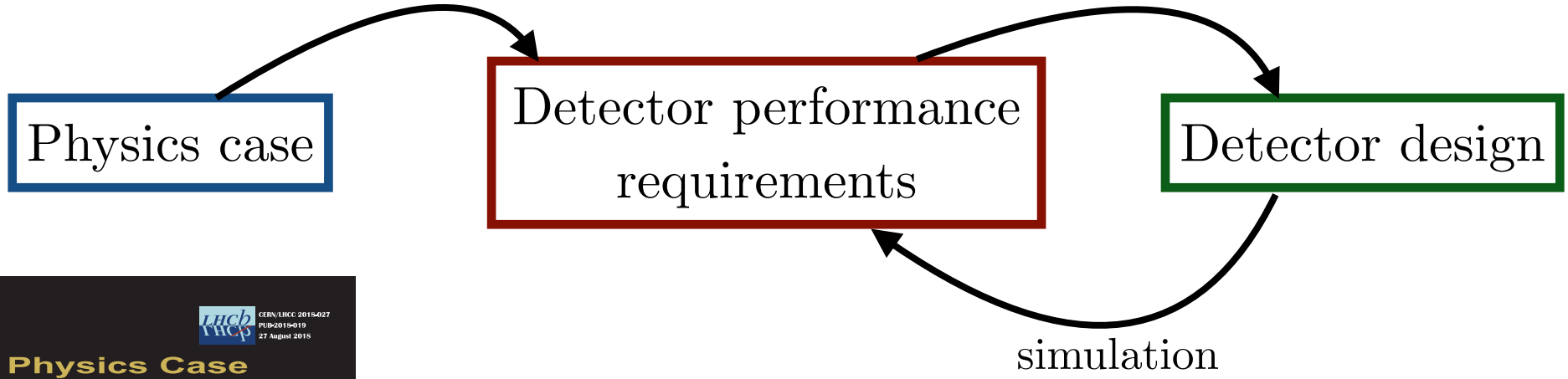
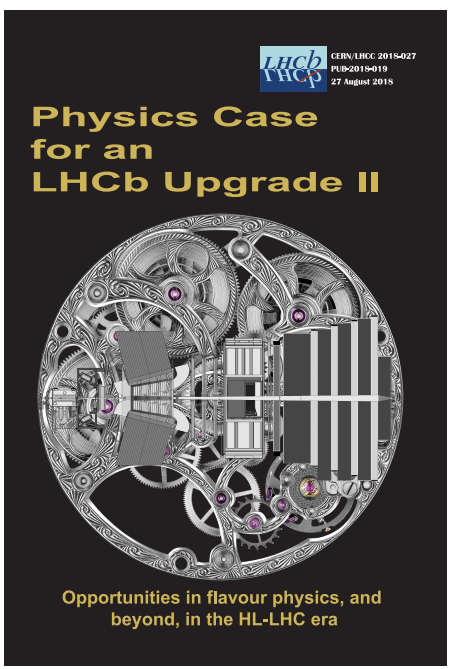
Tracking requirements for physics

Fred Blanc (EPFL)

LHCb Upgrade II Tracking Workshop
Evian-Les-Bains
6 March 2024

Process towards a detector design





CERN/LHCC 2018/027
PUB-2028-019

This talk:

- review some recent developments for the physics case
- qualitative statements on the requirements on the tracking/vertexing performance

PS: technological solutions to meet the physics requirements must be optimised in light of other inputs such as: cost, construction/installation time

Upgrade II environment for physics

- High luminosity
  - Instantaneous luminosity (levelled): $\mathscr{L}_{\text{inst}} = (1.0 - 1.5) \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
  - Pileup (levelled): $28 - 42$

