Probing CP Violation with Momentum Reconstruction at the LHC

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arXiv:0908.2631

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Motivation

- supersymmetry can introduce new sources of CP violation
- these may be needed to explain baryon asymmetry of the universe
- new CP phases can be measured in high energy physics experiments
  $\Rightarrow$ so far most analyses concentrated on the ILC
  see Kittel, arXiv:0904.3241 for a recent review
  $\Rightarrow$ challenging at the LHC
  Ellis, Moortgat, Moortgat-Pick, Smillie, Tattersall arXiv:0809.1607
  Deppisch, Kittel arXiv:0905.3088

We show that in spite of the difficult experimental environment the measurement of CP-odd effects may be possible at the LHC.

Outline

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Minimal Supersymmetric Standard Model

particles		spin 0	spin 1/2	$SU(3)_c, SU(2)_L, U(1)_Y$
squarks and quarks	Q	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(3 flavors)	U	$\tilde{u}^*_R$	$u^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	D	$\tilde{d}^*_R$	$d^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons and leptons	L	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e}_L \end{pmatrix}$	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(3 flavors)	E	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs bosons and	H_u	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
Higgsinos	H_d	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

particles	spin $\frac{1}{2}$	spin 1	$SU(3)_c, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm\ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Neutralino sector of MSSM

- neutralino mass matrix in gauge eigenstate basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

- diagonalization of mass matrix

$$\mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) = N^* M_{\tilde{\chi}^0} N^{-1}$$

- when M_1 and/or μ are complex mixing matrix N has non-trivial complex structure
- complex elements of N appear in neutralino couplings triggering CP-odd effects

CP phases in the MSSM

- CP phases enter in the gaugino/higgsino mass parameters and trilinear couplings:

$$M_i = |M_i| e^{i\phi_i}, \qquad \mu = |\mu| e^{i\phi_\mu}, \qquad A_f = |A_f| e^{i\phi_f}$$

$\Rightarrow$ strong bounds from EDMs
$\Rightarrow$ large phases possible if accidental cancellations occur
see e.g. Ellis, Lee, Pilaftsis arXiv:0808.1819
$\Rightarrow$ or 1st and 2nd generation of squarks are heavy

- CP phases can be probed by
asymmetries in cross sections and decay widths,
asymmetries of triple products of momenta and/or spins

$\Rightarrow$ such CP- and T-odd observables provide unambiguous way of detecting CP violation in the model

Triple products

Triple product correlations of momenta are a useful tool for studying CP violation effects

- construct a T_N-odd observable:

$$\mathcal{T} = \overrightarrow{p_1} \cdot (\overrightarrow{p_2} \times \overrightarrow{p_3})$$

- it is CP-odd if higher order effects and finite widths can be neglected
- originates from Dirac traces in matrix element

$$\mathrm{Tr}\left[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5\right] \longrightarrow i\epsilon_{\mu\nu\rho\sigma} p_a^\mu p_b^\nu p_c^\rho p_d^\sigma$$

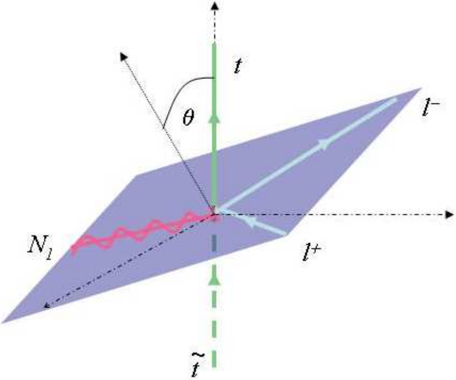
$\Rightarrow$ together with imaginary part of couplings gives rise to CP-odd asymmetries

