Aspects of Non-minimal Gauge Mediation

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Plan

1. Minimal and non−Minimal GMSB

2. Cosmology

3. LHC Signal

4. Summary

1. Minimal and non-Minimal GMSB

Origins of Soft Mass

Gravity Mediation

Anomaly Mediation

Gauge Mediation

$\vdots$

Origins of Soft Mass

Gravity Mediation

Anomaly Mediation

Gauge Mediation

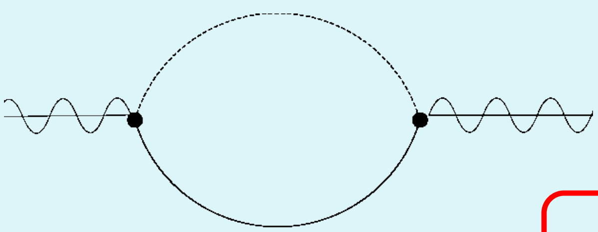
⋮

Gauge Mediation

Hidden $F \neq 0$

Messenger $(d, \bar{d}),\ (\ell, \bar{\ell}) \sim 5 + \bar{5}$

SM gauge interaction



MSSM

Feature of Gauge Mediation

No SUSY flavor problems

Gravitino LSP

Not rely on physics at the UV scale (Planck scale)

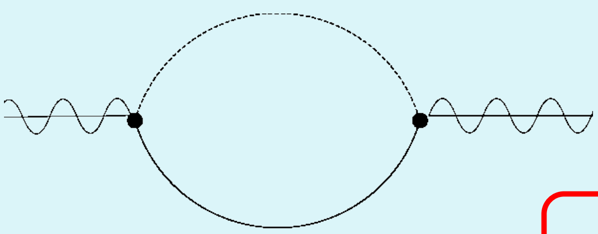
Minimal GMSB

Hidden $F \neq 0$

$k S \bar{\psi} \psi$ $\langle S \rangle = F\theta^2$

Messenger $\psi \sim (d, \ell)$

SM gauge interaction



MSSM

Minimal GMSB

$$
\begin{aligned}
m^2_{\rm scalar} \quad &= 2N_{\rm mess}\left(\frac{\alpha}{4\pi}\right)^2\left(\frac{kF}{M_{\rm mess}}\right)^2\left(1+\mathcal{O}\left(\frac{kF}{M^2_{\rm mess}}\right)\right) \\
m_{\rm gaugino} \quad &= N_{\rm mess}\left(\frac{\alpha}{4\pi}\right)\frac{kF}{M_{\rm mess}}\left(1+\mathcal{O}\left(\frac{kF}{M^2_{\rm mess}}\right)\right)
\end{aligned}
$$

$$M^2 > kF,\ N_{\rm mess} = \mathcal{O}(1)$$

Minimal GMSB

$$\begin{aligned} m^2_{\mathrm{scalar}} &= 2N_{\mathrm{mess}} \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\mathrm{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\mathrm{mess}}}\right)\right) \\ m_{\mathrm{gaugino}} &= N_{\mathrm{mess}} \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\mathrm{mess}}} \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\mathrm{mess}}}\right)\right) \end{aligned}$$

$$M^2 > kF,\ N_{\mathrm{mess}} = \mathcal{O}(1)$$

$$m_{\mathrm{scalar}} \approx m_{\mathrm{gaugino}}$$

Quark and Lepton Messenger

There are two types of messengers $(d, \bar{d}),\ (\ell, \bar{\ell})$

$$W = k_d S d\bar{d} + M_d d\bar{d} + k_\ell S \ell\bar{\ell} + M_\ell \ell\bar{\ell}$$

Quark and Lepton Messenger

There are two types of messengers $(d, \bar{d}), \ (\ell, \bar{\ell})$

$$W = k_d S d\bar{d} + M_d d\bar{d} + k_\ell S \ell\bar{\ell} + M_\ell \ell\bar{\ell}$$

At GUT scale $\quad k_d = k_\ell \qquad M_d = M_\ell$

Renormalization effect

At Messenger scale $\quad \dfrac{M_d}{M_\ell} = \dfrac{k_d}{k_\ell} > 1$

Quark and Lepton Messenger

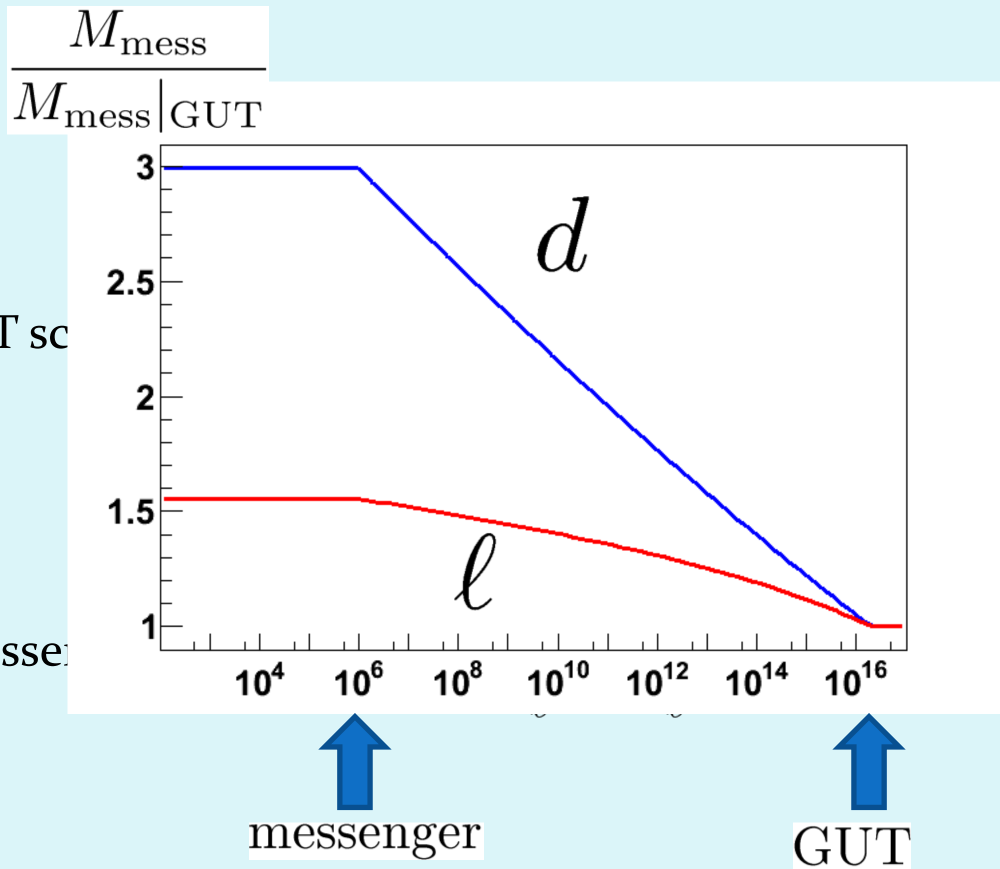
There are two types of messengers $(d, \bar{d}),\ (\ell, \bar{\ell})$

$- M_\ell \ell \bar{\ell}$

At GUT sc

alization effect

At Messe



Quark and Lepton Messenger

There are two types of messengers $(d, \bar{d}), \ (\ell, \bar{\ell})$

$$W = k_d S d\bar{d} + M_d d\bar{d} + k_\ell S \ell\bar{\ell} + M_\ell \ell\bar{\ell}$$

At GUT scale $k_d = k_\ell \qquad M_d = M_\ell$

Renormalization effect

At Messenger scale $$\frac{M_d}{M_\ell} = \frac{k_d}{k_\ell} = 2 \sim 3$$

Minimal GMSB

$$
\begin{aligned}
M_1 &= N_{\text{mess}} \frac{\alpha_1}{4\pi} \left(\frac{2}{5} \frac{k_d F}{M_d} + \frac{3}{5} \frac{k_\ell F}{M_\ell} \right) \\
M_2 &= N_{\text{mess}} \frac{\alpha_2}{4\pi} \frac{k_\ell F}{M_\ell} \\
M_3 &= N_{\text{mess}} \frac{\alpha_3}{4\pi} \frac{k_d F}{M_d}
\end{aligned}
$$

Minimal GMSB

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$\frac{k_d}{M_d} = \frac{k_\ell}{M_\ell}$ is maintained at Messenger scale

Minimal GMSB

$$\begin{aligned} M_1 &= N_{\rm mess}\frac{\alpha_1}{4\pi}\left(\frac{2}{5}\frac{k_d F}{M_d}+\frac{3}{5}\frac{k_\ell F}{M_\ell}\right) \\ M_2 &= N_{\rm mess}\frac{\alpha_2}{4\pi}\frac{k_\ell F}{M_\ell} \\ M_3 &= N_{\rm mess}\frac{\alpha_3}{4\pi}\frac{k_d F}{M_d} \end{aligned}$$

Same value

$\frac{k_d}{M_d} = \frac{k_\ell}{M_\ell}$ is maintained at Messenger scale

GUT-relation in Minimal GMSB

$$
\begin{aligned}
M_1 &= N_{\mathrm{mess}} \frac{\alpha_1}{4\pi} \Lambda \\
M_2 &= N_{\mathrm{mess}} \frac{\alpha_2}{4\pi} \Lambda \\
M_3 &= N_{\mathrm{mess}} \frac{\alpha_3}{4\pi} \Lambda
\end{aligned}
$$

$$\Lambda \equiv \frac{k_d F}{M_d} = \frac{k_\ell F}{M_\ell}$$

$$M_1 : M_2 : M_3 \approx \alpha_1 : \alpha_2 : \alpha_3$$

Minimal GMSB

GUT relation: $M_1 : M_2 : M_3 \approx \alpha_1 : \alpha_2 : \alpha_3$

Non-Splitting $M_{\rm scalar} \approx M_{\rm gaugino}$

(SUSY breaking vacuum is not stable)

