Physics opportunities with SM long-lived particles at LHCb

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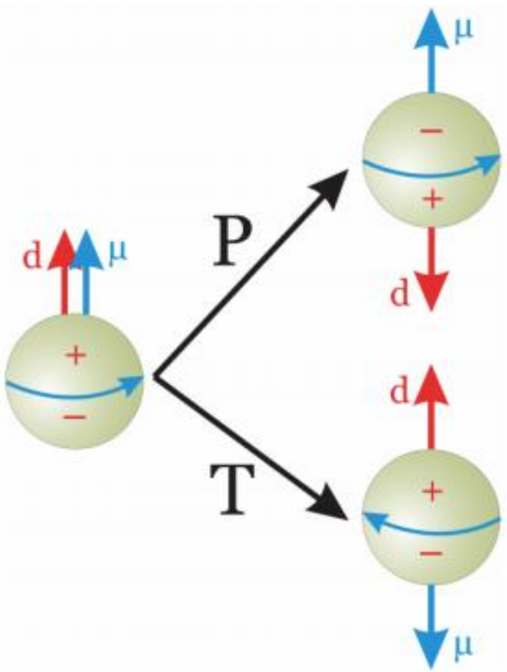
(On behalf of the Working Groups)

3rd workshop on EMDMs of unstable particles

Measurement of EMDMs

μ: magnetic dipole moment

d: electric dipole moment



Electric and Magnetic Dipole Moments of spin-$\frac{1}{2}$ particles

$$\delta = d\mu_N \frac{S}{2}, \quad \mu = g\mu_N \frac{S}{2}$$

$$\mathcal{H} = -\mu \cdot B - \delta \cdot E \xrightarrow{P} \mathcal{H} = -\mu \cdot B + \delta \cdot E$$

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

- **Non-zero EDM will violate P and T symmetry:**
  - ✓ T violation ↔ CP violation (if CPT holds)
- **The contribution of the Standard Model to EDM is very small:**
  - ✓ CKM: highly suppressed by loop level (>3) interaction
  - ✓ QCD $\bar{\theta}$ term: main SM contributors to the EDM, $\bar{\theta} < 10^{-10}$, limited by neutron EDM: $d_n < 1.6 \times 10^{-26}$ ecm

$$\mathcal{L}_{CPV} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}$$

Very sensitive to BSM physics, large windows of opportunity for observing New Physics!

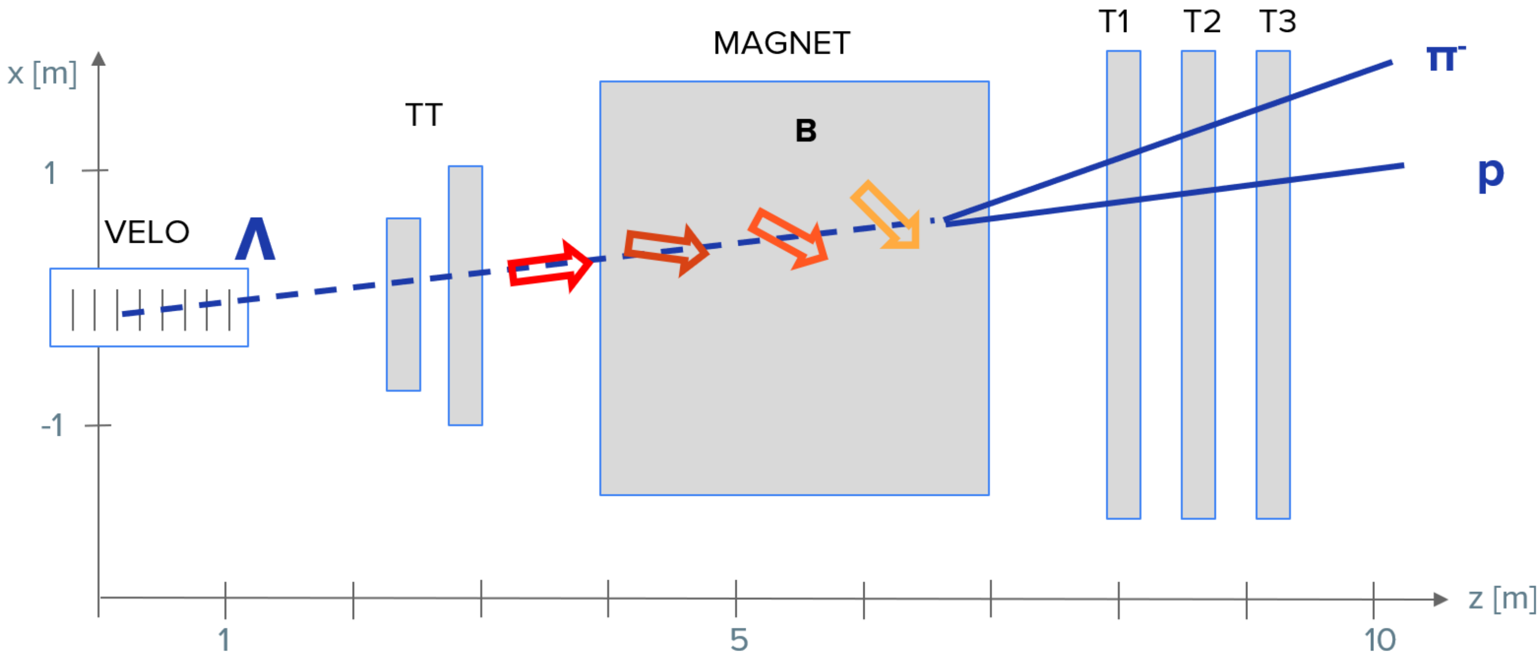
- **MDM measurement of particle and anti-particle**
  - ✓ CPT invariance test, test of low-energy QCD models

Measurement of Λ EDM/MDM

- **Spin-polarization vector s of Λ can be extracted by the angular distribution of the decay $\Lambda \rightarrow p\pi^-$**

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega'} = 1 + \alpha \boldsymbol{s} \cdot \boldsymbol{k}$$

- **Dynamics of the spin in an external magnetic field is given by the T-BMT equation**



