Squark-Gluino-Production at LO with Spin Correlations in the `POWHEG BOX`

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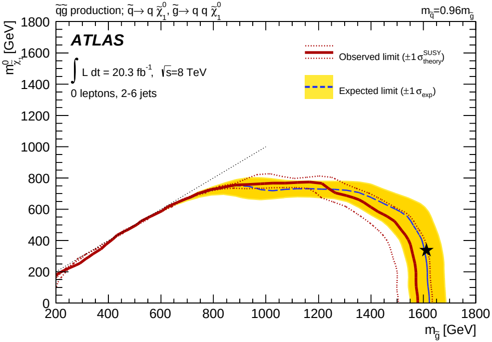
   - Status: Theoretical Predictions
   - Process
2. Polarization Effects
   - Example: Gluino Decay
   - Helicity Density Matrices
3. Results

Introduction: Squarks and Gluinos

Squarks and Gluinos

- SUSY $\Longrightarrow$ supersymmetric partners for SM particles:
  quarks $\longrightarrow$ squarks
  gluon $\longrightarrow$ gluino
- same color charges as their SM equivalents
- production via strong interaction $\longrightarrow$ searches at LHC



Introduction: Status of Theory

Status of Theory

- global K-factor by `Prospino` [Beenakker, Höpker, Spira '96]
- distributions not publicly available at NLO SUSY-QCD
- fully differential calculation of production and subsequent decays necessary
- already done for first two generations of squarks:
  1. $\tilde{q}\tilde{q}$ [Gavin, Hangst, Krämer, Mühlleitner, Pellen, Popenda, Spira '13]
  2. $\tilde{q}\bar{\tilde{q}}$ [Gavin, Hangst, Krämer, Mühlleitner, Pellen, Popenda, Spira '14]
- matching to parton showers $\longrightarrow$ `POWHEG BOX` [Alioli, Nason, Oleari, Re '10]
- here: $\tilde{q}\tilde{g}$ with spin correlations and decays $\tilde{q} \to q\tilde{\chi}_1^0$ and $\tilde{g} \to \tilde{q}\bar{q}$
- current status: LO

Introduction: Process (1)

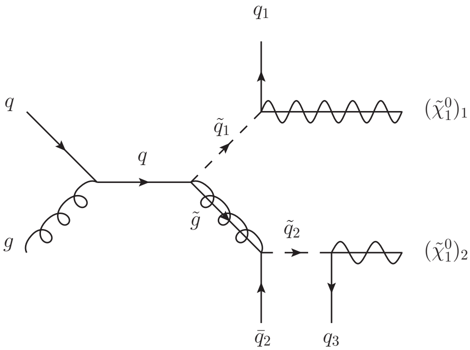
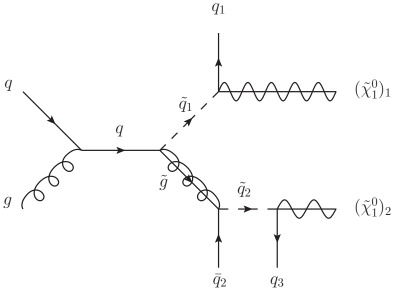


Figure : *s*-channel Feynman diagram for squark-gluino production at LO

- *s*-, *t*- and *u*-channel
- all combinations of flavors and squarks/anti-squarks

Introduction: Process (2)



- Narrow Width Approximation (NWA)

$\Rightarrow$ Factorization of production and decay

$$d\sigma_{\text{tot}} = d\sigma_{\text{prod}} \frac{d\Gamma^{\tilde{q}_1 \to q_1 \tilde{\chi}_1^0}}{\Gamma^{\tilde{q}_1}_{\text{tot}}} \frac{d\Gamma^{\tilde{g} \to \tilde{q}_2 \bar{q}_2}}{\Gamma^{\tilde{g}}_{\text{tot}}} \frac{d\Gamma^{\tilde{q}_2 \to q_3 \tilde{\chi}_1^0}}{\Gamma^{\tilde{q}_2}_{\text{tot}}}$$

Problem

- couplings $\propto P_{L,R}$ $\Rightarrow$ dependence on the gluino spin
- gluino spin info neglected in naive NWA

