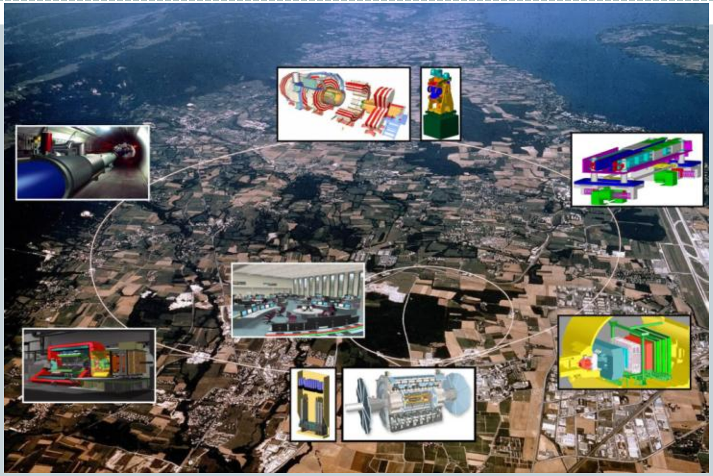
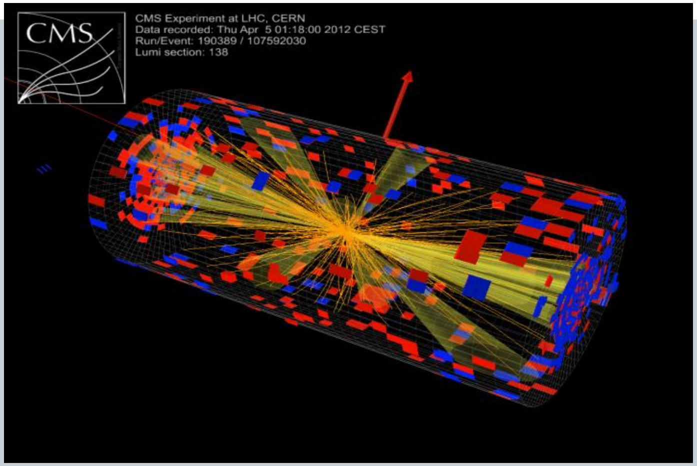
Searching for Top Squarks at the LHC





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Phys. Rev. D **87** (2013) 095007, hep-ph/1312.1348 (accepted by PRD).

OUTLINE

Supersymmetry Top Squark ($\tilde{t}$)

- Motivation
- LHC search status

Search from Cascade Decay

- $\tilde{t}$ - $\tilde{\chi}_1^0$ Coannihilation Scenario
- Endpoint measurements

Fully Hadronic Final State Scenario

- M3 technique

Bino-Higgsino Dark Matter Scenario

- Dilepton invariant mass distribution
- Light slepton & heavy slepton cases

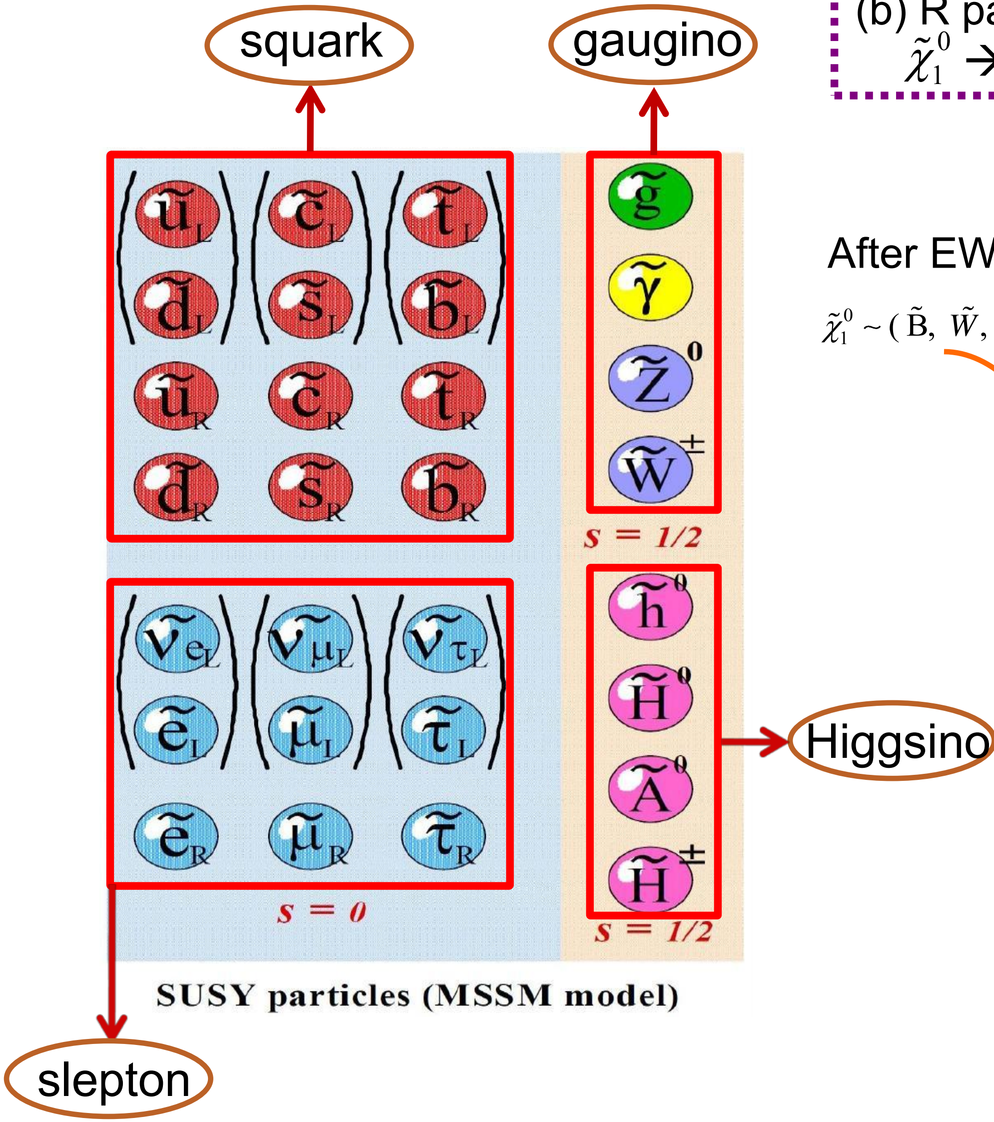
Compressed Scenario

- VBF topology selection
- Two-body decay & three-body decay cases

Conclusion

Supersymmetry

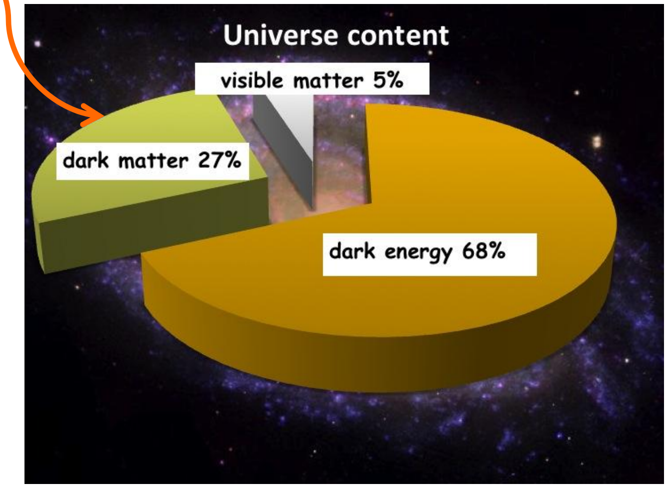
(a) Fermion $\leftrightarrow$ Boson
(b) R parity conserving SUSY, lightest neutralino $\tilde{\chi}_1^0$ → cold dark matter candidate



SUSY particles (MSSM model)

After EW symmetry breaking,

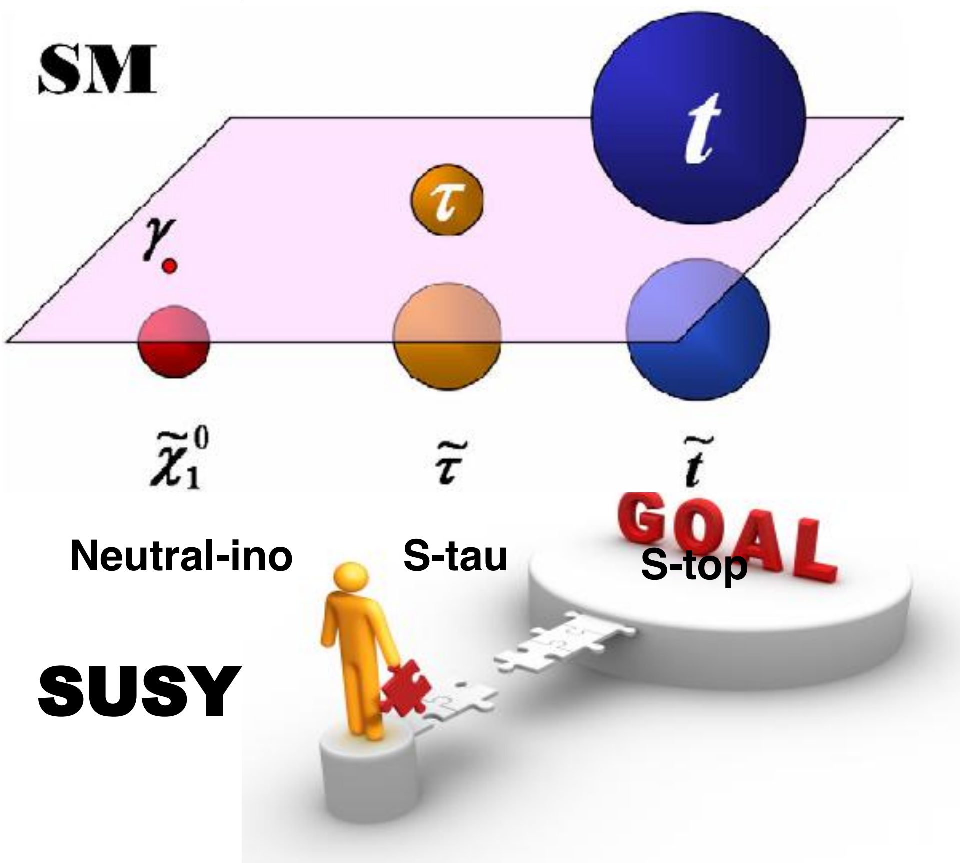
$\tilde{\chi}_1^0 \sim (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$ $\tilde{\chi}_1^+ \sim (\tilde{W}^+, \tilde{H}_u^+)$ $\tilde{\chi}_1^- \sim (\tilde{W}^-, \tilde{H}_d^-)$



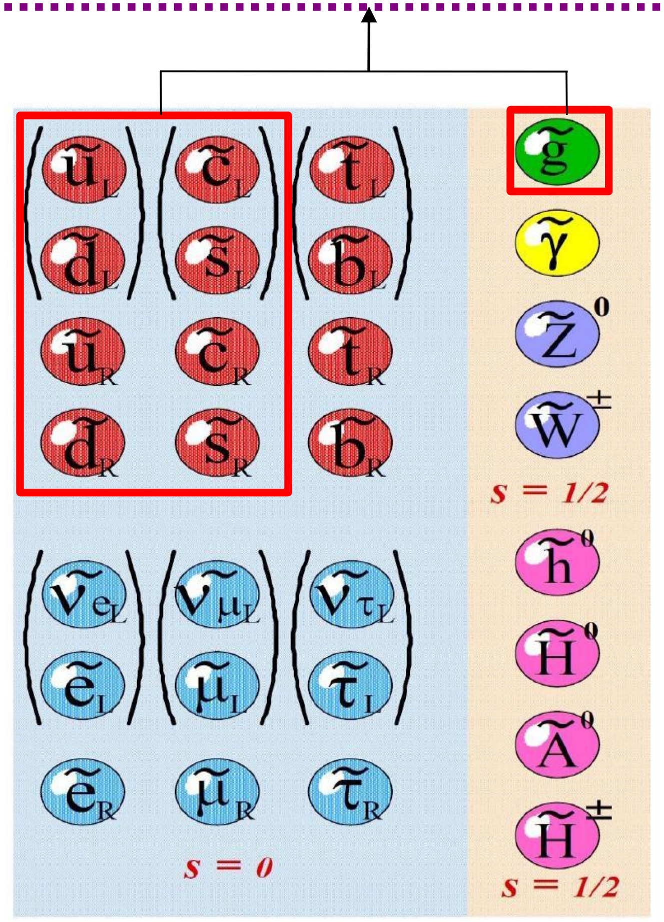
(Planck, 2013)

Top squark

- 3rd generation top squark could be light to give the Higgs mass a reasonable correction.
- Higgs boson at 126 GeV → light stop (at sub-TeV).



ATLAS and CMS 8-TeV
If $m_{\tilde{g}} \approx m_{\tilde{q}}$, >1.5 TeV
[hep-ex/1208.0949], [1206.1760], [1207.1898]



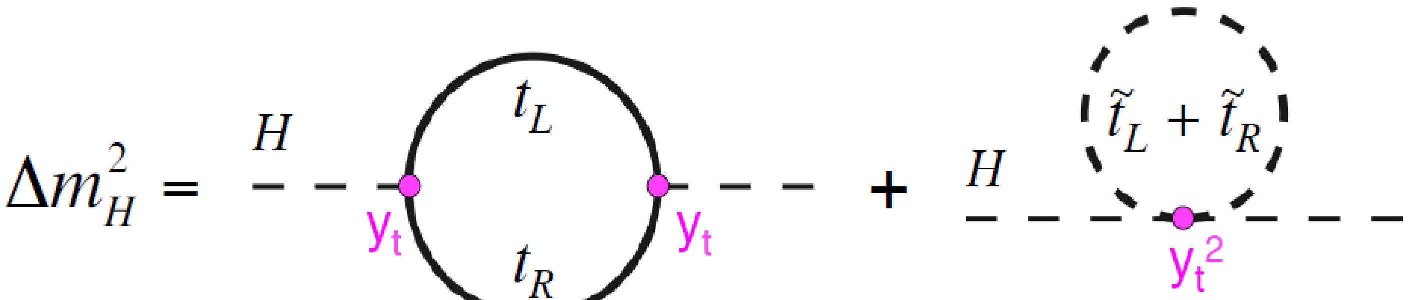
SUSY particles (MSSM model)

To show search strategies we developed for a light stop.

Why Stop can be light?

Hierarchy Problem, naturalness

$$\Delta m_H^2 \sim |y_t|^2 \left[-\Lambda_{UV}^2 + \frac{3}{2} m_t^2 \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right) + \Lambda_{UV}^2 - m_{\tilde{t}}^2 \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}\right) + \dots \right]$$



SUSY solution

- In SM enormous corrections to m_h : $\Delta m^2 \propto \Lambda_{UV}^2$ from top quark.
- In SUSY Stop loop cancels Λ_{UV}^2 term, and give a finite correction.
- Light stops (~TeV) needed for "natural" (not fine-tuned) solution to hierarchy problem.

4

Stop mixing

Tree level contribution

$$m_h^2 \sim m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\frac{\tilde{X}_t}{2} + \log\frac{M_{\text{Susy}}^2}{m_t^2}\right)$$

Stop loop contributions

Valid in the approximation $m_{Q3} \sim m_{u3}$

They have to lift the mass of the Higgs by ~ 35 GeV!

$$\begin{cases} \tilde{X}_t = \dfrac{2X_t^2}{M_{\text{Susy}}^2}\left(1 - \dfrac{X_t^2}{12M_{\text{Susy}}^2}\right) \\ X_t = A_t - \dfrac{\mu}{\tan\beta} \end{cases}$$

$$M_{stop}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_{u_3}^2 + m_t^2 + D_R \end{pmatrix}$$

- obtain mass matrix eigenstates $\tilde{t}_1$ and $\tilde{t}_2$

lighter stop → $\tilde{t}_1$

heavier stop → $\tilde{t}_2$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = U_{\tilde{t}} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}}\, e^{-i\phi_{\tilde{t}}} \\ -\sin\theta_{\tilde{t}}\, e^{i\phi_{\tilde{t}}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$m_h \approx 126\,\text{GeV}$ requires: see for example, M. Badziak *et. al.*, [hep/ph1205.1675]

Small mixing → *both stops in the multi-TeV scale*

OR

Large mixing → *Two stops close in mass, in the several hundred GeV scale.*

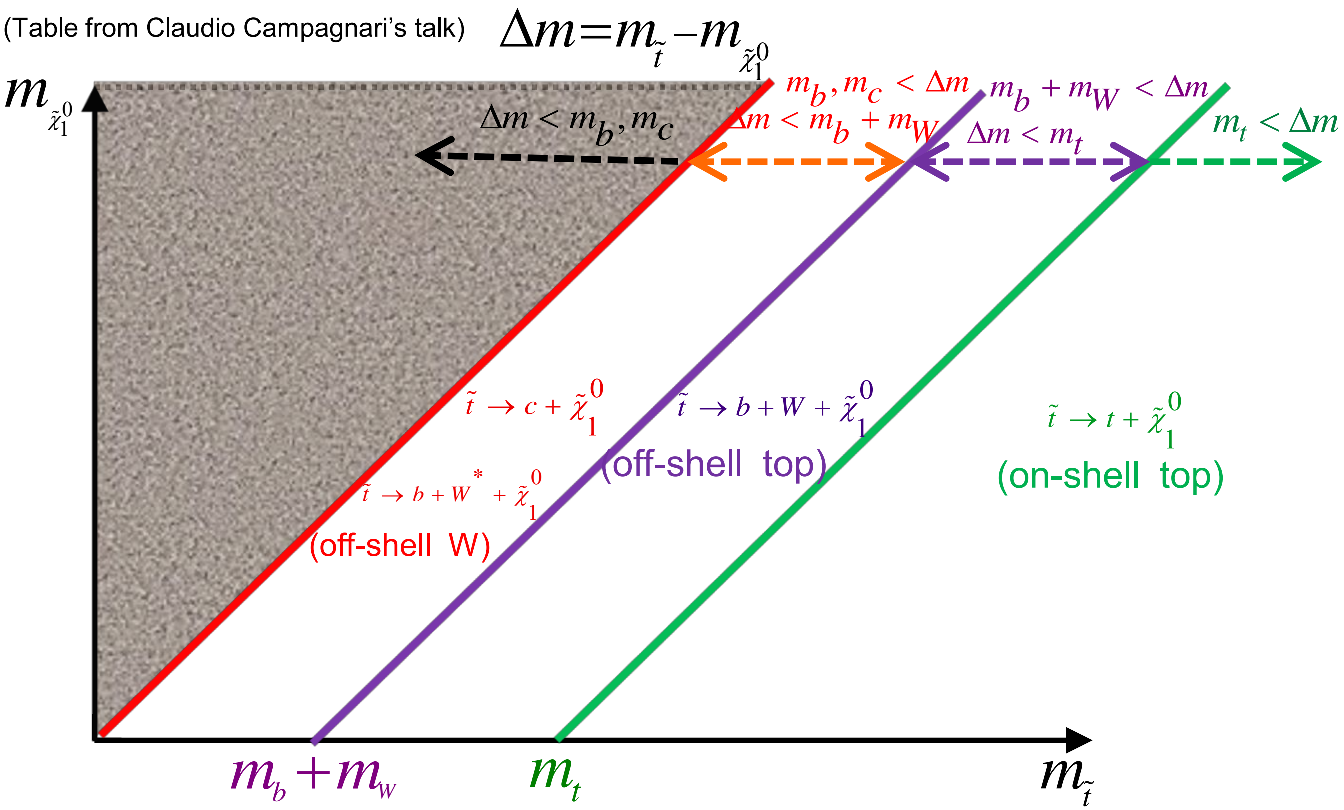
→ *Very large splitting between the two stops: one is very light (100-200 GeV)*

Top Squark Decay Modes (RPC)