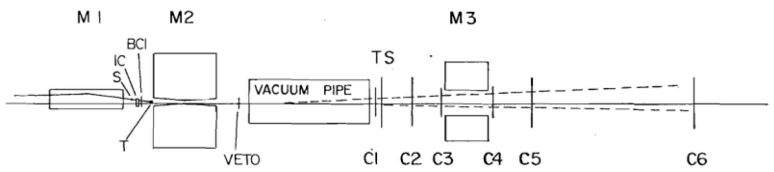
$$\vec{B} = (0, B_y, 0)$$

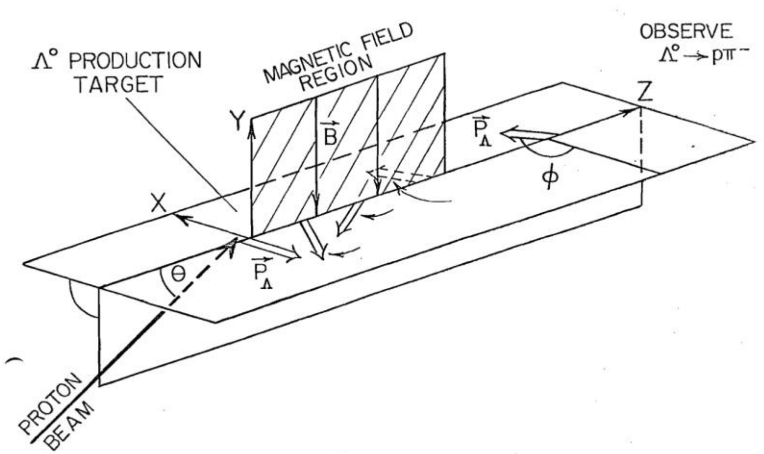
$$\vec{s}_0 = (0, 0, s_0) \longrightarrow \vec{s}_f = \left(-s_0 \sin\phi,\ -s_0 \frac{d\beta}{g} \sin\phi,\ s_0 \cos\phi\right)$$

precession angle

- **Higher $\vec{s}_0 \rightarrow$ higher sensibility on dipole moments**

Measurement of Λ EDM/MDM





- **Fixed target p-Be experiment at Fermilab**
- **Proton beam of 300 GeV**
- $\sim 3 \times 10^6$ Λ **events**
- **Strong Λ production with $\sim 8\%$ polarization**
- **No $\bar{\Lambda}$ polarization**

- **Measurement of the MDM of the Λ baryon**

$$\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$$

- **Measurement of the EDM of the Λ baryon**

$$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}\ e\text{cm}$$

It is time to revisit these 40-year-old results!

PRD 23, 814 (1981), PRL 41, 1348 (1978)

Measurement of Λ EDM/MDM at LHCb

- **Interaction of EDMs and MDMs with an external electromagnetic filed produces a spin precession.**
- **Three elements are necessary for the measurement of this effect:**

✓ **Source of polarized particles whose direction and polarization degree are known**

⇒ many ongoing analysis of the polarization measurement of b- and c-baryons in LHCb

✓ **Intense electromagnetic field able to induce a sizable spin precession angle**

⇒ a dipole magnet providing an integrated field of about 4Tm

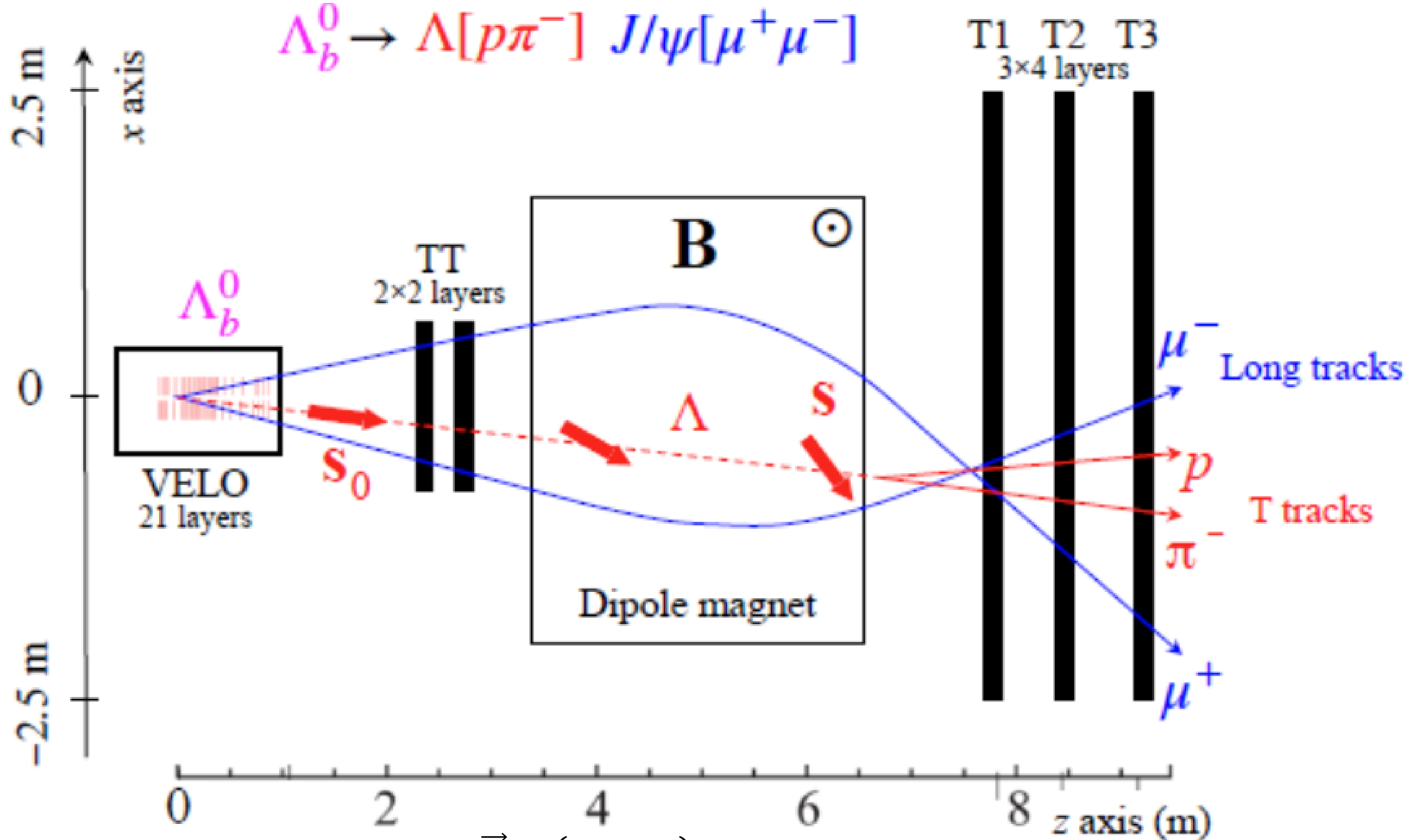
✓ **A detector to measure the final polarization vector by analyzing the angular distribution of the particle decays.**

⇒ three tracking stations T1-T3 (or SciFi tracker for Upgrade I)

LHCb is able to preform the measurement of Λ EDM/MDM

Most challenging part: first time to perform physics measurement with particles decaying at the end of magnetic file (poor resolution)

