NLO Predictions for New Physics in MadGOLEM

arXiv: hep/ph 1108.1250;1203.6358; 1211.0286

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Outline

We present some non trivial fully automized NLO QCD calculations for new physics:

- $pp \to \tilde{q}\tilde{\chi}$: Source of monojet + $\not{E}_T$ signatures [Phys. Rev. D 84, 075005 (2011)]
- $pp \to GG^*$: Sgluon pair production [Phys. Rev. D 85, 114024 (2012)]
- $pp \to \tilde{q}\tilde{q},\ \tilde{q}\tilde{q}^*,\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$: Squark and gluino pair production [Phys. Rev. D 87, 014002 (2013)]

- Structure of the NLO corrections:
  - Scale dependence
  - (MSSM) parameter space survey
- Comparison with multi-jet merging
- Impact of the usual simplifying assumptions, e.g. squark mass degeneracy

Structure of the NLO corrections

$$\delta\sigma^{\rm NLO} = \int_{m+1} d\sigma^{\rm real} + \int_m d\sigma^{\rm collinear} + \int_m d\sigma^{\rm virtual}$$

Real emission
Born matrix with n+1 partons

Collinear subtraction
From factorization of initial state collinear singularities

Virtual corrections
Interference term of 1-loop & Born matrix

UV divergent → Renormalization → UV finite

IR divergent + IR divergent + IR divergent

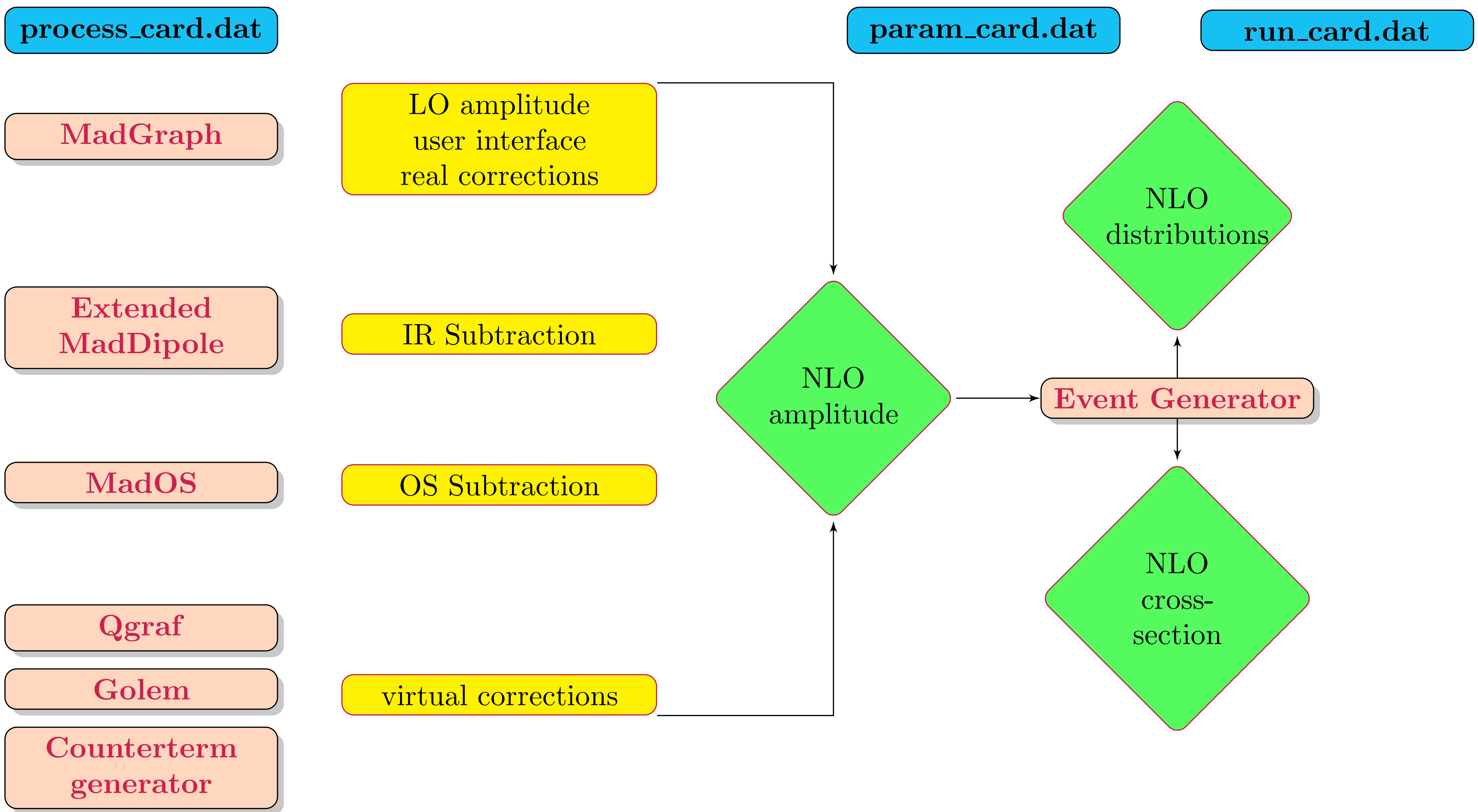
→ Finite and IR safe
(KLN & Factorization Theorem)

How to get finite individual contributions from MC methods?
Catani-Seymour subtraction method:

$$\delta\sigma^{NLO} = \int_{n+1} \left(d\sigma^{Real}_{\varepsilon=0} - d\sigma^{A}_{\varepsilon=0}\right) + \int_n \left(d\sigma^{Collinear} + d\sigma^{Virtual} + \int_1 d\sigma^{A}\right)_{\varepsilon=0}$$

MadGOLEM

Phys. Rev. D 84, 075005 (2011)



$$\sigma^{NLO} = \int_n d\sigma^{LO} + \int_{n+1} \left(d\sigma^{Real}_{\varepsilon=0} - d\sigma^{A}_{\varepsilon=0} - d\sigma^{OS}_{\varepsilon=0}\right) + \int_n \left(d\sigma^{Virtual} + \int_1 d\sigma^{A}\right)_{\varepsilon=0}$$

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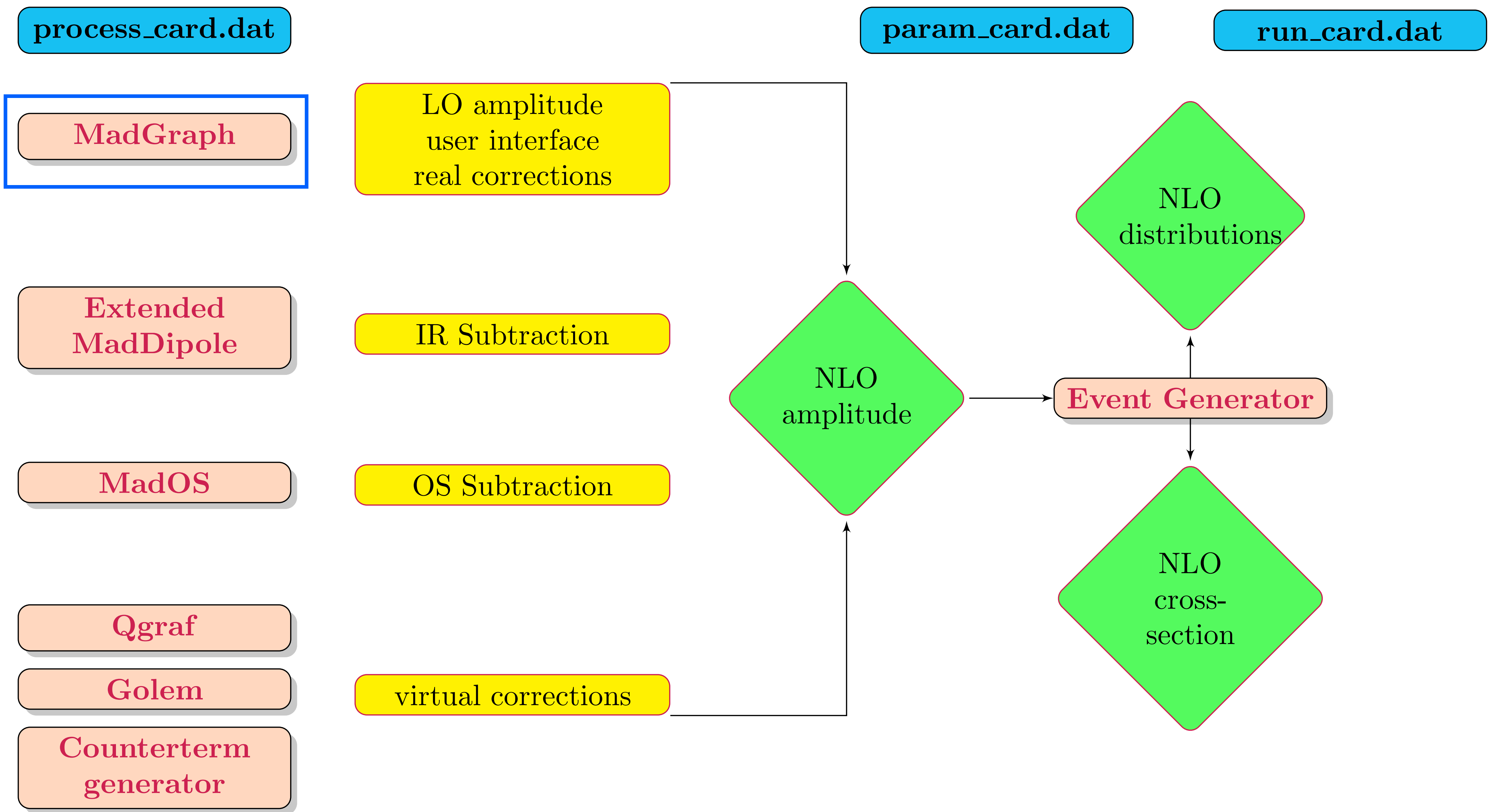

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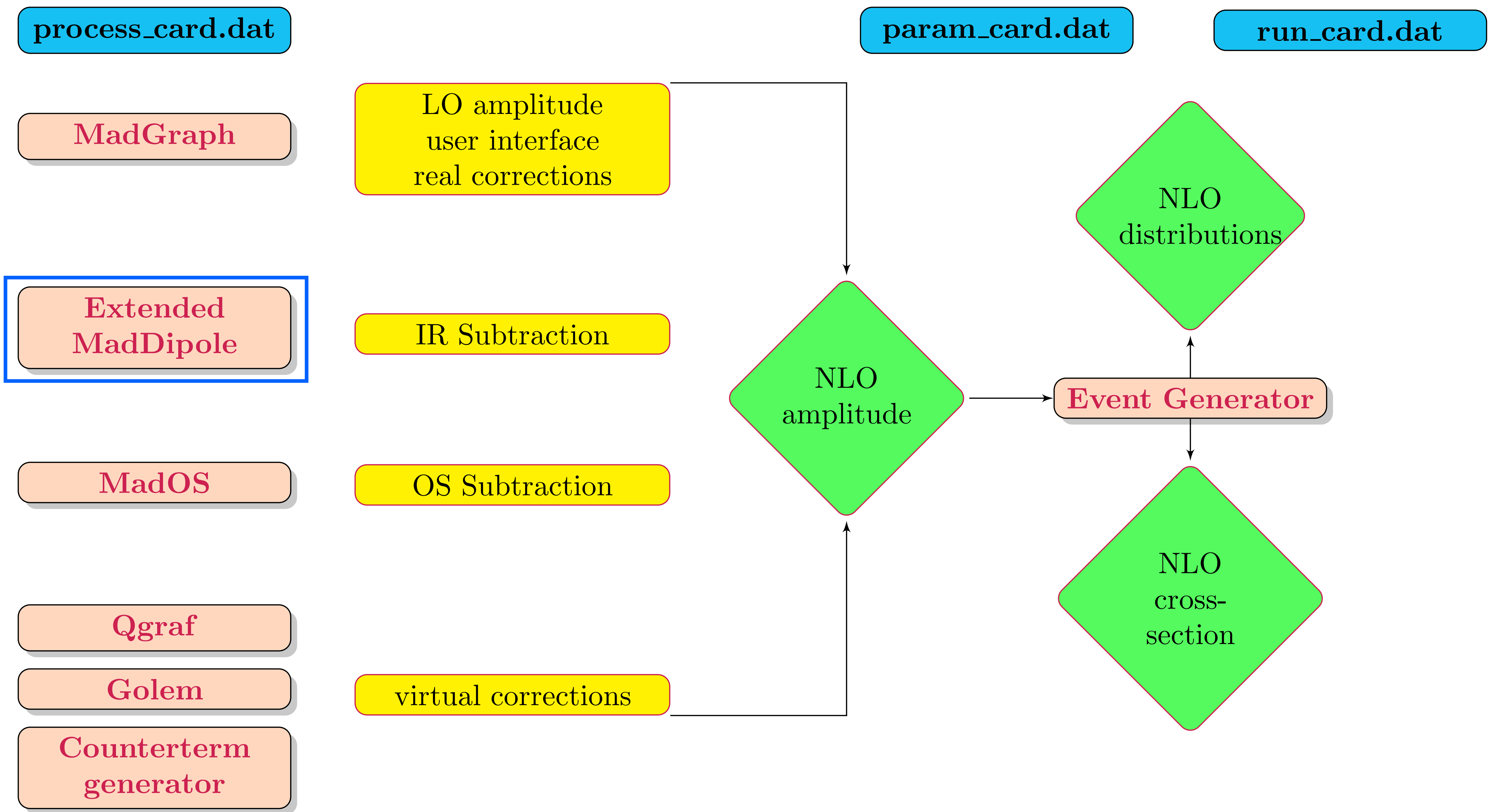