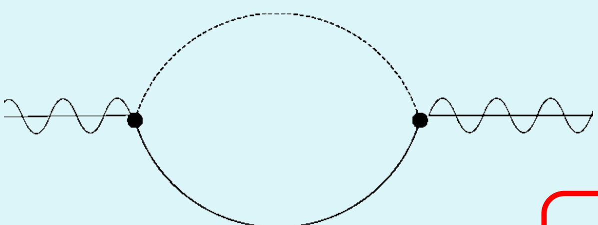
Non-Minimal GMSB

Hidden $F \neq 0$

$kS\bar{\psi}\psi$

Messenger

SM gauge interaction



MSSM

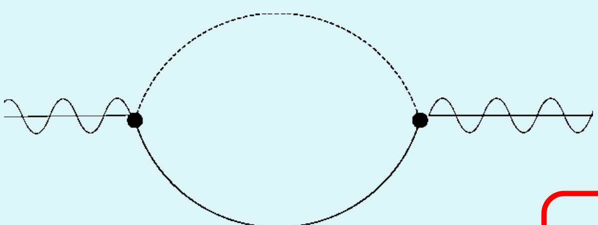
Non-Minimal GMSB

Hidden $F \neq 0$

$\cancel{kS\bar{\psi}\psi}$

Messenger

SM gauge interaction



MSSM

Non-Minimal GMSB

Hidden $F \neq 0$

Hidden Gauge interaction

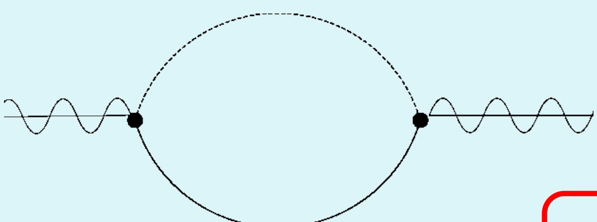
$\cancel{kS\bar{\psi}\psi}$

e.g. semi-direct GMSB

[N. Seiberg, et.al., 08]

Messenger

SM gauge interaction



MSSM

Non-Minimal GMSB

Hidden $F \neq 0$

$\cancel{kS\bar{\psi}\psi}$

$k_{ij}S\bar{\psi}_i\psi_j$

Hidden Gauge interaction

e.g. semi-direct GMSB

[N. Seiberg, et.al., 08]

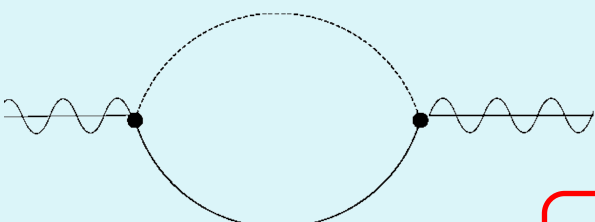
Flavor Structure

e.g. direct GMSB

[K. I. Izawa, et.al., 97]

Messenger

SM gauge interaction



MSSM

Mass Spectrum

$$
\begin{aligned}
m^2_{\text{scalar}} &\approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\text{mess}}}\right)\right) \\
m_{\text{gaugino}} &\approx \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\text{mess}}} \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\text{mess}}}\right)\right)
\end{aligned}
$$

$$M^2 > kF$$

Mass Spectrum

$$m^2_{\text{scalar}} \approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\text{mess}}}\right)\right)$$

$$m_{\text{gaugino}} \approx \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\text{mess}}} \left(\cancel{1} + \mathcal{O}\left(\frac{kF}{M^2_{\text{mess}}}\right)\right)$$

$$M^2 > kF$$

Mass Spectrum

$$
\begin{aligned}
m^2_{\text{scalar}} &\approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\text{mess}}}\right)\right) \\
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\end{aligned}
$$

$$M^2 > kF$$

- F-term gauge mediation with stable vacuum

  e.g. direct GMSB

- Messengers have only mass term in superpotential

  e.g. semi-direct GMSB

$$\vdots$$

Mass Spectrum

$$m^2_{\rm scalar} \approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\rm mess}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M^2_{\rm mess}}\right)\right)$$

$$m_{\rm gaugino} \approx \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\rm mess}} \cancel{\left(1\right.} + \mathcal{O}\underline{\left(\frac{kF}{M^2_{\rm mess}}\right)}\left.\right)$$

$$M^2 > kF$$

- F-term gauge mediation with stable vacuum

e.g. direct GMSB

- Messengers have only mass term in superpotential

e.g. semi-direct GMSB

$\vdots$

Scalar and Gaugino Mass

$$m_{\text{scalar}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right)$$

$$m_{\text{gaugino}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p$$

$$p > 0$$

$$M^2 > kF$$

Scalar and Gaugino Mass

$$m_{\text{scalar}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right)$$

$$< 1$$

$$m_{\text{gaugino}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p$$

$$p > 0$$

$$M^2 > kF$$

Suppression on gaugino mass

$$\frac{m_{\text{gaugino}}}{m_{\text{scalar}}} \approx \left(\frac{kF}{M_{\text{mess}}^2}\right)^p \ll 1$$

Scalar and Gaugino Mass

$$
\begin{aligned}
m_{\text{scalar}} &\approx \Lambda \left(\frac{\alpha}{4\pi}\right) \\
m_{\text{gaugino}} &\approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p
\end{aligned}
$$

< 1

$$p > 0$$

$$M^2 > kF$$

Suppression on gaugino mass

Typically, $\dfrac{m_{\text{gaugino}}}{m_{\text{scalar}}} \lesssim 0.1$

Gravitino Mass

(in perturbative models)

$$m_{\text{scalar}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right)$$

$$m_{\text{gaugino}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p \qquad < 1$$

$$p > 0$$

$$M^2 > kF$$

Suppression on gaugino mass

$$\Downarrow$$

$$m_{3/2} \simeq \frac{F}{M_P} > \mathcal{O}(1\ \text{keV} - 1\ \text{MeV}) \quad \text{for} \quad m_{\text{gaugino}} = \mathcal{O}(100)\ \text{GeV}$$

$$\Downarrow$$

Gravitino Problem

Relation of Gaugino Masses

$$m_{\text{gaugino}} \quad \approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p$$

$$\frac{M_d}{M_\ell} = \frac{k_d}{k_\ell} > 1 \quad \Rightarrow \quad \frac{k_d F}{M_d^2} < \frac{k_\ell F}{M_\ell^2}$$

Relation of Gaugino Masses

$$m_{\text{gaugino}} \approx \Lambda \left(\frac{\alpha}{4\pi}\right) \left(\frac{kF}{M_{\text{mess}}^2}\right)^p$$

$$\frac{M_d}{M_\ell} = \frac{k_d}{k_\ell} > 1 \quad \Longrightarrow \quad \frac{k_d F}{M_d^2} < \frac{k_\ell F}{M_\ell^2}$$

Quark Messenger Contribution is Reduced

$\Downarrow$

Small Gluino Mass

Violation of GUT-relation

$$\begin{aligned} M_1 &= \Lambda \frac{\alpha_1}{4\pi}\left(\frac{2}{5} r^{-p} + \frac{3}{5}\right) \\ M_2 &= \Lambda \frac{\alpha_2}{4\pi} \\ M_3 &= \Lambda \frac{\alpha_3}{4\pi} r^{-p} \end{aligned}$$

$$r \equiv \frac{M_d}{M_\ell} > 1$$

$$M_1 : M_2 : M_3 \approx \alpha_1 \left(\frac{2}{5} r^{-p} + \frac{3}{5}\right) : \alpha_2 : \alpha_3 r^{-p}$$

Deviation from GUT relation

In some cases, the gluino becomes the lightest

Non-minimal GMSB

Mass splitting

$$M_{\text{scalar}} \gg M_{\text{gaugino}}$$

Gravitino Mass > keV

Even if GUT respected, GUT relation violated

$$M_1 : M_2 : M_3 \neq \alpha_1 : \alpha_2 : \alpha_3$$

Gluino tends to be light

Non-minimal GMSB

Mass splitting

$$M_{\text{scalar}} \gg M_{\text{gaugino}}$$

Gravitino Mass > keV

Even if GUT respected, GUT relation violated

$$M_1 : M_2 : M_3 \neq \alpha_1 : \alpha_2 : \alpha_3$$

Gluino tends to be light

Bino NLSP or Gluino NLSP is plausible

2. Cosmology

Gravitino Problem of NLSP decay

LSP gravitino, NLSP gaugino

NLSP decays into LSP

Gravitino Problem of NLSP decay

LSP gravitino, NLSP gaugino

NLSP decays into LSP

$$\tau_{\rm NLSP} \sim 0.1 \ {\rm sec} \left(\frac{m_{3/2}}{1 \ {\rm MeV}} \right)^2 \left(\frac{M_{\rm NLSP}}{100 \ {\rm GeV}} \right)^{-5}$$

$$\tilde{B} \to \gamma + \tilde{G}_{3/2}$$

$$\tilde{g} \to g + \tilde{G}_{3/2}$$

Gravitino Problem of NLSP decay

LSP gravitino, NLSP gaugino

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$$\tau_{\mathrm{NLSP}} \sim 0.1\ \mathrm{sec} \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5}$$

