Using top polarization to probe sbottom decays

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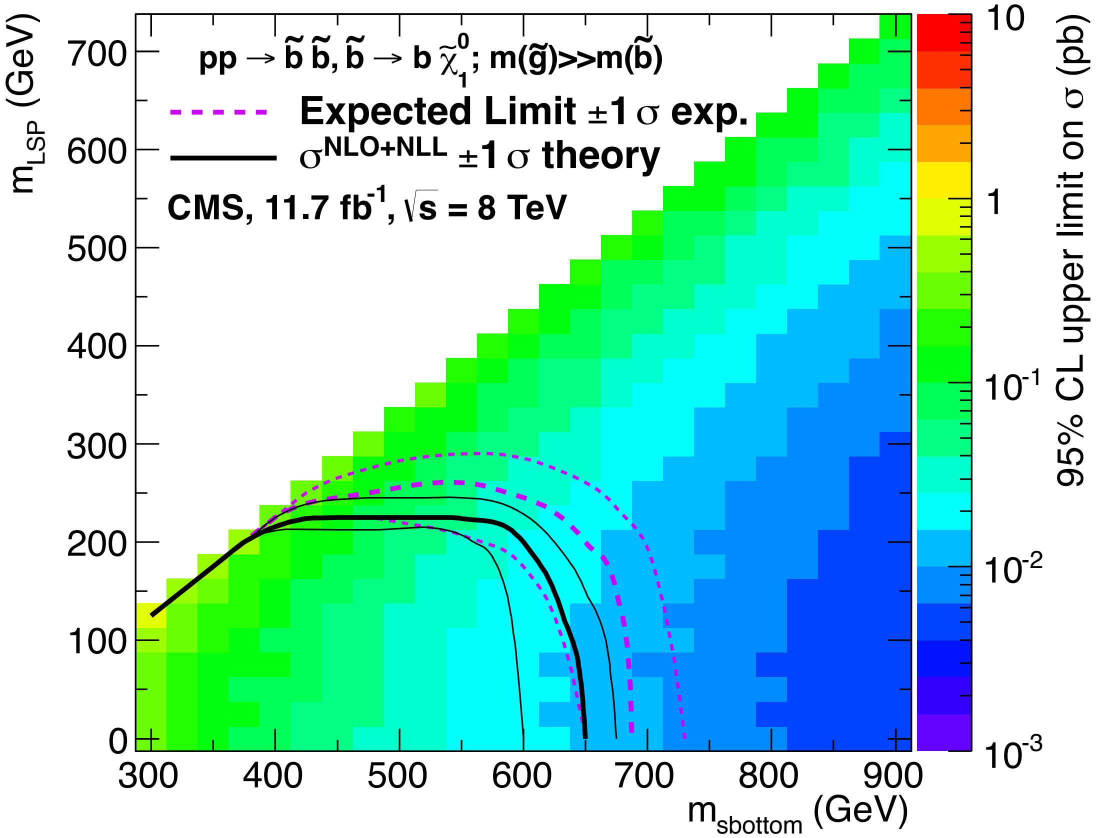
Motivation



CMS direct sbottom pair production

CMS-SUS-12-028

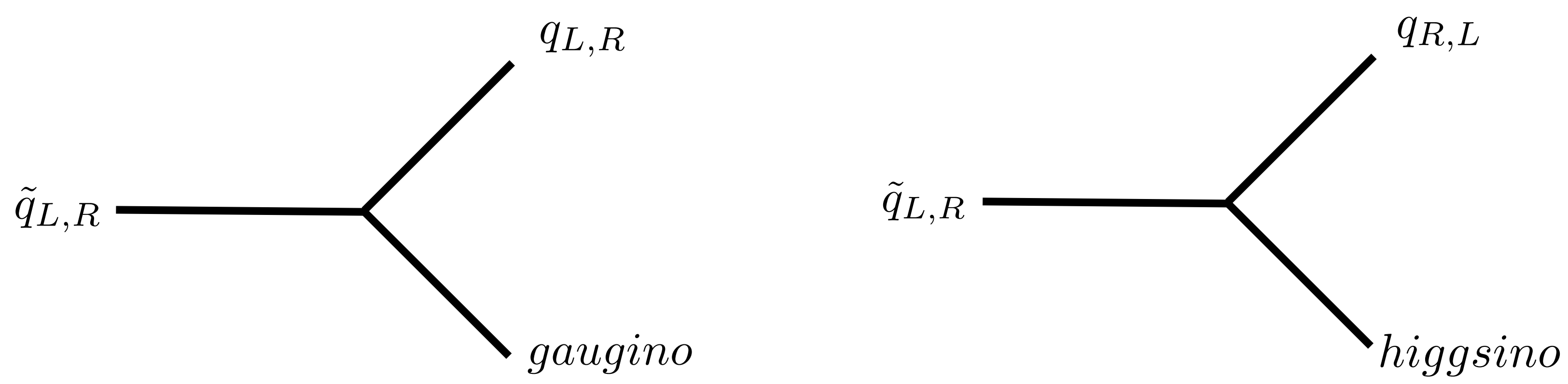
- Third generation squarks hold an important status as a possible key to Higgs hierarchy problem
- Light third generation squarks along with higgsinolike weakinos form the widely studied regime of natural SUSY
- Most of the search strategies use shape observables or kinematic distributions and are already giving us good results
- Question: Can we improve on the search strategies of third generation squarks using top polarization?
- In this talk I focus on sbottom searches below mass scale 1TeV

Why polarization?

- Definition of top polarization

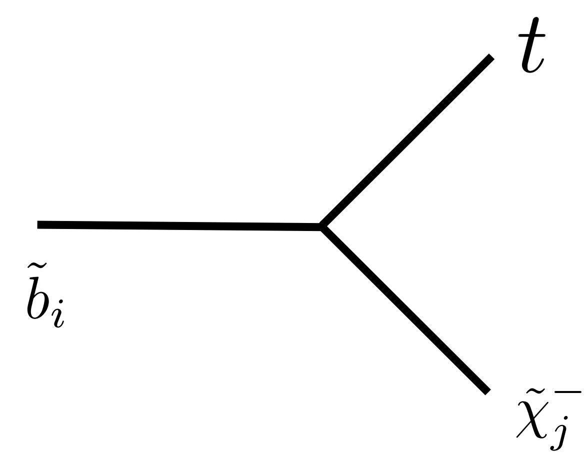
$$P_t = \frac{\sigma(+,+) - \sigma(-,-)}{\sigma(+,+) + \sigma(-,-)}$$

- In the Standard Model (SM) the polarization of top is always -1
- In case of SUSY the polarization can take different value depending on the nature of the mother squark and daughter weakino
- In general gaugino conserves the helicity of the interaction and higgsino flips the chirality



- Depending on these couplings intermediate values of polarization are possible

Scenario



- Consider sbottom decay in its rest frame

- The longitudinal top polarization is given by:

$$\mathcal{P}_t = \frac{\left[\, (k_{ij}^{\tilde{b}})^2 - (l_{ij}^{\tilde{b}})^2 \,\right] f_1}{(k_{ij}^{\tilde{b}})^2 + (l_{ij}^{\tilde{b}})^2 - 2\, k_{ij}^{\tilde{b}}\, l_{ij}^{\tilde{b}}\, f_2}\,,$$

- Characteristics of polarization:

  ★ Depends on the mixing in the sbottom and chargino sector encoded in couplings k, l

  ★ Depends on the mass difference between sbottom and chargino encoded in factors f1 and f2

  ★ For large mass differences $f_1 \to 1$ $f_2 \to 0$

Polarization behavior

Limiting cases for $\tilde{b}_i \to \tilde{\chi}_j^- + t$

- Purely winolike chargino conserves chirality, polarization of top always -1 irrespective of mixing in the sbottom sector

- Purely higgsinolike chargino flips chirality:

  ★ Left handed sbottom couples to right handed top

$$\tilde{b}_L : \cos\theta_{\tilde{b}} = 1\,, \quad \mathcal{P}_t \to +f_1 \to +1$$

  ★ Right handed sbottom couples to left handed top

$$\tilde{b}_R : \cos\theta_{\tilde{b}} = 0\,, \quad \mathcal{P}_t \to -f_1 \to -1$$

