

Naturalness of MSSM Dark Matter

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Supersymmetry searches in the LHC

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

Model	e, μ, t, b	Jets	E_{miss}^{true}	$\int \mathcal{L} dt / (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	US(LG) + CMSSM	0-3 jets	$t \rightarrow 2t - 2b$	20 pb	20.3	8.2	1.0 TeV	1507.0655
		0 jets	$t \rightarrow 2t$	20 pb	13.3	8.2	1.0 TeV	ATLAS-CDF-2014-378
	tt, $t\bar{t} \rightarrow t\bar{t}$ (compressed)	mono-jet	$t \rightarrow 1t$	20 pb	3.2	8.2	800 GeV	1604.0773
		0 jets	$t \rightarrow 2t$	20 pb	13.3	8.2	1.0 TeV	ATLAS-CDF-2014-379
	tt, $t\bar{t} \rightarrow t\bar{t}$ (soft)	mono-jet	$t \rightarrow 1t$	20 pb	3.2	8.2	1.0 TeV	ATLAS-CDF-2014-379
		0 jets	$t \rightarrow 2t$	20 pb	13.3	8.2	1.0 TeV	ATLAS-CDF-2014-379
	tt, $t\bar{t} \rightarrow t\bar{t}$ (soft)	2+ μ	$t \rightarrow 1t$	20 pb	13.2	8.2	1.0 TeV	ATLAS-CDF-2014-379
		4 jets	$t \rightarrow 1t$	20 pb	13.2	8.2	1.0 TeV	ATLAS-CDF-2014-379
	tt, $t\bar{t} \rightarrow t\bar{t}$ (soft)	2+ μ	$t \rightarrow 2t$	20 pb	13.2	8.2	1.0 TeV	ATLAS-CDF-2014-379
	GMSB (fNLSP)	1+2 jets	$t \rightarrow 1t$	20 pb	3.2	8.2	1.0 TeV	1607.0579
τ^+, τ^- final state	GGF (one NLSP)	2 τ	$t \rightarrow 1t$	20 pb	3.2	8.2	1.0 TeV	1606.0810
		7 jets	$t \rightarrow 1t$	20 pb	3.2	8.2	1.0 TeV	1606.0810
	GGM (higgsino NLSP)	2 τ	$t \rightarrow 2t$	20 pb	13.3	8.2	1.0 TeV	ATLAS-CDF-2014-396
	GGM (higgsino NLSP)	2 τ , 2 jets	$t \rightarrow 1t$	20 pb	20.3	8.2	1.0 TeV	1503.0590
	GGM (higgsino NLSP)	0 jets	$t \rightarrow 1t$	20 pb	20.3	8.2	1.0 TeV	1503.0518
	Growthfit (SP)	0 jets	$t \rightarrow 1t$	20 pb	20.3	8.2	300 GeV, 600 GeV	1604.0773
		0 jets	$t \rightarrow 1t$	20 pb	20.3	8.2	300 GeV, 600 GeV	1604.0773
	tt, $t\bar{t} \rightarrow t\bar{t}$	0 jets	$t \rightarrow 1t$	20 pb	14.8	8.2	1.0 TeV	ATLAS-CDF-2014-352
	tt, $t\bar{t} \rightarrow t\bar{t}$	0 jets	$t \rightarrow 1t$	20 pb	14.8	8.2	1.0 TeV	ATLAS-CDF-2014-352
	tt, $t\bar{t} \rightarrow t\bar{t}$	0 jets	$t \rightarrow 1t$	20 pb	20.1	8.2	1.0 TeV	1407.0890
τ^+, τ^- final state + 1 jet	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	8.2	8.2	1.0 TeV	1608.0772
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	13.2	8.2	1.0 TeV	CONF-2014-337
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	4.7 TeV	1309.2021, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	4.7 TeV	1306.0861, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	1604.0773
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	1403.0322
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	1508.0616
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	1405.0244
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	ATLAS-CDF-2014-352
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	1.0 TeV	1405.0244
EW directed production	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	8.2	8.2	800 GeV	1608.0772
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	13.2	8.2	800 GeV	CONF-2014-337
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1309.2021, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	800 GeV	1306.0861, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1604.0773
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	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1508.0616
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	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1405.0244
EW directed production	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	13.3	8.2	800 GeV	1608.0772
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	14.8	8.2	800 GeV	CONF-2014-337
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1309.2021, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	800 GeV	1306.0861, ATLAS-CDF-2015-077
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1604.0773
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1403.0322
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1508.0616
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1405.0244
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	ATLAS-CDF-2014-352
	$\tilde{g}, \tilde{b}_1, \tilde{b}_2 \rightarrow \tau^+\tau^-$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1405.0244
Long-lived	Direct $t \rightarrow$ prod, long-lived \tilde{t}_1	Dropout	1 jet	20 pb	20.3	8.2	270 GeV	1511.0375
	Direct $t \rightarrow$ prod, long-lived \tilde{t}_1	Dropout	0 jets	20 pb	18.3	8.2	270 GeV	1511.0375
	Stable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	14.8	8.2	270 GeV	1511.0375
	Stable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	CONF-2014-337
	Stable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	270 GeV	1309.2021, ATLAS-CDF-2015-077
	Stable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1306.0861, ATLAS-CDF-2015-077
	Metastable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1604.0773
	Metastable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1403.0322
	Metastable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1508.0616
	Metastable \tilde{t}_1 + \tilde{b}_1 decay	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1405.0244
RPV	GGF (one NLSP)	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1507.0645
	GGM (one NLSP)	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1507.0645
	GGM (one NLSP)	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1507.0645
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	GGM (one NLSP)	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	270 GeV	1507.0645
Other	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	20.3	8.2	800 GeV	1501.0325
	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	13.3	8.2	800 GeV	1501.0325
	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1501.0325
	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	800 GeV	CONF-2014-337
	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	1.2	8.2	800 GeV	1309.2021, ATLAS-CDF-2015-077
	Stable charm, $t \rightarrow c\tilde{c}$	0 jets	$t \rightarrow 1t$	20 pb	4.7	8.2	800 GeV	1306.0861, ATLAS-CDF-2015-077
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**Only a selection of the available mass limits on new states or phenomena is shown.*



