Reconstructing CMSSM parameters at the LHC with $\sqrt{s} = 14$ TeV via the golden decay channel

arXiv:1106.5117, Dec 2014

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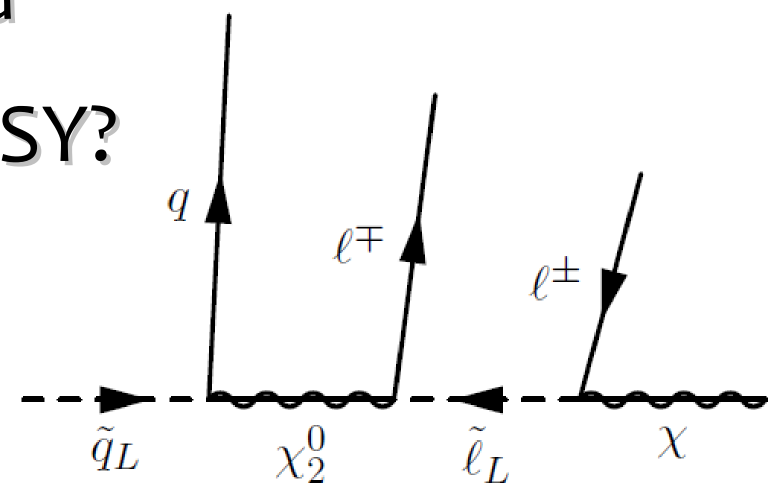
Motivation/Outline

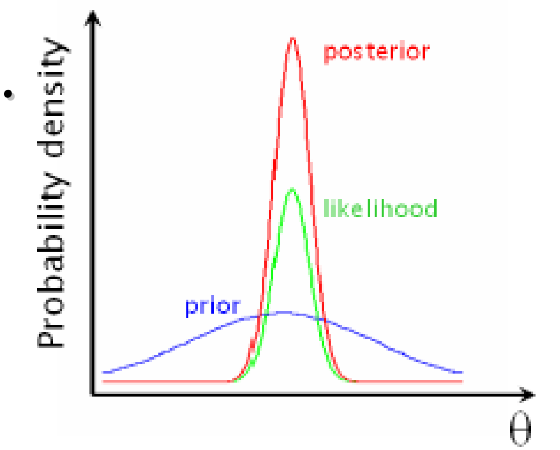
- **Supersymmetry** can not be excluded, SUSY can only be discovered
- What if we find a heavier SUSY?
  - What kind of SUSY it is?
- **Use a SUSY golden decay**
  - To recover masses of supersymmetric particles



- **Bayesian fit to reconstruct SUSY parameters:**
  - From golden decay only
  - Golden decay + Higgs
  - Golden decay + Higgs + Ωh^2

Bayesian theorem

In Bayesian theory, our degree of belief in the preposition changes rationally the probability of the posterior observation.



- Bayes' theorem: posterior pdf

$$\boxed{p(\theta,\psi|d) = \frac{p(d|\xi)\pi(\theta,\psi)}{p(d)}}$$

- $p(d|\xi) = \mathcal{L}$: likelihood
- $\pi(\theta,\psi)$: prior pdf
- $p(d)$: evidence (normalization factor)

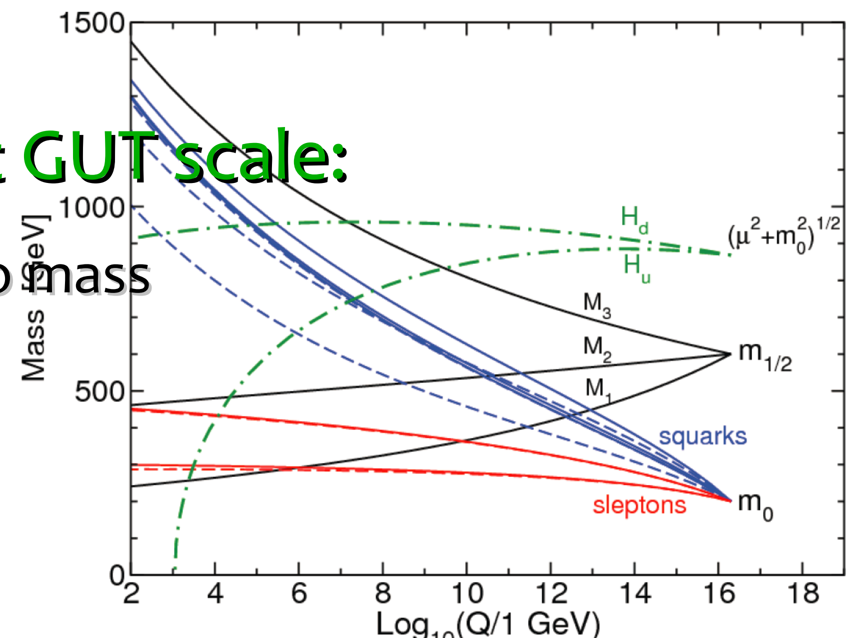
$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

- usually marginalize over SM (nuisance) parameters $\psi \Rightarrow \boxed{p(\theta|d)}$

  - $\boxed{m = (\theta,\psi)}$ – model's all relevant parameters
  - model parameters $\boxed{\theta}$
  - relevant SM param's $\boxed{\psi = M_t, m_b(m_b)^{\overline{MS}}, \alpha_s^{\overline{MS}}, \alpha_{\rm em}(M_Z)^{\overline{MS}}}$
  - $\xi = (\xi_1, \xi_2, \ldots, \xi_m)$: set of derived variables (observables): $\boxed{\xi(m)}$
  - d: data $(\Omega_{\rm CDM}h^2$, $b \to s\gamma$, m_h, etc)

Focus on CMSSM

- Constrained Minimal Supersymmetric Standard Model
- **Might appear less natural than before, however:**
  - It correctly reproduces both the Higgs boson mass and the DM relic abundance in the "unnatural" multi-TeV regions of mass parameters
  - It also remains compatible with all experimental data, **with the exception of $(g\text{-}2)_\mu$**
- Unification of MSSM soft masses at GUT scale:
  - **m1/2 = M1 = M2 = M3** → Common gaugino mass
    m0 → Common scalar mass
    A0 → Common trilinear
    tan β → Ratio of Higgs vevs
    sgn μ



  - Run parameters to low scale with renormalisation group equations to calculate masses at 1 TeV scale

