

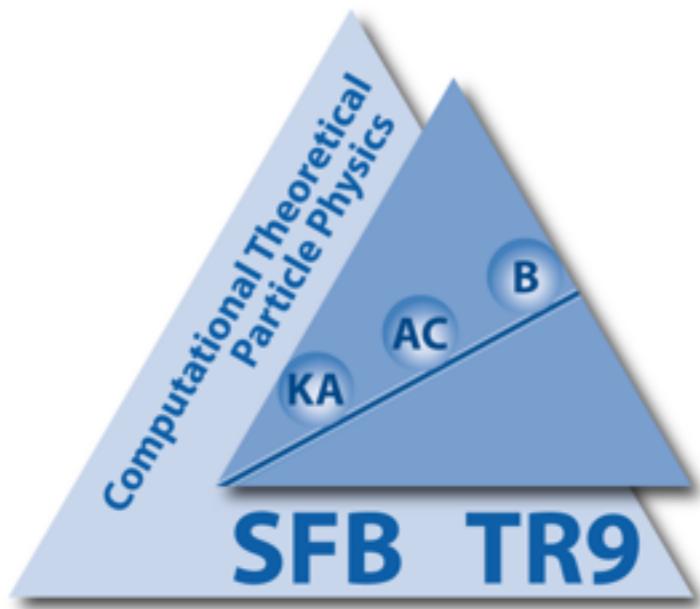


NATIONAL
ACCELERATOR
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Squark and gluino production at the LHC

Michael Krämer (SLAC / RWTH Aachen University)

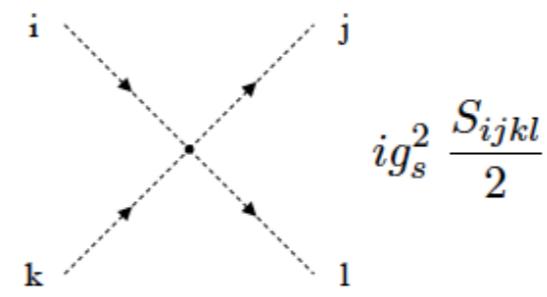
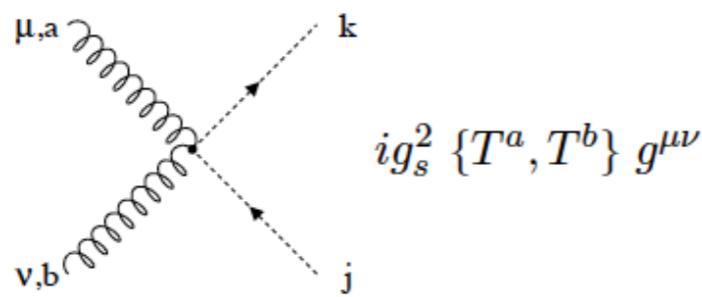
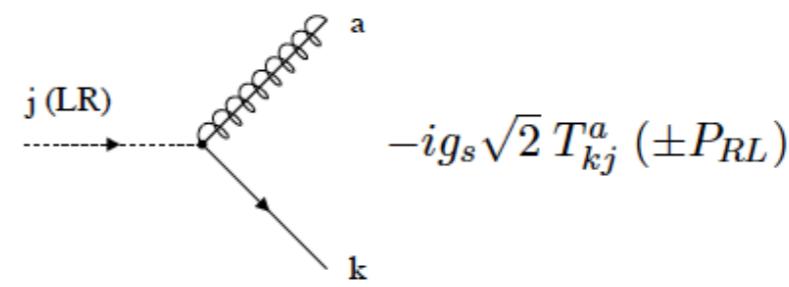
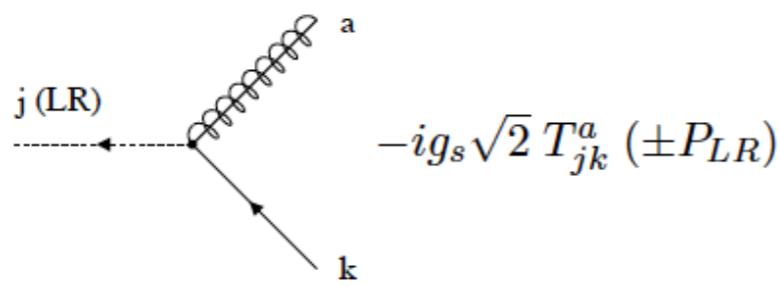
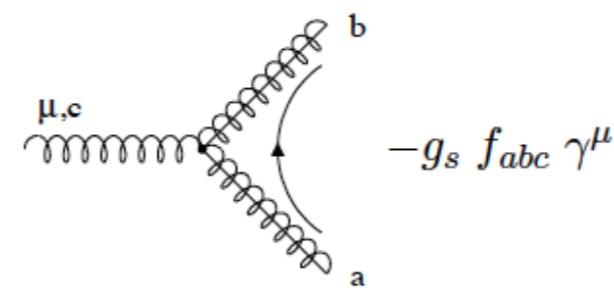
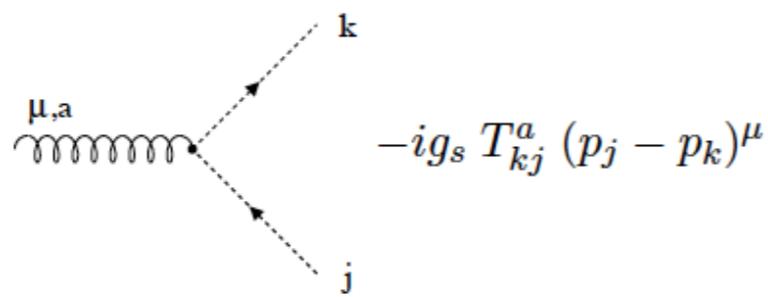


Supersymmetric QCD

$$\begin{aligned}\mathcal{L}_{\text{SUSY-QCD}} = & -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a} + \frac{i}{2}\tilde{g}^a \gamma^\mu (\partial_\mu \delta^{ac} - g_s f^{abc} g_\mu^b) \tilde{g}^c + |D^\mu \tilde{q}_{jL}|^2 + |D^\mu \tilde{q}_{jR}|^2 + i\bar{q}_j \gamma^\mu D_\mu q_j \\ & - \frac{1}{2}m_{\tilde{g}} \tilde{\bar{g}}^a \tilde{g}^a - m_{\tilde{q}_{jL}}^2 \tilde{q}_{jL}^* \tilde{q}_{jL} - m_{\tilde{q}_{jR}}^2 \tilde{q}_{jR}^* \tilde{q}_{jR} - \frac{1}{2}g_s^2 (\tilde{q}_{jL}^* T^a \tilde{q}_{jL} - \tilde{q}_{jR}^* T^a \tilde{q}_{jR})^2 \\ & - \sqrt{2}g_s (\bar{q}_{jL} T^a \tilde{g}^a \tilde{q}_{jL} + \tilde{q}_{jL}^* \tilde{\bar{g}}^a T^a q_{jL} - \tilde{q}_{jR}^* \tilde{\bar{g}}^a T^a q_{jR} - \bar{q}_{jR} \tilde{g}^a T^a \tilde{q}_{jR})\end{aligned}$$

