Singlet Doublet Model: Dark Matter Searches and Collider Constraints

Pantelis Tziveloglou

Invisibles15, Madrid, 22/6/15

INTERNATIONAL SOLVAY INSTITUTES
BRUSSELS

1505.03867 with A. Mariotti and L. Calibbi

Singlet Doublet (SD) Dark Matter

Standard Model extended by a pair of fermionic electroweak doublets and a singlet

Arkani-Hamed, Dimopoulos, S. Kachru, 0501082
Mahbubani, Senatore, 0510064
Enberg, Fox, Hall, Papaioannou, Papucci, 0706.0918
Cohen, Kearney, Pierce, Tucker-Smith, 1109.2604
Cheung, Sanford, 1311.5896
...

Why SD Dark Matter?

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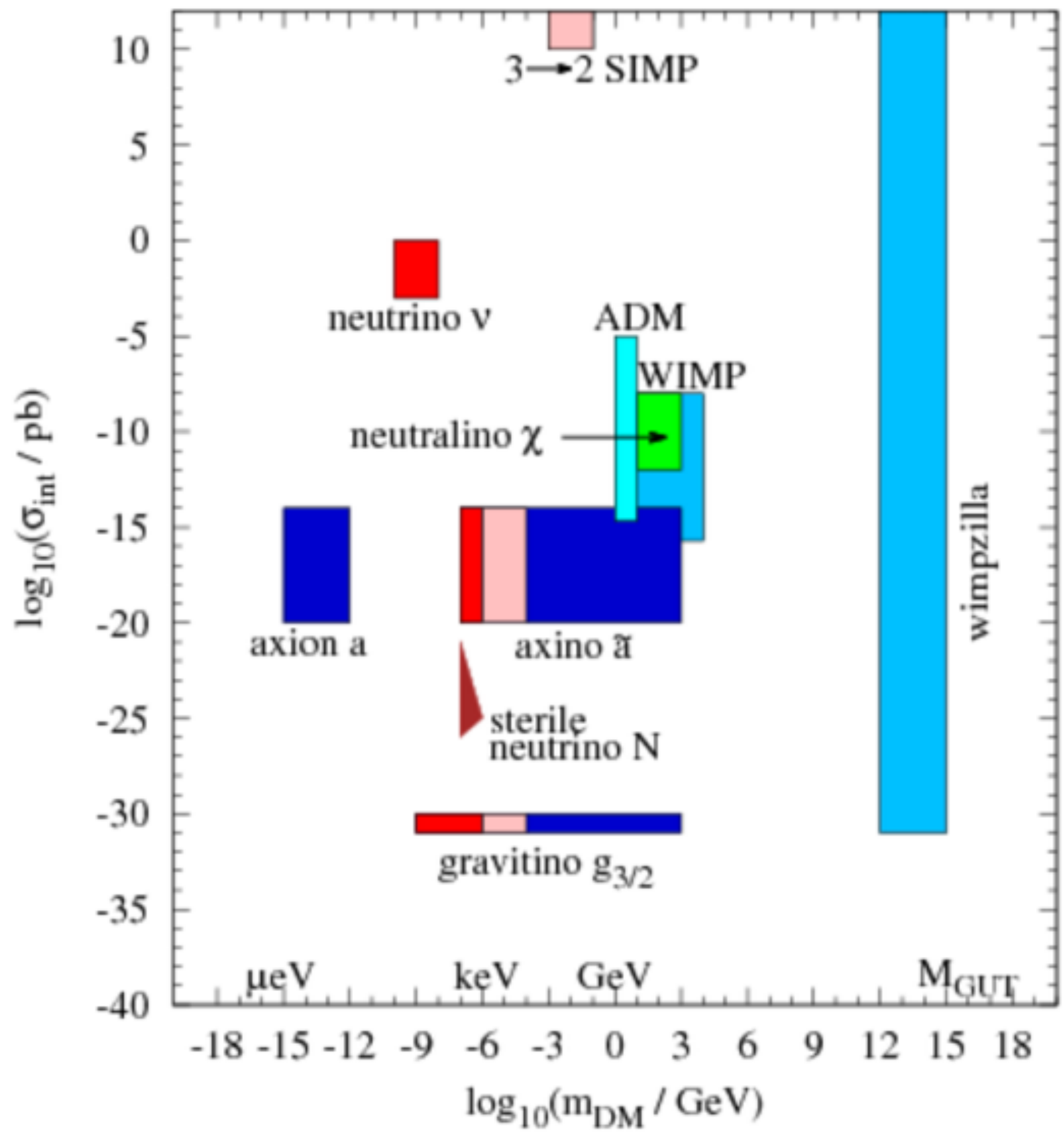
Honest answer:



taken from review by Baer, Choi, Kim, Roszkowski, 1407.0017

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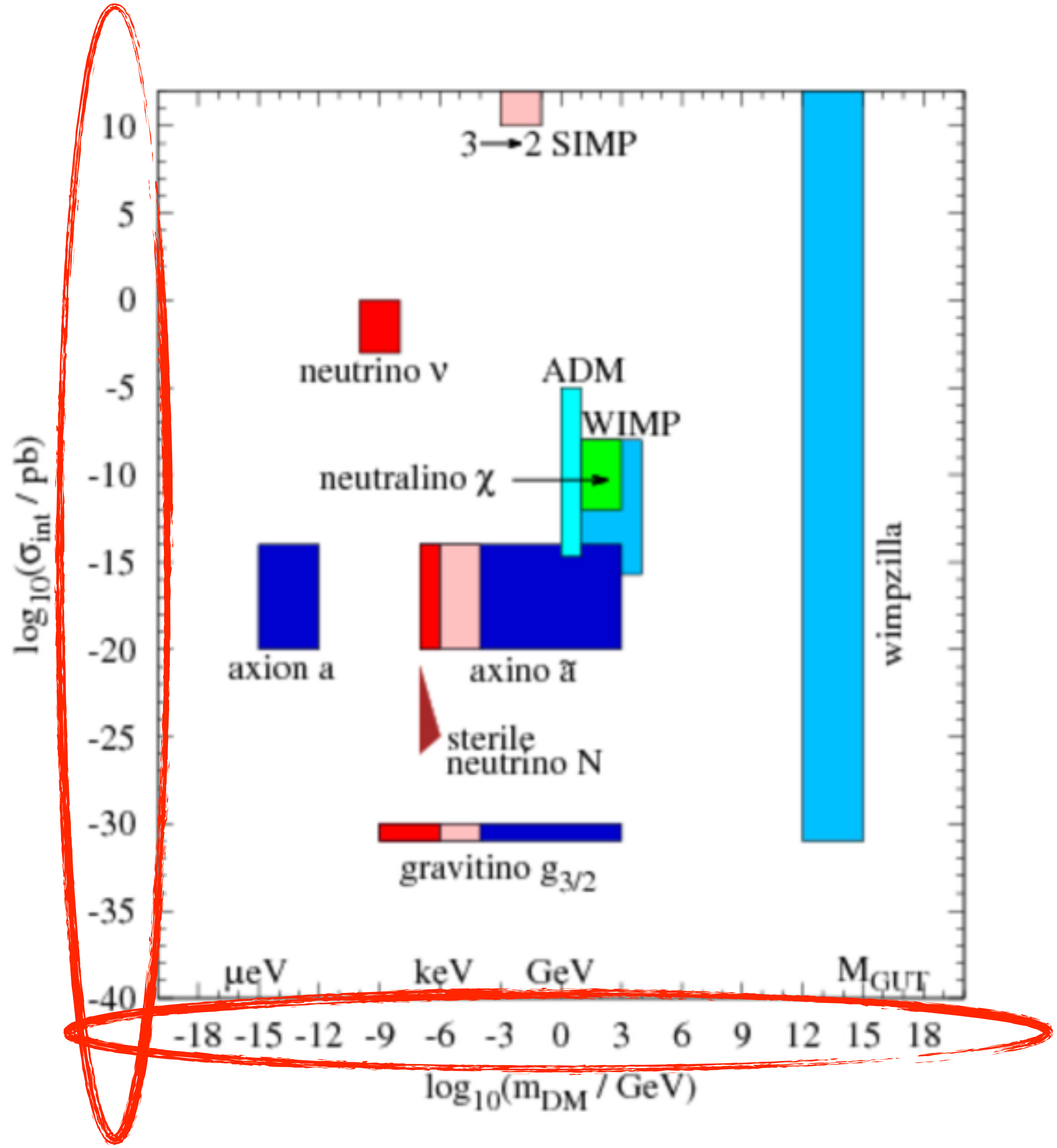

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Why SD Dark Matter?

1. **It's a WIMP**

Weakly Interacting Massive Particles (WIMPs):

- Can be thermal relics
- Interact with dynamics that exist (electroweak)
- Have masses that we can probe (around and below TeV range)

SD Dark Matter is an archetypical WIMP:

- It interacts with electroweak bosons
- Its mass is (partially) determined by EW symmetry breaking

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2. **It's a viable minimal WIMP**

Stability ensured by the typical dark matter parity*

for other realisations see eg
Dedes, Karamitros, 1403.7744

No spin independent interactions with nucleons via Z-boson exchange

*Minimal EW Dark Matter with stability ensured à la proton: "Minimal Dark Matter"
Cirelli, Fornengo, Strumia, 0512090

Why SD Dark Matter?

3. It is a simplified model of dark matter that captures many currently interesting possibilities

Experiment driven:

- Dark matter - nucleon interactions via Higgs boson: Current generation of direct search experiments are starting to probe Higgs mediated interactions

Model-building driven:

- It captures dynamics of SUSY-type models such as the bino - higgsino system in split-type SUSY and the singlino - higgsino system in singlet extensions

Arkani-Hamed, Dimopoulos, S. Kachru, 0501082
Mahbubani, Senatore, 0510064

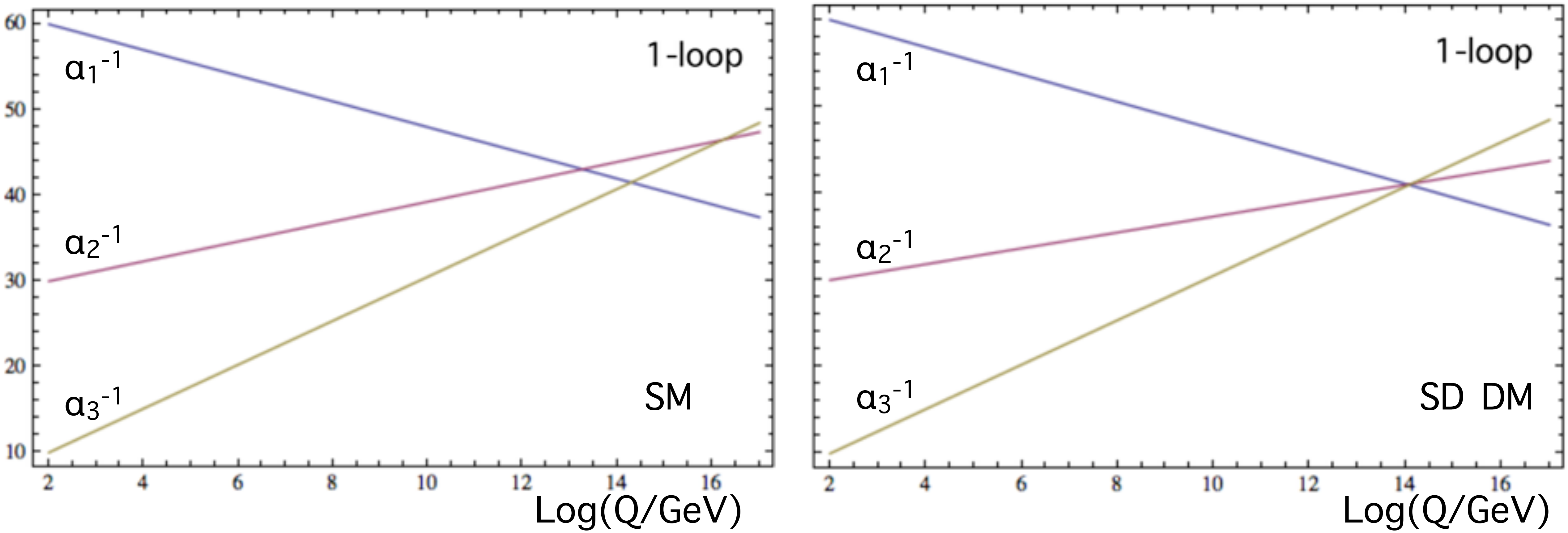
- It captures dynamics of EW composite dark matter models

Antipin, Redi, Strumia, Vigiani 1503.08749

Why SD Dark Matter?

4. It improves gauge coupling unification of the SM

Mahbubani, Senatore, 0510064



Why SD Dark Matter?

5. It can be tested

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Direct Searches

…

Indirect Searches

…

Colliders

Outline

- Singlet - Doublet Model details

- Dark Matter Searches
  1. Direct Searches
  2. Indirect Searches
  3. Combined Results
  4. Degenerate Spectra

- Constraints from Colliders
  1. Invisible Higgs and Z-boson decays
  2. Electroweak Precision Observables
  3. Leptons + MET

SD Model Details

SD Model details

Lagrangian

$$-\frac{m_S}{2}\lambda\lambda - m_D\,\psi_1\cdot\psi_2 - y_1\,\psi_1\cdot h\,\lambda - y_2\,\overline{\psi}_2\,\overline{\lambda}\,h$$

we will also use

$$y = \sqrt{y_1^2 + y_2^2}\,, \quad \tan\theta = \frac{y_2}{y_1}$$

Mass matrix

$$\mathbf{M}_{\chi_n} = \begin{pmatrix} m_S & \frac{y_1 v}{\sqrt{2}} & \frac{y_2 v}{\sqrt{2}} \\ \frac{y_1 v}{\sqrt{2}} & 0 & m_D \\ \frac{y_2 v}{\sqrt{2}} & m_D & 0 \end{pmatrix}$$

Dark matter candidate

$$\chi = Z_S\lambda + Z_{D1}\psi_1^0 + Z_{D2}\psi_2^0$$

Doublet components (Z_{D1}, Z_{D2})

Singlet component (Z_S)

