Next-to-leading order predictions for production and decay of squarks

in collaboration with Wolfgang Hollik and Davide Pagani

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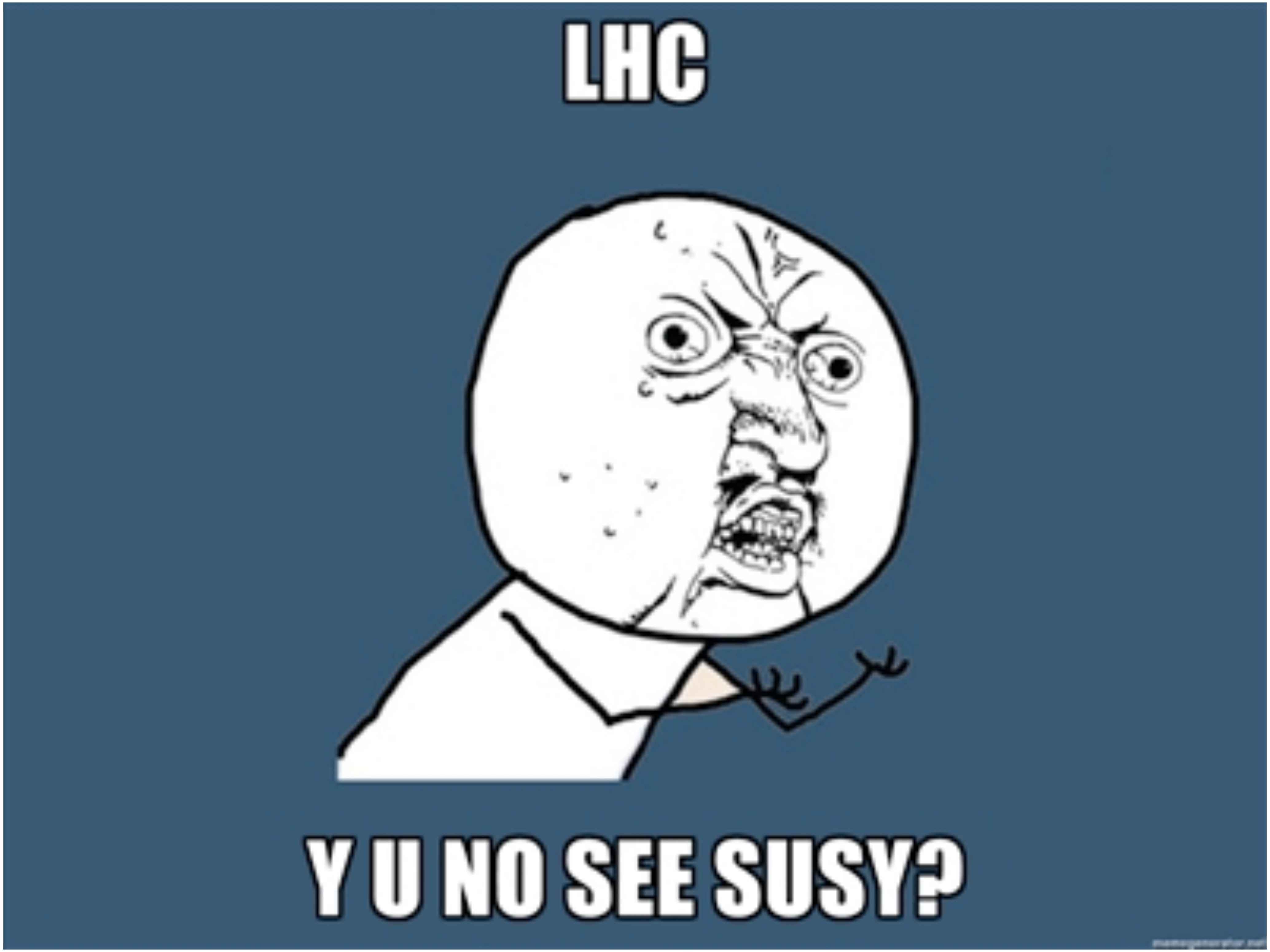
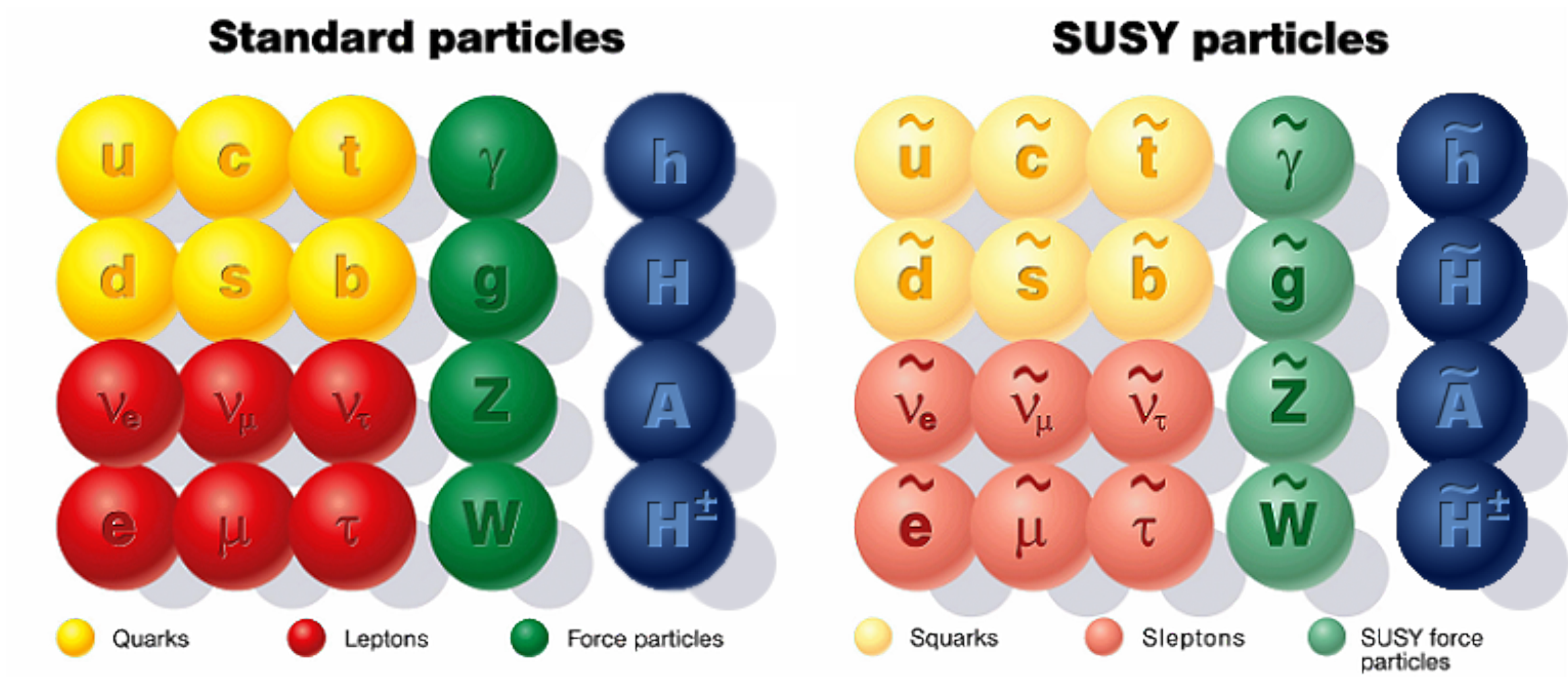
Particle Physics School Munich Colloquium
MPP, Munich, 11 January 2013

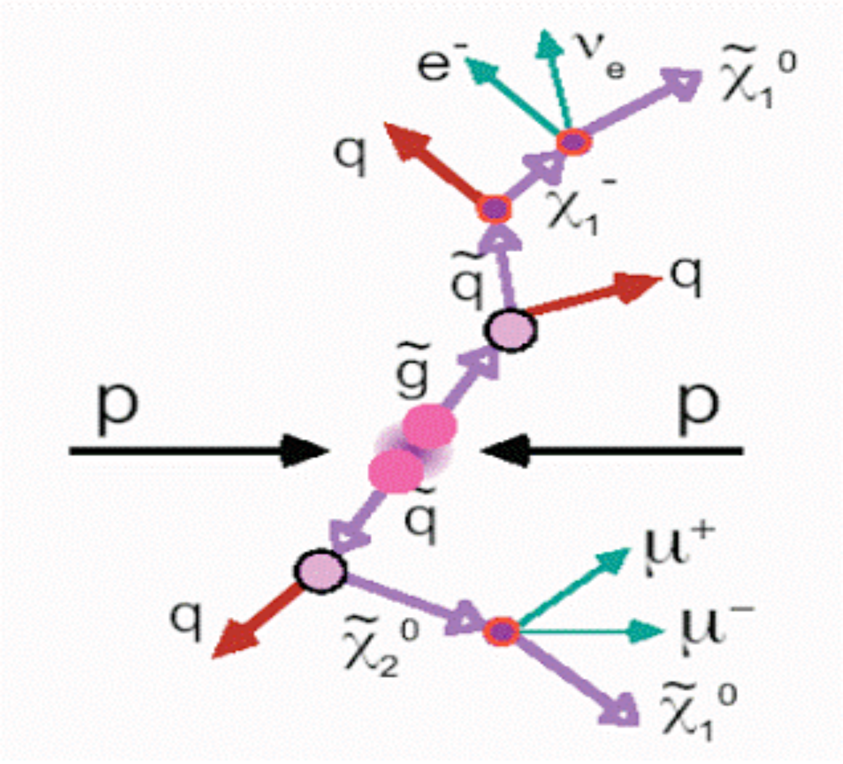

LHC
Y U NO SEE SUSY?

THE MSSM AT THE LHC



Often the lightest neutralino assumed to be the (stable) LSP ➜ missing Energy

e.g.



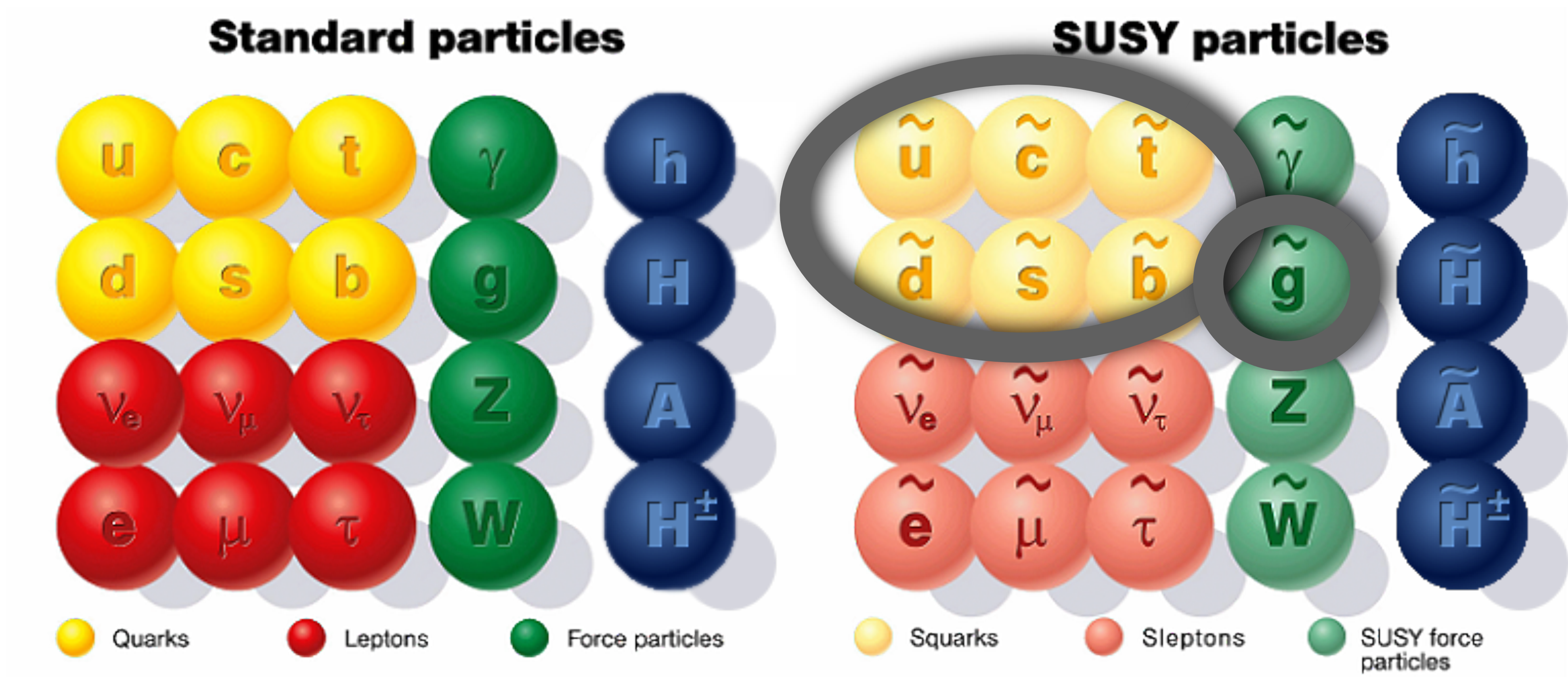
but also:

- more or less jets
- more or less leptons
- b-tagged jets

in general

- many particles in the final state

THE MSSM AT THE LHC



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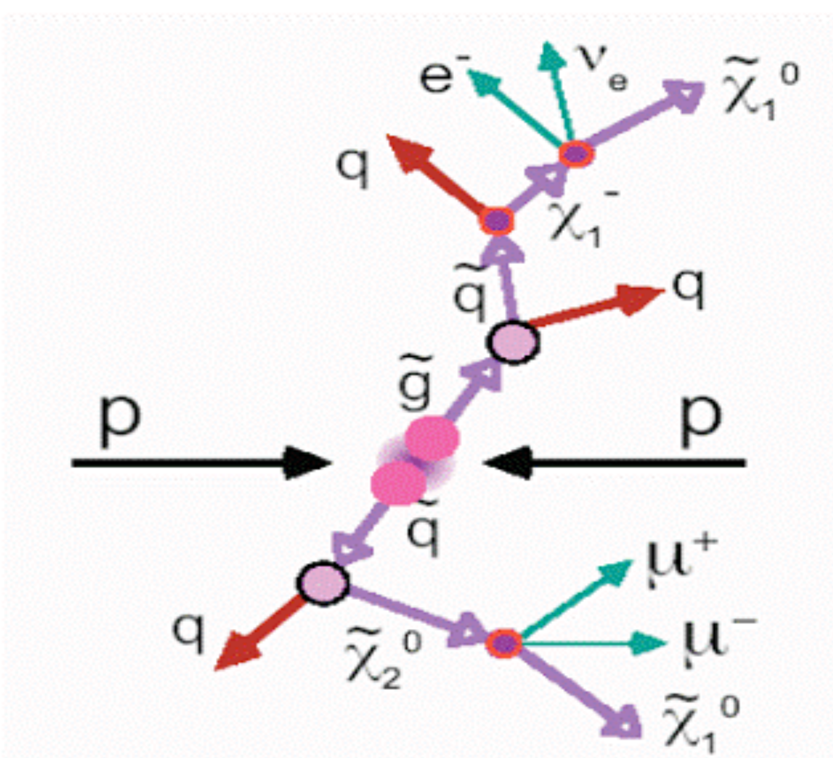

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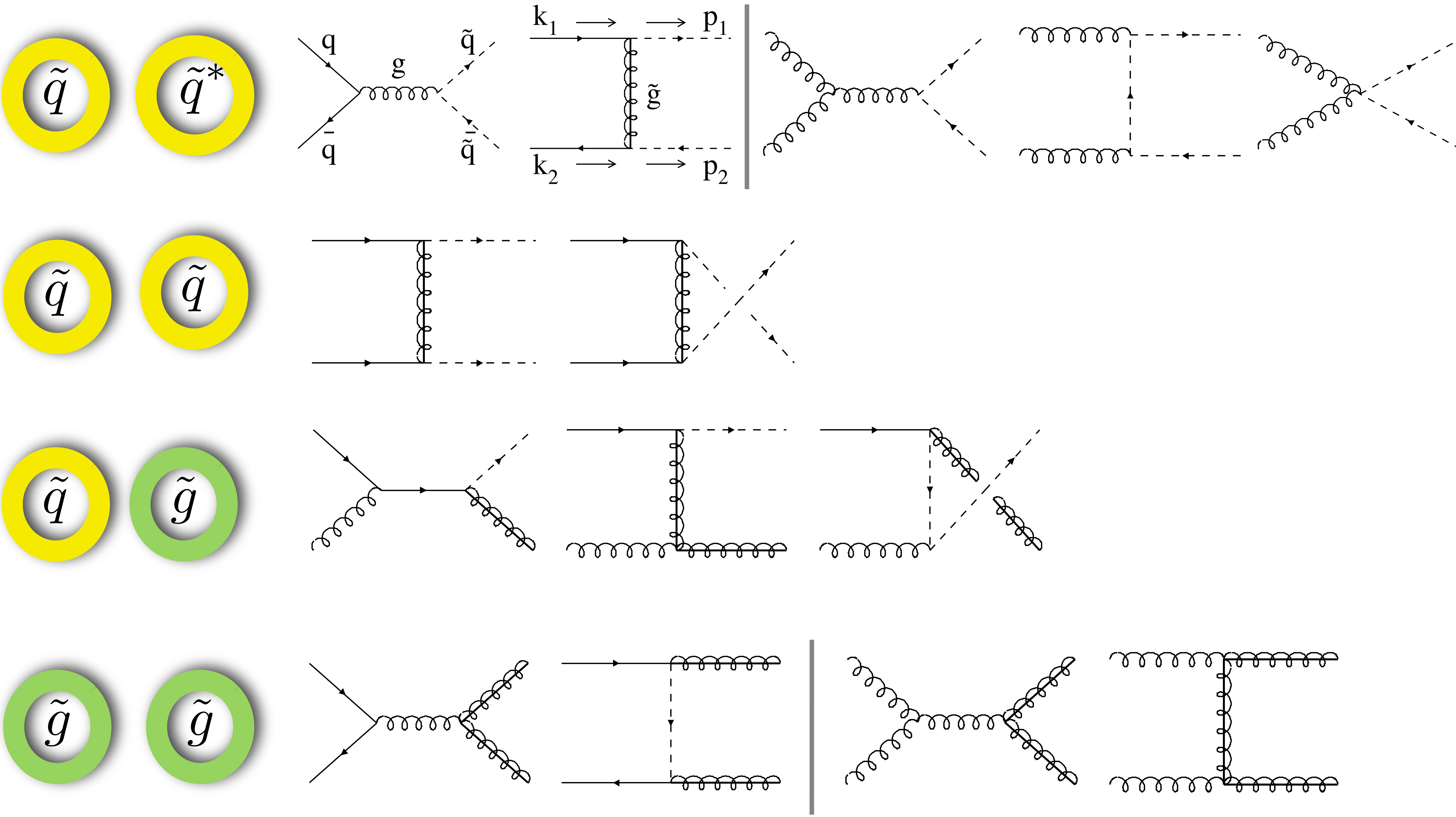
SQUARKS AND GLUINOS AT THE LHC

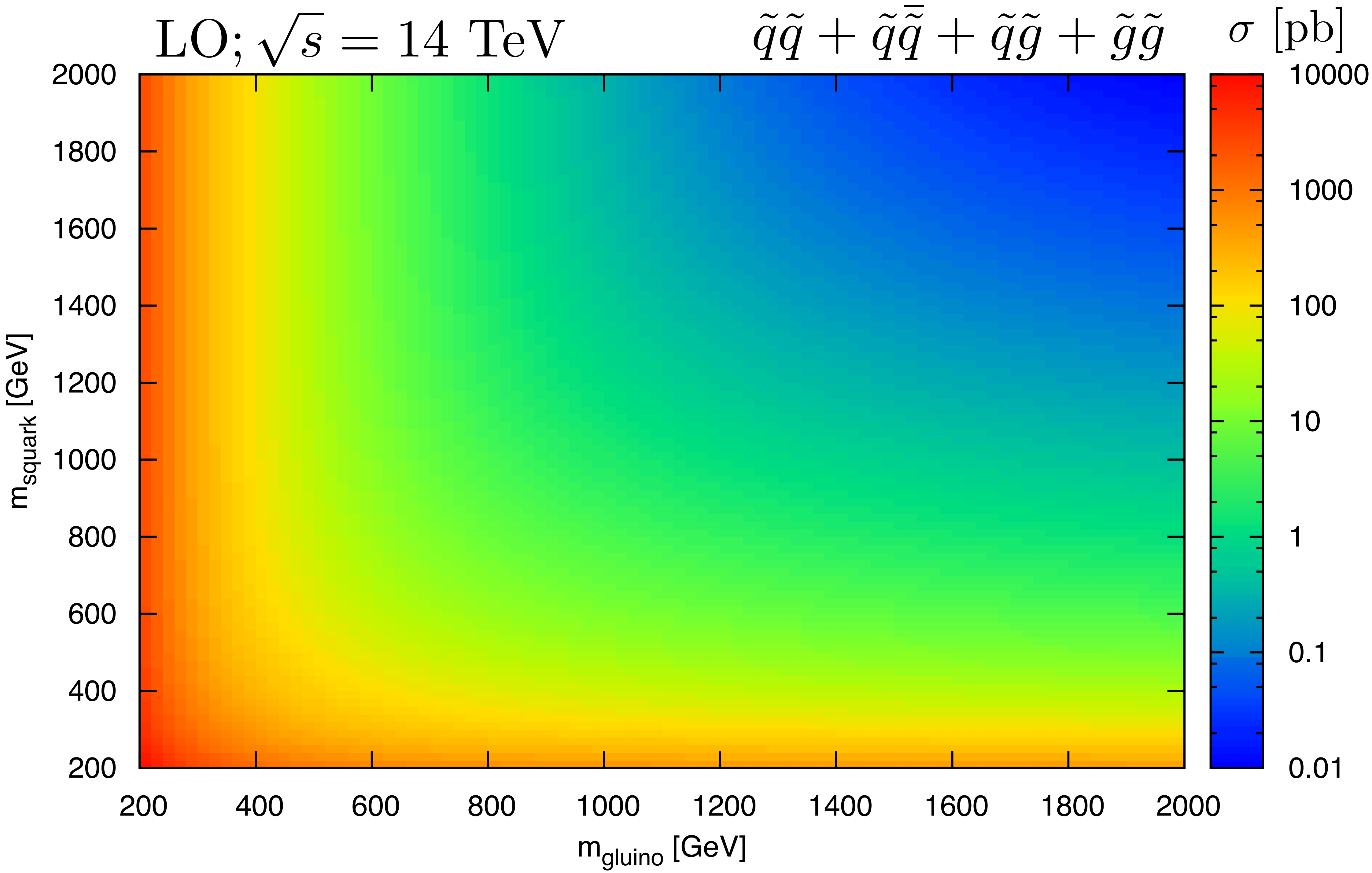
PRODUCTION



[Beenakker et al.'96]