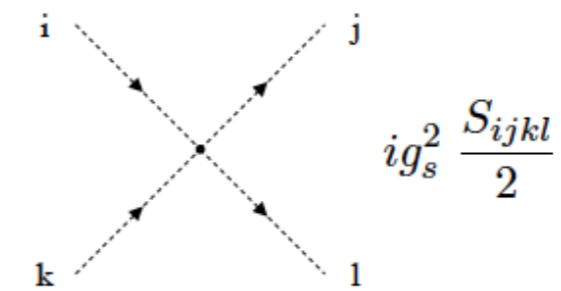
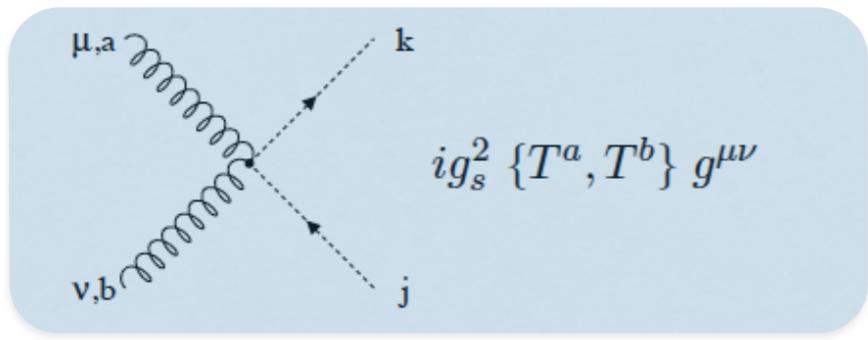
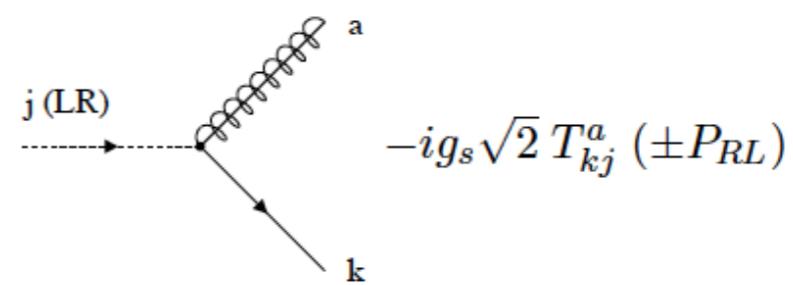
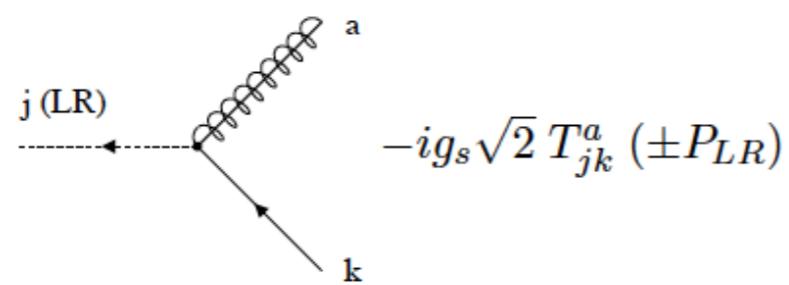
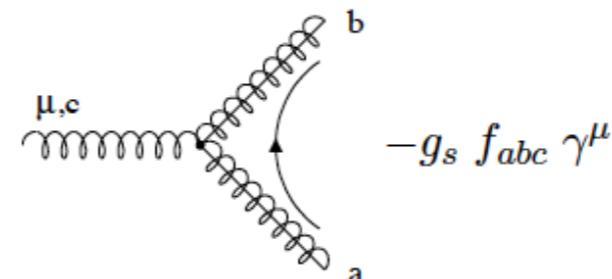
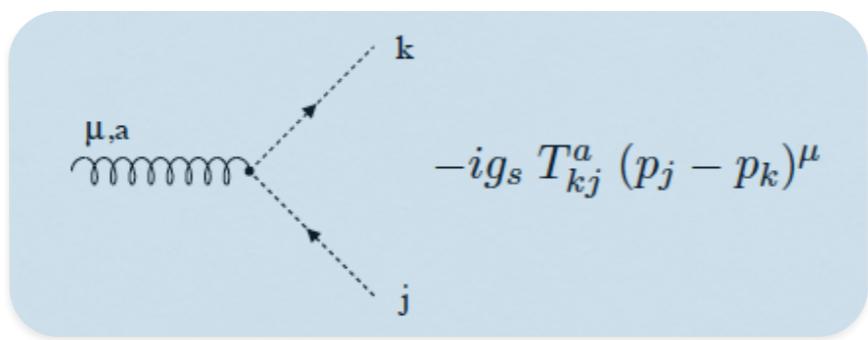
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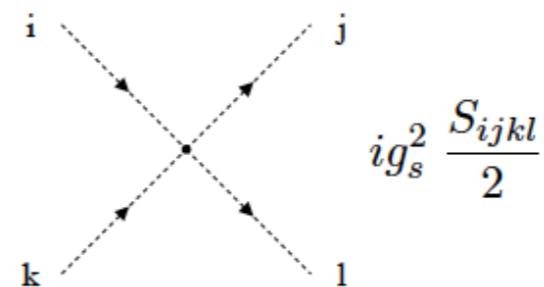
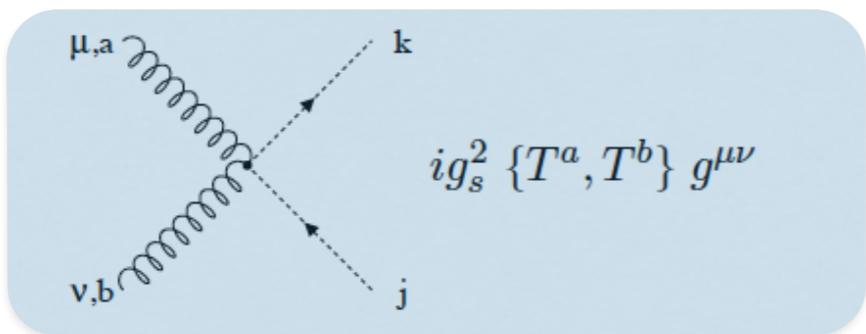
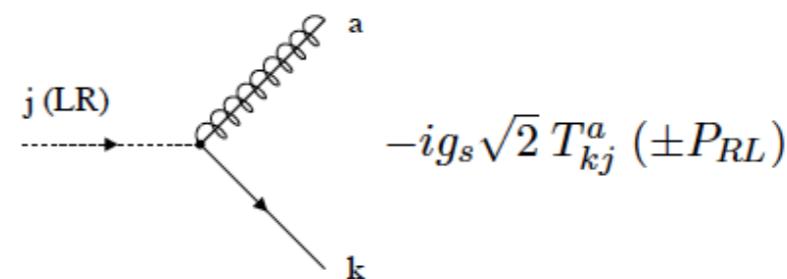
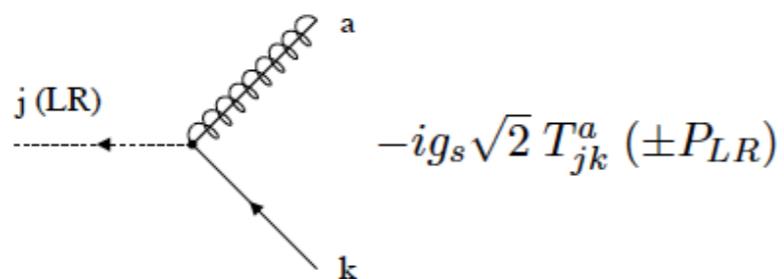
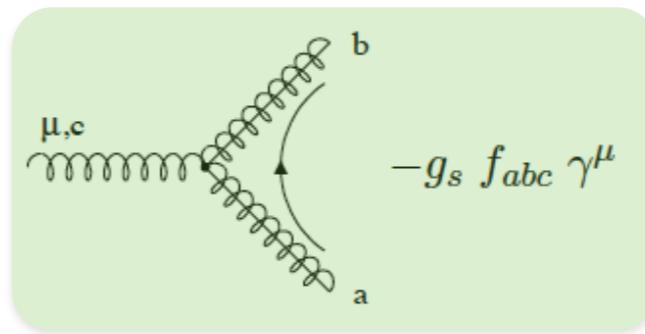
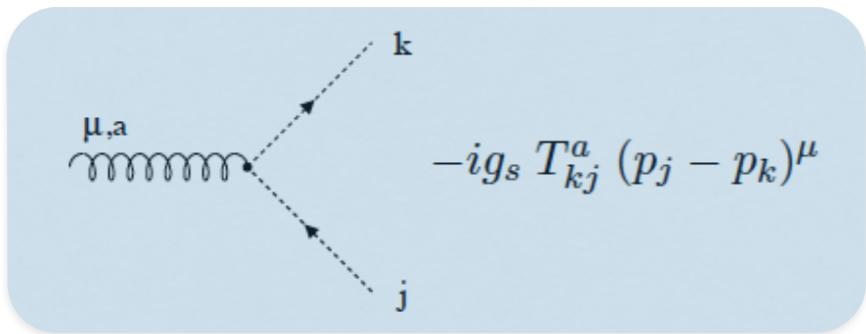
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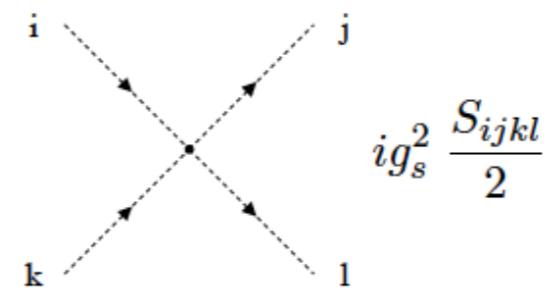
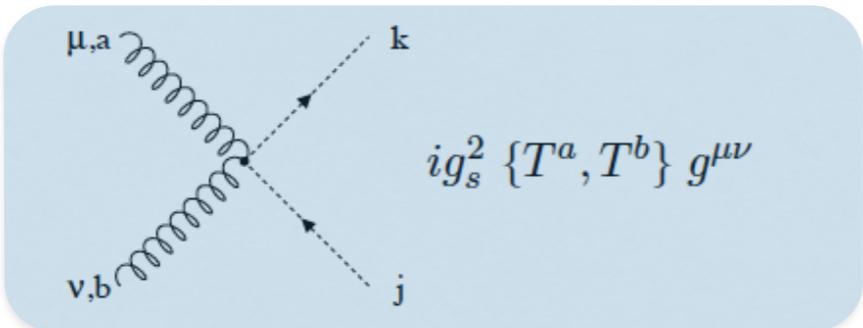
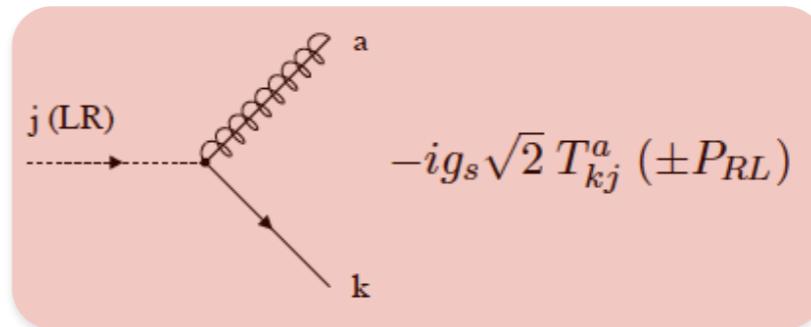
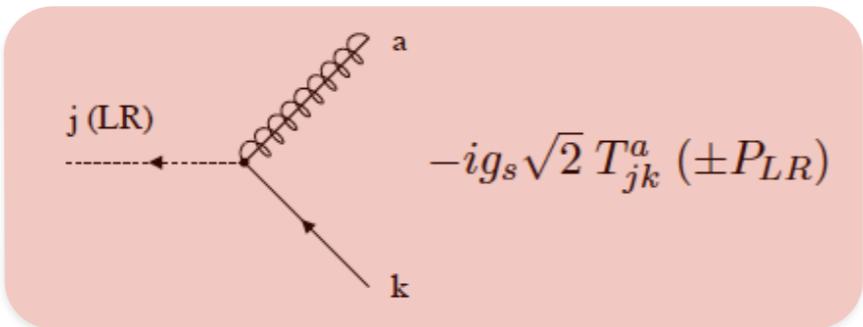
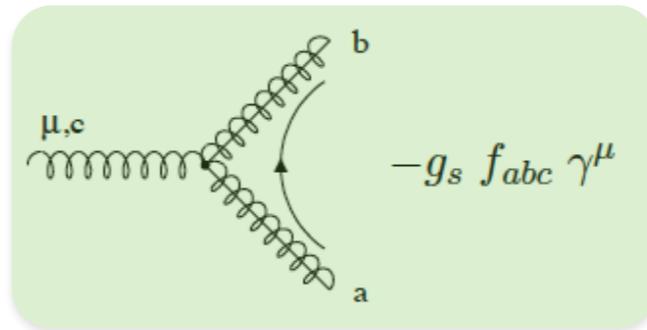
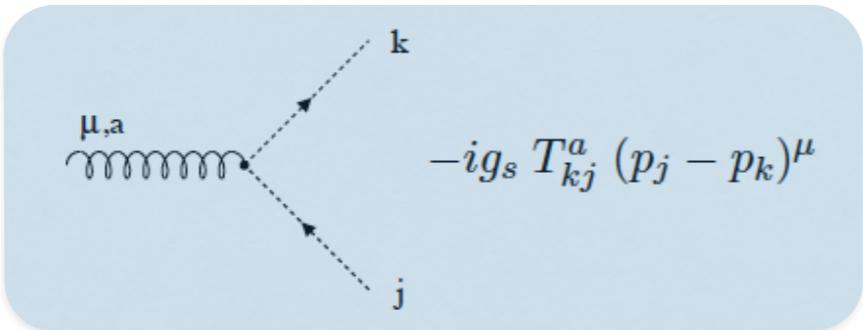
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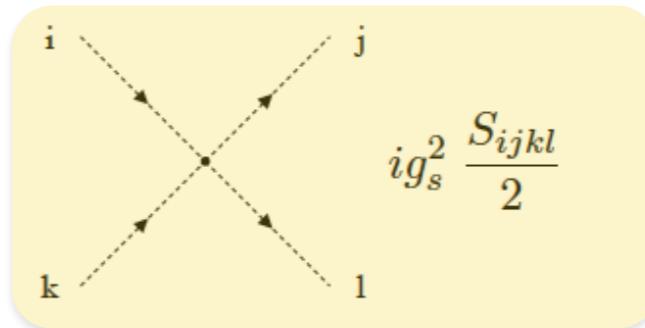
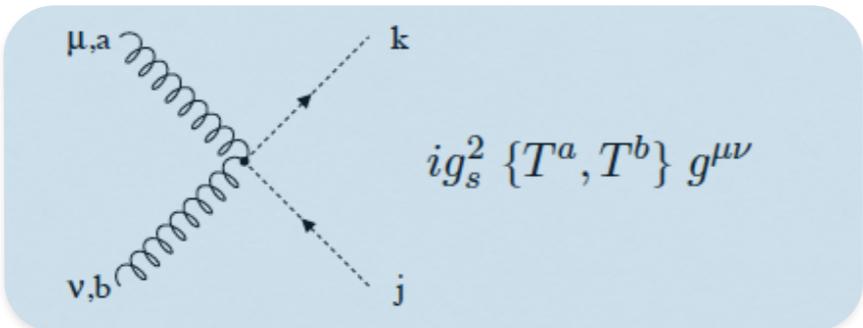
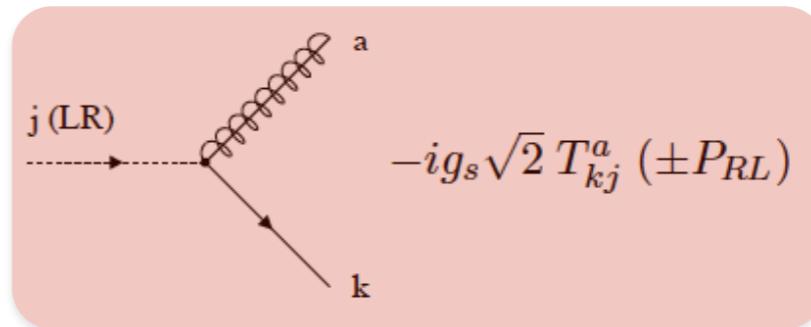
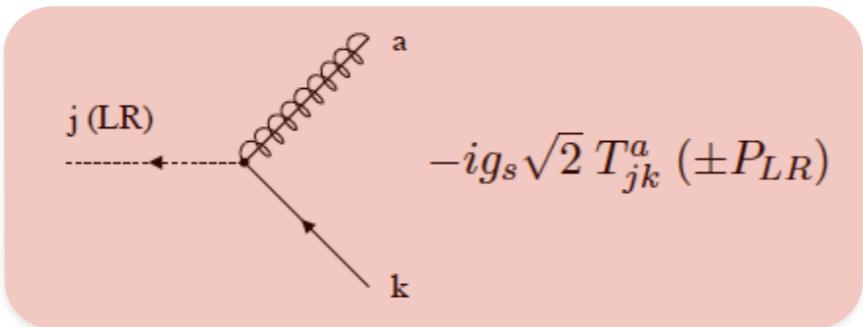
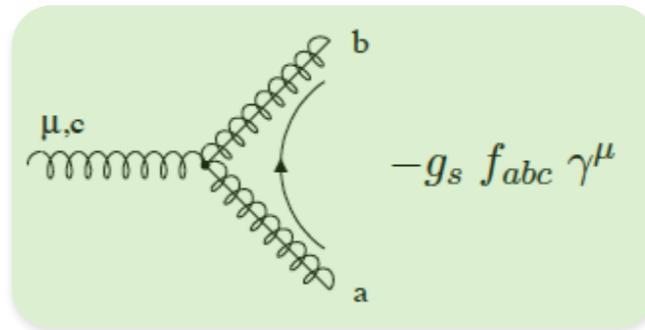
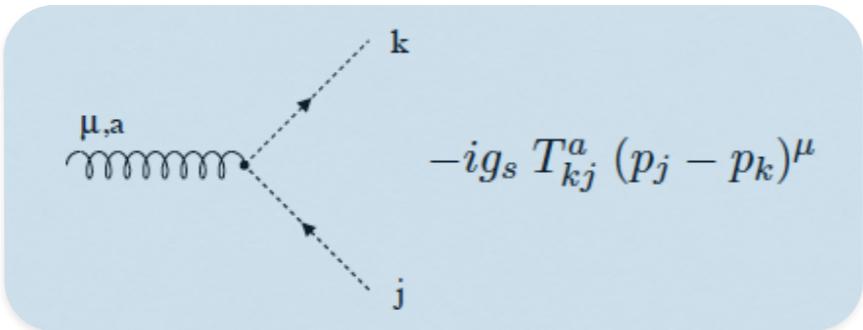
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We assume R-parity conservation

→ ~~$\mathcal{W} = \lambda''_{ijk} U_i^c D_j^c D_k^c$~~ etc.

