Cosmology at Colliders:

Possible LHC searches for RPV baryogenesis

Haipeng An

Perimeter Institute

In collaboration with Yue Zhang

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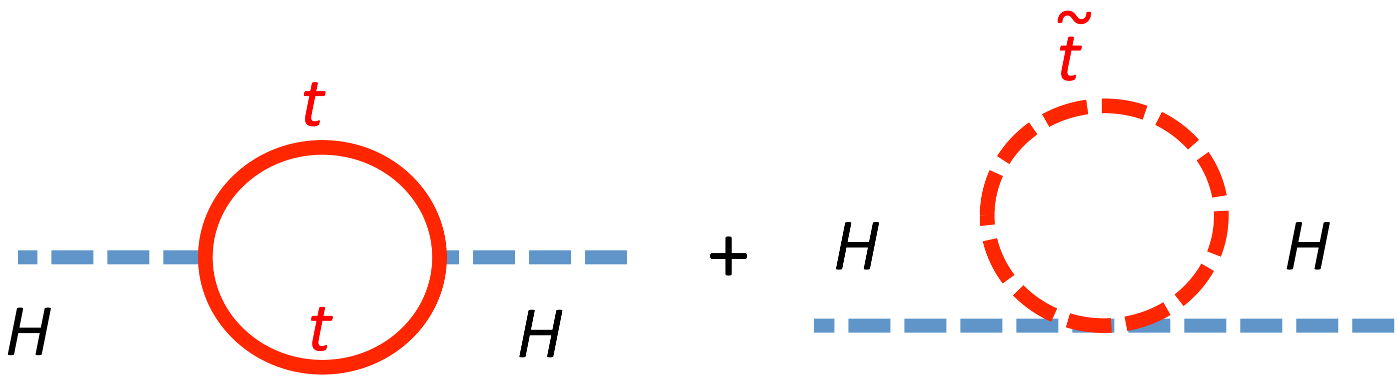
Motivations

- We are made of baryons and we have been living for a long time, not a lot of anti-baryon around us.
- There is a baryon-anti-baryon asymmetry
- Where does this asymmetry come from?
  - Initial condition?
  - Dynamics?
- If it is from some dynamics (mechanism, scenario ...), can we test it in today's laboratory?

Motivations

- Higgs is discovered
- Naturalness problem is still unsolved
- SUSY: sub-TeV scale top-partner is needed



- Constraints are strong for R-parity conserving SUSY

Motivations

- R-parity violation (RPV) extension can be used to kill the large missing energy, and therefore relax the constraints
- $W_{\mathrm{RPV}} = \lambda L L e^c + \lambda' Q L d^c + \lambda'' u^c d^c d^c + \mu' L H_u$

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✓ Usually invoked to trade large MET to jets.

✓ No proton decay

Motivations

- $\lambda'' u^c d^c d^c$ Hubble expansion

$$\langle \sigma v \rangle n \sim \frac{\lambda''^2 T}{8\pi} \qquad H \approx 1.66 g_\star^{1/2} \frac{T^2}{m_{\rm pl}}$$

- $\lambda'' \gtrsim 10^{-7}$ $\longrightarrow$ The primordial baryon number is washed out below TeV scale! New baryogenesis is in need!
- $\lambda'' \lesssim 10^{-7}$ $\longrightarrow$ Displaced vertices at the LHC (see Barry el al *1310.3853* for detail)

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Goal

- To propose an directly detectable low scale baryogenesis scenario within the RPV SUSY framework.

Outline

- Baryogenesis from squark decay
- Collider constraints and signatures
- Embed the baryogenesis scenario into realistic models
  - MSSM with a horizontal symmetry
  - MSSM case
- Summary

Baryogenesis from squark decay

- In RPV SUSY models, the RPV couplings are the sources to washout the baryon number.
- Can we make use of them to re-generate the baryon number?

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  - C and CP violations
  - Baryon number violation
  - Out-of-equilibrium

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- Can we make use of them to re-generate the baryon number?
- Sakharov conditions:
  - ✓ C and CP violations (Complex phases of λ' and λ'')
  - ✓ Baryon number violation (B-violating RPV)
  - ✓ Out-of-equilibrium (squark decay)

Baryogenesis from squark decay

- Squarks are complex scalars

CPT theorem $\longrightarrow$ $\Gamma_{\tilde{q}} = \Gamma_{\tilde{q}^\dagger}$

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- $W_{\rm RPV} = \lambda L L e^c + \underbrace{\lambda' Q L d^c + \lambda'' u^c d^c d^c}_{\text{invoked}} + \mu' L H_u$

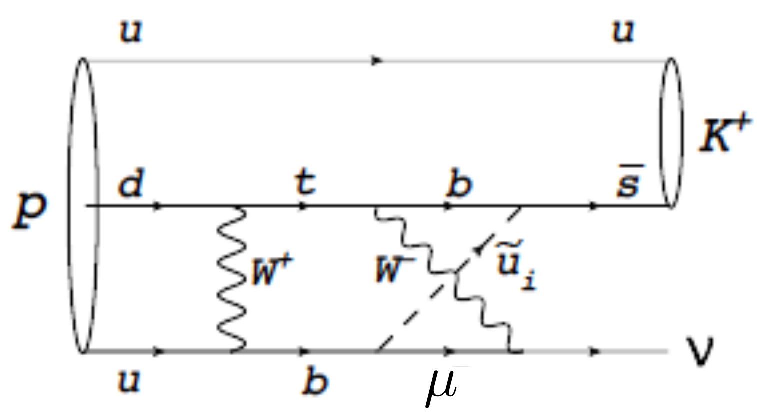
invoked $\longrightarrow$ Proton decay!

Baryogenesis from squark decay

- Proton decay constraints
  - If first generation quarks involved, $|\lambda'\lambda''| < 10^{-26}$.
  - If only second and third generations are involved, the proton decay is suppressed by the CKM.
  - In practice, the model we choose

$$\mathcal{L} \simeq \lambda''_i \bar{b}^c P_R c \tilde{d}_i + \lambda'_i (\bar{t} P_R \mu^c - b P_R \nu^c) \tilde{d}_i$$

$$|\lambda'\lambda''| < 10^{-12}$$



Baryogenesis from squark decay

- A toy model with down-type squarks
  - For right handed quarks, we can assume that there is no rotations, so we can avoid first generation by hand.

$$\mathcal{L} = \lambda_i'' \bar{b}^c P_R c \tilde{d}_i + \lambda_{ij}' (\bar{u}_j P_R \mu^c - V_{jk} \bar{d}_k P_R \nu^c) \tilde{d}_i$$

Quarks are in mass eigenstates

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Quarks are in mass eigenstates