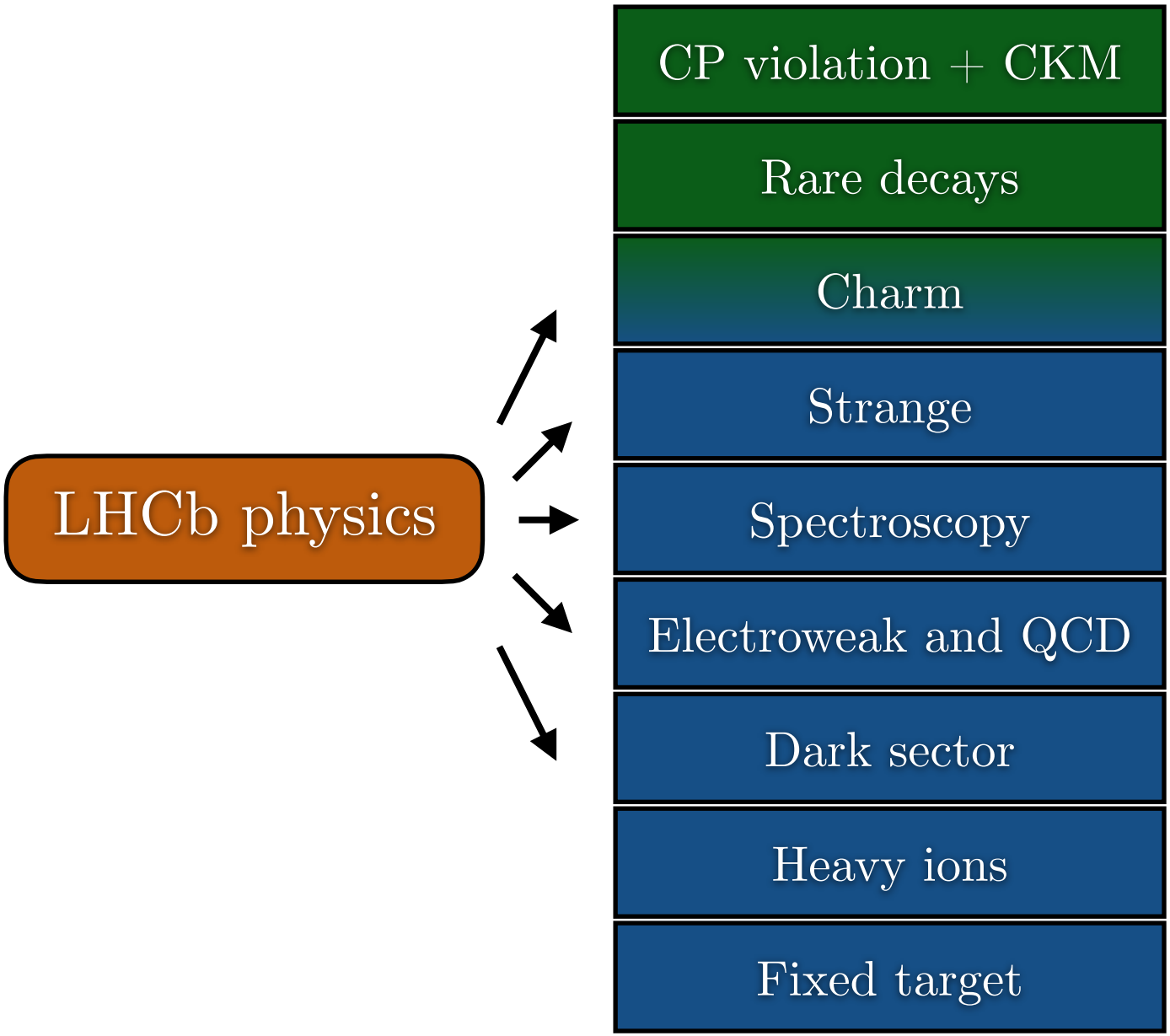
Matteo Palutan, U2 introduction
LHCb week, Feb 2024

  - The high pileup is the main modification to the reconstruction and analysis environment
    - allows for high statistics 
    - at the cost of increased occupancy, ambiguities, ghosts 

⇒ design the detector to be performant under these extreme conditions

- Fixed target physics
  - installation of a polarised gas target for fixed target physics?
  - SMOG system should have little impact on the tracker requirements (to be confirmed...)

