

SUSY (g-2)^μ With & Without Neutralino Dark Matter

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In collaboration with

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Based on [2202.12928]

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(g - 2)μ anomaly $M = Z_{\rm m}$ anomaly with the $P_{\rm m}$ \mathbf{P} SM WP20 prediction from the TI White Paper (0.37 ppm) and the TI White Paper (0.37 ppm) and the TI White Paper

 $M\zeta$

iviuon <u>c</u>

Motivation

• There are many BSM scenarios that can explain the $(g-2)_{\mu}$ anomaly:

Leptoquarks, Z', VLL, 2HDM, axion, ..

• Supersymmetry is particularly motivated since it offers:

Coupling Unification, Radiative EWSB, Baryogenesis, DM, …

• There are many studies on SUSY g-2 already:

[Athrona, Balazsa, Jacoba, Kotlarskic, Stockingerc, Stockinger-Kim]; [Chakraborti, Heinemeyer, Saha]; [Endo,Hamaguchi,Iwamoto,Kitahara]; [Cox, Han, Yanagida]; [Baum, Carena, Shah, Wagner]; [Badziak, KS]; [Hagiwara,Ma,Mukhopadhyay'18], …

- Most studies assume the neutralino is the Lightest SUSY Particle (LSP) and stable.
	- Q: What happens if neutralino is unstable? (e.g. RPV, Gravitino LSP)
	- A: DM constraints go away, but LHC constraints change. **How?**

- the name of the name construction of the name of the name in items in the space of the space ❖ **Bino** has very small annihilation cross-section
	- ⇨ **Tend to produce too much DM tension**
- where *_n* is the Higgsino mass parameter, tan **h**₀ ❖ Large off-diagonal term in stau mass matrix:
- for the Bino (U(1)*^Y* gaugino), the Wino (SU(2)*^L* gaugino), the left-handed slepton doublet and - charge breaking vacuum: m²stau1 > 0
- the universal species in the universal species and the universal species and the universal species μ \sim 90 GeV - LEP bound: $m_{\text{stau1}} > 90$ GeV
- stau LSP: $m_{\text{stau1}} > m_{\text{neutralino1}}$
	- Vacuum (meta-)stability

the name corresponding to sparticles taking part in it, e.g. *BHL* is a diagram involving Bino, Higgsino and **SUSY g-2 has a tension with:** SUSY g-2 has a tension with:

- where *DIVI* Direct Detection - DM Direct Detection
- (Bino-like) DM overproduction \longrightarrow consequence of **stable neutralino**
- lepton + large E_Tmiss @ LHC and free parameters we adopted parameters we adopted parameters we are parameters we adopted the number of θ the universal slepton mass assumption: ˜*ml*¹ = ˜*ml*²
	-

for the Bino (U(1)*^Y* gaugino), the Wino (SU(2)*^L* gaugino), the left-handed slepton doublet and *}* consequence of **stable neutralino**

- Vacuum stability (for BLR) How the situation improves / external processes such as *deteriorates* if **neutralino** is not the universal set of the univ necessary to avoid the LFV constraints. It is such that the charged slepton mass α matrices, matrices, matrix in the same basis in the same basis in the same basis in $\frac{1}{2}$ How the situation improves / deteriorates if **neutralino is unstable**? ⁷

Analysis

EXAMPLE IN LIGHT OF ATTLA CRACER atlas 1604 on Antonio 1604 on China atlas 1402 7029 8 20.3 3 leptons + MET (chargino+neutralino) s included in our analysis **direct** atlas 1403 5222 \pm 20.3 stop production with Z boson and b-jets production with Z **List of ATLAS & CMS searches included in our analysis**

atlas 13 TeV and 13 TeV 8 TeV atlas confidences confidences $\mathbf{1}$ $\mathbf{3}$.

$\frac{1}{\sqrt{2}}$ 20.3 $\frac{1}{\sqrt{2}}$ 305 $\frac{1}{\sqrt{2}}$ 305 8 TeV

All g-2 region will be probed by the next generation DM-DD experiments

Unstable Neutralino

We study **2** example-scenarios with *un*stable neutralino

UDD RPV stable neutralino
 $\tilde{m}_h = \min(M_2, |\mu|) + 20 \text{GeV}, \tan \beta = 50, A = 0, \ \tilde{m}_h = M_1 = 10 \text{TeV}$

 M_2 [GeV]

ATLAS multijet+l [2106.09609]

CMS multilepton [1709.05406]

ATLAS jets $+E$ Tmiss [ATLAS-CONF-2019-040]

UDD RPV stable neutralino

19

Gravitino LSP. Table 11: Analyses in CheckMATE which are relevant for GMSB scenario with neutralino NLSP.

making mass spectrum compressed.

Z

WHL plane:

$$
(M_2 \text{ vs } \mu) \text{ with } \tilde{m}_{l_L} = \min(M_2, \mu) + 20 \text{ GeV} \implies m_{l_L} = \min(M_2, \mu) - 20 \text{ GeV}
$$
\n**BHL plane:**

\n
$$
(M_1 \text{ vs } \mu) \text{ with } \tilde{m}_{l_L} = \min(M_2, \mu) + 20 \text{ GeV} \implies m_{l_L} = \min(M_2, \mu) - 20 \text{ GeV} \implies \tilde{U}_L \text{NLSP}
$$

$$
(M_1 \text{ vs } \mu) \text{ with } \tilde{m}_{l_L} = \min(M_1, \mu) + 20 \text{ GeV} \implies m_{l_L} = \min(M_2, \mu) - 20 \text{ GeV}
$$

BHR plane:

$$
(M_1 \text{ vs } \mu) \text{ with } \tilde{m}_{l_R} = \min(M_1, |\mu|) + 20 \text{ GeV} \implies m_{l_R} = \min(M_1, \mu) - 20 \text{ GeV} \quad \left\{ \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R \text{ NLSP} \right\}
$$

BLR plane:

$$
(\tilde{m}_{l_L} \text{ vs } \tilde{m}_{l_R}) \text{ with } M_1 = m_{\tilde{\tau}_1} - 20 \text{ GeV} \implies M_1 = m_{\tilde{\tau}_1} + 20 \text{ GeV} \quad \frac{\tilde{\tau}_1}{\tilde{\tau}_1} \text{ NLSP}
$$

 $\mathbf{\Lambda}$

MSSM with stable neutralino:

UDD RPV :

Summary

- SUSY might be a solution to the $(g-2)_{\mu}$ anomaly
	- stable LSP ${\tilde\chi_1^0} \implies$ LHC constraints from large $\not\hspace{-1.2mm}E_T^r$ search
	- slepton-gaugino-Higgsino are light \implies stringent constraint from DM-DD detection
	- LR slepton and Bino are light \implies Bino overproduction
- If $\tilde{\chi}^0_1$ is not stable LSP, DM constraints go away, and LHC signature changes.
	- \circlearrowleft RPV with UDD \Longrightarrow LHC constraints from multijet + lepton
	- ② Gravitino LSP with $\tilde{\chi}^0_1$ NLSP \implies (g-2)_μ region excluded by $\gamma+E_T$ channel
	- \circledS Gravitino LSP with *non* $\tilde{\chi}^0_1$ NLSP \implies LHC constraints from soft lepton/tau

Explanation for (g-2)μ anomaly is possible for the scenarios ① **and** ③

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Understanding the Early Universe: interplay of theory and collider experiments

