Rare Kaon and Charm Decays at LHCb

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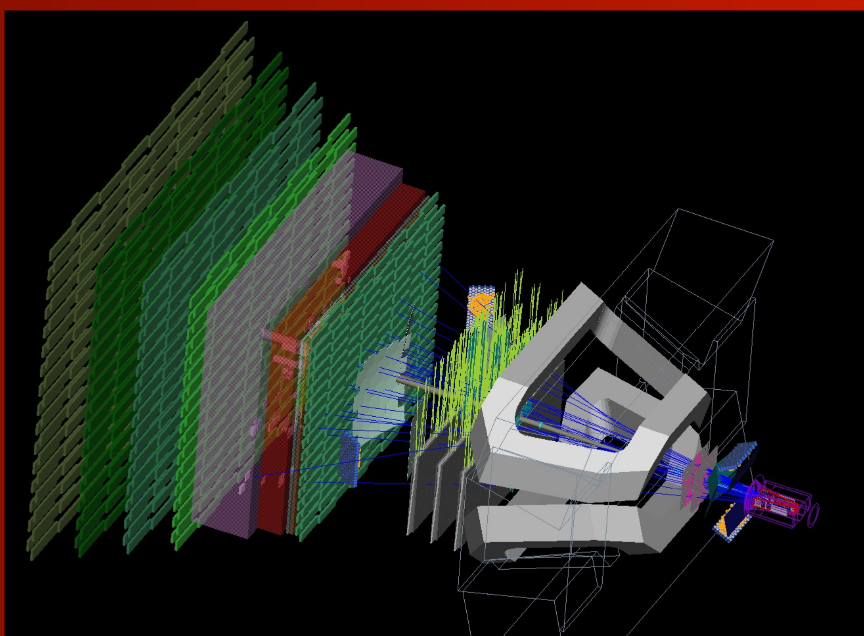
on behalf of the LHCb collaboration



Overview

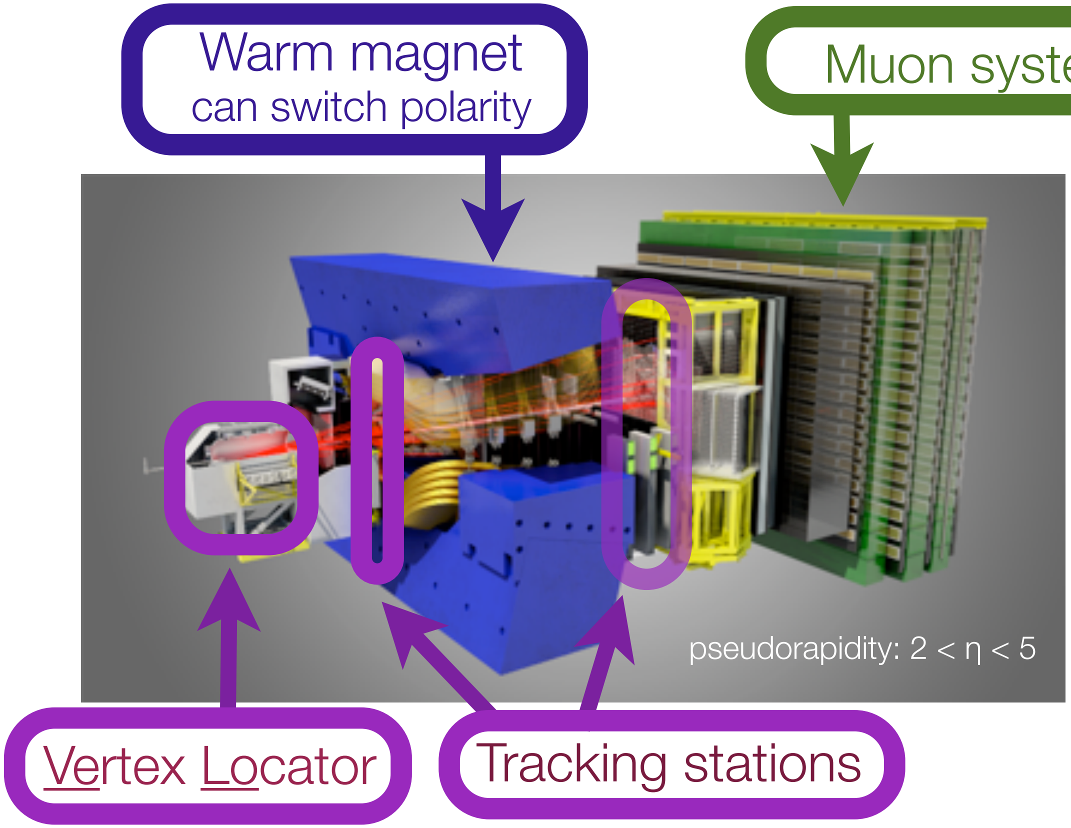
- LHCb searches for rare transitions that are highly suppressed or forbidden by the SM: mostly FCNCs (but also LFV).
- BSM scenarios could contribute at tree & loop level.
- Usually involve leptonic final states
  - Experimentally, muon signatures are usually easier to detect.

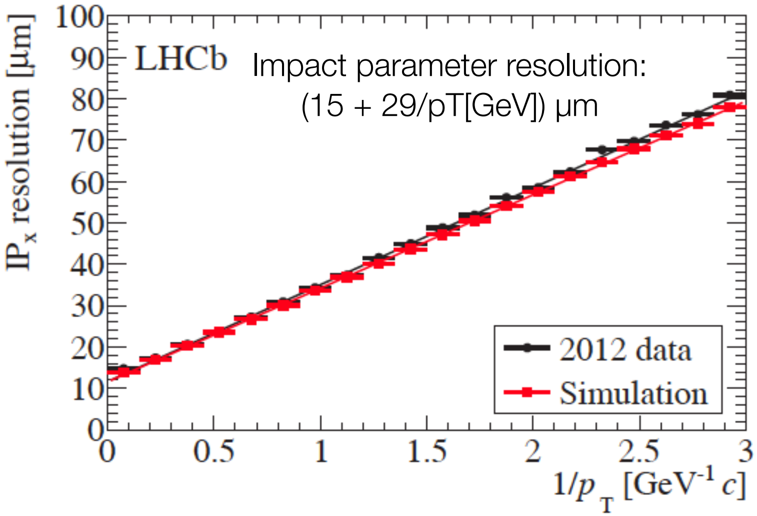
- Large Strange and Charm production from LHC collisions!

- Strange decay products can be low p_T (as low as 80 MeV), distinguished by looking for separation between the PV and the decay vertex.
  - Trigger improvements since Run 2 have increased selection efficiencies by an order of magnitude compared to Run 1.
- LHCb is designed for Charm, most originating near the PV with high p_T.

LHCb Experiment: Tracking

- Accurate decay time resolution from our vertex locator (VELO)
- High muon reconstruction efficiency from muon stations
- Good momentum resolution from tracking stations, Δp/p = 0.5% — 1.0%

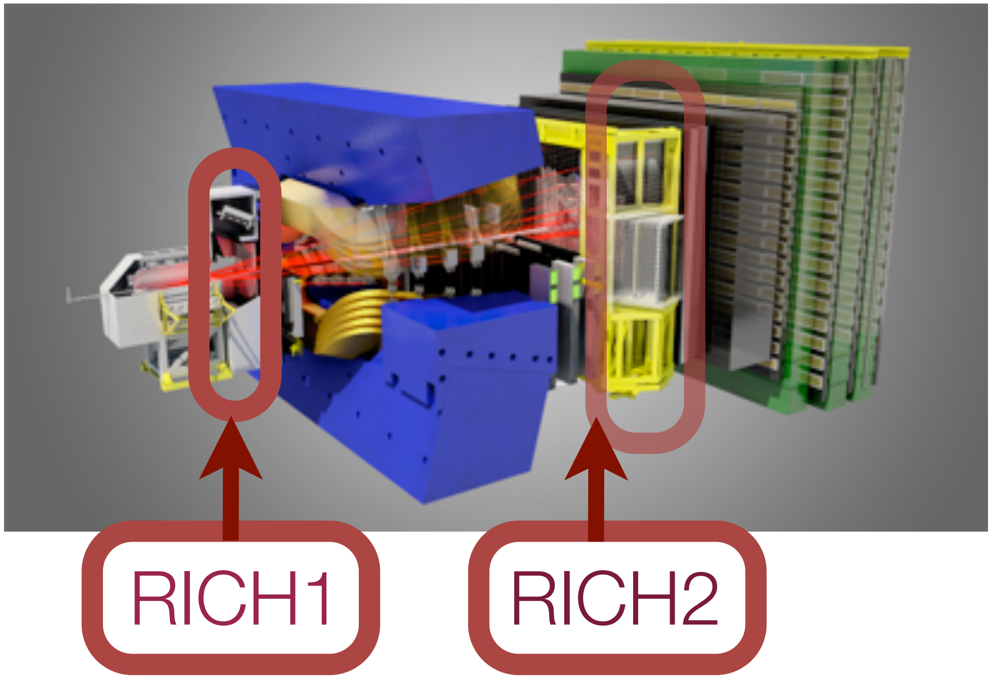


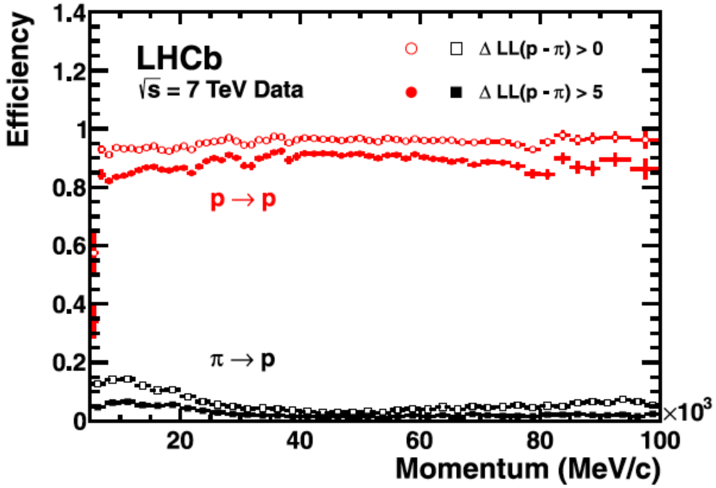


Int. J. of Mod. Phys A**30** 1530022 (2015)

LHCb Experiment: Particle ID and Trigger

- p/K/π separation provided by Ring Imaging Cherenkov (**RICH**) detectors



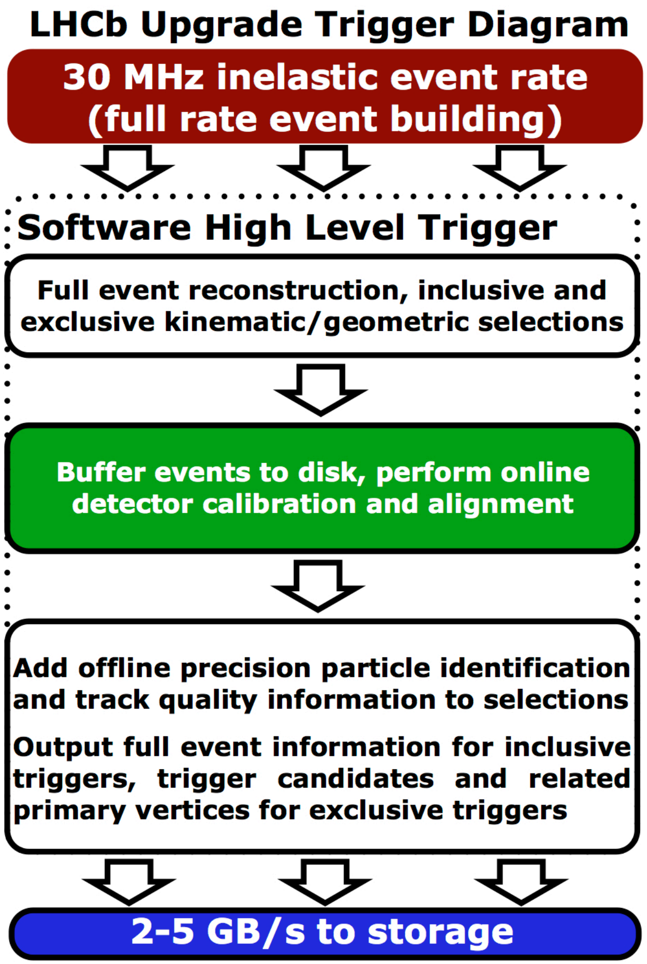


Eur. Phys. J. C**73** 2431 (2013)