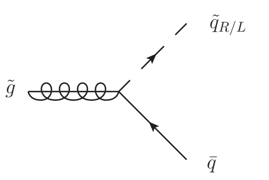
Example: Gluino Decay (1)

Gluino Decay (1)

- assumption: gluino with definite helicity λ

$$\longrightarrow \quad u(p_{\tilde g},\lambda)\bar u(p_{\tilde g},\lambda) = \tfrac{1}{2}(1+\gamma_5 \slashed{s})(\slashed{p}_{\tilde g} + m_{\tilde g})$$

$$s^\mu = \lambda \left(|\vec p_{\tilde g}|/m_{\tilde g},\ E_{\tilde g}\hat p_{\tilde g}/m_{\tilde g} \right)$$



- set $m_q = 0$, sum over quark helicities
- $C_A = 3,\ C_F = 4/3$

Then for $\tilde g \to \tilde q_L \bar q$

$$\sum_{\lambda_q} |\mathcal{M}_{\tilde q_L \bar q}|^2 = \frac{1}{4} g_S^2 C_A C_F \left((p_{\tilde g} p_q) - m_{\tilde g}(p_q s) \right) \ ,$$

and for $\tilde g \to \tilde q_R \bar q$

$$\sum_{\lambda_q} |\mathcal{M}_{\tilde q_R \bar q}|^2 = \frac{1}{4} g_S^2 C_A C_F \left((p_{\tilde g} p_q) + m_{\tilde g}(p_q s) \right) \ .$$

For anti-squarks: $\tilde g \to \bar{\tilde q}_L q \mathrel{\hat=} \tilde g \to \tilde q_R \bar q$ and $\tilde g \to \bar{\tilde q}_R q \mathrel{\hat=} \tilde g \to \tilde q_L \bar q$.

Example: Gluino Decay (2)

Gluino Decay (2)

- again for $\tilde{g} \to \tilde{q}_{R/L}\bar{q}$:

$$\sum_{\lambda_q} |\mathcal{M}_{\tilde{q}_{R/L}\bar{q}}|^2 = \frac{1}{4} g_S^2 C_A C_F \left((p_{\tilde{g}} p_q) \pm m_{\tilde{g}} (p_q s)\right)$$

- evaluation in rest frame of the gluino: $s^\mu = \lambda(0, \hat{s})$ with arbitrary spin direction $\hat{s}$

$$(p_q s) = E_q (\hat{p}_q \hat{s}) = E_q |\hat{p}_q||\hat{s}| \cos\theta = E_q \cos\theta$$

$$\Longrightarrow \quad \sum_{\lambda_q} |\mathcal{M}_{\tilde{q}_{R/L}\bar{q}}|^2 \propto m_{\tilde{g}} E_q (1 \pm \cos\theta)$$

- similar results for the production
- gluino spin correlated in production and decay $\lightning$ NWA

Density Matrices

Intro to Helicity Density Matrices (1)

[Haber '94]

- Idea: restore gluino polarization effects within NWA
- Density matrices defined by ($P \equiv$ production and $D \equiv$ decay)

$$(\rho_P)_{\lambda\lambda'} = \sum \mathcal{M}_{P\lambda}\mathcal{M}^*_{P\lambda'} \qquad \text{and} \qquad (\rho_D)_{\lambda\lambda'} = \sum \mathcal{M}_{D\lambda}\mathcal{M}^*_{D\lambda'}$$

- Bouchiat-Michel-Formula

[Bouchiat, Michel '58]

$$u(p_{\tilde{g}}, \lambda')\bar{u}(p_{\tilde{g}}, \lambda) = \frac{1}{2}\left(\delta_{\lambda\lambda'} + \gamma_5 \not{s}^a \sigma^a_{\lambda\lambda'}\right)\left(\not{p}_{\tilde{g}} + m_{\tilde{g}}\right)$$

with

$$\sigma^a_{\lambda\lambda'}\ ,\ a = 1, 2, 3 \ \hat{=}\ \text{Pauli matrices}$$

$$\{s^{a\mu}\ ,\ p^\mu_{\tilde{g}}/m_{\tilde{g}}\} = \text{ orthonormal set of four-vectors}$$

$$s^a_\mu s^a_\nu = -g_{\mu\nu} + \frac{p_{\tilde{g}\mu}p_{\tilde{g}\nu}}{m^2_{\tilde{g}}}$$

