Searching for the Compressed Spectrum of Natural Supersymmetry
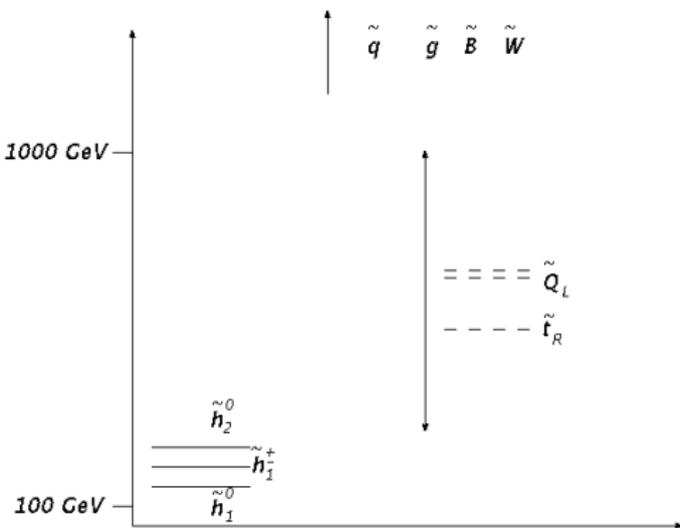
Arjun Menon

based on:
1401.1235 Zhenyu Han, Graham Kribs, Adam Martin, AM

May 4, 2014

Natural SUSY: "A definition"

- Spectrum: $m_{\tilde{i}} \propto$ inverse of the "leading log" contribution to EWSB scale.
- The lightest particles in the spectrum are: Higgsinos followed by $\tilde{t}_{1,2}, \tilde{b}_{1,2}$.

$$\frac{1}{2}m_Z^2 = \frac{\tan^2\beta + 1}{\tan^2\beta - 1}\frac{m_{H_d}^2 - m_{H_u}^2}{2} - \frac{1}{2}\left(m_{H_u}^2 + m_{H_d}^2\right) - |\mu|^2$$

Natural Higgsino and Stop masses

- Tree-level Higgsino: $\Delta(|\mu|^2) \simeq 10 \times \frac{|\mu|^2}{(200\text{GeV})^2}$

- 1-loop stop leading log contribution:

$$
\begin{aligned}
\Delta(\delta m_{H_u}^2|_{\text{stop}}) &= \frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\log\frac{\Lambda_{\text{mess}}}{(m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2}} \\
&\simeq 10 \times \frac{m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2}{2\times(450\text{ GeV})^2}\frac{\log\Lambda_{\text{mess}}/(m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2}}{3}
\end{aligned}
$$

Papucci et. al.

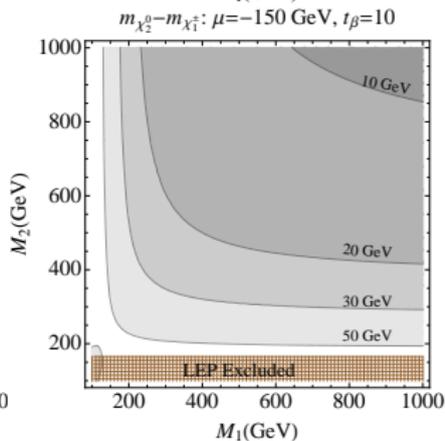Λ_{mess} is the messenger mass scale.

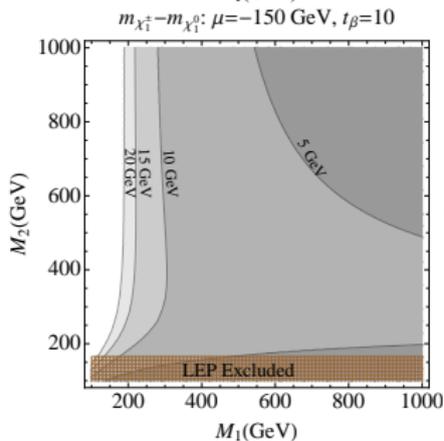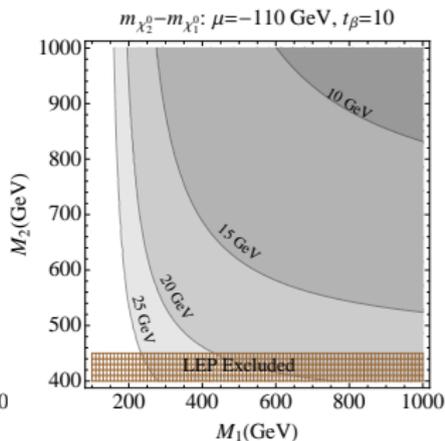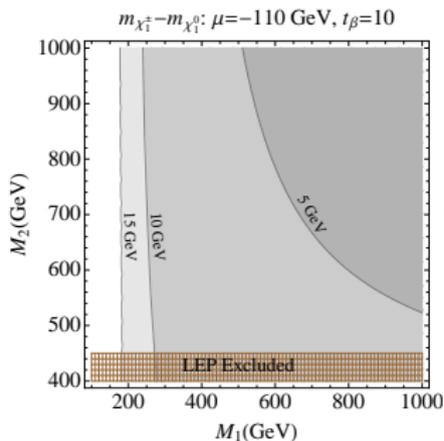- $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L$ typically heavier than Higgsinos.

Low mass states of Natural SUSY

- Only consider stops, sbottoms and Higgsinos
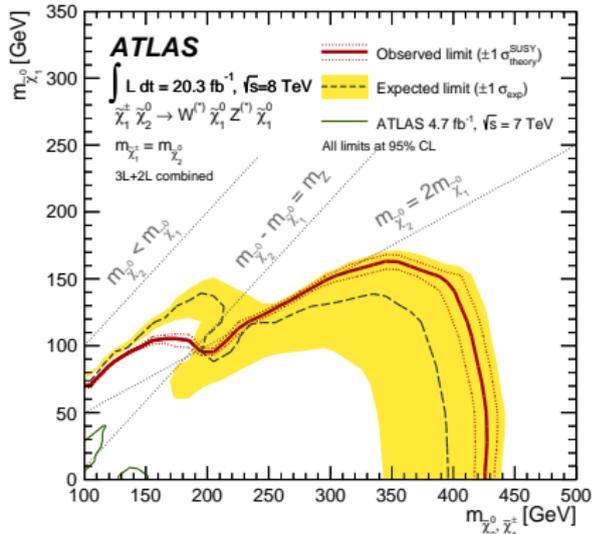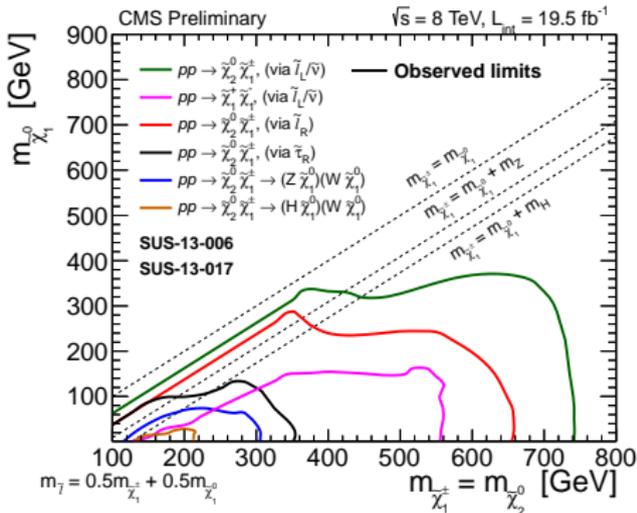- Higgsino mass splittings for natural gaugino masses:

$$m_{\chi_1^\pm} - m_{\chi_1^0} = \frac{M_W^2}{2M_2}\left(1 - \sin 2\beta - \frac{2\mu}{M_2}\right)$$

$$m_{\chi_2^0} - m_{\chi_1^\pm} = \frac{M_W^2}{2M_2}\left(1 - \sin 2\beta + \frac{2\mu}{M_2}\right)$$

$$+ \frac{M_W^2}{2M_1}\tan^2\theta_W(1 - \sin 2\beta)$$

- Small enough splitting to avoid triggering but large enough to not produce displaced vertices.
- Minimize stop contribution to EWSB scale
  $\Rightarrow A_t = 0 \Rightarrow \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$.
- Higgs mass set by enlarging Higgs sector (e.g. NMSSM).

The compressed Higgsinos

$m_{\chi_1^\pm} - m_{\chi_1^0}$: $\mu = -110$ GeV, $t_\beta = 10$

$m_{\chi_2^0} - m_{\chi_1^0}$: $\mu = -110$ GeV, $t_\beta = 10$

$m_{\chi_1^\pm} - m_{\chi_1^0}$: $\mu = -150$ GeV, $t_\beta = 10$

$m_{\chi_2^0} - m_{\chi_1^\pm}$: $\mu = -150$ GeV, $t_\beta = 10$

LHC Electroweak-ino Limits

Weak constraints on Compressed Higgsinos

Monojet Searches Limits on Higgsinos

| Channel	Obs. Limit	Exp. Limit	Cut (GeV).
ATLAS SR1	50 GeV	52 GeV	p_T^j, MET > 120
ATLAS SR2	70 GeV	69 GeV	p_T^j, MET > 220
ATLAS SR3	67 GeV	73 GeV	p_T^j, MET > 350
ATLAS SR4	103 GeV	63 GeV	p_T^j, MET > 500
CMS SR1	64 GeV	60 GeV	MET > 250
CMS SR2	68 GeV	63 GeV	MET > 300
CMS SR3	70 GeV	68 GeV	MET > 350
CMS SR4	71 GeV	71 GeV	MET > 400
CMS SR5	73 GeV	80 GeV	MET > 450
CMS SR6	71 GeV	74 GeV	MET > 500
CMS SR7	68 GeV	68 GeV	MET > 550
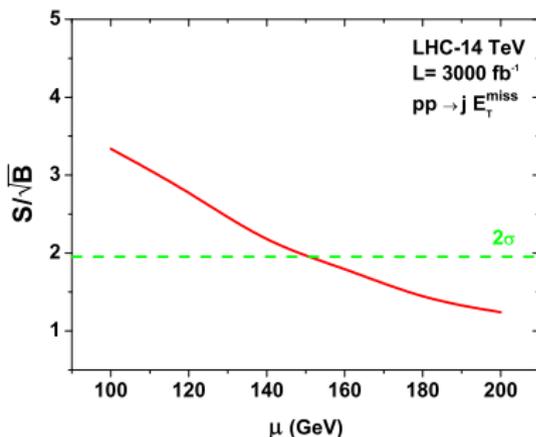
Han et. al.

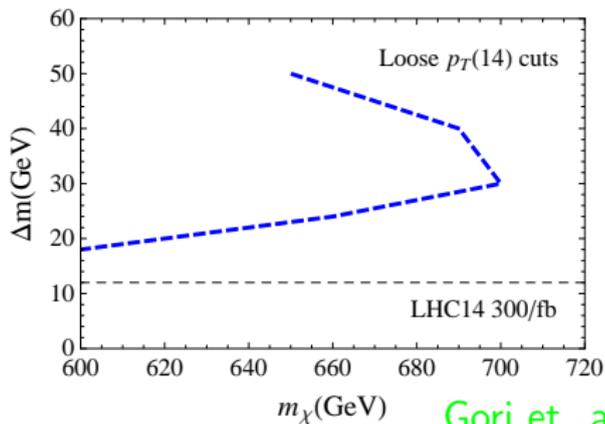LHC limits as weak and project reach requires large luminosity.

