Prospects for direct measurements of Λ baryon dipole moments

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Outline

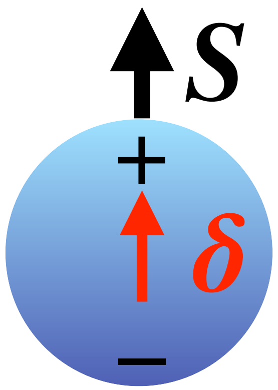
- Introduction
- Physics motivations for measurements of dipole moments
- Experimental method for strange baryons
- Preliminary studies and plans
- Summary

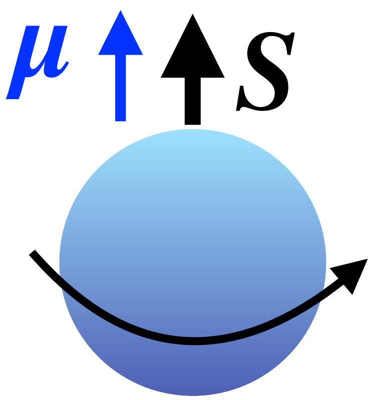
Introduction

- $\Lambda = [uds]$
  $m = 1115.683 \pm 0.006$ MeV
  $\tau = (2.617 \pm 0.010) \times 10^{-10}$ s
  Spin = $1/2$

$\boldsymbol{\delta}$= electric dipole moment (EDM)
$\boldsymbol{\mu}$= magnetic dipole moment (MDM)

$$\boldsymbol{\delta} = d\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar} \qquad \boldsymbol{\mu} = g\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar}$$





$$H = -\boldsymbol{\mu}\cdot\boldsymbol{B} - \boldsymbol{\delta}\cdot\boldsymbol{E}$$

Time reversal, Parity:

$$d\mu_N \boldsymbol{S}\cdot\boldsymbol{E} \xrightarrow{T,P} -d\mu_N \boldsymbol{S}\cdot\boldsymbol{E}$$

The EDM violates *T* and *P* and, via *CPT* theorem, violates *CP*

	C	P	T
$\boldsymbol{\mu}$	−	+	−
$\boldsymbol{\delta}$	−	+	−
$\boldsymbol{E}$	−	−	+
$\boldsymbol{B}$	−	+	−
$\boldsymbol{S}$	+	+	−

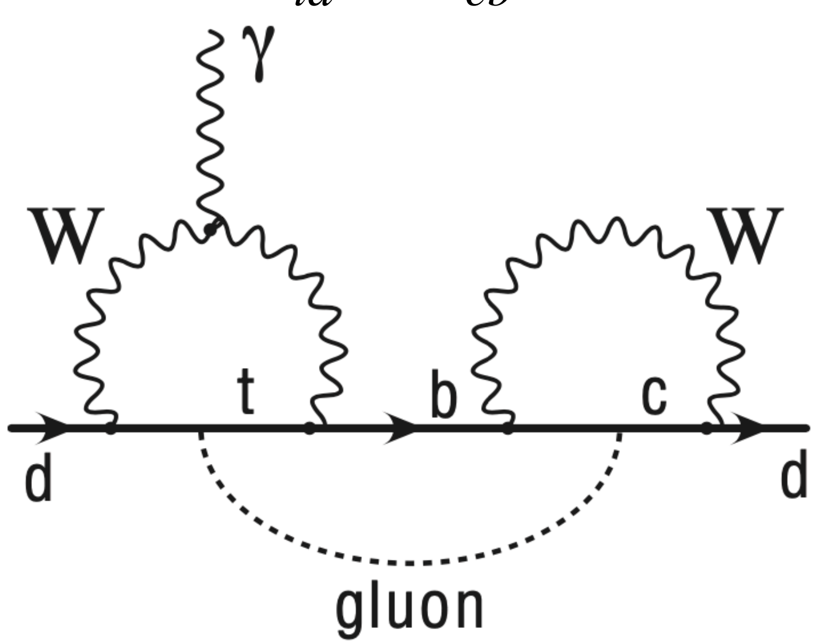
EDM: a probe for *CPV* beyond the SM

- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - SM: negligible CKM contribution; $\bar{\theta}$-QCD for possible *CPV* in strong interaction, $\bar{\theta} \lesssim 10^{-10}$ from neutron EDM limit

Rev. Mod. Phys. **91**, 015001 (2019)

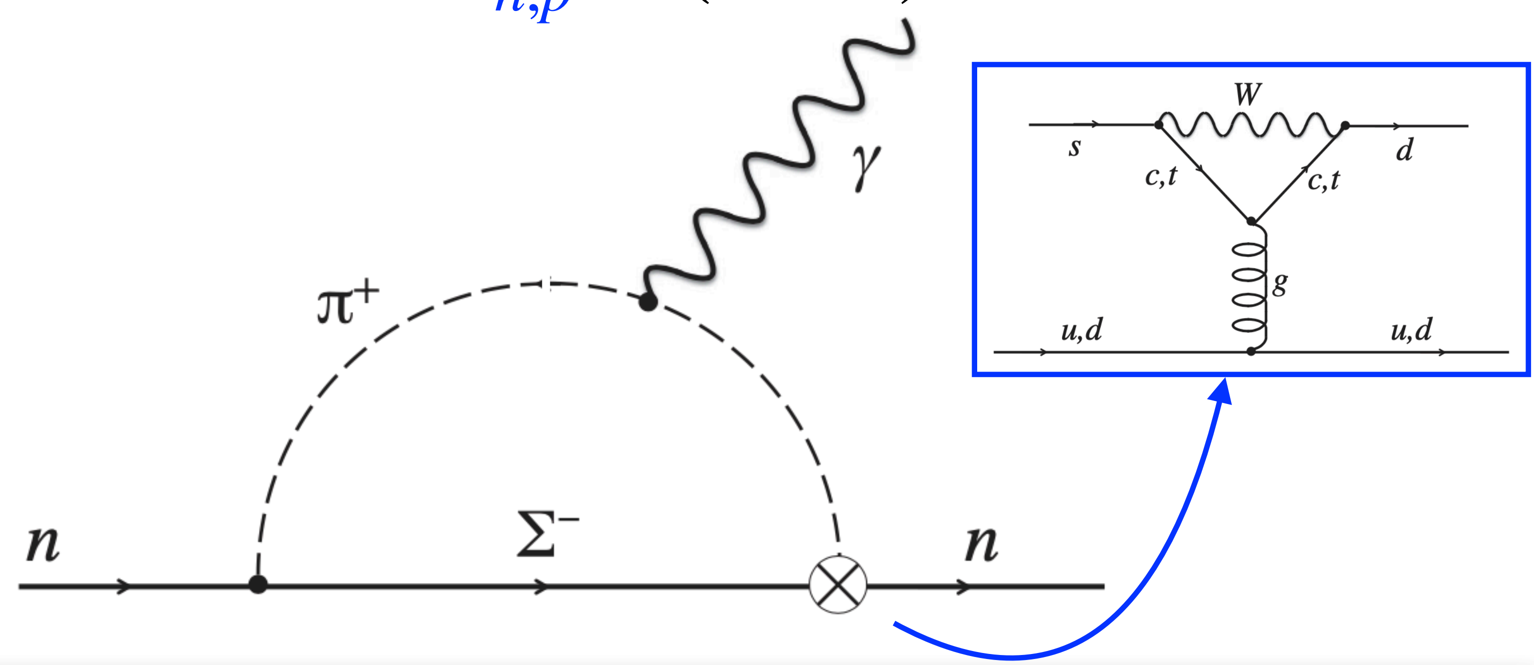
Example of SM CKM contributions

$$\delta_d \propto \mathrm{Im}(V_{tb}V^*_{td}V_{cd}V^*_{cb})m_d m_c^2 \alpha_s G_F^2 \approx 10^{-34} e\mathrm{cm}$$