Polarization behavior

Limiting cases for $\tilde{b}_i \to \tilde{\chi}_j^- + t$

Winolike chargino

$$U \to \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \qquad V \to \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\mathcal{P}_t = \frac{-(l_{11}^{\tilde{b}})^2 f_1}{(l_{11}^{\tilde{b}})^2} = -f_1$$

Higgsinolike chargino

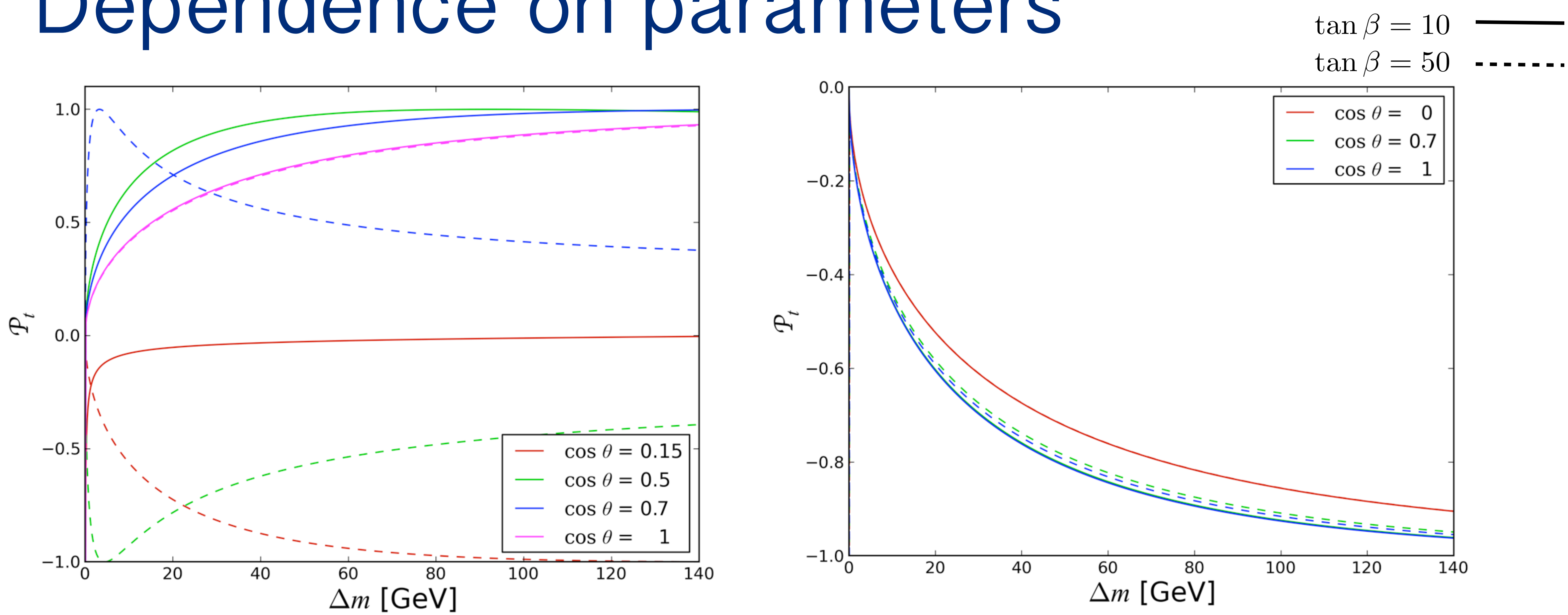
$$U \to \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad V \to \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\mathcal{P}_t = \frac{((h_t\,\cos\theta_{\tilde{b}})^2 - (h_b\,\sin\theta_{\tilde{b}})^2)\,f_1}{[(h_t\,\cos\theta_{\tilde{b}})^2 + (h_b\,\sin\theta_{\tilde{b}})^2 - h_t\,h_b\,\sin 2\theta_{\tilde{b}}\,f_2]}$$

$$\tilde{b}_L : \cos\theta_{\tilde{b}} = 1\,, \quad \mathcal{P}_t \to +f_1$$

$$\tilde{b}_R : \cos\theta_{\tilde{b}} = 0\,, \quad \mathcal{P}_t \to -f_1$$

Dependence on parameters



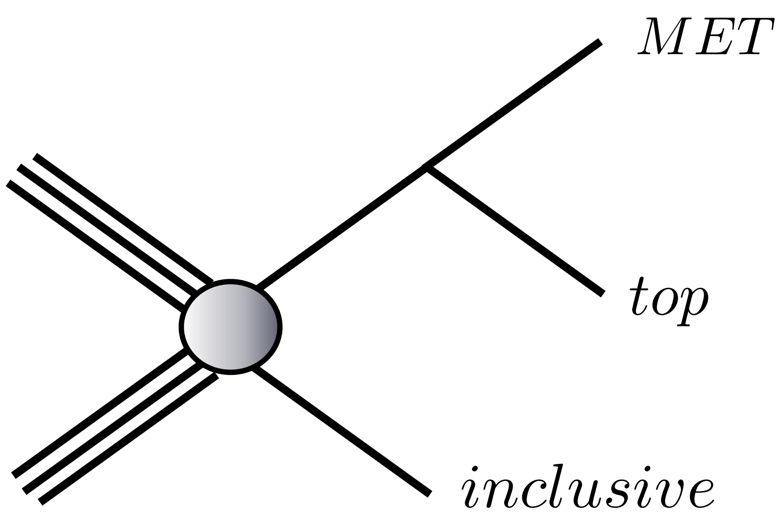
Higgsino

Wino

- The polarization drops to zero for small mass difference irrespective of the nature of the chargino
- For higgsinolike chargino, the exact behavior for small mass difference is controlled by the relative strengths of Yukawa coupling and mixing in the sbottom sector
- For the rest of the talk, consider only the case of large mass difference

Calculating net polarization

- When sbottom is left handed, the lightest stop and sbottom are almost mass degenerate
- Neutralino NLSP and lightest chargino are almost mass degenerate with neutralino LSP
- All stop and sbottom decays involving top in the final state will lead to a top + MET signature
- Hence add all such decays with similar stop and sbottom masses and similar weakino masses must be added
- System under consideration



$$\hat{P}_t = P_t(\tilde{b}_i \to \tilde{\chi}_j^- + t) + P_t(\tilde{t}_l \to \tilde{\chi}_m^0 + t)$$

Calculating the net polarization

- Net polarization depends on the production cross-section of stop and sbottom, their branching ratios to top final state and the polarization of top for individual stop and sbottom decays

- Consider the case of one light stop and a one or possibly both light sbottoms decaying into higgsinolike weakinos

- For an almost left handed sbottom decaying to higgsinolike weakinos the net polarization is almost +1, as the polarization resulting from both stop and sbottom is +1

- However it is possible to obtain intermediate values of the polarization for highly mixed sbottoms and left handed light stop

N.B. Maximum one stop can be light if we want to obtain the correct higgs mass

Utilizing top polarization at the LHC

- Top decay products carry information about the polarization
- In the top rest frame this is given by:

$$\frac{1}{\Gamma_t}\frac{\mathrm{d}\Gamma_l}{\mathrm{d}\cos\theta_{f,\mathrm{rest}}} = \frac{1}{2}\left(1 + \kappa_f \mathcal{P}_t \cos\theta_{f,\mathrm{rest}}\right),$$

- kf is the analyzing power and is the highest for leptons hence we use leptonic top decays in the following analysis
- Three factors responsible for the polarization - the transverse momentum of the top, the top polarization in sfermion rest frame, top boost in lab frame

