Exploring the CP-Violating Inert-Doublet Model

Per Osland
September 2011
QFTHEP 2011

work with
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PRD 2009, JHEP 2011

Dark Matter

- Astrophysical evidence: 85% of Universe matter is dark [list from Hooper & Baltz, 2008]
  - rotational speeds of galaxies
  - orbital velocities of galaxies within clusters
  - gravitational lensing
  - cosmic microwave background
  - light element abundance
  - large scale structure
- Not homogeneously distributed
- Many particle and astrophysical candidates

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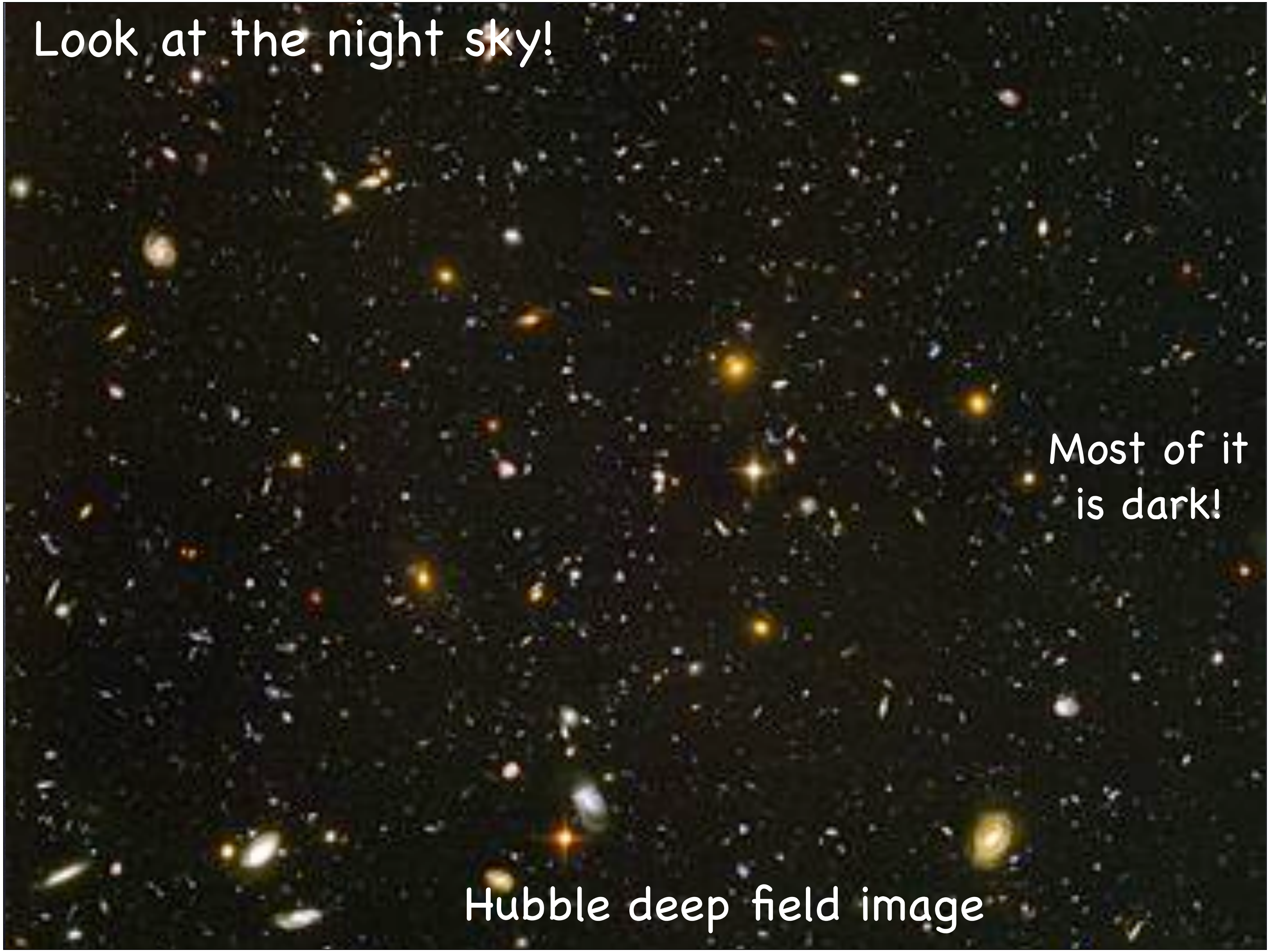
Local halo density: 0.22-0.75 GeV/cm^3 One per cup of coffee

Bullet cluster (Chandra/NASA)

Total mass (blue) from grav. lensing   Visible mass (red) from X ray emission


Look at the night sky!
Most of it
is dark!
Hubble deep field image

footnote: scales

1 light year $\approx (3\times10^8 m/s)\times(\pi\times10^7 s) \approx 10^{16} m$

galactic diameter $\approx$ 80,000 light years $\approx 10^{21}$m

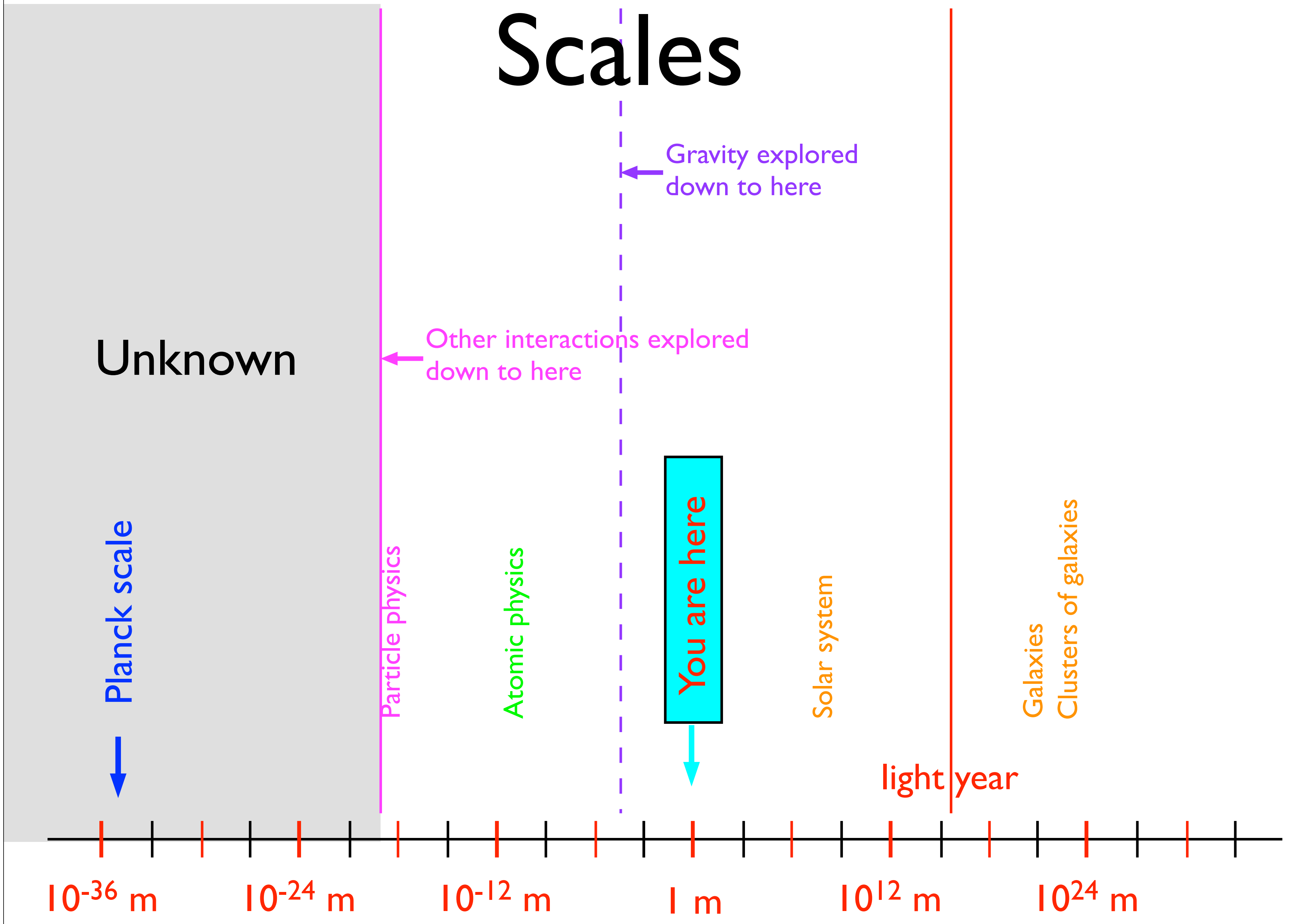
1 parsec = 1 pc $\approx$ 3.26 light years

Solar system: ~ 8.5 kpc from Galactic Center

8.5 kpc (~28,000 light years) vs 40,000 light years

➨ We are far from the galactic center

Scales

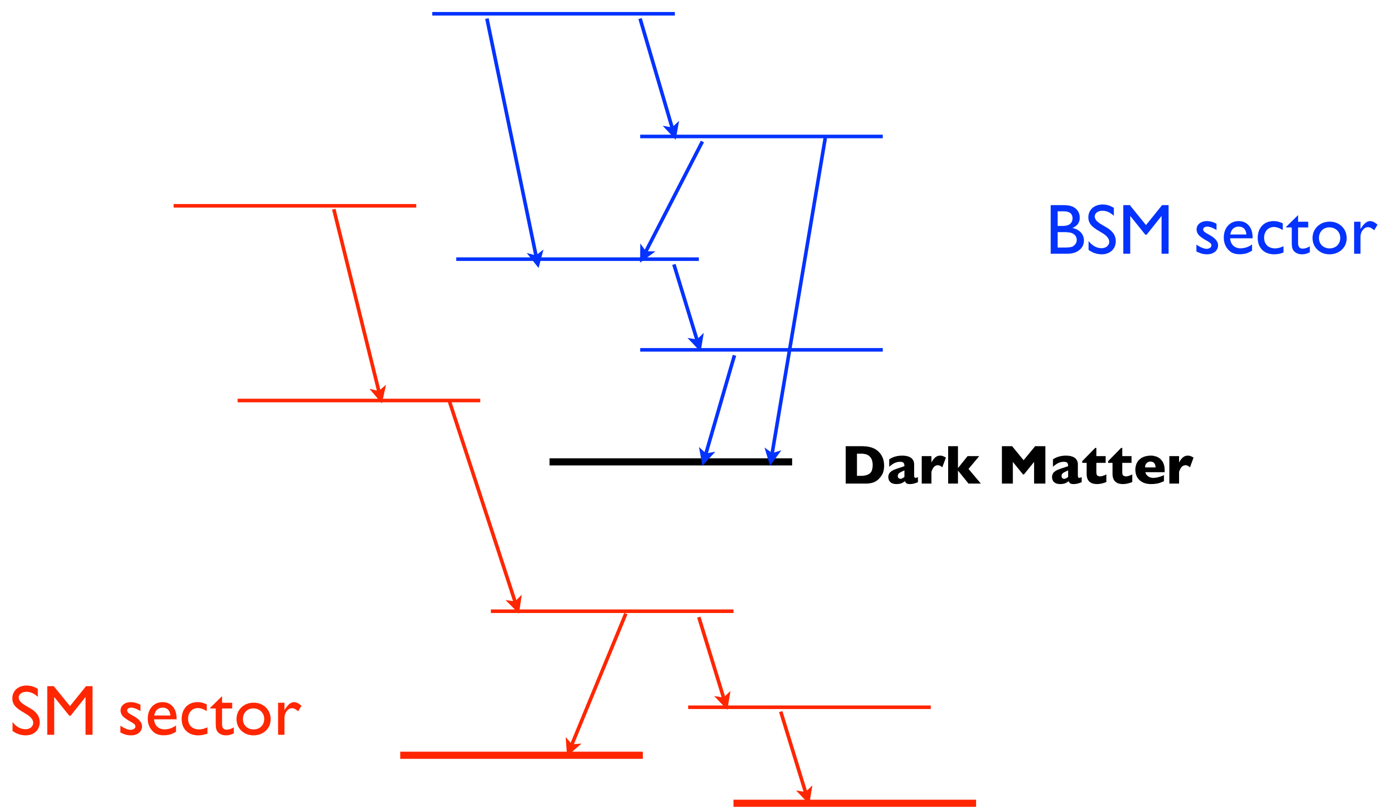

Unknown
Gravity explored
down to here
Other interactions explored
down to here
Planck scale
Particle physics
Atomic physics
You are here
Solar system
Galaxies
Clusters of galaxies
light year
10^{-36} m
10^{-24} m
10^{-12} m
1 m
10^{12} m
10^{24} m

