

# Supersymmetry with long-lived neutralinos at Belle II



Abi Soffer

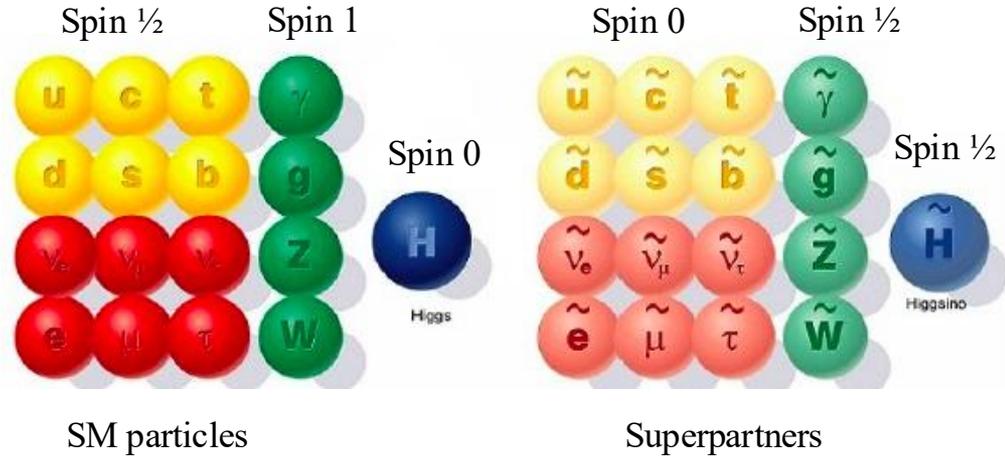
Josef Stefan Institute seminar, March 2026

# Outline

- Introduction to supersymmetry (SUSY)
  - Motivation, limits
- A new search region for SUSY at Belle II:
  - A light neutralino, heavy squarks, and R-parity violation (RPV)
- Scenario for missing-energy signature
  - Experimental results
- Scenario for displaced-vertex (DV) signature
  - Naïve expected sensitivities
  - Initial experimental ideas

# Supersymmetry

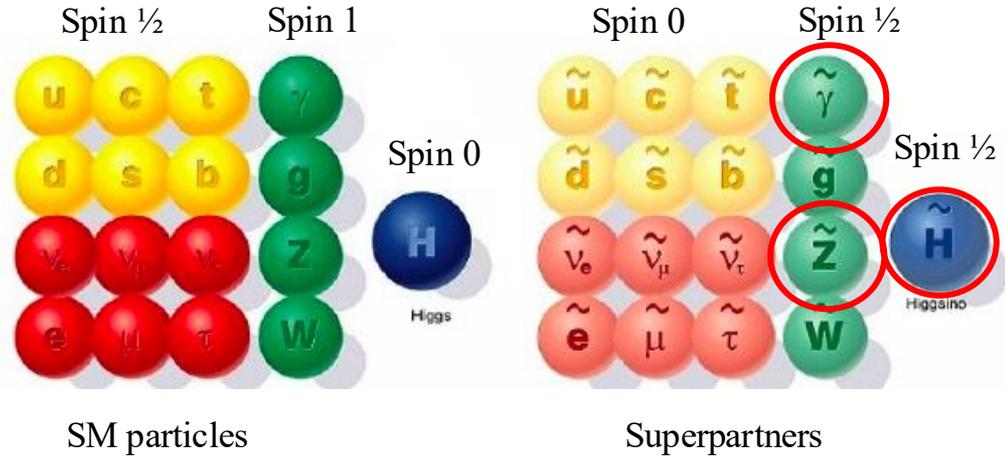
Each SM fermion (boson) has a “superpartner” boson (fermion) with the same gauge quantum numbers:



- If SUSY were a good symmetry: **superpartner masses = SM-particle masses**
- But superpartners not observed → **SUSY possibly broken, superpartners are heavy**

# Supersymmetry

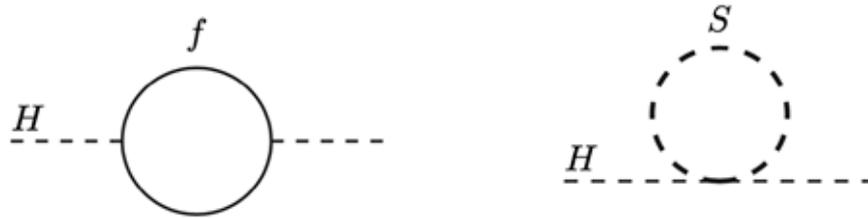
Each SM fermion (boson) has a “superpartner” boson (fermion) with the same gauge quantum numbers:



- If SUSY were a good symmetry: **superpartner masses = SM-particle masses**
- But superpartners not observed  $\rightarrow$  **SUSY possibly broken, superpartners are heavy**
- Important for us: the (scalar) squarks  $\tilde{q}$
- And the 4 neutral (fermion) superpartners:  $\tilde{\gamma}, \tilde{Z}, \tilde{H}_u, \tilde{H}_d$
- The mass eigenstates formed from their linear combinations: the neutralinos  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

# Traditional motivation for SUSY: fine-tuning / hierarchy problem

- SM Higgs mass gets quantum corrections up to the scale of new physics:
  - If quantum gravity is the only new physics,  $M_H \sim 10^{18}$  GeV



- The corrections are canceled by corrections from the superpartners:



Motivating SUSY particles at  $\sim 1$  TeV

# Superpartners not found up to O(1 TeV)

ATLAS SUSY Searches\* - 95% CL Lower Limits  
July 2024

ATLAS Preliminary  
 $\sqrt{s} = 13 \text{ TeV}$

	Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 $e, \mu$ 2-6 jets mono-jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140 140	$\tilde{q}$ [1x, 8x Degen] 1.0 1.85 $\tilde{q}$ [8x Degen] 0.9 $\tilde{g}$ 1.15-1.95 2.3 Forbidden $\tilde{g}$ 1.15 1.97 $\tilde{g}$ 1.25 2.45	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q})-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 700 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 600 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ $m(\tilde{\chi}_1^0) < 500 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	2010.14293 2102.10874 2010.14293 2010.14293 2101.01629 2204.13072 2008.05032 2307.01094 2211.08028 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 $e, \mu$ 2-6 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{g}$ 0.68 1.255 Forbidden $\tilde{g}$ 0.13-0.85 0.23-1.35	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $10 \text{ GeV} < \Delta m(\tilde{h}, \tilde{\chi}_1^0) < 20 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	2101.12527 2101.12527 1908.03122 2103.08189
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 $e, \mu$ 2-6 jets	$E_T^{\text{miss}}$	140	$\tilde{g}$ 1.25	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	2004.14060, 2012.03799
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(t)\tilde{\chi}_1^0$	$ee, \mu\mu$ 2 jets	$E_T^{\text{miss}}$	140	$\tilde{g}$ 1.05	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	2012.03799, 2401.13430
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(t)\tilde{\chi}_1^0$	0 $e, \mu$ 7-11 jets	$E_T^{\text{miss}}$	140	Forbidden 1.4	$m(\tilde{\chi}_1^0) = 800 \text{ GeV}$	2108.07665
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS $e, \mu$ 6 jets	$E_T^{\text{miss}}$	140	Forbidden 0.55 0.85	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}, \tilde{b})-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ 3 $b$ SS $e, \mu$ 6 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140 140	$\tilde{g}$ 0.067-1.18 $\tilde{g}$ 0.86	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$ $m(\tilde{t}, \tilde{b})-m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	2006.05880 2006.05880
	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$ 2 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{b}_1$ 1.255 Forbidden $\tilde{b}_1$ 0.13-0.85 0.23-1.35	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $10 \text{ GeV} < \Delta m(\tilde{h}, \tilde{\chi}_1^0) < 20 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	2101.12527 2101.12527 1908.03122 2103.08189
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0 $e, \mu$ 2 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{b}_1$ 1.25 Forbidden 1.05	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	2004.14060, 2012.03799 2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$ $\geq 1$ jet	$E_T^{\text{miss}}$	140	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	2004.14060, 2012.03799
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 $e, \mu$ 3 jets/1 $b$	$E_T^{\text{miss}}$	140	Forbidden 1.05	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	2012.03799, 2401.13430	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{b}\tilde{\chi}_1^0, \tilde{t}_1 \rightarrow \tau\tilde{G}$	1-2 $\tau$ 2 jets/1 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	Forbidden 1.4	$m(\tilde{\chi}_1^0) = 800 \text{ GeV}$	2108.07665	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{t} \rightarrow c\tilde{\chi}_1^0$	0 $e, \mu$ 2 $c$ mono-jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 140 140	$\tilde{t}$ 0.55 0.85 $\tilde{t}$ 0.55	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}, \tilde{b})-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 2102.10874	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/\tilde{h}\tilde{\chi}_1^0$	1-2 $e, \mu$ 1-4 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{t}_1$ 0.067-1.18 $\tilde{t}_1$ 0.86	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$ $m(\tilde{t}, \tilde{b})-m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	2006.05880 2006.05880	
$\tilde{b}_2\tilde{b}_2, \tilde{b}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ 1 $b$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	Forbidden 0.86	$m(\tilde{\chi}_1^0) = 360 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	2006.05880 2006.05880	
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WZ	Multiple $\ell$ /jets $ee, \mu\mu$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 0.205 0.96 $\tilde{\chi}_1^0\tilde{\chi}_2^0$	$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$ $m(\tilde{\chi}_1^0)-m(\tilde{\chi}_2^0) = 5 \text{ GeV}, \text{wino-bino}$	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WW	2 $e, \mu$	$E_T^{\text{miss}}$	140	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 0.42	$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$	1908.08215
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via Wh	Multiple $\ell$ /jets	$E_T^{\text{miss}}$	140	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 1.06	$m(\tilde{\chi}_1^0) = 70 \text{ GeV}, \text{wino-bino}$	2004.10894, 2018.07586
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via $\tilde{t}_1/\tilde{\nu}$	2 $e, \mu$ 2 $\tau$	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ 1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_2^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$	$E_T^{\text{miss}}$	140	$\tilde{\tau}$ [FR $\tilde{\tau}\tilde{\tau}$ ] 0.35 0.5	$m(\tilde{\chi}_1^0) = 0$	2402.00603
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$ $\geq 1$ jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140	$\tilde{t}$ 0.26 0.7	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{t})-m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1908.08215 1911.12606
	$\tilde{h}\tilde{h}, \tilde{h} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ $\geq 3$ $b$ 0 jets 0 jets 0 $e, \mu$ $\geq 2$ large jets 2 $e, \mu$ $\geq 2$ jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$ $E_T^{\text{miss}}$	140 140 140 140 140 140	$\tilde{h}$ 0.94 $\tilde{h}$ 0.55 0.45-0.93 $\tilde{h}$ 0.77	$\text{BR}(\tilde{h} \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{h} \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{h} \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{h} \rightarrow Z\tilde{G}) = \text{BR}(\tilde{h} \rightarrow h\tilde{G}) = 0.5$	2401.14922 2103.11684 2108.07586 2204.13072
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk 1 jet	$E_T^{\text{miss}}$	140	$\tilde{\chi}_1^+$ 0.66	Pure Wino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx	$E_T^{\text{miss}}$	140	$\tilde{g}$ 2.05	Pure higgsino	2201.02472
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	pixel dE/dx	$E_T^{\text{miss}}$	140	$\tilde{g}$ [r( $\tilde{g}$ ) = 10 ns] 2.2	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	2205.06013 2205.06013
$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Disp. lep	$E_T^{\text{miss}}$	140	$\tilde{\ell}$ 0.74	$\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 10 \text{ ns}$	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011 2205.06013	
pixel dE/dx	$E_T^{\text{miss}}$	140	$\tilde{\tau}$ 0.36 0.36				
RPV	$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^+ \rightarrow Z\ell\ell\ell$	3 $e, \mu$	140	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ [BR(Z $\nu$ )=1, BR(Z $e$ )=1] 0.625 1.05	Pure Wino	2011.10543	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	140	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ [ $\Delta\alpha_3 \neq 0, \Delta_{123} \neq 0$ ] 0.95 1.55	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	2103.11684	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	$\geq 8$ jets	$E_T^{\text{miss}}$	140	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 50 \text{ GeV}, 1250 \text{ GeV}$ ] 1.6 2.34	Large $\mu_{112}$	2401.16333
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}\tilde{\chi}_1^0$	Multiple	36.1 140	$\tilde{t}$ [ $\Delta_{123} = 2\sigma-4, 1\sigma-2$ ] 0.55 1.05	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}, \tilde{\chi}_1^0 \rightarrow b\tilde{s}$	$\geq 4b$	140	Forbidden 0.95	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	2010.01015	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 jets + 2 $b$	36.7	$\tilde{t}_1$ [qq, bb] 0.42 0.61		1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	2 $e, \mu$ 2 $b$	140 140	$\tilde{t}_1$ 0.4-1.85	$\text{BR}(\tilde{t}_1 \rightarrow b\tilde{e}/\tilde{h}\tilde{\nu}) = 20\%$	2406.18367	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	1 $\mu$ DV	136	$\tilde{t}_1$ [1e-10 < $\Delta_{123}$ < 1e-8, 3e-10 < $\Delta_{123}$ < 3e-9] 1.0 1.6	$\text{BR}(\tilde{t}_1 \rightarrow q\tilde{g}) = 100\%, \cos\theta_{12} = 1$	2003.11956	
	$\tilde{\chi}_1^0\tilde{\chi}_2^0/\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow b\tilde{s}$	1-2 $e, \mu$ $\geq 6$ jets	140	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609	

