [Nagy, Trocsanyi] and OS subtraction terms
- cancellation of IR/OS divergences – numerical stability and convergence

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DIRECT COMPARISON

when available, with independent NLO predictions in a process-by-process basis:

- $e^+e^- \to \tilde{u}_L \tilde{u}_L^*$: [Drees, Hikasa; Beenakker et al.]
- $pp \to \tilde{e}_L \tilde{e}_L$: [Beenakker, Klasen, Krämer, Plehn, Spira, Zerwas]

Performance of the loop calculator

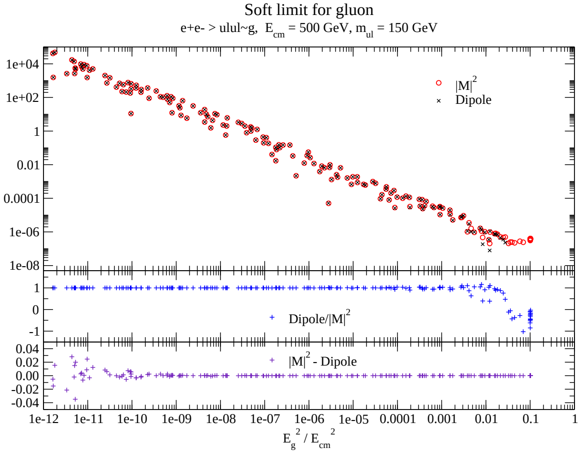
♠ An explicit example: SUSY-QCD 1-loop virtual corrections to $pp \to \tilde{u}_L \tilde{\chi}_1$

SPS1a

	σ^{NLO} (MadGOLEM)	σ^{NLO} (FormCalc)
$g - \tilde{u}_L - \tilde{u}_L^*$ vertex	$-1.173(2) \times 10^{-5}$	$-1.17(1) \times 10^{-5}$
$g - u - \bar{u}$ vertex	$8.202(7) \times 10^{-5}$	$8.20(8) \times 10^{-5}$
$\tilde{\chi}_1 - u - \tilde{u}_L$ vertex	$1.155(1) \times 10^{-4}$	$1.15(2) \times 10^{-4}$
u self-energy	$-5.006(4) \times 10^{-5}$	$-5.01(3) \times 10^{-5}$
$\tilde{u}_L$ self-energy	$1.173(2) \times 10^{-5}$	$1.17(1) \times 10^{-5}$
boxes	$9.576(8) \times 10^{-5}$	$9.57(1) \times 10^{-5}$

Performance of the SUSY dipoles

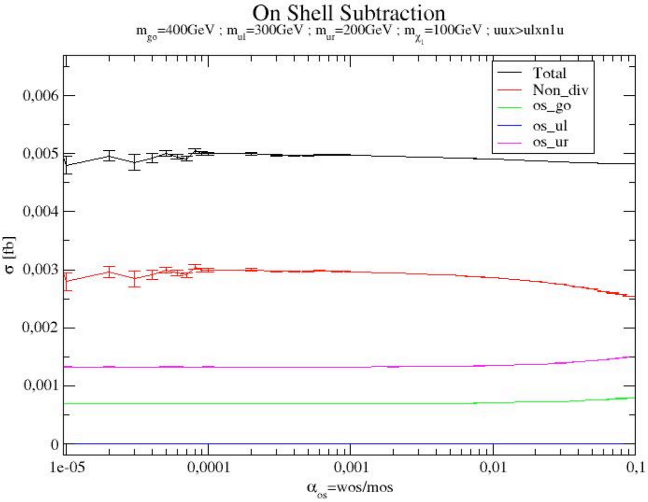
$$e^+e^- \longrightarrow \tilde{u}_L^* \tilde{u}_L$$



♠ For details cf. Gonçalves Netto, DLV, Mawatari, Plehn, Wigmore, to appear.