- The ability to identify particles at LHCb is crucial to many of our analyses.
- Excellent trigger allows us to trigger on tracks with lower pT

Trigger evolution for Run 3

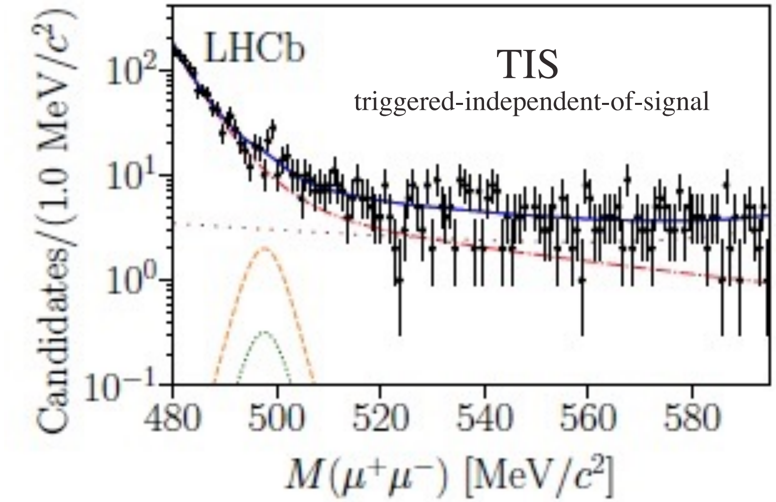
- LHCb has removed the Level-0 Hardware Trigger. In Run 3 we readout the full detector in every event (30 MHz).
- Run 1 + 2 hardware approach was based on simple detector signals to reduce rate to 1 MHz before events reach software trigger.
- Software trigger approach enables efficiency gain – typically factor between 3 and 10 for Heavy Flavour channels.
- First stage of software trigger is GPU based.
- With relatively little additional integrated luminosity, can get very large samples compared to existing datasets.

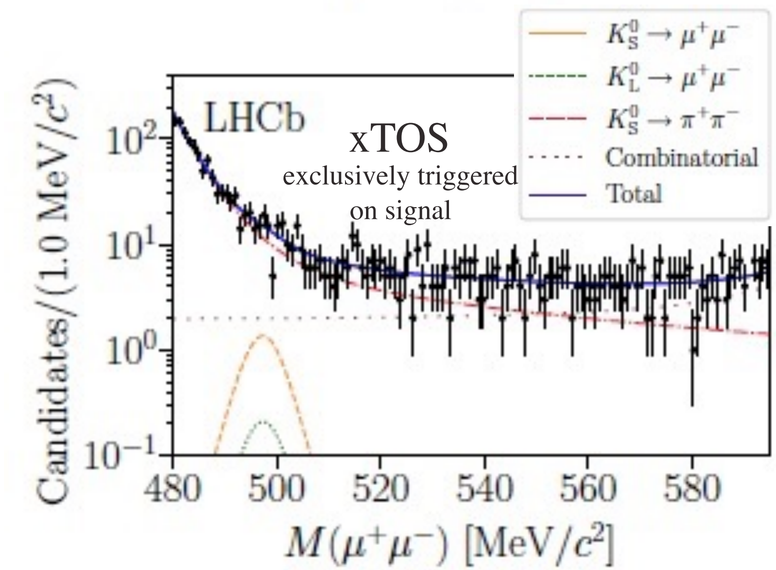


PRL 125 (2020) 231801

Search for $K^0_S \to \mu^+ \mu^-$ decays

- SM prediction is tiny
  $\mathcal{B}(K_S \to \mu^+\mu^-)_{\text{(SM)}}$ =
  [5.18 ± 1.50 (LD) ± 0.02 (SD)] × 10^{-12}
- BSM dynamics can induce higher $\mathcal{B}$
- Last LHCb publication studied full Run 2 data sample, limit uses Run 1 + Run 2
- $\mathcal{B}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ (90% CL)





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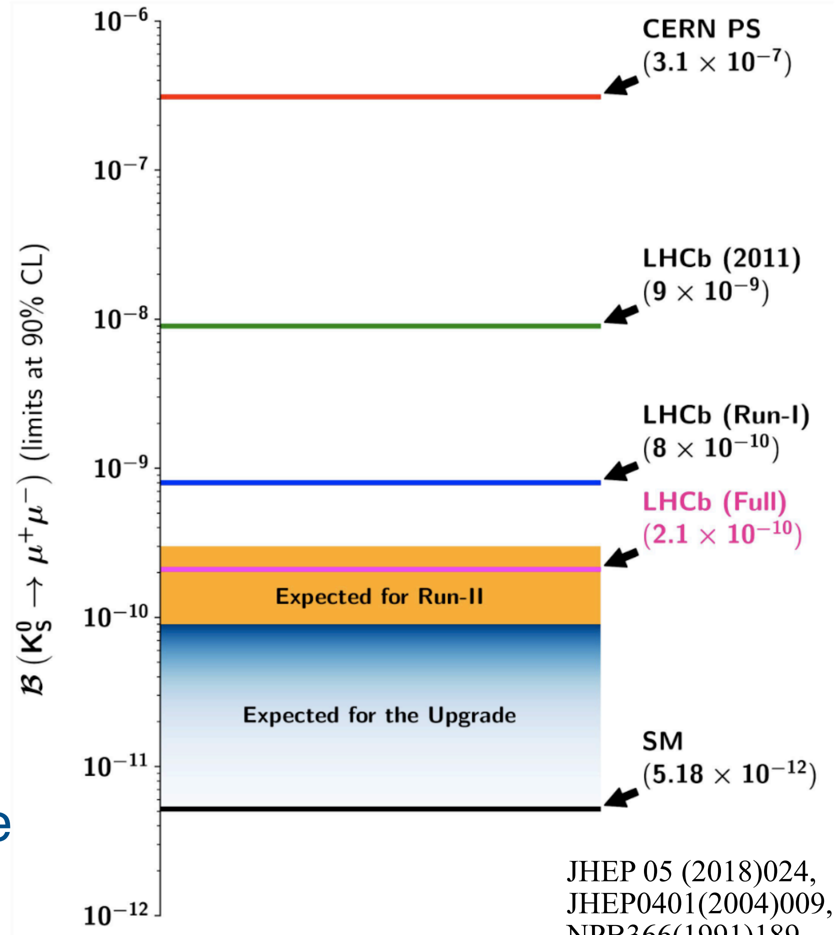
- $\mathscr{B}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ (90% CL)
- Expected to reach sensitivity close to the SM prediction with the Phase II upgrade (300 fb^{-1})



JHEP 05 (2018)024, JHEP0401(2004)009, NPB366(1991)189

Ranges shown for expected sensitivity are from LHCb-TALK-2017-164

PRD 108, L031102 (2023)

Search for $K^0_{S(L)} \to \mu^+ \mu^- \mu^+ \mu^-$ decays

- SM prediction [Eur. Phys. J. C 73 (2013) 2678]:
  $$\mathcal{B}(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14}(10^{-13})$$
- Models with Dark Photons can enhance the SM branching fraction prediction by two orders of magnitude.
  [Rep. Prog. Phys. 86 016201]
- Use 2016 – 2018 data (5.1 fb^{-1}). $K^0_{S(L)}$ coming from PV.
  K^0_S or K^0_L state hard to distinguish due to decay time acceptance.
  OK for placing limits, but an observation would simply be called K^0.
- Blind analysis with control mode $K^0_S \to \pi^+\pi^-$.
- Background contributions (combinatorial + inelastic collisions with material) minimized through BDT training.

PRD 108, L031102 (2023)

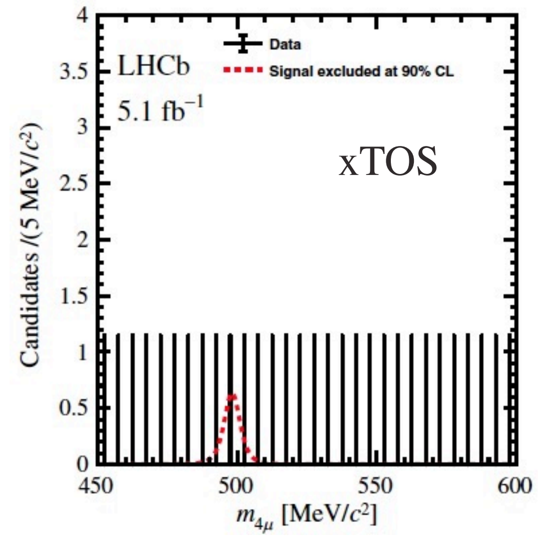
Search for $K^0_{S(L)} \to \mu^+ \mu^- \mu^+ \mu^-$ decays

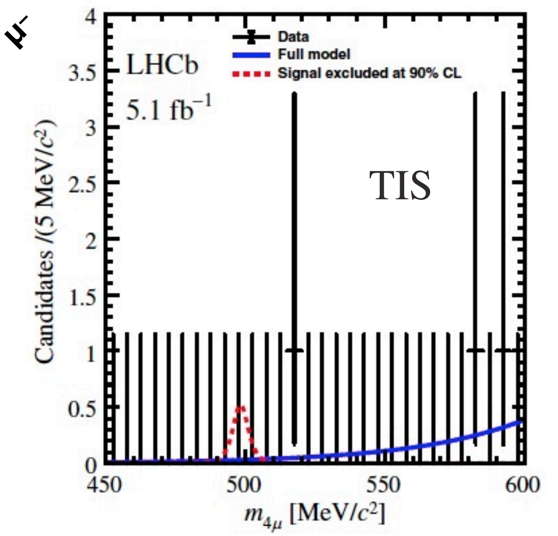
- Main source of systematic uncertainty comes from the trigger.
- K^0_S and K^0_L branching fraction limits are independent, each assuming negligible contributions from the other.
- No significant signal observed.
- Preliminary results: first upper limits set for both decays at 90% C.L.:

$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$

Background free

Better limit than $K^0_S \to \mu^+ \mu^-$





PRD 108, L031102 (2023)