No first generation $\longrightarrow \begin{cases} \lambda_{i1}' \approx 0 \\ V_{21}\lambda_{i2}' + V_{31}\lambda_{i3}' \approx 0 \end{cases}$

$$V_{31} \ll V_{21} \longrightarrow \lambda_{i3}' \gg \lambda_{i2}'$$

Baryogenesis from squark decay

- Decay channels: $\mathcal{L} \simeq \lambda_i'' \bar{b}^c P_R c \tilde{d}_i + \lambda_i' (\bar{t} P_R \mu^c - b P_R \nu^c) \tilde{d}_i$

$$\tilde{d}_i \to \bar{b}\bar{c},\ t\mu^-(b\nu)\ , \quad \tilde{d}_i^* \to bc,\ \bar{t}\mu^+(\bar{b}\bar{\nu})$$

$$\varepsilon_i \equiv \frac{\Gamma_{\tilde{d}_i \to \bar{b}\bar{c}} - \Gamma_{\tilde{d}_i^* \to bc}}{\Gamma_{\tilde{d}_i \to \bar{b}\bar{c}} + \Gamma_{\tilde{d}_i^* \to bc}}\ , \quad \mathrm{Br}_i \equiv \frac{\Gamma_{\tilde{d}_i \to \bar{b}\bar{c}}}{\Gamma_{\tilde{d}_i \to \bar{b}\bar{c}} + 2\Gamma_{\tilde{d}_i \to t\mu^-}}.$$

- All other branching ratios can be determined from ε_i and Br_i.

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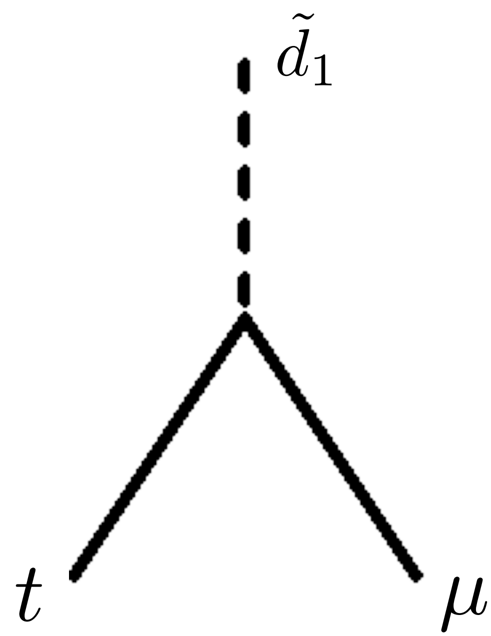
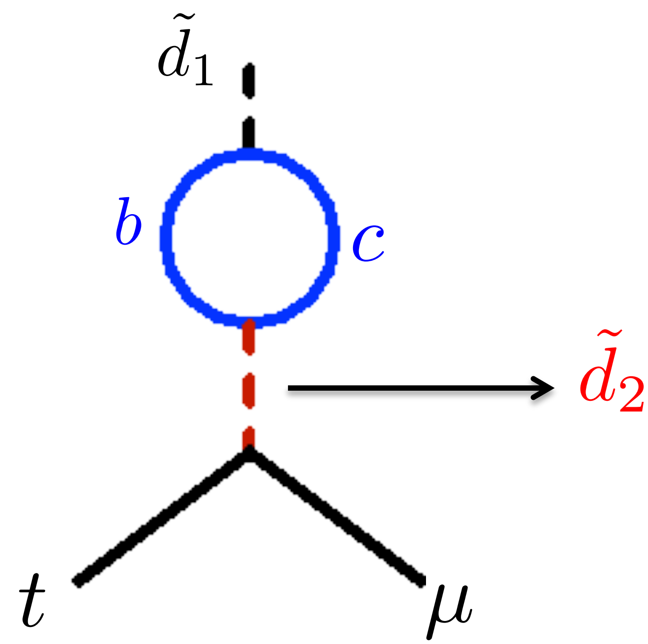
Baryogenesis from squark decay

- CP violation





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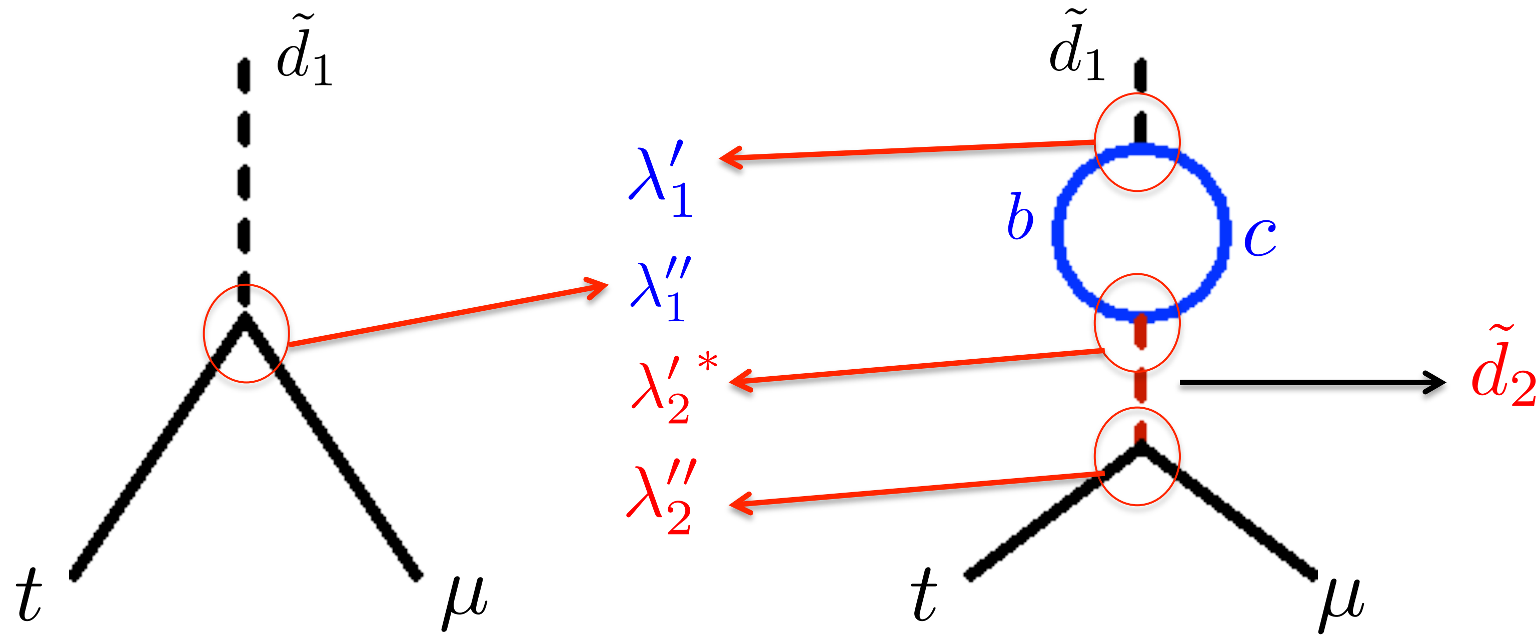