Ambition:

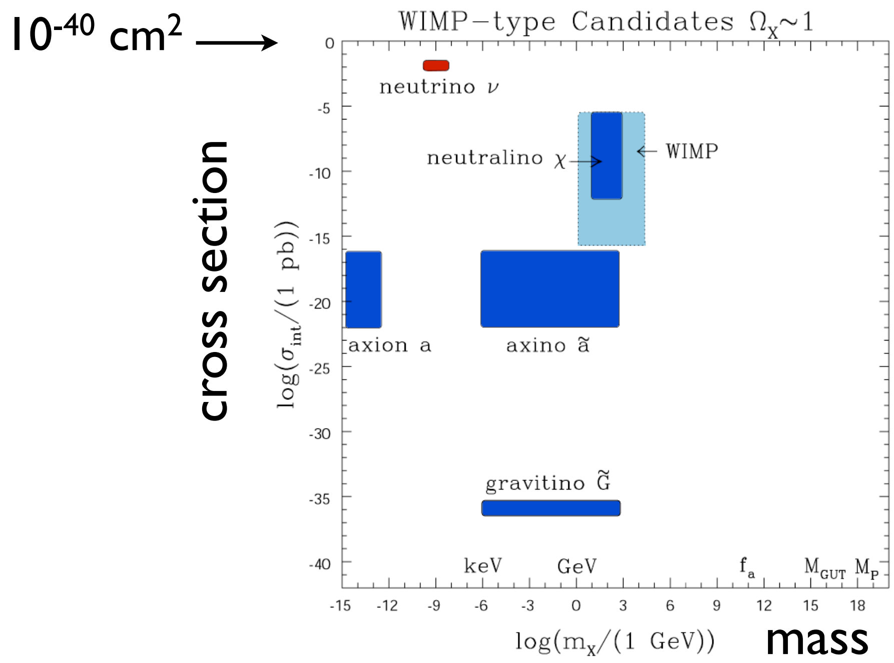
- Problem at scales of 10^{20} m
- Solution: new physics at scales below 10^{-18} m

!!!

Schematic spectrum



The Big Picture



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- ????

solution of DM: must go beyond SM!

Leszek Roszkowski, 2010

Popular Dark Matter candidates

- Neutralino of Supersymmetry
- Axions, axinos
- Neutrinos (exist!)
- Gravitinos
- Scalars

Simple estimate

Density of dark matter given by Early Universe consideration:

Equilibrium between Hubble expansion and annihilation

Calculable

$$\Omega_{\rm DM} h^2 = C \frac{T_0^3}{M_{\rm Pl}^3} \frac{1}{\langle \sigma v \rangle}$$

T_0 CMBR temp

WMAP: $\Omega_{\rm DM} h^2 = 0.1131 \pm 0.0034$ and $\langle \sigma v \rangle = \frac{\alpha^2}{m^2}$ ⇒ $m \sim 100 \text{ GeV}$

mass scale fits well with SUSY

Direct/indirect detection?

- Interacts very weakly with ordinary matter
- No strong (nuclear) interactions
- Might be local enhancement near solar system
- Ordinary particles might be scattered, recoil (CDMS-II)
- Might annihilate in sun, look for photons/positrons
- Might annihilate in space, Milky Way,...

PAMELA, ATIC, Fermi-LAT,...

Scalar DM

- "Inert (Scalar) Doublet Model", Barbieri et al, 2006

Extend SM with additional scalar doublet, unbroken Z_2 symmetry makes lightest "odd" particle stable. No vev, no direct coupling to SM matter.

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

2HDM

Unbroken Z_2: $H_1 \to H_1$ and $H_2 \to -H_2$.

$\langle H_2 \rangle = 0$.

Coupling to non-inert Higgs → $\lambda_L = (\lambda_3 + \lambda_4 + \lambda_5)/2$

Motivation (Barbieri et al)

May alleviate Little Hierarchy Problem, by allowing heavier SM Higgs (400 GeV) without conflict with "electroweak precision data" (S and T).

Also work by:

- Ma; Kubo, Ma, Suematso; Cao, Ma, Rajasekaran
- Lopez Honorez, Nezri, Oliver, Tytgat
- Gustafsson, Lundstrom, Bergstrom, Edsjo
- Cirelli, Strumia, Tamburini
- Andreas, Hambye, Tytgat
- Dolle, Su
- Pierce, Thaler
- ...

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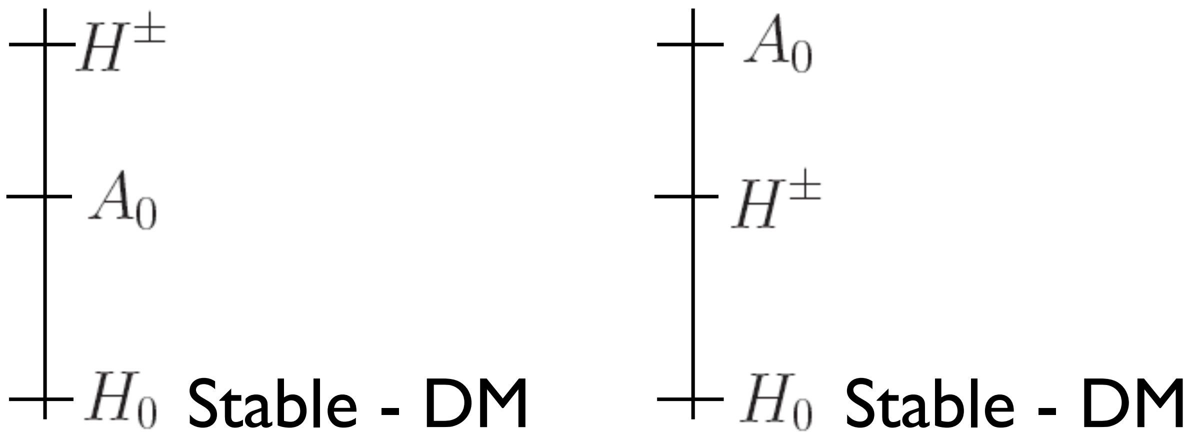
New particles (from isospin doublet):



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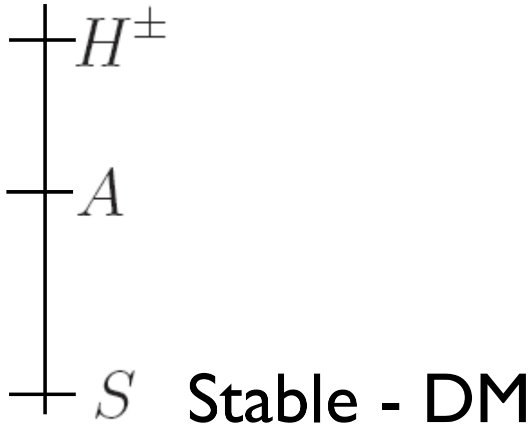
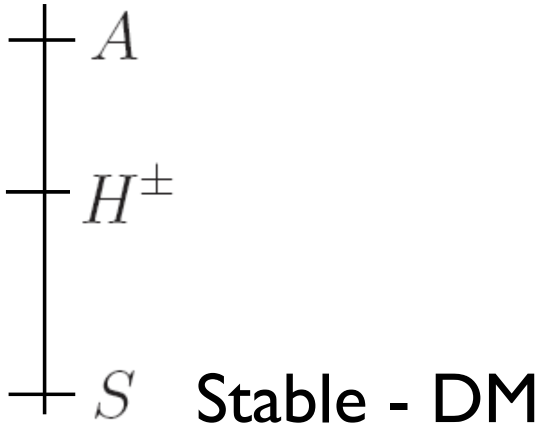




Laura Lopez Honorez, Emmanuel Nezri, Josep F. Oliver, Michel H.G. Tytgat

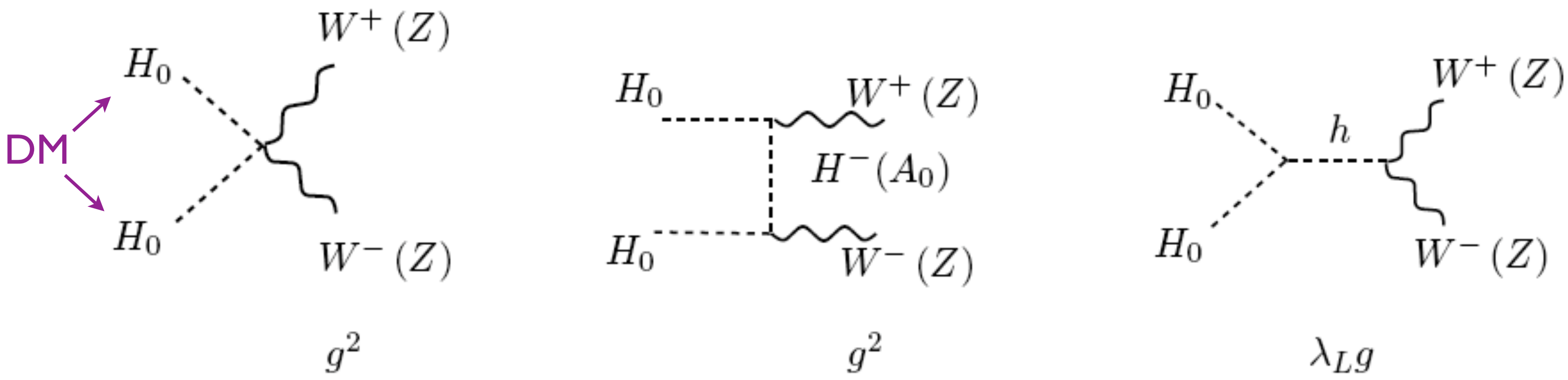


Figure 1: Annihilation channels into gauge bosons final state with corresponding couplings.

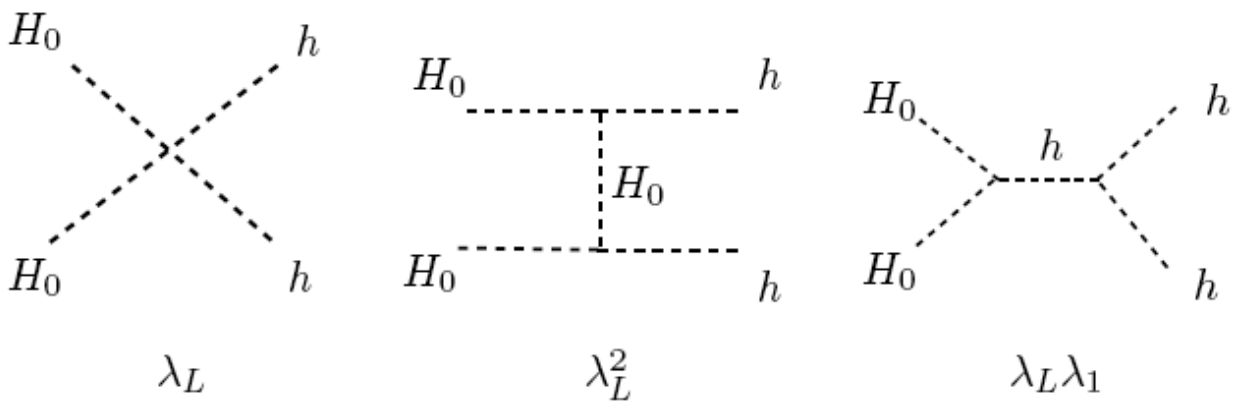
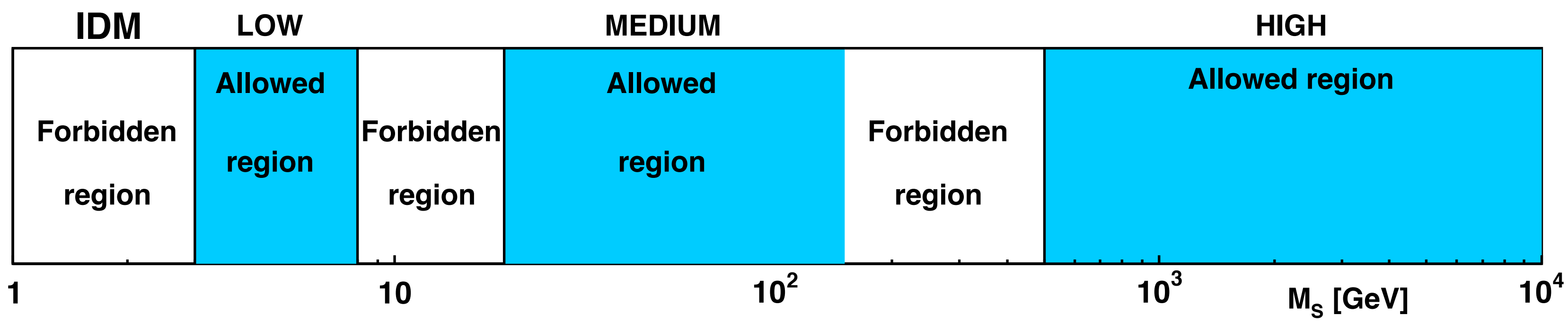


Figure 2: Annihilation channels into Higgs final state.