CP-sensitive asymmetries

Example: triple product in decay chain $\tilde{t} \to \tilde{\chi}_2^0\, t \to \tilde{\chi}_1^0\, l^+\, l^-\, t$

$$\mathcal{T}_t = \vec{p}_t \cdot (\vec{p}_{l^+} \times \vec{p}_{l^-})$$

Langacker ea hep-ph/0702068



- count the number of events N_+ where $\vec{p}_t$ points above the plane defined by leptons vs. the number of events N_- when it points below it
- define the asymmetry as:

$$A_{\mathrm{CP}} = \frac{N_+ - N_-}{N_+ + N_-}$$

- $A_{\mathrm{CP}} = 0$ when phases vanish

Outline

Chosen scenario

- mSUGRA parameters:
  $m_0 = 150$ GeV, $m_{1/2} = 200$ GeV, $A_0 = -650$ GeV, $\tan\beta = 10$
- resulting masses in GeV and branching ratios:

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{g}}$	$m_{\tilde{q}_L}$	$m_{\tilde{t}_1}$
78.1	148.4	148.2	496.5	480	171.0

Mode	$\tilde{g} \to \tilde{t}_1 \bar{t} + \mathrm{c.c.}$	$\tilde{q}_L \to \tilde{\chi}_1^\pm q'$	$\tilde{q}_L \to \tilde{\chi}_2^0 q$	$\tilde{t}_1 \to \tilde{\chi}_1^+ b$
BR	53.8%	65%	33%	98.1%
Mode	$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \tau^+ \nu_\tau$	$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu_\ell$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$
BR	37.2%	$2 \times 12.2\%$	59.3%	$2 \times 4.5\%$

- introduce the complex phase for the bino mass parameter

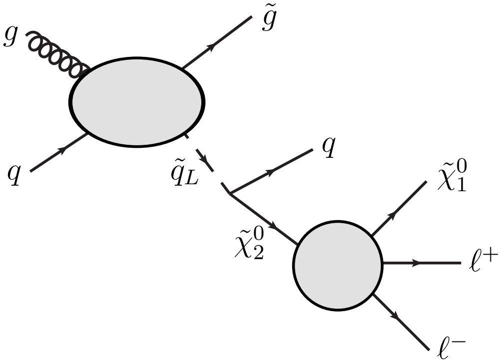
$$M_1 = |M_1| \mathrm{e}^{\mathrm{i}\phi_1} \qquad 0 \leq \phi_1 < 2\pi$$

Squarks production and decay

- production rates at 14 TeV

Particle	Total Coloured	$\tilde{g}$	$\tilde{q}_L$	$\tilde{q}_L^*$	$\tilde{q}_L + \tilde{g}$	$\tilde{q}_L^* + \tilde{g}$
Cross Section (pb)	148	59.2	30.0	8.3	18.2	3.1

- high production rate of squarks
- squarks dominate over antisquarks
- left squarks decay to $\tilde{\chi}_2^0$ with $BR = 33\%$



CP asymmetry in neutralino 3-body decay

- neutralinos $\tilde{\chi}_2^0$ appear copiously in the $\tilde{q}_L$ decay chain
- leptonic 3-body decay of neutralino

Choi, Chung, Kalinowski, Kim, KR hep-ph/0504122
Aguilar-Saavedra hep-ph/0403243

$$\tilde{q}_L \to \tilde{\chi}_2^0 + q \to \tilde{\chi}_1^0\, \ell^+\, \ell^- + q$$

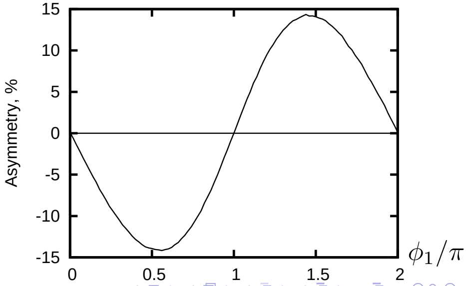
- triple product of lepton momenta and a quark from $\tilde{q}_L$ decay

$$\mathcal{T}_{q\ell\ell} = \vec{p}_q \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$

