

Searching for apparent baryon number violation in Λ_c^+ decays at STCF

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Motivation

- Observation of **BNV** at laboratory experiments \Rightarrow new physics
- **No observation of BNV processes experimentally so far** and **Increasingly stringent bounds**
- Study neutrino-extended EFTs with BNV and ν_s : ν SMEFT & ν LEFT



- **STCF**, large $\Lambda_c^+ \bar{\Lambda}_c^-$ production rates \Rightarrow study $\Lambda_c^+ \rightarrow \pi^+ / K^+ + \nu_s$
- ν_s **very long-lived**
- **Apparent BNV** in Λ_c^+ decays at STCF

Model frameworks – the ν LEFT

- dim-6 operators

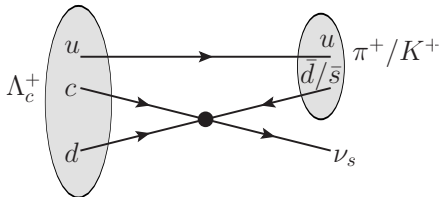
$$\mathcal{O}_{cdd}^{S,RR} = \epsilon^{\alpha\beta\gamma} (\overline{c}_{R\alpha}^c d_{R\beta}) (\overline{\nu}_L d_{R\gamma})$$

$$\mathcal{O}_{c ds}^{S,RR} = \epsilon^{\alpha\beta\gamma} (\overline{c}_{R\alpha}^c d_{R\beta}) (\overline{\nu}_L s_{R\gamma})$$

$$\mathcal{O}_{csd}^{S,RR} = \epsilon^{\alpha\beta\gamma} (\overline{c}_{R\alpha}^c s_{R\beta}) (\overline{\nu}_L d_{R\gamma})$$

$$\mathcal{L}_{\text{eff}}^{cdd} \supset \frac{C_{211}}{\Lambda^2} \mathcal{O}_{cdd}^{S,RR} + \text{h.c.}$$

$$\mathcal{L}_{\text{eff}}^{c ds, csd} \supset \frac{C_{212}}{\Lambda^2} \mathcal{O}_{c ds}^{S,RR} + \frac{C_{221}}{\Lambda^2} \mathcal{O}_{csd}^{S,RR} + \text{h.c.}$$

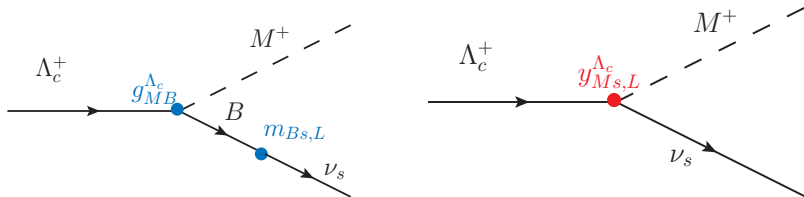


ν LEFT matched to BChPT

- To compute $\Gamma(\Lambda_c^+ \rightarrow \pi^+/K^+ + \nu_s)$, we follow the literature for **matching the ν LEFT to the BChPT**
- However, BChPT is rigorously applicable only to the **light-flavor baryon octet**, and its direct use for the charmed baryon Λ_c^+ **lies outside its formal domain of validity**
- To account for this mismatch, we **promote** the light-baryon-level (**proton**) matrix elements to the Λ_c^+ case and apply a **conservative order-unity variation** to the corresponding hadronic form factors
- We vary each Λ_c^+ matrix element by a multiplicative factor of **2 and 1/2** as a **theoretical uncertainty** associated with extrapolating the low-energy EFT matching into the heavy-flavor sector
- Captures the expected size of SU(3)-breaking and heavy-quark-symmetry-breaking effects in the absence of a controlled chiral expansion for charm baryons.

