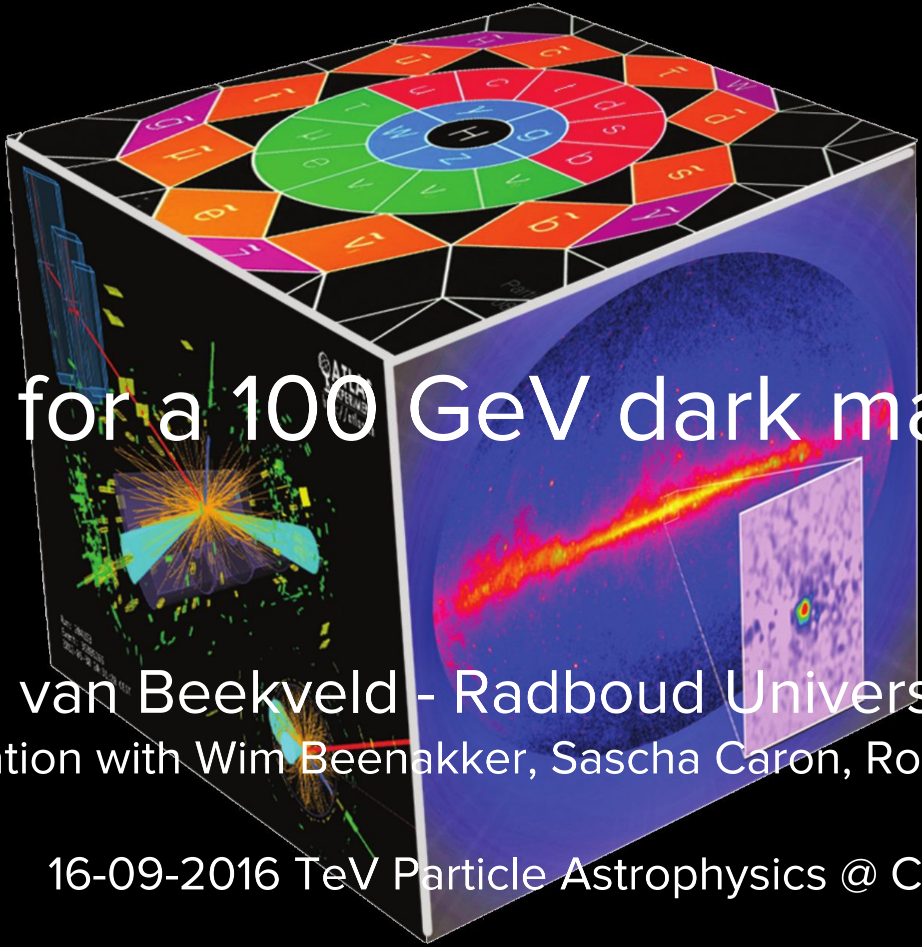

# The case for a 100 GeV dark matter particle


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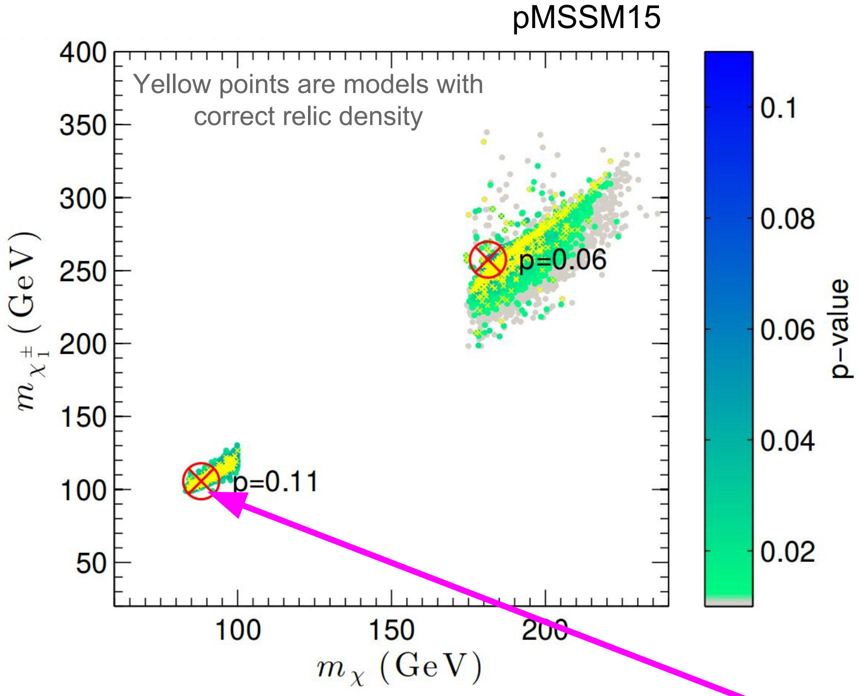
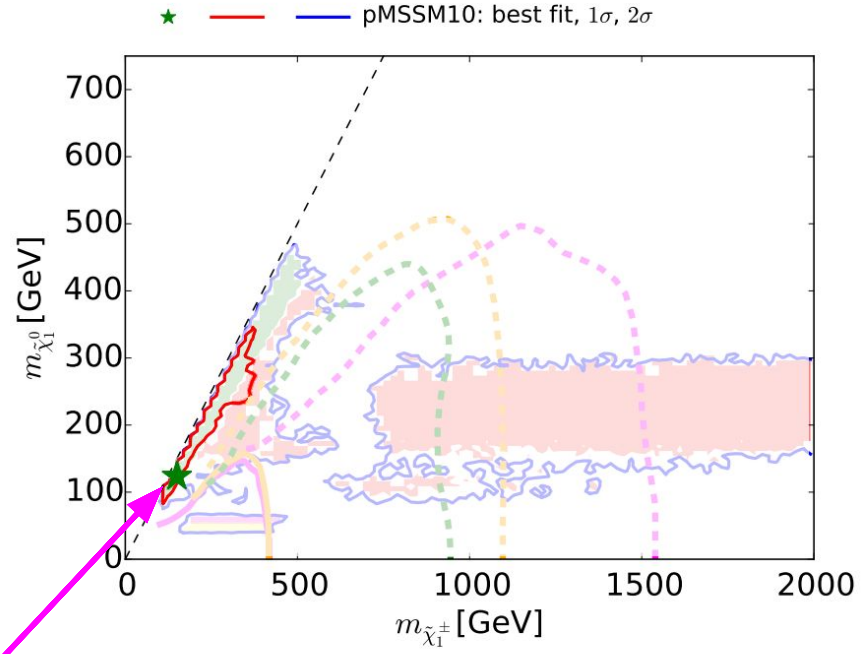
In collaboration with Wim Beenakker, Sascha Caron, Roberto Ruiz de Austri


16-09-2016 TeV Particle Astrophysics @ CERN


[mcbeekveld@gmail.com]

# Motivation: Where to find SUSY and DM?




**Best fit**

(1507.07008 - CheckMATE)

(1508.01173 - MasterCode)

Are we sensitive to these models using mono-X + MET searches?

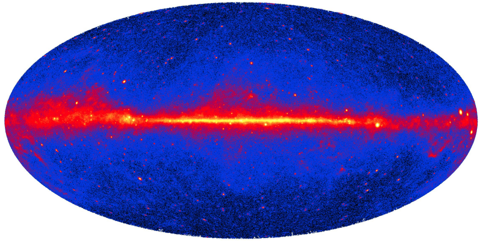
# Are we sensitive to these models using ~~mono-X + MET~~ any SUSY search?

Spoiler: the answer to both questions is NO

# Outline

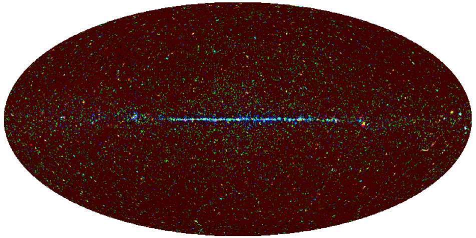
- Galactic Center photon excess and its pMSSM interpretation
- Third hint of the ~100 GeV dark matter particle
- Why are we not sensitive right now?
- Can we get sensitive?

# Galactic center photon excess



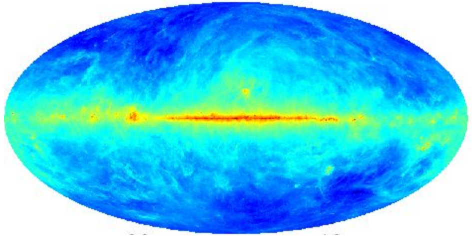
total γ-ray emission

=



point sources

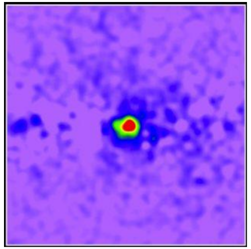
+



background

Photons with energy 0.1-300 GeV

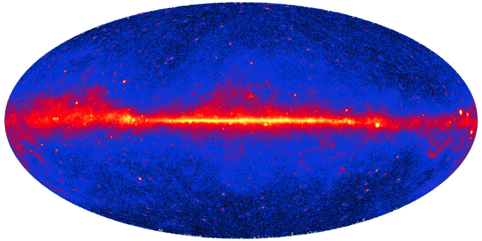
+



???

[see for extensive background analysis 1511.02938]

# Galactic center photon excess



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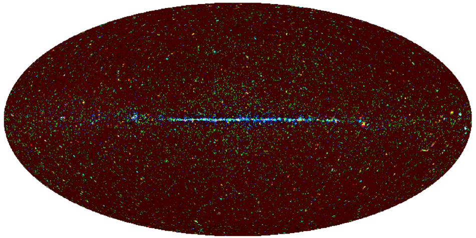

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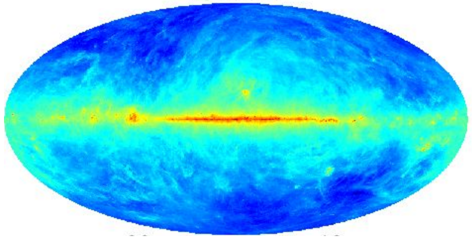
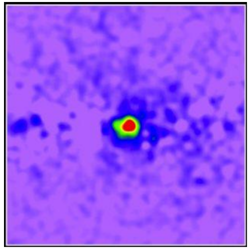


total γ-ray emission

point sources

background

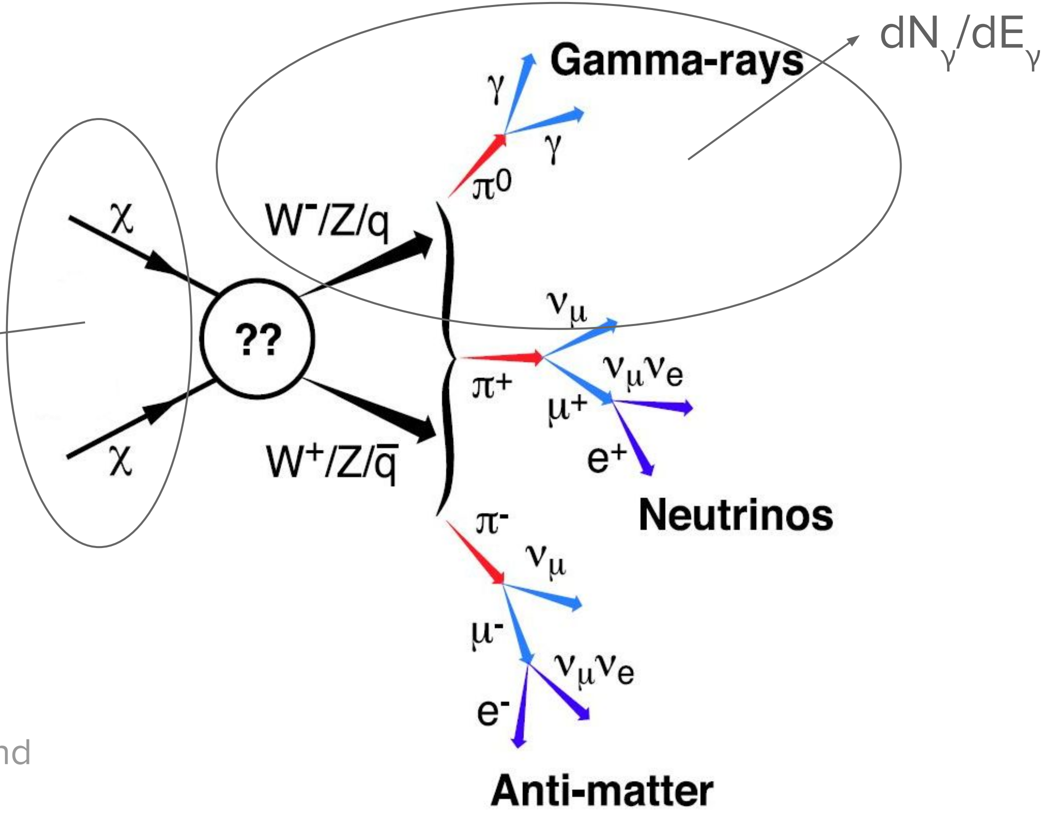
+



Pulsars? => see e.g. 1104.0010, 1412.6099 and 1506.05124

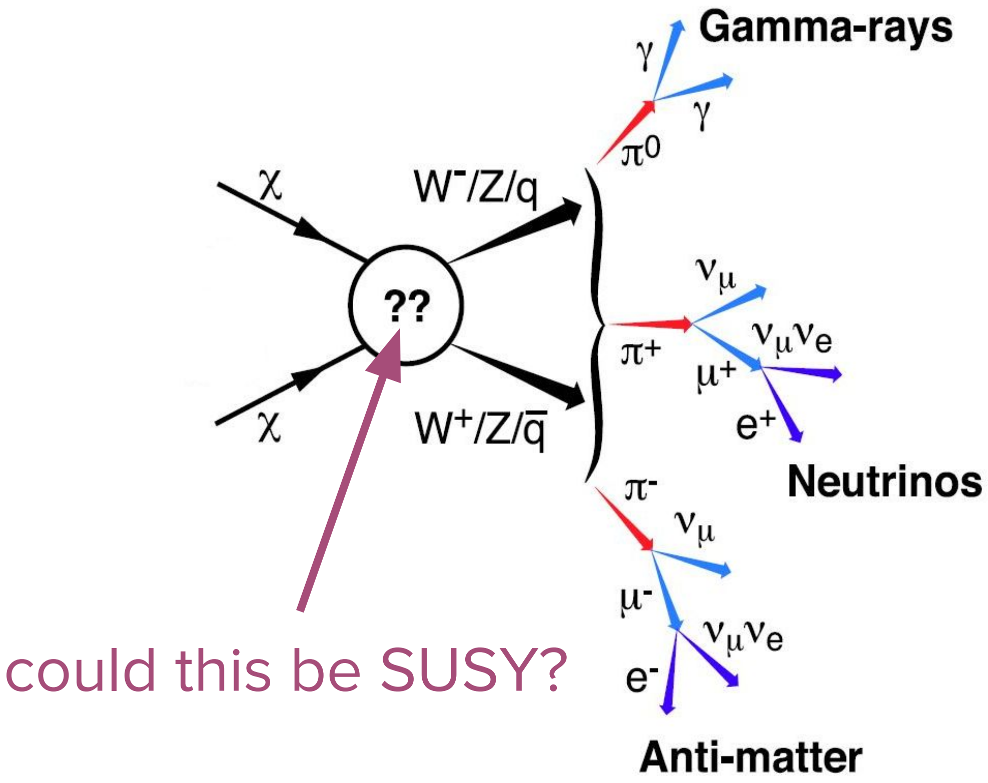
# Or… Dark Matter annihilation?