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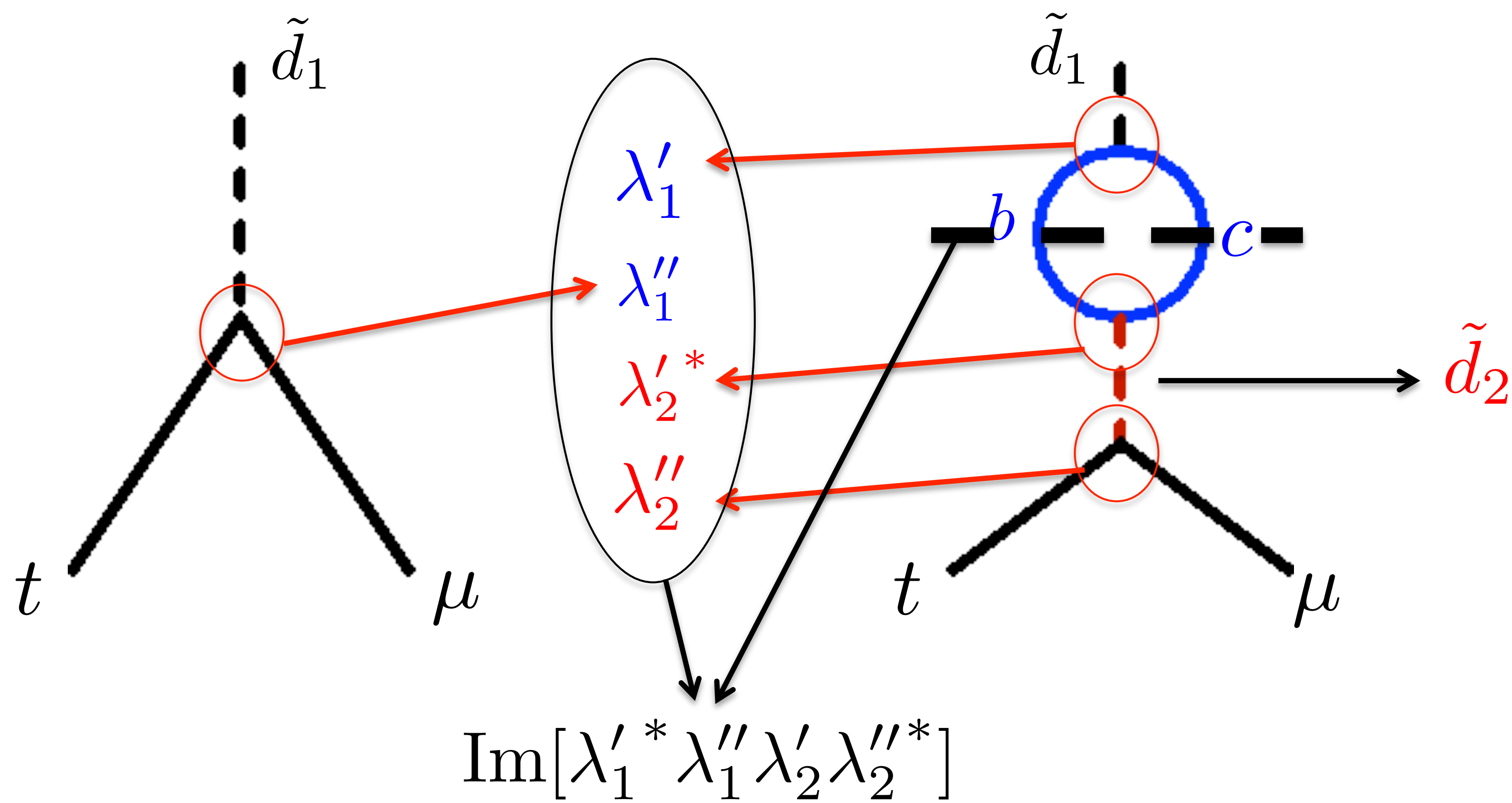

Baryogenesis from squark decay

- Boltzmann equations
  - Squarks freeze out and decay $Y = n/s$

$$\frac{dY_{\tilde{d}_i}}{dz} = -\frac{\langle \Gamma_i \rangle}{H(z)z}(Y_{\tilde{d}_i} - Y_{\tilde{d}_i}^{\rm eq}) - \frac{s\langle \sigma v_i \rangle}{H(z)z}(Y_{\tilde{d}_i}^2 - (Y_{\tilde{d}_i}^{\rm eq})^2)$$

  - Evolution of baryon number

$$\frac{dY_B}{dz} = -\frac{2\varepsilon_i \Gamma_i''}{H(z)z}(Y_{\tilde{d}_i} - Y_{\tilde{d}_i}^{\rm eq}) + \text{washout terms}$$

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Dominated by strong interaction

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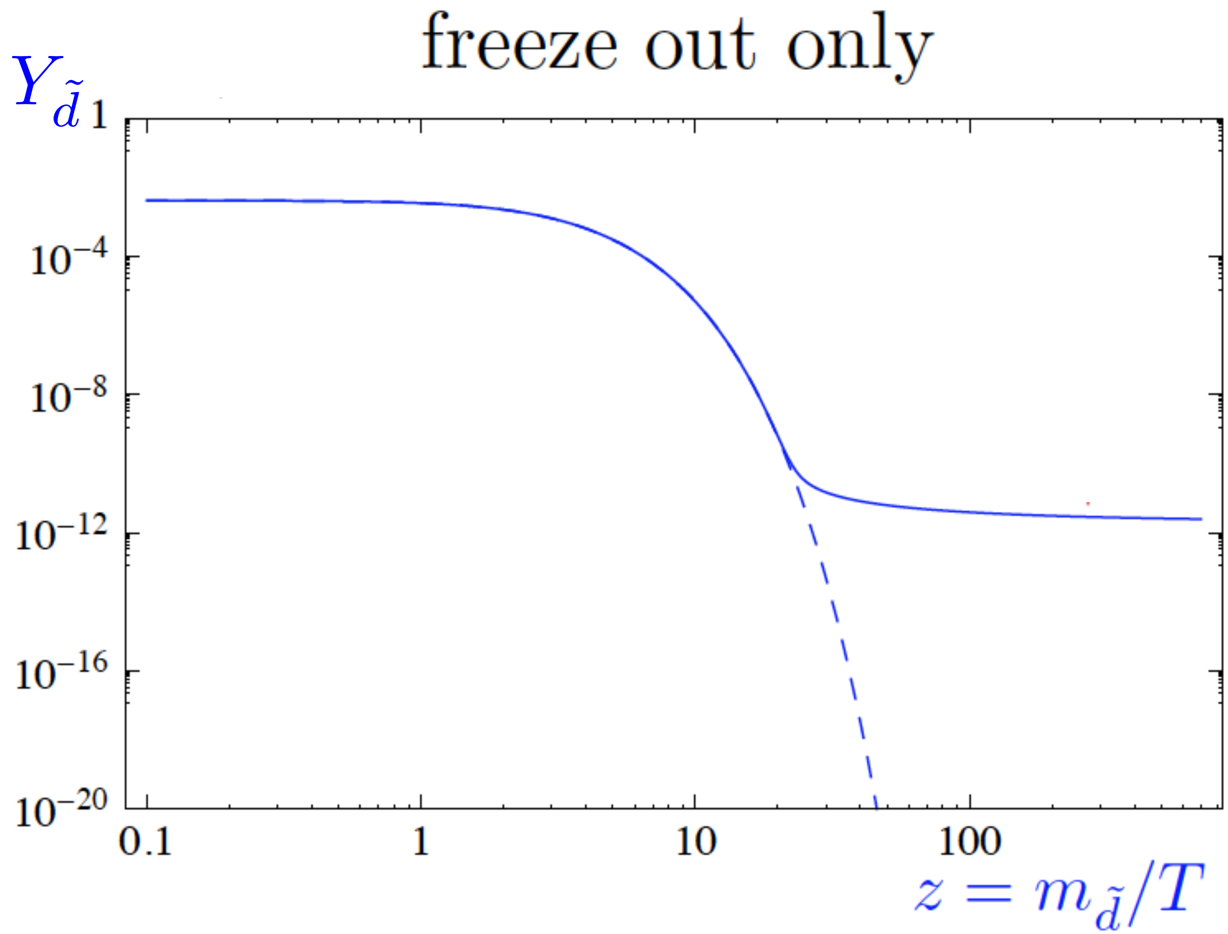
Source term:
$\tilde{d}_i \to \bar{b}\bar{c}$

