Testing Single RPV Squark Production at the LHC

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work in progress, arXiv:151x.yyyyy

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Status of Natural (vanilla) SUSY

At the end of Run I,

- $m_{\tilde{g}} \gtrsim 1.4$ TeV
- $m_{\tilde{q}_{1,2}} \gtrsim 1 - 1.3$ TeV
- $m_{\tilde{t}} \gtrsim 700 - 800$ GeV

- $m_H = 125$ GeV $\overset{?}{\to} \tilde{m} \sim 1 - 10$ TeV

Upper limits on fine-tuning at least at the % level.

This has lead to renewed interest on alternatives, such as R-parity violation (RPV), on both the experimental and theory side.

$$W_{RPV} \sim \mu'_i L_i H_u + \lambda_{ijk} L_i L_j \ell^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \lambda''_{ijk} u^c_i d^c_j d^c_k$$

B and L violation, leading to rapid proton decay, e.g.

$$\tau_p > 10^{34}\text{years} \implies |\lambda'_{l1k}\lambda''_{11k}| \lesssim 2 \times 10^{-27} \left(\frac{m_{\tilde{d}\,kR}}{100\ \text{GeV}}\right)^2$$

A Z_2 symmetry, $R_p = (-1)^{2S+3B+L}$ removes the problem.
Also stable LSP (DM), MET at colliders.

Baryonic RPV

Still, proton is stable is B or L separately conserved($*$). I will consider baryonic RPV,

$$W = \frac{\lambda''_{ijk}}{2} u^c_i d^c_j d^c_k, \quad i,j,k = 1,2,3,\ j \neq k$$

Flavor physics constraints ($\Delta B = 2$ transitions, $K - \bar{K}$, $n - \bar{n}$):

[Barbier et al., hep-ph/0406039]

$$|\lambda''_{11k}| \lesssim 10^{-7} \left(\frac{\tilde{m}}{100\ \text{GeV}}\right)^{5/2} \qquad n - \bar{n}$$

$$|\lambda''_{312,313}| \lesssim O(10^{-2}), \qquad (100\ \text{GeV} \lesssim \tilde{m} \lesssim 200\ \text{GeV}) \qquad n - \bar{n}$$

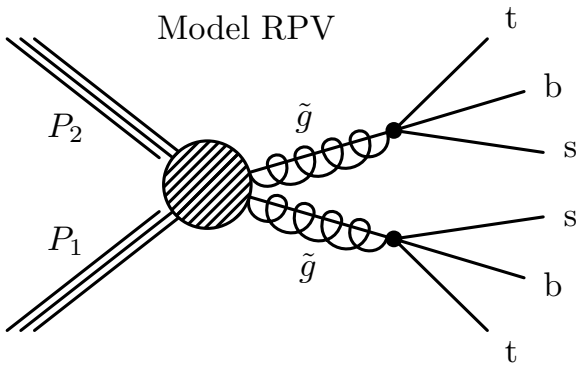
$$|\lambda''^{*}_{i23}\lambda''_{i13}|_{i=2,3} \lesssim 10^{-3} \left(\frac{m_{\tilde{u}_i}}{100\ \text{GeV}}\right) \qquad K - \bar{K}$$

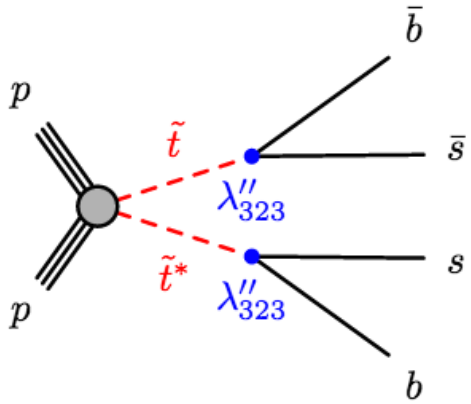
Matter bias, or suggesting a 3^{rd} generation dominance?

Flavor symmetries automatically generate hierarchies. (see backup slides)

RPV - LHC limits (so far)

No MET but large multiplicities, large H_T.





- gluino $\to$ 3j: [CMS, 1208.2931], [ATLAS, 1502.05686]

$$m_{\tilde{g}} \gtrsim 1 \text{ TeV(model-independent)}$$

[Evans,Kats,Shih,Strassler, 1310.5758]
[Graham, Rajendran, Saraswat, 1403.7197]

- squark $\to$ 2j: first limits on LSP squarks

$$m_{\tilde{t}} \gtrsim 350 - 400 \text{ GeV}$$

[CMS, 1412.7706], [ATLAS, ATLAS-CONF-2015-026]

GREAT! Finally limits on RPV squarks. Any blind spot?

RPV - a step back to baryogenesis

udd breaks baryon number:

$$\text{washout of } \Delta B \implies \lambda''_{all} < 10^{-7} \quad \text{for } T_{BG} \gtrsim \tilde{m}/10$$

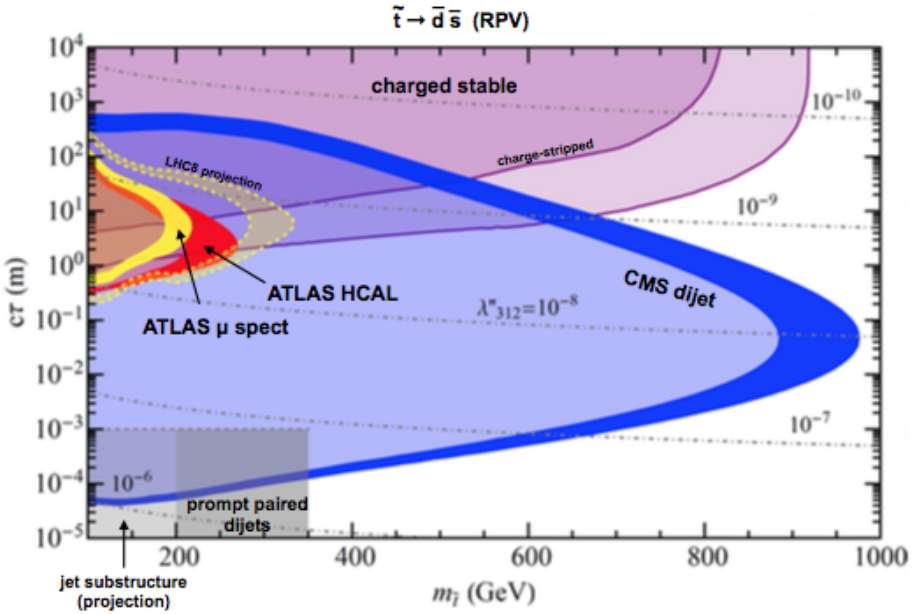
[Dreiner,Ross, Nucl.Phys.B 1993]

Coincidentally, $\lambda'' < 10^{-7} \implies$ displaced vertices at LHC!

[Barry, Graham, Rajendran, 1310.3853]

Limits are even stronger than prompt RPV! (see JP Chou's talk)

[Liu,Tweedie, 1503.05923]



$$m_{\tilde{t}} \gtrsim 800 - 1000 \text{ GeV}$$

[Csaki et al., 1505.00784]

[Zwane, 1505.03479]

Large RPV

On the other hand, if ΔB generated at $T < \tilde{m}/10 \approx \mathcal{O}(10 - 100)$ GeV, no washout.

Many models use baryonic RPV for Baryogenesis:

Dimopoulos, Hall (1987), Cline, Raby (1991), Cui (2013), AM, Shin (2014), Arcadi, Covi, Nardecchia (2015)

For all models, $X \to B, \bar{B}$

$$\varepsilon \equiv \frac{\Gamma_{X\to B} - \bar{\Gamma}_{X\to \bar{B}}}{2\Gamma} \propto \frac{|\lambda''|^2}{(16\pi^2)^{\#}} \Phi_{CP}\, f(\tilde{m}_i \ldots)$$

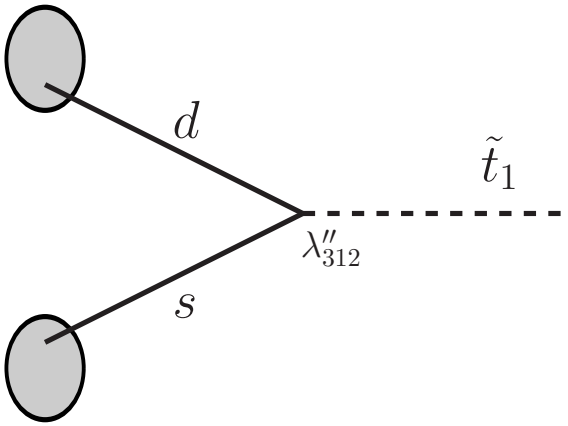
$$10^{-10} \simeq \frac{n_B}{s} = \varepsilon \left(\frac{n_X}{s}\right)_{t=\frac{1}{\Gamma}} \implies \boxed{|\lambda''| \gtrsim \mathcal{O}(10^{-2} - 10^{-3})} \qquad (*)$$

(*loopholes: if X non-thermal. . .)