Natural Supersymmetry \Rightarrow small EW fine-tuning

The Hierarchy problem

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

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

- ▶ The MSSM
 - EW fine-tuning \Rightarrow light gluinos, stops, higgsinos

- ▶ $\Delta^{(\text{EW})}$ dominated by the gluino-mass.
 $m_{\tilde{g}} \gtrsim \mathcal{O}(100)$ \rightarrow fine-tuning at the level of $\lesssim 1\%$.

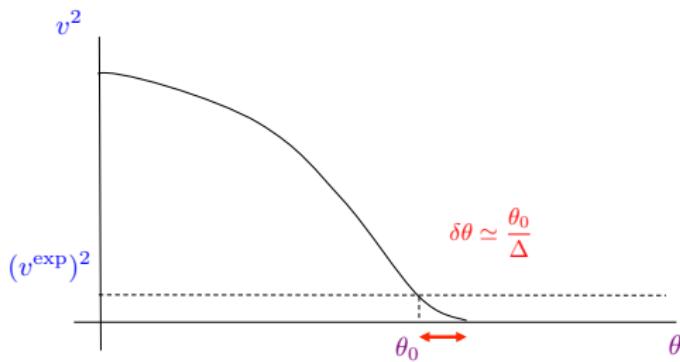
- ▶ What about the fine-tuning related to the generation of the right amount of dark matter?

