Supersymmetry at FCC

Prateek Agrawal

Harvard University

1st FCC Physics Workshop
CERN

[1606.00947]

with JiJi Fan, Matt Reece,Wei Xue

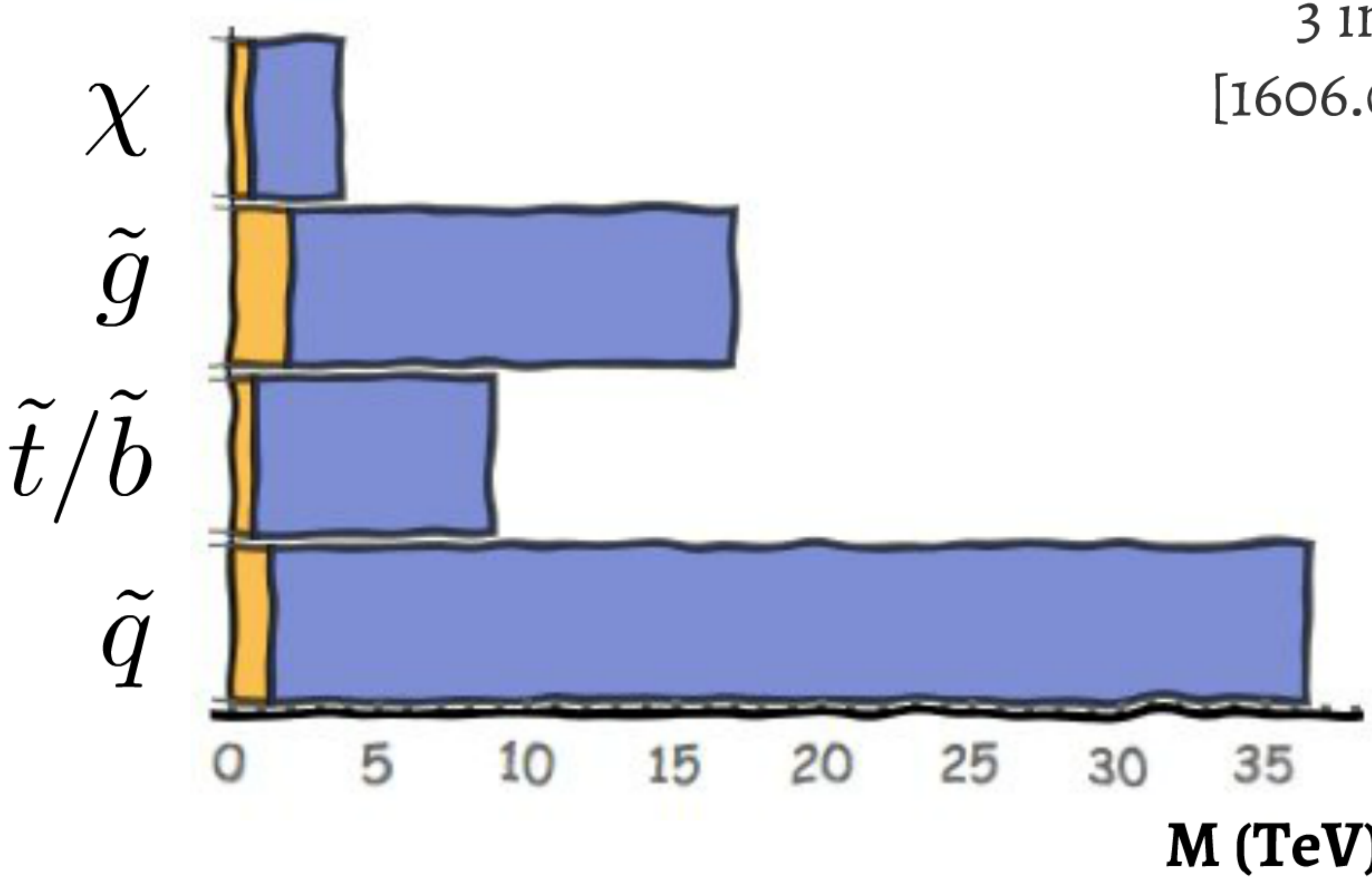
to appear

SUSY searches

Current limits and discovery potential at FCC-hh

3 inv. ab

[1606.0094]



Split Supersymmetry

Naturalness?

A quantitative problem: prefer low scalar masses values

A new qualitative input: what holds down scalar scale then?

Flavor constraints prefer $m_0 > 100\text{–}1000\ \text{TeV}$

Dark Matter, unification still preserved for ~TeV gauginos

Scalar mass scale is not fixed

Arkani-Hamed, Dimopoulos [hep-th/0405159]
Giudice, Romanino [hep-ph/0406088]

The Higgs mass in the MSSM

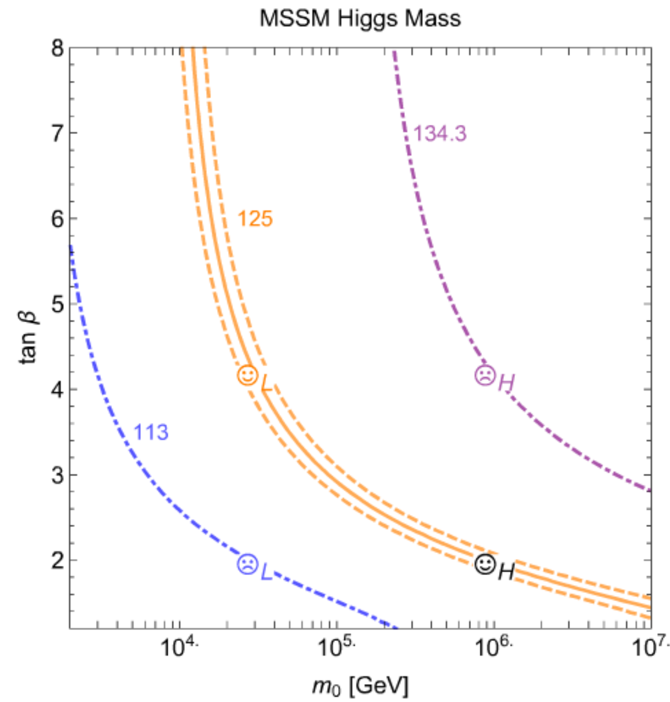
(Mini)-split

Arvanitaki, Craig, Dimopoulos, Villadoro [1210.0555]

1 crucial piece of data

$$m_h = 125.09 \text{ GeV}$$

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} - \frac{X_t^4}{12 m_{\tilde{t}}^4}\right)$$



Bonus: Not Planck-scale tuned, maybe points to a combo solution to the hierarchy problem? e.g. relaxion

Setting a target

(How far) can we test the origin of the Higgs mass?