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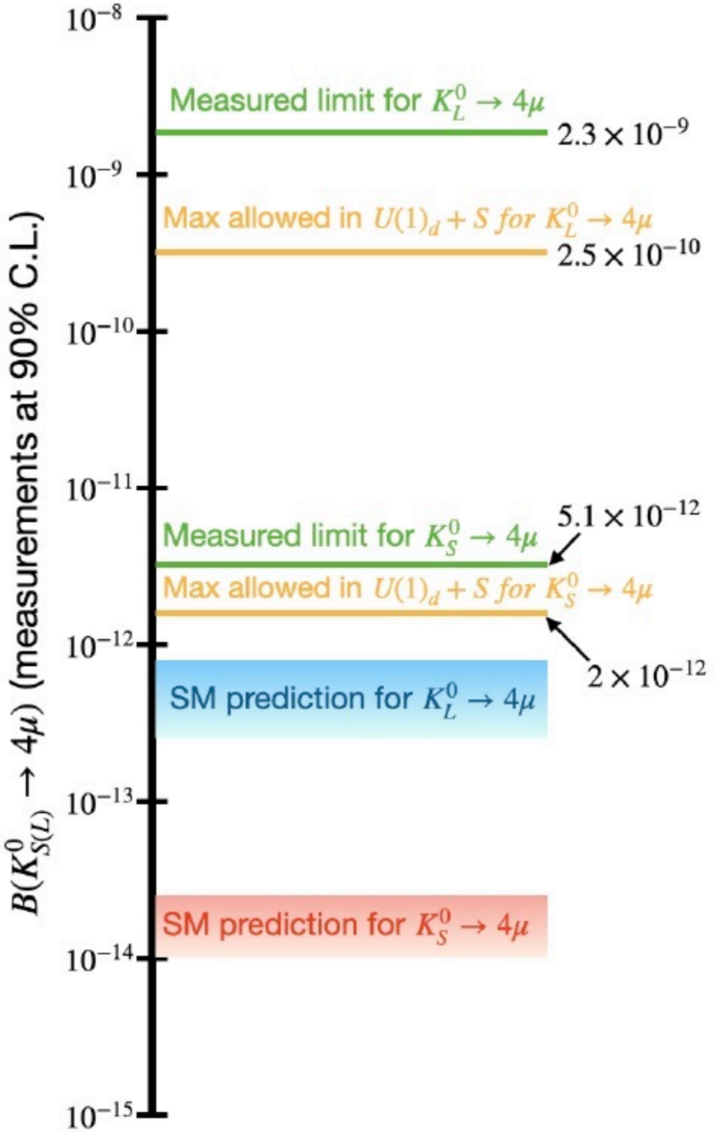
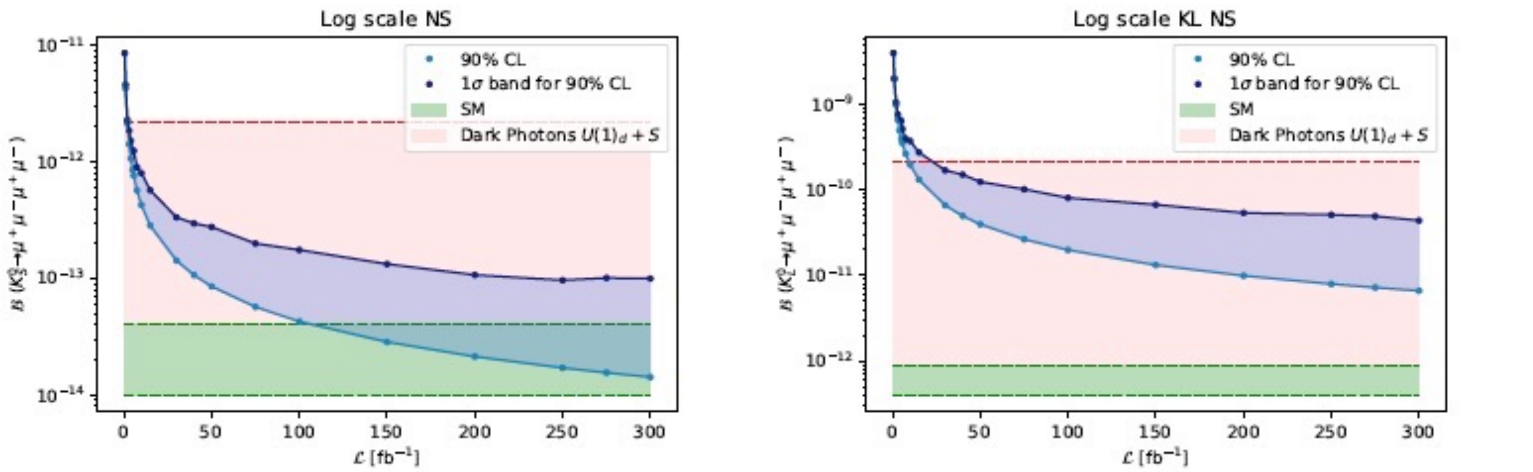


Rare Strange Future Prospects

- Expect to gain an order of magnitude in $B(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-)$ after Upgrade I (also $K^0_S \to \mu^+\mu^-$).



- Interesting channels:
  - $K^0_S \to \pi^+\pi^-\mu^+\mu^-$ → highly constrained by phase space
  - $K^0_S \to (\pi/\mu/e)^+(\pi/\mu/e)^-e^+e^-$ → very low electron efficiencies.
  - $\Sigma^+ \to p\mu^+\mu^-$ (Run 2 update, in progress)
  - $K^0_S \to e\mu$, $K^+ \to \pi^+e\mu$ → Lepton flavor violation

PRL 131, 041804 (2023)

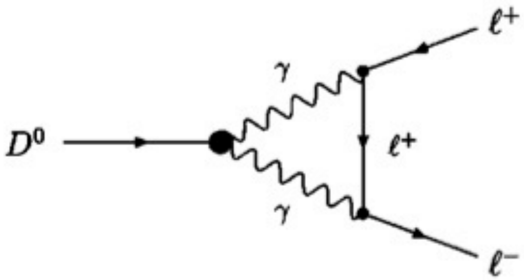
Search for $D^0 \to \mu^+ \mu^-$ decays

- FCNC + helicity suppression [Branching fraction expected at $O(10^{-11})$]
  PRD 66 (2002) 014009

- Current world-best limit (1 fb^{-1}): $\mathscr{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ (90% C.L.) [PLB 725 (2013) 15]

- Leptoquark models explaining B anomalies contribute at tree level for D [PRD 79 (2009) 114030]

- Selection strategy chosen to minimise the combinatorial + misID backgrounds: BDT + PID

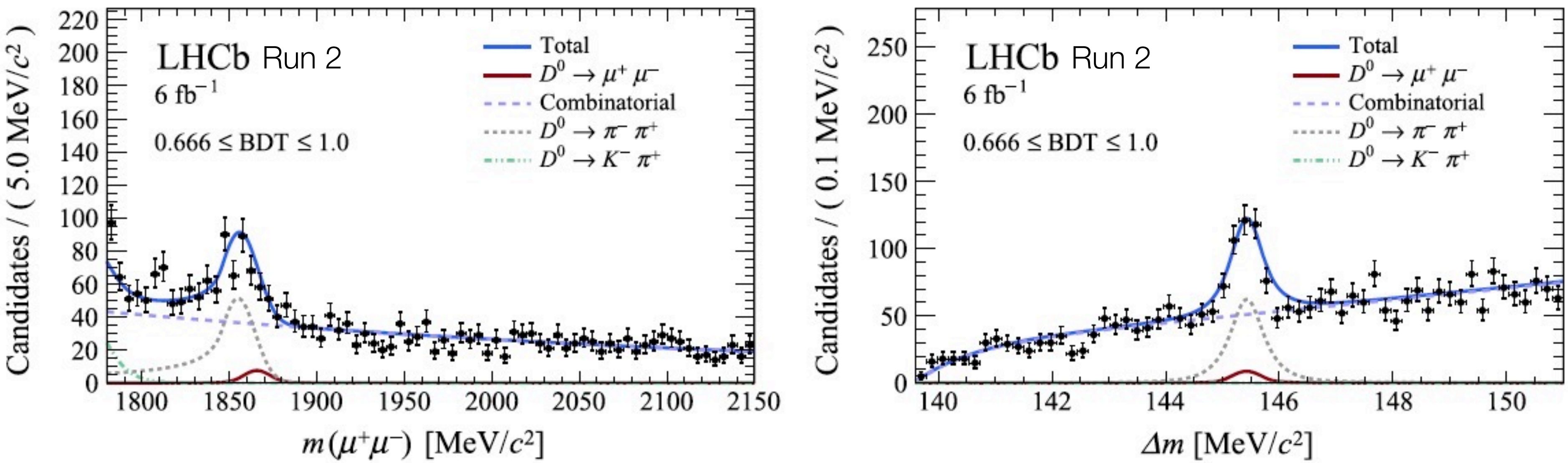


PRD 66 (2002) 014009

PRL 131, 041804 (2023)

Search for $D^0 \to \mu^+ \mu^-$ decays

- Full Run 1 + 2 analysis (9 fb^{-1}). D^0 from $D^{*+} \to D^0\pi^+$.
- Signal yield measured from a 2D unbinned ML fit to $m(D^0)$ and Δm.
- Peak is mostly $D^0 \to \pi^+\pi^-$ mis-ID ($D^0 \to h^-\pi^+$ used as normalization mode)
- Main systematic uncertainty comes from normalization mode trigger.



$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \text{ at } 90(95)\%\text{C.L.}$$

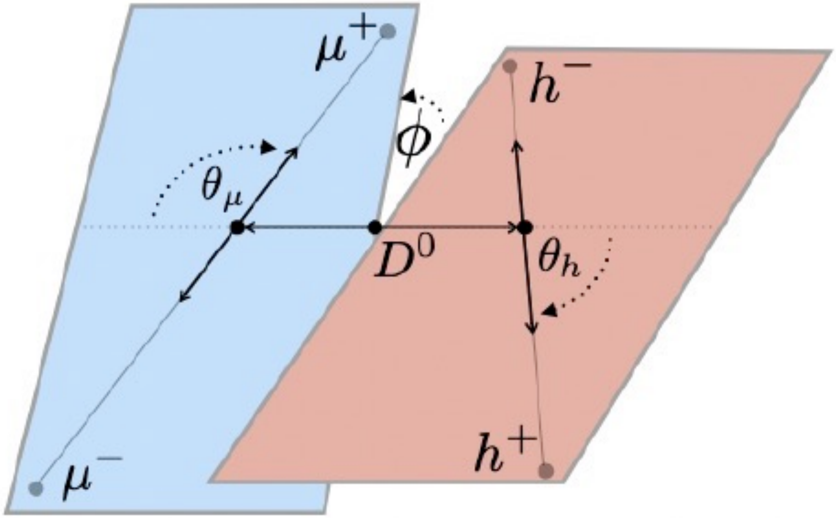
PRL 128 (2022) 221801

$D^0 \to h^+ h^- \mu^+ \mu^-$ Angular Analysis

- Sensitive to FCNCs.
- Final state observed by LHCb with 2012 data → Compatible with SM. [PRL 119 (2017)181805]
  - Five kinematic variables: $q^2 \equiv m^2(\mu^+\mu^-)$, $p^2 \equiv m^2(h^+h^-)$, θ_μ, θ_h, ϕ.
  - Differential decay rate:

$$\frac{d^5\Gamma}{dq^2dp^2d\Omega} = \frac{1}{2\pi}\sum_{i=1}^{9} c_i I_i$$

$c_{1-9} \to$ angular basis
$I_{1-9} \to$ angular coefficients



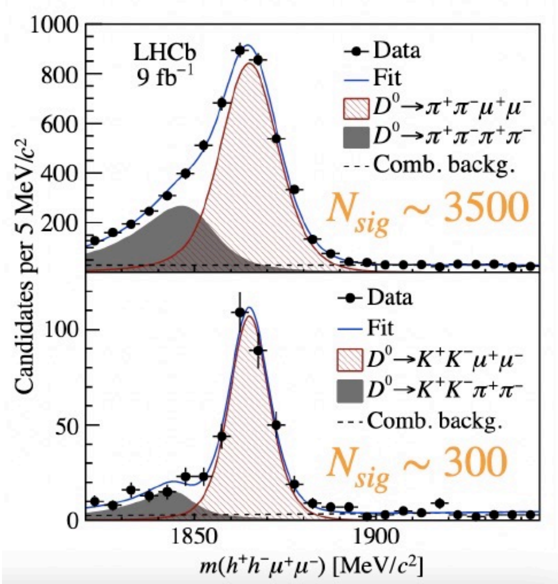
- Coefficients measured integrating out the hadronic system.
- Experimentally, *I* are computed as the decay-rate asymmetries of the data split by angular tags, for example:

$$\langle I_2 \rangle = \frac{1}{\Gamma}\left(\Gamma(|\cos\theta_\mu| > 0.5) - \Gamma(|\cos\theta_\mu| < 0.5)\right)$$

PRL 128 (2022) 221801

$D^0 \to h^+ h^- \mu^+ \mu^-$ Angular Analysis

- Measure separately for D^0 and $\bar{D}^0$ (Run 1 + 2).



