Reconstruction and physics opportunities of long-lived particles decaying downstream of the LHCb magnet

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on behalf of the **LHCb** collaboration

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Reporting on
CERN-LHCb-DP-2022-001 (in preparation)

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ICHEP 2022
XLI
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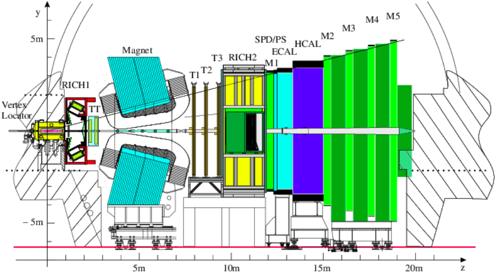
on High Energy Physics
Bologna (Italy)
6
13 07 2022

LHCb detector and track types

Int.J.Mod.Phys.A 30 (2015) 07, 1530022

LHCb detector

- Optimized for c- and b-hadron physics, fully instrumented at high η
- Physics program expanded beyond this
- Excellent PID: RICH1-2, colorimeters (ECAL, HCAL), muon chambers (M1-M5)
- Tracking system: three subdetectors (VELO, TT, T1-T3), dipole magnet



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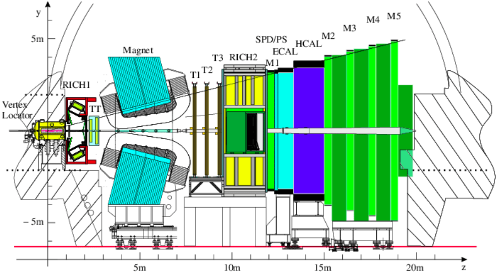
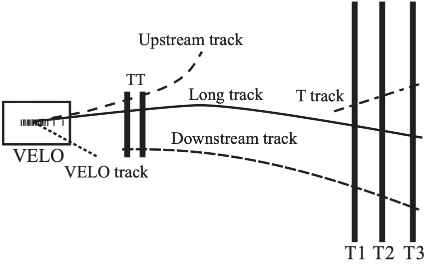
Track types

- Core LHCb physics program: Long (and Downstream) tracks
- This talk: opportunities with **unused T tracks**





Physics Goals

Λ hyperon dipole moments

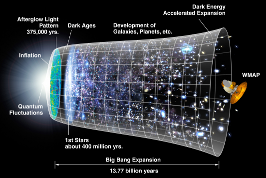
BSM long-lived particle searches

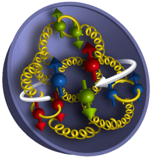
…

Electric and magnetic dipole moments

Electric Dipole Moment (EDM)

- Matter–antimatter asymmetry
- Sakharov conditions $\supset$ C and CP violation
- Sources of CP Violation: SM (not enough) and BSM
- A golden observable for new CPV sources:
  Electric Dipole Moment (EDM)





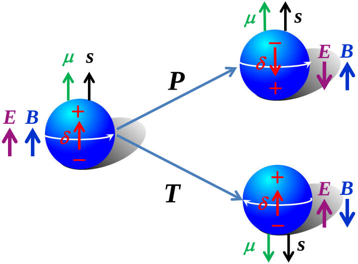
Magnetic Dipole Moment (MDM)

- Gives information on the baryon **spin structure**
- MDM of lowest-lying baryon octet (p, n, Λ, Σ, ...) was key to assess the quark model
- Baryon MDM nowadays: recurrent benchmark to compare **non-perturbative QCD** methods

Electric and magnetic dipole moments

Definitions. EDM ($\boldsymbol{\delta}$) and MDM ($\boldsymbol{\mu}$)

$$\boldsymbol{\delta} = \int \boldsymbol{r}\rho(\boldsymbol{r})d^3r \qquad \boldsymbol{\mu} = \frac{1}{2}\int \boldsymbol{r}\times\boldsymbol{J}(\boldsymbol{r})d^3r$$



Quantum-mechanical description:

$$\boldsymbol{\delta} = d\mu_N\frac{\boldsymbol{S}}{2} \qquad \boldsymbol{\mu} = g\mu_N\frac{\boldsymbol{S}}{2}$$