Fine tuning

The standard fine-tuning criterion

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

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



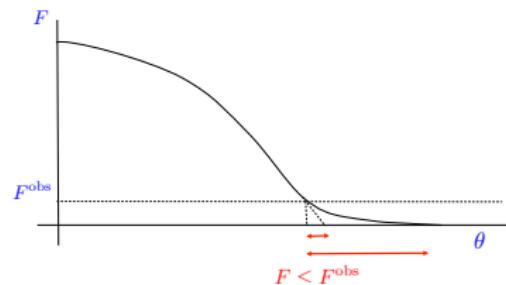
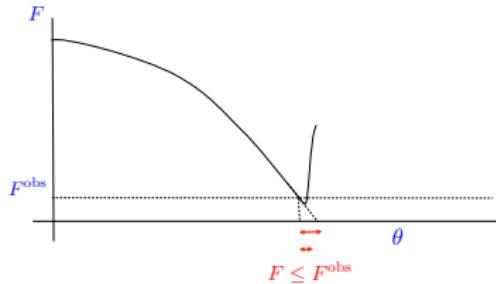
The probabilistic interpretation of Δ : $p\text{-value} \simeq \left| \frac{\delta\theta}{\theta_0} \right| \equiv \Delta^{-1}$

Dark Matter

Fine tuning associated to get the correct relic density

Standard parameter	VRS	p-value
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Underestimation and overestimation of the fine-tuning:

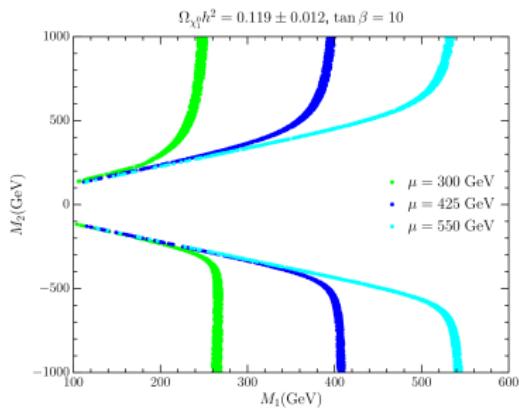
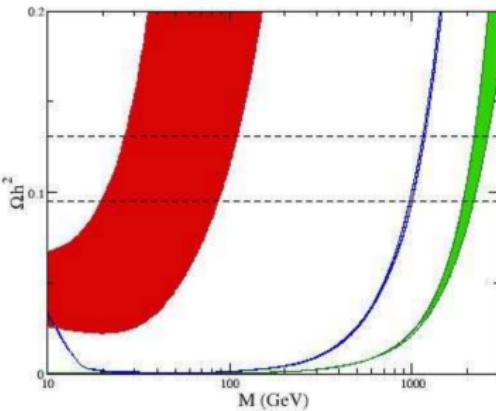


The correct definition of the fine-tuning \Rightarrow the p-value.

Well tempered neutralino

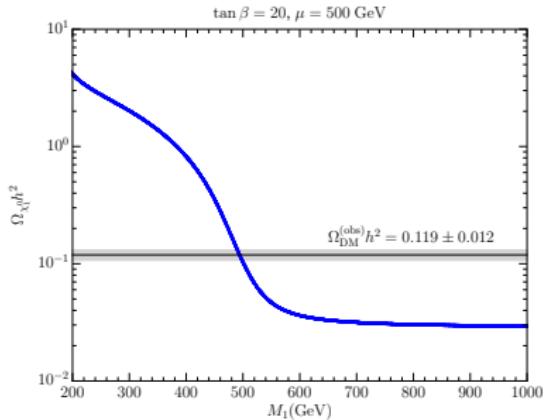
2006 Arkani-Hamed et. al.

- ▶ 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

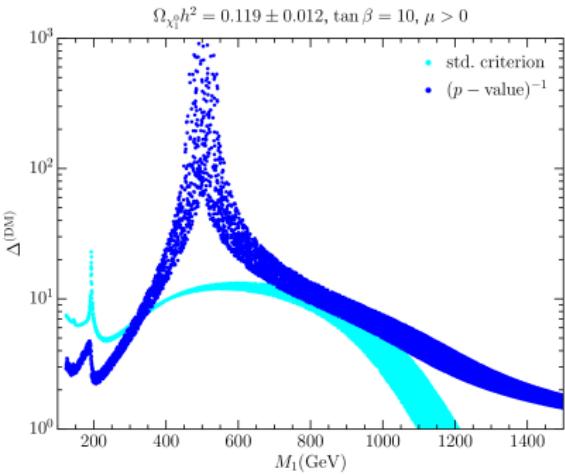
p-value($\Omega < \Omega^{\text{obs}}$) → range of M_1