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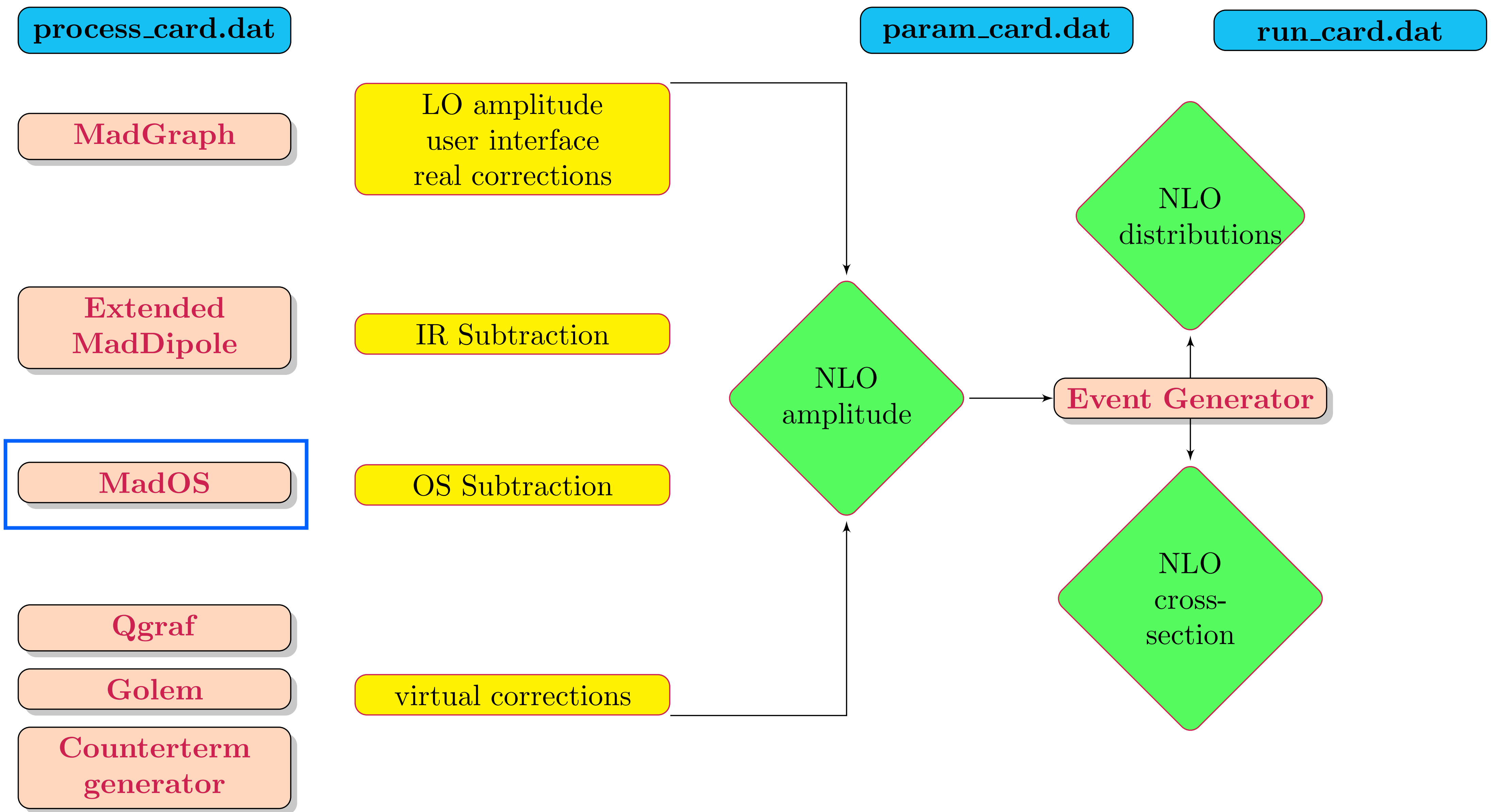

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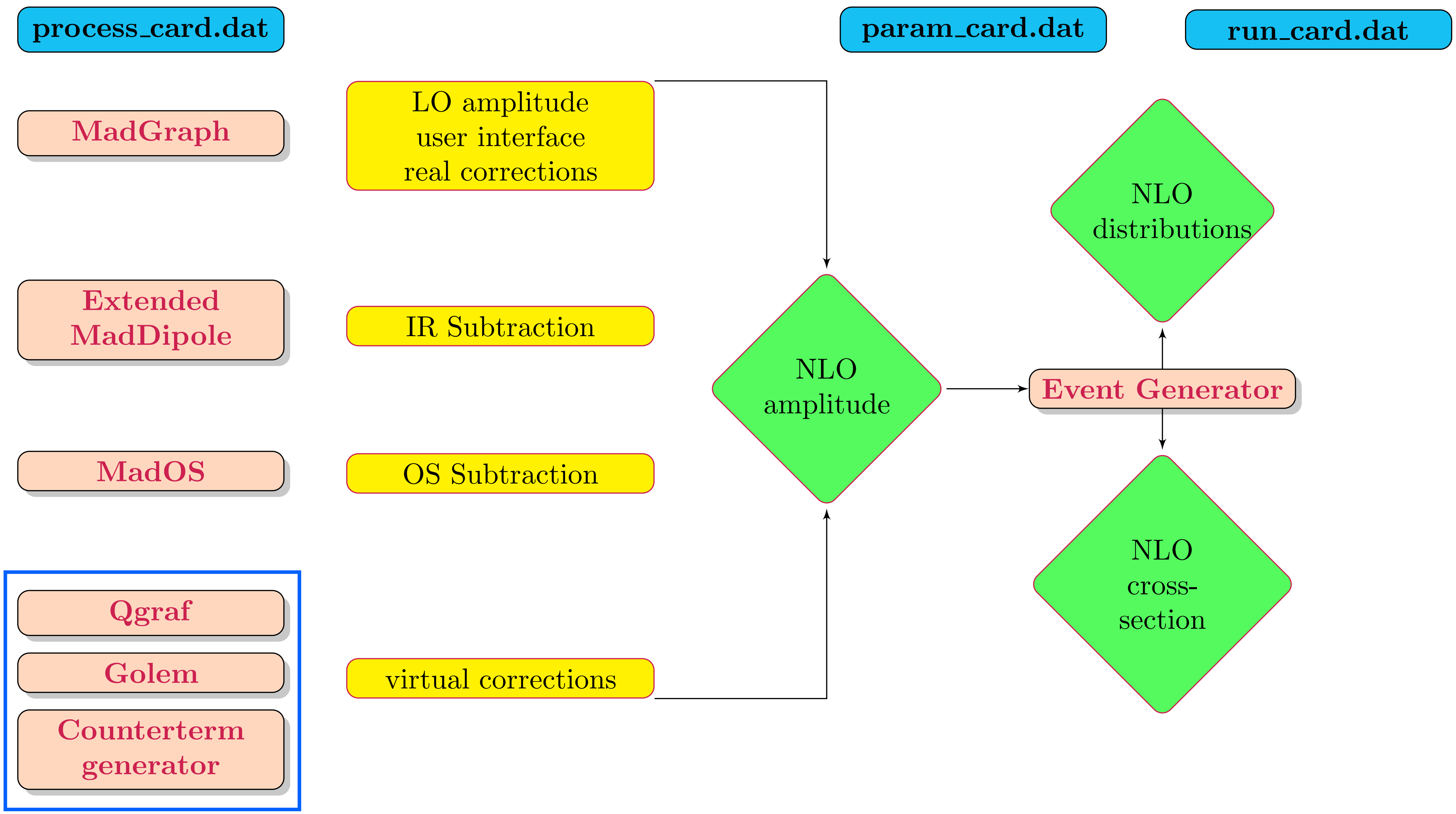

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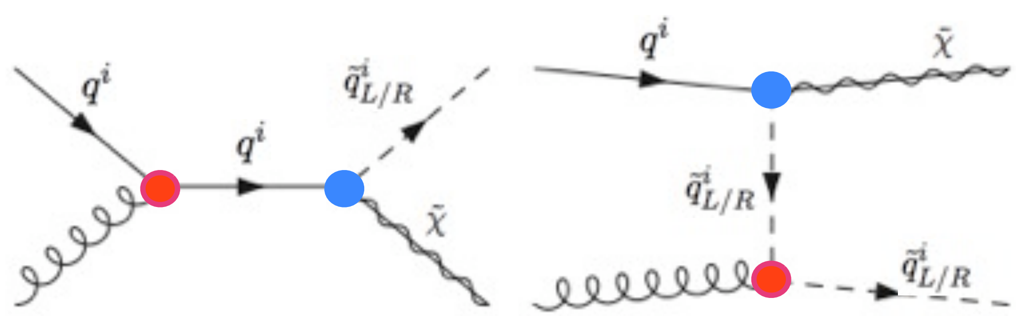
Squark–Neutralino Production at NLO

- $pp \to \tilde{q}\tilde{\chi}$: Source of monojet+$\not{E}_T$ signatures

  Flavor-locked & semi-weak process sensitive to $q\tilde{q}\tilde{\chi}_1$ coupling: $\sigma^{LO} \sim \mathcal{O}\left(\alpha_{EW}\alpha_s\right)$



- Semi-weak process, but favored by $m_{\tilde{\chi}_1^0} \ll m_{\tilde{q}},\ m_{\tilde{g}}$

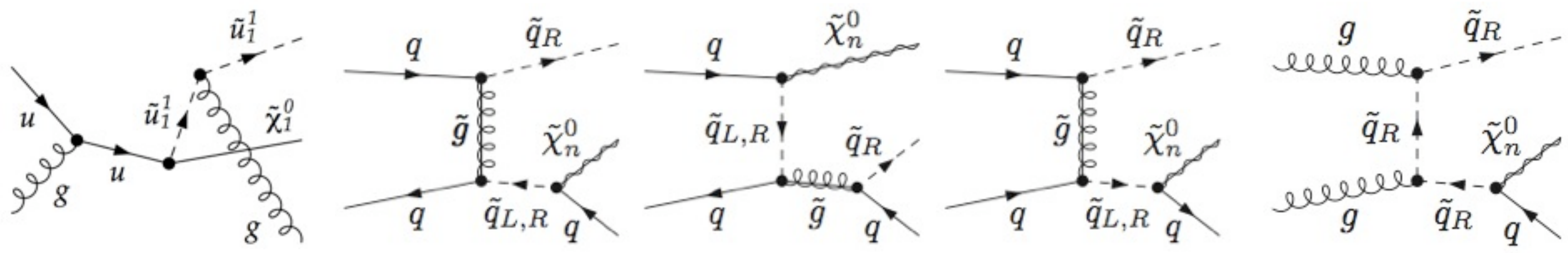
- Couplings size $q\tilde{q}\tilde{\chi}_1$ correlated with SUSY breaking - LSP (bino or wino-like)

- Analysis @LO [Allanach, Grab, Haber arXiv:1010.4261]
  Process not yet studied @NLO!

- First application of MadGOLEM [Phys. Rev. D 84, 075005 (2011)]

Structure of the NLO corrections

- **Real emission** diagrams $pp \to \tilde{q}\tilde{\chi}_1 j$: quark or gluon emission



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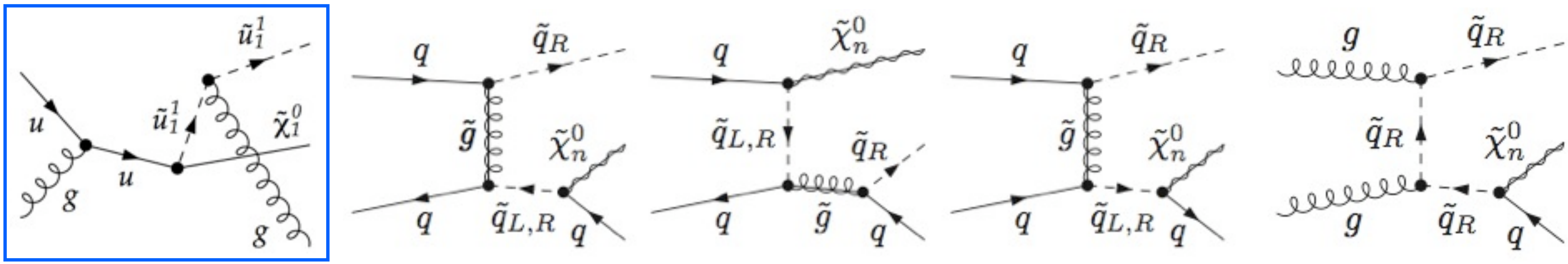
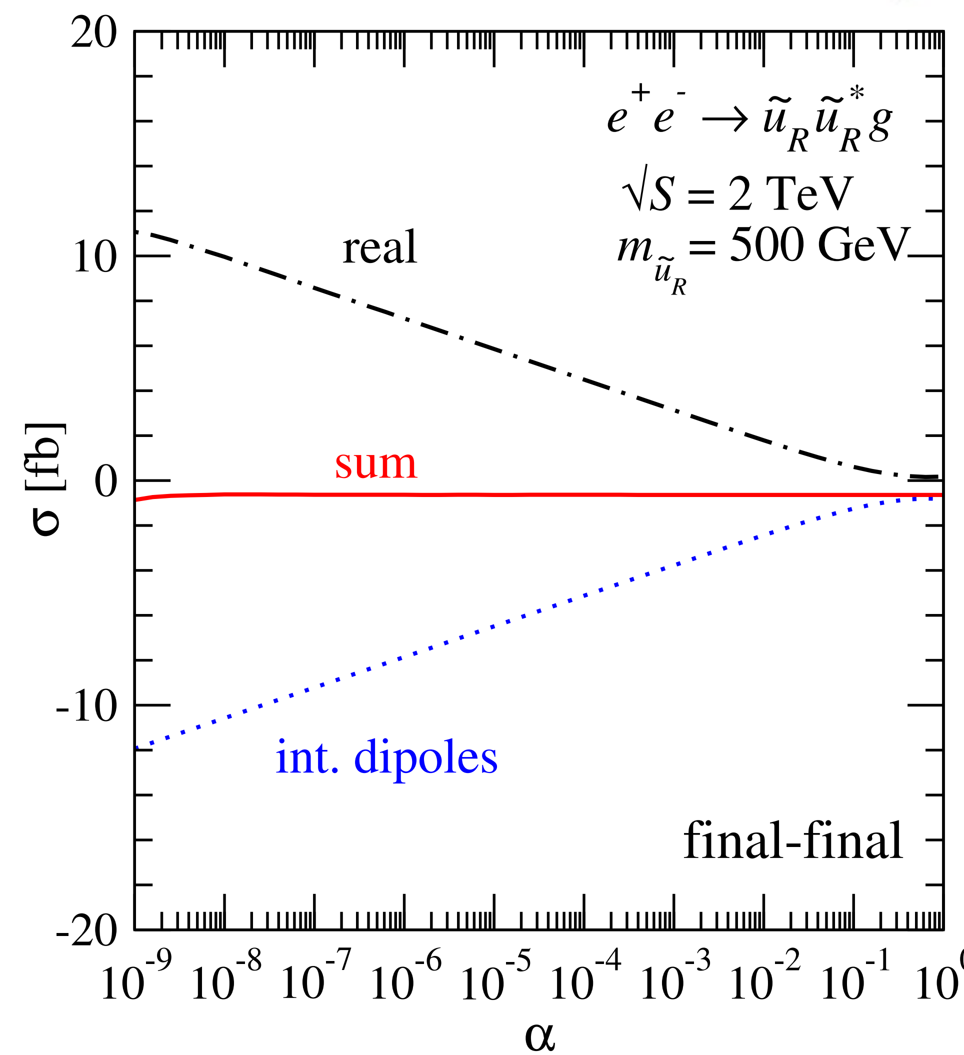


- $|D_\mu \tilde{q}|^2$ & $\bar{\tilde{g}} \not{D} \tilde{g}$ induces a gluon emission from the squark & gluino legs:

➡ IR singularities in the real emission

➡ Need of SUSY dipoles



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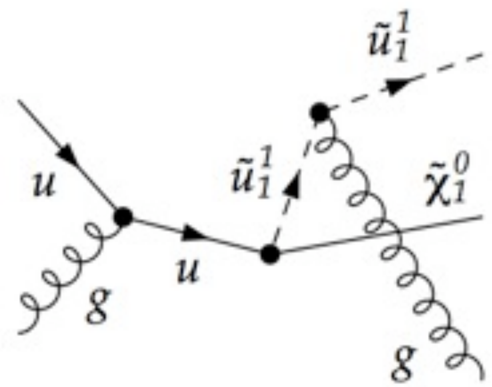
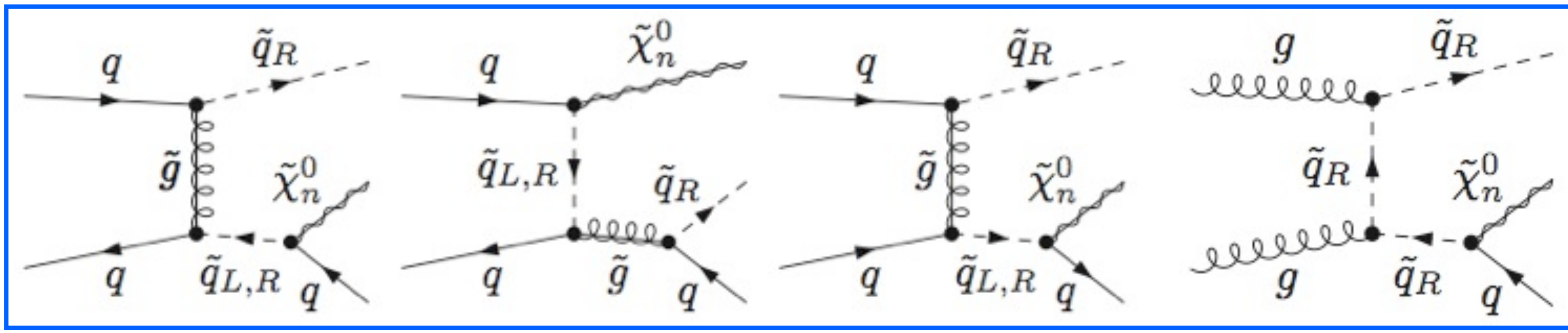
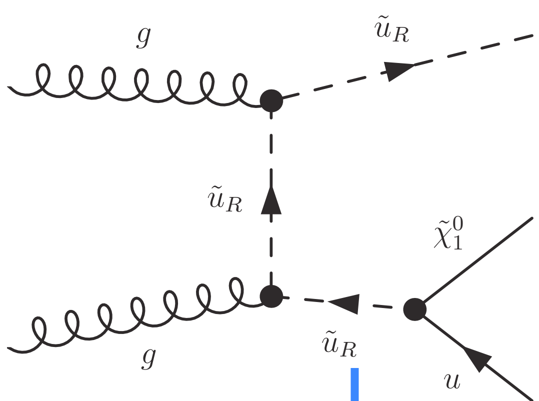




➡ On-Shell Subtraction Method to avoid double counting instances involved in the production and decay of on shell heavy states

Structure of the NLO corrections

- On-shell subtraction method: differentiation between off & on-shell production to avoid double counting [Beenakker, Hopker, Spira, Zerwas '97] (Prospino scheme)

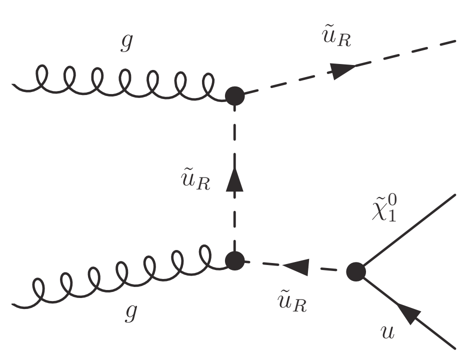


- $gg \to \tilde{q}\bar{\tilde{q}}^* \to \tilde{q}\chi_1\bar{q}$ squark neutralino production
- $gg \to \tilde{q}\bar{\tilde{q}} * BR(\bar{\tilde{q}} \to \chi_1\bar{q})$ squark pair production

$$\frac{i}{p^2 - m_{os}^2} \to \frac{i}{p^2 - m_{os}^2 + i m_{os}\Gamma_{os}}$$

Γ_{OS} is regarded as a regulator

- To avoid double counting subtract on-shell amplitudes:



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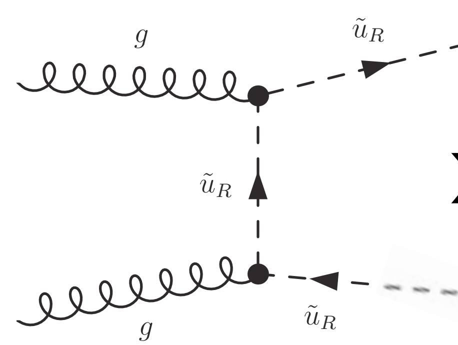
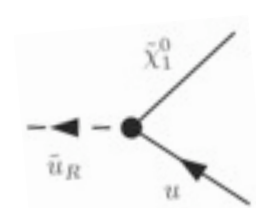


x

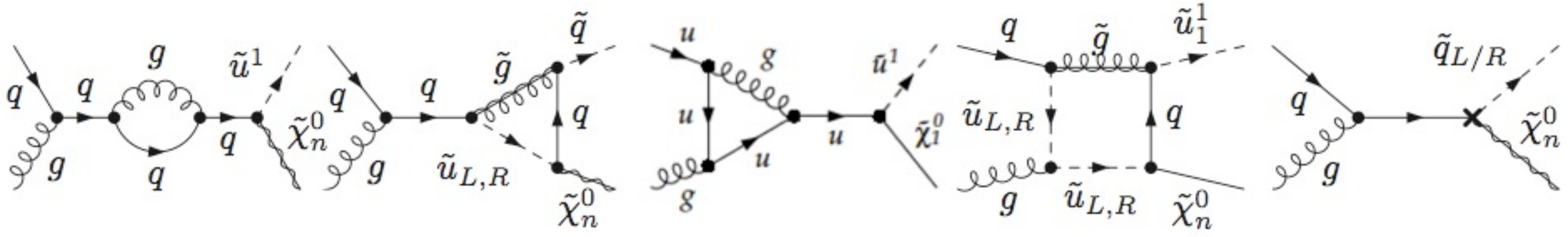


$\sigma\,(gg \to \tilde{q}\chi_1\bar{q})$ $\qquad$ $\sigma\,(gg \to \tilde{q}\bar{\tilde{q}}) * BR(\bar{\tilde{q}} \to \chi_1\bar{q})$

- MadGOLEM: first full automation in a process and model independent way

Structure of the NLO corrections

- **Virtual** QCD and SUSY-QCD corrections:



- a) self energy corrections; b) vertex corrections; c) box diagrams; d) UV counter terms

- Renormalization scheme:
  - α_s in the $\overline{MS}$ scheme, massive particles decoupled [Beenakker et.al. '97]
  - OS renorm. for massive particles
  - SUSY restoring counter term for $q\tilde{q}\tilde{\chi}_1$ coupling [Martin, Vaughn '93]

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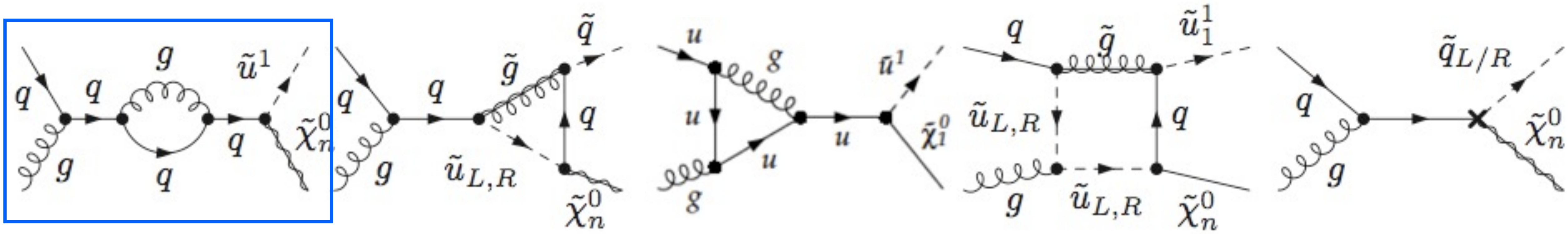

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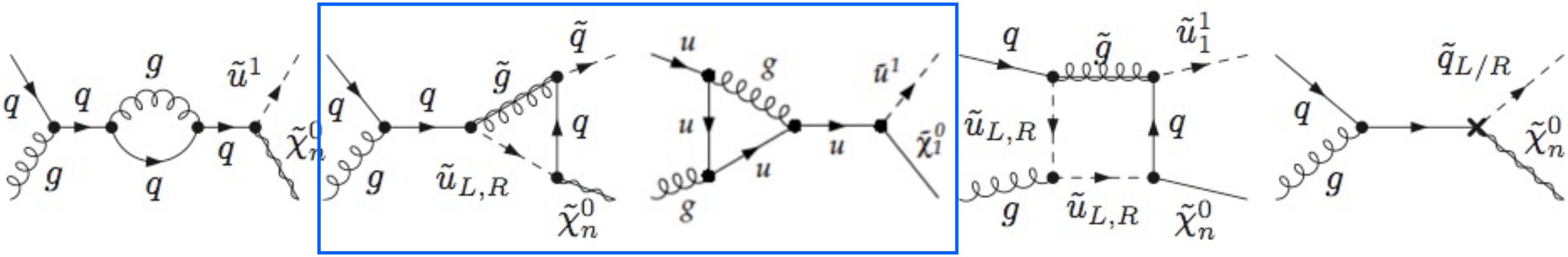

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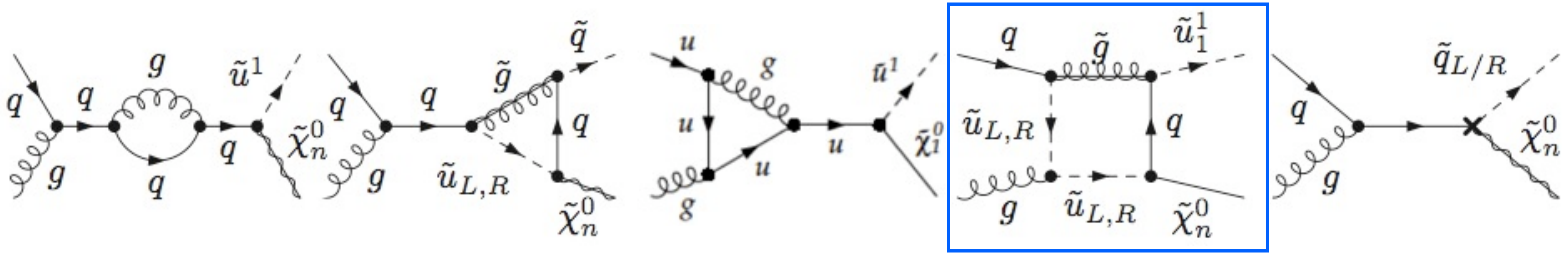

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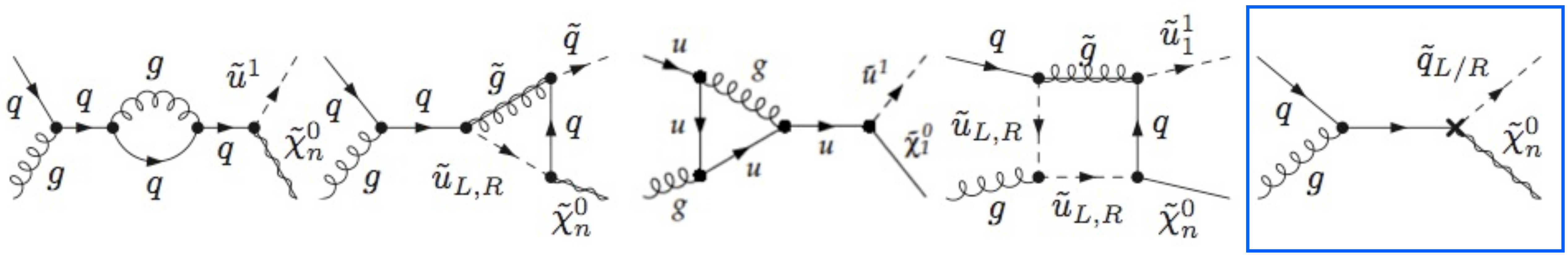