J-factor
(DM density)




$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma}$$

[1010.2752, 1501.03507, 1505.06055, 1507.05536 and many more…]



Gamma-rays
γ
γ
π0
χ
W-/Z/q
??
χ
W+/Z/q̄
νμ
π+
νμνe
μ+
e+
Neutrinos
π-
νμ
μ-
νμνe
e-
Anti-matter
could this be SUSY?

# pMSSM (phenomenological Minimal Supersymmetric Model)

| Names | Spin | $P_R$ | Gauge Eigenstates | Mass Eigenstates |
|---|---|---|---|---|
| Higgs bosons | 0 | +1 | $H_u^0\ H_d^0\ H_u^+\ H_d^-$ | $h^0\ H^0\ A^0\ H^\pm$ |
| squarks | 0 | −1 | $\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ | (same) |
| | | | $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ | (same) |
| | | | $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$ | $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$ |
| sleptons | 0 | −1 | $\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ | (same) |
| | | | $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ | (same) |
| | | | $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$ | $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$ |
| neutralinos | 1/2 | −1 | $\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$ | $\widetilde{\chi}_1^0\ \widetilde{\chi}_2^0\ \widetilde{\chi}_3^0\ \widetilde{\chi}_4^0$ |
| charginos | 1/2 | −1 | $\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$ | $\widetilde{\chi}_1^\pm\ \widetilde{\chi}_2^\pm$ |
| gluino | 1/2 | −1 | $\widetilde{g}$ | (same) |

# Remove irrelevant d.o.f.

125 GeV Higgs boson

| Names | Spin | $P_R$ | Gauge Eigenstates | Mass Eigenstates |
|---|---|---|---|---|
| Higgs bosons | 0 | $+1$ | $H_u^0 \; H_d^0 \; H_u^+ \; H_d^-$ | $h^0 \; H^0 \; A^0 \; H^\pm$ |
| | | | | 4 TeV |
| | | | $\tilde{t}_L \; \tilde{t}_R \; \tilde{b}_L \; \tilde{b}_R$ | $\tilde{t}_1 \; \tilde{t}_2 \; \tilde{b}_1 \; \tilde{b}_2$ |
| | | | | 4 TeV |
| neutralinos | $1/2$ | $-1$ | $\widetilde{B}^0 \; \widetilde{W}^0 \; \widetilde{H}_u^0 \; \widetilde{H}_d^0$ | $\tilde{\chi}_1^0 \; \tilde{\chi}_2^0 \; \tilde{\chi}_3^0 \; \tilde{\chi}_4^0$ |
| charginos | $1/2$ | $-1$ | $\widetilde{W}^\pm \; \widetilde{H}_u^+ \; \widetilde{H}_d^-$ | $\tilde{\chi}_1^\pm \; \tilde{\chi}_2^\pm$ |
| | | | | 4 TeV |

LSP ⇒ DM!

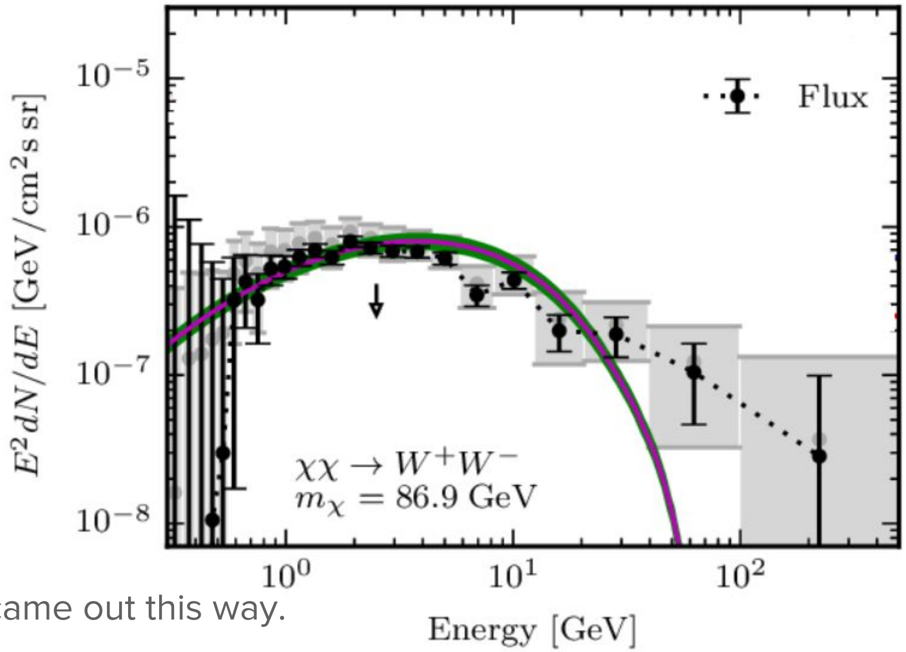
# Solution to GC excess

**bino LSP → $W^+W^-$, wino NLSP**

**( where $M_{LSP}$ ~ 90 GeV, $M_{NLSP}$ ~ 110 GeV)**

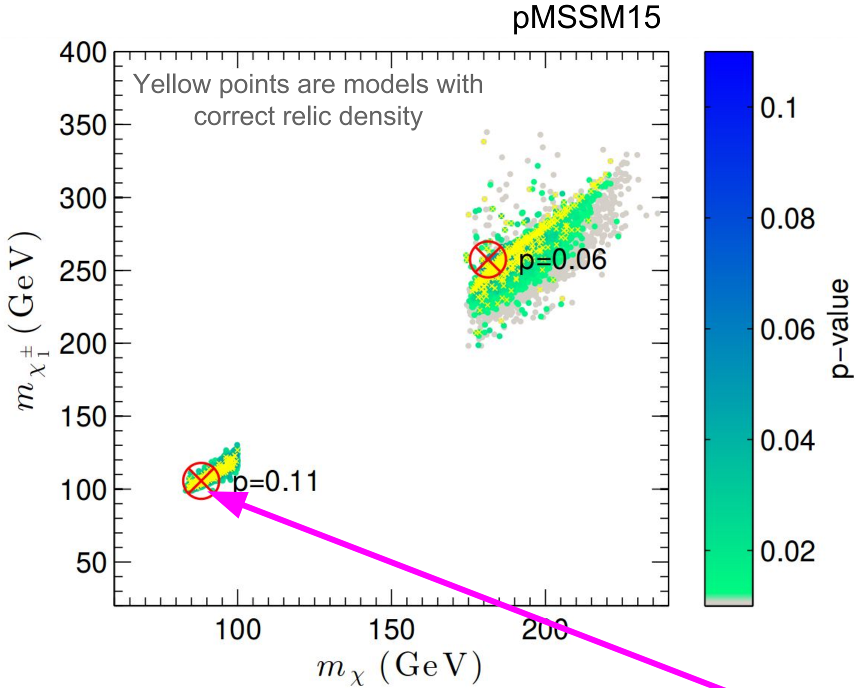
Compatible with all constraints e.g.:

- Dwarf galaxies
- Icecube (2015)
- LUX (2016)
- LEP/LHC bounds on SUSY/Higgs
- DM relic density
  - This was not put in as a constraint! Just came out this way.

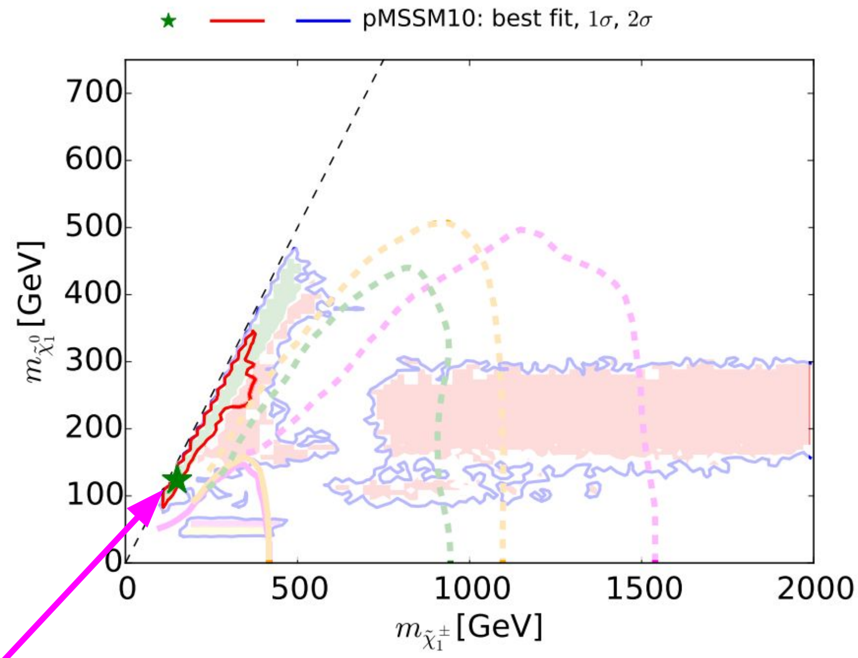



See 1502.05703 for details

# But these solutions are also consistent with the global fits!




(1507.07008 - CheckMATE)



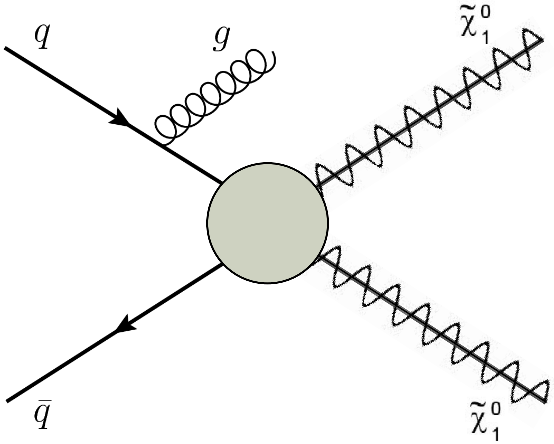

**Best fit**

(1508.01173 - MasterCode)

(We have $M_{LSP}$ ~ 90 GeV and $M_{NLSP}$ ~ 110 GeV)

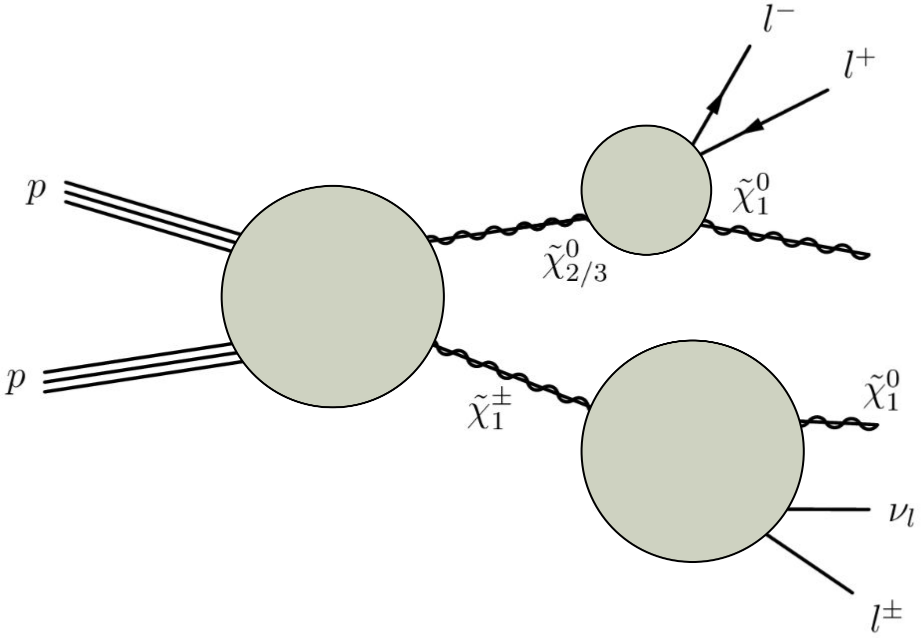
# LHC searches - mono-jet (or mono-photon)?

