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Theoretical aspects of early SUSY searches at the LHC

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Outline

- SUSY particle production at the LHC:
  MSSM cross section calculations
- Exploring SUSY at the LHC I:
  constraining SUSY models from current and future exclusions
- Exploring SUSY at the LHC II:
  parameter determination from cross sections and kinematic edges

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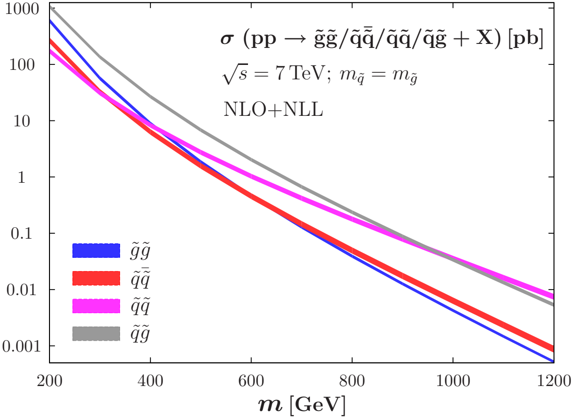
NLO+NLL QCD cross section

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



Squark and gluino production at the LHC

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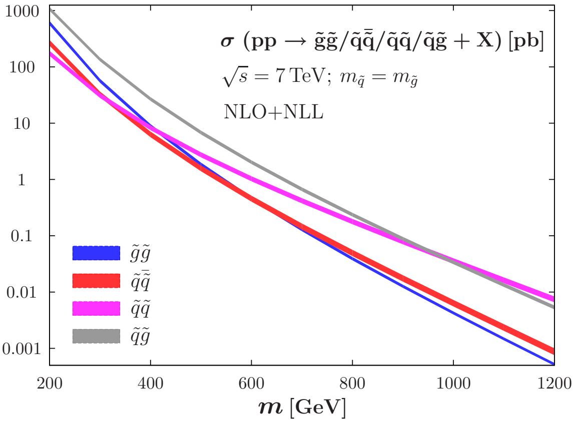

→ $\sigma \approx 100$ fb for $m \approx 1000$ GeV at the LHC with 7 TeV

Squark and gluino production at the LHC

NLO+NLL QCD cross section

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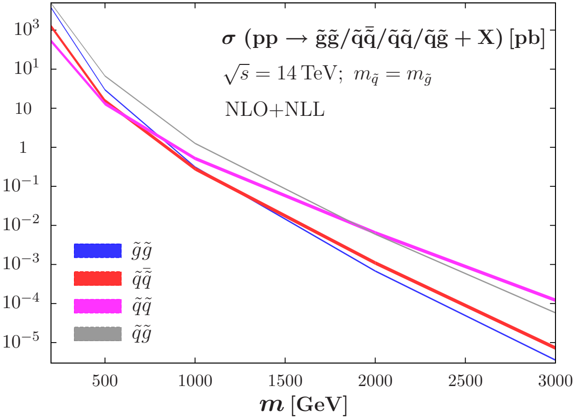
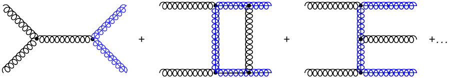


$\to \sigma \approx 2.5$ pb for $m \approx 1000$ GeV at the LHC with 14 TeV

NLO+NLL QCD corrections

Take gluino-pair production as an example



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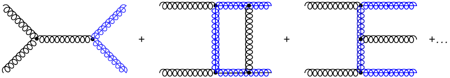
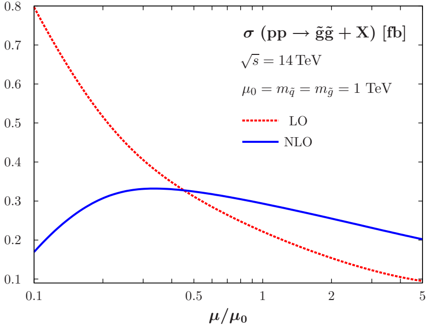


Scale dependence



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

NLO+NLL QCD corrections

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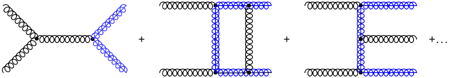
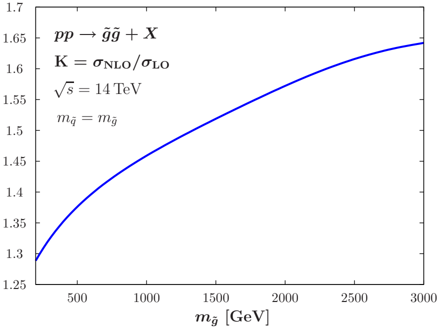


K-factor



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

Threshold summation

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

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

Threshold summation

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

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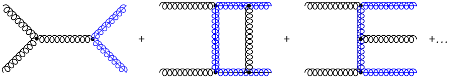
→ requires all-order summation of large logarithmic corrections:

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

[Kulesza, Motyka; Beenakker, Brensing, MK, Kulesza, Laenen, Niessen '09
cf. Kidonakis, Sterman; Bonciani, Catani, Mangano, Nason; ...]

