Squark/neutralino production at NLO: a fully automated calculation with MadGolem

David López-Val

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

Based on **arXiv:1108.1250 [hep-ph]**

ITP, Ruprecht-Karls Universität Heidelberg

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Outline

1. Motivation
2. MadGolem: describing the tool
3. Squark/neutralino production at NLO: Phenomenogical analysis
   - Structure of the NLO corrections
   - Scale dependence
   - MSSM parameter space survey
   - Comparison with multi-jet merging
4. Summary

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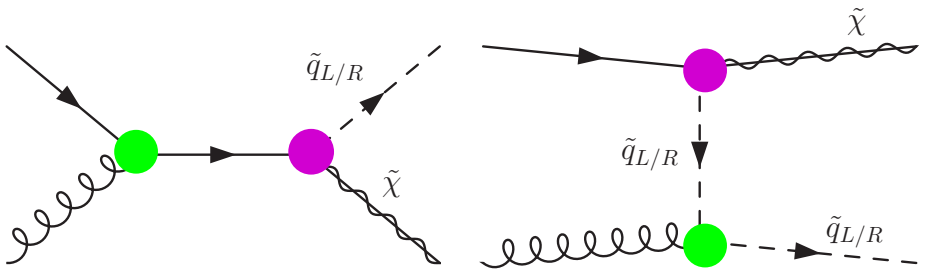
Phenomenological motivation

$$pp \to \tilde{q}\,\tilde{\chi}^0$$



- Potential source of hard decay monojet + $\not{E}_T$ 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

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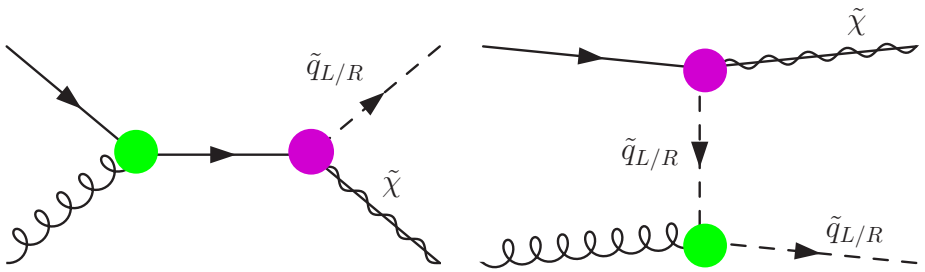

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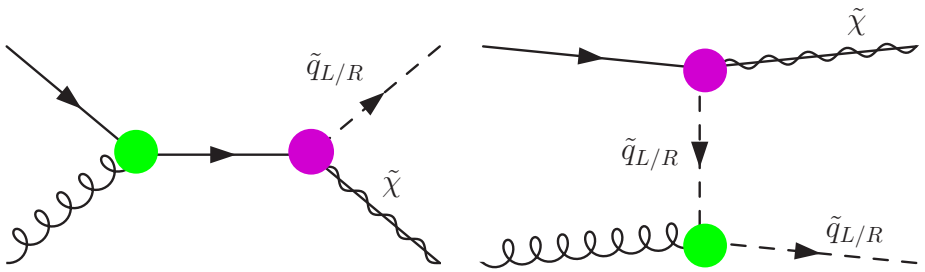

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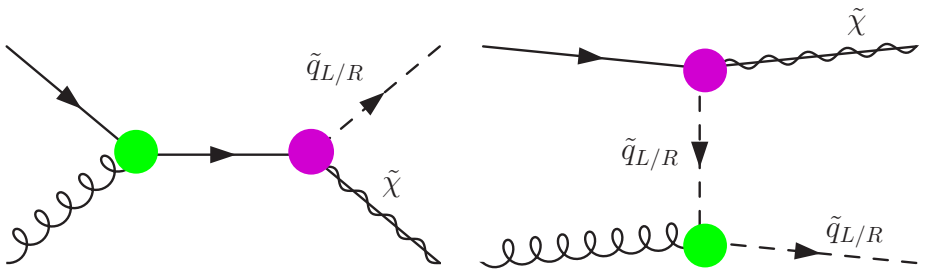

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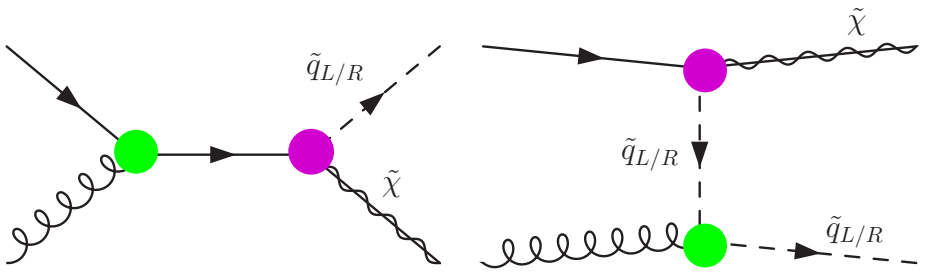

