NLO corrections to squark-squark production and decay at the LHC

in collaboration with W. Hollik and D. Pagani
arXiv:1207.1071

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Jonas M. Lindert

Max Planck Institut für Physik, München

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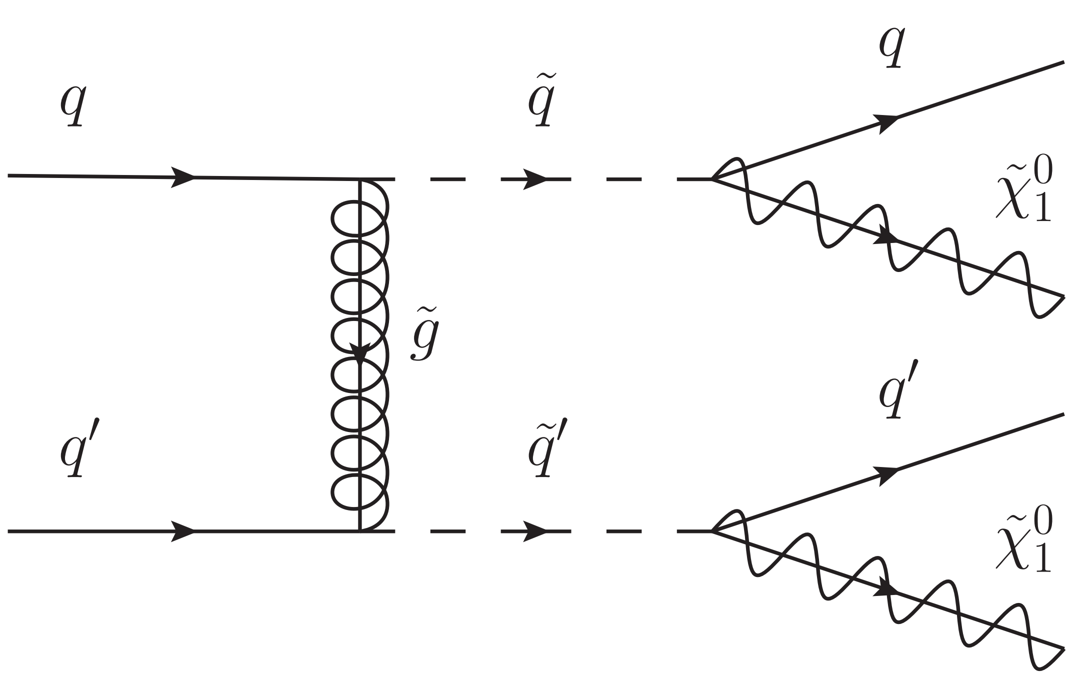
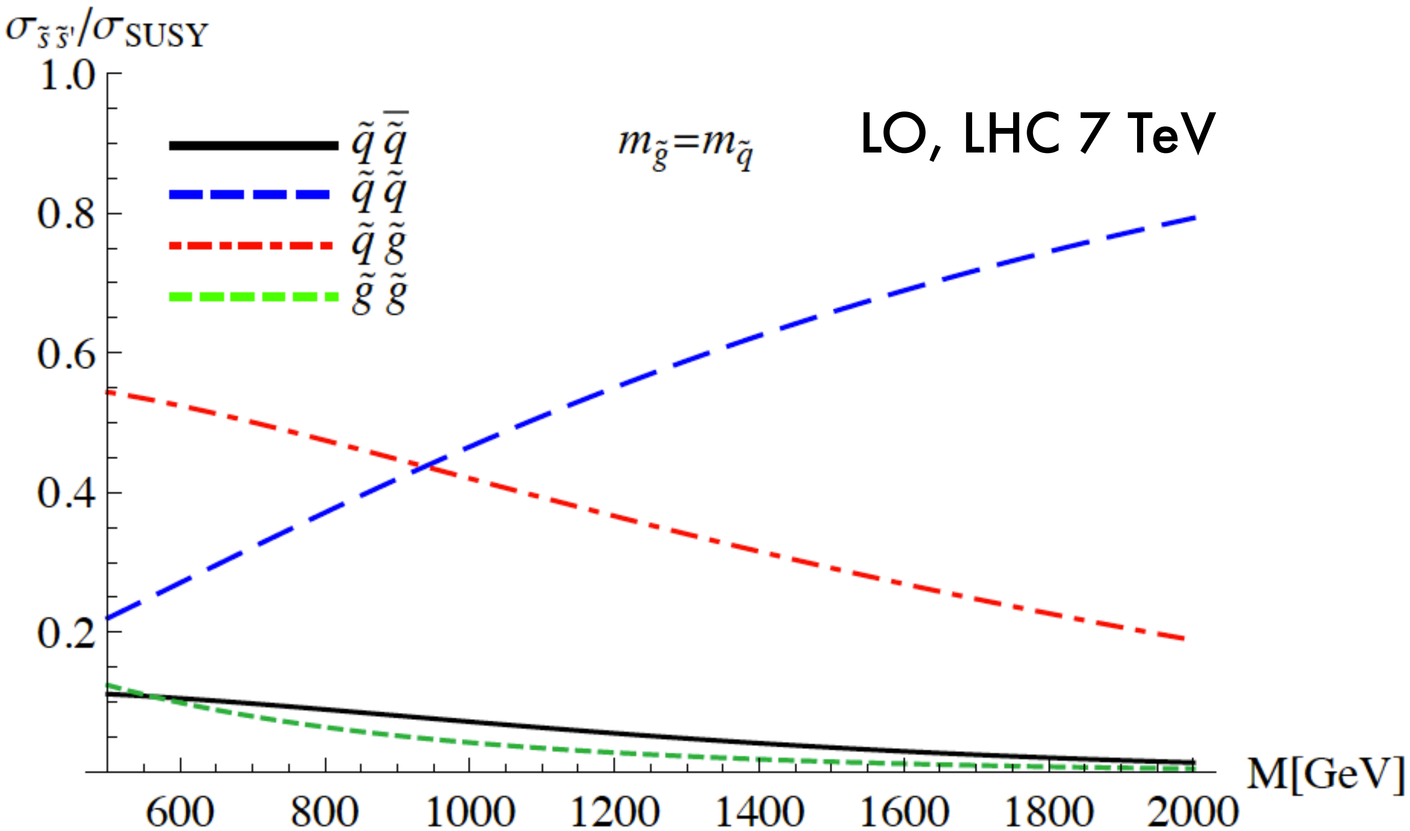
We study the experimental signature $2j + \not{E}_T(+X)$

via squark-squark production and direct decay into the lightest neutralino. $pp \to \tilde{q}\tilde{q}' \to qq'\tilde{\chi}_1^0\tilde{\chi}_1^0(+X)$

Full LO process



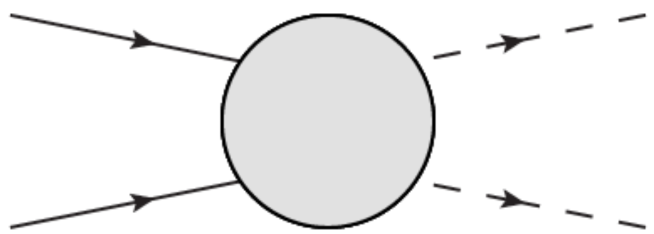
Why squark-squark channel?



[Falgari, Schwinn, Wever, '12]

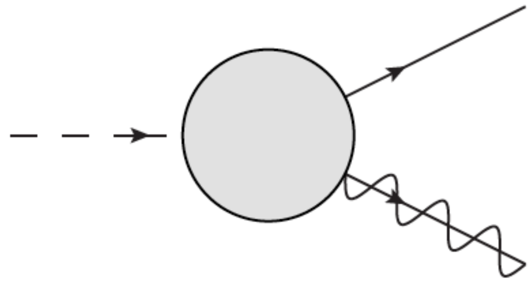
SUSY PARTICLES AT THE LHC

Production



Squark-Squark production:
LO QCD: *Baer, Tata '85*
NLO QCD: *Beenakker et al.'96*
Tool: PROSPINO2 *(*inclusive*), Plehn et al.*
LO EW: *Bornhauser et.al.* '07, **NLO**: *Germer et al. '10*
Beyond NLO (resummed):
Beenakker et al. '09 (soft)
Falgari, Schwinn, Wever '12 (soft+coulomb) [see C. Wever's talk]

Decay



Squark decay:
NLO QCD: *Djouadi, Hollik, Junger '96*
Tool: SDECAY (integrated widths), *Mühlleitner et al.*
NLO EW: *Guasch, Hollik, Sola '02*

Higher-order corrections are generally large for inclusive cross sections.

Differential distributions at NLO in terms of experimental signatures have not been studied.

For a systematic treatment at NLO production and decays have to be combined.

We study the experimental signature

$$2j + \not{E}_T (+X)$$

via squark-squark production and direct decay into the lightest neutralino.

$$pp \to \tilde{q}\tilde{q}' \to qq'\tilde{\chi}_1^0\tilde{\chi}_1^0 (+X)$$

Standard procedure:

Production of events with a parton shower generator with LO matrix elements and rescaling with a global K factor for NLO(+NLL) QCD corrections to the total cross-section of squark-squark production (calculated with Prospino or NLL-Fast).

We study the experimental signature

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Standard procedure:

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Our procedure:

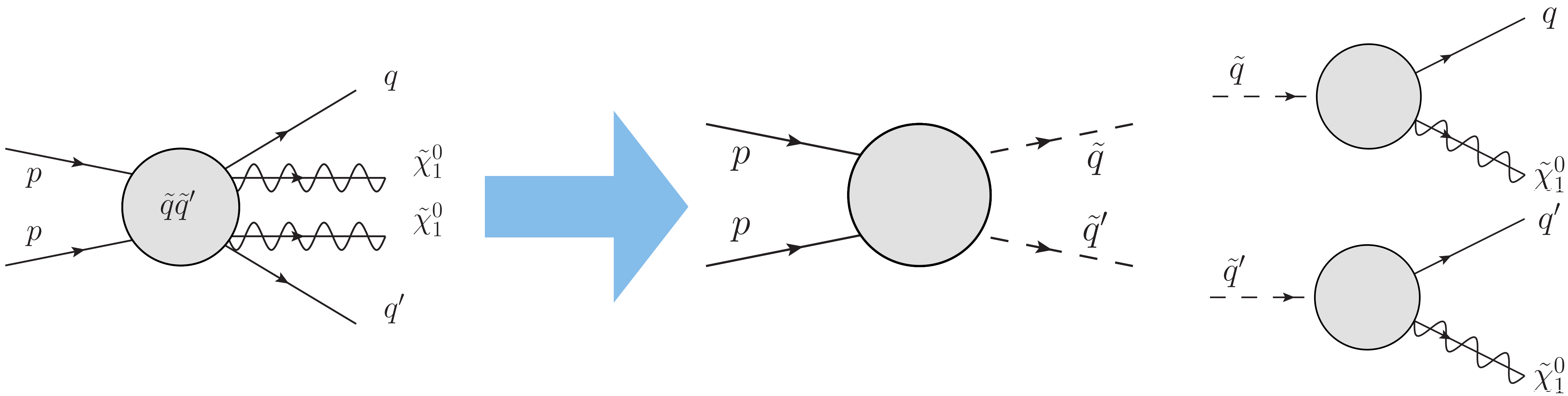
Including fully differential NLO corrections to both the decay and production, where in the calculation all flavour and chirality configurations of intermediate squarks are treated independently.

