Combining squark production and decay at NLO QCD

in collaboration with Wolfgang Hollik and Davide Pagani

MAX-PLANCK-GESELLSCHAFT

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

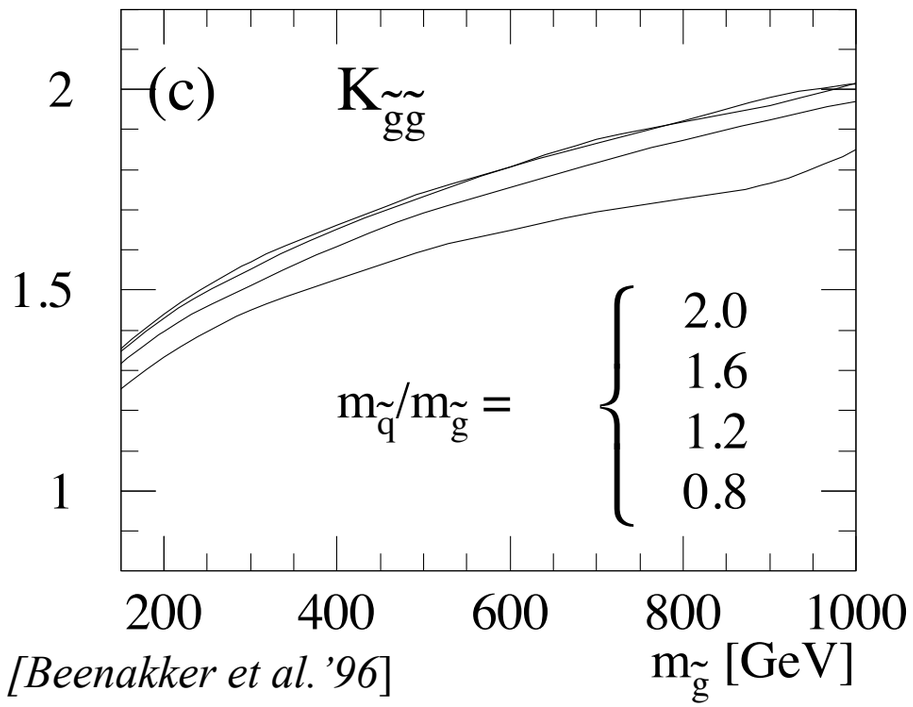
Jonas M. Lindert

Max Planck Institut für Physik, München

DPG-Frühjahrstagung 2013
Dresden, 6 March 2013

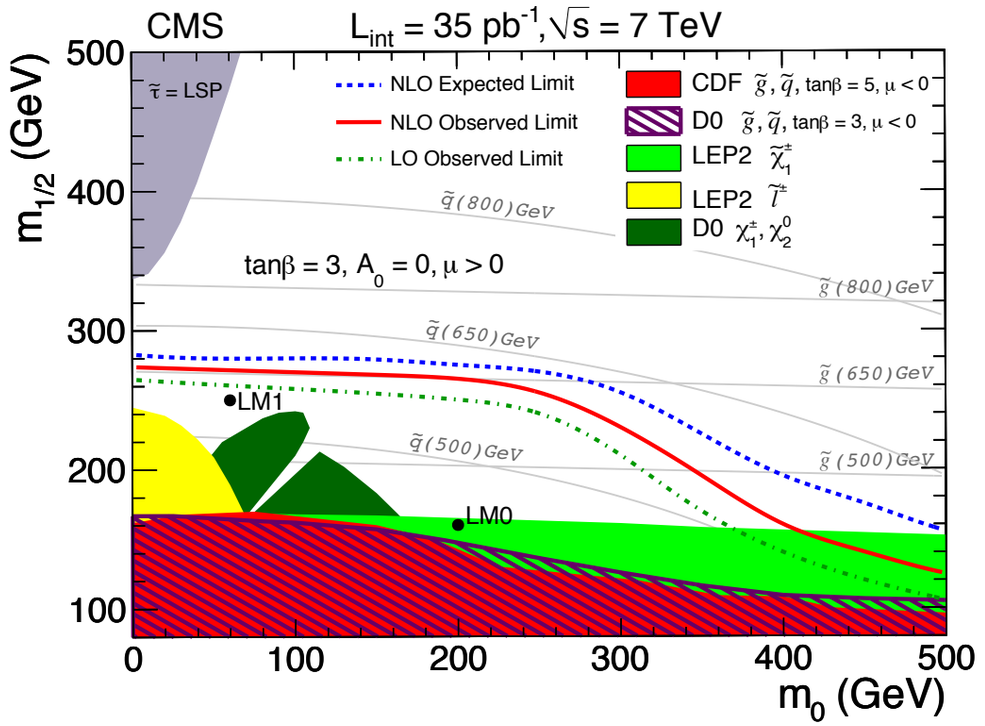
Why Higher Orders?

Corrections can be large!

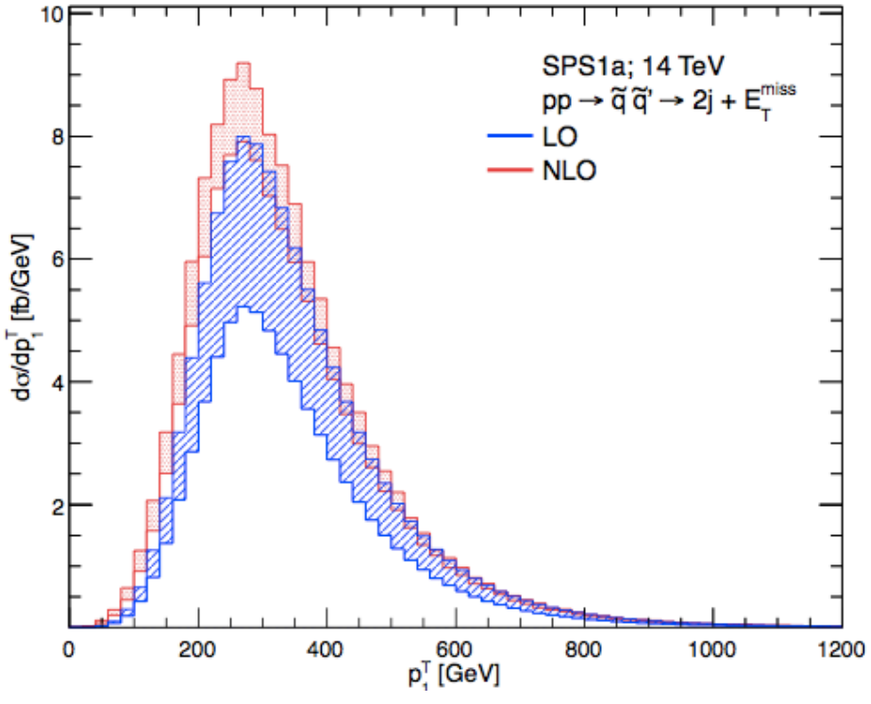


[Beenakker et al.'96]

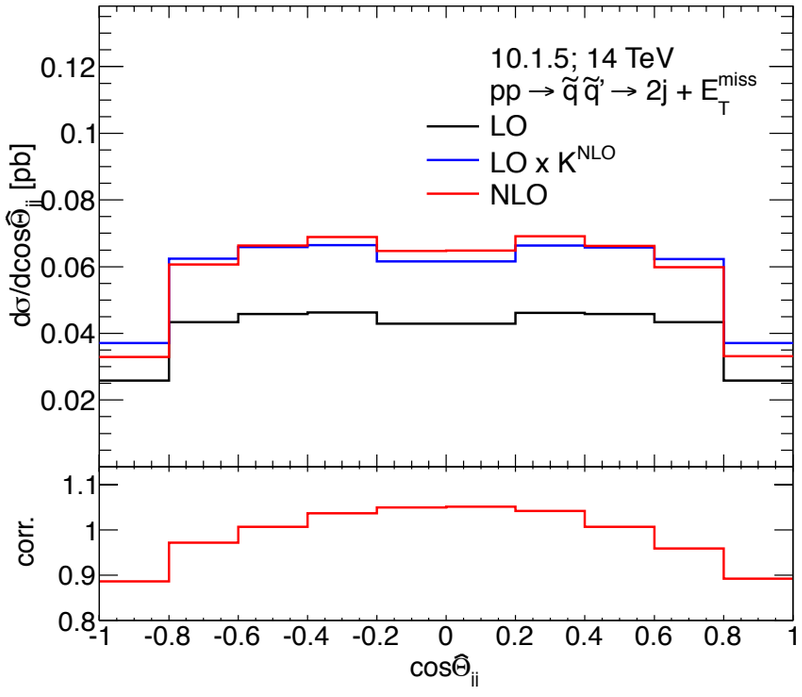
Accurate exclusion limits.



Study & reduce theoretical uncertainties.

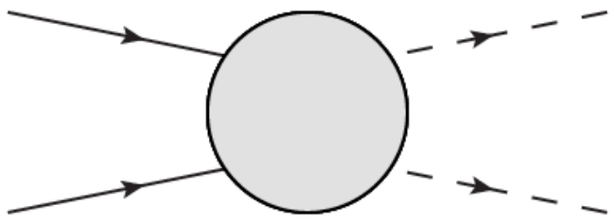


Necessary for parameter determination.



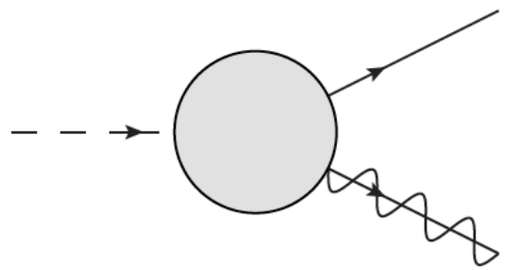
SQUARKS AT THE LHC

Production



Squark-Squark production:
LO QCD: *Baer, Tata '85*
NLO QCD: *Beenakker et al.'96*
Tool: PROSPINO2 *(*inclusive*), Plehn*
Automatization: *Goncalves-Netto et al. '12*
LO EW: *Bornhauser et.al.* '07, **NLO**: *Germer et. al. '10*
Beyond NLO (resummed):
Beenakker et al. '09 (soft)
Falgari, Schwinn, Wever '12 +'13 (soft+coulomb)

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.

