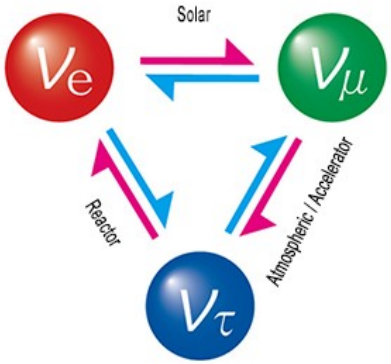
Shining the torch on stops and sbottoms

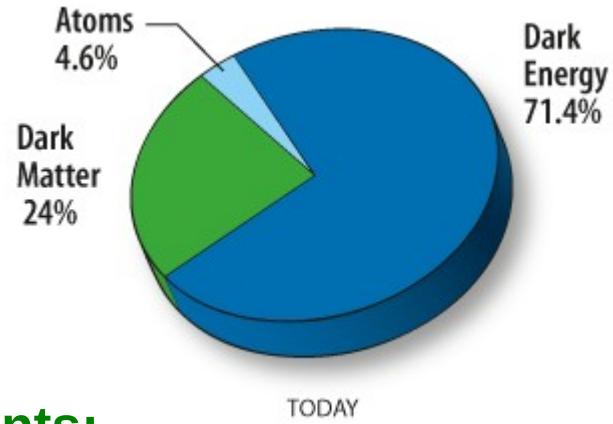
Fermilab Theory Seminar

Diptimoy Ghosh
INFN, Rome

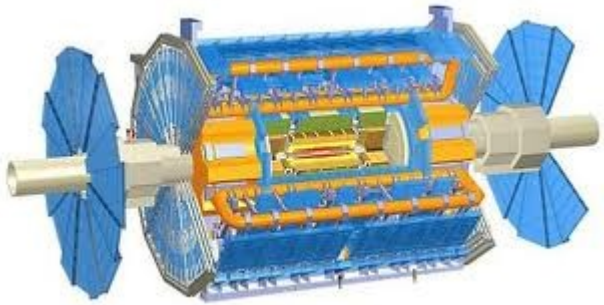
Why do we need to go beyond the Standard Model :



- **Neutrino mass : Weinberg's dim-5 operator**
- **Cosmic baryon-antibaryon asymmetry**
- **Dark Matter**
- **Dark Energy**
- **.....**
- **.....**



- **Some observations in particle physics experiments:**



(g-2) of muon, $\Delta A_{CP}(\pi\pi, KK)$, like-sign dimuon Asymmetry, top quark FB asymmetry, ...

Unfortunately, only the last one in this list requires new physics at TeV energies

“Hierarchy” or “Naturalness” problem

- ‘t Hooft: parameter is naturally small if, when it is zero, a new symmetry emerges
  - electron mass = 0: chiral symmetry
  - gauge coupling = 0: gauge fields are free particles, separately conserved
  - but scalar mass = 0, no extra symmetry

- Such symmetries protect the parameters
  - corrections to the electron mass are multiplicative
- But the Higgs mass is unprotected, so corrections can be very large
  - top is the worst bully here

“Hierarchy” or “Naturalness” problem

Three solutions known

1. Shift symmetry:

The entire Higgs multiplet are Goldstone bosons of a global Symmetry Broken spontaneously at high energy.

2. Rotation into a gauge boson:

The Higgs fields are the 5th component of gauge fields in a model with extra space dimensions.

3. Rotation into a fermion:

Supersymmetry.

Higgs sector in the MSSM

Need (at least) two $SU(2)_L$ higgs doublets :

- Cancel the $\mathbf{U(1)_Y^3}$ and $\mathbf{U(1)_Y \times SU(2)_L^2}$ gauge anomalies due to new contribution from the higgsinos.
- Need an even number of (weyl) fermion doublets to avoid the Witten anomaly for $SU(2)_L$
- Yukawa couplings for both the up and down type fermions in a SUSY(holomorphy of the Superpotential) invariant way

$$\mathrm{H}_1 = \begin{pmatrix} \mathrm{H}_1^0 \\ \mathrm{H}_1^- \end{pmatrix} \quad \text{and} \quad \mathrm{H}_2 = \begin{pmatrix} \mathrm{H}_2^+ \\ \mathrm{H}_2^0 \end{pmatrix}$$

Five physical higgs bosons after EWSB : $\mathrm{h},\ \mathrm{H},\ \mathrm{A},\ \mathrm{H}^{\pm}$

Only few free parameters at the tree level : $\mu, \mathrm{m_A}, \tan\beta$

$$M^2_{h,H} = \frac{1}{2}\left[M^2_A + M^2_Z \mp \sqrt{(M^2_A + M^2_Z)^2 - 4M^2_A M^2_Z \cos^2 2\beta}\right]$$

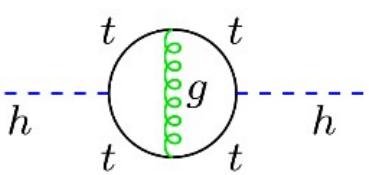
$$M^2_{H^\pm} = M^2_A + M^2_W$$

$$\tan 2\alpha = \tan 2\beta\,(M^2_A + M^2_Z)/(M^2_A - M^2_Z)$$

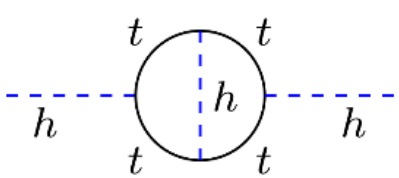
We have important constraint on the MSSM Higgs boson masses:

$$M_h \leq \min(M_A, M_Z)\cdot|\cos 2\beta| \leq M_Z,\ M_{H^\pm} > M_W, M_H > M_A \ldots$$

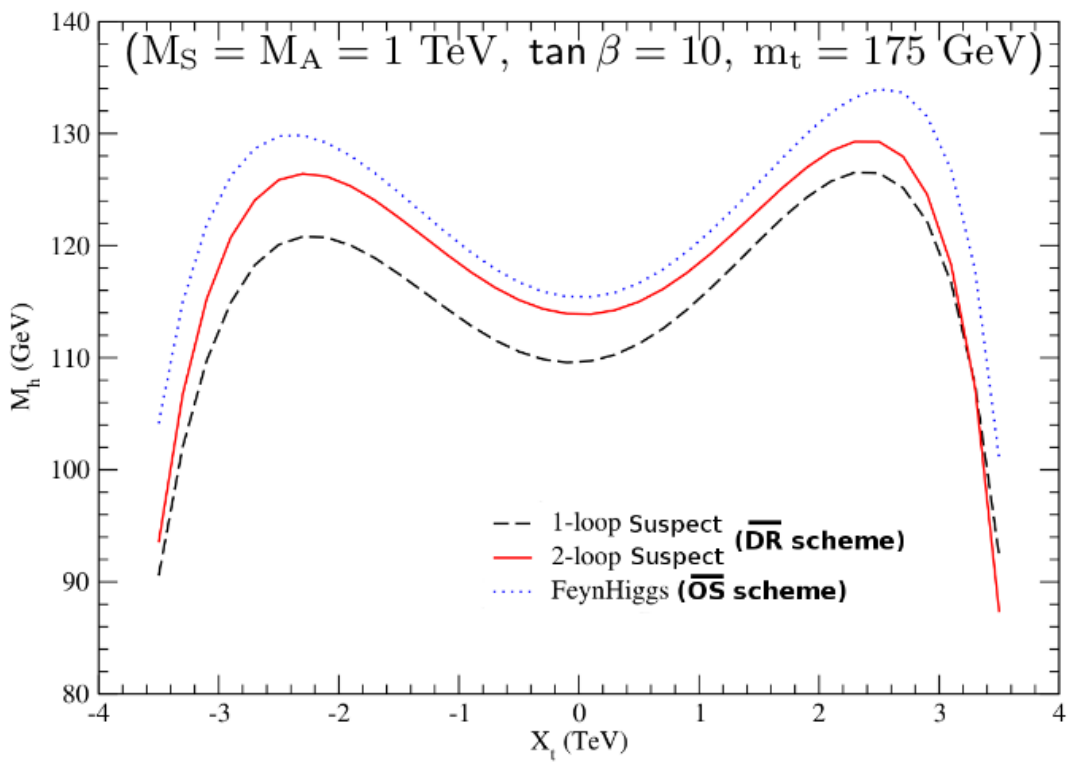
$$\Delta m_h^2 \approx \frac{3\,m_t^4}{2\,\pi^2\,v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right] + \ldots$$



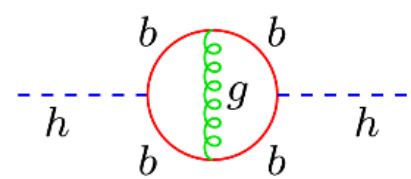
$\mathcal{O}(\alpha_t\alpha_s)$



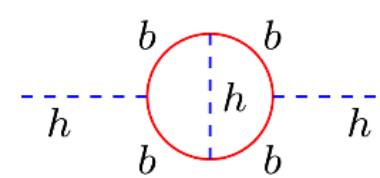
$\mathcal{O}(\alpha_t^2)$



$$X_t = A_t - \frac{\mu}{\tan\beta},\quad M_S^2 = M_{\tilde{t}_1}M_{\tilde{t}_2}$$



$\mathcal{O}(\alpha_b\alpha_s)$

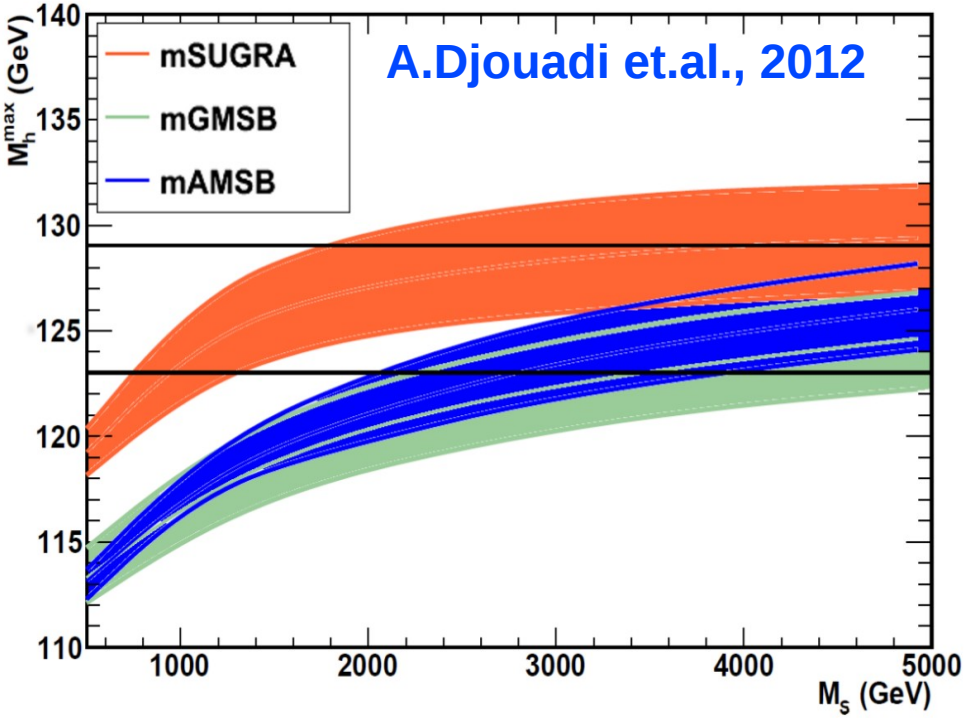


$\mathcal{O}(\alpha_b^2)$

mSUGRA:

1) Flavor protection is not automatic but imposed.

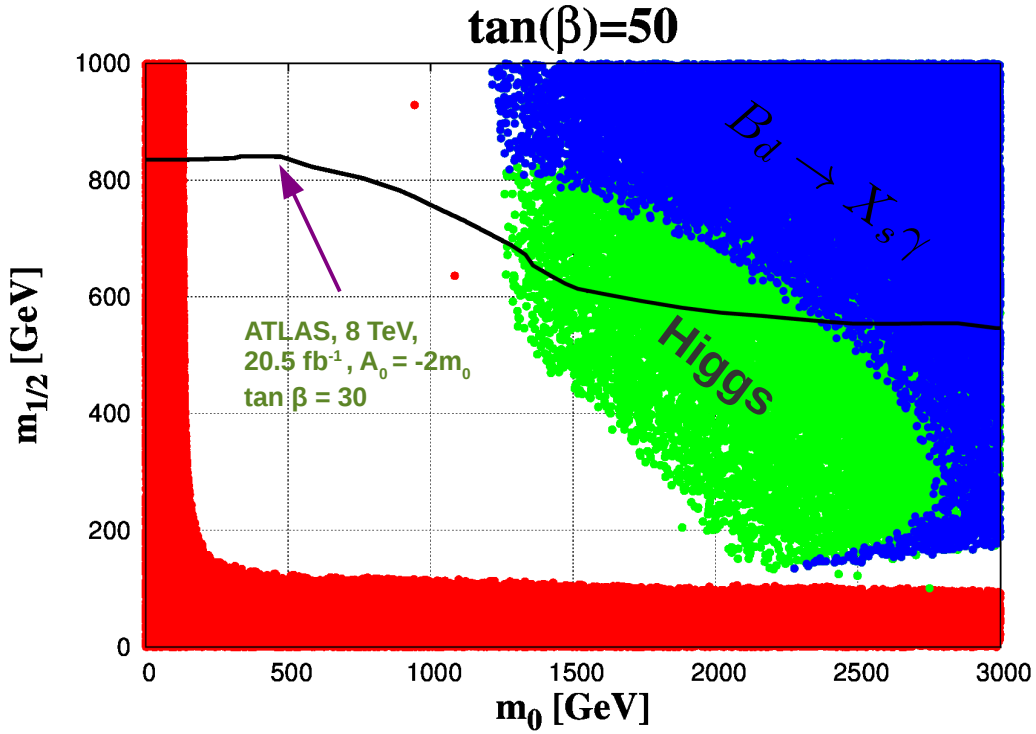
2) Phenomenologically interesting : Large A-terms are allowed

