HEAVY NEW PHYSICS IN $b \to s\nu\nu$

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Rare b-decays in $b \to s\nu\nu$: Motivation

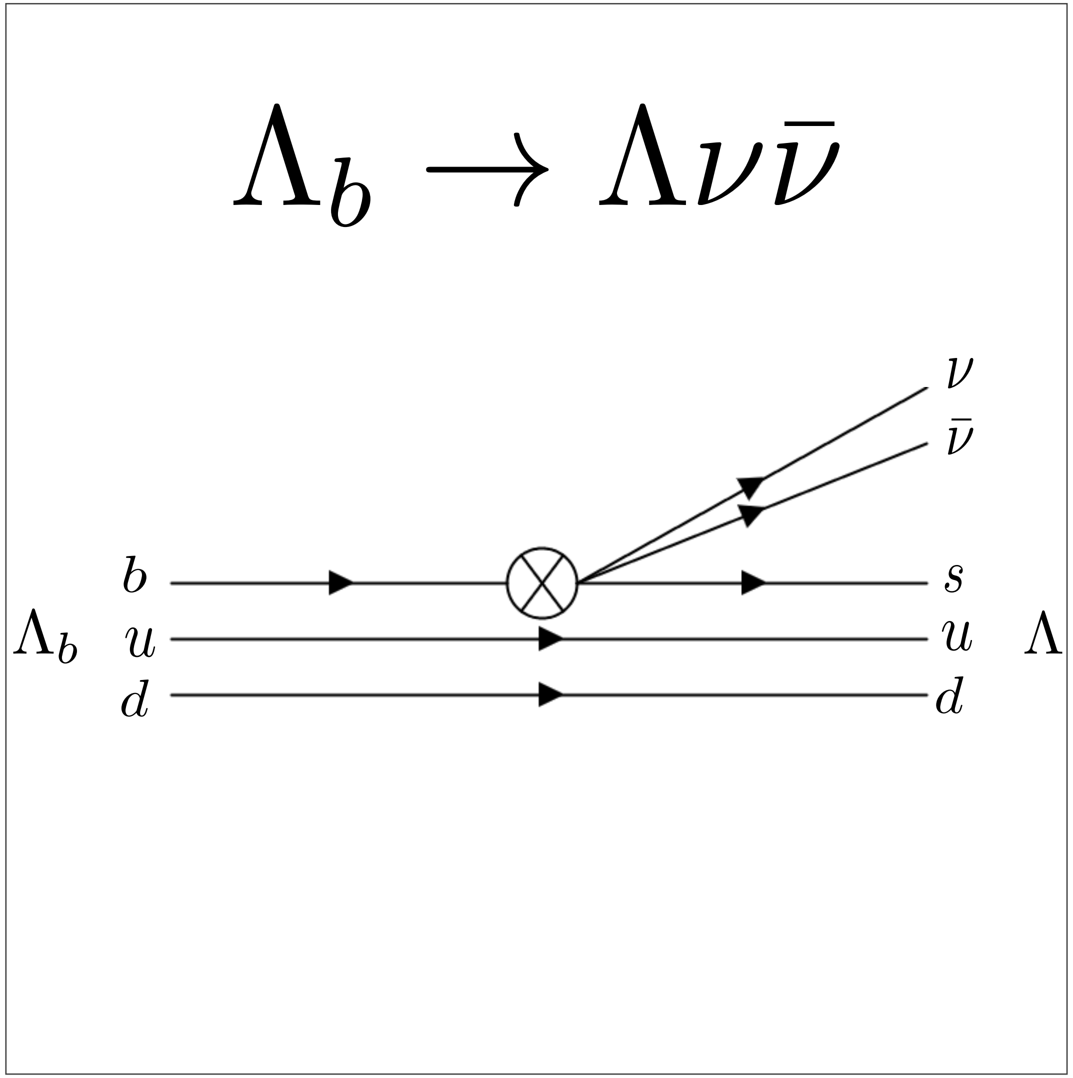
Theoretical

- GIM and CKM suppression makes these decays of b quarks rare
- Sensitive probes of New Physics (NP)
- Cleaner theoretical predictions than for $b \to s\ell^+\ell^-$
- Complementary NP information to the above and clean ratios of branching fractions

