Precision calculations for BSM searches at the LHC

Michael Krämer (RWTH Aachen)

Sponsored by:

SFB/TR 9 “Computational Particle Physics”, Helmholtz Alliance “Physics at the Terascale”, BMBF-Theorie-Verbund, Marie Curie Research Training Network “Heptools”, Graduiertenkolleg “Elementarteilchenphysik an der TeV-Skala”
Many model for new physics are addressing two problems:

- the hierarchy/naturalness problem
- the origin of dark matter

→ spectrum of new particles at the TeV-scale with weakly interacting & stable particle
BSM searches at the LHC

Many model for new physics are addressing two problems:

– the hierarchy/naturalness problem
– the origin of dark matter

→ spectrum of new particles at the TeV-scale with weakly interacting & stable particle
→ generic BSM signature at the LHC involves cascade decays with missing energy, eg. supersymmetry
Precision calculations for BSM physics at the LHC

- no excess over SM expectations
  → exclude models / set limits on model parameters

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

- exploring BSM models (later LHC phase)
  → determine masses & spins
Precision calculations for BSM physics at the LHC

- no excess over SM expectations
  - exclude models / set limits on model parameters

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  - discriminate BSM models

- exploring BSM models (later LHC phase)
  - determine masses & spins
Precision calculations for BSM physics at the LHC

- no excess over SM expectations
  → exclude models / set limits on model parameters

mass limits (roughly)

\[ M_{\tilde{g}} \gtrsim 350 \text{ GeV} \]
\[ M_{\tilde{q}} \approx M_{\text{ gluino }} \gtrsim 450 \text{ GeV} \]
\[ M_{\tilde{t}_1} \gtrsim 100 \text{ GeV} \]
\[ M_{\tilde{\chi}^0_1} \gtrsim 50 \text{ GeV} \]
\[ M_{\tilde{\chi}^\pm_1} \gtrsim 100 \text{ GeV} \]
\[ M_{\text{ sleptons}} \gtrsim 100 \text{ GeV} \]

→ needs accurate theoretical predictions
Precision calculations for BSM physics at the LHC

- no excess over SM expectations
  - exclude models / set limits on model parameters

mass limits (roughly)

- \( M_{\tilde{g}} \gtrsim 350 \text{ GeV} \)
- \( M_{\tilde{q}} \approx M_{\tilde{g}} \gtrsim 450 \text{ GeV} \)
- \( M_{\tilde{t}_1} \gtrsim 100 \text{ GeV} \)
- \( M_{\tilde{\chi}_1^0} \gtrsim 50 \text{ GeV} \)
- \( M_{\tilde{\chi}_1^\pm} \gtrsim 100 \text{ GeV} \)
- \( M_{\tilde{s} \text{leptons}} \gtrsim 100 \text{ GeV} \)

→ model dependence: \( M_{\tilde{\chi}_1^0} \approx 0 \text{ GeV} \) possible

(Dreiner, Grab, Koschade, MK, Langenfeld, O’Leary, arXiv:0905.2051)
SUSY particle production at hadron colliders

SUSY particles would be produced copiously at hadron colliders via QCD processes, eg.

\[ \sigma_{\text{jet}}(E_{T\text{jet}} > \sqrt{s}/4) \]

\[ \sigma_{\text{ttbar}} \]

\[ \sigma_{\text{Higgs}}(M_H = 500 \text{ GeV}) \]

\[ \sigma_{\text{Z}} \]

\[ \sigma_{\text{jet}}(E_{T\text{jet}} > 100 \text{ GeV}) \]

\[ \sigma_{\text{Higgs}}(M_H = 150 \text{ GeV}) \]

\[ \sigma_{\text{W}} \]

\[ \sigma_{\text{jet}}(E_{T\text{jet}} > \sqrt{s}/20) \]

\[ \sigma_{\text{bbar}} \]

\[ \sigma_{\text{tot}}(\text{nb}) \]

\[ \frac{\text{events/sec}}{\sqrt{s} \text{ (TeV)}} \text{ for } L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \]
SUSY particle production at hadron colliders

SUSY particles would be produced copiously at hadron colliders via QCD processes, eg.

\[ \sigma(\tilde{q}\tilde{q} + \tilde{g}\tilde{g} + \tilde{g}\tilde{q}) \approx 2 \text{ nb} \quad (M_{\tilde{q},\tilde{g}} \approx 300 \text{ GeV}) \]
SUSY particles would be produced copiously at hadron colliders via QCD processes, eg.

