

Direct stau production at the LHC

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in collaboration with Frank D. Steffen & Maike K. Trenkel

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

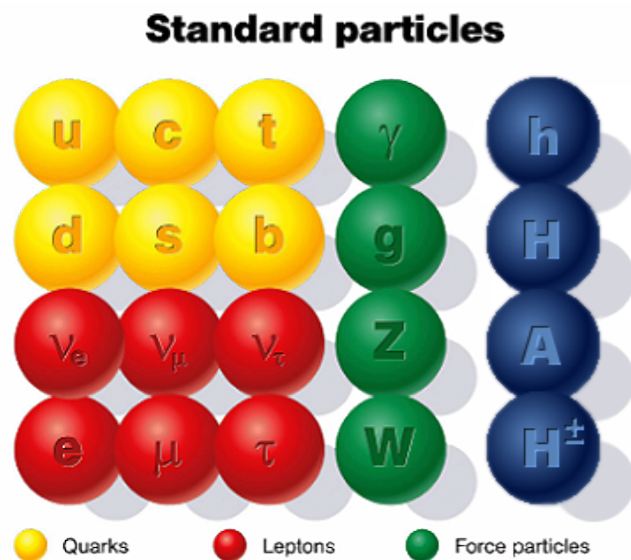


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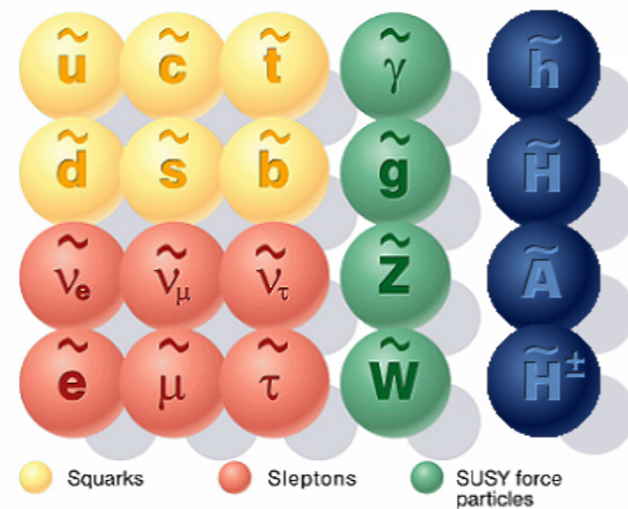
Phenomenology 2012 Symposium
Pittsburgh, 8. Mai 2012

Stau as the LOSP

MSSM:

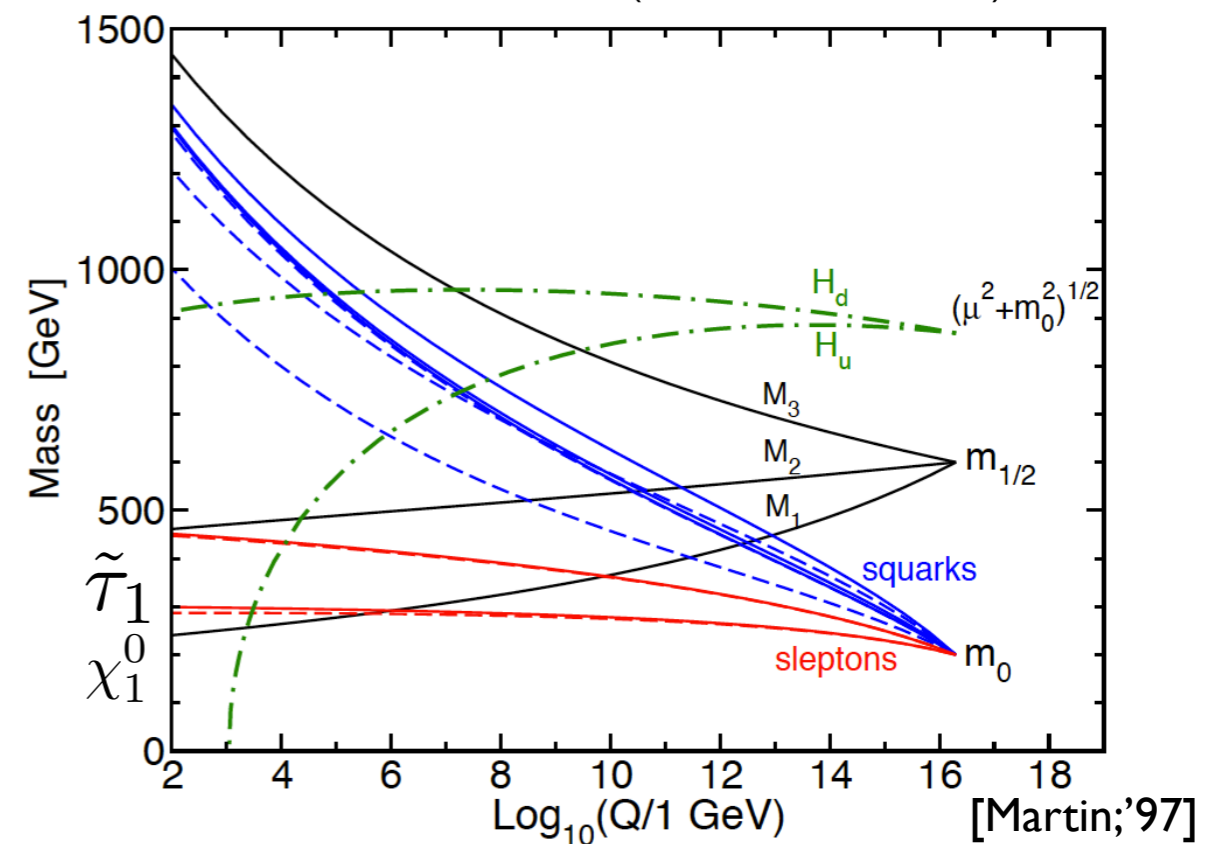


SUSY particles



CMSSM:

$m_0, m_{1/2}, A_0,$
 $\tan \beta, \text{sign}(\mu)$
 defined at GUT scale.
 (benchmark model)

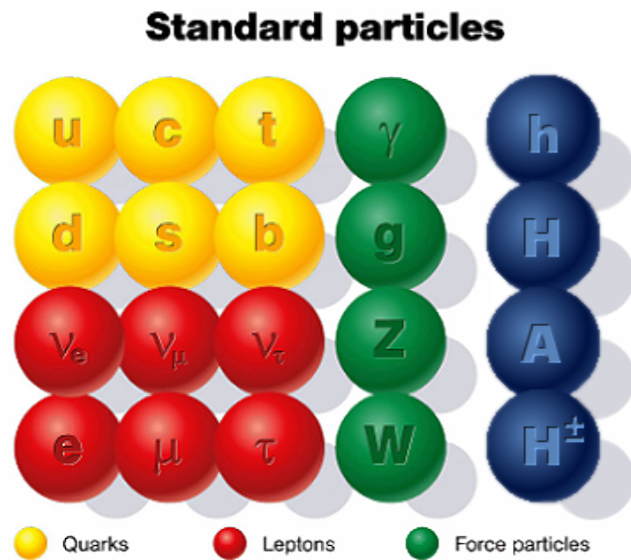


← RGE running \propto -Yukawa coupling

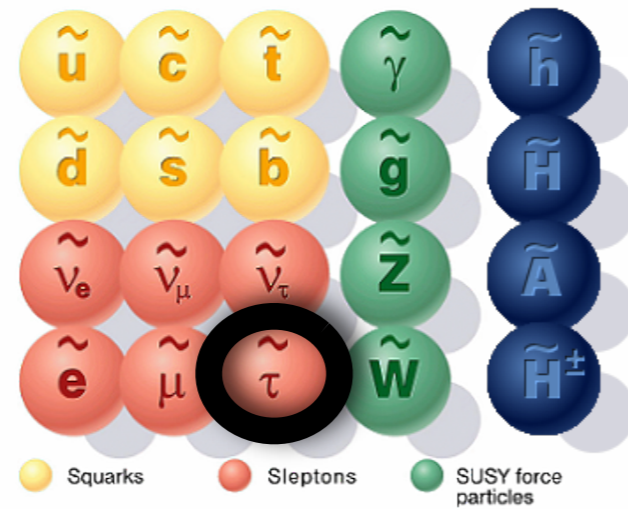
- However: charged stau can not be the (stable) LSP!
- e.g. light gravitino \tilde{G} is viable DM and stau is LOSP.
 - Due to small couplings stau might be long-lived.
 - Strong bounds from BBN for long-lived stau.

Stau as the LOSP

MSSM:

