Searching for a long-lived neutralino with R-parity violation at Belle II: 2 scenarios

Abi Soffer
Tel Aviv University

Thank you for hosting us

From my September 2017 visit

Feb-Mar 2023, https://indico.belle2.org/event/8771/

Asia/Jerusalem A. Soffer

TAU-Yonsei symposium

28 Feb 2023, 11:00 → 1 Mar 2023, 17:00 Asia/Jerusalem

319 Kaplun (Kaplun)

Description Zoom link: https://tau-ac-il.zoom.us/j/2966583871?pwd=bINKOURMZFVwcmRLWXkrUDJCLzF0Zz09

Meeting ID: 296 658 3871
Passcode: 366812

Tuesday 28 February

11:30 → 12:10	**Search for long-lived heavy neutral lepton at Belle** Speaker: Ori Fogel (BELLE (BELLE II Experiment)) 2023 Thesis.pdf	40m	319 Kaplun
12:10 → 13:30	Lunch	1h 20m	319 Kaplun
13:30 → 14:10	**EWP studies in B -> K \ell \tau (Belle) and B -> \rho \gamma (Belle+Belle II)** Speaker: Shun Watanuki (BELLE (BELLE II Experiment)) TelAviv_workshop_...	40m	319 Kaplun
14:10 → 14:50	**Absolute measurement of Br(B-->X(3872)K)** Speaker: Emilie Bertholet (Tel Aviv University) 2023_02_28_TAU-Y...	40m	319 Kaplun
14:50 → 15:20	Coffee break	30m	319 Kaplun
15:20 → 16:00	**inclusive B -> X_s \nu \bar{\nu}, B -> K A' A' (A' -> \ell^+ \ell^-) and rare D^0 decays** Speaker: Prof. Youngjoon Kwon (Yonsei University) TAU_yjKwon_talk1...	40m	319 Kaplun
16:00 → 16:40	**pi0 efficiency and systematic-less measurement of Br(B-->D*pi) / Br(B-->Dpi)** Speaker: Dey sdey Sourav (BELLE (BELLE II Experiment)) TAU_symposium_0...	40m	319 Kaplun

Wednesday 1 March

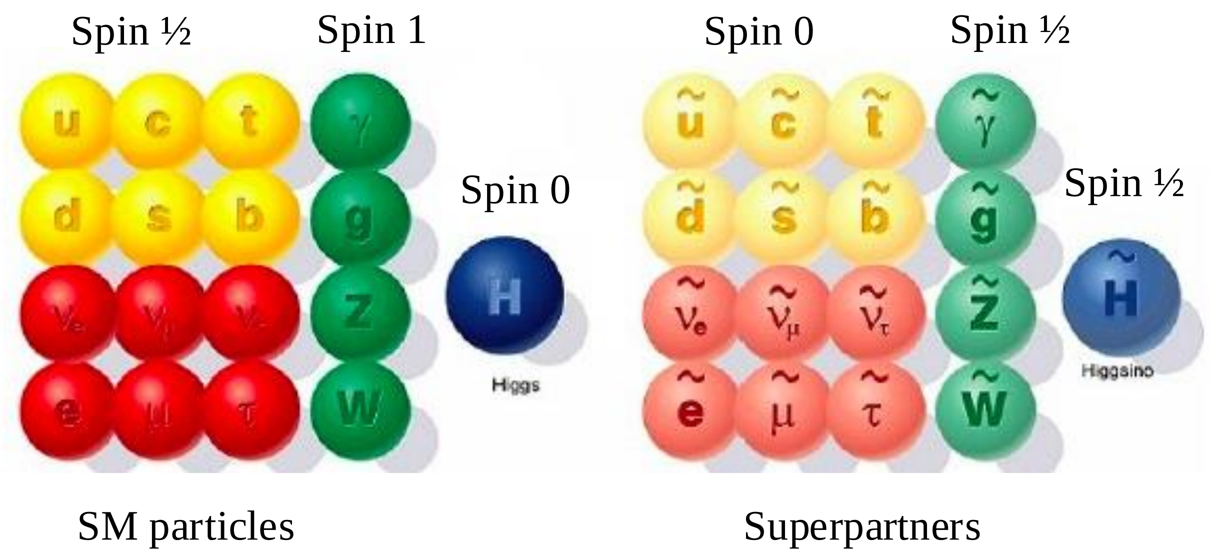
12:00 → 13:00	Lunch	1h	319 Kaplun
13:00 → 13:30	**ATLAS 2022 upgrade and Small-strip Thin Gap (STG) chambers** Speaker: Dr Margaret Lutz (Tel Aviv University)	30m	319 Kaplun
14:00 → 15:00	**Department seminar: A tale of Two Leptons** Speaker: Prof. Youngjoon Kwon (Yonsei University) TAU_yjKwon_semin...	1h	008 Schreiber
15:10 → 15:40	Coffee break	30m	319 Kaplun
15:40 → 16:20	**ALP search in B -> K a (a -> \gamma \gamma)** Speaker: Sungjin Cho (BELLE (BELLE II Experiment)) TAU230301 (1).pdf	40m	319 Kaplun
16:20 → 17:00	**HNL search at ATLAS, heavy QCD axion search at Belle II, Crazy ideas for Belle II upgrades** Speaker: Abner Soffer (BELLE (BELLE II Experiment))	40m	319 Kaplun

Outline

- Supersymmetry
- R-parity violation (RPV)
- Searching for a long-lived light neutrino (missing-energy signature)
- Searching for a long-lived light neutrino (displaced-vertex signature)
- Potential applications of the method
- Summary

Supersymmetry (SUSY)

Each SM particle has a "superpartner" with the same gauge quantum numbers and mass:



Why SUSY is interesting:

- Elegant: extension of the Poincare group, with operators that transform as spinors
- Needed for string theory
- Solves the hierarchy problem (next slide)
- Better gauge-coupling unification

If SUSY exists, it is broken at low energies

- e.g., we don't see a 511 keV selectron

The neutrlainos $\tilde{\chi}^0_{1-4}$ are mass-eigenstate superpositions of

$$\tilde{B}, \widetilde{W}^0, \widetilde{H}^0_u, \widetilde{H}^0_d,$$

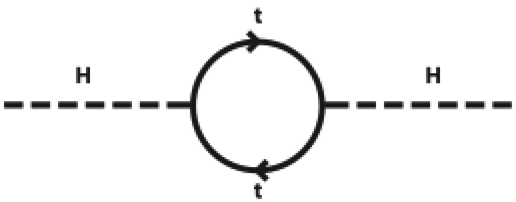
superpartners of the SM with 2 Higgs doublets:

$$B, W^0, H_u, H_d$$

The hierarchy problem

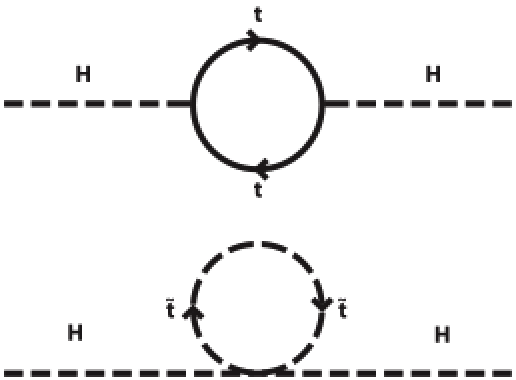
- The hierarchy problem:
  Since the Higgs is a fundamental scalar, its squared mass gets quantum corrections to the scale of new physics

$$m_h^2 = m^2(0) + \Delta m^2$$



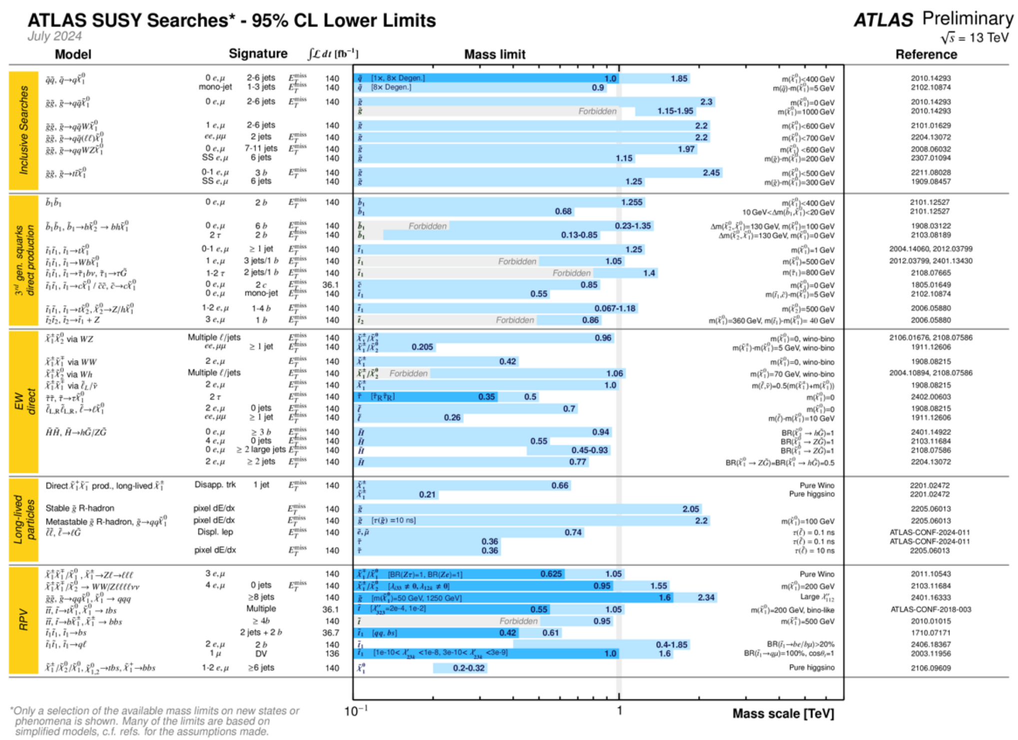
- If no NP up to Planck scale $\sim 10^{19}$ GeV → fine tuning of the bare mass $m^2(0)$ to >30 orders of magnitude!