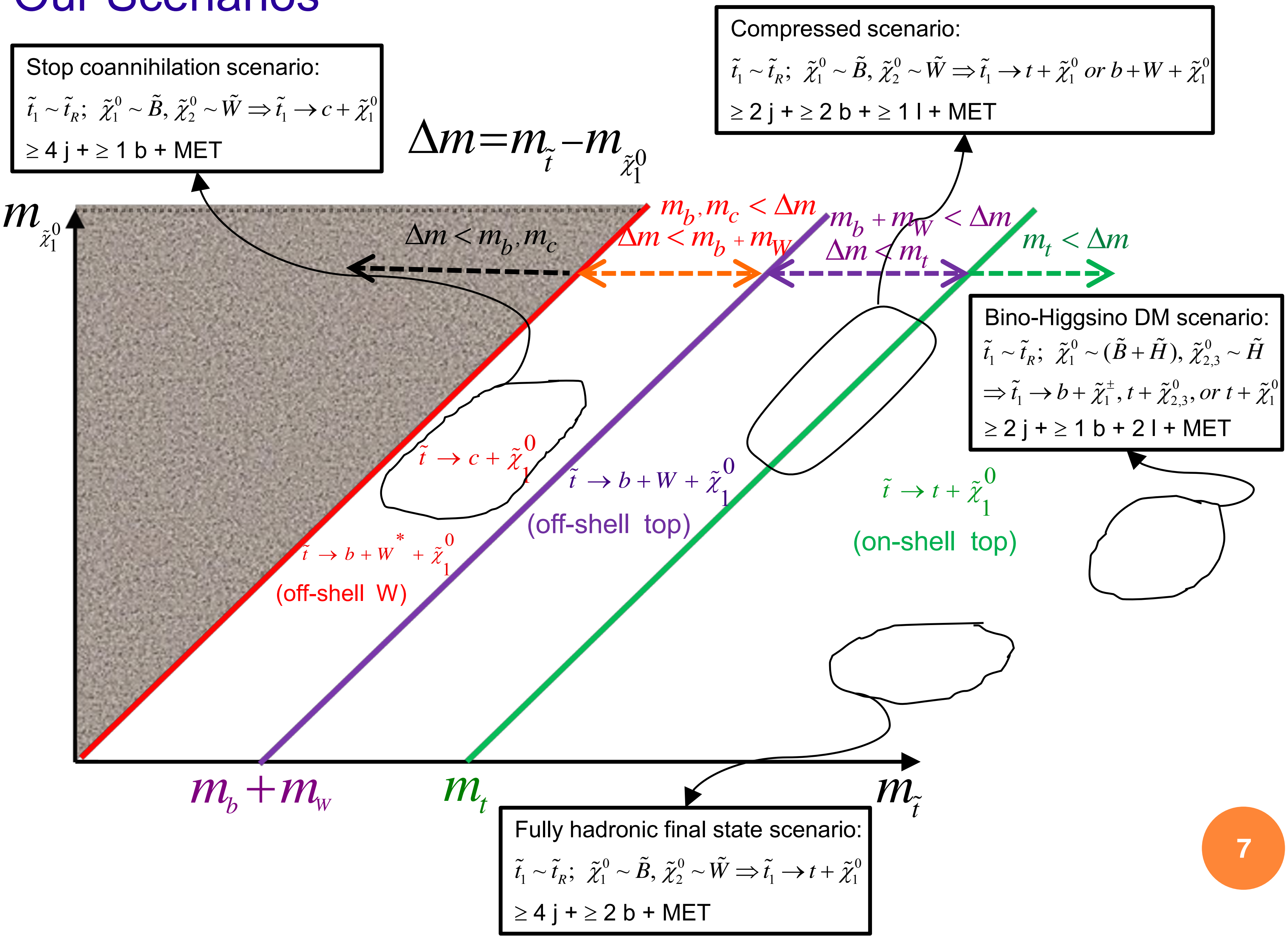
Stop decay ← Stop mixing & neutralino/chargino composition & $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

LSP	Allowed stop decays	Why
$\tilde{\chi}_1^0 = \tilde{B}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_R \tilde{\chi}_1^0$	U(1) couples L to L and R to R
$\tilde{\chi}_1^0 = \tilde{W}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0$	SU(2) only acts on L
$\tilde{\chi}_1^0 = \tilde{H}_d^0$	none	Only couples to down-type
$\tilde{\chi}_1^0 = \tilde{H}_u^0$	$\tilde{t}_L \to t_R \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_L \tilde{\chi}_1^0$	Higgs couple L to R (mass term)

(Table from Claudio Campagnari's talk)

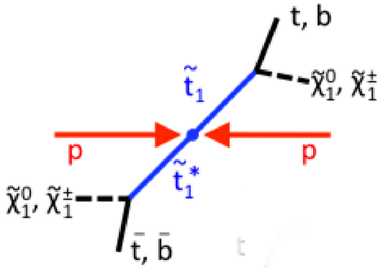


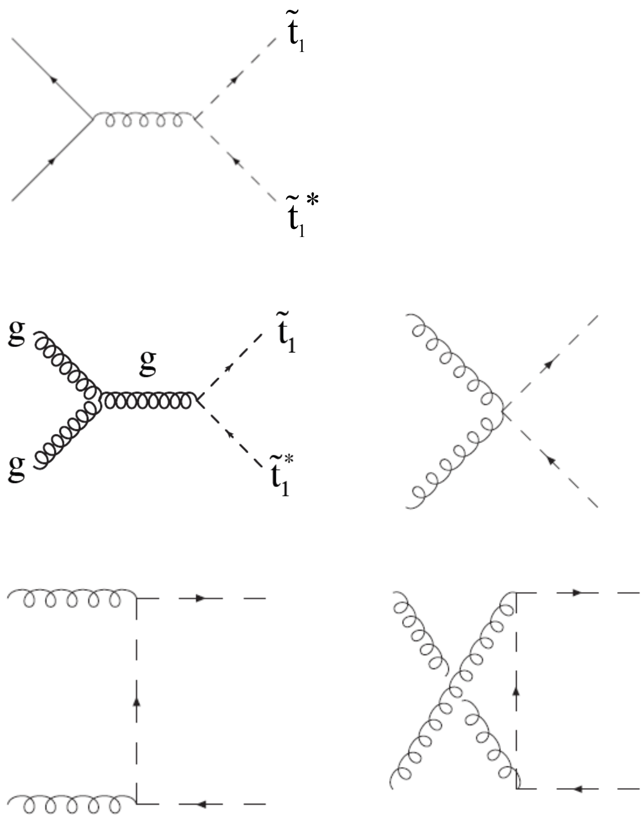
Our Scenarios



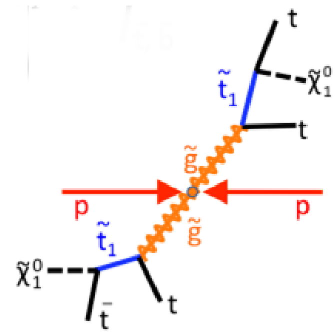
Top Squark Production Processes

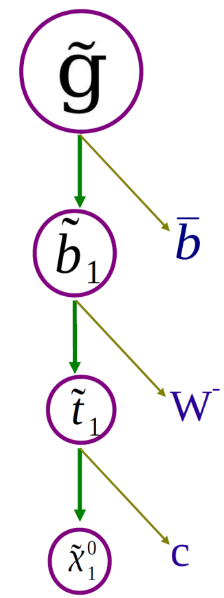
Direct production in pairs





Production from cascade decay



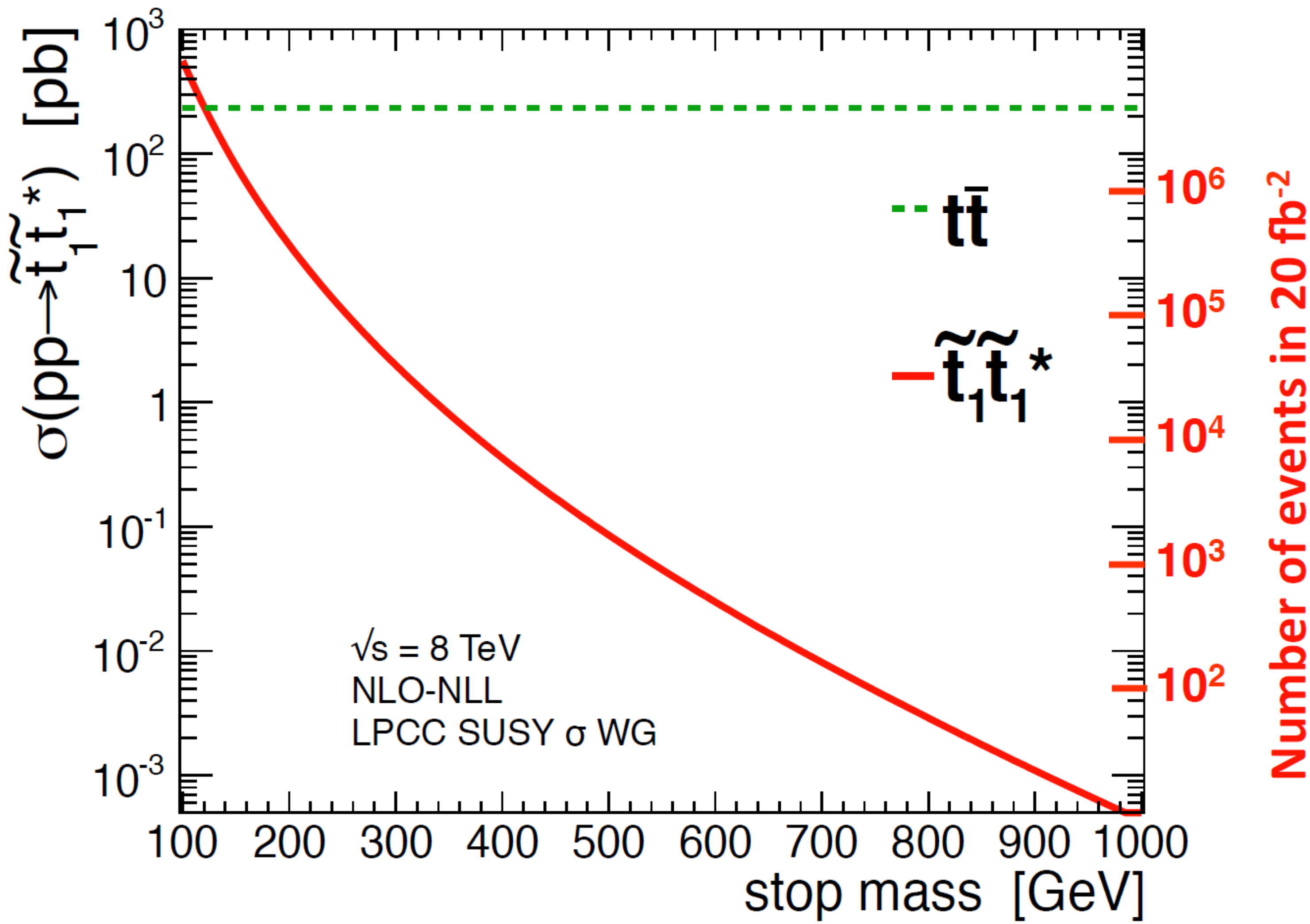


8

Top Squark Search Challenge

- Small production cross section.
- t tbar background is huge.

(Plot from Claudio Campagnari's talk)

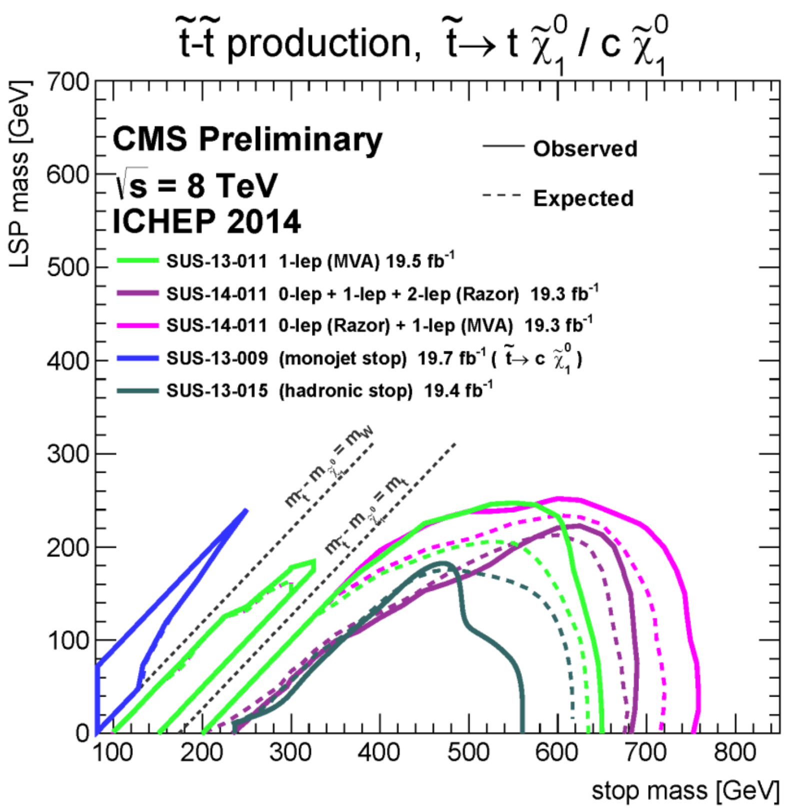


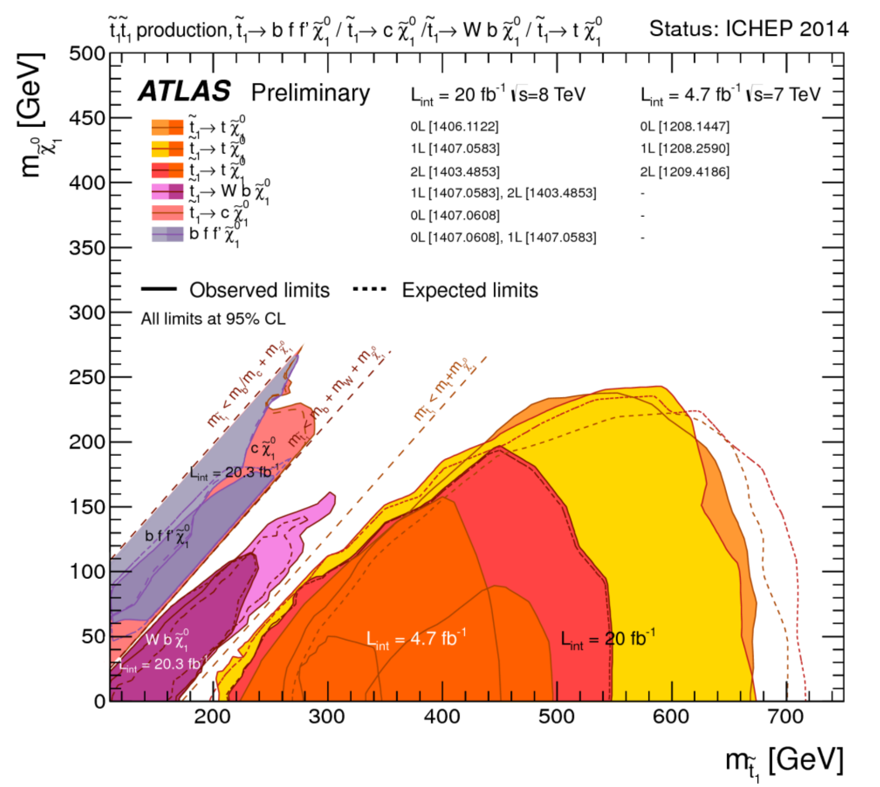
9

LHC status of Stop searches

ATLAS

CMS

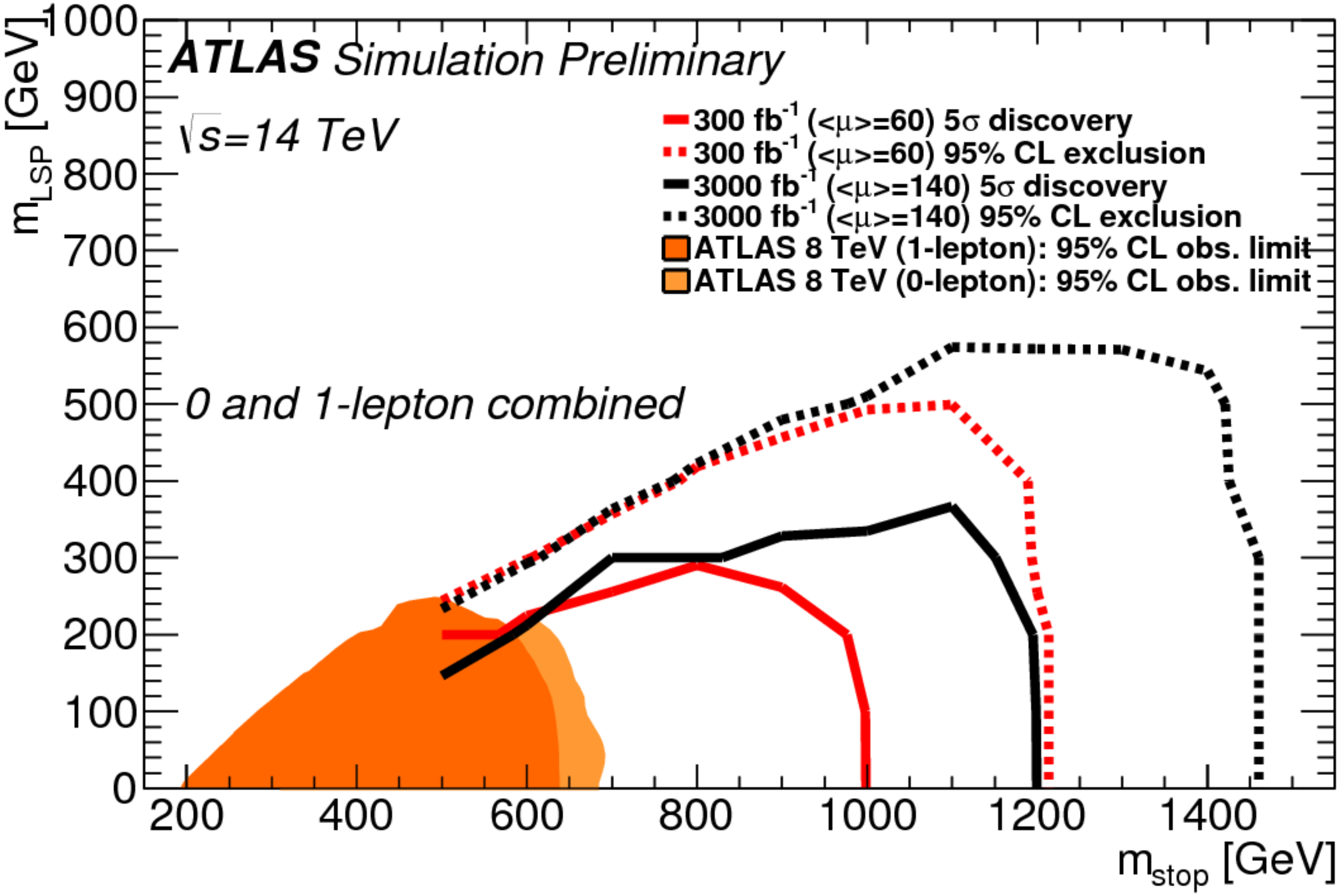




10

LHC projection analysis of Stop searches

ATLAS 14 TeV Projection analysis [ATL-PHYS-PUB-2013-011]



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- Two-body decay & three-body decay cases

Conclusion

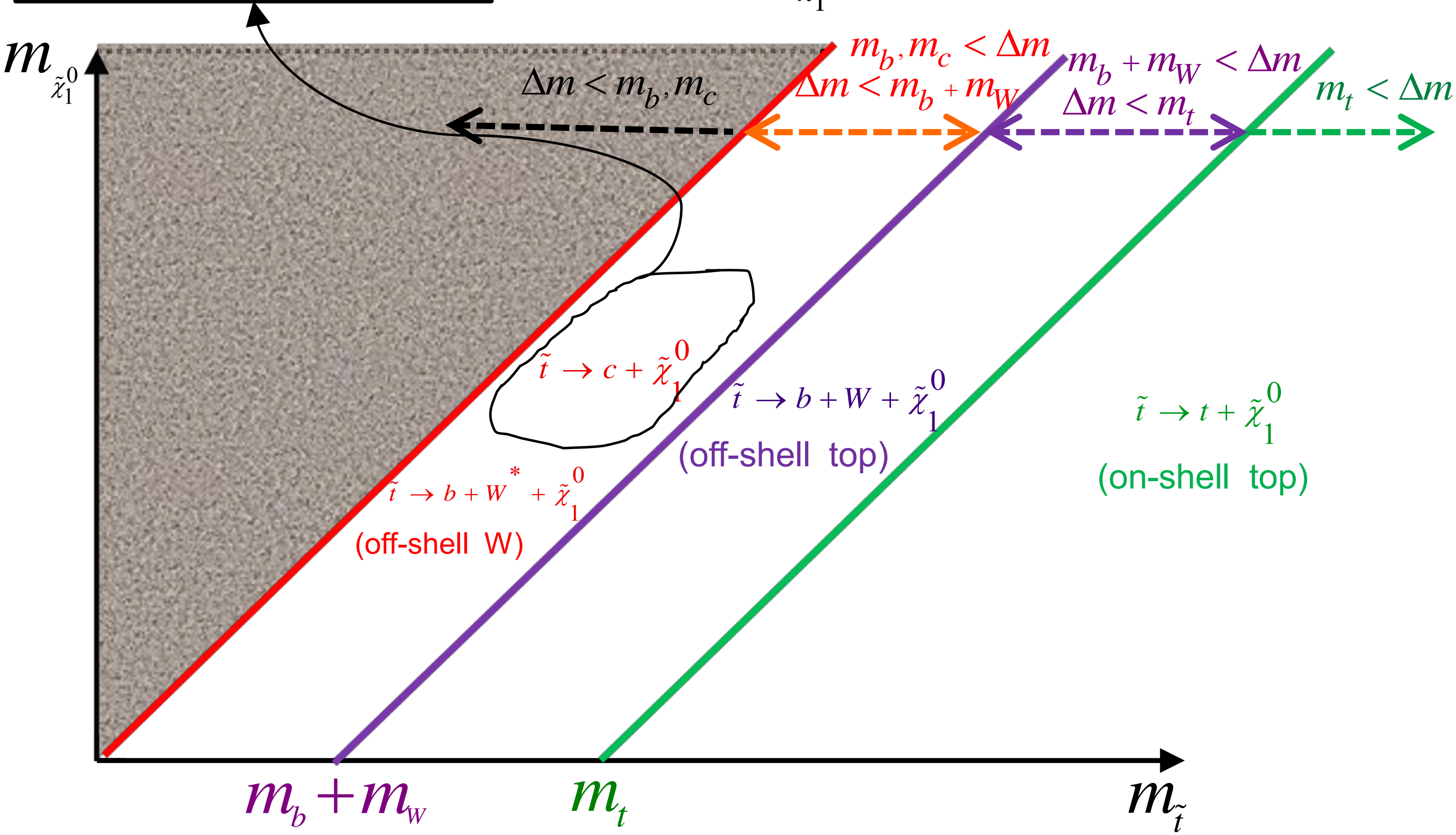
Stop-neutralino coannihilation scenario

Stop coannihilation scenario:

$\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B},\ \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to c + \tilde{\chi}_1^0$

$\geq$ 4 j + $\geq$ 1 b + MET

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$$



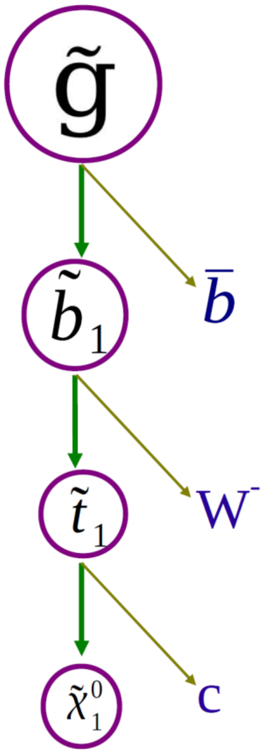
Stop-neutralino coannihilation scenario

B. Dutta, T. Kamon, A. Krislock, K. Sinha and **K. Wang**, Phys. Rev. D**85** (2012) 115007 [hep-ph/1112.3966].

$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 53\ \text{GeV} < m_W$ $\quad \tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to c + \tilde{\chi}_1^0$

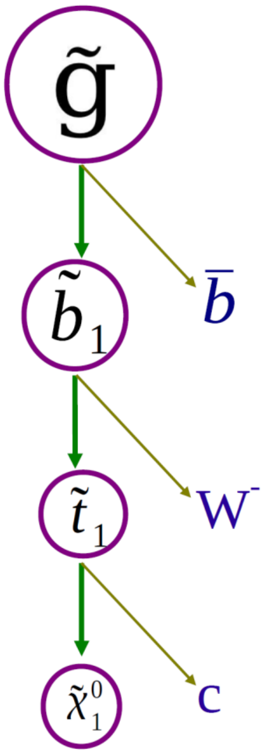
DM relic density satisfied by the coannihilation mechanism.
Mass spectrum (GeV).

Particle	Mass	Particle	Mass	Particle	Mass
$\tilde{d}_L$	653	$\tilde{e}_L$	437	$\tilde{\chi}_1^0$	286
$\tilde{d}_R$	636	$\tilde{e}_R$	411	$\tilde{\chi}_2^0$	338
$\tilde{u}_L$	648	$\tilde{\tau}_1$	315	$\tilde{\chi}_3^0$	477
$\tilde{u}_R$	635	$\tilde{\tau}_2$	418	$\tilde{\chi}_4^0$	503
$\tilde{b}_1$	520			$\tilde{\chi}_1^\pm$	337
$\tilde{b}_2$	596			$\tilde{\chi}_2^\pm$	500
$\tilde{t}_1$	339			$\tilde{g}$	650
$\tilde{t}_2$	616				



Search strategy

- $\geq$ 4 j + $\geq$ 1 b + MET, $\tilde{g} \rightarrow \tilde{b} + b \rightarrow \tilde{t} + W + b \rightarrow \tilde{\chi}_1^0 + c + W + b$
- Endpoint measurements $M_{bW}, M_{jW} \Rightarrow m_{\tilde{t}}, m_{\tilde{b}}$ @ 14 TeV
- Bi-Event Subtraction Technique (BEST) is performed to get rid of uncorrelated jet background.

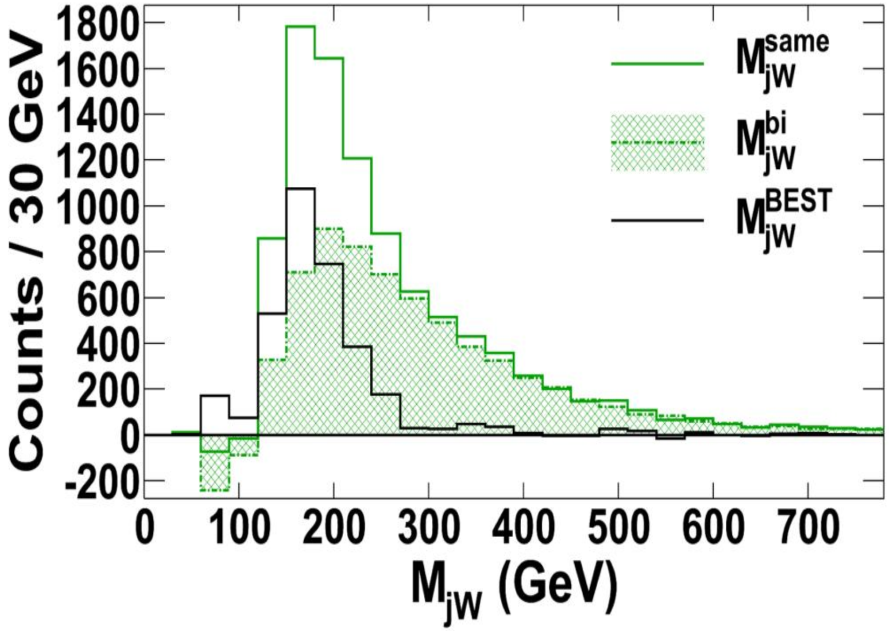


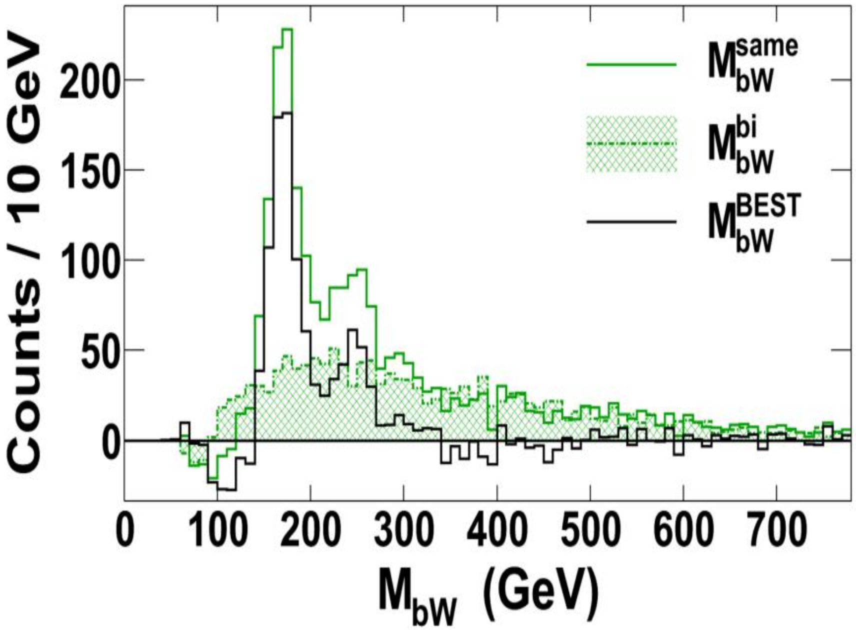
Event selection:
(a) $p_T(j_{1,2}) \geq 200$ GeV, in $|\eta| \leq 2.5$
(b) $\geq$ 4 jets, with $p_T(j) \geq 30$ GeV in $|\eta| \leq 2.5$
(c) MET > 180 GeV
(c) $p_T(j_1) + p_T(j_2)$ + MET $\geq$ 600 GeV
(d) For M_{bW}, $\geq$ 1 tightly tagged b jets (42% efficiency, 2% fake rate).

Data simulation:
ISAJET + PYTHIA + PGS4

End points & Stop mass

50 fb^{-1} @ 14 TeV





Observable	Value	50 fb^{-1} Stat.	100 fb^{-1} Stat.
M_{jW}^{end}	287.55	0.74	0.52
M_{bW}^{end}	325.67	4.50	3.18

$$M_{bW} = M_{bW}(m_{\tilde{b}}, m_{\tilde{t}}, m_{\tilde{g}})$$

$$M_{jW} = M_{jW}(m_{\tilde{b}}, m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$$

Particle	Mass	50 fb^{-1} Stat.	100 fb^{-1} Stat.
$\tilde{b}$	531	-60, +60	-47, +47
$\tilde{t}$	326	-5, +8	-4, +7

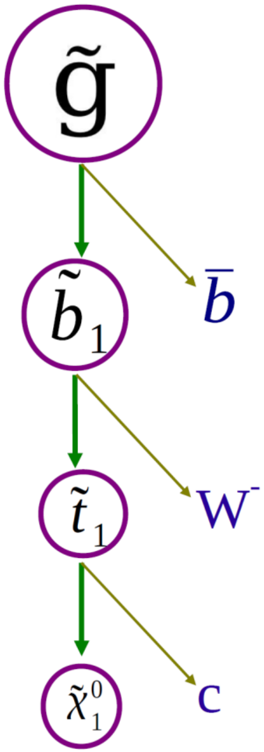
Results for a heavy mass spectrum

Our strategy works for heavy mass spectrum ← need more luminosity.

$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 39\ \text{GeV} < m_W$

Particle	Mass	Particle	Mass	Particle	Mass
$\tilde{d}_L$	1190	$\tilde{e}_L$	888	$\tilde{\chi}_1^0$	666
$\tilde{d}_R$	1169	$\tilde{e}_R$	850	$\tilde{\chi}_2^0$	740
$\tilde{u}_L$	1188	$\tilde{\tau}_1$	721	$\tilde{\chi}_3^0$	836
$\tilde{u}_R$	1167	$\tilde{\tau}_2$	840	$\tilde{\chi}_4^0$	870
$\tilde{b}_1$	980			$\tilde{\chi}_1^\pm$	739
$\tilde{b}_2$	1084			$\tilde{\chi}_2^\pm$	868
$\tilde{t}_1$	705			$\tilde{g}$	1187
$\tilde{t}_2$	1044				

Particle	Mass	200 fb^{-1} Stat.
$\tilde{b}$	690	± 6
$\tilde{t}$	1002	± 126



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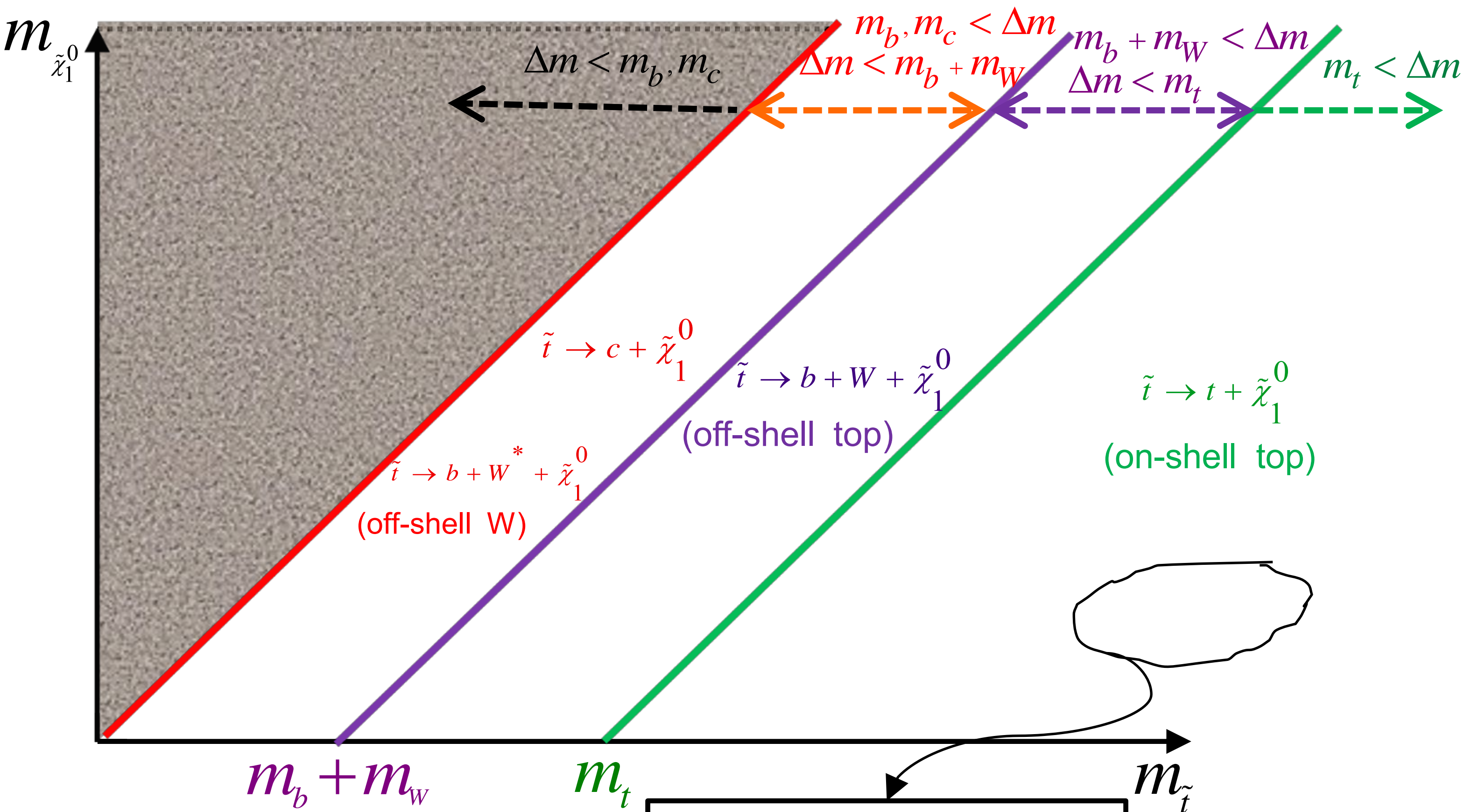
Conclusion

Fully hadronic final state scenario

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$$



Fully hadronic final state scenario:

$\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B},\ \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to t + \tilde{\chi}_1^0$

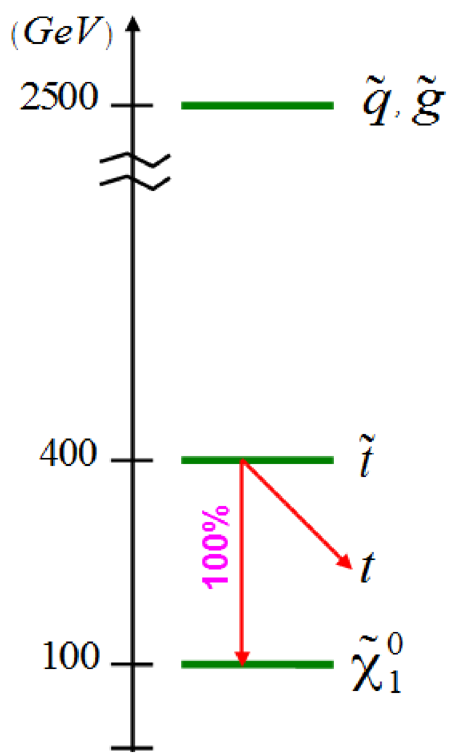
$\geq$ 4 j + $\geq$ 2 b + MET

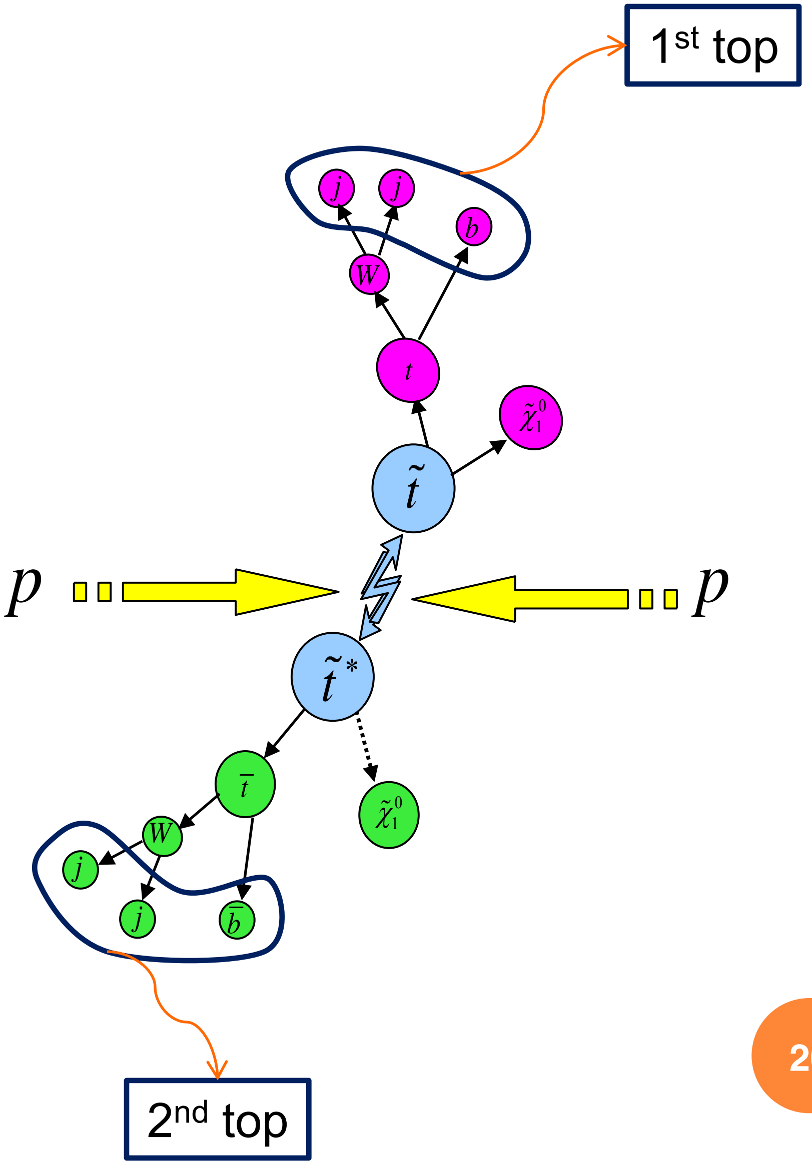
Fully hadronic final state scenario

B. Dutta, T. Kamon, N. Kolev, K. Sinha, and **K. Wang**, Phys.Rev. D**86** (2012) 075004 [hep-ph/1207.1873].

$\Delta m > m_t$; $\tilde{t}_1 \sim \tilde{t}_R$; $\tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to t + \tilde{\chi}_1^0$