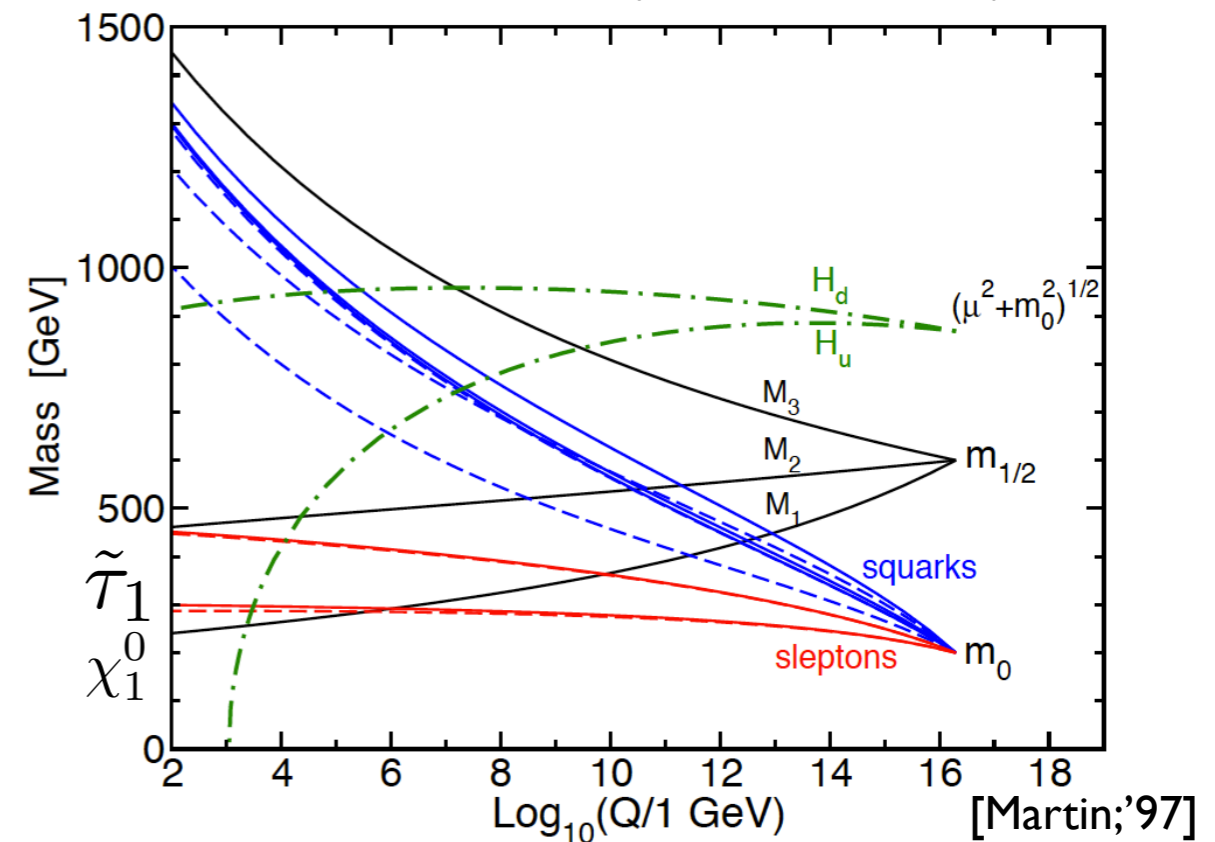


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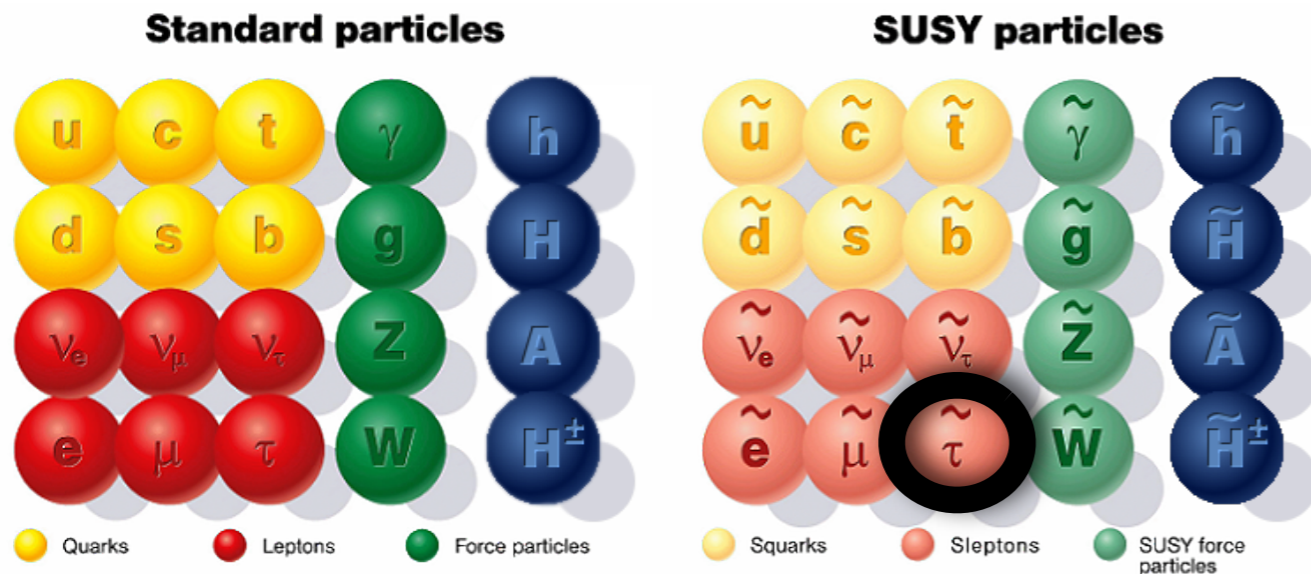


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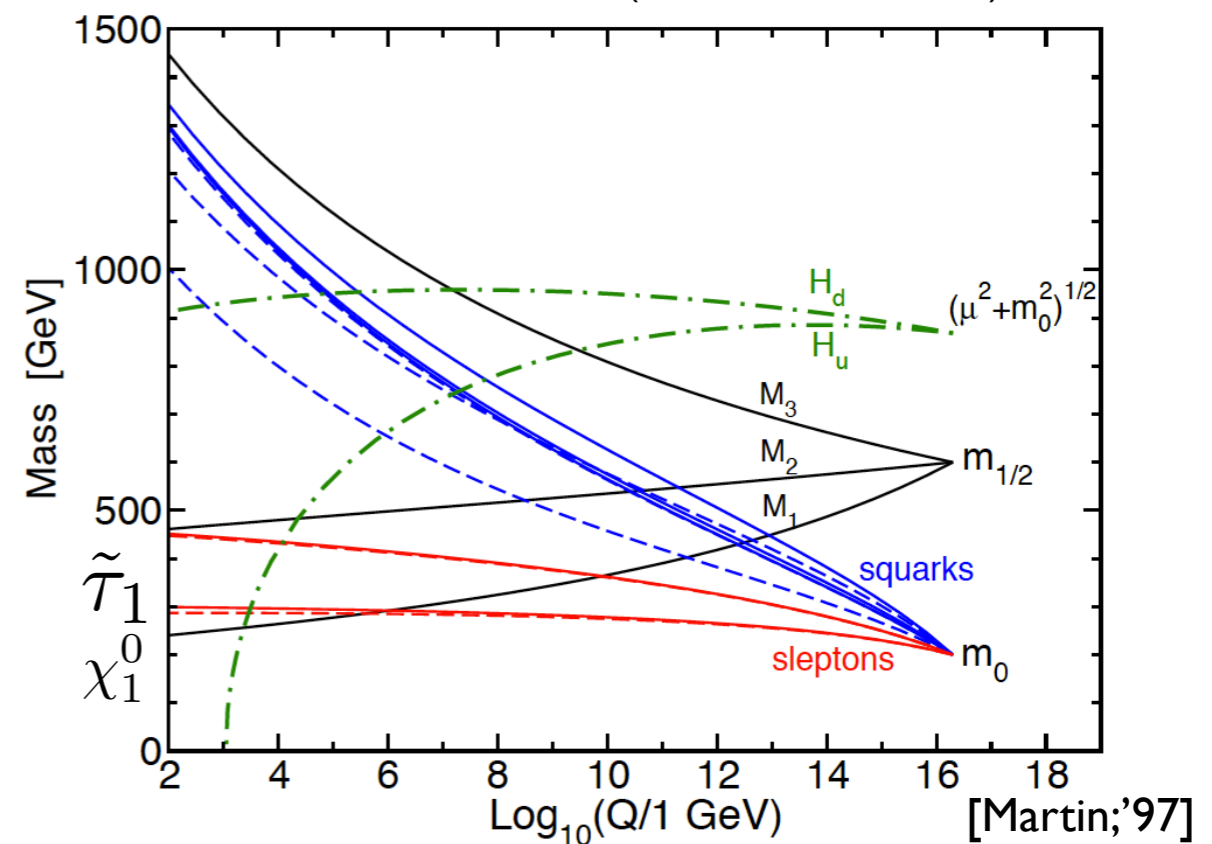
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CMSSM:

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← RGE running \propto -Yukawa coupling

gauge SUSY \rightarrow Gravitino \tilde{G}

+ introduce Pecci-Quinn symmetry \rightarrow Axino \tilde{a}

introduce additional singlet field \rightarrow NMSSM singlino

However: charged stau can not be the (stable) LSP!

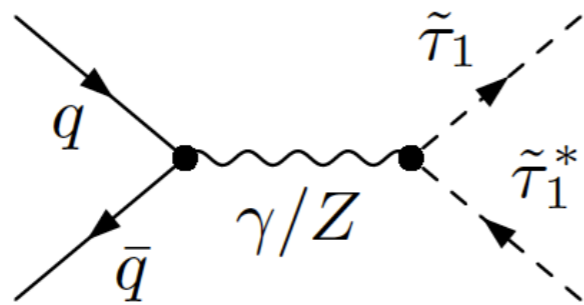
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Production of staus at the LHC

- Direct production



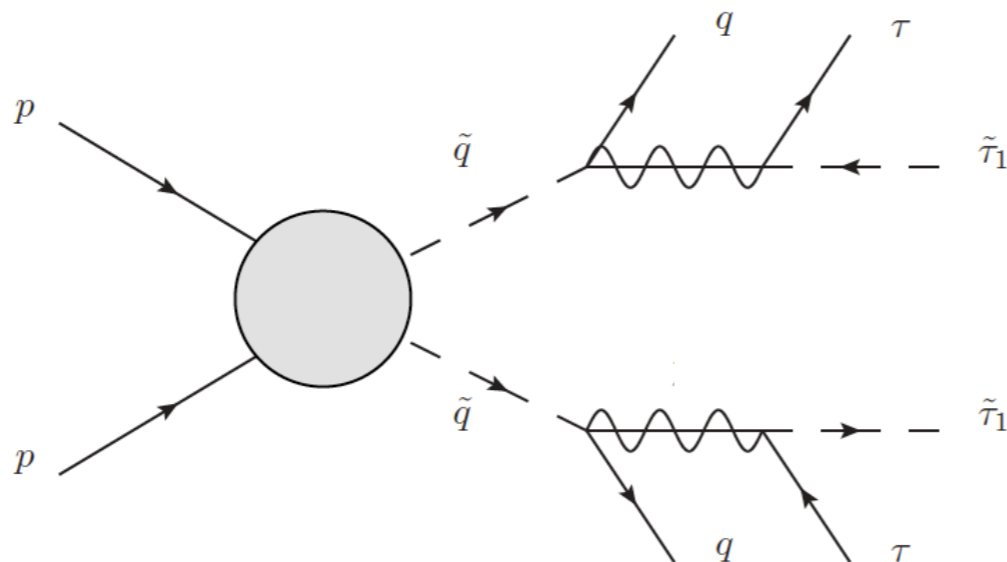
Drell-Yan

(known @ NLO (S)QCD

[Benakker, Klasen, Krämer, Plehn, Spira; '99]

and @ NLL [Bozzi, Fuks, Klasen; '06])

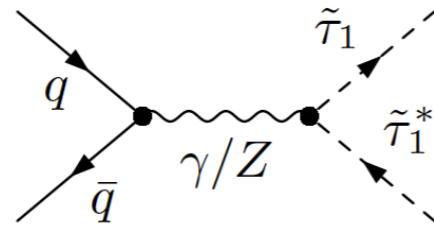
- Production in cascade decays



determined by
squark + gluino production
(& BRs)

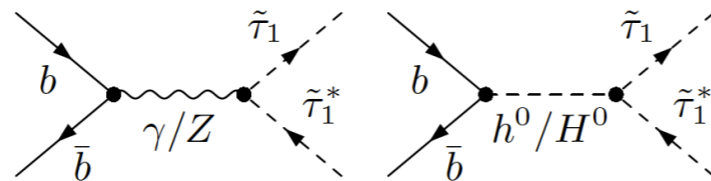
Direct Production of staus at the LHC

Drell-Yan



$O(\alpha^2)$ & NLO (S)QCD $O(\alpha_s^2 \alpha^2)$

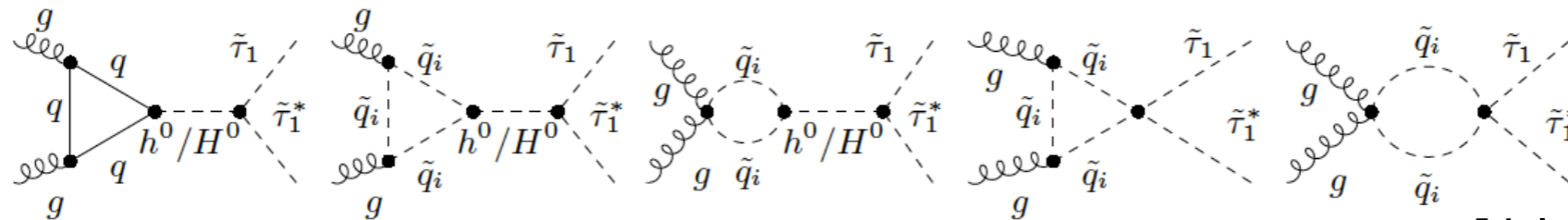
$b\bar{b}$



$O(\alpha^2)$ + bottom PDFs

[del Aguila, Ametller; '91; Bisset, Raychaudhuri; '96]

gluglu



$O(\alpha_s^2 \alpha^2)$

[del Aguila, Ametller; '91; Borzumati, Hagiwara; '09]

on-shell: $\frac{1}{p^2 - m_{H^0}^2} \longrightarrow \frac{1}{p^2 - m_{H^0}^2 + im_{H^0}\Gamma_{H^0}}$

Technical detail: higher order corrections of $b\bar{b}h/H$ - vertex drive *down* cross sections (especially for large $\tan \beta$).