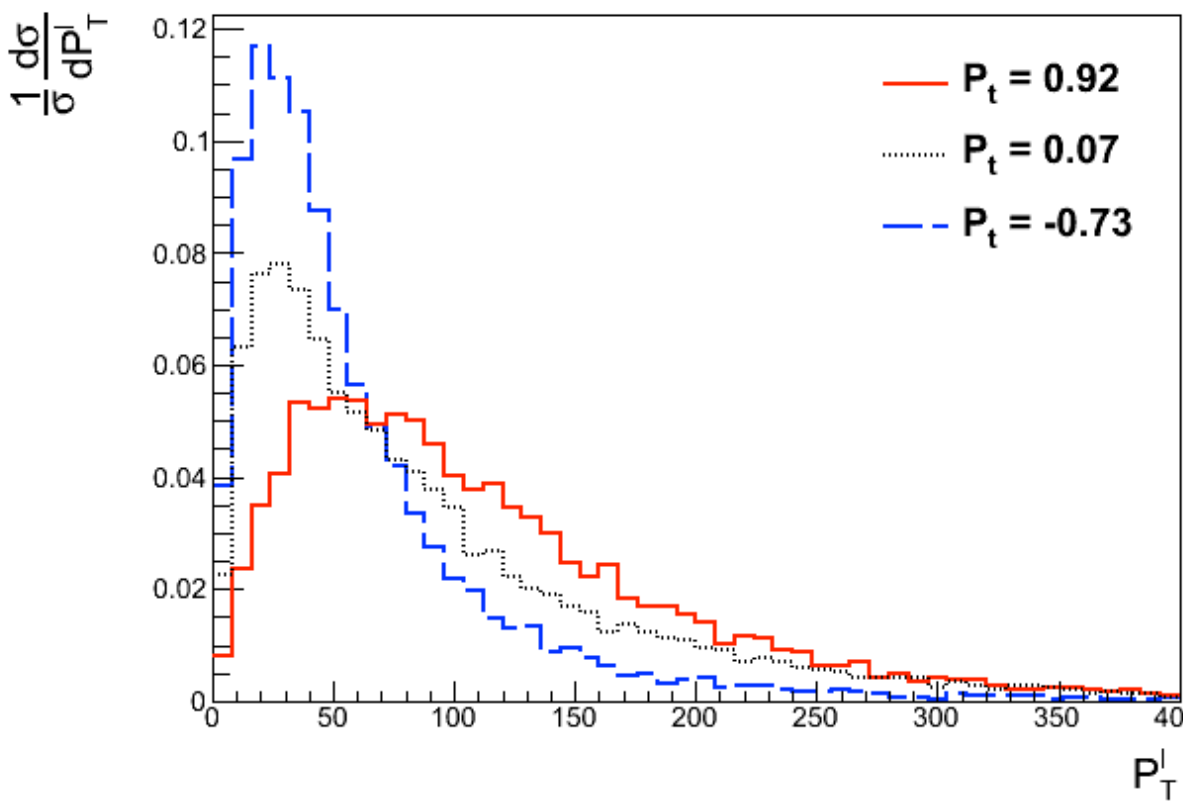
Utilizing top polarization at the LHC

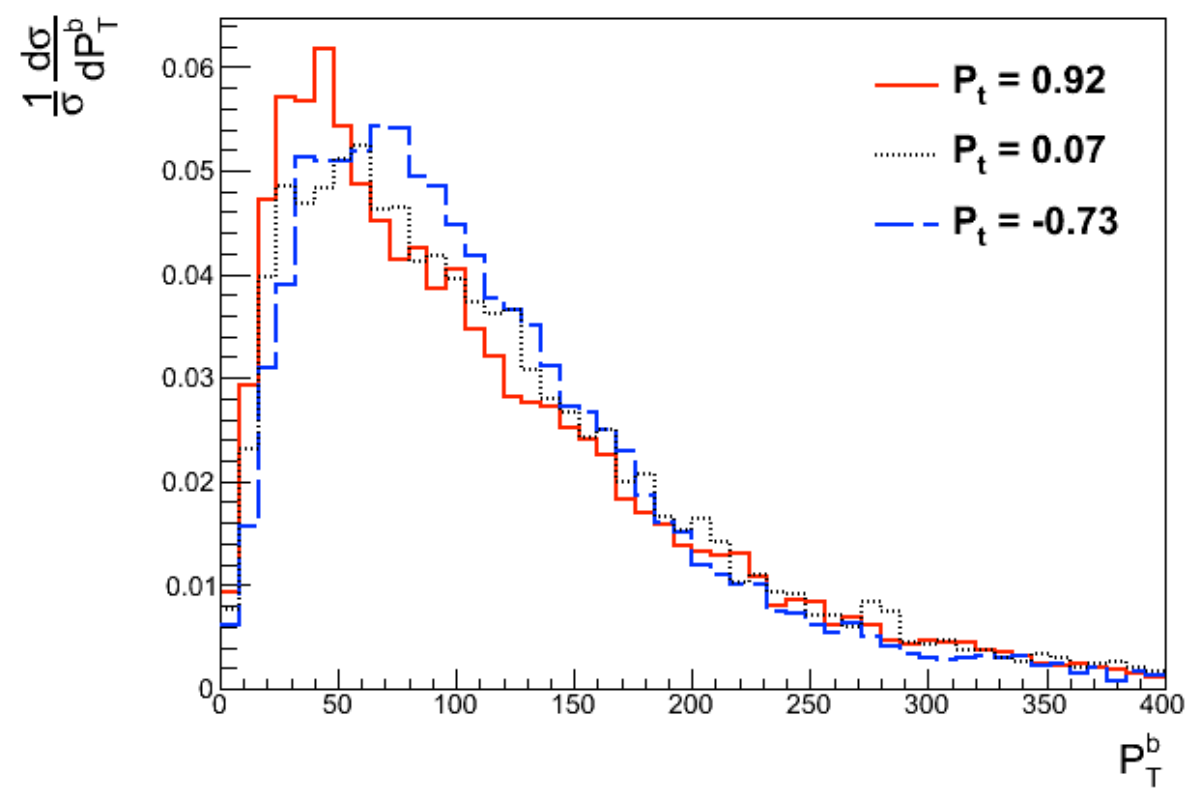
- Polarization information can be used in two ways:
  - ★ To improve the search strategies and obtain better results
  - ★ If SUSY is found, measuring the polarization in order to obtain information on the soft parameters
- All observables are constructed in the lab frame removing the need of top quark rest frame reconstruction
- The leptons generally gain more energy when the top is +vely polarized as compared to unpolarized or -vely polarized case, this can be used at the LHC to improve on the search strategies
- Angular distributions of the decay leptons get affected when a polarized top decays - asymmetries constructed out of these distributions can act as measure of polarization

Benchmarks points

	bm1	bm2	bm3
$m_{\tilde{b}_1}$	650	650	650
$m_{\tilde{b}_2}$	1329.77	1538.10	884.47
$\cos\theta_{\tilde{b}}$	0.006	0.99	0.02
$m_{\tilde{t}_1}$	1236.2	633.84	818.99
$m_{\tilde{t}_2}$	1560.58	2212.19	1518.19
$\cos\theta_{\tilde{t}}$	0.85	0.996	0.96
$m_{\tilde{\chi}_1^-}$	352.73	144.16	352.05
$m_{\tilde{\chi}_2^-}$	1021.05	430.32	1016.09
$m_{\tilde{\chi}_1^0}$	343.39	126.52	343.13
$m_{\tilde{\chi}_2^0}$	358.22	159.18	357.22
Net polarization	-0.73	0.92	0.07

Effect on PT





- The two PT distributions have opposite behavior
- PT of b is not so strongly affected
- Should be careful for PT distributions due to anomalous tbW couplings
- This behavior of PT spectra can be used to improve search strategies at the LHC

Energy ratio observables

- At LHC 14TeV the tops are going to be highly boosted, depending on the angular distributions might not be a good idea - use of energy ratios