Baryogenesis from squark decay

- Thermal evolution



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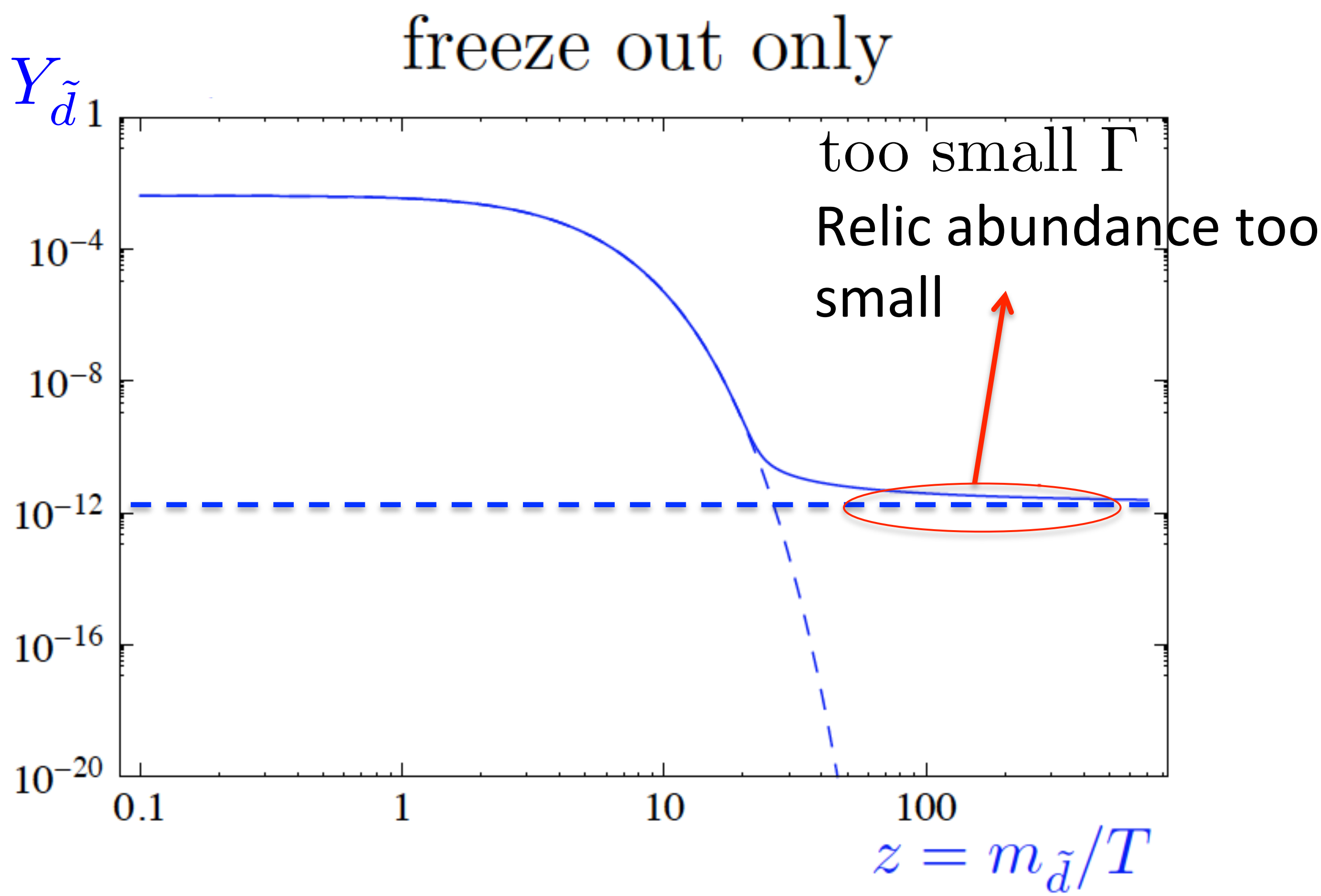