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- Cost & time saving, robustness, accessibility
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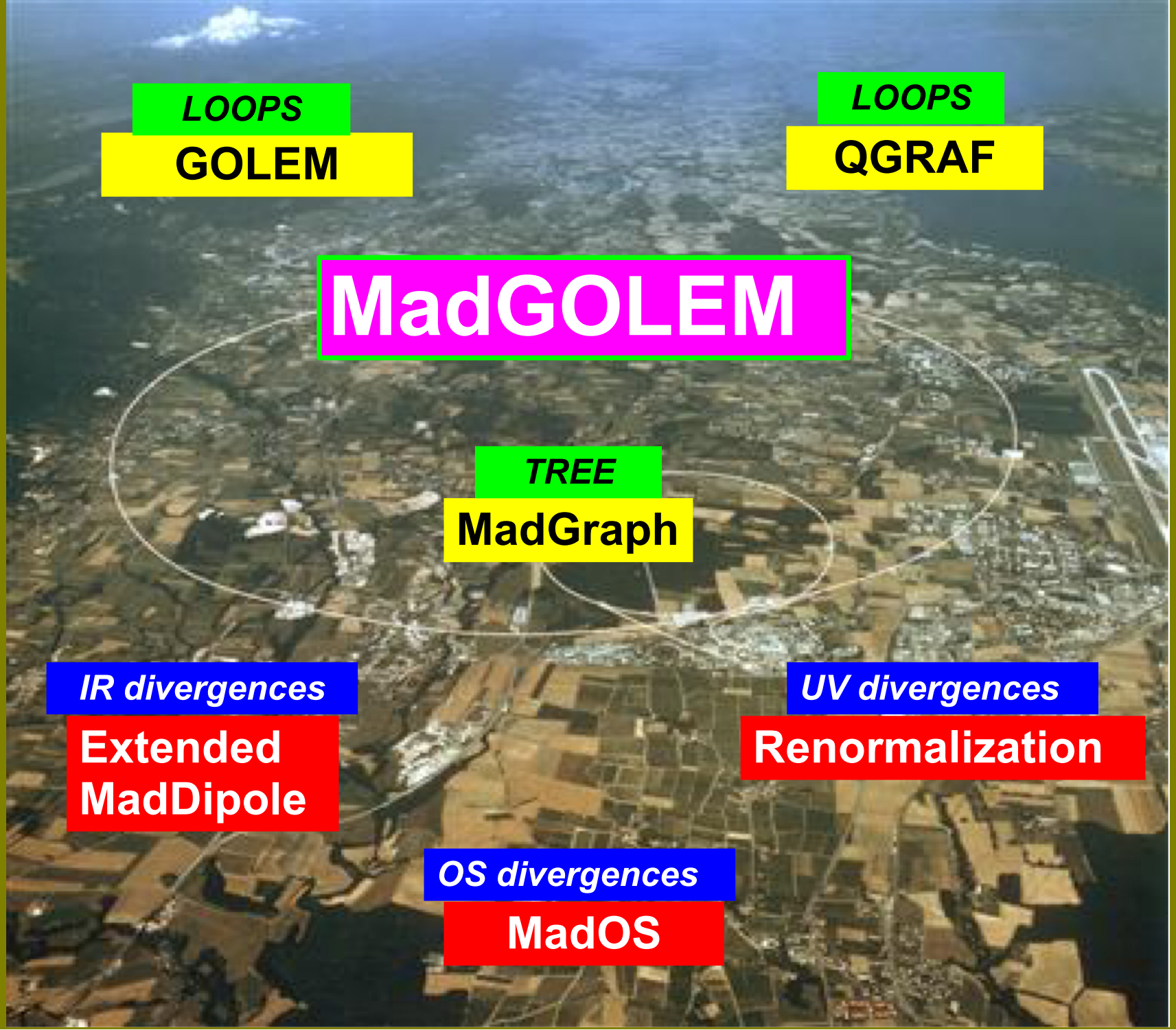
LOOPS
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TREE
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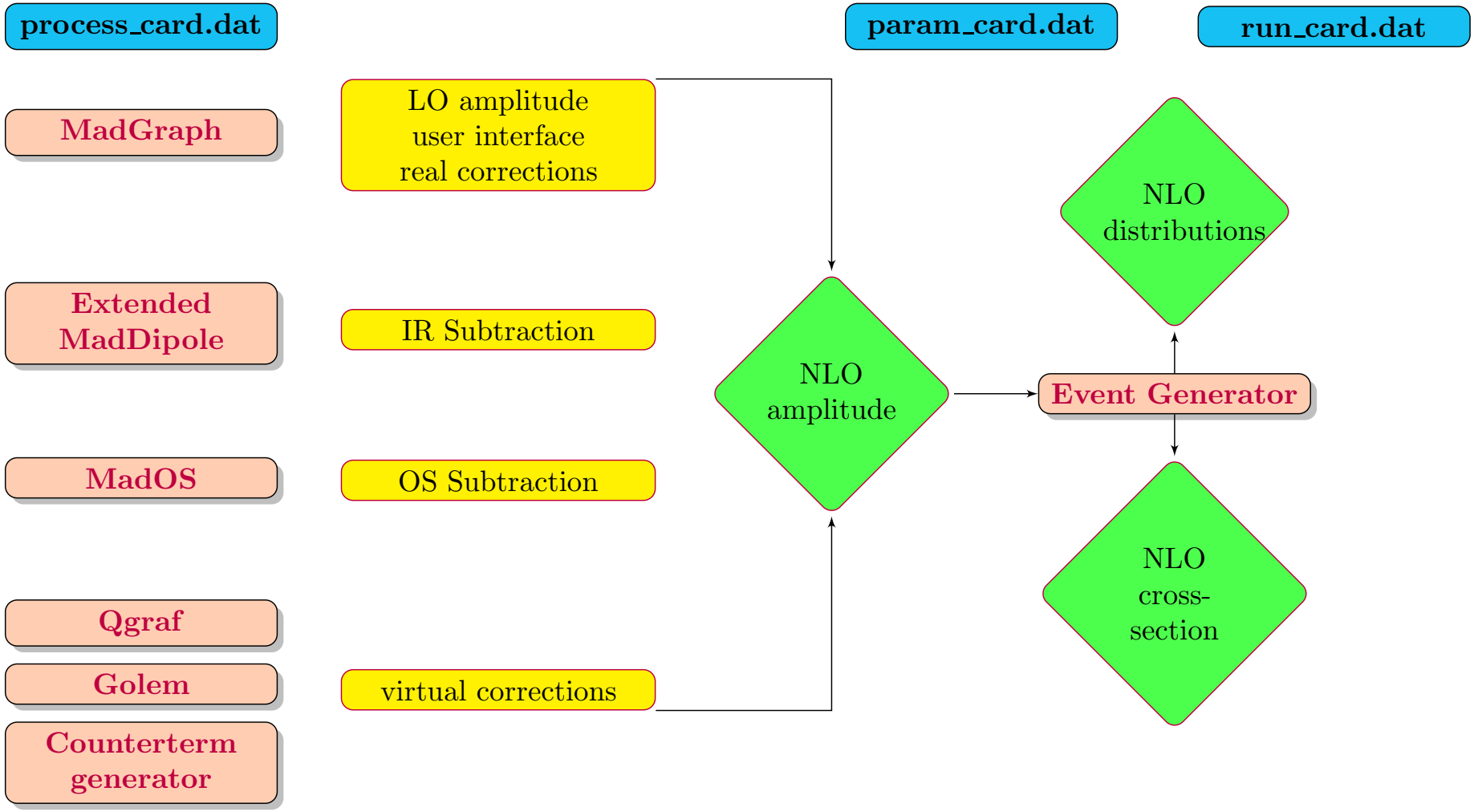
IR divergences
Extended MadDipole
UV divergences
Renormalization
OS divergences
MadOS

MadGolem from inside: modules and flowchart



MadGolem from inside: virtual corrections

♠ GENERATION $\longleftrightarrow$ Qgraf [Nogueira]

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

Handling the UV divergences

Including the Counterterms

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

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Renormalization scheme

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

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

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Local (pointwise) subtraction of the IR poles

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

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

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

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

Testing MadGolem: IR divergences

♠ Validation strategies

- α dependence & behavior in the soft and collinear limits, for all dipoles [Nagy, Trocsanyi]
- cancellation of IR divergences – numerical stability and convergence

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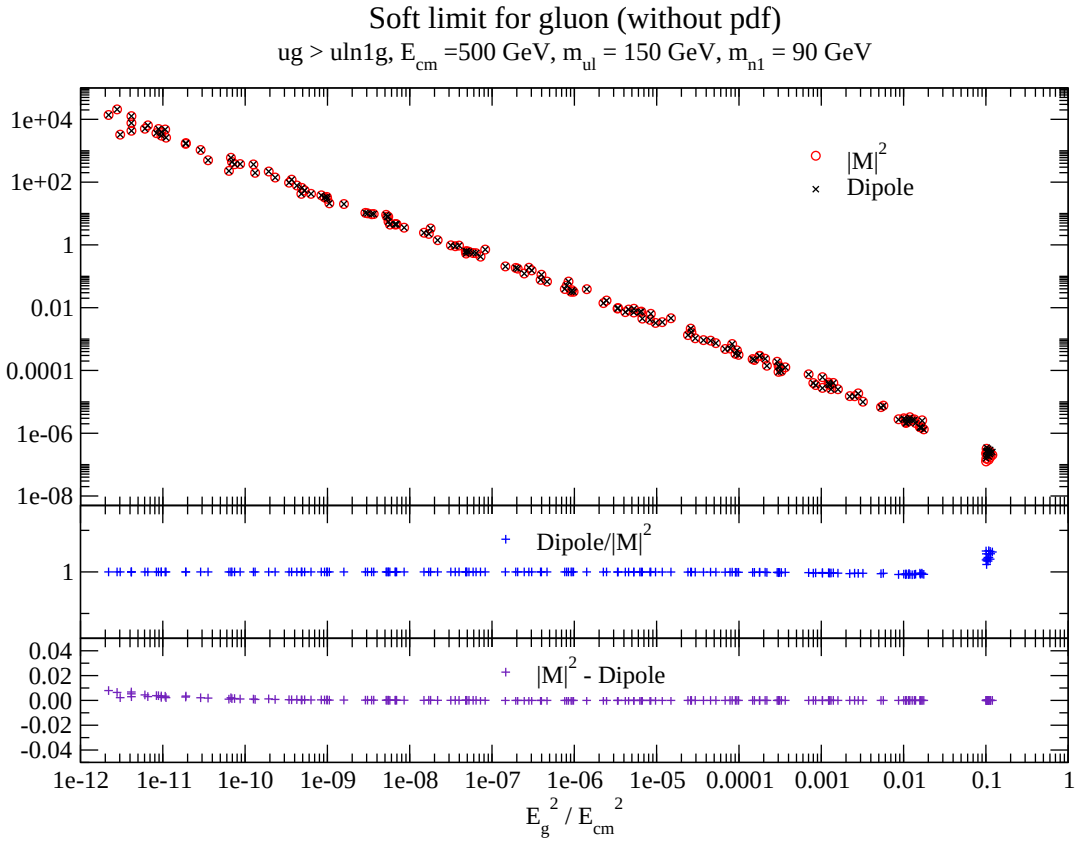
Performance of the SUSY dipoles: $pp(ug) \to \tilde{u}_L \tilde{\chi}_1$



