

# NLO calculations & automated tools for new physics searches

David López-Val

together with D. Gonçalves Netto, T. Plehn (Heidelberg U.), I. Wigmore (Edinburgh U.), K. Mawatari (Vrije U.)

ITP - Universität Heidelberg

[arXiv:1108.1250](#)



[arXiv:1203.6358](#)



[arXiv:1209.2797](#)



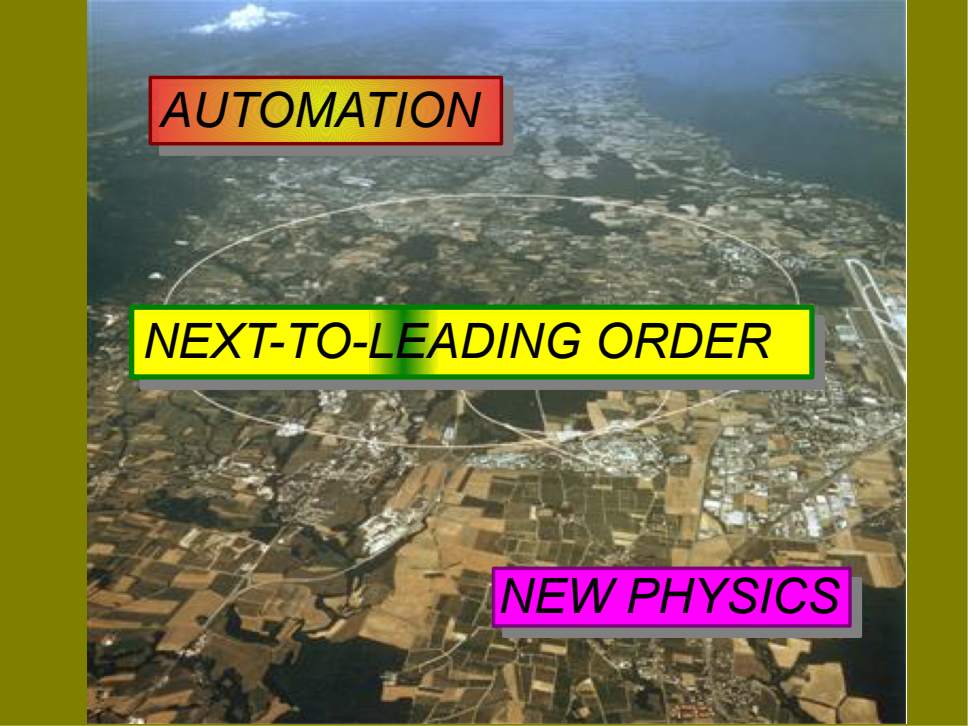
**CP3 - Université Catholique de Louvain - Sept 26th 2012**

# Outline

- 1 Motivation & overview
  - Motivation: the Physics side
  - Motivation: the technical side
- 2 The architecture of a NLO cross section
- 3 MadGolem – an automated tool
  - Describing MadGolem: structure & performance
  - Running MadGolem
- 4 Applications to phenomenology
  - Sgluon pair production to NLO
  - NLO distributions
- 5 Summary & outlook

*One path to follow . . .*



An aerial photograph of a landscape featuring a large, winding circular path or road that loops through a mix of brown, agricultural fields and green, wooded areas. In the upper right corner, a body of water is visible under a blue sky with some clouds. The image is framed by a thick green border.

*AUTOMATION*

*NEXT-TO-LEADING ORDER*

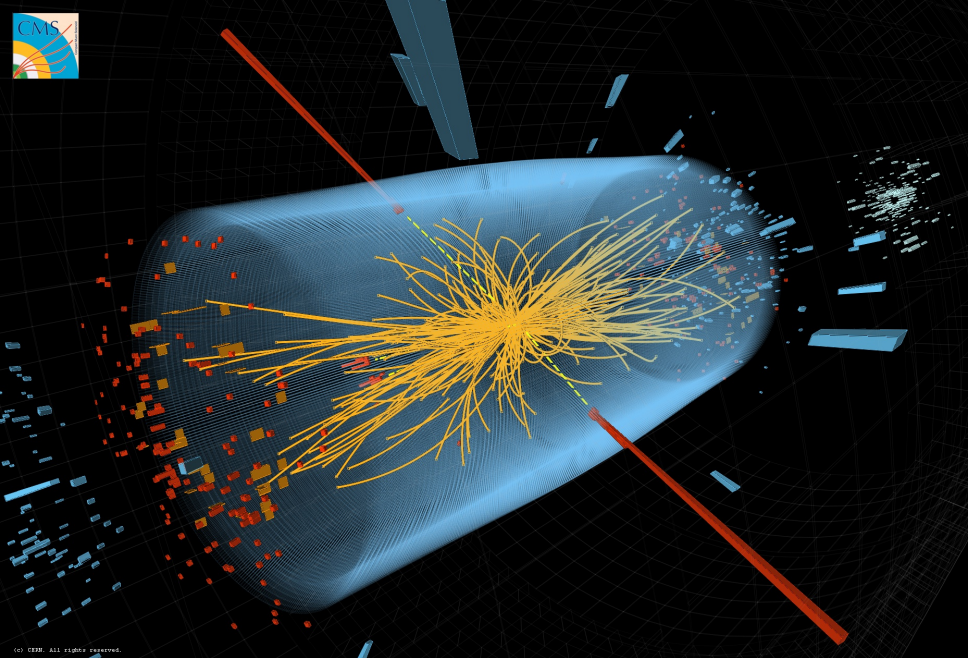
*NEW PHYSICS*

# *The dreamt destination . . .*



# *Physics motivation*







*What is the mechanism ?*

*What stabilizes this scale ?*

***EWSB***

*How does it confront with naturalness ?*



What is the mechanism ?

*EWSB*

What stabilizes this scale ?

How does it confront with naturalness ?

# *TeV-scale New Physics*

Supersymmetry

Compositeness

Extra dimensions



What is the mechanism ?

*EWSB*

What stabilizes this scale ?

How does it confront with naturalness ?

# *TeV-scale New Physics*

Supersymmetry

$(0,3)$

$(1/2,8)$

Squarks, gluinos

Compositeness

$(0,8)$

sgluons

Extra dimensions

$(1,8)$

KK gluons



What is the mechanism ?

*EWSB*

What stabilizes this scale ?

How does it confront with naturalness ?

## *TeV-scale New Physics*

Supersymmetry

Compositeness

Extra dimensions

$(0,3)$

$(1/2,8)$

$(0,8)$

$(1,8)$

Squarks, gluinos

sgluons

KK gluons

*Colored Heavy Resonances*



What is the mechanism ?

*EWSB*

What stabilizes this scale ?

How does it confront with naturalness ?

## *TeV-scale New Physics*

Supersymmetry

Compositeness

Extra dimensions

$(0,3)$

$(1/2,8)$

$(0,8)$

$(1,8)$

Squarks, gluinos

sgluons

KK gluons

## *Colored Heavy Resonances*

rates

QCD

shapes

uncertainties

# *Technical motivation*



# Whys and wherefores

## Why NLO ?

- QCD corrections quantitatively relevant :  $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shapes, gluon radiation ...

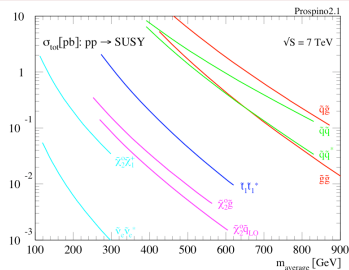
# Whys and wherefores

## Why NLO ?

- QCD corrections quantitatively relevant :  $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shapes, gluon radiation ...

## Why Automation ?

- Many models & processes  $\leftrightarrow$  analogue technical challenges
- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange [Hirsch et al.], arXiv:1103.0621, aMC@NLO [Frederix et al.] arXiv:1104.5613



Benakker, Höper, Krämer, Plehn, Spira,

# Whys and wherefores

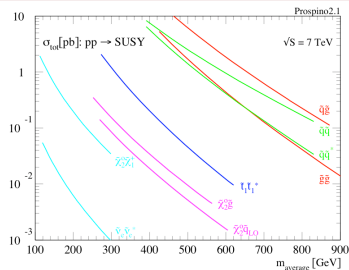
## Why NLO ?

- QCD corrections quantitatively relevant :  $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shapes, gluon radiation ...

## Why Automation ?

- Many models & processes  $\leftrightarrow$  analogue technical challenges
- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange [Hirsch et al.], arXiv:1103.0621, aMC@NLO [Frederix et al.] arXiv:1104.5613

**PROSPINO**



Benakker, Höper, Krämer, Plehn, Spira,

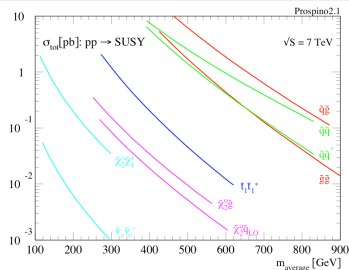
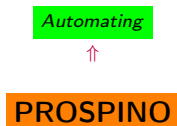
# Whys and wherefores

## Why NLO ?

- QCD corrections quantitatively relevant :  $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shapes, gluon radiation ...

## Why Automation ?

- Many models & processes  $\leftrightarrow$  analogue technical challenges
- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange [Hirsch et al., arXiv:1103.0621, aMC@NLO [Frederix et al.] arXiv:1104.5613]



Benakker, Höper, Krämer, Plehn, Spira,

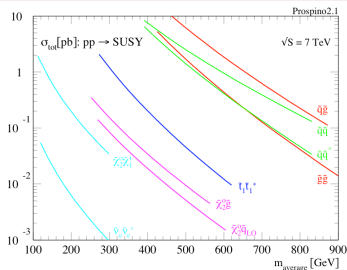
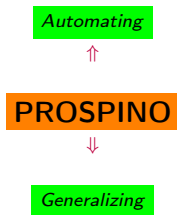
# Whys and wherefores

## Why NLO ?

- QCD corrections quantitatively relevant :  $K \sim 1.5$
- QCD corrections qualitatively relevant: scale dependence, normalization & shapes, gluon radiation ...

## Why Automation ?

- Many models & processes  $\leftrightarrow$  analogue technical challenges
- Cost & time saving, robustness, accessibility
- Eases validation, engages Theory/Experiment interchange [Hirsch et al., arXiv:1103.0621, aMC@NLO [Frederix et al.] arXiv:1104.5613



Benakker, Höper, Krämer, Plehn, Spira,

# *The starting point*



# Factorizing & convoluting the soft and hard scattering pieces



## Master Equation

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

- $f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) :$

$\Rightarrow$  long-distance, universal, (non)-perturbative

# Factorizing & convoluting the soft and hard scattering pieces



## Master Equation

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

- $\underbrace{f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2)} :$

$\Rightarrow$  long-distance, universal, (non)-perturbative

- $\tilde{\sigma}_{p_1 p_2 \rightarrow X}(x_1, x_2, \alpha_s(\mu_R^2), Q^2/\mu_F^2, Q^2/\mu_R^2) :$

$\Rightarrow$  short-distance, process-dependent, perturbative

# Computing the Leading-order contributions

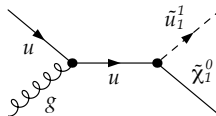
## Master Formula

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

$$d\tilde{\sigma}^{NLO} = \left[ \underbrace{\mathcal{B}(\Phi_{p_1 p_2})}_{\text{Born}} + \alpha_s \mathcal{V}(\Phi_{p_1 p_2}) \right] d\Phi_{p_1 p_2} + \alpha_s \mathcal{R}(\Phi_{p_1 p_2 j}) d\Phi_{p_1 p_2 j}$$



Leading-order



# Virtual corrections

## Master Formula

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

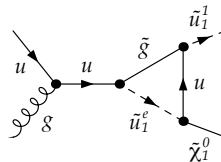
$$d\tilde{\sigma}^{\text{NLO}} = \left[ \mathcal{B}(\Phi_{p_1 p_2}) + \underbrace{\alpha_s \mathcal{V}(\Phi_{p_1 p_2})}_{\text{Virtual corrections}} \right] d\Phi_{p_1 p_2} + \alpha_s \mathcal{R}(\Phi_{p_1 p_2 j}) d\Phi_{p_1 p_2 j}$$



UV divergences



RENORMALIZATION



# Real corrections

## Master Formula

$$\sigma_{\text{pp}(p_1, p_2) \rightarrow X}^{\text{NLO}} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \underbrace{\sigma_{p_1 p_2 \rightarrow X}^{\text{NLO}}(x_1, x_2, \alpha_s(\mu_R^2), Q^2/\mu_F^2, Q^2/\mu_R^2)}$$

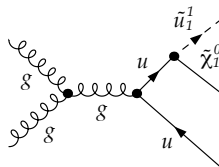
$$d\tilde{\sigma}^{\text{NLO}} = [\mathcal{B}(\Phi_{p_1 p_2}) + \alpha_s \mathcal{V}(\Phi_{p_1 p_2})] d\Phi_{p_1 p_2} + \underbrace{\alpha_s \mathcal{R}(\Phi_{p_1 p_2 j}) d\Phi_{p_1 p_2 j}}$$