A new channel at LHC

Experimental constraints and connection to baryogenesis *strongly suggests* that natural RPV SUSY involves large couplings (at least one):

resonant RPV production of squarks!

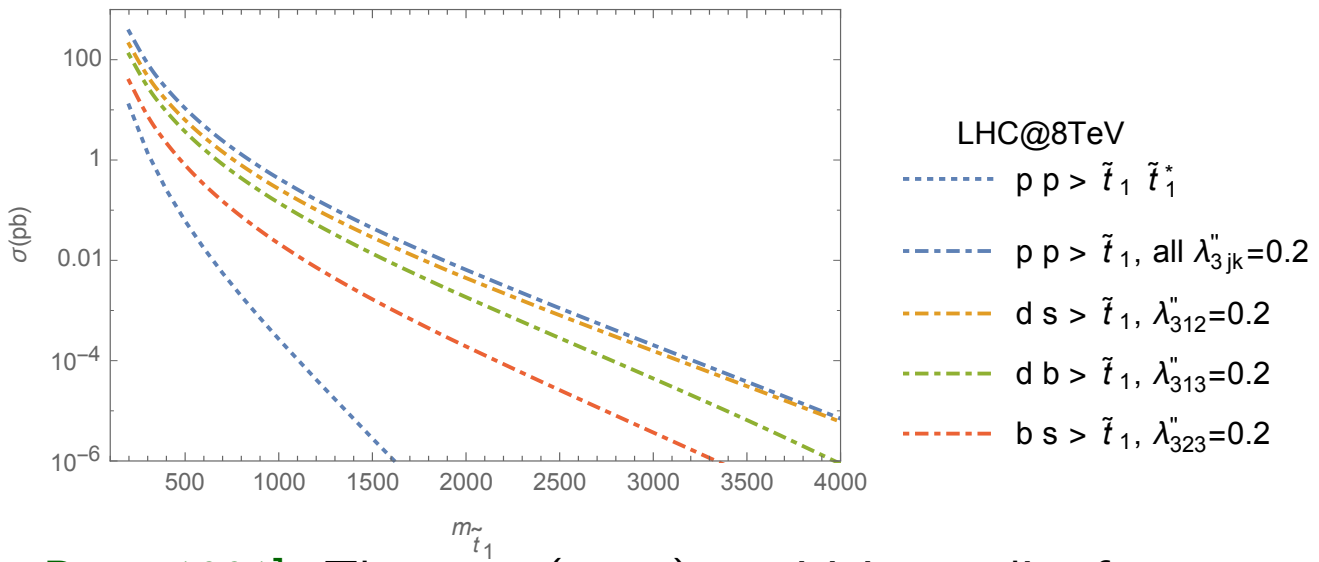


(will focus on 3rd gen. couplings for rest of talk)

λ''_{3ij}, $3ij \equiv tds, tdb, tbs$

$$\hat{\sigma} = \frac{8\pi}{3} \frac{|\lambda''_{ijk}|^2}{m^2_{\tilde{t}}} \sin^2\theta_{\tilde{t}}\, \delta(\hat{s} - m^2_{\tilde{t}})$$

Large cross sections:
(even *tbs*!)



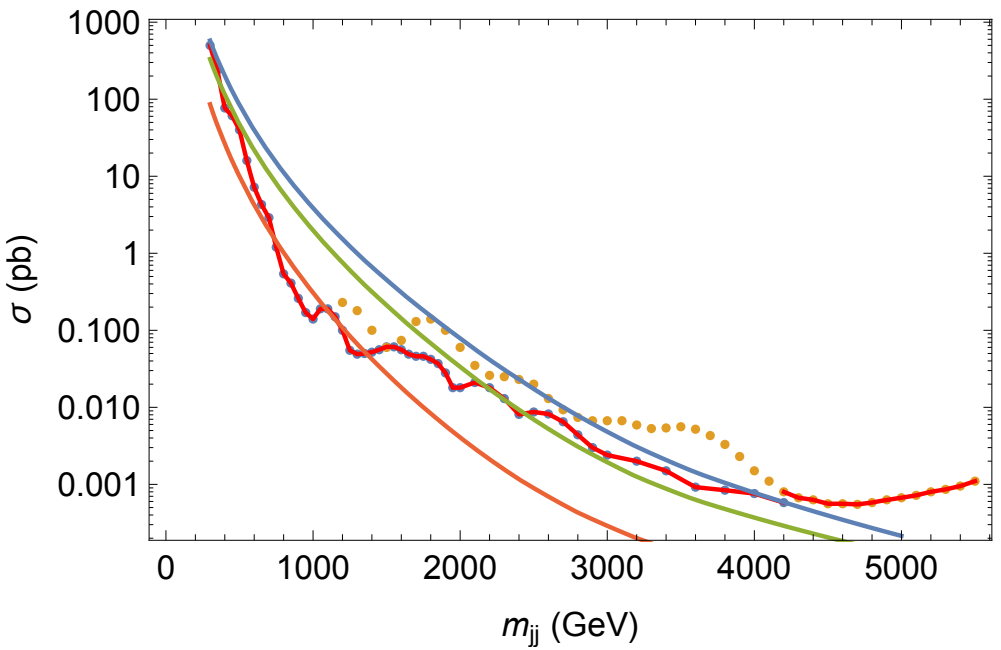
Disclaimer: old idea. [Dreiner,Ross, 1991]. There are (some) sensitivity studies for Tevatron [Berger,Harris,Sullivan, 1999] and LHC [Choudhury,Datta,Maity, 2011]. Also, CMS and ATLAS do a resonant $\tilde{\nu}$ search (LRPV).

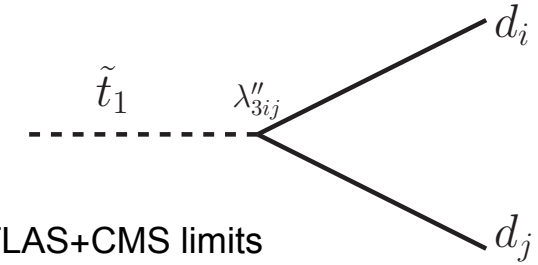
Search strategies I: dijet resonance

$pp \to \tilde{t}_1 \to ds, db, bs$: dijet resonance

[ATLAS-EXOT-2013-11, 20.3fb^{-1}@8TeV]

[CMS-EXO-12-059, 19.7fb^{-1}@8TeV]





ATLAS+CMS limits

d s → $\tilde{t}_1$ → d s, λ''_{312}=1

d b → $\tilde{t}_1$ → d b, λ''_{313}=1

b s → $\tilde{t}_1$ → b s, λ''_{323}=1

No signal $\Longrightarrow$ Limits from 500 GeV to 5+ TeV.