Joint research project between the University of Warsaw & University of Bergen

Parameter planes definition

name	axes	range $[{\rm TeV}]$	other parameters	$\tan\beta$
\mathbf{WHL}_μ	(M_2,μ)	([0.2, 4], [0.2, 4])	$\tilde{m}_{l_{\rm L}} = \min(M_2,\mu) + 20\,{\rm GeV},~~M_1 = \tilde{m}_{l_{\rm R}} = 10\,{\rm TeV}$	50
\mathbf{WHL}_L	$(M_2,\tilde m_{l_{\scriptscriptstyle\rm L}})$	([0.2, 4], [0.2, 2])	$\mu = \min(M_2, \tilde{m}_{l_L}) - 20 \,\text{GeV}, \ \ M_1 = \tilde{m}_{l_B} = 10 \,\text{TeV}$	50
\mathbf{BHL}_μ	(M_1,μ)	([0.12, 0.6], [0.12, 0.35])	$\tilde{m}_{l_{\rm L}} = \min(M_1,\mu) + 20\,{\rm GeV},~~M_2 = \tilde{m}_{l_{\rm R}} = 10\,{\rm TeV}$	50
\mathbf{BHL}_L	$(M_1,\tilde m_{l_1})$	([0.12, 0.8], [0.14, 0.22])	$\mu = \min(M_1, \tilde{m}_{l_L}) - 20 \,\text{GeV}, \ \ M_2 = \tilde{m}_{l_B} = 10 \,\text{TeV}$	50
\mathbf{BHR}_μ	(M_1, μ)	([0.12, 0.7], [0.12, 0.7])	$\tilde{m}_{l_{\rm B}} = \min(M_1, \mu) + 20\,{\rm GeV},~~M_2 = \tilde{m}_{l_{\rm L}} = 10\,{\rm TeV}$	50
\mathbf{BHR}_L	$(M_1,\tilde m_{l_{\rm B}})$	([0.12, 0.8], [0.14, 0.25])	$-\mu = \min(M_1, \tilde{m}_{l_B}) - 20 \,\text{GeV}, \ \ M_2 = \tilde{m}_{l_L} = 10 \,\text{TeV}$	50
BLR_{50}	$(\tilde{m}_{l_{\rm\scriptscriptstyle L}},\tilde{m}_{l_{\rm\scriptscriptstyle B}})$	([0.15, 0.6], [0.12, 1.2])	$M_1 = m_{\tilde \tau_1} - 20\,{\rm GeV},\;\; \mu = \mu_{\rm max},\;\; M_2 = 10\,{\rm TeV}$	50
BLR_{10}	$(\tilde{m}_{l_{\rm L}},\tilde{m}_{l_{\rm B}})$	([0.15, 0.6], [0.12, 1.2])	$M_1 = m_{\tilde{\tau}_1} - 20 \,\text{GeV}, \ \ \mu = \mu_{\text{max}}, \ \ M_2 = 10 \,\text{TeV}$	10

Table 1: The parameter planes and choices of the other parameters. μ_{max} is defined as the maximum value allowed by the vacuum stability constraint.

For GMSB we modify the planes to ensure that slepton/stau/sneutrino is the NLSP.

$$
a_{\mu}^{\text{theo}} = 0.00 \quad 1165 \quad 91 \quad 810 \tag{43}
$$
\n
$$
a_{\mu}^{\text{exp}} = 0.00 \quad 1165 \quad 92 \quad 061 \tag{41}
$$

• The deviation is size of the EW correction in SM:

$$
a_{\mu}^{\text{exp}} - a_{\mu}^{\text{theo}} \simeq (25 \pm 6) \times 10^{-10} \sim \mathcal{O}\left(\Delta a_{\mu}^{\text{SM,EW}}\right)
$$

• We need very light BSM particles **OR** enhancement from couplings

$$
\Delta a_{\mu}^{\text{BSM}} \sim \Delta a^{\text{SM,EW}} \cdot \left(\frac{m_W^2}{m_{\text{BSM}}^2}\right) \cdot \left(\frac{g_{\text{BSM}}}{g_{\text{SM}}}\right)
$$

$$
\widehat{\mathcal{O}}(1)
$$

Chiral (tanβ) enhancement in SUSY

• (g-2) operator requires chirality flip:

$$
\mathcal{L}_{\rm eff} \ni i \widetilde{a}_{\mu} \cdot \bar{\psi}_L \sigma^{\mu \nu} \psi_R F_{\mu \nu}
$$

$$
\overrightarrow{\mu} = g\left(\frac{e}{2m}\right) \overrightarrow{s}
$$

$$
a_{\mu} = \frac{(g-2)}{2} \equiv m_{\mu}\widetilde{a}_{\mu}
$$

SM: $\widetilde{a}_{\mu}^{\rm SM}$ \propto $Y_{\mu} \langle H \rangle = m_{\mu}$

Chiral (tanβ) enhancement in SUSY

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$$

$$
\text{SM:} \quad \widetilde{a}_{\mu}^{\text{SM}} \quad \propto \ Y_{\mu} \langle H \rangle = m_{\mu}
$$

SUSY:
$$
\Delta \widetilde{a}_{\mu}^{SUSY} \propto Y_{\mu} \langle H_u \rangle = m_{\mu} \cdot \tan \beta
$$

$$
m_{\mu} = Y_{\mu} \langle H_d \rangle \quad \tan \beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}
$$

 μ_R $\tilde{\nu}_{\mu}$ μ_L \tilde{H}^+_d \tilde{M} + \tilde{H}_{u}^{+} \tilde{W}^+ $H\setminus$ $\langle H_u \rangle$ *γ*

$$
\langle H_u \rangle^2 + \langle H_d \rangle^2 = \langle H \rangle^2
$$

\n
$$
\uparrow
$$

\n
$$
(246 \,\text{GeV})^2
$$

Chiral (tanβ) enhancement in SUSY

- Due to strong LHC constraints, we *decouple coloured SUSY particles* (they do not contribute to $(g-2)_{\mu}$ anyway).
- a_μSUSY depends on 5 mass parameters and tanβ :

no LFV due to universal soft masses: avoid strong constraint from $\mu \rightarrow e \gamma$

$$
\Delta a_{\mu}^{\text{SUSY}} = \Delta a_{\mu}^{\text{WHL}} + \Delta a_{\mu}^{\text{BHL}} + \Delta a_{\mu}^{\text{BHR}} + \Delta a_{\mu}^{\text{BLR}}
$$

$$
\Delta a_{\mu}^{\text{WHL}}(M_2, \mu, m_{\tilde{l}_L}) = \frac{\alpha_W}{8\pi} \frac{m_{\mu}^2}{M_2 \mu} \tan \beta \cdot f_{\text{W}}(\{\mathbf{m}\})
$$

\n
$$
\Delta a_{\mu}^{\text{BHL}}(M_1, \mu, m_{\tilde{l}_L}) = \frac{\alpha_Y}{8\pi} \frac{m_{\mu}^2}{M_1 \mu} \tan \beta \cdot f_{\text{N}}(\{\mathbf{m}\})
$$

\n
$$
\Delta a_{\mu}^{\text{BHR}}(M_1, \mu, m_{\tilde{l}_R}) = -\frac{\alpha_Y}{8\pi} \frac{m_{\mu}^2}{M_1 \mu} \tan \beta \cdot f_{\text{N}}(\{\mathbf{m}\})
$$

 $\frac{1}{2}$ M_1 : Bino (\tilde{B}) mass μ : Higgsino (\tilde{H}_u , \tilde{H}_d) mass

e gaugino-Higgsino ino mixing
. .
اتا Large gaugino-Higgsino mixing leads to a large cross-section for DM Direct Detection: $\frac{1}{2}$ m $\frac{1}{2}$ m $\frac{1}{2}$ m $\frac{1}{2}$ m $\frac{1}{2}$ \mathbf{r} e cross-section for Dl
. $\overline{}$ Direct

$$
\frac{\left(\Delta a_{\mu}^{\text{SUSY}} = \Delta a_{\mu}^{\text{WHL}} + \Delta a_{\mu}^{\text{BHL}} + \Delta a_{\mu}^{\text{BHR}} + \Delta a_{\mu}^{\text{BLR}}\right)}{B}
$$
\n
$$
\mu_{\text{L}} \qquad \frac{\mu \cdot \langle H_{u} \rangle}{\tilde{\mu}_{\text{L}}} \qquad \frac{\Delta a_{\mu}^{\text{BLR}}(M_{1}, m_{\tilde{l}_{L}}, m_{\tilde{l}_{R}}; \mu) = \frac{\alpha_{\text{Y}}}{4\pi} \frac{m_{\mu}^{2} M_{1} \mu}{m_{\mu_{\text{L}}}^{2} m_{\mu_{\text{R}}}^{2}} \tan \beta \cdot f_{\text{BLR}}(\{\mathbf{m}\})
$$
\n
$$
\mu_{\text{L}} \qquad \frac{\mu \cdot \langle H_{u} \rangle}{\tilde{\mu}_{\text{L}}} \qquad \mu_{\text{R}} \qquad \text{large } \mu \text{ needed}
$$

Constraints: \mathbf{H} by given by \mathbf{H}

❖ Stau mass² becomes negative or too small!
◆ Stau mass² becomes negative or too small! $s²$ beco ∪∪∪UTIL is negative or too small!