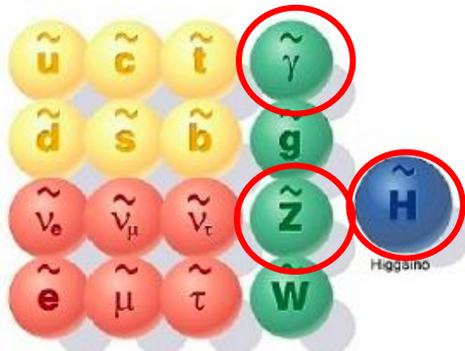
\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# Traditional motivation for SUSY: Dark matter

- A multiplicative quantum number: R parity,

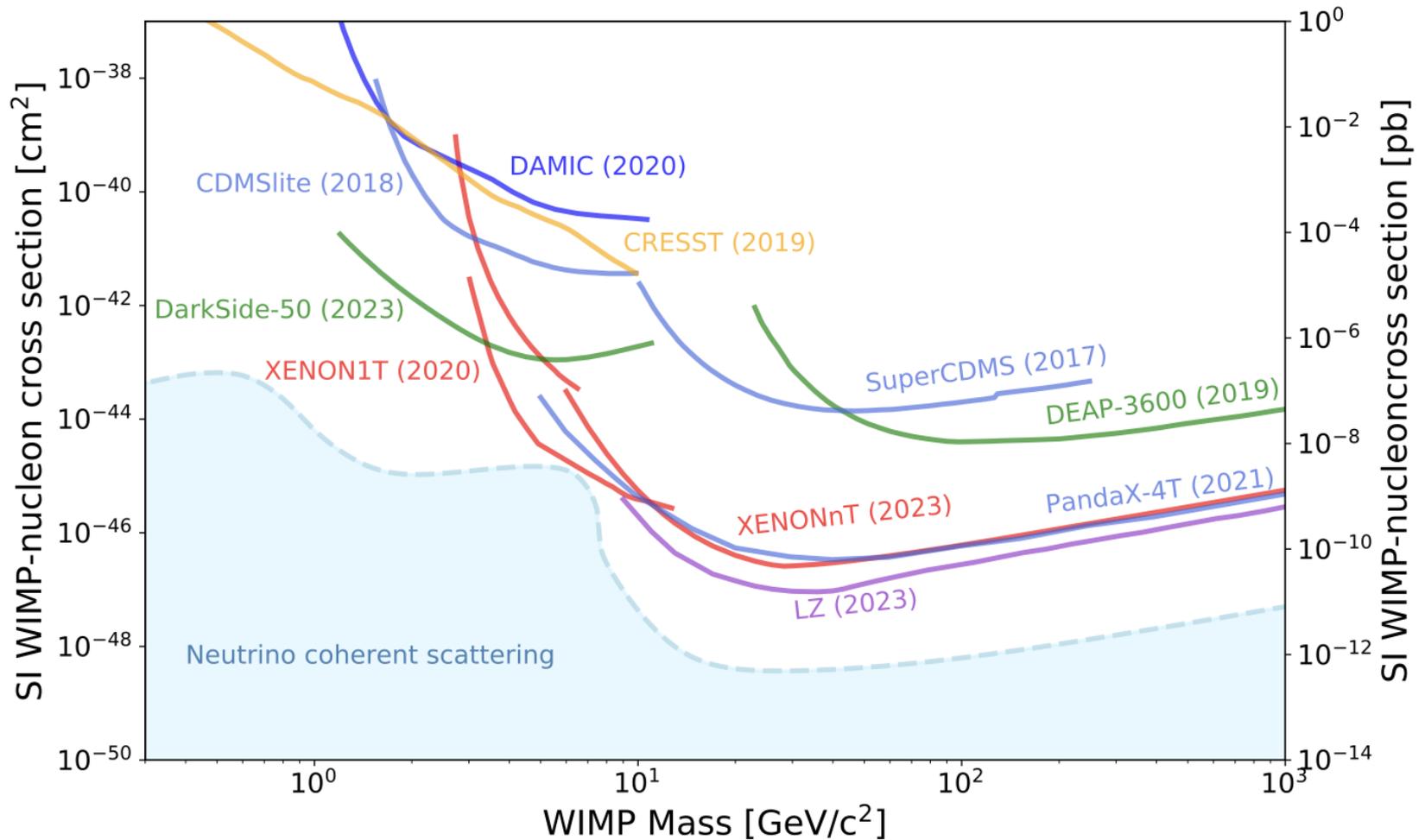
$$R_p = \begin{cases} 1 & \text{SM particles} \\ -1 & \text{Superpartners} \end{cases}$$

- If  $R_p$  is conserved, then
  - a superpartner ( $R_p = -1$ ) must decay to an odd number of superpartners
  - The lightest superpartner (LSP) cannot decay so is stable
  - If it is neutral under QCD and EM it can be the **dark matter particle**



- A natural DM candidate: the lightest neutralino  $\tilde{\chi}_1^0$

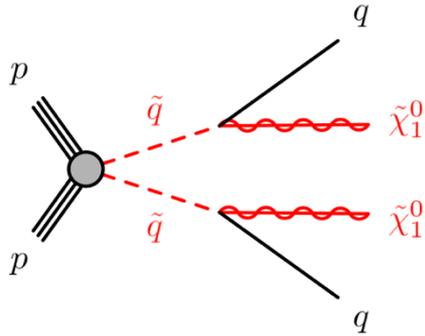
# Limits on such DM particles



# A new region to search for SUSY

- Minimal TeV-scale SUSY is not as favored as before
- But SUSY is still allowed in many regions of parameter space
- Our parameter-space region of interest:
  1. The lightest neutralino  $\tilde{\chi}_1^0$  has mass  $\sim O(\text{GeV})$ 
    - This means that  $\tilde{\chi}_1^0$  is mostly the  $\tilde{B}$ , but it's not important for this talk
  2. All other superpartners, particularly the squarks, are too heavy for LHC discovery
  3. R-parity is violated (RPV), so  $\tilde{\chi}_1^0$  can decay

# How heavy should the $\tilde{q}$ be to hide the light $\tilde{\chi}_1^0$ ?

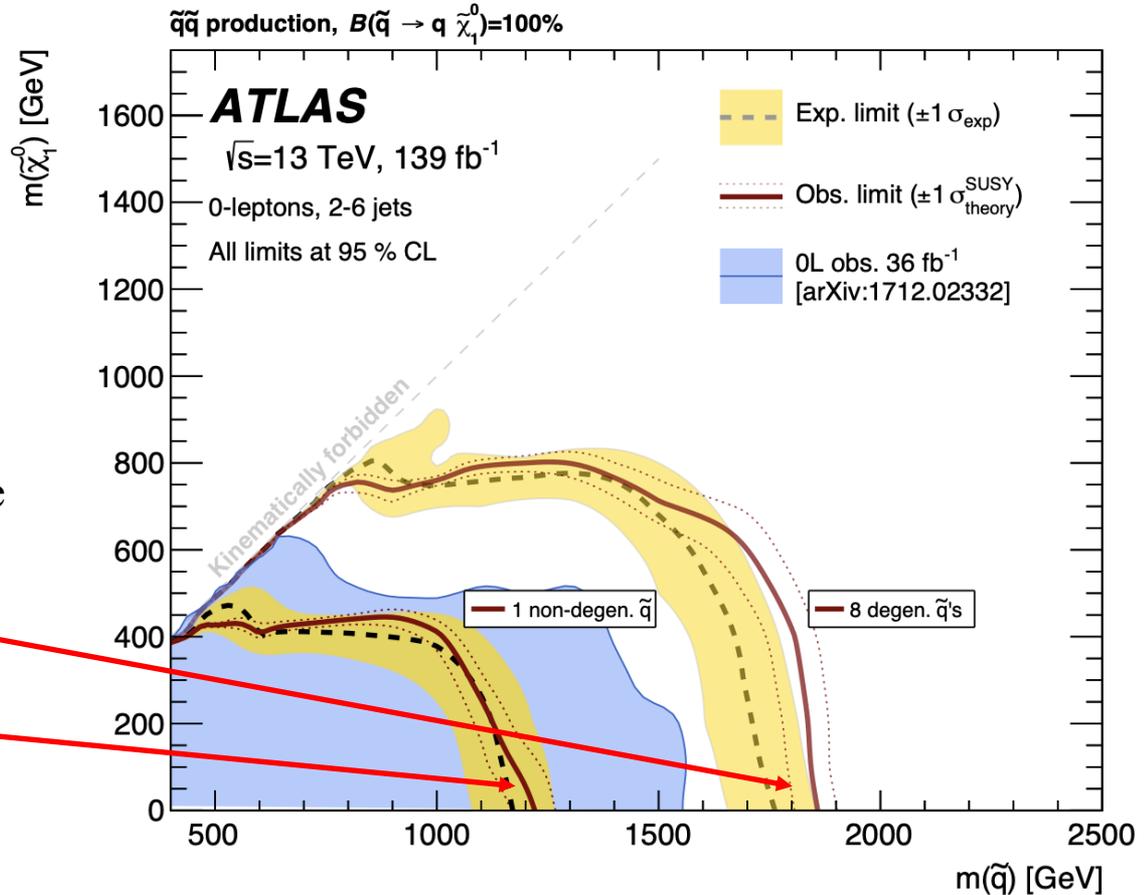


- 1<sup>st</sup>- & 2<sup>nd</sup>-generation squarks are mass-degenerate:

$$m_{\tilde{q}} > 1.85 \text{ TeV}$$

- Only 1 light squarks:

$$m_{\tilde{q}} > 1.23 \text{ TeV}$$



# R-parity violation (RPV)

- R-parity conservation is motivated by the dark-matter explanation
- But is not fundamentally required
- I will focus on the following RPV terms in the Lagrangian:

Generation indices  
(quark-mass basis)

Right-handed squark and quark fields

$$L \supset \frac{1}{2} \sum_{ijk} \lambda''_{ijk} \left[ \tilde{u}_i^c d_j^c d_k^c + u_i^c \tilde{d}_j^c d_k^c + u_i^c d_j^c \tilde{d}_k^c \right] + h.c.$$

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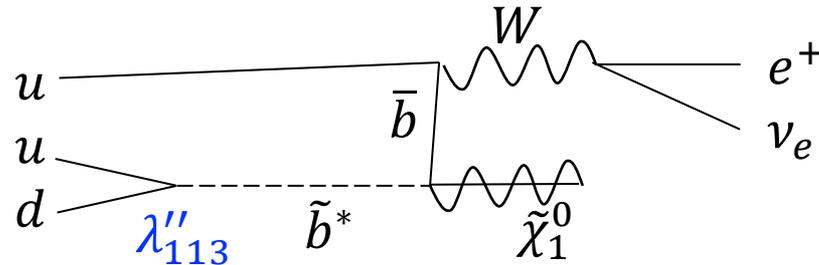
$$L \supset \frac{1}{2} \sum_{ijk} \lambda''_{ijk} \left[ \tilde{u}_i^c d_j^c d_k^c + u_i^c \tilde{d}_j^c d_k^c + u_i^c d_j^c \tilde{d}_k^c \right] + h.c.$$