"Long distance" contribution

$$\delta_{n,p} \approx (1-6) \times 10^{-32} e\mathrm{cm}$$



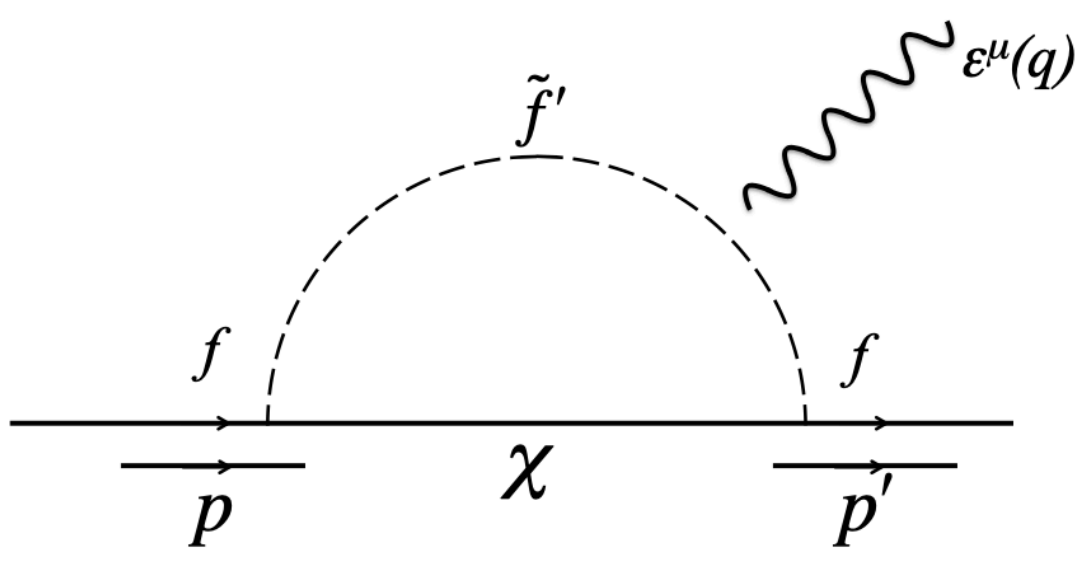
EDM: a probe for *CPV* beyond the SM

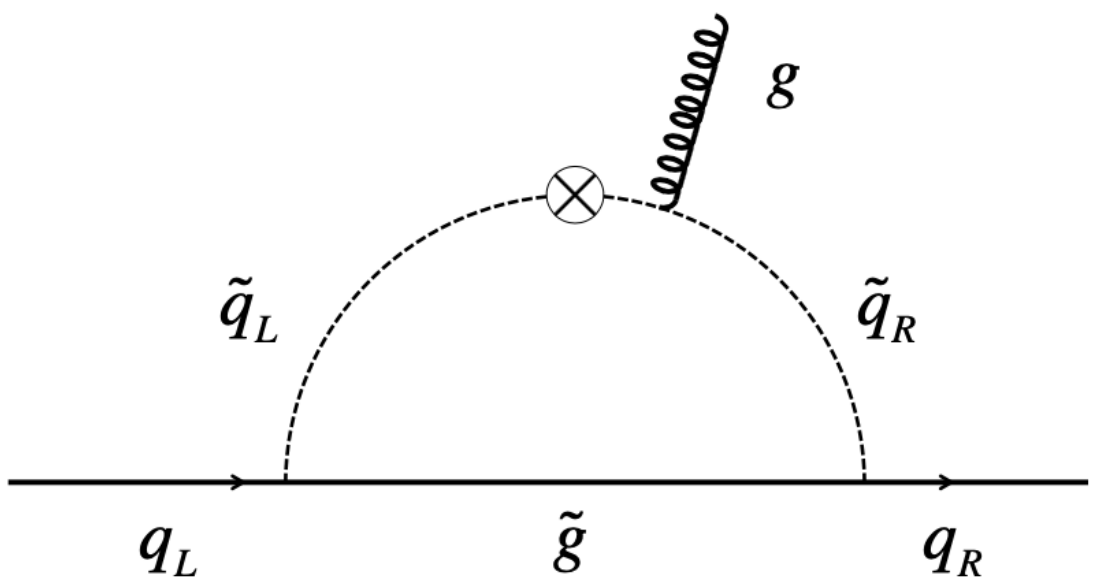
- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - BSM: potential large contributions by new physics scale Λ_{NP} and CP-violating phase ϕ_{CPV}

$$\delta_{BSM} \approx (10^{-16} e\text{cm}) \left(\frac{250 \text{ GeV}}{\Lambda_{NP}} \right)^2 \sin \phi_{CPV} y_f F$$

Examples of BSM contributions

Rev. Mod. Phys. **91**, 015001 (2019)