Couplings of χ

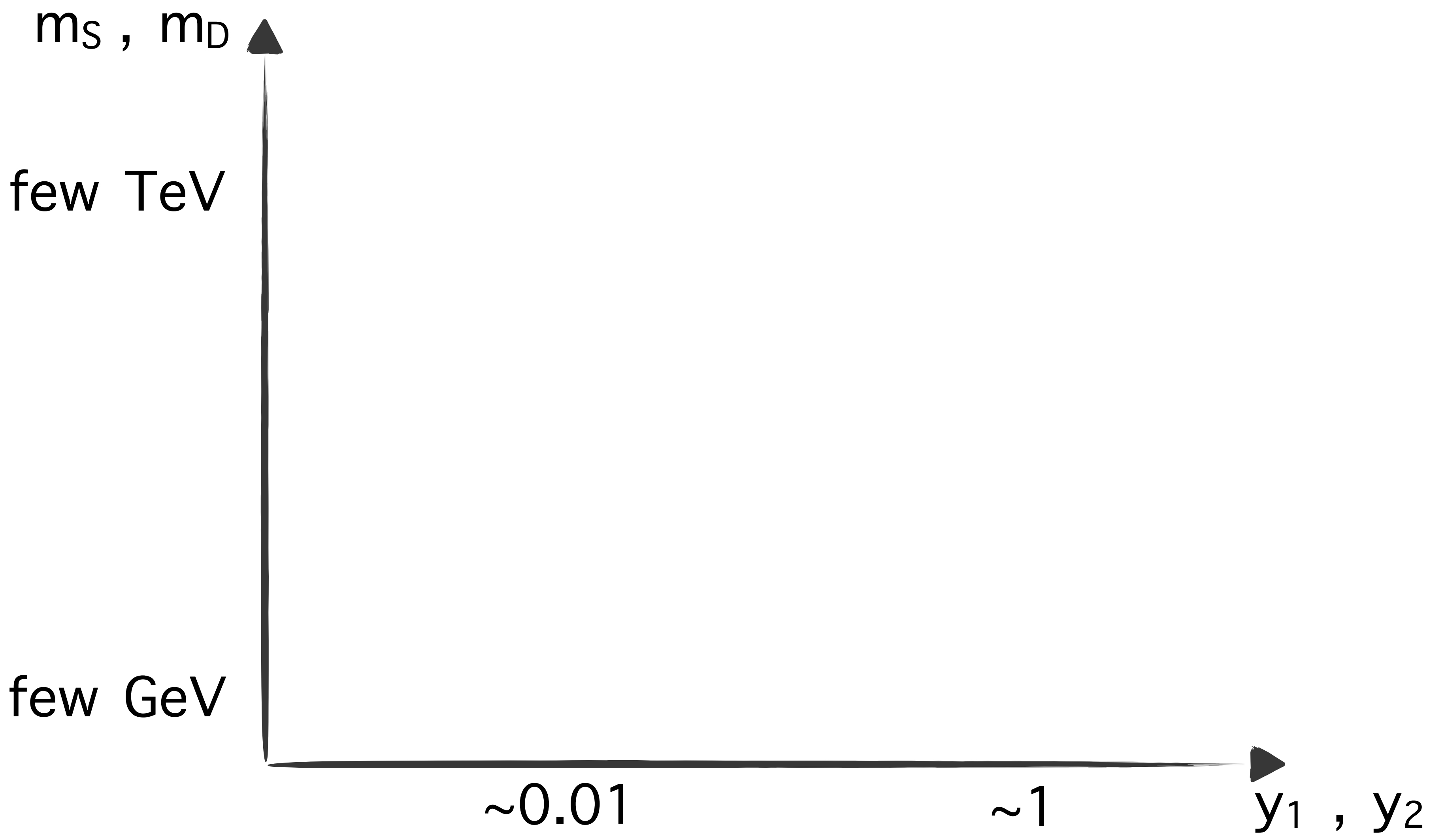
$$c_{\chi\chi Z} = \frac{g_2}{4c_W}(|Z_{D2}|^2 - |Z_{D1}|^2)$$

$$c_{\chi\chi h} = \frac{1}{\sqrt{2}}(y_1 Z_{D1}^* Z_S^* + y_2 Z_{D2}^* Z_S^*)$$

$$c_{\chi\chi^+ W^-} = \frac{g_2}{\sqrt{2}}(Z_{D2}P_L + Z_{D1}^* P_R)$$

Parameter space of SD model

$$-\frac{m_S}{2}\lambda\lambda - m_D\,\psi_1\cdot\psi_2 - y_1\,\psi_1\cdot h\,\lambda - y_2\,\overline{\psi}_2\,\overline{\lambda}\,h$$



We look into DIRECT + INDIRECT + COLLIDER constraints

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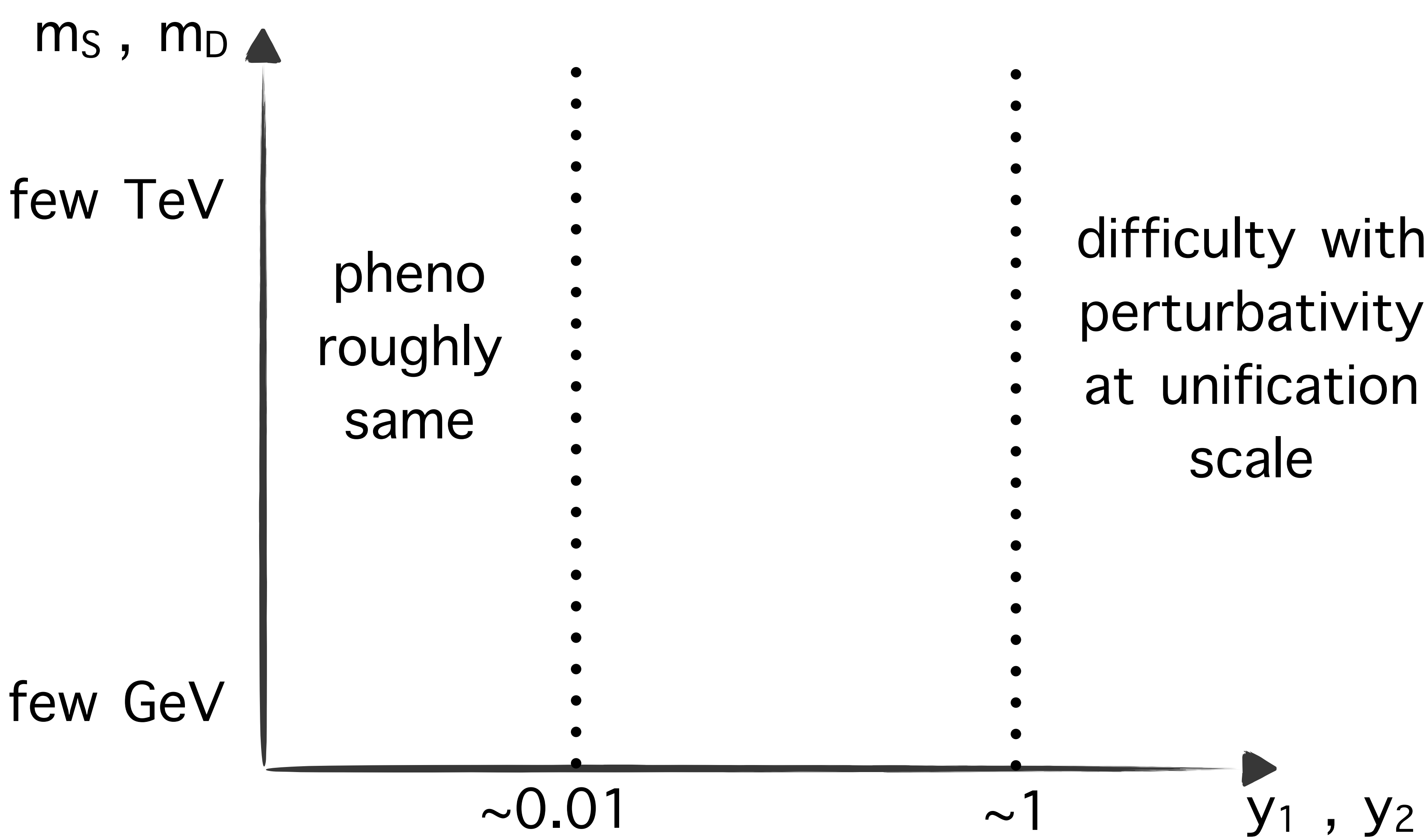

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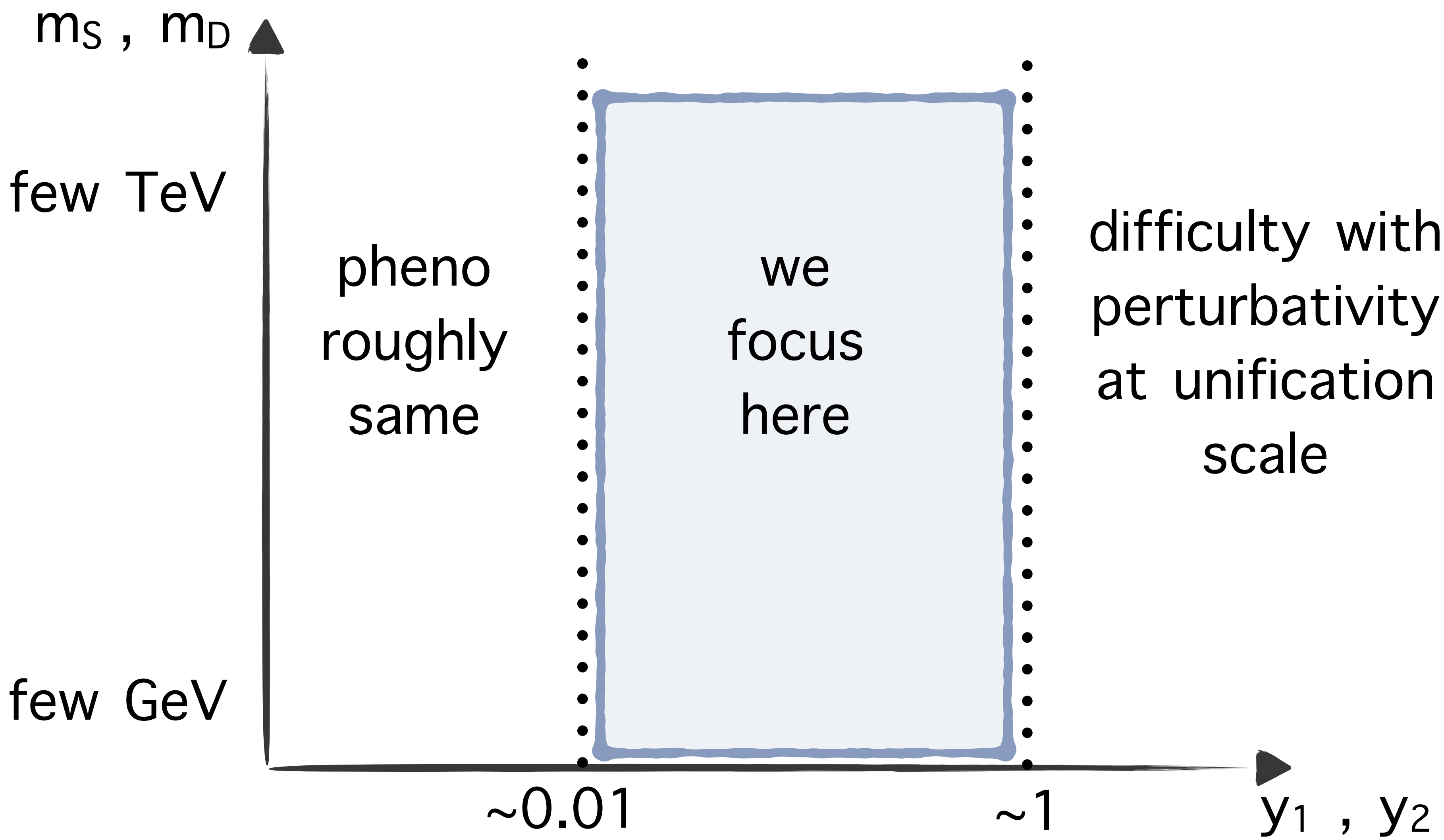
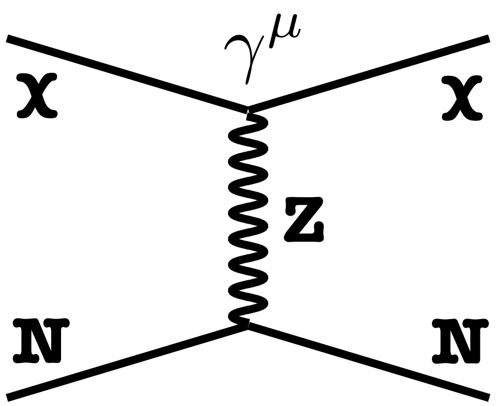


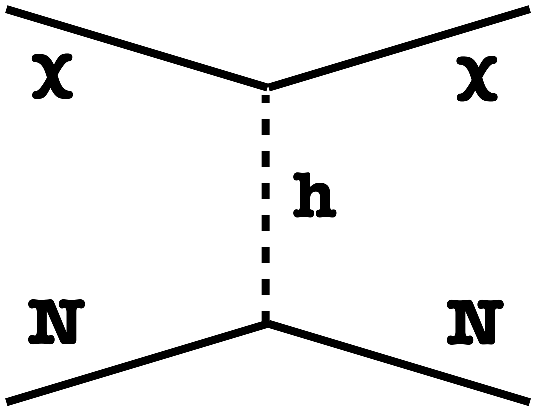
We look into DIRECT + INDIRECT + COLLIDER constraints

Dark Matter Searches

Direct dark matter searches

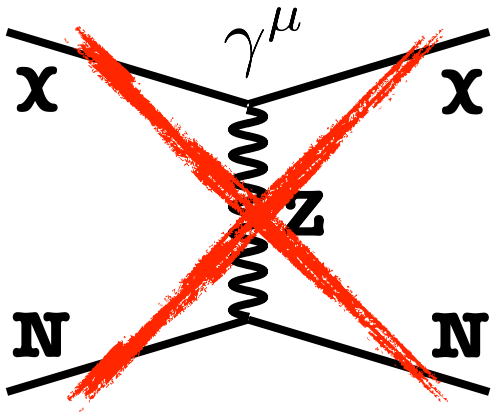
Spin Independent



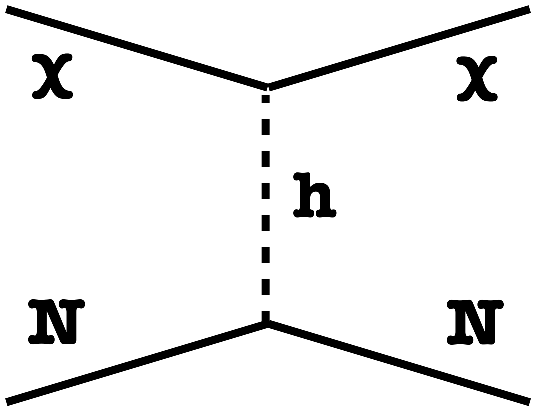


Direct dark matter searches

Spin Independent



- Dark Matter is a Majorana particle (mixed state)



- Often the most stringent bounds
- Xsec increases with Yukawa
- Exhibit "blind spots" around $\sin(2\theta)m_D + m_1 = 0$

Cheung, Sanford, 1311.5896

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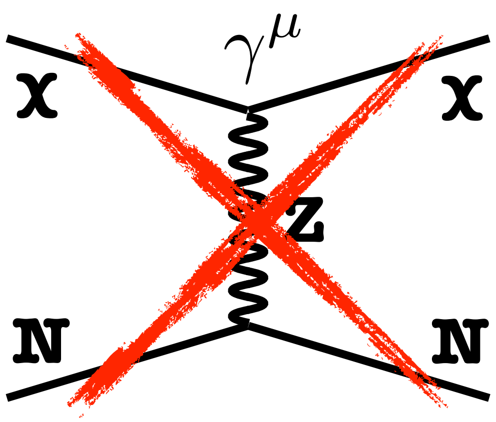
Spin Independent



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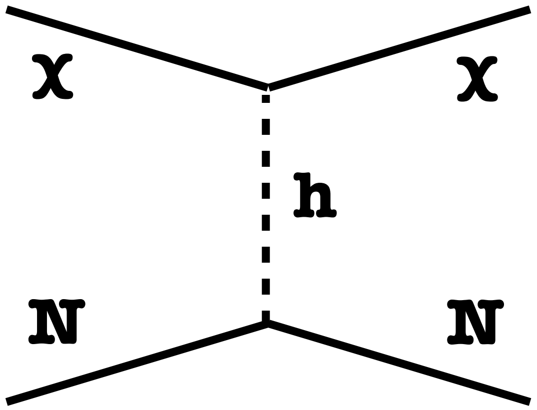