NLO+NLL QCD corrections

Take gluino-pair production as an example



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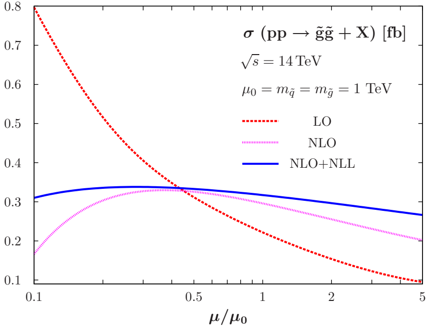
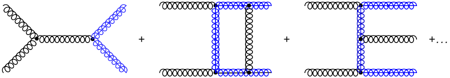


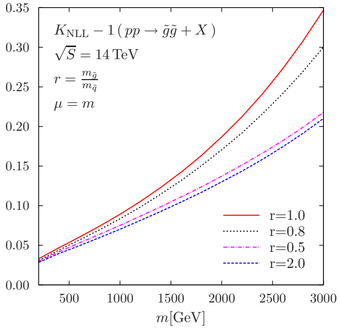
→ $\Delta\sigma \lesssim \pm 10\%$ at NLO+NLL [Kulesza, Motyka; Beenakker et al.]

NLO+NLL QCD corrections

Take gluino-pair production as an example



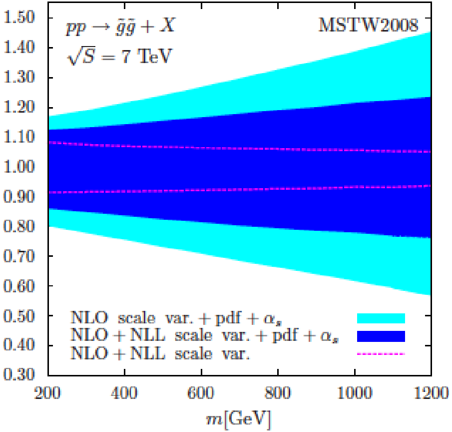
NLL K-factor



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

Theory uncertainty

Theory uncertainty: $\Delta\sigma = \Delta\mu \pm \sqrt{\Delta(\text{pdf})^2 + \Delta(\alpha_\text{s})^2}$



→ $\Delta\sigma \lesssim \pm 20\%$ at NLO+NLL [Beenakker et al.]

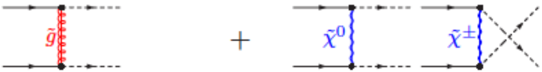
Progress in precision calculations for squark and gluino production

- NLO QCD → public computer code PROSPINO
  [Beenakker, Höpker, MK, Plehn, Spira, Zerwas]
- Threshold summation
  [Kulesza, Motyka; Langenfeld, Moch; Beenakker, Brensing, MK, Kulesza, Laenen, Niessen; Beneke, Falgari, Schwinn]
- Electroweak corrections
  [Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim; Bozzi, Fuks, Klasen; Beccaria, Macorini, Panizzi, Renard, Verzegnassi]
- Bound state effects
  [Hagiwara, Yokoya; Kauth, Kühn, Marquard, Steinhauser]

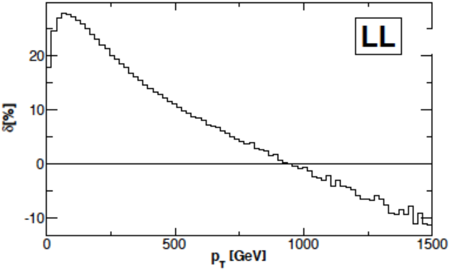
and more for SUSY models beyond the MSSM...

Squark pair production with EWK corrections

EWK effects include $\mathcal{O}(\alpha)$ loop corrections and QCD/EWK interference



$p_t(\tilde{q})$ distribution:



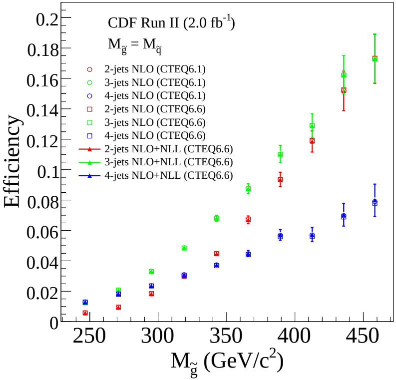
[Germer et al.]

