Detecting Higgsino Dark Matter at Colliders

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SUSY and Dark Matter

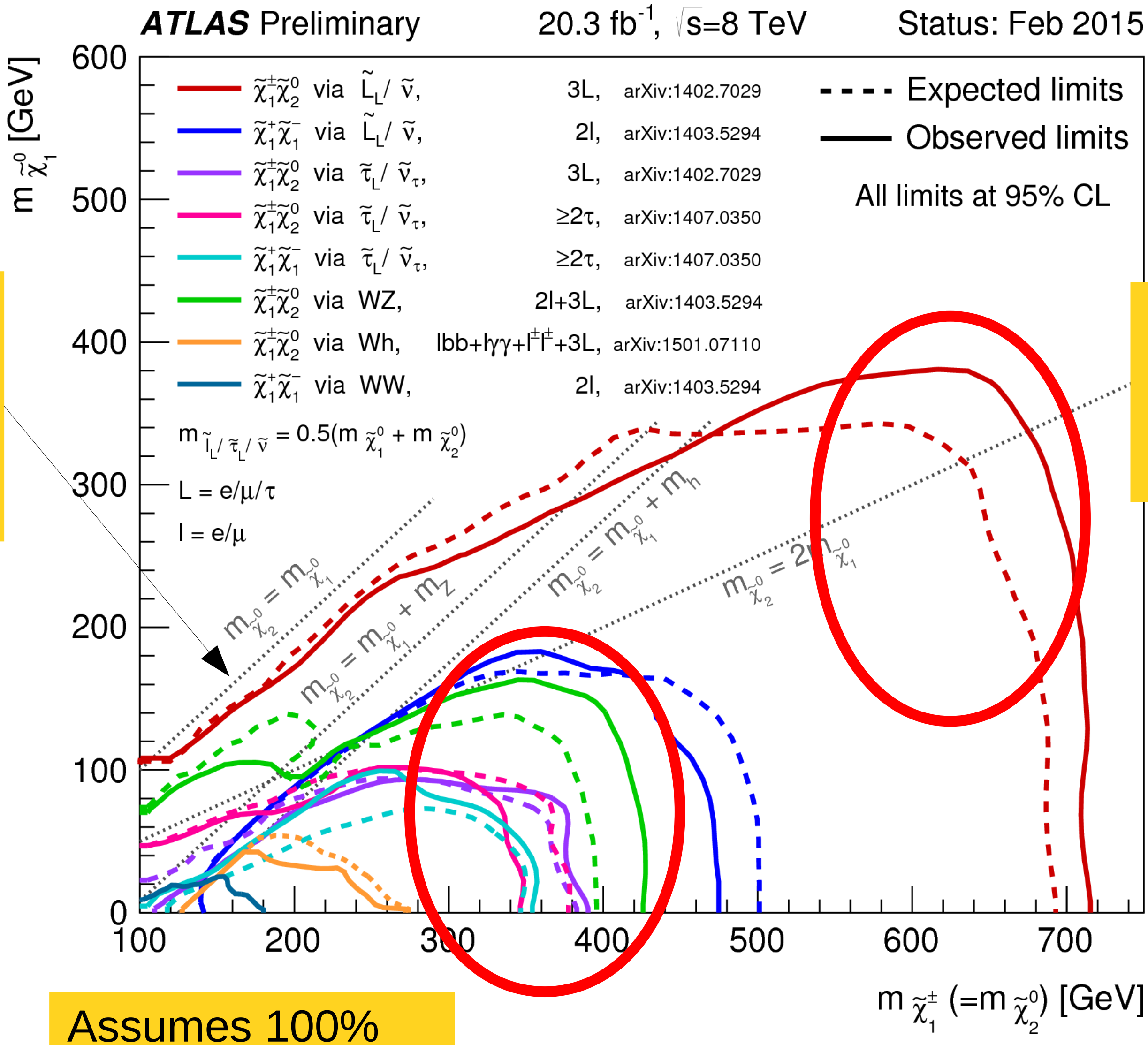
- SUSY has “natural” Dark Matter candidate, once R-parity is imposed: neutralino LSP
- Pure states have annih. cross section very large (Wino & Higgsino => right RD at ~2TeV) or very small (Bino)
- Many ways to achieve right RD with sub-TeV Higgsinos:
  - Non-thermal from decays of moduli
    [Allahverdi, Dutta, Sinha]
  - Higgsinos + axions
  - Higgsinos/axinos/axions in SUSY KSVZ model
    [Bae, Baer, Lessa]
  - ...
- Can we discover sub-TeV higgsino-like neutralino at colliders?

Motivation 2: SUSY and Naturalness

- In MSSM naturalness requires light higgsinos
- For m_h ~ 125 GeV and $\Delta_{EW} < 30$ (see talks by H.Baer and X.Tata):
  - μ ~ 100-300 GeV
  - stop_1 ~ 1-2 TeV, stop_2 = sbottom_1 ~ 2-4 TeV, highly mixed by large A_t
  - gluino ~ 1-5 TeV
  - bino/wino – upto ~ 8 TeV
  - 1^{st}/2nd generation squarks ~ 1-10 TeV
  - sleptons – upto ~ 30 TeV
- Higgsinos are the only ones fully accessible at LHC. Can we detect them?

Current EW-ino searches at LHC

Weak constraints on compressed spectrum



Assumes wino NLSP and light sleptons –> lepton rich final states.