Handling the OS Divergences

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

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

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

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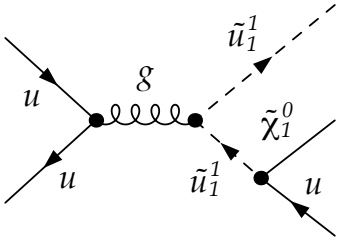

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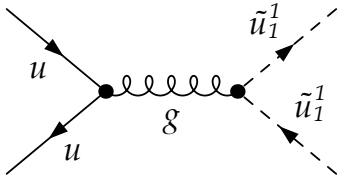

$$uu \to \tilde{u}_L\tilde{u}_L^* \to \tilde{u}_L\tilde{\chi}_1 j \quad - \quad uu \to \tilde{u}_L\tilde{u}_L \times \mathcal{B}(\tilde{u}_L \to \tilde{\chi}_1 j)$$

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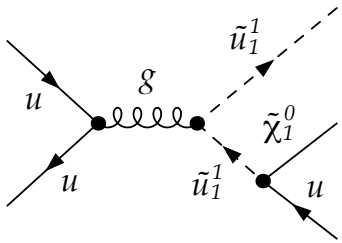

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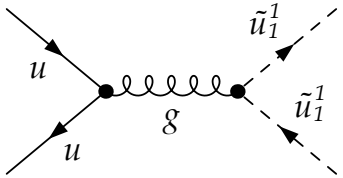

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$$\frac{d\sigma^{OS}}{dM^2} = \sigma^{Born}\,\frac{m_{\tilde{u}_L}\,\Gamma_{\tilde{u}_L}/\pi}{(M^2 - m^2_{\tilde{u}_L}) + m^2\,\Gamma^2_{\tilde{u}_L}} + \mathcal{O}\left(\frac{1}{(M^2 - m^2_{\tilde{u}_L})}\right)$$

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

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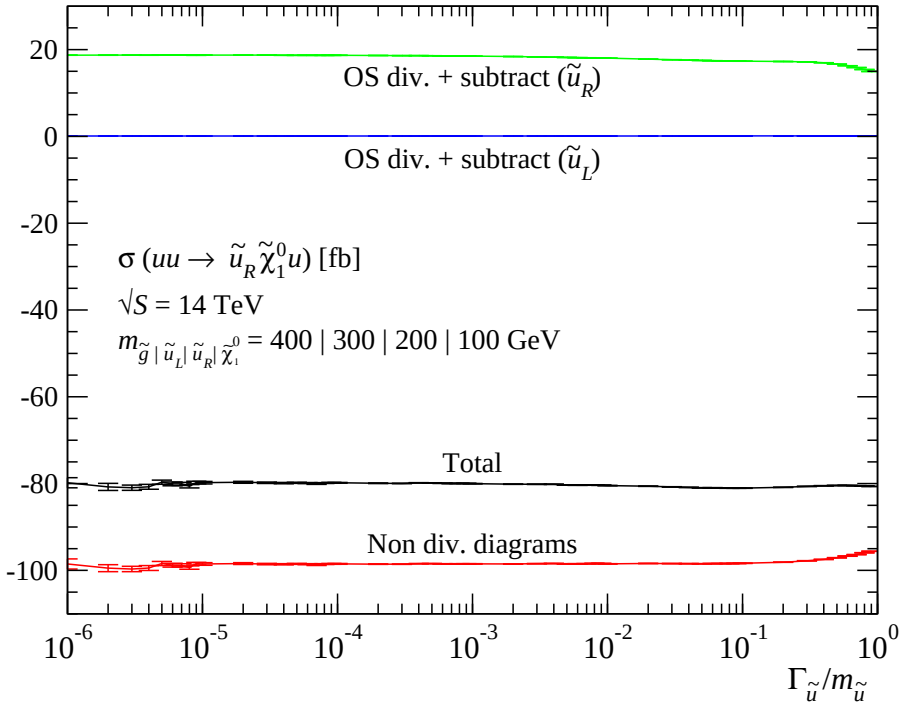

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$pp \to \tilde{q}\tilde{\chi}_n^0$ at Leading-Order

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

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

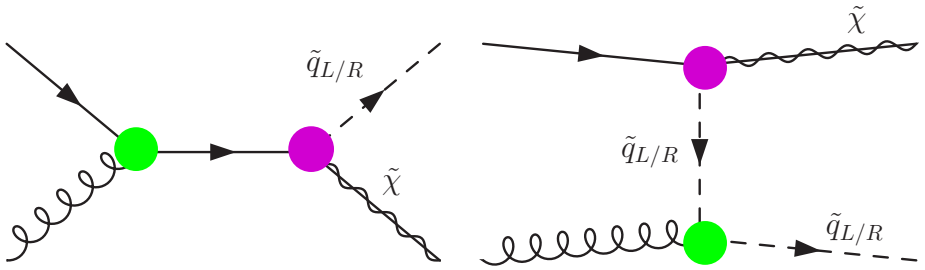
SUSY gauge interactions $\longleftrightarrow$ neutral gauginos $\longleftrightarrow$ weak hypercharges

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

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

$$g_L^{\tilde{\chi}^0_n\, q\, \tilde{q}^*_L} = 0 \qquad g_R^{\tilde{\chi}^0_n\, q\, \tilde{q}^*_R} = 0$$

$$g_R^{\tilde{\chi}^0_n\, q\, \tilde{q}^*_L} = -\frac{e}{3\sqrt{2}\, s_W\, c_W}\left(s_W\, N^*_{n1} + 3\, c_W\, N^*_{n2}\right) \qquad g_L^{\bar{q}\, \tilde{\chi}^0_n\, \tilde{q}_R} = 0 \quad .$$



