Inspecting the Higgs for New Weakly Interacting Particles

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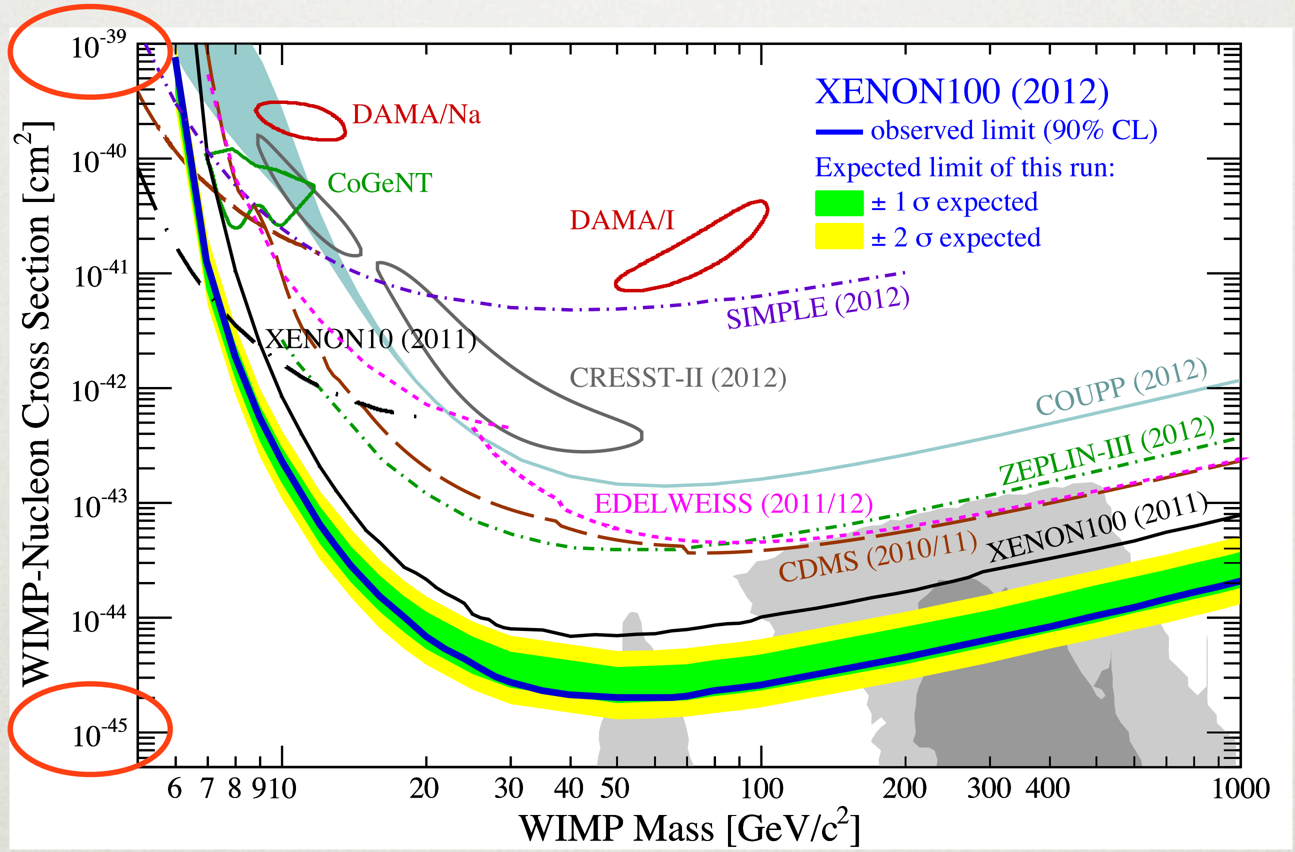
Based on:
Cheung, Papucci, KZ 1203.5106
Cheung, McDermott, KZ 1302.0314

The WIMP Has Not Revealed Itself Underground...

Scattering through the Z boson: ruled out

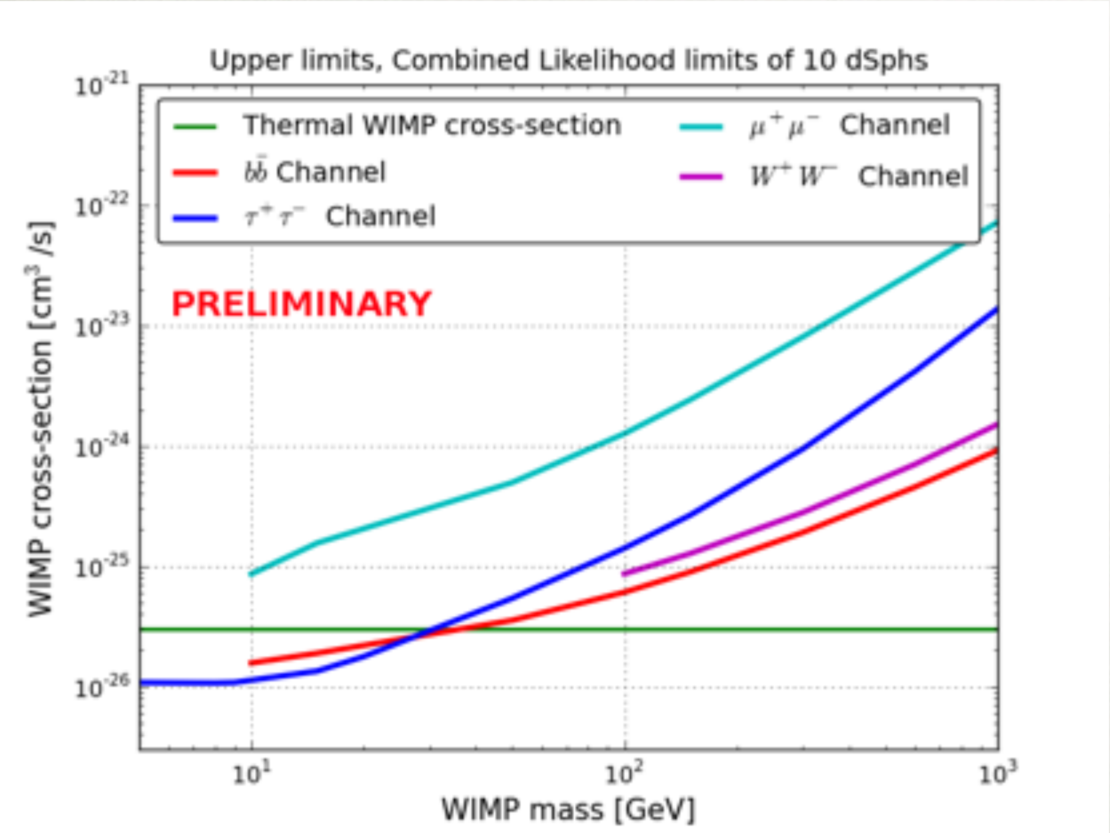
$$\sigma_n \sim 10^{-39}\ \mathrm{cm}^2$$



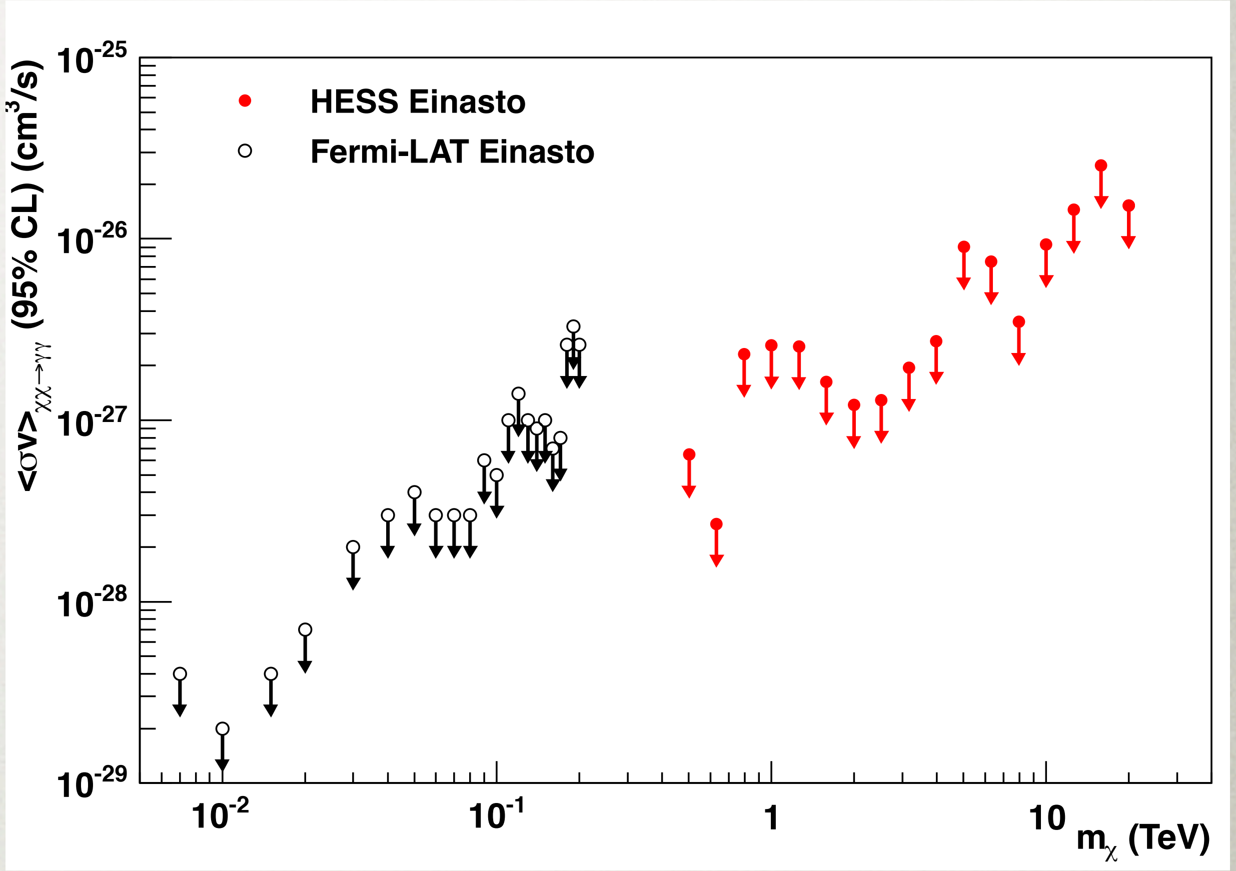
Next important benchmark:
Scattering through the Higgs