Can we measure m_0 and $\tan\beta$ at FCC-hh?

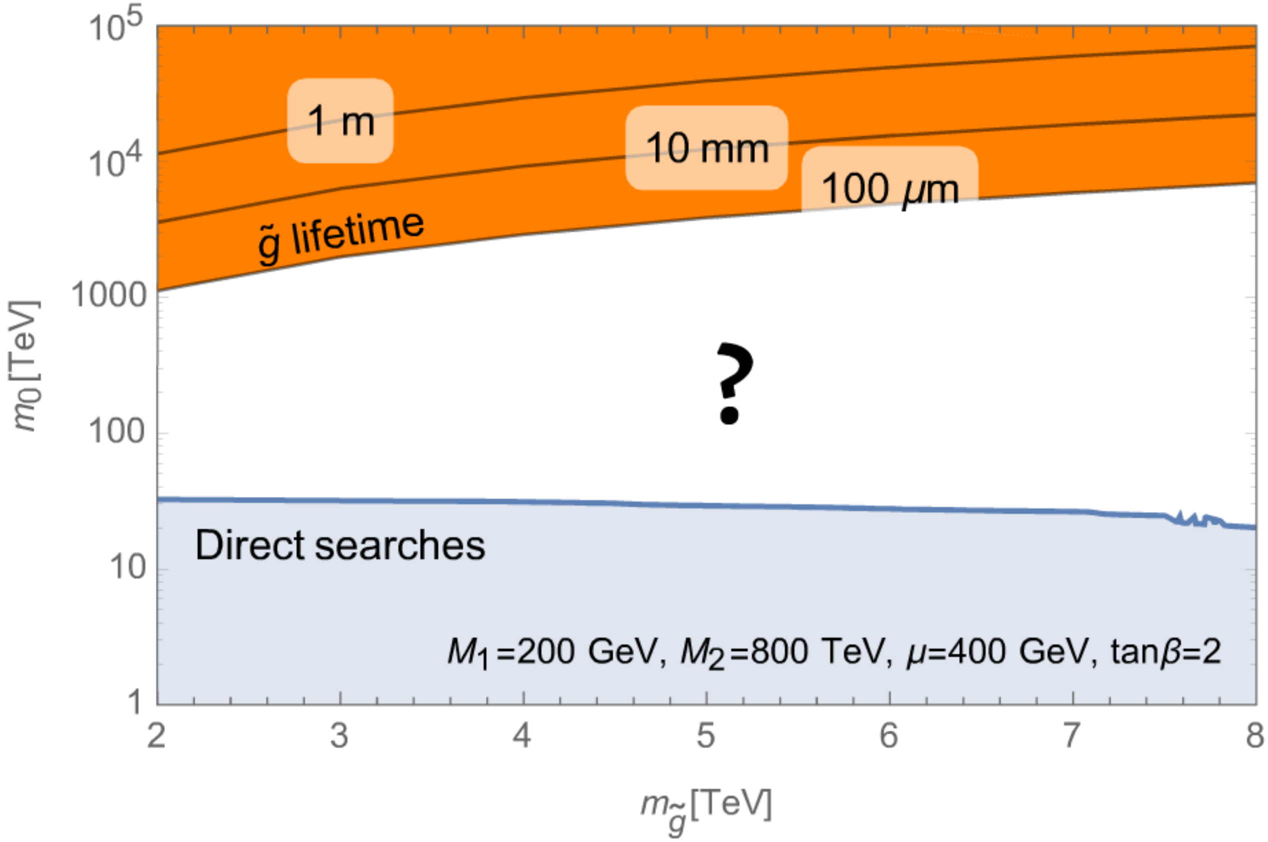
[post-discovery]

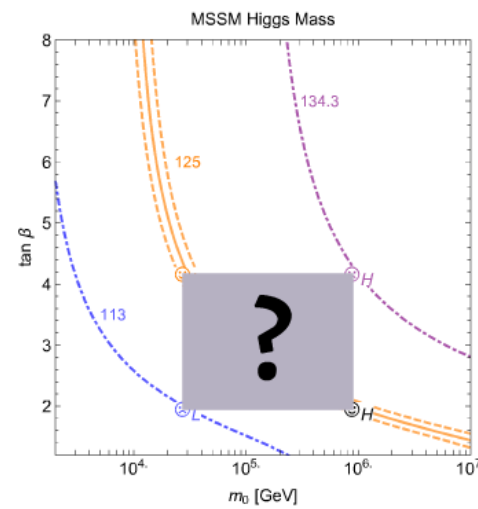
Q: Why not wait for discovery before measuring parameters?

Sharpens the physics case

Tells us what we would need in terms of energies, luminosity, detectors, technology

Gauginos





Scalar superpartners might be out of reach

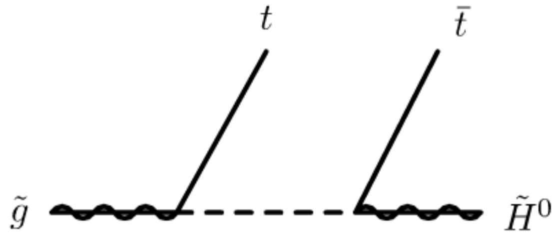
Gauginos are often 1-loop (or more) suppressed relative to scalar masses

Anomaly mediation

No-scale structure

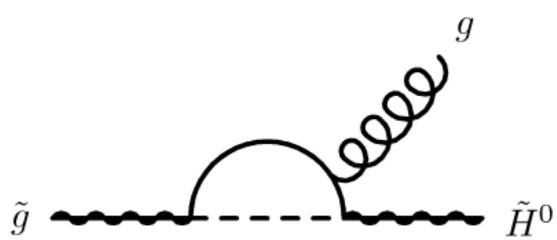
Gluino branching fractions

Tree level branching ratios are independent of m_0



$$\sim \quad \frac{m_{\tilde{g}}^5}{m_{\tilde{t}}^4}$$

One-loop decay to gluon+higgsino logarithmically sensitive



$$\sim \quad \frac{m_{\tilde{g}}^3 m_t^2}{m_{\tilde{t}}^4} \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} \right)^2$$