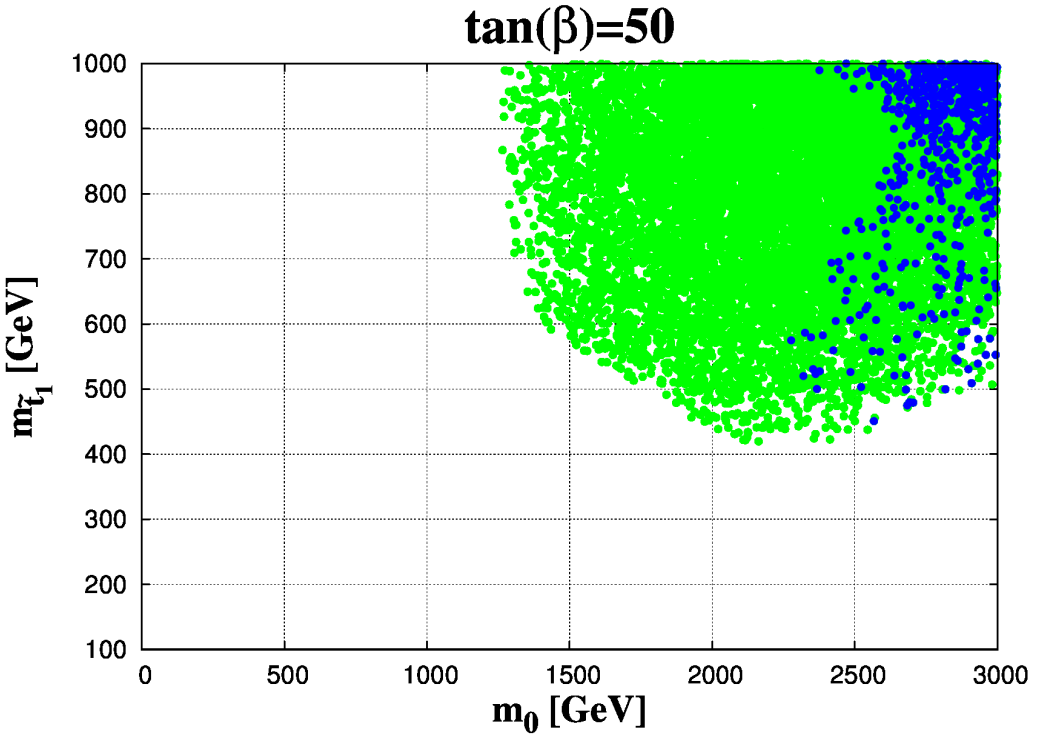


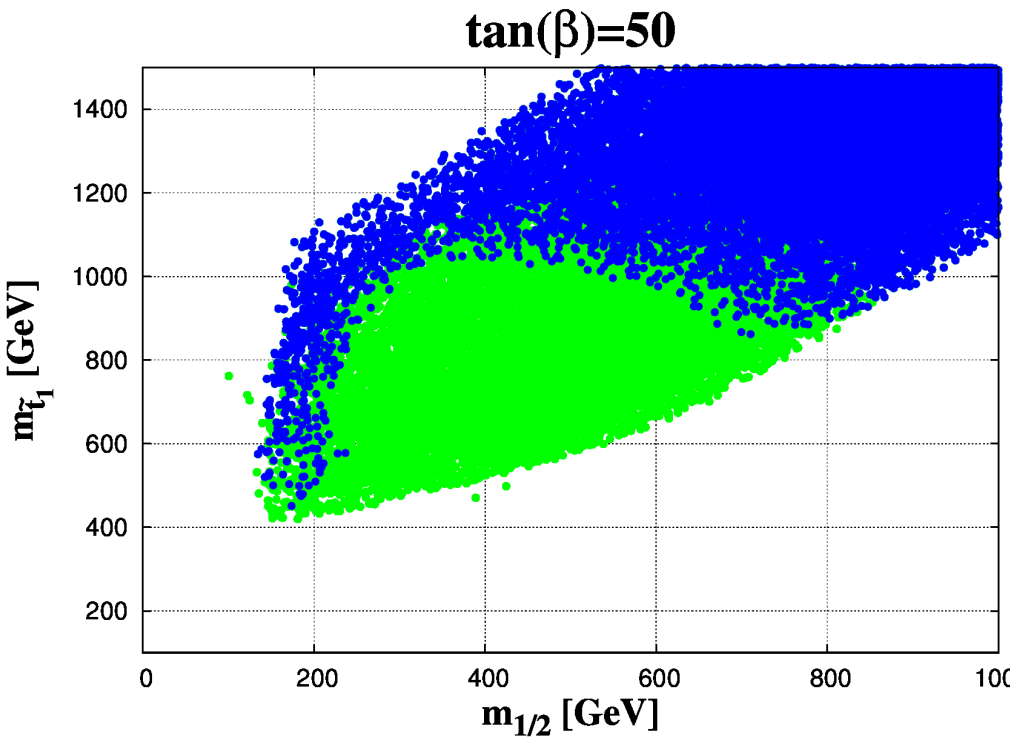
GMSB :

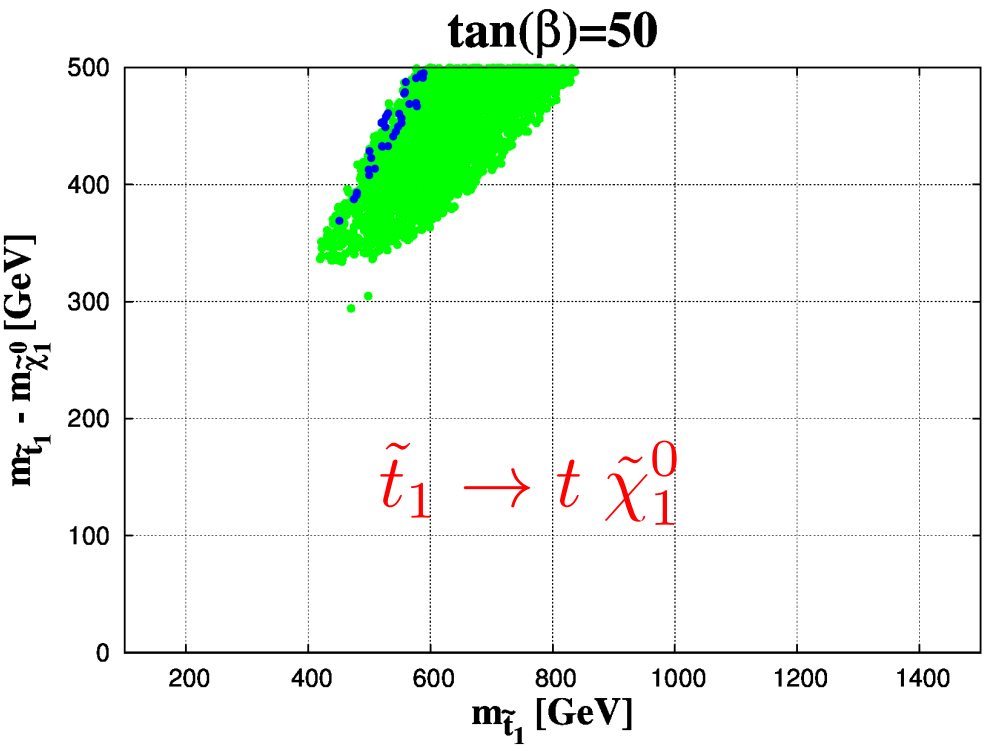
MSSM + mGMSB + 125 GeV higgs :

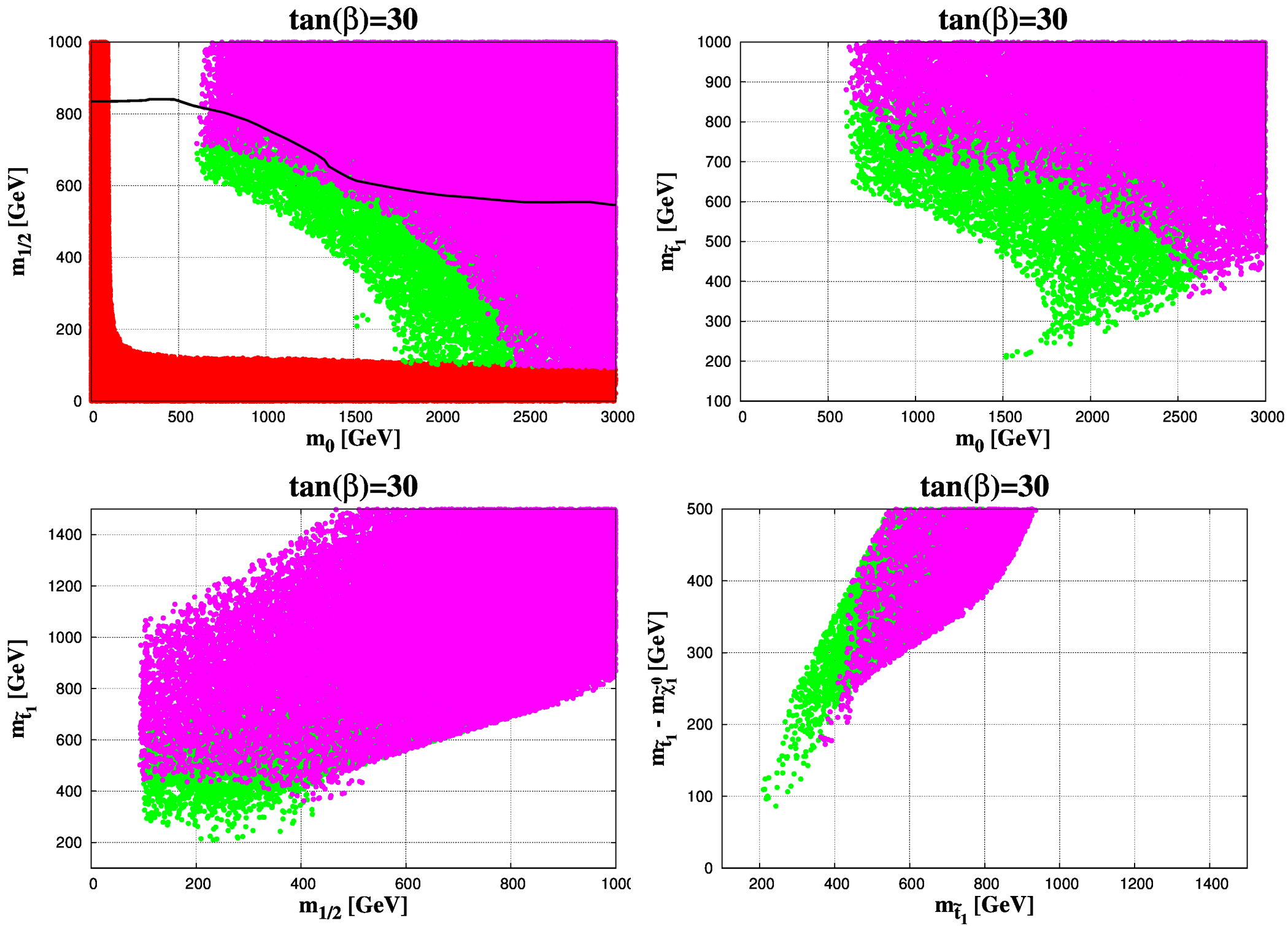
1) Modify GMSB to achieve large A-terms at the messenger scale
2) Modify the MSSM

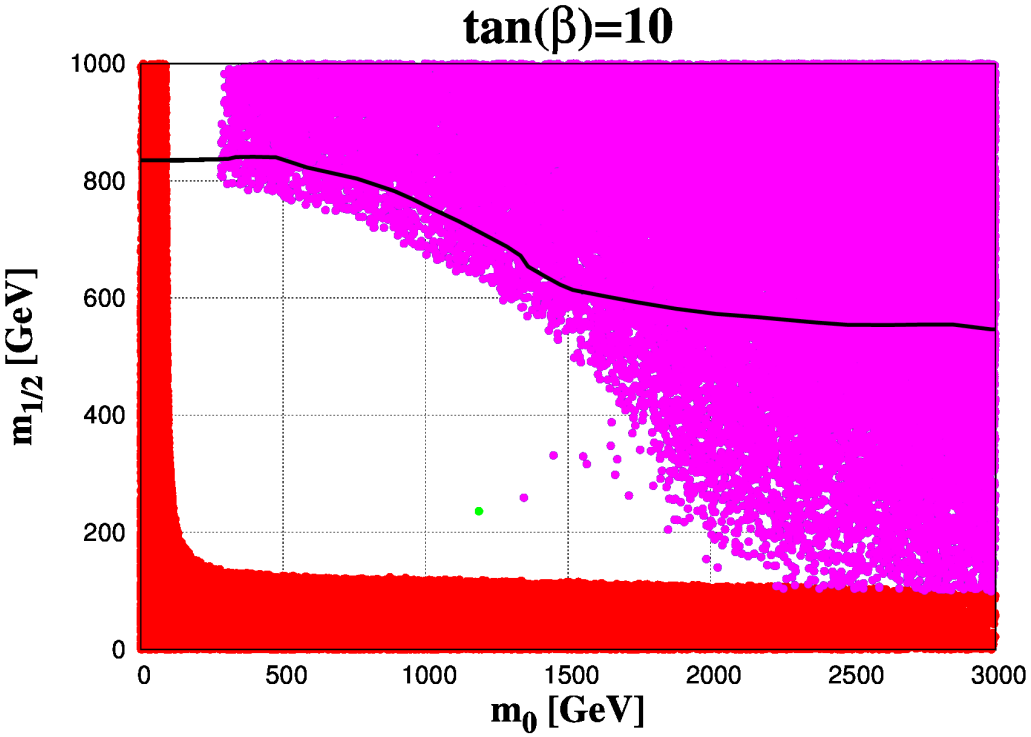

tan(β)=50
$B_d \to X_s \gamma$
Higgs
ATLAS, 8 TeV,
20.5 fb^{-1}, A_0 = -2m_0
tan β = 30
$m_{1/2}$ [GeV]
m_0 [GeV]

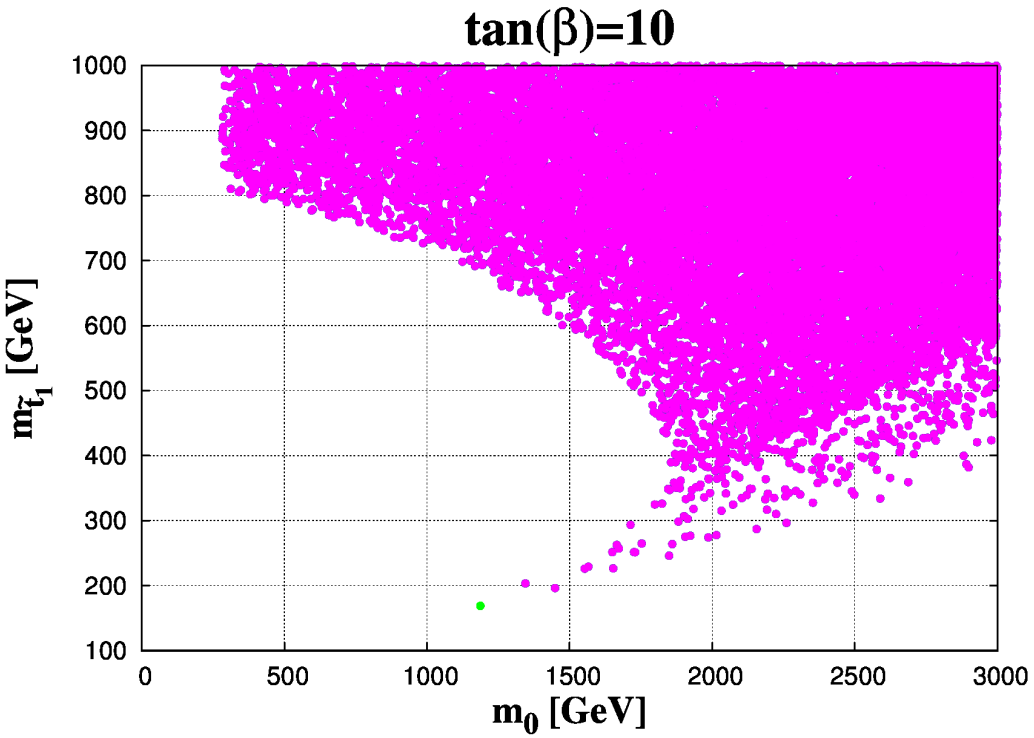

tan(β)=50
$m_{\tilde{t}_1}$ [GeV]
m_0 [GeV]