- SUSY fixes this: equal-mass bosons and fermions cancel each other's contributions:



The experimental status of SUSY

- SUSY particles haven’t been found at LHC
- But large parameter-space regions haven’t/can’t be explored experimentally
- A ~GeV-scale neutralino is allowed in some scenarios
- It has to decay to avoid too much dark matter
- Since it’s the LSP, it must decay to SM particles
- It can decay if we have R-parity violation (RPV)



R-parity (R_p)

- $R_p = \begin{cases} 1 & \text{SM particles} \\ -1 & \text{superpartners} \end{cases}$
- If R_p is conserved:
  - A superpartner must decay to a state with an odd number of lighter superpartners, e.g., $\tilde{b} \rightarrow b\tilde{\mathrm{Z}}$
  - The lightest superpartner (LSP) is stable, since it can decay only to SM particles
- But there is no requirement that R_p should be conserved
  - So it's worth exploring scenarios with R_p violation (RPV)
- In particular, I will focus on an RPV scenario in which
  - The LPS is the neutralino $\tilde{\chi}_1^0$,
    which is mostly the "Bino": superpartner of the SM hypercharge gauge boson B

RPV terms in the SUSY Lagrangian

$$W_{RPV} = \sum_{ijk} \left(\frac{1}{2} \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2} \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k \right)$$

Generation indices

LH (s)leptons

RH (s)leptons

LH (s)quarks

RH up-type (s)quarks

RH down-type (s)quarks

Each term has dimension 4, i.e.,

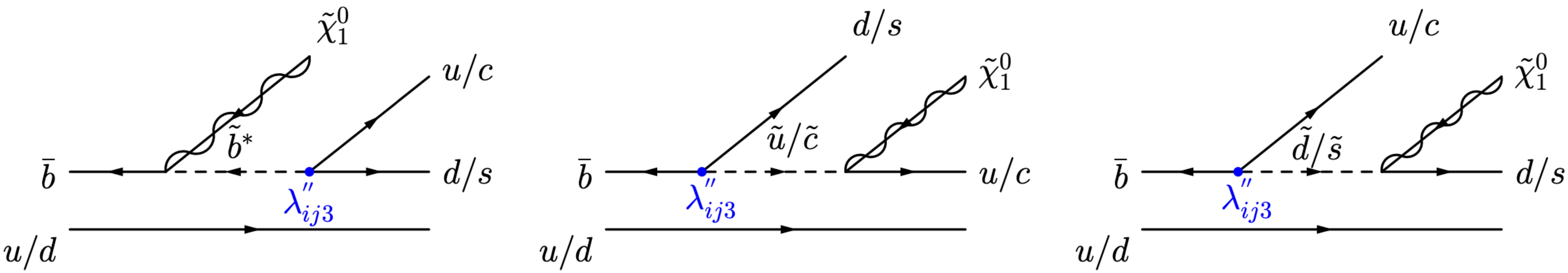
- 2 quarks (fermions, dim $= \frac{3}{2}$)
- 1 squarks (boson, dim $= 1$)

These terms violate baryon number, so they must be suppressed → small couplings

RPV in B decays @ Belle II

JHEP 02 (2023) 224, Dib, Helo, Liubovitskij, Neill, Soffer, Wang

- Focus on $\lambda''_{ij3} \neq 0$ (where $ij = 1,2$), so we have the decays $B^+ \to \tilde{\chi}^0_1 +$ baryon

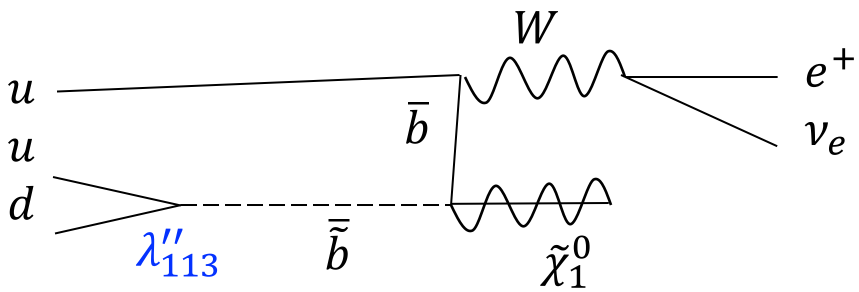


We considered $\lambda''_{ij3} =$

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

Lower limit on $m_{\tilde{\chi}_1^0}$

- If $m_{\tilde{\chi}_1^0} < m_p$, the proton can decay, e.g., $p \to \tilde{\chi}_1^0\, e^+ \nu$



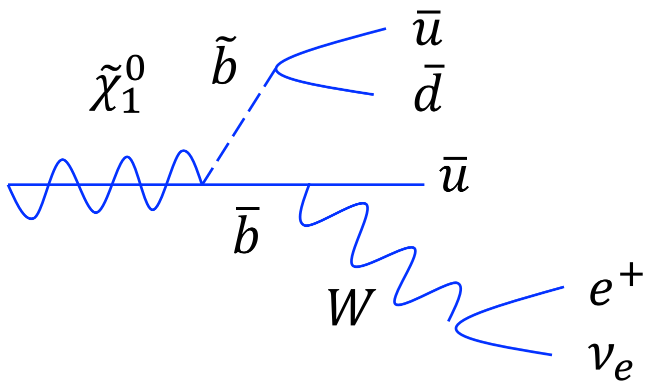
- Limits on the proton lifetime are greater than $\sim 10^{29}$ years

- So we conclude $m_{\tilde{\chi}_1^0} > m_p$

- (This condition applies even if we turn on only another RPV coupling via SM flavor transitions)

Does the neutralino decay?

- Yes, e.g., $\tilde{\chi}_1^0 \rightarrow p e^- \bar{\nu}_e$



- But it's a 2nd order process, so $\tilde{\chi}_1^0$ decays far outside the detector

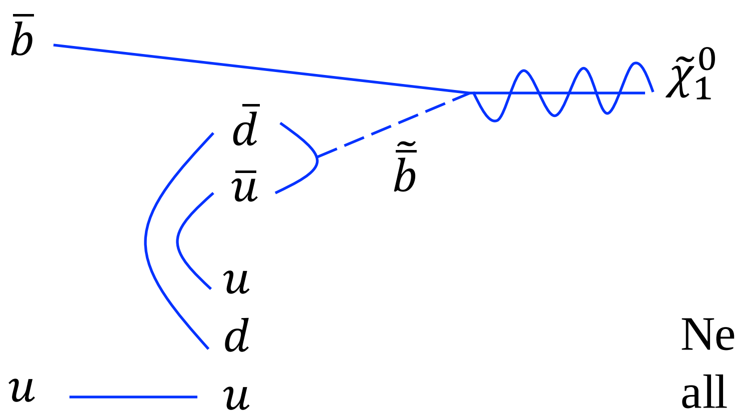
- → The experimental signature is $B^+ \rightarrow$ baryon + missing

Form factor calculation

- Due to boson (squark) propagator, we have :

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

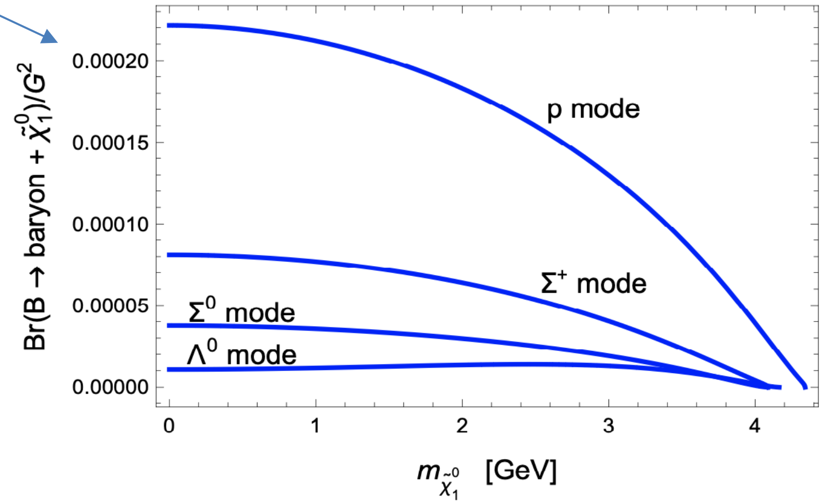
- Also $\propto$ hadronic form factors for the B meson $\rightarrow$ baryon transition.
- We base our calculations on form factors others calculated for proton decay (e.g., $p \rightarrow \pi^0 e^+$) with proper adjustment.
- E.g., for $B^+ \rightarrow \tilde{\chi}_1^0 p$ there is a direct contribution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



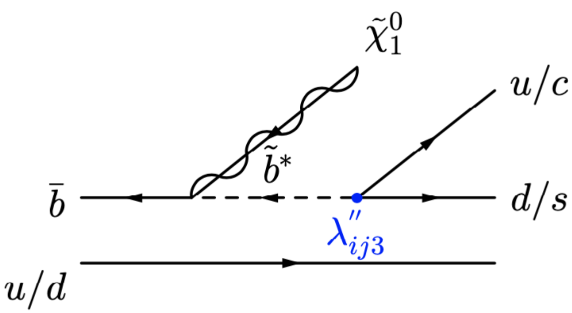
Need to add all the terms from
all the diagrams with the right signs

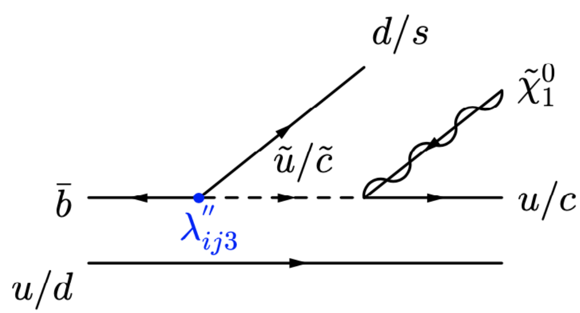
Form factors suppress the signal decay

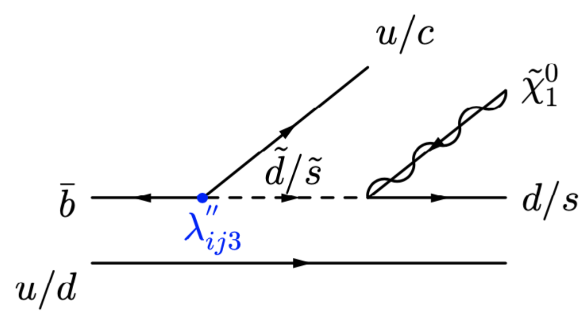
$$G^2 \equiv \left(\frac{\lambda''_{ij3}}{m^2_{\tilde{q}}}\right)^2$$