Moortgat-Pick, KR, Tattersall, Wienemann

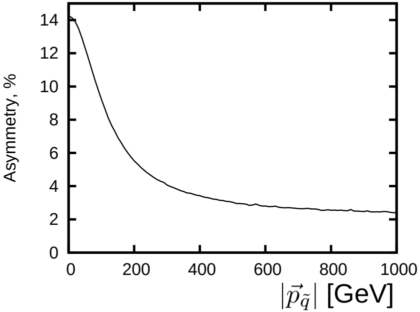
- sensitive to the phase of M_1
- asymmetry up to 15% in $\tilde{q}_L$ rest frame

$$\mathcal{A}_{CP} = \frac{N(\mathcal{T}_{q\ell\ell} > 0) - N(\mathcal{T}_{q\ell\ell} < 0)}{N(\mathcal{T}_{q\ell\ell} > 0) + N(\mathcal{T}_{q\ell\ell} < 0)}$$



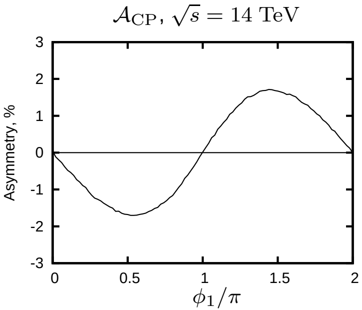
Dilution due to boosts

$$\mathcal{A}_{\mathcal{T}} = \overrightarrow{p}_q \cdot (\overrightarrow{p}_{\ell+} \times \overrightarrow{p}_{\ell-})$$



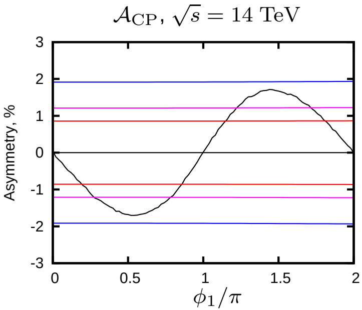
- asymmetry as a function of the squark momentum in the laboratory frame
- high and undetermined boost decreases the asymmetry
- the highest asymmetry in the squark rest frame

Hadron level asymmetry



- dilution due to boost of squarks and admixture of antisquarks ($\#\tilde{q}_L/\#\tilde{q}_L^* \sim 3.6$)
- high production rate of $\tilde{q}_L + \tilde{q}_L^* \sim 38$ pb gives high statistics
- hints could be seen at the LHC at higher luminosity
- if we could go back to the neutralino rest frame...

Hadron level asymmetry



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Purple: 50 fb^{-1}
Blue: 20 fb^{-1}
3σ statistical

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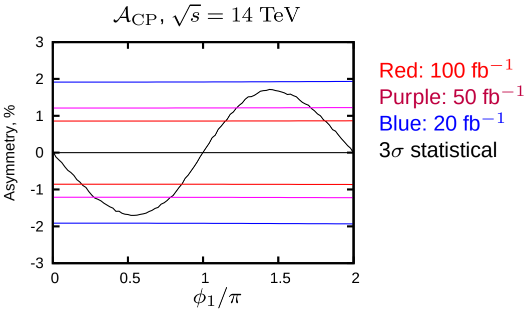

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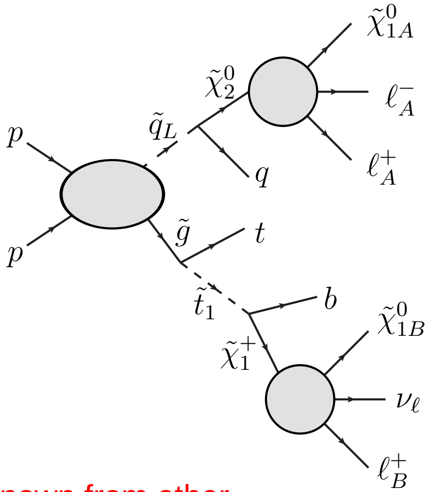
3. CP-odd asymmetry after momentum reconstruction
4. Conclusions