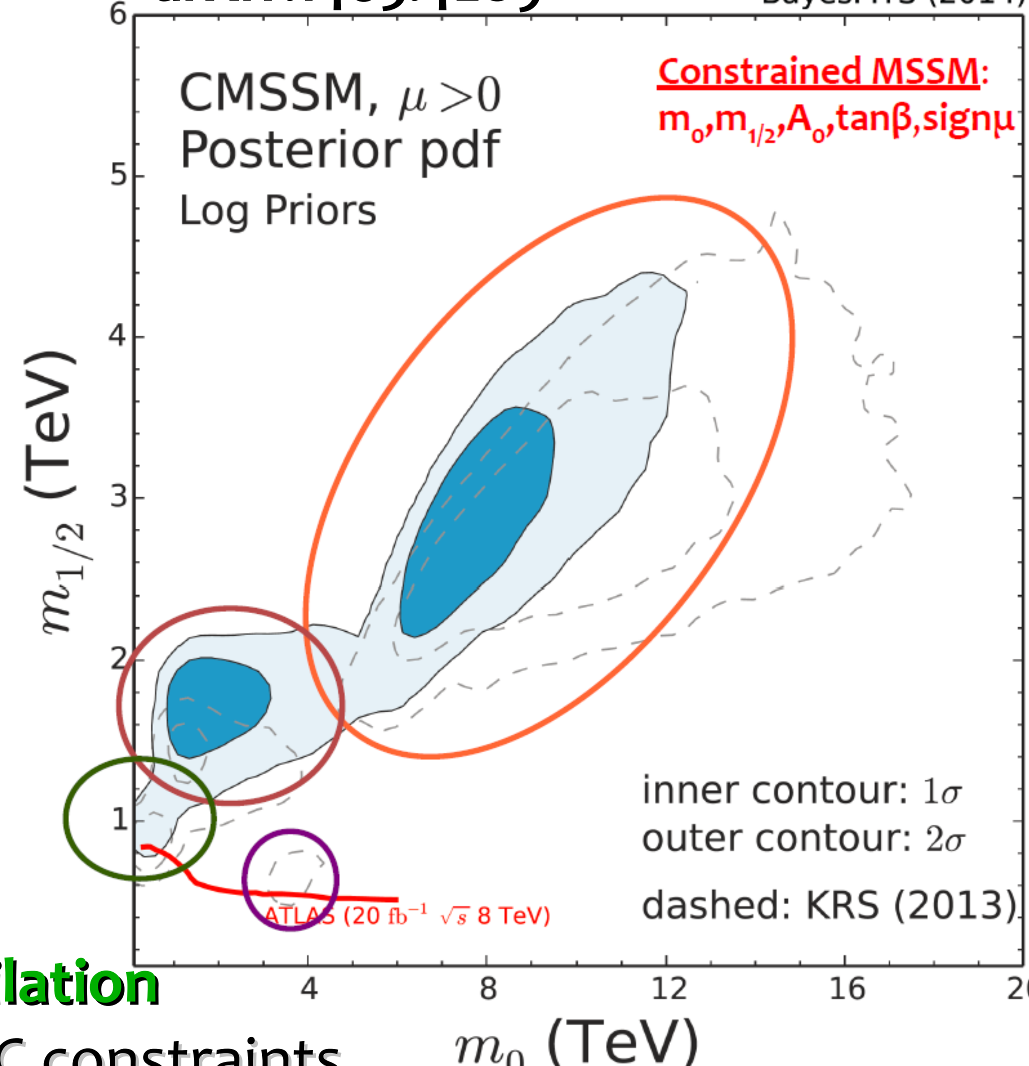
SUSY must be heavier

From our recent fit:

- M_{SUSY} > than expected
- Decreased **m0** in **~1TeV higgsino region** due to higgs corrections
- Posterior in **A-funnel region** increases due to better fit to higgs mass
- **Focus point region** disfavoured by LUX
- Reduced posterior in **stau-coannihilation region** (Bino DM region) due to LHC constraints,

but M_{SUSY} < 1 TeV still probable

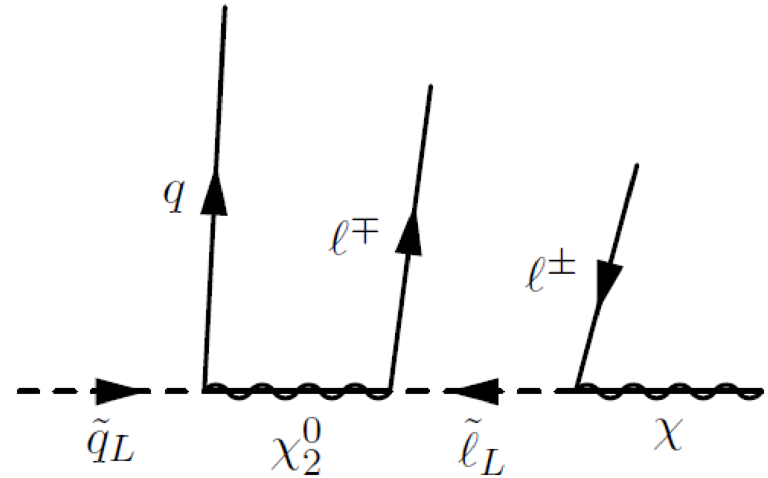
arXiv:1405.4289



$\blacksquare / \square = 68\%/95\%$ region

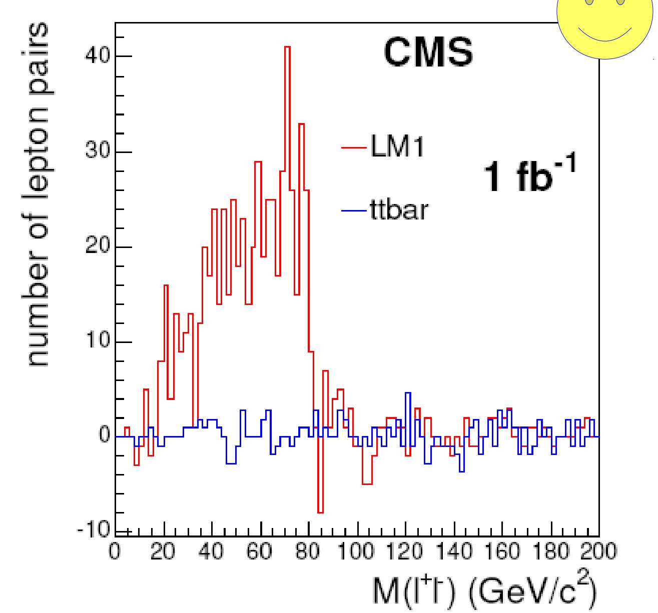
Signature of SUSY

- **Golden channel**
- Allows to reconstruct sparticle masses from kinematic edges