Allowed regions

$M_{H^\pm} > 79.3$ GeV   LEP (PDG)

$M_A \gtrsim 110$ GeV   LEP, Lundquist et al



Three (4) regions allowed for $M_S \equiv M_{H_0}$

LOW: Andreas, Hambye, Tytgat; Hambye, Tytgat

MEDIUM: Barbieri, Hall, Rychkov; Lopez Honorez, Nezri, Oliver, Tytgat

"NEW, VIABLE": Lopez Honorez, Yaguna

HIGH: Lopez Honorez, Nezri, Oliver, Tytgat; Hambye, Ling, Lopez Honorez, Rocher; Cirelli, Fornengo, Strumia

IDM2: 2HDM + inert doublet

Grzadkowski et al, 2009

Motivation: IDM + CP violation

Fields:

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\boxed{\eta = \begin{pmatrix} \eta^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}}$$

Coupling:

Potential:

$$V(\Phi_1, \Phi_2, \eta) = V_{12}(\Phi_1, \Phi_2) + V_3(\eta) + V_{123}(\Phi_1, \Phi_2, \eta)$$

$$V_{12}(\Phi_1,\Phi_2) = -\frac{1}{2}\left\{m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]\right\}$$

(standard)

$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

$$V_3(\eta) = m_\eta^2\eta^\dagger\eta + \frac{\lambda_\eta}{2}(\eta^\dagger\eta)^2$$

Coupling:

$$V_{123}(\Phi_1,\Phi_2,\eta) = \lambda_{1133}(\Phi_1^\dagger\Phi_1)(\eta^\dagger\eta) + \lambda_{2233}(\Phi_2^\dagger\Phi_2)(\eta^\dagger\eta)$$

$$+\lambda_{1331}(\Phi_1^\dagger\eta)(\eta^\dagger\Phi_1) + \lambda_{2332}(\Phi_2^\dagger\eta)(\eta^\dagger\Phi_2)$$

(most general)

$$+\tfrac{1}{2}\left[\lambda_{1313}(\Phi_1^\dagger\eta)^2 + \text{h.c.}\right] + \tfrac{1}{2}\left[\lambda_{2323}(\Phi_2^\dagger\eta)^2 + \text{h.c.}\right]$$

Many parameters...

Many parameters! Simplify!

"Dark democracy":
$$\lambda_a \equiv \lambda_{1133} = \lambda_{2233},$$
$$\lambda_b \equiv \lambda_{1331} = \lambda_{2332},$$
$$\lambda_c \equiv \lambda_{1313} = \lambda_{2323} \text{ (real)}.$$

Masses of inert sector:

$$M^2_{\eta^\pm} = m^2_\eta + \tfrac{1}{2}\lambda_a v^2,$$
$$M^2_S = m^2_\eta + \tfrac{1}{2}(\lambda_a + \lambda_b + \lambda_c)v^2 = M^2_{\eta^\pm} + \tfrac{1}{2}(\lambda_b + \lambda_c)v^2,$$
$$M^2_A = m^2_\eta + \tfrac{1}{2}(\lambda_a + \lambda_b - \lambda_c)v^2 = M^2_{\eta^\pm} + \tfrac{1}{2}(\lambda_b - \lambda_c)v^2$$

Important:

These $\lambda_{a,b,c}$ characterize coupling of inert sector to non-inert sector, and also mass splitting in inert sector

“Dark democracy”

Constraints

- positivity (rather complicated), 20% excluded
- unitarity, 60% excluded
- global minimum, 10% excluded
- additional 2HDM constraints: $T, \quad b \to s\gamma$ etc
- DM

determined by MicrOMEGAs

EW "precision data"

Positivity

Define:

$$\begin{aligned}\lambda_x &= \lambda_3 + \min\left(0, \lambda_4 - |\lambda_5|\right)\\ \lambda_y &= \lambda_{1133} + \min\left(0, \lambda_{1331} - |\lambda_{1313}|\right)\\ \lambda_z &= \lambda_{2233} + \min\left(0, \lambda_{2332} - |\lambda_{2323}|\right)\end{aligned}$$

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_\eta > 0, \quad \lambda_x > -\sqrt{\lambda_1 \lambda_2}$$

$$\lambda_y > -\sqrt{\lambda_1 \lambda_\eta}, \quad \lambda_z > -\sqrt{\lambda_2 \lambda_\eta}$$

Plus additional constraint, which in the case of Dark democracy $\lambda_y = \lambda_z$ takes the form:

$$\lambda_y \geq 0 \vee \left(\lambda_\eta \lambda_x - \lambda_y^2 > -\sqrt{(\lambda_\eta \lambda_1 - \lambda_y^2)(\lambda_\eta \lambda_2 - \lambda_y^2)}\right)$$

Getting correct DM density

Main Early Universe annihilation mechanisms:

- Annihilation to $W^+ W^-$, effective above 75 GeV
- Annihilation via real or virtual neutral Higgs

like IDM...

Annihilation in the Early Universe

The DM particles can annihilate via the gauge coupling:

$$SSW^+W^- : \quad \frac{ig^2}{2}$$

$$SSZZ : \quad \frac{ig^2}{2\cos^2\theta_W}$$

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or to non-inert scalars via trilinear

Note

$$SSH_j : \quad -2iF_{SSj}\lambda_L v$$

$$F_{SSj} = \cos\beta R_{j1} + \sin\beta R_{j2}$$

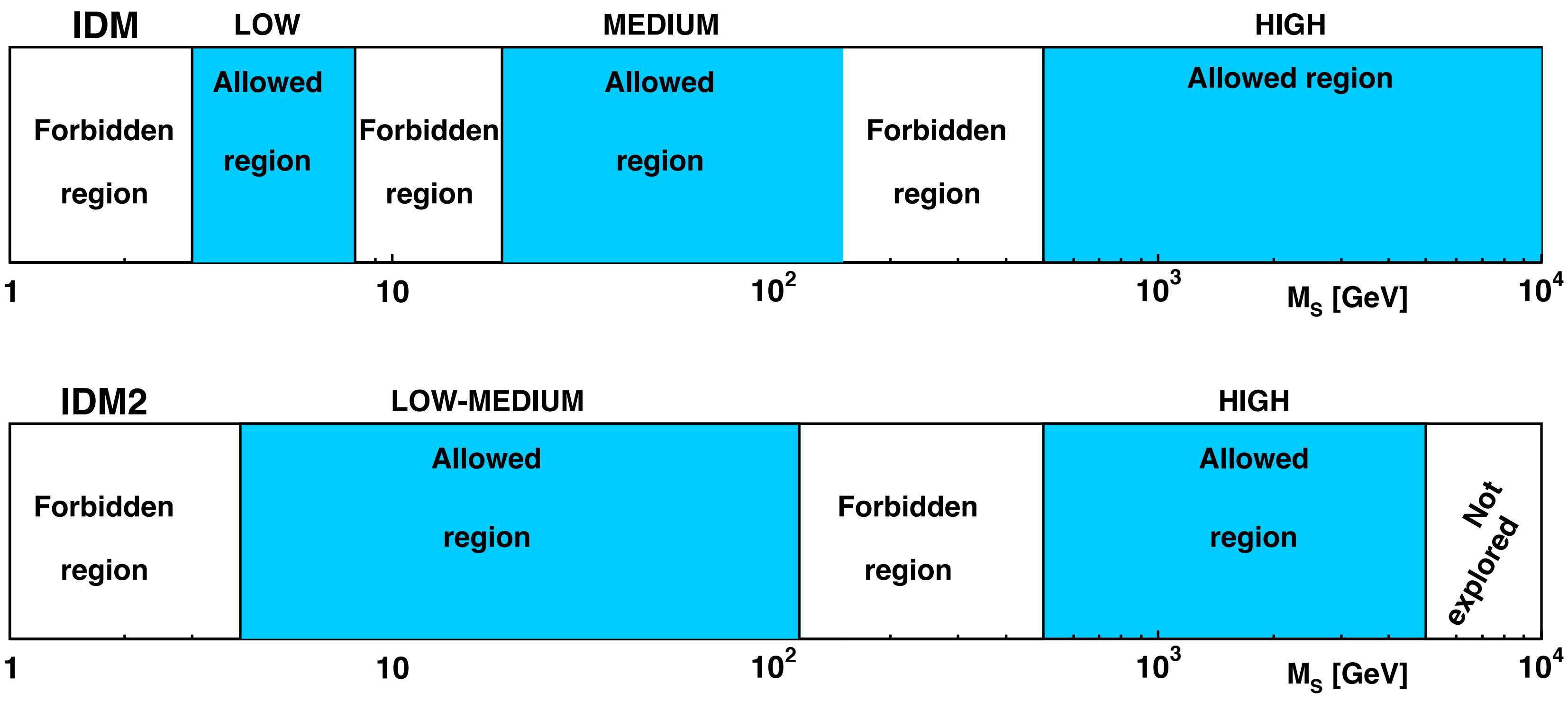
or quartic couplings:

$$SSH_jH_j : \quad -2i(\lambda_L - \lambda_c R_{j3}^2)$$

$$SSH_jH_k : \quad 2i\lambda_c R_{j3}R_{k3}$$

$$SSH^+H^- : \quad -i\lambda_a$$

Allowed regions in M_S

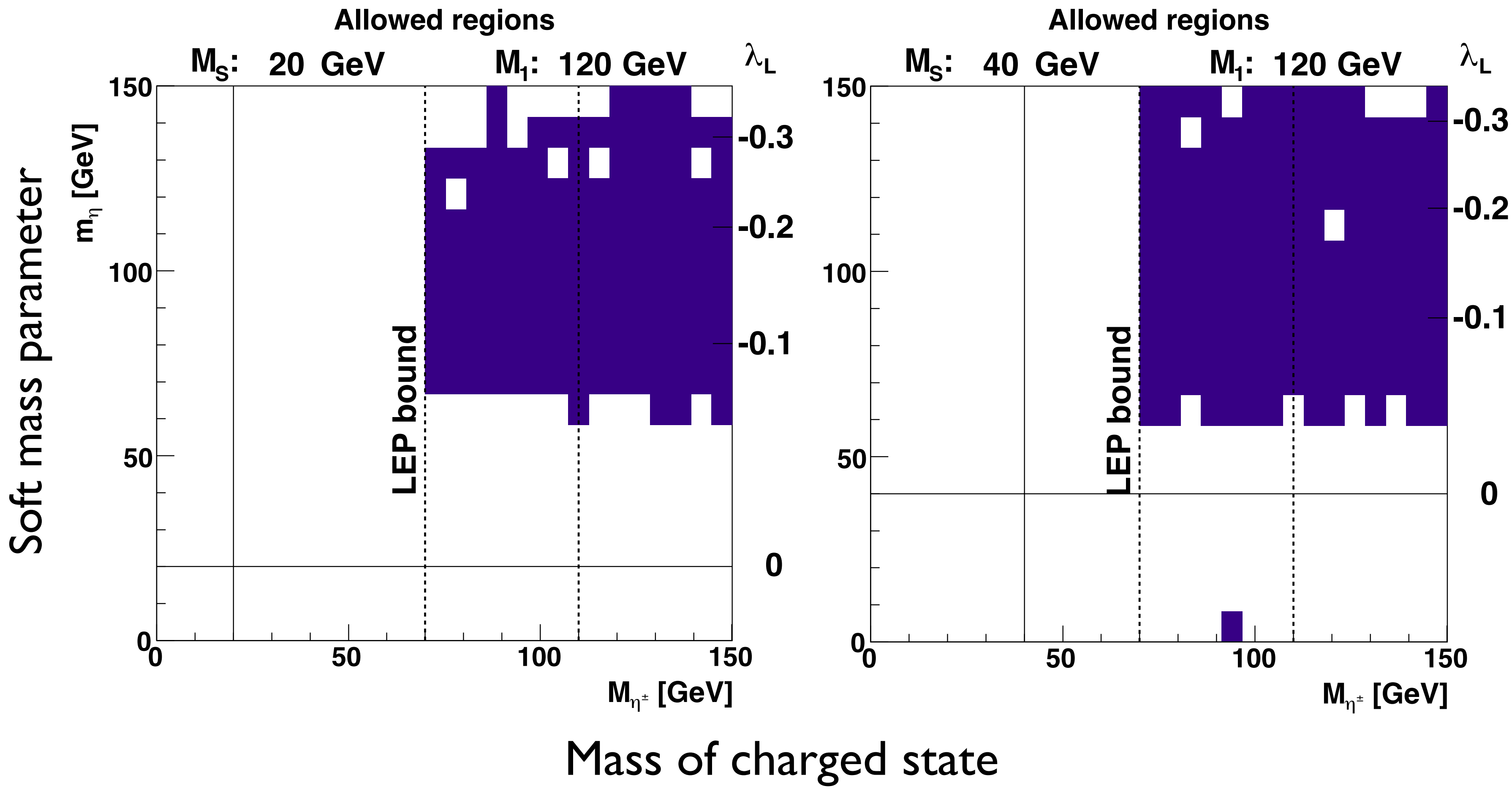


Scan over parameters

1. M_S, M_1 (lowest masses of inert and 2HDM sectors, fixed)
2. M_A, $M_{\eta^\pm}$ (inert sector, physical masses, fixed).
3. M_2, μ (2HDM sector parameters)
4. m_η (inert sector, soft mass parameter, fixed).
5. $\tan\beta$, $M_{H^\pm}$ (2HDM sector),
   $0.5 \leq \tan\beta \leq 50$, 300 GeV $\leq M_{H^\pm} \leq 700$ GeV.
6. α_1, α_2, α_3 (2HDM sector),
   $-\pi/2 \leq \alpha_{1,2} \leq \pi/2$, and $0 \leq \alpha_3 \leq \pi/2$.