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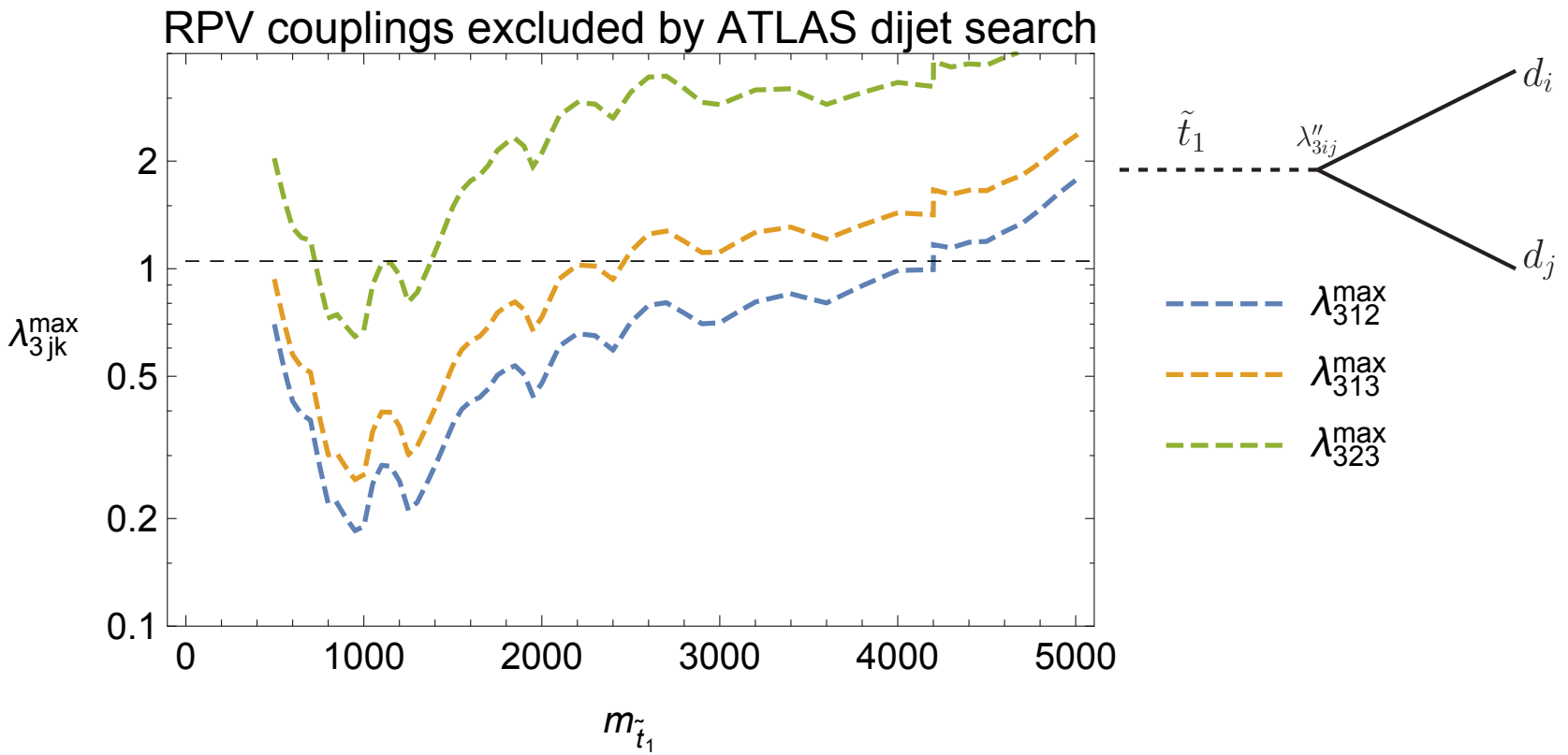
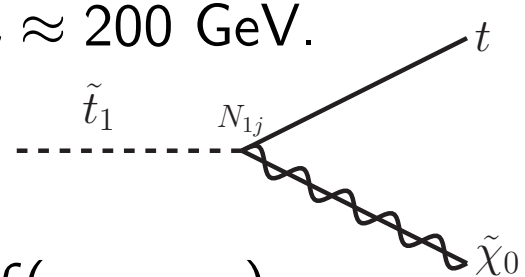


Best limits around 1 TeV. Worst at low E (background), some searches did not even look. (CMS had specific trigger at end of Run I). (see backup slides)

Search strategies II: add a neutralino

A light higgsino is also favored by naturalness, $\mu \approx 200$ GeV.

With $\tilde{\chi}_0$ LSP, dijet signal suppressed,



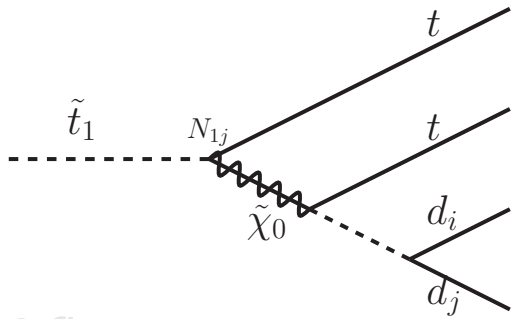
$$Br(\tilde{t} \to jj) \approx \frac{\lambda''^2}{\lambda''^2 + (g^2 N_{11}^2 + \ldots)} f(m_{\tilde{t}}, m_{\tilde{\chi}_0})$$

$$Br(\tilde{t} \to t\tilde{\chi}_0) \approx \frac{(g^2 N_{11}^2 + \ldots)}{\lambda''^2 + (g^2 N_{11}^2 + \ldots)} h(m_{\tilde{t}}, m_{\tilde{\chi}_0})$$

Dominant decay channel for $\lambda'' \lesssim 0.1$. Even for $\lambda'' > 0.1$, $\sigma \times Br_{t\tilde{\chi}_0} \approx const$.

Signatures? LSP is unstable:

- $c\tau > 10m \implies$ monotop? *unlikely*.
- $c\tau \ll 1m \implies$ prompt decays:



SS tops, contrained by CMS-SUS-13-013,

$\sigma(pp \to tt, \bar{t}\bar{t}) < 720fb$

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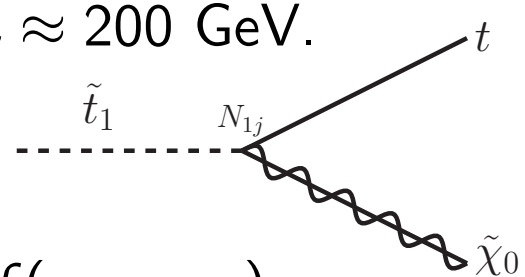

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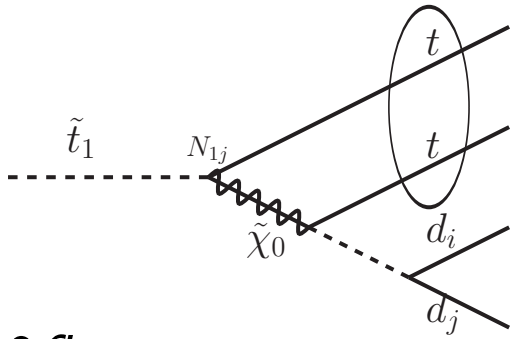
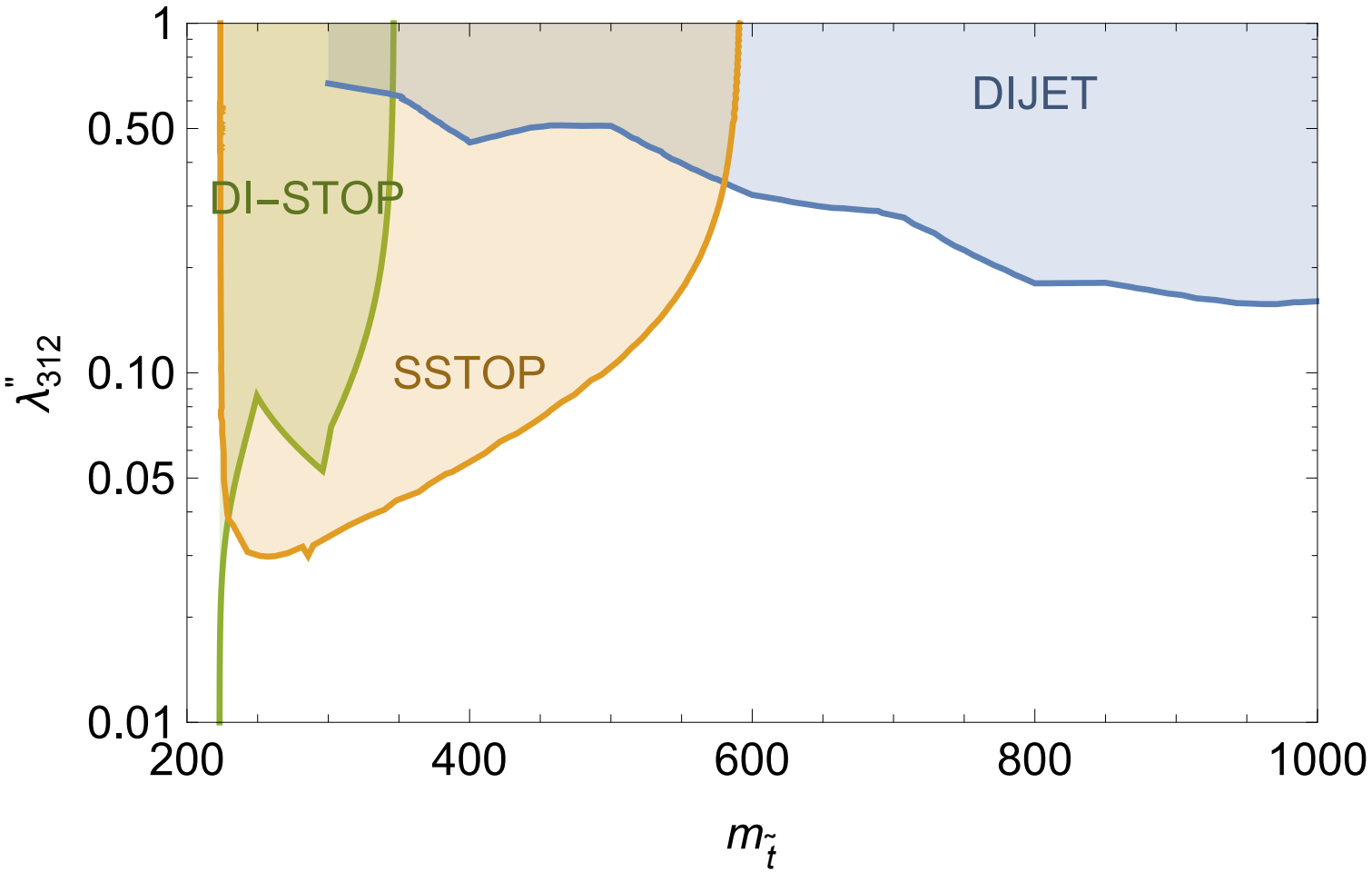