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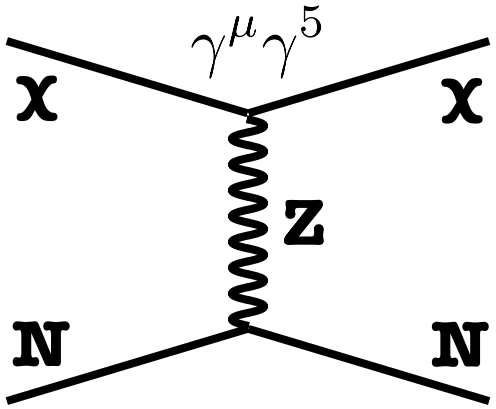
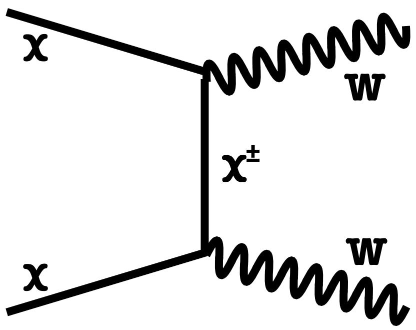
Spin Dependent

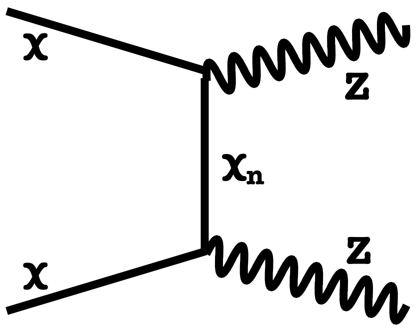


- They don't have the same blind spots
- Complementary to Spin Independent
- Xsec increases with mixing (thus Yukawa)

Indirect dark matter searches

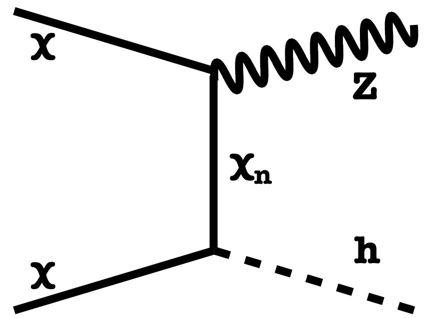
$$\chi\chi \to WW/ZZ$$

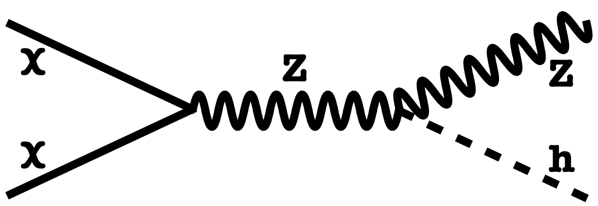




- No mixing required for WW
- The only constraint in the absence of Yukawa

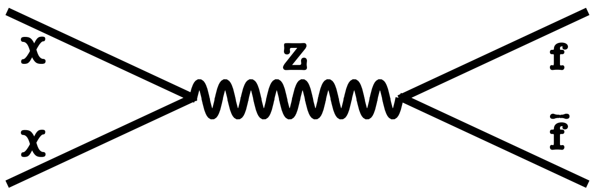
$$\chi\chi \to Zh$$





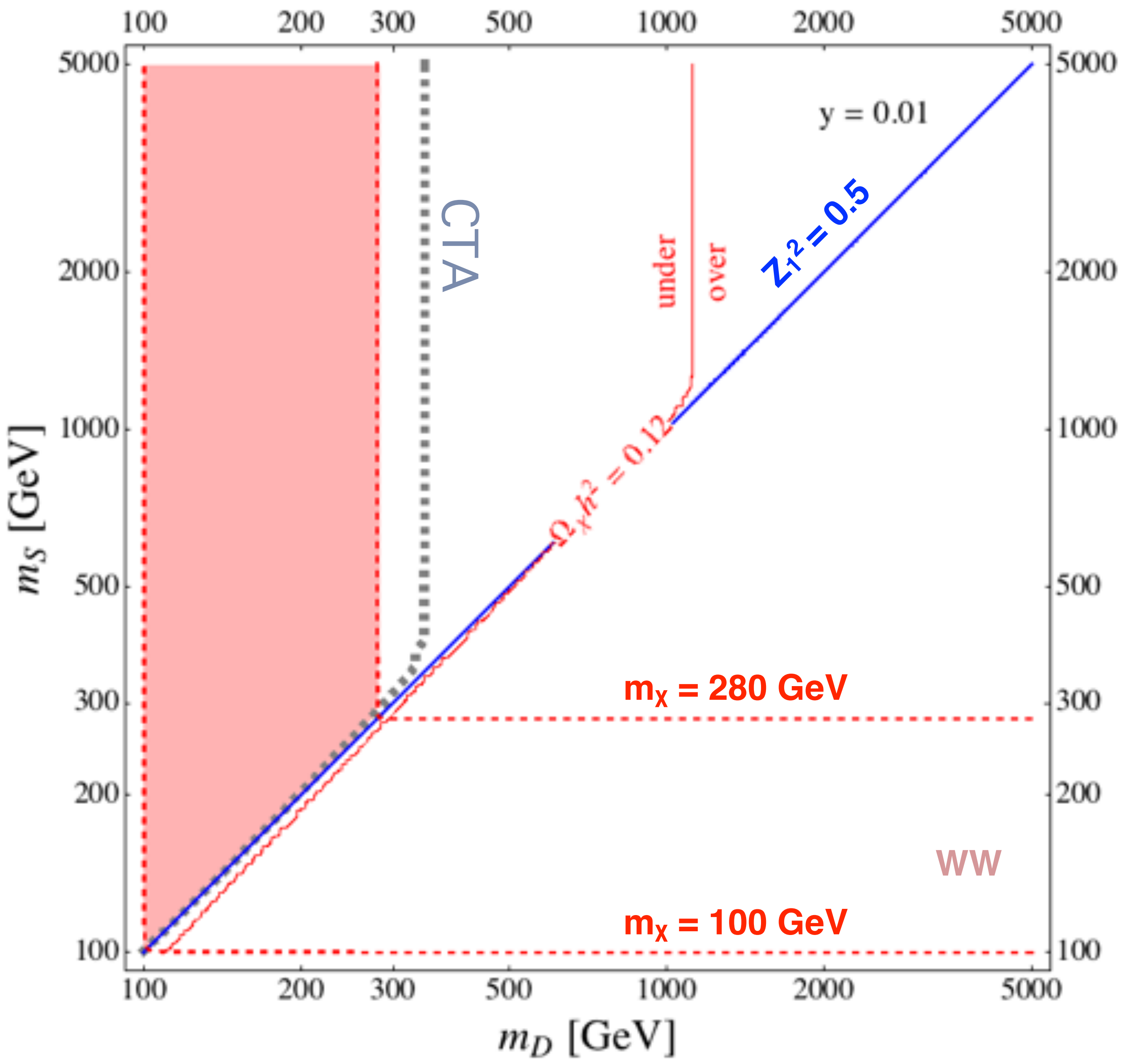
- Strong only at large Yukawa
- Mixing is required

$$\chi\chi \to \bar{t}t$$



- (Once kinematically allowed) $t\bar{t}$ dominates over other fermionic final states
- Mixing is required

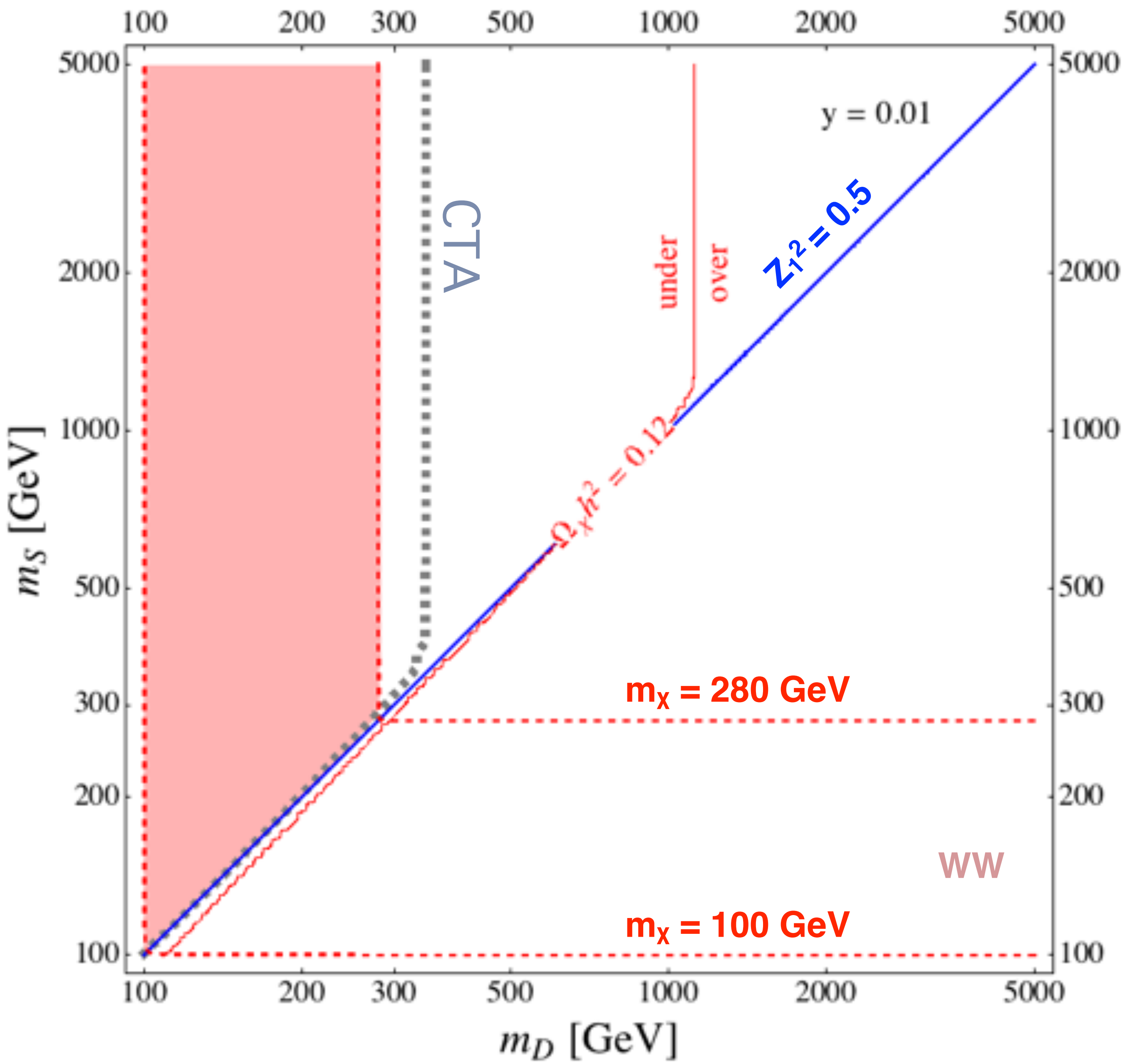
Bounds from dark matter searches



Small Yukawas

- Only $\chi\chi \to WW$

Bounds from dark matter searches



Small Yukawas

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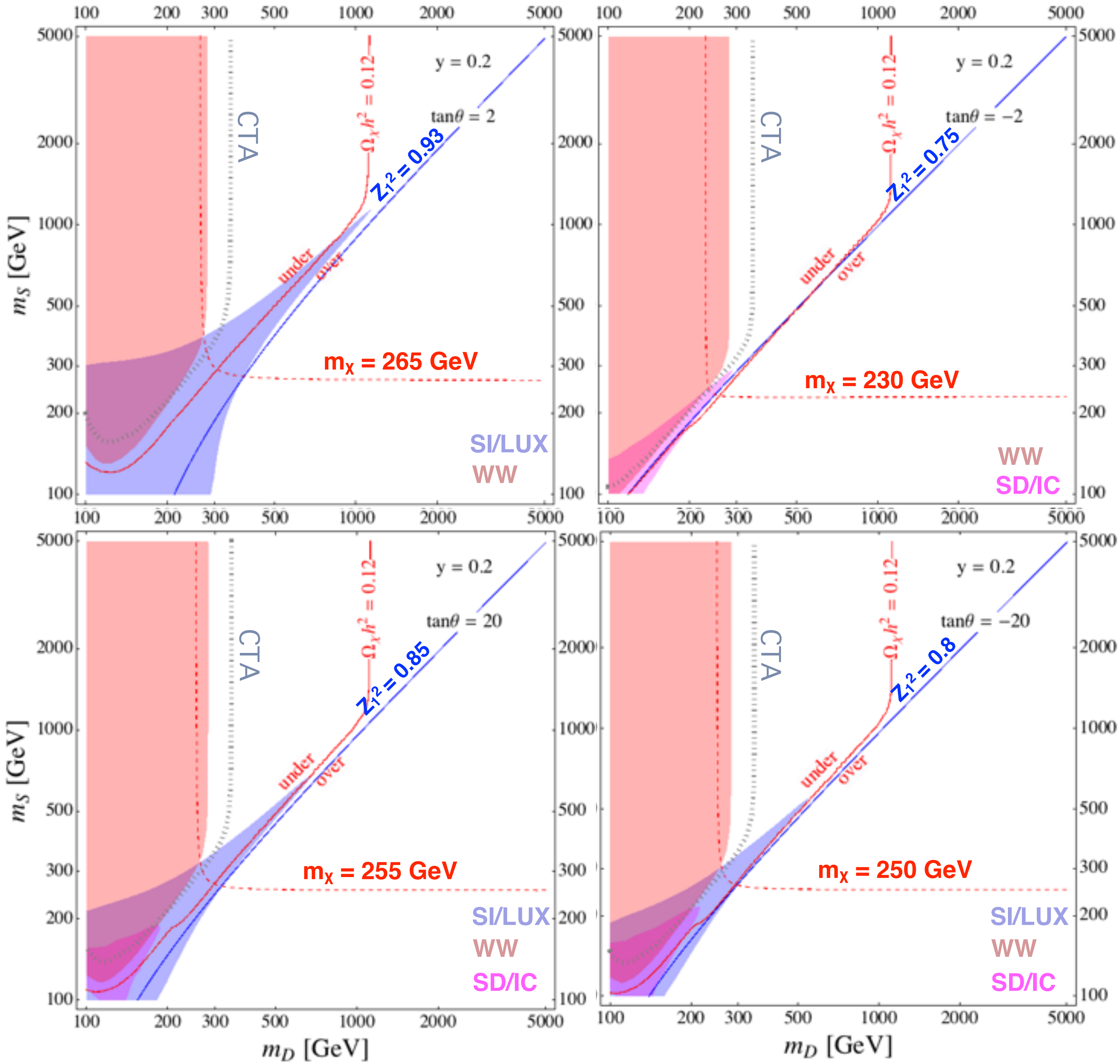
m_χ < 280 GeV & Z_1^2 < 0.5