For  $ijk = 1,1,3$ :

- These terms violate baryon number
  - That's OK since baryon number is only an accidental symmetry of the SM
  - As long as we agree with lack of observation of BNV

# BNV terms can make the proton decay

1. The proton could decay if, e.g.,  $\lambda''_{113} \neq 0$ :



- But there are strong constraints on the proton lifetime
  - E.g.,  $\tau_p > 10^{33}$  years in  $p \rightarrow e^+ + \text{meson}$  [1]
- This constraint is evaded if

$$M_\chi > M_p$$

2. There are also constraints on  $\lambda''_{ijk}$  coefficients

- Will discuss later

# Our work

# Our work



# Our work

1. Only one nonzero RPV coupling:  $\lambda''_{ij3}$ , with  $ij = 11, 12, 21, 22$ .

Probe with a search for

$B \rightarrow \text{baryon} + \text{invisible } \tilde{\chi}_1^0$

– [2208.06421](#), JHEP 02 (2023) 224

- C.O. Dib, J.C. Helo, V.E. Lyubovitskij, N.A. Neill, AS, Z.S Wang

– Experimental limits from BABAR and Belle

2. Add nonzero  $\lambda''_{212}$ , facilitating neutralino decay.

Probe with a search for

$B \rightarrow \text{baryon} + \text{long lived, decaying } \tilde{\chi}_1^0$

– [2507.00359](#), JHEP 10 (2025) 076

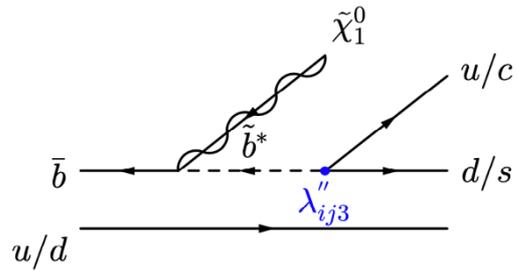
- E. Bertholet, C.O. Dib, S.P. Gandelman, J. C. Helo, V. E. Lyubovitskij, M. Nayak, N.A. Neill, AS, Z.S.Wang

– We just launched the search at Belle II

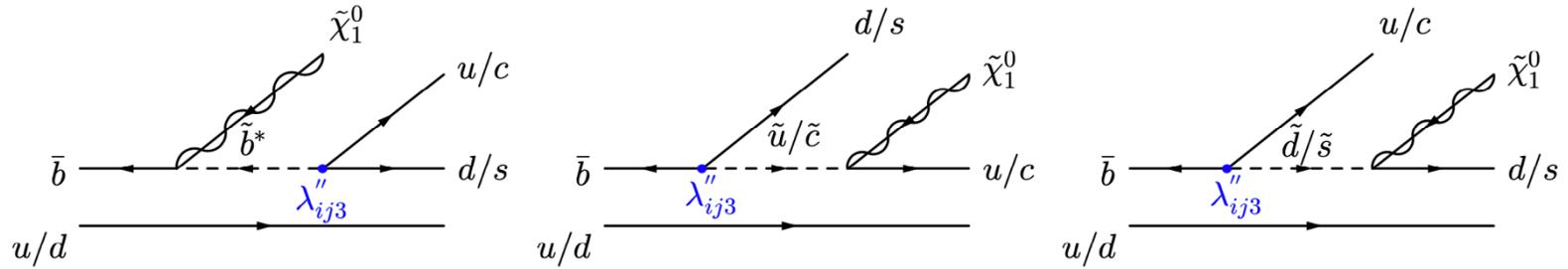
3. A phenomenologist's tool for estimating long-lived-particle efficiency at Belle II and similar detectors

– [2501.00857](#)

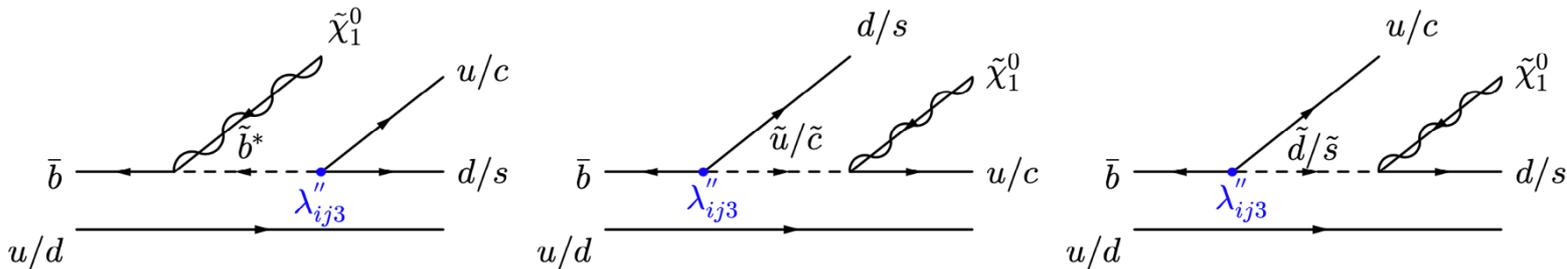
# B-meson decays and final-state baryons



# B-meson decays and final-state baryons



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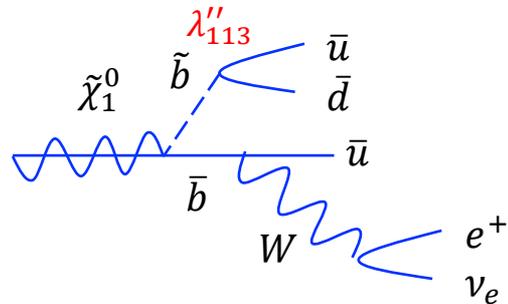


Consider  $\lambda''_{ij3} =$

- $\lambda''_{113}$ :  $B^+ \rightarrow \tilde{\chi}_1^0 p$  ( $uud$ )
- $\lambda''_{123}$ :  $B^0 \rightarrow \tilde{\chi}_1^0 \Lambda/\Sigma^0$  ( $uds$ ),  $B^+ \rightarrow \tilde{\chi}_1^0 \Sigma^+$  ( $uus$ )
- $\lambda''_{213}$ :  $B^+ \rightarrow \tilde{\chi}_1^0 \Lambda_c^+/\Sigma_c^+$  ( $udc$ ),  $B^0 \rightarrow \tilde{\chi}_1^0 \Sigma_c^0$  ( $ddc$ )
- $\lambda''_{223}$ :  $B^+ \rightarrow \tilde{\chi}_1^0 \Xi_c^+$  ( $usc$ ),  $B^0 \rightarrow \tilde{\chi}_1^0 \Xi_c^0$  ( $dsc$ )

The neutralino decay is suppressed,  
so it ~always decays outside the detector

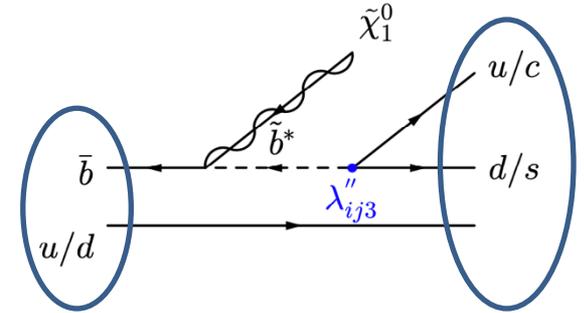
→ “Baryon + missing” signature



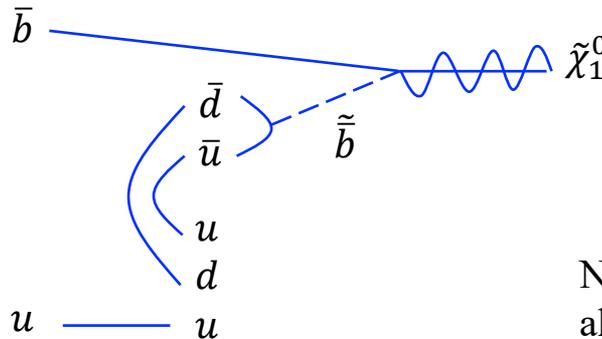
# Hadronic form factors

- From the diagrams, conclude that

$$Br \propto \left( \frac{\lambda''_{ij3}}{m_q^2} \right)^2$$



- Also  $\propto$  hadronic form factors for the  $B$  meson  $\rightarrow$  baryon transition.
- We base our calculations on form factors calculated for proton decay (e.g.,  $p \rightarrow \pi^0 e^+$ ) with proper adjustment.
- E.g., for  $B^+ \rightarrow \tilde{\chi}_1^0 p$  there is a **direct** contribution and a **pole** contribution from, e.g.,  $B^+ \rightarrow \bar{\Lambda}_b^* p$  with  $\bar{\Lambda}_b^* \rightarrow \tilde{\chi}_1^0$ :

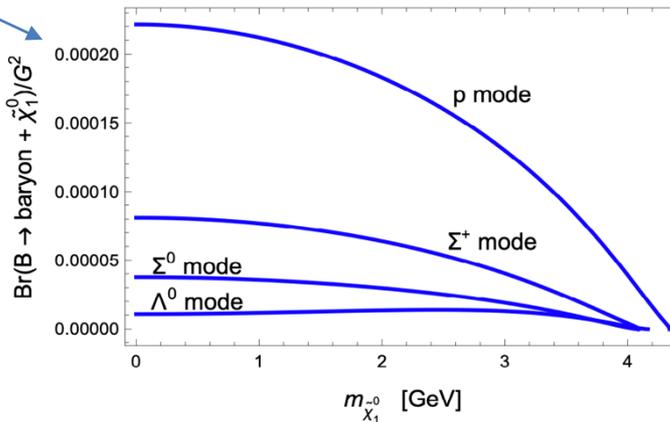


Need to add all the terms from all the diagrams with the right signs

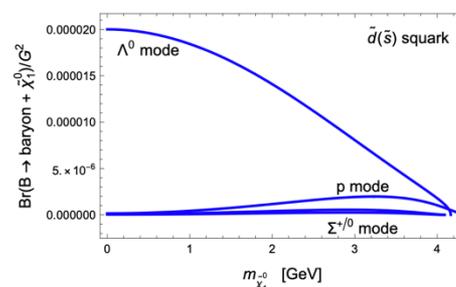
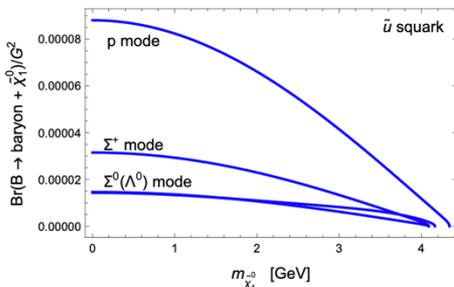
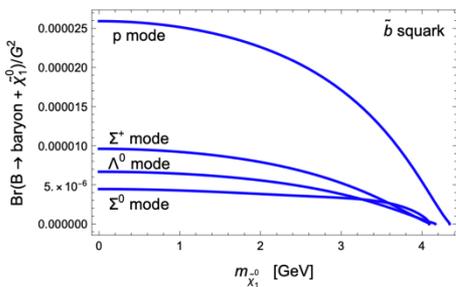
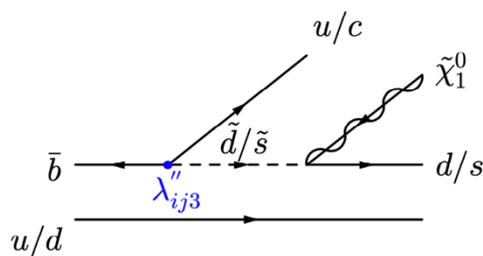
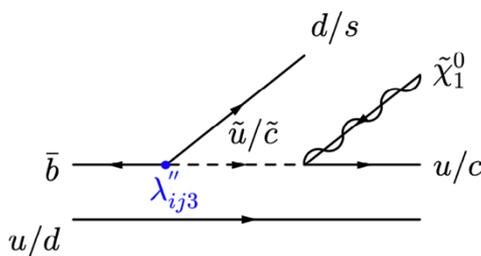
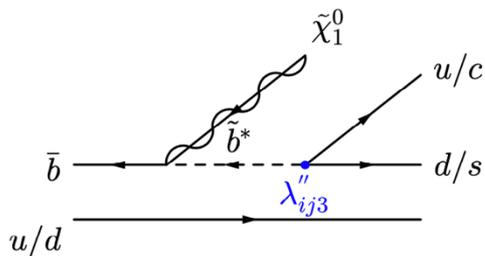
# Hadronic form factors & phase space