- sparticles are produced in pairs;
the LSP is stable

Supersymmetric QCD

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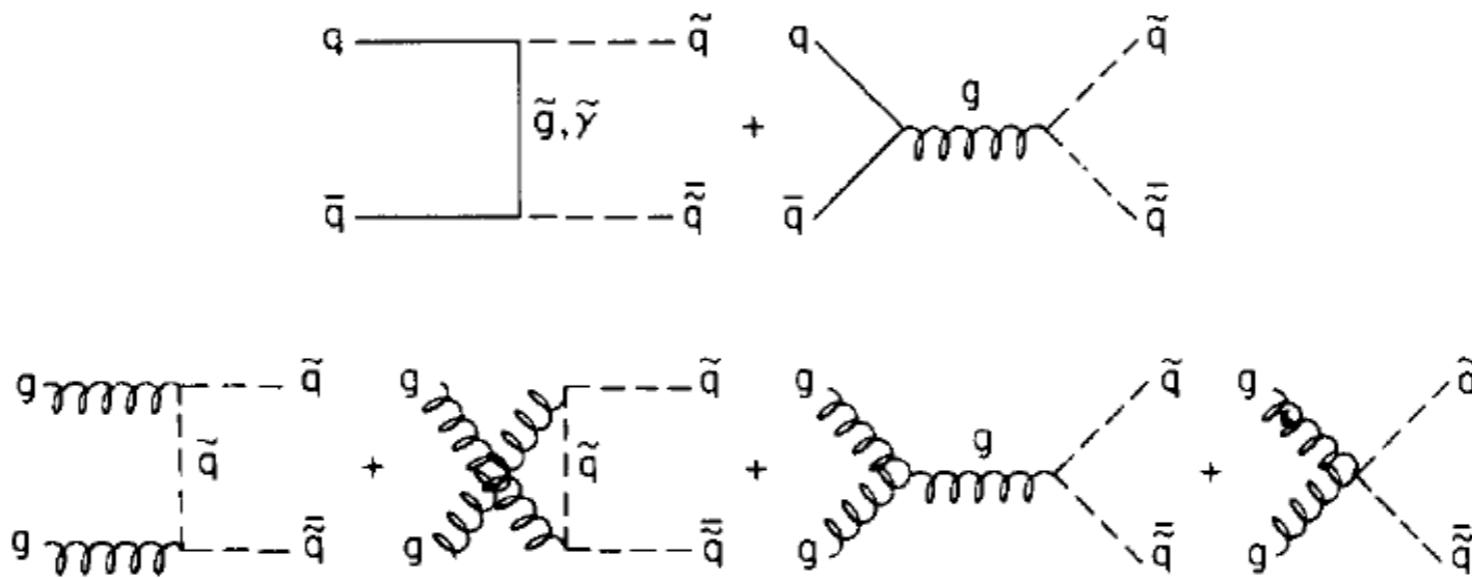
Squarks mix to form mass eigenstates

$$\mathcal{M}^2 = \begin{pmatrix} m_Q^2 + m_q^2 + \left(\frac{1}{2} - \frac{2}{3}s_w^2\right)m_Z^2 \cos(2\beta) & -m_q(A_q + \mu \cot \beta) \\ -m_q(A_q + \mu \cot \beta) & m_U^2 + m_q^2 + \frac{2}{3}s_w^2 m_Z^2 \cos(2\beta) \end{pmatrix}$$

- the mixing is proportional to the quark mass
- mixing is relevant for the 3rd generation

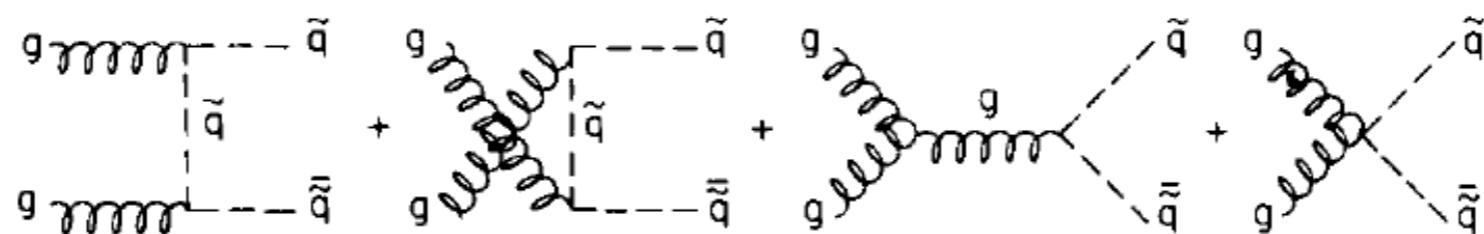
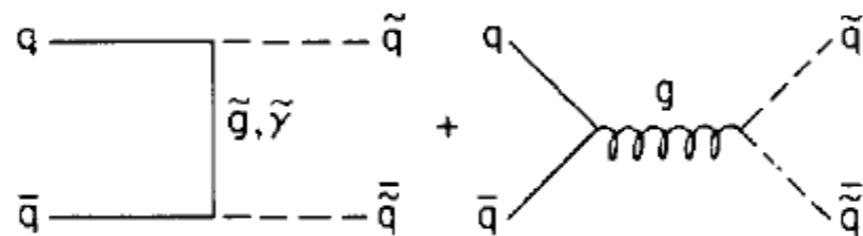
Squark and gluino production

squark-antisquark production

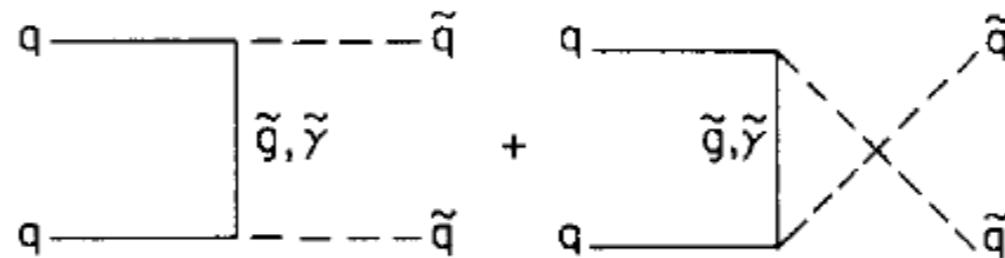


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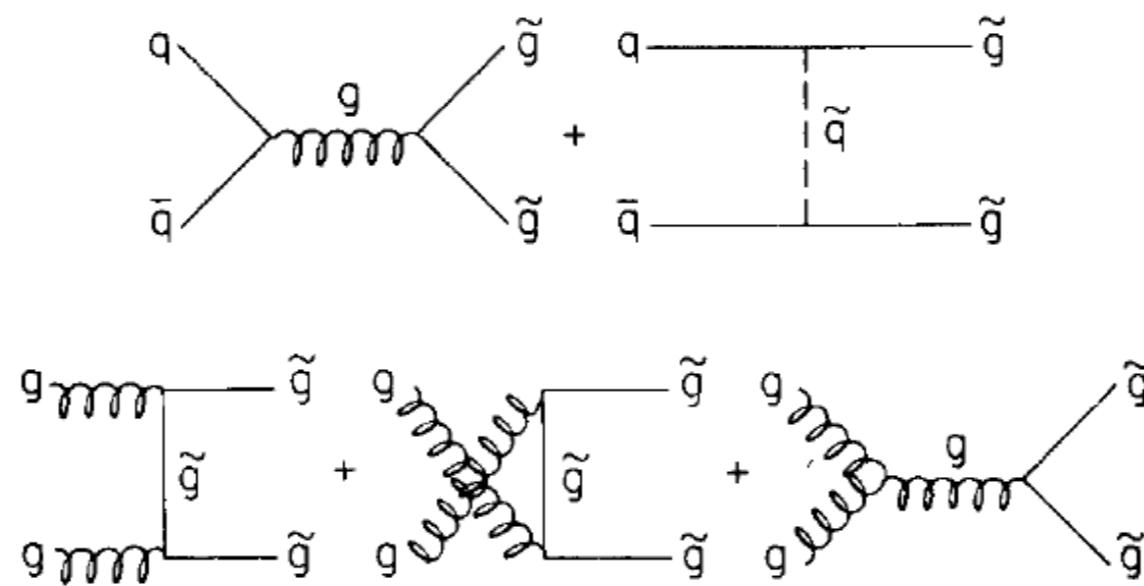


squark-squark production



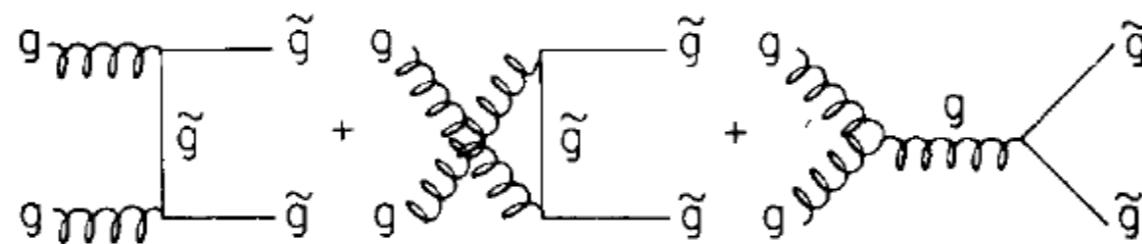
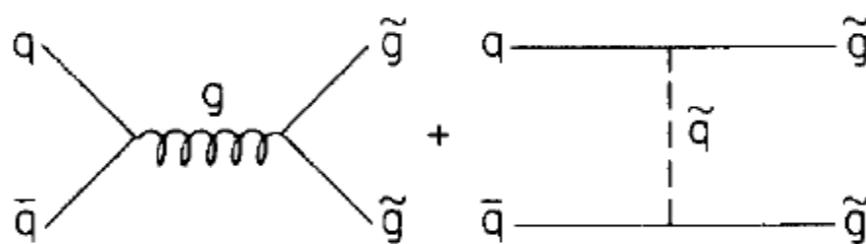
Squark and gluino production

gluino pair production

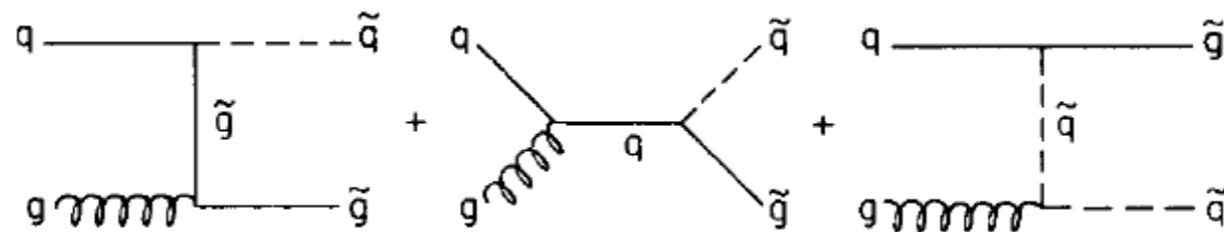


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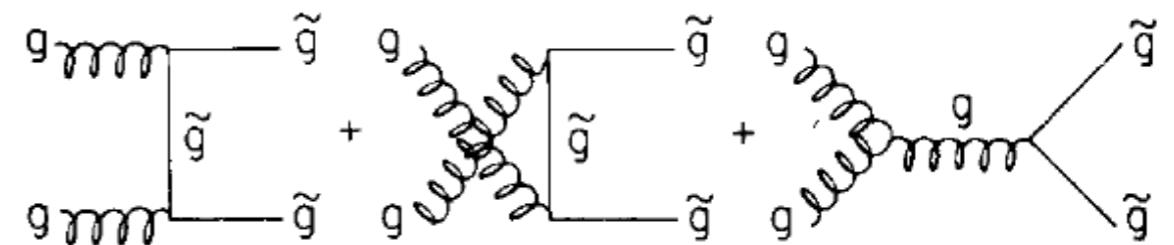
squark-gluino production