SQUARKS AND GLUINOS AT THE LHC

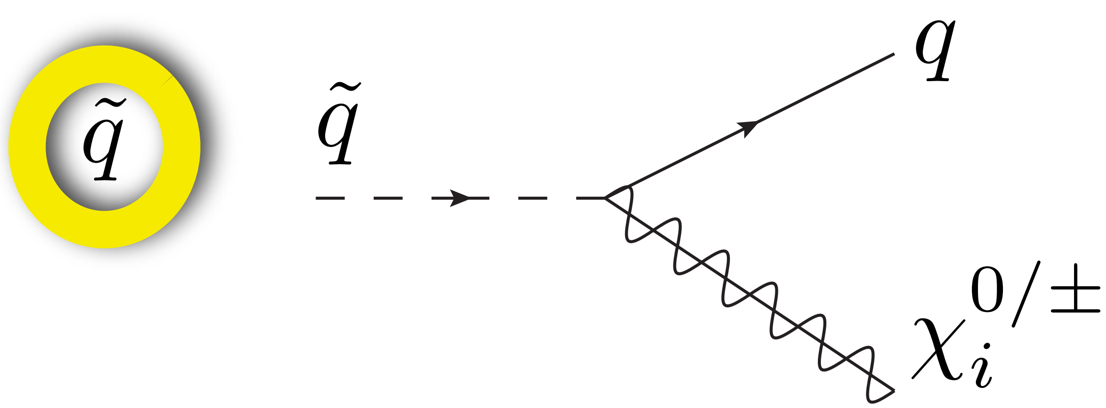
PRODUCTION

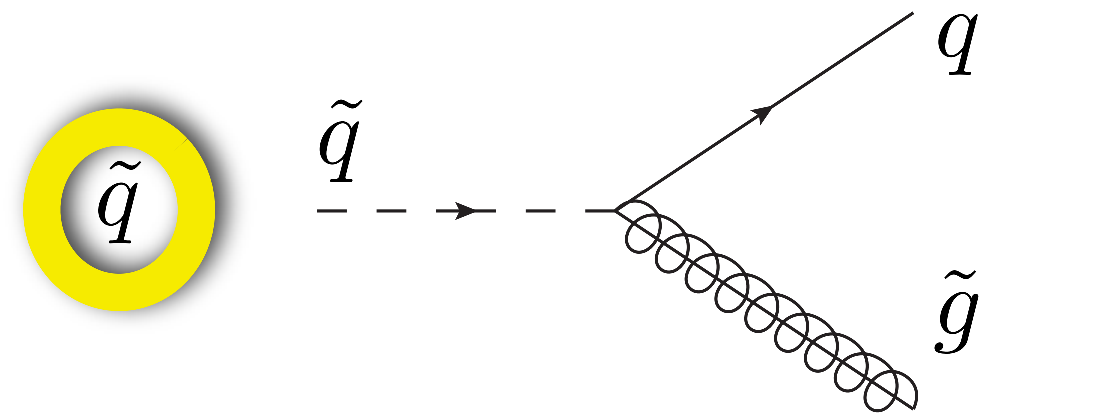


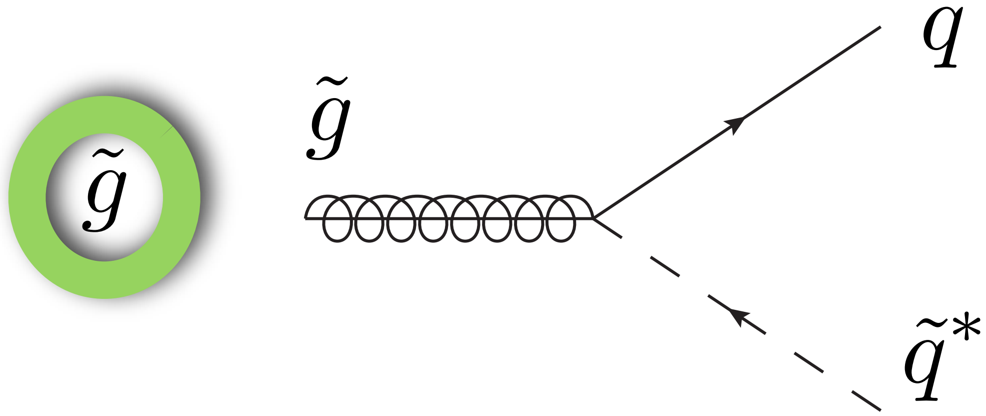
SQUARKS AND GLUINOS AT THE LHC

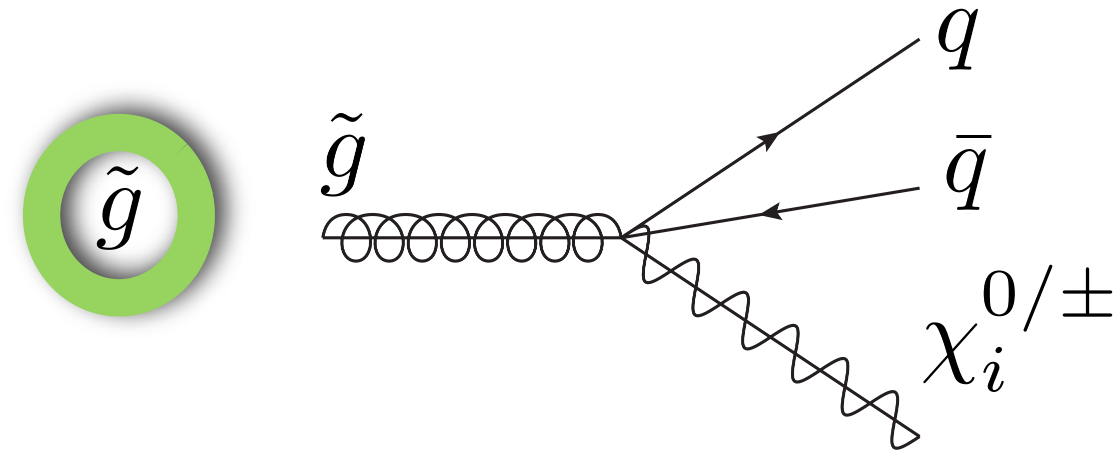
DECAY

$m_{\tilde{g}} > m_{\tilde{q}}$	$m_{\tilde{q}} > m_{\tilde{g}}$



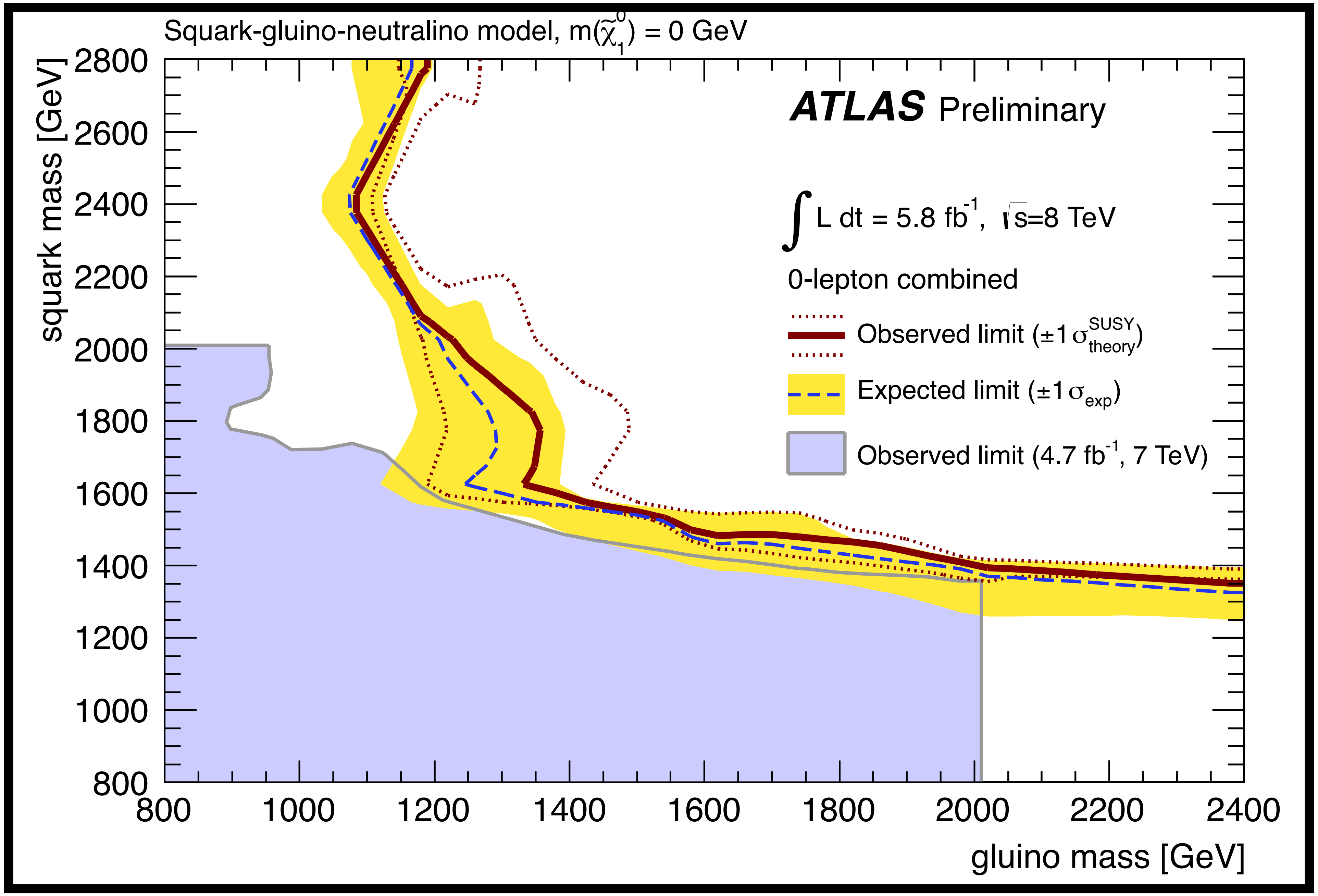






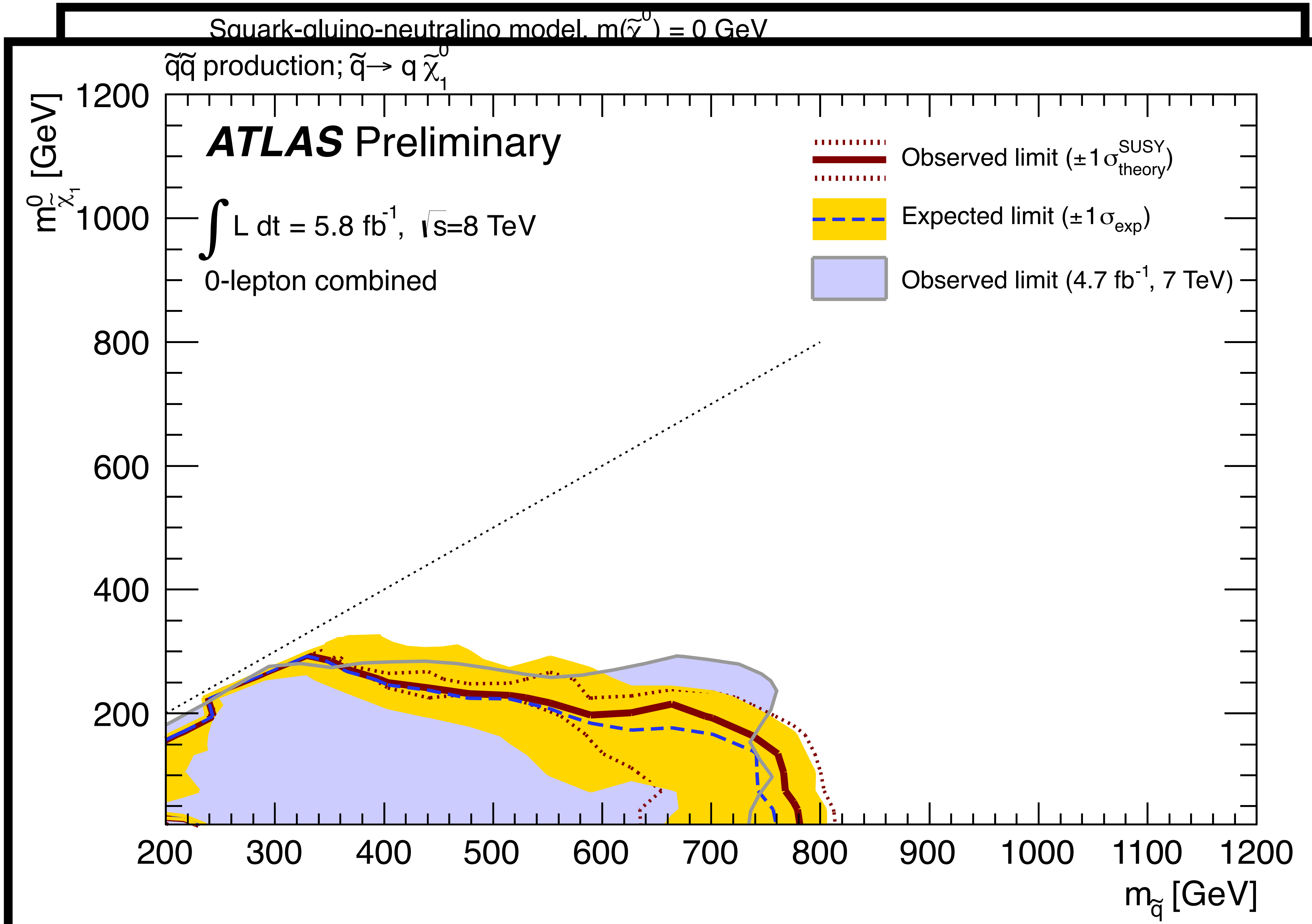
SQUARKS AND GLUINOS AT THE LHC

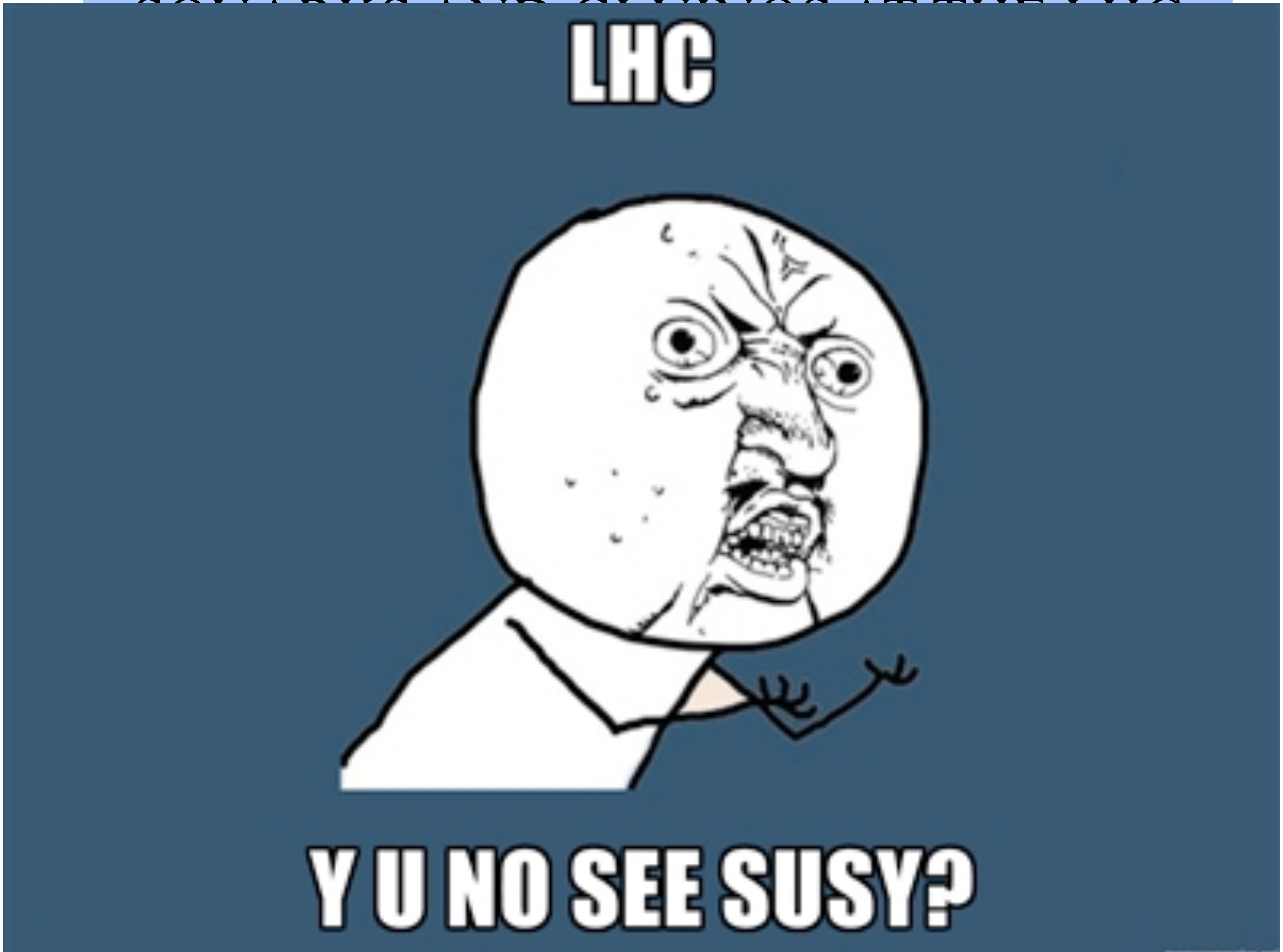
EXCLUSION LIMITS



SQUARKS AND GLUINOS AT THE LHC

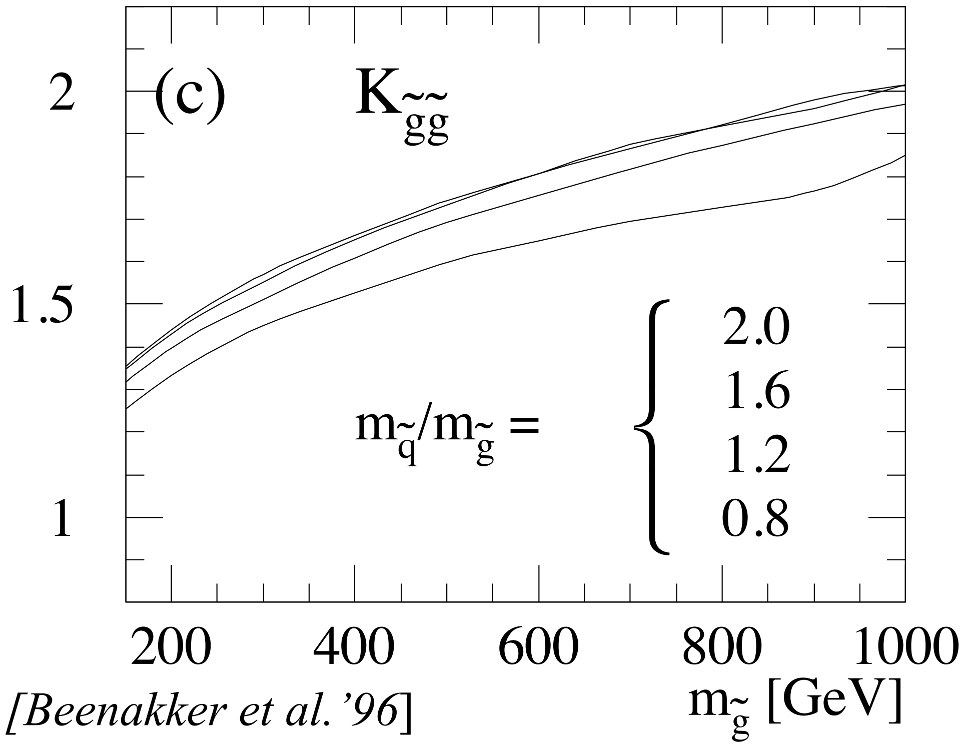
EXCLUSION LIMITS




LHC
Y U NO SEE SUSY?

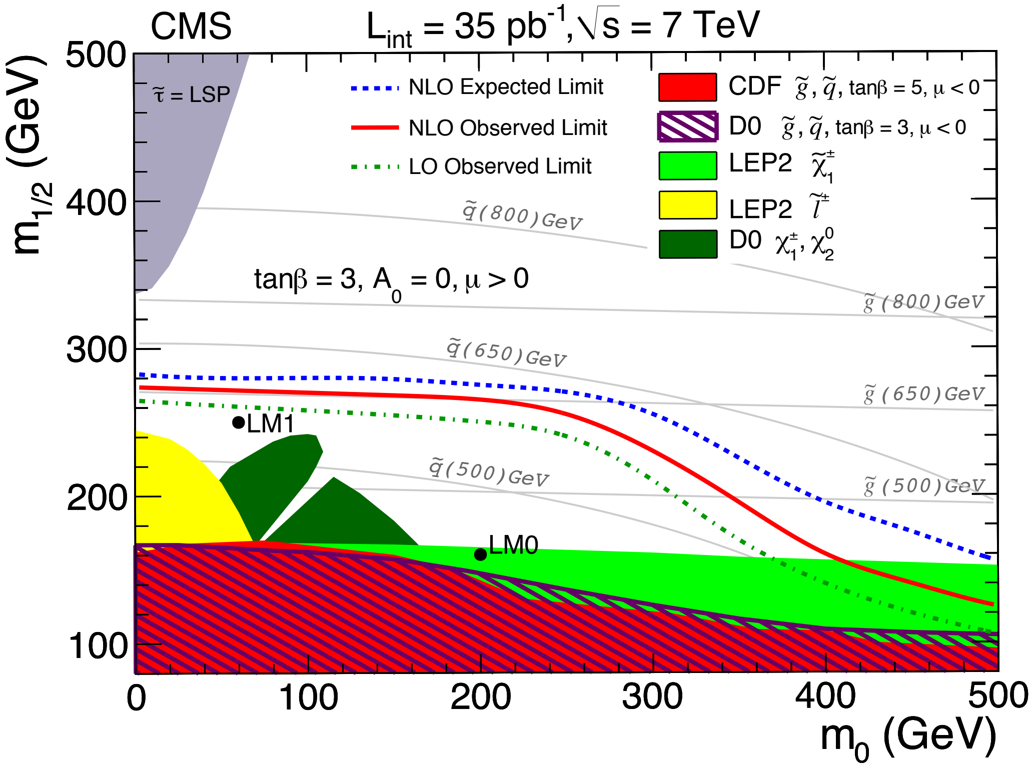
Why Higher Orders?

Corrections can be large!

