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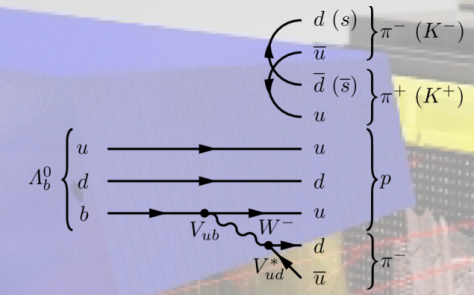
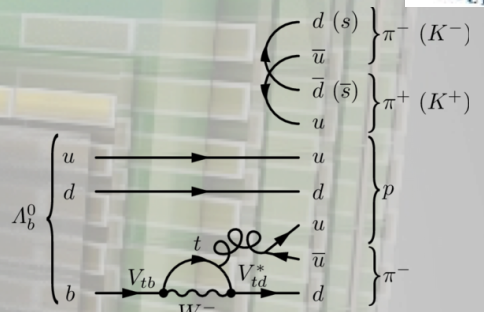
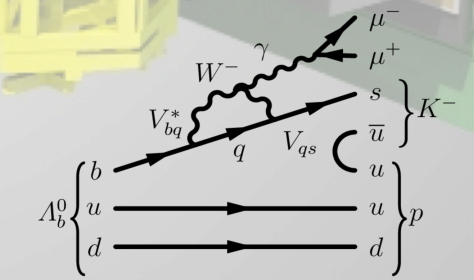
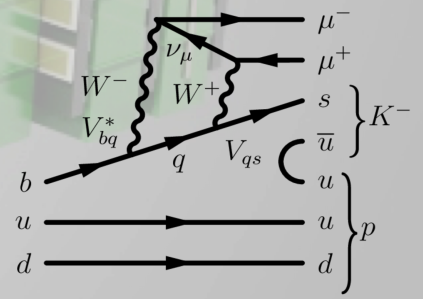
On behalf of LHCb

Search for CPV in b baryon decays









Why

- Measurements of CPV provide sensitive probes of BSM physics.
- CPV has traditionally been studied in meson systems. Looking at baryons is the next natural step.
- Our universe is made up of spin carrying matter!!
- LHCb produces copious amounts of Λ_b^0 baryons.
- Charmless decays of Λ_b^0 are predicted to have sizeable CP asymmetries. [arXiv:1412.1899]

CP Violating observables

Two complementary approaches!

CP - odd ($\hat{T}$ even)

- $\mathcal{A}_{CP} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\bar{\Lambda}_b^0 \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\bar{\Lambda}_b^0 \to \bar{f})}$
- $\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP} - \mathcal{A}_{CP,control}$
- Sensitive to interference of $\hat{T}$-even amplitudes
- Dependent on presence of strong phases
- $\mathcal{A}_{CP}$ sensitive to production and detector induced charge asymmetries

$\hat{T}$ - motion reversal operator. Reverses momenta and helicities

$\hat{T}$ odd

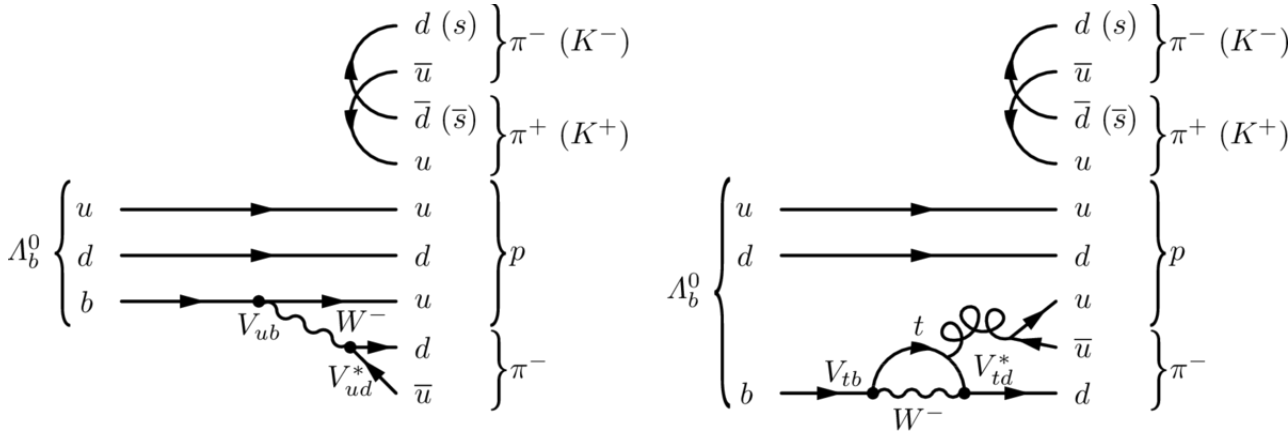
- $C_{\hat{T}} = \vec{p}_h . (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$, $\bar{C}_{\hat{T}} = \vec{p}_{\bar{h}} . (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$
- $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)}$,
- $\bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{N}(-\bar{C}_{\hat{T}}>0) - \bar{N}(-\bar{C}_{\hat{T}}<0)}{\bar{N}(-\bar{C}_{\hat{T}}>0) + \bar{N}(-\bar{C}_{\hat{T}}<0)}$
- $a_{CP}^{\hat{T}_{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}})$
- Sensitive to interference of $\hat{T}$-even & $\hat{T}$-odd amplitudes w/ different weak phases.
- Does not need non-zero strong phase differences.
- Largely insensitive to production and detector induced charge asymmetries.