$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

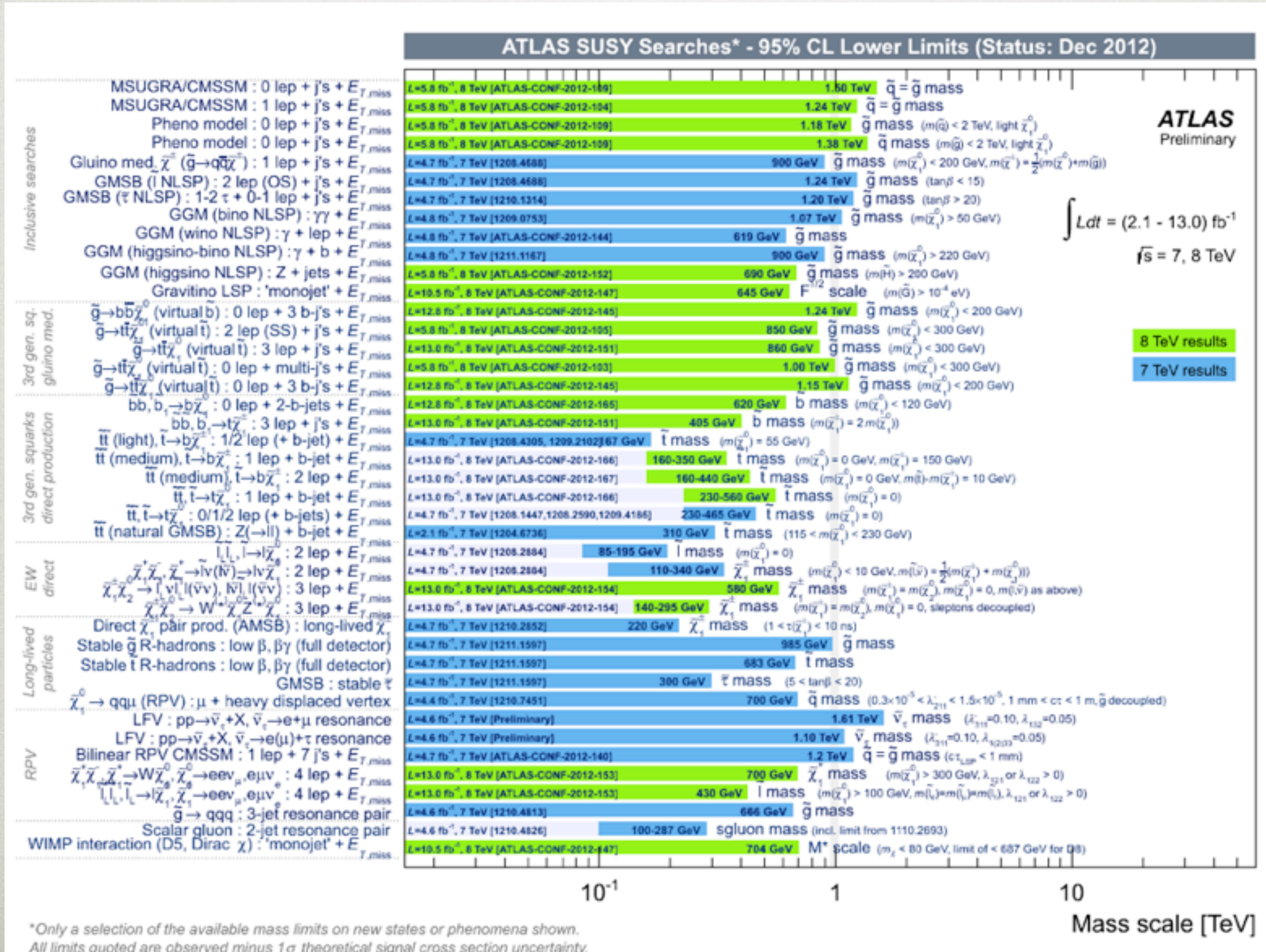
...in Space...



Fermi



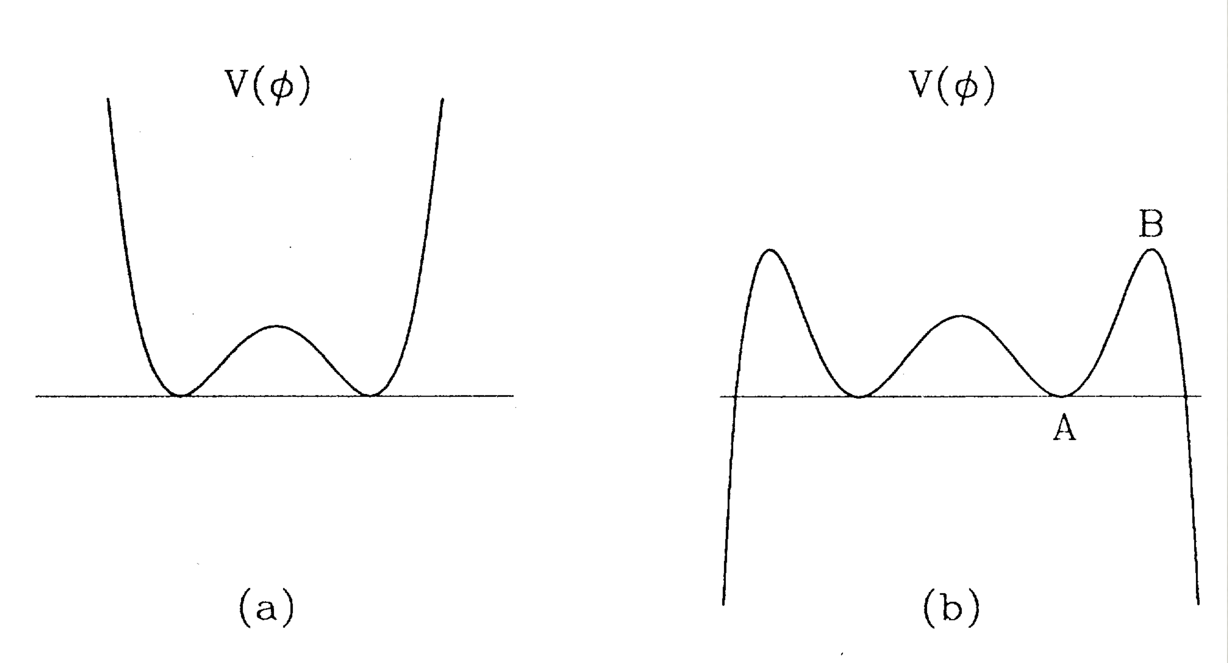
...or at Colliders



What Next?

- We have the Higgs, and nothing else
- ((Panic. The end of particle physics is nigh.))
- (Bigger detectors, higher energies.)
- Look in new places
- Optimize existing searches
- Get over naturalness addiction
- Use DM as a motivating principle for where to look

Inspecting the Higgs …



- … through vacuum stability and DM
- Quartic runs to smaller values via RGEs.

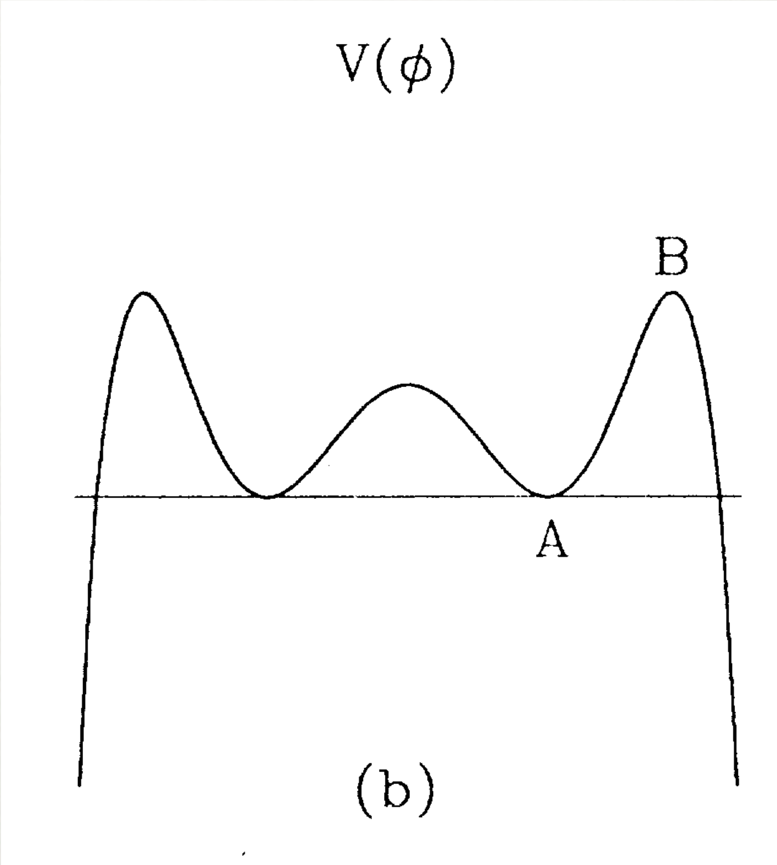
$$b^{(1)}_{\lambda_H} = 12y_b^2\lambda_H - 12y_b^4 - \frac{9}{5}g_1^2\lambda_H - 9g_2^2\lambda_H + \frac{27g_1^4}{100} + \frac{9}{10}g_2^2g_1^2 + \frac{9g_2^4}{4} + 12\lambda_H y_t^2 + 4\lambda_H y_\tau^2 + 12\lambda_H^2 - 12y_t^4 - 4y_\tau^4$$

- Depending on IR value, quartic can become negative at high scale.

$$\frac{dg}{dt} = \frac{b_g^{(1)}}{(4\pi)^2}$$

Inspecting the Higgs ...

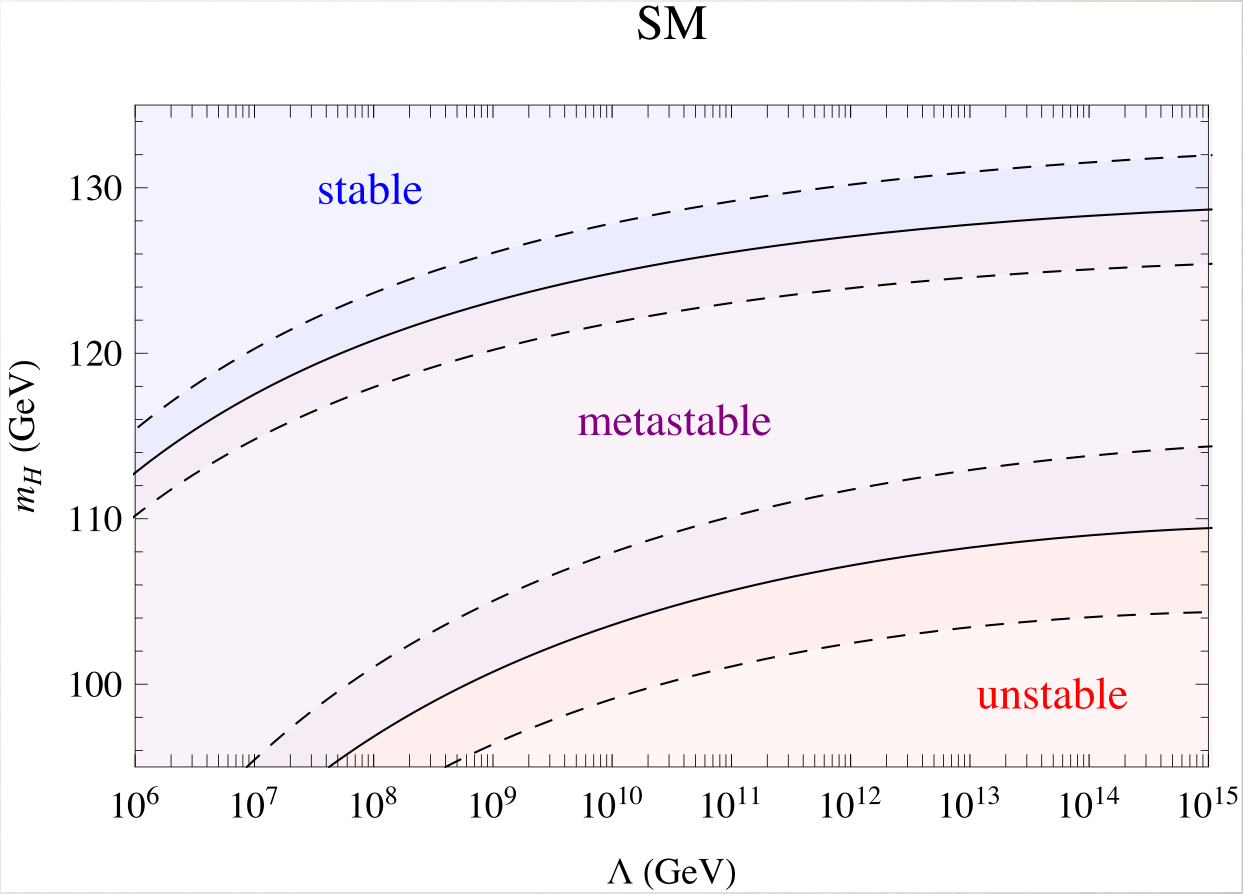
- ... through vacuum stability and DM
- Don't require absolute stability, only stability on timescales of the order of the age of the universe
- Can compute tunneling probability as a function of length scale of bounc



$$\Gamma = \max\left[R^{-4}\exp(-16\pi^2/3|\hat{\lambda}_H|)\right]\Big|_{R^{-1}<\Lambda}$$

Inspecting the Higgs ...