SUSY signal Tevatron

\[ \sigma(\tilde{q}\tilde{q} + \tilde{g}\tilde{g} + \tilde{g}\tilde{q}) \approx 2 \text{ pb} \quad (M_{\tilde{q},\tilde{g}} \approx 300 \text{ GeV}) \]
MSSM particle production at the LHC

NLO SUSY-QCD corrections for MSSM particle production at hadron colliders

→ public code **PROSPINO** (Beenakker, Höpker, MK, Plehn, Spira, Zerwas)

![Graph showing cross-section as a function of mass (GeV) for various particles: μμ, ττ, t₁t₁, χ₂χ₁, χ₀g, χ₂q, gg.]

→ determination of mass (limits) & tests of BSM models
**Example: top-squark searches**

- Top-squark search in $p\bar{p} \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$ channel (CDF PRD 2007)
Example: top-squark searches

Top-squark search in $p\bar{p} \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$ channel  

CDF Run II Preliminary (295 pb$^{-1}$)

CDF Upper Limit, 95% CL

$\Rightarrow 105 \text{ GeV} \leq M_{\tilde{t}_1} \leq 130 \text{ GeV}$
Example: top-squark searches

Top-squark search in $p\bar{p} \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$ channel (CDF PRD 2007)

$\rightarrow$ no exclusion based on LO cross sections
MSSM particle production at the LHC

NLO SUSY-QCD corrections for MSSM particle production at hadron colliders

→ public code PROSPINO (Beenakker, Höpker, MK, Plehn, Spira, Zerwas)

→ large corrections of $\mathcal{O}(100\%)$ for $\tilde{m} \gtrsim 500$ GeV
Threshold summation for SUSY cross sections

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

$$\sigma^{NLO}[q\bar{q} \to \tilde{t}_1\tilde{t}_1 + X] \approx \frac{\alpha_s^2(\mu^2)}{m^2} \frac{\pi}{54} \beta^3 \left(1 + 4\pi\alpha_s(\mu^2) \left\{ -\frac{1}{48\beta} + \frac{2}{3\pi^2} \ln^2(8\beta^2) ight. \right.$$ 

$$- \frac{107}{36\pi^2} \ln(8\beta^2) - \frac{2}{3\pi^2} \ln(8\beta^2) \ln \left( \frac{\mu^2}{m^2} \right) \left. \right\}$$

$$\sigma^{NLO}[gg \to \tilde{t}_1\tilde{t}_1 + X] \approx \frac{\alpha_s^2(\mu^2)}{m^2} \frac{7\pi}{384} \beta \left(1 + 4\pi\alpha_s(\mu^2) \left\{ \frac{11}{336\beta} + \frac{3}{2\pi^2} \ln^2(8\beta^2) \right. \right.$$ 

$$- \frac{183}{28\pi^2} \ln(8\beta^2) - \frac{2}{3\pi^2} \ln(8\beta^2) \ln \left( \frac{\mu^2}{m^2} \right) \left. \right\}$$

→ large universal corrections $\propto \ln^{(1,2)}(\beta)$

→ all order summation of large logarithmic corrections

(Beenakker, Brensing, MK, Kulesza, Laenen, Niessen, arXiv:0909.4418 [hep-ph])
Threshold summation for SUSY cross sections

Schematic perturbative expansion of the cross section \((L = \log(\beta^2))\):

\[
d\sigma = d\sigma_{\text{LO}} \times (1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots + \alpha_s^n(L^{2n} + \sum_{i=1}^{2n-1} L_i^n + \ldots))
\]

Resummation = organisation of large logs in perturbative expansion:

\[
d\sigma^{\text{res}} \propto d\sigma_{\text{LO}} \times \exp\left(Lg_1(\alpha_s L) + g_2(\alpha_s L) + \ldots\right) + \text{sub-leading terms}
\]