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- Virtual corrections: virtual gluon (QCD) and gluino (SUSY-QCD) interchange
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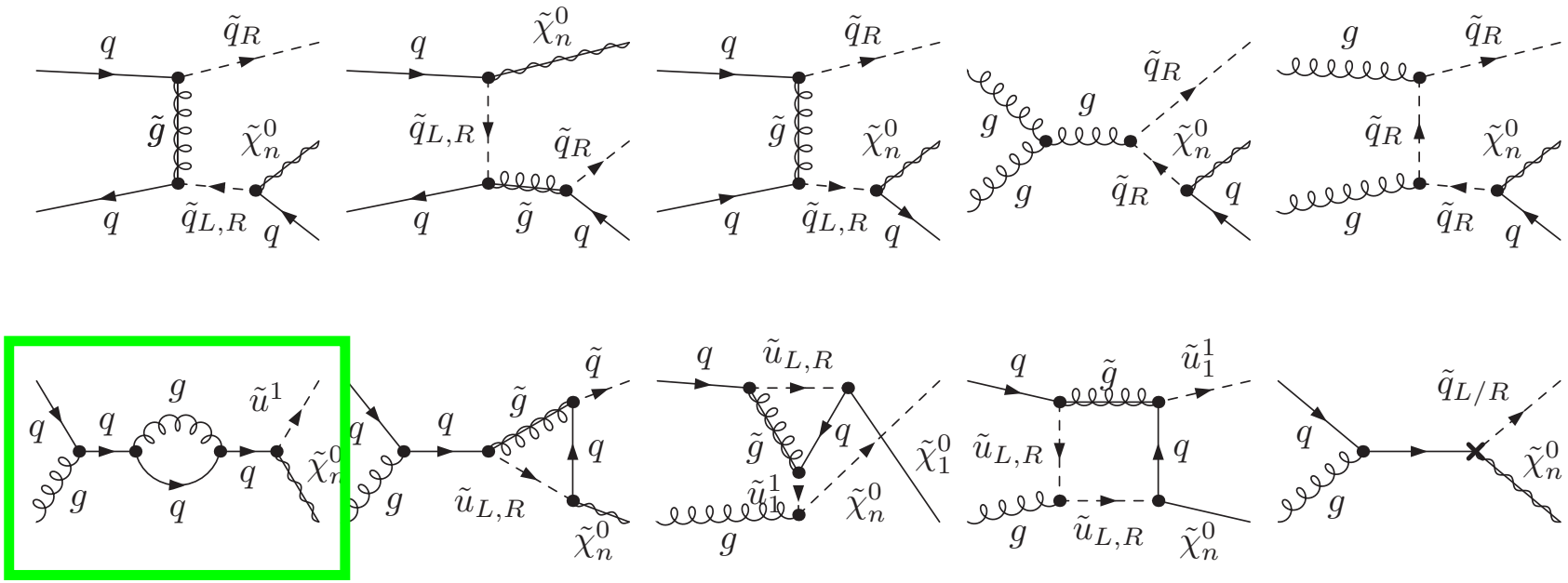

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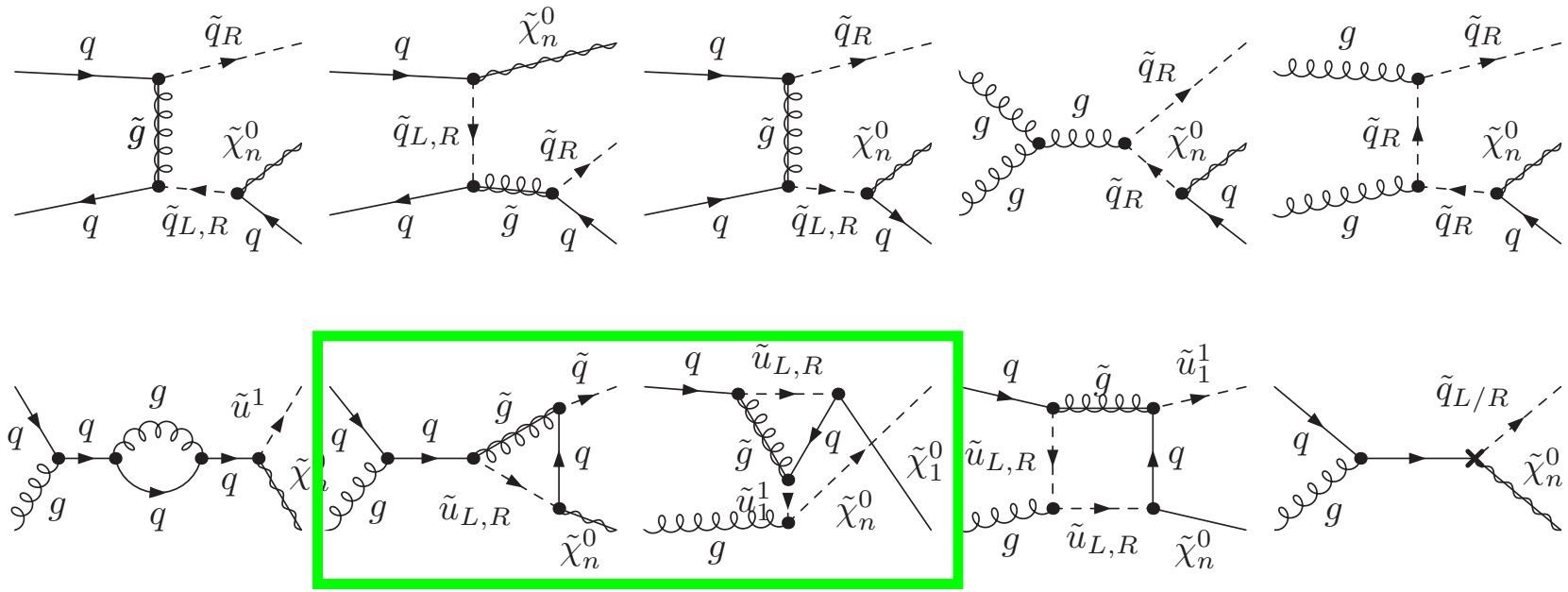

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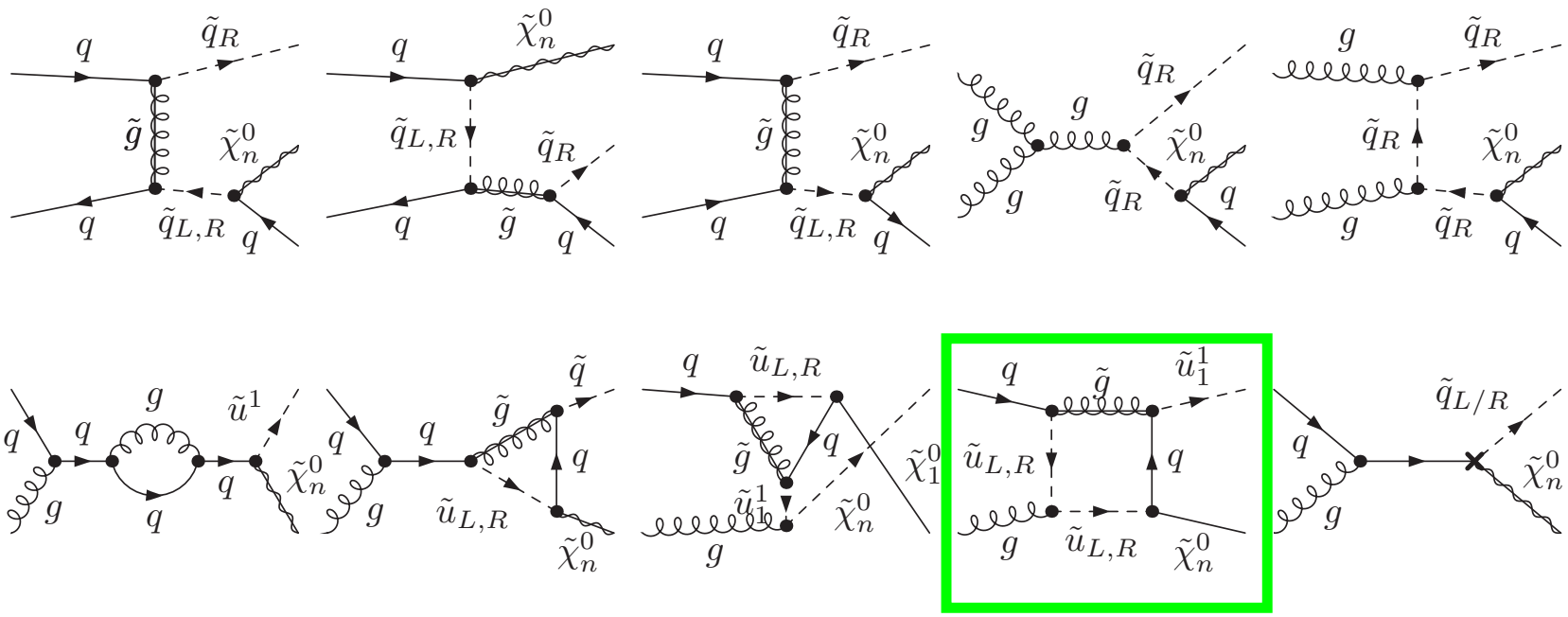