- ... through vacuum stability and DM
- Suppose we have electroweak DM interacting with the Higgs and nothing else.
- What does that imply about where New Physics must enter?



Inspecting the Higgs For Stability

- Start with a minimal DM set-up; Higgs + DM and nothing else

Bino/Higgsino DM

$$\text{singlet/doublet fermion:} \quad -\Delta\mathcal{L} = \frac{1}{2}m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$$

Wino/Higgsino DM

$$\text{triplet/doublet fermion:} \quad -\Delta\mathcal{L} = \frac{1}{2}m_T T^2 + m_D D D^c + y_T H T D + y_T^c H^c T D^c$$

- Important effects on vacuum stability

Stability and DM

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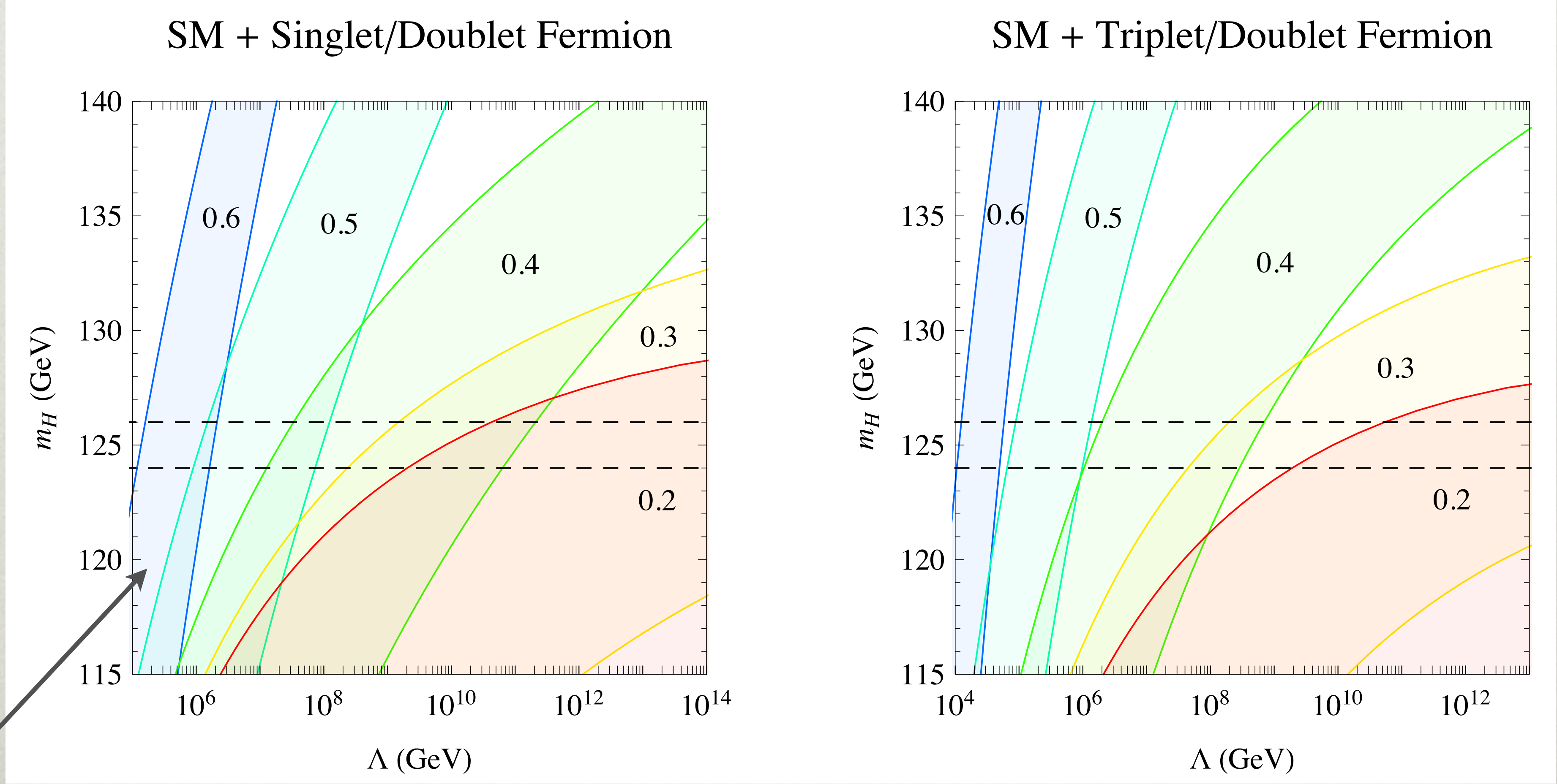


Metastability bands

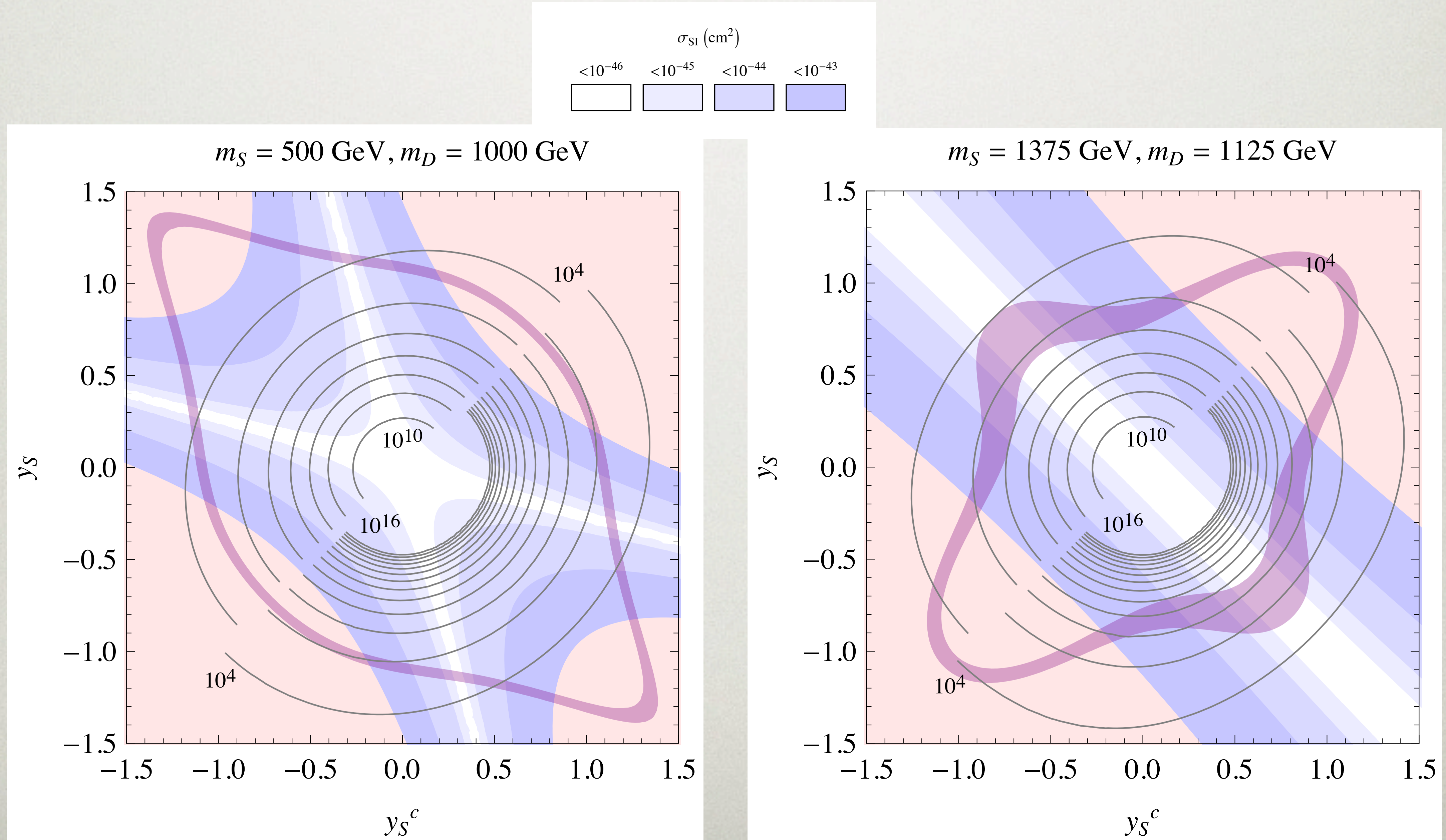
Stability and DM

- Direct Detection and Relic Density can probe the couplings

- Relic density in particular can place a "floor" on the size of the couplings to the Higgs