Momentum reconstruction

Mass conditions:

$$
\begin{aligned}
m^2_{\tilde{q}_L} &= (p_{\tilde{\chi}^0_2} + p_q)^2 \\
m^2_{\tilde{\chi}^0_2} &= (p_{\tilde{\chi}^0_{1A}} + p_{\ell^+_A} + p_{\ell^-_A})^2 \\
m^2_{\tilde{g}} &= (p_{\tilde{t}_1} + p_t)^2 \\
m^2_{\tilde{t}_1} &= (p_{\tilde{\chi}^+_1} + p_b)^2 \\
m^2_{\tilde{\chi}^0_1} &= p^2_{\tilde{\chi}^0_{1A}} \\
m^2_{\tilde{\chi}^+_1} &= (p_{\tilde{\chi}^0_{1B}} + p_{\ell_B} + p_{\nu_\ell})^2 \\
\vec{p}^{\,miss}_T &= \vec{p}^{\,\tilde{\chi}^0_{1A}}_T + \vec{p}^{\,\tilde{\chi}^0_{1B}}_T + \vec{p}^{\,\nu_\ell}_T
\end{aligned}
$$



- 8 unknowns vs. 8 equations
- assuming particle masses are known from other measurements, momenta of intermediate particles can be reconstructed

Momentum reconstruction

Further steps

- combine the momenta of $\tilde{\chi}^0_{1B}$ and ν_ℓ as they cannot be resolved

$$P_{\tilde{g}ME} = P_{\tilde{\chi}^0_{1B}} + P_{\nu_\ell}$$

- 8 unknowns:

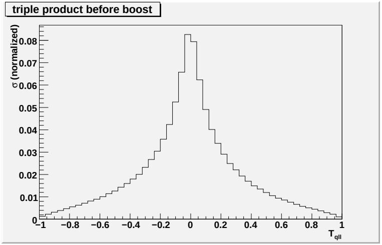
$$\left(E_{\tilde{\chi}^0_{1A}},\ p_{\tilde{\chi}^0_{1A}}(x),\ p_{\tilde{\chi}^0_{1A}}(y),\ p_{\tilde{\chi}^0_{1A}}(z)\right)$$
$$\left(E_{\tilde{g}ME},\ p_{\tilde{g}ME}(x),\ p_{\tilde{g}ME}(y),\ p_{\tilde{g}ME}(z)\right)$$

- form the system of 6 linear and 2 quadratic equations

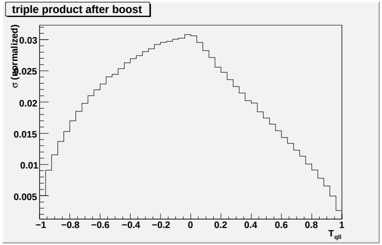
Some tricky details

- up to 4 possible real solutions
  $\Rightarrow$ take only events where all solutions have the same sign of triple product
- background due to signal process with $\tilde{\chi}_2^0$ decaying to taus followed by leptonic tau decays to same flavor leptons
  $$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \, \tau^+ \, \tau^- \to \tilde{\chi}_1^0 \, \ell^+ \, \nu_\ell \, \bar{\nu}_\tau \, \ell^- \, \bar{\nu}_\ell \, \nu_\tau$$
  $\Rightarrow$ usually does not give the same sign triple product for different solutions
- combinatorics
  $\Rightarrow$ no real solutions in case of wrong assignments of particles in most cases

Effect of boost on triple product



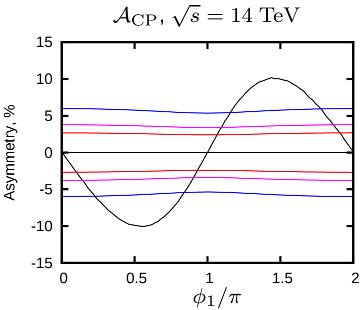
$\mathcal{T}_{q\ell\ell}$



$\mathcal{T}_{q\ell\ell}$

- using reconstructed momenta we can calculate triple product in the rest frame of the neutralino $\tilde{\chi}_2^0$
- asymmetry becomes clearly visible after boost in the triple product distribution
- use `Herwig++` to validate analytical results and generate the events