Improving on the Trilepton Search

2σ Exclusions

No sleptons
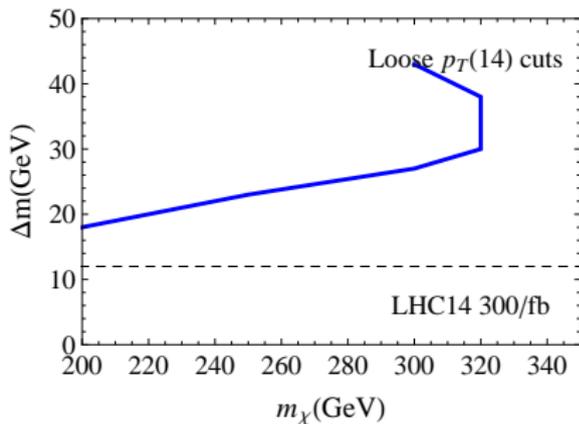
$m_{\tilde{l}} = (m_{\tilde{\chi}^{\pm}} - m_{\chi^0})/2$

Gori et. al.

- ▶ Required ISR jet to boost leptons: $p_T^j > 30$ GeV
- ▶ Use $\Delta\phi(j_1, \mathrm{MET})$, $\mathrm{MET}/p_T^{j_1}$ and $p_T^{\ell_1}/p_T^{j_1}$ to suppress bkg.
- ▶ The 3ℓ channel is technically challenging for mass gaps below ~ 12 GeV

Going beyond Monojet and tri-lepton Signals

Signal: $1j + 1\ell + \text{MET}$

- $\frac{\sigma_{\text{signal}}}{\sigma_{Wj}} \sim 1/500$.

- Signal also peaks at low $m_T = 2\,\text{MET}\,p_T^\ell(1 - \cos\phi_{\ell\,MET})$ (due to low p_T of the leptons) like the background.

- Not many other handles.

Signal: $2j + 1\ell + \text{MET}$

- Signal: $pp \to j + \chi_1^{\pm}\chi_1^{\mp} \to j\ell^+\ell'^-\nu\bar{\nu}\chi_1^0\chi_1^0$
  $\quad\quad\quad pp \to j + \chi_2^0\chi_1^0 \to j\ell^+\ell^-\chi_1^0\chi_1^0$
  $\quad\quad\quad pp \to j + \chi_2^0\chi_1^{\pm} \to jj\ell^+\ell^-\chi_1^0\chi_1^0, j\ell^+\ell^-\ell'^{\pm}\nu\chi_1^0\chi_1^0$

- Backgrounds: VVj, $t\bar{t}$, $Zj \to j\tau^+\tau^- \to j\ell^+\ell^- + 4\nu$, fakes: $Wb\bar{b}$, $W + jets$, $j + 3\ell\nu$ ...

More handles and lower bkg. $\sigma \Rightarrow 2j + 1\ell + \text{MET}$ more promising.

Simulation Details

- Events generated with Madgraph5+Pythia8.
- Particles (except for leptons) grouped into 0.1×0.1 bins in (η, ϕ) corresponding to HCAL granularities.
- Jets clustered using the anti-kt with $R = 0.4$.
- MET > 100 GeV and exactly 1j with $p_T > 100$ GeV (to pass event trigger)
- No smearing of leptons
- Require > 2 isolated leptons with $p_T > 7$ GeV

Background Reduction

- Suppress $t\bar{t}$ by requiring no second jet with $p_T > 30$ GeV and bjet veto.
- $Zj \to j\tau^+\tau^-$ suppressed by cutting on the reconstructed Z mass in the collinear approximation.
  - Assume $\nu\bar{\nu}$ pairs are collinear with the lepton.
  - Solve for the magnitude of pairs, subject MET constraint.
  - Require $m_{\tau\tau} > 150$ GeV.
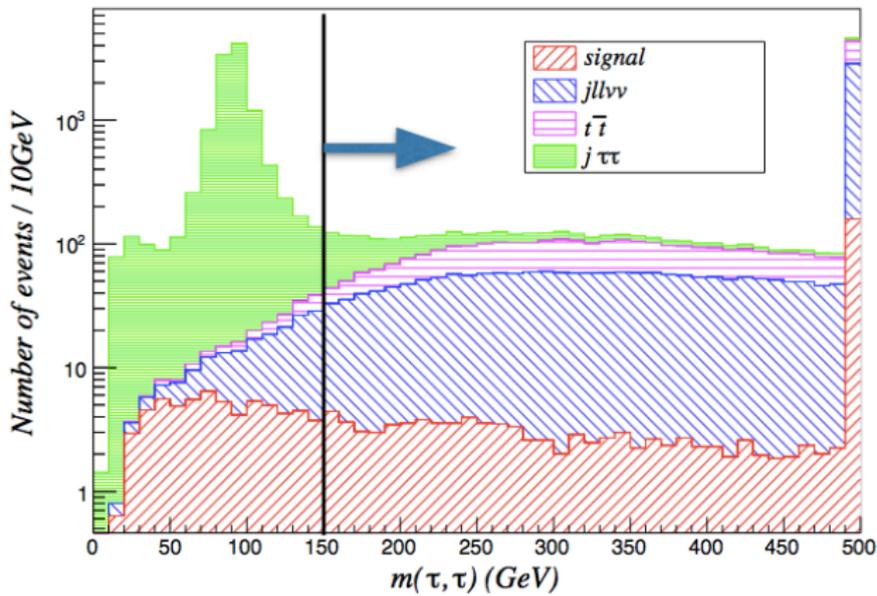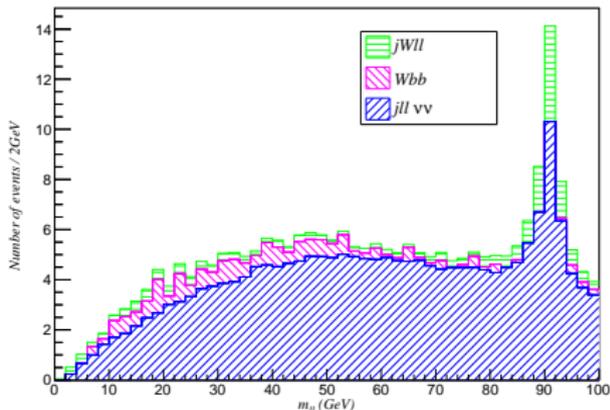
Additional Backgrounds

Light flavor fakes (estimate): $\sigma \sim 0.06 \times \sigma_{WWj}$

- $W(\to l\nu) + j$: $p_T^{j_1}$ and MET cut at 8 TeV $\Rightarrow \sigma \sim 38$ pb.
- Showered/hadronized jets replaced by lepton $\Rightarrow \sigma \sim 10.2\epsilon$ pb
- Fake rate $\epsilon = (0.6 - 3) \times 10^{-5}$ Curtin et. al.

Heavy flavor fakes (estimate): $\sigma \sim 0.05 \times \sigma_{WWj}$

- $W(\to l\nu)b\bar{b}$: Isolation, clustering and clustering.

Tri-leptons: $WZ + j$ and $W\gamma^* + j$

- One lepton lost in detector

DPS: $\sigma_{\text{tot}} \sim \sigma_{W/Z+j}\sigma_B/12\text{mb}$

- B = (Drell-Yan: $\sigma_{tot} \sim 10^{-2}$ fb $\gg$ QCD resonances $\sim$ heavy flavors)

Cut Table

	σ(fb) at 8 TeV			
	$j\ell\ell\nu\nu$	$t\bar{t}$	$j\tau\tau$	signal (110 GeV)
p_T^j, MET > 100 GeV	19.0	9.6	130.4	5.2
two isolated leptons	17.8	8.8	46.5	0.8
$m_{\tau\tau} > 150$ GeV	17.3	8.6	3.7	0.6

	σ(fb) at 14 TeV				
	$j\ell\ell\nu\nu$	$t\bar{t}$	$j\tau\tau$	signal (110 GeV)	signal (150 GeV)
p_T^j, MET > 100 GeV	48.4	30.8	339.0	14.0	5.8
two isolated leptons	45.2	28.0	120.9	2.2	0.9
$m_{\tau\tau} > 150$ GeV	43.9	27.6	9.7	1.7	0.7