\(\rightarrow\) summation of large logs to all orders
Threshold summation for SUSY cross sections

$$\sigma_{\text{matched}} = \sigma_{\text{resummed}} + \sigma_{\text{NLO}} - \sigma_{\text{resummed}}|_{\text{NLO}}$$

$$\sigma( pp \rightarrow \tilde{q}\tilde{g} + X ) [\text{fb}]$$

$$\sqrt{S} = 1.96 \text{ TeV}$$

$$\mu_0 = m = 500 \text{ GeV}$$

→ reduction of scale dependence
Threshold summation for SUSY cross sections

\[ K_{\text{NLL}} \equiv \sigma(\text{resummed} + \text{NLO} - \text{resummed}|_{\text{NLO}}) / \sigma(\text{NLO}) \]
Threshold summation for SUSY cross sections

\[ K_{\text{NLL}} \equiv \sigma(\text{resummed} + \text{NLO} - \text{resummed}|_{\text{NLO}})/\sigma(\text{NLO}) \]
Threshold summation for SUSY cross sections

\[ K_{\text{NLL}} \equiv \sigma(\text{resummed} + \text{NLO} - \text{resummed}|_{\text{NLO}})/\sigma(\text{NLO}) \]

\[ K_{\text{NLL}} - 1 \left( p\bar{p} \rightarrow \tilde{q}\tilde{g} + X \right) \]
\[ \sqrt{S} = 1.96 \text{ TeV} \]
\[ r = \frac{m_{\tilde{q}}}{m_{\tilde{q}}} \]
\[ \mu = m \]

→ enhancement of cross section near central scales between
5% for \( \tilde{q}\tilde{q} \) and 50% for \( \tilde{q}\tilde{g} \)
Precision calculations for BSM physics at the LHC

• no excess over SM expectations
  → exclude models / set limits on model parameters

• excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

• exploring BSM models (later LHC phase)
  → determine masses & spins
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

“look-alike models” (Hubisz, Lykken, Pierini, Spiropulu)

![Diagram showing mass spectrum of Higgs particles and SUSY models: LH2, NM6, NM4, CS7]
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

“look-alike models” (Hubisz, Lykken, Pierini, Spiropulu)

- Little Higgs model LH2 and SUSY models NM4 and CS7 give same number of events after cuts
- “twin models” LH2 and NM6 (SUSY) have different cross sections and event counts
  → distinguish models with same spectrum but different spins through event count
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  $\rightarrow$ discriminate BSM models

"ancient wisdom": cross sections depend on spin, e.g.

$q + \bar{q} \rightarrow \tilde{q} + \tilde{q}$

\[
\hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow \tilde{q}\tilde{q}] = \frac{\alpha_s^2\pi}{s} \frac{4}{27} \beta^3 \quad (\beta^2 = 1 - 4m^2/s)
\]
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

“ancient wisdom”: cross sections depend on spin, e.g.

\[
q + \bar{q} \rightarrow \tilde{q} + \tilde{q}
\]

\[
\hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow \tilde{q}\tilde{q}] = \frac{\alpha_s^2 \pi}{s} 4 \frac{4}{27} \beta^3 \quad (\beta^2 = 1 - 4m^2/s)
\]

c.f. top production:

\[
\hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow Q\bar{Q}] = \frac{\alpha_s^2 \pi}{s} 8 \frac{(s + 2m^2)}{27 s^2} \beta
\]

→ $\sigma^{\text{top}}/\sigma^{\text{stop}} \sim 10$ at the Tevatron
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

“ancient wisdom”: cross sections depend on spin

→ no production of scalar quarks (assuming same mass and couplings as top...)