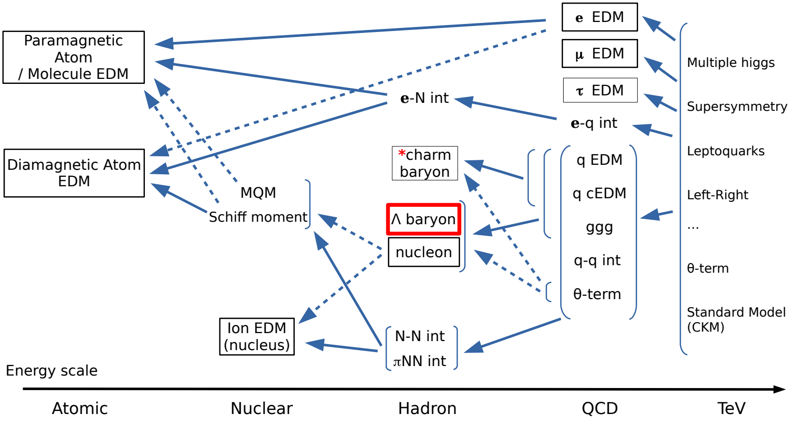
Energy of a system

$$H = -\delta\cdot\boldsymbol{E} - \mu\cdot\boldsymbol{B} \qquad \xrightarrow{T} \qquad +\delta\cdot\boldsymbol{E} - \mu\cdot\boldsymbol{B}$$

$$\xrightarrow{P} \qquad +\delta\cdot\boldsymbol{E} - \mu\cdot\boldsymbol{B}$$

The EDM violates T and P $\Rightarrow$ **CP violation**

Map of the EDM Field



Inspired by N. Yamanaka. Springer Theses (2014)

- Any signal of nonzero EDMs **originates in new physics** (in current/planned experiments)

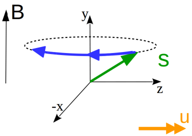
* see poster by Giorgia Tonani

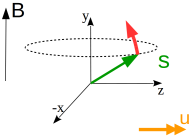
Measurement at LHCb

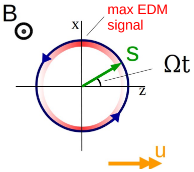
Proposed in Eur.Phys.J.C 77 (2017) 3, 181

Experiment concept: spin precession in EM field

$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{s} \times \boldsymbol{\Omega} \,, \qquad \boldsymbol{\Omega} = \frac{\mu_N}{\hbar}\left[g \left(\boldsymbol{B} - \frac{\gamma - 1}{\gamma}(\boldsymbol{u} \cdot \boldsymbol{B})\boldsymbol{u} \right) + d\beta \boldsymbol{u} \times \boldsymbol{B} \right] .$$







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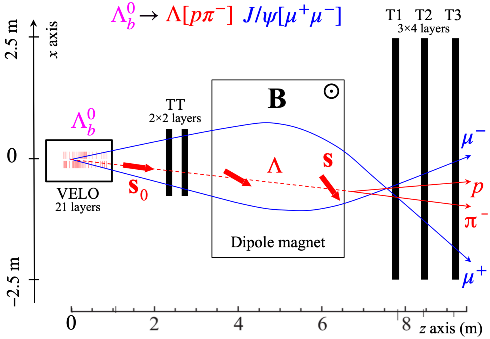
Proposal for Λ baryons at LHCb

- Large initial longitudinal pol. from weak decays *e.g.* $\Lambda_b^0 \to \Lambda J/\psi\,,\ |\boldsymbol{s}_\Lambda| \approx 100\%$
- Fit angular distribution with T tracks
  → get final polarization
- Expected improvement on Λ dipole moments by **two orders of magnitude** (Run1-Run4)



Previous measurements at Fermilab: PRD 23 (1981) 814 (EDM), PRL 41 (1978) 1348 (MDM)

BSM long-lived particle searches

- Long-lived particles predicted by a plethora of new physics models
  see reviews in *e.g.* Rept.Prog.Phys. 85 (2022) 2, 024201 ; Eur.Phys.J.C 80 (2020) 12, 1177
- Several searches by LHCb using long and downstream tracks
  see last analyses Eur.Phys.J.C 77 (2017) 12, 812 ; Phys.Rev.Lett. 124 (2020) 4, 041801 ; Eur.Phys.J.C 81 (2021) 3, 261 ; Eur.Phys.J.C 82 (2022) 4, 373
- **T tracks**: give access to decays taking place at 3-7 meters from the *pp* collision point → **greatly extending the lifetime coverage**, up to ∼ few ns