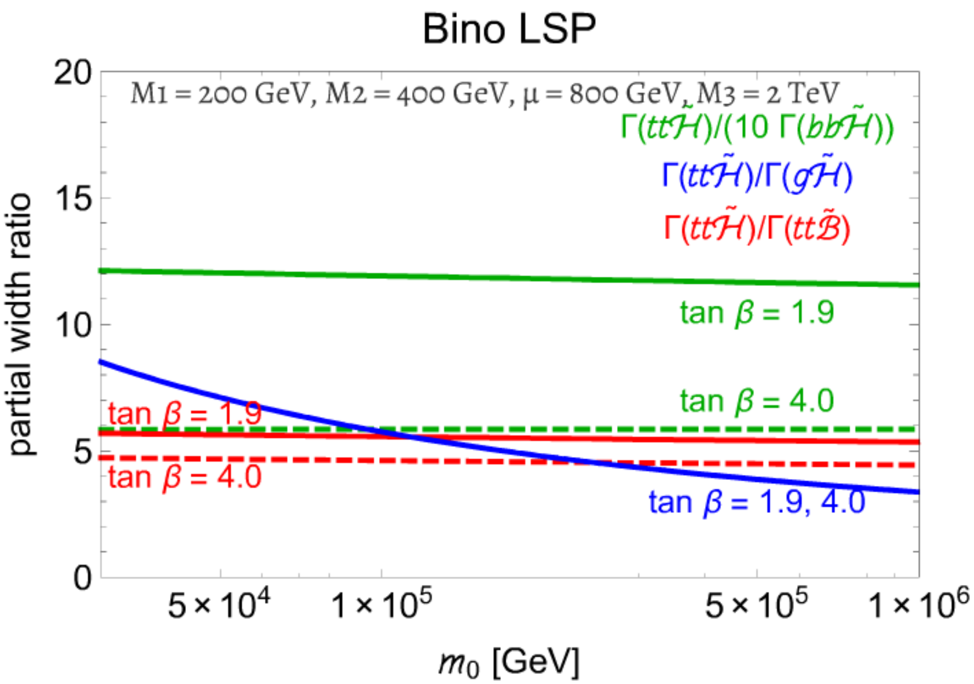
Toharia, Wells: hep-ph/0503175

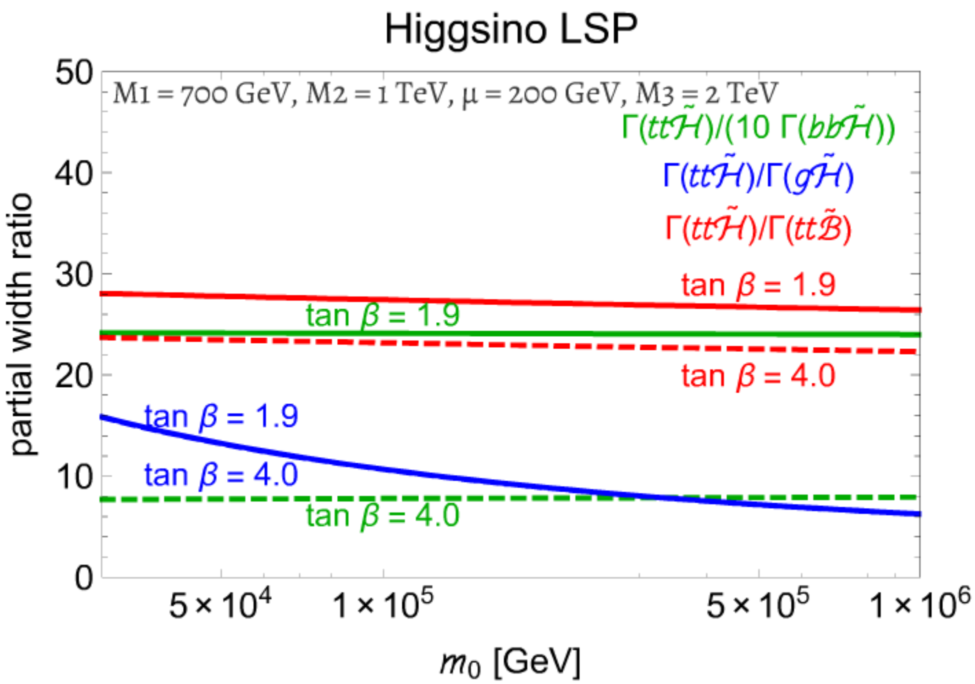
Gambino, Giudice, Slavich: hep-ph/0506214

Sato, Shirai, Tobioka: 1207.3608

Gluino branching fractions

$$\frac{\Gamma(g\tilde{H}^0)}{\Gamma(t\bar{t}\tilde{H}^0)} \propto \frac{m_t^2}{m_{\tilde{g}}^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2}\right)^2$$

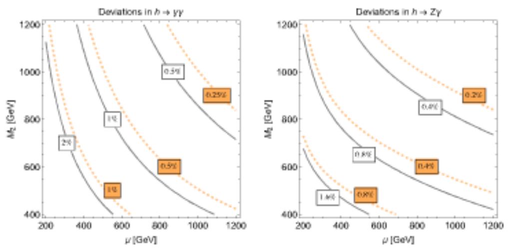




Observables for $\tan\beta$

Assuming scalars are inaccessible

Higgs branching ratios



$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} \approx 1 + \frac{0.82 m_W^2 \sin(2\beta)}{\mu M_2 - m_W^2\sin(2\beta)}$$

Higgs Couplings

FCC-ee projection: 1.5%

d'Enterria[1701.02663]

see Aram Apyan's talk

FCC-hh stat reach (20 inv ab) ~1% at pT(H)~100 GeV

Measure ratios to reduce uncertainties

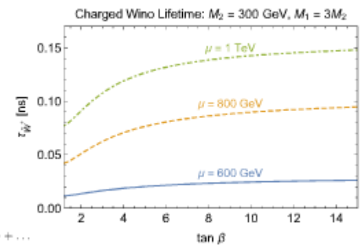
see Michelangelo's talk

Chargino lifetime

Wino LSP

Disappearing tracks

Low , Wang [1404.0682]