Effects of DD and Relic Density

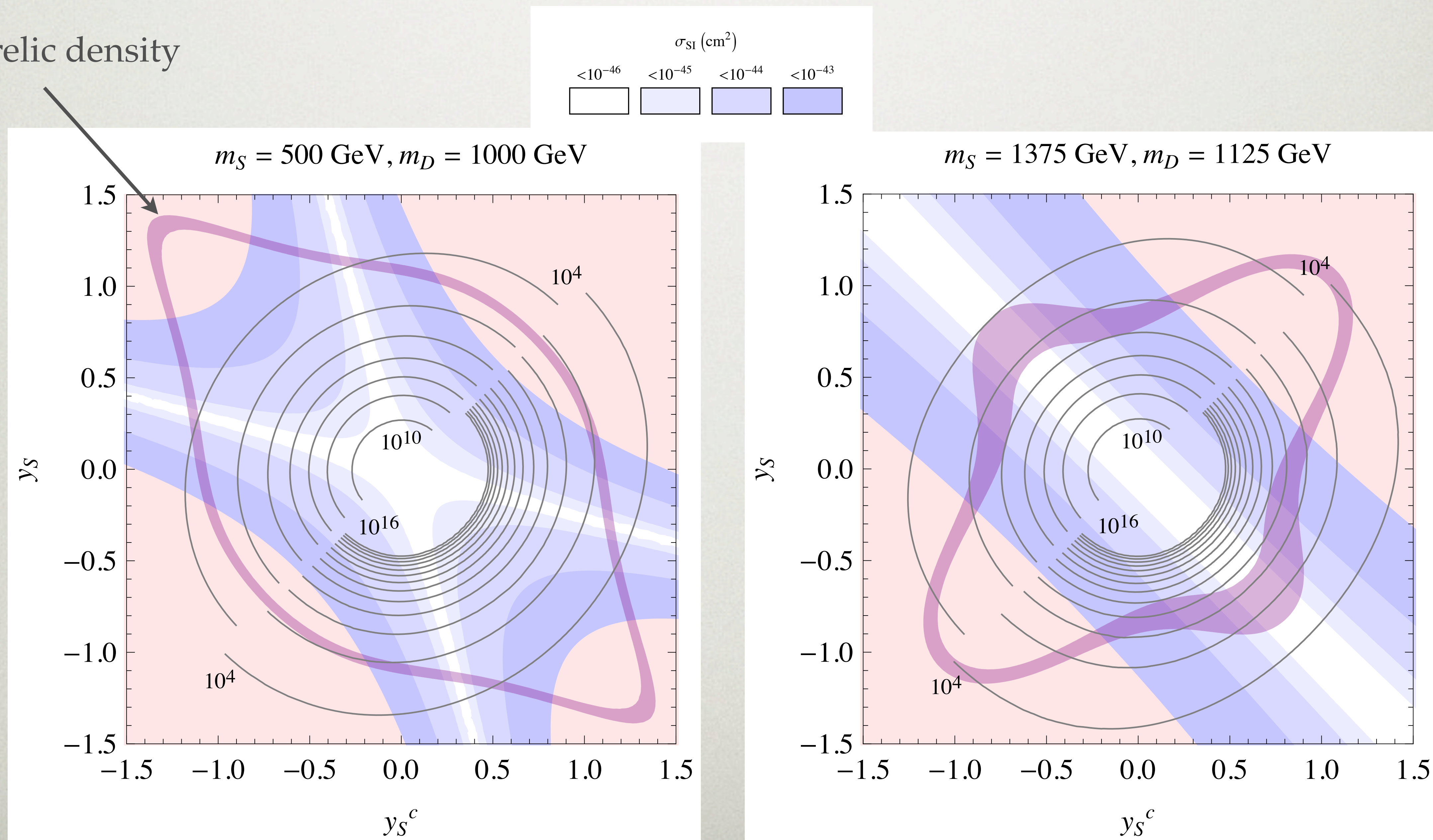
singlet/doublet fermion: $$-\Delta\mathcal{L} = \frac{1}{2}m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$$



Effects of DD and Relic Density

singlet/doublet fermion: $$-\Delta\mathcal{L} = \frac{1}{2}m_S S^2 + m_D D D^c + y_S H S D + y_S^c H^c S D^c$$

Correct relic density



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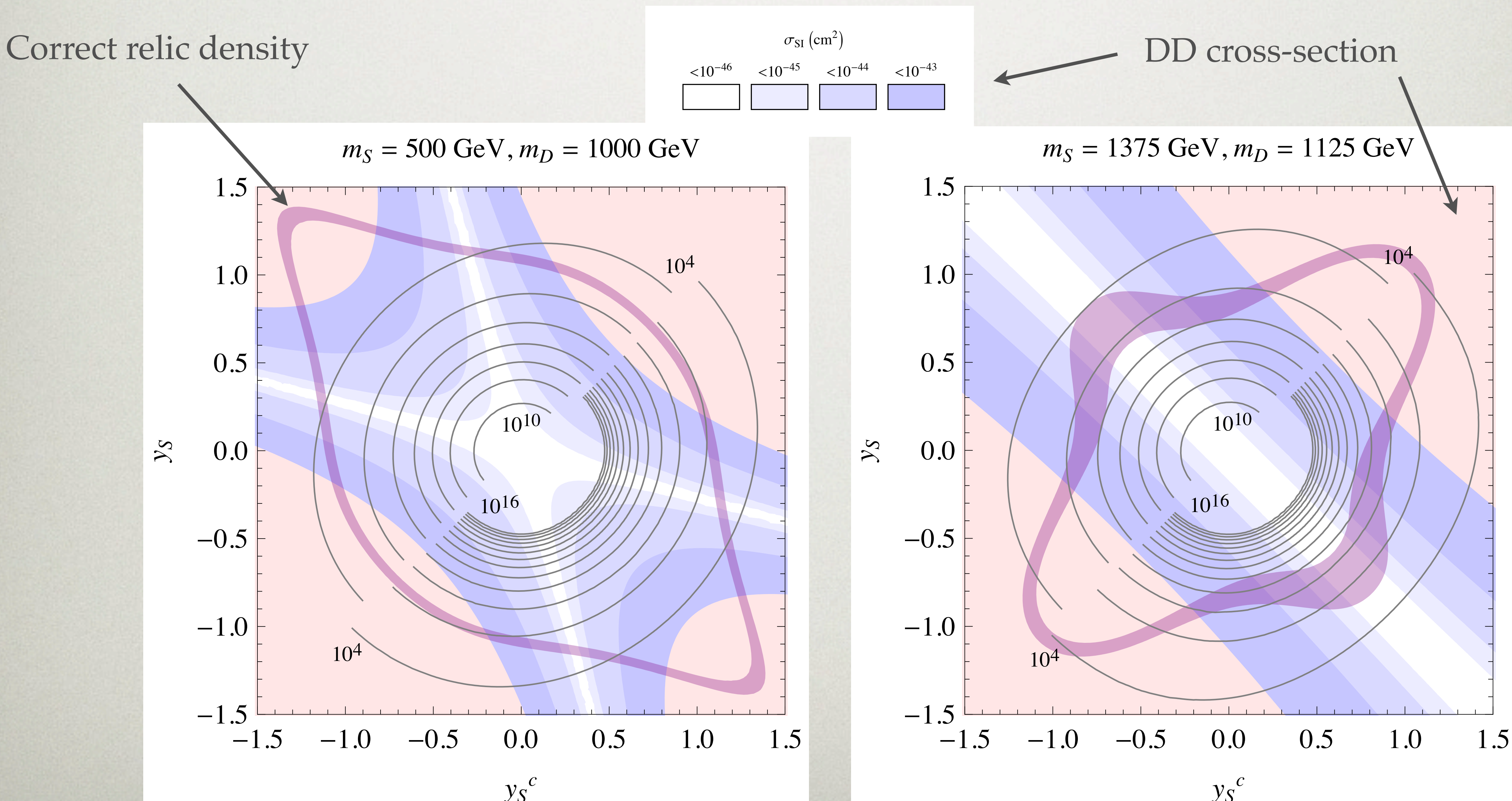

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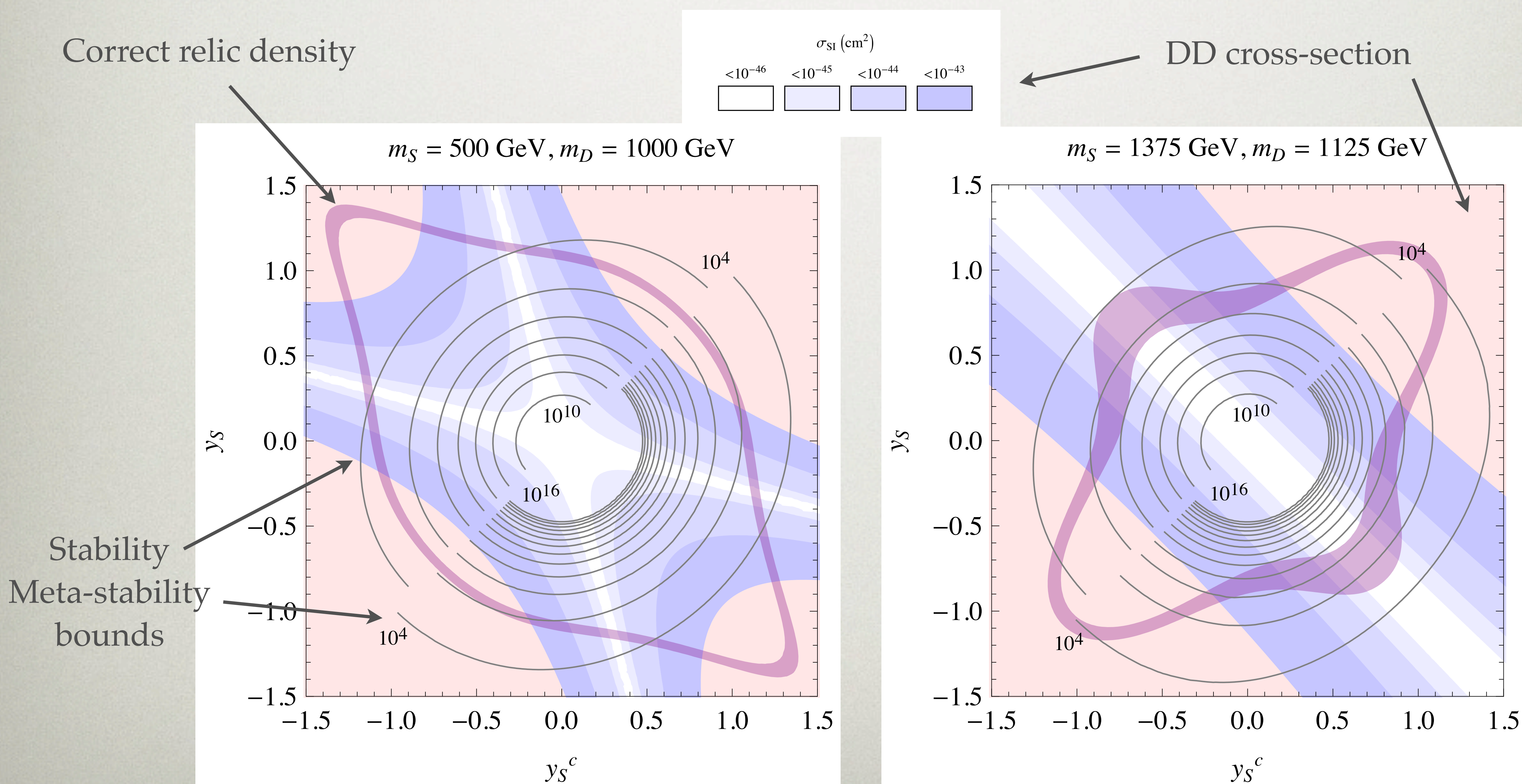
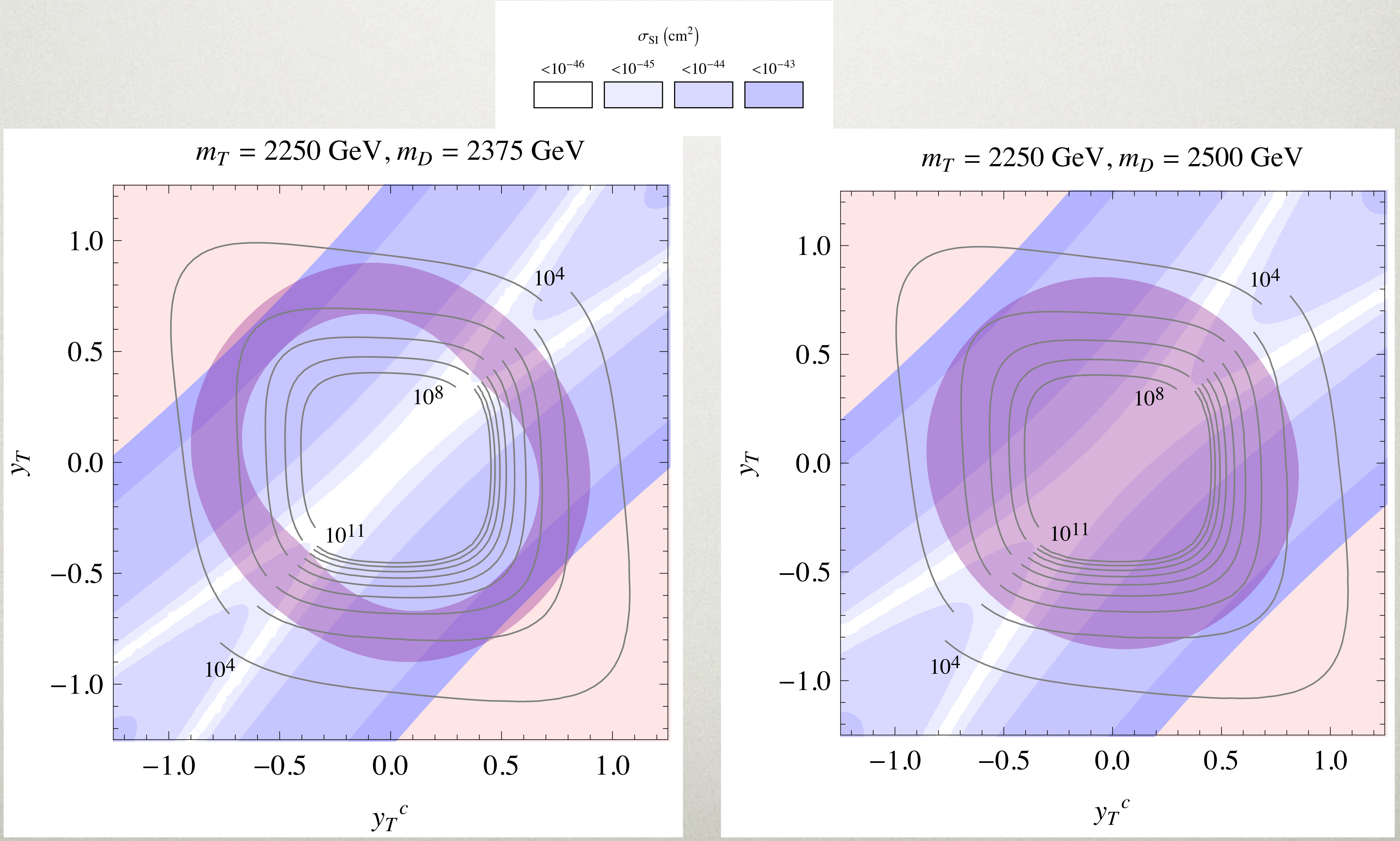


