Direct stau production at hadron colliders in cosmologically motivated scenarios

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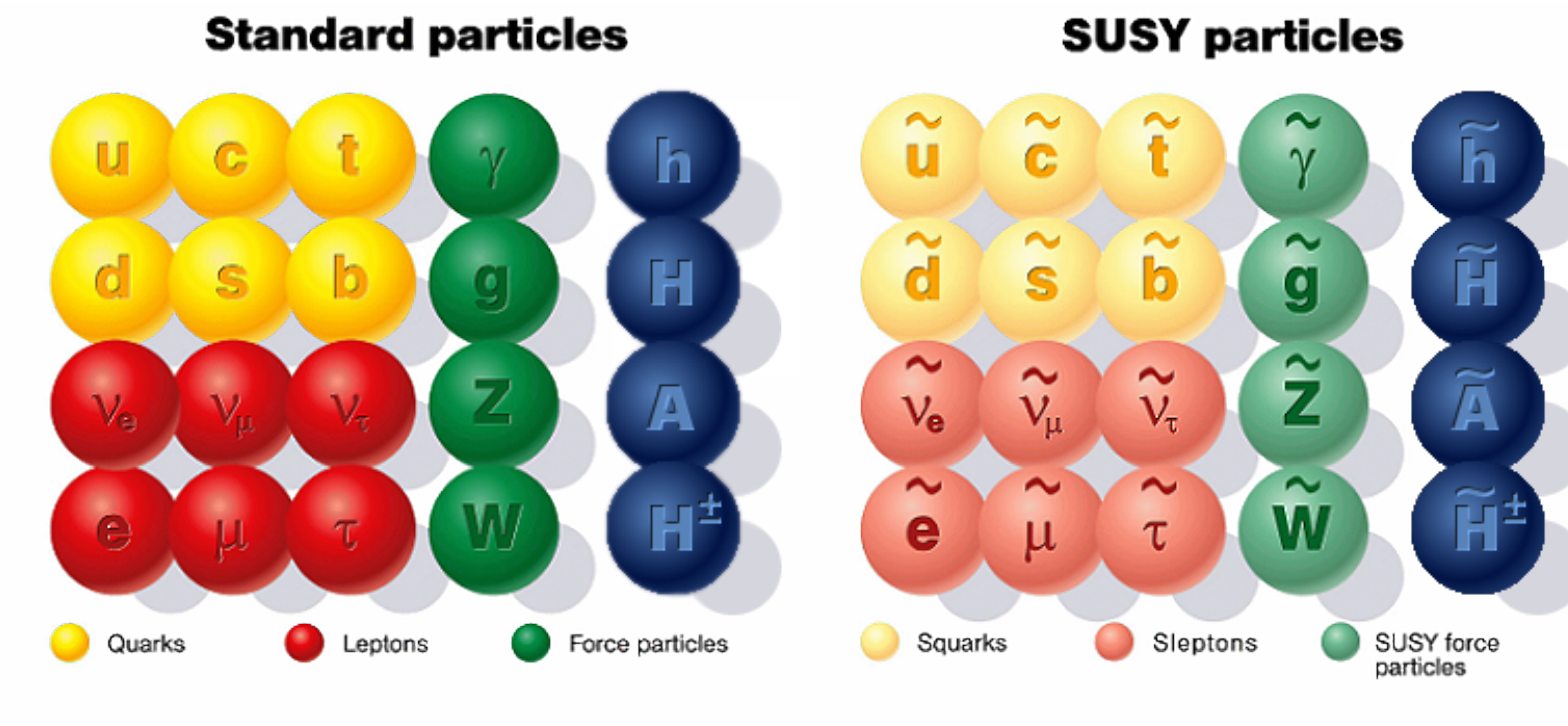
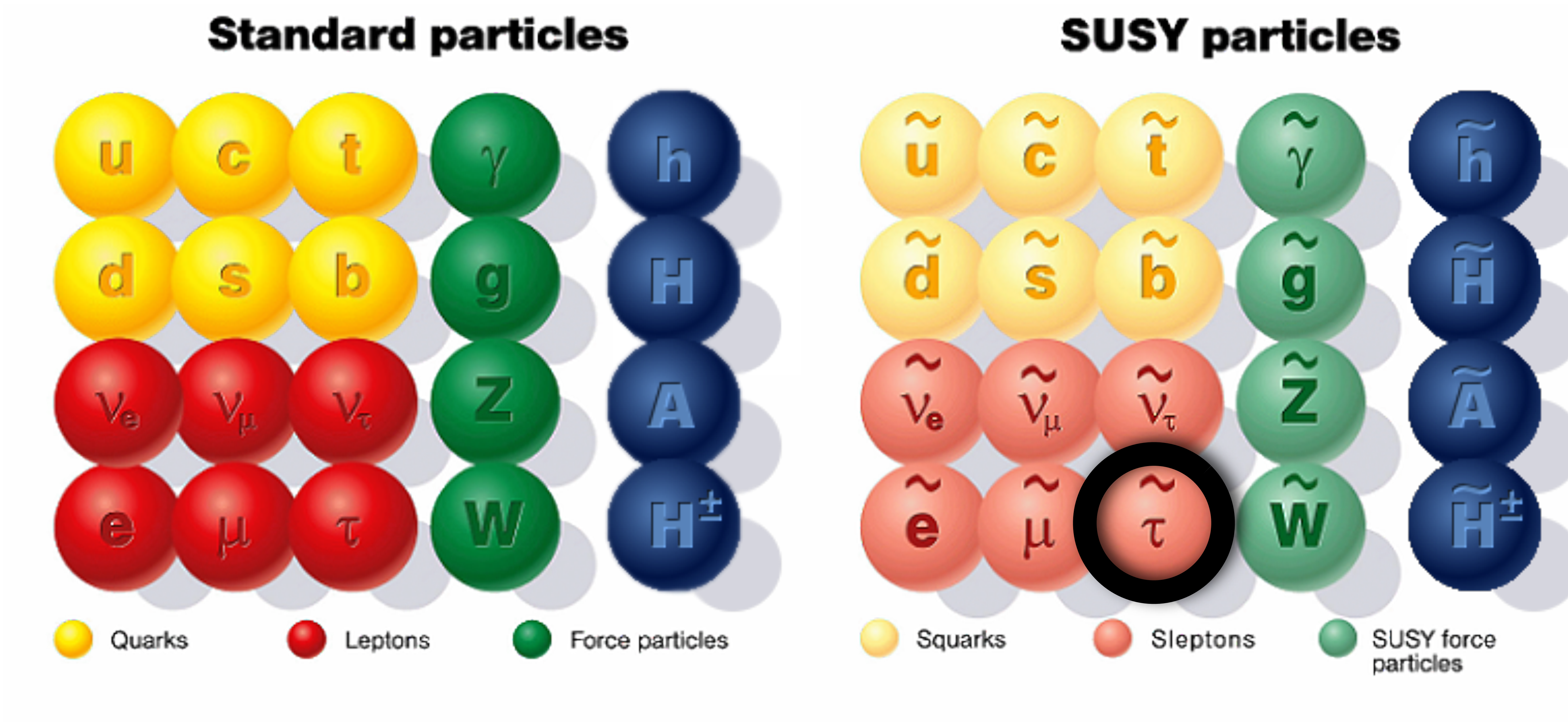
THE UNIVERSITY of WISCONSIN MADISON

1st School of ITN: Unification in the LHC Era
Corfu, September 2011

The MSSM


Standard particles
SUSY particles
u c t γ h
d s b g H
ν_e ν_μ ν_τ Z A
e μ τ W $H^\pm$
$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{\gamma}$ $\tilde{h}$
$\tilde{d}$ $\tilde{s}$ $\tilde{b}$ $\tilde{g}$ $\tilde{H}$
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$ $\tilde{Z}$ $\tilde{A}$
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{W}$ $\tilde{H}^\pm$
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

The MSSM



Standard particles
SUSY particles
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

Motivation

- Usual SUSY signature: missingET + jets (+ leptons) (assuming $\tilde{\chi}_1^0$ dark matter).
- But MSSM also offers other well motivated LOSPs, e.g. the lighter stau $\tilde{\tau}_1$ (Now **gravitino** and/or axino are assumed to be dark matter).
- Due to small couplings (suppressed by M_{Planck}/f_a) $\tilde{\tau}_1$ is long-lived.
- Signature: Charged Massive Particles (CHAMP), i.e. slow but high p^T.
- SM Background: Slow moving high p^T muons.
    - Charged : leaves tracks in the detector
    - Massive : moves slowly (small β), 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)

Connection with cosmological constraints

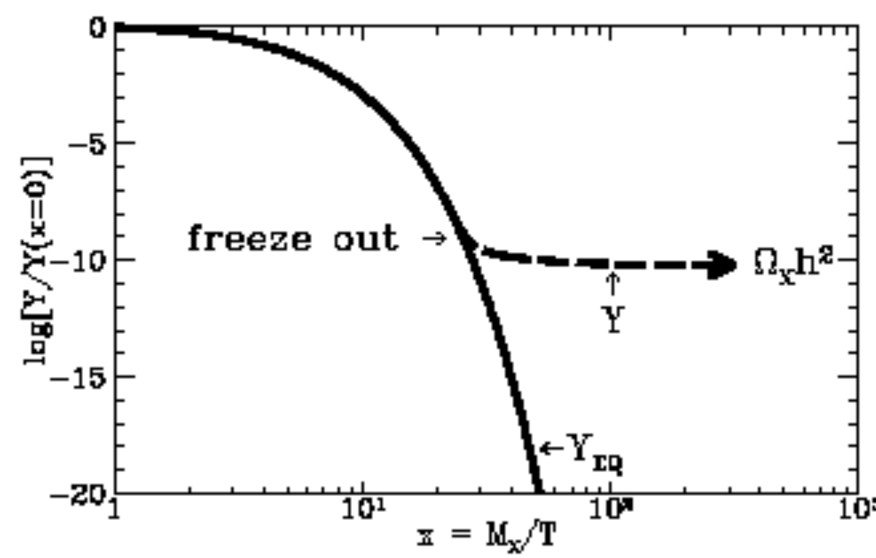
- Gravitino LSP can solve the gravitino problem of thermal leptogenesis.
  (= Decay products of gravitino $\Psi_{3/2}$ might spoil BBN)

