Probing High-Scale SUSY

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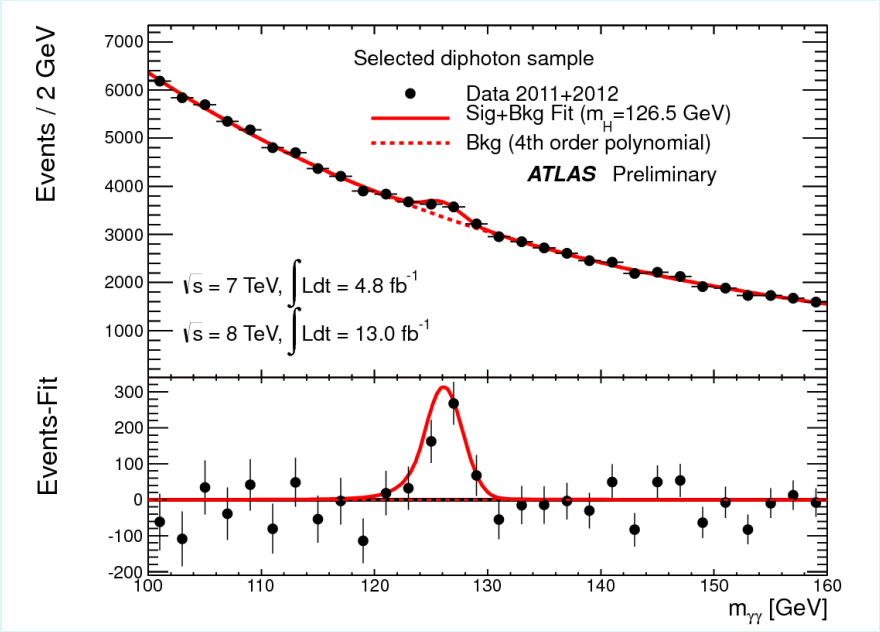
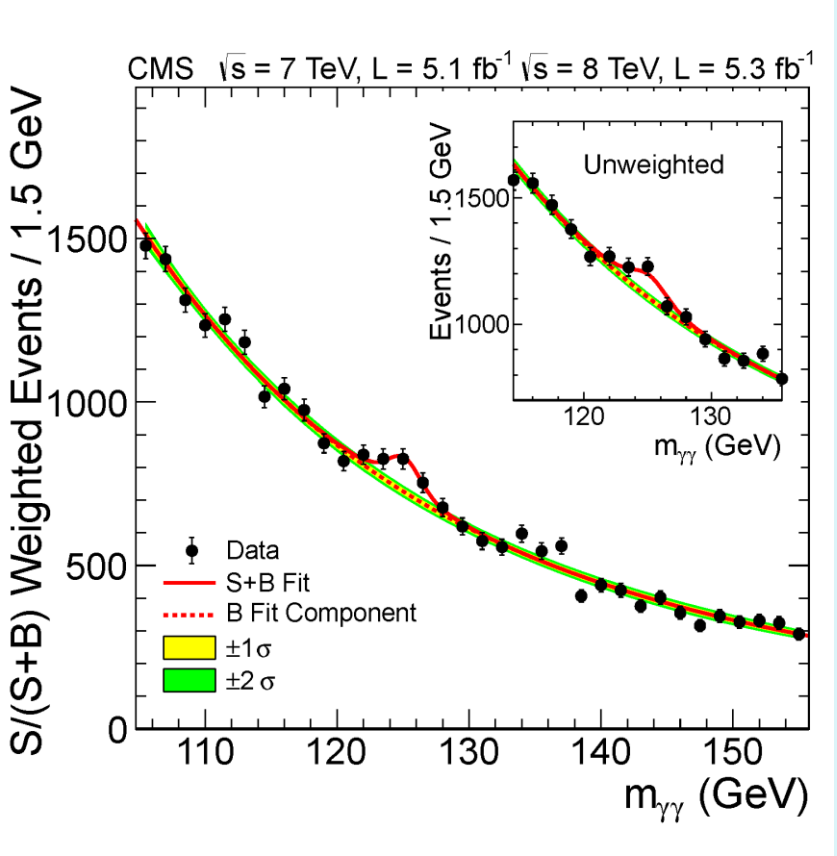
Based on

Lawrence J. Hall, Yasunori Nomura, SS, 1210.2395
Ryosuke Sato, SS Kohsaku Tobioka, 1207.3608, 1307.7144
and work in progress

“Higgs” Discovered!





SUSY Higgs

$$V(H) = \frac{\lambda}{2}(HH^\dagger - v^2)^2$$

In MSSM

$$\lambda = \frac{1}{4}(g_2^2 + \frac{3}{5}g_1^2)\cos^2(2\beta)$$

$$m_h = m_Z \cos(2\beta) \lesssim 91 \text{ GeV}$$

$$\lambda = \lambda_{\text{MSSM}} + \lambda_{\text{SUSY-breaking}} + \lambda_{\text{new-interaction}}$$

How to make 125 GeV Higgs

Scalar top
- Large mass
- A-term

"4-th" family

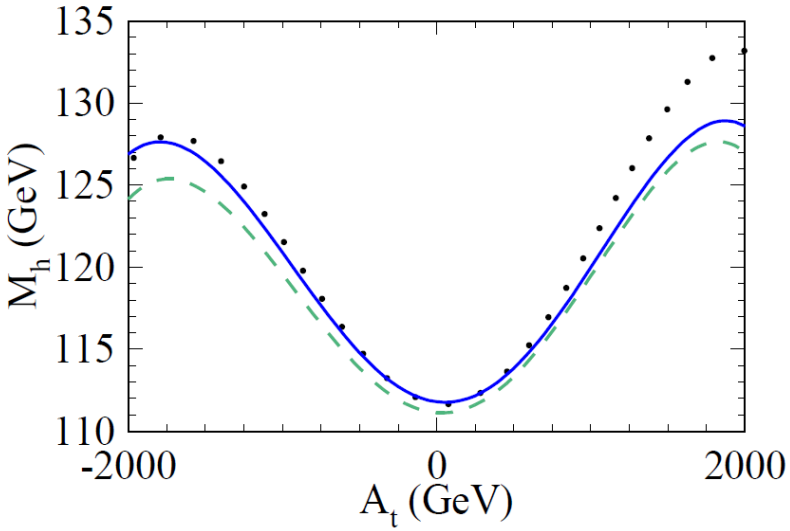
NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

Higgs Mass from Stop

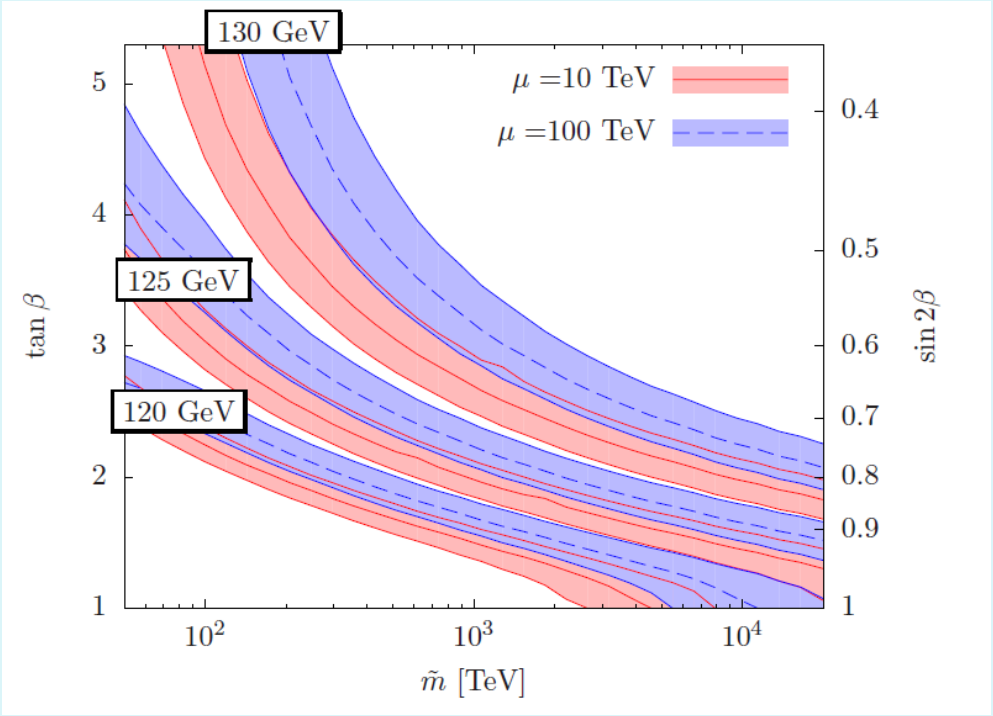
Large A-term

[1005.5709]



$$
\begin{aligned}
m_{\tilde{t}_1} &= 500\ \text{GeV}, \\
m_{\tilde{t}_2} &= 1000\ \text{GeV}, \\
m_{\tilde{g}} &= 500\ \text{GeV}, \\
m_{\tilde{q}} &= 2000\ \text{GeV}, \\
\mu_{\text{SUSY}} &= 800\ \text{GeV}, \\
\tan\beta &= 10, \\
M_A &= 1500\ \text{GeV}.
\end{aligned}
$$

A = 0



Benefit and demerit

Benefit

- Hierarchy Problem
- GUT unification
- DM

Possible demerit

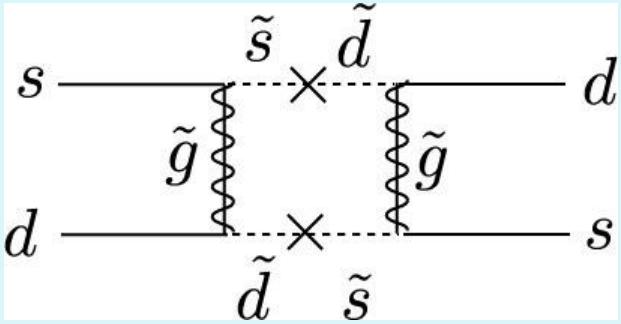
- Flavor/CP Problem
- Cosmological Gravitino Problem
- UV completion

Flavor/CP Problem

Flavor violating soft terms

$$\tilde{s}\tilde{d}^{\dagger}$$

Flavor violating operator



$$\frac{m^2_{\tilde{s}\tilde{d}}}{m^2_{\tilde{s}}} \lesssim 10^{-2} \quad \text{for } M_{\rm SUSY} = 500 \text{ GeV}$$

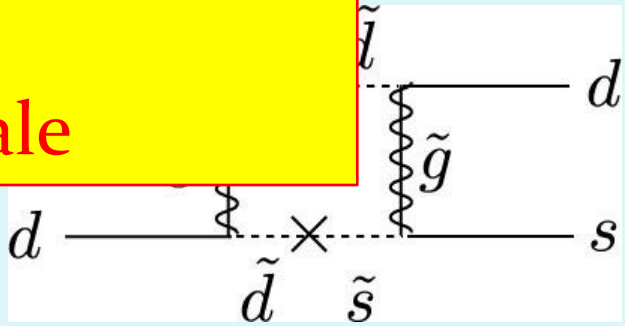
Flavor/CP Problem

Flavor violating soft terms

$\tilde{s}\tilde{d}^{\dagger}$

fine-tuning to forbid such terms
or
Large SUSY scale

Flavor violat



$$\frac{m^2_{\tilde{s}\tilde{d}}}{m^2_{\tilde{s}}} \lesssim 10^{-2} \quad \text{for } M_{\rm SUSY} = 500 \text{ GeV}$$

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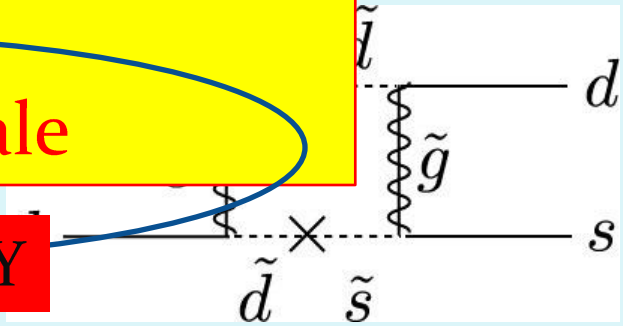

"Unnatural" SUSY

$$\frac{m^2_{\tilde{s}\tilde{d}}}{m^2_{\tilde{s}}} \lesssim 10^{-2} \quad \text{for } M_{\rm SUSY} = 500 \text{ GeV}$$

Benefit and demerit

Benefit

- ~~Hierarchy Problem~~
- GUT unification
- DM

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- ~~Cosmological Gravitino Problem~~
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SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term

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Scalar >>O(100) TeV

Flavor/CP problem

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Scalar >>O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term