Experimental

- Good missing energy detection
- Future e^+e^-colldiers = excellent probe: 10^{12} Z events at the Z pole[1]
  - Currently only weakly probed through meson decays
  - No polarization – chiral information is yet to be probed
  - Polarization can be measured - passes to fermionic children

[1]Alimena et al.: 2203.05502



Conclusion: Soap from Friend!

bud to *sud*

Polarized: probes chiral NP structure	• Polarization measurements have been made[1] and will improve
Predicted[2] to be measured at future colliders	• No current bounds
Additional observable: A_{FB}	• Conditioned on $\cos\theta = \hat{p}_\Lambda \cdot \hat{s}_{\Lambda_b}$

[1]Buskulic et al.: 10.1016/0370-2693(95)01433-0
[2]Amhis, Kenzie, Reboud, Wiederhold: 2309.11353

The Framework: $\Lambda_b \to \Lambda \nu \bar{\nu}$

- Compute double differential decay rate of the Standard Model process
  - Polarized initial state (sample fraction)
  - Correlate initial spin and Λ momentum

$$\mathcal{P}_{\Lambda_b} = \frac{N^{\uparrow}_{\Lambda_b} - N^{\downarrow}_{\Lambda_b}}{N^{\uparrow}_{\Lambda_b} + N^{\downarrow}_{\Lambda_b}}$$

- Produce observables in different frames

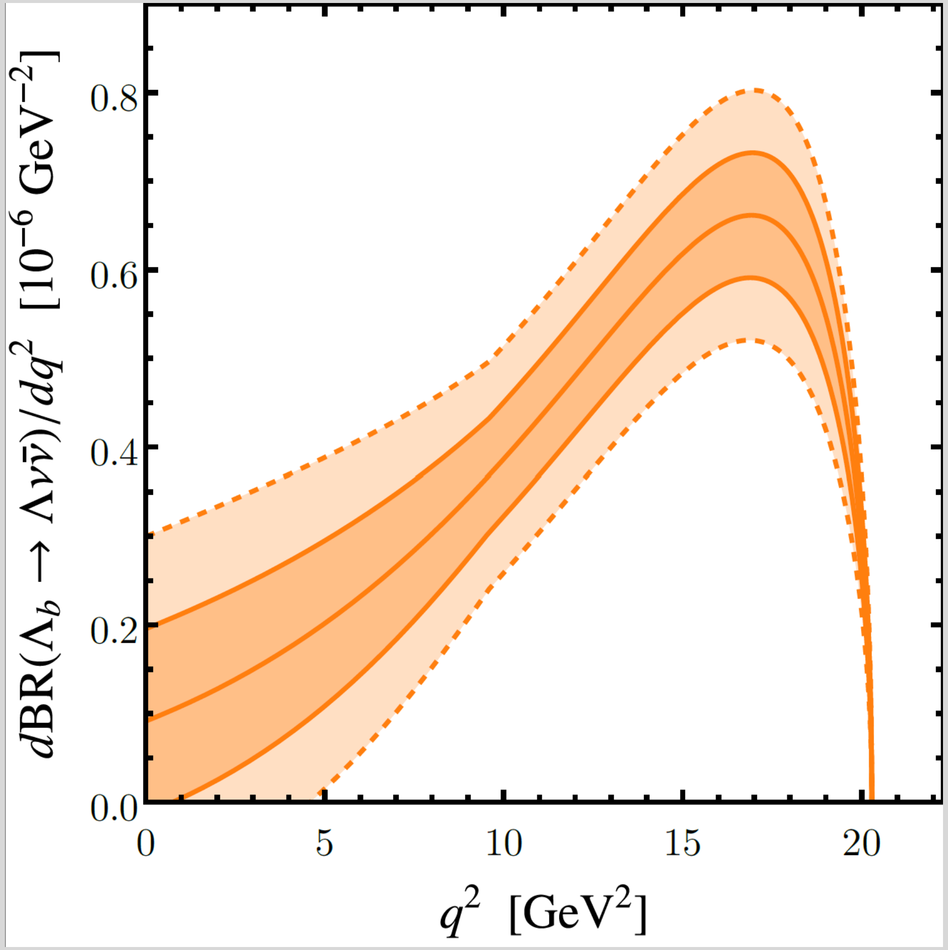
$$\frac{d\mathrm{BR}(\Lambda_b \to \Lambda \nu \bar{\nu})}{dq^2\, d\cos\theta_\Lambda} = \frac{d\mathrm{BR}(\Lambda_b \to \Lambda \nu \bar{\nu})}{dq^2} \left(\frac{1}{2} + A^{\uparrow}_{\mathrm{FB}} \cos\theta_\Lambda \right)$$