Squark and gluino production

The cross sections only depend on the SUSY masses

e.g. gluino pair production

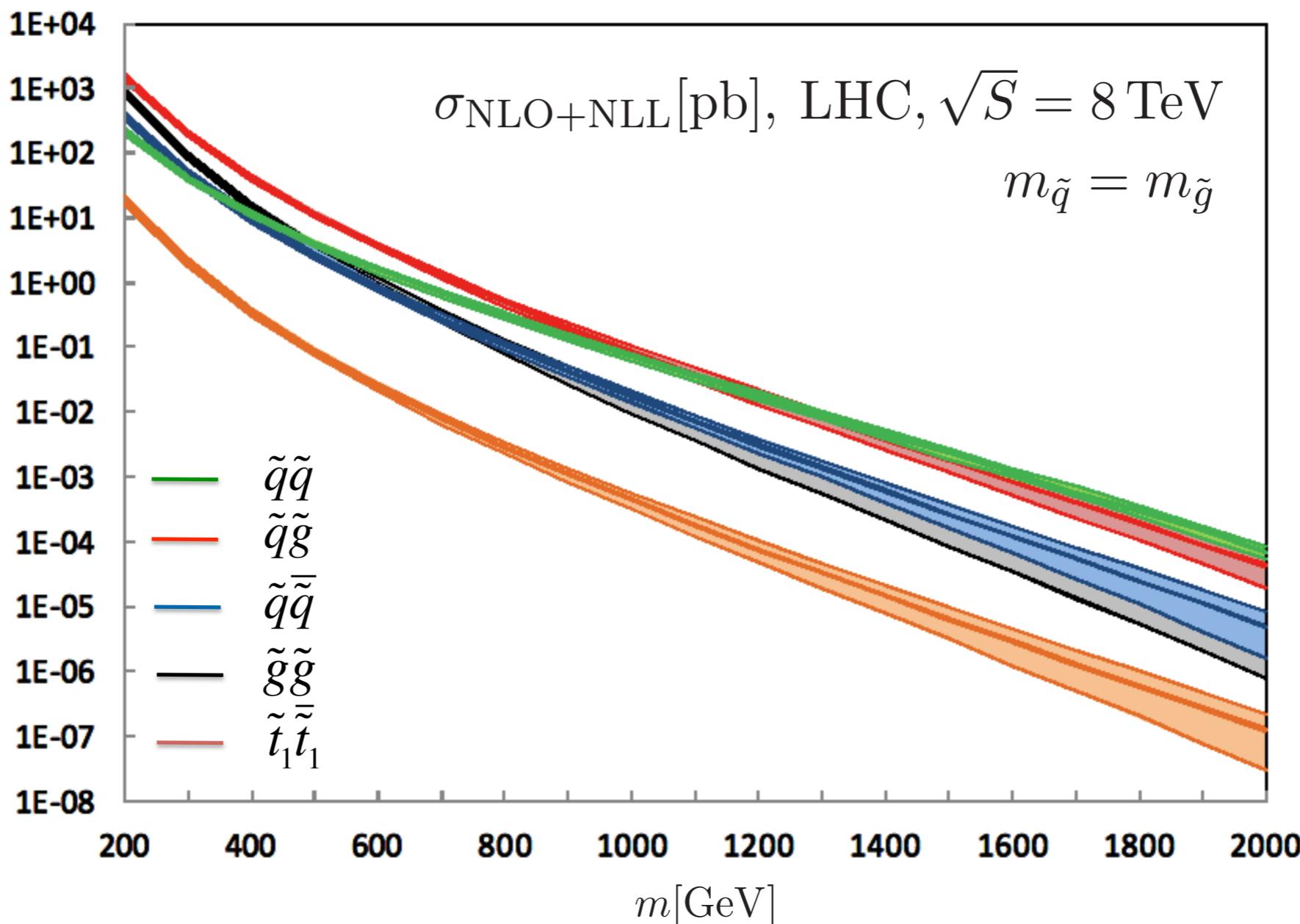


$$\sigma^B(gg \rightarrow \tilde{q}\bar{\tilde{q}}) = \frac{n_f \pi \alpha_s^2}{s} \left[\beta_{\tilde{q}} \left(\frac{5}{24} + \frac{31m_{\tilde{q}}^2}{12s} \right) + \left(\frac{4m_{\tilde{q}}^2}{3s} + \frac{m_{\tilde{q}}^4}{3s^2} \right) \log \left(\frac{1 - \beta_{\tilde{q}}}{1 + \beta_{\tilde{q}}} \right) \right]$$

where $\beta_{\tilde{g}} = \sqrt{1 - 4m_{\tilde{g}}^2/s} \rightarrow 0$ at threshold

Squark and gluino production

LHC cross section predictions



Squark and gluino production

Why do we bother to calculate SUSY-QCD corrections?

Squark and gluino production

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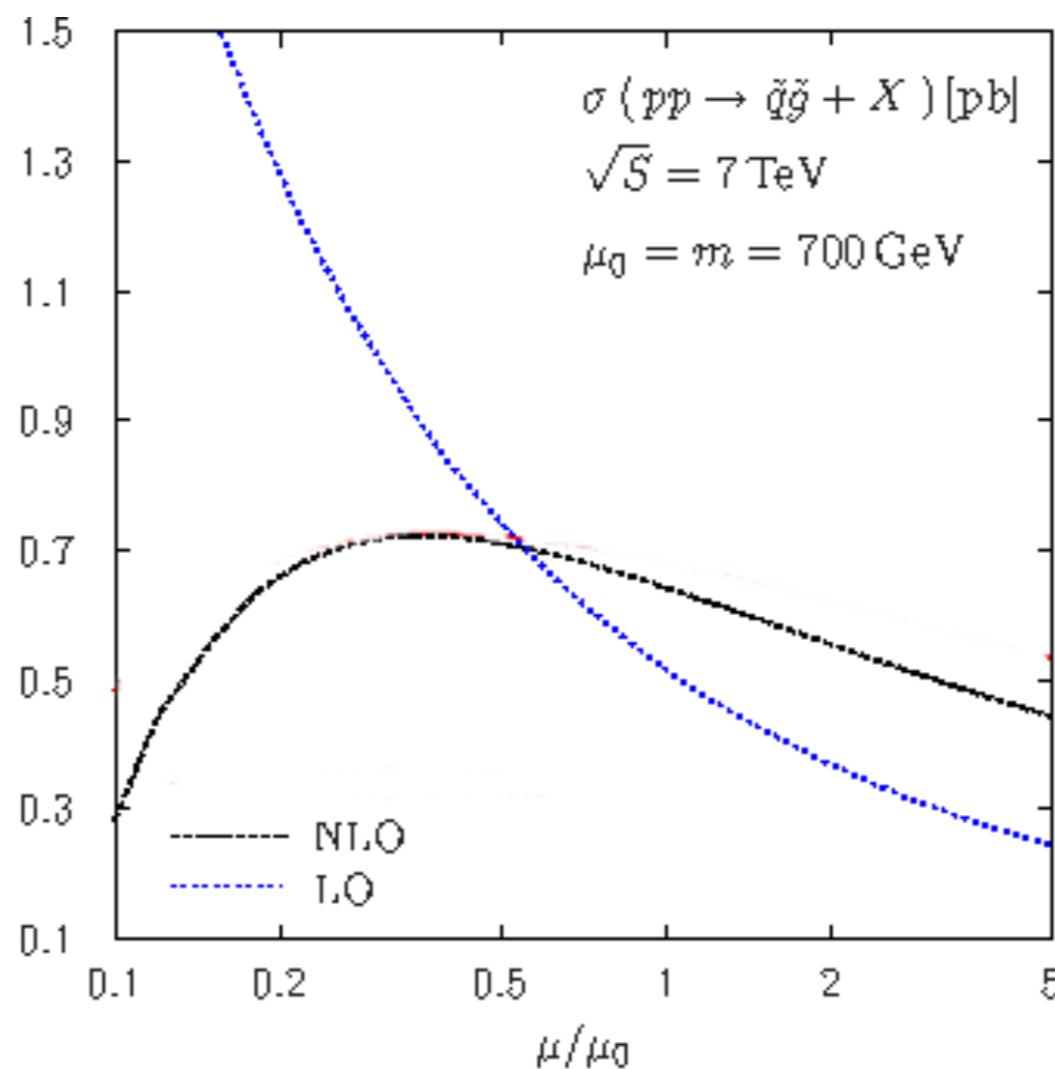
Higher-order corrections

- reduce the scale dependence
- introduce new parton processes
- add new kinematic features

Squark and gluino production

Why do we bother to calculate SUSY-QCD corrections?

Higher-order corrections reduce the scale dependence

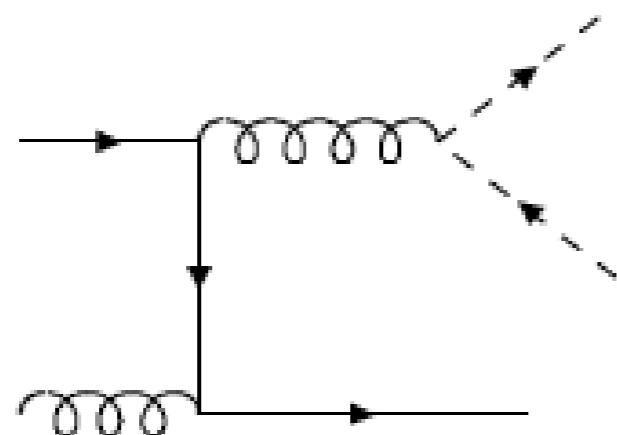


Squark and gluino production

Why do we bother to calculate SUSY-QCD corrections?

Higher-order corrections introduce new parton processes

e.g. squark-antisquark production

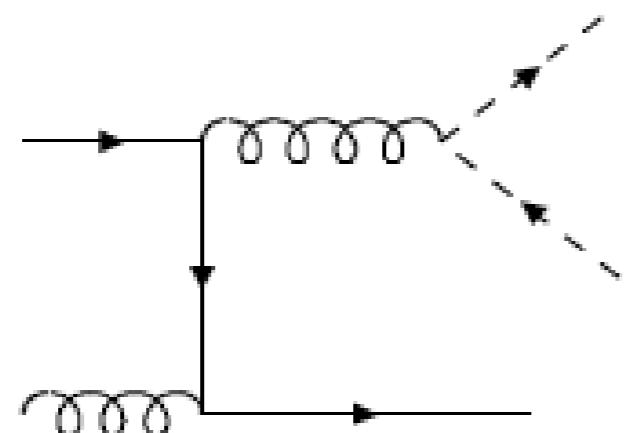


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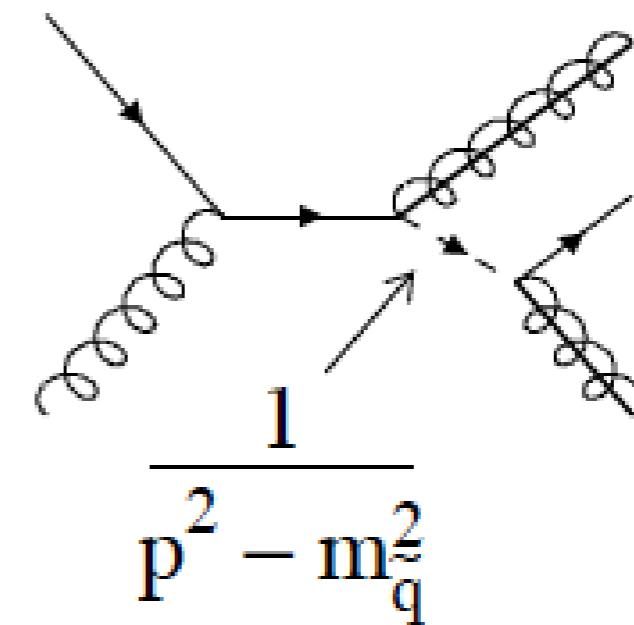
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gluino pair production



Squark and gluino production

Why do we bother to go beyond NLO?

