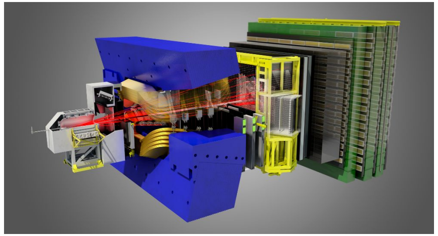


Overview of LHCb results

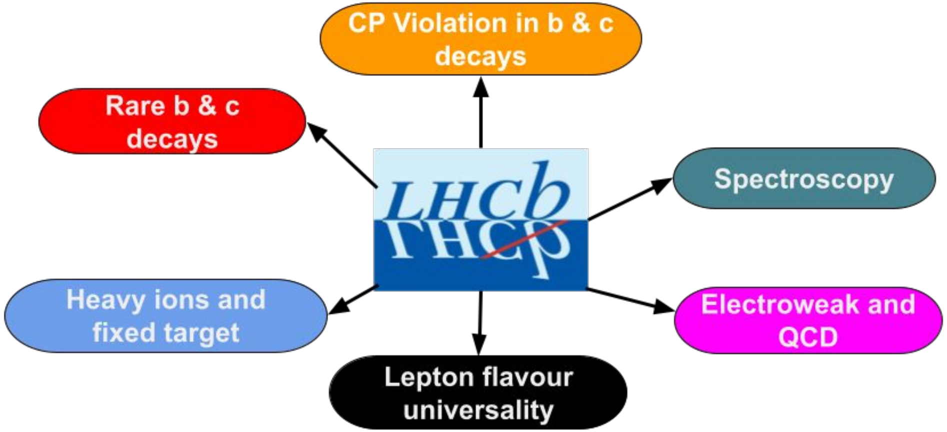
Michele Veltri

on behalf of the LHCb Collaboration

INFN Sez. Firenze & Università Urbino

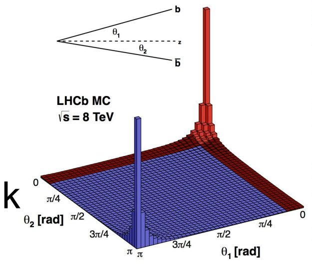
Overview

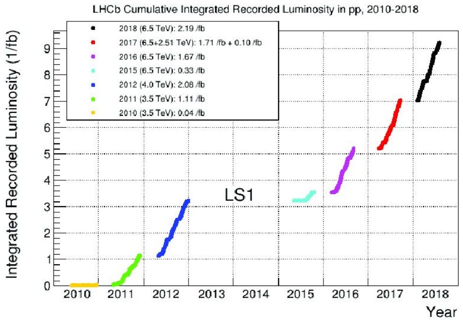
- LHCb is a community of 1700 members from 103 institutes from 22 countries
- Originally designed to measure CP violation in the b sector
- Evolved over time into a general purpose experiment active in many research areas
- Selection of some of the latest results:
  - γ angle
  - $B^{*0}_{(s)} \to \mu^+\mu^-$ in B_c^+ decays
  - Antihelium production in $\overline{\Lambda}^0_b$ decays
  - Λ^0 transverse polarization
- Not covering spectroscopy (see Paras talk) and weak mixing angle (see Heather talk)