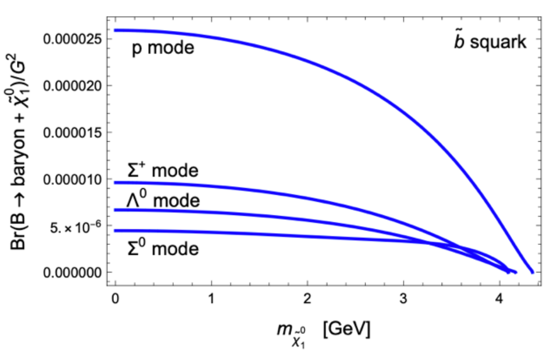


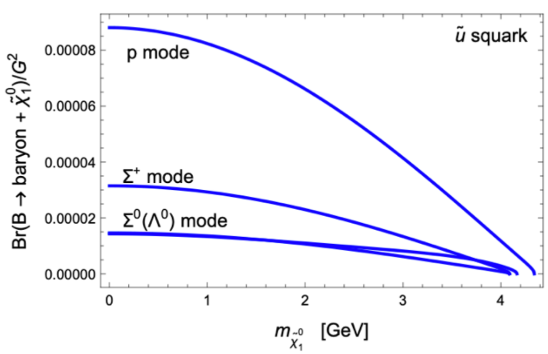
Contributions from the 3 squark diagrams:

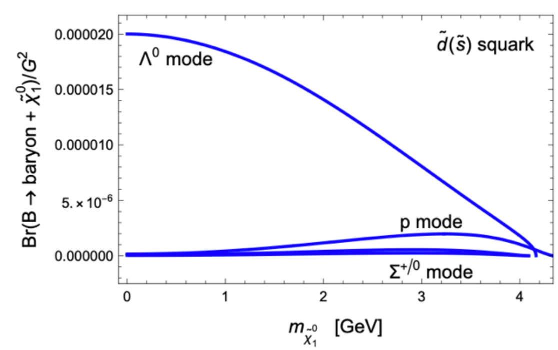












Experimental analysis technique

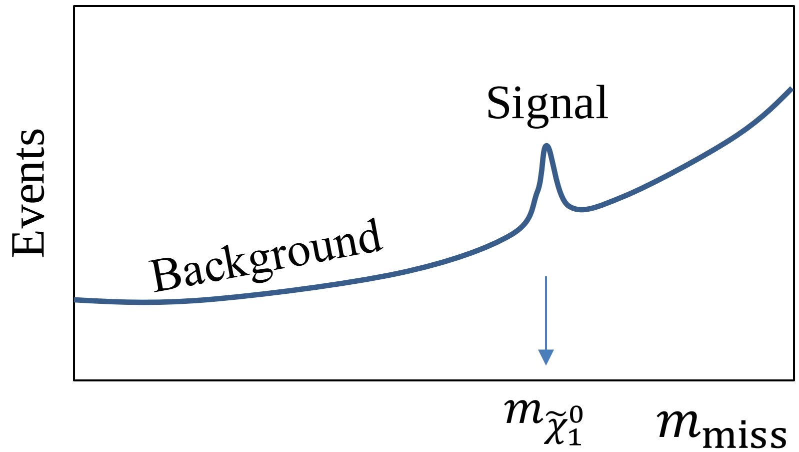
- The "missing" neutralino is an experimental challenge. To address it we use knowledge of the initial state, i.e., $e^+e^- \to B_{\text{tag}}B_{\text{sig}}$
- B factories regularly study rare B_{sig} decays into missing particles, e.g.,
  $B \to K^{(*)}\nu\bar{\nu}$, $B \to \tau\nu$, $B \to D^{(*)}\tau\nu$, $B \to \pi\ell\nu$
- 3 techniques:
  - Hadronic tagging: fully reconstruct B_{tag} in a hadronic decay (e.g., $B \to D\pi$. Actually O(1000) decay modes are used)
  - Semileptonic tagging: partially reconstruct the B_{tag} in a semileptonic decay $B \to D^{(*)}\ell\nu$
  - Inclusive tagging: combine all the non- B_{sig} particles in the event and use various techniques to separate signal from background

Experimental analysis technique

- The 3 techniques typically have similar sensitivities.
- We considered only hadronic tagging, where it is simplest to estimate the background in a phenomenological study like this.
- In hadronic tagging one can calculate the missing (neutralino) mass:

$$m^2_{\text{miss}} = \left(p_{ee} - p_{\text{tag}} - p_{\text{baryon}}\right)^2$$

- So a signal looks like a peak in the m_{miss} distribution:



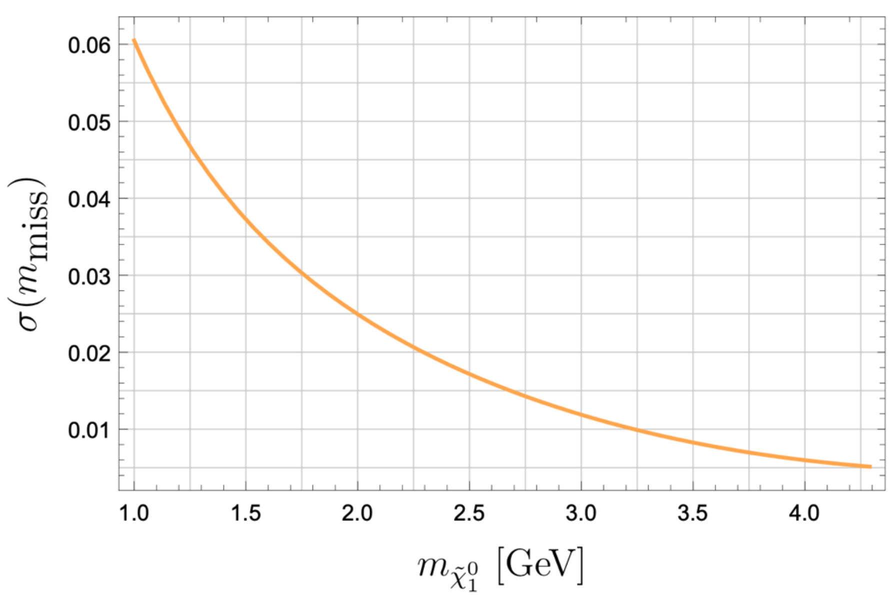
- Bump-hunt analysis: look for such a peak (bump)

Background estimation for the $B \to \tilde{\chi}_1^0 p$ bump hunt

- The idea is to estimate the number of background events in a region of m_{miss} whose width is the m_{miss} resolution $\sigma_{m_{\text{miss}}}$
- The resolution $\sigma_{m_{\text{miss}}}$ is dominated by the resolution on the transverse momentum of the proton. We used the Belle resolution,

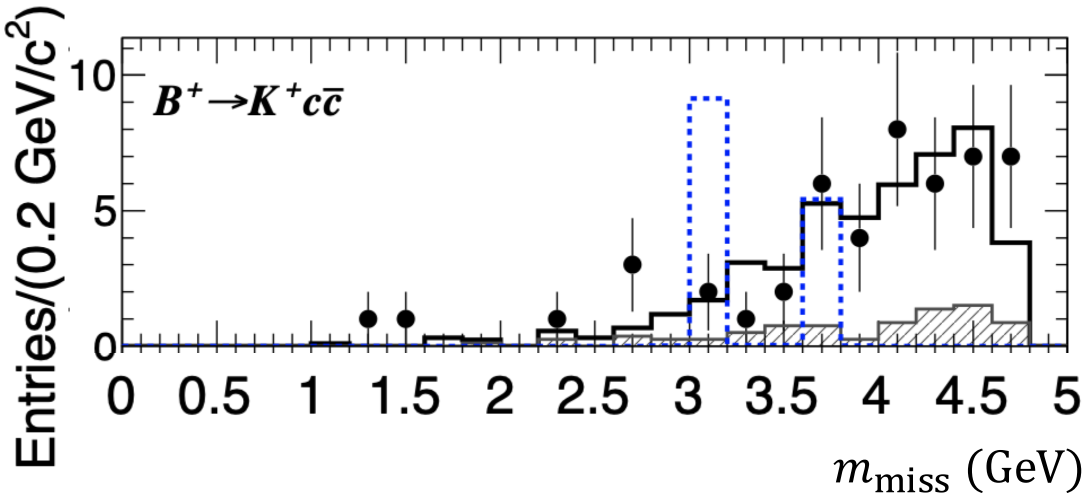
$$\left(\frac{\sigma(p_T)}{p_T}\right)^2 = \left(0.0019\frac{p_T}{\text{GeV}}\right)^2 + \left(0.003\frac{1}{\beta}\right)^2$$

- Propagating this to $\sigma_{m_{\text{miss}}}$:



Background estimation for the $B \to \tilde{\chi}_1^0 p$ bump hunt

- We used a $B^+ \to K^+ \nu\bar{\nu}$ study by BABAR (1303.7465)
- We parameterized their background as a function of m_{miss}:

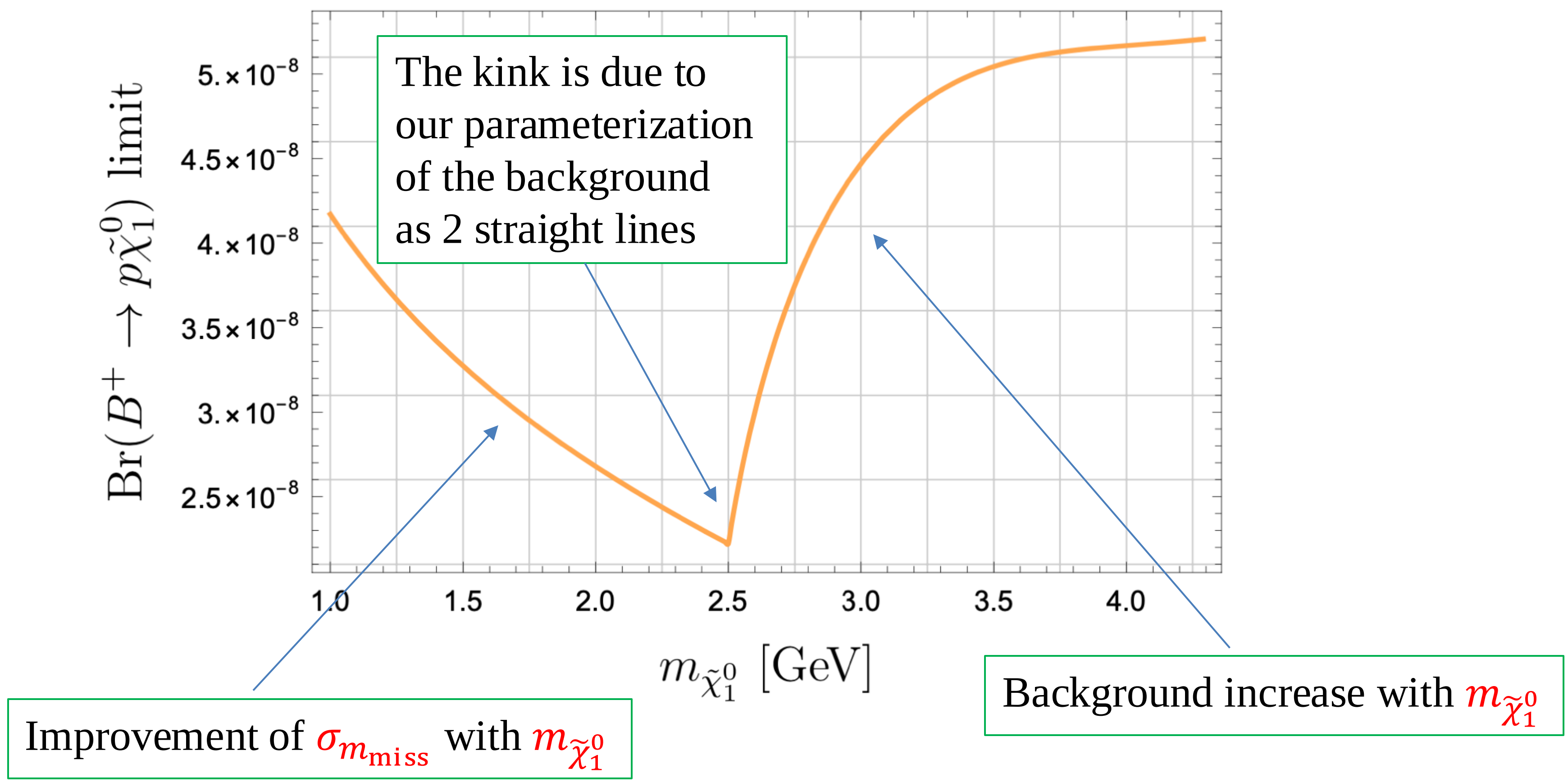


- and reduced it by the the ratio of proton to kaon production,

$$\frac{Br(B^+ \to p + X)}{Br(B^+ \to K^+ + X)} \approx \frac{1}{16}$$

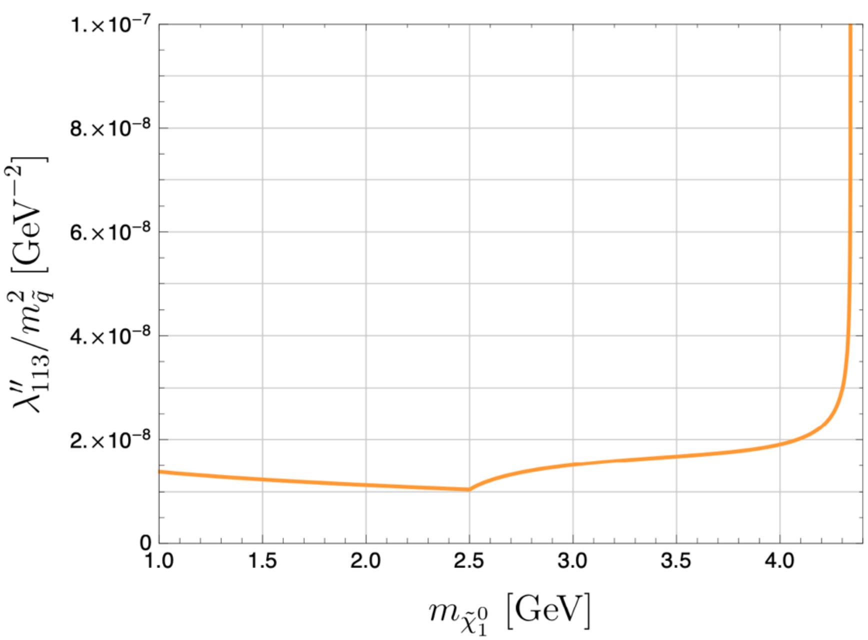
Belle II sensitivity to $B^+ \to \tilde{\chi}_1^0 p$

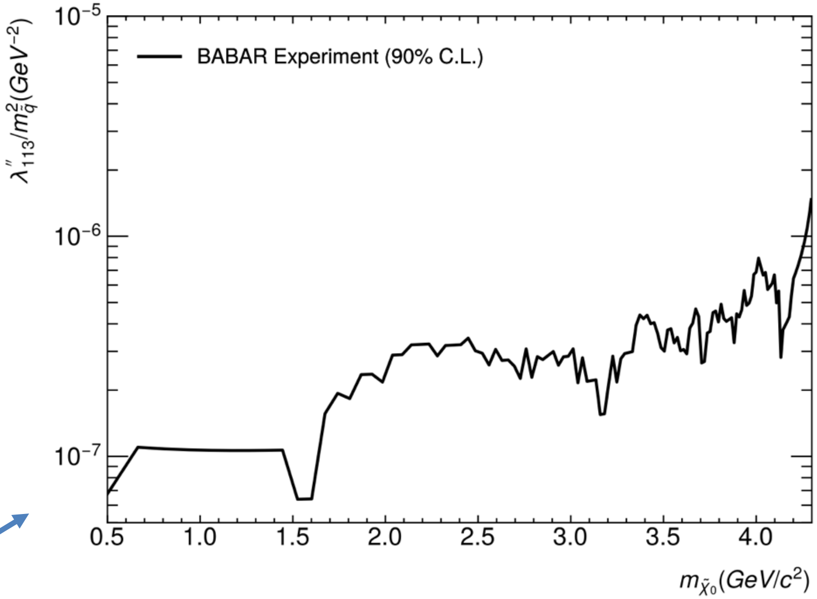
- Assuming Belle II will have an integrated luminosity of $50\ \mathrm{ab}^{-1}$, we estimate that it can set this limit on $\mathrm{Br}(B^+ \to \tilde{\chi}_1^0\, p)$ as a function of $m_{\tilde{\chi}_1^0}$



Belle II sensitivity to $\lambda''_{113}/m^2_{\tilde{q}}$

- Since we calculated $\mathrm{Br}(B^+ \to \tilde{\chi}^0_1\, p)$ as a function of $\lambda''_{113}/m^2_{\tilde{q}}$, we can calculate the expected limit on $\lambda''_{113}\,/m^2_{\tilde{q}}$ for each value of $m_{\tilde{\chi}^0_1}$:





- BABAR (2302.00208) obtained limits weaker by ~10.
- Expect $3 \approx 100^{1/4}$ from luminosity
- The rest is from larger background / smaller efficiency wrt. my estimate

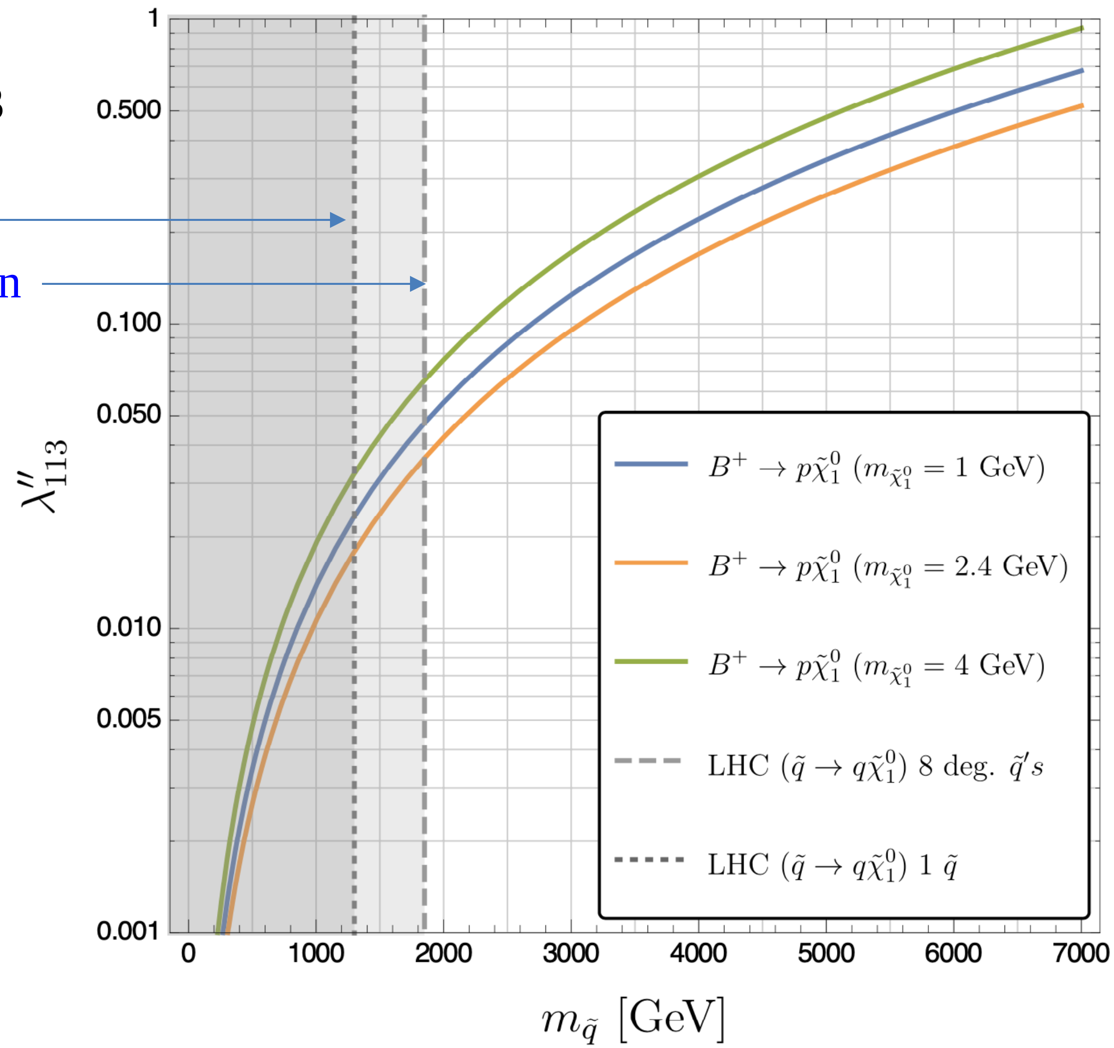
Belle II sensitivity to λ''_{113}

- Convert this to the expected limit on λ''_{113} as a function of $m_{\tilde{q}}$ for various values of $m_{\tilde{\chi}_0^1}$