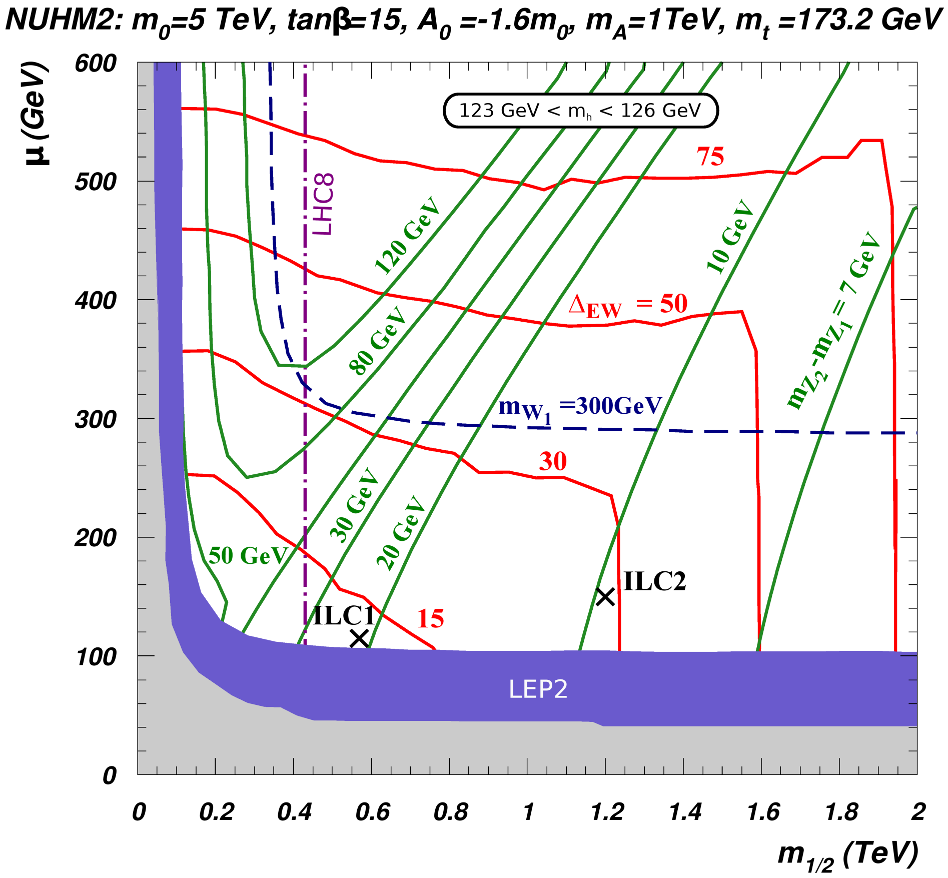
Assumes 100% BF to WZ

Higgsino mass splittings

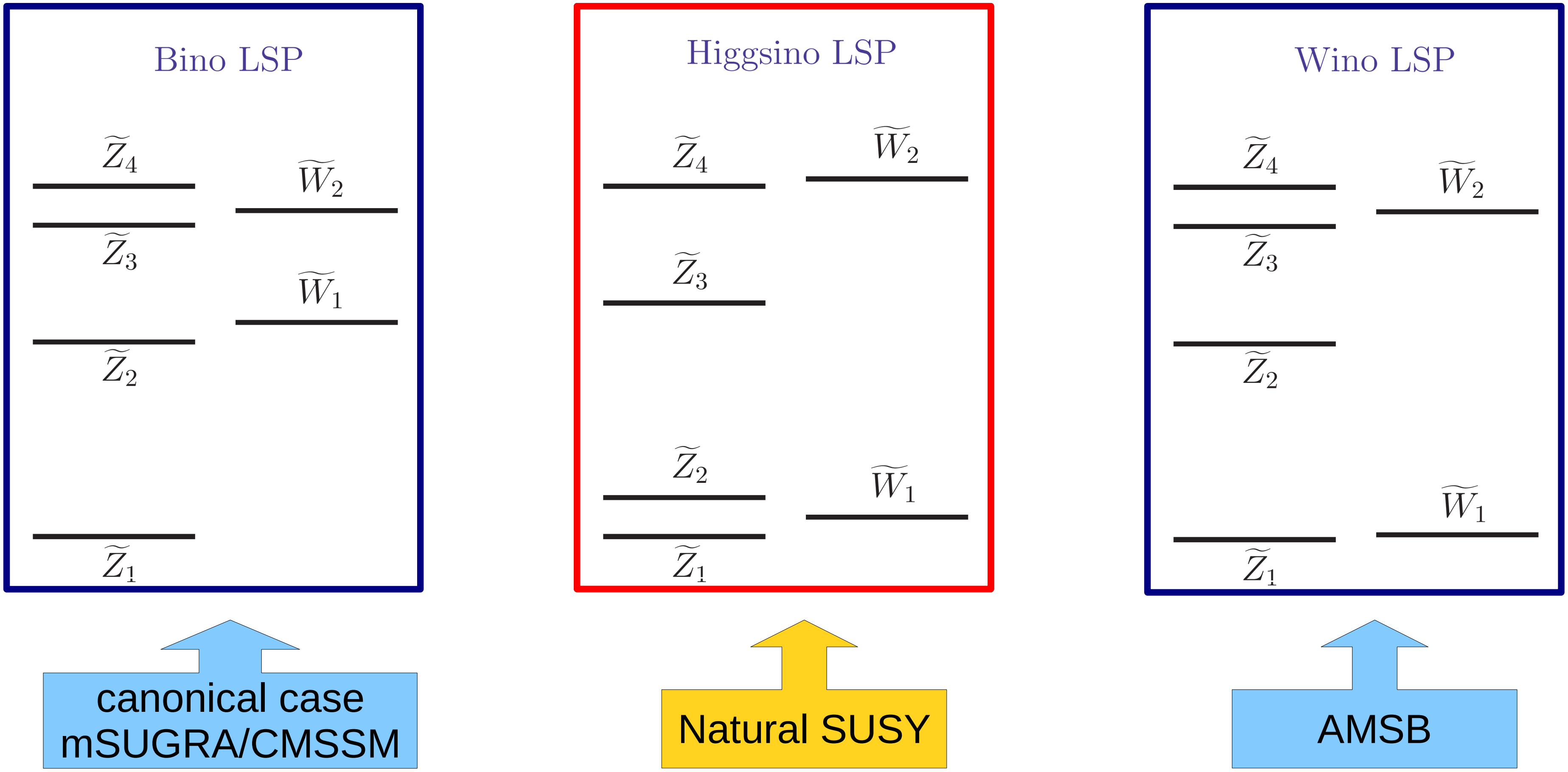
- For $|\mu| \ll M_{1,2}$ lightest states $\widetilde{Z}_1,\ \widetilde{Z}_2,\ \widetilde{W}_1^\pm$ are higgsino-like and have small mass gap $\lesssim$30 GeV

$$m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \simeq M_Z^2\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)$$

$$m_{\widetilde{W}_1} - m_{\widetilde{Z}_1} \simeq \frac{M_Z^2}{2}\left(\frac{s_W^2}{M_1}+\frac{c_W^2}{M_2}\right)$$



EW-ino spectrum



canonical case
mSUGRA/CMSSM

Natural SUSY

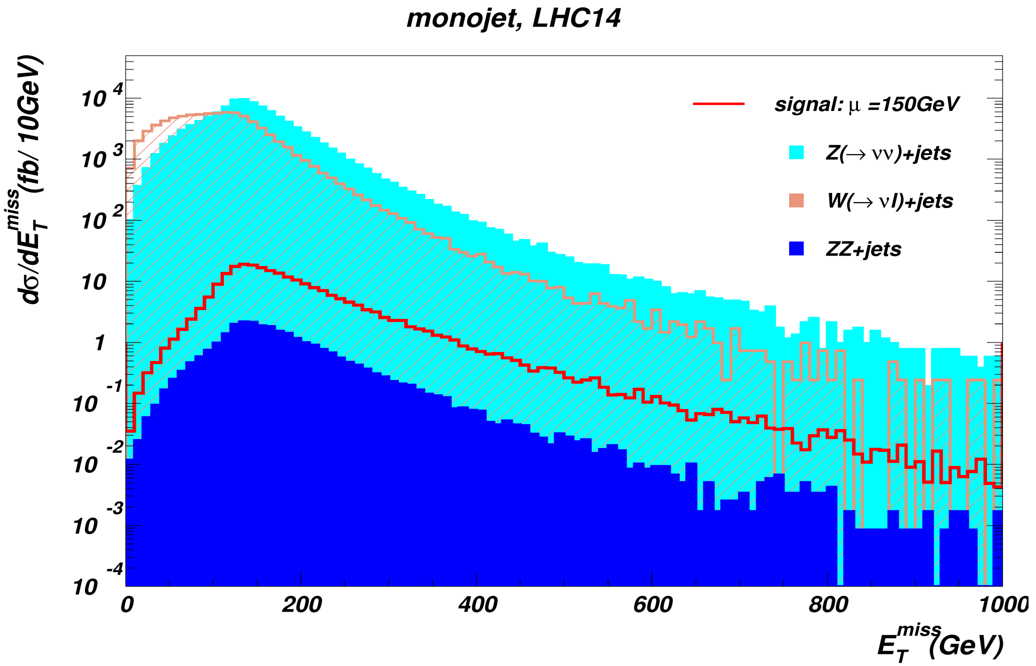
AMSB

- Higgsino mass splitting is small enough to see decay products, but too large to see disappearing charge track