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}
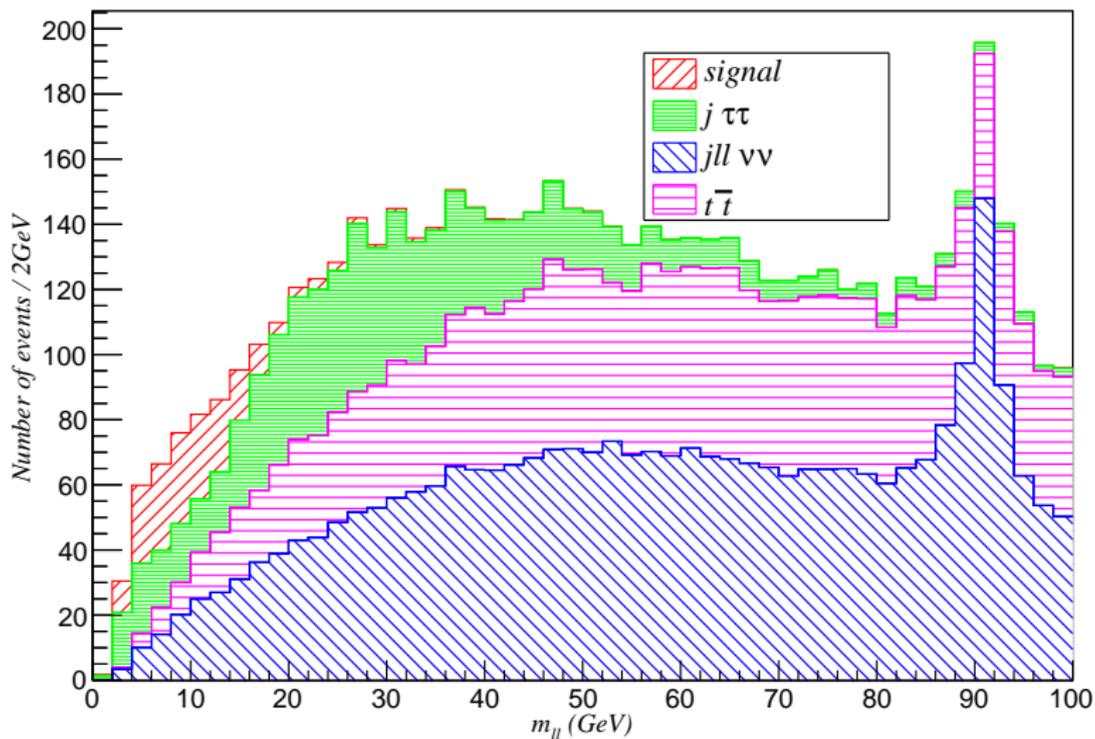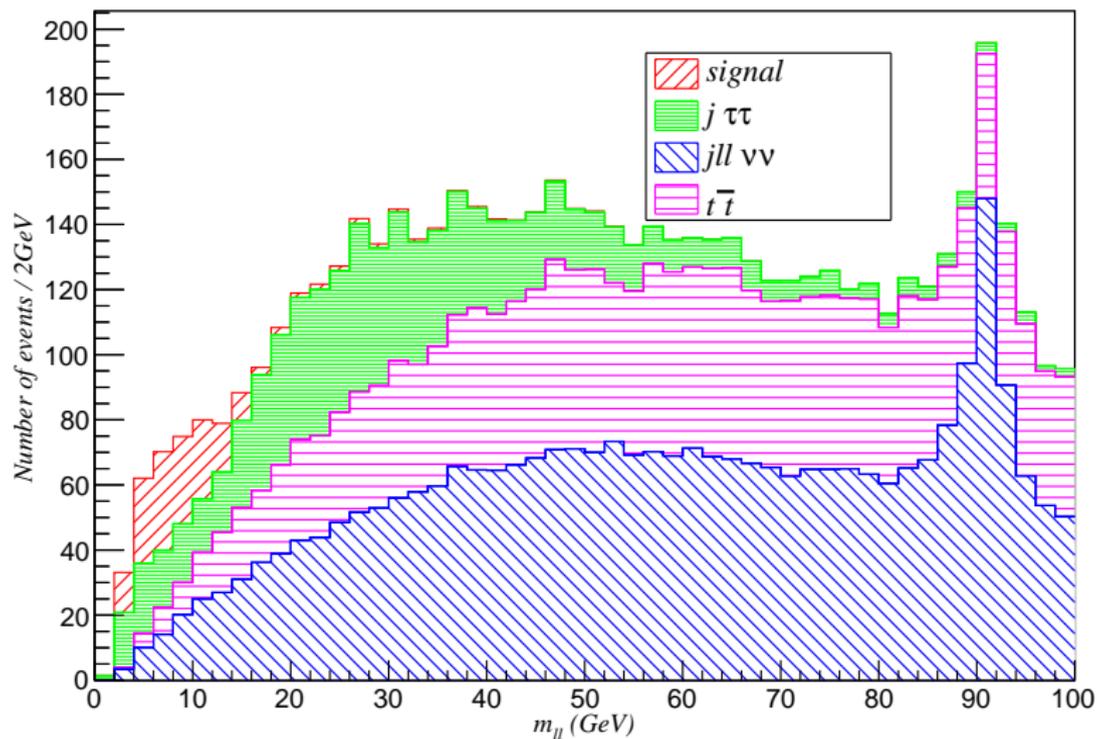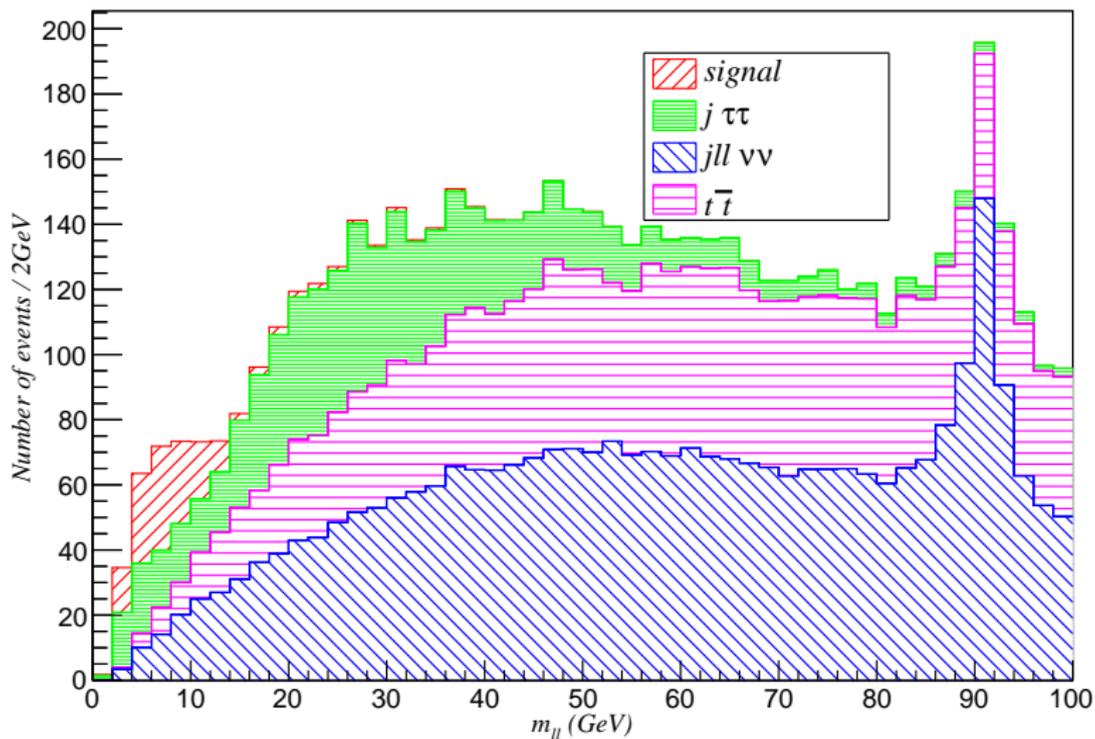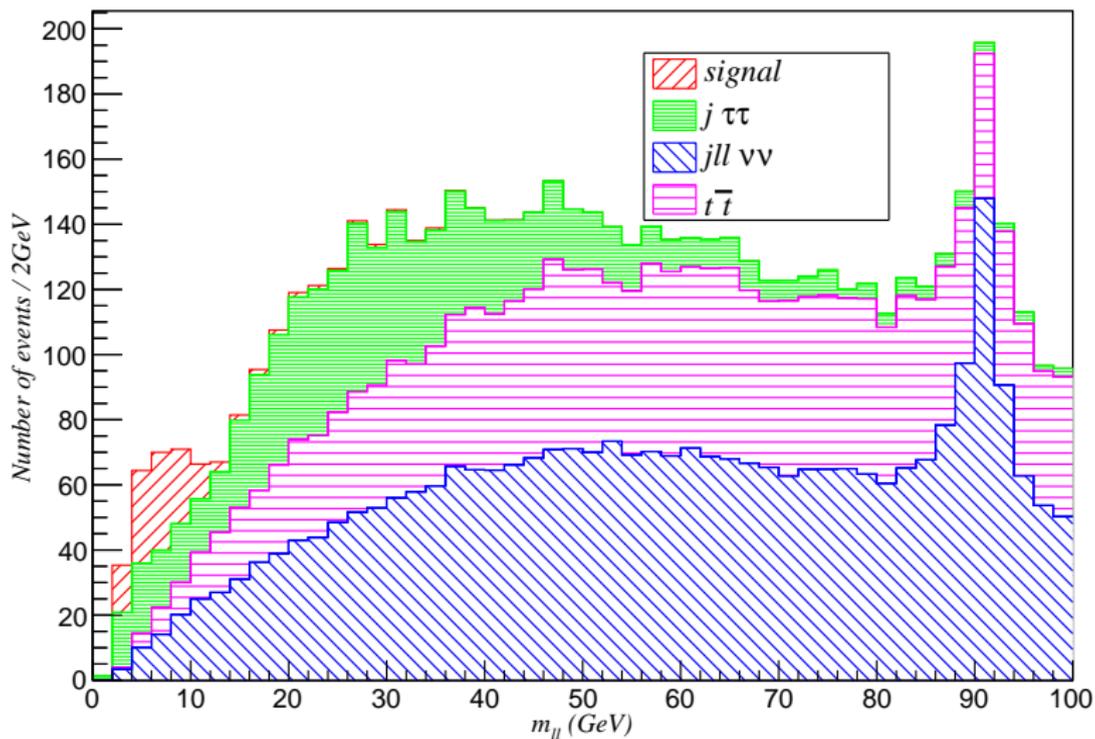

M1=1000, M2=150, μ=110, tanβ=10
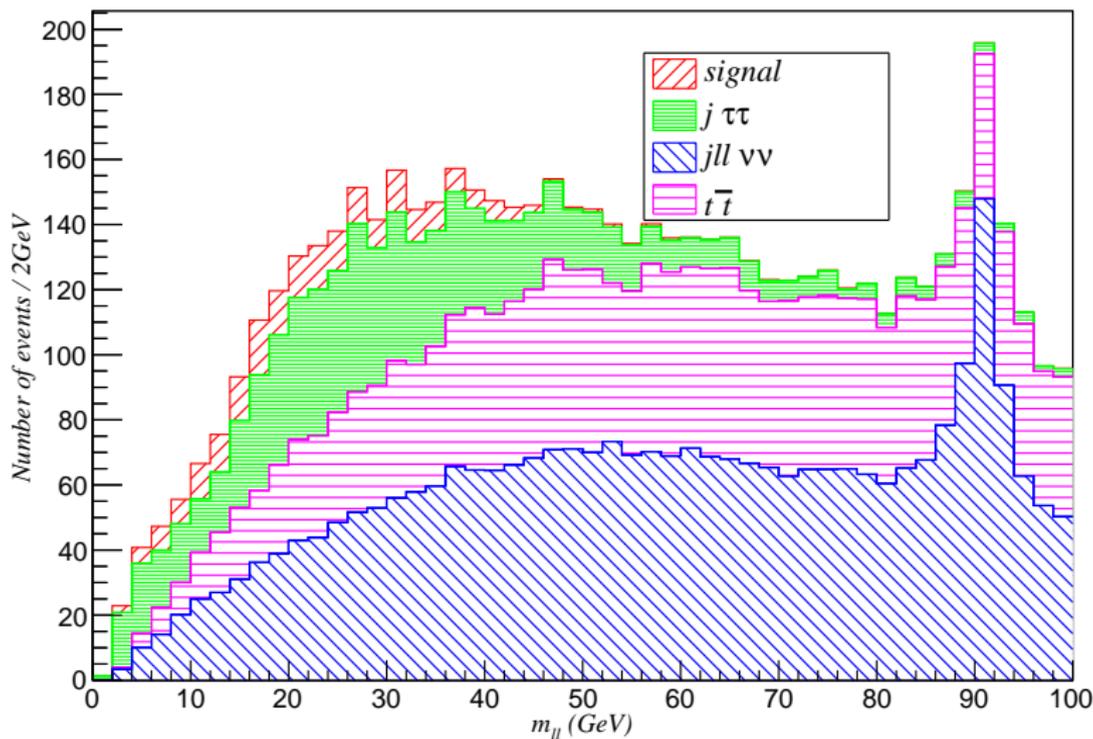
The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=200, μ=110, tanβ=10
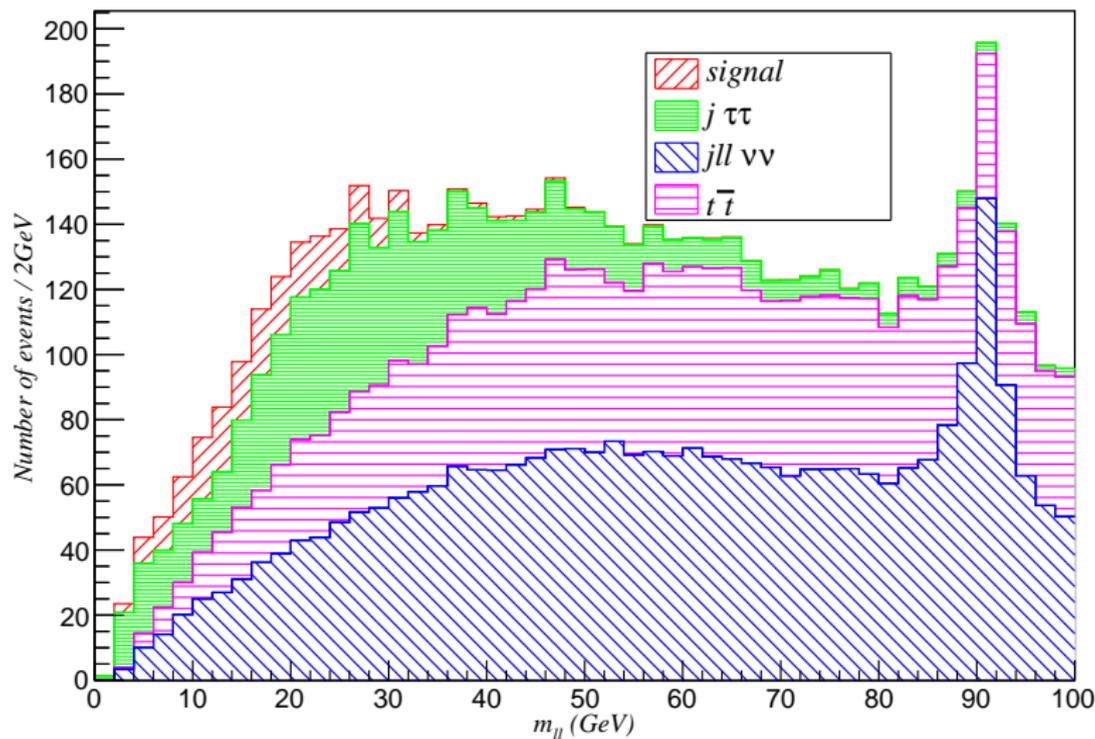
The Dilepton invariant mass @ 14 TeV 100 fb^{-1}
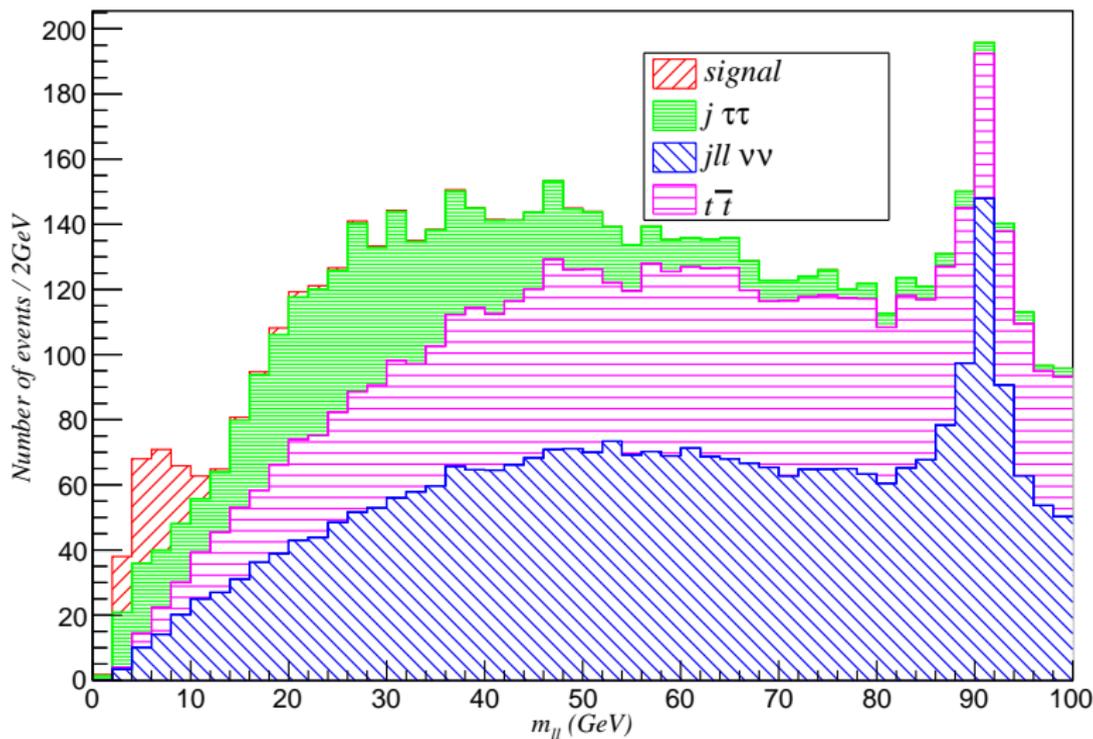