Suppressed: 0.01 - 0.001 pb **production** cross section



# EW SUSY searches?

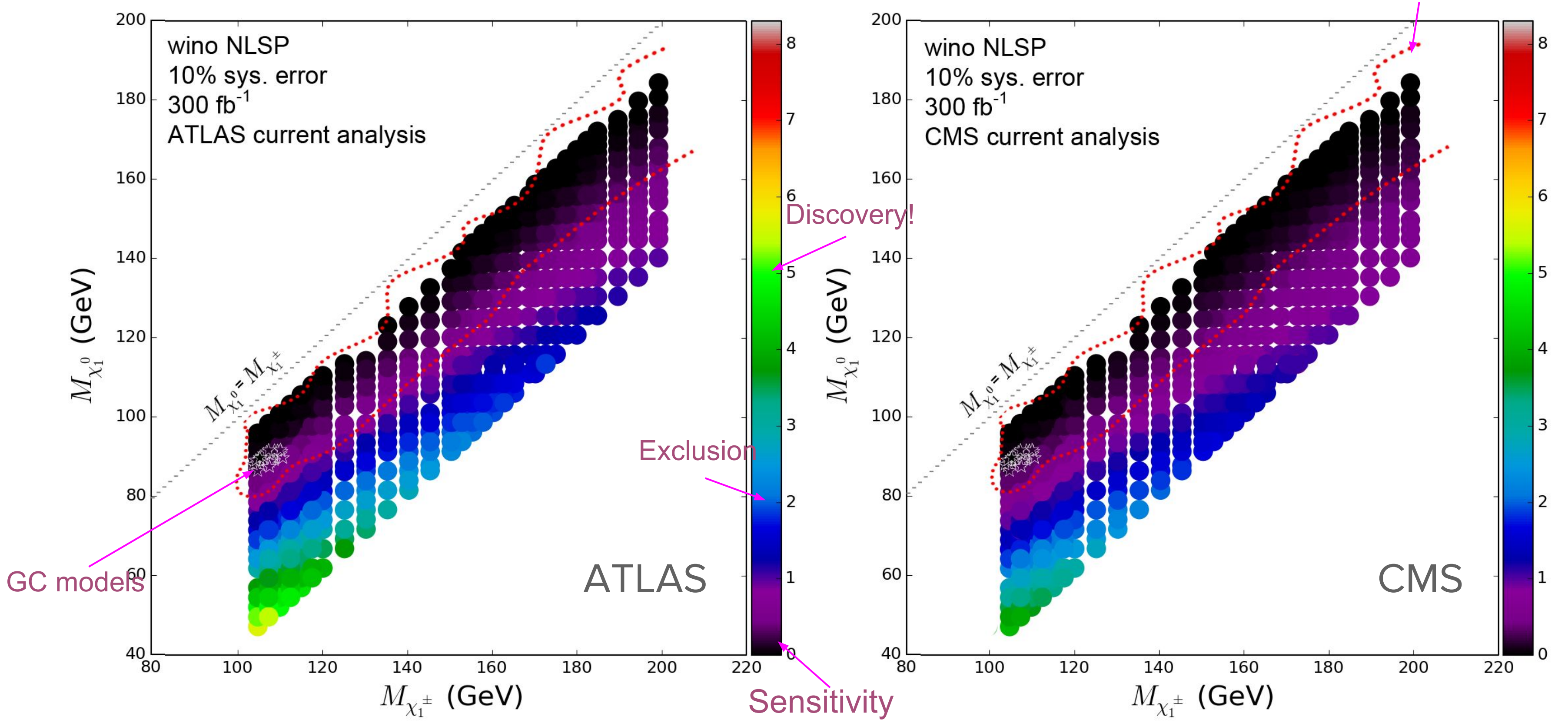
## Tri-lepton final state!




- Events are generated with Madgraph and Pythia (13 TeV)
- FastJet to cluster jets, anti-kt alg. with R = 0.4 and PT = 20 GeV
- Delphes for fast detector simulation (using CMS or ATLAS cards)
- No k-factors

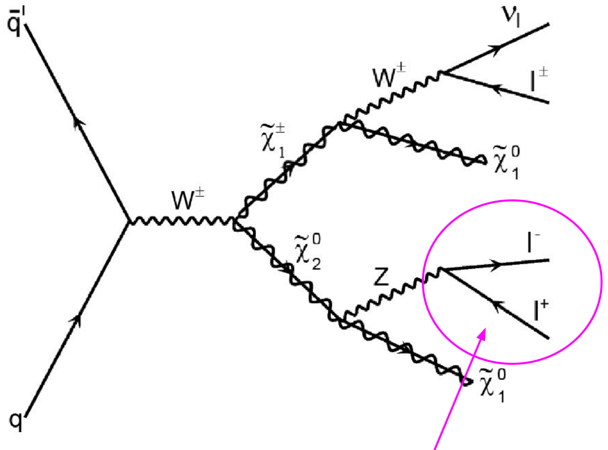
# Limits - ATLAS and CMS reach

within dotted red line = favored by global fits

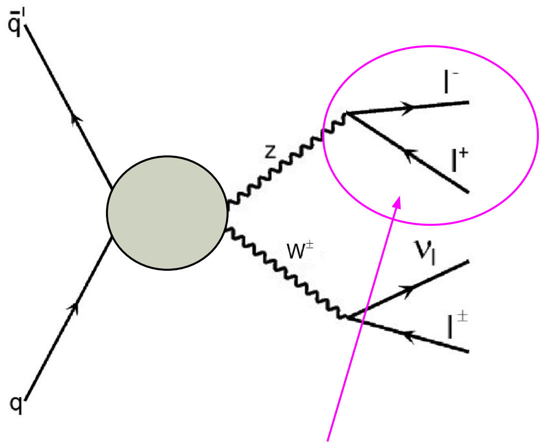


# How can we do better?

# 1. Make use of the small mass gap

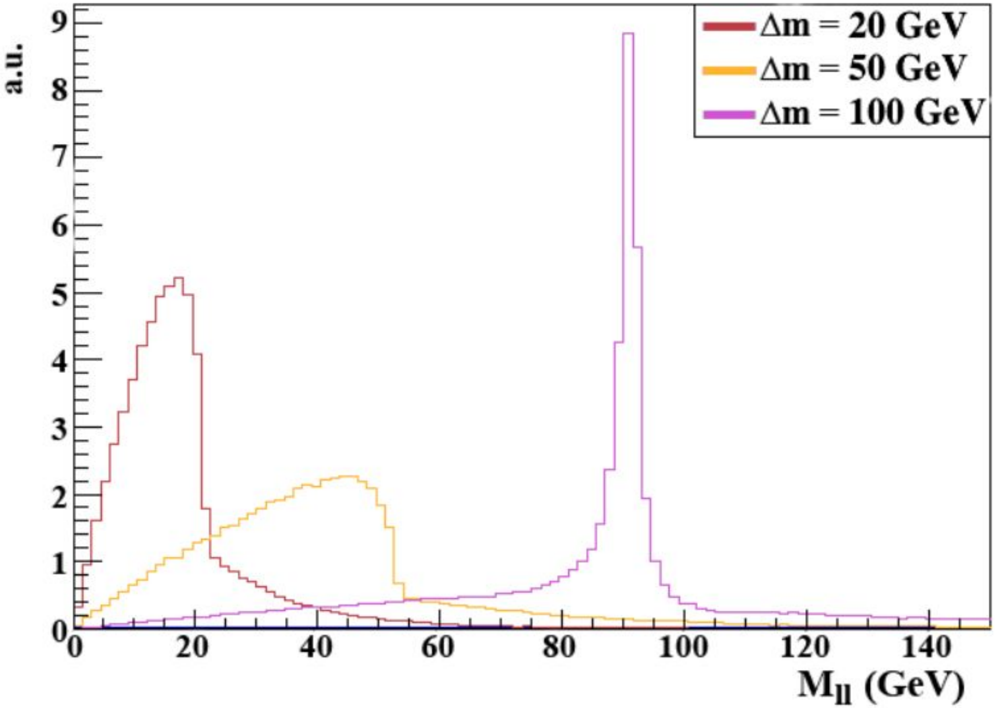



$m_{l+l-} \simeq \Delta m << m_Z$



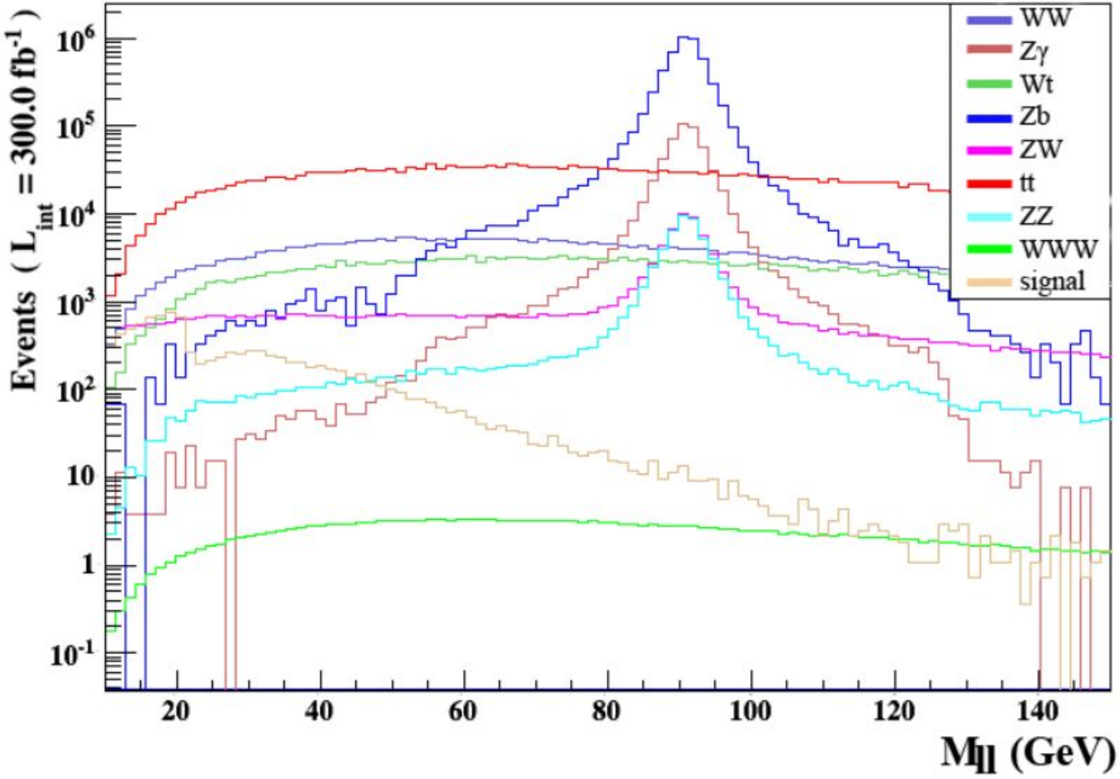

$m_{l+l-} \simeq m_Z$

# Higher mass gaps



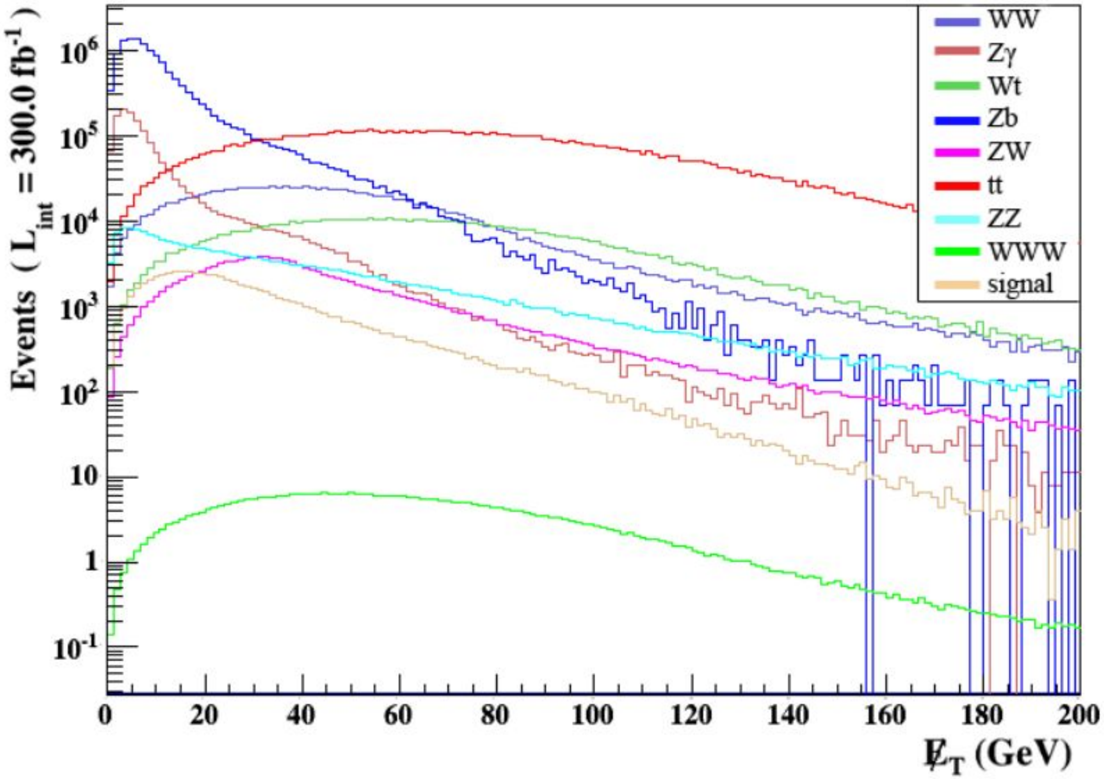

If you increase the mass gap, the invariant mass of the lepton pair gets higher. If the mass gap is large enough to produce an on-shell Z boson, you will see a resonance.

# Use the signal topology!



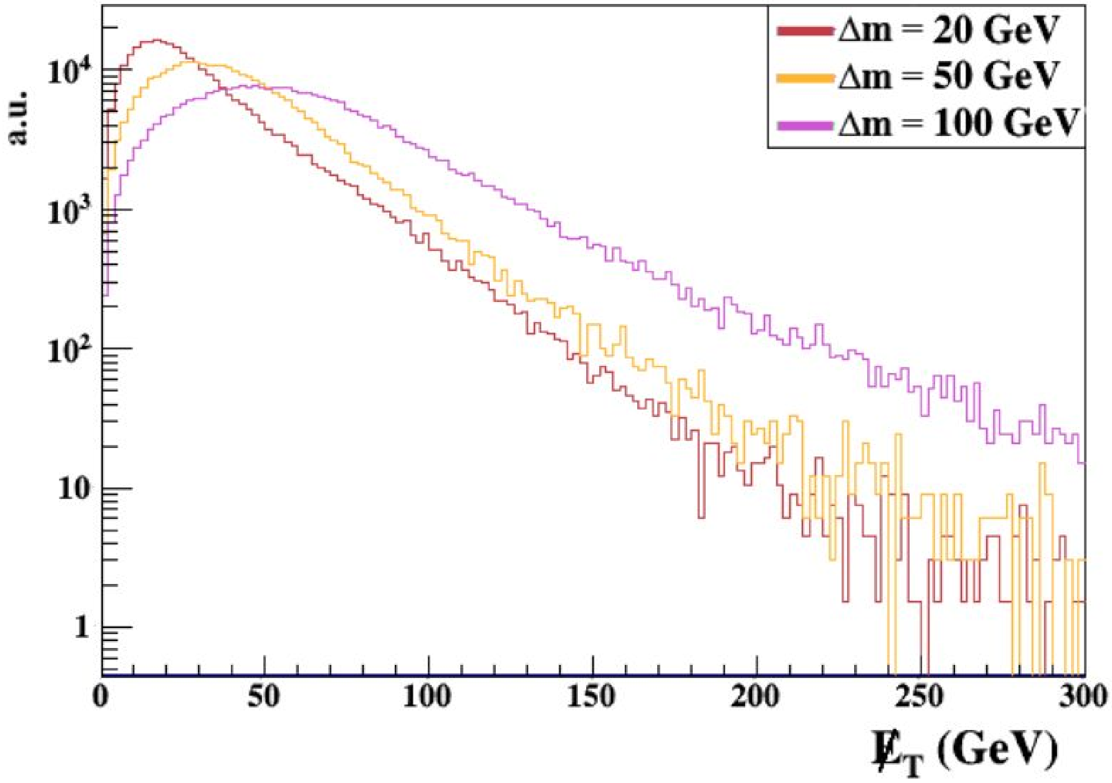

The resonance appears in half of the SM backgrounds.