Mono-jets and mono-photons

arXiv: 1401.1162

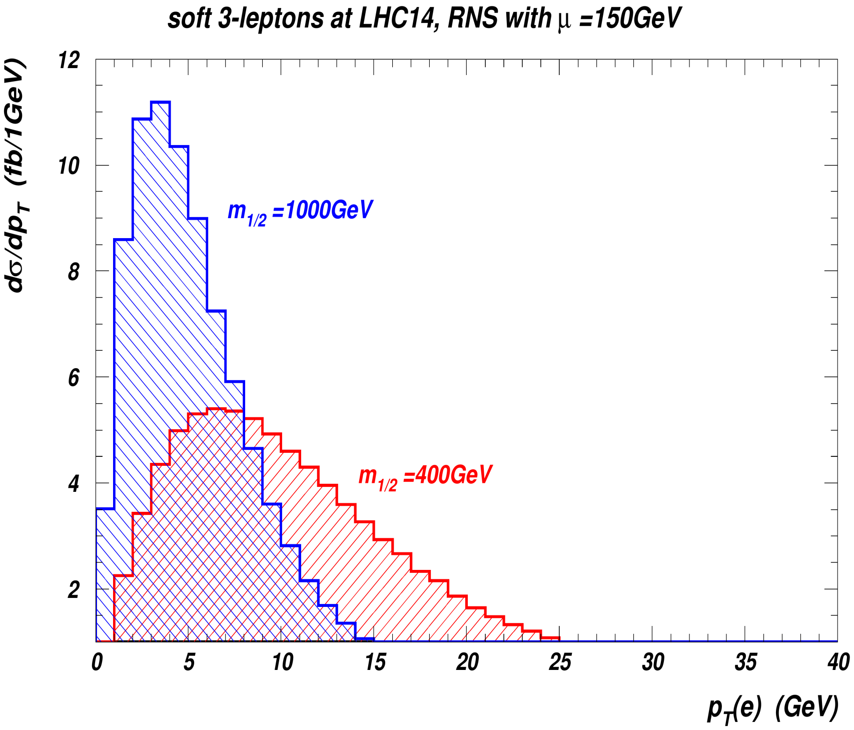
- Higgsinos have compressed spectrum with mass gap 10-30 GeV – only soft visible energy ==> higgsinos mostly appear as MET.
- $pp \to \widetilde{Z}_{1,2}\widetilde{Z}_{1,2}/\widetilde{Z}_{1,2}\widetilde{W}_1/\widetilde{W}_1\widetilde{W}_1 + (j \text{ or } \gamma)$
- Contact interaction, used in ATLAS/CMS search, not applicable: mediator mass $M_Z \ll \sqrt{\hat{s}} \sim p_T(jet) + E_T^{miss}$ leading to extra 1/s suppression for ME
- Signal has same shape as BG and S/B ≈1%. Detection is very challenging!



Soft trileptons

arXiv: 1302.5816

- Mass gap between higgsinos is <30 GeV ⇒ very soft leptons for higgsino pair production. But ATLAS/CMS can detect soft leptons $p_T(\mu) > 5\ \mathrm{GeV},\ p_T(e) > 10\ \mathrm{GeV}$
- $pp \longrightarrow \widetilde{W}_1 \widetilde{Z}_2 \longrightarrow (e\nu_e \widetilde{Z}_1) + (\mu^+\mu^- \widetilde{Z}_1)$
- For $m_{1/2} < 400 - 500\ \mathrm{GeV}$
  and μ=150GeV
  most e pass trigger threshold



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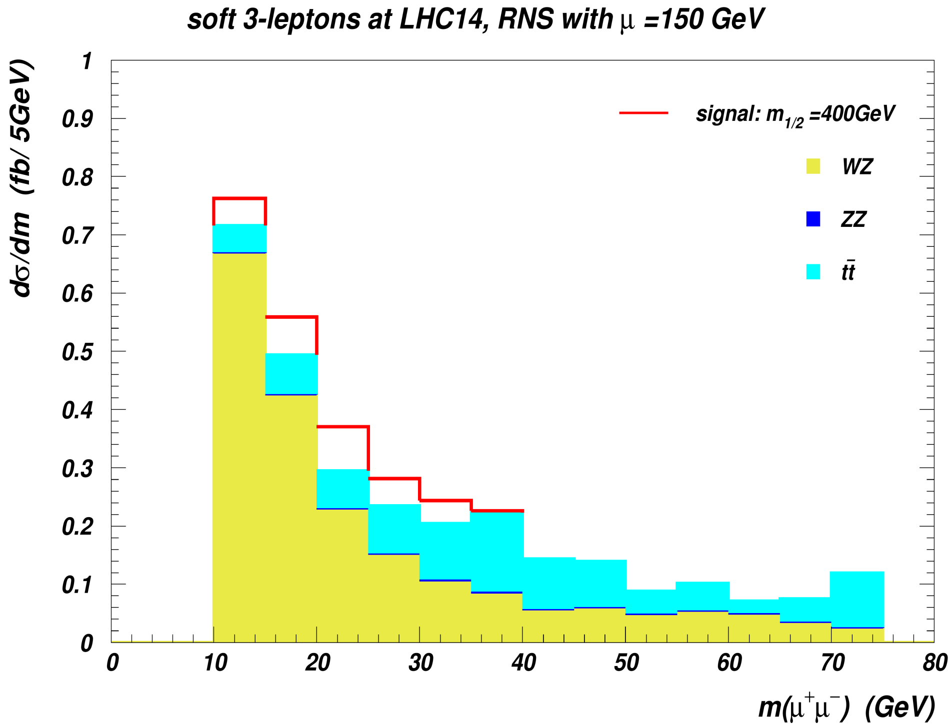
- A shape analysis may allow to claim a signal with high luminosity – confirmation channel