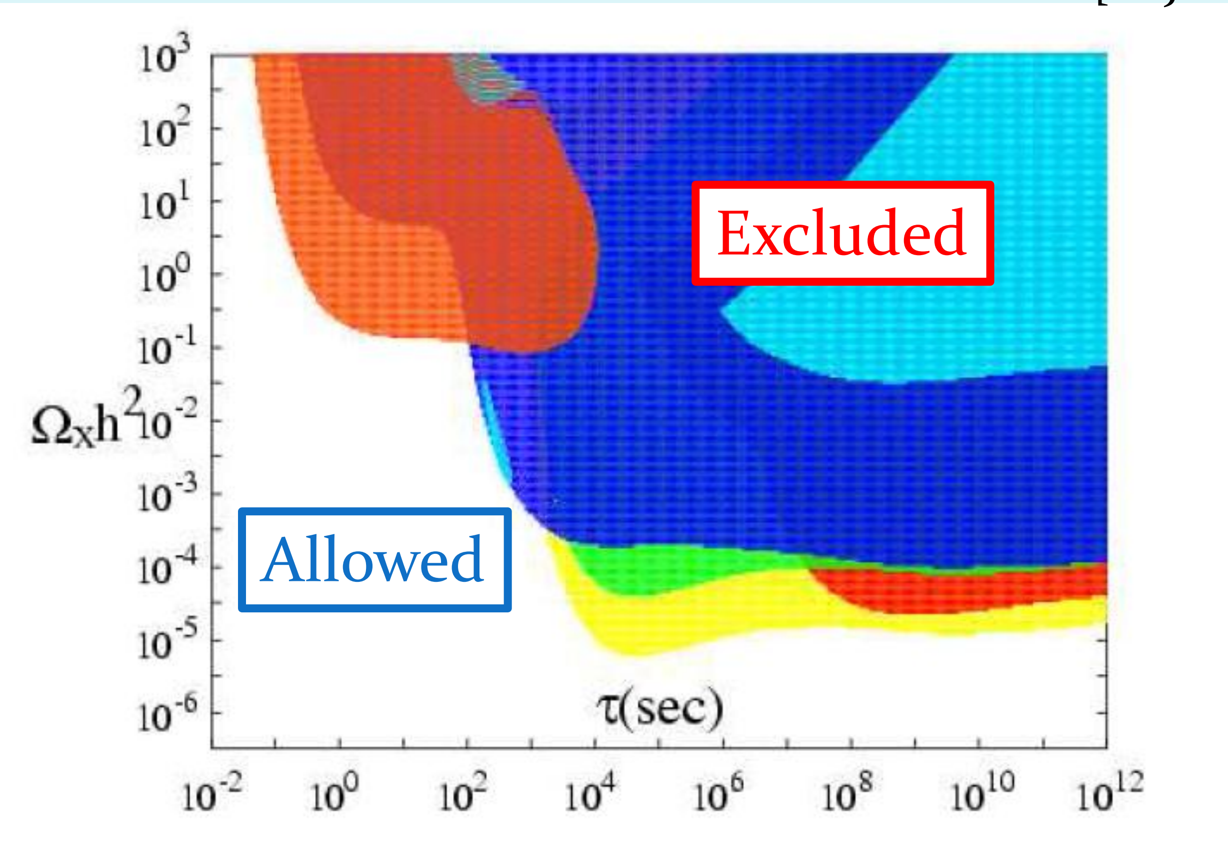
$$\tilde{B} \to \gamma + \tilde{G}_{3/2}$$

$$\tilde{g} \to g + \tilde{G}_{3/2}$$

$\longrightarrow$ Destroy light Element in BBN period

Gravitino Problem of NLSP decay

[K. Jedamzik, 06]

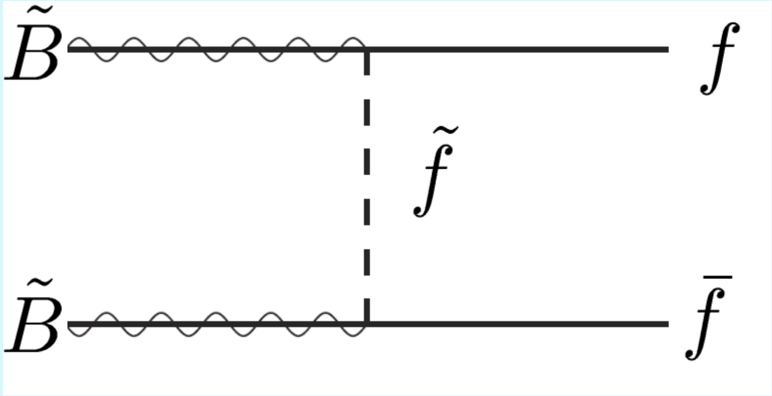


NLSP Abundance

$\boxed{\text{NLSP abundance}}$ ⟸ $\boxed{\text{Annihilation cross section}}$

$$\Omega h^2 \sim \mathcal{O}(1)\left(\frac{\langle\sigma v\rangle_{\mathrm{Anni}}}{10^{-9}\ \mathrm{GeV}^{-2}}\right)^{-1}$$

Bino Abundance

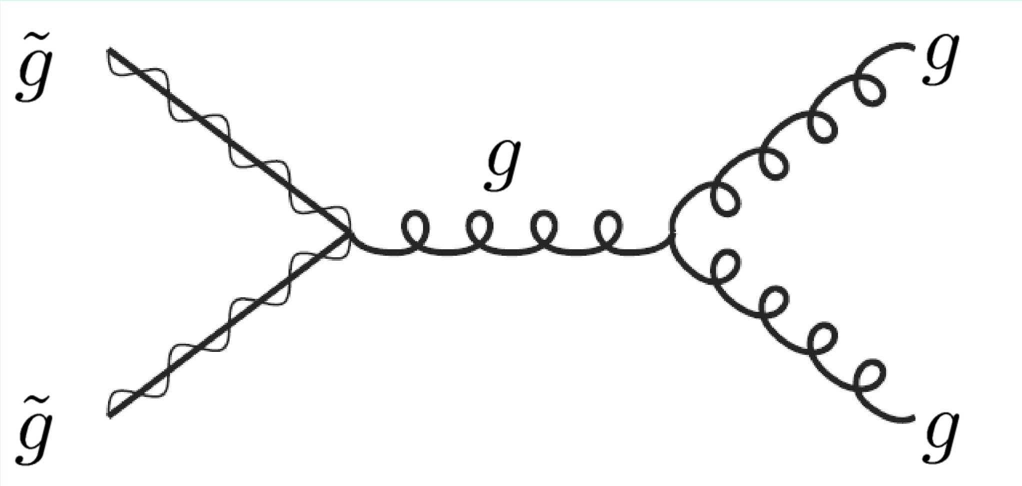


$$\sigma \propto \frac{M_{\tilde{B}}^2}{M_{\tilde{s}}^4}$$

$$\Omega_{\tilde{B}} h^2 \sim \mathcal{O}(10) \times \left(\frac{100\ \text{GeV}}{M_{\tilde{B}}}\right)^2 \left(\frac{M_s}{1\ \text{TeV}}\right)^4$$

Large Scalar Mass → Large Bino Abundance

Gluino Abundance



$$\Omega_{\tilde{g}} h^2 \sim 10^{-3} \left(\frac{M_{\tilde{g}}}{1 \text{ TeV}} \right)^2$$

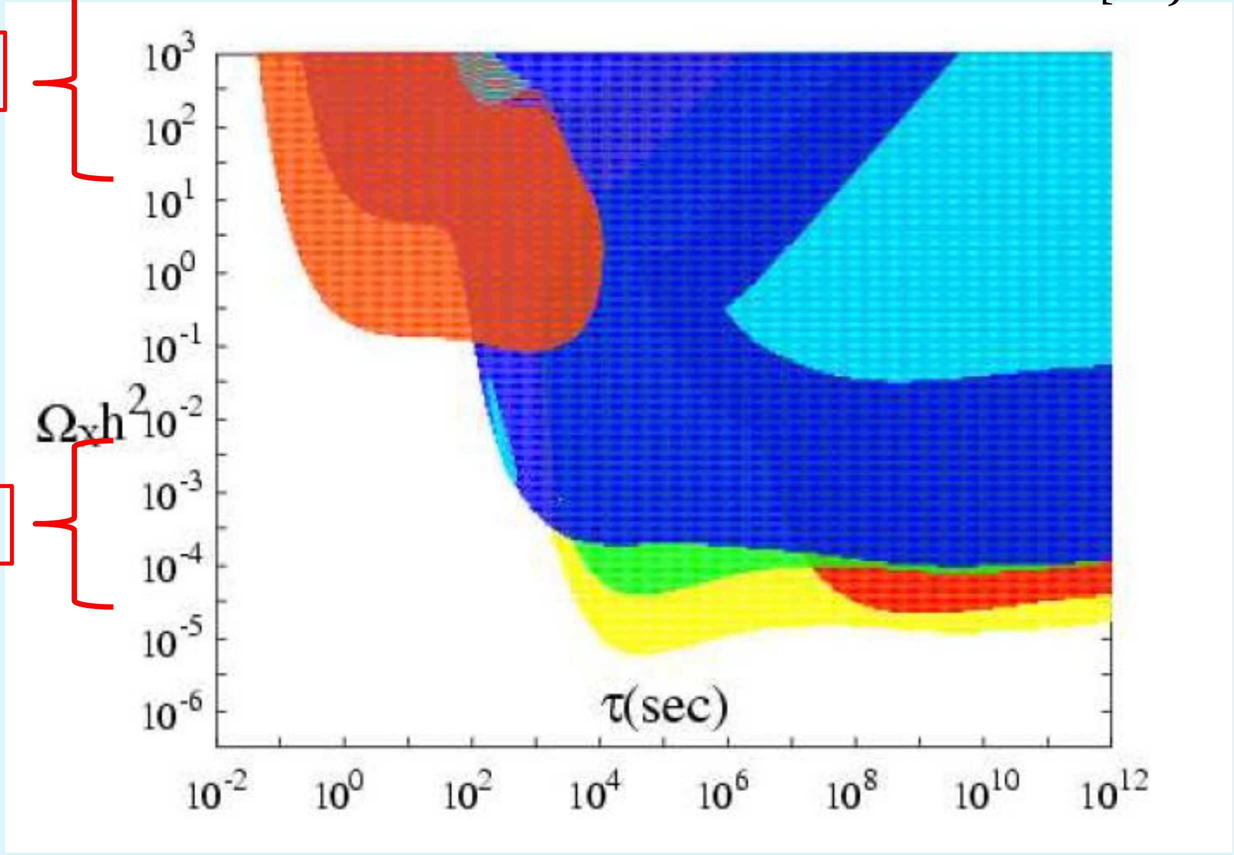
$\boxed{\text{Independence on Scalar Mass}}$

