

Top Squark Searches via
Vector Boson Fusion, Bino/Higgsino Dark Matter, and M3

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Theoretical Motivations for Stop Searches

Lots of recent studies on the meaning/definition of SUSY naturalness

- Stops play an important role in supersymmetric naturalness arguments, since they couple significantly to the Higgs.
- Light stops feature in other contexts such as EW baryogenesis

Top Squark Production via

1. **Vector Boson Fusion processes:** can probe the compressed scenario $m_{\tilde{t}} \simeq m_t + m_{\text{LSP}}$ which is challenging for QCD-pair produced stop studies due to small MET. The VBF jets are effective in reducing background.

“Stealthy and/or light stop”

Study 1

2. QCD pair production

- (a) LSP is a **well-tempered Bino/Higgsino**, $\tilde{t} \rightarrow \tilde{\chi}_{3,2}^0 + t$ (39%)
 which satisfies relic density.

OSSF - OSDF subtraction in
dilepton mass distribution
 gives clear edge

$$\tilde{t} \rightarrow \tilde{\chi}_1^+ + b \quad (53\%)$$

ATLAS bounds apply for
 $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ 100% (pure Bino LSP)

“To Bino/Higgsino LSP”

Study 2

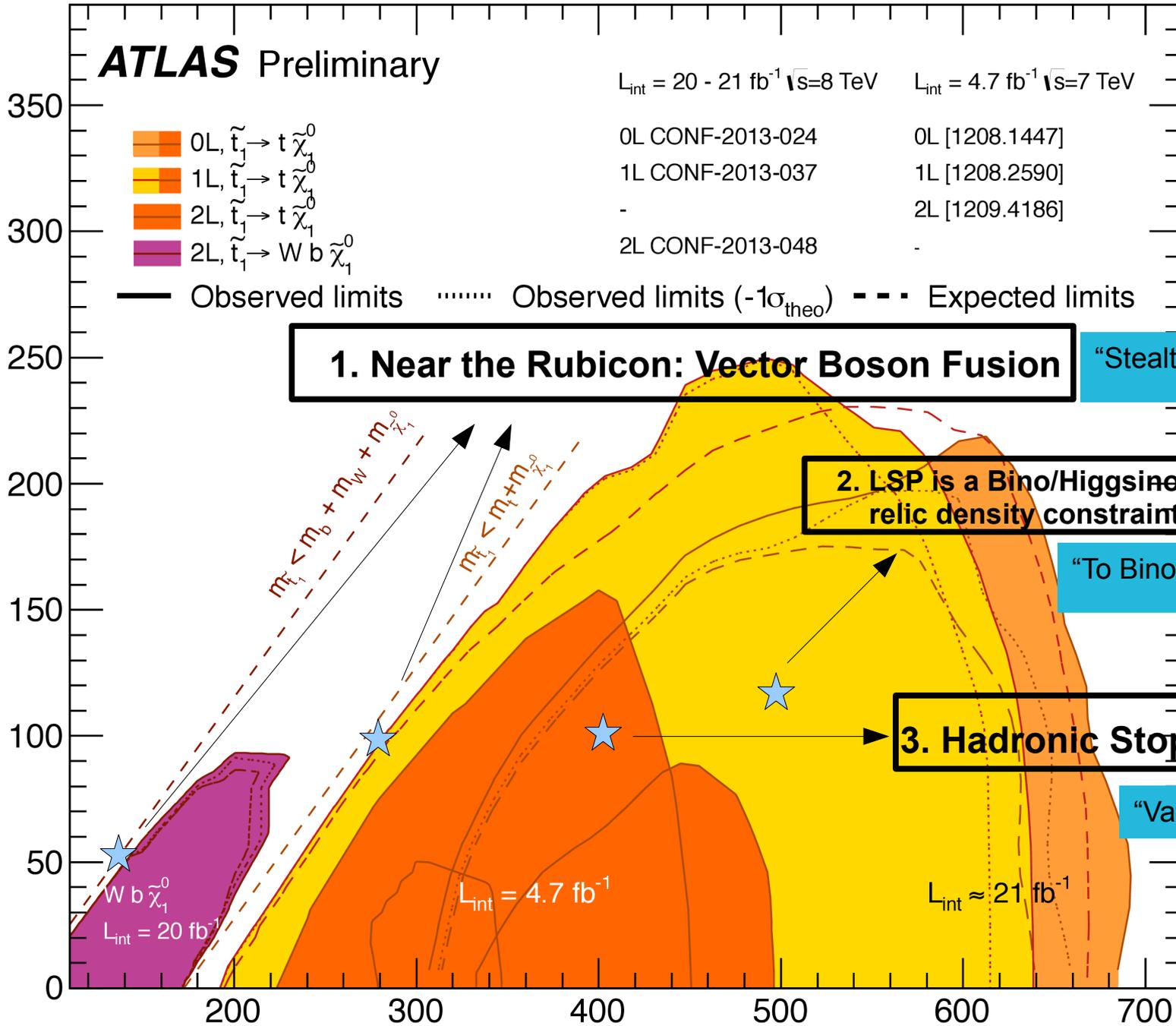
- (b) LSP is a pure Bino, $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 = 100\%$

Stop probed in fully hadronic final state
 using **trijet invariant mass M3**

“Vanilla Bino LSP, Hadronic Stop”

Study 3

$m_{\tilde{\chi}_1^0}$ [GeV]



Vector Boson Fusion

$$1. \quad pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm jj, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp jj, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 jj, \tilde{\chi}_2^0 \tilde{\chi}_2^0 jj$$

PRD 2013 [arXiv:1210.0964]

$$2. \quad pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj$$

Talk by Alfredo Gurrola, Sunday

arXiv:1304.7779

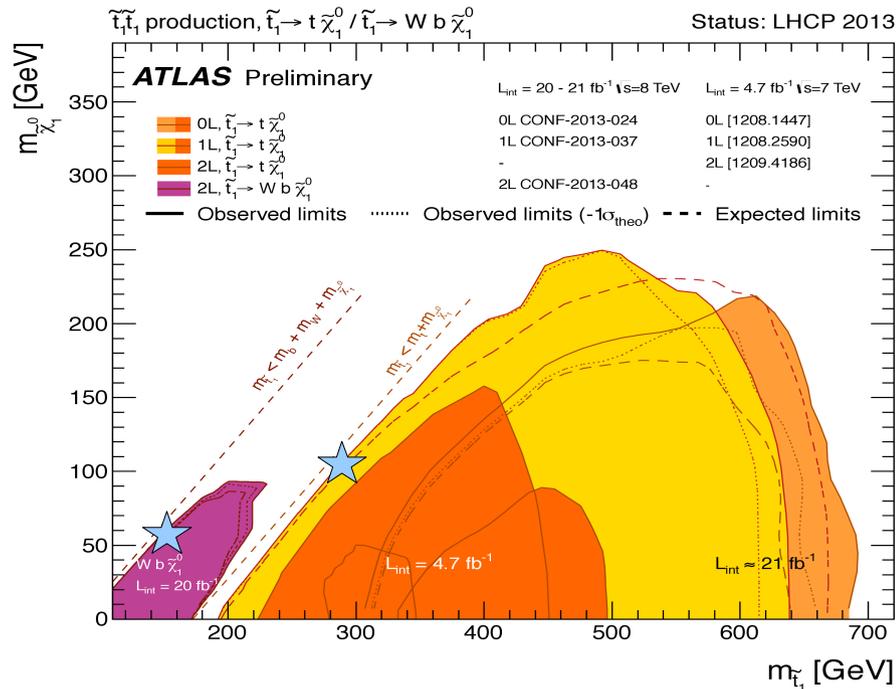
$$3. \quad pp \rightarrow \tilde{e}\tilde{e}jj, \tilde{\mu}\tilde{\mu}jj, \tilde{\tau}\tilde{\tau}jj, \tilde{\mu}\tilde{\nu}jj, \tilde{\tau}\tilde{\nu}jj$$



$$4. \quad pp \rightarrow \tilde{t}\tilde{t}jj$$



1. VBF Stops - Stealth/Rubicon/Light

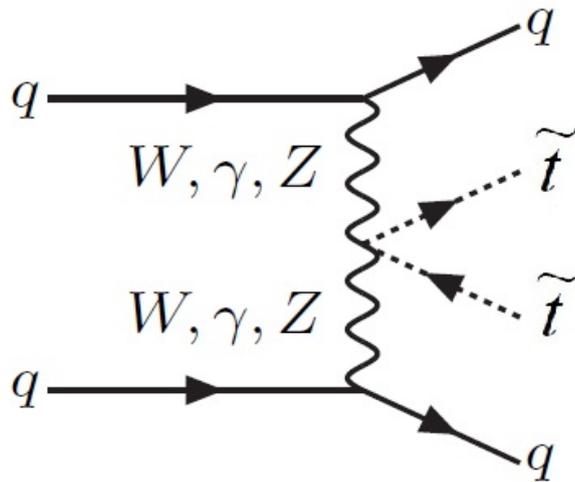
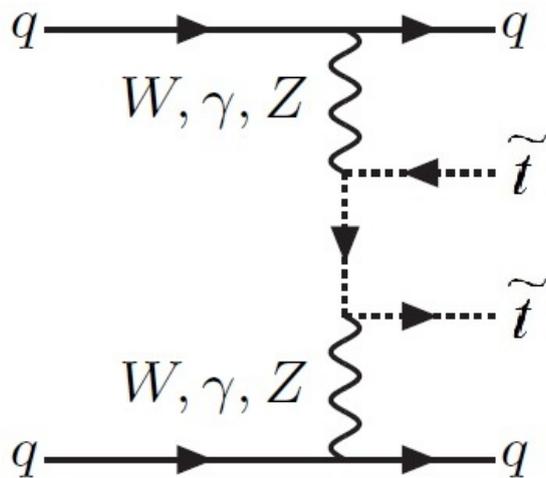


“Stealthy and/or light”

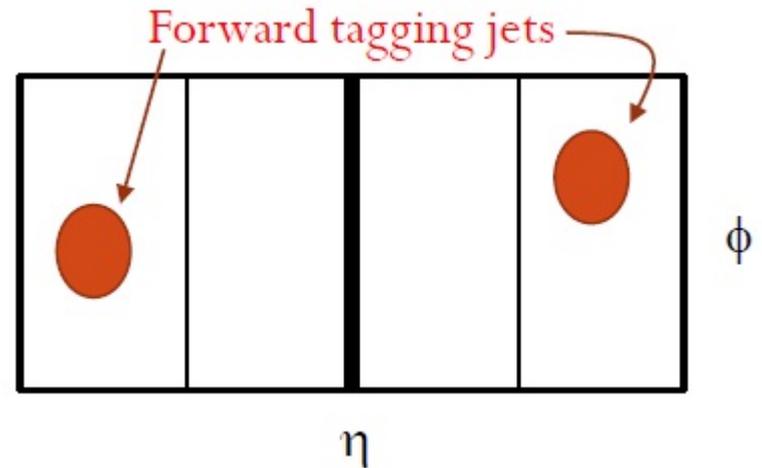
Andres G. Delannoy, Bhaskar Dutta, Will Flanagan, Alfredo Gurrola, Will Johns, Teruki Kamon, Eduardo Luiggi, Andrew Melo, Paul Sheldon, KS, Kechen Wang, Sean Wu

(Texas A&M University, Vanderbilt University, UC Boulder)

VBF Stops - Stealth/Rubicon/Light



BG + Signal data simulation:
MadGraph 5 + PYTHIA + PGS4



Benchmark points:

stop (LSP) = 110 (50), 233 (50), 277 (90) GeV

$2b + 2j + \text{MET}$

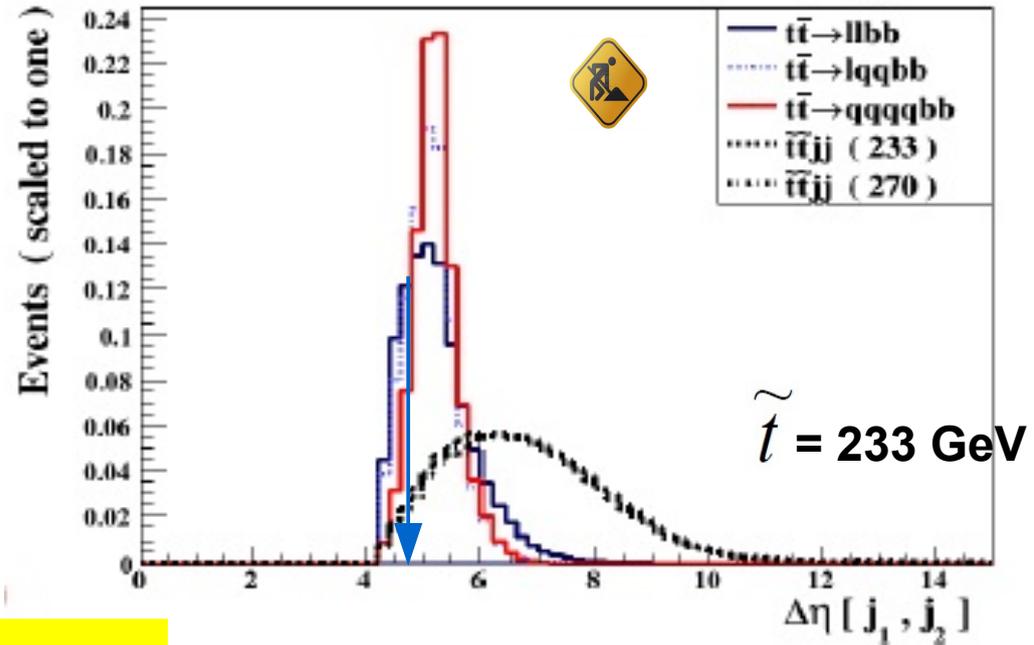
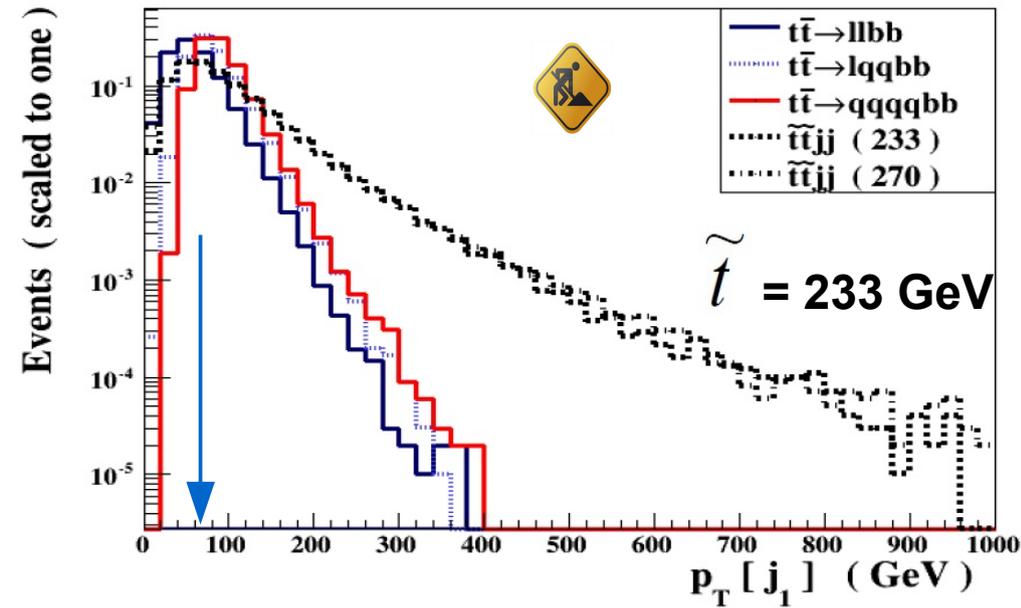
2 jets, each with $p_T > 50$ GeV

