Precision Calculations for SUSY Searches at Hadron Colliders

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Outline

- Higher-order corrections to SUSY particle production:
  squark & gluino production at the Tevatron and the LHC
- SUSY searches at the Tevatron:
  current limits on squark and gluino masses
- Exploring SUSY at the LHC:
  parameter determination using cross sections

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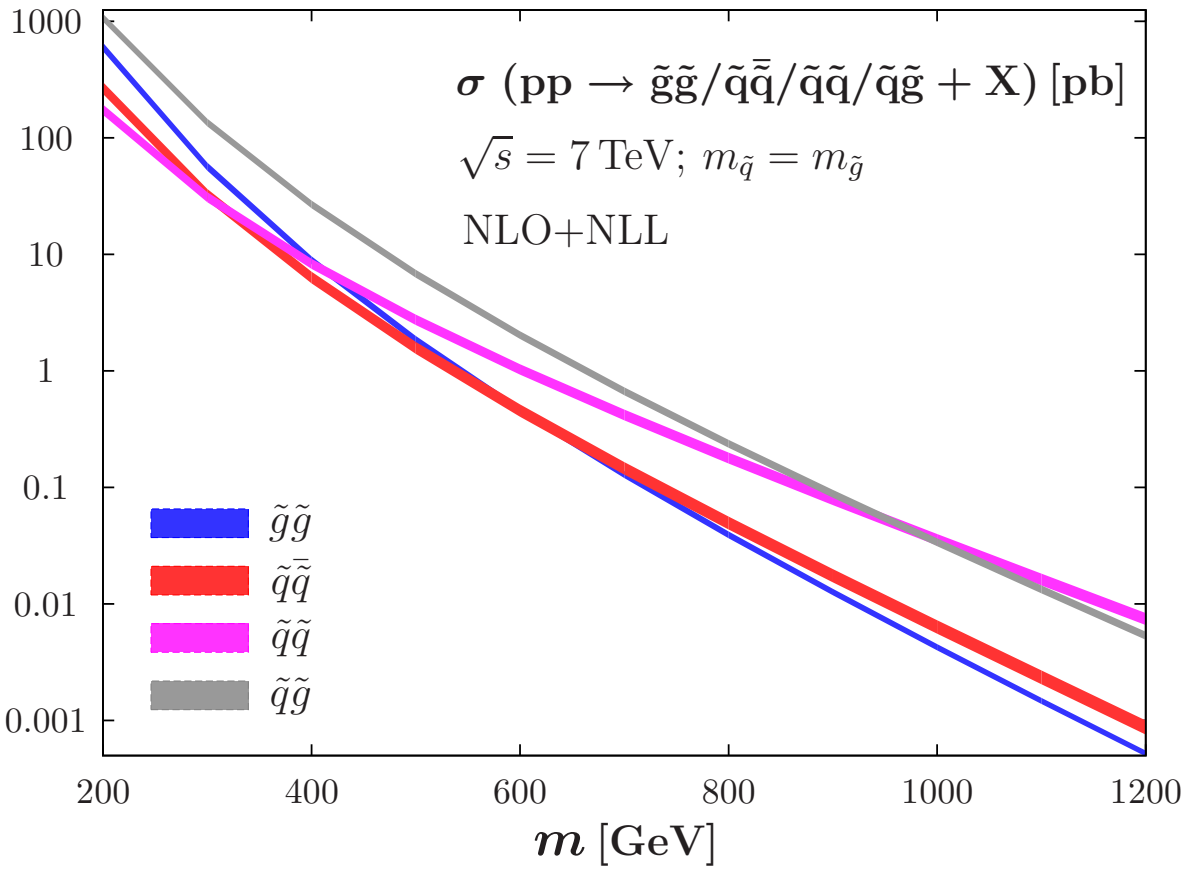
NLO+NLL QCD cross section

[Beenakker, Höpker, Spira, Zerwas '96; Beenakker, Brensing, MK, Laenen, Kulesza, Niessen '09]



Squark and gluino production at the LHC

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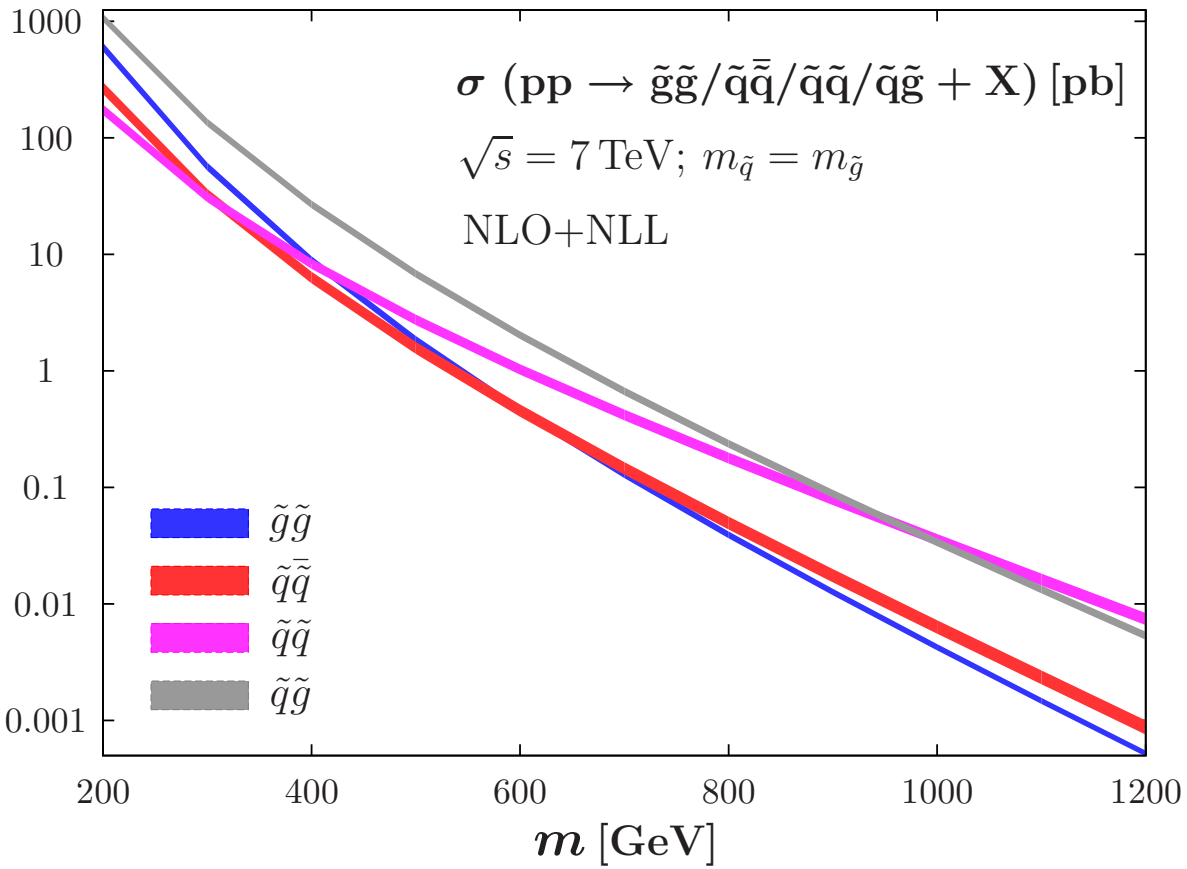