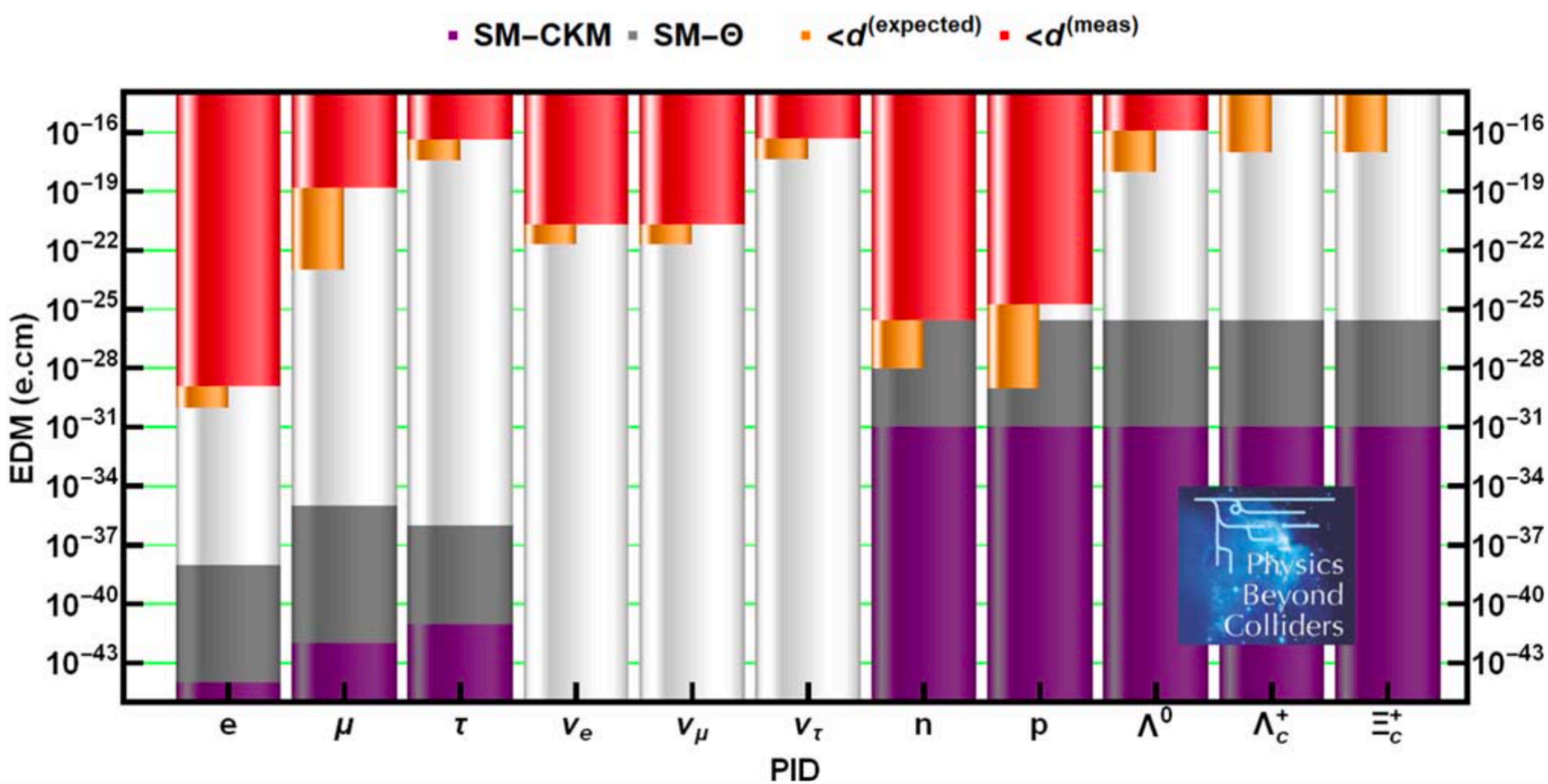




Status of EDM measurements

- Need to measure many systems to disentangle the underlying source of *CPV*

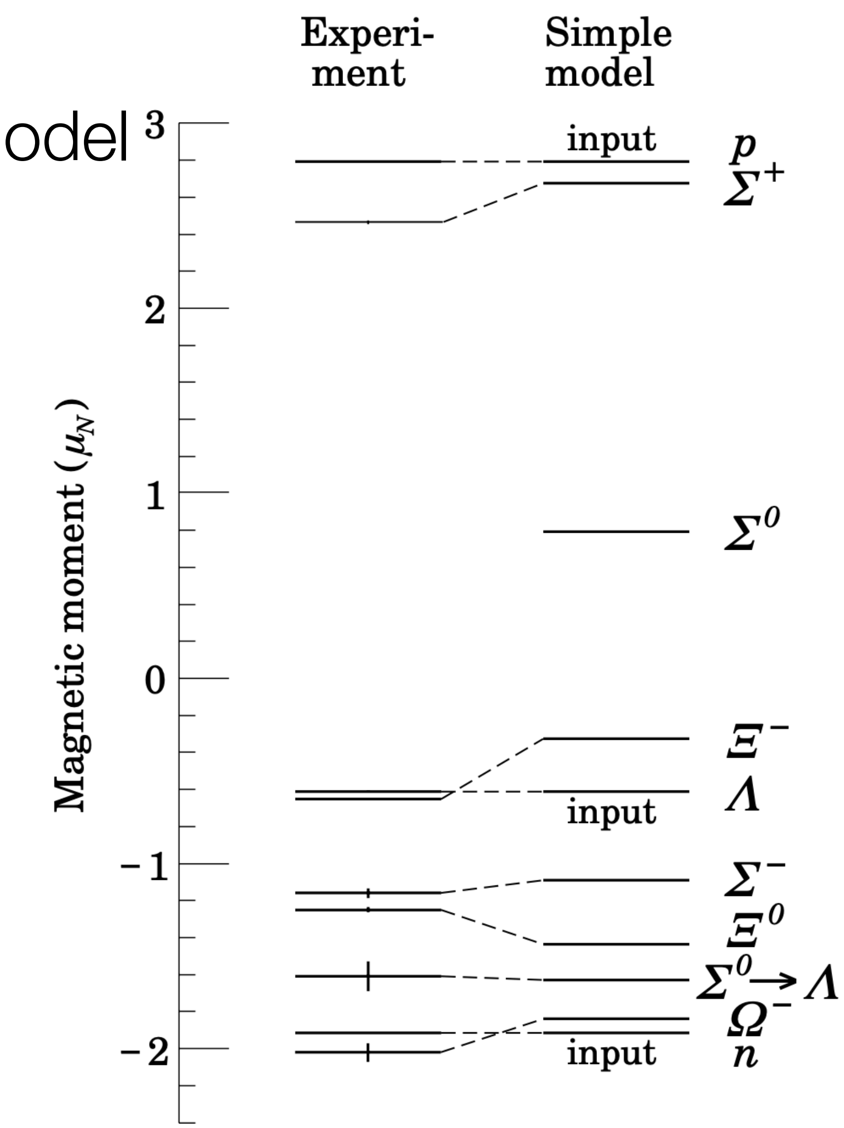
- World-wide experimental effort is ongoing to improve current measurements and explore new systems



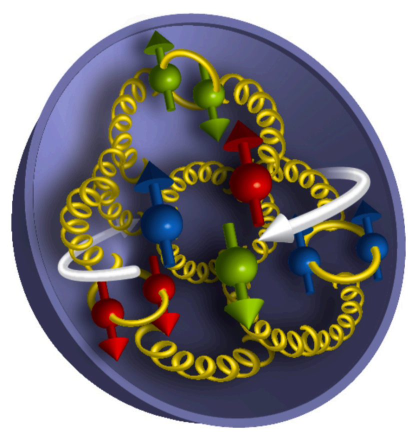
Baryon magnetic moments

- $g \neq 2$ due to internal substructure, not point-like fermions
- From Λ baryon MDM to s quark MDM using quark model

$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$
$$\mu_{\Omega^-} = 3\mu_s$$



$$\mu_q = \frac{Q_q \hbar}{2m_q}$$ quark MDM



From simple quark model

$$\mu_s = -0.613\mu_N$$
$$m_s = 510 \text{ MeV}$$

- Precise measurement of Λ MDM
- Test of *CPT* symmetry with $\overline{\Lambda}$ MDM

Corresponding proton measurements

$\mu_p = 2.79284734462\,(82)\ \mu_N$

G. Schneider et al., Science **358**, 1081 (2017)

$\mu_{\overline{p}} = -2.7928473441(42)\mu_N$

C. Smorra et al., *Nature* 550 (2017) 7676, 371-374

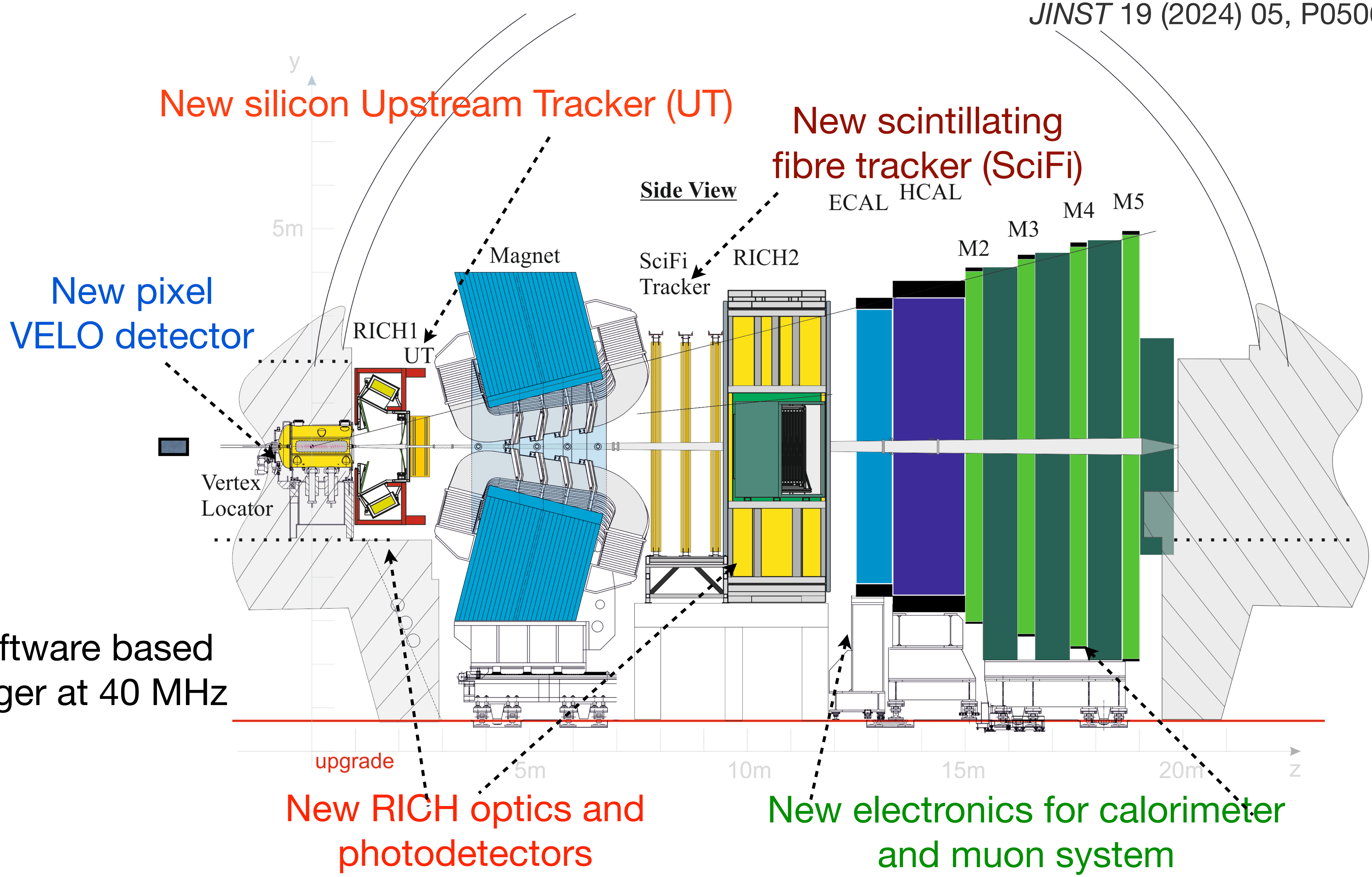
Proposed experimental method for neutral long-lived Λ baryons in LHCb