(Kane, Petrov, Shao, Wang)
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

how to discriminate “look-alike models”? (Hubisz, Lykken, Pierini, Spiropulu)

- consider ratios of event counts, e.g.
  $\sigma(p_T > 250, 500, \ldots \text{GeV})/\sigma$
  → systematic uncertainties cancel
  → normalization important
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

how to discriminate “look-alike models”? (Hubisz, Lykken, Pierini, Spiropulu)

- consider ratios of event counts, e.g.
  $\sigma(p_T > 250, 500, \ldots \text{ GeV}) / \sigma$
  → systematic uncertainties cancel
  → normalization important

- NLO affects shape of distributions:

$$K \equiv \frac{\sigma^{NLO}(pp \rightarrow \tilde{t}\tilde{t})}{\sigma^{LO}(pp \rightarrow \tilde{t}\tilde{t})}$$

$$= \begin{cases} 
1.4 & (p_T > 100 \text{ GeV}) \\
0.5 & (p_T > 1000 \text{ GeV})
\end{cases}$$
Discriminate BSM physics at the LHC

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  -> discriminate BSM models

how to discriminate “look-alike models”? (Hubisz, Lykken, Pierini, Spiropulu)

- consider ratios of event counts, e.g.
  $\sigma(p_T > 250, 500, \ldots \text{GeV}) / \sigma$
  -> systematic uncertainties cancel
  -> normalization important

- NLO affects shape of distributions:
  $$K = \frac{\sigma^\text{NLO}(pp \rightarrow \tilde{t}\tilde{t})}{\sigma^\text{LO}(pp \rightarrow \tilde{t}\tilde{t})} = \begin{cases} 1.4 & (p_T > 100 \text{ GeV}) \\ 0.5 & (p_T > 1000 \text{ GeV}) \end{cases}$$

-> no proper tools to perform realistic NLO analysis of BSM decay chains
Precision calculations for BSM physics at the LHC

- no excess over SM expectations
  → exclude models / set limits on model parameters

- excess in inclusive jets + $E_{T,\text{miss}}$ signal (early LHC phase)
  → discriminate BSM models

- exploring BSM models (later LHC phase)
  → determine masses & spins
BSM parameter determination

Mass measurements from cascade decays, e.g.

$\rightarrow$ kinematic endpoint sensitive to masses: 

$$(m_{ll}^{\text{max}})^2 = (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R^+}^2)(m_{\tilde{l}_R^+}^2 - m_{\tilde{\chi}_1^0}^2)/(m_{\tilde{l}_R^+}^2)$$
BSM parameter determination

Mass measurements from cascade decays, e.g.

\[ (m_{ll}^{\text{max}})^2 = (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)/(m_{\tilde{l}_R}^2) \]

→ kinematic endpoint sensitive to masses:

mSUGRA fit based on kinematic edges using **Fittino** (Bechtle, Desch, Wienemann)

<table>
<thead>
<tr>
<th>parameter</th>
<th>nominal value</th>
<th>fit</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tan \beta$</td>
<td>10</td>
<td>9.75</td>
<td>±4.75</td>
</tr>
<tr>
<td>$m_0$ [GeV]</td>
<td>100</td>
<td>96.74</td>
<td>±4.17</td>
</tr>
<tr>
<td>$m_{1/2}$ [GeV]</td>
<td>250</td>
<td>248.8</td>
<td>±3.5</td>
</tr>
<tr>
<td>$A_0$ [GeV]</td>
<td>-100</td>
<td>-106.8</td>
<td>±58.3</td>
</tr>
</tbody>
</table>
work in progress: use shape and cross sections to further constrain BSM models
(MK, Lindert, O’Leary)

→ differences in shapes are small for SPS1a-type mSUGRA scenarios
work in progress: use shapes and cross sections to further constrain BSM models
(MK, Lindert, O’Leary)

→ cross sections can help to improve sensitivity to BSM parameters

work in progress: include cross sections × branching ratios into Fittino
**BSM parameter determination: resolve ambiguities?**

SPS1a scenario \((M_0 = 100 \text{ GeV}, M_{1/2} = 250 \text{ GeV})\)