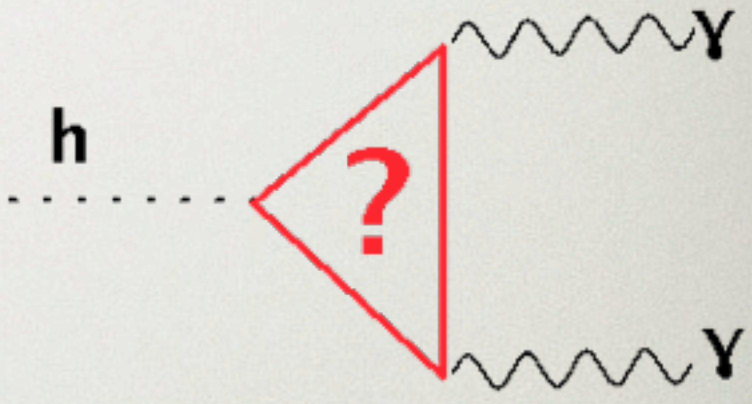
Effects of DD and Relic Density

triplet/doublet fermion: $$-\Delta\mathcal{L} = \frac{1}{2}m_T T^2 + m_D D D^c + y_T H T D + y_T^c H^c T D^c$$



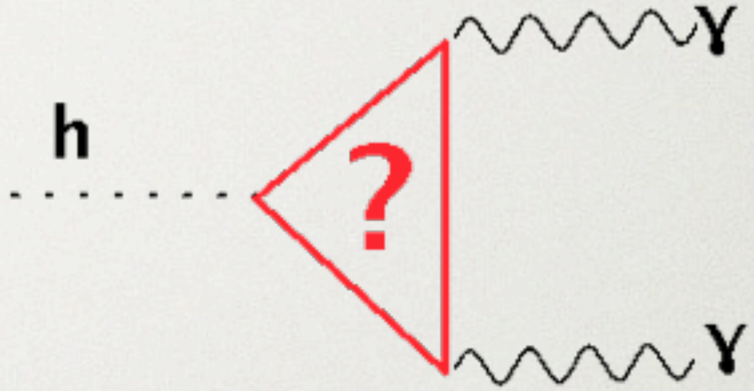
Inspecting the Higgs ...

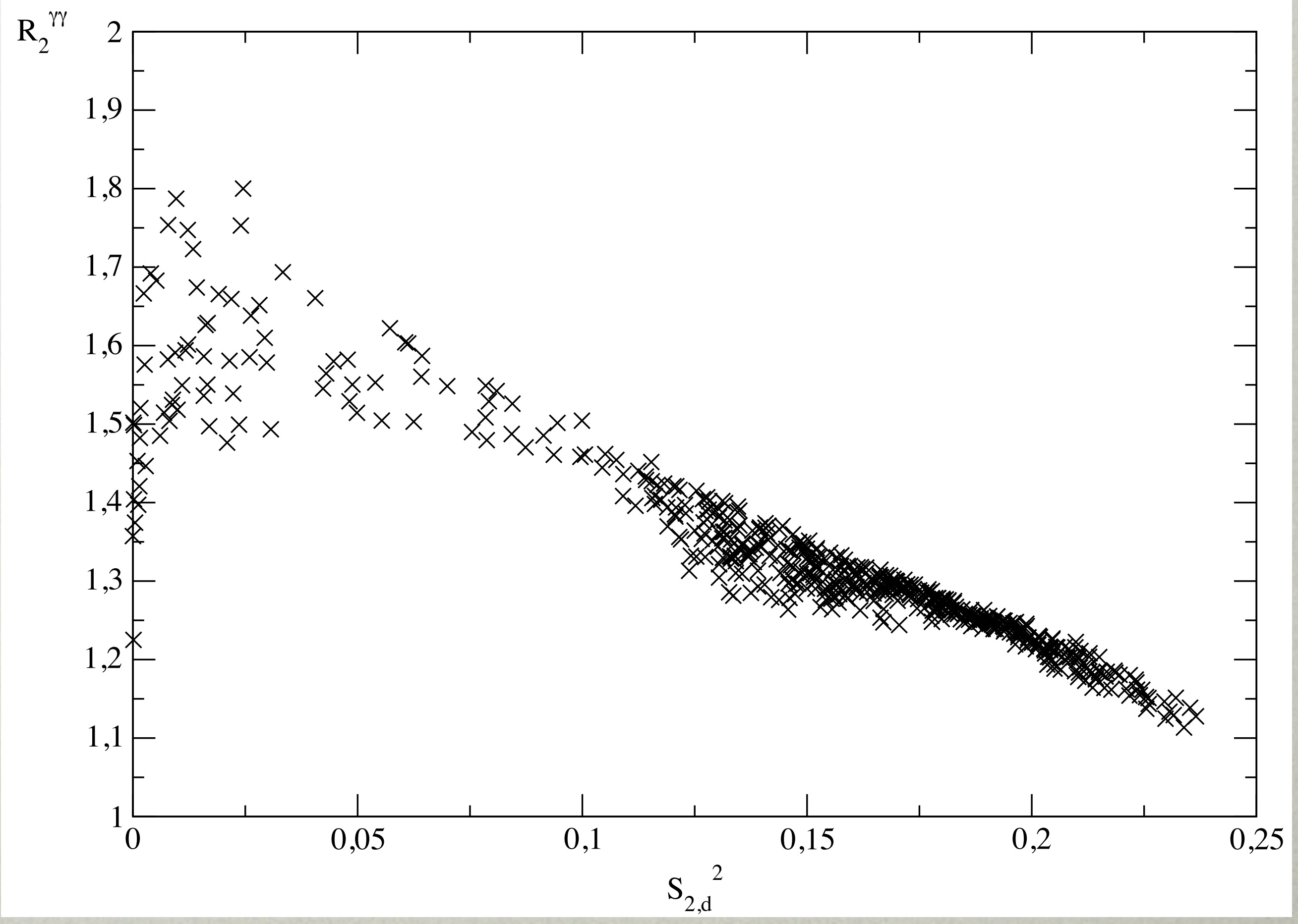
- ... for new weakly interacting particles through its decay modes
- Plenty of scanning in the literature.
- How do we think about separating which combinations of observables are relevant for which combinations of theoretical parameters?



Inspecting the Higgs

- Embed in specific models, e.g. NMSSM
- Boost $h \to \gamma\gamma$ by depleting total width





Ellwanger
1112.3458

Inspecting the Higgs

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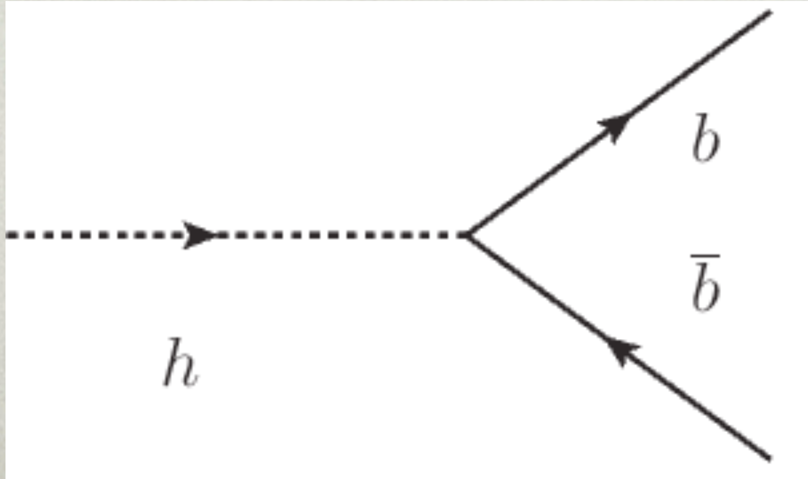
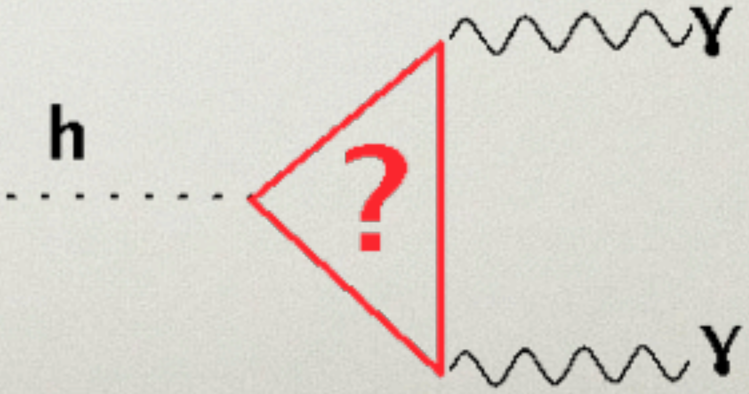
- More general question: how to map Higgs physics to new physics from Higgs observations?
- Basic observables: $R[\mathcal{O}] = \mathcal{O}/\mathcal{O}_{\rm SM};$ $R_i^j \equiv R[\sigma(jj \to h) \times {\rm Br}(h \to ii)]$
- Mixing and loop effects





Trees and Loops

- Can easily separate tree level effects from loop effects by looking at *ratios* of observables
- Example of a story: Singlet + 2 HDM + new EW states
- Suppose new colored particles will show up elsewhere first