$\tau \approx 10^{-10}$ s

F. J. Botella et al., Eur.Phys.J.C 77 (2017) 181

LHCb Upgrade detector

JINST 19 (2024) 05, P05065



Software based trigger at 40 MHz

Status of art for Λ baryon EDM/MDM

- Current limit on Λ baryon **EDM** $< 1.5 \times 10^{-16} e$cm at 95% CL L. Pondrom et al., Phys. Rev. D **23**, 814 (**1981**)
- Measurement of **MDM** $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$ but no measurement for $\overline{\Lambda}$ exists Phys.Rev.Lett. 41 (**1978**) 1348
- Measurement of MDM of $\overline{\Lambda}$ is needed for a **CPT** test
- New BESIII measurement of Λ **decay parameter** inconsistent with previous results
  $\alpha = 0.750 \pm 0.009 \pm 0.004$ Nature Phys. 15 (2019) 631-634
- Need **new measurements** to improve previous results, also based on wrong α value

Λ baryon precession in the magnet

- Long-lived Λ baryons can travel through the LHCb **dipole magnet**
- **Spin precession** occurs in B field

$$\frac{d\boldsymbol{S}}{d\tau} = \boldsymbol{\mu} \times \boldsymbol{B}^{*} + \boldsymbol{\delta} \times \boldsymbol{E}^{*}$$

- Select Λ (anti-Λ) from **weak decays**
  - $\Lambda_b^0 \to J/\psi\Lambda$, $\Xi_c^0 \to \Lambda K^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$, $\Xi_c^0 \to \Xi^-(\Lambda\pi^-)\pi^+$, etc.
  - Large longitudinal **polarisation** (up to 100%) due to parity violation in the weak decay
- Challenge: reconstruct Λ baryon decays after the magnet using **T tracks**

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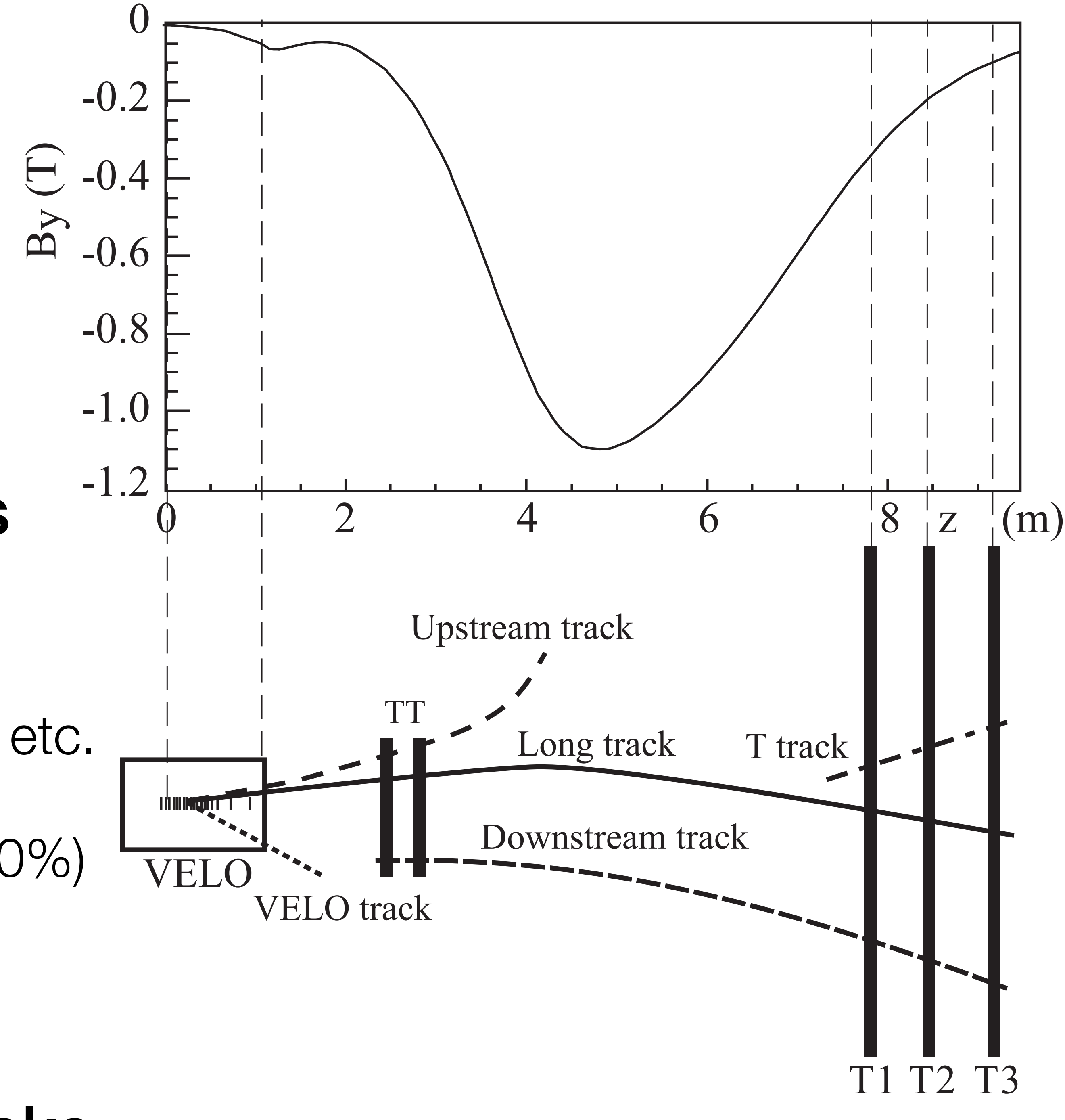
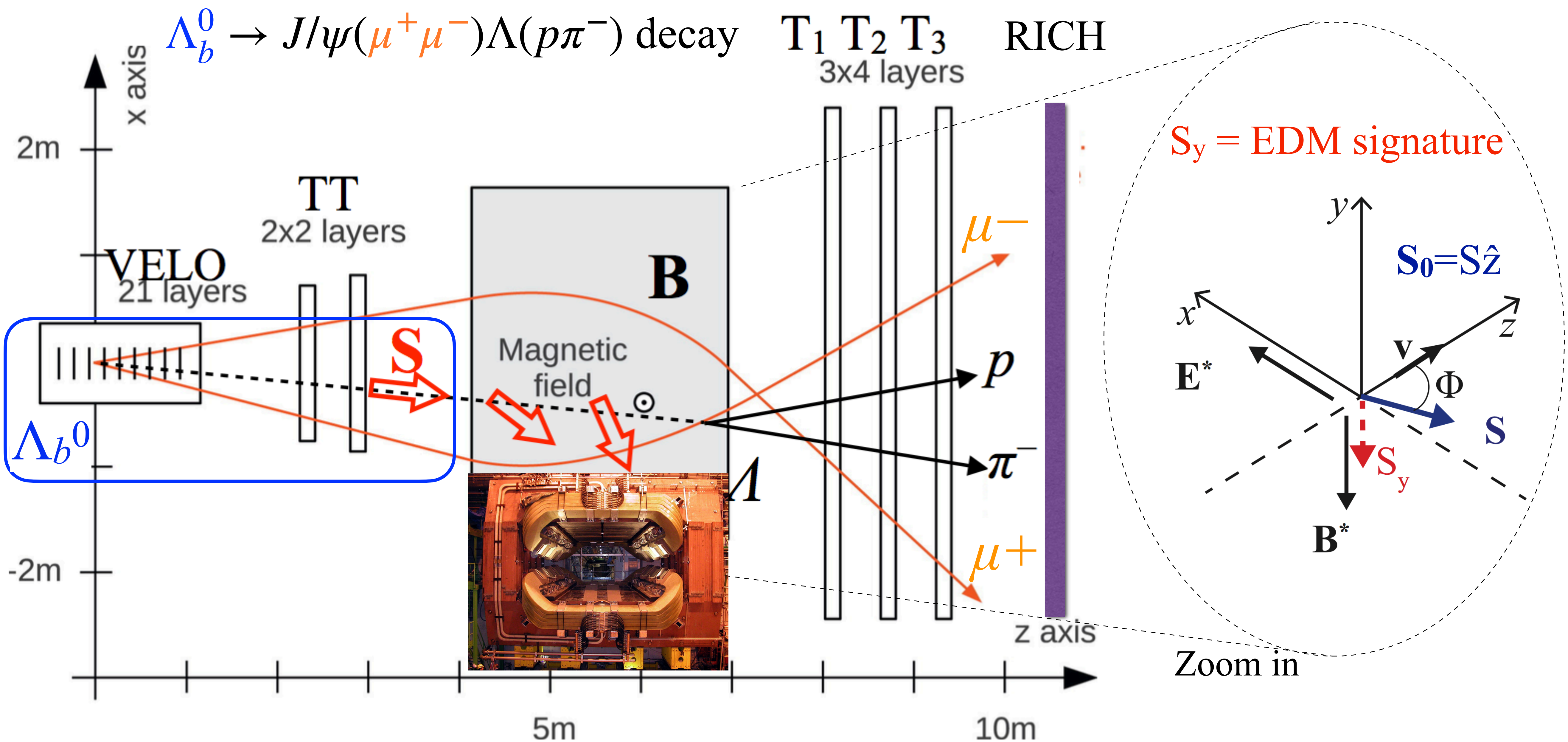