<table>
<thead>
<tr>
<th></th>
<th>(m_{\tilde{\chi}^0_1})</th>
<th>(m_{\tilde{\chi}^0_2})</th>
<th>(m_{\tilde{\chi}^0_2})</th>
<th>(m_{\tilde{q}_L})</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>97.2</td>
<td>142.8</td>
<td>180.1</td>
<td>564.5</td>
</tr>
<tr>
<td>mimic</td>
<td>112.9</td>
<td>160.8</td>
<td>196.5</td>
<td>584.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>(m_{\ell\ell}^{\text{max}})</th>
<th>(m_{q\ell\ell}^{\text{max}})</th>
<th>(m_{q\ell}^{\text{(high)}})</th>
<th>(m_{q\ell}^{\text{(low)}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>edges</td>
<td>80.4</td>
<td>450.4</td>
<td>391.9</td>
<td>316.2</td>
</tr>
</tbody>
</table>
**BSM parameter determination: resolve ambiguities?**

SPS1a scenario ($M_0 = 100$ GeV, $M_{1/2} = 250$ GeV)

<table>
<thead>
<tr>
<th></th>
<th>$m_{\tilde{\chi}_1^0}$</th>
<th>$m_{\tilde{l}_R}$</th>
<th>$m_{\tilde{\chi}_2^0}$</th>
<th>$m_{\tilde{q}_L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>97.2</td>
<td>142.8</td>
<td>180.1</td>
<td>564.5</td>
</tr>
<tr>
<td>mimic</td>
<td>112.9</td>
<td>160.8</td>
<td>196.5</td>
<td>584.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$m_{ll}^{max}$</th>
<th>$m_{qll}^{max}$</th>
<th>$m_{ql}^{max} (high)$</th>
<th>$m_{ql}^{max} (low)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>edges / GeV</td>
<td>80.4</td>
<td>450.4</td>
<td>391.9</td>
<td>316.2</td>
</tr>
</tbody>
</table>

**Shapes** (e.g. $m_{ql}^{max} (low)$):

→ SPS1a and its mimic point cannot be distinguished by shapes
**BSM parameter determination: resolve ambiguities?**

**Alternative scenario** \((M_0 = 200 \text{ GeV}, M_{1/2} = 350 \text{ GeV})\)

<table>
<thead>
<tr>
<th>masses / GeV</th>
<th>(m_{\tilde{\chi}_1^0})</th>
<th>(m_{\tilde{\chi}_2^0})</th>
<th>(m_{\tilde{\chi}_2^0})</th>
<th>(m_{\tilde{q}_L})</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>140.6</td>
<td>241.6</td>
<td>263.7</td>
<td>779.6</td>
</tr>
<tr>
<td>mimic</td>
<td>103.1</td>
<td>116.1</td>
<td>219.7</td>
<td>736.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>edges / GeV</th>
<th>(m_{ll}^{max})</th>
<th>(m_{qll}^{max})</th>
<th>(m_{qll}^{max}(high))</th>
<th>(m_{qll}^{max}(low))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>86.0</td>
<td>620.7</td>
<td>596.6</td>
<td>294.3</td>
</tr>
</tbody>
</table>
BSM parameter determination: resolve ambiguities?

Alternative scenario \((M_0 = 200 \text{ GeV}, M_{1/2} = 350 \text{ GeV})\)

<table>
<thead>
<tr>
<th>masses / GeV</th>
<th>(m_{\tilde{\chi}_1^0})</th>
<th>(m_{\tilde{\eta}_R})</th>
<th>(m_{\tilde{\chi}_2^0})</th>
<th>(m_{\tilde{q}_L})</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>140.6</td>
<td>241.6</td>
<td>263.7</td>
<td>779.6</td>
</tr>
<tr>
<td>mimic</td>
<td>103.1</td>
<td>116.1</td>
<td>219.7</td>
<td>736.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>edges / GeV</th>
<th>(m_{ll}^{max})</th>
<th>(m_{qll}^{max})</th>
<th>(m_{ql}^{max} (high))</th>
<th>(m_{ql}^{max} (low))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>86.0</td>
<td>620.7</td>
<td>596.6</td>
<td>294.3</td>
</tr>
</tbody>
</table>

Shapes (e.g. \(m_{ql}^{max} (low)\)):

→ looks more promising, but...
BSM parameter determination: resolve ambiguities?