Collect results in $M_{\eta^\pm}, m_\eta$ plane

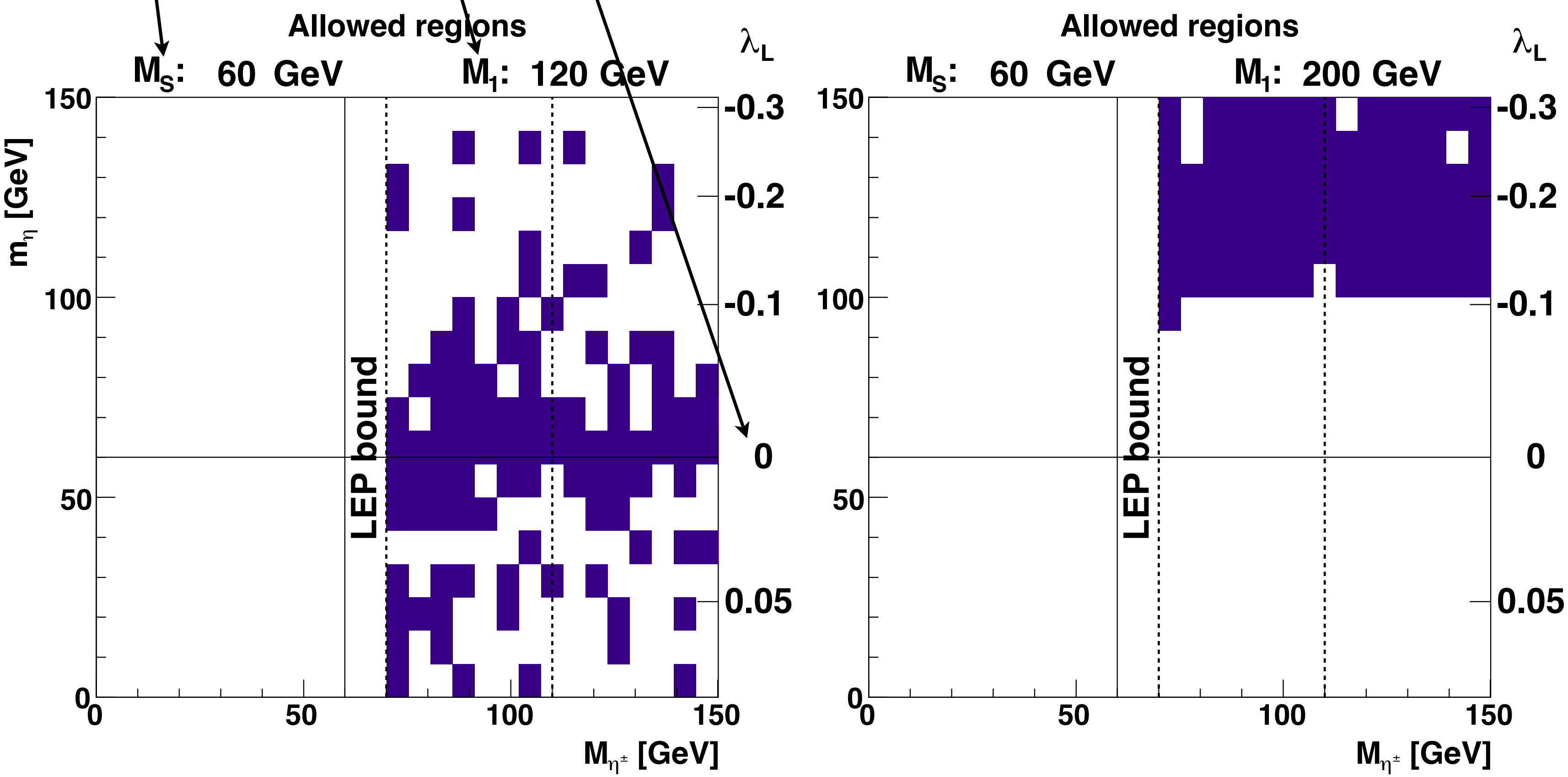
Light DM: coupling to Higgs, $|\lambda_L|$ can not be too small



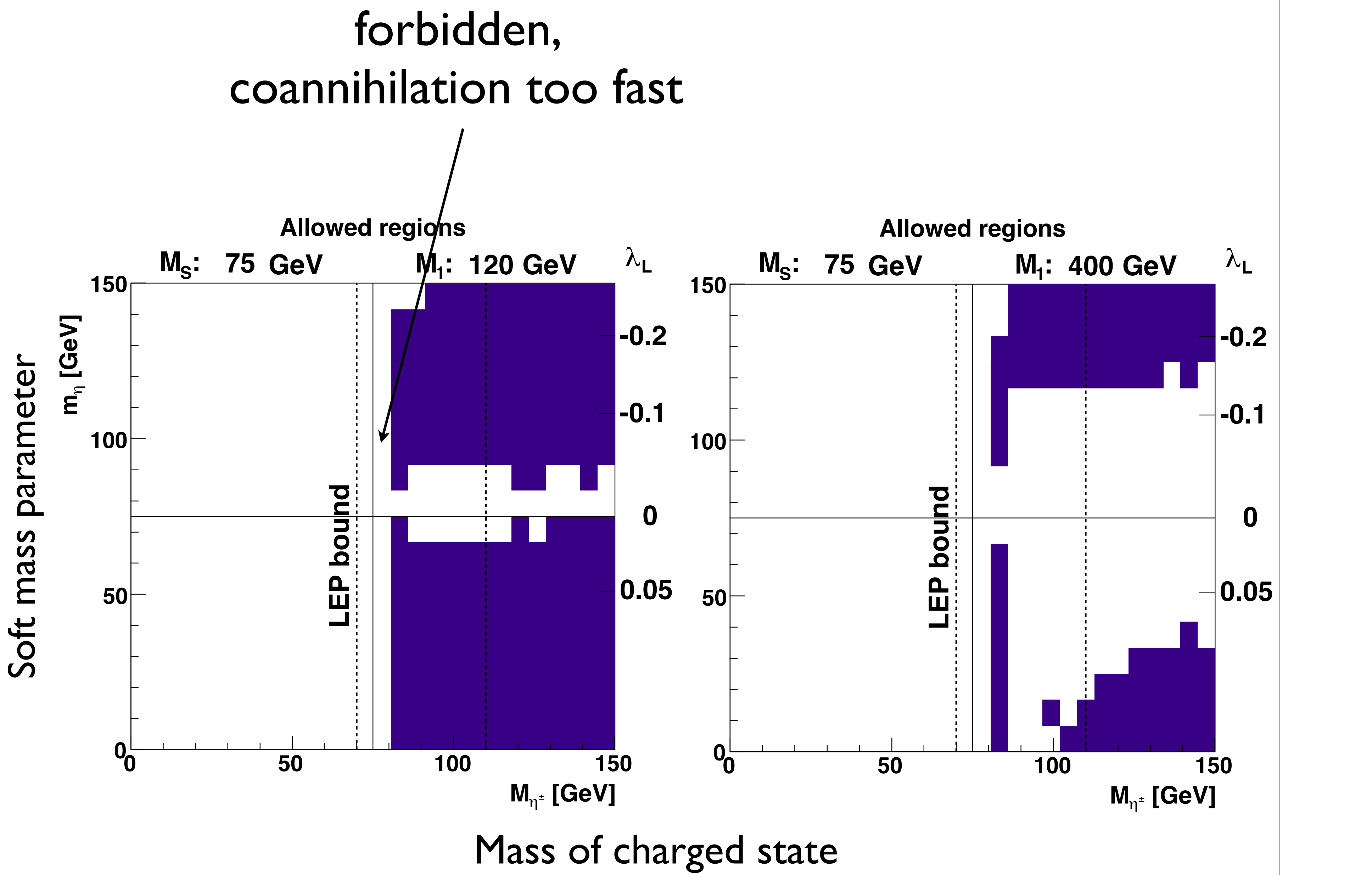
$2 \times 60\ \mathrm{GeV} = 120\ \mathrm{GeV}$ resonant annihilation

λ_L small

Soft mass parameter



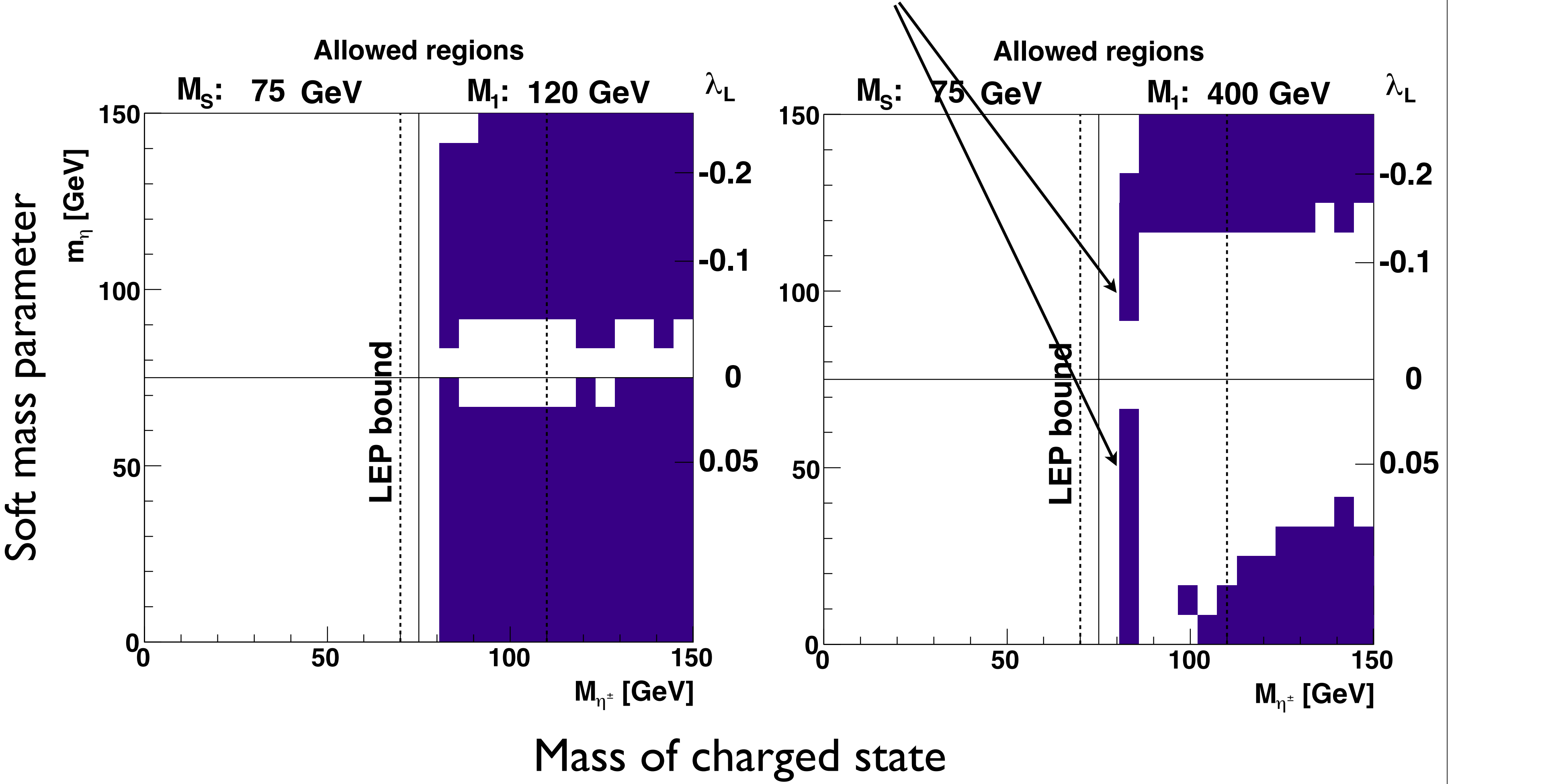
Mass of charged state


forbidden,
coannihilation too fast
Allowed regions
M_S: 75 GeV
M_1: 120 GeV
λ_L
m_η [GeV]
LEP bound
-0.2
-0.1
0
0.05
0
50
100
150
$M_{\eta^\pm}$ [GeV]
Allowed regions
M_S: 75 GeV
M_1: 400 GeV
λ_L
LEP bound
-0.2
-0.1
0
0.05
$M_{\eta^\pm}$ [GeV]
Soft mass parameter
Mass of charged state