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to p\pi^-K^+K^-$

arXiv:1609.05216

Run 1 - 3 fb^{-1}

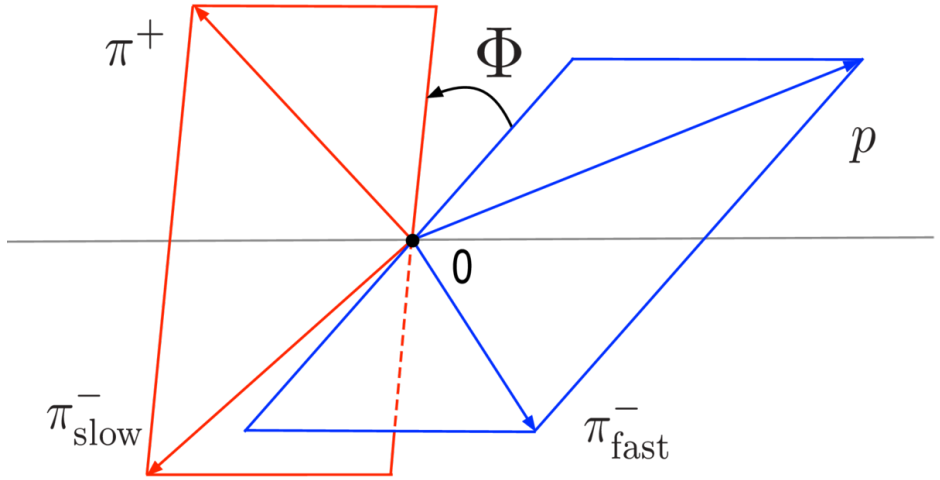
- **First observation of these decay modes.**
- **So far, CP violation has not been observed in the baryonic sector.**



- Study asymmetries in $\hat{T}$ using scalar triple products
- CP asymmetries vary over phase space, may cancel out when integrated
  - Measure integrated and well as in different regions

$$C_{\hat{T}} = \mathbf{p}_p \cdot (\mathbf{p}_{h_1^-} \times \mathbf{p}_{h_2^+}) \propto \sin(\Phi)$$

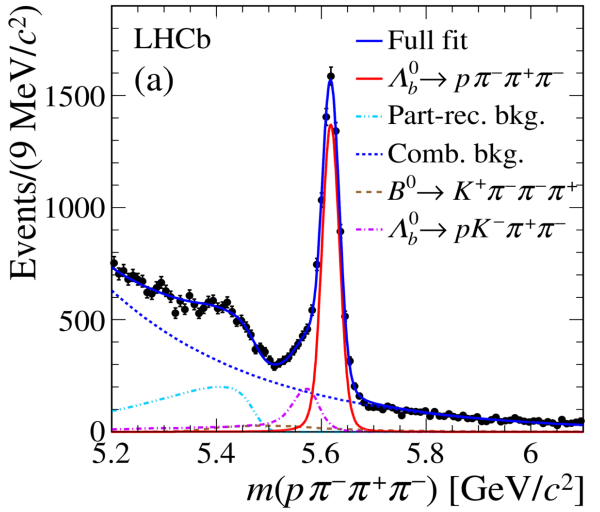
- Two binning schemes
  - Scheme A - isolate phase space according to dominant resonant contributions
  - Scheme B - exploit interference of resonant contributions as function of angle Φ



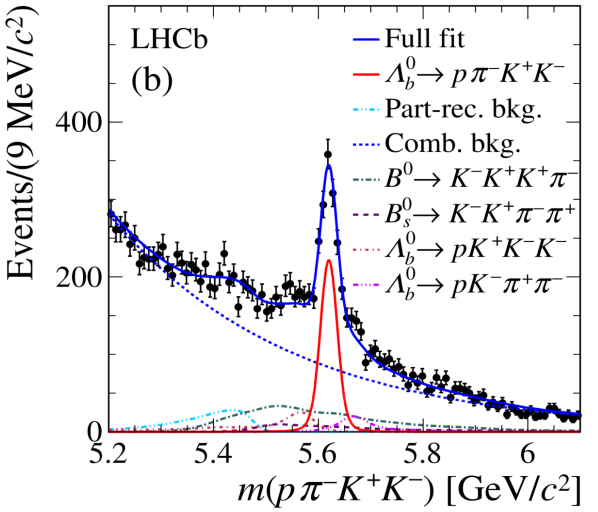
CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to p\pi^-K^+K^-$

- Integrated measurements consistent with no CPV
  - $a_{CP}^{\hat{T}\,odd}(\Lambda_b^0 \to p\pi^-\pi^+\pi^+) = 1.15 \pm 1.45 \pm 0.32$
  - $a_{CP}^{\hat{T}\,odd}(\Lambda_b^0 \to p\pi^-K^+K^+) = -0.93 \pm 4.54 \pm 0.42$