$|\Delta\eta(j1, j2)| > 4.2, \eta_{j1}\eta_{j2} < 0$

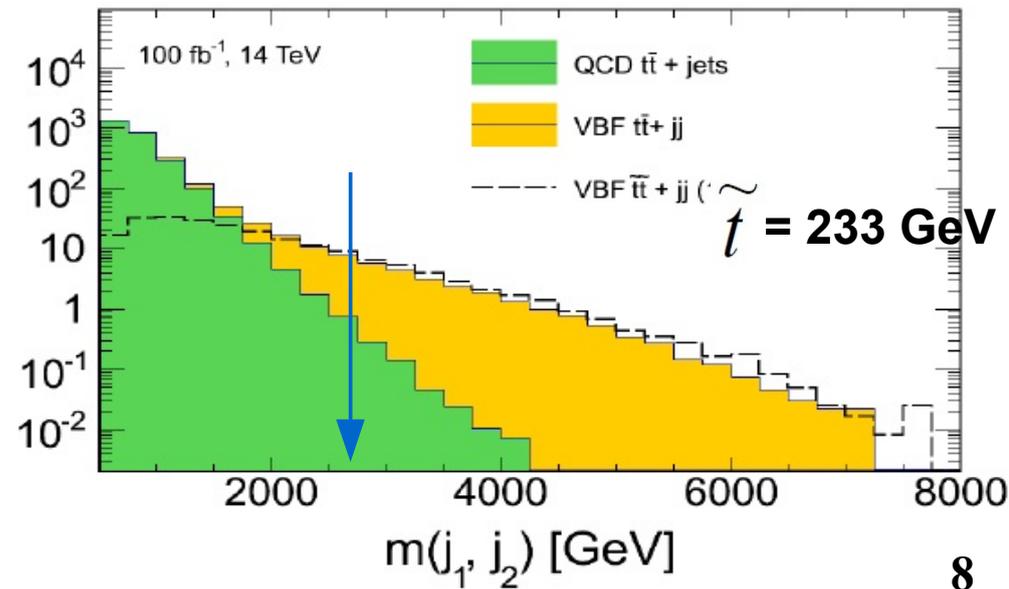
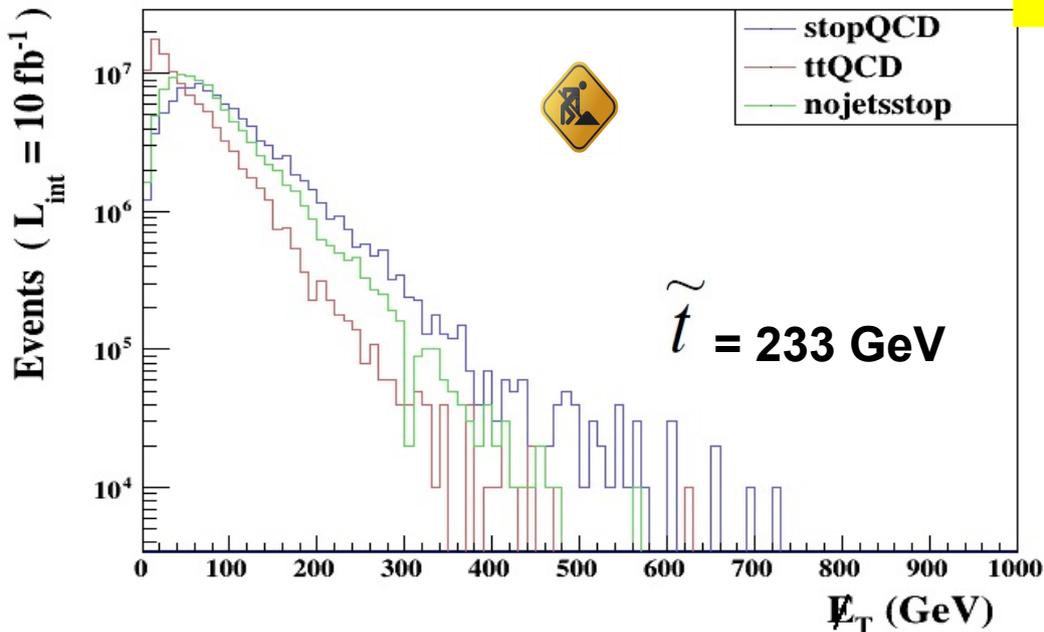
$M(j1j2) > 2750$ GeV

$\text{MET} > 75$ GeV

VBF Stops - Stealth/Rubicon/Light



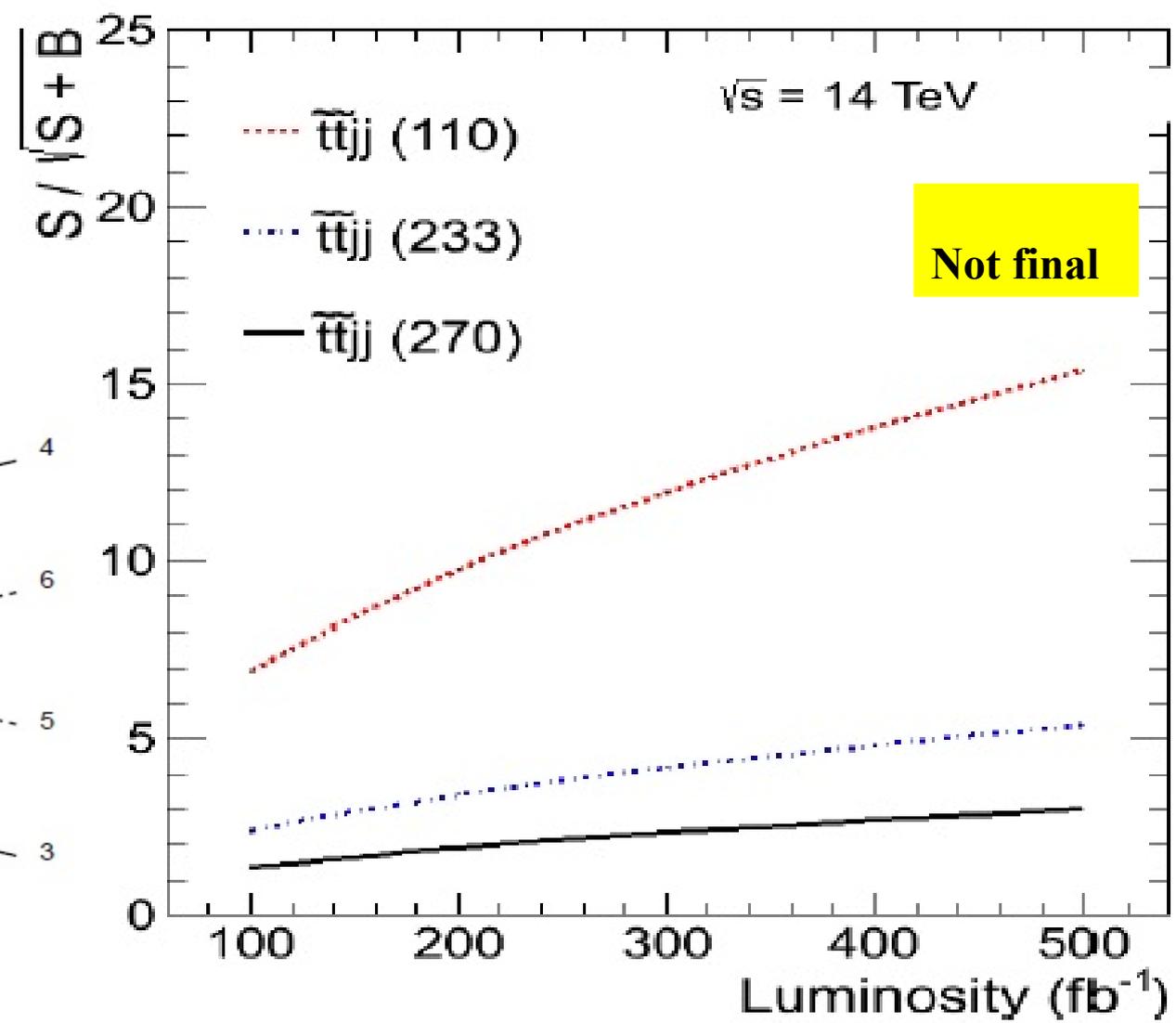
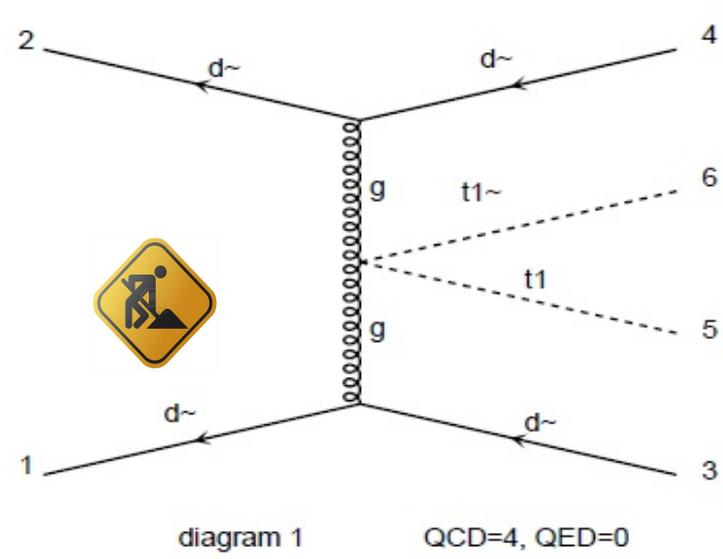
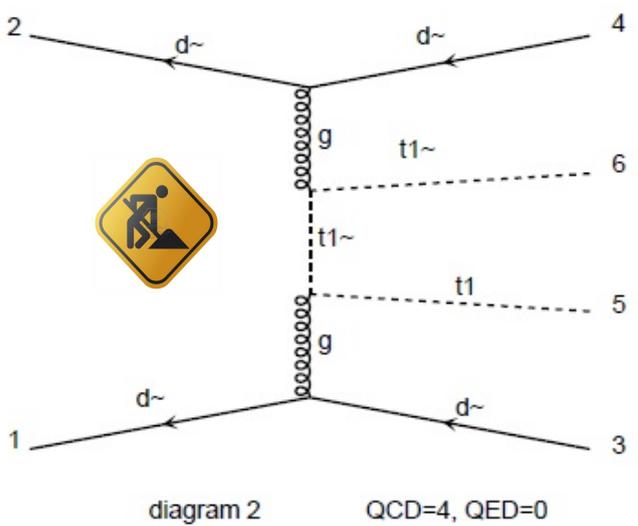
LHC14



VBF Stops - Stealth/Rubicon/Light

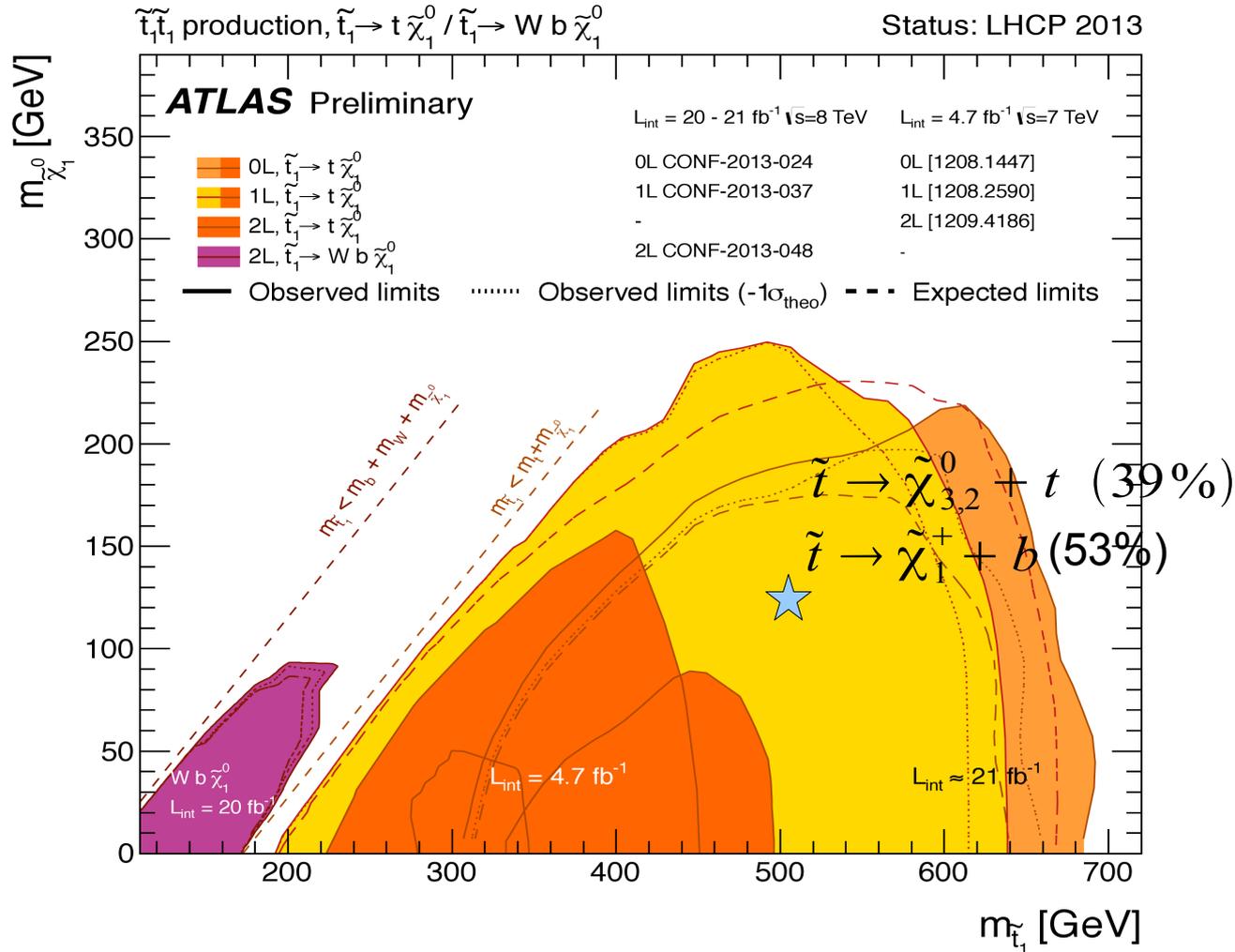
LHC14

Signal significance vs luminosity



2. Stop to Bino/Higgsino LSP

Bhaskar Dutta, Teruki Kamon, Nikolay Kolev, KS, Kechen Wang, Sean Wu



“To Bino/Higgsino LSP”