A better estimation:

$$\Omega \rightarrow |\tan 2\theta|$$

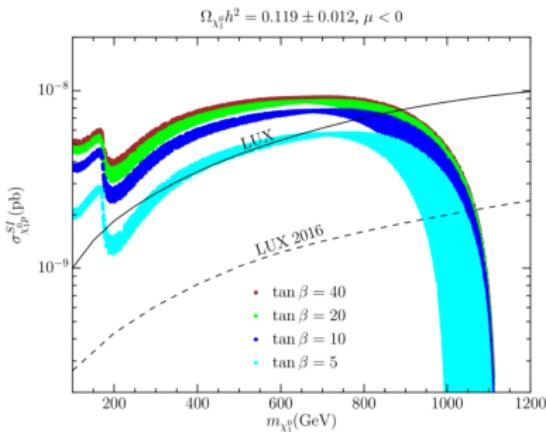
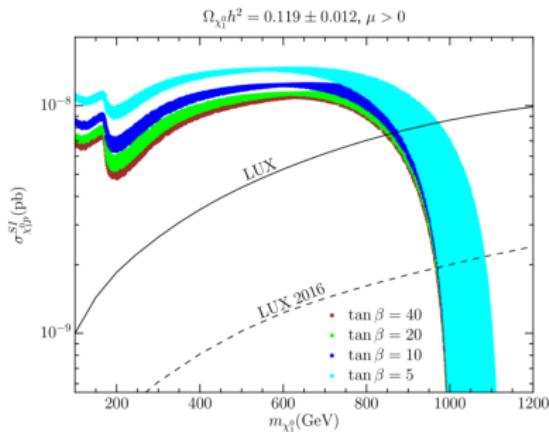
then

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



Well tempered bino-higgsino

Severely constrained by Direct Detection



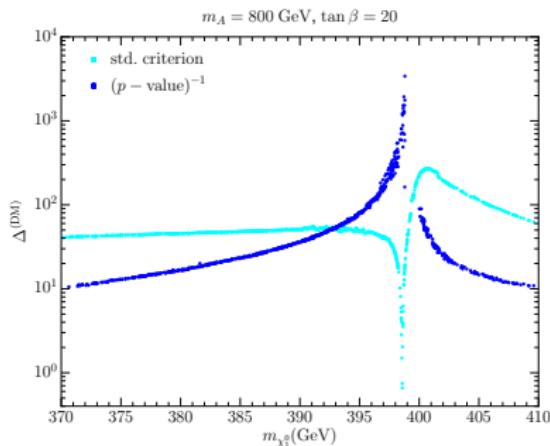
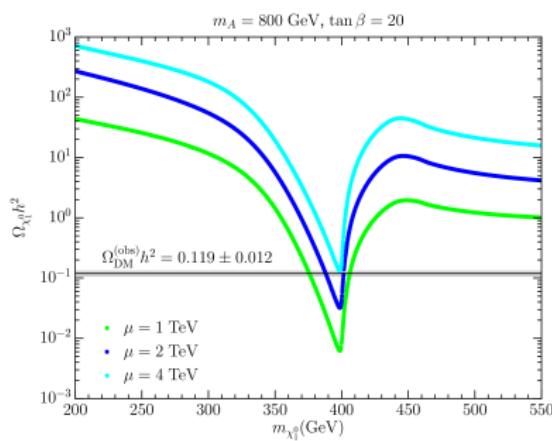
Blind spots for small $\tan \beta$ **but** huge EW fine-tuning

A-funnel

$\langle \sigma v \rangle$ may increase due to resonance annihilations.