M1=1000, M2=250, μ=110, tanβ=10
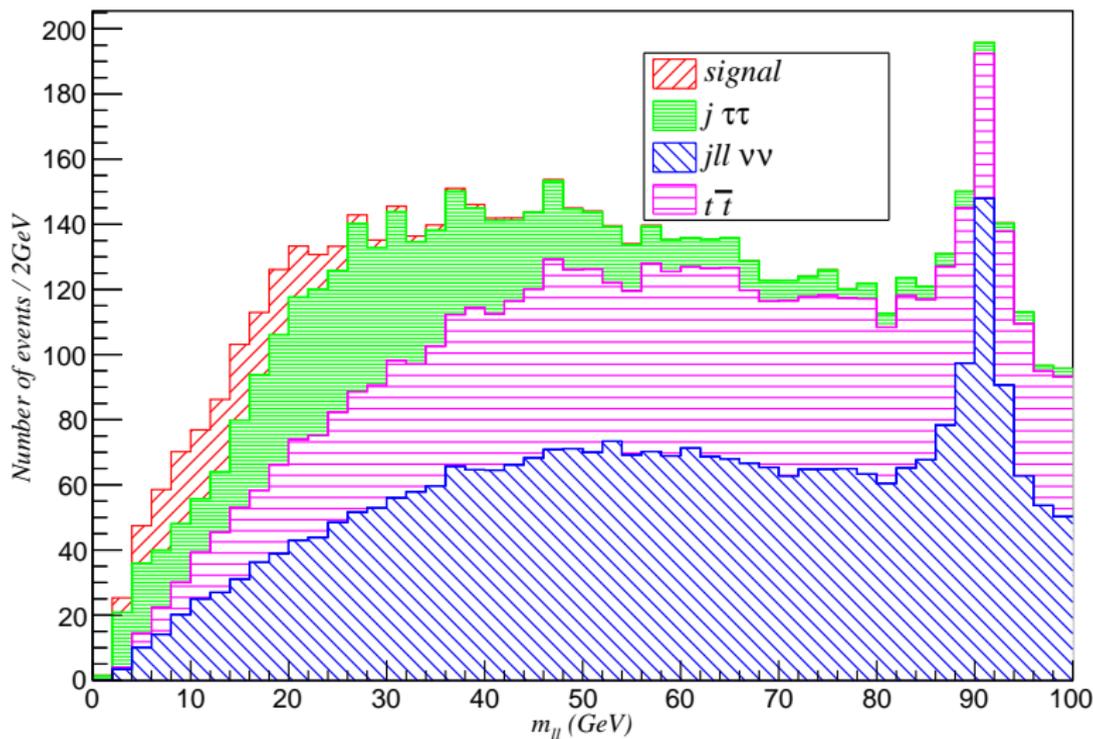
The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=300, μ=110, tanβ=10
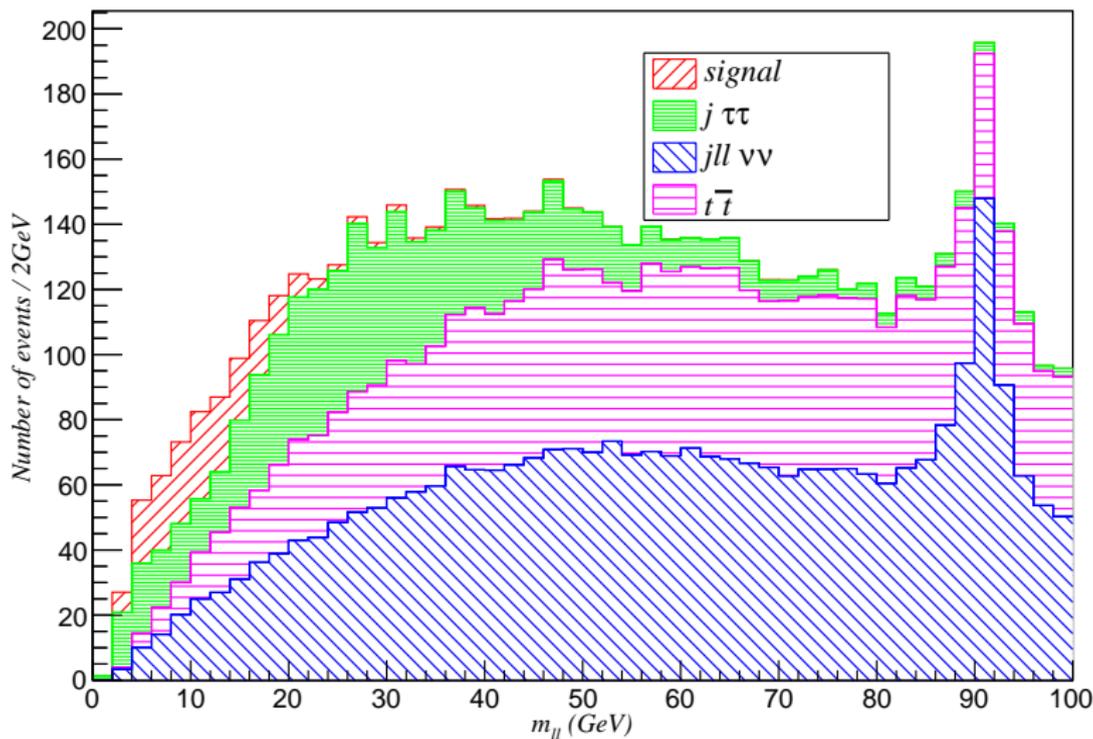
The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=350, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}
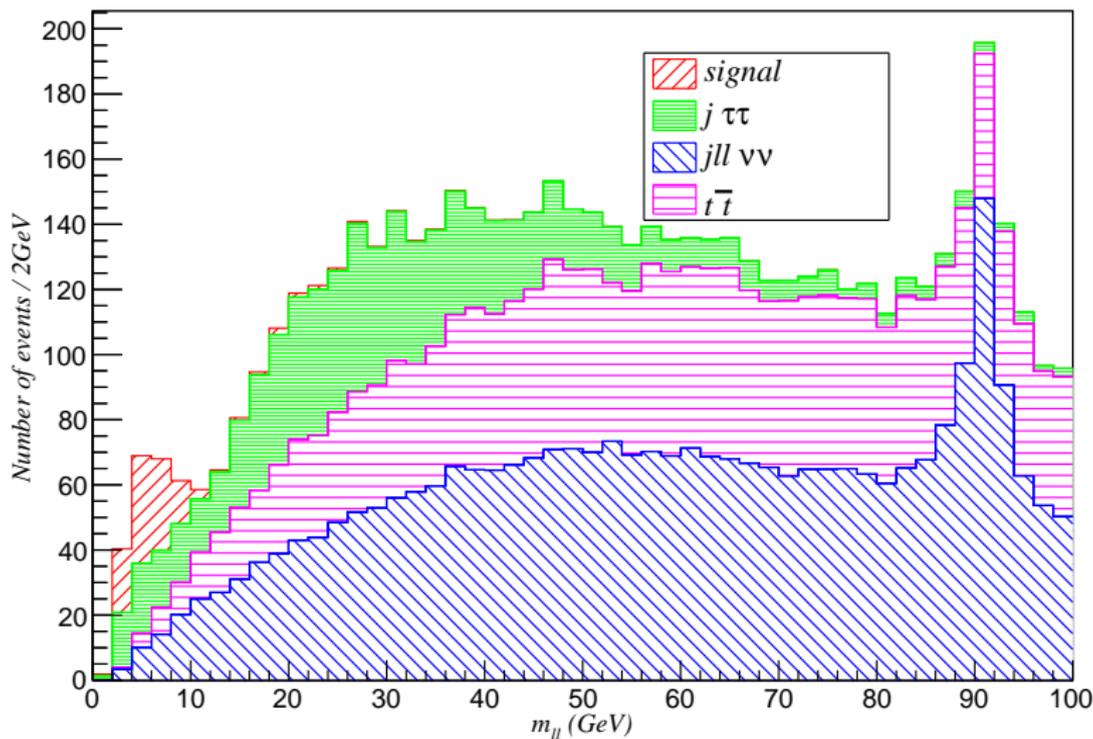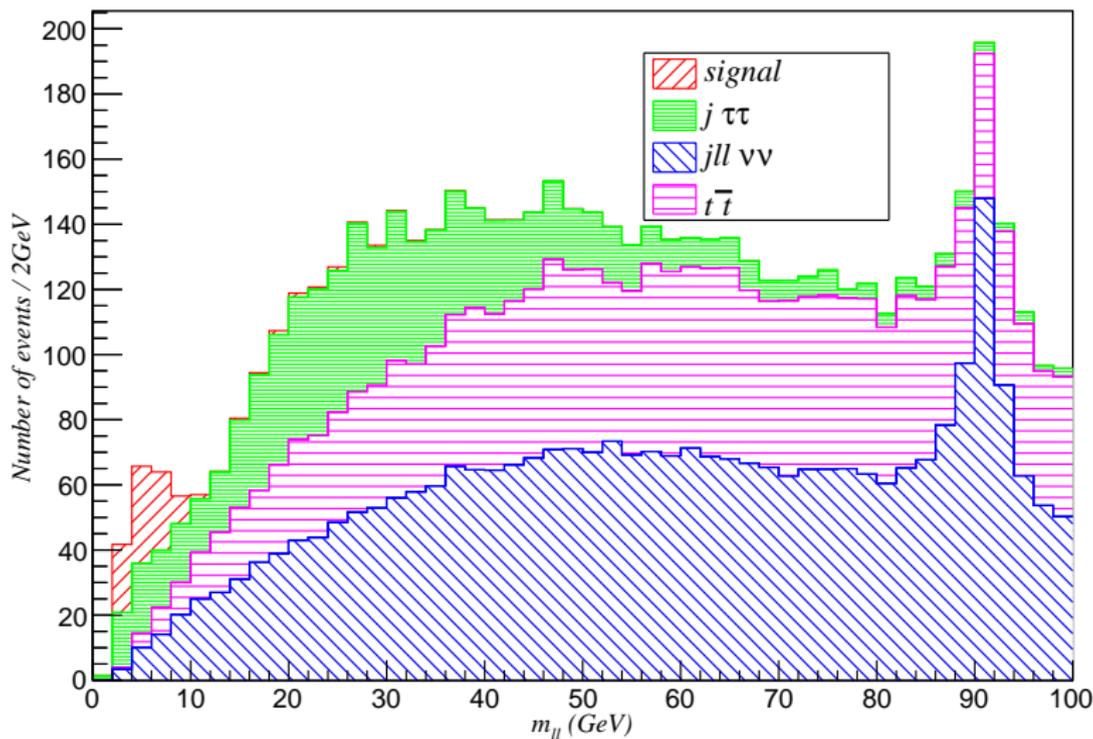