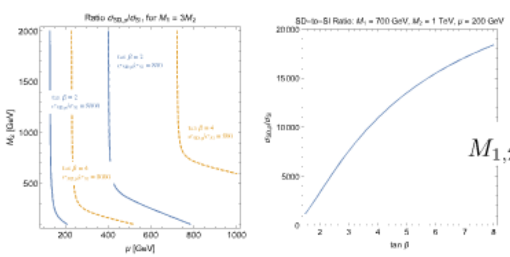
$$\delta m_{\widetilde{W}}^{\rm tree} \approx \frac{m_W^4 \sin^2(2\beta)}{(M_1-M_2)\mu^2}\tan^2\theta_W + 2\frac{m_W^4 M_2 \sin(2\beta)}{(M_1-M_2)\mu^3}\tan^2\theta_W + \frac{m_W^4 M_2}{2\mu^4} + \dots$$

$$\delta m_{\widetilde{W}}^{\rm loop} \approx \frac{\alpha m_W}{2(1+\cos\theta_W)} \approx 165\ \text{MeV},$$

$$\Gamma(\chi^\pm \to \chi_0 \pi^\pm) = \Gamma(\pi^\pm \to \nu_\mu \mu^\pm) \times 16 \frac{(\delta m_{\widetilde{W}})^3}{m_\pi m_\mu^2}\left(1 - \frac{m_\pi^2}{(\delta m_{\widetilde{W}})^2}\right)^{1/2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2}$$

Ibe,Matsumoto, Sato [1212.5989]

Direct detection (SD vs SI)



$M_{1,2} \gg \mu > 0$

$$c_{h\chi\chi}^* \approx \frac{g m_W (1+\sin(2\beta))}{2}\left[\frac{1}{M_2-\mu} + \frac{\tan^2\theta_W}{M_1-\mu}\right]$$

$$c_{Z\chi\chi} \approx \frac{g m_W^2}{4\mu\cos\theta_W}\cos(2\beta)\left[\frac{1}{M_2-\mu} + \frac{\tan^2\theta_W}{M_1-\mu}\right]$$

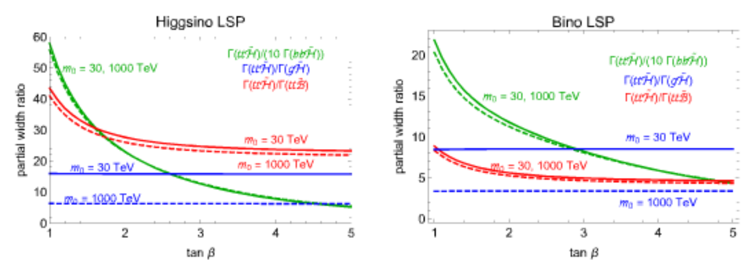
$$\sigma_{\rm SI} = |c_{h\chi\chi}|^2 \times (5.3\times 10^{-43}\ {\rm cm}^2)$$

$$\sigma_{{\rm SD},p} = |c_{Z\chi\chi}|^2 \times (2.9\times 10^{-37}\ {\rm cm}^2)$$

$$\sigma_{{\rm SD},n} = |c_{Z\chi\chi}|^2 \times (2.2\times 10^{-37}\ {\rm cm}^2)$$

Gluino branching fractions

$$\frac{\Gamma(\tilde g \to t\bar t \widetilde{H}^0)}{\Gamma(\tilde g \to t\bar t \widetilde{B}^0)}, \frac{\Gamma(\tilde g \to t\bar t \widetilde{H}^0)}{\Gamma(\tilde g \to t\bar t \widetilde{W}^0)} \propto \frac{1}{\sin^2\beta} \qquad \frac{\Gamma(\tilde g \to b\bar b \widetilde{H}^0)}{\Gamma(\tilde g \to t\bar t \widetilde{H}^0)} \propto \tan^2\beta$$



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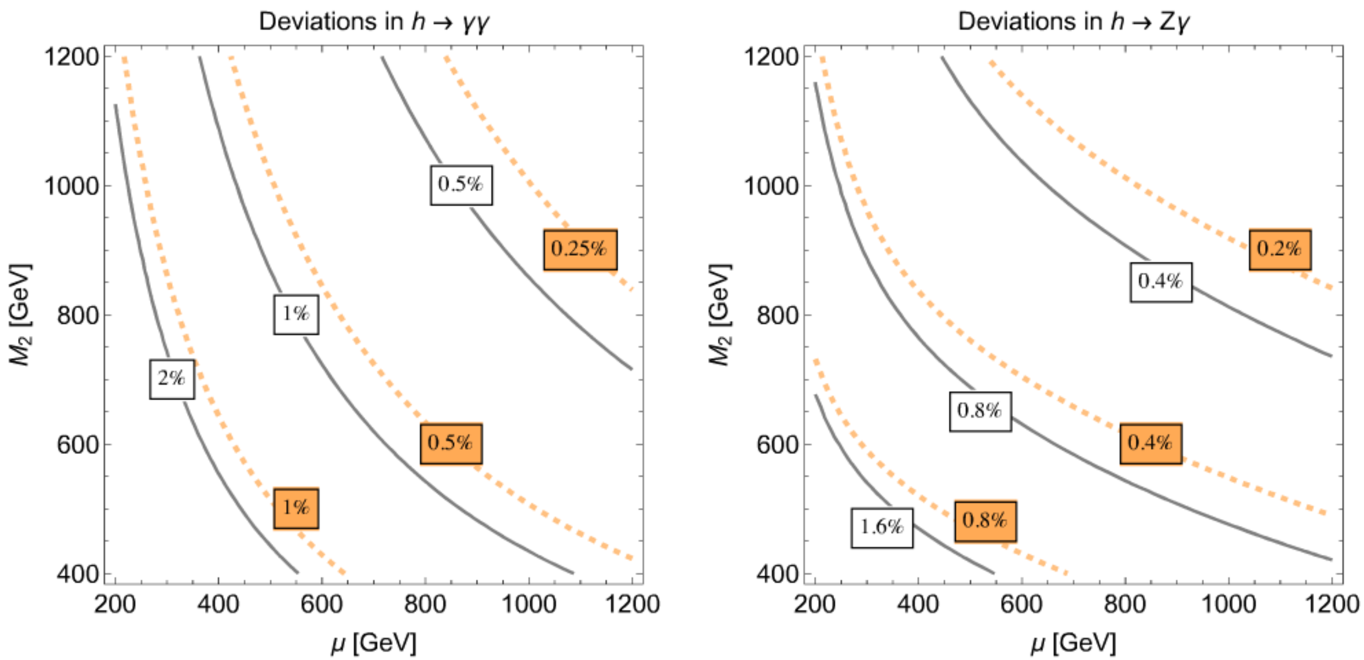
Higgs branching ratios