Gravitino Problem of NLSP decay

[K. Jedamzik, 06]

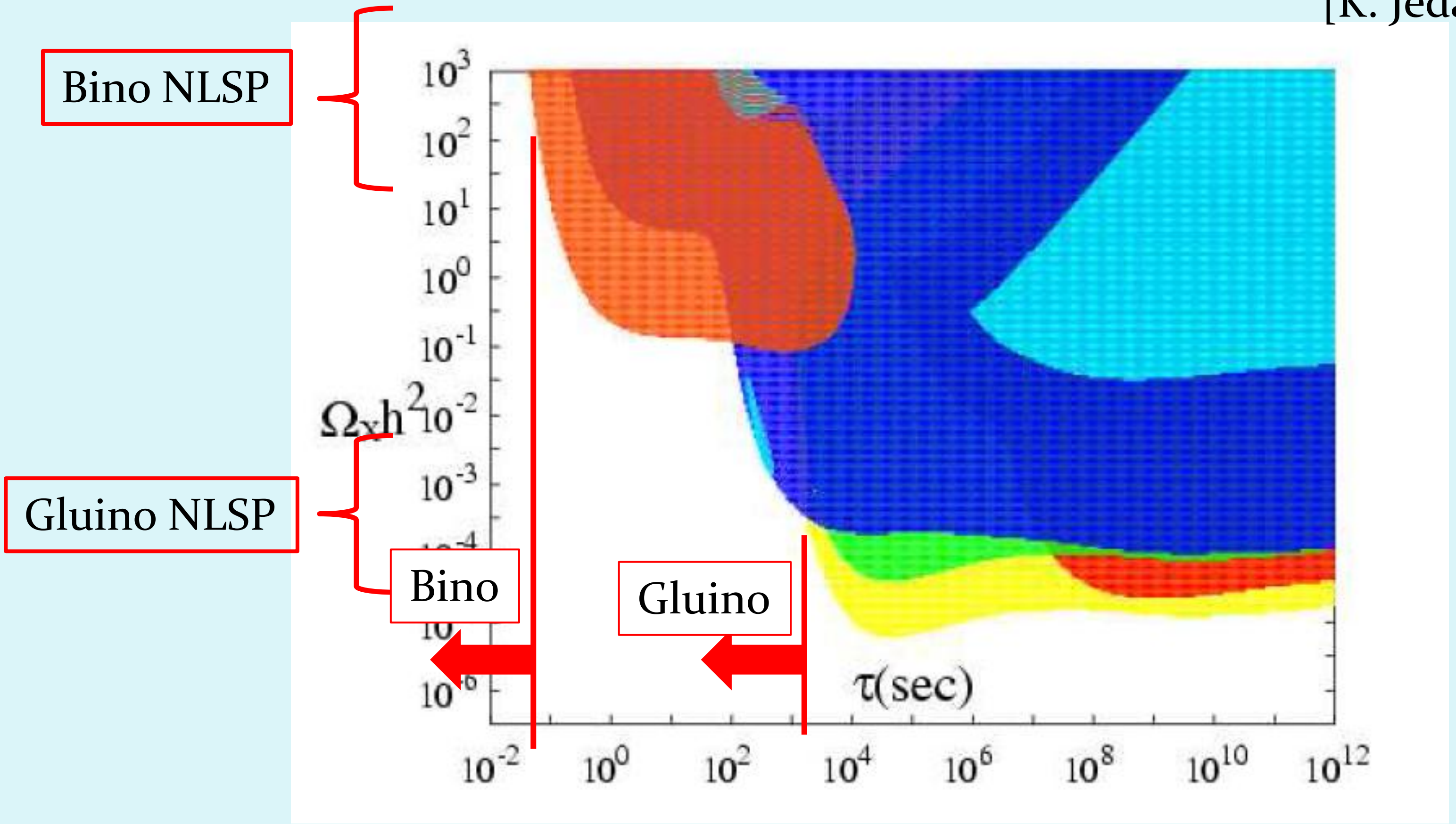
Bino NLSP

Gluino NLSP



Gravitino Problem of NLSP decay

[K. Jedamzik, 06]



Lifetime of NLSP

$\boxed{\text{Bino NLSP}}$

$$\tau_{\text{Bino}} \lesssim 0.1 \text{ sec}$$

$\boxed{\text{Gluino NLSP}}$

$$\tau_{\text{Gluino}} \lesssim 1000 \text{ sec}$$

3. LHC Signal

NLSP Decay

$$m_{3/2} > \mathcal{O}(1\ \mathrm{keV} - 1\ \mathrm{MeV}) \quad \tau_{\mathrm{NLSP}} \sim 0.1\ \mathrm{sec} \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5}$$

$$\Downarrow$$

$$c\tau_{\mathrm{NLSP}} > \mathcal{O}(10)\ \mathrm{m} \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5}$$

NLSP Decay

$$m_{3/2} > \mathcal{O}(1\ \mathrm{keV} - 1\ \mathrm{MeV}) \quad \tau_{\mathrm{NLSP}} \sim 0.1\ \mathrm{sec} \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5}$$

$$c\tau_{\mathrm{NLSP}} > \mathcal{O}(10)\ \mathrm{m} \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-5}$$