- Flavor average and CP asymmetries:

$$\langle S_i \rangle = \frac{1}{2}(\langle I_i \rangle \pm \langle \bar{I}_i \rangle) \qquad + \rightarrow \text{CP even}$$

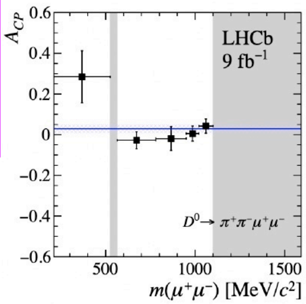
$$- \rightarrow \text{CP odd}$$

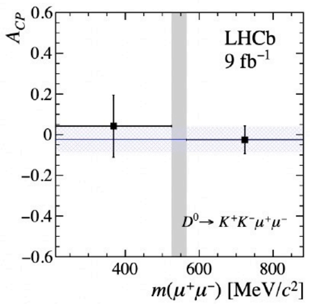
$$\langle A_i \rangle = \frac{1}{2}(\langle I_i \rangle \mp \langle \bar{I}_i \rangle) \qquad I_i(\bar{I}_i) \rightarrow \text{ coefficient for } D^0(\overline{D}^0)$$

- CP asymmetry of the decay angular integrated rate:

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

- If only SM contributions: $\langle S_{5-7} \rangle = 0$
- $\langle A_{2-9} \rangle$, A_{CP} → Expected to be below current sensitivity.
- Results: SM null tests consistent with zero within ~1%.
- Global p-value ~ 79% for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ (0.3σ)
- Global p-value ~ 0.8% for $D^0 \to K^+K^-\mu^+\mu^-$ (2.7σ)
- First full angular analysis in a rare charm decay.

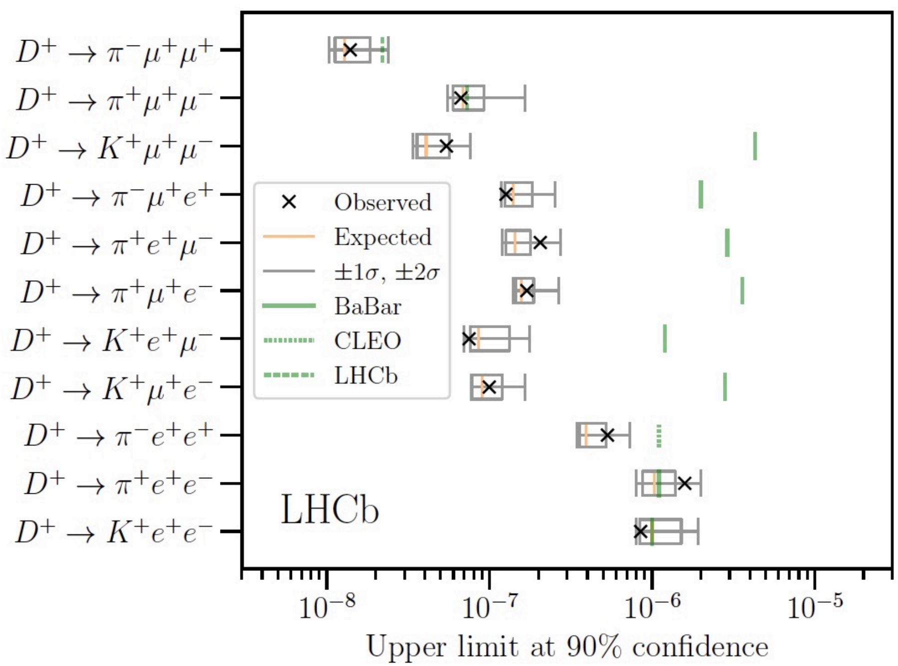


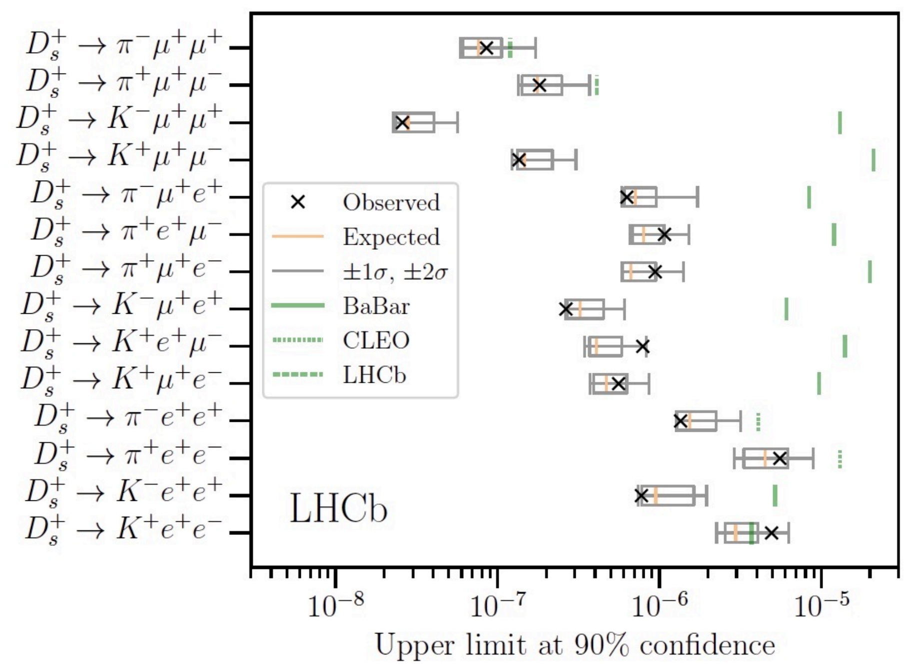


JHEP06(2021)044

D^+ and D_s^+: Search for Rare and Forbidden Decays

- Searches for 25 rare and forbidden decays of $D_{(s)}^+$ performed by LHCb
- FCNC [branching fractions $O(10^{-12})$ predicted], LFV, LNV modes
- Upper limits established for all decay modes
- These results (from 1.6 fb^{-1} of 2016 data) represent an improvement on existing limits by one to two orders of magnitude, in most cases.

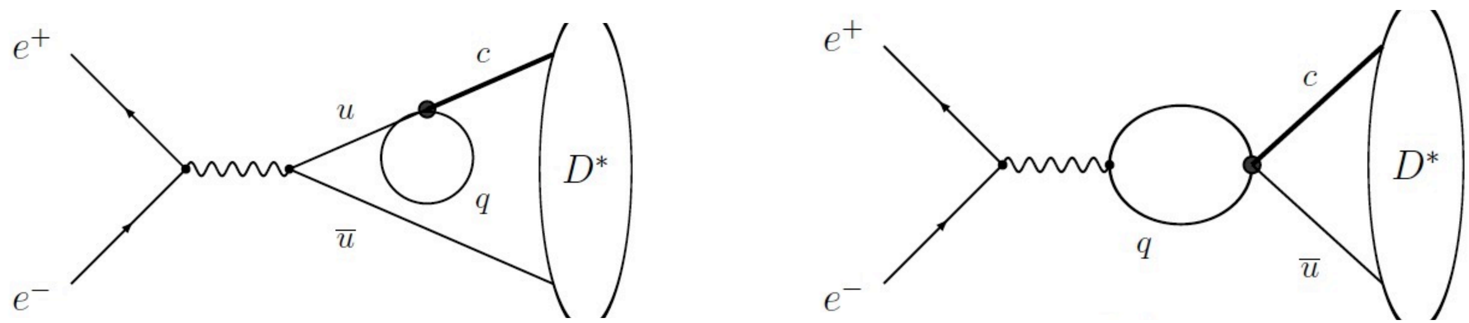




Eur. Phys. J. C (2023) 83:666

Search for $D^{*0} \to \mu^+ \mu^-$ decays (New!)

- Leptonic decays of vector mesons are highly suppressed [$O(10^{-19})$]
  - Partially due to large widths of strong decays like D^{*0}
- CMD-3 measured $\mathcal{B}(D^{*0} \to e^+e^-) < 1.7 \times 10^{-6}$ at 90% CL
  Phys. Atomic Nuclei 83 (2020) 954
- Absence of chiral suppression predicts $\mathcal{B}(D^{*0} \to e^+e^-) = \mathcal{B}(D^{*0} \to \mu^+\mu^-)$
- Use $B^- \to (D^{*0} \to \mu^+\mu^-) \pi^-$ decays as a source of D^{*0} for this study
  - Displaced vertex and exclusive final state provide powerful background rejection capabilities
  - $B^- \to (J/\psi \to \mu^+\mu^-) K^-$ used as normalisation channel

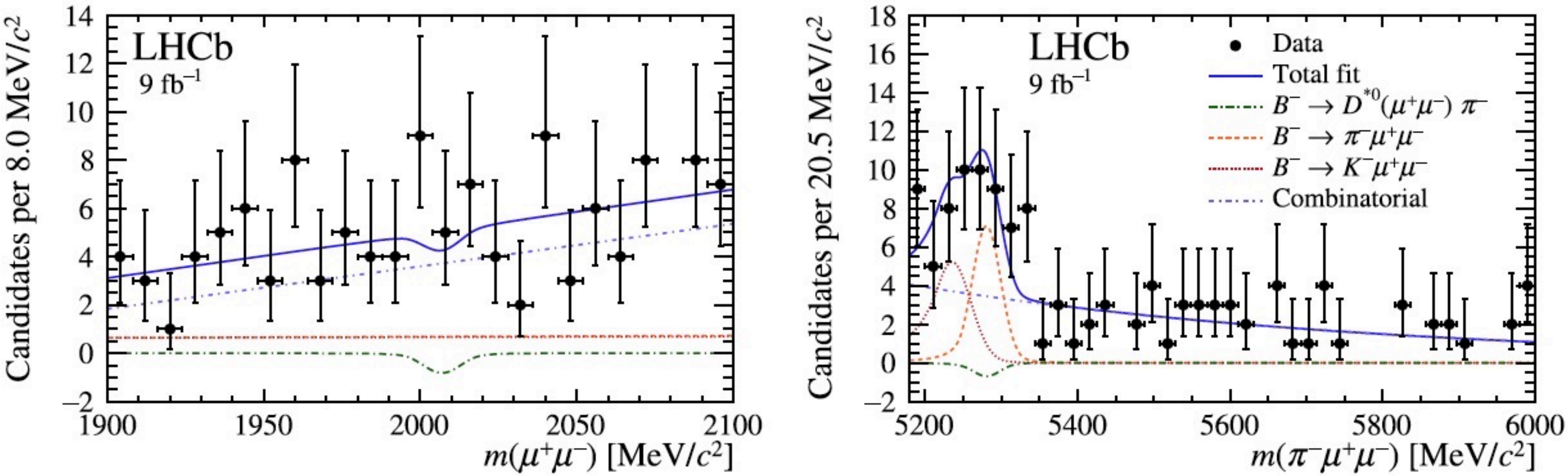


JHEP 11 (2015) 29142

Eur. Phys. J. C (2023) 83:666

Search for $D^{*0} \to \mu^+ \mu^-$ decays (New!)