LO in NWA

$$qq' \to \tilde{q}\tilde{q}' \to q\tilde{\chi}_1^0 q'\tilde{\chi}_1^0$$

$$\Gamma_{\tilde{q}}/m_{\tilde{q}} \to 0$$

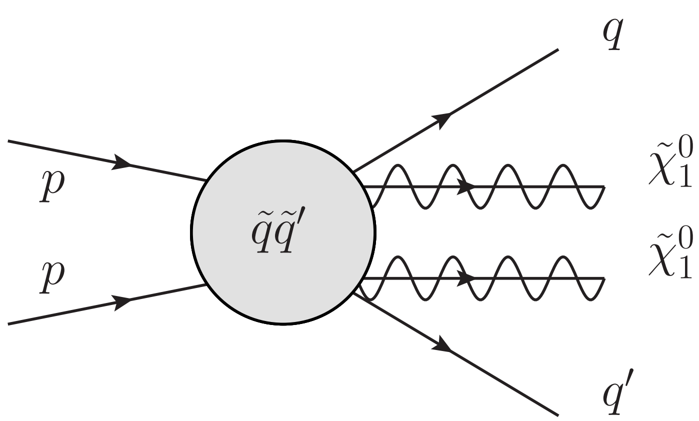
$$\hat{\sigma}^{(0)}_{\text{NWA}} = \hat{\sigma}^{(0)}(qq' \to \tilde{q}\tilde{q}') \times BR^{(0)}(\tilde{q} \to q\tilde{\chi}_1^0) \times BR^{(0)}(\tilde{q}' \to q'\tilde{\chi}_1^0)$$

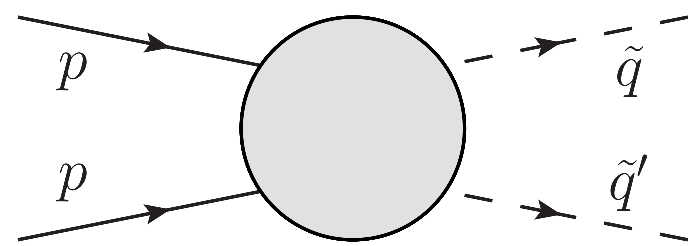


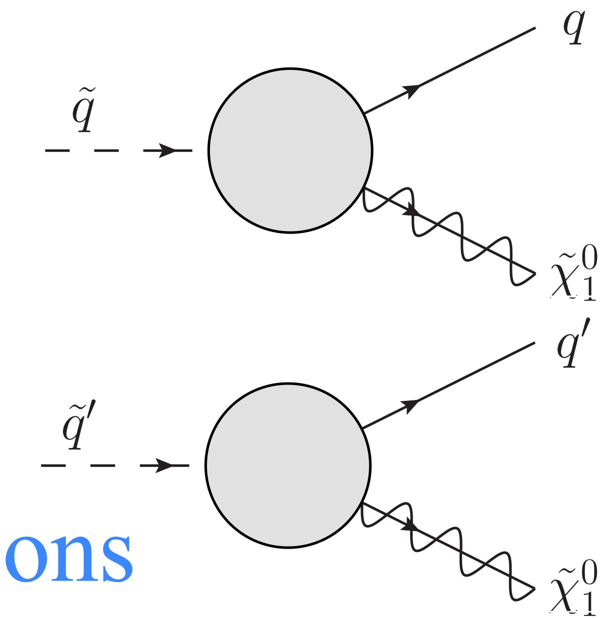
Hadronic differential LO cross section in NWA

$$d\sigma^{(0)}_{\text{NWA}}(pp \to \tilde{q}\tilde{q}' \to q\tilde{\chi}_1^0 q'\tilde{\chi}_1^0(+X)) = \frac{1}{\Gamma^{(0)}_{\tilde{q}}\Gamma^{(0)}_{\tilde{q}'}}\left[d\sigma^{(0)}_{pp\to\tilde{q}\tilde{q}'}\, d\Gamma^{(0)}_{\tilde{q}\to q\tilde{\chi}_1^0}\, d\Gamma^{(0)}_{\tilde{q}'\to q'\tilde{\chi}_1^0}\right]$$

NLO in NWA







factorizable corrections

Formal expansion in α_s:

Born

$$d\sigma^{(0+1)}_{\mathrm{NWA}}(pp \to \tilde{q}\tilde{q}' \to q\tilde{\chi}_1^0 q'\tilde{\chi}_1^0(+X)) = \frac{1}{\Gamma^{(0)}_{\tilde{q}}\Gamma^{(0)}_{\tilde{q}'}}\Big[d\sigma^{(0)}_{pp\to\tilde{q}\tilde{q}'}\, d\Gamma^{(0)}_{\tilde{q}\to q\tilde{\chi}_1^0}\, d\Gamma^{(0)}_{\tilde{q}'\to q'\tilde{\chi}_1^0}\left(1 - \frac{\Gamma^{(1)}_{\tilde{q}}}{\Gamma^{(0)}_{\tilde{q}}} - \frac{\Gamma^{(1)}_{\tilde{q}'}}{\Gamma^{(0)}_{\tilde{q}'}}\right)$$

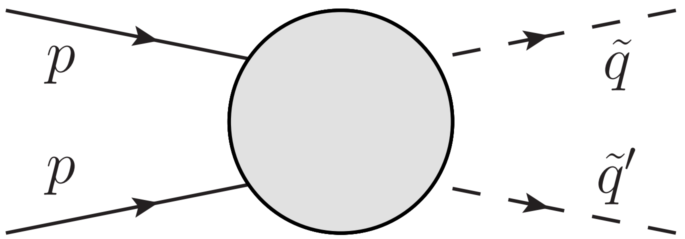
NLO decay $$+d\sigma^{(0)}_{pp\to\tilde{q}\tilde{q}'}\, d\Gamma^{(1)}_{\tilde{q}\to q\tilde{\chi}_1^0}\, d\Gamma^{(0)}_{\tilde{q}'\to q'\tilde{\chi}_1^0} + d\sigma^{(0)}_{pp\to\tilde{q}\tilde{q}'}\, d\Gamma^{(0)}_{\tilde{q}\to q\tilde{\chi}_1^0}\, d\Gamma^{(1)}_{\tilde{q}'\to q'\tilde{\chi}_1^0}$$

NLO production $$+d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'}\, d\Gamma^{(0)}_{\tilde{q}\to q\tilde{\chi}_1^0}\, d\Gamma^{(0)}_{\tilde{q}'\to q'\tilde{\chi}_1^0}\Big]$$

“master formula”

NLO production

For every chirality and flavour configuration:

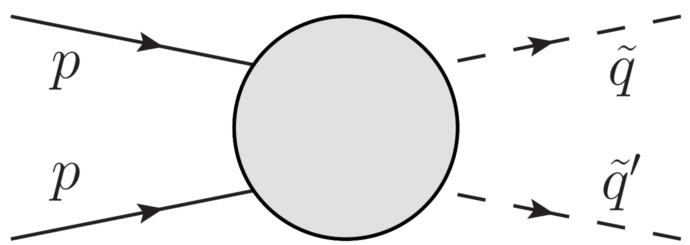


$$d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'(+X)} = d\sigma^{\text{virtual+soft}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{coll}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{hard}}_{pp\to\tilde{q}\tilde{q}'g} + d\sigma^{\text{real-quark}}_{pp\to\tilde{q}\tilde{q}'\bar{q}^{(\prime)}}$$

Fully differential cross-section.

NLO production

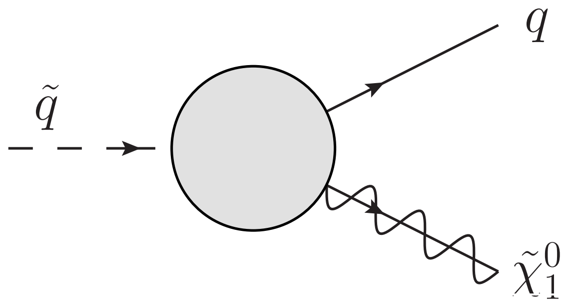
For every chirality and flavour configuration:



$$d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'(+X)} = d\sigma^{\text{virtual+soft}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{coll}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{hard}}_{pp\to\tilde{q}\tilde{q}'g} + d\sigma^{\text{real-quark}}_{pp\to\tilde{q}\tilde{q}'\bar{q}^{(\prime)}}$$

Fully differential cross-section.

NLO decay

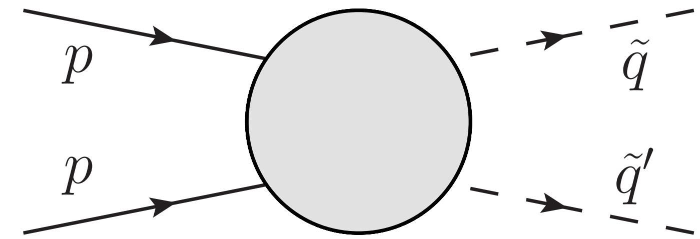


$$d\Gamma^{(1)}_{\tilde{q}\to q\tilde{\chi}_1^0} = d\Gamma^{\text{virtual+soft}}_{\tilde{q}\to q\tilde{\chi}_1^0(g)} + d\Gamma^{\text{coll}}_{\tilde{q}\to q\tilde{\chi}_1^0(g)} + d\Gamma^{\text{hard}}_{\tilde{q}\to q\tilde{\chi}_1^0 g}$$

Fully differential decay.

NLO production

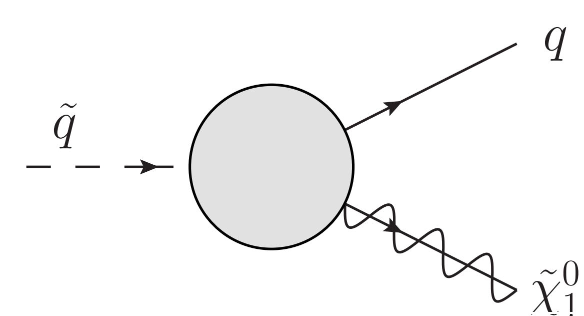
For every chirality and flavour configuration:



$$d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'(+X)} = d\sigma^{\text{virtual+soft}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{coll}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{hard}}_{pp\to\tilde{q}\tilde{q}'g} + d\sigma^{\text{real-quark}}_{pp\to\tilde{q}\tilde{q}'\bar{q}^{(\prime)}}$$

Fully differential cross-section.