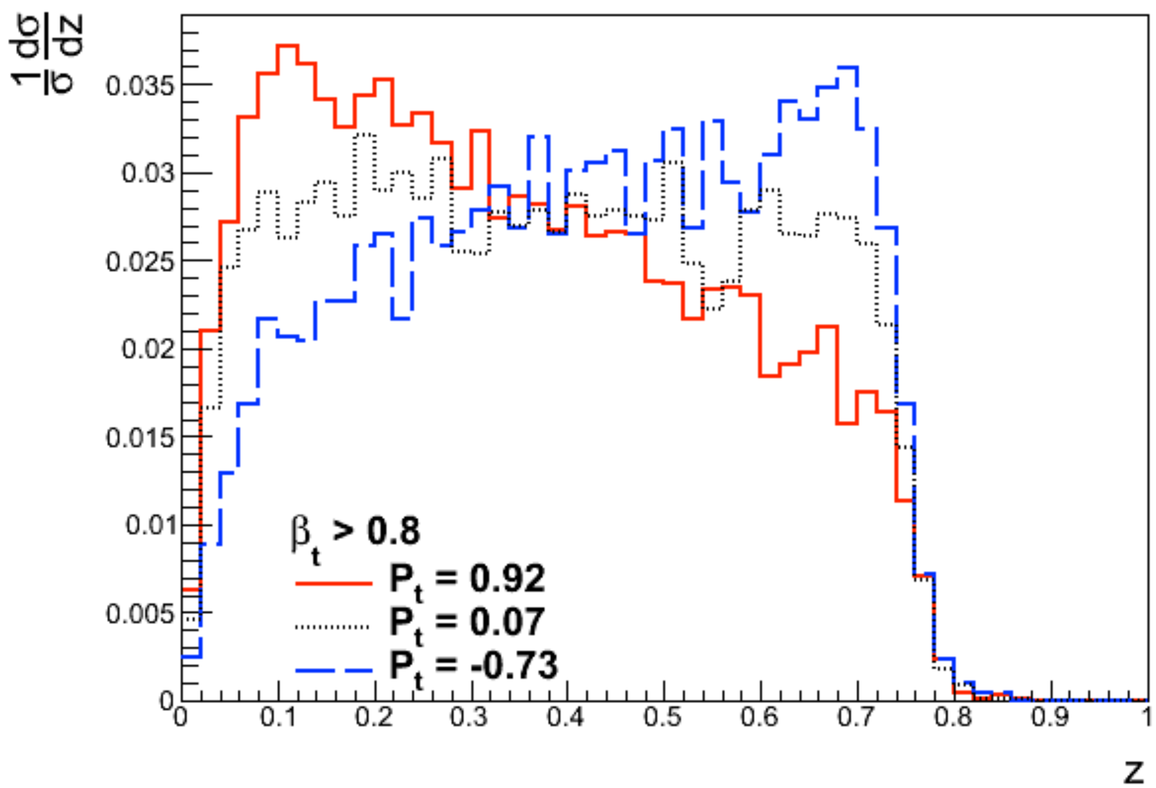
- Consider:

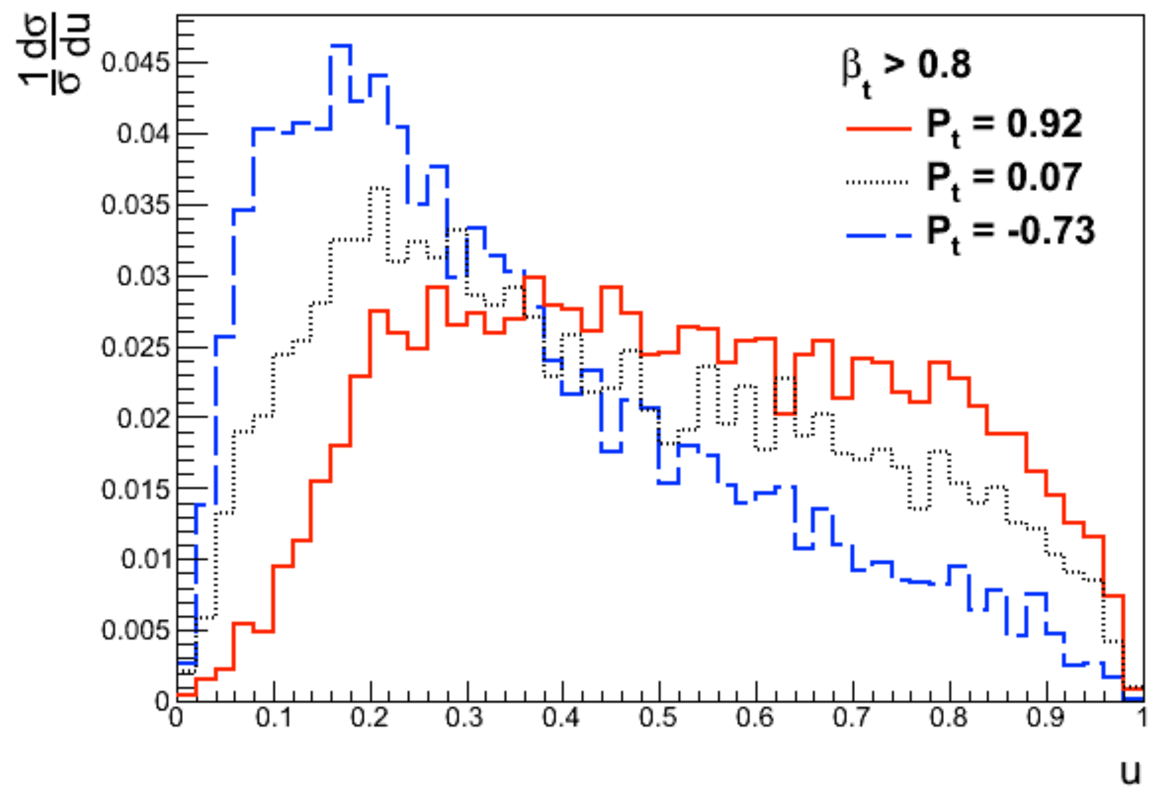
$$z = \frac{E_b}{E_t} \qquad\qquad u = \frac{E_l}{E_l + E_b}$$

- Note that z can be used even in the case of hadronic top decays

Energy ratio observables

- At LHC 14TeV the tops are going to be highly boosted, depending on the angular distributions might not be a good idea - use of energy ratios





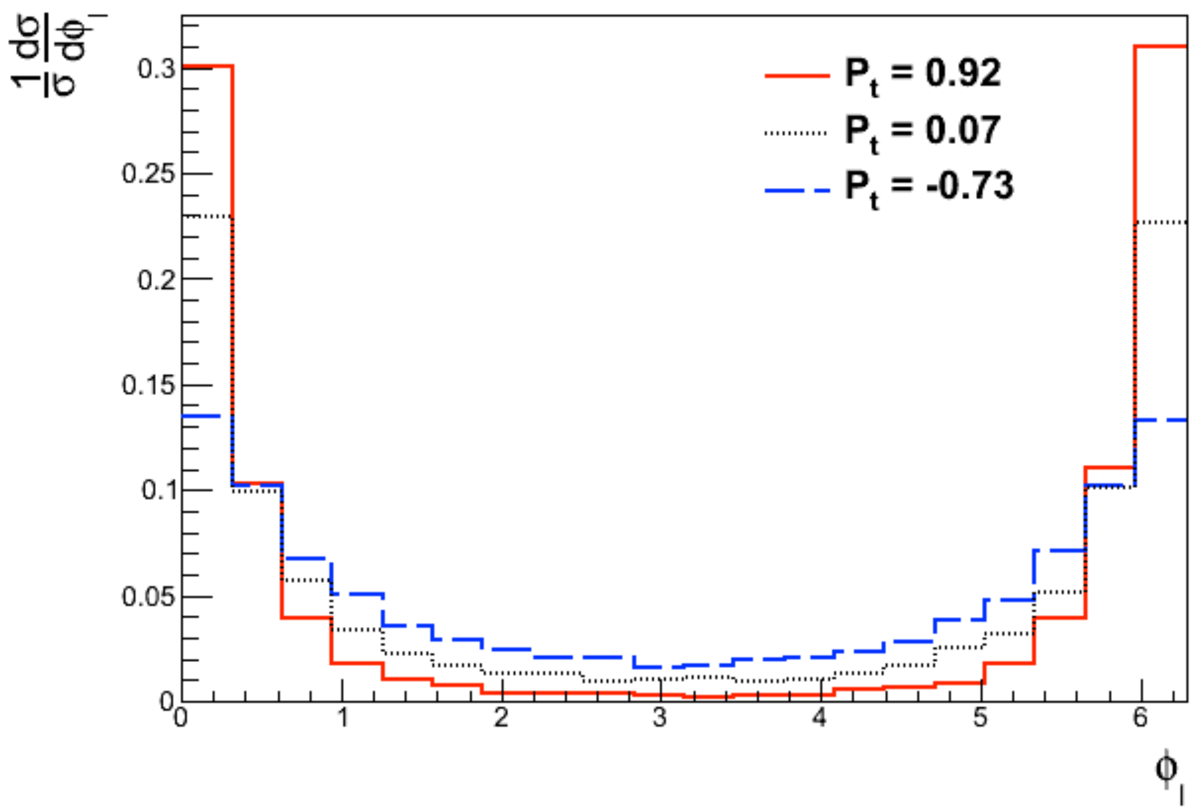
- Behavior of z and u is complimentary
- Cut offs at lower and higher ends are caused by the finite b and W masses
- It is also possible to define asymmetries using this shape of distribution

