The Relic Neutralino Surface at a 100 TeV Collider

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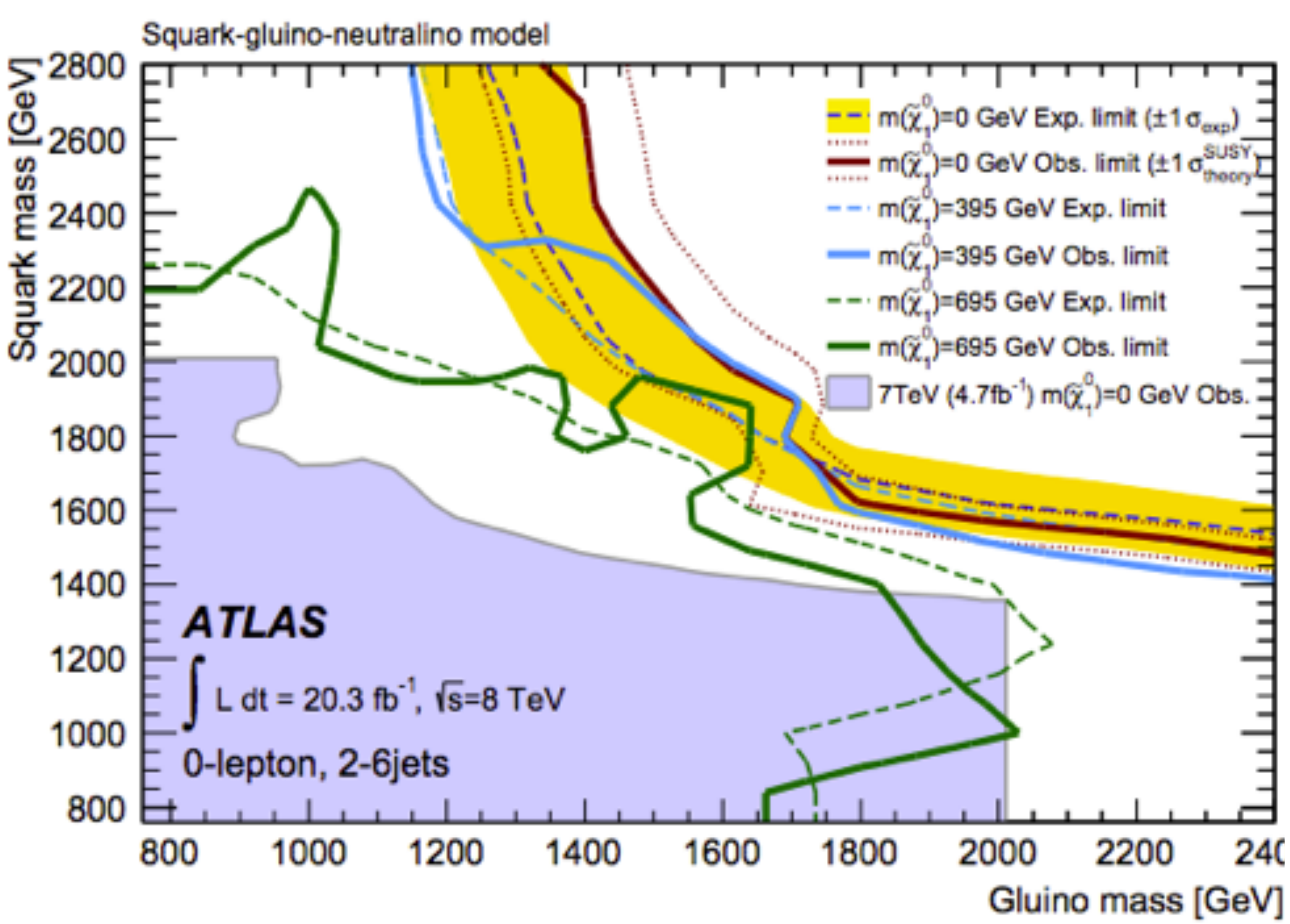
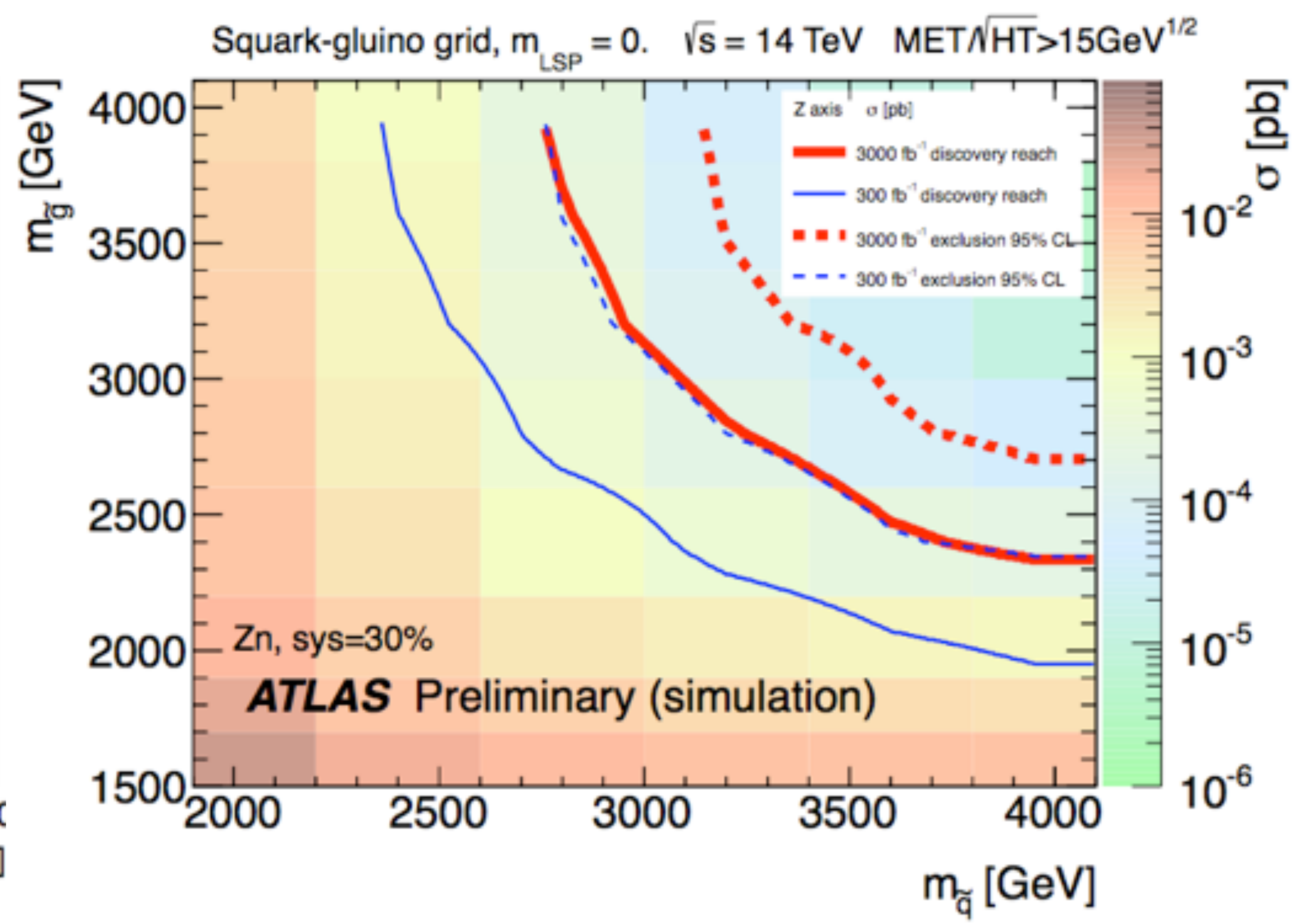
in collaboration with J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T.Plehn, T. Schell

No colored new particles beyond SM at LHC so far

We are searching for new physics beyond SM.





$m_{\tilde{q}} \sim 1.4\text{TeV} \quad m_{\tilde{g}} \sim 1.3\text{TeV}$

excluded for $m_\chi = 0$

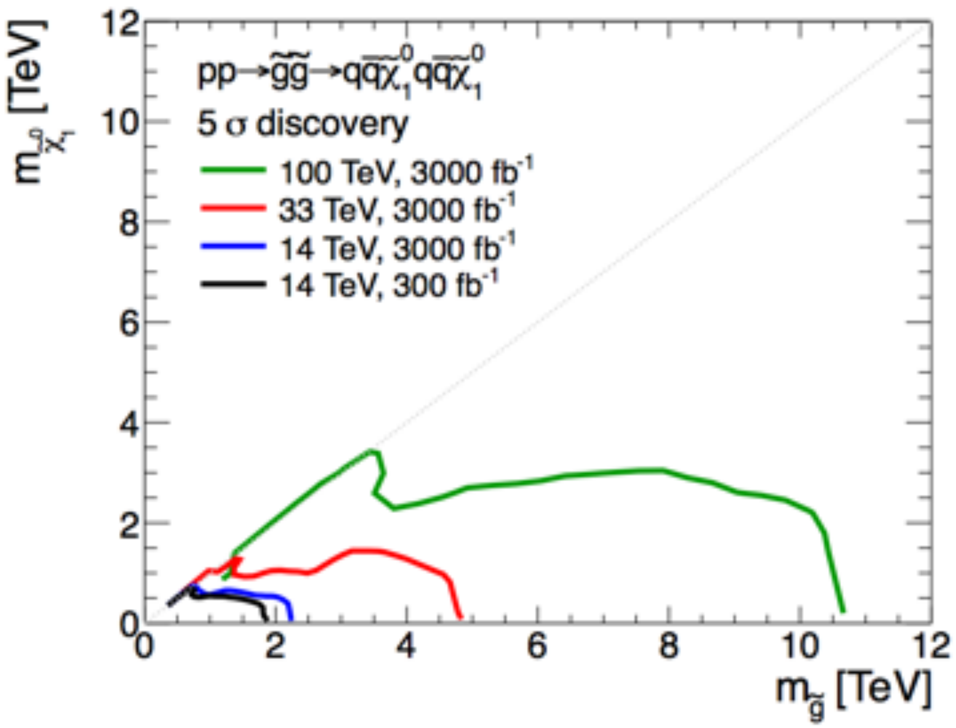
$m_{\tilde{q}} \sim 3\text{TeV} \quad m_{\tilde{g}} \sim 2.7\text{TeV}$

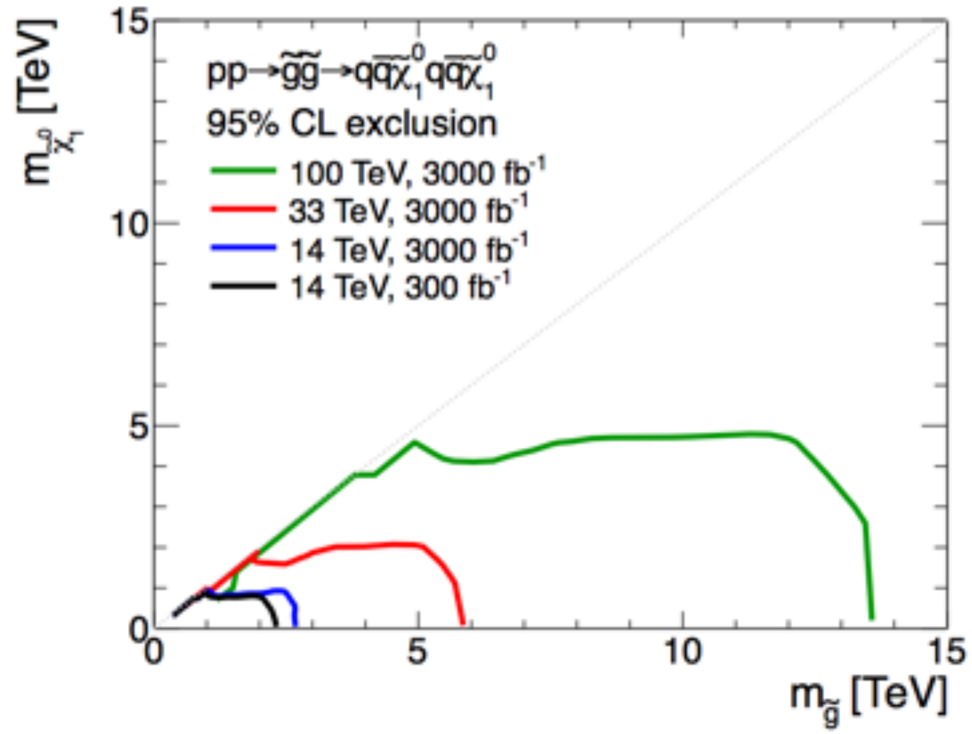
possible to exclude

100 TeV prospect

arXiv:1311.6480

T. Cohen, T. Golling, M. Hance, A. Henrichs, K. Howe, J. Loyal, S. Padhi, J. Wacker

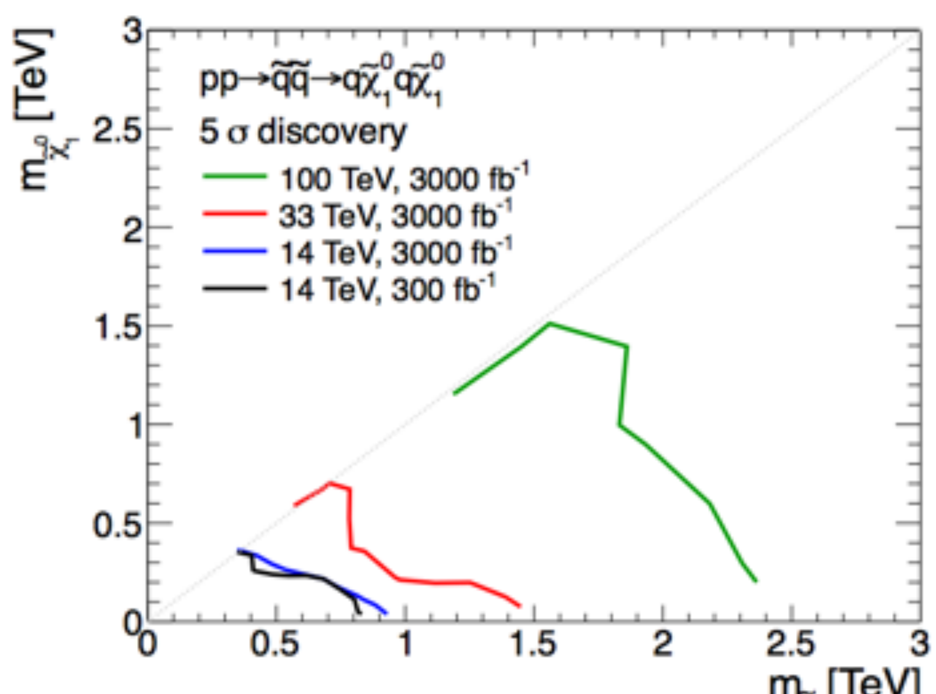


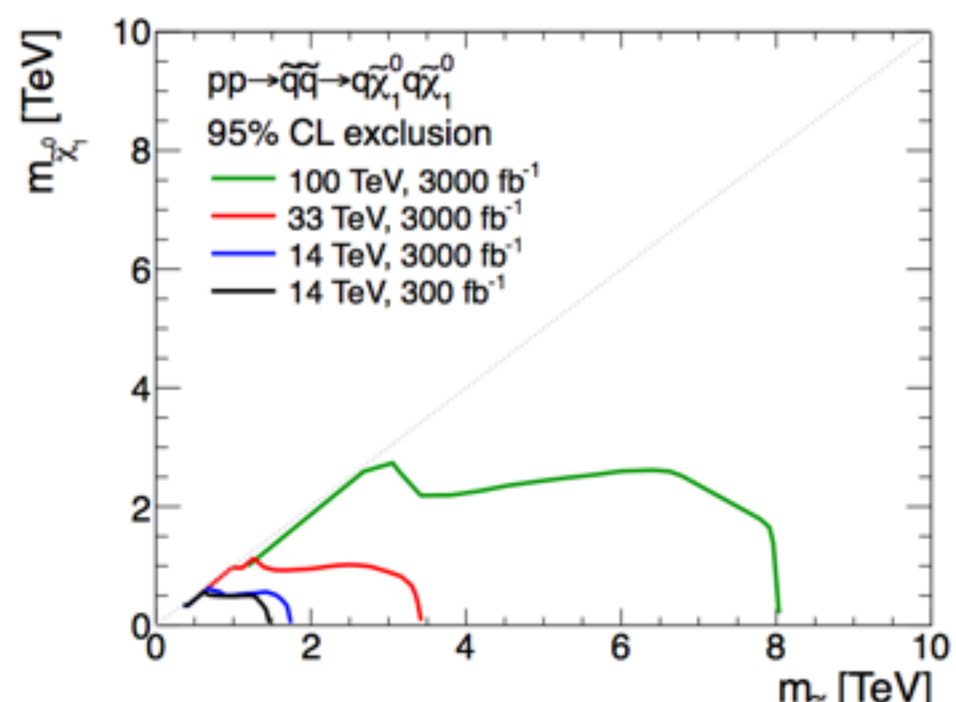


$m_{\tilde{g}} \sim 14\text{TeV}$

possible to exclude

for $m_\chi < 4$ TeV





$m_{\tilde{q}} \sim 8\text{TeV}$

($\tilde{g}$ decoupled)