Mono-jets plus soft dilepton

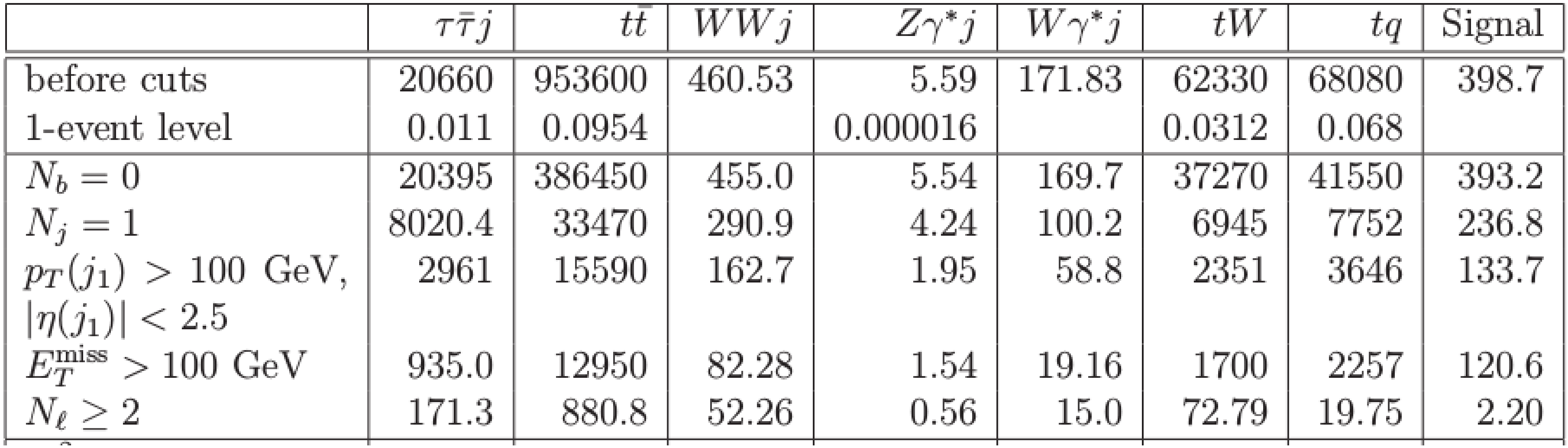
arXiv: 1409.7058

- Soft leptons can provide additional handles, improving monojet detection prospects [Giudice, T.Han, Wang and L.T.Wang PRD'10]
- $$pp \to \widetilde{Z}_1\widetilde{Z}_2/\widetilde{Z}_2\widetilde{Z}_2/\widetilde{Z}_{1,2}\widetilde{W}_1/\widetilde{W}_1^+\widetilde{W}_1^- + j$$
  $$\widetilde{W}_1 \to \ell\nu\widetilde{Z}_1,\ \widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$$
- Production cross section ~(10-100) fb times leptonc BF.
- Signals:
    - 1l+j+MET from $\widetilde{W}_1\widetilde{Z}_1 j$ - obscured by large Wj and ttbar
    - 3l+j+MET from $\widetilde{W}_1\widetilde{Z}_2 j$ - severely rate limited
    - 2l+j+MET is the most promising
- Recent works: Schwaller and Zurita (2014), Z.Han et al (2014)

Backgrounds

arXiv: 1409.7058

- $(\mathrm{Z}/\gamma^* \to \ell\bar{\ell}) + j$ removed by MET cut
- $(Z/\gamma^* \to \tau\bar{\tau}) + j,\ W^+W^-j,\ (Z \to \nu\bar{\nu}) + (Z/\gamma^* \to \ell\bar{\ell}/\tau\bar{\tau}) + j$
- ttbar and single-top, where leptons come from W and b
- $(Z \to \nu\bar{\nu}) + b\bar{b} + j$, where leptons come from b quarks
- $(W \to \ell/\tau + \nu) + (Z/\gamma^* \to \ell\bar{\ell}/\tau\bar{\tau}) + j \to \ell\ell\ell' j + E_T^{\rm miss}$



	$\tau\bar{\tau}j$	$t\bar{t}$	WWj	$Z\gamma^*j$	$W\gamma^*j$	tW	tq	Signal
before cuts	20660	953600	460.53	5.59	171.83	62330	68080	398.7
1-event level	0.011	0.0954		0.000016		0.0312	0.068	
$N_b = 0$	20395	386450	455.0	5.54	169.7	37270	41550	393.2
$N_j = 1$	8020.4	33470	290.9	4.24	100.2	6945	7752	236.8
$p_T(j_1) > 100$ GeV, $\lvert\eta(j_1)\rvert < 2.5$	2961	15590	162.7	1.95	58.8	2351	3646	133.7
$E_T^{\rm miss} > 100$ GeV	935.0	12950	82.28	1.54	19.16	1700	2257	120.6
$N_\ell \geq 2$	171.3	880.8	52.26	0.56	15.0	72.79	19.75	2.20

Suppressing Z+j

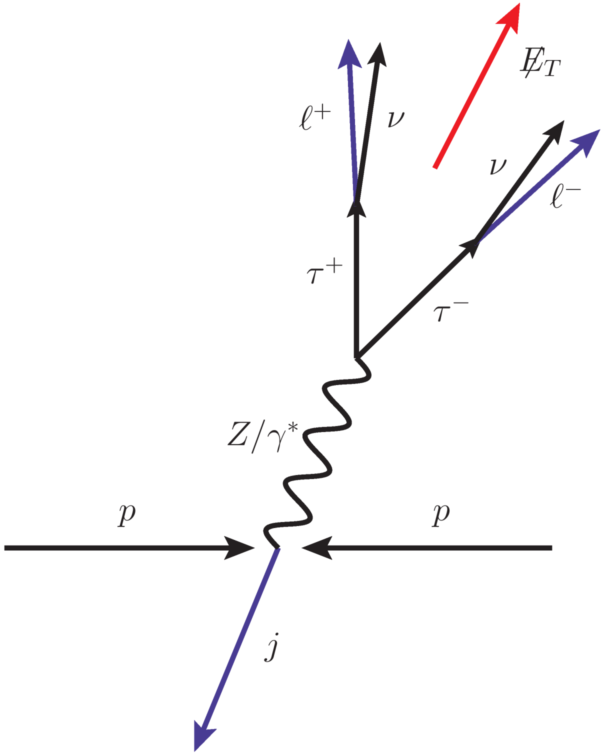
arXiv: 1409.7058

- $(Z/\gamma^* \to \tau\bar{\tau}) + j$ allows reconstruction of Z mass in the collinear approximation [Ellis, Hinchliffe, Soldate, van der Bij NPB'88]
  - Z is boosted and taus decay products are collinear