Lower limits on $m_{\tilde{q}}$ from 2010.14293 (ATLAS) for

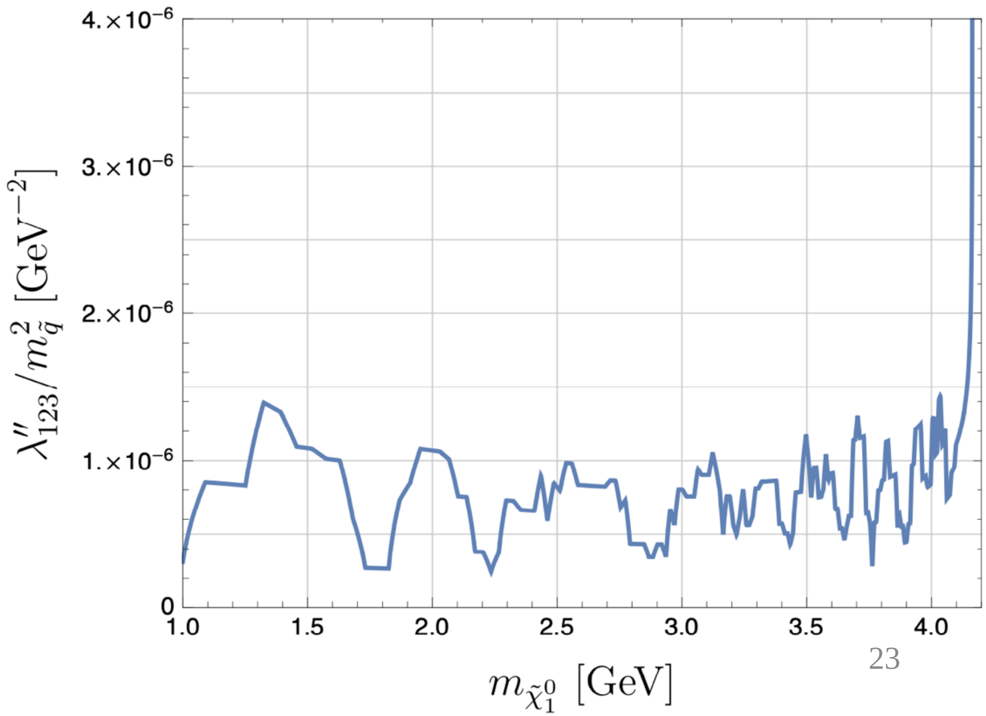
- 1 light squark
- 8 degenerate 1st- and 2nd-generation light squarks

There are no other relevant limits (more on that later)



BABAR limits on $\lambda''_{123}/m_{\tilde{q}}^2$

- We also obtained limits on λ''_{123} using older searches on $B^0 \to \Lambda + \text{missing}$
- Used the tighter limits of BABAR (2302.00208) rather than Belle (2110.14086)
- We estimate the sensitivity on λ''_{213}, λ''_{223} to be worse by about a factor of 15-70, mostly due to form factors and reconstruction efficiency for charmed baryons



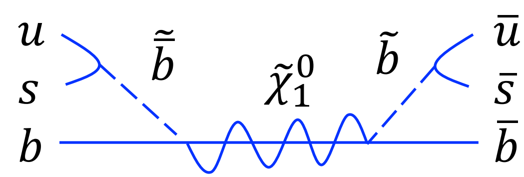
~50 times weaker than our prediction for $B^0 \to \tilde{\chi}_1^0 p$ at Belle II:

- $(22)^{1/2}$ from form factor
- $(125)^{1/4}$ from luminosity
- $(1/0.64)^{1/2}$ from $\Lambda \to p\pi^-$

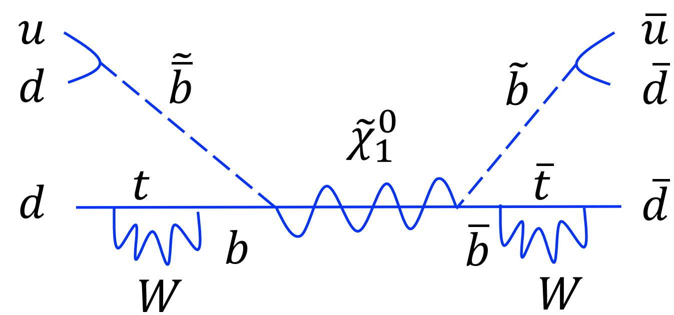
} 20

Limits from other processes are much weaker

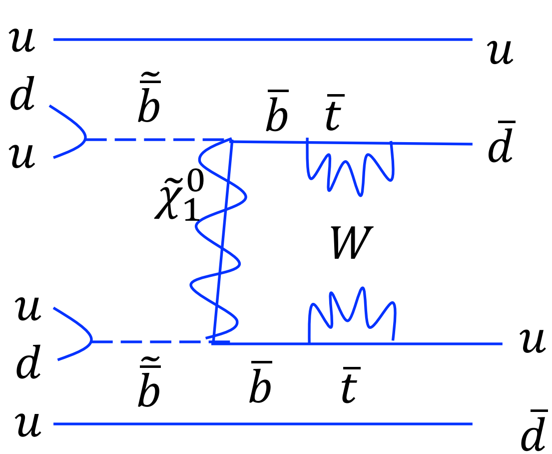
- $\Xi_b^0 - \bar{\Xi}_b^0$ oscillations (LHCb, 1708.05808):
  We estimate $\lambda''_{123}/m_{\tilde{b}}^2 < 4 \times 10^{-4}\ \mathrm{GeV}^{-2}$
  (for $m_{\tilde{\chi}_1^0} = 2.5$ GeV)



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



- The same holds for dinucleon decays:



From these we estimate:

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

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

$$\lambda''_{213}/m_{\tilde{q}}^2 \lesssim 5 \times 10^{-6}\,\mathrm{GeV}^{-2},$$ → Only this one beats our method

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

What if the neutralino decays inside the detector?

- The tracks produced in the decay of a long-lived neutralino that decays inside the detector form a displaced vertex (DV)
- The DV signature is a great background suppressor
- We can take advantage of an experimental idea:

Experimental idea

$$B \to F\ D$$

- Fully reconstructed final state

- Heavy "displaced" particle decaying hadronically.
- Not practical to reconstruct it in a clean final state with high branching fraction.
- So reconstruct only the DV from 2 or more tracks.

Can we reconstruct what we need?

We have:

- 8 unknowns:
  - p4 of D and B
- 8 constraints at an $e^+e^- \to B\bar{B}$ machine:
  - p4 conservation in the B decay
  - m_B
  - E_B in the e^+e^- system
  - $\hat{p}_D$ from the location of the displaced vertex

Analytic solution for m_D

$$p_D = \frac{1}{2(1-c_D^2\beta^2)}\left[-\left(2p_F c_{FD} - 2p_F^z c_D \beta^2 - 2\frac{E_b}{\gamma}\beta c_D\right) \pm \sqrt{\left(2p_F c_{FD} - 2p_F^z c_D\beta^2 - 2\frac{E_b}{\gamma}\beta c_D\right)^2 - 4(1-c_D^2\beta^2)\left(M_B^2 + p_F^2 - \left(\frac{E_b}{\gamma}\right)^2 - \beta^2 {p_F^z}^2 - 2\frac{E_b}{\gamma}\beta p_F^z\right)}\right]$$

$$E_D = E_B - E_F$$

$$m_D^2 = E_D^2 - p_D^2$$

Terms that arise from the collider boost

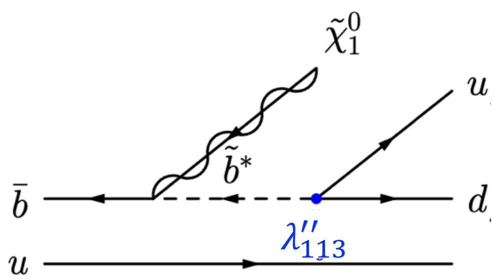
where β is the speed of the e^+e^- frame in the lab, $\gamma = (1-\beta^2)^{-1/2}$

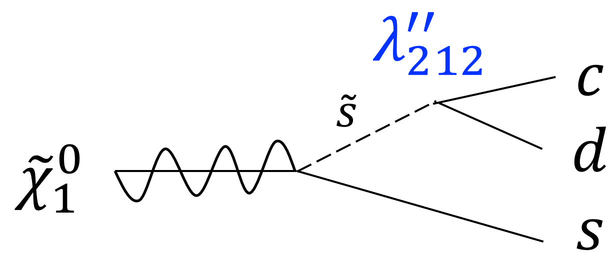
Requiring a solution to the quadratic equation
removes >90% of the background and only 20% of the signal

Enable $\tilde{\chi}_1^0$ decay with $\lambda''_{212} \neq 0$

To be submitted soon
Bertholet, Dib, Gandelman, Helo, Liubovitskij, Nayak, Neill, Soffer, Wang

- For the neutralino to decay in the detector, we need a second nonzero RPV coupling:





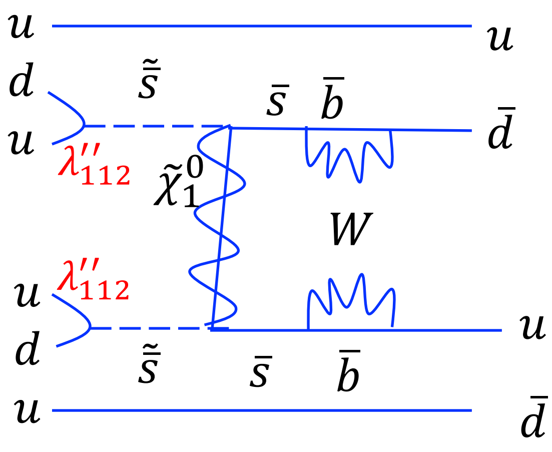
λ''_{113} controls the neutralino production rate in $B^+ \to p\, \chi_1^0$

λ''_{212} controls the neutralino decay rate ($=1/\tau_{\tilde{\chi}_1^0}$) in $\chi_1^0 \to csd$

Heavy csd final state well-suited to the experimental method

Why specifically λ''_{212}?