 $\left(\begin{array}{cc} m^2 & V \end{array} \right)$ charge-breaking minima in the scalar potential become deeper, and our electroweak in the scalar potential become deeper, and our electroweak in the scalar potential become definition of $m_{\tilde{\tau}_R}$ $\forall \tau$ mass matrix) \sim $\left\lfloor \frac{1}{\tau} \right\rfloor$

 $\sum_{i=1}^{N}$

 $m_{\tilde{\tau}_R}^2$ $Y_\tau \mu \langle H_u \rangle$

 $\left(\frac{1}{2} \right)$

 $(\tilde{\tau} \text{ mass matrix}) \sim \begin{pmatrix} \frac{R}{\tau} & \frac{R}{\tau} & \frac{R}{\tau} \\ Y_{\tau} \mu \langle H_u \rangle & m_{\tilde{\tau}_L}^2 \end{pmatrix}$

 $Y_{\tau}\mu\langle H_u \rangle$ $m_{\tilde{\tau}_I}^2$

(τ mass matrix) \sim $\frac{1}{Y_{\tau} \mu \langle H_{\nu} \rangle}$

- charge breaking vacuum: $m²_{\text{stau1}} > 0$ e hreal breaking \sim charge breaking vacuum: m^2 _{stau} \sim 0

- LEP bound: m_{stau1} > 90 GeV \overline{a} 175 Gev is the tried increases vectors \overline{a} charge-breaking minima in the scalar potential become determined in the Higgs VeV. As the trial >90 GeV charge-breaking minima in the scalar potential become deeper, and our electroweak
- stau LSP: m_{stau1} > m_{neutralino1} vacuum could decay to the lifetime of $m_{\tilde{\tau}_P}^2 = Y_\tau \mu \langle H_u \rangle$ and the estate of the electroweak of the e
- other contributions on the contributions of $\mathcal{L}_\mathcal{R}$, with see M. Endo, K.R very split see M. Endo, K.R - Vacuum (meta-)stability: 1.01 × 102 GeV#m ^m˜!^R + 1.⁰¹ [×] ¹⁰² GeV(m˜!^L + 1.03m˜!^R) (τ mass matrix) \sim $\begin{pmatrix} Y_{\tau} \mu \langle H_u \rangle & m_{\tilde{\tau}_L}^2 \end{pmatrix}$ age vacuum

$$
\left| m_{\tilde{\ell}_{LR}}^2 \right| \leq \left[1.01 \times 10^2 \,\text{GeV} \sqrt{m_{\tilde{\ell}_L} m_{\tilde{\ell}_R}} + 1.01 \times 10^2 \,\text{GeV} (m_{\tilde{\ell}_L} + 1.03 m_{\tilde{\ell}_R}) - 2.27 \times 10^4 \,\text{GeV}^2 + \frac{2.97 \times 10^6 \,\text{GeV}^3}{m_{\tilde{\ell}_L} + m_{\tilde{\ell}_R}} - 1.14 \times 10^8 \,\text{GeV}^4 \left(\frac{1}{m_{\tilde{\ell}_L}^2} + \frac{0.983}{m_{\tilde{\ell}_R}^2} \right) \right]
$$

[Kitahara, Yoshinaga 13]; [Endo, Hamaguchi, Kitahara, Yoshinaga 13] I \overline{a} ara
E oshinaga 13]: [Endo, Hamaguchi, Kitahara, Yoshinaga 13] witanara, Yoshinaga T3j; [Endo, Hamaguchi, Kitanara, Yoshinaga T3j] a, Y $^{\rm H}$ iaga 13]; \lbrack LIUU, [Kitahara, Yoshinaga 13]; [Endo, Hamaguchi, Kitahara, Yoshinaga 13]

[❖] Overproduction of Bino-like neutralinos in the early universe: S **Overproduction of Bino-like neutralinos** in the early u while decoupling the Wino. Since they are enhanced only by tan ${\mathbb R}$, superparticles are required to tan ${\mathbb R}$ $\, \Omega_{\widetilde{\chi}_{1}^{0}} \, < \, \Omega_{\rm DM} \,$

SICPION-COANNINIIA STOLE SOME \cong Mslepton \sim MBino be light to explain (1). They are detectable in colliders. In particular, the Higgsino production can slepton-coannihilation needed ⇒ m_{slepton} ~ m_{Bino}

Unstable Neutralino (Gravitino, RPV)

$$
\Delta a_{\mu}^{\text{SUSY}} = \Delta a_{\mu}^{\text{WHL}} + \Delta a_{\mu}^{\text{BHL}} + \Delta a_{\mu}^{\text{BHR}} + \Delta a_{\mu}^{\text{BLR}}
$$

 $\Delta a_\mu^{\rm WHL}(M_2,\mu,m_{\tilde{l}_L})$ $\Delta a_\mu^{\rm BHR}(M^{}_1,\mu,m_{\tilde{l}_R})$ $\Delta a_\mu^{\rm BHL}(M^{}_1,\mu,m_{\tilde{l}_L})$

Higgsino, one gaugino, one slepton all must be light: gaugino-Higgsino mixing ^{→ **DM direct detection**} **← Modified** ⇨ **LHC constraint with large ET**

 $\Delta a_\mu^{\mathrm{BLR}}(M_1, m_{\tilde{l}_L}, m_{\tilde{l}_R}; \mu)$ large Bino and both L and R sleptons must be light: \Rightarrow <mark>Bino abundance Ω $_{\tilde{\chi}_{1}^{0}} < \Omega_{\rm DM}$ </mark> **⇒ LHC constraint with large** $\cancel{E_1}$ **← Modified** ⇨ **Charged LSP, Vacuum stability**

- I HESE LETTING SIVE THASS LOCTORIZED THE CASE OF THE CASE OF THESE LETTING STRUCTUAL SQUARGE STRUCTUAL MASSES, The mass to quark squark masses to the masses of the ma \bullet inese terms give midss to qualis and reducins. • These terms give mass to quarks and leptons.
	-

R-Parity Violation; UDD

No missing energy, but multi-jet (b) (c) (a) (b) $\mathcal{F}_{\mathcal{F}}$ is diagrams representing the two-lepton final state of $\mathcal{F}_{\mathcal{F}}$ production of electroweakinos energy $\mathcal{F}_{\mathcal{F}}$ Figure 1: Diagrams representing the two-lepton final state of $\frac{1}{2}$

- LHC signature is the most challenging: \tilde{v}^0 ne no h-iate in the neutraling decay. no leptons, no b-jets in the neutralino decay weight the mission of u

R-Parity Violation; UDD

F**NY**
SLI a gravitino, *c* gions above the contours satisfy the assumption that the N1 $\frac{\text{area}}{\text{a}}$ gravitino, $c\tau_{\tilde{\chi}_{1}^{0}} < 1$ mm. In the lower right region, the NSL not be applied.