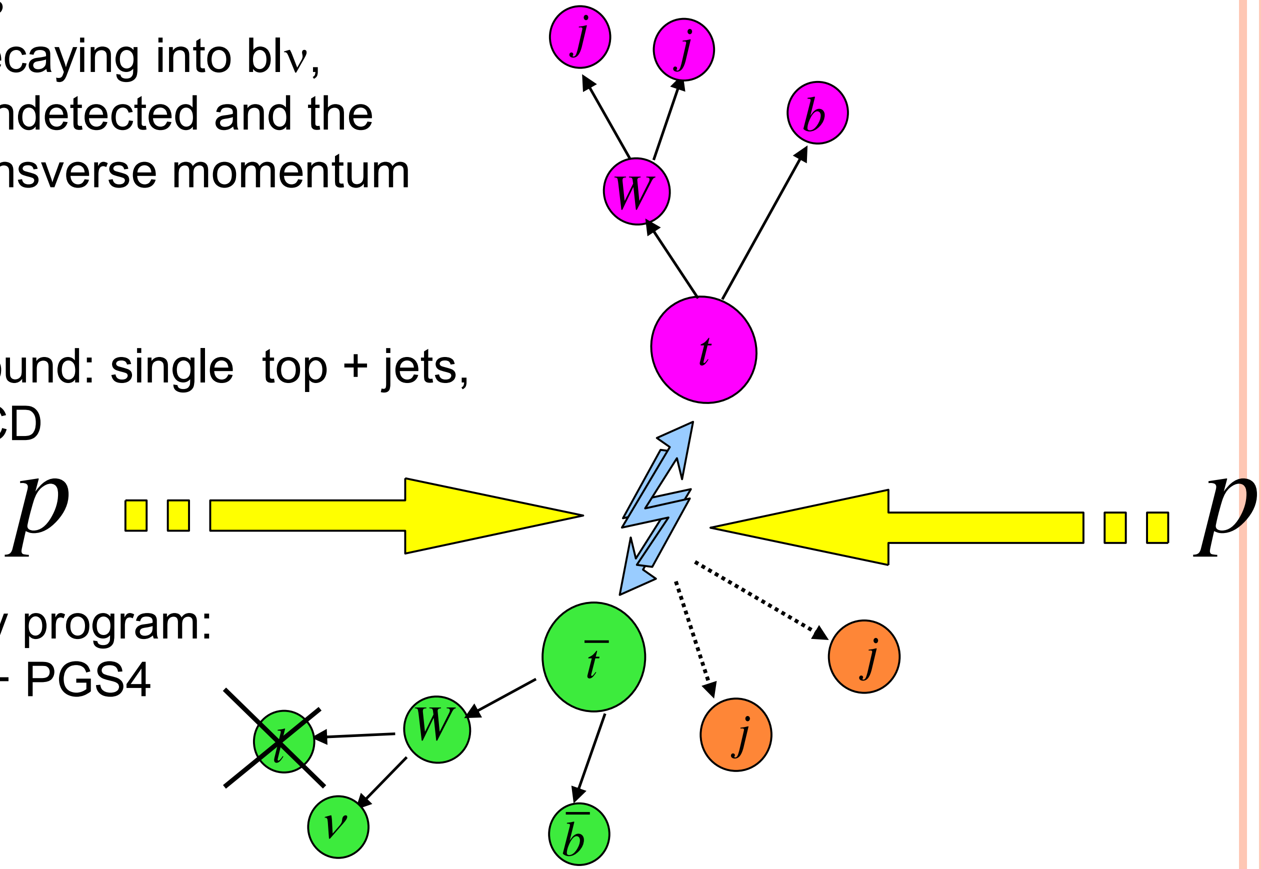
$$pp \to \tilde{t}\,\tilde{t}^* \to (t\tilde{\chi}_1^0)(t\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0)$$





Background

Dominant: t tbar + jets
With one top quark decaying into blν,
where the lepton is undetected and the
produces missing transverse momentum

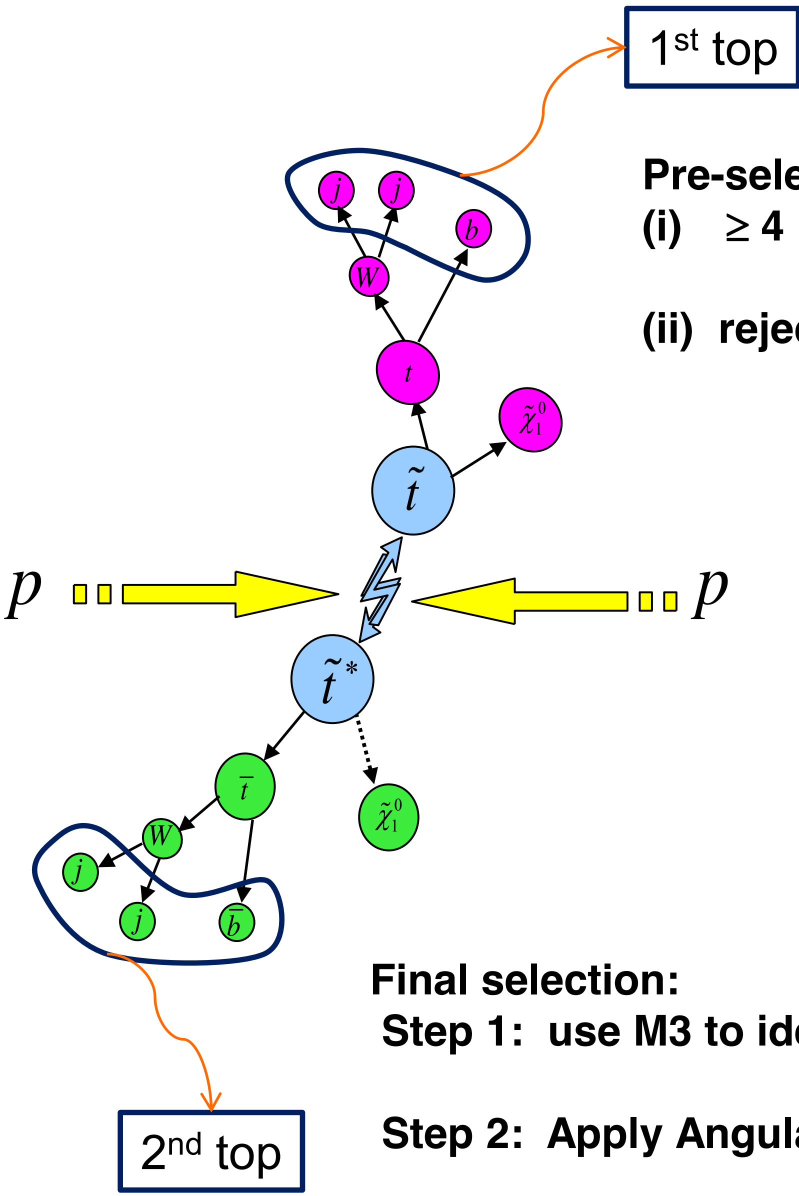


Others small background: single top + jets,
W + jets, Z + jets, QCD

BG data simulated by program:
ALPGEN + PYTHIA + PGS4

Signal data simulated by program:
ISAJET + PYTHIA + PGS4

Search strategy



Pre-selection:

(i) $\geq$ 4 non-b jets + $\geq$ 2 loosely tagged b jets + large MET

(ii) reject events with any lepton (electron, muon), or tau.

Event selection:

(a) $p_T(j) \geq 30$ GeV, in $|\eta| \leq 2.5$

(b) $p_T(j_1) \geq 100$ GeV

(c) $\geq$ 4 non b jets, $\geq$ 2 loosely tagged b jets

(d) MET > 100 GeV

(e) veto leptons (electrons or muons) with $p_T \geq 10$ GeV in $|\eta| \leq 2.5$, and $\sum p_{T,iso}^{track} \leq 5$ GeV and ΔR=0.4

(f) veto hadronically decaying tau, with $p_T \geq 20$ GeV in $|\eta| \leq 2.1$ (60% efficiency, 2% fake rate).

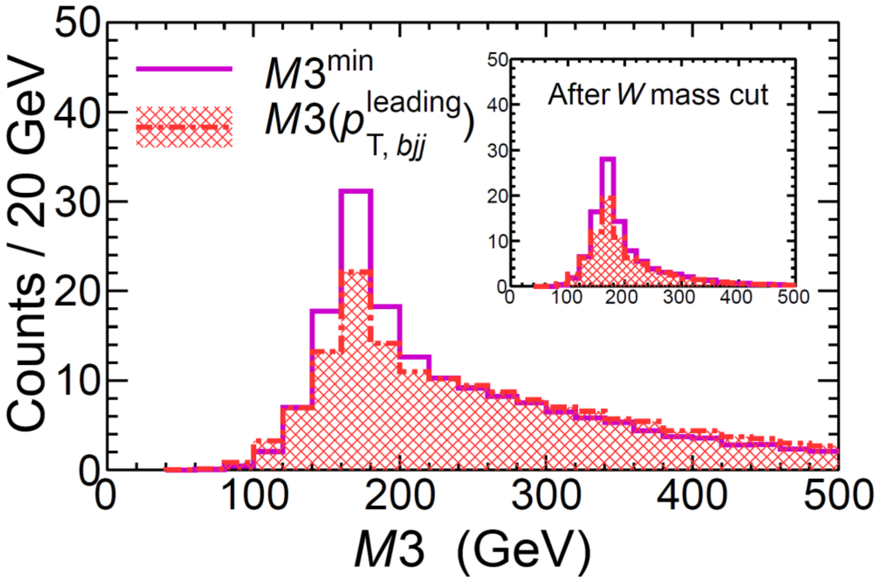
Final selection:

Step 1: use M3 to identify the 1st top, (b, j, j) system.

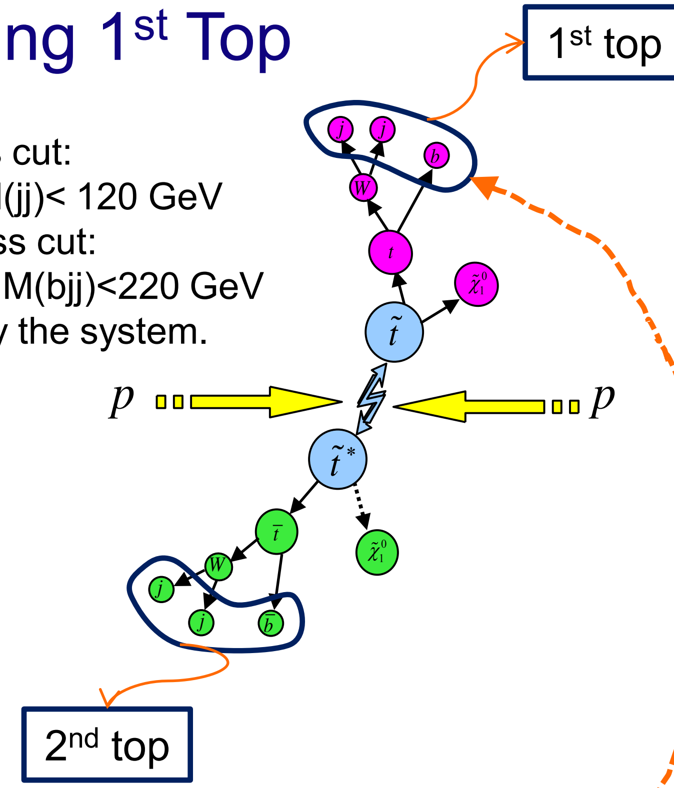
Step 2: Apply Angular and M_T cuts to reduce SM background.

Step 3: Use M3 again to reconstruct the 2nd top.

M3 Technique: Identifying 1st Top



W mass cut:
40<M(jj)< 120 GeV
Top mass cut:
120< M(bjj)<220 GeV
To purify the system.



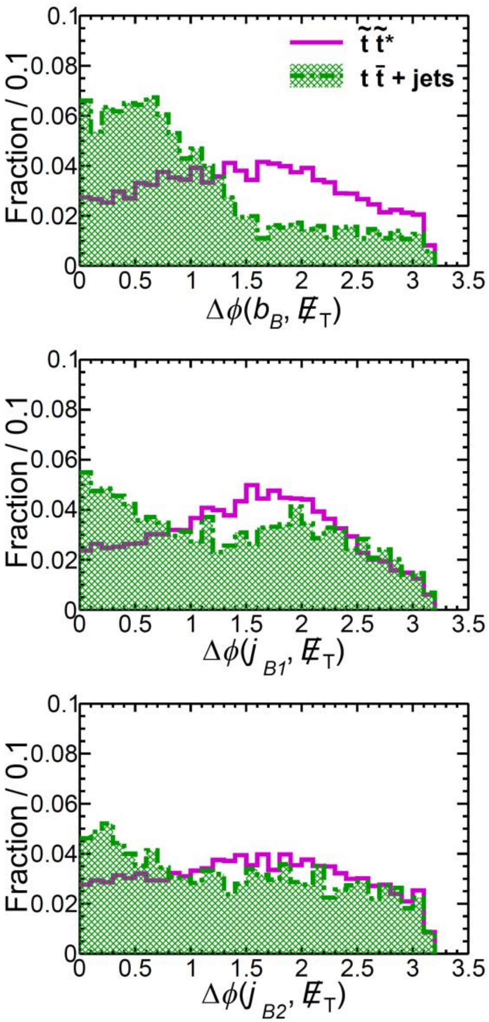
M3 has been improved to identify hadronic decaying top.
Use minimal χ^2 to pick up a better one.

$$\left\{\begin{matrix} b,\ b \\ j,\ j,\ j,\ j \\ \not{E}_T \end{matrix}\right\} \xrightarrow[\text{(b, j, j)}]{\text{all possible}} \left\{\begin{matrix} PT^{1st}(\overbrace{b,\ j,\ j}^{M3 = M(bjj)}) \quad \chi^2 = \frac{(M3-170)^2}{15^2} + \frac{(M2-80)^2}{10^2} \\ PT^{2nd}(b,\ \underbrace{j,\ j}_{M2 = M(jj)}) \\ \ldots\ldots \end{matrix}\right. \longrightarrow \left\{\begin{matrix} \chi_1^2 \\ \chi_2^2 \end{matrix}\right. \xrightarrow{if\ \chi_2^2 < \chi_1^2} (b,\ j,\ j)$$

1st tagged top

23

Angular and M_T cuts to reduce SM BG



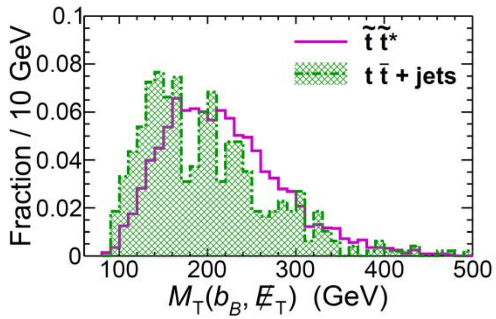
MET:

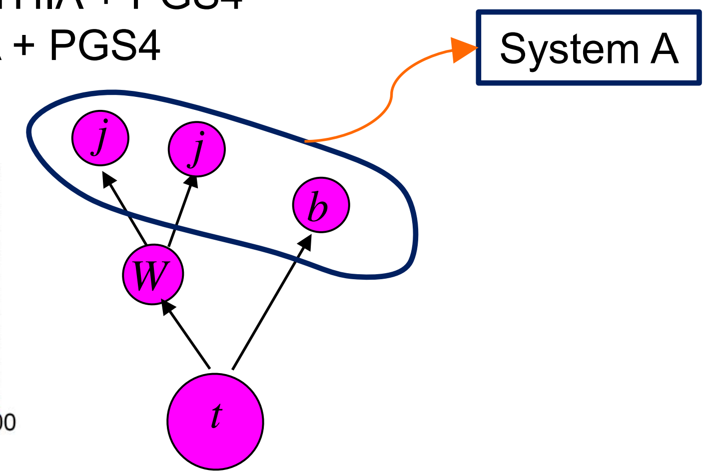
t tbar + jets --- neutrino from lepton side

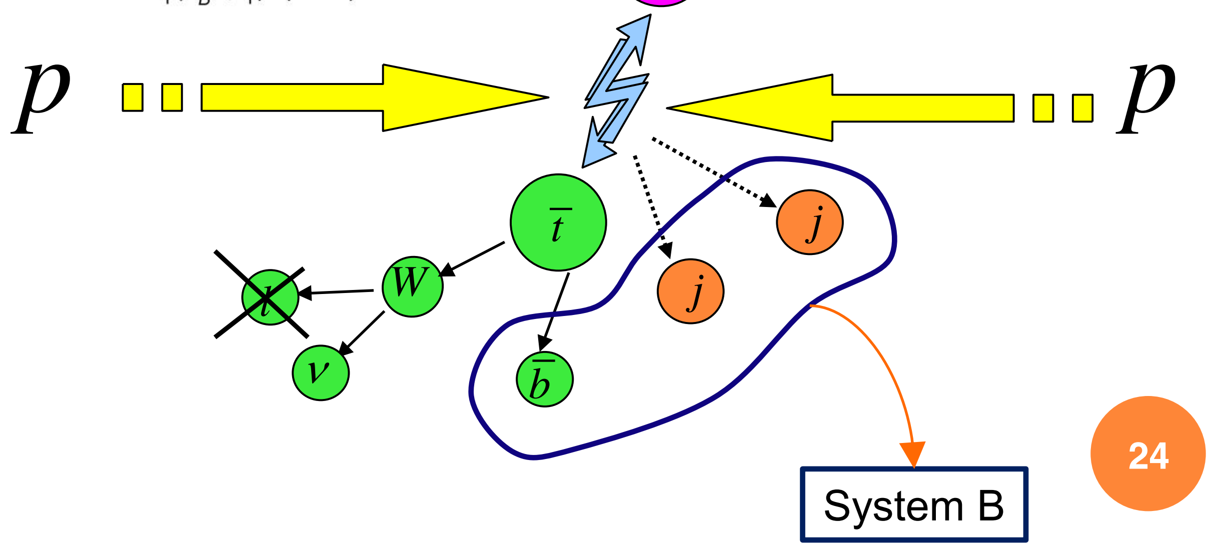
Stop pair ------ neutralino from both sides