- Cosmological implications depend on $m_{\tilde{\tau}_1}$,$\tau_{\tilde{\tau}_1}$ and $Y_{\tilde{\tau}_1} = n_{\tilde{\tau}_1}/s$

$$\frac{dY_{\tilde{\tau}}}{dt} = -s\langle\sigma v\rangle\left[Y_{\tilde{\tau}}^2 - (Y_{\tilde{\tau}}^{\rm eq})^2\right]$$

$$T \lesssim T_{\rm f} \rightarrow Y_{\tilde{\tau}} \approx Y_{\tilde{\tau}}^{\rm eq}(T_{\rm f})$$

"freeze out"



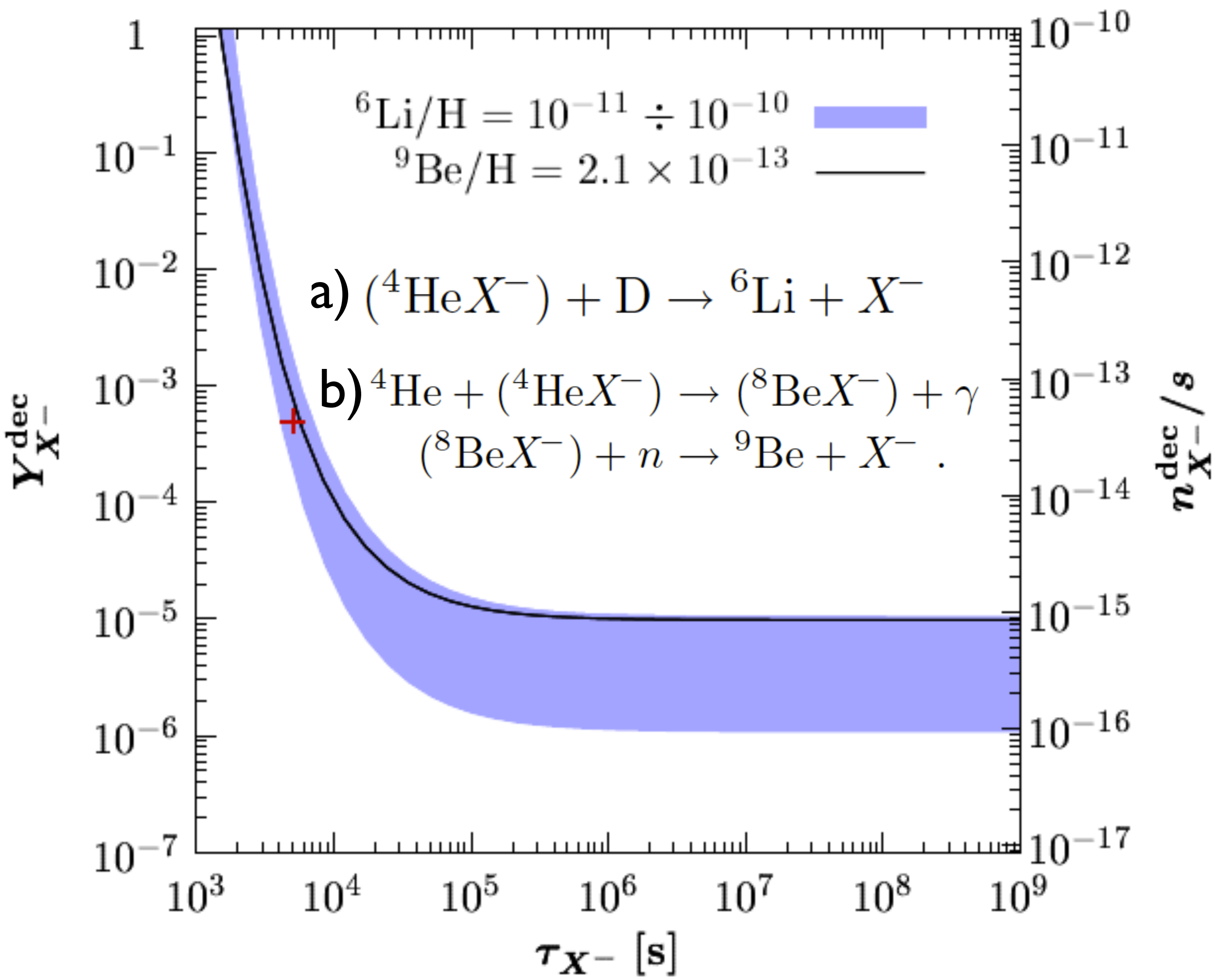
- Each $\tilde{\tau}_1$ decays into LSP and thus contributes to Ω_{DM}

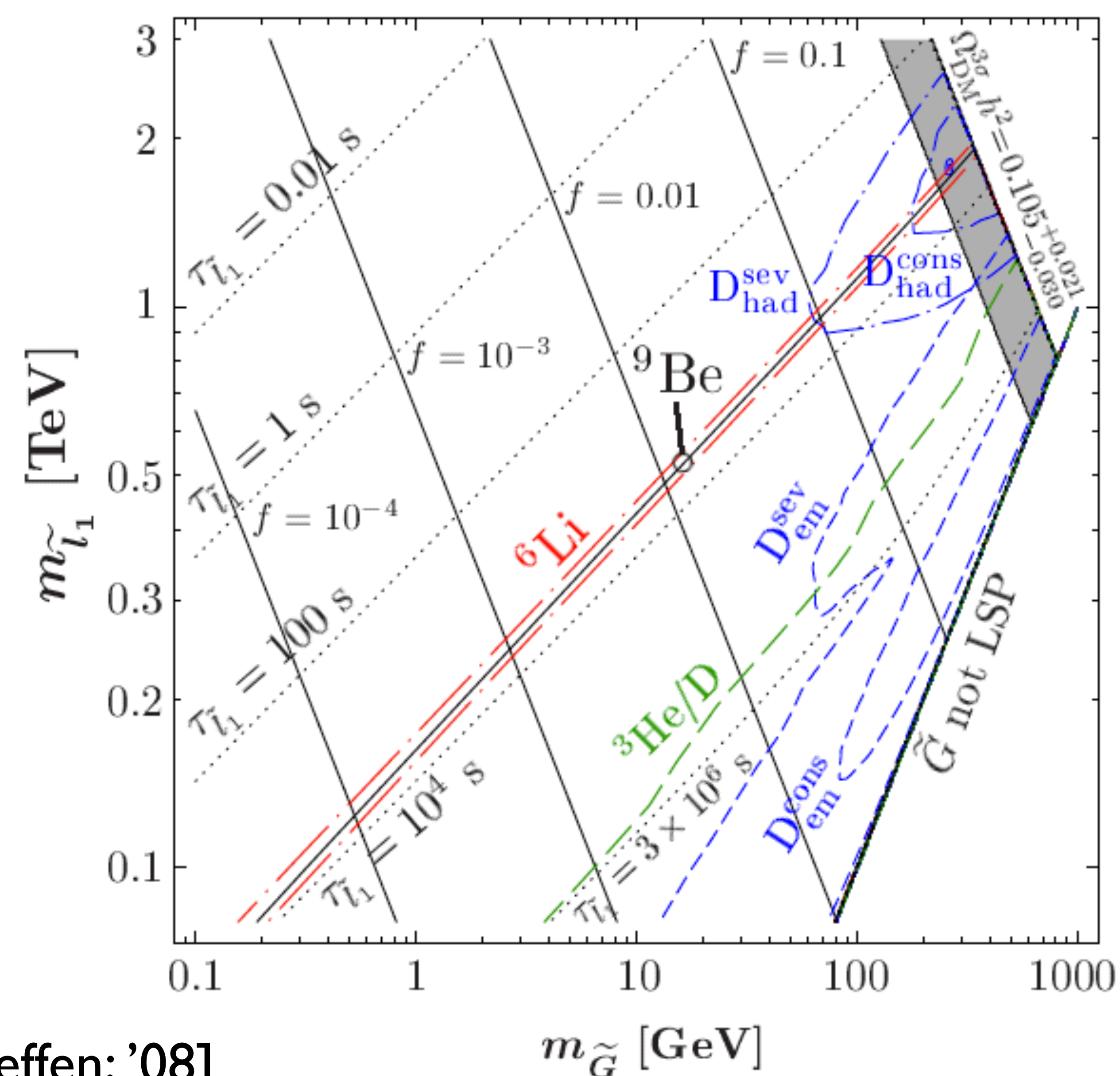
- Late decays & possible bound states of $\tilde{\tau}_1$ might again spoil BBN. → Upper limit on $\tau_{\tilde{\tau}_1}$ (and thus on $m_{\Psi_{3/2}}$) .