Top Squark Searches Using Dilepton Invariant Mass Distributions and Bino-Higgsino Dark Matter
Phys Rev D.87.095007 [arXiv:1302.3231]

Stop to Bino/Higgsino LSP

- Vanilla stop decay mode: to Bino LSP + top quark
 - Stealth/Rubicon studies
- Non-vanilla stop decay modes are important to investigate
 - Bino/Higgsino LSP using dilepton mass distribution
 - Pure Higgsino LSP (Asymmetric Stops) using “topness”

Graesser, Shelton

Stop to Bino/Higgsino LSP

If Higgsinos are light due to naturalness arguments then

- Non-thermal dark matter
 - Indirect/direct detection bounds, cosmological motivations
Allahverdi, Dutta, KS [arXiv: 1208.0115]
- Well-tempered dark matter
 - Bino/Higgsino LSP from stop decay (this talk)
 - Direct Bino/Higgsino LSP probe with VBF
[arXiv: 1304.7779]
- Multi-component dark matter

Stop to Bino/Higgsino LSP

Goal:

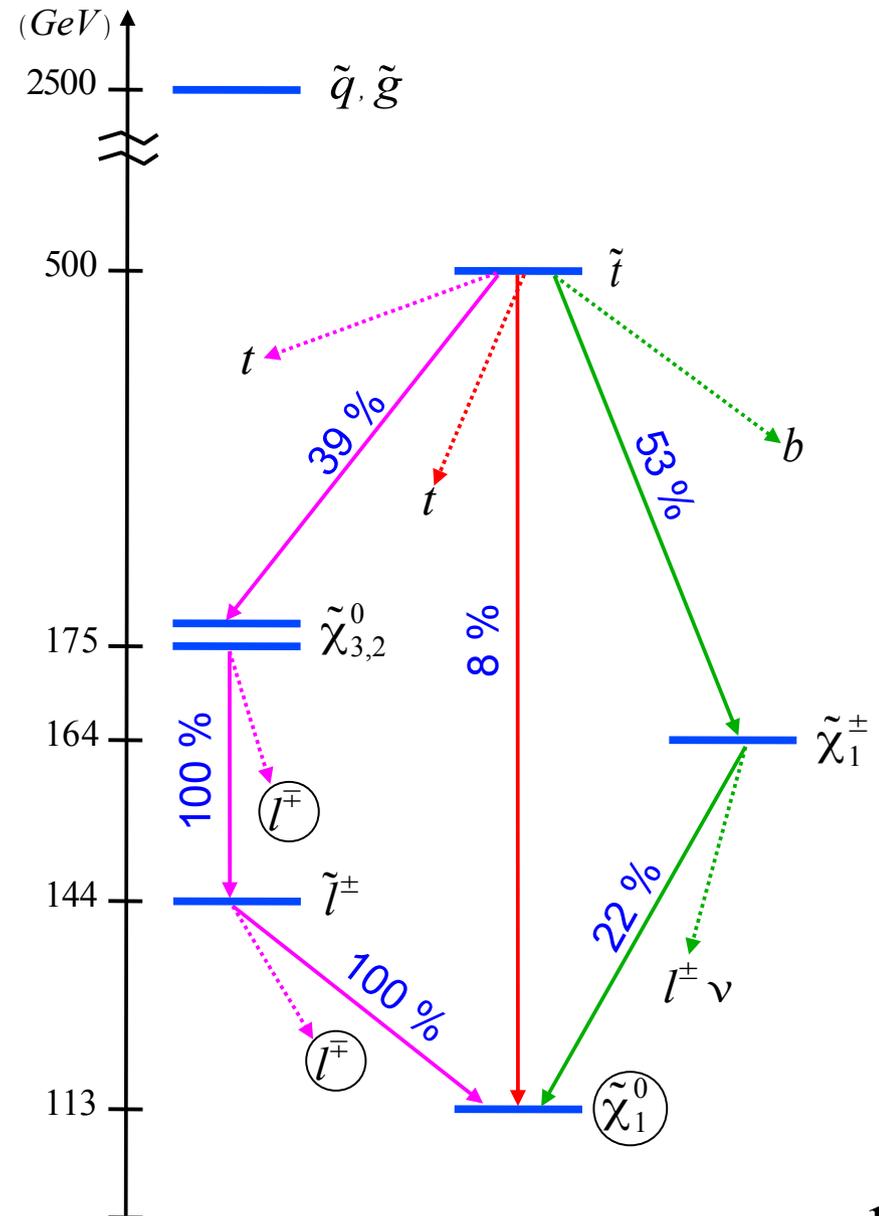
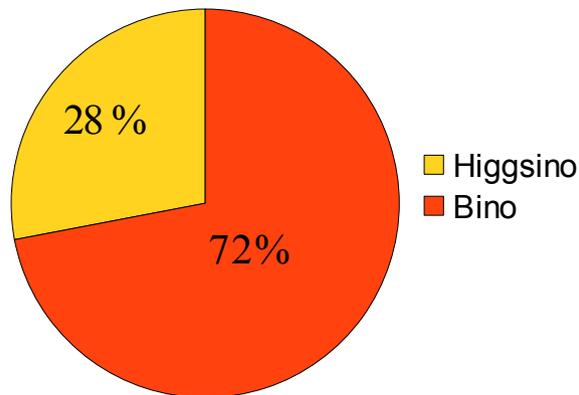
\tilde{t} decay \longrightarrow dark matter sector
in a scenario: $\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})$

Motivation:

Light \tilde{t} and light \tilde{H} \longleftarrow Naturalness
 $\tilde{\chi}_1^0 \sim (\tilde{B} + \tilde{H})$ \longleftarrow Correct relic density

Since if $\tilde{\chi}_1^0 \sim \tilde{H}$ \longrightarrow small relic density

Composition of $\tilde{\chi}_1^0$
in our light slepton case



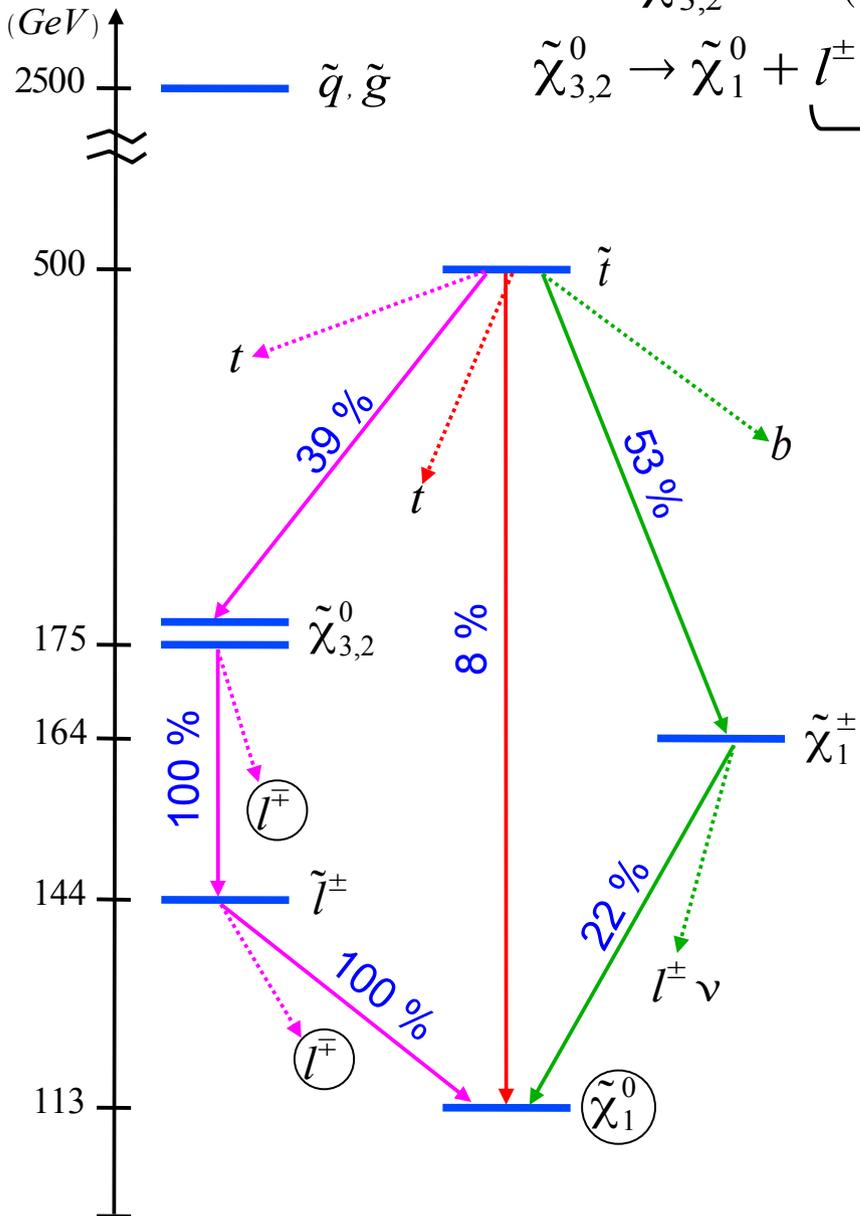
Stop to Bino/Higgsino LSP

$\tilde{\chi}_{2,3}^0, \tilde{\chi}_3^0$ almost degenerate

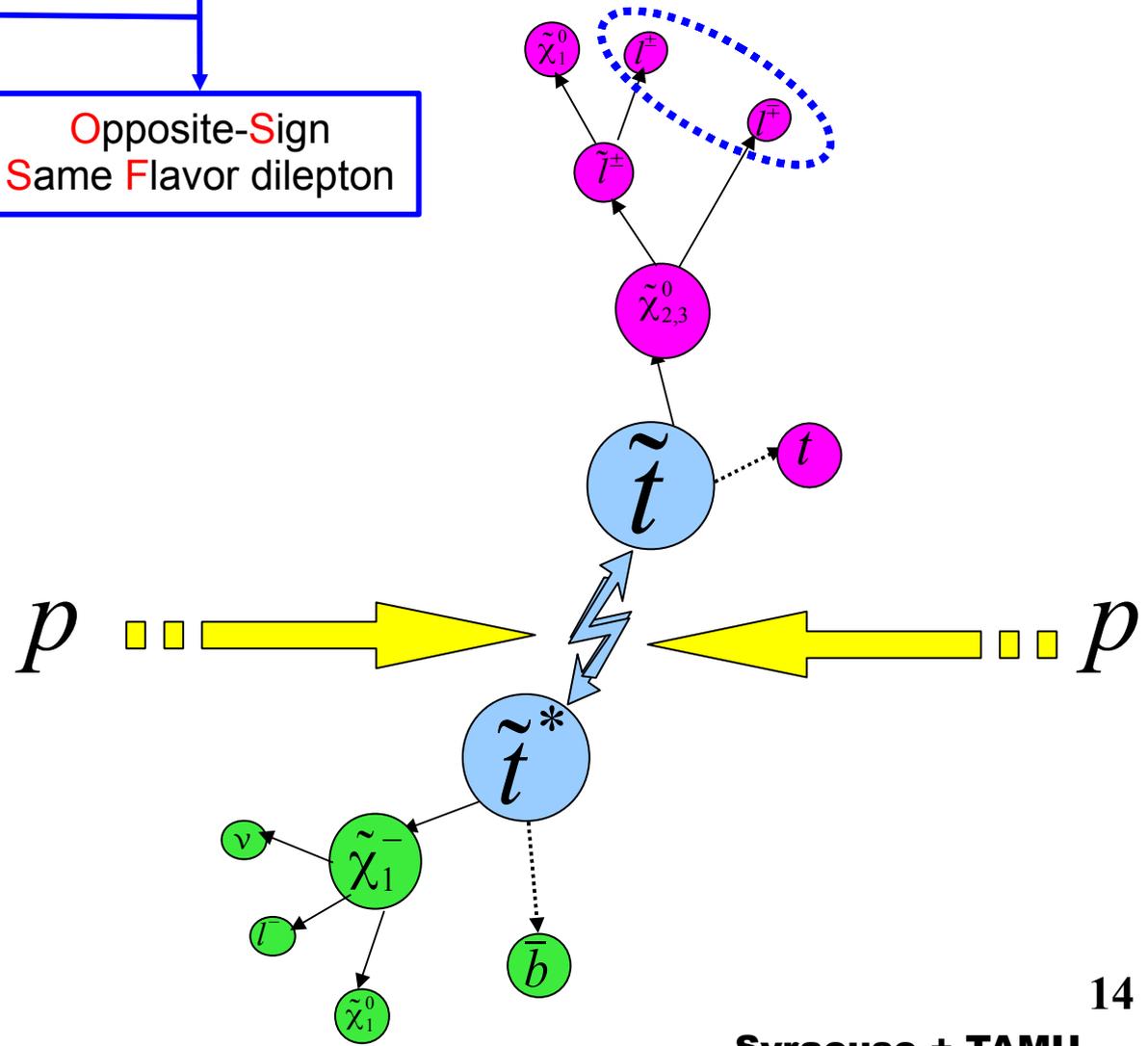
$$M_{ll}^{edge} \sim \Delta M = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