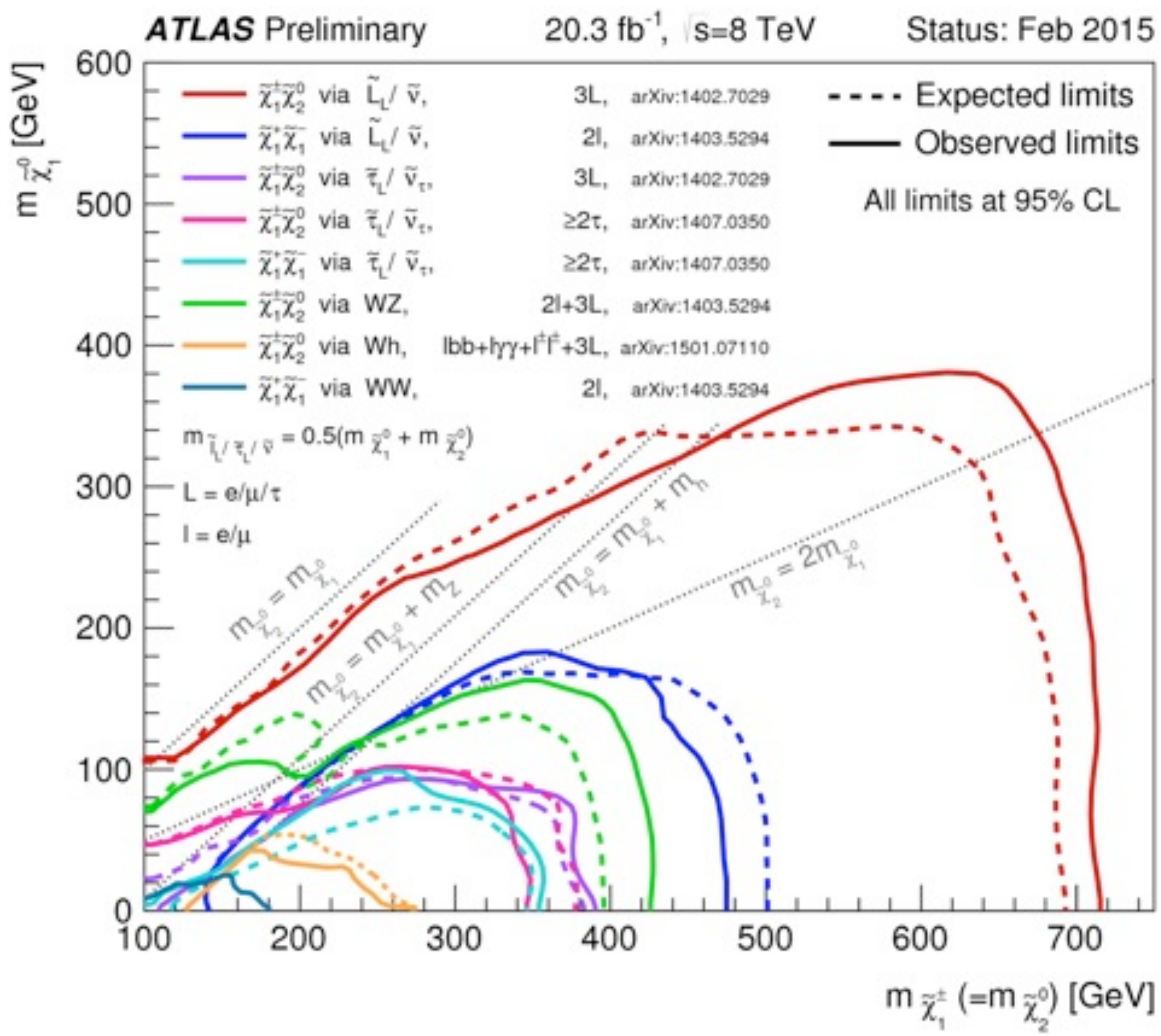
We know there are DM (not colored particle)

$$\Omega_{\rm DM} h^2 \simeq 0.12 \simeq 1/ < \sigma_a v > \simeq 1/\mathrm{pb}$$

Lightest Neutralino is a good candidate for DM $\tilde{B}, \tilde{W}, \tilde{H}_1, \tilde{H}_2$

Split-SUSY type spectrum getting popular

Traditional EWkino search : 3 leptons



dominant production

$$\sigma(\chi_1^{\pm}\chi_2^0)$$

$$\chi_1^{\pm} \to W^{\pm}\chi_1^0$$

$$\chi_2^0 \to Z\chi_1^0$$

with slepton: easy

decay to W, Z: less sensitive due to BR

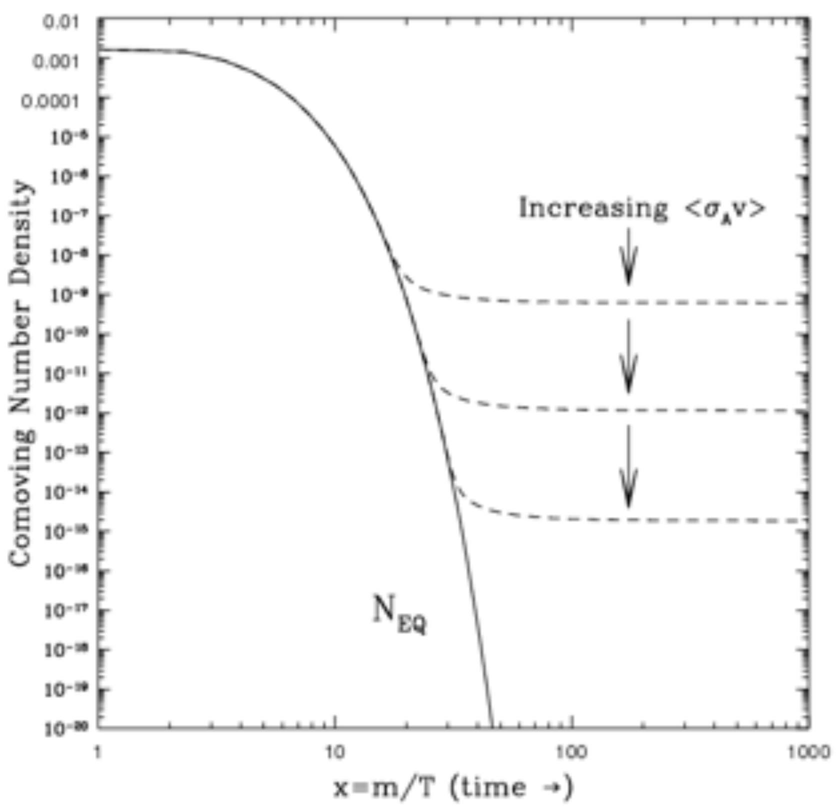
Rely on lepton trigger, need enough mass splitting

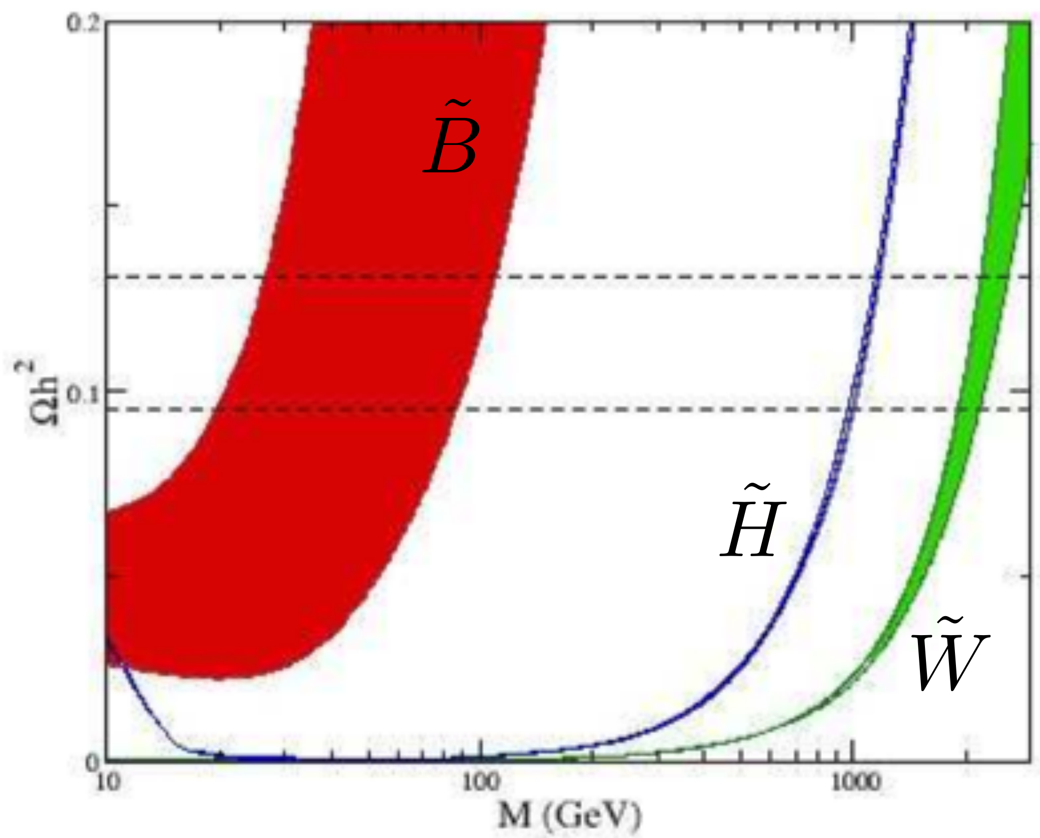
$$\Delta m = m_{\chi_1^+, \chi_2^0} - m_{\chi_1^0} > m_W, m_Z$$

$$\tilde{W} > 420 \text{ GeV}$$

ElectroWeakinos as thermal relic

Nucl.Phys.B741:108-130,2006 N. Arkani-Hamed, A. Delgado, G.F. Giudice





$$0.3 < M_1/m_{\tilde{e}_R} < 0.9$$

$$1.5 < m_{\tilde{t}}/\mu < \infty$$

$$1.5 < m_{\tilde{\ell}_L}/M_2 < \infty$$

Higgsino: $\langle\sigma_{eff}v\rangle = \frac{g^4}{512\pi\mu^2}\left(21 + 3\tan^2\theta_W + 11\tan^4\theta_W\right),$

$$\Omega_{\tilde{H}}h^2 = 0.10\left(\frac{\mu}{1\,\text{TeV}}\right)^2,$$

Wino: $\langle\sigma_{eff}v\rangle = \frac{3g^4}{16\pi M_2^2},$

$$\Omega_{\tilde{W}}h^2 = 0.13\left(\frac{M_2}{2.5\,\text{TeV}}\right)^2.$$

Higgsino: 1.1 TeV

Wino: 2.1TeV (~3TeV including SE)

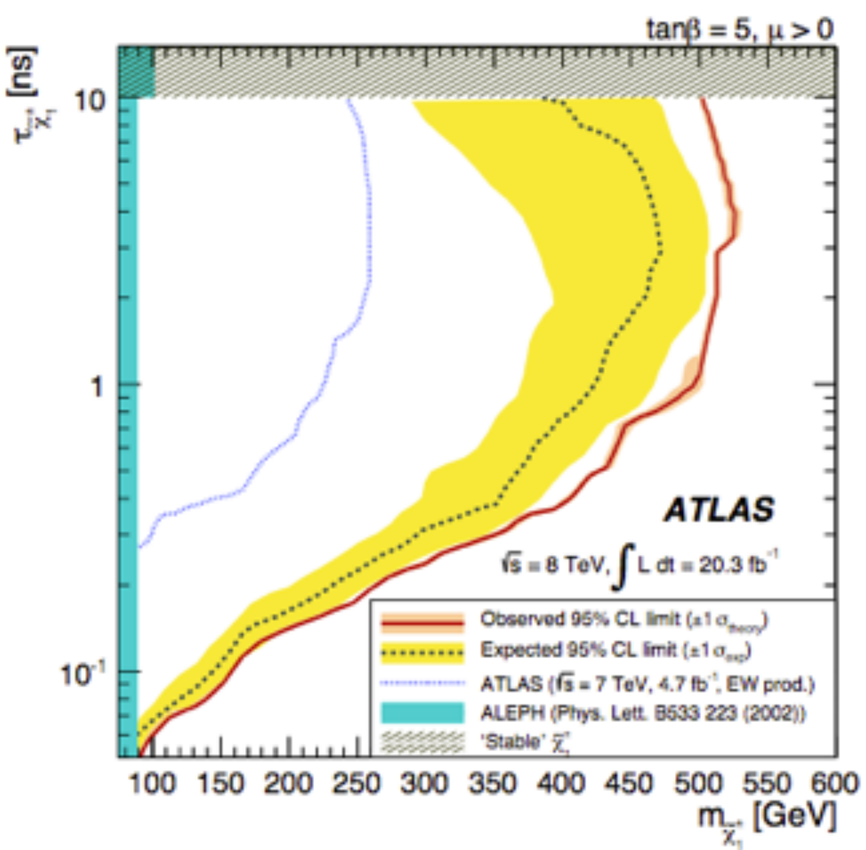
Pure states search

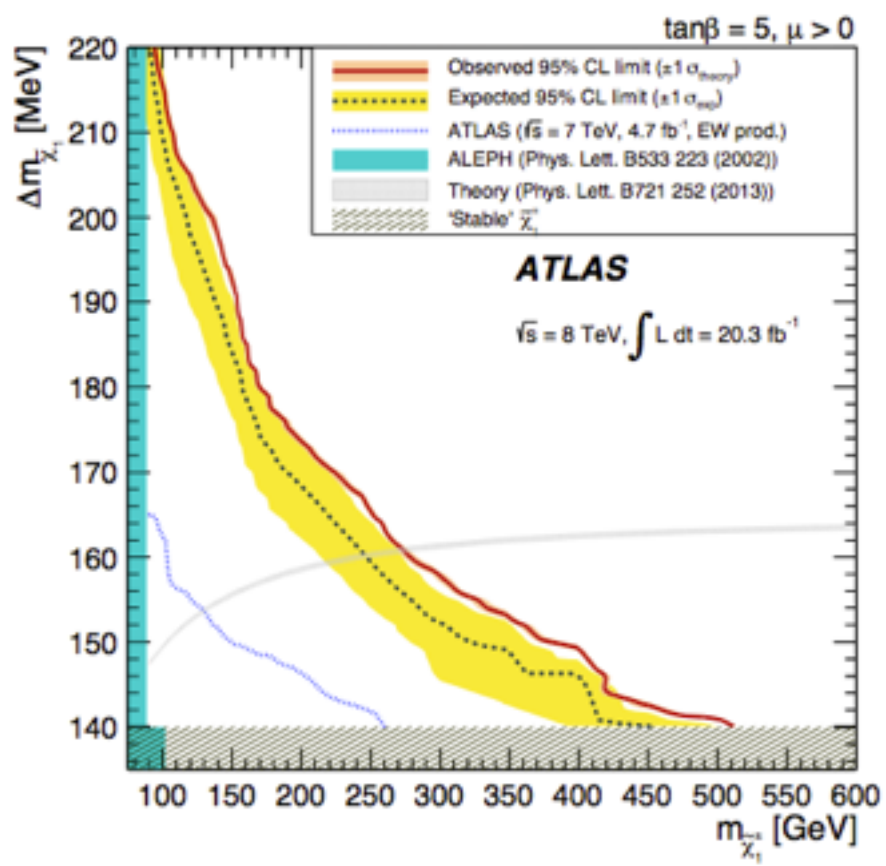
Disappearing track
ATLAS arxiv:1310.3675

pure Wino, pure Higgsino

higly degenerate with chargino $\Delta m \sim \mathcal{O}(100\mathrm{MeV})$ -> long lifetime
-> disappearing charged track

