Searching for New Physics in rare Λ_b^0 decays at LHCb

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(on behalf of the LHCb collaboration)

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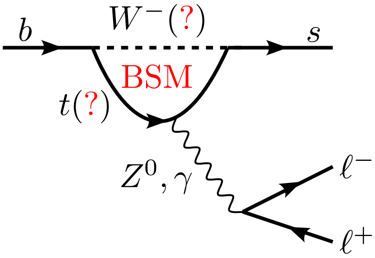
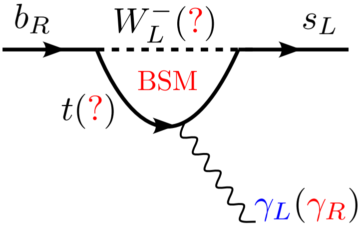
LHCb

Introduction

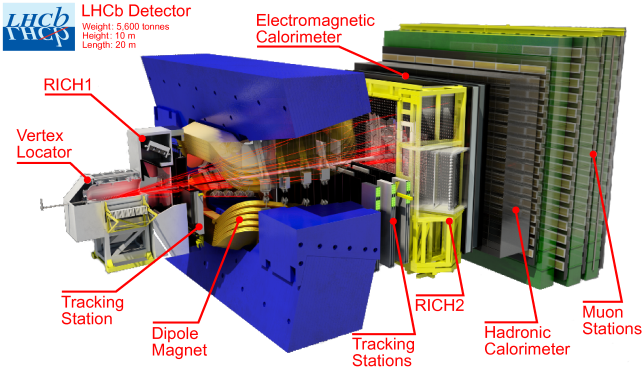
- $b \to s\ell\ell$ and $b \to s\gamma$:
  - Rare FCNC decays with BF $< 10^{-6}$
  - Forbidden at tree level $\to$ loop factor
  - Suppressed by CKM elements
- Several Observables:
  - Branching fractions and CPV
  - Angular analyses
  - Photon polarization
- b-hadrons @LHCb
  - Unique access to all b-hadron species
  - Production ratio of $B_{u,d} : \Lambda_b^0 : B_s^0 \approx$ 4:2:1
- Λ_b^0 baryon
  - Spin-1/2 particle. Complementary to $B_{u,d,s}$.
  - ud diquark behaves as a "spectator".
  - Richer angular structure than b-meson decays.
  - High sensitivity to NP.





The LHCb Detector (Run 1 and 2)

- Single arm forward ($2 < \eta < 5$) spectrometer primed for b- and c-hadrons
- Vertex locator (VeLo):
  - decay time resolution: 45 fs
  - IP resolution: 20 μm
- Dipole magnet:
  - Bending power: 4 Tm
- Tracking stations, TT & OT
  - Momentum resolution $\Delta p/p = 0.5\% - 1.0\%$ (5 GeV-100 GeV)
- RICH1 & RICH2
  - K/π/p separation, $\epsilon(K \to K) \sim 95\%$, Mis-ID $\epsilon(\pi \to K) \sim 5\%$



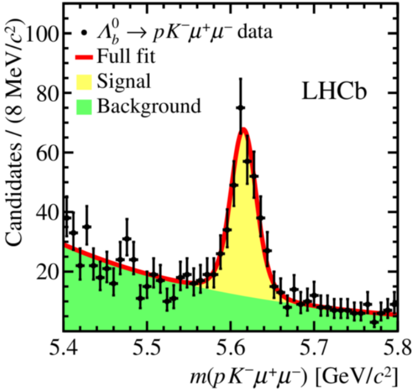
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

- Calorimeters (ECAL & HCAL): e/γ ID, $\sigma_E/E = 10\%/\sqrt{E(\mathrm{GeV})} \bigoplus 1\%$
- Muon stations: μ identification $\epsilon(\mu \to \mu) \sim 97\%$, mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

First observation: $\Lambda_b^0 \to pK^-\mu^+\mu^-$ and $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

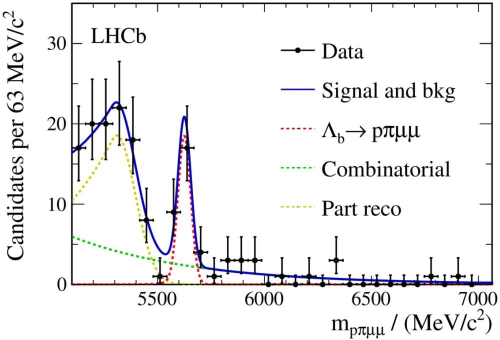
- Run 1-only first observations including CS $b \to d$ mode.