- Full Run 1 + Run 2 data sample (9/fb)
- Two-dimensional fit to B and D* candidate distributions



- LHCb measures $\mathscr{B}(D^{*0} \to \mu^+\mu^-) < 2.6 \times 10^{-8}$ at 90% CL

PRD 97, 091101(R) (2018)

Rare and forbidden Λ_c decays

- Analogies exist between rare tau and rare Λ_c decay
  - $\tau \to 3\mu$ (LFV) :: $\Lambda_c \to 3\mu$ (B-L)
  - $\tau \to p\mu^+\mu^-$ (B-L) :: $\Lambda_c \to p\mu^+\mu^-$ (FCNC)
  - $\tau \to \bar{p}\mu^+\mu^+$ (B-L) :: $\Lambda_c \to \bar{p}\mu^+\mu^+$ (B-L)

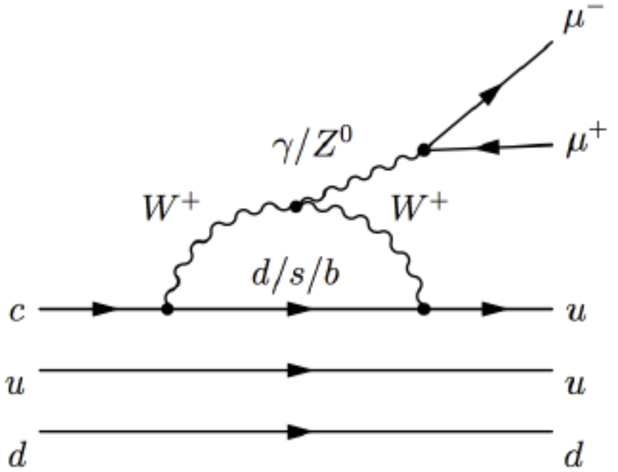
- Experimental limits before LHCb
  - $B(\Lambda_c \to p\mu^+\mu^-) < 4.4 \times 10^{-5}$ (90% CL)
  - $B(\Lambda_c \to \bar{p}\mu^+\mu^+) < 9.4 \times 10^{-6}$ (90% CL)

Babar, Phys. Rev. D**840** 072006 (2011)

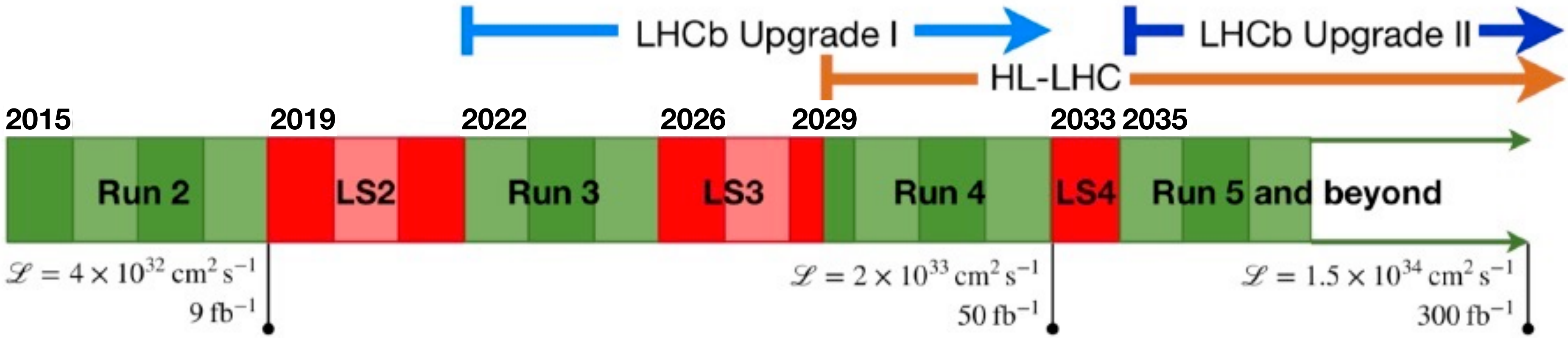
- With Run 1 data (3 fb^{-1}), LHCb finds

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7(9.6) \times 10^{-8} \text{ at } 90\%(95\%) \text{ confidence level}$$

  - Expect a Run 2 update in the near future
  - Expect upper limit of $\mathcal{O}(10^{-8})$ after Run 3



Rare Charm Future Prospects



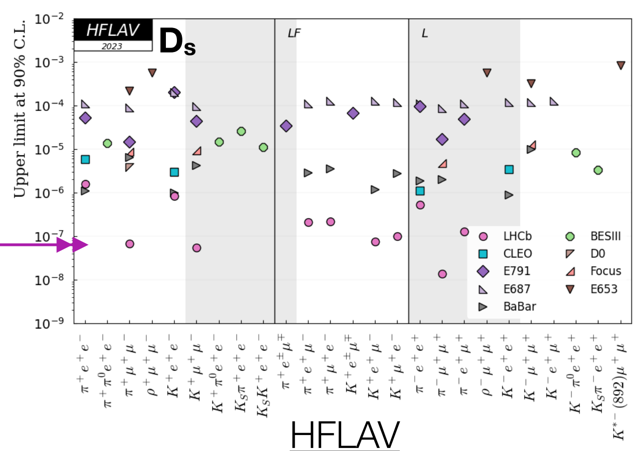
- Expectations for the Upgrade:
  - Upgrade I ($50\ \mathrm{fb}^{-1}$): $B(D^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$
  - Upgrade II ($300\ \mathrm{fb}^{-1}$): $B(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-10}$

- Di-electron modes will follow soon.
- Radiative decays should be possible too, though background rejection is non-trivial.

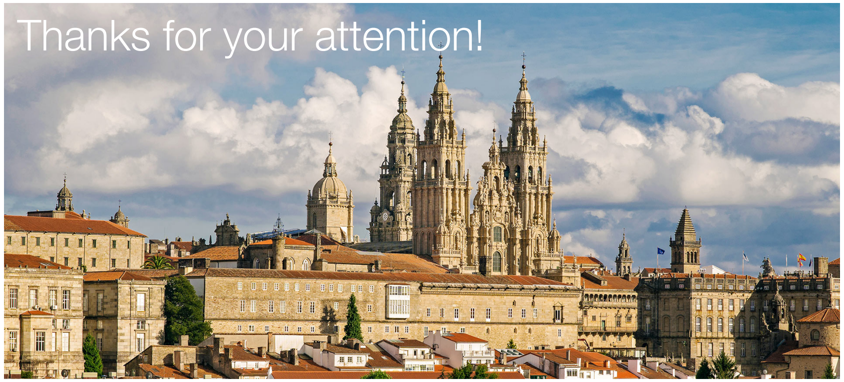
Conclusion

- Our detector has worked "like a charm" but seen "nothing strange"… yet
  - LHCb in its first two runs has published several rare strange and charm results, now often providing the best available limits.
  - LHCb is continuing to exploit its unique data set to investigate rare decays. Several Run (1&)2 analyses have approached final stages.

- New analyses are on the horizon; datasets at LHCb are becoming vast.
  - Expect LHCb rare decay results from Run 3 (and 4) in the near future!



HFLAV



Additional Slides

PRL 131, 041804 (2023)

Search for $D^0 \to \mu^+ \mu^-$ decays

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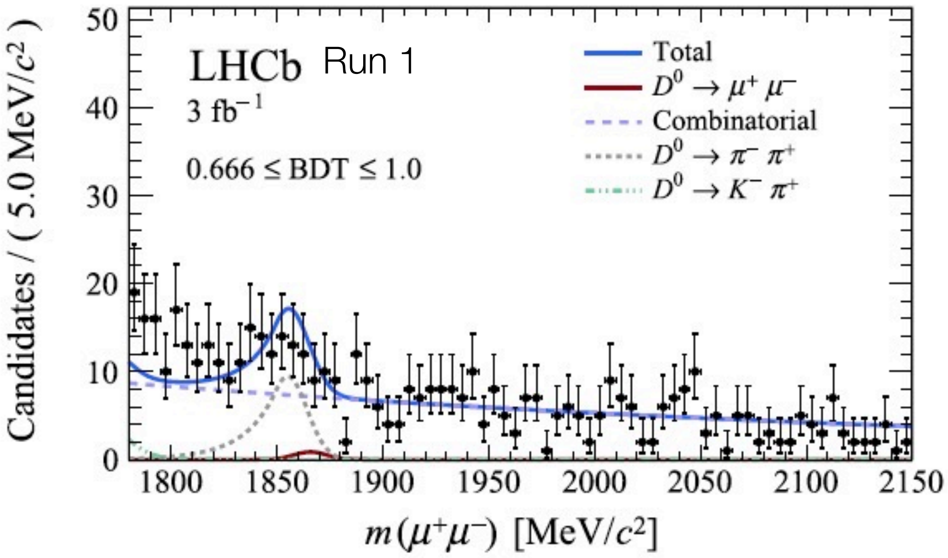
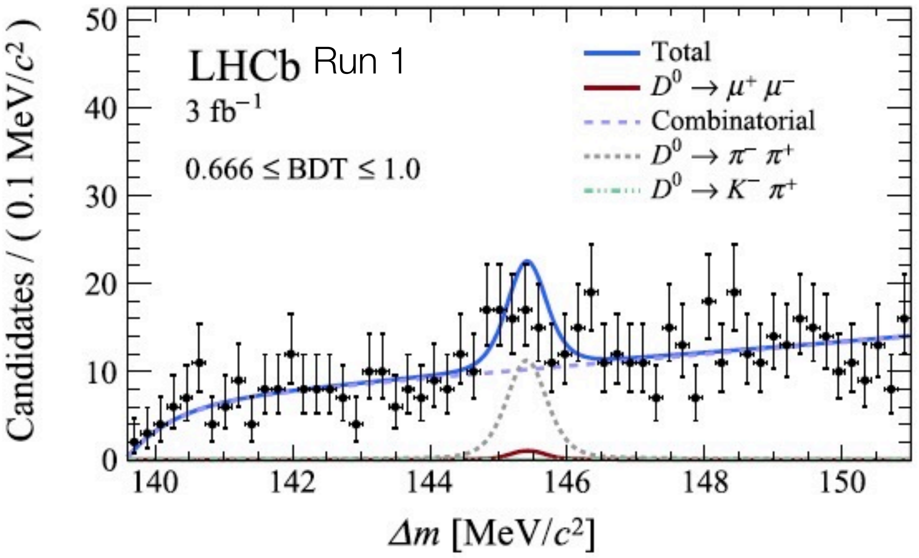




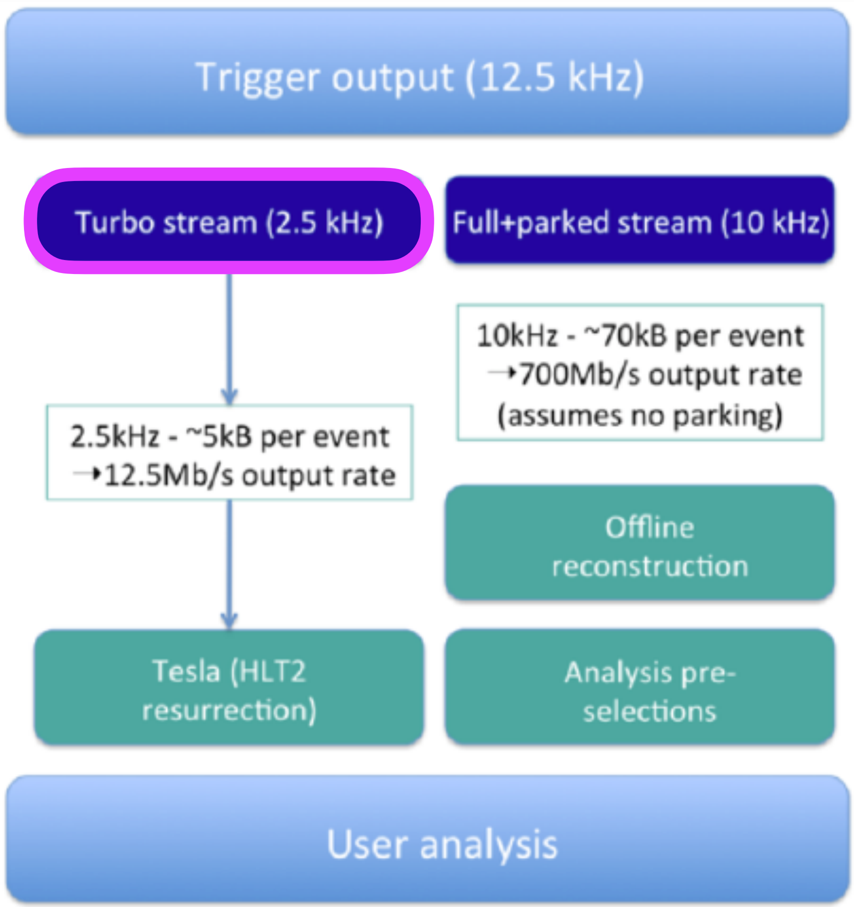
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9(3.3) \times 10^{-9} \text{ at } 90(95)\% \text{ C.L.}$$

Prospects for charm measurements

	Mode	Upgrade (50 fb^{-1})	Upgrade II (300 fb^{-1})
Limits on BFs	$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
	$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
	$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
	$\Lambda_c^+ \to p\mu^+\mu^-$	1.1×10^{-8}	4.4×10^{-9}
	$D^0 \to e\mu$	10^{-9}	4.1×10^{-9}
Stat. precision on asymmetries	$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
	$D^0 \to \pi^+K^-\mu^+\mu^-$	0.3%	0.13%
	$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
	$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

Trigger strategy evolution

- New "Turbo stream" for Run 2.
- Reconstruct full signal candidates directly in the trigger ("Tesla"), and not offline.
- Analyses thus performed directly on the trigger output.
- Smaller event sizes lead to increased yields within a limited bandwidth.
- Real-time alignment and calibration makes "Turbo" possible.