We can set bound in mass and lifetime, or Δm





AMSB wino

$$\tilde{W} > 270\mathrm{GeV}$$

excluded at 95%CL at 8TeV

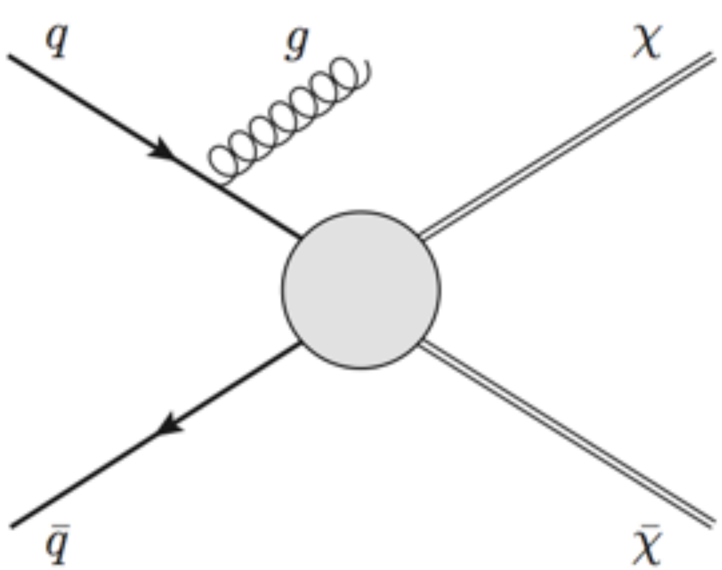
rapidly loose sensitivity with $\Delta m > 0.2\mathrm{GeV}$

mono-jet

Wino, Higgsino

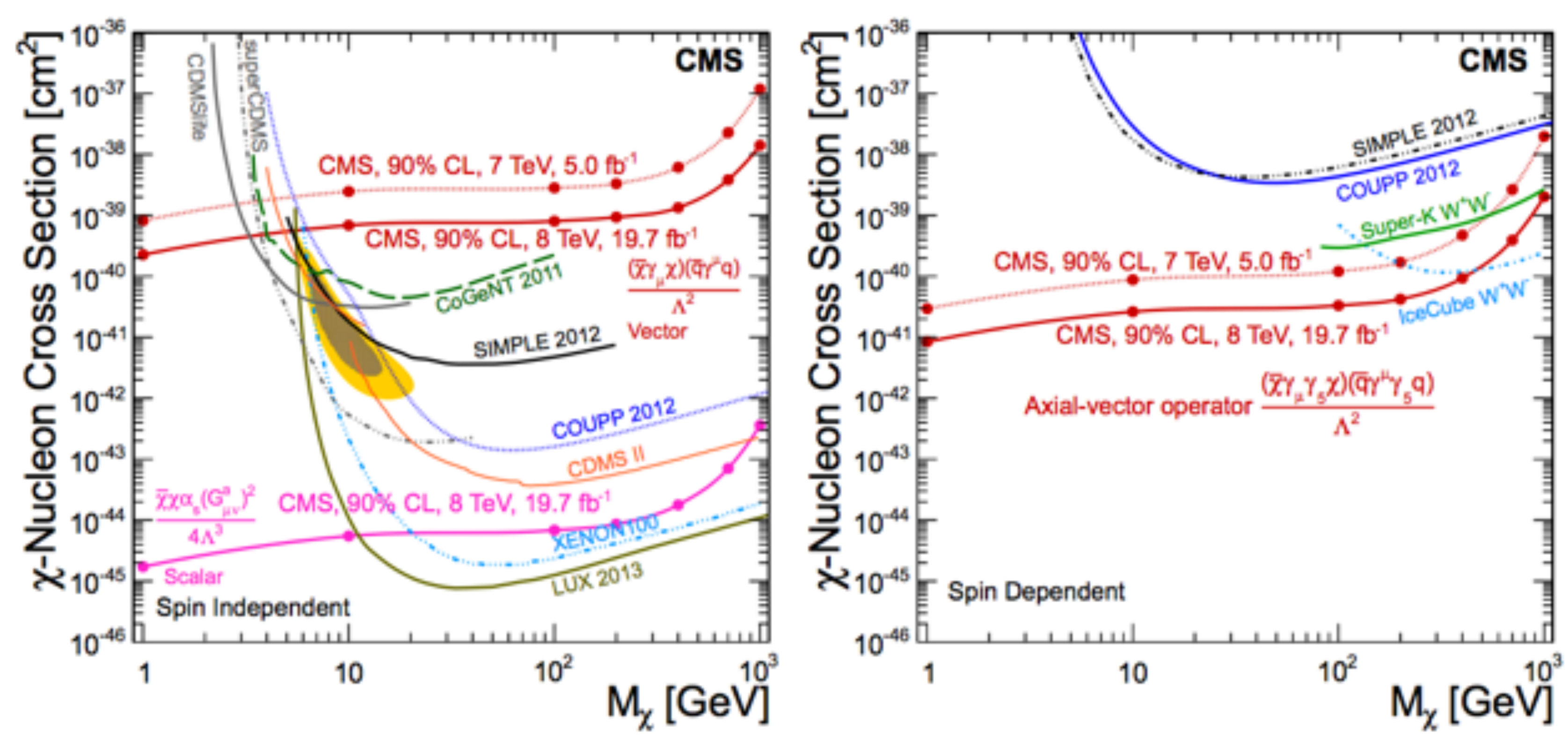
Once Δm is getting larger $\Delta m = 1 \sim 10\mathrm{GeV}$

They are degenerate -> decay into LSP + too soft decay products



We can set the limit on contact interaction operators

arXiv:1408.3583

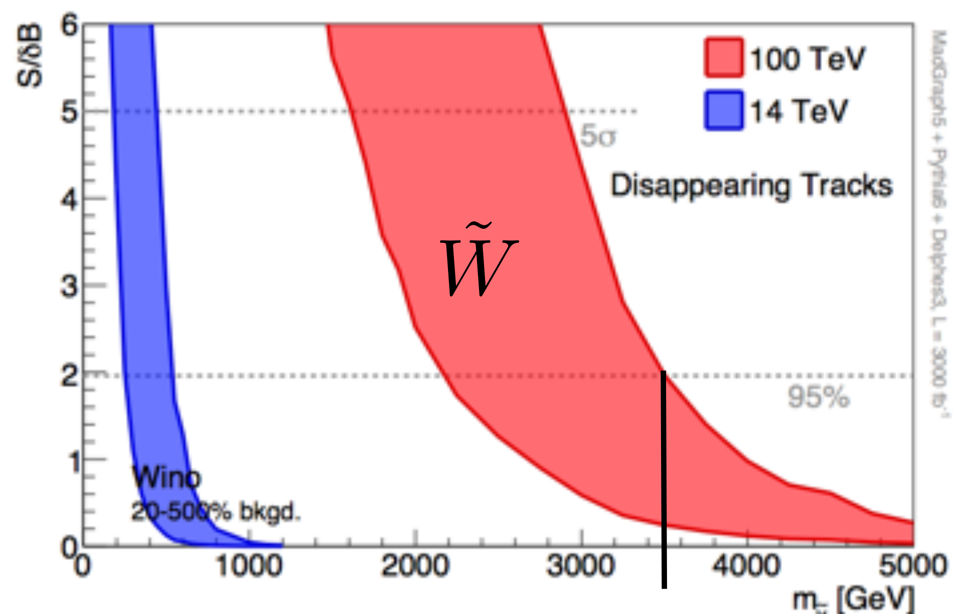


8TeV is not yet sensitive for Wino, Higgsino

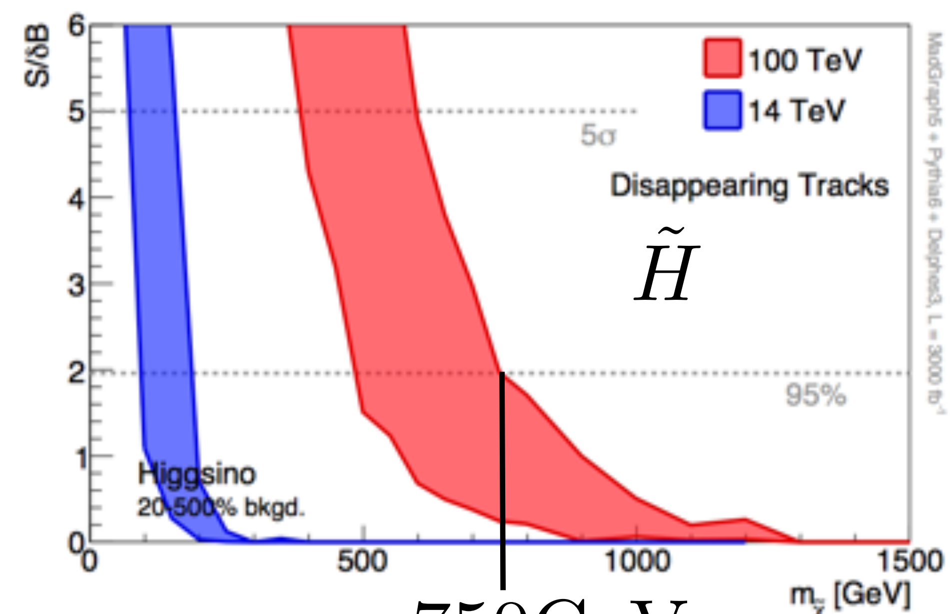
pure Wino, Higgsino LSP at 14 TeV and 100 TeV

arXiv:1404.0682 Mattew Low, L-T Wang,

Disappering tracks

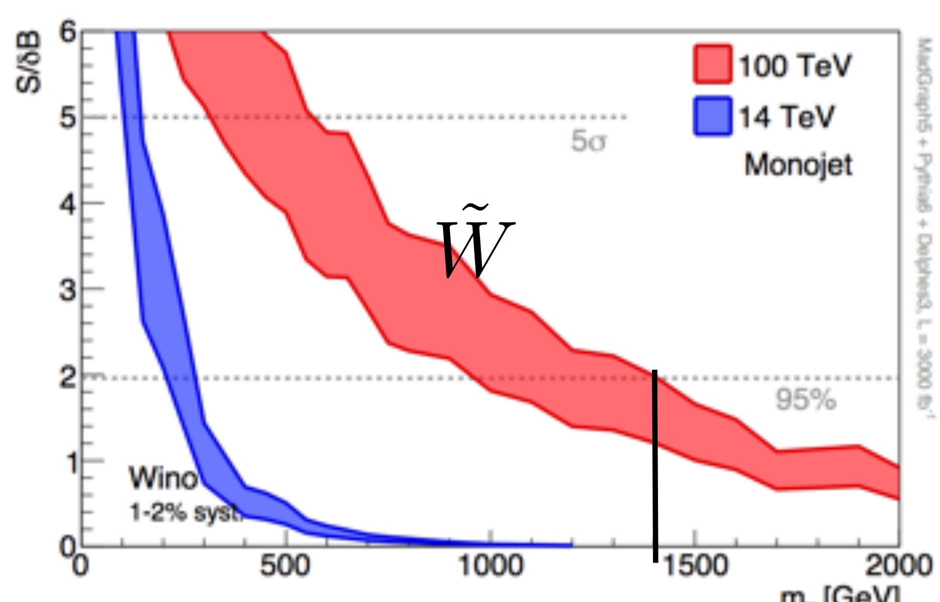


3.5TeV

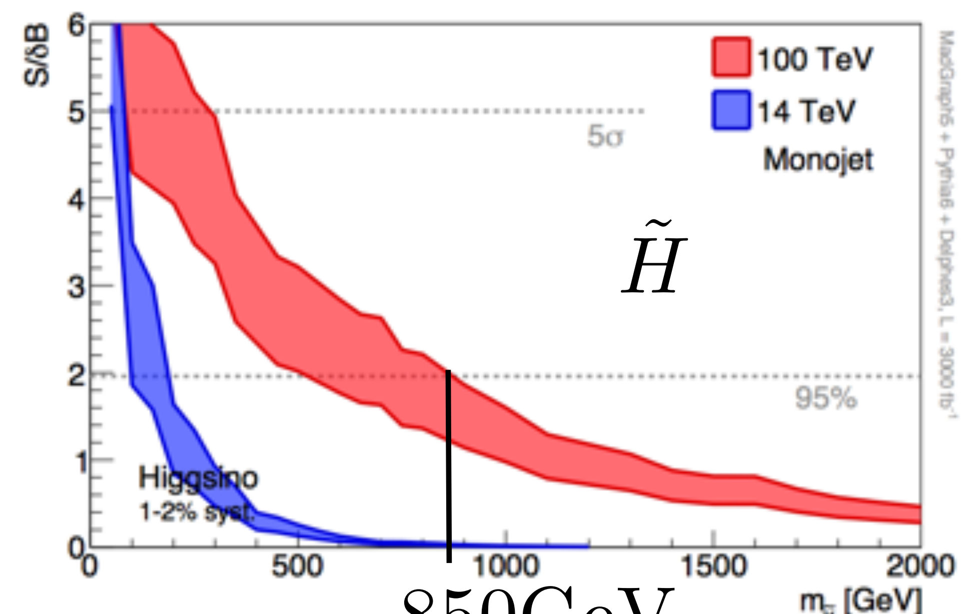


750GeV

monojet



1.4 TeV



850GeV

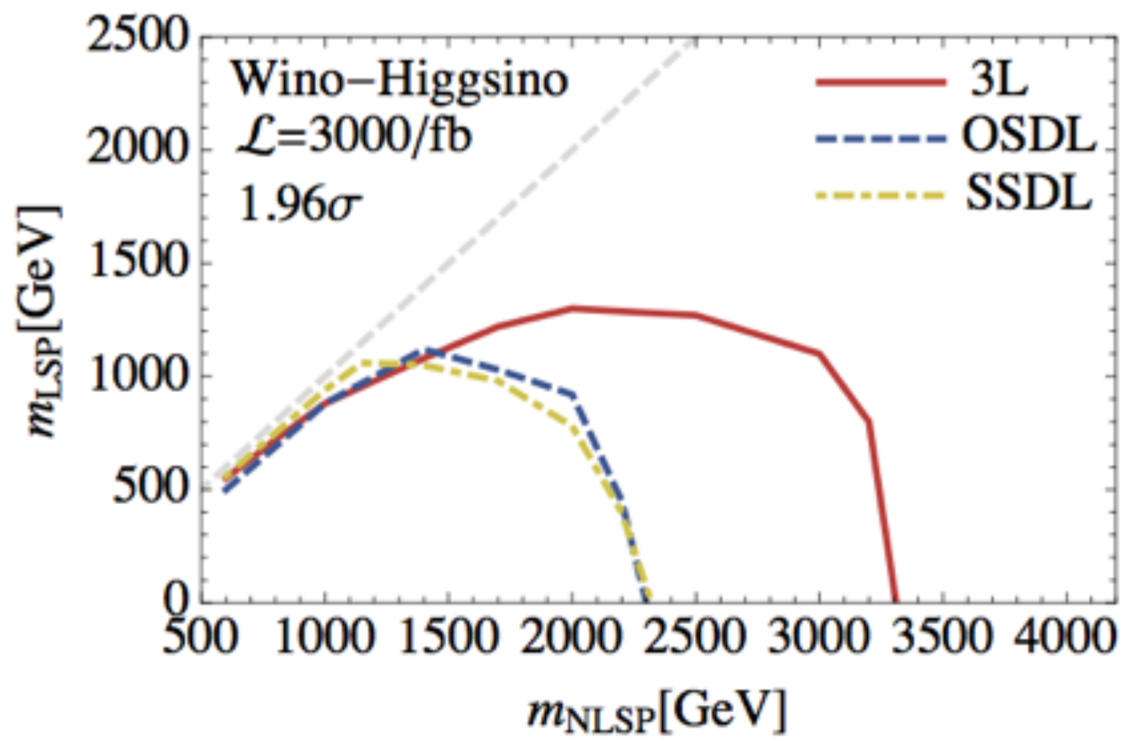
$\tilde{W}$ saturating relic abandance, might be found with disappering tracks but $\tilde{H}$ difficult.

pure Wino, Higgsino LSP at 100 TeV with “NLSP”

Consider NLSP EWkinos productions at 100 TeV

NLSP		LSP
$\tilde{W}$	$\longrightarrow$	$\tilde{H}$
$\tilde{H}$	$\longrightarrow$	$\tilde{W}$
$\tilde{H}$	$\longrightarrow$	$\tilde{B}$
$\tilde{W}$	$\longrightarrow$	$\tilde{B}$

arXiv:1410.6287 S. Gori, S. Jung, L-T. Wang, and J. D. Wells



Even for Higgsino, accessible with NLSP EWkinos assuming enough mass splittings

similar work done by arXiv:1410.1532
B. Acharya, K. Bozek, C. Pongkitivanichkul, K. Sakurai

if Wino NLSPs are lighter than about 3.2 TeV

Higgsino thermal dark matter ~ 1.1TeV excluded

Compressed spectra (ISR + soft-dileptons)