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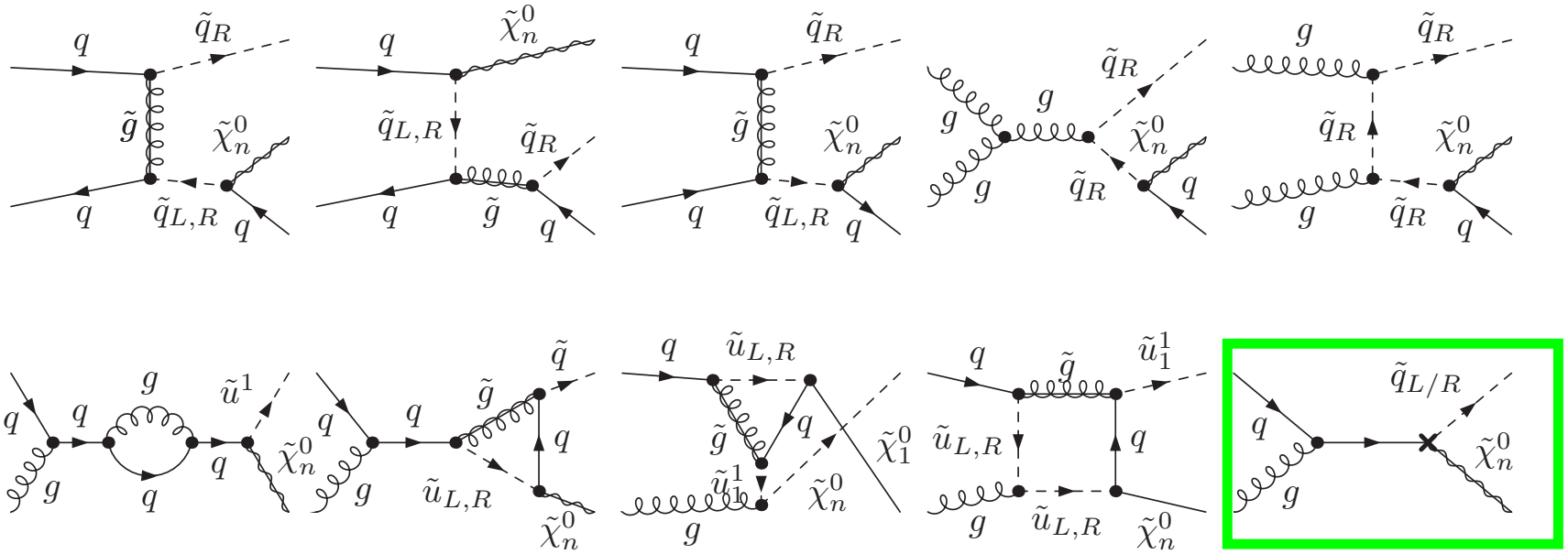

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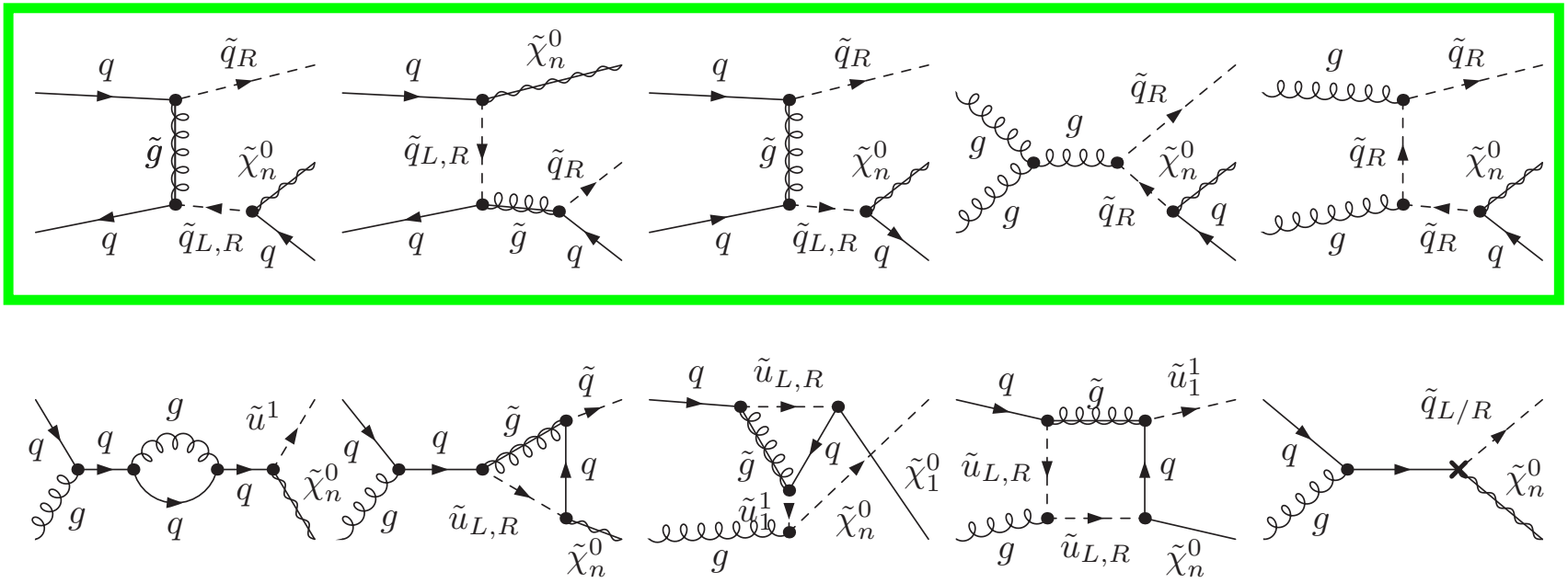

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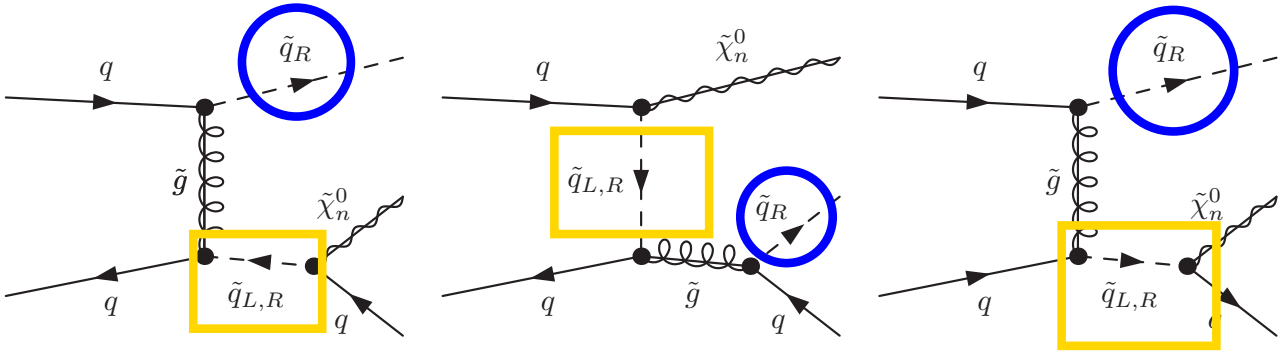
$\Rightarrow$ for SPS1a$_{1000}$ the neutralino is mostly bino