- Many studies made in pre-LHC era for light SUSY
  - Our previous analysis (arXiv:1106.5117, arXiv:0907.0594)

Example from the past



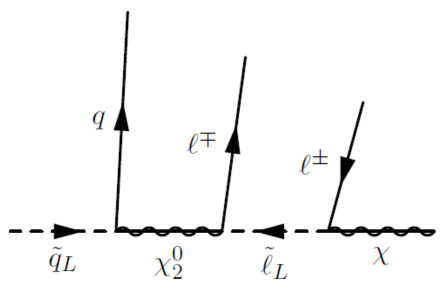
- **Our goal:** check if we can **recover sparticles masses** from kinematic edges for higher SUSY and **reconstruct model parameters** ?

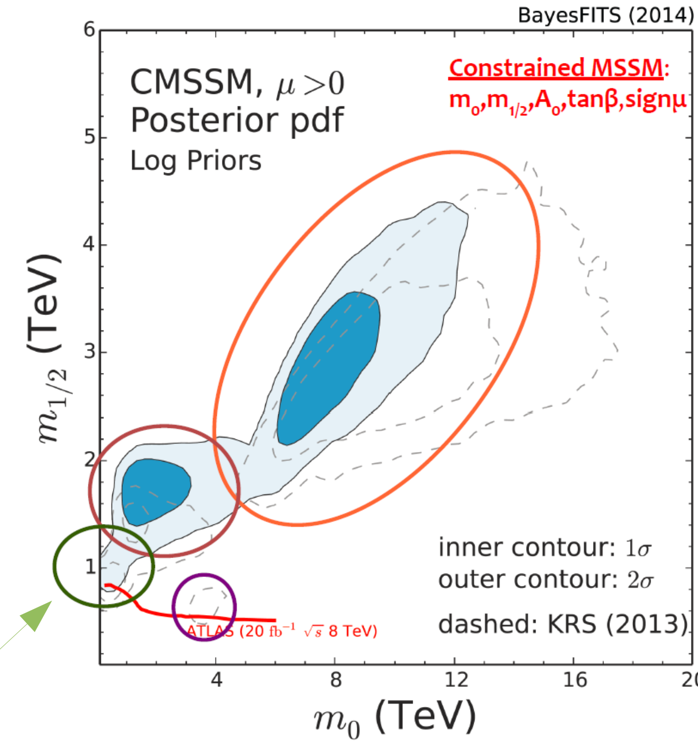
Methodology

- **Pick a CMSSM point allowed by experiments** (e.g. m_h, Planck relic density Ωh^2, direct searches)
- **Monte Carlo analysis for CMSSM point at 14 TeV**
  - Perform MC simplified (Gen Level) analysis to simulate sparticle mass measurements from golden decay
- **Bayesian reconstruction** of CMSSM parameters with simulated sparticle mass measurements

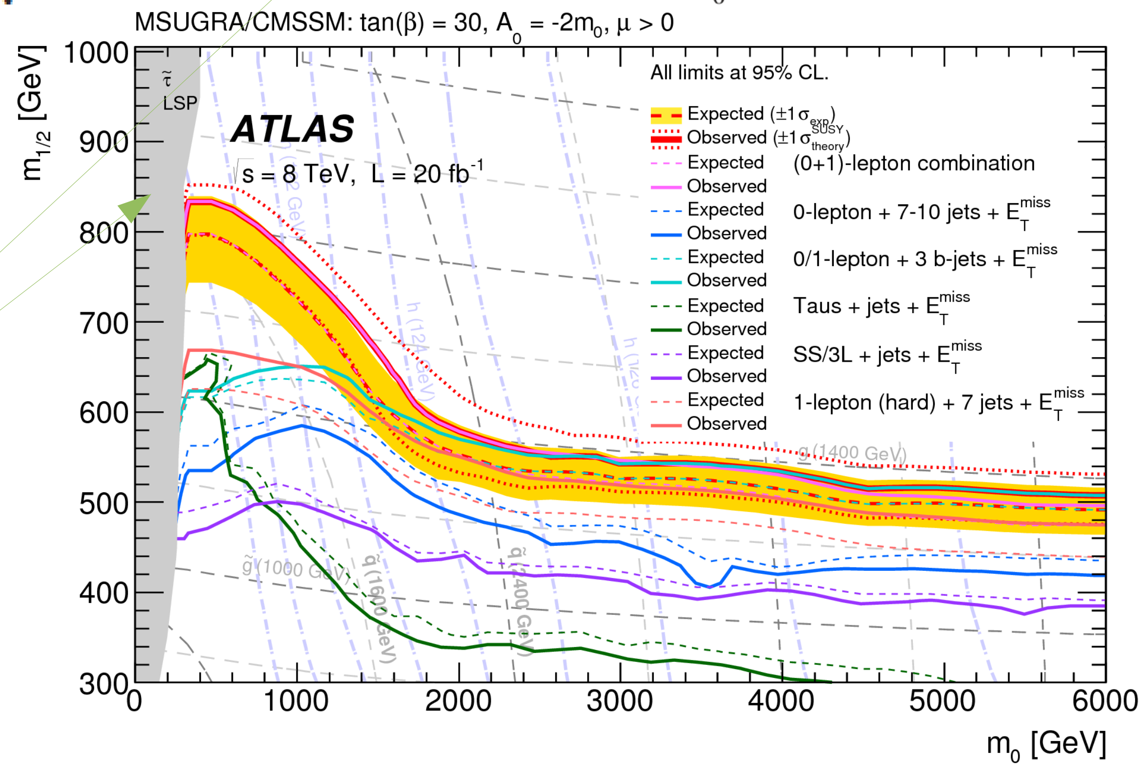
CMSSM point

- Golden decay requires hierarchy:
  $\tilde{q} > \tilde{\chi}_2^0 > \tilde{\ell}$
  $\tilde{g} > \tilde{q}$ to shut $\tilde{q} \to \tilde{g} q$ spoiler





- Actually, $\tilde{\chi}_2^0 > \tilde{\ell} + 50\,\mathrm{GeV}$ to avoid phase space suppression of BR
  → In CMSSM, it means m1/2 > m0