NLO decay



$$d\Gamma^{(1)}_{\tilde{q}\to q\tilde{\chi}^0_1} = d\Gamma^{\text{virtual+soft}}_{\tilde{q}\to q\tilde{\chi}^0_1(g)} + d\Gamma^{\text{coll}}_{\tilde{q}\to q\tilde{\chi}^0_1(g)} + d\Gamma^{\text{hard}}_{\tilde{q}\to q\tilde{\chi}^0_1 g}$$

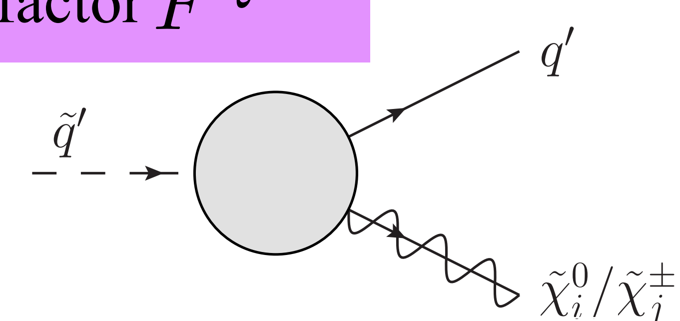
Fully differential decay.

NLO total decay width

$$\Gamma^{(0+1)}_{\tilde{q}\to q\tilde{\chi}^0_j} = \Gamma^{(0)}\left[1 + \frac{4}{3}\frac{\alpha_s}{\pi}F^{QCD}\left(\frac{m_{\tilde{\chi}^0_j}}{m_{\tilde{q}}}, \frac{m_{\tilde{g}}}{m_{\tilde{g}}}\right)\right]$$

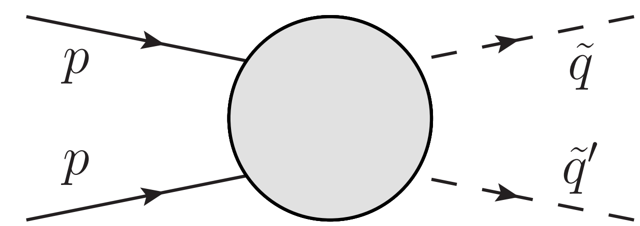
Universal form factor F^{QCD}

$$\sum_{\chi^0_i,\chi^\pm_j}$$

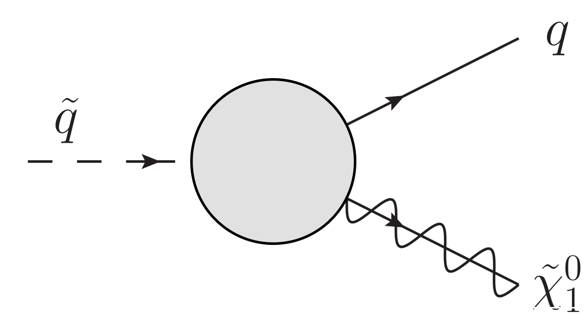


COMBINATION

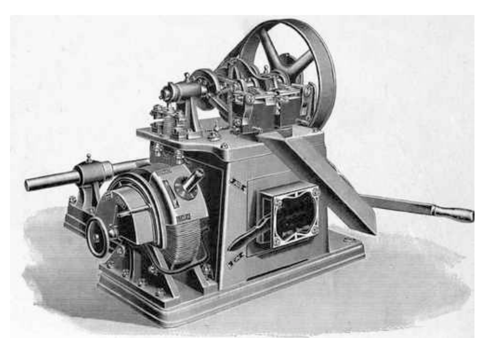
For all different combinations of light flavours and chiralities, weighted events for squark-squark production are produced in the LAB frame.



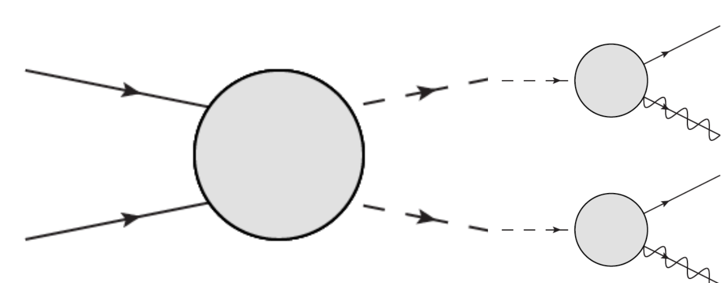
Weighted decay events are generated in the respective squark rest-frame.



boost of decay events + “master formula”



Fully differential distributions of factorizable NLO contributions in NWA.



NUMERICAL RESULTS

We cluster partons into jets with anti-kT algorithm, R=0.4 (ATLAS) and R=0.5 (CMS) and we always select jets according to:

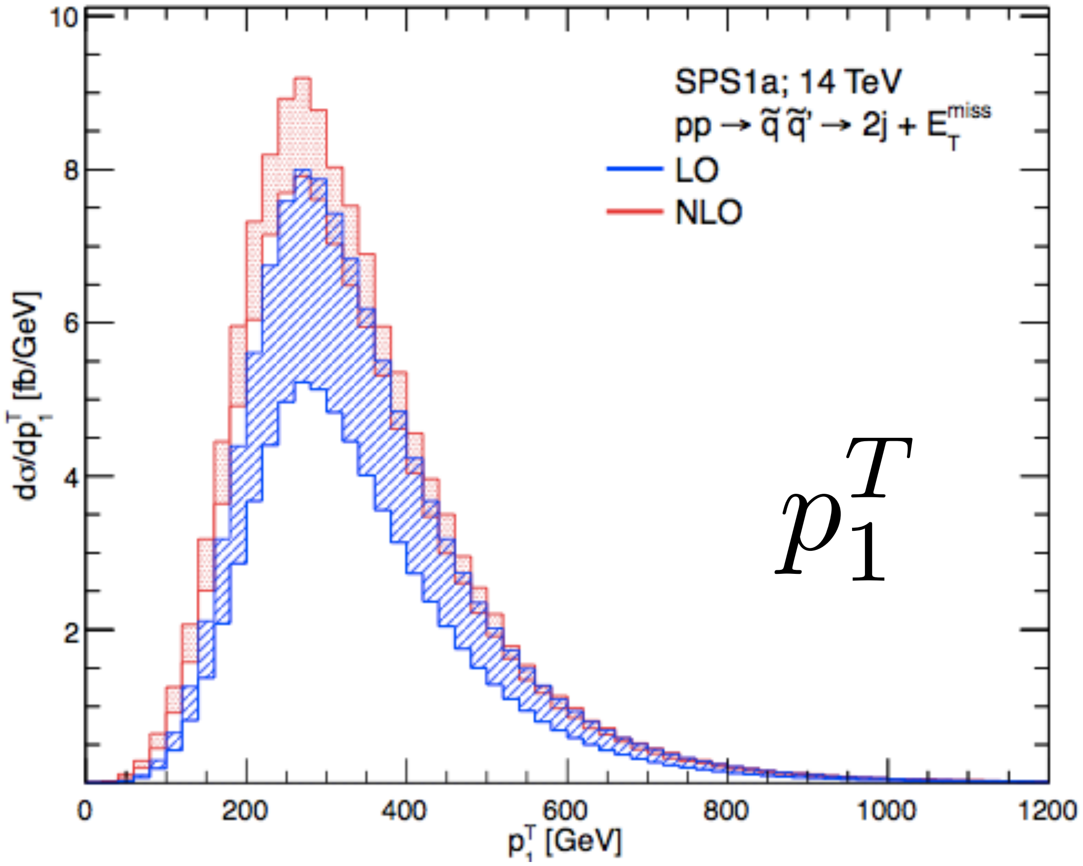
$$p^{\mathrm{T}}_{j_{1/2}} > 20\ \mathrm{GeV} \quad |\eta_j| < 2.8,$$
$$p^{\mathrm{T}}_{j_i} > 50\ \mathrm{GeV} \quad |\eta_j| < 3.0\ \text{(for CMS observables)}$$

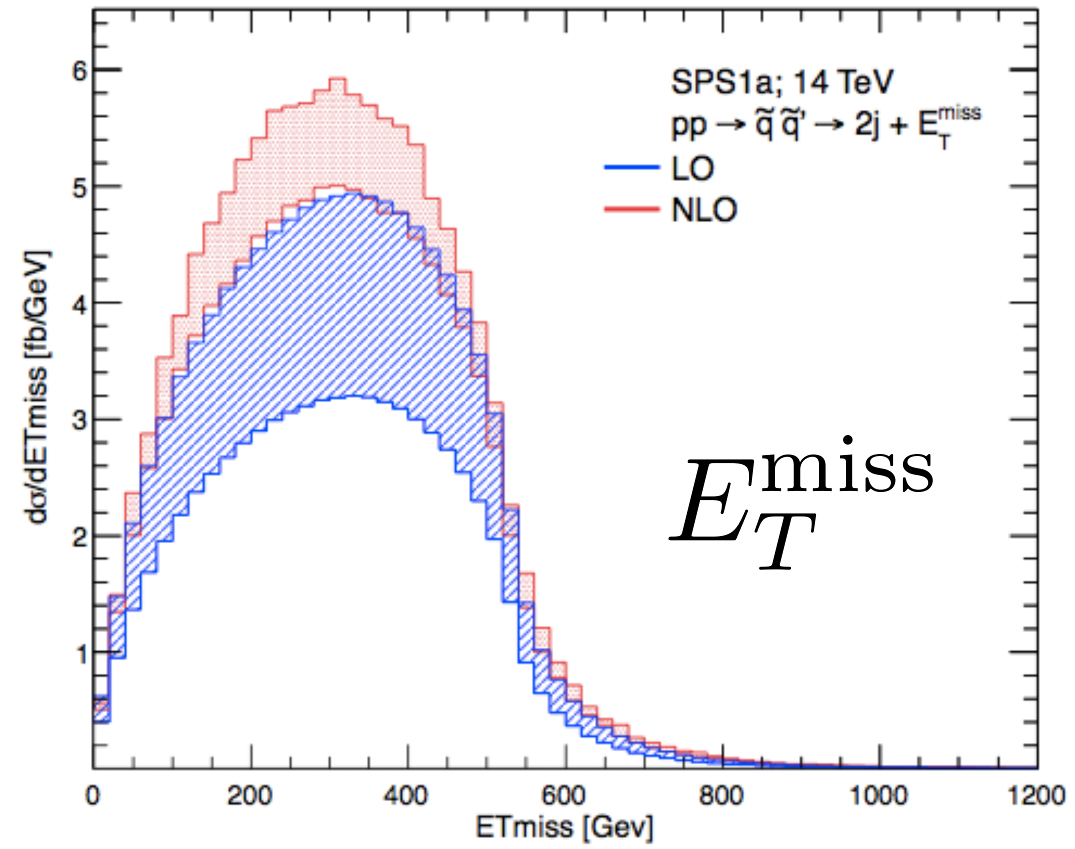
SPS1a (14 TeV)

Scale variation: **$\mu_f = \mu_r$ =(m/2,m,2m)**, m: average squark mass

SPS1a	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}^0_1$
mass (GeV)	563.6	546.7	569.0	546.6	608.5	97.0

(PDFs: CTEQ6.6 both for LO and NLO)