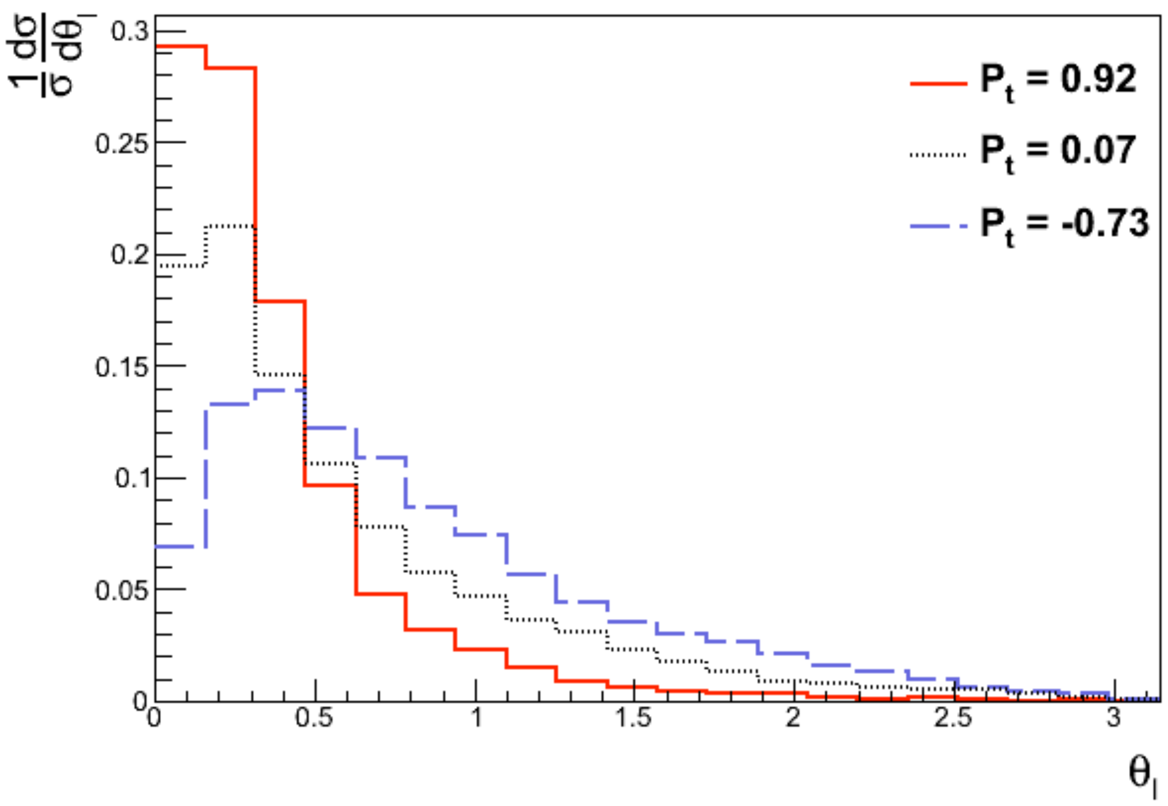
Polarization asymmetries

- We consider two angular distributions:
  - ★ Lab frame polar angle of the lepton w.r.t top, due to top boost the distribution is more strongly peaked at 0 for +vely polarized top
  - ★ Azimuthal angle between the lepton and the x-axis when x-axis is defined to be in the direction of top quark - peaks at 0 and 2*pi because of kinetic effects which is further enhanced for a +vely polarized top
  - ★ The shape of the distributions lead to the definition of asymmetries

$$A_{\theta_l} = \frac{\sigma(\theta_l < \pi/4) - \sigma(\theta_l > \pi/4)}{\sigma(\theta_l < \pi/4) + \sigma(\theta_l > \pi/4)} \qquad A_{\phi_l} = \frac{\sigma(\cos\phi_l > 0) - \sigma(\cos\phi_l < 0)}{\sigma(\cos\phi_l > 0) + \sigma(\cos\phi_l < 0)}$$

Polarization asymmetries





- Both the distributions are peaked stronger for +vely polarized tops
- The peaking at 0 and 2*pi for phi distribution is a also an effect of the kinematics and is present even for unpolarized tops

Conclusions

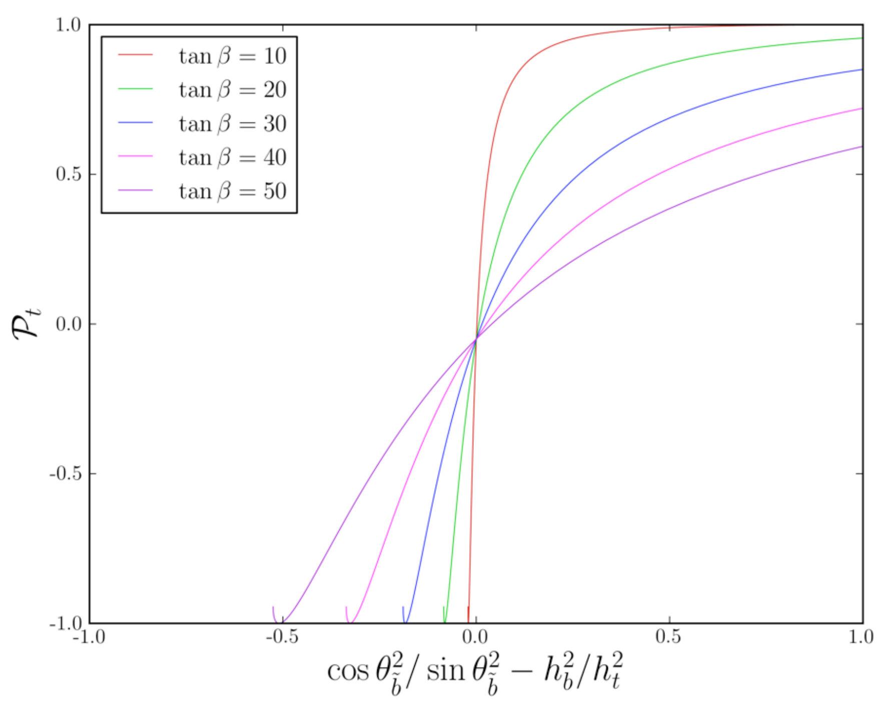
- A non-zero or +ve value of top polarization at the LHC will certainly point towards existence of BSM physics
- In case of sbottom decaying into charginos, the polarization is always -1 for winolike chargino, for higgsinolike charginos, it varies between +1 to -1
- When considering the case of left handed sbotttoms decaying into higgsinolike chargino, polarized tops coming from stop decays must be taken into account
- Kinematic distributions of top decay products can be used to improve third generation searches at the LHC
- Asymmetries in the angular distributions can be used to measure the polarization
- Top polarization can be used as a possible way to hunt for otherwise difficult natural SUSY scenarios

Back-ups

Effect of Yukawa coupling

- The Yukawa couplings in SUSY are a function of tan beta
- For small tan beta the bottom Yukawa coupling is negligible, for large tan beta the top and bottom Yukawa couplings start to play an important role
- The sign of the polarization depends on the relative sign between the terms in the numerator