- 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



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

♠ **Structure of the NLO corrections**

- Quantum effects moderately large $(\sim 30/40\%)$ and largely insensitive to the details of the SUSY spectrum
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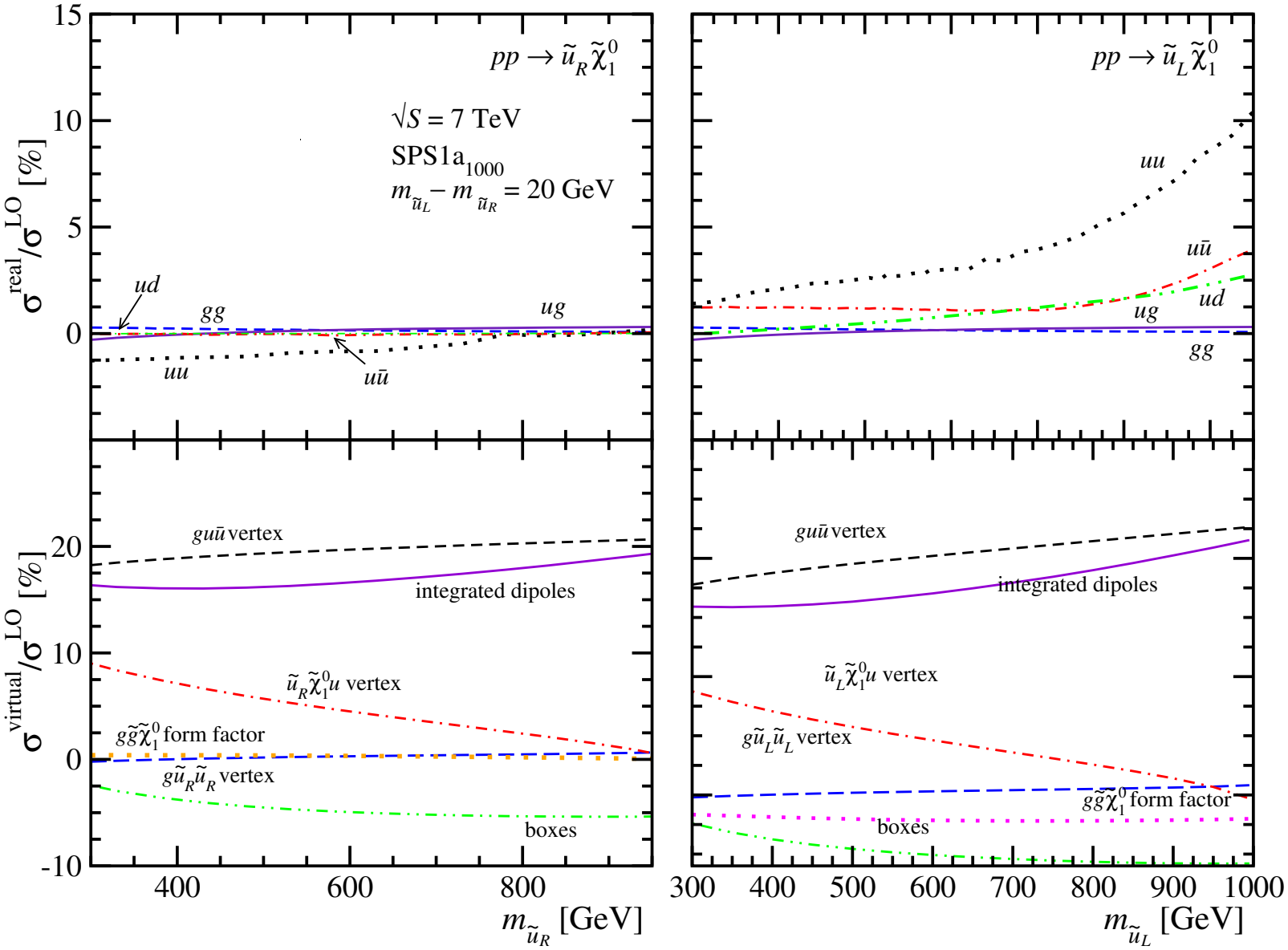

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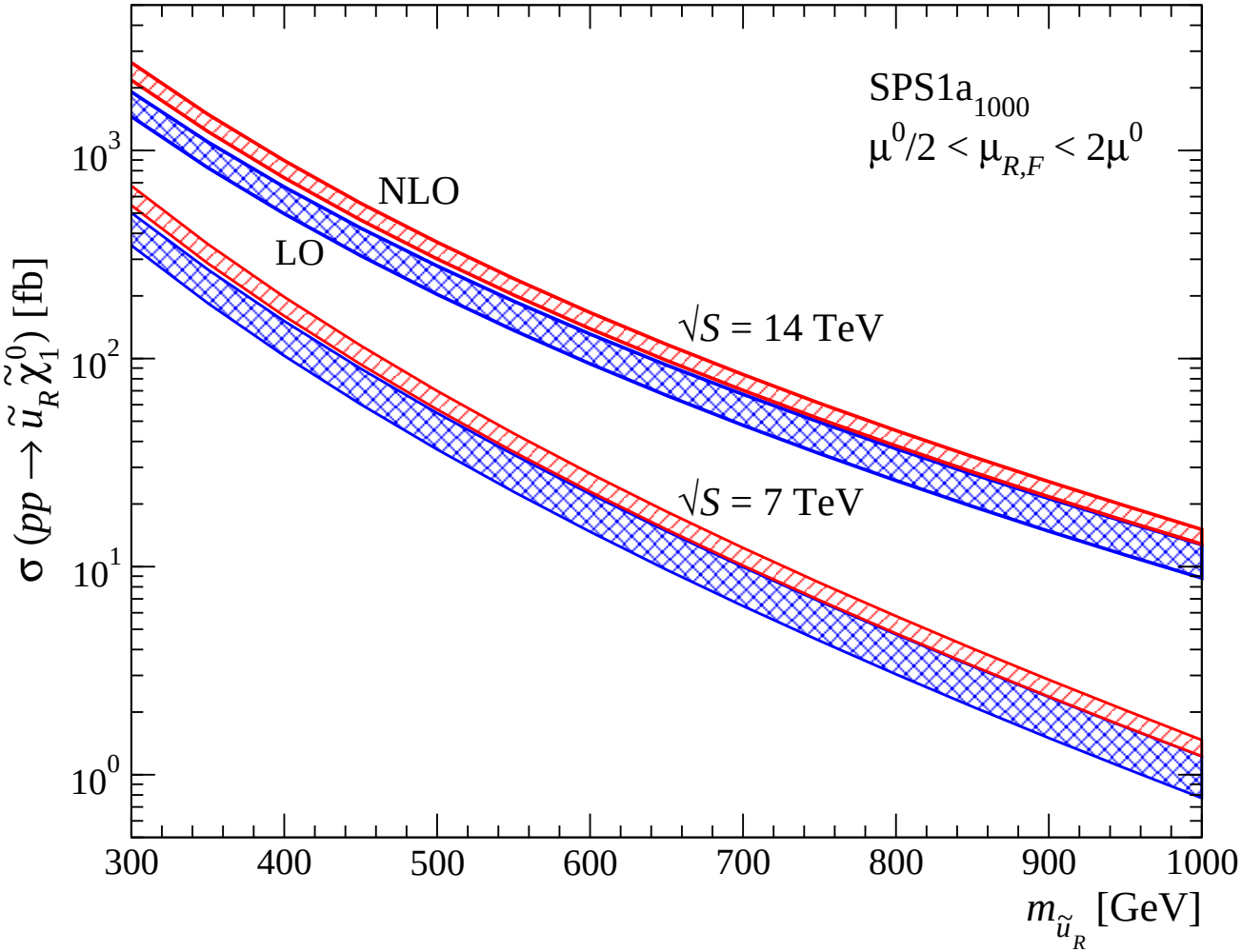

