Naturalness of MSSM Dark Matter

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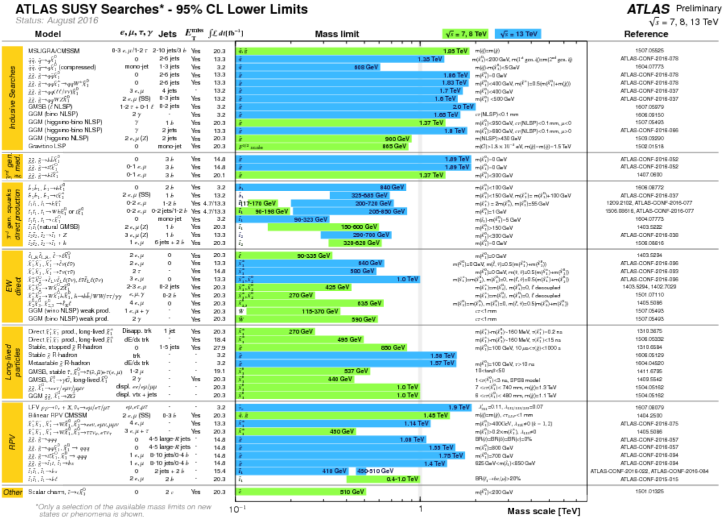
Supersymmetry searches in the LHC



Natural Supersymmetry $\Rightarrow$ small EW fine-tuning

The Hierarchy problem

- Supersymmetry as as solution to the hierarchy problem.
- The standard measurement of fine-tuning.

$$\Delta_i^{(\mathrm{EW})} = \frac{d \log v^2}{d \log \theta_i} \; ; \qquad \Delta^{(\mathrm{EW})} \equiv \max \left\{ \Delta_i^{(\mathrm{EW})} \right\}$$

- The MSSM

EW fine-tuning $\Rightarrow$ light gluinos, stops, higgsinos

- $\Delta^{(\mathrm{EW})}$ dominated by the gluino-mass.

$m_{\tilde{g}} \gtrsim \mathcal{O}(100) \rightarrow$ fine-tuning at the level of $\lesssim 1\,\%$.

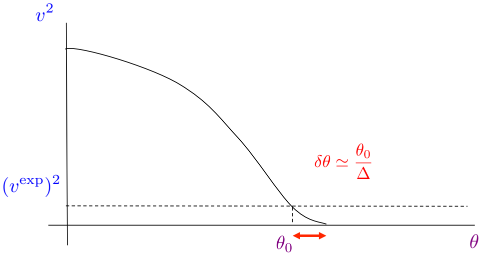
- What about the fine-tuning related to the generation of the right amount of dark matter?

Fine tuning

The standard fine-tuning criterion

$$\Delta_\theta = \frac{\partial \log v^2}{\partial \log \theta}$$

Expanding v^2 around θ_0, $v^2(\theta_0 + \delta\theta) \simeq v^2(\theta_0) + (\partial v^2(\theta)/\partial\theta)_{\theta_0}\ \delta\theta$



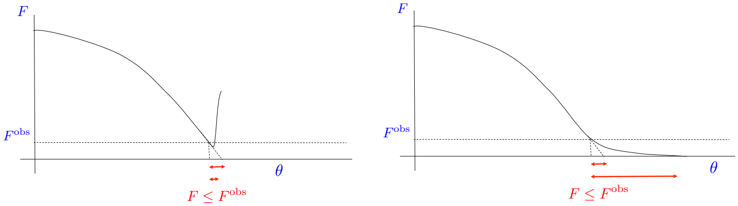
The probabilistic interpretation of Δ: p-value $\simeq \left|\frac{\delta\theta}{\theta_0}\right| \equiv \Delta^{-1}$

Dark Matter

Fine tuning associated to get the correct relic density

Standard parameter VRS **p-value**

Underestimation and overestimation of the fine-tuning:

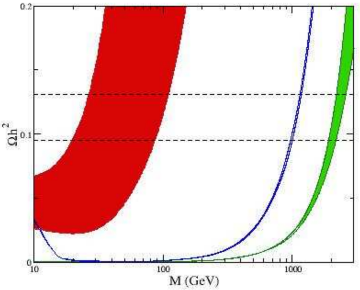


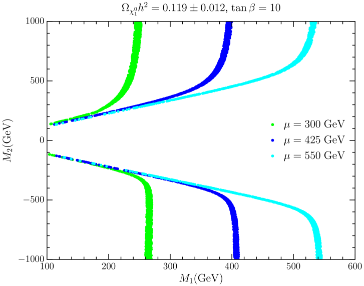
The correct definition of the fine-tuning $\Rightarrow$ the p-value.

Well tempered neutralino

2006 Arkani-Hamed et. al.

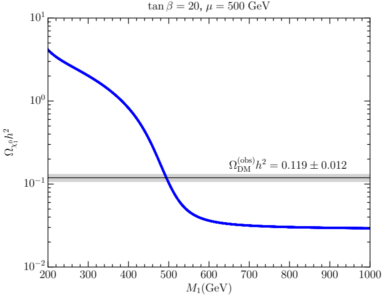
- Bino-like
- Higgsino-like
- Wino-like





- bino-wino
- bino-higgsino
- bino-wino-higgsino

Well-tempered bino-higgsino



p-value of $\mathcal{O}(1)$

The standard criteria fails

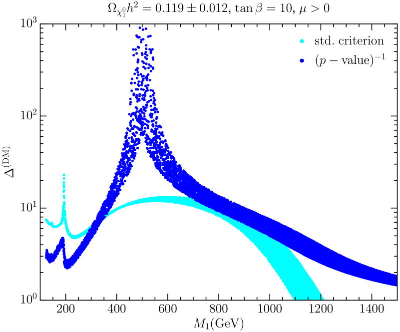
p-value($\Omega < \Omega^{\rm obs}$) $\rightarrow$ range of M_1