Measurement of Λ EDM/MDM via $\Lambda_b^0 \to \Lambda\, J/\psi$



$$\vec{B} = (0, B_y, 0)$$

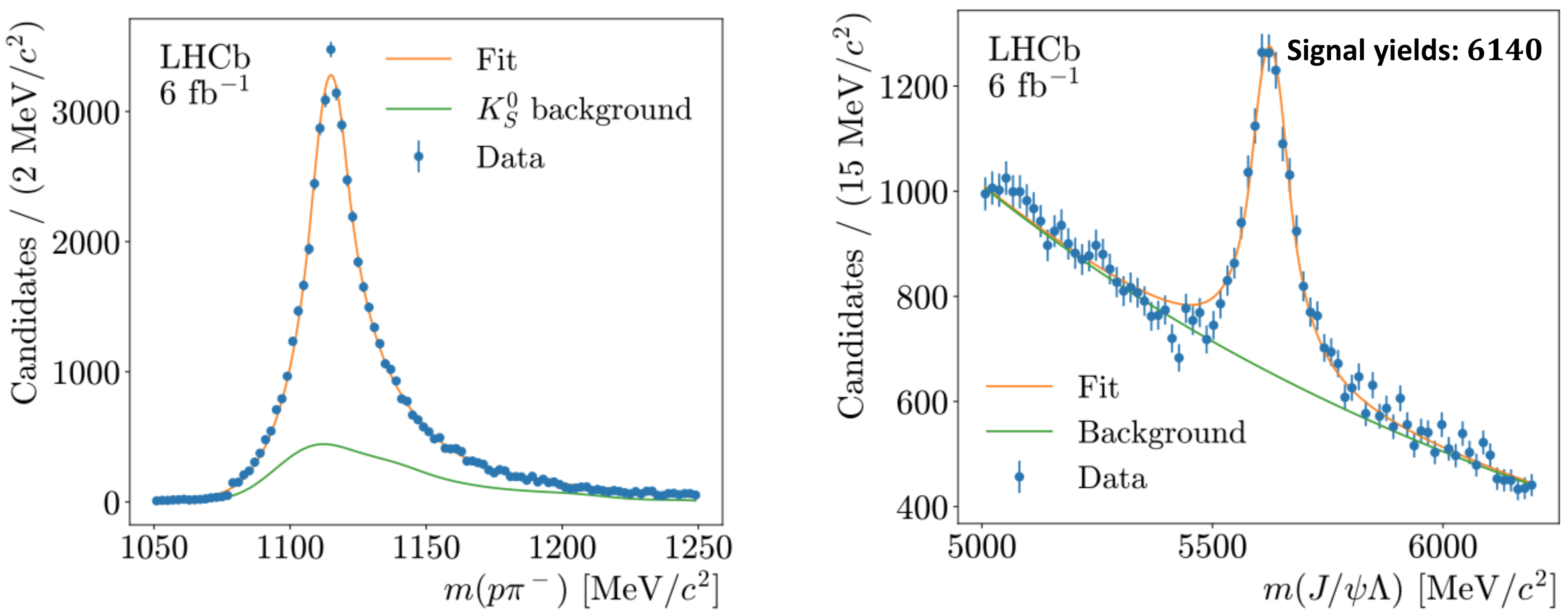
$$\vec{s}_0 = (0, 0, s_0) \longrightarrow \vec{s}_f = \left(-s_0 \sin\phi,\ -s_0 \frac{d\beta}{g} \sin\phi,\ s_0 \cos\phi\right)$$

- **Λ decay angular distribution in Λ helicity frame $(1/2 \to 1/2\ 0)$**

$$\frac{d\Gamma}{d\Omega}(\cos\theta_p, \phi_p, \vec{S}) \propto 1 + \alpha_\Lambda S_x \sin\theta_p \cos\phi_p + \alpha_\Lambda S_y \sin\theta_p \sin\phi_p + \alpha_\Lambda S_z \cos\theta_p$$

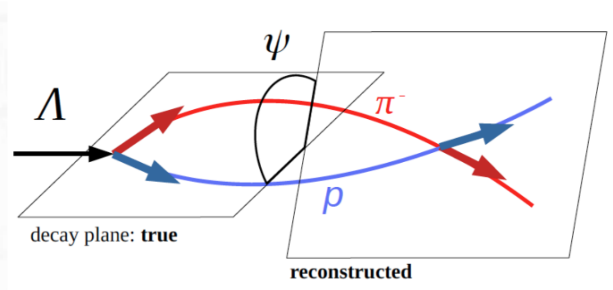
Measurement of Λ EDM/MDM via $\Lambda_b^0 \to \Lambda J/\psi$

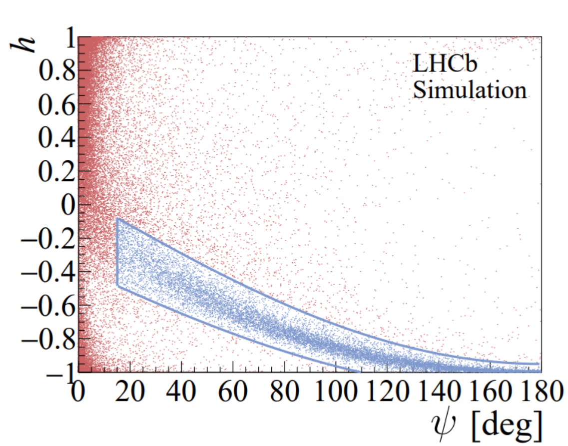
- Best channel to preform the first EDM/MDM measurement
  - ✓ Large production cross-section of Λ_b^0 at LHCb
  - ✓ Triggered by $J/\psi \to \mu^+\mu^-$ decays
  - ✓ Λ produced with large longitudinal polarization ($\sim 100\%$) [LHCB-PAPER-2020-005]
- Reconstruct Λ decay after the LHCb magnet ($6.0 \sim 7.0$m) [CERN-LHCb-DP-2022-001]
  - ✓ The first time to perform a physics measurement at the end of the magnetic field

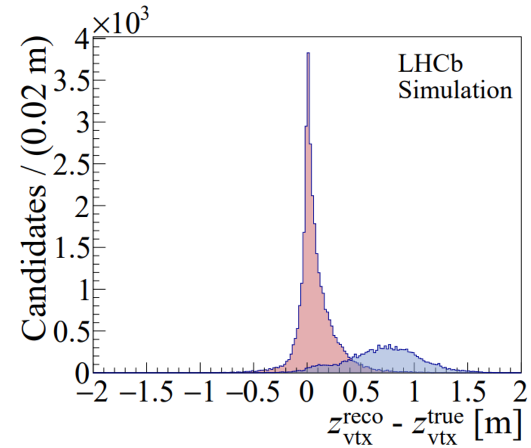


Measurement of Λ EDM/MDM via $\Lambda_b^0 \to \Lambda J/\psi$

- **Ghost vertex: Trajectories, with two (consistent within track uncertainties) crossing points, are assigned with the wrong vertex**







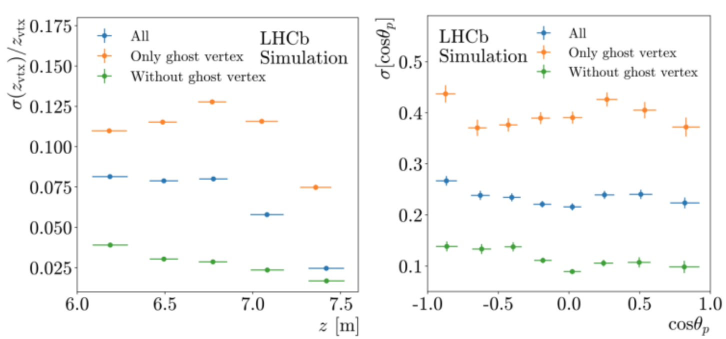
✓ **BDT classifier is used to remove the ghost vertex**

