# Probing Heavy Sfermion via Gluino Decay

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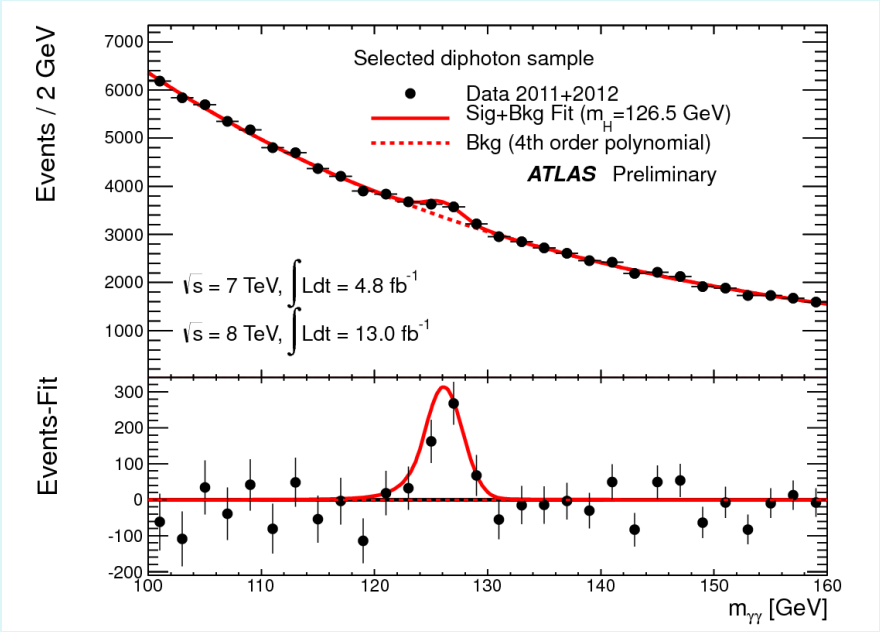
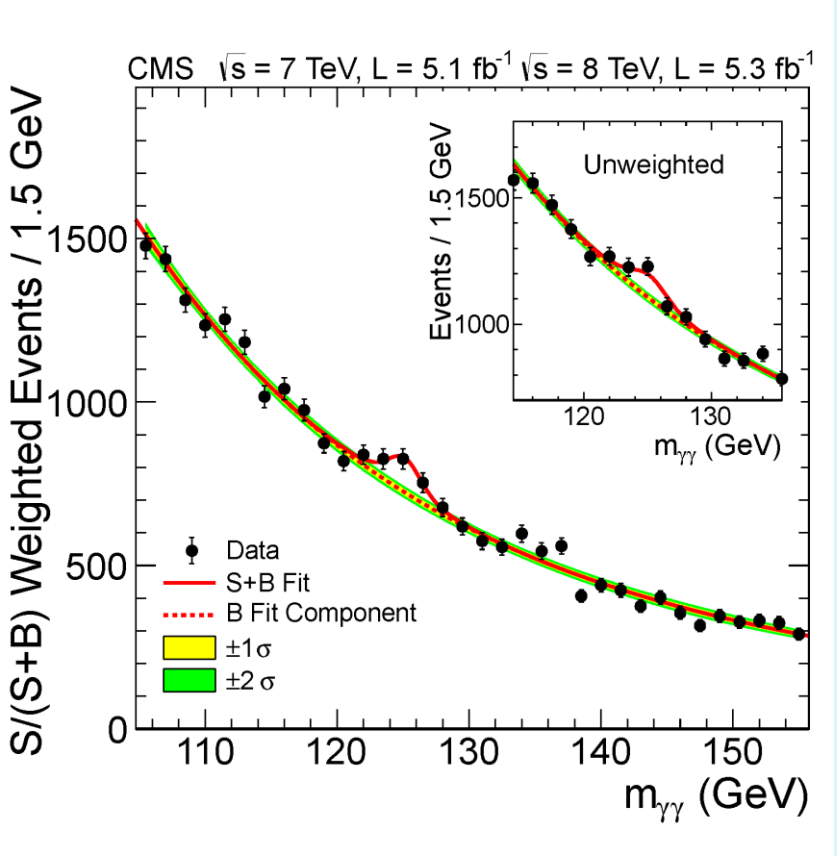
Based on