Scalar >>O(100) TeV

Flavor/CP problem

Light fermion

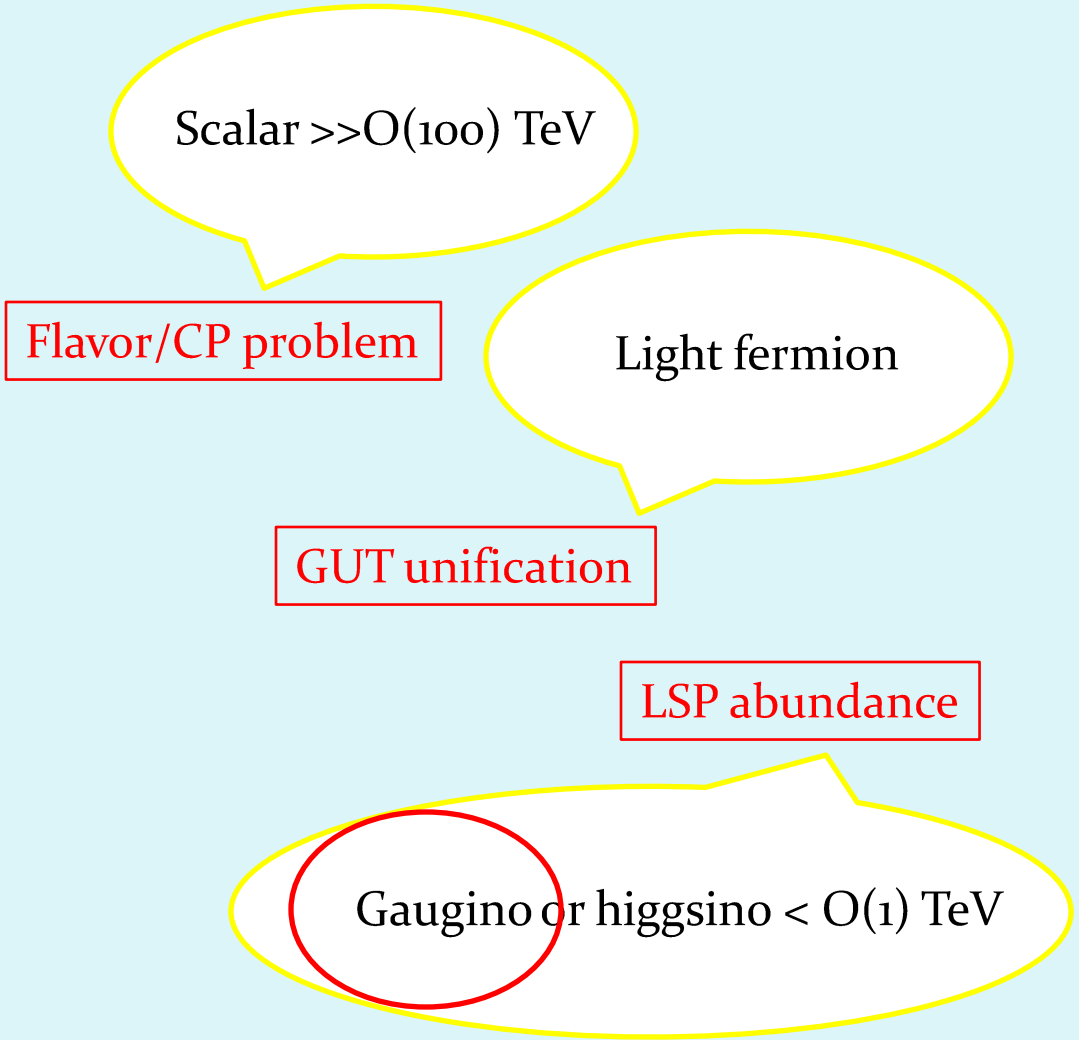
GUT unification

LSP abundance

Gaugino or higgsino < O(1) TeV

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term



Simple Realization

SUSY breaking field X has a charge

- Scalar mass

$$K \ni -\frac{c}{M_*^2} X^\dagger X \Phi^\dagger_{\rm MSSM} \Phi_{\rm MSSM}$$

- Gaugino mass

- Mu term

Simple Realization

SUSY breaking field X has a charge

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Not necessarily planck scale
Lower M* ➡ Heavy scalar

- Gaugino mass

- Mu term

Simple Realization

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$$\cancel{X W^\alpha W_\alpha}$$

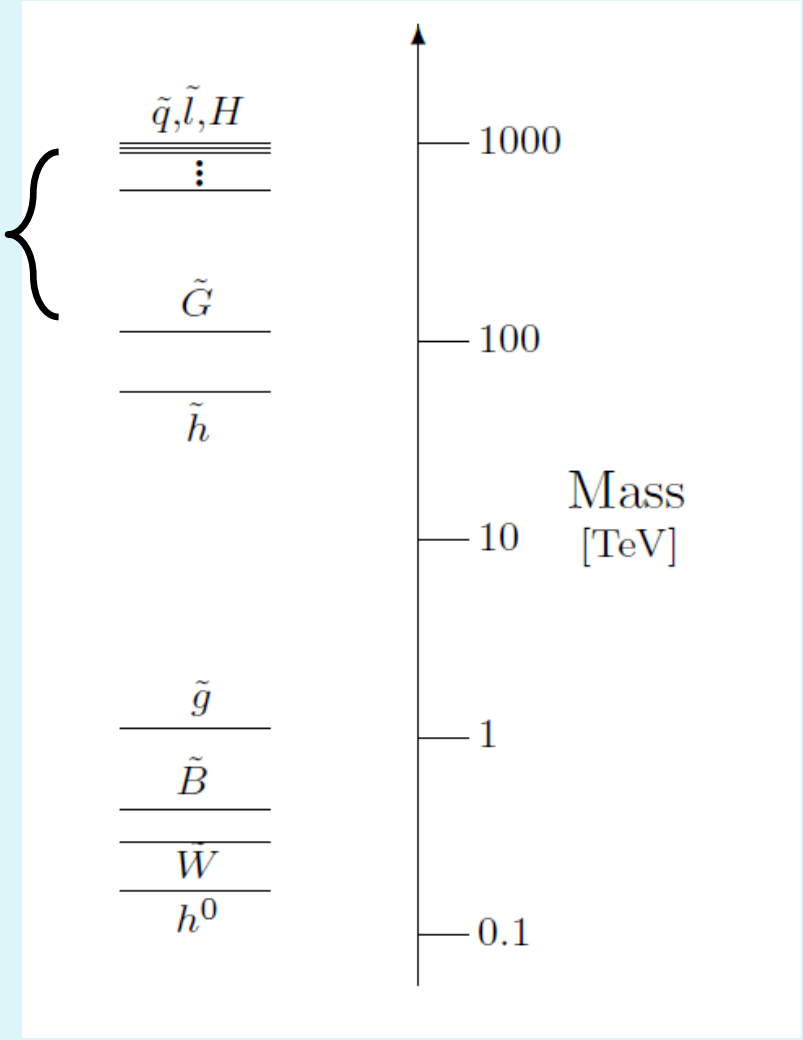
AMSB effect

- Mu term

$$K \ni c H_u H_d$$

Mass Spectrum

$$r_* \equiv \frac{\sqrt{3}M_{\rm Pl}}{M_*}$$



Sfermion Constraint

Cosmology and Flavor Physics

Gravitino Coupling

SUSY breaking field X has a charge

- Scalar mass

$$K \ni -\frac{c}{M_*^2} X^\dagger X \Phi^\dagger_{\rm MSSM} \Phi_{\rm MSSM}$$

$$X \sim (A + \theta\Psi + \theta^2 F)$$

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$$X \sim (A + \theta\Psi + \theta^2 F)$$

Goldstino ~ Gravitino

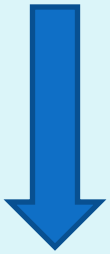
$$K \to \frac{F}{M_*^2} \Psi \phi_{\rm MSSM} \psi_{\rm MSSM}$$

Small M* leads strong coupling to goldstino (~gravitino)

Dark matter abundance

Small M* leads strong coupling to goldstino (~gravitino)

$$\phi_{\rm MSSM} \to \tilde{G}_{3/2}\psi_{\rm MSSM}$$ (Freeze –in contribution)