Reconstruction challenges

Momentum resolution

Track extrapolation

Vertex efficiency

Crossing vertices

misID Λ/K^0_S

Reconstruction challenges (I)

CERN-LHCb-DP-2022-001

Low momentum resolution

foremost source of challenges

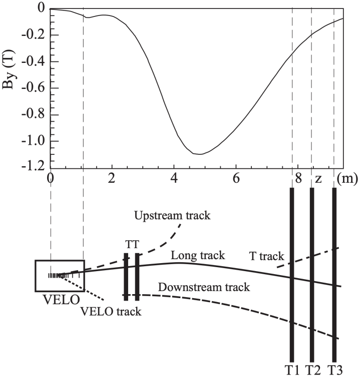
$$\left.\frac{\sigma_p}{p}\right|_{T\ \ track} \sim 30\% \qquad \left.\frac{\sigma_p}{p}\right|_{Long} \sim 0.5\%$$

- Measured **track curvature** induced by residual $\boldsymbol{B}$ in between T1-T3

- **Improved to 10%** by constraining masses and vertex positions with Decay Tree Fitter (DTF)
  → exclusive Λ production modes

$$\Lambda_b^0 \to \Lambda(\to \underbrace{p\,\pi^-}_{T\ \ tracks}\,)\; J/\psi\,(\to \underbrace{\mu^+\mu^-}_{Long})$$

DTF Nucl.Instrum.Meth.A 552 (2005) 566-575



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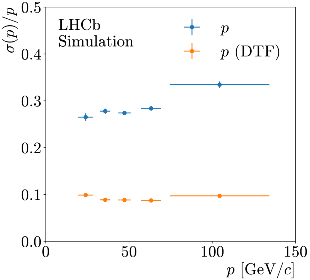
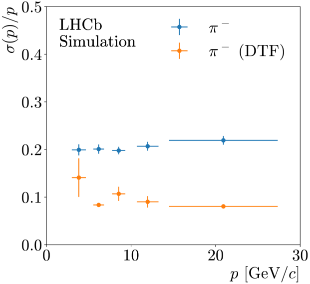
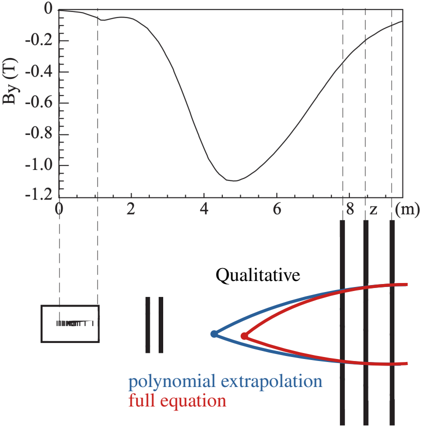




Reconstruction challenges (II)

Extrapolation of the T track
through an intense and inhomogeneous magnetic field over long distances

- Fast polynomial extrapolation not accurate
- **Overcome** by using full equation of motion, solved numerically with 5th-order Runge-Kutta method



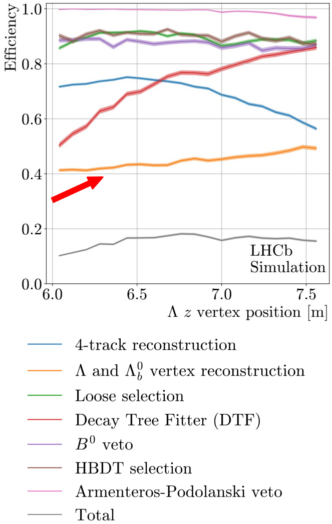
Extrapolation tools CERN-LHCB-2007-140

Reconstruction challenges (III)

CERN-LHCb-DP-2022-001

Low vertex efficiency

- Find decay vertices with T track pairs
- **Steps forward** with *ad hoc* vertexing algorithms
  - Recovered 20% of events by adjusting convergence criteria in x/y coordinates
  - Investigating effects of kinematically constrained fits and tracking errors



Reconstruction challenges (IV)