➔ Use resummed effective mass m_b^{eff} and effective couplings.

[Carena, et. al.; '94; Heinemeyer et. al.; '05]

Stau sector in the MSSM

- Stau mass eigenstates

$$\mathcal{M}_{\tilde{\tau}}^2 = \begin{pmatrix} m_{\tau}^2 + m_{\text{LL}}^2 & m_{\tau} X_{\tau} \\ m_{\tau} X_{\tau} & m_{\tau}^2 + m_{\text{RR}}^2 \end{pmatrix} = (R_{\tilde{\tau}})^{\dagger} \begin{pmatrix} m_{\tilde{\tau}_1}^2 & 0 \\ 0 & m_{\tilde{\tau}_2}^2 \end{pmatrix} R_{\tilde{\tau}}$$

$$m_{\text{LL}}^2 = m_{\tilde{L}_3}^2 + \left(-\frac{1}{2} + \sin^2 \theta_W \right) M_Z^2 \cos 2\beta$$

$$m_{\text{RR}}^2 = m_{\tilde{E}_3}^2 - \sin^2 \theta_W M_Z^2 \cos 2\beta,$$

$$X_{\tau} = A_{\tau} - \mu \tan \beta .$$

$$R_{\tilde{\tau}} = \begin{pmatrix} \cos \theta_{\tilde{\tau}} & \sin \theta_{\tilde{\tau}} \\ -\sin \theta_{\tilde{\tau}} & \cos \theta_{\tilde{\tau}} \end{pmatrix} \longrightarrow \tilde{\tau}_1 = \cos \theta_{\tilde{\tau}} \tilde{\tau}_L + \sin \theta_{\tilde{\tau}} \tilde{\tau}_R$$

- Stau-stau-Higgs coupling:

$$\mathcal{L}_{\tilde{\tau}\tilde{\tau}\mathcal{H}} = \frac{g}{M_W} \sum_{I,J=L,R} \tilde{\tau}_I^* \tilde{C}[\tilde{\tau}_I^*, \tilde{\tau}_J, \mathcal{H}] \tilde{\tau}_J \mathcal{H}$$

$$\longrightarrow C^{\text{DL}}[\tilde{\tau}_1^*, \tilde{\tau}_1, h^0] \simeq \left(\frac{1}{2} c_{\theta_{\tilde{\tau}}}^2 - s_W^2 c_{2\theta_{\tilde{\tau}}} \right) M_Z^2 c_{2\beta} - m_{\tau}^2 - \frac{m_{\tau}}{2} X_{\tau} s_{2\theta_{\tilde{\tau}}}$$

(DL: decoupling limit, $m_{A^0} \gg m_Z$)

- However, can not become arbitrarily large:
charge-breaking minima (CCB) !

[Hisano, Sugiyama; '10]

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[Hisano, Sugiyama; '10]

Connection with Cosmology

- **Late decays** & possible **bound states** of might easily spoil Big Bang Nucleosynthesis (BBN).
- Cosmological implications depend on $m_{\tilde{\tau}_1}, \tau_{\tilde{\tau}_1}$ and $Y_{\tilde{\tau}_1} = n_{\tilde{\tau}_1}/s$.
- E.g. for $\tilde{\tau}_1 = \tilde{\tau}_R$:

$$Y_{\tilde{\tau}_1} \simeq (0.4 - 2.0) \times 10^{-13} \left(\frac{m_{\tilde{\tau}_1}}{100 \text{ GeV}} \right) \quad (\text{I})$$

[Berger, Covi, Kraml, Palorini; '08]

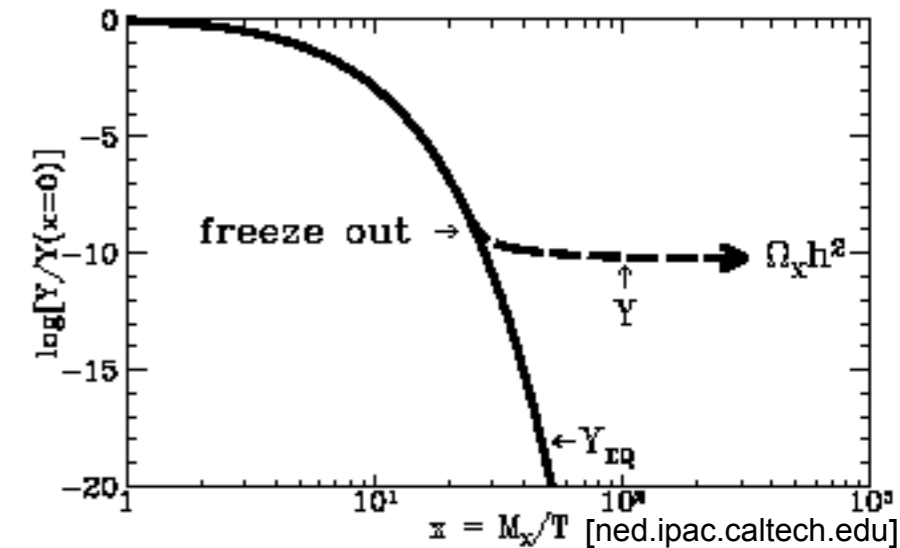
- However, $Y_{\tilde{\tau}_1}$ can also be much smaller, due to **efficient annihilation** (II)

processes: $Y_{\tilde{\tau}_1} \lesssim 2 \times 10^{-15}$

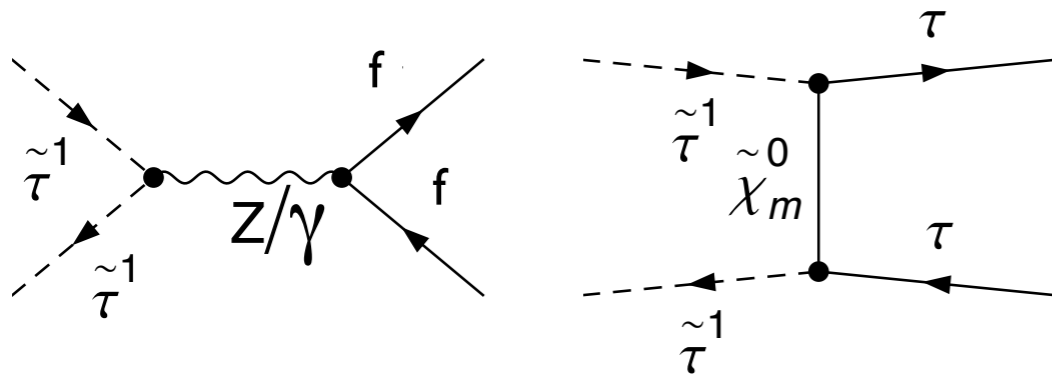
[Ratz, Schmidt-Hoberg, Winkler; '08
Pradler, Steffen; '09;]

- Thus, constraints from BBN can be evaded!
- Need: a) large stau-stau-Higgs coupling or b) $2m_{\tilde{\tau}} \approx m_{H^0}$.

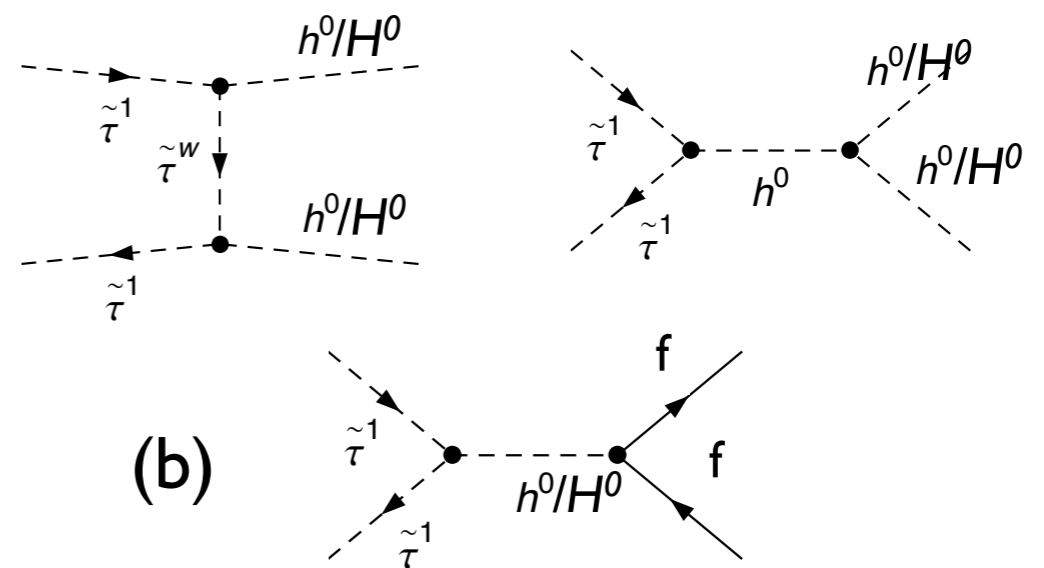
“freeze out”



(I)



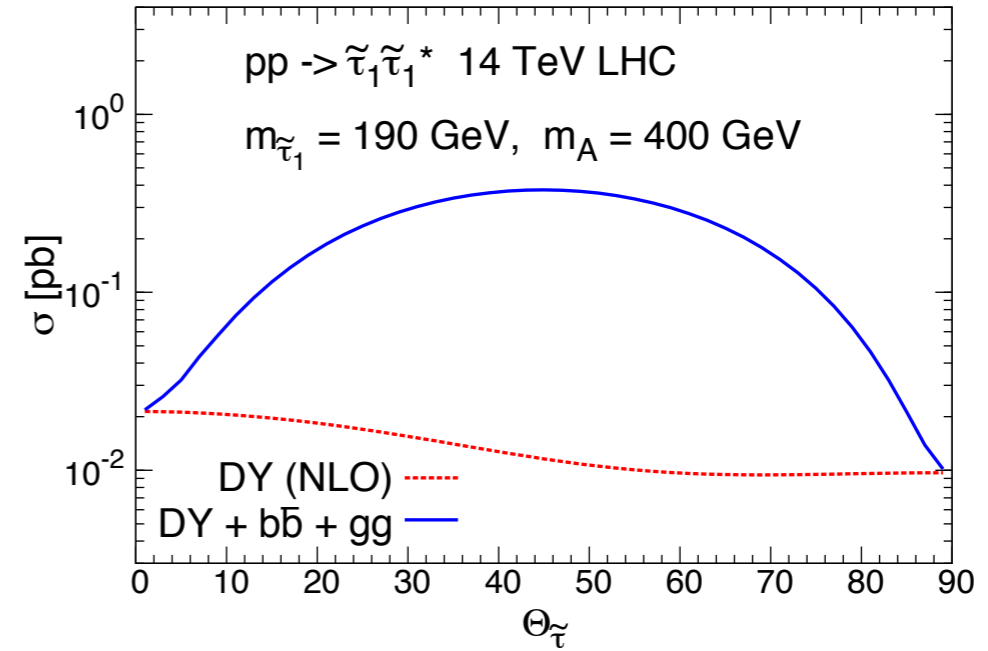
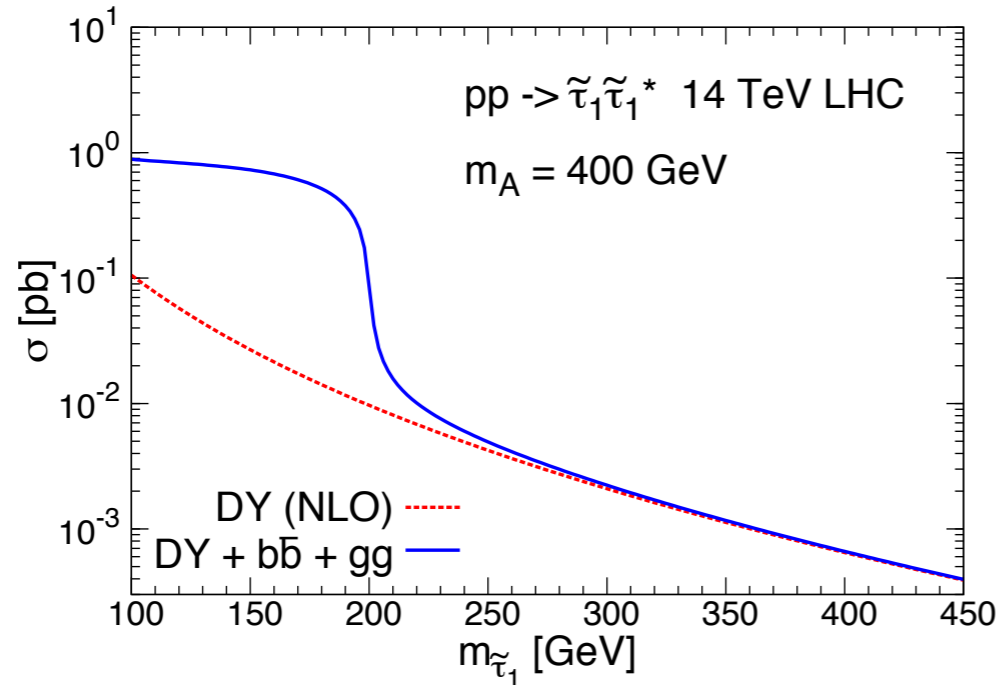
(a)