Degenerate squarks:

$$G^2 \equiv \left( \frac{\lambda''_{ij3}}{m_{\tilde{q}}^2} \right)^2$$

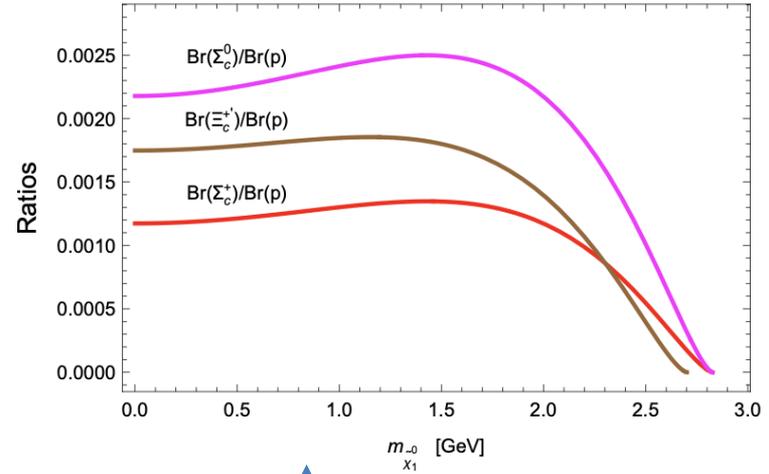
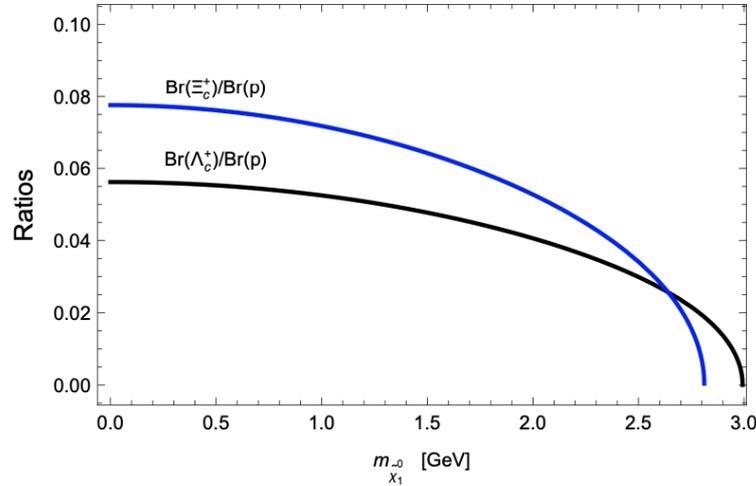


Only 1 light squark:



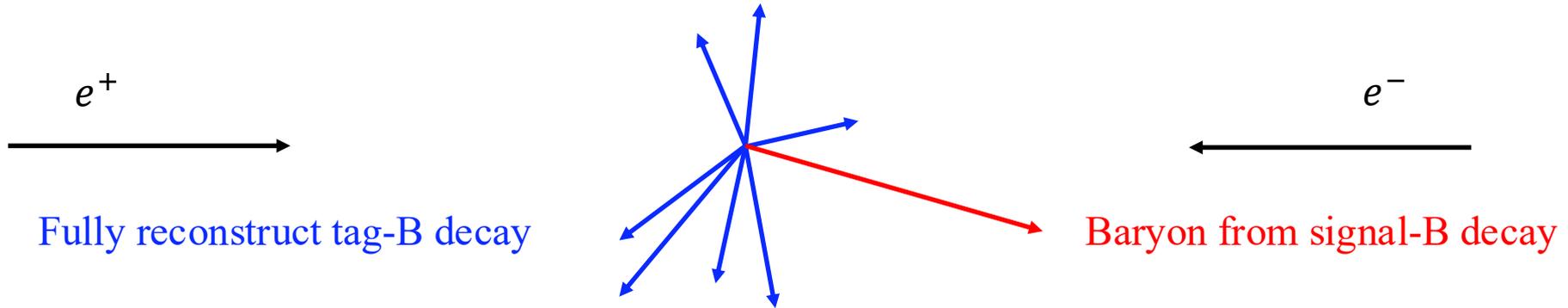
# Greater suppression for charmed baryons:

Degenerate squarks:



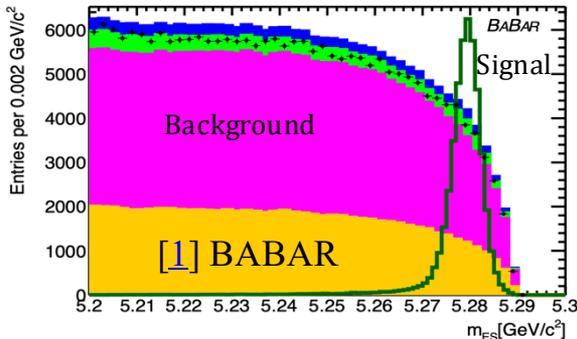
We didn't follow up on  $\Sigma_c^0$ ,  $\Sigma_c^+$ ,  $\Xi_c^+$

# Experimental technique



Require

- $\Delta E = E_{\text{tag}} - E_{\text{beam}} \sim 0$
- $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2} \sim 5.28 \text{ GeV}$



- Veto events with additional tracks or energetic  $\gamma$ s.
- From 4-momentum conservation:

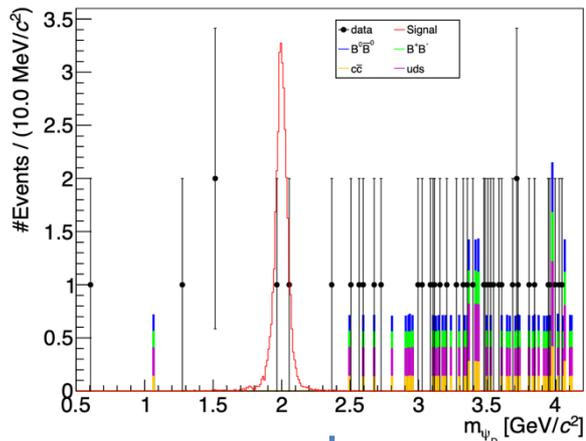
$$p_{ee} = p_{\text{tag}} + p_{\text{baryon}} + p_{\chi}$$

Calculate the neutralino mass (“recoil mass”):

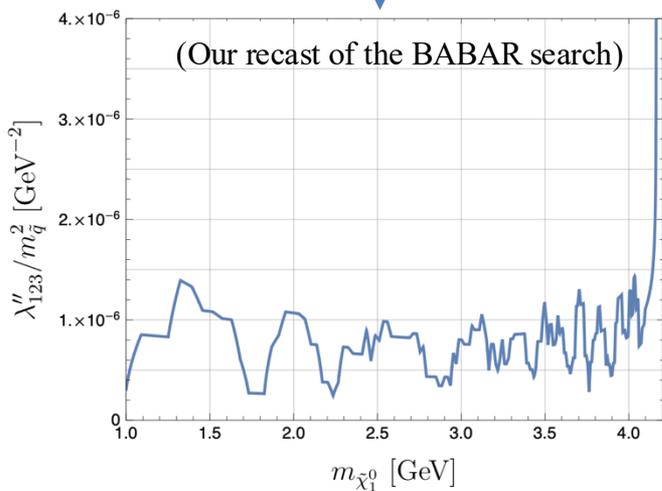
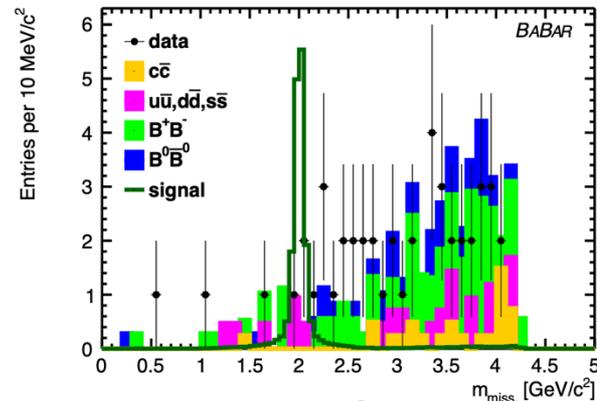
$$m_{\text{recoil}}^2 = p_{\chi}^2 = (p_{ee} - p_{\text{tag}} - p_{\text{baryon}})^2$$

# Search for a peak in the recoil-mass spectrum

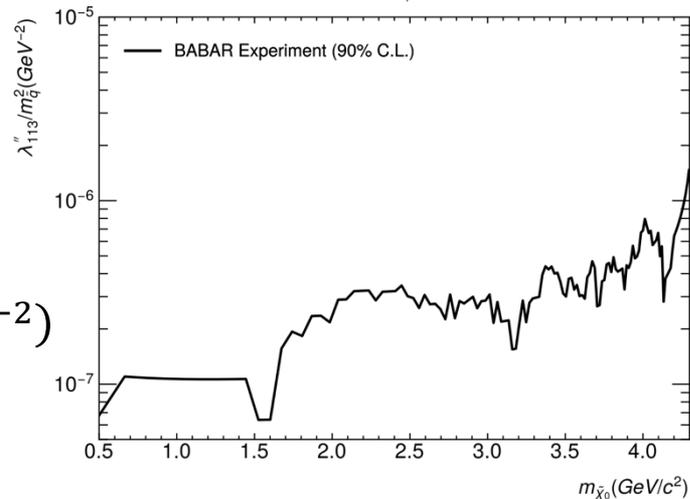
BABAR, baryon =  $\Lambda$  [1]



BABAR, baryon =  $p$  [2]



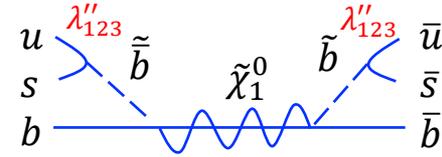
Limits on  
 $\frac{\lambda''_{1j3}}{m_{\tilde{q}}^2}$  ( $\text{GeV}^{-2}$ )



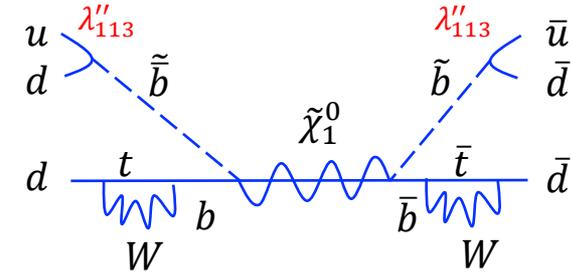
Also limits from  
 - BABAR  $\Lambda_c$  [3]  
 - Belle  $\Lambda$  [4]

# What about limits from other processes?

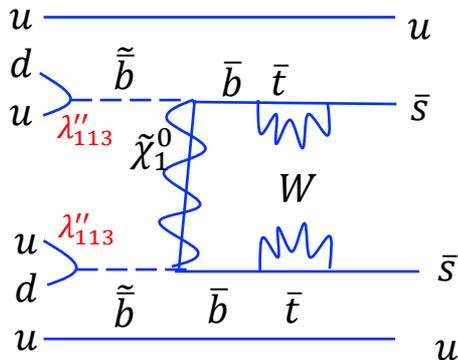
- $\Xi_b^0 - \bar{\Xi}_b^0$  oscillations (LHCb [1]):  
We estimate  $\lambda''_{123}/m_{\tilde{b}}^2 < 4 \times 10^{-4} \text{ GeV}^{-2}$  (for  $m_{\tilde{\chi}_1^0} = 2.5$  GeV)



- Limits on  $n - \bar{n}$  oscillations are much tighter, but their impact is suppressed by 2 weak loops due to lack of  $b$  content in the neutron:



- Weak loops also suppress dinucleon decays:



Recasting calculations in Ref. [2], we estimate:

$$\lambda''_{113}/m_{\tilde{q}}^2 \lesssim 6 \times 10^{-4} \text{ GeV}^{-2}$$

$$\lambda''_{123}/m_{\tilde{q}}^2 \lesssim 2 \times 10^{-2} \text{ GeV}^{-2},$$

$$\lambda''_{213}/m_{\tilde{q}}^2 \lesssim 5 \times 10^{-6} \text{ GeV}^{-2},$$

$$\lambda''_{223}/m_{\tilde{q}}^2 \lesssim 2 \times 10^{-4} \text{ GeV}^{-2}$$

Only this one beats our method

Neutralino not found, but might still be there!

