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

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对撞机上新物理寻找研讨会

中国江苏苏州

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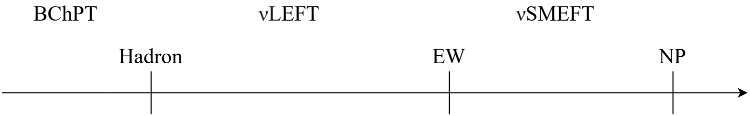
Motivation

- 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: νSMEFT & νLEFT



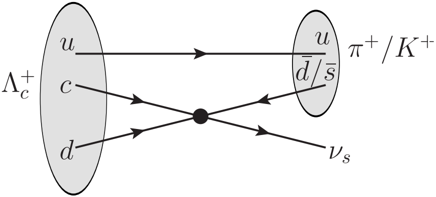
- STCF, large $\Lambda_c^+ \overline{\Lambda}_c^-$ production rates $\Rightarrow$ study $\Lambda_c^+ \to \pi^+/K^+ + \nu_s$
- ν_s very long-lived
- *Apparent* BNV in Λ_c^+ decays at STCF

Model frameworks – the νLEFT

- dim-6 operators

$$
\begin{aligned}
\mathcal{O}^{S,RR}_{cdd} &= \epsilon^{\alpha\beta\gamma}(\overline{c^c_{R\alpha}} d_{R\beta})(\overline{\nu_L} d_{R\gamma}) \\
\mathcal{O}^{S,RR}_{cds} &= \epsilon^{\alpha\beta\gamma}(\overline{c^c_{R\alpha}} d_{R\beta})(\overline{\nu_L} s_{R\gamma}) \\
\mathcal{O}^{S,RR}_{csd} &= \epsilon^{\alpha\beta\gamma}(\overline{c^c_{R\alpha}} s_{R\beta})(\overline{\nu_L} d_{R\gamma})
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}^{cdd}_{\text{eff.}} &\supset \frac{c_{211}}{\Lambda^2}\mathcal{O}^{S,RR}_{cdd} + \text{h.c.} \\
\mathcal{L}^{cds,csd}_{\text{eff.}} &\supset \frac{c_{212}}{\Lambda^2}\mathcal{O}^{S,RR}_{cds} + \frac{c_{221}}{\Lambda^2}\mathcal{O}^{S,RR}_{csd} + \text{h.c.}
\end{aligned}
$$

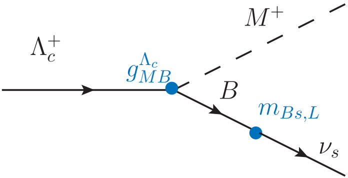


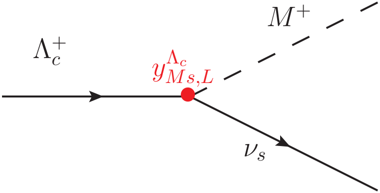
νLEFT matched to BChPT

- To compute $\Gamma(\Lambda_c^+ \to \pi^+/K^+ + \nu_s)$, we follow the literature for matching the νLEFT 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 treat the corresponding hadronic form factor as an effective normalization parameter, to which we apply an order-unity variation
- We vary each Λ_c^+ matrix-element form factor by 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

$$\mathcal{L}_{\rm eff} = g_{MB}^{\Lambda_c^+}\overline{B}\gamma^\mu\gamma_5\Lambda_c^+\partial_\mu M + m_{Bs,L}\overline{\nu_s}P_R B + i y_{Ms,L}^{\Lambda_c^+}\overline{\nu_s}P_R\Lambda_c^+ M$$





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

$$-\sum_B \mathrm{Re}(y_{Ms,L}^{\Lambda_c^+} m_{Bs,L}^* g_{MB}^{\Lambda_c^+\,*}) h(x_B)$$

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

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

The RPV-SUSY

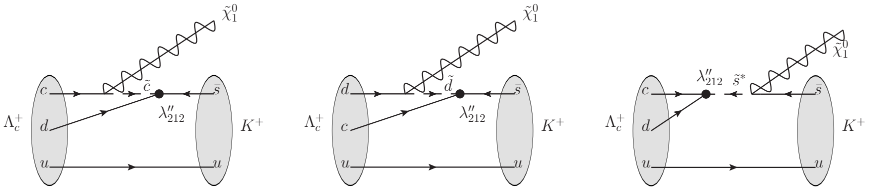
- A light bino neutralino $\tilde{\chi}_1^0$ allowed by all constraints