- **Stau-coannihilation region** allowed in CMSSM with golden decay

Benchmark CMSSM point

- Search for a good point with golden decay
  - High mass, above LHC limits: **m1/2 = 900GeV**
- *Minuit* to find the point with:
  - m_h = 125GeV within errors
  - $\Omega h^2 \approx$ WMAP/PLANCK (0.1197)
  - Golden decay
- The benchmark CMSSM point: satisfies reasonable 9 measurements: m_h, DM relic density, $b \to s\gamma$, $B_u \to \tau\nu$, $B_s \to \mu^+\mu^-$, m_W, $\sin^2\theta_{\rm eff}$, M_t ΔM_{B_s}
- Ωh^2 =0.1390 ~ agreement with the Plack measurements

CMSSM:
m1/2 = 900GeV
m0 = 315GeV
tan β = 11
A0 = −2550GeV
sgn μ = + 1

Particle Mass (GeV):							
$\chi_1^0 = \chi$	382.8	$\tilde{e}_L$	679.8	$\tilde{d}_L$	1835	h	124.1
χ_2^0	728.7	$\tilde{e}_R$	463.4	$\tilde{d}_R$	1754	H	1741
χ_3^0	1645	$\tilde{\nu}_e$	675.1	$\tilde{u}_L$	1834	A	1742
χ_4^0	1649	$\tilde{\tau}_1$	384.6	$\tilde{u}_R$	1762	$H^\pm$	1744
$\chi_1^\pm$	728.9	$\tilde{\tau}_2$	659.9	$\tilde{b}_1$	1509		
$\chi_2^\pm$	1649	$\tilde{\nu}_\tau$	651.4	$\tilde{b}_2$	1726		
$\tilde{g}$	1985			$\tilde{t}_1$	984.1		
				$\tilde{t}_2$	1552		

MC Simuations

- **MC Pythia (Gen Level)** simulation for **@ 14 TeV**
  - Particle mass spectrum from SoftSUSY
- CMSSM **σ = 34.5/fb**
  - Run III LHC **L = 300/fb** → N_{total} = ~10.000 events
- Selection – classical SUSY with lepton cuts

  Very simplified assumptions:

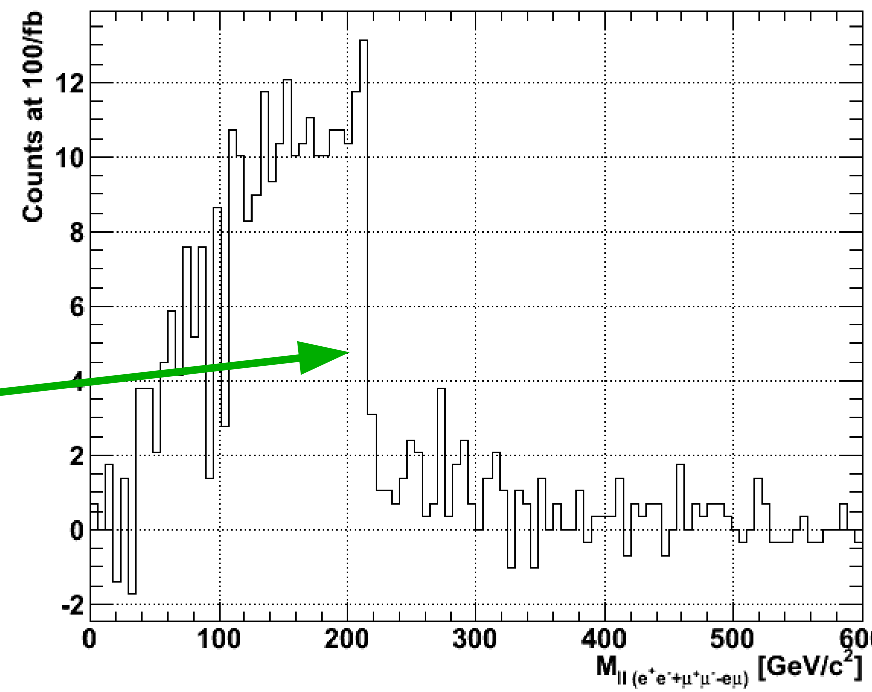
- **Detector acceptance:**
  - Isolated leptons:
    pt > 10 GeV, $|\eta^{e}| < 2.4$, $|\eta^{\mu}| < 2.4$
  - AntikT jets: pt > 50 GeV, $|\eta^{jet}| < 5$
- Total selection efficiency: 0.10

- **Event selection:**
  - At least 2 opposite sign leptons
  - At least 4 jets
  - $pt^{1st\ jet} > 100$ GeV
  - Z peak veto:
    89 GeV > minv_ll > 95 GeV

Endpoints

- Reconstruction of **mass invariant distribution with endpoints:**

  1 lepton pair ($\ell\ell$) OSSF (ee+μμ-μe)
  2-3 each lepton with the jet (ℓq and ℓ'q)
  4 the jet and both leptons ($\ell\ell$q)
  5 threshold $\ell\ell$q, with θ > π/2 between leptons in slepton frame



- To recover masses from functions

$$m^2_{\ell\ell} = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}}}$$

$$m^2_{\ell q,\,\mathrm{near}} = \frac{\left(m^2_{\tilde{q}} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}}\right)}{m^2_{\tilde{\chi}^0_1}}$$

$$m^2_{\ell q,\,\mathrm{far}} = \frac{\left(m^2_{\tilde{q}} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}}}$$

$$m^2_{\ell qq} = \max\left[\frac{\left(m^2_{\tilde{q}} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{\chi}^0_2}}, \frac{\left(m^2_{\tilde{q}} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}}}\right]$$

arXiv:0410303

Sparticle mass recovery

- Five mass invariant distribution fitted
  to the get endpoint position with the error in Root
- Fit unknown sparticle masses to five endpoints with Root
  - **Single solution for a sparticle mass with statistical errors**
- **Errors are correlated ⇒ covariance matrix**
- **C matrix** basis in GeV^2
  $(m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}}, m_{\tilde{\chi}_2^0}, m_{\tilde{q}})$

$$\sigma = \begin{pmatrix} 132.0 & 18.4 & 31.9 & 175.8 \\ \cdot & 25.5 & 24.2 & 21.3 \\ \cdot & \cdot & 24.8 & 39.6 \\ \cdot & \cdot & \cdot & 401.1 \end{pmatrix}$$