→ potentially significant effects, depending in detail on the process and the SUSY scenario

Impact of precision calculations on CDF SUSY limits

[Beenakker et al. with Martinez and D'Onofrio]

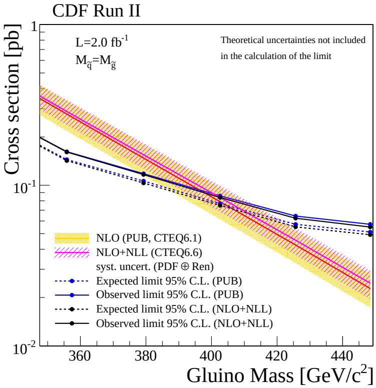
- relative weight of $\tilde{g}\tilde{g}/\tilde{q}\tilde{q}/\tilde{q}\tilde{g}$ enters efficiency and thus cross section limit



Impact of precision calculations on CDF SUSY limits

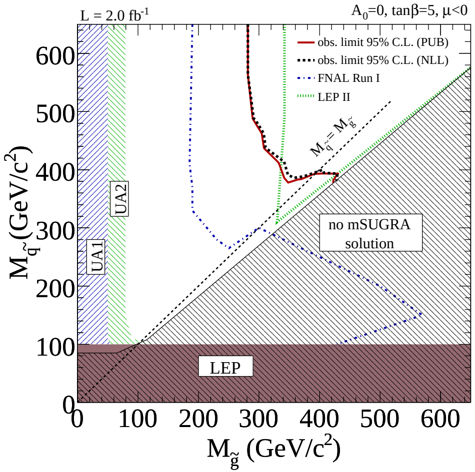
[Beenakker et al. with Martinez and D'Onofrio]

- 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



Impact of precision calculations on CDF SUSY limits

[Beenakker et al. with Mario Martinez and Monica D'Onofrio]



Squark and gluino searches at the LHC

SUSY searches are often interpreted in the constrained MSSM, where the breaking is universal at the GUT scale

- universal scalar masses: $M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}} \to M_0^2$ at $M_{\rm GUT}$
- universal gaugino masses: M_1, M_2, $M_3 \to M_{1/2}$ at $M_{\rm GUT}$
- universal trilinear couplings $A^e_{ij}, A^d_{ij}, A^u_{ij} \to A \cdot h^e_{ij}, A \cdot h^d_{ij}, A \cdot h^u_{ij}$ at $M_{\rm GUT}$

The masses at the weak scale are determined through the RGE.

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The masses at the weak scale are determined through the RGE.

In the CMSSM the sparticle masses are strongly correlated, e.g.

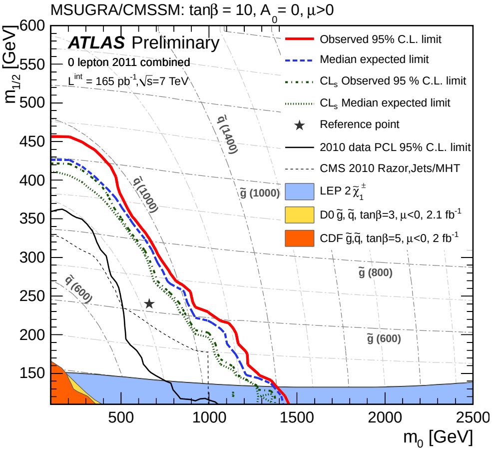
$$M_{\tilde{g}} \simeq 3M_{\tilde{\chi}^\pm} \simeq 3M_{\tilde{\chi}^0_2} \simeq 6M_{\tilde{\chi}^0_1}$$

and

$$\begin{aligned} m^2_{\tilde{u}_L} &\simeq M_0^2 + 6.3\, M^2_{1/2} + D_{\tilde{u}_L} \\ m^2_{\tilde{e}_L} &\simeq M_0^2 + 0.5\, M^2_{1/2} + D_{\tilde{e}_L} \end{aligned}$$