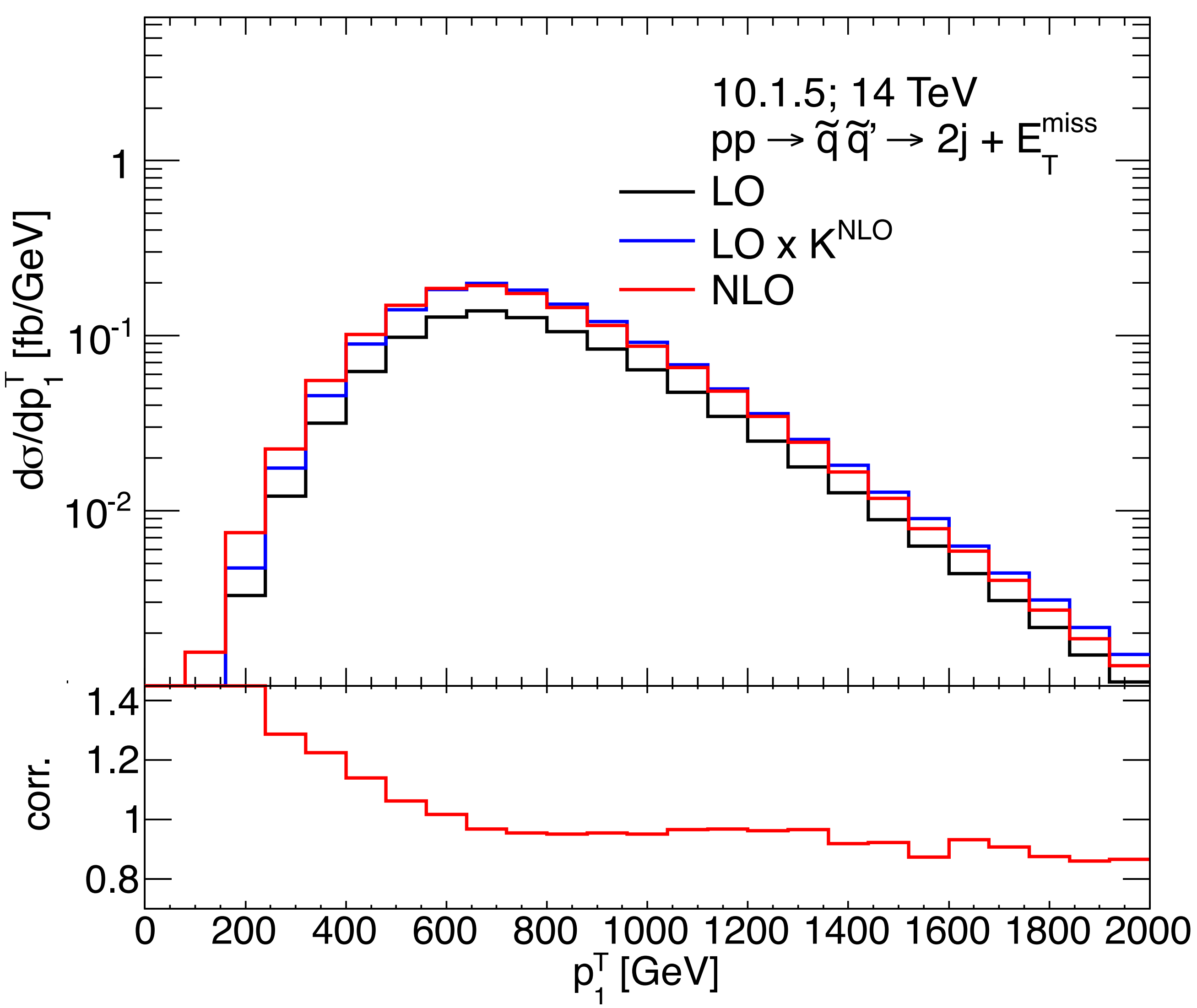


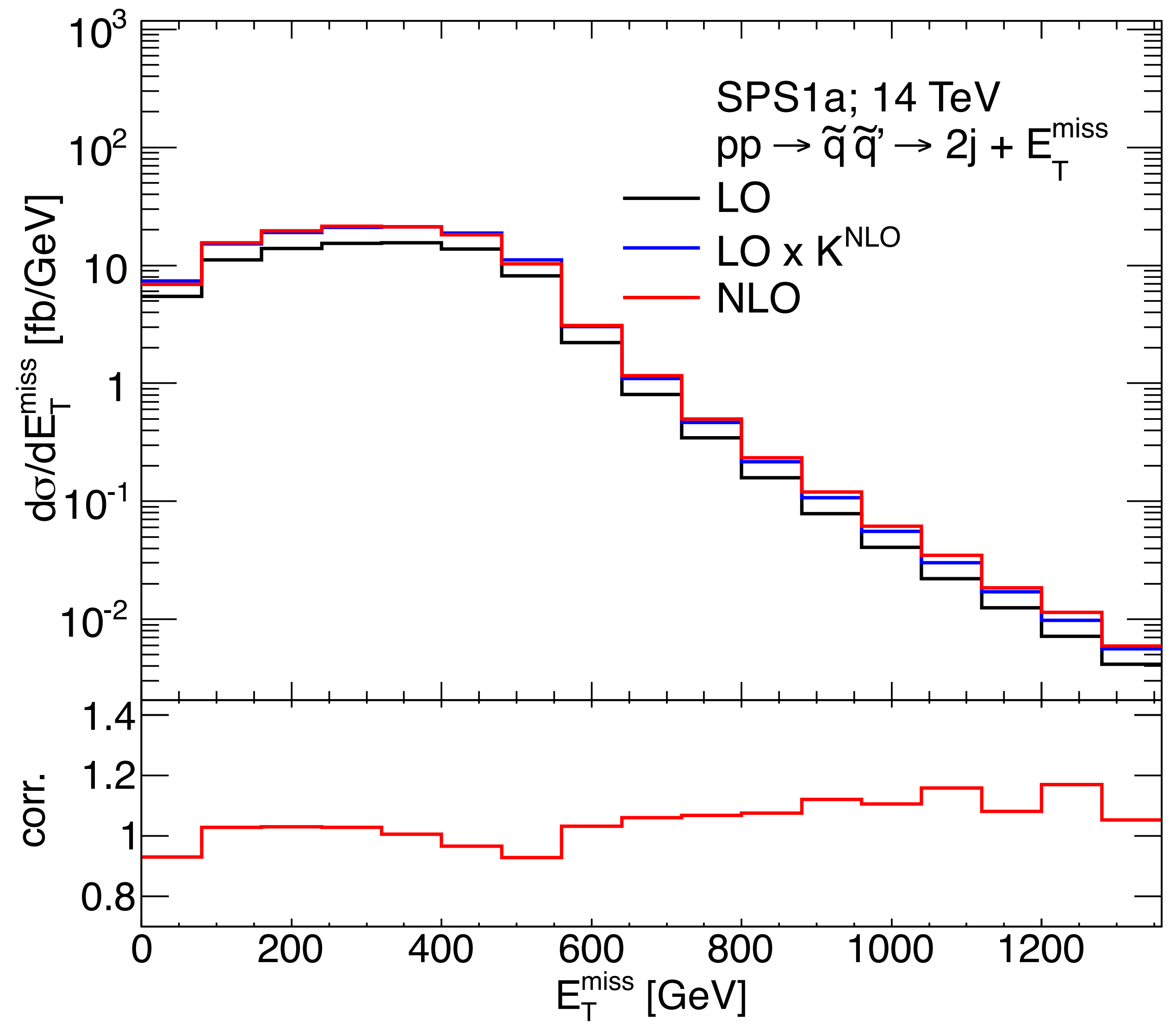


CMSSM 10.1.5 (14 TeV)

Comparison between NLO and LO rescaled by global K-factor: corrections purely in the **shapes**

10.1.5	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
mass (GeV)	1437.7	1382.3	1439.7	1376.9	1568.6	291.3





$$p_1^T \qquad E_T^{\text{miss}}$$

CMSSM 10.1.5 (14 TeV)
Comparison between NLO and LO rescaled by global K-factor:
corrections purely in the **shapes**

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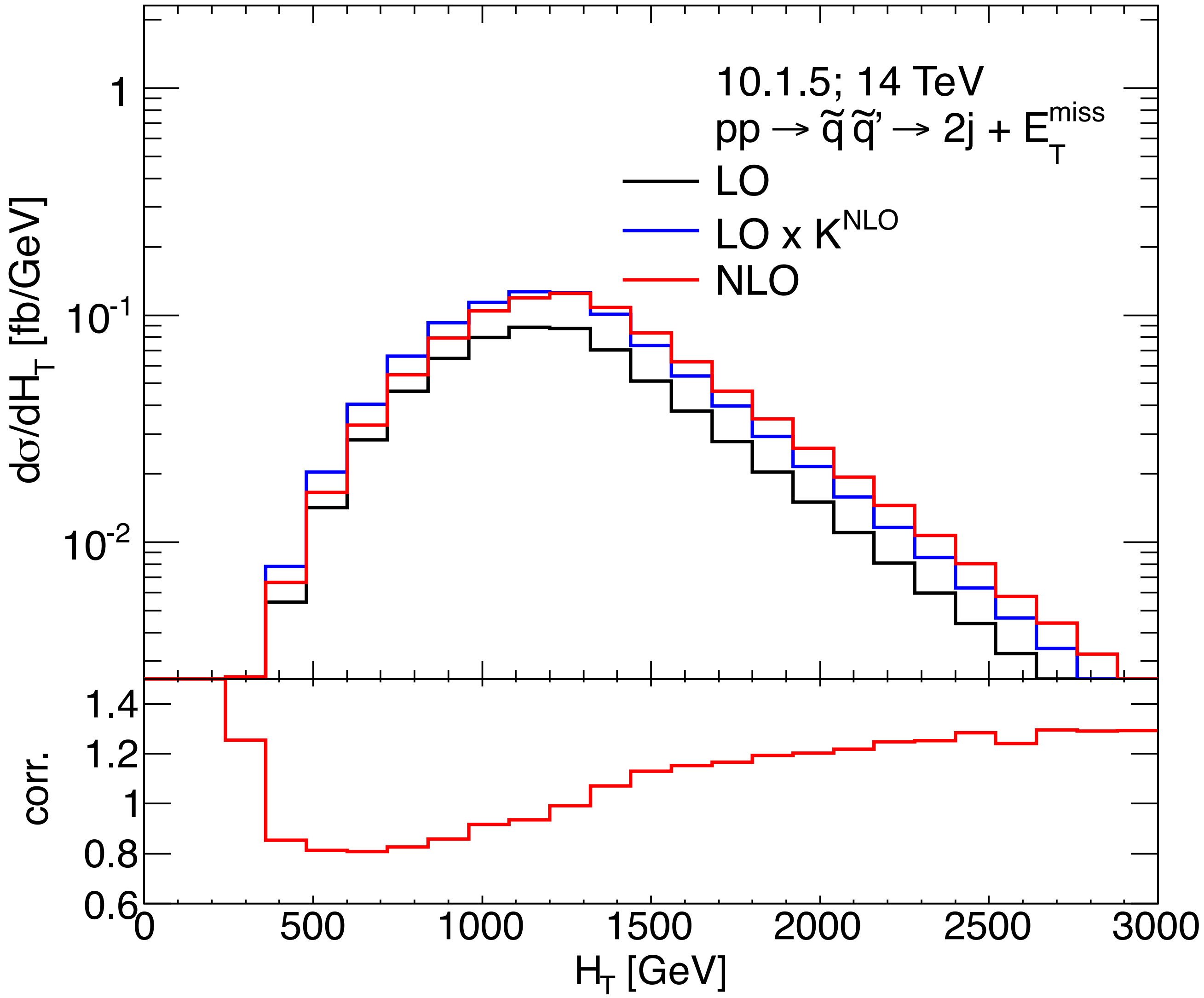