M1=1000, M2=400, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=450, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=500, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=550, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}
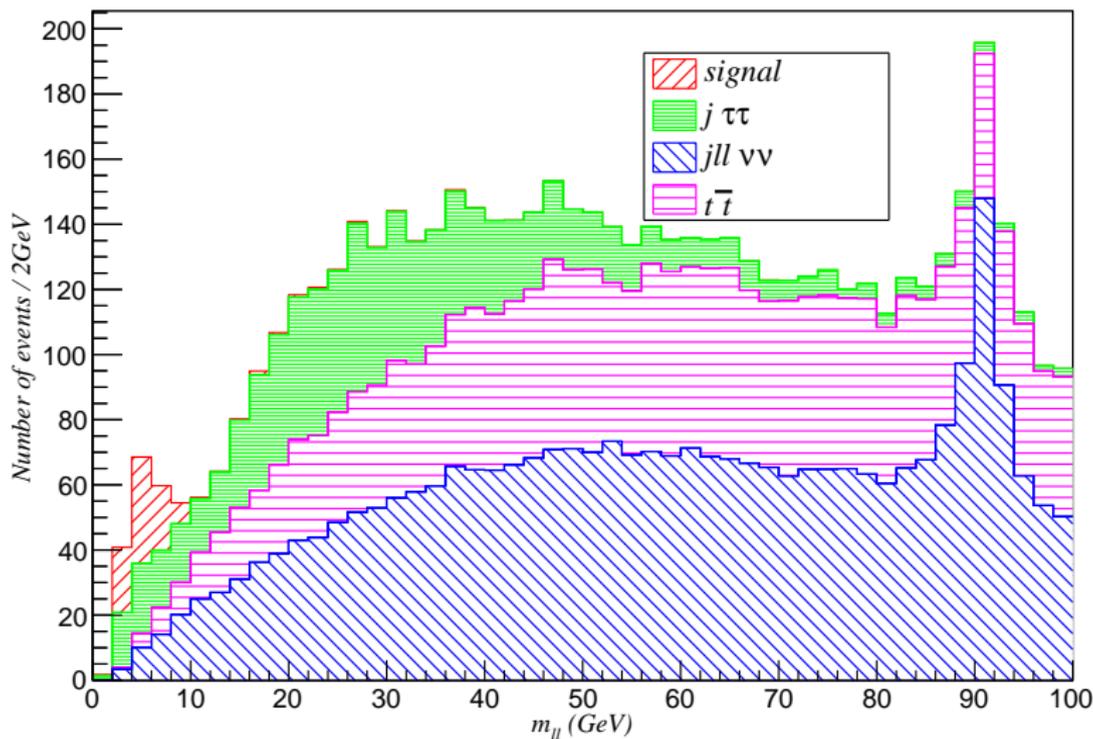

M1=1000, M2=600, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=650, μ=110, tanβ=10

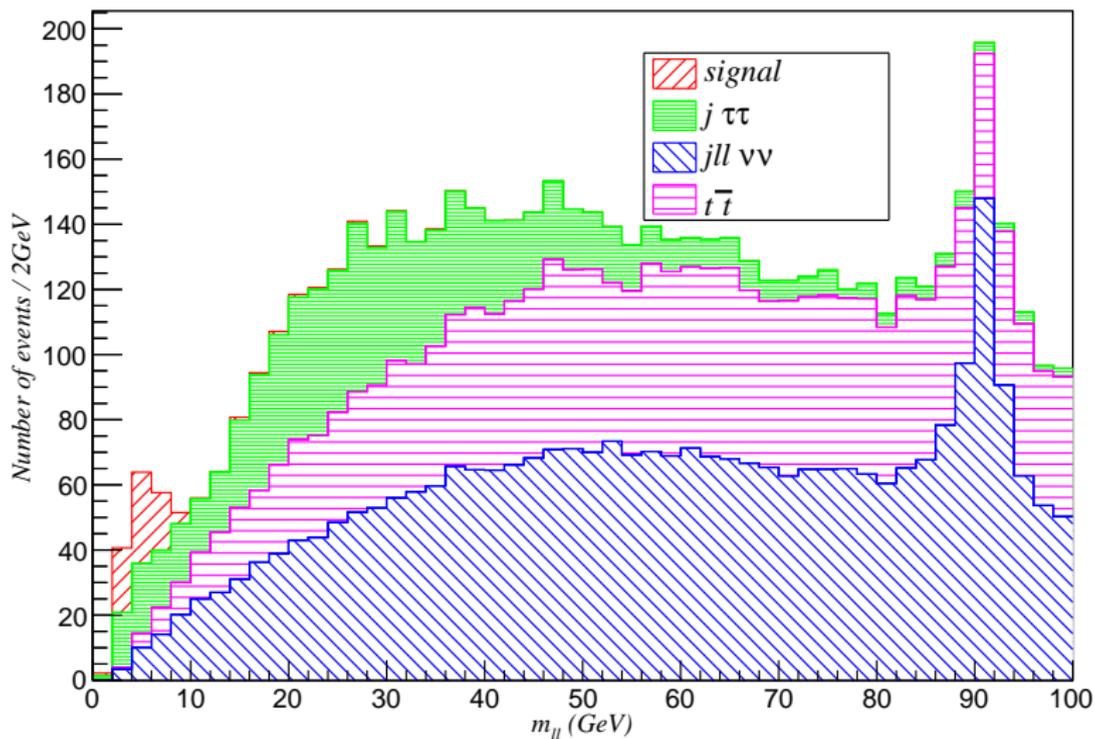# The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=700, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=750, μ=110, tanβ=10

Legend:
- signal
- $j\,\tau\tau$
- $jll\,\nu\nu$
- $t\bar{t}$

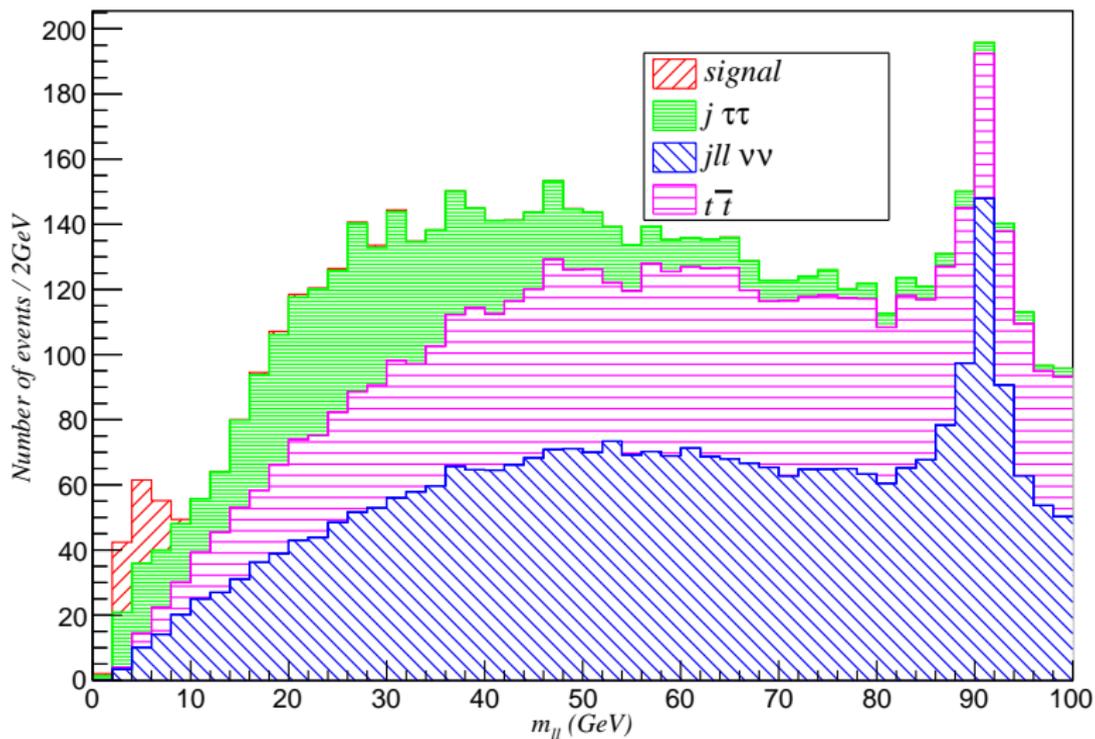Y-axis: Number of events / 2GeV
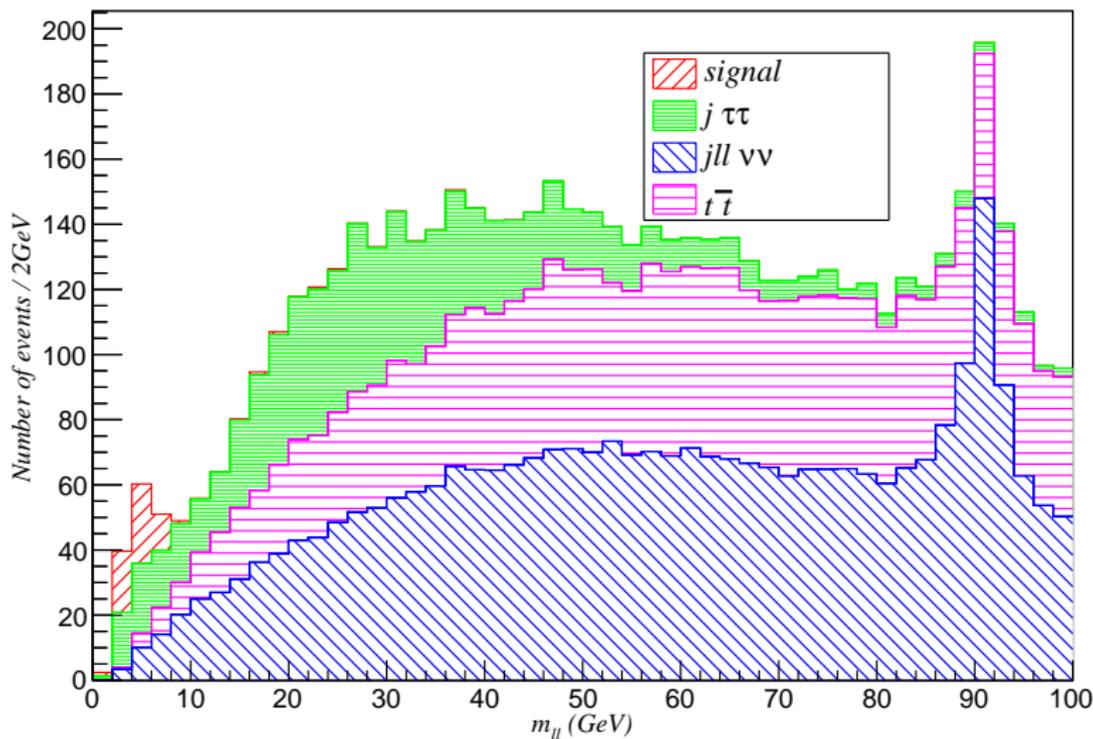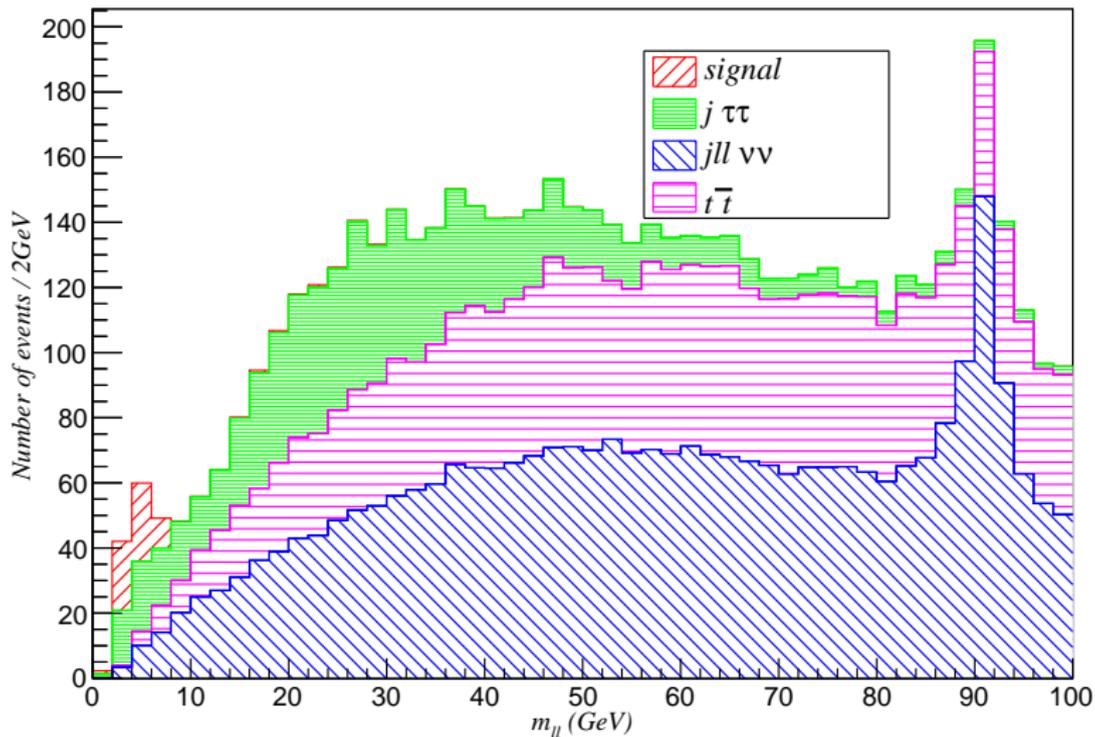
X-axis: m_{ll} (GeV)