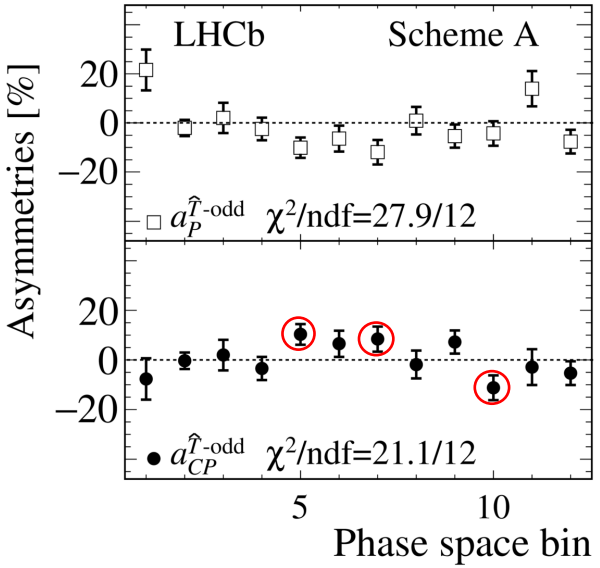
- Localized CPV – deviation from CP symmetry
  - Scheme A – by 2.0σ
  - Scheme B – by 3.4σ
  - **Overall 3.3σ deviation. First evidence in baryon sector!!**

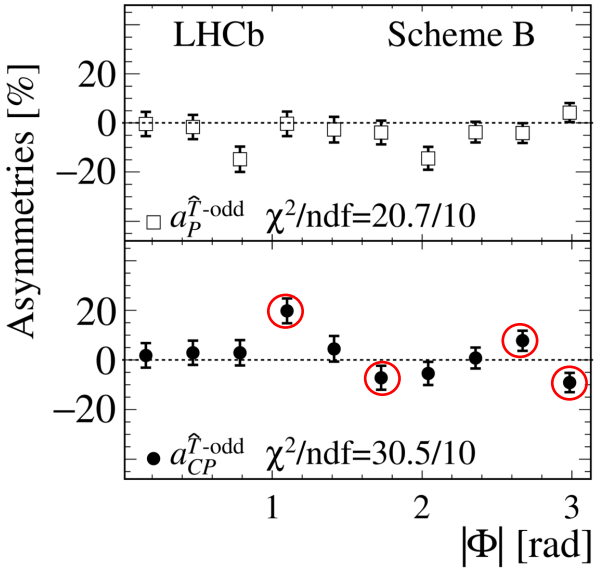


6646 ± 105 signal events



1030 ± 56 signal events





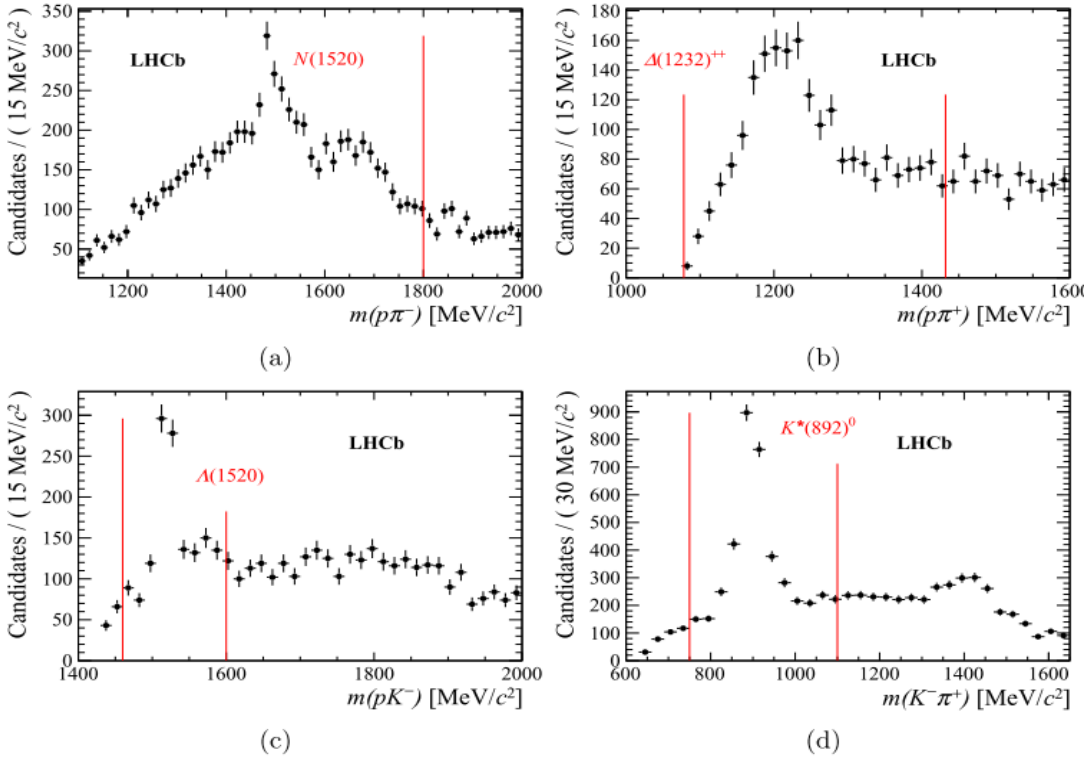
Search for CPV in charmless 4 body Λ_b^0 decays