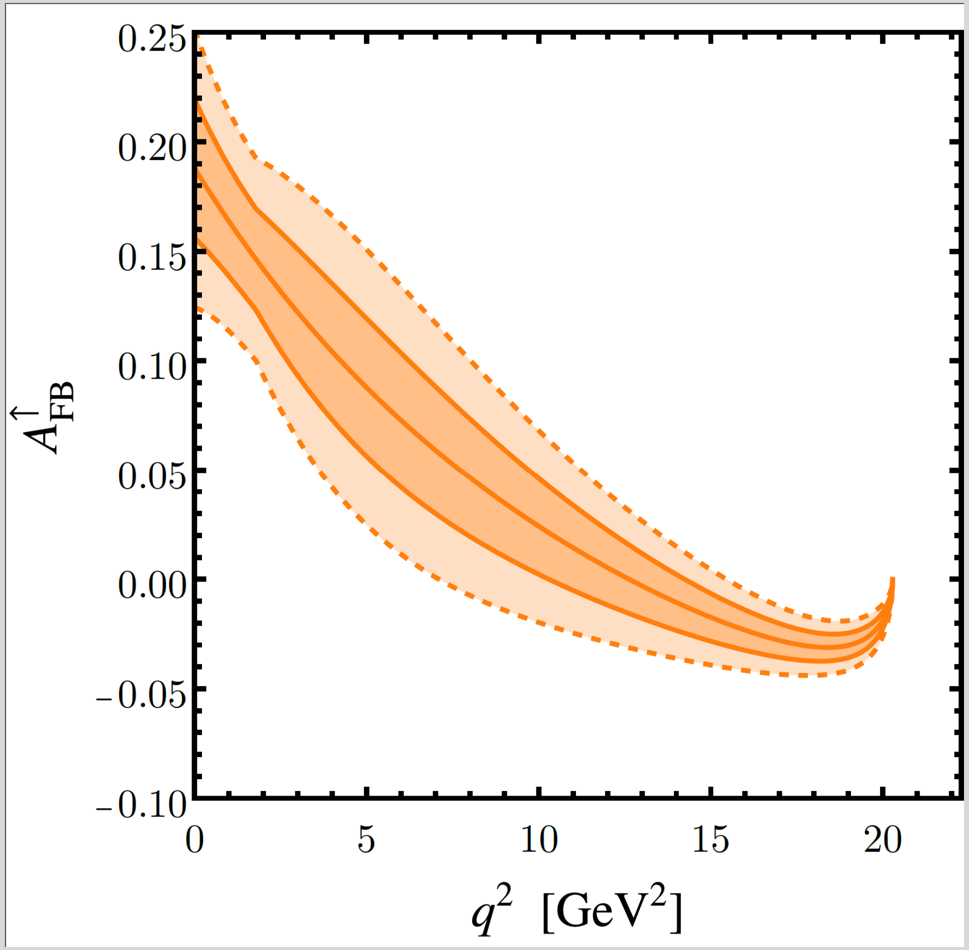
- Propagate input uncertainties: prediction uncertainty (simulation)
- Compute an NP double differential decay rate:

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V^*_{ts} V_{tb} 2 \Big(C_L (\bar{s}\gamma^\mu P_L b)(\bar{\nu}\gamma_\mu P_L \nu) + C_R (\bar{s}\gamma^\mu P_R b)(\bar{\nu}\gamma_\mu P_L \nu) \Big) + \mathrm{h.c.}$$

- Evaluate the bound on $C_{R,L}$

Observables





The Particles were Framed

Lab Frame

- Observed: $\hat{E}_\Lambda$ distribution
- Assumption: Initial Λ_b energy reconstruction
- Differential width dependence on $\hat{E}_\Lambda$
  - Non-trivial kinematic limits
- Obtain observable distributions dependent on initial energy distribution