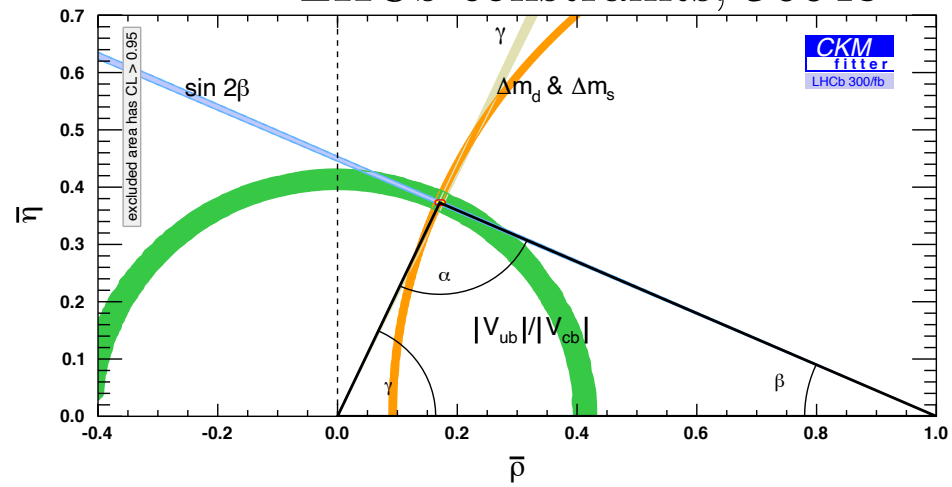
LHCb Upgrade II physics programme



CP violation and rare decays

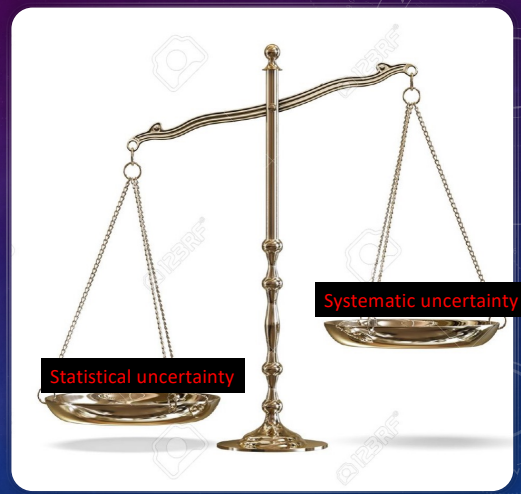
- cf. talk by Sneha Malde, "LHCb Upgrade 2 uniqueness in flavour physics" at LHCb week, Feb 2024
- CKM phases:
  - CPV in B mixing
  - angle γ from in time integrated decays
  - CPV in b baryons
- Rare decays:
  - $B^0_{(s)} \to \mu^+\mu^-$
  - $b \to s\ell^+\ell^-$ $(\ell = e, \mu, \tau)$
  - etc.
- Requirements ("usual suspects")
  - vertexing
  - tracking, momentum resolution
  - PID (RICH, MUON, CALO)
  - flavour tagging

LHCb constraints, $300\,\mathrm{fb}^{-1}$



PRECISION?

- My grant applications have liberally thrown the word "precision" around
- But nothing close to the precision I'll be speaking of today
- Not discussed detector limitations or systematics
- We'll need to maintain
  - Vertex capabilities
  - PID (inc leptons)
  - Flavour tagging
  - Etc etc etc
- I've focused on items where we think we can control systematics
- But its going to be really really hard work



22nd February 2024 3

[source: Sneha Malde, 02/24]