Coannihilation just right:

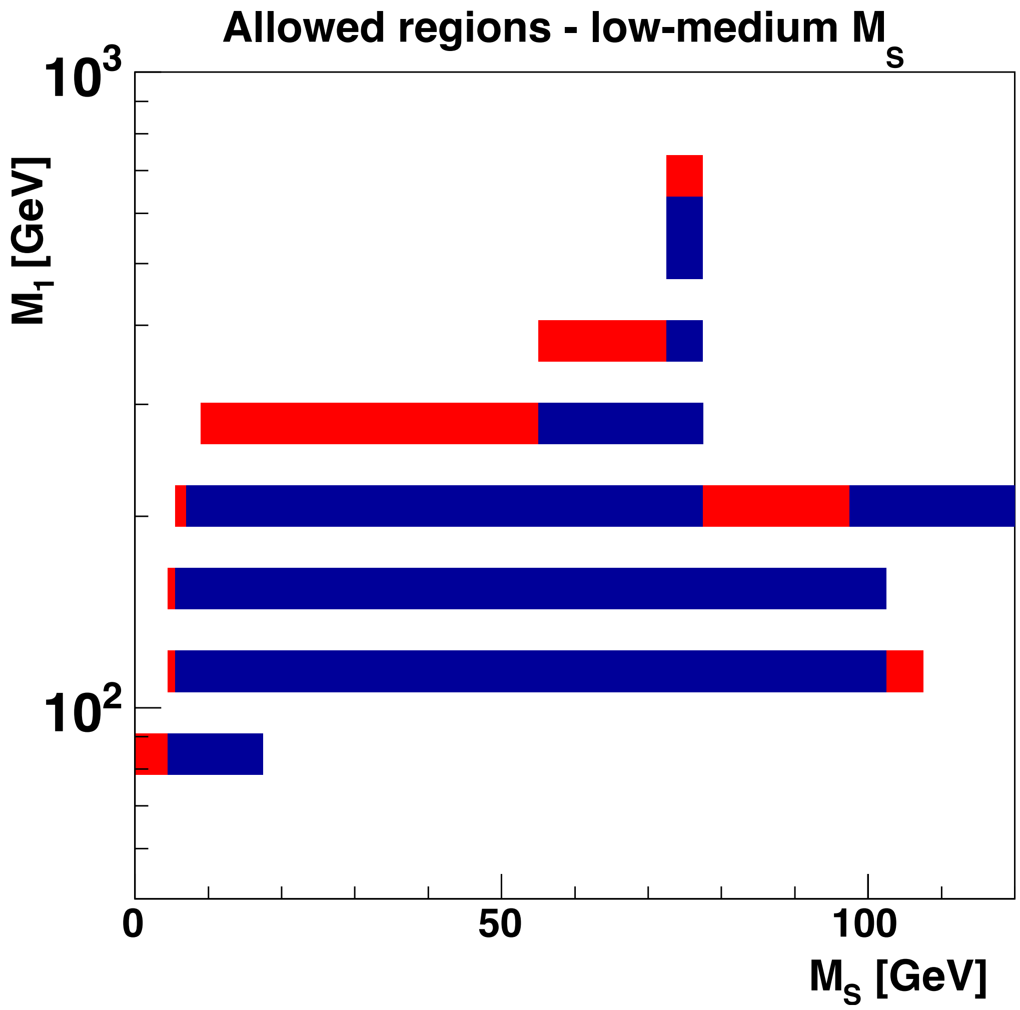
$$S\eta^{\pm} \to W^{\pm}\gamma$$

$$S\eta^{\pm} \to W^{\pm\star} \to u\bar{d},\ d\bar{u},\ c\bar{s},\ s\bar{c}$$



Allowed regions in M_S, M_1

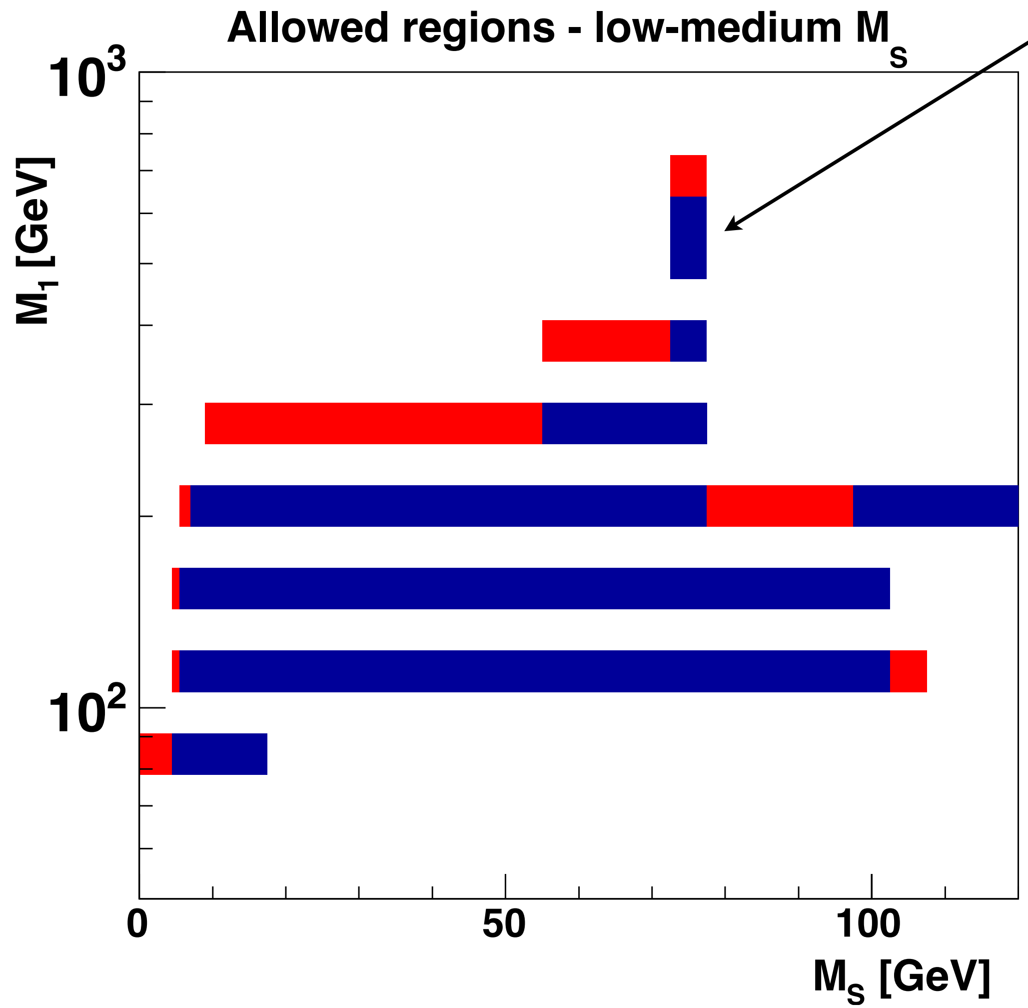
Lightest neutral Higgs



red: forbidden

blue: allowed

Allowed regions in M_S, M_1



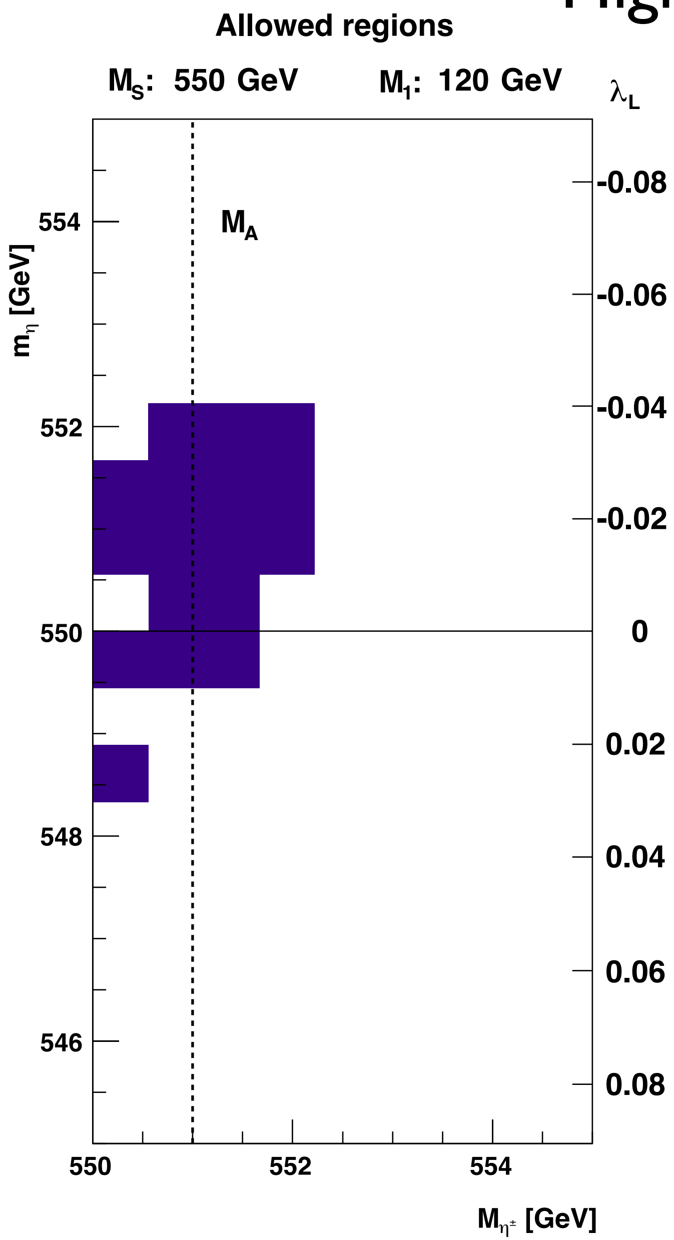
Lightest neutral Higgs

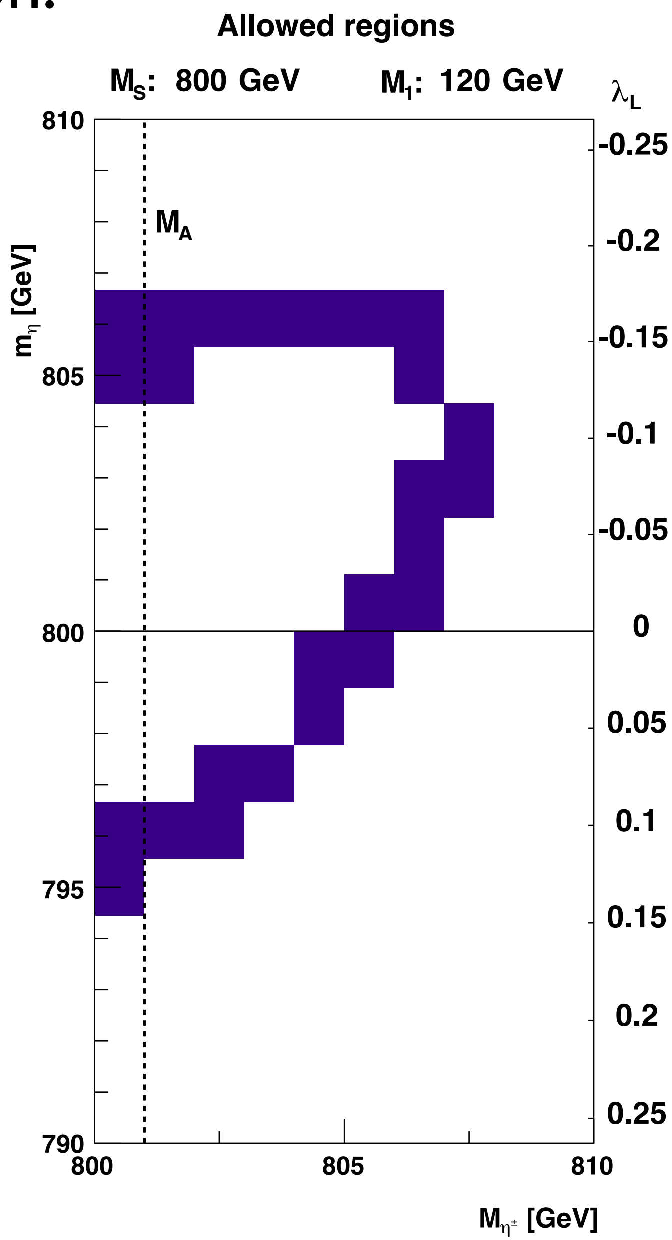
Little hierarchy problem alleviated

red: forbidden

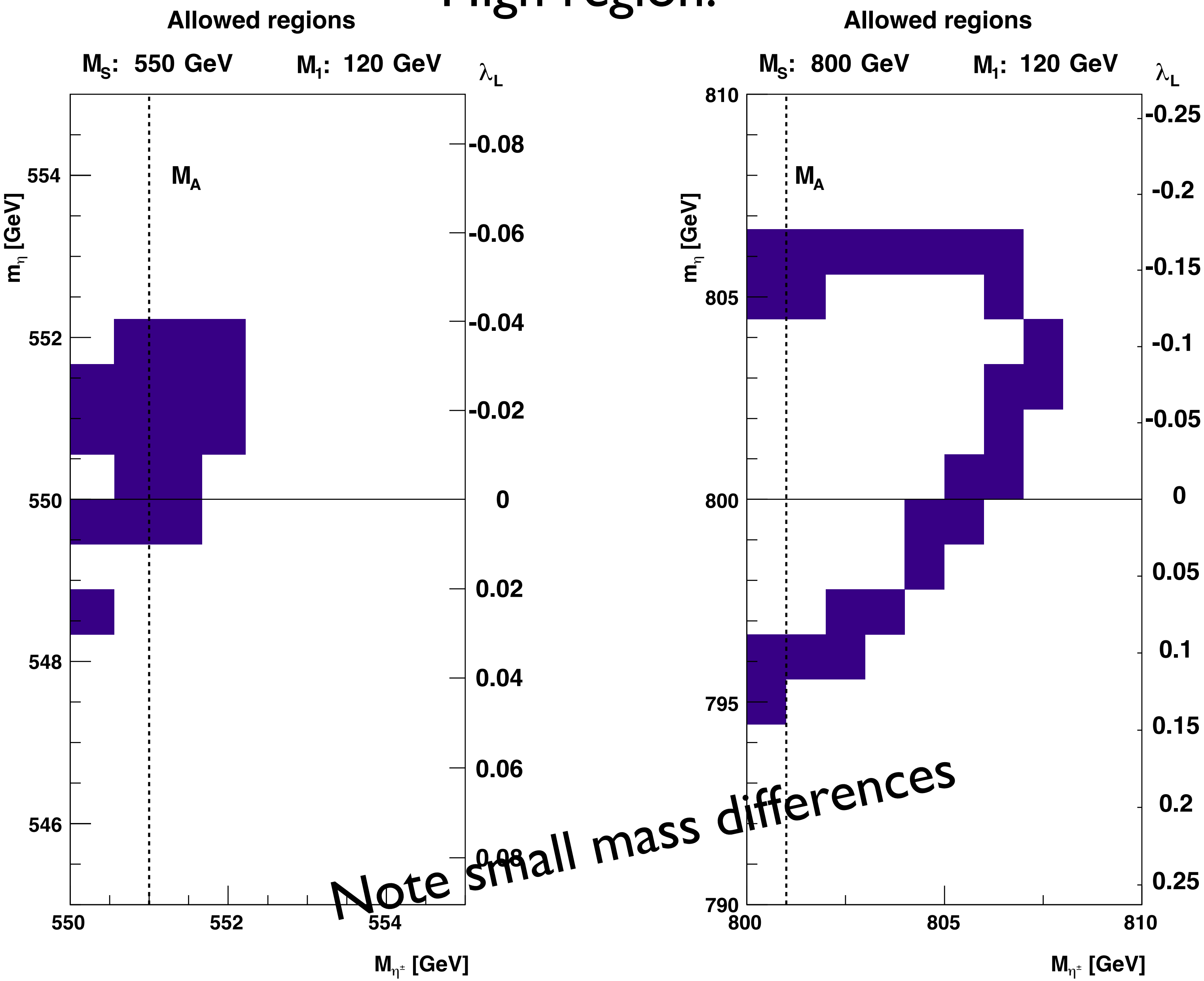
blue: allowed

High region:


Allowed regions
M_S: 550 GeV
M_1: 120 GeV
λ_L
M_A
m_η [GeV]
554
552
550
548
546
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
550
552
554
$M_{\eta^\pm}$ [GeV]


Allowed regions
M_S: 800 GeV
M_1: 120 GeV
λ_L
M_A
m_η [GeV]
810
805
800
795
790
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
800
805
810
$M_{\eta^\pm}$ [GeV]

High region:



Note small mass differences

CP violation

Measured in terms of invariants (Gunion and Haber, 2005):