[JHEP 06 (2017) 108]



$\Lambda_b^0 \to pK^-\mu^+\mu^-$

[JHEP 04 (2017) 029]



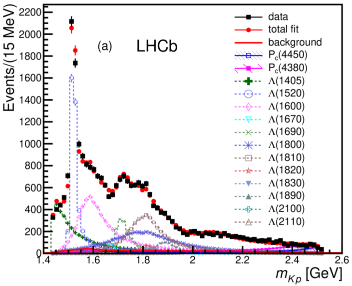
$\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

- CP asymmetries and triple product asymmetries are also checked for CF $\Lambda_b^0 \to pK^-\mu^+\mu^-$. No CPV found.

The complicated $\Lambda^* \to pK^-$ and $N^* \to p\pi^-$ spectra

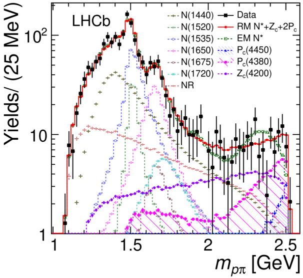
- Major challenge: broad overlapping resonances. Run 1 spectra:

[PRL 115, 072001 (2015)]



$\Lambda_b^0 \to J/\psi\, pK^-$

[PRL 117, 082003 (2016)]



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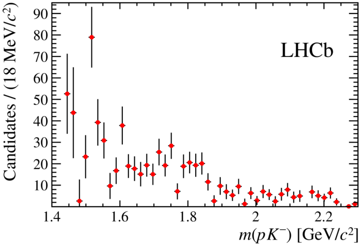


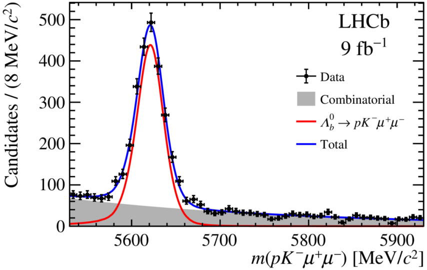
$\Lambda_b^0 \to pK^-\mu^+\mu^-$

- Interpretation needs FFs (hard!). Quark model $\Lambda_b^0 \to \Lambda^*$ FFs from Mott-Roberts. Lattice FFs only for the narrow $\Lambda(1520)$ state.

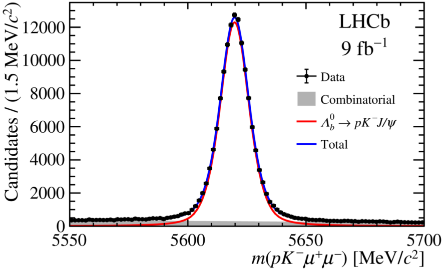
$\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ differential BFs

- Full Run 1+2 ($9\,\text{fb}^{-1}$) study of the narrow ($\Gamma_0 \sim 16$ MeV) $J^P = (3/2)^-$ state, $\Lambda(1520)$

[arXiv:2302.08262] (accepted by PRL)



$\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$



$\Lambda_b^0 \to pK^-J/\psi$

- $\Lambda_b^0 \to pK^-J/\psi$ as normalization mode.
- Signal yield for the rare mode $= 2250 \pm 57$

$\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ differential BFs (cntd.)

- Extraction of $\Lambda(1520)$ from other states by fitting $m(pK^-)$ using background subtracted data. Interferences between Λ^* states found to be small and included in systematics.