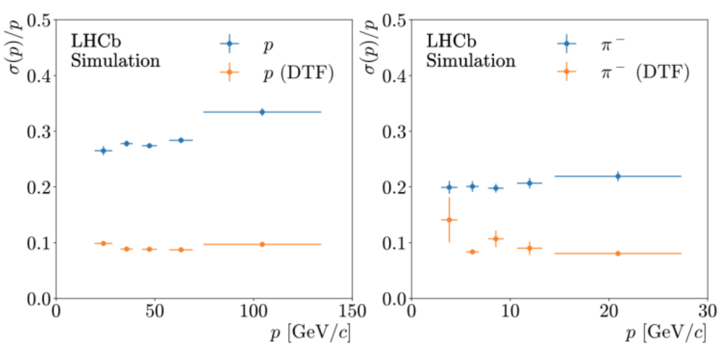
[CERN-LHCb-DP-2022-001]

- **Resolution**

✓ **Vertex resolution is improved by removing the ghost vertex**

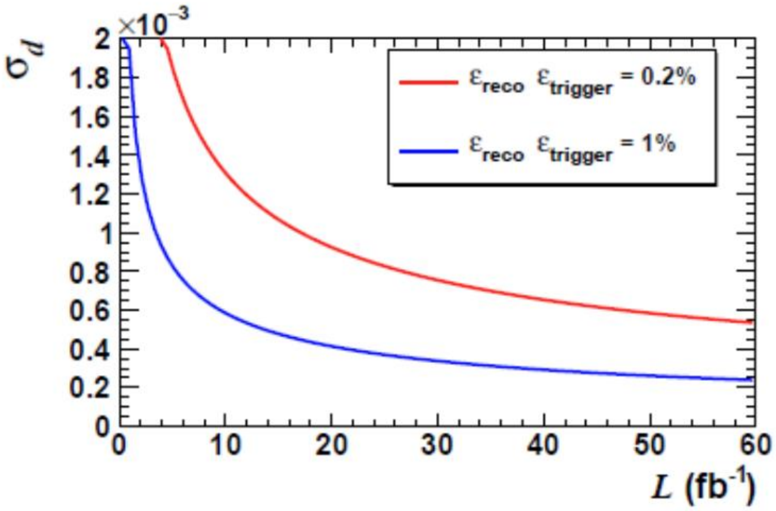
✓ **The resolutions of p, π^- momentum improve after DTF (J/ψ and Λ mass constraints)**

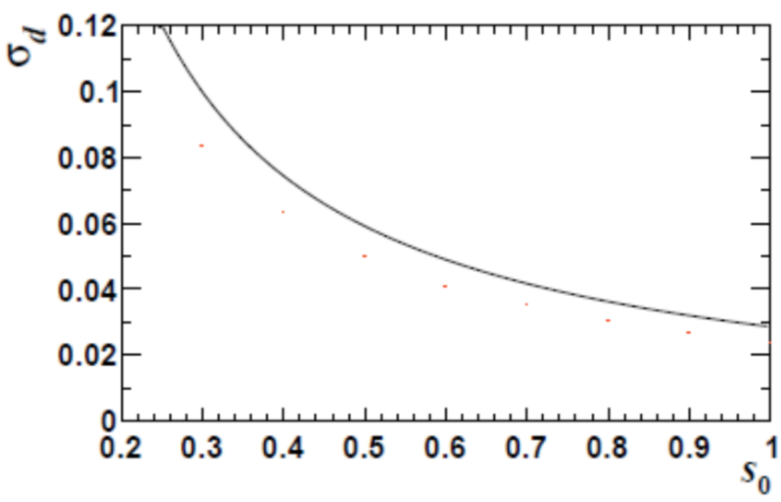




Measurement of Λ EDM/MDM via $\Lambda_b^0 \to \Lambda\, J/\psi$

- **The polarization and first electromagnetic dipole moments measurements based on Run 1 and 2 data sets are ongoing**
- **The physics trigger line (HLT2) for $\Lambda_b^0 \to \Lambda\, J/\psi$ (also $\Lambda_b^0 \to K_S^0\, J/\psi$) is ready for the next year data taking**

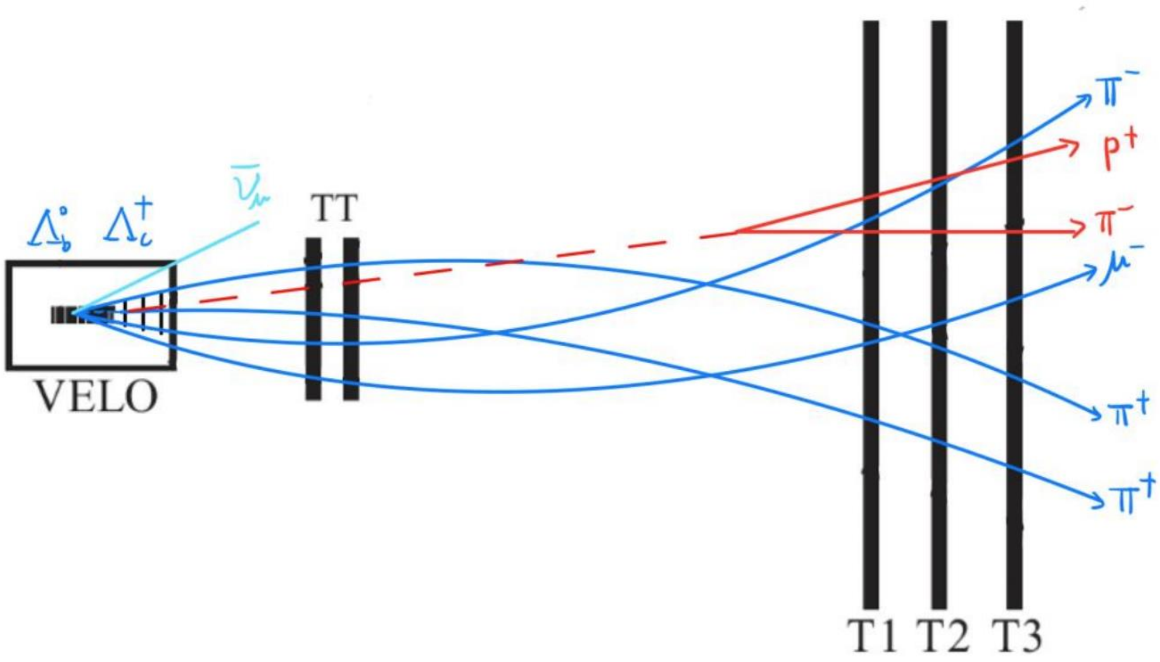




- **At $\mathcal{L}\sim 50\text{fb}^{-1}$, $\sigma_d \approx 1.3 \times 10^{-18}\, e\text{cm}$**
  - ✓ **Improved limit on the MDM of $\sim 10^{-4}\mu_N$**
- **$\Lambda_b^0 \to \Lambda J/\psi$ offers $\sim 100\%$ initial polarized Λ**
  - ✓ **Can achieve a higher sensitivity**