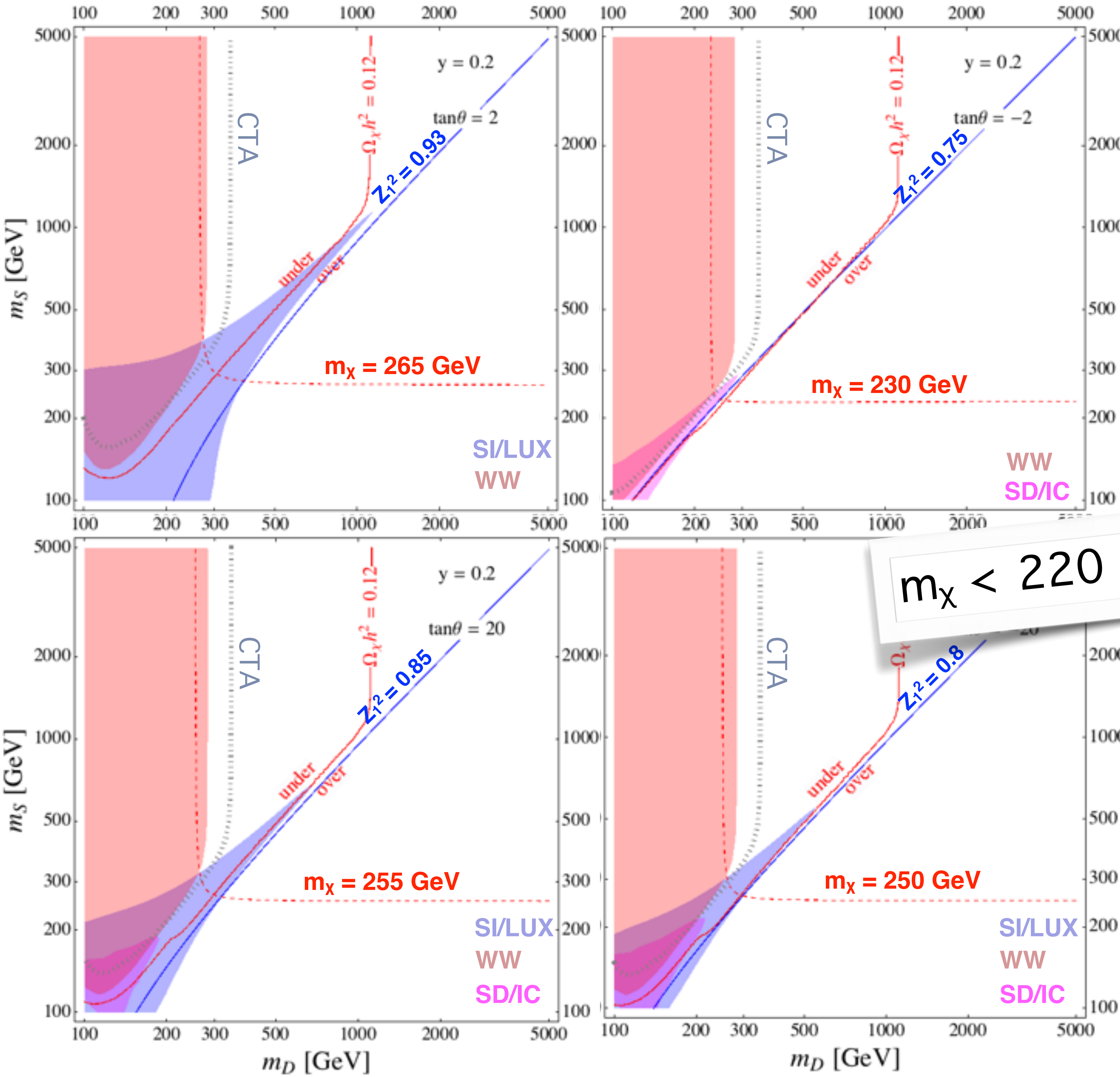
Bounds from dark matter searches



MSSM-like Yukawas

- $\chi\chi \to WW$
- Spin Independent
- Spin Dependent

Bounds from dark matter searches



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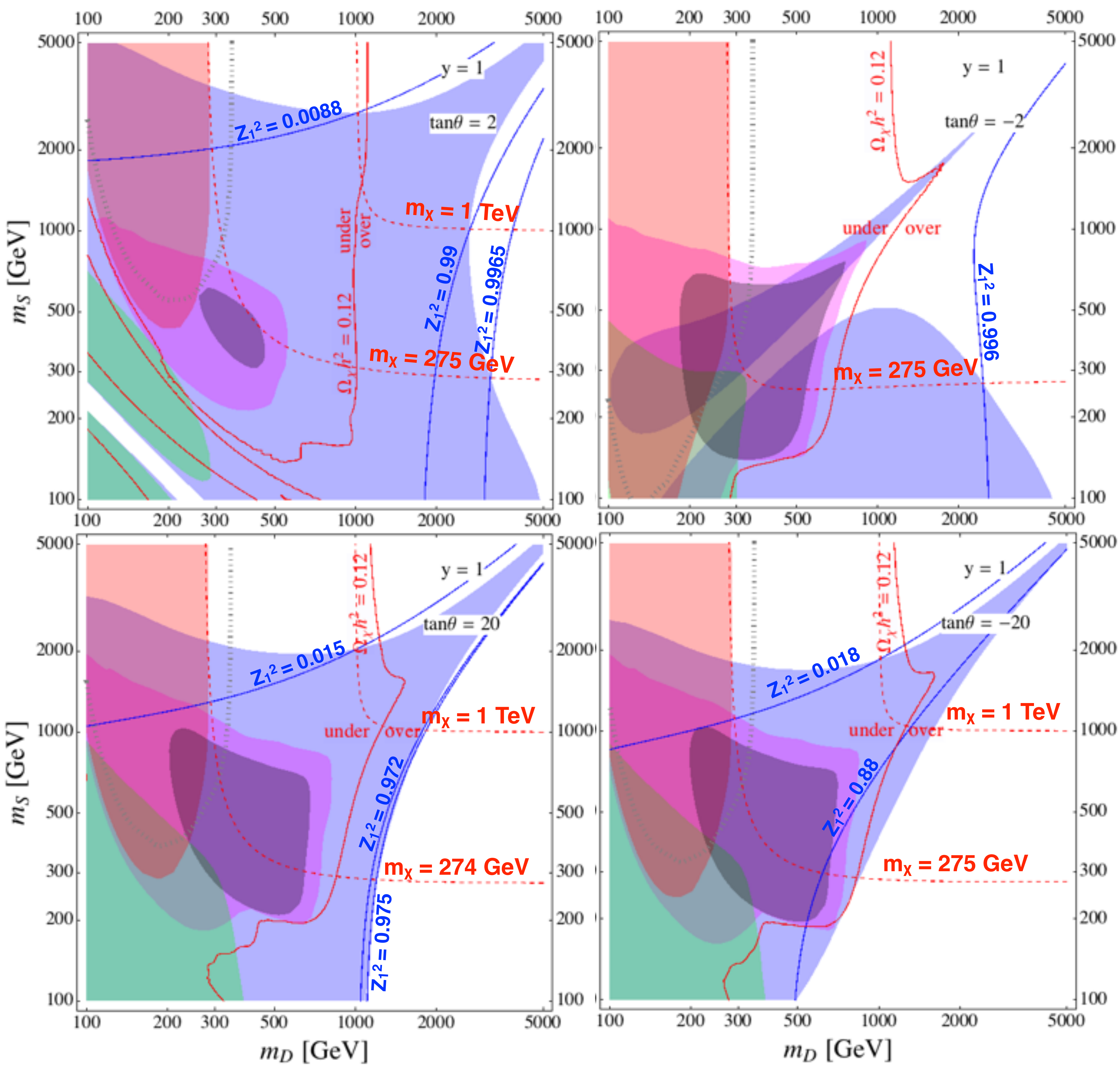
m_χ < 220 GeV & $Z_1{}^2$ < 0.65



Large Yukawas

- $\chi\chi \to WW$
- $\chi\chi \to \bar{t}t$
- Spin Independent
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- $\chi\chi \to Zh$
  (for y >1.5)

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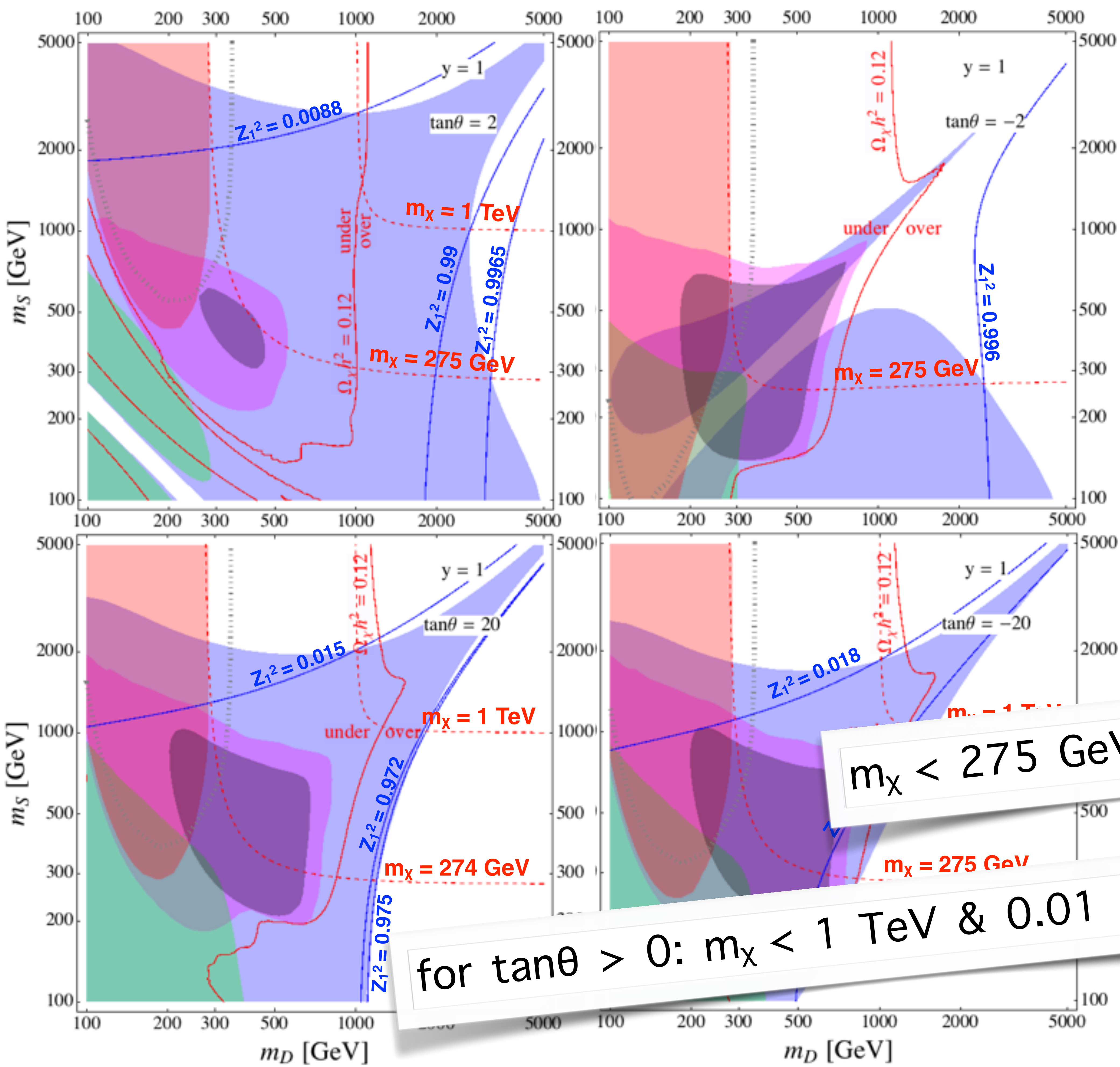
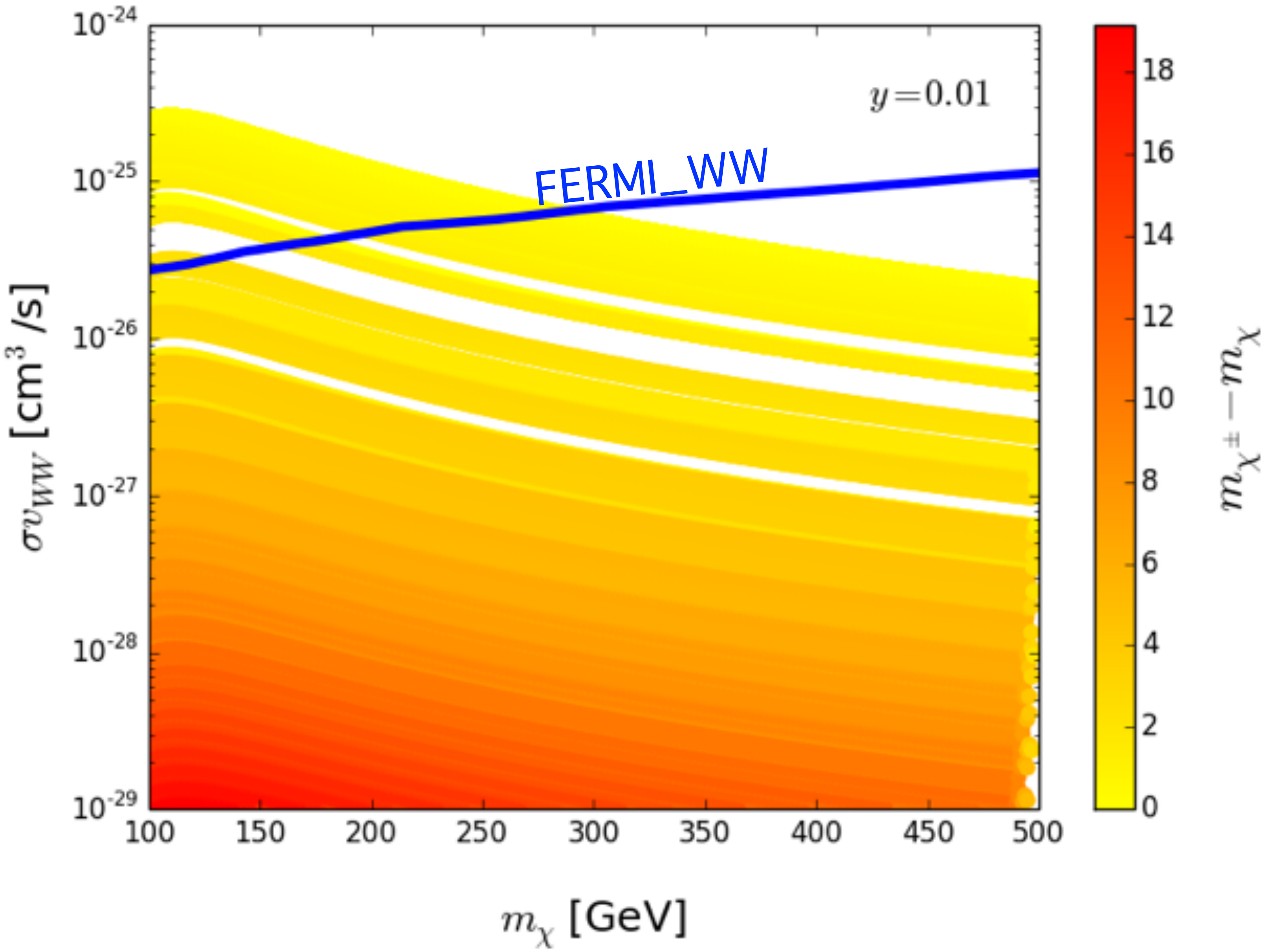