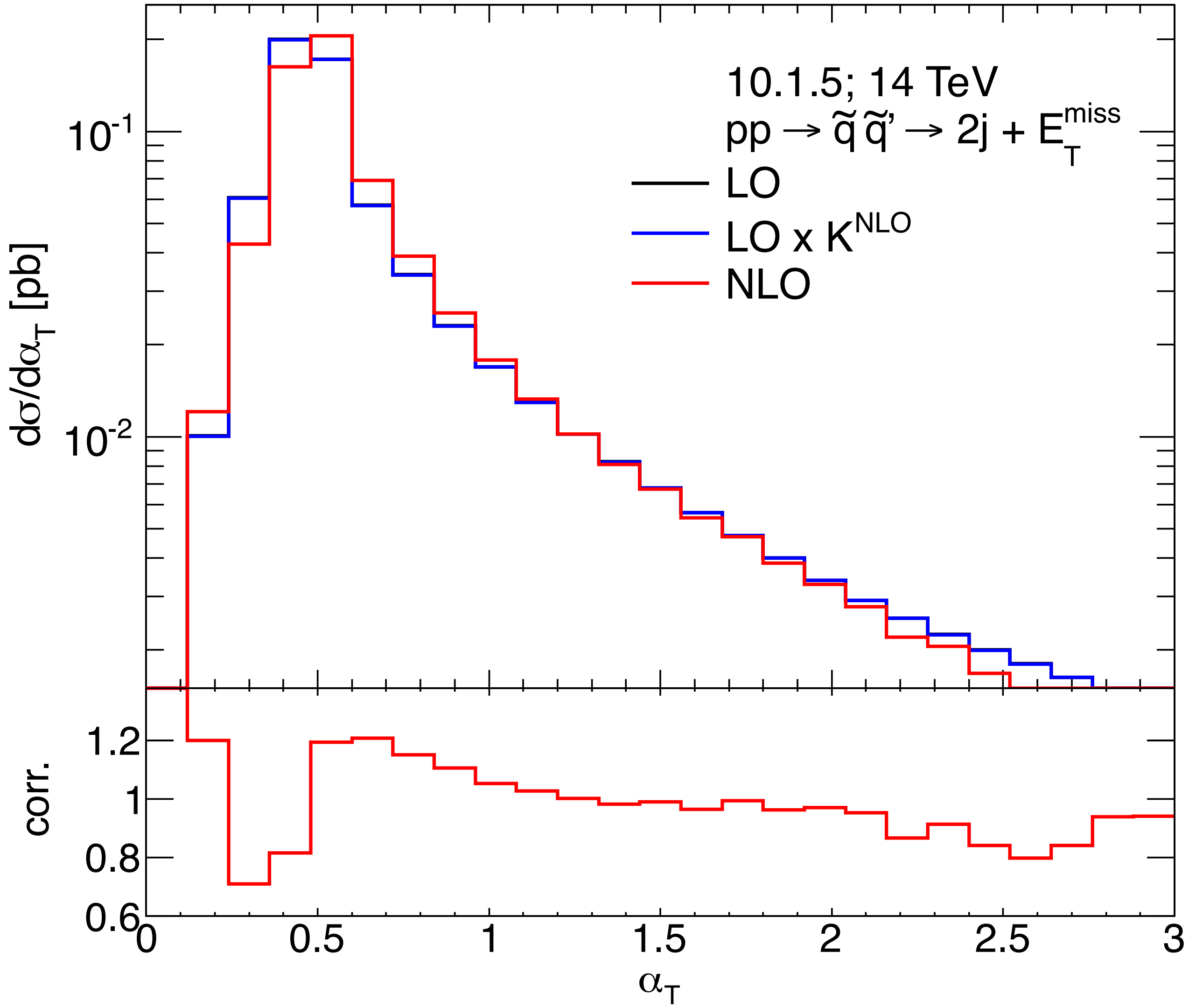

$$H_T = \sum_{i=1,2(,3)} p_i^{\mathrm{T}}$$

$$\alpha_{\mathrm{T}} = E_{\mathrm{T}}^{j_2} / M_{\mathrm{T}}$$

CMSSM 10.1.5 (14 TeV)
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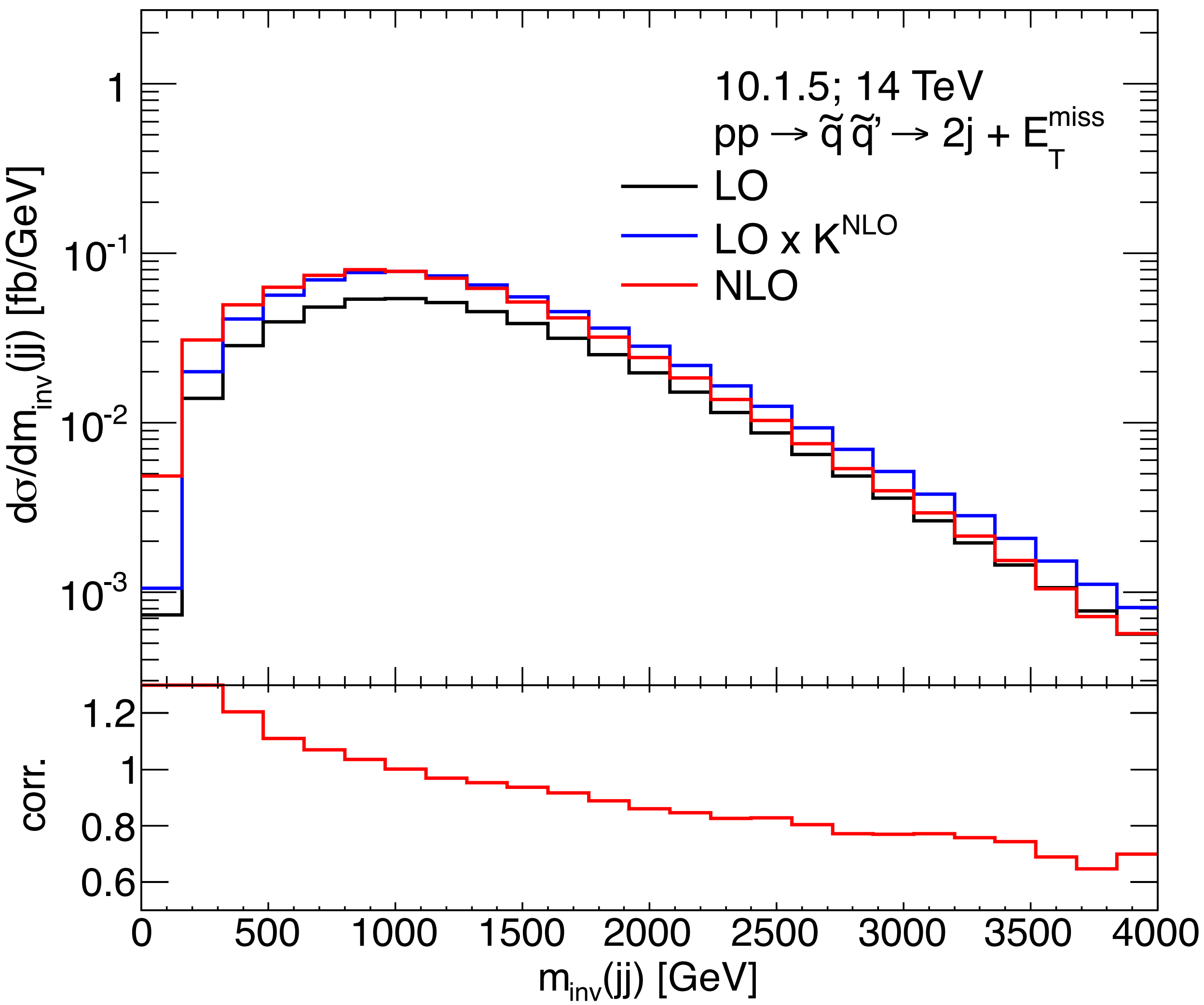
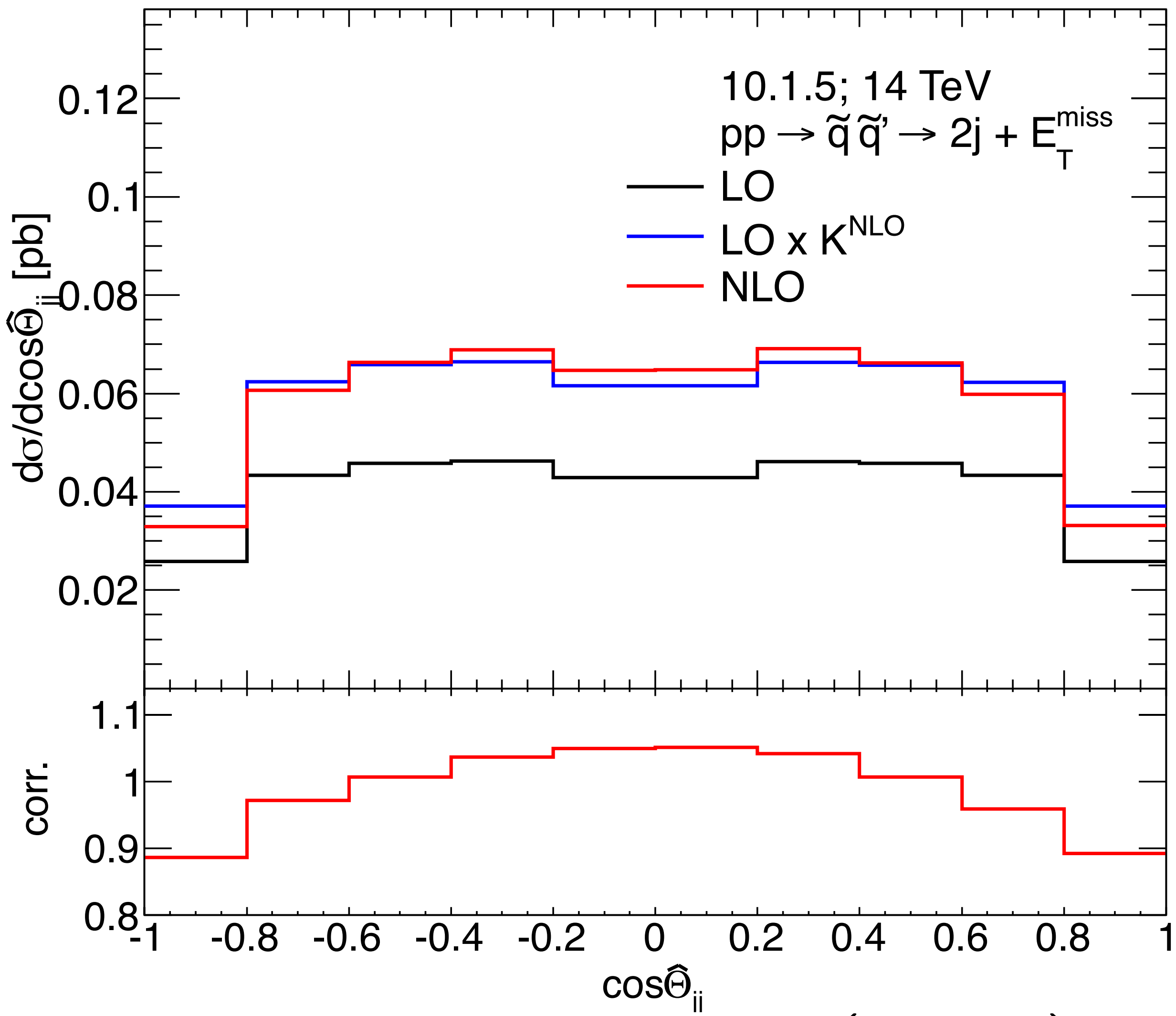