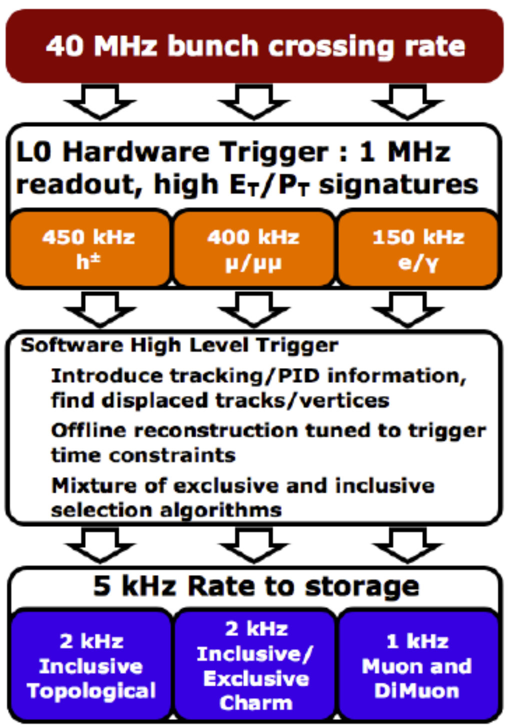
Trigger evolution

- Charm production very large at the LHC

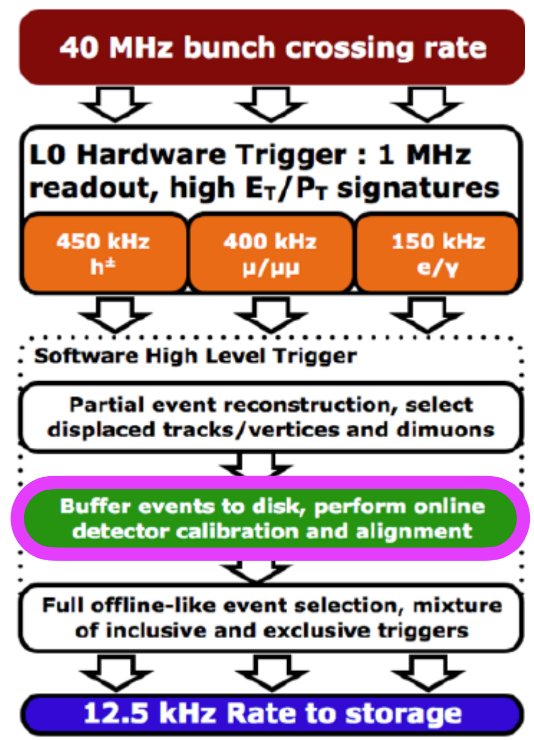
13 TeV $\sigma(pp \to c\bar{c}X)_{p_{\mathrm{T}} < 8\ \mathrm{GeV}/c,\, 2.0 < y < 4.5} = 2840 \pm 3 \pm 170 \pm 150\,\mu\mathrm{b}$ JHEP **03** 159 (2016) Erratum-ibid JHEP **09** 013 (2016)

- However we can only keep what we trigger
  - Several improvements made from Run 1 to Run 2

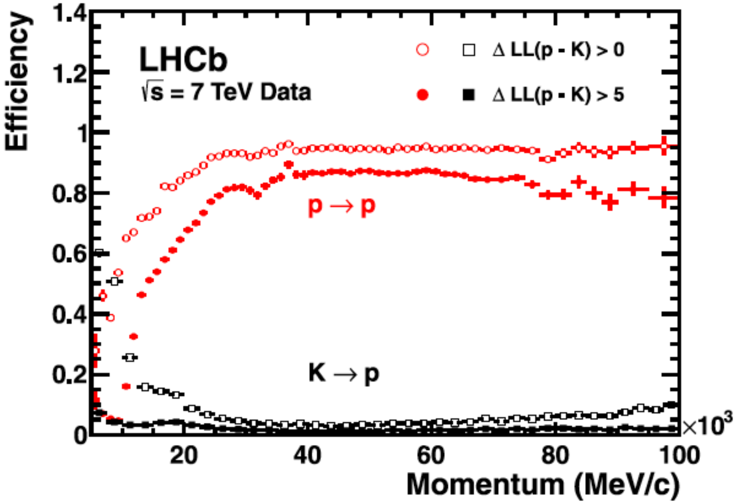
Run 1

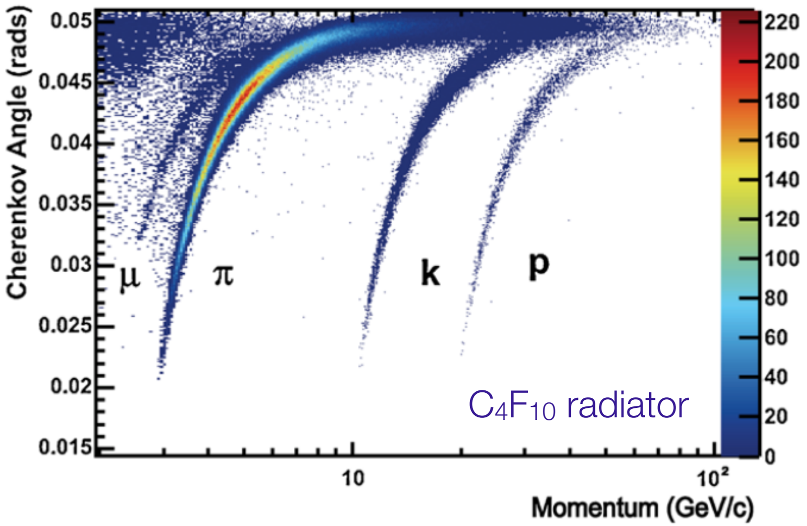


Run 2



RICH performance plots



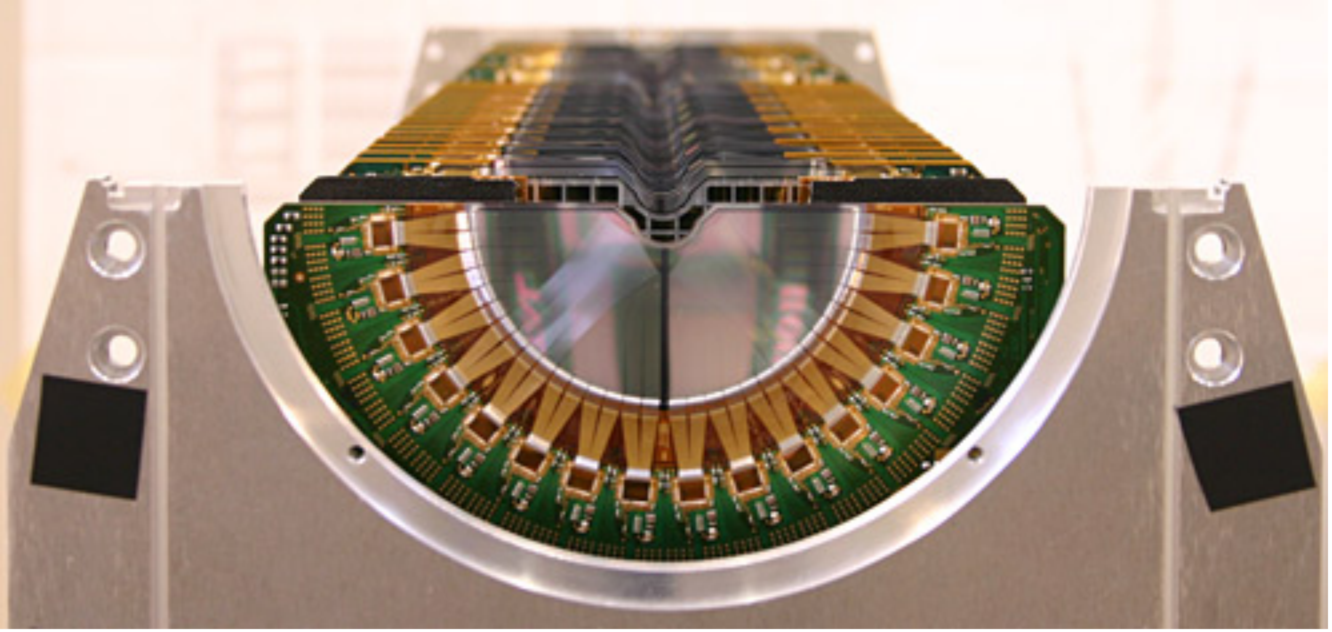


Eur. Phys. J. C**73** 2431 (2013)

Backup

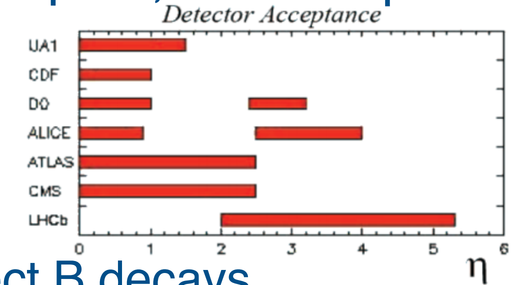
Vertex Locator (VELO)

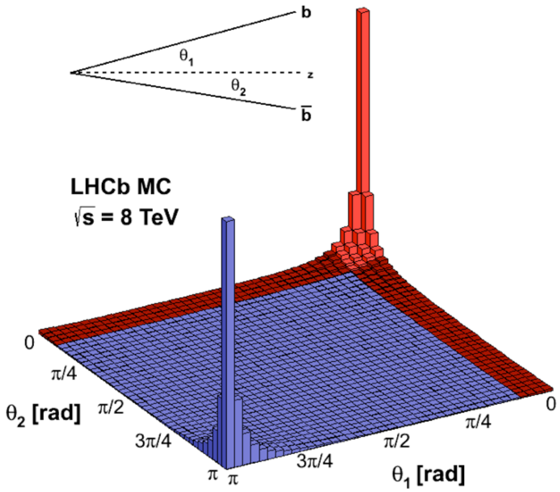
- Reconstruction of primary and (displaced) secondary vertices
- Excellent Impact Parameter resolution of ~ 20 μm
- Proper time resolution 30 to 50 fs