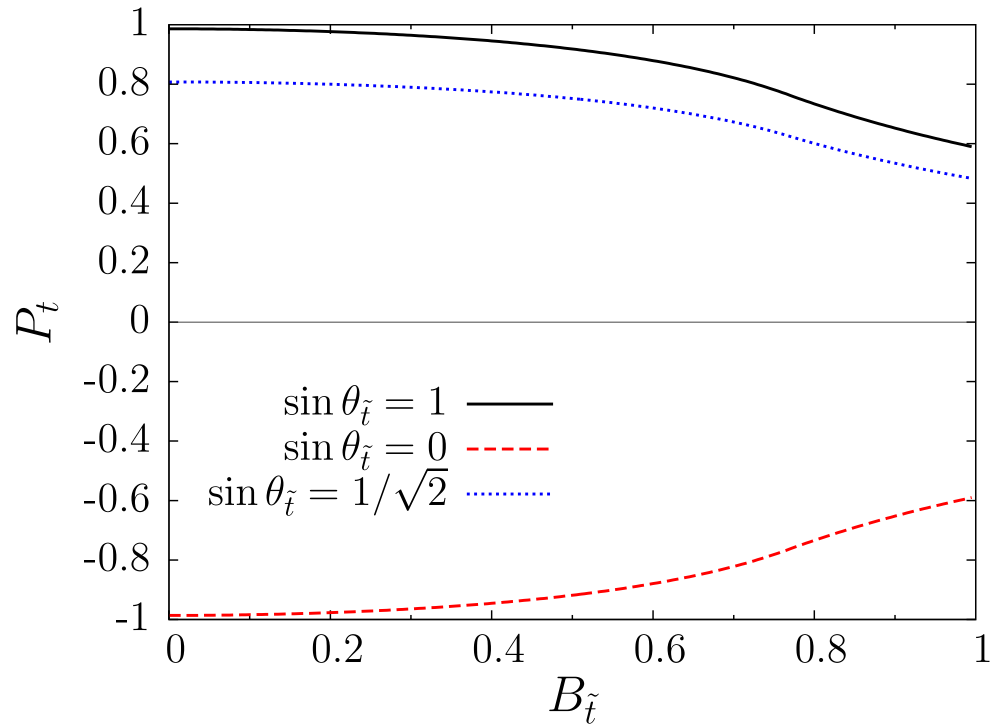
$$\mathcal{P}_t = \frac{\left(\frac{\cos^2\theta_{\tilde{b}}}{\sin^2\theta_{\tilde{b}}} - \frac{h_b^2}{h_t^2}\right) f_1}{\left(\frac{\cos^2\theta_{\tilde{b}}}{\sin^2\theta_{\tilde{b}}} + \frac{h_b^2}{h_t^2}\right) - 2\,\frac{\cos\theta_{\tilde{b}}}{\sin\theta_{\tilde{b}}}\,\frac{h_b}{h_t}\,f_2}$$



Boost treatment

- Polarization is not a Lorentz invariant quantity
- The dependence comes as the spin is not Lorentz vector
- Need to take into account the sbottom boost when going from the sbottom rest frame to the lab frame

$$\mathcal{P}_t = \frac{(k_{ij}^2 - l_{ij}^2)\int m_t\,(p_{\tilde{\chi}_1^-}\cdot s_t^3)d\cos\vartheta}{(k_{ij}^2 + l_{ij}^2)\int(p_t\cdot p_{\tilde{\chi}_1^-})d\cos\vartheta - 2k_{ij}\,l_{ij}\int m_t\,m_{\tilde{\chi}_1^-}\,d\cos\vartheta}$$



Angular distributions

A closer look

- Lab frame polar angle is just a boosted version of the one appearing in the angular distribution
- It is generally smaller than it’s counterpart in the rest frame, hence the distribution is more strongly peaked towards zero
- For azimuthal angle, the symmetry in the distribution comes from the symmetry in the beam axis
- The peaking at 0 and 2*pi can be caused by non-zero Pt of top and further enhanced by the polarization for +vely polarized tops
- For -vely polarized tops, the peaking is reduced, sometimes it can overcome the kinematic effects and the peaks might shift away from 0 and 2*pi

Calculating net polarization

Other scenarios

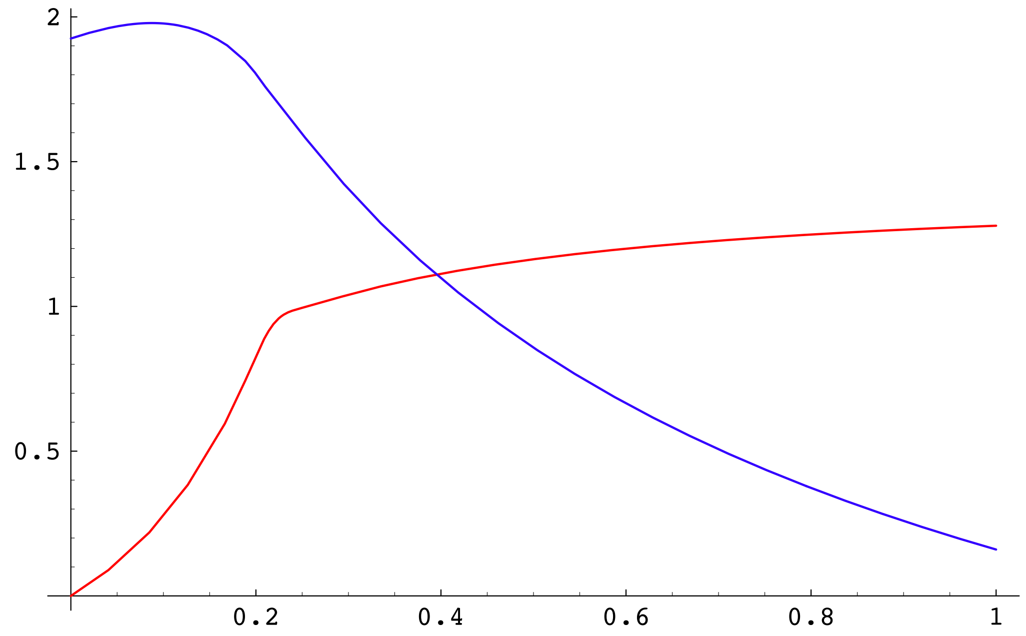
- For a right handed sbottom, the stop mass needs to be deliberately adjusted
- For a winolike chargino, the signature at the LHC could long lived charged particle
- When neutralino LSP is binolike, it need not be mass degenerate with chargino

Energy ratio observables

Looking in details

- Shoulder in the u distribution comes from the finiteness of masses in final state

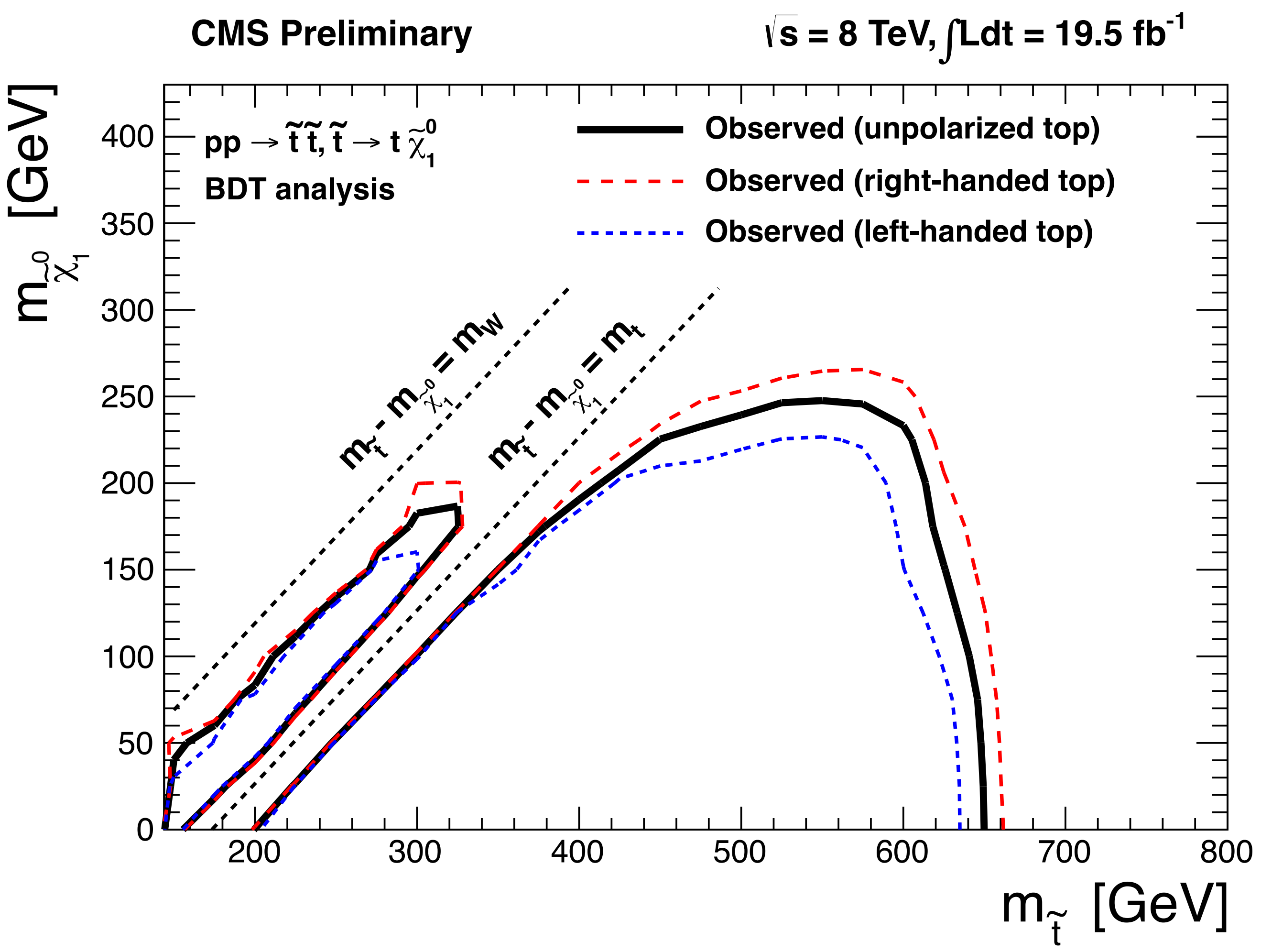
$$u = \frac{2m_t E_{l,min}}{2m_t E_{l,min} + (m_t^2 - m_W^2)} = \frac{m_W^2}{m_t^2} \approx 0.215$$