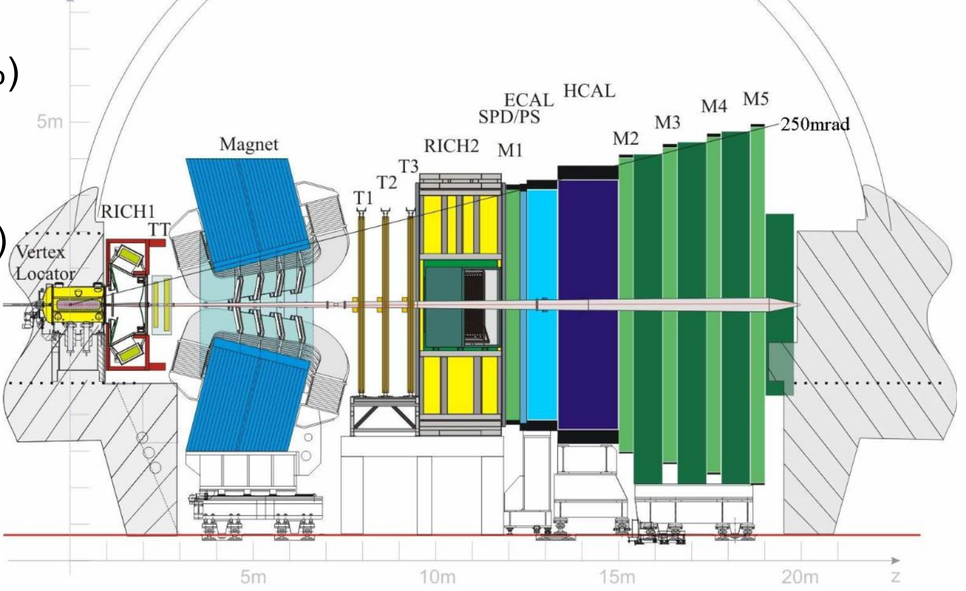
The (Old) LHCb Detector

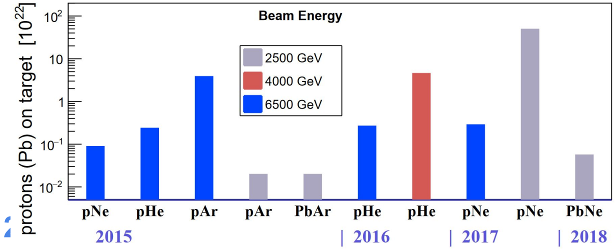
- **Run 1** (2011-2012) → 3/fb at 7-8 TeV
- **Run 2** (2015-2018) → 6/fb at 13 TeV
- For the new detector (and future upgrades) see Biljana's talk
- Single arm forward spectrometer (2<η<5)
- High precision vertexing and tracking
- Excellent timing resolution
- High performance PID (Efficiency: K=95%, μ=97%)
- **SMOG**→ **S**ystem for **M**easuring **O**verlap with **G**as
- Injection of noble gases inside the LHC beam pipe around (±20 m) the LHCb IP (100x vac. press.)
- Highest energy ever fixed target experiment
- Rich IFT research program





[JINST 3 (2008) S08005](https://doi.org/10.1088/1748-0221/3/08/S08005)

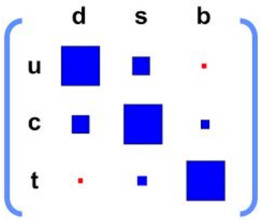




CKM angle ɣ

- In the Standard Model the CKM matrix is the only source of CP violation
- This matrix describes the rotation between flavour and mass eigenstates of quarks

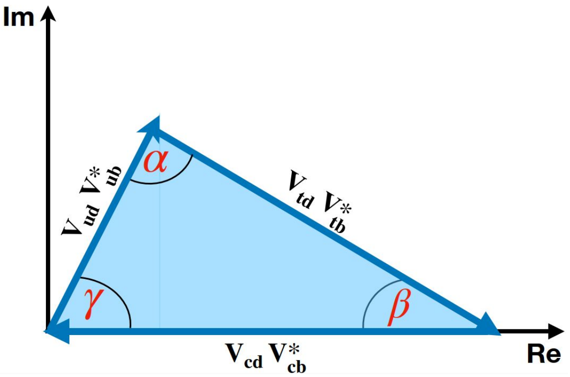
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- The unitarity of V_{CKM} provides relations like (this one for b decays):

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

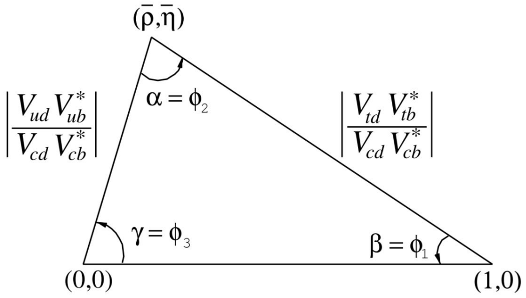
- These relations can be visualized as triangles in the complex plane
- Key test of the SM → Verify the unitarity of CKM matrix
  - Overconstrain the UT with measurement of CKM parameters
  - Check for global consistency
- ɣ angle from UT → Benchmark measurement in the SM



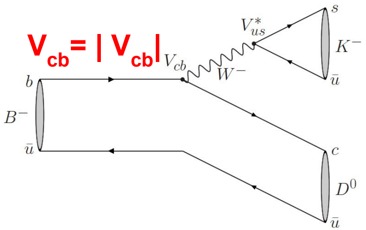
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

CKM angle ɣ

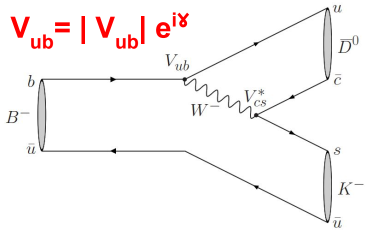
- The only angle in the UT accessible via tree level processes
- Negligible theoretical uncertainty
- Determined in the interference of transitions $b \to c\bar{u}s$ and $b \to u\bar{c}s$
- The most sensitive decay channels are $B^{\pm} \to D K^{\pm}$ ($D = D^0, \bar{D}^0$) where D meson decay to the same final state
- Search for physics beyond SM → Compare direct (tree-level) vs. indirect measurements which are based on independent observables (loop-induced) and assume unitarity