Binoth, Gonçalves-Netto, DLV, Mawatari, Plehn, Wigmore, arXiv:1108.1250 [hep-ph]

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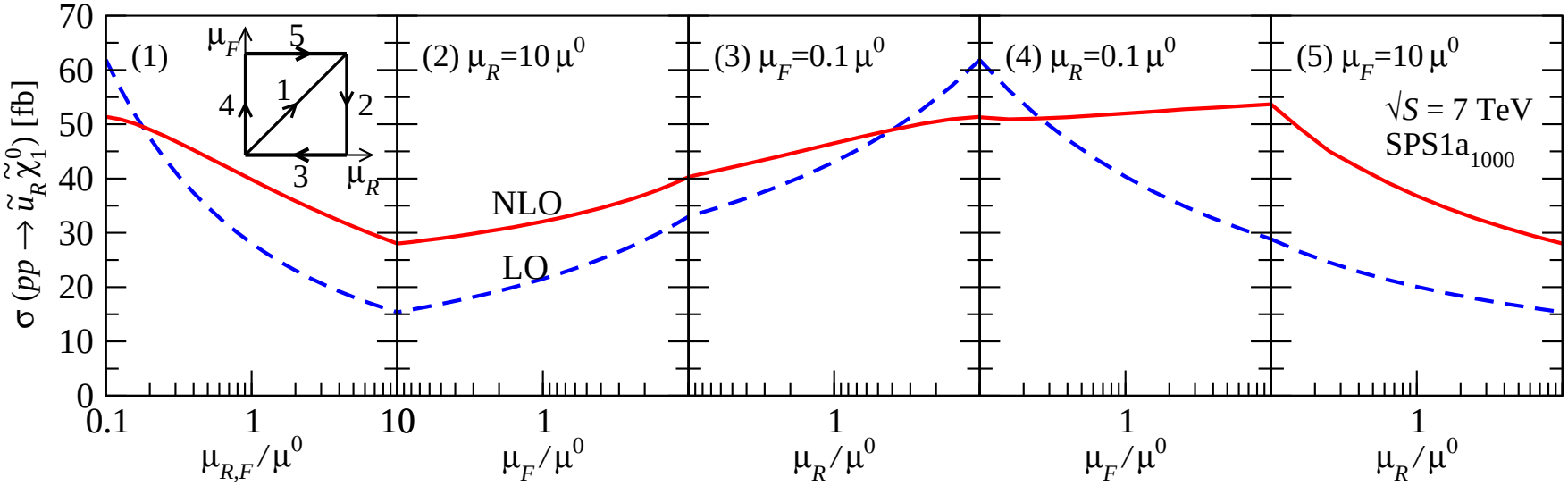

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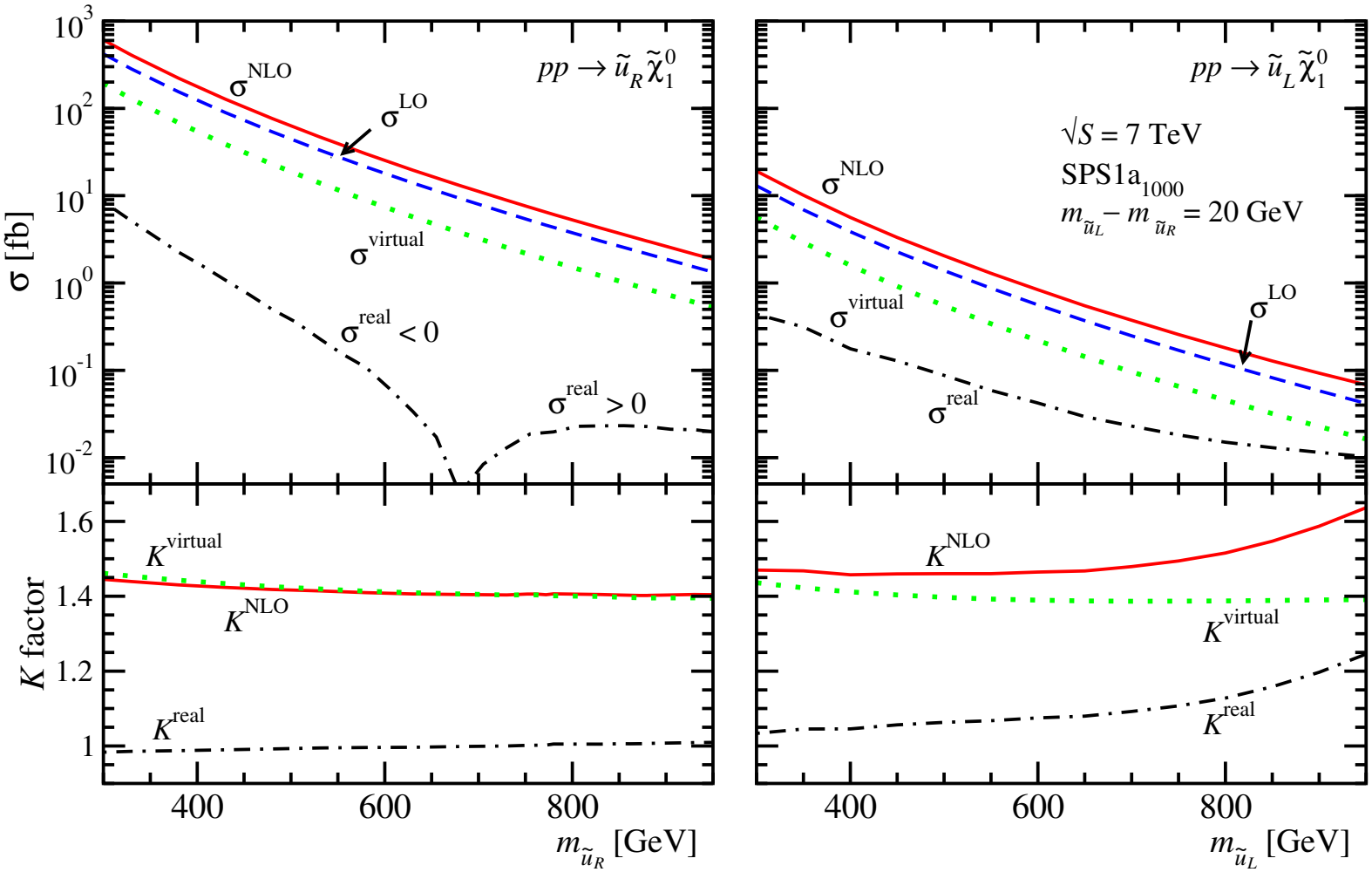

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MSSM parameter space survey

	$\sqrt{S}$	σ^{LO}	σ^{NLO}	K	$m_{\tilde{u}}$	$m_{\tilde{d}}$	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1}$
SPS1a$_{1000}$	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	$\tilde{u}_R : 1282$	$\tilde{d}_R : 1289$		