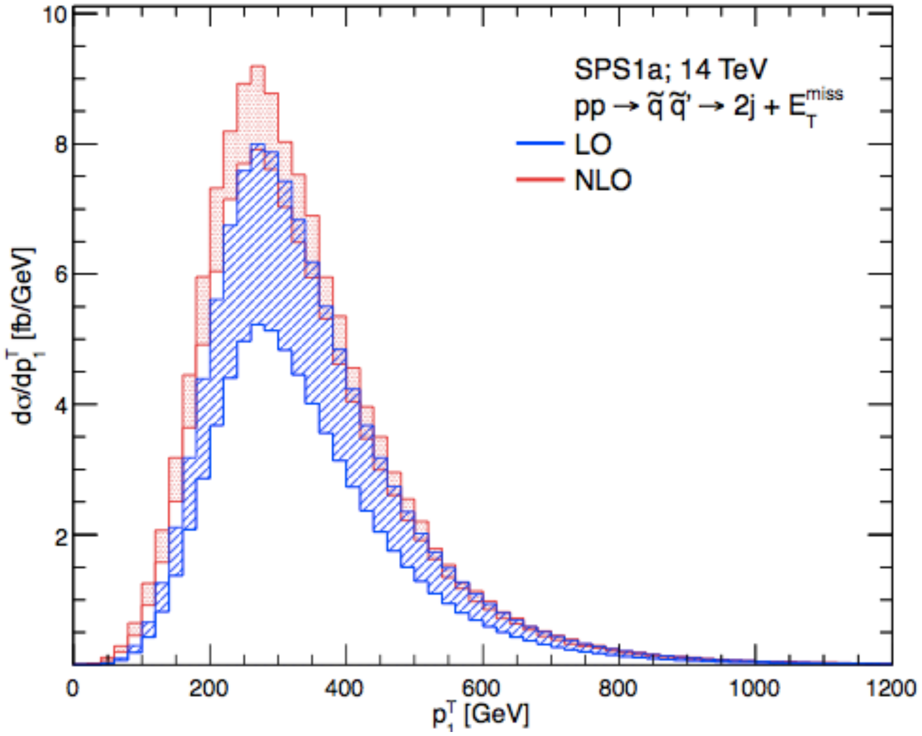


[Beenakker et al.'96]

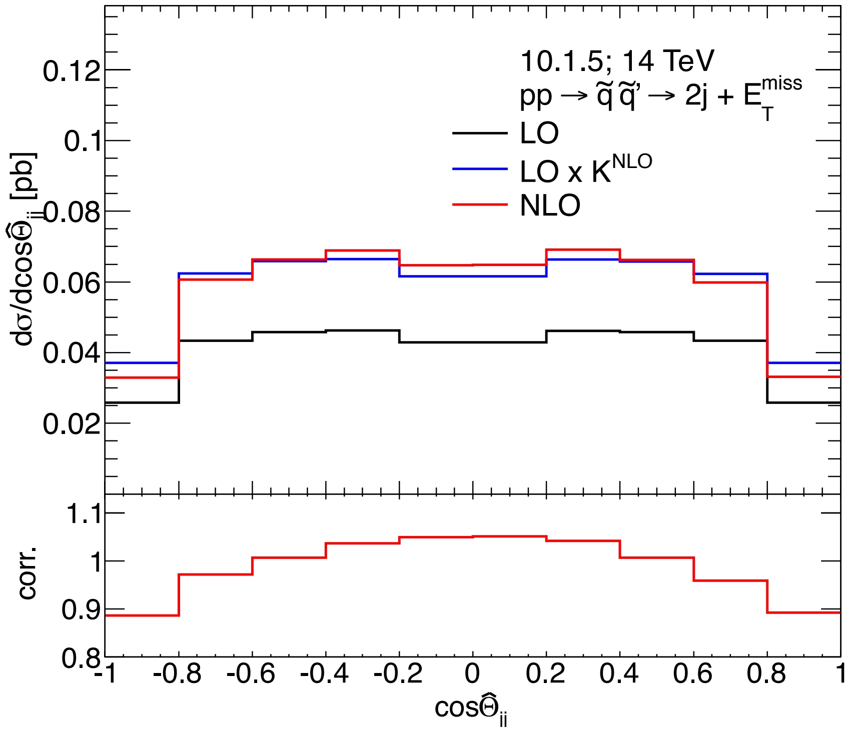
Accurate exclusion limits.



Study & reduce theoretical uncertainties.



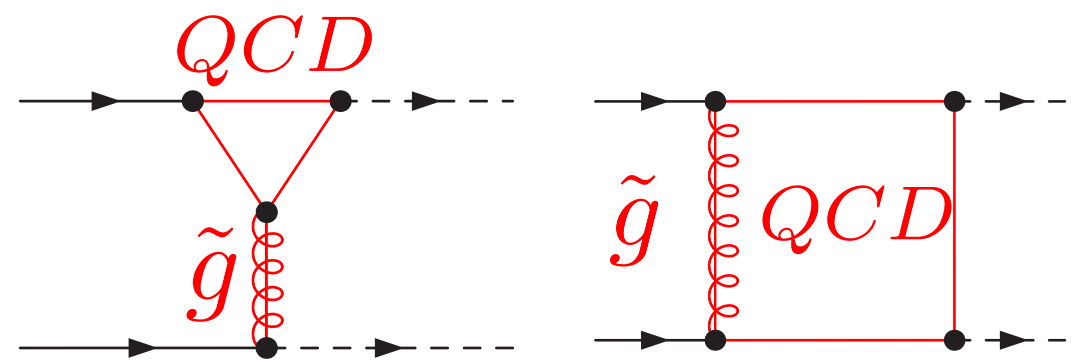
Necessary for parameter determination.



Higher Order Corrections to Production

NLO QCD/SUSY-QCD

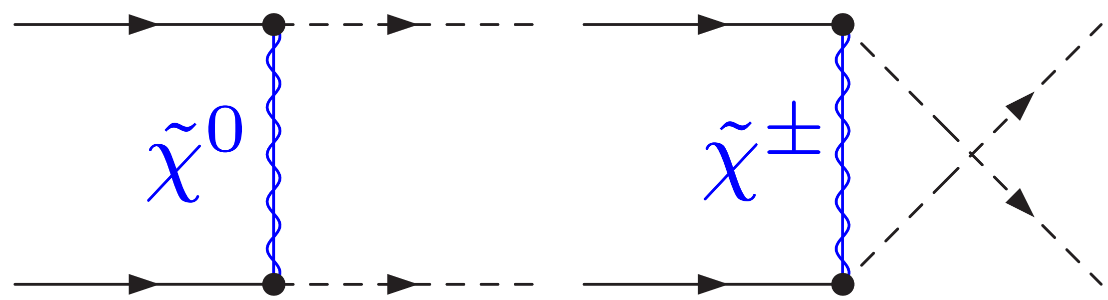
Beenakker et al.'96, Goncalves-Netto et al. '12



α_s^2

LO EW

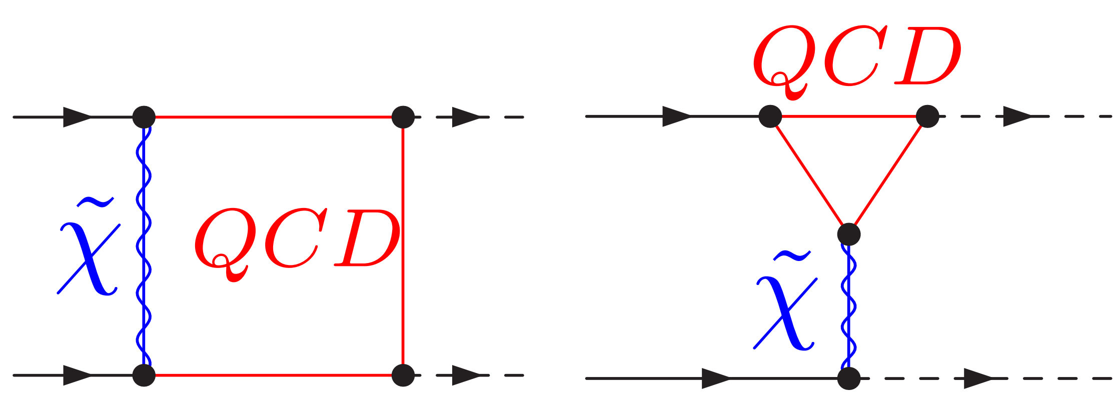
Bornhauser et al. '07



α

NLO EW

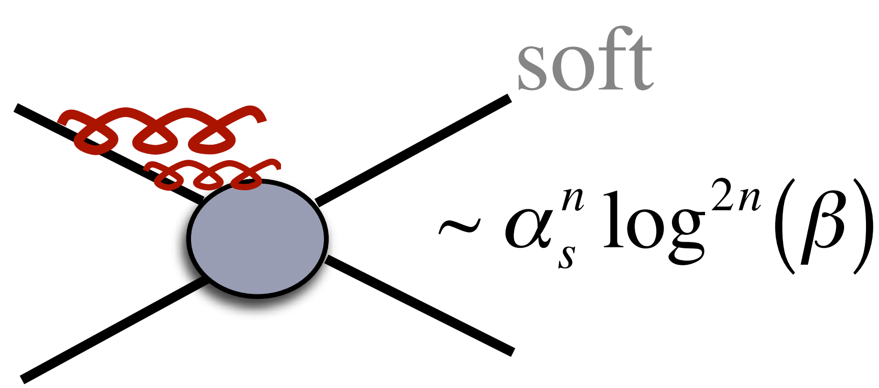
Germer, Hollik, Mirabella,Trenkel '10, ...

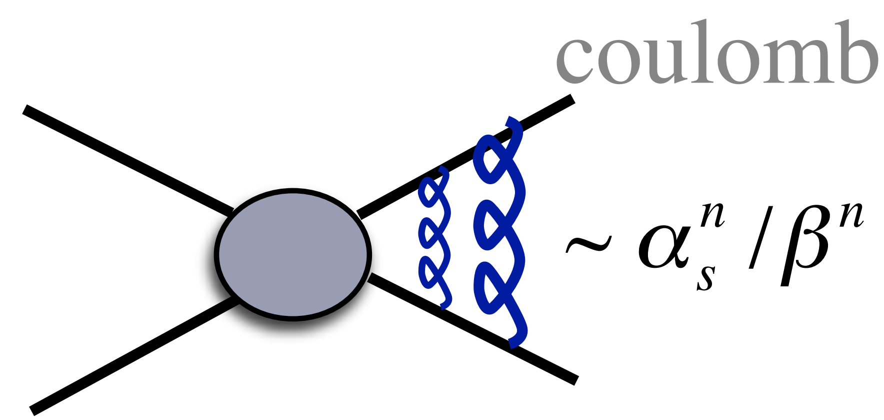


$\alpha_s \alpha$

Beyond NLO (resummed)

Beenakker et al. '09, Falgari, Schwinn, Wever '12, ...





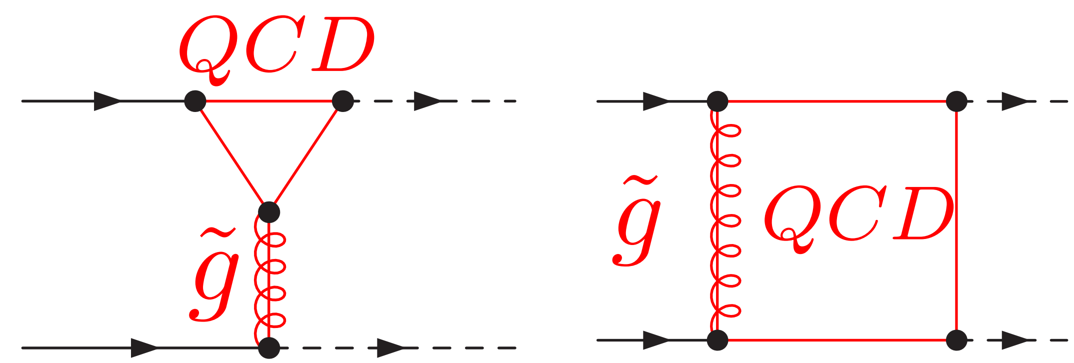
[Kulesza'12]

$\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

Higher Order Corrections to Production

NLO QCD/SUSY-QCD

Beenakker et al.'96, Goncalves-Netto et al. '12



α_s^2

LO EW

Bor

α

mostly corrections to inclusive cross sections or unphysical states!

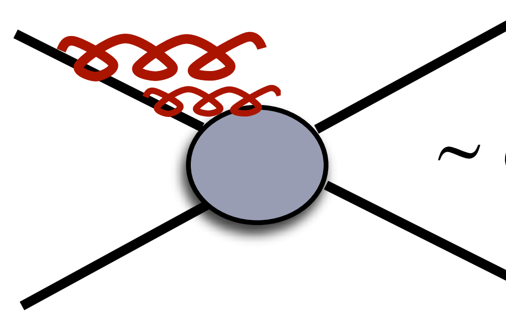
NL

Germer, Hollik, Mirabella, Trenkel '10, ...

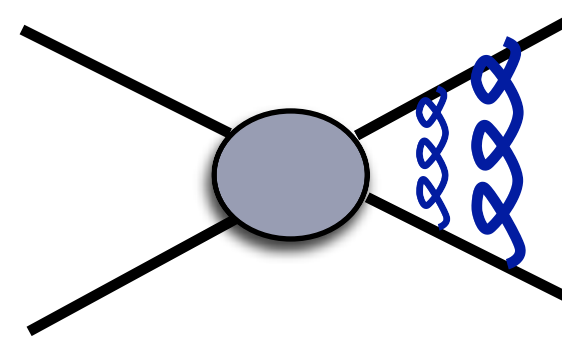
$\alpha_s\alpha$

Beyond NLO (resummed)

Beenakker et al. '09, Falgari, Schwinn, Wever '12, ...



$\sim \alpha_s^n \log^{2n}(\beta)$



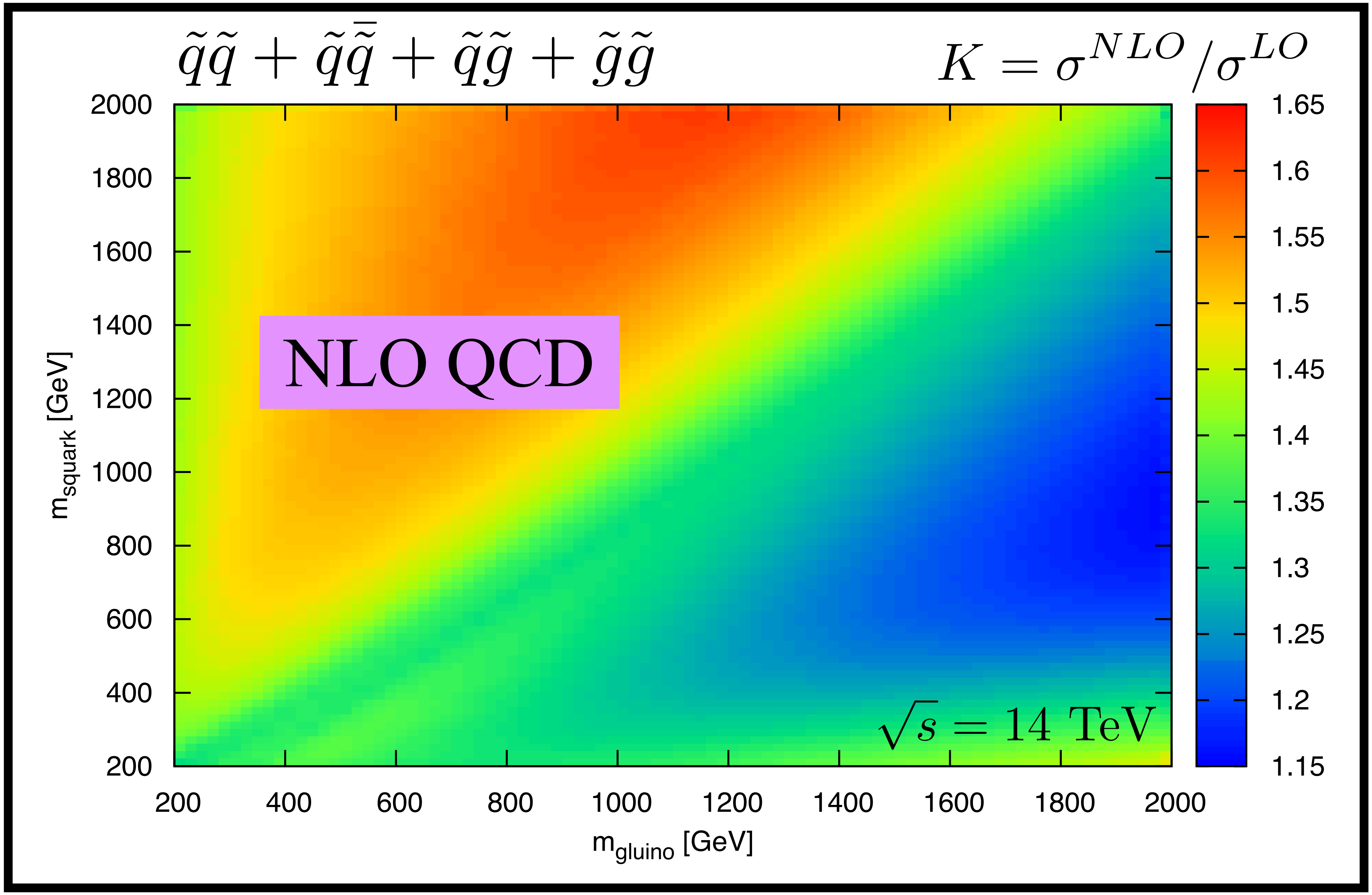
$\sim \alpha_s^n / \beta^n$

[Kulesza'12]