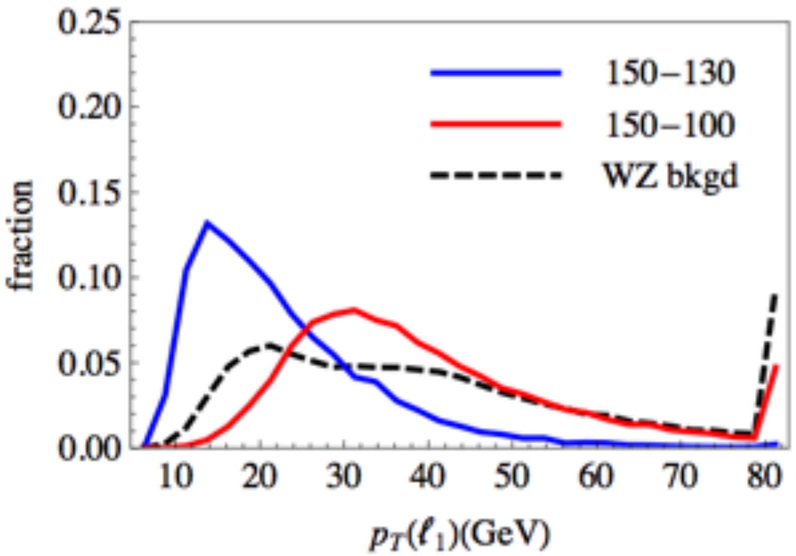
$\Delta m = 10 \sim 50\mathrm{GeV}$

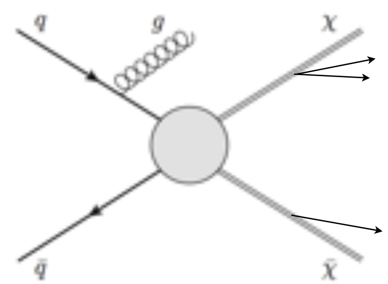
$\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$ via Z^*

less signal lepton acceptance

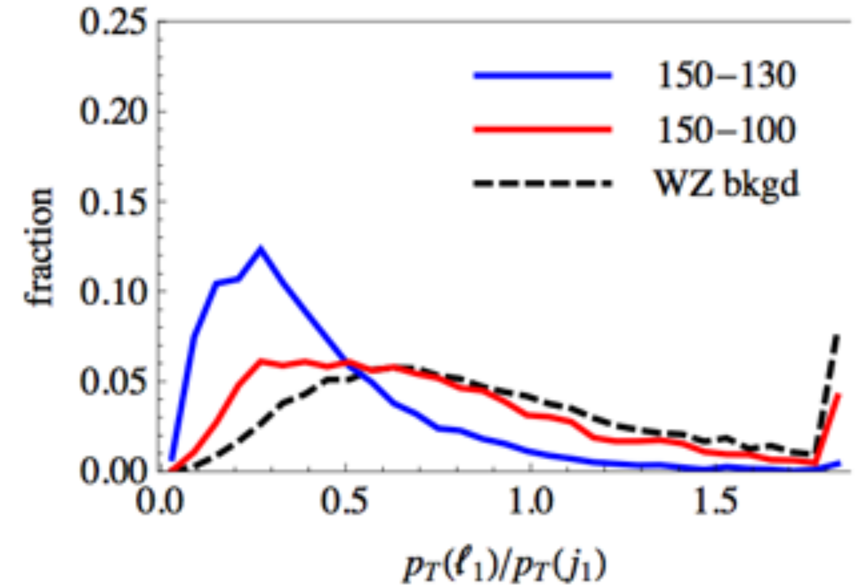
focus on $\sigma(\chi_1^\pm \chi_2^0 j)$ other than $\sigma(\chi_1^\pm \chi_2^0)$

1307.5952 S. Gori, S. Jung, L-T. Wang





ISR used for trigger



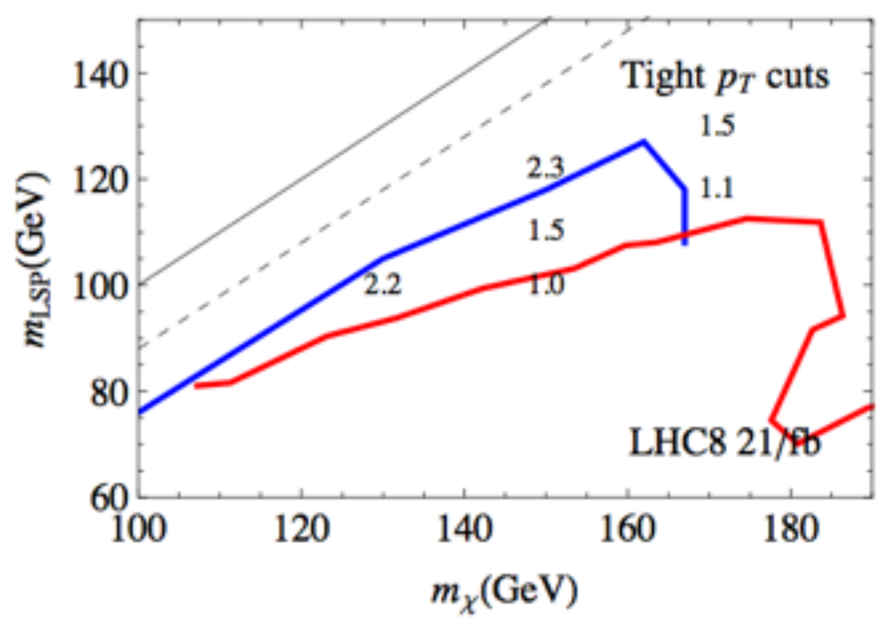
$$-\vec{E}_T^{\mathrm{miss}} = \vec{p}_T(j_1) + \sum \vec{p}_T(\ell), \qquad |\vec{p}_T(\ell)| \sim \gamma E_\ell^0.$$

$$E_\ell^0 \sim \Delta m \qquad \gamma \sim \frac{\sqrt{p_T^2(j_1)/4 + M^2}}{M}.$$

$M = m_\chi$ for signal, $m_{W/Z}$ for BG

for $m_\chi > m_{W/Z}$, $\gamma_{\mathrm{signal}} < \gamma_{\mathrm{BG}}$

For the same trigger ISR jet pT, BG is more boosted.



$m_{NLSP} \sim 220$ GeV ($\Delta m \sim 20$ GeV)

$m_{NLSP} \sim 320$ GeV ($\Delta m \sim 30$ GeV)

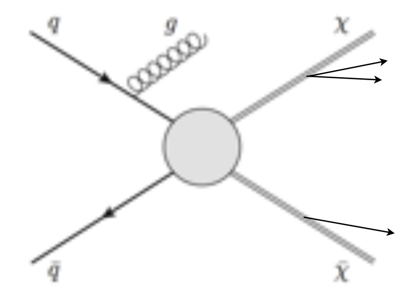
at 14 TeV 300fb^{-1}

Compressed spectra (ISR + soft-dileptons)

$\Delta m = 10 \sim 50\text{GeV}$ similar analysis done also for higgsinos arXiv:1401.1235

Z. Han, G. Kribs, A. Martin, and A. Menon

1.) $pp \to \chi_1^{\pm}\chi_1^{\mp} + j \to \ell^+\ell'^-\nu\bar{\nu}\chi_1^0\chi_1^0 + j$
2.) $pp \to \chi_2^0\chi_1^0 + j \to \ell^+\ell^-\chi_1^0 + j$
3.) $pp \to \chi_1^{\pm}\chi_2^0 + j \to \ell^+\ell^- jj\chi_1^0\chi_1^0 + j,\ \ell^+\ell^-\ell'^{\pm}\nu\chi_1^0\chi_1^0 + j,$



$\not{E}_T > 100$ GeV
exactly 1 hard jet: $p_{T,j} > 100$ GeV(veto second jet > 30 GeV)
2 isolated ℓ: $p_{T,\ell} > 7$ GeV
$m_{\tau\tau} > 150$ GeV (reject Zj)

$m_\chi \sim 200$ GeV can be excluded at 14 TeV 100fb^{-1}

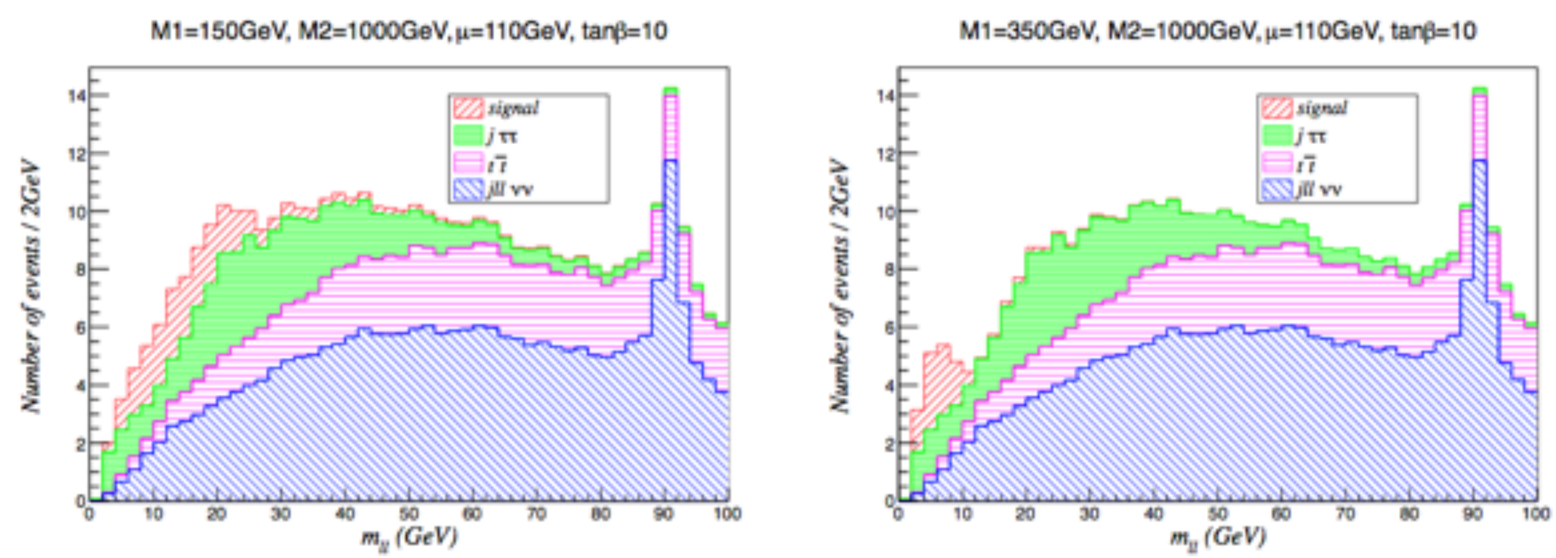


FIG. 5. Example $m_{\ell\ell}$ distributions after all other cuts, for case II, 20 fb^{-1} at the 8 TeV LHC.

$m_\chi \sim 300$ GeV can be excluded at 14 TeV 3ab^{-1}

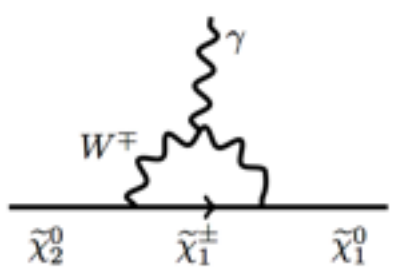
arXiv:1404.0682 Mattew Low, L-T Wang,

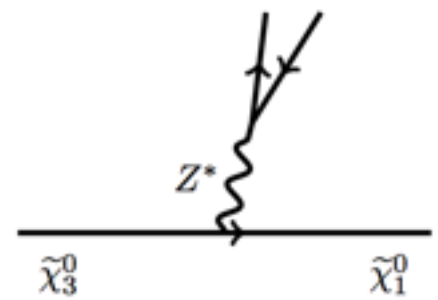
For the same trigger ISR jet pT, BG is more boosted.

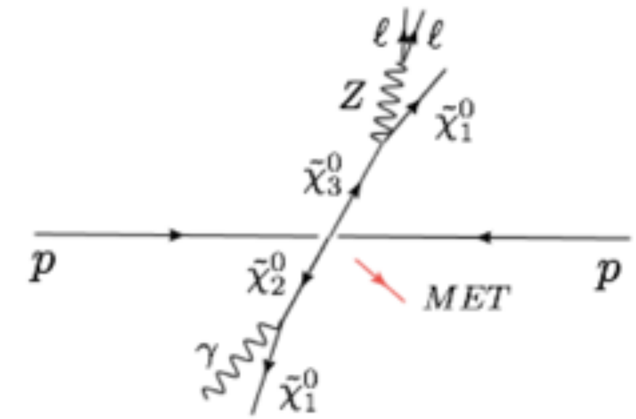
Compressed spectra (photon+leptons)

$\Delta m = 5 \sim 15\mathrm{GeV}$ bino/higgsino arXiv:1408.6530

Joseph Bramante, Antonio Delgado, Fatemeh Elahi, Adam Martin, and Bryan Ostdiek







$\chi_2^0 \rightarrow \chi_1^0\gamma$ (1-loop) $\Longleftrightarrow$ $\chi_2^0 \rightarrow \chi_1^0\ell^+\ell^-$ via Z^*

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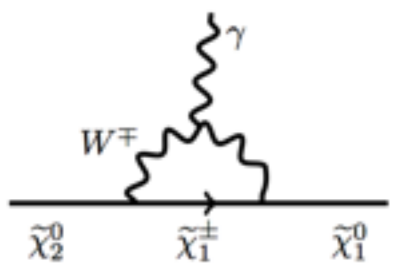
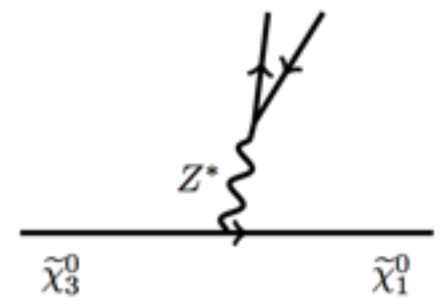
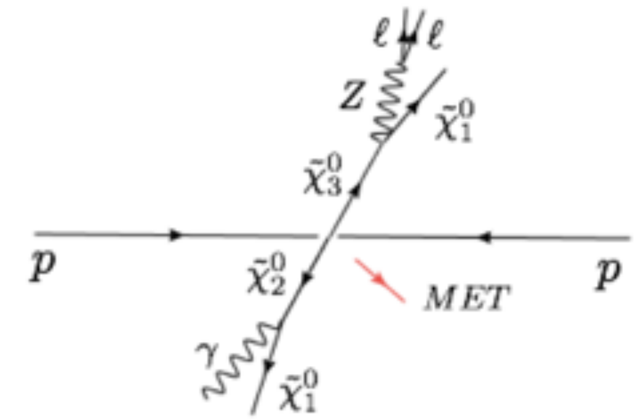






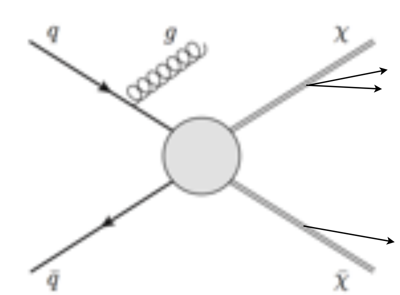
$\chi_2^0 \to \chi_1^0\gamma$ (1-loop) $\Longleftrightarrow$ $\chi_2^0 \to \chi_1^0 \ell^+\ell^-$ via Z^*

ISR + photon+lepton

arXiv:1409.4533 Chengcheng Han, Lei Wu, Jin Min Yang, Mengchao Zhang, Yang Zhang

bino/wino

$\chi_2^0\chi_1^{\pm}j \to (\chi_1^0\gamma)(\chi_1^0\ell^{\pm}\nu)j$



$\not{E}_T > 300$ GeV, only one jet with $p_{T,j} > 300$ GeV,
$10 < p_{T,\ell} < 25$ GeV, $10 < p_{T,\gamma} < 40$ GeV

5σ ($\Delta m = 5$ GeV), 2σ ($\Delta m = 15$ GeV) $m_\chi \sim 150$ GeV at 14 TeV with 0.5 ab^{-1}

For the same trigger ISR jet pT, BG is more boosted.