Covariance matrix

- Covariance matrix is diagonalised to find errors:

$$V\,\sigma^{-1}\,V^T \approx \mathrm{diag}\left[(0.3\,\mathrm{GeV})^{-2}, (5.6\,\mathrm{GeV})^{-2}, (7.5\,\mathrm{GeV})^{-2}, (22.3\,\mathrm{GeV})^{-2}\right]$$

[GeV]

$$\mathbf{0.3} = 0.1 \cdot m_{\chi_1^0} + 0.7 \cdot m_{\tilde{\ell}} - 0.8 \cdot m_{\chi_2^0} + 0.0 \cdot m_{\tilde{q}} \approx \frac{1}{\sqrt{2}}(m_{\tilde{\ell}} - m_{\chi_2^0}),$$

$$\mathbf{5.6} = 0.6 \cdot m_{\chi_1^0} - 0.6 \cdot m_{\tilde{\ell}} - 0.4 \cdot m_{\chi_2^0} - 0.2 \cdot m_{\tilde{q}},$$

$$\mathbf{7.5} = 0.6 \cdot m_{\chi_1^0} - 0.4 \cdot m_{\tilde{\ell}} - 0.5 \cdot m_{\chi_2^0} + 0.4 \cdot m_{\tilde{q}},$$

$$\mathbf{22.3} = 0.4 \cdot m_{\chi_1^0} + 0.1 \cdot m_{\tilde{\ell}} + 0.1 \cdot m_{\chi_2^0} + 0.9 \cdot m_{\tilde{q}} \approx m_{\tilde{q}}.$$

- Two (one very) well determined directions σ ≤ (1) 10 GeV

Statistical method

- To **recover original CMSSM parameters** from simulated sparticle mass measurements

- Use Bayesian statistics . Bayes theorem:

$$\underbrace{p\left(m_0, m_{1/2}, \tan\beta, A_0 | \mathbf{D}\right)}_{\text{Posterior density}} \propto \underbrace{\mathcal{L}\left(\mathbf{D} | m_0, m_{1/2}, \ldots\right)}_{\text{Likelihood}} \times \underbrace{\pi\left(m_0, m_{1/2}, \ldots\right)}_{\text{Prior}}$$

- We want to find posterior density for CMSSM , given golden decay measurements

- Marginalise posterior, to remove parameter dependencies, e.g.,

$$p\left(m_0, m_{1/2} | \mathbf{D}\right) = \int p\left(m_0, m_{1/2}, \tan\beta, A_0 | \mathbf{D}\right) \, dA_0 \, d\tan\beta$$

- Find **"credible regions:"** Smallest region A such that

$$\int_A p\left(m_0, m_{1/2} | \mathbf{D}\right) \, dm_0 \, dm_{1/2} = 95\%$$

Statistical method

- Priors reflect **“prior belief”** in parameter space
- Choose **flat priors**, expect prior independence
- Likelihood is a multivariate Gaussian from our golden decay simulations

$$\boxed{\mathcal{L}_{\text{golden decay}} = \exp\left[-\frac{1}{2}(M - M_{\text{benchmark}})C^{-1}(M - M_{\text{benchmark}})^T\right]}$$

- **M is a function of** $M = (m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}}, m_{\tilde{\chi}_2^0}, m_{\tilde{q}})$ and C is a covariance matrix from our MC
- In the next step, apply **Gaussian likelihoods** for $\Omega h^2 = 0.1186 \pm 0.0031 \pm 10\%$ and $m_h = 125.8 \pm 0.5 \pm 3\text{GeV}$
- **Posteriors** are calculated with MultiNest from all priors and likelihoods

Parameter	Prior range	Distribution
m_0	$(0.1,\ 4)$ TeV	Flat
$m_{1/2}$	$(0.1,\ 2)$ TeV	Flat
A_0	$(-4,\ 4)$ TeV	Flat
$\tan\beta$	$(3,\ 62)$	Flat
sign μ	$+1$	Fixed
M_t	173.5 GeV	Fixed
$m_b(m_b)^{\overline{MS}}$	4.18 GeV	Fixed
$1/\alpha_{\text{em}}(M_Z)^{\overline{MS}}$	127.944	Fixed
$\alpha_s(M_Z)^{\overline{MS}}$	0.1184	Fixed