A better estimation:

$$\Omega \longrightarrow |\tan 2\theta|$$

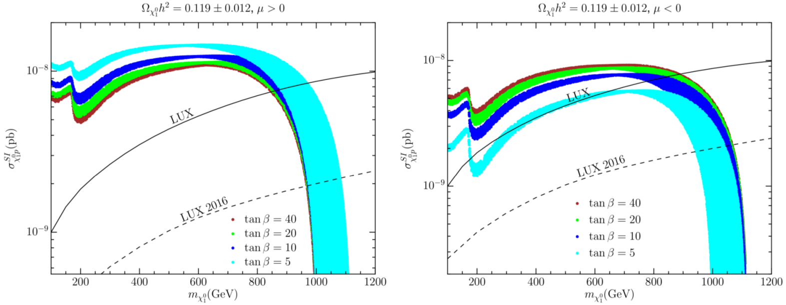
then

$$\mathrm{p-value} \equiv \frac{2|\mu - M_1|}{M_1}$$



Well tempered bino-higgsino

Severely constrained by Direct Detection



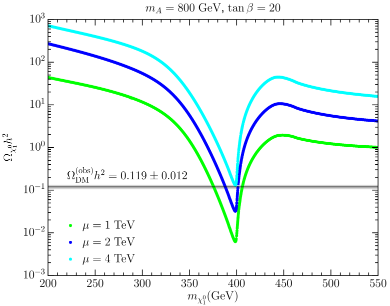
Blind spots for small $\tan\beta$ **but** huge EW fine-tuning

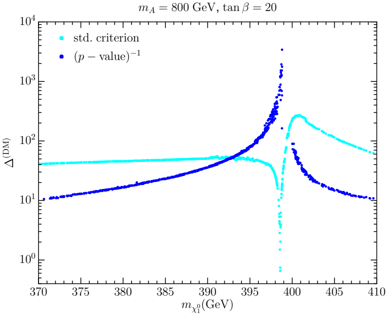
A-funnel

$< \sigma v >$ may increase due to resonance annihilations.

$$\chi_1 \chi_1 \to A \to b\bar{b}$$

Requires $\tilde{B}/\tilde{H}$ composition.

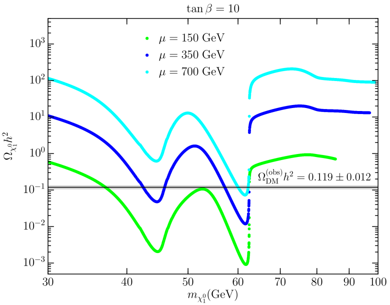


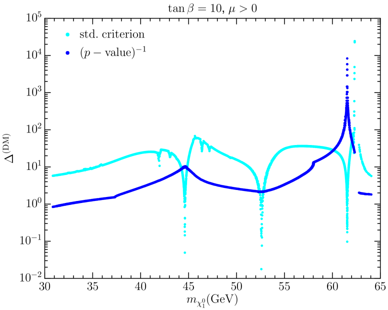


Small fine-tuning for $M_1 < m_A/2$ but $s \simeq m_A$

Higgs and Z funnel

The standard criteria overestimate and underestimate the fine-tuning dramatically.





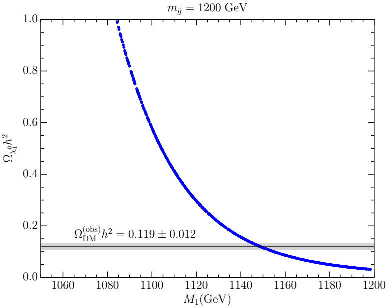
The p-value is computed by adding $\Delta m_Z/2$ and $\Delta m_h/2$.

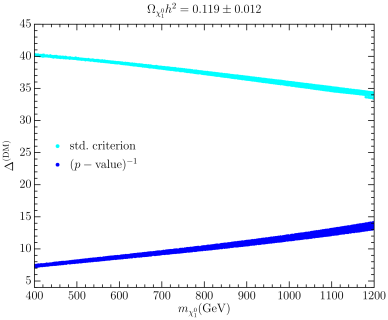
Blind spots in direct detection

Co-annihilation

Particles with masses close to the LSP annihilate efficiently

$$< \sigma_{\rm eff} v > = \frac{\sum_{ij} w_i w_j \sigma_{ij} x^{-n}}{(\sum_i w_i)^2}, \qquad w_i = \left(\frac{m_i}{m_1}\right)^{3/2} e^{-x\left(\frac{m_i}{m_1}-1\right)}$$





$$\Delta_{M_1} = \mathcal{O}(20 - 40) \frac{m_{\tilde g}}{M_1} \qquad \text{p} - \text{value} \simeq \frac{\Delta m}{M}$$

Connection to the EW fine-tuning

- The DM fine-tuning must be combined with the EW one
- Typically, EW fine-tuning is $\mathcal{O}(10)$ more severe than the DM one, though the DM one can be extremely larger at special places.
- Statistical interpretation of p-value: both fine-tunings should be multiplicatively combined
- Pure Higgsino, pure Wino: no DM fine-tuning
  But to heavy SUSY spectrum and large EW fine-tuning
  Therefore Difficult to see at the LHC
  Notice that $M_{\chi_1} \sim \mu \simeq 1$ TeV $\rightarrow \Delta_{\mu}^{EW} \sim \mathcal{O}(200)$.
- DM fine-tuning is mild in several cases: funnels (not close to the twice the resonance), co-annihilation, Bino-higgsino.

Thanks

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