Λ_b Rest Frame

- Observed: Channel Decay Rate, $A_{\mathrm{F}B}$
- Assumption: $\hat{p}_{\Lambda_b}$ axis reconstruction
- Momentum gives us the spin quantization axis for $A_{\mathrm{F}B}$
- Reconstruction uncertainty and propagation (hadronics enter here)
- Observable distributions are calculable without hadronic simulation

Form Factors

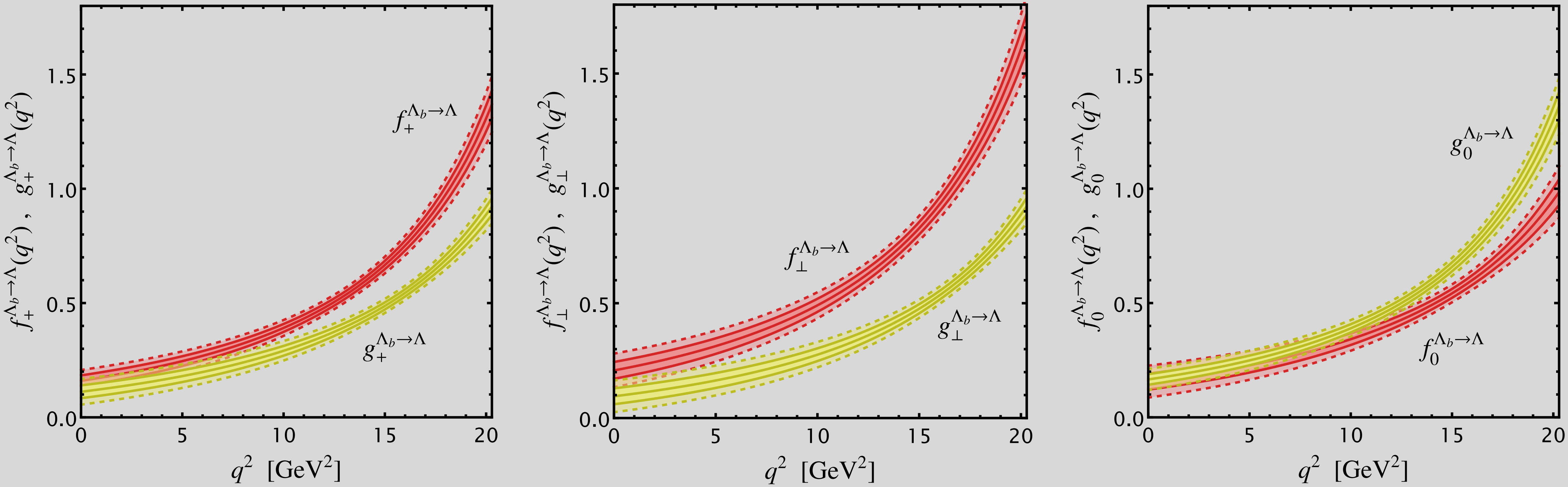
$$\langle\Lambda|\bar{s}\gamma^\mu b|\Lambda_b\rangle = \bar{u}_\Lambda\Bigg[f_t^V(q^2)(m_{\Lambda_b}-m_\Lambda)\frac{q^\mu}{q^2} + f_\perp^V(q^2)\left(\gamma^\mu - \frac{2(m_\Lambda P^\mu + m_{\Lambda_b}p^\mu)}{(m_{\Lambda_b}+m_\Lambda)^2-q^2}\right) + f_0^V(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{(m_{\Lambda_b}+m_\Lambda)^2-q^2}\left(P^\mu + p^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)\Bigg]u_{\Lambda_b}$$

$$\langle\Lambda|\bar{s}\gamma^\mu\gamma_5 b|\Lambda_b\rangle = -\bar{u}_\Lambda\gamma_5\Bigg[f_t^A(q^2)(m_{\Lambda_b}+m_\Lambda)\frac{q^\mu}{q^2} + f_\perp^A(q^2)\left(\gamma^\mu + \frac{2(m_\Lambda P^\mu - m_{\Lambda_b}p^\mu)}{(m_{\Lambda_b}-m_\Lambda)^2-q^2}\right) + f_0^A(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{(m_{\Lambda_b}-m_\Lambda)^2-q^2}\left(P^\mu + p^\mu - (m_{\Lambda_b}^2 - m_\Lambda^2)\frac{q^\mu}{q^2}\right)\Bigg]u_{\Lambda_b}$$