Inspecting the Higgs

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- Singlet + 2 HDM + new EW states
- Mixing: two angles

$$h = \sum_I P_I H_I \qquad I = u, d, s$$

$$P_I = (\cos\alpha\cos\gamma, -\sin\alpha\cos\gamma, -\sin\gamma)$$

- Singlet mixing and deviation from SM decoupling limit

$$\delta = \alpha - \beta + \pi/2,$$

Inspecting the Higgs

$$h = \sum_I P_I H_I$$

$$P_I = (\cos\alpha\cos\gamma, -\sin\alpha\cos\gamma, -\sin\gamma)$$

Tree:

$$\begin{aligned} d_t &= \cos\gamma\cos\alpha/\sin\beta &&= \cos\gamma\cos\delta\,(1+\tan\delta\cot\beta) \\ d_b &= -\cos\gamma\sin\alpha/\cos\beta &&= \cos\gamma\cos\delta\,(1-\tan\delta\tan\beta) \end{aligned}$$

$$d_V = \cos\gamma\sin(\beta-\alpha) = \cos\gamma\cos\delta$$

$$d_i = \sum_I P_I \eta_{I,i}$$

$$\eta_{I,i} = \frac{v}{m_i}\frac{\partial m_i}{\partial v_I},$$

Extract
$\tan\beta\ ,\ \tan\delta$

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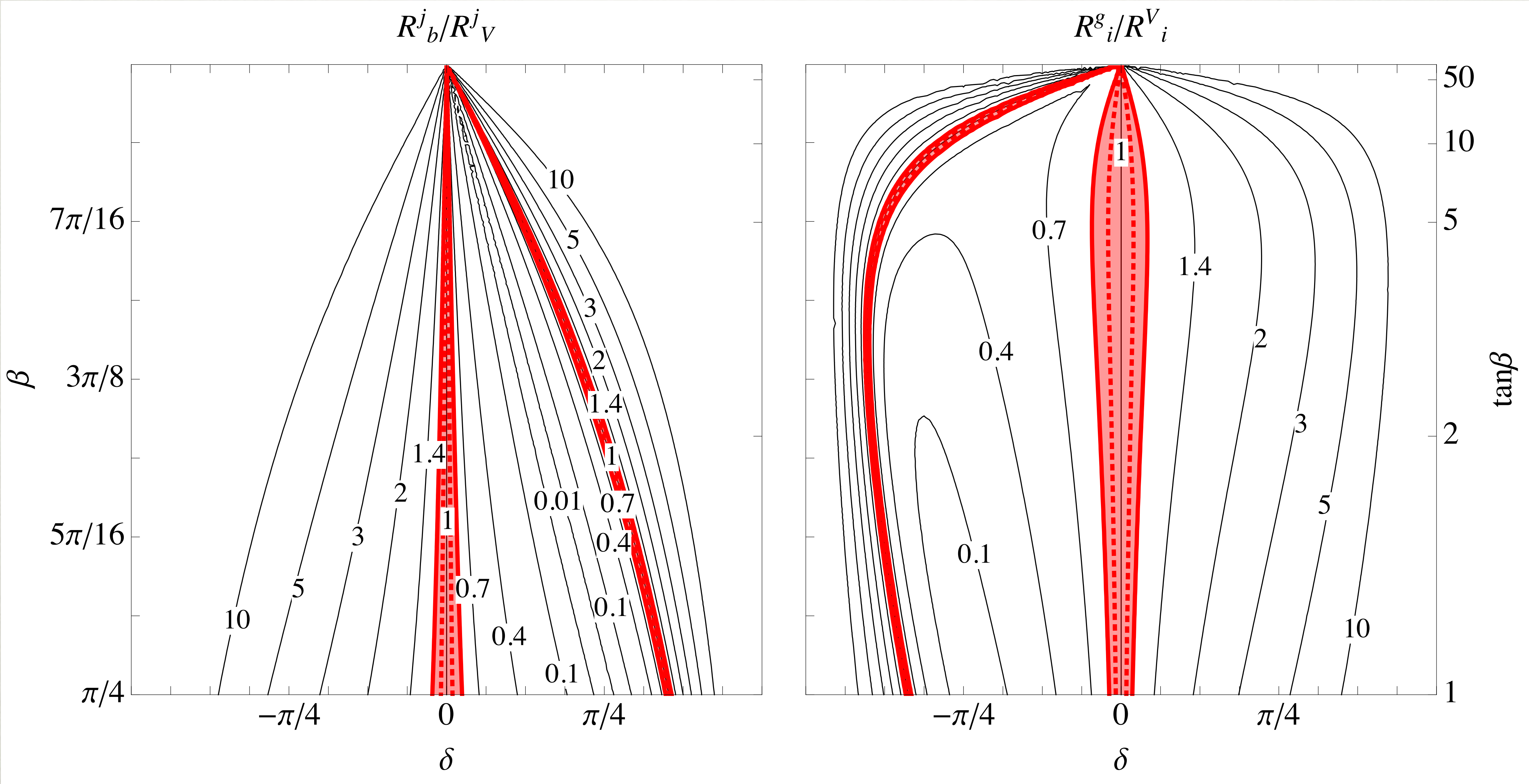

$$\frac{R_b^j}{R_V^j} = \frac{R_\ell^j}{R_V^j} = \frac{|d_b|^2}{|d_V|^2} = (1 - \tan\delta\tan\beta)^2 \qquad \frac{R_i^g}{R_i^V} \simeq \ |\mathcal{A}_{g,t}(1 + \tan\delta\cot\beta) + \mathcal{A}_{g,b}(1 - \tan\delta\tan\beta)|^2$$

Extract
$\tan\beta$, $\tan\delta$

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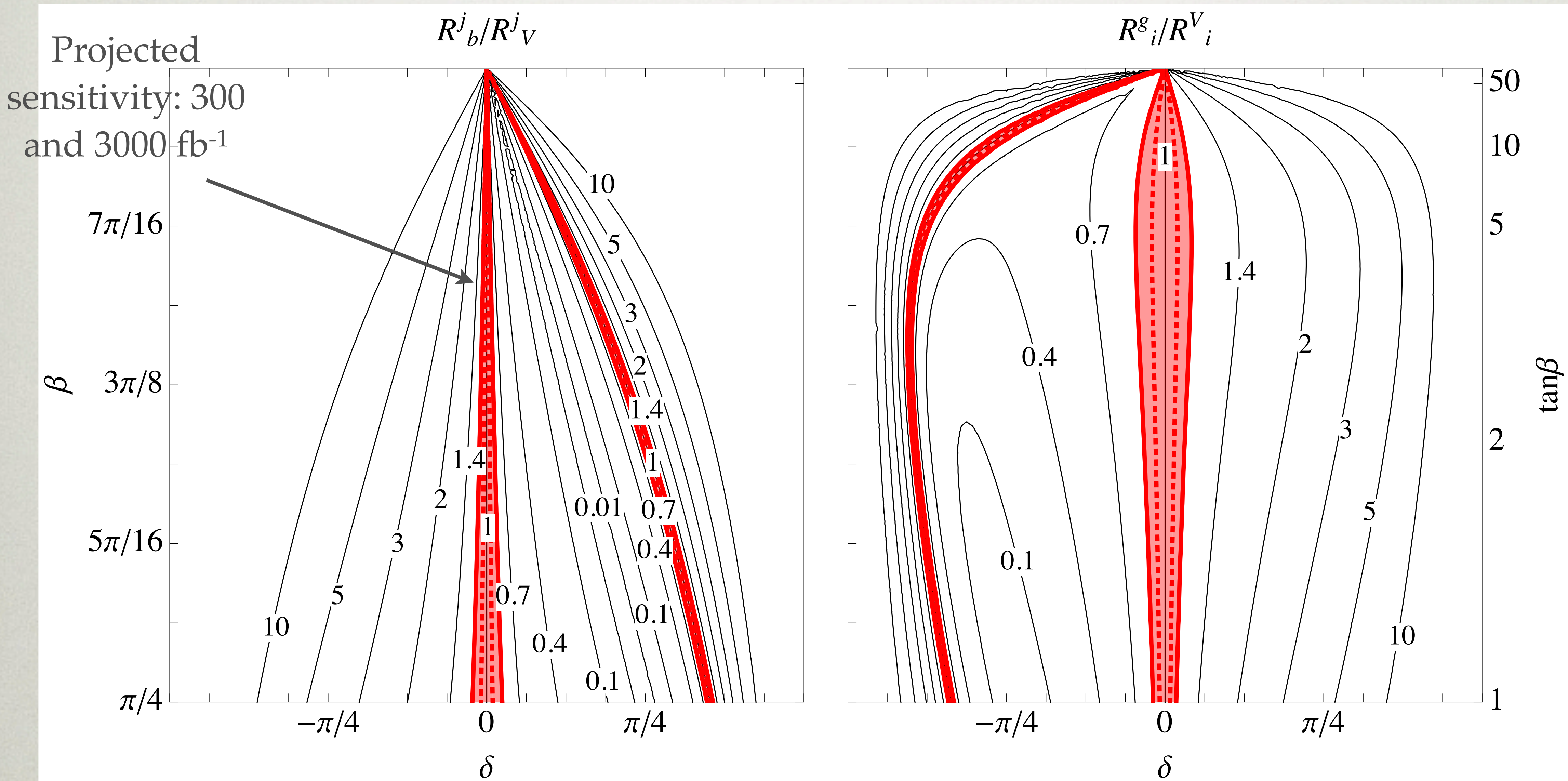