# 2. Surprisingly... Low MET requirement



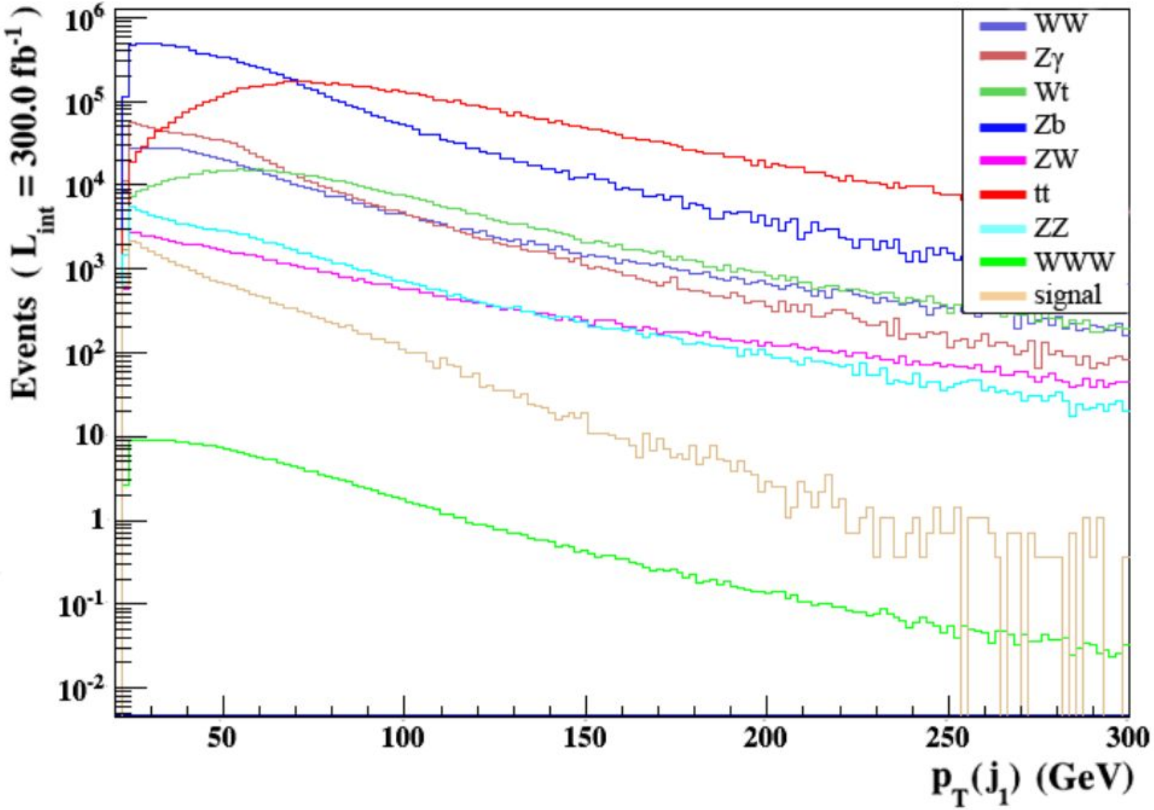

It is unwise to make a large MET requirement, as the neutralinos are often produced in a back-to-back configuration due to the small mass gap.

# Higher mass gaps



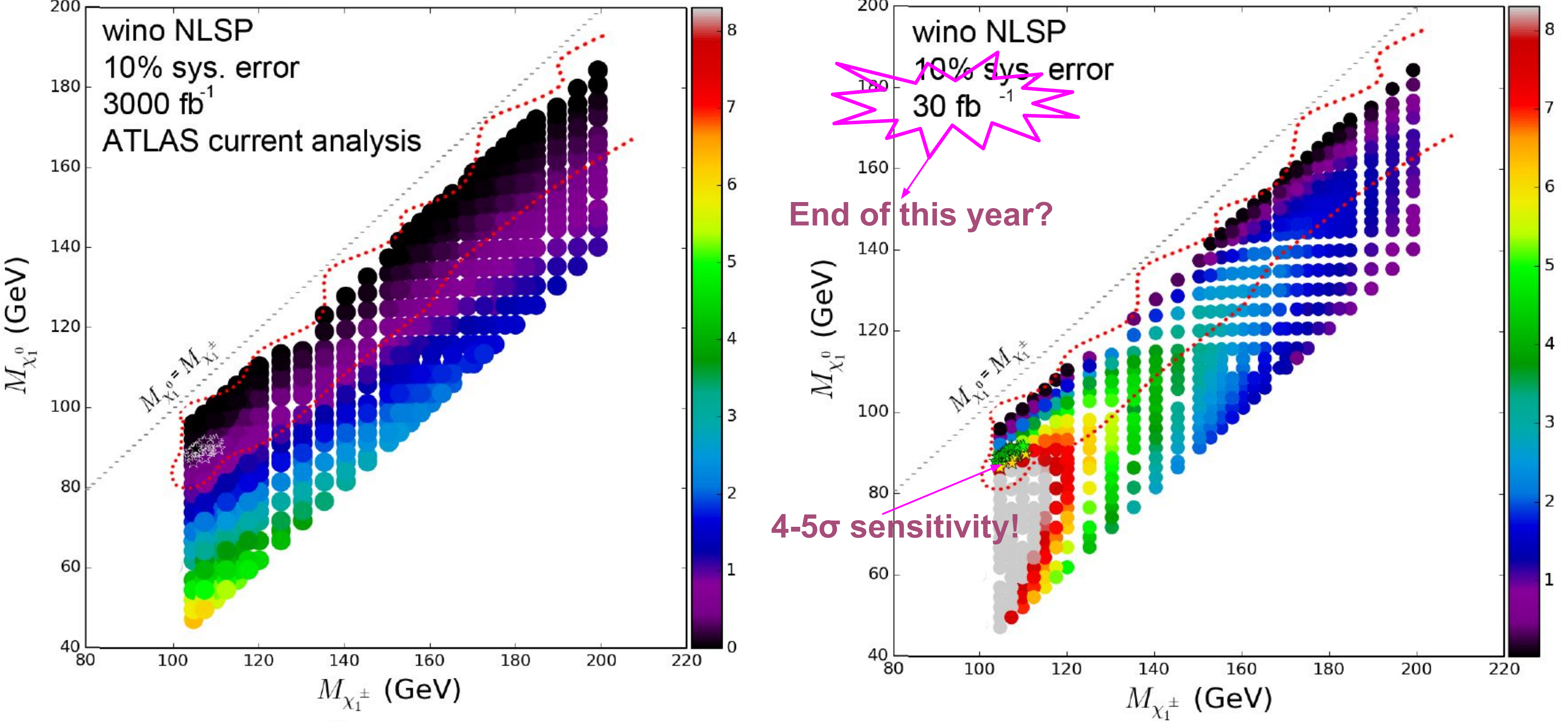

If you increase the mass gap, the MET gets larger as well

# 3. Veto on high $p_T$ jets



Details in 1602.00590

# Using the updated analysis...



# Conclusions

- GC photon excess pMSSM solutions consistent with global fits
- Resulting in models with ~100 GeV bino-like DM particle
- ATLAS/CMS not sensitive to these regions of pMSSM
- Regions can be probed easily if we update the search strategy!

# Extra slides

# Could this be DM annihilation?

annihilation cross section

$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma} = \frac{\langle\sigma v\rangle}{2} \frac{1}{4\pi m_{\mathrm{DM}}^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \underbrace{\int \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(l)\mathrm{d}l}_{\text{J-factor (DM density)}}$$

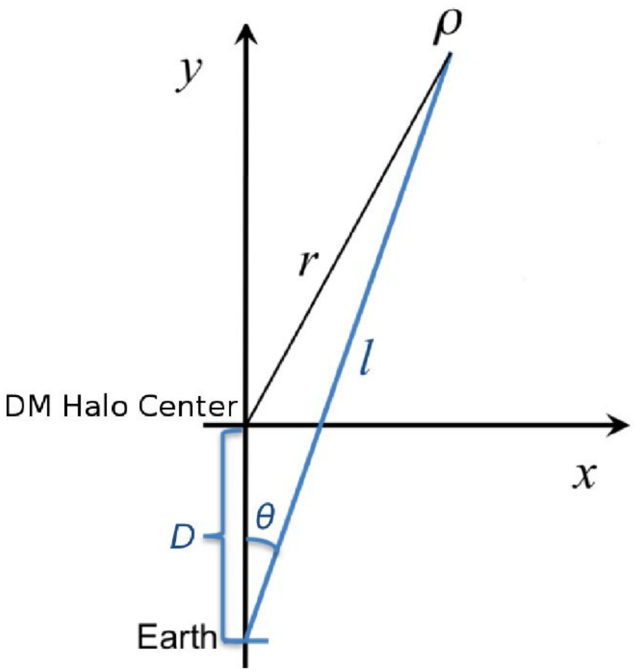
Photon spectrum per annihilation product

# DM annihilation

$$\Gamma_{\text{ann}} \propto \frac{1}{2}\langle\sigma v\rangle n_{\text{DM}}^2(r) = \langle\sigma v\rangle \frac{\rho_{\text{DM}}^2(r)}{2m_{\text{DM}}^2}$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}\Omega} \propto \int_{\text{l.o.s.}} \Gamma_{\text{ann}}(l)\mathrm{d}l = \frac{\langle\sigma v\rangle}{2m_{\text{DM}}^2}\int_{\text{l.o.s.}} \rho_{\text{DM}}^2(l)\mathrm{d}l$$

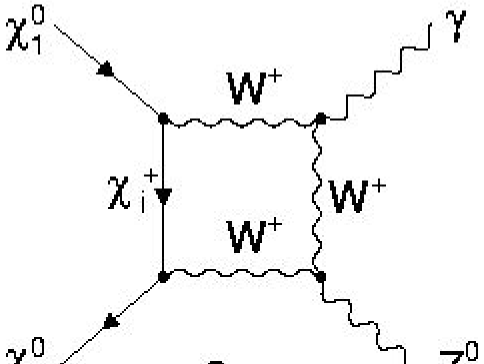
$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma} = \frac{\langle\sigma v\rangle}{2}\frac{1}{4\pi m_{\text{DM}}^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\int \mathrm{d}\Omega \int_{\text{l.o.s.}} \rho_{\text{DM}}^2(l)\mathrm{d}l$$



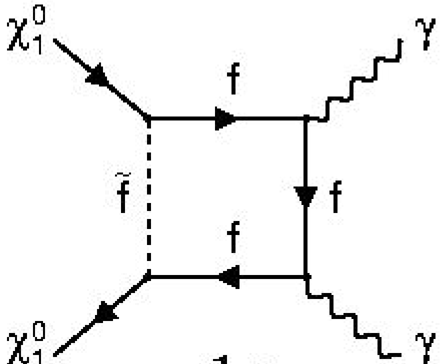
# Photon-lines

Neutralinos annihilate to γ and Z final states

- Distinctive spectral line features
- However! Depends on resolution telescope!