Our method

[1] **Assume** SUSY **CMSSM benchmark point is "true"**

[2] **Assume** sparticle **masses measured by golden decay** at LHC √s = 14 TeV

[3] **Find** expected errors (**covariance matrix**) from MC

[4] **Assume flat priors** for CMSSM parameters m0, m1/2, A0, tan β

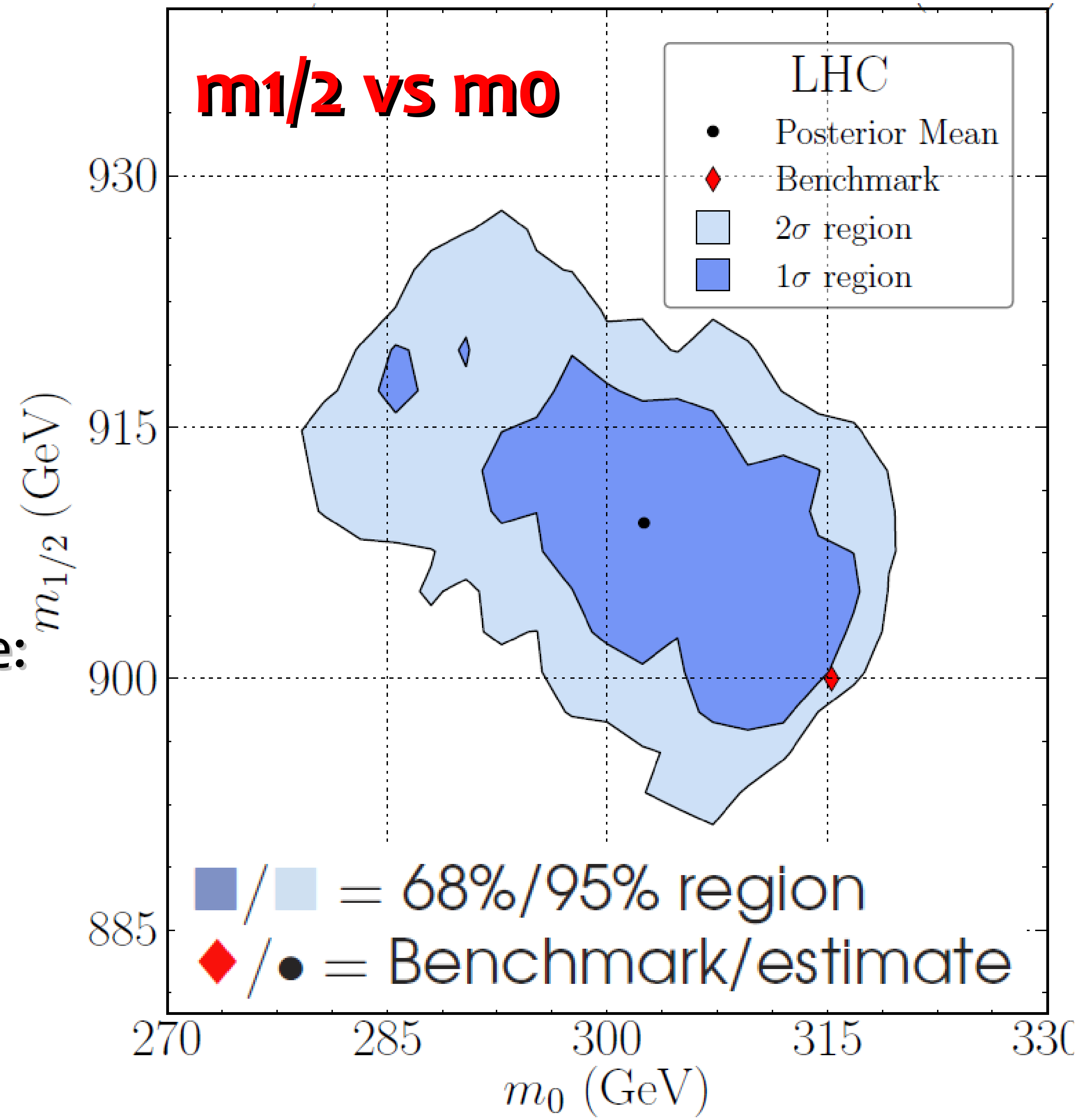
[5] **Fit CMSSM** to golden decay measurements **with Bayesian statistics**

[6] Afterwards, **add information** from m_h and Ωh^2 to see how much it improves recovery

- **How well do we recover the original benchmark parameters?**

Results – CMSSM reco

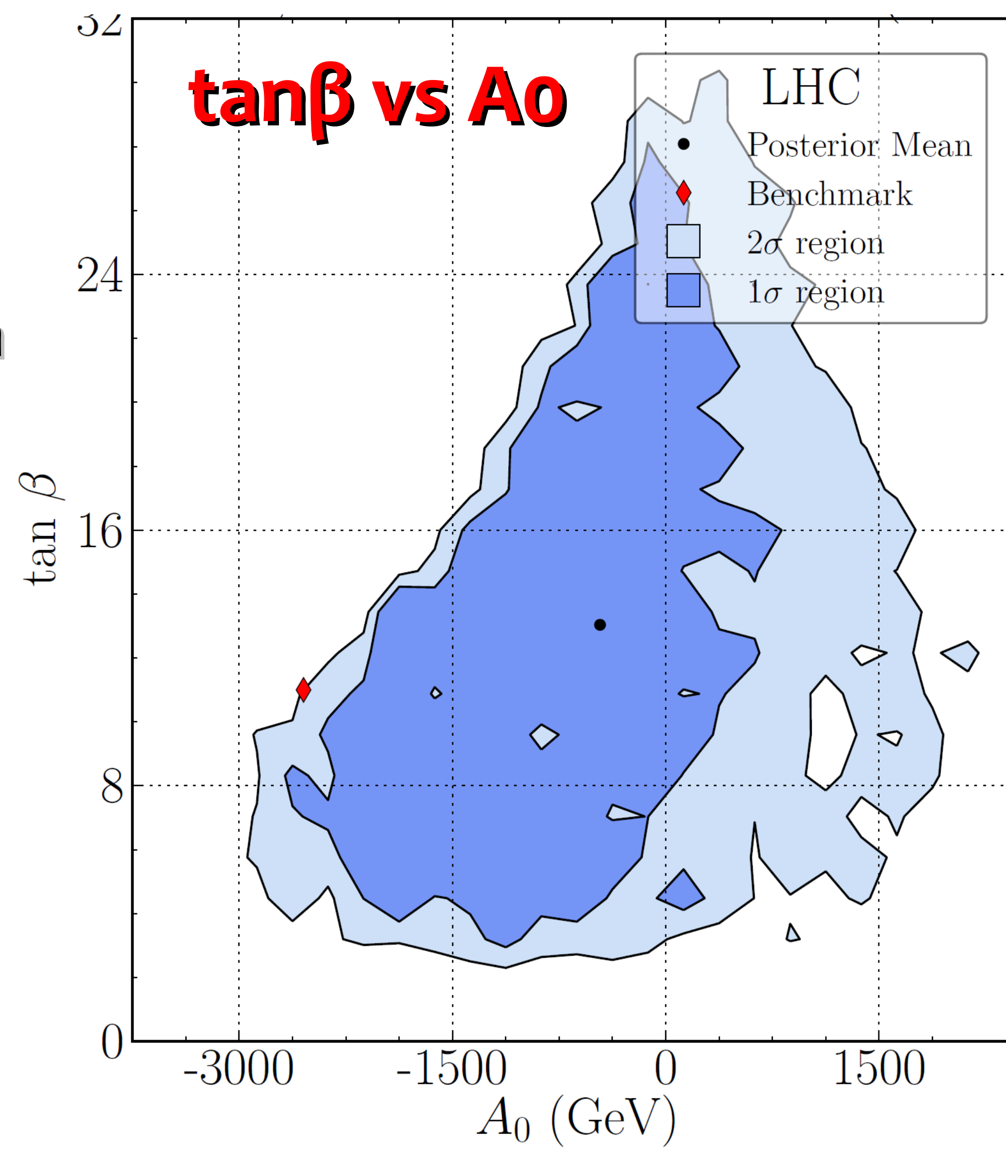
- With the endpoint information alone, **recovered "true" benchmark point**
- **Single correct solution found, the benchmark point is in 68% region**
- Two orthogonal directions in the parameter space are visible: **anti-diagonal m0-m1/2** and **diagonal m0+m1/2,** which **correspond to the first (0.3 GeV) and second (5.6 GeV) eigenvectors of C matrix**



CMSSM reconstruction

- **Ao is not well reconstructed**
- Broadened the credible region in the m0-m1/2 direction
- **tan β determined to within a few units**