$$-\vec{p}_T(j) = (1+\xi_1)\vec{p}_T(\ell_1) + (1+\xi_2)\vec{p}_T(\ell_2)$$

- Solve for $\xi_{1,2}$

$$m^2_{\tau\tau} = (1+\xi_1)(1+\xi_2)m^2_{\ell\ell}$$



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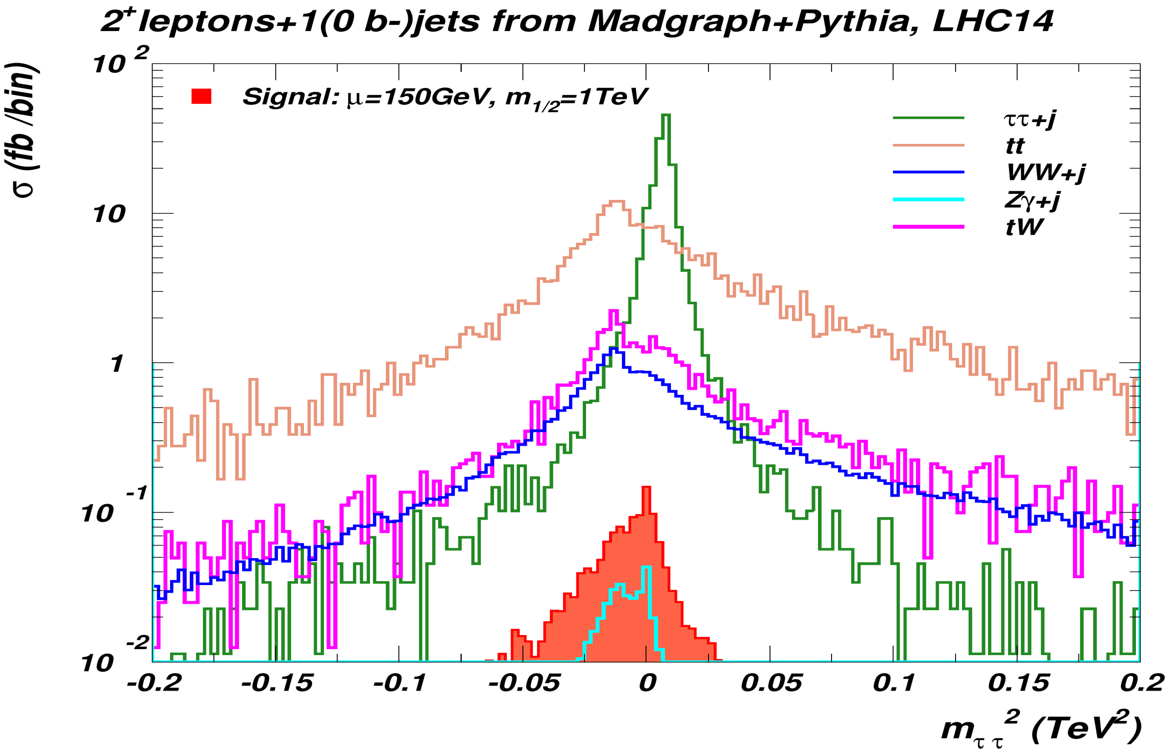
- Solve for $\xi_{1,2}$

$$m_{\tau\tau}^2 = (1+\xi_1)(1+\xi_2)m_{\ell\ell}^2$$

- Require $m_{\tau\tau}^2 < 0$



Enhancing the Signal

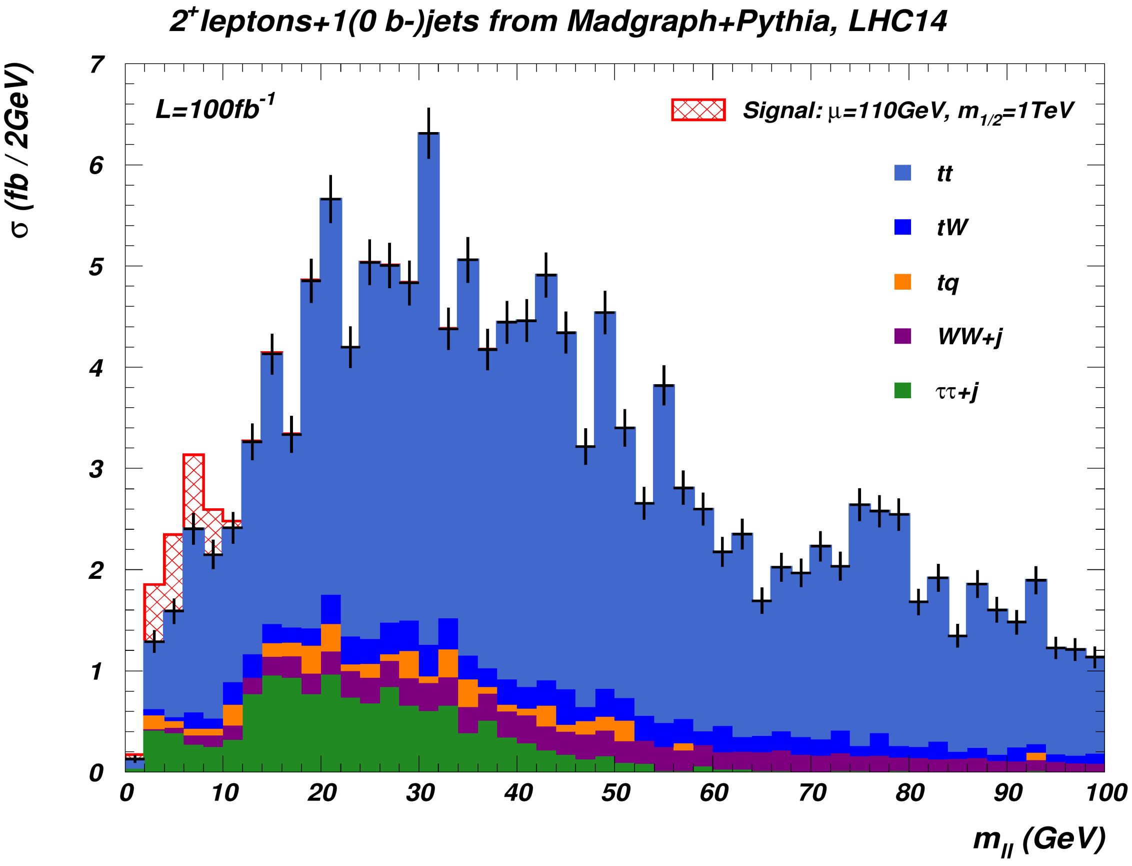
- Require OS/SF leptons, since most of the signal come from

  $\widetilde{Z}_2 \to \ell^+\ell^-\widetilde{Z}_1$

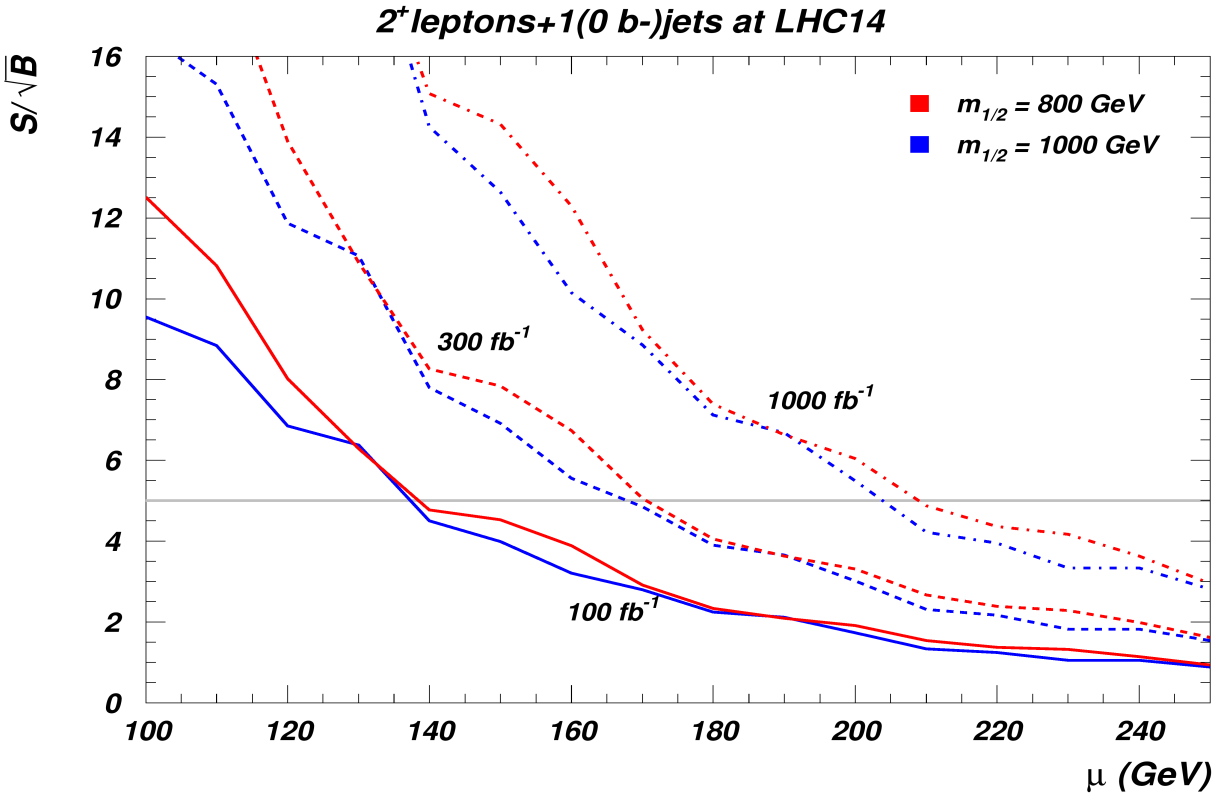
- Dilepton mass is bounded by $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap. Require