- We focus on λ''_{212} since other relevant couplings are strongly excluded by nuclear-physics experiments
- E.g., λ''_{112} from dinucleon decays:



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

$$\lambda''_{212}/m_{\tilde{q}}^2 \lesssim 6 \times 10^{-6}/\mathrm{GeV}^2 \ \text{(dinucleon/collider)},$$

Hadronization of the *cds* final state

- We consider 2-body decays to a charmed baryon plus meson:

$$\tilde{\chi}_1^0 \to \Sigma_c^0 + \bar{K}^0 , \quad \tilde{\chi}_1^0 \to \Omega_c^0 + K^0 ,$$
$$\tilde{\chi}_1^0 \to \Lambda_c^+ + K^- , \quad \tilde{\chi}_1^0 \to \Xi_c^+ + \pi^- .$$

- We ignore decays to $D_{(s)}^{(*)}$+ baryon, which we find to have small form factors

- We calculate the relevant form factor & the neutralino lifetime

Table 1: Classification of the relevant baryons: quantum numbers, masses, and coupling constants, extracted from Refs. [49, 50].

Notation	Content	J^P	S_d	Mass (GeV)	Coupling β (in units of $10^{-2}\times$ GeV^3)
Λ_c^+	$c[ud]$	$1/2^+$	0	2.28646	0.835
Σ_c^0	$c\{dd\}$	$1/2^+$	1	2.45375	1.125
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Table 2: Classification of the relevant mesons: quantum numbers, masses, and leptonic decay constants, extracted from Ref. [38].

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π^-	$d\bar{u}$	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

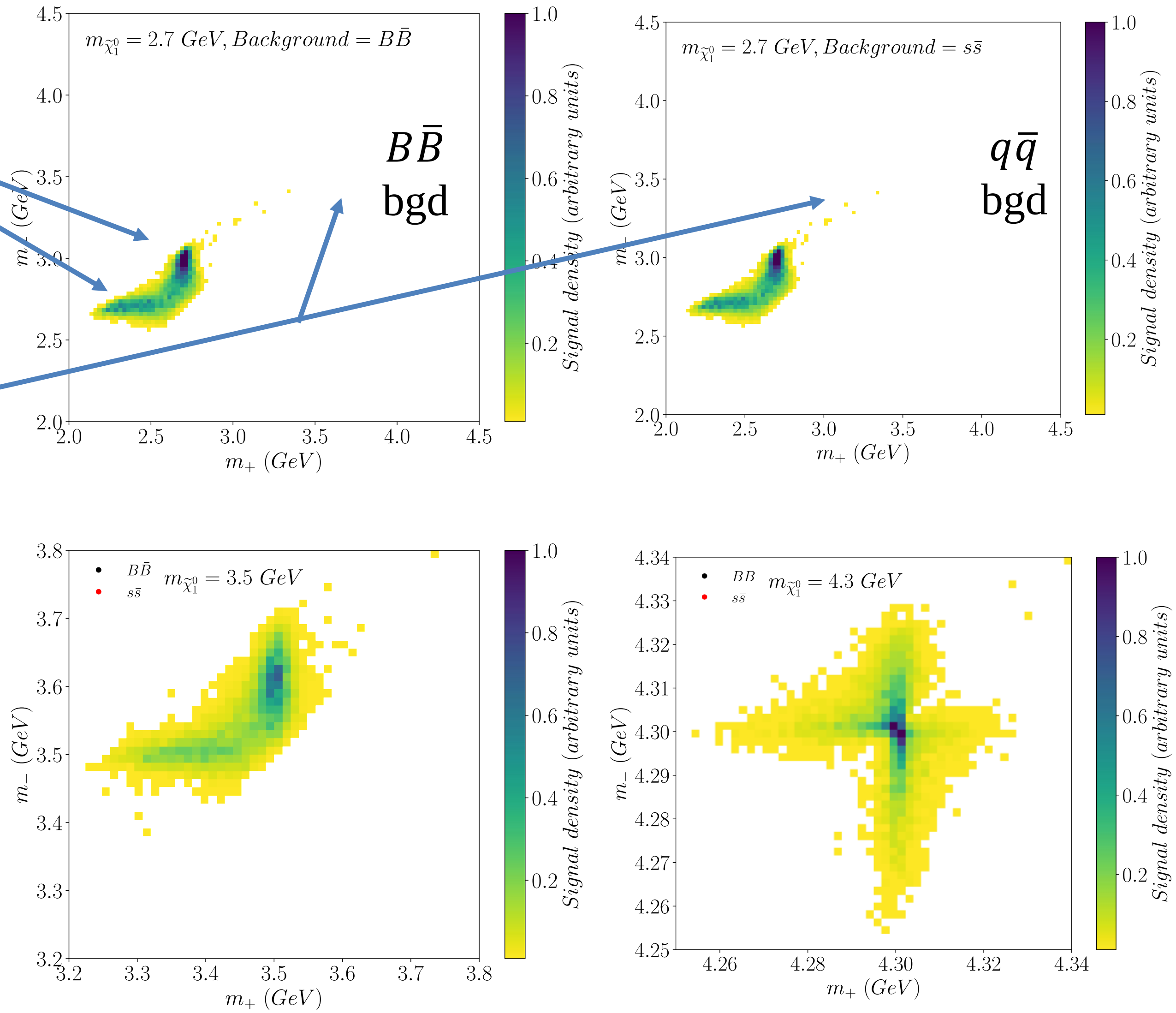
Event selection

We propose to:

- Reconstruct a proton (λ''_{113}) and at least 3 tracks that form a DV (λ''_{212})
  - With 2 tracks we expect too much background, extrapolated from our HNL search at Belle, 2402.02580
- DV radial displacement: $r_{\rm DV} > 1$ cm
  - Removes prompt background, keeps high efficiency
- Invariant mass of the DV daughters $m_{\rm DV} > 1$ GeV
  - Removes background from $K_S \to \pi^+\pi^-$, $K_L \to \ell^\pm\pi^\mp\nu$, $K_L \to \pi^+\pi^-\pi^0$, etc.
  - Suppresses background from misreconstructed tracks and material interactions

Applying the calculation

- 2 solutions (m_+, m_-) for each event
- Signal peaks in one of the two solutions
- We model the background with a proton and a K_S vertex.
- Background is distributed in a ~triangle

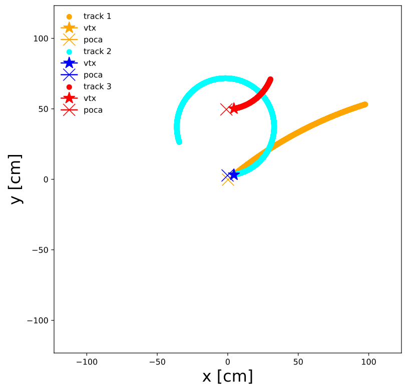


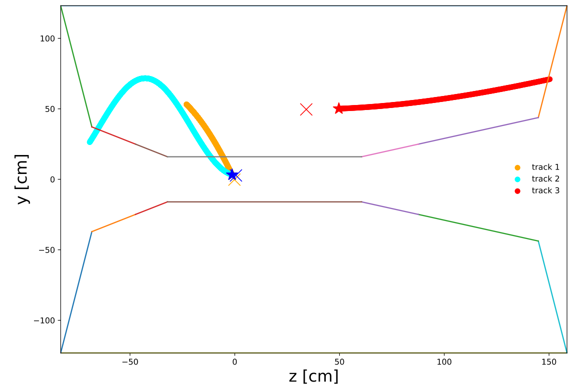
- We cut in (m_+, m_-) so as to retain 90% of the signal.
- This rejects between 0.5% (for small $m_{\tilde{\chi}_1^0}$) and 7% (for large $m_{\tilde{\chi}_1^0}$) of the background.

Estimating the efficiency

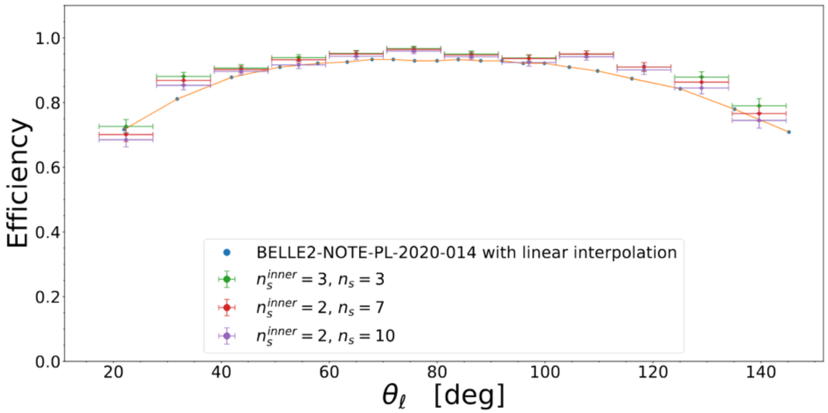
E. Bertholet, A. Soffer, 2501.00857, to appear in Int. J. Mod. Phys. A

- GEANT4 MC can't be used in a pheno paper→ hard to obtain efficiency of displaced tracks
- Solution: a truth-based package B2Track written by Emilie Bertholet:
  - A track is reconstructed if it has at least 20 drift-chamber hits (user-tunable)
  - The number of hits is estimated geometrically with simplified CDC cells.
  - A cell produces a hit if the track passes a minimal distance inside the cell