Asymmetry after reconstruction



Red: 100 fb^{-1}
Purple: 50 fb^{-1}
Blue: 20 fb^{-1}
3σ statistical

- asymmetry returns to parton level magnitude
- substantially increases statistical significance of any result
- good prospects for 3σ discovery or exclusion for wide range of ϕ_1 values

Experimental factors

- selection cuts

$$E_T(j_1) \geq 100 \text{ GeV}, \qquad E_T(j) \geq 25 \text{ GeV}$$
$$E_T(\ell_{e,\mu}) \geq 10 \text{ GeV}, \qquad M_{\ell^+\ell^-} \geq 20 \text{ GeV}, \qquad |\eta| \leq 2.5$$

- momenta of final particles smeared in the detector

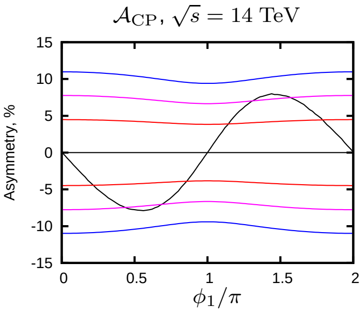
$$\frac{\sigma_E}{E} = \frac{a_{j,e}}{\sqrt{E}} \oplus \frac{b_{j,e}}{E} \oplus c_{j,e}$$

  - for jets $a_j = 0.6 \text{ GeV}^{\frac{1}{2}}$, $b_j = 1.5 \text{ GeV}$ and $c_j = 0.03$
  - for electrons $a_e = 0.12 \text{ GeV}^{\frac{1}{2}}$, $b_e = 0.2 \text{ GeV}$ and $c_e = 0.01$

- missing energy resolution

$$\frac{\sigma^x_{MET}}{E_T} = \frac{\sigma^y_{MET}}{E_T} = \frac{0.57}{\sqrt{E_T/\text{GeV}}}$$

Asymmetry with experimental effects



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Purple: 100 fb^{-1}
Blue: 50 fb^{-1}
3σ statistical

- momentum smearing reduces the number of reconstructed events and increases dilution
- includes uncertainty in particle masses

With high luminosity wide range of ϕ_1 covered:

$$0.2\,\pi \lesssim \phi_1 \lesssim 0.85\,\pi \quad \cup \quad 1.15\,\pi \lesssim \phi_1 \lesssim 1.8\,\pi$$

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Conclusions

- squark decays are a promising channel for studying CP violation at the LHC
- suppression of asymmetries by boosts can be overcome by momentum reconstruction
- reconstruction significantly improves sensitivity by enhancing the signal
- information from LHC on CP violation could direct future searches at a linear collider
- Outlook:
  $\Rightarrow$ more detailed experimental study is in progress