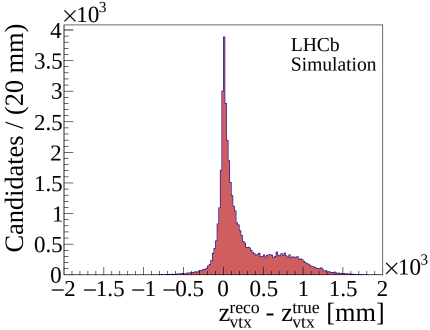
CERN-LHCb-DP-2022-001

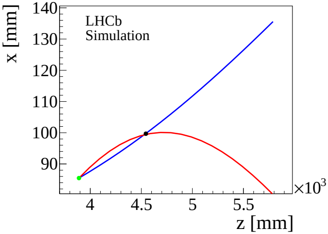
Vertices from crossing tracks

Strong bias on vertex z position ($\sim 1\,\mathrm{m}$)

Wrongly assigned to 2nd track-crossing point

Worsens **helicity angle resolution**





Impractical to use the event displays. Need for topological variables to separate these events and study them.

⇒ **horizontality**

Reconstruction challenges (IV)

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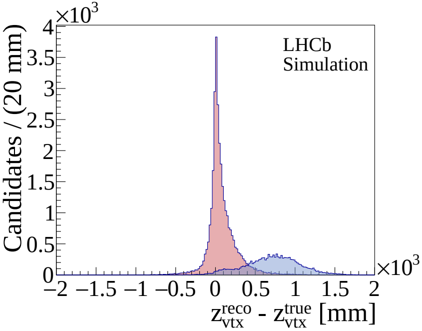
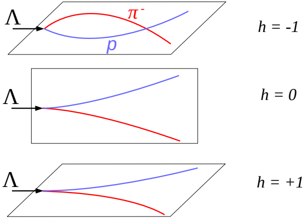




$\Rightarrow$ **horizontality**

$$h \equiv sgn(Q_p) M_{\mathrm{pol}} \left(\frac{p_p \times p_{\pi^-}}{|p_p \times p_{\pi^-}|} \right)_y$$

Source of bias identified. Exploring new variables and custom vertexing algorithms to recover true vertex

Effect reduced in decays with larger Q-value (larger opening angle): $K_{\mathrm{S}}^0 \to \pi^+\pi^-$

Reconstruction challenges (V)

CERN-LHCb-DP-2022-001

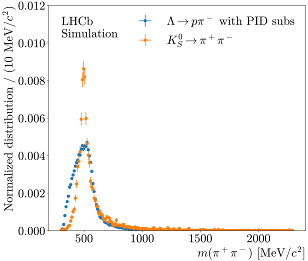
Particle identification for $\varLambda$ / K_{S}^{0}

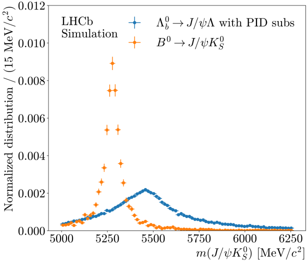
- Misidentified p / π^{+} results in cross contamination of

$$\varLambda \to p\pi^{-} \text{ and } K_{\mathrm{S}}^{0} \to \pi^{+}\pi^{-}$$

- Low momentum resolution: overlapping mass peaks

- PID information not used in Run II





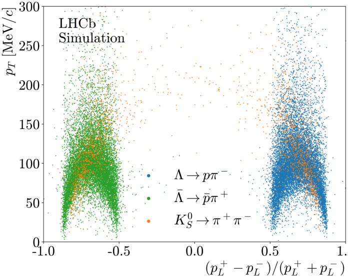
Reconstruction challenges (V)

CERN-LHCb-DP-2022-001

Particle identification for Λ / K^0_S

- Misidentified p / π^+ results in cross contamination of

$$\Lambda \to p\pi^- \text{ and } K^0_S \to \pi^+\pi^-$$



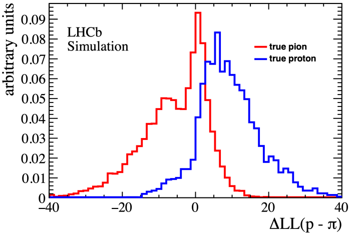
- Low momentum resolution: overlapping mass peaks

- PID information not used in Run II

- **Discrimination possible** with Armenteros-Podolanski method
  Different $\vec{p}$ carried by p/π^- vs. π^+/π^-