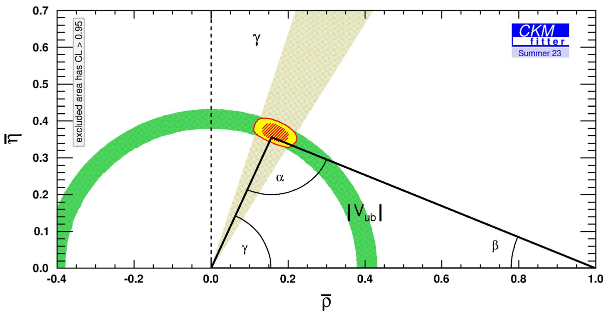


$V_{cb} = |V_{cb}|$

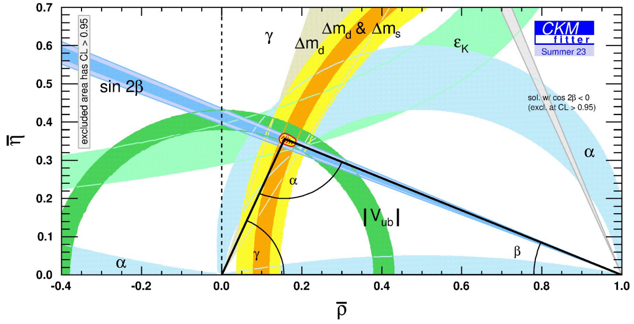


$V_{ub} = |V_{ub}|\, e^{i\gamma}$





Any difference signals physics BSM



CKMfitter2023

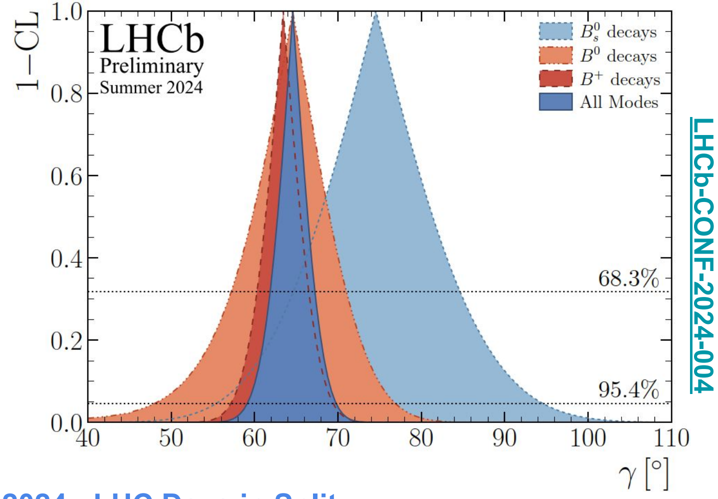
$$\gamma_{dir} = \left(65.9^{-3.5}_{+3.3}\right)^{\circ}$$

$$\gamma_{ind} = \left(66.23^{-1.43}_{+0.6}\right)^{\circ}$$

CKM angle ɣ from LHCb

- Small BR → Combination of all LHCb results on ɣ
- 4 new and few updated measurements
- Hadronic parameters of B and D decays
  → External inputs from BESIII and CLEO data
- 198 input observables to determine 53 parameters

$$\gamma_{LHCb} = (64.6 \pm 2.8)^\circ$$



LHCb-CONF-2024-004

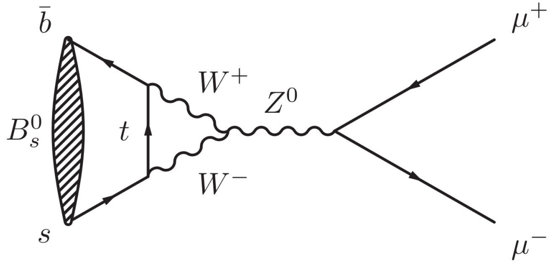
B decay	D decay	Ref.	Dataset	Status since Ref. [13]
$B^\pm \to Dh^\pm$	$D \to h^+h'^-$	[32]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$	[19]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[33]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^+h'^-\pi^0$	[34]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[35]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[36]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to h^+h'^-$ (PR)	[32]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (PR)	[20]	Run 1&2	**New**
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (FR)	[21]	Run 1&2	**New**
$B^\pm \to DK^{*\pm}$	$D \to h^+h'^-$	[22]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[22]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-$	[22]	Run 1&2	**New**
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h'^-$	[37]	Run 1	*As before*
$B^0 \to DK^{*0}$	$D \to h^+h'^-$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	[24]	Run 1&2	**Updated**
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[38]	Run 1	*As before*
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[25, 39]	Run 1&2	**Updated**
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[40]	Run 1&2	*As before*