$\to \sigma \approx 20$ pb for $m \approx 500$ GeV at the LHC with 7 TeV

Squark and gluino production at the LHC

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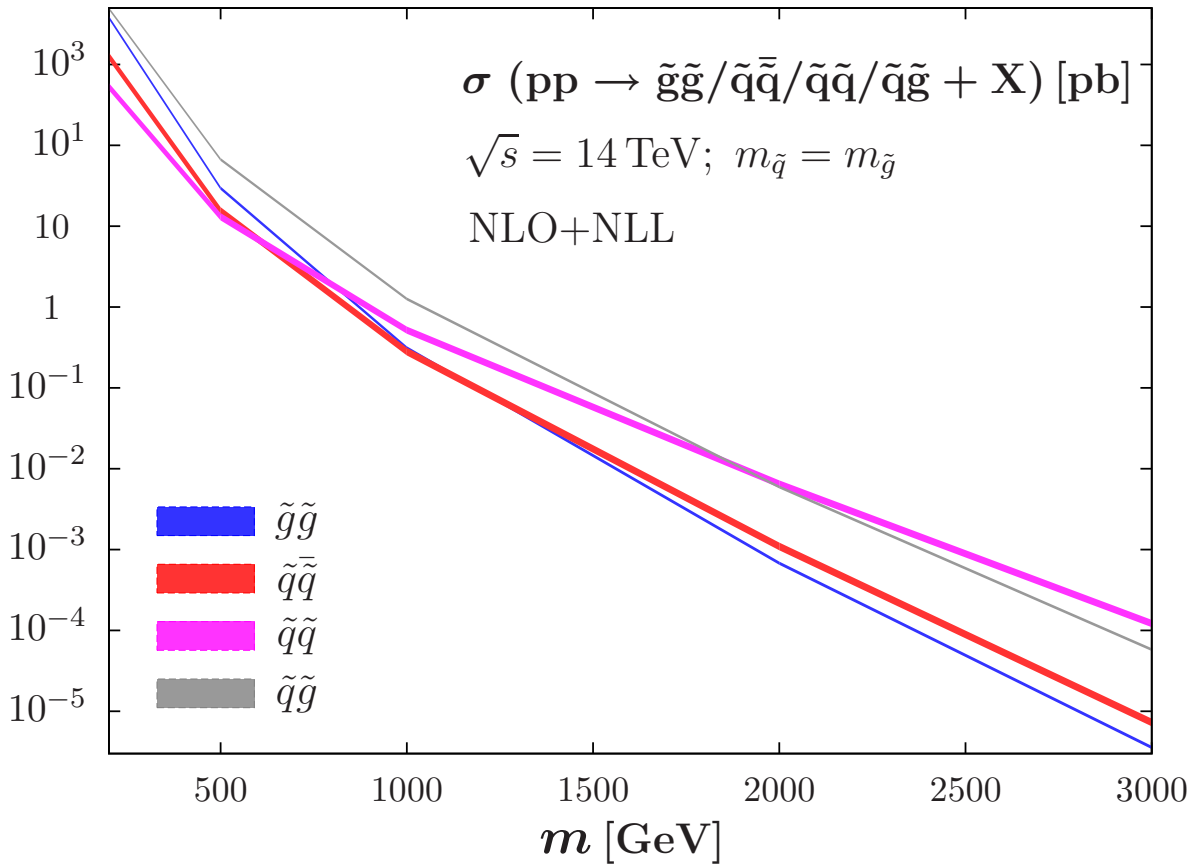
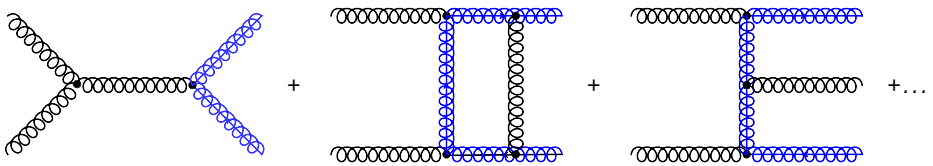


$\longrightarrow \sigma \approx 2.5$ pb for $m \approx 1000$ GeV at the LHC with 14 TeV

NLO+NLL QCD corrections

Take gluino-pair production as an example



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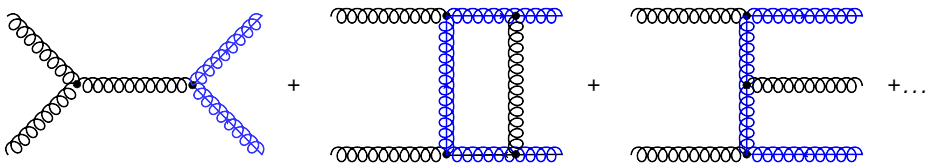
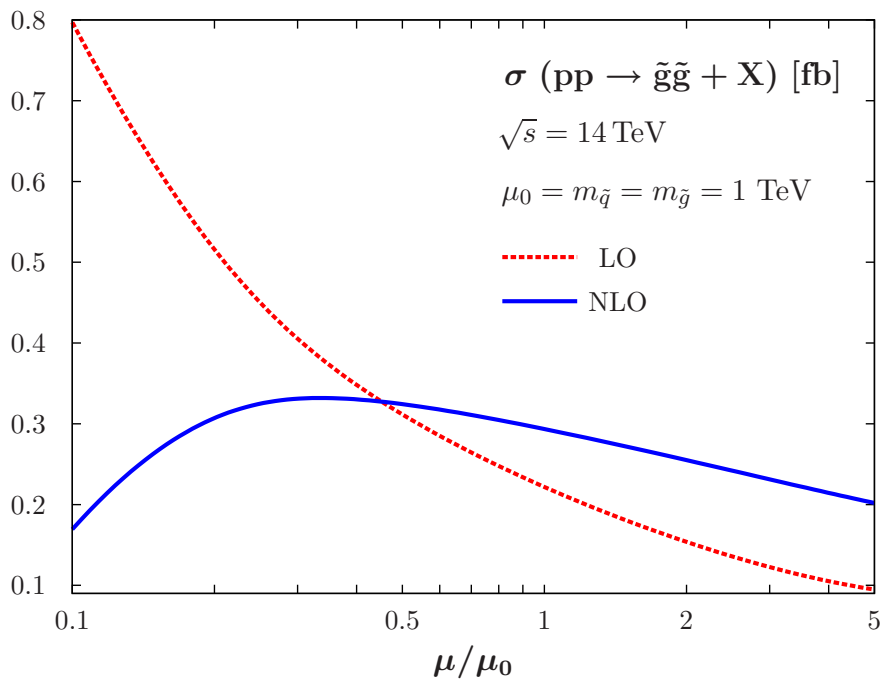


Scale dependence



$\longrightarrow \Delta\sigma \approx \pm$ 20% at NLO [Beenakker, Höpker, Spira, Zerwas '96]