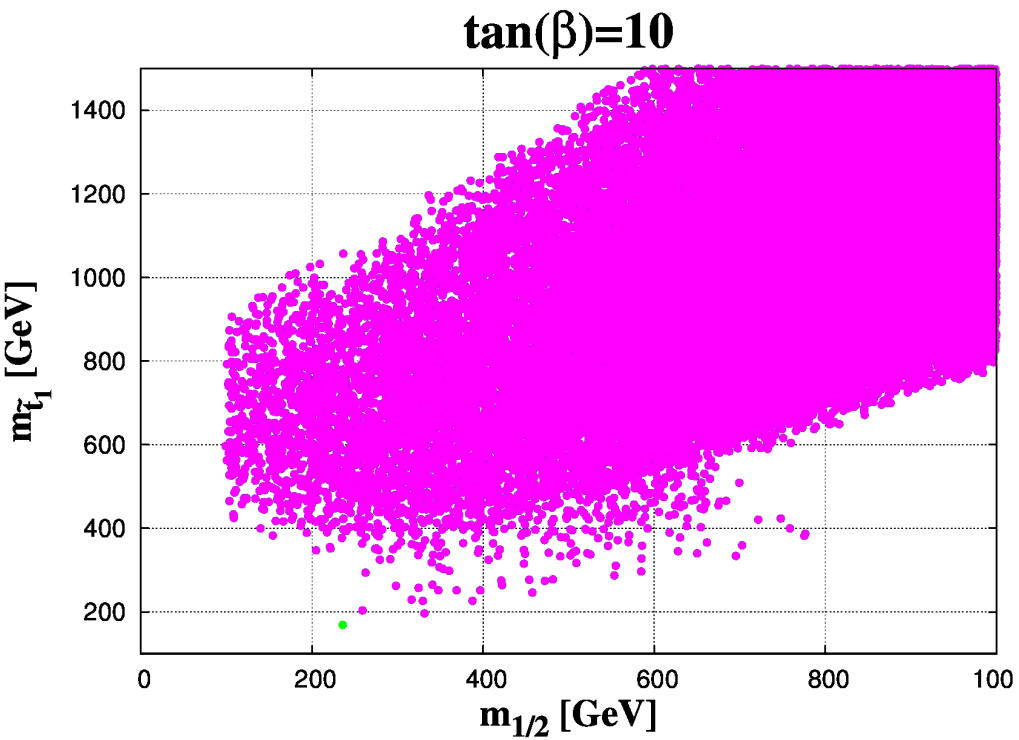

tan(β)=50
$m_{\tilde{t}_1}$ [GeV]
$m_{1/2}$ [GeV]

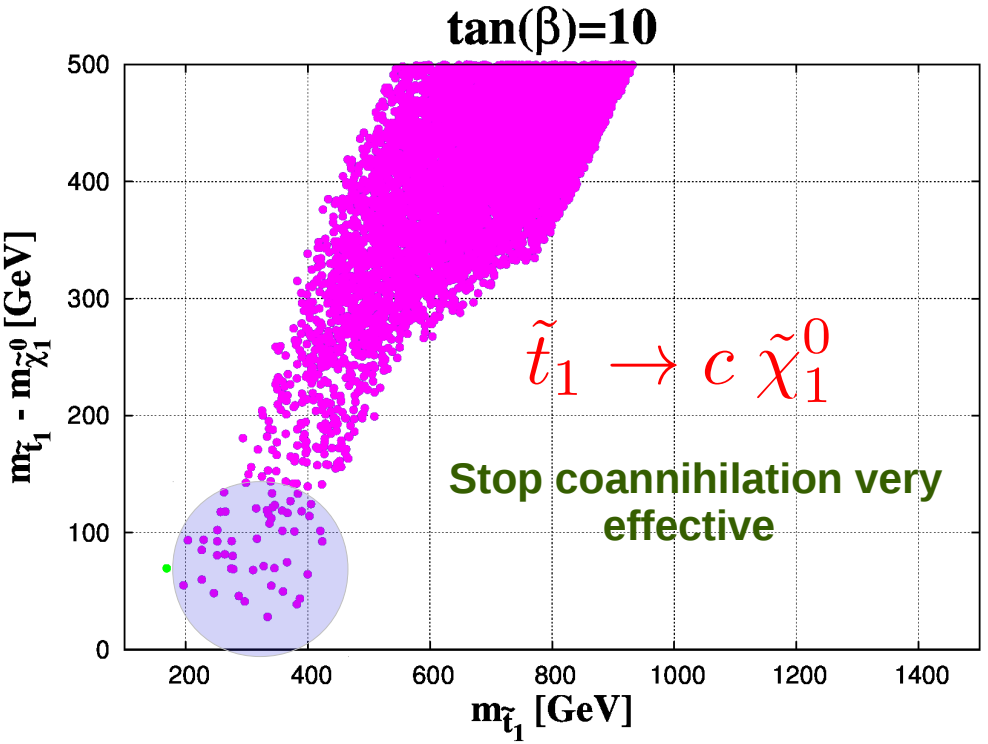

tan(β)=50
$\tilde{t}_1 \to t\ \tilde{\chi}_1^0$
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]


tan(β)=30
m1/2 [GeV]
m0 [GeV]
tan(β)=30
mt̃1 [GeV]
m0 [GeV]
tan(β)=30
mt̃1 [GeV]
m1/2 [GeV]
tan(β)=30
mt̃1 - mχ̃01 [GeV]
mt̃1 [GeV]

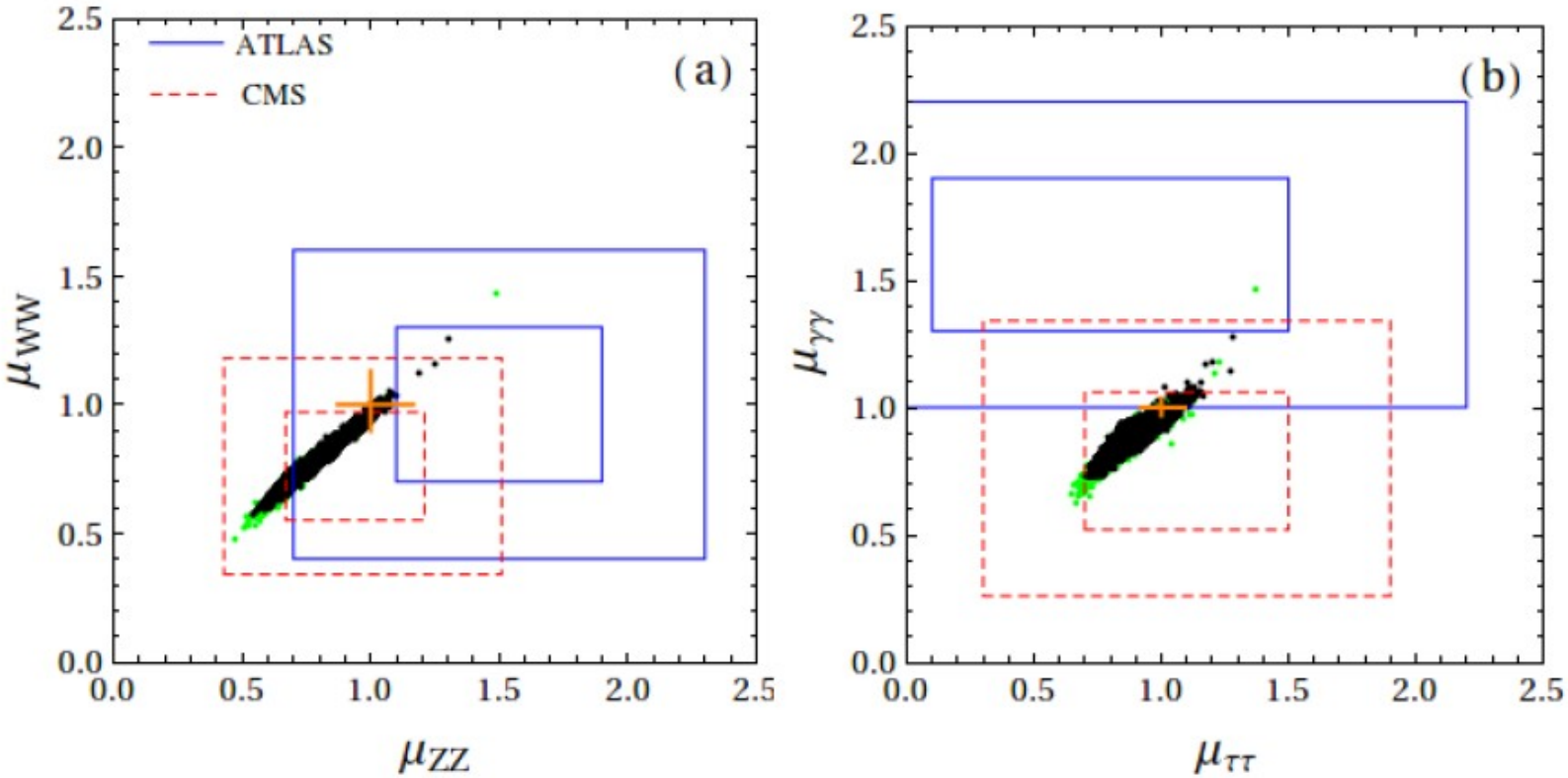

tan(β)=10
m1/2 [GeV]
m0 [GeV]


tan(β)=10
mt̃1 [GeV]
m0 [GeV]


tan(β)=10
mt̃1 [GeV]
m1/2 [GeV]


tan(β)=10
mt̃1 - mχ̃01 [GeV]
mt̃1 [GeV]
$\tilde{t}_1 \to c\ \tilde{\chi}_1^0$
Stop coannihilation very effective

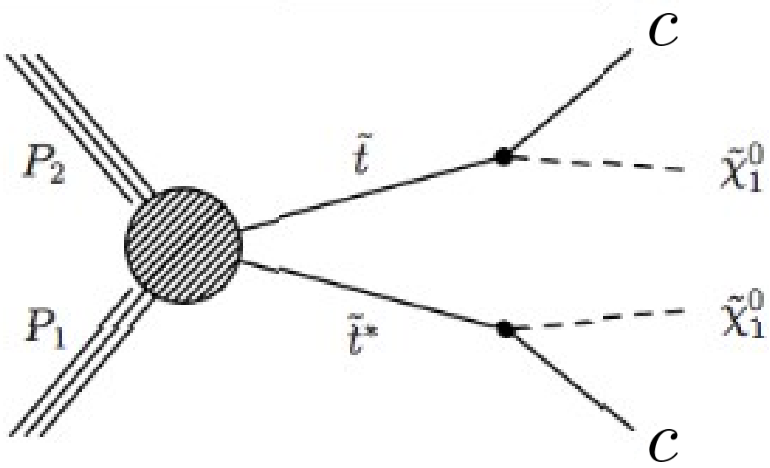
$$\mu_{X\bar{X}} \equiv \frac{N_{X\bar{X}}}{N_{X\bar{X}}^{\rm SM}} = \frac{\sigma(pp \to h^0)}{\sigma_{\rm SM}(pp \to h^0)} \times \frac{\mathcal{B}(h^0 \to X\bar{X})}{\mathcal{B}_{\rm SM}(h^0 \to X\bar{X})}$$

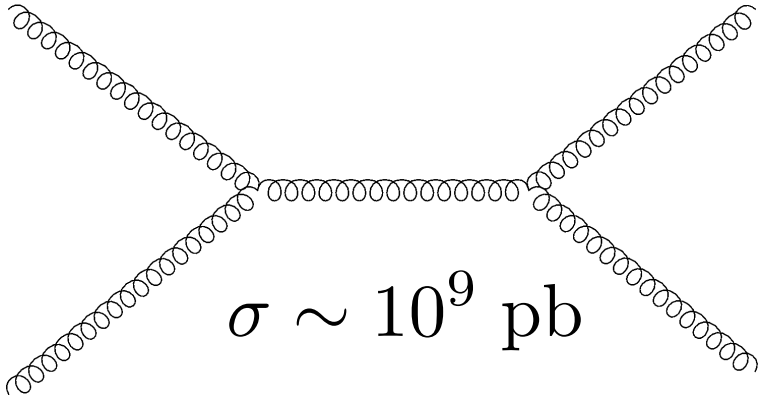


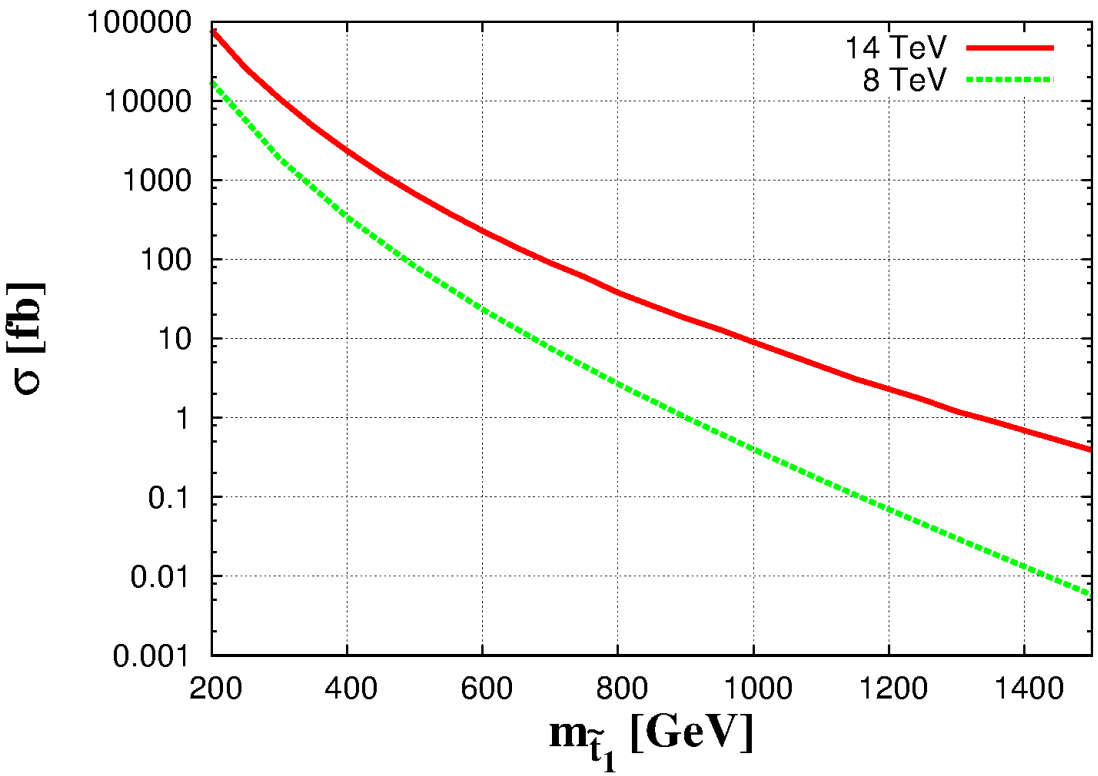
$\mathrm{B_d} \to X_s\gamma$
$\mathrm{B_s} \to \mu^+\mu^-$
$\mathrm{B_d} \to \mu^+\mu^-$
$\mathrm{B}^+ \to \tau^+\nu$
$\mathrm{K}^+ \to \mu^+\nu$