Density Matrices

Intro to Helicity Density Matrices (2)

[Haber '94]

- result:

$$(\rho_P)_{\lambda\lambda'} = \frac{1}{2}|\mathcal{M}_{P,0}|^2(\delta_{\lambda\lambda'} + P_\mu s^\mu_{\lambda\lambda'}) \, ,$$
$$(\rho_D)_{\lambda\lambda'} = \frac{1}{2}|\mathcal{M}_{D,0}|^2(\delta_{\lambda\lambda'} + D_\mu s^\mu_{\lambda\lambda'}) \, ,$$

  with $s^\mu_{\lambda\lambda'} = \sigma^a_{\lambda\lambda'} s^{a\mu}$
  $|\mathcal{M}_{P/D,0}|^2$: amplitudes without polarization effects
  P_μ and D_μ: spin dependent parts

- amplitudes:

$$|\mathcal{M}_{P,0}|^2 = \mathrm{Tr}\{\rho_P\} \quad \text{and} \quad |\mathcal{M}_{D,0}|^2 = \mathrm{Tr}\{\rho_D\}$$
$$|\mathcal{M}_{\text{tot}}|^2 = \mathrm{Tr}\{\rho_P \rho_D\}$$

Density Matrices

Combination of Production and Decay

[Haber '94]

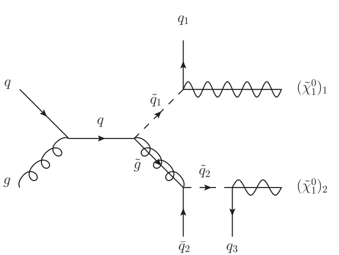
- explicitly:

$$|\mathcal{M}_{\text{tot}}|^2 = \text{Tr}\{\rho_P \rho_D\}$$
$$= \frac{1}{2}|\mathcal{M}_{P,0}|^2 |\mathcal{M}_{D,0}|^2 \left[1 + k\left(P_\mu \left(-g^{\mu\nu} + \frac{p^\mu_{\tilde{g}} p^\nu_{\tilde{g}}}{m^2_{\tilde{g}}}\right) D_\nu\right)\right]$$

- $k = \pm 1$ depending on combinations of $\tilde{q}_L,\ \bar{\tilde{q}}_L,\ \tilde{q}_R,\ \bar{\tilde{q}}_R$ in production and decay

Table : Value for k

	$\tilde{q}_L$	$\tilde{q}_R$	$\bar{\tilde{q}}_L$	$\bar{\tilde{q}}_R$
$\tilde{q}_L$	-1	+1	+1	-1
$\tilde{q}_R$	+1	-1	-1	+1
$\bar{\tilde{q}}_L$	+1	-1	-1	+1
$\bar{\tilde{q}}_R$	-1	+1	+1	-1



Density Matrices

Combination of Production and Decay

- Ingredients:

$$|\mathcal{M}_{P,0}|^2,\ |\mathcal{M}_{D,0}|^2,\ P^\mu,\ D^\mu$$

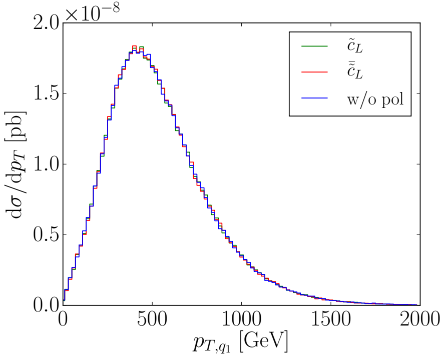
- For extracting P^μ and D^μ:

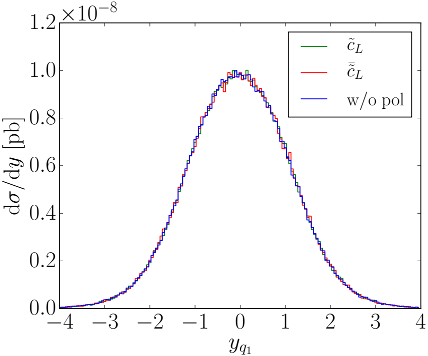
$$u(p_{\tilde{g}},\lambda)\bar{u}(p_{\tilde{g}},\lambda) = \frac{1}{2}\left(1+\gamma_5 \not{s}\right)\left(\not{p}_{\tilde{g}} + m_{\tilde{g}}\right)$$