$$m_{\rm inv}(jj)$$

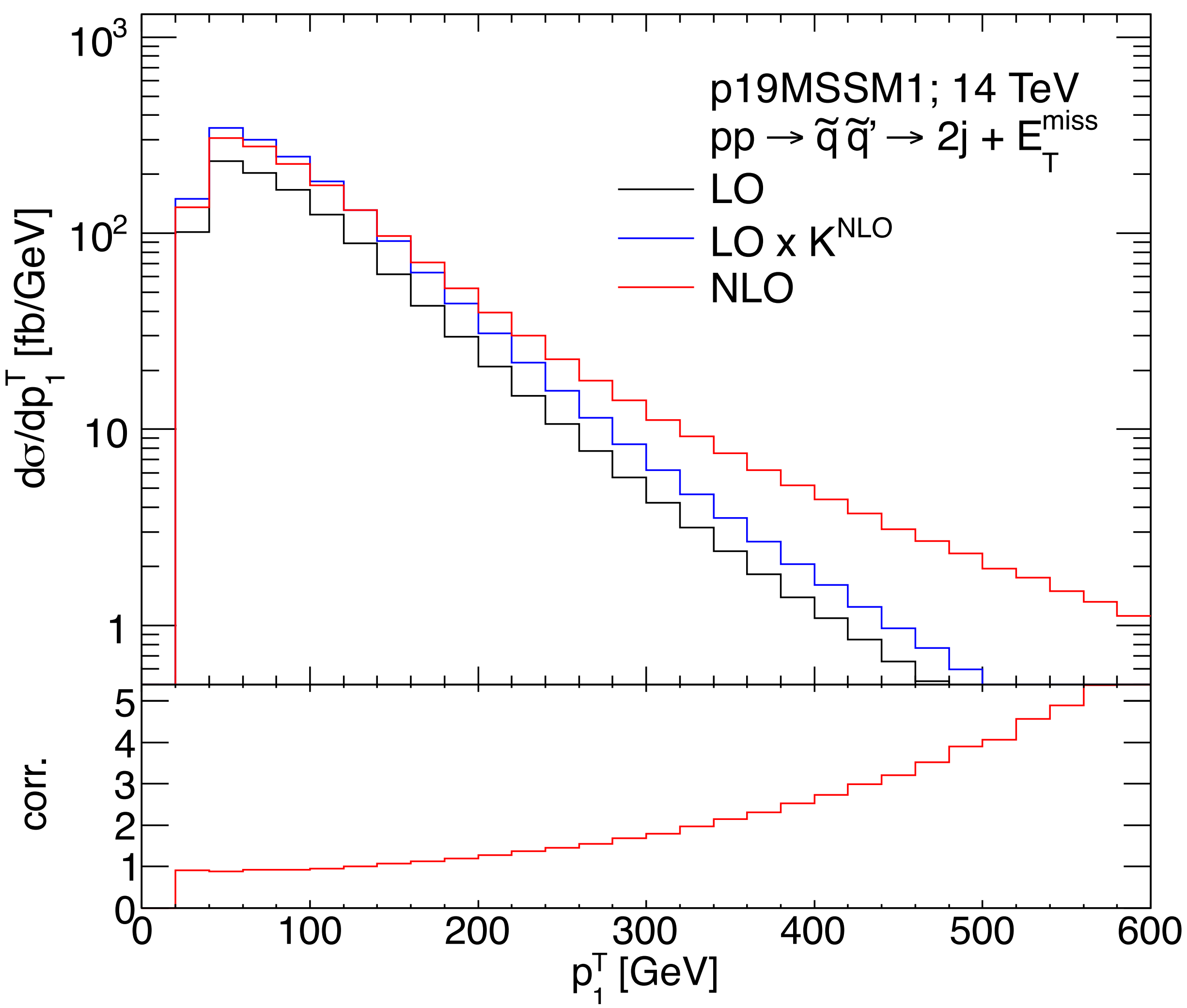


$$\cos\hat{\Theta} = \tanh\left(\frac{\Delta\eta_{jj}}{2}\right)$$

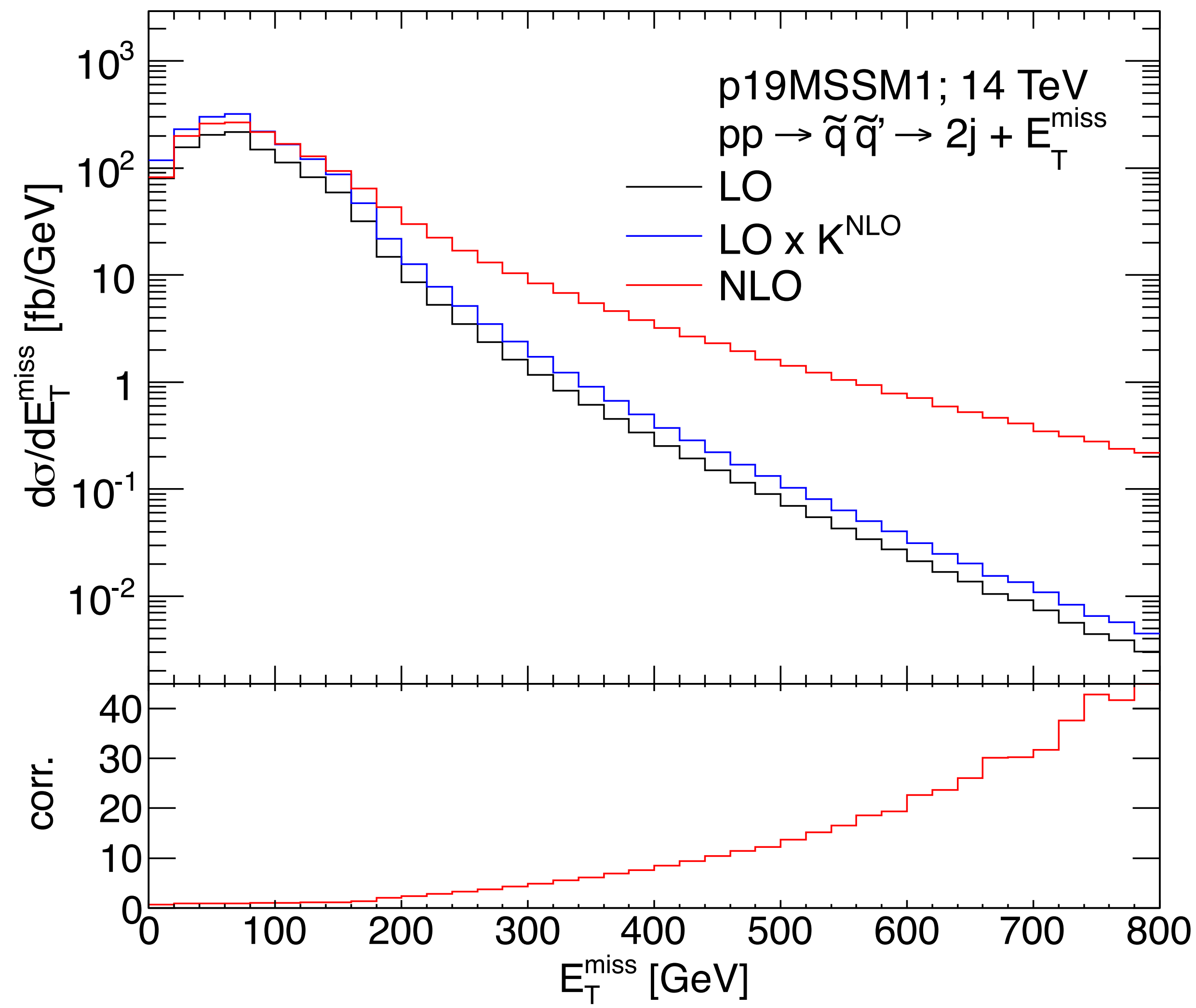
p19MSSM1A (14 TeV)

Comparison between NLO and LO rescaled by global K-factor:
corrections purely in the **shapes**

p19MSSM1	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
mass (GeV)	339.6	394.8	348.3	392.7	414.7	299.1



p_1^T



$E_T^{\rm miss}$

see also: Plehn, Rainwater, Skands '07;
Alwall, de Visscher, Maltoni '08

Effect on cut-and-count searches performed by **ATLAS**.

Signal Region:

$$p^{\mathrm{T}}_{j_1} > 130\ \mathrm{GeV},\ p^{\mathrm{T}}_{j_2} > 40\ \mathrm{GeV},\ |\eta_{j_{1/2}}| < 2.8,\ \Delta\phi(j_{1/2}, \vec{\not{E}}_T) > 0.4$$

$$m_{\mathrm{eff}} > 1\ \mathrm{TeV},\ \not{E}_T/m_{\mathrm{eff}} > 0.3$$

benchmarkpoint	**Energy [TeV]**	$N^{(0)}_{\mathrm{ATLAS}}$	$N^{(0+1)}_{\mathrm{ATLAS}}$	$K_{N_{\mathrm{ATLAS}}}$	$K_{pp\to\tilde{q}\tilde{q}'}$
SPS1a	7	0.066 pb	0.083 pb	1.26	1.37
	8	0.097 pb	0.121 pb	1.25	1.35
	14	0.347 pb	0.424 pb	1.22	1.28
10.1.5	7	0.313 fb	0.503 fb	1.61	1.57
	8	0.861 fb	1.344 fb	1.56	1.52
	14	13.82 fb	19.77 fb	1.43	1.40
p19MSSM1	7	0.140 fb	20.76 fb	~ 150	1.40
	8	0.339 fb	37.96 fb	~ 110	1.39
	14	0.0044 pb	0.264 pb	~ 60	1.34

Effect on cut-and-count searches performed by **CMS**.