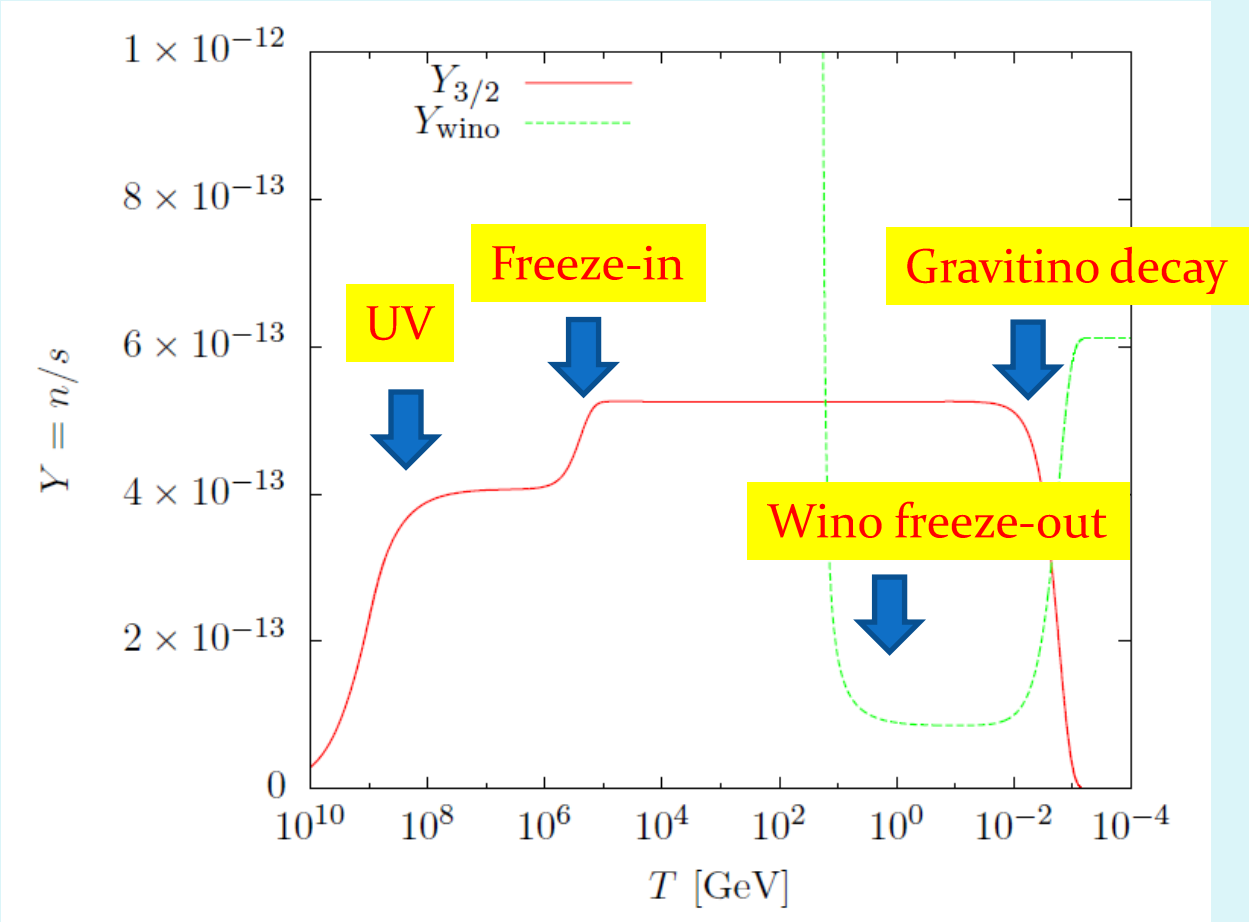


Lower Temperature

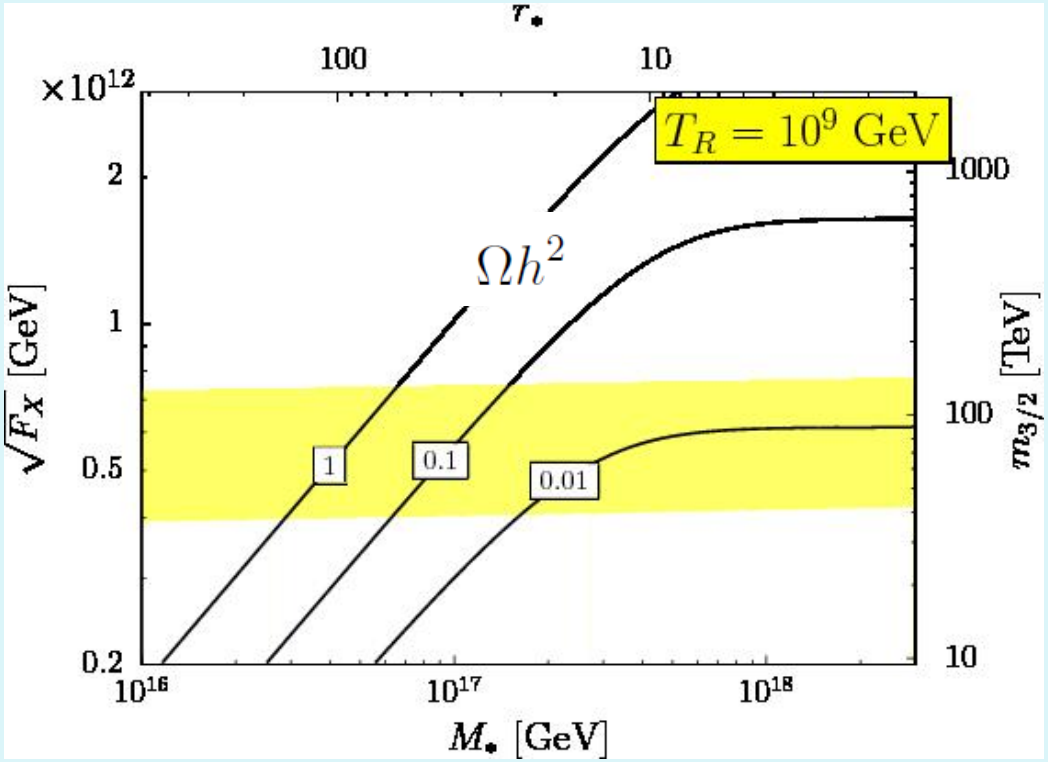
$$\tilde{G}_{3/2} \to \tilde{W}W$$

$$\Omega_{\tilde{W}^0}h^2 \lesssim 0.1$$

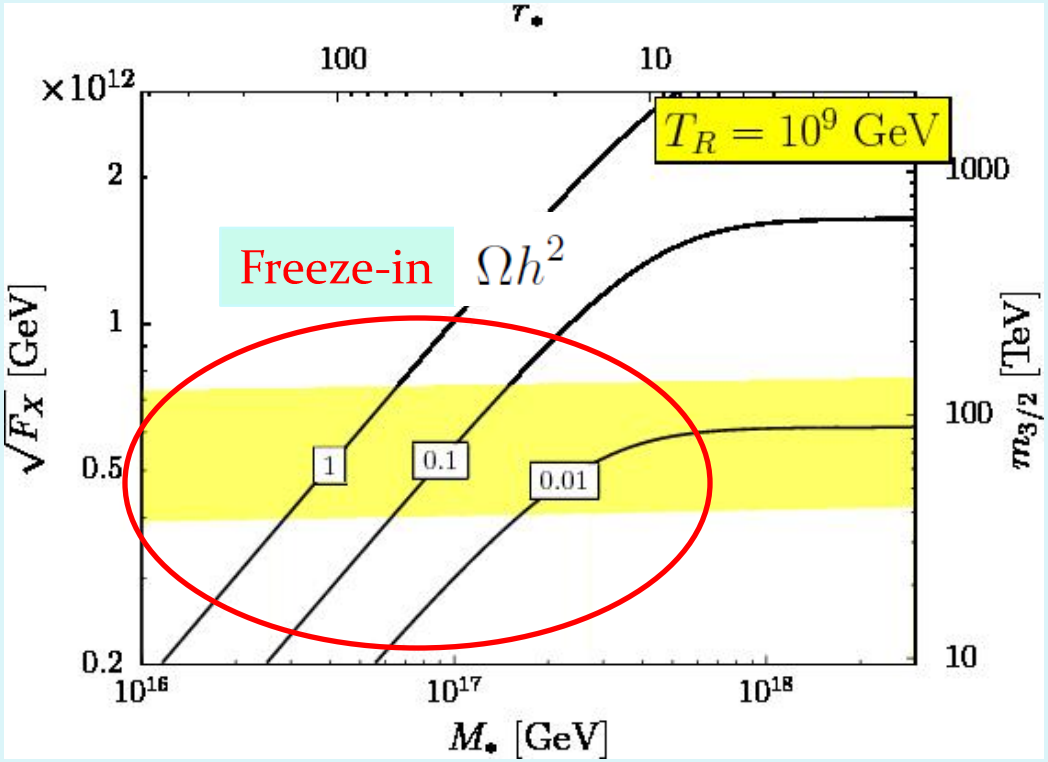
Thermal history



Abundance


T_*
100
10
$\times 10^{12}$
2
1
0.5
0.2
$T_R = 10^9$ GeV
Ωh^2
1
0.1
0.01
1000
100
10
$\sqrt{F_X}$ [GeV]
$m_{3/2}$ [TeV]
10^{16}
10^{17}
10^{18}
M_* [GeV]

Abundance


r_*
100
10
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$\sqrt{F_X}$ [GeV]
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Freeze-in
Ωh^2
1
0.1
0.01
1000
100
10
$m_{3/2}$ [TeV]
10^{16}
10^{17}
10^{18}
M_* [GeV]

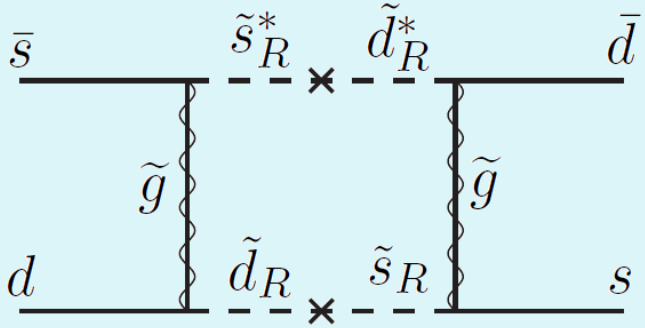
Sfermion Mass Upper Bound

Cosmological Bound

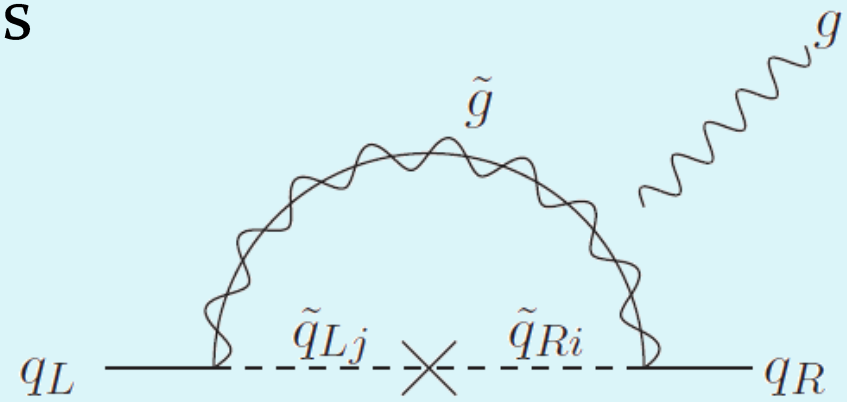
$$m_0 \lesssim 10^3 - 10^4 \text{ TeV}$$

Flavor Physics

- Delta F =2 process

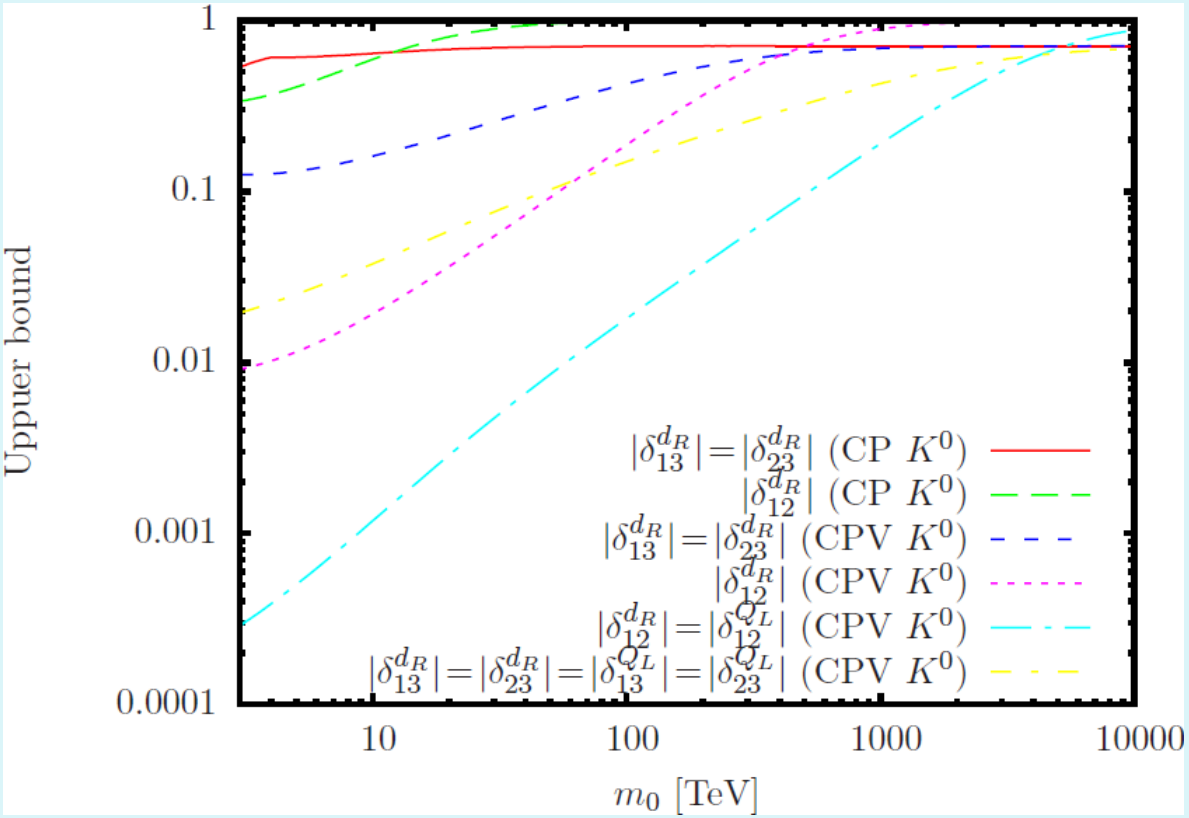


- Delta F= 0 process

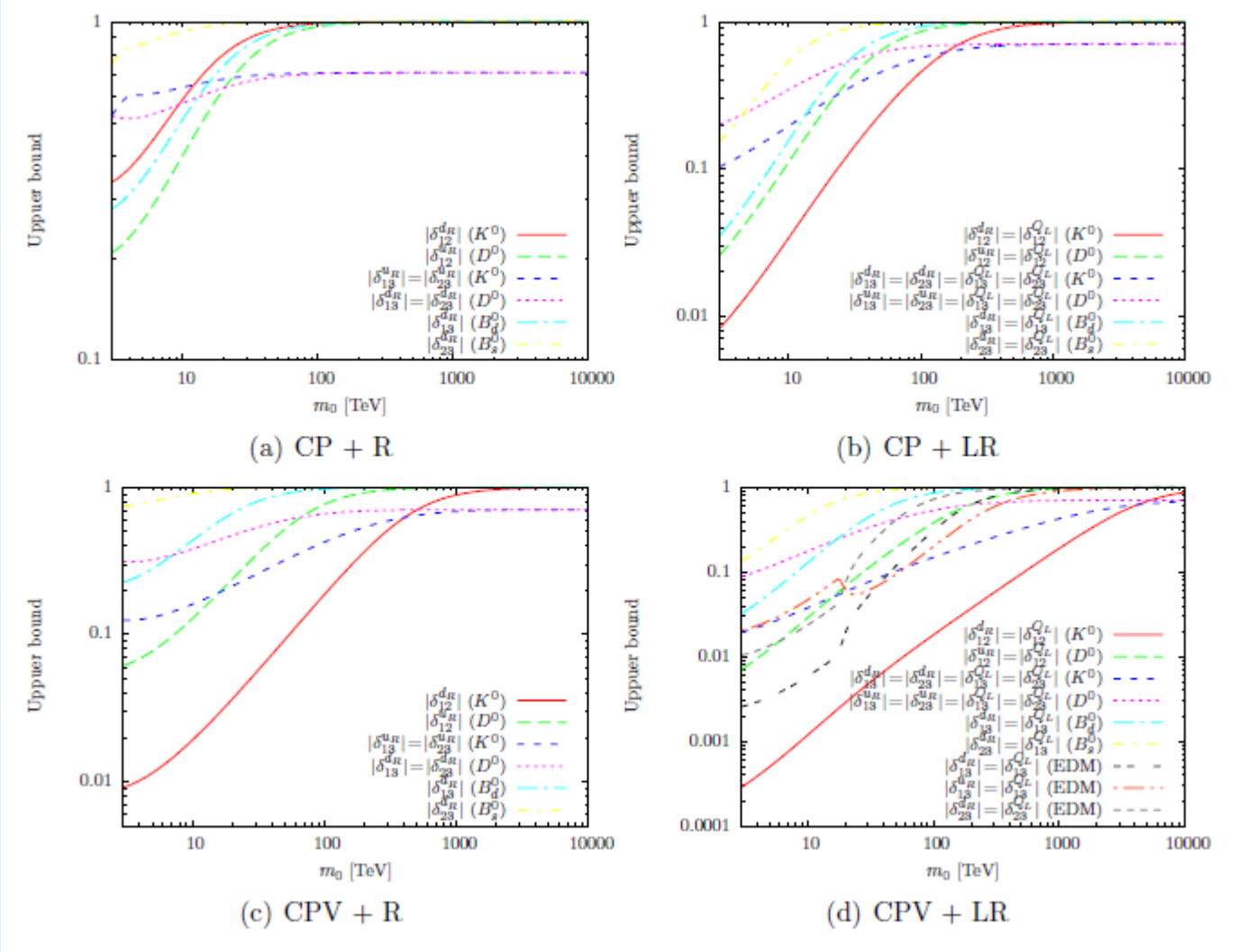


Example

$$m^2_{d_R} = m^2_0 \begin{pmatrix} 1 & \delta^{d_R}_{12} & \delta^{d_R}_{13} \\ \delta^{d_R *}_{12} & 1 & \delta^{d_R}_{23} \\ \delta^{d_R *}_{13} & \delta^{d_R *}_{23} & 1 \end{pmatrix}$$