Stop pair: ISAJET + PYTHIA + PGS4

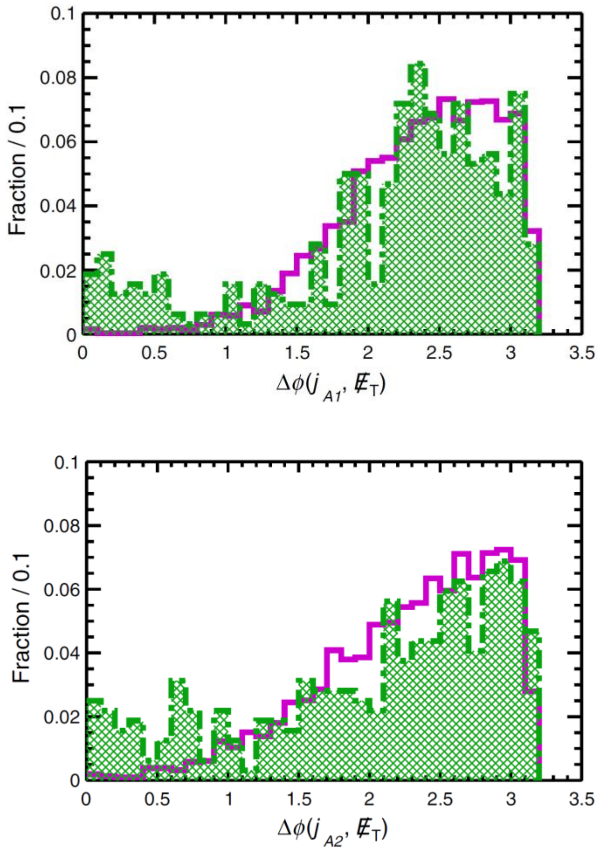
BG: ALPGEN + PYTHIA + PGS4

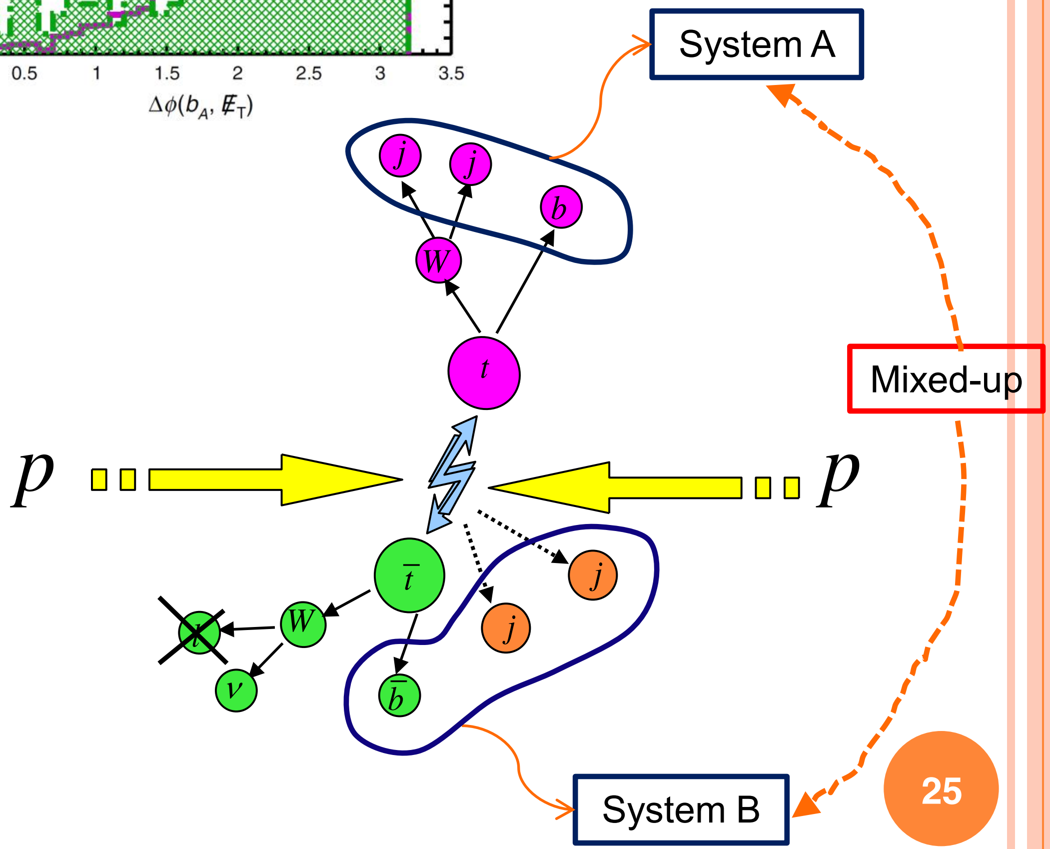




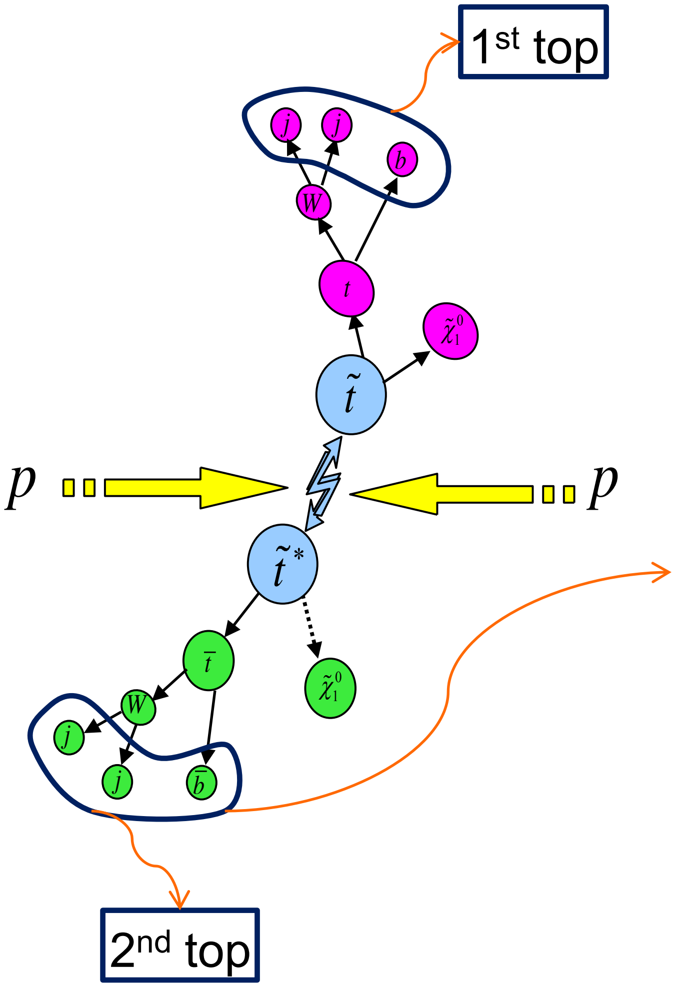


Angular and M_T cuts to reduce SM BG



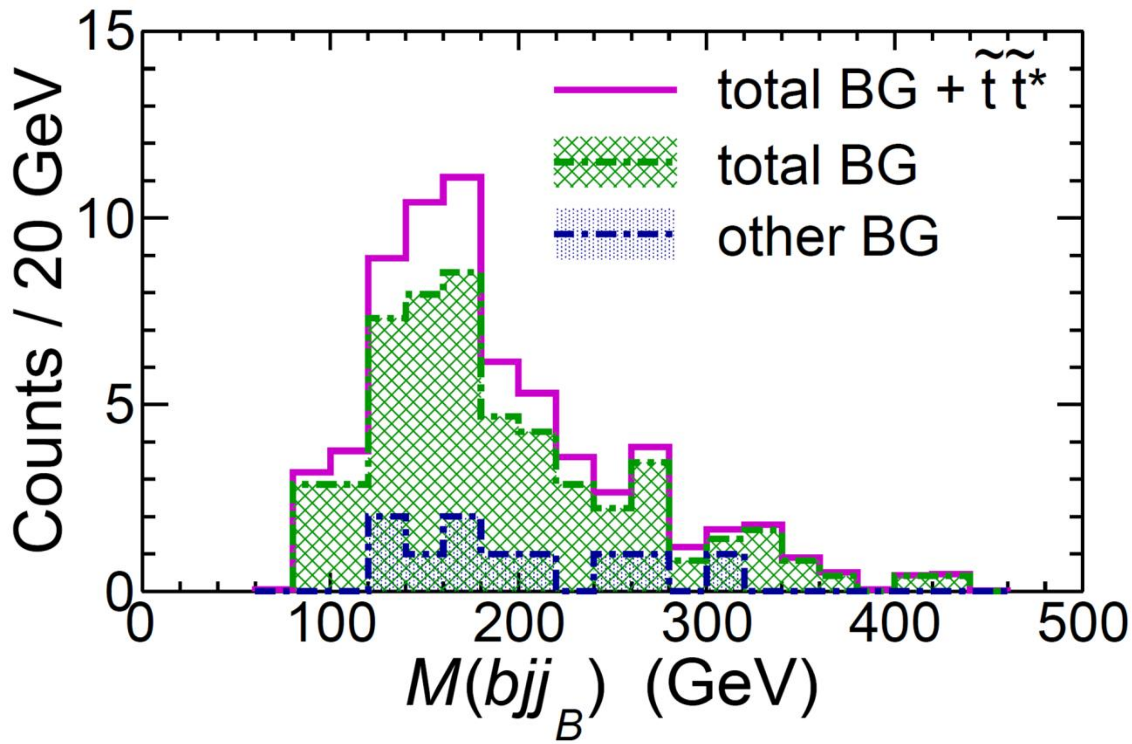


M3 Technique: Identifying 2nd Top



2nd top

8 TeV, 50 fb^{-1}
After W mass window cut: 40< M(jj$_B$)< 120 GeV



other BG: single top + jets, W + n jets, Z + n jets with n ≤ 6
total BG: other BG, t tbar + n jets with n ≤ 6

Significance

S ~ B @ 50 fb^{-1}, 8 TeV.
Stop mass: 350 ~ 550 GeV

Cuts are optimized for each point.

TABLE IV. Final significance for various choices of masses. All masses are in GeV. The luminosity is 50 fb^{-1}.

$\tilde{t}$	350	400	450	500	550	400	400
$\tilde{\chi}_1^0$	100	100	100	100	100	150	200
$S/\sqrt{B}$	1.29	1.71	1.39	0.81	0.35	0.94	0.47

1st top

Cross section (fb)

		Signal	$t\bar{t} + n(\leq 2)$jets	$t\bar{t} + n(\geq 3)$jets	Others
$m_{\tilde{t}} = 400$ $m_{\tilde{\chi}_1^0} = 100$	Initial	337	2.0×10^5	0.24×10^5	2.8×10^6
	Baseline Cuts (Sec. III B)	5.55	192	147	31.7
	$\not{E}_T > 170$ GeV	3.62	53, 4	47.0	11.1
	System A: $M3$ (Sec. III C)	1.46	15.4	9.73	1.82
	Angular and M_T cuts (Sec. III D)	0.44	0.96	1.06	0.54
	System B: $M3$ (Sec. III E)	0.20	0.26	0.28	0.14
	Significance ($S/\sqrt{B}$)		1.71		

2nd top

0.20

0.68

27

OUTLINE

Supersymmetry Top Squark ($\tilde{t}$)

- Motivation
- LHC search status

Search from Cascade Decay

- $\tilde{t}$ - $\tilde{\chi}_1^0$ Coannihilation Scenario
- Endpoint measurements

Fully Hadronic Final State Scenario

- M3 technique

Bino-Higgsino Dark Matter Scenario

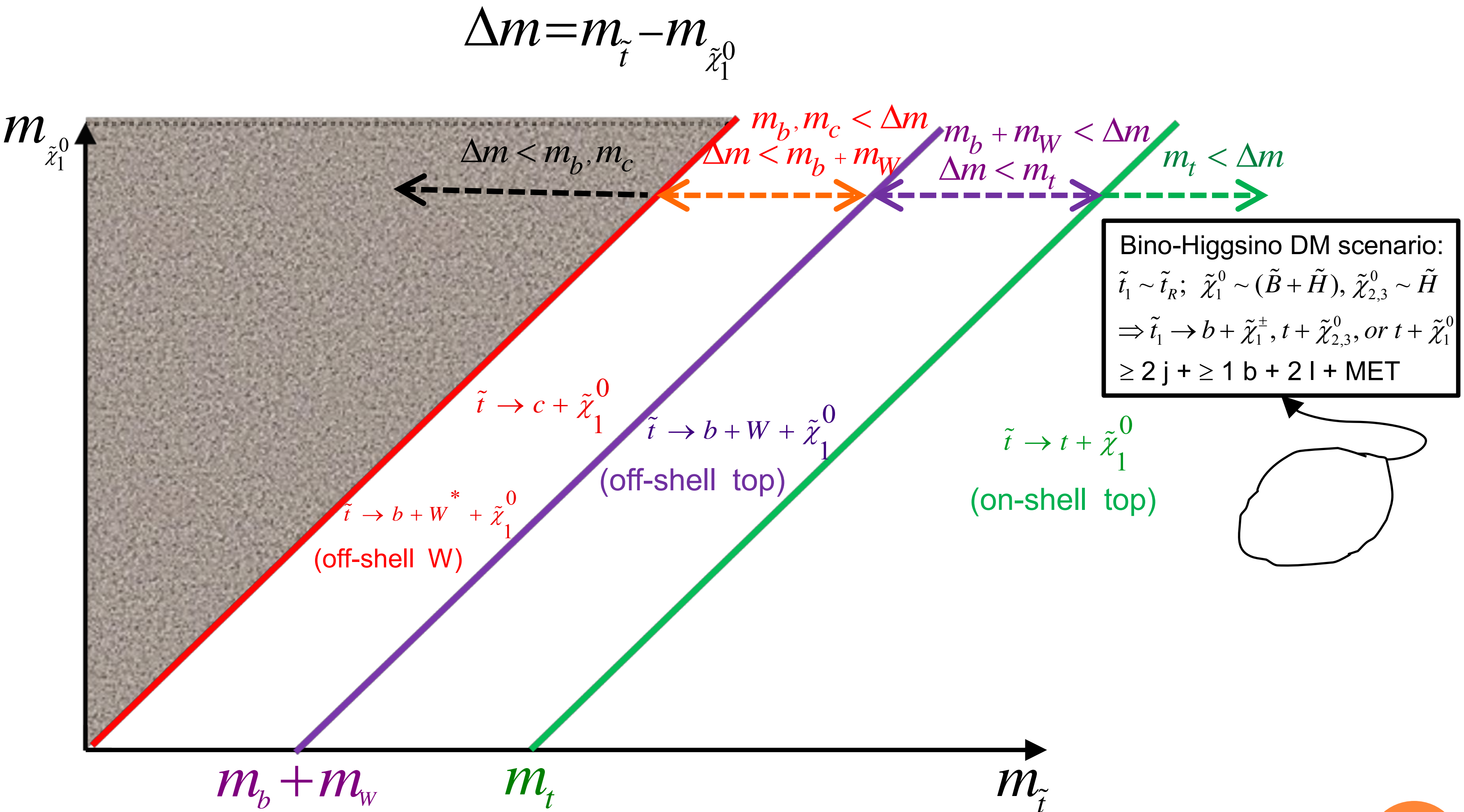
- Dilepton invariant mass distribution
- Light slepton & heavy slepton cases

Compressed Scenario

- VBF topology selection
- Two-body decay & three-body decay cases

Conclusion

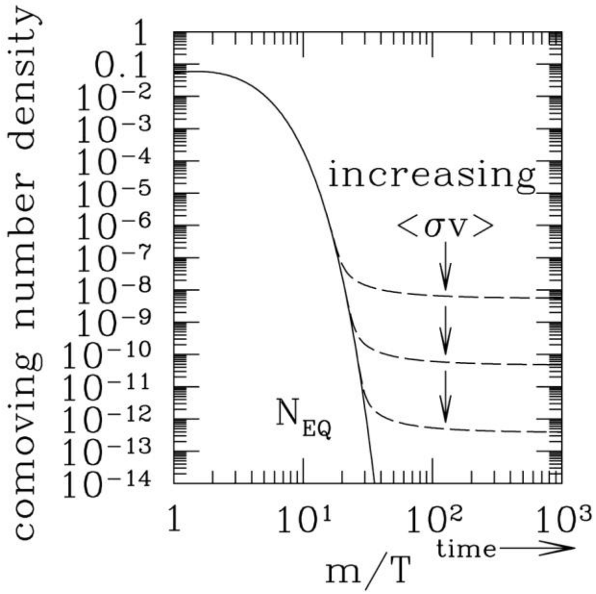
Bino-Higgsino DM Scenarios



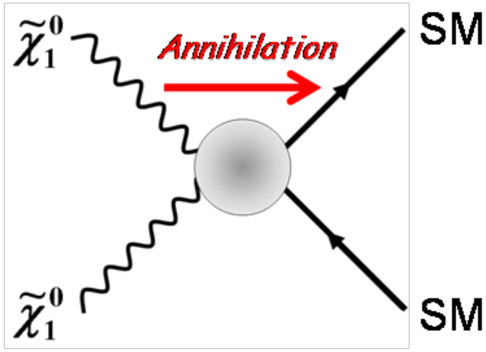
Bino-Higgsino DM scenario

B. Dutta, T. Kamon, N. Kolev, K. Sinha, **K. Wang** and S. Wu, Phys. Rev. D**87** (2013) 095007 [hep-ph/1302.3231].

$\Delta m > m_t$; $\tilde{t}_1 \sim \tilde{t}_R$; $\tilde{\chi}_1^0 \sim (\tilde{B}+\tilde{H})$, $\tilde{\chi}_{2,3}^0 \sim \tilde{H} \Rightarrow \tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, t+\tilde{\chi}_{2,3}^0$, or $t+\tilde{\chi}_1^0$



After EW symmetry breaking, $\tilde{\chi}_1^0 \sim (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$ $\tilde{\chi}_1^+ \sim (\tilde{W}^+, \tilde{H}_u^+)$ $\tilde{\chi}_1^- \sim (\tilde{W}^-, \tilde{H}_d^-)$



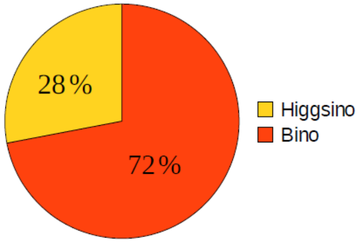
Composition	To satisfy relic density	Generic case			Comments
		σ_{ann}	Relic density	Possible mechanism	
Bino	20 - 100 GeV, depending on a slepton mass	small	large	Non-thermal, resonance, coannihilation,	Dominant: t channel slepton exchange
Wino	~ 2.4 TeV	large	small	Non-thermal, multi-component, well-tempering mixture, etc.	
Higgsino	~ 1 TeV	large	small		Strong bound from direct production

30

Search Strategy

$$\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim (\tilde{B}+\tilde{H}),\ \tilde{\chi}_{2,3}^0 \sim \tilde{H}$$

$$\tilde{t} \to \tilde{\chi}_{3,2}^0 + t \to \tilde{\chi}_1^0 + l^{\pm} + l^{\mp} + t\ (\text{via}\ \tilde{l}\ or\ Z)$$



- $\geq$ 2 j + $\geq$ 1 b + 2 l (OSSF) + MET,
- Di-lepton invariant mass distribution (OSSF-OSDF).

Event selection:

(a) p_T (j) $\geq$ 30 GeV, in $|\eta| \leq 2.5$

(c) $\geq$ 2 jets

(d) $\geq$ 1 b jets

(e) 2 leptons (electrons or muons) with $p_T \geq$ 20 GeV and 10 GeV in $|\eta| \leq 2.5$, and $\sum p_{T,iso}^{track} \leq 5$ GeV and ΔR=0.4

(d) MET > 150 GeV

(e) H_T > 100 GeV.

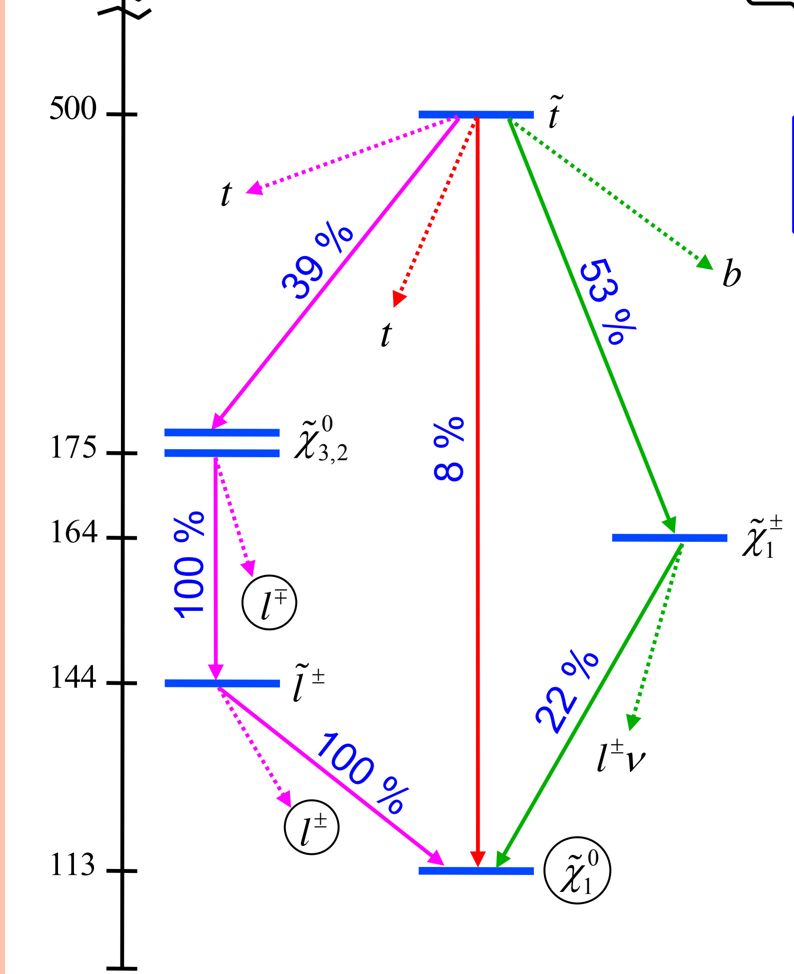
Light slepton case

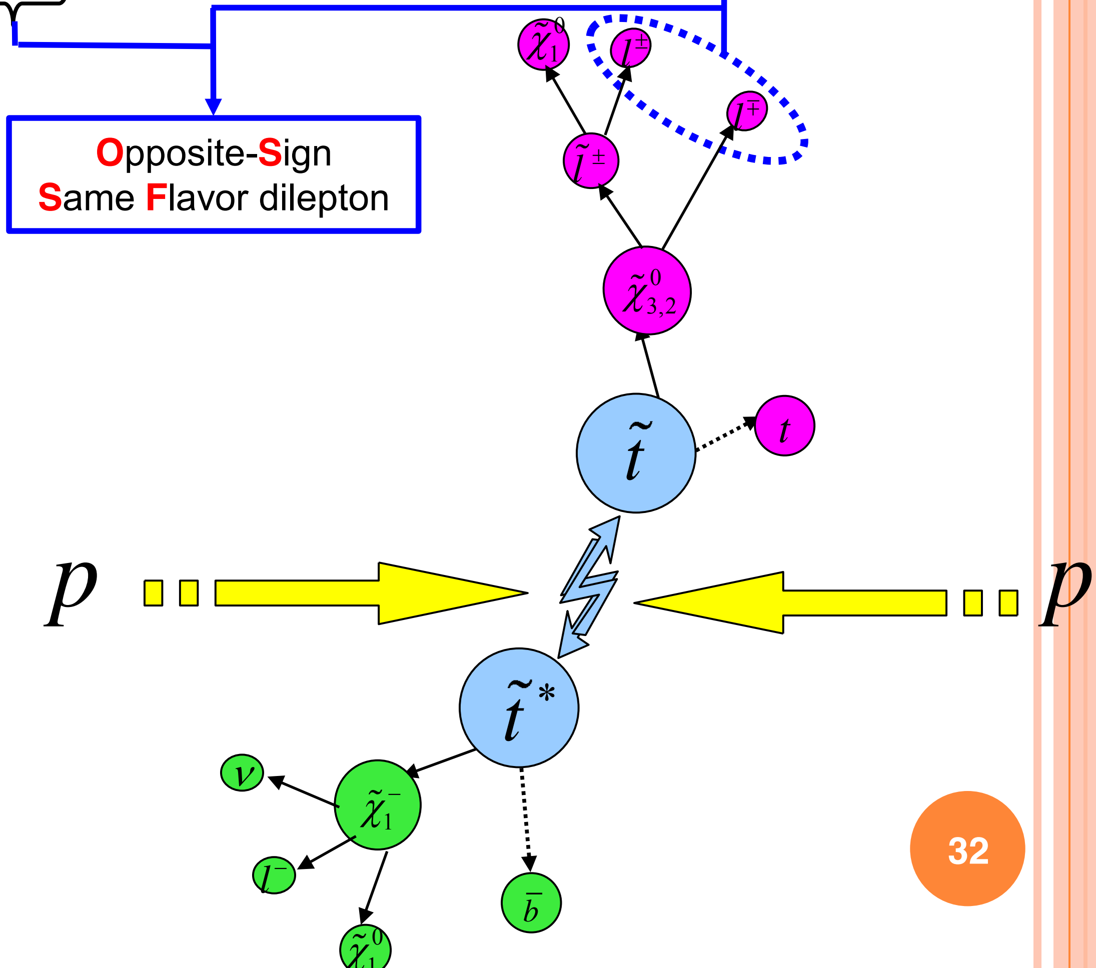
$\tilde{\chi}^0_{2,3} \sim \tilde{\text{H}}$ almost degenerate.