IR & OS divergences



SUBTRACTION



## *The right equipment*



*LOOPS*

**GOLEM**

*LOOPS*

**QGRAF**

**MadGOLEM**

*TREE*

**MadGraph**

*IR divergences*

**Extended  
MadDipole**

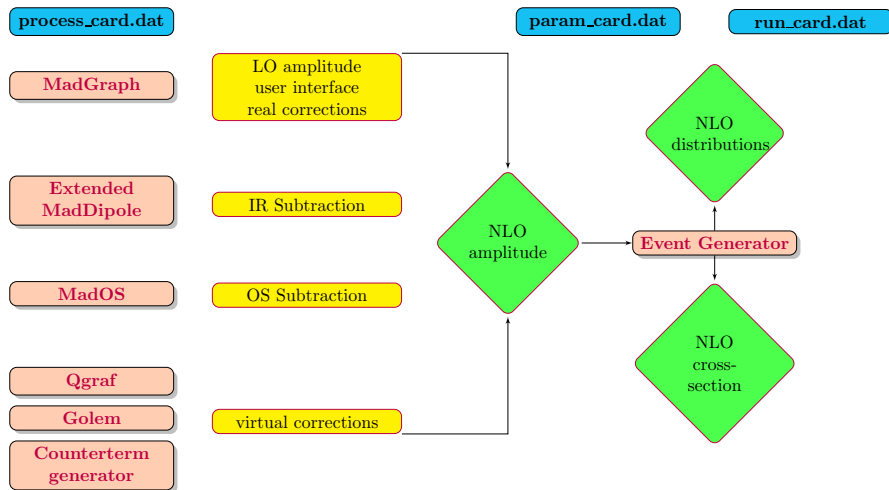
*UV divergences*

**Renormalization**

*OS divergences*

**MadOS**

# MadGolem's architecture: modules and flowchart



# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices   propagators   color   Lorentz structures   rel. signs   sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

# Handling the virtual parts

**GENERATION****Qgraph** [Nogueira]

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

**TRANSLATION****Qgraf-Golem**

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

vertices    propagators    color    Lorentz structures    rel. signs    sym. factors

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

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

# Handling the virtual parts

♠ GENERATION ↔ Qgraph [Nogueira]

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

♠ TRANSLATION ↔ Qgraf-Golem

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

vertices   propagators   color   Lorentz structures   rel. signs   sym. factors

♠ CALCULATION ↔ Golem [Binoth et al.]

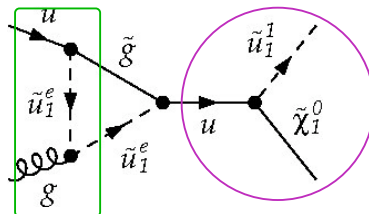
Amplitude  $\xrightarrow{\text{BASH,PERL,FORM,MAPLE}}$  Reduced amplitude

$$\mathcal{M}^{\text{NLO}} = \underbrace{\mathcal{M}_{[\text{color/helicity/11-function}]}}_{\text{partial amplitudes}} \times \underbrace{\mathcal{B}_{\text{color}} \otimes \mathcal{B}_{\text{hel}} \otimes \mathcal{B}_{\text{1Lfunction}}}_{\text{basis}}$$

# 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.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,GQLG0P ,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

Systematically translated ...

```
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)*
e2(Lorhx2)*GULN1P2 );
```

## 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 UV divergences

## Including the Counterterms

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

# Handling the UV divergences

## Including the Counterterms

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

$$\underbrace{\delta \mathcal{L}(\delta Z_\phi, \delta Z_g)}_{\text{Model file + Qgraph}} \Leftrightarrow \underbrace{\Sigma_q, \Sigma_{\tilde{q}}, \Sigma_g, \Sigma_{\tilde{g}}}_{\text{External library}} @ \mathcal{O}(\alpha_s)$$

# Handling the UV divergences

## Including the Counterterms

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

$$\underbrace{\delta \mathcal{L}(\delta Z_\phi, \delta Z_g)}_{\text{Model file + Qgraph}} \Leftrightarrow \underbrace{\Sigma_q, \Sigma_{\tilde{q}}, \Sigma_g, \Sigma_{\tilde{g}}}_{\text{External library}} @ \mathcal{O}(\alpha_s)$$

## Renormalization scheme

- OS for masses
- $\overline{\text{MS}}$ + decoupling of heavy colored-particles, 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]

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

# Handling the IR divergences

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

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

# Handling the IR divergences

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

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

Local (pointwise) subtraction of the IR poles

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

# Handling the IR divergences

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

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

Local (pointwise) subtraction of the IR poles

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

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

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

**SUSY dipoles** (including the MadFKS-like  $\alpha$ -dependence) as an **extended MadDipole** module  
[Frederix, Gehrmann, Greiner '07]

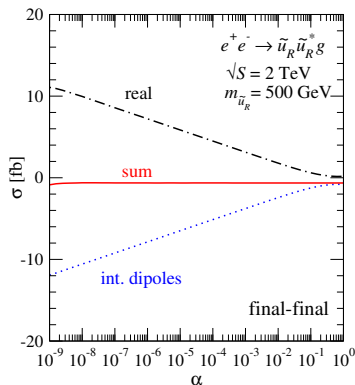
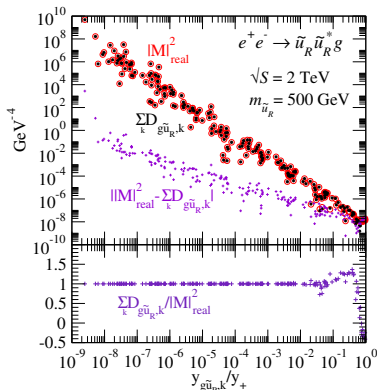
# Handling the IR divergences

Performance of the SUSY Catani-Seymour dipoles

# Handling the IR divergences

## Performance of the SUSY Catani-Seymour dipoles

digging into the soft/collinear region for  $e^+e^- \rightarrow \tilde{u}_R \tilde{u}_R^*$



# Handling the OS Divergences

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

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

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

# Handling the OS Divergences

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

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

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

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

# Handling the OS Divergences

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

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

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

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

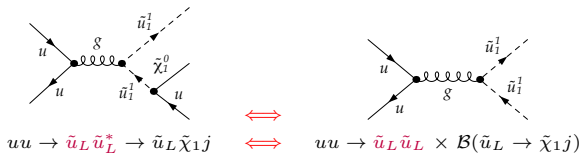
# Handling the OS Divergences

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

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

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

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



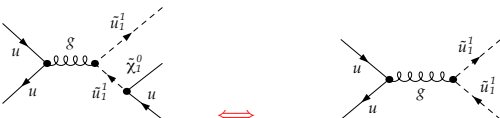
# Handling the OS Divergences

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

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

$$ug \rightarrow \tilde{u}_L \tilde{\chi}_{1j} + uu \rightarrow \tilde{u}_L \tilde{u}_L^* \rightarrow \tilde{u}_L \tilde{\chi}_{1j}$$

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



$$uu \rightarrow \tilde{u}_L \tilde{u}_L^* \rightarrow \tilde{u}_L \tilde{\chi}_{1j} \iff uu \rightarrow \tilde{u}_L \tilde{u}_L \times \mathcal{B}(\tilde{u}_L \rightarrow \tilde{\chi}_{1j})$$

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

- 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

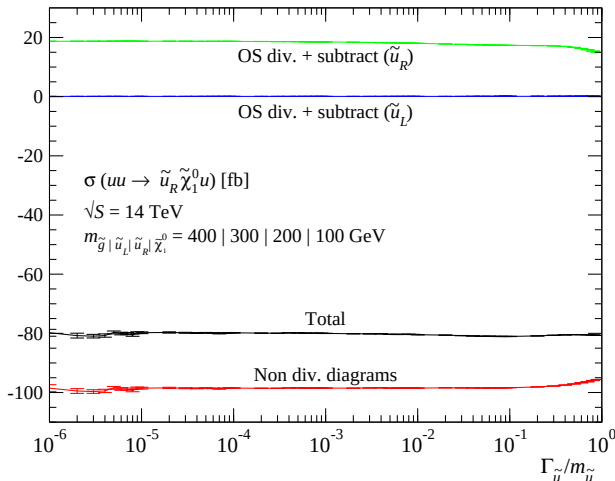
# Handling the OS divergences

## Performance of the OS subtraction

# Handling the OS divergences

## Performance of the OS subtraction

♠ approaching the squark on-shell region for  $pp(uu) \rightarrow \tilde{u}_R(\tilde{u}_R^*)^* \rightarrow \tilde{u}_R\tilde{\chi}_1^0 u$



# From the user's viewpoint ...

3-stage procedure – 3 interfaces ↔ 3 executables

## Stage 1: DEFINING THE PROCESS

process\_card ↔ ./newprocess\_nlo

# From the user's viewpoint ...

3-stage procedure – 3 interfaces ↔ 3 executables

## Stage 1: DEFINING THE PROCESS

process\_card ↔ ./newprocess\_nlo

## 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!)

# From the user's viewpoint ...

3-stage procedure – 3 interfaces ↔ 3 executables

## Stage 1: DEFINING THE PROCESS

process\_card ↔ ./newprocess\_nlo

## 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!)

## 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

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

**K-factor =  $(P1+P2+P3)/P1 = 1.119$**

| Graph                                         | Cross Sect(ab)           | Error(ab)    | Events (K) | Eff        | Unwgt | Luminosity |
|-----------------------------------------------|--------------------------|--------------|------------|------------|-------|------------|
| <b>Sum</b>                                    | <b>8533.480</b>          | <b>0.793</b> | <b>0</b>   | <b>0.0</b> |       |            |
| LEADING ORDER                                 |                          |              |            |            |       |            |
| <a href="#">P1_e-e+_ululx</a>                 | <a href="#">7625.900</a> | 0.506        | 0          | 0.0        |       | 0.00       |
| total LO = 7625.8999999999996                 |                          |              |            |            |       |            |
| NLO CONTRIBUTION: Virtual part                |                          |              |            |            |       |            |
| <a href="#">P2_e-e+_ululxg</a>                | <a href="#">578.990</a>  | 0.068        | 0          | 0.0        |       | 0.00       |
| total NLO (virtual part)= 578.990000000000001 |                          |              |            |            |       |            |
| NLO CONTRIBUTION: Real part                   |                          |              |            |            |       |            |
| <a href="#">P3_e-e+_ululxg</a>                | <a href="#">328.590</a>  | 0.219        | 0          | 0.0        |       | 0.00       |
| total NLO (real part) = 328.590000000000003   |                          |              |            |            |       |            |

# MadGolem underway

## Processes

### SM processes

$$\spadesuit \quad pp \rightarrow e^+ e^-$$

$$\spadesuit \quad u\bar{u} \rightarrow d\bar{d}; \quad gg \rightarrow d\bar{d}$$

$$\spadesuit \quad u\bar{u} \rightarrow t\bar{t}; \quad gg \rightarrow t\bar{t}$$

### SUSY pair (EW)

$$\clubsuit \quad pp \rightarrow \tilde{l}\tilde{l}^*$$

$$\clubsuit \quad pp \rightarrow \tilde{\chi}\tilde{\chi}; \quad pp \rightarrow \tilde{g}\tilde{\chi}$$

$$\clubsuit \quad pp \rightarrow \tilde{q}\tilde{\chi}$$

### SUSY pair (QCD)

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{q}^*; \quad pp \rightarrow \tilde{q}\tilde{q}$$

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{g}$$

$$\diamondsuit \quad pp \rightarrow \tilde{g}\tilde{g}$$

### heavy colored BSM resonances

$$\blacktriangle \quad pp \rightarrow GG^*$$

### other BSM processes

$$\blacktriangle \quad pp \rightarrow t + X \text{ with } \hat{O}^{\text{d}=6}$$

$$\blacktriangle \quad pp \rightarrow H^\pm t \text{ @ 2HDM}$$

# MadGolem underway

## Processes

SM processes

$$\spadesuit \quad pp \rightarrow e^+ e^-$$

$$\spadesuit \quad u\bar{u} \rightarrow d\bar{d}; \quad gg \rightarrow d\bar{d}$$

$$\spadesuit \quad u\bar{u} \rightarrow t\bar{t}, \quad gg \rightarrow t\bar{t}$$

SUSY pair (EW)

$$\clubsuit \quad pp \rightarrow \tilde{l}\tilde{l}^*$$

$$\clubsuit \quad pp \rightarrow \tilde{\chi}\tilde{\chi}; \quad pp \rightarrow \tilde{g}\tilde{\chi}$$

$$\clubsuit \quad pp \rightarrow \tilde{q}\tilde{\chi}$$

SUSY pair (QCD)

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{q}^*; \quad pp \rightarrow \tilde{q}\tilde{q}$$