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=800, μ=110, tanβ=10

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=850, μ=110, tanβ=10

Legend:
- signal
- $j\,\tau\tau$
- $jll\,\nu\nu$
- $t\bar{t}$

Y-axis: Number of events / 2GeV

X-axis: m_{ll} (GeV)

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=900, μ=110, tanβ=10

Legend:
- signal
- $j\,\tau\tau$
- $jll\,\nu\nu$
- $t\bar{t}$

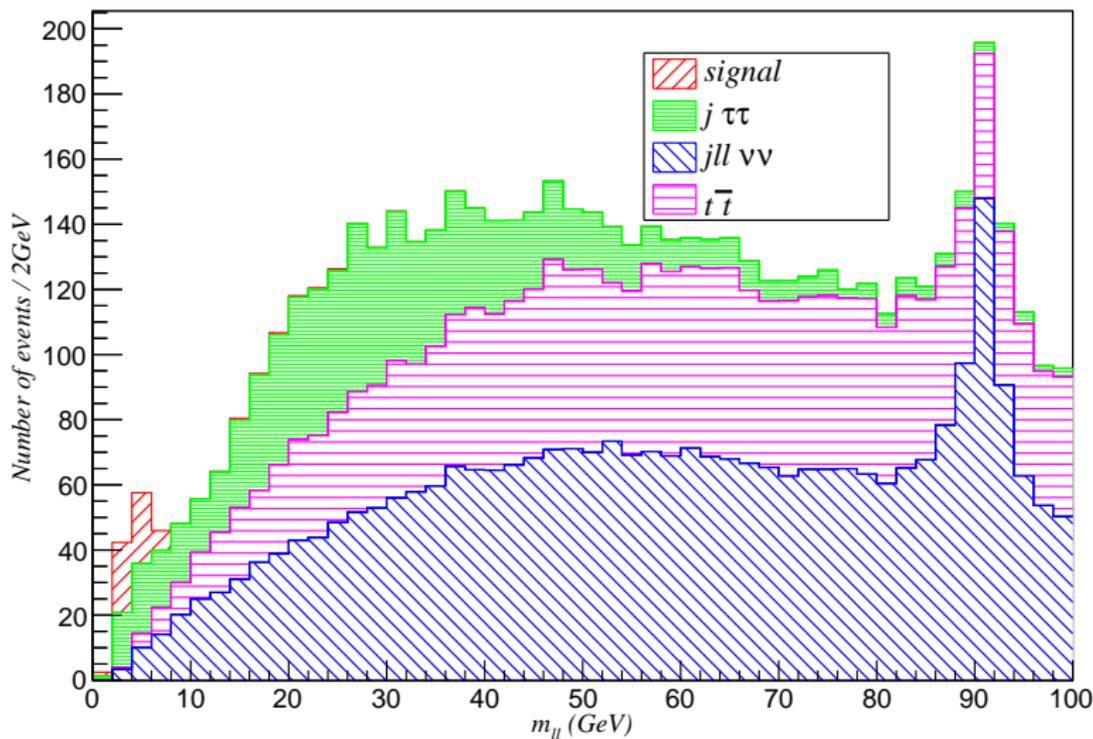X-axis: m_{ll} (GeV)
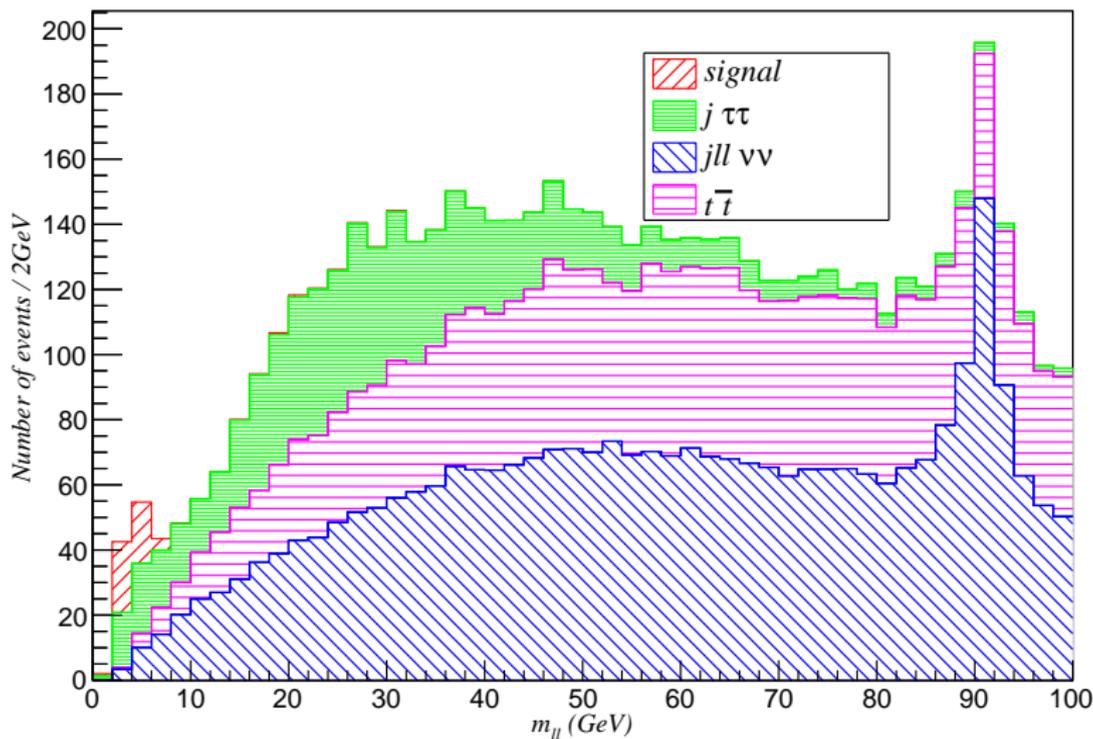Y-axis: Number of events / 2GeV

The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=950, μ=110, tanβ=10
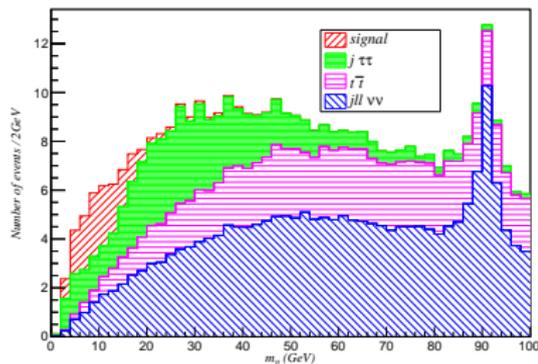
The Dilepton invariant mass @ 14 TeV 100 fb^{-1}

M1=1000, M2=1000, μ=110, tanβ=10
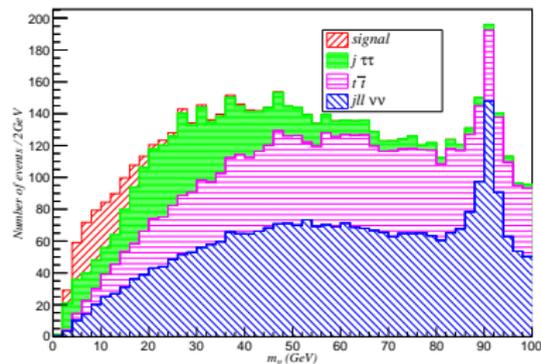
The dilepton invariant mass cut: 8 TeV vs 14 TeV

Cut on m_{ll} to maximize $S/\sqrt{B}$

Larger $M_1, M_2 \Rightarrow$ smaller mass splittings.

Smaller mass splitting $\Rightarrow$ greater efficiency.