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

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



Opposite-Sign
Same Flavor dilepton



Stop to Bino/Higgsino LSP

Final State:

2 l + 2 j + 1 b + large MET

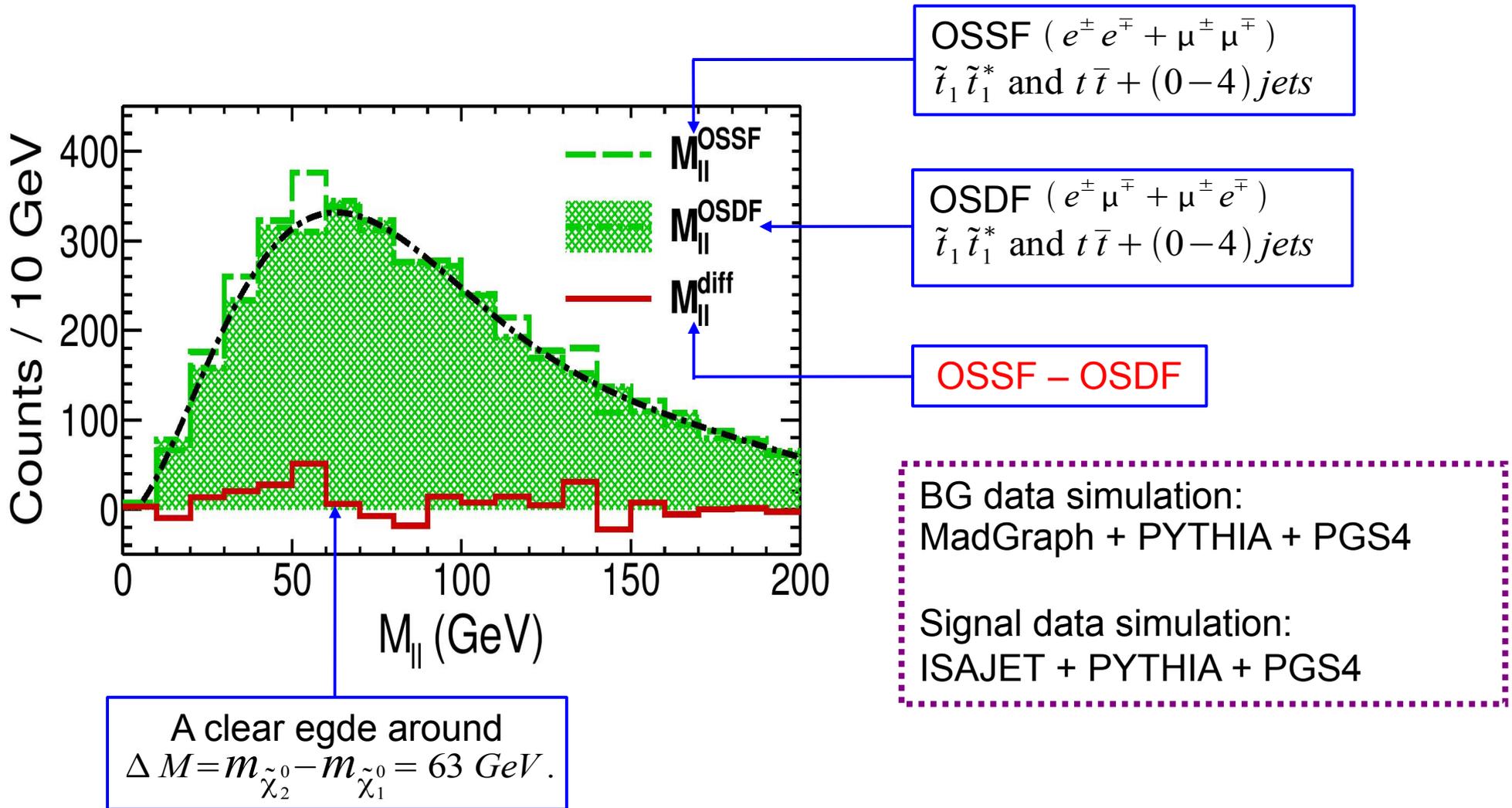
MET > 150 GeV

H_T > 100 GeV

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

30 fb
LHC8

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + l^\pm + l^\mp$$

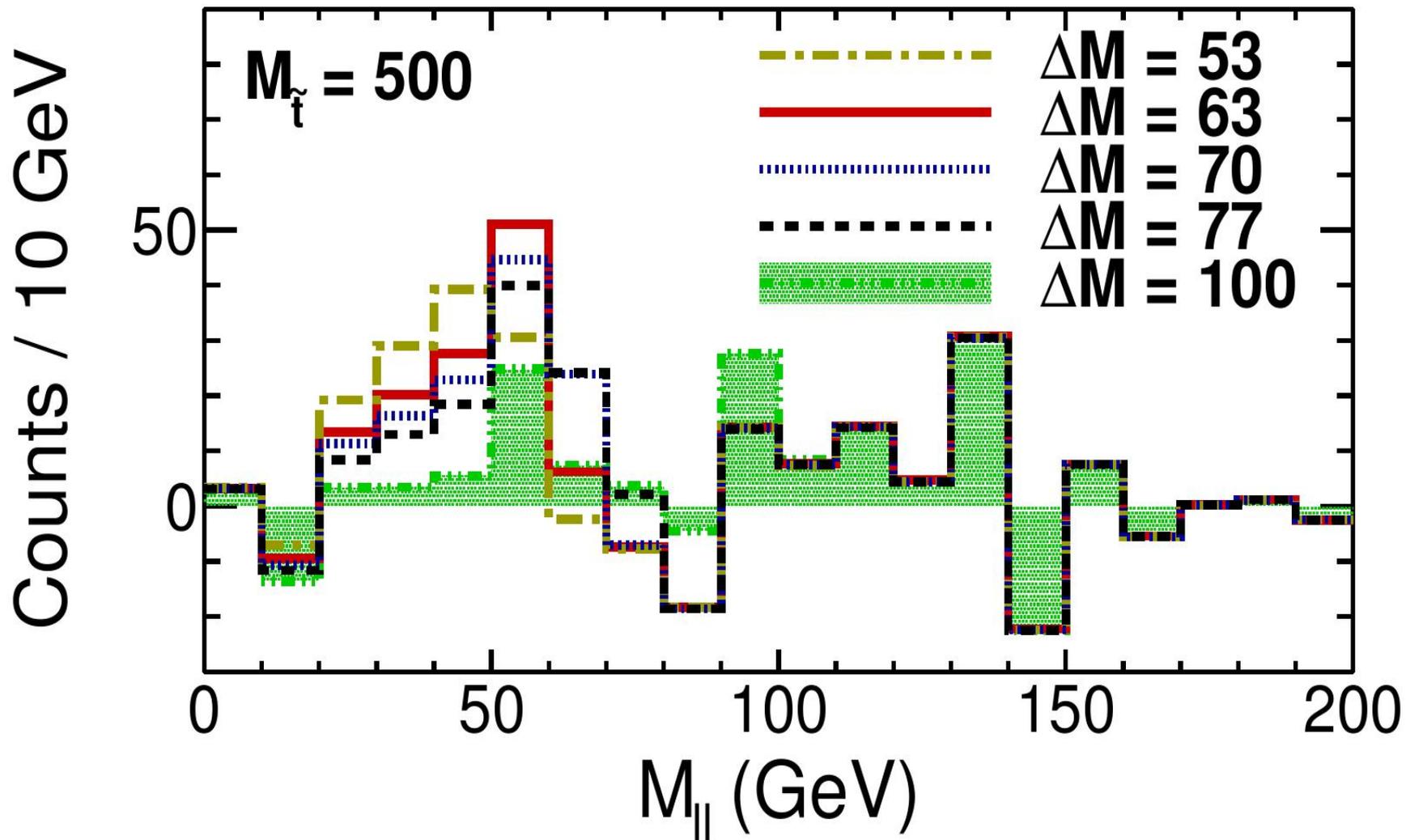


Stop to Bino/Higgsino LSP

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

30 fb
LHC8

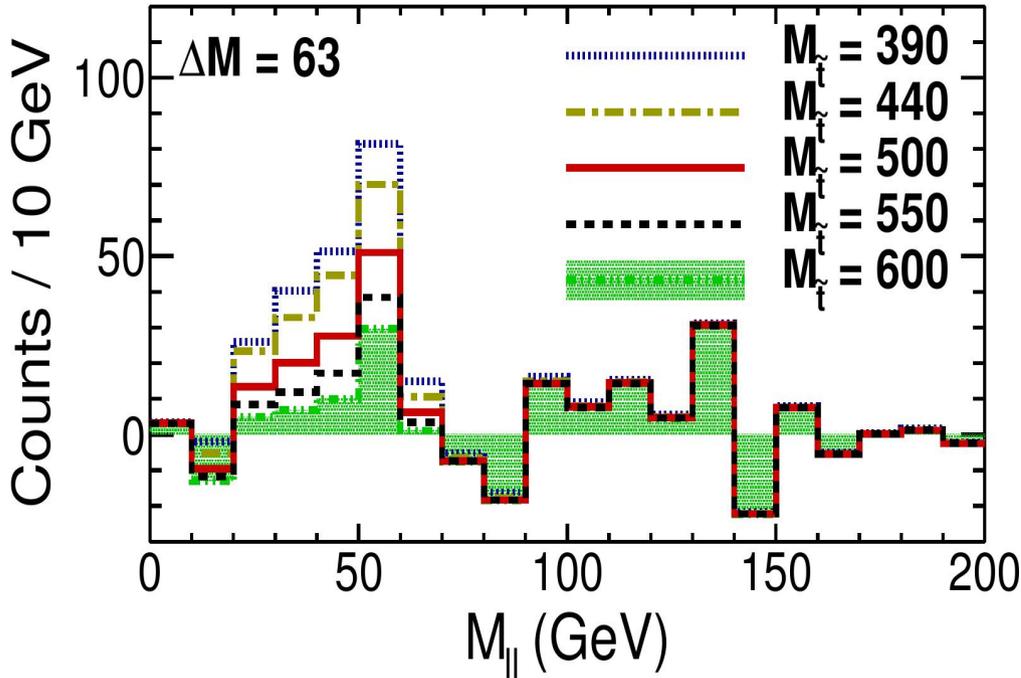
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^-$ (100%, via \tilde{e}^\pm or $\tilde{\mu}^\pm$)



Stop to Bino/Higgsino LSP

30 fb
LHC8

30 fb⁻¹ luminosity, 8 TeV



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

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

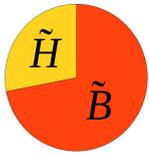
$m_{\tilde{\chi}}$ (GeV)	Signal (N_S)	Background (N_B)	significance (s)
390	212	1392	5.3
440	180	1368	4.6
500	117	1354	3.1
550	78	1348	2.1
600	51	1345	1.4

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

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

Stop to Bino/Higgsino LSP

30 ifb
LHC8



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

Masses (GeV)	\tilde{B} (%)	\tilde{H} (%)	Ωh^2	s (30 fb ⁻¹)	Comments
$\Delta M = 160$					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 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} ,
 $Z \rightarrow ll \longrightarrow$ small significance.

Stop to Bino/Higgsino LSP

(take-home message)

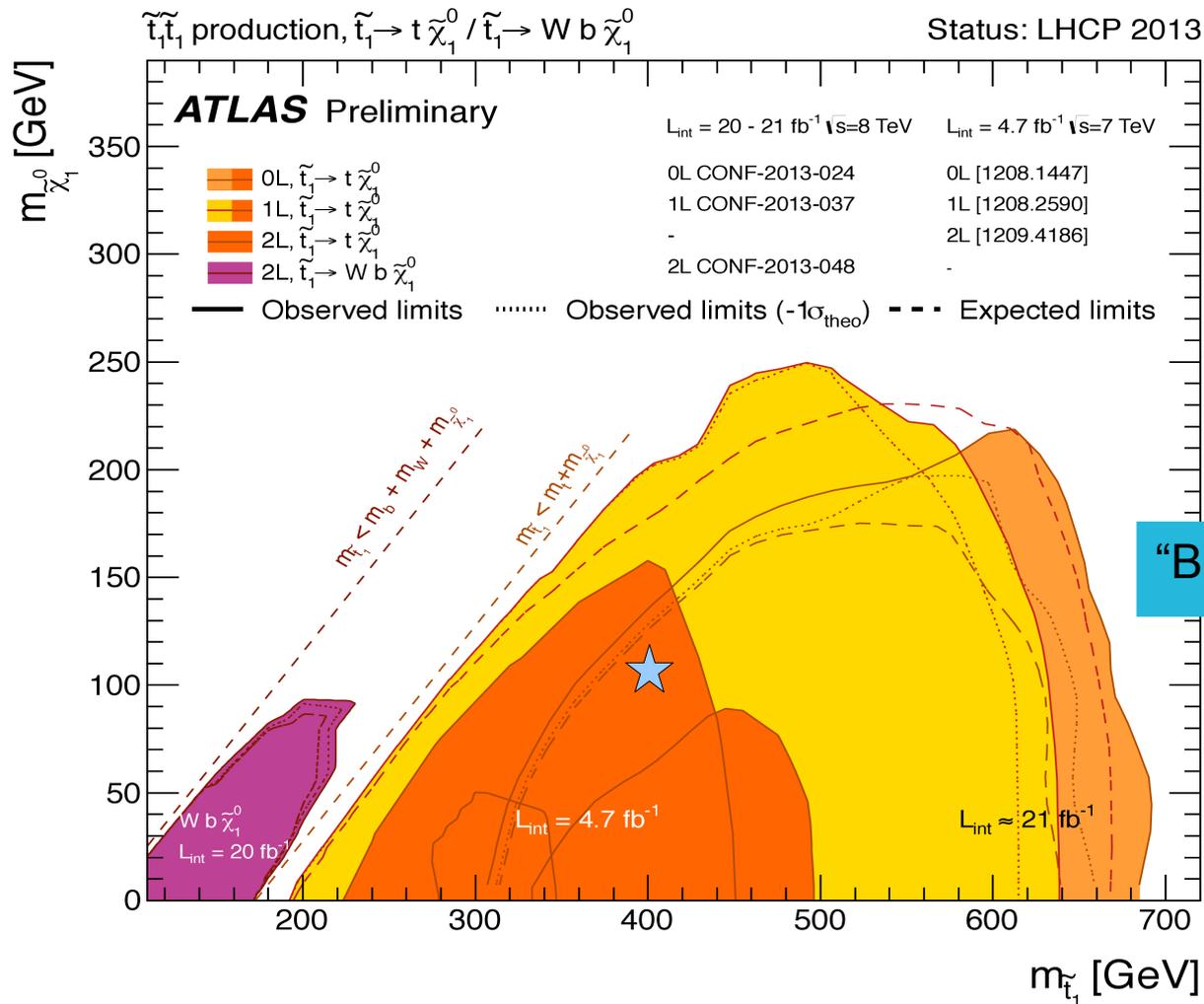
significance $\sim 3\sigma$, for $m_{\tilde{\tau}} = 500 \text{ GeV}$.

for light slepton, at LHC8

LHC14 study underway!