  $$0 \leq m_{\ell\ell} \leq m^{\rm cut}$$

  to maximize significance



Reach via cut-and-count



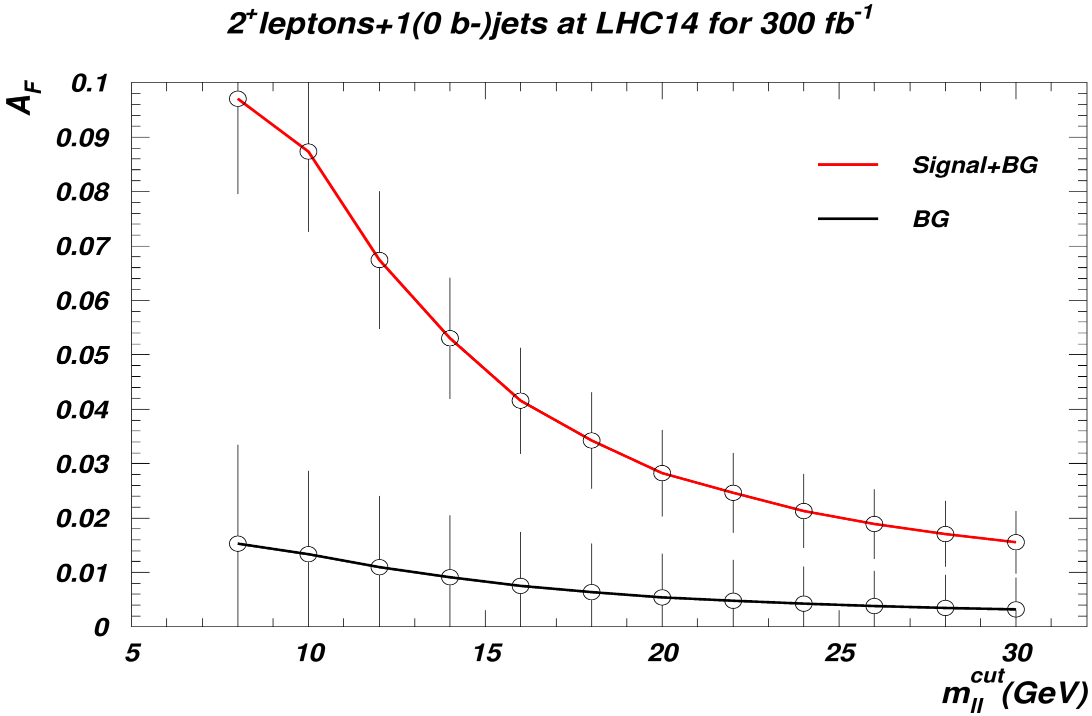
Note: requires control of systematic erros on BG normalization at better than 5% to claim detection.

Lepton flavor asymmetry

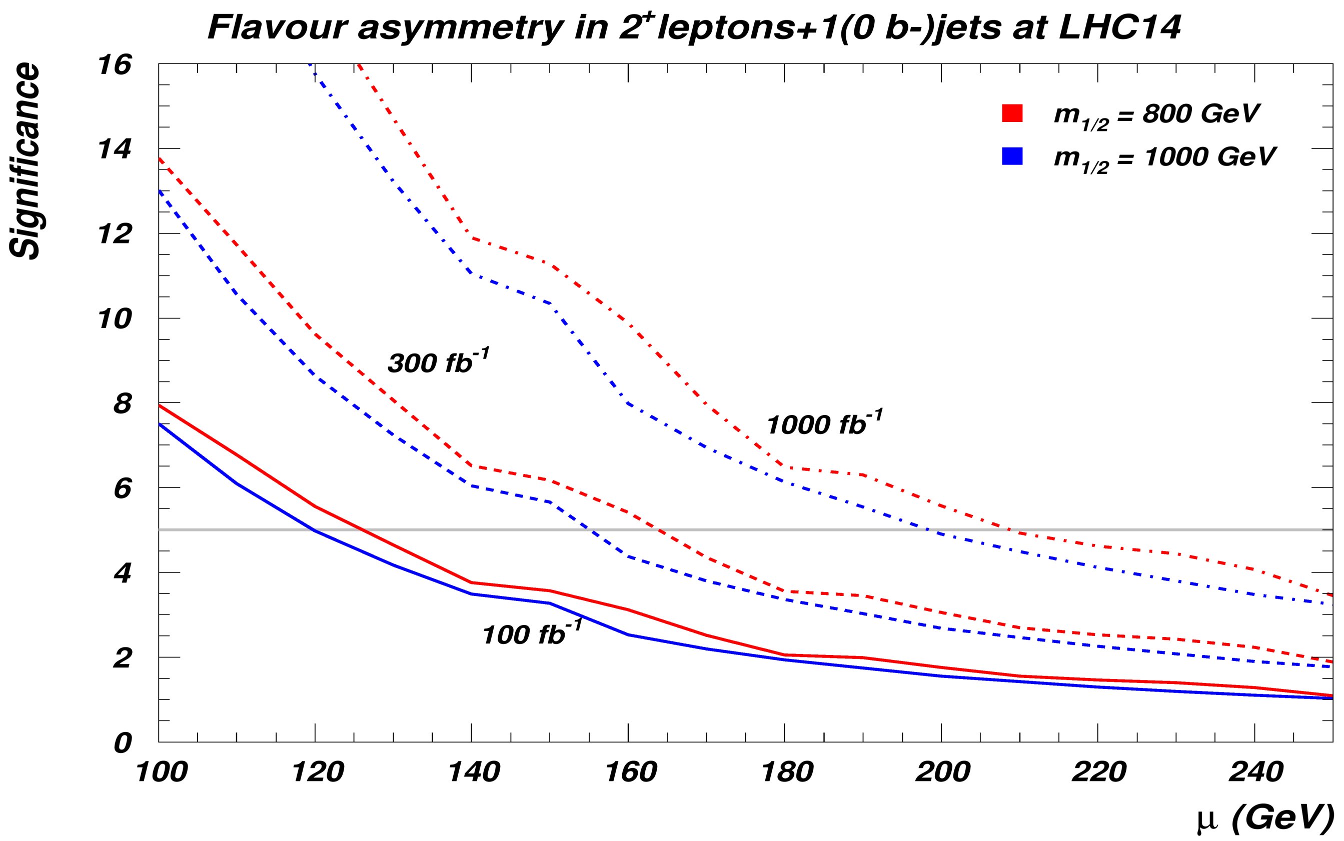
- Signal mostly has SF dileptons, while BG has equal number of SF and OF ==> use dilepton flavor asymmetry