NLO+NLL QCD corrections

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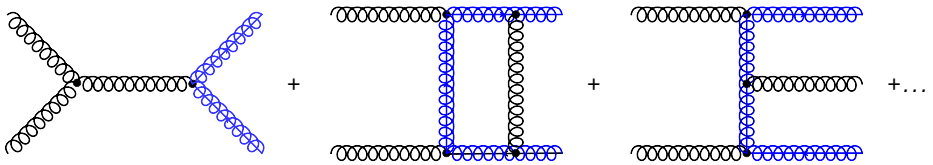
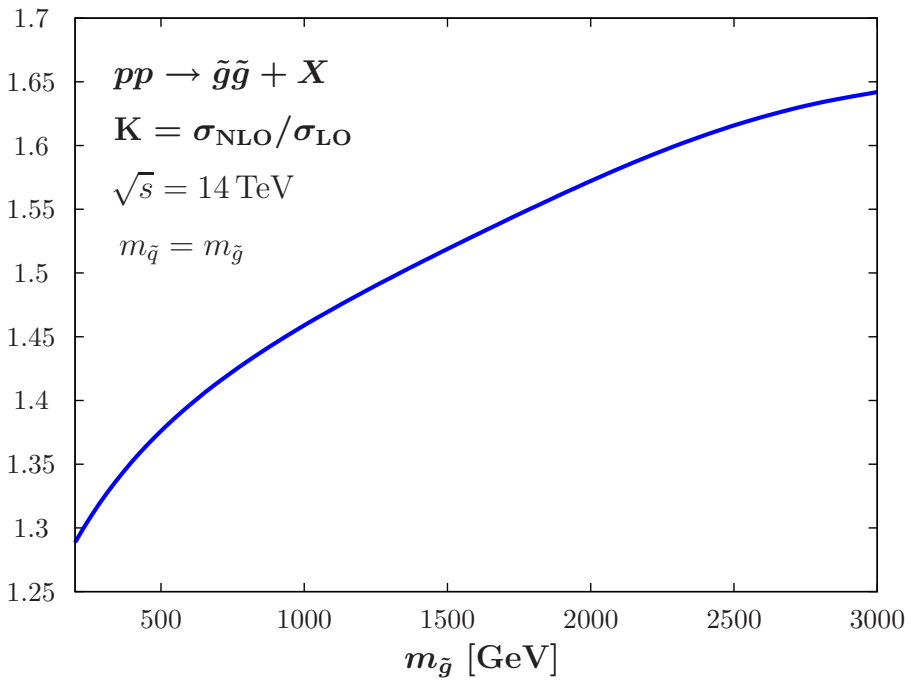


K-factor



$\longrightarrow$ large NLO corrections for $m_{\tilde{g}} \gtrsim 1$ TeV

Threshold summation

NLO cross section near threshold $\beta = \sqrt{1 - 4m^2/s} \ll 1$:

$$\sigma^{\mathrm{NLO}}[gg \to \tilde{g}\tilde{g} + X] \approx \frac{\alpha_s^2(\mu^2)}{m^2} \frac{27\pi}{64} \beta \left(1 + 4\pi\alpha_s(\mu^2) \left\{ \frac{1}{16\beta} + \frac{3}{2\pi^2} \ln^2(8\beta^2) - \frac{29}{4\pi^2} \ln(8\beta^2) - \frac{3}{2\pi^2} \ln(8\beta^2) \ln\left(\frac{\mu^2}{m^2}\right) \right\}\right)$$

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$$\left.\left. + \frac{3}{2\pi^2}\ln^2(8\beta^2) - \frac{29}{4\pi^2}\ln(8\beta^2) - \frac{3}{2\pi^2}\ln(8\beta^2)\ln\left(\frac{\mu^2}{m^2}\right)\right\}\right)$$

$\longrightarrow$ requires all order summation of large logarithmic corrections:

$$d\sigma^{\mathrm{res}} \propto d\sigma_{\mathrm{LO}} \times \exp\left(\underbrace{\log\beta^2 g_1(\alpha_s \log\beta^2)}_{\mathrm{LL}} + \underbrace{g_2(\alpha_s \log\beta^2)}_{\mathrm{NLL}} + \ldots\right) + \ldots$$

[Kulesza, Motyka; Beenakker, Brensing, MK, Kulesza, Laenen, Niessen '09

cf. Kidonakis, Sterman; Bonciani, Catani, Mangano, Nason; ...]

NLO+NLL QCD corrections

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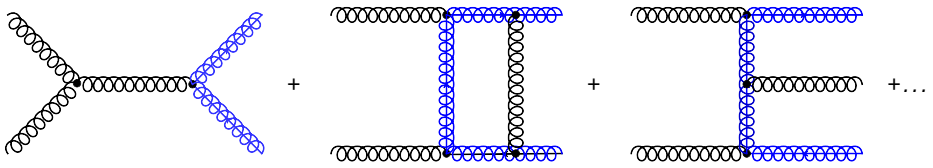

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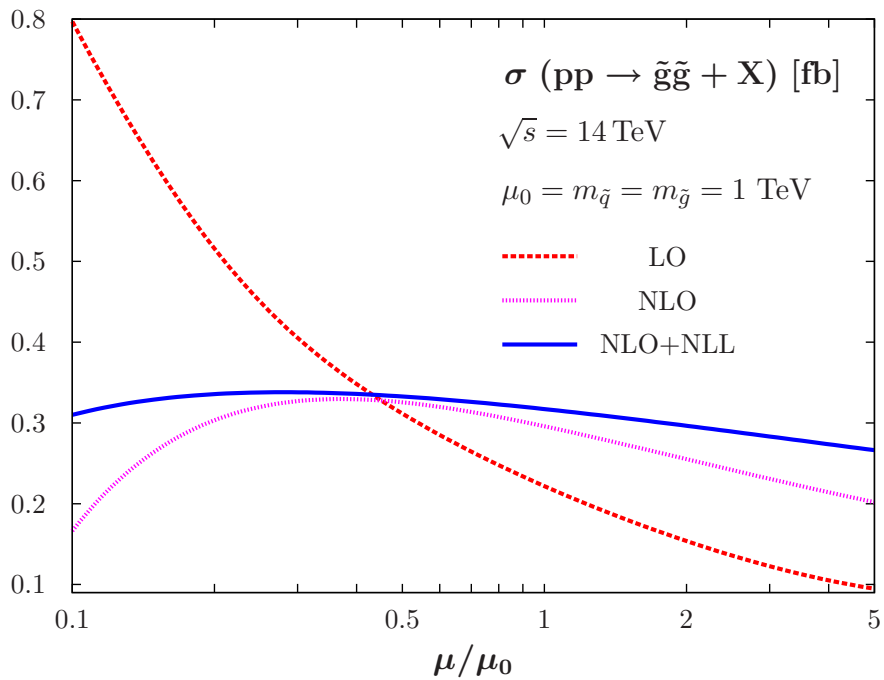

$\to \Delta\sigma \lesssim \pm 10\%$ at NLO+NLL [Kulesza, Motyka; Beenakker et al.]