- Constraints depend **crucially** on $Y_{\tilde{\tau}_1}$.

[ned.ipac.caltech.edu]

Connection with cosmological constraints





[Pospelov, Pradler, Steffen; '08]

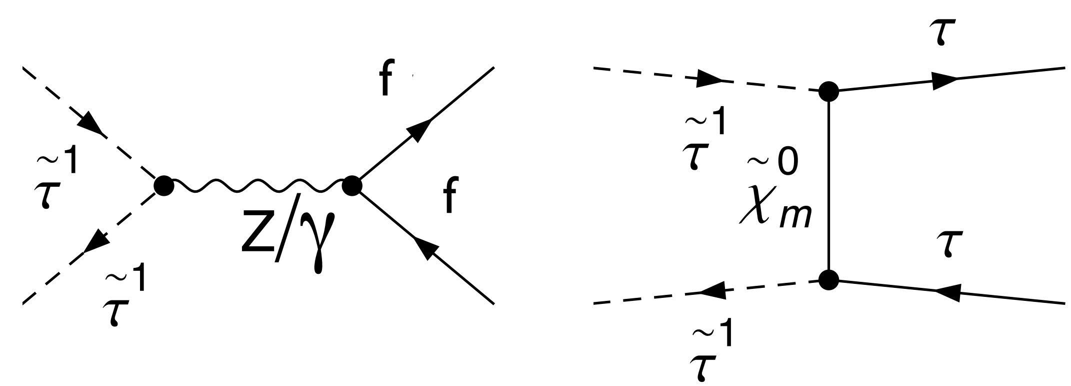
$$\tilde{\tau}_1 = \tilde{\tau}_R$$

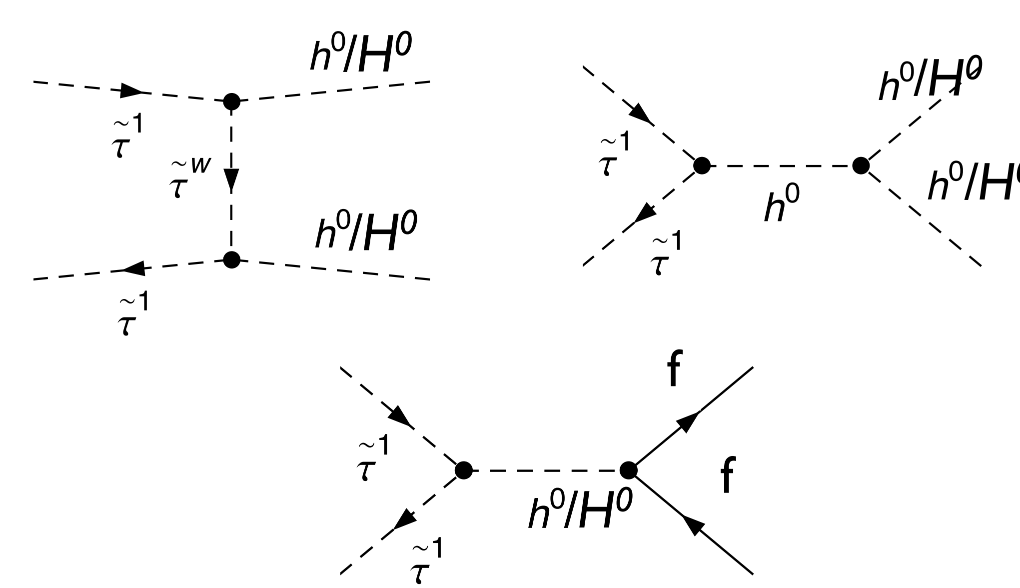
$$\rightarrow Y_{\tilde{\tau}_1} \simeq (0.4 - 2.0) \times 10^{-13} \left(\frac{m_{\tilde{\tau}_1}}{100\ \mathrm{GeV}}\right)$$

$$\tau_{\tilde{\tau}_1} \simeq \Gamma^{-1}(\tilde{\tau}_1 \to \tilde{G} l) = \frac{48\pi m^2_{\tilde{G}} M^2_{\mathrm{P}}}{m^5_{\tilde{\tau}_1}} \left(1 - \frac{m^2_{\tilde{G}}}{m^2_{\tilde{\tau}_1}}\right)^{-4}$$

Thermal relic abundance of long-lived staus

- Assuming standard thermal history of the Universe, yield $Y_{\tilde{\tau}_1}$ can be calculated from Boltzmann equations.
- E.g. for $\tilde{\tau}_1 = \tilde{\tau}_R$: $$Y_{\tilde{\tau}_1} \simeq (0.4 - 2.0) \times 10^{-13} \left(\frac{m_{\tilde{\tau}_1}}{100 \text{ GeV}}\right)$$
- For the CMSSM this implies: $$m_{1/2} \geq 0.9 \text{ TeV} \left(\frac{m_{\widetilde{G}}}{10 \text{ GeV}}\right)^{2/5} ,$$ $$T_{\rm R} \leq 4.9 \times 10^7 \text{ GeV} \left(\frac{m_{\widetilde{G}}}{10 \text{ GeV}}\right)^{1/5}$$
- However, $Y_{\tilde{\tau}_1}$ can also be much smaller, due to **efficient annihilation processes**: $Y_{\tilde{\tau}_1} \lesssim 2 \times 10^{-15}$
- Now, standard thermal leptogenesis with $T_{\rm R} \gtrsim 10^9$ GeV might be viable.
- Need: a) large stau-stau-Higgs coupling or b) $2m_{\tilde{\tau}} \approx m_{H^0}$.





Stau sector in the MSSM

- Stau mass eigenstates

$$m^2_{\mathrm{LL}} = m^2_{\tilde{L}_3} + \left(-\frac{1}{2} + \sin^2\theta_W\right) M^2_{\mathrm{Z}} \cos 2\beta$$

$$m^2_{\mathrm{RR}} = m^2_{\tilde{E}_3} - \sin^2\theta_W M^2_{\mathrm{Z}} \cos 2\beta,$$

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

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

$$R_{\tilde{\tau}} = \begin{pmatrix} \cos\theta_{\tilde{\tau}} & \sin\theta_{\tilde{\tau}} \\ -\sin\theta_{\tilde{\tau}} & \cos\theta_{\tilde{\tau}} \end{pmatrix} \longrightarrow \quad \tilde{\tau}_1 = \cos\theta_{\tilde{\tau}}\tilde{\tau}_{\mathrm{L}} + \sin\theta_{\tilde{\tau}}\tilde{\tau}_{\mathrm{R}}$$

- Stau-stau-Higgs coupling:

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

$$\longrightarrow \quad C^{\mathrm{DL}}[\tilde{\tau}^*_1, \tilde{\tau}_1, h^0] \simeq \left(\frac{1}{2}c^2_{\theta_{\tilde{\tau}}} - s^2_{\mathrm{W}} c_{2\theta_{\tilde{\tau}}}\right) M^2_{\mathrm{Z}} c_{2\beta} - m^2_\tau - \frac{m_\tau}{2} X_\tau s_{2\theta_{\tilde{\tau}}}$$

(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]

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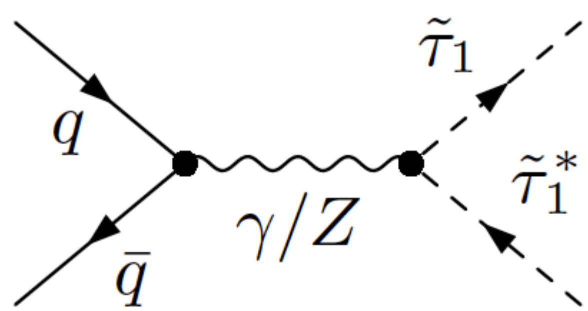
- However, can not become arbitrarily large: charge-breaking minima (CCB) !

[Hisano, Sugiyama; '10]

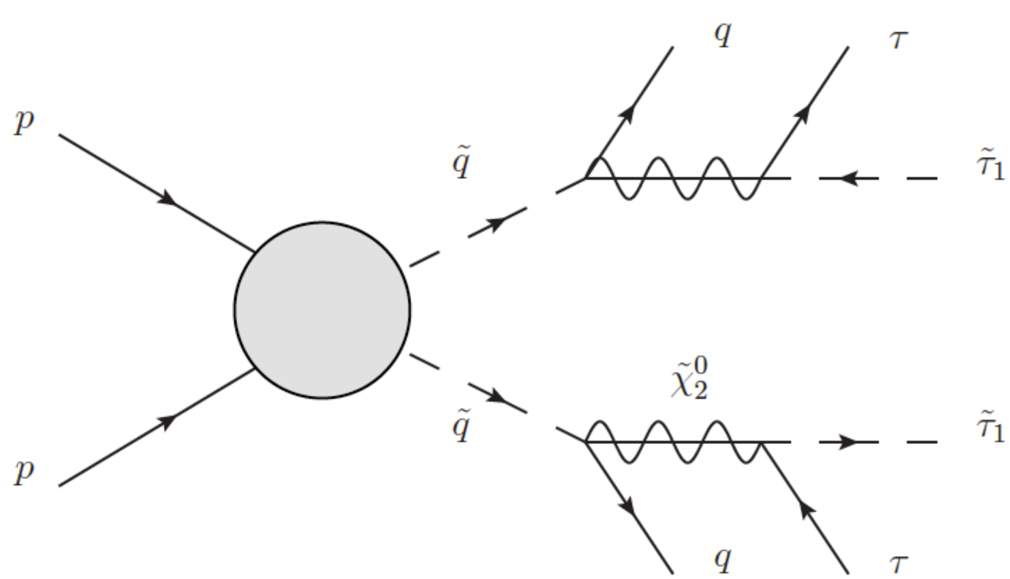
Production of staus at hadron colliders

- Direct production



Drell-Yan
(known @ NLO (S)QCD
[Benakker, Klasen, Krämer, Plehn, Spira; '99]
and @ NLL [Bozzi, Fuks, Klasen; '06])