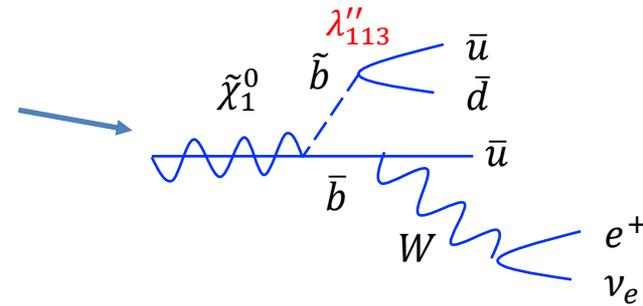


You have to look in the right direction at the right time:  
Another way to search



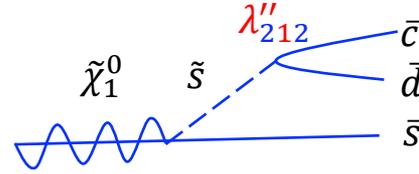
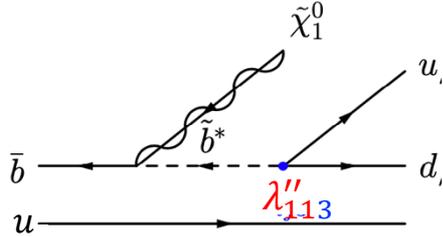
# The other way to look: Neutralino decay via a second nonzero $\lambda''_{ijk}$ 's

- So far we discussed the case of one nonzero RPV coupling  $\lambda''_{ij3}$ 
  - Same coupling controls  $\tilde{\chi}_1^0$  production and decay rates
  - The  $\tilde{\chi}_1^0$  is very long-lived, decays outside the detector ([2208.06421](#))



- What if we have an **additional nonzero RPV coupling** that causes the  $\tilde{\chi}_1^0$  to decay inside the detector? ([2507.00359](#))
- Experimental advantages:
  - Don't need to reconstruct the tag B (efficiency  $< 1\%$ )
  - Great background reduction if the neutralino is long-lived – displaced vertex (DV) signature

# Example: $\lambda''_{113}$ and $\lambda''_{212}$ are non-0

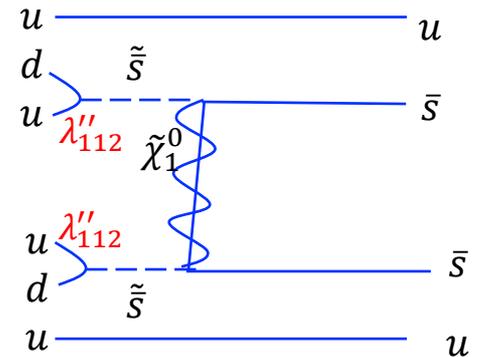


- $\lambda''_{113}$  determines  $\tilde{\chi}_1^0$  production rate
- $\lambda''_{212}$  determines  $\tilde{\chi}_1^0$  lifetime
  - The  $\tilde{\chi}_1^0$  decays to a  $csd$ -flavor baryonic state

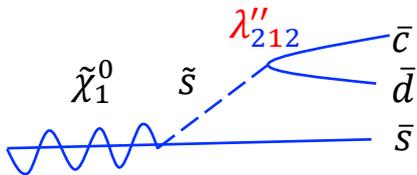
- What about  $\lambda''_{112}$ ?
  - Already strongly constrained from dinucleon decays
  - We estimate:

$$\lambda''_{112}/m_{\tilde{q}}^2 \lesssim 9.8 \times 10^{-13}/\text{GeV}^2$$

$$\lambda''_{212}/m_{\tilde{q}}^2 \lesssim 6 \times 10^{-6}/\text{GeV}^2$$



# Hadronization of the $c\bar{s}d$ final state



$$\tilde{\chi}_1^0 \rightarrow \Sigma_c^0 \bar{K}^0 + \text{c.c.}, \quad \tilde{\chi}_1^0 \rightarrow \Omega_c^0 K^0 + \text{c.c.},$$

$$\tilde{\chi}_1^0 \rightarrow \Lambda_c^+ K^- + \text{c.c.}, \quad \tilde{\chi}_1^0 \rightarrow \Xi_c^+ \pi^- + \text{c.c.}, \quad \tilde{\chi}_1^0 \rightarrow \Xi_c^0 \pi^0 + \text{c.c.}$$

- We consider 2-body decays to a charmed baryon plus meson:
- Decays to  $D_{(s)}^{(*)+}$  baryon have small form factors & are ignored

Notation	Content	$J^P$	$S_d$	Mass $m_B$ (GeV)	Coupling $\beta_B$ (in units of $10^{-2} \times \text{GeV}^3$ )
$\Lambda_c^+$	$c[ud]$	$1/2^+$	0	2.28646	0.835
$\Sigma_c^0$	$c\{dd\}$	$1/2^+$	1	2.45375	1.125
$\Xi_c^+$	$c[us]$	$1/2^+$	0	2.46771	1.021
$\Xi_c^0$	$c[ds]$	$1/2^+$	0	2.47044	1.021
$\Omega_c^0$	$c\{ss\}$	$1/2^+$	1	2.6952	2.325

**Table 1:** Classification of the relevant baryons, including their quantum numbers, masses, and coupling constants, extracted from Refs. [54, 55].

Notation	Content	$J^P$	Mass $m_M$ (GeV)	Decay constant $f_M$ (GeV)
$\pi^0$	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	$0^-$	0.1349768	0.1302
$\pi^-$	$d\bar{u}$	$0^-$	0.13957	0.1302
$K^-$	$s\bar{u}$	$0^-$	0.493677	0.1557
$K^0$	$d\bar{s}$	$0^-$	0.497611	0.1557
$\bar{K}^0$	$s\bar{d}$	$0^-$	0.497611	0.1557

**Table 2:** Classification of the relevant mesons, including their quantum numbers, masses, and leptonic decay constants, extracted from Ref. [7].

# $\tilde{\chi}_1^0$ decay branching fractions

- The width of the neutralino decay to a baryon and meson final state

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \mathcal{B}M) = \frac{\lambda^{1/2}(m_{\tilde{\chi}_1^0}^2, m_B^2, m_M^2)}{32\pi m_{\tilde{\chi}_1^0}^3} \sum_{\text{pol.}} |\mathcal{M}|^2,$$

Phase space
Matrix element

↓
↓

$$\sum_{\text{pol.}} |\mathcal{M}|^2 = \left\{ \left( (m_{\tilde{\chi}_1^0} - m_B)^2 - m_M^2 \right) (\mathcal{X}^2 + \mathcal{Y}^2) + 2m_B m_{\tilde{\chi}_1^0} (\mathcal{X} - \mathcal{Y})^2 \right\} \left( \frac{\lambda''_{212}}{m_q^2} \right)^2$$

Baryon polarizations

↙ ↘

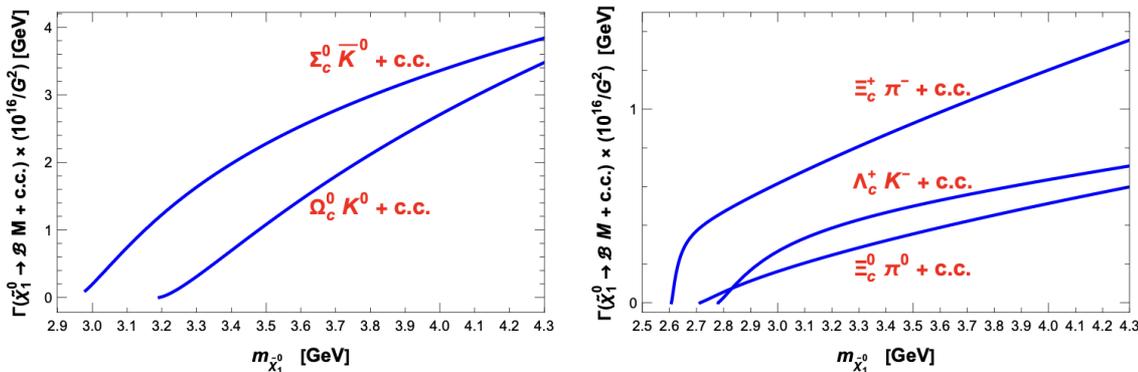
Form factors  
 parameterize the hadronic transition

# $m_{\tilde{\chi}_1^0}$ -dependent $cds$ form factors & phase space

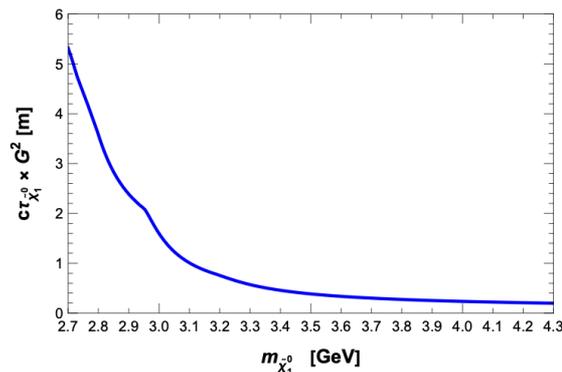
- Shown in terms of  $\Gamma(\tilde{\chi}_1^0 \rightarrow BM) \times 10^5 / G_0^2$

$$G_0 = \frac{\lambda''_{212}}{m_{\tilde{q}}^2}$$

- The form factors and phase space also impact the neutralino lifetime:



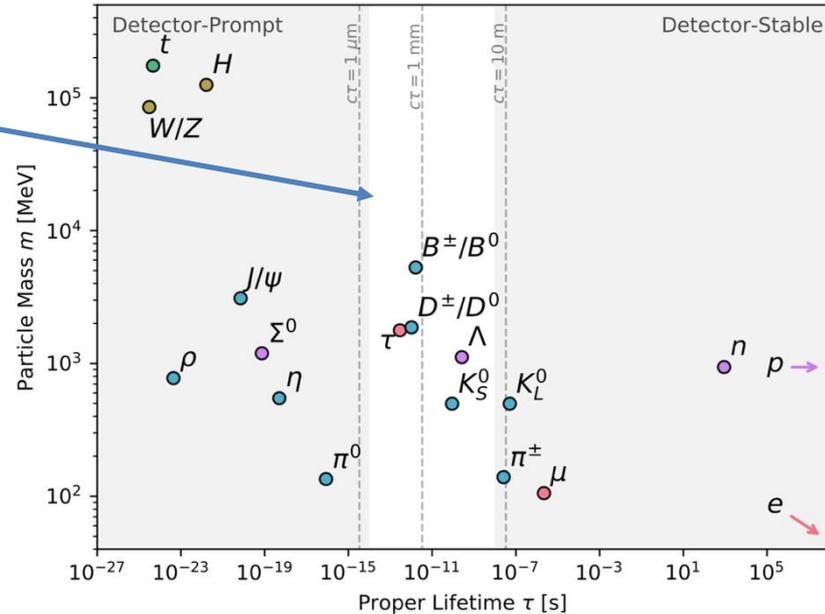
**Figure 3:** Decay rates  $\Gamma(\tilde{\chi}_1^0 \rightarrow BM)$ , including the charge-conjugate mode, multiplied by  $(10^{16}/G^2)$ , where  $G^2 = (\lambda''_{212})^2 \times (1 \text{ TeV}/m_{\tilde{q}})^4$ .



**Figure 4:** The average proper decay length  $c\tau_{\tilde{\chi}_1^0}$  of the neutralino, multiplied by  $G^2 = (\lambda''_{212})^2 \times (1 \text{ TeV}/m_{\tilde{q}})^4$ , as a function of  $m_{\tilde{\chi}_1^0}$ .