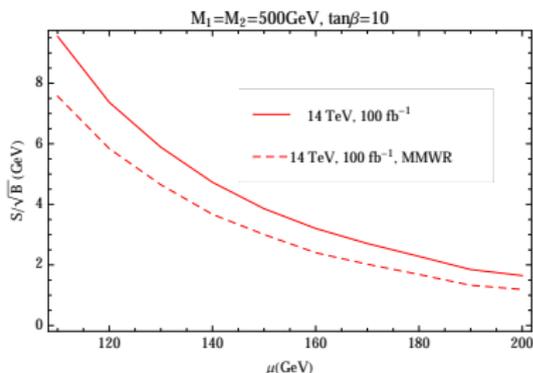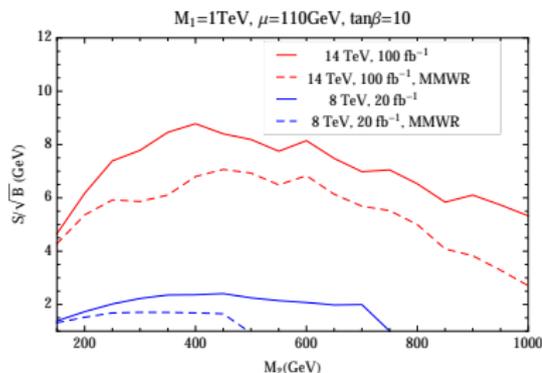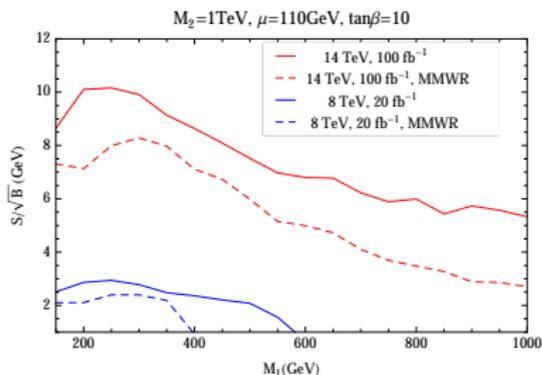# What is OSSF fraction in the m_{ll}?

μ=110GeV, fraction of opposite sign same flavor dileptons
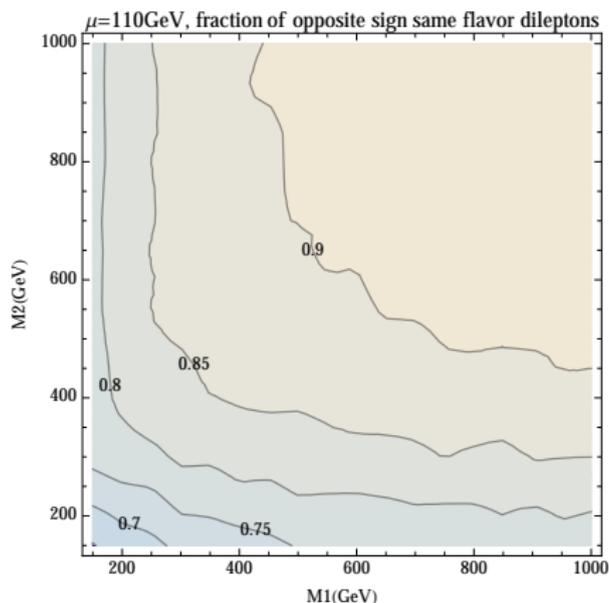
Low $m_{ll} \Rightarrow$ 90% of signal is OSSF

Large m_{ll} smaller OSSF events

Significance

Relevance of (Υ and J/ψ) +j + MET production
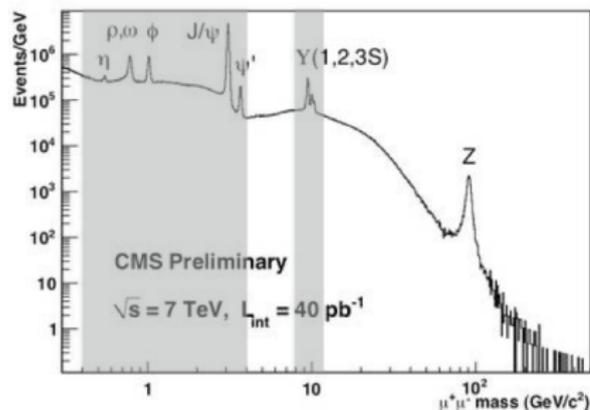
Reach @ 100 fb^{-1}
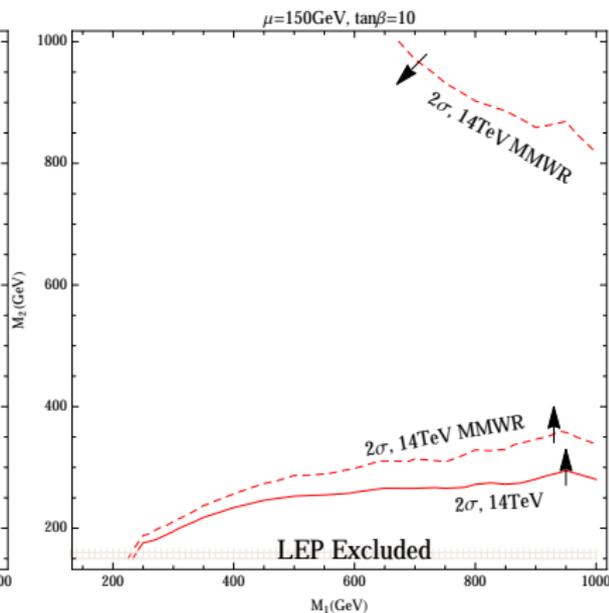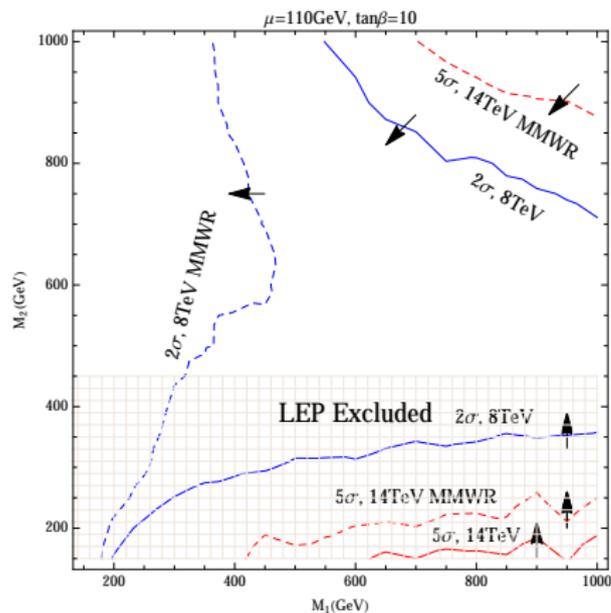
$\mu = 110$ GeV: 5σ discovery for most regions
$\mu = 150$ GeV: 2σ evidence for most regions

Conclusions

- The combined stop and sbottom limits lead to two regions of parameter space.
- Either a compressed neutralino-stop spectrum or heavy stops are possible.
- In the compressed region $\sigma_{ggh(\to\gamma\gamma)}$ is enhanced at $10-15\%$.
- The heavy stop region has SM like Higgs rates.
- Tri-lepton and mono jet searches are weak probes of compressed Higgsinos.
- $j + 2\ell + $MET with $p_T^{j^1}$,MET > 100 GeV channel an alternate channel
- Can achieve $5(2)\sigma$ significance for most regions of parameter space at $14(8)$ TeV with $100(20)$ fb^{-1}

What we know?

Found the Higgs

SM Higgs rates known to $\sim 20\%$.

No SUSY so far

Constraints: Strong $\tilde{q}_{1,2}^{st}$, $\tilde{g}$, moderate on $\tilde{t}\tilde{b}$, weak χ_0, $\chi_{\pm}$

The EWSB Scale and Fine Tuning

▶ At leading order and large $\tan\beta$ EWSB condition

$$\tfrac{1}{2}m_Z^2 \approx -m_{H_u}^2 - |\mu|^2$$
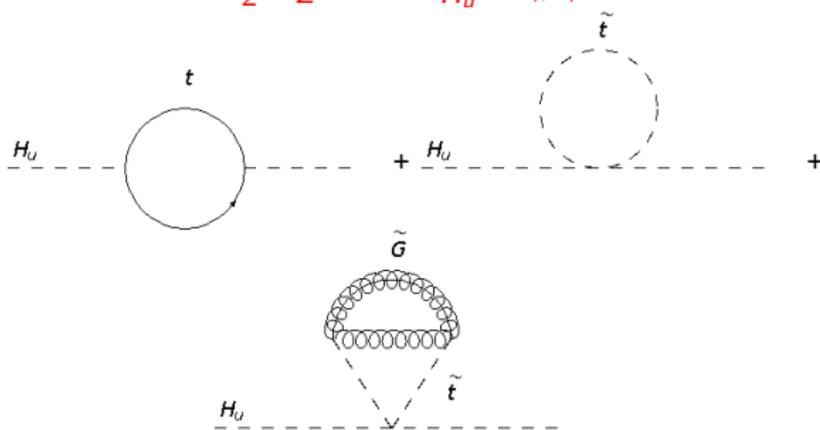
▶ Characterize contributions to EWSB as $\Delta a = \left| \dfrac{a^2}{m_Z^2/2} \right|^2$

Barbieri et. al.

▶ Larger stop masses and $A_t \Rightarrow$ greater fine tuning.

Delgado et. al.

Gaugino Contributions

- 1-loop Majorana Wino:

$$\Delta(\delta m_{H_u}^2|_{\text{wino}}) = \frac{3g_2^2}{8\pi^2}|M_2|^2 \log \frac{\Lambda_{\text{mess}}}{|M_2|}$$

$$\simeq 10 \times \frac{|M_2|^2}{(930 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}}/|M_2|}{3}$$

- 2-loop Gluino:

$$\Delta(\delta m_{H_u}^2|_{\text{gluino}}) = \frac{2\alpha_s y_t^2}{\pi^3}|M_3|^2 \log \frac{\Lambda_{\text{mess}}}{(m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}} \log \frac{\Lambda_{\text{mess}}}{|M_3|}$$

$$= 10 \times \frac{|M_3|^2}{(1200 \text{ GeV})^2} \frac{\log \Lambda_{\text{mess}}/(m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}}{3}$$

$$\frac{\log \Lambda_{\text{mess}}/|M_3|}{1.5}$$

1-loop gluino log enhancement to the stop 1-loop log enhancement to $m_{H_u}^2$.

Dirac Gauginos

- Dirac gluinos contribution to stop mass is finite

$$\delta m_{\tilde{f}}^2 = \sum_i \frac{C_i(f)\alpha_i M_i^2}{\pi} \log \frac{\tilde{m}_0}{M_i^{\mathrm{adj}}}$$

- In the presence of D-term breaking, $M_i^{\mathrm{adj}} \sim M_{\tilde{g}}^{\mathrm{Dirac}}$.

  Fox et. al.

- Dirac gluino $\Rightarrow$ finite 2-loop contribution to EWSB scale.
- A $M_{\tilde{g}}^{\mathrm{Dirac}} = 5 M_{\tilde{g}}^{\mathrm{Majorana}}$ gives the same contribution to EWSB scale.

  Kribs et. al.

Gaugino contributions to fine tuning are model dependent.