$$\mathrm{Im}\, J_1 = -\frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)\mathrm{Im}\,\lambda_5$$

$$\mathrm{Im}\, J_2 = -\frac{v_1^2 v_2^2}{v^8}\left[\left((\lambda_1 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_1^4 + 2(\lambda_1 - \lambda_2)\mathrm{Re}\,\lambda_5 v_1^2 v_2^2 - \left((\lambda_2 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_2^4\right] \mathrm{Im}\,\lambda_5$$

$$\mathrm{Im}\, J_3 = \frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)(\lambda_1 + \lambda_2 + 2\lambda_4 + 2\lambda_b)\mathrm{Im}\,\lambda_5$$

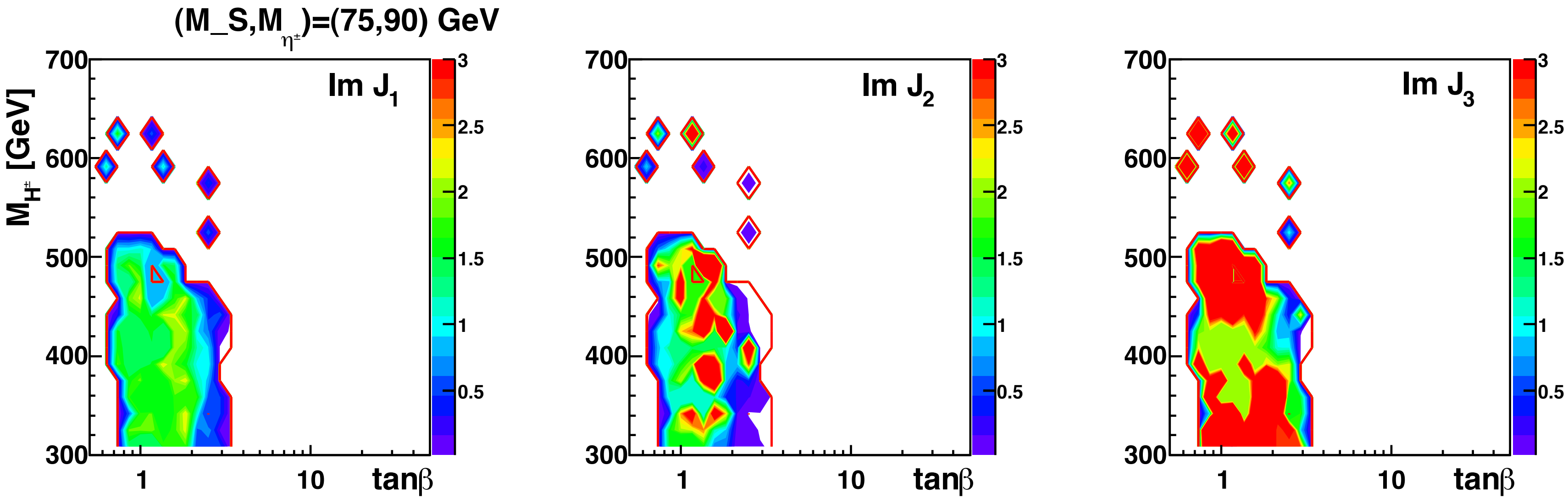
small extra contribution

CP violation if at least one of these is non-zero

CP violation

A “representative” case:

$$(M_S, M_A, M_{\eta^\pm}, m_\eta) = (75, 110, 90, 100)\ \mathrm{GeV}$$
$$(M_1, M_2, \mu) = (120, 300, 200)\ \mathrm{GeV}$$

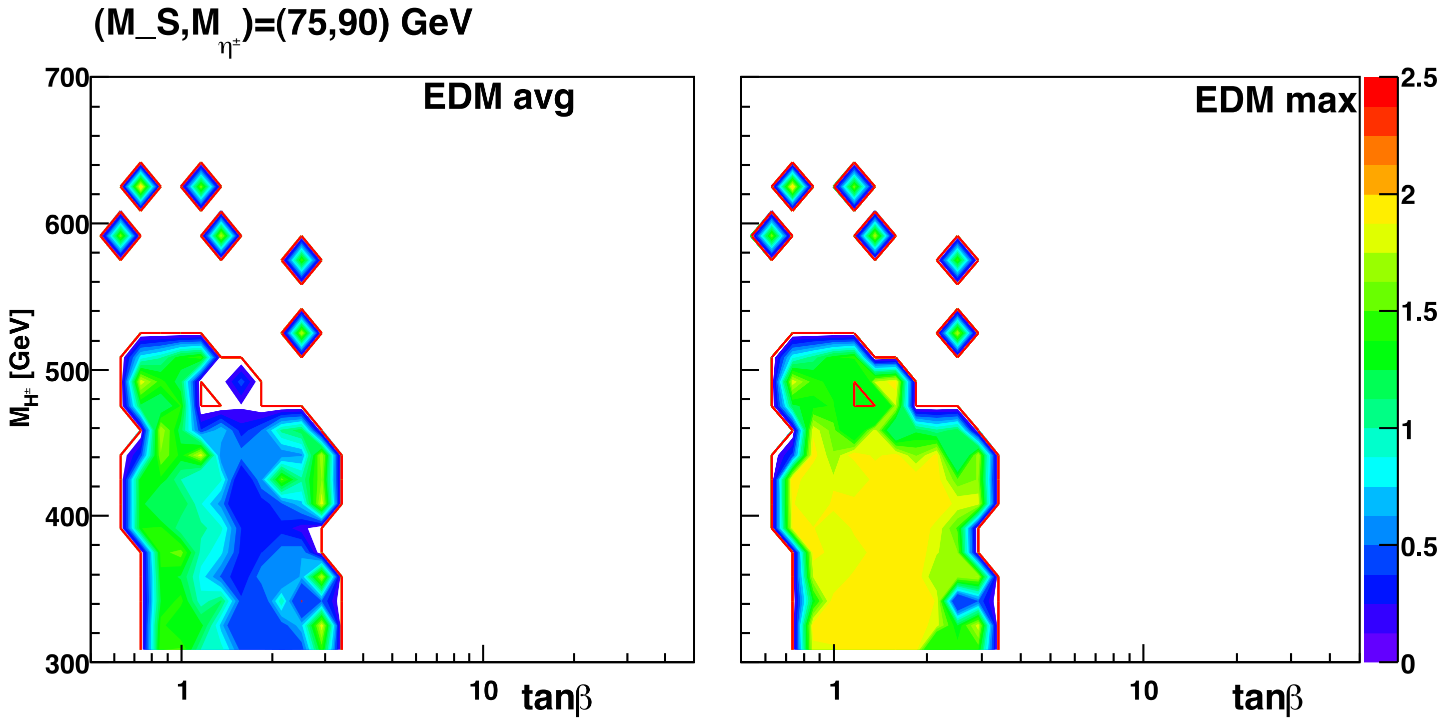


orders of magnitude higher than in SM

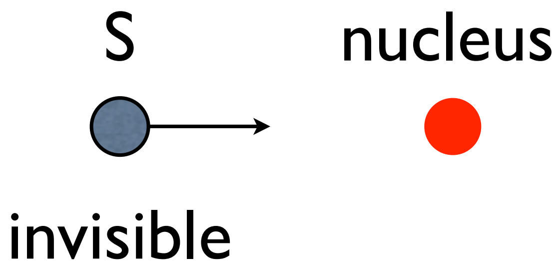
(No solution found for large tanβ)