Present data does not resolve between SM and mSUGRA

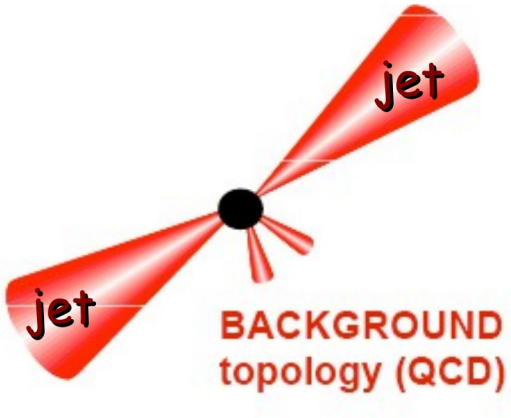
A Dighe, DG, K Patel, S Raychaudhuri, 1303.0721


P_2
P_1
$\tilde{t}$
$\tilde{t}^*$
c
c
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$


$\sigma \sim 10^9$ pb


14 TeV
8 TeV
σ [fb]
100000
10000
1000
100
10
1
0.1
0.01
0.001
200
400
600
800
1000
1200
1400
$m_{\tilde{t}_1}$ [GeV]

$$\alpha_T = \frac{p_T^{j2}}{\sqrt{H_T^2 - \not{H}_T^2}} \qquad H_T = \sum_j |\overrightarrow{p_T}| \qquad \not{H}_T = |\sum_j \overrightarrow{p_T}|$$



Jets are back-to-back in ϕ

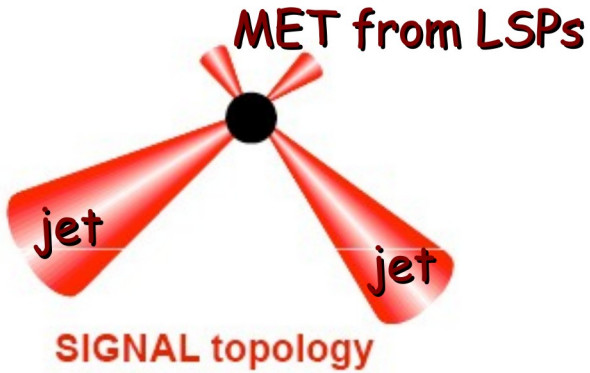
$$\alpha_T = 0.5$$

in the case of an imbalance in the measured p_Ts of back-to-back jets

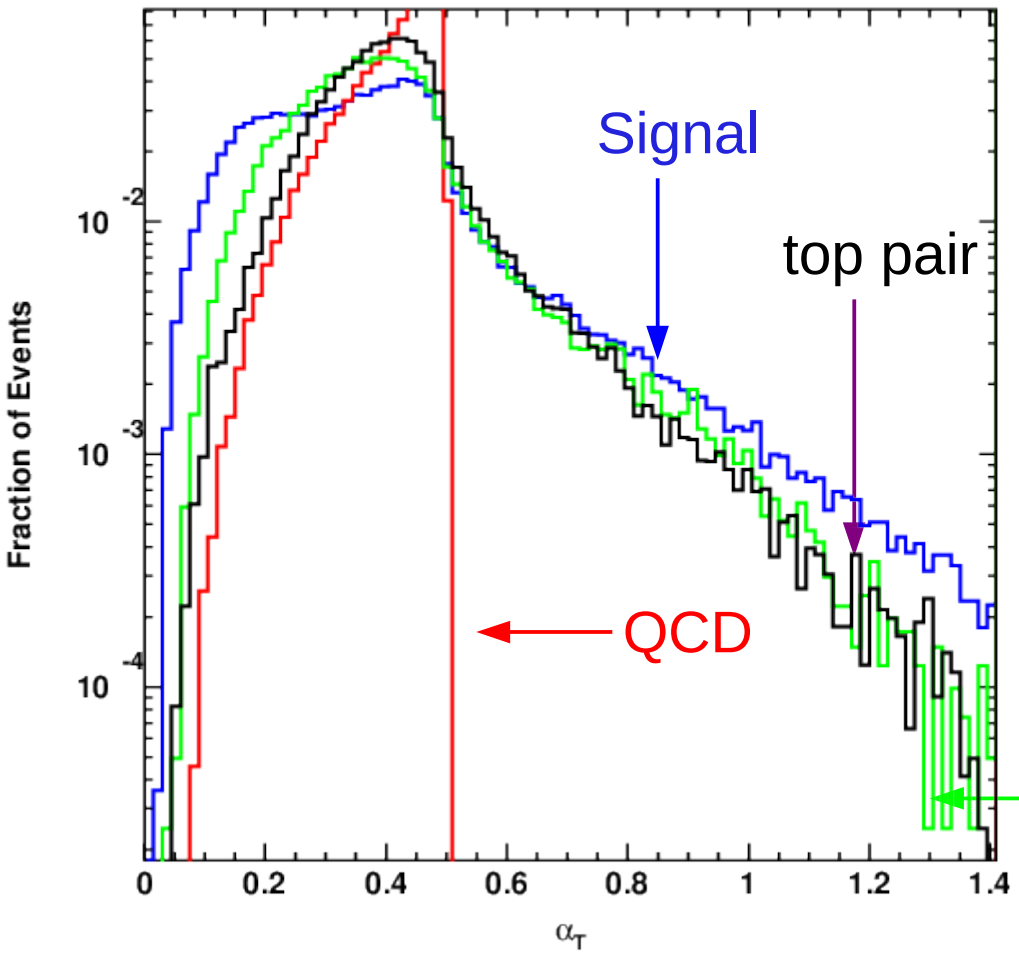
$$\alpha_T < 0.5$$

when the two jets are not back-to-back and balancing genuine MET

$$\alpha_T > 0.5$$



$$
\begin{aligned}
m_0 &= 2589 \\
m_{1/2} &= 695 \\
A_0 &= -5849 \\
\tan\beta &= 10 \\
m_{\tilde{t}_1} &= 331 \\
m_{\tilde{\chi}_1^0} &= 306 \\
\mathrm{BR}(\tilde{t}_1 \to c\,\tilde{\chi}_1^0) &= 97\%
\end{aligned}
$$



Z + 2 jets

$\alpha_T > 0.55$

~~QCD~~

G Belanger, DG, R Godbole, M Guchait, D Sengupta, in preparation

$A \rightarrow B\,\tilde{\chi}$

$$m_A^2 = m_B^2 + m_{\tilde{\chi}}^2 + 2(E_{TA}E_{T\tilde{\chi}}\cosh(\Delta\eta) - \mathbf{p}_{TB}.\mathbf{p}_{T\tilde{\chi}})$$

$$\eta = \tfrac{1}{2}\ln[(E+p_z)/(E-p_z)]$$

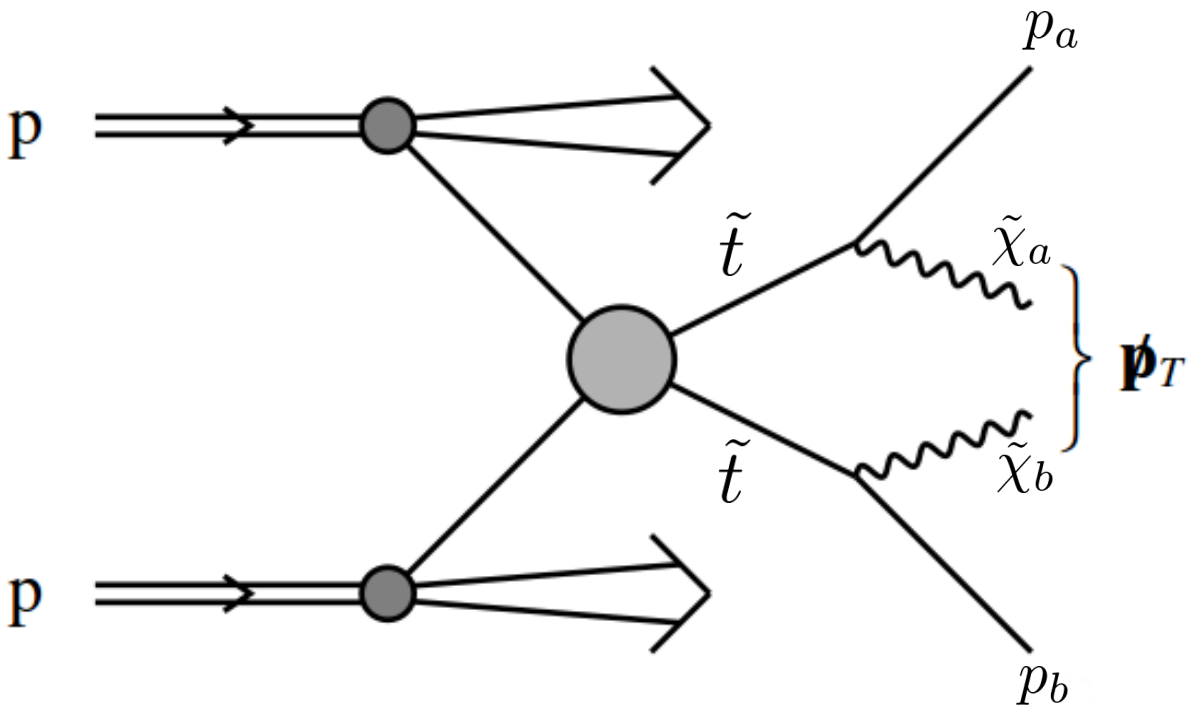
$$E_T = \sqrt{\mathbf{p}_T^2 + m^2}$$

$$m_A^2 \geq m_B^2 + m_{\tilde{\chi}}^2 + 2(E_{TA}E_{T\tilde{\chi}} - \mathbf{p}_{TB}.\mathbf{p}_{T\tilde{\chi}})$$

$$\cosh(\Delta\eta) \geq 1$$

$$m_T^2(\mathbf{p}_{TB}, \mathbf{p}_{T\tilde{\chi}})$$

C. G. Lester and D. J. Summers, 1999

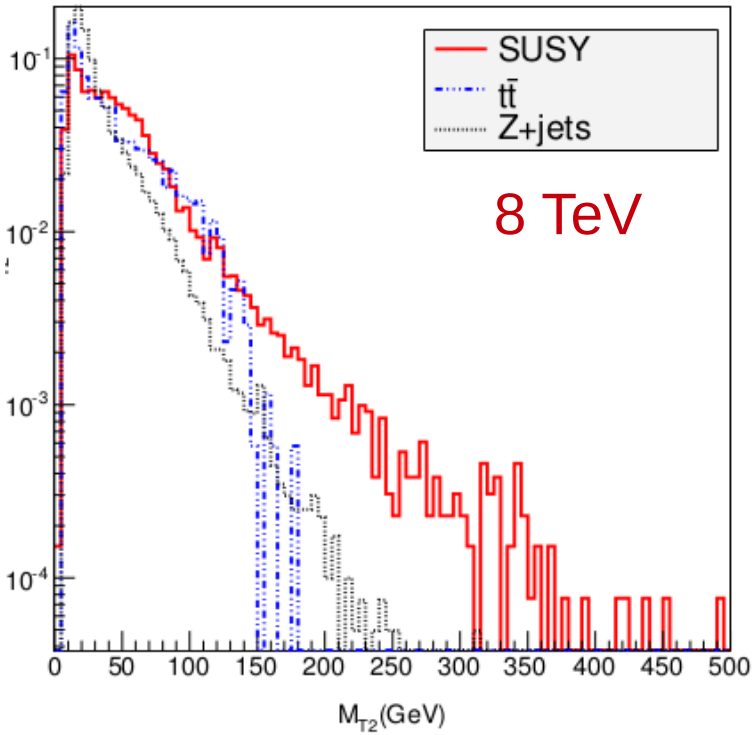


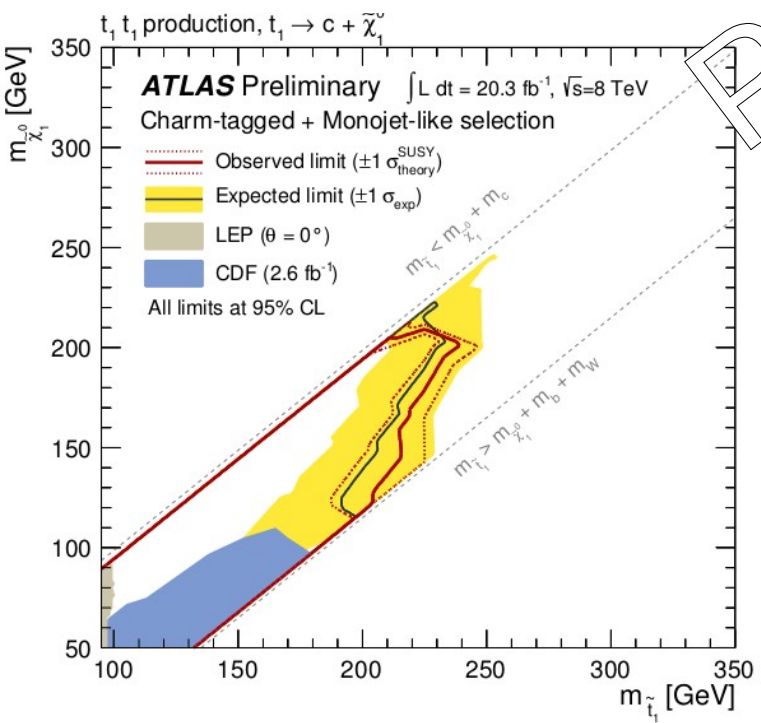
$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

$$m_{\tilde{t}}^2 \geq \qquad m_T^2(\mathbf{p}_{Ta}, \mathbf{p}_{T\tilde{\chi}_a})$$

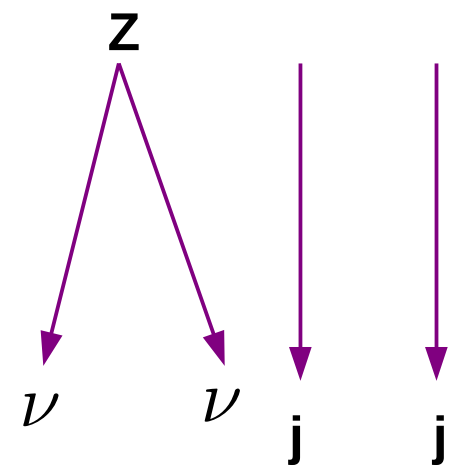
$$m_{\tilde{t}}^2 \geq \underbrace{\min_{\not{\mathbf{p}}_T = \not{\mathbf{p}}_{T1} + \not{\mathbf{p}}_{T2}} \left[\max\{ m_T^2(\mathbf{p}_{Ta}, \not{\mathbf{p}}_{T1}), m_T^2(\mathbf{p}_{Tb}, \not{\mathbf{p}}_{T2}) \} \right]}_{M_{T2}^2(\mathbf{p}_{Ta}, \mathbf{p}_{Tb}, \not{\mathbf{p}}_T)}$$