$$\sigma(pp \to tt, \bar{t}\bar{t}) < 720fb$$

Combined New Limits below 1 TeV



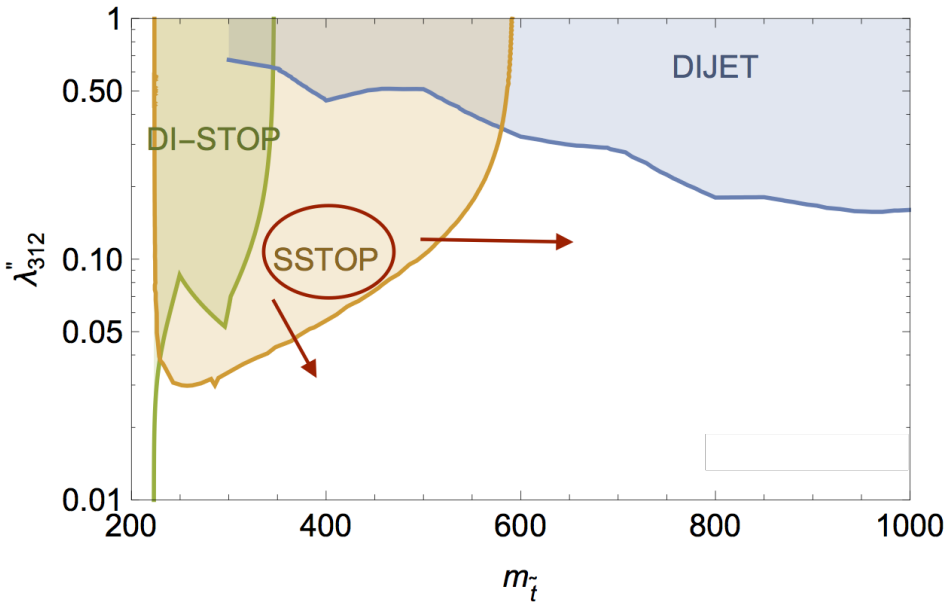
Here limits on λ''_{312} (tds).(check out backup slides for $\lambda''_{313}, \lambda''_{323}$.)

Experimental outlook

How to close those gaps and improve limits/discover something:

(recommendations + new proposed searches in RED)

- SStop: $\tilde{t} \to SS\ell{+}2j$: count extra jets, higher luminosity, more data.
- jj searches: more data, but do not forget low masses (trigger level?).
- Di-stop: more data, complementary $4t + 4j$ search.



- λ''_{2ij} couplings could also be large $\Longrightarrow$ 4j resonances instead of SStop. Currently not looked for.

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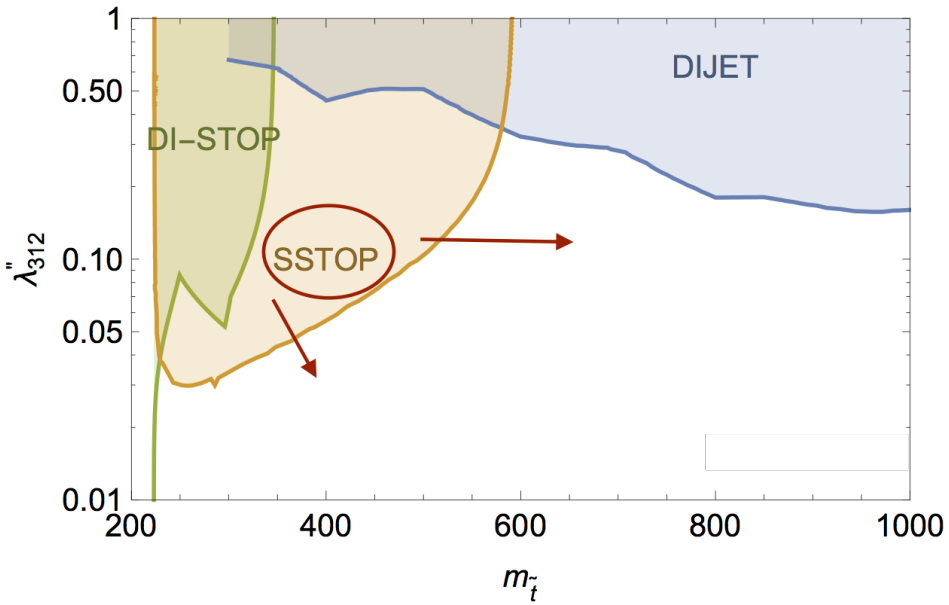

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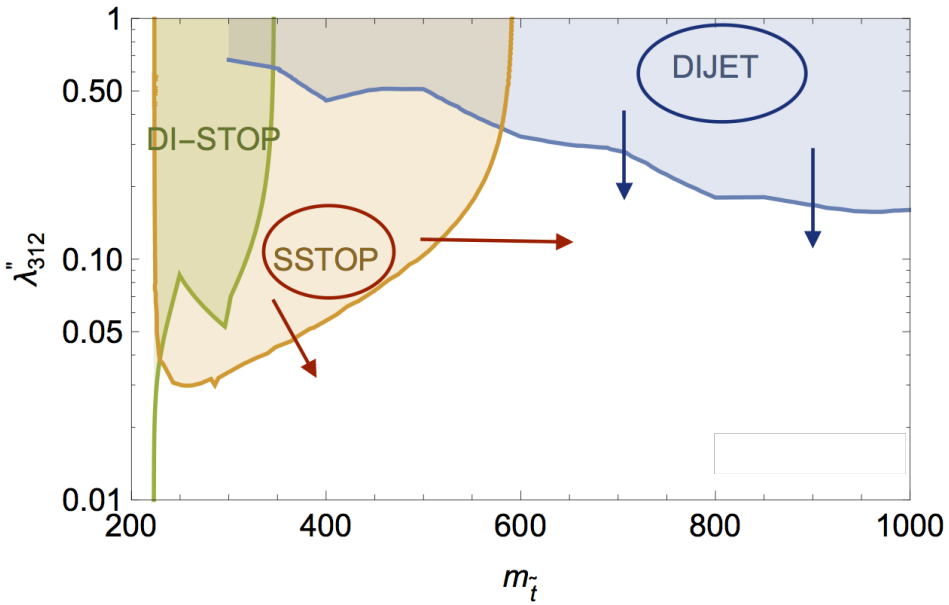