If $c\tau_{\mathrm{NLSP}} > \text{detector size}$

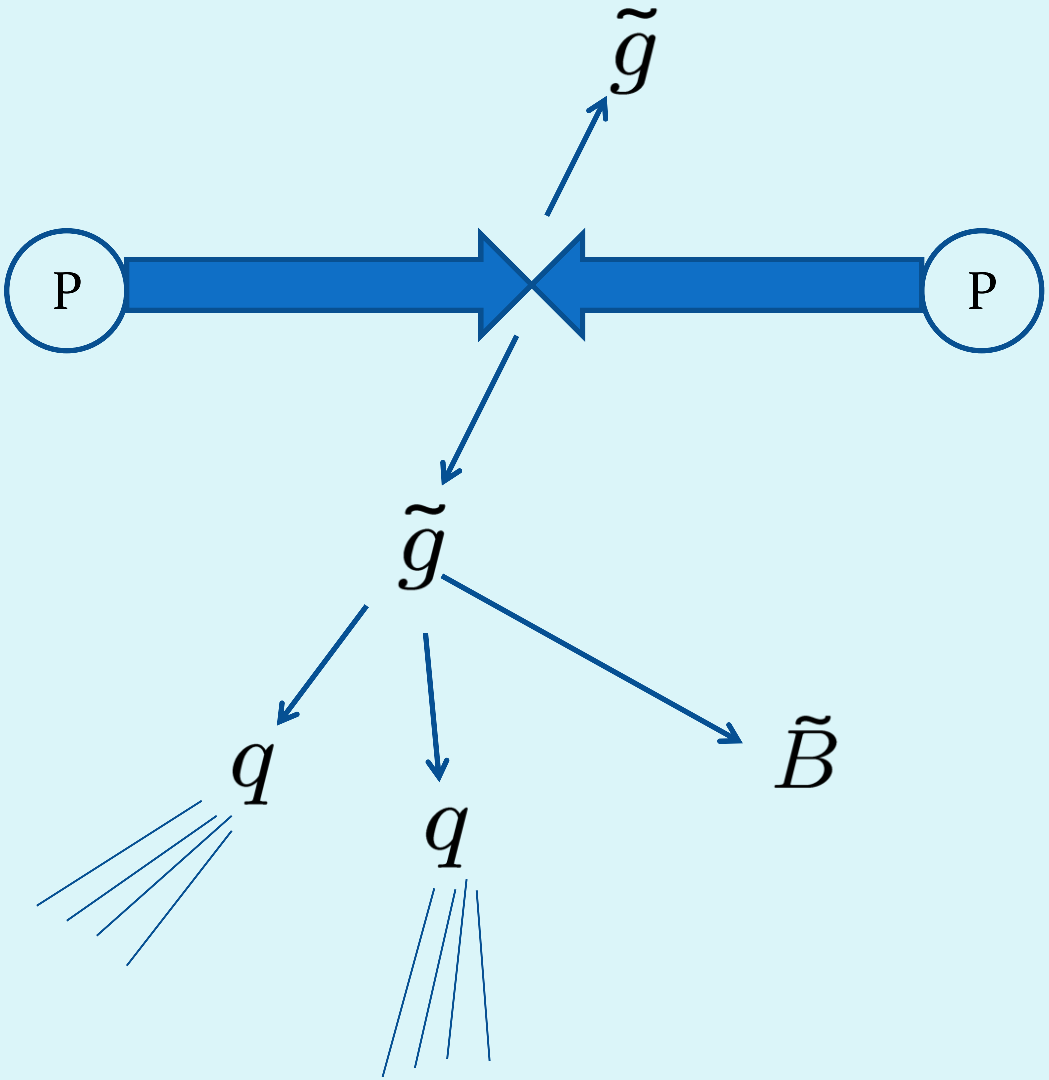
NLSP seems to be "stable" particle

Bino NLSP

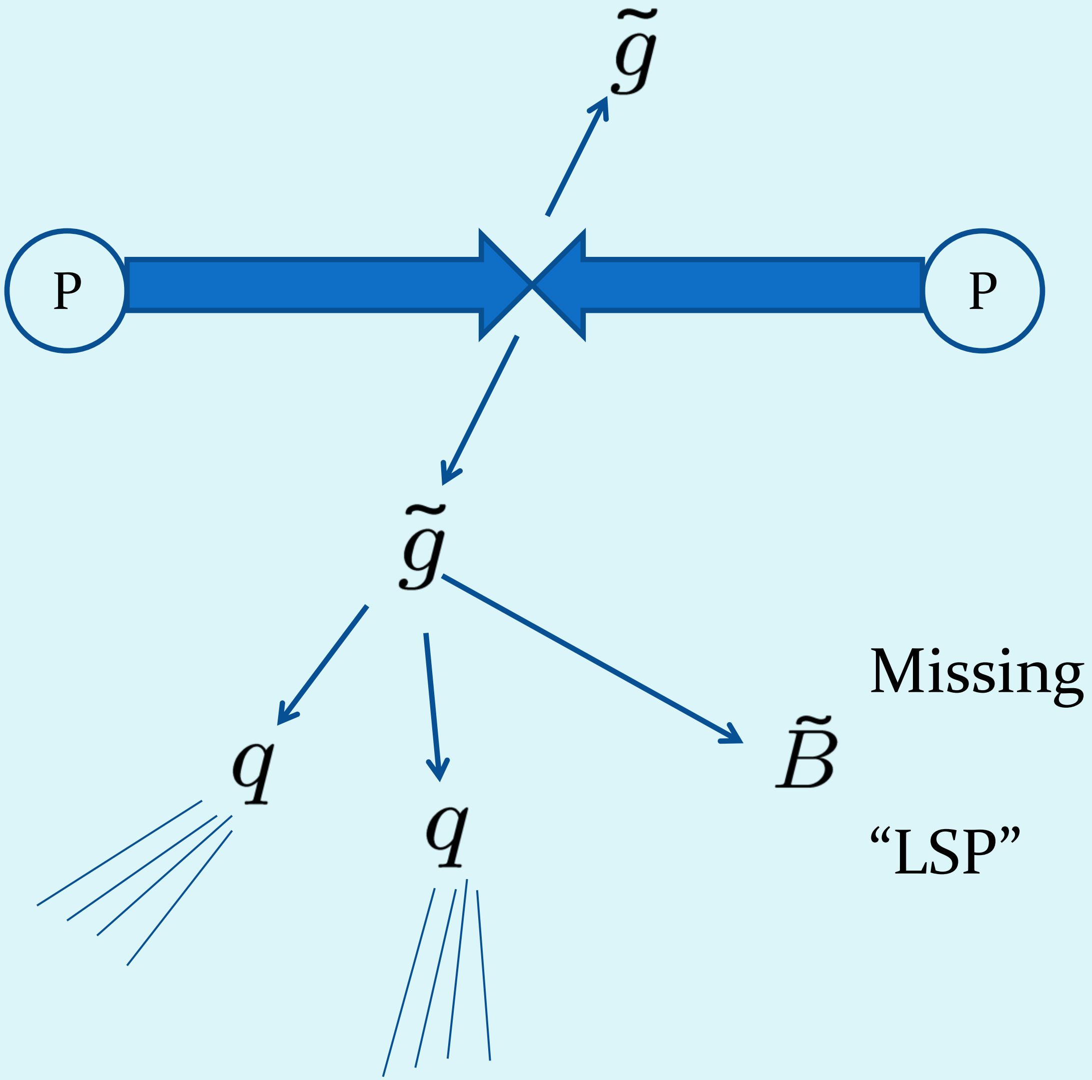
$$c\tau_{\rm NLSP} > \mathcal{O}(10)\ {\rm m} \left(\frac{M_{\rm NLSP}}{100\ {\rm GeV}}\right)^{-5}$$

$$c\tau_{\rm Bino} \lesssim 10^7\ {\rm m} \sim 0.1\ {\rm sec}$$ ⟸ Cosmology

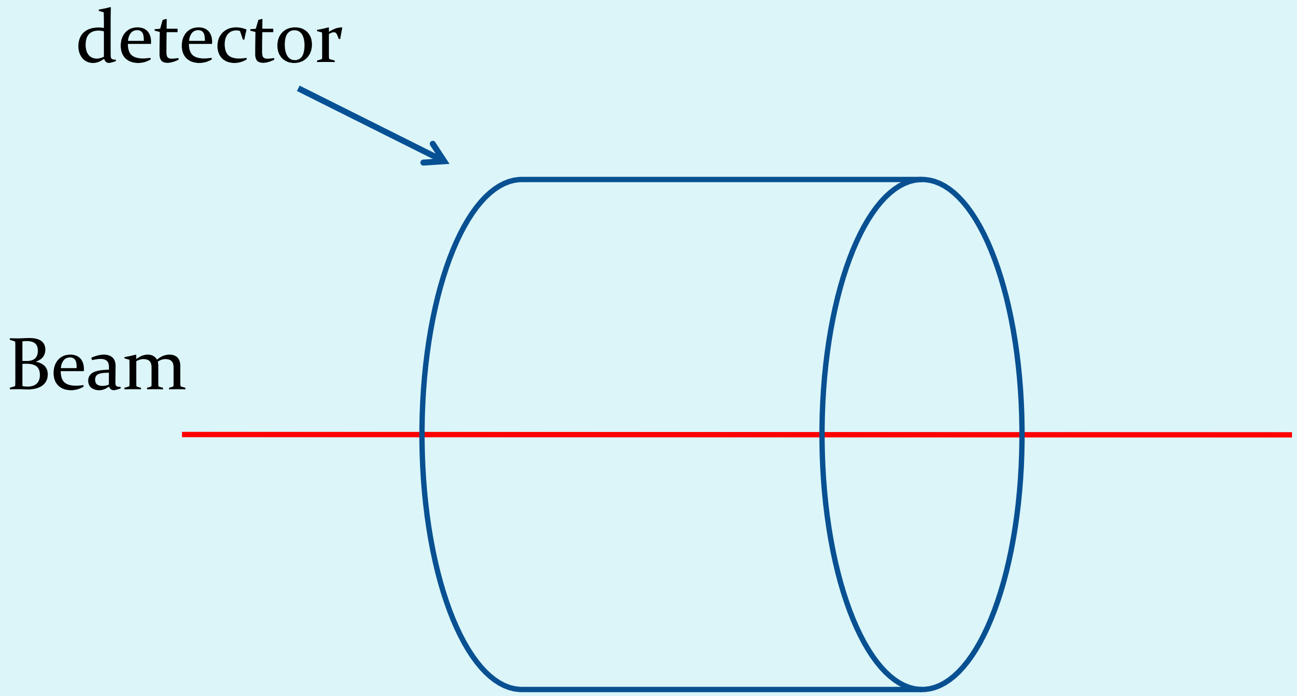
Event Topology at LHC (Bino NLSP)



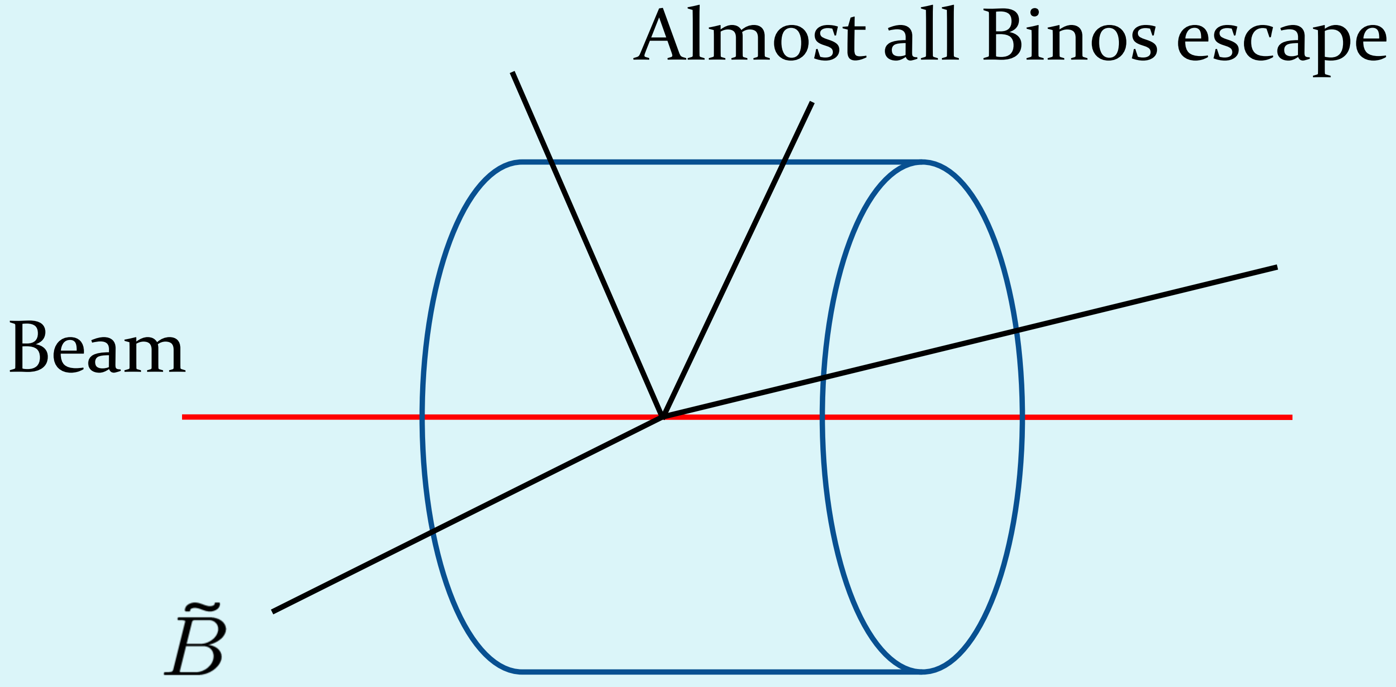
Event Topology at LHC (Bino NLSP)