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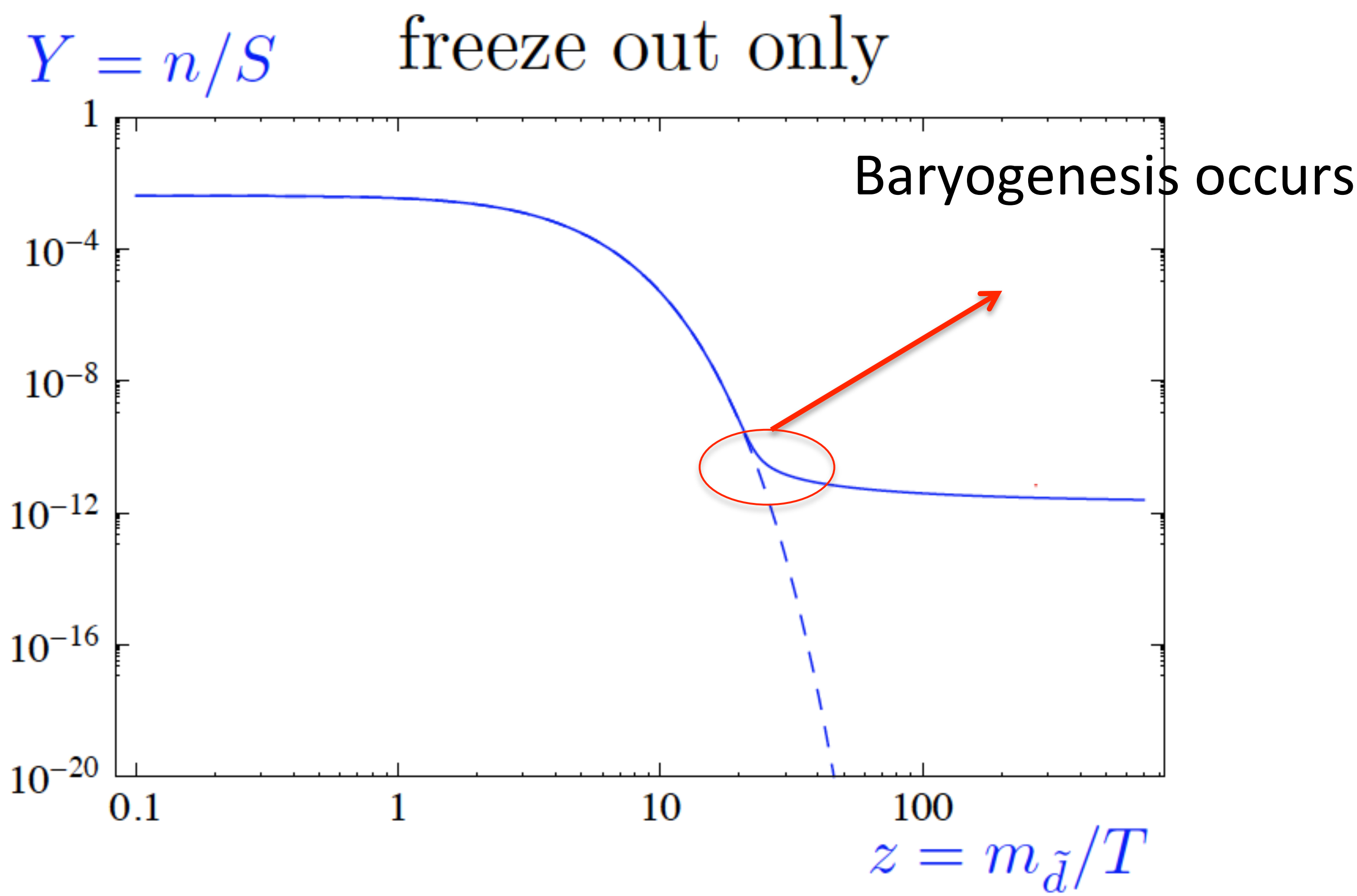

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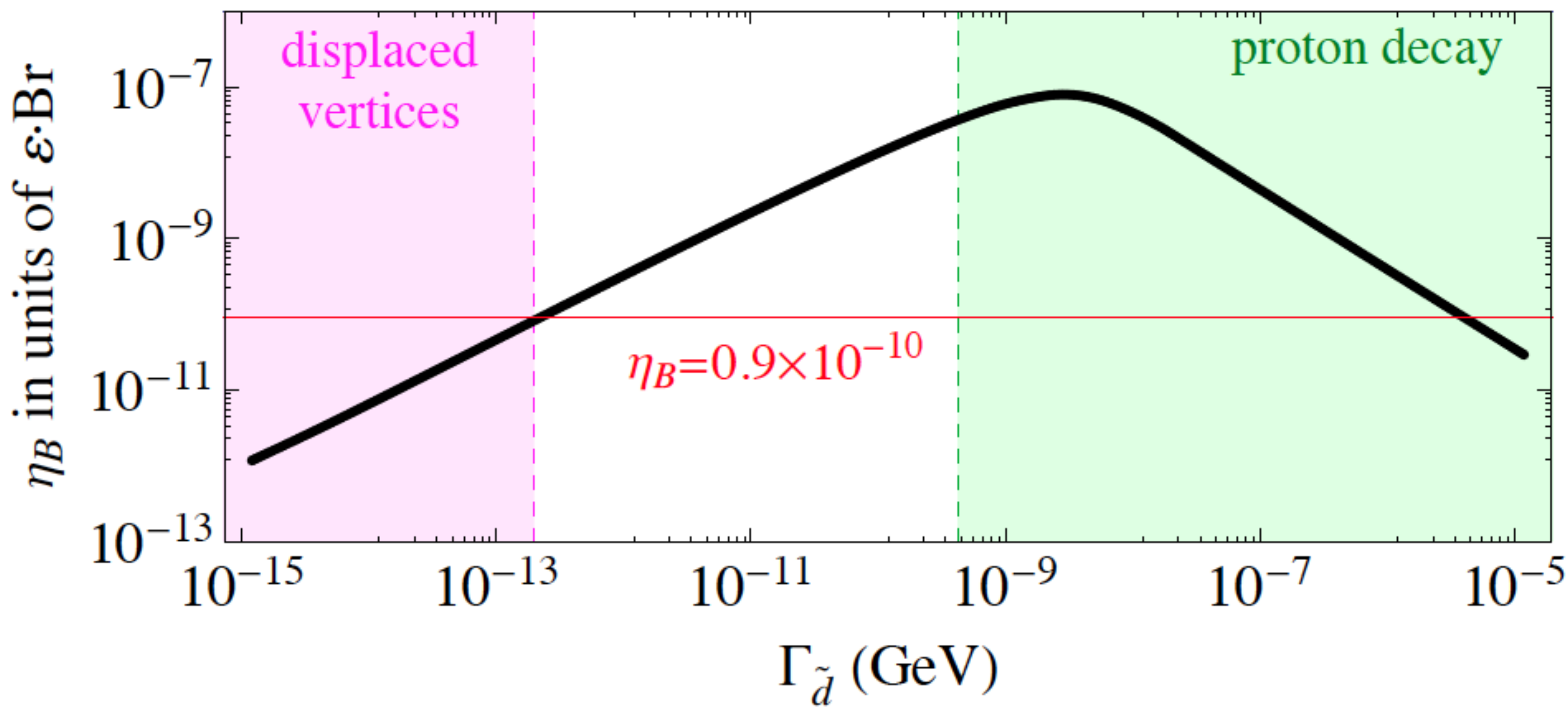

Large CP violation is needed: $\varepsilon \mathrm{Br} \gtrsim 0.01$ $\quad \eta_B \equiv n_B/n_\gamma$

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Collider signature

At the early Universe

$$\tilde{d}_i \ , \ \tilde{d}_i^\dagger$$

Boltzmann distribution

Inside the LHC

$$\tilde{d}_i \ , \ \tilde{d}_i^\dagger$$

$$f_{\text{parton}} \times \hat{\sigma}_{gg \to \tilde{d}_i \tilde{d}_i^\dagger}$$