# Focus on the case of a long-lived neutralino

- For small  $\frac{\lambda''_{212}}{m_q^2}$ , the  $\tilde{\chi}_1^0$  is long lived.
- Average flight distance =  $\gamma\beta c\tau = \frac{p}{m} c\tau$
- The tracks produced in the  $\tilde{\chi}_1^0$  decay form a displaced vertex (DV)
- DVs are also produced by SM particles
- Requiring a DV greatly suppresses background
  - So a DV-based search for new particles is the most sensitive
  - for regions of parameter space in which the new particle is indeed long-lived



# Experimental method 1: full reconstruction in exclusive decay modes

- Reconstruct  $\tilde{\chi}_1^0$  in dominant decays into 4 or 6 tracks and no neutrals:

- $\tilde{\chi}_1^0 \rightarrow \Xi_c^+ \pi^-, \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+, \Xi^- \rightarrow \Lambda \pi^-, \Lambda \rightarrow p \pi^-$ .  $N_t = 6, \text{BR} = 1.9\%$
- $\tilde{\chi}_1^0 \rightarrow \Sigma_c^0 \bar{K}^0, \Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ \rightarrow p K^- \pi^+, \bar{K}^0 \rightarrow \pi^+ \pi^-$   $N_t = 6, \text{BR} = 2.2\%$
- $\tilde{\chi}_1^0 \rightarrow \Lambda_c^+ K^-, \Lambda_c^+ \rightarrow p K^- \pi^+$ .  $N_t = 4, \text{BR} = 6.4\%$

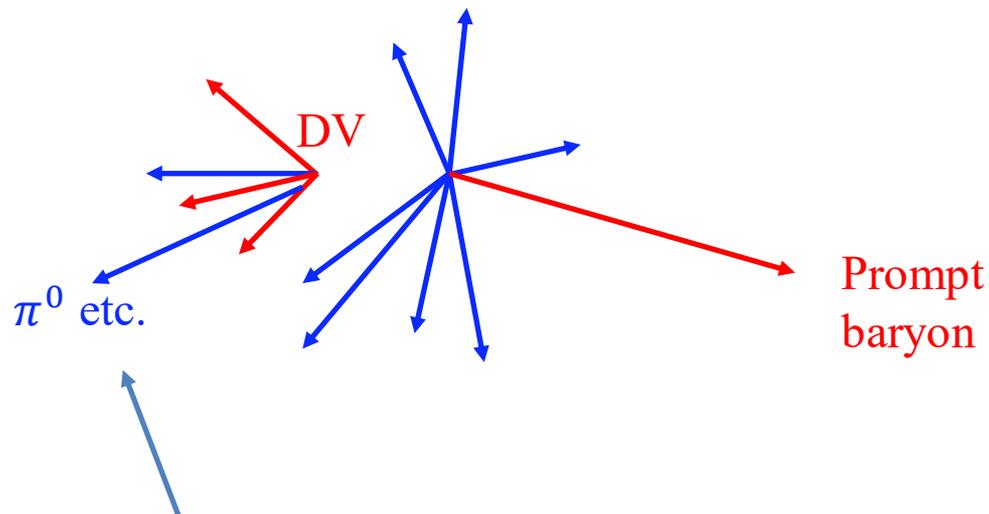
- Extract the signal with

- $\Delta E = E_{\text{tag}} - E_{\text{beam}} \sim 0$
- $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2} \sim 5.28 \text{ GeV}$
- Presence of a DV

Expect background  $\ll 1$  event!  
But these BRs are small.  
Maybe there is a better way?

# Experimental method 2: partial reconstruction, inclusive decay modes

- Reconstruct only:
  - The prompt baryon
  - The DV with at least 3 tracks



- It's OK if we miss some of the  $\tilde{\chi}_1^0$  daughters (photons from  $\pi^0$ s, tracks)
  - We can still calculate the  $\tilde{\chi}_1^0$  4-momentum!

# How to fully calculate the kinematics

- Consider the decay chain

$$B^+ \rightarrow p\tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \rightarrow DV + \text{any}$$

- We have 8 unknowns:

- $p_{\tilde{\chi}_1^0}^\mu = 4$
- $p_{B^+}^\mu = 4$

Observe only these

- But also 8 constraints:

- 4-momentum conservation in the  $B^+$  decay = 4
- The mass of the  $B^+ = 1$
- The energy of the  $B^+$  in the center-of-mass frame = 1
- The flight direction of the  $\tilde{\chi}_1^0$  from the DV = 2

- The constraints yield a quadratic equation
- So there are 2 solutions, one correct and one wrong

# Solution for $m_\chi$ in $B^+ \rightarrow p\chi, \chi \rightarrow DV + \text{any}$

- $E_\chi^* = E_B^* - E_p^* = E_b^* - E_p^*$  (In the center-of-mass frame)

- $p_\chi$  (In the laboratory frame)

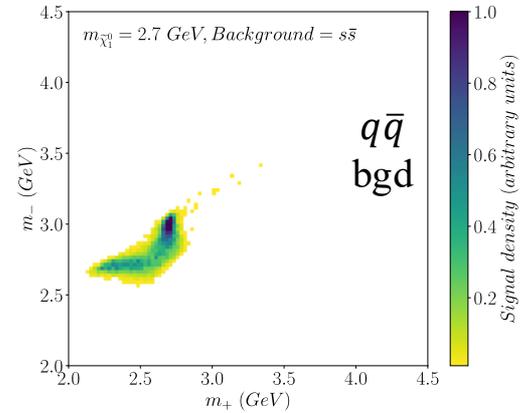
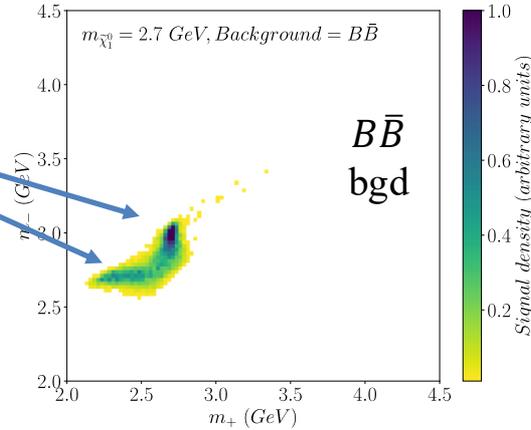
$$= \frac{1}{2(1 - c_\chi^2 \beta^2)} \left[ - \left( 2p_p c_{p\chi} - 2p_p^z c_\chi \beta^2 - 2 \frac{E_b}{\gamma} \beta c_\chi \right) \right. \\ \left. \pm \sqrt{\left( 2p_p c_{p\chi} - 2p_p^z c_\chi \beta^2 - 2 \frac{E_b}{\gamma} \beta c_\chi \right)^2 - 4(1 - c_\chi^2 \beta^2) \left( M_B^2 + p_p^2 - \left( \frac{E_b}{\gamma} \right)^2 - \beta^2 p_p^{z2} - 2 \frac{E_b}{\gamma} \beta p_p^z \right)} \right]$$

- $m_\chi^2 = E_\chi^2 - p_\chi^2$

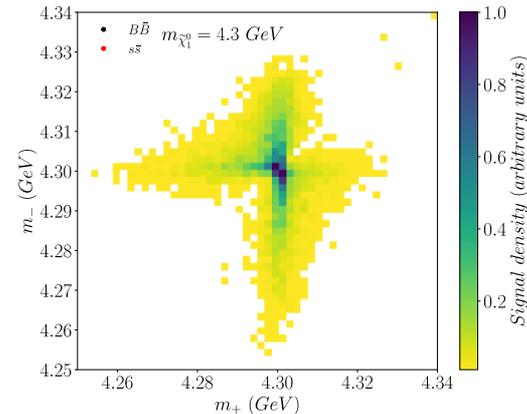
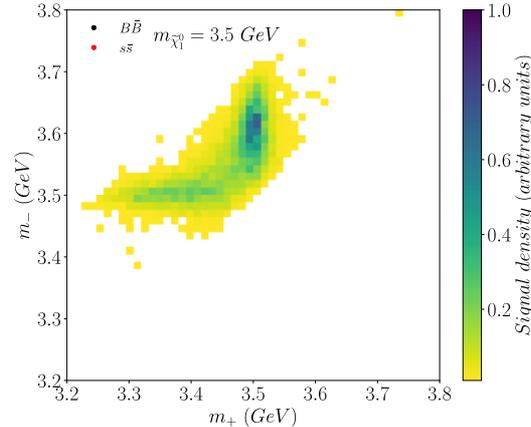
- $E_b = \sqrt{s}/2 =$  collider beam energy in CM frame
- $\beta, \gamma =$  collider boost
- $p_p =$  proton momentum
- $p_p^z =$  proton momentum z component
- $c_\chi = \cos \theta_\chi$  (polar angle)
- $c_\chi = \cos \theta_{p\chi}$  (angle between  $p$  and  $\chi$ )
- **Red terms** arise from the collider boost

# What the solution looks like

- 2 solutions ( $m_+$ ,  $m_-$ ) for each event
- No solution in 12-25% of signal
- Signal peaks in one of the two solutions
- We model the background with a proton and a  $K_S$  vertex in MC, arbitrary yield.
- No solution for background in 94% (BB) 91% (qq) of events

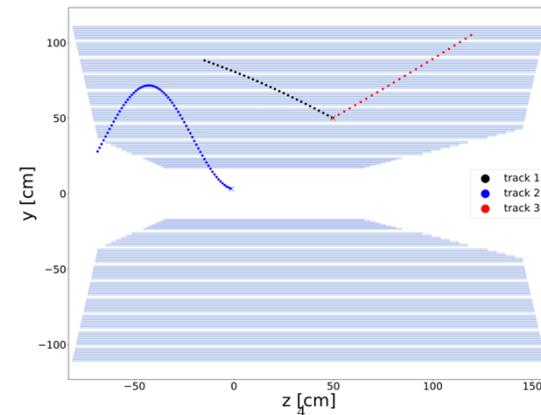
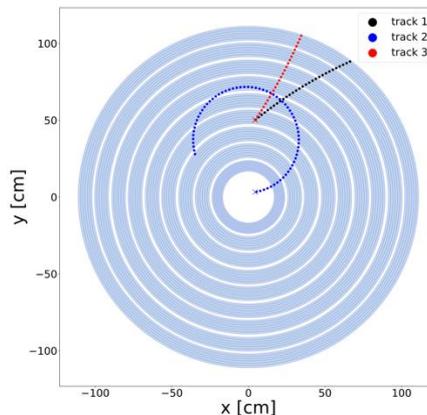


- To estimate the sensitivity, we cut in ( $m_+$ ,  $m_-$ ) so as to retain 90% of signal.
- This rejects between 99.5% (for small  $m_{\tilde{\chi}_1^0}$ ) and 93% (for large  $m_{\tilde{\chi}_1^0}$ ) of the background.



# Estimating signal reconstruction efficiency

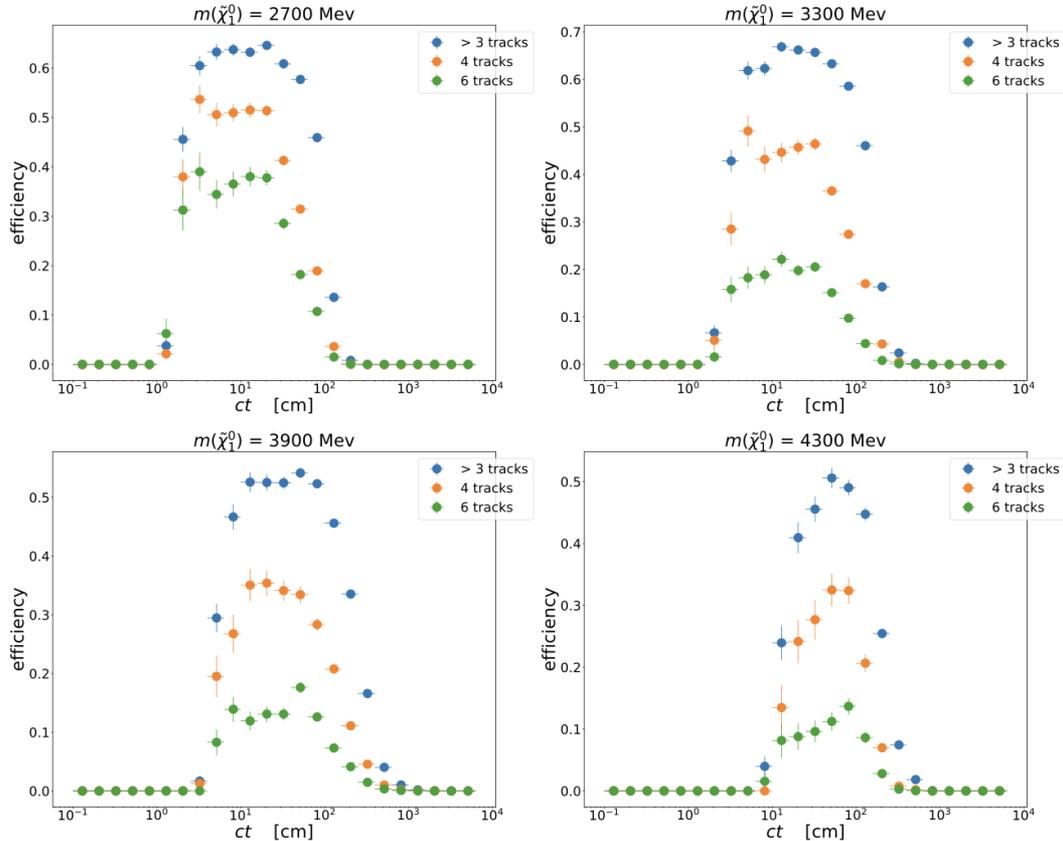
- GEANT4 MC can't be used in a pheno paper, so hard to estimate efficiency for displaced tracks
- Solution: a truth-based package [B2TrEst](#) written by Emilie Bertholet [1]:
  - Use simple geometric model of the Belle II drift chamber (CDC) to count the hits that a track makes
  - A track makes a “hit” in a CDC cell if it track passes at least 3 mm (tunable) inside the cell
  - A track is reconstructed if it has at least 20 hits (tunable)