“Heavy” slepton scenario may be interesting at high luminosities.

3. Searching for Top Squarks in Fully Hadronic Final State



Bhaskar Dutta, Teruki Kamon, Nikolay Koley, KS, Kechen Wang, Sean Wu
Phys Rev D.87.095007 [arXiv:1302.3231]

SM processes: $T\bar{T}$ + jets, Single stop production, W + jets, Z + jets, QCD

Once we require large MET, a major surviving decay mode is “Lost Lepton” + Jets + MET ...

Baseline Selection:

4 jets + 2 loose b 's (>100 , 30's) + MET (> 100) + Lepton veto

- $p_T(e) > 10$, Iso < 5 GeV
- $p_T(m) > 10$, Iso < 5 GeV
- $p_T(th) > 20$, e = 60%, f = 2%

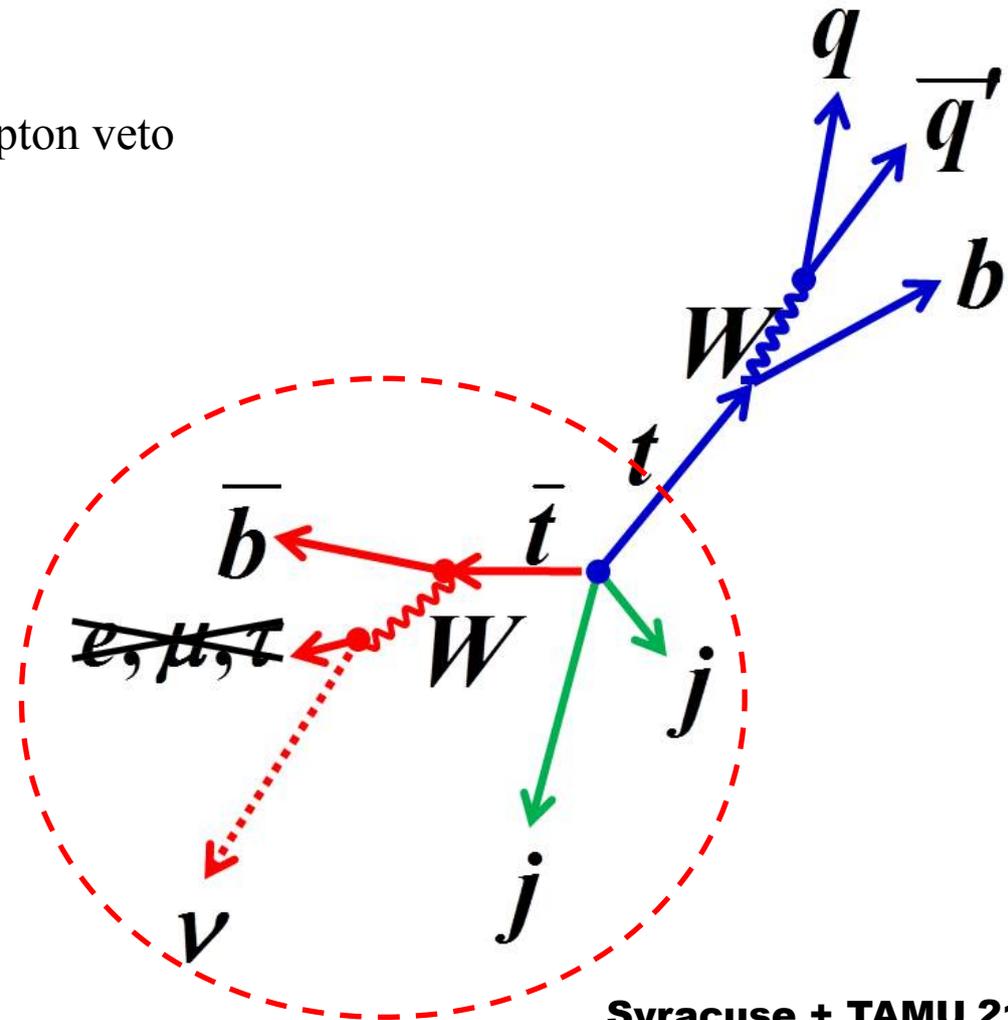
Final selection cuts

Stage 1: Tagging leading

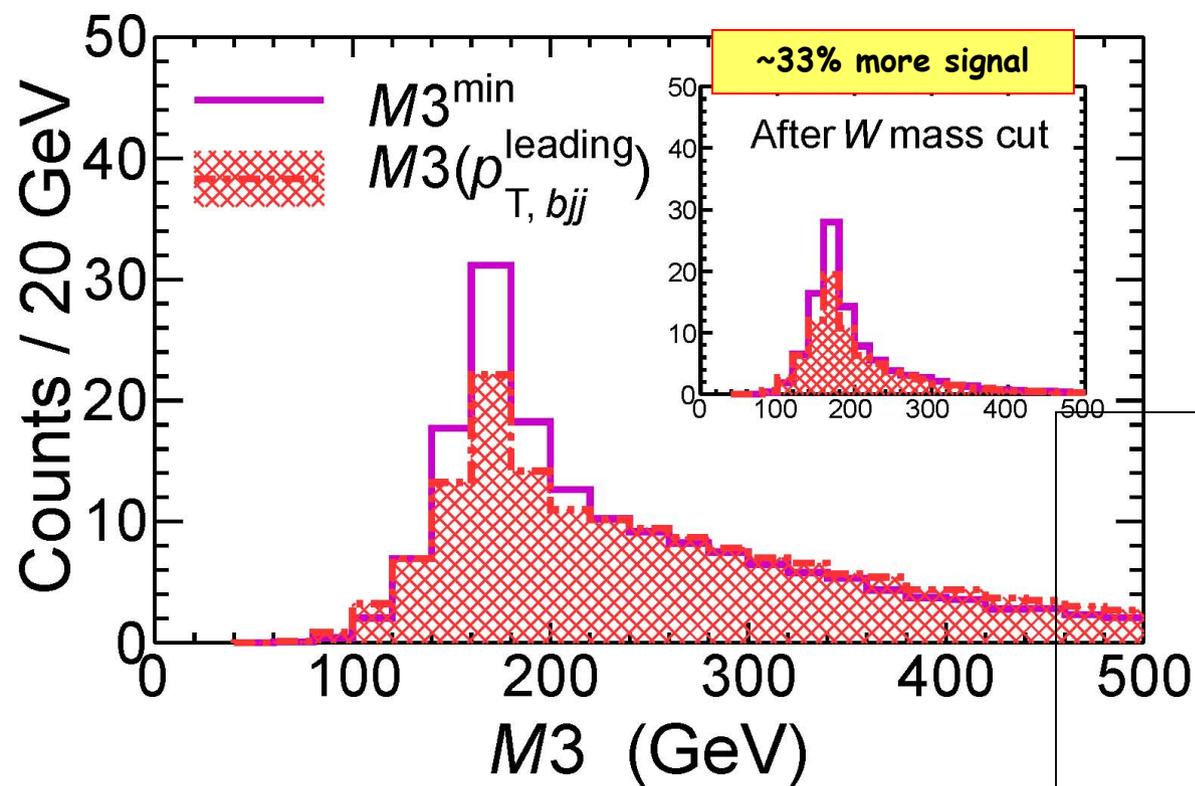
p_T top (j1, j2, b) with M3

Stage 2: Kinematic cuts

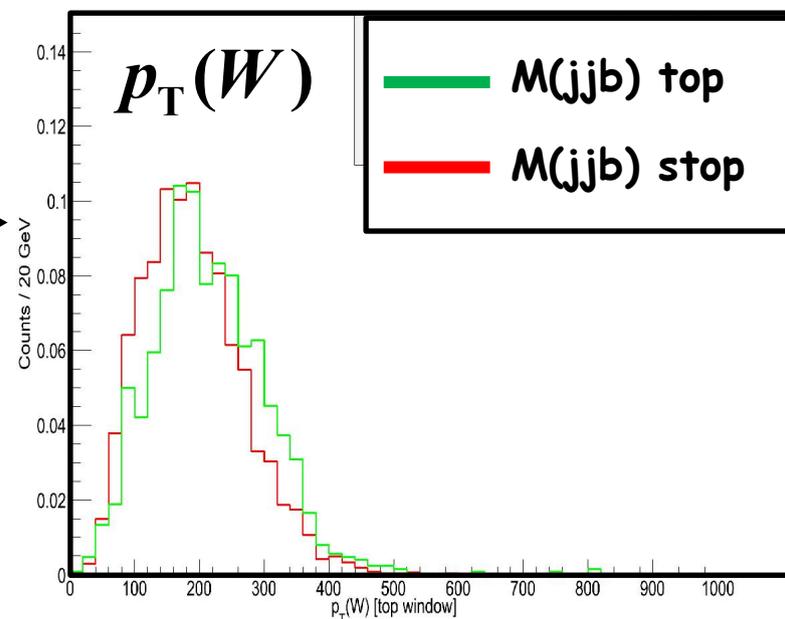
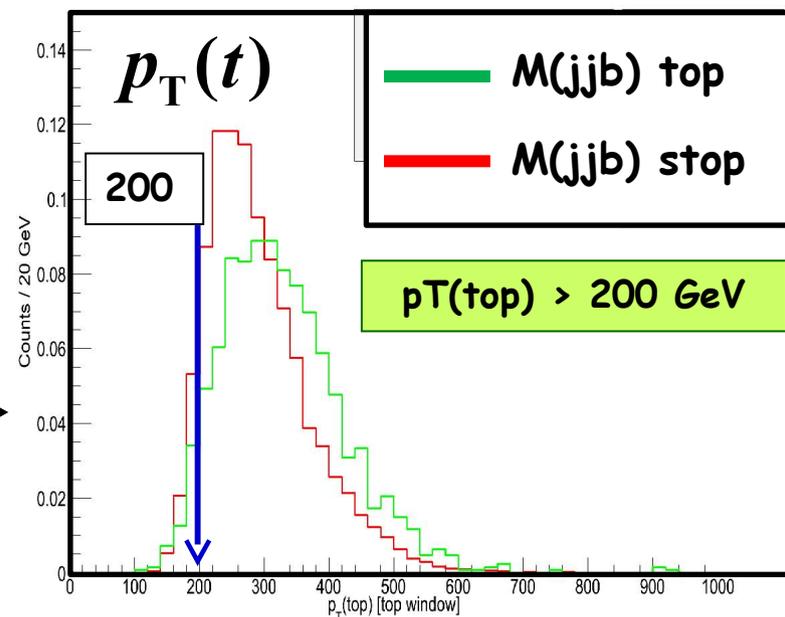
Stage 3: Tagging other top with M3