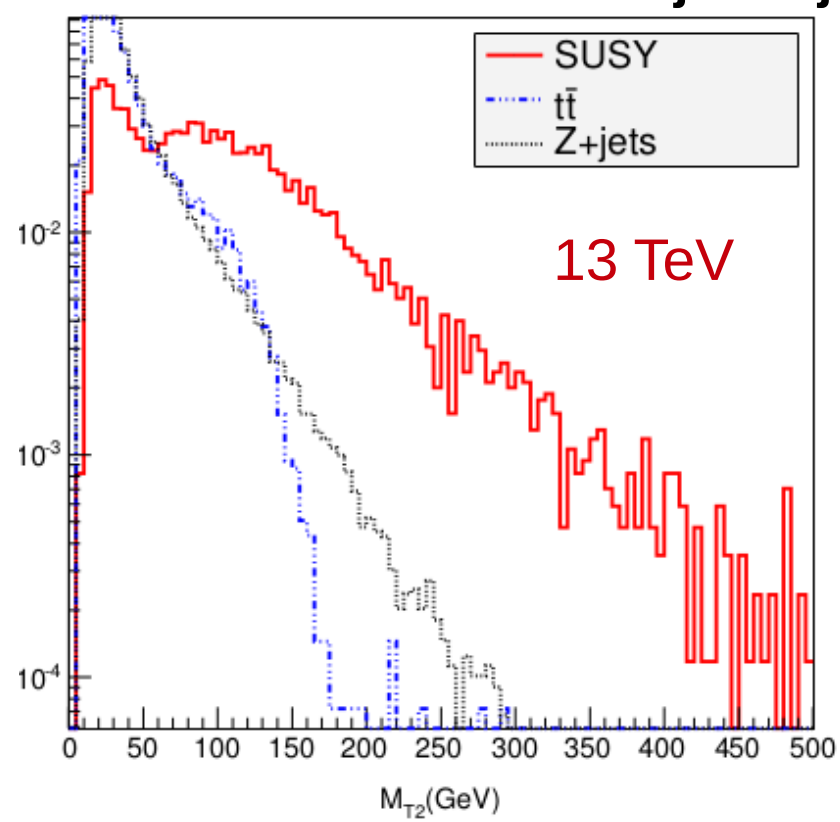
$$M_{T2}(\vec{p}_T^{\,j1}, \vec{p}_T^{\,j2}, \vec{\not{p}}_T) = \min_{\vec{\not{p}}_T = \vec{\not{p}}_T^{\,1} + \vec{\not{p}}_T^{\,2}} \left[\max\{ M_T(\vec{p}_T^{\,j1}, \vec{\not{p}}_T^{\,1}), M_T(\vec{p}_T^{\,j2}, \vec{\not{p}}_T^{\,2}) \} \right]$$