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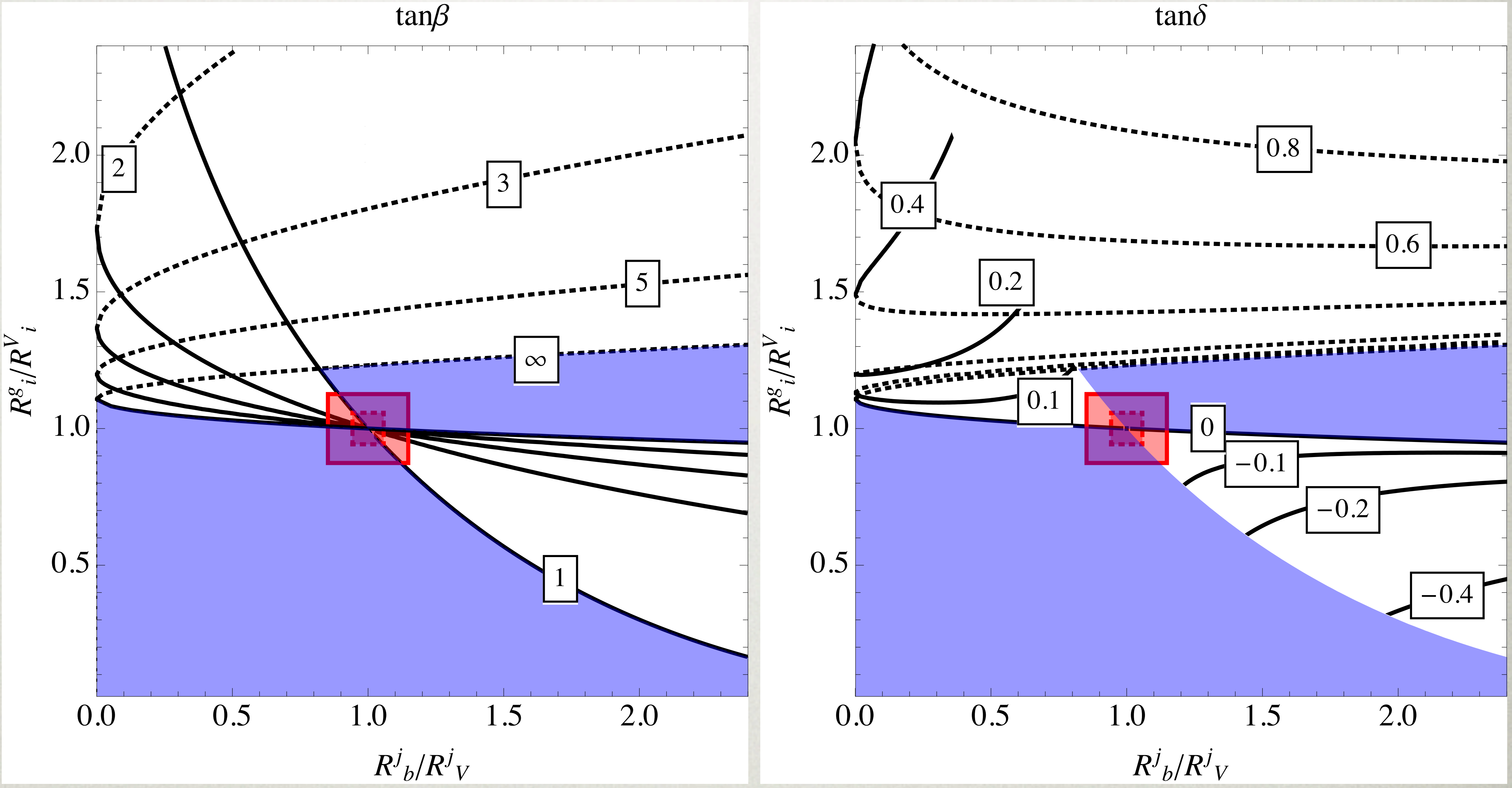
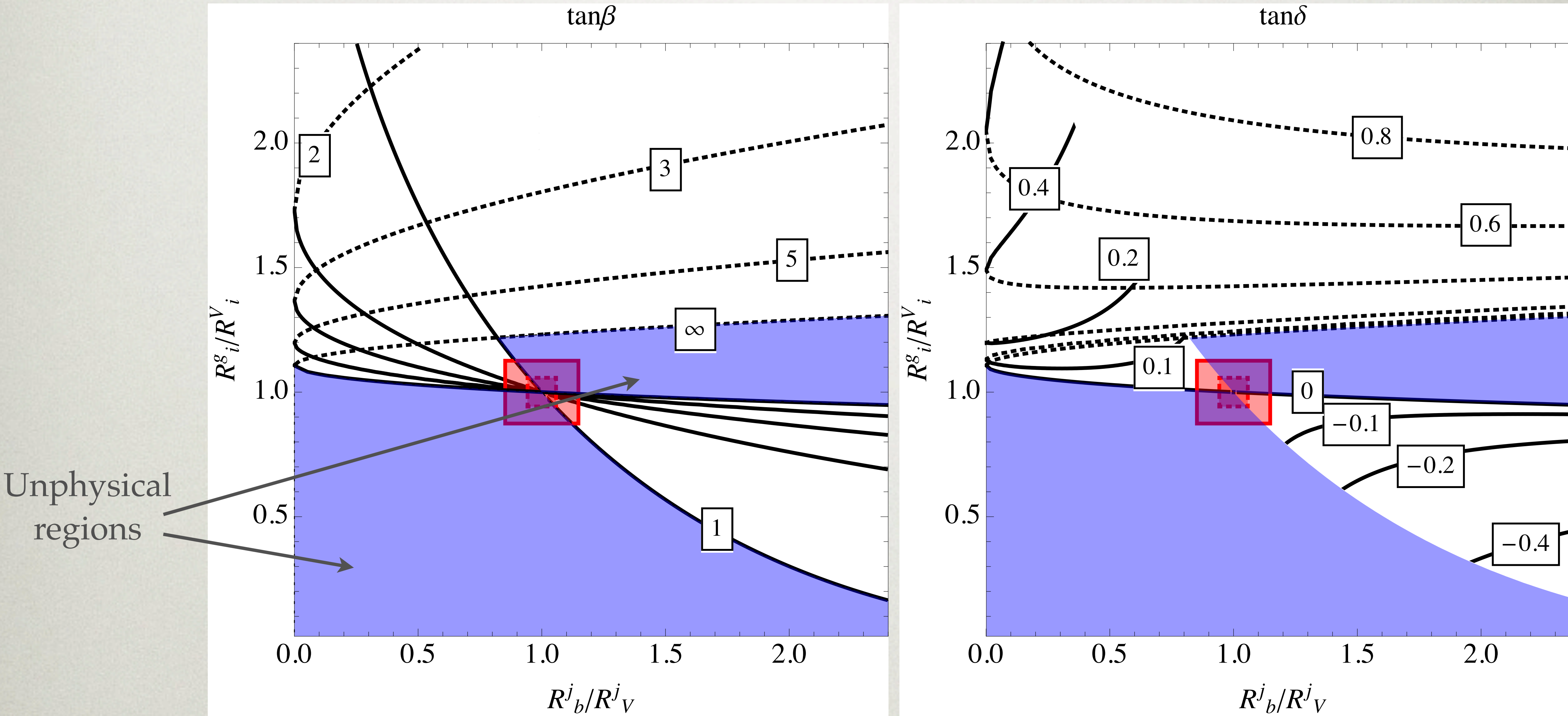
Extract

$\tan\beta$, $\tan\delta$



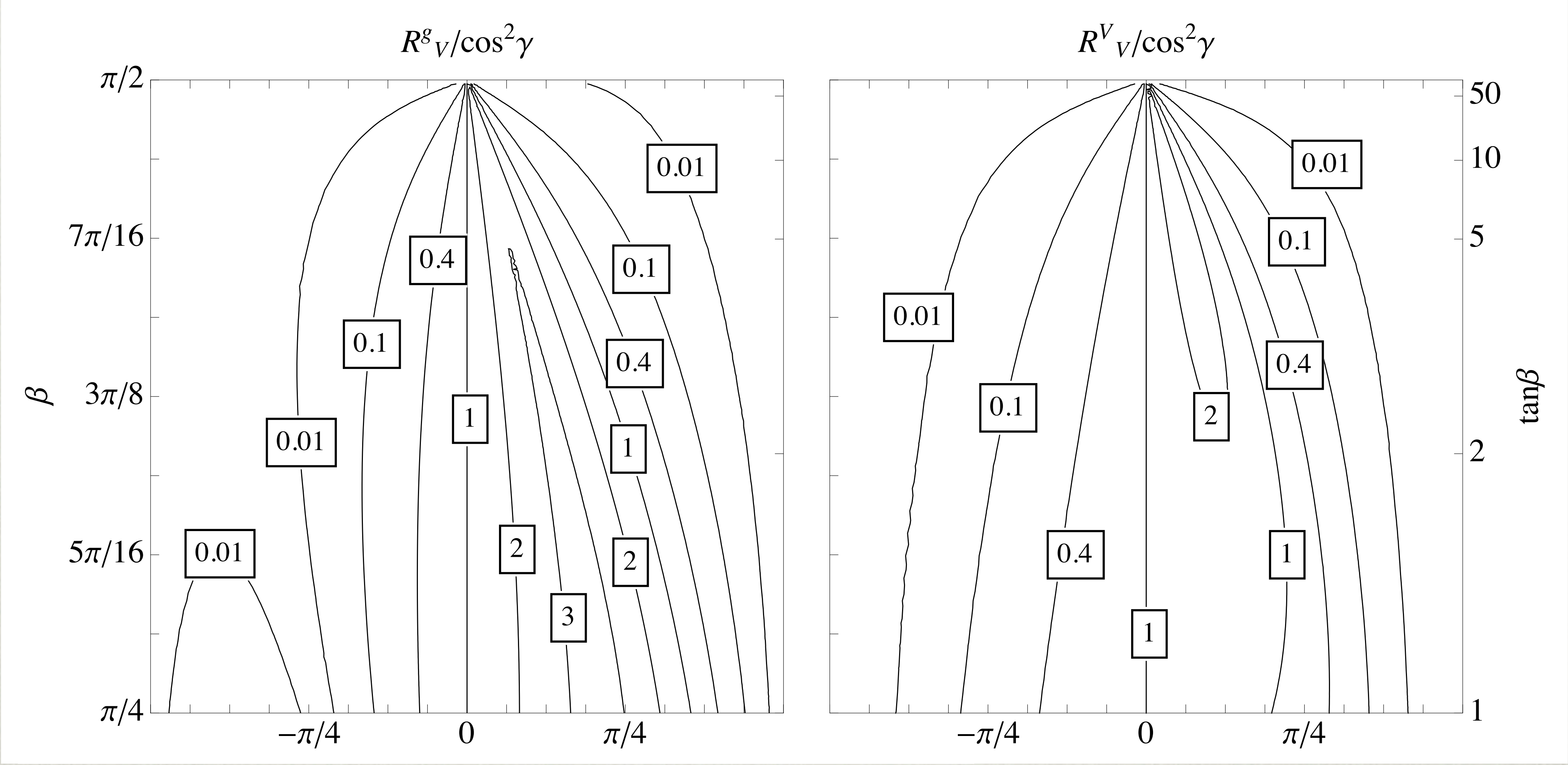
Extract

$\tan\beta\ ,\ \tan\delta$



Extract $\cos\gamma$

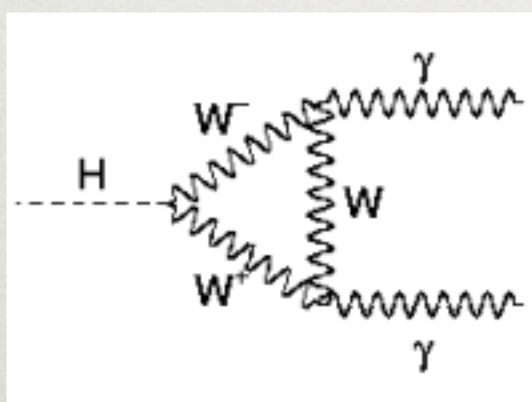
$$R_i^j \equiv R[\sigma(jj \to h) \times \mathrm{Br}(h \to ii)]$$