NLO+NLL QCD corrections

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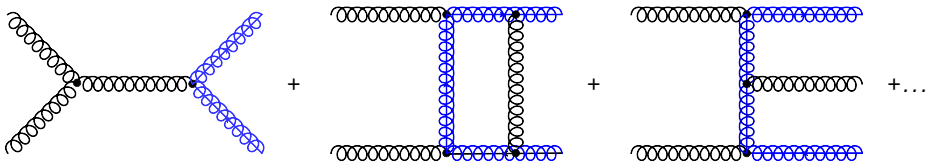
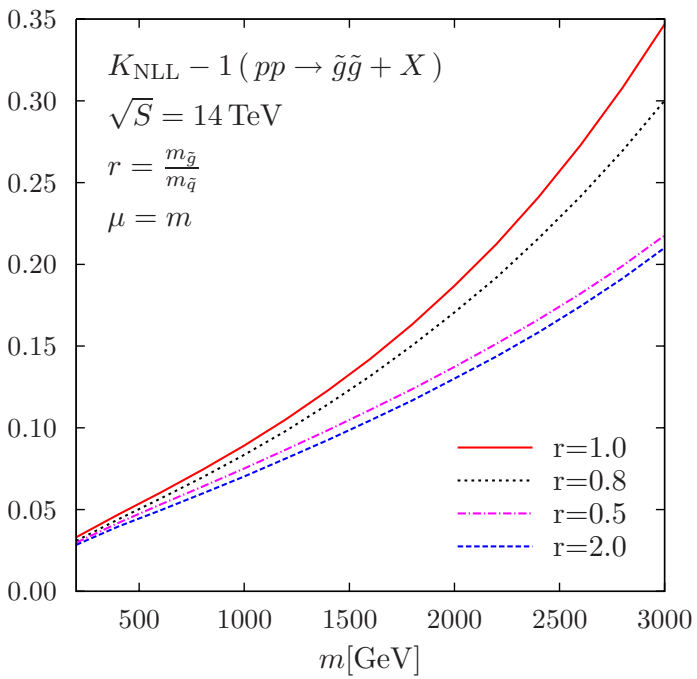


NLL K-factor



$\longrightarrow$ up to 30% increase from NLL summation [Kulesza, Motyka; Beenakker et al.]

PDF uncertainty: MSTW error pdf sets

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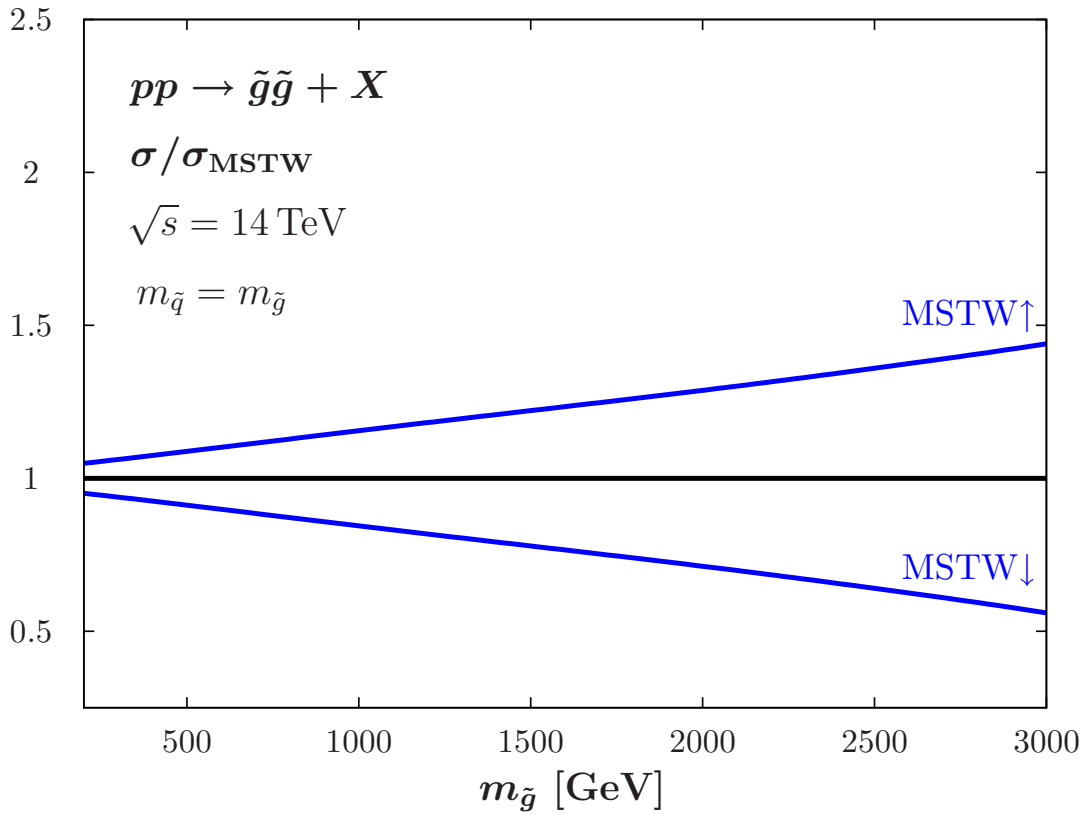
gluino-pair production:

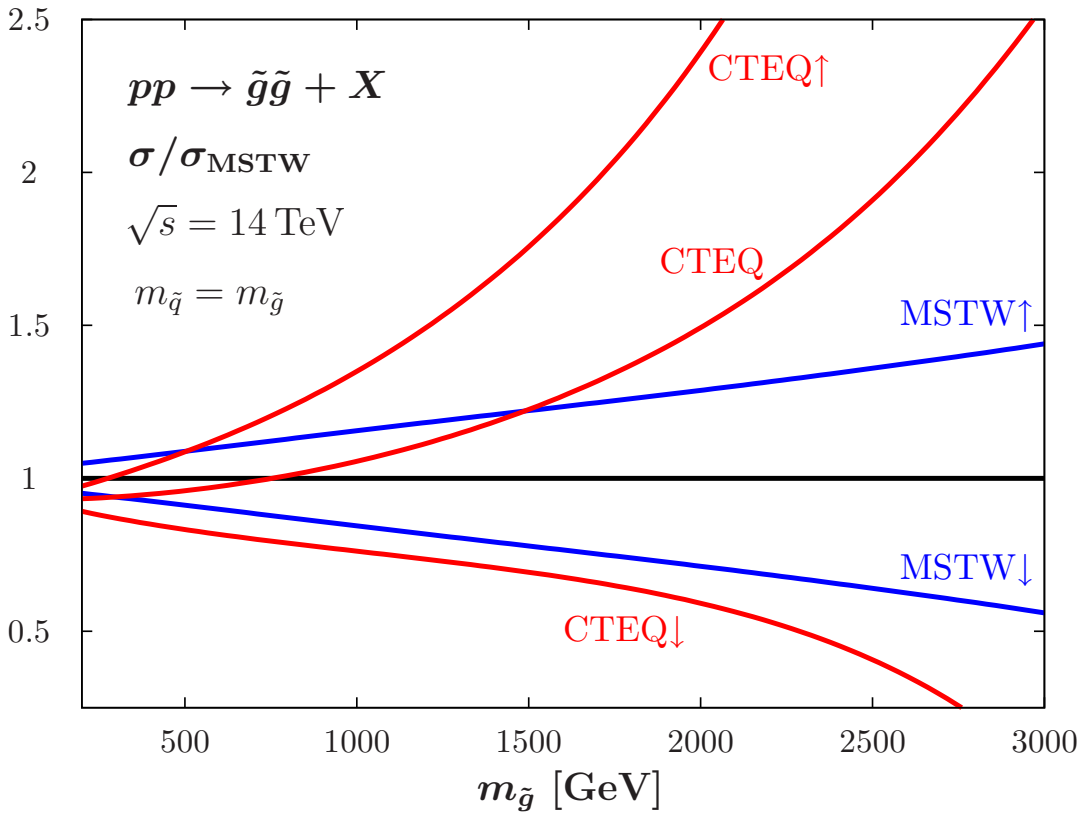


$\longrightarrow$ driven by gluon pdf at large x

$\longrightarrow$ sizeable uncertainty $\approx \pm 15\%$ for $m \approx 1$ TeV

PDF uncertainty: MSTW and CTEQ6.6 error pdf sets

gluino-pair production:

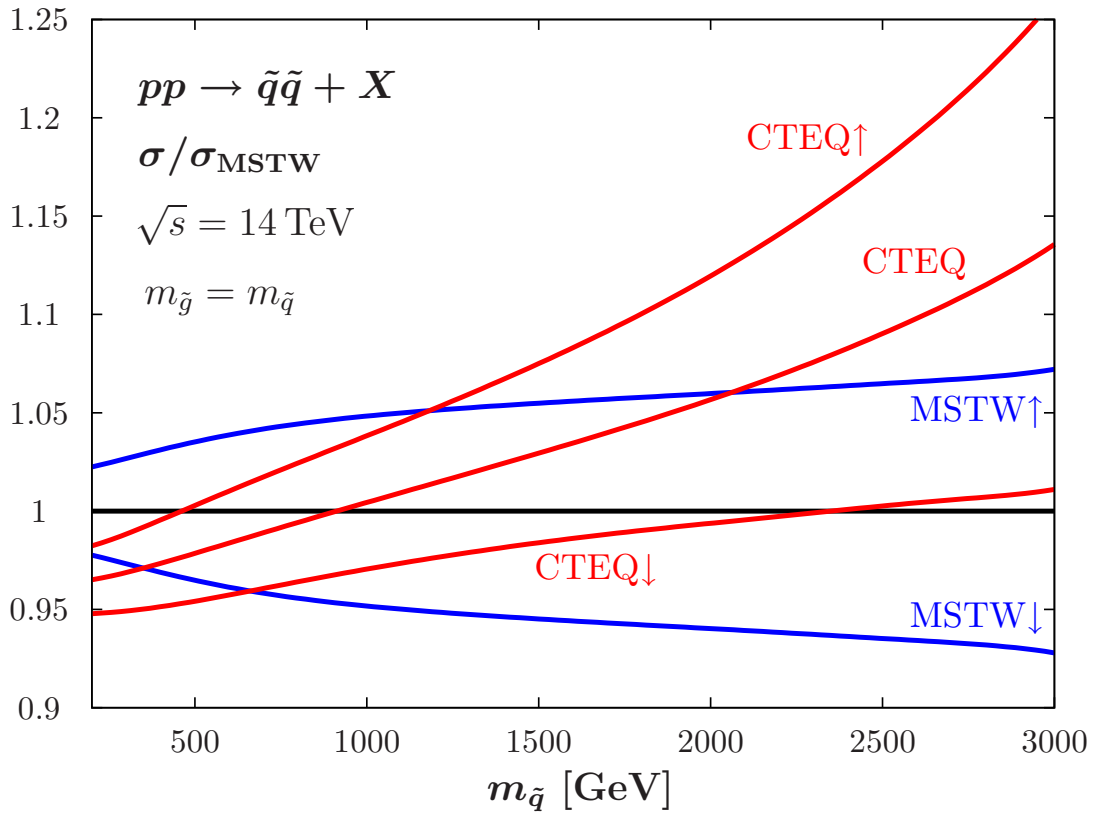


$\longrightarrow$ driven by gluon pdf at large x

$\longrightarrow$ sizeable uncertainty $\approx \pm 25\%$ for $m \approx 1$ TeV

PDF uncertainty: MSTW and CTEQ6.6 error pdf sets

squark-squark production:



$\longrightarrow$ driven by valence quark pdfs at large x

$\longrightarrow$ small uncertainty $\approx \pm 5\%$ for $m \approx 1$ TeV

Progress in precision calculations for squark and gluino production

- NLO QCD → public computer code PROSPINO

  [Beenakker, Höpker, MK, Plehn, Spira, Zerwas]

- NLL threshold summation

  [Kulesza, Motyka; Langenfeld, Moch; Beenakker, Brensing, MK, Kulesza, Laenen, Niessen; Beneke, Falgari, Schwinn]

  → see talk by Silja Brensing

- Electroweak corrections

  [Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim; Beccaria, Macorini, Panizzi, Renard, Verzegnassi]

  → see talks by Edoardo Mirabella and Jong Soo Kim

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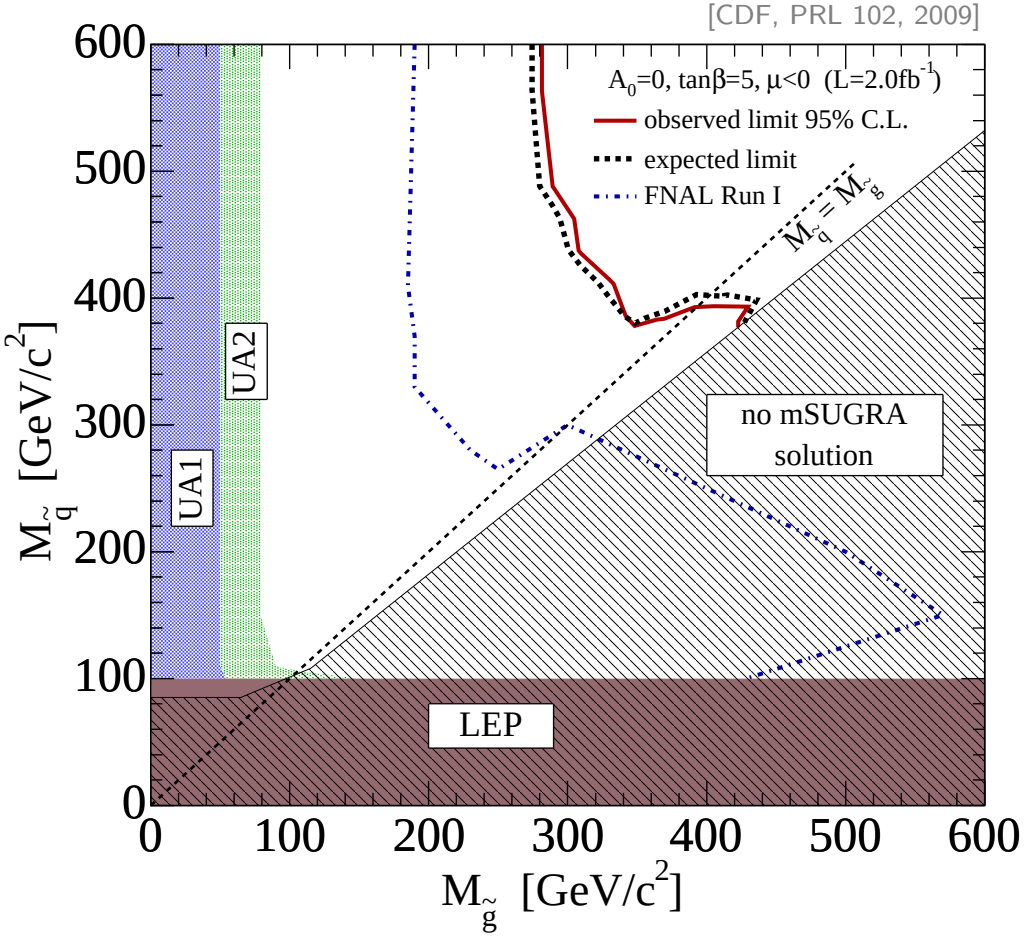
Squark and gluino searches at the Tevatron