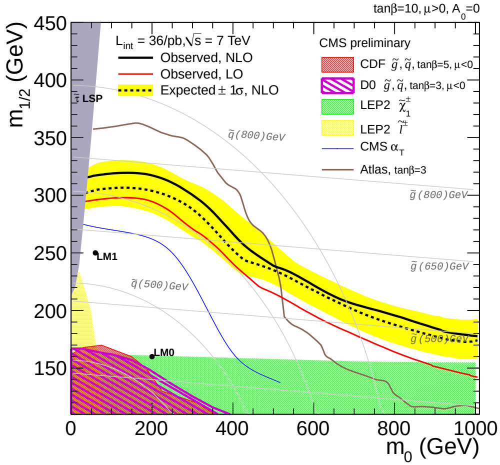
where $D_{\tilde{f}_L} = M_Z^2 \cos(2\beta)(T_{3_f} - Q_f \sin(2\theta_W))$

Atlas limits (165 pb^{-1})



$\longrightarrow m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 950$ GeV

CMS limits (36 pb^{-1})



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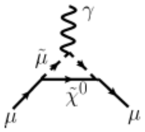
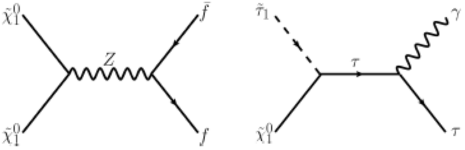
- SUSY particle production at the LHC:
  MSSM cross section calculations
- Exploring SUSY at the LHC I:
  constraining SUSY models from current and future exclusions
  [P. Bechtle, K. Desch, H.K. Dreiner, M.K., B. O'Leary, C. Robens, B. Sarrazin, and P. Wienemann]
- Exploring SUSY at the LHC II:
  parameter determination from cross sections and kinematic edges

There is a wealth of precision measurements
from B/K physics, $(g-2)$, astrophysics (DM) and collider limits
which show sensitivity to supersymmetry, in particular

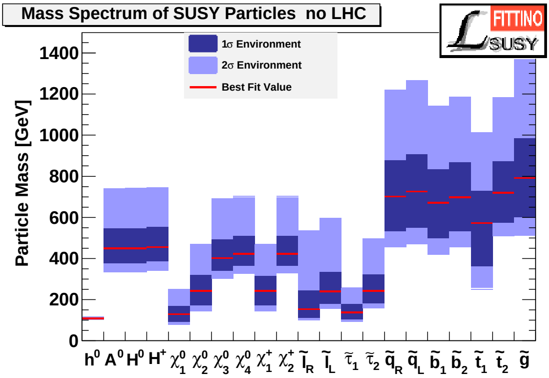
- $(g-2)_\mu$



- DM relic abundance



→ global fit of constrained SUSY models



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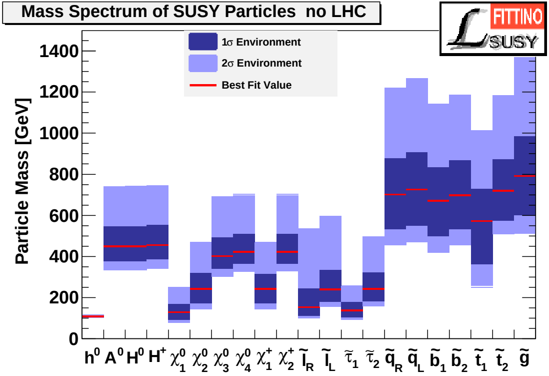
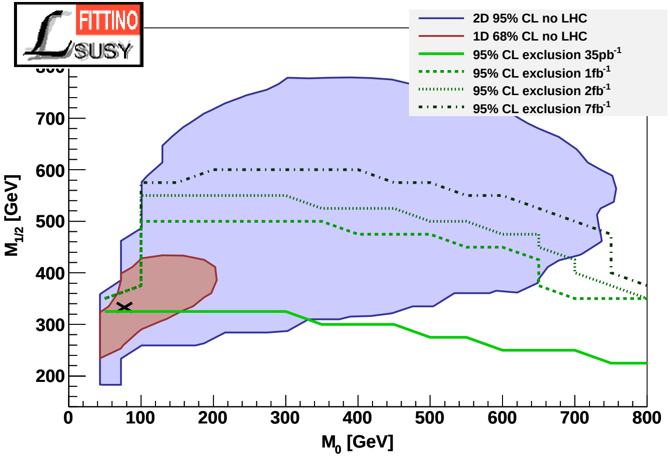


- global fits point to light sparticle spectrum with $\tilde{m} < 1$ TeV
- current data cannot constrain more general SUSY models