Collider signature

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Boltzmann distribution

Non-equilibrium decay, preferably

- $\tilde{d}_i \to t\mu^-(b\nu)$
- $\tilde{d}_i^\dagger \to b^c c^c$

Inside the LHC

$$\tilde{d}_i \ , \ \tilde{d}_i^\dagger$$

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Just decay, preferably (Non-equilibrium for sure)

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Collider signature

At the early Universe

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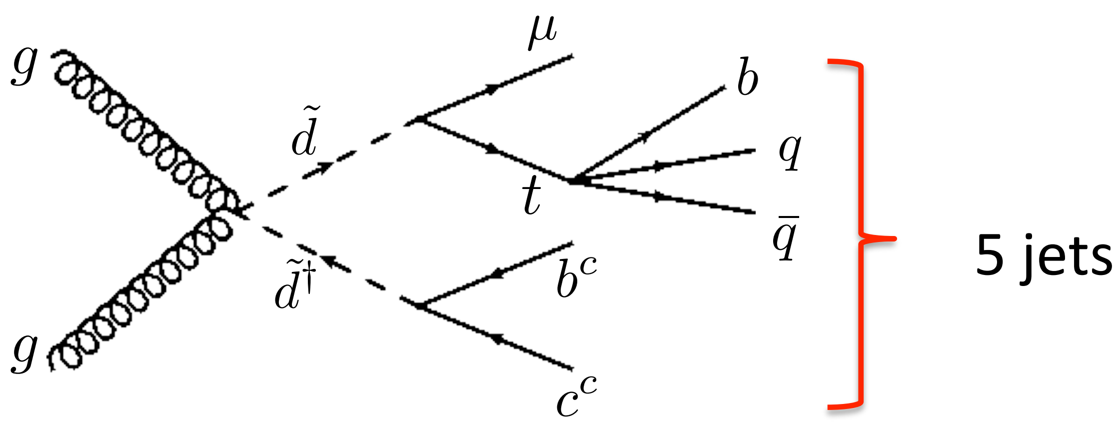
Baryogenesis once more, at the LHC.

Collider signature



- For simplicity, only consider hadronic top
- Signal: 5 jets + muon
- Charge asymmetry $\sigma_{\mu^- + 5j} > \sigma_{\mu^+ + 5j}$

Collider signature

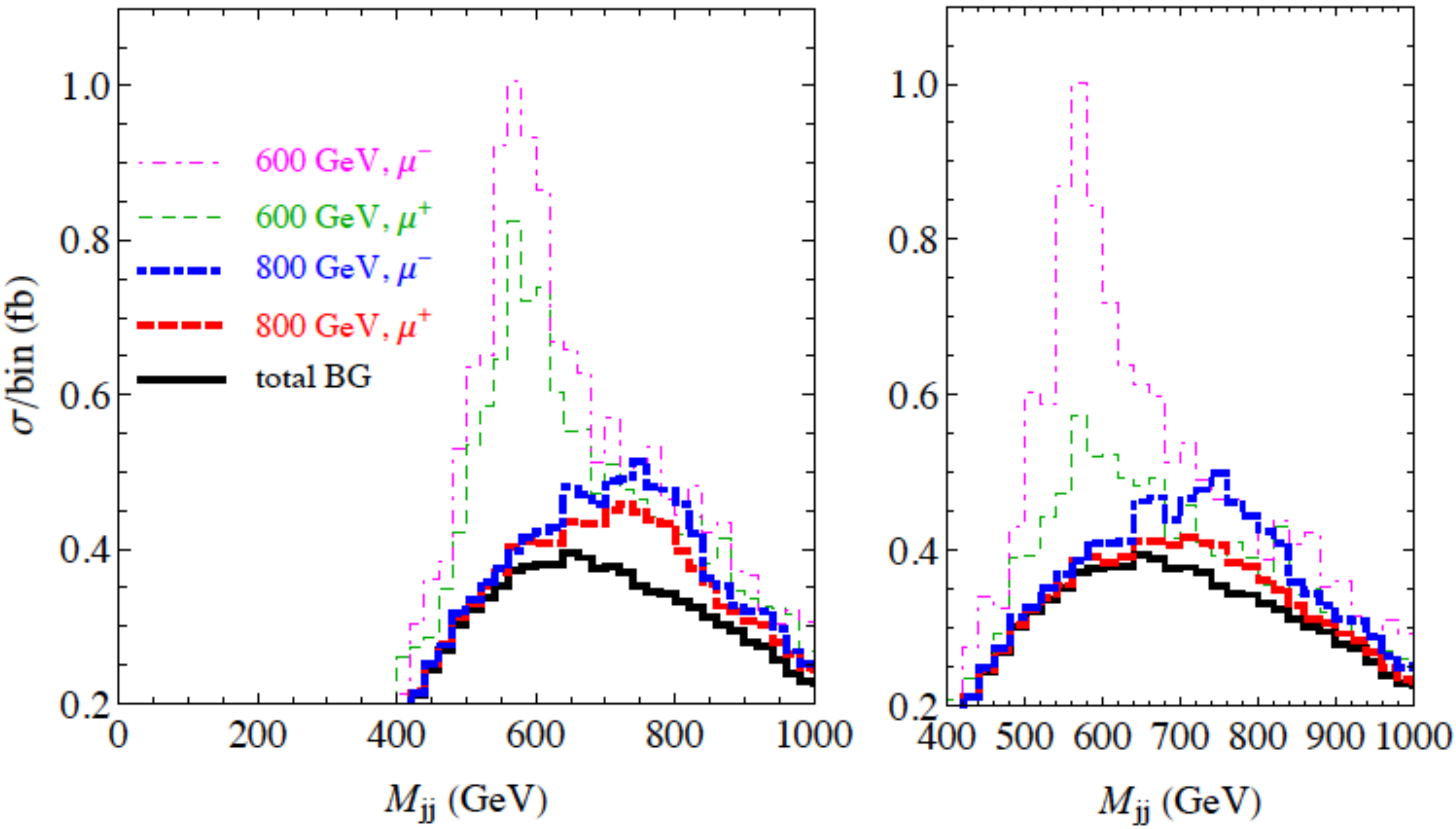
- Cuts:
  - A hard muon and at least three hard jets

    $p_T(\mu) > 170\ \mathrm{GeV} \quad p_T(j_{1,2}) > 200\ \mathrm{GeV} \quad p_T(j_3) > 150\ \mathrm{GeV}$
  - To reduce the W+jets background