Constraint on Structure



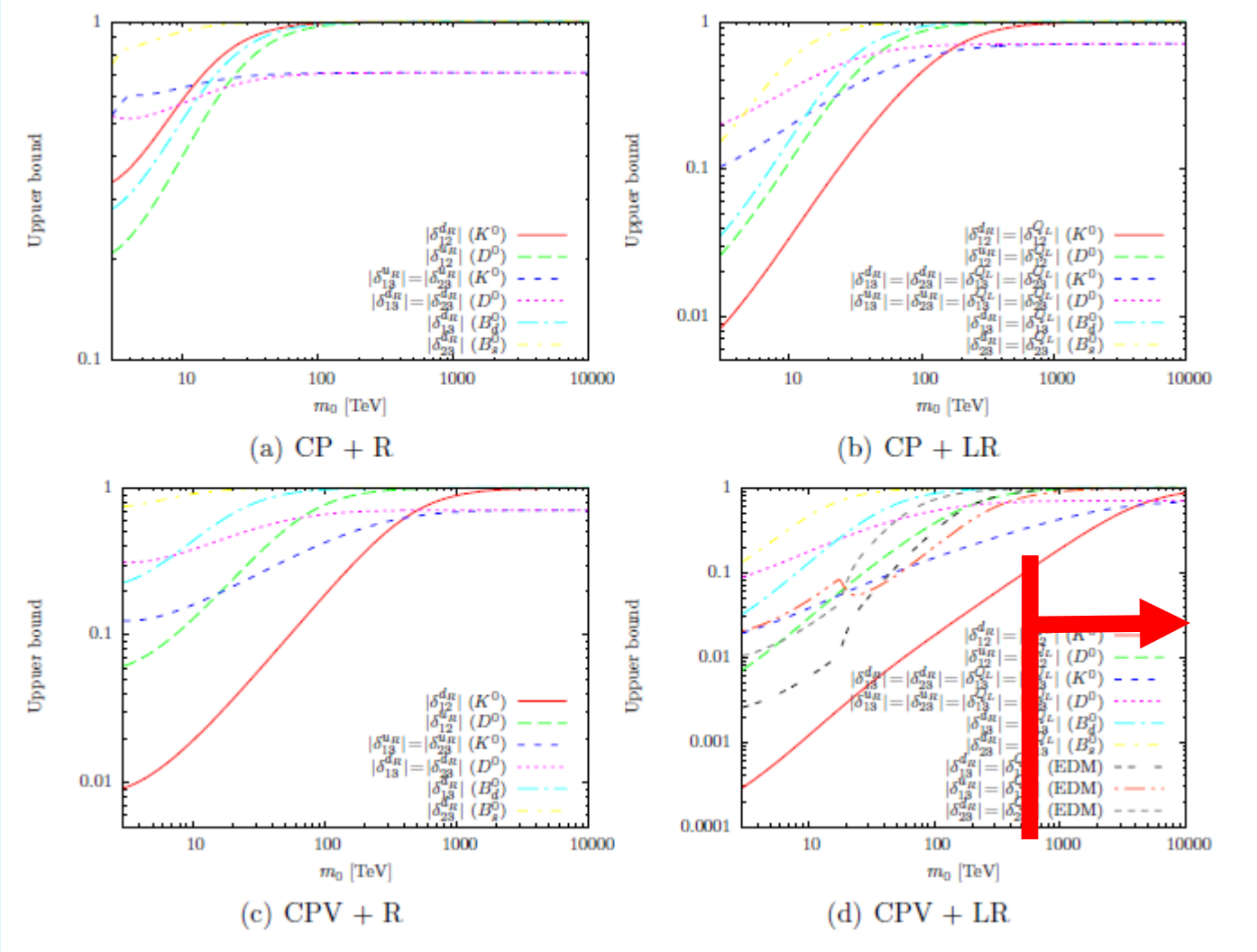
(a) CP + R

(b) CP + LR

(c) CPV + R

(d) CPV + LR

Constraint on Structure



Sfermion sector

Cosmological Bound

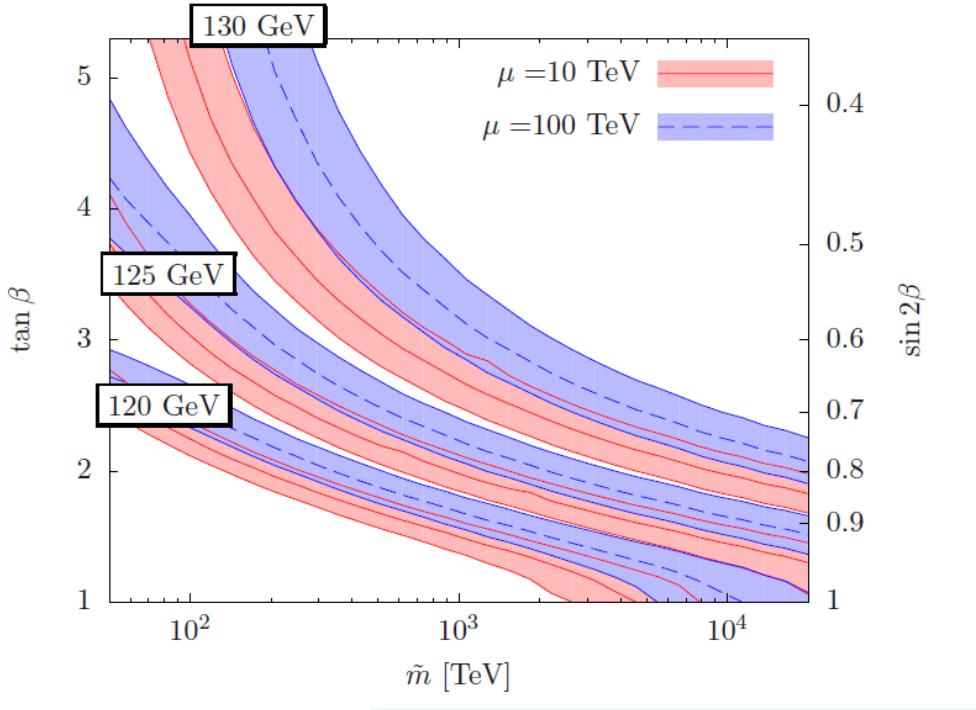
$$m_0 \lesssim 10^3 - 10^4 \text{ TeV}$$

Bound from Flavor violation

$$m_0 \gtrsim 10^3 \text{ TeV}$$

Sfermion secto

Cosmological Bound



$$m_0 \lesssim 10^{3}$$

Bound from Flavor violation

$$m_0 \gtrsim 10^3 \text{ TeV}$$

Sfermion Signal

$$m_0 \sim 1000 \text{ TeV}$$

- Cosmological Probe such as GW
- Gluino Decay

Sfermion Signal

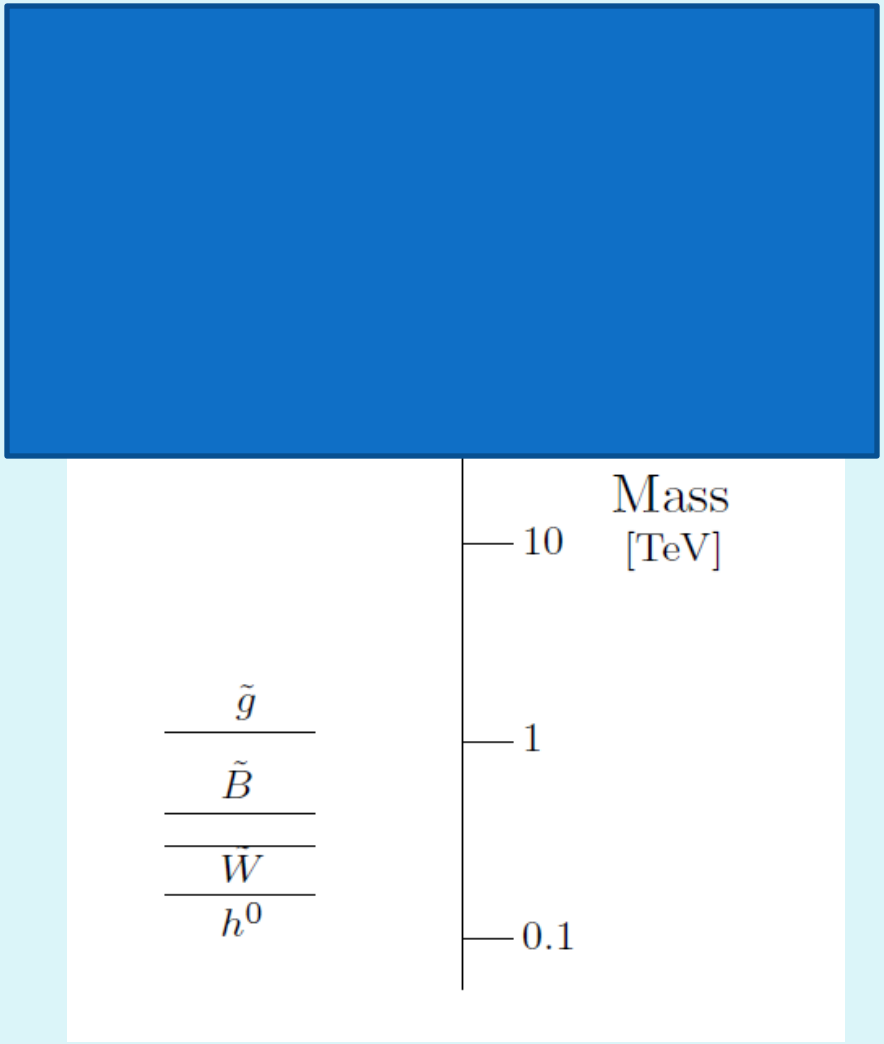
$$m_0 \sim 1000 \text{ TeV}$$

- Cosmological Probe such as GW
- Gluino Decay

Gluino Decay

Gluino is Stable

Integrated out Sfermions,
Gluino has “G-parity”