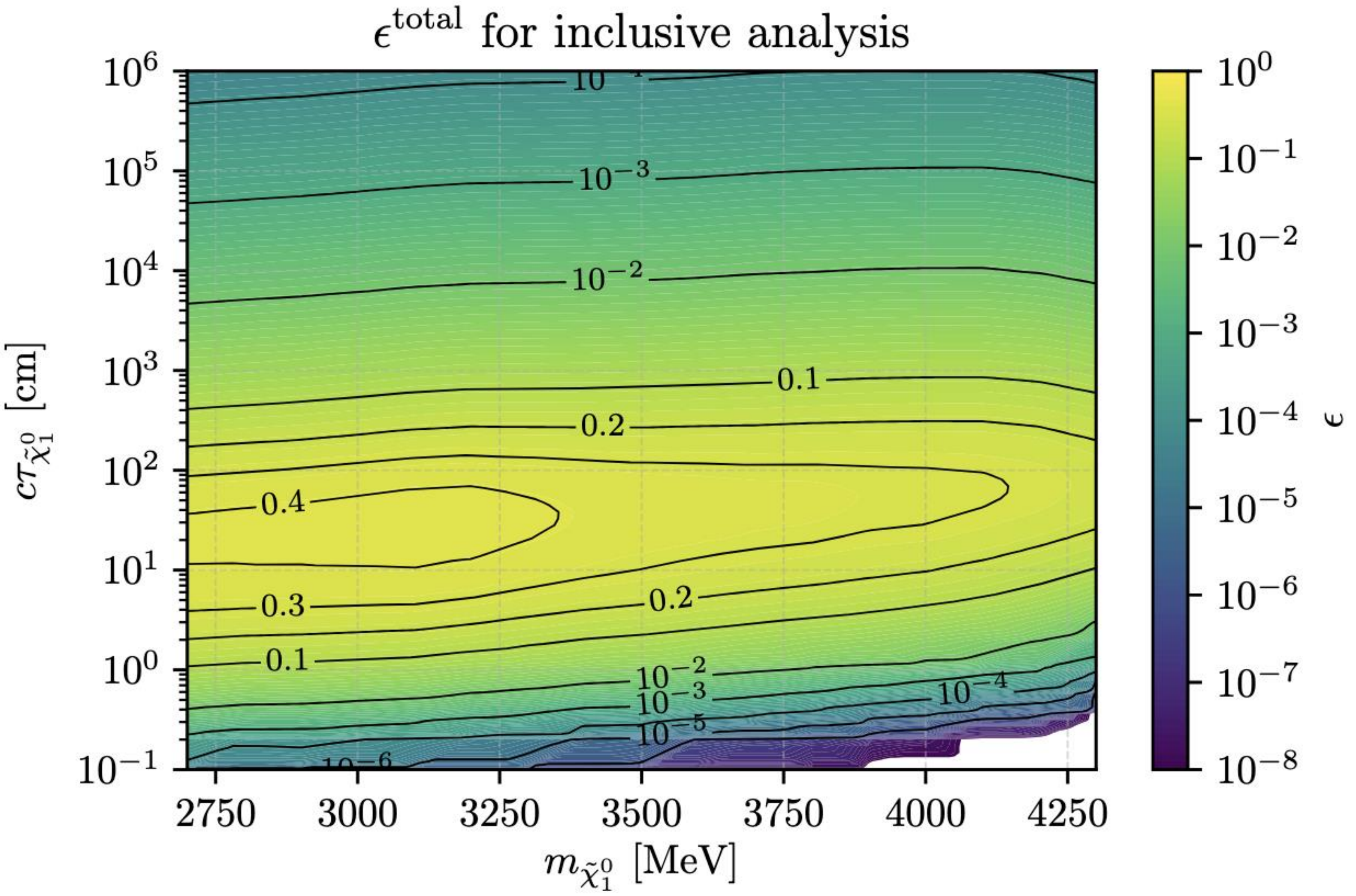




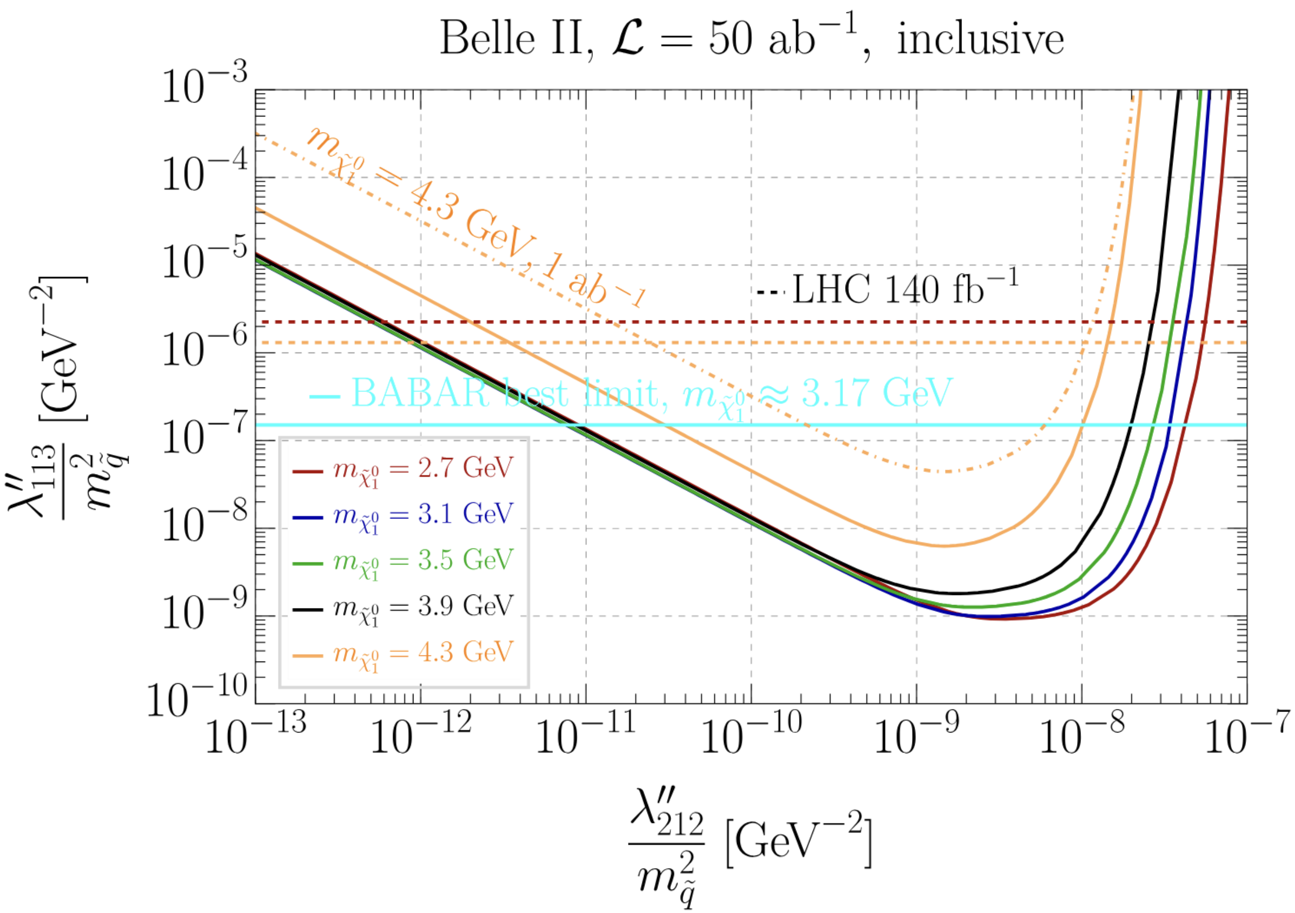
Tuned the model parameters with published Belle II tracking efficiency:



Efficiency results



Estimated sensitivity



We also estimate the sensitivity for fully reconstructing the neutralino decay in a specific mode.
The resulting sensitivity to $\lambda''_{212}/m^2_{\tilde{q}}$ is weaker by a factor of 10.

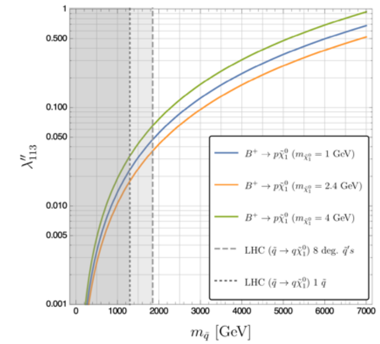
Applying the reconstruction idea to other models

- The same can be done with
  - $B^+ \to K^+ +$ a scalar or pseudoscalar
  - $B^+ \to \ell^+ +$ a heavy neutral lepton

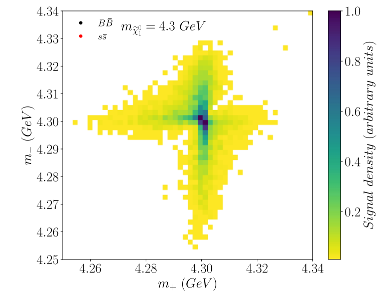
- Submitted a grant to explore this together with Uli Nierste, Monika Blanke, Felix Kahlhoefer.

- Others welcome to join as well!

Summary



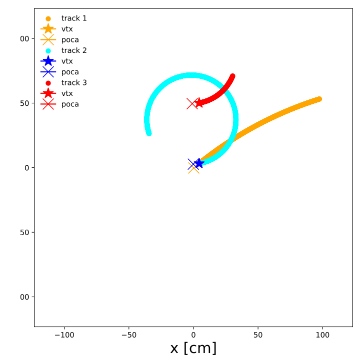
SUSY hasn't been found at LHC



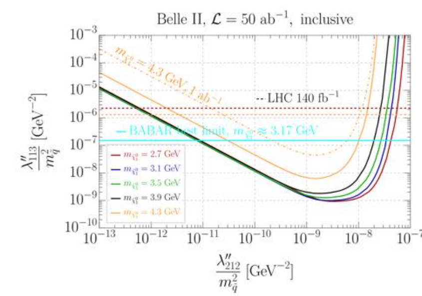
But it has an allowed parameter space accessible at B factories:
GeV-scale neutralino with RPV

We proposed 2 methods for 2 cases:

- Only $\lambda''_{ij3} \neq 0$ → $B \to$ baryon + missing
- λ''_{ij3} and $\lambda''_{212} \neq 0$ → $B \to$ baryon + DV partial reconstruction



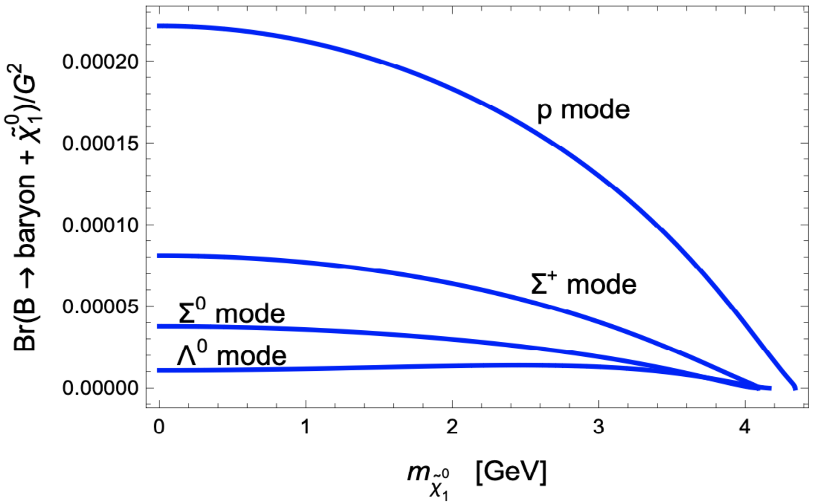
The partial reconstruction method can be used for (pseudo)scalar or heavy-neutral-lepton searches, but the models need to be refined.