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{g}$$

$$\diamondsuit \quad pp \rightarrow \tilde{g}\tilde{g}$$

heavy colored BSM resonances

$$\blacktriangle \quad pp \rightarrow GG^*$$

other BSM processes

$$\blacktriangle \quad pp \rightarrow t + X \text{ with } \hat{O}^{\text{d}=6}$$

$$\blacktriangle \quad pp \rightarrow H^\pm t \text{ @ 2HDM}$$

CROSS-CHECKS: i) gauge invariance ;

# MadGolem underway

## Processes

SM processes

$$\spadesuit \quad pp \rightarrow e^+ e^-$$

$$\spadesuit \quad u\bar{u} \rightarrow d\bar{d}; \quad gg \rightarrow d\bar{d}$$

$$\spadesuit \quad u\bar{u} \rightarrow t\bar{t}, \quad gg \rightarrow t\bar{t}$$

SUSY pair (EW)

$$\clubsuit \quad pp \rightarrow \tilde{l}\tilde{l}^*$$

$$\clubsuit \quad pp \rightarrow \tilde{\chi}\tilde{\chi}; \quad pp \rightarrow \tilde{g}\tilde{\chi}$$

$$\clubsuit \quad pp \rightarrow \tilde{q}\tilde{\chi}$$

SUSY pair (QCD)

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{q}^*; \quad pp \rightarrow \tilde{q}\tilde{q}$$

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{g}$$

$$\diamondsuit \quad pp \rightarrow \tilde{g}\tilde{g}$$

heavy colored BSM resonances

$$\blacktriangle \quad pp \rightarrow GG^*$$

other BSM processes

$$\blacktriangle \quad pp \rightarrow t + X \text{ with } \hat{O}^{\text{d}=6}$$

$$\blacktriangle \quad pp \rightarrow H^\pm t \text{ @ 2HDM}$$

CROSS-CHECKS: i) gauge invariance ; ii) UV/IR cancellation ;

# MadGolem underway

## Processes

### SM processes

$$\spadesuit \quad pp \rightarrow e^+ e^-$$

$$\spadesuit \quad u\bar{u} \rightarrow d\bar{d}; \quad gg \rightarrow d\bar{d}$$

$$\spadesuit \quad u\bar{u} \rightarrow t\bar{t}; \quad gg \rightarrow t\bar{t}$$

### SUSY pair (EW)

$$\clubsuit \quad pp \rightarrow \tilde{l}\tilde{l}^*$$

$$\clubsuit \quad pp \rightarrow \tilde{\chi}\tilde{\chi}; \quad pp \rightarrow \tilde{g}\tilde{\chi}$$

$$\clubsuit \quad pp \rightarrow \tilde{q}\tilde{\chi}$$

### SUSY pair (QCD)

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{q}^*; \quad pp \rightarrow \tilde{q}\tilde{q}$$

$$\diamondsuit \quad pp \rightarrow \tilde{q}\tilde{g}$$

$$\diamondsuit \quad pp \rightarrow \tilde{g}\tilde{g}$$

### heavy colored BSM resonances

$$\blacktriangle \quad pp \rightarrow GG^*$$

### other BSM processes

$$\blacktriangle \quad pp \rightarrow t + X \text{ with } \hat{O}^{\text{d}=6}$$

$$\blacktriangle \quad pp \rightarrow H^\pm t \text{ @ 2HDM}$$

**CROSS-CHECKS:** i) gauge invariance ; ii) UV/IR cancellation ; Finite parts – with FeynArts/FormCalc/LoopTools [Hahn]

# *Landmarks*



# Exploring the BSM landscape with MadGolem

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

# Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

## Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

**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*

# Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

## 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*

# Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

**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*

## Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

### 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*

# Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

$$pp \rightarrow GG^*$$

arXiv:1203.6358

## 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*

# Exploring the BSM landscape with MadGolem

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

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

arXiv:1108.1250

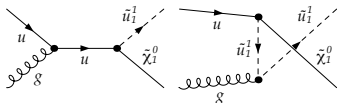
$$pp \rightarrow GG^*$$

arXiv:1203.6358

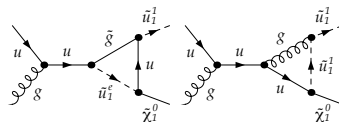
## BSM phenomenology @ NLO

- **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*

# MadGolem taking off



tree-level

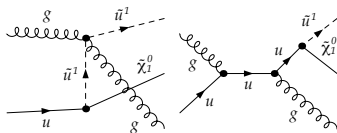


virtual corrections  $\mathcal{O}(\alpha_{ew} \alpha_s^2)$



MSSM renormalization

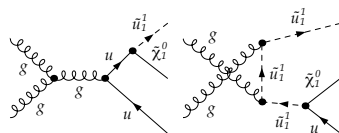
& SUSY-restoration



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

# Sgluons into context

♠ **Sgluons** [ $G$ ] as  $SU(3)_C$  octet , weak singlet, electrically neutral, complex scalar field

# Sgluons into context

♠ Sgluons  $[G]$  as  $SU(3)_C$  **octet** , weak singlet, electrically neutral, complex scalar field

# Sgluons into context

♠ Sgluons  $[G]$  as  $SU(3)_C$  octet , **weak singlet**, electrically neutral, complex scalar field

# Sgluons into context

♠ Sgluons  $[G]$  as  $SU(3)_C$  octet , weak singlet, **electrically neutral**, complex scalar field

# Sgluons into context

♠ Sgluons  $[G]$  as  $SU(3)_C$  octet , weak singlet, electrically neutral, **complex scalar field**

# Sgluons into context

- ♠ **Sgluons**  $[G]$  as  $SU(3)_C$  octet , weak singlet, electrically neutral, complex scalar field

## Some possible UV completions

- ♠ **SUSY** –  $G$  as spartner of a (Dirac)  $\tilde{g}$ 
  - $\mathcal{N} = 1/\mathcal{N} = 2$  [Choi, Drees et al. '08]
  - R-symmetric MSSM [Hall, Randall '91], [Kribs, Poppitz, Weiner '08]
- ♠ **Compositeness & strongly interacting sectors** –
  - $G$  from fundamental color-charged fermions  $3 \otimes \bar{3} = 0 \oplus 8$ 
    - Technicolor, top-color [Farhi, Susskind, Hill, Simmons]
    - Vector-like confinement [Cilik, Okui, Sundrum '10]
- ♠ **Extra dimensions** –  $G$  as 5th component of KK gluons [Burdman, Dobrescu, Pontón '06]
- ♠ **GUT's** – [Fileviez Pérez, Gavin, McElmurry, Petriello ['08]]
- ♠ **Simplified model approaches** – [Manohar, Wise '06]; [Burgess, Trott, Zuberi '09]

# Sgluon dynamics



Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

# Sgluon dynamics



Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



# Sgluon dynamics



Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



# Sgluon dynamics



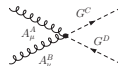
Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^{*} D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



# Sgluon dynamics

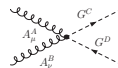
♠ Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



## Most relevant features

- $\mathcal{O}(\alpha_s)$ -mediated pairwise production  $\Rightarrow$  **copiously produced !**
- Indirect (loop-suppressed) couplings to matter  $\Rightarrow$  **no dijet bounds !**

# Sgluon dynamics

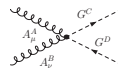
♠ Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



## Most relevant features

- $\mathcal{O}(\alpha_s)$ -mediated pairwise production  $\Rightarrow$  **copiously produced !**
- Indirect (loop-suppressed) couplings to matter  $\Rightarrow$  **no dijet bounds !**

# Sgluon dynamics

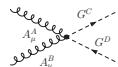
♠ Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



## Most relevant features

- $\mathcal{O}(\alpha_s)$ -mediated pairwise production  $\Rightarrow$  **copiously produced !**
- Indirect (loop-suppressed) couplings to matter  $\Rightarrow$  **no dijet bounds !**

Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, PRD 85 (2012) 114024, arXiv:1203.6358 [hep-ph]

# Sgluon dynamics

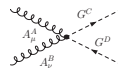
♠ Scalar octet minimally coupled to gluons

$$D_\mu G^A \equiv \partial_\mu G^A + g_s f^{ABC} G^B A_\mu^C$$

$$\mathcal{L} \supset D_\mu G^* D^\mu G - m_G^2 G G^*$$

$$\supset -g_s f^{ABC} \left[ G^{A*} (\partial^\mu G^B) - (\partial^\mu G^{A*}) G^B \right] A_\mu^C$$

$$+ g_s^2 \left[ f^{ACE} f^{BDE} + f^{ADE} f^{BCE} \right] G^{C*} G^D A_\mu^A A^{B\mu}$$



## Most relevant features

- $\mathcal{O}(\alpha_s)$ -mediated pairwise production  $\Rightarrow$  **copiously produced !**
- Indirect (loop-suppressed) couplings to matter  $\Rightarrow$  **no dijet bounds !**

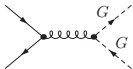
Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, PRD 85 (2012) 114024, arXiv:1203.6358 [hep-ph]

$\Rightarrow$  Analogous interactions govern coloron [(vector color-adjoint)] production – [Chivukula, Farzinnia, Simons, Foadi '12]

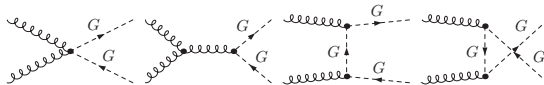
# Sgluon dynamics



## Leading-order dynamics



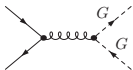
$$u\bar{u} \rightarrow GG^*$$



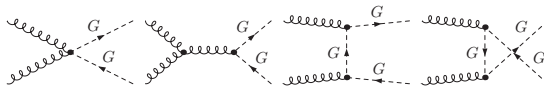
$$gg \rightarrow GG^*$$

# Sgluon dynamics

## ♠ Leading-order dynamics



$$u\bar{u} \rightarrow GG^*$$



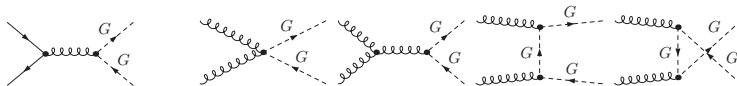
$$gg \rightarrow GG^*$$

## ♠ Computational setup

- PDF set : CTEQ6L1-CTEQ6M with 5 active flavors
- $\alpha_s$  @ consistent 2-loop running
- central scale choice:  $\mu_F = \mu_R = m_G$

# Sgluon dynamics

## ♠ Leading-order dynamics



$$u\bar{u} \rightarrow GG^*$$

$$gg \rightarrow GG^*$$

## ♠ Computational setup

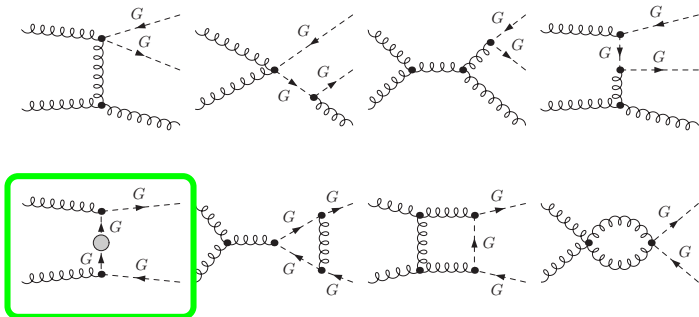
- PDF set : CTEQ6L1-CTEQ6M with 5 active flavors
- $\alpha_s$  @ consistent 2-loop running
- central scale choice:  $\mu_F = \mu_R = m_G$

## ♠ Trademark final-state signatures

- $pp \rightarrow GG^* \rightarrow 4 \text{ jets}$  [Bai, Dobrescu '07; Arnold, Fornal '11]
- $pp \rightarrow GG^* \rightarrow t\bar{q}tq$  [Plehn, Tait '09]
- $pp \rightarrow GG^* \rightarrow t\bar{t}t\bar{t} \rightarrow 8j + 2\ell + \cancel{E}_T$  [Chivukula, Golden, Simmons '91; Kilic, Schumann, Son '09; Han, Lewis, Liu '10]

# $pp \rightarrow GG^*$ at Next-to-Leading Order

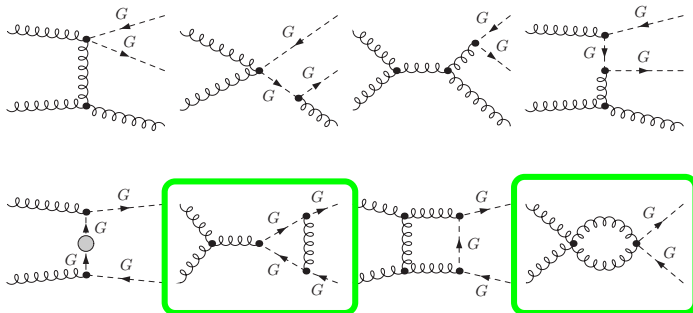
- **Virtual corrections** –  $\mathcal{O}(\alpha_s)$  virtual (s)gluon exchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state sgluon