$\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

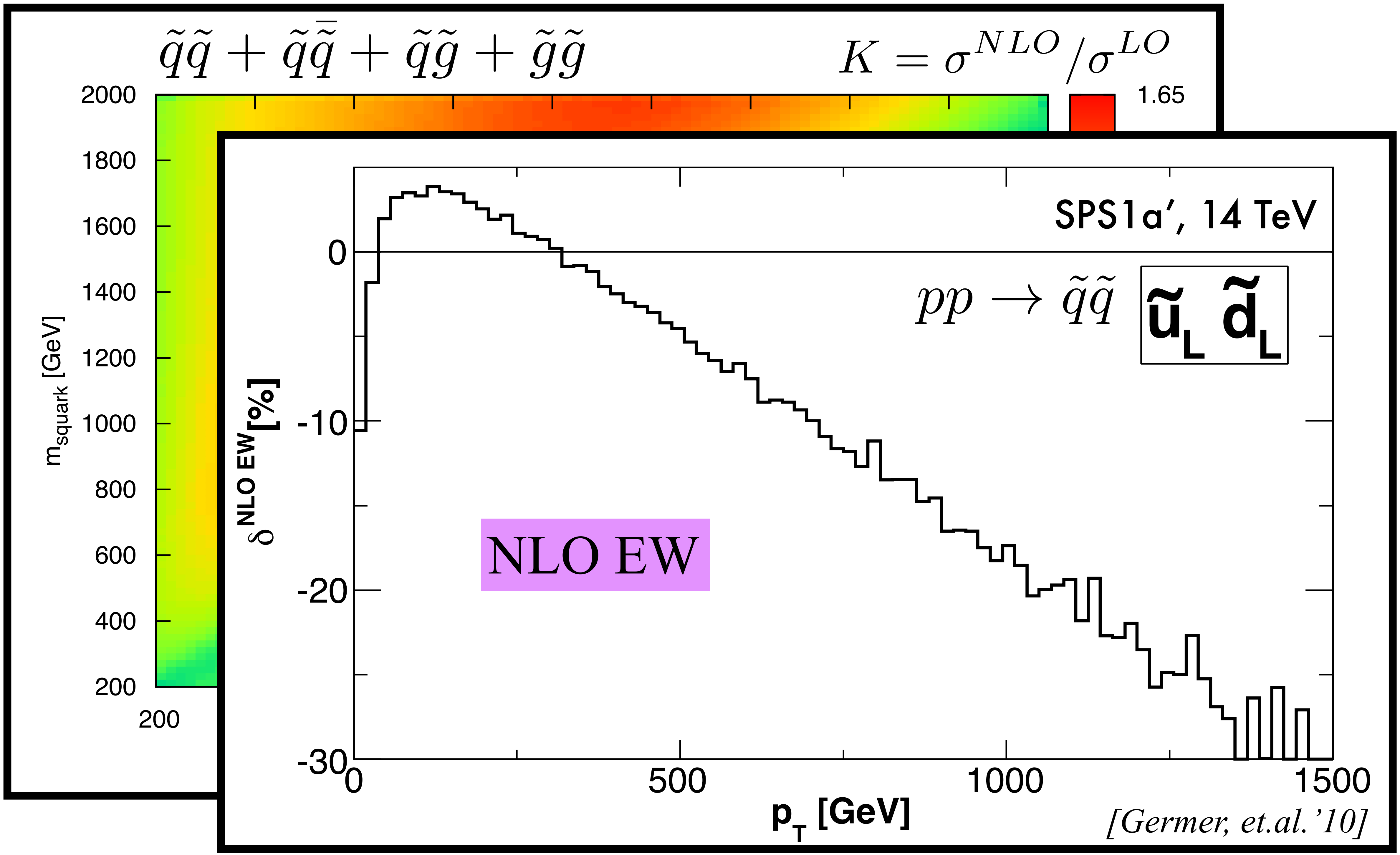
Higher Order Corrections to Production

some examples



Higher Order Corrections to Production

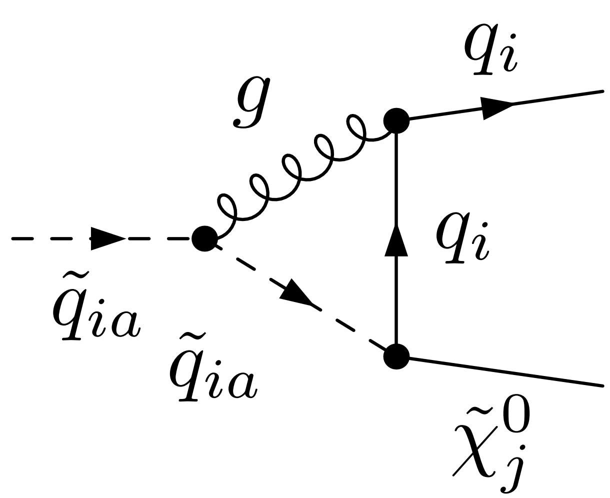
some examples



Higher Order Corrections to Decay

NLO QCD/
SUSY-QCD

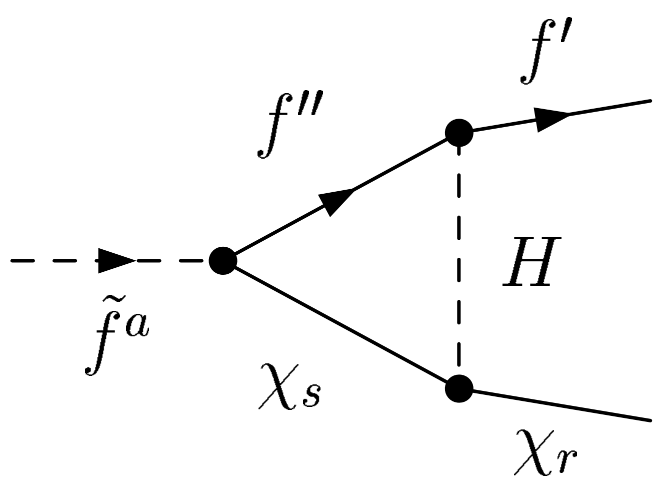
Djouadi, Hollik, Junger '96

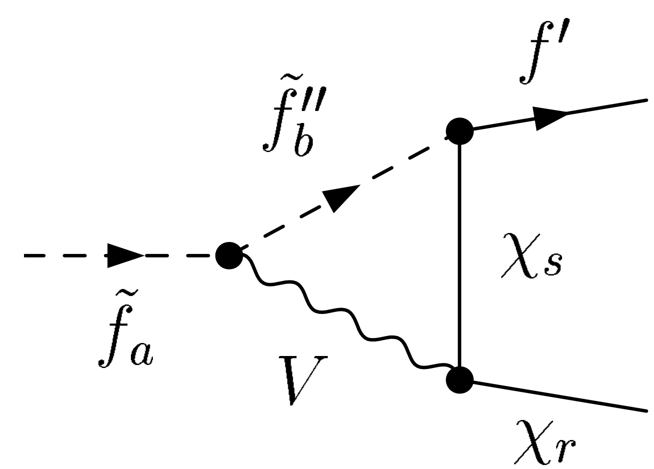


α_S

NLO EW

Guasch, Hollik, Sola '02

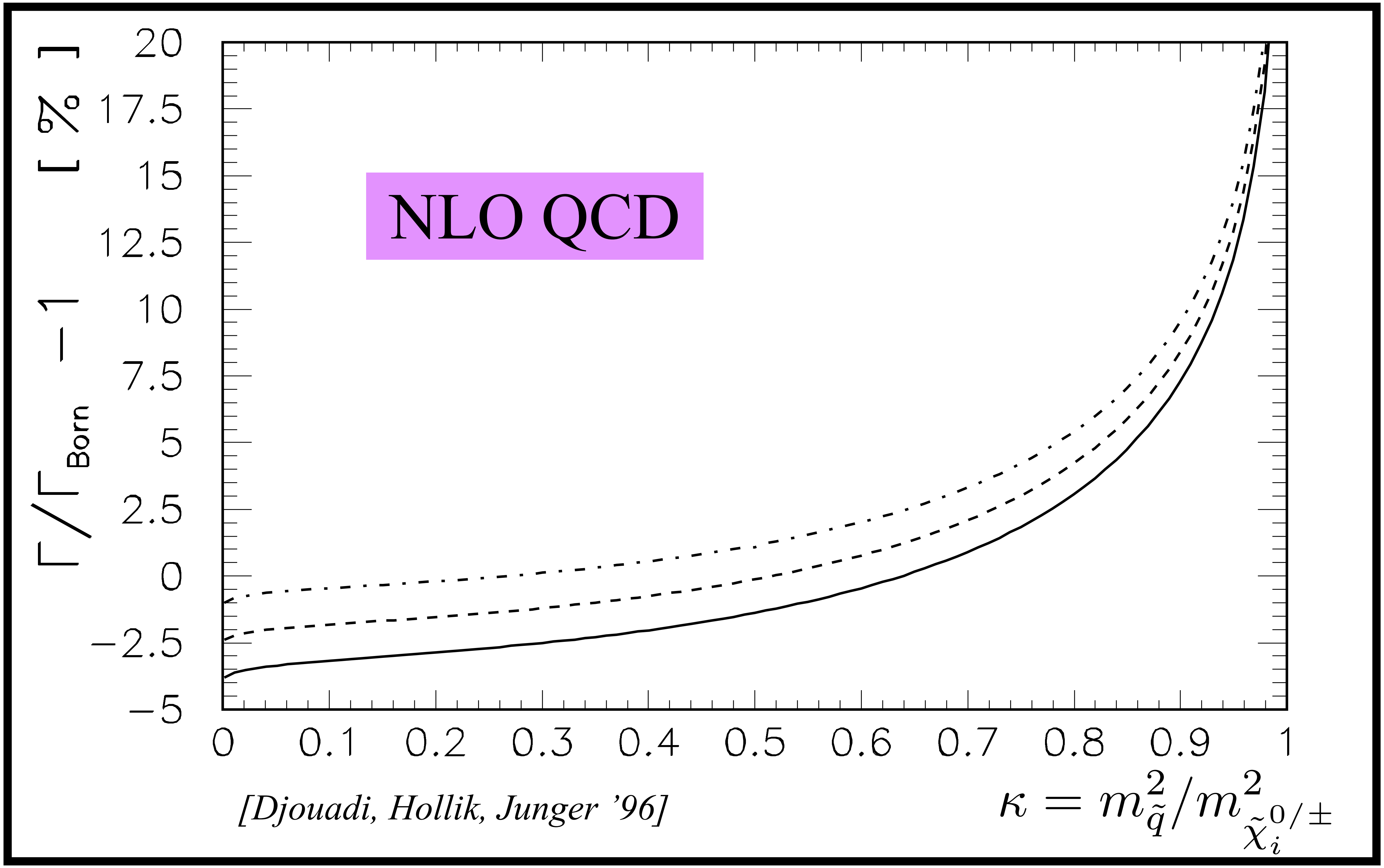


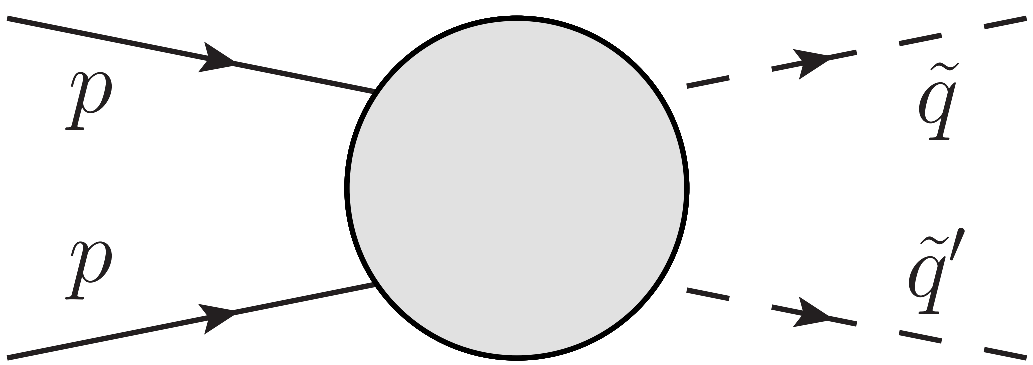


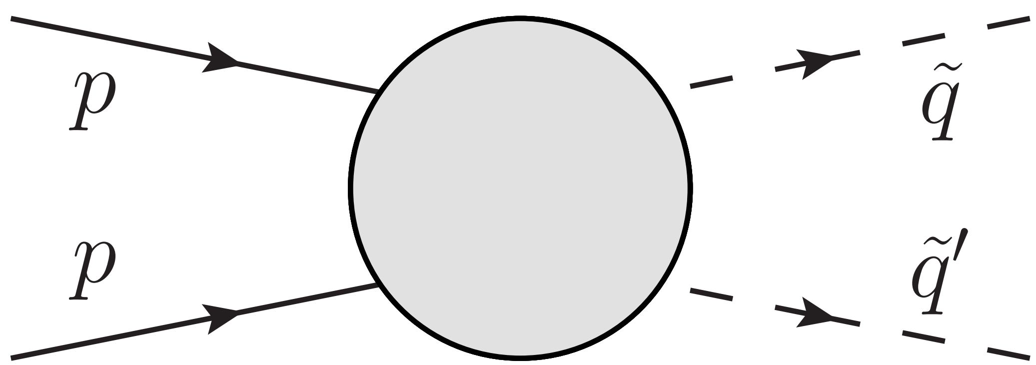
α

Higher Order Corrections to Decay

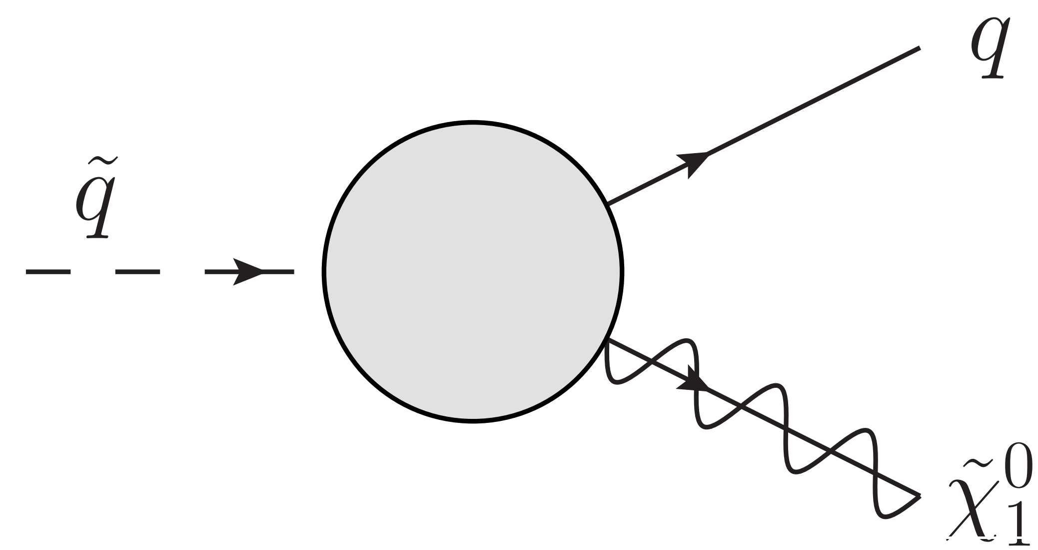
one example



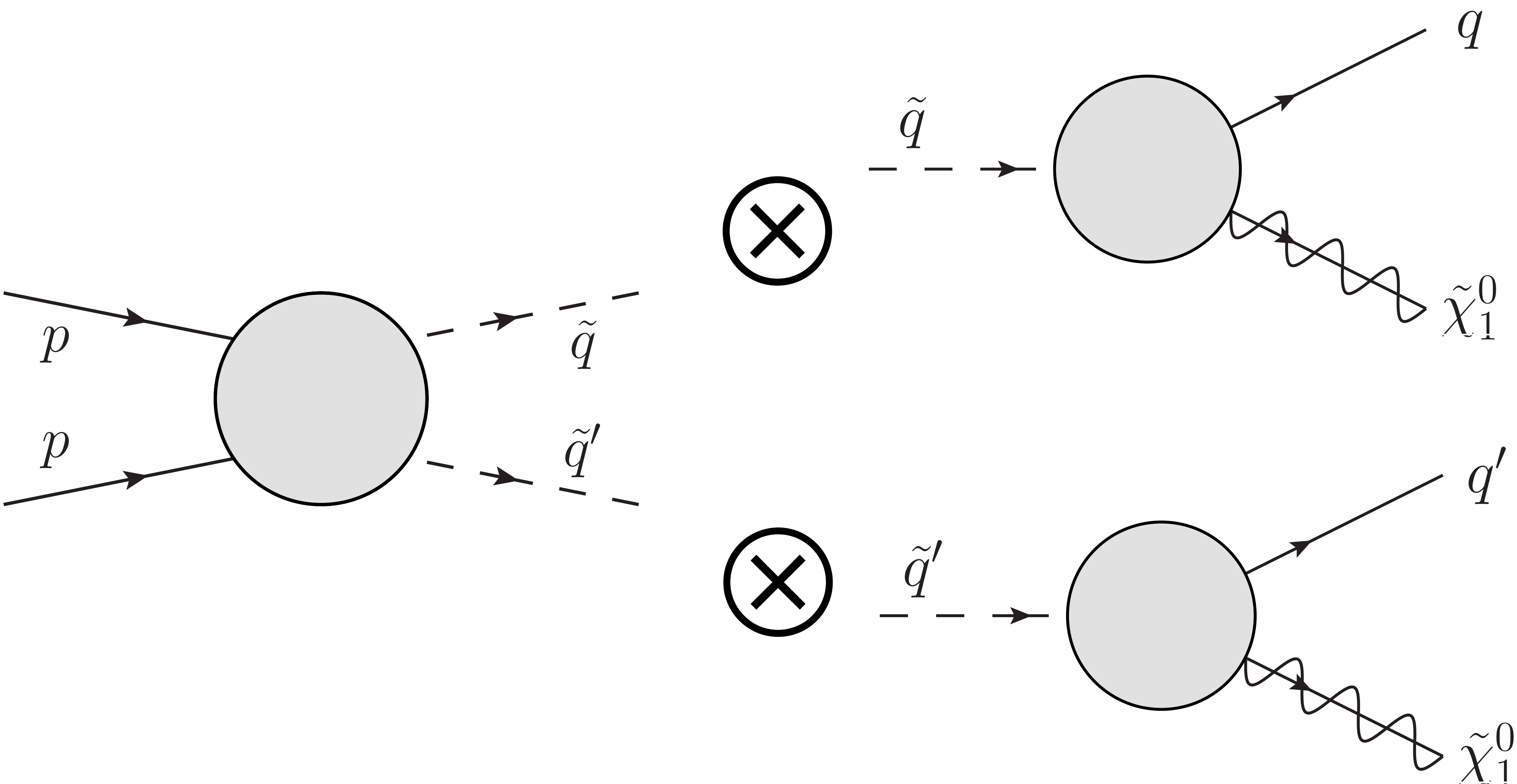

p
p
$\tilde{q}$
$\tilde{q}'$



p
p
$\tilde{q}$
$\tilde{q}'$

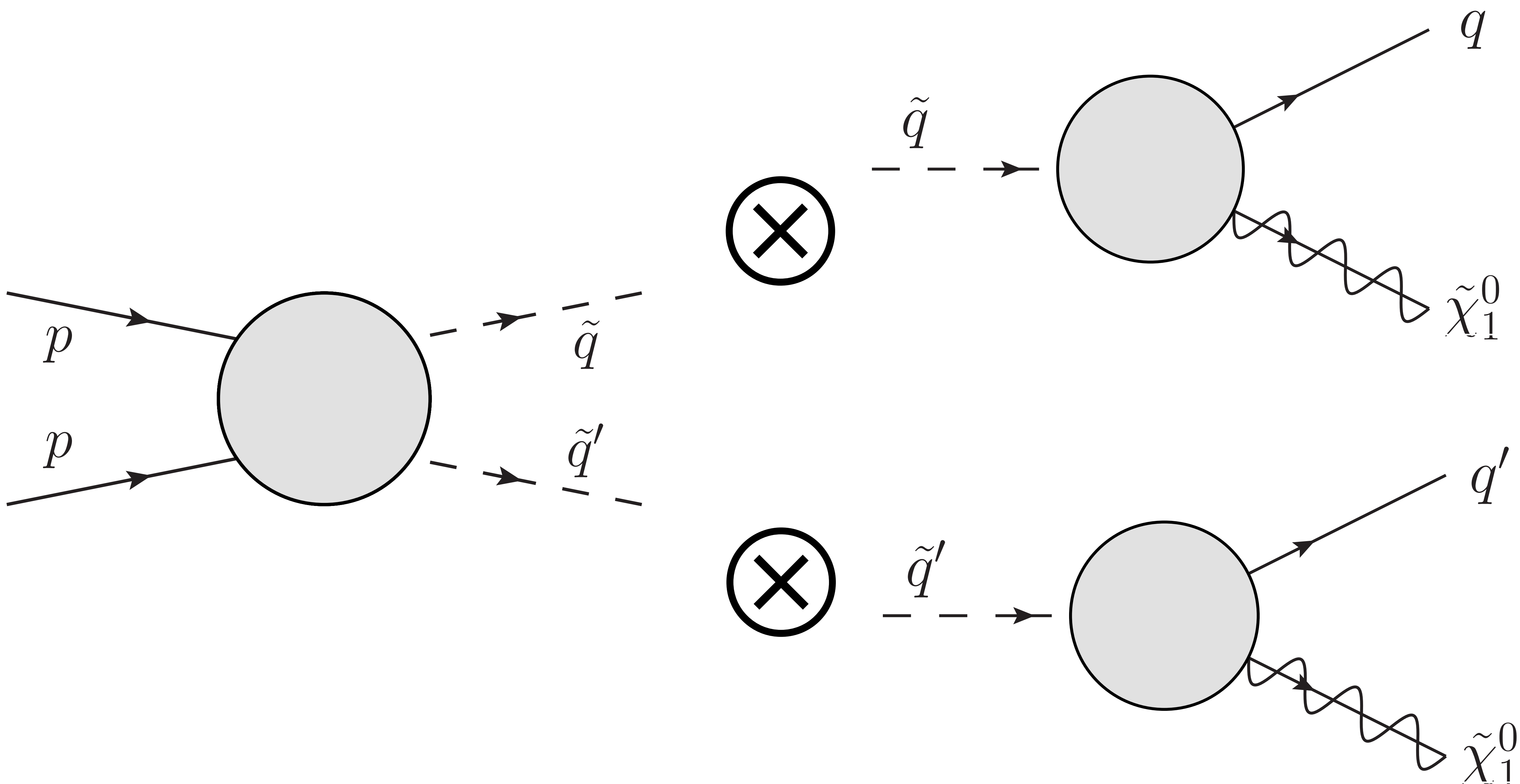


$\tilde{q}$
q
$\tilde{\chi}_1^0$



p
p
$\tilde{q}$
$\tilde{q}'$
$\tilde{q}$
q
$\tilde{\chi}_1^0$
$\tilde{q}'$
q′
$\tilde{\chi}_1^0$

Combining Production and Decay at NLO

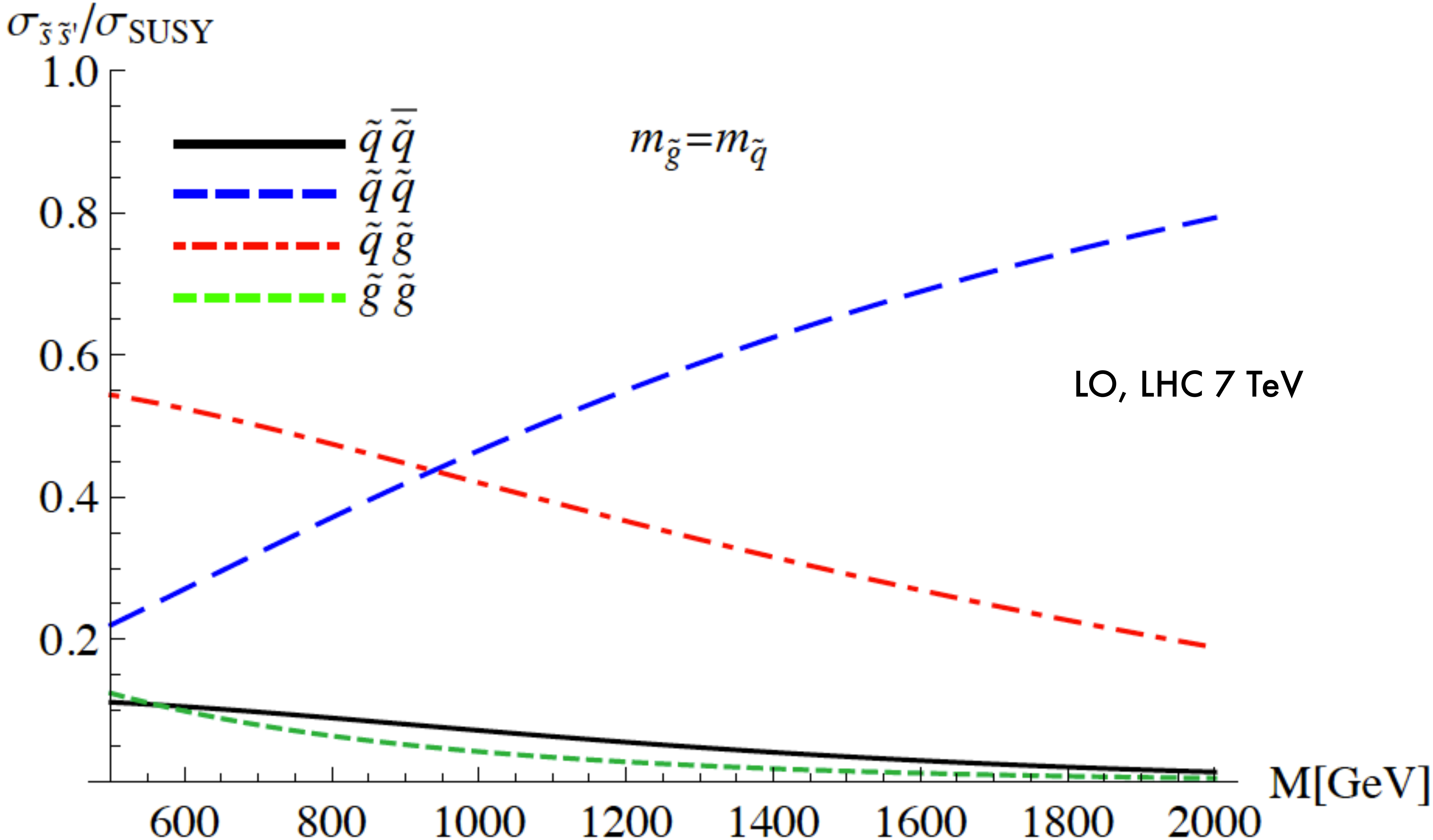


We study the experimental signature $\quad 2j + \not{E}_T(+X)$

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

Combining Production and Decay at NLO

Why squark-squark channel?

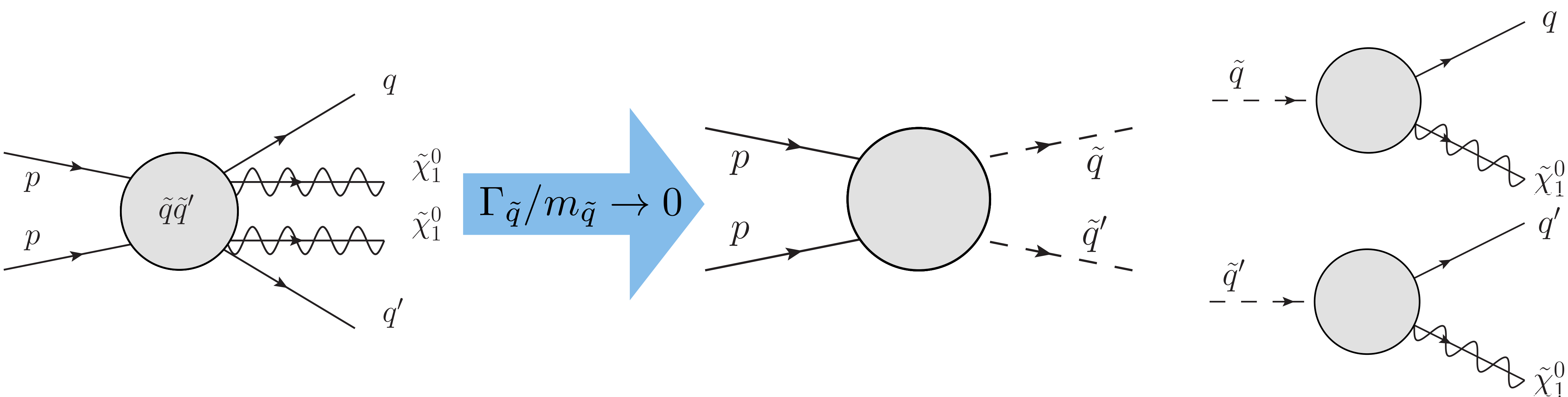


[Falgari, Schwinn, Wever, '12]

LO in NWA

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

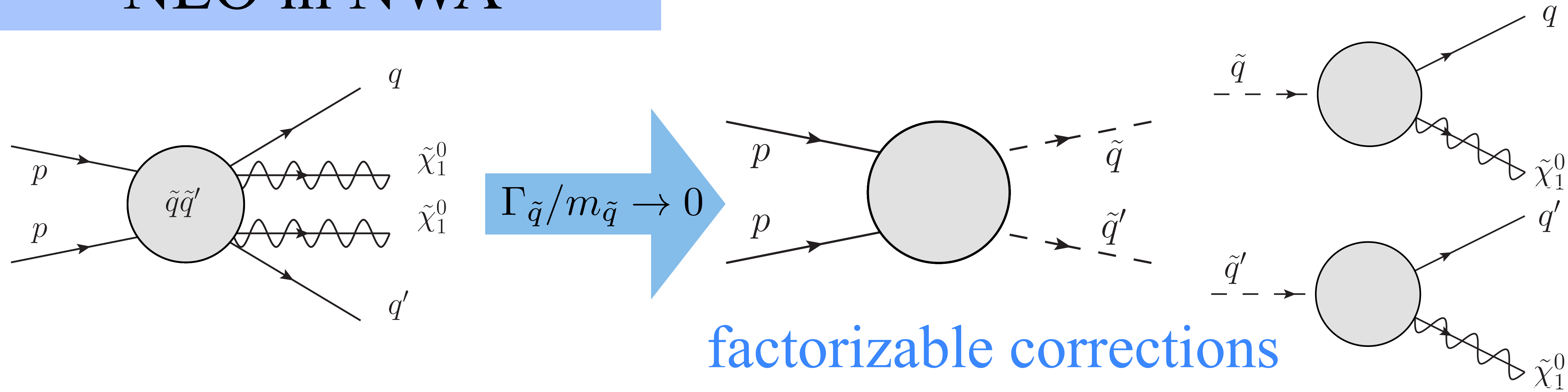
$$\Gamma_{\tilde{q}}/m_{\tilde{q}} \rightarrow 0 \qquad \boxed{\hat{\sigma}^{(0)}_{\text{NWA}} = \hat{\sigma}^{(0)}(qq' \rightarrow \tilde{q}\tilde{q}') \times BR^{(0)}(\tilde{q} \rightarrow q\tilde{\chi}_1^0) \times BR^{(0)}(\tilde{q}' \rightarrow q'\tilde{\chi}_1^0)}$$



Hadronic differential LO cross section in NWA

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

NLO in NWA



Formal expansion in α_s:

Born

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

NLO decay

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

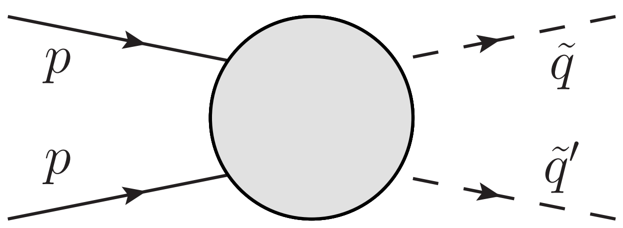
NLO production

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

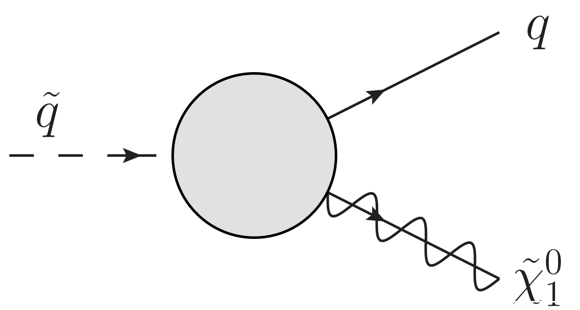
“master formula”

COMBINATION

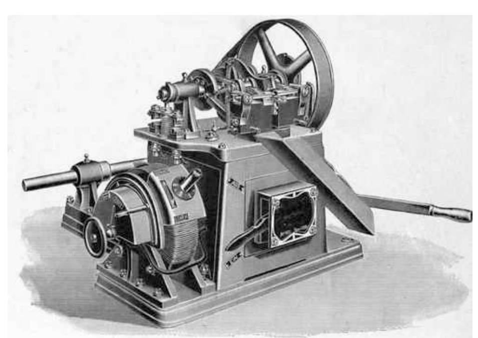
For all different combinations of light flavours and chiralities, weighted events for squark-squark production are produced in the LAB frame.