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

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

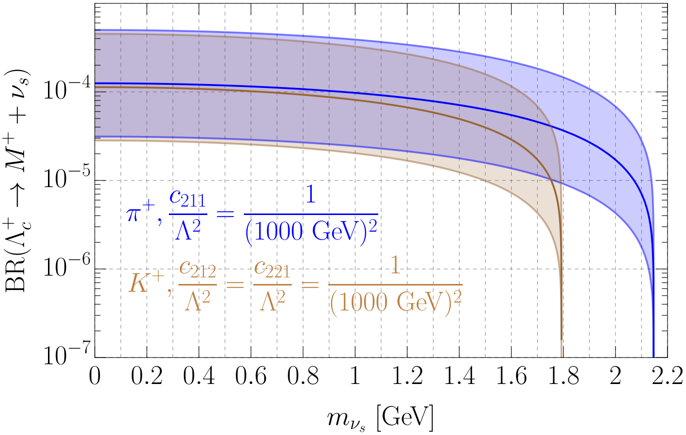
$$\mathcal{L}_{\text{RPV}} = \lambda''_{212}\, \epsilon_{abc} \left(\tilde{c}^*_{Ra}\, \bar{d}_{Rb}\, s^C_{Rc} + \tilde{d}^*_{Ra}\, \bar{c}_{Rb}\, s^C_{Rc} + \tilde{s}^*_{Ra}\, \bar{c}_{Rb}\, d^C_{Rc} \right) + \text{h.c.}$$

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



- Can be matched to the EFT operators we consider

$\mathrm{BR}(\Lambda_c^+ \to M^+ + \nu_s)$



- 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

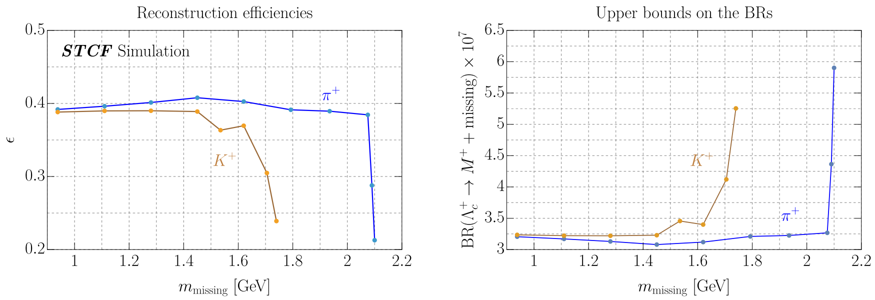
- STCF: an energy-symmetry $e^- e^+$ collider,
  $E_{\text{COM}} = 4.682$ GeV$\Rightarrow N_{\Lambda_c^+ \overline{\Lambda}_c^-} = 1.881 \times 10^8$ per year with 1 ab^{-1}
- Simulate signal events with OSCAR
- $e^+ e^- \to \Lambda_c^+ \overline{\Lambda}_c^-$: tag $\overline{\Lambda}_c^-$ and $\Lambda_c^+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

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

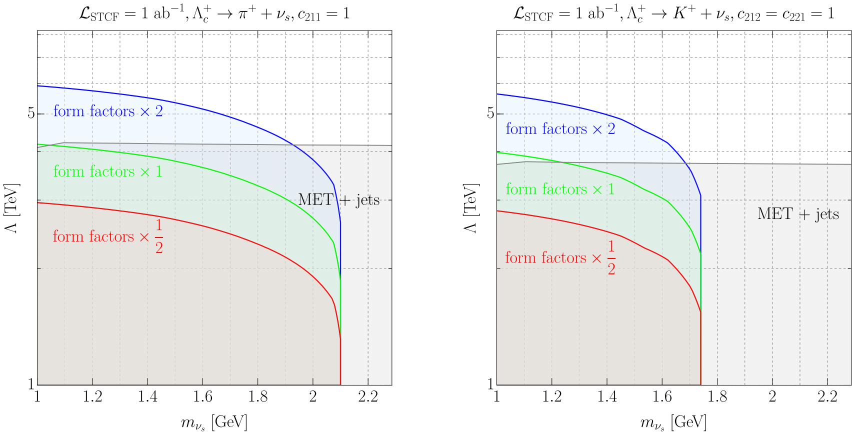
- Expect low background levels
- For the analysis assume zero backgrounds to be achieved and $N_S = 3$ corresponds to 95% C.L. exclusion limits

Numerical results – observable level

- `OSCAR`-derived efficiencies

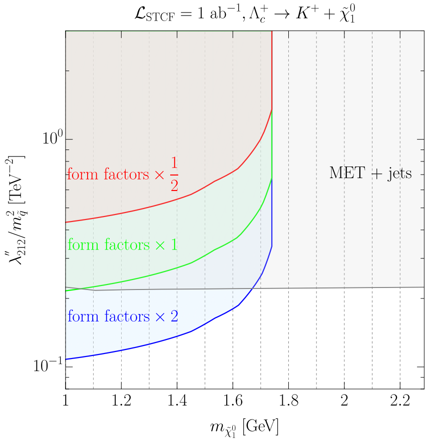


Numerical results – EFT



- 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 $\lambda''_{212}/m^2_{\tilde{q}}$ down to $\mathcal{O}(0.1)$ TeV^{-2}