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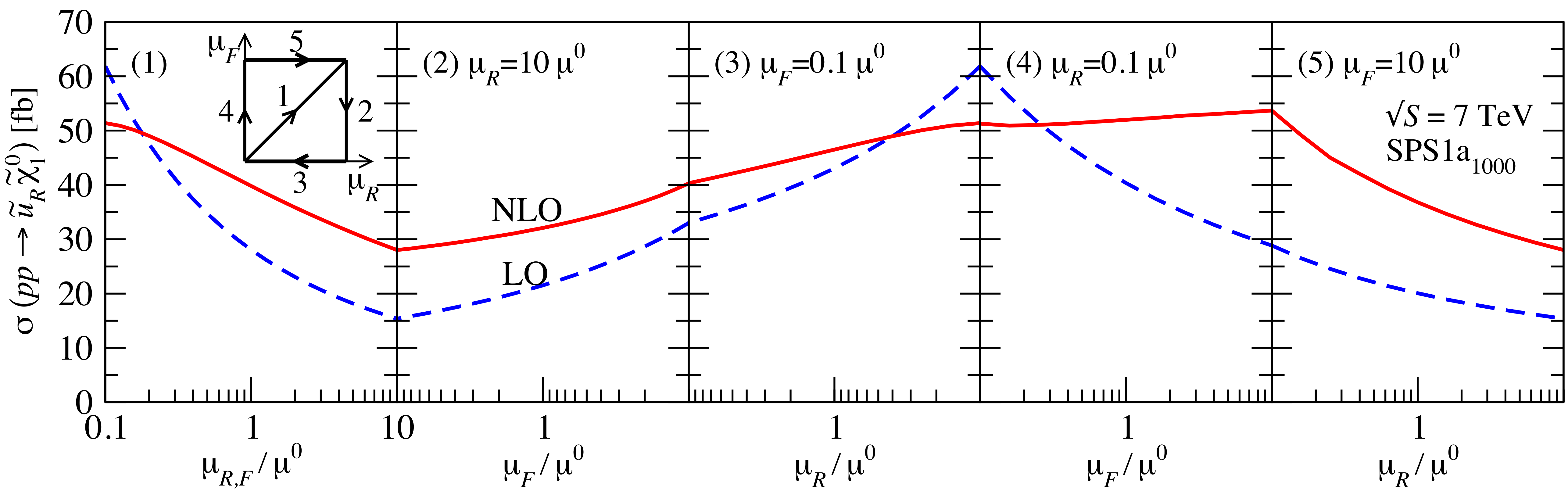
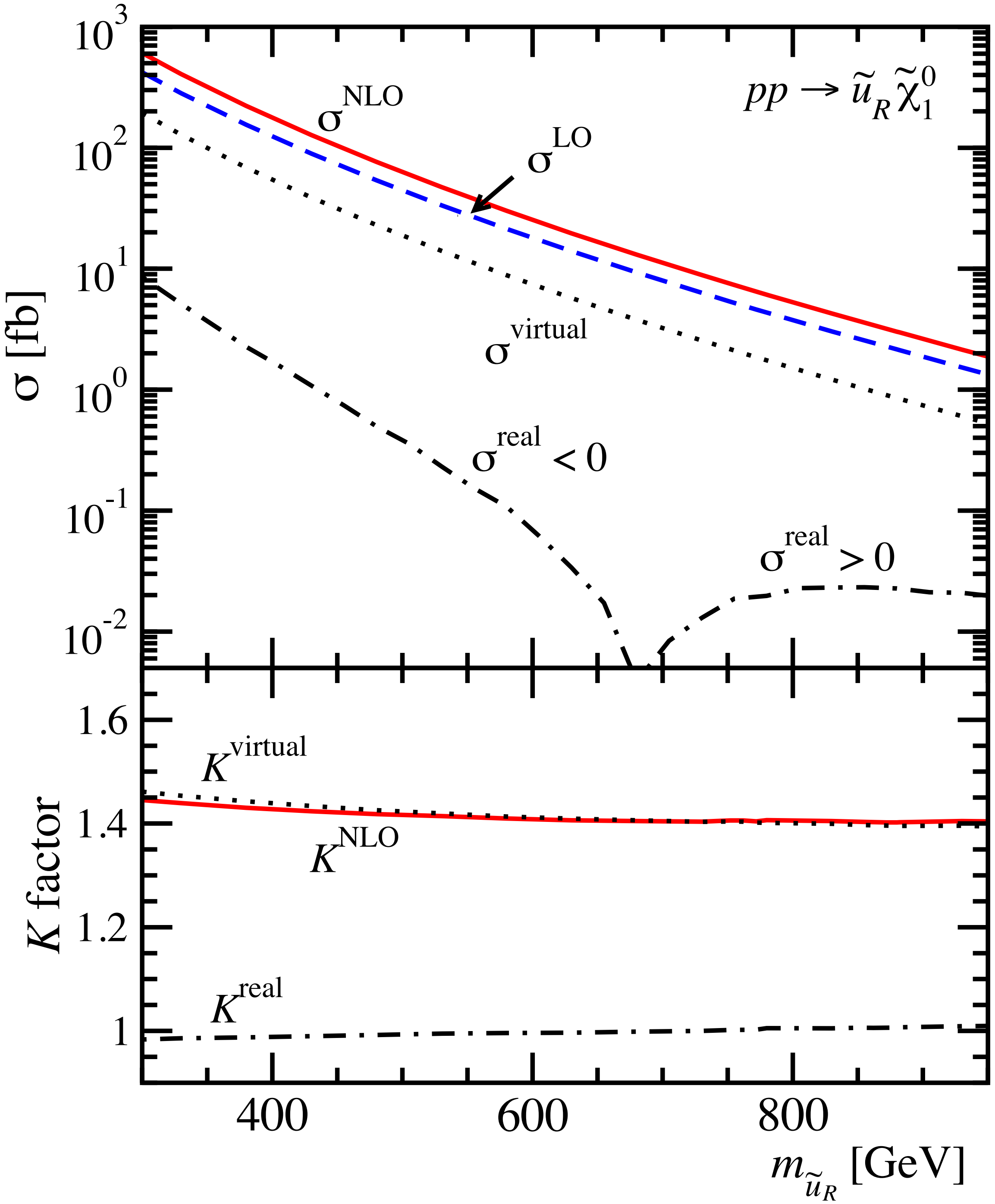
Scale Dependence

- Stabilization of the scale dependence on the unphysical μ_R & μ_F



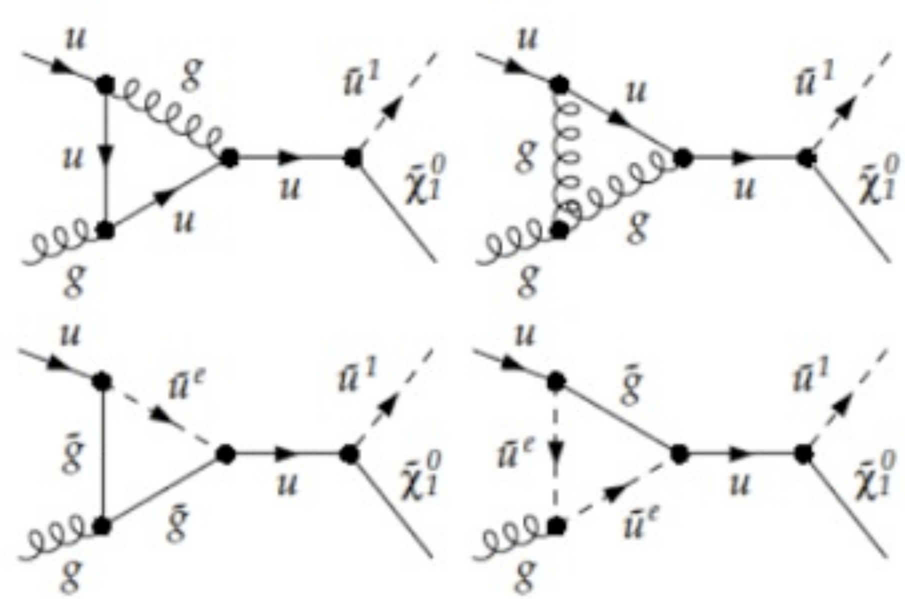
- Theory uncertainty largely reduced: $\frac{\delta\sigma^{NLO}}{\sigma^{NLO}} \leq 20\%$, down from up to $\frac{\delta\sigma^{LO}}{\sigma^{LO}} \leq 70\%$

NLO corrections



- SQCD effects have a subleading contribution supressed by $\frac{1}{M_{SUSY}}$

➡ Dominance by genuine QCD effects



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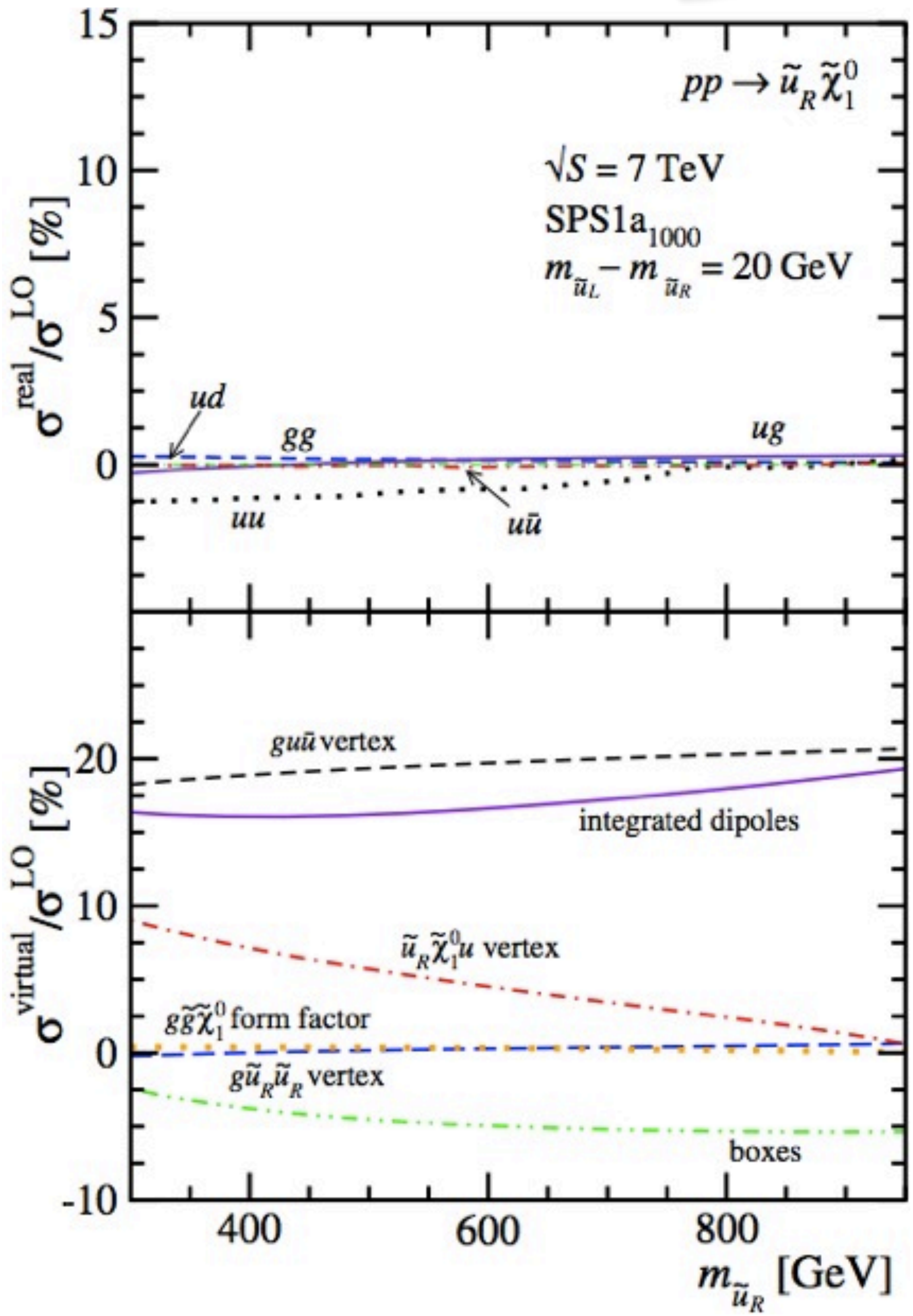
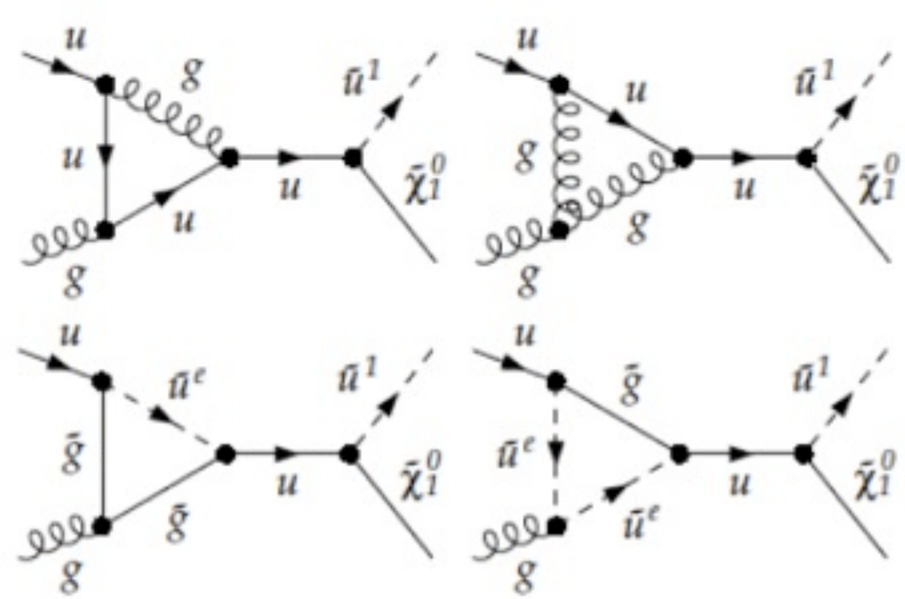


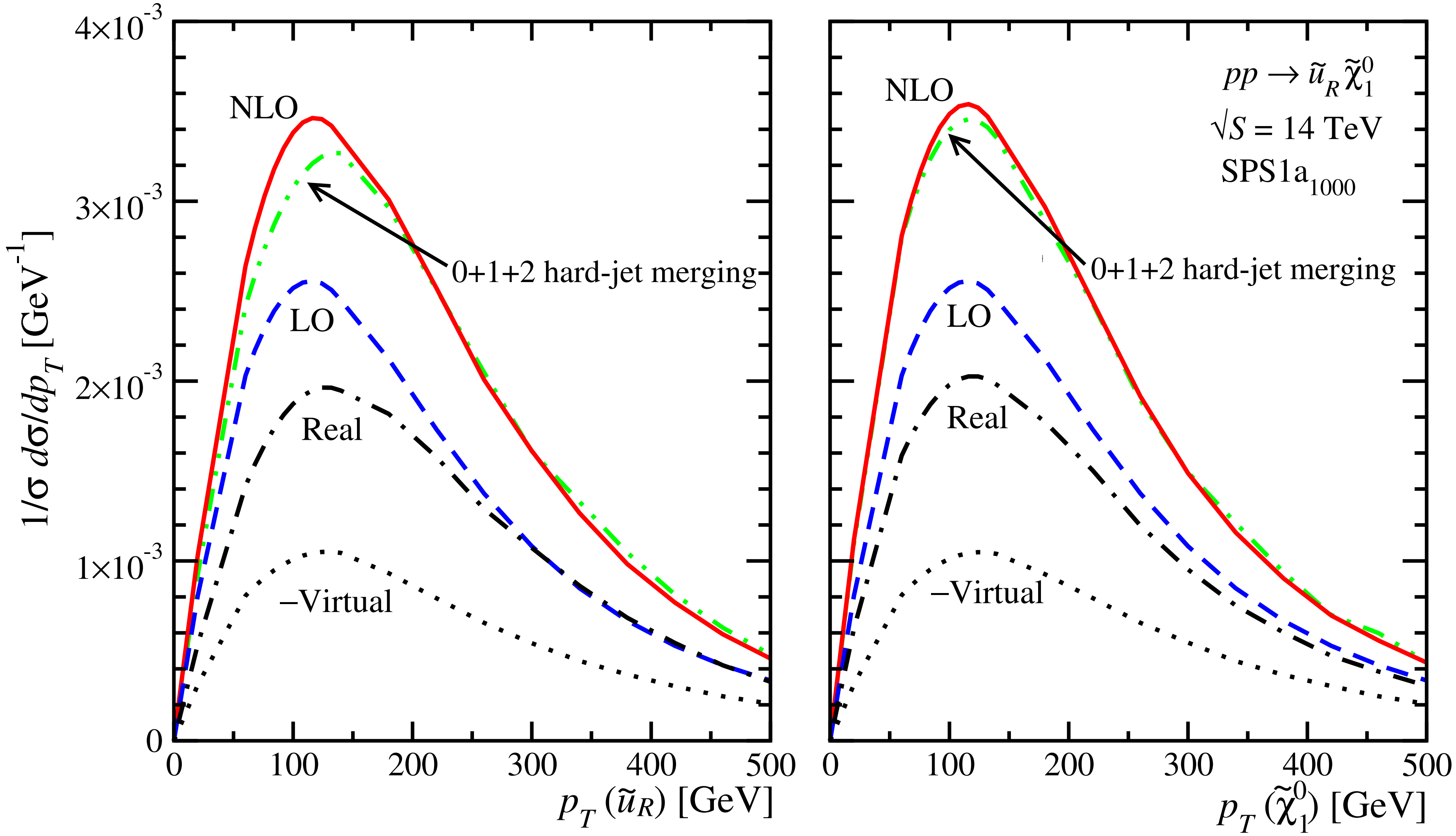
- SQCD effects have a subleading contribution supressed by $\frac{1}{M_{SUSY}}$