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

# $pp \rightarrow GG^*$ at Next-to-Leading Order

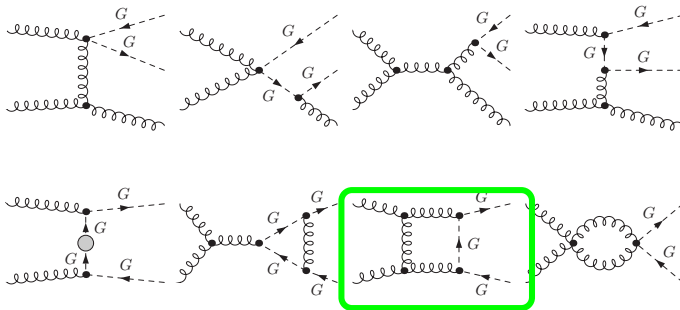
- **Virtual corrections** –  $\mathcal{O}(\alpha_s)$  virtual (s)gluon exchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state sgluon



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

# $pp \rightarrow GG^*$ at Next-to-Leading Order

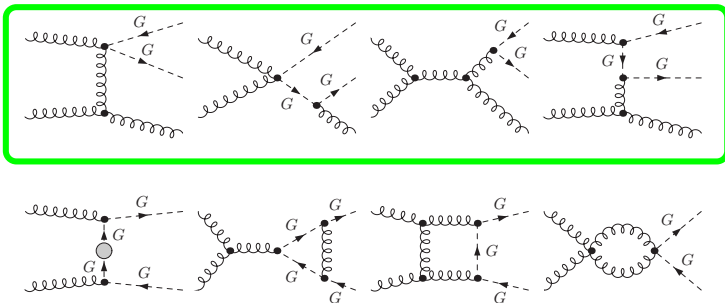
- **Virtual corrections** –  $\mathcal{O}(\alpha_s)$  virtual (s)gluon exchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state sgluon



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

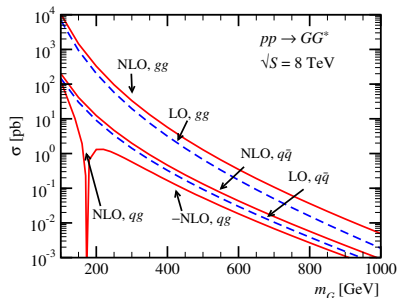
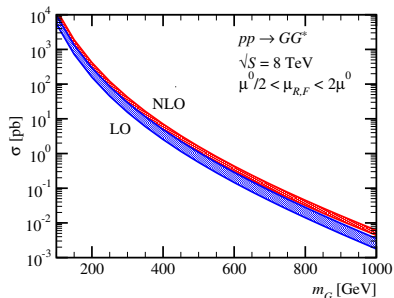
# $pp \rightarrow GG^*$ at Next-to-Leading Order

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



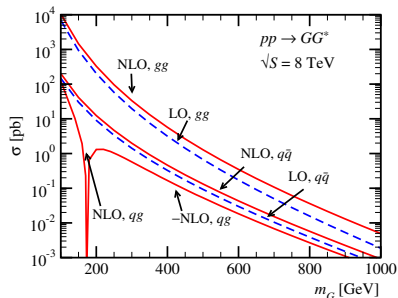
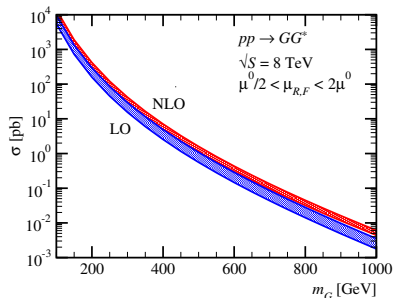
i) self-energy insertions; ii) vertex corrections; iii) box diagrams; iv) **real emission**

# NLO rates & K-factors



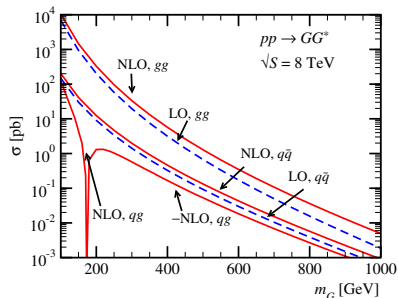
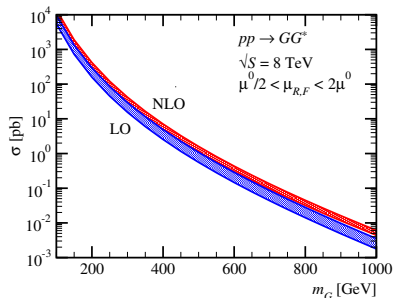
- Dominance of  $gg \rightarrow GG^* \Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# NLO rates & K-factors



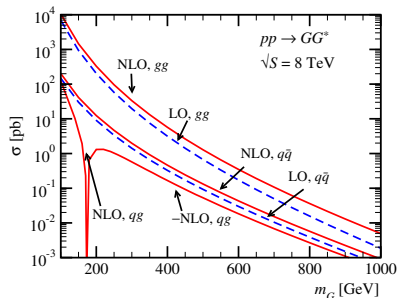
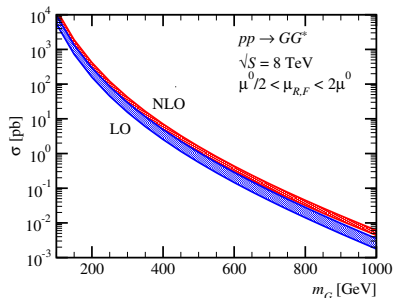
- Dominance of  $gg \rightarrow GG^*$   $\Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# NLO rates & K-factors



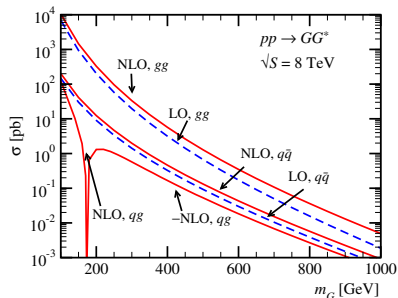
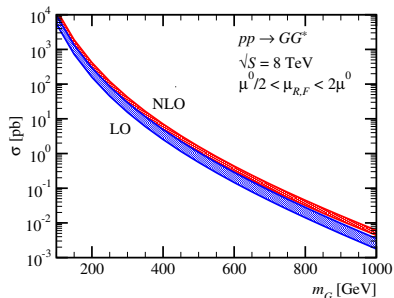
- Dominance of  $gg \rightarrow GG^*$   $\Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# NLO rates & K-factors



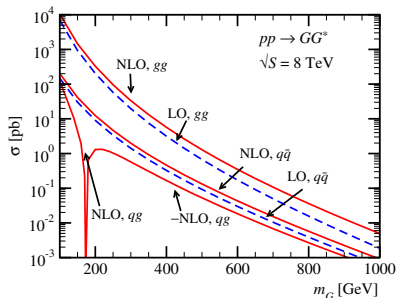
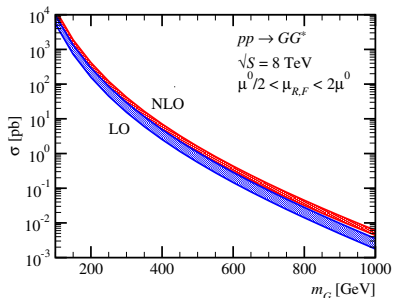
- Dominance of  $gg \rightarrow GG^*$   $\Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# NLO rates & K-factors



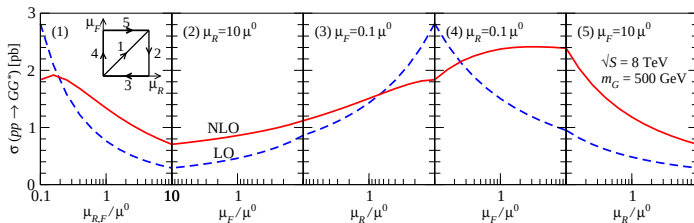
- Dominance of  $gg \rightarrow GG^*$   $\Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# NLO rates & K-factors



- Dominance of  $gg \rightarrow GG^*$   $\Rightarrow$  **larger color charges** & **s-wave kinematics**
- Large rates:  $\sigma \sim \mathcal{O}(1)$  pb for  $m_G = 0.5$  TeV  
 $[\sigma(gg \rightarrow \tilde{t}\tilde{t}^*)/\sigma(gg \rightarrow GG^*) \simeq 1/20]$
- Sizable NLO effects:  $K \gtrsim 1.5$  – as compared to squark-pairs [ $K(\tilde{q}\tilde{q}) \sim 1.3$ ]
- Decreasing rates & Growing K-factor with  $m_G \iff$  **kinematics** & **Threshold enhancements**

# Scale dependences



- Canonical estimate of the theory uncertainties:

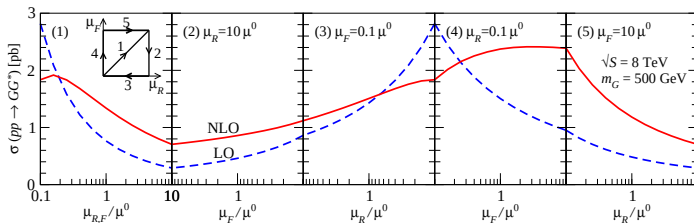
$$\Delta\sigma^{\text{th}} = \sigma(\mu = \mu_0/2) - \sigma(\mu = 2\mu_0)$$

- 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  $\mu_R$

# Scale dependences



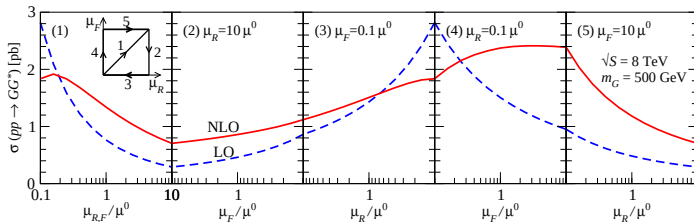
- Canonical estimate of the theory uncertainties:  $\Delta\sigma^{\text{th}} = \sigma(\mu = \mu_0/2) - \sigma(\mu = 2\mu_0)$

- 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  $\mu_R$

# Scale dependences



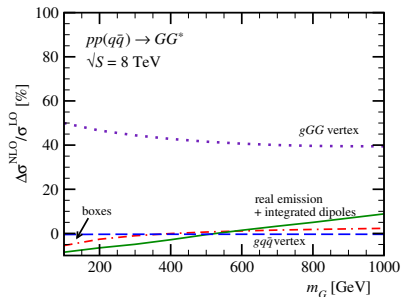
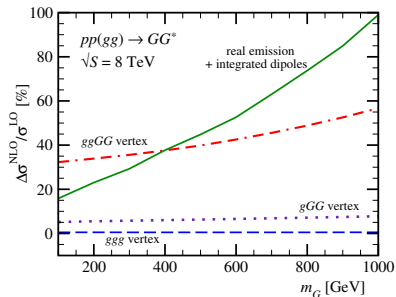
- Canonical estimate of the theory uncertainties:  $\Delta\sigma^{\text{th}} = \sigma(\mu = \mu_0/2) - \sigma(\mu = 2\mu_0)$

- Remarkable scale stabilization

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

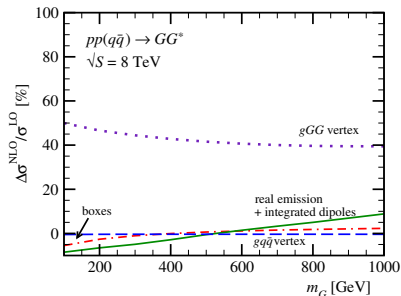
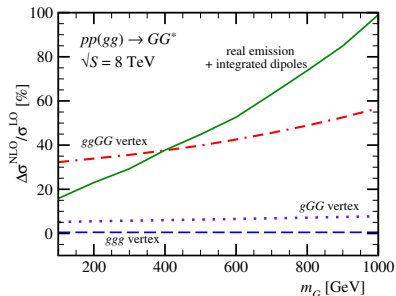
- Larger sensitivity to  $\mu_R$

# Anatomy of the virtual corrections



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

# Anatomy of the virtual corrections



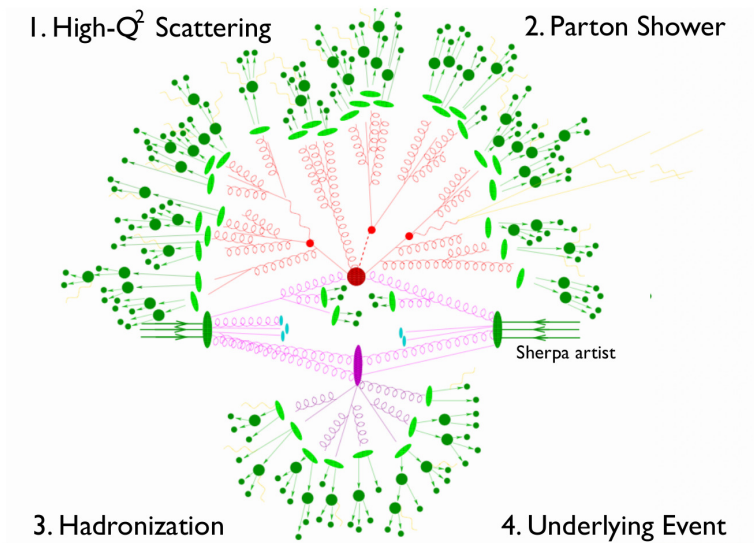
♠ Dominance of the  $gGG$  &  $ggGG$  vertex corrections and the real gluon emission