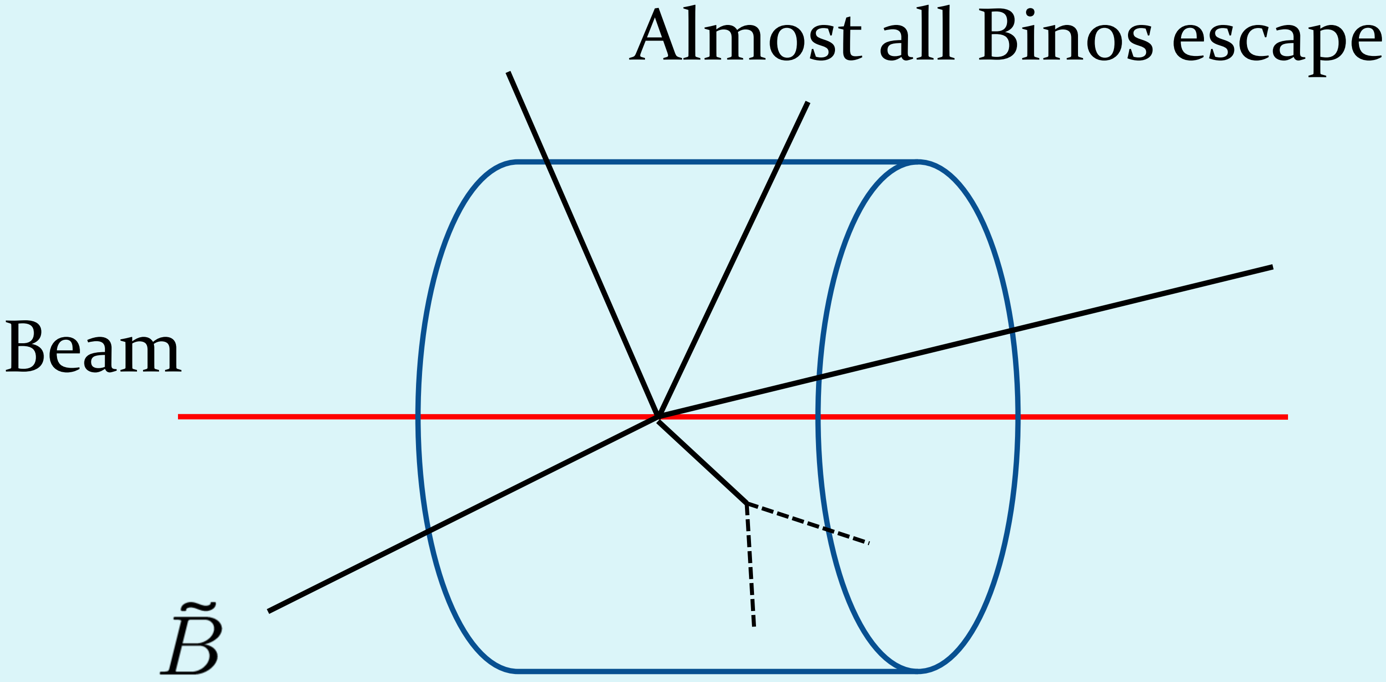
In-flight Decay of the Bino



In-flight Decay of the Bino



In-flight Decay of the Bino

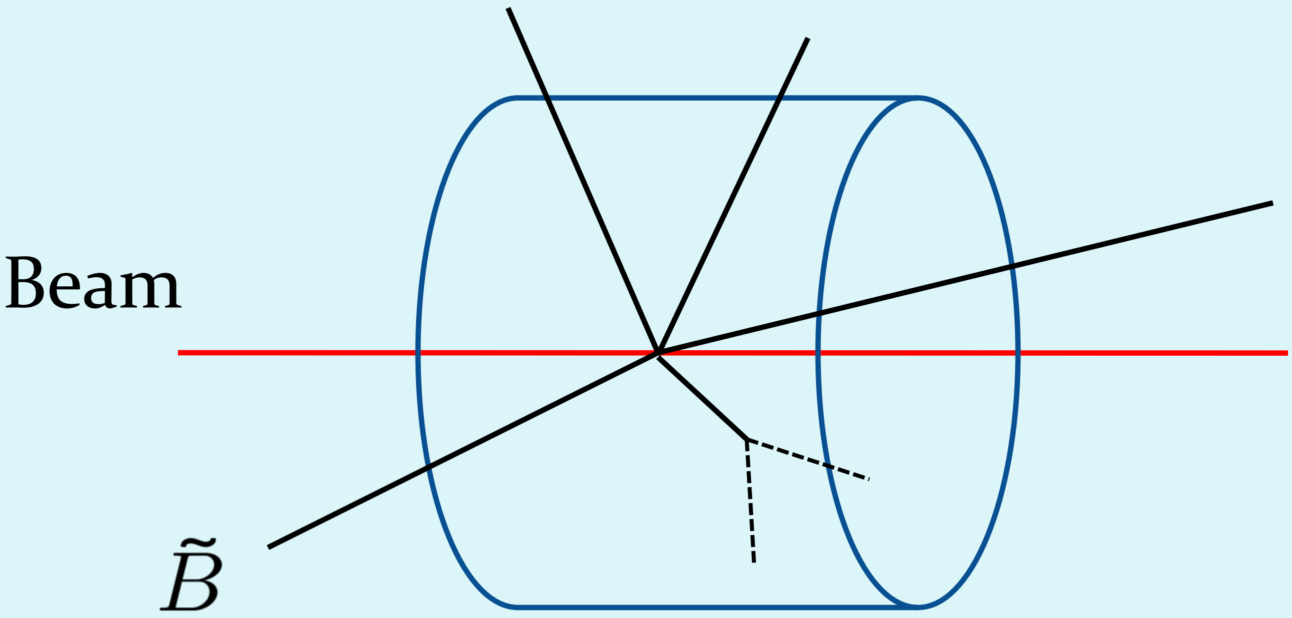


Fraction of decays occur in detector

In-flight Decay of the Bino

$$c\tau_{\rm Bino} \lesssim 10^7\ {\rm m} \sim 0.1\ {\rm sec}$$

Almost all Binos escape



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In-flight Decay of the Bino

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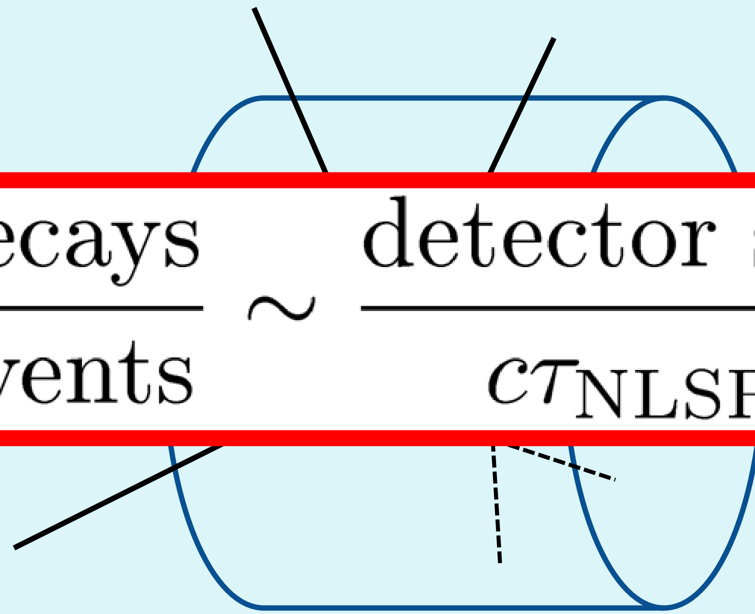


$$\frac{\#\ \text{of decays}}{\#\ \text{of events}} \sim \frac{\text{detector size}}{c\tau_{\text{NLSP}}} \gtrsim 10^{-6}$$