Run 1 - 3 fb^{-1}

arXiv:1903.06792

- Potential CPV from interference between charged $b \to u$ and neutral $b \to s, d$
- $\Delta\mathcal{A}^{CP} = \mathcal{A}^{CP}_{no-c} - \mathcal{A}^{CP}_{c}$
  - Cancel production and detection asym. to first order using charmed control channel
  - No CPV expected in control channel in SM
- Rich 2 and 3 body resonance structures can enhance CPV due to strong phase differences
  - Low-mass two body baryon resonances $(pK^-, p\pi^-, p\pi^+)$
  - Two body non-baryonic resonances $(\pi^+\pi^-, K^\pm\pi^\mp, K^+K^-)$
- Potential CPV difficult to relate to CKM weak phase
  - Non-predictable strong phases

Charmless mode	Control channel
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$



Search for CPV in charmless 4 body Λ_b^0 decays

- Total of 16 CP asymmetries measured
  - $\Delta\mathcal{A}^{CP}$ integrated over full phase space
  - Specific kinematic regions also explored
- No significant CPV observed.
- Quest for first observation of baryonic CPV continues!

Quasi two body $\Delta\mathcal{A}^{CP}$ results:

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pa_1(1260)^-) = (-1.5 \pm 4.2 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0\rho(770)^0) = (+2.0 \pm 4.9 \pm 0.4)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-) = (+0.1 \pm 3.2 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK_1(1410)^-) = (+4.7 \pm 3.5 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\rho(770)^0) = (+0.6 \pm 6.0 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0K^*(892)^0) = (+5.5 \pm 2.5 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-) = (+4.4 \pm 2.6 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\phi(1020)) = (+4.3 \pm 5.6 \pm 0.4)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to (pK^-)_{\text{high-mass}}\phi(1020)) = (-0.7 \pm 3.3 \pm 0.7)\,\%$$

Integrated $\Delta\mathcal{A}^{CP}$ results:

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$

Two body low mass $\Delta\mathcal{A}^{CP}$ results:

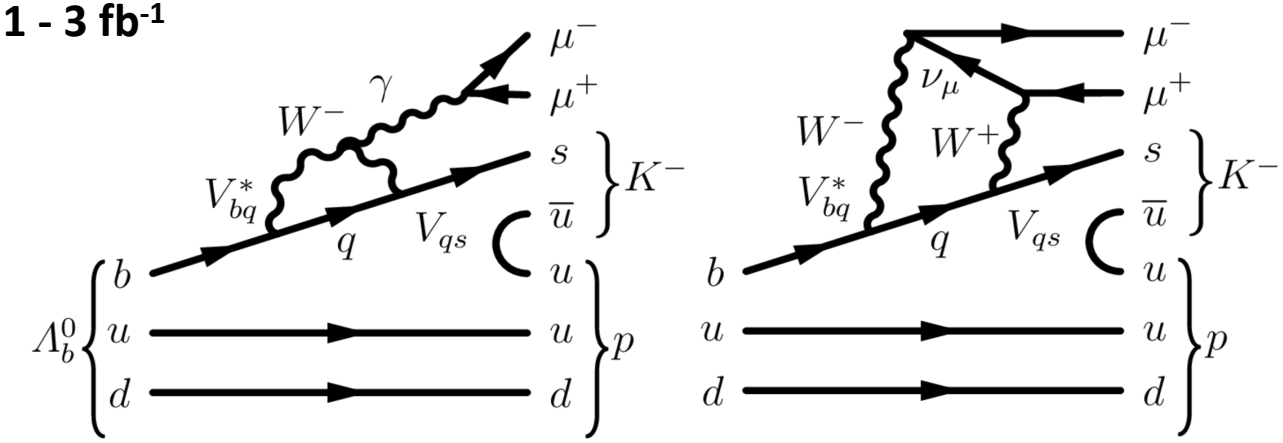
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+3.7 \pm 4.1 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.5 \pm 1.5 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (+2.7 \pm 2.3 \pm 0.6)\,\%$$

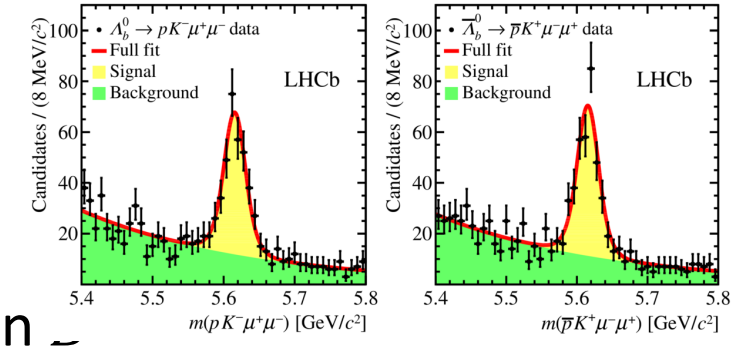
Search for CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$