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

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

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

# An LHC event



# A glimpse at jet merging (I)

## Matrix Element

Fixed-order calculation

Hard / separated partons

- perturbative approach
- computationally expensive
- Limited # of partons
- Full account of quantum effects

## Parton Shower

Resummed  $\mathcal{O}(\alpha_s \log(\mu^2/m^2))$

soft / collinear partons

- perturbative approach
- computationally unexpensive
- unlimited # of partons
- partial account of quantum effects

# A glimpse at jet merging (I)

## Matrix Element

Fixed-order calculation

Hard / separated partons

- perturbative approach
- computationally expensive
- Limited # of partons
- Full account of quantum effects

## Parton Shower

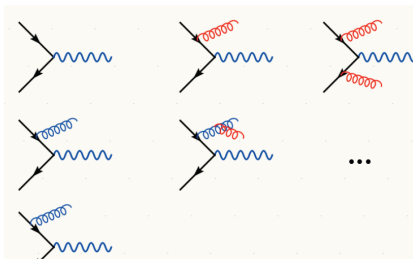
Resummed  $\mathcal{O}(\alpha_s \log(\mu^2/m^2))$

soft / collinear partons

- perturbative approach
- computationally unexpensive
- unlimited # of partons
- partial account of quantum effects

PS →

ME  
↓



## A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

# A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

## MATCHING

- The idea:
  - Use ME (resp. PS) for well separated (resp. soft/collinear) jets
  - Set a phase space cutoff separating both regimes
  - $\Rightarrow$  combined ME+PS description that sidesteps the double counting
- The requirements:
  - Smooth transition between the two regimes
  - Small phase-space cutoff & multiplicity dependence
- The implementation
  - Leading-order ME from MadGraph5 [Alwall et al.]
  - Jet merging using MadGraph5/Pythia
  - MLM as matching prescription [Mangano, Moretti, Pittau '02]
  - Matched samples including up to (0+1+2) hard jets

# Comparison with multi-jet merging

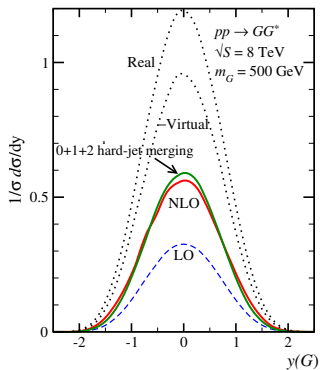
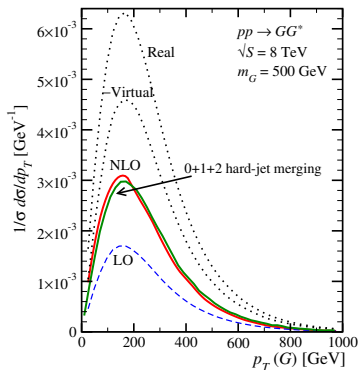


(fixed-order) NLO

VS

multi-jet merging

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



# Comparison with multi-jet merging

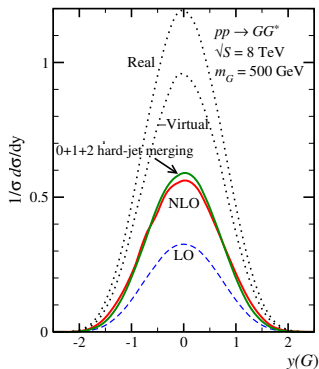
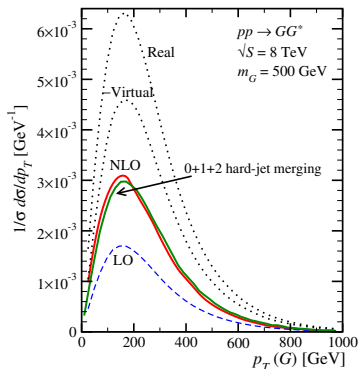


(fixed-order) NLO

VS

multi-jet merging

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

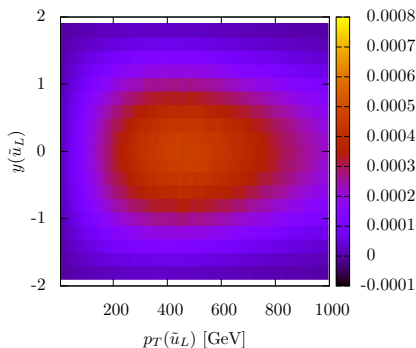
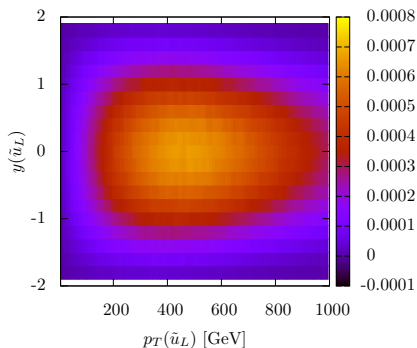


- Normalized distributions in **very good agreement**
- Common to **heavy particle** production – [Plehn, Rainwater, Skands '07], [Alwall, de Visscher, Maltoni '09]

## 2D distributions



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

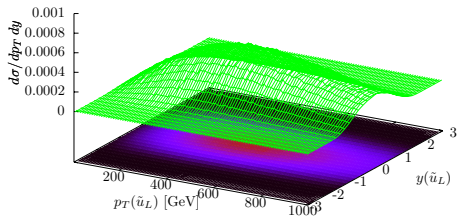
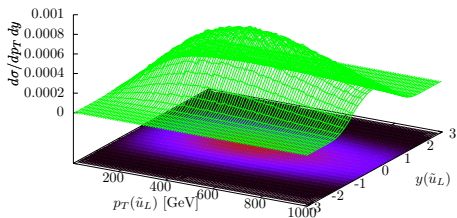


## 2D distributions



Cross-section behavior across a  $p_T/y$  patch

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



## *Wrapping up*



# Take-home ideas

## THE TOOL

### MadGolem

- automates the calculation of NLO cross-sections and distributions for generic  $2 \rightarrow 2$  processes
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Fully automated UV renormalization, and subtraction of IR and OS divergences
- Highly modular, independent add-on to MadGraph/MadEvent
- Tailored for BSM studies: Majorana fermions, SUSY-restoration, effective  $\hat{\mathcal{O}}^{d>4}$ , most easily extendable to new models.

# Take-home ideas

## THE TOOL

### MadGolem

- automates the calculation of NLO cross-sections and distributions for generic  $2 \rightarrow 2$  processes
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Fully automated UV renormalization, and subtraction of IR and OS divergences
- Highly modular, independent add-on to MadGraph/MadEvent
- Tailored for BSM studies: Majorana fermions, SUSY-restoration, effective  $\hat{\mathcal{O}}^{d>4}$ , most easily extendable to new models.

# Take-home ideas

## THE TOOL

### MadGolem

- automates the calculation of NLO cross-sections and distributions for generic  $2 \rightarrow 2$  processes
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Fully automated UV renormalization, and subtraction of IR and OS divergences
- Highly modular, independent add-on to MadGraph/MadEvent
- Tailored for BSM studies: Majorana fermions, SUSY-restoration, effective  $\hat{\mathcal{O}}^{d>4}$ , most easily extendable to new models.

# Take-home ideas

## THE TOOL

### MadGolem

- automates the calculation of NLO cross-sections and distributions for generic  $2 \rightarrow 2$  processes
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Fully automated UV renormalization, and subtraction of IR and OS divergences
- Highly modular, independent add-on to MadGraph/MadEvent
- Tailored for BSM studies: Majorana fermions, SUSY-restoration, effective  $\hat{\mathcal{O}}^{d>4}$ , most easily extendable to new models.

# Take-home ideas

## THE TOOL

### MadGolem

- automates the calculation of NLO cross-sections and distributions for generic  $2 \rightarrow 2$  processes
- Analytical, Feynman-diagrammatic one-loop amplitudes
- Fully automated UV renormalization, and subtraction of IR and OS divergences
- Highly modular, independent add-on to MadGraph/MadEvent
- Tailored for BSM studies: Majorana fermions, SUSY-restoration, effective  $\hat{\mathcal{O}}^{d>4}$ , most easily extendable to new models.

# Take-home ideas

## THE PHYSICS

### Heavy BSM states @ NLO

- Large rates, correlated to spin & charges, strongly mass-dependent
- Large K-factors ( $K \sim 1.3 - 1.7$ )
- NLO  $\mathcal{O}(\alpha_s)$  corrections
  - Dominated by pure QCD  $\longleftrightarrow$  gluon exchange/radiation
  - Highly responsive to color charges & threshold effects
  - **Independent** of the new physics scales –e.g. mass spectrum of the heavy states
- Strongly reduced theoretical uncertainties
- Fixed-order distributions in **very good agreement** with a multi-jet merging description

# Take-home ideas

## THE PHYSICS

### Heavy BSM states @ NLO

- Large rates, correlated to spin & charges, strongly mass-dependent
- Large K-factors ( $K \sim 1.3 - 1.7$ )
- NLO  $\mathcal{O}(\alpha_s)$  corrections
  - Dominated by pure QCD  $\longleftrightarrow$  gluon exchange/radiation
  - Highly responsive to color charges & threshold effects
  - **Independent** of the new physics scales –e.g. mass spectrum of the heavy states
- Strongly reduced theoretical uncertainties
- Fixed-order distributions in **very good agreement** with a multi-jet merging description

# Take-home ideas

## THE PHYSICS

### Heavy BSM states @ NLO

- Large rates, correlated to spin & charges, strongly mass-dependent
- Large K-factors ( $K \sim 1.3 - 1.7$ )
- NLO  $\mathcal{O}(\alpha_s)$  corrections
  - Dominated by pure QCD  $\longleftrightarrow$  gluon exchange/radiation
  - Highly responsive to color charges & threshold effects
  - **Independent** of the new physics scales –e.g. mass spectrum of the heavy states
- Strongly reduced theoretical uncertainties
- Fixed-order distributions in **very good agreement** with a multi-jet merging description

# Take-home ideas

## THE PHYSICS

### Heavy BSM states @ NLO

- Large rates, correlated to spin & charges, strongly mass-dependent
- Large K-factors ( $K \sim 1.3 - 1.7$ )
- NLO  $\mathcal{O}(\alpha_s)$  corrections
  - Dominated by pure QCD  $\longleftrightarrow$  gluon exchange/radiation
  - Highly responsive to color charges & threshold effects
  - **Independent** of the new physics scales –e.g. mass spectrum of the heavy states
- Strongly reduced theoretical uncertainties
- Fixed-order distributions in **very good agreement** with a multi-jet merging description

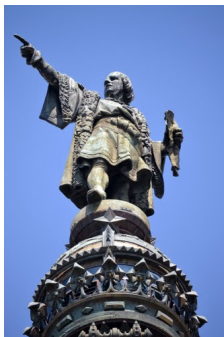
# Take-home ideas

## THE PHYSICS

### Heavy BSM states @ NLO

- Large rates, correlated to spin & charges, strongly mass-dependent
- Large K-factors ( $K \sim 1.3 - 1.7$ )
- NLO  $\mathcal{O}(\alpha_s)$  corrections
  - Dominated by pure QCD  $\longleftrightarrow$  gluon exchange/radiation
  - Highly responsive to color charges & threshold effects
  - **Independent** of the new physics scales –e.g. mass spectrum of the heavy states
- Strongly reduced theoretical uncertainties
- Fixed-order distributions in **very good agreement** with a multi-jet merging description

*And looking ahead . . .*



# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

## And going beyond ...

- ♠ MadGolem & MadGraph5 : [Alwall et al.]:  
recode the extended MadDipole module of MadGolem into MadGraph5

# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

## And going beyond ...

- ♠ MadGolem & MadGraph5 : [Alwall et al.]:  
recode the extended MadDipole module of MadGolem into MadGraph5
- ♠ MadGolem & MadDM : [Alwall, Backovic, Kong, McCasey]:  
loop-induced DM decay processes

# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

## And going beyond ...

- ♠ MadGolem & MadGraph5 : [Alwall et al.]:  
recode the **extended MadDipole** module of **MadGolem** into **MadGraph5**
- ♠ MadGolem & MadDM : [Alwall, Backovic, Kong, McCasey]:  
loop-induced DM decay processes
- ♠ MadGolem & FeynRules : [Christensen, Duhr, Fuks]:  
Automating the generation of UV counterterms for generic New Physics setup.

# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

## And going beyond ...

- ♠ MadGolem & MadGraph5 : [Alwall et al.]:  
recode the extended MadDipole module of MadGolem into MadGraph5
- ♠ MadGolem & MadDM : [Alwall, Backovic, Kong, McCasey]:  
loop-induced DM decay processes
- ♠ MadGolem & FeynRules : [Christensen, Duhr, Fuks]:  
Automating the generation of UV counterterms for generic New Physics setup.
- ♠ MadGolem & MadWeight : [Artoisenet, Lemaitre, Maltoni, Mattelaer]:  
Extending the Matrix Element Method @ NLO

# Future plans

## Complete the MadGolem program

- Prepare the code for public release
- Extend the supported BSM scenarios
- Consider some further phenomenology applications
- And there is always room for improvement ! [size& speed]

## And going beyond ...

- ♠ MadGolem & MadGraph5 : [Alwall et al.]:  
recode the extended MadDipole module of MadGolem into MadGraph5
- ♠ MadGolem & MadDM : [Alwall, Backovic, Kong, McCasey]:  
loop-induced DM decay processes
- ♠ MadGolem & FeynRules : [Christensen, Duhr, Fuks]:  
Automating the generation of UV counterterms for generic New Physics setup.
- ♠ MadGolem & MadWeight : [Artoisenet, Lemaitre, Maltoni, Mattelaer]:  
Extending the Matrix Element Method @ NLO
- ♠ And Pheno, Pheno, Pheno !! : automated tools analysis techniques search strategies

Higgs & top physics  $\longleftrightarrow$  EWSB

# 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

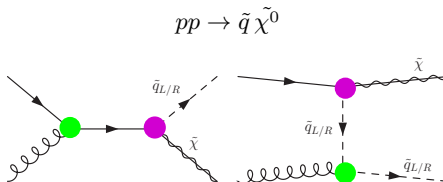
**THANKS A LOT !!**

Experiment

BACKUP

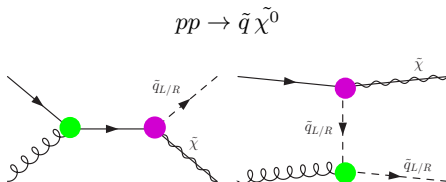
SLIDES

# Phenomenological motivation



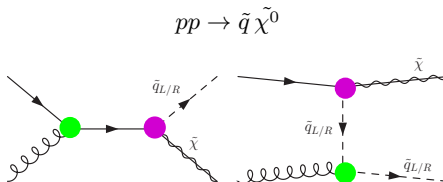
- Potential source of **hard decay monojet +  $\cancel{E}_T$**  signatures
- Directly sensitive to the  **$q\tilde{q}\tilde{\chi}$**  coupling  $\Rightarrow$  **measure might be feasible ?**  
Allanach, Grab, Haber arXiv:1010.426 [hep-ph]
  - Probes the **composition** and **dynamics** of the **LSP**
  - Probes the **SUSY relations** between the **gauge couplings** and the **gaugino-quark-squark couplings**
  - Probes the **SUSY-breaking pattern**

# Phenomenological motivation



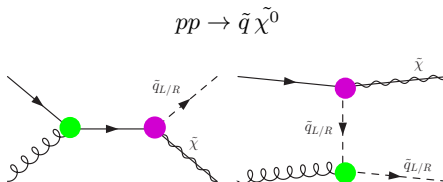
- Potential source of **hard decay monojet +  $\cancel{E}_T$**  signatures
- Directly sensitive to the  **$q\tilde{q}\tilde{\chi}$**  coupling  $\Rightarrow$  **measure might be feasible ?**  
 Allanach, Grab, Haber arXiv:1010.426 [hep-ph]
  - Probes the **composition** and **dynamics** of the **LSP**
  - Probes the **SUSY relations** between the **gauge couplings** and the **gaugino-quark-squark couplings**
  - Probes the **SUSY-breaking pattern**

# Phenomenological motivation



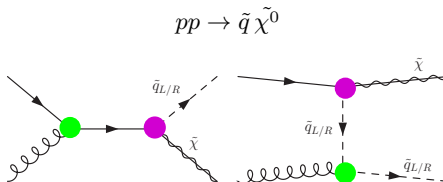
- Potential source of **hard decay monojet +  $\cancel{E}_T$**  signatures
- Directly sensitive to the  **$q\tilde{q}\tilde{\chi}$**  coupling  $\Rightarrow$  **measure might be feasible ?**  
Allanach, Grab, Haber arXiv:1010.426 [hep-ph]
  - Probes the **composition** and **dynamics** of the **LSP**
  - Probes the **SUSY relations** between the **gauge couplings** and the **gaugino-quark-squark couplings**
  - Probes the **SUSY-breaking pattern**

# Phenomenological motivation



- Potential source of **hard decay monojet +  $\cancel{E}_T$**  signatures
- Directly sensitive to the  **$q\tilde{q}\tilde{\chi}$**  coupling  $\Rightarrow$  **measure might be feasible ?**  
Allanach, Grab, Haber arXiv:1010.426 [hep-ph]
  - Probes the **composition** and **dynamics** of the **LSP**
  - Probes the **SUSY relations** between the **gauge couplings** and the **gaugino-quark-squark couplings**
  - Probes the **SUSY-breaking pattern**

# Phenomenological motivation



- Potential source of **hard decay monojet +  $\cancel{E}_T$**  signatures
- Directly sensitive to the  **$q\tilde{q}\tilde{\chi}$**  coupling  $\Rightarrow$  **measure might be feasible ?**  
Allanach, Grab, Haber arXiv:1010.426 [hep-ph]
  - Probes the **composition** and **dynamics** of the **LSP**
  - Probes the **SUSY relations** between the **gauge couplings** and the **gaugino-quark-squark couplings**
  - Probes the **SUSY-breaking pattern**

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Leading-Order

**Flavor-locked**

$$pp(\textcolor{red}{u}g) \rightarrow \tilde{u}\tilde{\chi}_n^0 \text{ @LO}$$

$$pp(\textcolor{red}{u}g, uu, ud, u\bar{u}, gg) \rightarrow \tilde{u}\tilde{\chi}_n^0 \text{ @NLO}$$

# $pp \rightarrow \tilde{q} \tilde{\chi}_n^0$ at Leading-Order

♠ Flavor-locked  $pp(\underline{u}g) \rightarrow \tilde{u} \tilde{\chi}_n^0$  @LO  $pp(\underline{u}g, uu, ud, u\bar{u}, gg) \rightarrow \tilde{u} \tilde{\chi}_n^0$  @NLO

♠ Sensitive to the  $q\tilde{q}\tilde{\chi}^0$  coupling  $\Rightarrow \sigma^{LO} \sim \mathcal{O}(\alpha_{ew} \alpha_s)$

SUSY gauge interactions  $\longleftrightarrow$  neutral gauginos  $\longleftrightarrow$  weak hypercharges

Yukawa interactions  $\longleftrightarrow$  neutral higgsinos  $\longleftrightarrow$  light quark masses

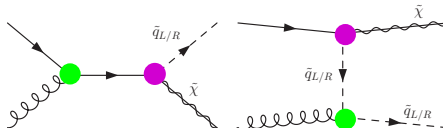
$$C(\tilde{\chi}_n^0 q \tilde{q}_s^*) = i \left( g_L^{\tilde{\chi}_n^0 q \tilde{q}_s} P_R + g_R^{\tilde{\chi}_n^0 q \tilde{q}_s} P_L \right)$$

$$g_L^{\tilde{\chi}_n^0 q \tilde{q}_L^*} = 0$$

$$g_R^{\tilde{\chi}_n^0 q \tilde{q}_L^*} = -\frac{e}{3\sqrt{2} s_W c_W} (s_W N_{n1}^* + 3 c_W N_{n2}^*)$$

$$g_R^{\tilde{\chi}_n^0 q \tilde{q}_R^*} = 0$$

$$g_L^{\tilde{\chi}_n^0 q \tilde{q}_R^*} = 0$$

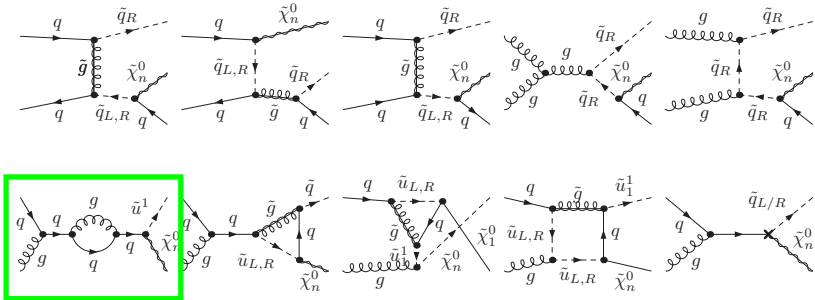


# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Next-to-Leading Order

- **Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state squark

# $pp \rightarrow \tilde{q} \tilde{\chi}_n^0$ at Next-to-Leading Order

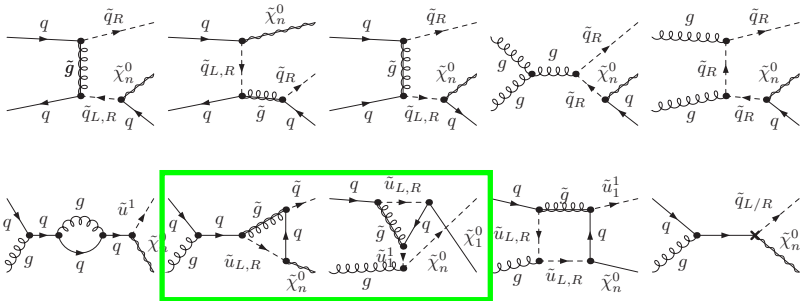
- **Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state squark



- i) (s)quark self-energy insertions; ii) vertex corrections &  $\tilde{\chi}_1 q \tilde{q}$  loop-induced form-factor; iii) box diagrams; iv) UV counterterms; v) real quark/gluon emission

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Next-to-Leading Order

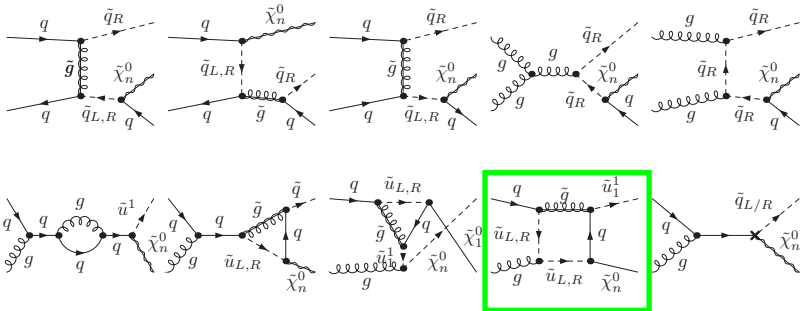
- **Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state squark



- i) (s)quark self-energy insertions; ii) **vertex corrections &  $\tilde{\chi}_1 q \tilde{q}$  loop-induced form-factor** ; iii) box diagrams; iv) UV counterterms; v) real quark/gluon emission

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Next-to-Leading Order

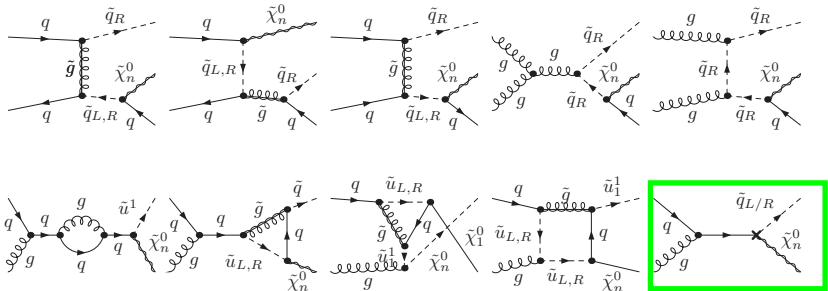
- **Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state squark



- i) (s)quark self-energy insertions; ii) vertex corrections &  $\tilde{\chi}_1 q \tilde{q}$  loop-induced form-factor; iii) **box diagrams**; iv) UV counterterms; v) real quark/gluon emission

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Next-to-Leading Order

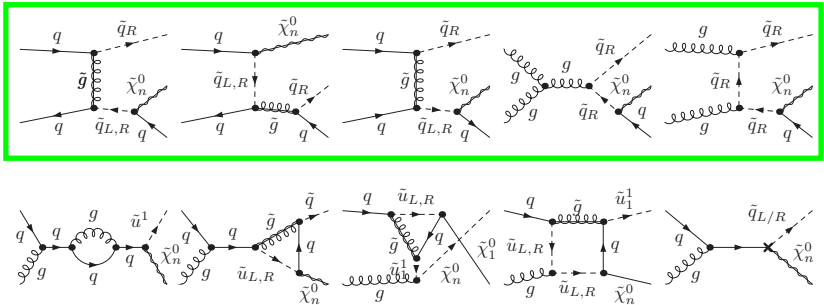
- Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- Real corrections**: quark and gluon emission off the initial partons and the final-state squark