CP violation: electron edm

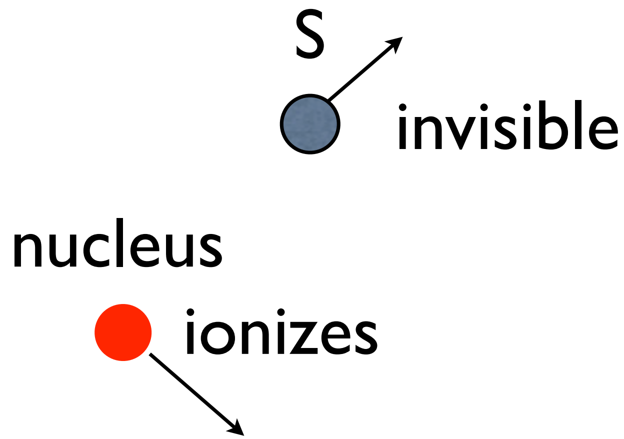
Unit: $e\ 10^{-27}$ cm (~ current limit)



Direct detection

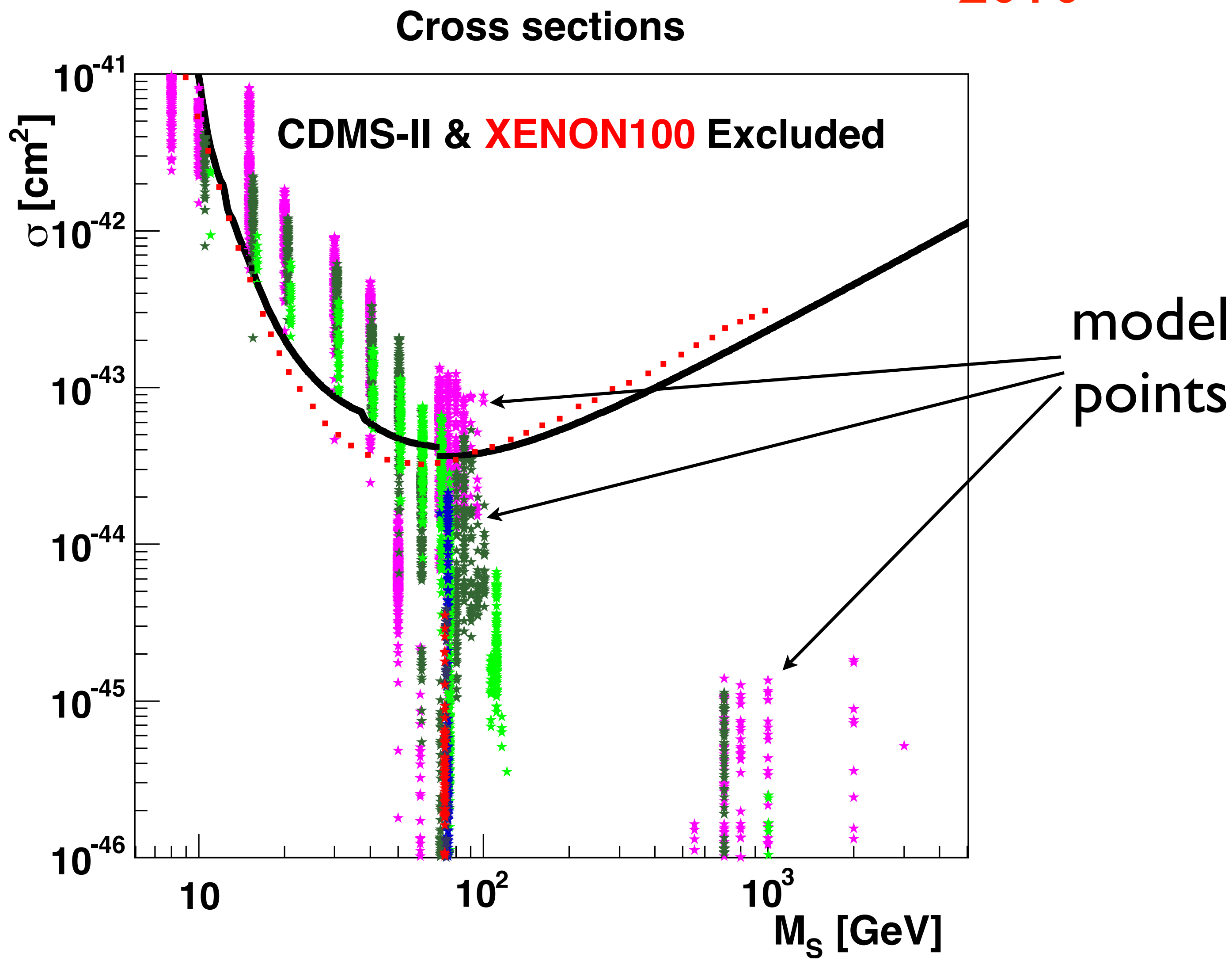


Direct detection

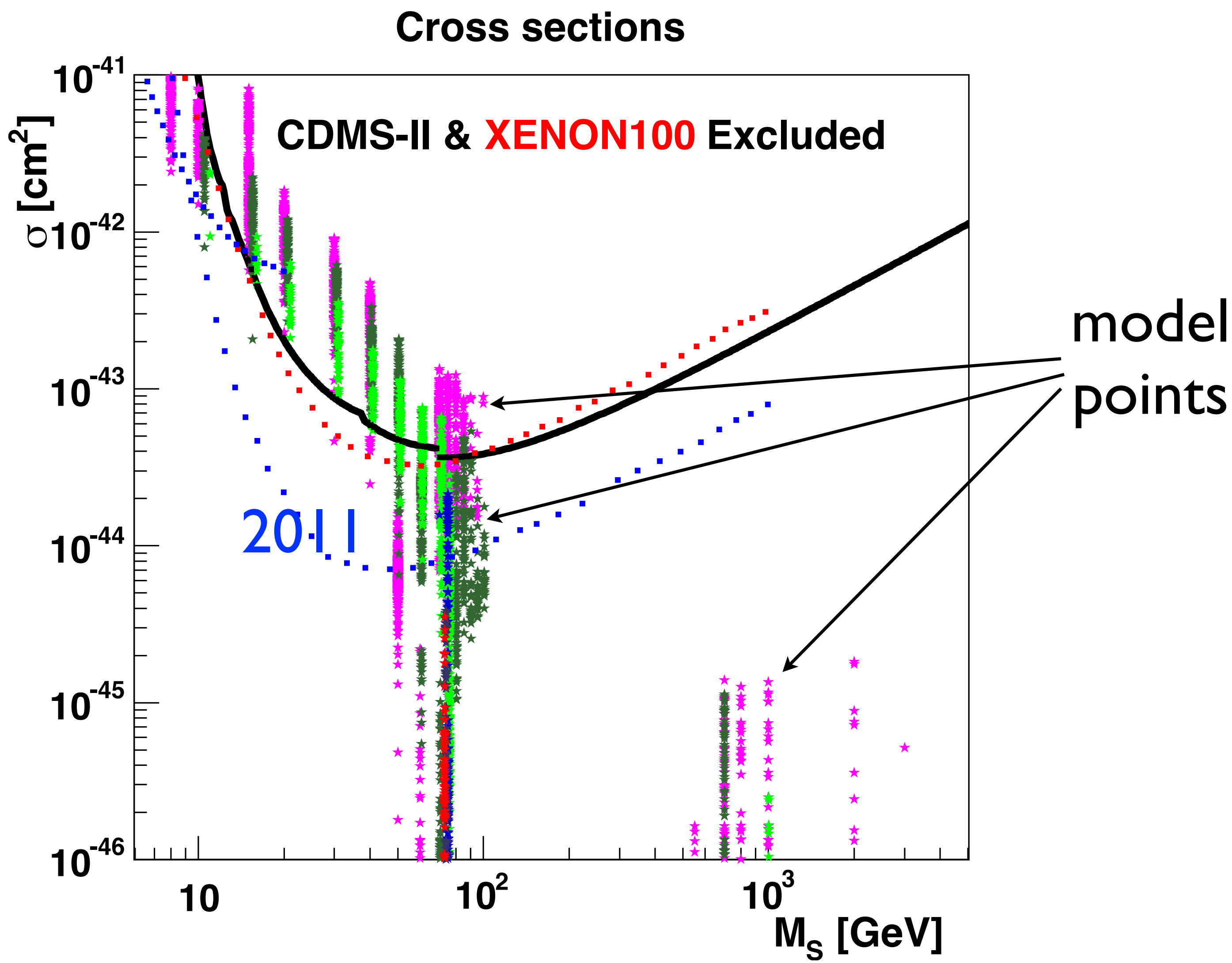


Compare CDMS-II and XENON100

2010



Compare CDMS-II and XENON100



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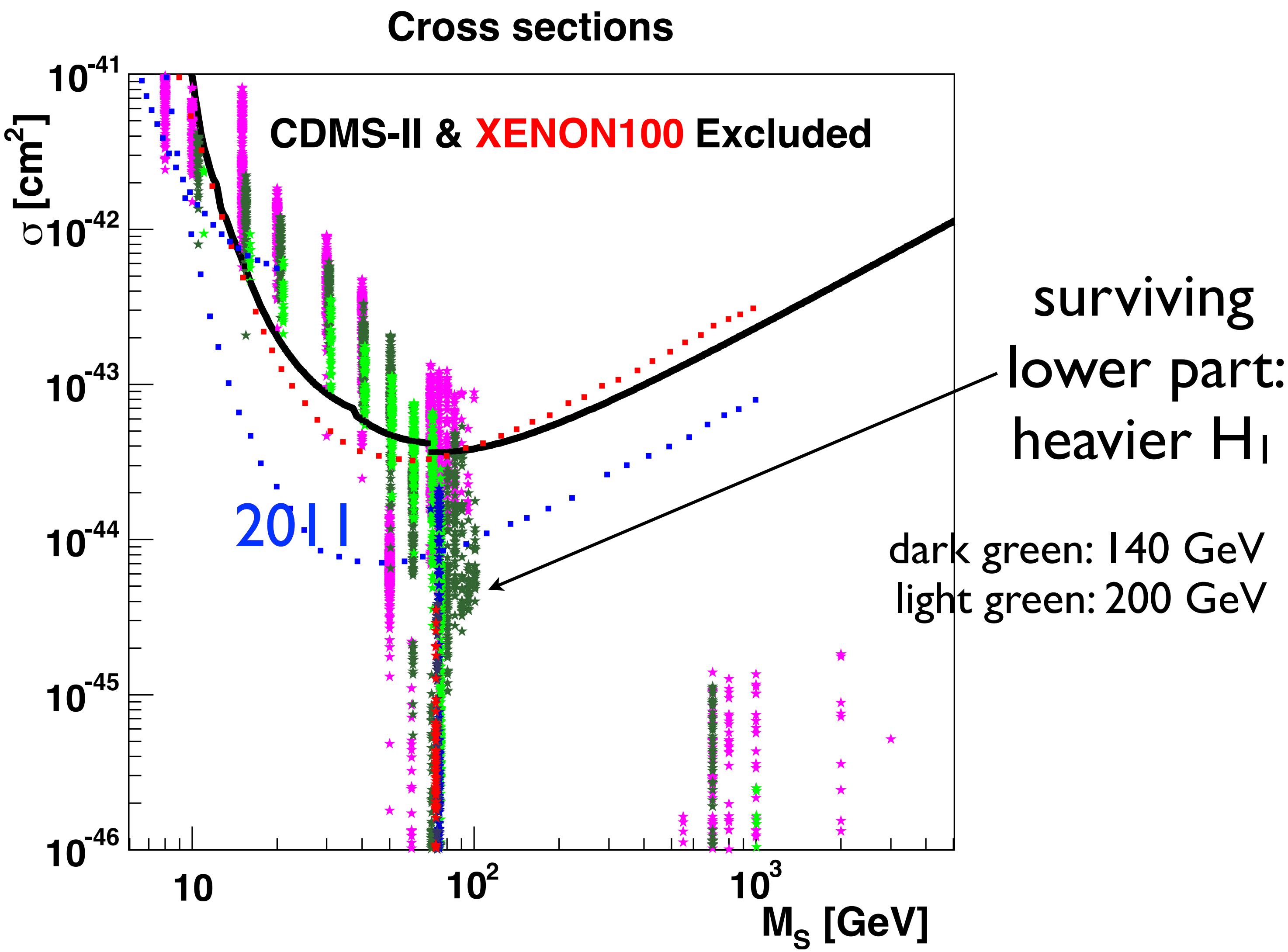

Surviving lower part: heavier H_1

Interaction between DM (S) and ordinary matter (Xe) proceeds via Higgs exchange.
For heavier (lightest) Higgs, this exchange is suppressed