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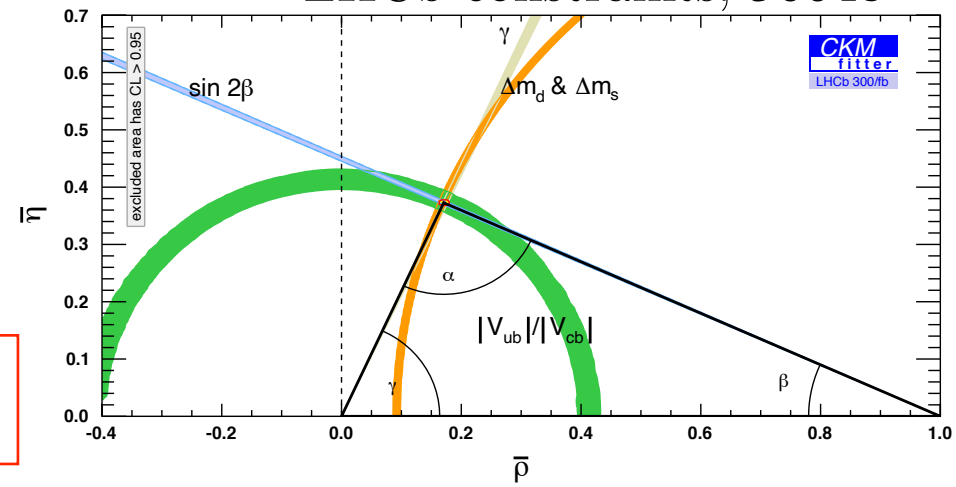
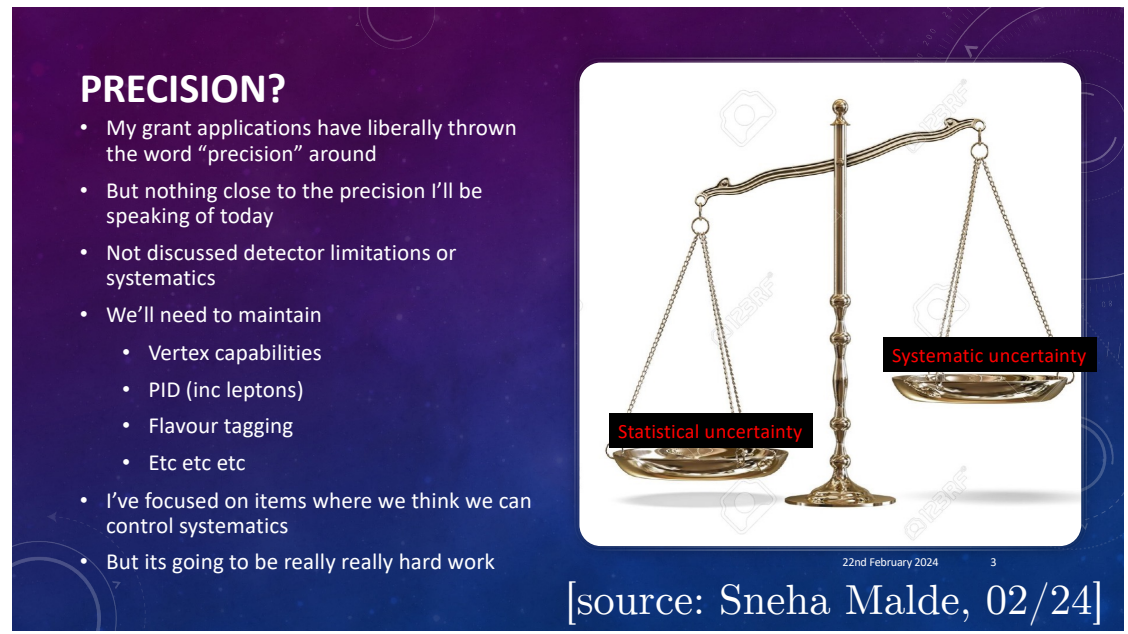
  - etc.

need excellent $\tau^{\pm}$ reconstruction capability

- Requirements ("usual suspects")
  - vertexing
  - tracking, momentum resolution
  - PID (RICH, MUON, CALO)
  - flavour tagging

LHCb constraints, 300 fb^{-1}





[source: Sneha Malde, 02/24]

Tools: PID and Flavour tagging

- PID
  - tracking and ghost rejection are essential input to:
    - the RICH performance (track direction)
    - identifying neutrals in the calorimeter
- Flavour tagging
  - cf. talk by Claire Prouve, "Update on flavour tagging", at LHCb week, Feb 2024

Upgrade 2 studies

Sara Celani, Veronika Chobanova, Quentin Fuehring, Stephanie Hansmann-Menzemer, Christoph Langenbruch, Peilian Li, Diego Martinez-Santos, Micol Olocco, Claire Prouve, Lennart Uecker

Studies to determine the performance of the flavour tagging for different Upgrade 2 conditions.

Use Run 3 MC and reweight/smear different variables → retrain the flavour tagging classifiers and determine tagging power.