The $|\Delta(B - L)| = 2$ effective Lagrangian

$$\mathcal{L}_{\text{eff}} = g_{MB}^{\Lambda_c^+} \bar{B} \gamma^\mu \gamma_5 \Lambda_c^+ \partial_\mu M + m_{Bs,L} \bar{\nu}_s P_R B + i y_{Ms,L}^{\Lambda_c^+} \bar{\nu}_s P_R \Lambda_c^+ M$$



$$\begin{aligned} \overline{|\mathcal{M}|^2} / m_{\Lambda_c^+}^2 &= \frac{1}{2} |y_{Ms,L}^{\Lambda_c^+}|^2 (1 + x_s^2 - x_M^2) + \frac{1}{2} \sum_{B, B'} g_{MB}^{\Lambda_c^+} g_{MB'}^{\Lambda_c^+*} m_{Bs,L} m_{B's,L}^* g(x_B, x_{B'}) \\ &\quad - \sum_B \text{Re}(y_{Ms,L}^{\Lambda_c^+} m_{Bs,L}^* g_{MB}^{\Lambda_c^+*}) h(x_B) \end{aligned}$$

$$x_s = m_{\nu_s} / m_{\Lambda_c^+}, \quad x_M = m_M / m_{\Lambda_c^+}, \quad x_{B^{(\prime)}} = m_{B^{(\prime)}} / m_{\Lambda_c^+}$$

$$\Gamma(\Lambda_c^+ \rightarrow M^+ + \nu_s) = m_{\Lambda_c^+} \frac{\lambda^{1/2}(1, x_M^2, x_s^2)}{16\pi} \frac{\overline{|\mathcal{M}|^2}}{m_{\Lambda_c^+}^2}, \quad M = \pi, K$$

The RPV-SUSY

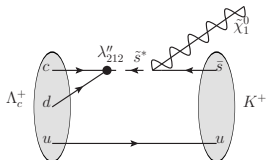
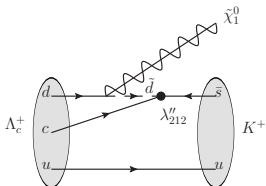
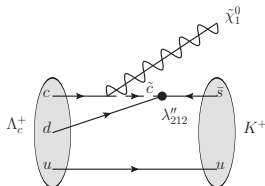
- A light bino neutralino $\tilde{\chi}_1^0$ allowed by all constraints

$$\mathcal{L}_{\text{BNV-bino}} = \mathcal{L}_{\text{bino}} + \mathcal{L}_{\text{RPV}}$$

$$\mathcal{L}_{\text{bino}} = - \sum_{q=d,s,c} g_{1R}^{\tilde{q}} (\bar{q}_{R,a} P_L \tilde{\chi}_1^0) \tilde{q}_{R,a} + \text{h.c.} + \dots$$

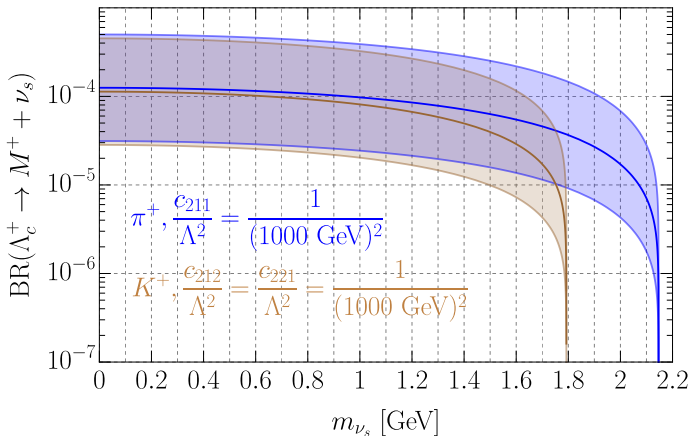
$$\mathcal{L}_{\text{RPV}} = \lambda''_{212} \epsilon_{abc} \left(\tilde{c}_{Ra}^* \bar{d}_{Rb} s_{Rc}^C + \tilde{d}_{Ra}^* \bar{c}_{Rb} s_{Rc}^C + \tilde{s}_{Ra}^* \bar{c}_{Rb} d_{Rc}^C \right) + \text{h.c.}$$

$$g_{1R}^{\tilde{q}} = -\sqrt{2} g_W e_q \tan \theta_W$$



- Can be matched to the EFT operators we consider

BR($\Lambda_c^+ \rightarrow M^+ + \nu_s$)