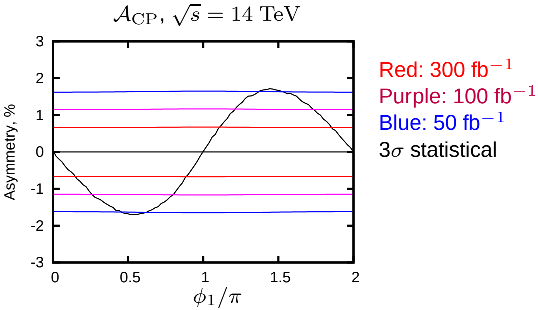
Momentum reconstruction matrix

$$\mathcal{M}\begin{pmatrix} A \\ B \\ C \\ D \\ E \\ F \end{pmatrix} = \begin{pmatrix} \frac{1}{2}(m^2_{\tilde\chi^0_1} - m^2_{\tilde\chi^0_2}) + P_{\ell^+_a}\cdot P_{\ell^-_a} + E_{\tilde\chi^0_{1a}}(E_{\ell^+_a} + E_{\ell^-_a}) \\ \frac{1}{2}(m^2_{\tilde\chi^0_2} - m^2_{\tilde q}) + P_{\ell^+_a}\cdot P_q + P_{\ell^-_a}\cdot P_q + E_{\tilde\chi^0_{1a}} E_q \\ \frac{1}{2}(m^2_b + m^2_{\tilde\chi^+_1} - m^2_{\tilde t}) + P_{\ell^+_b}\cdot P_b + E_{\tilde g ME} E_b \\ \frac{1}{2}(m^2_{\tilde t} + m^2_t - m^2_{\tilde g}) + P_{\ell^+_b}\cdot P_t + P_b\cdot P_t + E_{\tilde g ME} E_t \\ p^T_{miss}(x) \\ p^T_{miss}(y) \end{pmatrix},$$

where

$$\mathcal{M} = \begin{pmatrix} \vec p_{\ell^+_a \ell^-_a}\vec p_{\ell^+_a} & \vec p_{\ell^+_a \ell^-_a}\vec p_{\ell^-_a} & \vec p_{\ell^+_a \ell^-_a}\vec p_q & 0 & 0 & 0 \\ \vec p_{\ell^+_a}\vec p_q & \vec p_{\ell^-_a}\vec p_q & \vec p_q\vec p_q & 0 & 0 & 0 \\ 0 & 0 & 0 & \vec p_b\vec p_{\ell^+_b} & \vec p_b\vec p_b & \vec p_b\vec p_t \\ 0 & 0 & 0 & \vec p_t\vec p_{\ell^+_b} & \vec p_b\vec p_t & \vec p_t\vec p_t \\ p_{\ell^+_a}(x) & p_{\ell^-_a}(x) & p_q(x) & p_{\ell^+_b}(x) & p_b(x) & p_t(x) \\ p_{\ell^+_a}(y) & p_{\ell^-_a}(y) & p_q(y) & p_{\ell^+_b}(y) & p_b(y) & p_t(y) \end{pmatrix}$$

Asymmetry before reconstruction with cuts



With high luminosity wide range of ϕ_1 covered:

$$0.15\,\pi \lesssim \phi_1 \lesssim 0.9\,\pi \quad \cup \quad 1.1\,\pi \lesssim \phi_1 \lesssim 1.85\,\pi$$

Backgrounds

- SUSY backgrounds:

$$\tilde{g}\tilde{q}_L \to (\tilde{b}_{1,2}b) + (\tilde{\chi}^0_2 q) \to (\tilde{\chi}^-_1 tb) + (\tilde{\chi}^0_2 q) \to (\ell tb) + (\ell\ell q) + E_{miss}$$

$$\tilde{g}\tilde{q}_L \to (\tilde{b}_{1,2}b) + (\tilde{\chi}^0_2 q) \to (\tilde{t}_1 Wb) + (\tilde{\chi}^0_2 q) \to (\ell bWb) + (\ell\ell q) + E_{miss}$$

$$\tilde{g}\tilde{g} \to (\tilde{t}_1 t) + (\tilde{b}_{1,2}b) \to (\tilde{\chi}^-_1 bt) + (\tilde{t}_1 Wb) \to (\ell bt) + (\ell b\ell b) + E_{miss}$$

$$\tilde{g}\tilde{g} \to (\tilde{t}_1 t) + (\tilde{t}_1 t) \to (\tilde{\chi}^-_1 bt) + (\tilde{\chi}^-_1 b\ell b) \to (\ell bt) + (\ell b\ell b) + E_{miss}$$

$\Rightarrow$ need further studies

$\Rightarrow$ hopefully cannot pass reconstruction process