Measurement of Λ EDM/MDM via inclusive $\Lambda_c^+ \to \Lambda + nh$

- Λ_b^0 semi-leptonic decay $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu + n(\pi^+\pi^-)$
  ✓ larger branching fraction → possible larger yield
  ✓ week decay → polarized Λ_c^+, improve the sensitivity of Λ related parameters
- $\Lambda_c^+ \to \Lambda + n\pi^{+/-}$
  ✓ week decay → large longitudinal polarization ($\sim 80\%$)



Measurement of Λ EDM/MDM via inclusive $\Lambda_c^+ \to \Lambda + \mathrm{n}h$

- **Estimation of signal yield (based on Run2 data sets)**

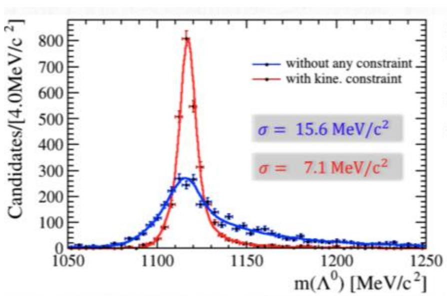
Decay channel	$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\mu^-\bar{\nu}_\mu$ $\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\mu^-\bar{\nu}_\mu$ $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$
expected yields (w/o stripping eff.)	55k	160k	59k

✓ **A dedicated stripping line was performed in the 2023 re-stripping campaign**

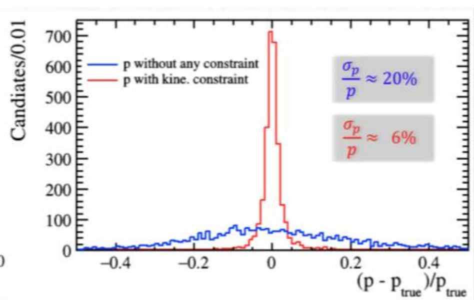
✓ **Due the lack of T-Track information in Run 2, the efficiency of re-stripping line is very low (<0.1%) → HLT2 lines for Run 3 is in development**

- **The resolution can be improved by removing ghost vertex and applying DTF**

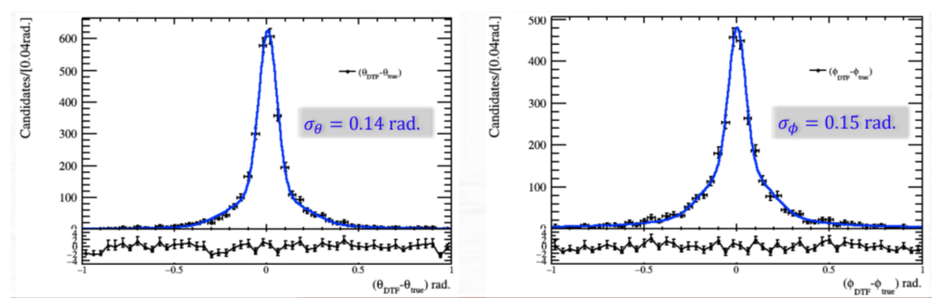
✓ **Invariant mass of Λ**



✓ **Momentum of proton**



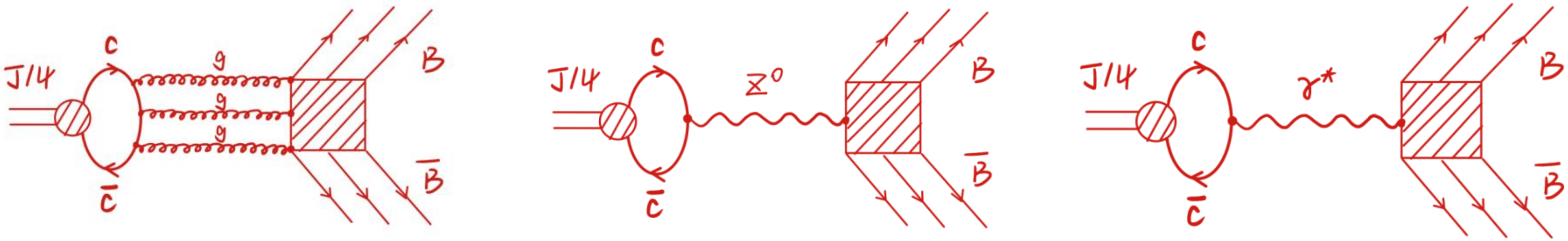
✓ **Helicity angels of Λ**



[Tianze's talk for Summer Student Presentation]

- **Further studies of all the channels based on MC simulation is ongoing**

Measurement of Λ EDM/MDM via $J/\psi \to \Lambda\bar{\Lambda}$



- **Measure the EDM/MDM with two methods**

  ✓ **Direct method: spin-polarization precession in LHCb magnetic filed**

  ✓ **Indirect method: using CP-odd observable**

$$B = \hat{P}_\Lambda \cdot (\hat{q}_p \times \hat{q}_{\bar{p}}), |< B >| = 3.2 \times 10^{-3}\delta_\Lambda$$

Sensitivity study ($\mathcal{L}_{\rm int} = 50\text{fb}^{-1}$)

  ✓ **Direct method: $\sigma_\mu = 1.5 \times 10^{-4}\mu_B, \sigma_\delta = 2.0 \times 10^{-18}e\text{cm}$**