- pileup
- PID efficiencies
- IP resolution
- (in)correct PV association efficiency
- ghostrate

⇐ parameters directly impacting flavour tagging performance (timing will be of help too)

Spectroscopy

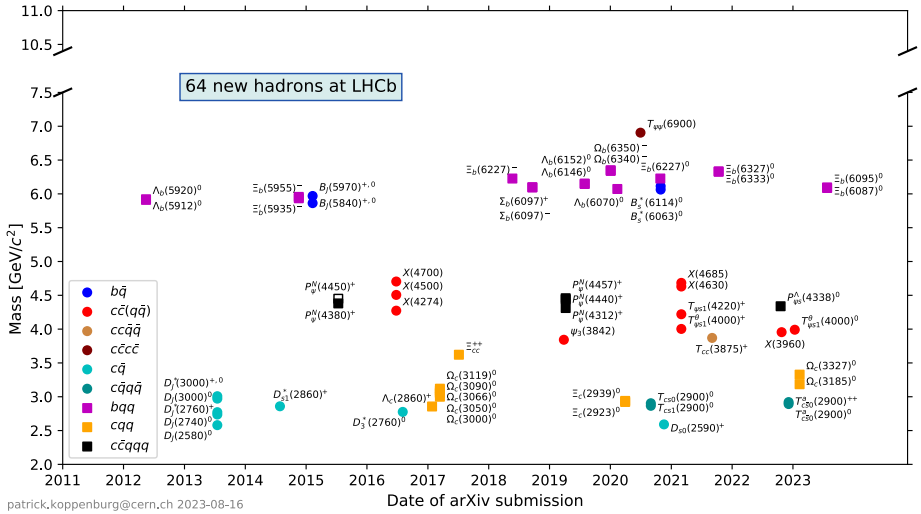
- cf. talk by Mengzhen Wang, "LHCb Upgrade 2 uniqueness in hadron spectroscopy", at LHCb week, Feb 2024

- Search for new hadrons
- Measure hadron properties

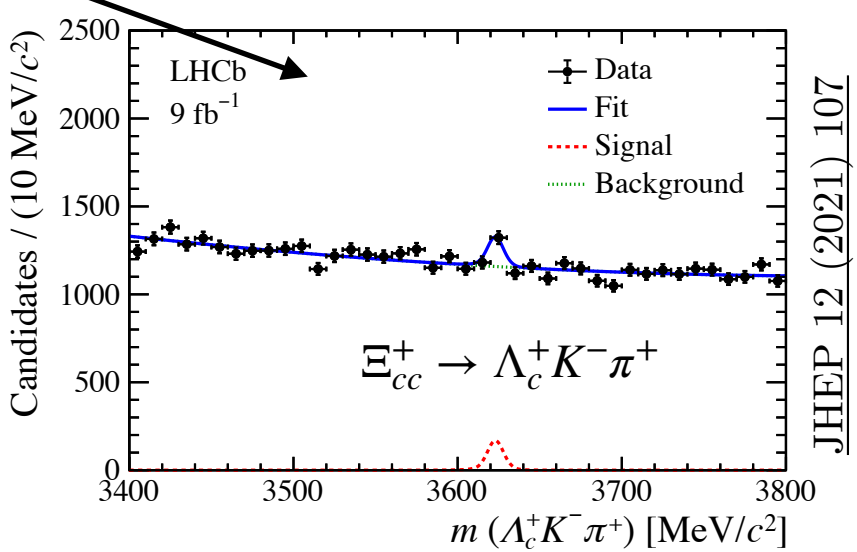
  → exotic states (tetra- penta-quarks)

  → double-heavy baryons ($\tau \sim 0.1\,\text{ps}$)

  → ...



- VELO performance is essential to:
  - reduce the background level
  - measure short lifetimes



Heavy ions and fixed target

- cf. talk by Matt Durham, "LHCb Upgrade 2 uniqueness in IFT physics", at LHCb week, Feb 2024

Summary

- Upgrade 2 provides us with an opportunity to do truly unique heavy ion physics:
  - Gluon dynamics at low-x will always be interesting, field rapidly evolving
  - Our unique strengths measuring *b* hadrons directly enhance heavy ion program
  - Heavy ion collisions lets us answer fundamental question about the nature of exotic hadrons, expanding LHCb's proven expertise and leadership
  - Bedrock heavy ion physics with charm/bottomonia suppression
- Upcoming IFT workshop: Heavy Ion Physics with Upgrade 2
- Santiago de Compostela, 1-3 July 2024

[source: Matt Durham, 02/24]