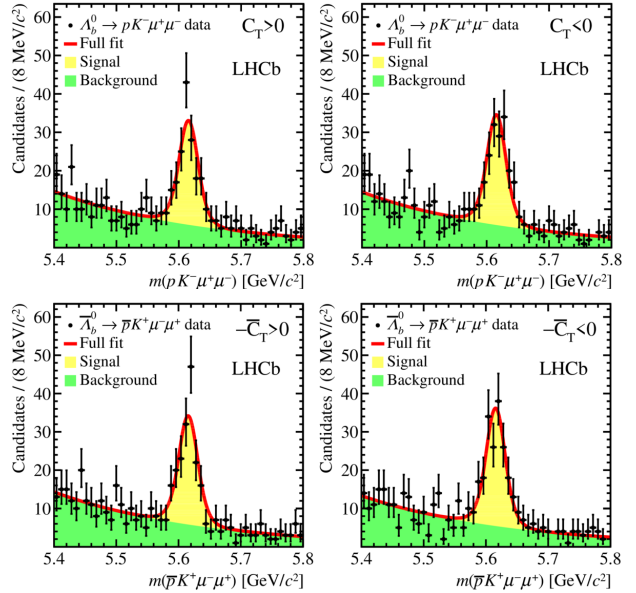
arXiv:1703.00256

- First observation of decay mode
- $b \to s\mu^+\mu^-$ transition
  - Expected CPV $< 1\%$ in SM
  - Susceptible to NP in loops
  - BSM models predict CPV in this transition
- Probe CPV in 2 different ways: $\Delta\mathcal{A}_{CP}$, $a_{CP}^{\hat{T}_{odd}}$
- $\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \pm 0.2)\times10^{-2}$
- $a_{CP}^{\hat{T}_{odd}} = (1.2 \pm 5.0 \pm 0.7)\times10^{-2}$
- Results are compatible with SM CPV predictions and $b \to s\mu^+\mu^-$ transitions in B^+ and B^0 decays.