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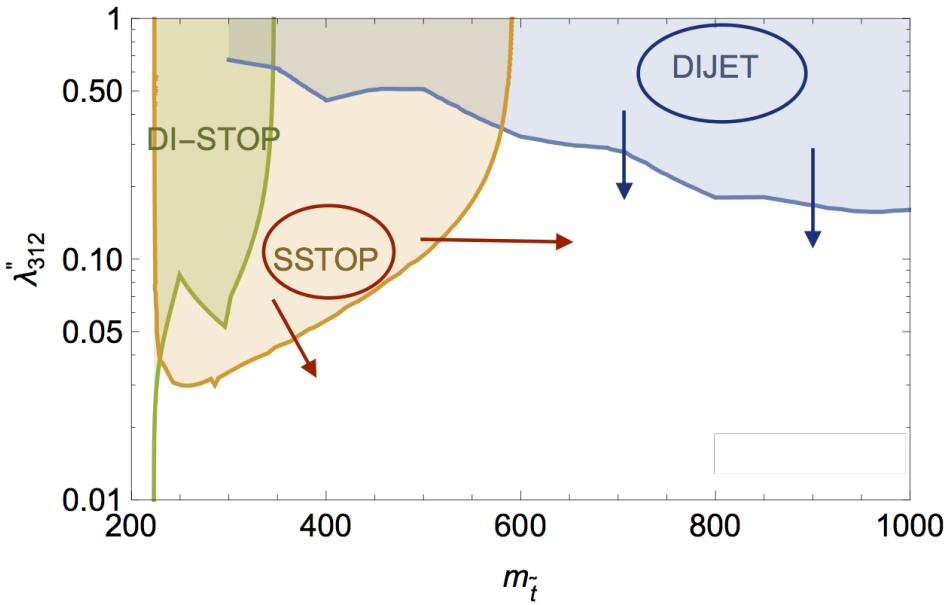

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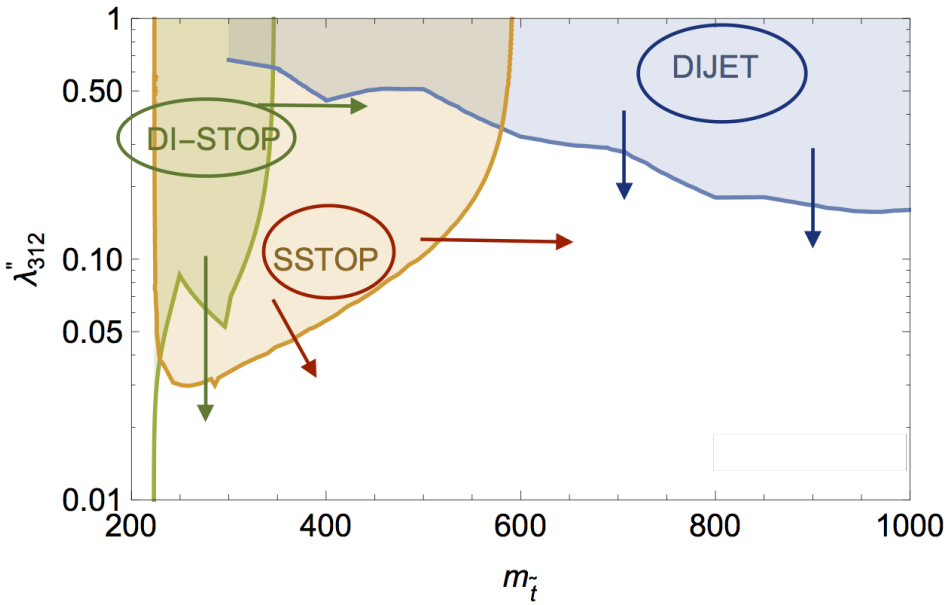

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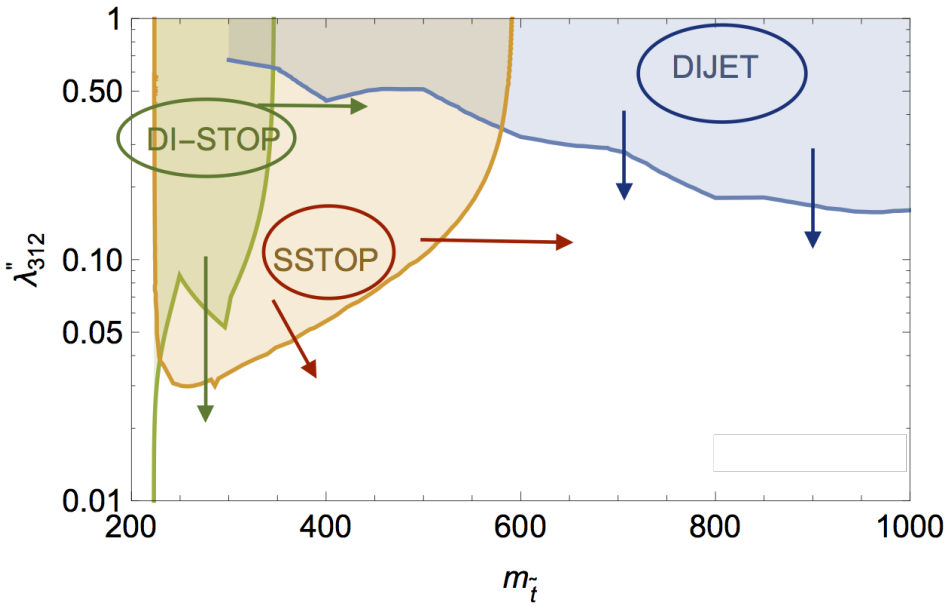

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Conclusions

I have presented a series of NEW limits on RPV stops when those are produced through resonant scattering through the RPV interaction.

This was motivated by both null experimental searches for RPV below 1 TeV as well as the role of BNV interactions in baryogenesis.

Although mentioned before in the literature, it was overlooked so far in the analysis of LHC data. These are the first direct limits on individual RPV couplings, as opposed to flavor physics constraints.

At 13 TeV, cross section increases by a factor of ~ 10. We should keep looking at low mass range, interesting surprises can hide around the corner.

Thanks for listening!

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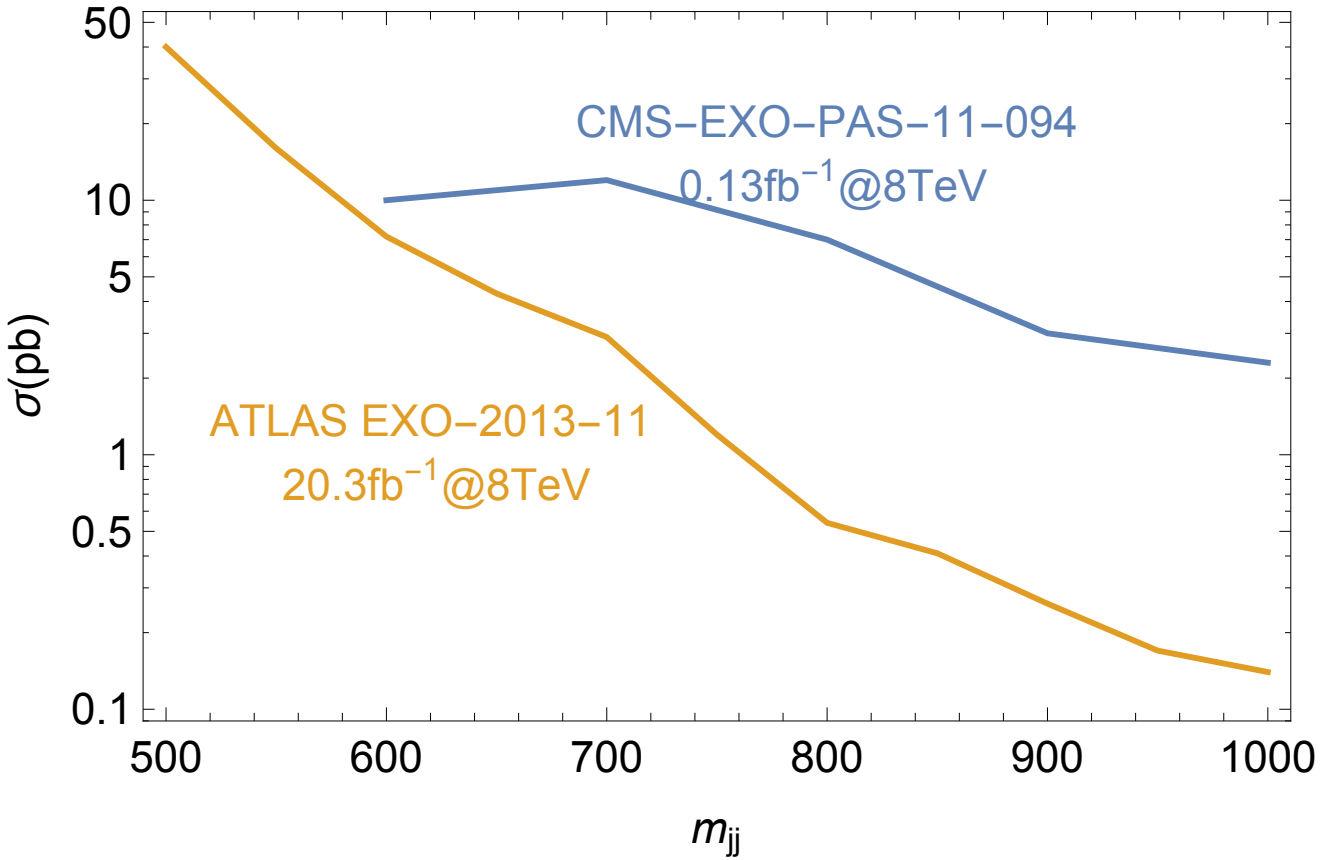
Thanks for listening!