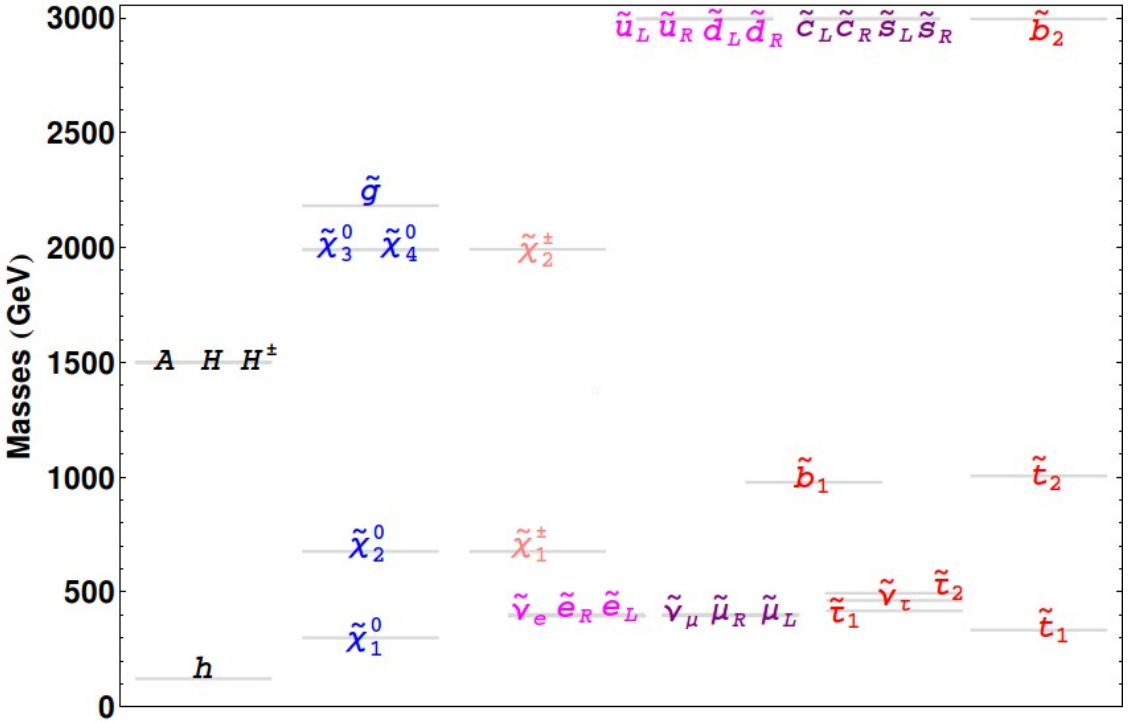


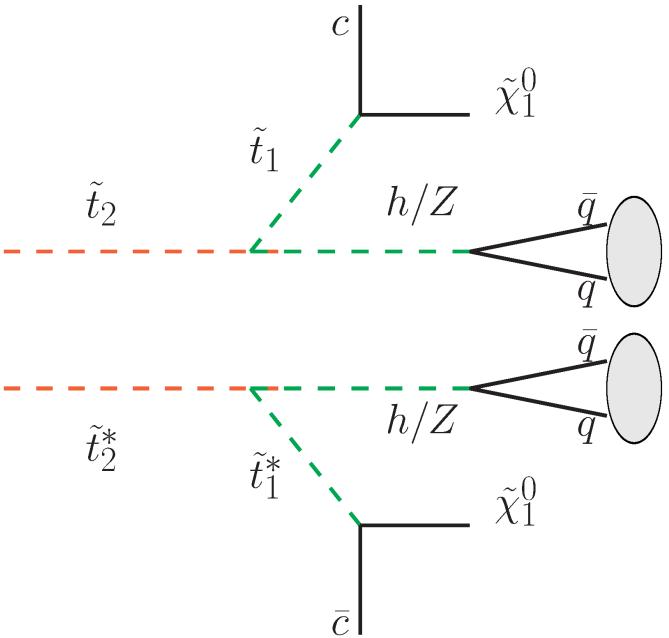
PRELIMINARY

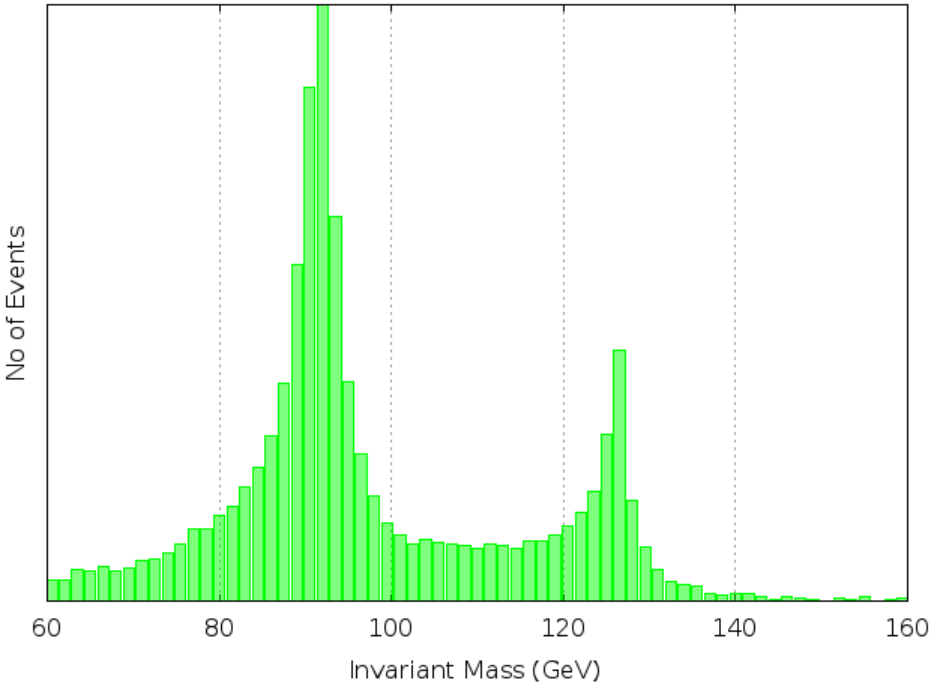




G Belanger, DG, R Godbole, M Guchait, D Sengupta, in preparation



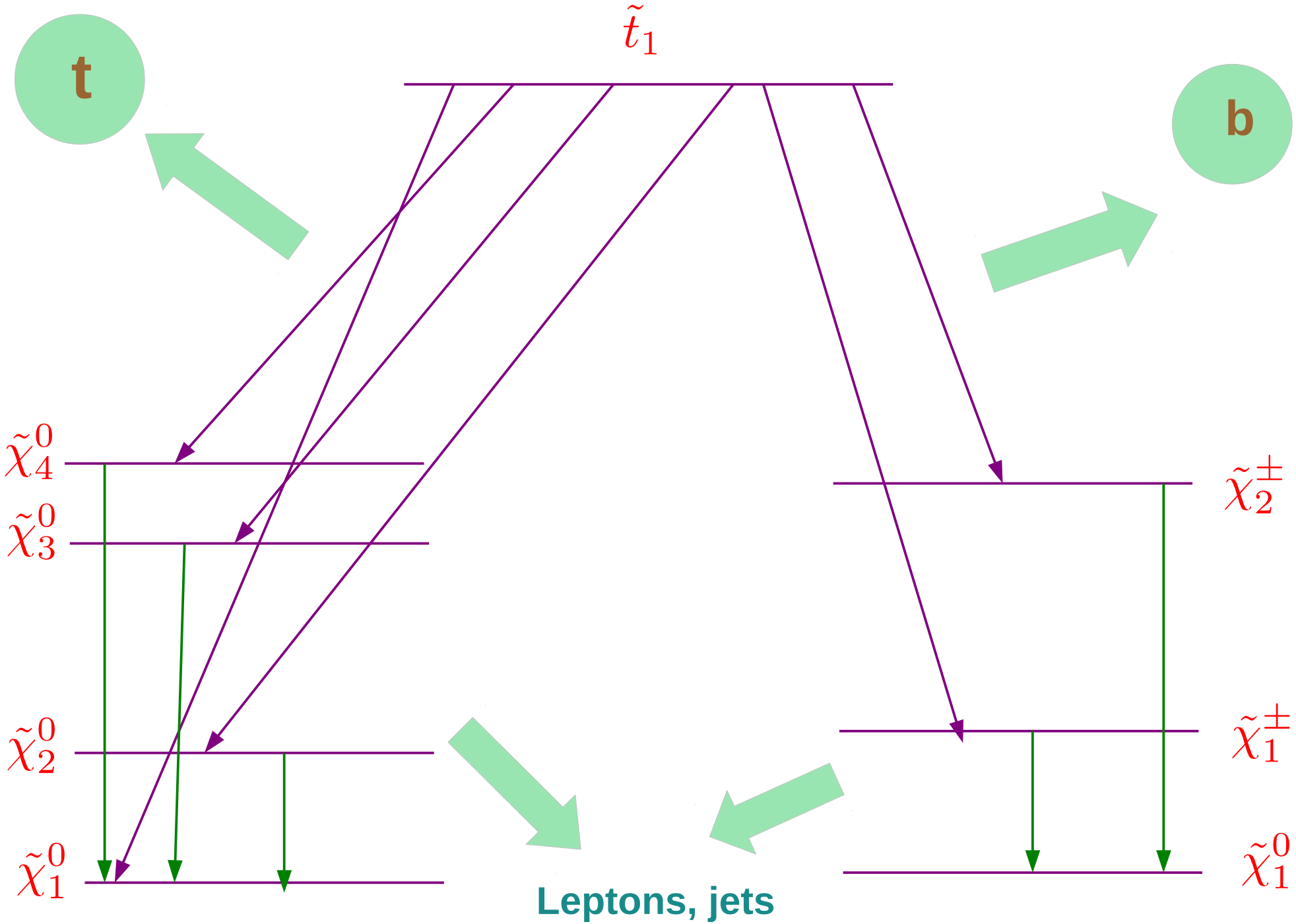


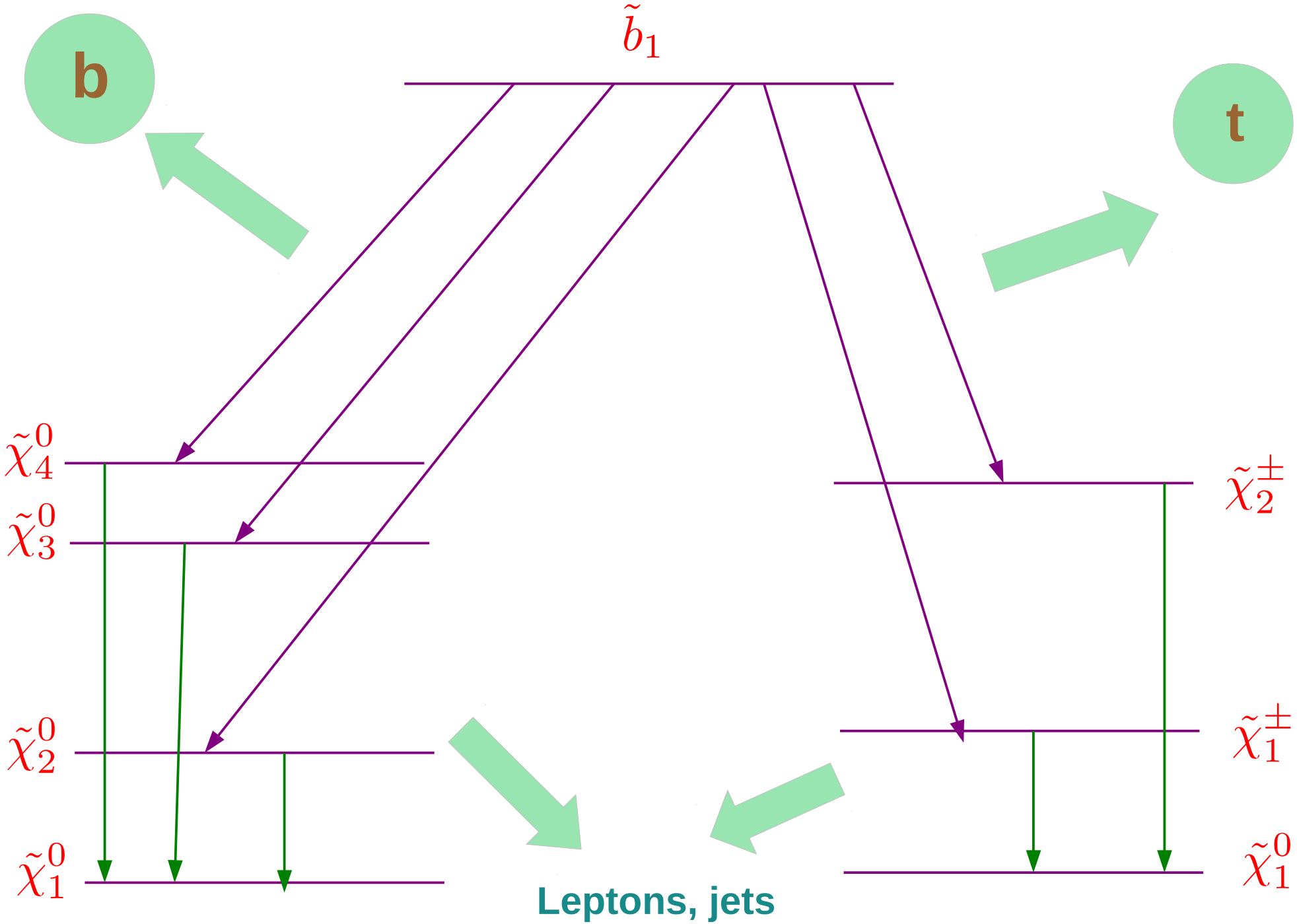


DG, arXiv:1308.0320

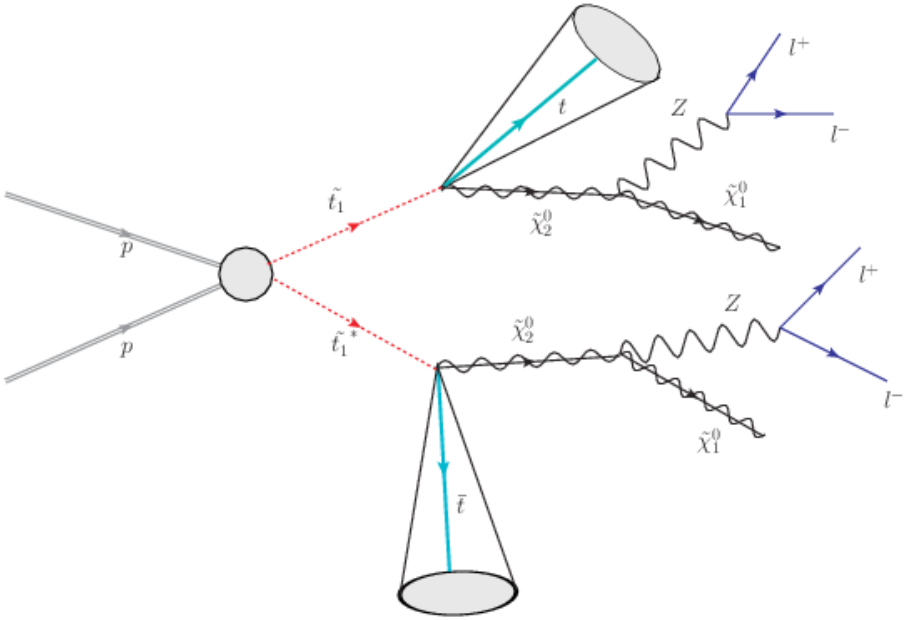
NLSP and Heavy stop ($\widetilde{t}_1$) (with $\widetilde{\chi}_1^0$)

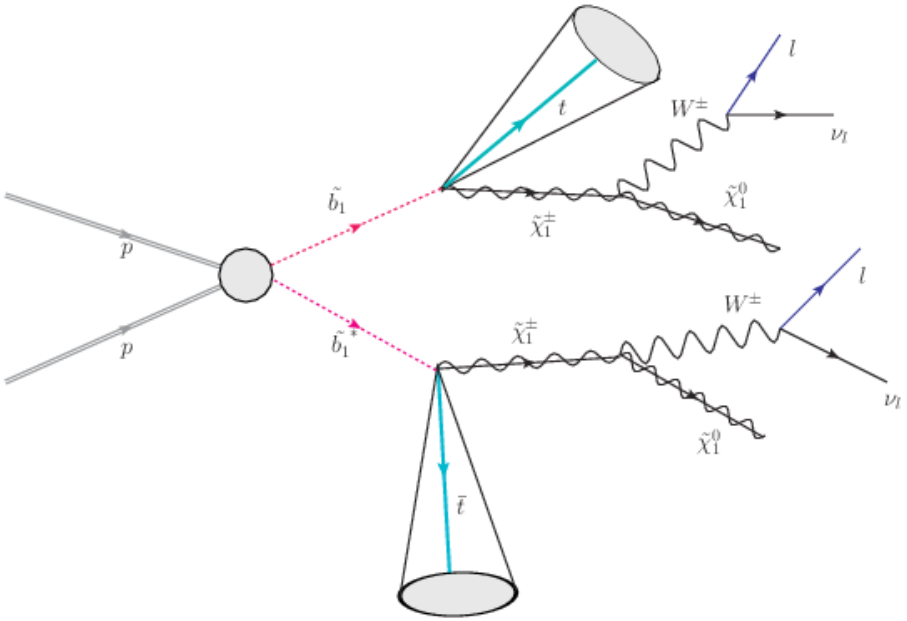
Heavy stop


$\tilde{t}_1$
t
b
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
Leptons, jets


$\tilde{b}_1$
b
t
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
Leptons, jets

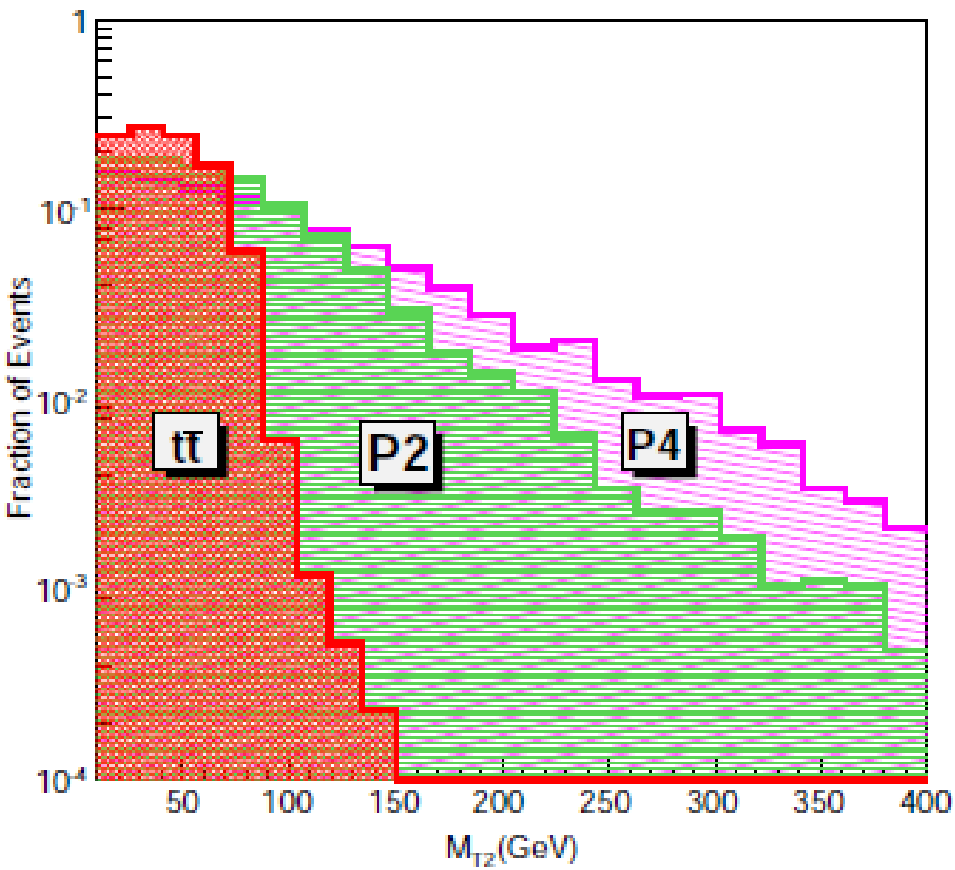
Hadronic top + di-lepton + jets + MET

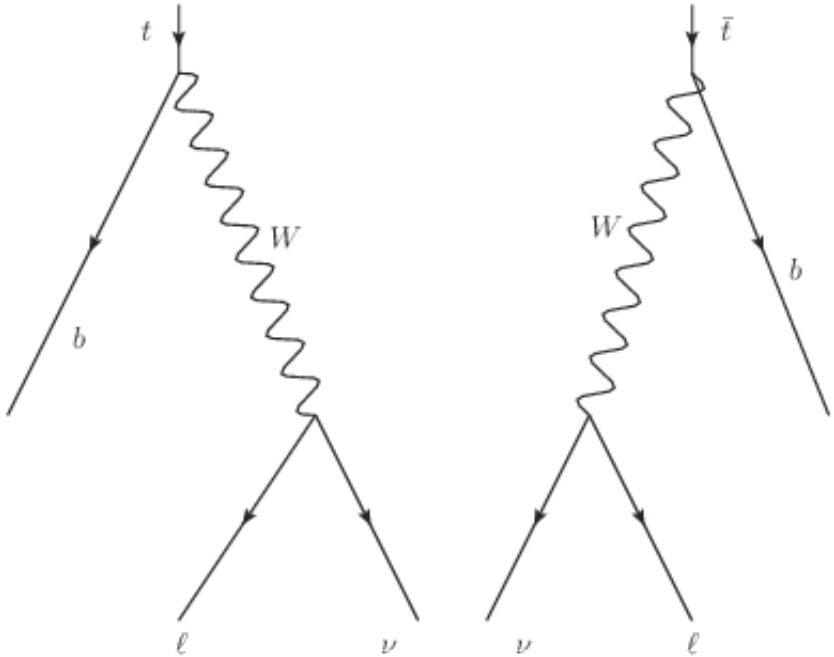




$$
\begin{array}{lllllllll}
\mathrm{pp} & \to & \widetilde{\mathrm{t}}_1\,\widetilde{\mathrm{t}}_1^* & \to & \mathrm{t}\,\bar{\mathrm{t}}\,\widetilde{\chi}_2^0\,\widetilde{\chi}_2^0 & \to & \mathrm{t}\,\bar{\mathrm{t}} + 2\mathrm{Z} + 2\widetilde{\chi}_1^0 & \to & \mathrm{t}/\bar{\mathrm{t}} + \ell\,\ell + \not{\mathbf{p}}_{\mathrm{T}} + \mathrm{X} \\
\mathrm{pp} & \to & \widetilde{\mathrm{t}}_1\,\widetilde{\mathrm{t}}_1^* & \to & \mathrm{t}\,\bar{\mathrm{b}}\,\widetilde{\chi}_2^0\,\widetilde{\chi}_1^- & \to & \mathrm{t}\,\bar{\mathrm{b}} + \mathrm{W}^-\mathrm{Z} + 2\widetilde{\chi}_1^0 & \to & \mathrm{t} + \ell\,\ell + \not{\mathbf{p}}_{\mathrm{T}} + \mathrm{X} \\
\mathrm{pp} & \to & \widetilde{\mathrm{t}}_1\,\widetilde{\mathrm{t}}_1^* & \to & \mathrm{t}\,\bar{\mathrm{b}}\,\widetilde{\chi}_2^0\,\widetilde{\chi}_1^- & \to & \mathrm{t}\,\bar{\mathrm{b}} + \mathrm{W}^-\mathrm{h} + 2\widetilde{\chi}_1^0 & \to & \mathrm{t} + \ell\,\ell + \not{\mathbf{p}}_{\mathrm{T}} + \mathrm{X} \\
\mathrm{pp} & \to & \widetilde{\mathrm{b}}_1\,\widetilde{\mathrm{b}}_1^* & \to & \mathrm{t}\,\bar{\mathrm{t}}\,\widetilde{\chi}_1^+\,\chi_1^- & \to & \mathrm{t}\,\bar{\mathrm{t}} + \mathrm{W}^+\mathrm{W}^- + 2\chi_1^0 & \to & \mathrm{t}/\bar{\mathrm{t}} + \ell\,\ell + \not{\mathbf{p}}_{\mathrm{T}} + \mathrm{X} \\
\mathrm{pp} & \to & \widetilde{\mathrm{b}}_1\,\widetilde{\mathrm{b}}_1^* & \to & \mathrm{t}\,\bar{\mathrm{b}}\,\widetilde{\chi}_1^-\,\chi_2^0 & \to & \mathrm{t}\,\bar{\mathrm{b}} + \mathrm{W}^-\mathrm{Z} + 2\chi_1^0 & \to & \mathrm{t} + \ell\,\ell + \not{\mathbf{p}}_{\mathrm{T}} + \mathrm{X}\,.
\end{array}
$$

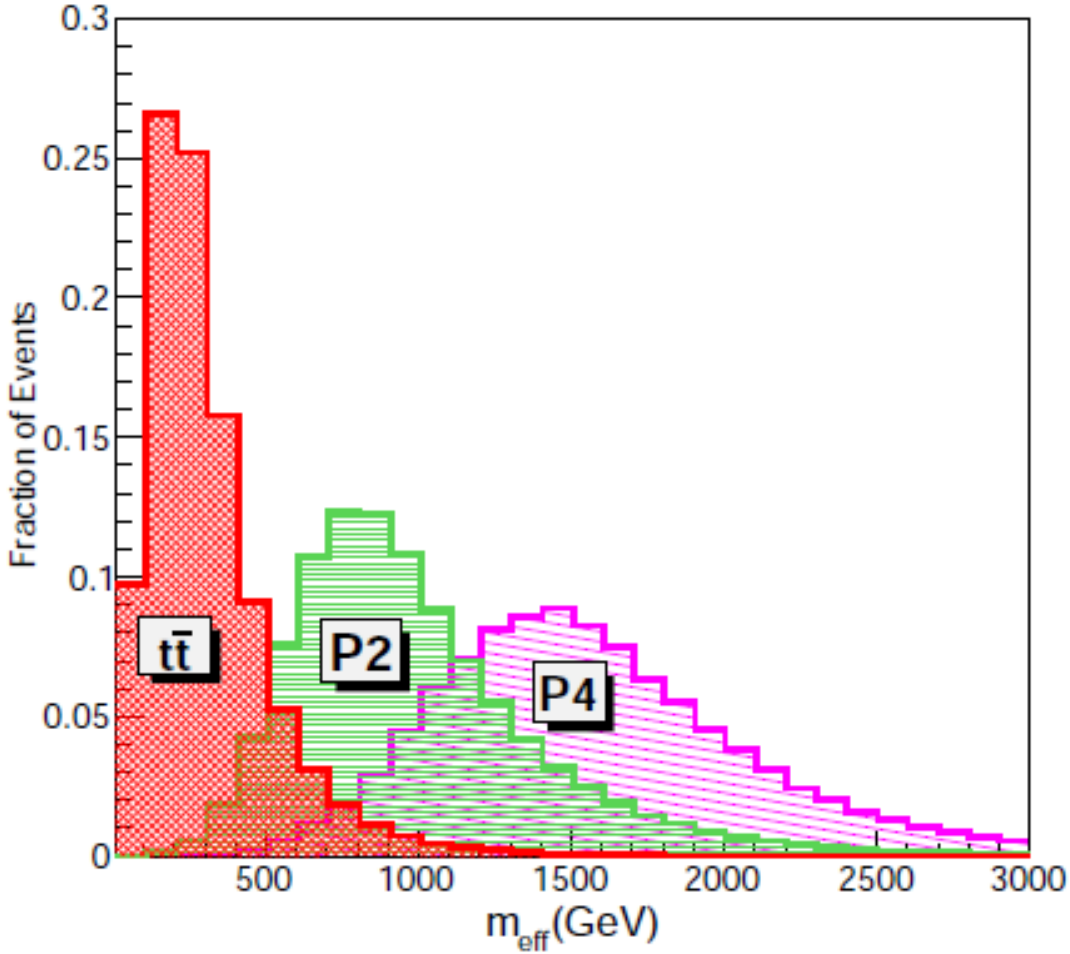
$$M_{T2}(\vec{p}_T^{\,\ell 1}, \vec{p}_T^{\,\ell 2}, \vec{\not{p}}_T) = \min_{\vec{\not{p}}_T = \vec{\not{p}}_T^{\,1} + \vec{\not{p}}_T^{\,2}} \left[\max\{ M_T(\vec{p}_T^{\,\ell 1}, \vec{\not{p}}_T^{\,1}), M_T(\vec{p}_T^{\,\ell 2}, \vec{\not{p}}_T^{\,2}) \} \right]$$