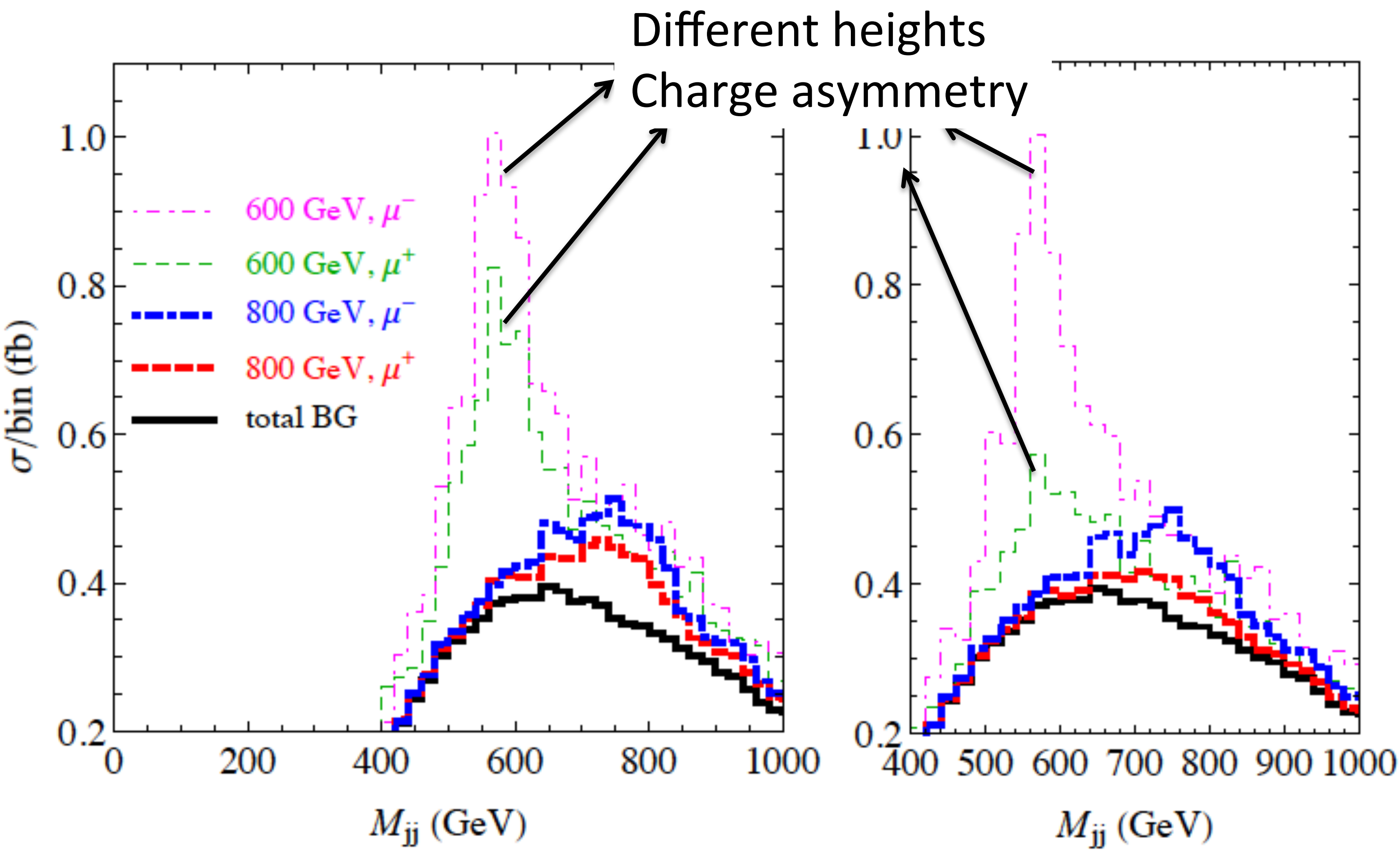
    $\mathrm{MET} < 30\ \mathrm{GeV}$
- Main background from QCD: jet faking muon.
  - Fake rate < 10^{-4} ATL-PHYS-PUB-2009-068
- Reconstruct the $\tilde{d},\ \tilde{d}^\dagger$ peak
  - For each events, find the closest $M(j_1,j_2)$ and M(mu,rest).

Collider signature

14 TeV LHC



Collider signature



Collider constraints

- $\mathcal{L} \simeq \lambda_i'' \bar{b}^c P_R c \tilde{d}_i + \lambda_i' (\bar{t} P_R \mu^c - b P_R \nu^c) \tilde{d}_i$

process	signal	relevant data
$(\bar{b}\bar{c})(bc)$	$4j$	—
$(t\mu^-)(\bar{t}\mu^+)$	$\mu^+\mu^- 2b4j$ $\mu^+\mu^-\ell^\pm 2b2j\not{E}_T$ $\mu^+\mu^-\ell^+\ell'^- 2b\not{E}_T$	Leptoquark Chargino-Neutralino
$(t\mu^-)(\bar{b}\bar{\nu}),\ (\bar{t}\mu^+)(b\nu)$	$\mu^\pm 2b2j\not{E}_T$ $\mu^\pm\ell^\mp 2b\not{E}_T$	Leptoquark Stop
$(b\nu)(\bar{b}\bar{\nu}),$	$2b\not{E}_T$	Sbottom
$(b\nu)(bc),\ (\bar{b}\bar{\nu})(\bar{b}\bar{c})$	$2b1j\not{E}_T$	Multijet+$\not{E}_T$
$(t\mu^-)(bc),\ (\bar{t}\mu^+)(\bar{b}\bar{c})$	$\mu^\pm 2b3j$ $\mu^\pm\ell^\mp 2b1j\not{E}_T$	Our signal

Collider constraints

- $\mathcal{L} \simeq \lambda_i'' \bar{b}^c P_R c \tilde{d}_i + \lambda_i' (\bar{t} P_R \mu^c - b P_R \nu^c) \tilde{d}_i$

$$\sigma_{\text{prod}} \frac{1-\varepsilon}{1+\varepsilon} \text{Br}$$

4 jets

$$\sigma_{\text{prod}} \left[\frac{1}{1+\varepsilon} \text{Br} + \frac{1-\varepsilon}{1+\varepsilon} \text{Br}^2 \right]$$