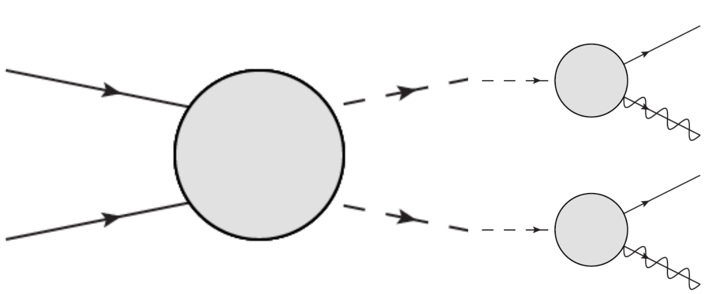
Weighted decay events are generated in the respective squark rest-frame.



boost of decay events + “master formula”



Fully differential prediction of factorizable NLO contributions in NWA.

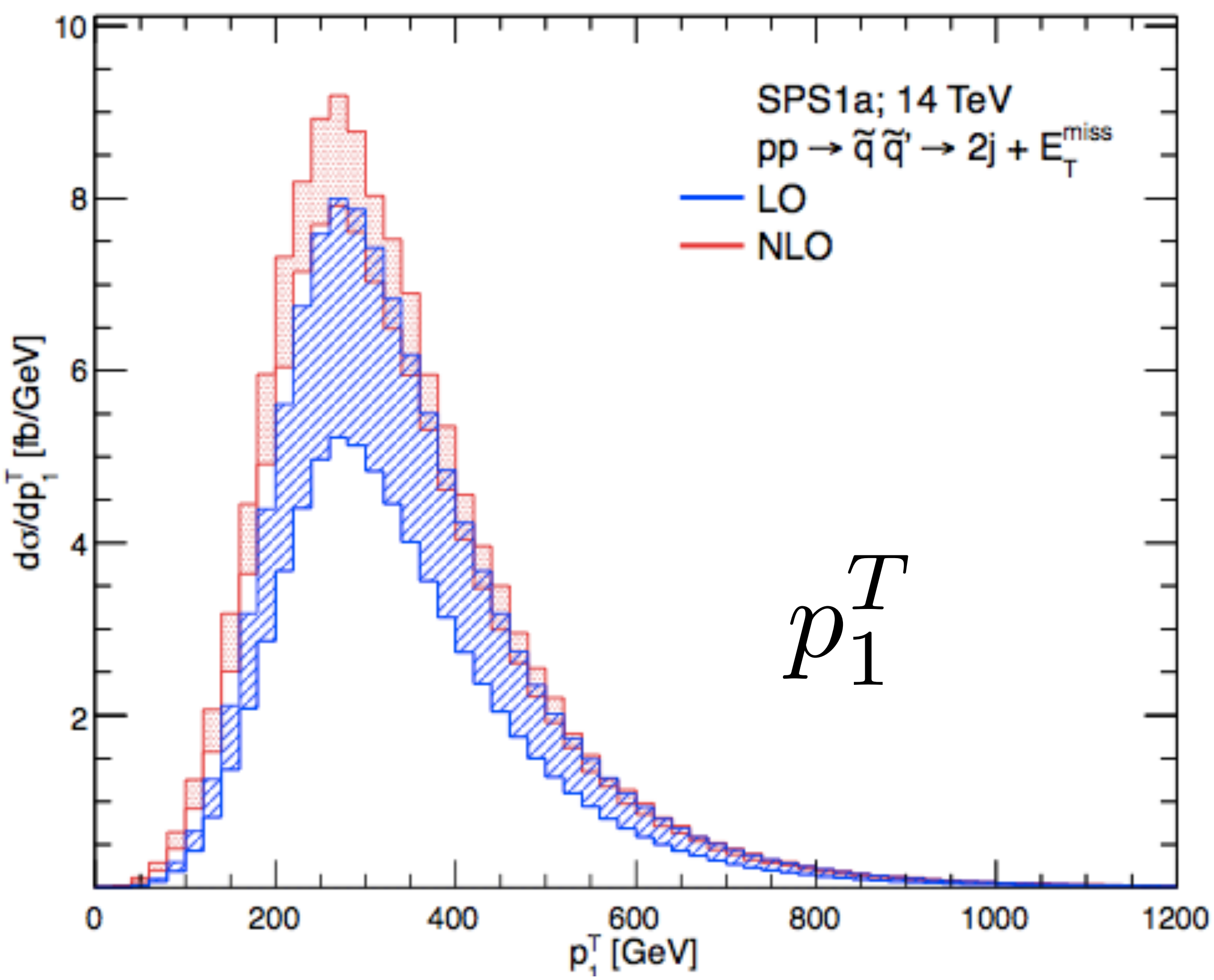


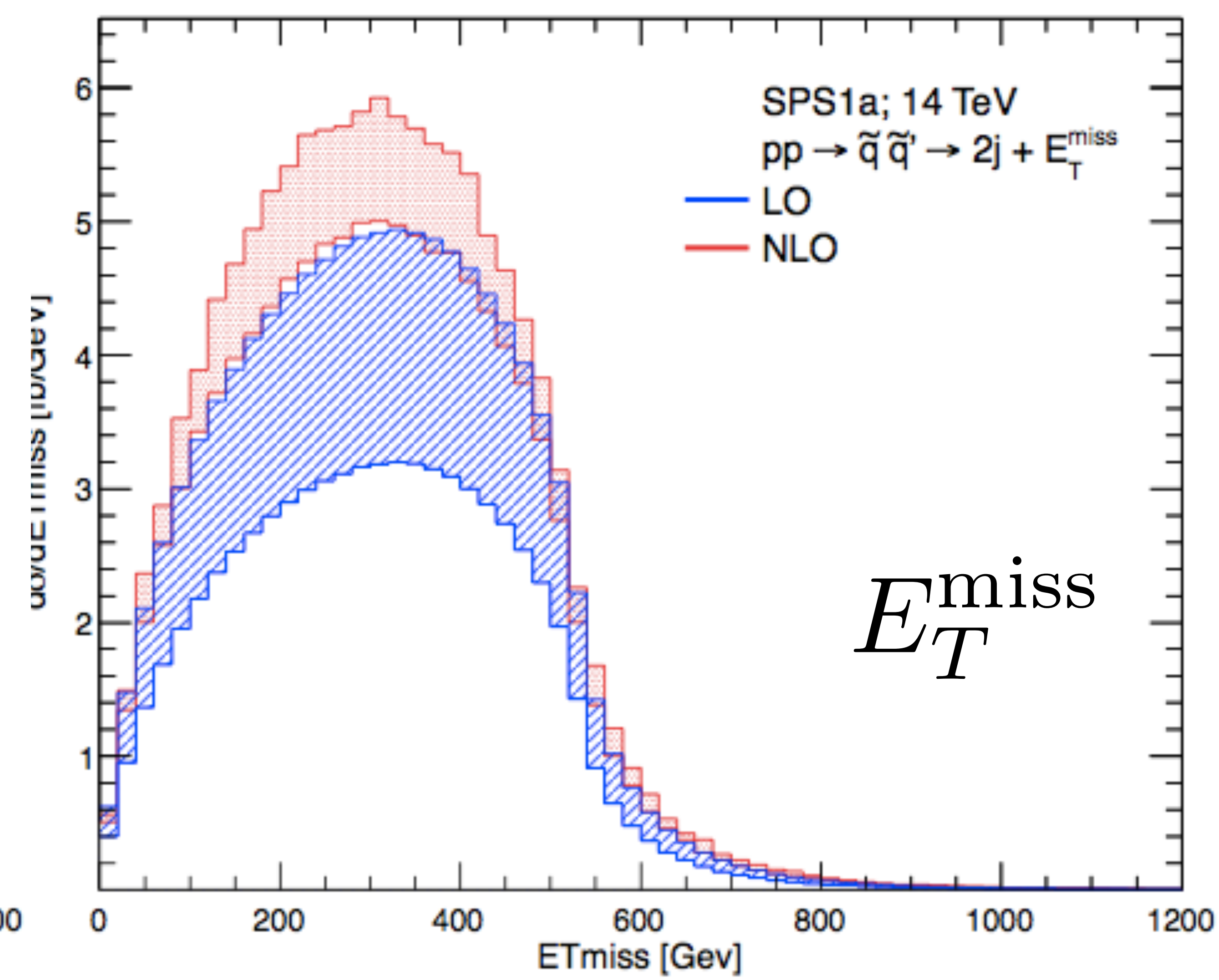
NUMERICAL RESULTS

For **SPS1a (14 TeV)**: Scale variation: $\boldsymbol{\mu_f = \mu_r = (m/2, m, 2m)}$, m: average $\tilde{q}$ 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 both for LO and NLO)

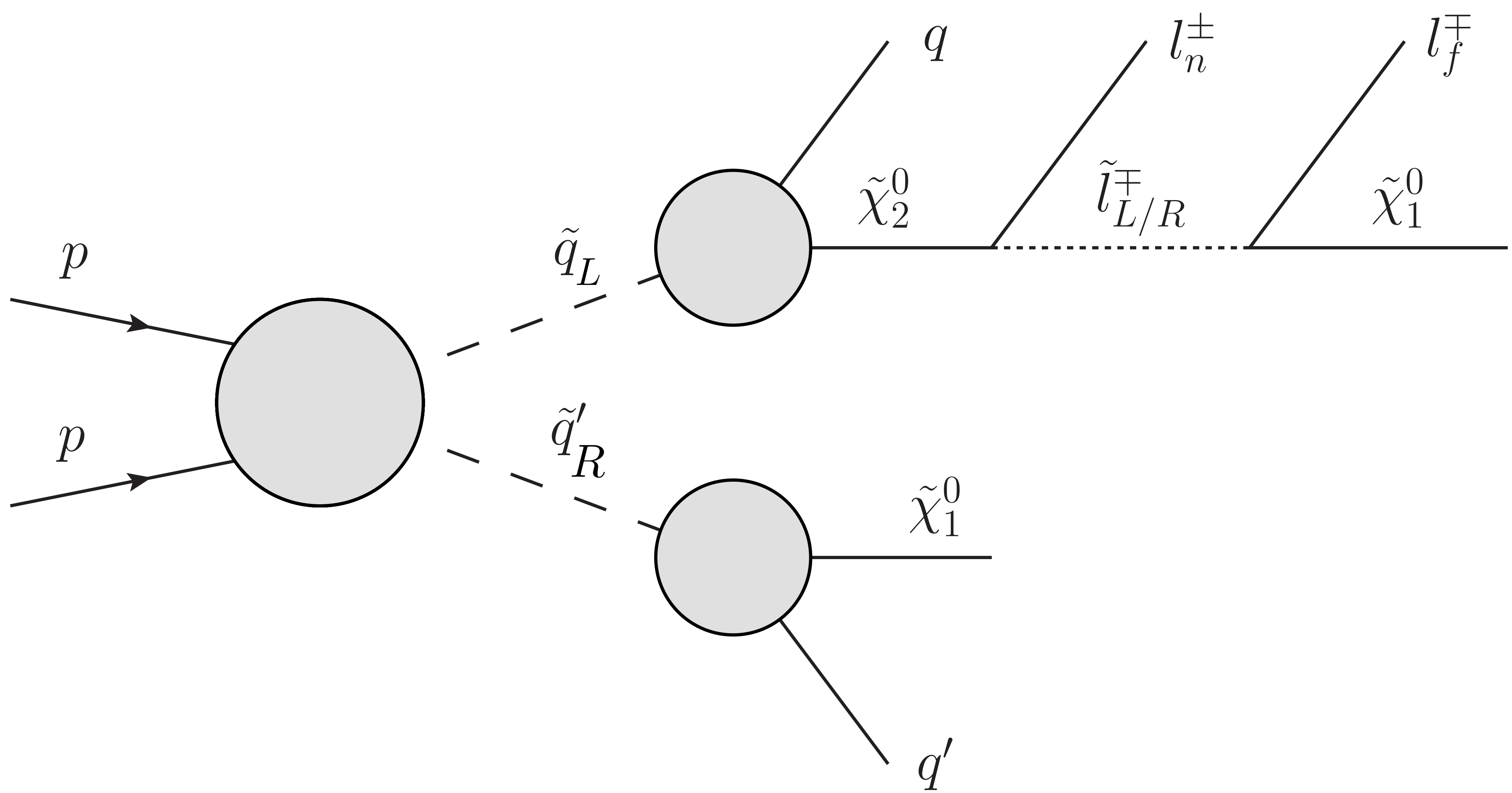




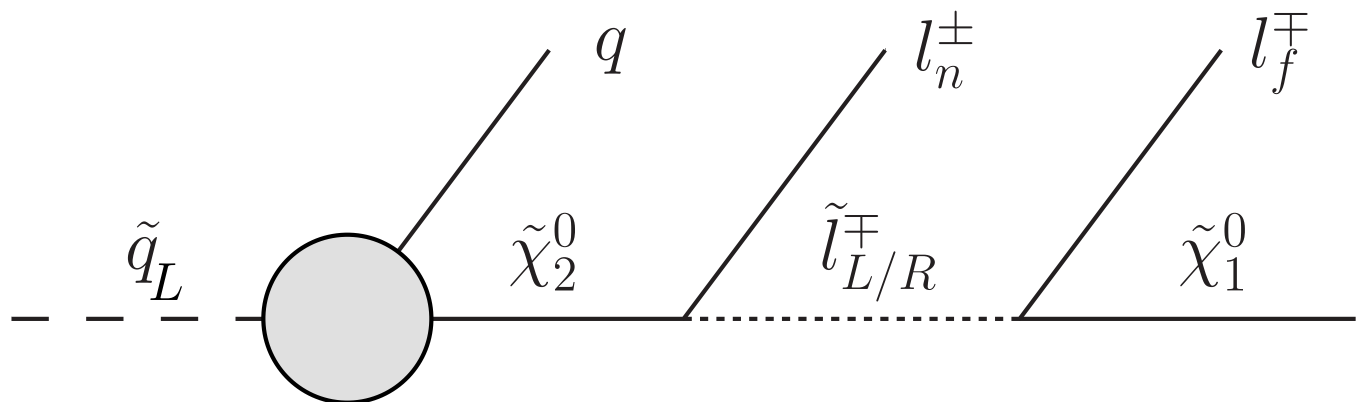
Combining Production and a Decay Chain at NLO

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

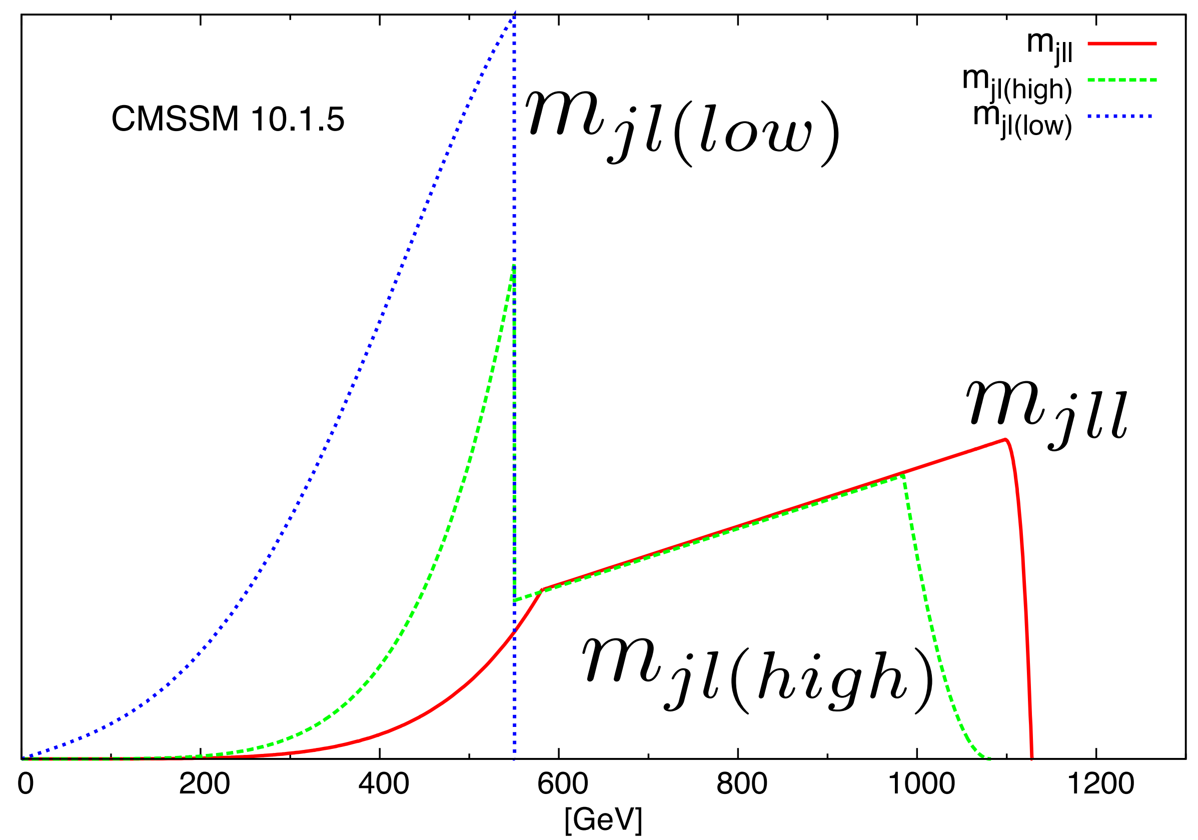
via squark-squark production and an attached EW decay chain. $pp \to \tilde{q}_L \tilde{q}'_R \to q\tilde{\chi}^0_1 q' l^+ l^- \tilde{\chi}^0_1 (+X)$

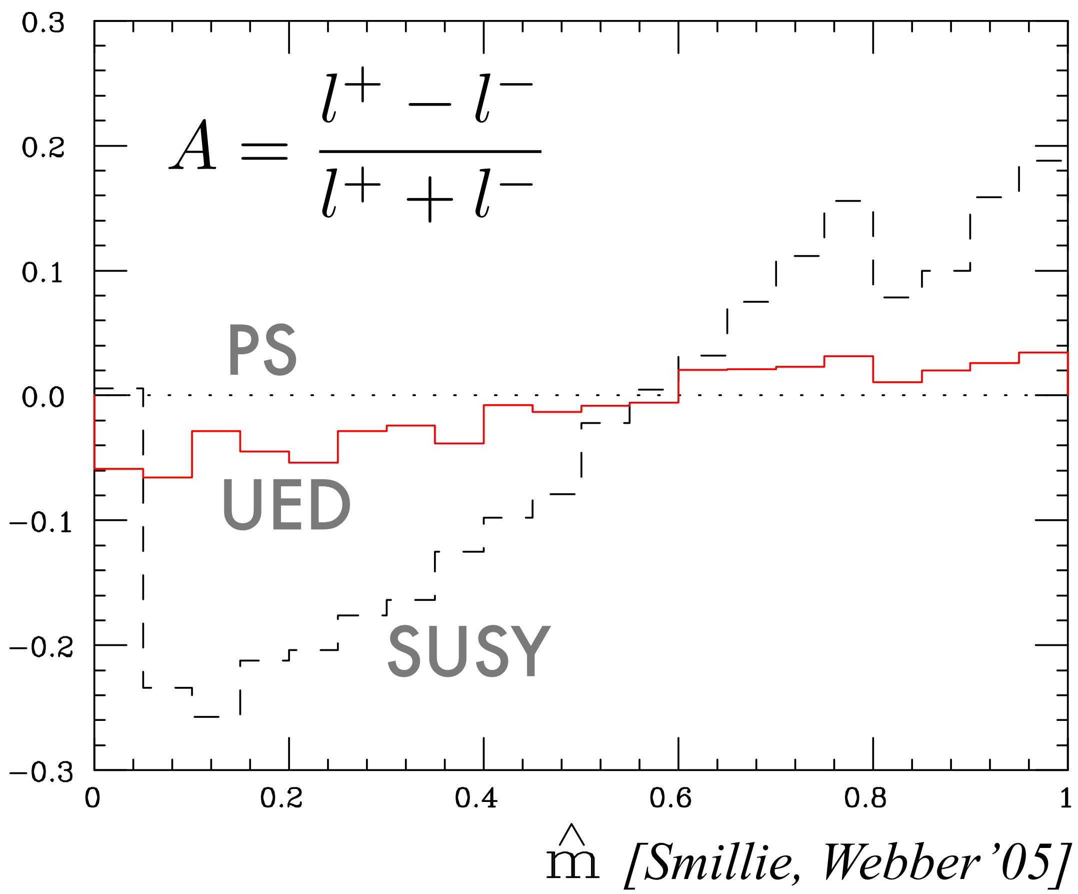


The "golden" decay chain



- 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.