→ Dominance by genuine QCD effects

- $u\bar{u}g$ vertex correction basically independent on $m_{\tilde{u}}$



Comparison with Multi-jet Merging



- Jet merging: combine ME + Parton Shower without double counting

  Partons are hard and well separated → Complementary ← Partons are soft/collinear (resums large logs)

  Complementary

- NLO distributions for the heavy final states in good agreement with multi-jet merged calculation via MLM matching with MadGraph

Sgluon pair production at NLO

Scalar gluons (sgluons) are color octet scalars without electroweak charges

- Appear in various extensions to SM as composite or fundamental degrees of freedom:

➡ **Extra Dimensions**: color octet scalars emerge as low-lying KK modes of the bulk gluon field

Burdman, Dobrescu, Ponton Phys. Rev. D 74, 075008 (2006)

➡ **SUSY**: sgluons emerge as scalar partners of a Dirac gluino

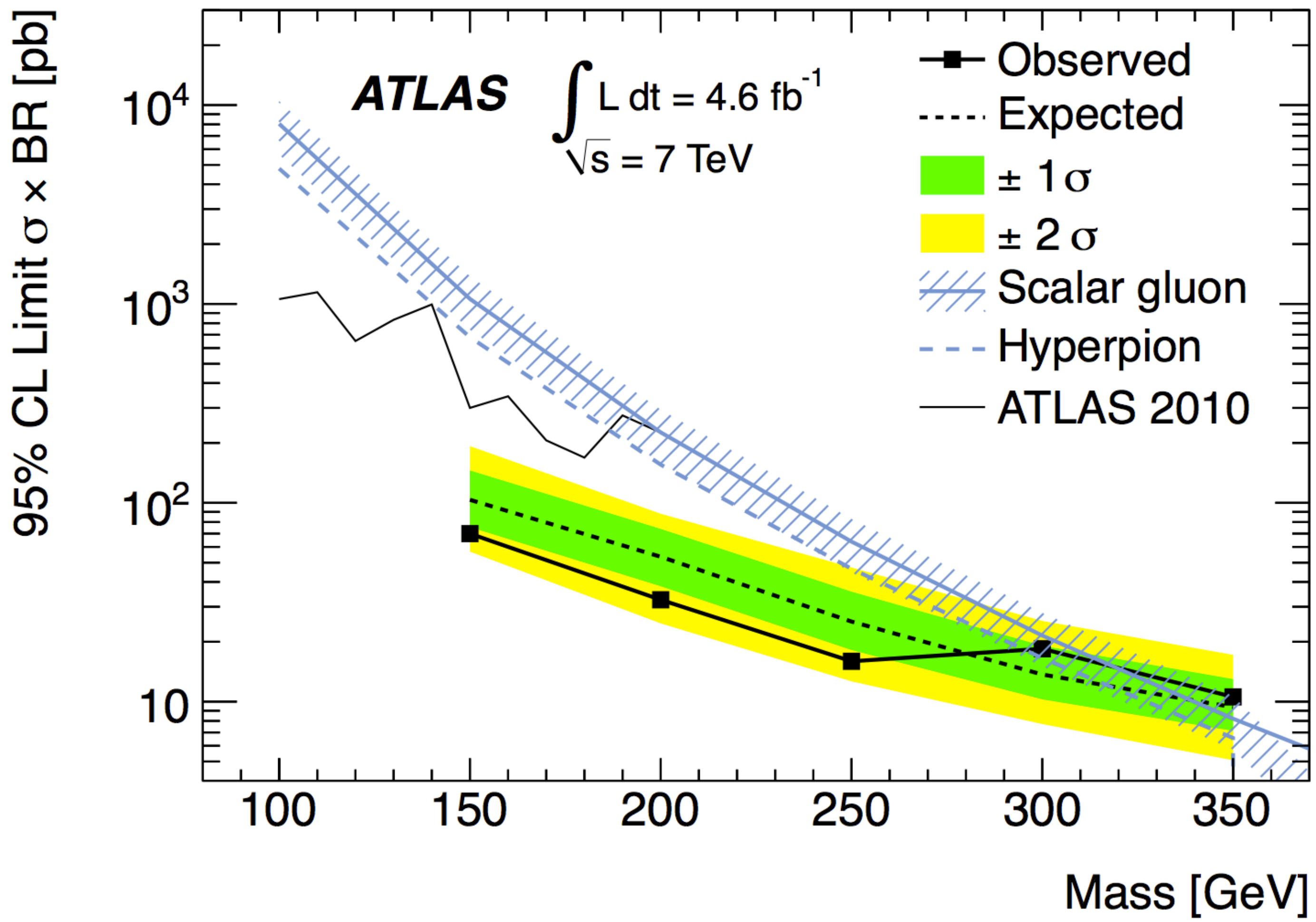
Plehn, Tait J. Phys. G 36, 075001 (2009)
Schumann, Renaud, Zerwas JHEP 1109 (2011) 074

- At the LHC sgluon pairs will be copiously produced by their coupling to gluons

- The most generic pheno signature is $pp \to GG^* \to 4jets$

➡ Enormous background - exceeds the signal by orders of magnitude. So it can be relatively light

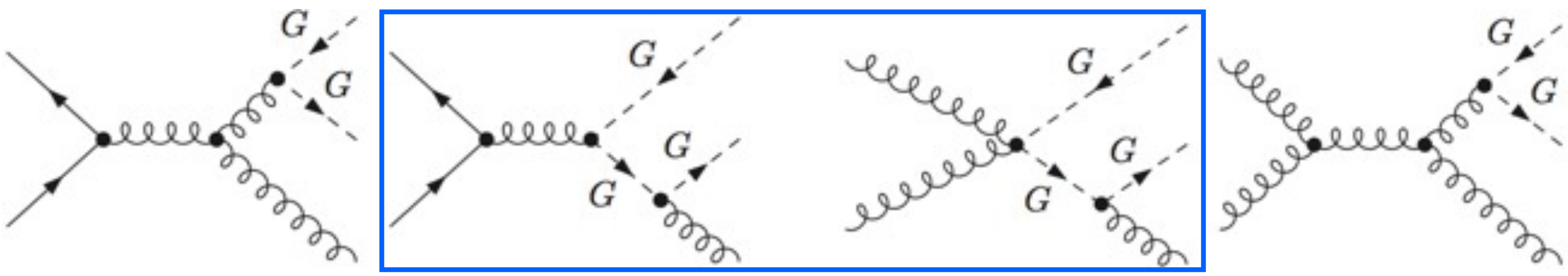
Status of the current searches



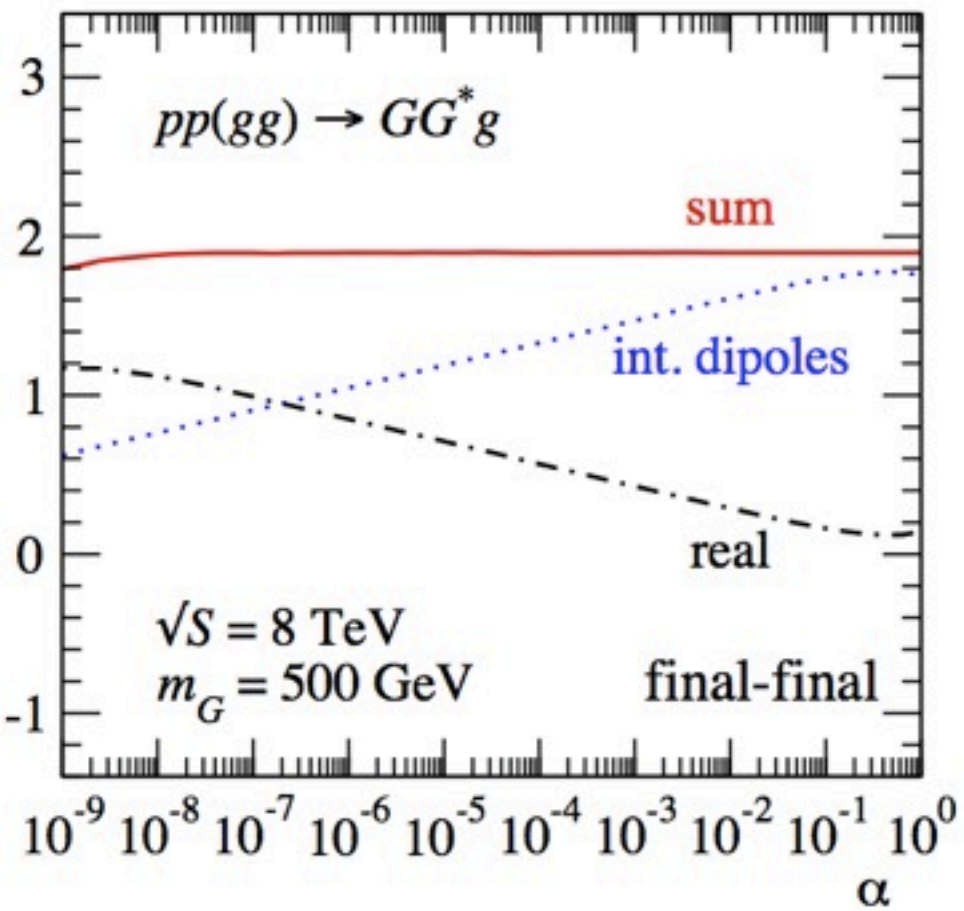
- NLO calculation generated by MadGolem
- Sgluons with masses 150-287 GeV are excluded at 95% C.L. by ATLAS 2011 data

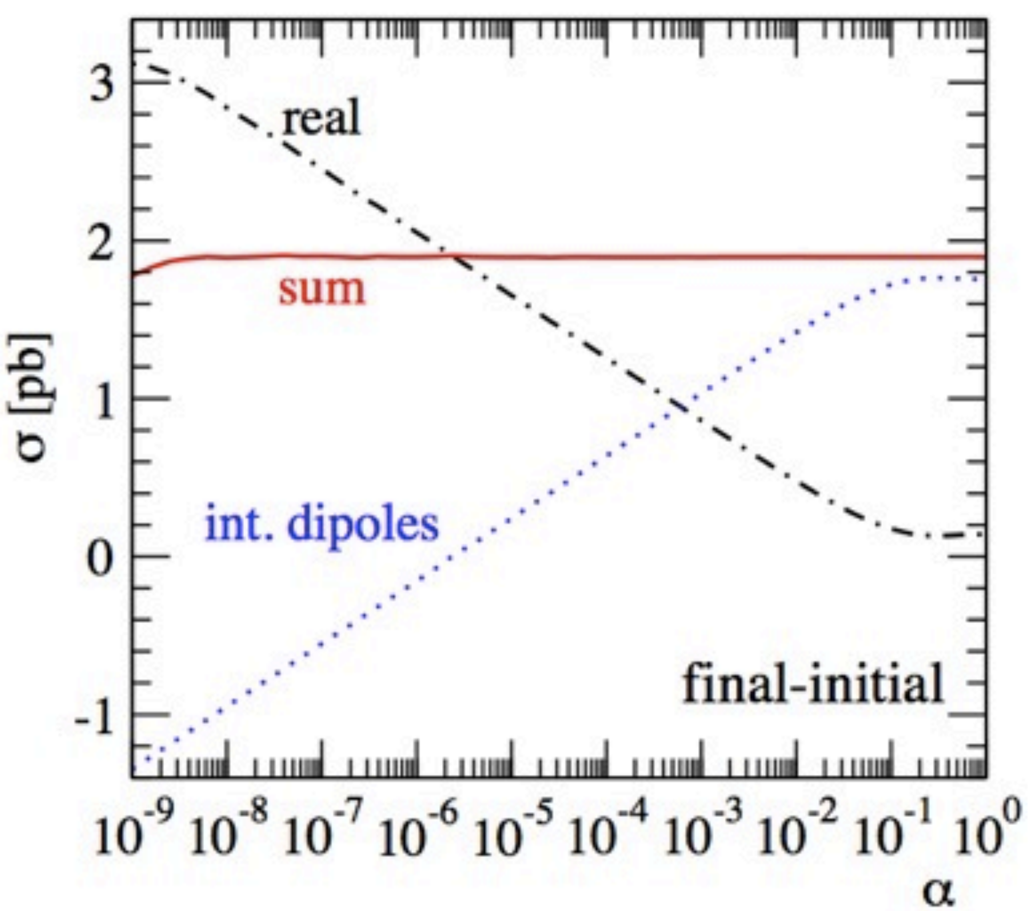
Structure of the NLO corrections

- Real emission corrections:



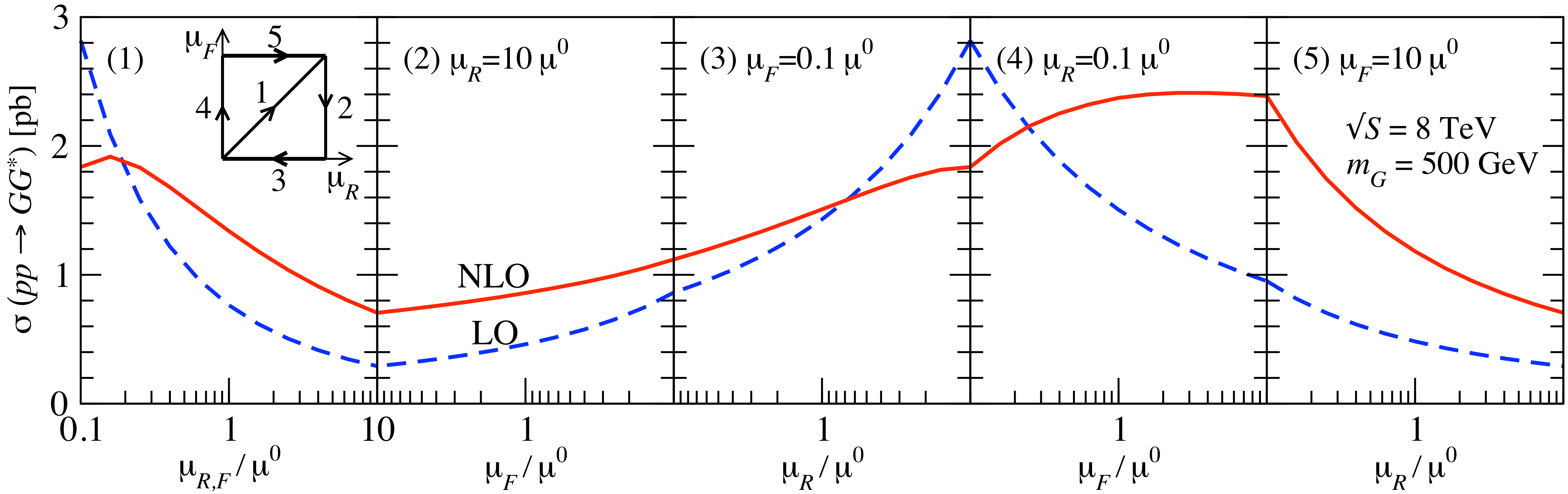
Sgluon dipoles:





Scale Dependence

- Stabilization of the scale dependence on the unphysical μ_R & μ_F

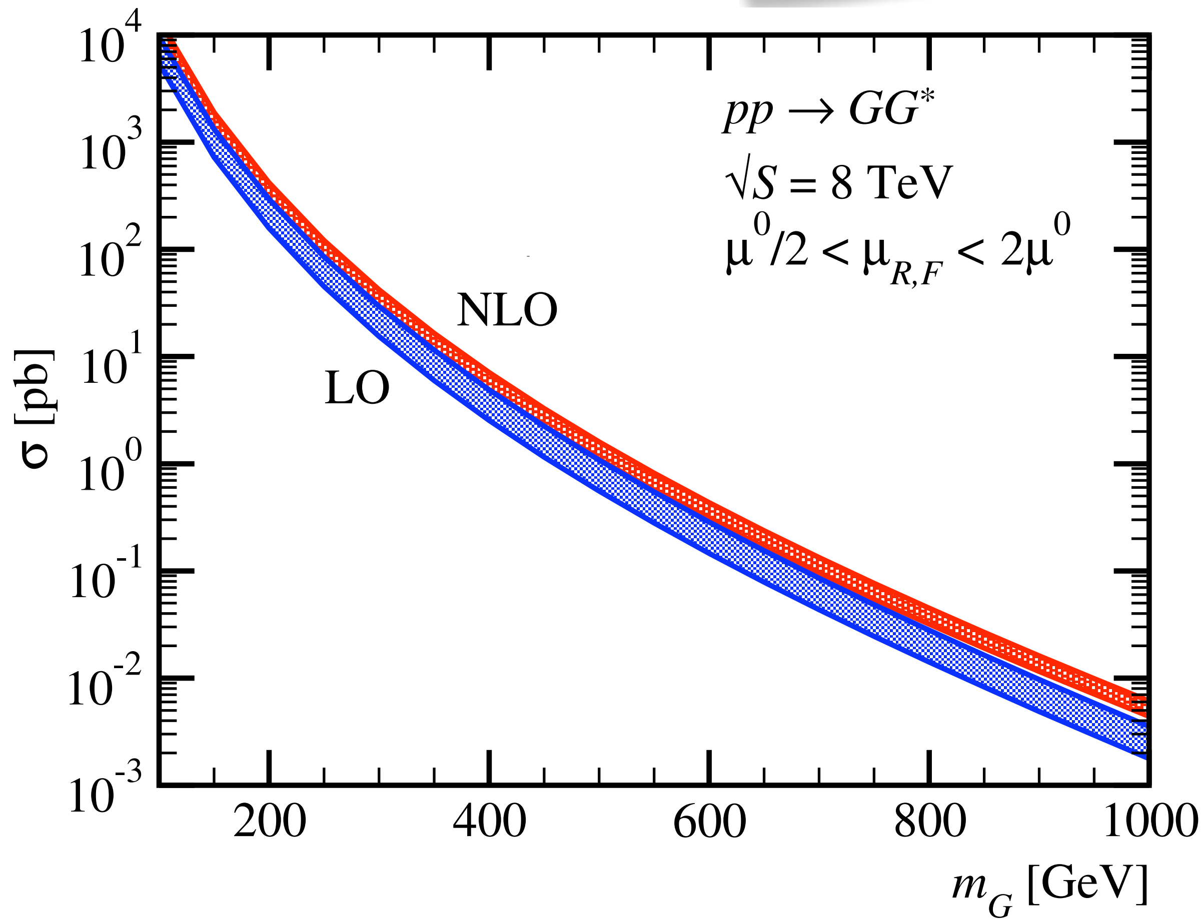


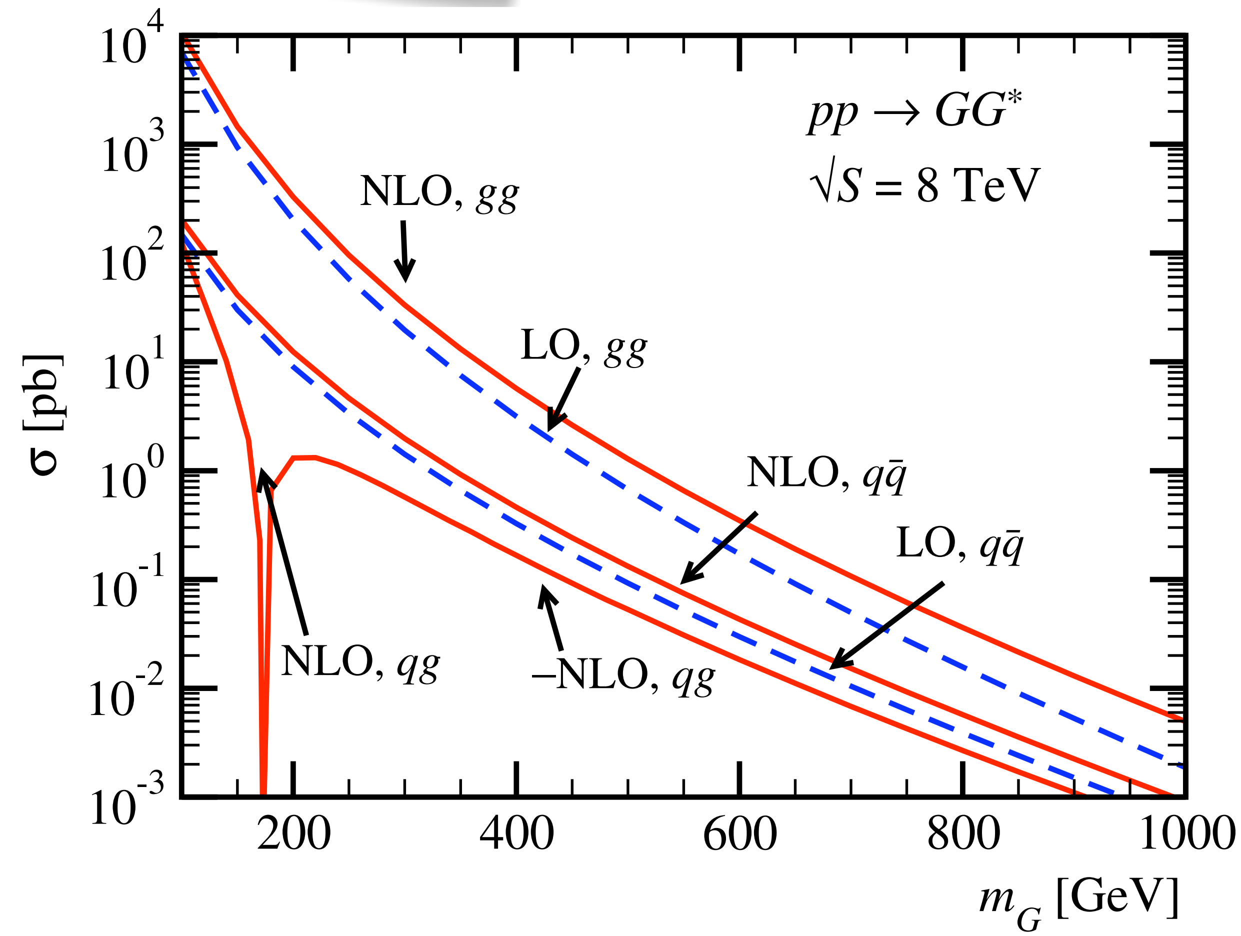
$\Delta\sigma^{\rm NLO}/\sigma^{\rm NLO} \sim \mathcal{O}(30\%)$, down from up to $\Delta\sigma^{\rm LO}/\sigma^{\rm LO} \sim \mathcal{O}(80\%)$

- Unlike Drell-Yan-type channels there is μ_R dependence at LO: $\sigma^{LO} \sim \alpha_s^2$

➡ The bulk of the scale dependence comes from μ_R

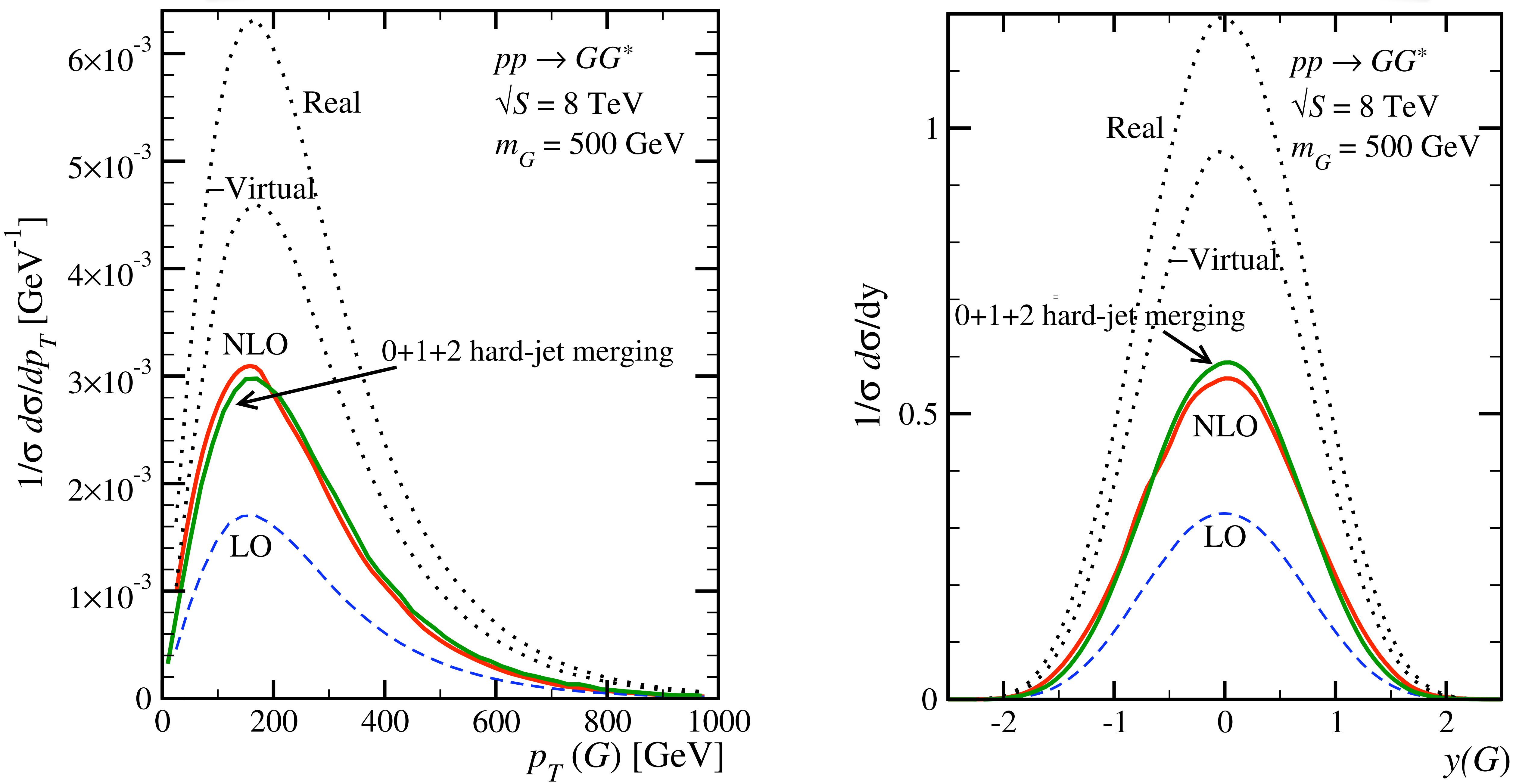
NLO corrections





- NLO corrections increase for increasing m_G
- Dominance of $gg \to GG^*$
  - ➡ color charge
  - ➡ threshold effects: $\begin{cases} \sigma_{gg} \sim \beta, & \text{s-wave component of } \sigma_{gg} \\ \sigma_{q\bar{q}} \sim \beta^3, & \text{p-wave component of } \sigma_{q\bar{q}} \end{cases}, \quad \beta = \sqrt{1 - 4m_G^2/s}$

Comparison with Multi-jet Merging



- NLO distributions for the heavy final states in good agreement with multi-jet merged calculation via MLM matching with MadGraph

Squark and gluino pair production at NLO

- $pp \to \tilde{q}\tilde{q},\ \tilde{q}\tilde{q}^*,\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$: Main discovery channels for SUSY at the LHC

- MadGOLEM presents significant improvements:
  - Fully automized
  - Can single out specific elements of the NLO QCD corrections e.g.