Grawithe lightest heutralino into **a** and the given by $\begin{bmatrix} 10, 00 \end{bmatrix}$ **Neutralino into the gravitino are given by [13,35]** of the lightest neutralino into the gravitino are given by [13,35]

 $\frac{1}{2}$

scalars = |y3!S"|

5

² ± |y3!FS"[|] . (7.7.11)

1

2

 \int

 $\ddot{}$

 $\langle F_S^{\rm{T}}\rangle$ • In the gauge-mediated SUSY breaking (GMSB) scenario, light gravitino is motivated by naturalness: of the lightest neutralino into the gravitino are given by $[$ $E\left(\tilde{X}_{1\right)}^{0}\rightarrow \tilde{G}\left(\mathcal{W}_{12}\right)_{\widetilde{CW}}\rightarrow \mathcal{W}_{11}^{1}G\mathcal{W}_{V} \Vdash \mathcal{W}_{12}^{1}S\mathcal{W}_{11}$ $\frac{1}{2}$ $\Gamma(\tilde{\chi}_1^0 \to \tilde{G} \tilde{Z}) \tilde{\chi}_{1\rightleftharpoons}^0 \to \tilde{\bigoplus} \chi_{12} \bar{c}_W^- \to N_{11} G_W \Vdash \frac{\Lambda}{2} \frac{1}{\langle F_S^1 \rangle^2} c_{\beta}^A \, .$ **MICH EXECUTE SECUTE SECUTE SECURE AND**
MICHT SCENATIO, Yight gravitin 1 2 gra
0 1 s $\overline{}$ $^{\circ}_{+}$ $\frac{1}{2} \frac{1}{2} \left| \frac{1}{F_S^3} \right|^2 \frac{A}{G} - N_{14} s_{\beta}$ $\overline{}$ 2λ