$$\mathcal{A}_{\mathcal{F}} = \frac{N(SF) - N(OF)}{N(SF) + N(OF)}$$

- Insensitive to BG normalization!



Reach via lepton flavor asymmetry

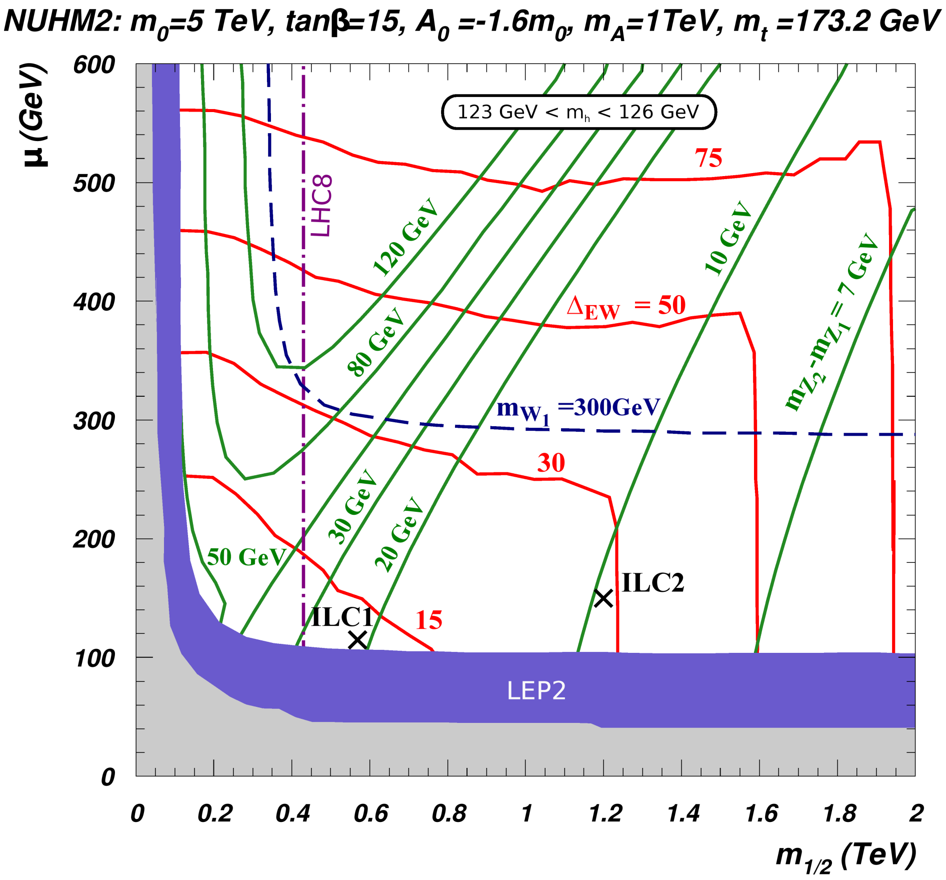


- Smaller by 10-15 GeV reach due to ~√2 smaller significance, but not sensitive to BG systematics.

Signatures at ILC

arXiv: 1404.7510

- Detection of light higgsinos is very challenging at LHC due to compressed spectrum. ILC with ~600 GeV will be able to produce charginos covering region with
  $$\Delta_{EW} < 30$$
- Higgsino production ~100-1000fb is 5-10 larger than Zh
  ==> Higgsino factory!
- Beam polarization allows to establish higgsino nature of inos
- Consider two cases:
  ILC1 with mass gap ~20 GeV,
  ILC2 with near minimal mass gap ~10 GeV



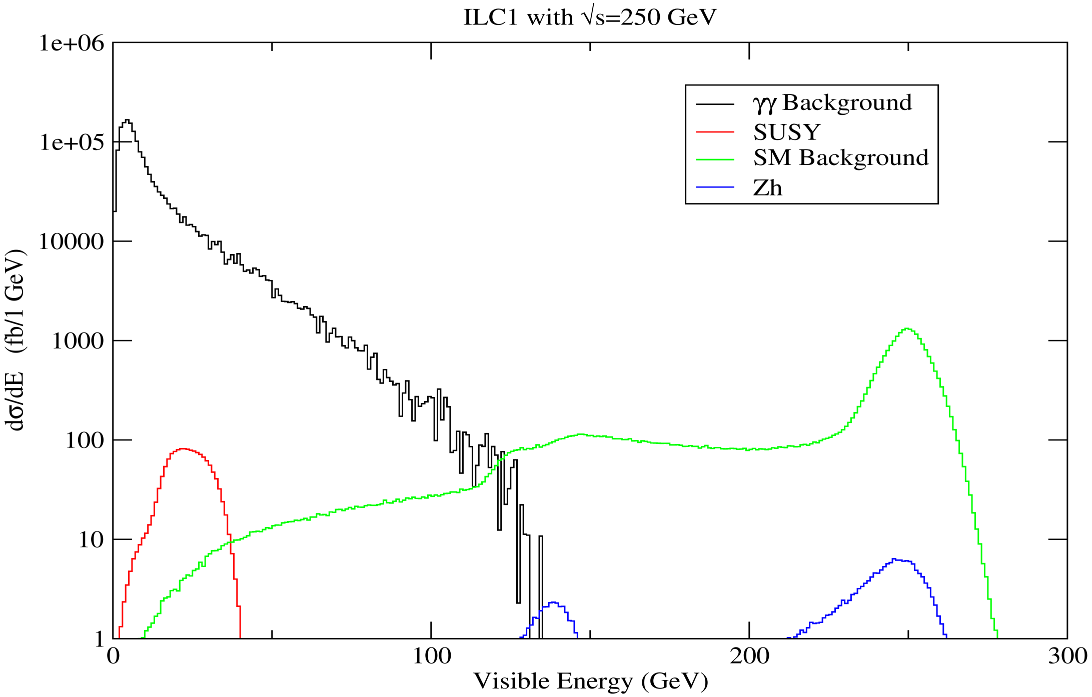
Benchmark ILC1 at 250GeV

arXiv: 1404.7510

- $m_{\widetilde{Z}_1} = 102.7\ \mathrm{GeV},\ m_{\widetilde{Z}_2} = 124\ \mathrm{GeV},\ m_{\widetilde{W}_1} = 117.3\ \mathrm{GeV}$
- 2->2 SM background mostly has larger visible energy $\mathrm{E}_{\mathrm{vis}}$
- 2->4 “two-photon” BG are back-to-back with essentially no MET
- $e^+e^- \to \widetilde{W}_1\widetilde{W}_1 \to q\bar{q}\widetilde{Z}_1 + l\nu\widetilde{Z}_1$

  leads to 2j+1l+MET with 6.43 fb after cuts; BG ≈ 0.018 fb.
- $e^+e^- \to \widetilde{Z}_1\widetilde{Z}_2 \to \widetilde{Z}_1 + l\bar{l}\widetilde{Z}_1$

  leads to acoplanar dileptons with 19.55 fb after cuts and BG = 0.44 fb. Need polarized beam to reduce WW BG.