- Bands: theoretical uncertainty

The very long decay lengths of ν_s and $\tilde{\chi}_1^0$

- For the considered mass range of interest, their decays are **highly suppressed**
- ν_s : decay amplitudes suppressed by the small values of the Wilson coefficients, off-shell propagators of a W and a down-type quark
- $\tilde{\chi}_1^0$: decay amplitudes suppressed by three off-shell propagators (a squark, a W -boson, and a down-type quark), CKM matrix elements, tiny RPV couplings, as well as the absence of squark mixing
- \Rightarrow Both ν_s and $\tilde{\chi}_1^0$ appear as **missing energy** in the main detector

The STCF and search analysis

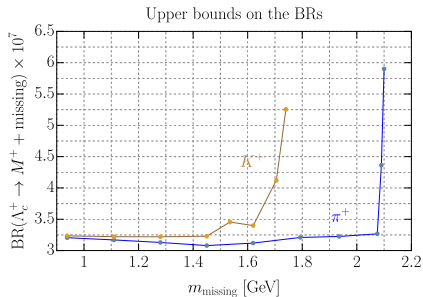
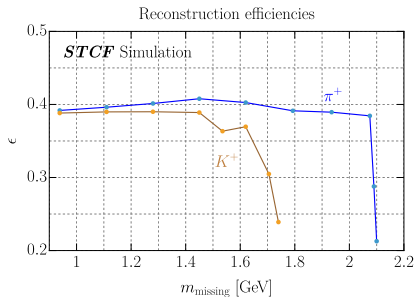
- **STCF**: an **energy-symmetry** e^-e^+ collider,
 $E_{\text{COM}} = 4.682 \text{ GeV} \Rightarrow N_{\Lambda_c^+\bar{\Lambda}_c^-} = 1.881 \times 10^8$ per year with 1 ab^{-1}
- Simulate signal events with **OSCAR**
- $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$: tag $\bar{\Lambda}_c^-$ and $\Lambda_c^+ \rightarrow \pi^+/K^+ + \nu_s/\tilde{\chi}_1^0$
- **Signature**: $\bar{\Lambda}_c^-$ and $\pi^+/K^+ + \text{missing}$
- Tagging channel: $\bar{p}K^+\pi^-$ (**dominant**) (BR= 6.35%)

$$N_S = 2 \cdot N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \text{BR}(\Lambda_c^+ \rightarrow M^+ + \nu_s/\tilde{\chi}_1^0) \cdot \text{BR}(\bar{\Lambda}_c^- \rightarrow \bar{p}K^+\pi^-) \cdot \epsilon$$

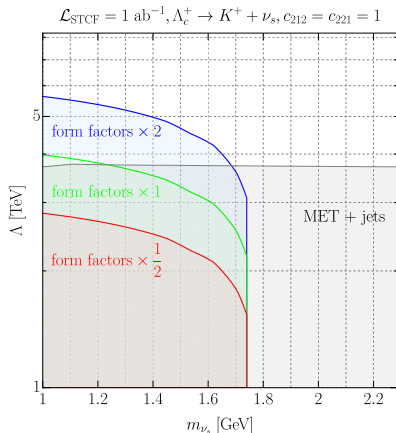
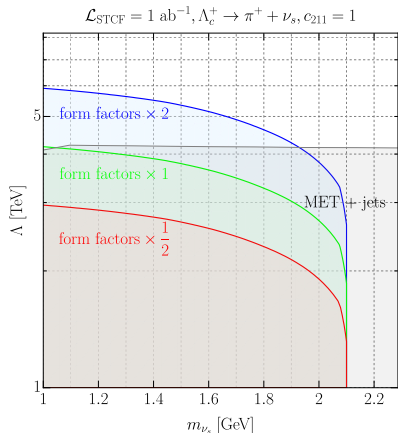
- Expect low background levels
- For the analysis assume zero backgrounds to be achieved and $N_S = 3$ corresponds to 95% C.L. exclusion limits