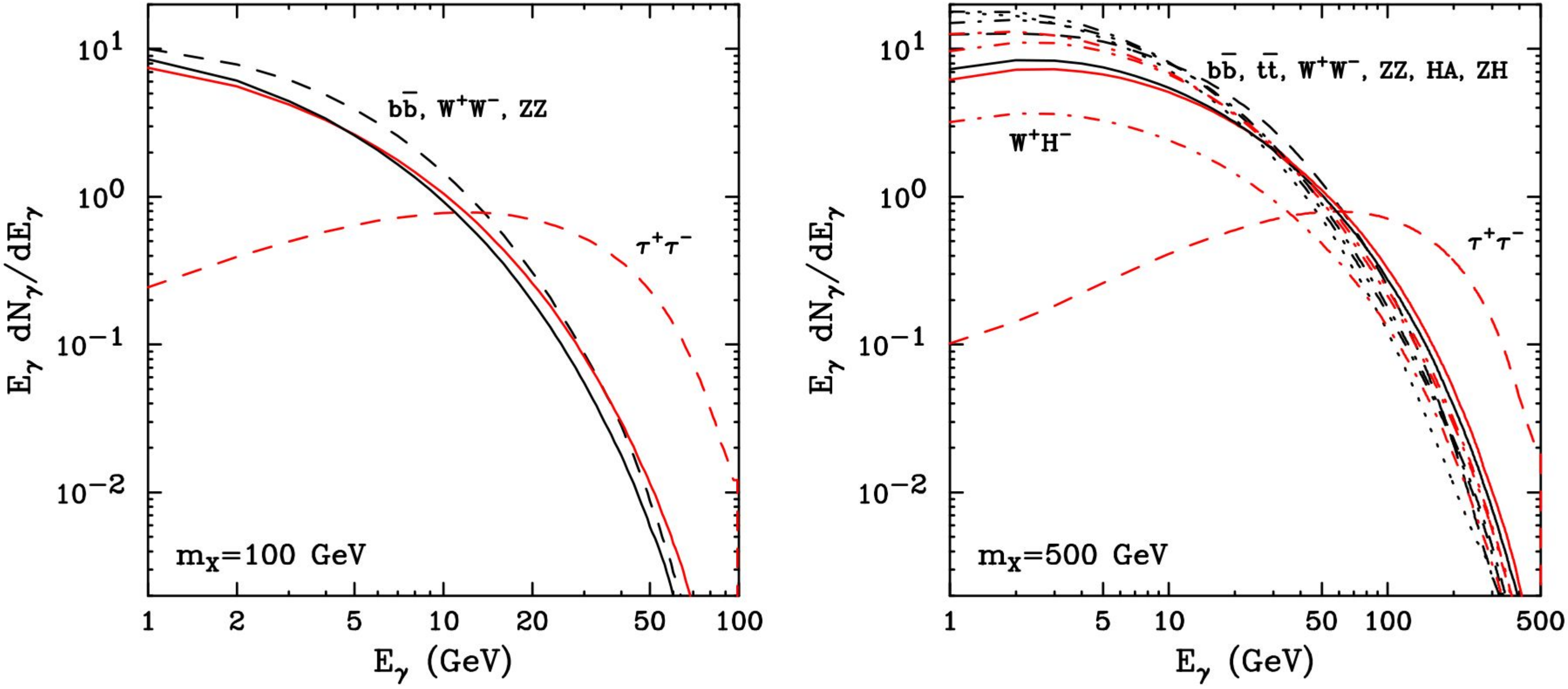



**3 a**




**1 a**

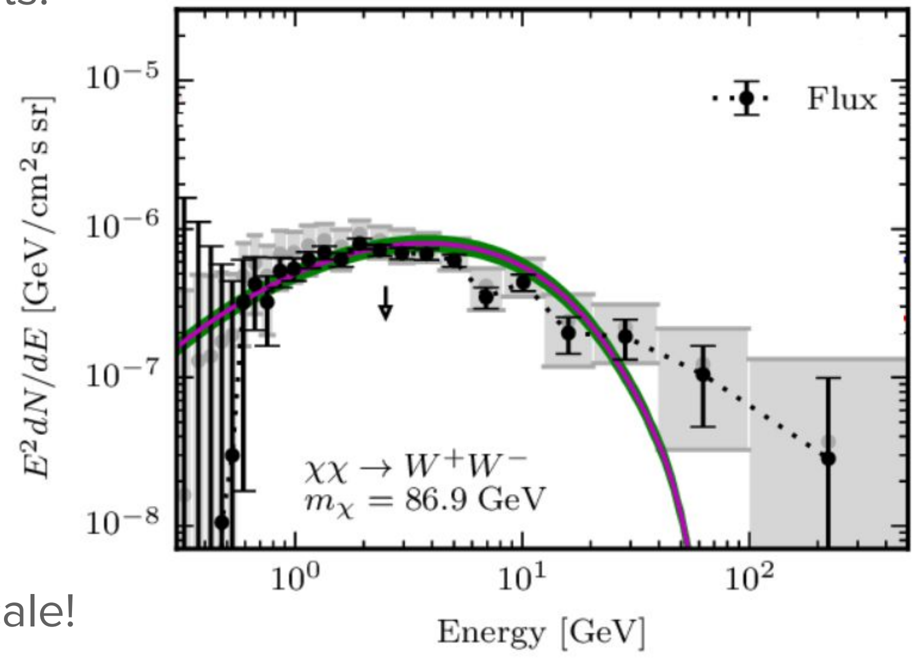
# Spectrum per annihilation



# Solutions GC excess

3 solutions, compatible with all constraints:

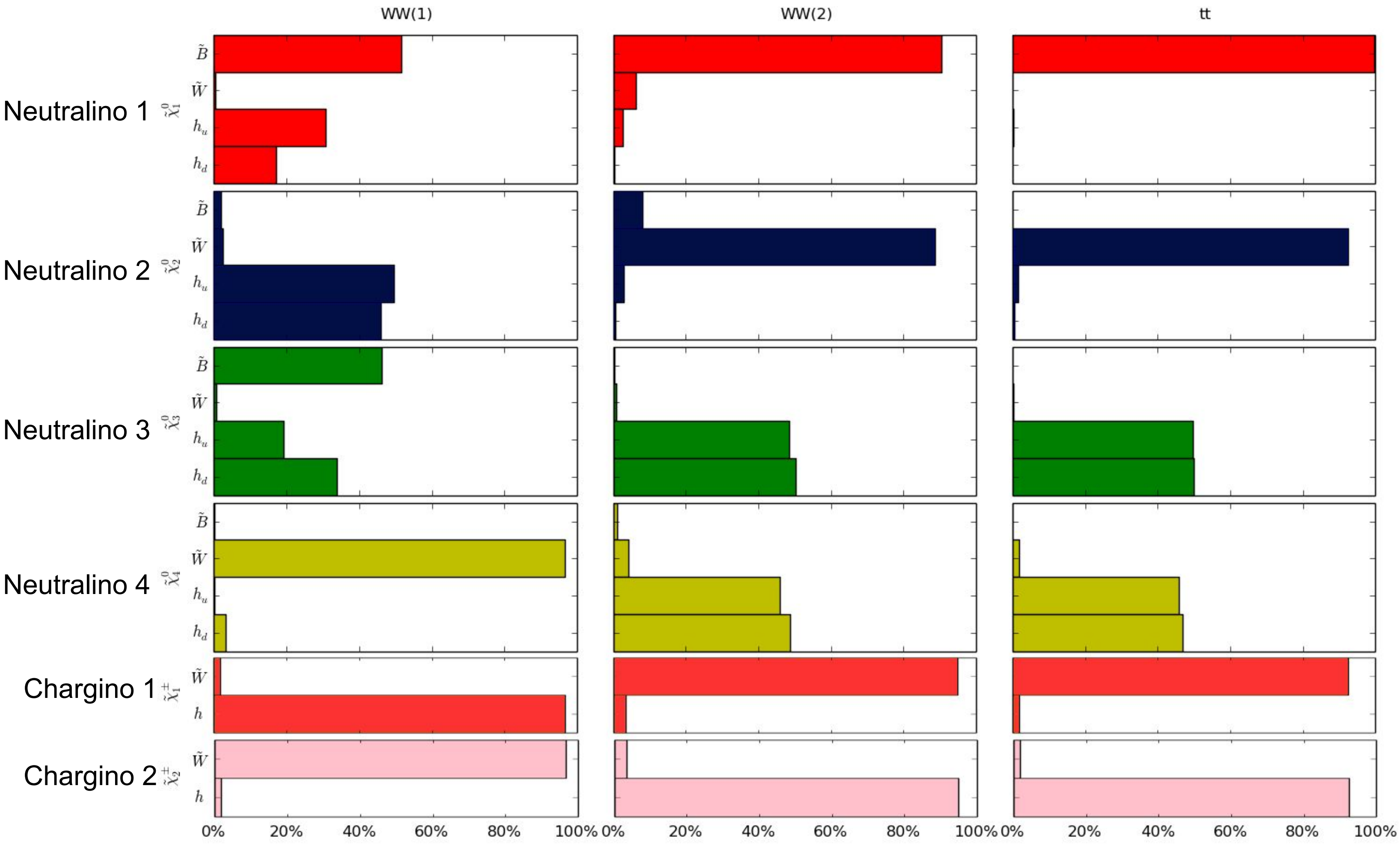
- bino LSP → $W^+W^-$, higgsino NLSP
  - $M_{LSP}$ ~ 90 GeV, $M_{NLSP}$ ~ 110 GeV
- bino LSP → $W^+W^-$, wino NLSP (best)
  - $M_{LSP}$ ~ 90 GeV, $M_{NLSP}$ ~ 110 GeV
- bino LSP → $t\bar{t}$, wino NLSP
  - $M_{LSP}$ ~ 180 GeV, $M_{NLSP}$ ~ 400 GeV




All sfermion masses are at (multi-)TeV scale!

See 1502.05703 for details

# Model characteristics



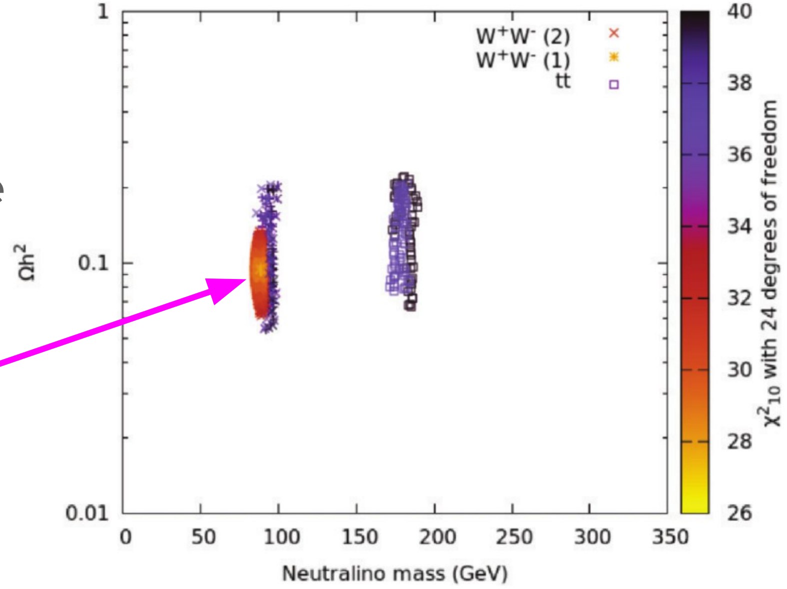
# Dark matter relic density

Plank: $\Omega h^2 = 0.118$

Our GC models consistent with this value

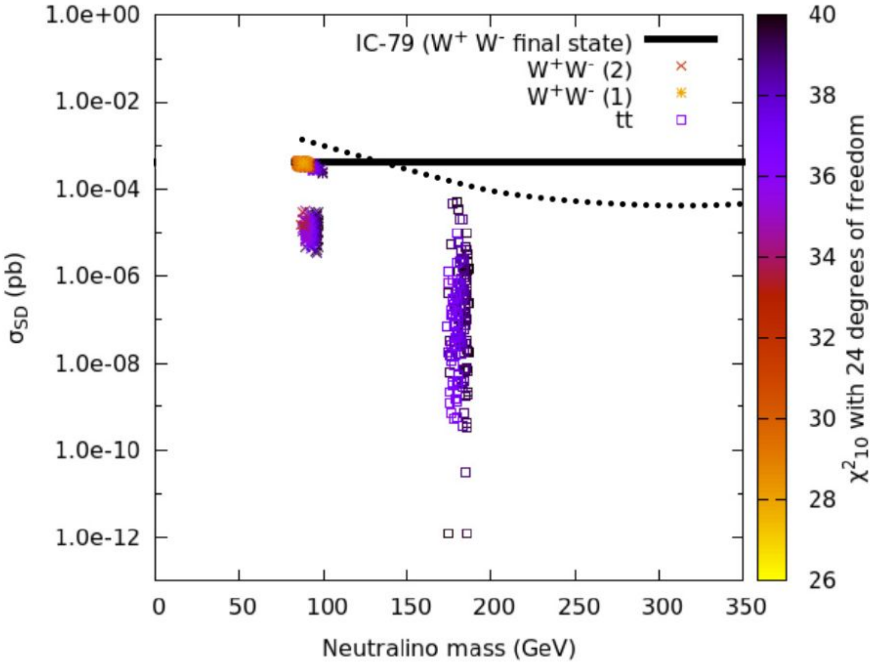
*This was not put in as a constraint,*

*It just came out this way!*

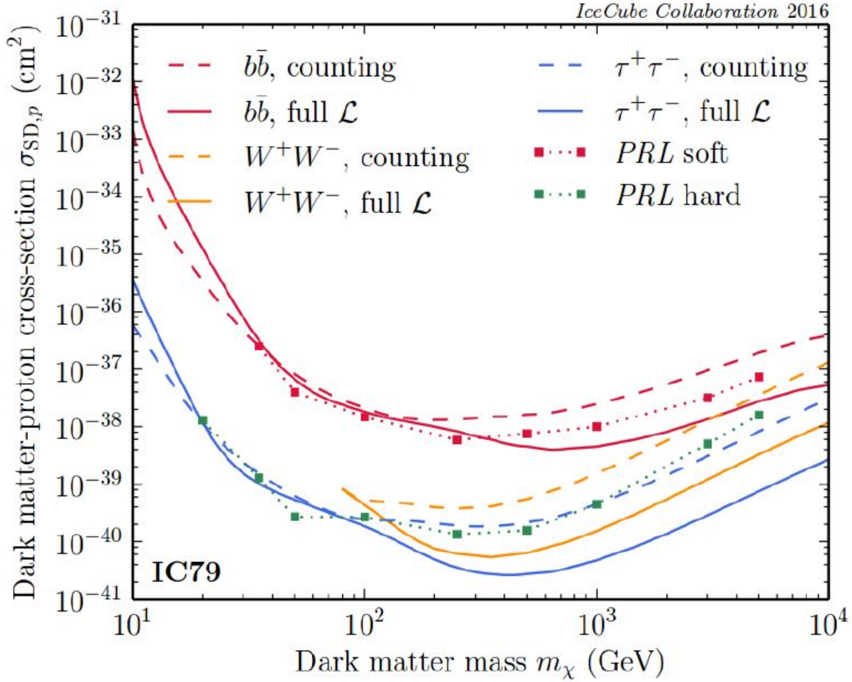



(1502.05703)

# Icecube



IC-79 (W+ W- final state)
W+W- (2)
W+W- (1)
tt
1.0e+00
1.0e-02
1.0e-04
1.0e-06
1.0e-08
1.0e-10
1.0e-12
σSD (pb)
0 50 100 150 200 250 300 350
Neutralino mass (GeV)
40 38 36 34 32 30 28 26
χ2 10 with 24 degrees of freedom

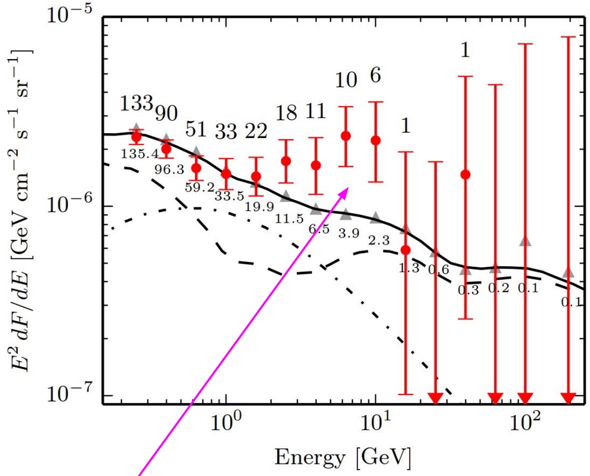
IceCube Collaboration 2016
bb̄, counting
bb̄, full L
W+W−, counting
W+W−, full L
τ+τ−, counting
τ+τ−, full L
PRL soft
PRL hard
IC79
Dark matter-proton cross-section σSD,p (cm2)
Dark matter mass mχ (GeV)

# Where else to look? - more evidence!

$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma} \propto \ J\text{-factor} \longrightarrow$$

look for places with high DM density!