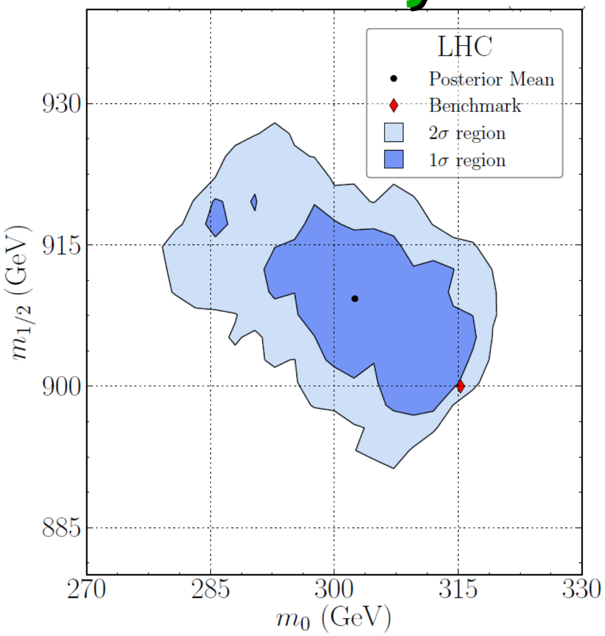
■/■ = 68%/95% region
◆/● = Benchmark/estimate