m_χ < 275 GeV & $Z_1^2 < 0.8$

for tanθ > 0: m_χ < 1 TeV & 0.01 < $Z_1^2 < 0.95$

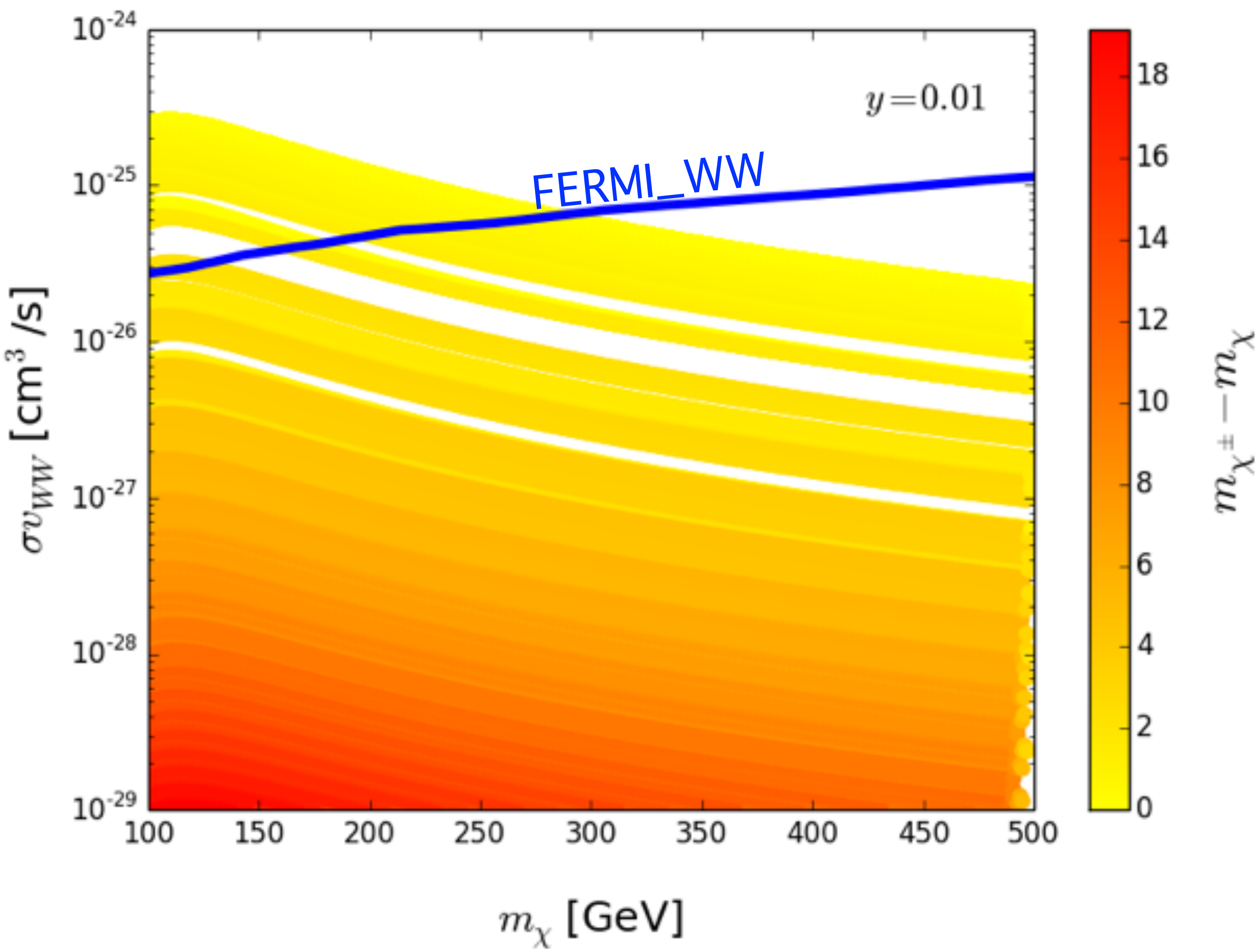
Bounds on degenerate spectra



For small mass splitting:

- Colliders lose sensitivity

Bounds on degenerate spectra



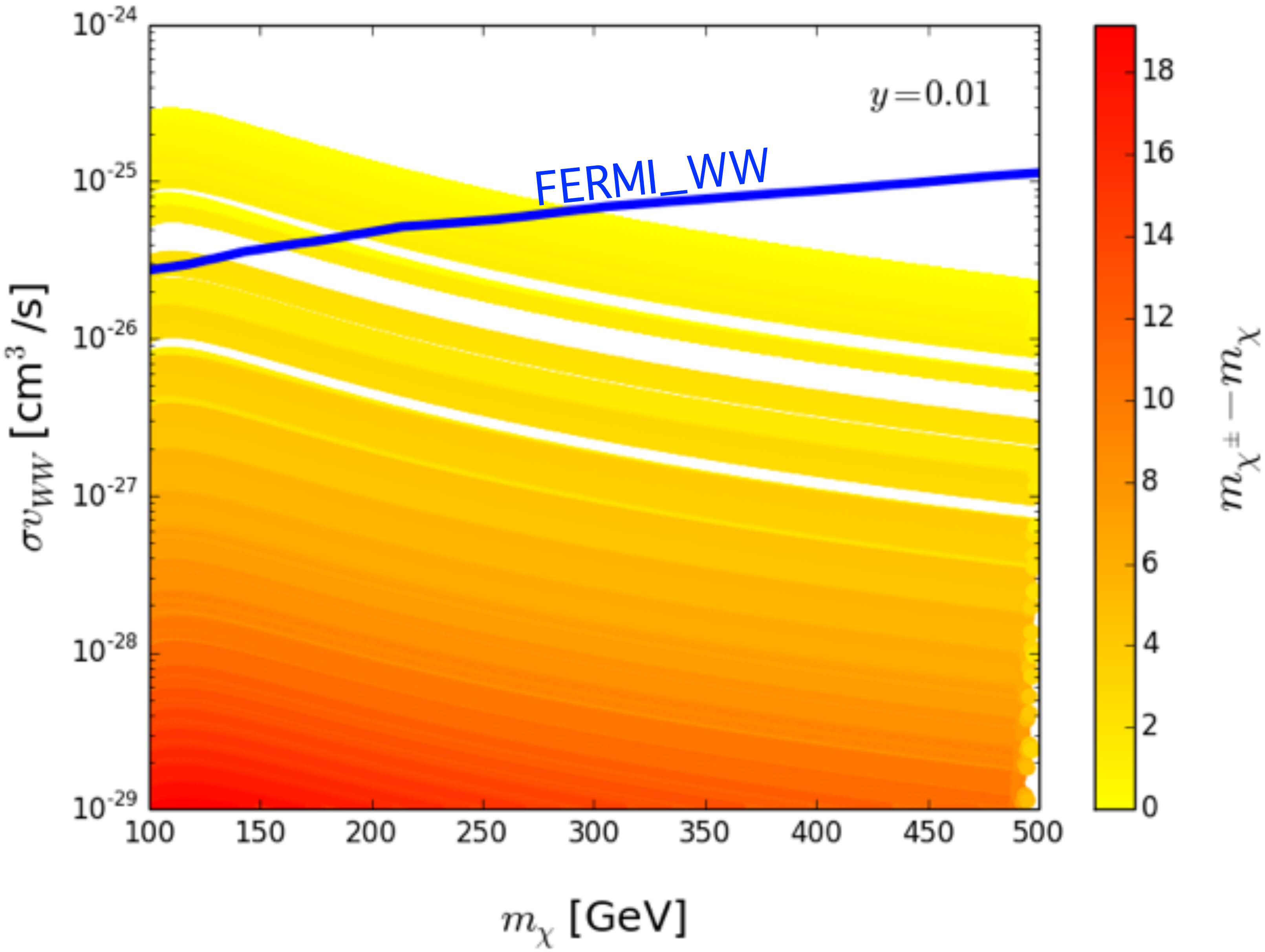
For small mass splitting:

- Colliders lose sensitivity
- Direct Search experiments lose sensitivity

$$c_{\chi\chi Z} \sim Z_{\rm D1}^2 - Z_{\rm D2}^2$$

$$c_{\chi\chi h} \sim y Z_{\rm S}(c_\theta Z_{\rm D1} + s_\theta Z_{\rm D2})$$

Bounds on degenerate spectra



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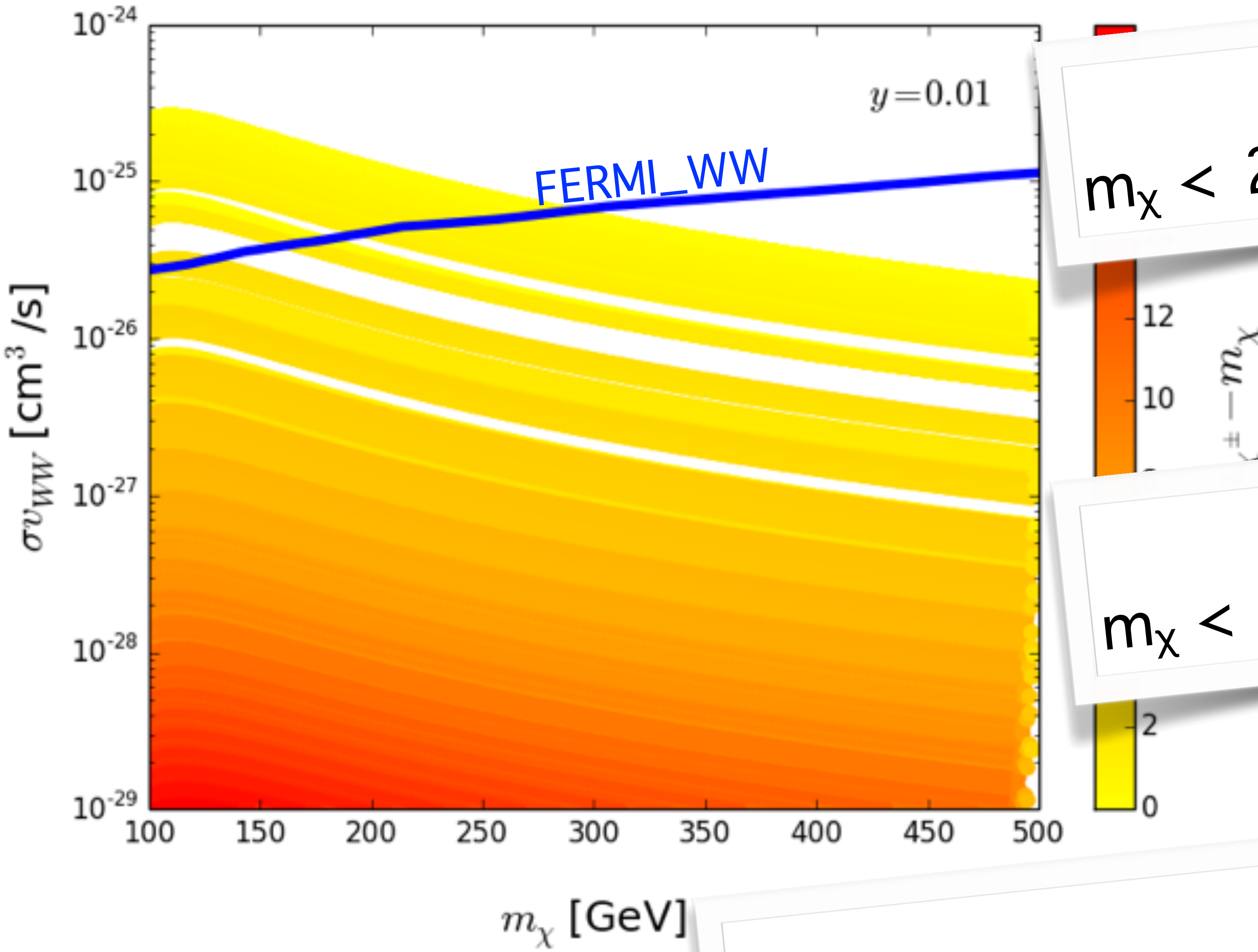
$$c_{\chi\chi h} \sim y Z_{\mathrm{S}} (c_\theta Z_{\mathrm{D1}} + s_\theta Z_{\mathrm{D2}})$$

- Annihilation to WW and ZZ is enhanced!