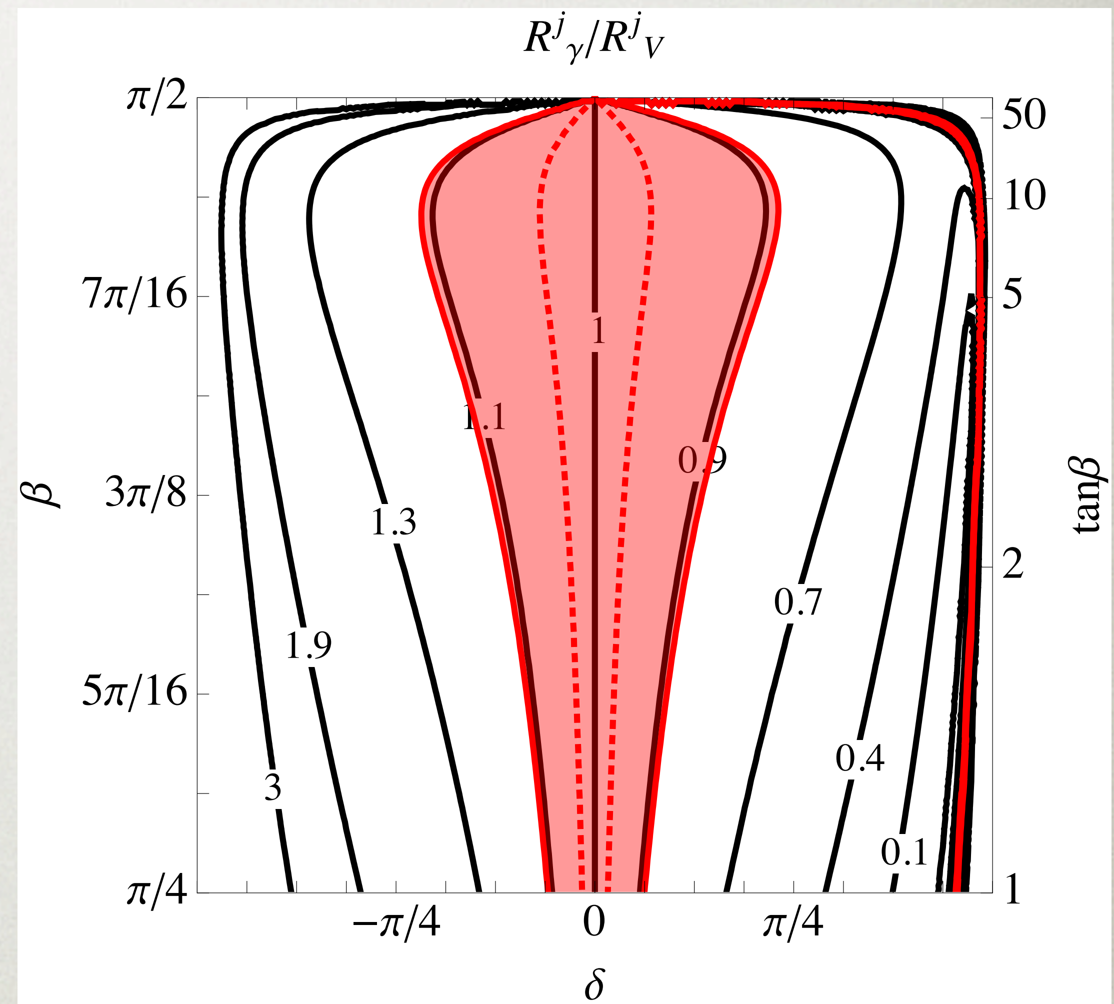
δ

Virtual Effects

- R^j_γ / R^j_V not very sensitive to tree level parameters



- Extract virtual EW states



$$\frac{R^j_\gamma}{R^j_V} = |1 + \epsilon(\beta)\tan\delta|^2$$

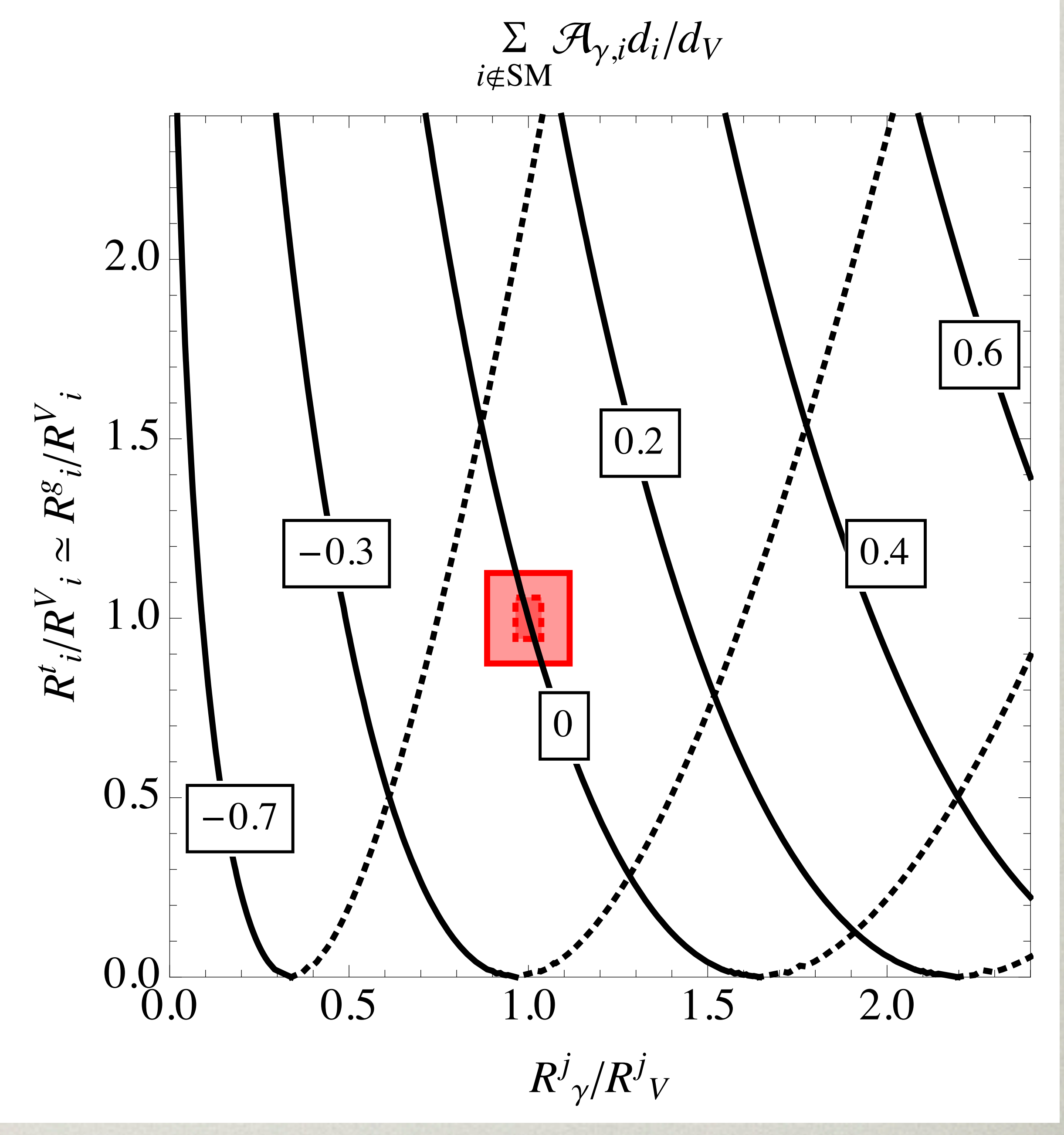
Extract the Loop Parameters

All new physics in this black box!
(easily calculable)

$$\frac{R^j_\gamma}{R^j_V} \simeq \left| 1 + \epsilon(\beta)\tan\delta + \frac{1}{d_V}\sum_{i\notin \mathrm{SM}} \mathcal{A}_{\gamma,i} d_i \right|^2$$

$$d_i = \sum_I P_I \eta_{I,i}$$

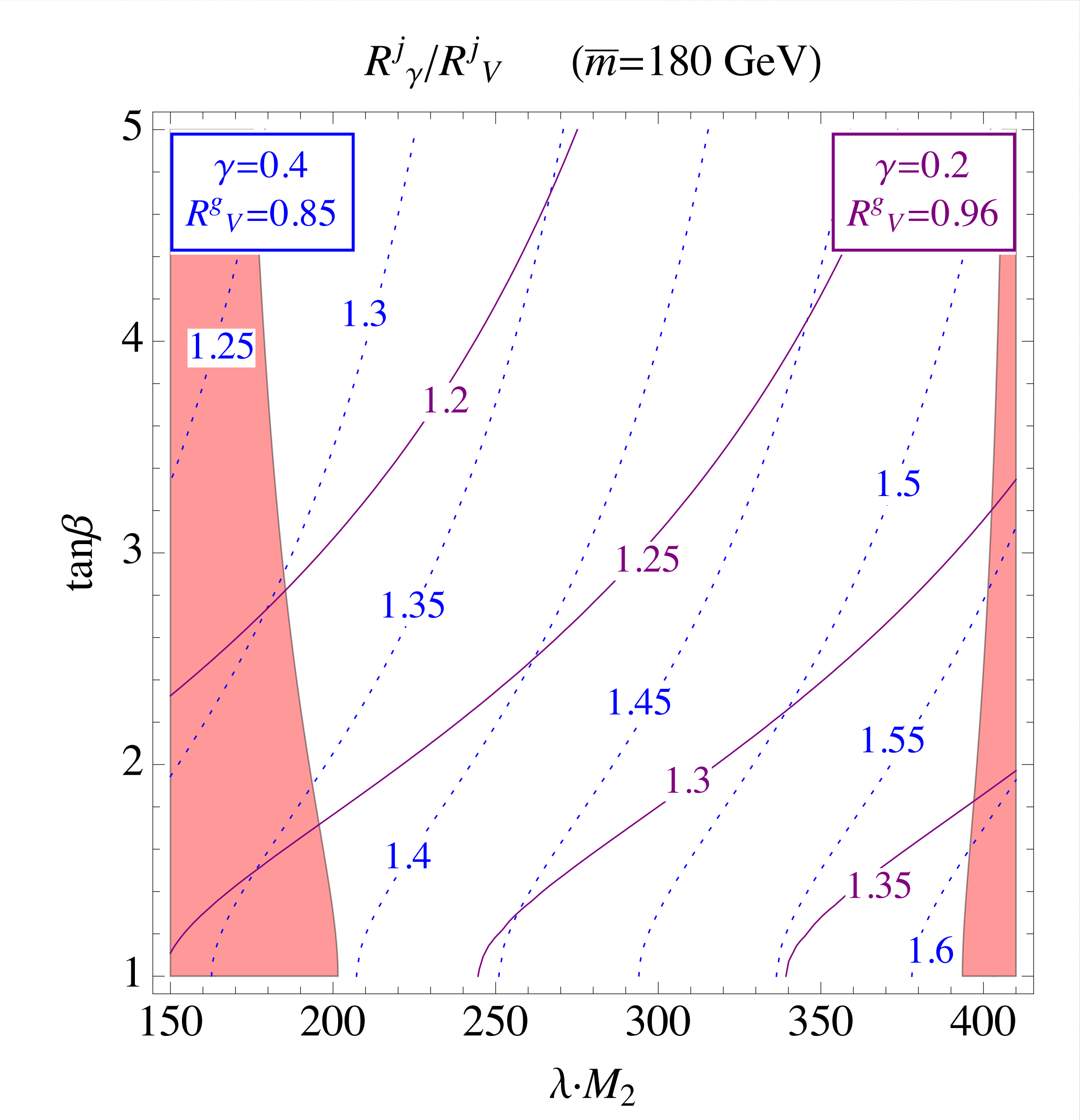
$$\eta_{I,i} = \frac{v}{m_i}\frac{\partial m_i}{\partial v_I},$$



Application: NMSSM

$$\eta_{I,\chi^\pm} = \frac{2m_W^2}{\overline{m}^2}\left(-\cos\beta, -\sin\beta, \frac{\lambda M_2}{\sqrt{2}g_2 m_W}\right)$$

$$\left(\overline{m}^2\right)^2 = \left(m_{\chi_1^\pm} m_{\chi_2^\pm}\right)^2 = \det\left(\mathcal{M}^\dagger_{\chi^\pm}\mathcal{M}_{\chi^\pm}\right)$$



Summary

- Traditional probes are closing an increasing fraction of the window for new EW states
- To close (or observe!) the remaining part of the window, need to use complementary probes
- Higgs provides an opportunity through indirect probes -- stability and production/ decay
- These can be more effectively utilized by looking at correlations between observables that can be mapped uniquely to a theory

SUMMARY

- Haven't discussed but there are important correlations with direct and indirect detection experiments if these states are connected to the DM (another talk)
- Flavor too
- Multi-pronged approach!