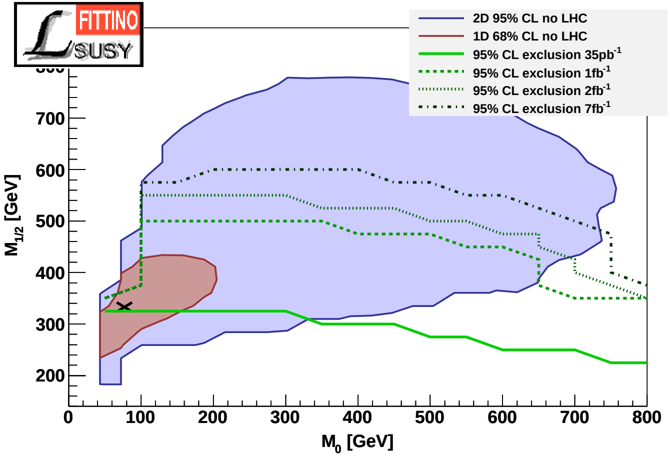
Direct SUSY searches at the LHC: expected limits

The LHC is probing the preferred region of SUSY parameter space

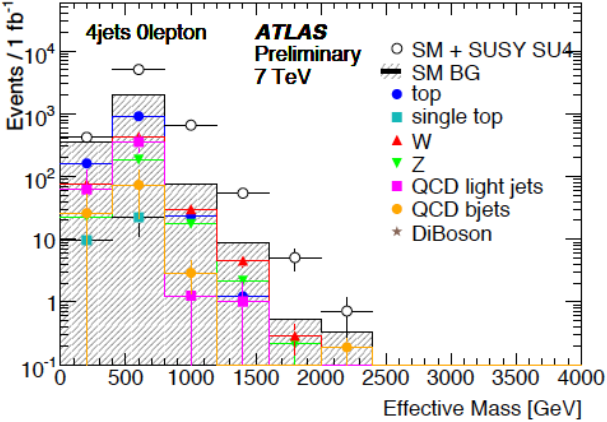


Direct SUSY searches at the LHC: expected limits

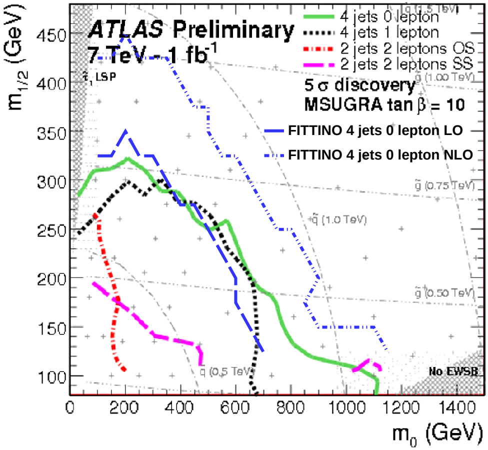
But what if we do not see any SUSY signal at the LHC?



We have considered the SUSY search in the 4 jets + $E_{T,\mathrm{miss}}$ signature with $M_{\mathrm{eff}} = \sum_i p_{T,i} + E_{T,\mathrm{miss}}$

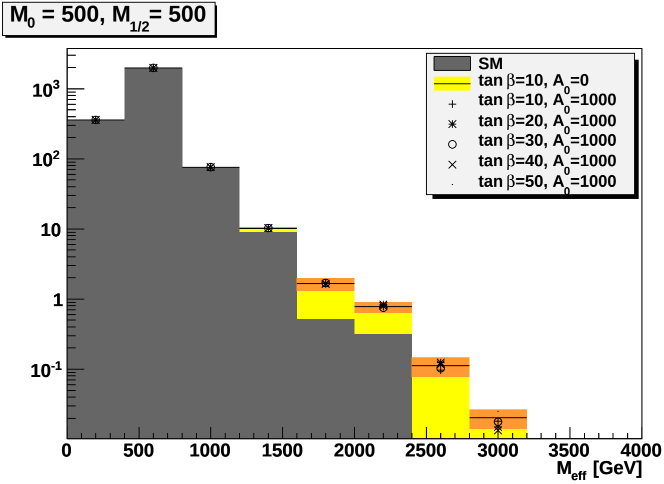


- The simulation of M_{eff} is based on `Herwig++`, `Delphes` and NLO+NLL K-factors.