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

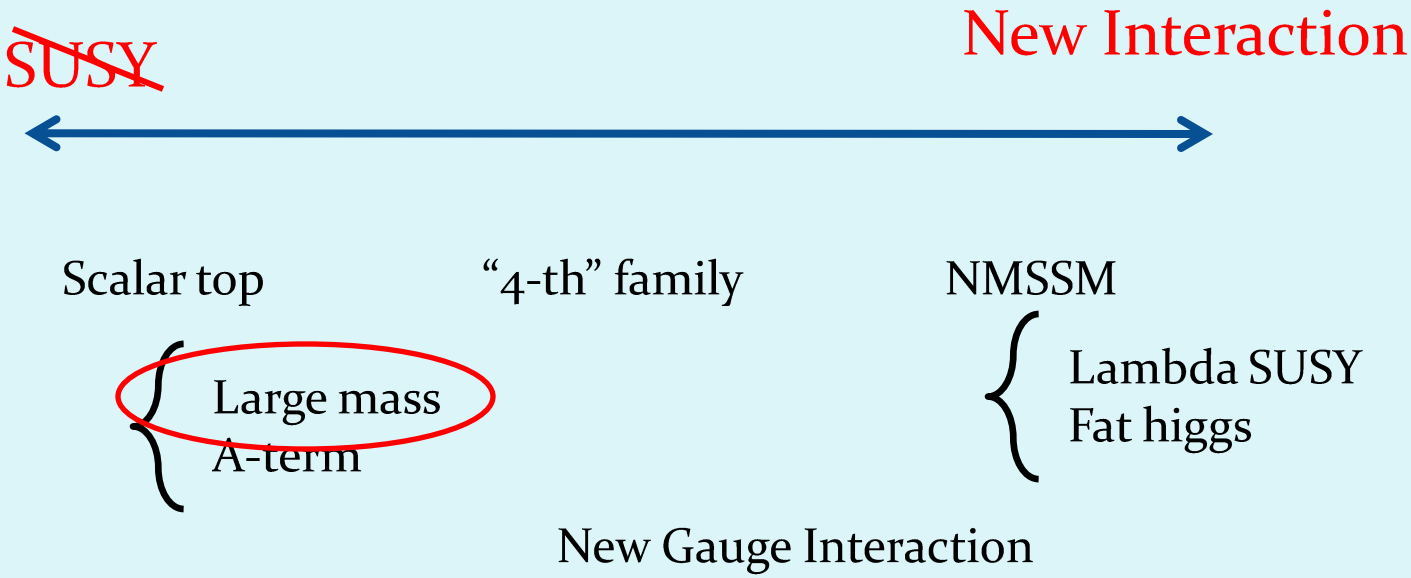

Scalar top
- Large mass
- A-term

"4-th" family

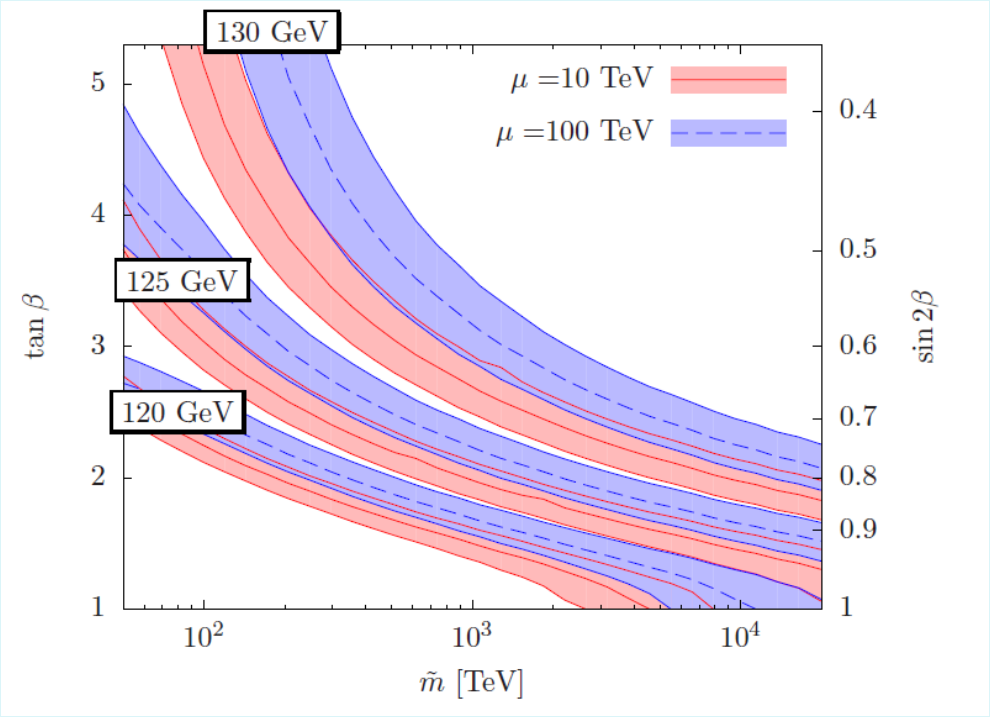
NMSSM
- Lambda SUSY
- Fat higgs

New Gauge Interaction

# How to make 125 GeV Higgs



# Higgs Mass from Heavy Stop



# Benefit and demerit of SSM

Benefit

- Hierarchy Problem
- GUT unification
- DM

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Possible demerit

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

# Benefit and demerit of SSM

Benefit

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

Possible demerit

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

# SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term

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Scalar >O(100) TeV

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Light fermion

GUT unification

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- Gaugino mass
- Mu term

Scalar >O(100) TeV

Flavor/CP problem

Light fermion

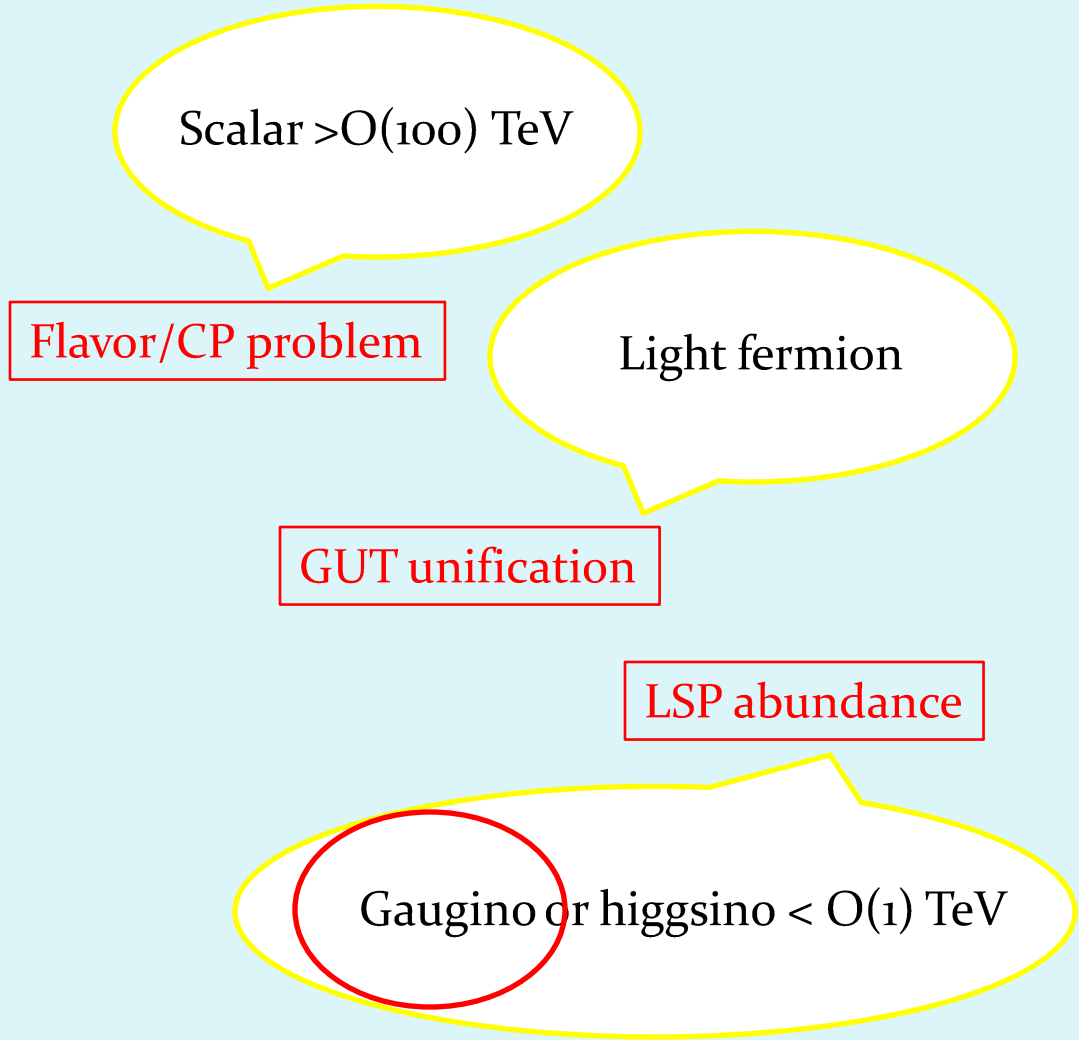
GUT unification

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

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Lower M* ➡ Heavy scalar

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