$$\tilde{t} \to \tilde{\chi}^0_{3,2} + t \quad (39\%)$$

$$\tilde{\chi}^0_{3,2} \to \tilde{\chi}^0_1 + l^\pm + l^\mp \quad (100\%, \text{ via } \tilde{e}^\pm \text{ or } \tilde{\mu}^\pm)$$

$$M_{ll}^{edge} \sim \Delta M = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$$



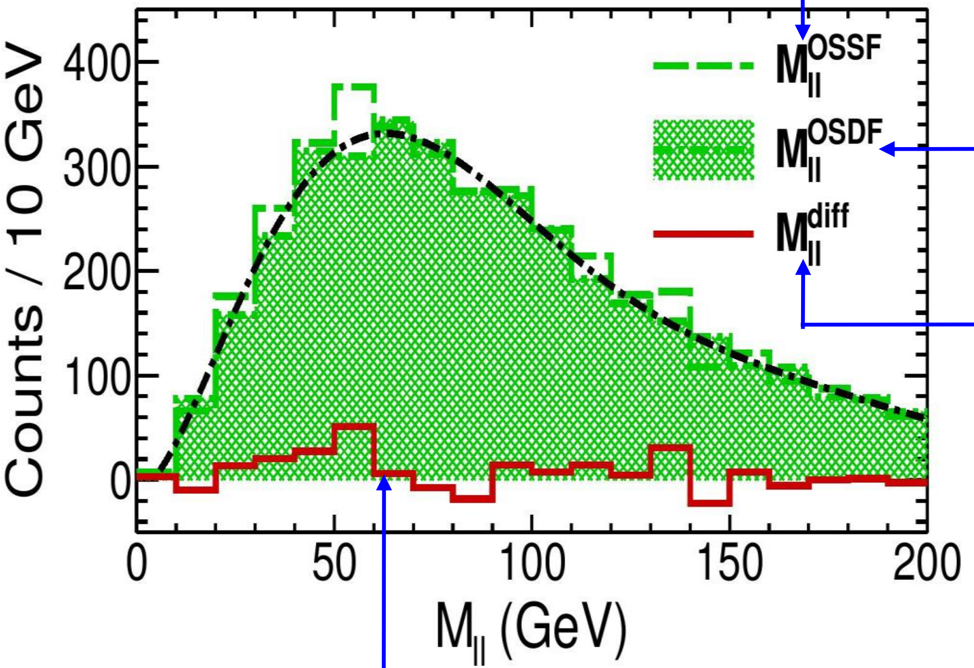


Dilepton mass distribution

Final State:
≥ 2 j + ≥ 1 b + 2 l (OSSF) + MET
MET > 150 GeV
H_T > 100 GeV

Dominant SM BG: $t\bar{t} + jets$

30 fb^{-1} luminosity, 8 TeV



OSSF $(e^{\pm}e^{\mp} + \mu^{\pm}\mu^{\mp})$
$\tilde{t}\tilde{t}^*$ and $t\bar{t} + (0-4)$ jets

OSDF $(e^{\pm}\mu^{\mp} + \mu^{\pm}e^{\mp})$
$\tilde{t}\tilde{t}^*$ and $t\bar{t} + (0-4)$ jets

OSSF – OSDF

A clear edge around
$\Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 63\, GeV$

BG data simulation:
MadGraph + PYTHIA + PGS4

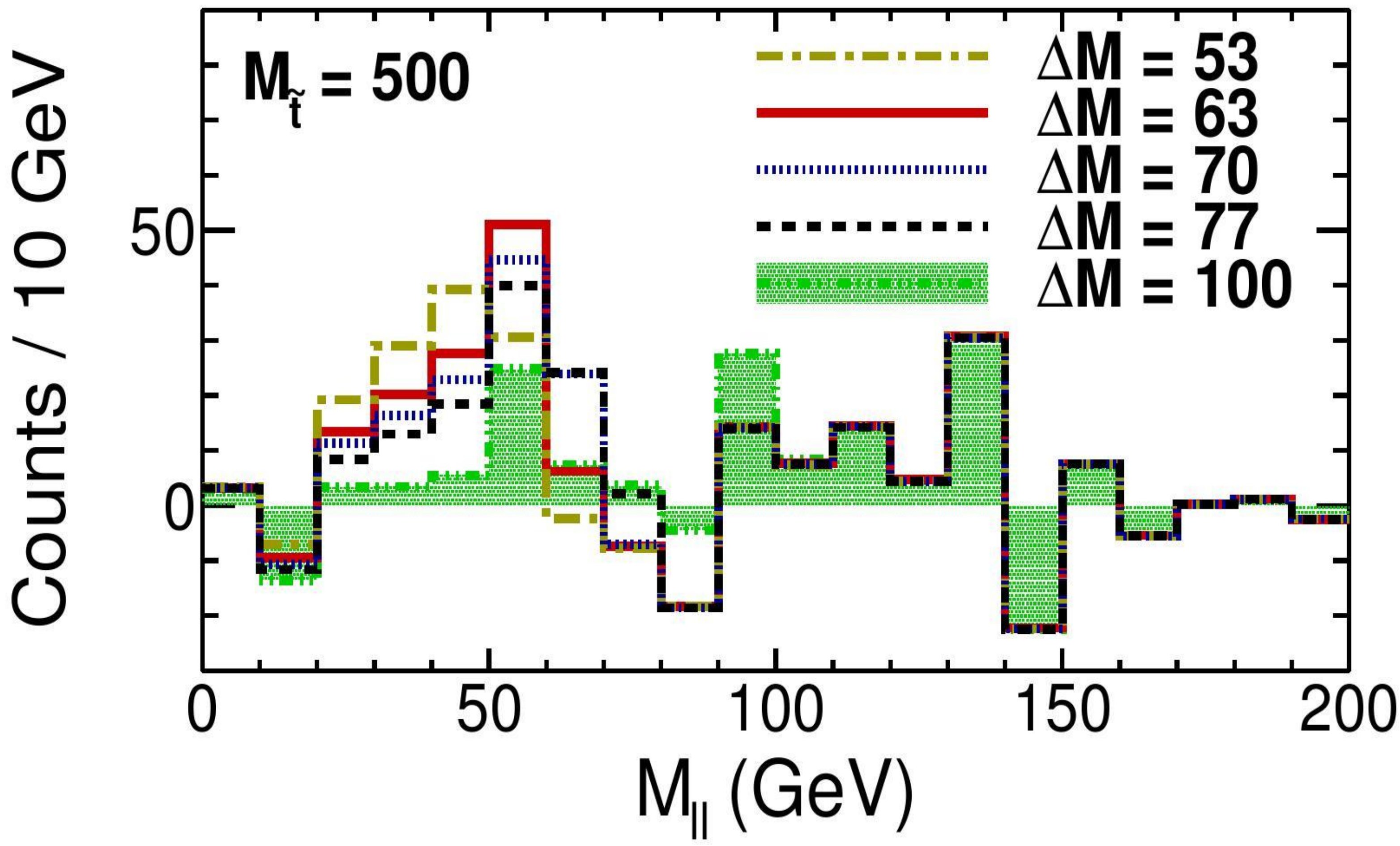
Signal data simulation:
ISAJET + PYTHIA + PGS4

Dilepton mass distribution

The edge shifts with $\Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

30 fb[-1] luminosity, 8 TeV

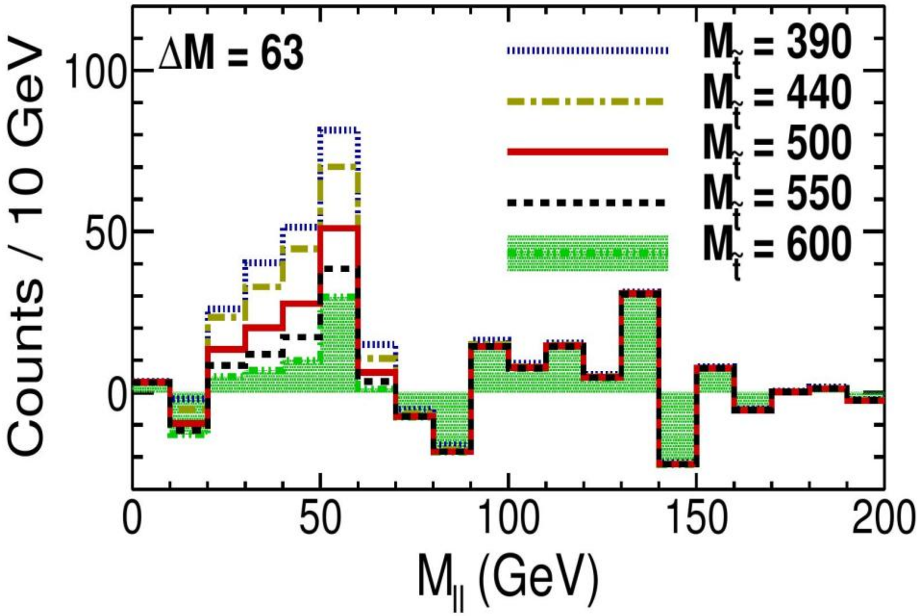
$\tilde{\chi}_{3,2}^0 \rightarrow \tilde{\chi}_1^0 + l^{\pm} + l^{\mp}$ (100%, via $\tilde{e}^{\pm}$ or $\tilde{\mu}^{\pm}$)



34

Significance

30 fb^{-1} luminosity, 8 TeV



30 fb^{-1} luminosity, 8 TeV

$$20\,GeV < M_{ll} < 70\,GeV$$

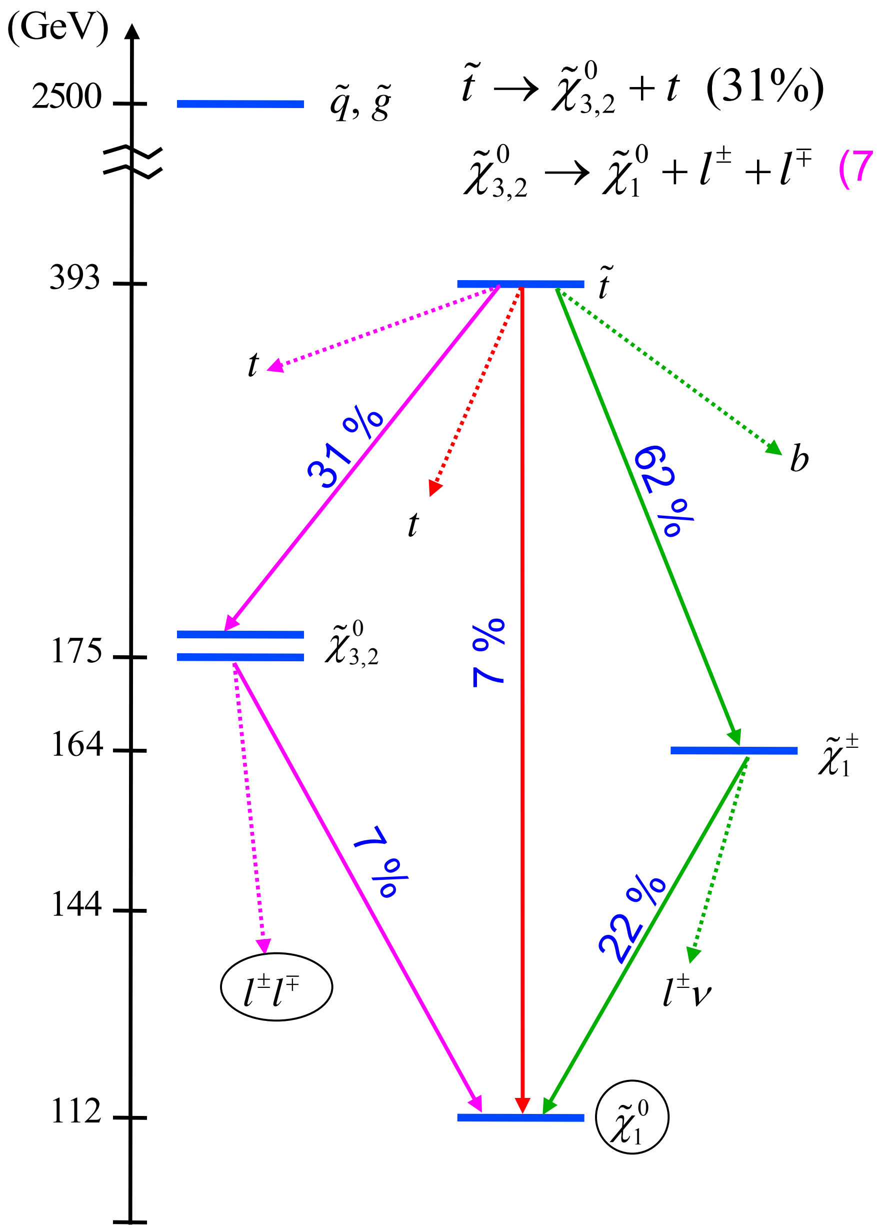
$$s = \frac{N_S}{\sqrt{N_S + N_B}}$$

$m_{\tilde{t}}$	Signal	Background	significance
(GeV)	(N_S)	(N_B)	(s)
390	212	1392	5.3
440	180	1368	4.6
500	117	1354	3.1
550	78	1348	2.1
600	51	1345	1.4

distinguishable edge, for $m_{\tilde{t}} \leq 550\,GeV$.

significance $\sim 3\sigma$, for $m_{\tilde{t}} = 500\,GeV$.

Heavy slepton case



$\tilde{t} \to \tilde{\chi}^0_{3,2} + t \ \ (31\%)$

$\tilde{\chi}^0_{3,2} \to \tilde{\chi}^0_1 + l^\pm + l^\mp$ (7%, via Z boson)

30 fb^{-1} luminosity, 8 TeV

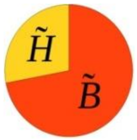
$$20\,GeV < M_{ll} < 70\,GeV$$

$$s = \frac{N_S}{\sqrt{N_S + N_B}}$$

$m_{\tilde{t}}$ (GeV)	Signal (N_S)	Background (N_B)	significance (s)
393	22	395	1.1

Small value of $Z \to ll$ branch ratio causes smaller significance.

$\tilde{B}$-$\tilde{H}$ Dark Matter



$$m_{\tilde{\chi}_1^0} = 113\, GeV \qquad \Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

Masses	$\tilde{B}$	$\tilde{H}$	Ωh^2	s	Comments
(GeV)	(%)	(%)		(30 fb^{-1})	
$\Delta M = 160$					Mainly Bino DM
$m_{\tilde{l}} = 123$	96	4	0.11	0.44	(Coannihilation)
$m_{\tilde{t}} = 500$					
$\Delta M = 63$					Bino-Higgsino DM
$m_{\tilde{l}} = 144$	72	28	0.11	3.1	(Light slepton scenario)
$m_{\tilde{t}} = 500$					
$\Delta M = 62$					Bino-Higgsino DM
$m_{\tilde{l}} = 4000$	67	33	0.11	1.1	(Heavy slepton scenario)
$m_{\tilde{t}} = 390$					

(a) $\tilde{\chi}_1^0 \sim \tilde{B}$,need $\tilde{\chi}_1^0 - \tilde{l}$ coannihilation.
a low p_T lepton $\longrightarrow$ small significance.

(b) $\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})$ and light $\tilde{l}$,
$\longrightarrow$ edge around ΔM .

(c) $\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})$ and heavy $\tilde{l}$,
$Z \to ll$ $\longrightarrow$ small significance.

OUTLINE

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- Dilepton invariant mass distribution
- Light slepton & heavy slepton cases

Compressed Scenario

- VBF topology selection
- Two-body decay & three-body decay cases

Conclusion

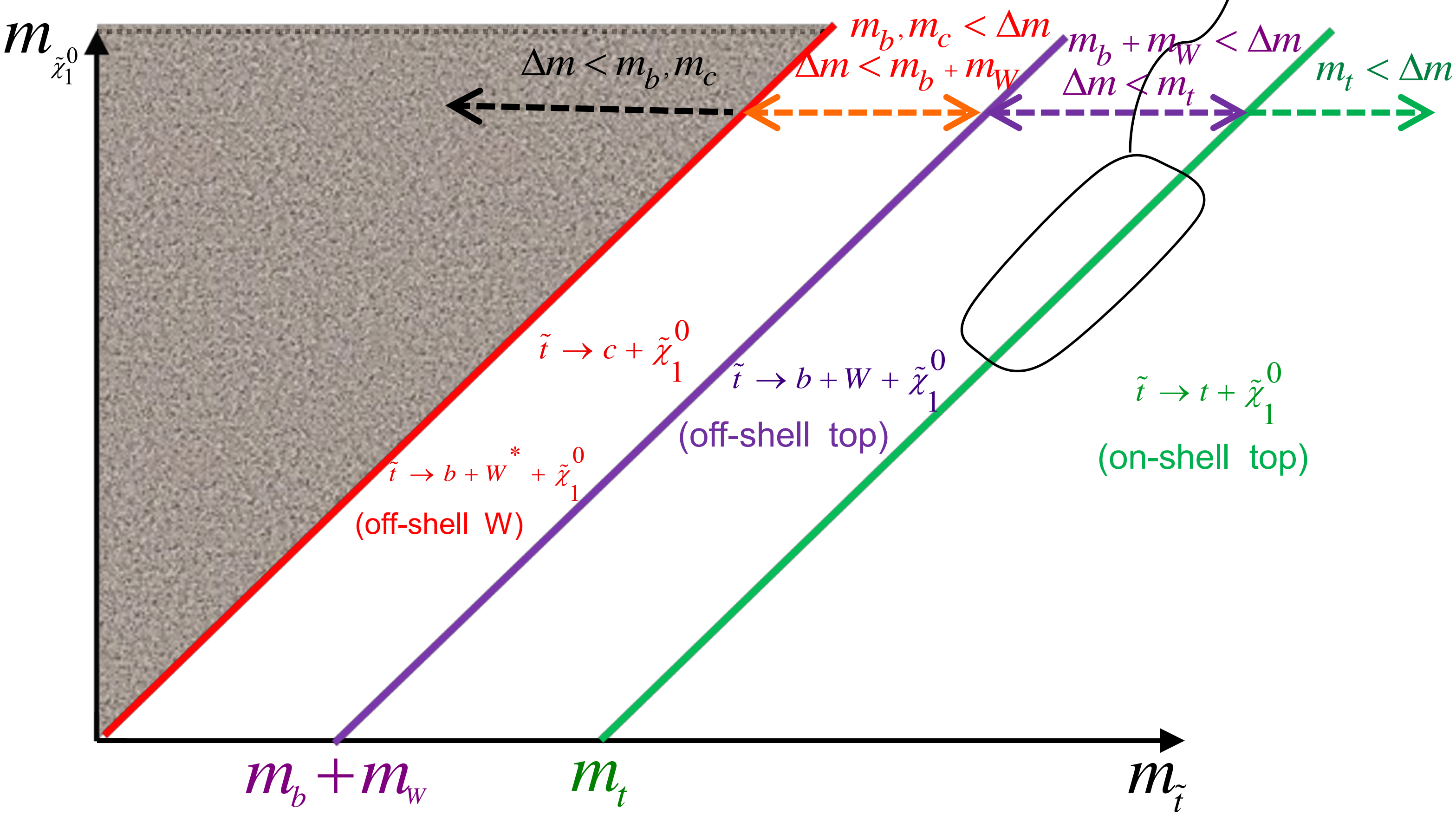
Compressed scenario

Compressed scenario:

$\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B},\ \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to t + \tilde{\chi}_1^0 \text{ or } b + W + \tilde{\chi}_1^0$

≥ 2 j + ≥ 2 b + ≥ 1 l + MET

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$$



Compressed Scenario

B. Dutta, W. Flanagan, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, **K. Wang** and S. Wu, [hep-ph/1312.1348].

$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \sim m_t$ $\quad \tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W}$

Two-body decay case: $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0}) = (200, 20)$ GeV

$\Delta m = m_t + 7\ \text{GeV}, m_t = 173\ \text{GeV}$

$\tilde{t}_1 \to t + \tilde{\chi}_1^0$

On-shell top, but soft jets/leptons

Three-body decay case: (200, 35) GeV

$\Delta m = m_t - 7\ \text{GeV} < m_t$

$\tilde{t}_1 \to b + W + \tilde{\chi}_1^0$

Off-shell top, even softer jets/leptons

Search strategy

- ≥ 2 j + ≥ 2 b + ≥ 1 l + MET. $pp \to \tilde{t}\,\tilde{t}^* + \text{jets} \to (bW\tilde{\chi}_1^0)(\bar{b}W\tilde{\chi}_1^0) + \text{jets}$
- VBF topology selection.

