MadGolem: automating NLO corrections for New Physics

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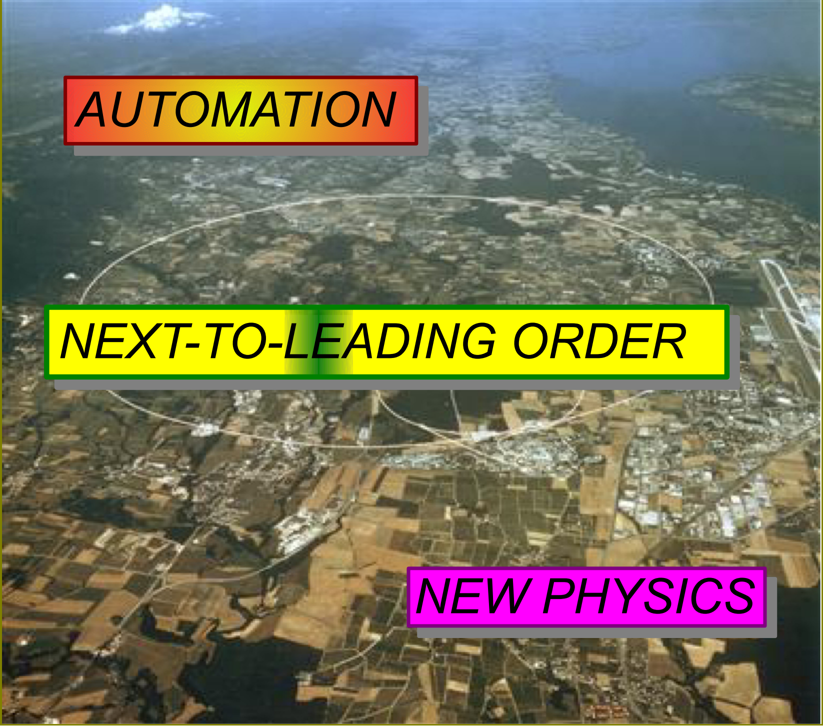
arXiv:1108.1250 arXiv:1203.6358

PHENO 12 – May 12th, Pittsburg University, Pennsylvania, USA

Outline

Outline



AUTOMATION

NEXT-TO-LEADING ORDER

NEW PHYSICS

MadGolem: *raison-d'etre*

Why NLO ?

- QCD corrections quantitatively relevant : $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shape of distributions, gluon radiation, new partonic subprocesses . . .

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- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange

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[Binoth, Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, arXiv:1108.1250 [hep-ph]]

- Fully automated calculation of NLO QCD corrections for arbitrary $2 \to 2$ processes in a generic BSM framework soon to be public !

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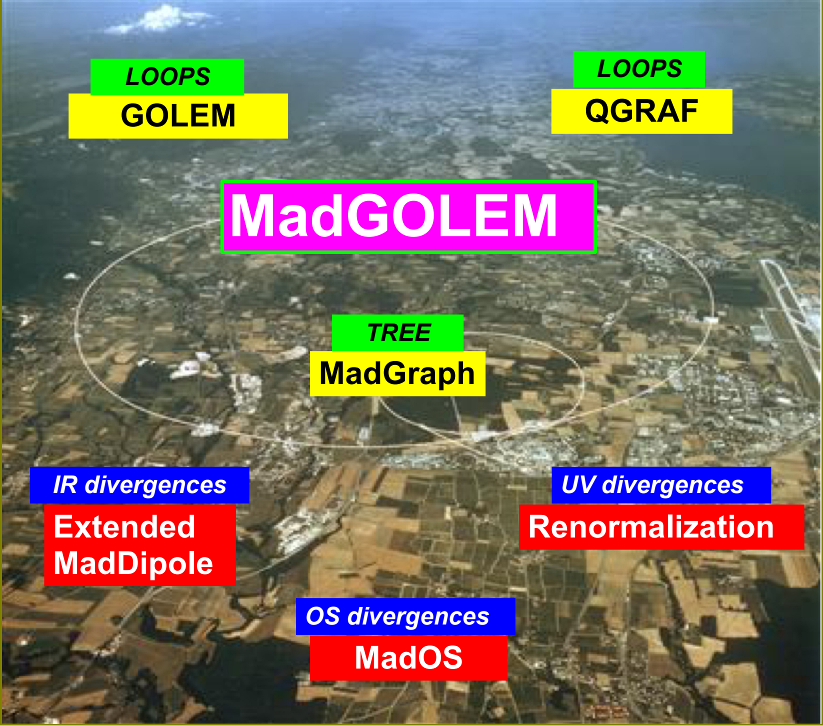
LOOPS
GOLEM
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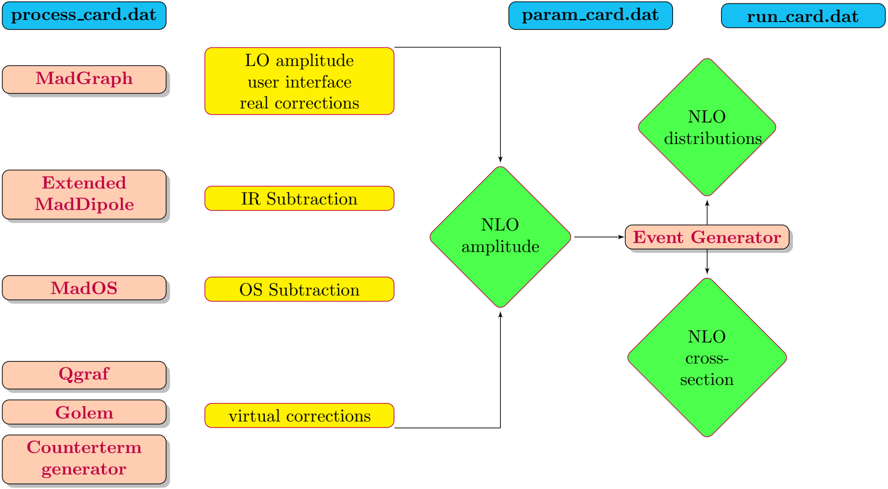
QGRAF
MadGOLEM
TREE
MadGraph
IR divergences
Extended MadDipole
UV divergences
Renormalization
OS divergences
MadOS