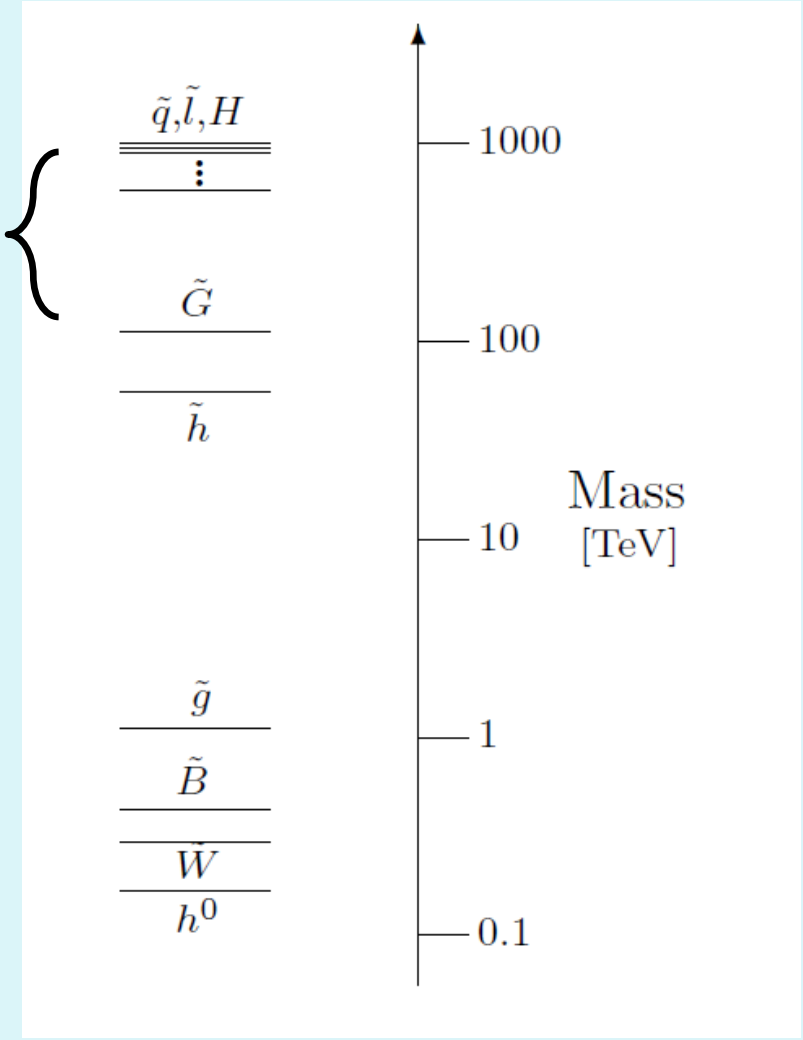
AMSB effect

- Mu term

$$K \ni c H_u H_d$$

# Mass Spectrum

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

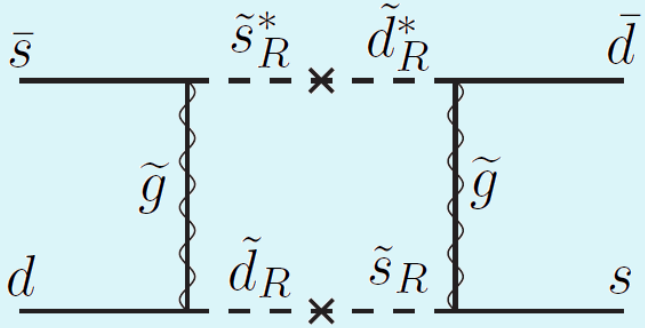


# Sfermion Constraint

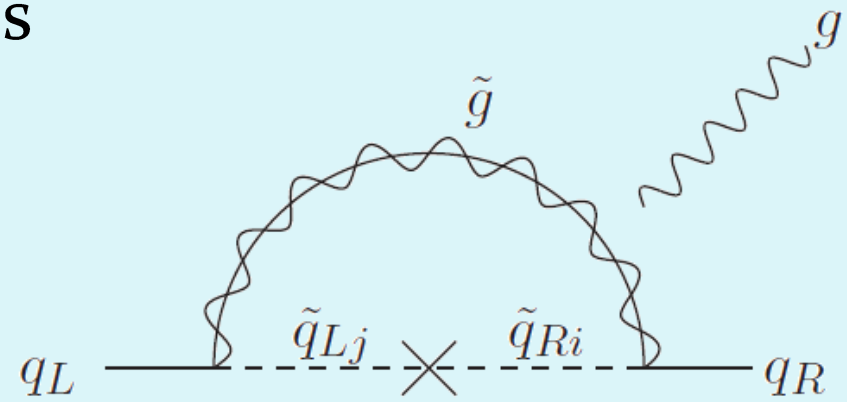
(Cosmology and) Flavor Physics

# Flavor Physics

- Delta F =2 process

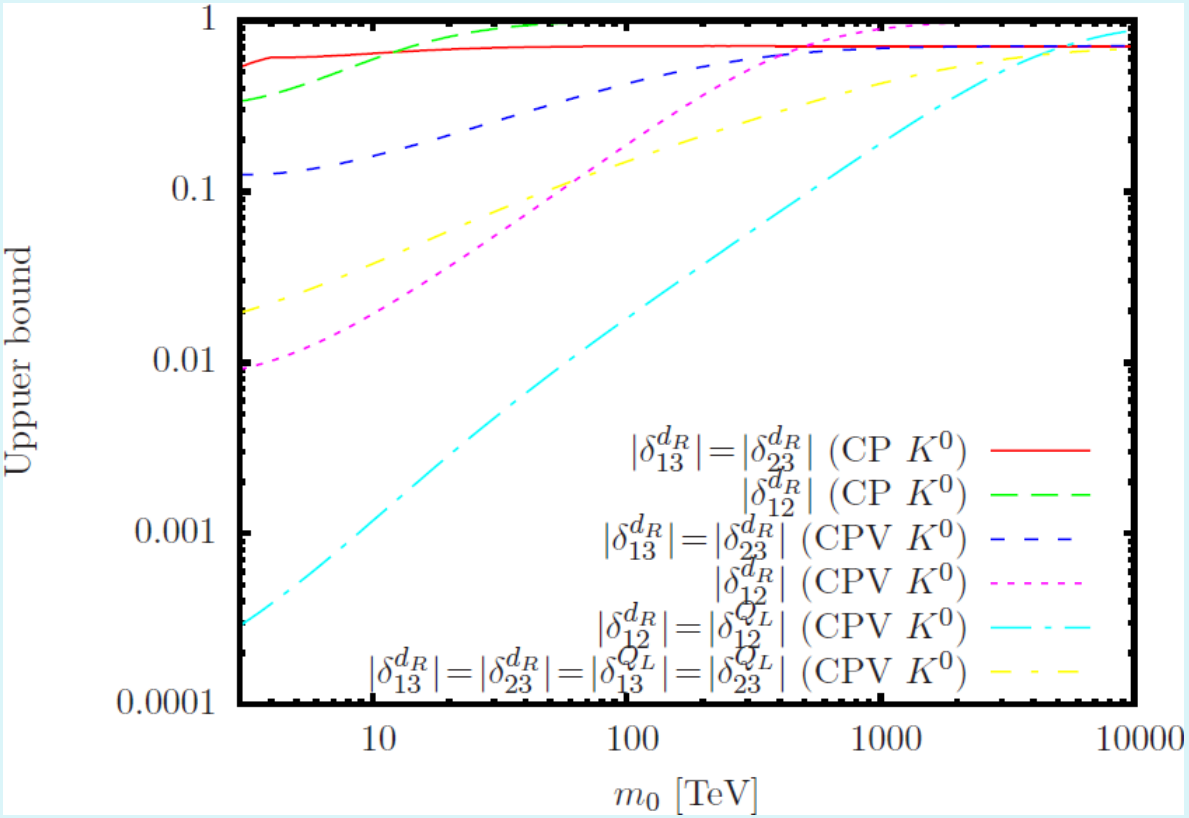



- Delta F= 0 process

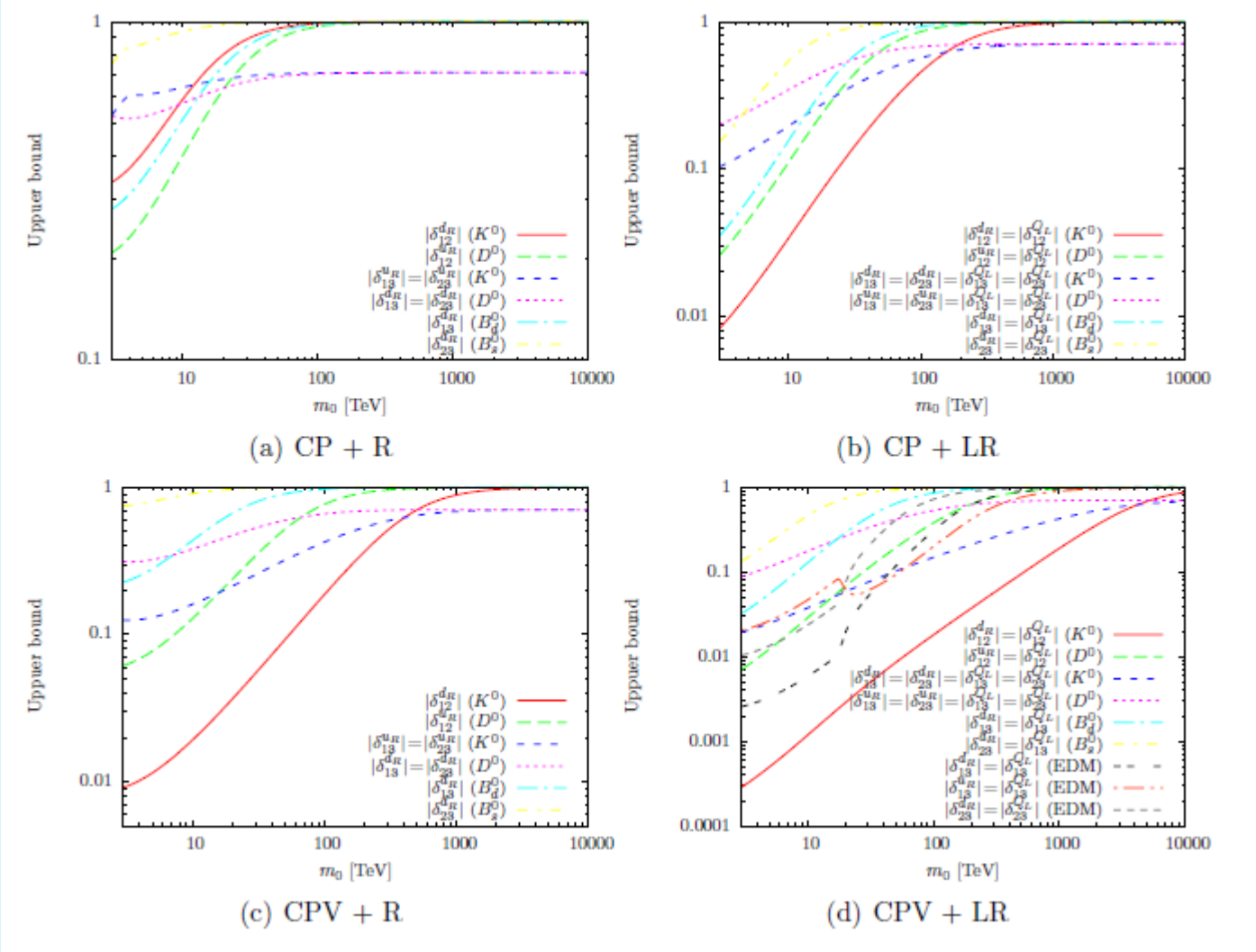


# Example

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



# Constraint on Structure



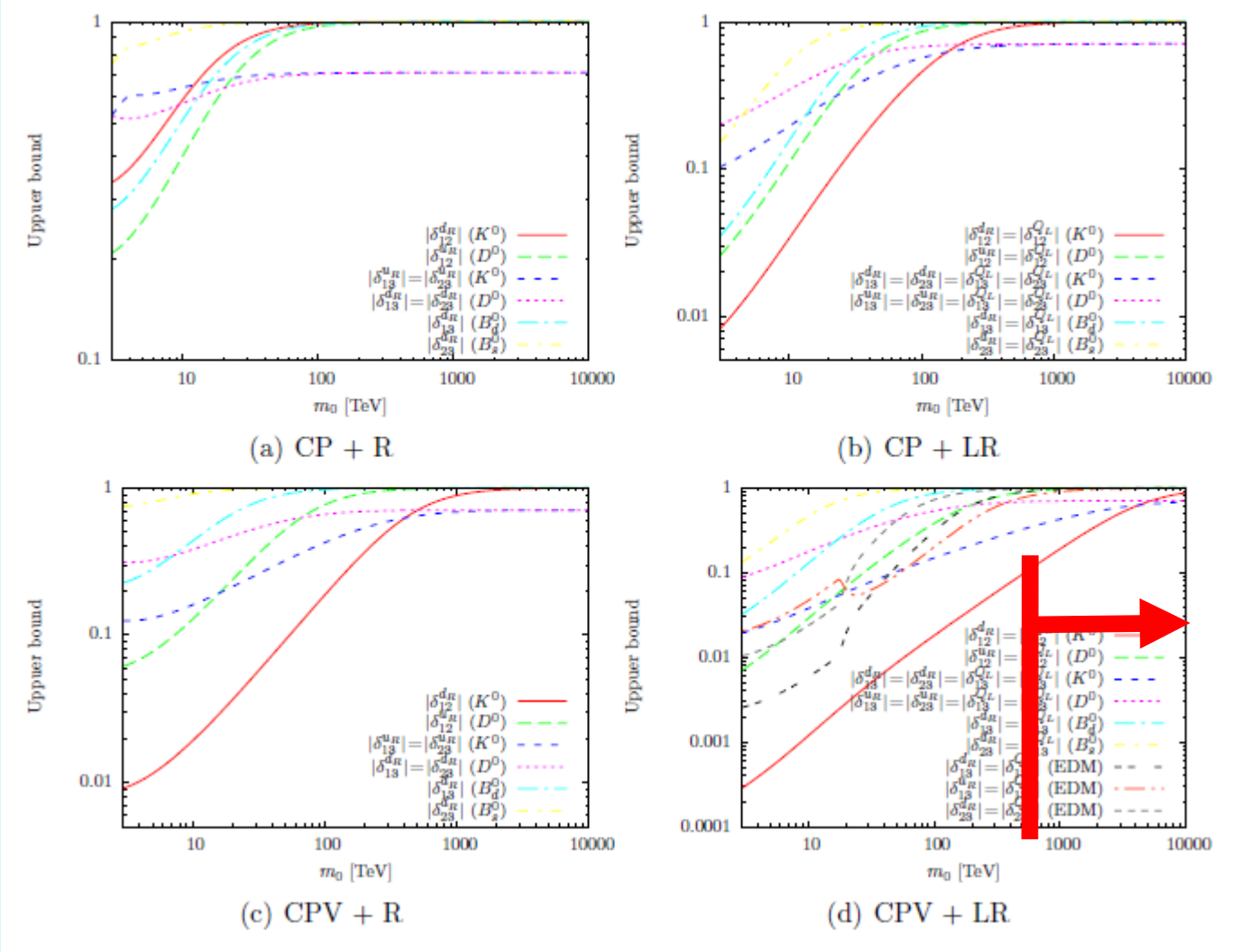

(a) CP + R

(b) CP + LR

(c) CPV + R

(d) CPV + LR

# Constraint on Structure



# Sfermion sector

Bound from Flavor violation

$$m_0 \gtrsim 10^2 - 10^3 \text{ TeV}$$

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Cosmological Bound

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

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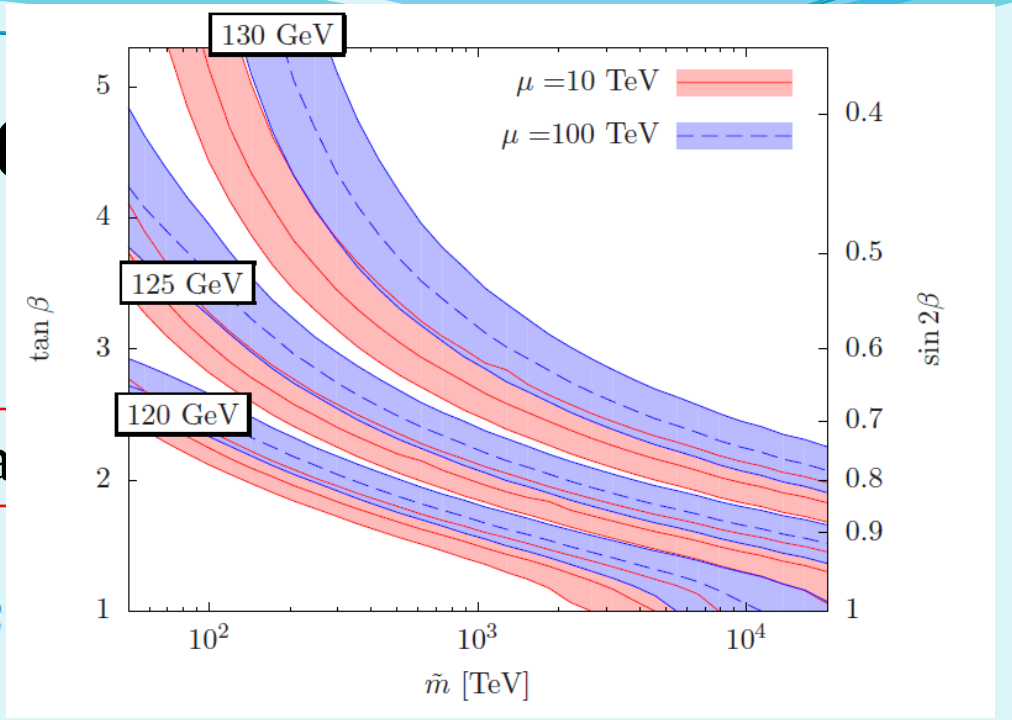
Bound from Flavor viola

$$m_0 \gtrsim 10^2$$



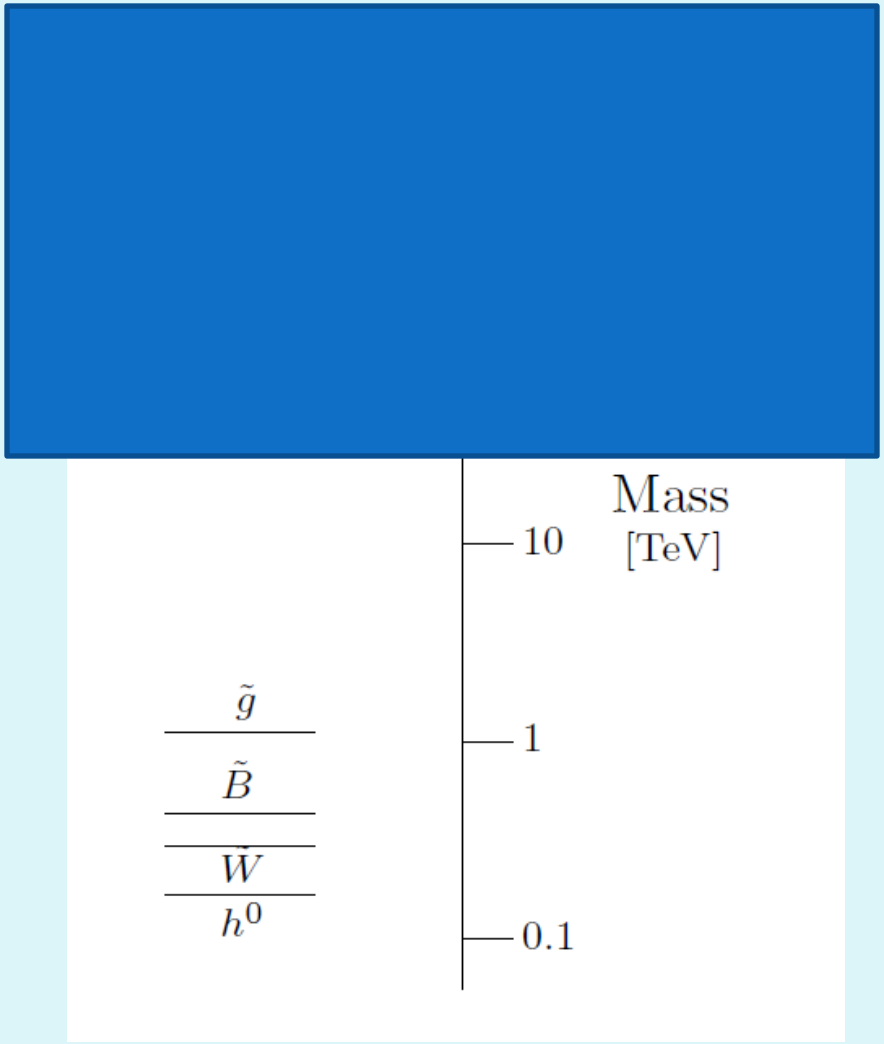

Cosmological Bound

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

# Gluino Decay

# Gluino is “Stable”

Integrated out Sfermions,
Gluino has “G-parity”