Combining production and direct decay at NLO

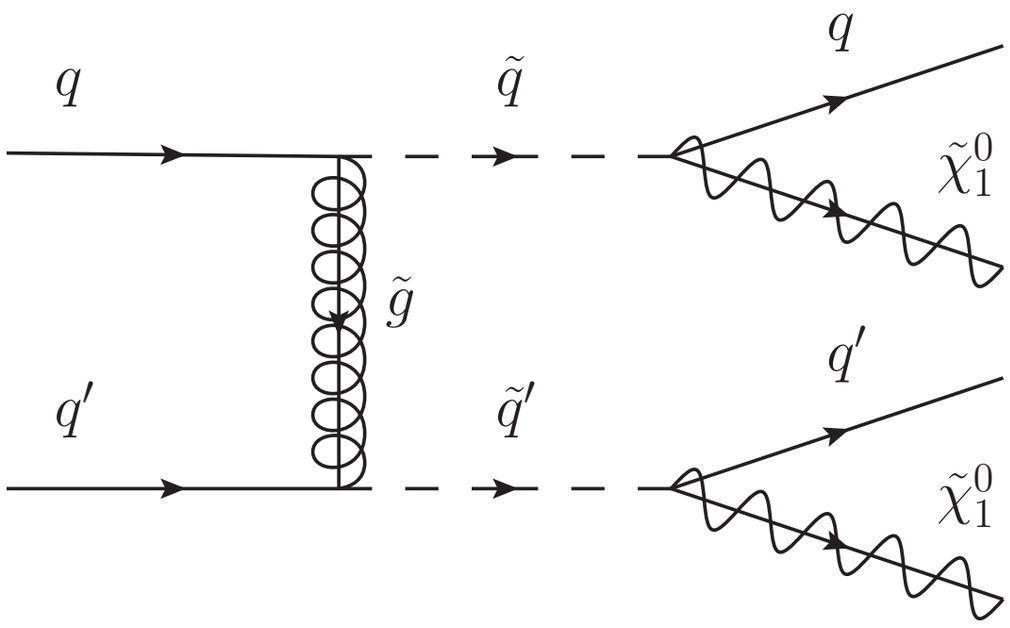
We study the experimental signature

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

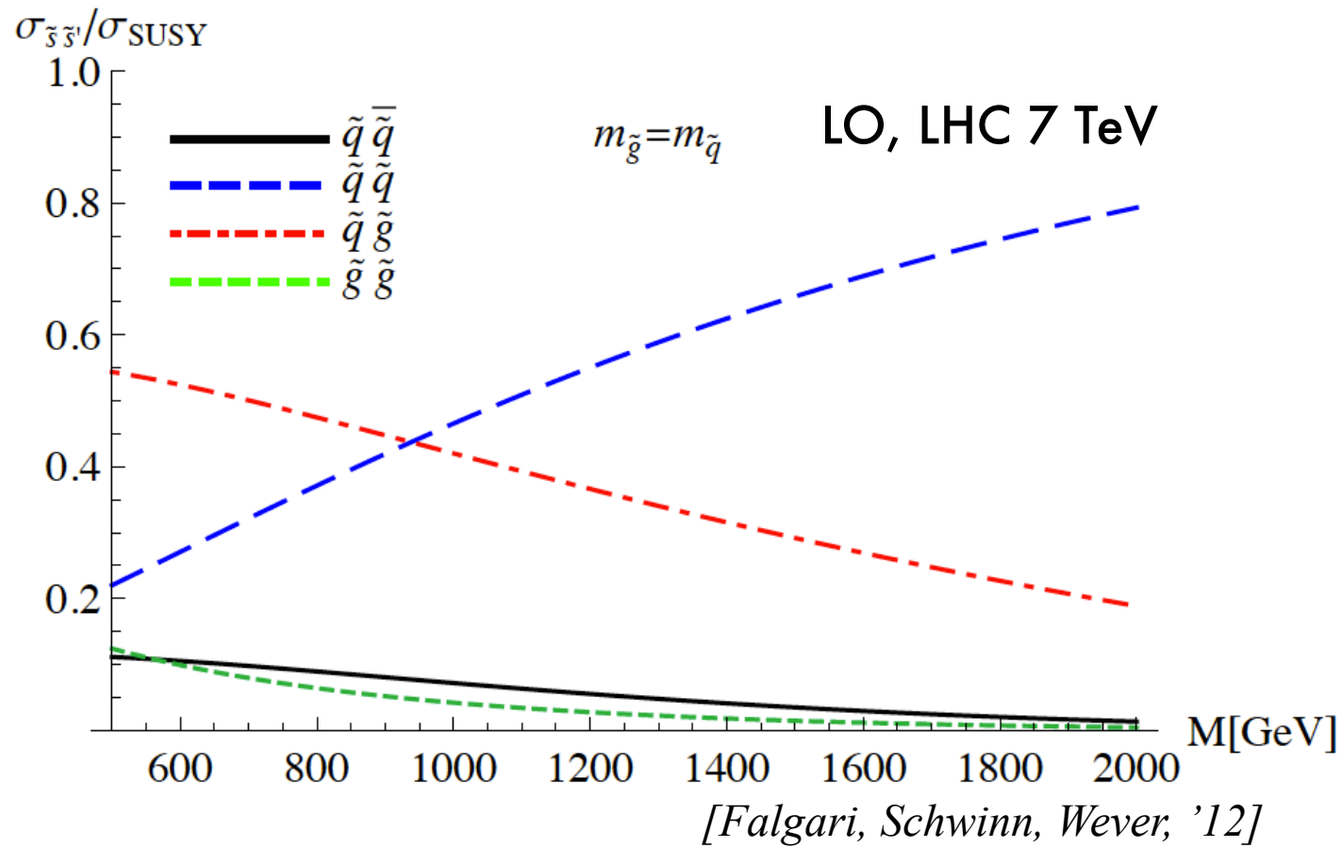
via squark-squark production and direct decay into the lightest neutralino.

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

Full LO process



Why squark-squark channel?



[Falgari, Schwinn, Wever, '12]

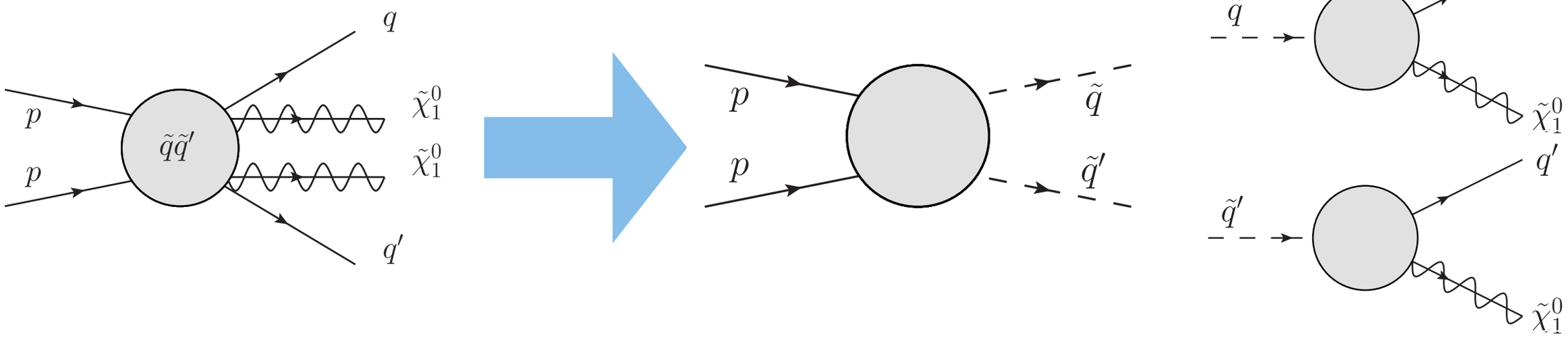
LO in NWA

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

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

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

NLO in NWA



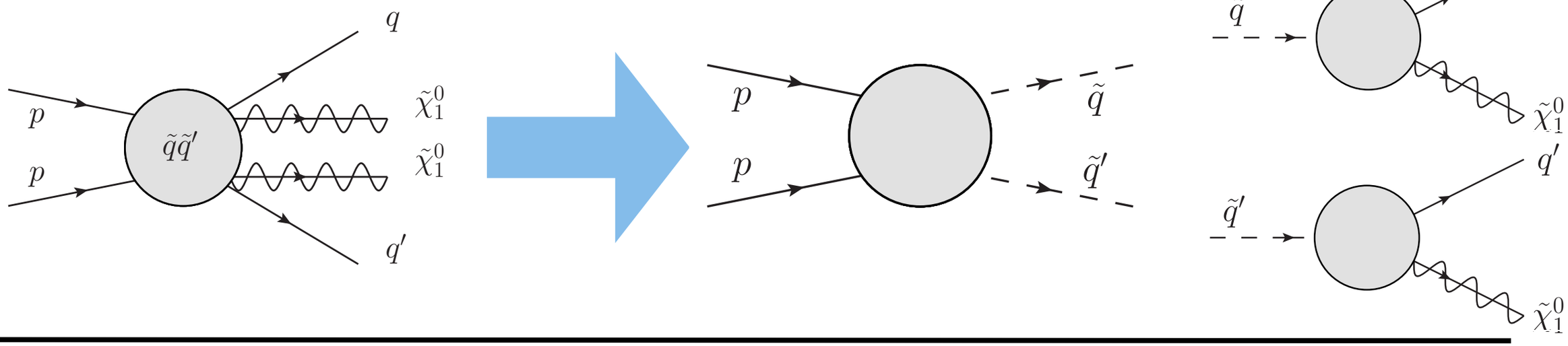
LO in NWA

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

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

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

NLO in NWA



Formal expansion in α_s:

"master formula"

Born

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

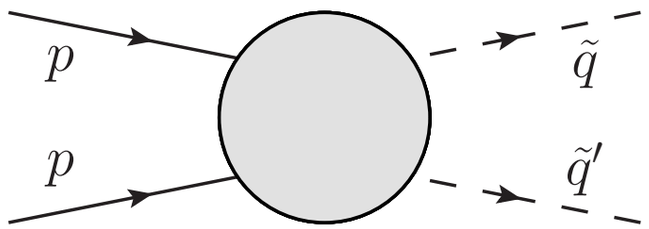
NLO decay

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

NLO production

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

NLO production



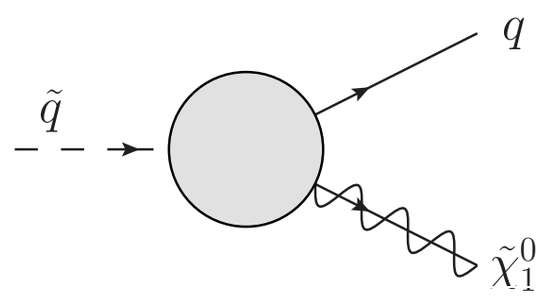
For every chirality and flavour configuration:

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

Fully differential cross-section.