EWkino search summary at LHC

$\Delta m = m_{NLSP} - m_{LSP}$

$\Delta m > m_Z, m_W$	$\not{E}_T + 3\ell$
$0.2\text{GeV} < \Delta m < m_W$	$j^{\text{ISR}} + \not{E}_T + 2^+\ell^{\text{soft}}$ $j^{\text{ISR}} + \not{E}_T + \ell^{\text{soft}} + \gamma$ $\not{E}_T + 2^+\ell^{\text{soft}} + \gamma$ For the same trigger ISR jet pT, BG is more boosted. $j^{\text{ISR}} + \not{E}_T$ (mono-jet)
$\Delta m < 0.2\text{GeV}$	Disappearing tracks $+j^{\text{ISR}} + \not{E}_T$

Mainly working on pure states, (target: 1.1TeV Higgsino, 3 TeV Wino)
~400 GeV would be the best reach at LHC14 once the mass splitting small

Question to ask:
All possible relic EWkino DM accesible at 100 TeV?

we check it explicitly (not working on pure states)

arXiv:1412.4789 Joseph Bramante, Patrick J. Fox, Adam Martin, Bryan Ostdiek, Tilman Plehn, Torben Schell, and MT

Well Tempered relic neutralino surface

arXiv:1412.4789

J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, and MT

Split-susy type spectrum, EWkino sector has 4 parameters $M_1, M_2, \mu, \tan\beta$

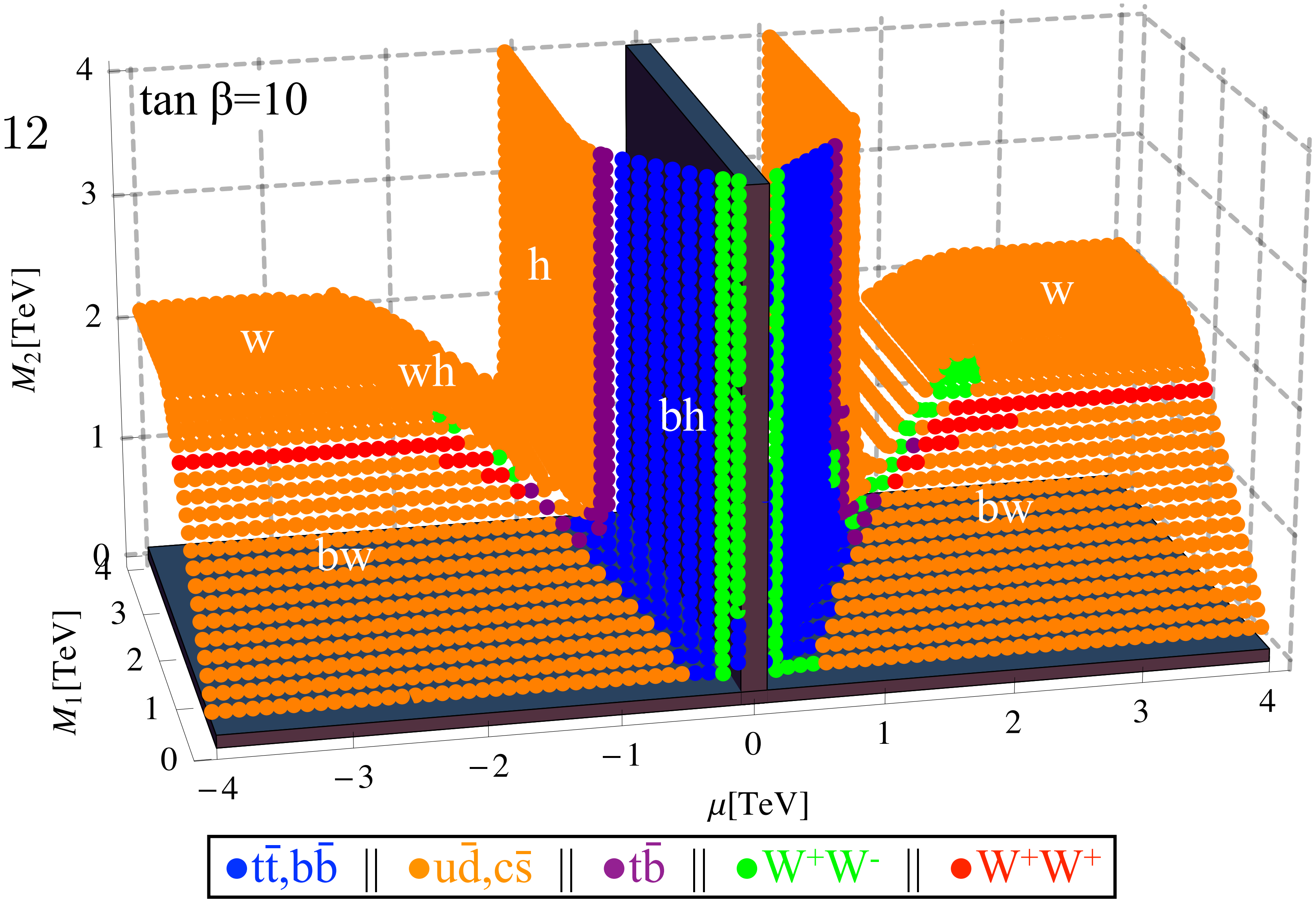
We fix $\tan\beta = 10$

We scan points giving $\Omega h^2 = 0.12$

SUSPECT3

micrOMEGAs3

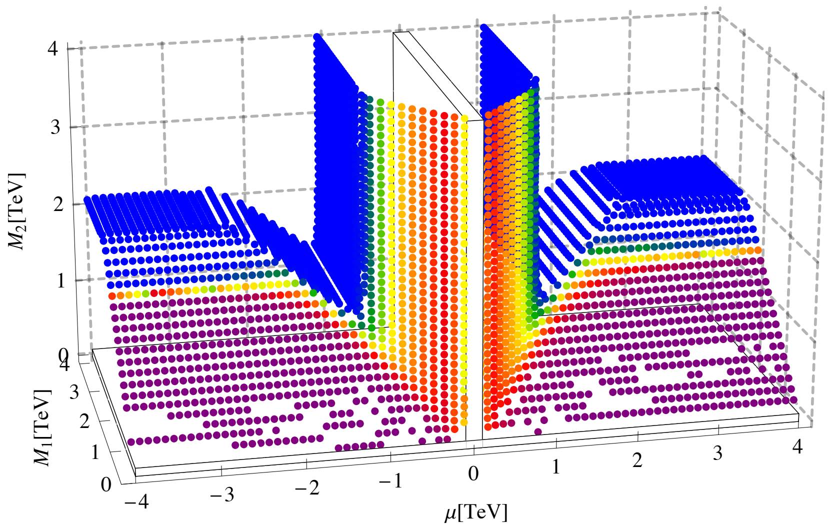
(no Sommerfeld Enhancement)



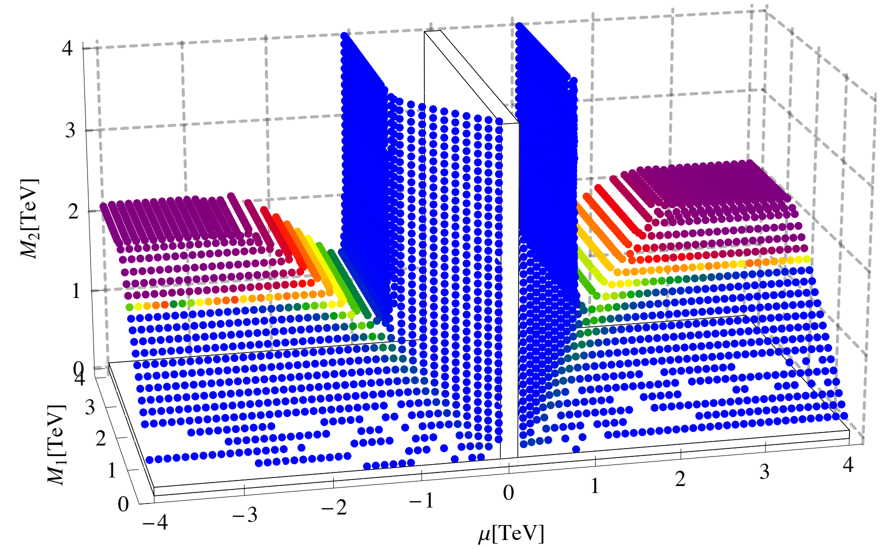
We first show 3D structure, moving animated plot available online:

http://www3.nd.edu/~bostdiek/research_welltmp.html

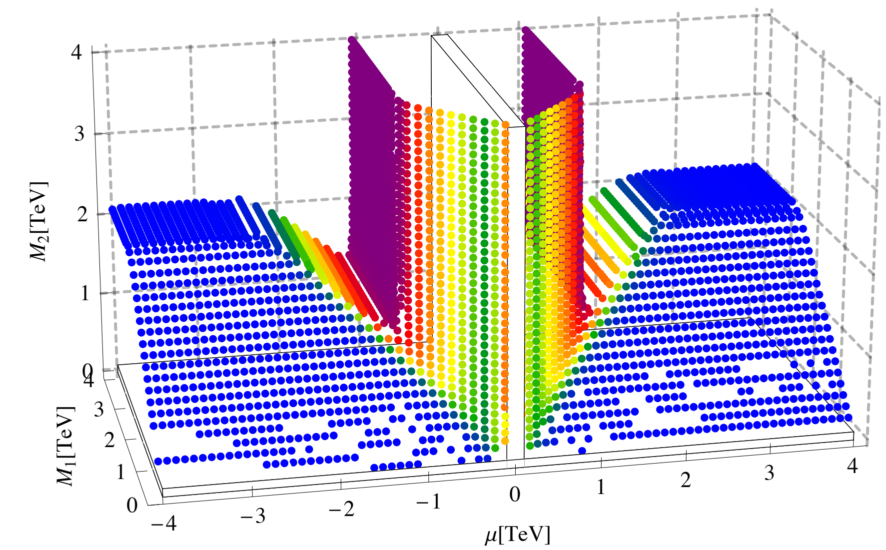
Mixing parameters



$$N^2_{1\tilde{B}}$$

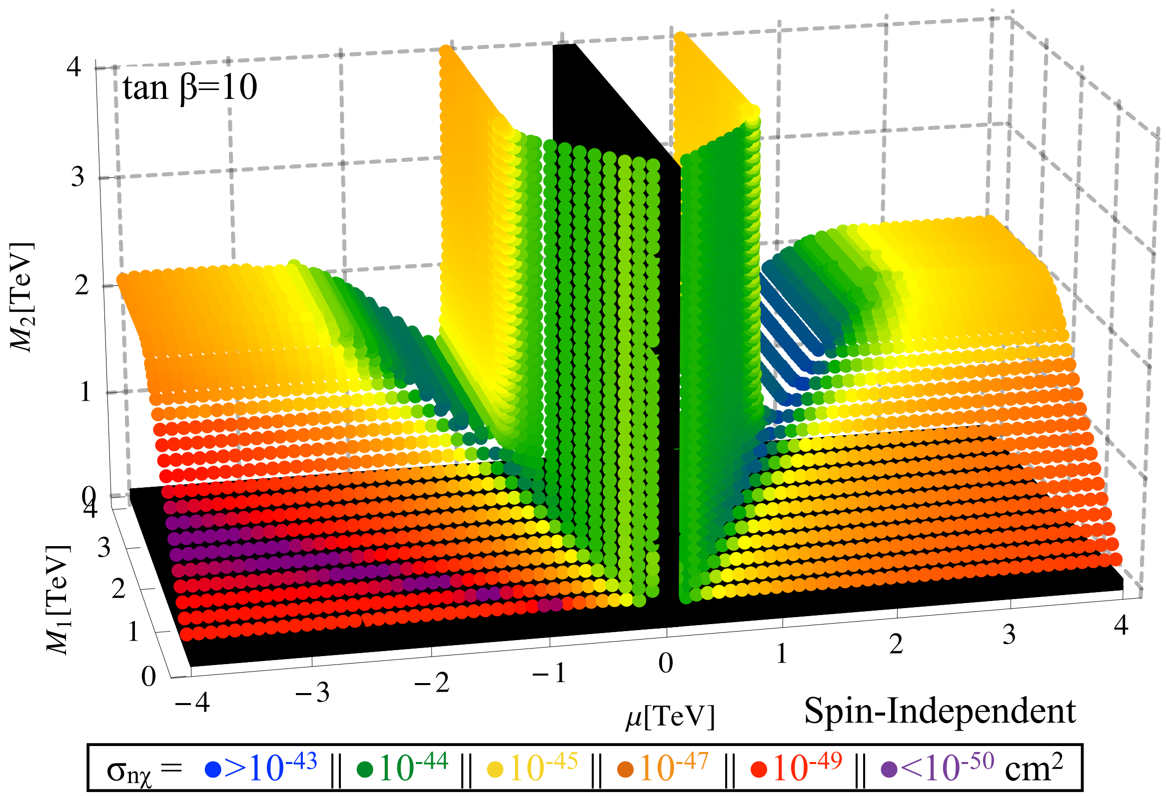


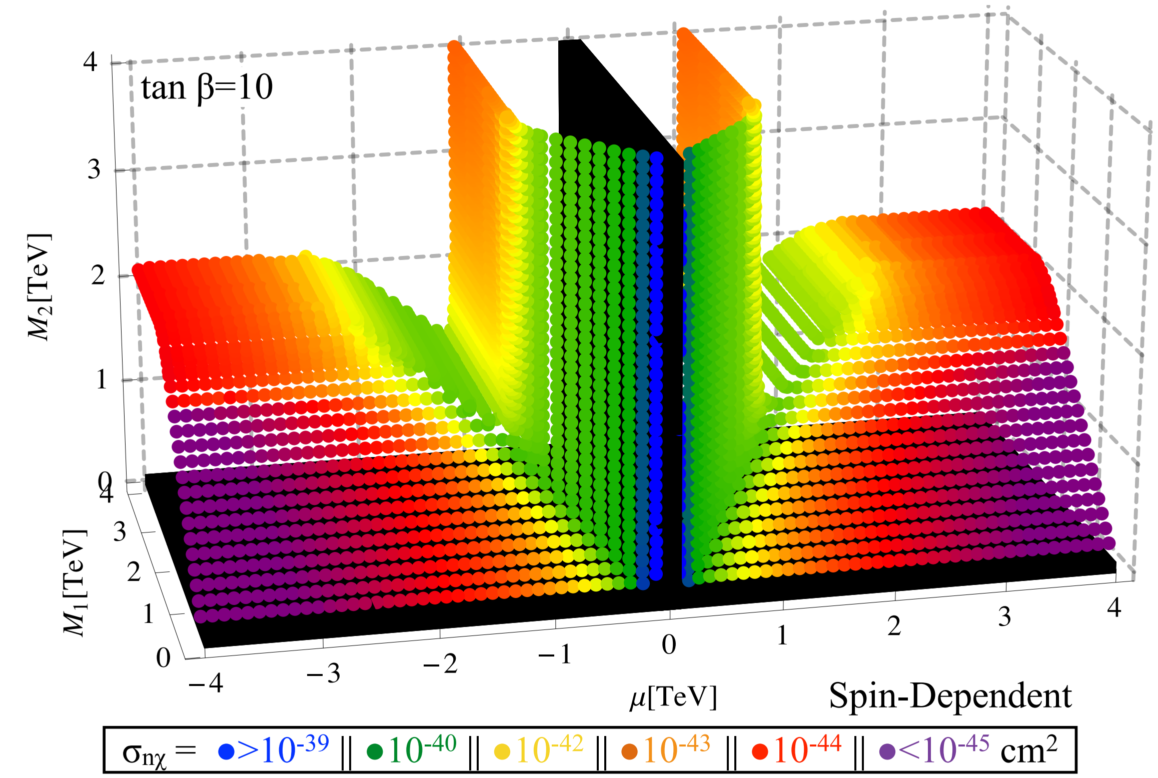
$$N^2_{1\tilde{W}}$$



$$N^2_{1\tilde{H}_1} + N^2_{1\tilde{H}_2}$$

Direct Detection (Blind spot, Neutrino BG)





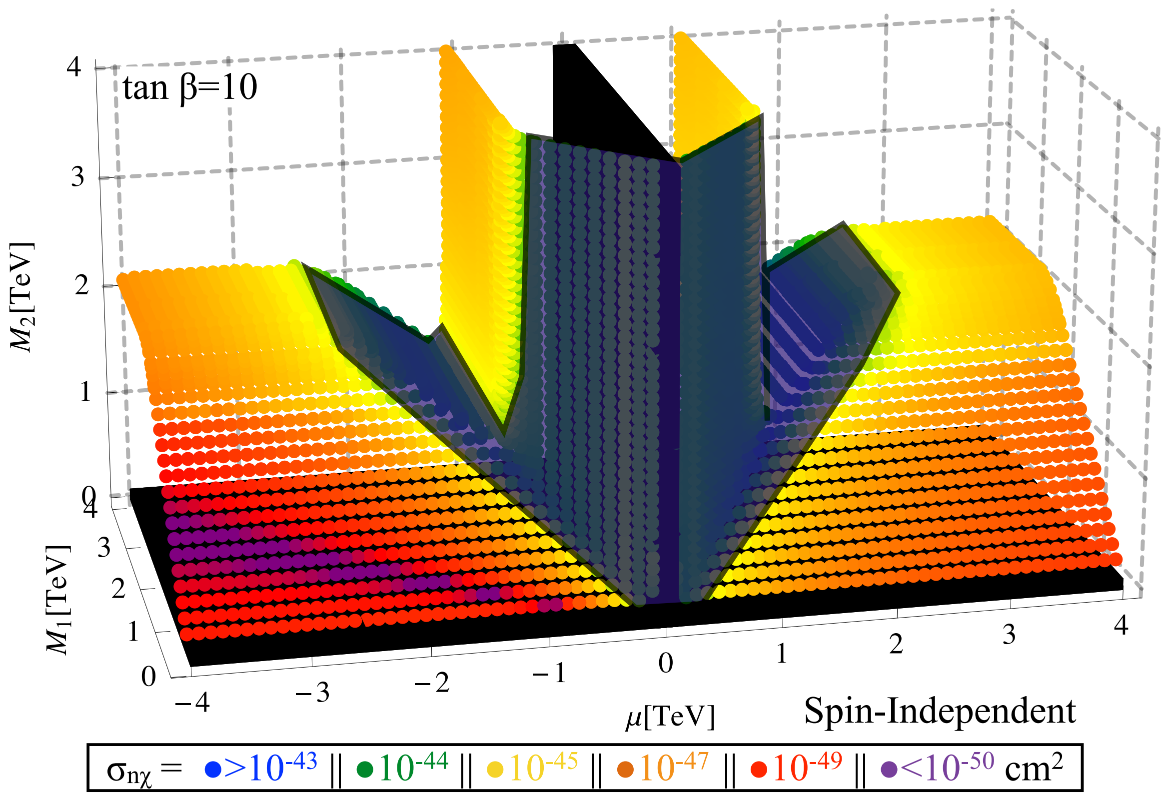
current bound
XENON100 (2012) $< 10^{-44}$
LUX (2013)