(II)

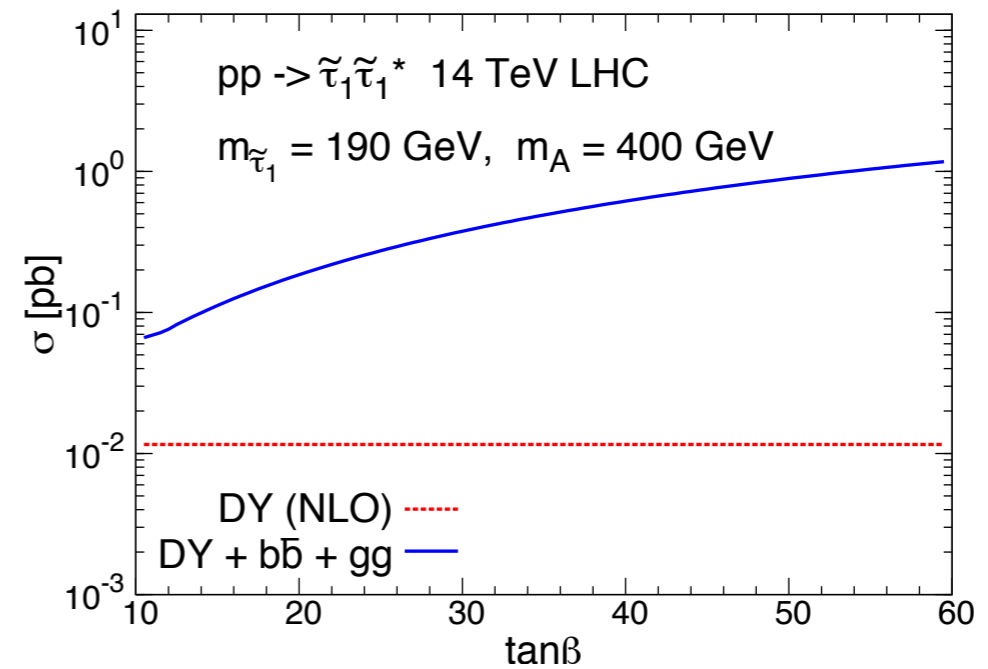
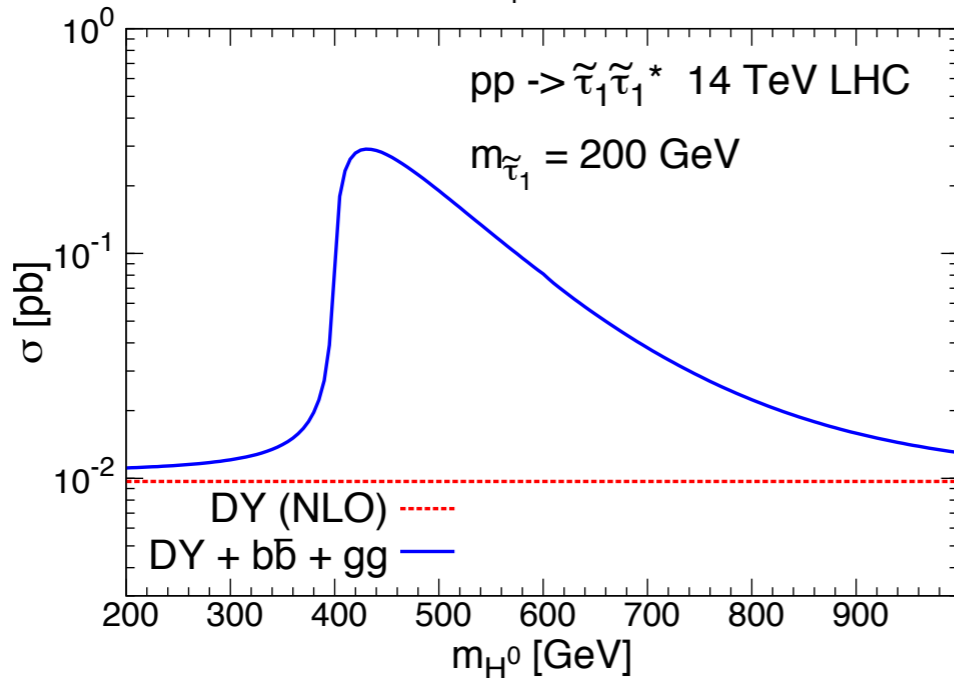
Numerical Results

$m_{\tilde{\tau}_1}$



$\Theta_{\tilde{\tau}}$

m_{H^0}



$\tan \beta$

Other SUSY parameters

$$\theta_{\tilde{\tau}} = 45^\circ, \quad m_{\tilde{\tau}_1} = 200 \text{ GeV},$$

$$\tan \beta = 30, \quad \mu = 500 \text{ GeV}, \quad m_A = 400 \text{ GeV}.$$

$$M_1 = M_2 = M_3 = 1.2 \text{ TeV}, \quad A_t = A_b = A_\tau = 600 \text{ GeV},$$

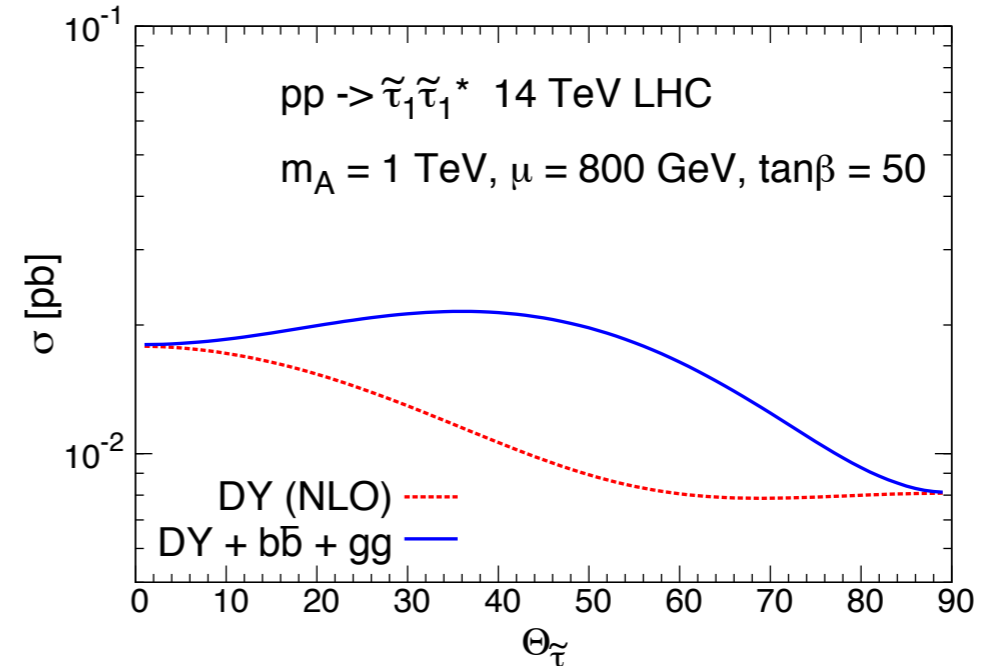
$$m_{\tilde{Q}_i} = m_{\tilde{U}_i} = m_{\tilde{D}_i} = 1 \text{ TeV}, \quad m_{\tilde{L}_{1/2}} = m_{\tilde{E}_{1/2}} = 500 \text{ GeV},$$

Numerical Results

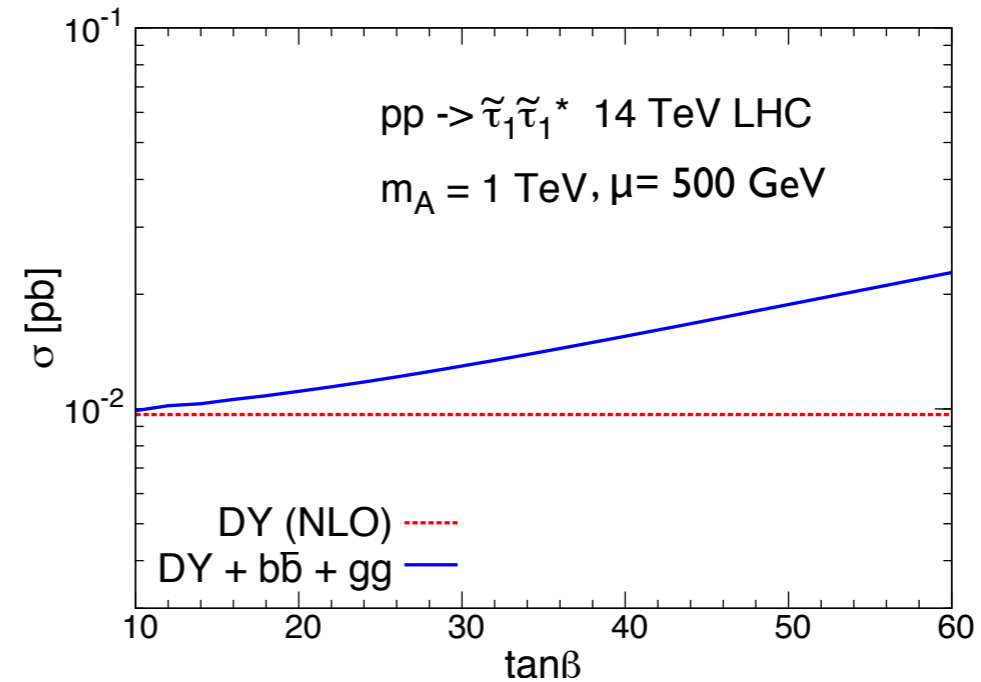
Now H^0 decoupled ($m_{A^0} = 1 \text{ TeV}$)