Run 1 - 3 fb^{-1}





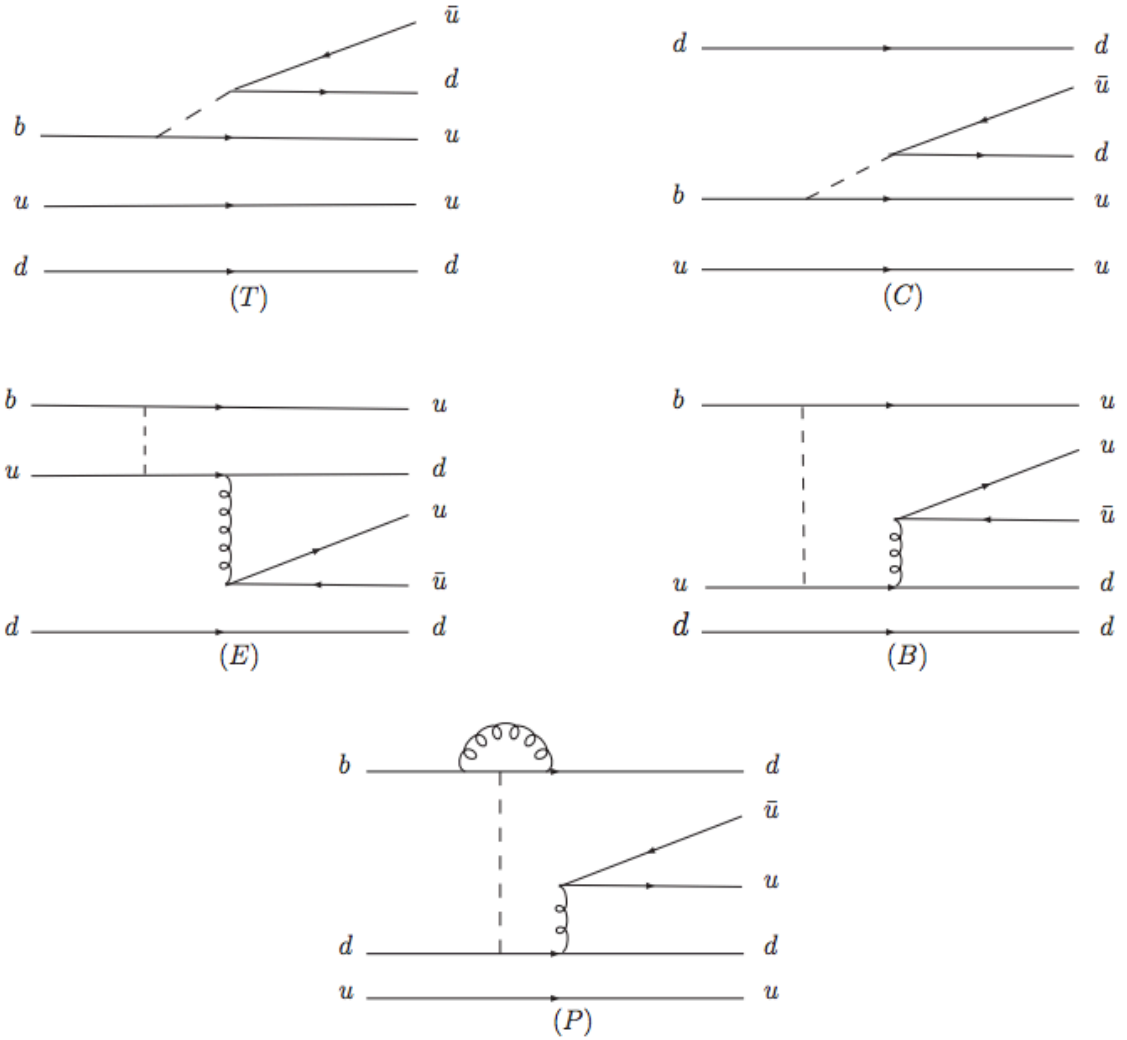


Search for CPV in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$

Run 1 - 3 fb^{-1}

arXiv:1807.06544

	Factorization	pQCD	Experimental
$\mathcal{B}(\Lambda_b^0 \to p\pi).10^{-6}$	4.20 ± 0.75	$4.66^{+2.22}_{-1.81}$	4.3 ± 0.8[1]
$\mathcal{B}(\Lambda_b^0 \to pK).10^{-6}$	4.80 ± 0.77	$1.82^{+0.96}_{-1.07}$	5.1 ± 0.9[1]
$\mathcal{R}_{\pi K}(\Lambda_b)$	0.84 ± 0.09	$2.6^{+1.8}_{-1.8}$	0.86 ± 0.1
$\mathcal{A}_{CP}(\Lambda_b^0 \to p\pi).10^{-2}$	-3.90 ± 0.20	-32^{+49}_{-1}	-10 ± 9[2]
$\mathcal{A}_{CP}(\Lambda_b^0 \to pK).10^{-2}$	5.80 ± 0.22	-3^{+25}_{-4}	6 ± 8[2]
	arXiv:1412.1899	arXiv:0906.1479	CDF LHCb [1]arXiv:0812.4271 [2]arXiv:1403.5586



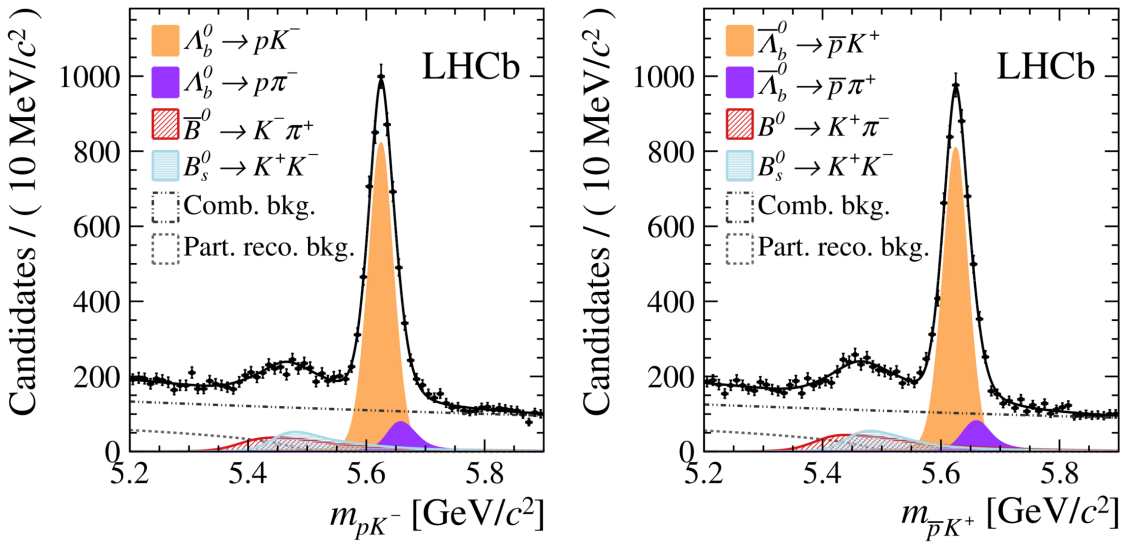
- CPV well established in charmless 2 body B meson decays (similar $b \to u$ transition)
  - $\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.004$
  - $\mathcal{A}_{CP}(B_s^0 \to K^-\pi^+) = -0.221 \pm 0.015$