Novel experimental technique for strange baryons

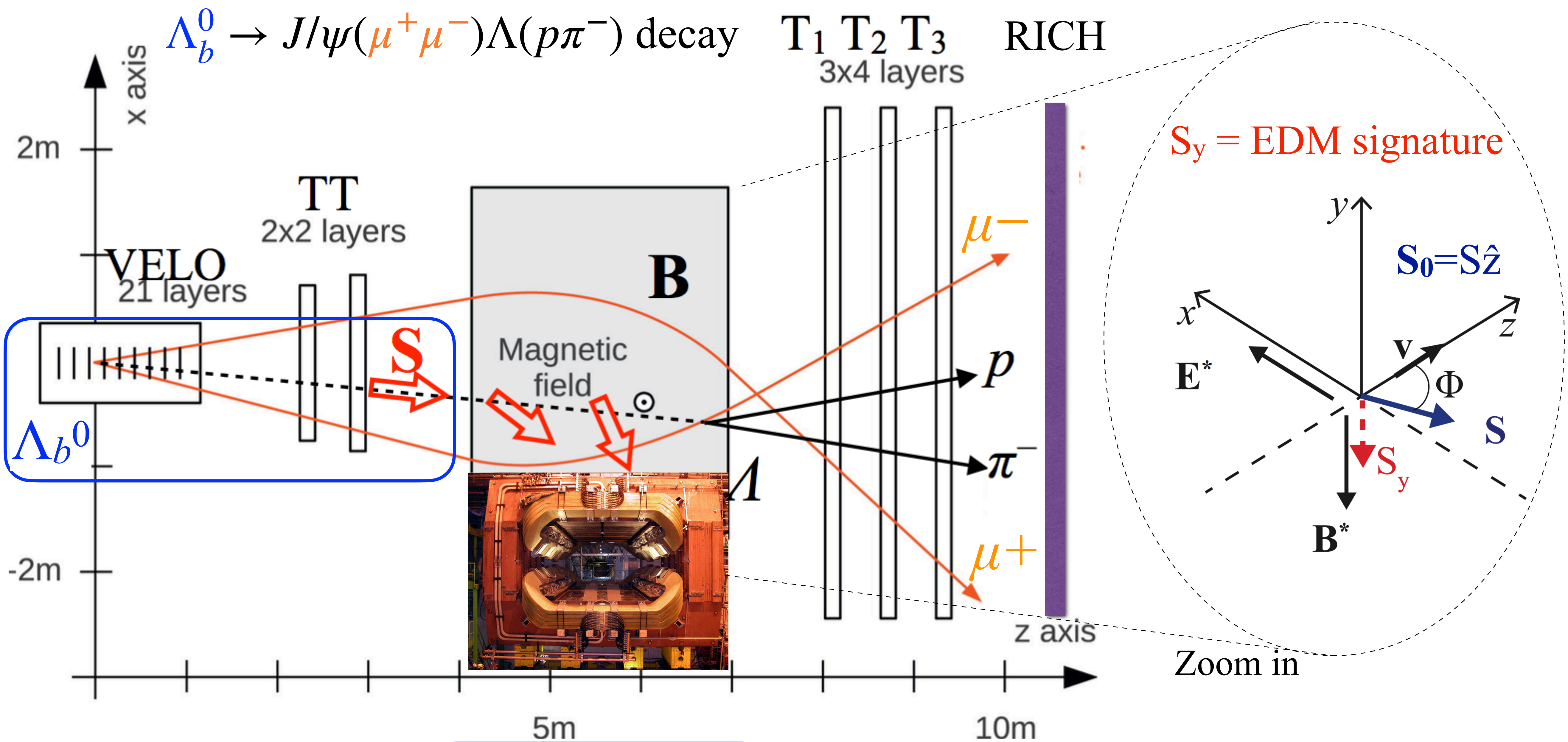
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production