# Where else to look? - more evidence



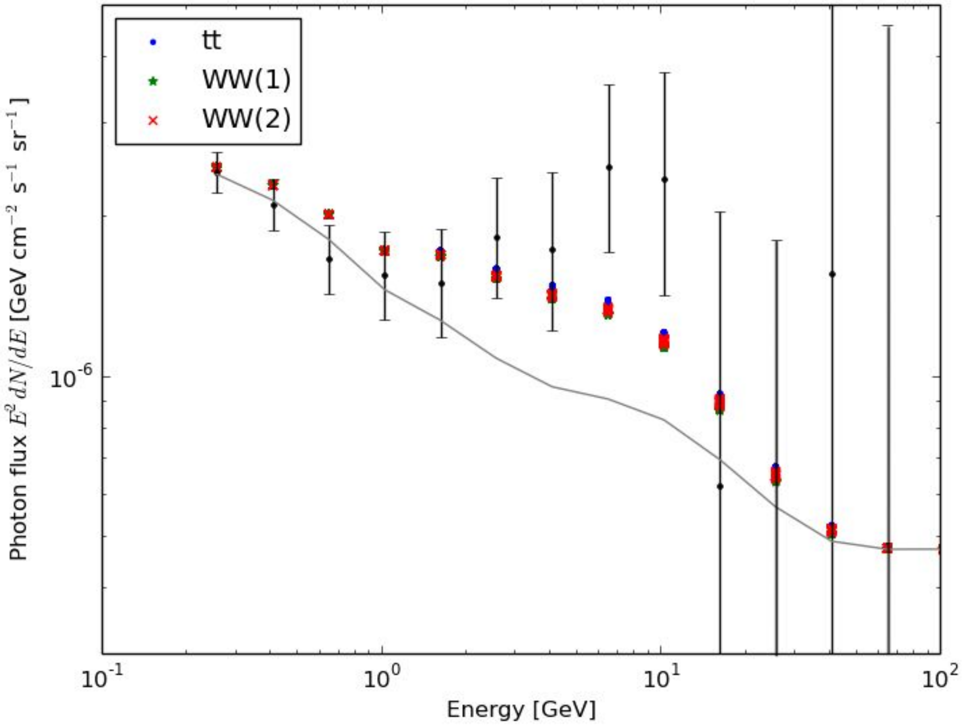

$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma} \propto J\text{-factor} \longrightarrow$$

Reticulum II

Small photon excess signal of ~2σ

(1503.02320)

# Reticulum II




GC models result in:

log(J) = 20.0-20.7 GeV$^2$ cm$^{-5}$ (1507.04644)

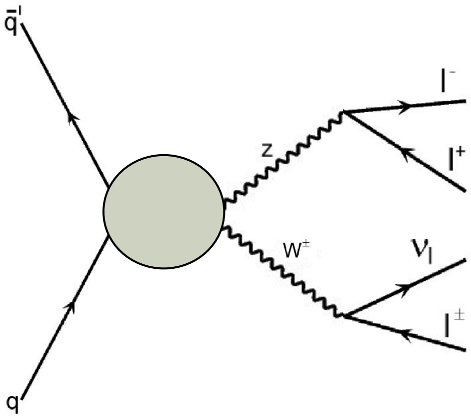
Consistent with:

log(J) = 19.0-20.7 GeV$^2$ cm$^{-5}$ (1506.08209)

New data (pass 8) ⇒ smaller `excess’

**Now doing full study with >20 dwarf galaxies!**

# How to distinguish from:




$pp \longrightarrow ZW \longrightarrow 3l + MET$ ?

or $pp \longrightarrow Zb, WW, ZZ, tt, Wt, Z\gamma, WWW$....

- Events are generated with Madgraph and Pythia (13 TeV)
- FastJet to cluster jets, anti-kt alg. with R = 0.4 and PT = 20 GeV
- Delphes for fast detector simulation (using CMS or ATLAS cards)
- No k-factors

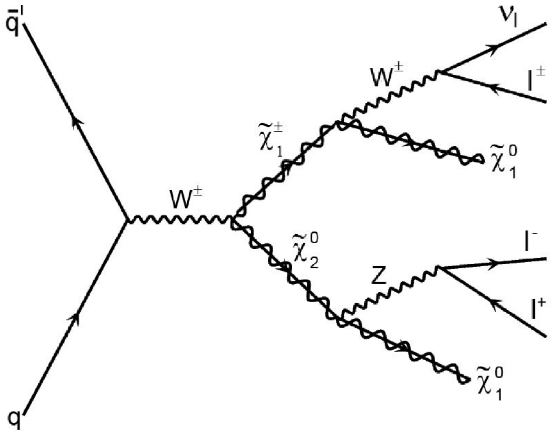
# Example dwarf galaxy included in full study: Tuc III

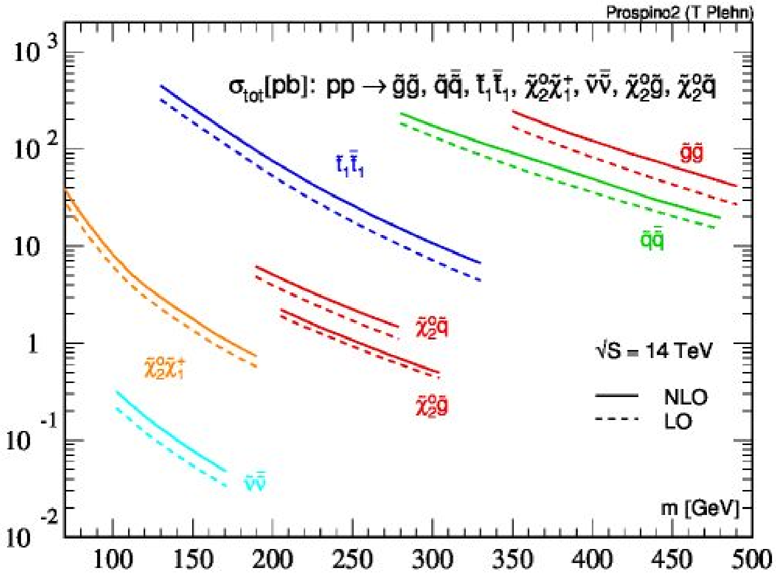
- TUC III excess photon flux with same characteristics (1511.09252)

tively a steady astrophysical source. Since the very weak signals in the directions of Reticulum 2 and Tuc III show some similarities (i.e., they may both resemble the Galactic GeV excess and are among the nearest dSphs galaxy candidates),

# LHC forecasts - WW solutions

Heavy sleptons, so dominant production is:

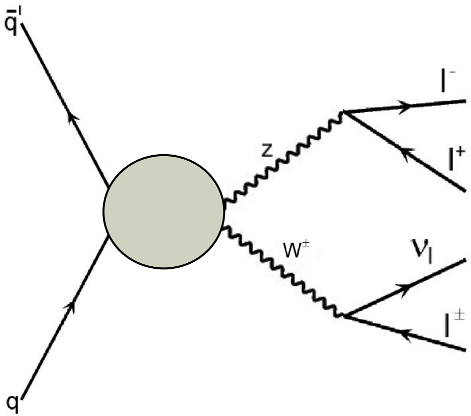


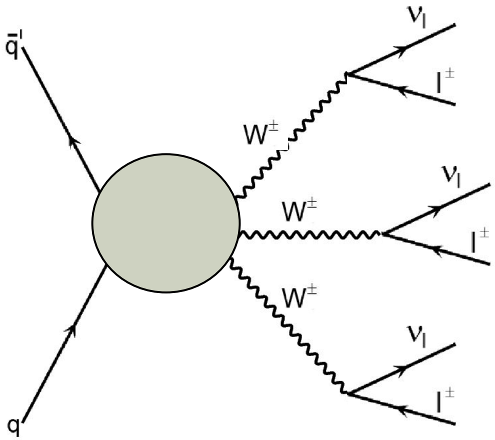
# Selection OSSF lepton pair

| Algorithm | $\Delta m = 20$ GeV | $\Delta m = 50$ GeV | $\Delta m = 100$ GeV | $WZ$ background |
|---|---|---|---|---|
| $\min_{i,j}\lvert M_{l_i,l_j} - M_Z\rvert$ | 0.622311 | 0.532023 | 0.042033 | 0.146657 |
| $\min_{i,j}\Delta R(l_i, l_j)$ | 0.343527 | 0.402548 | 0.470781 | 0.347207 |
| $\max_{i,j}(P_T(l_i), P_T(l_j))$ | 0.461444 | 0.486157 | 0.493636 | 0.388699 |
| $\min_{i,j}M_{l_i l_j}$ | 0.377509 | 0.422434 | 0.480262 | 0.347881 |