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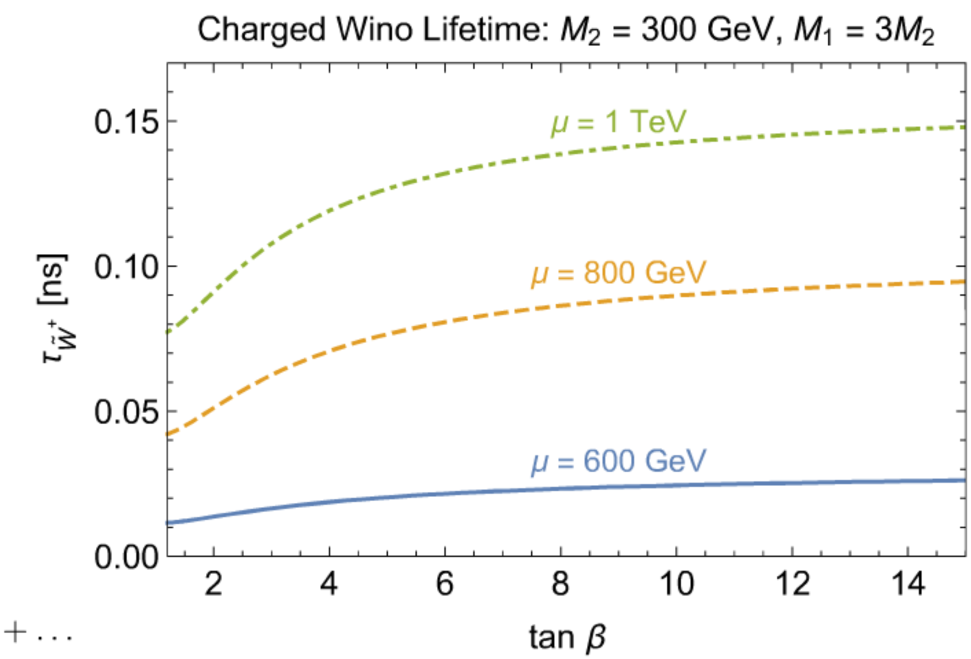

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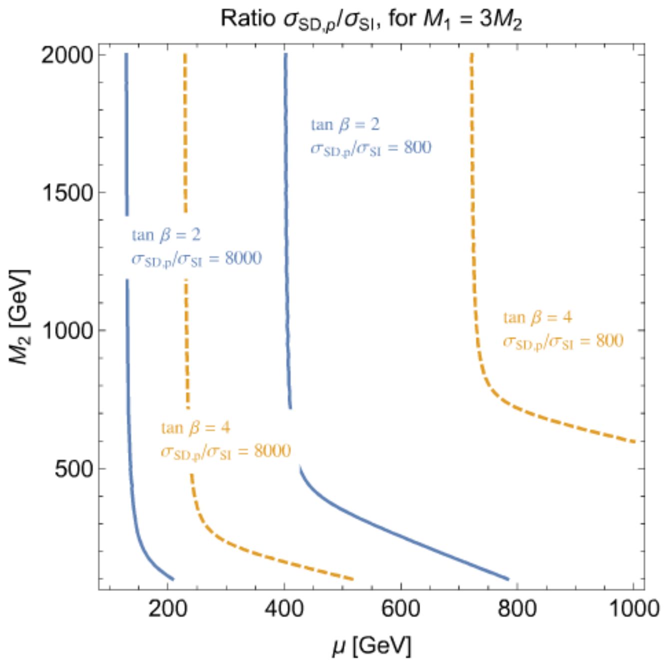