Performance of the OS subtraction

$pp \to \tilde{u}\tilde{\chi}_1$



Process-by-process cross-check: $e^+e^- \longrightarrow \tilde{u}_L^* \tilde{u}_L$

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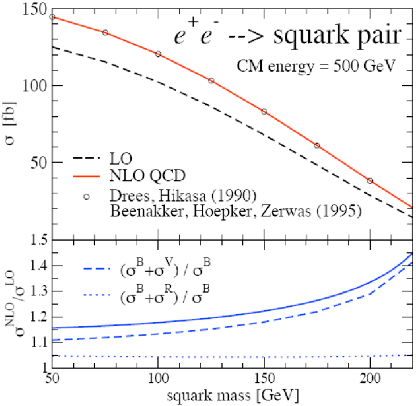
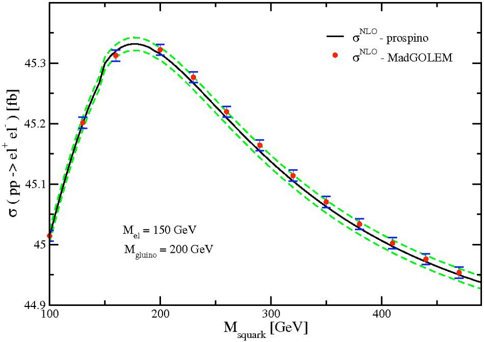


Process-by-process cross-check: pp $\longrightarrow \tilde{e}_L \tilde{e}_L^*$

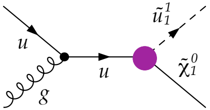
$\text{pp} \longrightarrow \tilde{e}_L \tilde{e}_L^*$

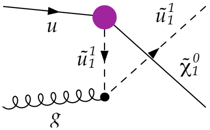


- Event rate as a function of the squark mass
- MadGOLEM vs **Prospino** – Excellent agreement within integration errors

Outline

MadGOLEM underway: pp $\to \widetilde{u}\widetilde{\chi}^0$ at NLO





$$pp \to \widetilde{u}_L\widetilde{\chi}^0{}_1 \to u\widetilde{\chi}^0{}_1\widetilde{\chi}^0{}_1$$

- Potential source of Monojet signatures
- Characteristic p_T spectrum
- Sensitivity to $q\tilde{q}\widetilde{\chi}^0{}_1$ couplings

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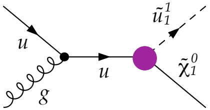

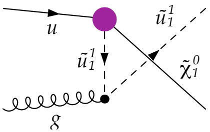

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- Potential source of Monojet signatures
- Characteristic p_T spectrum
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♠ Nature of the LSP (bino, wino-like ?)

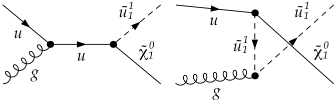
♠ Constraints on DM detection

♠ SUSY relations between couplings

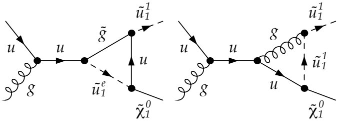
♠ Pattern of SUSY breaking $\Rightarrow$ handle on the fundamental SUSY breaking mecanism !

For a recent analysis of the collider signatures (@ LO), on Allanach, Grab & Haber arXiV:1010.4261

MadGOLEM underway: pp $\rightarrow \widetilde{u}\widetilde{\chi}^0$ at NLO



tree-level

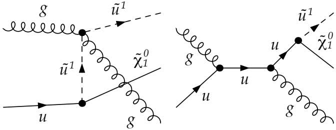


virtual corrections $\mathcal{O}(\alpha_s^2)$

$\Downarrow$

MSSM renormalization

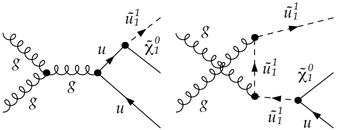
& SUSY-restoration



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

$\Downarrow$

ii, fi & if dipoles



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

$\Downarrow$

OS subtraction

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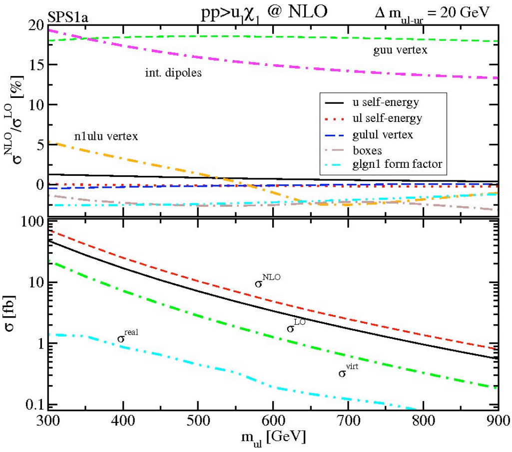