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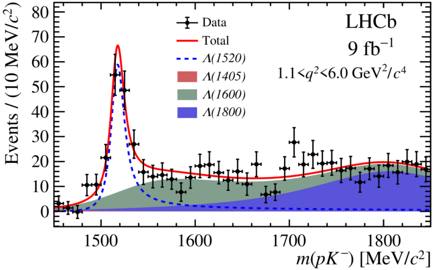
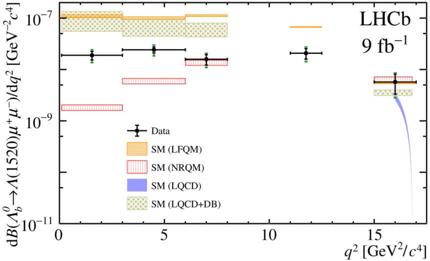


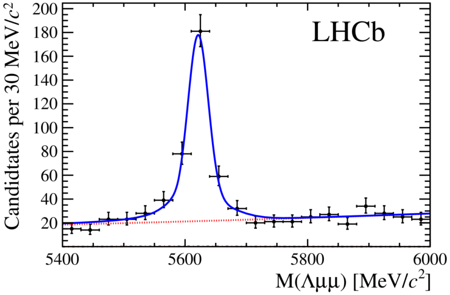


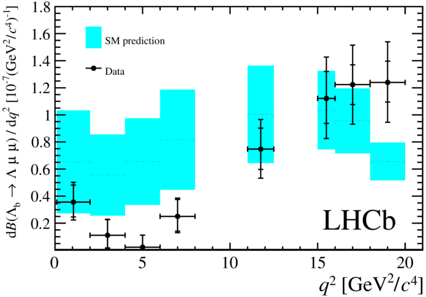
- Large differences with predictions at low and mid q^2. Need better theory understanding of the FFs.
- Reasonably consistent with lattice at high q^2.

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ differential BFs

- Study of decay with ground state $\Lambda(1115)$ in final state using Run 1 (3.0 fb^{-1}) data.
- Compared to excited Λ^* that decay strongly, $\Lambda(1115)$ is long-lived and more difficult to reconstruct.

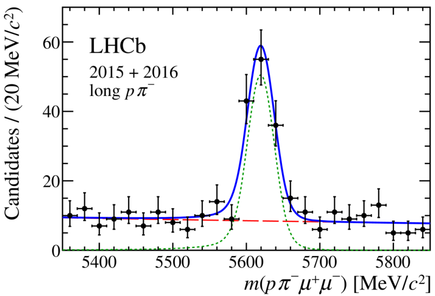
[JHEP 06 (2015) 115]

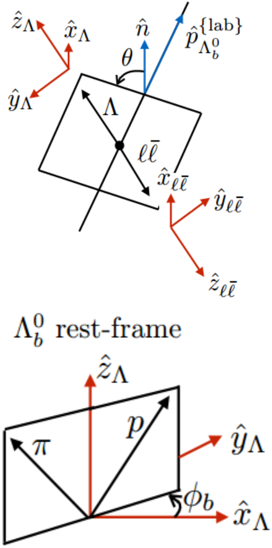




- BFs somewhat lower than theory in the low-q^2 region (as in other $b \to s\mu^+\mu^-$ modes), but consistent with SM.

[JHEP 09 (2018) 146]