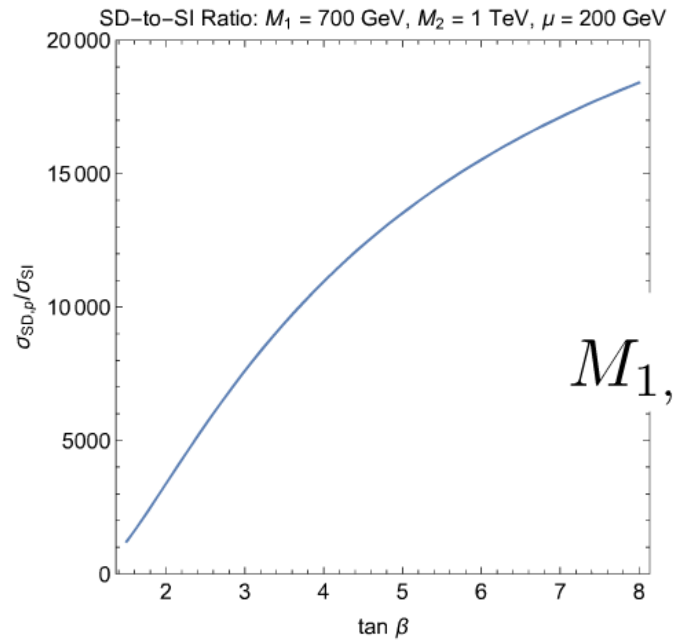

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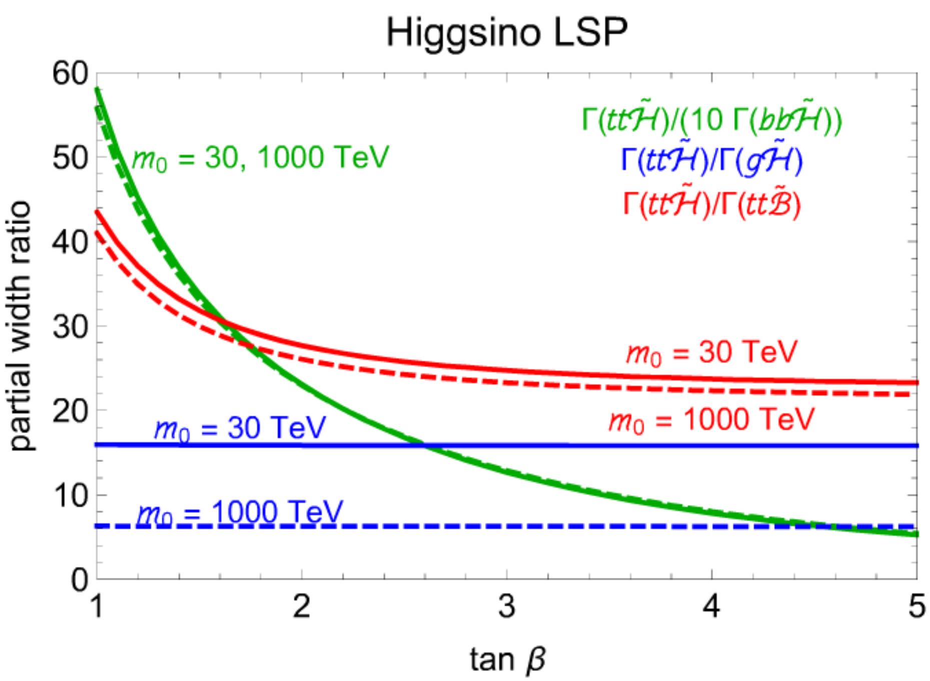

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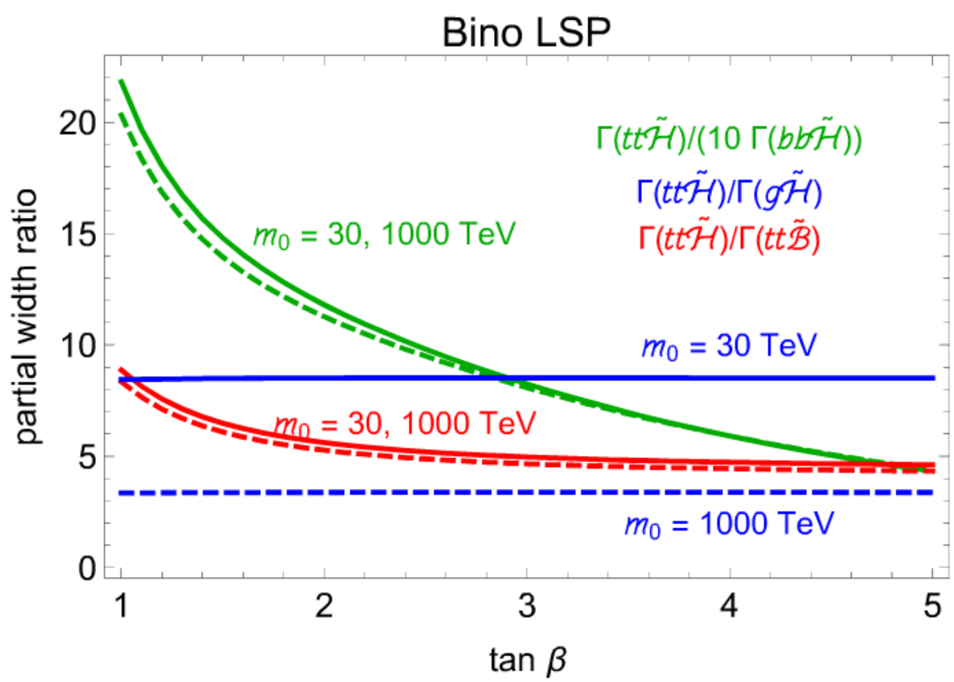


M1 = 200 GeV, M2 = 400GeV, μ= 800 GeV, M3 =2 TeV

Blind spot

$\tan\beta = 1$ is a special point

$$\widetilde{H}^0_\pm \equiv \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_u \pm \widetilde{H}^0_d\right)$$

Z couples off-diagonally

$$-\frac{1}{2}\mu \widetilde{H}^0_+ \widetilde{H}^0_+ + \frac{1}{2}\mu \widetilde{H}^0_- \widetilde{H}^0_- - \frac{eZ_\mu}{\sin(2\theta_W)}\left[\widetilde{H}^{0\dagger}_+ \overline{\sigma}^\mu \widetilde{H}^0_- + \widetilde{H}^{0\dagger}_- \overline{\sigma}^\mu \widetilde{H}^0_+\right]$$

$\widetilde{H}^0_-$ does not mix with $\tilde{B}^0, \tilde{W}^0$, or couple to Higgs

$$\begin{pmatrix} \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} & \frac{m_Z \cos\beta}{\sqrt{2}} \begin{bmatrix} (1+\tan\beta)s_W & (-1+\tan\beta)s_W \\ (1+\tan\beta)c_W & (1-\tan\beta)c_W \end{bmatrix} \\ \frac{m_Z \cos\beta}{\sqrt{2}} \begin{bmatrix} (1+\tan\beta)s_W & (1+\tan\beta)c_W \\ (-1+\tan\beta)s_W & (1-\tan\beta)c_W \end{bmatrix} & \begin{bmatrix} \mu & 0 \\ 0 & -\mu \end{bmatrix} \end{pmatrix}$$

(Direct detection blind spot)

Cheung, Hall, Pinner, Ruderman

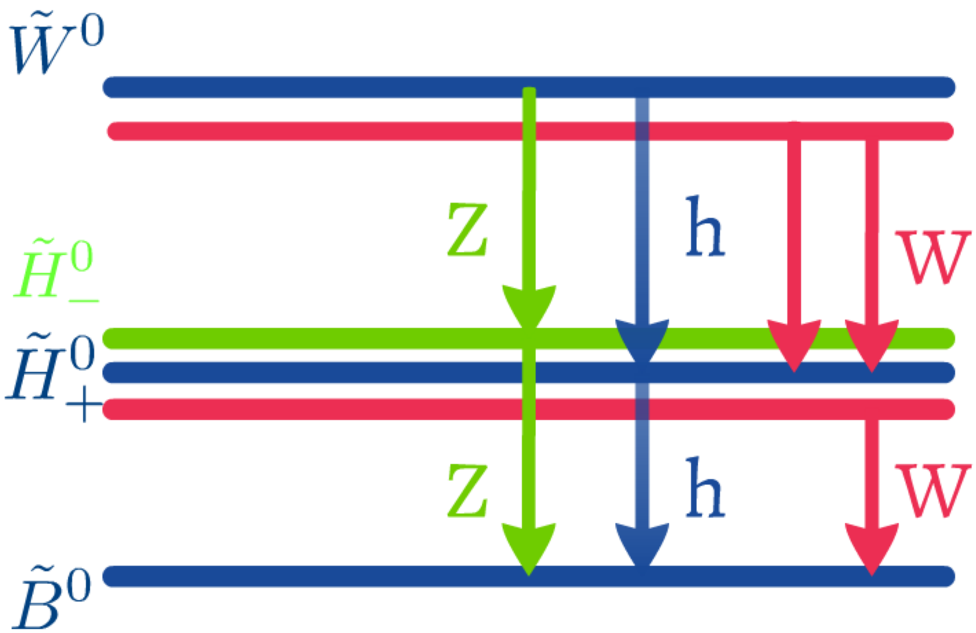
[1211.4873]