LHC prospects

If charged and neutral scalars of inert doublet are at electroweak scale, then scalars can be produced and perhaps even observed at the LHC:

$$pp \to SSX, AAX, SAX, S\eta^{\pm}X, A\eta^{\pm}X, \eta^{+}\eta^{-}X$$

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$$pp \to SSX, AAX, SAX, S\eta^{\pm}X, A\eta^{\pm}X, \eta^{+}\eta^{-}X$$

followed by:

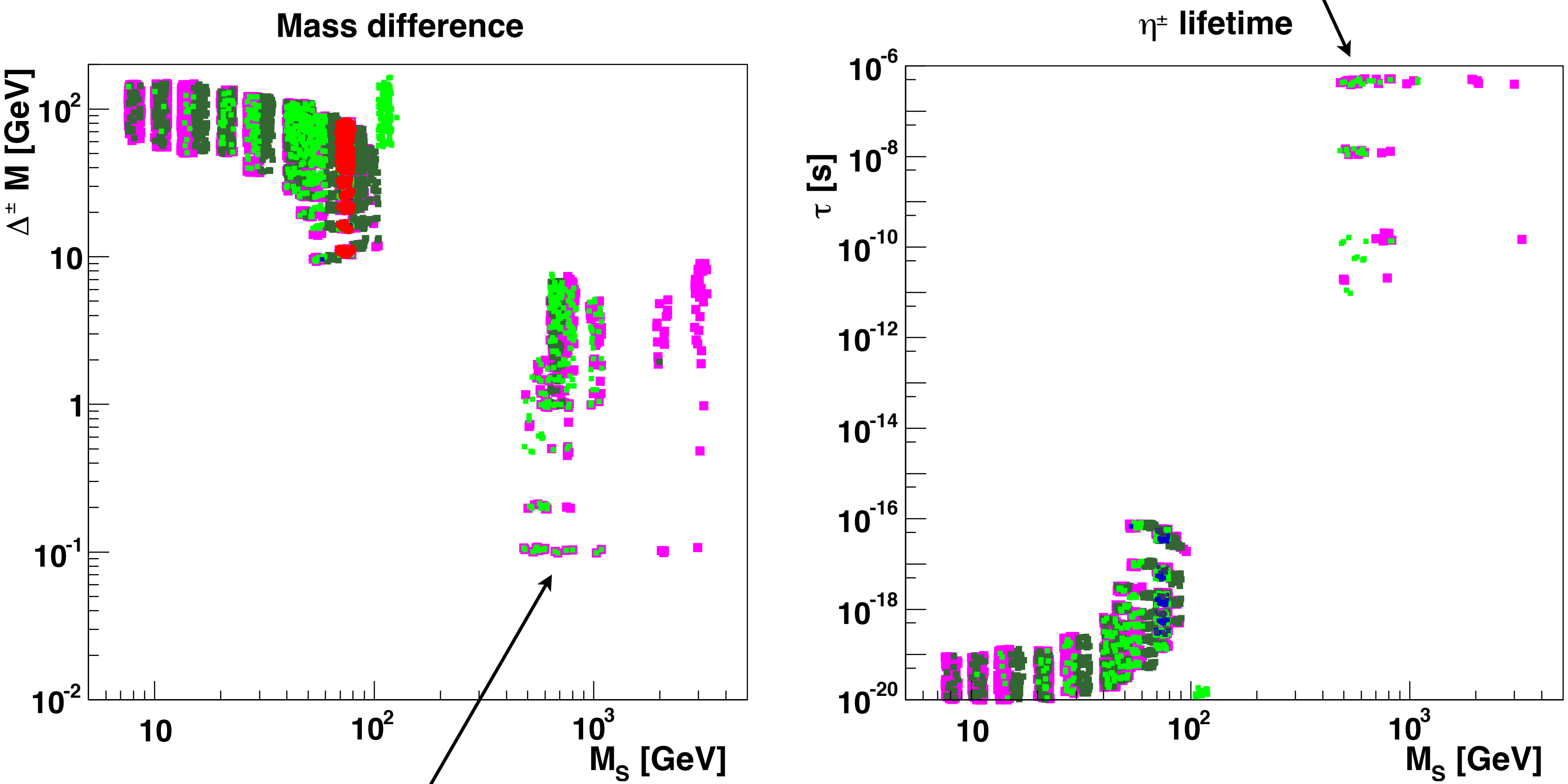
$$\eta^{+} \to S\ell^{+}\nu_{\ell}$$

Similar to muon decay, except that S is massive (and scalars, not fermions):

$$\Gamma_{\eta^{\pm}} = \frac{G_{\mathrm{F}}^{2}}{30\pi^{3}} \left(M_{\eta^{\pm}} - M_{S}\right)^{5}$$

$$\Delta^{\pm} M \equiv M_{\eta^{\pm}} - M_S$$

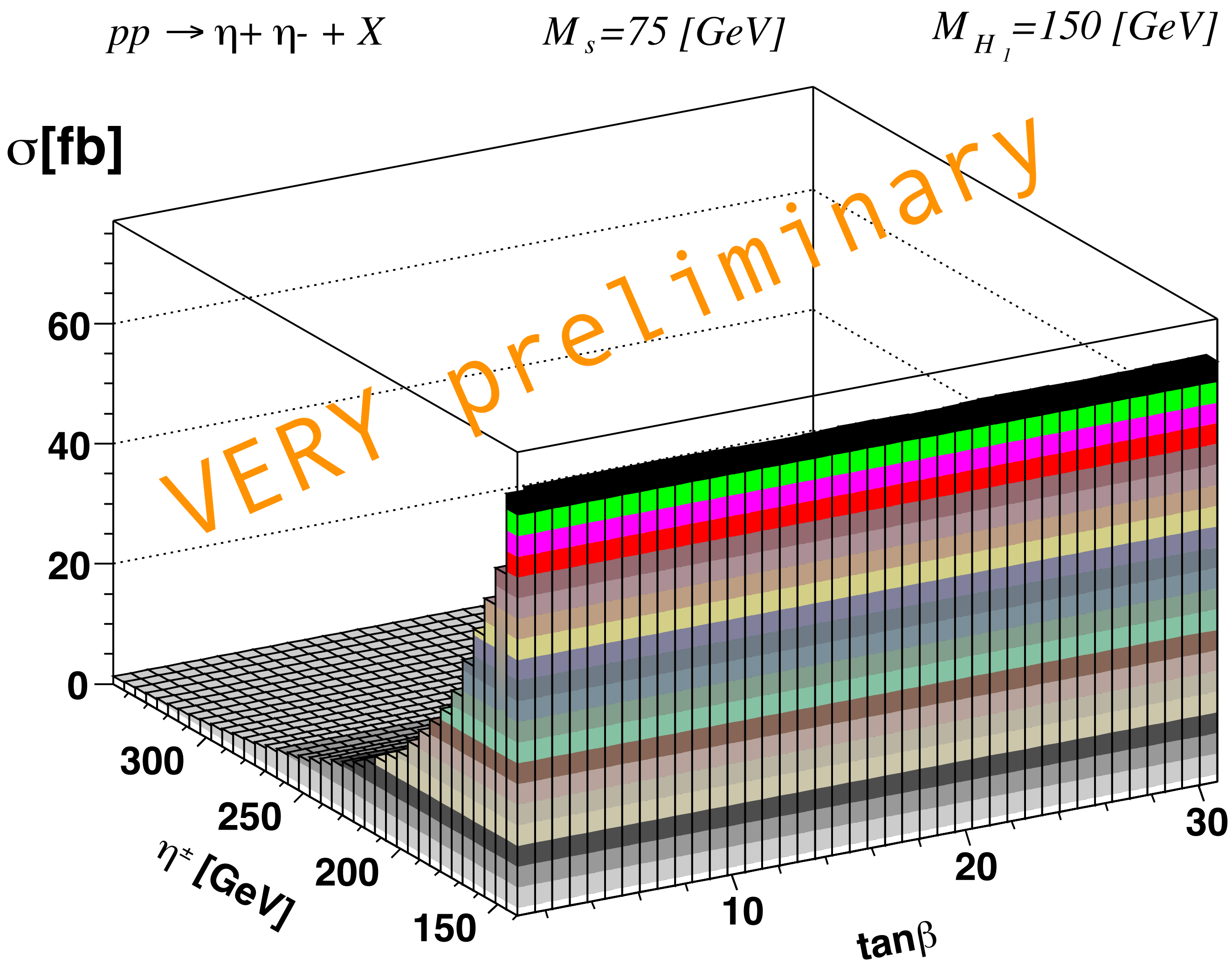
Long lifetime



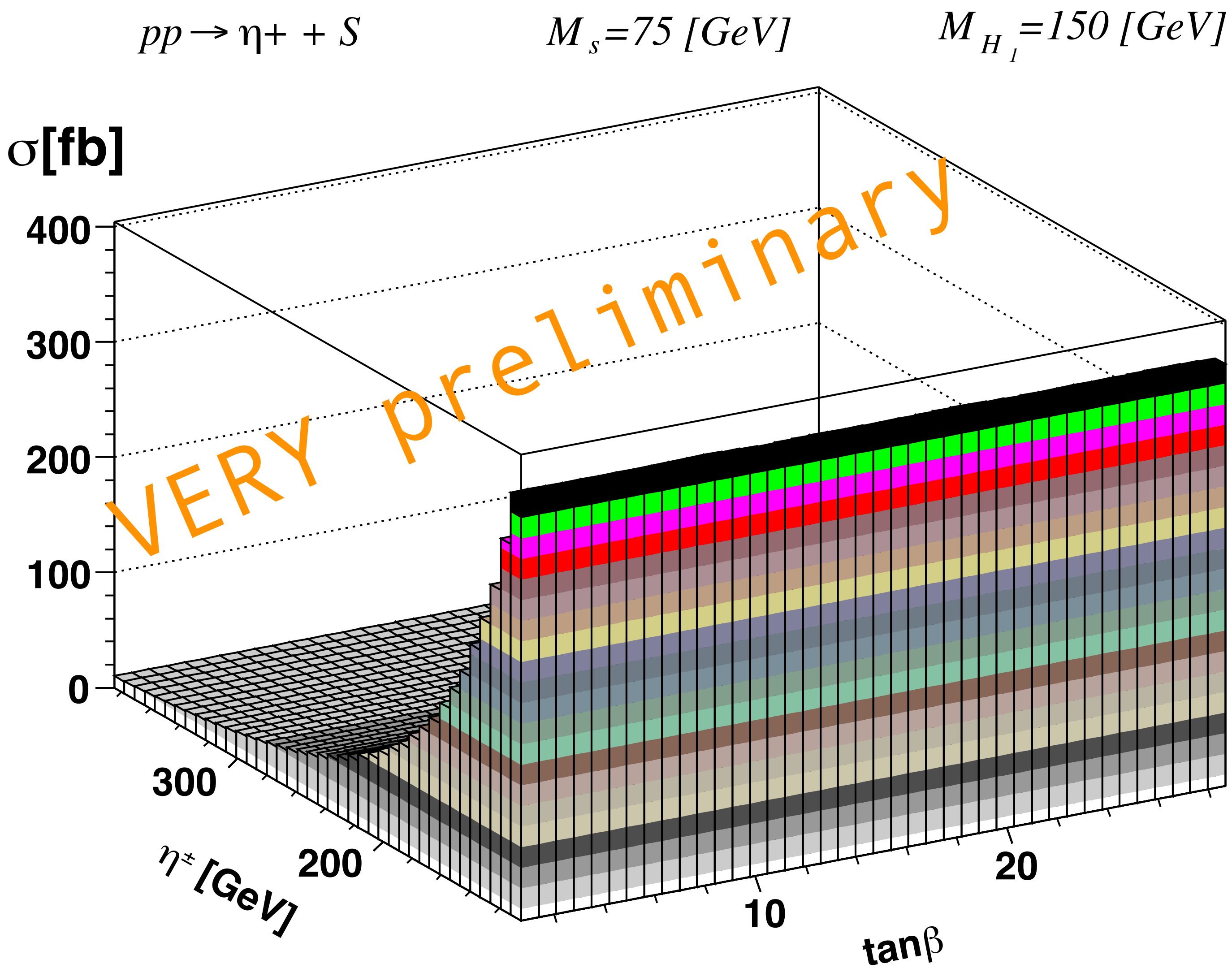
Degeneracy at high masses

but cross section would be small

Cross sections



Cross sections



Conclusions

...if scalars are dark matter...

- Scalar sector could be much more exciting than in the SM
- Possibly signals in Direct or Indirect detection experiments
- Possibly interesting signals at the LHC
- In the meantime, parts of parameter space will be excluded