Squark and gluino production

Why do we bother to go beyond NLO?

$$\begin{aligned}\sigma_{gg \rightarrow \tilde{t}\tilde{t}}^{(1,\text{thr})} = & \frac{\pi\alpha_s^2(\mu^2)}{16m^2} \frac{N_c^2 - 2}{N_c(N_c^2 - 1)} \beta \left(1 + 4\pi\alpha_s(\mu^2) \left\{ \frac{2C_F - \frac{N_c^2 - 4}{N_c^2 - 2} C_A}{16\beta} - \frac{N_c^2 - 4}{N_c^2 - 2} \frac{C_A}{4\pi^2} \log(8\beta^2) \right. \right. \\ & \left. \left. + \frac{2C_A}{4\pi^2} \left[\log^2(8\beta^2) - 4\log(8\beta^2) - \log(8\beta^2) \log\left(\frac{\mu^2}{m^2}\right) \right] \right\} \right).\end{aligned}$$

Higher-order corrections introduce large logarithms

Squark and gluino production

Why do we bother to go beyond NLO?

$$\begin{aligned}\sigma_{gg \rightarrow \tilde{t}\tilde{t}}^{(1,\text{thr})} = & \frac{\pi\alpha_s^2(\mu^2)}{16m^2} \frac{N_c^2 - 2}{N_c(N_c^2 - 1)} \beta \left(1 + 4\pi\alpha_s(\mu^2) \left\{ \frac{2C_F - \frac{N_c^2 - 4}{N_c^2 - 2} C_A}{16\beta} - \frac{N_c^2 - 4}{N_c^2 - 2} \frac{C_A}{4\pi^2} \log(8\beta^2) \right. \right. \\ & \left. \left. + \frac{2C_A}{4\pi^2} \left[\log^2(8\beta^2) - 4\log(8\beta^2) - \log(8\beta^2) \log\left(\frac{\mu^2}{m^2}\right) \right] \right\} \right).\end{aligned}$$

Higher-order corrections introduce large logarithms

These logarithms can be summed to all orders

Squark and gluino production

Threshold resummation

$$\sigma = \sigma_0 [\alpha_s (L^2 + L + 1) + \alpha_s^2 (L^4 + L^3 + L^2 + L + 1) + \dots]$$

$$= \sigma_0 \exp \left(\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots \right) \underbrace{C(\alpha_s)}_{\text{constants}}$$

$\underbrace{}_{\text{NLL}}$

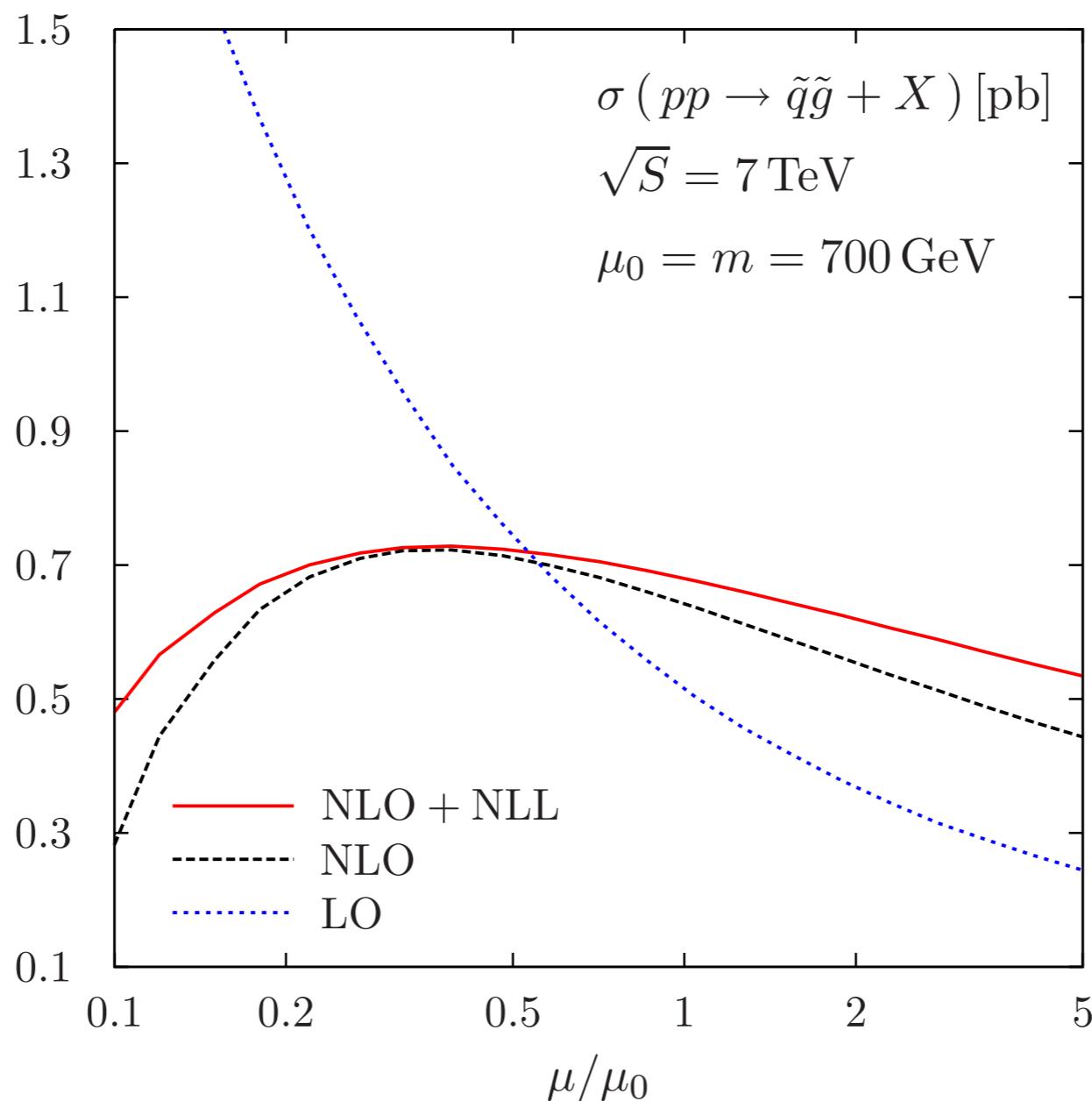
$\underbrace{}_{\text{NNLL}}$

+ suppressed terms

Kidonakis, Sterman; Bonciani, Catani, Mangano, Nason; Kidonakis, Oderà, Sterman;
Catani, Mangano, Nason, Trentadue ('97-'03)

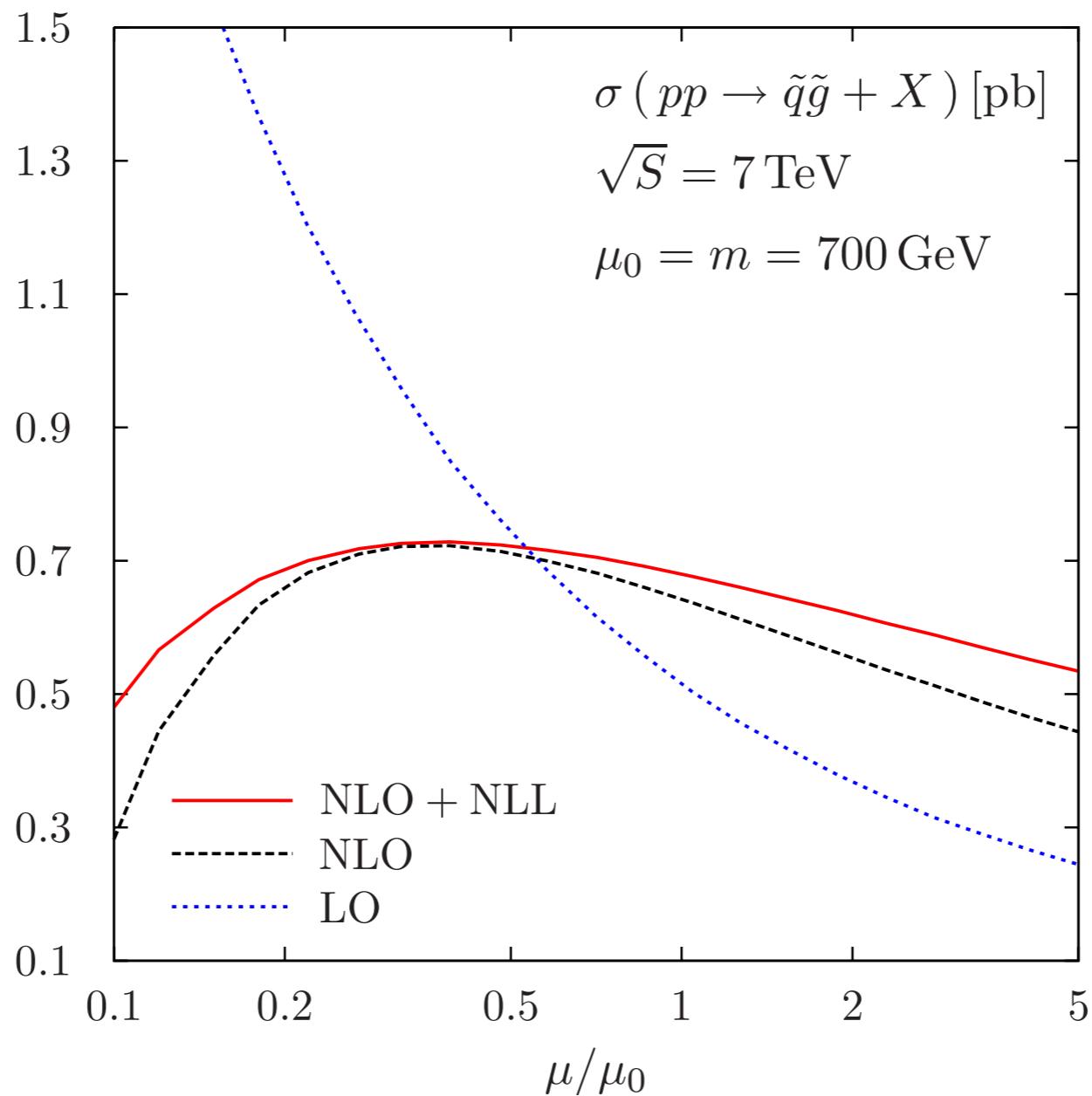
Squark and gluino production

NLL threshold resummation



Squark and gluino production

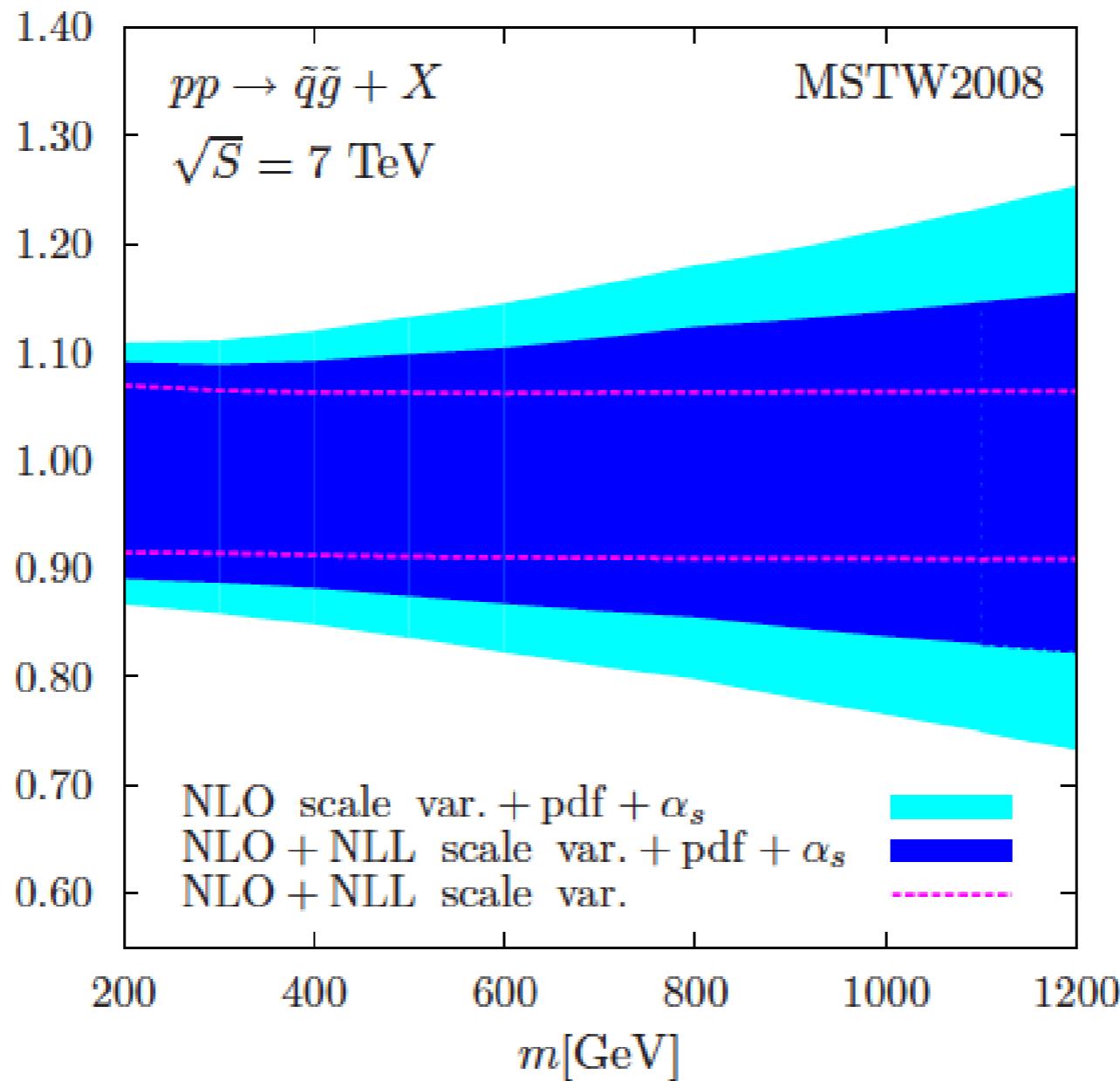
NLL threshold resummation



cf. Langenfeld, Moch, Pfoh; Beneke, Falgari, Schwinn, Wever; Kauth, Kress, Kühn; Broggio et al.