Signal Region:

$$p^{\mathrm{T}}_{j_{1/2}} > 100\ \mathrm{GeV},\ |\eta_{j_1}| < 2.5,\ |\eta_{j_2}| < 3.0,$$

$$H_T > 350\ \mathrm{GeV},\ \not{H}_T/\not{E}_T < 1.25,\ \alpha_T > 0.55,$$

benchmarkpoint	**Energy [TeV]**	$N^{(0)}_{\mathrm{CMS}}$	$N^{(0+1)}_{\mathrm{CMS}}$	$K_{N_{\mathrm{CMS}}}$	$K_{pp\to\tilde{q}\tilde{q}'}$
SPS1a	7	0.112 pb	0.141 pb	1.26	1.37
	8	0.157 pb	0.197 pb	1.25	1.35
	14	0.488 pb	0.614 pb	1.26	1.28
10.1.5	7	0.201 pb	0.261 pb	1.30	1.57
	8	0.542 fb	0.674 fb	1.24	1.52
	14	8.129 fb	8.884 fb	1.09	1.40
p19MSSM1	7	10^{-6} pb	0.095 pb	$\mathcal{O}(10^4)$	1.40
	8	10^{-6} pb	0.151 pb	$\mathcal{O}(10^4)$	1.39
	14	$2\cdot 10^{-5}$ pb	0.687 pb	$\mathcal{O}(10^4)$	1.34

CONCLUSION

We provide a consistent fully differential calculation of factorizable NLO QCD corrections in NWA for squark-squark production and decay.

These NLO corrections are important for precise description of physical observables and thus for setting accurate limits and even more for future parameter determination.

In particular cases they can be essential for a realistic description.

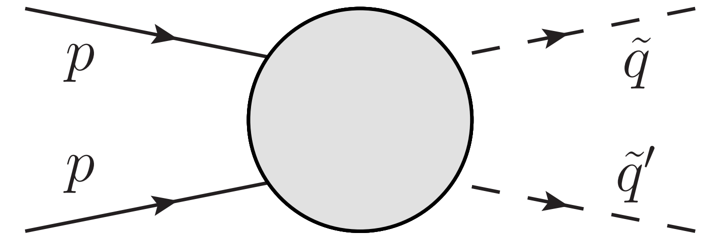
OUTLOOK

Study of further experimental signatures (monojets, attached EW decay chains) under way.

Study of off-shell and non-factorizable NLO effects also under way.

Fully differential NLO QCD predictions of combined production and decay for all squark/gluino channels are desirable (matched to a NLO PS).

Thank you for your attention.



All counterterms, but the one for the QCD coupling $\delta g_s = g_s \delta Z_{g_s}$ are renormalized according to the **on-shell** scheme.

Choice of scheme for the renormalization of the QCD coupling is fixed by definition of α_s in the PDF distributions: $\overline{MS}$ + 5 flavour scheme.

$$\delta Z_{g_s} = -\frac{\alpha_s}{4\pi}\left[\Delta\frac{\beta_0}{2} + \frac{1}{3}\log\frac{m_t^2}{\mu_F^2} + \log\frac{m_{\tilde{g}}^2}{\mu_F^2} + \frac{1}{12}\sum_{\tilde{q}}\log\frac{m_{\tilde{q}}^2}{\mu_F^2}\right]$$

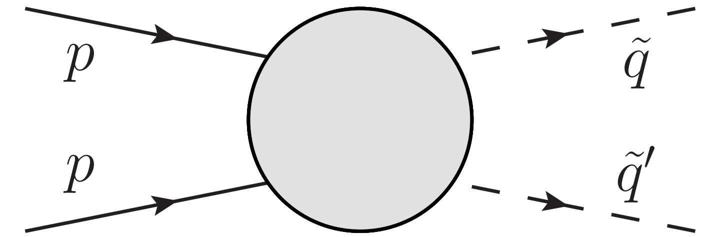
Using $\overline{MS}$ and thus Dim. Reg. breaks supersymmetric Slavnov-Taylor identity, that relates the QCD coupling in the qqg QCD vertex and the $\hat{g}_s$ coupling in the $q\tilde{q}\tilde{g}$ SQCD vertex.

Can be restored:

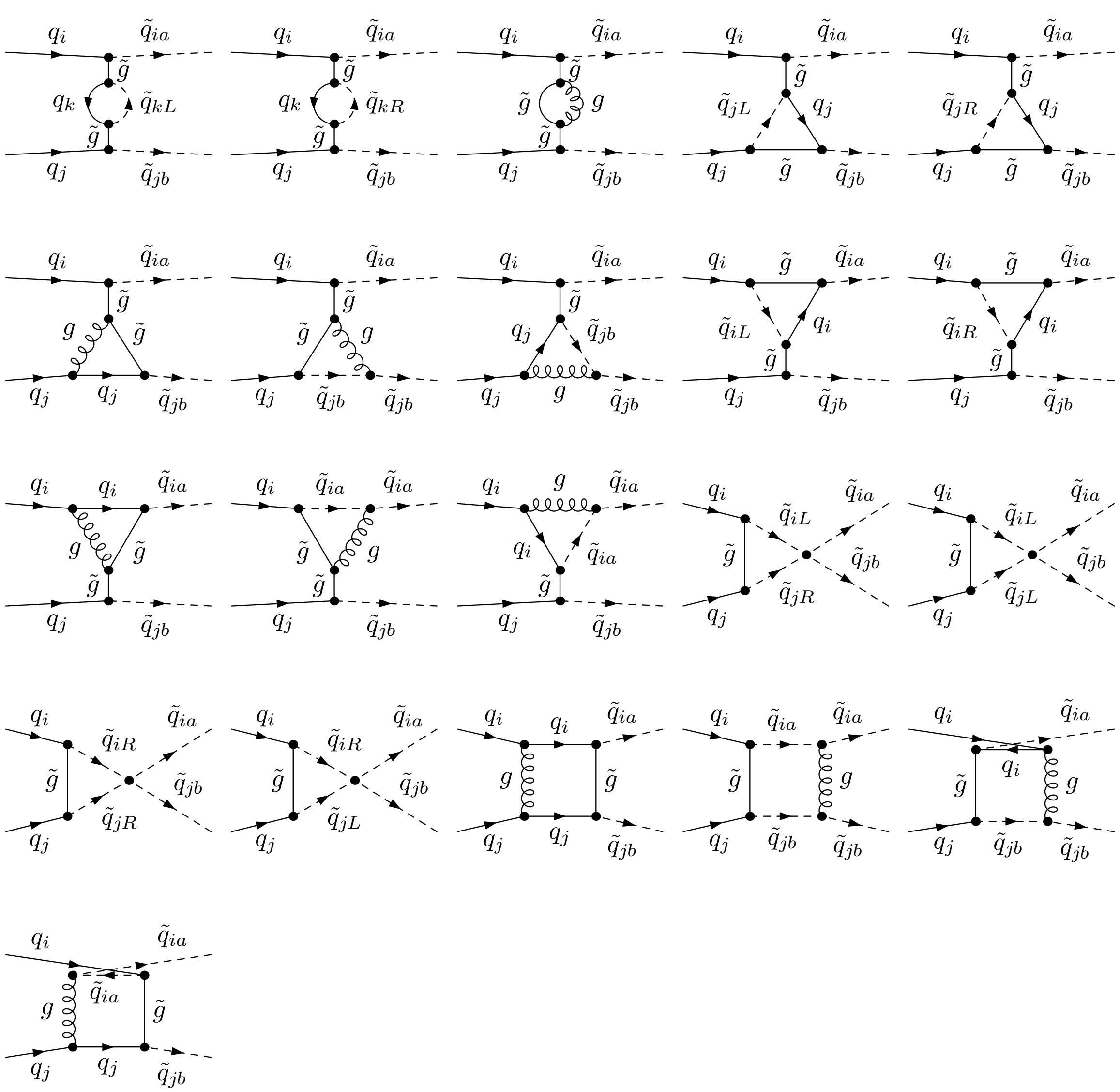
$$\delta Z_{\hat{g}_s} = \delta Z_{g_s} + \frac{\alpha_s}{3\pi}$$

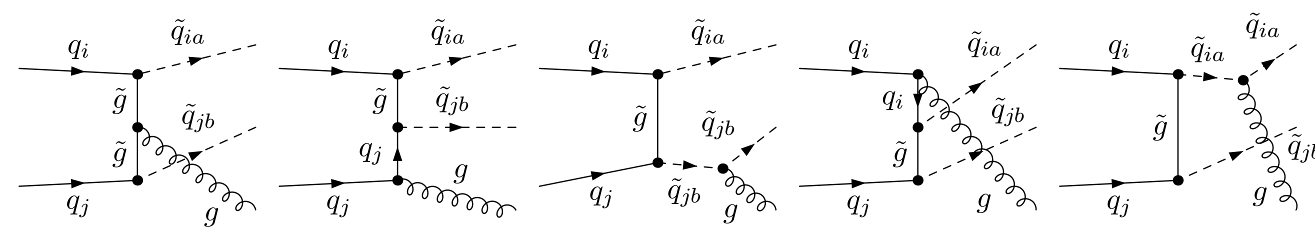
[Beenakker et al. '96; Hollik, Stöckinger '01]

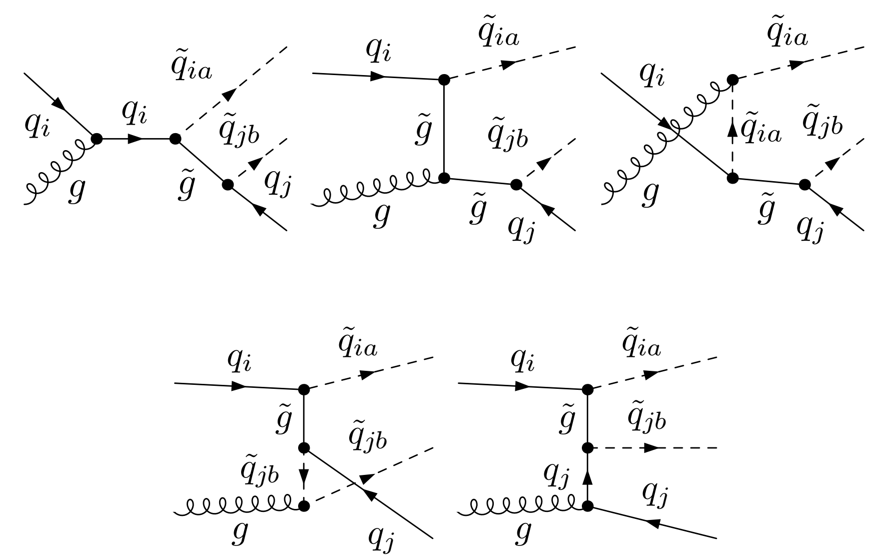
NLO production



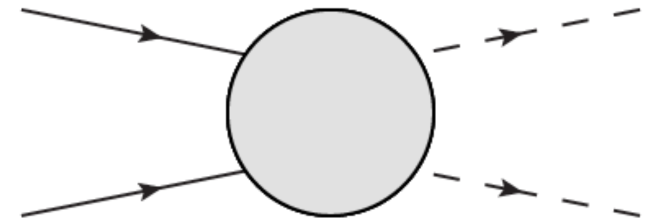
$$d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'(+X)} = d\sigma^{\text{virtual+soft}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{coll}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{hard}}_{pp\to\tilde{q}\tilde{q}'g} + d\sigma^{\text{real-quark}}_{pp\to\tilde{q}\tilde{q}'\bar{q}^{(\prime)}}$$