- Excellent agreement with the global CKM fit and compatible with previous LHCb combinations (almost 1° more precise w.r.t. 2022 result)
- The most precise direct measurement
- Uncertainties are dominated by statistics
- Improve with Run3 and aim to sub-degree precision with the future Upgrade II

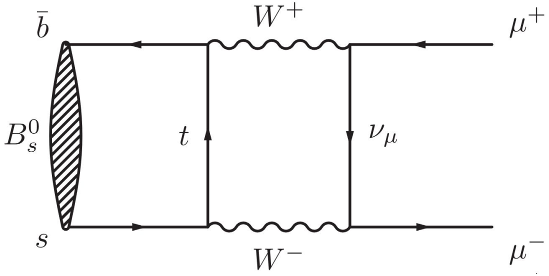
$B^{*0}_{(s)} \to \mu^+\mu^-$ in B_c^+ decays

LHCb-CONF-2024-003
LHCb-PAPER-2024-026

- FCNC not allowed at tree level in the SM
- Decay can only proceed through loops
  → Very rare processes
- Important test of SM
  → Sensitive to new physics contributions
- As an example $B^0_s \to \mu^+\mu^-$ is a golden channel to study FCNC decays
- In this new analysis study the excited vector counterparts → B^{*0} and B^{*0}_s using the full Run1+2 data



$B^0_s \to \mu^+\mu^-$

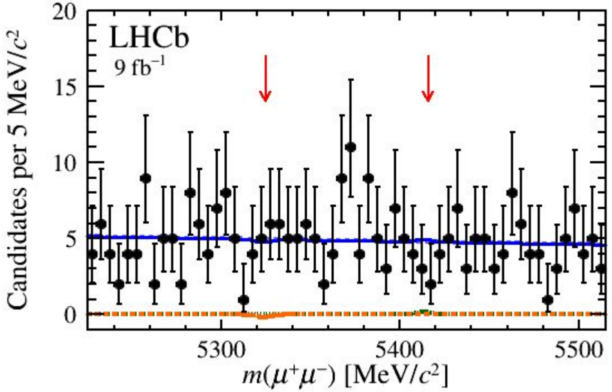


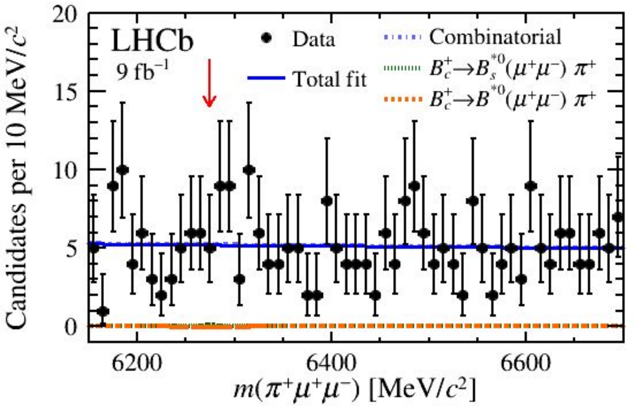
$B^{*0}_{(s)} \to \mu^+\mu^-$ in B_c^+ decays

LHCb-CONF-2024-003
LHCb-PAPER-2024-026

- First search of $B^{*0} \to \mu^+\mu^-$ and $B^{*0}_s \to \mu^+\mu^-$ decays
- Excited vector mesons
  → Not helicity suppresses as their pseudoscalar companions
- However very rare week decay → Electromagnetic mode dominates
- Sensitivity to different Wilson coefficients
- SM prediction: $B \sim 10^{-11}$ [PRL 116 (2016) 141801]
- Search using $B_c^+ \to B^{*}_{(s)}{}^0 \pi^+ \to \mu^+\mu^- \pi^+$ decay chain
  → Exploit B_c^+ vertex signature to suppress prompt background
- Simultaneous fit to $m(\mu^+\mu^-)$ and $m(\mu^+\mu^- \pi^+)$
- No signal observed in both decay modes
- BF relative to $B_c^+ \to J/\Psi\ \pi^+$ at 90% CL:

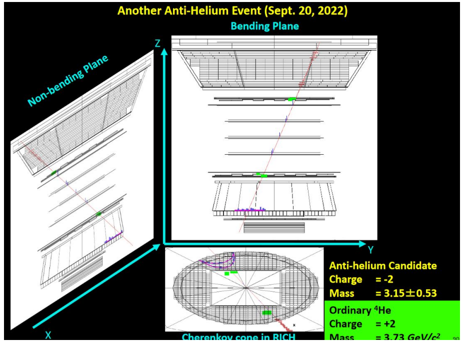
$$\mathcal{R}_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 3.8 \times 10^{-5}$$
$$\mathcal{R}_{B_s^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 5.0 \times 10^{-5}$$