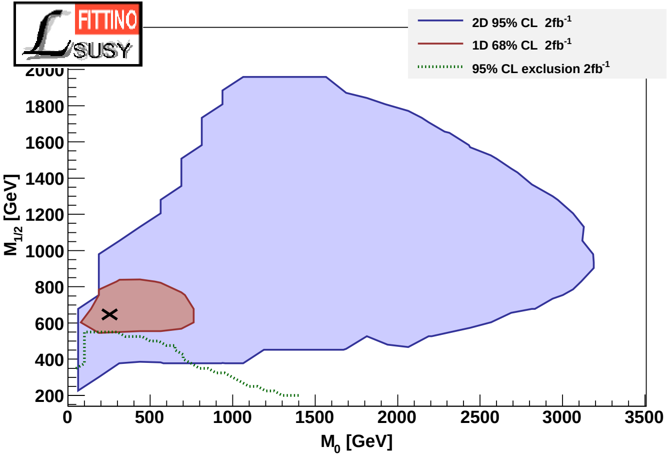
Direct SUSY searches at the LHC: expected limits

- The 4 jets $+E_{T,\mathrm{miss}}$ signature is rather independent of $\tan\beta$ and A_0



Global SUSY fits with projected LHC exclusions

- Low-energy observables, DM and LHC exclusions with 2 fb^{-1}



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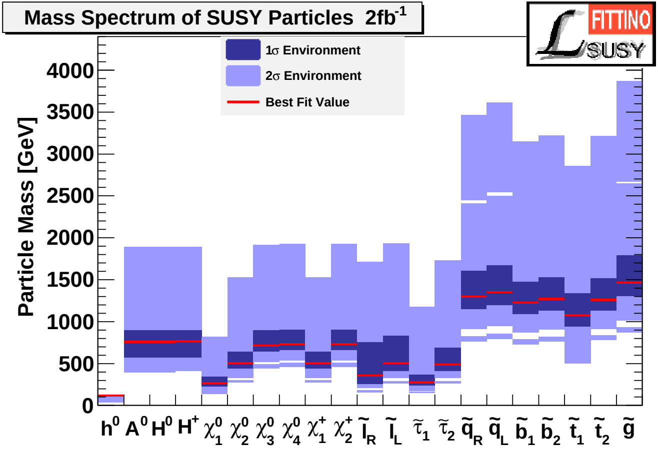
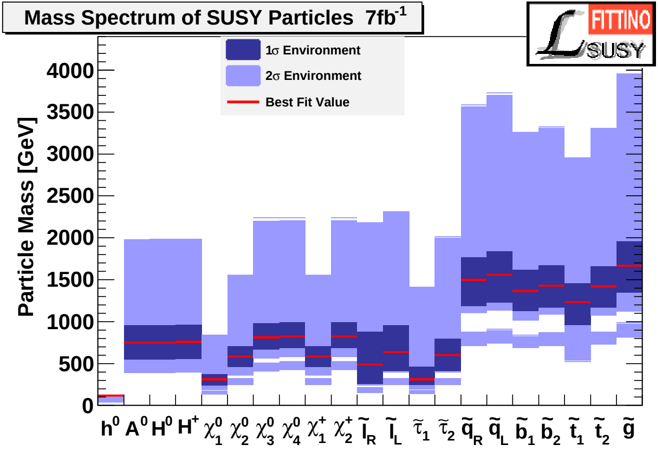


Global SUSY fits with projected LHC exclusions

- Low-energy observables, DM and LHC exclusions with 7 fb^{-1}



Global SUSY fits with projected LHC exclusions

- what happens if we take out $(g-2)_\mu$ and $\Omega_{\rm DM}$?

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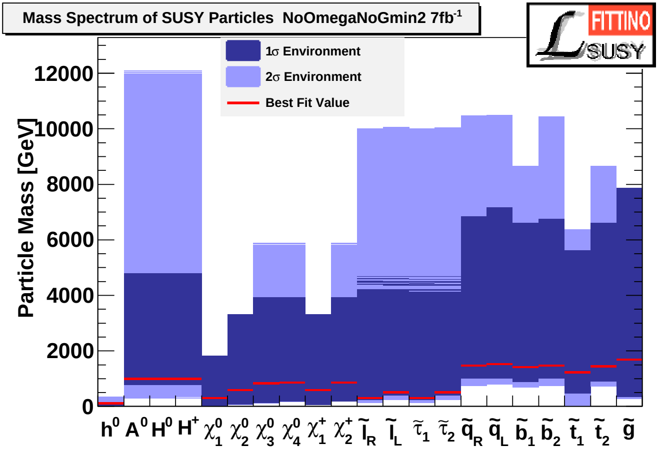
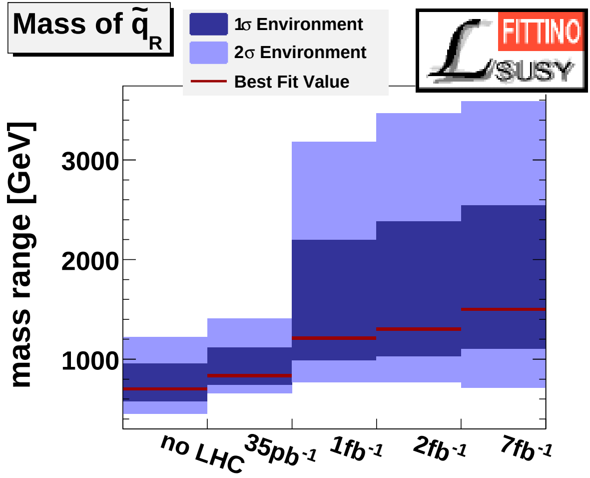