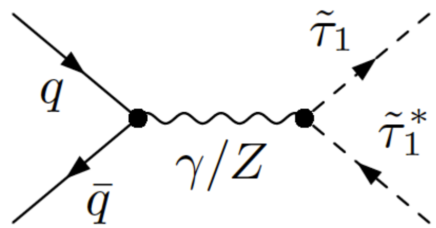
- Production in cascade decays



determined by
squark + gluino production
(& BRs)

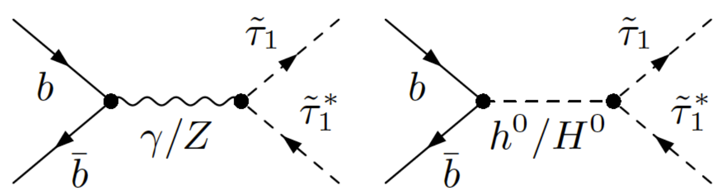
Direct Production of staus at hadron colliders

Drell-Yan



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

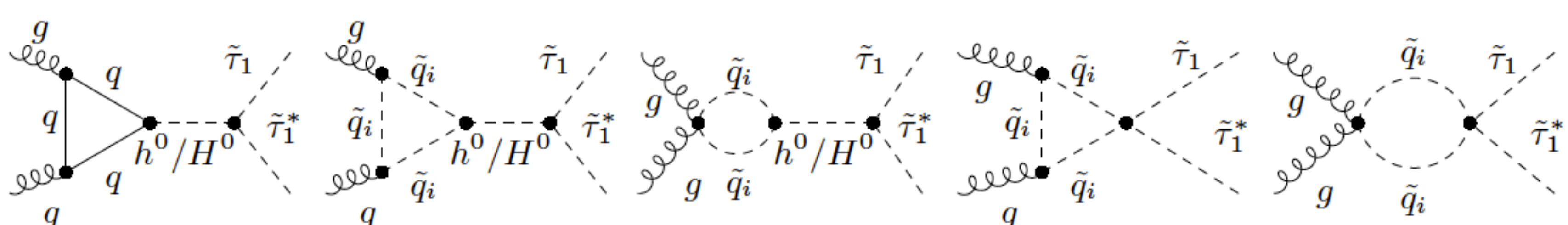
$b\bar{b}$



$O(\alpha^2)$ + 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: $\frac{1}{p^2 - m_{H^0}^2} \longrightarrow \frac{1}{p^2 - m_{H^0}^2 + i m_{H^0}\Gamma_{H^0}}$

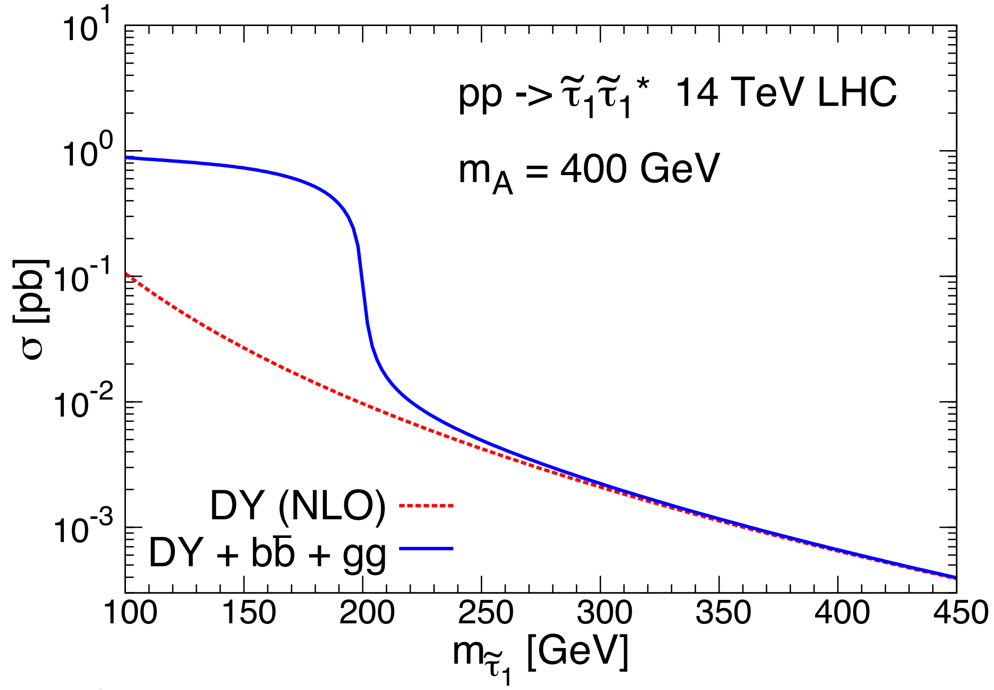
Technical detail: higher order corrections of bbh/H - vertex drive *down* cross sections (especially for large $\tan\beta$).

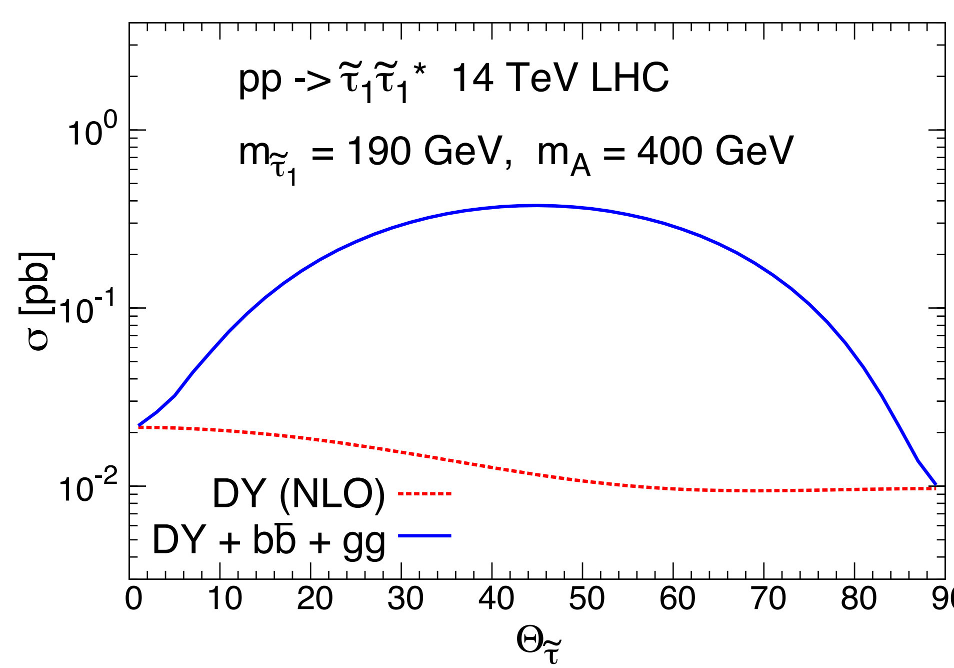
➔ Use resummed effective mass $m_b^{\rm eff}$ and effective couplings.