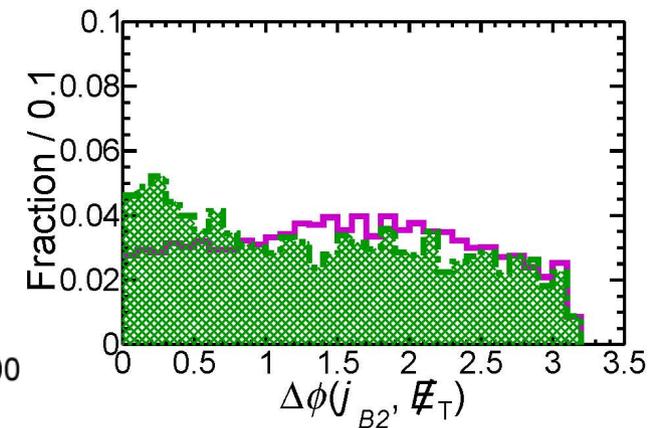
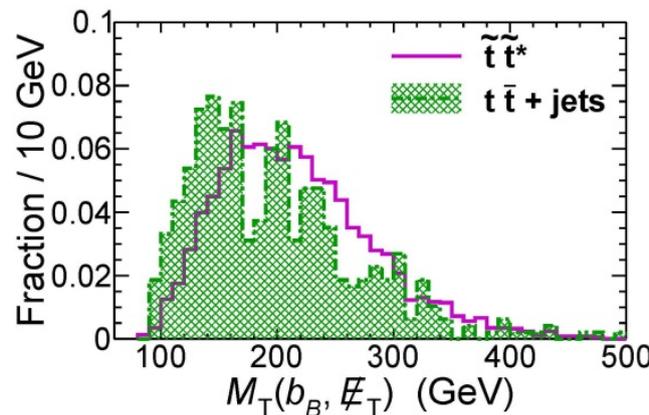
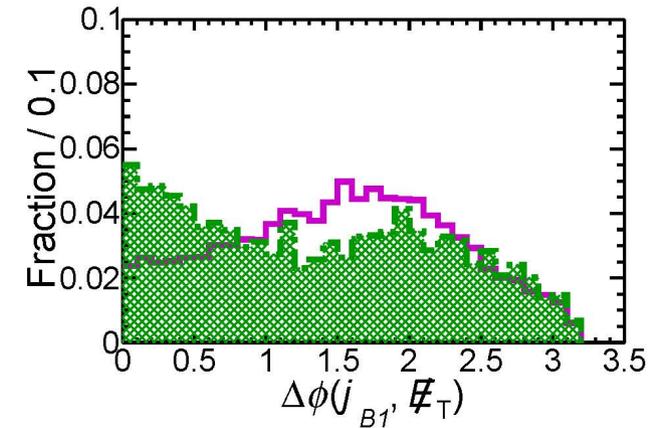
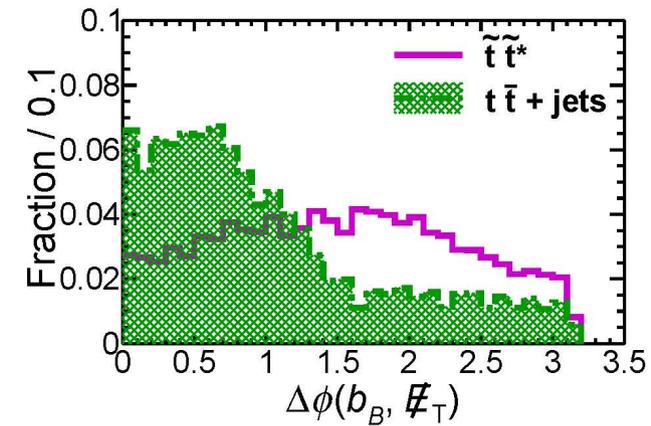
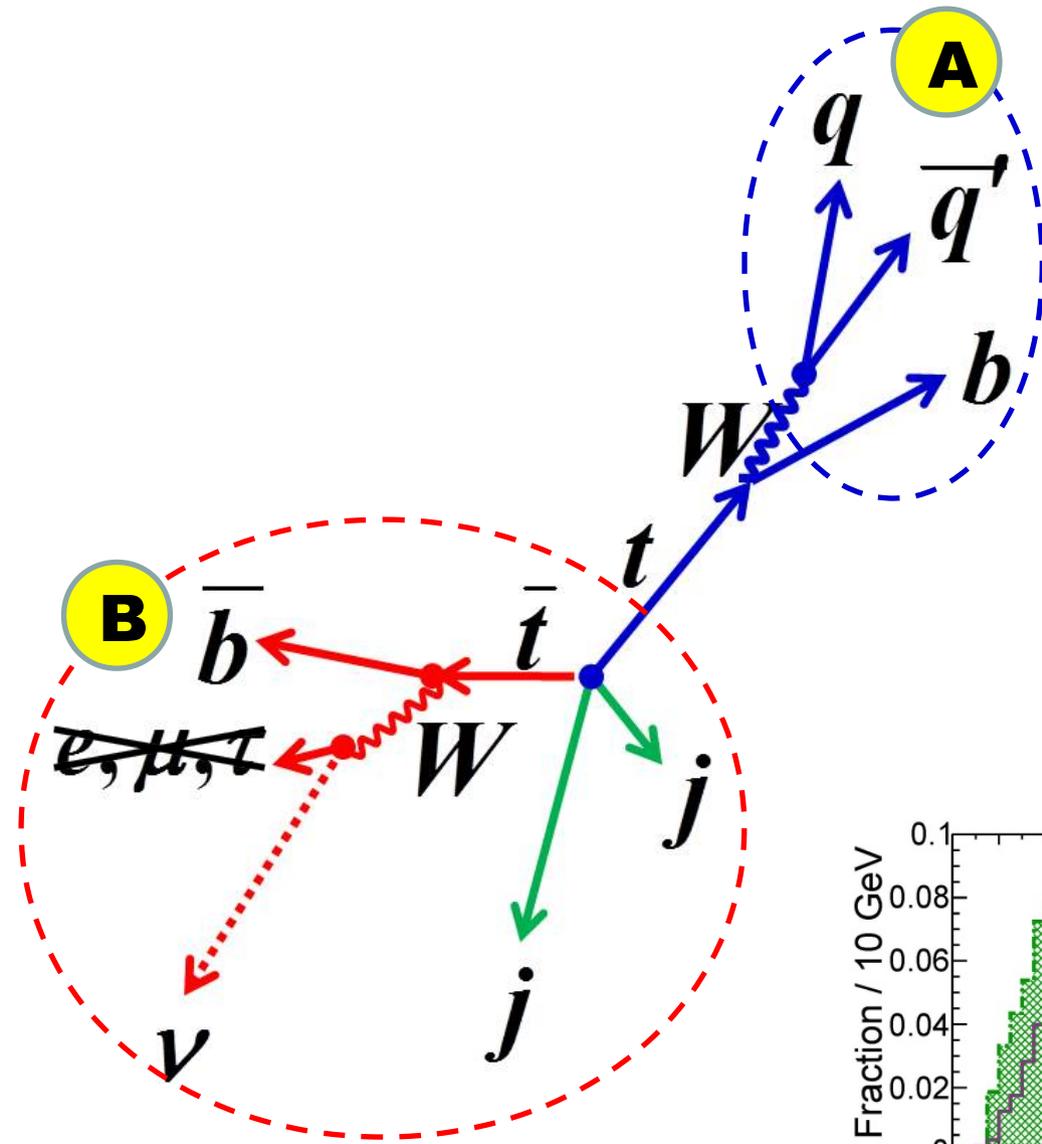
Stage 1: Tagging 1st Top



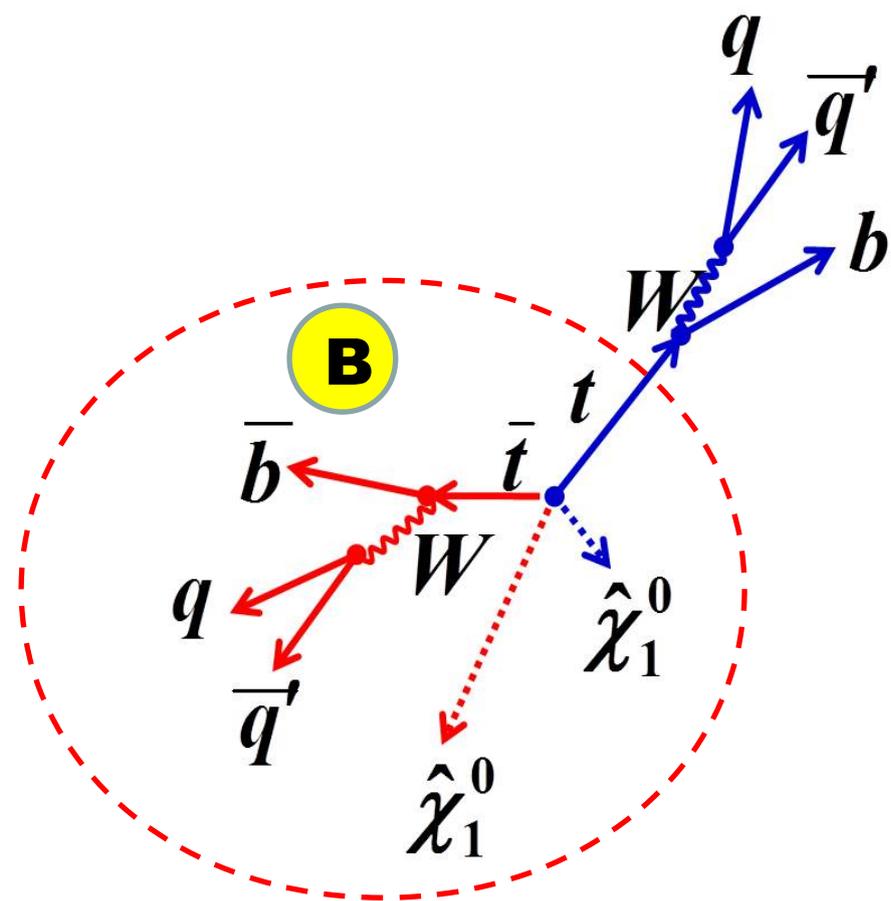
$40 < M(jj) < 120$
& $120 < M(jjb) < 220$



Stage 2: Kinematic Cuts

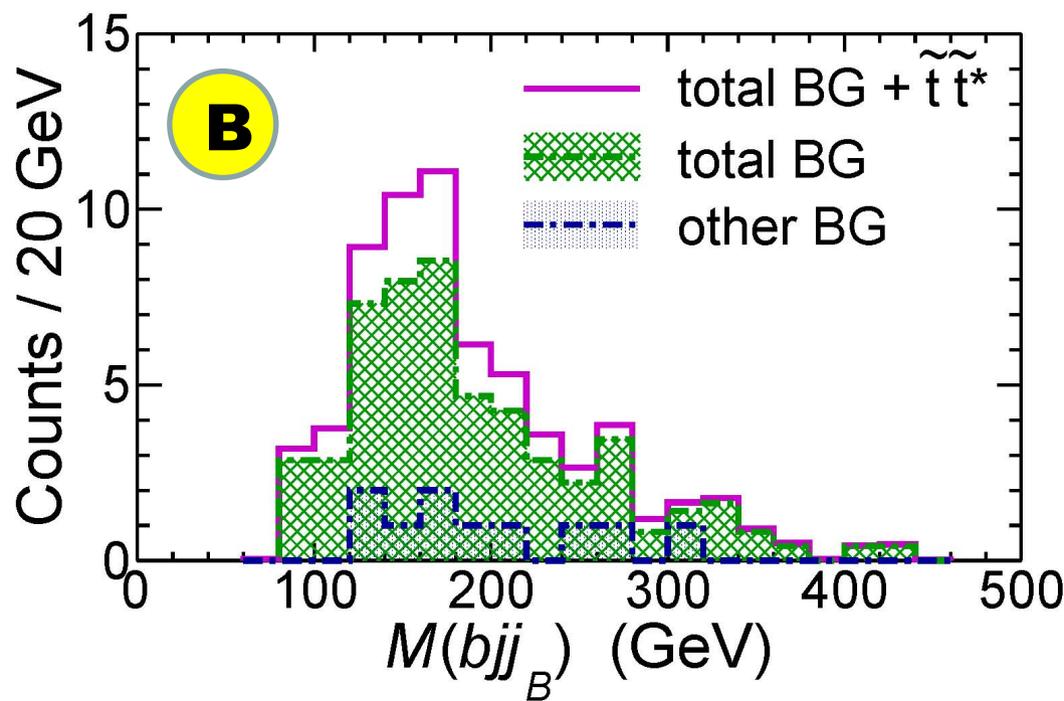


Stage 3: Tagging other Top with M3



$40 < M(jj) < 120$ & $120 < M(jjb) < 220$

$40 < M(jj) < 120$



M3 and HEPTOPTAGGER

TABLE V: Summary of effective cross sections (fb) for stop pair production and the SM background events in our stop search feasibility study. Masses and momenta are in GeV. “Other” sources of background include single top + jets, $W + n$ jets and $Z + n$ jets with $1 \leq n \leq 6$. The significance is given at 50 fb^{-1} .

		Signal	$t\bar{t} + n(\leq 2)\text{jets}$	$t\bar{t} + n(\geq 3)\text{jets}$	Others
$m_{\tilde{t}} = 450$ $m_{\tilde{\chi}_1^0} = 100$	Initial	160	2.0×10^5	0.24×10^5	2.8×10^5
	Baseline Cuts (Sec. IIIB)	2.52	192	147	31.7
	$\cancel{E}_T > 195 \text{ GeV}$	1.61	34.5	31.9	8.08
	System A: M3 (Sec. IIIC)	0.62	9.17	6.32	1.30
	Angular and M_T cuts (Sec. IIID)	0.25	0.55	0.69	0.40
	System B: M3 (Sec. IIIE)	0.12	0.17	0.14	0.06
Significance (S/\sqrt{B})				1.39	

$$\frac{\bar{t}\bar{t} + \geq 3j}{\bar{t}\bar{t} + \leq 2j} \approx 0.8$$

arXiv:1205.2696v1 [hep-ph]

$\bar{t}\bar{t} + 0,1,2j$

$\sqrt{s} = 8 \text{ TeV}$	$\bar{t}\bar{t}^*$						$t\bar{t}$	QCD	$W+\text{jets}$	$Z+\text{jets}$	S/B	$S/\sqrt{B}_{10\text{fb}^{-1}}$
$m_{\tilde{t}}[\text{GeV}]$	350	400	450	500	600	700						400
cross section [fb]	760	337	160	80.5	23.0	7.19	$2.3 \cdot 10^5$	$6.5 \cdot 10^8$	$1.6 \cdot 10^6$	$1.2 \cdot 10^4$	$< 10^{-6}$	0.04
ℓ veto	488	215	101	50.5	14.4	4.46	$1.6 \cdot 10^5$	$6.5 \cdot 10^8$	$1.3 \cdot 10^5$	$1.2 \cdot 10^4$	$< 10^{-6}$	0.03
$n_{\text{fat}} \geq 2$	167	88.3	48.0	26.6	8.71	2.96	$3.7 \cdot 10^4$	$2.0 \cdot 10^7$	$1.1 \cdot 10^5$	$1.3 \cdot 10^3$	$< 10^{-5}$	0.06
$\cancel{p}_T > 100 \text{ GeV}$	104	65.0	38.5	22.5	7.76	2.74	$1.6 \cdot 10^3$	$2.0 \cdot 10^8$	$1.9 \cdot 10^3$	694	$3 \cdot 10^{-4}$	0.45
$n_{\text{tag}} \geq 1$	27.5	18.5	11.87	7.60	2.91	1.12	375	$2.5 \cdot 10^3$	36.7	17.0	$6 \cdot 10^{-3}$	1.1
$n_{\text{tag}} \geq 2$	2.34	1.65	1.12	0.76	0.34	0.14	6.40	18	0.5	-	0.07	1.0
b tag inside top	0.74	0.58	0.35	0.25	0.11	0.05	1.92	0.18	-	-	0.27	1.3
$m_{T2} > 250 \text{ GeV}$	0.24	0.30	0.22	0.18	0.09	0.04	0.34	0.03	-	-	0.79	1.5

Table II: Analysis flow for the two-top analysis. All numbers are given in fb. The symbol “-” denotes less than 0.01 fb.

More or less consistent ...

Conclusions

- VBF is effective in probing light and/or compressed stops
 - Weak boson fusion contributions can give a 5 sigma mass reach of 200-250 GeV with 300 fb at 14 TeV.
 - Study incomplete, the mass reach will probably be more
- Non-vanilla stop decays are important for dark matter/naturalness.
 - Bino/Higgsino LSP from stop decay with light slepton
 - For a 110 GeV LSP, the 3 sigma mass reach is a 500 GeV stop with with 30 fb at 8 TeV.
 - Heavy slepton case suffers from low branching, situation will improve with high luminosity study at 14 TeV.
 - Studies for 14 TeV ongoing.
- Explored M3 and simple kinematic cuts to study hadronic stops at 8 TeV

Backups

VBF Stops - Stealth/Rubicon/Light

Cut-flow chart

100 fb

LHC14

$\tilde{t} = 233 \text{ GeV}$

- How to compare signal (S) and background (B): $S/\sqrt{S+B}$.
- Associated uncertainty: $1./\text{pow}(S+B,3./2.)*\text{sqrt}((S+2*B)**2*ES**2+S**2*EB**2)$.