  ✓ **Indirect method: $\sigma_\delta = 1.3 \times 10^{-18}e\text{cm}$**

Current exp. limits

$\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$

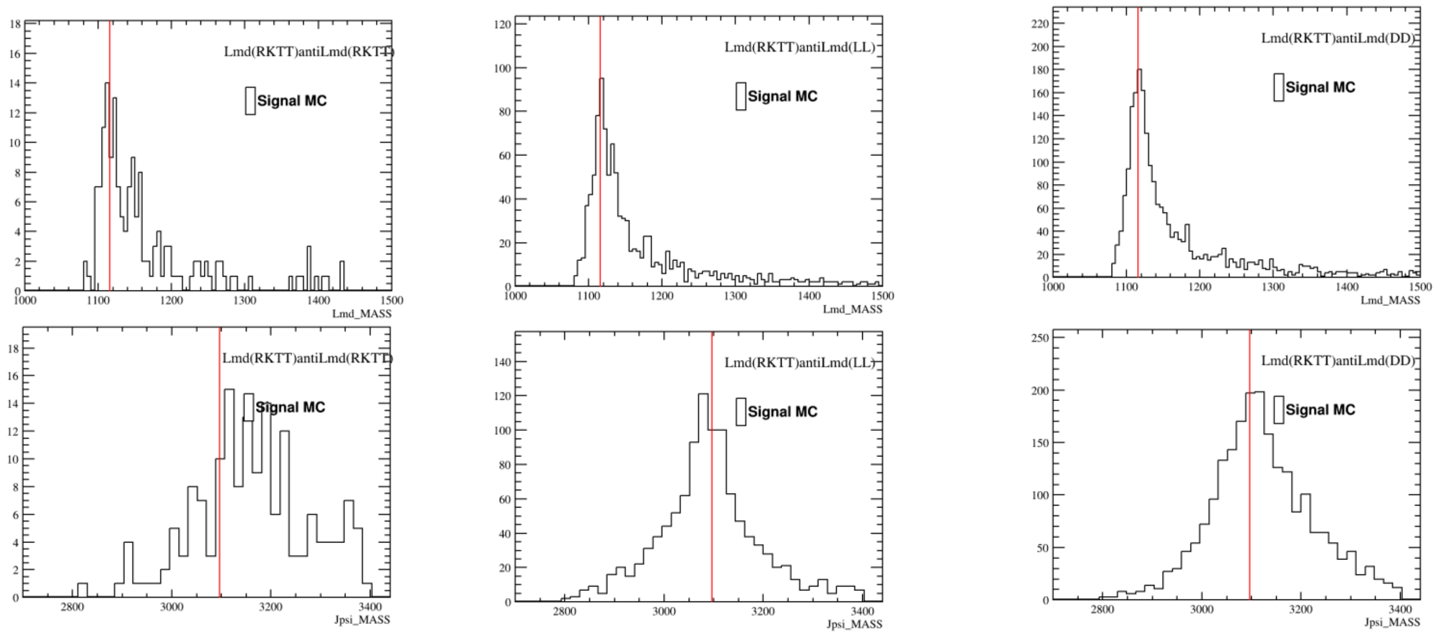
$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}\ e\text{cm}$

- **First test of CPT symmetry at 10^{-4} level and 1 order of magnitude improvement on EDM sensitivity**
- **Will benefit a lot from an efficient HLT1 Downstream track trigger**

Measurement of Λ EDM/MDM via $J/\psi \rightarrow \Lambda\bar{\Lambda}$

- **The development of HLT2 trigger lines for Run 3 is ready**

Combinations	$\Lambda(\mathrm{TT})\bar{\Lambda}(\mathrm{LL})$	$\Lambda(\mathrm{TT})\bar{\Lambda}(\mathrm{DD})$	$\Lambda(\mathrm{TT})\bar{\Lambda}(\mathrm{TT})$
Reconstruction efficiency (take ϵ_{HLT1} as 100%)	0.11%	0.24%	0.02%



✓ **Very preliminary results based on Run 3 MC simulation**

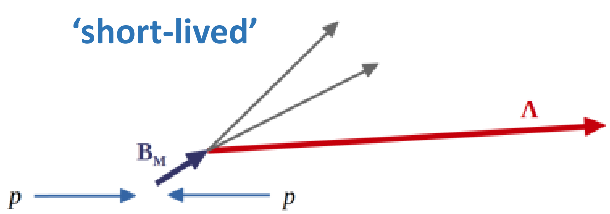
✓ **There is the ability to reconstruct the Λ from two T-Tracks**

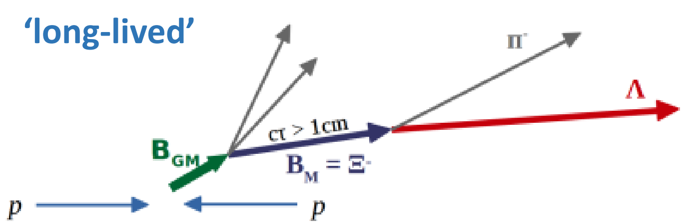
✓ **Further studies are needed to improve the resolution and optimize the selection**

Source and production of Λ (c-baryon decays)

Table 1: Dominant Λ production mechanisms from heavy baryon decays and estimated yields produced per fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$, shown separately for SL and LL topologies. The Λ baryons from Ξ^- decays, produced promptly in the pp collisions, are given in terms of the unmeasured production cross section. [*]

SL events	$N_\Lambda/\,\text{fb}^{-1}$ $(\times 10^{10})$	LL events, $\Xi^- \to \Lambda\pi^-$	$N_\Lambda/\,\text{fb}^{-1}$ $(\times 10^{10})$
$\Xi_c^0 \to \Lambda K^-\pi^+$	7.7	$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	23.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.3	$\Xi_c^0 \to \Xi^-\pi^+$	7.1
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	2.0	$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	6.1
$\Lambda_c^+ \to \Lambda\pi^+$	1.3	$\Lambda_c^+ \to \Xi^-K^+\pi^+$	0.6
$\Xi_c^0 \to \Lambda K^+K^-$ (no ϕ)	0.2	$\Xi_c^0 \to \Xi^-K^+$	0.2
$\Xi_c^0 \to \Lambda\phi(K^+K^-)$	0.1	Prompt Ξ^-	$0.13 \times \sigma_{pp\to\Xi^-}$ [μb]





- **Trigger lines are ready for Run3:**

  ✓ $\Xi_c^0 \to \Xi^-(\to \Lambda\pi^-)\pi^+$ ✓ $\Xi_c^0 \to \Lambda K^-\pi^+$ ✓ $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

- **And more in development:**

  ✓ $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$ ✓ $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$ ✓ $\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$

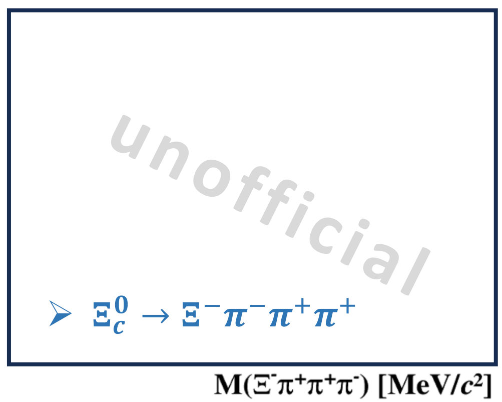
[*] F. J. Botella, L. M. Garcia Martin, D. Marangotto, F. M. Vidal, A. Merli, N. Neri, A. Oyanguren and J. R. Vidal, Eur. Phys. J. C77, 181 (2017)

Ongoing polarization analysis

- **Expected signal yields and the sensitivity of polarization**

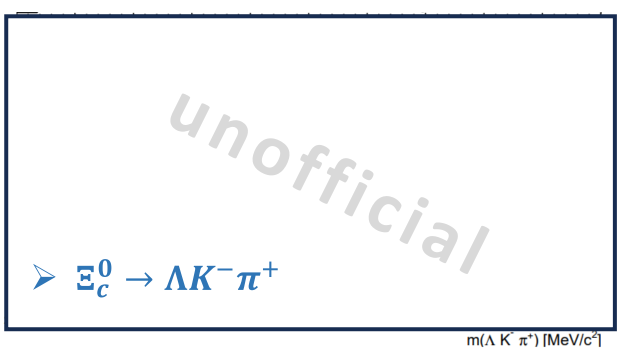
Decays	Data sets	Yields	Purity	$\sigma(P_x)$	$\sigma(P_y)$	$\sigma(P_z)$
$\Xi_c^0 \to \Xi^-\pi^+$	2017	$\sim$30k	$\sim$80%	± 0.007	± 0.007	± 0.014
$\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$	2017MagUp	$\sim$0.4k	$\sim$15%	--	--	--
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	2018	$\sim$112k	$\sim$93%	--	--	--
$\Xi_c^0 \to \Lambda K^-\pi^+$	2015/16/17	$\sim$60k	$\sim$50%	$\pm 0.01 \pm 0.01$	$\pm 0.013 \pm 0.005$	$\pm 0.014 \pm 0.004$
$\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$	2016	$\sim$24k	$\sim$54%	$\pm 0.02 \pm 0.01$	$\pm 0.02 \pm 0.02$	$\pm 0.02 \pm 0.01$