Fraction of decays occur in detector

Gluino NLSP

$$m_{3/2} > \mathcal{O}(1\ \mathrm{keV} - 1\ \mathrm{MeV})$$

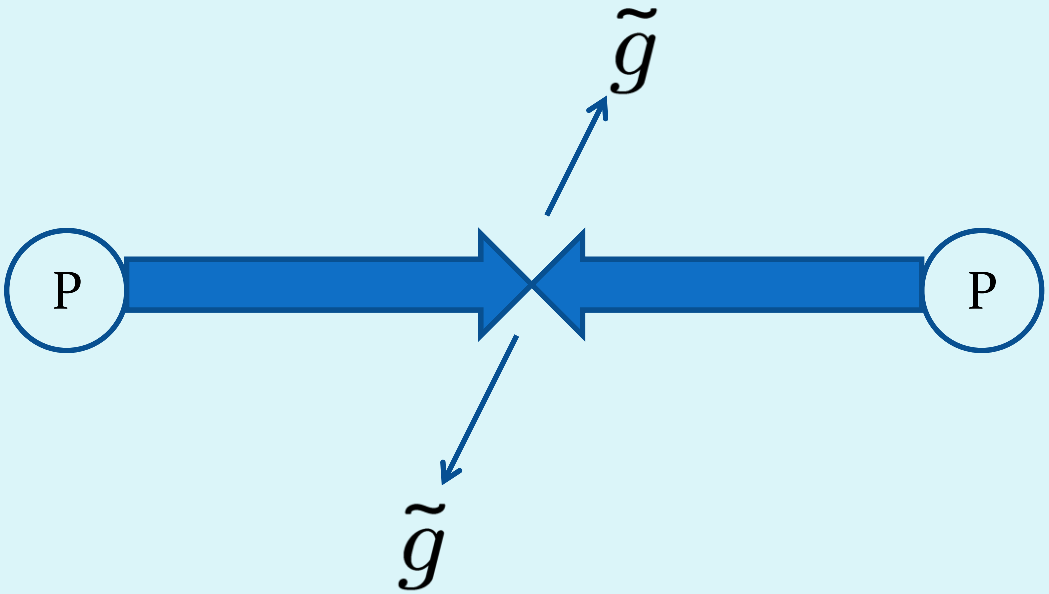
$$c\tau_{\mathrm{NLSP}} > \mathcal{O}(10)\ \mathrm{m} \left(\frac{M_{\mathrm{NLSP}}}{100\ \mathrm{GeV}} \right)^{-5}$$

From Cosmology

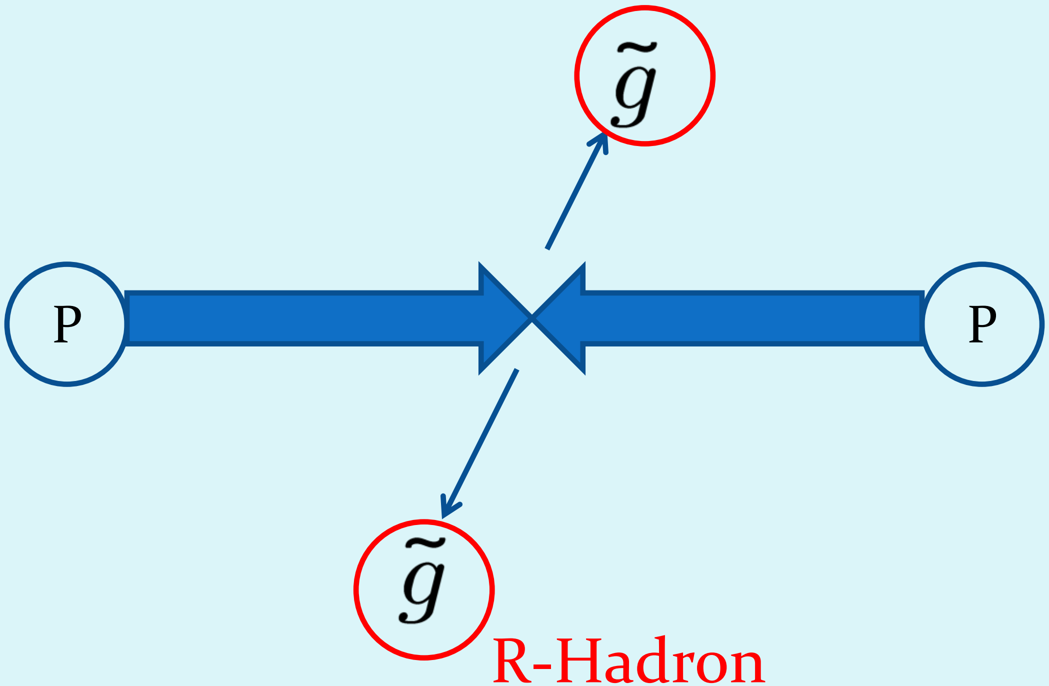
$$c\tau_{\mathrm{Gluino}} \lesssim 10^{11}\ \mathrm{m} \sim 1000\ \mathrm{sec}$$

Too long to observe in-flight decay

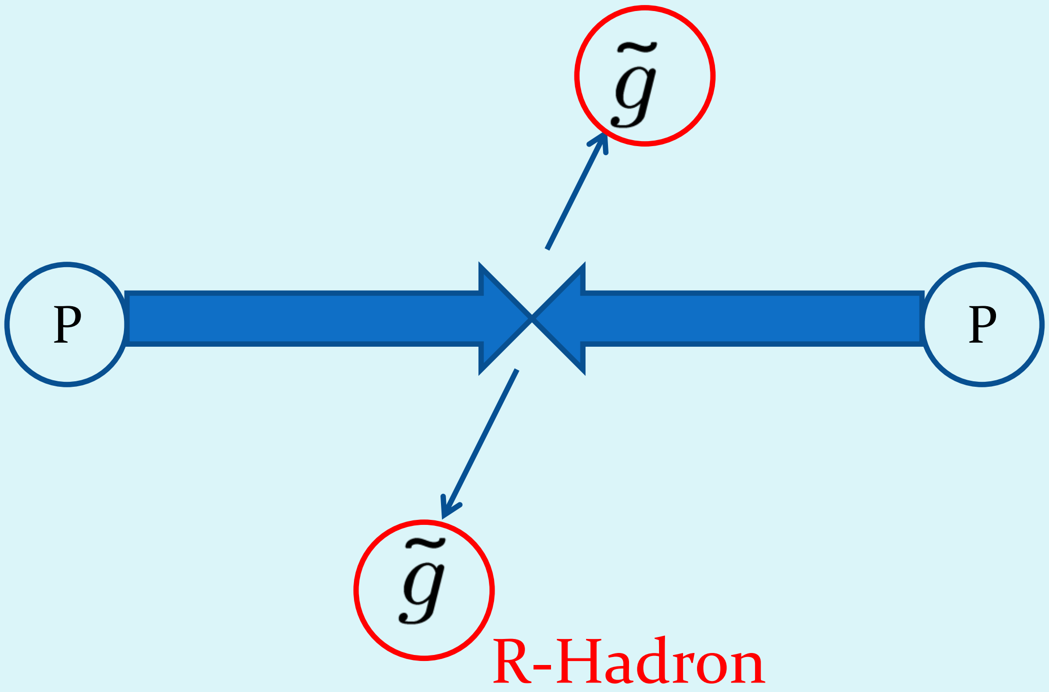
Event Topology at the LHC



Event Topology at the LHC



Event Topology at the LHC



Some of R-hadron $\approx$ "Heavy muon"

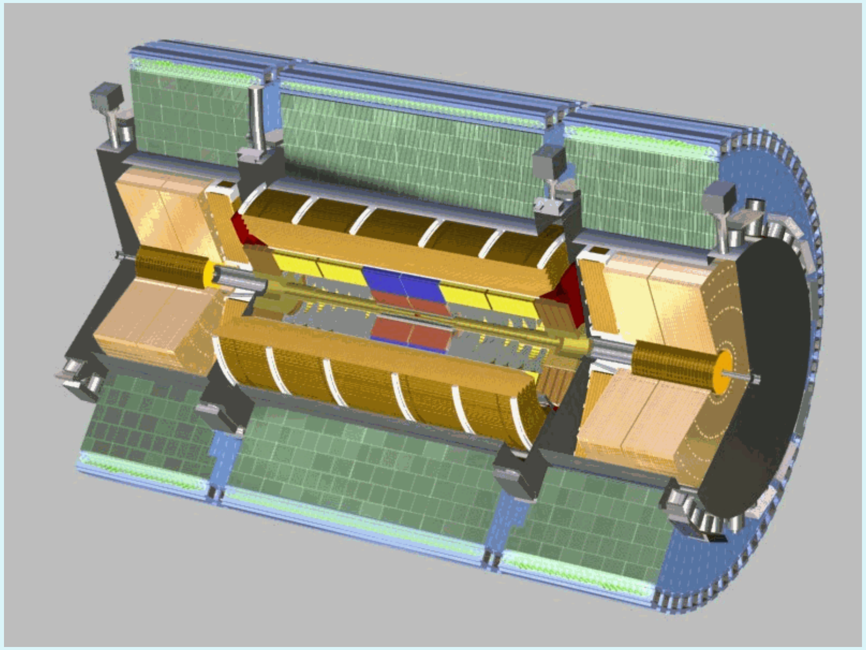
Stopped Gluino

Detector as stopper

For ATLAS HCAL

Barrel 1440 mm Fe

Endcap 1400 mm Cu



Stopped Gluino

Detector as stopper

For ATLAS HCAL

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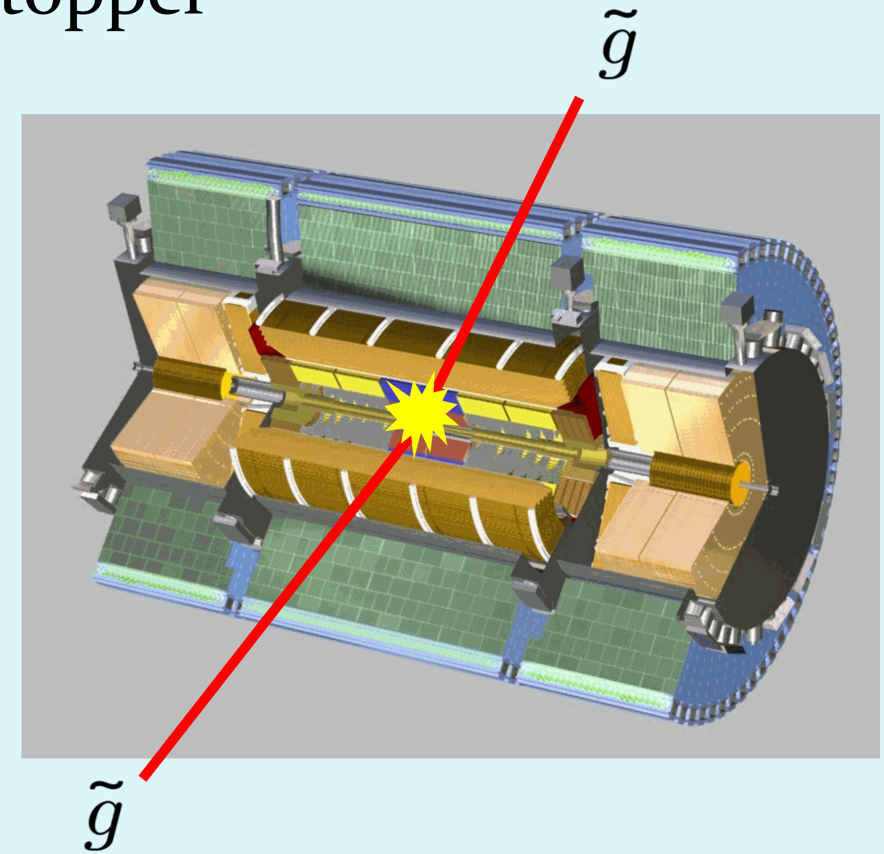
Endcap 1400 mm Cu