→ $b\bar{b}$ & gg channels dominated by $\tilde{\tau}_1 \tilde{\tau}_1^* h^0$ coupling

$$C^{\text{DL}}[\tilde{\tau}_1^*, \tilde{\tau}_1, h^0] \simeq \left(\frac{1}{2} c_{\theta_{\tilde{\tau}}}^2 - s_W^2 c_{2\theta_{\tilde{\tau}}} \right) M_Z^2 c_{2\beta} - m_{\tilde{\tau}}^2 - \frac{m_{\tilde{\tau}}}{2} X_{\tilde{\tau}} s_{2\theta_{\tilde{\tau}}}$$



$\Theta_{\tilde{\tau}}$



$\tan\beta$

Other SUSY parameters:

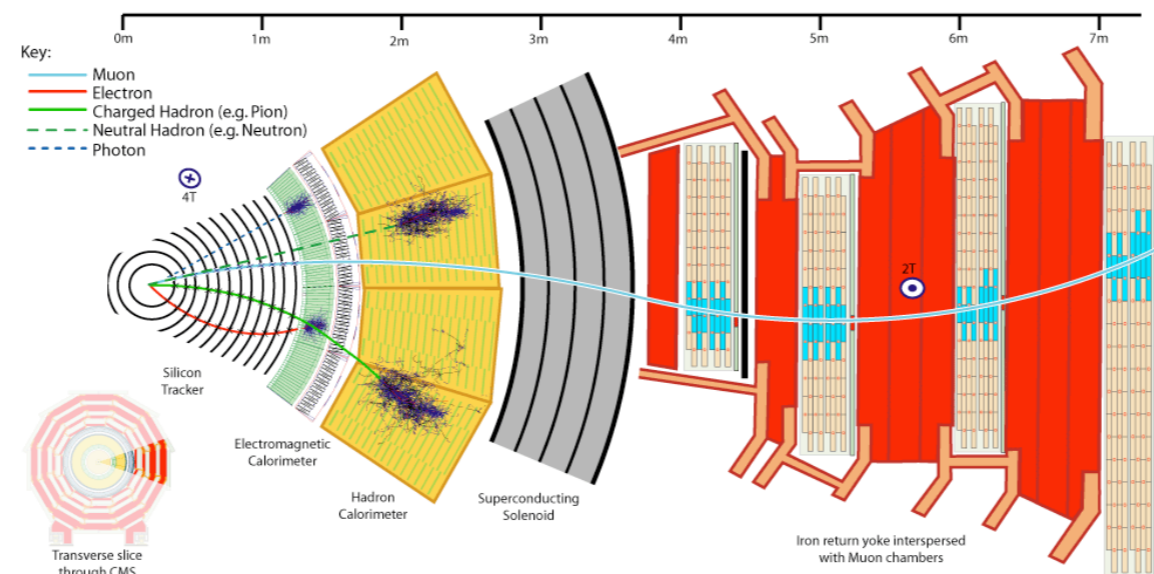
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Long-lived staus at the LHC

- NOT: usual SUSY signature, missing ET + jets (+ leptons) (assuming $\tilde{\chi}_1^0$ dark matter).
- BUT: Charged Massive Particles (CHAMP), i.e. slow but high p^T .
- (almost) only SM Background: Slow moving high p^T muons.
 - ▶ **Charged**: leaves **tracks** in the detector
 - ▶ **Massive**: moves **slowly** (small β , measured via TOF), and **deposits more energy** (large dE/dx)
 - ▶ **Long-Lived**: has **long life time**, leaves the detector without decaying
 - **detected by Muon system** (or gets **stopped** within detector)

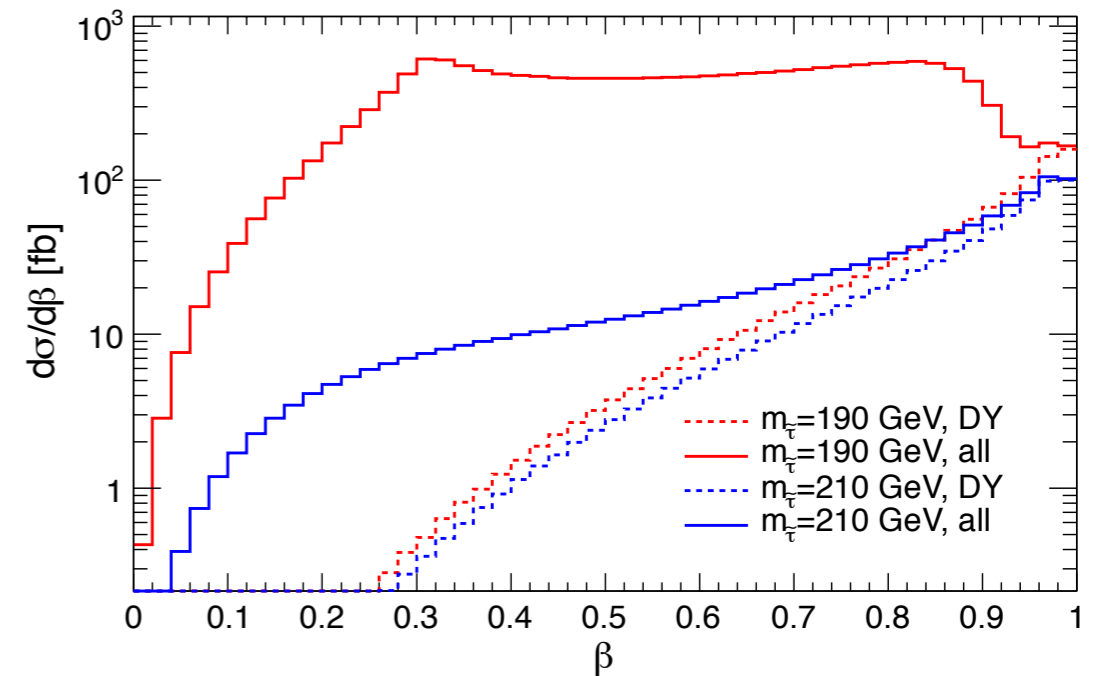
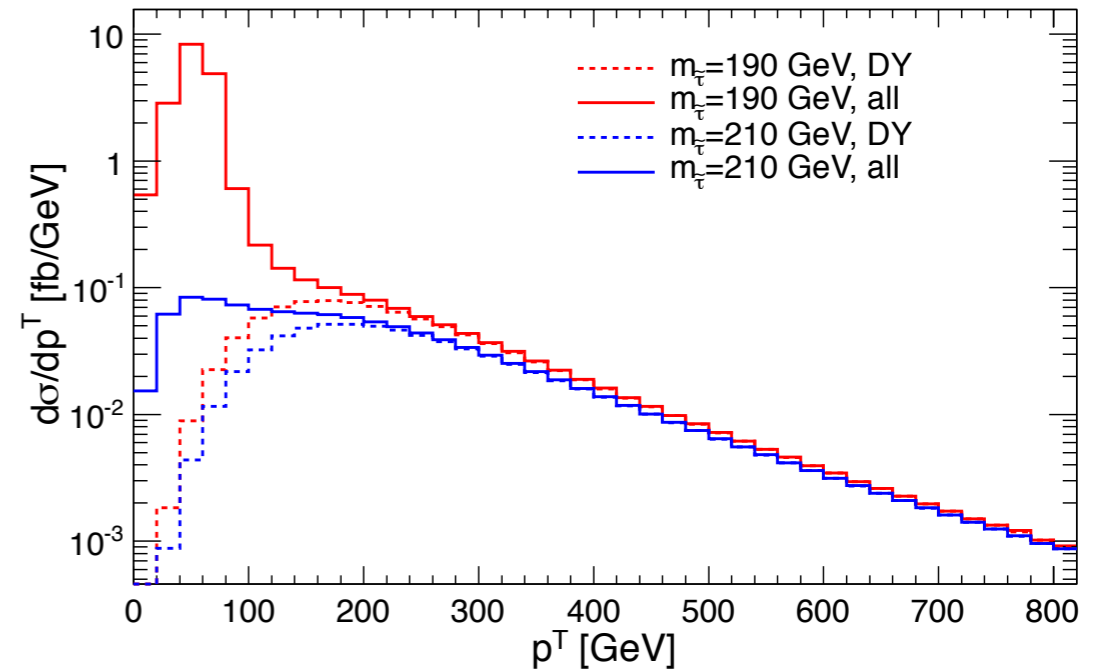
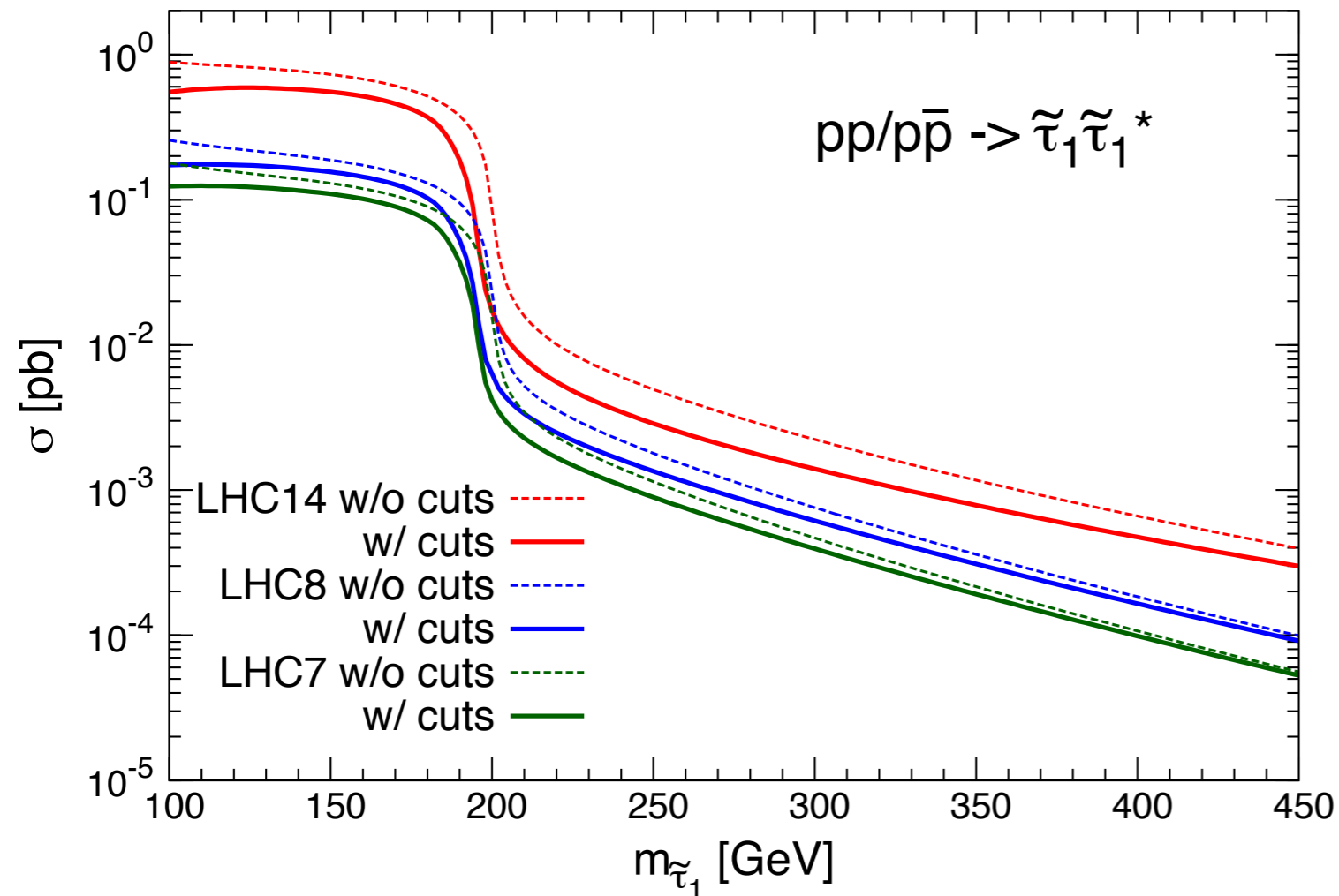