 $\frac{\delta M_B}{\delta} \propto \frac{m_{\tilde{M}_S}}{2}$ $\mathcal{A}_{\boldsymbol{\pi}} \stackrel{1}{\sim} (\chi_1 \stackrel{\sim}{\wedge} \mathbf{G}^2)$ mess in $m_{\text{max}} = \frac{\Gamma(\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow G/\chi)}{\Gamma(\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow G/\chi)}$ plane. Right: $c\tau_{\tilde{\chi}_1^0} = \Psi h/m$ contours σ as $\tau \sim 2$ $M \sim$ BOCIL plots, the red-solid,"
both plots the red-solid i $\mathbb{R}_l W_s \tilde{g}$ $\langle S \rangle$ The first line into the graviting can be calculated (For in $\frac{1000}{2}$ elts) at the neutraling decays are promoted $m_{z0}^{\rm 6.3\,mm\,100\,GeV}$, $m_{z0}^{\rm eV}$ \mathscr{F} $\left[\frac{13}{3}, \frac{36}{39}\right]$. The summer decays are prompt. $\mathcal{A} = \frac{1}{100} \frac{1}{2} \frac{1}{100} \sim$ 800 <u>|</u> Bino: 700 \vert - - Wino: $c\tau_{\tilde{W}} = 1 \,\mathrm{mm}$ 2 \$ $\sqrt[3]{\frac{4}{\mathcal{A}}}\cdot\frac{1}{2} |N_{13}C_{\beta} - N_{14}S_{\beta}| \int (1 - \frac{1}{m_{\tilde{\chi}}^2 \sqrt[3]{4}}) \frac{\mathcal{A}}{N_{\tilde{\chi}}^2}$ $\approx 600 \frac{|\text{m} \cdot \text{m} \cdot \$ $\frac{y^{3}}{2}$ $\left(1-\frac{m_h^2}{2}\right)^4$ \overline{h} or \overline{h} $\left(-\frac{n}{m_{\tilde{\chi}_1^0}^2}\right)$ A, lighter the $\left|\frac{1}{2}\right|$ 500 multiplet pair apart: $\frac{1}{4}$, $\frac{1}{2}$ fermions =
 \sum_{100}^{1400} ² , m² $2 + 1/7$ *m*3*/*² = [√]3*M^P* $\overline{}$ Φ $\delta m_{\rm hm}^2 \propto M_{\rm st}^2$ $\delta m_{\rm s/2}^2 \frac{1}{\sin m}$ $\delta m_{\rm s}$ and $\delta m_{\rm s/2}$ $\delta m_{\rm s/2}$ $\delta m_{\rm s/2}$ $\Lambda_{\rm mess}$ **mess**
 M₃ plane. Right: $c\tau_{\tilde{\chi}^0} = 3/m$ con
 Mane. Right: $\epsilon \tilde{\tau}_{\tilde{\chi}^1} \equiv 1$ mm contains the red-solid, blue-day 4*π* $3\alpha_W$ $M₂$ Δ mess M P $\tilde{\mathbb{G}}$ $\Gamma(\tilde{\chi}^0_1 \bigwedge \hat{\tilde{G}}Z) = \left(\frac{1}{6} N_{12} c_W \frac{\Phi}{\tilde{G}^2} \left(\frac{\Phi}{\tilde{G}^2} \right) \right)$ \int $\frac{2}{\ast}$ + 2 $N_{13}c_{\beta}$. $\Gamma(\tilde{\chi}_1^0 M \tilde{\chi}_1^2 h) = \frac{1}{2}$ 2 $N_{13}c_{\beta} + N_{14}s_{\beta}^{\chi_{1}^{\vee}}$ \downarrow $\frac{2}{\sqrt{1-\frac{m_h^2}{m^2}}}$ *h* $m_{\tilde{\chi}^0_1}^2$ \setminus^4 *A ,* (4) where N_{ij} is the neutralino mixing matrix and \mathcal{A} = $m_{\tilde{\chi}^0_1}^{\mathbf{5}}$ 16³ 17⁰ \sim \sharp 0*.*3 mm $\alpha \propto \frac{m_{\rm FQ}}{M}$ 100×10^{-4} In the left panel of Figure ¹ we plot contours of a fixed neutralino lifetime *^c*⌧e⁰ 600 $\left\{\begin{array}{ccc} -\cdot & \text{Higgsino: } c\tau_{\tilde{h}} = 1 \text{ mm} \\ 600 & \text{Higgsino: } c\tau_{\tilde{h}} = 1 \text{ mm} \end{array}\right.$ the which is predominantly bino (red-solid), wind higher distribution (pink-dashed) and higher distribution (pink-dashed) and higher distribution (pink-dashed) and higher distribution (pink-dashed) and higher distribution \int is defined above contours (the top-left above) is defined as \int particl_e the prompt graviting fairly light graviting $\frac{1}{2}$ $\lim_{T\to\infty}$ $\Gamma(\tilde{\chi}_1^{\cancel{d}}\mathcal{I}\rightarrow \tilde{G}M)$ \cong $\frac{\text{meas}}{2}$ $\frac{1}{2}N_{13}c_{\beta}+\frac{R_{7}W_{33}}{N_{14}s_{\beta}}$ \downarrow $\begin{array}{c} \begin{array}{c} 2 \ 2 \ \end{array} \\ \begin{array}{c} \begin{array}{c} \end{array} \\ \end{array} \\ \begin{array}{c} \end{array} \end{array} \end{array}$ *h* $m_{\tilde{\chi}^0_4}^2$ \setminus *A ,* (4) **Where** *N* is the neutralino mixing matrix and $\frac{1}{2}$ ንቅ፡
አይደግል
ነ**ገ** ላይ $\frac{16\pi m^2}{2}$ $M_{\rm pl}^2$ ⇠ 1
H 0*.*3 mm ւնTix_{*ղ*∄me
1 Eorึ4} 100 GeV \mathcal{H}^{5} / $m_{3/2}$ $10\,\mathrm{eV}$ In the left pane $\begin{array}{c} 800 \end{array}$ $\frac{1}{2}$ \oint gravitino-ne $\left| \begin{array}{c} \boxed{}$ Bino: $c\tau_{\tilde{B}} = 1 \text{ mm} \end{array} \right|$ $\begin{pmatrix} 0 \ \frac{1}{2} \ \frac{1}{2} \end{pmatrix}$ $\begin{pmatrix} 0 \ \frac{1}{2} \ \frac{1}{2} \ \frac{1}{2} \end{pmatrix}$ $\begin{pmatrix} 1 \ \frac{1}{2} \ \frac{1}{2} \ \frac{1}{2} \ \frac{1}{2} \ \frac{1}{2$ definite the property of $\left(1-\frac{mg}{m_{\tilde{\chi}}^2(4)}\right)$ denotes Δ 600 $\left(1-\frac{mg}{m_{\tilde{\chi}}^2(4)}\right)$ \mathbb{R} 1 mm part of the plots with $\lim_{n\to\infty}$ $\lim_{n\to\infty}$ $\begin{array}{ccc} \n \text{massless} & \text{partial} \ \text{first} & \text{on} \ \text{on} & \text{or} \ \text{on} &$ $\frac{1}{2}$ eV throughout $\frac{1}{2}$ ⁴⁰⁰] $\text{Left: } c \neq \{1, 2, \ldots\} \equiv 1 \text{ film captures in the } m_3/2 \text{ wA} \text{ sample. Right: } c \neq \{1, 2, \ldots\} \equiv 1 \text{ mm} \text{ capture-qasine}$ $\begin{bmatrix} m_{\lambda} & m_{\lambda} \ m_{\lambda} & m_{\lambda} & m_{\lambda} \end{bmatrix}$ in the $\begin{bmatrix} 0 & 0 & 1 \ 0 & 1 & 1 \end{bmatrix}$ for $\begin{bmatrix} 0 & 0 & 1 \ 0 & 0 & 0 \end{bmatrix}$ for $\begin{bmatrix} 1 & 0 & 0 \ 0 & 0 & 0 \end{bmatrix}$ for $\begin{bmatrix} 1 & 0 & 0 \ 0 & 0 & 0 \end{bmatrix}$ for $\begin{bmatrix} 0 & 0 & 0 \ 0 & 0 & 0 \end$ a_1 ashed curves correspond to the bino, wino and higgsino NLSPs, respectively. The $e^{\frac{1}{2}t}$ $e^{\frac{1}{2}t}$ $e^{\frac{1}{2}t}$ $e^{\frac{1}{2}t}$ the assumption that the NLSP neutralino decays promptly into ϵ ϵ $\frac{1}{2}$ \approx $\frac{1}{2}$ mm. In the lower right region, the NSLP is long-lived and our analysis may i ed. est neutr**alna virtimos** divisind **0e di 00 be V3, 35the neutralino decays are given by [13, 35the neutralino decays are** $\mathbb{G} \rightrightarrows \mathbb{G} \gamma \rightrightarrows \rightrightarrows$ $\left[\frac{N_{11}^{11}CW}{N_{11}^{12}EW} \right]$ \vert $^2\cancel{\mathcal{A}}$; $\overline{}$ $^{\frac{3}{2}}\ddot+$ 里 $\overline{2}$ $\left[\begin{matrix} N_{13}c_{\beta} & N_{14} s_{\beta} \ N_{13}e_{\beta} & N_{14} s_{\beta} \end{matrix}\right]$ \vert $\left(\frac{1}{2}\right)\left(1-\frac{m_2^2}{m_2^2}\right)$ *Z* $\widetilde{m}_{\tilde{\ast}}^2$ $\tilde{\chi}^0_1$ ₩ *A ,* $\bigotimes_{k=1}^{\infty} \bigoplus_{j=1}^{\infty} \bigotimes_{k=1}^{k} h \bigwedge_{k=1}^{k} \bigoplus_{k=1}^{k} \bigotimes_{k=1}^{k} \bigotimes_{k=1}^{k$ $|\hat{N}_1 36 \hat{\mathbf{\beta}} + \hat{N}_1 48 \hat{\mathbf{\beta}}|$ \vert $\frac{2}{3}\left(1-\frac{N}{m^2}\right)$ *h* $\overline{m}_{\tilde{\chi}}^2$ $\tilde{\chi}^0_1$ $\sqrt{4}$ $A, \frac{2}{\sqrt{3}}$ (4) **is the** neutralino mixing matrix and $A \equiv \frac{m_3^2}{16\pi m_4^3}$ $\mathbf{\hat{x}}$ $\approx \frac{1}{\sqrt[3]{3}\,\mathrm{mm}}$ $\sqrt{\frac{m}{100}}$ ⌘⁵⇣ *m*3*/*² ∖)≡≱ nt to plane assuming 0.01 = mstrsy''="/FTeX'.' **AP BeU** plats, the red-solid, blue-dashed \rightarrow UW 1