Extra slides

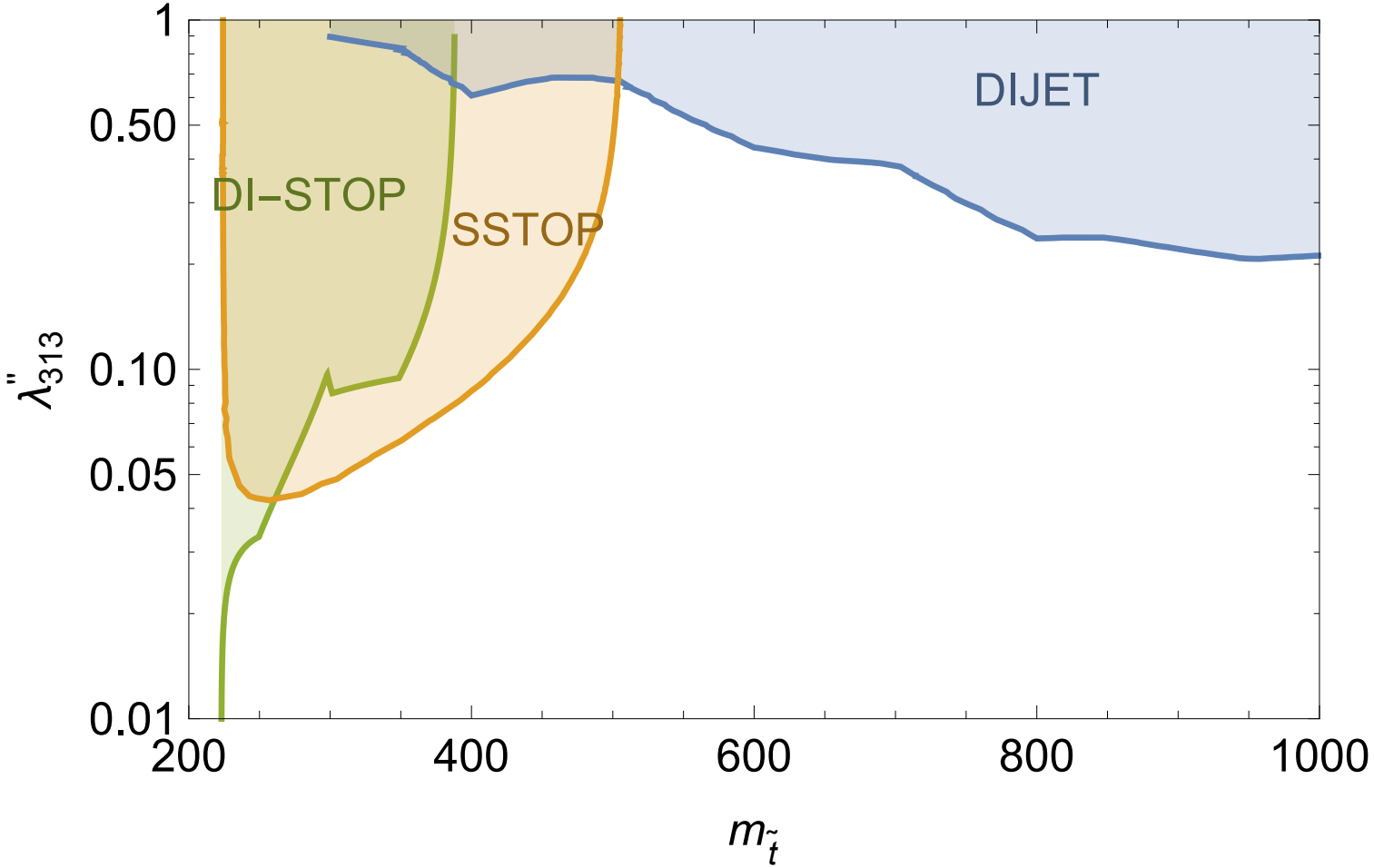
Low-mass trigger: CMS-EXO-PAS-11-094

L1 trigger: $H_T > 100$ GeV
HLT; $H_T > 350$ GeV $\quad | \quad (m_{jj} > 400$ GeV & $|\Delta\eta_j j| < 2)$;
throw away most of event to reduce bandwidth.
Trigger active only at end of Run I: only $0.13 fb^{-1}$! Limits are quite good