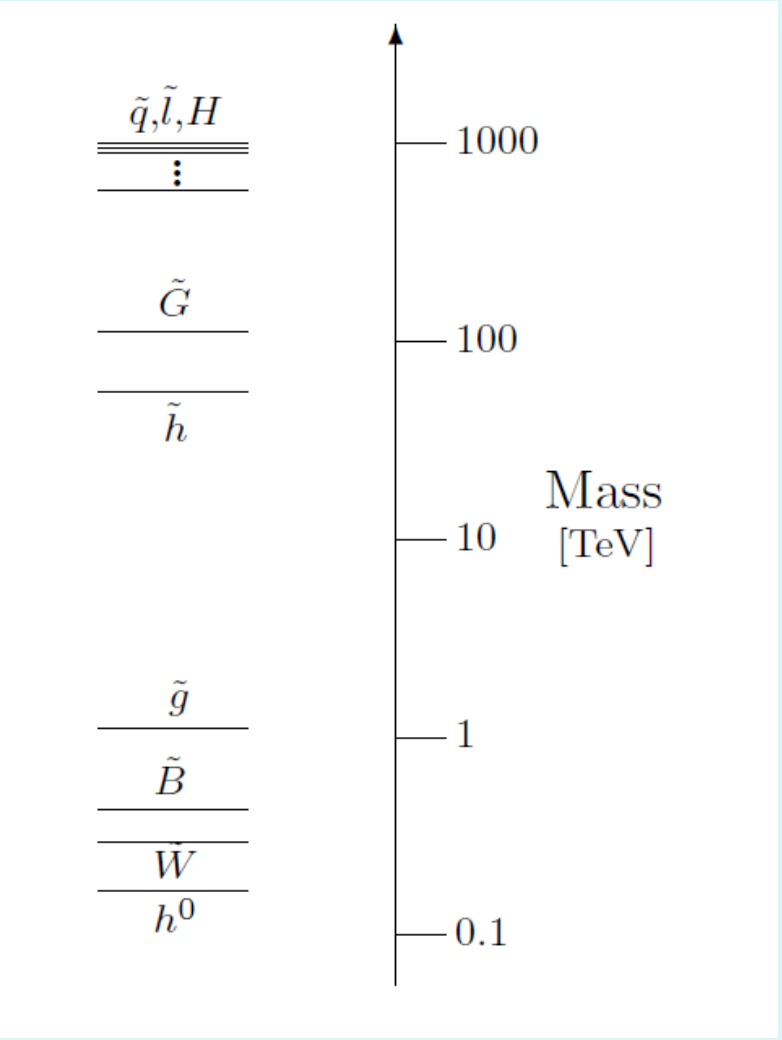



Stable at low energy

# Gluino is “Stable”

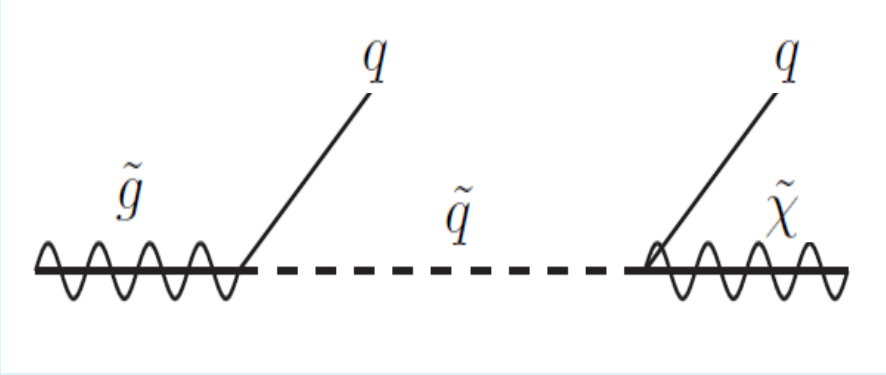
“G-parity” is broken via higher. Dim op. with squark exchange

Gluino decay is sensitive to sfermions.

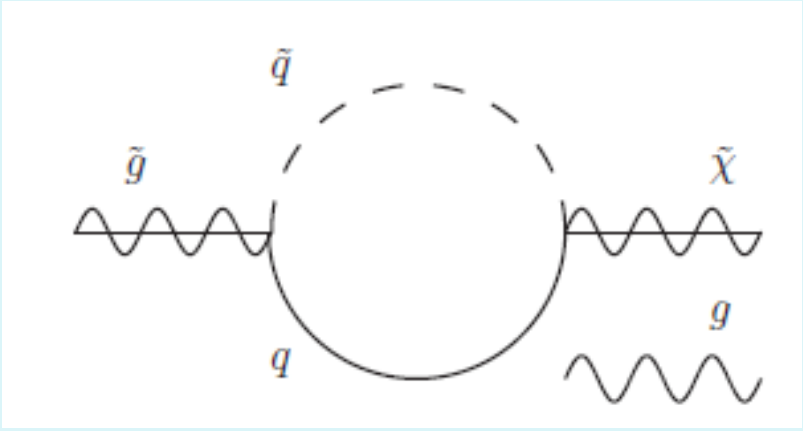


# Gluino Decay

Mainly three body decay

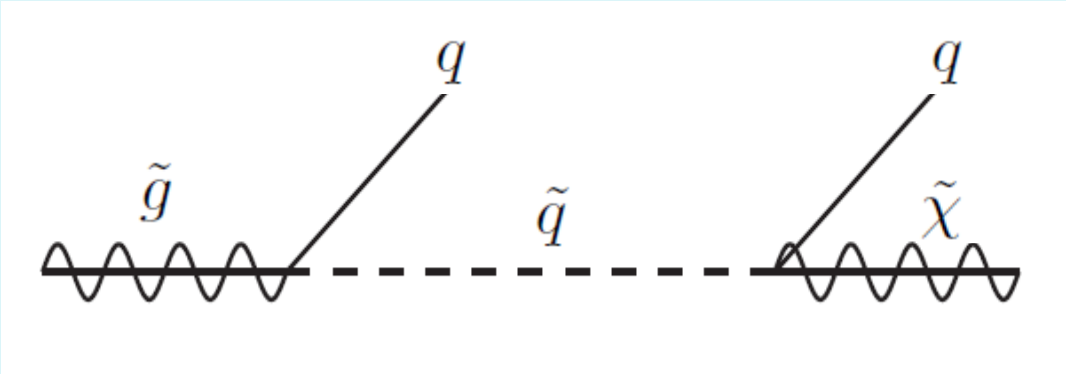



Tiny two body decay



# Gluino Decay Width

- Gluino




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

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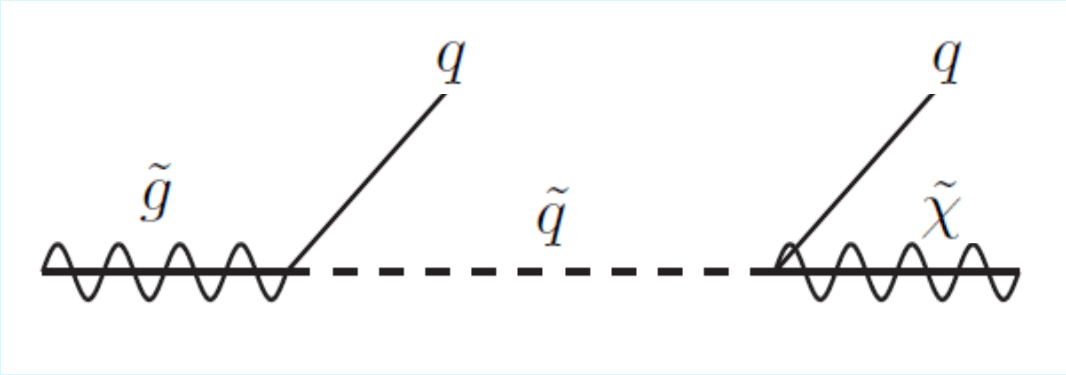
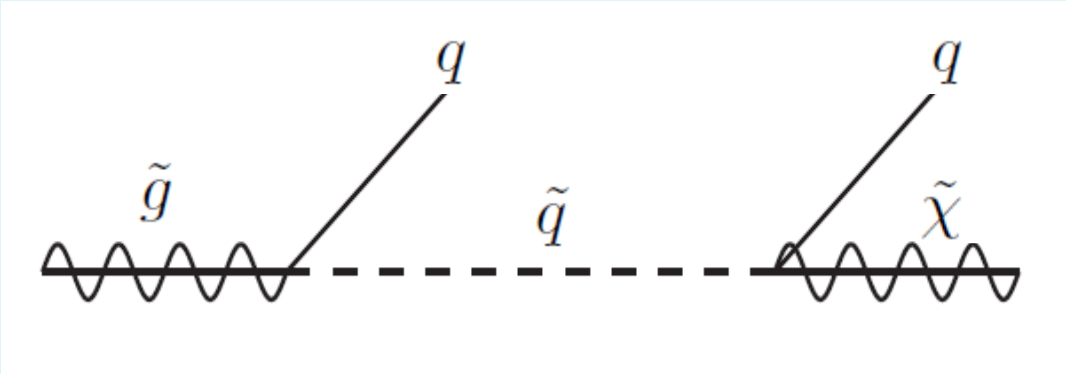



$$c\tau_{\tilde{g}} = O(1\ \mathrm{cm}) \left(\frac{M_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{-5} \left(\frac{\tilde{m}}{1000\ \mathrm{TeV}}\right)^{4}$$

Long enough to probe at collider

# Decay mode

- Gluino



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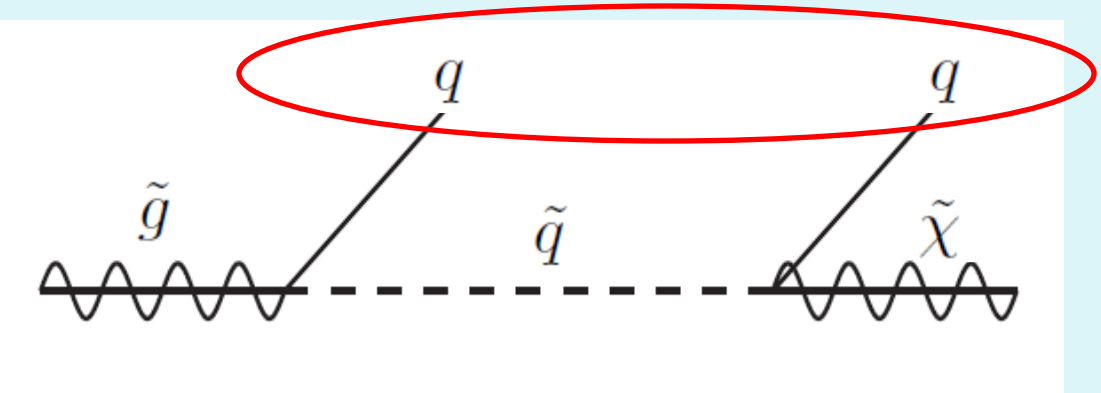