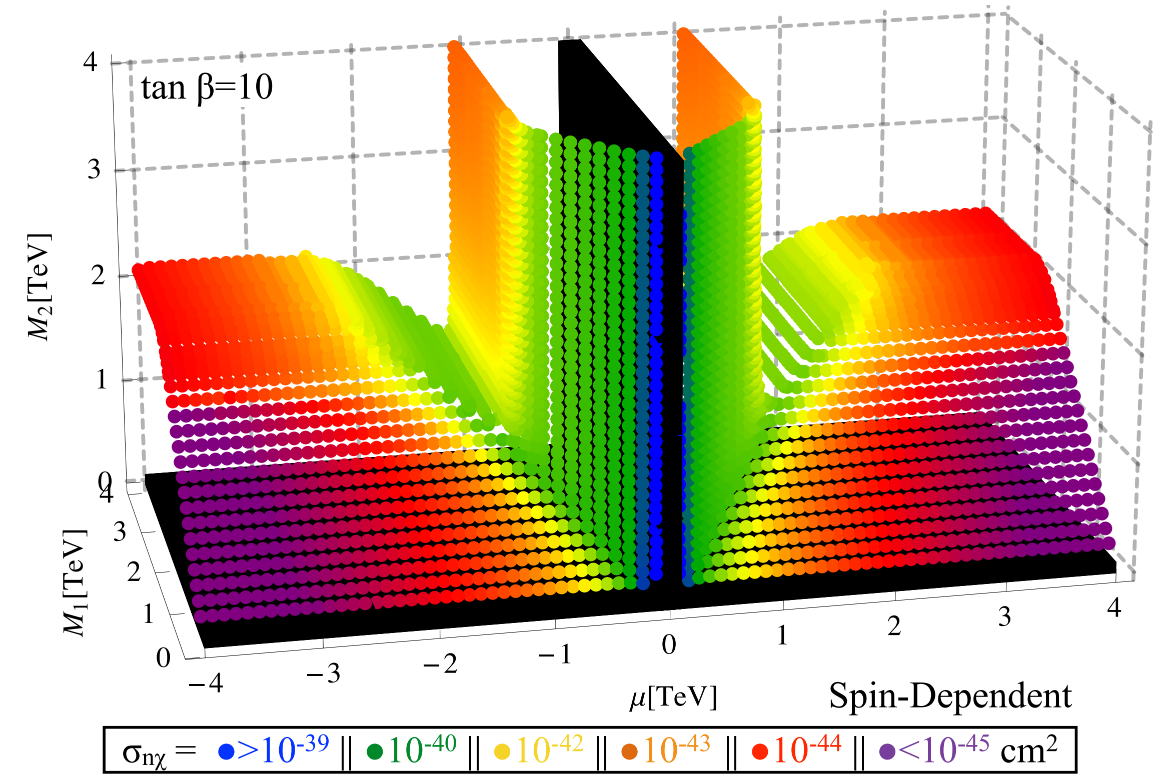
current bound
XENON100 (2013) $< 10^{-39} \sim 10^{-40}$

coherent neutrino scattering $\sim 10^{-48}$ for 1TeV

Blind spot condition: $m_{\chi_1} + \mu \sin 2\beta = 0$

Direct Detection (Blind spot, Neutrino BG)





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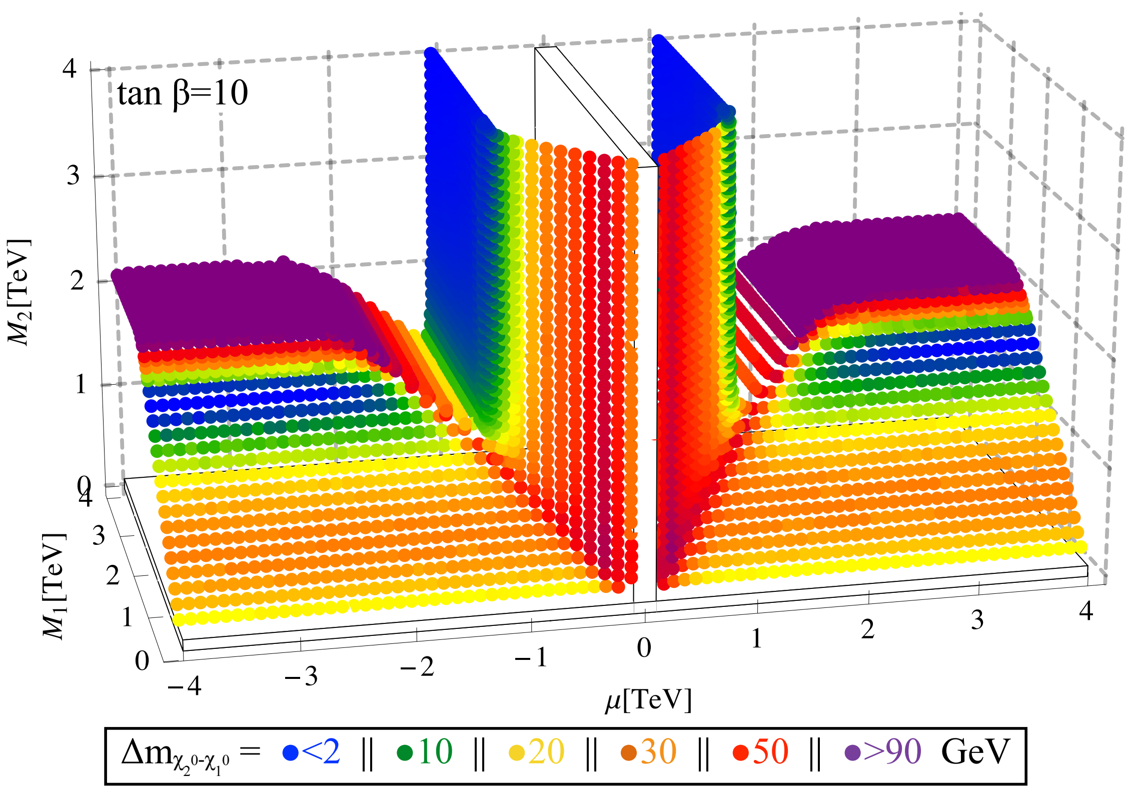
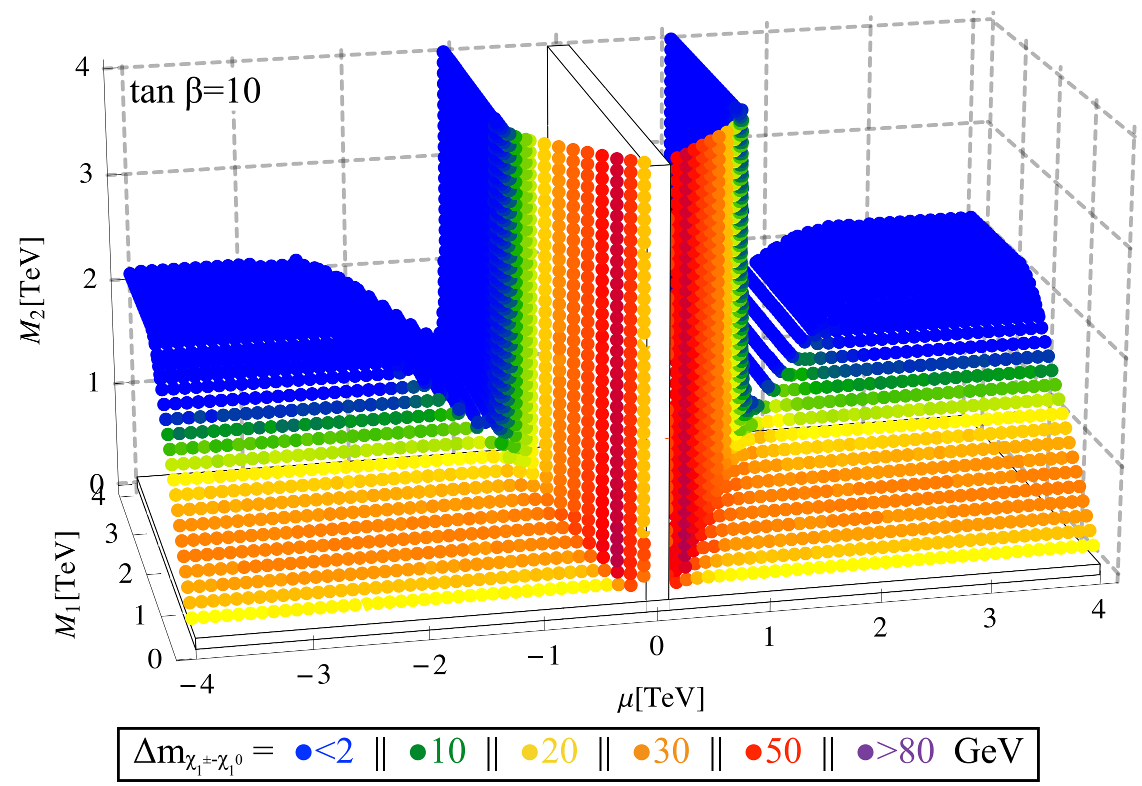
small Δm

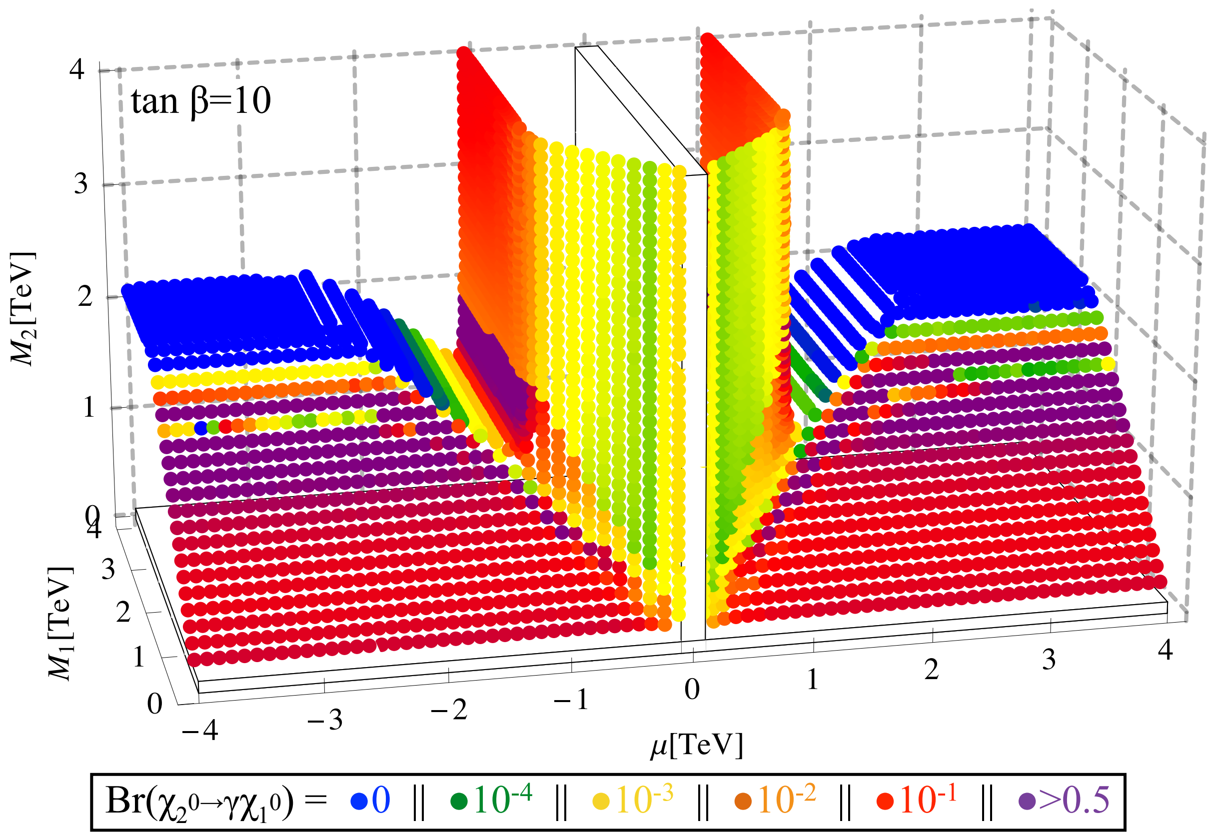


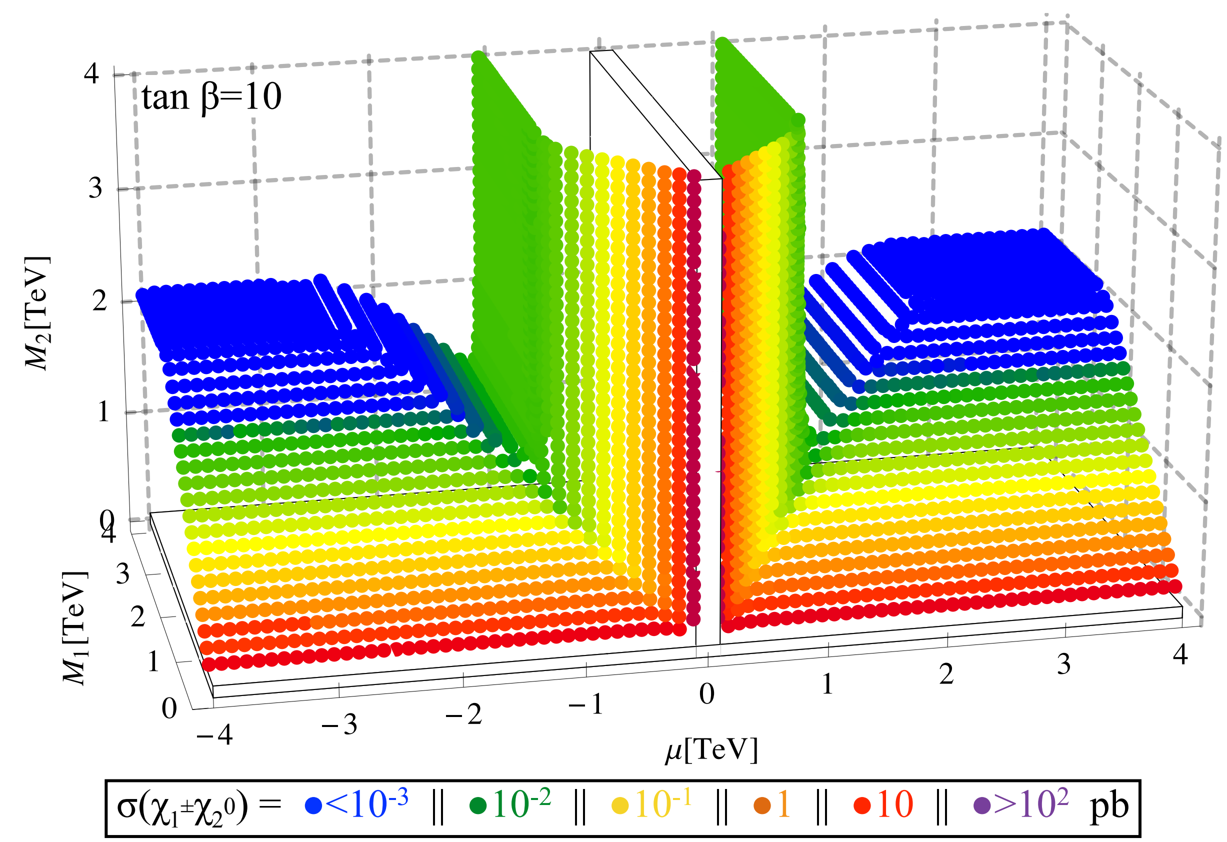


other than Bino/Higgsino slope, almost entirely $\Delta m < 30 \text{ GeV}$

We cannot use standard EWkino search strategy: 3leptons
have to work on soft-leptons, photons