# How to distinguish from:




or

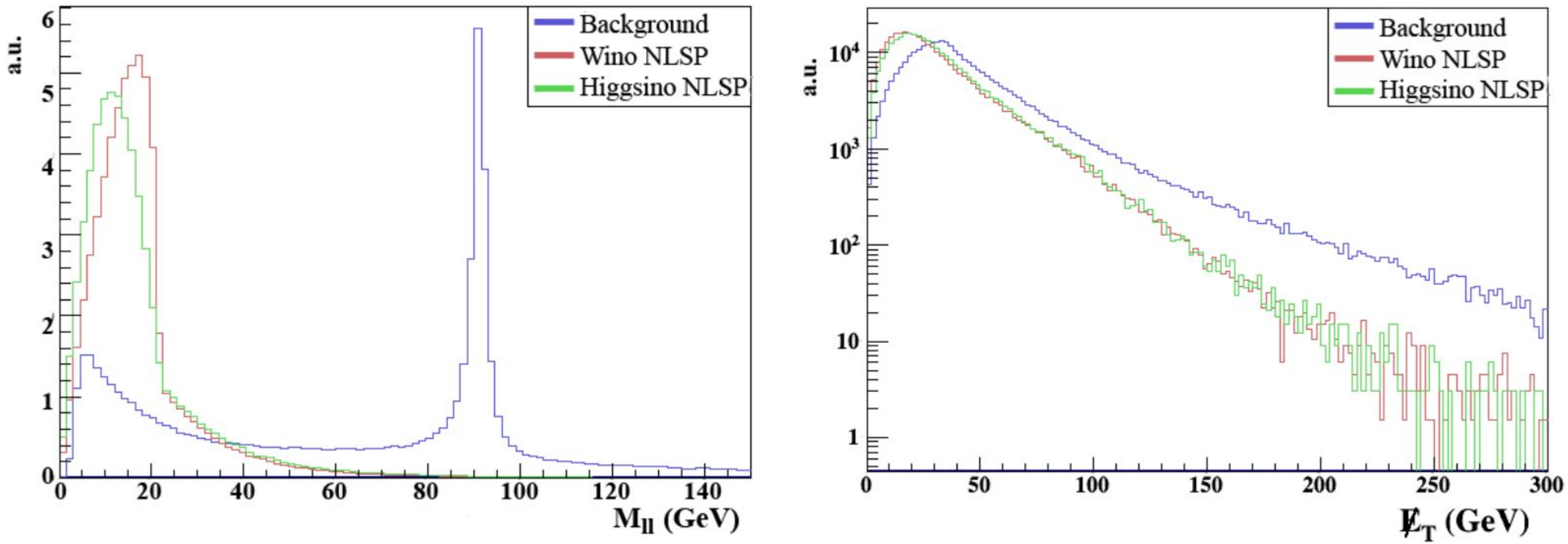



and pp $\longrightarrow$ Zb, WW, ZZ, $t\bar{t}$, Wt, Z$\gamma$

MET and additional leptons may originate from ISR/FSR/fake identification

See 1602.00590 for explanation + details of the analysis

# Use the signal topology!

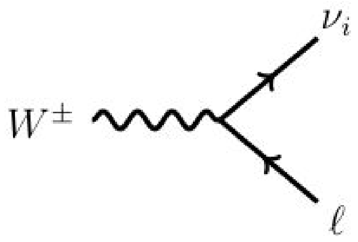


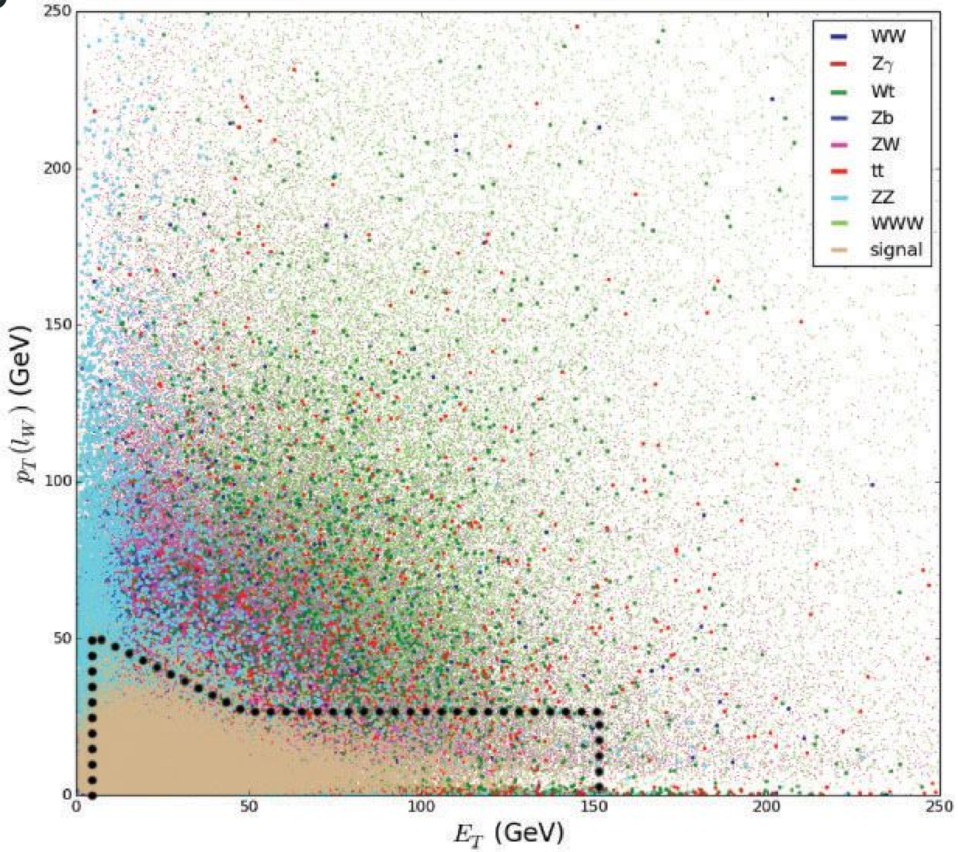

m(n1) = 90 GeV, m(n2, x1) = 110 GeV

events normalized to 1 pb

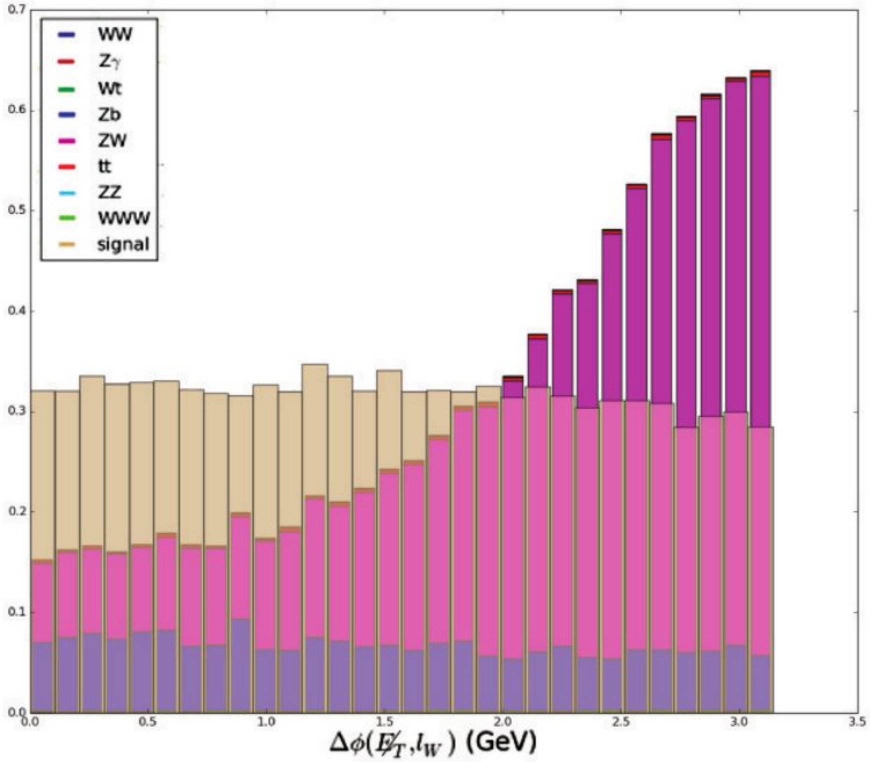
# To further reduce backgrounds: Funnel cut

Remember:



# To further reduce backgrounds



# Cross section backgrounds

- WW: 4.2pb
- Zγ: 4.9pb
- Wt: 2.4pb
- tt: 45pb
- ZW: 0.44pb
- Zb: 29pb
- ZZ: 0.8pb
- WWW: 0.0013 pb

# Final cuts

- 3 leptons, at least one OSSF lepton pair
- 5 (10) GeV < $p_T(\mu(e))$ < 50 GeV
- 12 GeV < $m_{l+l-}$ < 60 GeV
- $p_T(j)$ < 30 or 50 GeV ($t\bar{t}$ reduction, slide 42)
- Funnel cut: 5 GeV < MET < 150 GeV and (slide 41)
  - if MET < 50 GeV: $p_T(l_W)$ +3/5MET < 50 GeV
  - else: $p_T(l_W)$ < 20 GeV
- $\Delta\varphi(\mathrm{MET}, l_W) < 2$ (slide 43)

See 1602.00590 for cut flow diagram

# ATLAS cuts (8 TeV search, 1403.5294)

single $e$ and $\mu$ trigger: $p_T(l_1) > 25$ GeV

symmetric di-muon trigger: $p_T(\mu_1)$ and $p_T(\mu_2) > 14$ GeV

asymmetric di-muon trigger: $p_T(\mu_1) > 18$ GeV and $p_T(\mu_2) > 10$ GeV

symmetric di-electron trigger: $p_T(e_1)$ and $p_T(e_2) > 14$ GeV

asymmetric di-electron trigger:

$$p_T(e_1) > 25 \text{ GeV and } p_T(e_2) > 10 \text{ GeV}$$

electron-muon (muon-electron) combi trigger:

$$p_T(e_1) > 14(10) \text{ GeV and } p_T(\mu_1) > 10(18) \text{ GeV}$$

at least one OSSF[1] lepton pair with $12 < M_{l^+l^-} < 60$ GeV

$\not{E}_T > 50$ GeV

$p_T(l_3) > 10$ GeV

Does not work => lepton triggers demand too high PT

# CMS cuts (8 TeV search, SUS-13-006)

single $e$ and $\mu$ trigger: $p_T(e) > 27$ GeV or $p_T(\mu) > 24$ GeV

di-muon or di-electron or combination: $p_T(l_1) > 20$ and $p_T(l_2) > 10$ GeV

at least one OSSF lepton pair with $12 < M_{l^+l^-} < 75$ GeV

$\not{E}_T > 50$ GeV

$p_T(l_3) > 8$ GeV

Does not work => lepton triggers demand too high PT

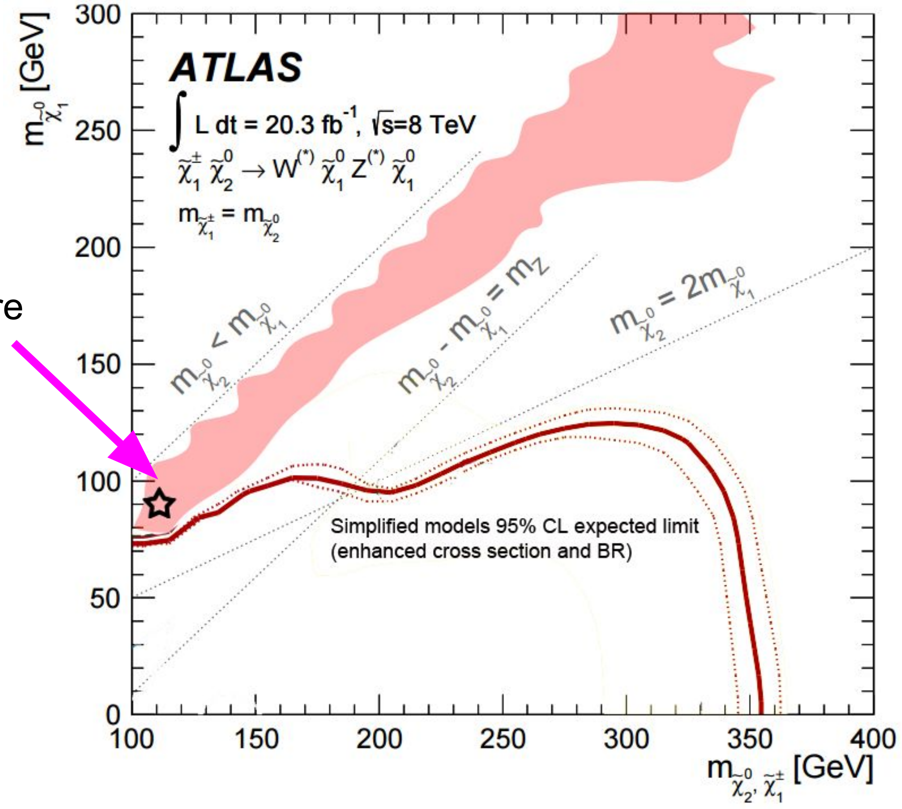
# CMS cuts (13 TeV search for soft leptons,

| Variable | SR selection criteria |
|---|---|
| $N_\ell$ | $= 2$ (ee,$\mu\mu$, e$\mu$) |
| $Q(\ell_1)Q(\ell_2)$ | $-1$ |
| $p_T(\ell_1)$, $p_T(\ell_2)$ | $[5, 30]$ GeV |
| $p_T(jet1)$ | $> 25$ GeV |
| $\|\eta\|(jet1)$ | $< 2.4$ |
| $N_b$ (>25 GeV, CSVL) | $= 0$ |
| $M(\ell\ell)$ | $< 50$ GeV |
| $p_T(\ell\ell)$ | $> 3$ GeV |
| $E_T^{miss}$ | $> 125$ GeV |
| $E_T^{miss}$ (muon subtracted) | $> 125$ GeV |
| $E_T^{miss} / H_T$ | $[0.6, 1.4]$ |
| $H_T$ | $> 100$ GeV |
| $M(\ell\ell)$ | $> 4$ GeV |
| $M(\ell\ell)$ | veto$[9, 10.5]$ GeV |
| $M_{\tau\tau}$ | veto$[0, 160]$ GeV |
| $M_T(\ell_x, E_T^{miss}), x = 1, 2$ | $< 70$ GeV (for electroweakino selection only) |

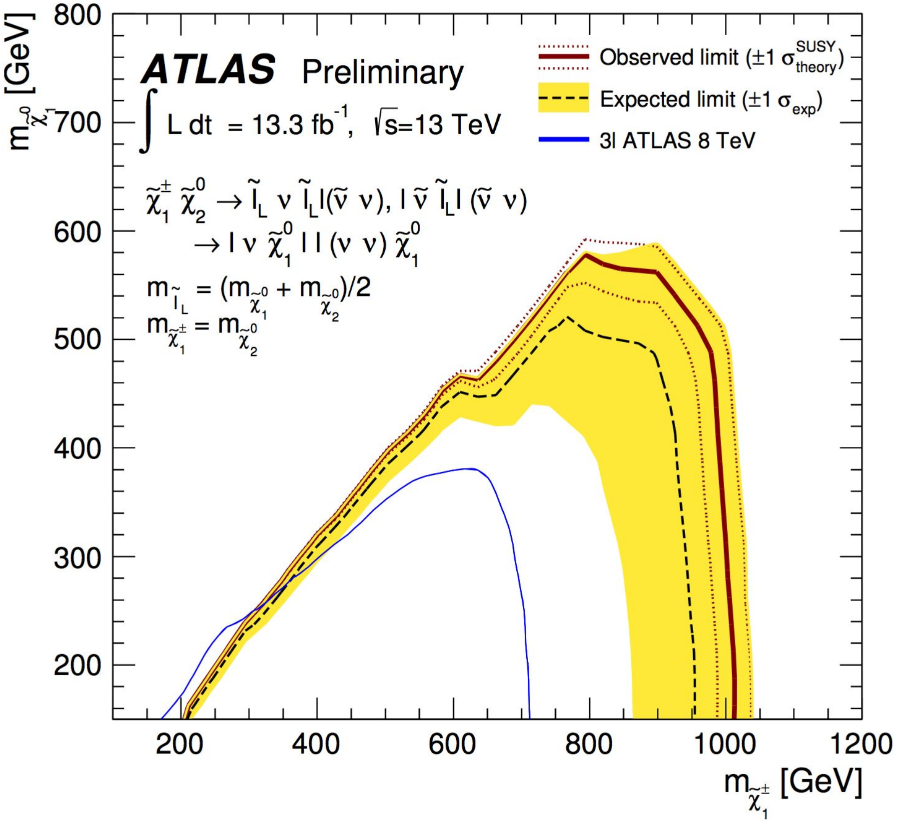
They lowered the lepton PT triggers, but the killer cut is the high ET that is demanded

# Optimistic model limits

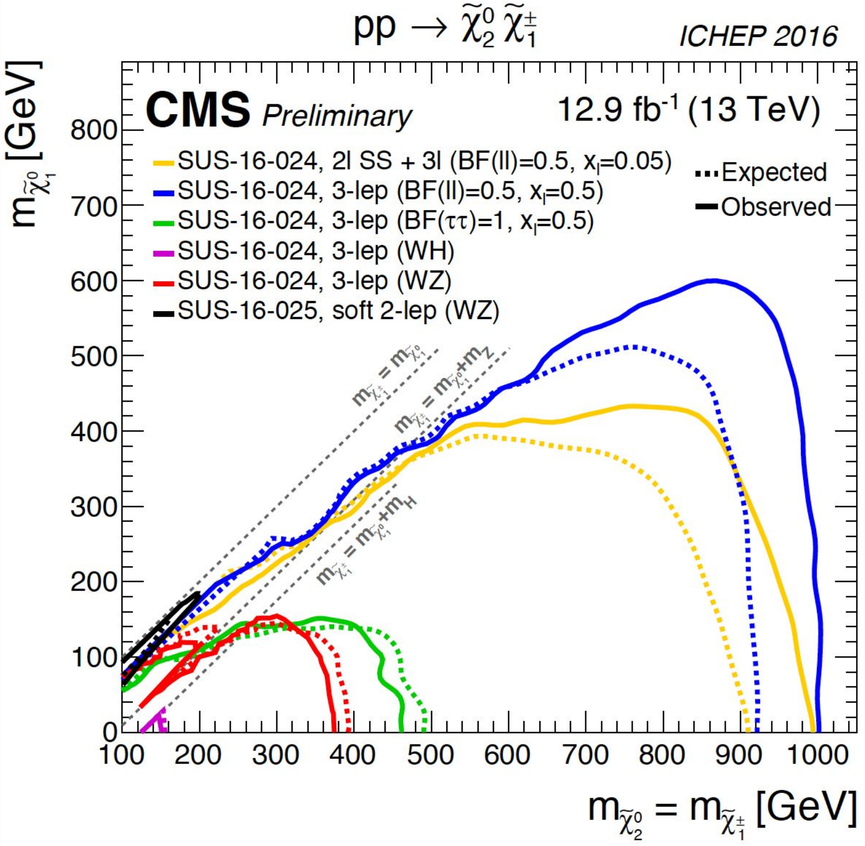
Important region not probed, not even by limits imposed via simplified models where couplings are set very high!