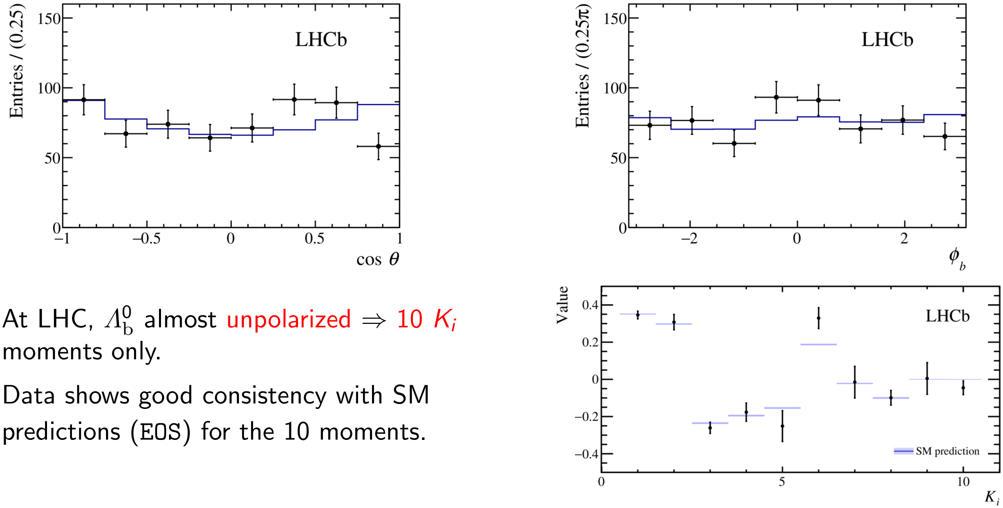
- Uses 5 fb^{-1} data in $q^2 \in [15, 20]$ GeV^2.
- 34 q^2-dependent angular moments,

  $$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega}) \ ,$$

  where $\vec{\Omega} \equiv (\cos\theta, \cos\theta_l, \phi_l, \cos\theta_b, \phi_b)$ for polarized Λ_b^0 .
- K_i determination by moments analysis

- The angular moments model reproduces the 1-d distributions:

[JHEP 09 (2018) 146]

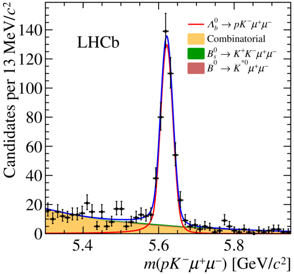


- At LHC, Λ_b^0 almost unpolarized $\Rightarrow$ 10 K_i moments only.
- Data shows good consistency with SM predictions (EOS) for the 10 moments.

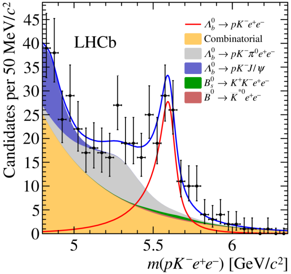
Lepton Flavour Universality tests in $\Lambda_b^0 \to pK^-\ell^+\ell^-$

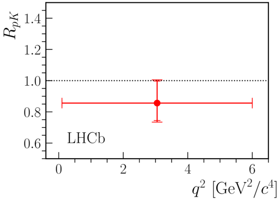
- First test of LFU in b-baryons using 4.7 fb^{-1} data. [JHEP 2020, 40 (2020)]

Muon:



Electron:

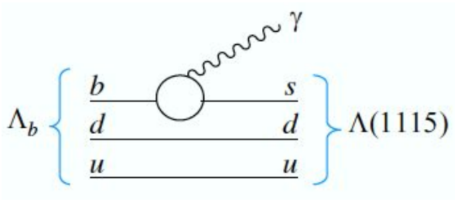




- $$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}$$
- $$R_{pK}|_{0.1<q^2<6\text{GeV}^2} = 0.86^{+0.14}_{-0.11} \pm 0.05$$
- Compatible with unity at 1 σ. Full Run1+2 analysis ongoing.

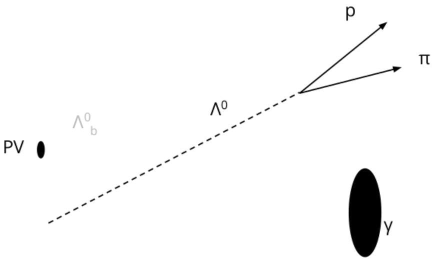
First Observation of $\Lambda_b^0 \to \Lambda\gamma$

- Baryonic $b \to s\gamma$ not observed previously BF $< 10^{-3}$ CDF: [PRD.66.112002]



- While $\mathrm{BF_{SM}} \in [0.06, 1] \times 10^{-5}$ [Wang et al., Mannel et al., Gan et al., Faustov et al.]
- Access to photon polarization, thanks to self-analyzing $\Lambda^0 \to p\pi^-$ weak decay. [Mannel/Recksiegel, Hiller/Kagan]

- Experimentally, very challenging. Λ_b^0 vertex reconstruction is not possible.