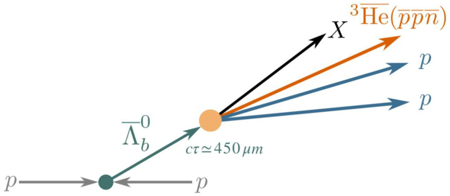


Antihelium production in $\overline{\Lambda}^0_b$ decays

LHCB-CONF-2024-005

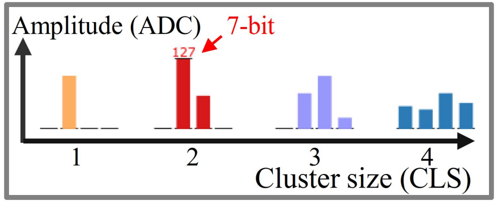


- Antihelium in cosmic rays → "Smoking gun" for new physics
- The possible detection of several antihelium nuclei by AMS-02 has triggered a lot of interest in the astrophysical community
- Possible explanations: the existence of nearby antimatter regions in space [PRD103 (2021) 083016] or dark matter annihilations to $b\overline{b}$ pairs [PRL 126 (2021) 101101]
- In this scenario $\overline{\Lambda}^0_b$ produced in DM annihilation could have a significant BR to $^3\overline{\text{He}}$ in decays to five (anti)nucleons
- The authors predict a BR of up to $3\text{x}10^{-6}$ which could produce a signal in AMS

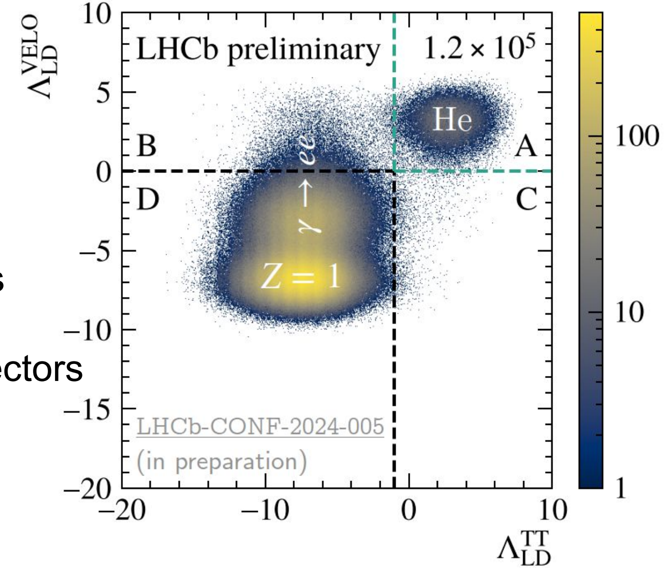


Antihelium production in $\bar{\Lambda}^0_b$ decays

LHCB-CONF-2024-005

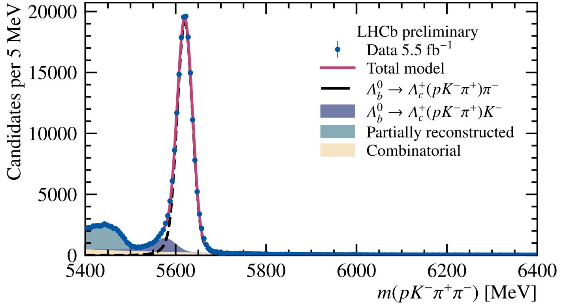


- LHCb, has recently developed a technique to identify ^{3}He [JINST 19 (2024) P02010] and can provide input complementing the cosmic rays investigations
- The ^{3}He identification @ LHCb is achieved measuring the ionization losses in the silicon sensors
  $\rightarrow Z^2$ dependence, helium is heavily ionizing
- Build log-likelihood estimators based on cluster size and ADC counts
- Background rejection improved using information from other subdetectors
- Excellent separation between He and Z=1 background