Inclusive search in jets + $\not{E}_{\mathrm{T,miss}}$ → see talk by Gianluca De Lorenzo

[CDF, PRL 102, 2009]



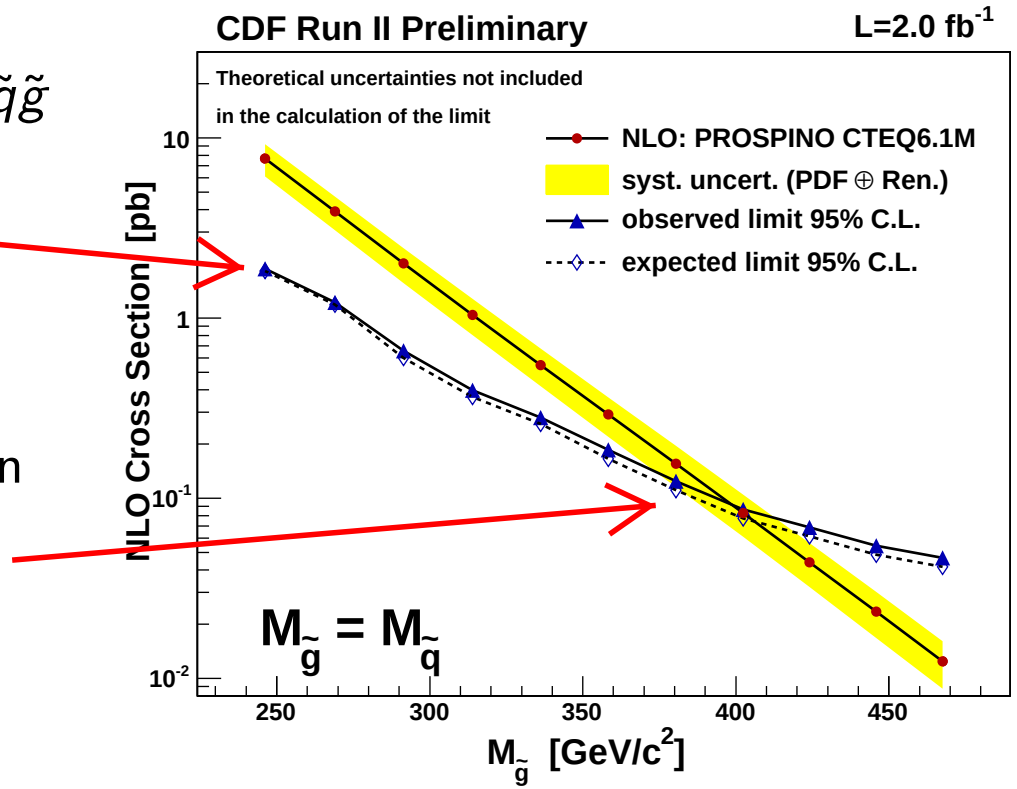
→ mass limits

$$M_{\tilde{g}} \gtrsim 280 \text{ GeV}$$

$$M_{\tilde{q}} \approx M_{\tilde{g}} \gtrsim 400 \text{ GeV}$$

Impact of precision calculations on SUSY limits

- relative weight of $\tilde{g}\tilde{g}/\tilde{q}\tilde{q}/\tilde{q}\tilde{g}$ enters efficiency and thus cross section limit
- mass limit from comparison of cross section limit and theory prediction



re-analysis of CDF limits with NLO+NLL theory in progress...

[D'Onofrio, MK, Martinez, ...]

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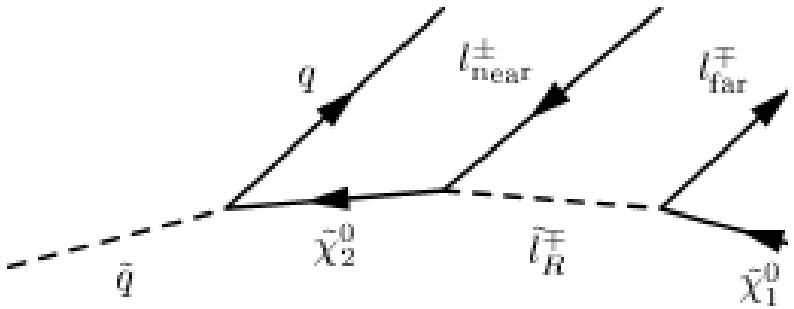
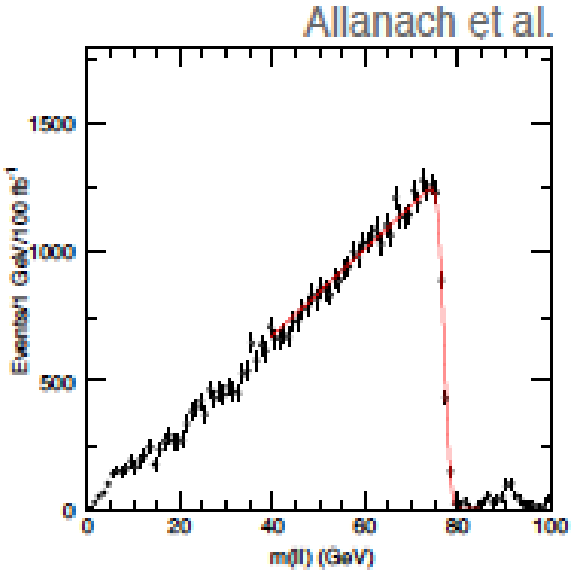
Mass measurements from cascade decays, e.g.