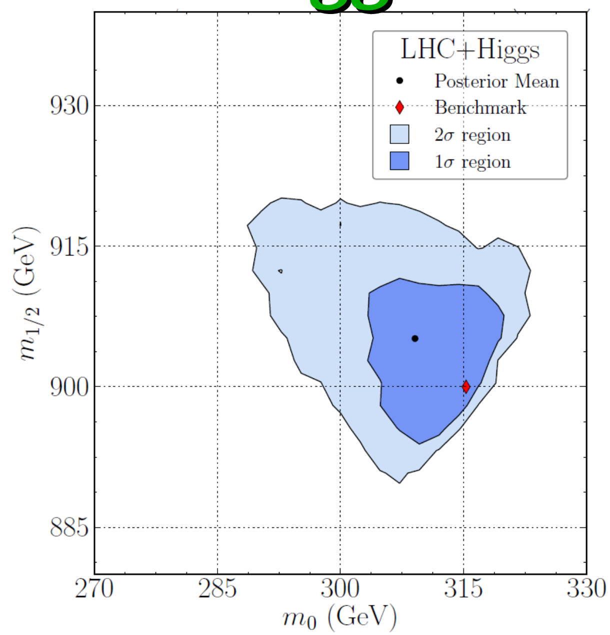


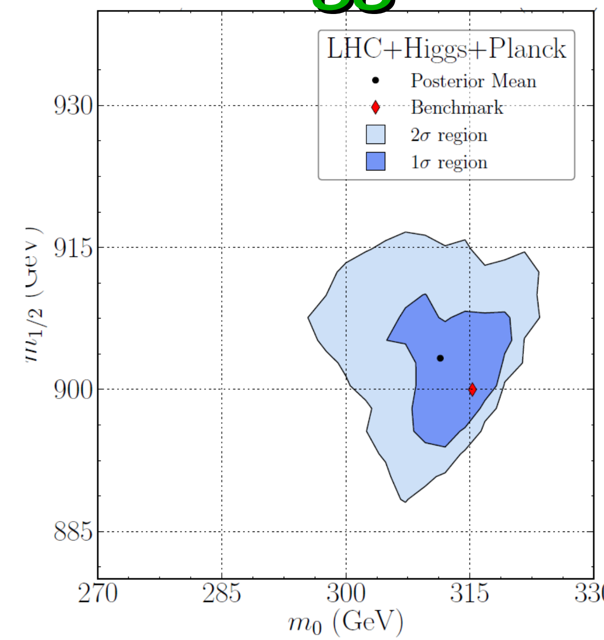
CMSSM reco

Gold decay | **LHC+higgs** | **LHC+higgs+Planck**

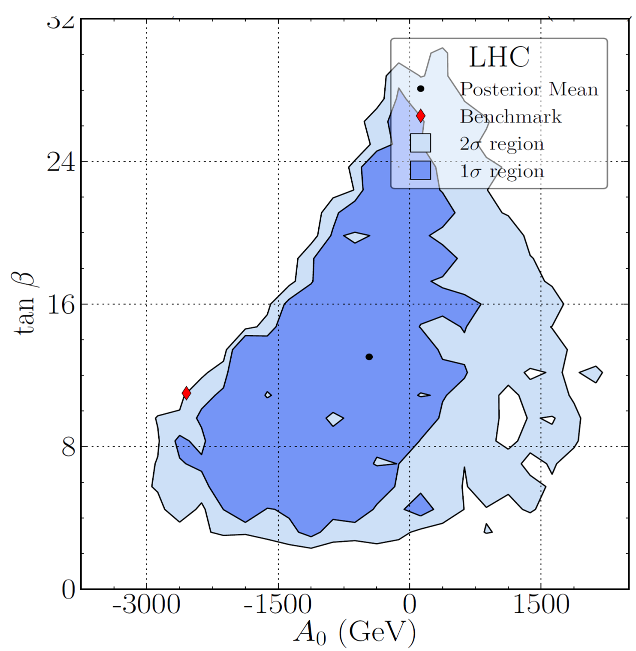
m1/2 vs m0

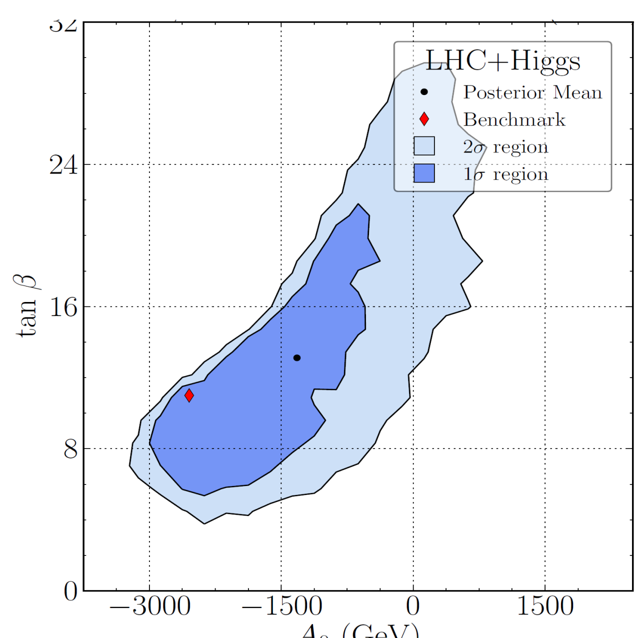


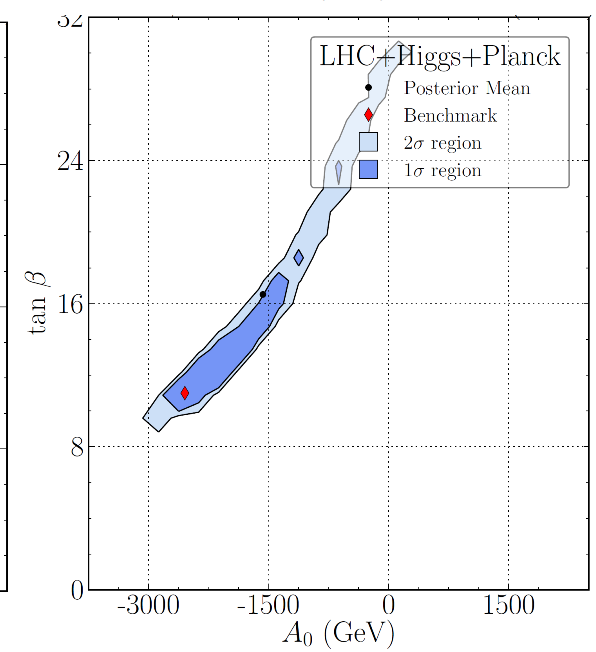




tanβ vs A0





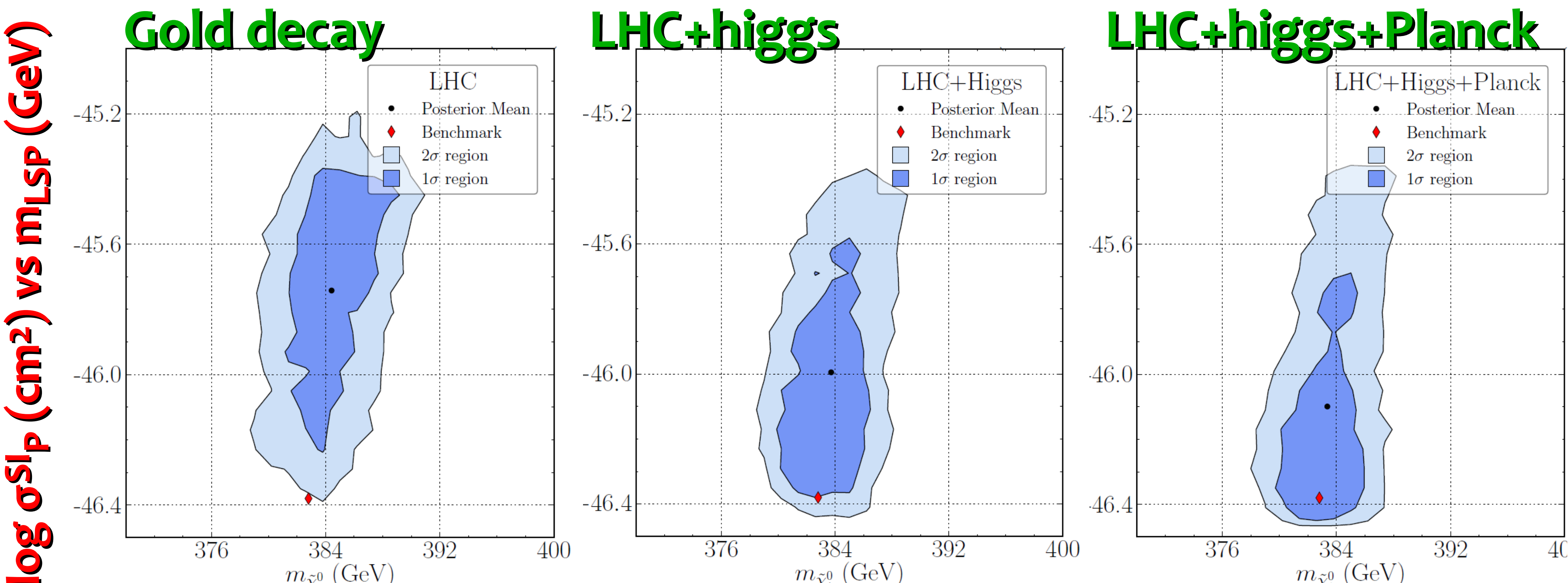


Adding more data to fit

- The **credible regions shrink successively as the data is added**, though two orthogonal directions in the parameter space remain visible
  - The diagonal **m0+m1/2** direction of the is **only marginally shrunk,** whereas the anti-diagonal **m0-m1/2** direction is **squashed** for (A0, tan β)
- When we add **higgs**, A0 must be < 0.5 TeV to increase the Higgs boson mass via maximal mixing $m_{\tilde{\tau}_1} \approx m_{\chi_1^0}$
  Increases in Higgs boson mass from increasing m1/2 and m0 to increase stop masses are negligible
- When we add **Planck**, we enforce mass degeneracy so that staus and neutralinos coannihilate effectively and **reduce the relic density to the Planck value**
- **This is rather fortunate –** **higgs** and **Planck** constrain the direction of parameter space that was poorly constrained by LHC

Direct Dark Matter searches

- LHC prediction indicate that in our discovery scenario the **DM might be within reach of direct detection experiments**
  - should be accessible at a 1-tonne detectors whose reach is expected to be < 10^{-46} cm^2
- **The resolution and bias of σ^{SI} improves slightly as data is added,** especially Planck, but the resolution of the neutralino mass is not much improved



Conclusions

- We demonstrated the possibility of reconstructing CMSSM parameters with Bayesian statistics
- If SUSY is found in the LHC, we can check existence of the golden decay
- **We found that sparticle masses can be measured with good precision for high mass CMSSM benchmark point**
- **We found that CMSSM parameters can be well recovered**
  - Improved when additional information from Ωh^2 is added, but less so for m_h

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP
Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

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References:

[1] A. Fowlie, M. Kazana, L. Roszkowski, *Reconstructing CMSSM parameters at the LHC with s√=14 TeV via the golden decay channel,* **arXiv:1106.5117, Dec 2014**