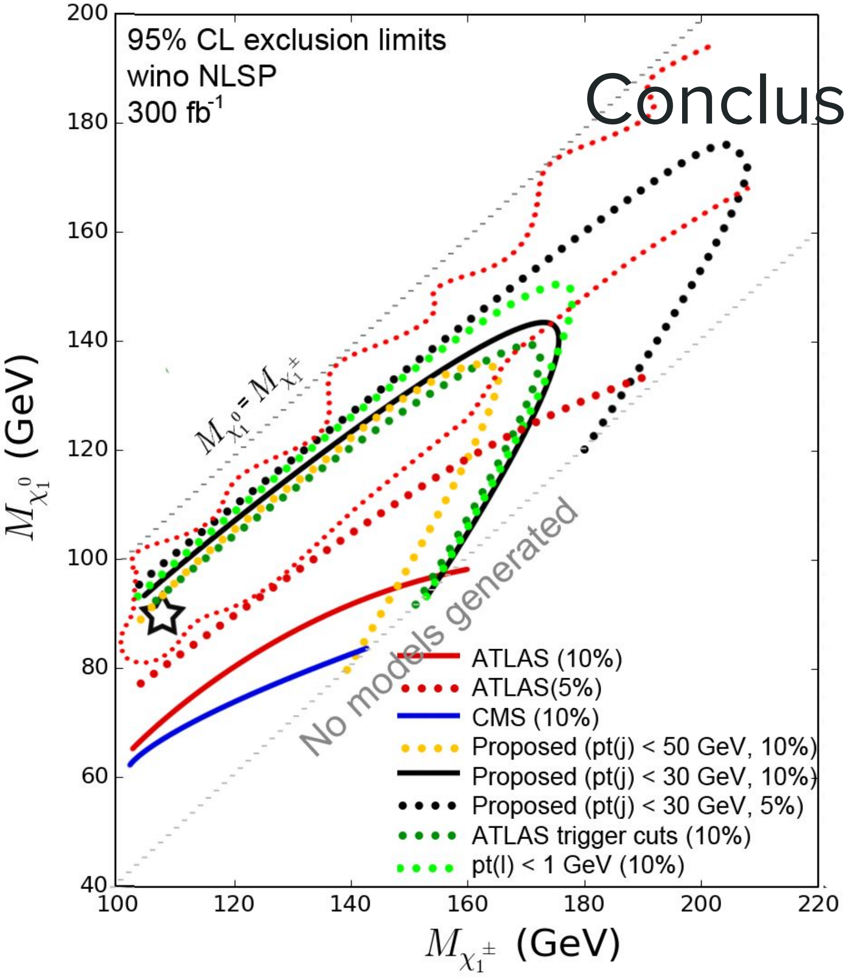
# Optimistic model limits - ATLAS 13 TeV

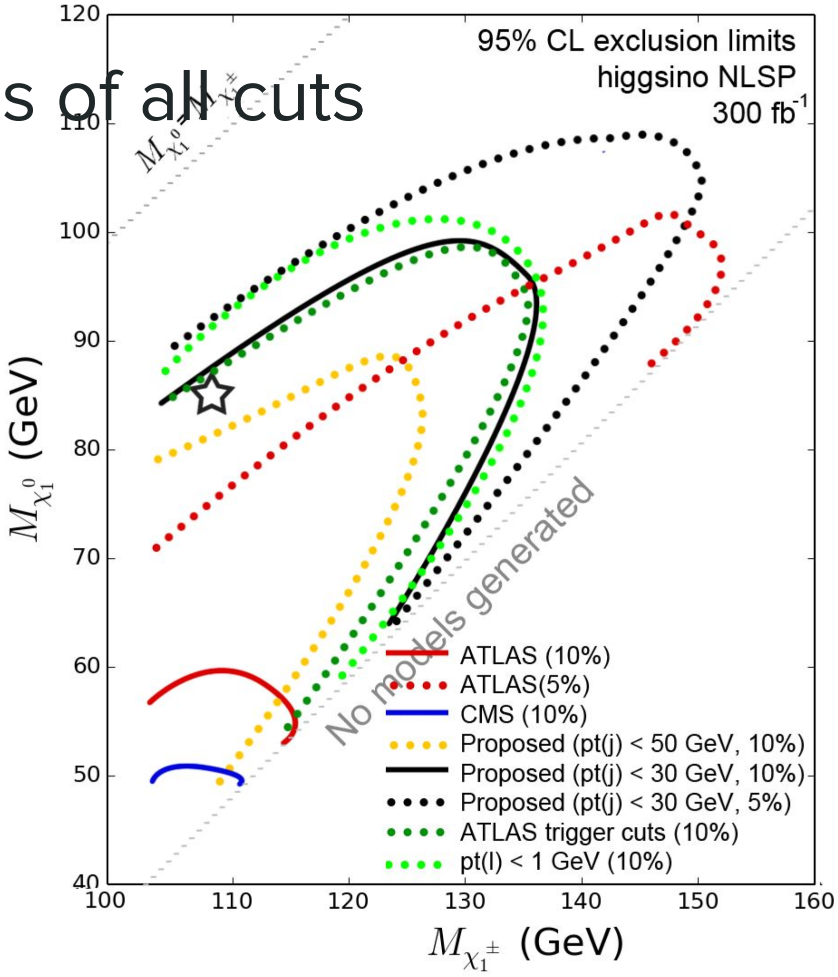


# Optimistic model limits - CMS 13 TeV

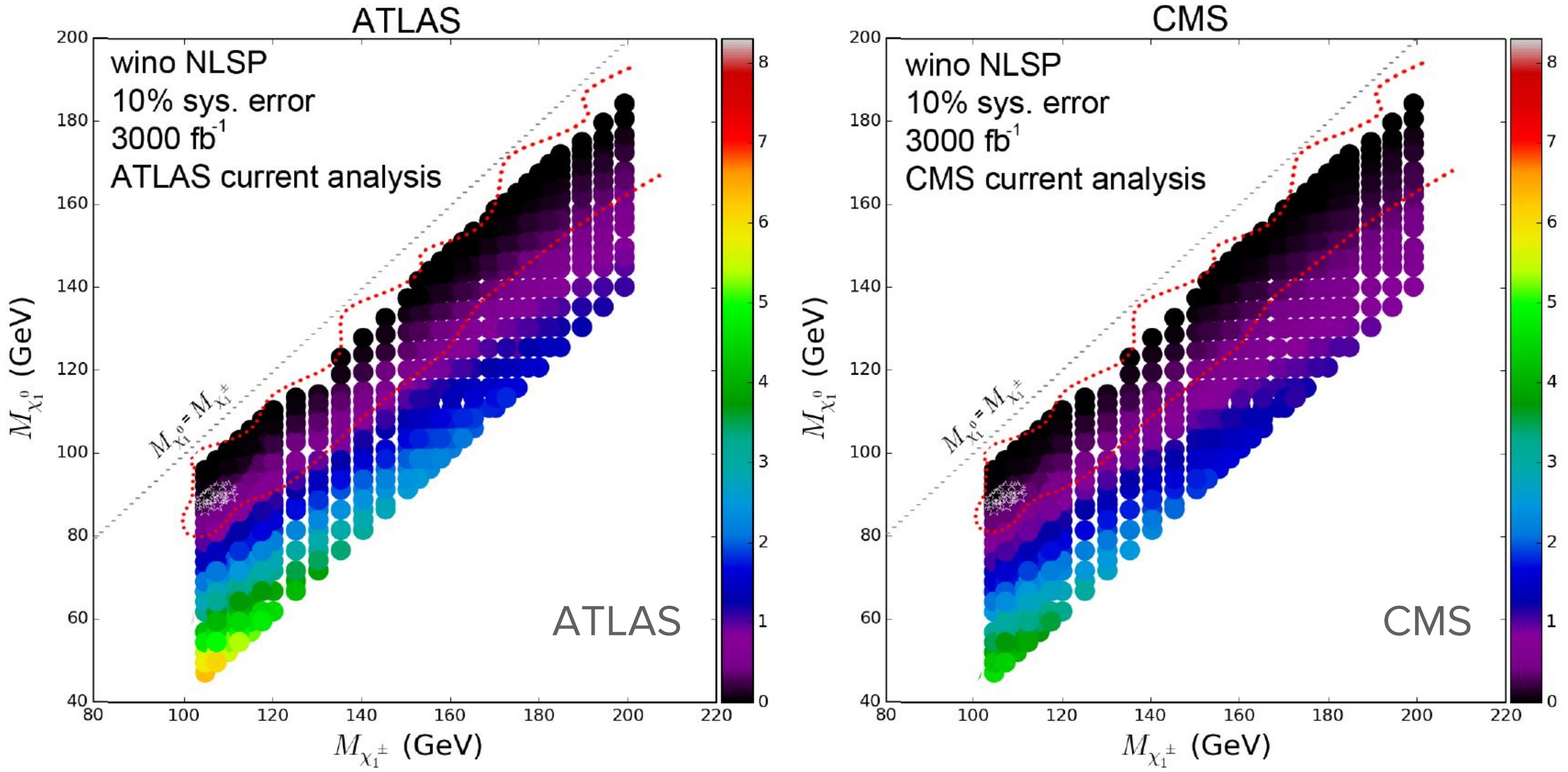


# Conclusions of all cuts



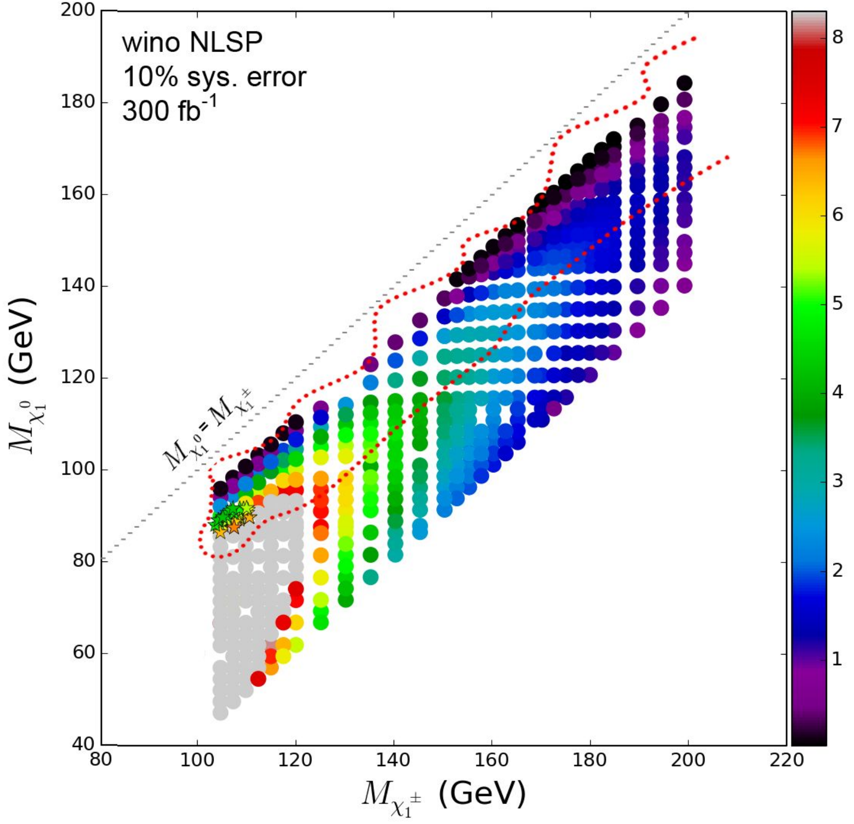



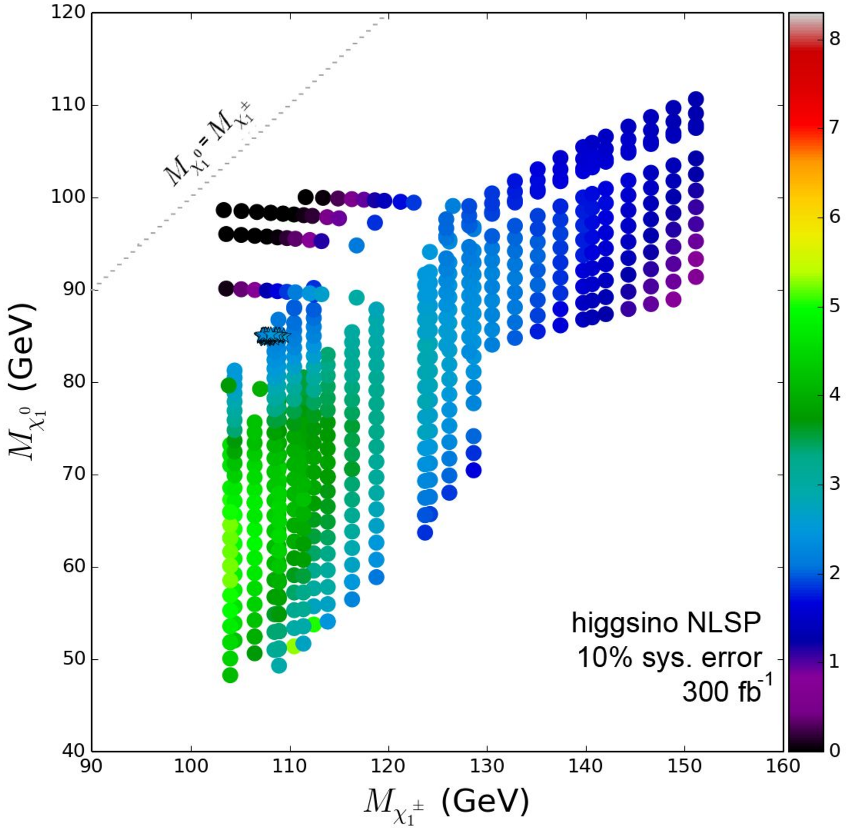
# Even at 3000 fb$^{-1}$



# Including higgsino models

1602.00590



# By the end of this year...