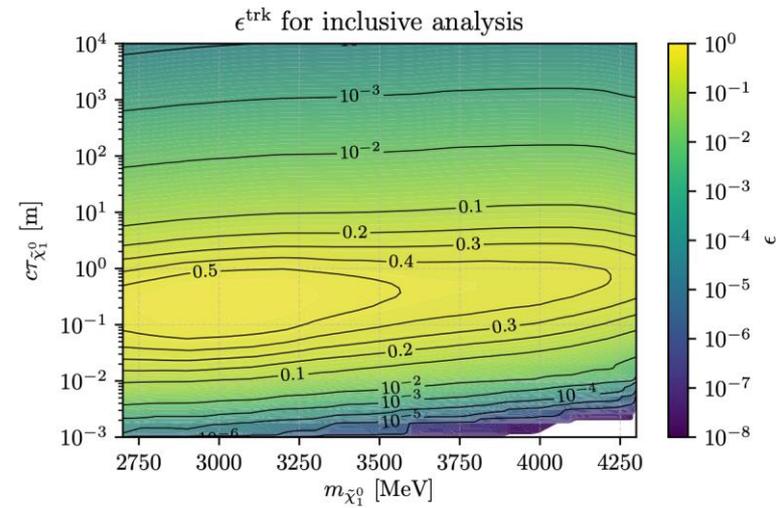
- Validated against published data in our HNL search @ Belle [2]
- We have models for Belle & Belle II, in contact with other Re BESIII & STCF
- We encourage phenomenologists to use this package! See above references

# Efficiency results

As a function of decay time for different  $\tilde{\chi}_1^0$  masses

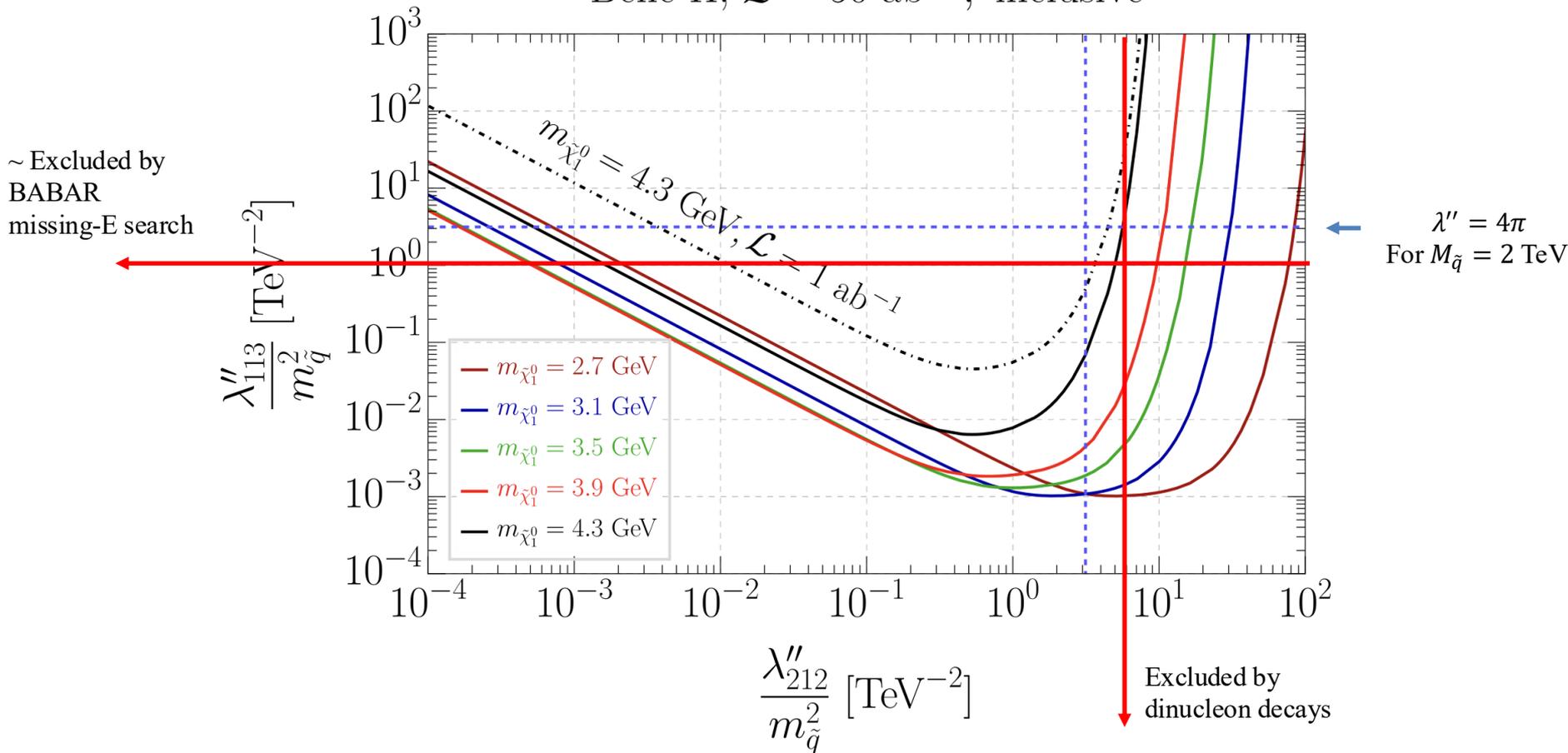


As a function of lifetime and  $\tilde{\chi}_1^0$  mass



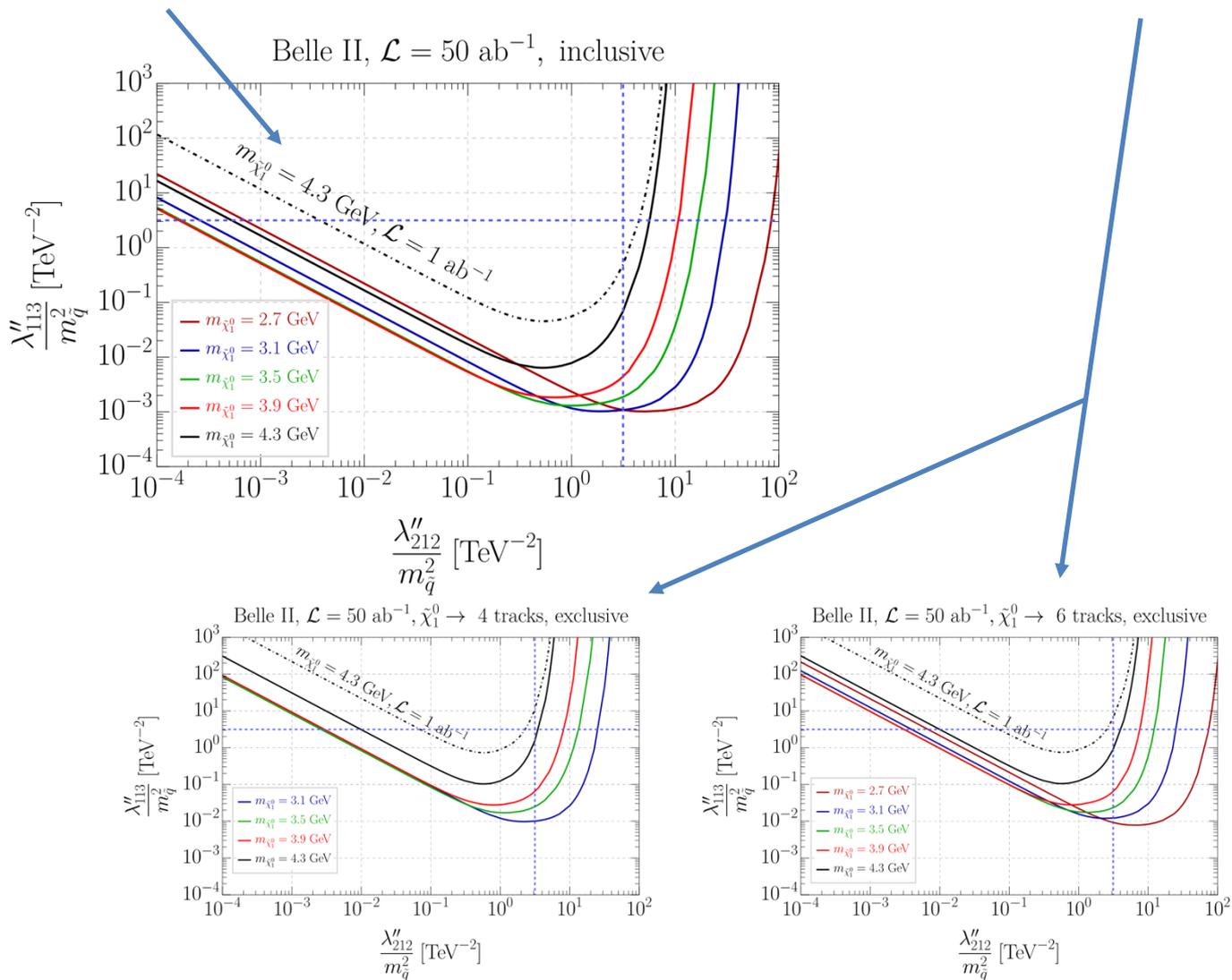
# Inclusive-method sensitivity for proton, 0 background

Belle II,  $\mathcal{L} = 50 \text{ ab}^{-1}$ , inclusive



Assuming  $\sim 0$  background

# Inclusive sensitivity $\sim 10$ times better than exclusive



# What about the experimental search?

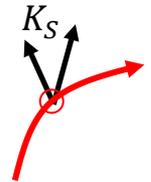
We just launched it at Belle II

This isn't me  
on Mt. Fuji,  
but I do have  
such a picture,  
on film...