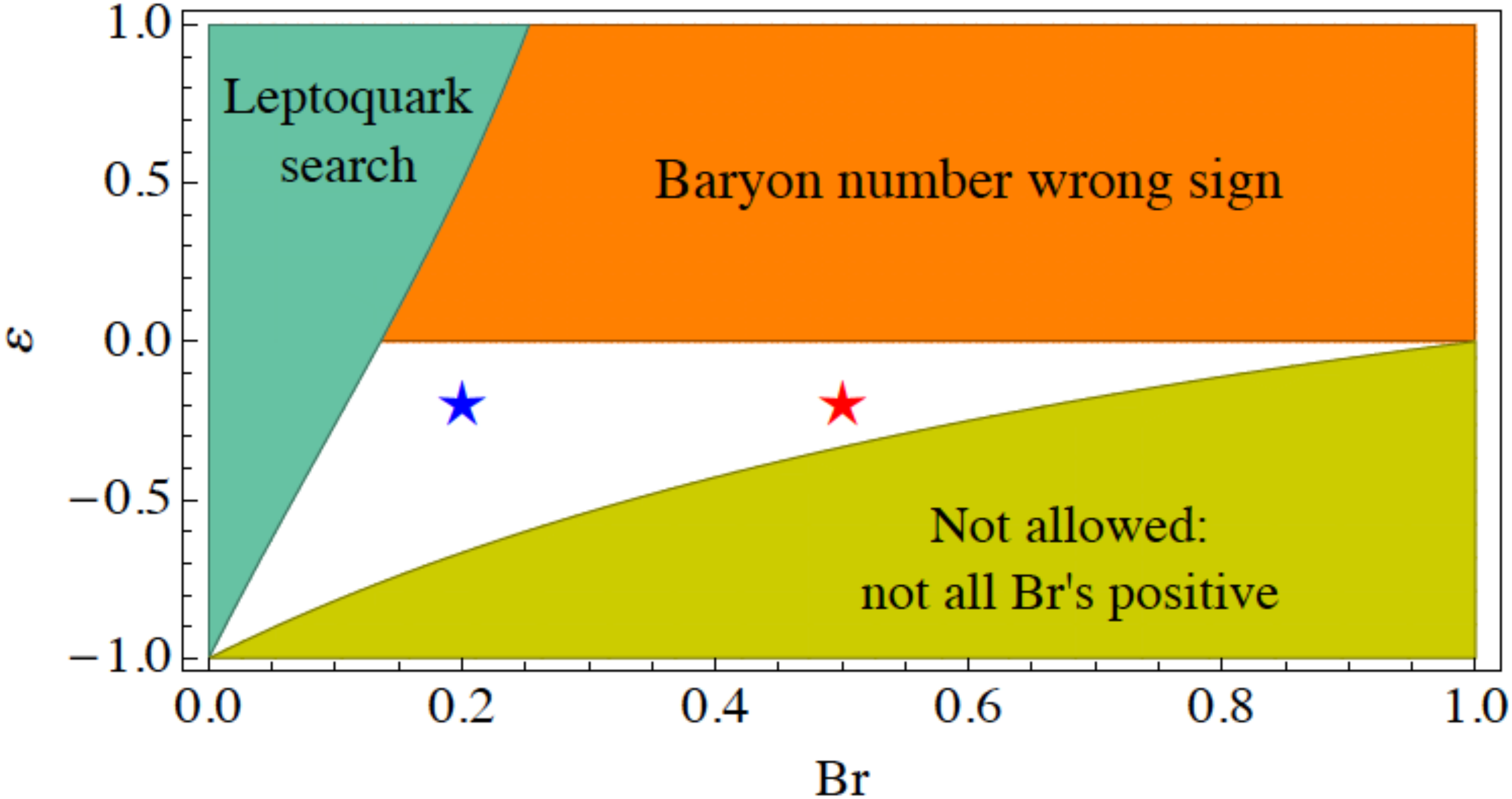
$\mathrm{t\bar{t}} + \mu^+ \mu^-$

$b\bar{b} + \nu\bar{\nu}$

$\mathrm{t}\mu^- \mathrm{\bar{b}}\nu$

Collider constraints

- $m_{\tilde{d}} = 600\ \mathrm{GeV}$



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Realistic model

- CP violation (re-visit)
  - Non-degenerate case $(|m_{\tilde{d}_1} - m_{\tilde{d}_2}| \gg \Gamma_{\tilde{d}})$

$$\epsilon_1 \mathrm{Br}_1 = \frac{\mathrm{Im}(\lambda_1'' \lambda_1'^{\,*} \lambda_2' \lambda_2''^{*})}{(|\lambda_1''|^2 + |\lambda_1'|^2)(|\lambda_2''|^2 + |\lambda_2'|^2)} F_2(m_{\tilde{d}_2}^2 / m_{\tilde{d}_1}^2)$$

$$\downarrow$$

$$\frac{2\Gamma_2}{m_{\tilde{d}_2}} \left[\frac{1}{1-x} - 3 + (2+3x) \log\left(\frac{1+x}{x}\right) \right]$$

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$$\frac{2\Gamma_2}{m_{\tilde{d}_2}} \left[\frac{1}{1-x} - 3 + (2+3x) \log\left(\frac{1+x}{x}\right) \right]$$

$$\sim |\lambda_2|^2 \sim 10^{-12}$$

  - A resonance is in need!

Realistic model

- CP violation (re-visit)
  - Resonant case $\quad (|m_{\tilde{d}_1} - m_{\tilde{d}_2}| \approx \Gamma_{\tilde{d}})$

$$\epsilon_1 \mathrm{Br}_1 = \frac{\mathrm{Im}(\lambda_1'' \lambda_1'^{\,*} \lambda_2' \lambda_2''^{*})}{(|\lambda_1''|^2 + |\lambda_1'|^2)(|\lambda_2''|^2 + |\lambda_2'|^2)} \frac{(m_{\tilde{d}_1} - m_{\tilde{d}_2})(\Gamma_{\tilde{d}_2}/2)}{(m_{\tilde{d}_1} - m_{\tilde{d}_2})^2 + (\Gamma_{\tilde{d}_2}/2)^2}$$

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$\Gamma_{\tilde{d}} \sim \lambda^2$ 14 orders smaller than $m_{\tilde{d}}$

  – How to generate such a small mass gap naturally?

Realistic model

- SU(2) horizontal symmetry between $\tilde{d}_1\ ,\ \tilde{d}_2$
  - Explicitly broken only by the RPV interactions
  - Loop induced mass splitting is just comparable to Γ
- In SUSY models, we introduce superfields

$$D_1', D_2', \bar{D}_1', \bar{D}_2'$$

- For grand unification, we lift them to vector-like “5” representation in SU(5). Gauge couplints are still perturbative at the Unification scale.

Realistic model

- A spectrum

d'	Spinor part of D’	$d' \to \tilde{t}\mu$
$\tilde{t}$	stop	$\tilde{t} \to qq$ SM quarks
$\tilde{d}$	Scalar part of D’	

MSSM

- Can we realize this model in MSSM?
  - Who can be the decaying squarks?
  - $m^2_{\tilde{d}_1} - m^2_{\tilde{d}_2} < (\mathrm{MeV})^2$ requires a tuning
  - Finite temperature correction due to different Yukawa couplings (Higgs thermal loop).

$$(m_1 - m_2)(T) \approx \Delta m_0 + \frac{y_1^2 - y_2^2}{2m_{\tilde{q}_1} M_h} \left(\frac{M_h T}{2\pi}\right)^{3/2} e^{-M_h/T}$$

  - Only Yukawa couplings for *d* and *s* are small enough to suppress the thermal effect.

Summary

- We proposed a baryogenesis model, in which the baryon number is generated through the decay of squarks.
- The baryogenesis process “repeates” at the LHC.
- The smoking gun signal is the lepton-charge asymmetry.
- This model can be realized in RPV SUSY models.