Squark and gluino production

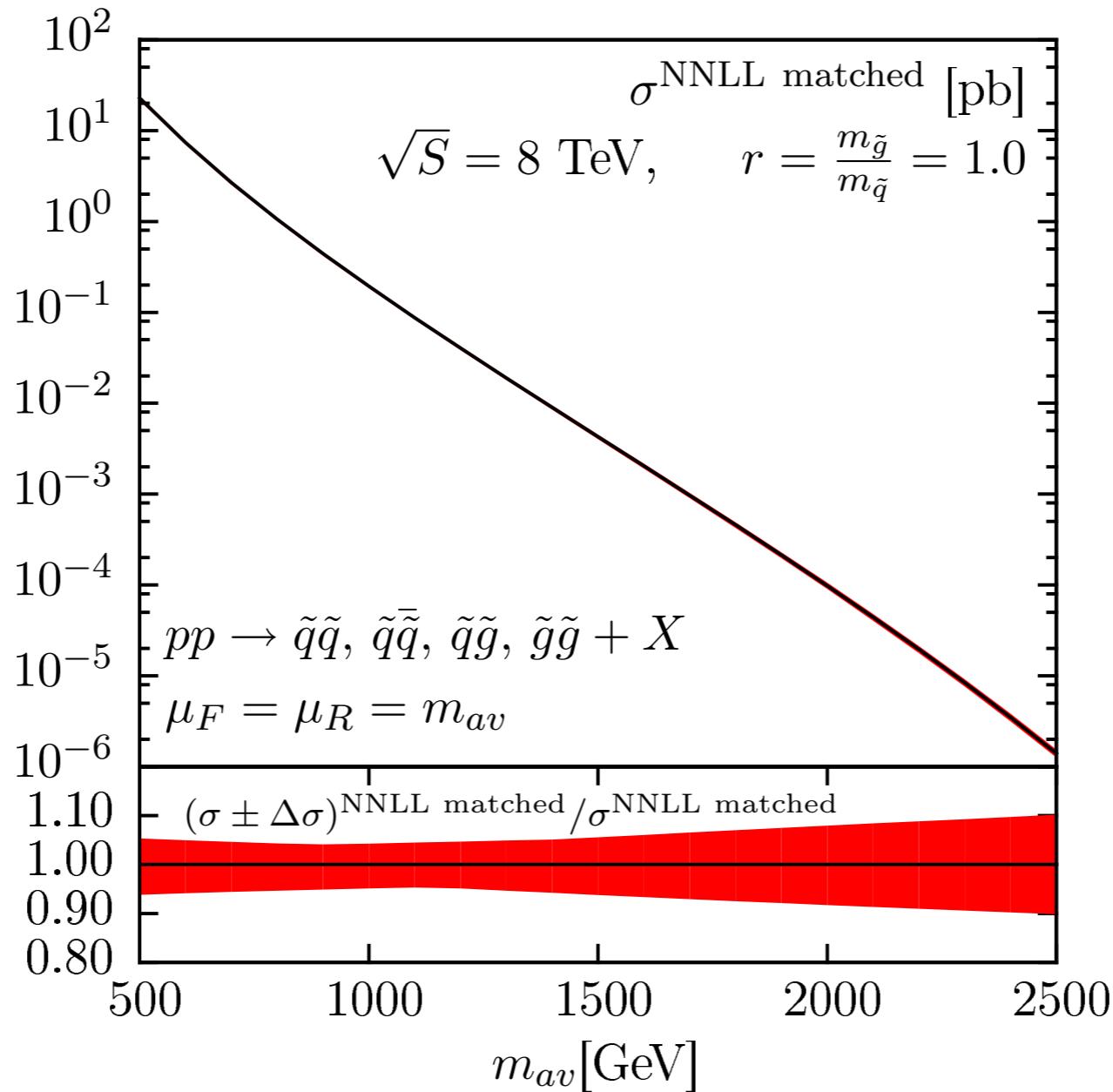
NLL threshold resummation



LHC recommendation: MK, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell (12)

Squark and gluino production

NNLL threshold resummation



Squark and gluino production

So far, to calculate the SUSY-QCD corrections we have assumed that

$u_{L/R}, d_{L/R}, s_{L/R}, c_{L/R}, b_{L/R}$ are mass degenerate

and we have summed over a swath of subprocesses

$$q_i \bar{q}_j \rightarrow \tilde{q}_k^{c1} \tilde{q}_l^{* c2} \quad \text{and} \quad g g \rightarrow \tilde{q}_i^c \tilde{q}_i^{* c}.$$

How good an approximation is that?

Squark and gluino production

Let us look at a random cMSSM scenario with

$m_0/m_{1/2}/A_0 = 825/550/0$ GeV, $\tan(\beta) = 10$ and $\text{sgn}(\mu) = +1$

corresponding to masses

$m_{\tilde{u}_L} = m_{\tilde{c}_L}$	$m_{\tilde{u}_R} = m_{\tilde{c}_R}$	$m_{\tilde{d}_L} = m_{\tilde{s}_L}$	$m_{\tilde{d}_R} = m_{\tilde{s}_R}$	$m_{\tilde{g}}$
1799.53	1760.21	1801.08	1756.40	1602.96

Taking the average squark mass as an input and summing over all subprocesses for squark-antisquark production one gets

$$K = 1.39$$

Squark and gluino production

Looking at the individual channels, we find

Process	$\sigma_{\text{LO}}[\text{fb}]$	$\sigma_{\text{NLO}}[\text{fb}]$	K-factor
$\tilde{u}_L \tilde{u}_L$	$9.51 \cdot 10^{-2}$	$1.43 \cdot 10^{-1}$	1.50
$\tilde{u}_R \tilde{\bar{u}}_R$	$1.14 \cdot 10^{-1}$	$1.72 \cdot 10^{-1}$	1.51
$\tilde{d}_L \tilde{\bar{d}}_L$	$5.50 \cdot 10^{-2}$	$8.79 \cdot 10^{-2}$	1.60
$\tilde{d}_R \tilde{\bar{d}}_R$	$6.89 \cdot 10^{-2}$	$1.11 \cdot 10^{-1}$	1.61
$\tilde{u}_L \tilde{\bar{u}}_R$	$3.75 \cdot 10^{-1}$	$5.12 \cdot 10^{-1}$	1.37
$\tilde{d}_L \tilde{\bar{d}}_R$	$1.41 \cdot 10^{-1}$	$1.70 \cdot 10^{-1}$	1.21
$\tilde{u}_L \tilde{\bar{d}}_L$	$6.98 \cdot 10^{-2}$	$7.89 \cdot 10^{-2}$	1.13
$\tilde{u}_L \tilde{\bar{d}}_R$	$2.98 \cdot 10^{-1}$	$3.54 \cdot 10^{-1}$	1.19
$\tilde{u}_R \tilde{\bar{d}}_L$	$2.94 \cdot 10^{-1}$	$3.49 \cdot 10^{-1}$	1.19
$\tilde{u}_R \tilde{\bar{d}}_R$	$8.36 \cdot 10^{-2}$	$9.54 \cdot 10^{-2}$	1.14
Sum	1.59	2.07	1.30

Squark and gluino production

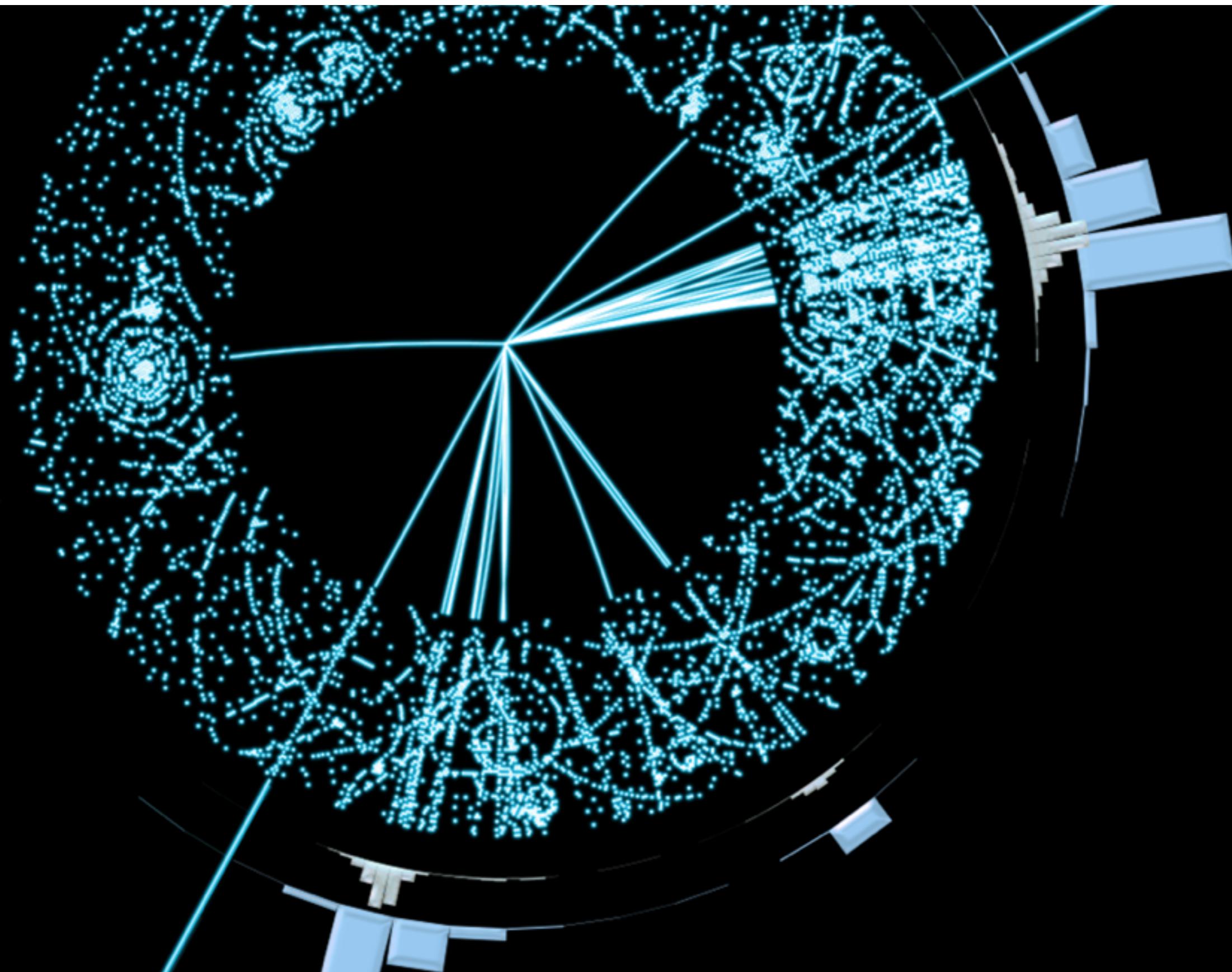
Looking at the cross section x decay we find

$$\sum_{\text{channels}} \sigma_{\text{NLO}} \cdot \text{BR}^{\text{LO}} (\tilde{q} \rightarrow \tilde{\chi}_0 q) \cdot \text{BR}^{\text{LO}} (\tilde{q}^* \rightarrow \tilde{\chi}_0 \bar{q}) = 0.139 \text{ fb.}$$