# Expected background sources (inclusive)

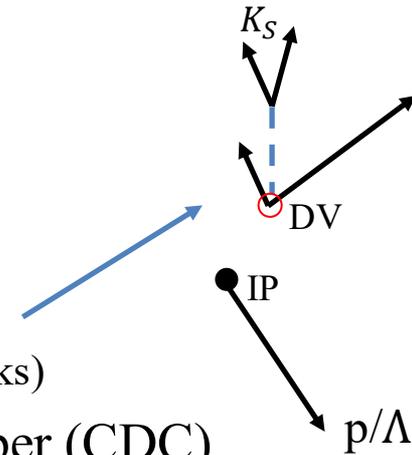
- Misreconstruction and hard scatters of  $K_S \rightarrow \pi^+ \pi^-$ ,  $\Lambda \rightarrow p \pi^-$ 
  - Resulting in  $M_{DV}$  far from  $M_{K_S}$
- Long-lived hyperon decays, E.g.,  $\Sigma^+ \rightarrow \pi^0 (\rightarrow e^+ e^- \gamma) p$
- Coincidental crossing of a vertex by a hard-scatter track
- Particle-material interactions
  - Photon conversion into  $e^+ e^-$
  - Scattering in material resulting in pions, nuclear fragments
  - Antinucleon annihilation: most dangerous due to high  $M_{DV}$



# Event selection

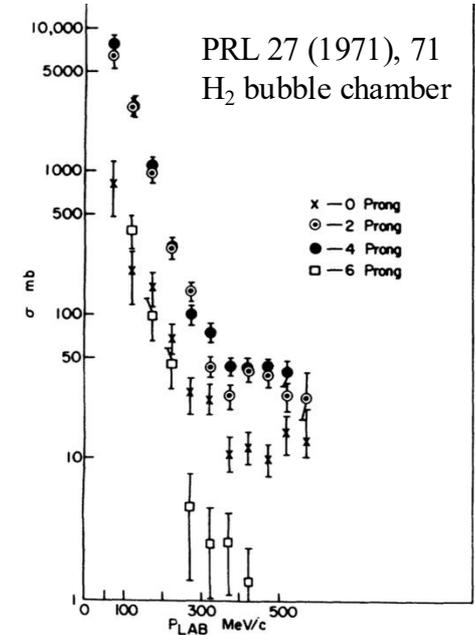
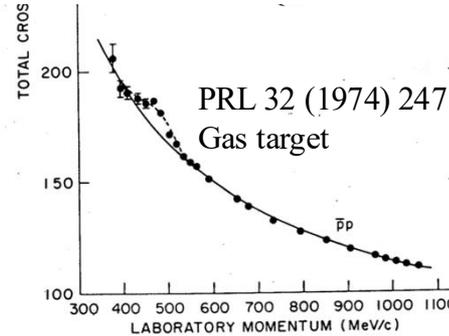
## Initial “guessed” cuts:

- Reconstruct a prompt  $p/\Lambda$  and a DV with **at least 3 tracks**
  - Consider  $K_S \rightarrow \pi^+\pi^-$  and  $\Lambda \rightarrow p\pi^-$  as “tracks” (final state has 2 s quarks)
- DV displacement:  $r_{DV} > 17$  cm inside the central drift chamber (CDC)
  - Avoid dense material
- Invariant mass of the DV daughters  $m_{DV} > 1.5$  GeV
  - Suppresses material interactions and long-lived hyperons
- Any DV-track pair must satisfy  $m_{\pi\pi} > M_{K_S}$ ,  $m_{p\pi} > M_{\Lambda}$ 
  - Suppresses background from  $K_S \rightarrow \pi^+\pi^-$ ,  $K_L \rightarrow \ell^\pm\pi^\mp\nu$ ,  $\Lambda \rightarrow p\pi^- \dots$
- Any DV-track pair must satisfy  $m_{ee} > M_{\pi^0}$ 
  - Suppresses background from photon conversions,  $\pi^0 \rightarrow e^+e^-\gamma$  (from hyperon decays)

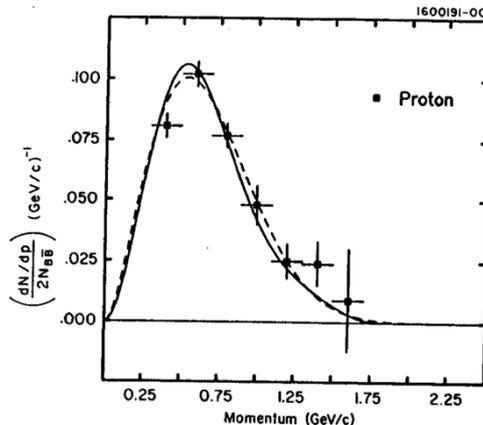


# Antinucleon-annihilation background

- Pointed out to me by Daniel Ivanov (Nagoya)
- The cross section is huge for soft antinucleons (in mb), but there is some disagreement among measurements:
- Little is known about the antinucleon spectrum:



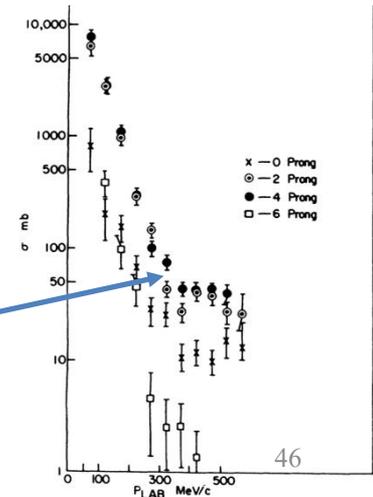
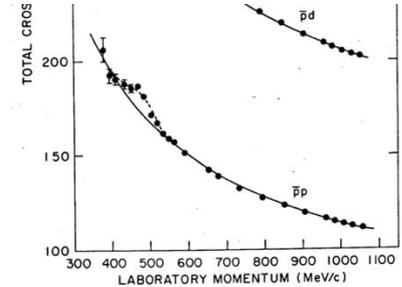
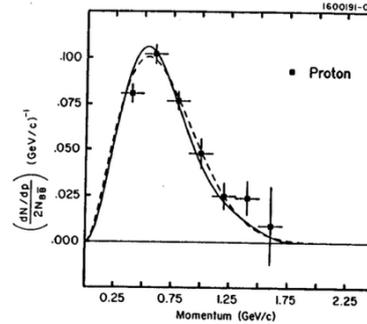
PRD 45 (1992) 752  
CLEO



- $Br(B \rightarrow p/\bar{p}) = (8 \pm 0.4)\%$   
(CLEO & ARGUS)

# Rough estimate of number of antinucleon annihilations

- Need to integrate the product of the cross section and the spectrum
- But they are inaccurate, so just take  $p \sim 400 \text{ MeV} \rightarrow \sigma \sim 200 \text{ mb}$
- The CDC is filled with a 50/50 helium-ethane mixture
- Along a  $\sim 1$ -meter-long path in the CDC, an antinucleon sees  $\sim 4 \times 10^{25} \text{ nucleons/m}^2$  (ignoring the CDC wires)
- $\rightarrow$  Antiproton interaction probability  $\sim 8 \times 10^{-4}$
- $\sim 80\text{M}$  antiprotons in a  $1 \text{ ab}^{-1}, 10^9 B\bar{B}$  sample
- $\rightarrow \sim 64,000$  annihilations,  $\sim 1/2$  producing 4 tracks or more.



# Antinucleon-annihilation mitigation options

- Utilize the local background suppression of the kinematic constraints
  - Expected to be  $4 \times 10^{-3}$  ( $3 \times 10^{-4}$ ) for heavy (light) neutralino
- Require at least one  $K^\pm$ ,  $K_S$ , or  $\Lambda$  coming from the DV
  - Signal contains 2 strange quarks, but their production is suppressed in background processes
- Compare  $B^+ \rightarrow p\chi_1^0$  with  $B^- \rightarrow \bar{p}\chi_1^0$ 
  - Antinucleon probability for the latter is  $\sim 4\%$  (coming from the other B)

# Possible method for data-driven background estimation

- Hypothesis

$$P_{DV+p} = P_{DV} \cdot P_p$$

- Proton-shuffling method:

- Make a large sample of “fake” events: combine each DV with the proton from  $N_{p'}$  different events
- Expected background = (fake sample size)  $\times$   $\frac{\text{fraction of events containing a proton}}{N_{p'}}$

- Conincidental-crossing method:

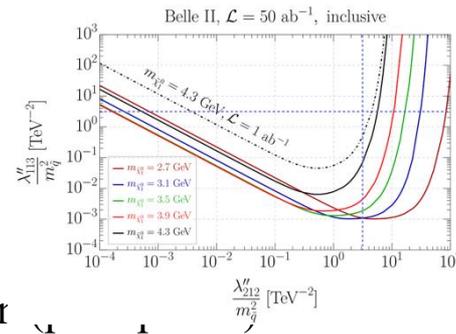
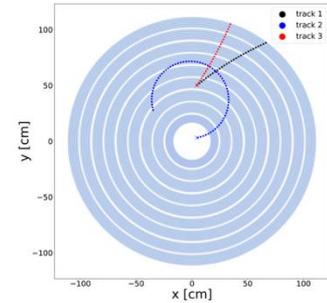
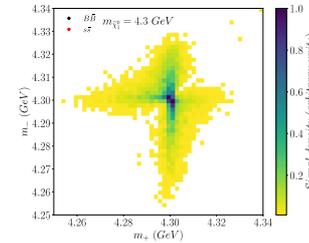
- Calculate crossing probability from  
(Number of 3 – track DVs containing a  $K_S$ )/(Number of  $K_S$  DVs)
- Use it to predict the number of  $n$ -track DVs from the number of  $(n - 1)$ -track DVs

- Method validation:

- Perform background estimation on MC
- Replace proton by pion (more stat)
- Loosen some cuts (more stat).

# Summary

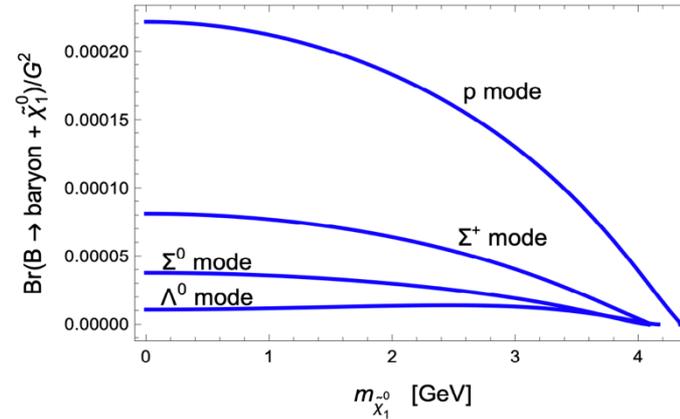
- SUSY is theoretically attractive
  - Studied a lot in the context of LHC
  - We described a scenario relevant for Belle II
  - We studied the case  $\lambda''_{ij3} \neq 0$ 
    - Experimental limits from BABAR and Belle
  - And the case with also  $\lambda''_{212} \neq 0$ 
    - Experimental advantages  $\rightarrow$  higher sensitivity
  - New inclusive-reconstruction method:
    - Potentially 10 times the sensitivity of exclusive
    - If the background can be kept under control
    - Started the search at Belle II
    - Potentially applicable to other new particles: axion/scalar (prompt =  $K/\pi$ ), heavy neutral lepton
- Working with Uli Nierste on models.



# Backup slides

# Considerations Re $B^0 \rightarrow \tilde{\chi}_1^0 \Sigma^0$ and $B^+ \rightarrow \tilde{\chi}_1^0 \Sigma^+$

- These probe  $\lambda''_{123}$  with larger form factors than  $B^0 \rightarrow \tilde{\chi}_1^0 \Lambda$ :  
So potentially advantageous.



- But:
  - $\Sigma^0 \rightarrow \Lambda \gamma$  ~100% of the time with a soft photon that is hard to detect
  - $\Sigma^+ \rightarrow p \pi^0$  and  $n \pi^+$ , each ~50%, with low efficiency and high background
- $\rightarrow$  harder than  $B^0 \rightarrow \tilde{\chi}_1^0 \Lambda$  with no advantage

# Considerations $\text{Re } B^+ \rightarrow \tilde{\chi}_1^0 \Lambda_c^+ / \Xi_c^+$

- The best decay mode for  $\Lambda_c^+$  is  $\Lambda_c^+ \rightarrow pK^-\pi^+$ , BR = 6.3%
- The squared form factor is 0.02 – 0.08 that of  $B^+ \rightarrow \tilde{\chi}_1^0 p$
- Most of the background is from random combinations of  $pK^-\pi^+$ .  
We estimate its level to be similar to that of  $B^+ \rightarrow \tilde{\chi}_1^0 p$
- $\rightarrow$  Expect  $\sim 15\text{-}35$  weaker limits on  $\lambda''_{213}$  than for  $B^+ \rightarrow \tilde{\chi}_1^0 p$  ( $\lambda''_{113}$ )
- Reconstruct  $\Xi_c^+$  in , e.g.,  $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ ,  $\Xi^- \rightarrow \Lambda\pi^-$ ,  $\Lambda \rightarrow p\pi^-$ ,  
BR = 2.9%  $\times$  100%  $\times$  64%
- Form factor similar to that of  $B^+ \rightarrow \tilde{\chi}_1^0 \Lambda_c^+$
- We estimate the background to be similar
- $\rightarrow$  Expect  $\sim 2.5$  weaker limits on  $\lambda''_{223}$  than for  $B^+ \rightarrow \tilde{\chi}_1^0 \Lambda_c^+$  ( $\lambda''_{213}$ )