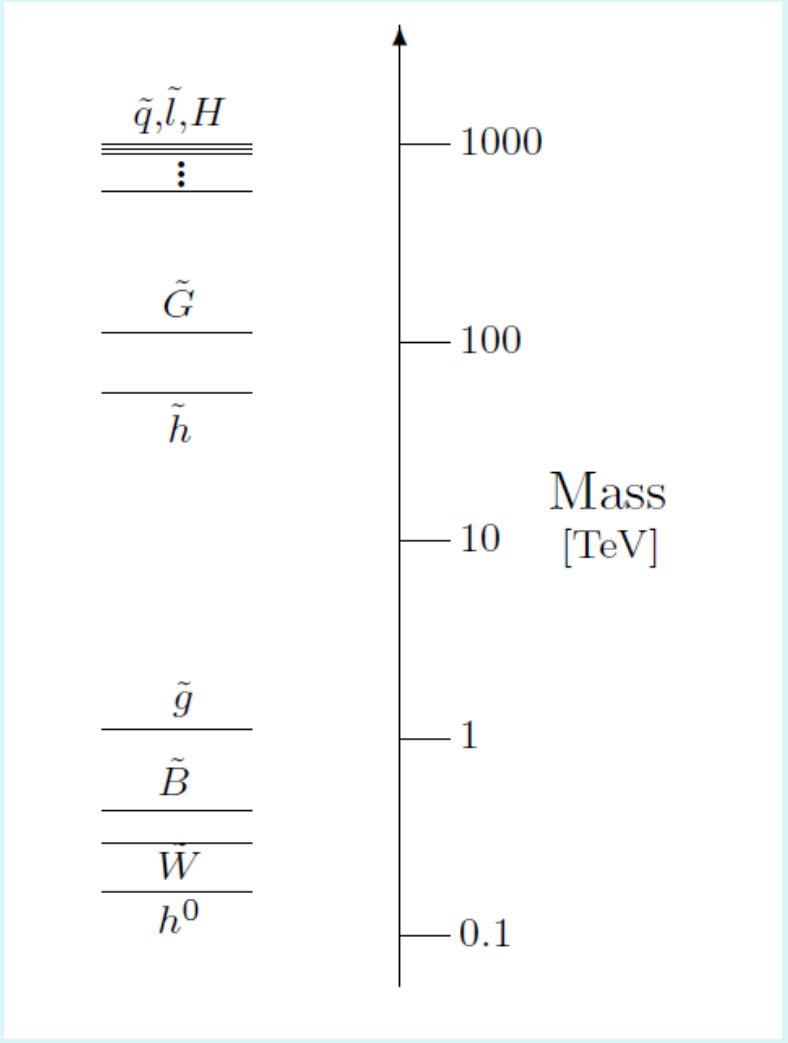


Stable at low energy

Gluino is Stable

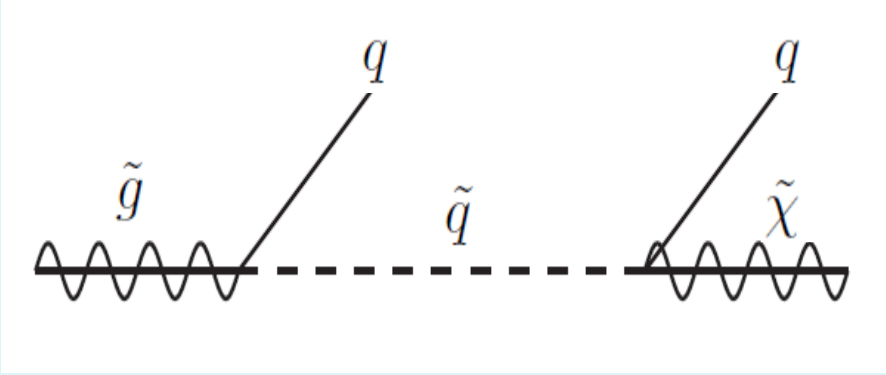
"G-parity" is broken via higher. Dim op. with squark exchange

Gluino decay is sensitive to sfermions.

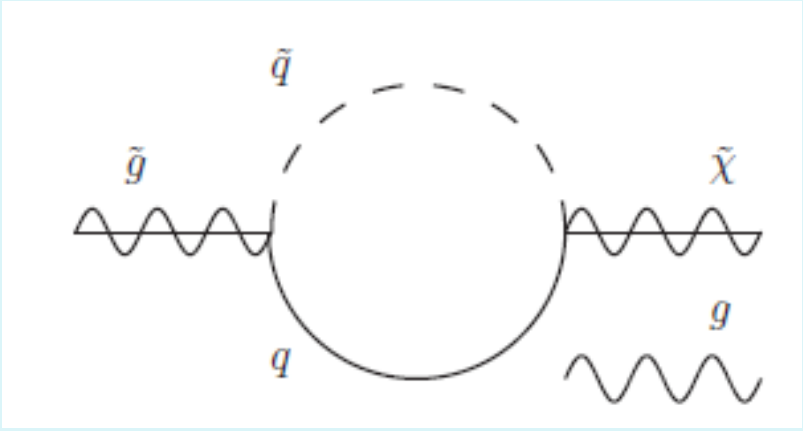


Gluino Decay

Mainly three body decay

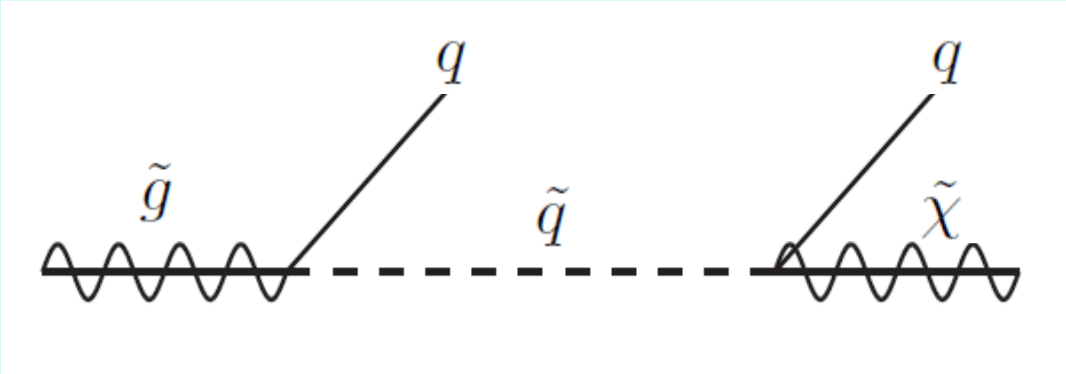


Tiny two body decay



Gluino Decay Width

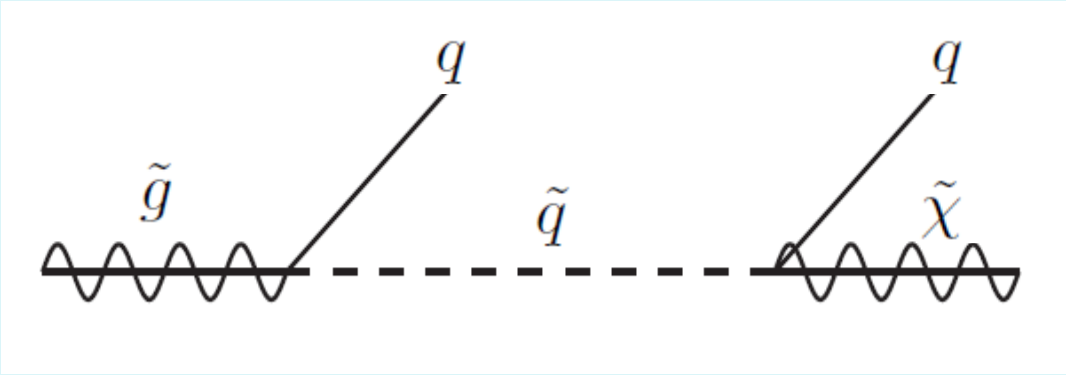
- Gluino



$$c\tau_{\tilde{g}} = O(1\text{ cm}) \left(\frac{M_{\tilde{g}}}{1\text{ TeV}}\right)^{-5} \left(\frac{\tilde{m}}{1000\text{ TeV}}\right)^{4}$$

Gluino Decay Width

- Gluino

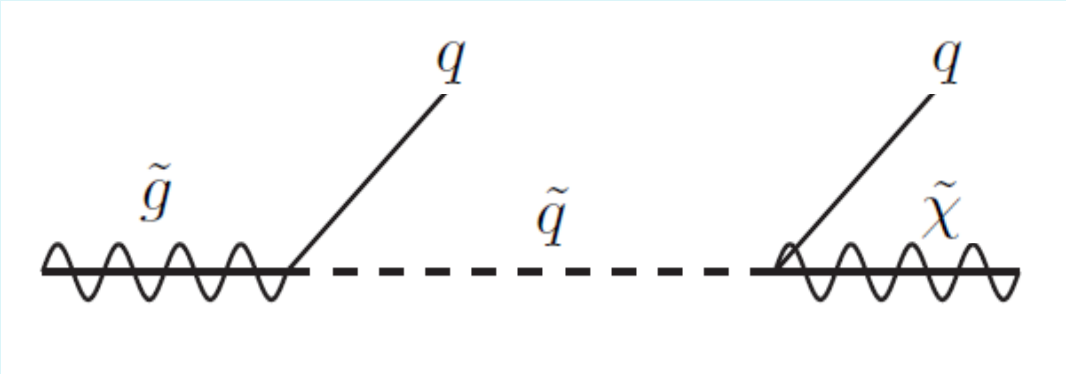


$$c\tau_{\tilde{g}} = O(1\ \mathrm{cm}) \left(\frac{M_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{-5} \left(\frac{\tilde{m}}{1000\ \mathrm{TeV}}\right)^{4}$$

Long enough to probe at collider

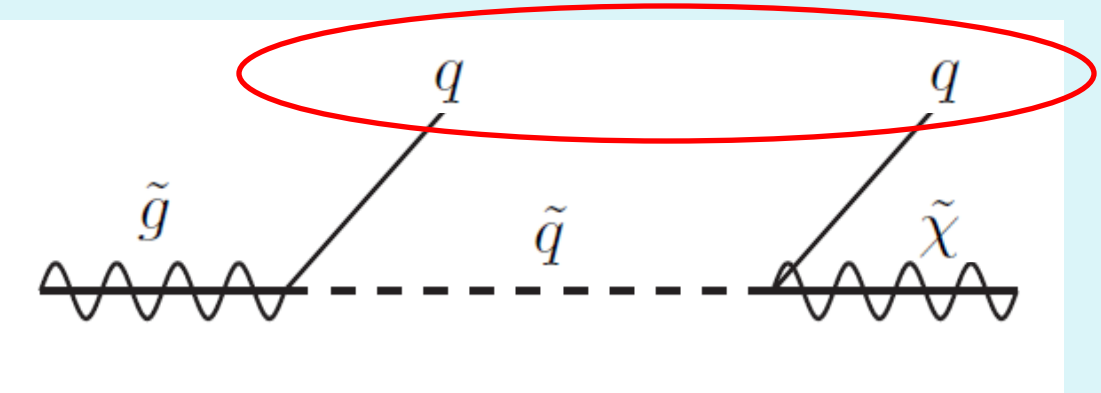
Decay mode

- Gluino



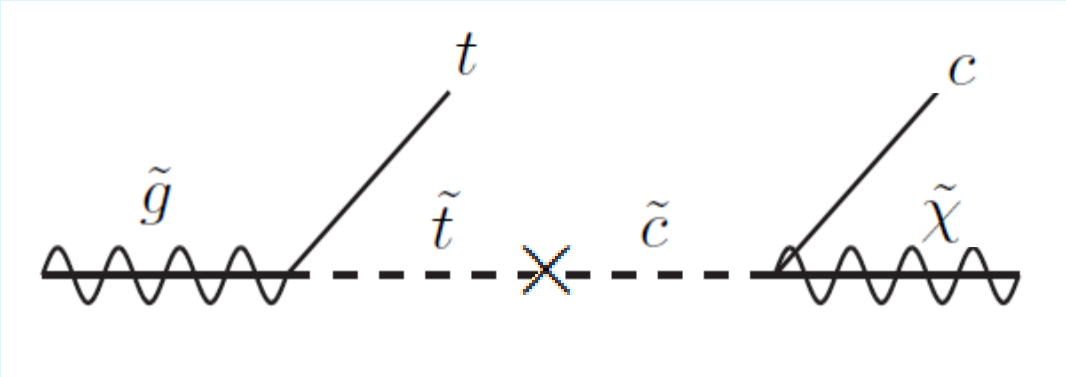
Decay mode

- Gluino



Decay mode

- Gluino

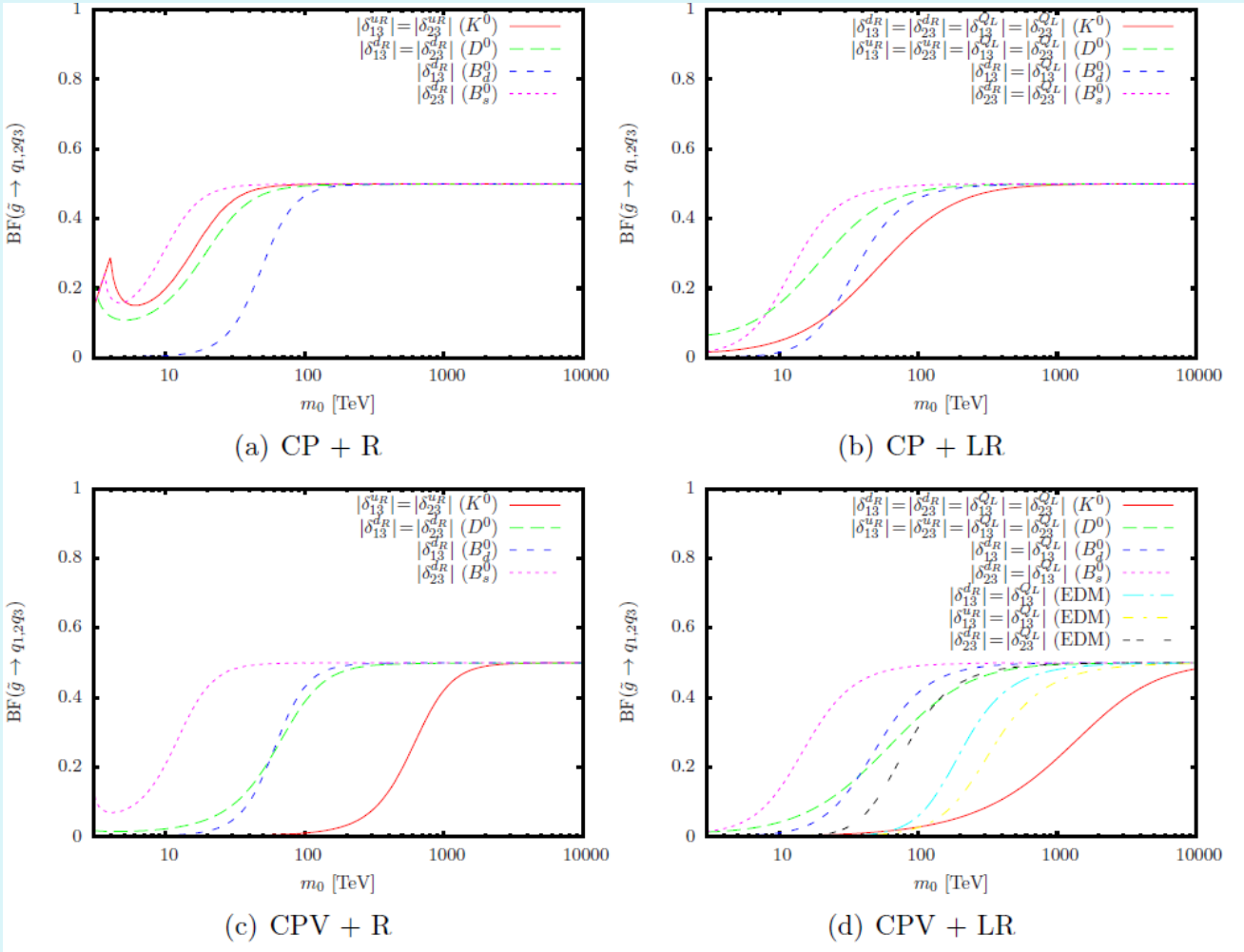


Squark can have flavor-violating structure

Flavorful gluino decay

How large FLV?