Event selection:

(a) VBF topology selection: ≥ 2 non b-tagged jets, j_1, j_2
  (1) $p_T(j_1) \geq 75$ GeV, $p_T(j_2) \geq 50$ GeV, in $|\eta| \leq 4$;
  (2) $|\Delta\eta(j_1, j_2)| > 3.5,\ \eta_{j_1}\eta_{j_2} < 0$
  (3) $m(j_1, j_2) > 500$ GeV
  This reduces the W+jets and Z+jets backgrounds.

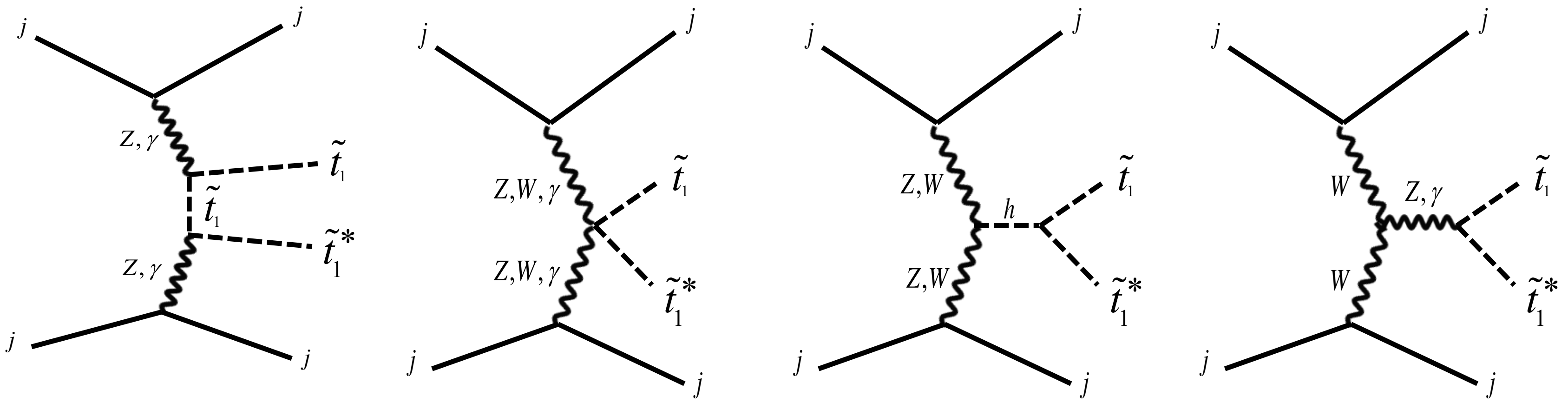
(b) ≥ 2 loosely tagged b jets with $p_T \geq 30$ GeV in $|\eta| \leq 2.5$,
  (70% efficiency, 1% fake rate).

(c) ≥ 1 leptons with $p_T \geq 20$ GeV

(d) Big MET requirement, optimized for each mass point.

VBF topology production

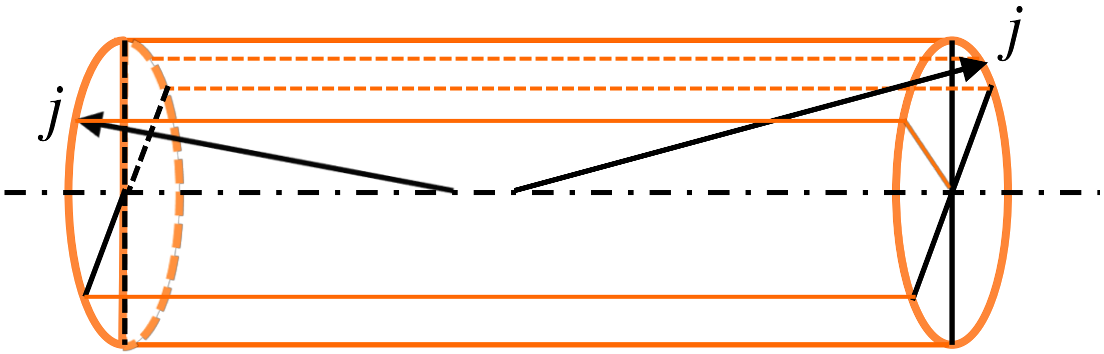
Vector Boson Fusion (VBF) production



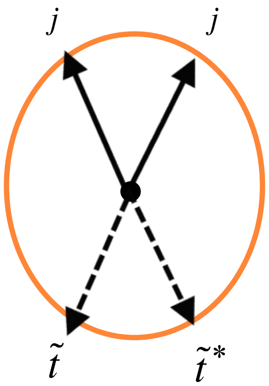
$pp \to \tilde{t}\,\tilde{t}^* + (0-3)$ jets, inclusively, QCD=4 QED=4

Samples are generated:
MadGraph + PYTHIA + PGS4

VBF topology signature



VBF tagged jets (2 energetic jets: large m_{jj} , forward region, opposite hemispheres)

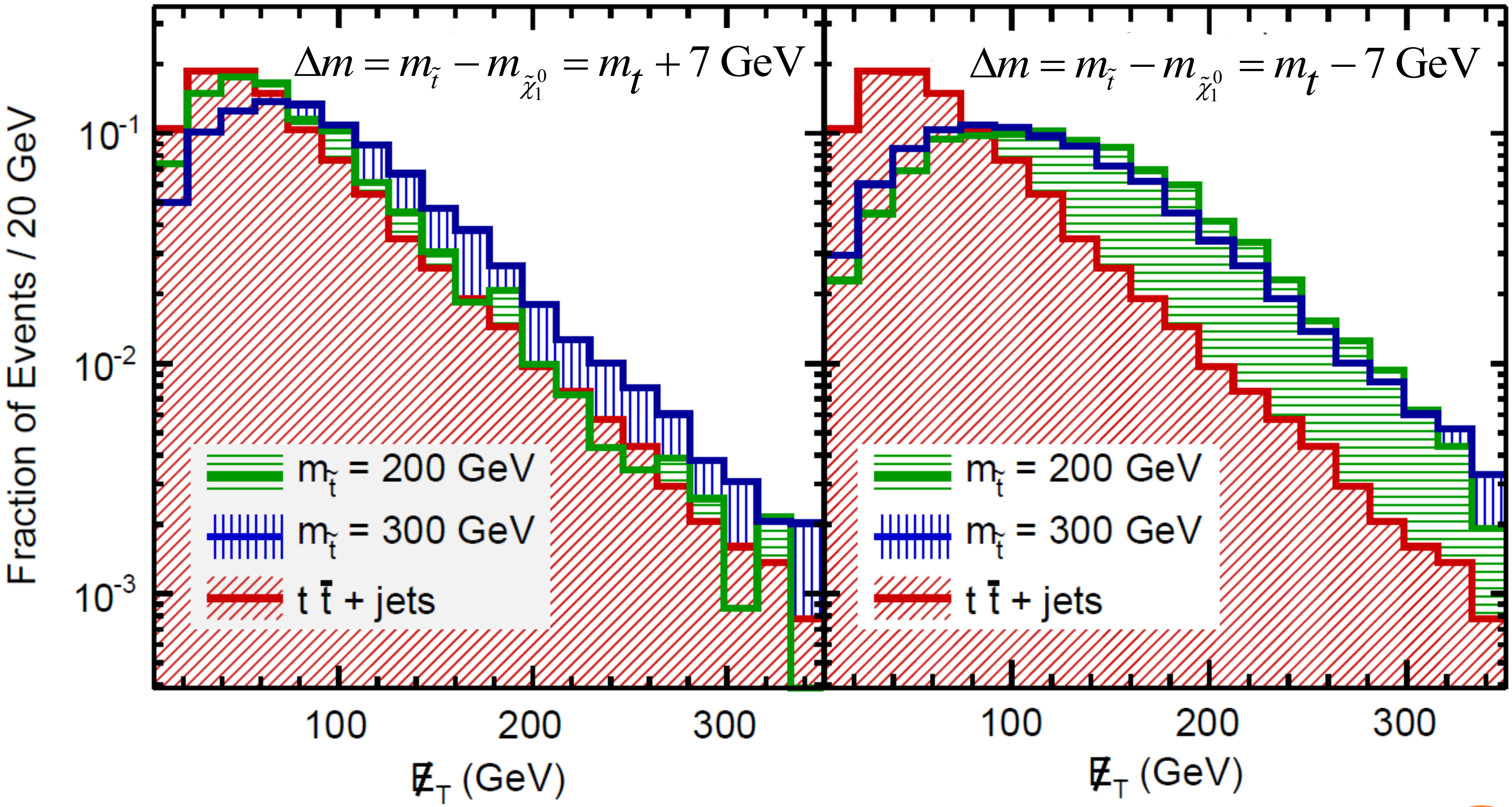


VBF production topology
Transverse plane

Advantages of VBF topology selection:

(a) VBF tagging jets
(b) Broad enhancements in MET
(c) Compressed scenarios
(d) Free from trigger bias
(e) Direct probing EW sector, complementary
← agnostic about colored sector

MET distribution



$\tilde{t}_1 \to t + \tilde{\chi}_1^0$

$\tilde{t}_1 \to b + W + \tilde{\chi}_1^0$

Cross sections (fb)

$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_t + 7$ GeV

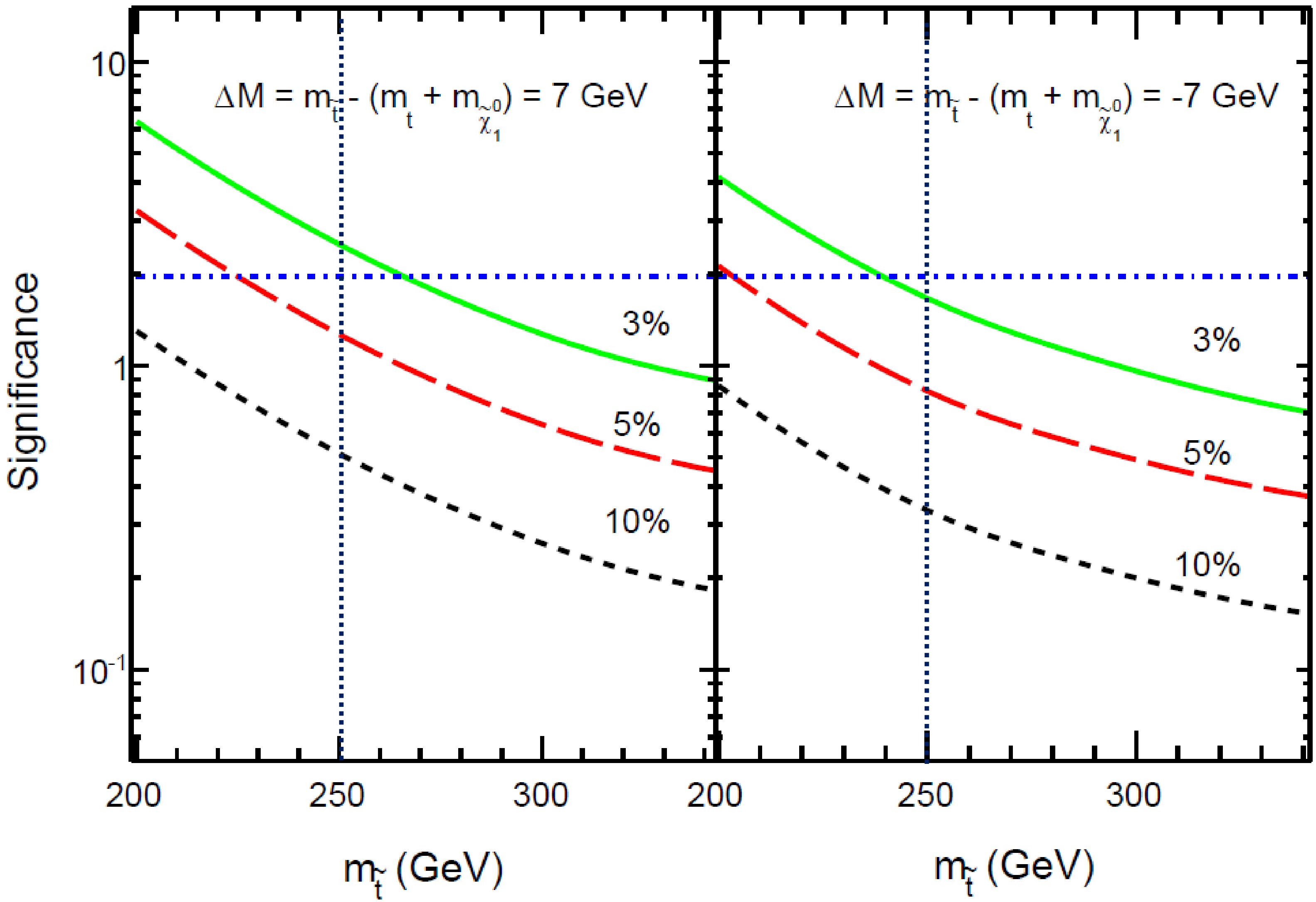
$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$+jets	S/B
(200, 20)	Pre cut	5.4×10^4	6.9×10^5	—
$\Delta M = 7$	VBF	1.8×10^3	3.8×10^4	—
	1 lepton	390	8.1×10^3	—
	2 b-jets	170	3.1×10^3	5.6×10^{-2}
	$\not{E}_T > 100$	44	680	6.5×10^{-2}
(300, 120)	Pre cut	7.4×10^3	6.9×10^5	—
$\Delta M = 7$	VBF	250	3.8×10^4	—
	1 lepton	56	8.1×10^3	—
	2 b-jets	32	3.1×10^3	1.0×10^{-2}
	$\not{E}_T > 100$	8.9	680	1.3×10^{-2}
(400, 220)	Pre cut	1.6×10^3	6.9×10^5	—
$\Delta M = 7$	VBF	62	3.8×10^4	—
	1 lepton	14	8.1×10^3	—
	2 b-jets	8.4	3.1×10^3	2.7×10^{-3}
	$\not{E}_T > 100$	4.8	680	7.0×10^{-3}
(500, 320)	Pre cut	460	6.9×10^5	—
$\Delta M = 7$	VBF	19	3.8×10^4	—
	1 lepton	4.2	8.1×10^3	—
	2 b-jets	2.4	3.1×10^3	7.9×10^{-4}
	$\not{E}_T > 150$	1.5	250	6.0×10^{-3}

$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_t - 7$ GeV

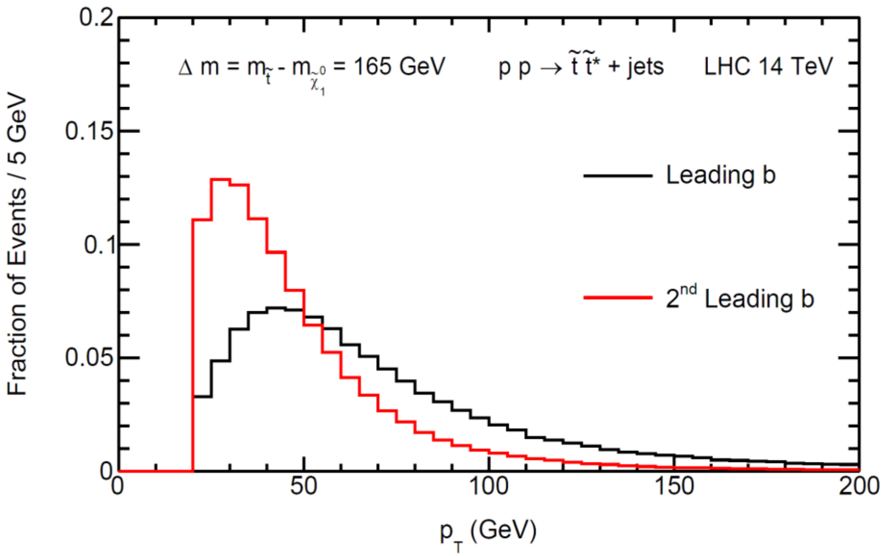
$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$+jets	S/B
(200, 35)	Pre cut	5.4×10^4	6.9×10^5	—
$\Delta M = -7$	VBF	1.4×10^4	3.8×10^4	—
	1 lepton	270	8.1×10^3	—
	2 b-jets	79	3.1×10^3	2.5×10^{-2}
	$\not{E}_T > 100$	29	680	4.3×10^{-2}
(300, 135)	Pre cut	7.4×10^3	6.9×10^5	—
$\Delta M = -7$	VBF	220	3.8×10^4	—
	1 lepton	43	8.1×10^3	—
	2 b-jets	12	3.1×10^3	3.7×10^{-3}
	$\not{E}_T > 100$	6.7	680	9.8×10^{-3}
(400, 235)	Pre cut	1.6×10^3	6.9×10^5	—
$\Delta M = -7$	VBF	51	3.8×10^4	—
	1 lepton	10.	8.1×10^3	—
	2 b-jets	2.8	3.1×10^3	8.9×10^{-4}
	$\not{E}_T > 200$	0.7	100	6.6×10^{-3}

Experiment reach with systematic uncertainty

LHC preliminary reach @ 300 fb^{-1}, 14 TeV

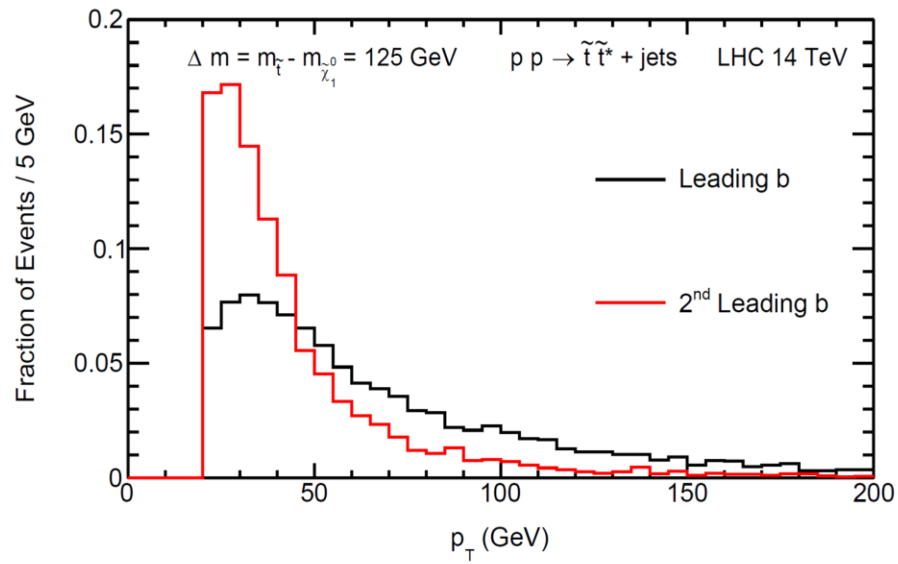


PT distribution of b jet in Three-Body Decay Case



$$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0}) = (300, 135)\ \text{GeV}$$

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 165\ \text{GeV} < m_t$$



$$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0}) = (300, 175)\ \text{GeV}$$

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 125\ \text{GeV} < m_t$$

Lower p_T threshold of b-jet → improve significance

Conclusion

→ Production from cascade decay $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

Stop coannihilation scenario:

- $\Delta m < m_W$; $\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to c + \tilde{\chi}_1^0$
- ≥ 4 j + ≥ 1 b + MET, $\tilde{g} \to \tilde{b} + b \to \tilde{t} + W + b \to \tilde{\chi}_1^0 + c + W + b$
- Endpoint measurements $M_{bW}, M_{jW} \Rightarrow m_{\tilde{t}}, m_{\tilde{b}}$ @ 14 TeV

→ Direct production of $\tilde{t}\,\tilde{t}^*$

Fully hadronic final state scenario:

- $\Delta m > m_t$; $\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to t + \tilde{\chi}_1^0$
- ≥ 4 j + ≥ 2 b + MET, $pp \to \tilde{t}\,\tilde{t}^* \to (t\tilde{\chi}_1^0)(t\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)(\bar{b}jj\tilde{\chi}_1^0)$
- M3 technique, reconstruct 2 top, S ~ B, 500 GeV @ 50 fb^{-1}, 8 TeV.

$\tilde{B}$ - $\tilde{H}$ DM scenario:

- $\Delta m > m_t$; $\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H}), \tilde{\chi}_{2,3}^0 \sim \tilde{H} \Rightarrow \tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}, t + \tilde{\chi}_{2,3}^0$, or $t + \tilde{\chi}_1^0$
- ≥ 2 j + ≥ 1 b + 2 l (OSSF) + MET, $\tilde{t} \to \tilde{\chi}_{3,2}^0 + t \to \tilde{\chi}_1^0 + l^{\pm} + l^{\mp} + t$
- Di-lepton invariant mass distribution (OSSF-OSDF):
  - Light $\tilde{l}$: Sensitivity up to 600 GeV @ 30 fb^{-1}, 8 TeV.
  - Heavy $\tilde{l}$: Small significance.