NLO decay

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



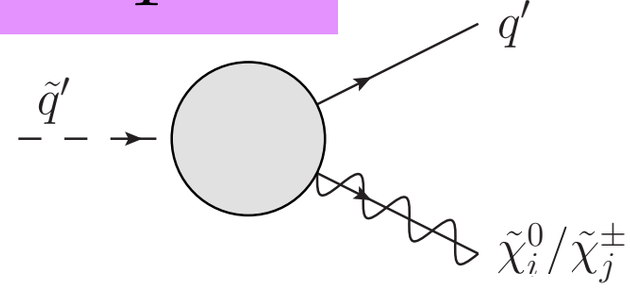
Fully differential decay.

NLO total decay width

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

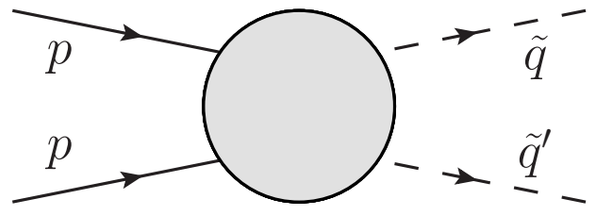
Universal form factor F^{QCD}

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

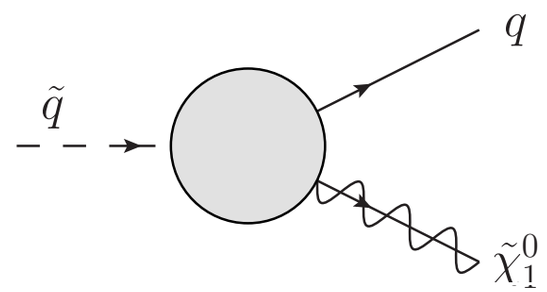


COMBINATION

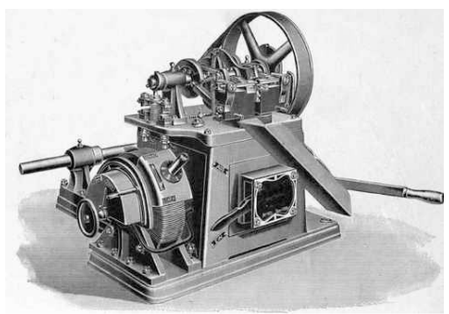
For all different combinations of light flavours and chiralities, weighted events for squark-squark production are produced in the LAB frame.



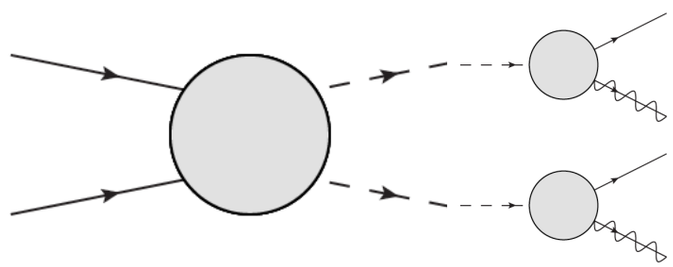
Weighted decay events are generated in the respective squark rest-frame.



boost of decay events + “master formula”



Fully differential distributions of factorizable NLO contributions in NWA.



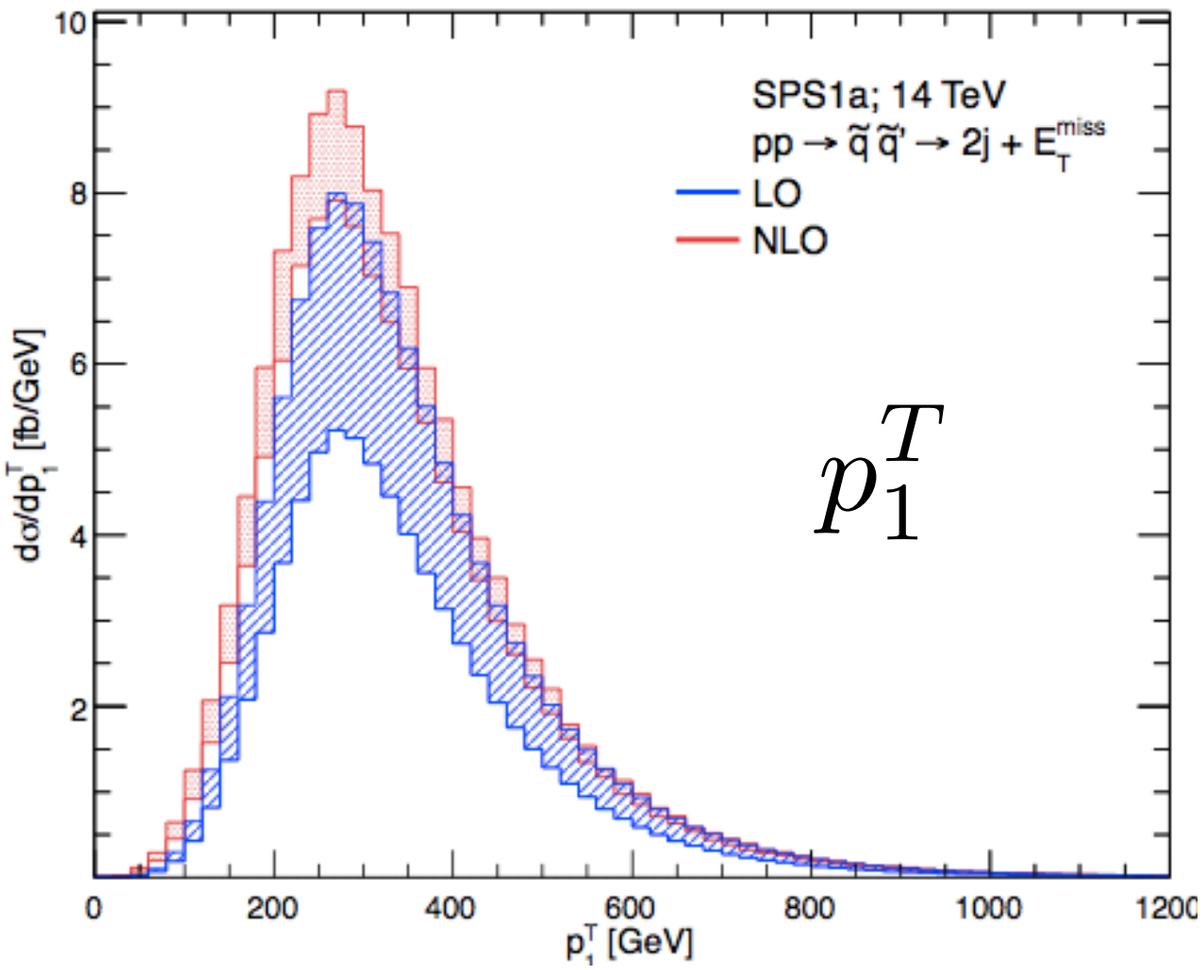
NUMERICAL RESULTS

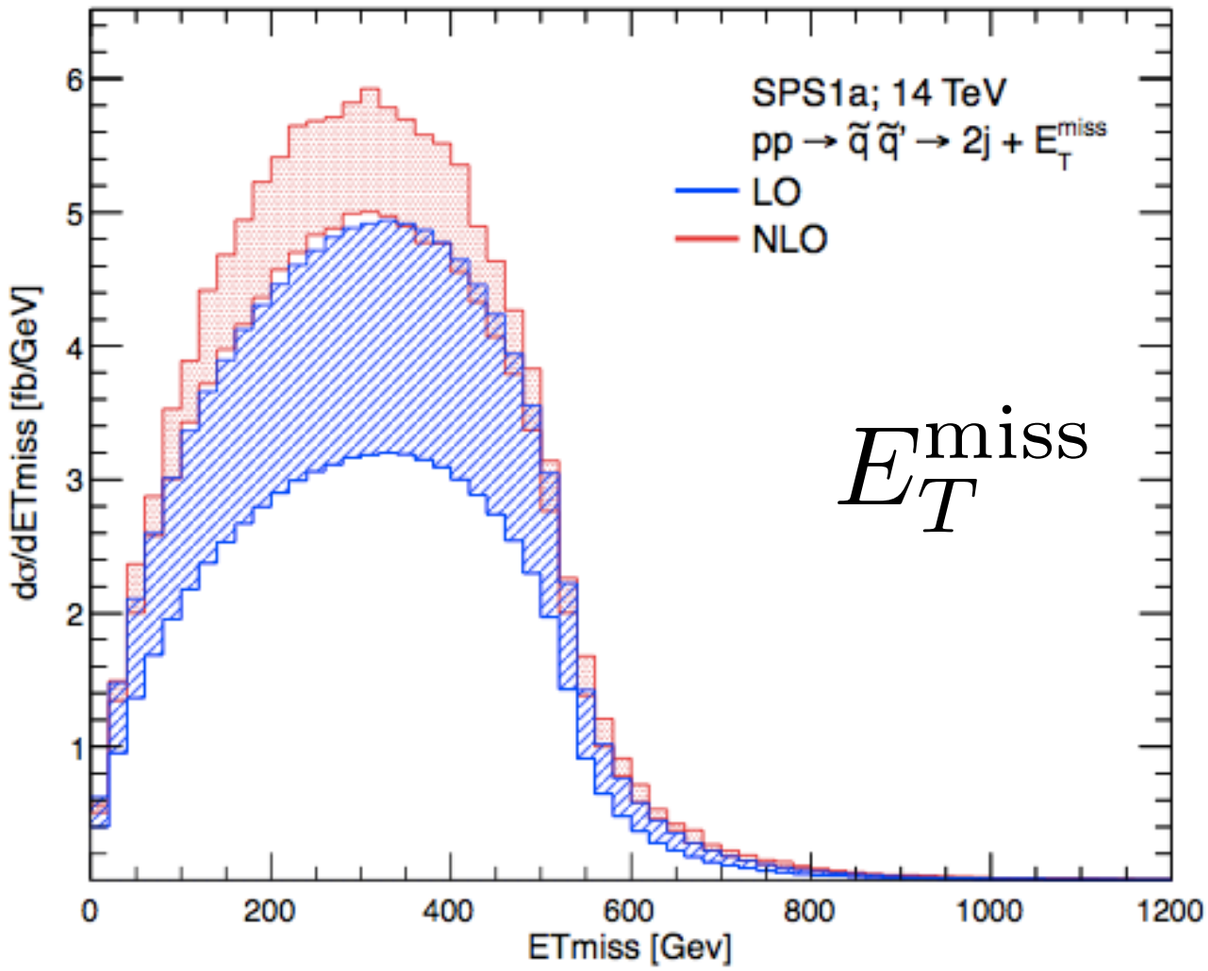
SPS1a (14 TeV)

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

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

(PDFs: CTEQ6.6)