- i) (s)quark self-energy insertions; ii) vertex corrections &  $\tilde{\chi}_1 q \tilde{q}$  loop-induced form-factor; iii) box diagrams; iv) **UV counterterms**; v) real quark/gluon emission

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ at Next-to-Leading Order

- **Virtual corrections**: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
- **Real corrections**: quark and gluon emission off the initial partons and the final-state squark



- i) (s)quark self-energy insertions; ii) vertex corrections &  $\tilde{\chi}_1 q \tilde{q}$  loop-induced form-factor; iii) box diagrams; iv) UV counterterms; v) **real quark/gluon emission**

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ : computational setup



PDF set: CTEQ6L1-CTEQ6M with 5 active flavors

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ : computational setup



PDF set: CTEQ6L1-CTEQ6M with 5 active flavors



Renormalization/factorization scale choice:  $\mu_F = \mu_R = (m_{\tilde{q}} + m_{\tilde{\chi}_n^0})/2$

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ : computational setup

- ♠ PDF set: CTEQ6L1-CTEQ6M with 5 active flavors
- ♠ Renormalization/factorization scale choice:  $\mu_F = \mu_R = (m_{\tilde{q}} + m_{\tilde{\chi}_n^0})/2$
- ♠ Benchmark MSSM scenario: SPS1a<sub>1000</sub>

mSUGRA-like spectrum with  $m_{\tilde{g}} \sim 1$  TeV

# $pp \rightarrow \tilde{q}\tilde{\chi}_n^0$ : computational setup

- ♠ PDF set: CTEQ6L1-CTEQ6M with 5 active flavors
- ♠ Renormalization/factorization scale choice:  $\mu_F = \mu_R = (m_{\tilde{q}} + m_{\tilde{\chi}_n^0})/2$
- ♠ Benchmark MSSM scenario: SPS1a<sub>1000</sub>

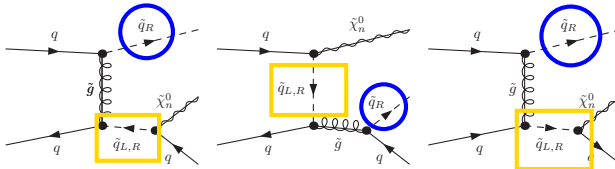
mSUGRA-like spectrum with  $m_{\tilde{g}} \sim 1 \text{ TeV}$

⇒ for SPS1a<sub>1000</sub> the neutralino is **mostly bino**

- quantitative differences:  $g_u \tilde{u}_L^* \tilde{\chi}_1 / g_u \tilde{u}_R^* \tilde{\chi}_1 \sim 1/6 \Rightarrow$

$$\sigma(\tilde{u}_R \tilde{\chi}_1) \gg \sigma(\tilde{u}_L \tilde{\chi}_1)$$

- qualitative differences: relative size & dominant sources of real & virtual corrections



# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO



## Structure of the NLO corrections

- Quantum effects moderately large ( $\sim 30/40\%$ ) and largely insensitive to the details of the SUSY spectrum
- dominated by pure QCD virtual gluon interchange & real gluon emission
- SUSY-QCD corrections entail a subleading contribution (suppressed by  $\sim 1/M_{SUSY}$ )

# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO



## Structure of the NLO corrections

- Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
- dominated by pure QCD **virtual gluon interchange & real gluon emission**
- **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )

# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO



## Structure of the NLO corrections

- Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
- dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
- **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )

# Phenomenological analysis

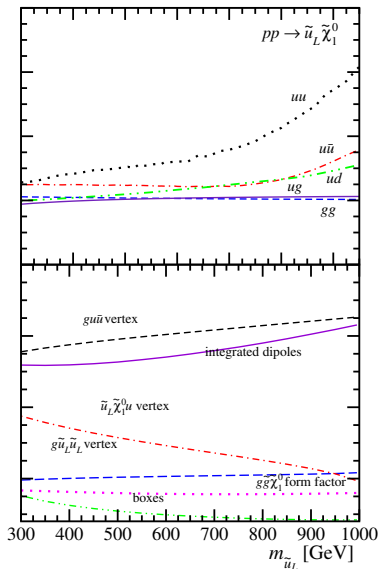
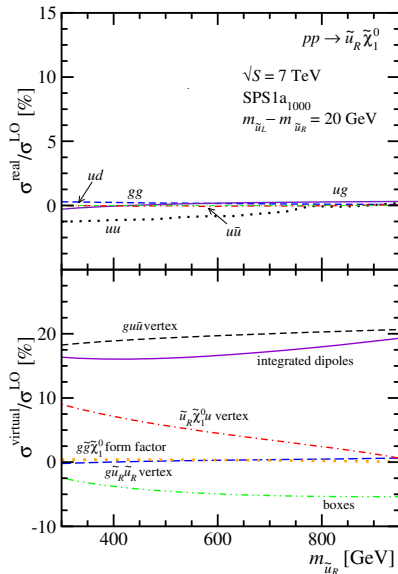
$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO



## Structure of the NLO corrections

- Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
- dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
- **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )

# Structure of the NLO corrections



# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ **Structure of the NLO corrections**
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ **Scale dependence**
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike

# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ Structure of the NLO corrections
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ Scale dependence
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike

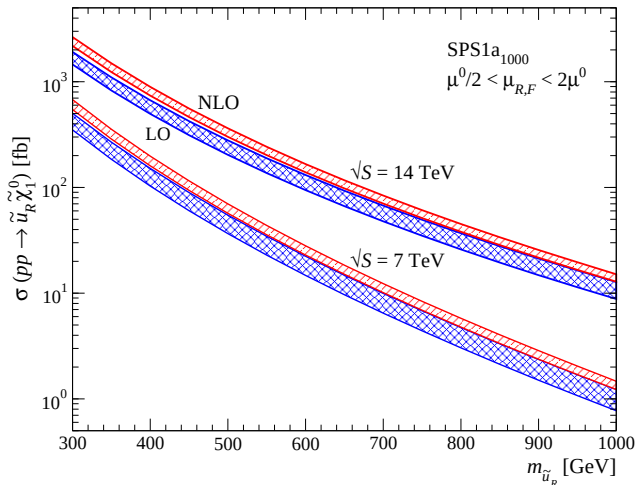
# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ **Structure of the NLO corrections**
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ **Scale dependence**
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike

# Scale dependence

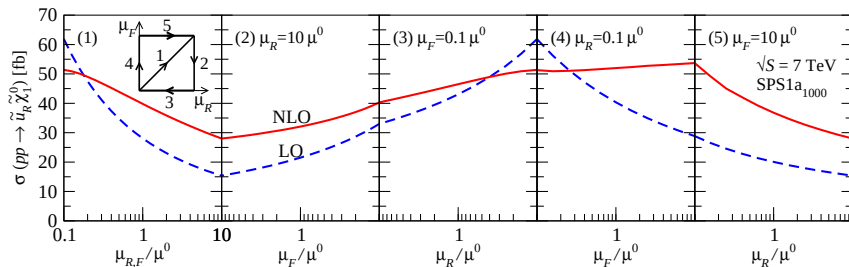
- Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @ NLO VS  $\sim 70\%$  @ LO



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

# Scale dependence

- Similarly sensitive to variations of  $\mu_F/\mu_R$  alike



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

# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ **Structure of the NLO corrections**
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ **Scale dependence**
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike
- ♠ **MSSM parameter space survey**
  - **Overall rates** :  $\sigma \sim \mathcal{O}(1 - 100)$  fb for LHC at  $\sqrt{S} = 14$  TeV.
    - **Strongly dependent** on the MSSM configuration  $\Rightarrow$  kinematics (phase space) & dynamics ( $q\tilde{q}\tilde{\chi}_n^0$  coupling-strength)
  - **K-factors** :  $K \sim \mathcal{O}(1.3 - 1.4)$ 
    - **Virtually insensitive** to the the MSSM configuration

# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ Structure of the NLO corrections
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ Scale dependence
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike
- ♠ MSSM parameter space survey
  - Overall rates :  $\sigma \sim \mathcal{O}(1 - 100)$  fb for LHC at  $\sqrt{S} = 14$  TeV.
    - **Strongly dependent** on the MSSM configuration  $\Rightarrow$  kinematics (phase space) & dynamics ( $q\tilde{q}\tilde{\chi}_n^0$  coupling-strength)
  - K-factors :  $K \sim \mathcal{O}(1.3 - 1.4)$ 
    - **Virtually insensitive** to the the MSSM configuration

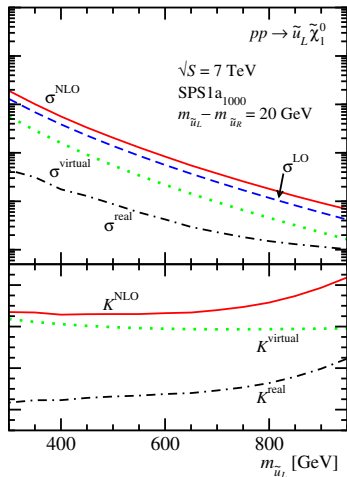
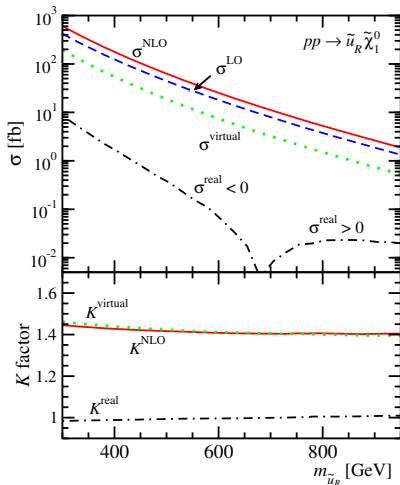
# Phenomenological analysis

$pp \rightarrow \tilde{q}\tilde{\chi}_n^0$  at NLO

- ♠ **Structure of the NLO corrections**
  - Quantum effects **moderately large** ( $\sim 30/40\%$ ) and **largely insensitive** to the details of the **SUSY spectrum**
  - dominated by pure QCD **virtual gluon interchange** & **real gluon emission**
  - **SUSY-QCD** corrections entail a **subleading** contribution (suppressed by  $\sim 1/M_{SUSY}$ )
- ♠ **Scale dependence**
  - Strongly reduced theory uncertainty:  $\Delta\sigma/\sigma \sim 20\%$  @NLO VS  $\sim 70\%$  @LO
  - Similarly sensitive to variations of  $\mu_F/\mu_R$  alike
- ♠ **MSSM parameter space survey**
  - **Overall rates** :  $\sigma \sim \mathcal{O}(1 - 100)$  fb for LHC at  $\sqrt{S} = 14$  TeV.
    - **Strongly dependent** on the MSSM configuration  $\Rightarrow$  kinematics (phase space) & dynamics ( $q\tilde{q}\tilde{\chi}_n^0$  coupling-strength)
  - **K-factors** :  $K \sim \mathcal{O}(1.3 - 1.4)$ 
    - **Virtually insensitive** to the the MSSM configuration

# MSSM parameter space survey

- Overall rates:  $\sigma \sim \mathcal{O}(1 - 100)$
- K-factors:  $K \sim \mathcal{O}(1.3 - 1.4)$



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

## MSSM parameter space survey

|                       | $\sqrt{S}$ | $\sigma^{\text{LO}}$ | $\sigma^{\text{NLO}}$ | $K$  | $m_{\tilde{u}}$      | $m_{\tilde{d}}$      | $m_{\tilde{g}}$ | $m_{\tilde{\chi}_1}$ |
|-----------------------|------------|----------------------|-----------------------|------|----------------------|----------------------|-----------------|----------------------|
| SPS1a <sub>1000</sub> | 7          | 35.27                | 50.44                 | 1.43 | $\tilde{u}_L : 561$  | $\tilde{d}_L : 568$  | 1000            | 97                   |
|                       | 14         | 215.02               | 301.27                | 1.40 | $\tilde{u}_R : 549$  | $\tilde{d}_R : 545$  |                 |                      |
| SPS1b                 | 7          | 2.77                 | 3.99                  | 1.45 | $\tilde{u}_L : 872$  | $\tilde{d}_L : 878$  | 938             | 162                  |
|                       | 14         | 27.21                | 37.46                 | 1.38 | $\tilde{u}_R : 850$  | $\tilde{d}_R : 843$  |                 |                      |
| SPS2                  | 7          | 0.04                 | 0.07                  | 1.52 | $\tilde{u}_L : 1554$ | $\tilde{d}_L : 1559$ | 782             | 123                  |
|                       | 14         | 1.21                 | 1.64                  | 1.36 | $\tilde{u}_R : 1554$ | $\tilde{d}_R : 1552$ |                 |                      |
| SPS3                  | 7          | 3.15                 | 4.55                  | 1.44 | $\tilde{u}_L : 854$  | $\tilde{d}_L : 860$  | 935             | 161                  |
|                       | 14         | 30.20                | 41.59                 | 1.38 | $\tilde{u}_R : 832$  | $\tilde{d}_R : 824$  |                 |                      |
| SPS7                  | 7          | 2.19                 | 3.17                  | 1.45 | $\tilde{u}_L : 896$  | $\tilde{d}_L : 904$  | 950             | 163                  |
|                       | 14         | 22.36                | 30.80                 | 1.38 | $\tilde{u}_R : 875$  | $\tilde{d}_R : 870$  |                 |                      |
| SPS8                  | 7          | 0.65                 | 0.95                  | 1.45 | $\tilde{u}_L : 1113$ | $\tilde{d}_L : 1122$ | 839             | 139                  |
|                       | 14         | 8.73                 | 11.79                 | 1.35 | $\tilde{u}_R : 1077$ | $\tilde{d}_R : 1072$ |                 |                      |
| SPS9                  | 7          | 0.39                 | 0.58                  | 1.49 | $\tilde{u}_L : 1276$ | $\tilde{d}_L : 1279$ | 1872            | 187                  |
|                       | 14         | 7.65                 | 10.42                 | 1.36 | $\tilde{u}_R : 1282$ | $\tilde{d}_R : 1289$ |                 |                      |

$\sigma$  in fb,  $\sqrt{S}$  in TeV,  $m$  in GeV.