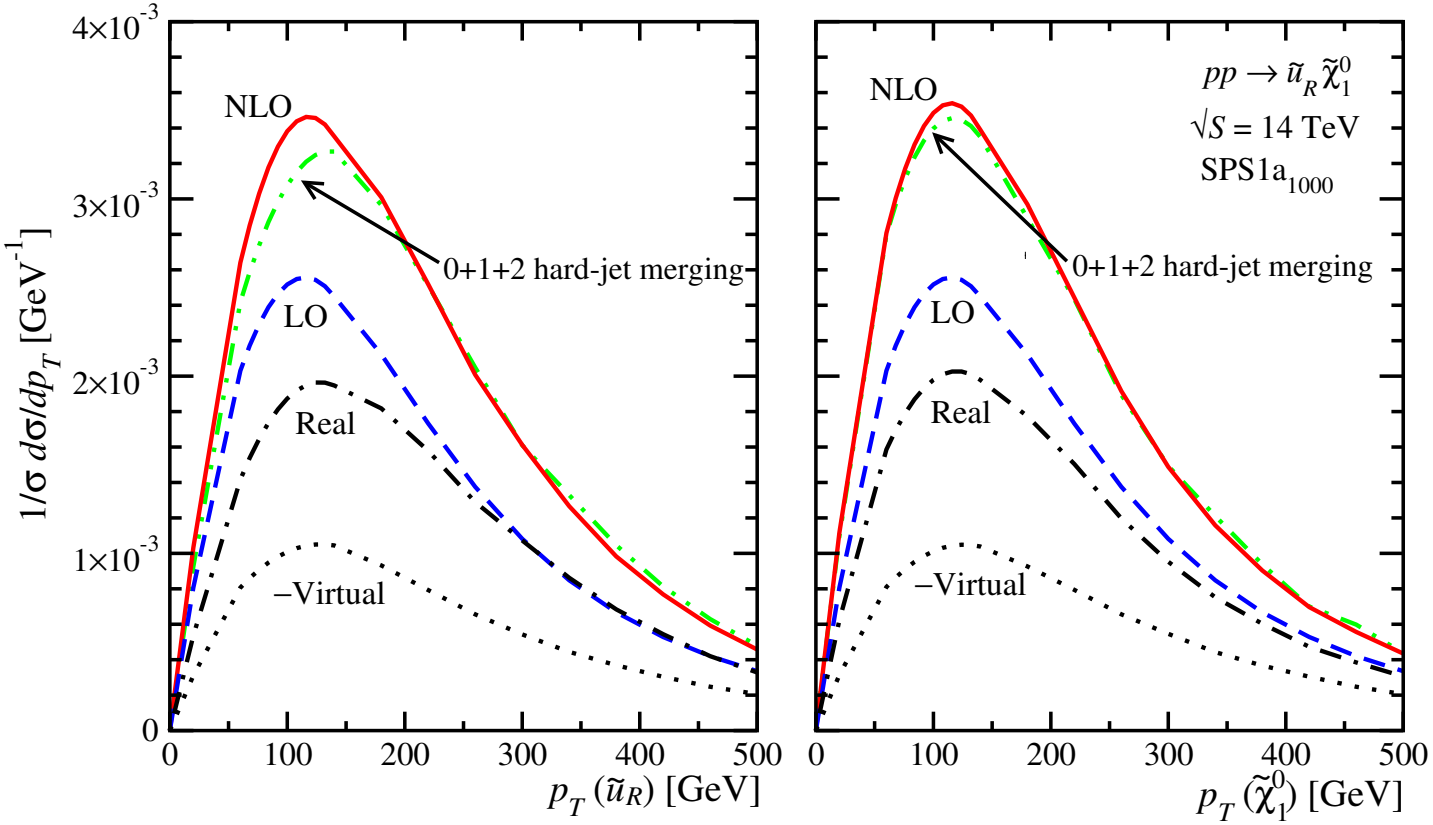
σ in fb, $\sqrt{S}$ in TeV, m in GeV.

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

Comparison with multi-jet merging

♠ NLO Kinematic distributions for the heavy final-states $(\tilde{q}, \tilde{\chi}_n^0)$ in good agreement with a multi-jet merged calculation via MLM matching – with MADGRAPH 5 [Alwall et al.]

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



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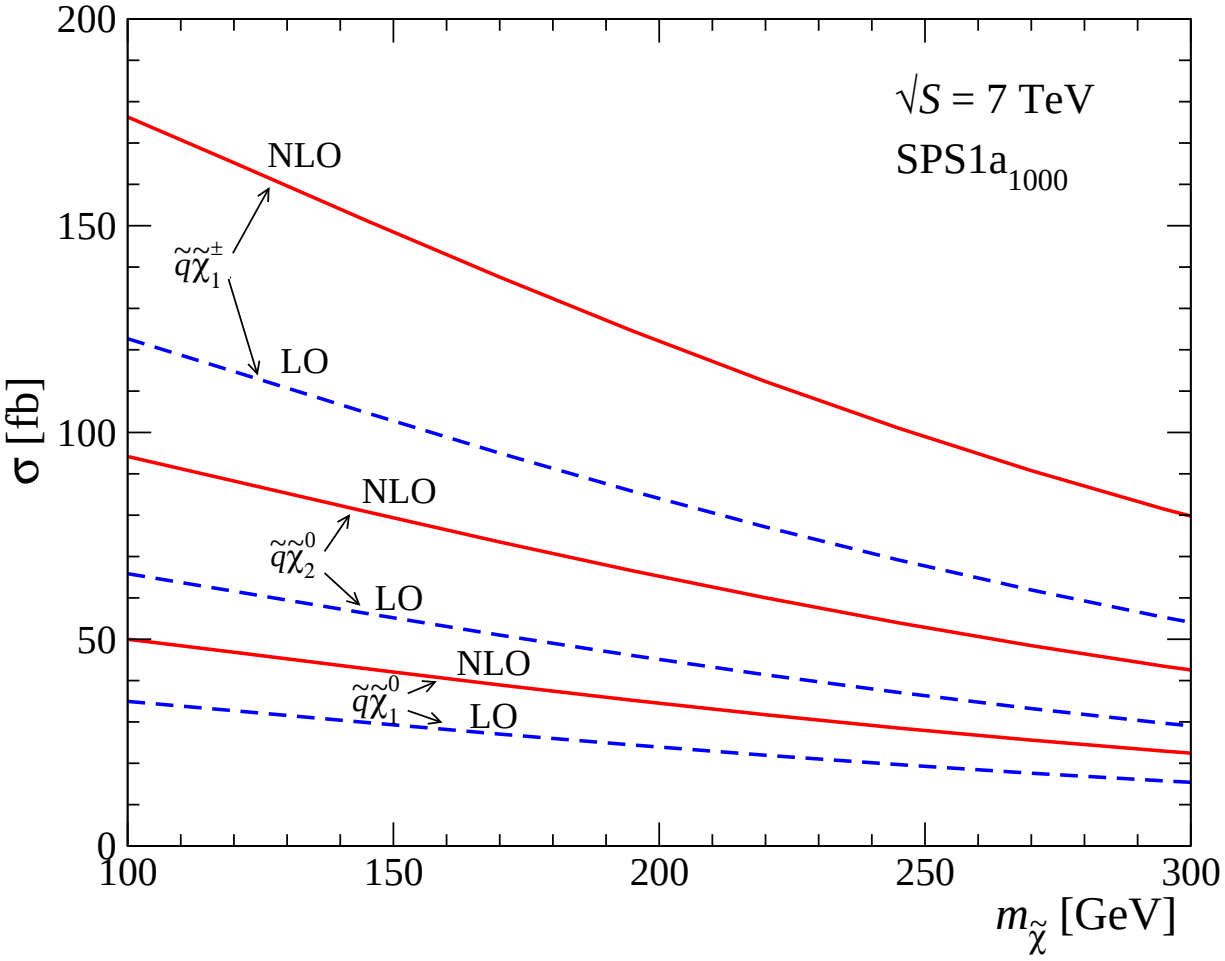
Squark/neutralino & squark/chargino channels

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



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Outline

1. Motivation
2. MadGolem: describing the tool
3. Squark/neutralino production at NLO: Phenomenogical analysis
   - Structure of the NLO corrections
   - Scale dependence
   - MSSM parameter space survey
   - Comparison with multi-jet merging
4. Summary

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First public release in $\mathcal{O}$(months) $\Rightarrow$ Stay tuned !!

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