- no explicit helicity density matrices needed
- NLO: same framework, determine ingredients at NLO

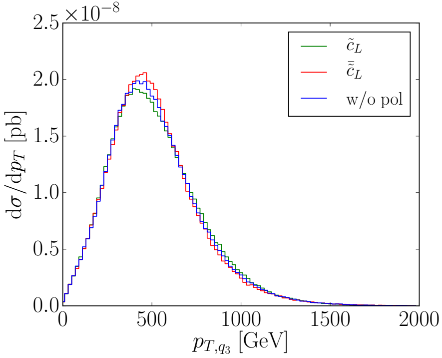
Preliminary Results at LO

- test-scenario: $m_{\tilde{g}} \approx 1468$ GeV, $m_{\tilde{u}_L} \approx m_{\tilde{c}_L} \approx 1174$ GeV and $m_{\tilde{\chi}} \approx 305$ GeV
- C.M. energy: 14 TeV
- CTEQ6LO PDFs
- $\sigma_{\text{tot}} \approx 5.59 \cdot 10^{-7}$ pb

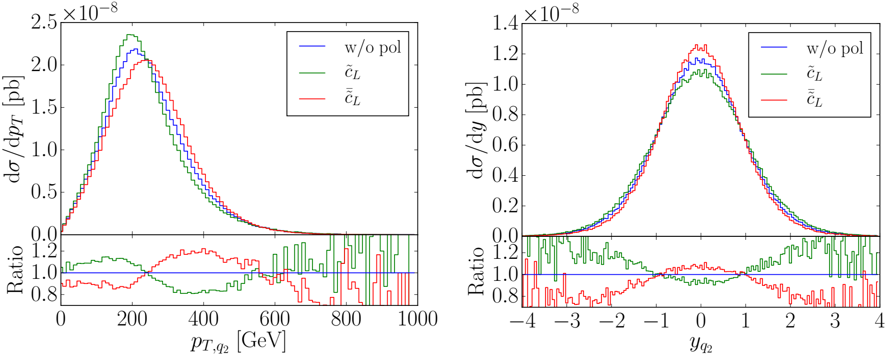




Results



$\times10^{-8}$
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
$d\sigma/dp_T$ [pb]
p_{T,q_3} [GeV]
$\tilde{c}_L$
$\bar{\tilde{c}}_L$
w/o pol
$\times10^{-8}$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−4
−3
−2
−1
0
1
2
3
4
$d\sigma/dy$ [pb]
y_{q_3}
$\tilde{c}_L$
$\bar{\tilde{c}}_L$
w/o pol



$$\mathit{Ratio} = \frac{d\sigma(\text{with polarization effects})}{d\sigma(\text{without polarization effects})}$$

Conclusion

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- $\tilde{q}\tilde{g}$-production with subsequent decays implemented in the POWHEG BOX
- spin correlations between gluino production and decay included
- polarization effects amount up to 20% compared to the case without polarization effects
- differences between $k = +1$ and $k = -1$ up to 40% possible at LO
- NLO calculation in progress

Thanks for listening!

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Thanks for listening!

Backup: Possible Spin Basis

A possible basis for the orthonormal set of four-vectors of slide 9 is given by

$$s^{1\mu} = (0; \cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\phi) \ , \tag{1}$$

$$s^{2\mu} = (0; -\sin\phi, \cos\phi, 0) \ , \tag{2}$$

$$s^{3\mu} = \left(\frac{|\vec{p}|}{m}; \frac{E}{m}\hat{p}\right) \ . \tag{3}$$

Then

$$p_\mu s^{a\mu} = 0 \ , \tag{4}$$

$$s^a_\mu s^{b\mu} = -\delta_{ab} \ , \tag{5}$$

$$s^a_\mu s^a_\nu = -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \ , \tag{6}$$

and

$$\gamma_5 \not{s}^a u(p,\lambda') = \sigma^a_{\lambda\lambda'} u(p,\lambda) \tag{7}$$

$$\gamma_5 \not{s}^a v(p,\lambda') = \sigma^a_{\lambda'\lambda} v(p,\lambda) \tag{8}$$