  ➡ different partonic sub-channels or different 1-loop topologies
  - Provides systematic study at the distribution level
  - Does not require assumptions on the SUSY mass spectra

  ➡ precise scan in the MSSM parameter space

MSSM parameter space

- Distinct realizations of the MSSM in full agreement with the current constraints
[Eur. Phys. J. C 71, 1835 (2011)]

	$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$	mass hierarchy
CMSSM 10.2.2	1162	1120	1165	1116	1255	$\tilde{q}_R < \tilde{q}_L < \tilde{g}$
CMSSM 40.2.2	1200	1168	1202	1165	1170	$\tilde{q}_R < \tilde{g} < \tilde{q}_L$
CMSSM 40.3.2	1299	1284	1301	1284	932	$\tilde{g} < \tilde{q}_R < \tilde{q}_L$
mGMSB 1.2	899	868	902	867	946	$\tilde{q}_R < \tilde{q}_L < \tilde{g}$
mGMSB 2.1.2	933	897	936	895	786	$\tilde{g} < \tilde{q}_R < \tilde{q}_L$
mAMSB 1.3	1274	1280	1276	1289	1282	$\tilde{u}_L < \tilde{u}_R < \tilde{g}$, $\tilde{d}_L < \tilde{g} < \tilde{d}_R$

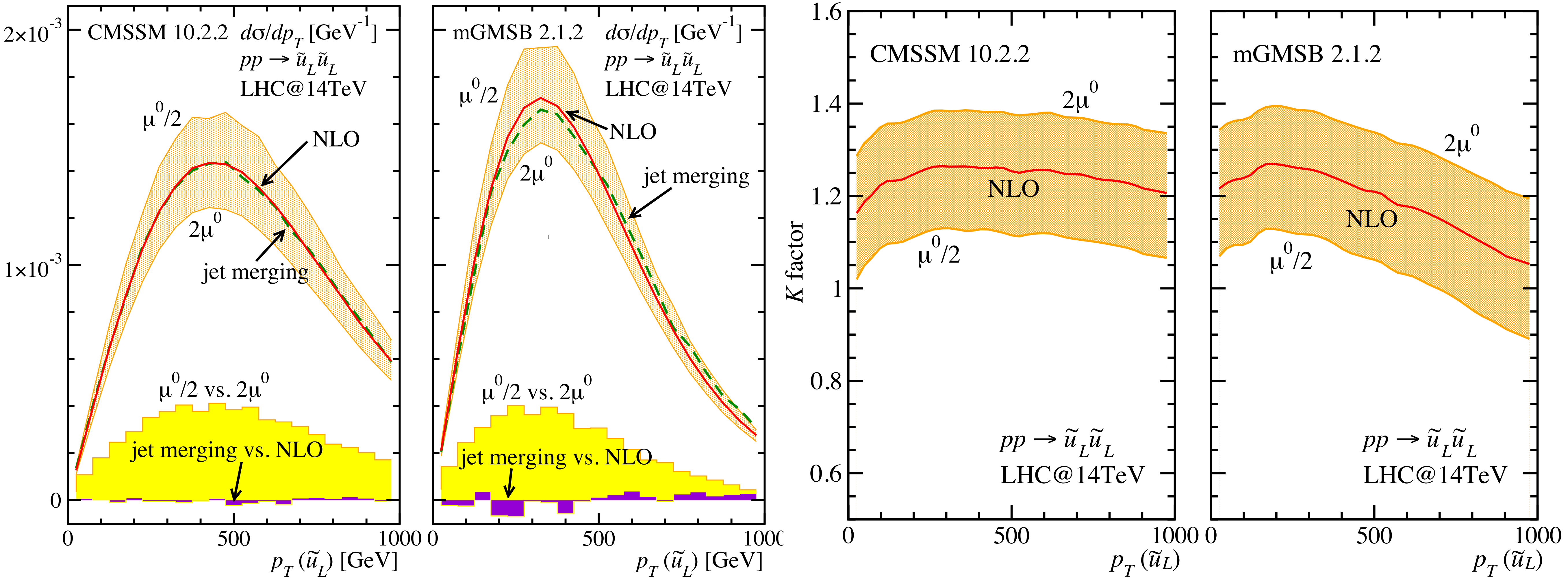
	$\tilde{u}_L\tilde{u}_L$			$\tilde{u}_R\tilde{u}_R$			$\tilde{u}_L\tilde{u}_R$			$\tilde{u}\tilde{d}$		
	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K	σ^{LO}	σ^{NLO}	K
CMSSM 10.2.2	26.2	29.2	1.11	31.0	34.3	1.11	26.2	30.7	1.17	87.7	104.8	1.19
CMSSM 40.2.2	22.8	26.0	1.14	26.0	29.4	1.13	25.2	30.2	1.20	75.2	91.2	1.21
CMSSM 40.3.2	14.8	18.1	1.22	15.8	19.1	1.21	23.1	29.9	1.29	49.8	63.6	1.28
mGMSB 1.2	85.3	97.0	1.14	98.1	110.7	1.13	99.7	120.4	1.21	316.6	387.8	1.22
mGMSB 2.1.2	73.9	88.7	1.20	87.6	104.5	1.19	113.9	144.5	1.27	293.3	372.6	1.27
mAMSB 1.3	16.8	18.9	1.13	16.4	18.4	1.12	16.1	19.1	1.19	48.3	58.1	1.20

- General fully unconstrained scan - no simplifying assumptions in the calculation

- K-factor largely insensitive to the specific MSSM scenario

➡ Dominance by genuine QCD effects

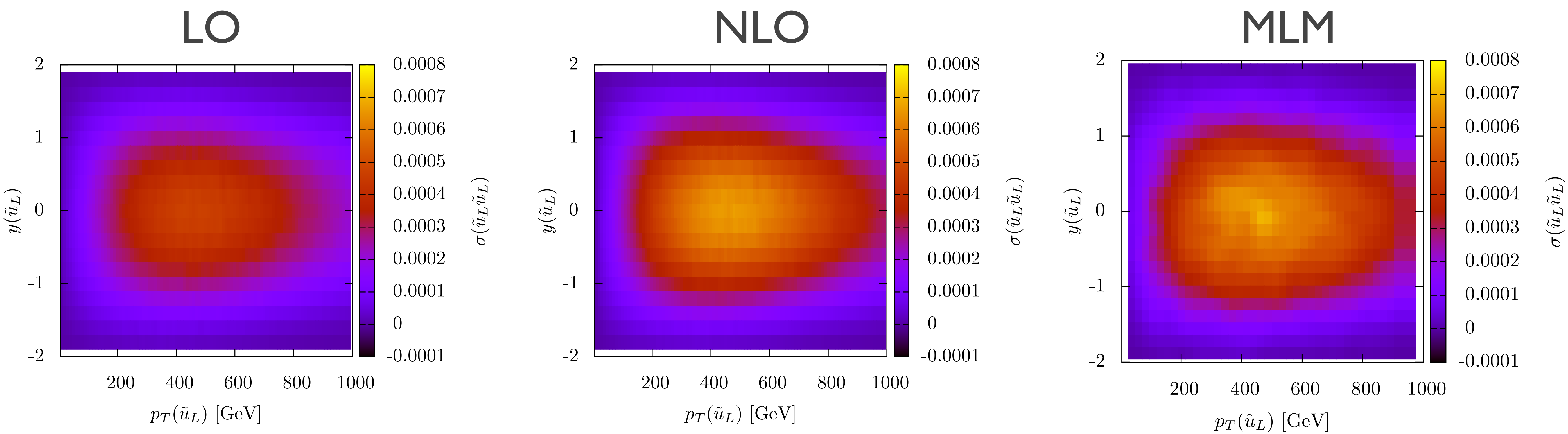
Comparison with Multi-jet Merging



- NLO and MLM agree very well - within the NLO uncertainty
- K-factors remain stable for the transverse momentum

➡ Justify the conventional procedure of global K-factor to kinematic distributions

Comparison with Multi-jet Merging

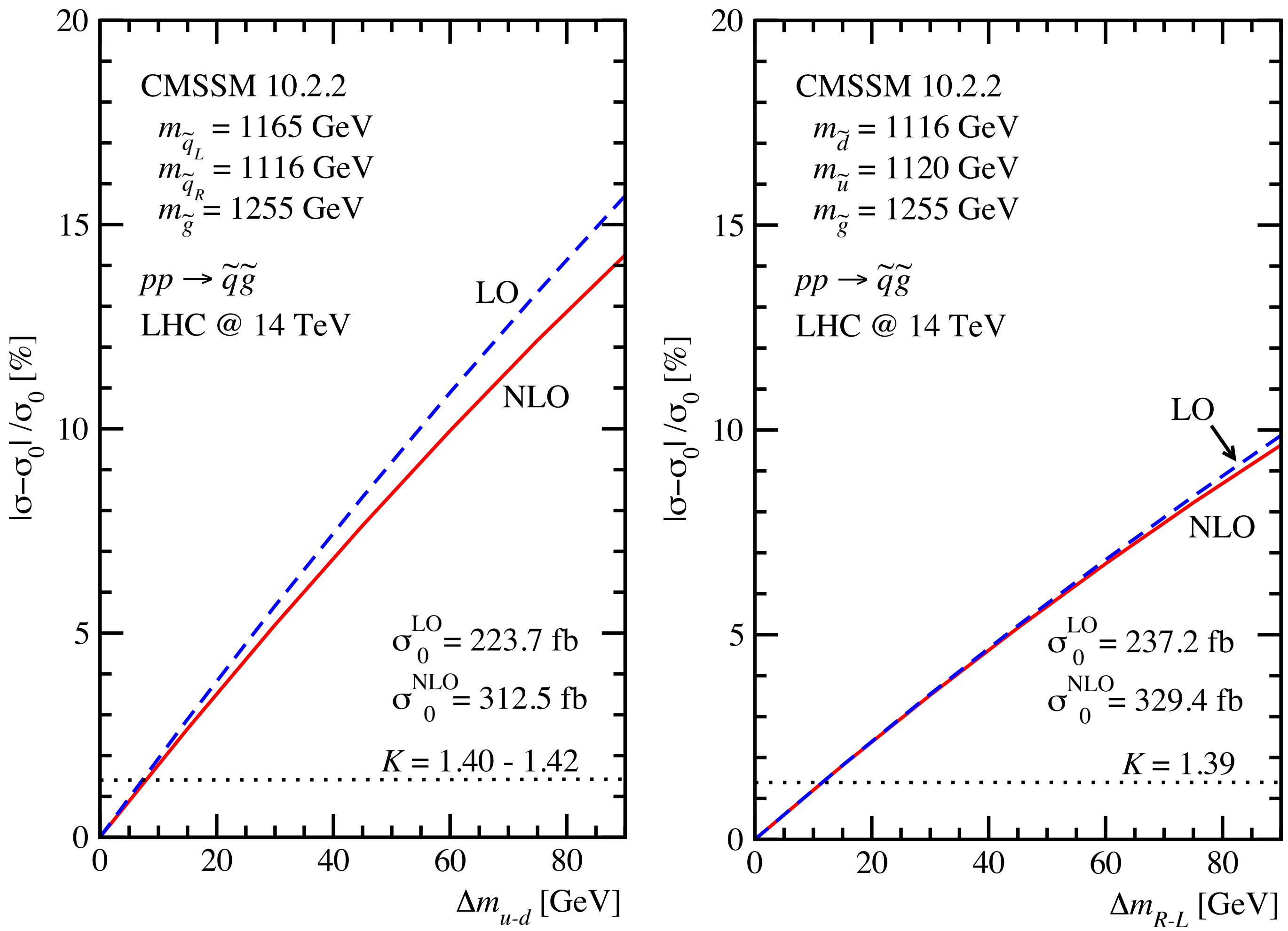


- NLO and MLM agree very well
  - No correlations between rapidity and transverse momentum
  - MLM slightly harder because of the extra recoil jets from the parton shower

Degenerate vs non-degenerate squarks

- Squark mass degeneracy is an usual assumption in the available NLO tools, e.g. Prospino
- These assumptions are not necessary in MadGolem - freely scan the parameter space

Total rates

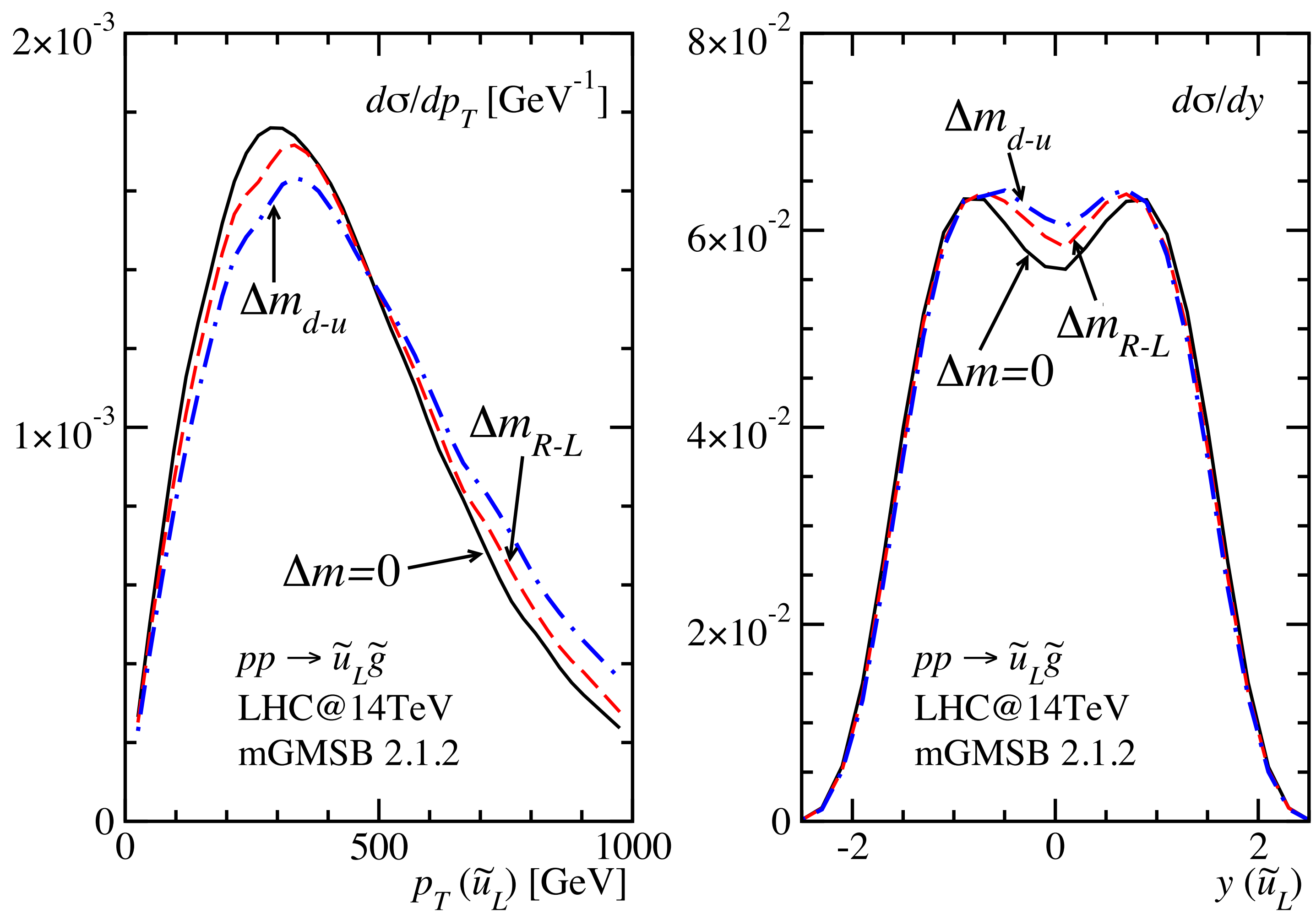


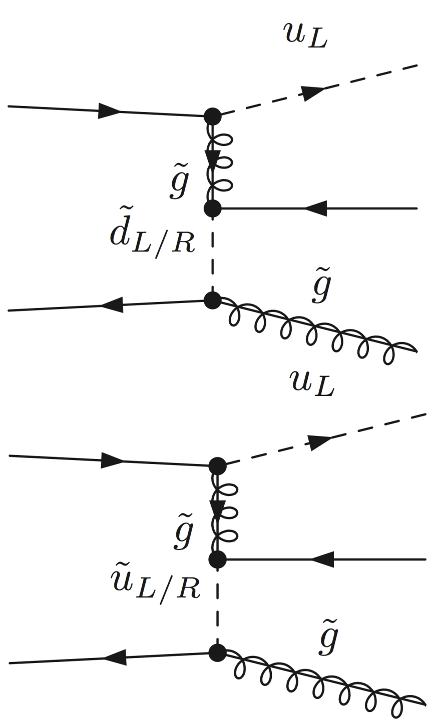
- LO and NLO rates scale in parallel - small deviation at the percent level

➡ K-factors essentially constant: $\sigma^{NLO}_{\text{Prospino}} = K_{\text{Prospino}}\,\sigma^{LO}_{\text{non-degenerate}}$

Degenerate vs non-degenerate squarks

Distributions





- Deviations become much more apparent at the distribution level O(20%)

➡ Mass degeneracy is not suitable at the distribution level!