man plane assuming d.01 = mstrsy = 1 feV, In both plats, the red-solid, blue-dashed. in the street carves cosrespond to the pino. Who and megistic rustes, respectively puried still the net and pink-dot-data and pink-dot-distribution to the bino correspond to the bino product α into α the bino, we the contours satisfy, the assumption that the $NLSB$ neutralino decays promptly into $\epsilon_{\rm Fch}$ $\epsilon_{\rm T}$ initiating the lower right-region, the assumption tong-need and our analysis may here $N_{\rm eff}$ *ied:* • The decav rate of the NLSP neutralino into the graxnot be applied. \tilde{C} the light neutralino into the gravitino into the gravitino are given by \tilde{C} and \tilde{C} are given by $E_{\mathbf{z}}^{(\gamma)}(\tilde{\chi}_{1\rightleftharpoons}^{0}\rightarrow \tilde{G}_{\mathbf{W}_{12}}^{(\gamma_{11}\circ\gamma_{11})}\rightarrow \mathcal{N}_{\mathbf{z}11}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}}^{1}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}}^{1}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{\mathbf{z}W}\cdot \mathcal{N}_{$ l: $\partial^2_{3} A$, $\Gamma(\tilde{\chi}^0 \to \tilde{G}Z) = \left(\frac{N_{12}N_{12}c_W - N_{13}N_{11} + \frac{1}{2}N_{13}c_W}{N_{12}C_W - N_{13}C_W}\right)^2 +$ $\frac{2}{3}$ $\frac{2}{3}$ $\frac{1}{3}$ $\frac{1}{2} |N_{13}c_{\beta} - N_{14}s_{\beta}|^2 \bigg) \Big(1 - \frac{m_Z^2}{m_{\mathcal{A}_1}^2} \Big)^2$ *A ,* $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G}h) = \frac{1}{2}$ $|N_{13}c_8 + N_{14} s_8|$ ֡׀
׀ $\int_{2}^{1} \frac{m_h^2}{1-\frac{m_h^2}{n}}$ $\begin{array}{cc} \mathcal{H} & m^2 \end{array}$ + 4 $\frac{2}{1}$ $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G}h) = \frac{1}{2} |N_{13}c_{\beta} + N_{14} s_{\beta}^2|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2}\right)$ A_1 **part of the proof** \overline{Q} $m_{\mathbf{a}}^5$ is the neutralino mixing matrix $m_{\tilde{\phi}}$ is the neutralino mixing matrix $m_{\tilde{\phi}}$ is the mixing matrix $m_{\tilde{\phi}}$ is the mixing matrix of $m_{\tilde{\phi}}$ is the mixing matrix of $m_{\tilde{\phi}}$ is the mixing matrix Left: $c\tau_{\tilde{\chi}^0_1}$ Ω (h_pm contours in the $m_{3/2}$ vs $m_{\tilde{\chi}^0_1}$ plane. Right: $c\tau_{\tilde{\chi}^0_1} = \mathcal{D}$ ham contours that $m_{3/2}$ vs $m_{\tilde{\chi}^0_1}$ alane. Right: $c\tau_{\tilde{\chi}^0_1} = 1$ mm contours Left: ef% ≡ 1 mm e8#terirs in the m3@NXMMB6He; Hight: ef% ≡ 1 mm e8#tem?
m_vo plane assuming 0.01至 = m_{SUSY} 当@N. M both plots, the red-solid, blue-dashed
m3p plane assuming 0.01至 = msusy = 1 TeV. In both plots, the red η and η curves correspond to η curves to η of η in η and η and η and η and η and η and η \mathcal{R} in a contours satisfy the assumption that the anni decays the \mathcal{R} co-ays promptly into re the equippirs partise due assuming to the Light Figure model as equal that they be a contract that the value
Ca²h $\,\,\leq$ 1 mm. In the lower right region, the NSLB is long-lived and our analysis may ℓ đ est neutr**alita virtum a**re divising ble divelope V_3 35] $(\widetilde{\mathbf{G}}_1^0 \Rightarrow \widetilde{\mathbf{G}}_2^0) \equiv \parallel$ $\widetilde{E}_{\mathcal{A}}^{0} \rightarrow \widetilde{E}_{\mathcal{A}}^{0}$ \equiv $\mathbb{N}_{\text{11}}^{11}$ $\mathbb{C}_{W}^{11} + \mathbb{N}_{\text{12}}^{12}$ \mathbb{S}_{W}^{11} $\mathbb{Z}_{\mathcal{A}}^{2}$ $\mathbb{N}_{\text{13}}^{2}$ rdvi**gnd Qe diQQbe V3,35the neutralino decays a**
Favitine are given by [13,39]
M12*Sw|*3.4 $\widetilde{G}_{\mathbf{Z}}^{0} \rightarrow \widetilde{G}_{\mathbf{Z}}^{0} \widetilde{X}_{1}^{0} \rightarrow \widetilde{G}_{\mathbf{X}}^{0} \widetilde{X}_{2}^{0} \rightarrow \widetilde{G}_{\mathbf{X}}^{0} \widetilde{X}_{3}^{0} \widetilde{G}_{\mathbf{X}}^{0} \rightarrow \widetilde{X}_{11}^{1} \widetilde{G}_{\mathbf{X}}^{0} \widetilde{X}_{1}^{0}$ $\overline{}$ $\frac{p}{2}\,\frac{\Lambda}{l}$ $1 \,$ $\frac{1}{2}$ $\begin{bmatrix} 8\mathbf{N}_1 \ 3\mathbf{C}\beta - N_{14} \ 2\mathbf{N}_2 \ 6\mathbf{S} = N_{14} \ 8\mathbf{N}_3 \end{bmatrix}$ י
יון $\left(\frac{2}{3}\right) \left(\frac{1}{1-\frac{m_{Z}^{2}}{m_{Z}^{2}}}\right)$ *Z* 111<u>4</u>
MAS
MZ0 λ^4 $\mathbb{Z}^{N_{12}} = \left(\begin{array}{c} N_{12}C_{W} + N_{11}C_{W} + 2N_{11}C_{W} + 2N_{11}C_{W} + 2N_{11}C_{W} \ N_{12}C_{W} = N_{11}S_{W} \end{array} \right) = \left(\begin{array}{c} N_{14}S_{\beta} & N_{14}S_{\beta} \ N_{13}C_{\beta} = N_{14}S_{\beta} \end{array} \right)$ $\widetilde{\widetilde{\mathcal{L}}}^0_1 \rightrightarrows \widetilde{\widetilde{G}}h$) = $\frac{1}{2}$ $\begin{array}{l} \mathcal{L}(Z) = \left(\left| N_{12} c_W - N_{14} s_W^2 \right| \right) \ \left| N_{13} c_B \pm N_{14} s_B \right|^2 \left(1 = \frac{m_W^2}{\sqrt{2}} \right) \end{array}$ *h* $\frac{m_R^2}{m_{z0}^2}$ $\sqrt{\frac{2}{4}}$ \overline{A} , $\overline{2}$ $\left| \begin{array}{c} 1 \ \text{N} \ 13 \ \text{C} \end{array} \right|$ \overline{A} $\left| \begin{array}{c} 1 \ \text{C} \end{array} \right|$ $A \equiv \frac{m_2^5}{16 \pi m_3^5}$ ˜0 1 16πm3/2 M2 ⇠ ¹ 0*.*3 mm ℓ m \tilde{z}^0 100 Gevel ⌘⁵⇣ *m*3*/*² 10 av $A = \frac{m_{20}^2}{m_{20}^2} \sim \frac{1}{2} \left(\frac{m_{30}^2}{m_{30}^2} \right)^{\frac{5}{2}} \left(\frac{m_{3/2}}{m_{3/2}} \right)^{-2}$ \cdot (1 eV throw *m* a plane assuming 0.01 $\frac{\pi}{4}$ = *m*stra b = 1 key c + moth plots we fed=sulta, blue-dashed.
t-dashed curves correspond to the bino, wino and higgsino NLSDs, respectively. The IS the ne in the ⇤ vs *^m*e⁰ ¹ plane assuming 0*.*01*^F* ⇤ = *m*SUSY = 1 TeV. In both plots, the red-solid, blue-dashed α bine-corresponding to the down right region, the bist β is long lived and our analysis may Λ $\frac{d}{dt}$ $\frac{d}{dt}$ and $\frac{d}{dt}$ are $\frac{d}{dt}$ the contract the $\frac{d}{dt}$ neutralino into the $\frac{d}{dt}$ the $\frac{d}{dt}$ ^{ca.} The decay rate of the INLOT rieutralino into the gra est neut**ralñ2** י.