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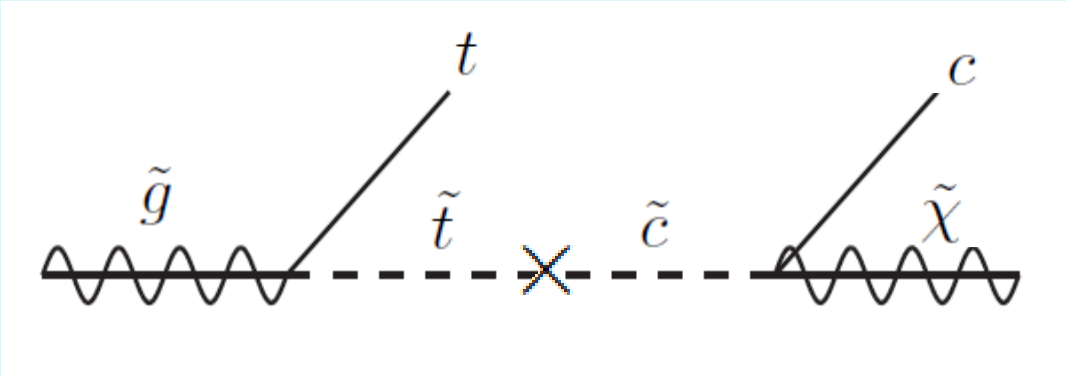
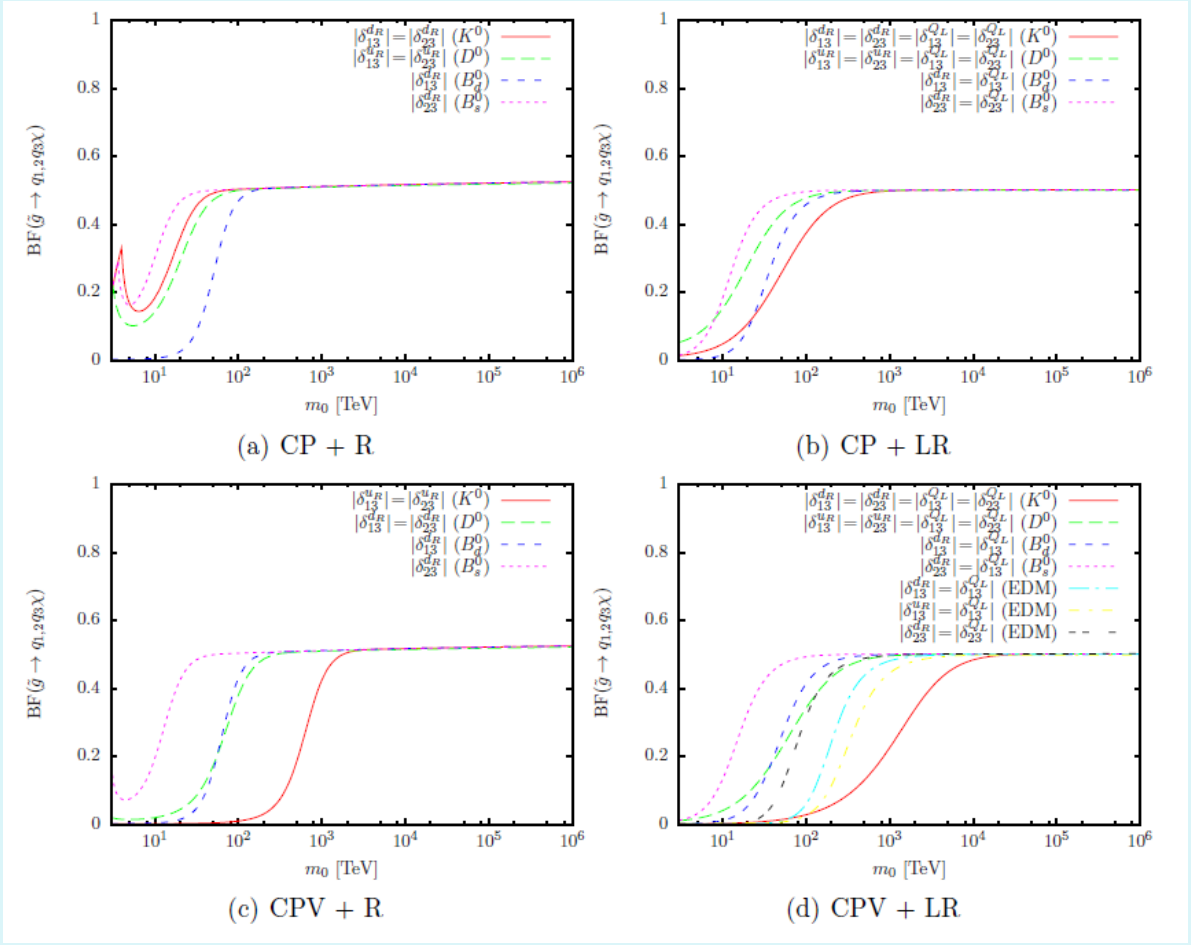



Squark can have flavor-violating structure

Flavorful gluino decay

# How large FLV?

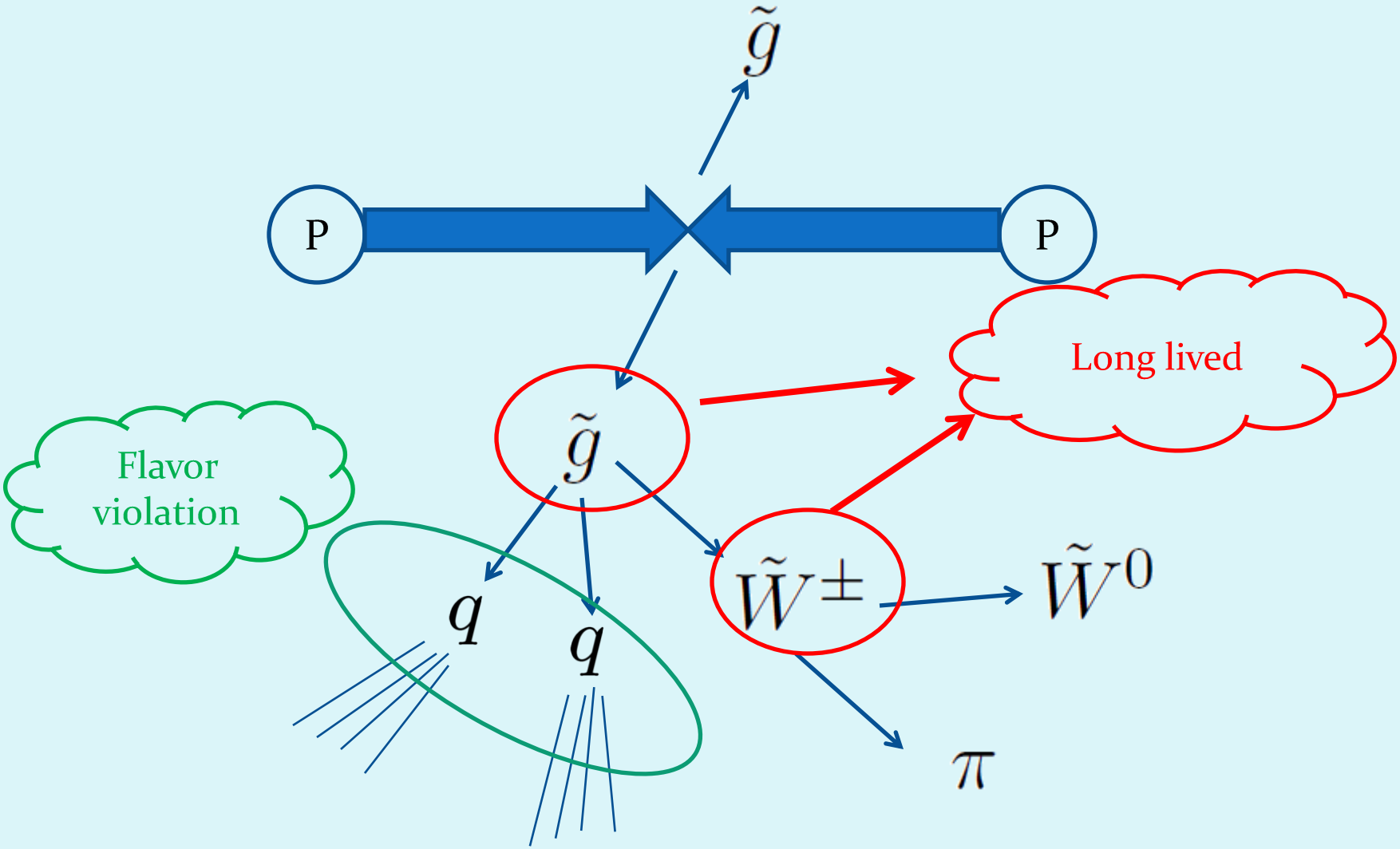
Upper bound on $\mathrm{BF}(\tilde{g} \to q^3 q^{1,2} \chi)$




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

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

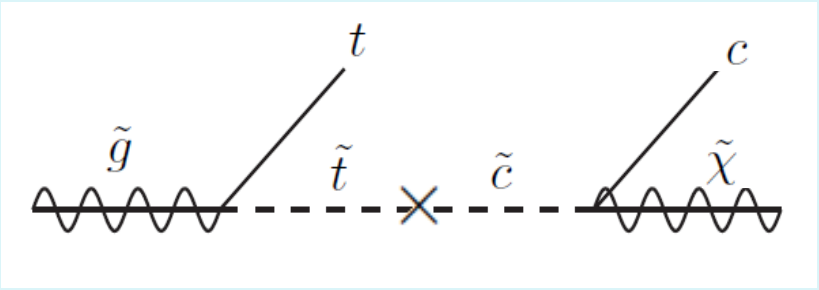
# Displaced and Flavorful SUSY



# Measurement of FLV Gluino Decay

Case of prompt decay

# Basic Strategy




Example point:

Gluino decay

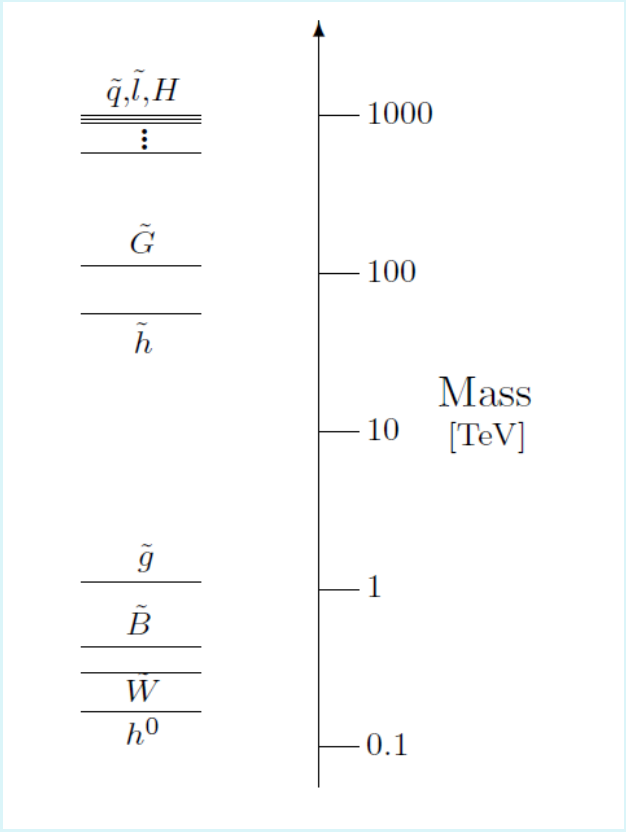
$$\tilde{g} \to tt\tilde{B}^0$$

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

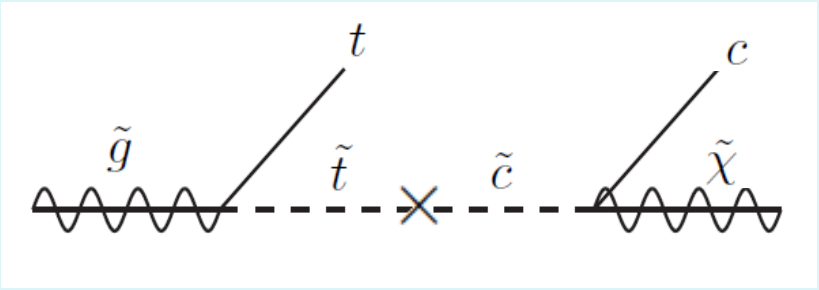
$$\tilde{g} \to uu\tilde{B}^0$$

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

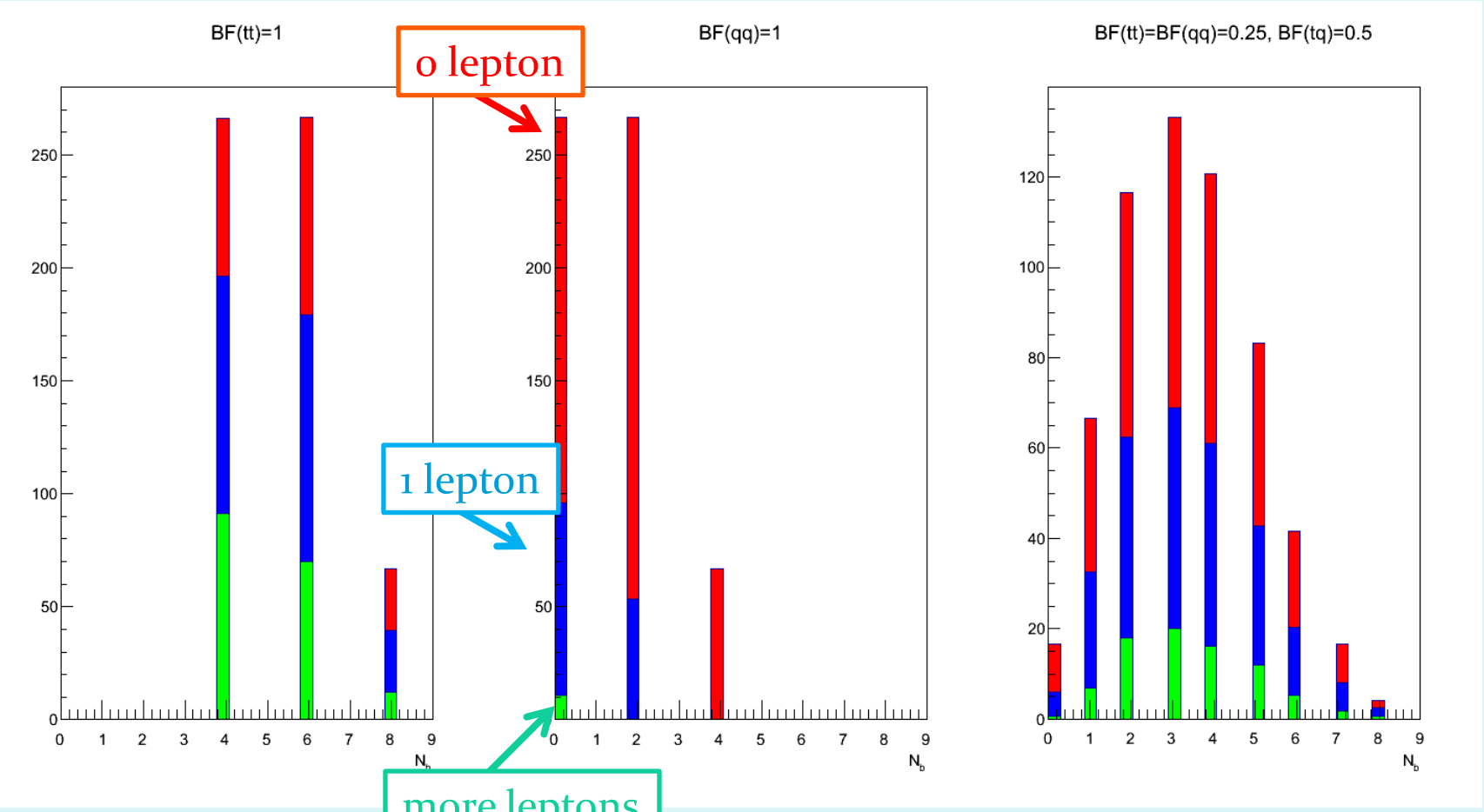
Simple b and lepton counting is useful

Bino decay

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

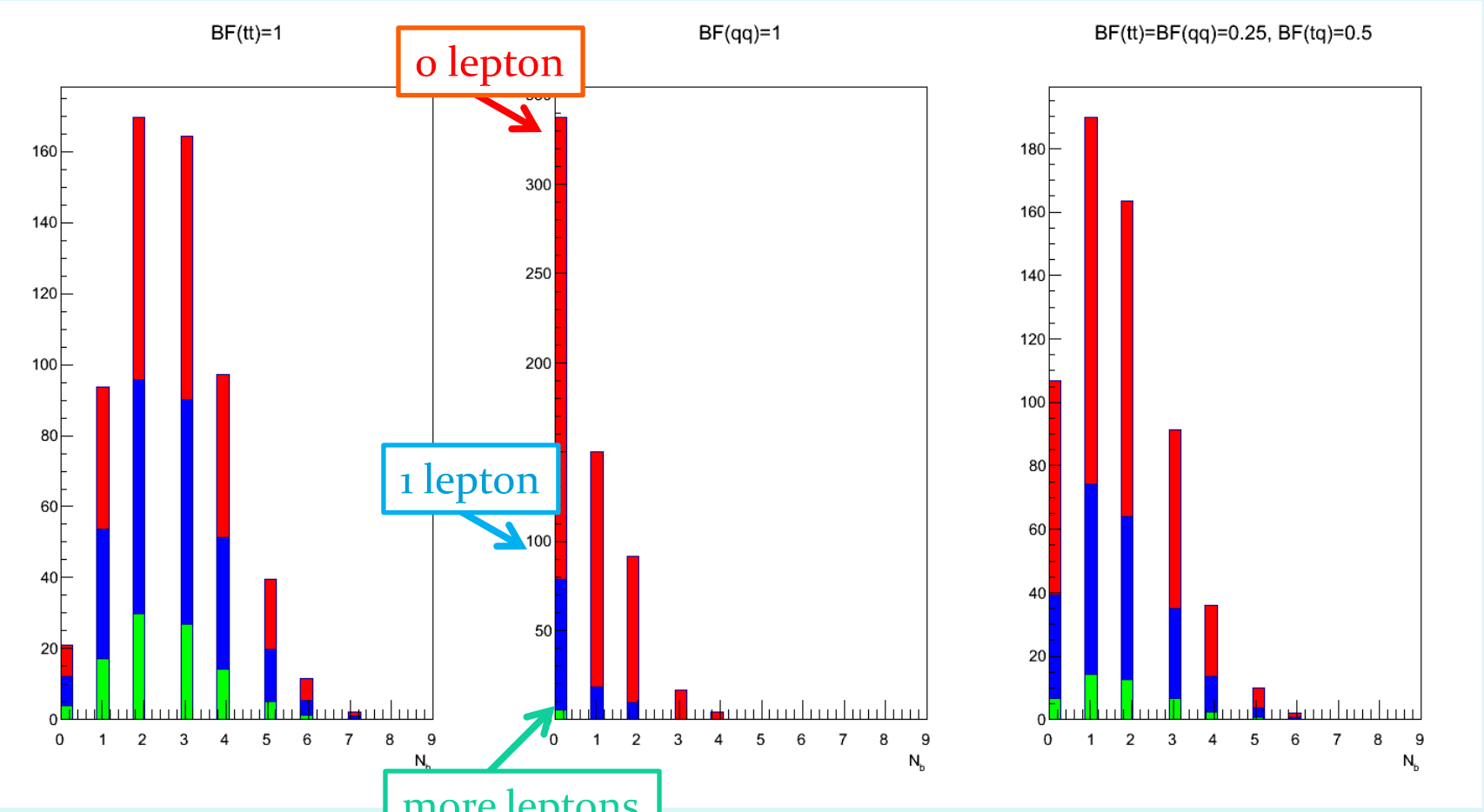
# Basic Strategy

Parton level



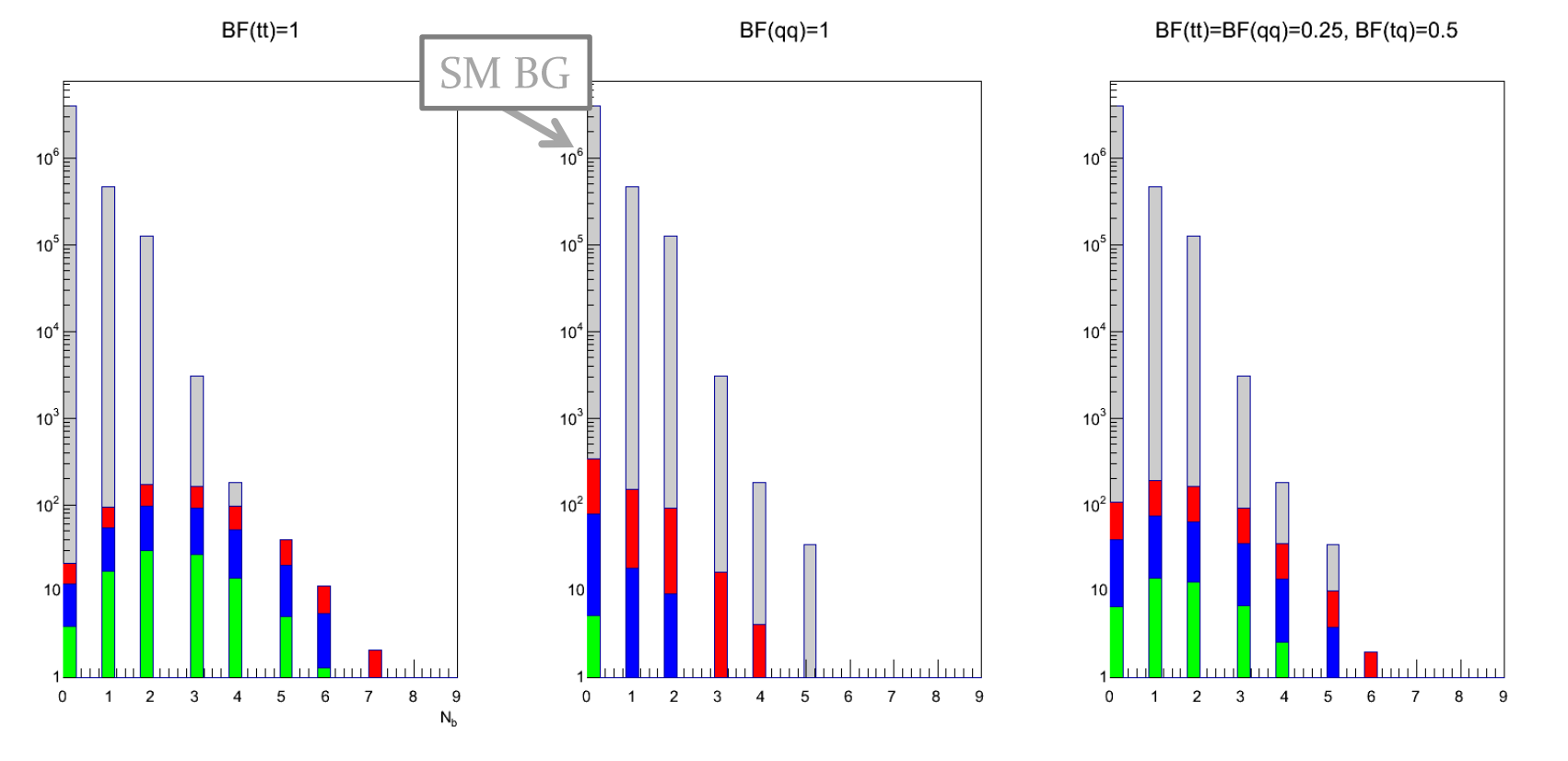
# Basic Strategy

Detector level



# Basic Strategy

Detector level + SM background



# Practice Procedure

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

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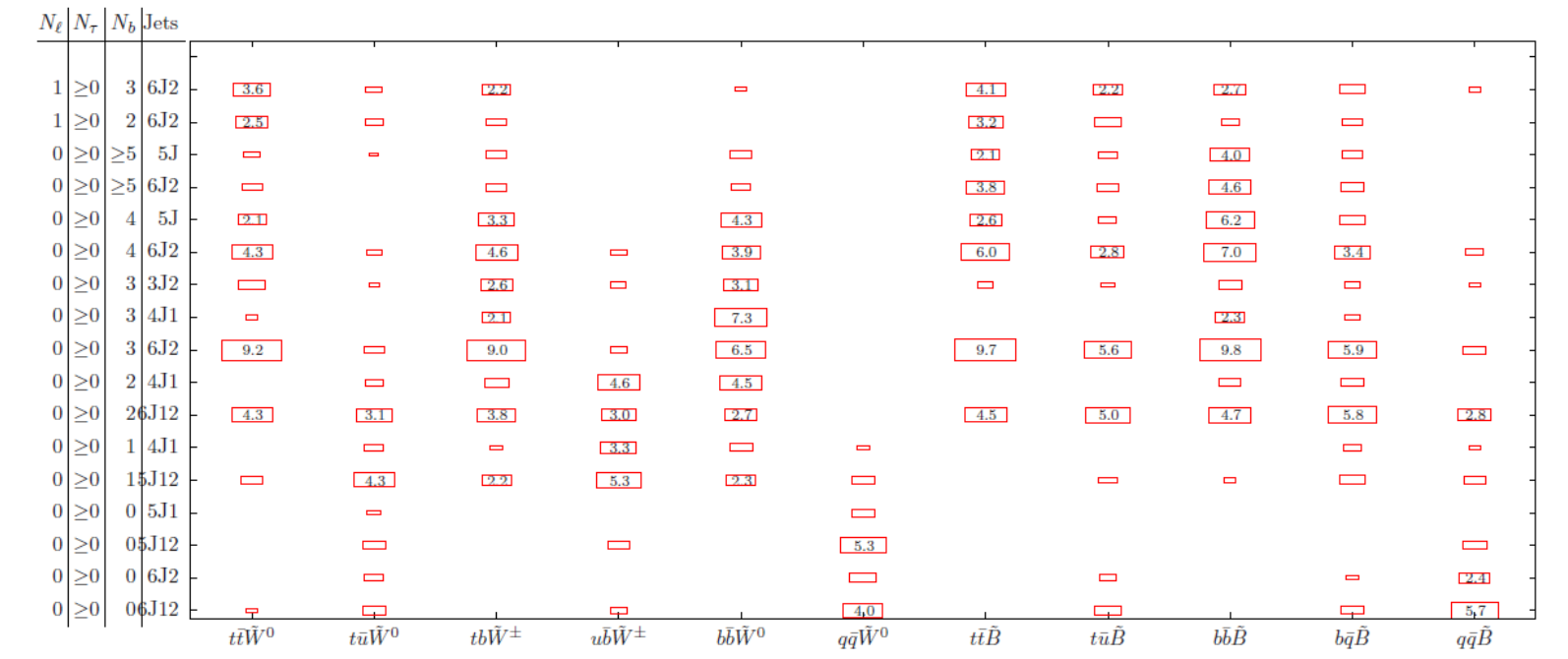