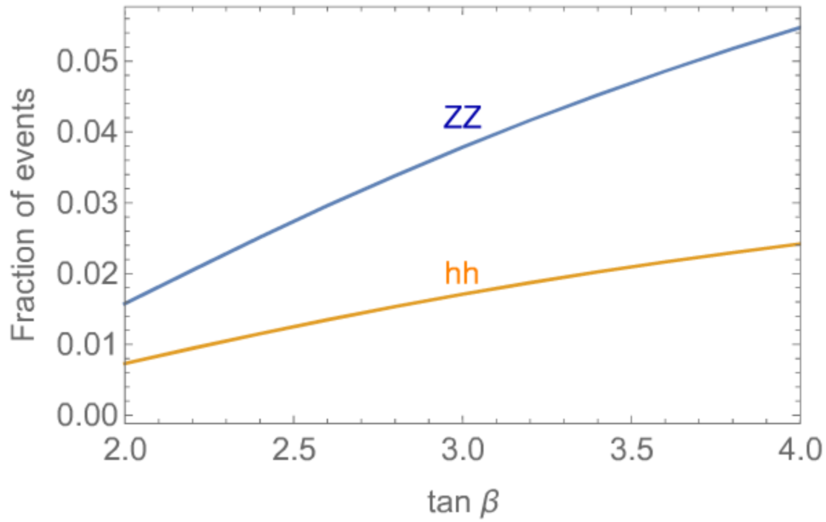
Electroweakino decays

$\tan\beta = 1$ is a special point

Electroweakino decays can help measure $\tan\beta$

$p\,p > \tilde{H}^0_+\ \tilde{H}^0_-$



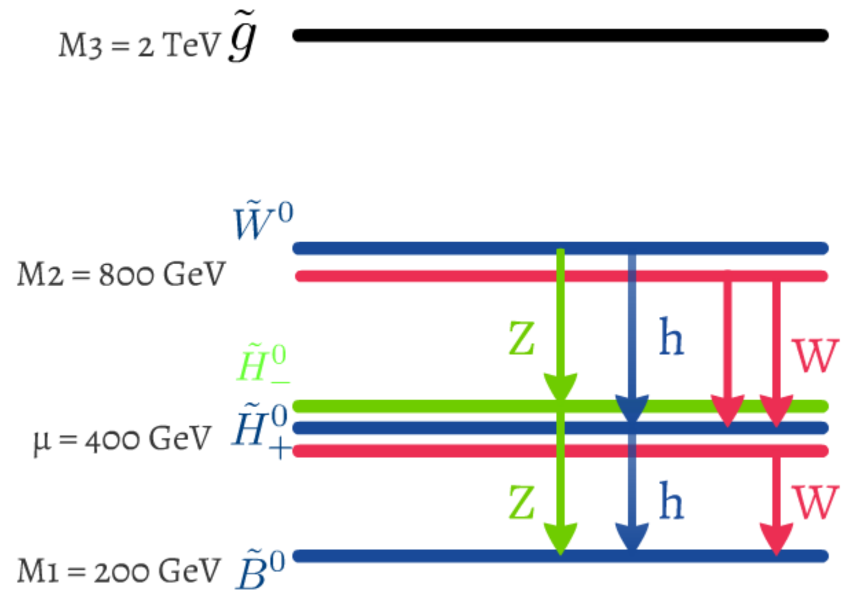


M1 = 200 GeV, M2 = 800 GeV, M3 = 2 TeV, μ = 400 GeV

Specific example @ FCC-hh

3 inv ab

5 % syst



$\tan\beta$

1. Two pairs of OSSF leptons, with $|m_{\ell\ell} - m_Z| < 10$ GeV
2. MET > 150 GeV
3. Scalar sum of pT of all visible particles < 600 GeV

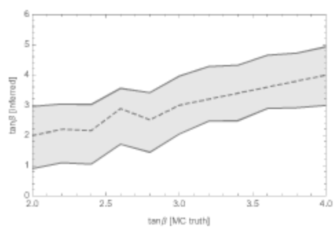
Signal

$pp \to \chi_2^0\chi_3^0 \to (Z \to \ell\ell)^2\chi_1^0\chi_1^0$ 8.4 - 28.8

Backgrounds

$ZZZ \to (Z \to \ell\ell)^2(Z \to \nu\nu)$
$hZ \to (h \to ZZ^* \to \ell\ell\nu\nu)(Z \to \ell\ell)$ } 86.4

$\chi\chi \to$ cascades
$\tilde{g}\tilde{g} \to$ cascades
$\chi_2\chi_3 \to hZ\chi_1^0\chi_1^0 \to (Z \to \ell\ell)^2\chi_1^0\chi_1^0 + X$ } 35.2



m_0

$H_T > 2$ TeV, $p_T^{\text{missing}} > 1$ TeV, $p_T(j_1) > 1$ TeV,
$N_{\text{jet}} < 5$, one leptonic Z (80 GeV $< m_{\ell\ell} <$ 100 GeV),
$m_{j_1 Z} > m_{\text{all other jets}}$.