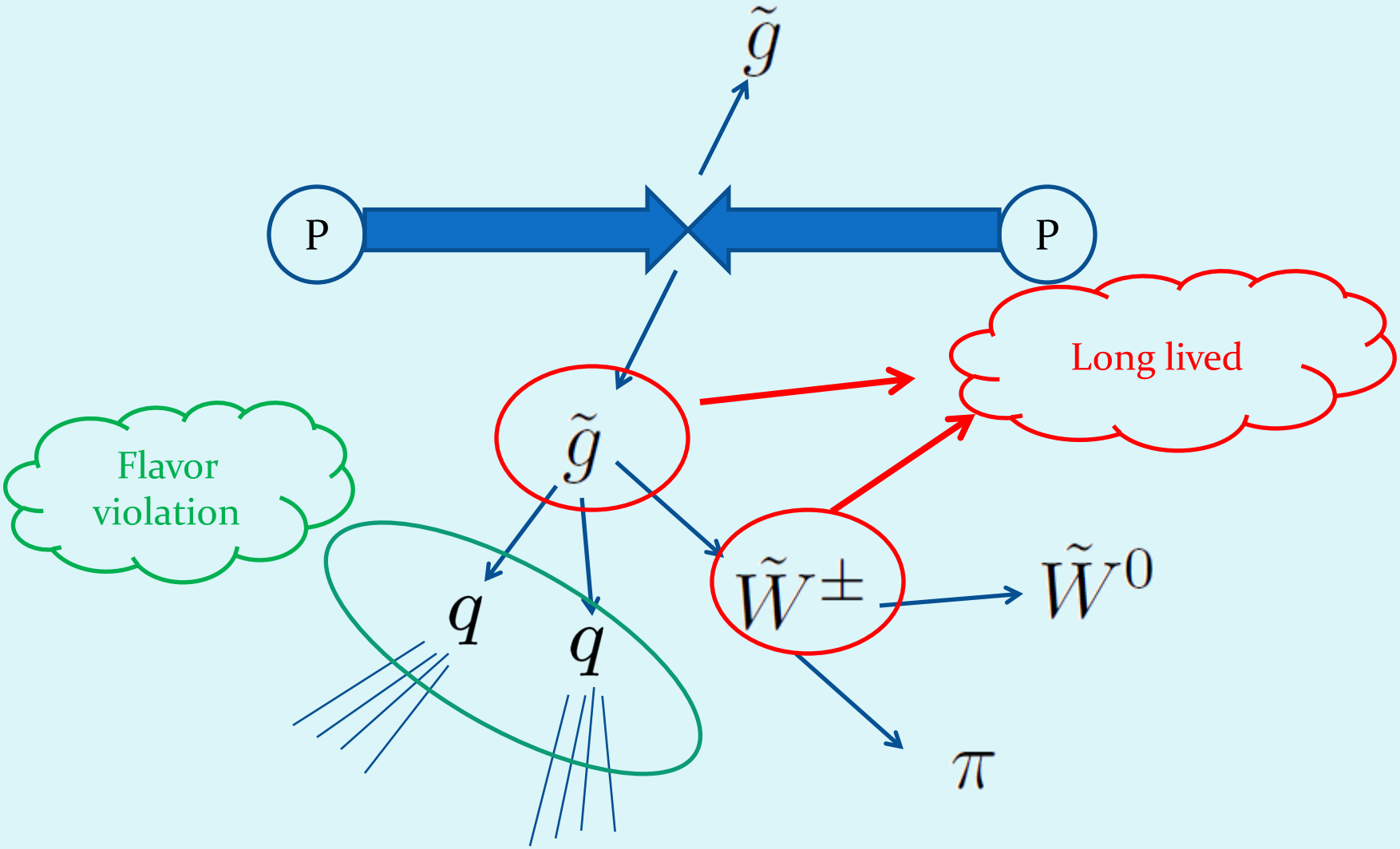
Upper bound on $\mathrm{BF}(\tilde{g} \to q^3 q^{1,2} \chi)$



(a) CP + R (b) CP + LR

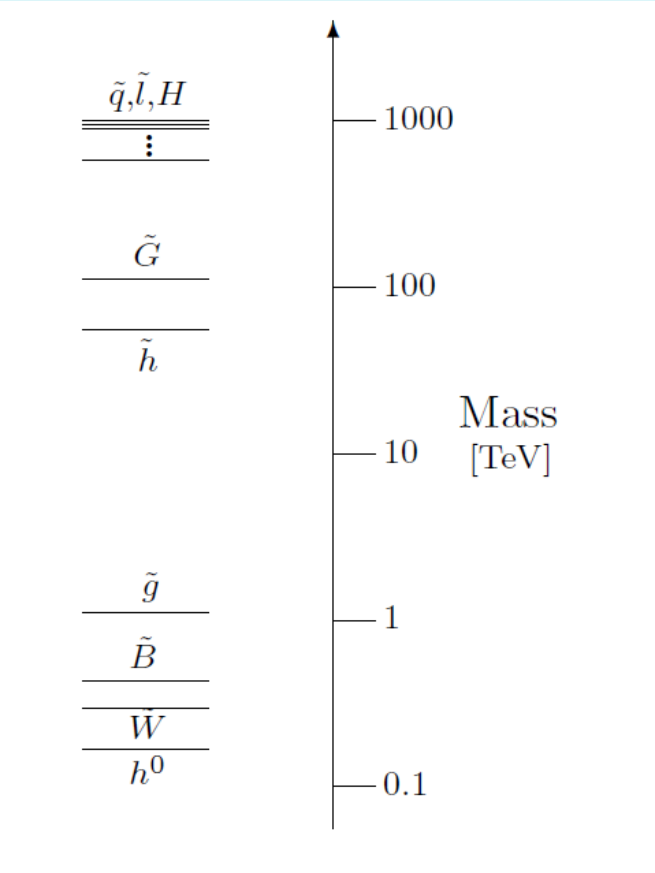
(c) CPV + R (d) CPV + LR

Displaced and Flavorful SUSY



Measurement of FLV Gluino Decay

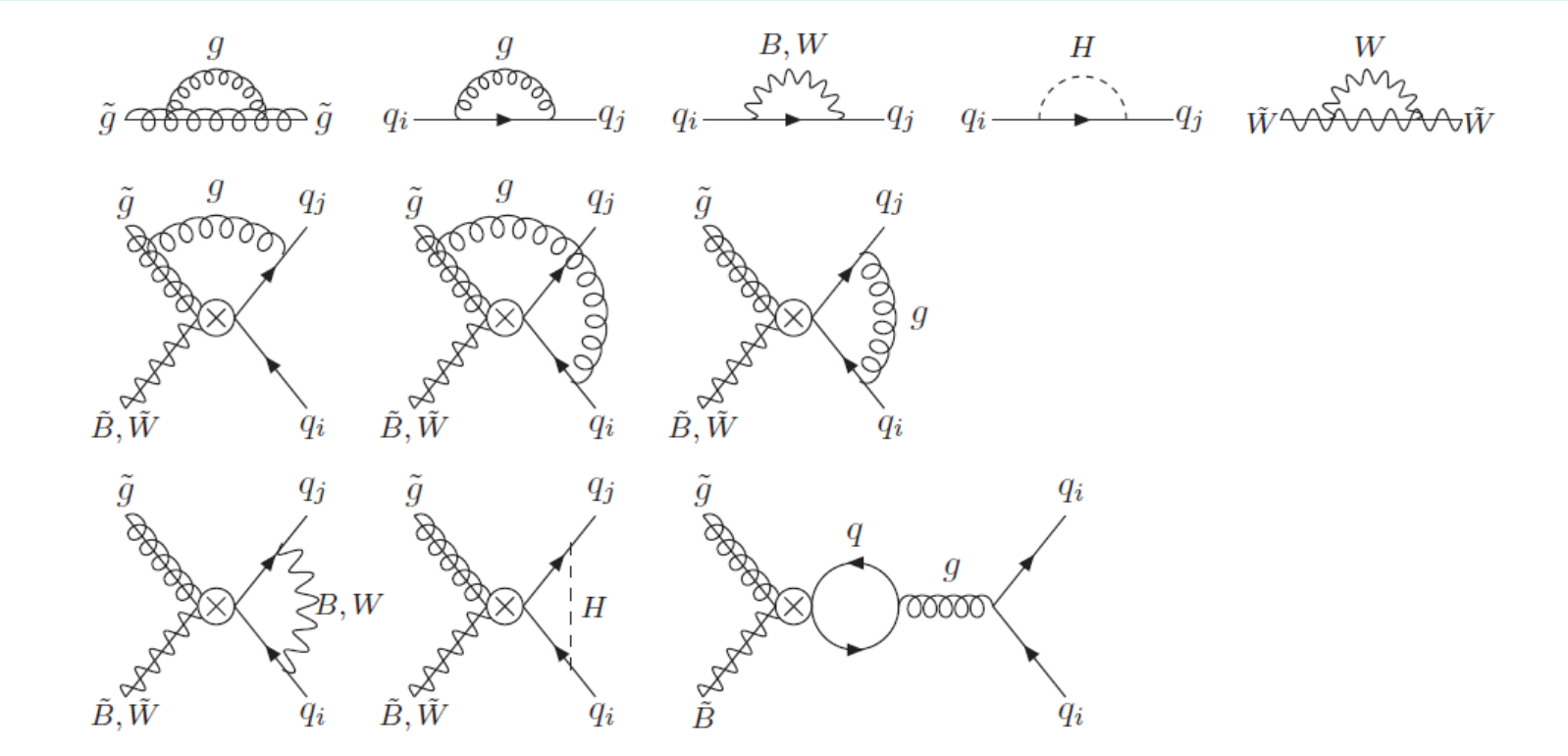
Gluino Decay



$$\mathcal{M}_{\text{gluino decay}} \sim (\text{tree}) + \frac{\alpha}{4\pi} \log\left(\frac{m_{\text{squark}}}{m_{\text{gluino}}}\right)$$