Alternative scenario \((M_0 = 200 \text{ GeV}, M_{1/2} = 350 \text{ GeV})\)

<table>
<thead>
<tr>
<th>masses / GeV</th>
<th>(m_{\tilde{\chi}^0_1})</th>
<th>(m_{\tilde{\ell} R})</th>
<th>(m_{\tilde{\chi}^0_2})</th>
<th>(m_{\tilde{q} L})</th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>140.6</td>
<td>241.6</td>
<td>263.7</td>
<td>779.6</td>
</tr>
<tr>
<td>mimic</td>
<td>103.1</td>
<td>116.1</td>
<td>219.7</td>
<td>736.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>edges / GeV</th>
<th>(m_{ll}^{\max})</th>
<th>(m_{qll}^{\max})</th>
<th>(m_{ql}^{\max} (\text{high}))</th>
<th>(m_{ql}^{\max} (\text{low}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>86.0</td>
<td>620.7</td>
<td>596.6</td>
<td>294.3</td>
</tr>
</tbody>
</table>

Shapes (e.g. \(m_{ql}^{\max} (\text{low})\)):

…smeared by SUSY backgrounds (combinatorics)
BSM parameter determination: spin

Spin measurements from shapes are hard! (Barr; Smillie, Webber; ...)

Compare Herwig++ with and without spin correlations

→ typically effects of \( O(10\%) \)

→ more spin information in cross section and primary distributions
BSM parameter determination: spin

can use shape of specific distribution to determine new particle spin

\[ q_L \quad \tilde{q}_L \quad l_R^+ \text{ (near)} \quad \chi_2 \quad \tilde{l}_R \quad (\text{far}) \quad \tilde{\chi}_1 \]

consider charge asymmetry (Barr)

\[ A = \frac{(d\sigma/dm_{ql^+} - d\sigma/dm_{ql^-})}{(d\sigma/dm_{ql^+} + d\sigma/dm_{ql^-})} \]
BSM parameter determination: spin

can use shape of specific distribution to determine new particle spin

\[ A = \frac{(d\sigma/dm_{qL^+} - d\sigma/dm_{qL^-})}{(d\sigma/dm_{qL^+} + d\sigma/dm_{qL^-})} \]

(Horsky, MK, Mück, Zerwas, PRD)

\[ M_{qL} \]

\[ q_L \]

\[ q_L^+ \text{ (near)} \]

\[ q_L^- \text{ (far)} \]

\[ \chi_2 \]

\[ \tilde{\chi}_1 \]

\[ \tilde{\chi}_1 \]

consider charge asymmetry (Barr)

\[ \bar{A} = \frac{1}{2} \left( \frac{d\sigma}{dm_{qL^+}} - \frac{d\sigma}{dm_{qL^-}} \right) \]

(A (Born))

(A (NLO))
BSM parameter determination: spin

Can use shape of specific distribution to determine new particle spin.

Consider charge asymmetry (Barr):

\[
A = \frac{(d\sigma/dm_{ql^+} - d\sigma/dm_{ql^-})}{(d\sigma/dm_{ql^+} + d\sigma/dm_{ql^-})}
\]
BSM parameter determination: spin

Can use shape of specific distribution to determine new particle spin

\[ A = \frac{(d\sigma/dm_{q1^+} - d\sigma/dm_{q1^-})}{(d\sigma/dm_{q1^+} + d\sigma/dm_{q1^-})} \]

Consider charge asymmetry (Barr)

Or consider jet events shapes (MK, Popenda, Spira, Zerwas, arXiv:0902.3795)

→ Spin effects are typically only around 10%, challenging for LHC analyses
Sparticle production cross sections

- NLO QCD $\rightarrow$ **Prospino**: Beenakker, Höpker, MK, Plehn, Spira, Zerwas
  (cf. Baer, Hall, Reno; Berger, Klasen, Tait)

- threshold summation for $M_{\tilde{q}}, M_{\tilde{g}} \gtrsim 1$ TeV
  (Bozzi, Fuks, Klasen; Kulesza, Motyka; Langenfeld, Moch; Beneke, Falgari, Schwinn;
  Beenakker, Brensing, MK, Kulesza, Laenen, Niessen)