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

## MSSM parameter space survey

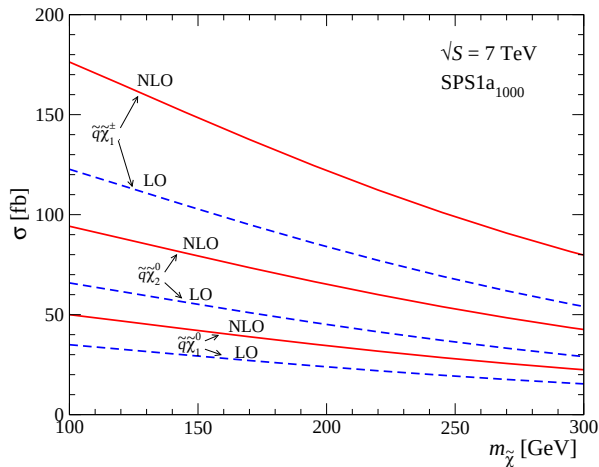
|                       | $\sqrt{S}$ | $\sigma^{\text{LO}}$ | $\sigma^{\text{NLO}}$ | $K$  | $m_{\tilde{u}}$      | $m_{\tilde{d}}$      | $m_{\tilde{g}}$ | $m_{\tilde{\chi}_1}$ |
|-----------------------|------------|----------------------|-----------------------|------|----------------------|----------------------|-----------------|----------------------|
| SPS1a <sub>1000</sub> | 7          | 35.27                | 50.44                 | 1.43 | $\tilde{u}_L : 561$  | $\tilde{d}_L : 568$  | 1000            | 97                   |
|                       | 14         | 215.02               | 301.27                | 1.40 | $\tilde{u}_R : 549$  | $\tilde{d}_R : 545$  |                 |                      |
| SPS1b                 | 7          | 2.77                 | 3.99                  | 1.45 | $\tilde{u}_L : 872$  | $\tilde{d}_L : 878$  | 938             | 162                  |
|                       | 14         | 27.21                | 37.46                 | 1.38 | $\tilde{u}_R : 850$  | $\tilde{d}_R : 843$  |                 |                      |
| SPS2                  | 7          | 0.04                 | 0.07                  | 1.52 | $\tilde{u}_L : 1554$ | $\tilde{d}_L : 1559$ | 782             | 123                  |
|                       | 14         | 1.21                 | 1.64                  | 1.36 | $\tilde{u}_R : 1554$ | $\tilde{d}_R : 1552$ |                 |                      |
| SPS3                  | 7          | 3.15                 | 4.55                  | 1.44 | $\tilde{u}_L : 854$  | $\tilde{d}_L : 860$  | 935             | 161                  |
|                       | 14         | 30.20                | 41.59                 | 1.38 | $\tilde{u}_R : 832$  | $\tilde{d}_R : 824$  |                 |                      |
| SPS7                  | 7          | 2.19                 | 3.17                  | 1.45 | $\tilde{u}_L : 896$  | $\tilde{d}_L : 904$  | 950             | 163                  |
|                       | 14         | 22.36                | 30.80                 | 1.38 | $\tilde{u}_R : 875$  | $\tilde{d}_R : 870$  |                 |                      |
| SPS8                  | 7          | 0.65                 | 0.95                  | 1.45 | $\tilde{u}_L : 1113$ | $\tilde{d}_L : 1122$ | 839             | 139                  |
|                       | 14         | 8.73                 | 11.79                 | 1.35 | $\tilde{u}_R : 1077$ | $\tilde{d}_R : 1072$ |                 |                      |
| SPS9                  | 7          | 0.39                 | 0.58                  | 1.49 | $\tilde{u}_L : 1276$ | $\tilde{d}_L : 1279$ | 1872            | 187                  |
|                       | 14         | 7.65                 | 10.42                 | 1.36 | $\tilde{u}_R : 1282$ | $\tilde{d}_R : 1289$ |                 |                      |

$\sigma$  in fb,  $\sqrt{S}$  in TeV,  $m$  in GeV.

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

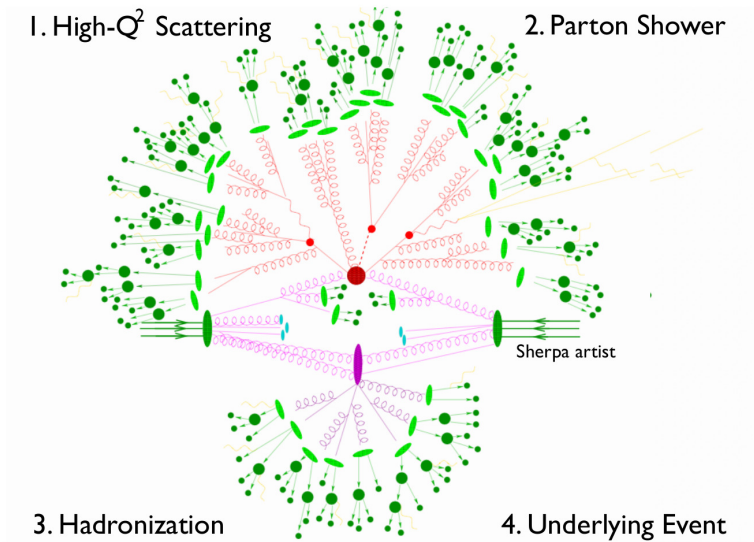
# Squark/neutralino & squark/chargedino channels

♠ If final-state leptons are considered  $\Rightarrow$  sensitivity to squark + heavier neutralinos & charginos



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

# An LHC event



# A glimpse at jet merging (I)

## Matrix Element

Fixed-order calculation

Hard / separated partons

- perturbative approach
- computationally expensive
- Limited # of partons
- Full account of quantum effects

## Parton Shower

Resummed  $\mathcal{O}(\alpha_s \log(\mu^2/m^2))$

soft / collinear partons

- perturbative approach
- computationally unexpensive
- unlimited # of partons
- partial account of quantum effects

# A glimpse at jet merging (I)

## Matrix Element

Fixed-order calculation

Hard / separated partons

- perturbative approach
- computationally expensive
- Limited # of partons
- Full account of quantum effects

## Parton Shower

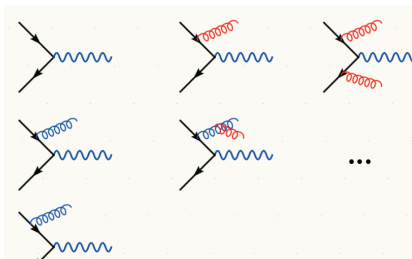
Resummed  $\mathcal{O}(\alpha_s \log(\mu^2/m^2))$

soft / collinear partons

- perturbative approach
- computationally unexpensive
- unlimited # of partons
- partial account of quantum effects

PS →

ME  
↓



## A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

# A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

## MATCHING

- The idea:
  - Use ME (resp. PS) for well separated (resp. soft/collinear) jets
  - Set a phase space cutoff separating both regimes
  - $\Rightarrow$  combined ME+PS description that sidesteps the double counting
- The requirements:
  - Smooth transition between the two regimes
  - Small phase-space cutoff & multiplicity dependence
- The implementation
  - Leading-order ME from MadGraph5 [Alwall et al.]
  - Jet merging using MadGraph5/Pythia
  - MLM as matching prescription [Mangano, Moretti, Pittau '02]
  - Matched samples including up to (0+1+2) hard jets

# A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

## MATCHING

- The idea:
  - Use ME (resp. PS) for well separated (resp. soft/collinear) jets
  - Set a phase space cutoff separating both regimes
  - $\Rightarrow$  combined ME+PS description that sidesteps the double counting
- The requirements:
  - Smooth transition between the two regimes
  - Small phase-space cutoff & multiplicity dependence
- The implementation
  - Leading-order ME from MadGraph5 [Alwall et al.]
  - Jet merging using MadGraph5/Pythia
  - MLM as matching prescription [Mangano, Moretti, Pittau '02]
  - Matched samples including up to (0+1+2) hard jets

# A glimpse at jet merging (II)

correct overlap  $\Rightarrow$  avoid double counting !!

## MATCHING

- The idea:
  - Use ME (resp. PS) for well separated (resp. soft/collinear) jets
  - Set a phase space cutoff separating both regimes
  - $\Rightarrow$  combined ME+PS description that sidesteps the double counting
- The requirements:
  - Smooth transition between the two regimes
  - Small phase-space cutoff & multiplicity dependence
- The implementation
  - Leading-order ME from MadGraph5 [Alwall et al.]
  - Jet merging using MadGraph5/Pythia
  - MLM as matching prescription [Mangano, Moretti, Pittau '02]
  - Matched samples including up to (0+1+2) hard jets

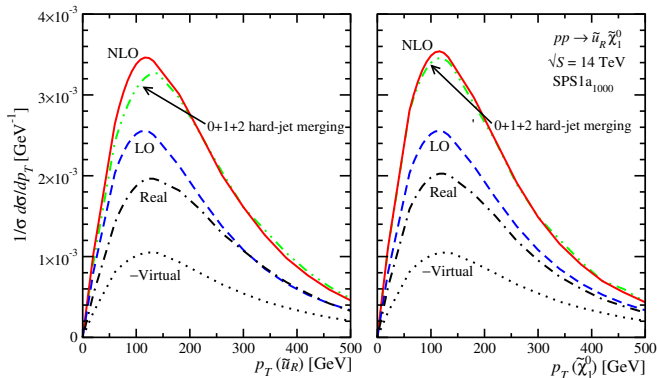
# Comparison with multi-jet merging



(fixed-order) NLO

VS

multi-jet merging



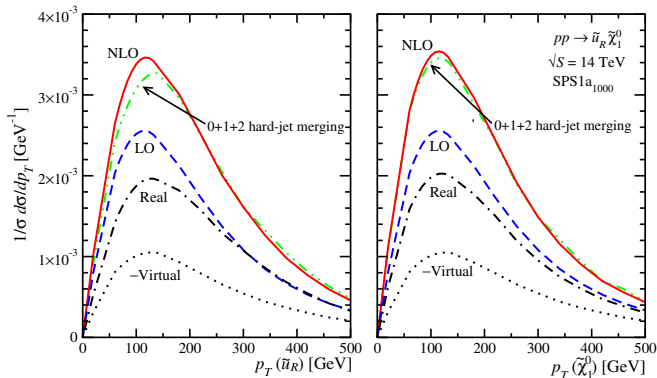
# Comparison with multi-jet merging



(fixed-order) NLO

VS

multi-jet merging

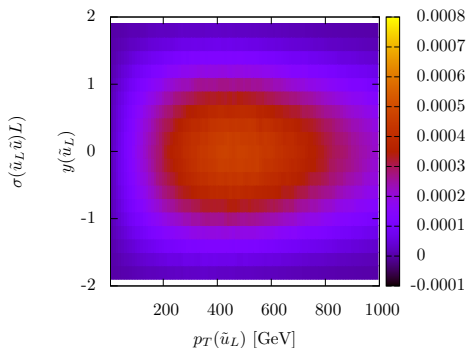
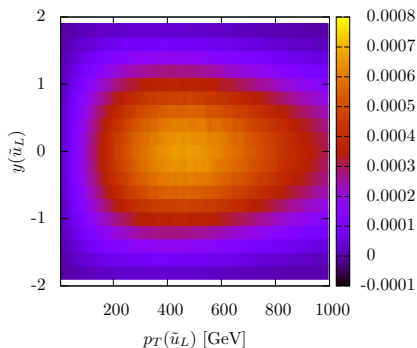


- Normalized distributions in **very good agreement**
- Common to **heavy particle** production – [Plehn, Rainwater, Skands '07], [Alwall, de Visscher, Maltoni '09]

## 2D distributions



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



# 2D distributions



Cross-section behavior across a  $p_T/y$  patch

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