$\longrightarrow$ kinematic endpoints sensitive to masses:

$$
\begin{aligned}
(m^2_{ll})^{\max} &= (m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})/m^2_{\tilde{l}_R} \\
(m^2_{qll})^{\max} &= (m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})/m^2_{\tilde{\chi}^0_2} \\
(m^2_{ql,\min})^{\max} &= (m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})/m^2_{\tilde{\chi}^0_2} \\
(m^2_{ql,\max})^{\max} &= (m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})/m^2_{\tilde{l}_R}
\end{aligned}
$$

[cf. talks by Matchev, Robens, Cho, Sakurai, Mura, ...]

SUSY parameter determination at the LHC

14 TeV & 10 fb^{-1}: SPS1a with kinematic edges + additional observables

mSUGRA fit using FITTINO [Bechtle, Desch, Wienemann]

[cf. Allanach et al., Lafaye et al., Roszkowski et al., Flächer et al., AbdusSalam et al., Buchmüller et al., Akrami et al., ...]

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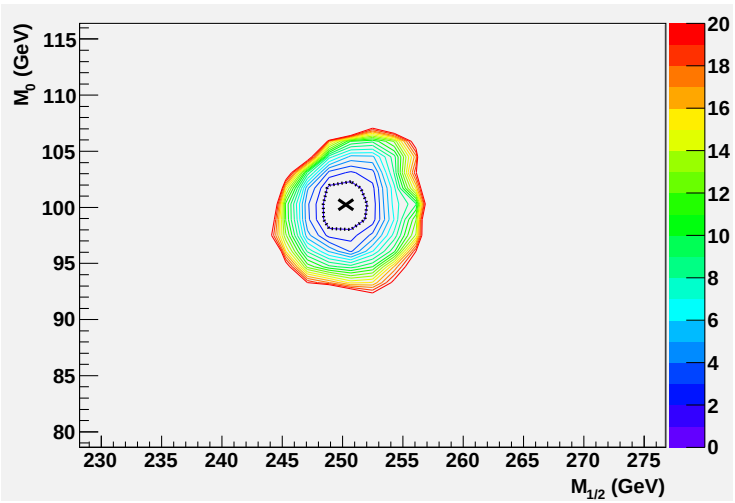
parameter	nominal	fit	error
m_0 [GeV]	100	100.2	± 1.5
$m_{1/2}$ [GeV]	250	250.3	± 1.2
$\tan\beta$	10	10.1	± 1
A_0 [GeV]	-100	-95	± 50

[Dreiner, MK, Lindert, O'Leary]



→ accurate determination of model parameters

SUSY parameter determination with cross sections

How well can we do at 7 TeV and 1 fb^{-1}? [Dreiner, MK, Lindert, O'Leary]

[cf. Baer et al., Altunkaynak et al., talks by Tata, Nath,... and various ATLAS and CMS talks]

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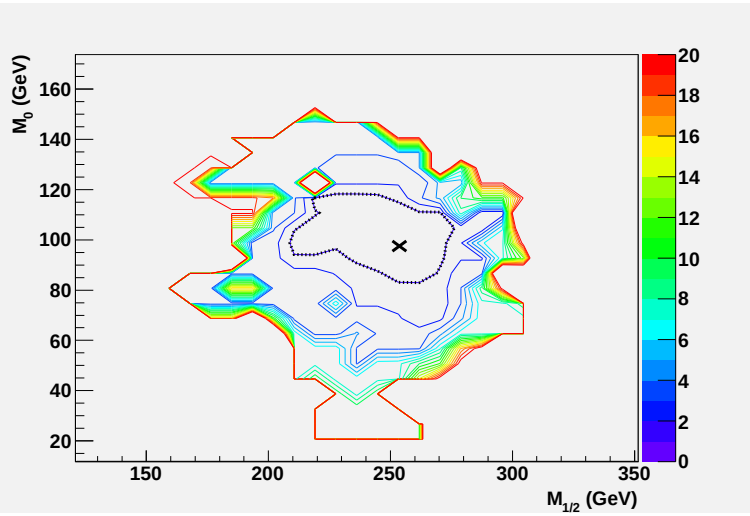

SPS1a with 4 kinematic edges only

$\longrightarrow$ no stable fit

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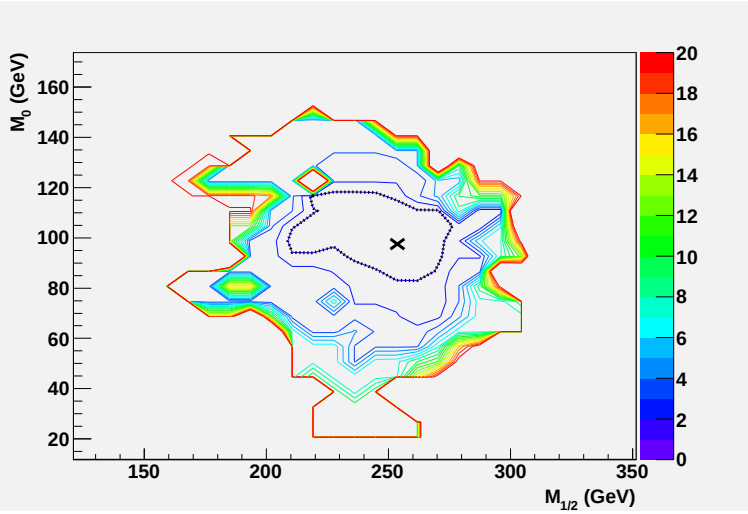

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$\longrightarrow$ add cross sections:
sensitive to masses and spins

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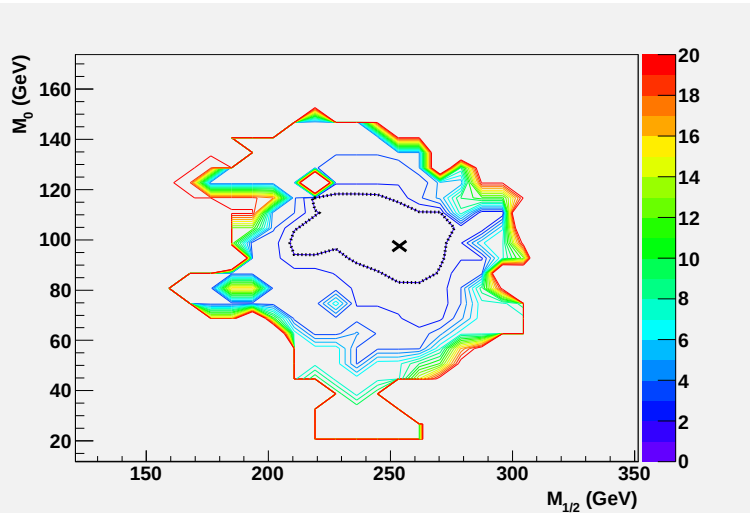