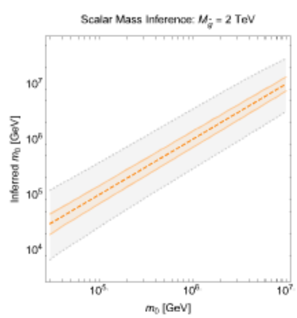
Signal

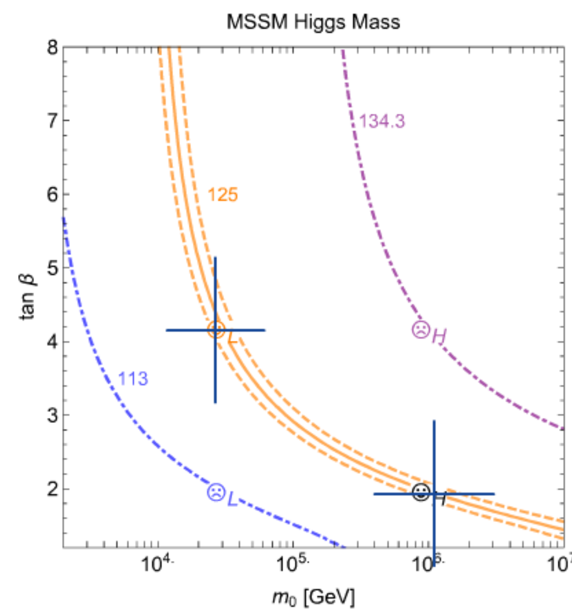
$(\tilde{g} \to \chi_3^0\, g \to Z\, \chi_1^0\, g)(\tilde{g} \to X)$ O(500) 17-35% of the SUSY sample

Backgrounds

$(\tilde{g} \to q\bar{q}(\chi \to \text{cascades}))^2$

$ZZ+$ jets $\to (Z \to \ell^+\ell^-), (Z \to \nu\nu)$
$t\bar{t} \to (W \to \ell\nu)^2$
$t\bar{t}Z \to t\bar{t}(Z \to \ell\ell)$ } 1680





for a few other examples see [1606.00947]

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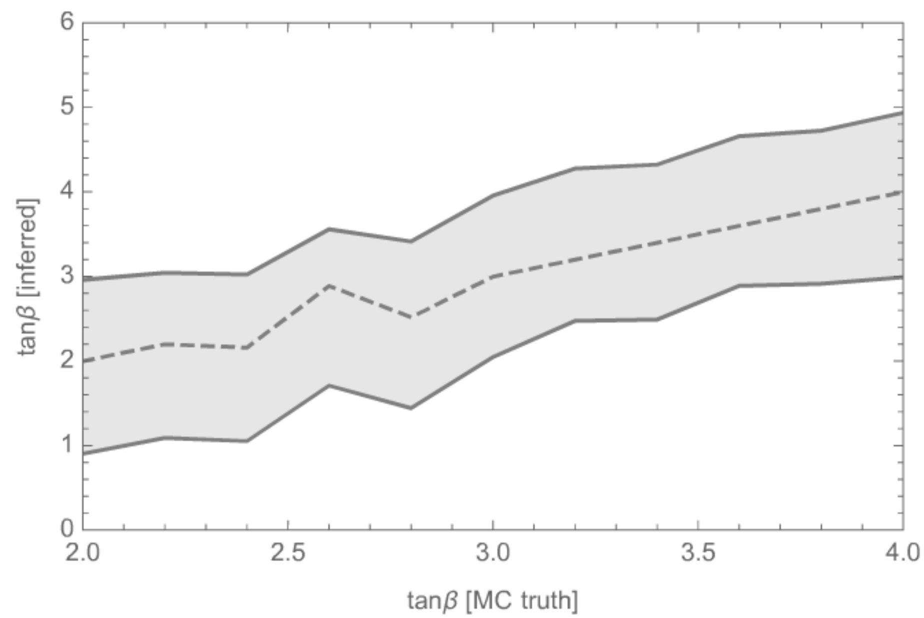

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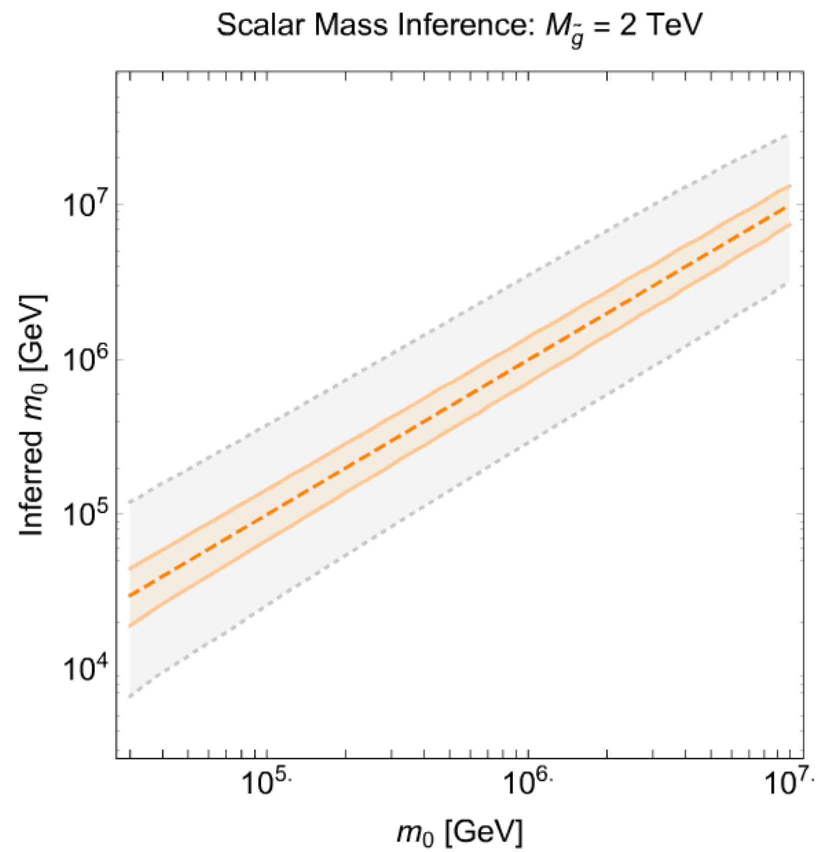

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$$t\bar{t} \to (W \to \ell\nu)^2$$
$$t\bar{t}Z \to t\bar{t}(Z \to \ell\ell)$$

1680

Conclusions

The simplest supersymmetric model consistent with the Higgs mass is a reasonable candidate for new physics

A class of theories predicts gauginos will be kinematically accessible at FCC-hh

It will be valuable to further develop observables and analyses at FCC that can test the origin of the Higgs mass

Interesting to think about other bracketed questions that we care about and can answer at future colliders