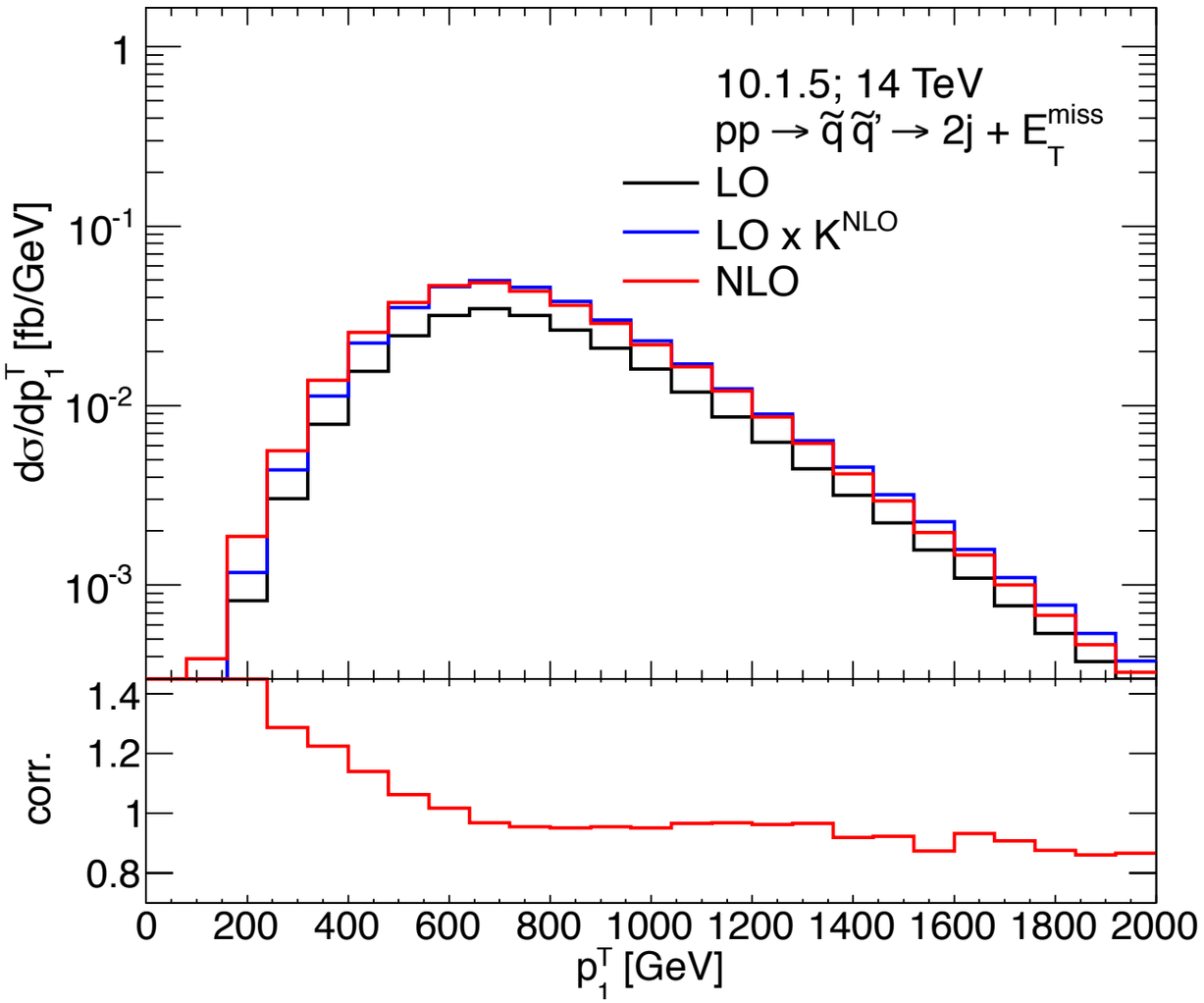




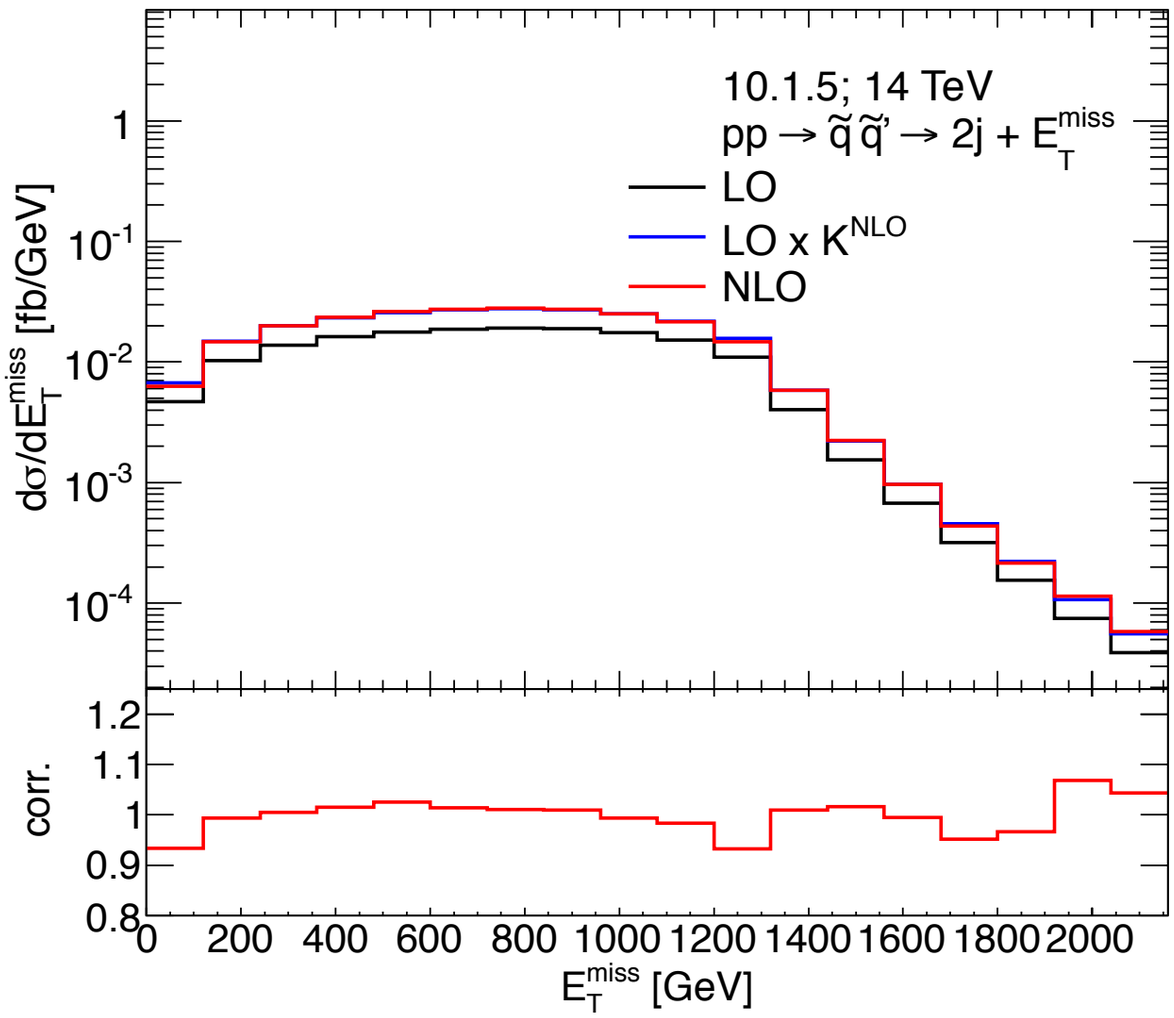
CMSSM 10.1.5 (14 TeV)