- electroweak corrections
  (Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim;
  Beccaria, Macorini, Panizzi, Renard, Verzegnassi)

- beyond MSSM: NLO QCD for RPV SUSY
  (Debajyoti Choudhury, Swapan Majhi, V. Ravindran; Yang, Li, Liu, Li; Dreiner, Grab, MK, Trenkel)
Progress in SUSY precision calculations at the LHC

**Sparticle production cross sections**

- **NLO QCD** → *Prospino*: Beenakker, Höpker, MK, Plehn, Spira, Zerwas
  (cf. Baer, Hall, Reno; Berger, Klasen, Tait)

- **threshold summation for** $M_{\tilde{q}}, M_{\tilde{g}} \gtrsim 1$ TeV
  (Bozzi, Fuks, Klasen; Kulesza, Motyka; Langenfeld, Moch; Beneke, Falgari, Schwinn;
  Beenakker, Brensing, MK, Kulesza, Laenen, Niessen)

- **electroweak corrections**
  (Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim;
  Beccaria, Macorini, Panizzi, Renard, Verzegnassi)

- **beyond MSSM: NLO QCD for RPV SUSY**
  (Debajyoti Choudhury, Swapan Majhi, V. Ravindran; Yang, Li, Liu, Li; Dreiner, Grab, MK, Trenkel)

**Sparticle decays**

- **total rates** → *Sdecay*: (Mühlleitner, Djouadi, Mambrini) plus work by many authors...

- **only few results for shapes** (Drees, Hollik, Xu; Horsky, MK, Mück, Zerwas)
Progress in SUSY precision calculations at the LHC

**Sparticle production cross sections**

- NLO QCD → **Prospino**: Beenakker, Höpker, MK, Plehn, Spira, Zerwas
  (cf. Baer, Hall, Reno; Berger, Klasen, Tait)

- threshold summation for $M_q, M_g \gtrsim 1$ TeV
  (Bozzi, Fuks, Klasen; Kulesza, Motyka; Langenfeld, Moch; Beneke, Falgari, Schwinn; Beenakker, Brensing, MK, Kulesza, Laenen, Niessen)

- electroweak corrections
  (Hollik, Kollar, Mirabella, Trenkel; Bornhauser, Drees, Dreiner, Kim; Beccaria, Macorini, Panizzi, Renard, Verzegnassi)

- beyond MSSM: NLO QCD for RPV SUSY
  (Debajyoti Choudhury, Swapan Majhi, V. Ravindran; Yang, Li, Liu, Li; Dreiner, Grab, MK, Trenkel)

**Sparticle decays**

- total rates → **Sdecay**: (Mühlleitner, Djouadi, Mambrini) plus work by many authors. . .

- only few results for shapes (Drees, Hollik, Xu; Horsky, MK, Mück, Zerwas)

**Sparticle production ⊕ decay**: generic BSM cascades (SUSY, UEDs, LH, . . .)

- so far only tree level → need NLO tools for cascades. . .
SUSY cross sections at the LHC are (or will rather soon be) known at NLO+NLL accuracy

- theoretical uncertainty \( \lesssim 15\% \) for inclusive cross sections
- larger uncertainty for exclusive observables
- can predict distributions and observables with cuts
- in general no parton showers/hadronization
SUSY cross sections at the LHC are (or will rather soon be) known at NLO+NLL accuracy

- theoretical uncertainty $\lesssim 15\%$ for inclusive cross sections
- larger uncertainty for exclusive observables
- can predict distributions and observables with cuts
- in general no parton showers/hadronization

Progress in matching NLO calculations with parton showers and hadronization
SUSY cross sections at the LHC are (or will rather soon be) known at NLO+NLL accuracy

- theoretical uncertainty $\lesssim 15\%$ for inclusive cross sections
- larger uncertainty for exclusive observables
- can predict distributions and observables with cuts
- in general no parton showers/hadronization

Progress in matching NLO calculations with parton showers and hadronization

Many backgrounds (multi-leg processes) are only know at LO
(Need breakthrough in techniques to do $pp \rightarrow> 4$ partons at NLO?)
LHC data will allow us to focus on the important things...