Novel experimental technique for strange baryons

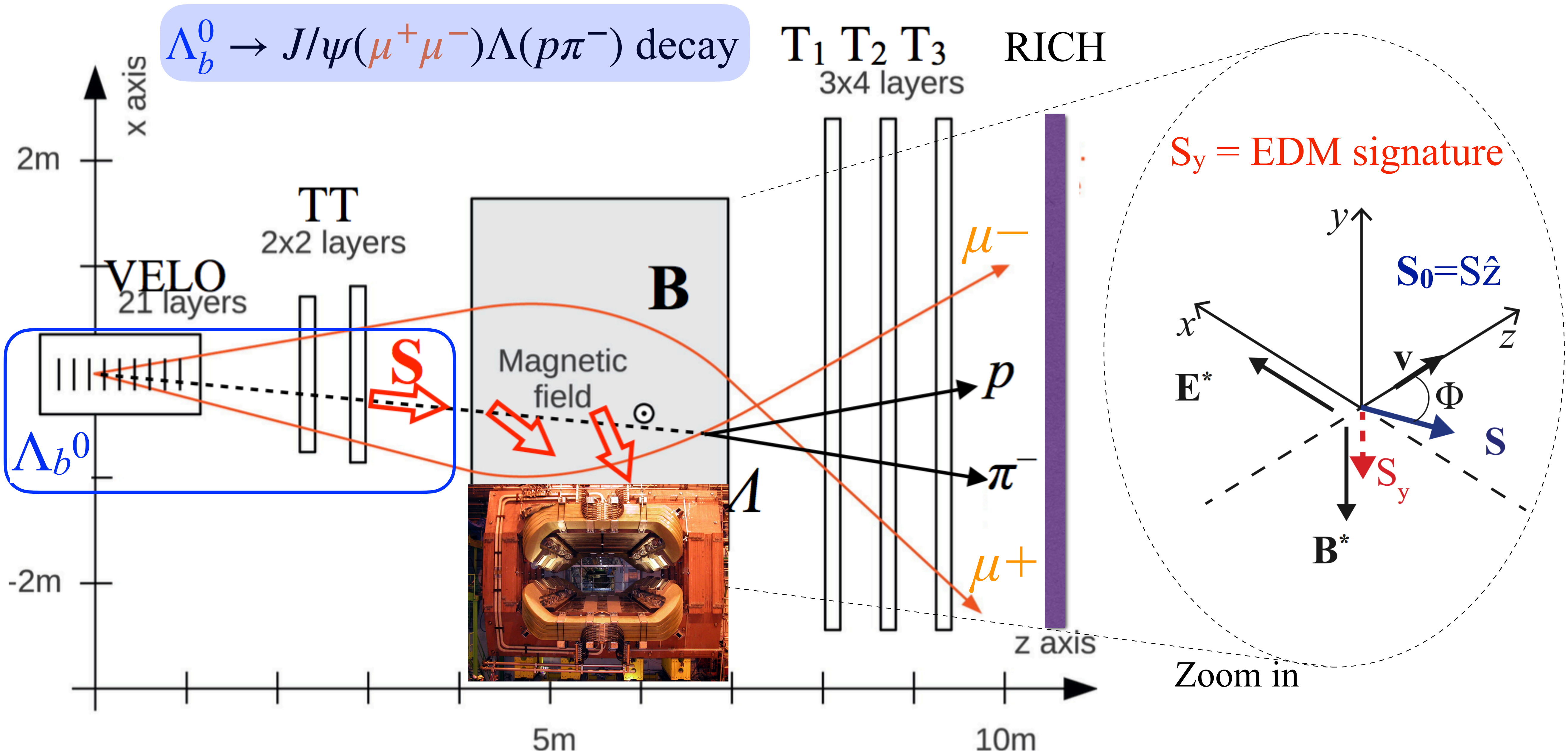
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production spin precession

Novel experimental technique for strange baryons

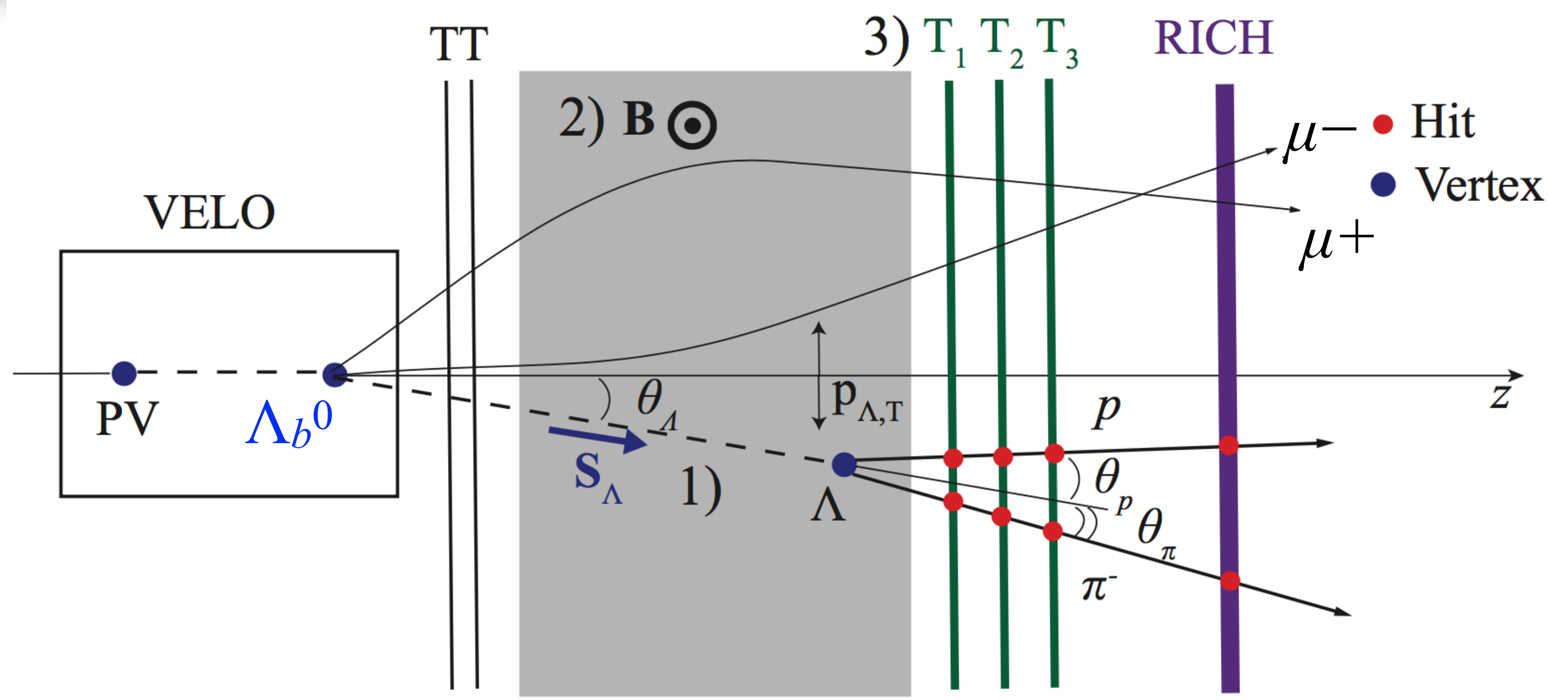
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



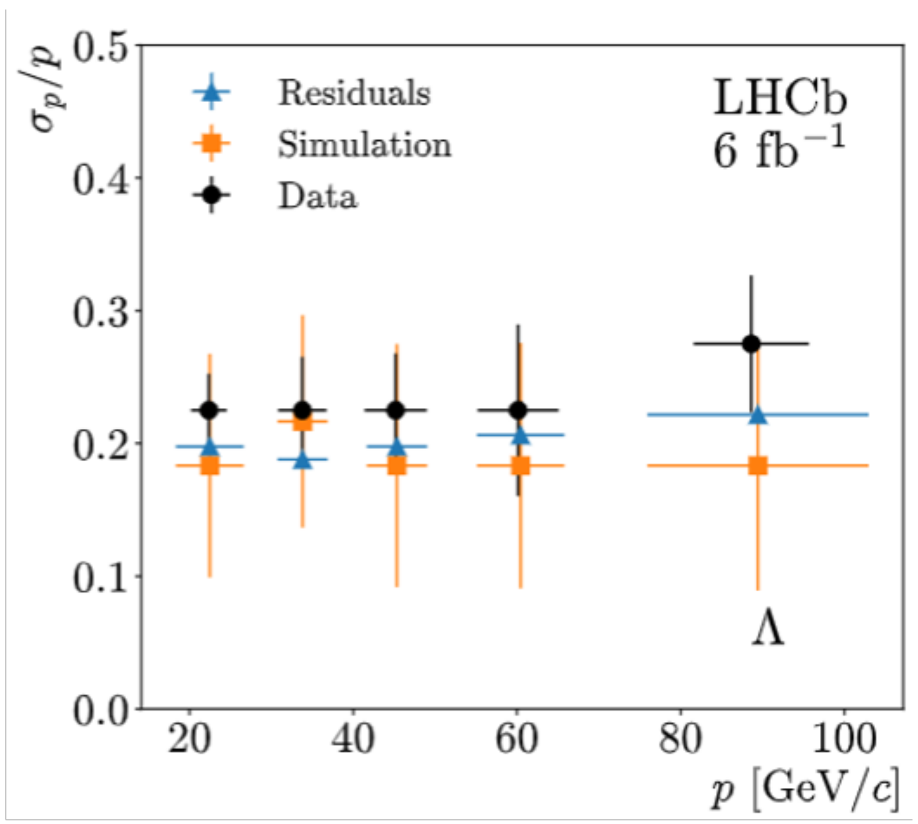
Λ polarised production   spin precession   event reconstruction