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

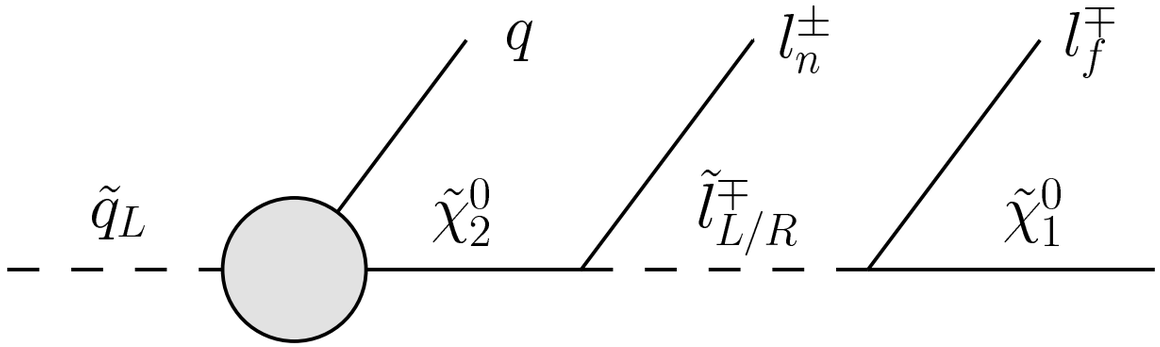


p_1^T

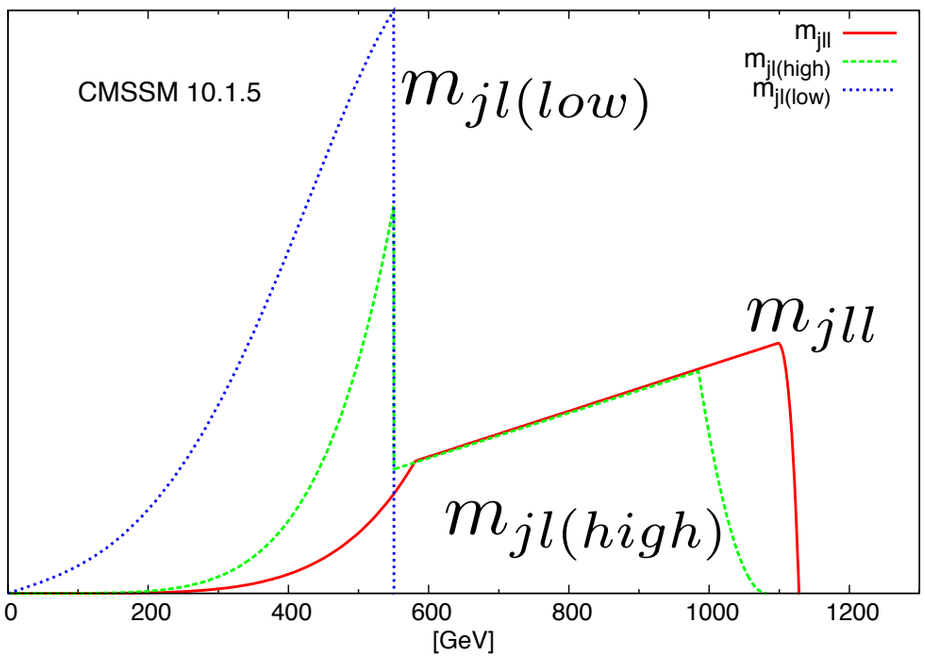


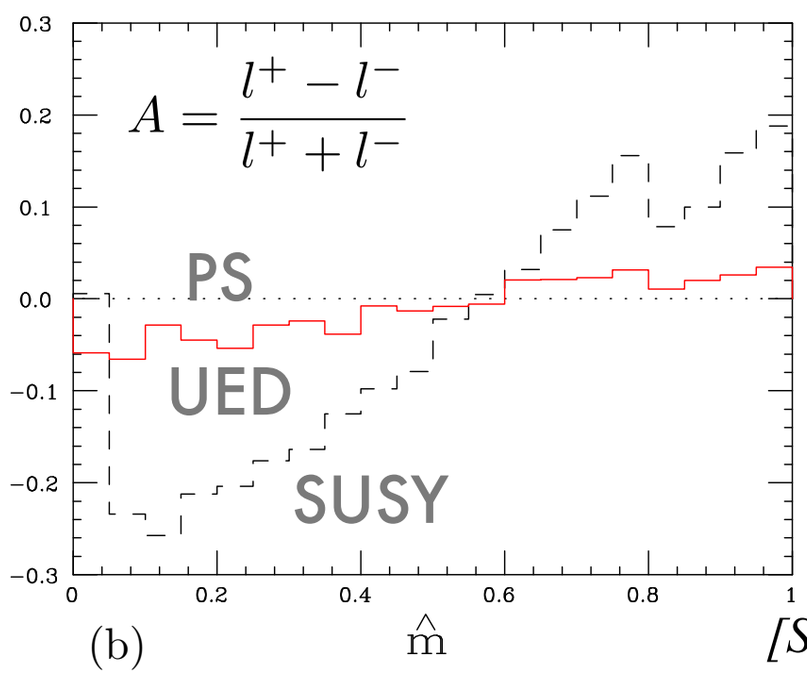
E_T^{miss}

The ‘golden’ decay chain



- Search for SUSY in ‘jets + OSSF leptons’ channel
- Possible to measure **masses** of intermediate sparticles from invariant mass distribution endpoints and shapes (m_{jll},$m_{jl(high)}$,$m_{jl(low)}$, ...).
- Possible to measure **spin** of sparticles via charge asymmetries.





[Smillie, Webber’05]

NLO QCD corrections calculated in [*Horsky, Krämer, Mück, Zerwas ’08*]

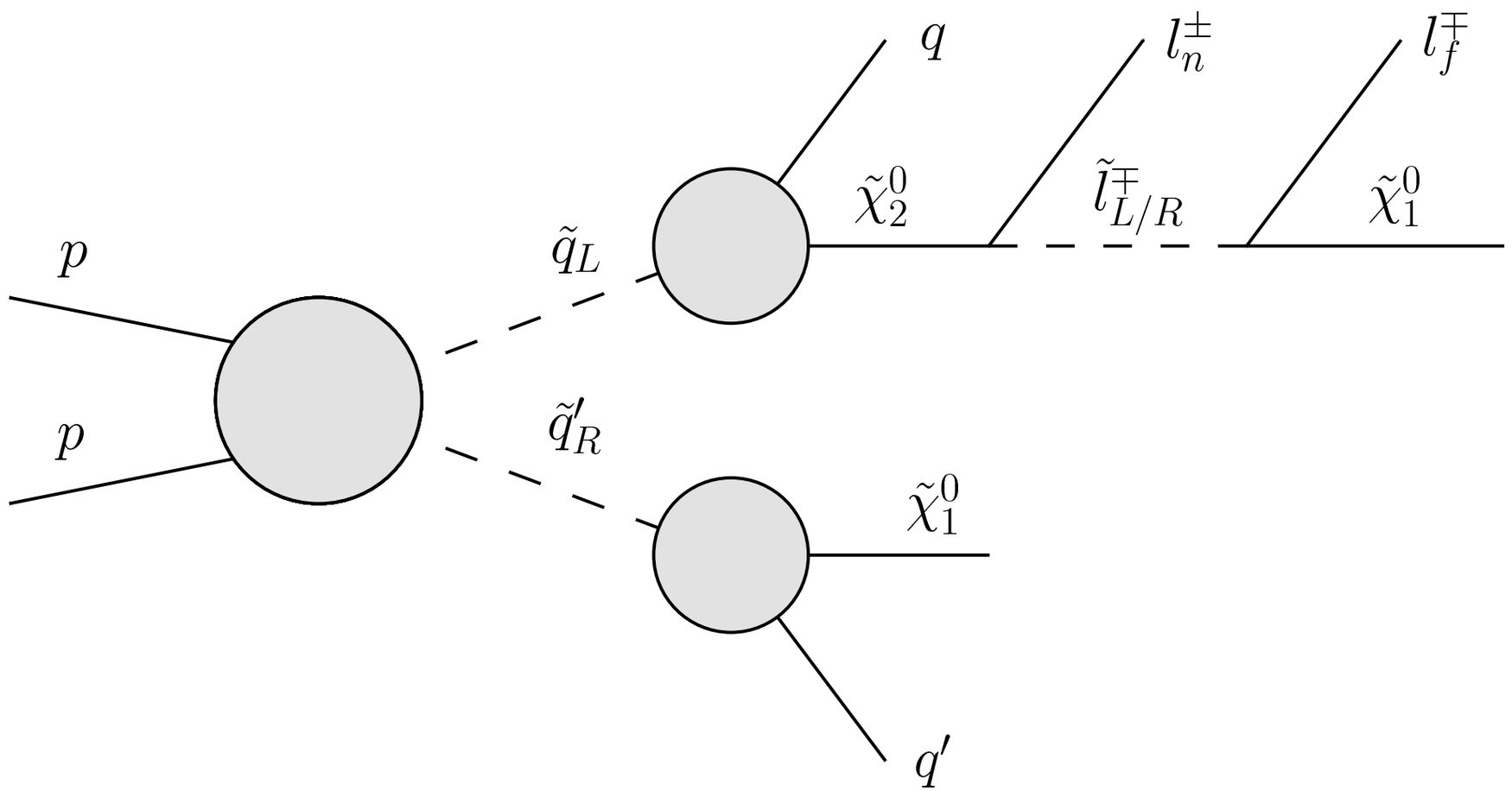
Combining production and the 'golden' decay chain

We study the experimental signature

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

via squark-squark production and an attached EW decay chain.

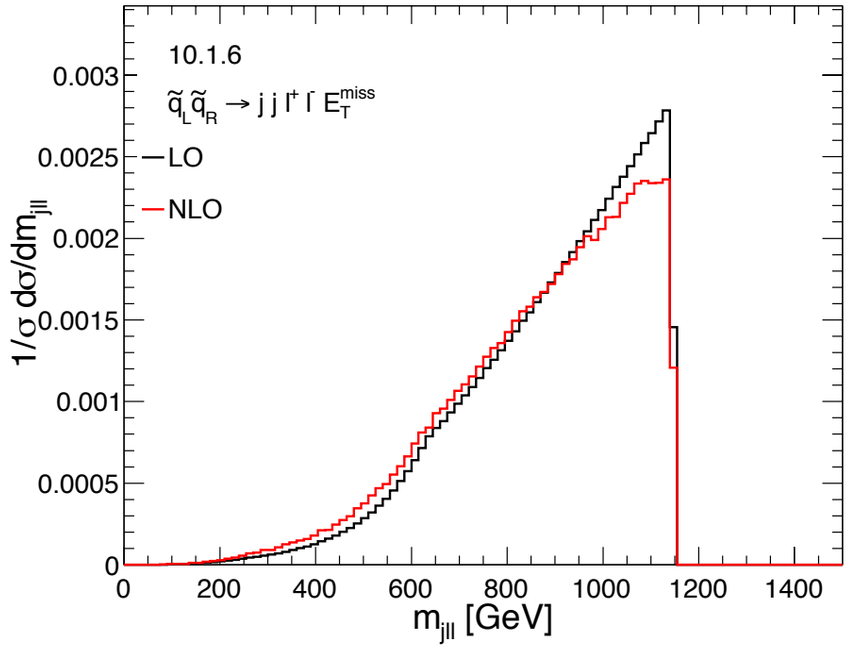
$$pp \to \tilde{q}_L \tilde{q}'_R \to q\tilde{\chi}_1^0 q' l^+ l^- \tilde{\chi}_1^0 (+X)$$

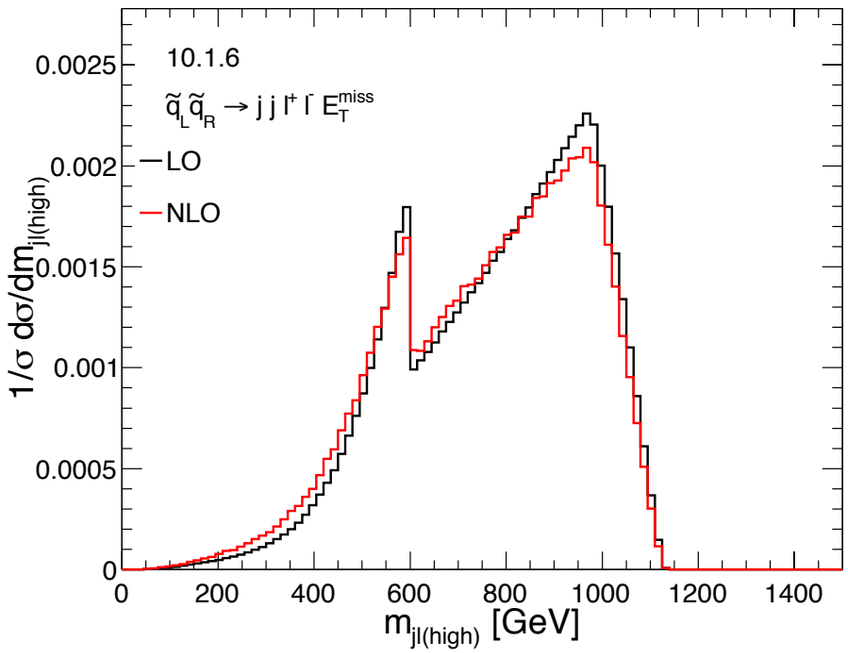


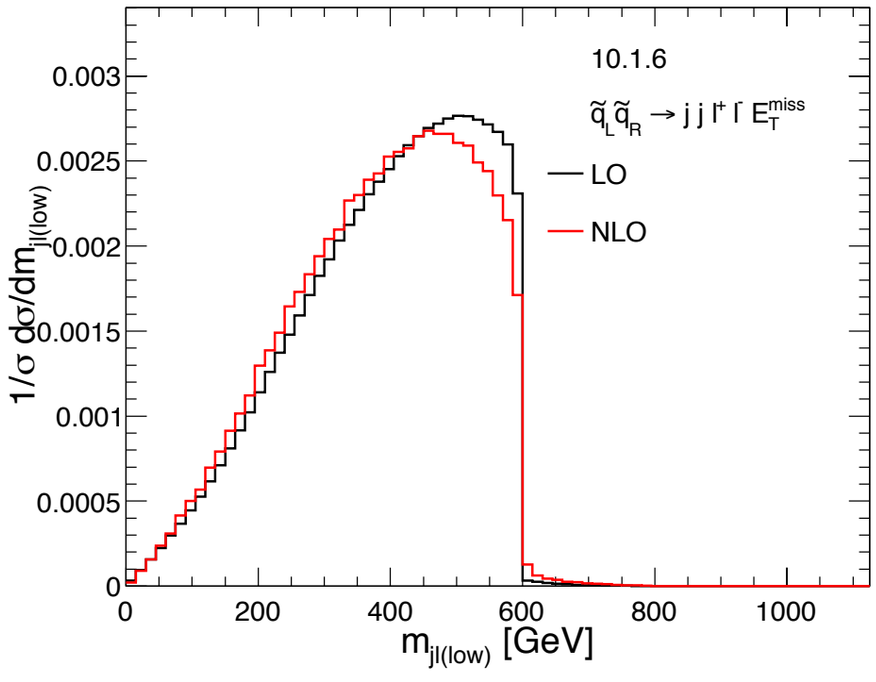
Comparison between normalized LO and NLO prediction. Corrections purely in the **shapes** of distributions.