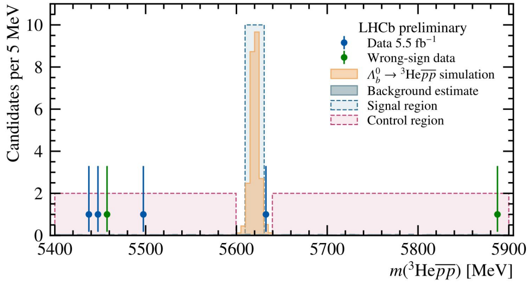


Antihelium production in $\bar{\Lambda}^0_b$ decays

LHCB-CONF-2024-005

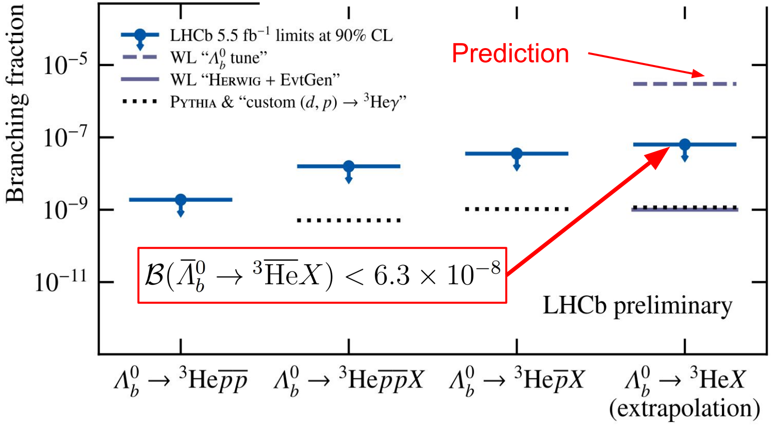


- ~$\mathcal{O}(10^{11})$ Λ^0_b produced in pp collisions at 13 TeV recorded by LHCb
- Measure the relative BF of three decay channels
- To exploit full/partial cancellation of systematic uncertainties the $\Lambda^0_b \to \Lambda^+_c (p K^- \pi^+) \pi^-$ channel has been used for normalization
- In absence of significant signals the first upper limits on this process are derived (X=not reconstructed particles)



$$\mathcal{B}(\bar{\Lambda}_b^0 \to {}^3\overline{\text{He}}pp) < 1.9 \times 10^{-9} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\bar{\Lambda}_b^0 \to {}^3\overline{\text{He}}ppX) < 1.6 \times 10^{-8} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(\bar{\Lambda}_b^0 \to {}^3\overline{\text{He}}pX) < 3.6 \times 10^{-8} \text{ at } 90\% \text{ CL}.$$

- Large theoretical DM estimate ruled out by more than one order of magnitude
- These results significantly restrict scenarios for antihelium production through dark matter annihilation in space



$\Lambda^0/\bar{\Lambda}^0$ Transverse polarization

arXiv:2405.11324
JHEP09 (2024) 082

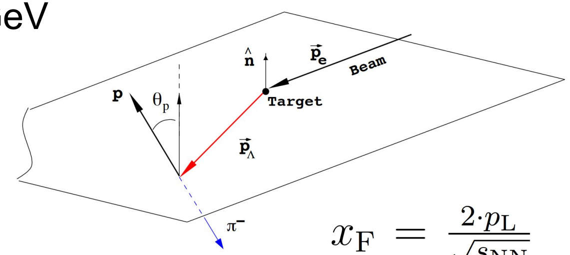
- First observation of Λ^0 transverse polarization in 1976 in unpolarized pBe collisions at 300 GeV
- Completely unexpected: Collision of two unpolarized objects and high energy interactions provide a large number of final states → The polarization effects should disappear
- Cause not yet understood
  - Observed effects cannot be explained by asymmetries at the hard partonic process
  - Polarizing fragmentation function
  - Soft process not calculable with QCD → Measurement needed
- Experiments show that
  - Polarization increases with x_F and p_T (up to ≈ 1 GeV) for higher p_T becomes flat
  - No dependence on the beam energy or colliding system
  - Same magnitude for other hyperons

$\Lambda^0/\bar{\Lambda}^0$ Transverse polarization @ LHCb

arXiv:2405.11324
JHEP09 (2024) 082

- LHCb measurement in fixed-target configuration, pNe data @ $\sqrt{s_{NN}}$=68.4 GeV
- Using the $\Lambda^0 \rightarrow p\,\pi^-$ (and CC) decays $\rightarrow$ Strong parity violation
- Large asymmetry in the angular distribution of the p in Λ^0 rest frame
  - The p is preferably emitted along the Λ^0 spin direction

$$\frac{dN}{d\cos\theta} = \frac{dN_0}{d\cos\theta}(1 + \alpha P_\Lambda \cos\theta)$$