- PID information to be used for Run III

LHCB-FIGURE-2022-008



very preliminary

Real data: first results

Analysis strategy

Objective: demonstrate feasibility of analysis with T tracks by accurately determining mass peaks in data

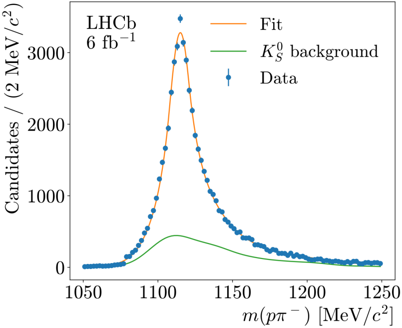
$\Lambda_b^0 \to \Lambda J/\psi$ decays: analysis of Run II data (6 fb^{-1})

- **Trigger** on detached muon pair from $J/\psi \to \mu^+\mu^-$
- Full-event information saved on disk, allowing to rerun reconstruction algorithms offline
- Selections
  - Preselection based on kinematical variables
  - **Multivariate classifie**r HBDT with kinematical, topological, and fit quality variables
  - **Veto on physical backgrounds** using (1) Λ_b^0 mass and (2) Armenteros-Podolanski method

Invariant mass

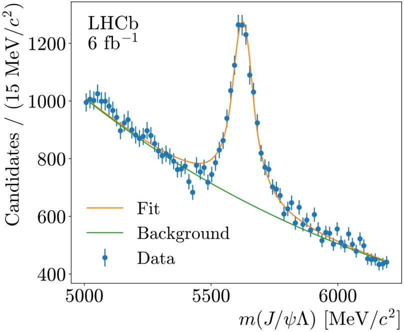
CERN-LHCb-DP-2022-001
LHCB-FIGURE-2022-009

$\Lambda \to p\pi^-$



$\sigma_{m(\Lambda)} \approx 8$ MeV

$\Lambda_b^0 \to \Lambda J/\psi$



$\sigma_{m(\Lambda_b^0)} \approx 41$ MeV

Mass peaks with reconstructed and combined T tracks at LHCb

6140 $\Lambda_b^0 \to \Lambda J/\psi$ signal candidates

Prospects and conclusions

Prospects

- Custom vertexing algorithms to increase efficiency and avoid crossing-track vertices
- Exploit RICH2 information to improve momentum resolution
- **Run I+II**: pilot measurement of Λ dipole moments with $\Lambda_b^0 \to \Lambda J/\psi$ decays
- **Run III**: versatile software-based trigger system in Run III
  - gives access to more abundant Λ production modes (approx. $\times 10^4$) *e.g.* $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, $\Xi_c^0 \to \Lambda K^-\pi^+$, $\Xi_c^0 \to \Xi^-(\to \Lambda\pi^-)\pi^+$;
  - allows to search for elusive BSM LLP signals

Conclusion

- Adding spin precession measurements and extending the range of LLP searches to the LHCb physics program
- Challenging reconstruction of decays downstream of the LHCb magnet
- **Demonstrated feasibility** with $\Lambda_b^0 \to \Lambda J/\psi$ and $B^0 \to K_S^0 J/\psi$
- All the details in a **new article to appear in the next few weeks**

CERN-LHCb-DP-2022-001

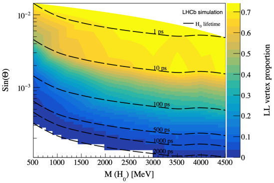
backup

LLP lifetime coverage with T tracks

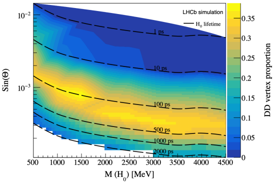
LHCB-FIGURE-2022-011

Lifetime coverage (dashed lines) of different track types through their reconstructibility in LHCb (colour axis) for $B^0 \rightarrow K^{(*)} h^0 (\rightarrow \mu^+ \mu^-)$.

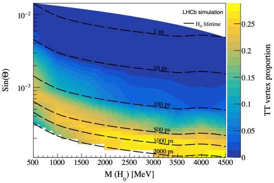
Decay channel motivated in Eur.Phys.J.C 80 (2020) 7, 669



Long tracks



Downstream tracks



T tracks