Cuts	Signal (S)	Background (B)	S vs B
Initial (no cut)	248.224 +/- 0.238	48136.5 +/- 15.0	1.12847 +/- 0.00219
Cut 1	193.69 +/- 6.53	48136.5 +/- 15.0	0.8810 +/- 0.0593
Cut 2	66.60 +/- 6.98	48136.4 +/- 15.0	0.3034 +/- 0.0636
Cut 3	66.60 +/- 6.98	48136.4 +/- 15.0	0.3034 +/- 0.0636
Cut 4	66.51 +/- 6.98	47041.2 +/- 35.8	0.3065 +/- 0.0643
Cut 5	63.60 +/- 6.88	25026 +/- 109	0.4015 +/- 0.0868
Cut 6	56.3 +/- 6.6	9004.6 +/- 85.4	0.592 +/- 0.138
Cut 7	47.32 +/- 6.19	3126.5 +/- 54.0	0.840 +/- 0.219
Cut 8	38.5 +/- 5.7	1129.4 +/- 33.2	1.13 +/- 0.33
Cut 9	30.77 +/- 5.19	421.7 +/- 20.4	1.447 +/- 0.476
Cut 10	24.5 +/- 4.7	160.3 +/- 12.6	1.805 +/- 0.658
Cut 11	19.21 +/- 4.21	64.96 +/- 8.05	2.094 +/- 0.837
Cut 12	15.02 +/- 3.76	27.41 +/- 5.23	2.305 +/- 0.991
Cut 13	11.4 +/- 3.3	11.42 +/- 3.38	2.39 +/- 1.09
Cut 14	8.65 +/- 2.89	5.33 +/- 2.31	2.31 +/- 1.13
Cut 15	4.90 +/- 2.19	0.962 +/- 0.981	2.02 +/- 1.11
Cut 16	3.60 +/- 1.88	0.47 +/- 0.69	1.78 +/- 1.08
Cut 17	2.6 +/- 1.6	0.192 +/- 0.438	1.55 +/- 1.05

DijetMass > 500

DijetMass > 1500

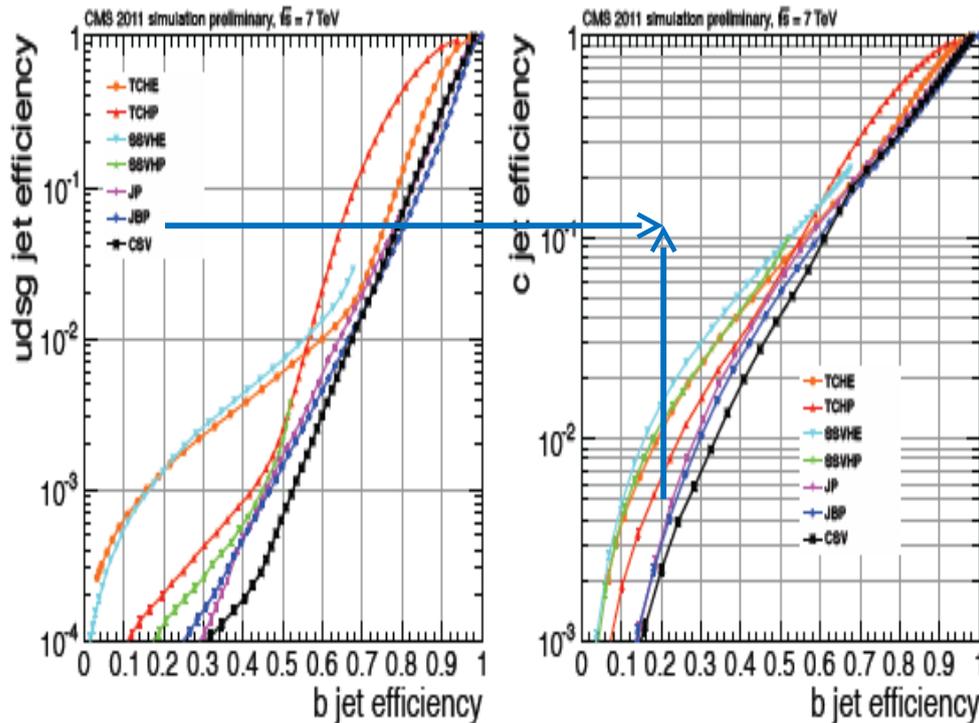
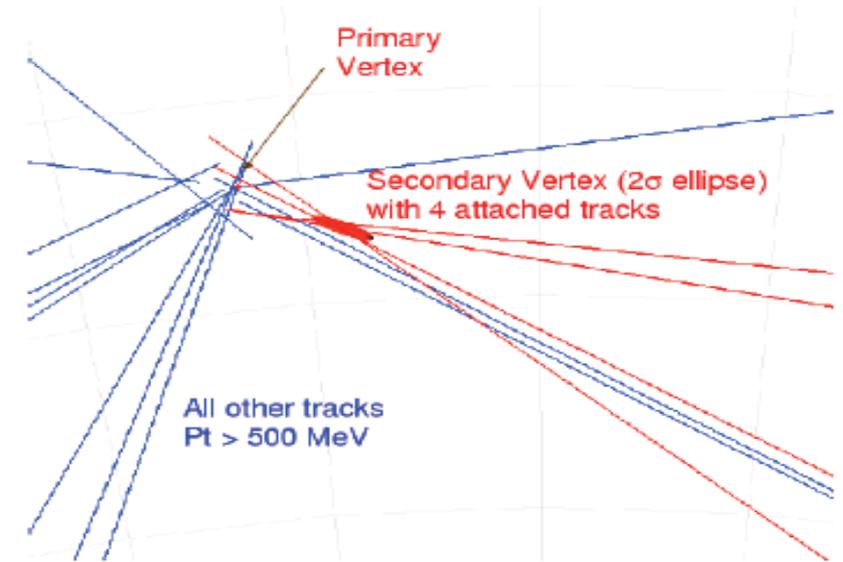
DijetMass > 2750

Signal and Background comparison

B-Tagging (at CMS)

❖ Properties used to identify b-jets

- Hard fragmentation functions
- Relatively large mass
- Long lifetime
- Semi-leptonic decays



❖ b-Tagging Variables

- 2D and 3D impact parameters (closest approach to primary vertex)
- Flight distance
- Invariant mass of tracks at vertex
- Number of tracks at vertex (~ 5 for b)
- Likelihood variables based on these parameters
- $\sim 70\%$ eff. with light mistag rate $\sim 2\%$

M3(TOP-10-009-PAS)

We define as M3 the invariant mass of those three jets that yield the vectorial sum with maximum p_T , including exactly one b-tagged jet and two untagged jets. This observable is an estimator of the mass of the hadronically decaying top quark. We include all selected jets in the reconstruction of M3, i.e. not only the four leading jets. We take M2 as the invariant mass of the two untagged jets that were assigned to M3. M2 is an estimator of the mass of the hadronically decaying W boson. The resulting M3 and M2 distributions can be found in Fig. 4, which also shows the distribution of the event-wise mass difference $\Delta M_{32} = M3 - M2$. While M3 and M2 are strongly correlated, there is only a modest correlation between M2 and ΔM_{32} . We therefore choose to use M2 and ΔM_{32} for a simultaneous measurement of m_t and JES.

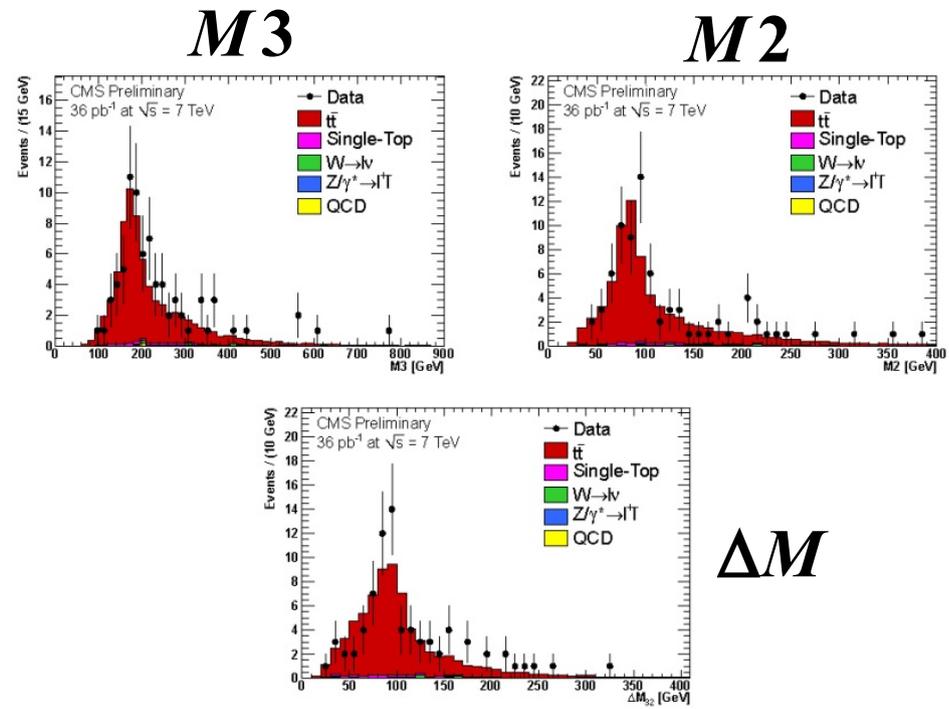
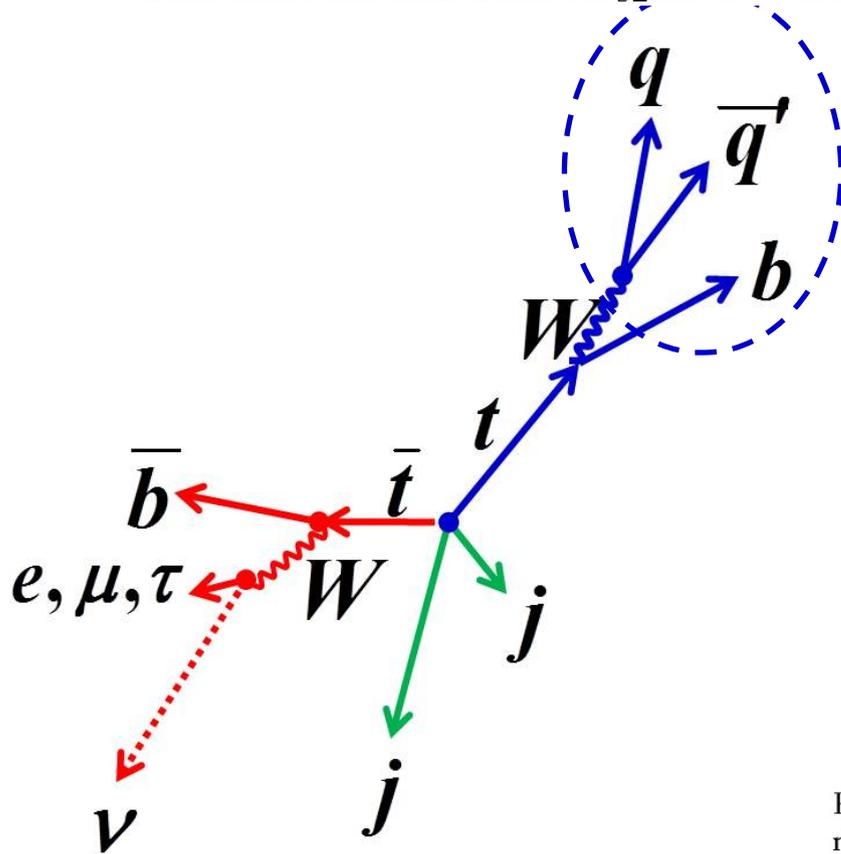
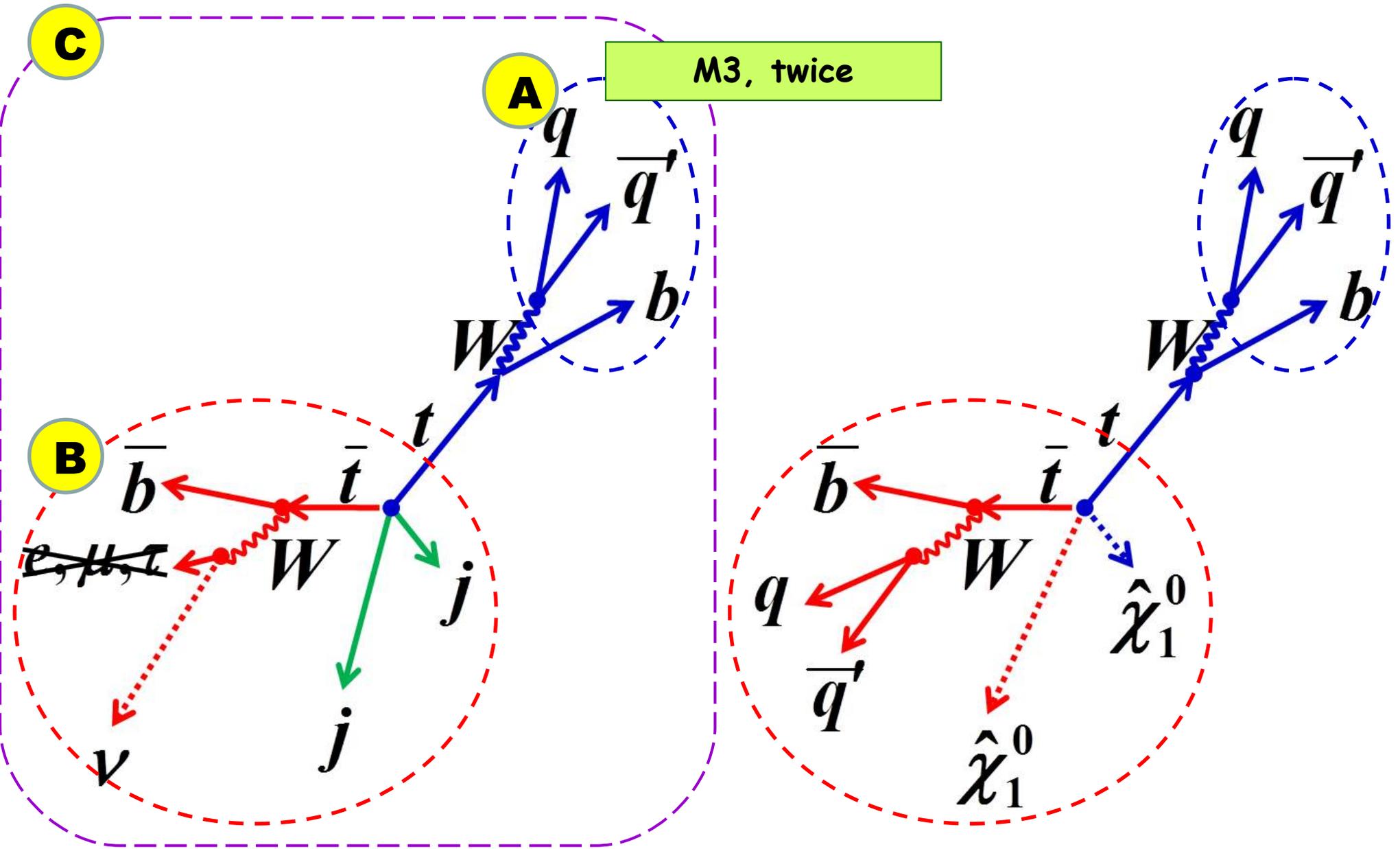