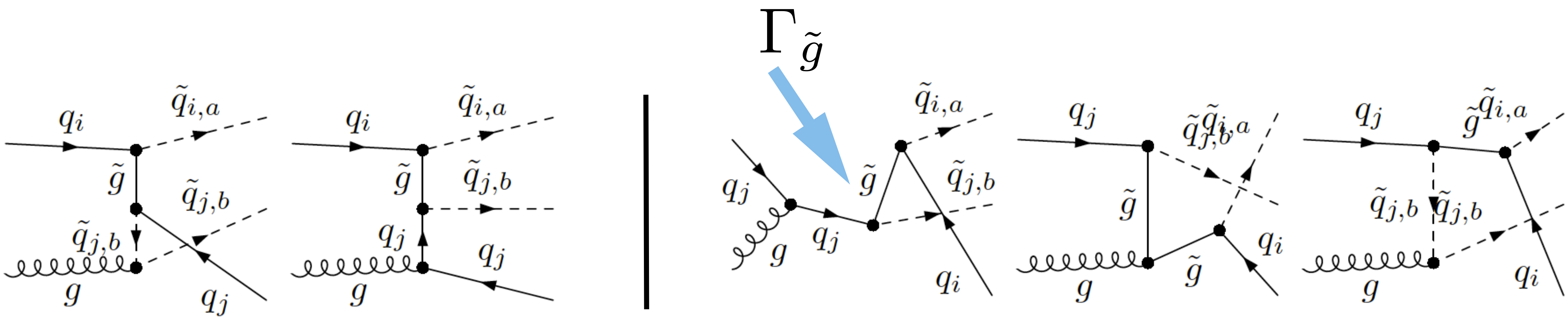






Real quark radiation





non-resonant | resonant

$$d\hat\sigma(q_i g \to \tilde q_{i,a}\tilde q_{i,b} q_i) = \frac{1}{\Phi}\left[\overline{|\mathcal{M}_{\text{nonres}}|}^2 + 2\text{Re}\overline{(\mathcal{M}_{\text{ nonres}}\mathcal{M}^*_{res})}\right]$$

“Prospino scheme” changes

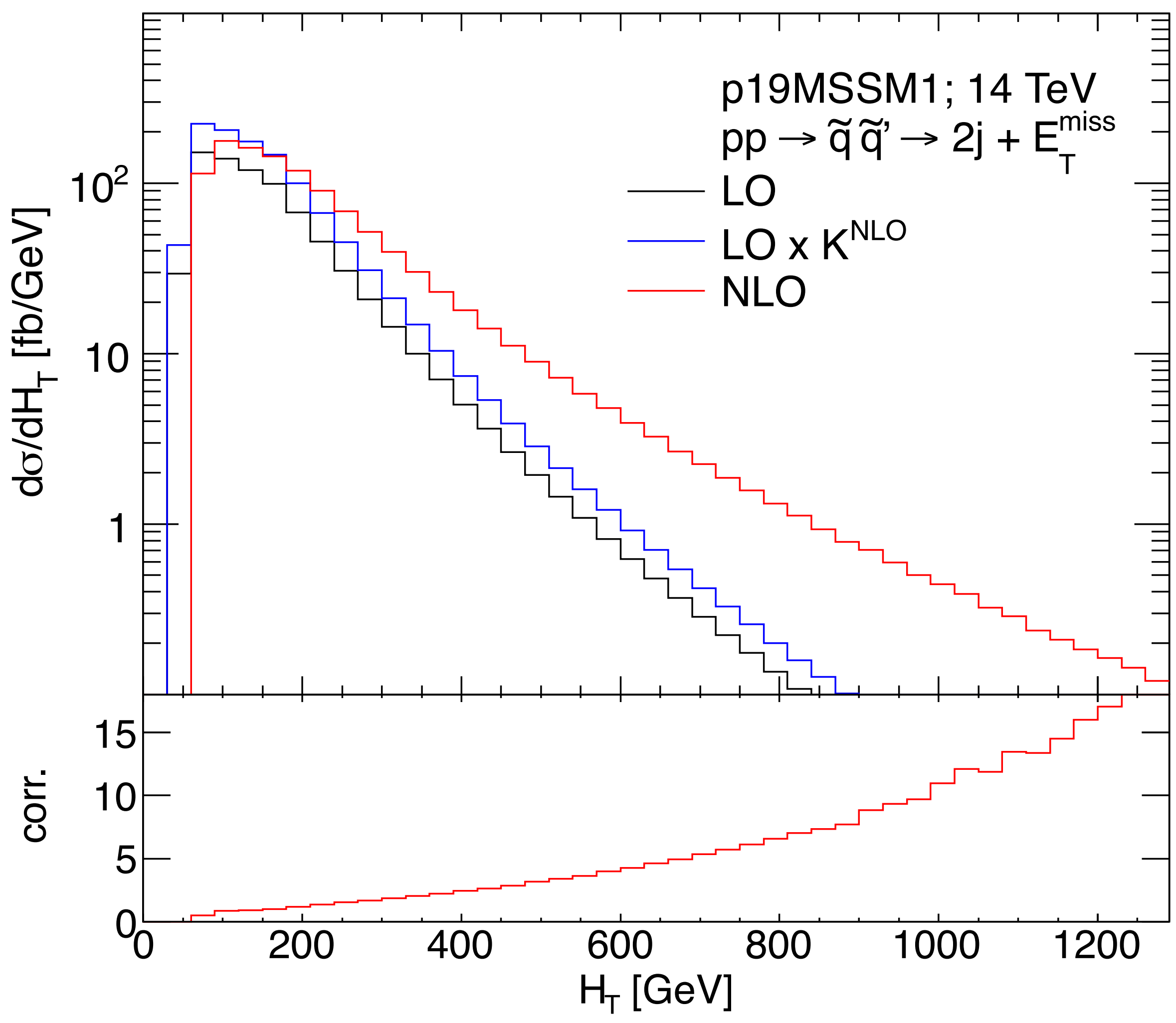
[Binoth et. al.; ’11]

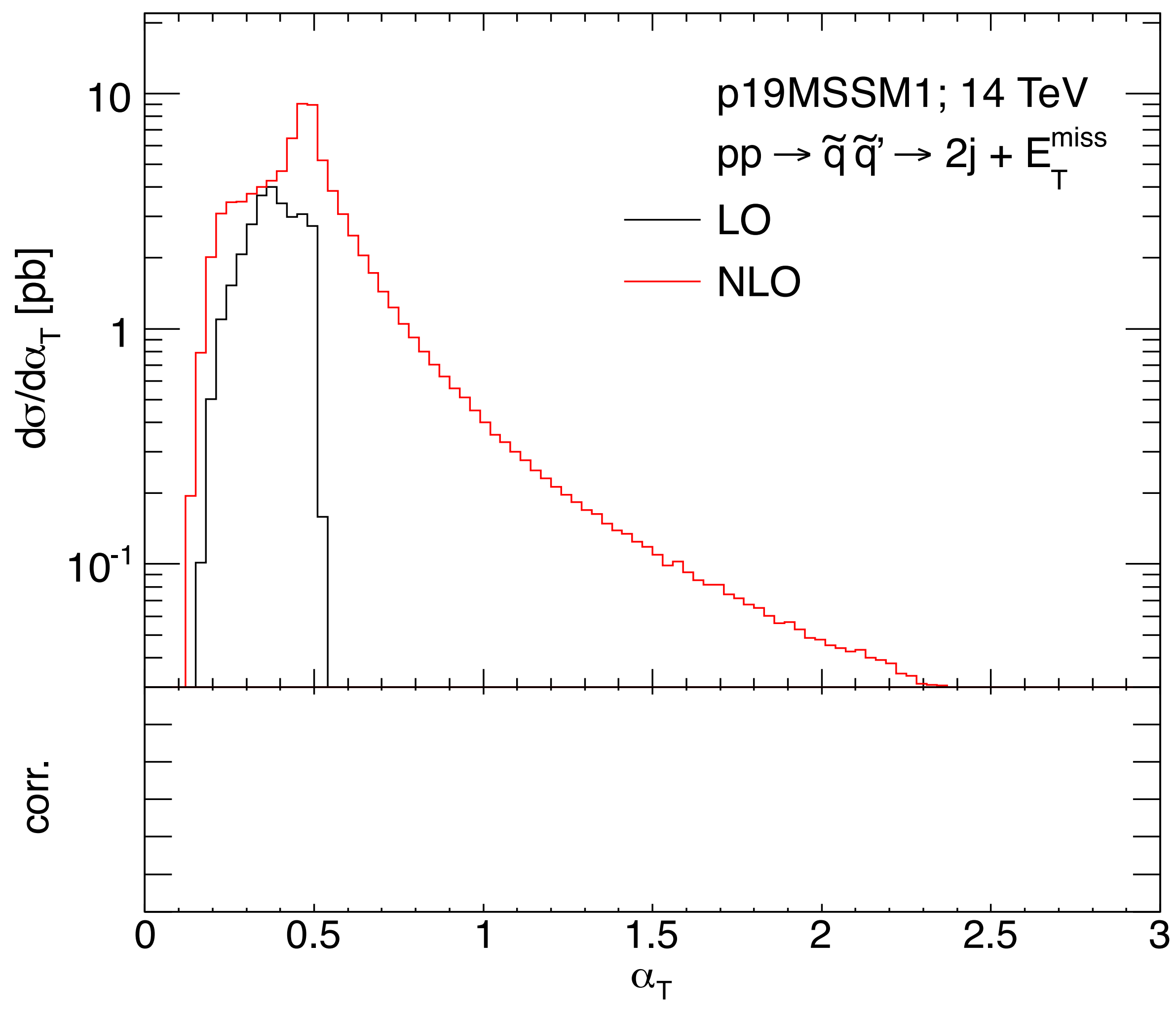
$$\frac{|\mathcal{M}|^2(s_{q\tilde q})}{(s_{q\tilde q}-m_{\tilde g}^2)^2+m_{\tilde g}^2\Gamma_{\tilde g}^2} \longrightarrow \frac{|\mathcal{M}|^2(s_{q\tilde q})}{(s_{q\tilde q}-m_{\tilde g}^2)^2+m_{\tilde g}^2\Gamma_{\tilde g}^2} - \frac{|\mathcal{M}|^2(m_{\tilde g}^2)}{(s_{q\tilde q}-m_{\tilde g}^2)^2+m_{\tilde g}^2\Gamma_{\tilde g}^2}$$

and usually: $\Gamma \to 0$ numerically.

p19MSSM1A (14 TeV)
Comparison between NLO and LO rescaled by global K-factor: corrections purely in the **shapes**

p19MSSM1	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
mass (GeV)	339.6	394.8	348.3	392.7	414.7	299.1





$$H_T = \sum_{i=1,2(,3)} p_i^{\mathrm{T}}$$

$$\alpha_{\mathrm{T}} = E_{\mathrm{T}}^{j_2} / M_{\mathrm{T}}$$