Realistic Numerical Results

Kinematical Cuts: $|\eta| \leq 2.4$

$$p^T \geq 40 \text{ GeV}$$

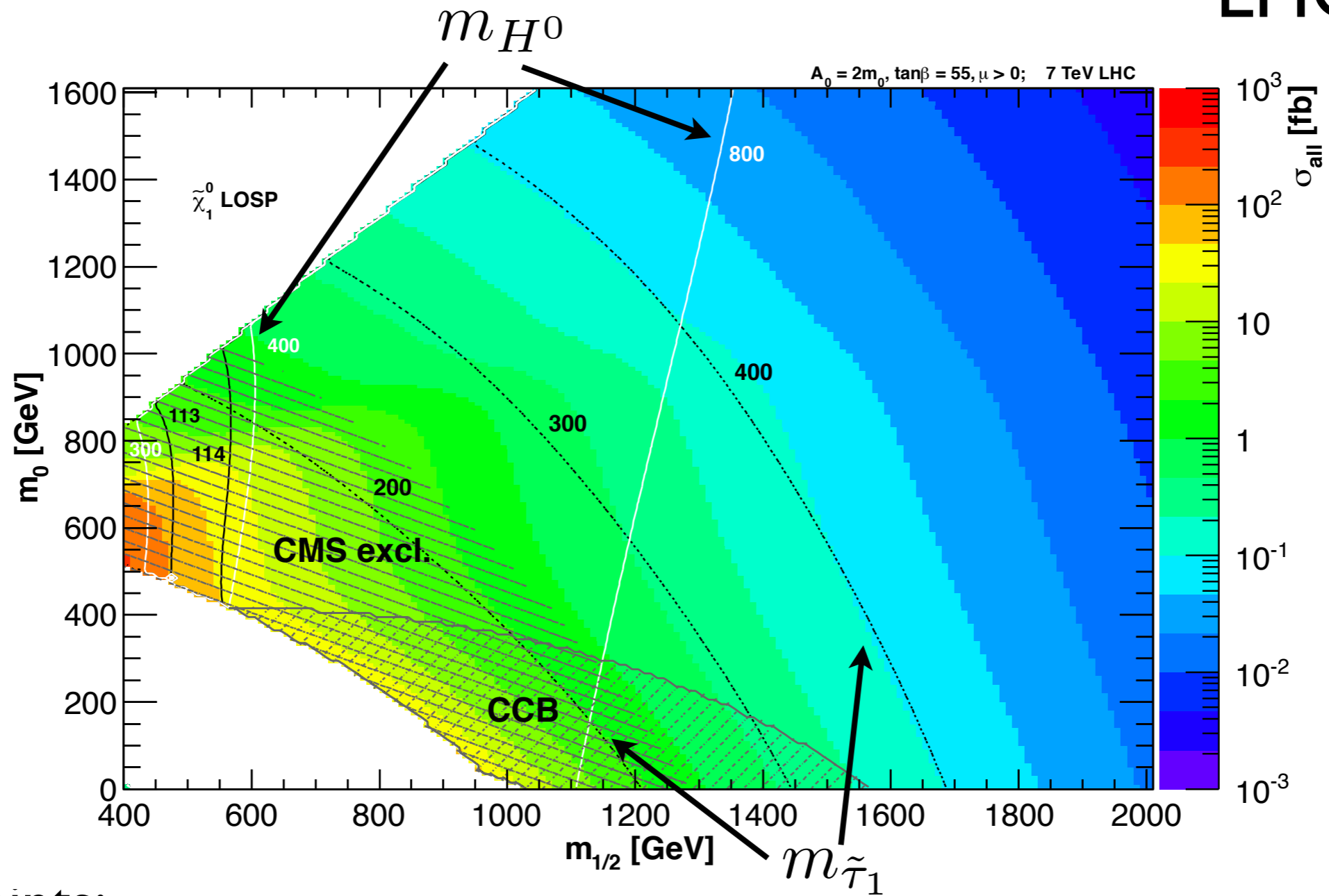
$$0.4 \leq \beta \leq 0.9$$



➡ slow staus might be stopped in detectors.

Stau production in the CMSSM

LHC 7 TeV



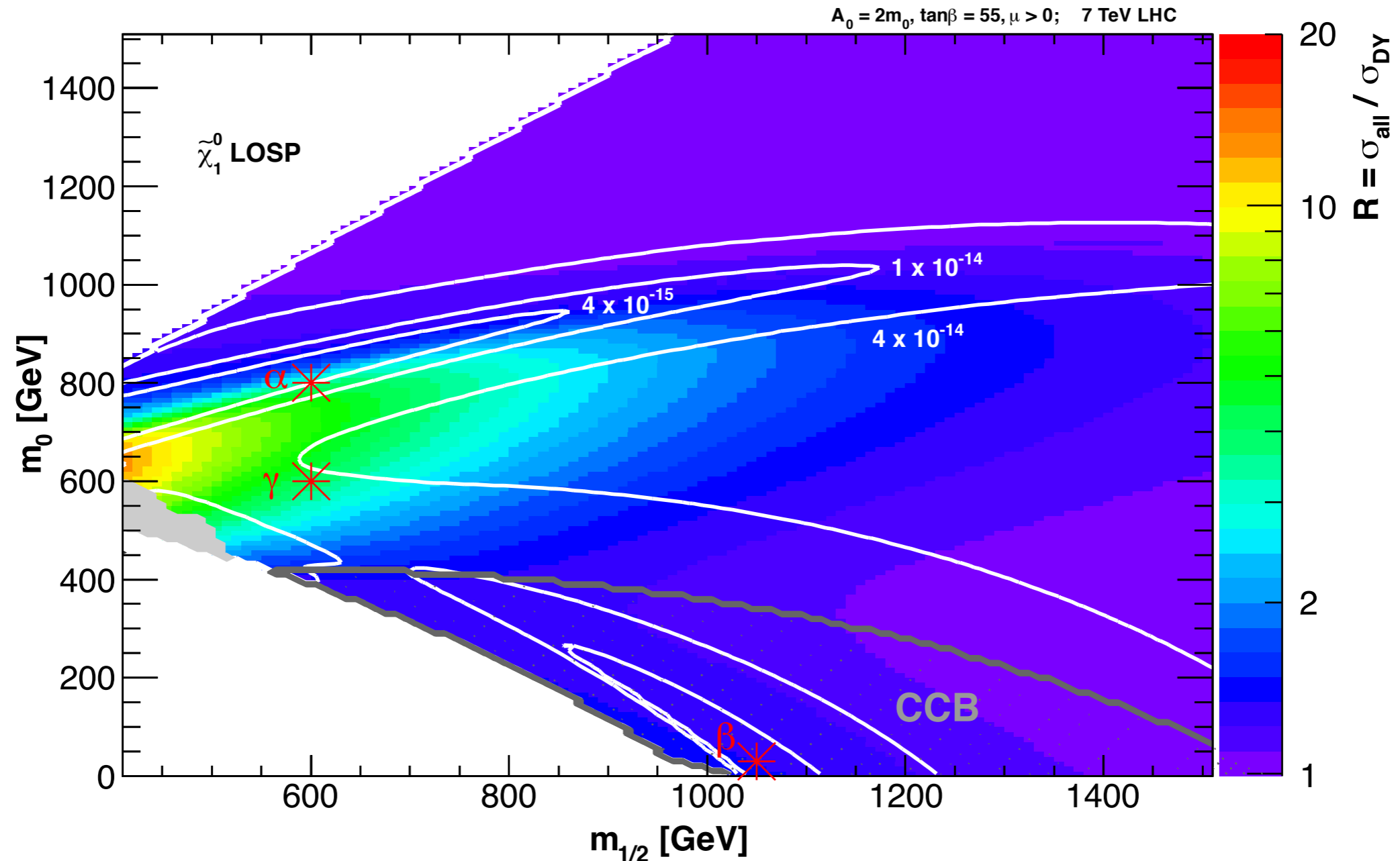
Constraints:

$$m_{\tilde{\tau}} > 223 \text{ GeV}$$

[CMS, arXiv:1205.0272]

$$A_0 = 2m_0, \quad \tan\beta = 55$$

Exceptionally small stau yields in the CMSSM



LHC 7 TeV

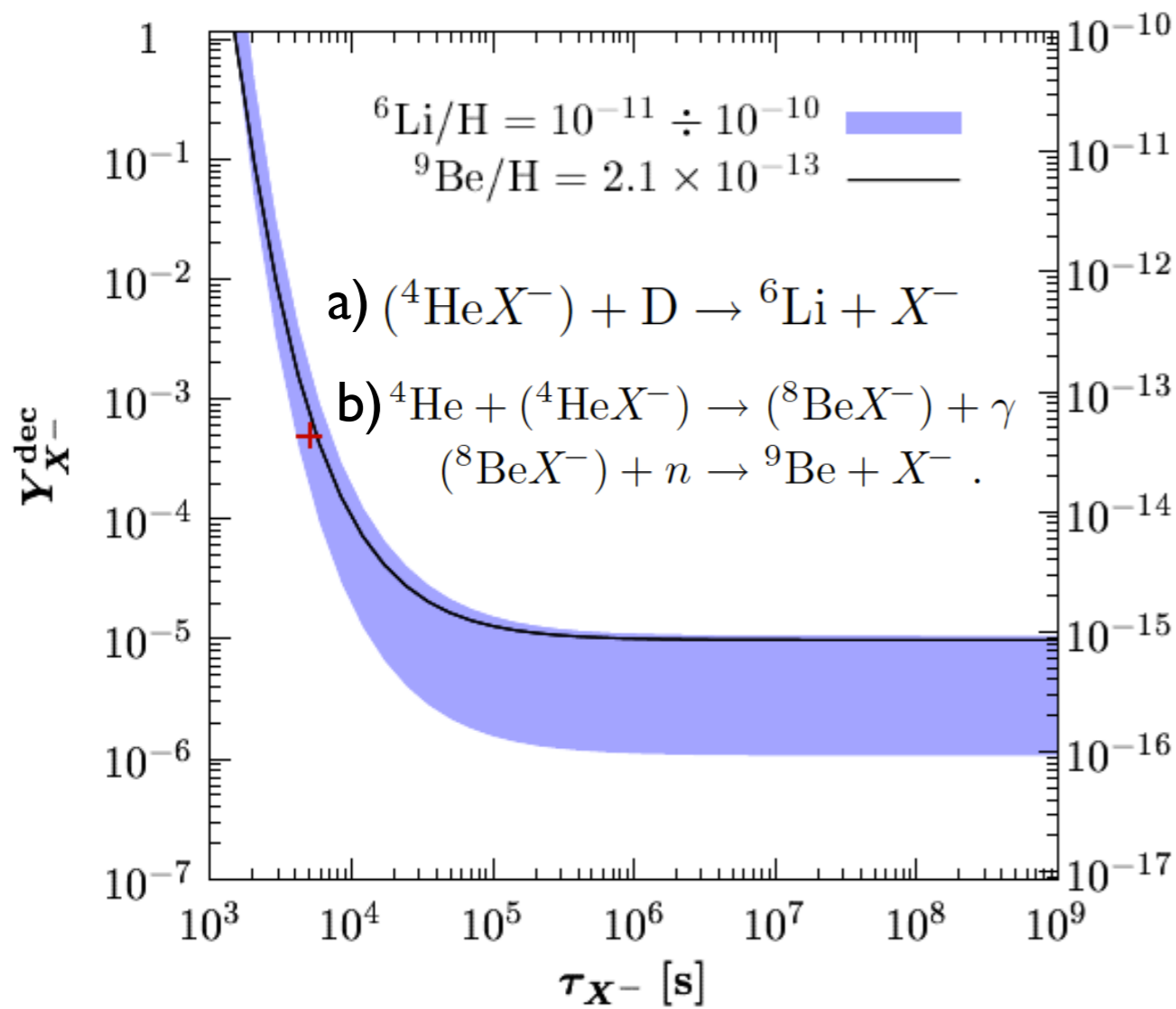
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calculate: $\sigma_{DY} = \sigma_{DY}(m_{\tilde{\tau}_1}, \Theta_{\tilde{\tau}}) \longrightarrow R$