Significance variable Z ~ # signals / BG fluctuation



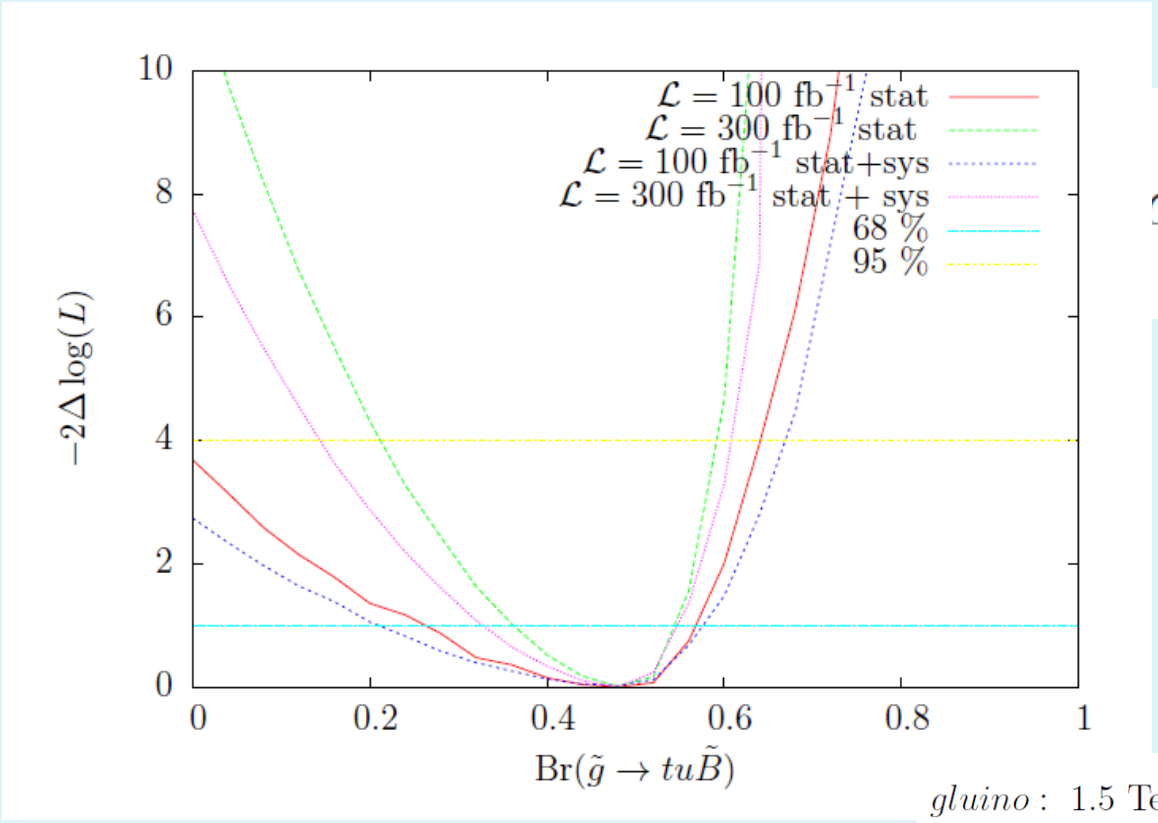
# Practice Procedure

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) %

# Summary

- "Unnatural" SUSY is  natural candidate of SUSY models

- Unconventional collider signals

# Prospect (Prompt decay)

- More kinematic information
- Boost top tagging
- …

# Prospect (general case)

- Decay vertex of gluino
- Charged wino track
- …

# 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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Goldstino ~ Gravitino

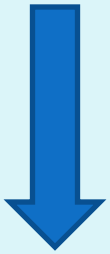
$$K \to \frac{F}{M_*^2} \Psi \phi_{\rm MSSM} \psi_{\rm MSSM}$$

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)