Gluino Decay RGE

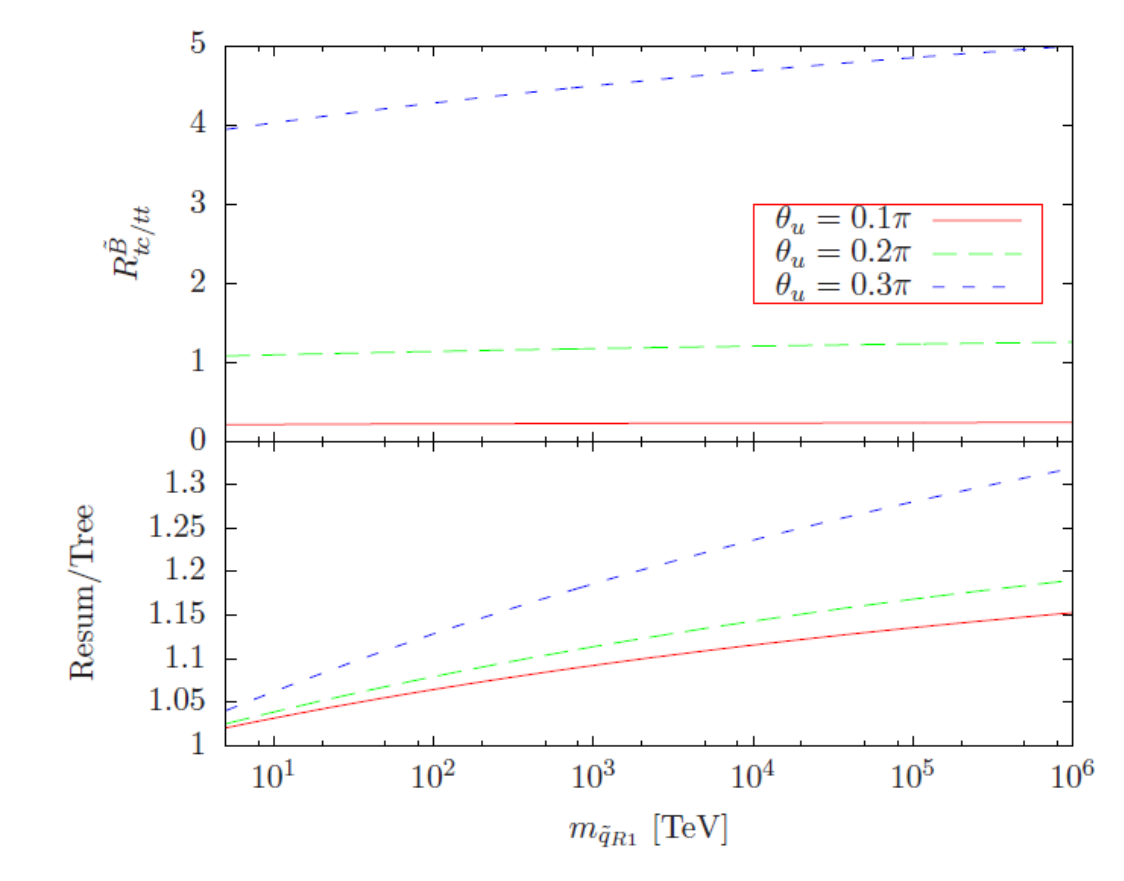
[R. Sato, SS, K.Tobioka, 1307.7144]



Tree vs RGE

$$\tilde{q}_{R1} = \cos\theta_u \tilde{t}_R + \sin\theta_u \tilde{c}_R.$$

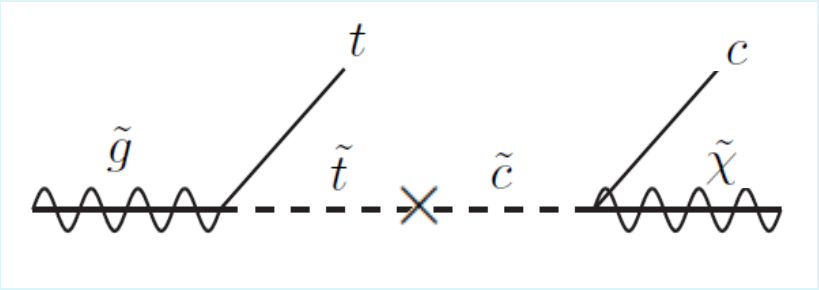
$$R^{\tilde{B}}_{tc/tt} = \frac{\Gamma(\tilde{g} \to \tilde{B} t\bar{c}/\tilde{B}\bar{t}c)}{\Gamma(\tilde{g} \to \tilde{B} t\bar{t})}$$



Measurement of FLV Gluino Decay

Case of prompt decay

Basic Strategy



Example point:

Gluino decay

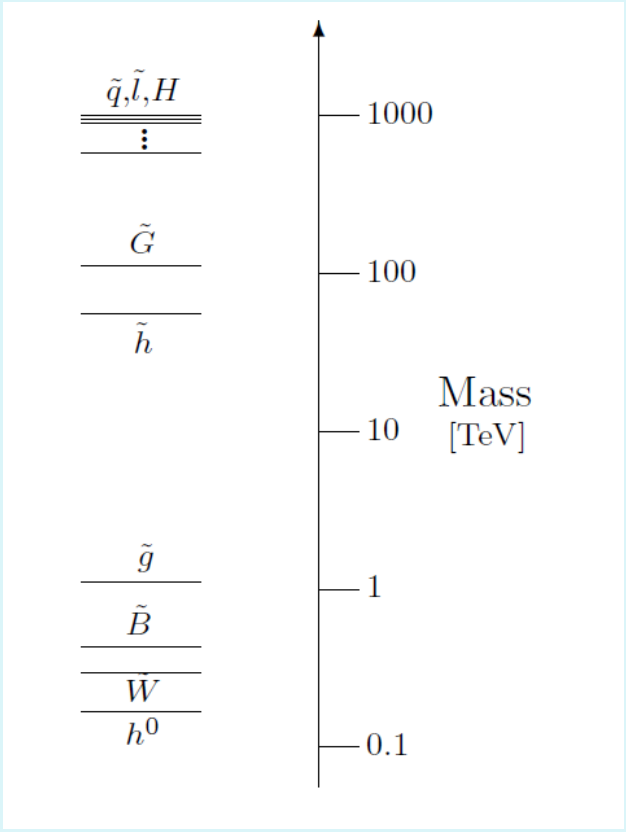
$$\tilde{g} \to tt\tilde{B}^0$$

$$\tilde{g} \to ut\tilde{B}^0$$

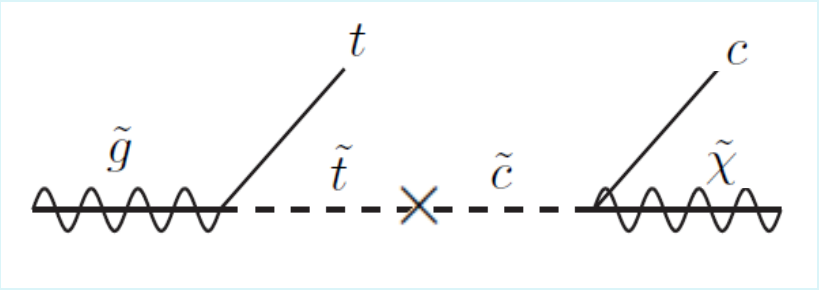
$$\tilde{g} \to uu\tilde{B}^0$$

Bino decay

$$\tilde{B} \to W(h)\tilde{W}$$



Basic Strategy



Example point:

Gluino decay

Induces b-jet and leptons (from W decay)