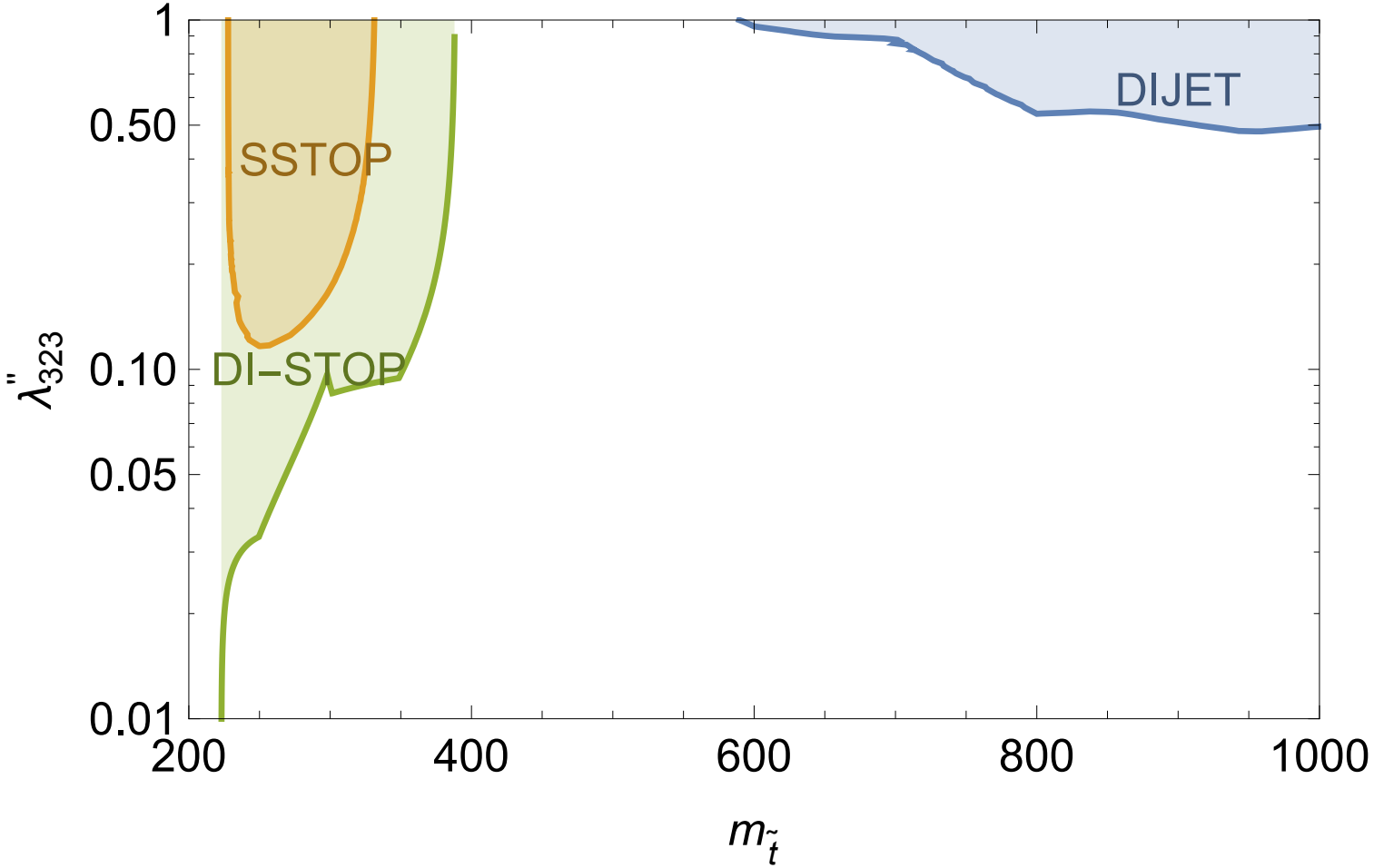


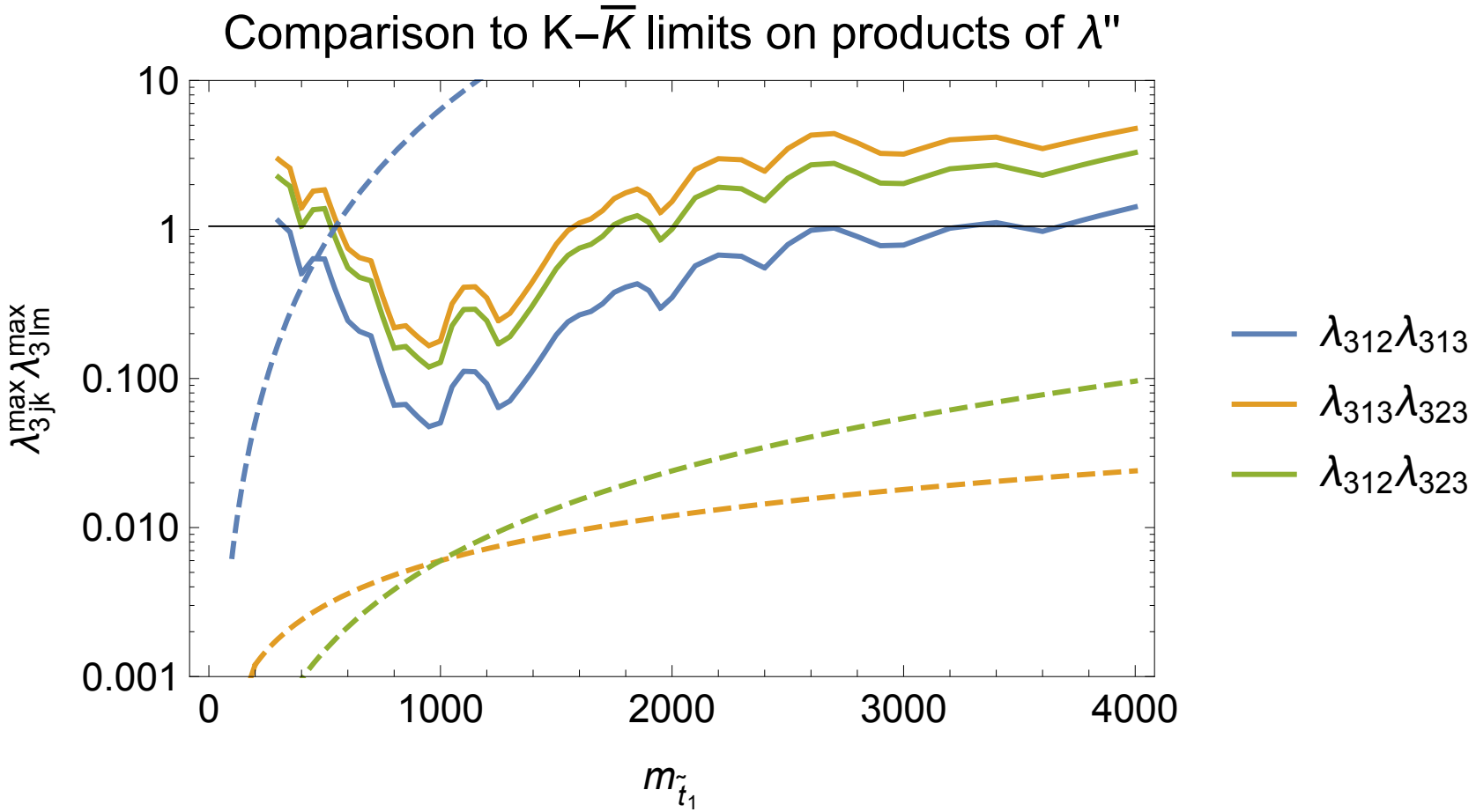
With $20 fb^{-1}$, probe
$0.1 pb \to \lambda'' \gtrsim 0.01$!

Limits on λ''_{313} (tdb)



Limits on λ''_{323} (tbs)