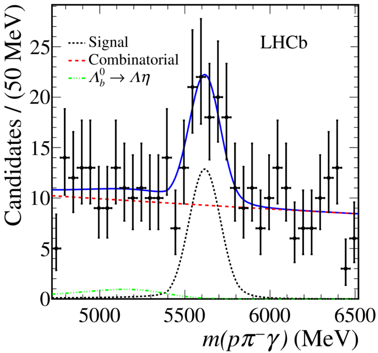


- Huge combinatorial background mitigated with MVA. Dedicated trigger added in Run2.

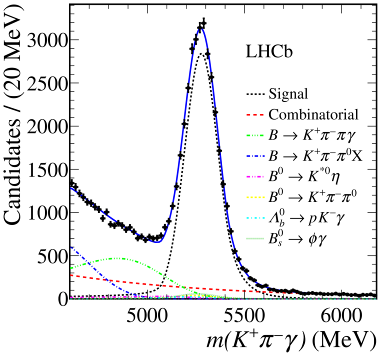
First observation of $\Lambda_b^0 \to \Lambda\gamma$ (cntd.)

- Using Run2 2016 dataset ($1.7\ \mathrm{fb}^{-1}$), first observation at 5.6σ [PRL 123, 031801 (2019)]

Signal, $\Lambda_b^0 \to \Lambda\gamma$



Normalization, $B^0 \to K^*\gamma$

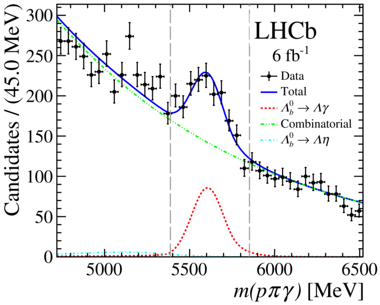


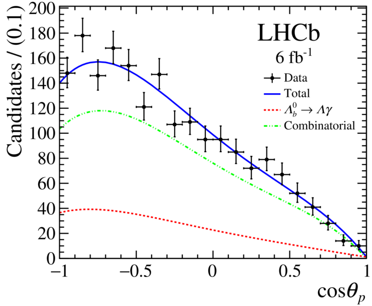
- Branching fraction: $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5\ (\mathrm{stat}) \pm 0.6\ (\mathrm{syst}) \pm 0.7\ (\mathrm{external})) \times 10^{-6}$
- In agreement with theoretical prediction

Photon polarization in $\Lambda_b^0 \to \Lambda\gamma$

- In SM, photon predominantly LH for b-quark decay. γ_{pol} highly sensitive to RH currents from NP. Large effort from various b-decays at LHCb.
- γ_{pol} measured for the first time in radiative b-baryon decays using 6 fb^{-1} data (Run 2).

[PRD 105 (2022) L051104]