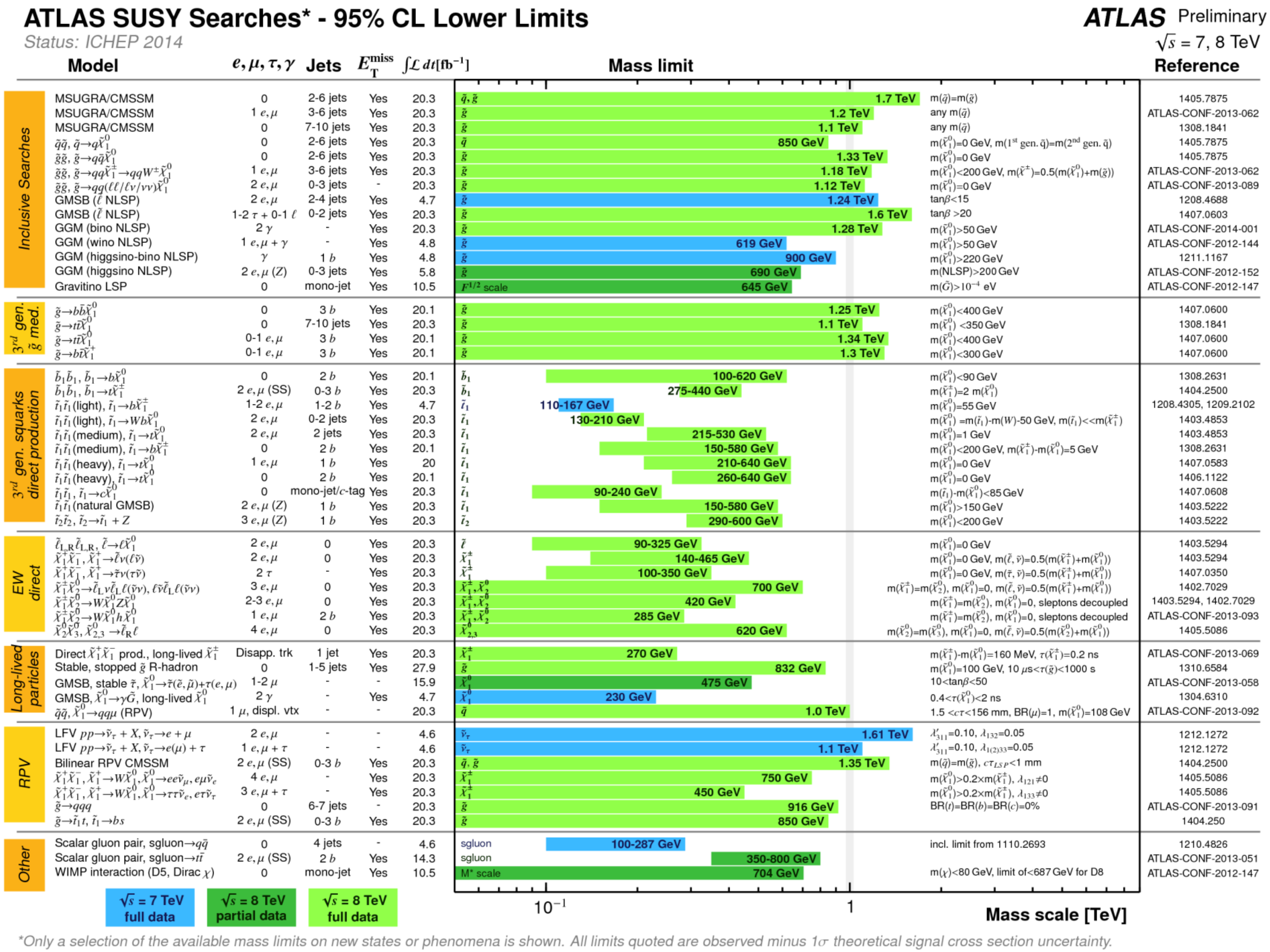
Compressed scenario:

- $\Delta m \sim m_t$; $\tilde{t}_1 \sim \tilde{t}_R;\ \tilde{\chi}_1^0 \sim \tilde{B}, \tilde{\chi}_2^0 \sim \tilde{W} \Rightarrow \tilde{t}_1 \to t + \tilde{\chi}_1^0$ or $b + W + \tilde{\chi}_1^0$
- ≥ 2 j + ≥ 2 b + ≥ 1 l + MET, $pp \to \tilde{t}_1\,\tilde{t}_1^* + jets$
- VBF topology selection: $\Delta m = m_t \pm 7$ GeV
  - 2-body decay: For 200 GeV, 6σ @ 300 fb^{-1}, 14 TeV.
  - 3-body decay: For 200 GeV, 4σ @ 300 fb^{-1}, 14 TeV.

48

Backup Slide

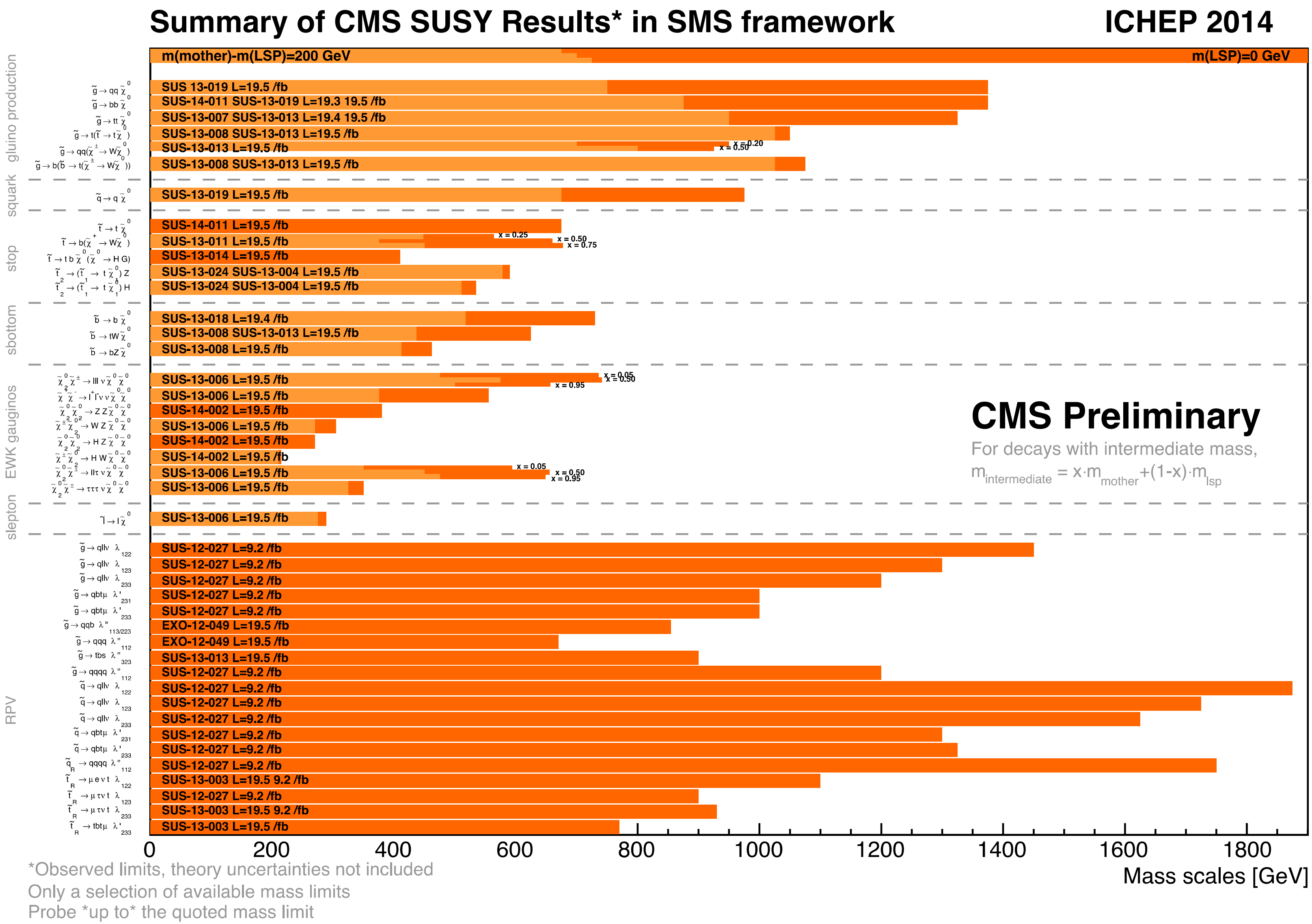
ATLAS LHC status of SUSY searches



Backup Slide

CMS

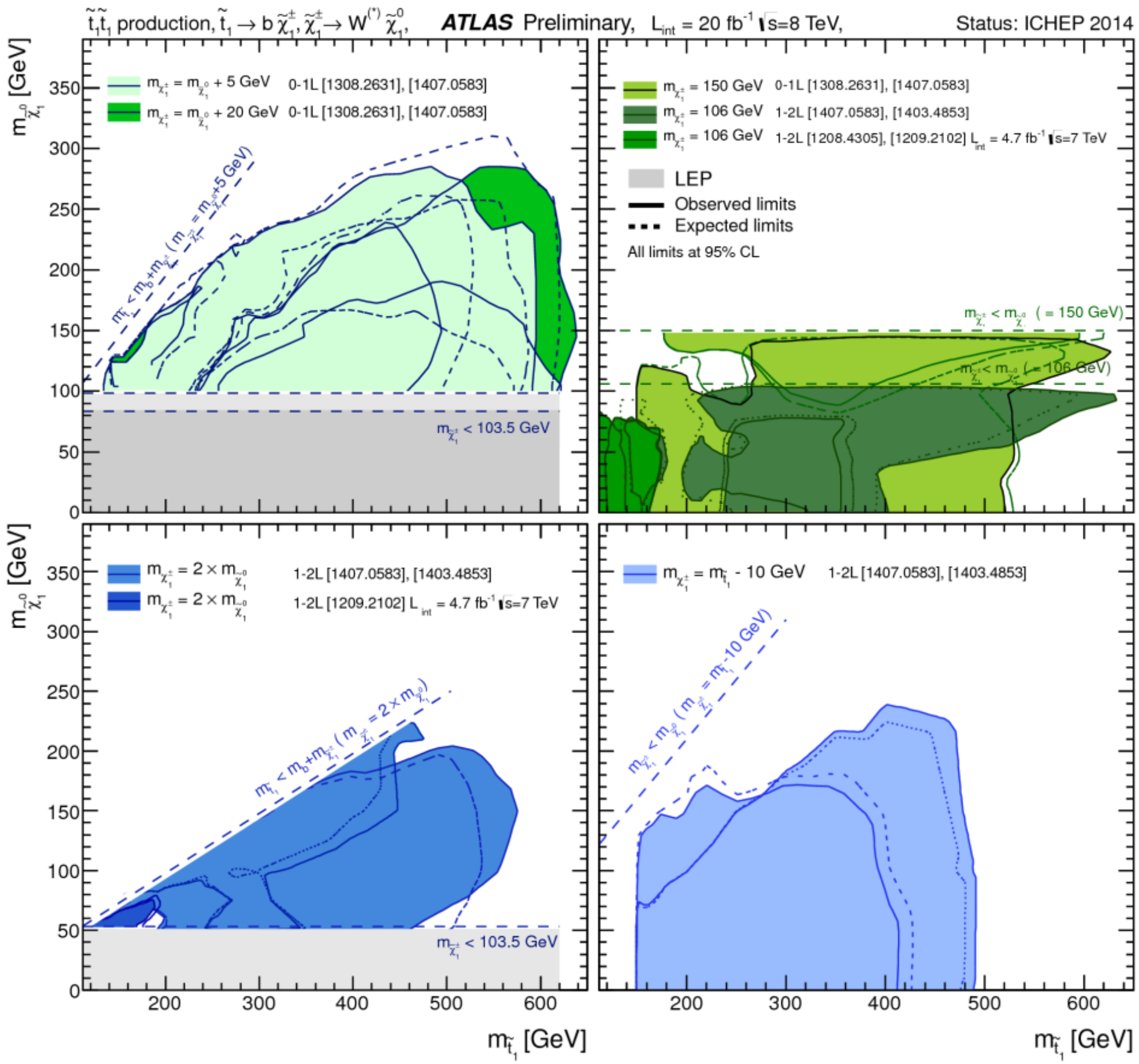
LHC status of SUSY searches



Backup Slide

LHC status of SUSY Stop searches

ATLAS

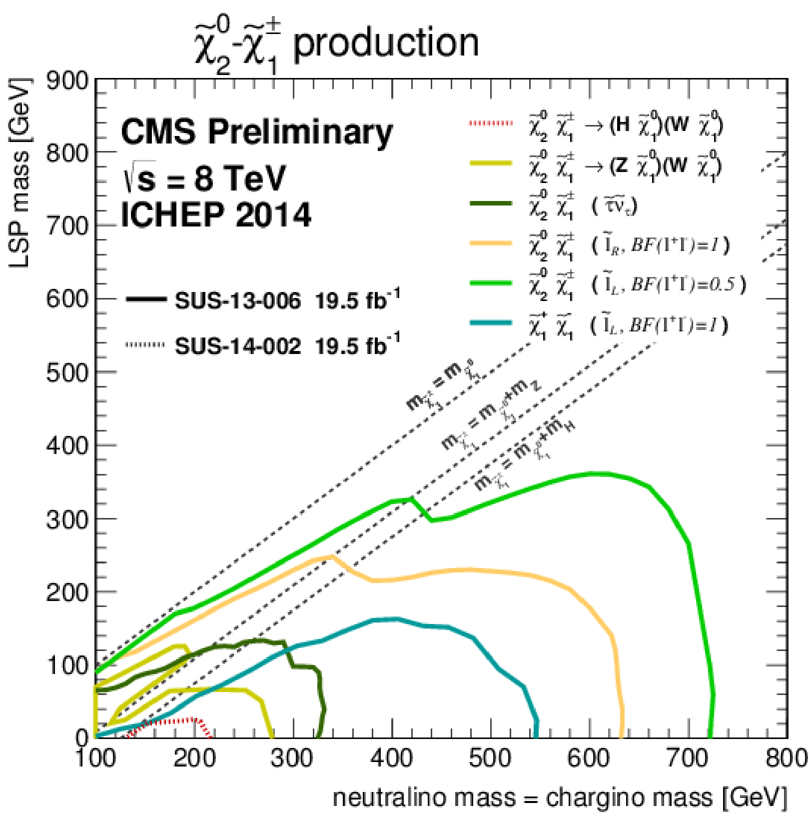


Backup Slide

LHC status of SUSY DM searches

Challenge: small production cross section of EW sector.

CMS



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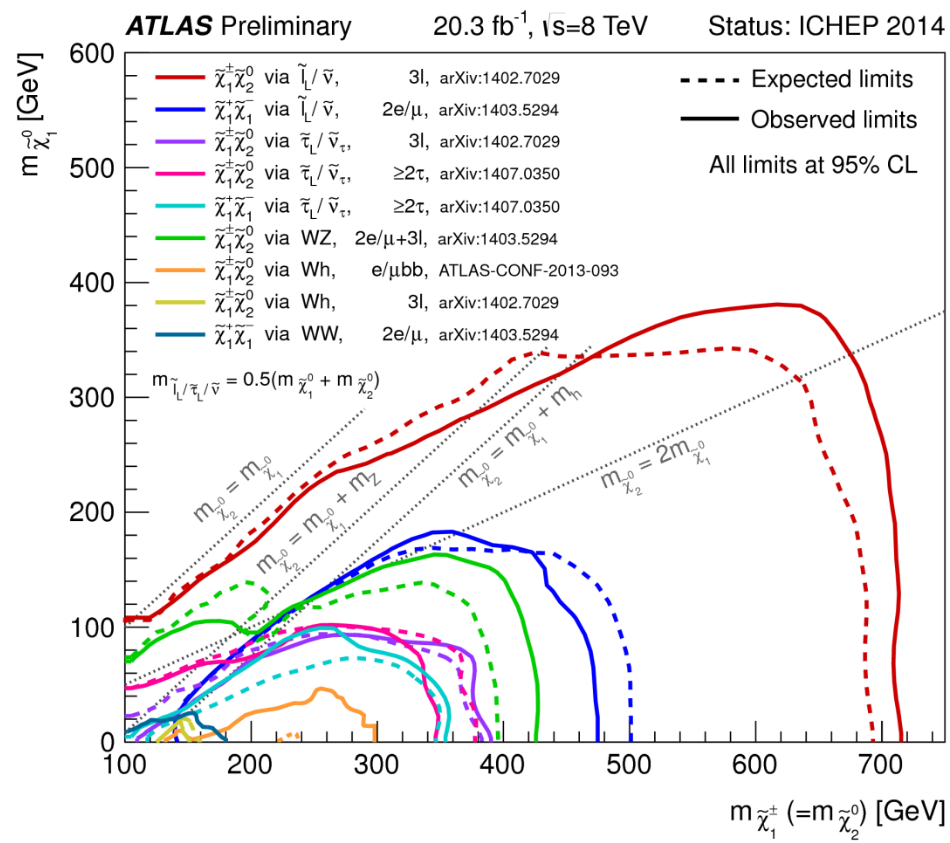
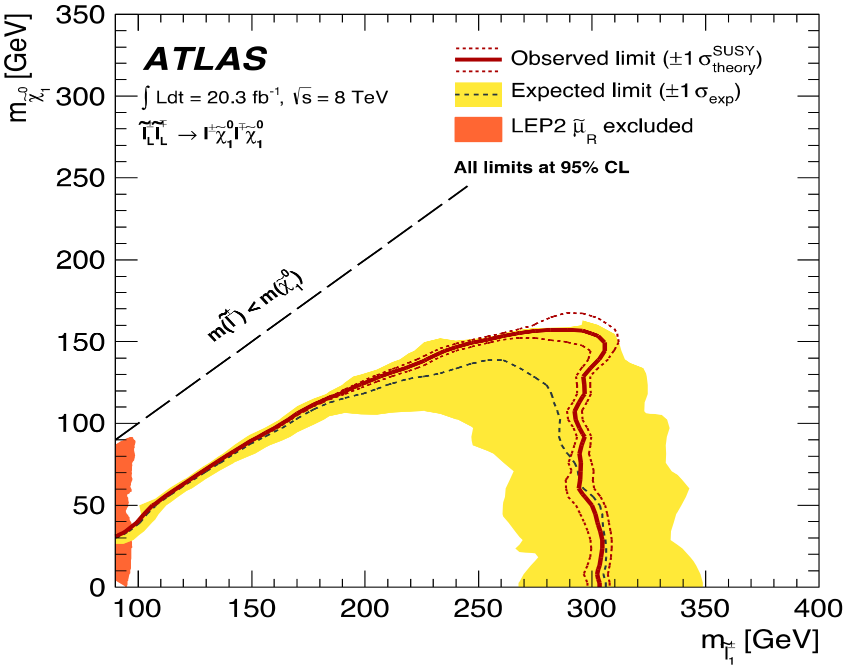


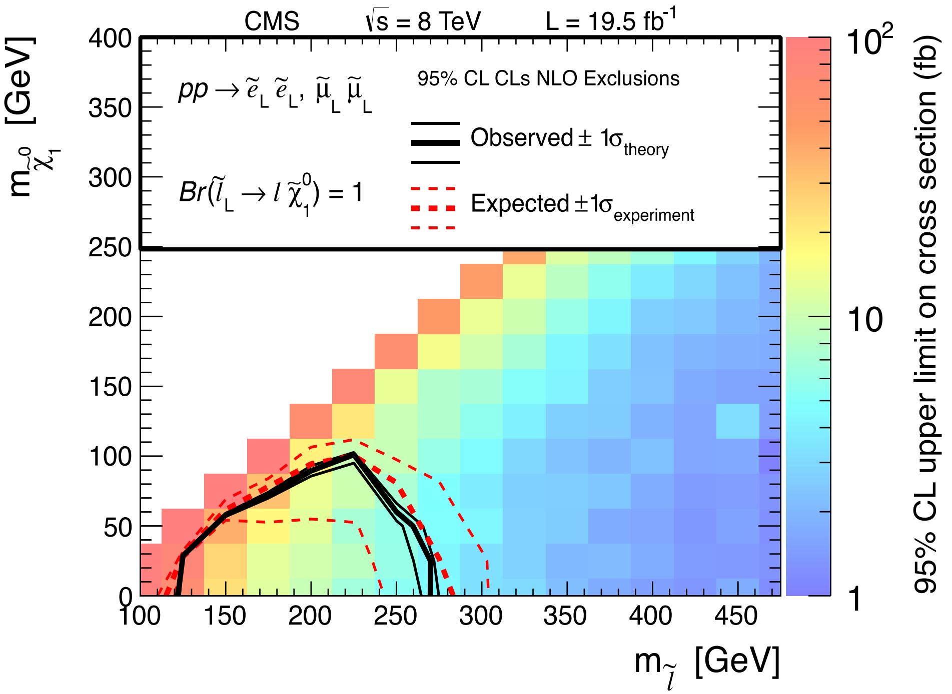
Backup Slide

LHC status of SUSY Slepton searches

ATLAS



CMS



Backup Slide