➢ $\Xi_c^0 \to \Xi^-(\to \Lambda\pi^-)\pi^+$

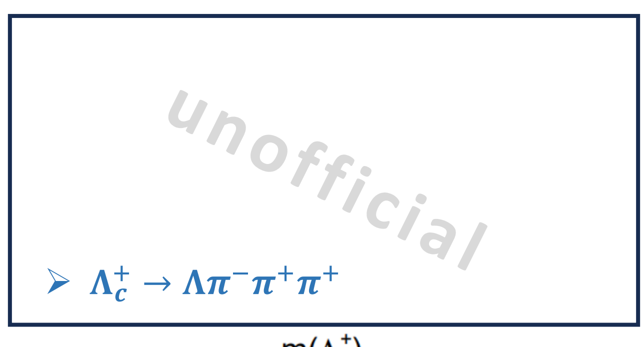


➢ $\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$

➢ $\Xi_c^+ \to \Xi^-\pi^+\pi^+$



➢ $\Xi_c^0 \to \Lambda K^-\pi^+$



➢ $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$

Model independent analysis of $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

- **Separate prompt and detached samples with discriminating variables in MVA**

- **Model independent fit strategy**

Adaptive binning (KDTreeBins, 20 bins)

Partition-based clustering (k-means algorithm, 20 clusters)

Density-based clustering with noise (DBSCAN algorithm, minPts=80, eps=0.028)

✓ **Background subtracted data**

✓ **prompt/detached separation**

✓ **Adaptive binning/clustering algorithms**

[Sergio's talk in the 110th LHCb Week]

Λ baryon polarization dilution

- **The Lambda polarization is much reduced in multiple-body decays** [PRC 95, 054902 (2017)]

$$P_\Lambda = C \cdot P_M, C < 1$$

P_M: polarization of the mother particle

Decay	C
parity-conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+\ 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+\ 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$

- **Interference of polarization of different decay chains for $\Xi_c^0 \to \Lambda K^- \pi^+$**

$\Xi_c^0 \to \Lambda K^*(892)^0$

$\Xi_c^0 \to \Sigma^*(1385)^+ K^-$

$\Xi_c^0 \to \Xi^*(1690)^- \pi^+$

$\Xi_c^0 \to \Xi^*(1820)^- \pi^+$

Λ baryon polarization dilution in $\Xi_c^0 \to \Lambda K^- \pi^+$

✓ Only 2-body week decay

✓ Interference of different resonances

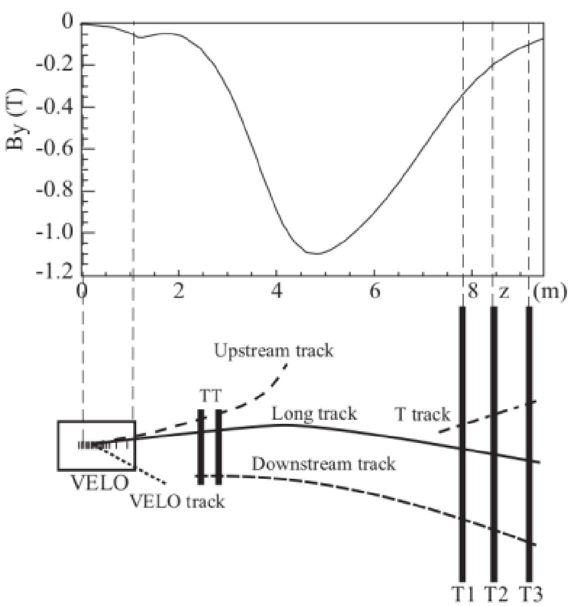
✓ strong decays

Decay		$\|\vec{P}\|$
$\Xi_c^0 \to \Lambda K^*(892)^0$	Only 2-body week decay	$\sim 0.4x$
	Interference of different resonances	$\sim 0.2x$
$\Xi_c^0 \to \Sigma^*(1385)^+ K^-$	$\Sigma^*(1385)^+ \to \Lambda\pi^+$ $(3/2^- \to 1/2^+ 0^+)$	$\sim 0.1x$
$\Xi_c^0 \to \Xi^* \pi^+$	$\Xi^*(1690)^- \to \Lambda K^-$ $(1/2^- \to 1/2^+ 0^+)$	$\sim 0.2x$
	$\Xi^*(1820)^- \to \Lambda K^-$ $(3/2^+ \to 1/2^+ 0^+)$	$\sim 0.0x$

- Could improve the sensitivity if rule out the intermediate processes with small factors

Summary

Tracks that leave only hits after the magnet have never been used for analysis at LHCb