Λ baryon reconstruction downstream of the magnet

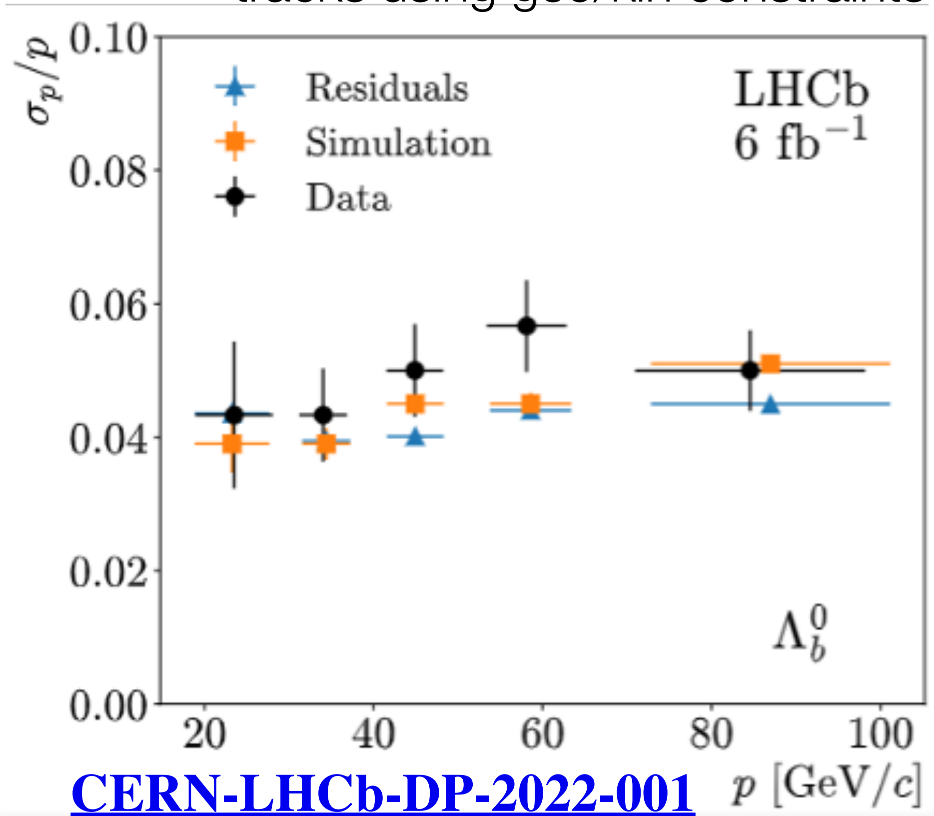
- Fit the entire decay chain $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ imposing geometric and kinematic constraints



Momentum resolution on T tracks



Improved momentum resolution on T tracks using geo/kin constraints



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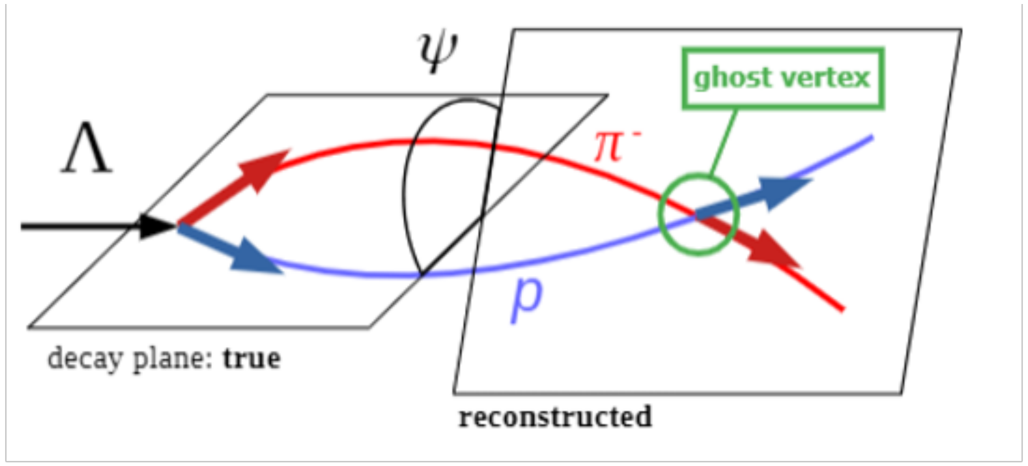
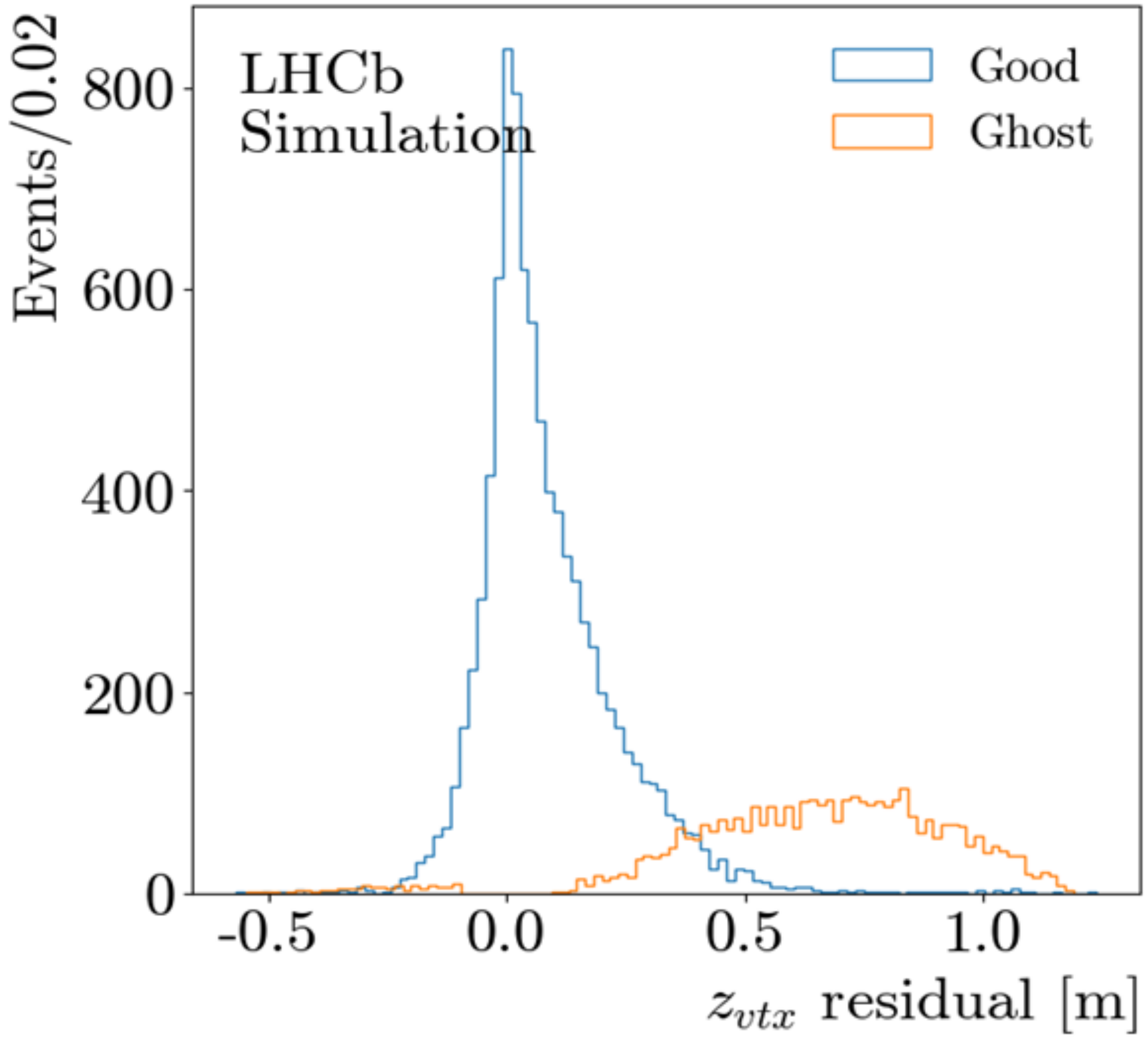
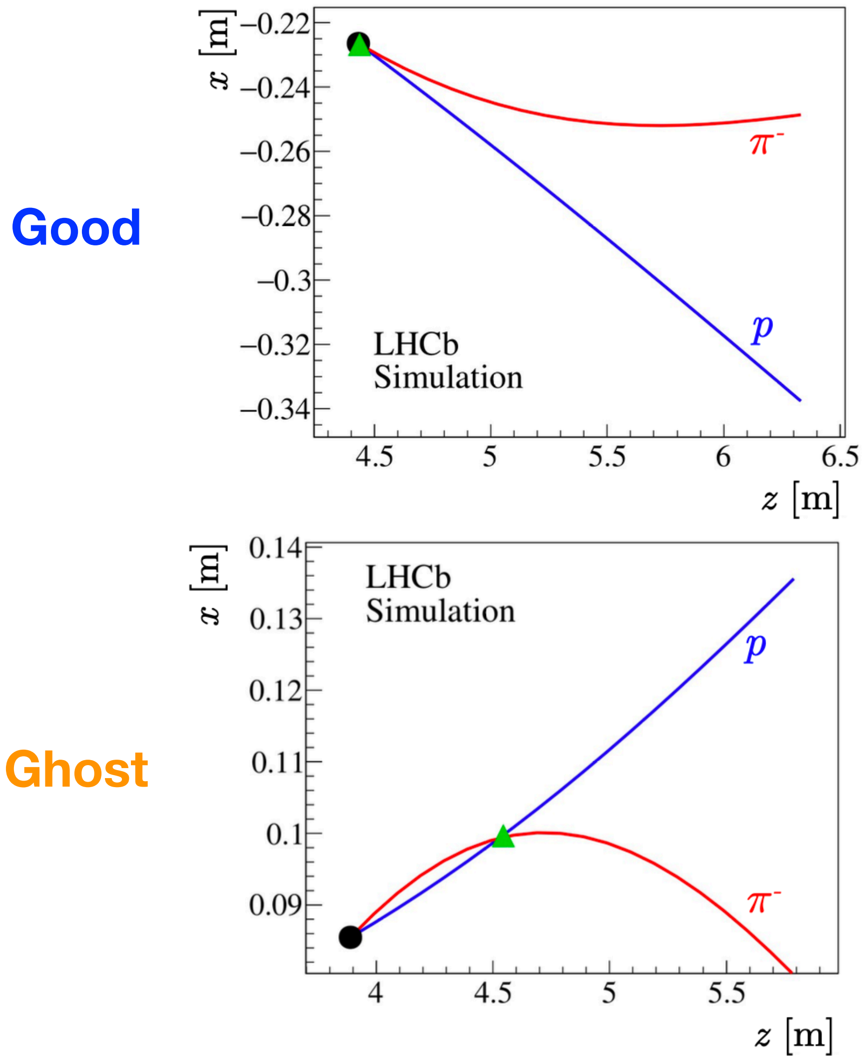
Λ baryon reconstruction downstream of the magnet