Including polarization

Experimental efforts

- Recent CMS study SUS-13-011 takes into account the top polarization
- Results vary by about 10-20 GeV



Benchmark points

Details - soft parameters, Mass spectrum

	bm-1	bm-2	bm-3
$M_{\tilde{Q}_3}$	1300	582	850
$M_{\tilde{D}_3}$	572	1500	601.5
$M_{\tilde{U}_3}$	1300	2200	1500
M_1	500	200	500
M_2	1000	400	1000
μ	350	150	350
$m_{\tilde{b}_1}$	650.44	650.08	650.17
$m_{\tilde{b}_2}$	1329.77	1538.10	884.47
$\cos\theta_{\tilde{b}}$	0.006	0.999	0.02
$m_{\tilde{t}_1}$	1236.20	633.84	818.99
$m_{\tilde{t}_2}$	1560.58	2212.19	1518.19
$\cos\theta_{\tilde{t}}$	0.85	0.996	0.96
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$m_{\tilde{\chi}_1^0}$	343.39	126.52	343.13
$m_{\tilde{\chi}_2^0}$	358.22	159.18	357.22
$m_{\tilde{\chi}_3^0}$	500.89	213.20	502.61
$m_{\tilde{\chi}_4^0}$	1021.33	431.95	1016.63
$\mathrm{BR}_{B\to X_s\gamma}$	3.61	3.26	3.78
$\mathrm{BR}_{B_s\to\mu^+\mu^-}$	3.04	3.04	3.03

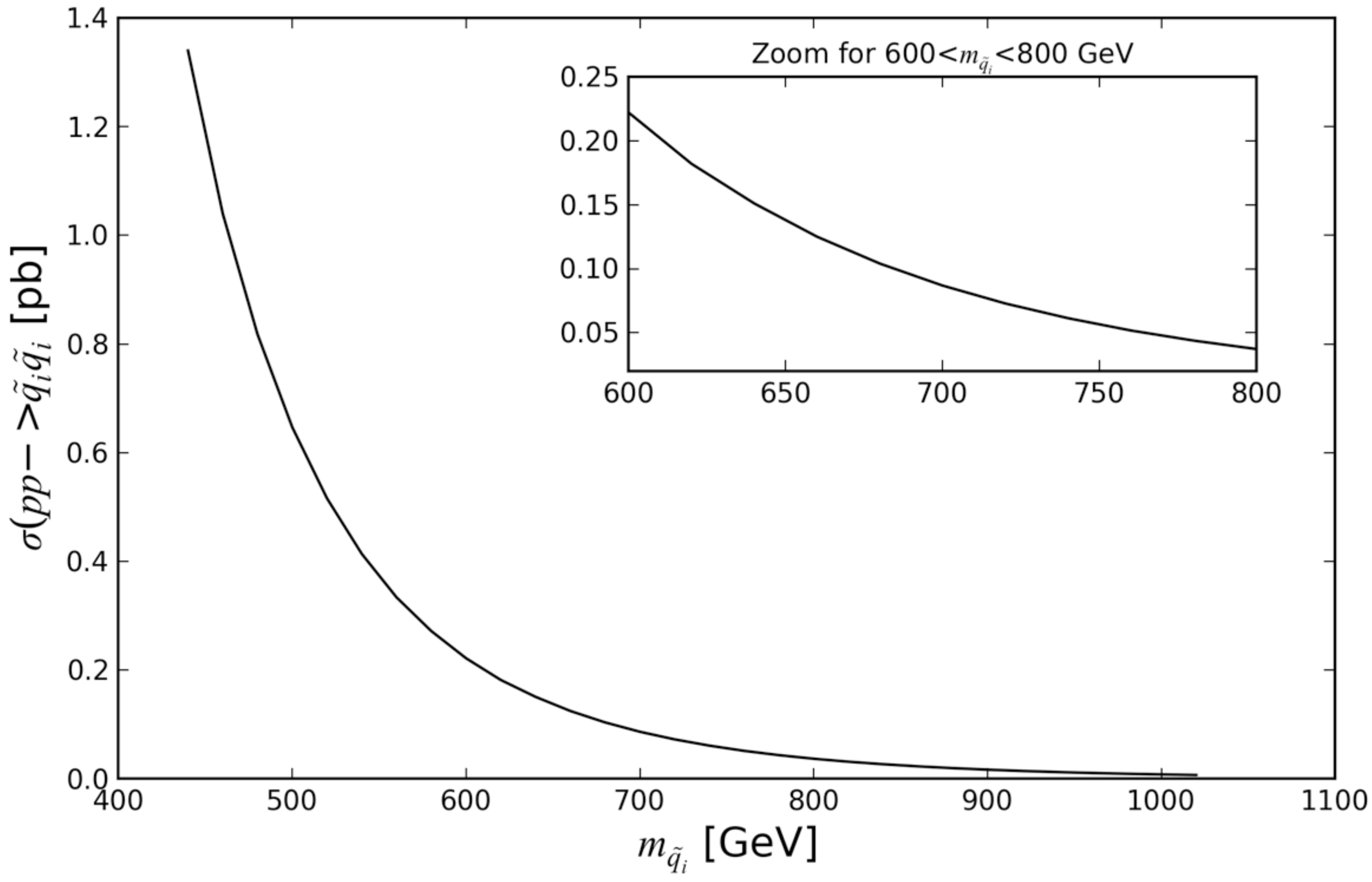
Benchmark points

Details - branching ratios, production cross-section, polarization

	`bm-1`	`bm-2`	`bm-3`
$\sigma(pp \to \tilde{b}_1 \tilde{b}_1^*)$ [pb]	0.137	0.137	0.137
$\sigma(pp \to \tilde{b}_2 \tilde{b}_2^*)$ [pb]	0.001	$< 10^{-3}$	0.019
$\sigma(pp \to \tilde{t}_1 \tilde{t}_1^*)$ [pb]	0.002	0.157	0.033
$\mathrm{BR}(\tilde{b}_1 \to t\,\tilde{\chi}_1^-)$	0.34	0.72	0.32
$\mathrm{BR}(\tilde{b}_1 \to t\,\tilde{\chi}_2^-)$	–	0.16	–
$\mathrm{BR}(\tilde{b}_2 \to t\,\tilde{\chi}_1^-)$	0.82	0.29	0.96
$\mathrm{BR}(\tilde{b}_2 \to t\,\tilde{\chi}_2^-)$	0.09	0.01	–
$\mathrm{BR}(\tilde{t}_1 \to t\,\tilde{\chi}_1^0)$	0.33	0.27	0.47
$\mathrm{BR}(\tilde{t}_1 \to t\,\tilde{\chi}_2^0)$	0.35	0.40	0.42
$\mathcal{P}_t\,(\tilde{b}_1 \to t\,\tilde{\chi}_1^-)$	-0.92	0.99	-0.98
$\mathcal{P}_t\,(\tilde{b}_1 \to t\,\tilde{\chi}_2^-)$	–	-0.29	–
$\mathcal{P}_t\,(\tilde{b}_2 \to t\,\tilde{\chi}_1^-)$	0.99	-0.99	0.99
$\mathcal{P}_t\,(\tilde{b}_2 \to t\,\tilde{\chi}_2^-)$	-0.67	-0.99	–
$\mathcal{P}_t\,(\tilde{t}_1 \to t\,\tilde{\chi}_1^0)$	0.40	0.99	0.94
$\mathcal{P}_t\,(\tilde{t}_1 \to t\,\tilde{\chi}_2^0)$	0.50	0.99	0.99
$\widehat{\mathcal{P}}_t$ (total)	-0.73	0.92	0.07
A_{θ_l}	0.14	0.80	0.47
A_{ϕ_l}	0.57	0.92	0.76