}} $\begin{array}{c} 3\ \epsilon_\beta\ \epsilon_\beta=0 \end{array}$ $\int_{\tilde{\mathbf{M}}} (\tilde{\chi}_1^0 \rightarrow \tilde{\hat{\mathbf{q}}} Z) = \left(\begin{matrix} N_{12}c_W - N_{1M}c_W \end{matrix} \right)$ ⇃ $^{2}_{4}$ + 1 2 $\left| N_{13}c_{\beta} - N_{14}s_{\beta}^{\ast} \right|$ $\overline{}$ $\sum_{1}^{\frac{3}{2}} \left(1 - \frac{m_Z^2}{m^2}\right)$ *Z* $m_{\tilde{\chi}^0_1}^2$ \setminus^4 *A ,* $\left| N_{13}c_{\beta} + N_{14}s_{\beta}^{\prime 1} \right|$ \vert $\frac{2}{2}\left(1-\frac{m_h^2}{m_{\gamma}^2}\right)$ *h* $m_{\tilde{\chi}^0_1}^2$ $\big)^4$ \mathcal{A} , \qquad lighter the about \mathcal{A} $\begin{array}{rcl} \text{Left:} \ \epsilon \neq \text{the} \ = \ 1 \ \text{dim} \ \epsilon \neq \text{in} \ \text{for} \ \epsilon \neq \text{in} \ \text{if} \ \epsilon \neq \text{in} \ \text$ $m_{\rm A}^{\rm A}$ plane assuming 0.01 $F = m_{\rm BUSY}^{\rm C} = 1$ TeV. In both plots, the red-solid, blue-dashed
U dashed curves correspond to the bino, wino and biggsino NT SPs, respectively The at-dashed curves correspond to the bino, wino and differeino NLSPs, respectively. The
effection curves adstespond assumptibilities wino and spectularino decays bromptly the regions above the contours satisfy the assumption that the NLSP neutralino decays promptly into $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ mm. In the lower right region, the NSLP is long-lived and our analysis may e est neut**ralita vittimos**ravitin<mark>d Qe diQObe V3.)35</mark>the neutralino decays a
est neutralino into the gravitino are given by [13,35] $\left[\frac{N_{11}}{N_{11}}\mathcal{E}_{W} + \frac{N_{12}}{N_{12}}\mathcal{E}_{W}\right]\mathcal{A},$ \vert $\widetilde{G}_1^0 \rightarrow \widetilde{GZ}^{\chi\chi}_{2}$ ^{$\chi_1 = '$} $\left(\sqrt[\chi]{\chi_12}C_W + \chi_1 \chi_2\chi_W\right)$ $\overline{}$ $^{\frac{2}{}}$ ま $\frac{1}{2}$ $\left| \widetilde{N}^{13}_{13}\widetilde{e}_{\beta}\right| =\widetilde{N}^{14}_{14}\widetilde{s}_{\beta}\right|$ $\overline{1}$ $\left(\frac{1}{4}-\frac{\dot{m}^2_2}{\dot{m}^2_2}\right)$ *Z* \dot{m} $\tilde{\tilde{x}}$ $\mathbb{X}_2^{\mathfrak{g}}$ $\mathbb{V}^{\scriptscriptstyle\sharp}$ *A ,* $(\hat{\vec{g}}_1 \vec{\theta}) \rightarrow (\hat{\vec{g}}_1 \vec{\theta})$ = $(\frac{4}{2} + \hat{\vec{g}}_1 \vec{\theta})$ + $(\frac{1}{2} + \hat{\vec{g}}_1 \vec{\theta})$ $\tilde{C}^{(k)} = \frac{1}{2} \begin{bmatrix} N_{12}c_{11} & N_{21}c_{12} \\ N_{21}c_{21} & N_{21}c_{22} \end{bmatrix}$ $\begin{array}{c} \hline \end{array}$ $\frac{2}{2} \left(1 - \frac{1}{m_{\gamma}^2} \right)$ *h* ⌘4 A_1^2 M_2^2 A_3 M_4 $\mathbb{\tilde{B}}$ ifie peutralino mixing matrix and $A \equiv \frac{\dot{m}_s^2}{16\pi m_b^2}$ <u>∦¶</u> $\approx \frac{1}{0.3}$ mm **∤ _***m* ⌘⁵⇣ *m*3*/*² ∖)≡≱ *. .**i* ev through $m_{\rm b}^{\rm M}$ plane assuming 0.01 , $E = m_{\rm b}^{\rm s}$ in $E = 1$ flew. In poth plats, the red-solid, blue-dashed V
Construct curves correspond to the bino, wino and biggsing NEGBs, respect to the in the IS the ne it-dashed curves correspond to the bino, wino and diference NLSDs, respectively. The ¹⁵ UIC IIC
The diferent ours saysty the assumption that the NLSD neutraling decays promptly into $\delta_{\rm F}^{\rm CO}$ and pink-dot-dashed curves correspond to the $\delta_{\rm F}^{\rm CO}$ is hencefulled and $\delta_{\rm F}^{\rm CO}$ and $\delta_{\rm F}^{\rm CO}$ $r_{\rm eff}$ \approx 1 mm. In the lower right region, the NSLP is long-hved and our analysis may 11 CIC 1 V_{i} **^{188:} •** The decay rate of the NLSP neutralino into the gra \cot pout C ¹⁶⁰ $\zeta_{\rm th}^0 \rightarrow \mathcal{G}_{\rm N} \chi = \sqrt{N_{\rm d1} c_W + N_{\rm d2} s_W} \zeta_2^2 \mathcal{A} \, ,$ $\mathbb{Z}[\mathcal{X}] = \begin{cases} \mathcal{X}_1 = \mathcal{X}_2 = \mathcal{X}_3 = \mathcal{X}_4 = \mathcal{X}_5 = \mathcal{X}_6 = \mathcal{X}_7 = \mathcal{X}_7 = \mathcal{X}_7 = \mathcal{X}_8 = \mathcal{X}_7 = \mathcal{X}_7 = \mathcal{X}_8 = \mathcal{X}_7 = \mathcal{X}_8 = \mathcal{X}_9 = \math$ ון
}} $\widetilde{G}_{\mathcal{H}}^{0}\rightarrow\widetilde{G}_{\mathcal{H}}^{0}\widetilde{Z}_{\mathcal{H}}^{0}\quad\equiv\quad\left(\begin{matrix}N_{12}\bar{c_{W}}+N_{11}\bar{c_{W}}\bar{c_{W}}\ N_{12}\bar{e_{W}}=N_{11}\bar{s_{W}}\end{matrix}\begin{matrix}\frac{\mu}{2} & \frac{\mu}{2}\bar{c_{W}}\ \frac{\mu}{2} & \frac{\mu}{2}\end{matrix}\begin{matrix}N_{13}\bar{c_{W}}\ N_{13}\bar{e_{W}}\end{matrix}\right),$ $\Gamma(\tilde{\chi}^0_1 \rightarrow \tilde{\mathbf{\Phi}}Z) = \begin{pmatrix} |N_{12}c_W - N_{12}c_W \end{pmatrix}$ \rfloor $\frac{2}{4} +$ 1 $\overline{2}$ $N_{13}c_{\beta} - N_{14}s_{\beta}$ $\Big\}$ $\binom{2}{2} \left(1 - \frac{m_Z^2}{m_Z^2}\right)$ \tilde{z} $\overline{m_{\tilde\chi^0_1}^2}$ $\sqrt{4}$ *A ,* $\Gamma(\tilde{\chi}_1^0 \rightarrow \tilde{G}h) = \frac{1}{2}$ $\left| N_{13}c_{\beta} + N_{14}s_{\beta}^{X_1} \right|$ $\overline{}$ $\sqrt{2}\left(1-\frac{m_h^2}{m^2}\right)$ *h* $m_{\tilde{\chi}^0_1}^2$ \tilde{x}_{12}^{02} $\left(1 - m_h^2\right)^4$ $\begin{array}{ccc} & m_{11} & m_{12} & m_{13} & m_{14} & m_{15} & m_{16} & m_{17} & m_{18} & m_{19} & m_{19} & m_{19} & m_{19} & m_{10} & m_{10} & m_{10} & m_{10} & m_{10} & m_{10} & m_{11} & m_{$ $\text{Left: } c \neq \{1, 2, 1, \ldots, 2\}$ $\equiv 1 \text{ mm}$ contours in the $m_3/2$ vs m_3^2 value. Right: $c \neq \{1, 2, 1, \ldots, 2\}$ $\equiv 1 \text{ mm}$ contours m_{∞} plane. Right: $c \neq \{1, 2, 1, \ldots, 2\}$ $\equiv 1 \text{ mm}$ contours $\begin{bmatrix} m_{\chi}^2 & m_{\chi}^$ and pink-dot-dashed curves correspond to the bino, wino and higgsino NLSPs, respectively. The ve the contours satisfy the assumption that the $NESP$ neutralino decays promptly into $\mathscr{L}_\mathcal{X}$ \leq 1 mm. In the lower right region, the NSLP is long-lived and our analysis may $\widetilde{\mathsf{ied}}$: of the lightest neutralino into the gravitino are given by [13, 35] ⊈ $\bar{2}$ $\left[\begin{smallmatrix} N & 1 & 3 \ N & 1 & 3 \ \end{smallmatrix}\begin{smallmatrix} S & - \ N & 1 & 4 \ \end{smallmatrix}\begin{smallmatrix} N & 1 & 4 \ N & 1 & 4 \ \end{smallmatrix}\begin{smallmatrix} S & 0 \ N & 1 & 4 \ \end{smallmatrix}\right]$ ľ $\binom{2}{2}\left(1-\frac{m_2^2}{m_2^2}\right)$ *Z* 1922