ILC1 mass measurements

arXiv: 1404.7510

- For chargino pairs, E(jj) upper endpoint is sensitive to $\widetilde{W}_1$ and $\widetilde{Z}_1$ masses. Fit shapes of theory samples to “data” → masses to 2-3%

$$m_{\widetilde{W}_1} = 117.8 \pm 2.8 \text{ GeV } (1\sigma)$$

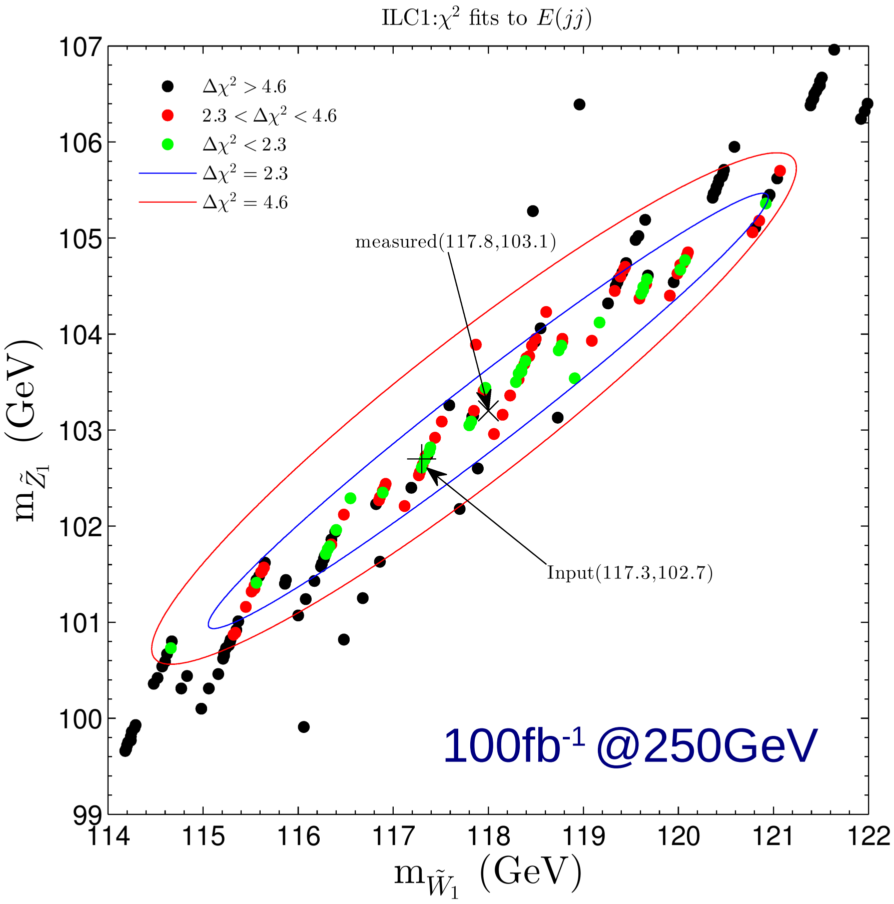
$$m_{\widetilde{Z}_1} = 103.1 \pm 2.2 \text{ GeV } (1\sigma)$$

- For neutralino pairs, $m(l^+l^-)$ shape fit gives mass gap to 1%

$$m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} = 21.0 \pm 0.2 \text{ GeV } (1\sigma)$$

- Energy of daughter leptons depends on $\widetilde{Z}_2$ boost
  ==> fit to E(l+l-) shape gives

$$m_{\widetilde{Z}_2} = 123.7 \pm 0.2 \text{ GeV } (1\sigma)$$



Benchmark ILC2 at 340GeV

arXiv: 1404.7510

- $m_{\widetilde{Z}_1} = 148 \text{ GeV}, \; m_{\widetilde{Z}_2} = 157.8 \text{ GeV}, \; m_{\widetilde{W}_1} = 158.3 \text{ GeV}$
- $e^+e^- \to \widetilde{W}_1\widetilde{W}_1 \to q\bar{q}\widetilde{Z}_1 + l\nu\widetilde{Z}_1$
  - 2j+1l -- signal resolution is difficult due to smaller mass gap
  - 1j+1l+MET is 7.1 fb with BG = 2.8 fb: discovery with a few fb^{-1}
- $e^+e^- \to \widetilde{Z}_1\widetilde{Z}_2 \to \widetilde{Z}_1 + l\bar{l}\widetilde{Z}_1$

  signal of 2.6 fb with BG = 0.15 fb after cuts
  - $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap measured at 2% from m(l^+l^-)
  - $\widetilde{Z}_2$ mass measured from E(l^+l^-) with sub-GeV precision

Conclusions

- Small μ is necessary (but not sufficient) condition for naturalness leading to light higgsino-like chargino and neutralinos with compressed spectrum
- Light Higgsinos are difficult to detect at LHC due to low visible energy release from their decays.
- Mono-jets and mono-photons are inefficient probes for higgsinos.
- Soft trileptons from compressed higgsinos can be used as confirmatory channel.
- Combining soft leptons with monojet in 2l+j+MET channel allows LHC to achieve 5σ for higgsinos < 170 GeV with S/B ~ 8.5% with 300 /fb, and extend over 200 GeV for 1000 /fb. Systematics can be controlled with use of lepton flavor asymmetry.
- ILC is necessary to fully probe light higgsinos. ILC can discover and measure higgsino masses at 2-3% even for small mass gap ~10 GeV.

EW Fine-tuning

arXiv: 1207.3343,
1404.1386

- Minimization condition for higgs scalar potential (1-loop)

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Naturalness requires all terms on RHS comparable to LHS
  $\Rightarrow$ fine-tuning parameter

$$\Delta_{EW} \equiv max\left(\frac{m_{H_u}^2}{M_Z^2/2}\frac{\tan^2\beta}{\tan^2\beta - 1}, \frac{\Sigma_u^u}{M_Z^2/2}\frac{\tan^2\beta}{\tan^2\beta - 1}, \frac{\mu^2}{M_Z^2/2}, \ldots\right)$$

- Δ_{EW}=100 corresponds to 1% EWFT, Δ_{EW}=30 is ~3% EWFT
- Limited value of Δ_{EW} $\Rightarrow$ upper limit on $m_{H_u}^2$ and μ^2
- Δ_{EW} is not a measure but a bound on FT, it measures minimal FT present in given spectrum