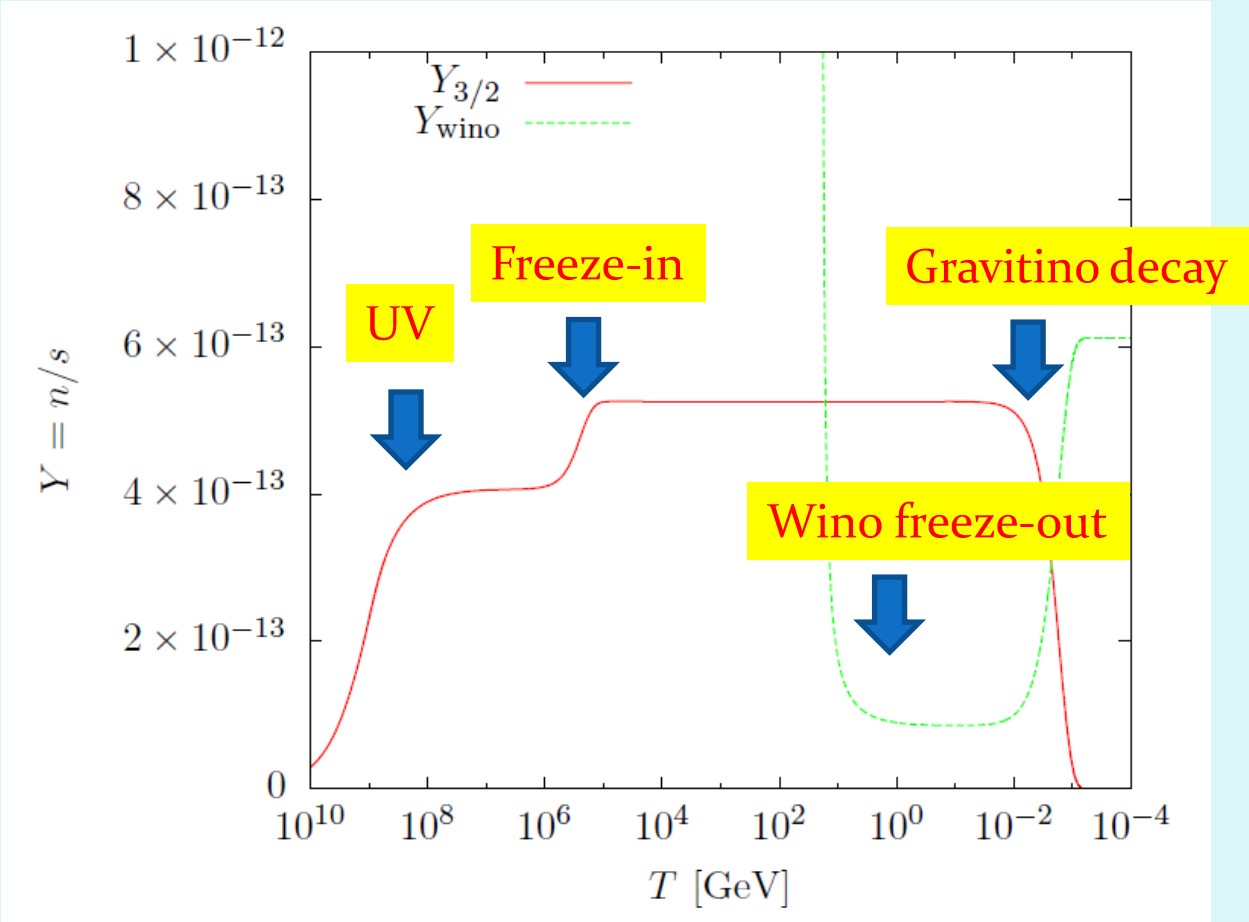


Lower Temperature

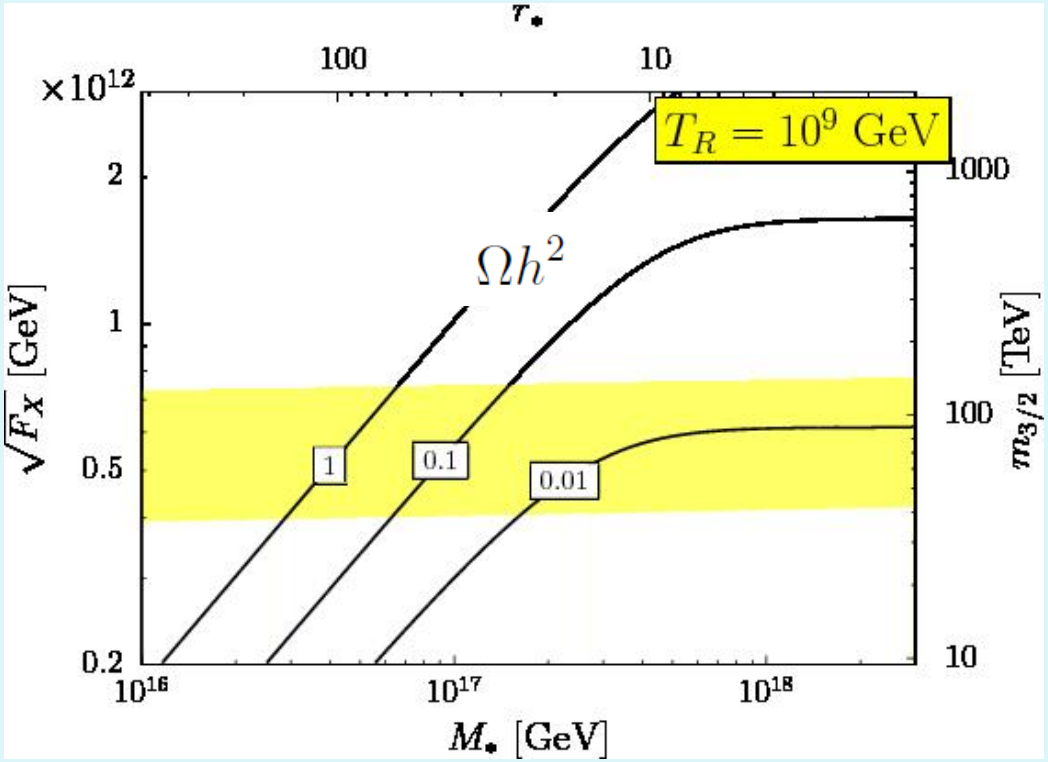
$$\tilde{G}_{3/2} \to \tilde{W}W$$

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

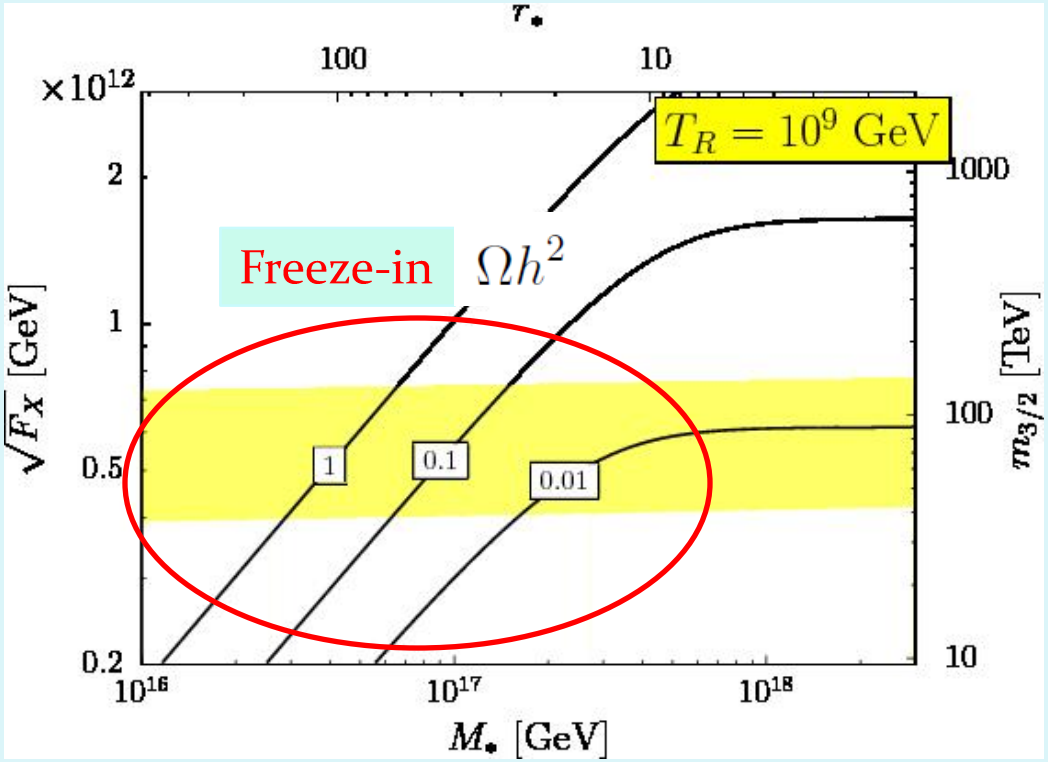
# Thermal history



# Abundance


$T_*$
100
10
$\times 10^{12}$
2
1
0.5
0.2
$T_R = 10^9$ GeV
$\Omega h^2$
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
$\times 10^{12}$
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0.5
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$\sqrt{F_X}$ [GeV]
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Freeze-in
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1000
100
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$m_{3/2}$ [TeV]
$10^{16}$
$10^{17}$
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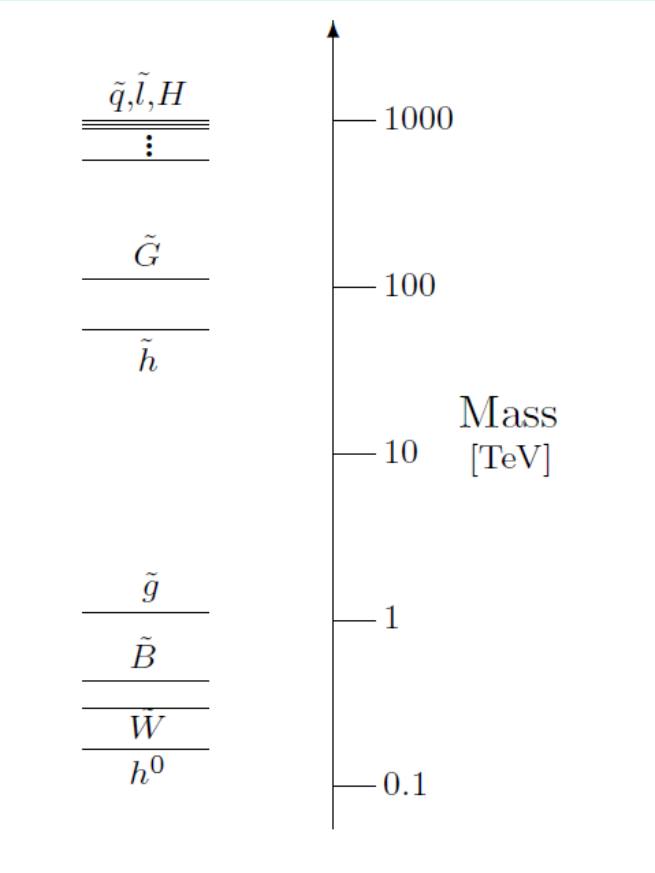
$M_*$ [GeV]

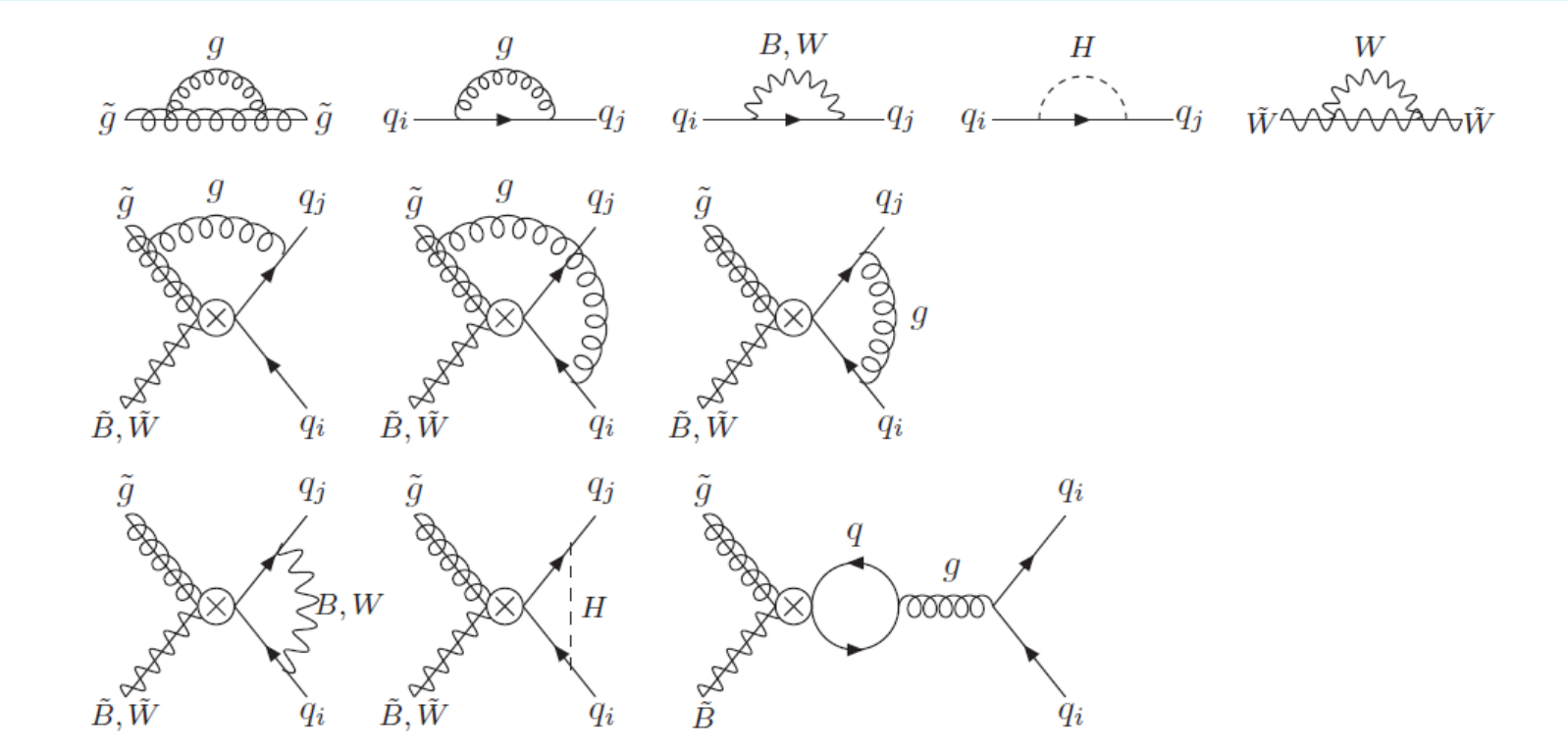
# Gluino Decay




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

# Gluino Decay RGE

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



# Tree vs RGE

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

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