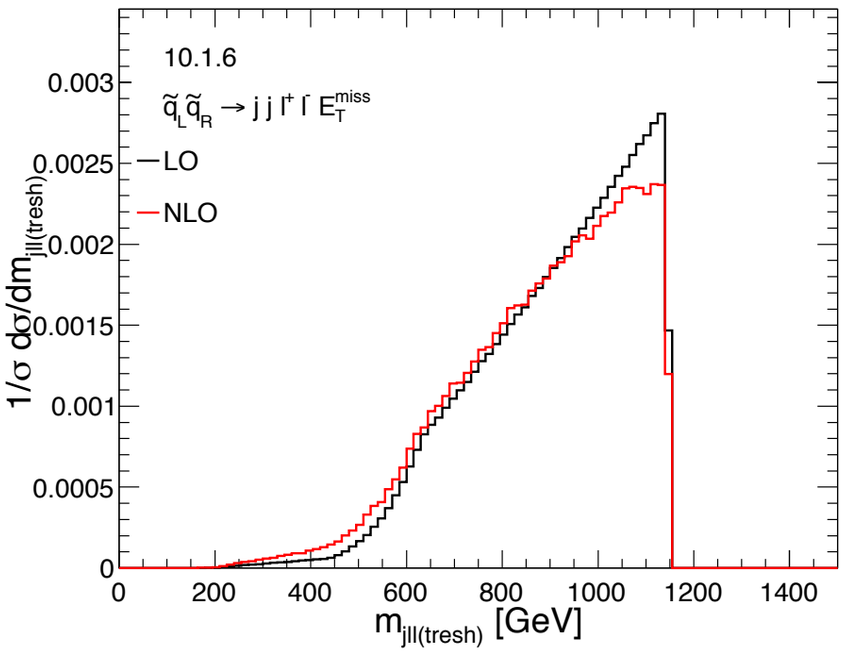
	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{l}_L$	$\tilde{l}_R$	$\tilde{\chi}_2^0$	$\tilde{\chi}_1^0$
10.1.6	1531.7	1472.2	1533.6	1466.1	1672.1	536.6	340.6	592.4	313.3

LHC 14 TeV





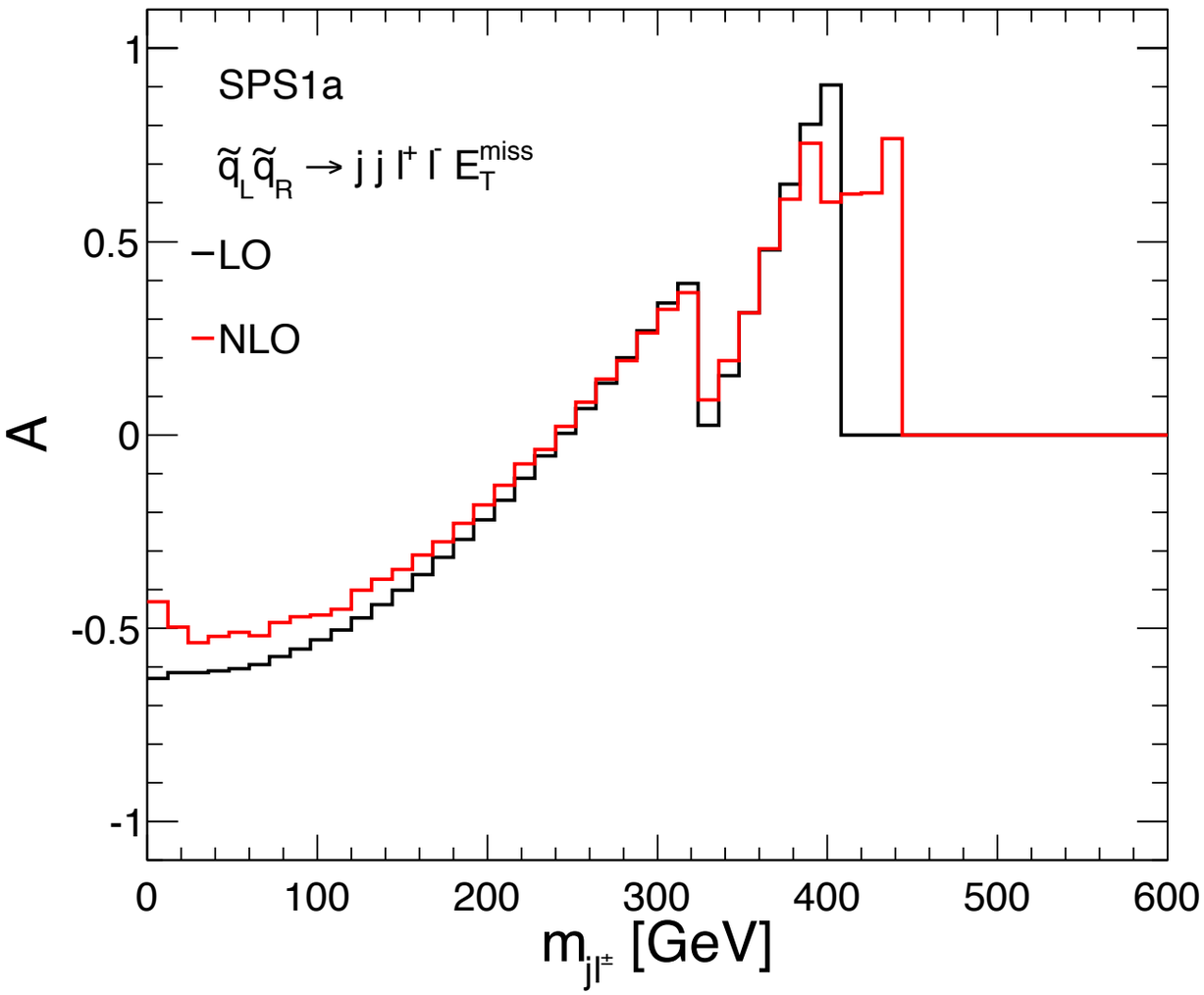


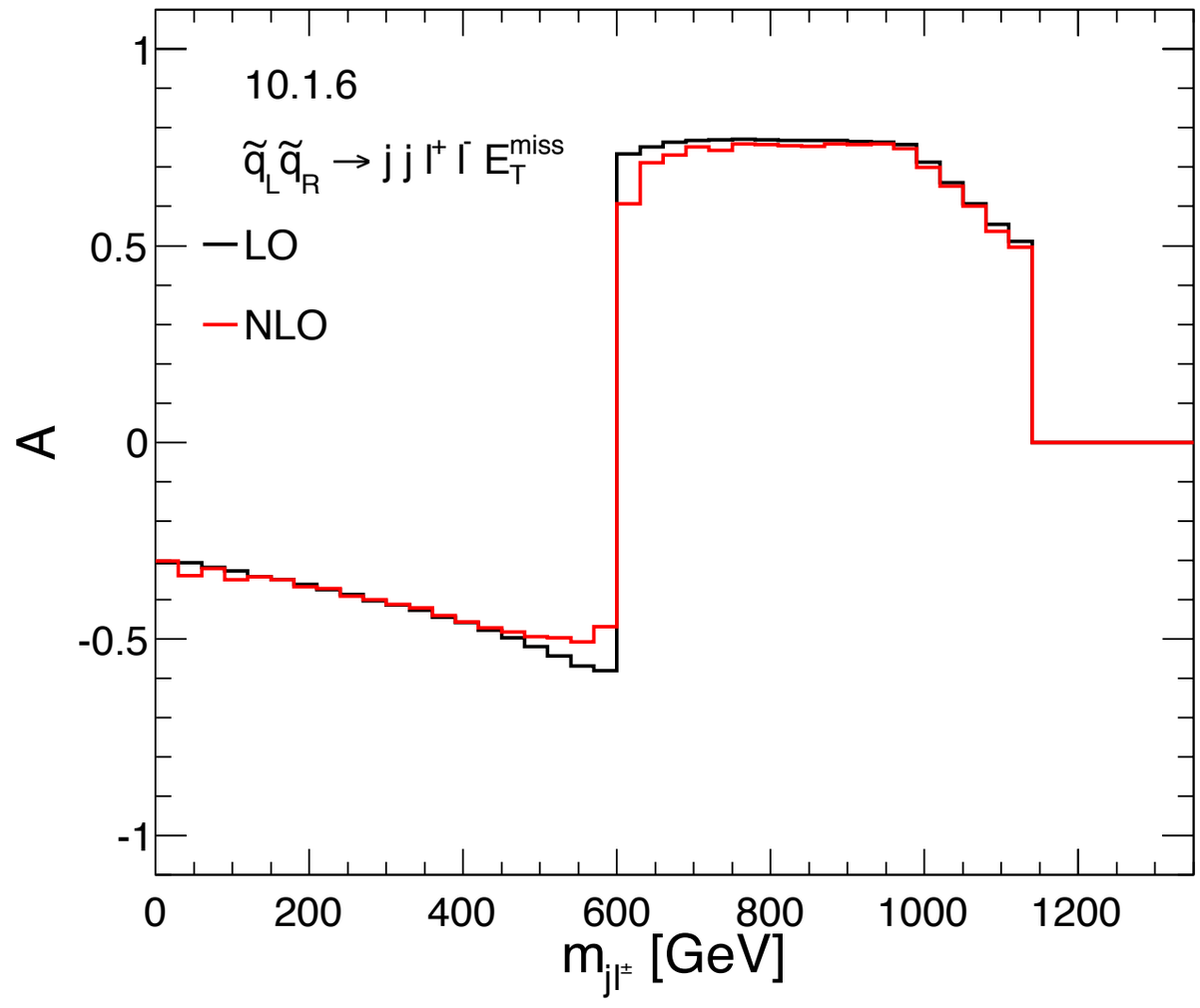


Consistency cuts applied to reduce jet combinatorial problem.