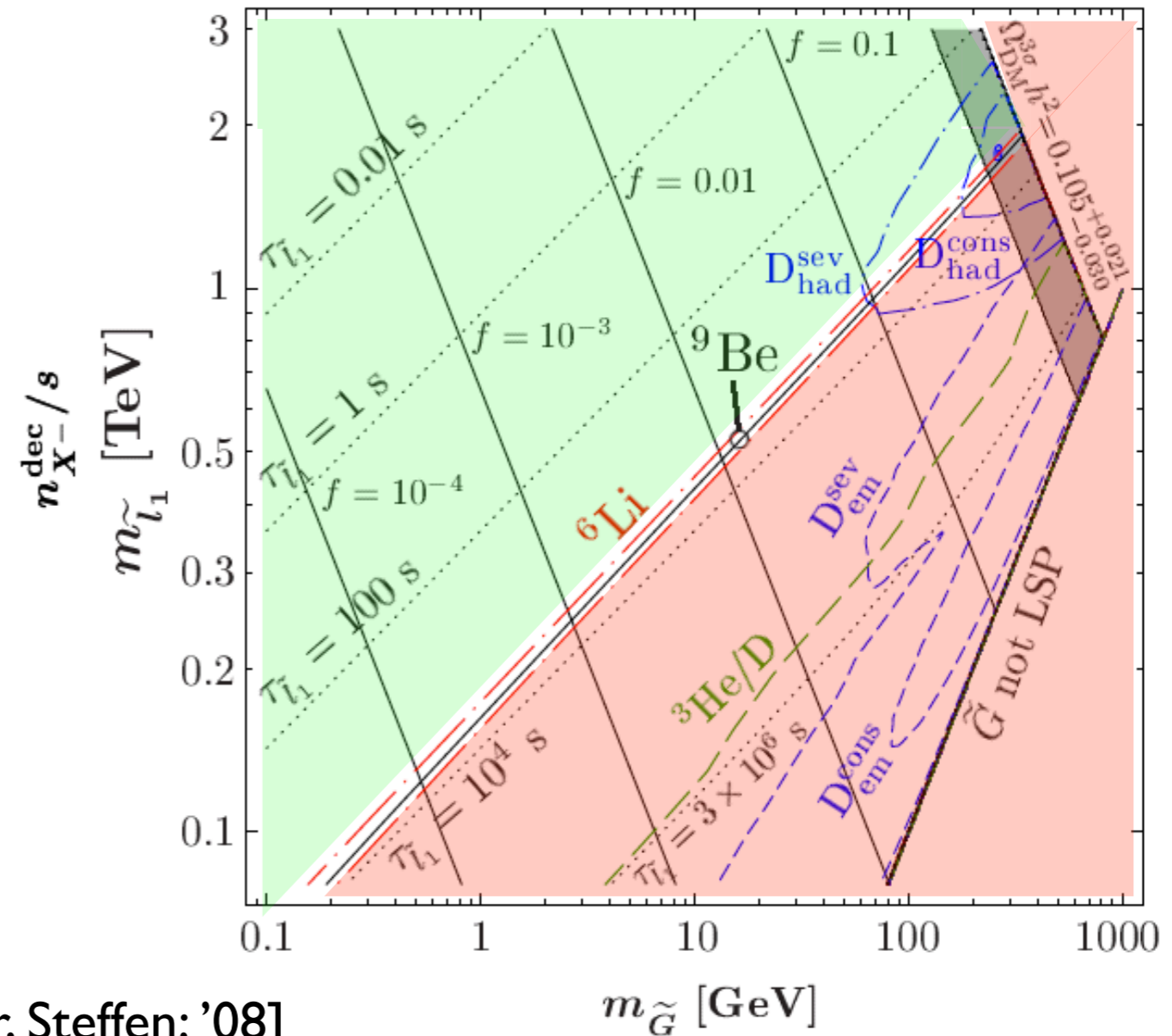
Conclusions

- jets + missingET is not the only channel for SUSY at the LHC.
- $b\bar{b}$ & gg **initial states can enhance direct stau production cross section significantly.**
- ... especially in regions motivated by cosmology.
- ... or motivated by latest Higgs results. [Talk by S. Gori]
- Good prospects for discovery/exclusion in the near future.
- Interesting (unusual) collider phenomenology with long-lived new particles.
- Possibility to test early universe cosmology in the laboratory.

Constraints from BBN



[Pospelov, Pradler, Steffen; '08]



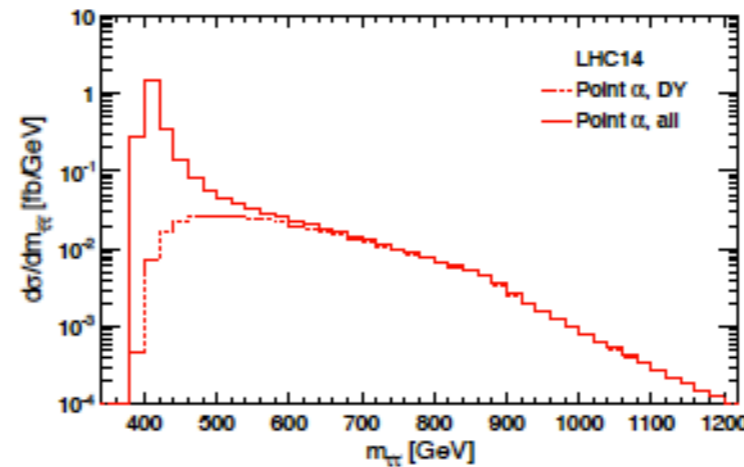
$$Y_{\tilde{\tau}_1} \simeq (0.4 - 2.0) \times 10^{-13} \left(\frac{m_{\tilde{\tau}_1}}{100 \text{ GeV}} \right)$$

$$\tau_{\tilde{\tau}_1} \simeq \Gamma^{-1}(\tilde{\tau}_1 \rightarrow \tilde{G}l) = \frac{48\pi m_{\tilde{G}}^2 M_{\text{P}}^2}{m_{\tilde{\tau}_1}^5} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2} \right)^{-4}$$

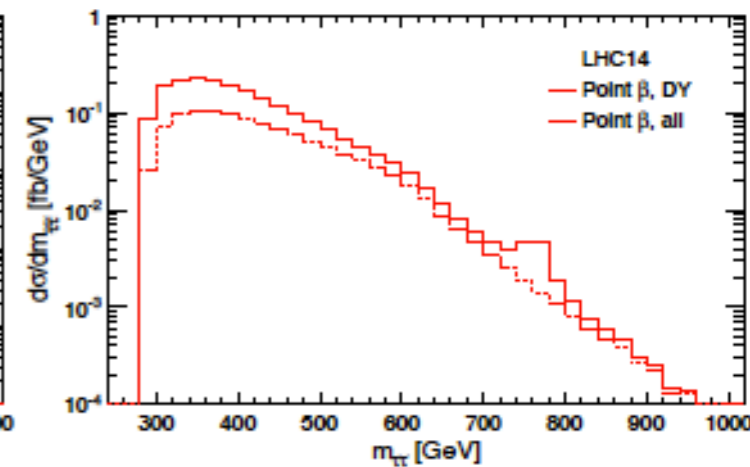
Parameter Determination

- Mass $m_{\tilde{\tau}_1}$ can be measured very accurately via ToF measurement.
- This can be used as a starting point to reconstruct other masses from decay chains: $m_{\tilde{q}}, m_{\tilde{\chi}_2^0}$.
- Additional approach: direct production.

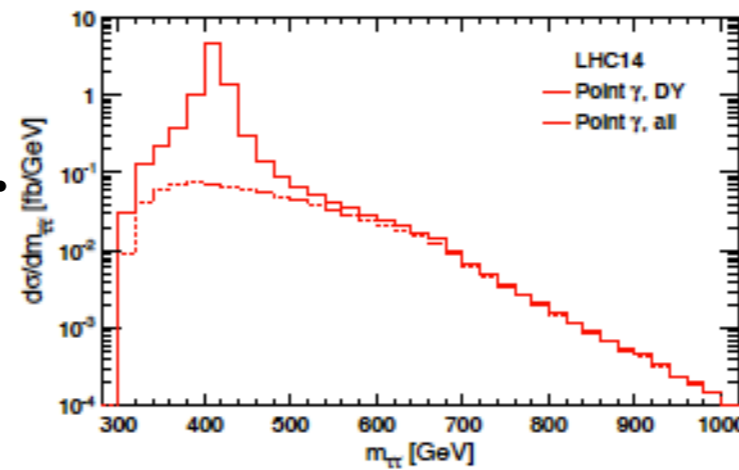
➡ Additional channel for MSSM-Higgs physics.



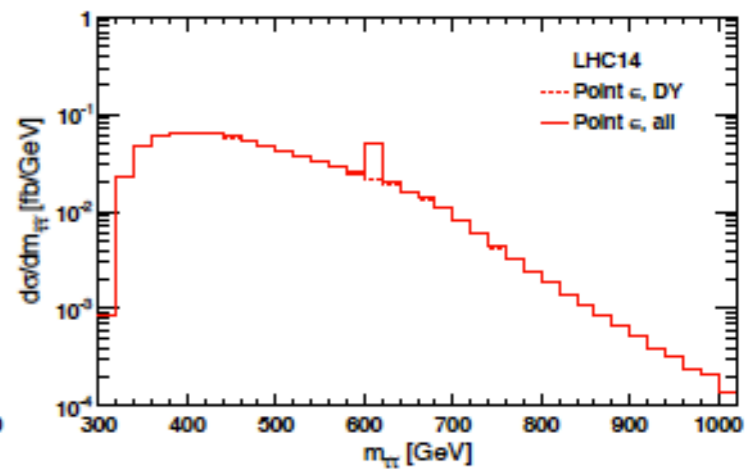
(a)



(b)



(c)



(d)

Benchmark Scenario		α	β	γ	ϵ
$m_{1/2}$	[GeV]	600	1050	600	440
m_0	[GeV]	800	30	600	20
$\tan \beta$		55	55	55	15
A_0	[GeV]	1600	60	1200	-250