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

Numerical Results

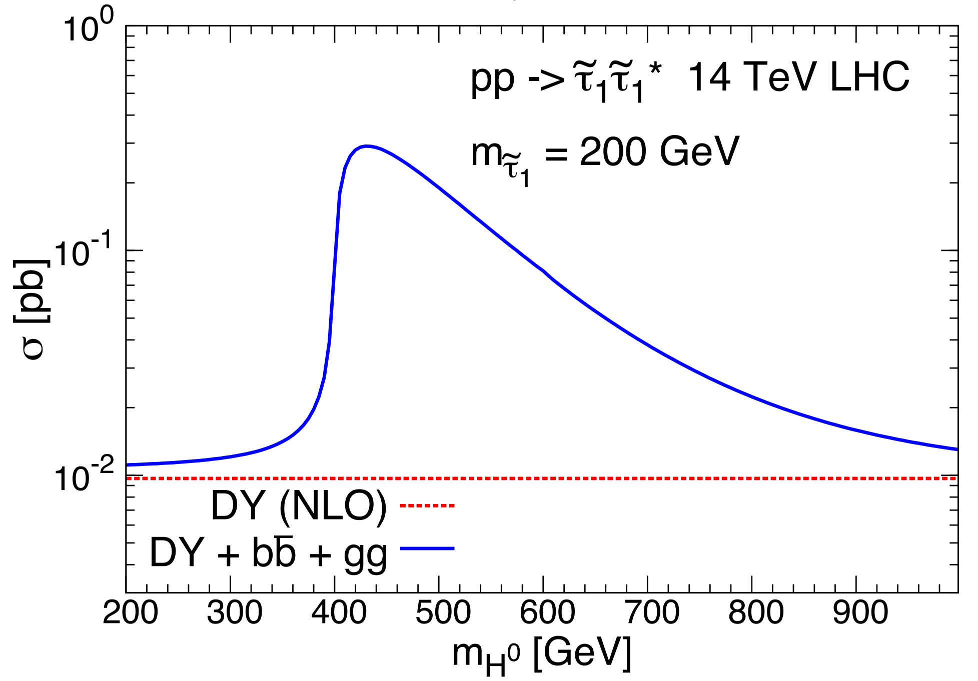
$m_{\tilde{\tau}_1}$

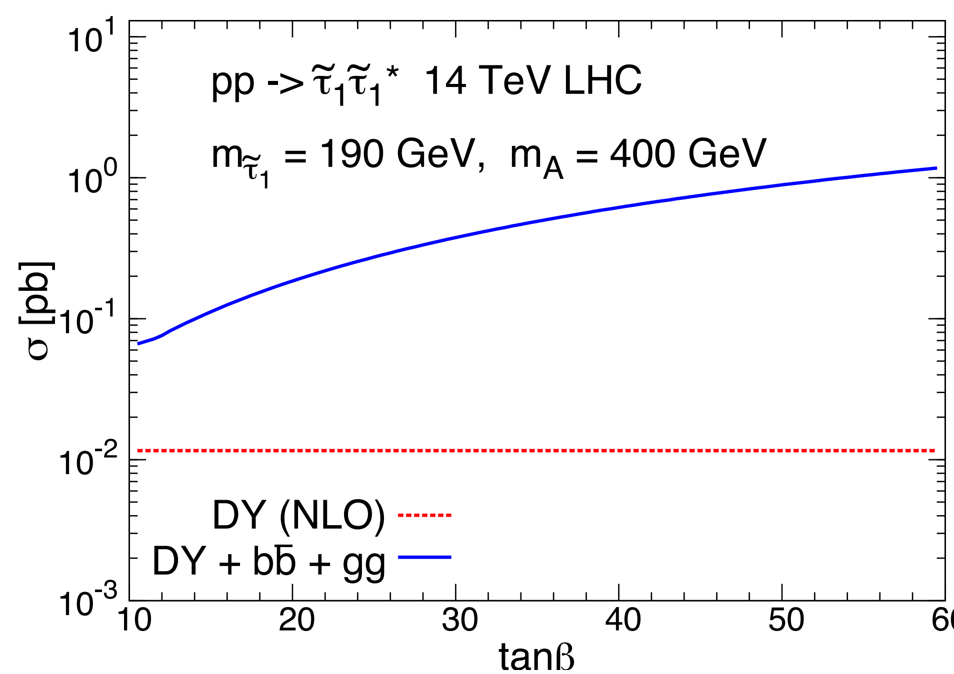




$\Theta_{\tilde{\tau}}$

m_{H^0}





$\tan\beta$

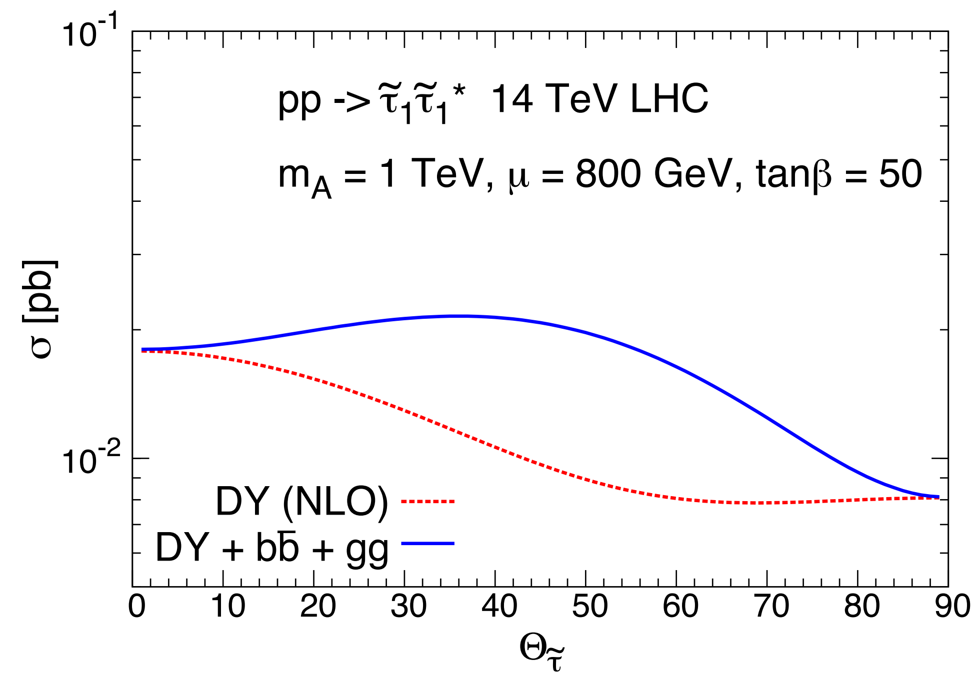
Other SUSY Parameters

$$\theta_{\tilde{\tau}} = 45^\circ, \qquad m_{\tilde{\tau}_1} = 200 \text{ GeV},$$
$$\tan\beta = 30, \qquad \mu = 500 \text{ GeV}, \qquad m_A = 400 \text{ GeV}.$$
$$M_1 = M_2 = M_3 = 1.2 \text{ TeV}, \qquad A_t = A_b = A_\tau = 600 \text{ GeV},$$
$$m_{\tilde{Q}_i} = m_{\tilde{U}_i} = m_{\tilde{D}_i} = 1 \text{ TeV}, \qquad m_{\tilde{L}_{1/2}} = m_{\tilde{E}_{1/2}} = 500 \text{ GeV},$$