Searches for gamma rays INCREASE sensitivity

Bounds on degenerate spectra



y = 0.01
m_χ < 280 GeV & δm < 0.8 GeV

- Direct Search experiments lose sensitivity

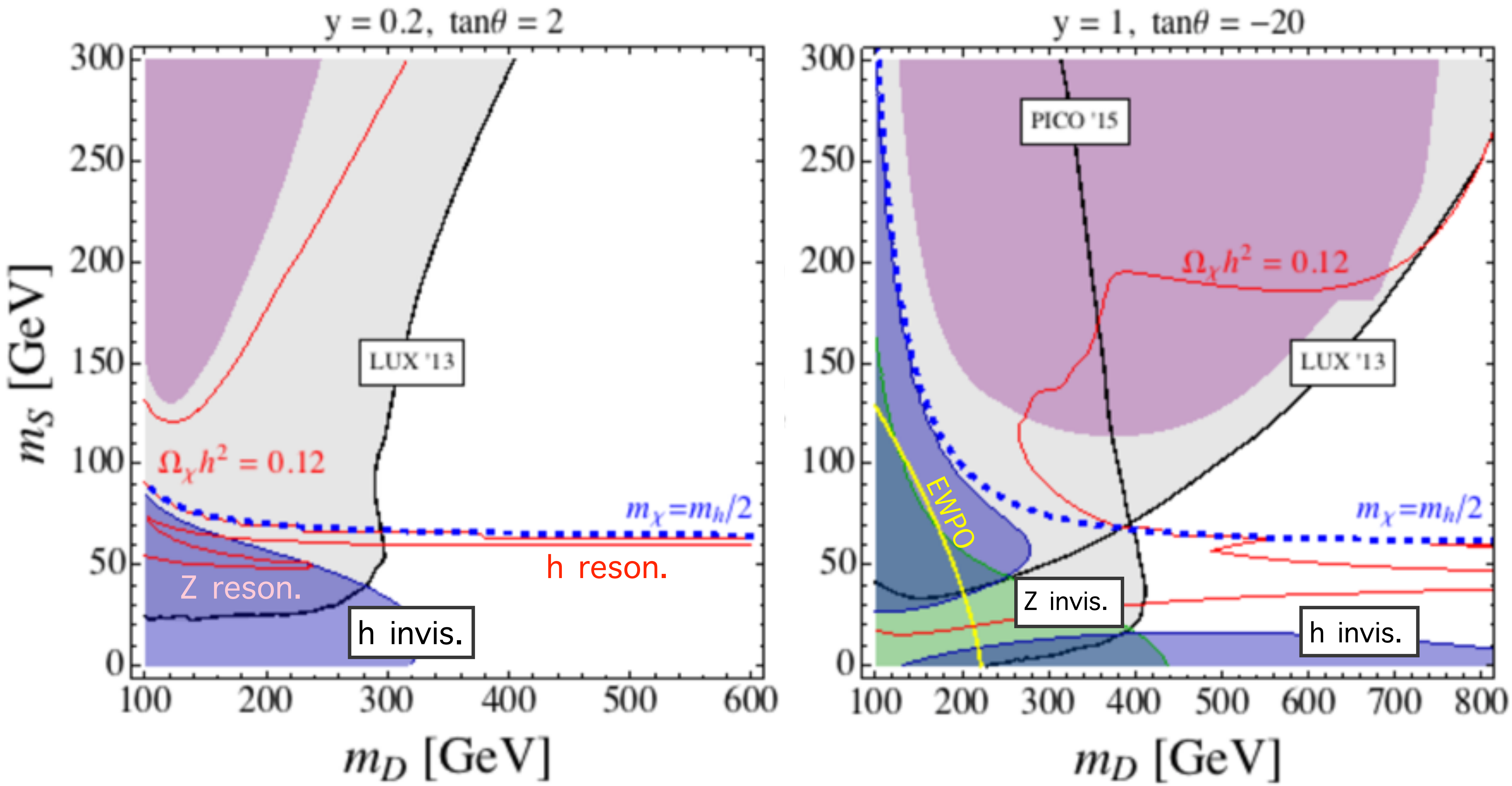
y = 0.2
m_χ < 220 GeV & δm < 20 GeV

y = 1
- m_χ < 275 GeV & all δm
- m_χ < 1 TeV & tanθ > 0 & δm > 15 GeV

Searches fo… INCREASE sensitivity

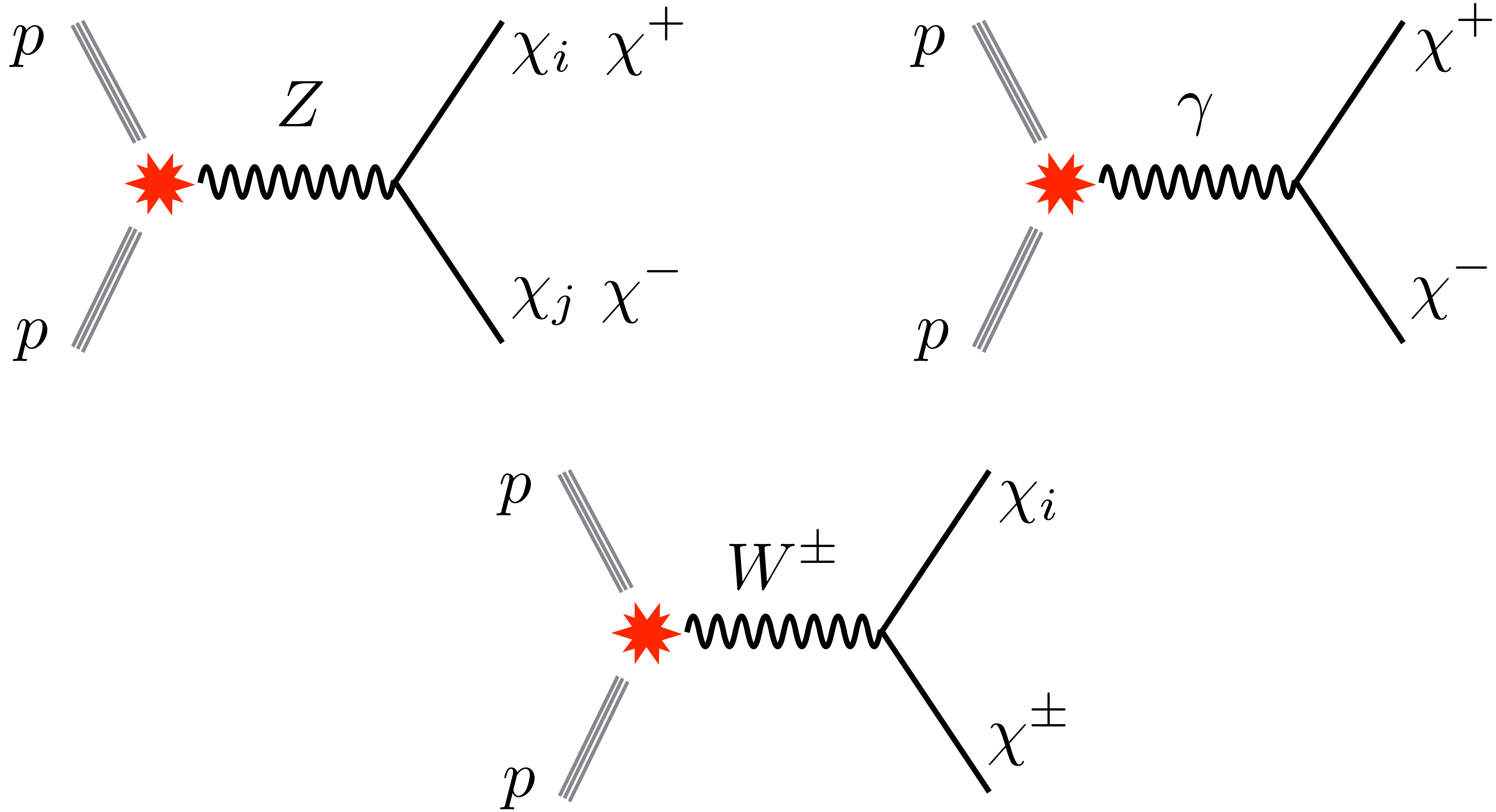
Collider Searches

Colliders constrain the low mass region

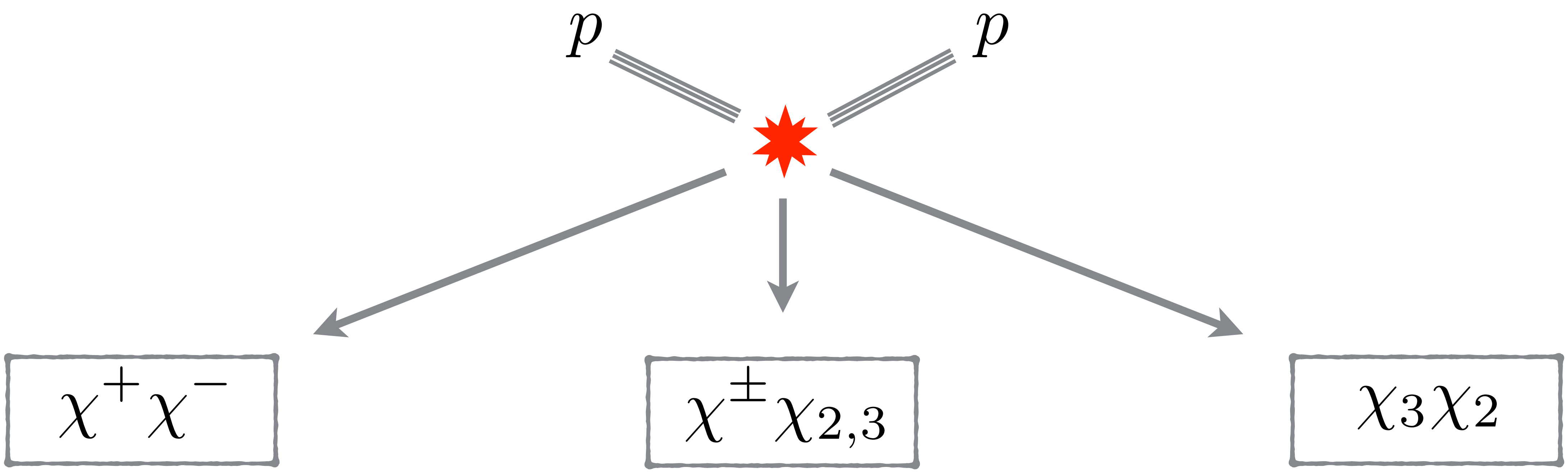


- EW precision observables — GFitter group, 1407.3792
- Invisible Higgs decays — $Br(h \to inv) < 26\%$ — Berchtle et al, 1403.1582
- Invisible Z-boson decays — $\Delta\Gamma_Z^{inv} < 3\,MeV$ — LEP, 0509008

LHC production channels



LHC final state topology



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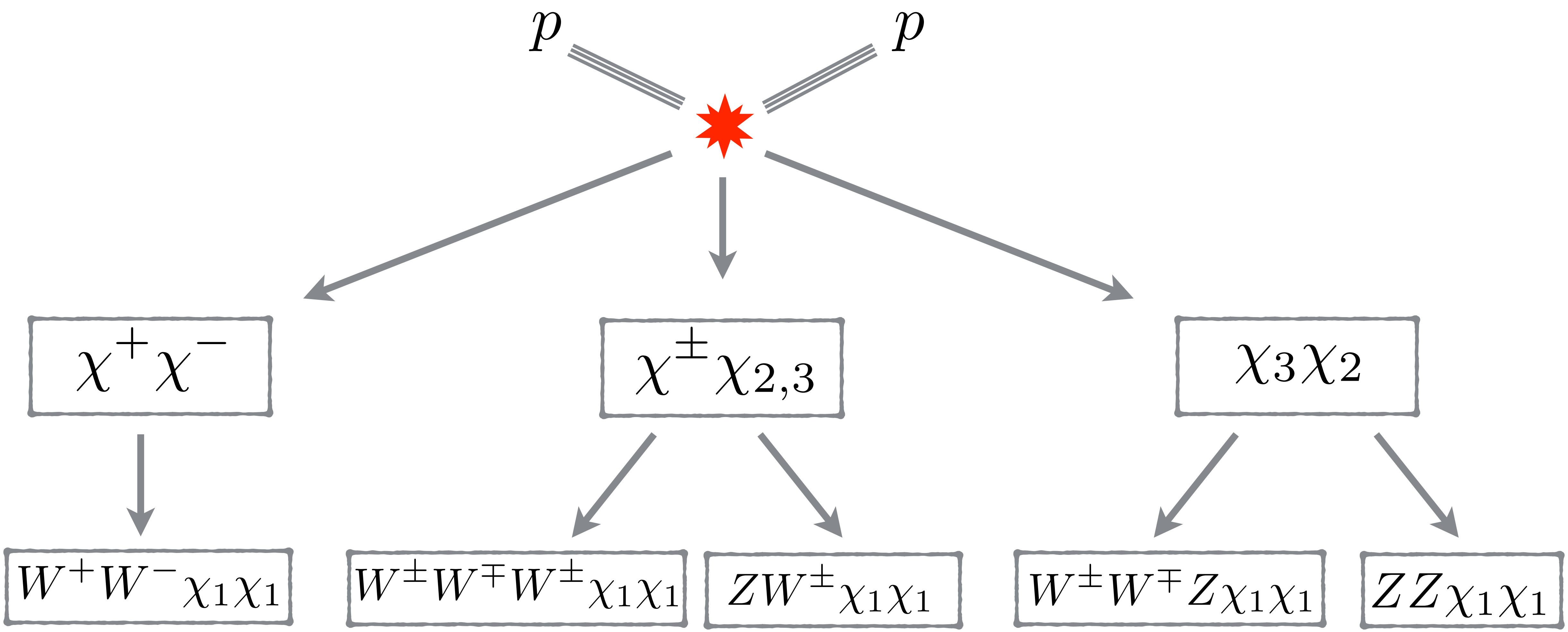

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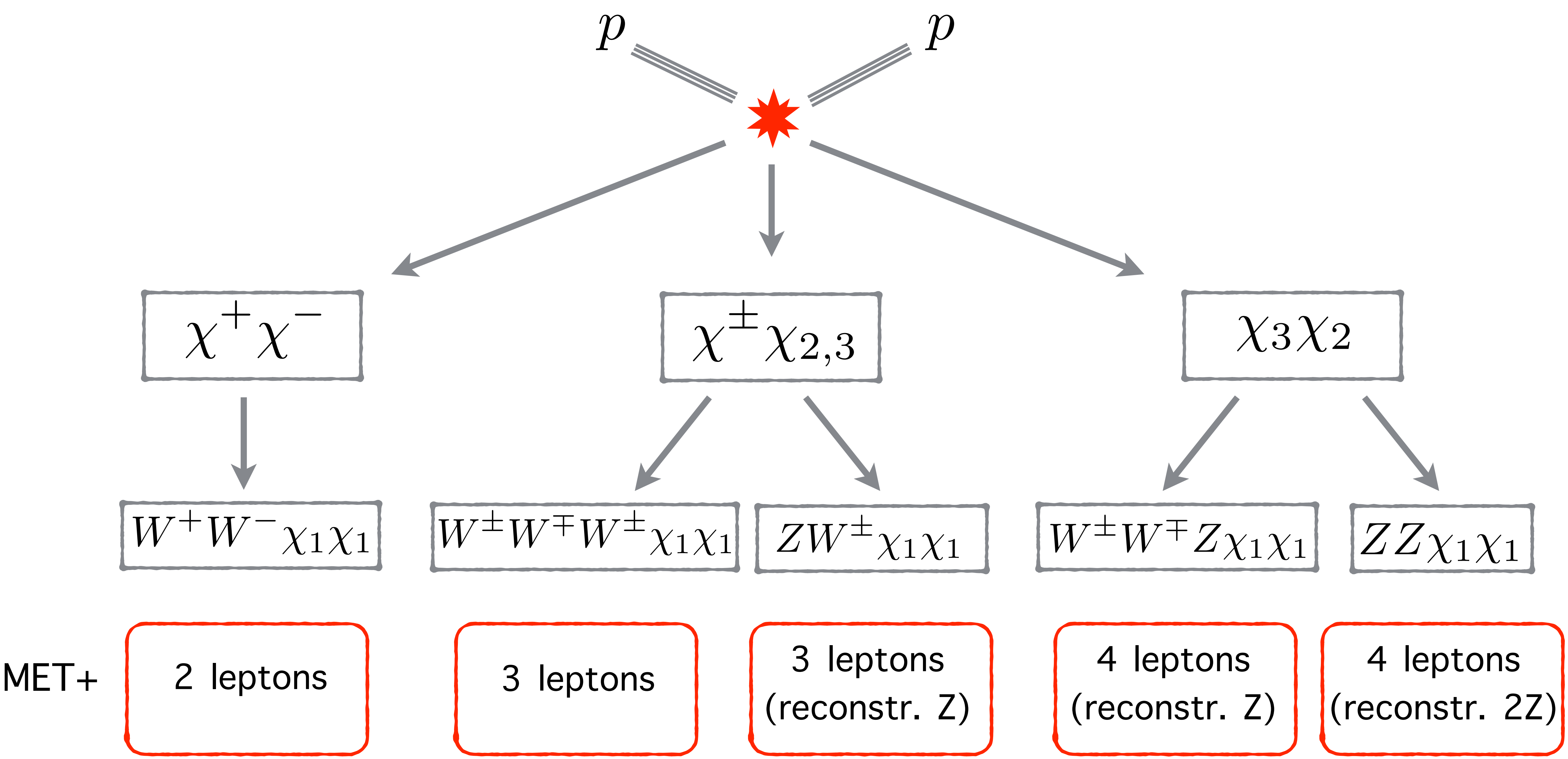


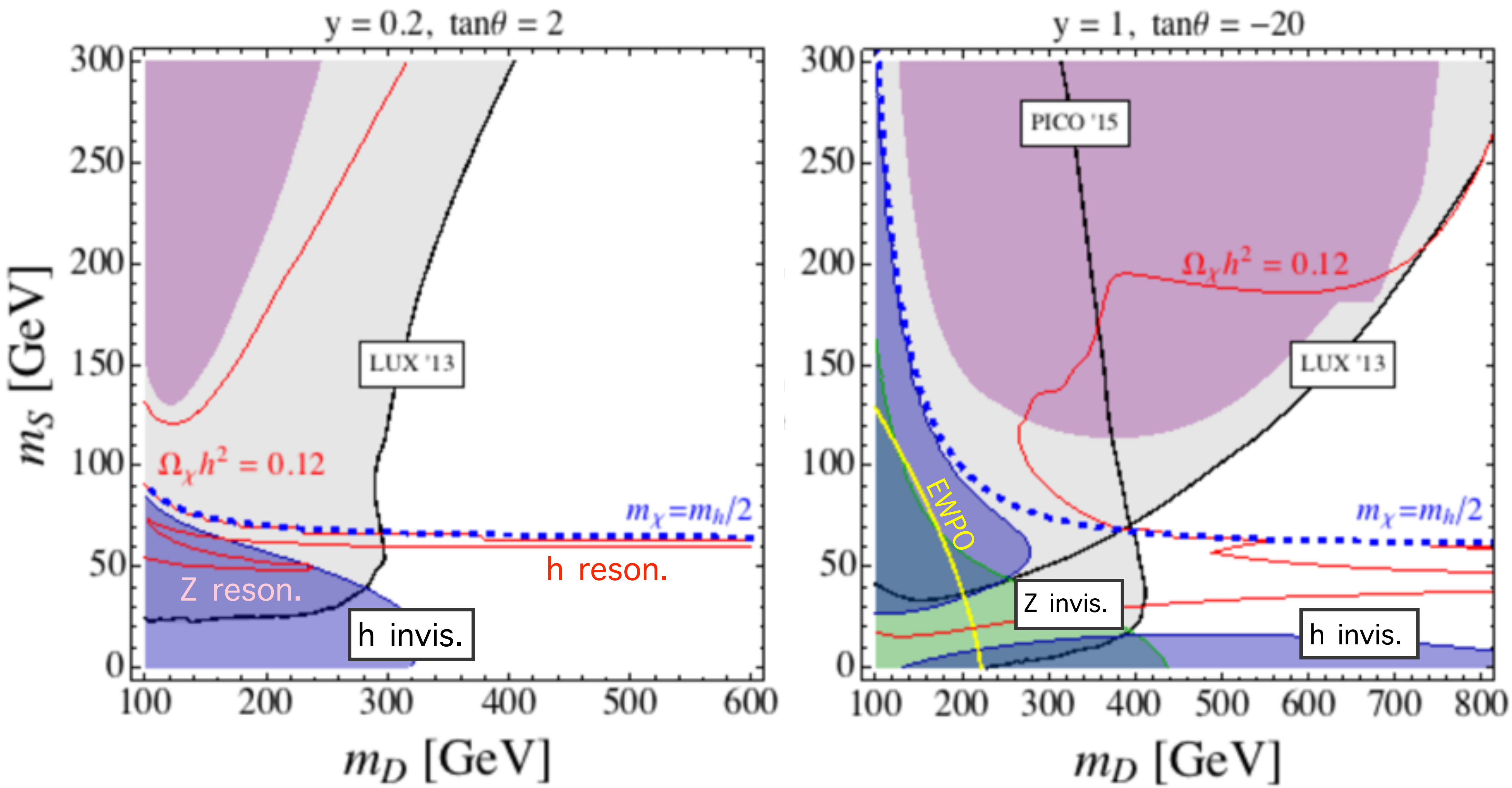
[like MSSM chargino]