Search for CPV in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$

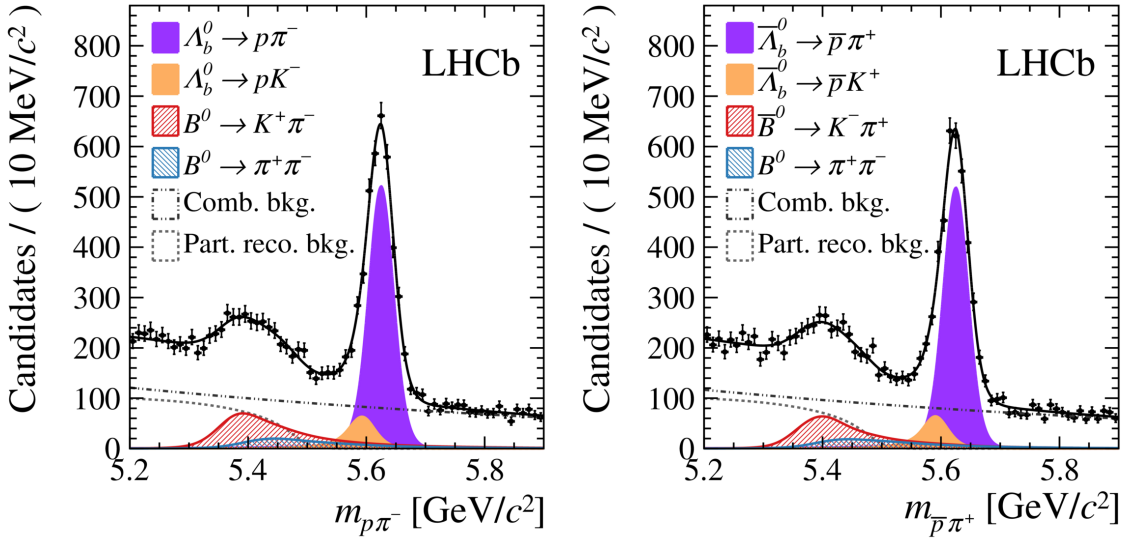
arXiv:1807.06544

- $\mathcal{A}_{CP}^{ph^-} = \mathcal{A}_{raw}^{ph^-} - \mathcal{A}_D^p - \mathcal{A}_D^{h^-} - \mathcal{A}_{PID}^{ph^-} - \mathcal{A}_P^{\Lambda_b^0} - \mathcal{A}_{trigger}^{pK}$
  - $\mathcal{A}_{raw}^{ph^-} = \frac{N(\Lambda_b^0 \to f) - N(\bar{\Lambda}_b^0 \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\bar{\Lambda}_b^0 \to \bar{f})}$, obtained from fits
  - $\mathcal{A}_D^{h^-} = \frac{\epsilon_{rec}^h - \epsilon_{rec}^{\bar{h}}}{\epsilon_{rec}^h + \epsilon_{rec}^{\bar{h}}}$, from charm control samples for K, π, from sim. for p
  - $\mathcal{A}_{PID}^{ph^-} = \frac{\epsilon_{PID}^h - \epsilon_{PID}^{\bar{h}}}{\epsilon_{PID}^h + \epsilon_{PID}^{\bar{h}}}$, from calibration samples
  - $\mathcal{A}_P^{\Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$, production asymmetry, external input
  - $\mathcal{A}_{trigger}^{pK}$ = trigger asymmetry

- $\mathcal{A}_{CP}{}^{pK^-} = (-2.0 \pm 1.3 \pm 1.9)\%$
- $\mathcal{A}_{CP}{}^{p\pi^-} = (-3.5 \pm 1.7 \pm 2.0)\%$
- $\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}{}^{pK^-} - \mathcal{A}_{CP}{}^{p\pi^-} = (1.4 \pm 2.2 \pm 1.0)\%$



$N(\Lambda_b^0 \to pK^-) = 8847 \pm 125$



$N(\Lambda_b^0 \to p\pi^-) = 6026 \pm 105$

CPV summary + implications

Mode	Result
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\Delta\mathcal{A}_{CP}$- no CPV $a_{CP}^{\hat{T}_{odd}}$ - 3.3σ evidence
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Delta\mathcal{A}_{CP}$- no CPV $a_{CP}^{\hat{T}_{odd}}$ - no CPV
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\Delta\mathcal{A}_{CP}$- no CPV
$\Lambda_b^0 \to pK^-K^+K^-$	$\Delta\mathcal{A}_{CP}$- no CPV $a_{CP}^{\hat{T}_{odd}}$ - no CPV
$\Lambda_b^0 \to pK^-\mu^+\mu^-$	$\Delta\mathcal{A}_{CP}$- no CPV

Mode	Result
$\Lambda_b^0 \to K_s^0 p\pi^-$	$\Delta\mathcal{A}_{CP}$- no CPV
$\Lambda_b^0 \to \Lambda K^-\pi^+$	$\Delta\mathcal{A}_{CP}$- no CPV
$\Lambda_b^0 \to \Lambda K^-K^+$	$\Delta\mathcal{A}_{CP}$- no CPV

Mode	Result
$\Lambda_b^0 \to \Lambda\phi$	Triple products - no CPV
$\Lambda_b^0 \to \Lambda K^-\pi^+$	$\Delta\mathcal{A}_{CP}$- no CPV
$\Lambda_b^0 \to \Lambda K^-K^+$	$\Delta\mathcal{A}_{CP}$- no CPV

- Results highlight importance of measuring CPV using complementary experimental approaches
  - $\Delta\mathcal{A}_{CP}$ & $a_{CP}^{\hat{T}_{odd}}$
  - Integrated & Localized CPV
- Will help direct theoretical approaches (factorization vs. perturbative QCD) to CPV in b-hadron decays.