Stop and sbottom decays

- Squark decays set by yukawa couplings:

$$
\begin{aligned}
W &= y_u u_R^c Q_L H_u + y_d d_R^c Q_L H_d \\
&\approx y_t u_R^c (u_L H_u^0 - d_L H_u^+)
\end{aligned}
$$

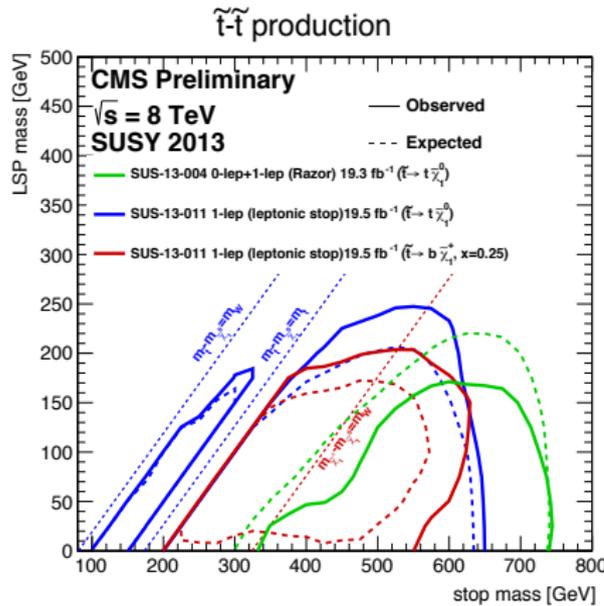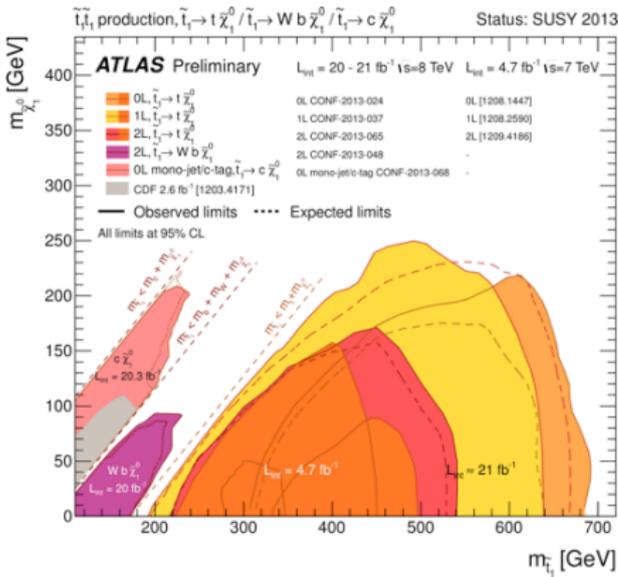- At $\tan \beta \sim 10$ $y_t \gg y_b$
- Upto $y_b \tan \beta$ corrections

$$
\mathcal{BR}(\tilde{t}_R \to b \chi_1^{\pm}) : \mathcal{BR}(\tilde{t}_R \to t \chi_1^0) \sim 1 : 1
$$
$$
\mathcal{BR}(\tilde{t}_L \to t \chi_1^0) \sim 1
$$
$$
\mathcal{BR}(\tilde{b}_L \to t \chi_1^{\pm}) \sim 1
$$

How do LHC limits translate to Natural SUSY?

LHC 3rd gen. searches

Many assumptions: Single $\tilde{t}$, $\tilde{b}$ production, Branching ratios, Mass hierarchies ...

Details of the Recast

- ▶ 3 simplified scenarios:

Scenario	$\mu < m <$ TeV	$m \gg 1$ TeV
I	$\tilde{t}_R$	$\tilde{t}_L, \tilde{b}_L, \tilde{b}_R$
II	$\tilde{t}_L, \tilde{b}_L$	$\tilde{t}_R, \tilde{b}_R$
III	$\tilde{t}_L, \tilde{b}_L, \tilde{t}_R$	$\tilde{b}_R$

- ▶ All remaining SUSY mass parameters $\gg$ TeV.
- ▶ Recasting the $\tilde{t}, \tilde{b}$ analyses from May 2013.
- ▶ Generated Signal using PYTHiA6, σ normalized to SUSY WG values and used the same pdf/tunes as CMS.
- ▶ DELPHES detector simulator along with b-tagging(fake rates) = 70%(10%)
- ▶ Limits calculated using the quoted backgrounds and systematic uncertainties.

Stop Searches: Semi-leptonic
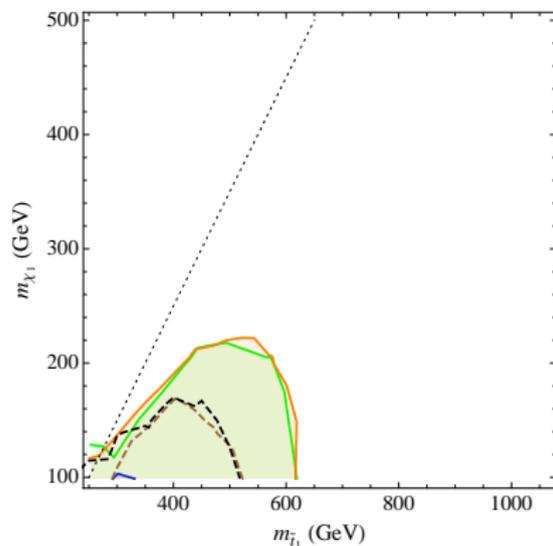
black dotted: $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 150$ GeV
black dashed: CMS Simp. T2tt Model
brown dashed: $\tilde{t}_R \to t\tilde{B}$ Model
blue solid: Scen. I 95% excl.
green solid: Scen. II 95% excl.
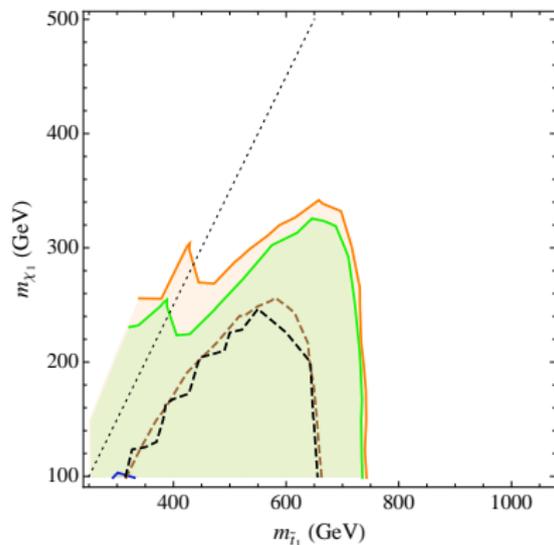orange solid: Scen. III 95% excl.

- Require $3j + 1\ell$+MET with one b-tag jet.

  ATLAS-CONF-2013-037
  CMS-SUS-12-023

- Bin signal and background in m_T and MET, ATLAS used an additional W tag for the top.

- Scen. I limit is weak due to only $\tilde{t}_R \to t\chi_1^0$ pass the cuts as leptons from $\tilde{t}_R \to b\chi_1^\pm$ are too soft.

- Strong limit on Scen. II and III

Stop Searches: All Hadronic

black dotted: $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 150$ GeV
black dashed: CMS Simp. T2tt Model
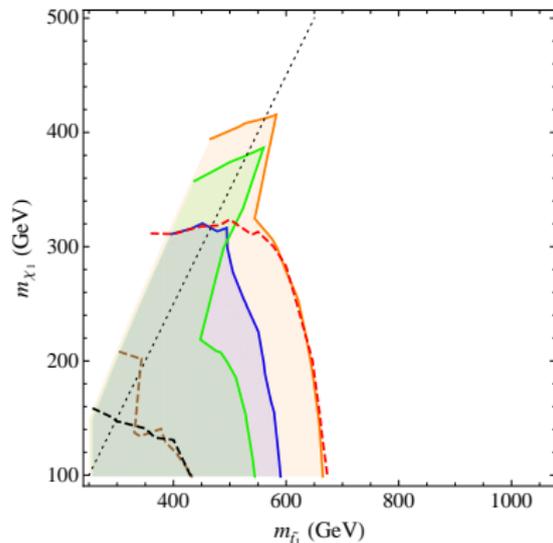brown dashed: $\tilde{t}_R \to t\tilde{B}$ Model
blue solid: Scen. I 95% excl.
green solid: Scen. II 95% excl.
orange solid: Scen. III 95% excl.

- > 6 jets+MET, with > 2 btags
  ATLAS-CONF-2013-024
- The 6 hardest jets form 2 three-jet 'top-candidates' with $80 \leq m_{jjj} \leq 270$ GeV
- Again Scen. I limit is weak due to only $\tilde{t}_R \to t\chi_1^0$ pass the cuts.
- Strong limit on Scen. II and III.
- Sharp increase in limit in compressed region due to $\tilde{b}_L \to t\chi^+$.

Sbottom Searches

black dotted: $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 150$ GeV
black dashed: CMS Simp. T2tt Model
brown dashed: $\tilde{t}_R \to t \tilde{B}$ Model
red dashed: CMS T2bb Simp. Model
blue solid: Scen. I 95% excl.
green solid: Scen. II 95% excl.
orange solid: Scen. III 95% excl.
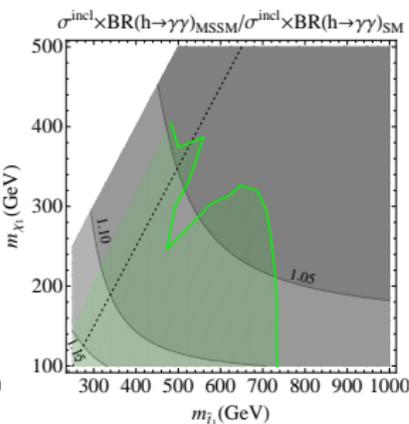
- ▶ 2j or 3j+MET with 1 or 2 btags, no leptons

  ATLAS-CONF-2012-165
  CMS-SUS-12-028

- ▶ Use α_T, H_T and MET to suppress backgrounds.

- ▶ No leptons and lower jet requirements ⇒ high efficiency for Scen. I

- ▶ Weaker limits on Scen. II and III due to their top rich events.

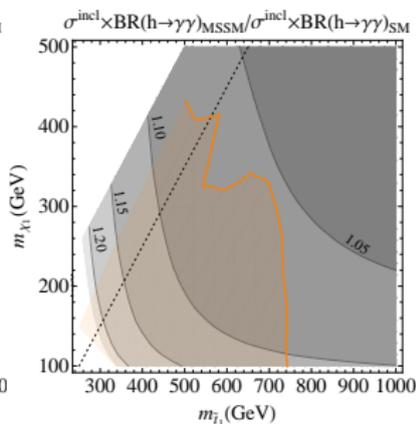- ▶ Lower Scen. I than T2bb efficiencies because lepton rejection.

Combining LHC Searches with Higgs Limits
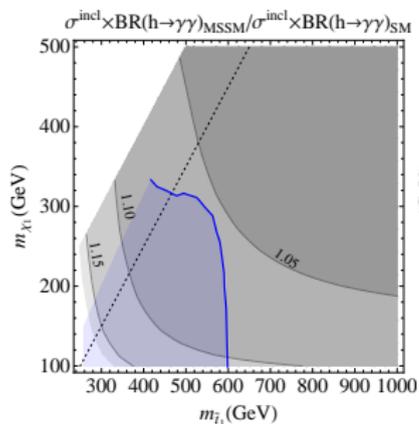
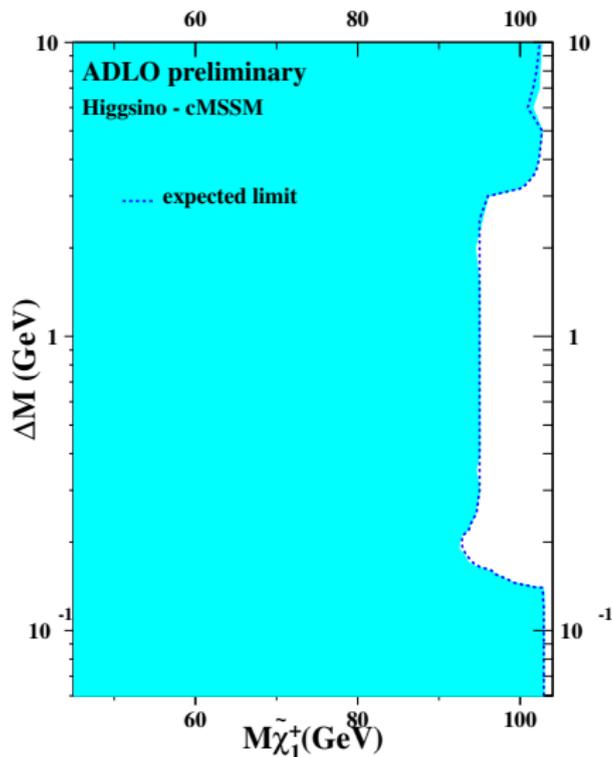Light $\tilde{t}_R$ Light $\tilde{t}_L, \tilde{b}_L$ Light $\tilde{t}_L, \tilde{b}_L, \tilde{t}_R,$

Preferred regions of Natural SUSY are the
"compressed wedge" and the "kinematic threshold".

LEP Limits on Charginos

LEP limit on Charged Higgsino ∼ 103 GeV