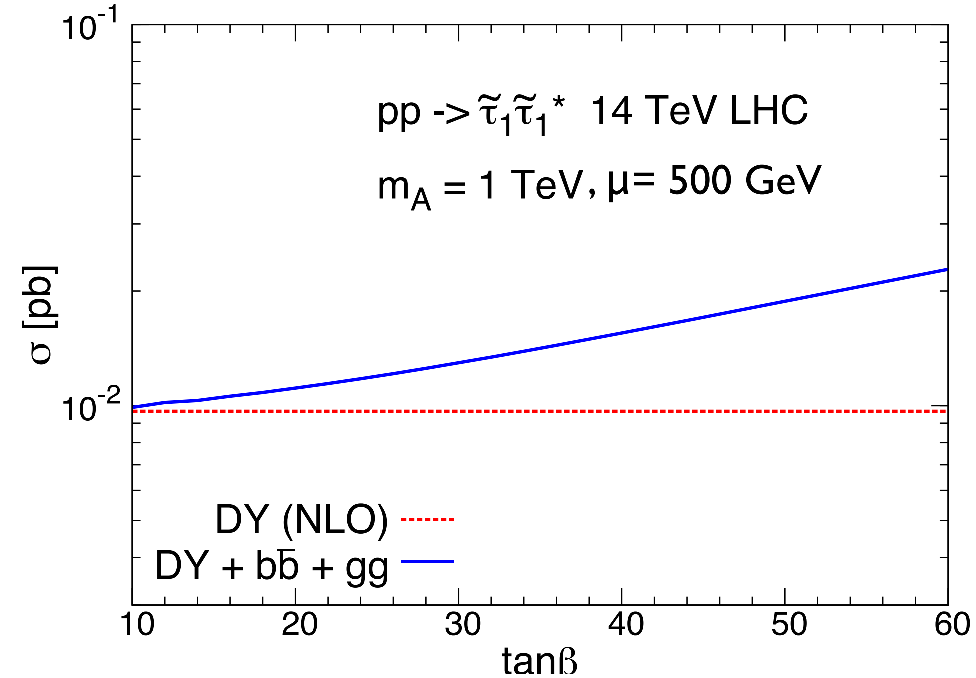
Numerical Results

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

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



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



$\tan\beta$

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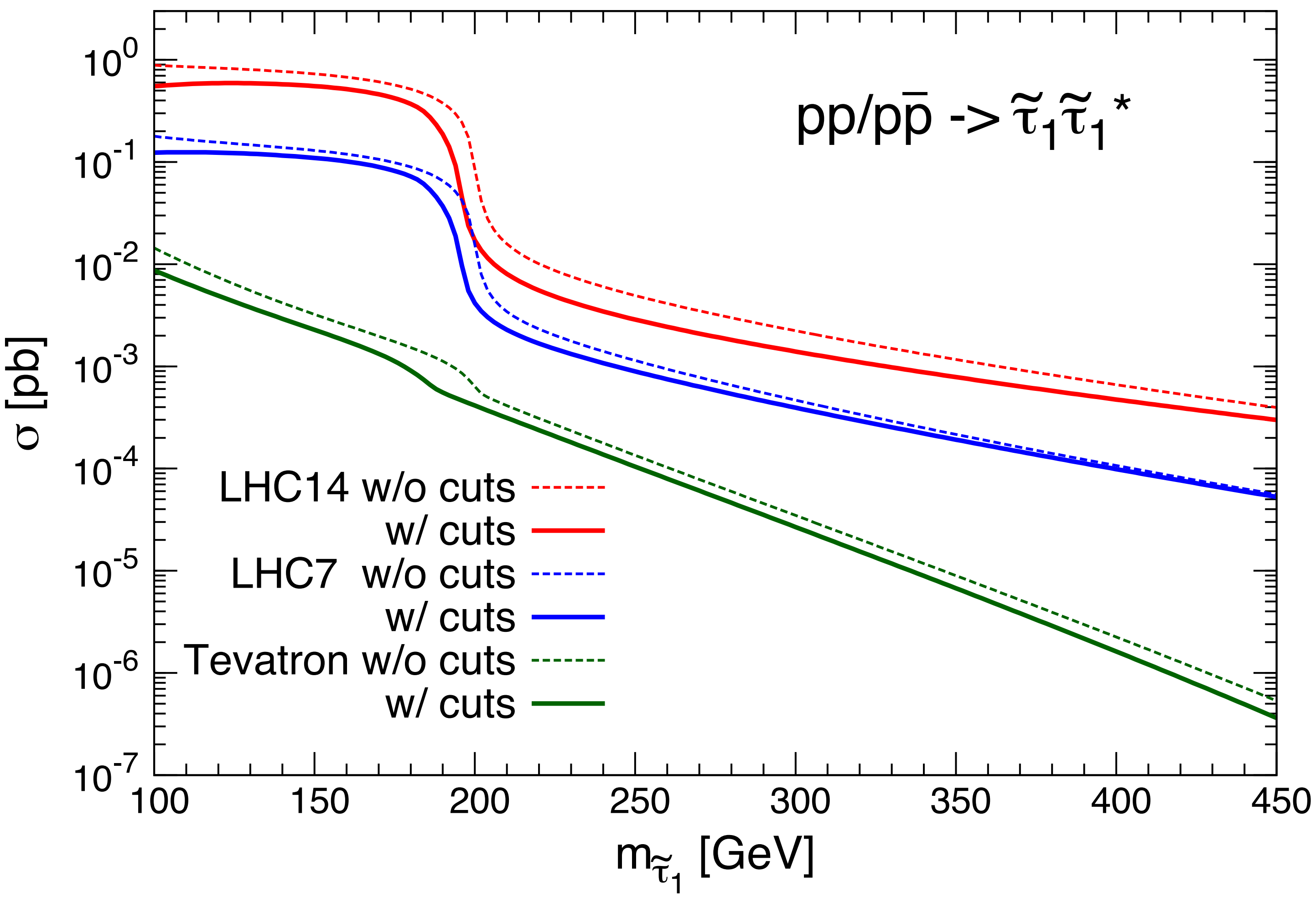
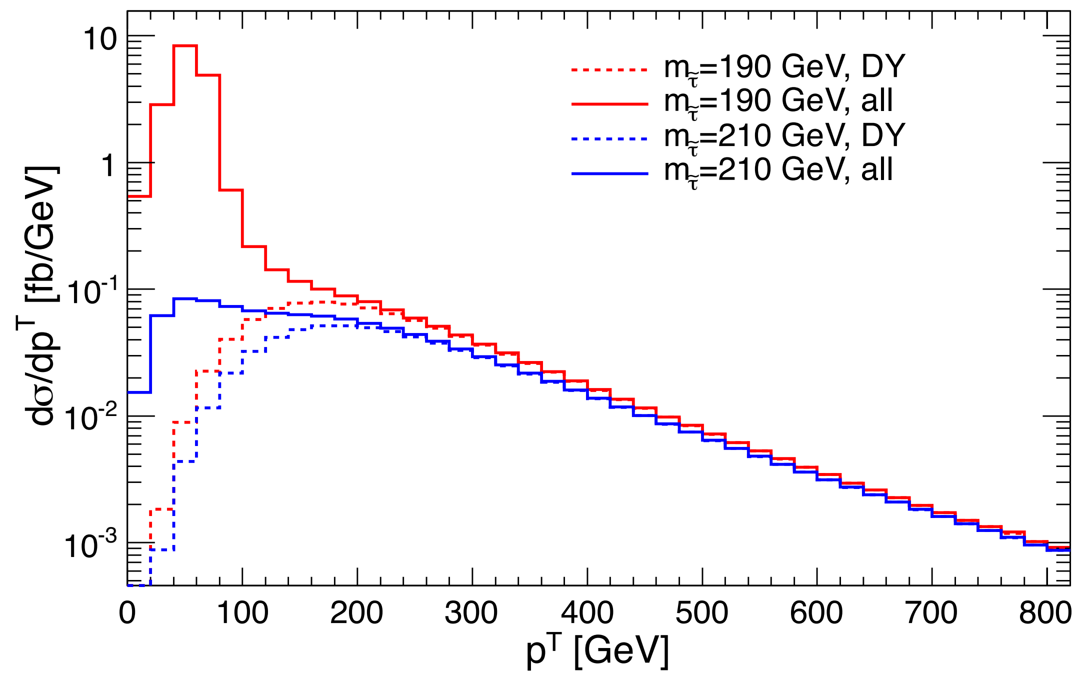
Realistic Numerical Results

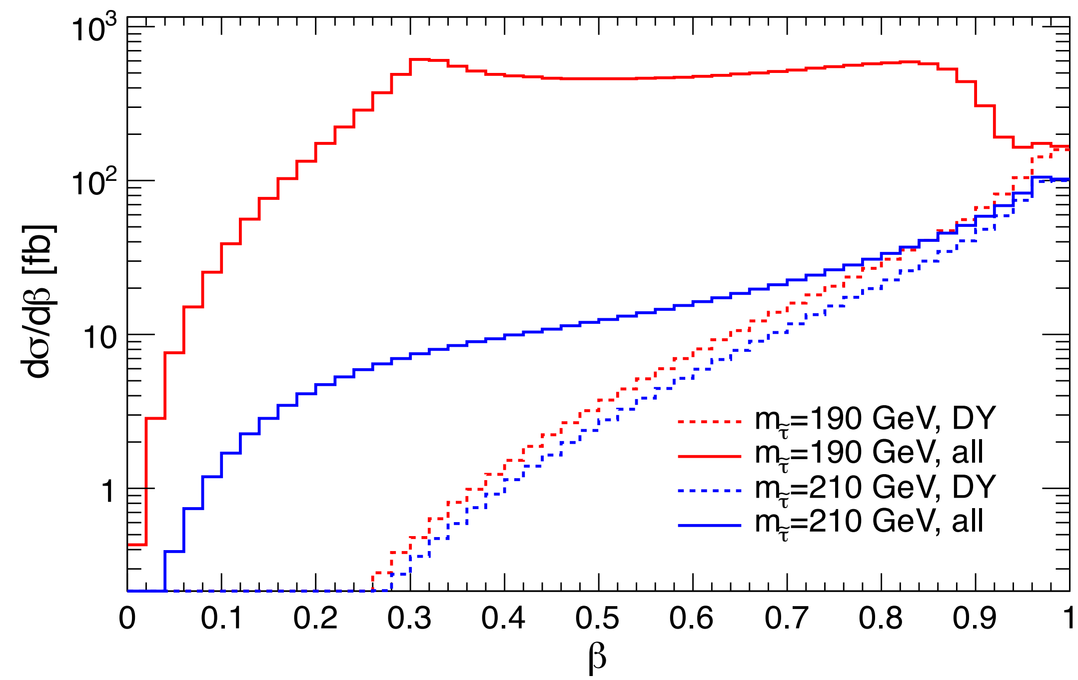
Kinematical Cuts: $|\eta| \leq 2.4$

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

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

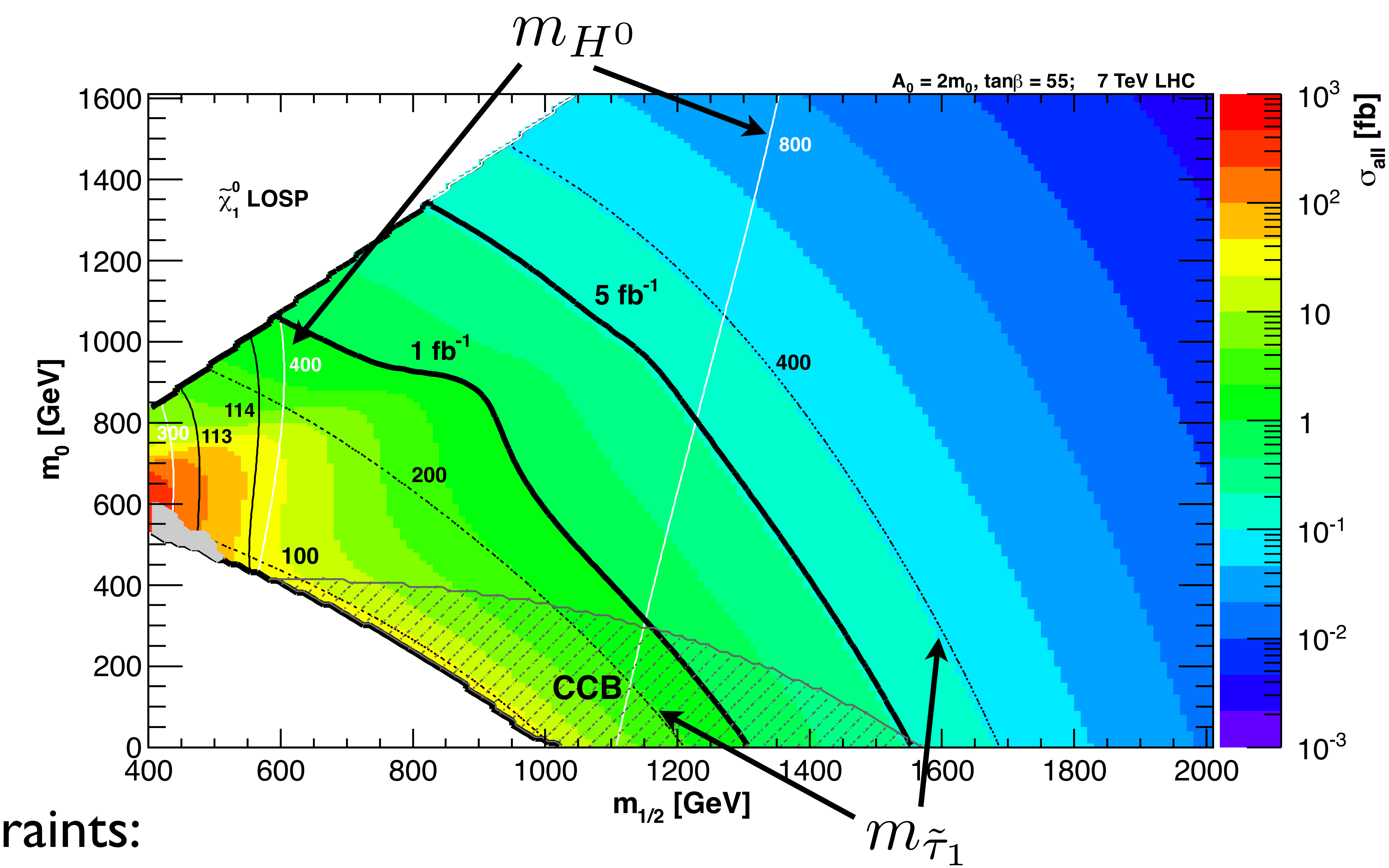






➡ slow staus might be stopped in detector

Stau production in the CMSSM



Constraints:

$m_{\tilde{\tau}_1} \gtrsim 82$ GeV $\quad \sigma(\sqrt{S} = 1.96 \text{ TeV}) \lesssim 10$ fb

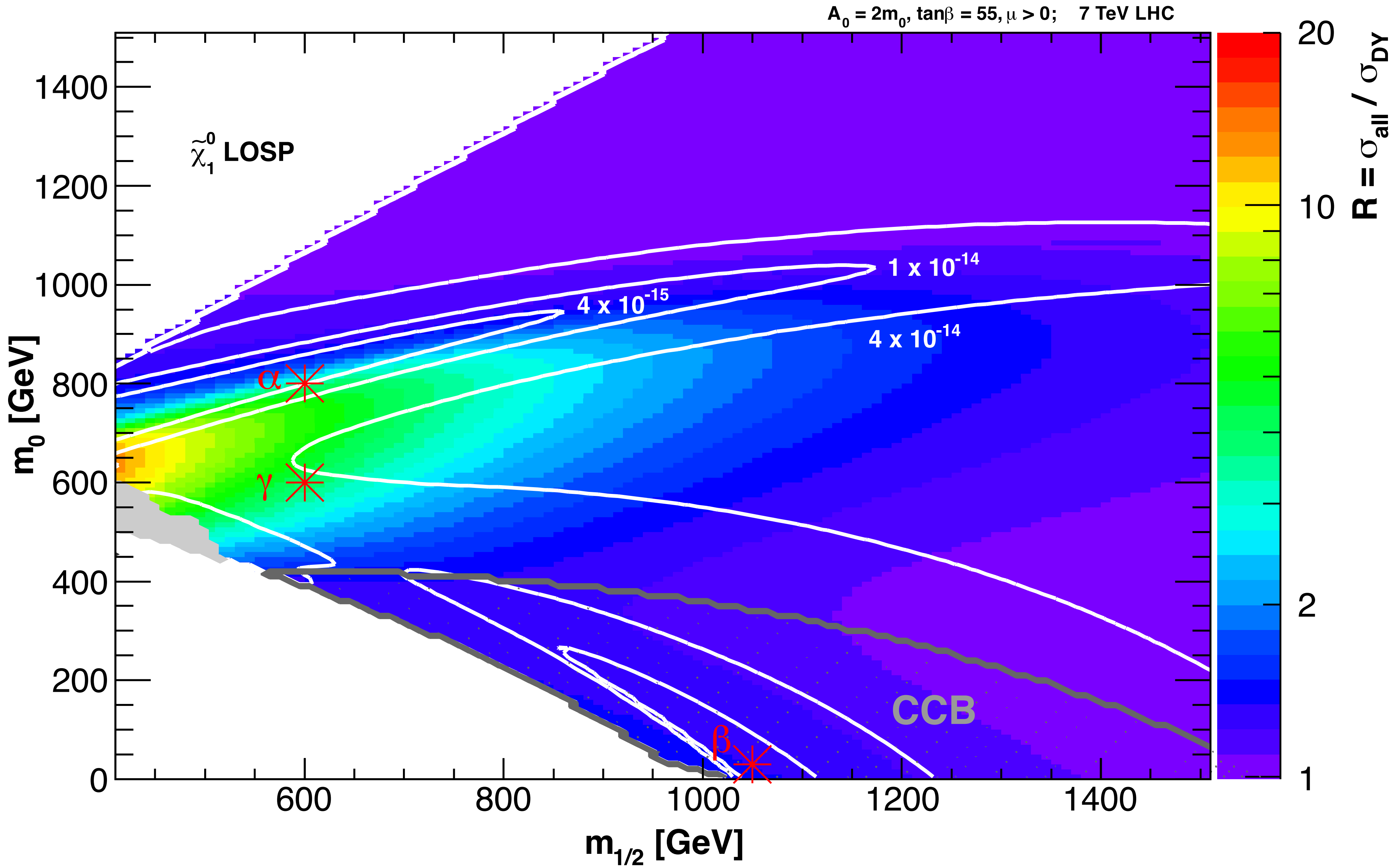
$\text{BR}(B_s \to \mu^+\mu^-) \quad \text{BR}(b \to s\gamma)$

CCB

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

LHC 7 TeV

Exceptionally small stau yields in the CMSSM



LHC 7 TeV $A_0 = 2m_0, \quad \tan\beta = 55$

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.
- Good prospects for discovery in the near future.
- Interesting (unusual) collider phenomenology with long-lived new particles.
- Possibility to test early universe cosmology in the laboratory

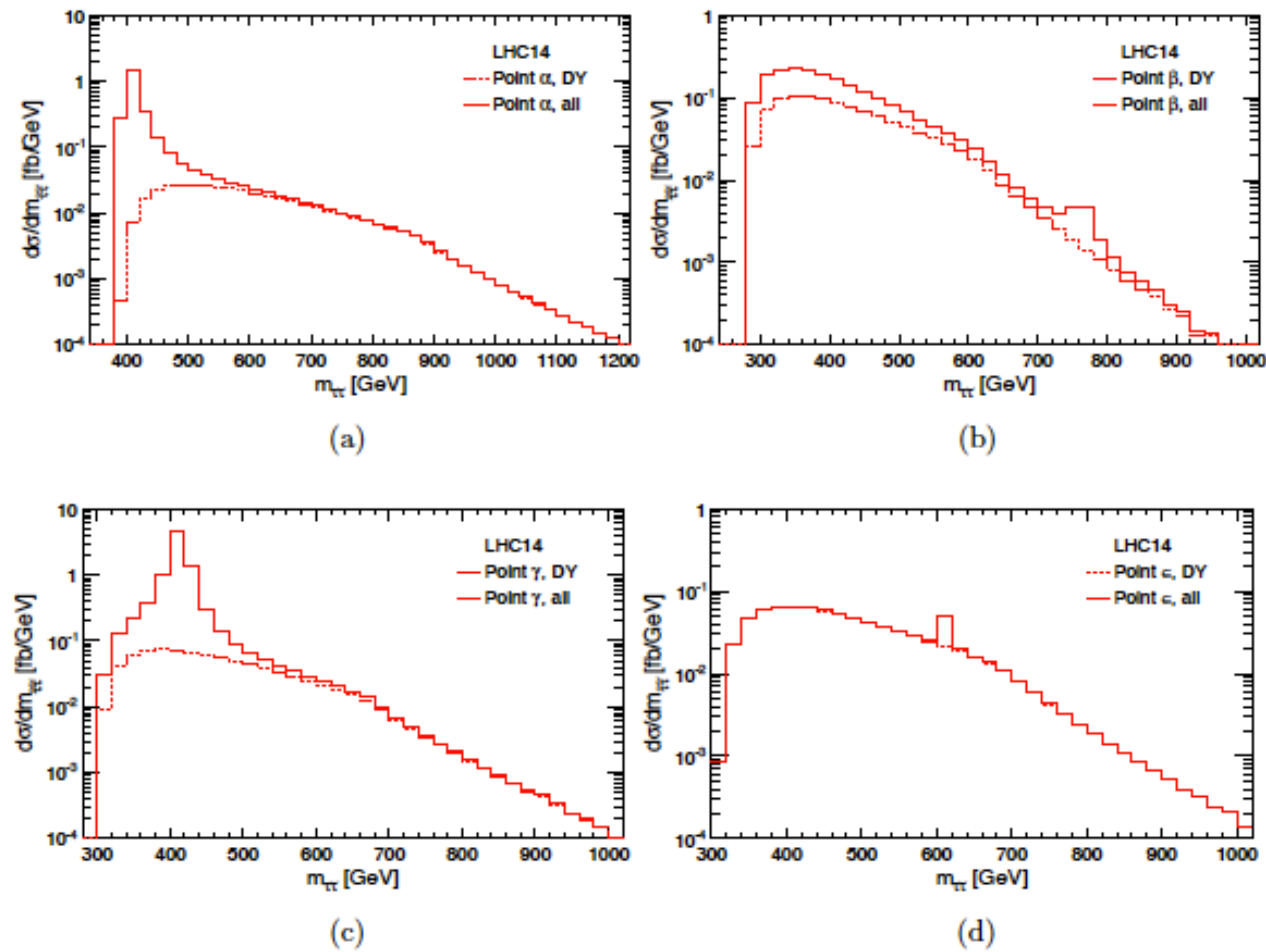
Exceptionally small stau yields in the CMSSM