Numerical results – observable level

- OSCAR-derived efficiencies

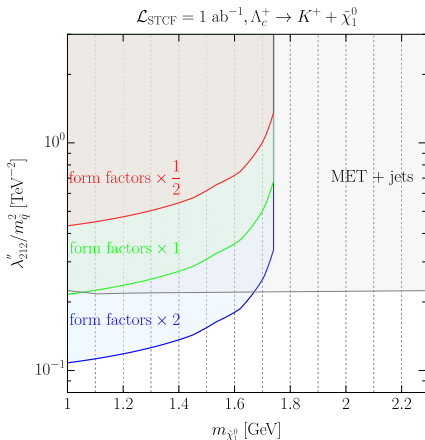


Numerical results – EFT



- MET + jets ATLAS [2403.02793](#) recast & reinterpreted in [2602.15936](#)
 - Probe Λ up to 3 – 6 TeV for $c = 1$

Numerical results – RPV-SUSY



- Probe λ''_{212}/m_q^2 down to $\mathcal{O}(0.1) \text{ TeV}^{-2}$

Summary

- Propose to search for a BNV signature: $\Lambda_c^+ \rightarrow \pi^+ / K^+ + \text{missing}$
- $\mathcal{O}(10^8)$ $\Lambda_c^+ \bar{\Lambda}_c^-$ events at STCF per year
- MC simulations with OSCAR to determine acceptance and reconstruction efficiencies of signal events
- Tag channel $\bar{p} K^+ \pi^-$
- Assume zero backgrounds
- Probing Λ up to 3 – 6 TeV depending on theo. uncertainty
- Including more tag channels can allow to probe Λ up to ~ 8 TeV

Thank You! 谢谢!

Back-up slides

Matching hadronic form factors

Process	$g_{MB}^{\Lambda_c^+}$	$m_{Bs,L}$	$y_{Ms,L}^{\Lambda_c^+}$
$\Lambda_c^+ \rightarrow \pi^+ \nu_s$	$g_{\pi\Sigma_c^0}^{\Lambda_c^+} = \frac{D+F}{f_\pi}$	$m_{\Sigma_{cs,L}^0} = \frac{c_{211}}{\Lambda^2}(\beta)$	$y_{\pi s,L}^{\Lambda_c^+} = \frac{c_{211}}{\Lambda^2}(-\frac{\beta}{f_\pi})$
$\Lambda_c^+ \rightarrow K^+ \nu_s$	$g_{K\Xi_c'^0}^{\Lambda_c^+} = \frac{D-F}{\sqrt{2}f_\pi}$ $g_{K\Xi_c^0}^{\Lambda_c^+} = \frac{D+3F}{\sqrt{6}f_\pi}$	$m_{\Xi_{cs,L}'^0} = \frac{c_{221}}{\Lambda^2}(\frac{\beta}{\sqrt{2}})$ $m_{\Xi_{cs,L}^0} = \frac{c_{221}}{\Lambda^2}(-\frac{\beta}{\sqrt{6}})$ $+ \frac{c_{212}}{\Lambda^2}(-\beta\sqrt{\frac{2}{3}})$	$y_{Ks,L}^{\Lambda_c^+} = \frac{c_{212}}{\Lambda^2}(-\frac{\beta}{f_\pi})$