Los Alamos NATIONAL LABORATORY

Matt Durham – 111th LHCb week

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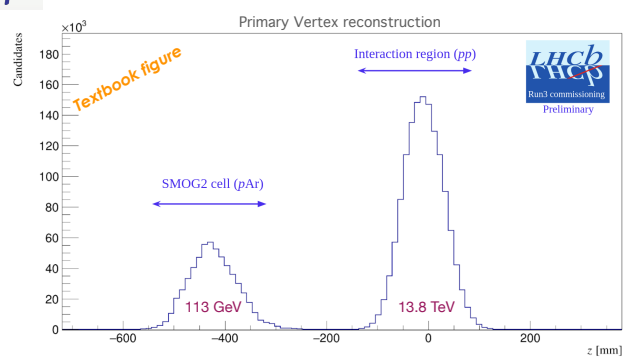
- LHCb can provide unique input to heavy ion physics
  - low-x physics
  - strong interest to reach approach central collisions ⇒ **high occupancy**

- Polarised gas target: LHCspin(SMOG3)
  - low-risk high-return programme
  - PV separated by 40cm from pp collisions

  ⇒ vertexing important, but timing probably not essential

SMOG2 ... wow-factor!

LHCb-FIGURE-2023-001



Two well separated and independent Interaction Points working simultaneously

[source: Pasquale Di Nezza]

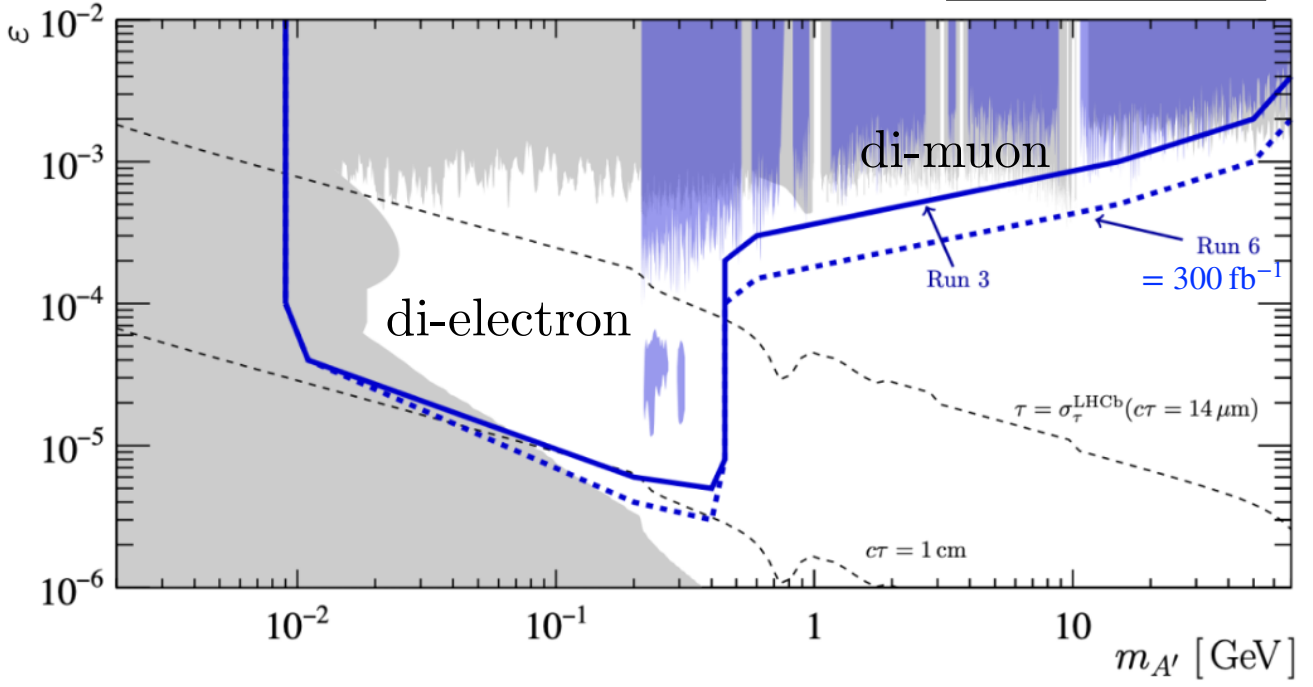
Input from Andrii Usachov

Dark sector

- $A' \to \mu\mu$ and $\pi^0/\eta \to \gamma(A' \to ee)$
  - from Run 3, LHCb is a major player, covers much of unexplored space
  - Upgrade II: significant increase in sensitivity ($\to$ high $m_{A'}$)