Backup slides

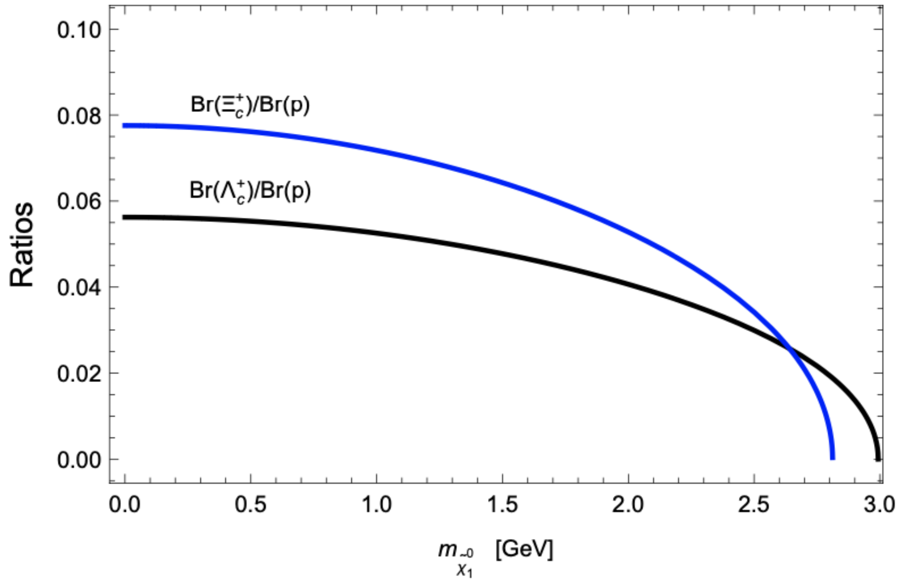
Considerations on $B^0 \to \tilde{\chi}_1^0 \Sigma^0$ and $B^+ \to \tilde{\chi}_1^0 \Sigma^+$

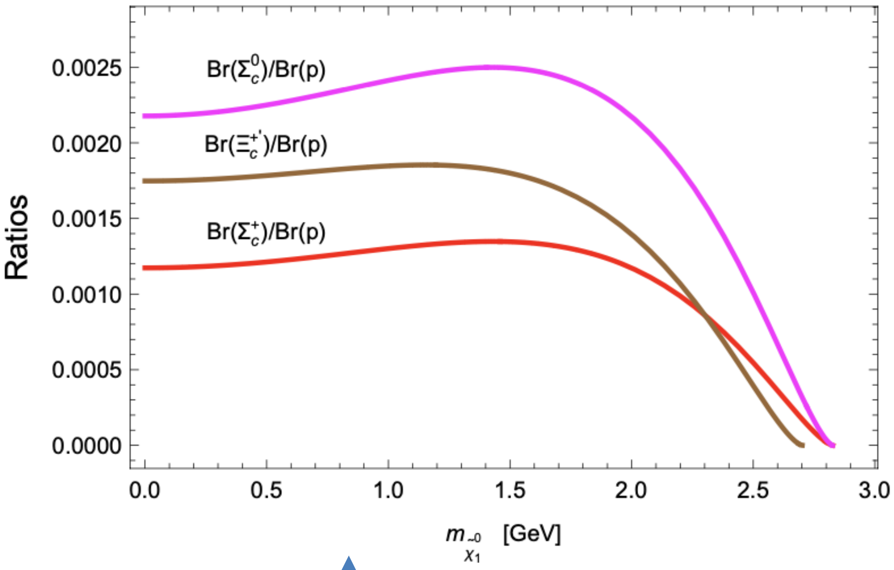
- These probe λ''_{123} with larger form factors than $B^0 \to \tilde{\chi}_1^0 \Lambda$: So potentially advantageous.



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

Greater suppression for charmed baryons:





We didn't follow up on Σ_c^0, Σ_c^+, Ξ'^+_c

Considerations on $B^+ \to \tilde{\chi}_1^0 \, \Lambda_c^+ / \Xi_c^+$

- The best decay mode for Λ_c^+ is $\Lambda_c^+ \to pK^-\pi^+$, BR = 6.3%
- The squared form factor is 0.02 – 0.08 that of $B^+ \to \tilde{\chi}_1^0 \, p$
- Most of the background is from random combinations of $pK^-\pi^+$. We estimate its level to be similar to that of $B^+ \to \tilde{\chi}_1^0 \, p$
- → Expect ~15-35 weaker limits on λ''_{213} than for $B^+ \to \tilde{\chi}_1^0 \, p$ (λ''_{113})

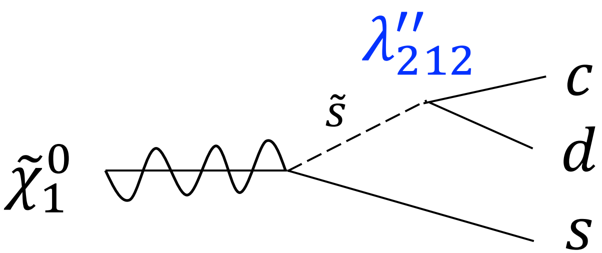
- Reconstruct Ξ_c^+ in , e.g., $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$, $\mathrm{BR} = 2.9\% \times 100\% \times 64\%$
- Form factor similar to that of $B^+ \to \tilde{\chi}_1^0 \, \Lambda_c^+$
- We estimate the background to be similar
- → Expect ~2.5 weaker limits on λ''_{223} than for $B^+ \to \tilde{\chi}_1^0 \, \Lambda_c^+$ (λ''_{213})

Hadronization of the *cds* final state

- We consider 2-body decays to a charmed baryon plus meson:

$$\tilde{\chi}_1^0 \to \Sigma_c^0 + \bar{K}^0\,, \quad \tilde{\chi}_1^0 \to \Omega_c^0 + K^0\,,$$
$$\tilde{\chi}_1^0 \to \Lambda_c^+ + K^-\,, \quad \tilde{\chi}_1^0 \to \Xi_c^+ + \pi^-\,.$$

- We ignore decays to $D_{(s)}^{(*)}$+ baryon, which we find to have small form factors



$$\Gamma(\tilde{\chi}_1^0 \to BM) \propto \left(\frac{\lambda''_{212}}{m_q^2}\right)^2 \equiv G^2$$

Table 1: Classification of the relevant baryons: quantum numbers, masses, and coupling constants, extracted from Refs. [49, 50].

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Table 2: Classification of the relevant mesons: quantum numbers, masses, and leptonic decay constants, extracted from Ref. [38].

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

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

Phase space

Matrix element

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

Baryon polarizations

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

Form factors

parameterize the hadronic transition

$m_{\tilde{\chi}_1^0}$ -dependent cds form factors

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

$$G_0 = \frac{\lambda''_{212}}{m_q^2/\mathrm{TeV}^2}$$

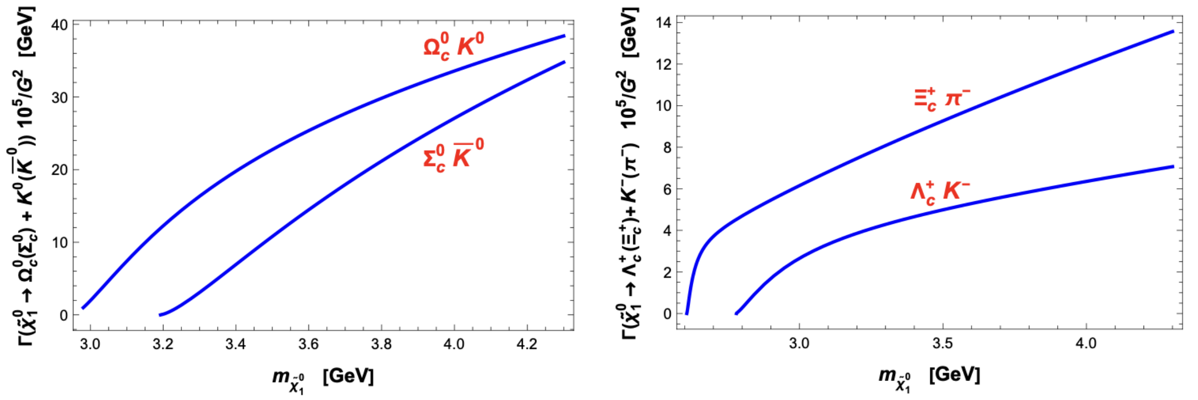

Figure 1: Two-body decay rates of the light bino multiplied by the factor $10^5/G^2$: $\tilde{\chi}_1^0 \to \Sigma_c^0 + \bar{K}^0$ and $\tilde{\chi}_1^0 \to \Omega_c^0 + K^0$ transitions (left panel); $\tilde{\chi}_1^0 \to \Lambda_c^+ + K^-$ and $\tilde{\chi}_1^0 \to \Xi_c^+ + \pi^-$ transitions (right panel).

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

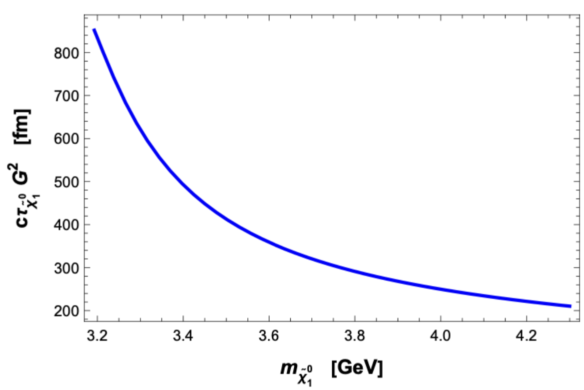

Figure 2: The proper decay length $c\tau_{\tilde{\chi}_1^0}$ of the light bino multiplied by the factor G^2, as a function of $m_{\tilde{\chi}_1^0}$. $c\tau_{\tilde{\chi}_1^0}$ is saturated by the four dominant decay modes shown in Fig. 1.