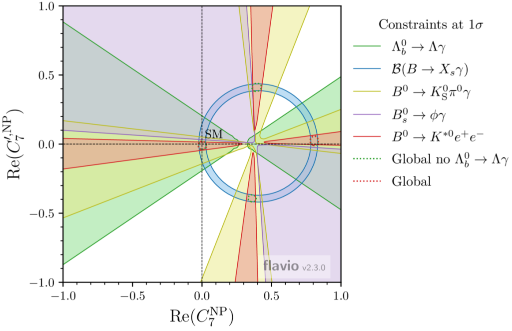


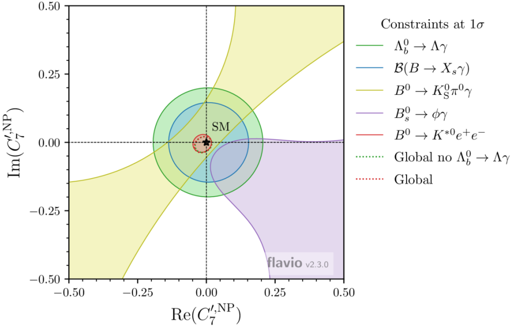


- $\frac{d\Gamma}{d\cos(\theta_p)} \propto 1 - \alpha_\gamma \alpha_\lambda \cos(\theta_p)$, where θ_p is the $\Lambda^0 \to p\pi^-$ decay helicity angle.
- Photon polarization, α_γ, is measured by fit to $\cos(\theta_p)$.
- $\alpha_\gamma = 0.82^{+0.17}_{-0.26}(\text{stat.})^{+0.04}_{-0.13}(\text{syst.})$. Compatible with SM prediction of $\alpha_\gamma \approx +1$.

- Constraints on the Wilson Coefficients of the effective Hamiltonian of the $b \to s\gamma$ transition.
- New constraint on C_7 and C_7': breaks 4-fold ambiguity to 2-fold remnant ambiguity:

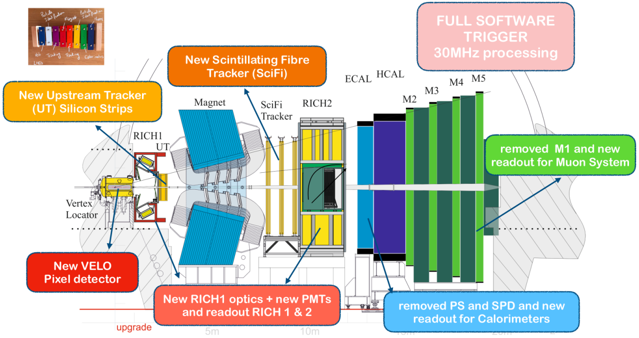
[PRD 105 (2022) L051104]

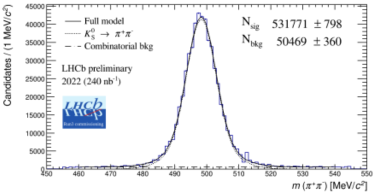




LHCb upgrade and status of Run 3

- Major upgrade during LS2 $\Rightarrow$ almost a brand new detector for Run3.
- Fully software trigger and real-time alignment+calibration.
- Commissioning and early measurements campaign ongoing (EMTF).





LHCb-FIGURE-2023-005

- Around 150 pb^{-1} *pp* data collected in summer 2023. Various expected peaks seen in EMTF.
- VeLo vacuum incident in January and LHC incident in summer. LHCb running with VeLo partially open. Heavy ion (PbPb) data-taking ongoing.

- Preparing for *pp* collisions in 2024 with all sub-detectors included.

Summary

- FCNC $b \to \{s, d\}$ decays are powerful tools to hunt NP.
- LHCb has unique access to b-baryons, complementary to $B_{u,d,s}$ mesons. Large program, especially with Λ_b^0 rare decays.
- At the moment all seems to be compatible with SM prediction.
- Many Run2 analyses (amplitude analyses, LFUV tests...) in the immediate pipeline. Stay tuned for Run3 as well...

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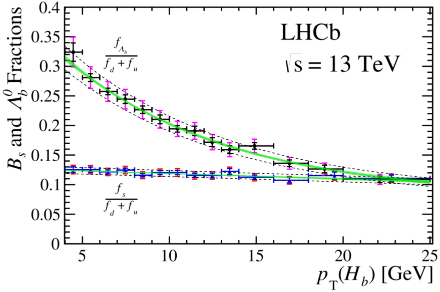
THANK YOU!