MadGolem from inside: modules and flowchart



Handling the loops

♠ GENERATION ⟷ Qgraf [Nogueira]

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

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- **TRANSLATION** $\longleftrightarrow$ **Qgraf-Golem**

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

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vertices propagators color Lorentz structures relative signs

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vertices   propagators   color   Lorentz structures   relative signs

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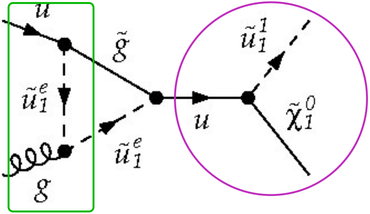
Amplitude $\xrightarrow{\text{BASH,PERL,FORM,MAPLE}}$ Reduced amplitude

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

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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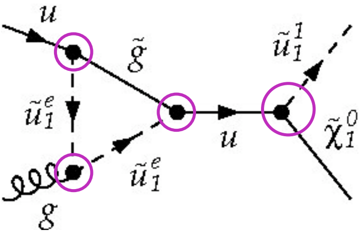
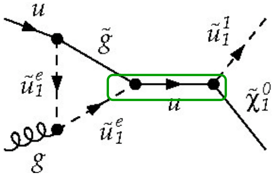
outlorentz(+0, iv1r3L0, p3, MUL   ) *
outcolor(1, iv1r3C3) *
out([field.n1], idx1r1, p4) *
outlorentz(+1, iv1r1L1, p4, MN1   ) *
outcolor(2, iv1r1C1) *
vertex(iv1,GULN1P   ,ONE,
[field.n1], idx1r1, +1, -p4, iv1r1L1, +1, iv1r1C1,
[field.u], idx1r2, +1, p3+p4, iv1r2L1, +3, iv1r2C3,
[field.ulx], idx1r3, -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) *
```



Step 1: Generation of the one-loop amplitude

One-loop amplitude from QGRAF: qgraf_nlo.dat

```
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) *
prop([field.ul], idx2r3, idx3r2) *
propcolor(+3, iv2r3C3, iv3r2C3) *
proplorentz(+0, k1, MUL   , iv2r3L0, iv3r2L0) *
prop([field.go], idx4r2, idx2r1) *
propcolor(+8, iv4r2C8, iv2r1C8) *
proplorentz(+1, k1-p1, MGO   , iv4r2L1, iv2r1L1) *
prop([field.ul], idx3r3, idx4r3) *
propcolor(+3, iv3r3C3, iv4r3C3) *
proplorentz(+0, k1+p2, MUL   , iv3r3L0, iv4r3L0)
```



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):
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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:
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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:
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GRAPH_COEFF[  1,  8,  2,  1,  5]:=0:
GRAPH_COEFF[  1,  8,  1,  1,  6]:=0:
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SPINOR_FAC[  1,  8   ] :=  InvSpaa(k1,k2)*InvSpaa(k1,k4)*InvSpaa(k2,k3)*InvSpbb(k1,k3):
```

Handling the UV divergences

Including the Counterterms

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

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

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Renormalization scheme

- $\overline{\text{MS}}$, for the field-strength RCs of the massless particles
- OS, for the field-strength RCs of the massive particles
- $\overline{\text{MS}}$/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, Trócsányi]

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

Handling the IR divergences

♠ **Dipole Subtraction:** [Catani, Seymour; Catani, Dittmaier, Seymour, Trócsányi]

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

Handling the IR divergences

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

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Local (pointwise) subtraction of the IR poles