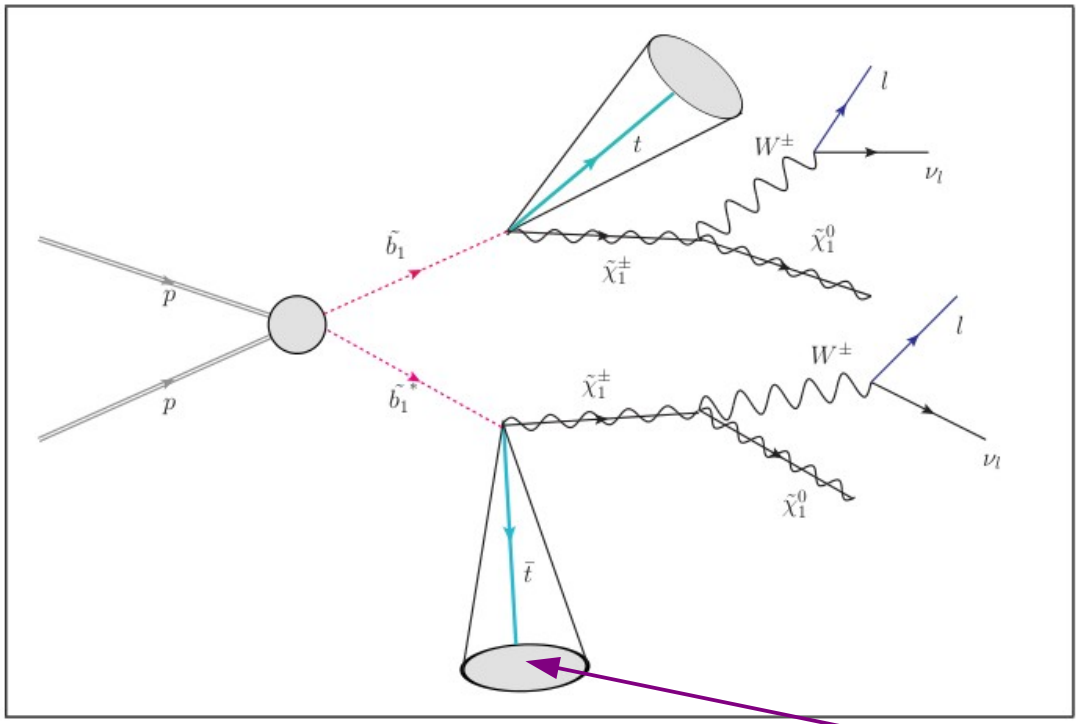
$$\mathrm{P2} : \tilde{t}_1 = 600\,\mathrm{GeV}$$

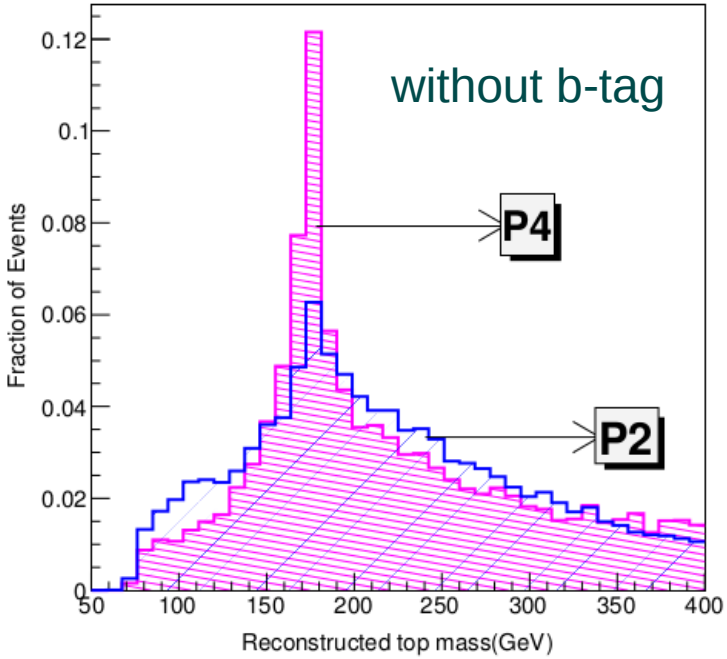
$$\mathrm{P4} : \tilde{t}_1 = 1\,\mathrm{TeV}$$



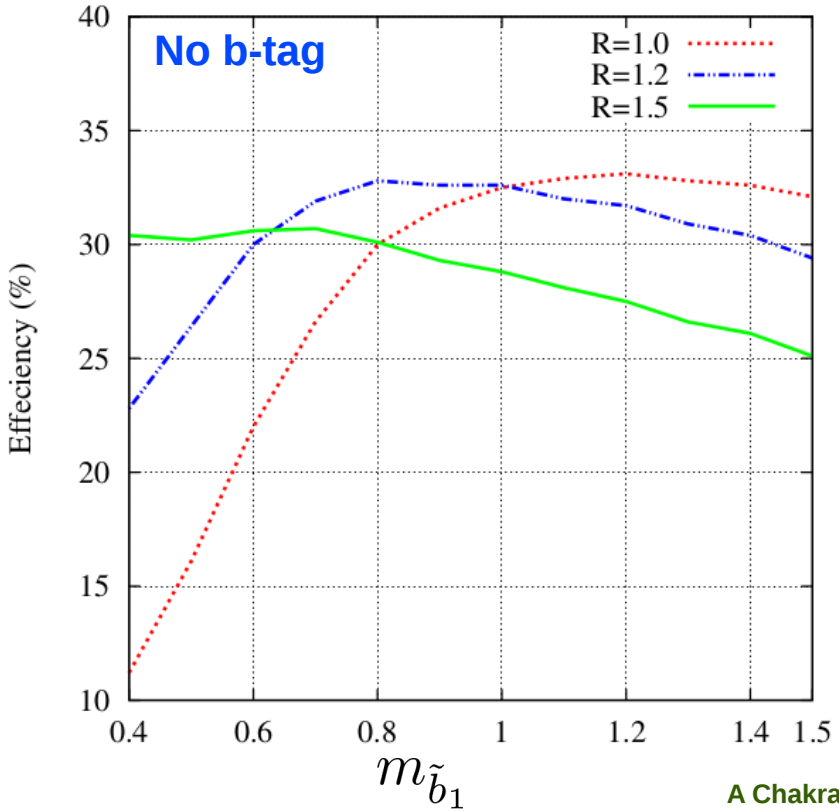
$$m_{\mathrm{eff}} = \sum_{j} |\overrightarrow{p_T}| + \sum_{\ell} |\overrightarrow{p_T}|$$

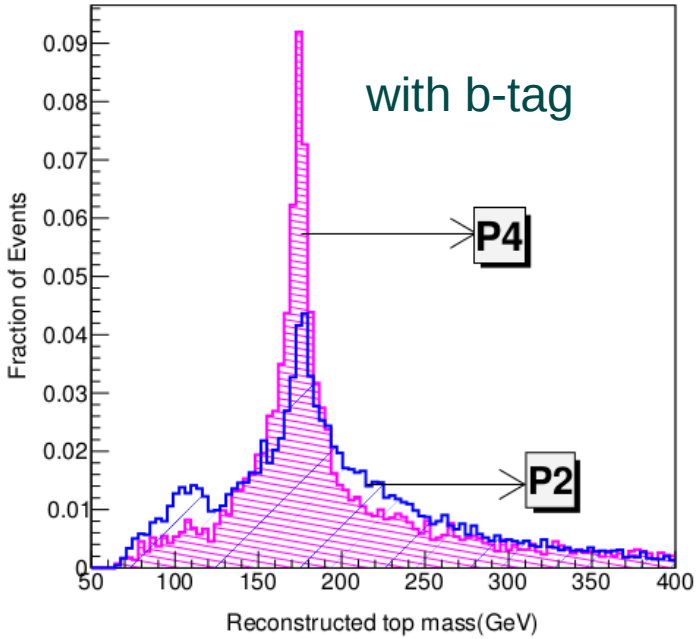
Correlated with the stop mass





JHToptagger





A Chakraborty, D K Ghosh, DG, D Sengupta, 1303.5776

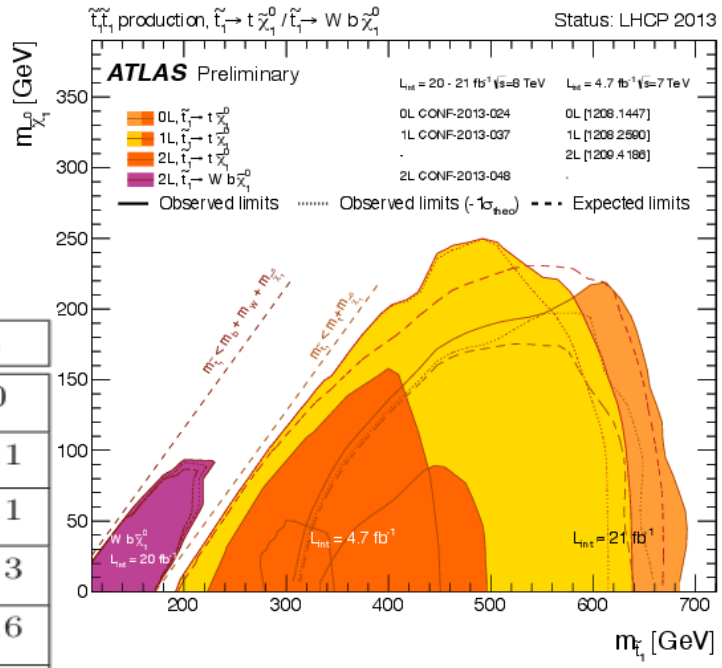
C1 : 2 hard isolated leptons C2 : $M_{T2} > 125\,\text{GeV}$ C3 : $m_{\text{eff}} > 800\,\text{GeV}$

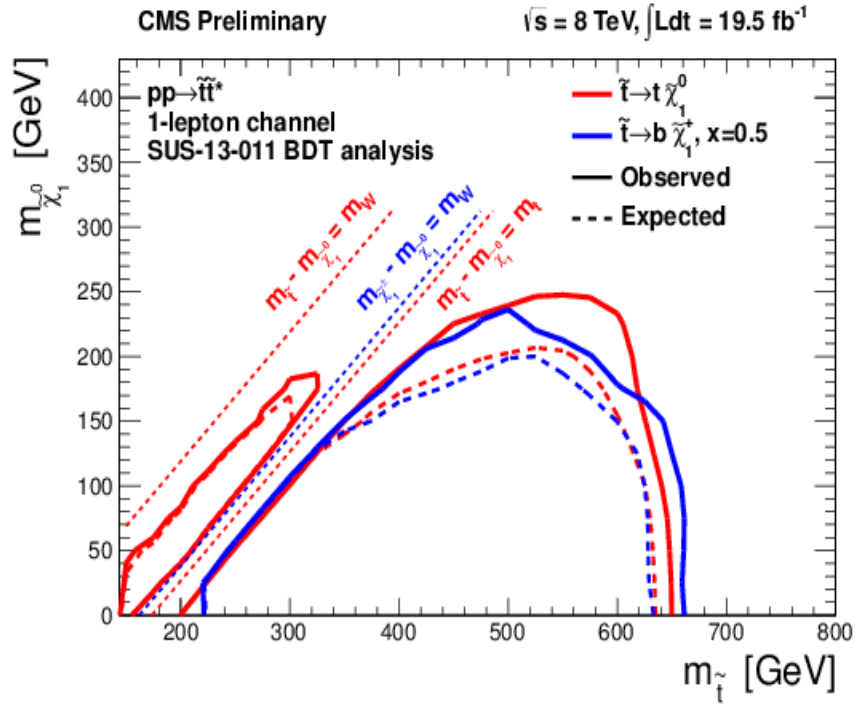
C4 : $\not{p}_T > 150\,\text{GeV}$ C5 : 1 hadronic top tag

			No. of events after the cut					
Signal	Production Cross-section (fb)	Simulated events (in units of 10^4)	C1	C2	C3	C4	C5	Final Cross-section (in units of 10^{-2} fb)
P1	1130	10	10573	821	339	267	55	62.2
P2	1130	10	11091	657	248	205	55	62.2
P3	135	5	8043	1132	712	645	153	41.3
P4	135	5	7713	1207	749	663	153	41.3
P5	27	5	8623	1720	1414	1322	295	15.9
P6	27	5	8543	1679	1343	1281	322	17.4

			No. of events after the cut					
SM backgrounds	Production Cross-section (fb)	Simulated events (in units of 10^4)	C1	C2	C3	C4	C5	Final Cross-section (in units of 10^{-2} fb)
$t\bar{t}$+ jets	918000	4320	1587596	601	39	29	4	8.5
tbW	61000	600	215807	80	4	2	1	1.0
$t\bar{t}Z$	1121	7	6255	253	52	20	2	3.2
$t\bar{t}W$	769	5	4471	31	3	2	1	1.5
$t\bar{t}W^+W^-$	10	1	1588	33	14	13	6	0.6
$t\bar{t}t\bar{t}$	10	1	1781	31	14	10	4	0.4
Total Background								15.2