Experiment Overview

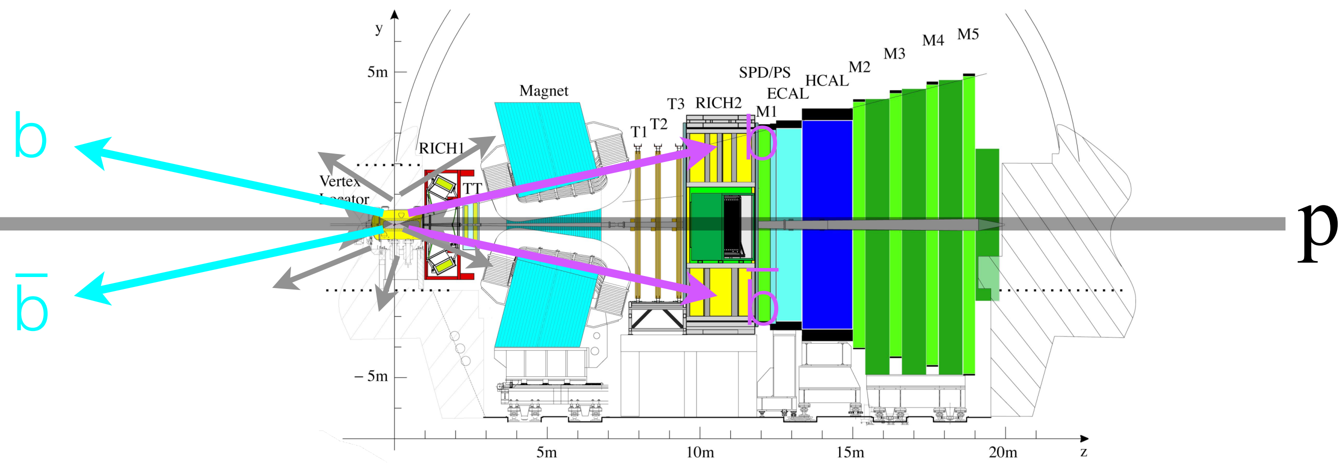
- The LHCb detector is a single arm forward spectrometer with a polar angular coverage from 10 to 300 mrad in the horizontal plane and 250 mrad in the vertical plane.
- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$





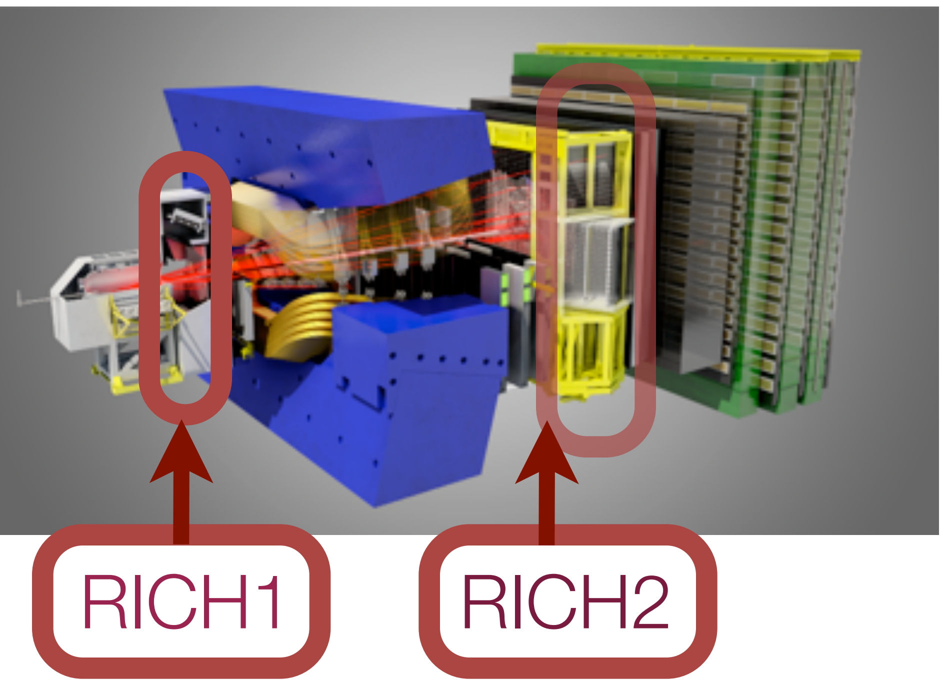
- Trigger
  - Designed to select B decays.
  - Also favors higher p_T secondary charm.

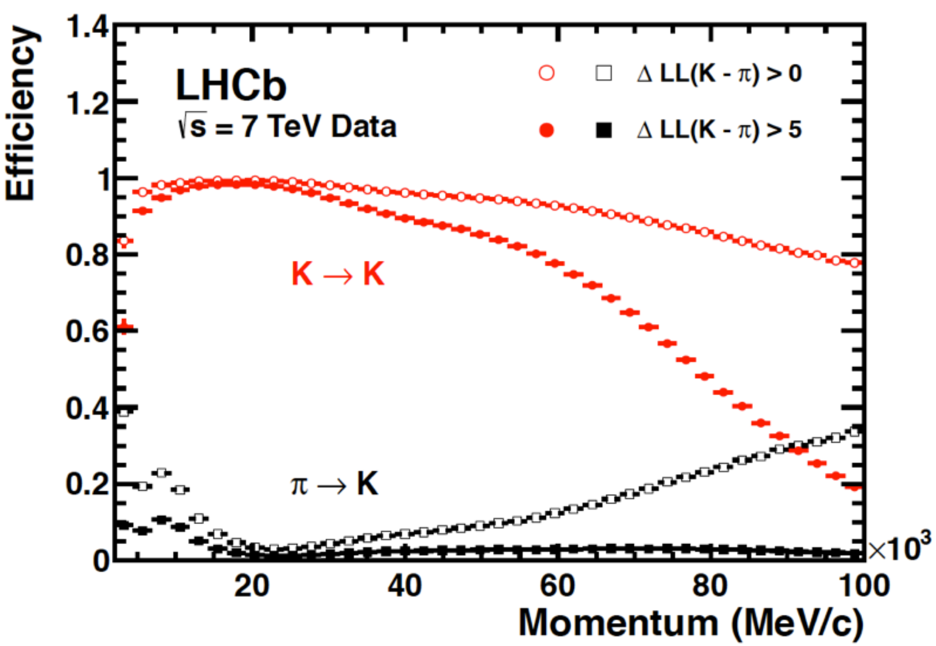
Designed for b!
(Also good for c!)



LHCb Experiment: Particle ID

- Particle ID provided by Ring Imaging Cherenkov (RICH) detectors
  - Particles traveling faster than the speed of light through a medium of refractive index n will emit photons through Cherenkov radiation:
    - $\cos(\theta) = 1/n\beta$
- The Cherenkov angle and the momentum of the particle allows PID.





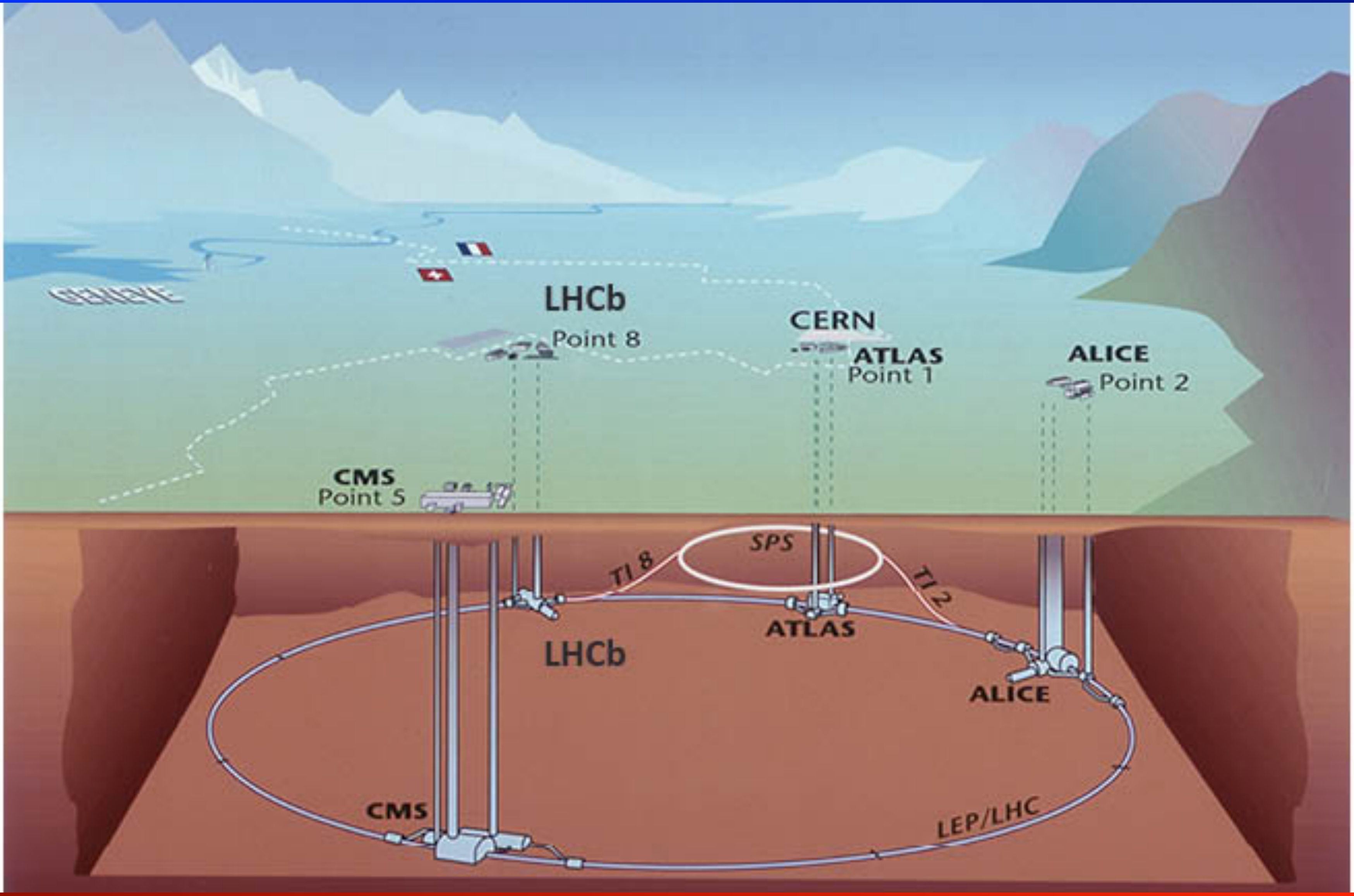
- The ability to identify particles at LHCb is critical to many of our analyses.