BR(photon), cross sections





For Wino/Bino LSP, photon BR is enough

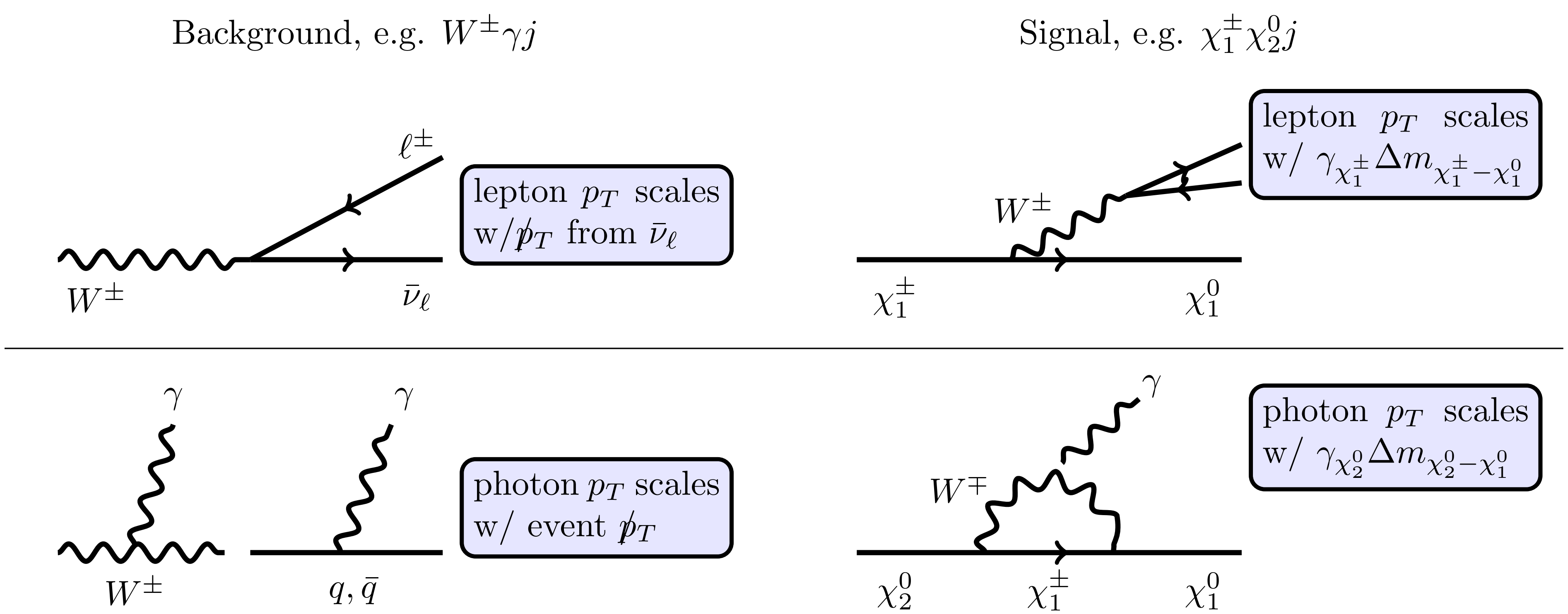
Cross sections just determined by the LSP mass

$$\chi_2^0\chi_1^\pm j \to (\chi_1^0\gamma)(\chi_1^0\ell^\pm\nu)j \qquad\qquad \chi\chi j \to \chi_1^0\chi_1^0\ell^+\ell^- X j$$

Analysis detail : photon + lepton

$\chi_2^0 \chi_1^\pm j \to (\chi_1^0 \gamma)(\chi_1^0 \ell^\pm \nu) j$

Madgraph5, Pythia6.4, Delphes3

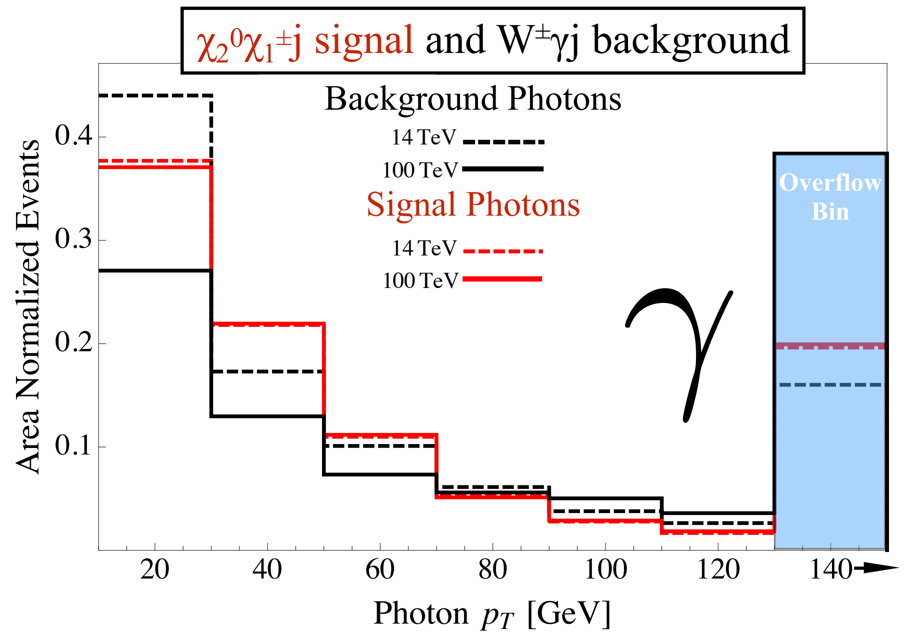


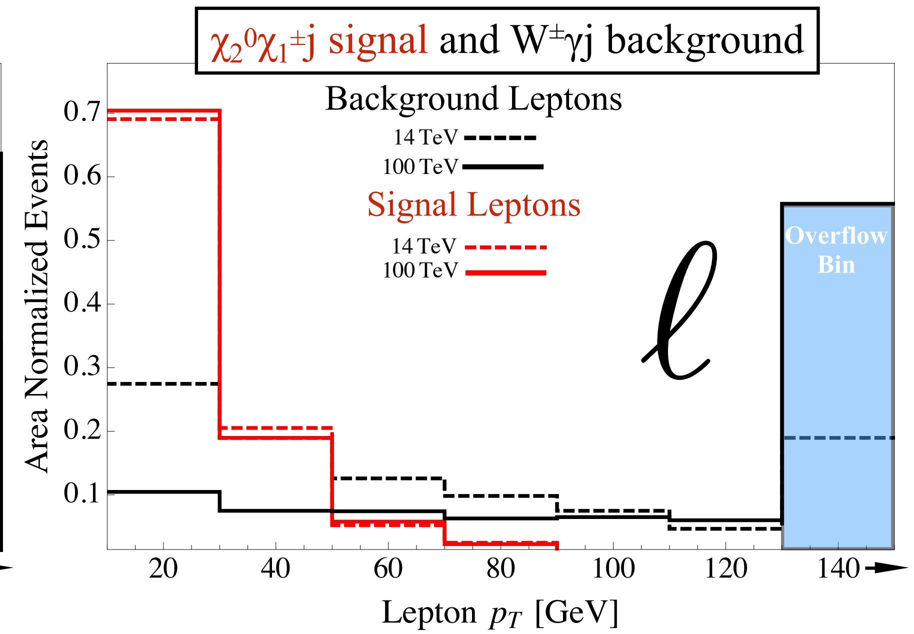
$\not{E}_T > 1.5$ TeV, only one jet with $p_{T,j} > 1$ TeV,
$5 < p_{T,\ell} < 80$ GeV, $5 < p_{T,\gamma} < 80$ GeV

as γ_χ is large at 100 TeV, we can resolve Δm down to ~ 1 GeV

For the same trigger ISR jet pT, BG is more boosted.

Analysis detail : photon + lepton



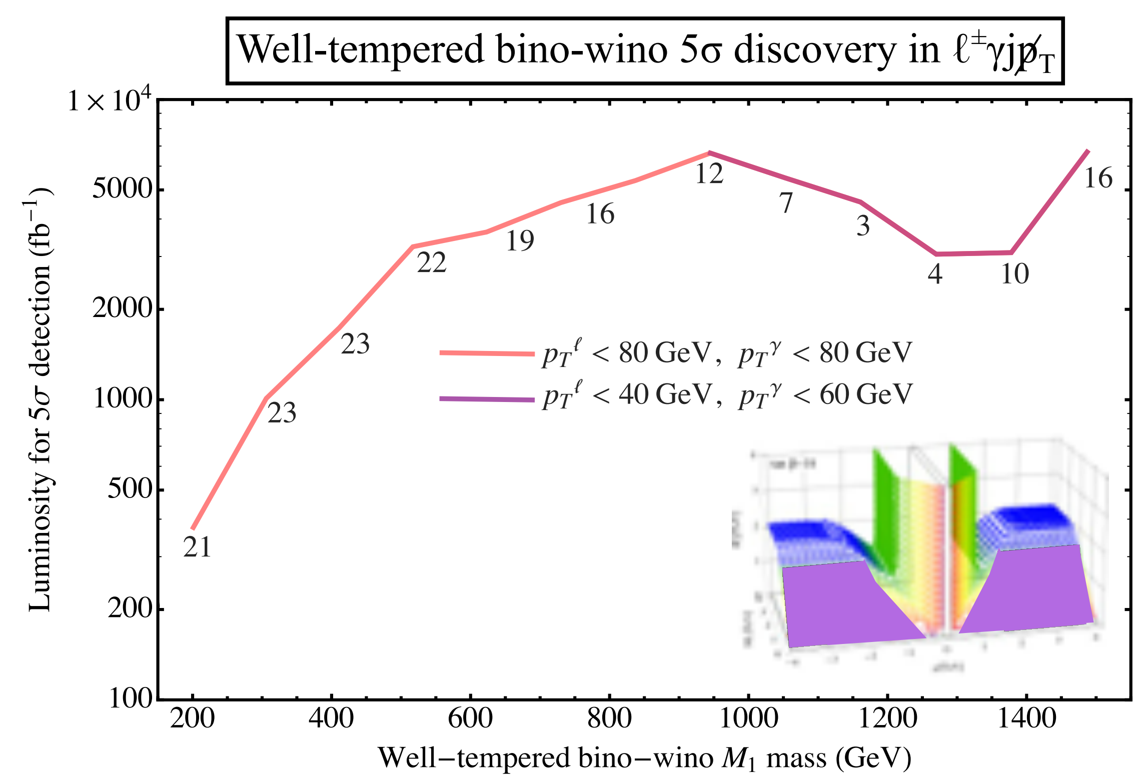


$\not{E}_T > 1.5$ TeV, only one jet with $p_{T,j} > 1$ TeV,

$5 < p_{T,\ell} < 80$ GeV, $5 < p_{T,\gamma} < 80$ GeV

with 7 ab^{-1} upto 1.5 TeV discovered

10% syst. err for signal, 2% for BG with $10\mathrm{ab}^{-1}$



Analysis detail : soft di-leptons

$$1.)\, pp \to \chi_1^\pm \chi_1^\mp + j \to \ell^+ \ell'^- \nu\bar{\nu}\chi_1^0\chi_1^0 + j$$
$$2.)\, pp \to \chi_2^0 \chi_1^0 + j \to \ell^+ \ell^- \chi_1^0 + j$$
$$3.)\, pp \to \chi_1^\pm \chi_2^0 + j \to \ell^+ \ell^- jj\chi_1^0\chi_1^0 + j,\, \ell^+\ell^-\ell'^\pm \nu\chi_1^0\chi_1^0 + j,$$

BG: $t\bar{t},\, W^+W^-j, \tau^+\tau^-j$

$\not{E}_T > 500$ GeV

exactly 1 hard jet: $p_{T,j} > 100$ GeV(veto second jet > 100 GeV)

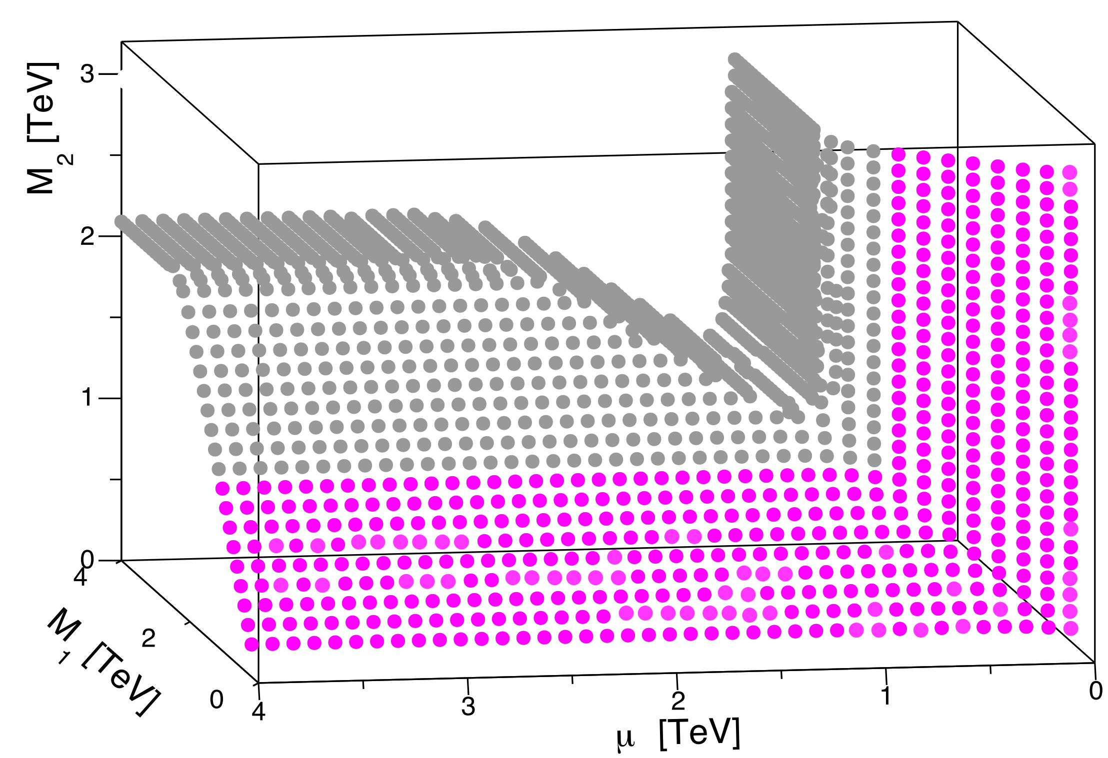
2 isolated ℓ: 10 GeV $< p_{T,\ell} <$ 50 GeV

$m_{\ell\ell} < m_{\ell\ell}^{\max}$

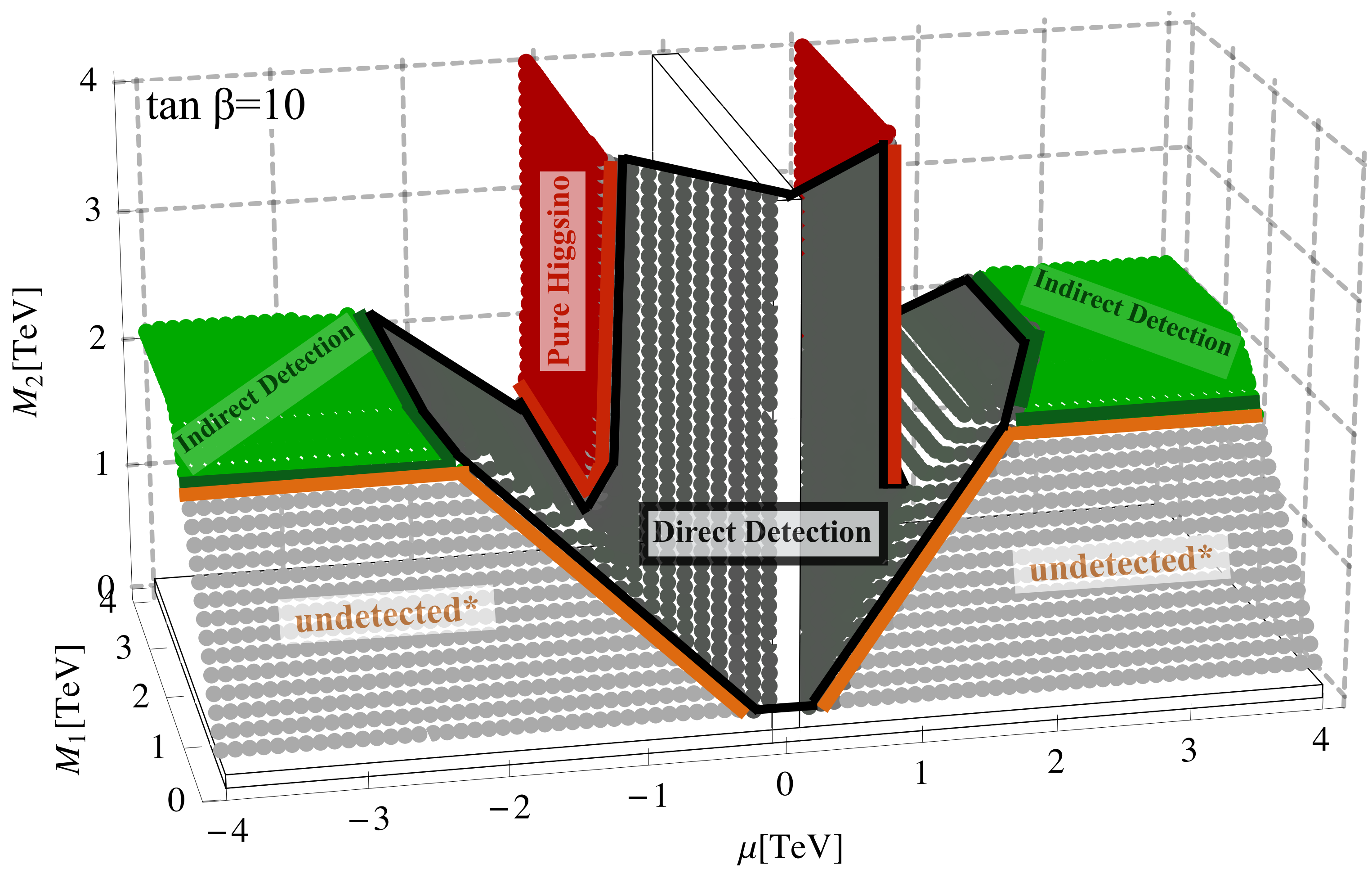
$m_{\ell\ell}^{\max}$ to optimize $S/\sqrt{B}$