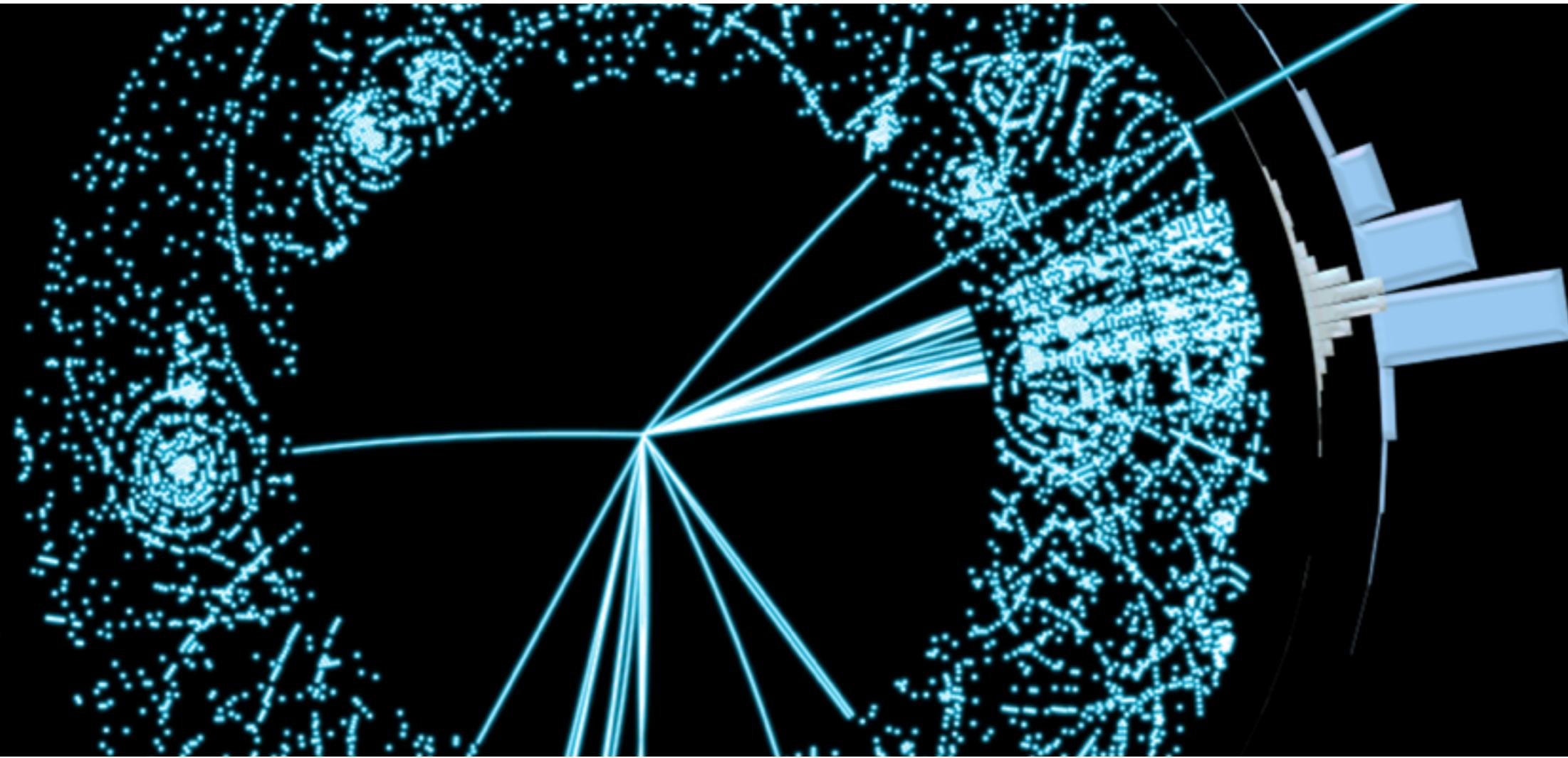
compared to the approximate (Prospino) calculation

$$\sum_{\text{channels}} \sigma_{\text{LO}} \cdot K^{\text{avg}} \cdot \text{BR}^{\text{LO}} (\tilde{q} \rightarrow \tilde{\chi}_0 q) \cdot \text{BR}^{\text{LO}} (\tilde{q}^* \rightarrow \tilde{\chi}_0 \bar{q}) = 0.126 \text{ fb.}$$

Squark & gluino production and decay



Squark & gluino production and decay



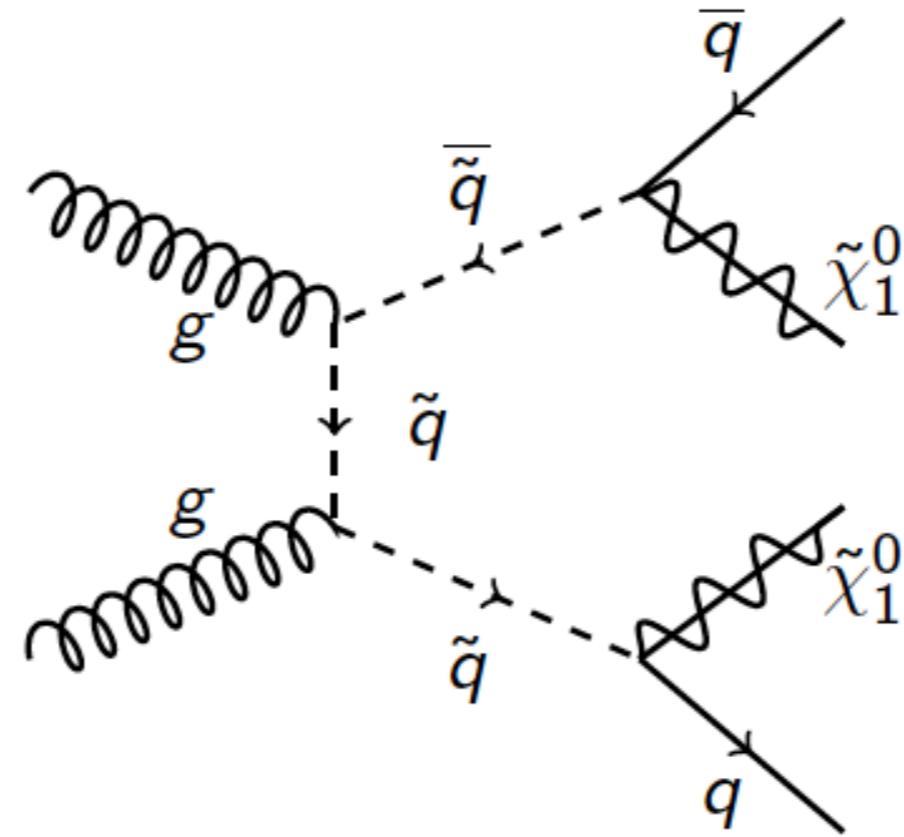
We need to describe **production & decay**
including higher-order effects

Squark & gluino production and decay

Calculate NLO SUSY-QCD corrections to sparticle production & decay in the narrow width approximation, but including spin effects

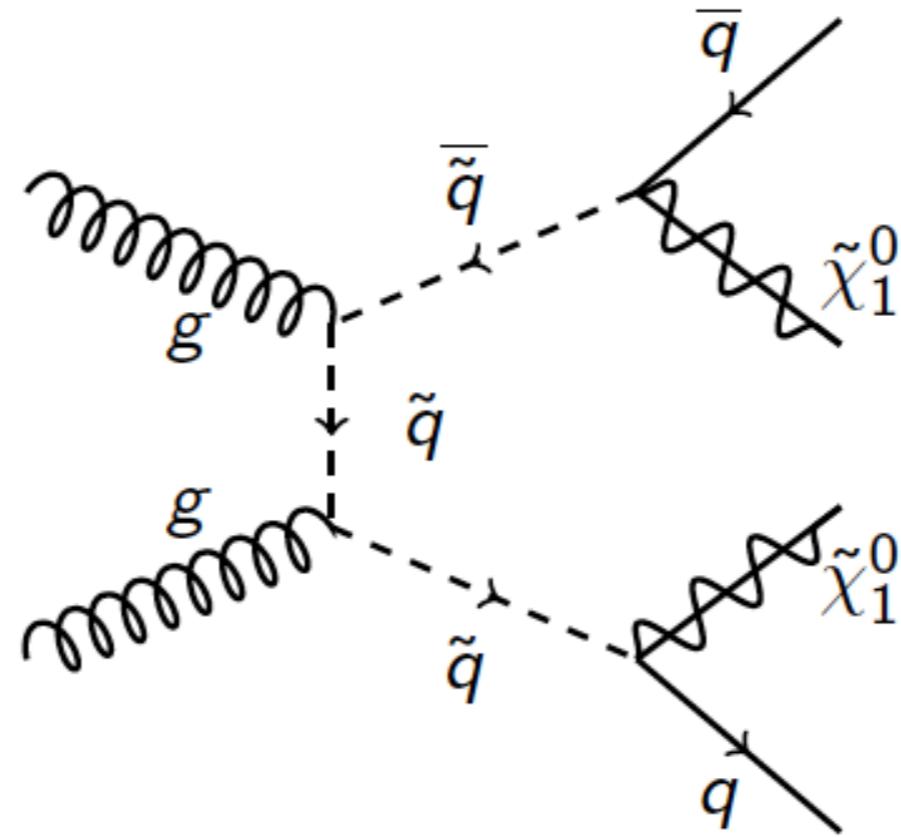
Squark & gluino production and decay

Calculate NLO SUSY-QCD corrections to sparticle production & decay in the narrow width approximation, but including spin effects



Squark & gluino production and decay

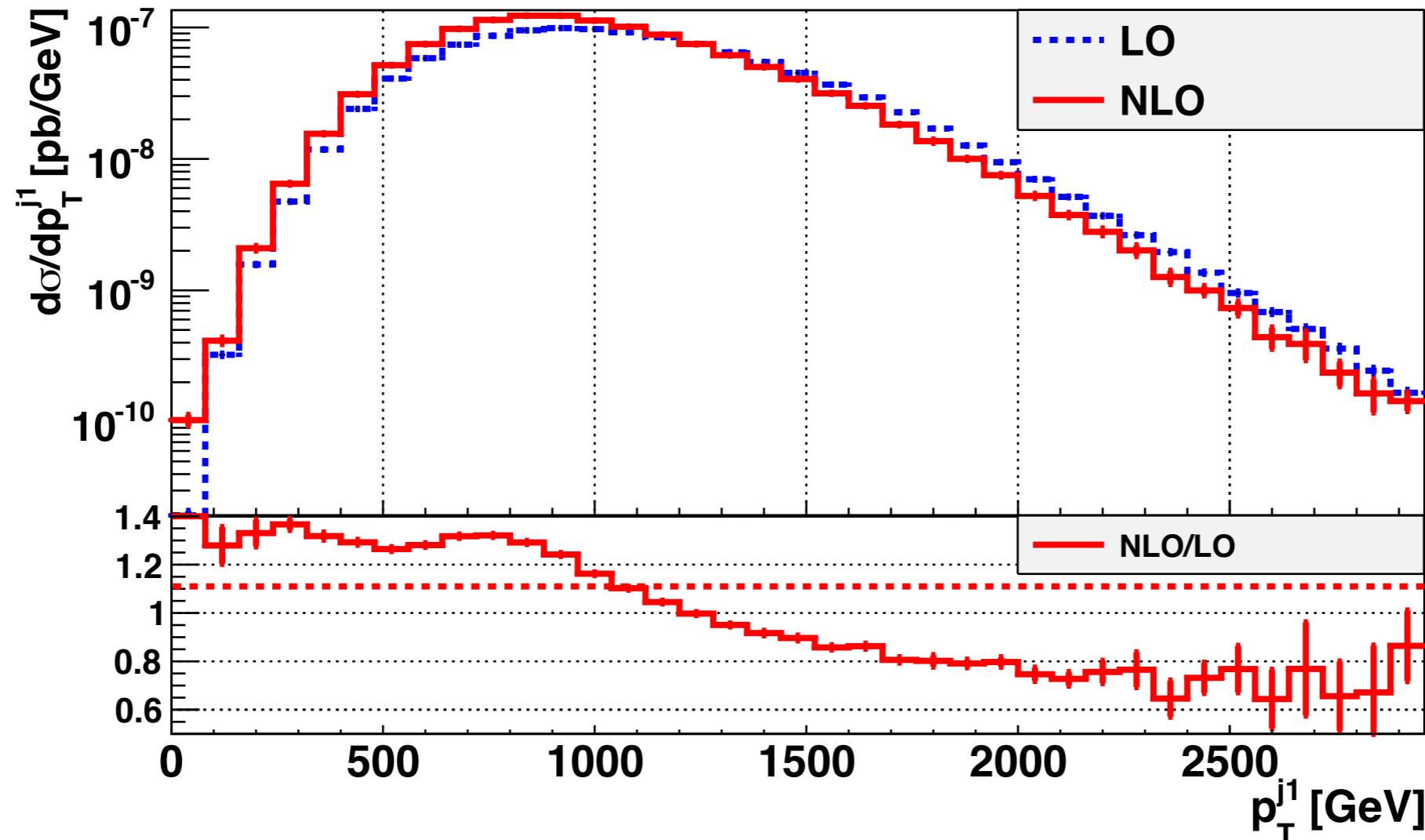
Calculate NLO SUSY-QCD corrections to sparticle production & decay in the narrow width approximation, but including spin effects



cf. Hollik, Lindert, Pagani; Boughezal, Schulze ('12,'13)