Future Investigations

1806.00861

- Baryon decays to purely baryonic final states are of interest
  - Exhibit a rich spin structure
  - Provide complementary info to mesonic decays or final states

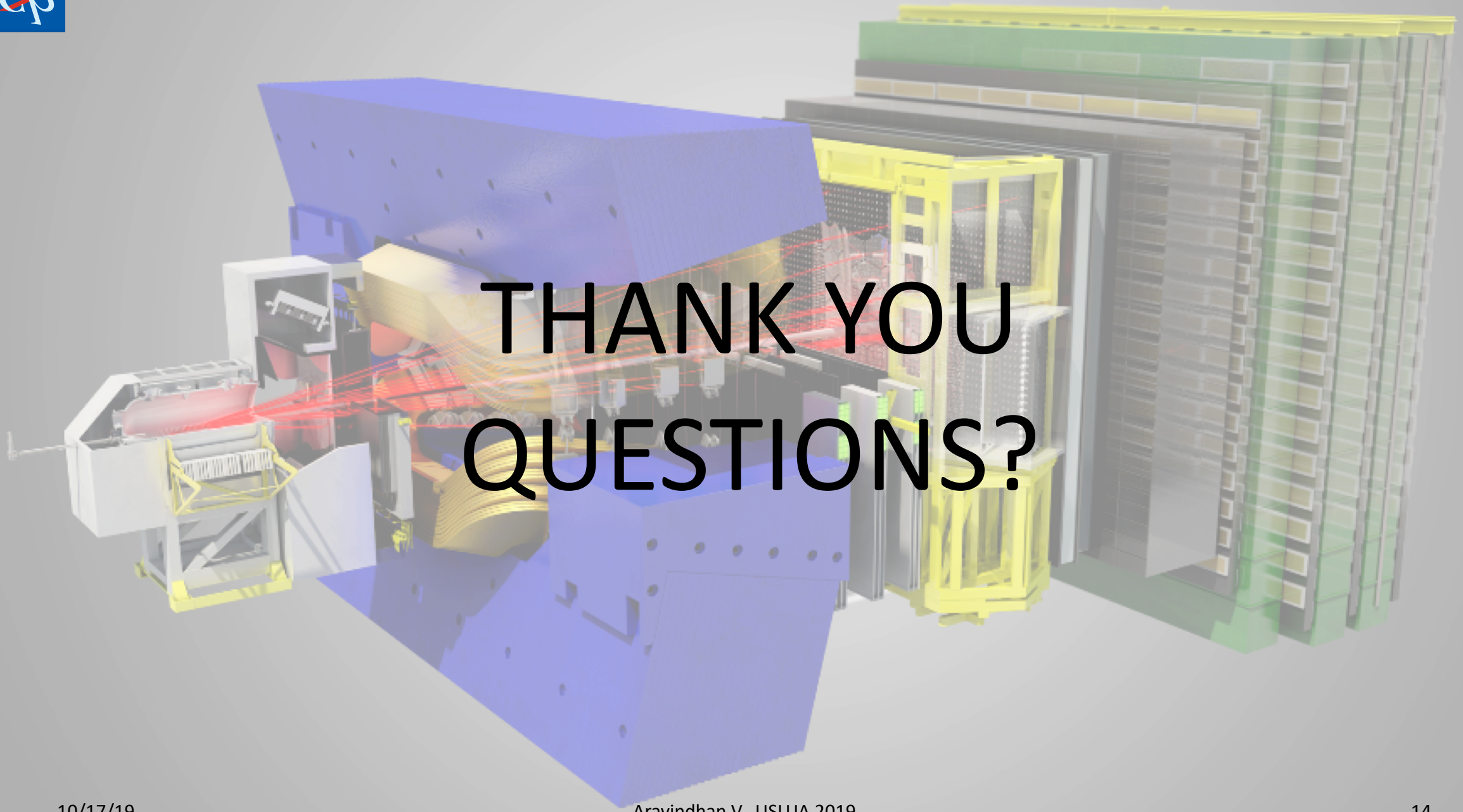
- Elementary decays exclusively involving baryons are only allowed with beauty baryons!
  - Need at least 3 baryons in final state

- "Ground state" reconstructible decays
  - $\Lambda_b^0 \to \Lambda p \overline{p}$
    - Predicted $B\left(\Lambda_b^0 \to \Lambda p \overline{p}\right) = \left(3.2^{+0.8}_{-0.3} \pm 0.4 \pm 0.7\right) \times 10^{-6}$
    - Predicted direct CPA = $(3.4 \pm 0.1 \pm 0.1 \pm 1.0)\%$
  - $\Xi_b^0 \to \Lambda p \overline{p}$
    - Predicted $B\left(\Xi_b^0 \to \Lambda p \overline{p}\right) = (1.4 \pm 0.1 \pm 0.1 \pm 0.4) \times 10^{-7}$
    - Predicted direct CPA = $(-13.0 \pm 0.5 \pm 1.5 \pm 1.1)\%$

Concluding remarks

- **LHCb has made new advances in measurements of CPV in Λ_b decays.**
  - **Besides 3.3σ evidence seen in $\Lambda_b \to p\pi^-\pi^+\pi^-$, all other modes are consistent with CP symmetry.**

- **Moving forward, with ever increasing datasets, LHCb will be shedding new light on baryonic CPV. Stay tuned!**



THANK YOU
QUESTIONS?