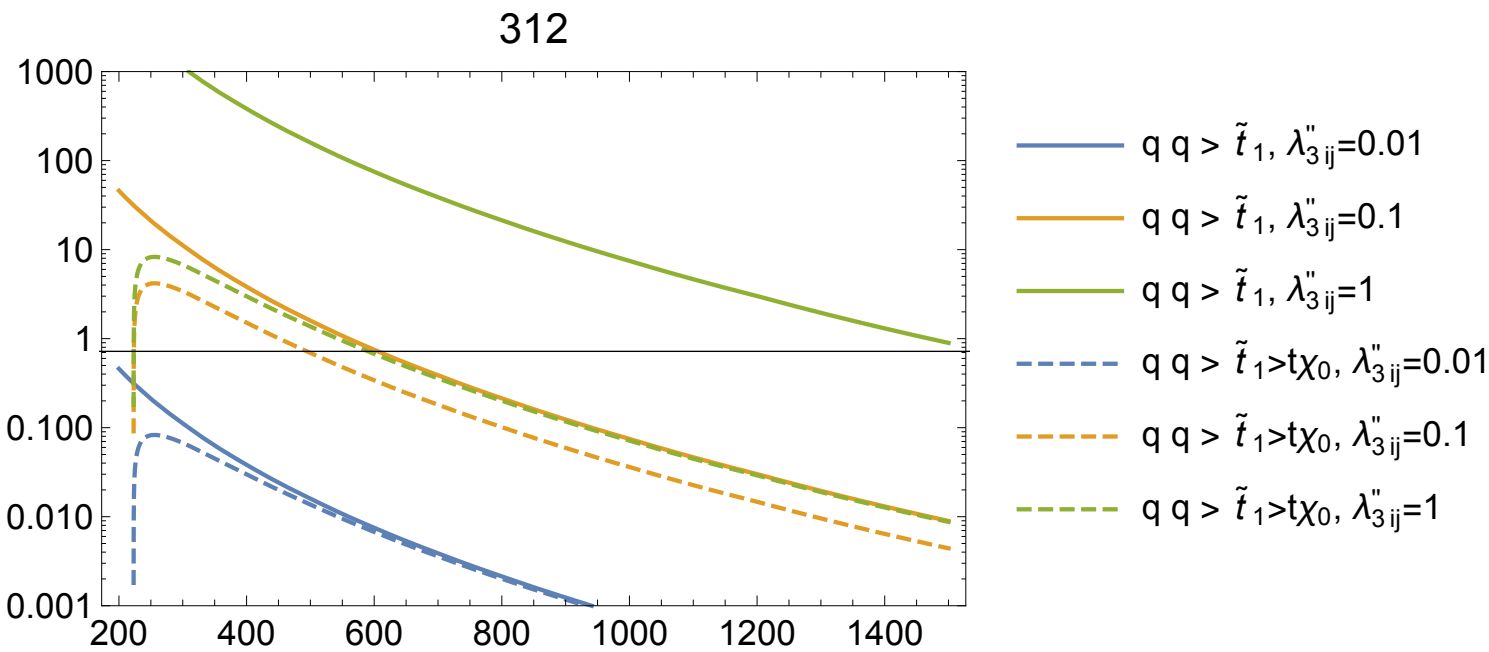


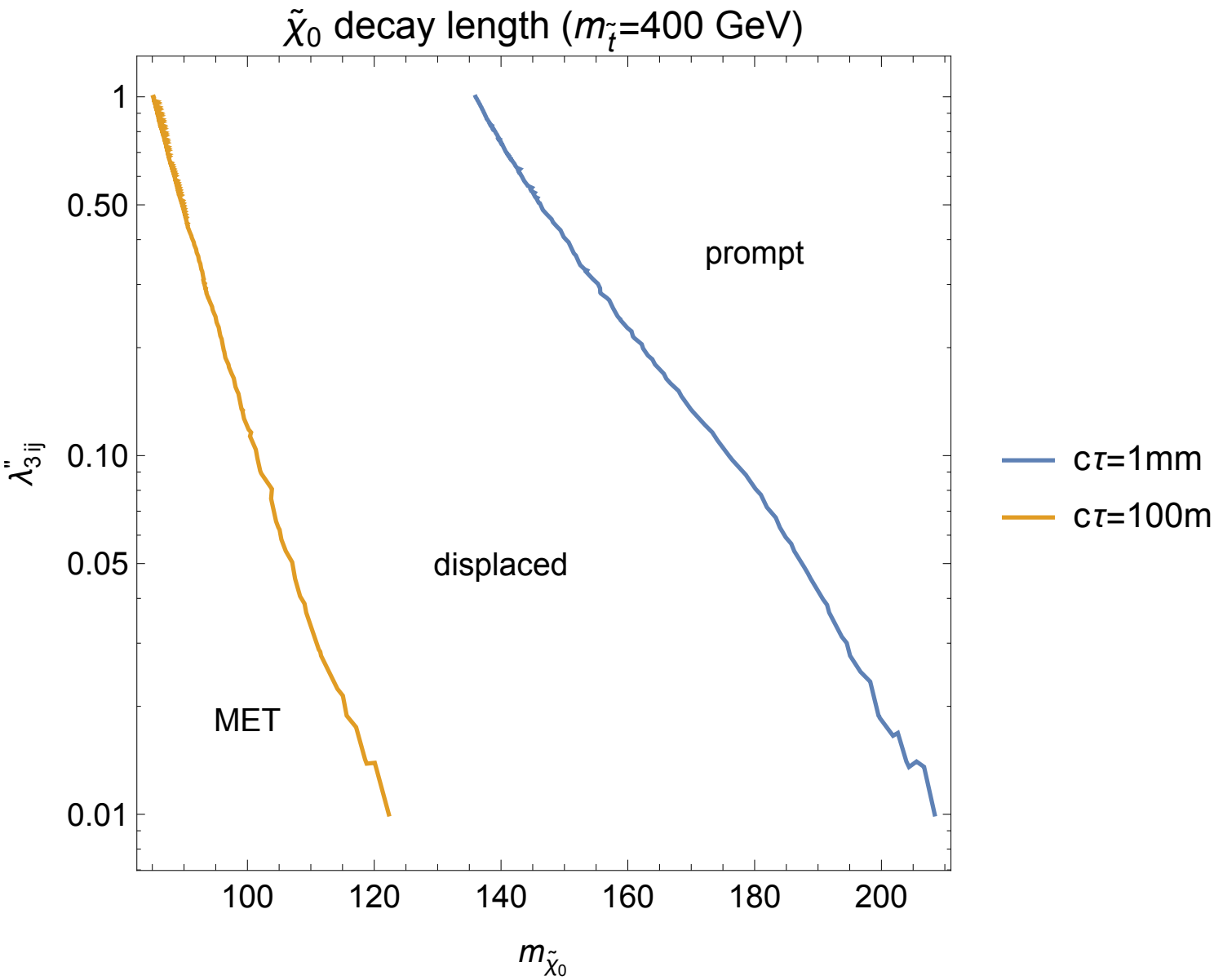

Comparison to K–$\overline{K}$ limits on products of λ''
10
1
0.100
0.010
0.001
0
1000
2000
3000
4000
$\lambda''^{max}_{3jk}\lambda''^{max}_{3lm}$
$m_{\tilde{t}_1}$
$\lambda_{312}\lambda_{313}$
$\lambda_{313}\lambda_{323}$
$\lambda_{312}\lambda_{323}$

$pp \to \tilde{t} \to t\tilde{\chi}_0$ independent of λ'' for large λ'':

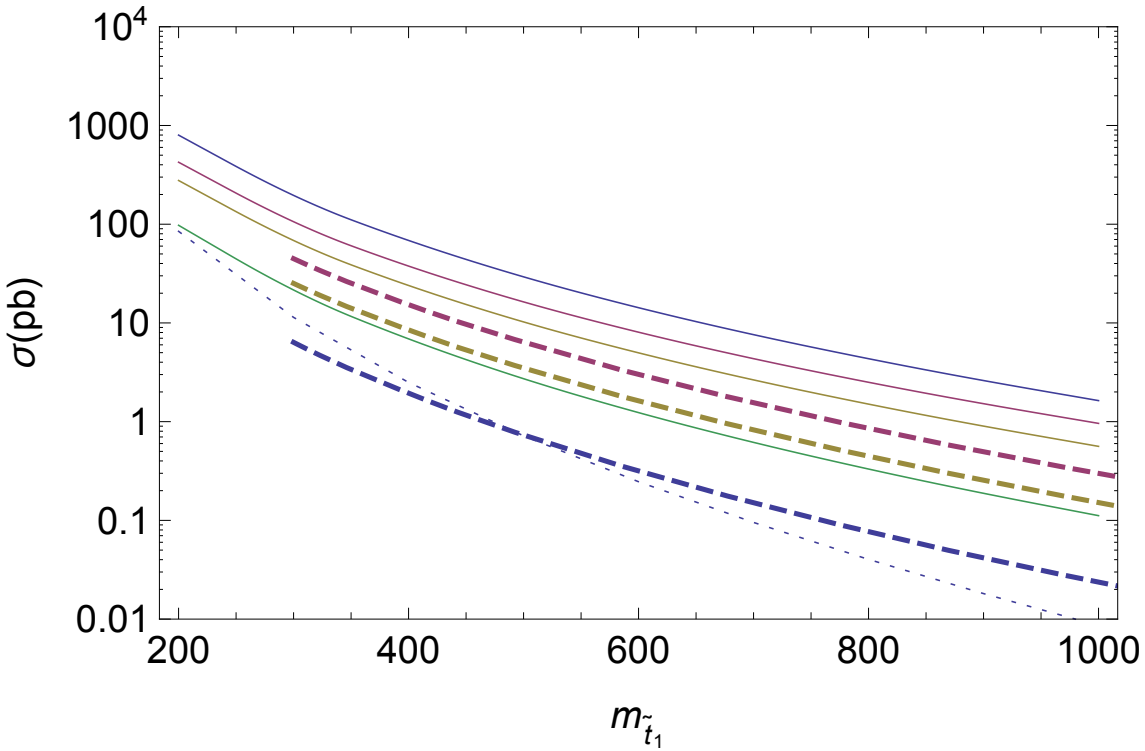
$$\sigma \times Br(\tilde{t} \to t\tilde{\chi}_0) \sim \lambda''^2 \times \frac{(g^2 N_{11}^2 + \ldots)}{\lambda''^2 + (g^2 N_{11}^2 + \ldots)}$$

$$\simeq \begin{cases} (g^2 N_{11}^2 + \ldots), & \lambda'' \gtrsim 0.1 \\ \lambda''^2 \times \mathcal{O}(1), & \lambda'' \lesssim 0.1 \end{cases}$$




$\tilde{\chi}_0$ decay length ($m_{\tilde{t}}$=400 GeV)
1
0.50
0.10
0.05
0.01
λ''_{3ij}
prompt
displaced
MET
100
120
140
160
180
200
$m_{\tilde{\chi}_0}$
cτ=1mm
cτ=100m

Cross sections at 13 TeV



LHC@13TeV

p p > $\tilde{t}_1$, all λ''_{ijk}=.1

d s > $\tilde{t}_1$, λ''_{312}=.1

d b > $\tilde{t}_1$, λ''_{313}=.1

b s > $\tilde{t}_1$, λ''_{323}=.1

LHC@8TeV

d s → $\tilde{t}_1$ → d s, λ''_{312}=.1

d b → $\tilde{t}_1$ → d b, λ''_{313}=.1

b s → $\tilde{t}_1$ → b s, λ''_{323}=.1

RPV - flavor symmetries

Flavor models also favor hierarchies with large 3^{rd} generation couplings.

- horizontal flavor symmetries: Froggatt-Nielsen mechanism, known fermion masses and mixing *imply* hierarchies in RPV sector.

[AM, 1305.2921]

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \lambda''_{323} \begin{pmatrix} 3\times 10^{-5} & 3\times 10^{-3} & 5\times 10^{-2} \\ 10^{-4} & 10^{-2} & 2\times 10^{-1} \\ 6\times 10^{-4} & 5\times 10^{-2} & 1 \end{pmatrix}$$

- MFV: assume Y^f_{ij} only flavor violation as spurion of SM flavor $SU(3)^5$.

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \frac{1}{2}\left(\frac{\tan\beta}{50}\right)^2 \begin{pmatrix} 10^{-8} & 10^{-4} & 2\times 10^{-1} \\ 3\times 10^{-5} & 5\times 10^{-2} & 3\times 10^{-1} \\ 2\times 10^{-3} & 2\times 10^{-1} & 1 \end{pmatrix}$$

[Nikolidakis,Smith, 0710.3129]
[Csaki,Grossman,Heidenreich, 1111.1239]