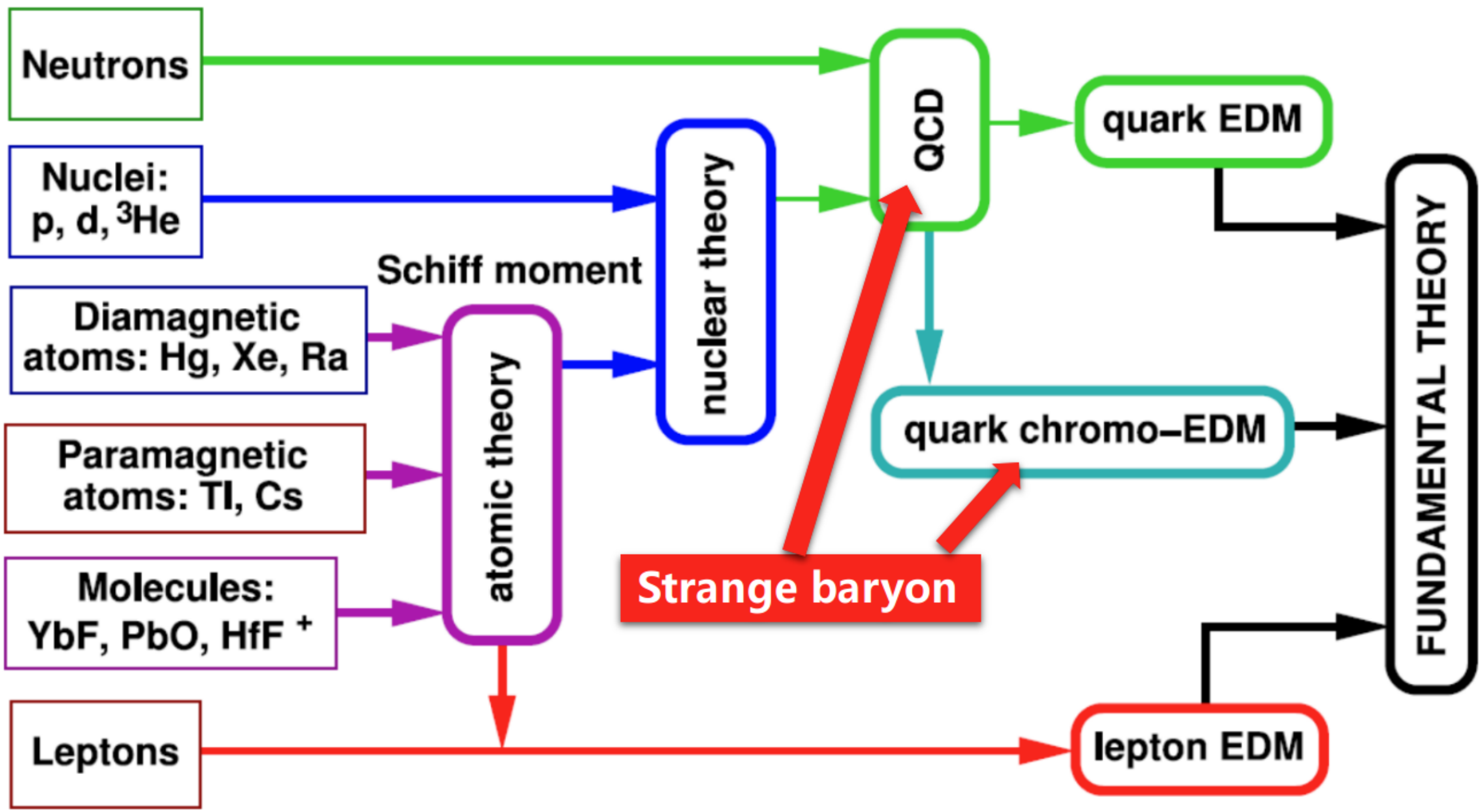


- **Opportunities:**
  - ✓ **Rich physical processes can be triggered by the TTracks**
  - ✓ **Many polarization analyses are work in progress**
  - ✓ **To push the boundary of experimental precision and Reduce the gap between theory and experiment**
  - ✓ **Observe new decay modes which are dominated by LLPs**
- **Challenge:**
  - ✓ **Poor momentum resolution → $20\sim30\%$ (0.1% for Long tracks)**
  - ✓ **Long propagation distances in the magnet region make track extrapolation more difficult**
  - ✓ **Low vertex reconstruction efficiencies and resolution**
  - ✓ **Lack of RICHI2 for TTracks in Run 1-2 makes background distintion harder (some progress is on the way)**

Backup

Map of EDM

The identification of the nature of the fundamental CP-violating mechanisms requires the study of EDMs in various systems



C. R. Physique 13 168 (2012)

Illustration of EDM status

Only Λ hyperon has been measured with a large uncertainty!

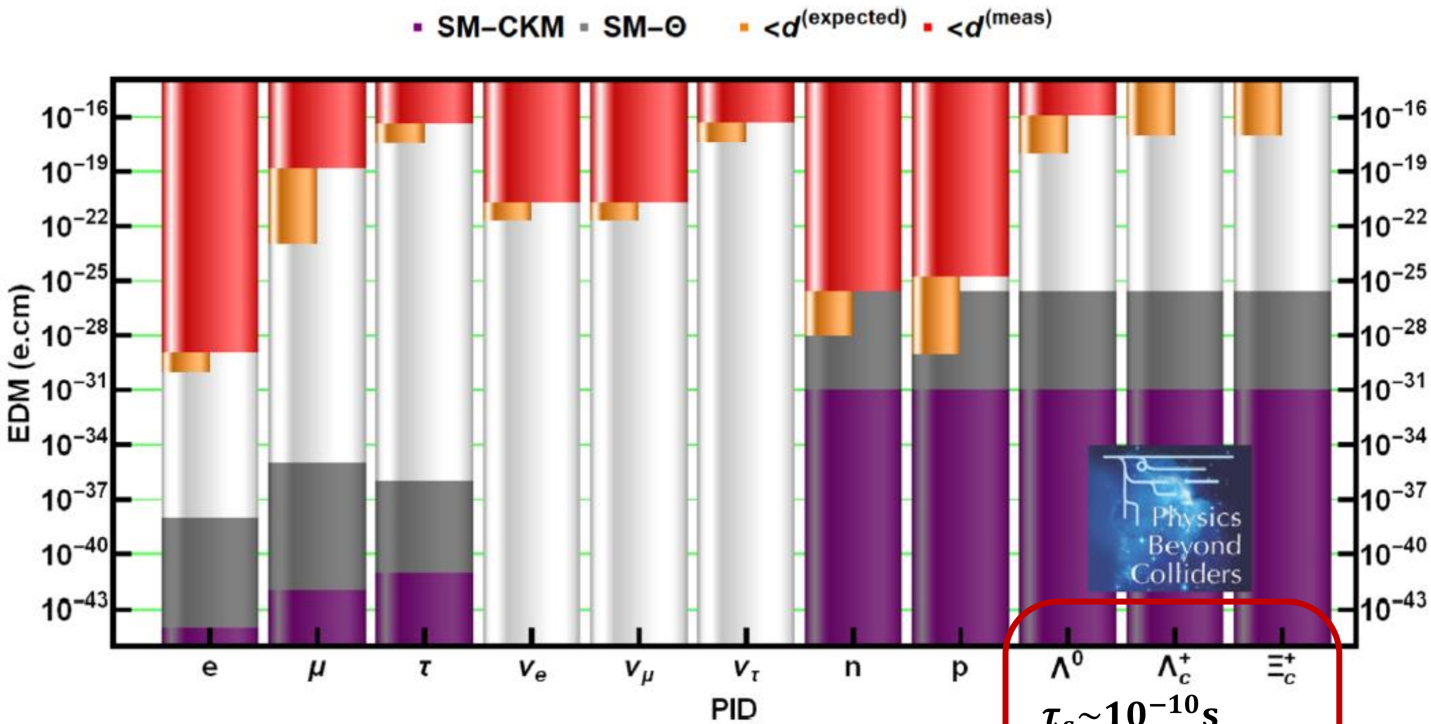
Best measurements
Limits from experimental result

Expected experimental results
in the next few years

Safe BSM discovery territory

SM estimates from QCD $\overline{\theta}$ term

SM estimated from CKM



$\tau_s \sim 10^{-10}$s

$\tau_c \sim 10^{-13}$s

Many opportunities in charmed baryons

J. Phys. G: Nucl. Part. Phys. **47** (2020) 010501

The same performance from in $\Lambda_b^0 \to K_S^0 J/\psi$ process

- **Reconstruct Λ decay after the LHCb magnet ($6.0 \sim 7.0$m)** [CERN-LHCb-DP-2022-001]