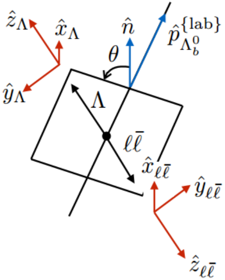
Backup: Ratio



$$\hat{z}_\Lambda = \hat{p}_\Lambda^{\{\Lambda_b^0\}}$$
$$\hat{y}_\Lambda = \hat{n} \times \hat{p}_\Lambda^{\Lambda_b^0}$$

$$\hat{z}_{\ell\bar{\ell}} = \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$$
$$\hat{y}_{\ell\bar{\ell}} = \hat{n} \times \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$$

Λ_b^0 rest-frame



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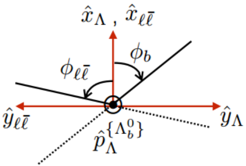
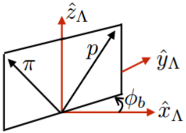
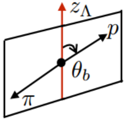


Λ_b^0 rest-frame

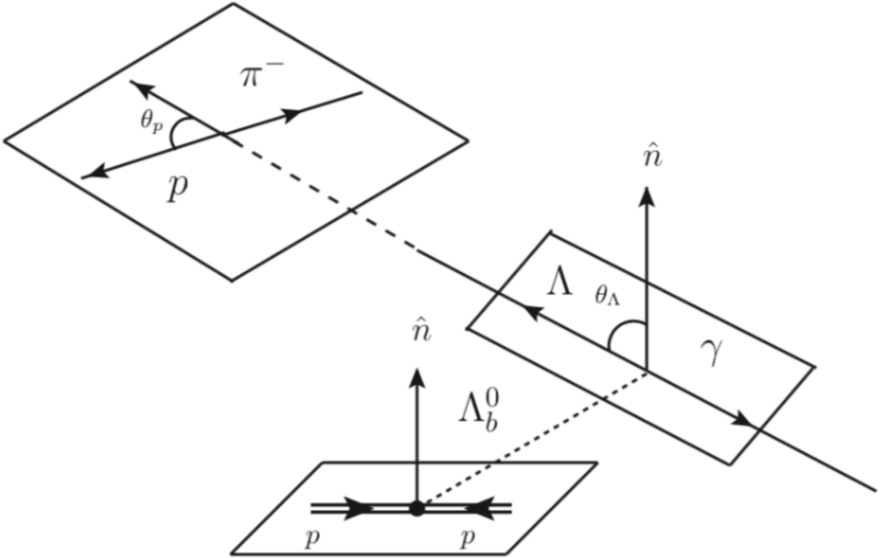


Λ rest-frame



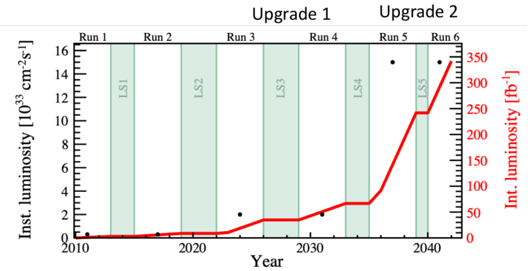
$$\hat{z}_\Lambda^{\{\Lambda\}} = -\hat{p}_{\ell\bar{\ell}}^{\{\Lambda\}}$$

Backup: Schematic view of $\Lambda_b^0 \to \Lambda\gamma$



Backup: LHCb upgrades

- Absence of evidence for New Physics implies that it is either very heavy or highly complex
- Flavor physics can probe New Physics before it is observed directly, by looking at indirect effects in already accessible energy scale processes
- Along with other flavor physics aspects, LHCb has a unique chance with Λ_b^0 decays.
- For all these efforts, we need huge statistics (high L), low systematics (very well-characterized detectors), and precise SM predictions.
- Upgrade 1:
  $L_{peak} = 2 \times 10^{33} cm^{-2} s^{-1}$
  $L_{int} = 50\ fb^{-1}$(Run 3 & 4)
- Upgrade 2:
  $L_{peak} = 1.5 \times 10^{34} cm^{-2} s^{-1}$
  $L_{int} = 300\ fb^{-1}$(Run 5 & 6)



Backup: Upgrade II

- After Expression of Interest (2017) & Physics Case (2018), Framework TDR approved in March 2022
- We need to complement it with more detailed plans / scoping scenarios, manpower, and funds, before moving to sub-detector TDRs
- Target: produce the Scoping Document within 2024