Squark & gluino production and decay

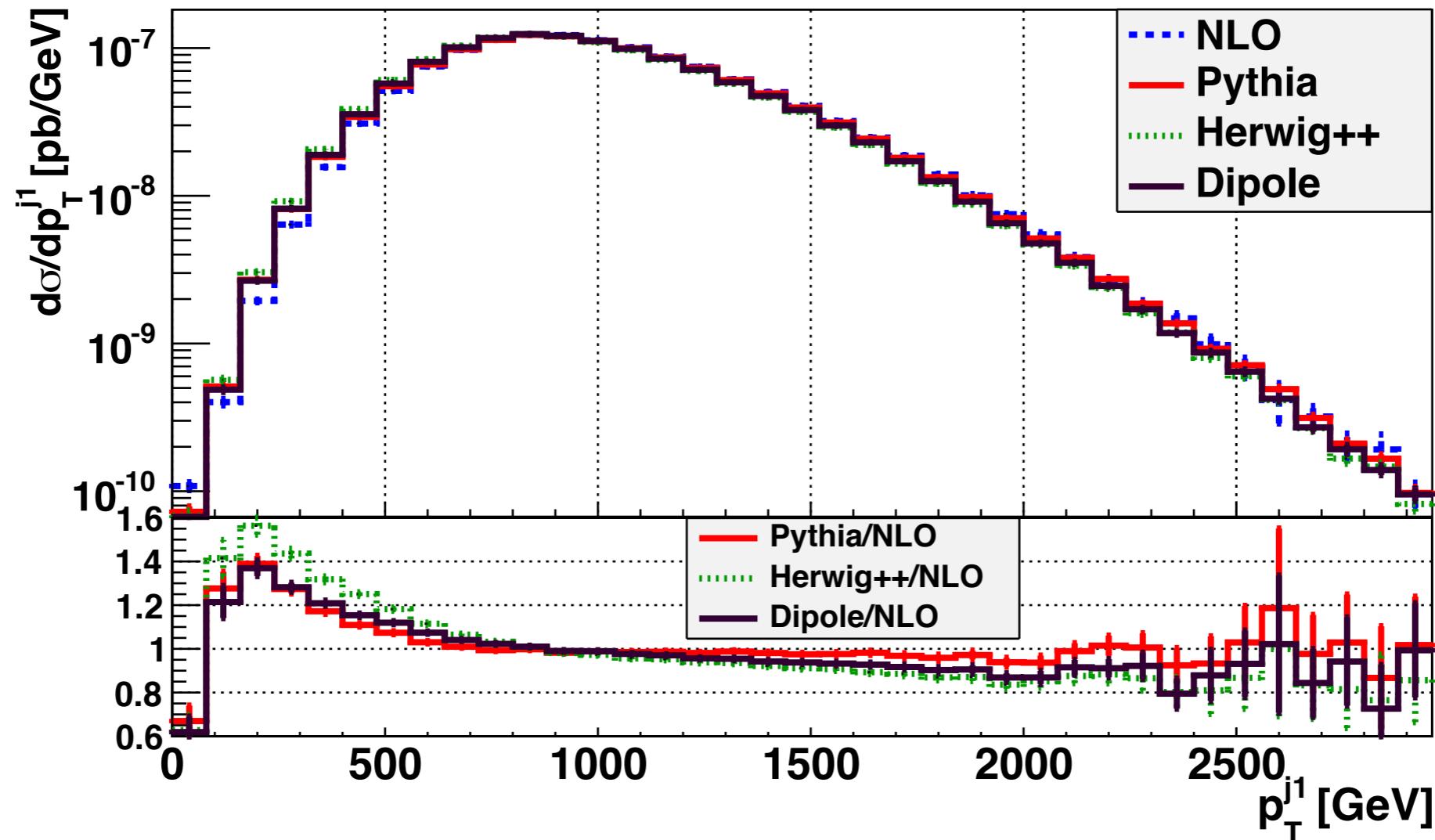
NLO differential distributions



Gavin, Hangst, MK, Mühlleitner, Pellen, Popenda, Spira ('14)

Squark & gluino production and decay

NLO differential distributions with parton showers



Gavin, Hangst, MK, Mühlleitner, Pellen, Popenda, Spira ('14)

Squark & gluino production and decay

NLO differential distributions with parton showers

ATLAS analysis

ATLAS-CONF-2013-047

$p_T^{j_1} > 130 \text{ GeV}$, $p_T^{j_2} > 60 \text{ GeV}$, $\cancel{E}_T > 160 \text{ GeV}$,
 $\frac{\cancel{E}_T}{m_{\text{eff}}} > 0.2$, $m_{\text{eff}}^{\text{incl}} > 1 \text{ TeV}$, $\Delta\phi(j_{1/2}, \cancel{E}_T) > 0.4$,
and $\Delta\phi(j_3, \cancel{E}_T) > 0.4$ if $p_T^{j_3} > 40 \text{ GeV}$

	$\tilde{q}\tilde{q}$	$\tilde{q}\bar{q}$
NLO	0.871 fb	0.0781 fb
PYTHIA	0.883 fb	0.0797 fb
HERWIG++	0.895 fb	0.0807 fb

Gavin, Hangst, MK, Mühlleitner, Pellen, Popenda, Spira ('14)

Squark and gluino production

Tools: Prospino, NLL-fast, sPOWHEG

+ MadGolem, MadGraph5_aMC@NLO, ...

Prospino: <http://www.thphys.uni-heidelberg.de/~plehn/index.php?show=prospino&visible=tools>

Our 20 year old warhorse, a bit worn down but still useful

Beenakker, Höpker, Klasen, MK,
Plehn, Spira, Zerwas ('94-'??)



Squark and gluino production

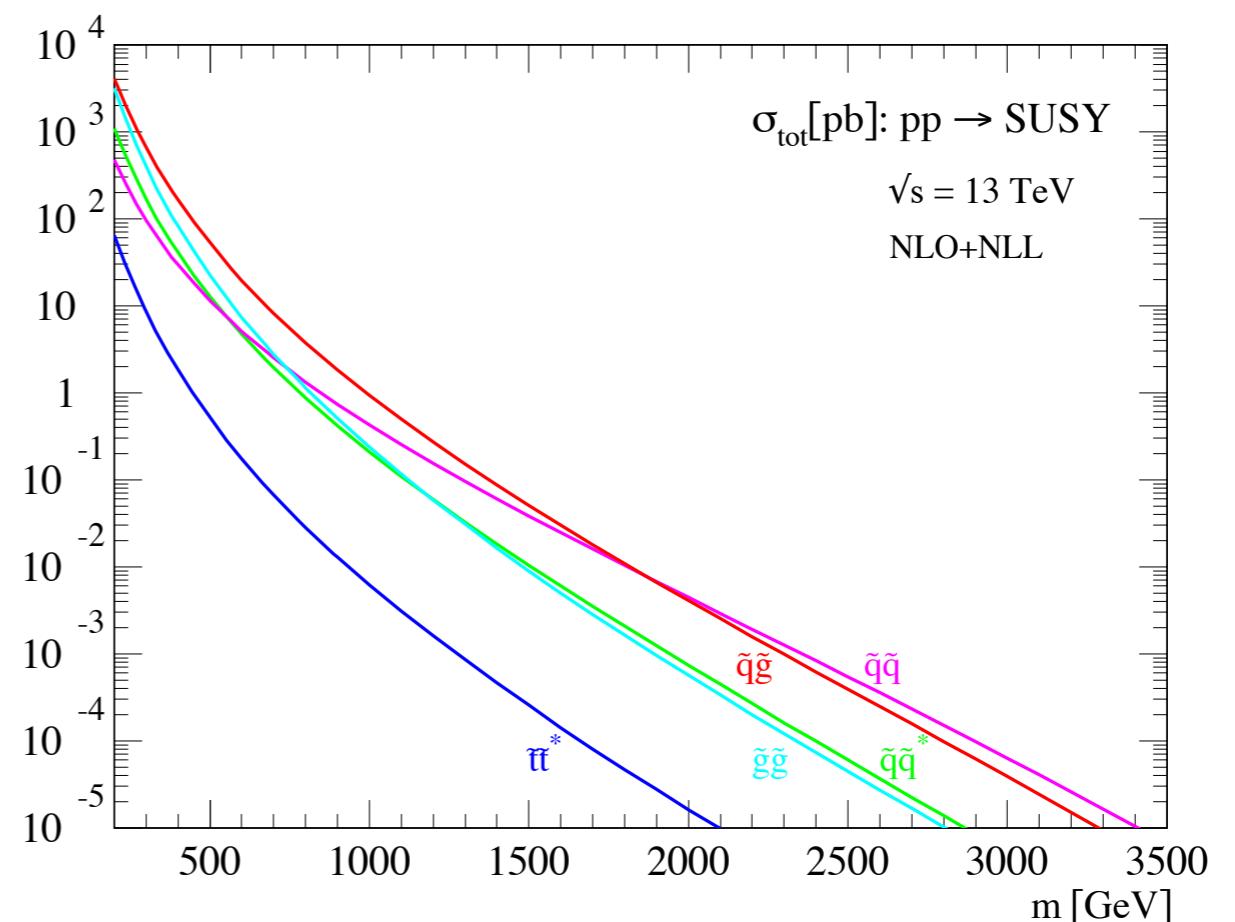
Tools: Prospino, NLL-fast, sPOWHEG

+ MadGolem, MadGraph5_aMC@NLO, ...

NLL-fast: http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast

The current standard tool
for inclusive NLO+NLL
cross section calculations

Beenakker, Borschensky, MK,
Kulesza, Laenen, Motyka, Niessen,
Thewes ('09-'14)



Squark & gluino production and decay

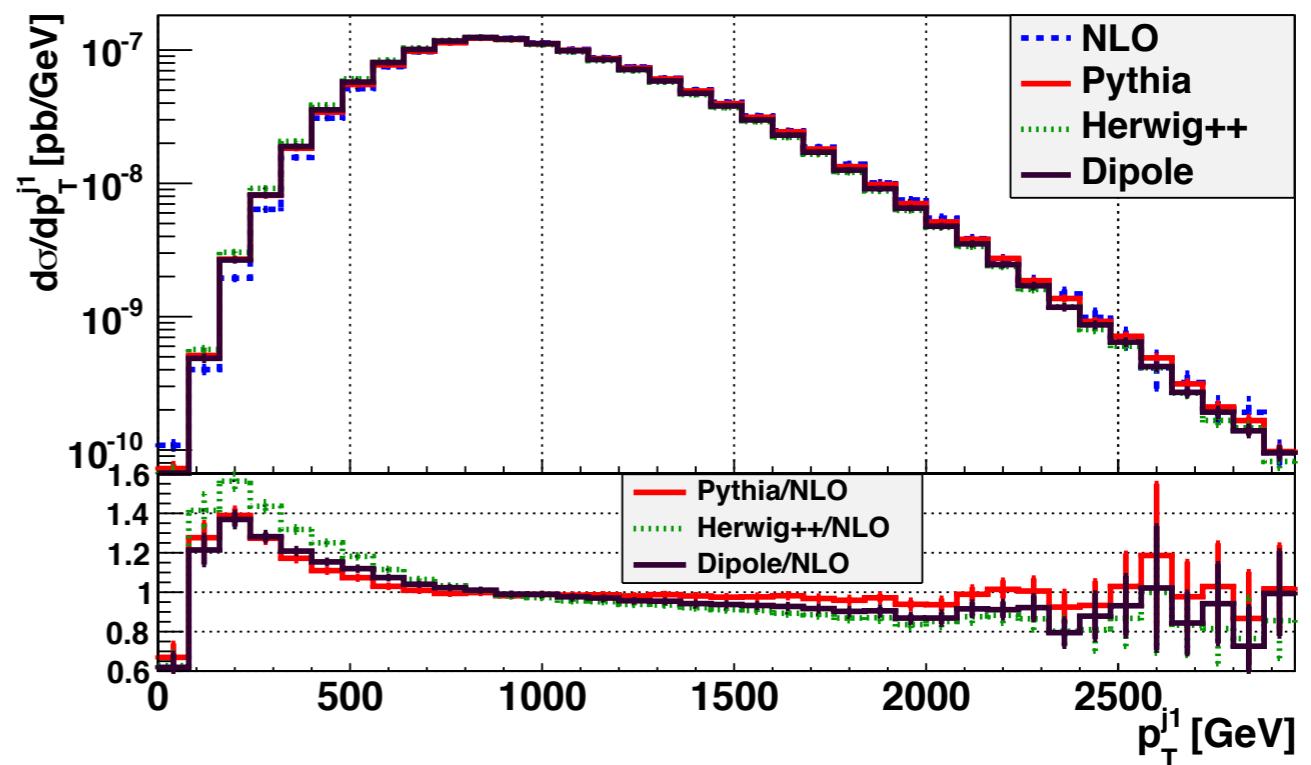
Tools: Prospino, NLL-fast, sPOWHEG

+ MadGolem, MadGraph5_aMC@NLO, ...

sPOWHEG: <http://powhegbox.mib.infn.it>

NLO squark production
and decay matched to
parton showers

POWHEG team + Gavin, Hangst,
MK, Mühlleitner, Pellen, Popenda,
Spira ('14)



Squark and gluino production

A lot of effort (> 20 years) went into calculating higher-order QCD corrections for squark and gluino production

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Squark and gluino production

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The theoretical uncertainty for inclusive cross sections is $\lesssim 15\%$, and is now dominated by the pdf error

In the future, we need to work towards automated NLO calculations for more generic models, including NLL resummation

Thank you!