- Hadronic $\mathcal{M}$: non-perturbative
- Form factors[1] approximate $\mathcal{M}$
- Depends on di-neutrino mass
  - $q^2 = (p_{\Lambda_b} - p_\Lambda)^2$
- Only vector and axial elements used
  - Couples to neutrinos – scalar and tensor elements ignored

[1]Detmold, Meinel: 1602.01399

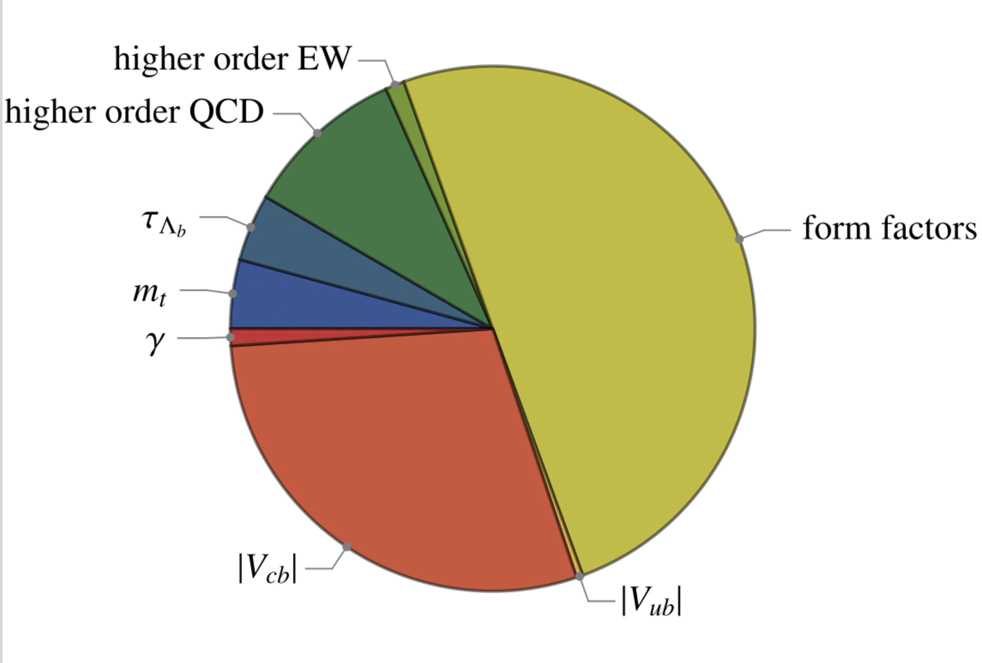
FORMING A PICTURE



Uncertainties in the SM Prediction

$$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})_{\mathrm{SM}} = (7.71 \pm 1.06) \times 10^{-6}$$