PRL 124 (2020) 041801

arXiv:2203.07048



- Similarly, unique sensitivity in other Dark Sector scenarios:
  - *dark scalar,*
  - *axion-like particles,*
  - *heavy neutral leptons,*
  - *dark hadrons*

Input from Andrii Usachov

Dark sector (II)

UNREALISED NEW PHYSICS SEARCHES

Rept.Prog.Phys. 85 (2022) 2, 024201

Unleashing the full power of LHCb to probe Stealth New Physics

Editors: M. Borsato[1], X. Cid Vidal[2], Y. Tsai[3,4], C. Vázquez Sierra[5], J. Zurita[6]

Authors: G. Alonso-Álvarez[7], A. Boyarsky[8], A. Brea Rodríguez[2], D. Buarque Franzosi[10,11], G. Cacciapaglia[12,13], A. Casais Vidal[2], M. Du[14], G. Elor[15], M. Escudero[16], G. Ferretti[10], T. Flacke [17], P. Foldenauer[18], J. Hajer[19,20], L. Henry[5], P. Ilten[21], J. Kamenik[22,23], B. Kishor Jashal[6], S. Knapen[5], F. L. Redi[24], M. Low[25], Z. Liu[14,26,27], A. Oyanguren Campos[6], E. Polycarpo[28], M. Ramos[29,30], M. Ramos Pernas[31], E. Salvioni[5], M. S. Rangel[28], R. Schäfer[9], L. Sestini[32], Y. Soreq [33], V. Q. Tran[14], I. Timiryasov[24], M. van Veghel[34], S. Westhoff[9], M. Williams[35], J. Zupan[21]

- Useful guide on exotic signatures with a sound theoretical motivation
- Significant and increasing attention to LHCb in the theory community over the last few years
- Well-aligned with the trend on dedicated **long-lived particle searches**
- New sensitivity due to e.g. **downstream tracking at HLT1**

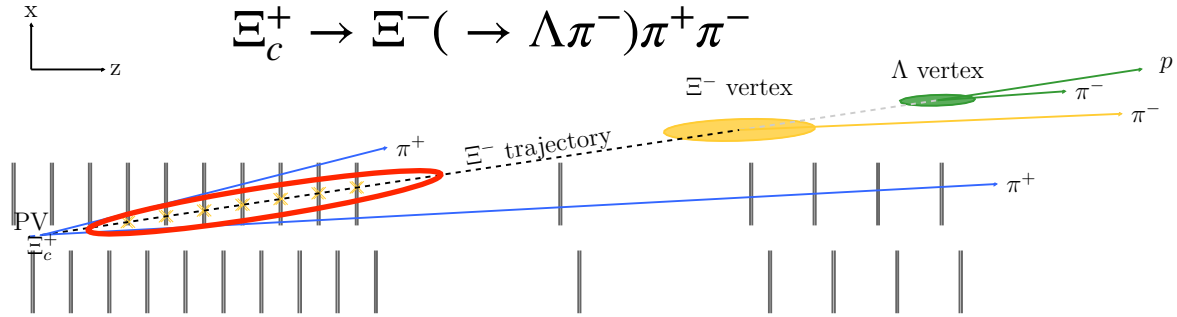
2

Medium- and Long-lived particle

- $K^0_S \to \pi^+\pi^-$ and $\Lambda \to p\pi$: essential inputs to much of the LHCb physics programme

- Long-lived particles, e.g. Heavy Neutral Leptons
  ⇒ need large tracker acceptance volume
  ⇒ downstream tracking and standalone T-tracking
  ⇒ what level of momentum resolution if T stations in fringe field?