Matrix element for $\Lambda_c^+ \rightarrow M^+ + \nu_s$ & Kinematic functions

$$i\mathcal{M} = \overline{u_{\nu_s}} P_R \left(-y_{Ms,L}^{\Lambda_c^+} + \sum_B m_{Bs,L} \frac{\not{k} + m_B}{k^2 - m_B^2} g_{MB}^{\Lambda_c^+} \not{p}_M \gamma_5 \right) u_{\Lambda_c^+}$$

$$g(x_1, x_2) = \frac{(x_s^2 + x_1 x_2)(1 - x_M^2 - x_s^2(2 + x_M^2) + x_s^4) - 2x_s^2 x_M^2 (x_1 + x_2)}{(x_1^2 - x_s^2)(x_2^2 - x_s^2)}$$

$$h(x_B) = \frac{x_B(1 - x_M^2 - x_s^2) - x_s^2(1 + x_M^2 - x_s^2)}{x_B^2 - x_s^2}$$

Numerical values of hadronic form factors

$$\beta_{\Lambda_c^+} = 0.835 \times 10^{-2} \text{ GeV}^3$$

deduced in [[Dib, Helo, Lyubovitskij, Neill, Soffer, ZSW 2023](#)] from predictions of QCD sum-rule approaches

$$D = 0.730, F = 0.447, f_\pi = 0.13041 \text{ GeV}$$

Derivation of the eff. Lagrangian from the RPV-SUSY – I

$$\mathcal{L}^{\text{BNV}} = \mathcal{L}^{\text{scd}}\tilde{\chi}_1^0 + \mathcal{L}^{\text{c ds}}\tilde{\chi}_1^0 + \mathcal{L}^{\text{d cs}}\tilde{\chi}_1^0$$

$$\mathcal{O}^{q_1 q_2 q_3}\tilde{\chi}_1^0 = \mathcal{O}^{q_1 q_2 q_3}\tilde{\chi}_1^0 + \text{h.c.}$$

$$\mathcal{O}^{q_1 q_2 q_3} = g^{\tilde{q}_1 R}\mathcal{O}_{q_1 q_2 q_3}^{LL}$$

$$g^{\tilde{q}R} = \frac{g_{1R}^{\tilde{q}}\lambda''_{212}}{m_{\tilde{q}}^2}$$

$$\mathcal{O}_{q_1 q_2 q_3}^{LL} = \varepsilon_{abc}(\bar{q}_{3,c}P_L C \bar{q}_{2,b}^T)\bar{q}_{1,a}P_L$$

$C = i\gamma^0\gamma^2$: the charge conjugation matrix.

and

$$\begin{aligned} \mathcal{O}_{c ds}^{S,RR} &= (\bar{c}_R^c d_R)(\bar{\nu}_L s_R) & \& \text{h.c.} & \tilde{\mathcal{O}}_{c ds}^{S,RR} &= (\bar{d}_R c_R^c)(\bar{s}_R \nu_L) \\ \mathcal{O}_{c sd}^{S,RR} &= (\bar{c}_R^c s_R)(\bar{\nu}_L d_R) & & & \tilde{\mathcal{O}}_{c sd}^{S,RR} &= (\bar{s}_R c_R^c)(\bar{d}_R \nu_L) \end{aligned}$$

Derivation of the eff. Lagrangian from the RPV-SUSY – II

The corresponding effective Lagrangian as

$$\mathcal{L}^{\text{BNV}} = \frac{\tilde{g}_{1R}^{\tilde{s}} \lambda''_{212}}{m_{\tilde{s}}^2} (\overline{d}_R c_R^c) (\overline{s}_R \tilde{\chi}_1^0) + \frac{\tilde{g}_{1R}^{\tilde{d}} \lambda''_{212}}{m_{\tilde{d}}^2} (\overline{s}_R c_R^c) (\overline{d}_R \tilde{\chi}_1^0) + \frac{\tilde{g}_{1R}^{\tilde{c}} \lambda''_{212}}{m_{\tilde{c}}^2} (\overline{s}_R d_R^c) (\overline{c}_R \tilde{\chi}_1^0)$$