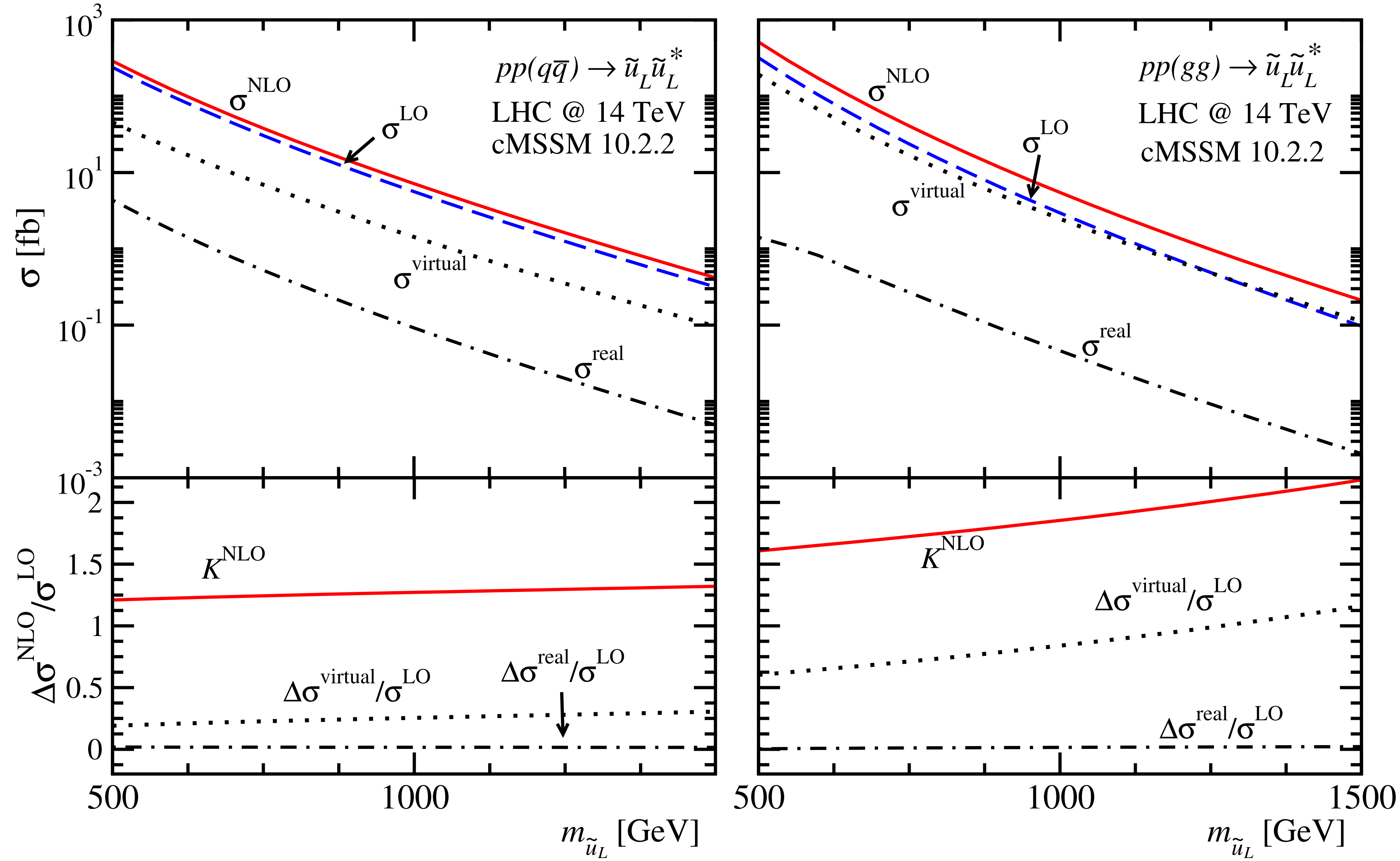
- fusion diagrams: bulk contribution from internal squark and gluino propagators at very small virtuality, i.e. almost on-shell. Particularly sensitive to squark masses.

Summary

MadGolem: Fully automized tool for NLO QCD calculations

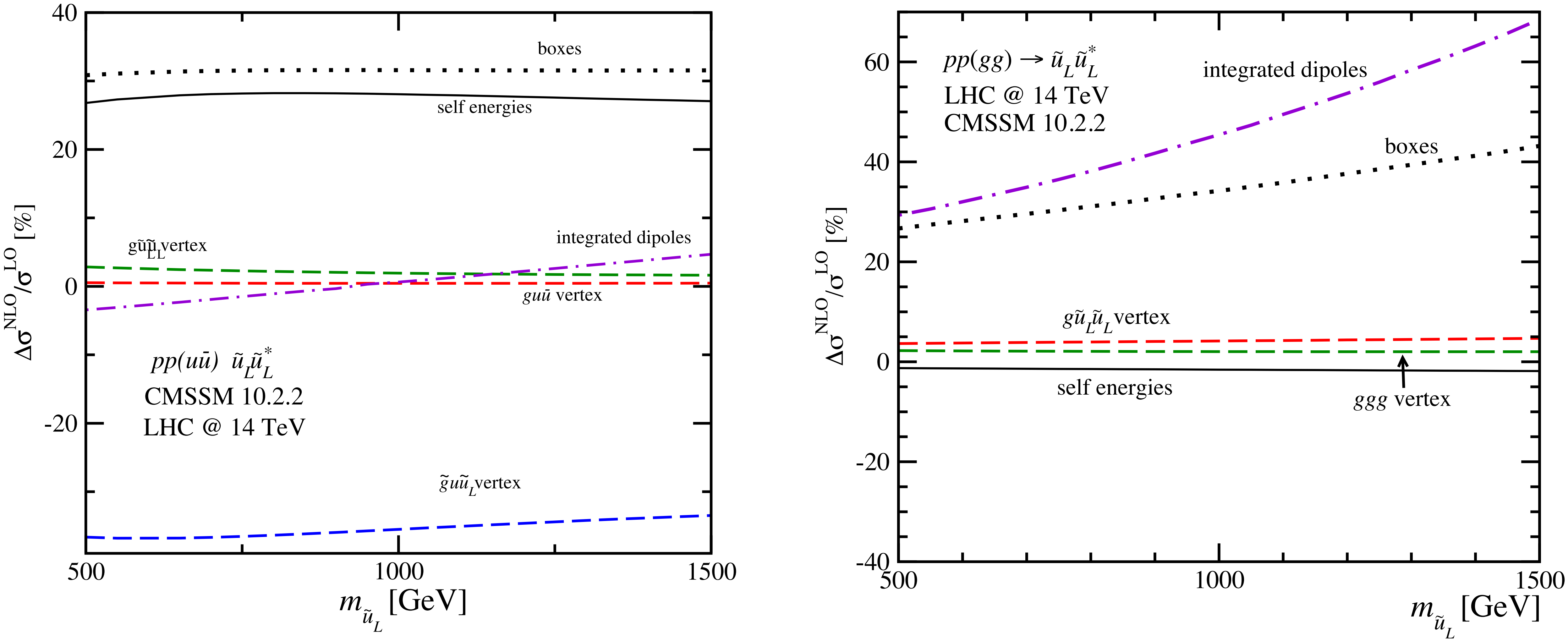
- First NLO calculation for sgluon pair and squark-neutralino production
- First NLO calculation for SUSY pairs without the simplifying squark mass degeneracy
- K-factors largely independent on the SUSY mass spectra
- NLO and MLM distributions in good agreement
- K-factors remain stable for all the kinematic relevant regions
- Squark mass degeneracy is not a good approximation at the distribution level

Backup: NLO corrections



- K-factor largely insensitive to the specific parameter point: Dominance by genuine QCD effects
- threshold effects: $\begin{cases} \sigma_{gg} \sim \beta, & \text{s-wave component of } \sigma_{gg} \\ \sigma_{q\bar{q}} \sim \beta^3, & \text{p-wave component of } \sigma_{q\bar{q}} \end{cases}, \quad \beta = \sqrt{1 - 4m_G^2/s}$

Backup: NLO corrections



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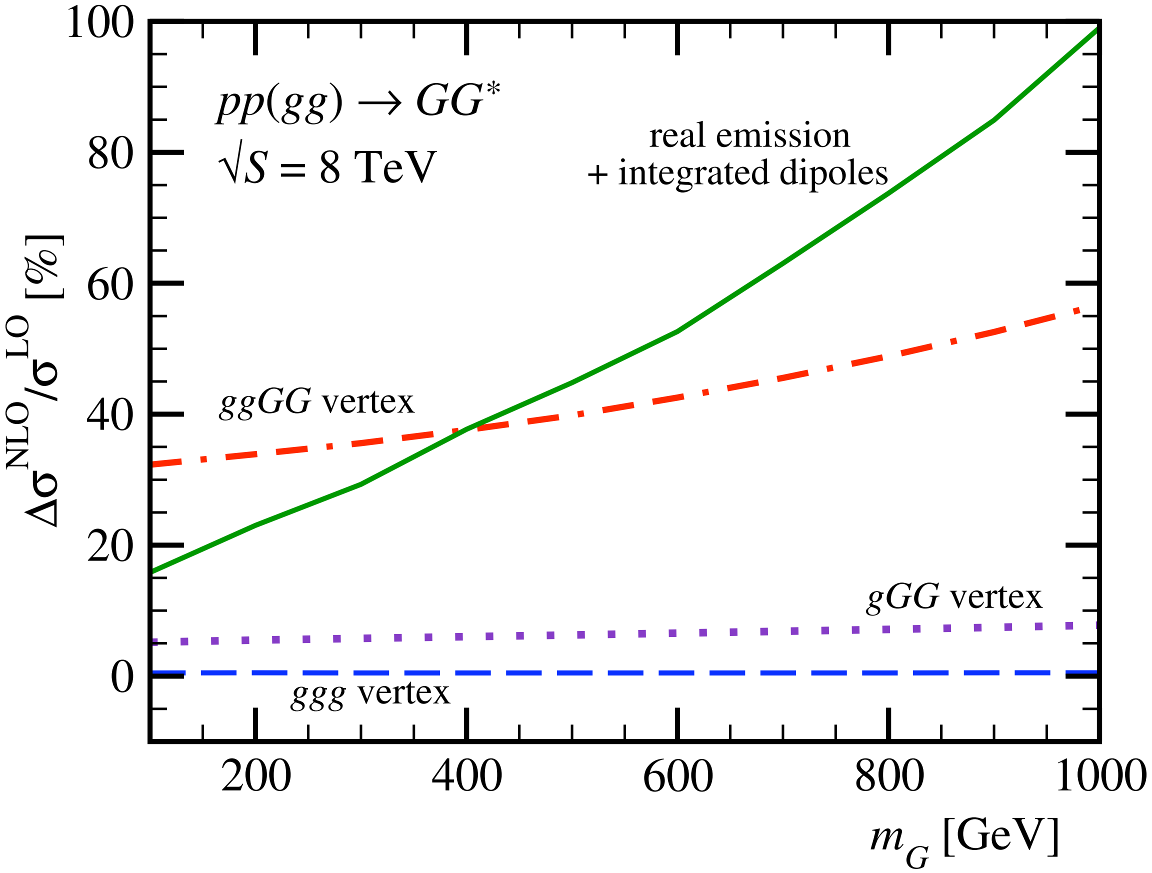
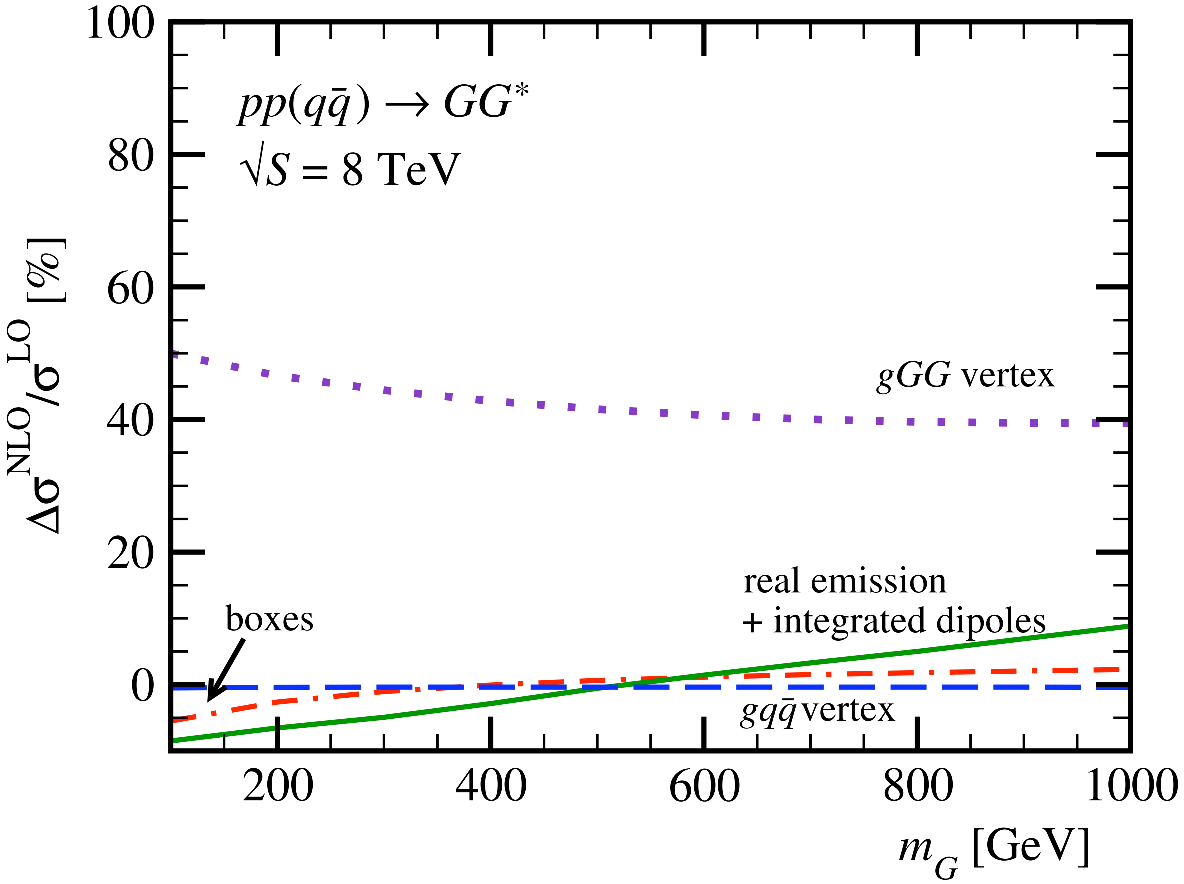
Backup: sgluons NLO corrections





- real emission and virtual box diagrams contributes to the bulk of the NLO quantum effects for σ_{gg}

➡ their size and increase with m_G come from the threshold behavior of the NLO corrections $\sigma_{gg} \sim \beta$