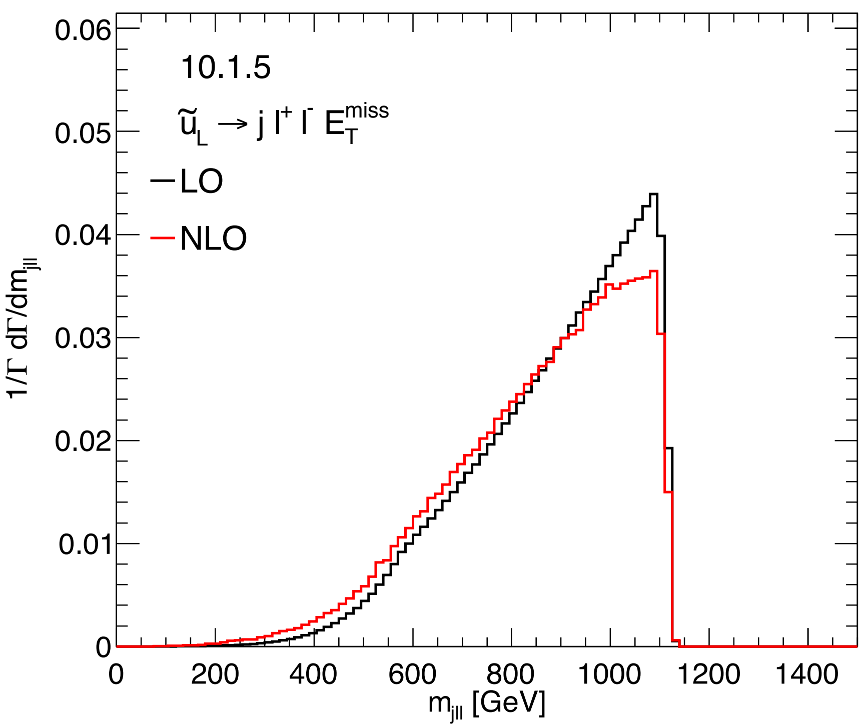


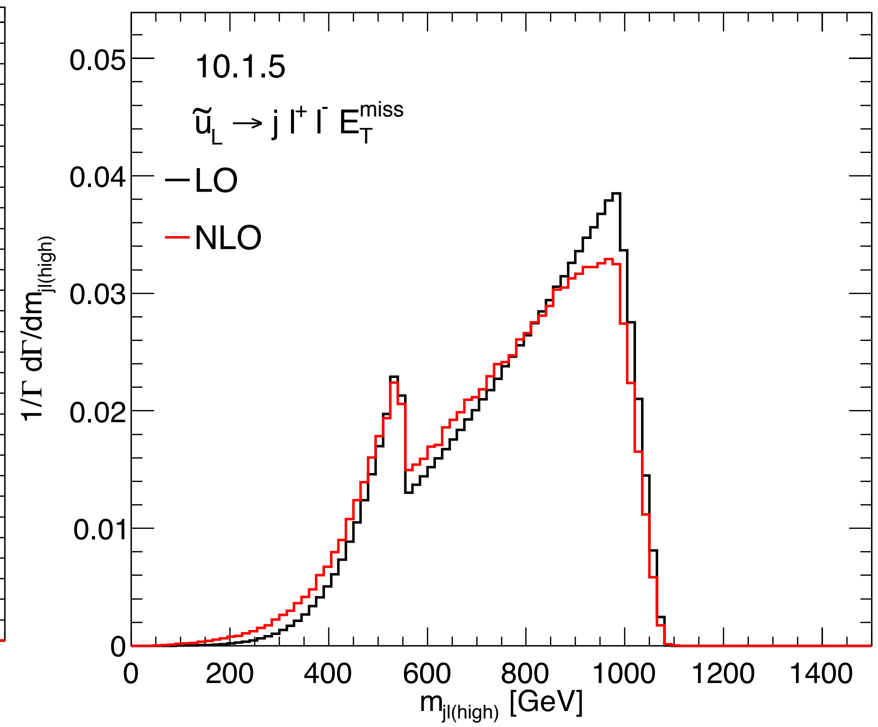
[Smillie, Webber '05]

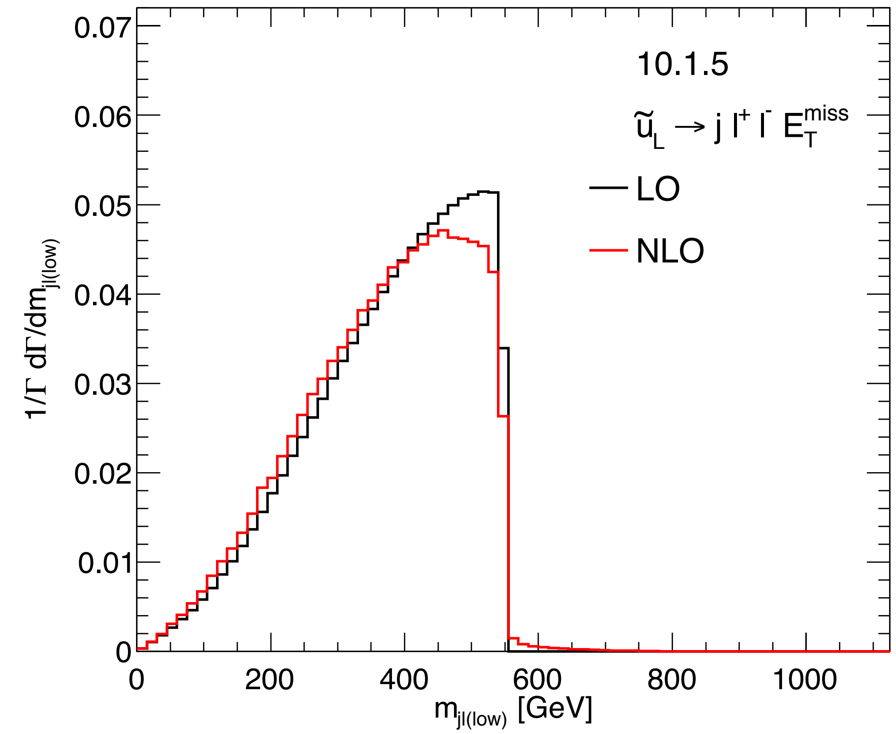
Comparison between NLO and LO corrections purely in the **shapes** of distributions.

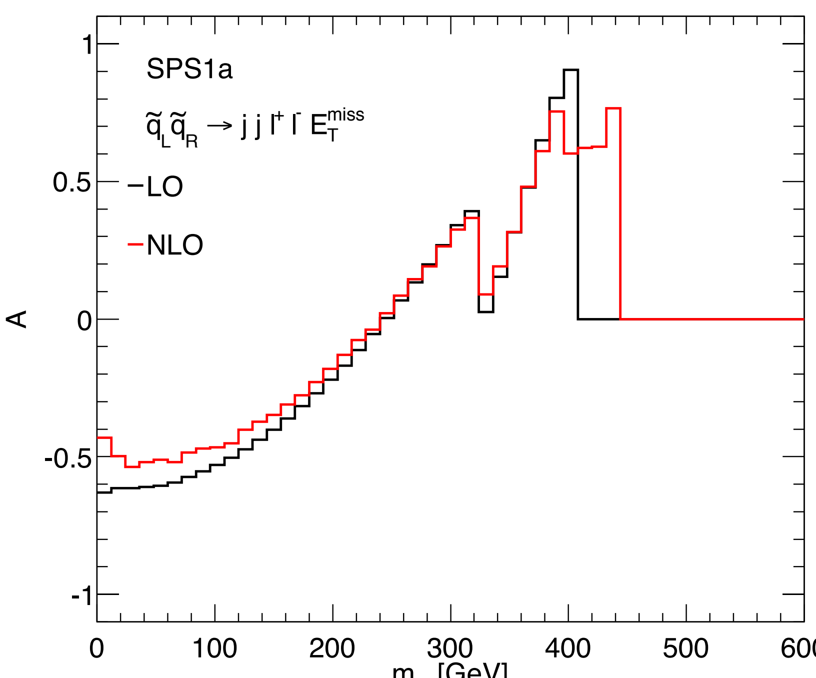
10.1.5	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
mass (GeV)	1437.7	1382.3	1439.7	1376.9	1568.6	291.3

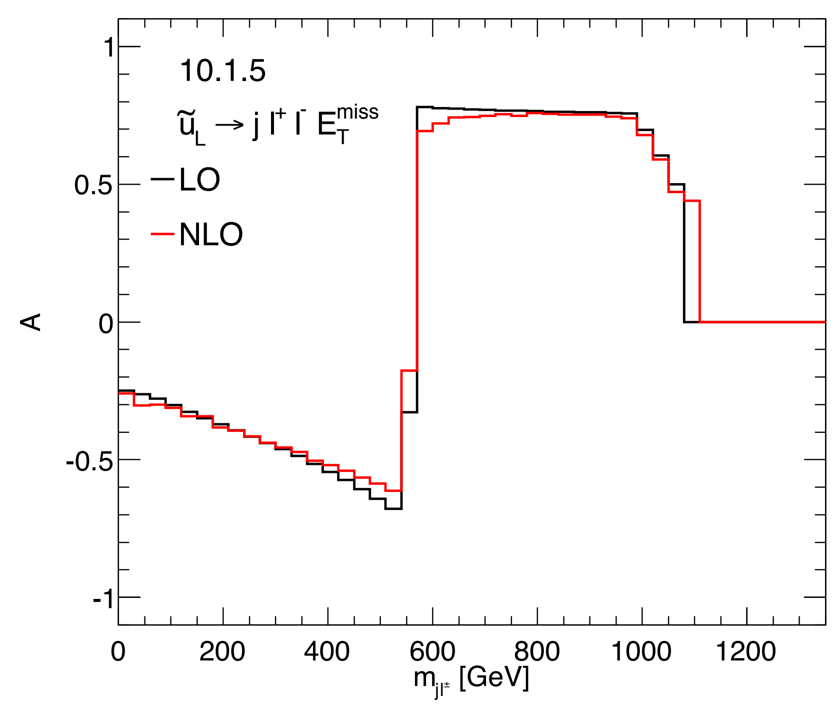
LHC 14 TeV











CONCLUSION

Knowledge of higher-order corrections to squark/gluino processes are important for precise description of physical observables and thus for setting **accurate limits** and even more for **parameter determination**.

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

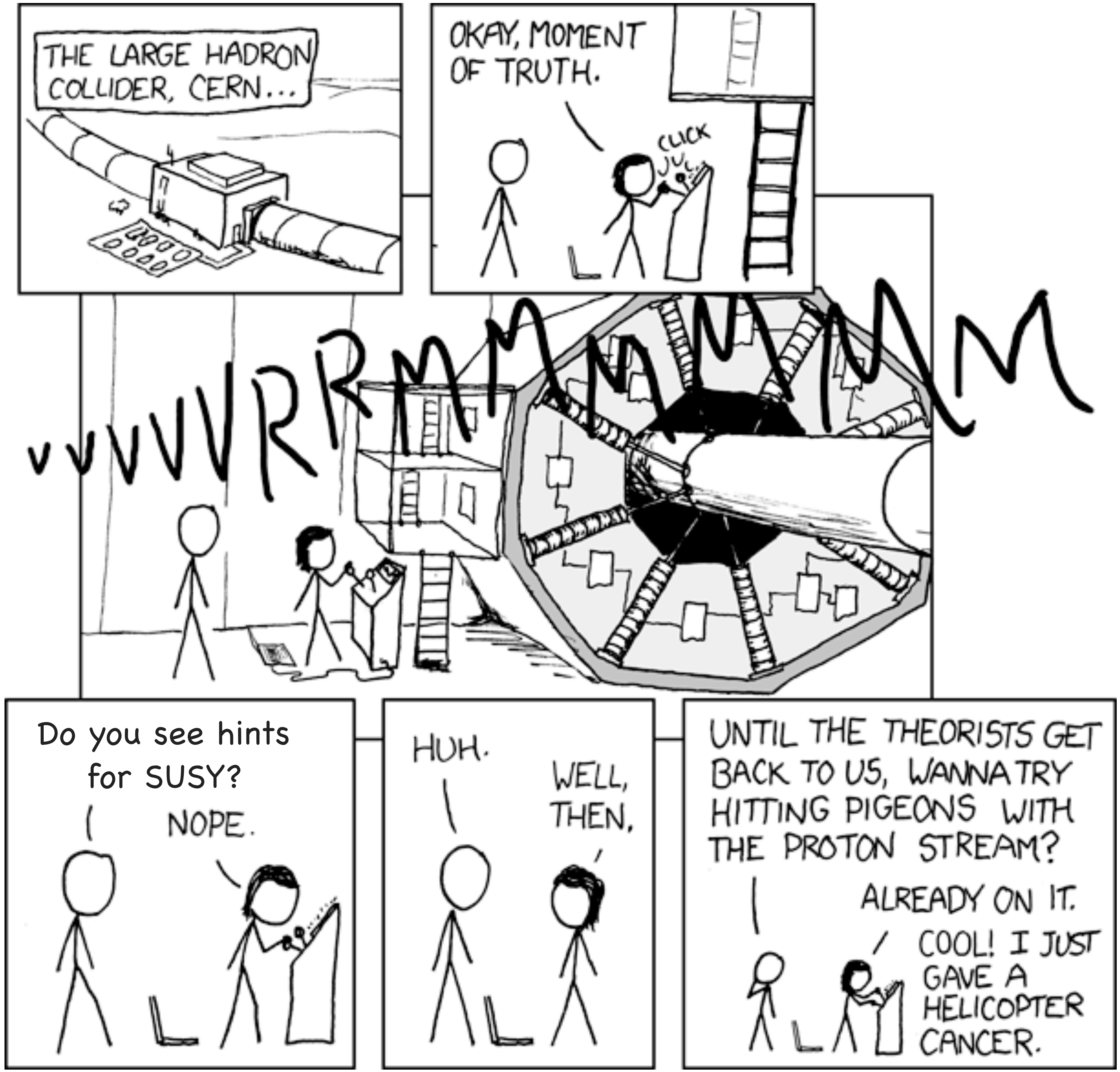
OUTLOOK

Study of further experimental signatures (monojets) under way.

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

Discovery of SUSY in the next run of the LHC.

T h a n k s !

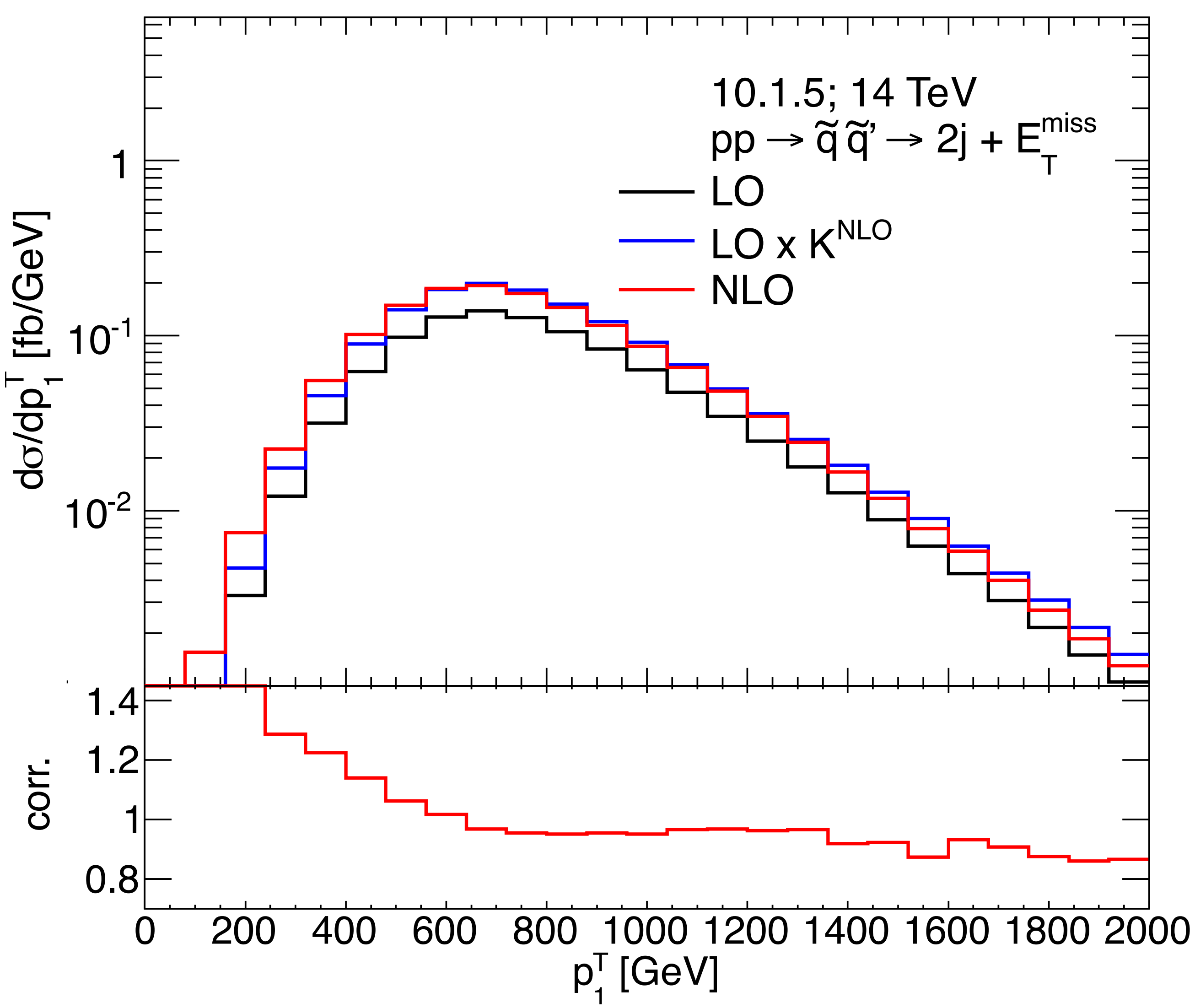


THE LARGE HADRON COLLIDER, CERN...
OKAY, MOMENT OF TRUTH.
CLICK
vvvVVVRRMMMMMMM
Do you see hints for SUSY?
NOPE.
HUH.
WELL, THEN,
UNTIL THE THEORISTS GET BACK TO US, WANNA TRY HITTING PIGEONS WITH THE PROTON STREAM?
ALREADY ON IT.
COOL! I JUST GAVE A HELICOPTER CANCER.

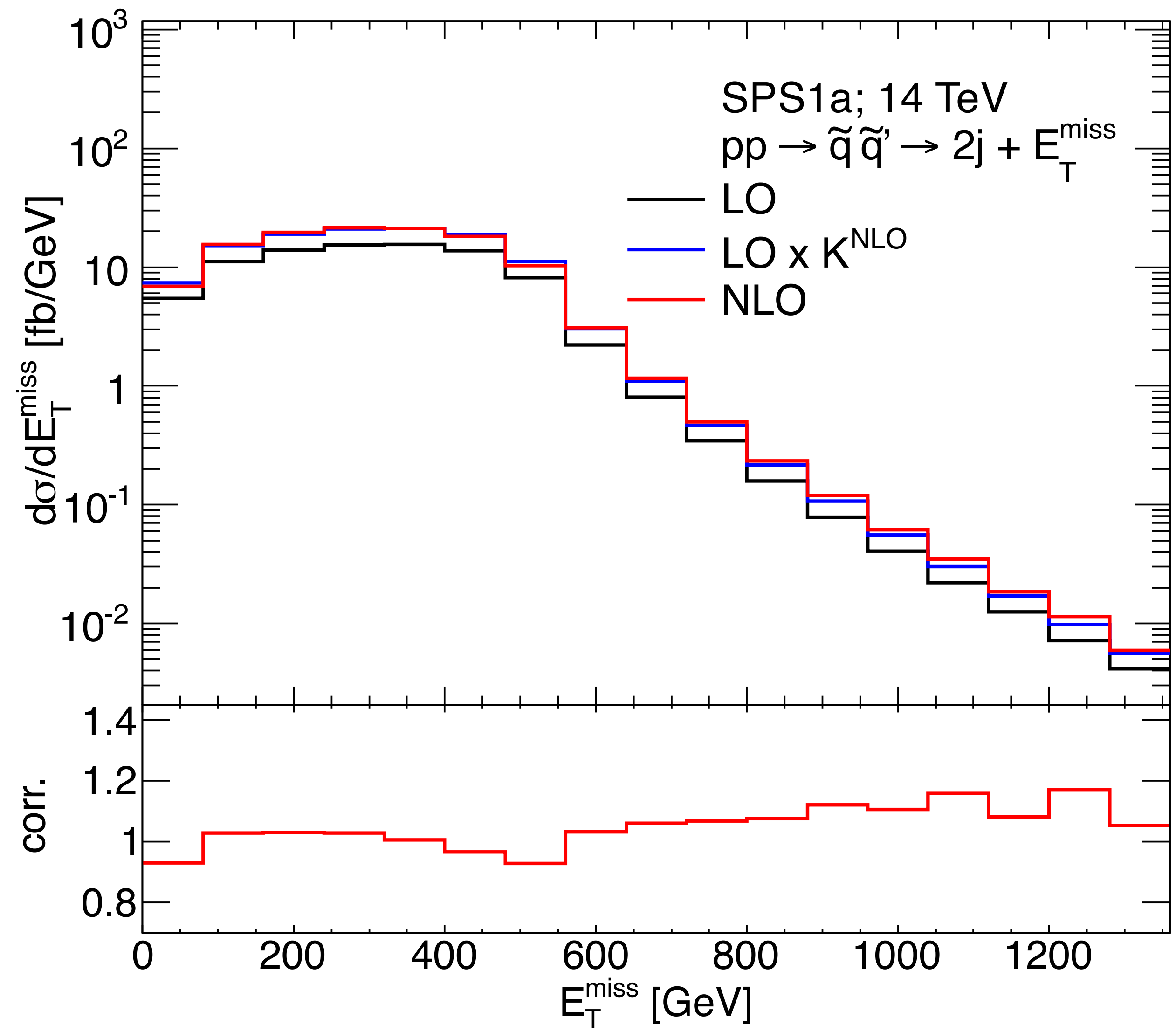
CMSSM 10.1.5 (14 TeV)