ATLAS, 1402.7029

$$m_{\chi_2}, m_{\chi_3}, m_{\chi^+} \lesssim 270\, GeV$$
$$m_{\chi_1} \lesssim 75\, GeV$$
$$Br(\chi_{2,3} \to Z\chi_1) \gtrsim 60\%$$

see also
Enberg et al, 0706.0918
Schwaller et al, 1312.7350
Freitas et al, 1506.04149

Colliders constrain the low mass region



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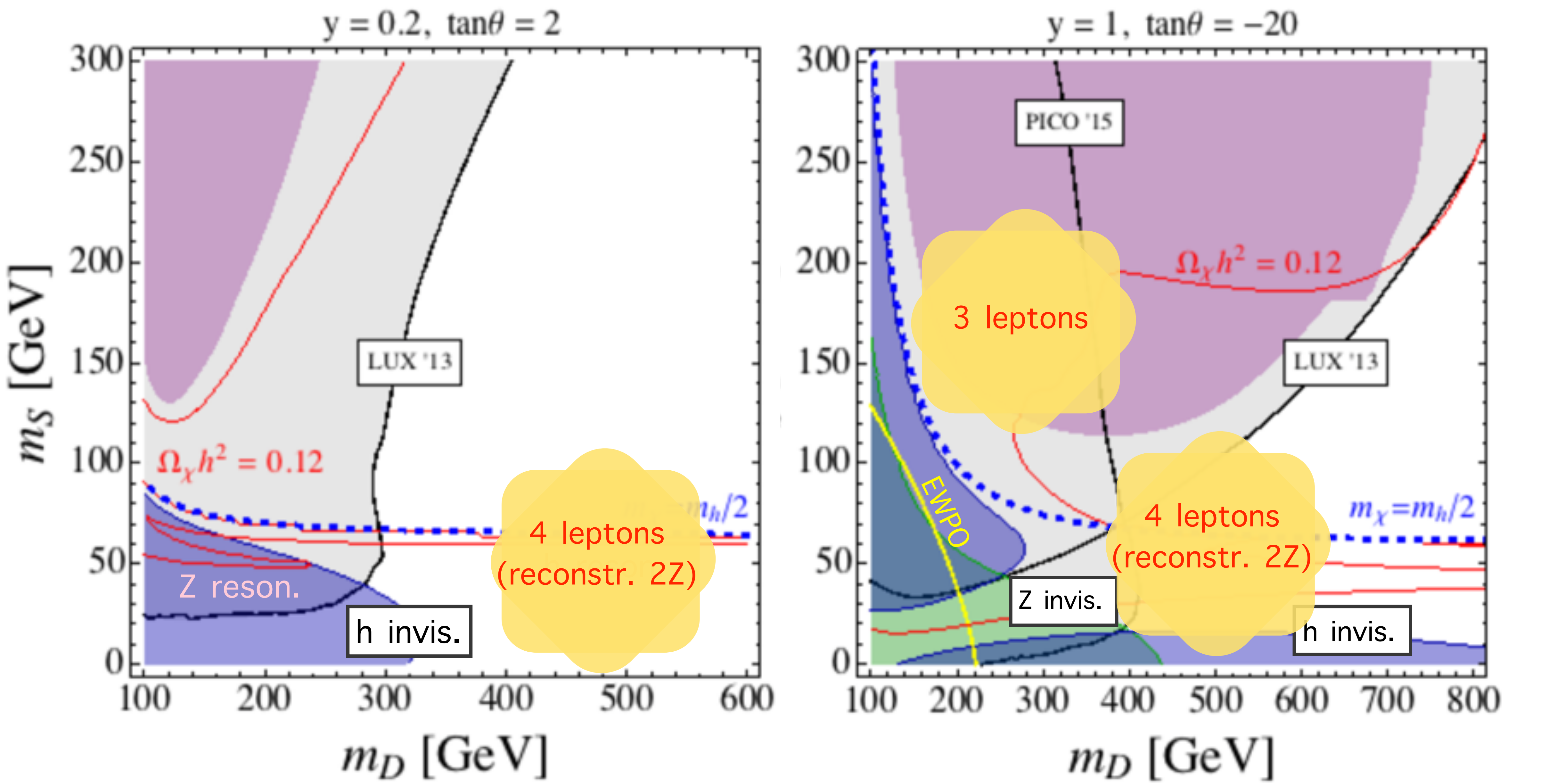

- Probe the Higgs resonance region
- Free from abundance arguments

Summary

- Singlet Doublet Dark Matter
  - A minimal WIMP dark matter that is stable by typical parity symmetry
  - Simplified Model of dark matter - nucleon interaction via Higgs
  - Simplified model of SUSY scenaria
  - Can be tested in almost all the experimental fronts
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  - Roughly: $m_\chi \lesssim 220$ GeV & $Z_1^2 \lesssim 0.65$ but can go up to multi-TeV
  - Indirect searches: The right place to look for degenerate spectra
  - CTA does not improve this picture by much

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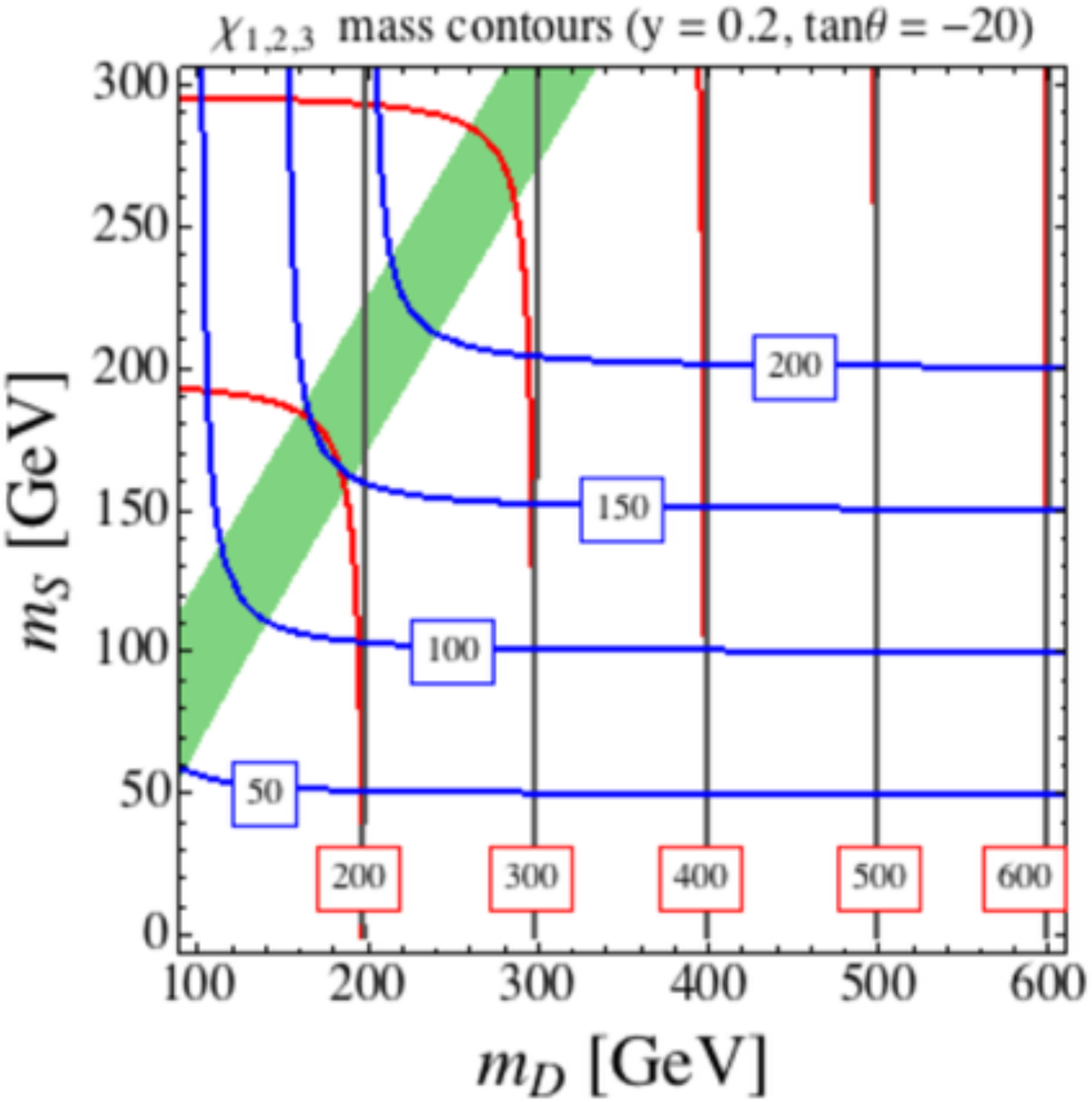
- Constraints form Colliders
  - Free from abundance considerations
  - Strong bounds from Higgs invisible decay
  - Multileptons + MET : Probe (among others) the Higgs resonance region

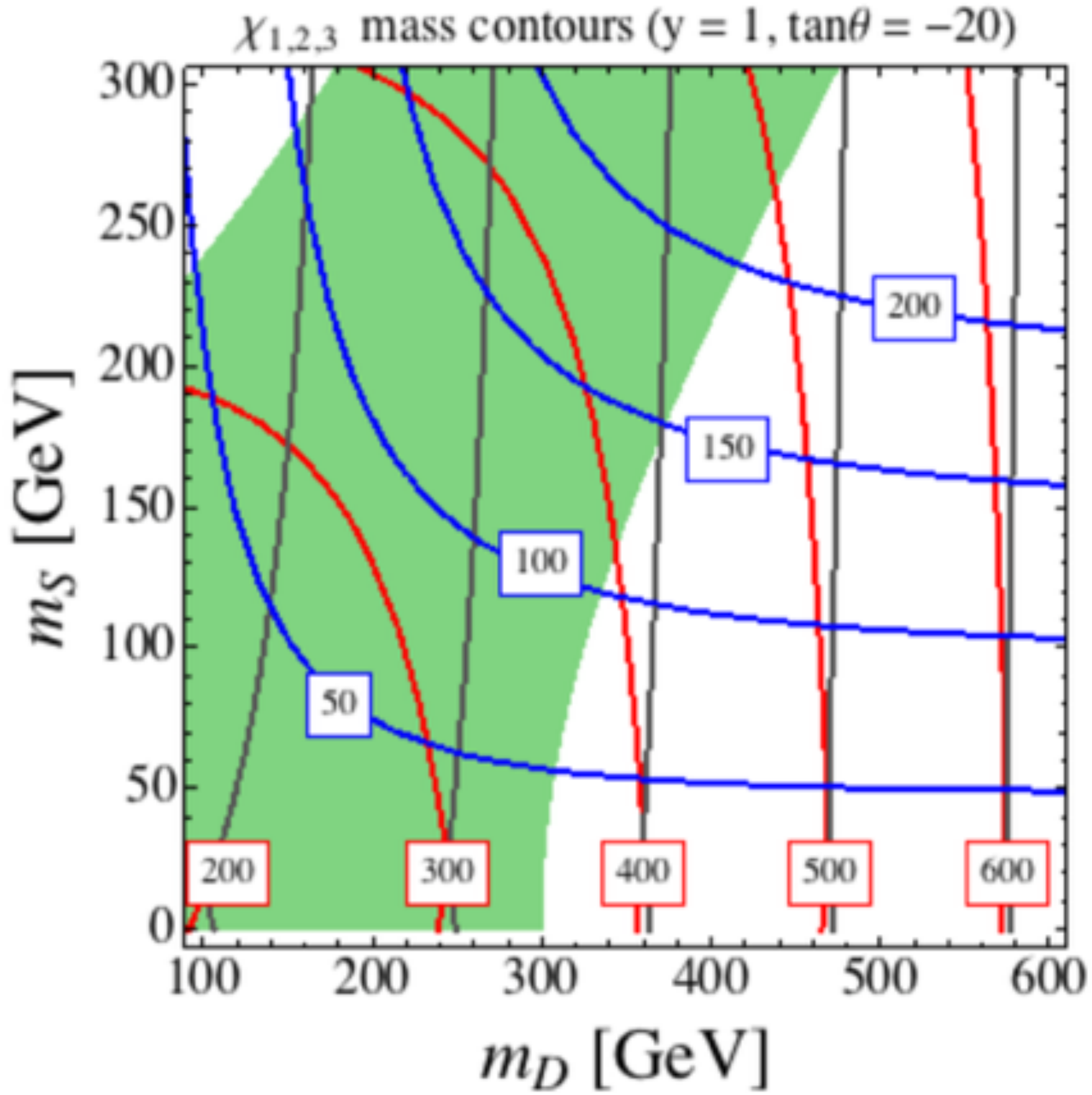
Future Directions

- Bounds from charged particles (positrons, antiprotons etc)
- Include loop contributions to dark matter - nucleon interactions
- Recast LHC searches