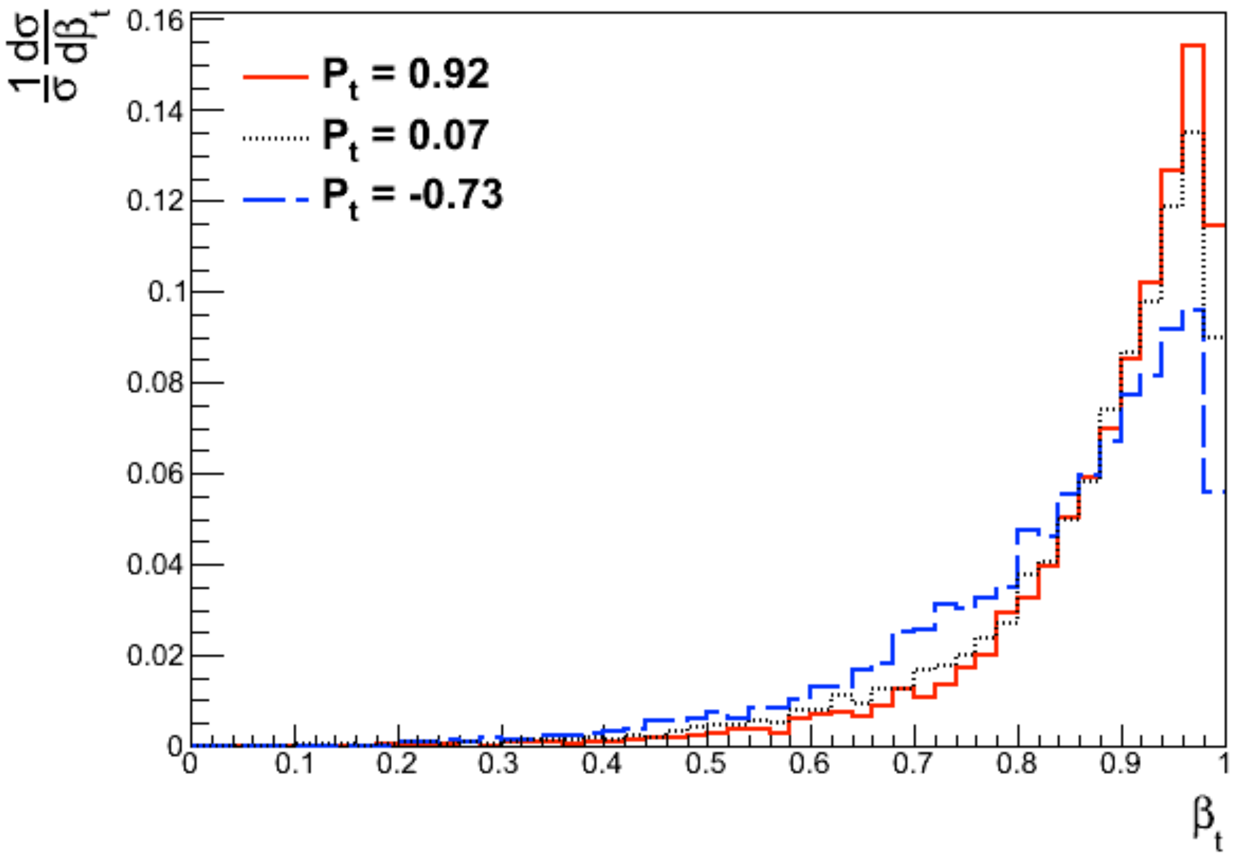
Benchmark points

Stop and sbottom production cross-sections at LHC14



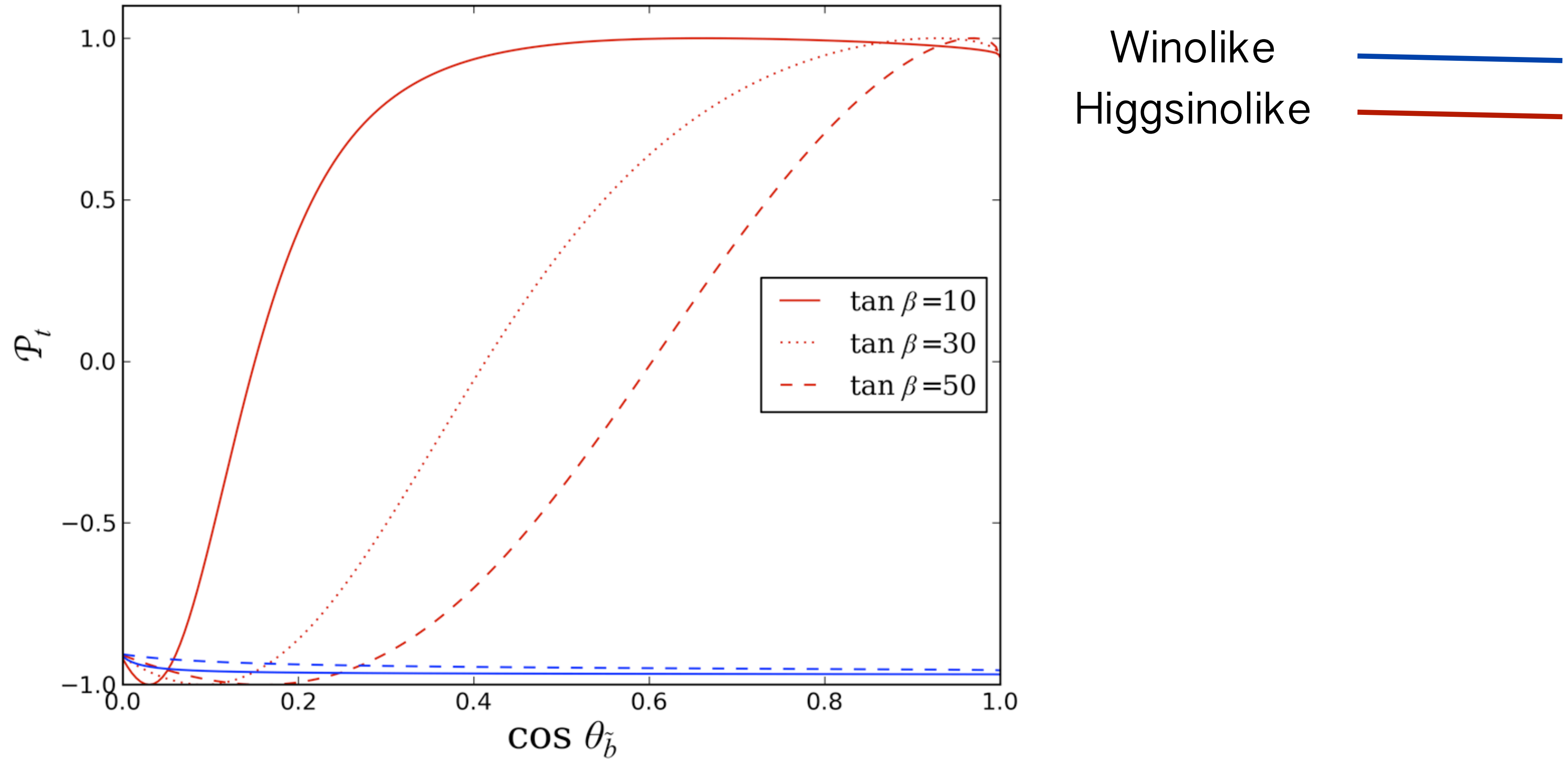
Benchmark points

Top boost distribution at LHC14



Dependence on parameters

Mixing angle in sbottom sector



- For winolike chargino, the polarization is always -1
- For higgsinolike chargino, the polarization varies between -1 to +1 and has a dependence on tan beta