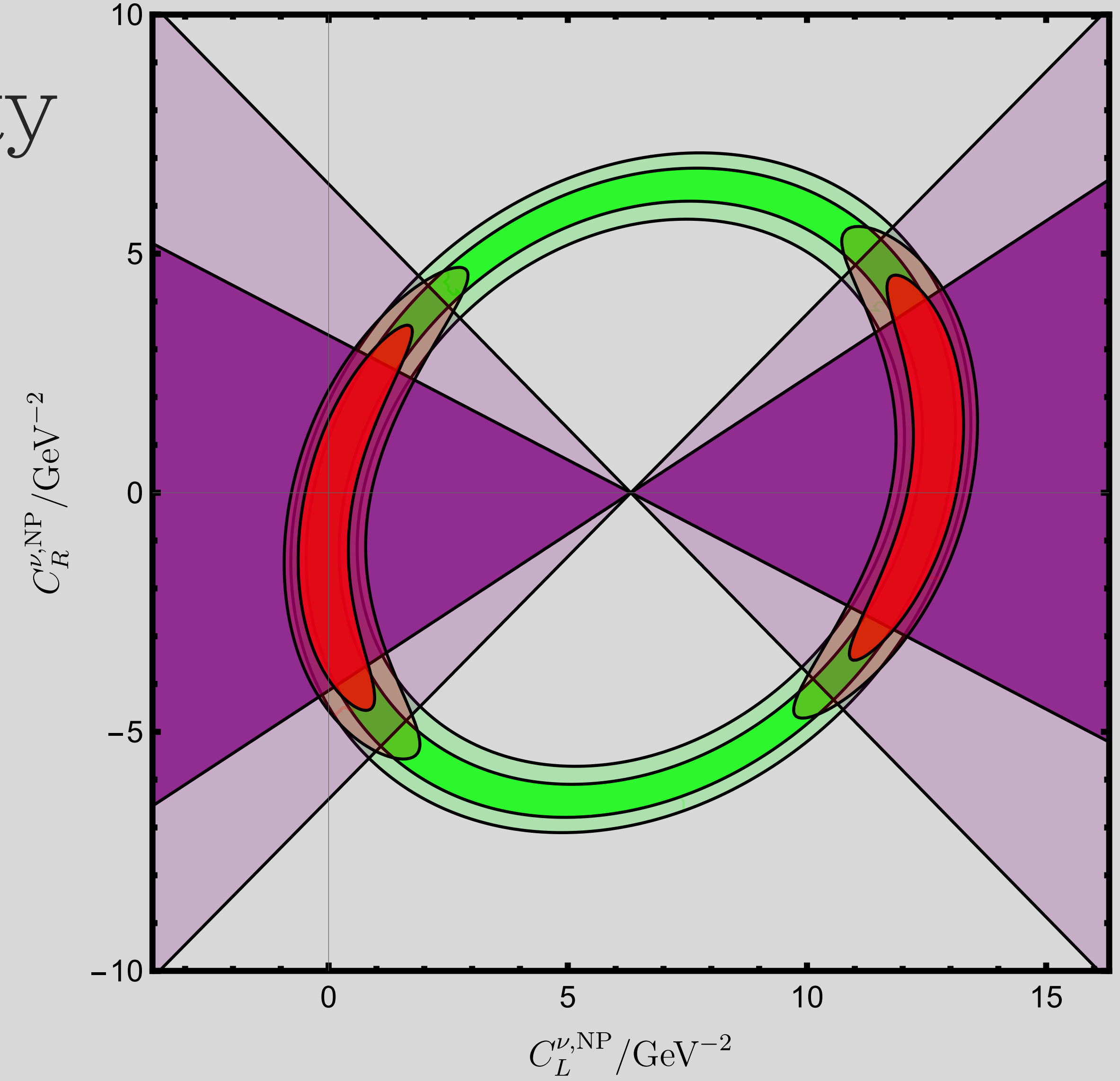
- Form Factors
  - Second order expansion
- CKM Uncertainties
  - Dominated by V_{ts}
  - Unitarity used to obtain tree-level determinations
- Top mass, higher order QCD and EW enter through the SM value of C_L^{ν}
- Uncertainty in the lifetime propagates into the branching fraction



[1]Brod, Gorbahn, Stamou: 1009.0947

New Physics Sensitivity

- Interpretation:
  - Green: Branching Ratio Constraints
  - Purple: A_{FB} Constraints
  - Red: Joint Exclusion
  - $\mathcal{P}_{\Lambda_b} = -0.4$
- Central value is SM Physics
- A_{FB} and branching ratio offer great complementarity



Conclusion

- Future e^+e^- colliders provide excellent prospects for NP detection via $\Lambda_b \to \Lambda\nu\bar{\nu}$
- Polarization measurements offer insight into chiral structure
- This information can be probed in the lab frame as well
- Currently unprobed: a trove of information!

Outlook

- Initial energy distribution: Pythia
- Background analysis
  - Σ_b, etc.
- *Dark* final states masquerade as $\not{E}$
  - Effect on observables - DM structure
  - Interesting mass/coupling enhancements (due to FFs as well)
- Meson decays: current/future data
  - $B \to K^{(*)}\,\nu\,\nu,\;\; B_s \to \phi\,\nu\,\nu$

QUESTIONS?

Thanks for attending!