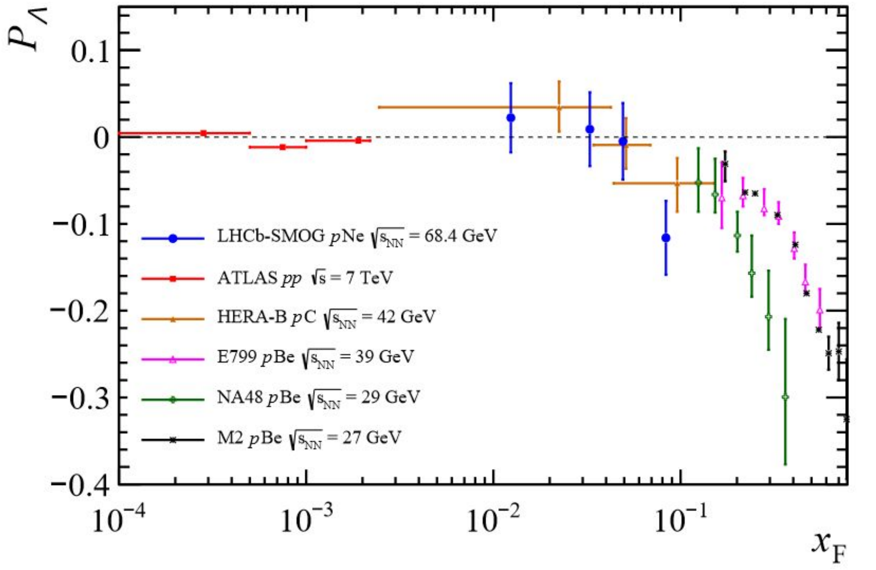


$$x_F = \frac{2 \cdot p_L}{\sqrt{s_{NN}}}$$

- Integrated polarization and studied also as a function of p_T, x_F, y, and η

$$P_\Lambda = 0.029 \pm 0.019\,(\text{stat}) \pm 0.012\,(\text{syst})$$

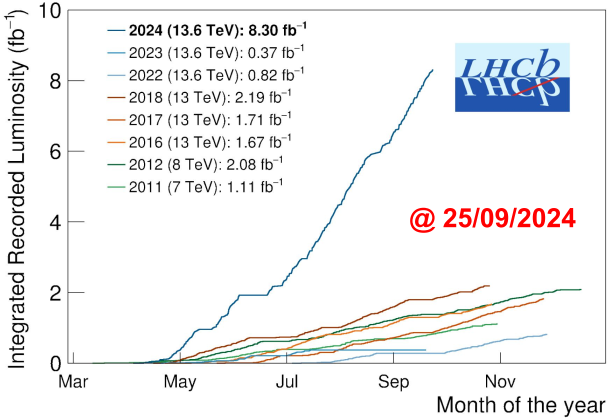
$$P_{\bar{\Lambda}} = 0.003 \pm 0.023\,(\text{stat}) \pm 0.014\,(\text{syst})$$

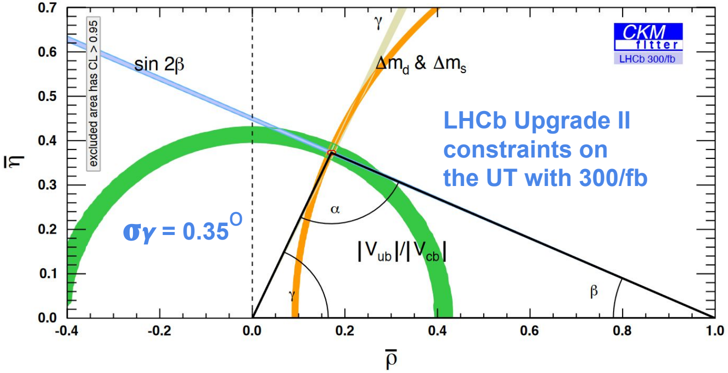


- The polarization values are compatible with previous measurements
- Uncertainty dominated by limited statistics
- Similar x_F interval as HERA-B but different energy and colliding system

Summary

- Few selected LHCb highlights from Run 1 and Run 2
- LHCb is not only CP violation & flavour physics
- A rich and varied physics program in continuous evolution
- Run 3 is in progress with the detector stably operating
- The larger data sample will improve the precision of key measurements and provide new ones
- Upgrade II phase is in preparation and the scoping document is right now under review of the LHCC





LHCB-TDR-023

Backup

How to measure ɣ → Direct CPV

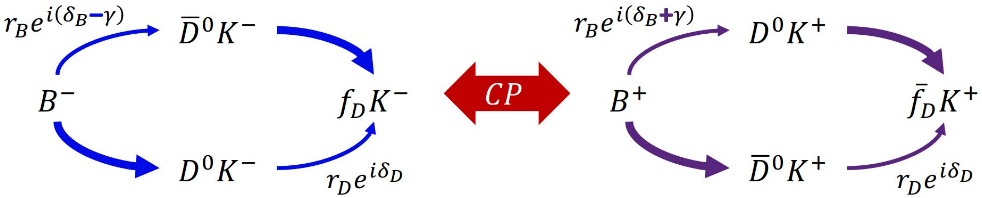
- Measured from the interference between the favoured b→c and suppressed b→u transitions
- The most sensitive decay channels are $B^{\pm}\rightarrow DK^{\pm}$ with D (= $D^0,\bar{D}^0$) decaying to the same final state f
- The decay rates can be expressed as:

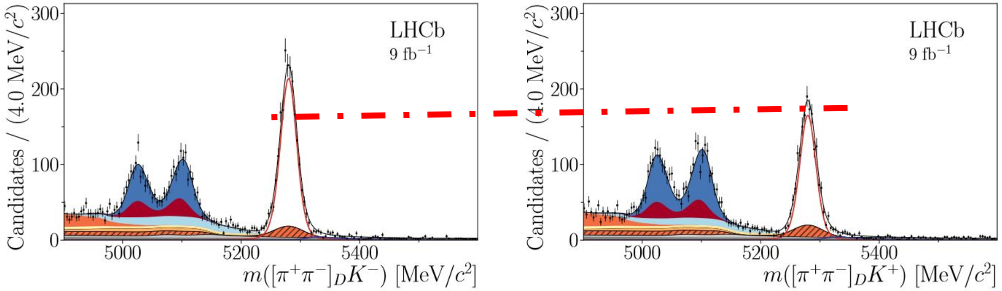
$$\Gamma_{B^-} \propto r_B^2 + r_D^2 + 2r_B r_D cos(\delta_B + \delta_D - \gamma)$$
$$\Gamma_{B^+} \propto r_B^2 + r_D^2 + 2r_B r_D cos(\delta_B + \delta_D + \gamma)$$

- r_B (r_D) are the amplitude ratio of B (D) decays

$$r_B = \frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)}$$

- ɣ is the weak phase: **CP**(ɣ) = -ɣ
- δ_B (δ_D) is the strong phase: **CP**(δ_B) = +δ_B
- The non zero angle ɣ introduce visible CPV in the decay rate
- Key observable: asymmetry between B^- and B^+ yields



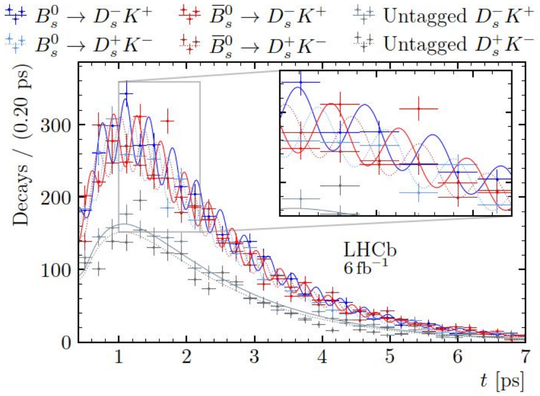


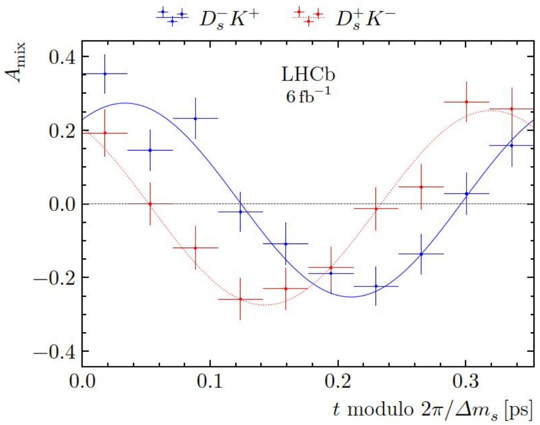
JHEP04 (2021) 081

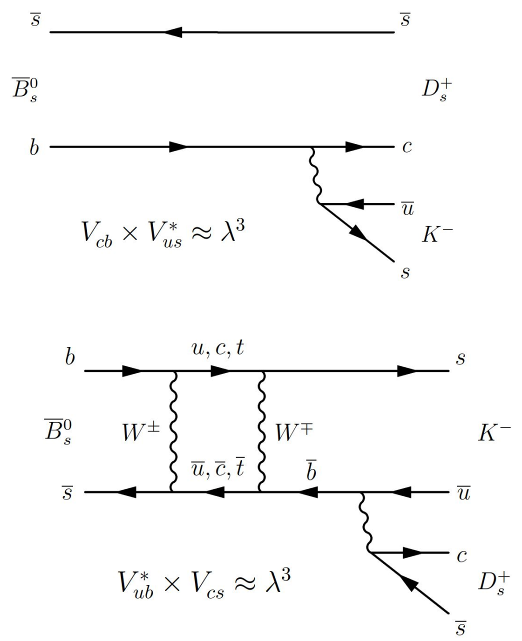
- Need to combine many decays mode
  - Small r_B
  - Small BR of decays sensitive to ɣ

How to measure ɣ → CPV in mixing & decay

- Golden channel: $B^0_s \to D^{\mp}_s K^{\pm}$
- CPV in B^0_s - $\overline{B}^0_s$ mixing and decay
- Decay time dependent analysis
- CP violating parameters are function of ɣ and mixing phase β_s
  - → $\beta_s \equiv \arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)$
- Ratio of amplitudes of interfering decays larger: $r_B \approx 0.4$
- Requires flavour tagging to determine the initial B^0_s flavour







LHCB-PAPER-2024-020