Summary

- Propose to search for a BNV signature: $\Lambda_c^+ \to \pi^+/K^+ + \text{missing}$
- $\mathcal{O}(10^8)$ $\Lambda_c^+\overline{\Lambda}_c^-$ events at STCF per year
- MC simulations with OSCAR to determine acceptance and reconstruction efficiencies of signal events
- Tag channel $\overline{p}K^+\pi^-$
- 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	$g_{MB}^{\Lambda_c^+}$	$m_{Bs,L}$	$y_{Ms,L}^{\Lambda_c^+}$
$\Lambda_c^+ \to \pi^+ \nu_s$	$g_{\pi\Sigma_c^0}^{\Lambda_c^+} = \frac{D+F}{f_\pi}$	$m_{\Sigma_{cs,L}^0} = \frac{c_{211}}{\Lambda^2}(\beta)$	$y_{\pi s,L}^{\Lambda_c^+} = \frac{c_{211}}{\Lambda^2}(-\frac{\beta}{f_\pi})$
$\Lambda_c^+ \to K^+ \nu_s$	$g_{K\Xi_c^{\prime 0}}^{\Lambda_c^+} = \frac{D-F}{\sqrt{2} f_\pi}$ $g_{K\Xi_c^0}^{\Lambda_c^+} = \frac{D+3F}{\sqrt{6} f_\pi}$	$m_{\Xi_{cs,L}^{\prime 0}} = \frac{c_{221}}{\Lambda^2}(\frac{\beta}{\sqrt{2}})$ $m_{\Xi_{cs,L}^0} = \frac{c_{221}}{\Lambda^2}(-\frac{\beta}{\sqrt{6}}) + \frac{c_{212}}{\Lambda^2}(-\beta\sqrt{\frac{2}{3}})$	$y_{Ks,L}^{\Lambda_c^+} = \frac{c_{212}}{\Lambda^2}(-\frac{\beta}{f_\pi})$

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

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

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

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

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

$$\mathcal{L}^{\text{BNV}} = \mathcal{L}^{scd\tilde{\chi}_1^0} + \mathcal{L}^{cds\tilde{\chi}_1^0} + \mathcal{L}^{dcs\tilde{\chi}_1^0}$$

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

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

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

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

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

and

$$\mathcal{O}^{S,RR}_{cds} = (\overline{c^c_R} d_R)(\overline{\nu_L} s_R) \quad \& \text{ h.c.} \quad \tilde{\mathcal{O}}^{S,RR}_{cds} = (\overline{d_R} c^c_R)(\overline{s_R} \nu_L)$$

$$\mathcal{O}^{S,RR}_{csd} = (\overline{c^c_R} s_R)(\overline{\nu_L} d_R) \quad \tilde{\mathcal{O}}^{S,RR}_{csd} = (\overline{s_R} c^c_R)(\overline{d_R} \nu_L)$$

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

The corresponding effective Lagrangian as

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

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.:

$$(\overline{s_R}d_R^c)(\overline{c_R}\tilde{\chi}_1^0) \overset{\text{Fierz}}{\approx} \frac{1}{2}(\overline{s_R}\tilde{\chi}_1^0)(\overline{c_R}d_R^c) = -\frac{1}{2}(\overline{d_R}c_R^c)(\overline{s_R}\tilde{\chi}_1^0)$$

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 $\tilde{\mathcal{O}}_{cds}^{S,RR}$

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

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

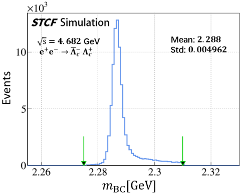
$$\frac{c_{212}}{\Lambda^2} = \frac{2\lambda''_{212}g_{1R}^{\tilde{s}}}{m_{\tilde{q}}^2}, \qquad \frac{c_{221}}{\Lambda^2} = \frac{\lambda''_{212}g_{1R}^{\tilde{d}}}{m_{\tilde{q}}^2}$$

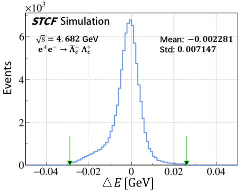
Track reconstruction

1. Good charged tracks selecton of K^+, $\bar{p}$, π^-, and π^+
   - $|V_z| < 1.0$ cm, $|V_{xy}| < 10.0$ cm
   - $|\cos\theta| < 0.93$
   - N(good charged tracks of K) ≥ 1
   - N(good charged tracks of p) ≥ 1
   - N(good charged tracks of π) ≥ 1
2. Good charged tracks selection of sig(K^+, N)
   - $N(K) \geq 2, N(p) \geq 1, N(\pi) \geq 1$
3. Good charged tracks selection of sig(π^+, 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 $\overline{\Lambda}_c^-$, requiring $\chi^2 > 0$
   - Beam-constrained mass $m_{\rm BC} \equiv |\mathbf{p}_{\rm cms} - \mathbf{p}_{\overline{\Lambda}_c^-}|$ should lie between 2.25 GeV and 2.4 GeV; $\Delta E \equiv E_{\overline{\Lambda}_c^-} - E_{\rm beam}$ 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 $\pi > 0$
   - $m^2_{\rm missing} > 0$





$m_{\rm missing} = 1.110$ GeV, $\Lambda_c^+ \to K^+ +$ missing

Main background sources

1. Neutron-induced activities
2. continuum $e^+e^- \to$ 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