Global SUSY fits with projected LHC exclusions

- LHC mass limits on squarks are rather model independent



Global SUSY fits with projected LHC exclusions: is there a tension?

$\rightarrow$ LEOs prefer low mass scales (for non-coloured sector)

$\rightarrow$ LHC prefers high mass scales (for coloured sector)

Is there a tension building up?

Global SUSY fits with projected LHC exclusions: is there a tension?

$\rightarrow$ LEOs prefer low mass scales (for non-coloured sector)

$\rightarrow$ LHC prefers high mass scales (for coloured sector)

Is there a tension building up?

Let us look at the best fit points:

	M_0	$M_{1/2}$	A_0	$\tan\beta$	χ^2/ndf
no LHC	77^{+114}_{-31}	333^{+89}_{-87}	426^{+70}_{-735}	13^{+10}_{-8}	19/20
35 pb^{-1}	126^{+189}_{-54}	400^{+109}_{-40}	724^{+722}_{-780}	17^{+14}_{-9}	20/21
1 fb^{-1}	235^{+389}_{-103}	601^{+148}_{-63}	627^{+1249}_{-717}	31^{+19}_{-18}	24/21
2 fb^{-1}	254^{+456}_{-128}	647^{+157}_{-74}	771^{+1254}_{-879}	30^{+20}_{-19}	24/21
7 fb^{-1}	403^{+436}_{-281}	744^{+142}_{-150}	781^{+1474}_{-918}	43^{+11}_{-33}	25/21

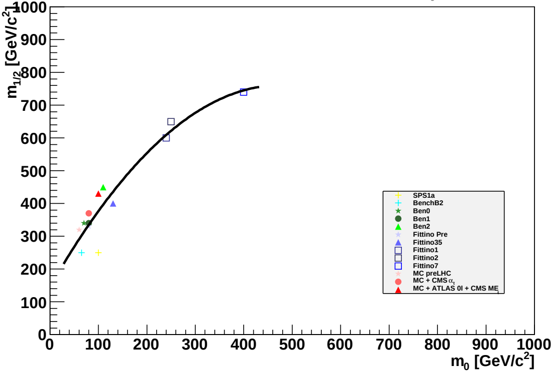
$\rightarrow$ even the CMSSM would "survive" the 2011/2012 LHC run

[Note: $a_\mu^{\mathrm{SUSY}} \sim \mathrm{sgn}(\mu)\tan\beta\, M_{\mathrm{SUSY}}^{-2}$ and Ω_{DM} require larger $\tan\beta$]

There has been a lot of activity recently, see e.g.

Allanach, arXiv:1102.3149 [hep-ph], Buchmueller et al., arXiv:1102.4585 [hep-ph], Bechtle et al., arXiv:1102.4693 [hep-ph], Allanach et al., arXiv:1103.0969 [hep-ph]

by John Ellis



→ the analyses differ in detail, but there is good agreement overall

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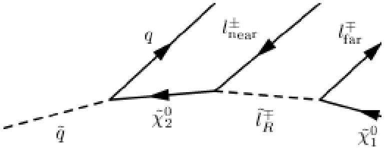
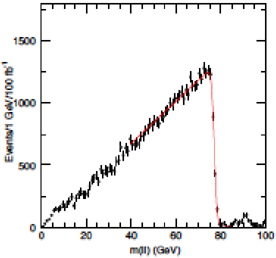
Mass measurements from cascade decays, e.g.



Allanach et al.



→ kinematic endpoints sensitive to masses:

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

SUSY parameter determination with cross sections

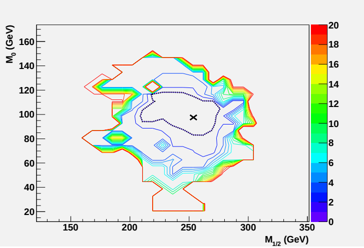
How well could we do at 7 TeV and 1 fb^{-1}? [Dreiner, MK, Lindert, O'Leary]

[cf. Baer et al., Altunkaynak et al., . . .]