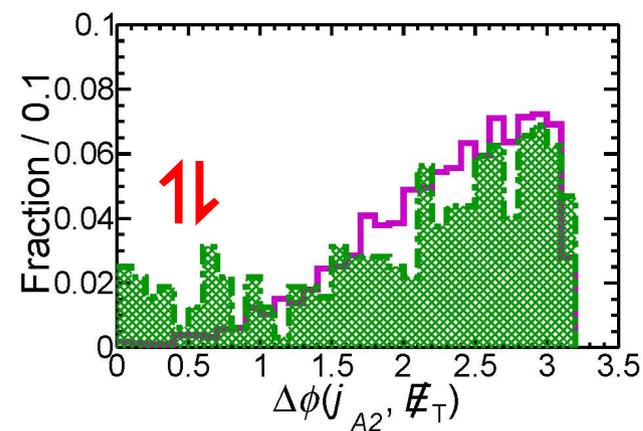
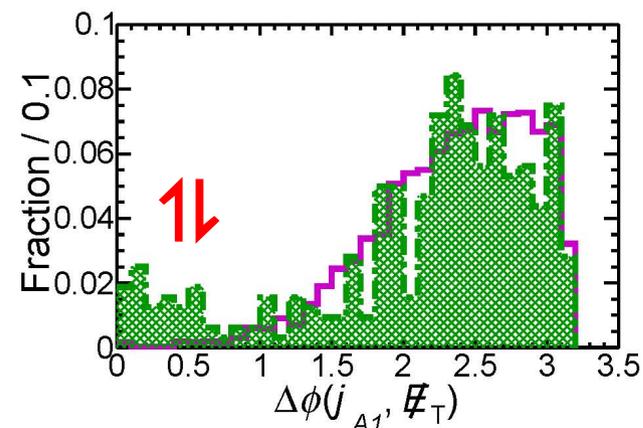
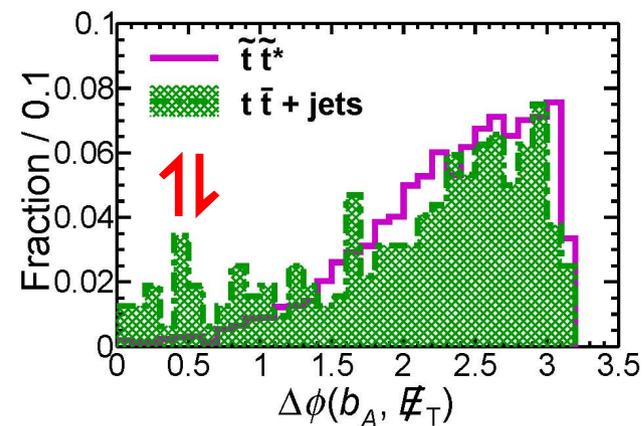
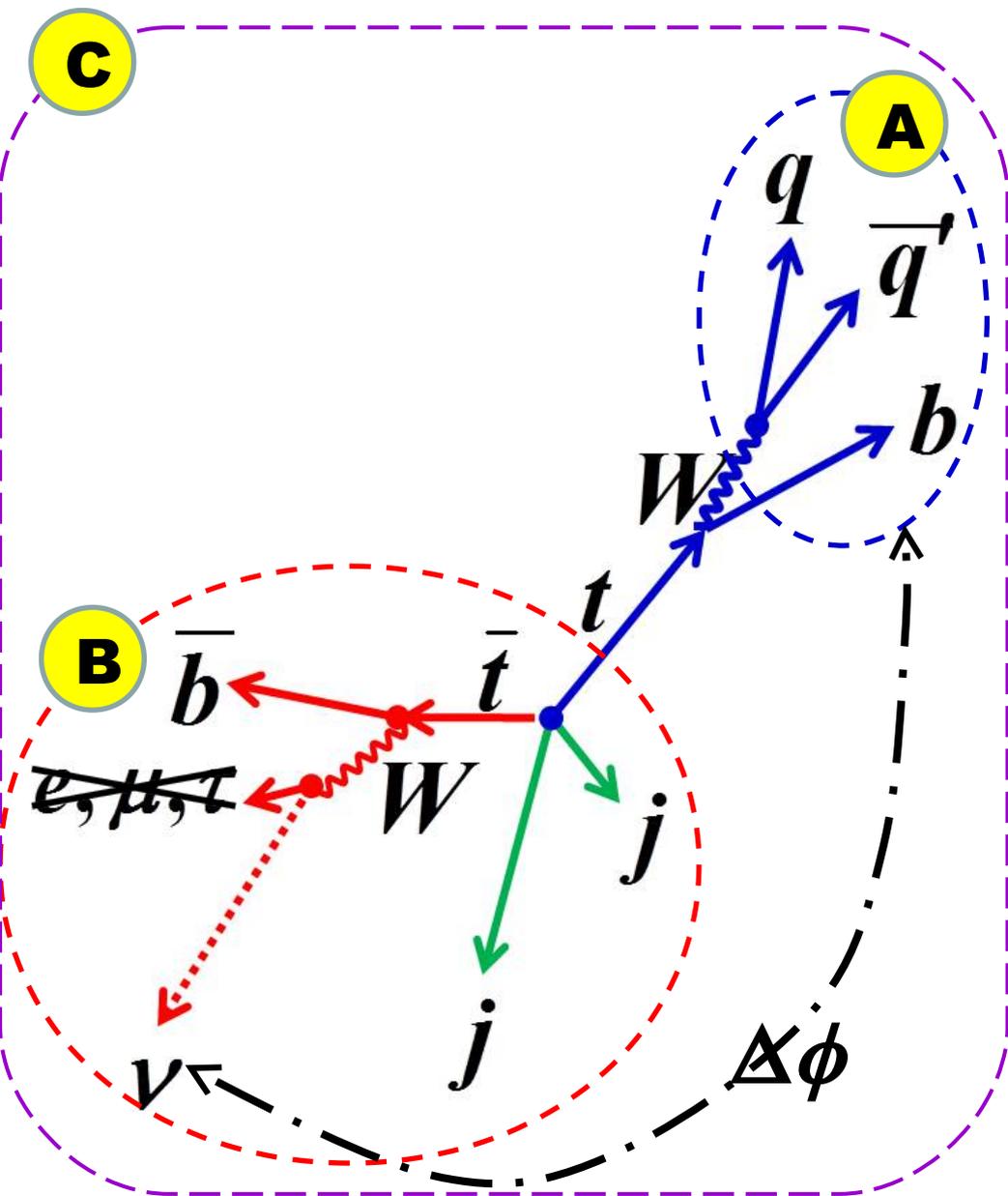
Figure 4: M3 (top left), M2 (top right) and ΔM_{32} (bottom) distributions for the muon+jets channel in data compared to the MC predictions, using the central sample with $m_t = 172.5$ GeV and JES = 1.

Stage 1

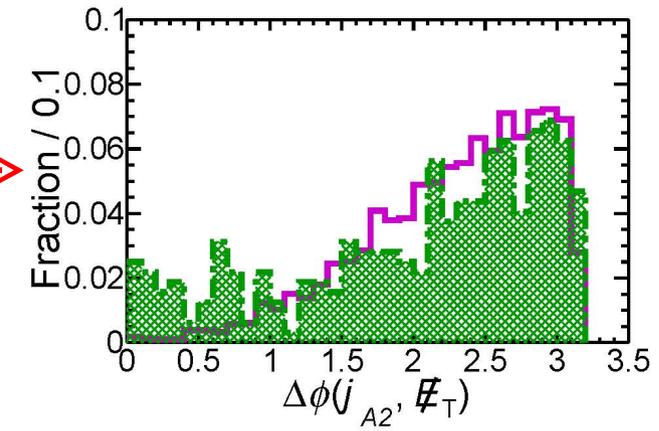
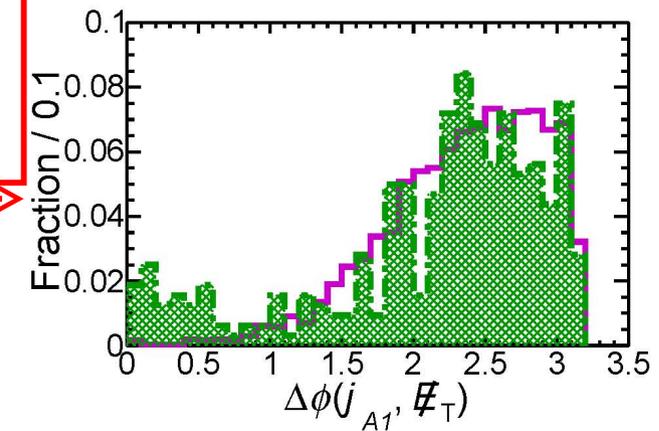
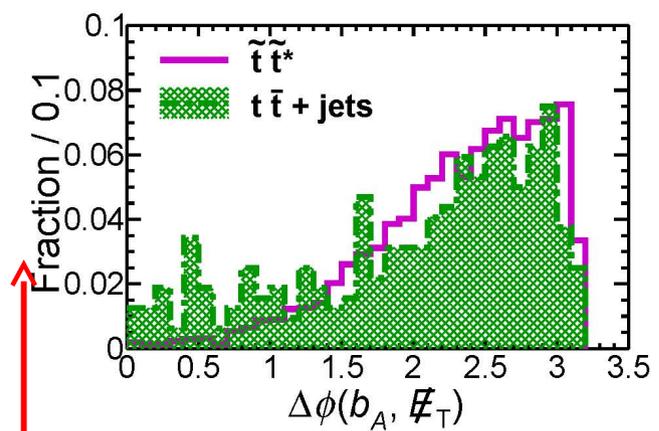
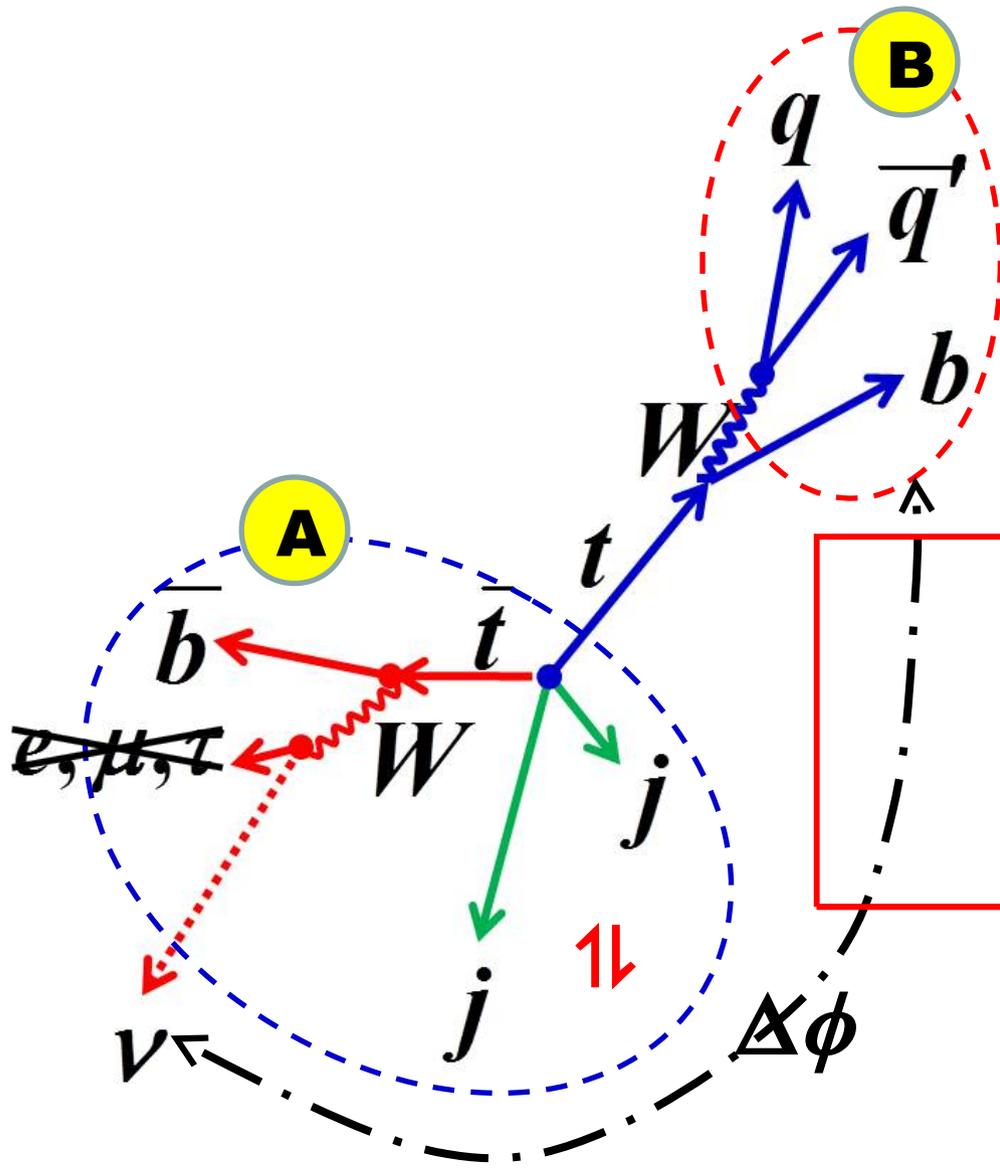
arXiv:1207.1873



Stage 3: Clean-up



Mixed up



Mixed up