$$\tilde{g} \to t t \tilde{B}^0$$

$$\tilde{g} \to u t \tilde{B}^0$$

$$\tilde{g} \to u u \tilde{B}^0$$

# of b –jets and leptons depends on BF

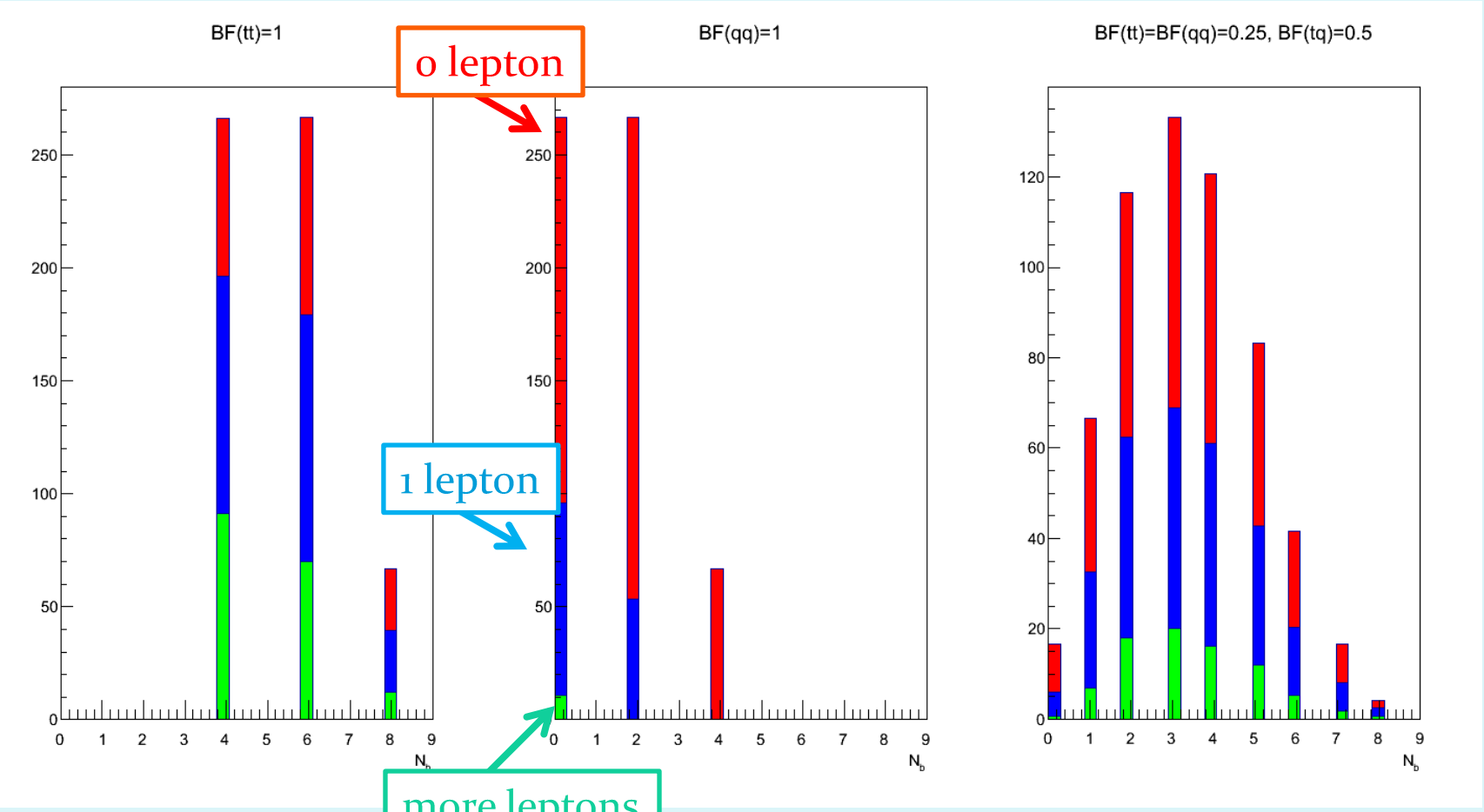
Simple b and lepton counting is useful

Bino decay

$$\tilde{B} \to W(h)\tilde{W}$$

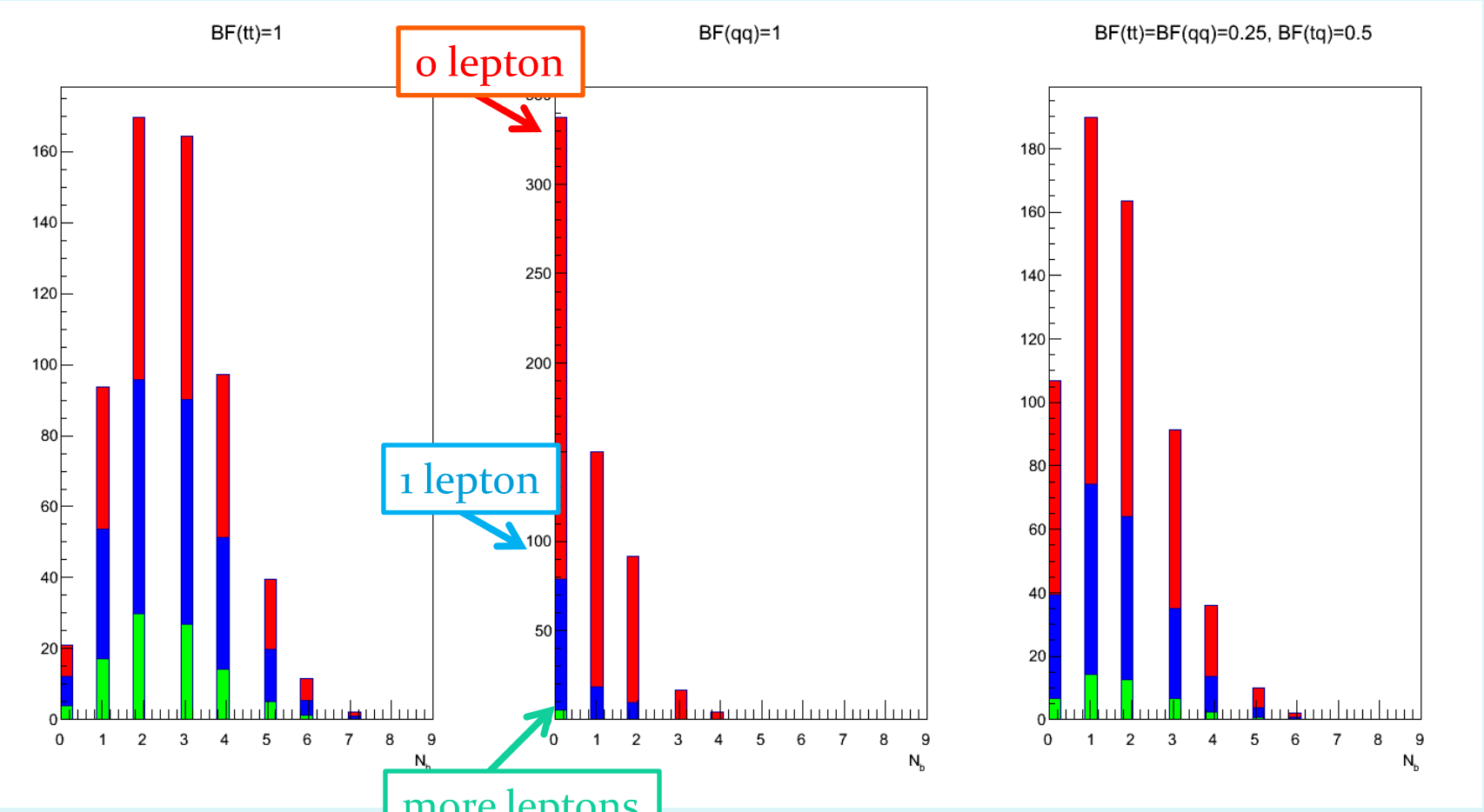
Basic Strategy

Parton level



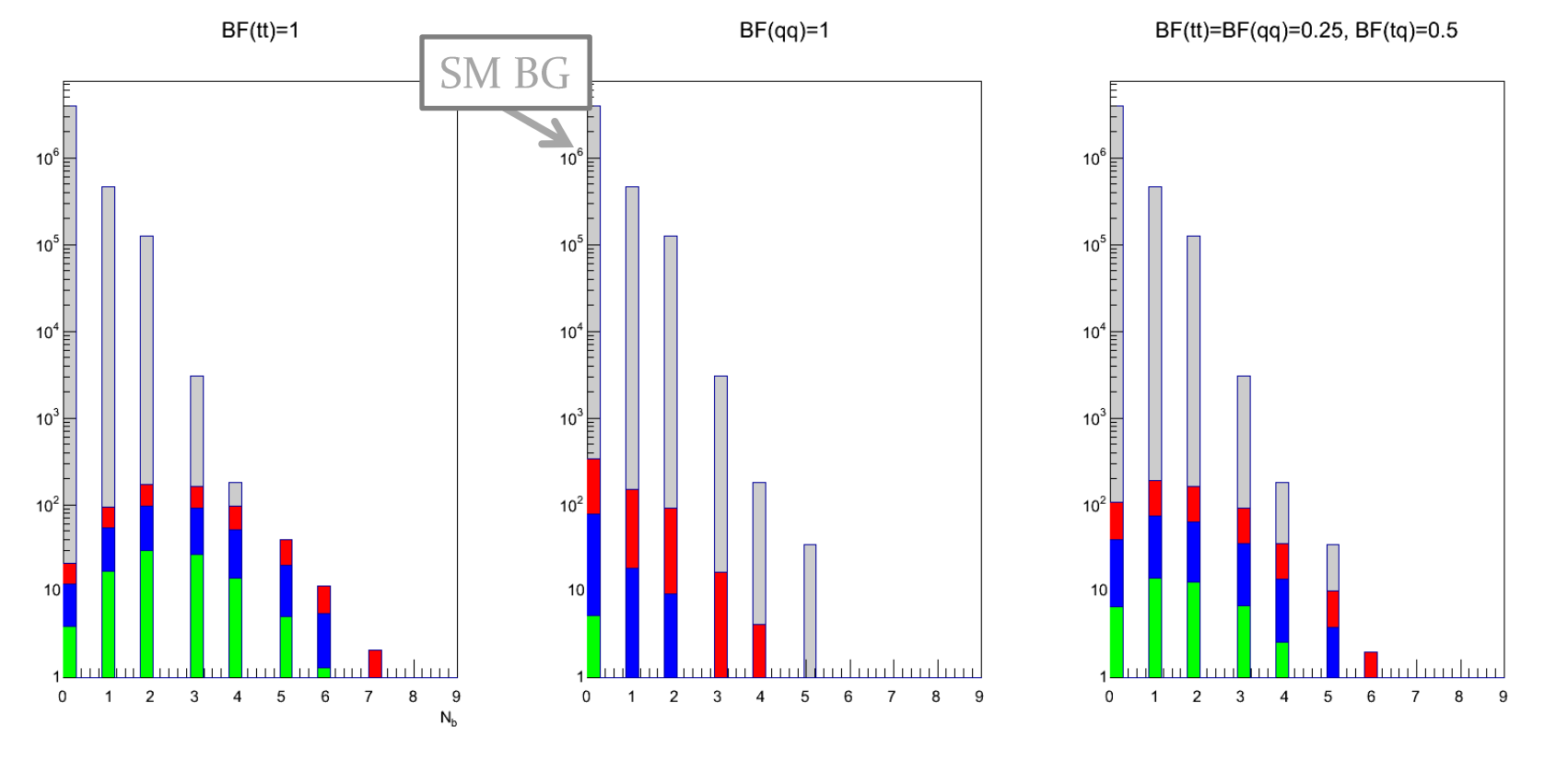
Basic Strategy

Detector level



Basic Strategy

Detector level + SM background



Practice Procedure

An event is classified with (Nb, Nleptons, Etmiss, Ptjets,…)

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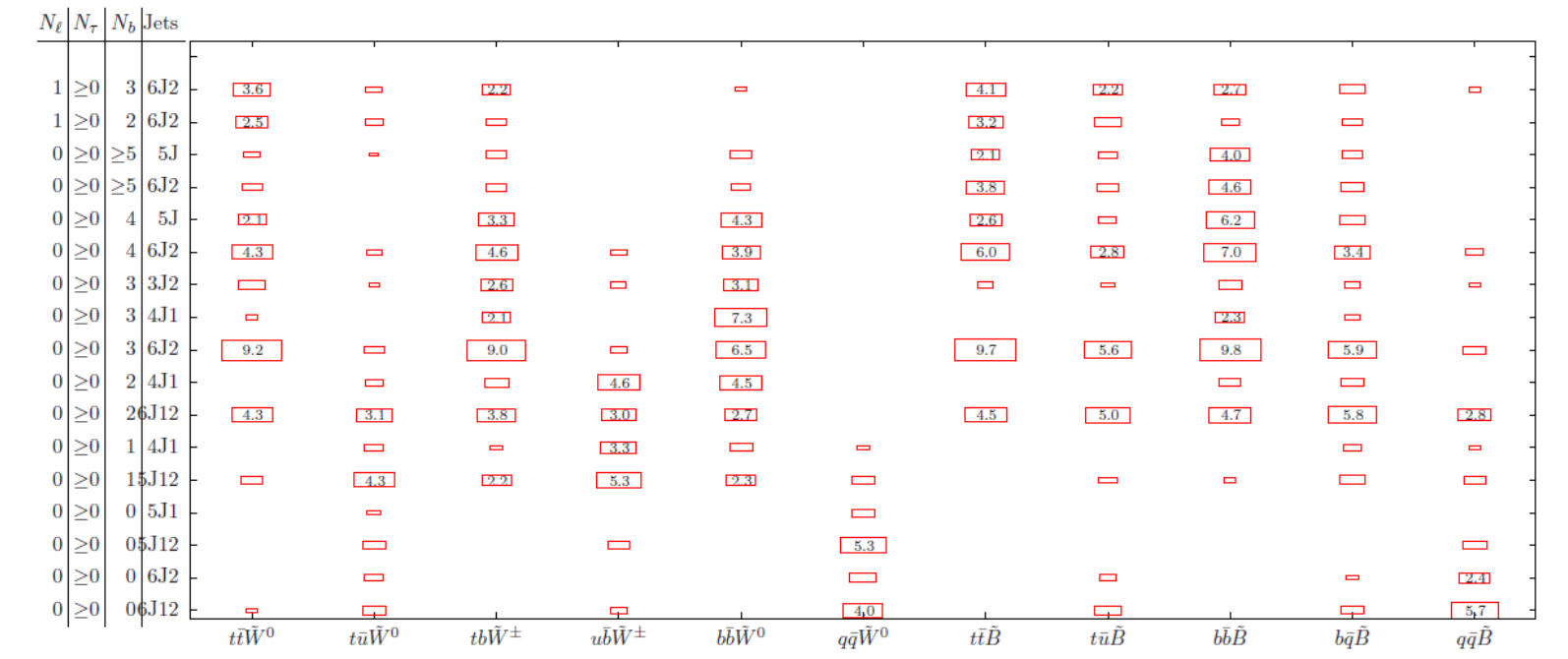
Significance variable Z ~ # signals / BG fluctuation



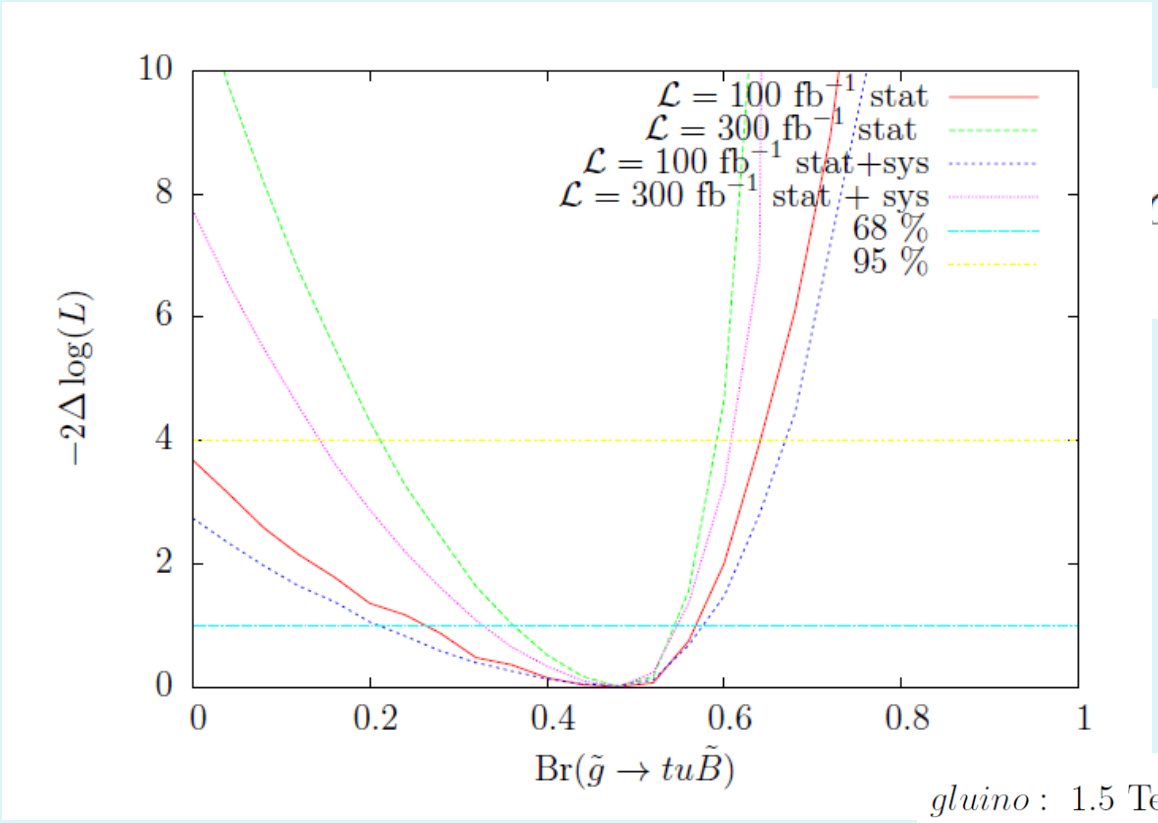
Practice Procedure

An event is classified with (Nb, Nleptons, Etmiss, Ptjets,…)

$$\mathcal{L} = \prod_{\text{modes}} \text{Prob}(N_{\text{mode}} | \{B_i, \sigma_{\tilde{g}\tilde{g}}\})$$

Practice Procedure

An event is classified with (Nb, Nleptons, Etmiss, Ptjets,…)



$\sigma_{\tilde{g}\tilde{g}}\}$)

gluino : 1.5 TeV, *wino* : 0.2 TeV, *bino* : 0.4 TeV

FLV Gluino Decay

O(a few 1000) gluino events

BF determination with accuracy O(1-10) %

Prospect (Prompt decay)

- More kinematic information
- Boost top tagging
- …

Prospect (general case)

- Decay vertex of gluino
- Charged wino track
- …

Summary 1

- "Unnatural" SUSY is natural candidate of SUSY models

- Unconventional collider signals

Summary 2

- Flavorが面白い
  - PeV Scaleまで探れる
  - 実験的発展
  - Latticeによる精密予言
  - GUTへの示唆
- DM