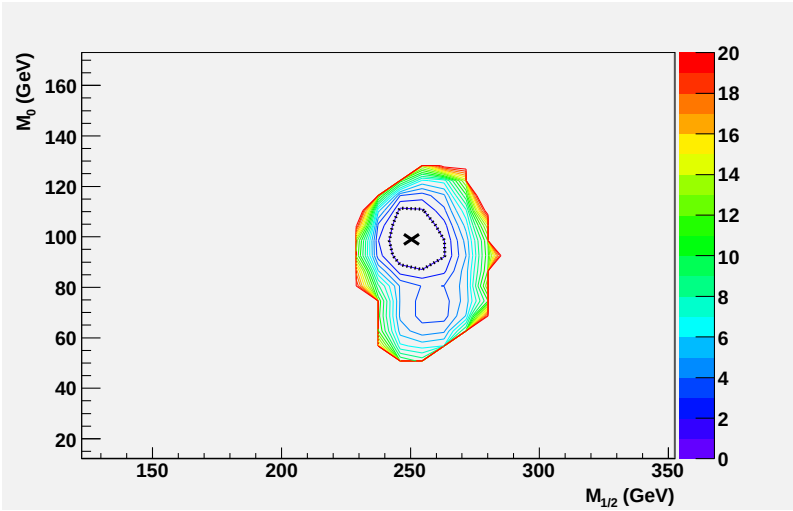

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kinematic edges $\oplus$ cross sections

$\longrightarrow$ $m_0 = 99 \pm 9$ GeV

$m_{1/2} = 250 \pm 7$ GeV

$\tan\beta = 11 \pm 6$

SUSY parameter determination with cross sections

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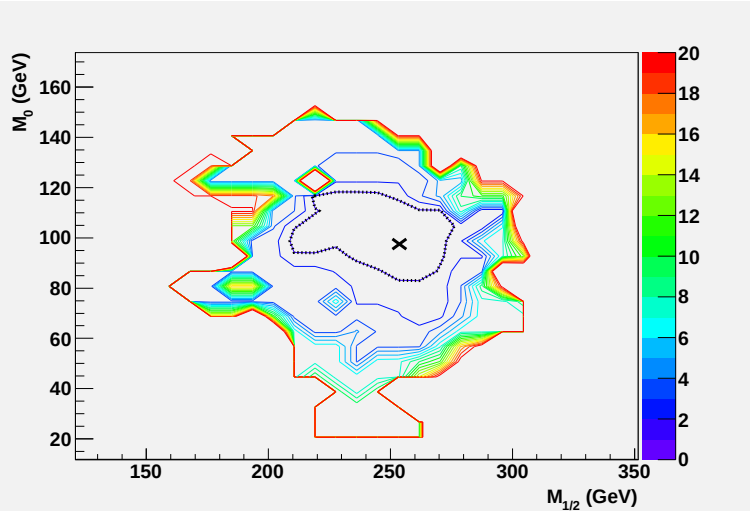

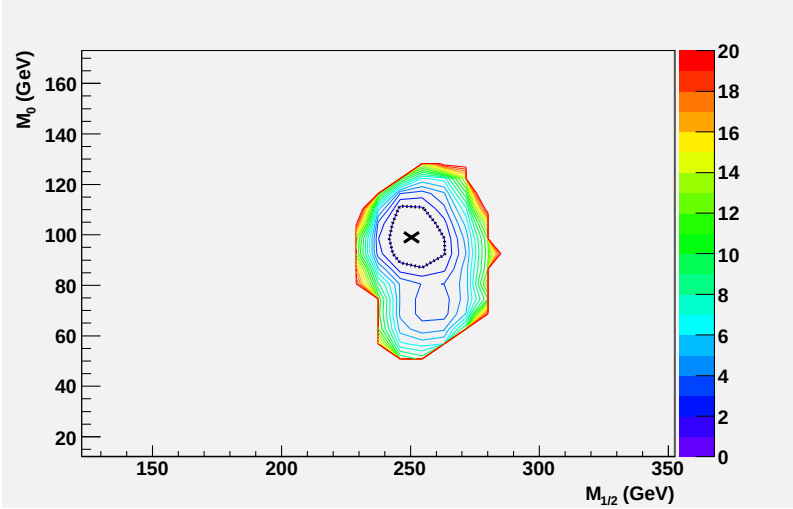

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$\longrightarrow$ cross sections are crucial to determine BSM parameters

SUSY parameter determination: exploring non-universal models

How well can we determine M_1, M_2 and M_3 individually?

7 TeV & 1 fb^{-1}: 4 kinematic edges + rates

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7 TeV & 1 fb^{-1}: 4 kinematic edges + rates

	M_1 [GeV]	M_2 [GeV]	M_3 [GeV]
edges + rates$_{\Delta=100\%}$	$242.3^{+173.7}_{-91.5}$	$241.8^{+186.0}_{-48.3}$	$249.3^{+68.5}_{-19.6}$
edges + rates$_{\Delta=50\%}$	$248.9^{+107.7}_{-82.4}$	$250.0^{+72.9}_{-46.1}$	$245.5^{+32.9}_{-9.8}$
edges + rates$_{\Delta=20\%}$	$236.5^{+67.1}_{-57.9}$	$242.6^{+51.6}_{-33.7}$	$251.0^{+9.5}_{-8.5}$

$\longrightarrow$ determination of $\left.\begin{matrix} M_1 \\ M_2 \\ M_3 \end{matrix}\right\}$ with $\left\{\begin{matrix} 25\% \\ 15\% \\ 5\% \end{matrix}\right.$ accuracy

[Dreiner, MK, Lindert, O'Leary]

SUSY parameter determination with cross sections

Why have cross sections so far not been included in LHC BSM fits?

- calculation time consuming [cf. Lester, Parker, White]
- large uncertainty at LO

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Our solution: combine parametrizations and analytical calculations

$\longrightarrow$ quick & accurate estimate of $\sigma \times \mathrm{BR} \times \mathrm{acceptance}$

[see talk by Ben O'Leary]

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[see talk by Ben O'Leary]

SUSY parameter determination at the LHC: current and future work

- add further LHC signatures and quantify detector effects
  [O'Leary, Robens, Sarrazin,...]
- explore mirage mediation models
  [Dreiner, MK, Löwen, Nilles, ...]
- explore regions with 3-body decays, e.g. DM focus point regions
  [cf. Baer et al.]

Conclusion & outlook

- squark and gluino cross section predictions are in good shape
  - NLO+NLL QCD is state-of-the-art with scale uncertainty $\lesssim \pm 10\%$
  - EWK corrections are significant for specific channels and/or phase space regions
  - bound state effects might be detectable in specific scenarios
    [see talks by Marquard and Yokoya]
  - the impact of squark generation mixing has been studied
    [see talk by Herrmann]
- theoretical precision currently limited by parton distributions
- shapes of cascade decays so far mostly LO

  [cf. Alwall, de Visscher, Maltoni; Drees, Hollik, Xu; Horsky, MK, Mück, Zerwas]

Conclusion & outlook

- cross sections are important input for LHC BSM parameter fits, in particular
  - for early LHC data
  - non-universal models with $M_1 \neq M_2 \neq M_3$
  - scenarios with 3-body decays
  - to disentangle models with different spin, eg. SUSY, UED, little Higgs, ...

- BSM parameter determination now coordinated effort within the "SUSY/BSM Fit Working Group"
  of the Terascale Alliance [Wienemann et al.]
  see `http://www.terascale.de/`