- Hyperon decays
  - charged hyperons decaying in the VELO
  - track hyperons in the VELO
  - significant improvement of the signal selection

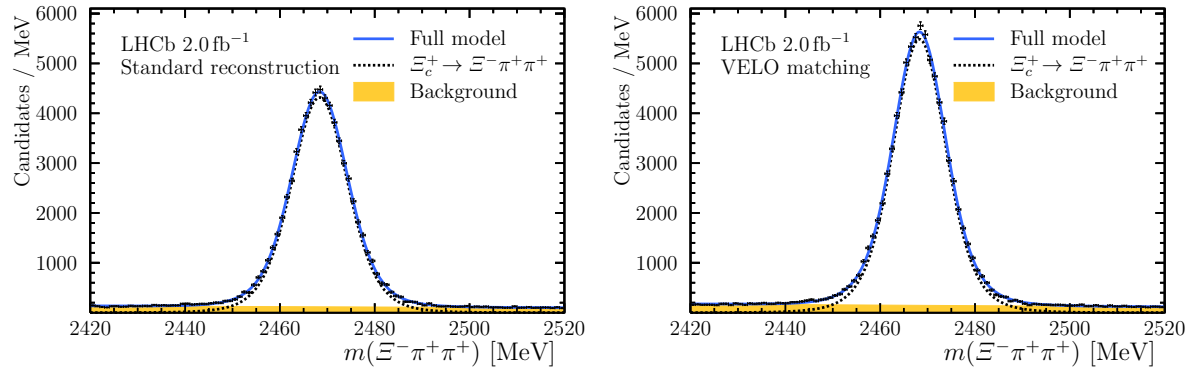


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-20XX-ZZZ
LHCb-DP-2023-004
February 16, 2024

Tracking of charged particles with nanosecond lifetimes at LHCb

LHCb collaboration



LHCb-DP-2023-004

The tracker requirements for physics

- The rule of thumb:

  "Same or better" detector performance as in Upgrade I

- Key tracking parameters
  - momentum resolution
  - vertexing (primary and secondary decays)
    - beauty, charm, $\tau^{\pm}$ lepton, flavour tagging
    - but also for spectroscopy, fixed target, medium-to-long lived particles
  - ghost rejection

  $\Rightarrow$ high segmentation (pixels where needed)

  $\Rightarrow$ keeping (very) low material budget

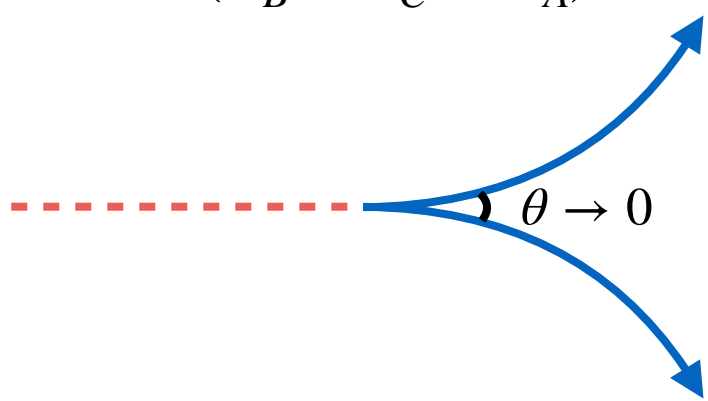
$\rightarrow$ Quantification of the requirement must come from simulation

Other points to consider

- Improved efficiency at low momentum
  - slow pions in D^* decays
  - multi-body channels
  - access to central heavy-ion collisions

  $\Rightarrow$ magnet stations (can we gain from UT in fringe magnetic field?)

- Vertexing for decays at or near threshold $A \to B + C$ $(m_B + m_C \approx m_A)$
  - e.g. $f_0 \to \pi^+\pi^-$, $\phi \to K^+K^-$, $\gamma \to e^+e^-$ conversion
  - Need excellent vertex resolution to improve the vertex resolution in direction of the boost



- Pseudo-rapidity acceptance:
  - well defined in the VELO + UT (straight tracks)
  - not same definition in terms of physics reach in T stations (after magnet)

→ talk by Mary Richardson-Slipper in this session

Conclusion

- VELO
  - vertex resolution is essential for all LHCb physics
  - VELO tracks fully part of Long tracks
  - VELO tracks now used for medium-to-long lived particles

  ⇒ no compromise on VELO tracking and vertexing capabilities

- Tracking (UT, MT, Magnet)
  - high tracking efficiency, in particular for high-multiplicity processes
  - low ghost level
  - excellent momentum resolution ⇒ mass resolution, background rejection

  ⇒ high granularity, low material budget tracker

- **Detector optimisation:**
  - **to be based on simulation of key physics channels** → talk by Matteo Palutan in this session
  - **a global optimisation is essential to maximise the physics output**