Exceptionally small stau yields in the CMSSM

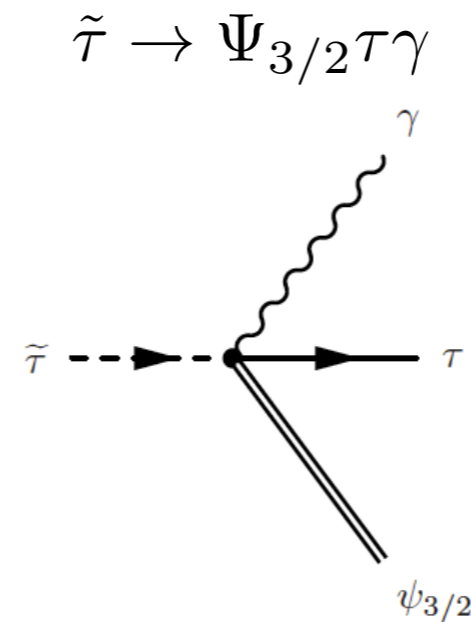
Benchmark point	α	β	γ
$m_{1/2}$ [GeV]	600	1050	600
m_0 [GeV]	800	30	600
$\tan \beta$	55	55	55
A_0 [GeV]	1600	60	1200
$m_{\tilde{\tau}_1}$ [GeV]	193	136	148
$\theta_{\tilde{\tau}}$	81°	73°	77°
m_{H^0} [GeV]	402	763	413
Γ_{H^0} [GeV]	15	26	16
$m_{\tilde{g}}$ [GeV]	1397	2276	1385
avg. $m_{\tilde{q}}$ [GeV]	1370	1943	1287
μ [GeV]	667	1166	648
A_τ [GeV]	515	-143	351
$\text{BR}(b \rightarrow s\gamma)$ [10^{-4}]	3.08	3.03	2.94
$\text{BR}(B_s^0 \rightarrow \mu^+\mu^-)$ [10^{-8}]	1.65	1.04	2.44
a_μ [10^{-10}]	13.2	11.5	16.8
CCB [107]	✓	-	✓
$Y_{\tilde{\tau}_1}$ [10^{-15}]	3.5	2.5	37.7

Benchmark point	α	β	γ
LHC 7 TeV			
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{DY}}$ [fb]	3.2(2.3)	12.5 (7.3)	9.0 (5.6)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{b\bar{b}}$ [fb]	9.8 (5.1)	0.03 (0.02)	19.2 (16.5)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{gg}}$ [fb]	0.1 (0.1)	3.3 (2.4)	0.32 (0.25)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{all}}$ [fb]	13.1 (7.5)	15.8 (9.7)	28.5 (22.4)
$\sigma(\tilde{g}\tilde{g})$ [fb]	0.05	10^{-6}	0.06
$\sigma(\tilde{g}\tilde{q})$ [fb]	0.63	4×10^{-4}	0.99
$\sigma(\tilde{q}\tilde{q})$ [fb]	1.18	0.006	2.41
$\sigma(\tilde{\chi}\tilde{q})+\sigma(\tilde{\chi}\tilde{g})$ [fb]	0.481	0.007	0.72
$\sigma(\tilde{\chi}\tilde{\chi})$ [fb]	20.4	0.29	19.8
LHC 14 TeV			
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{DY}}$ [fb]	11.2 (5.64)	37.5 (15.9)	28.0 (12.4)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{b\bar{b}}$ [fb]	58.4 (27.0)	0.7 (0.2)	113.3 (87.1)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{gg}}$ [fb]	0.7 (0.4)	17.4 (11.1)	1.8 (1.3)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\text{all}}$ [fb]	70.3 (33.1)	55.6 (27.2)	143.1 (100.8)
$\sigma(\tilde{g}\tilde{g})$ [fb]	20.2	0.12	20.8
$\sigma(\tilde{g}\tilde{q})$ [fb]	104.4	2.46	133.2
$\sigma(\tilde{q}\tilde{q})$ [fb]	92.5	6.46	139.0
$\sigma(\tilde{\chi}\tilde{q})+\sigma(\tilde{\chi}\tilde{g})$ [fb]	16.9	1.08	22.4
$\sigma(\tilde{\chi}\tilde{\chi})$ [fb]	134.5	6.40	131.1

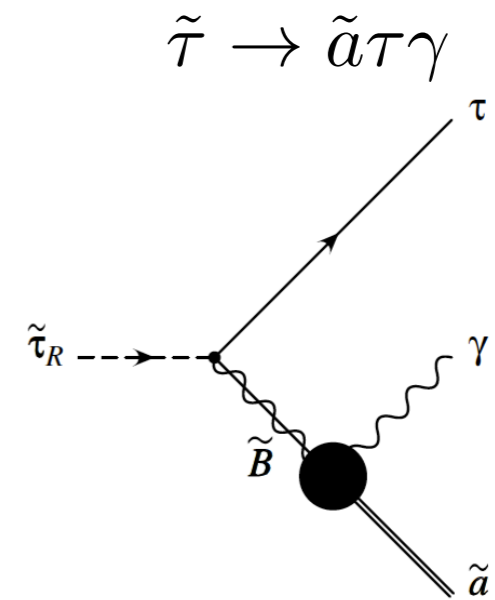
Stopping of long-lived staus

Observing stau decays:

Probing Supergravity and/or Pecci-Quinn mechanism at Colliders.



[Buchmüller, Hamaguchi, Ratz, Yanagida; '04]



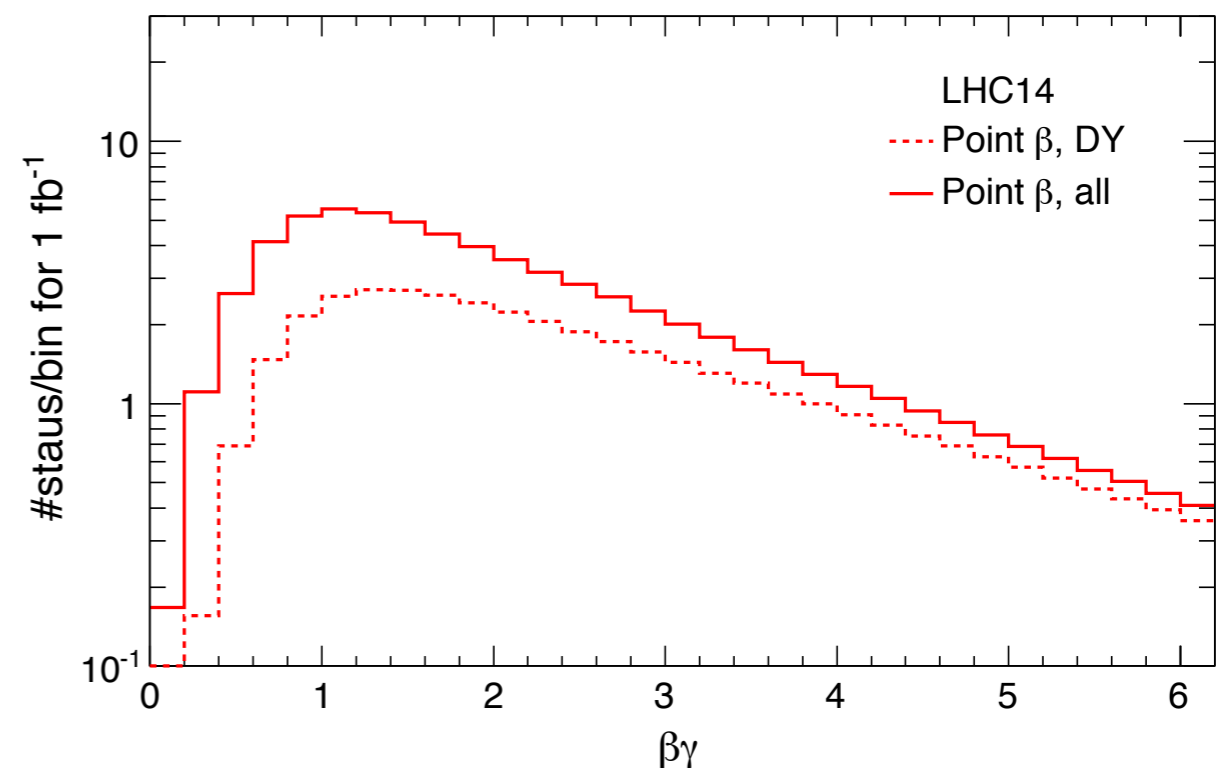
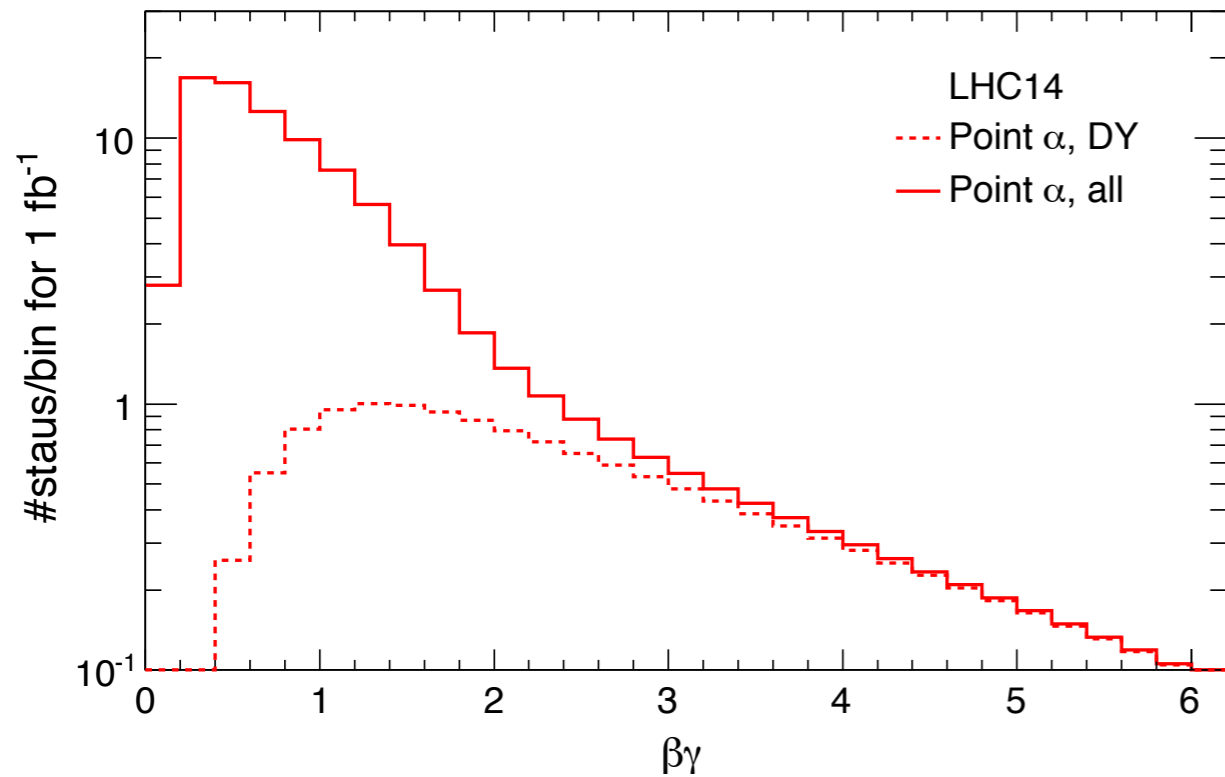
[Freitas, Steffen, Tajuddin, Wyler; '11]

From two body decay kinematics: mass $m_{\Psi_{3/2}} / m_{\tilde{a}}$
 & from decay width: couplings $\rightarrow M_{\text{Planck}} / f_a$

$$\Gamma_{\tilde{\tau}}^{2\text{-body}} = \frac{m_{\tilde{\tau}}^5}{48\pi m_{3/2}^2 M_{\text{P}}^2} \times \left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

From three body decay distributions: Spin $\rightarrow \Psi_{3/2} \leftrightarrow \tilde{a}$
 However, lots of stopped staus needed!

Stopping of long-lived staus



$\tilde{\tau}_1$ are stopped for: $\beta\gamma \lesssim 0.45$