LHCb Experiment

- Smooth running of the detector thanks to over 800 members.
- High beam quality provided by the LHC makes our analyses possible.

z ←

LHCb Experiment



Common Strategies for D Mixing & CP Violation

- Use control modes / normalization channels for initial studies with data

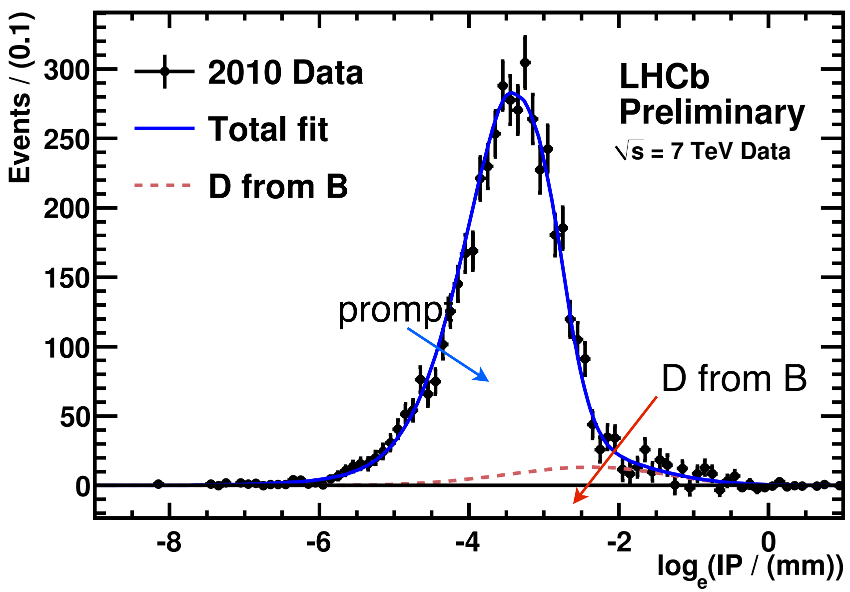
- Perform systematic studies on data
  - Prompt-secondary distinction
  - Lifetime acceptance correction

- Using prompt charm
  - More events
  - Need to measure contribution from secondary

- Using charm from B decays
  - Lower cross-section, but higher p_T = higher trigger efficiency
  - Need to precisely measure D production vertex

Prompt-Secondary Separation

- Separate prompt and secondary charm
  - Prompt charm
    - Defined as charm mesons produced at the primary interaction point.
    - This includes if they are from quickly decaying resonances
      - Examples: via D* decays, ψ(3770)
  - Secondary charm
    - Residual background from charm mesons decaying from long-lived particles.
- We can measure the prompt fraction
  - Look at impact parameter distribution of the charm meson



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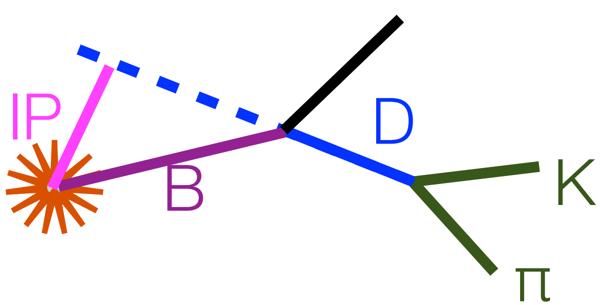
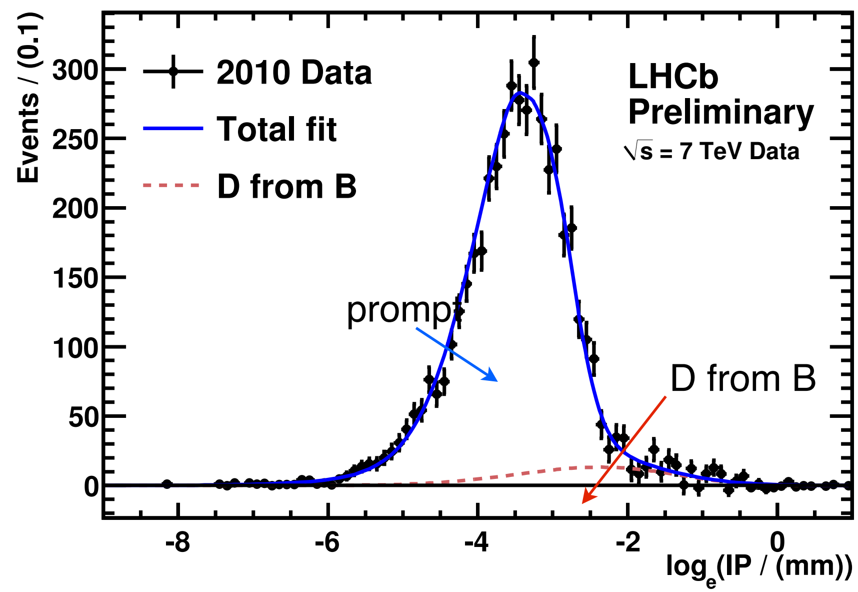
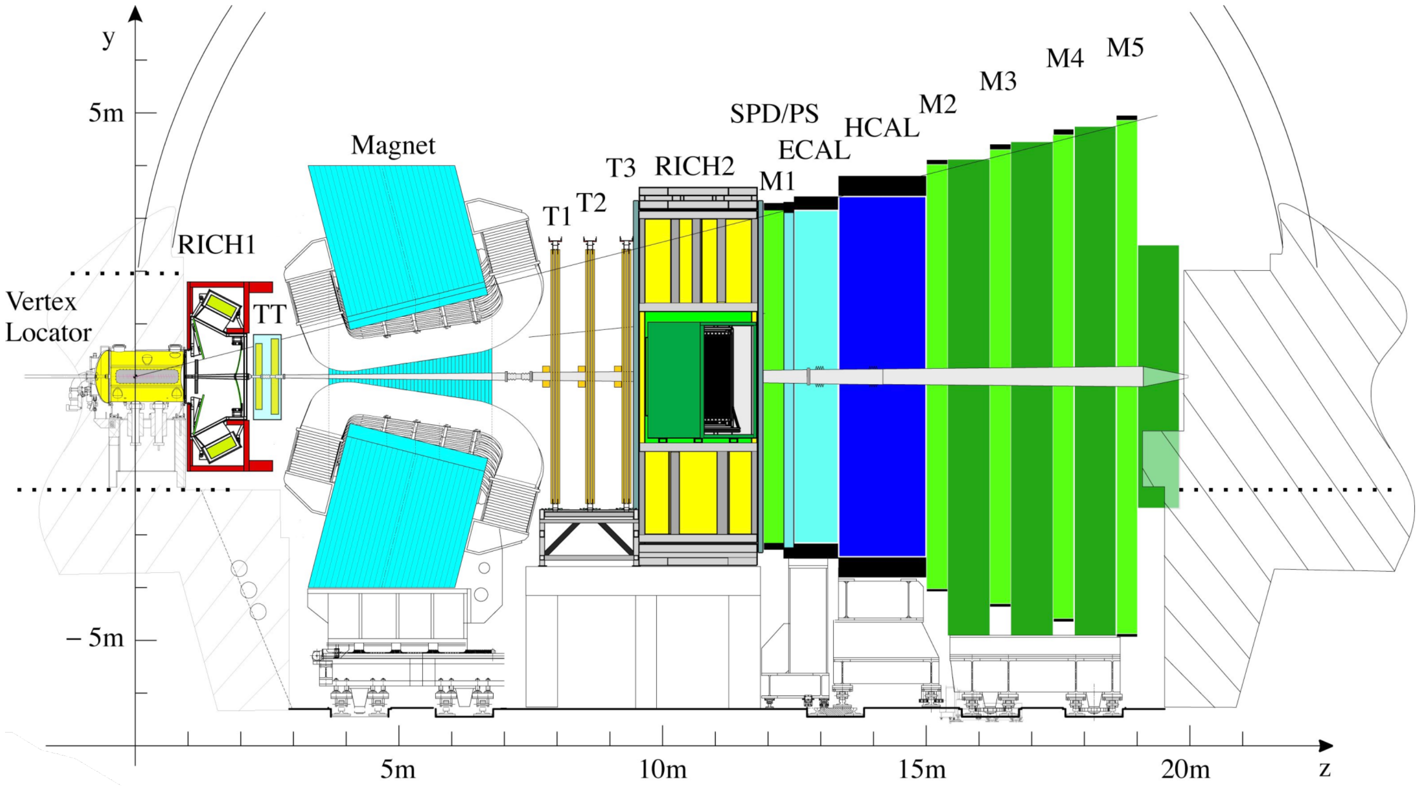


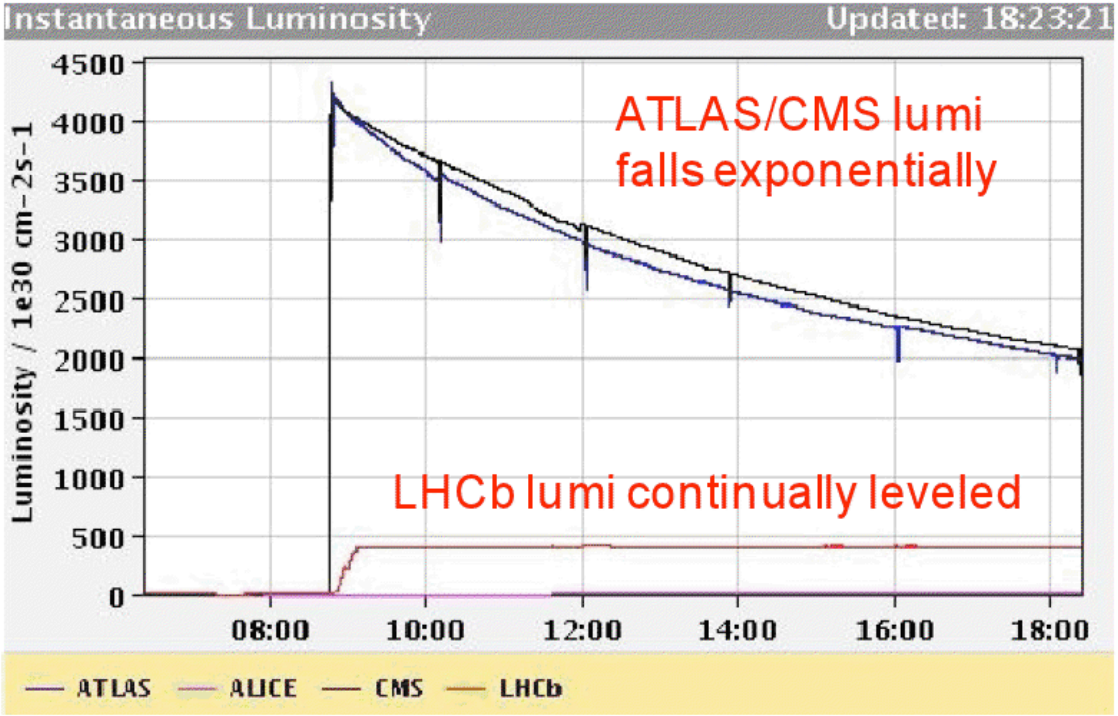


Experiment Overview (2)



Luminosity

- Nominal instantaneous luminosity: $\mathscr{L} = 4 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$
- LHCb instantaneous luminosity kept constant (luminosity leveling).



Charm at LHCb?

- We are most certainly a B physics experiment. However…
- The same properties that optimize LHCb for B physics also make LHCb **an excellent charm physics experiment**.

- The charm cross section is ~20 times larger than the b cross section.
  - **$\sigma(c\bar{c})_{LHCb}$ = 1419 ± 133 μb (Nucl. Phys. B 871 (2013), 1)** @ $\sqrt{s} = 7$ TeV
  - **$\sigma(b\bar{b})_{LHCb}$ = 75.3 ± 14.1 μb (Phys. Lett. B 694 (2010), 209)**
- ~5 trillion $c\bar{c}$ were produced during LHC Run 1, in our acceptance!

- LHCb can make precision measurements in charm with high sensitivity to New Physics hiding in quantum loops…
  - We have the world's best sensitivity to **CP violation** in charm.

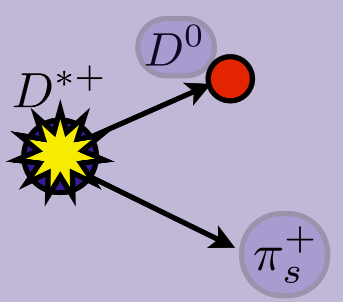
- Boosted quarks, high rapidities: ideal for studying time-dependent effects

Flavor tagging neutral D mesons at LHCb

- LHCb uses two methods to tag the flavor of neutral D mesons

D* decays (<u>Prompt</u>)

Use slow pion from D* decays to tag D flavor: $D^{*+} \to D^0\pi_s^+$ or $D^{*-} \to \bar{D}^0\pi_s^-$



Semileptonic (<u>SL</u>) B decay (<u>Secondary</u>)

Use muon charge to tag D flavor: $B \to \bar{D}^0\mu^+\nu_\mu X$ or $B \to D^0\mu^-\nu_\mu X$