Comparison between normalized LO and NLO prediction. Corrections purely in the **shapes** of distributions.

LHC 14 TeV





$$A = \frac{d\sigma/dm_{jl+} - d\sigma/dm_{jl-}}{d\sigma/dm_{jl+} + d\sigma/dm_{jl-}}$$

Effect on cut-and-count searches for SUSY in the ‘jets + OSSF leptons’ channel at the LHC

Signal region

$$p_{j_1}^T \geq 150 \text{ GeV}\,, \qquad p_{j_2}^T \geq 100 \text{ GeV}\,, \qquad |\eta_{j,l}| \leq 2.5\,,$$
$$p_{l_{1,2}}^T \geq 20 \text{ GeV (OS-SF)}\,, \qquad \not{E}_T \geq 100 \text{ GeV}\,,$$

Results

	$N^{(0)}_{2j+2l+\not{E}_T}$	$N^{(0),\text{cons. cuts}}_{2j+2l+\not{E}_T}$	$K_{N_{2j+2l+\not{E}_T}}$	$K^{\text{cons. cuts}}_{N_{2j+2l+\not{E}_T}}$	$K_{pp\to\tilde{q}_L\tilde{q}'_R}$	$K_{pp\to\tilde{q}\tilde{q}'}$
SPS1a	38.2 fb	23.0 fb	1.36	1.23	1.34	1.28
10.1.6	0.628 fb	0.243 fb	1.46	1.39	1.44	1.41

Effect on cut-and-count searches for SUSY in the 'jets + OSSF leptons' channel at the LHC

Signal region

$$p_{j_1}^T \geq 150 \text{ GeV}\,, \qquad p_{j_2}^T \geq 100 \text{ GeV}\,, \qquad |\eta_{j,l}| \leq 2.5\,,$$
$$p_{l_{1,2}}^T \geq 20 \text{ GeV (OS-SF)}\,, \qquad \not{E}_T \geq 100 \text{ GeV}\,,$$

Results

	$N^{(0)}_{2j+2l+\not{E}_T}$	$N^{(0),\text{cons. cuts}}_{2j+2l+\not{E}_T}$	$K_{N_{2j+2l+\not{E}_T}}$	$K^{\text{cons. cuts}}_{N_{2j+2l+\not{E}_T}}$	$K_{pp\to\tilde{q}_L\tilde{q}'_R}$	$K_{pp\to\tilde{q}\tilde{q}'}$
SPS1a	38.2 fb	23.0 fb	1.36	1.23	1.34	1.28
10.1.6	0.628 fb	0.243 fb	1.46	1.39	1.44	1.41

Additional consistency cuts

$$m_{j_i ll} < m_{jll}^{\max} < m_{j_k ll}$$

CONCLUSION

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

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

OUTLOOK

Study further experimental signatures (monojets,other EW decay chains).

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

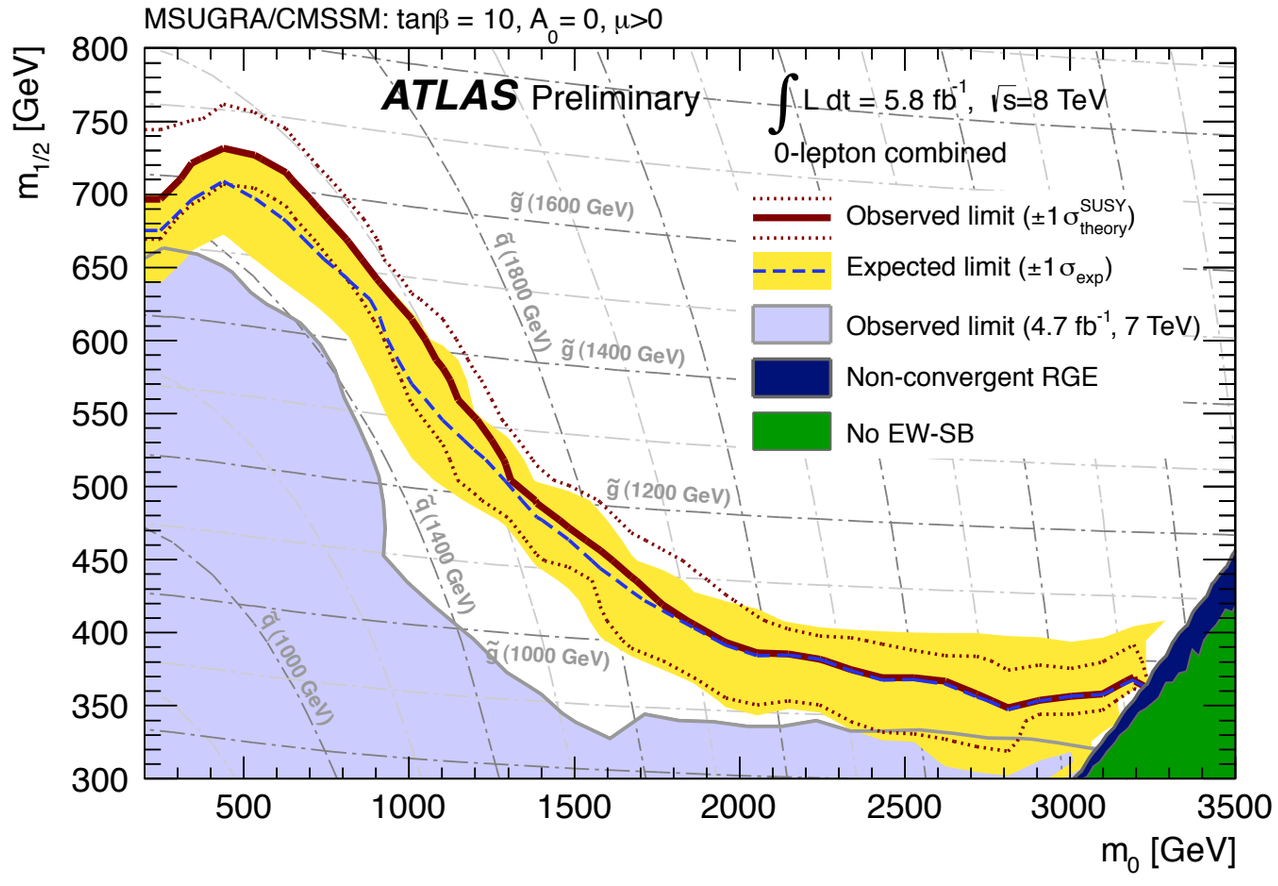
Fully differential NLO QCD predictions of combined production and decay for all squark/gluino channels are desirable (matched to a NLO PS).

Thank you for your attention.

SQUARKS AND GLUINOS AT THE LHC

Requirement	Channel				
	A 2-jets	B 3-jets	C 4-jets	D 5-jets	E 6-jets
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] >	160				
$p_{\mathrm{T}}(j_1)$ [GeV] >	130				
$p_{\mathrm{T}}(j_2)$ [GeV] >	60				
$p_{\mathrm{T}}(j_3)$ [GeV] >	–	60	60	60	60
$p_{\mathrm{T}}(j_4)$ [GeV] >	–	–	60	60	60
$p_{\mathrm{T}}(j_5)$ [GeV] >	–	–	–	60	60
$p_{\mathrm{T}}(j_6)$ [GeV] >	–	–	–	–	60
$\Delta\phi(\mathrm{jet}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ [rad] >	0.4 ($i = \{1, 2, (3)\}$)		0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_{\mathrm{T}} > 40$ GeV jets)		
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj)$ >	0.3/0.4/0.4 (2j)	0.25/0.3/– (3j)	0.25/0.3/0.3 (4j)	0.15 (5j)	0.15/0.25/0.3 (6j)
m_{eff}(incl.) [GeV] >	1900/1300/1000	1900/1300/–	1900/1300/1000	1700/–/–	1400/1300/1000

ATLAS search regions



Combining production and direct decay at NLO

We study the experimental signature

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

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

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

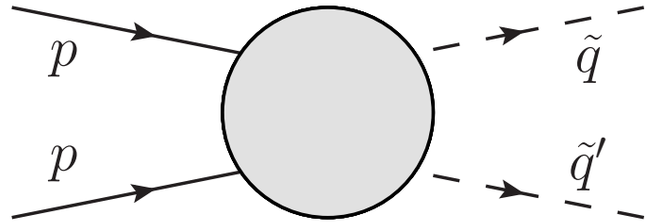
Standard procedure:

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

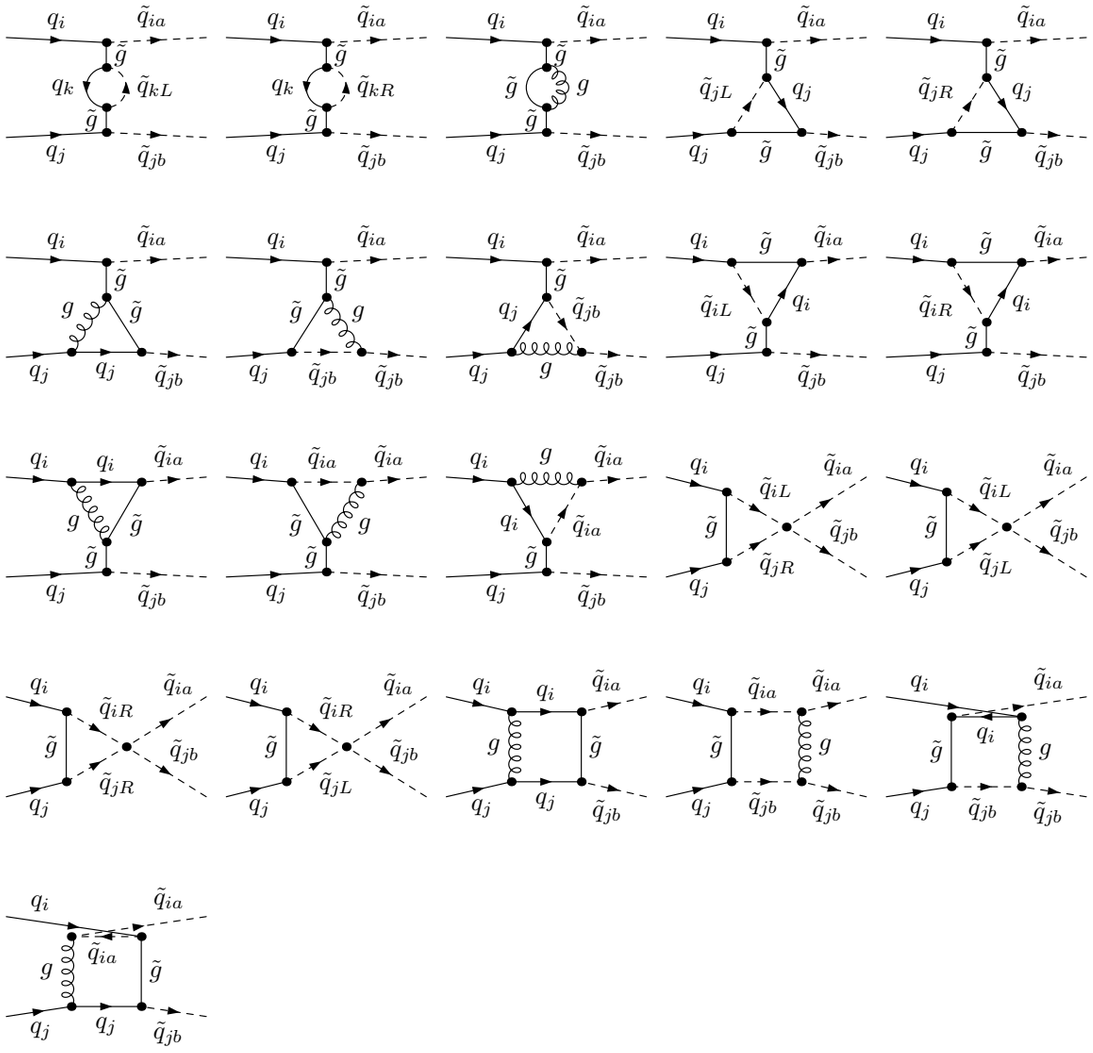
Our procedure:

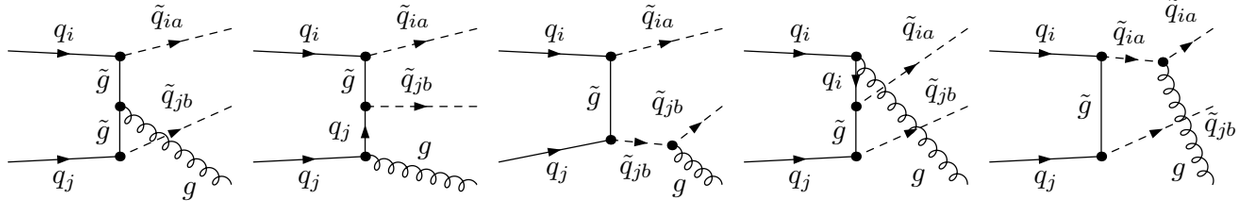
Including fully differential NLO corrections to both the decay and production, where in the calculation all flavour and chirality configurations of intermediate squarks are treated independently.

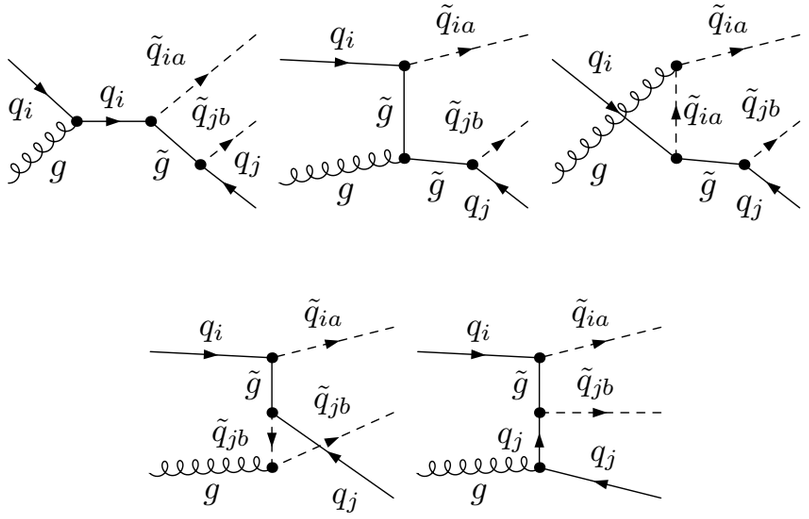
NLO production



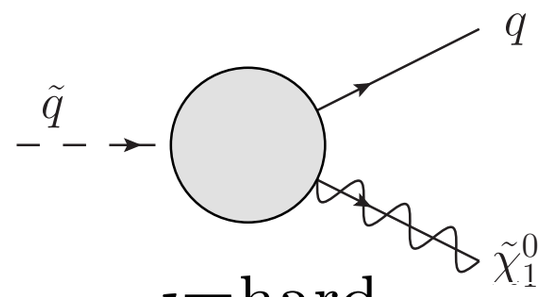
$$d\sigma^{(1)}_{pp\to\tilde{q}\tilde{q}'(+X)} = d\sigma^{\text{virtual+soft}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{coll}}_{pp\to\tilde{q}\tilde{q}'(g)} + d\sigma^{\text{hard}}_{pp\to\tilde{q}\tilde{q}'g} + d\sigma^{\text{real-quark}}_{pp\to\tilde{q}\tilde{q}'\bar{q}^{(\prime)}}$$



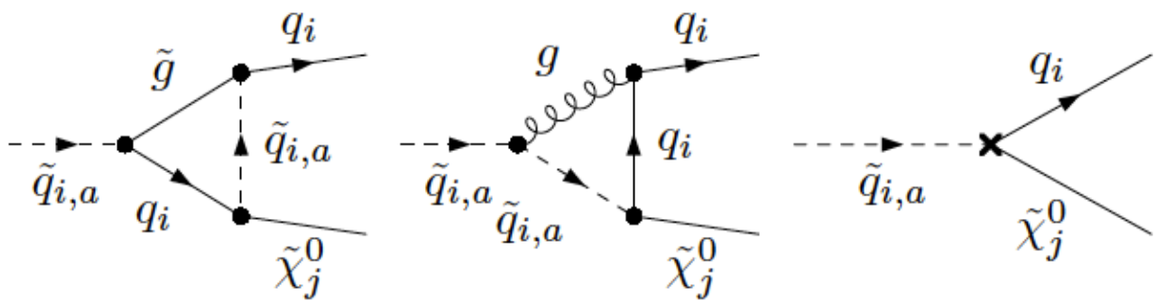


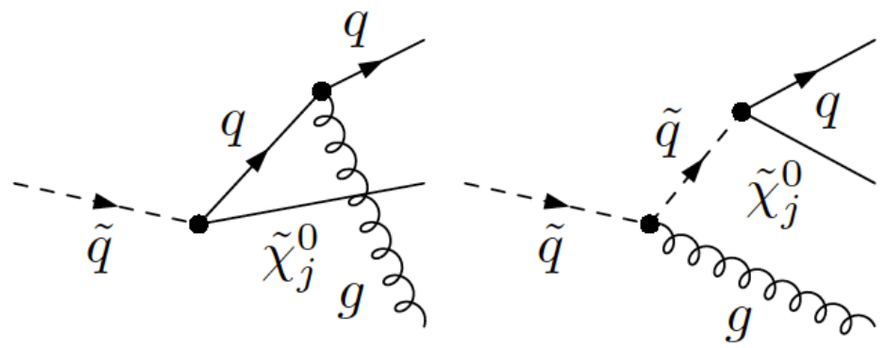


NLO decay



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





NLO total decay

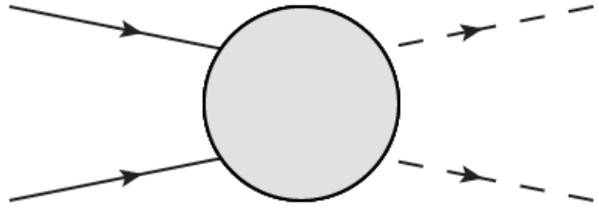
$$\Gamma^{(0+1)}_{\tilde{q}\to q\tilde{\chi}_j^0} = \Gamma^{(0)}\left[1 + \frac{4}{3}\frac{\alpha_s}{\pi}F^{QCD}\left(\frac{m_{\tilde{\chi}_j^0}}{m_{\tilde{q}}}, \frac{m_{\tilde{q}}}{m_{\tilde{g}}}\right)\right]$$

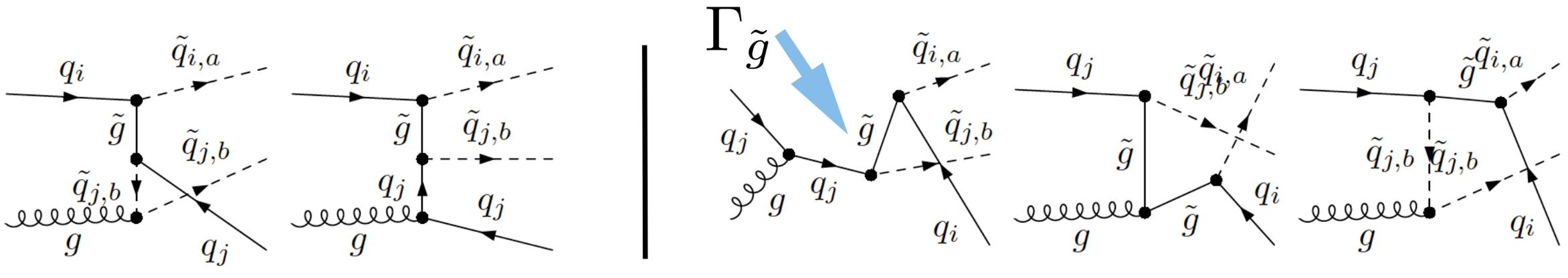
[Djouadi, Hollik, Jünger; '97]

analytical universal form factor,
recalculated with independent regulators

On-shell subtraction

DR scheme





non-resonant

resonant

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

DS scheme

[Binoth et. al.; '11]

$$\frac{|\mathcal{M}|^2(s_{q\tilde{q}})}{(s_{q\tilde{q}} - m^2_{\tilde{g}})^2 + m^2_{\tilde{g}}\Gamma^2_{\tilde{g}}} \longrightarrow \frac{|\mathcal{M}|^2(s_{q\tilde{q}})}{(s_{q\tilde{q}} - m^2_{\tilde{g}})^2 + m^2_{\tilde{g}}\Gamma^2_{\tilde{g}}} - \frac{|\mathcal{M}|^2(m^2_{\tilde{g}})}{(s_{q\tilde{q}} - m^2_{\tilde{g}})^2 + m^2_{\tilde{g}}\Gamma^2_{\tilde{g}}}$$

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