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
$\mathrm{BR}(b \to s\gamma)$	$[10^{-4}]$	3.08	3.03	2.94
$\mathrm{BR}(B_s^0 \to \mu^+\mu^-)$	$[10^{-8}]$	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				
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{DY}}$	[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)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{gg}}$	[fb]	0.1 (0.1)	3.3 (2.4)	0.32 (0.25)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{all}}$	[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				
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{DY}}$	[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)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{gg}}$	[fb]	0.7 (0.4)	17.4 (11.1)	1.8 (1.3)
$\sigma(\tilde{\tau}_1\tilde{\tau}_1^*)_{\mathrm{all}}$	[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

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



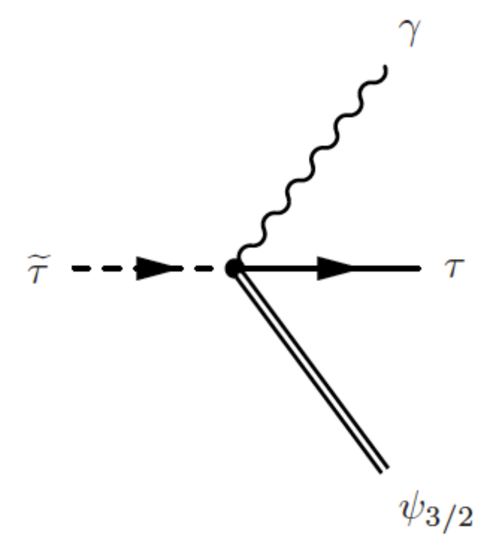
Benchmark Scenario		α	β	γ	ϵ
$m_{1/2}$	[GeV]	600	1050	600	440
m_0	[GeV]	800	30	600	20
$\tan\beta$		55	55	55	15
A_0	[GeV]	1600	60	1200	-250

Stopping of long-lived staus

Observing stau decays:

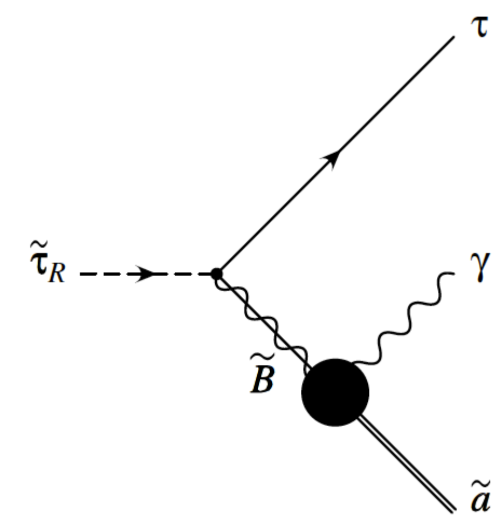
Probing Supergravity and/or Pecci-Quinn mechanism at Colliders.

$\tilde{\tau} \to \Psi_{3/2}\tau\gamma$



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

$\tilde{\tau} \to \tilde{a}\tau\gamma$



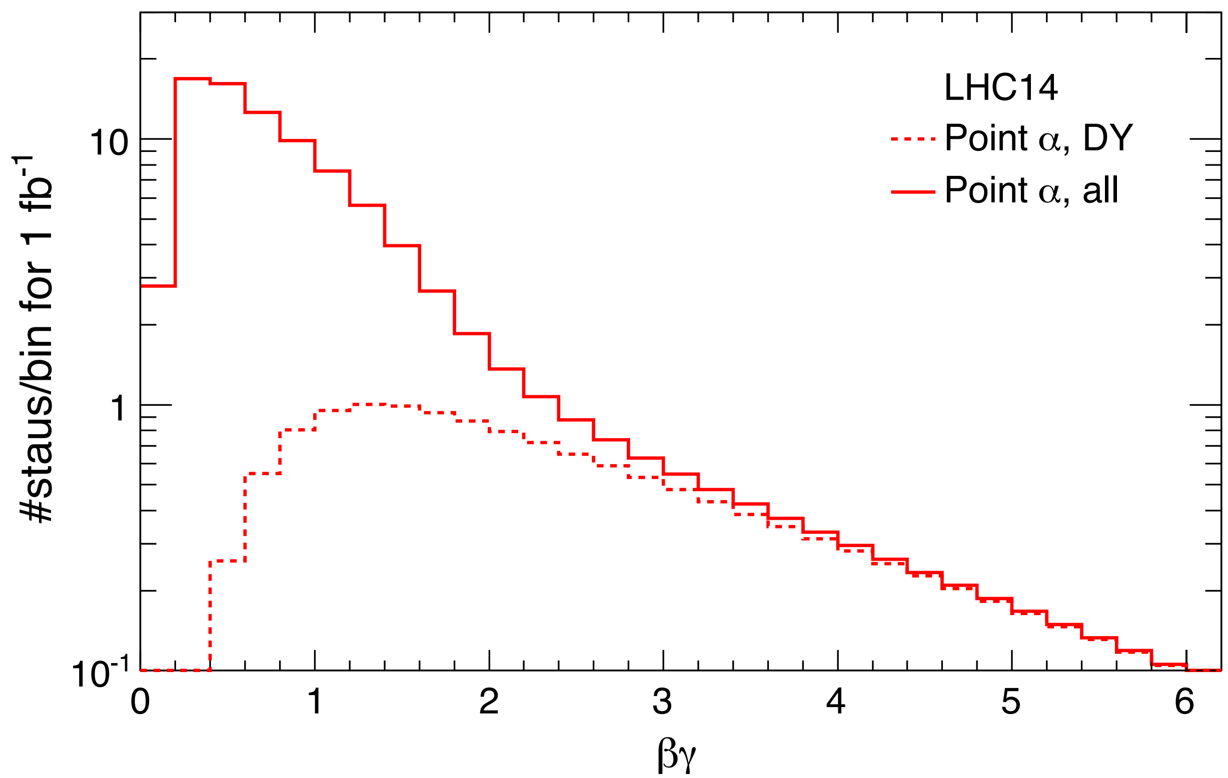
[Freitas, Steffen, Tajuddin, Wyler; '11]]

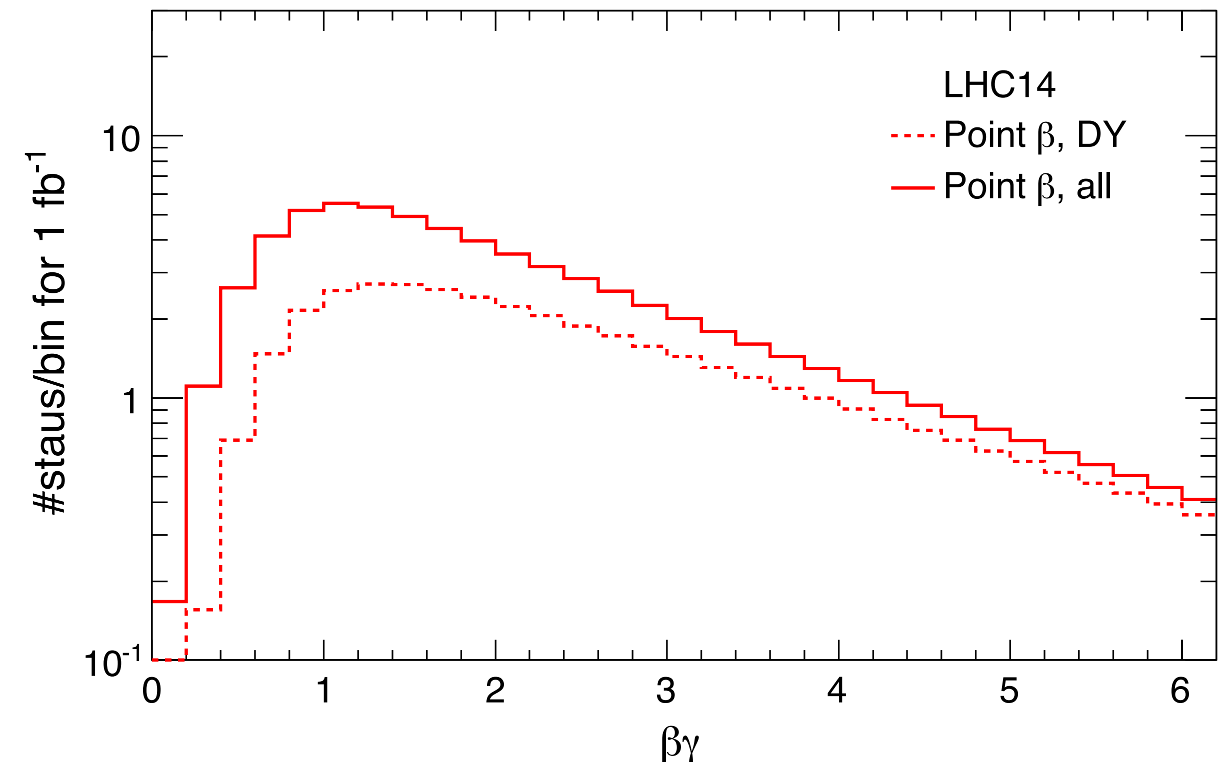
From two body decay kinematics: mass $m_{\Psi_{3/2}}$ / $m_{\tilde{a}}$
& from decay width: couplings → $M_{\rm Planck}/f_a$

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

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

Stopping of long-lived staus





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