The first two terms match with $\tilde{\mathcal{O}}_{cds}^{S,RR}$ and $\tilde{\mathcal{O}}_{csd}^{S,RR}$
 The operator in the third term – Fierz transf.:

$$(\overline{s}_R d_R^c) (\overline{c}_R \tilde{\chi}_1^0) \stackrel{\text{Fierz}}{\approx} \frac{1}{2} (\overline{s}_R \tilde{\chi}_1^0) (\overline{c}_R d_R^c) = -\frac{1}{2} (\overline{d}_R c_R^c) (\overline{s}_R \tilde{\chi}_1^0)$$

where an extra tensor term that originates from the Fierz transformation and is expected to give negligible contributions only, has been ignored

The last expression matches $\tilde{\mathcal{O}}_{cds}^{S,RR}$

$$\mathcal{L}^{\text{BNV}} = 2 \frac{\tilde{g}_{1R}^{\tilde{s}} \lambda''_{212}}{m_{\tilde{q}}^2} (\overline{d}_R c_R^c) (\overline{s}_R \tilde{\chi}_1^0) + \frac{\tilde{g}_{1R}^{\tilde{d}} \lambda''_{212}}{m_{\tilde{q}}^2} (\overline{s}_R c_R^c) (\overline{d}_R \tilde{\chi}_1^0)$$

with squark-mass degeneracy and the relation $\tilde{g}_{1R}^{\tilde{c}} = -2\tilde{g}_{1R}^{\tilde{s}}$

$$\frac{c_{212}}{\Lambda^2} = \frac{2\lambda''_{212}\tilde{g}_{1R}^{\tilde{s}}}{m_{\tilde{q}}^2}, \quad \frac{c_{221}}{\Lambda^2} = \frac{\lambda''_{212}\tilde{g}_{1R}^{\tilde{d}}}{m_{\tilde{q}}^2}$$

Track reconstruction

- ① Good charged tracks selection of K^+ , \bar{p} , π^- , and π^+
 - $|V_z| < 1.0$ cm, $|V_{xy}| < 10.0$ cm
 - $|\cos \theta| < 0.93$
 - $N(\text{good charged tracks of } K) \geq 1$
 - $N(\text{good charged tracks of } p) \geq 1$
 - $N(\text{good charged tracks of } \pi) \geq 1$
- ② Good charged tracks selection of $\text{sig}(K^+, N)$
 - $N(K) \geq 2, N(p) \geq 1, N(\pi) \geq 1$
- ③ Good charged tracks selection of $\text{sig}(\pi^+, N)$
 - $N(K) \geq 1, N(p) \geq 1, N(\pi) \geq 2$

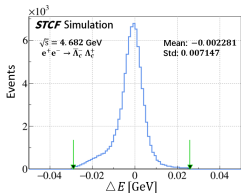
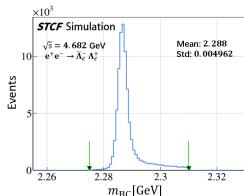
Double tagging

1 Tag side:

- proton and pion of the same sign, and proton and kaon of the opposite sign
- kinematic fit on the tag-side $\bar{\Lambda}_c^-$, requiring $\chi^2 > 0$
- Beam-constrained mass $m_{BC} \equiv |\mathbf{p}_{\text{cms}} - \mathbf{p}_{\bar{\Lambda}_c^-}|$ should lie between 2.25 GeV and 2.4 GeV; $\Delta E \equiv E_{\bar{\Lambda}_c^-} - E_{\text{beam}}$ between -29 and 26 MeV; selecting the smallest ΔE as the candidate on the tag side

2 Signal side:

- charge of $K > 0$ or charge of $\pi > 0$
- $m_{\text{missing}}^2 > 0$



$$m_{\text{missing}} = 1.110 \text{ GeV},$$
$$\Lambda_c^+ \rightarrow K^+ + \text{missing}$$

Main background sources

- 1 Neutron-induced activities
- 2 continuum $e^+e^- \rightarrow$ light-quark processes

\Rightarrow depositing energy in the ECAL and mimicing missing-energy signatures

- In a realistic analysis, such backgrounds can be substantially suppressed using optimized event selections, potentially assisted by advanced machine-learning techniques, while maintaining high signal efficiency
- A detailed evaluation of these effects is left for future experimental studies