1923

1923

1938

1938 $\tilde{\tilde{\chi}} \emptyset$ *A ,* $(\hat{\xi}_1^0 \Rightarrow \hat{G}h) = \frac{1}{2}$ $N_{13}e_{\beta}$ + $N_{14}e_{\beta}$ \mid $\frac{2}{2}\bigg(\frac{1}{1}=\frac{N_{12}}{m^2}\bigg)$ *h* $\overline{m}_{\tilde{\sqrt{\cdot}}}^2$ $\sqrt{4}$ A_1^2 $m_{\tilde{\chi}^0_1}^2$ $\frac{1}{18}$ $\frac{1}{18}$ peutralino mixing matrix and $\mathcal{A}\equiv\frac{m_{\chi}^{2}}{\sqrt{3}}% \sum_{k=1}^{N_{\chi}^{2}}\mathcal{A}_{k}^{2}$ ˜01 167 M2 /2 M2 ~ 1
◎ 行3 mm
0.3 抽抽 $\left(\frac{m}{\sqrt{2}} \right)$ ⌘⁵⇣ *m*3*/*² ∖)≡2 • The decay rate of the NLSP neutralino into the gravitino can be calculated. (E_0^{α} light) gravitinos $\frac{1}{2}$ in $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are prompt.

panel of Figure 1 we plot contours of a fixed neutralino lifetime $c_{\tilde{T}^{00}}$ = 1 mm in over $\sum_{i=1}^{\infty}$ 500
Banel of Figure 1 we plot contours of a fixed neutralino lifetime $c_{\tilde{T}^{00}}$ = 1 mm in over \sum \sum $\$ σ (blue-dashed) and higher σ and $\frac{1}{\sqrt{N}}$ σ is $\frac{1}{\sqrt{N}}$ σ $\frac{1}{\sqrt{N}}$ σ $\frac{100}{200}$ space computs (the $\frac{100}{200}$ $\frac{100}{200}$ $\frac{100}{200}$ $\frac{100}{200}$ $\begin{array}{ccccc}\n\text{H} & \text{Hil} & \text{Hil} \\
\text{Hil} & \text{Hil} & \text{Hil} \\
\text$ \mathbb{R} $\mathcal{O}(1)$ TeV. It justifies our assumption that the gravitino can be treated as a $\mathcal{O}(1)$ $\mathcal{O}(1$ $\frac{1}{2}$ in the gauge state $\frac{1}{2}$ in this way, gauge-mediation provides that $\frac{1}{2}$ messengers that $\frac{1}{2}$ m HamMn \mathbb{R} — m_{N} 200⁻ 200⁻ is the messenger scale and assuming \mathbb{R} . The branching ratio of the bino-like neutralino can be obtained by substituting *N*1*ⁱ* = 1*ⁱ* Λ ⁻ m_{NLSP} plassed; ϵ 300. fo-neutralino mass plane. The three contours correspond to the lightest neu-
19-16Utralino mass plane. The three contours correspond to the lightest neu
ch is predominantly bing (red-solid), wing (blue-dashed) and higgsing tralino which is predominantly bino (red-solid), wino (blue-dashed) and higgsino (pinkdotted. The prompt region (*cf*
dee). The prompt region (*cf*
protes). allowing fairly light <u>of</u> 1 ≤ 1 mm) is located above contours (the top-left β phots), allowing fairly light gravitinos with $m_3/2 \approx 5.6$ V $=$ I keV for neutralinos massless particle in dealing with its kinematics at colliders and we conveniently fix *m*3*/*² to 1 eV throughout our analysis. The right panel of Figure 1 recasts the calculation in the $\begin{array}{c} \frac{1}{2} M_{\rm B} \approx 0 \ \frac{1}{2} M_{\rm B} \approx 0 \end{array}$ 1977 Wight U. S MIN \ 100 GeV / \ 10 eV /
panel of Figure 1 we plot contours of a fixed neutralino lifetime *ct_ie* = 1 mm in **100 GeV** / \10eV / \ Λ - $m_{\rm NLSP}$ plasset ϵ $-m_{\rm N}$ ten is predominantly omo (red-soud); wino (blue-dashed) and higgsino (pink-
ned). The prompt region $\ell c \tau_{\approx 0} < 1$ mm) is located above contours the top-left. The $t_{\rm H}$ ino which is predominantly bino the solid is predominantly bino (red-solid), which is predominantly be the tell of the tell in the tell is predominant red-solid ($r_{\rm H}$), which is predominally be the tell in the dotted: altowing fully light gravitings w
process, altowing region assumption
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hed): The prompt region (*ch*ze 1 solution is located above contours the top-left $\sum_{i=1}^{N}$ bare of the plots of N is the plot of the plots of N for N for N is N for N lighter than *O*(1) TeV. It justifies our assumption that the gravitino can be treated as a massless particle in dealing with its kinematics at colliders and we conveniently fix *m*3*/*² to $\frac{1}{2}$ from $\frac{1}{2}$ events in the right panel of $\frac{1}{2}$ recasts the calculation in the **12**
32 **CONLOUTS**
32 **CONLOUTS** ⇠ ¹ 0*.*3 mm $\frac{1}{\sqrt{106}}$ LI allillo Raelattie *CI*
Fallillo Hietline *ET* $\frac{1}{2}$ imm $\frac{1}{2}$ in $\frac{1}{2}$ if $\frac{1}{2}$.
ב $\frac{-\mu_N}{\sigma}$ head , the prompt region $\langle \varepsilon \tau z_0 \rangle \leq 1 \min_i$ is located above contours the top-left \bot from the three contours is new-, prots.), anowing fairly light gravitinos with $m_3/3\,\approx\,9$ eV -1 keV for heutralinos
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18ª pl F18UFe 1 we plot contours of a fixed heutralino lifetime *cr3*0 = 1 mm in
19ª peutralino mass plane. The firee contours correspond to-neutralino mass plane. The three contours correspond to the tightest neu-
he heutralino mass plane. The three contours correspond to the namest neutralino which is predominantly bino (red-solid), wino (blue-dashed) and higgsino (pinkdee). The prompt region (*cr*
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profect in dealing with its kinematics at colliders and we conveniently fix $m_3/2$ to $\frac{2M_{\rm BH}^2}{\mu} \quad 0$ we plot conto μ *3 μ m / taa al aan ah / y taal / y ⇠ ¹ 0*.*3 mm 100 GeV 10 eV In the left panel of Figure ¹ we plot contours of a fixed neutralino lifetime *^c*⌧e⁰ 1 = 1 mm in $\sum_{i=1}^{\text{NLSP}} \sum_{i=1}^{\text{P}(\text{CALC})}$ In the predominantly bino (red-solid), wino (blue-dashed) and higgsino (pink
Ien is predominantly bino (red-solid), wino (blue-dashed) and higgsino (pink-្ត $t_{\rm{max}}$ and graviting mass $t_{\rm{max}}$ is the three contours $t_{\rm{max}}$ for the $t_{\rm{max}}$ in $t_{\rm{max}}$ is the top to the top to the $t_{\rm{max}}$ $\frac{1}{2}$ prots), allowing fairly light thravitinos with $m_{3/2} \leqslant 5$ eV -1 keV for heutralinos dotted: The production of the production o 1 hat the gravitino can be treated as a rhout our analysis. The right panel of Higure 1 recasts the calculation th_{ethe} to-neutralino mass plane. The three compours correspond to the lightest new
he-heutralino mass plane. The three contours correspond to the hentest helf tralino which is predominantly bino (red-solid), wino (blue-dashed) and higgsino (pinkdech). The prompt region (*c*²²⁰
Heel): The prompt region (*ers*)
Thots) allowing rairly light & 1 *<* 1 mm) is located above contours (the top-left p plots), allowing fairly light gravitinos with $m_3/2 \lessapprox 5$ eV=1 keV for neutralinos lighter than *O*(1) TeV. It justifies our assumption that the gravitino can be treated as a massless particle in dealing with its kinematics at colliders and we conveniently fix *m*3*/*² to $100\,\mathrm{m}$ and $100\,\mathrm{m}$ and $100\,\mathrm{m}$ and $100\,\mathrm{m}$ and $100\,\mathrm{m}$ and $100\,\mathrm{m}$ in the calculation in the calculat 40

100 GeV

100 GeV

100 GeV

10 eV

10 eV

10 eV

16 $\frac{1}{4}$ ($\frac{2}{\pi}$ $\frac{1}{2}$ $M_{\rm pl}$)

16*ima*

 $\hat{\mathbf{h}}$

Numerically, the e⁰

 \bigcirc of the motivations for a light gravitino is to relax the apparent fine-tuning in the apparent fine-tuni \bigcirc of motivations for a light gravitino is to relax the apparent fine-tuning in the \bigcirc in the Higgs \bigcirc in the Higgs \bigcirc \circ \circ \circ \circ \circ \circ \circ contours are shown in Fig. 9 in the ^g^e *^c*e⁰ 1/*c*e*[±]* $\mathbf{1}$ mass plane. This search can exclude gluino g and A and A or a A into account into account into account into account into account in the analysis, since the anal

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Analysis Framework

SUSY g-2: 1-loop + leading 2-loop GM2Calc [Eur.Phys.J. C76 (2016) no.2, 62]

Neutralino abundance, Direct Detection: MicrOMEGAs [2003.08621]

Decay of SUSY particles: SUSY-HIT [hep-ph/0609292]

LHC constraints:

- **MSSM:** ① Mapping simplified model limits to the model point (σ BR)
- **RPV:** ② Pythia 8 + CheckMATE 2 [1907.09874], [1611.09856]
- **Gravitino LSP:** Both ① and ②

Parameter planes

Non $\tilde{\chi}_1^0$ **NLSP (Short Summary)** 1

8⇡ *M*1*µ m*² *µ*˜*^L m*² *µ*˜*^L ^µ* (*M*1*, µ, ^m*˜ *^l^R*) = ↵*^Y* \bullet small $|\mu|$ region is compatible with (g-2)_μ