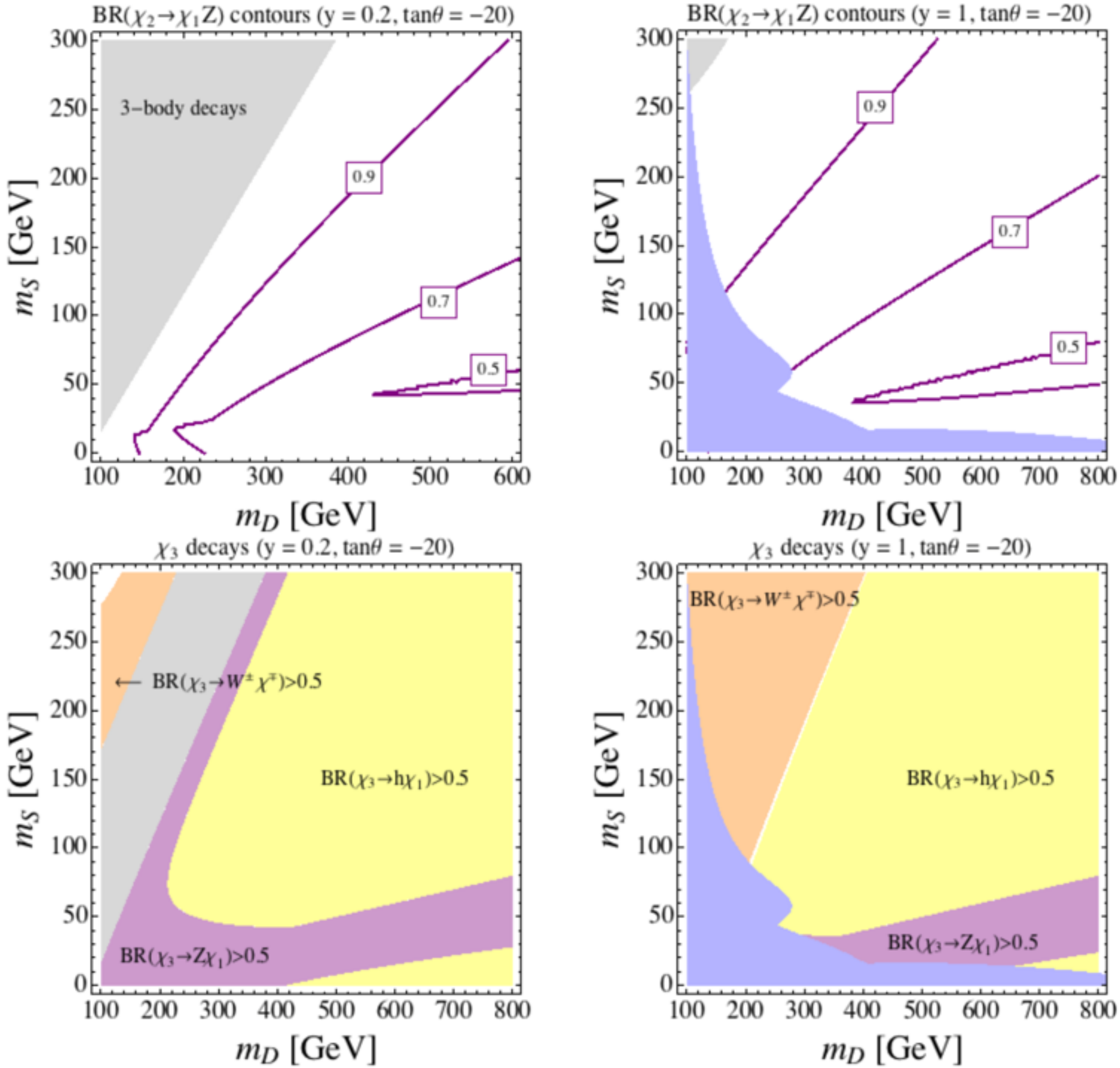
Extra slides



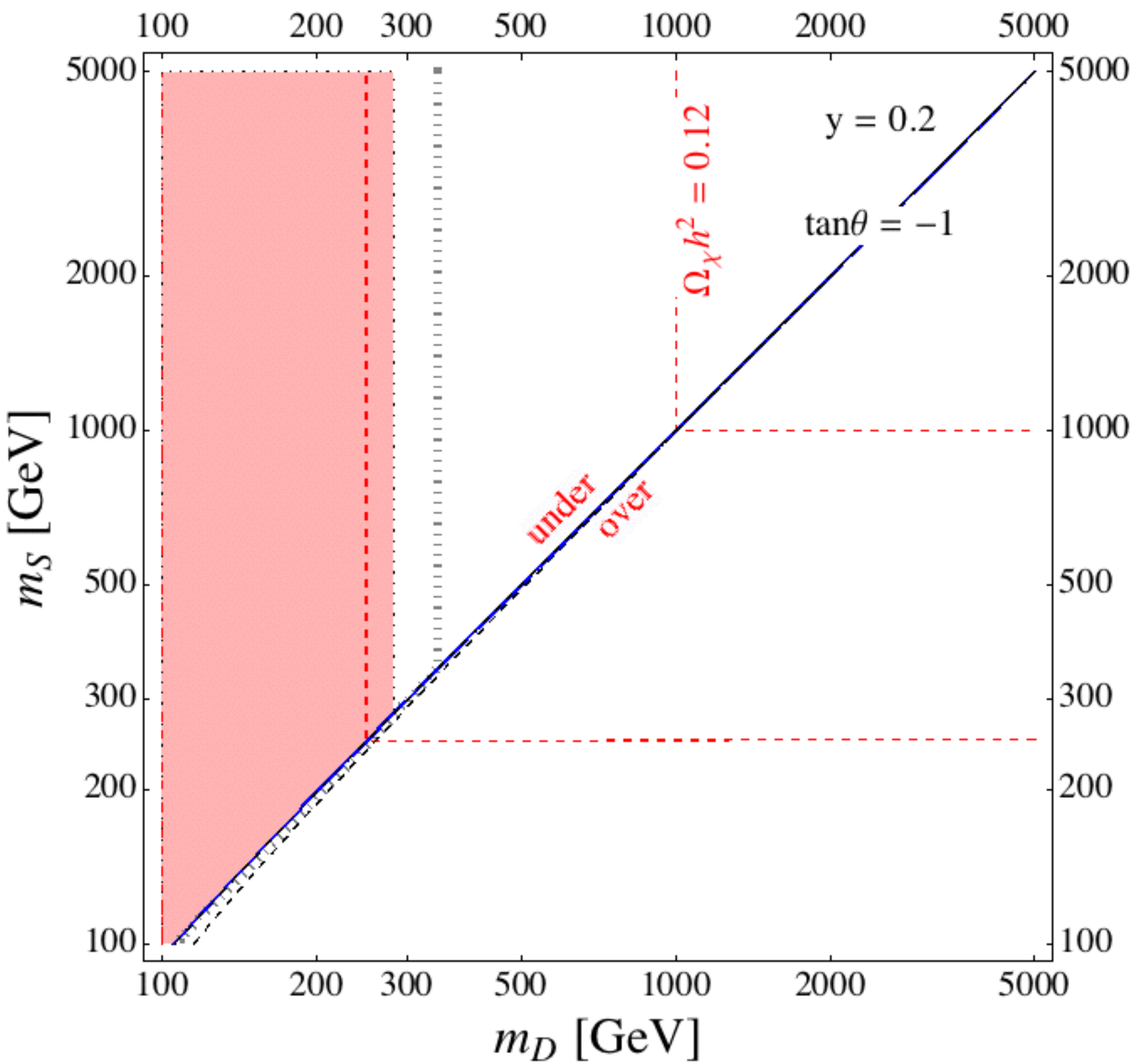
$\chi_{1,2,3}$ mass contours (y = 0.2, tanθ = −20)
m_S [GeV]
m_D [GeV]

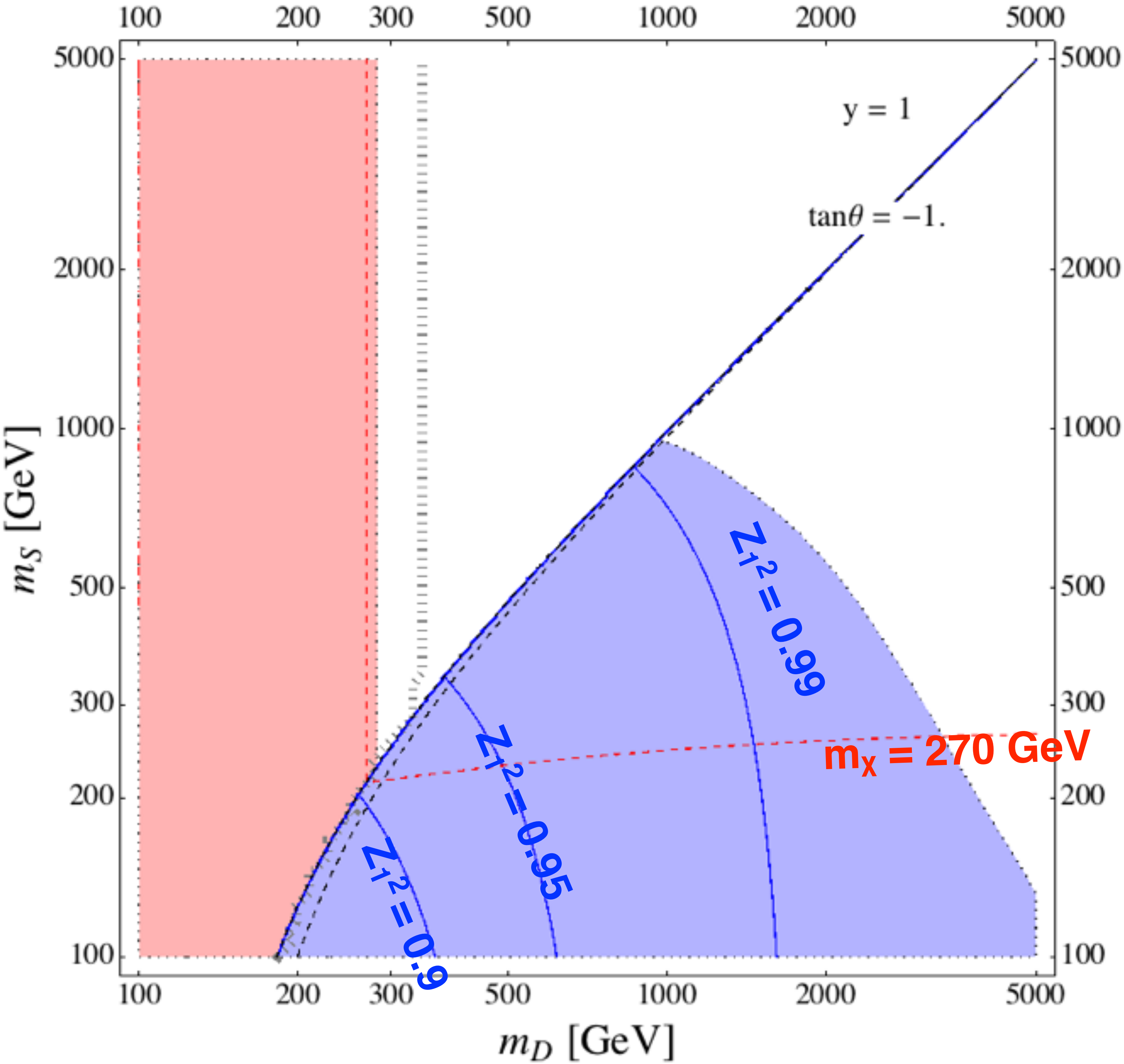


$\chi_{1,2,3}$ mass contours (y = 1, tanθ = −20)
m_S [GeV]
m_D [GeV]

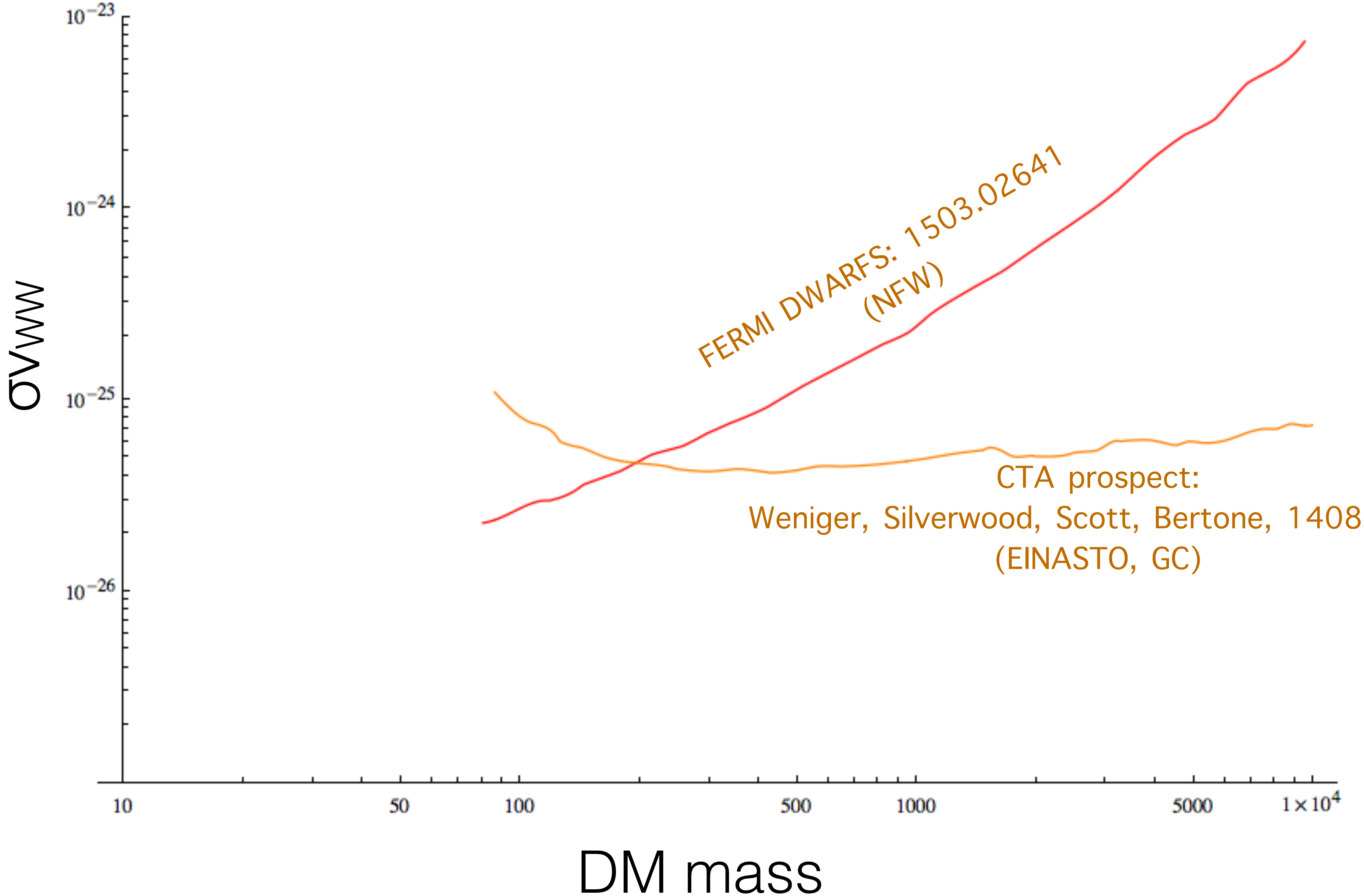


BR(χ2→χ1Z) contours (y = 0.2, tanθ = −20)
3−body decays
0.9
0.7
0.5
m_S [GeV]
m_D [GeV]
BR(χ2→χ1Z) contours (y = 1, tanθ = −20)
0.9
0.7
0.5
m_S [GeV]
m_D [GeV]
χ3 decays (y = 0.2, tanθ = −20)
← BR(χ3→W±χ∓)>0.5
BR(χ3→hχ1)>0.5
BR(χ3→Zχ1)>0.5
m_S [GeV]
m_D [GeV]
χ3 decays (y = 1, tanθ = −20)
BR(χ3→W±χ∓)>0.5
BR(χ3→hχ1)>0.5
BR(χ3→Zχ1)>0.5
m_S [GeV]
m_D [GeV]


100
200
300
500
1000
2000
5000
y = 0.2
tanθ = −1
$\Omega_\chi h^2 = 0.12$
under
over
m_S [GeV]
m_D [GeV]



100
200
300
500
1000
2000
5000
y = 1
tanθ = −1.
$Z_1^2 = 0.99$
$Z_1^2 = 0.95$
$Z_1^2 = 0.9$
m_X = 270 GeV
m_S [GeV]
m_D [GeV]


10^{-23}
10^{-24}
10^{-25}
10^{-26}
σvWW
FERMI DWARFS: 1503.02641
(NFW)
CTA prospect:
Weniger, Silverwood, Scott, Bertone, 1408.4131
(EINASTO, GC)
10
50
100
500
1000
5000
1×10^4
DM mass