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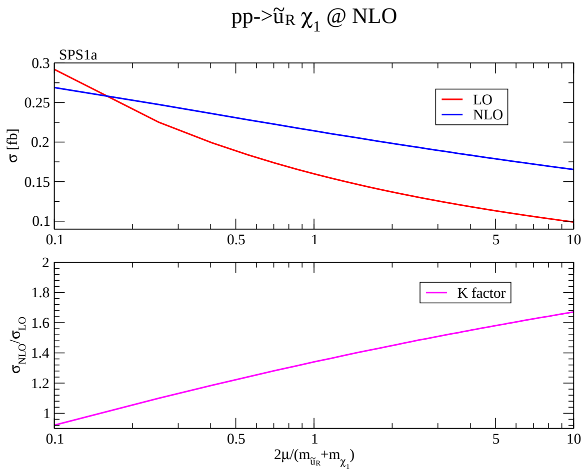

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MadGOLEM underway: $pp \to \widetilde{u}\widetilde{\chi}^0$ at NLO

	σ^{LO} [fb]	σ^{NLO} [fb]	K	$M_{\tilde{u}_L}$ [GeV]	$M_{\tilde{u}_R}$ [GeV]	$M_{\tilde{\chi}_1}$ [GeV]
SPS1a	160.339	216.647	1.351	561.119	549.259	181.696
SPS1b	22.178	29.743	1.341	871.658	850.474	161.764
SPS2	1.081	1.440	1.332	1554.313	1553.824	237.406
SPS3	24.475	32.868	1.343	853.684	831.809	160.546
SPS4	41.920	55.305	1.319	760.030	747.952	227.720
SPS5	74.398	100.282	1.348	674.953	657.290	231.186
SPS6	56.474	76.636	1.357	669.564	660.214	224.299
SPS7	18.063	24.261	1.343	895.986	874.580	268.970
SPS8	7.371	9.733	1.320	1113.372	1077.385	138.947
SPS9	5.246	6.930	1.321	1276.308	1281.497	187.173

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Outline

Summary & outlook

MadGOLEM

- is heading towards a fully automated calculation of NLO QCD corrections for generic BSM $2 \longrightarrow 2$ processes within the MadGraph/GOLEM framework
- supplies a generalization and automatization of PROSPINO
- three commands !! from BSM models to (parton-level) event rates @ NLO
  - **Generating** the amplitude: ./newprocess_nlo
  - **Processing** the amplitude perl run_golem.pl
  - **Evaluating** the cross-section: ./bin/generate_events_nlo 2 2 myprocess

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Current limitations

- Limited to $2 \to 2$ processes
- Several types of processes yet to be tested
- Some degree of model-dependence: CTs others than SM/MSSM are to be introduced by the user

Summary & Outlook

Current and near-future directions

- EXTEND & GENERALIZE : to make the code more flexible and adaptable to a completely generic BSM setup
- CLEAN-UP the code & REFINE the user interfaces: aiming at a truly user-friendly, handy layout – and a transparent internal structure.
- CROSS-CHECK : new processes against the available NLO calculators – e.g. all SUSY production channels in Prospino, $H^{\pm}$ with MC@NLO ...
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♠ First public release of the code in $\mathcal{O}$(few months) $\Rightarrow$ STAY TUNED !!

Summary & outlook

MadGOLEM contributes to extending bridges

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Theory

Experiment

Summary & outlook

MadGOLEM contributes to extending bridges

Theory THANKS A LOT !! Experiment