SUSY parameter determination with cross sections

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

[cf. Baer et al., Altunkaynak et al., . . .]



SPS1a with 4 kinematic edges only

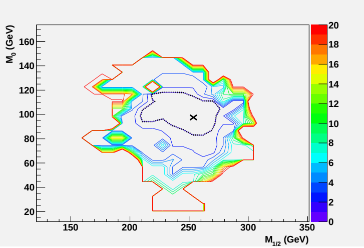
→ no stable fit

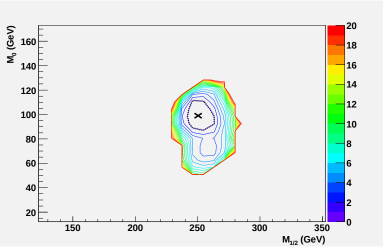
→ add cross sections:
sensitive to masses and spins

SUSY parameter determination with cross sections

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

[cf. Baer et al., Altunkaynak et al., ...]





SPS1a with 4 kinematic edges only

$\longrightarrow$ no stable fit

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

kinematic edges $\oplus$ cross sections

$$\longrightarrow m_0 = 99 \pm 9 \text{ GeV}$$
$$m_{1/2} = 250 \pm 7 \text{ GeV}$$
$$\tan\beta = 11 \pm 6$$

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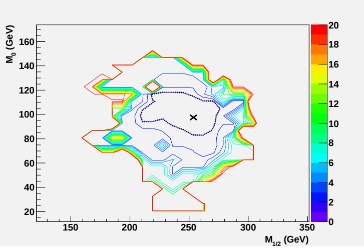

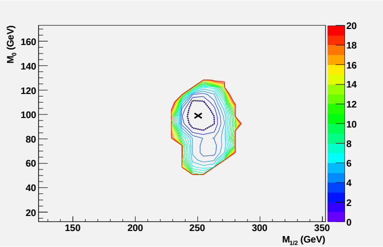

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kinematic edges ⊕ cross sections

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→ cross sections are crucial to determine BSM parameters

SUSY parameter determination with cross sections

Beyond mSUGRA: explore mirage mediation models

[Choi, Nilles, Falkowski, Ratz, Loewen and many others]

$\rightarrow$ characteristic pattern of soft SUSY-breaking terms

$M_1 : M_2 : M_3 \simeq (1 + 0.66\alpha) : (2 + 0.2\alpha) : (6 - 1.8\alpha)$

$\rightarrow$ relative size of modulus and anomaly mediation controlled by α

How well can we determine α from future LHC data?

SUSY parameter determination with cross sections

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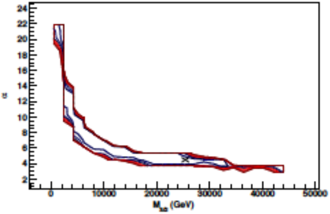
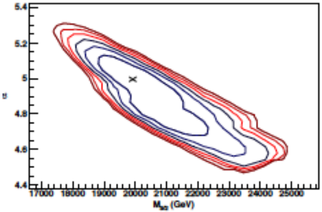
How well can we determine α from future LHC data?

Assume LHC @ 14 TeV with 1 fb^{-1}

[Conley, Dreiner, Glaser, MK, Tattersall]



kinematic edges only



kinematic edges $\oplus$ cross sections

$\rightarrow \alpha = 4.8 \pm 0.2$

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

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
- The LHC is now probing the SUSY parameter space favoured by low-energy observables and DM
  - It is possible to reconcile LE measurements (mostly $(g-2)_\mu$ and Ω_{DM}) with a possible non-discovery of SUSY in the 7 TeV run, even in very constrained models like the CMSSM.
  - LHC searches mostly constrain the coloured sparticle sector and can push squark and gluino mass limits up to about 1.5 TeV in 2011/2012.
  - The LHC limits on squarks and gluinos are rather model independent.

Conclusion & outlook

- Cross sections are important input for LHC BSM parameter fits, in particular
  - for early LHC data
  - for non-universal models
  - and to disentangle models with different spin, eg. SUSY, UED, little Higgs, . . .

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  - for early LHC data
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And if you want to know more. . .

SUSY/BSM cross section predictions are addressed within a LPCC working group [Mangano, MK et al.]

see http://web.physik.rwth-aachen.de/service/wiki/bin/view/Main/BSMCrossSectionWorkingGroup

BSM parameter determination now coordinated effort within the Terascale Alliance [Wienemann et al.]

see http://www.terascale.de