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



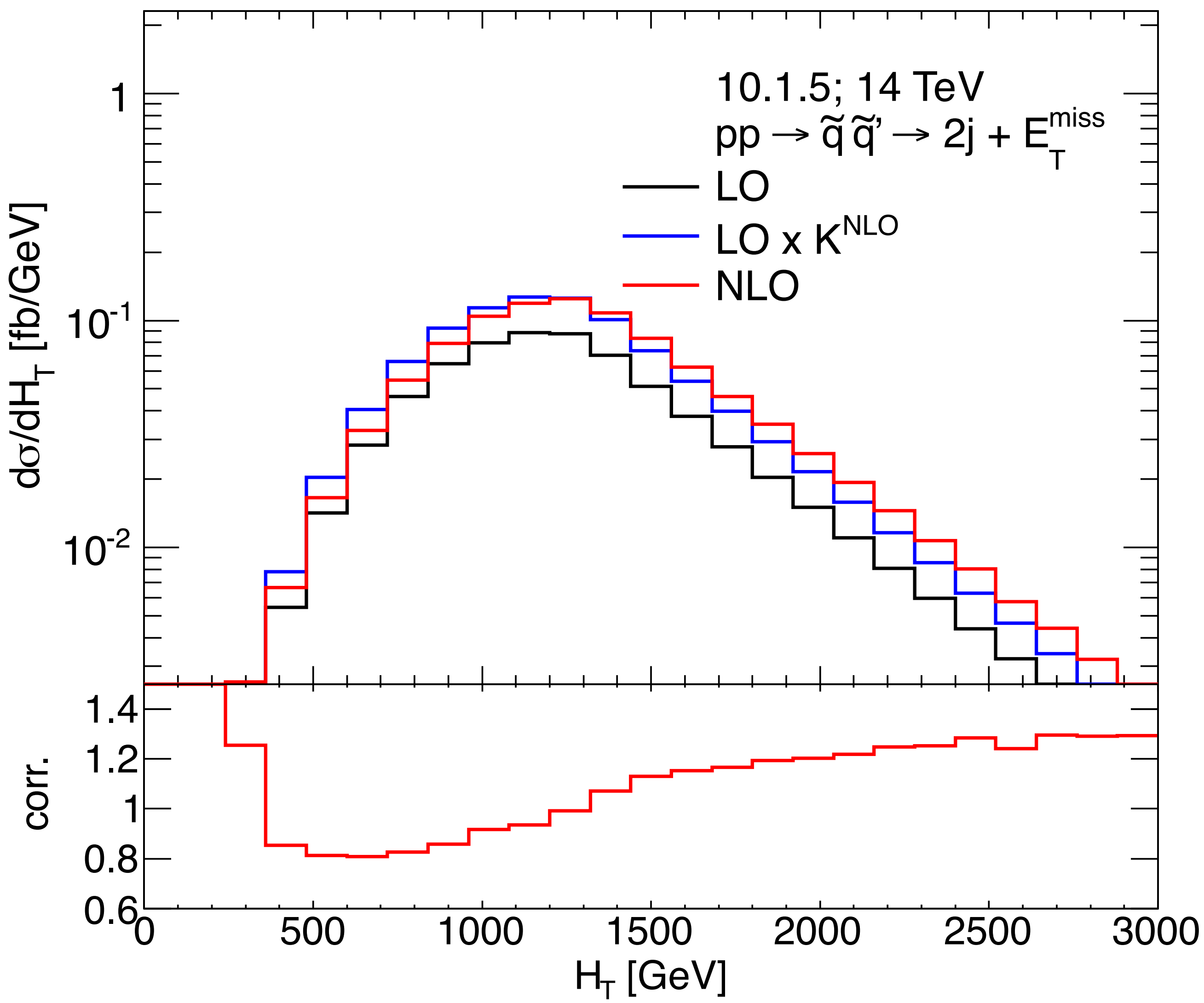
$$p_1^T$$

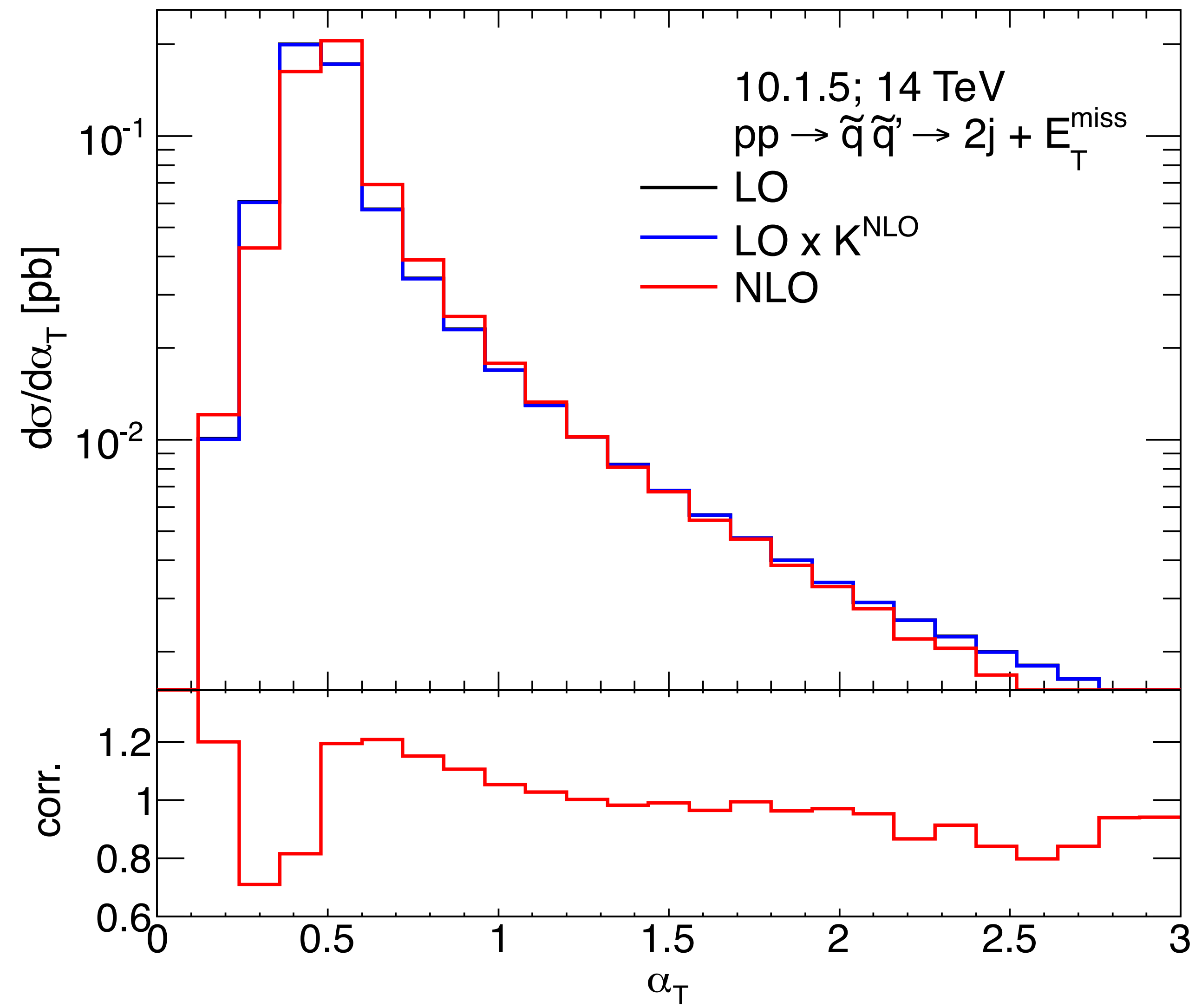


$$E_T^{\text{miss}}$$

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





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

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

CMSSM 10.1.5 (14 TeV)

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

10.1.5	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
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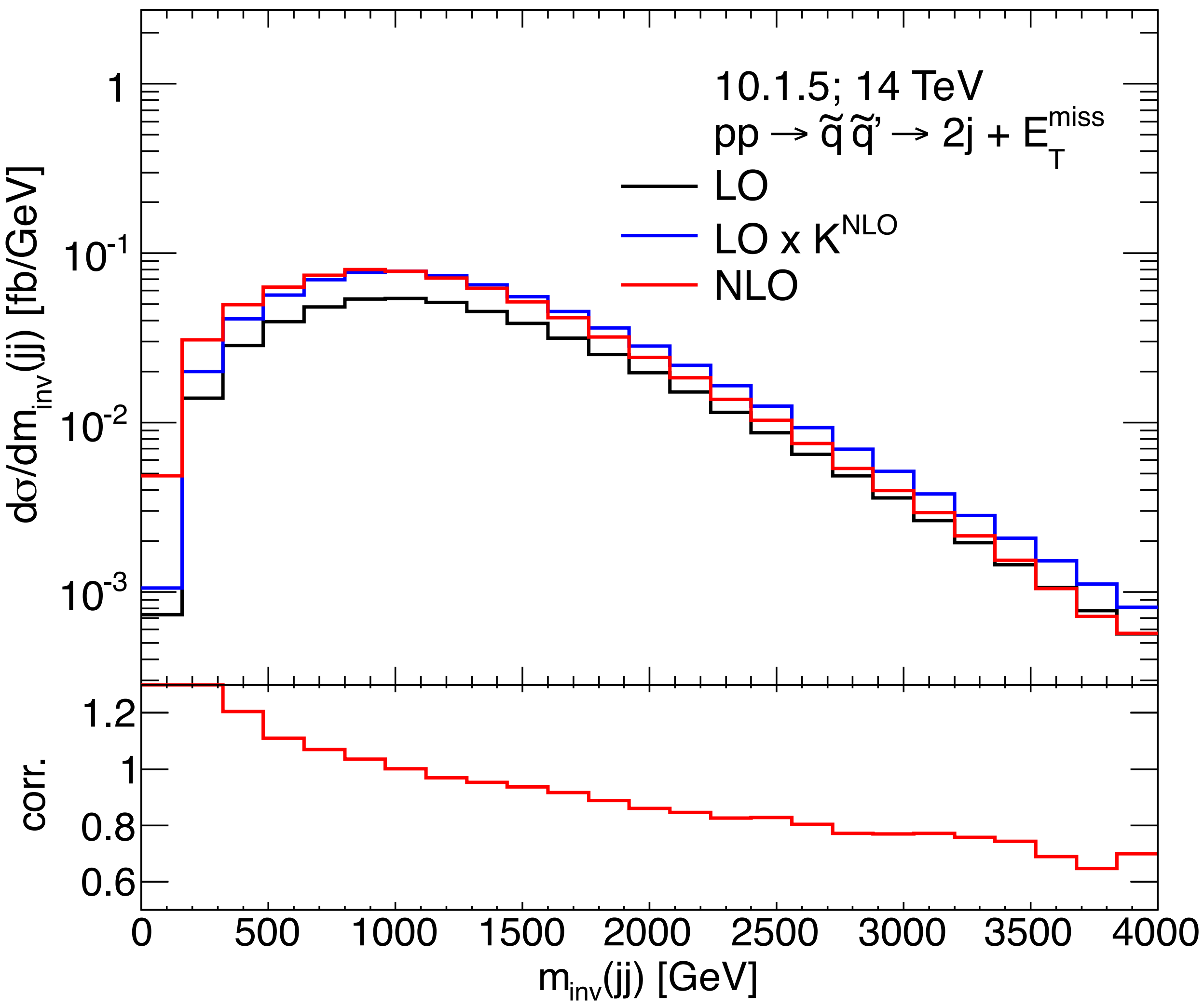
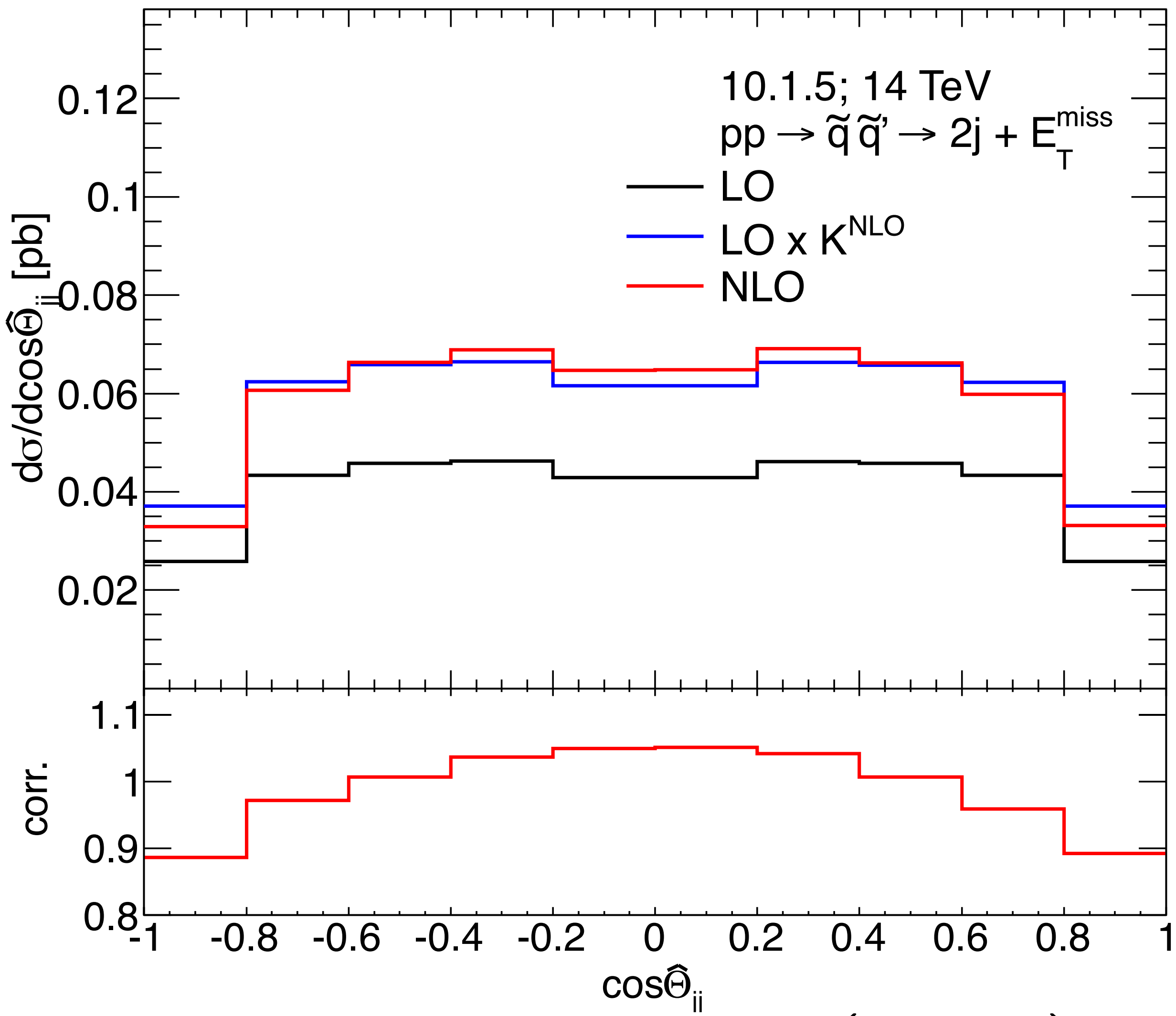


$$m_{\rm inv}(jj)$$

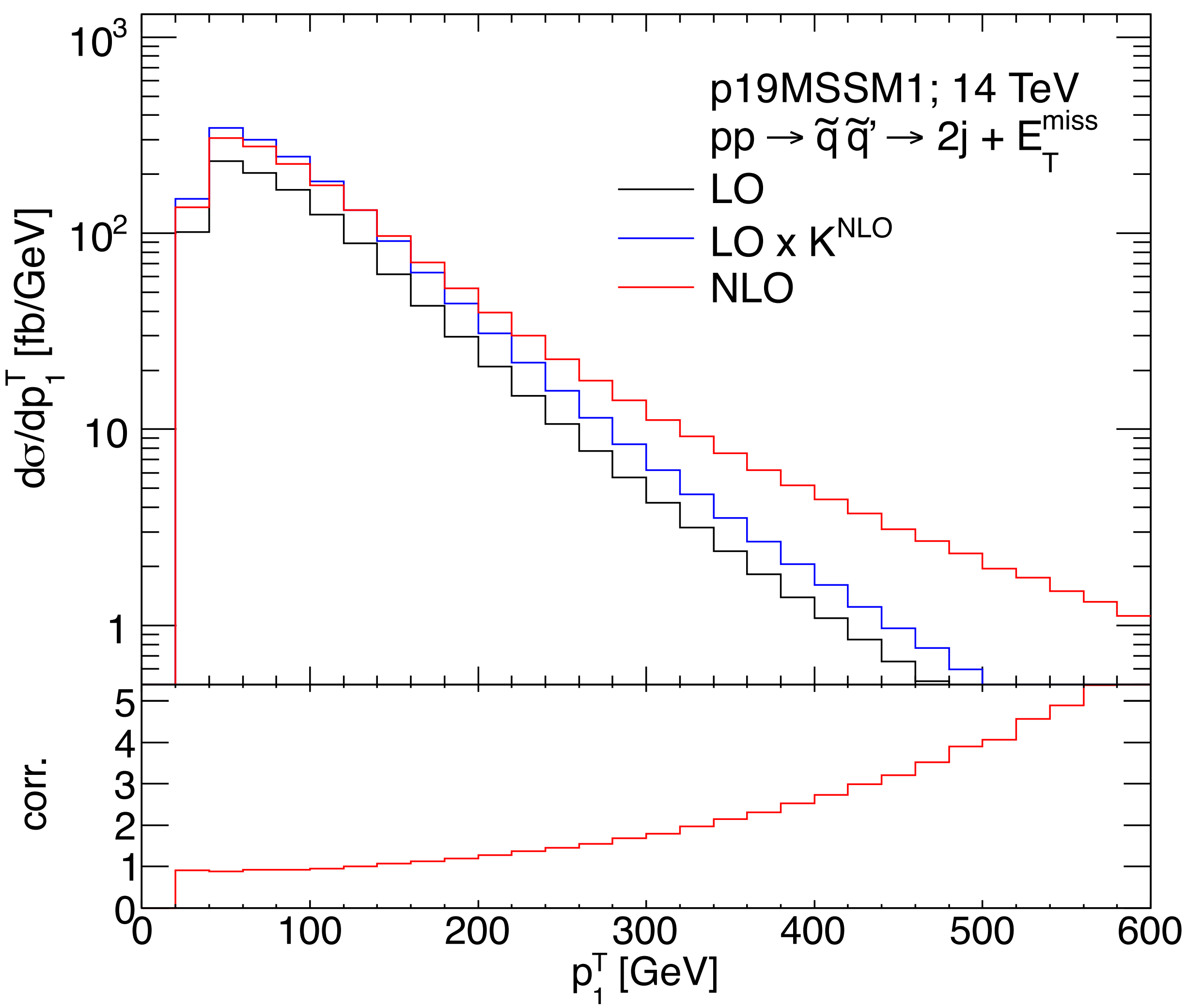


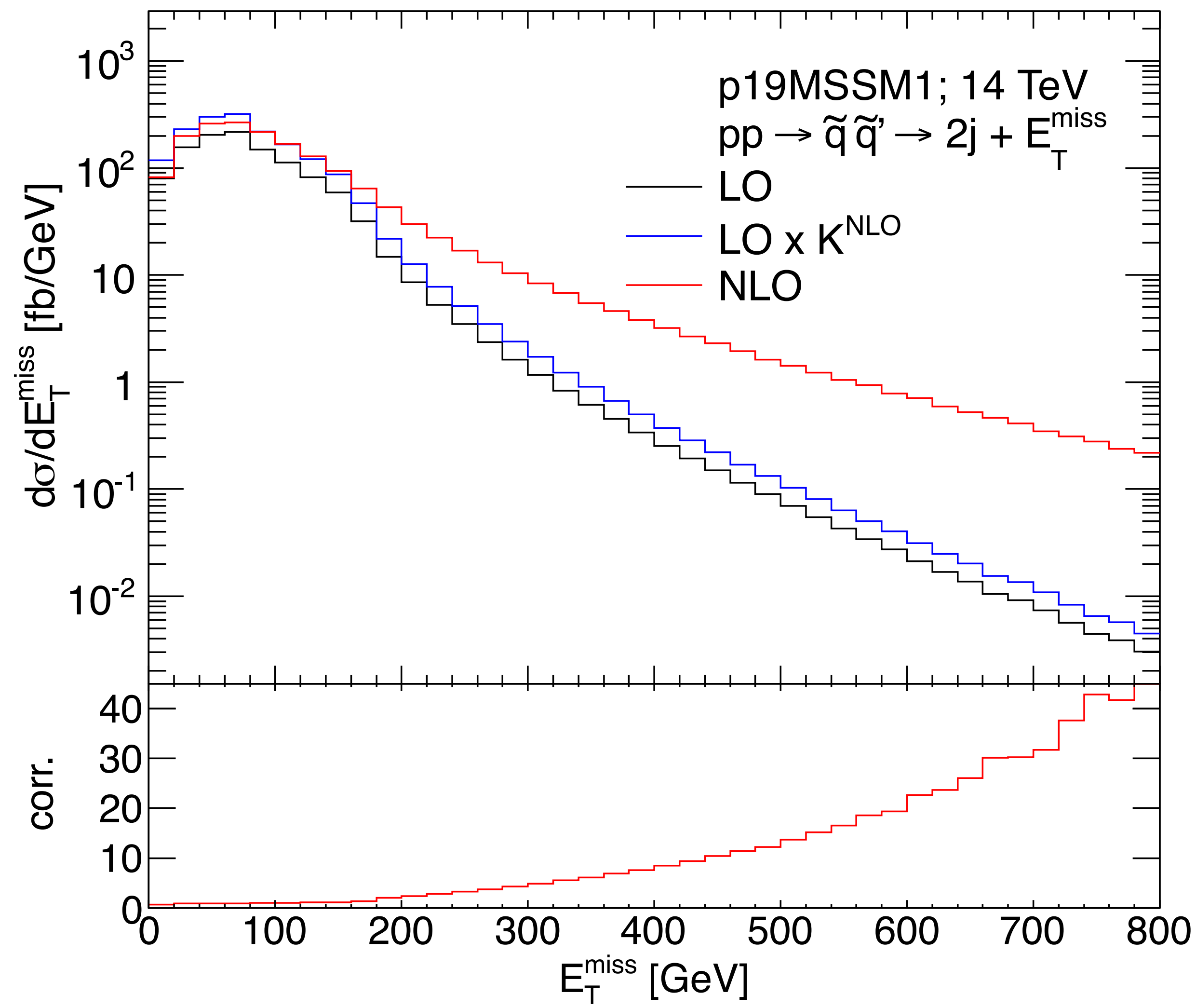
$$\cos\hat{\Theta} = \tanh\left(\frac{\Delta\eta_{jj}}{2}\right)$$

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^{miss}

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

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

2j - signal region:

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

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

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

differential combined NLO

flat K-factor of just production

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

α_T - 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

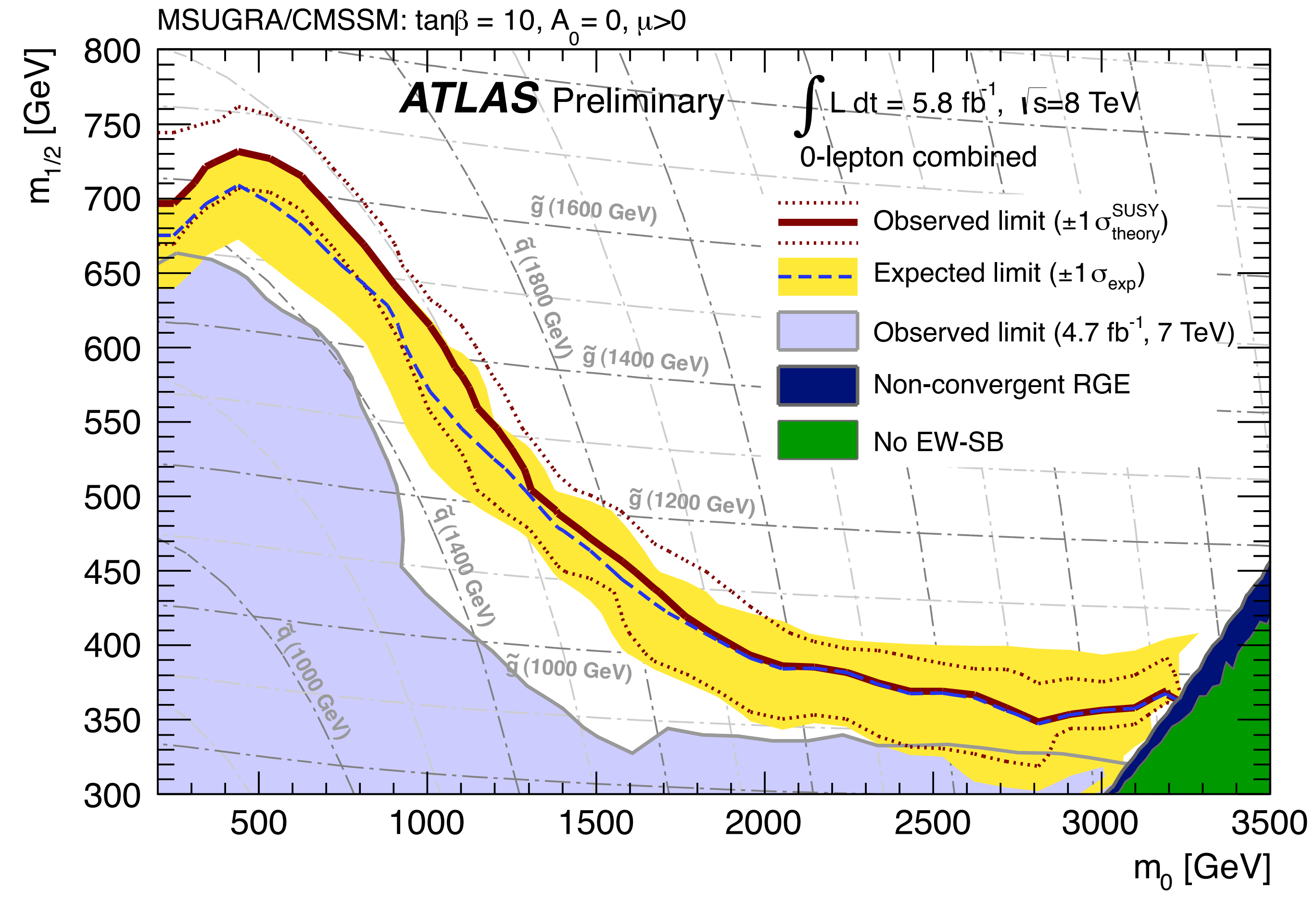
differential combined NLO

flat K-factor of just production

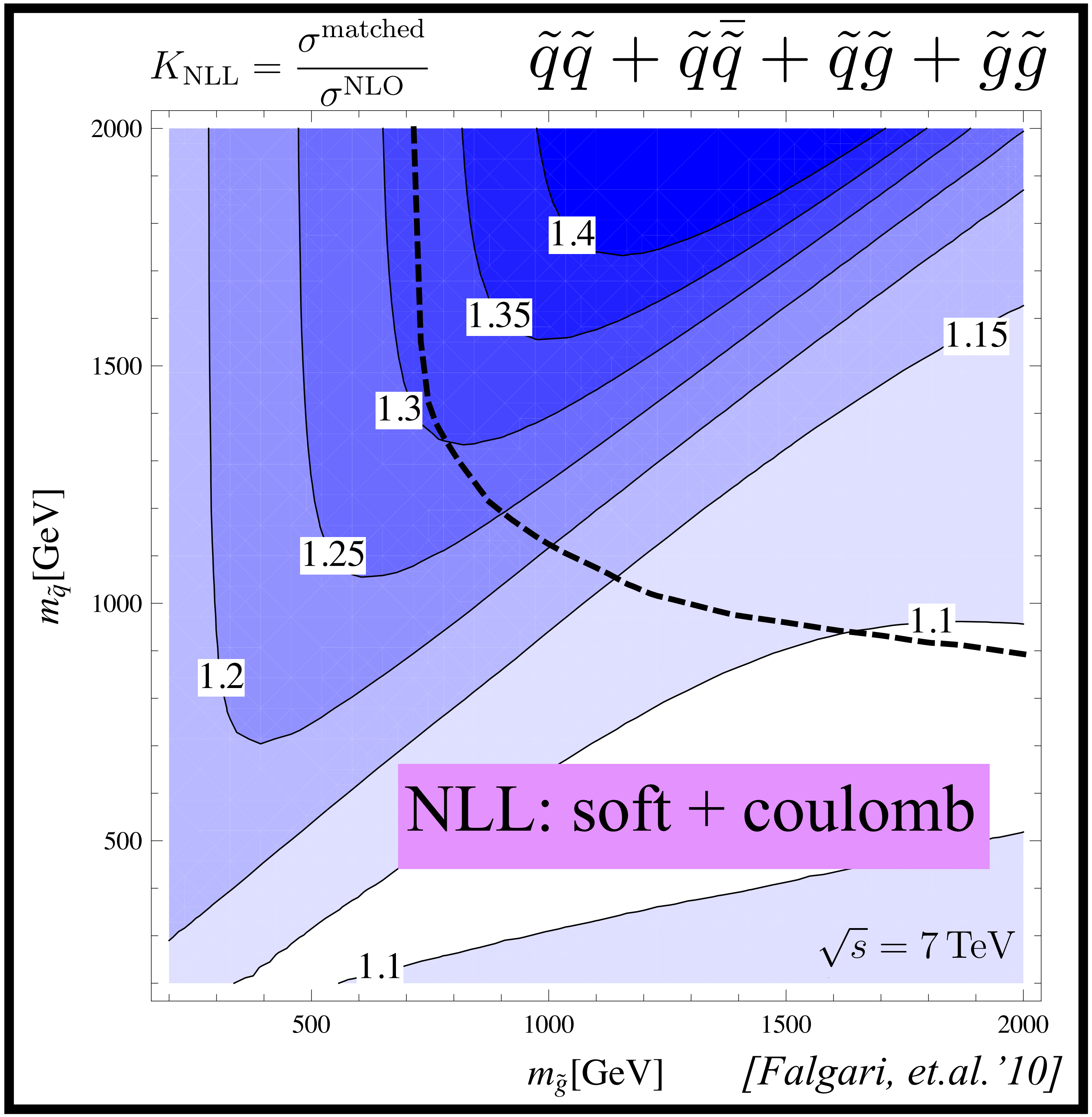
SQUARKS AND GLUINOS AT THE LHC

Requirement	Channel				
	A 2-jets	B 3-jets	C 4-jets	D 5-jets	E 6-jets
E_T^{miss}[GeV] >	160				
$p_T(j_1)$ [GeV] >	130				
$p_T(j_2)$ [GeV] >	60				
$p_T(j_3)$ [GeV] >	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	60	60
$p_T(j_6)$ [GeV] >	–	–	–	–	60
$\Delta\phi(\text{jet}, \mathbf{E}_T^{miss})_{min}$ [rad] >	0.4 ($i = \{1, 2, (3)\}$)		0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_T > 40$ GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	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

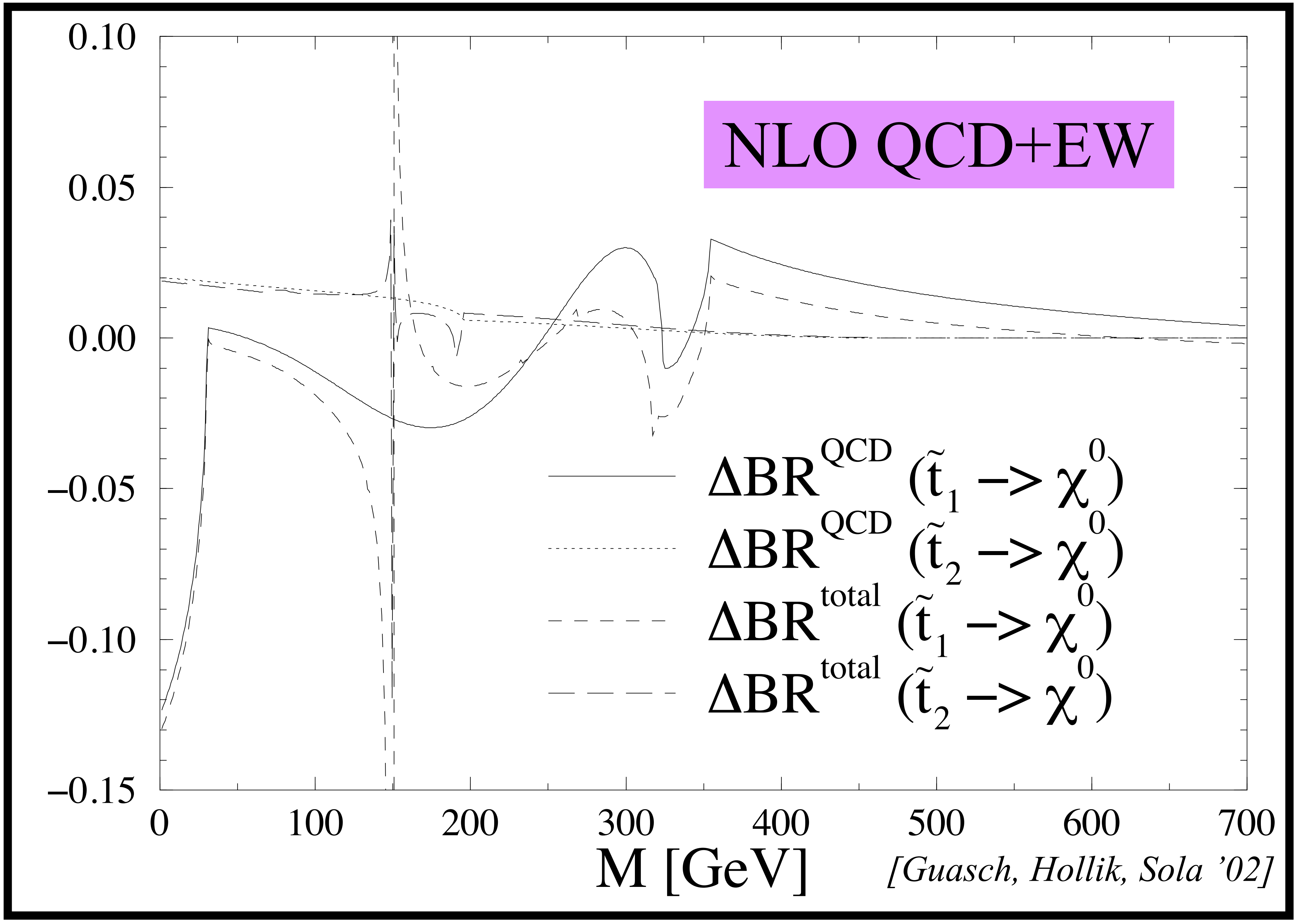
ATLAS search regions

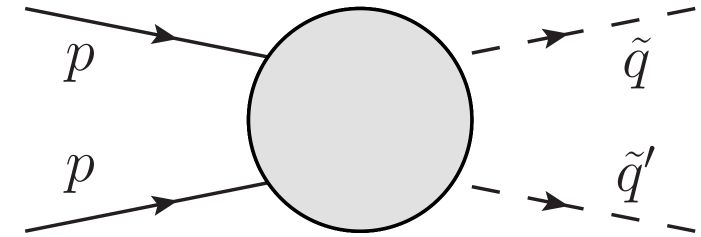


Higher Order Corrections to Production



Higher Order Corrections to Decay





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.

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

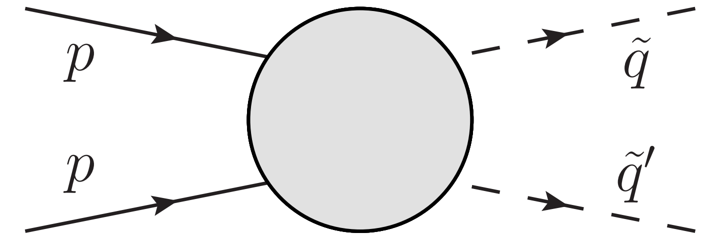
Using $\overline{MS}$ and Dim. Reg. breaks supersymmetric Slavnov-Taylor identity, that relates the QCD coupling in the qqg QCD vertex and the $\hat{g}_s$ coupling in the $q\tilde{q}\tilde{g}$ SQCD vertex.

Can be restored:

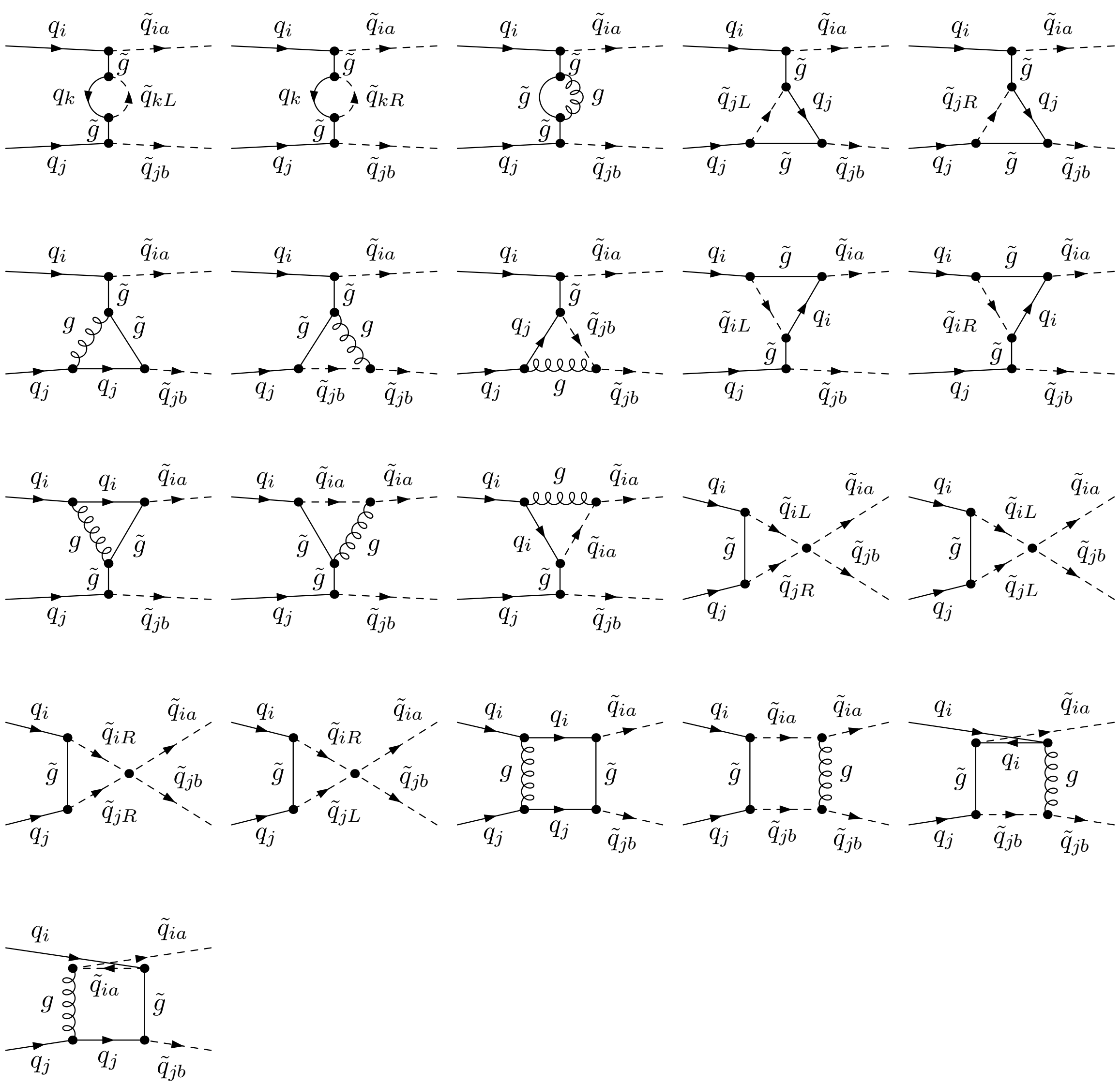
$$\delta Z_{\hat{g}_s} = \delta Z_{g_s} + \frac{\alpha_s}{3\pi}$$

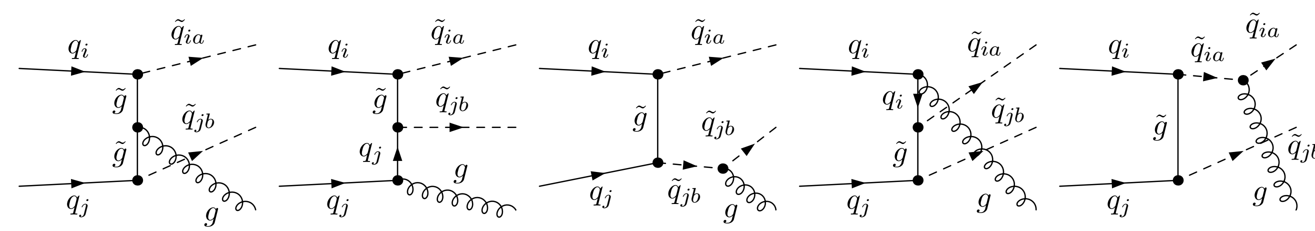
[Beenakker et al. '96; Hollik, Stöckinger '01]

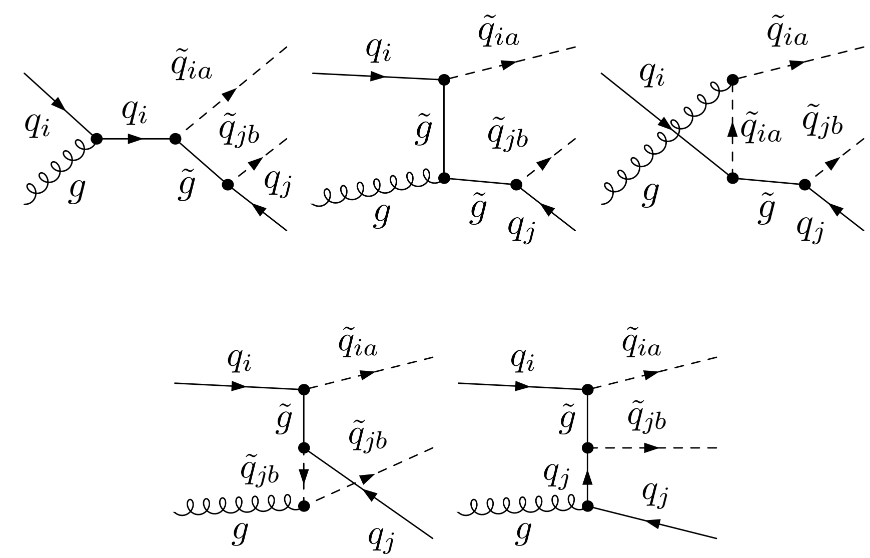
NLO production



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

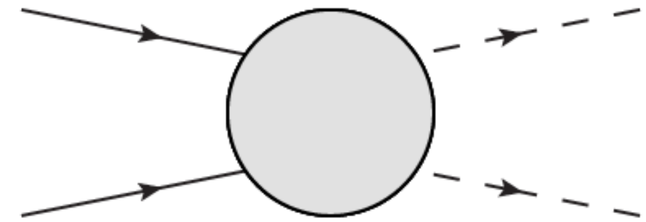


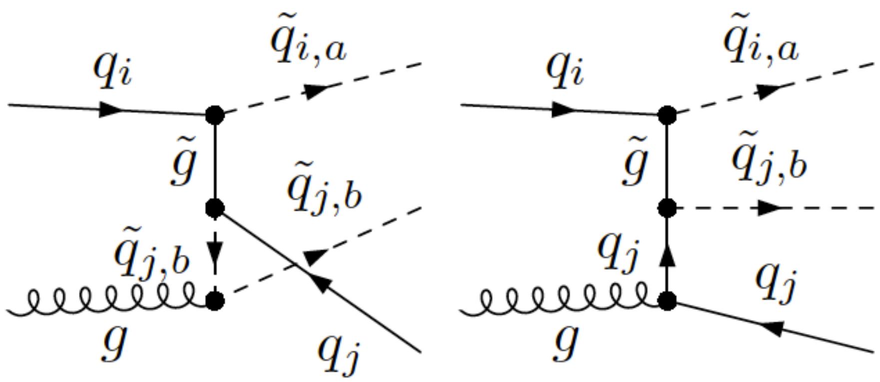


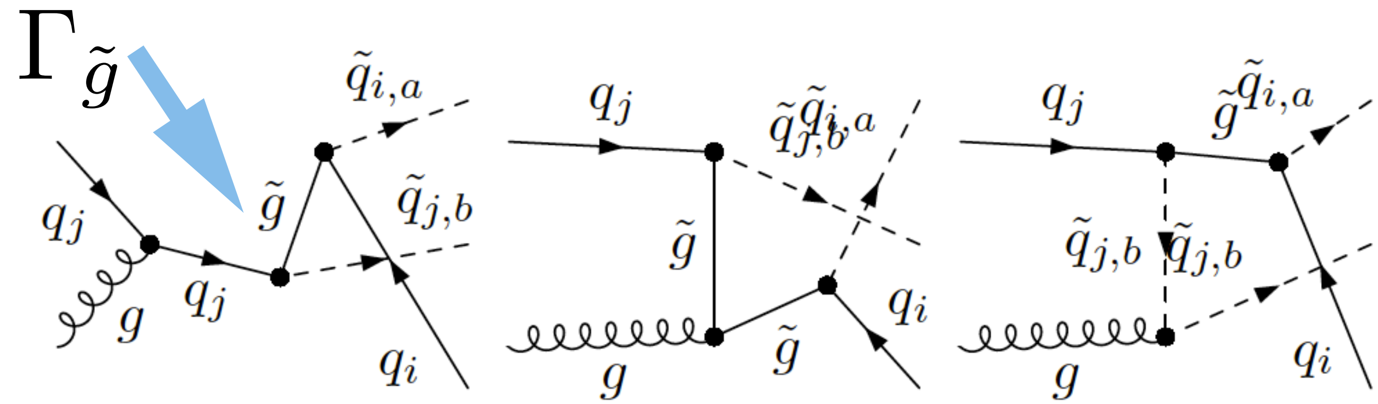


Real quark radiation

DR scheme







non-resonant | resonant

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

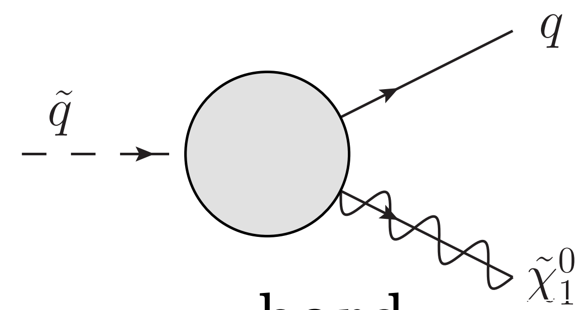
DS scheme

[Binoth et. al.; '11]

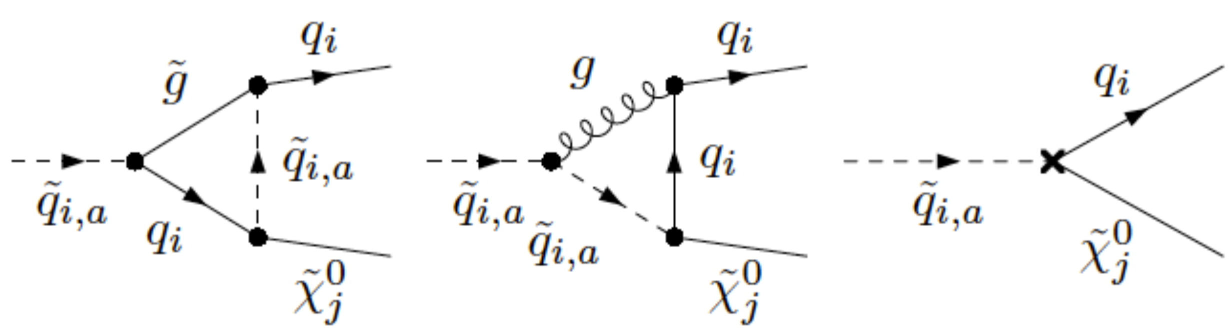
$$\frac{|\mathcal{M}|^2(s_{q\tilde{q}})}{(s_{q\tilde{q}} - m_{\tilde{g}}^2)^2 + m_{\tilde{g}}^2\Gamma_{\tilde{g}}^2} \longrightarrow \frac{|\mathcal{M}|^2(s_{q\tilde{q}})}{(s_{q\tilde{q}} - m_{\tilde{g}}^2)^2 + m_{\tilde{g}}^2\Gamma_{\tilde{g}}^2} - \frac{|\mathcal{M}|^2(m_{\tilde{g}}^2)}{(s_{q\tilde{q}}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

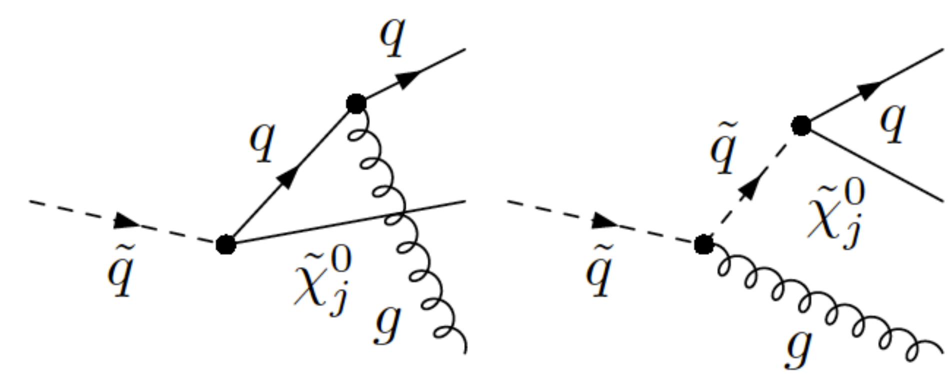
and usually: $\Gamma \to 0$ numerically.

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