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

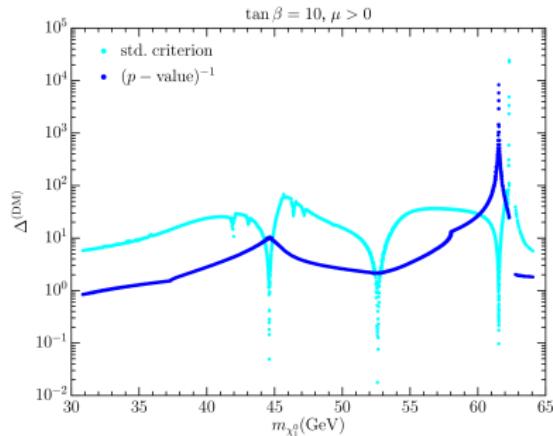
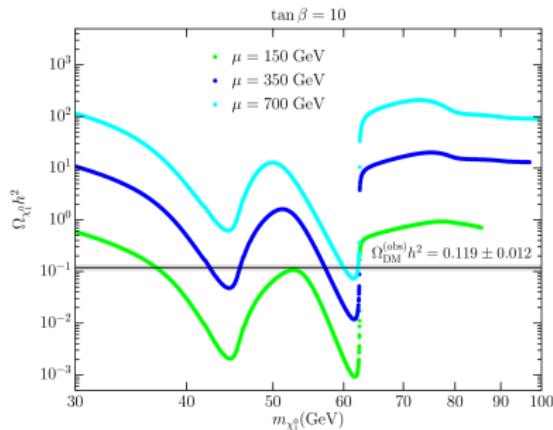
Requires \tilde{B}/\tilde{H} composition.



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.



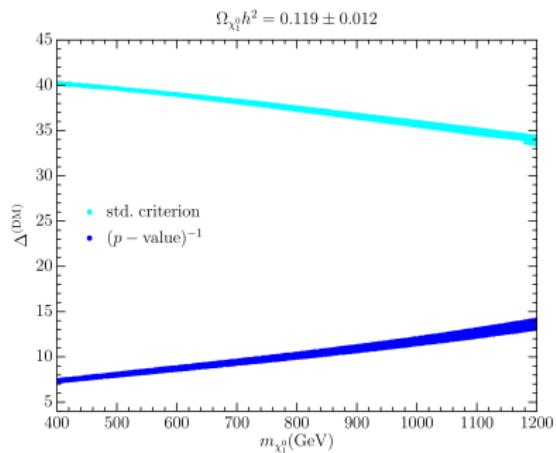
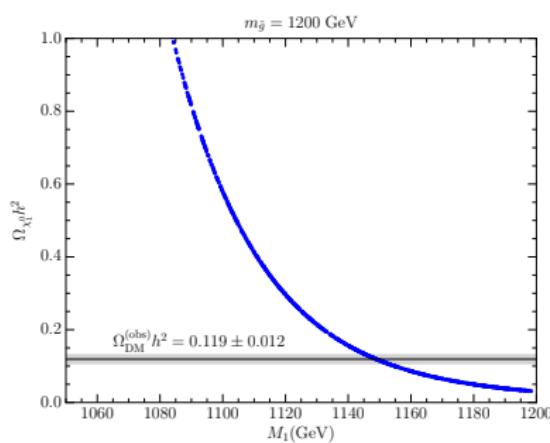
The p-value is computed by adding $\Delta m_Z/2$ and $\Delta m_h/2$.

Blind spots in direct detection

Co-annihilation

Particles with masses close to the LSP annihilate efficiently

$$\langle \sigma_{\text{eff}} v \rangle = \frac{\sum_{ij} w_i w_j \sigma_{ij} x^{-n}}{(\sum_i w_i)^2}, \quad w_i = \left(\frac{m_i}{m_1} \right)^{3/2} e^{-x \left(\frac{m_i}{m_1} - 1 \right)}$$



$$\Delta_{M_1} = \mathcal{O}(20 - 40) \frac{m_{\tilde{g}}}{M_1}$$

$$\text{p-value} \simeq \frac{\Delta m}{M}$$

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 $M_{\chi_1} \sim \mu \simeq 1 \text{ TeV} \rightarrow \Delta_{\mu}^{EW} \sim \mathcal{O}(200)$.
- ▶ DM fine-tuning is mild in several cases: funnels (not close to the twice the resonance), co-annihilation, Bino-higgsino.

Thanks