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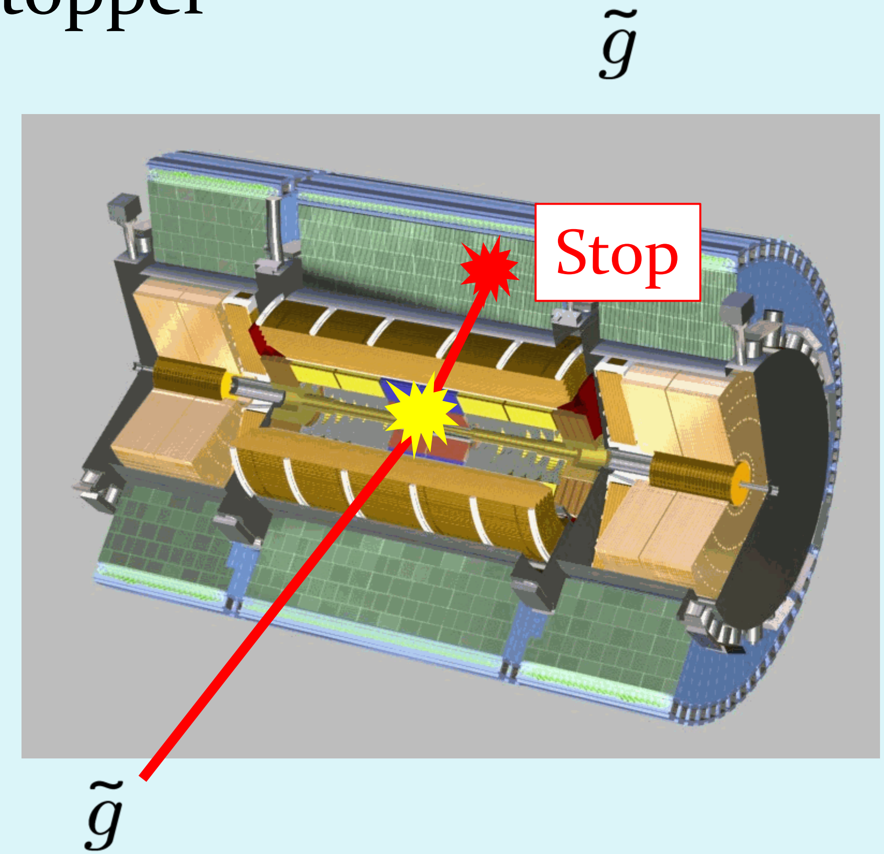


Observation of Late-time Decay

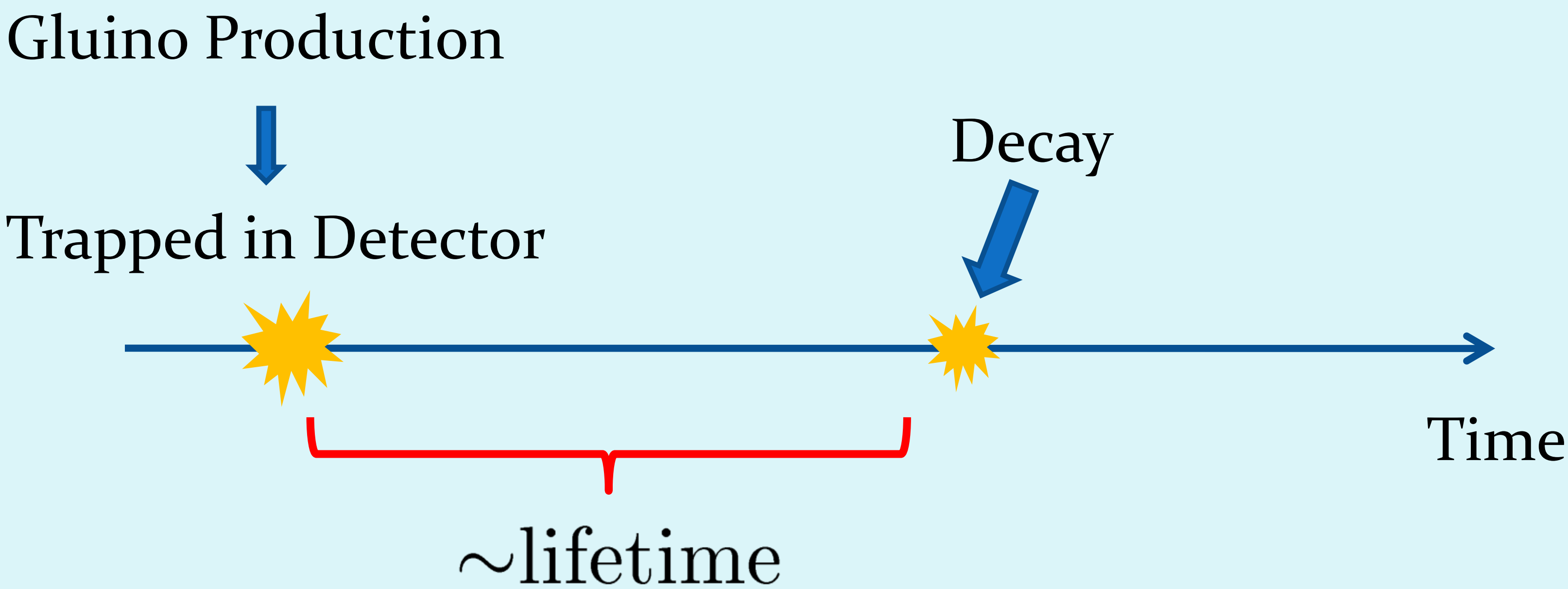
Gluino Production

⇓

Trapped in Detector

Time

Observation of Late-time Decay



Lifetime Measurement is Possible

Summary

In non-minimal GMSB,

$$M_{\mathrm{scalar}} \gg M_{\mathrm{gaugino}} \qquad M_1 : M_2 : M_3 \neq \alpha_1 : \alpha_2 : \alpha_3$$

The Gluino can be the NLSP

From cosmology, lifetime of NLSP is constrained

Decay of NLSP is observed at LHC

Example

$$R \equiv \frac{m_{\tilde{e}_R}}{M_1}$$

	$m_{3/2}$	R	p
minimal	$\gtrsim 1\ \mathrm{eV} \cdot \left(\frac{1}{N_5^2 \lambda}\right)$	$N_5^{-\frac{1}{2}}$	0
semi-direct	$\gtrsim 1\ \mathrm{MeV} \cdot \left(\frac{10^{-4}}{h h_g^{10/3} L_V^{4/3}}\right)$	$\gtrsim 10^2 \left(\frac{h h_g L_V}{10^{-2}}\right)^{\frac{1}{2}}$	2 or 4
stable F-term	$\gtrsim 10^2\ \mathrm{eV} \cdot \left(\frac{1}{n_5^2 \lambda}\right)$	$\gtrsim 10 \left(n_5^{3/4} \lambda\right)^{\frac{2}{5}}$	2

$$M_1 = 100\ \mathrm{GeV}$$

Expected Number of Decays

for $L = 1000 \text{ fb}^{-1}$

Gluino Mass[GeV]	# of Events	# of Decays
500	3×10^7	$\gtrsim 30$
750	3×10^6	$\gtrsim 3$
1000	4×10^5	$\gtrsim 0.4$
1250	10^5	$\gtrsim 0.1$

Vacuum of Minimal GMSB

$\langle S \rangle = F_S \theta^2$ $\Longleftarrow$ $W_{\cancel{\mathrm{SUSY}}}(S) = -F_S^\dagger S$

(Low-energy effective)

Including interaction with messengers

$$W = kS\bar{\psi}\psi + M\bar{\psi}\psi + W_{\cancel{\mathrm{SUSY}}}(S) \qquad \psi \sim (d, \ell)$$

$$F = \frac{\partial W}{\partial S} = \frac{\partial W_{\cancel{\mathrm{SUSY}}}(S)}{\partial S} + k\bar{\psi}\psi$$

$\langle \bar{\psi}\psi \rangle \neq 0$ $\Longrightarrow$ F-term condition satisfied

SUSY breaking vacua is not stable

R-Hadron

Hadronic Bound State with Quarks or Gluon

$\tilde{g}u\bar{d}$ $\tilde{g}g$ R-Hadron

Some have EM charge $\Rightarrow$ Interaction with ordinary matter

$\boxed{\text{Fractions of R-Hadrons can be trapped in Matters}}$