$m_\chi \sim 900$ GeV would be discovered

Relic neutralino 5σ discovery with soft dileptons (3 ab^{-1})

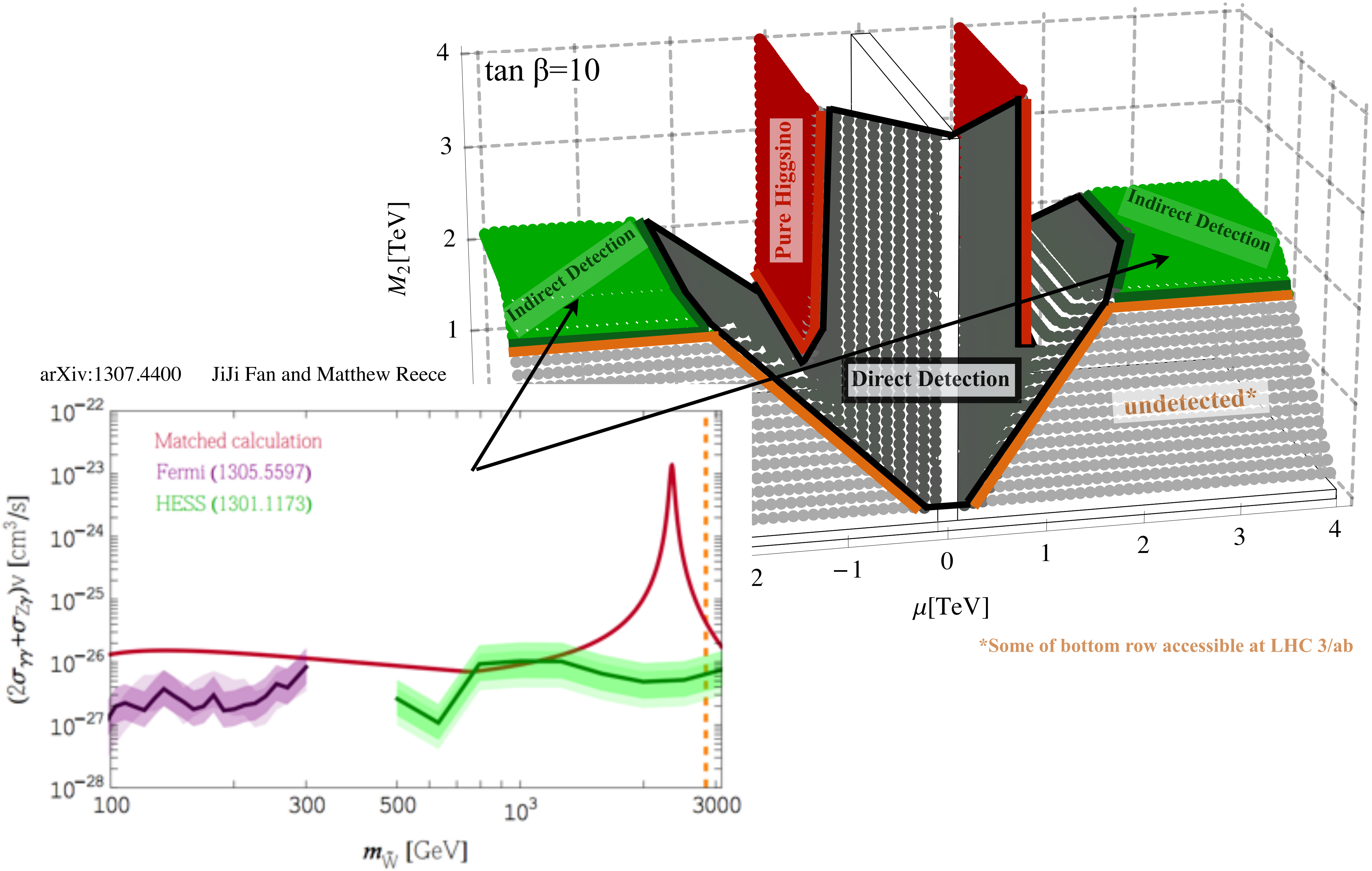


Summary

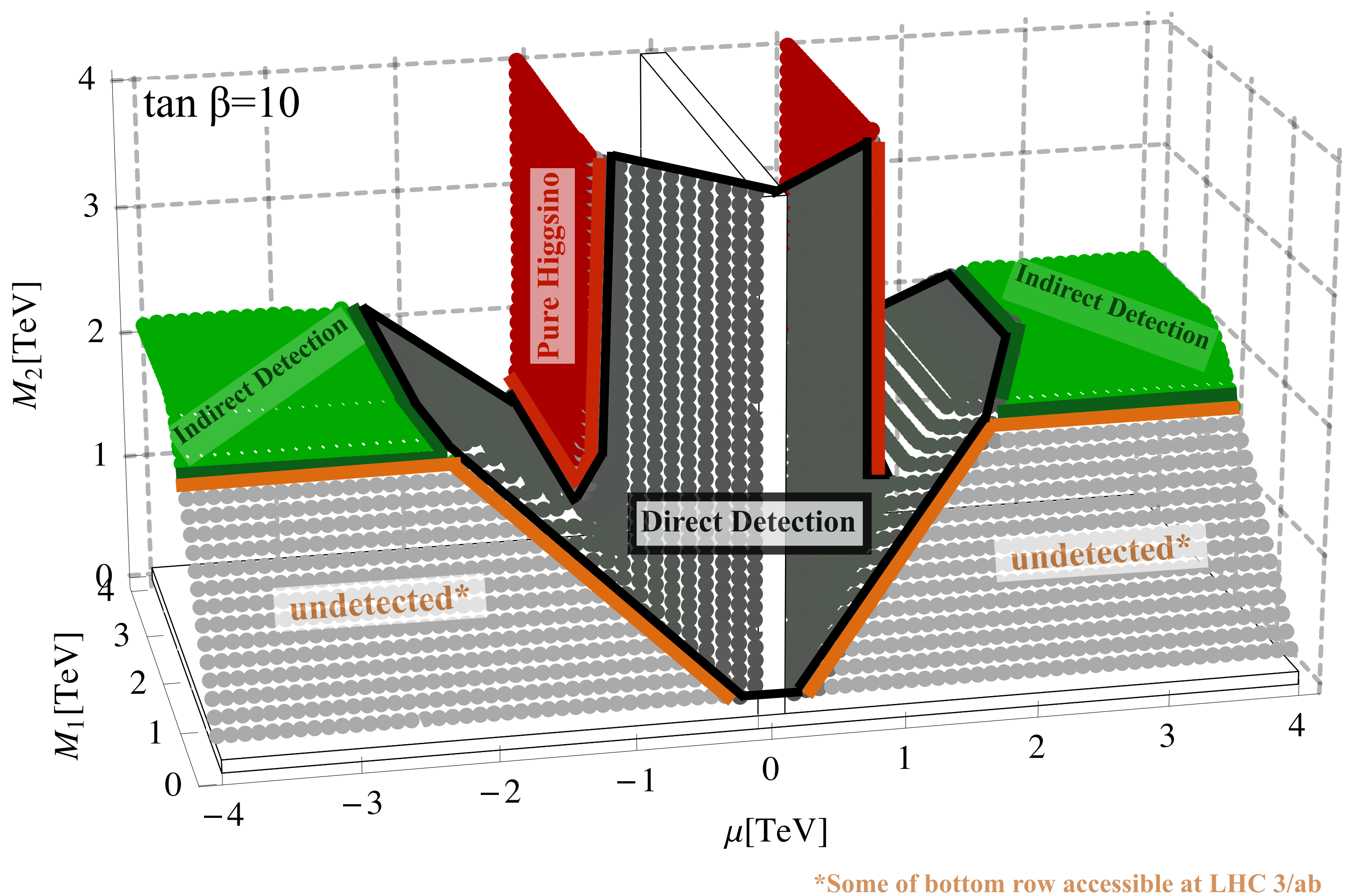


*Some of bottom row accessible at LHC 3/ab

Summary

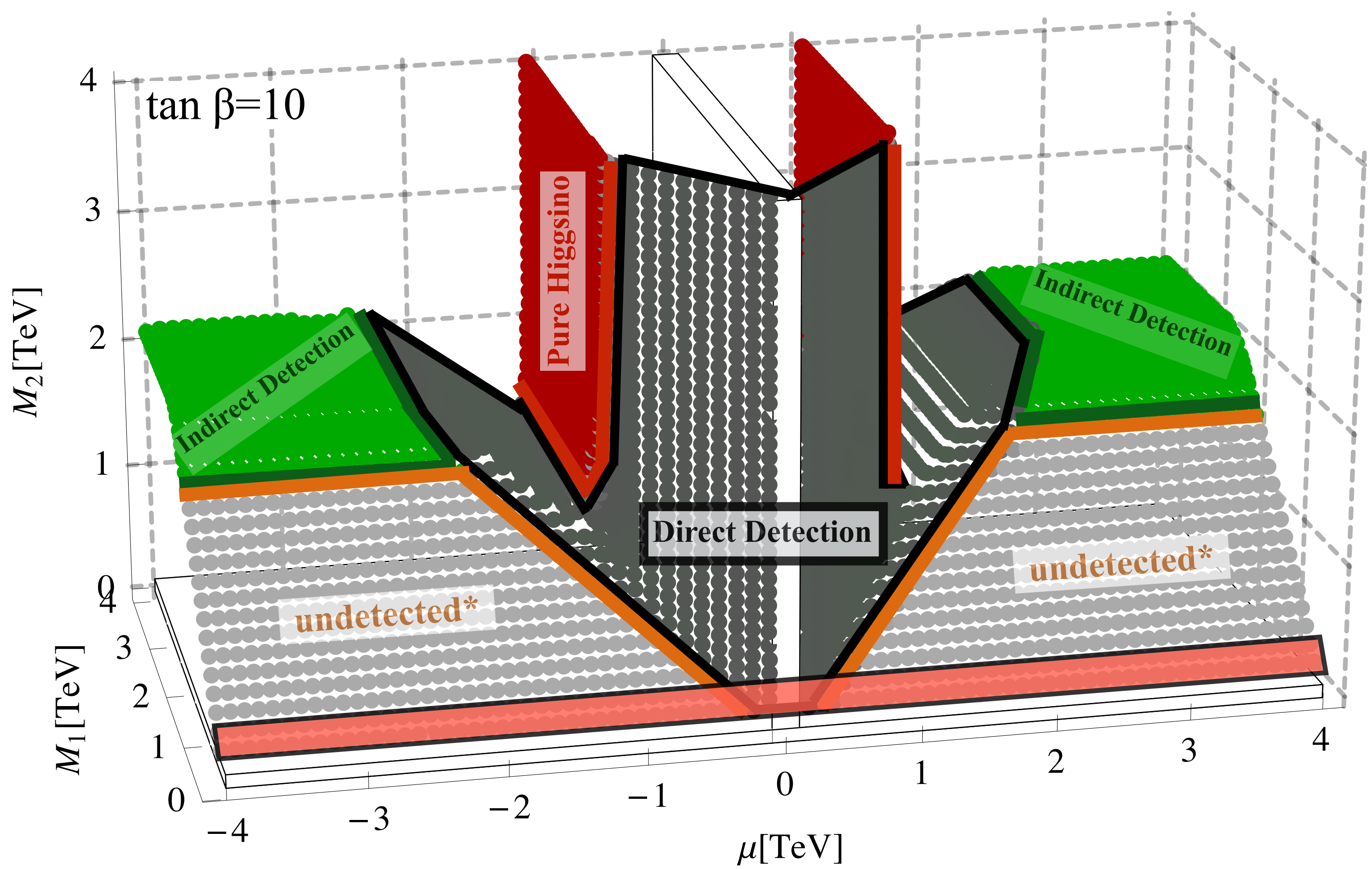

tan β=10
M_2[TeV]
μ[TeV]
Pure Higgsino
Indirect Detection
Indirect Detection
Direct Detection
undetected*
*Some of bottom row accessible at LHC 3/ab
arXiv:1307.4400 JiJi Fan and Matthew Reece
Matched calculation
Fermi (1305.5597)
HESS (1301.1173)
$(2\sigma_{\gamma\gamma}+\sigma_{Z\gamma})v$ [cm^3/s]
$m_{\tilde{W}}$ [GeV]

Summary



tan β=10
Pure Higgsino
Indirect Detection
Indirect Detection
Direct Detection
undetected*
undetected*
M_2[TeV]
M_1[TeV]
μ[TeV]
*Some of bottom row accessible at LHC 3/ab

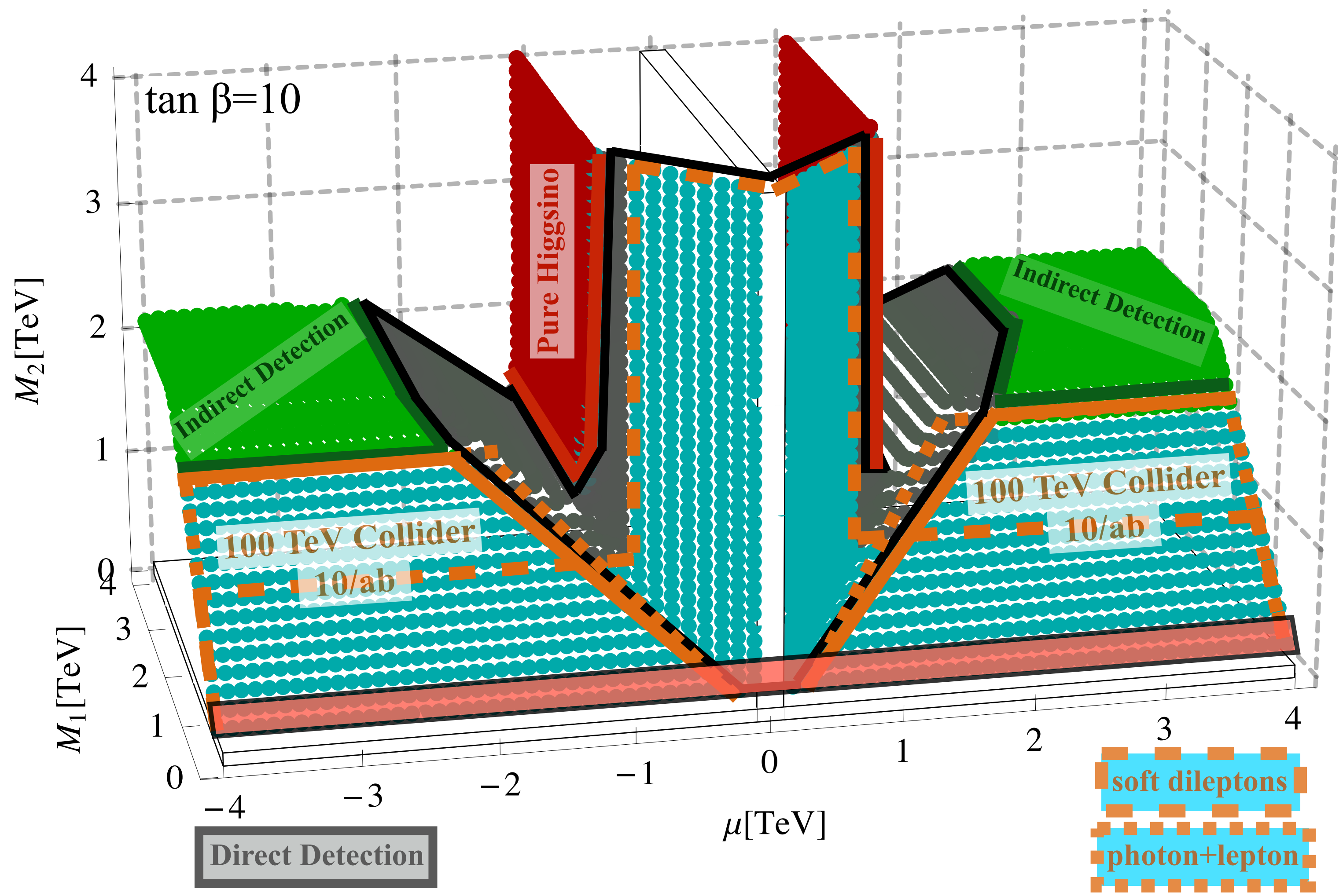
Summary



*Some of bottom row accessible at LHC 3/ab

350 GeV $\sim$ 400 GeV at 14 TeV with 3ab^{-1}

Summary



100 TeV collider covers the relic neutralino surface (other than pure Higgsino)