A Chakraborty, D K Ghosh, DG, D Sengupta, 1303.5776



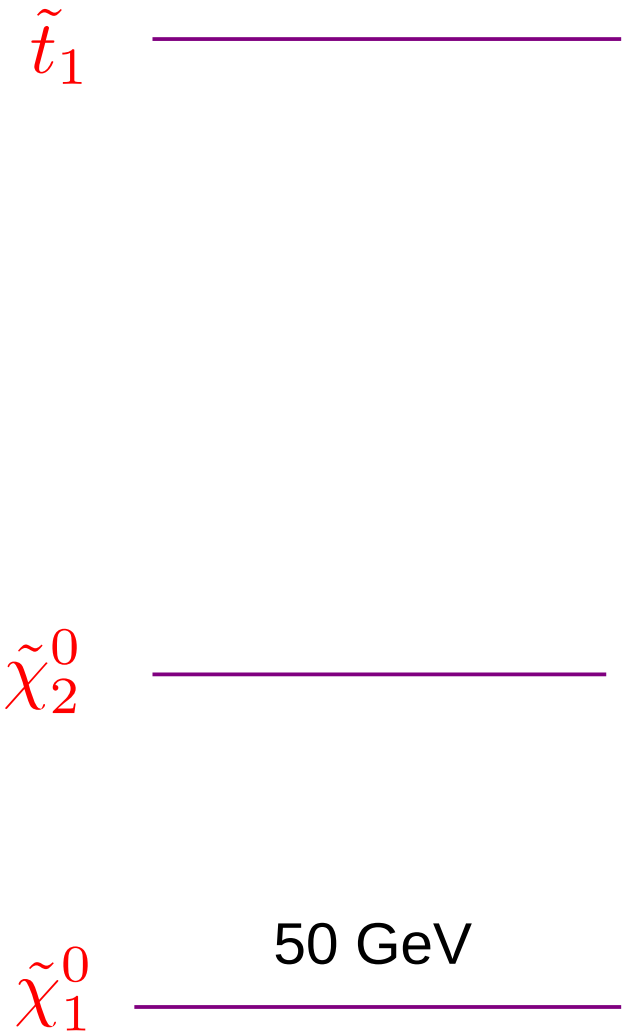


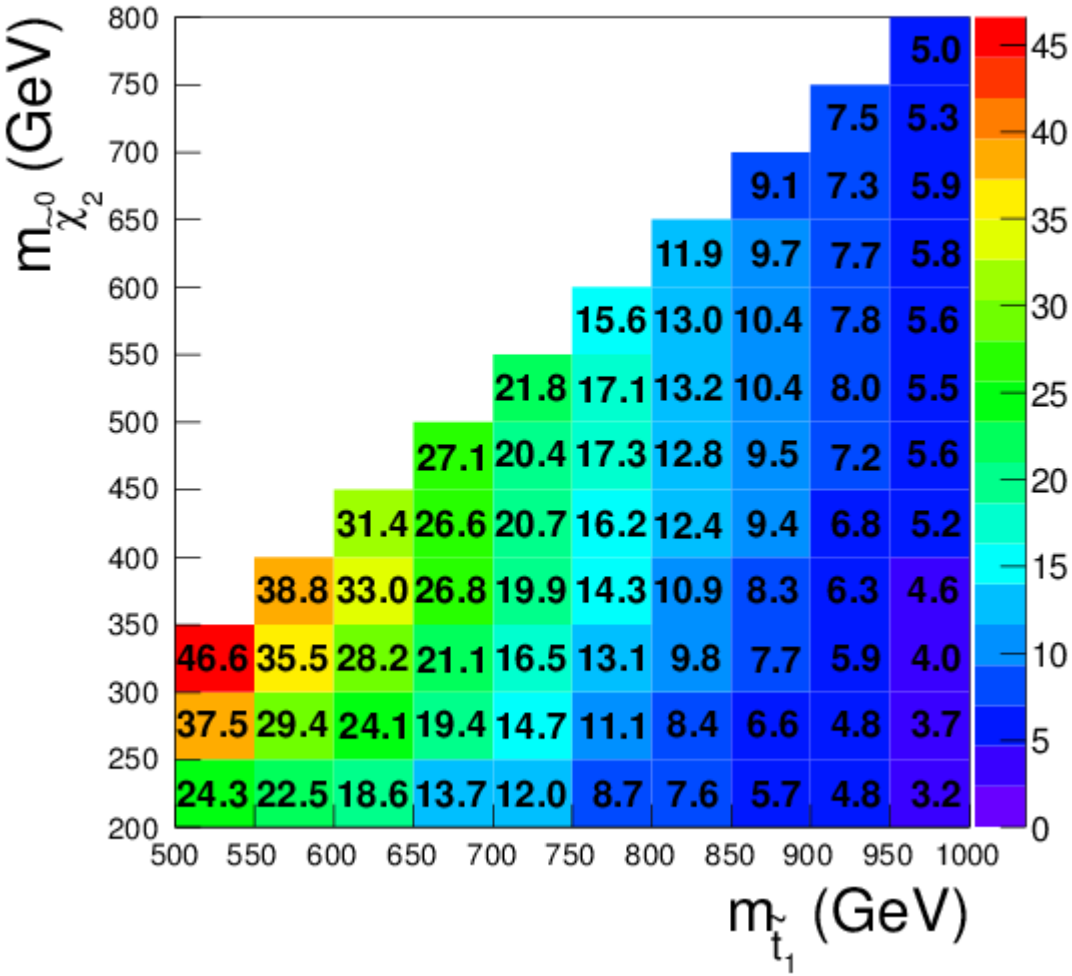
	P6
$m_{\widetilde{Q}_3}$	900
$m_{\tilde{t}_1}$	918.1
$m_{\tilde{b}_1}$	918.1
$m_{\tilde{\chi}^0_1}$	198.3
$m_{\tilde{\chi}^0_2}$	298.6
$m_{\tilde{\chi}^0_3}$	408.0
$m_{\tilde{\chi}^0_4}$	441.2
$m_{\tilde{\chi}^\pm_1}$	297.0
$m_{\tilde{\chi}^\pm_2}$	439.8
$BR(\tilde{b}_1 \to b\,\tilde{\chi}^0_{2,3,4})(\%)$	19.4
$BR(\tilde{b}_1 \to t\,\tilde{\chi}^\pm_{1,2})(\%)$	80.6
$BR(\tilde{t}_1 \to t\,\tilde{\chi}^0_{2,3,4})(\%)$	62.5
$BR(\tilde{t}_1 \to b\,\tilde{\chi}^\pm_{1,2})(\%)$	37.5
$BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z)(\%)$	100.0
$BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h)(\%)$	0.0
$\sigma(pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1)_{8\,\mathrm{TeV}}$ (pb)	0.110

$$\mathcal{S} = \frac{N_S}{\sqrt{N_B + (\kappa N_B)^2}}$$

		Signal(N_S) (Background(N_B))			Significance($\mathcal{S}$) for $\kappa = 10\%$ ($30\%, 50\%$)		
	$m_{\tilde{t}_1}$ (GeV)	10 fb^{-1}	50 fb^{-1}	100 fb^{-1}	10 fb^{-1}	50 fb^{-1}	100 fb^{-1}
P1	501.6	6.2(1.6)	31.1(8)	62.2(16)	4.9(4.6, 4.1)	10.8(8.4, 6.3)	14.4(9.9, 6.9)
P2	501.6	6.2(1.6)	31.1(8)	62.2(16)	4.9(4.6, 4.1)	10.8(8.4, 6.3)	14.4(9.9, 6.9)
P3	714.2	4.1(1.6)	20.7(8)	41.3(16)	3.2(3.0, 2.7)	7.0(5.6, 4.2)	9.6(6.6, 4.6)
P4	714.2	4.1(1.6)	20.7(8)	41.3(16)	3.2(3.0, 2.7)	7.0(5.6, 4.2)	9.6(6.6, 4.6)
P5	918.1	1.6(1.6)	7.9(8)	15.9(16)	1.3(1.2, 1.1)	2.7(2.1, 1.6)	3.7(2.5, 1.8)
P6	918.1	1.7(1.6)	8.7(8)	17.4(16)	1.3(1.2, 1.1)	2.9(2.3, 1.8)	4.0(2.8, 1.9)

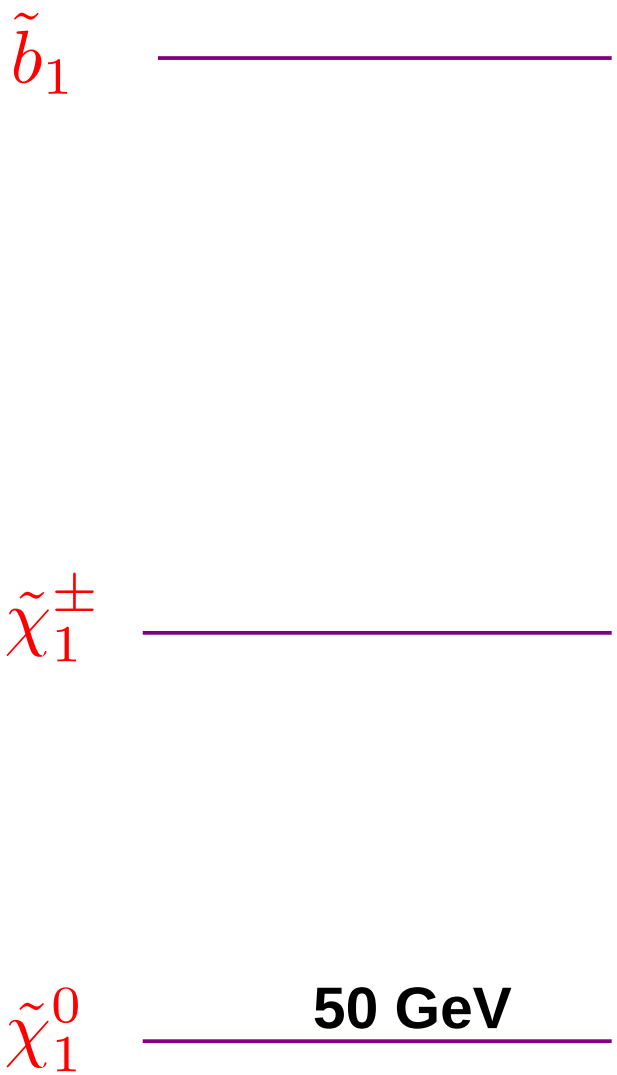
Simplified Model

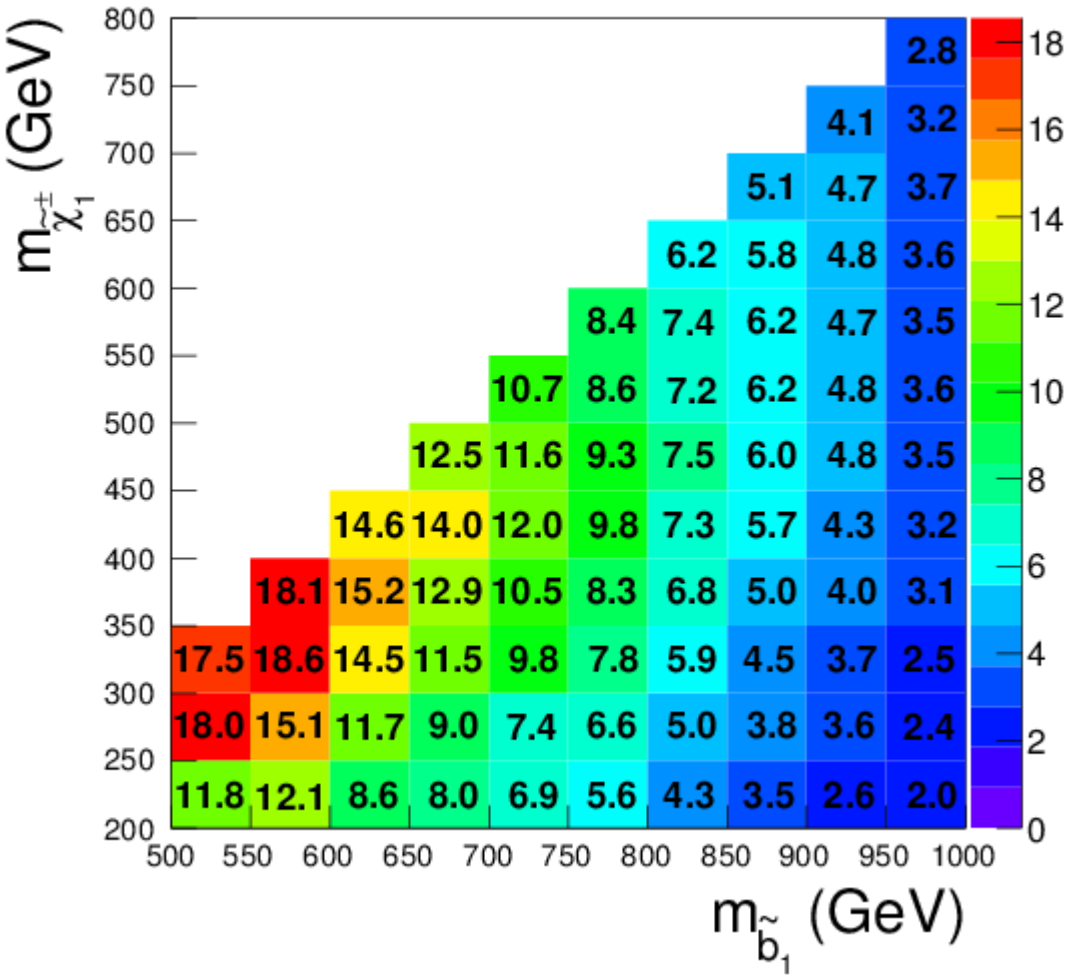




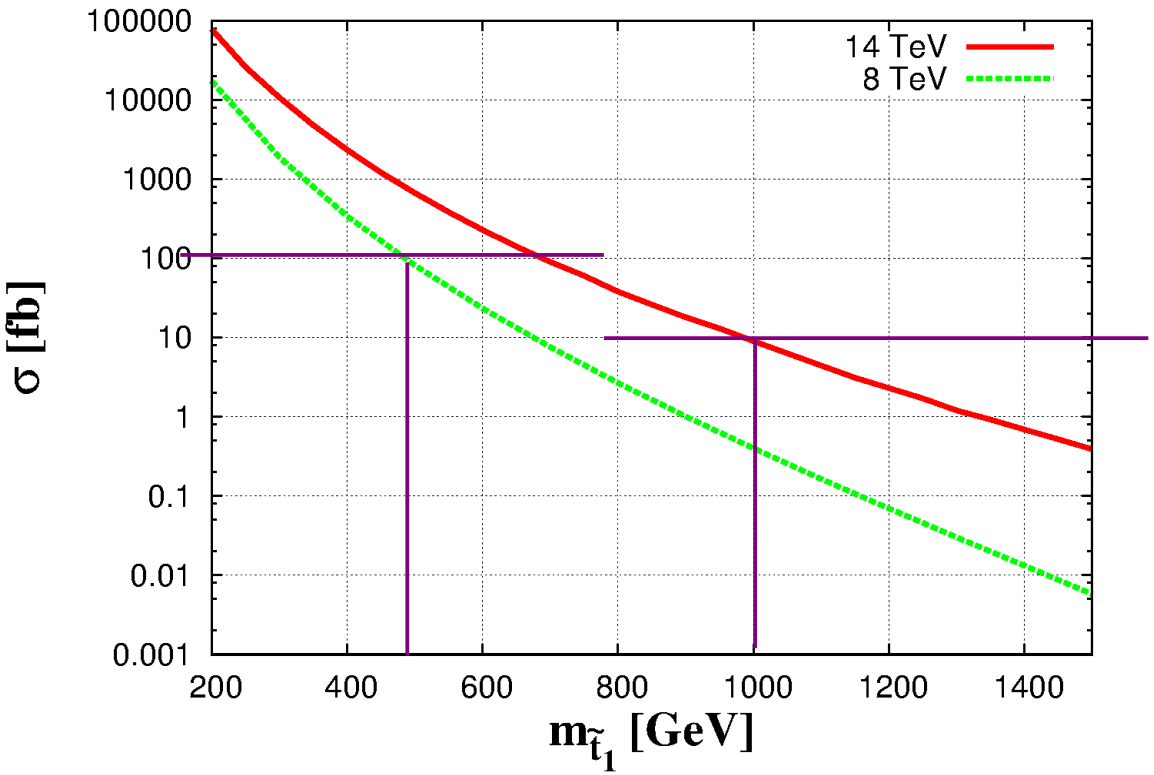
A Chakraborty, D K Ghosh, DG, D Sengupta, 1303.5776

Simplified Model





A Chakraborty, D K Ghosh, DG, D Sengupta, 1303.5776



$\sigma_{t\bar{t}} \sim 225$ pb 8TeV

$\sigma_{t\bar{t}} \sim 925$ pb 14TeV

Summary

ATLAS and CMS took a good bite out of the SUSY parameter space

Higgs mass has made it even worse

Light third generation squarks could be the culprit behind the relatively heavy higgs mass

A very light NLSP stop squark is allowed even in some of the minimal models

The stop NLSP region is very poorly constrained by ATLAS and CMS and dedicated searches are necessary to probe this region

Heavier stops will allow quite a large number of decay topologies, hence dedicated searches for various final states should be carried out.

Thank You
©FairizWingzCreationz