- Based on factorization of collinear&soft singularities
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$$d\sigma^A = \sum_l f(\epsilon_{IR}) \times d\sigma_l^B \otimes V_l$$

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

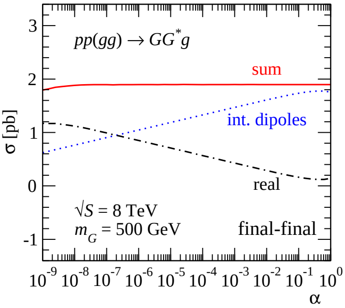
I_{SUSY} (including α-dependence [Nagy, Trócsányi]) available @ MadGolem

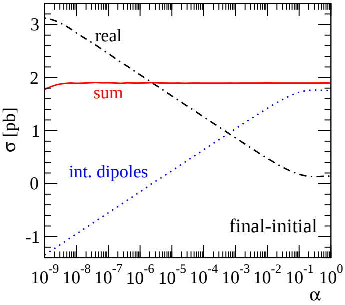
BSM dipoles: numerical performance

♠ Validation strategies

- α dependence [Nagy, Trócsányi] & behavior in the soft and collinear limits, for all dipoles
- Numerical stability and convergence

♠ Checking α-dependence for $pp \to GG^*$





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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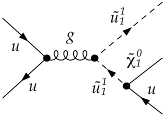

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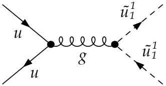

$$uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j \quad - \quad uu \to \tilde{u}_L \tilde{u}_L \times \mathcal{B}(\tilde{u}_L \to \tilde{\chi}_1 j)$$

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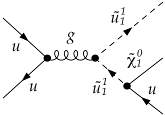

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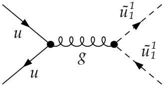

$$uu \to \tilde{u}_L \tilde{u}_L^* \to \tilde{u}_L \tilde{\chi}_1 j \quad - \quad uu \to \tilde{u}_L \tilde{u}_L \times \mathcal{B}(\tilde{u}_L \to \tilde{\chi}_1 j)$$

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

- 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

On-shell subtraction: numerical performance

♠ Validation strategies

- Independence with respect to the regulator choice Γ/m
- Numerical stability and convergence

On-shell subtraction: numerical performance

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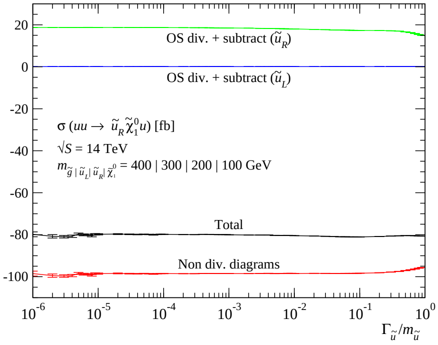
Performance of the OS Subtraction: $pp(uu \to \tilde{u}_R \tilde{\chi}_1 u)$



Outline

Running MadGolem: 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

Running MadGolem: the user's viewpoint

♠ And the user retrieves the results !

MadGolem results
s= 8533.480± 0.793(ab)

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 = 7625.8999999999996						
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						

Exploring New Physics with MadGolem

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

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Phenomenological analysis includes

- Total rates & K factors to NLO
- Structure of NLO corrections
- scale dependence
- parameter space dependence
- Distributions
- Fixed-order NLO VS multi-jet merging comparisons

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Don't miss the talk by Dorival Goncalves-Netto !

Outline

Take-home ideas

MadGolem

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AUTOMATION **NLO** **NEW PHYSICS**

♠ completely **AUTOMATES** the calculation of NLO QCD corrections for generic BSM $2 \to 2$ processes and their interface to Monte Carlo event generators

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Feynman diagrammatic / fully analytical approach

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- ♠ completely **AUTOMATES** the calculation of NLO QCD corrections for generic BSM $2 \to 2$ processes and their interface to Monte Carlo event generators

  Feynman diagrammatic / fully analytical approach

- ♠ Provides a **3-COMMAND PATHWAY** from BSM to (parton-level) event rates and distributions at NLO.

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♠ Provides a **3-COMMAND PATHWAY** from BSM to (parton-level) event rates and distributions at NLO.

- **Generating** the amplitude: ./newprocess_nlo
- **Processing** the amplitude perl run_golem.pl
- **Evaluating** the cross-section: ./bin/generate_events_nlo 2 2 myprocess

Closing remarks

MadGolem highlights

- Fully analytical procedure
- BSM-suitable loop calculator
- Broad coverage of spin & color structures
- Automated OS Subtraction
- Complete support of NLO QCD calculations for the SM, the MSSM and several other extensions.
  - **SUSY dipoles** (with α dependence)
  - **UV counterterms** & **SUSY restoration**
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Public code release in $\mathcal{O}(\text{months})$

Farewell

MadGolem contributes to extending bridges

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Theory Experiment

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Theory THANKS A LOT !! Experiment