- Due to the small Q-value in the $\Lambda \to p\pi^-$ decay a “ghost vertex” can be reconstructed







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Λ baryon reconstruction downstream of the magnet

- Ghost vertex contribution largely suppressed by using a multivariate classifier (CatBoost) based on kinematic and geometric variables: from 30% to 6%

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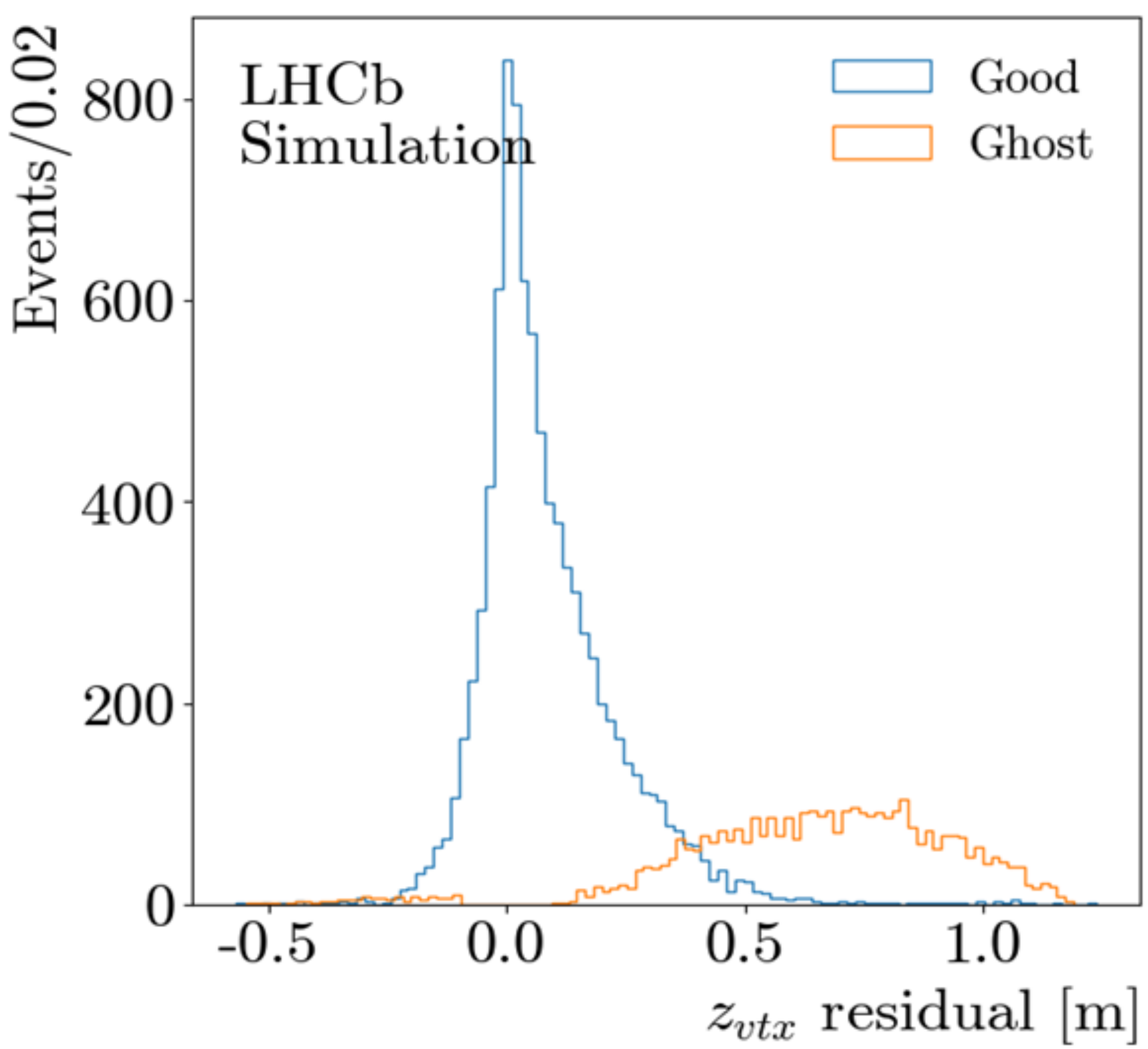
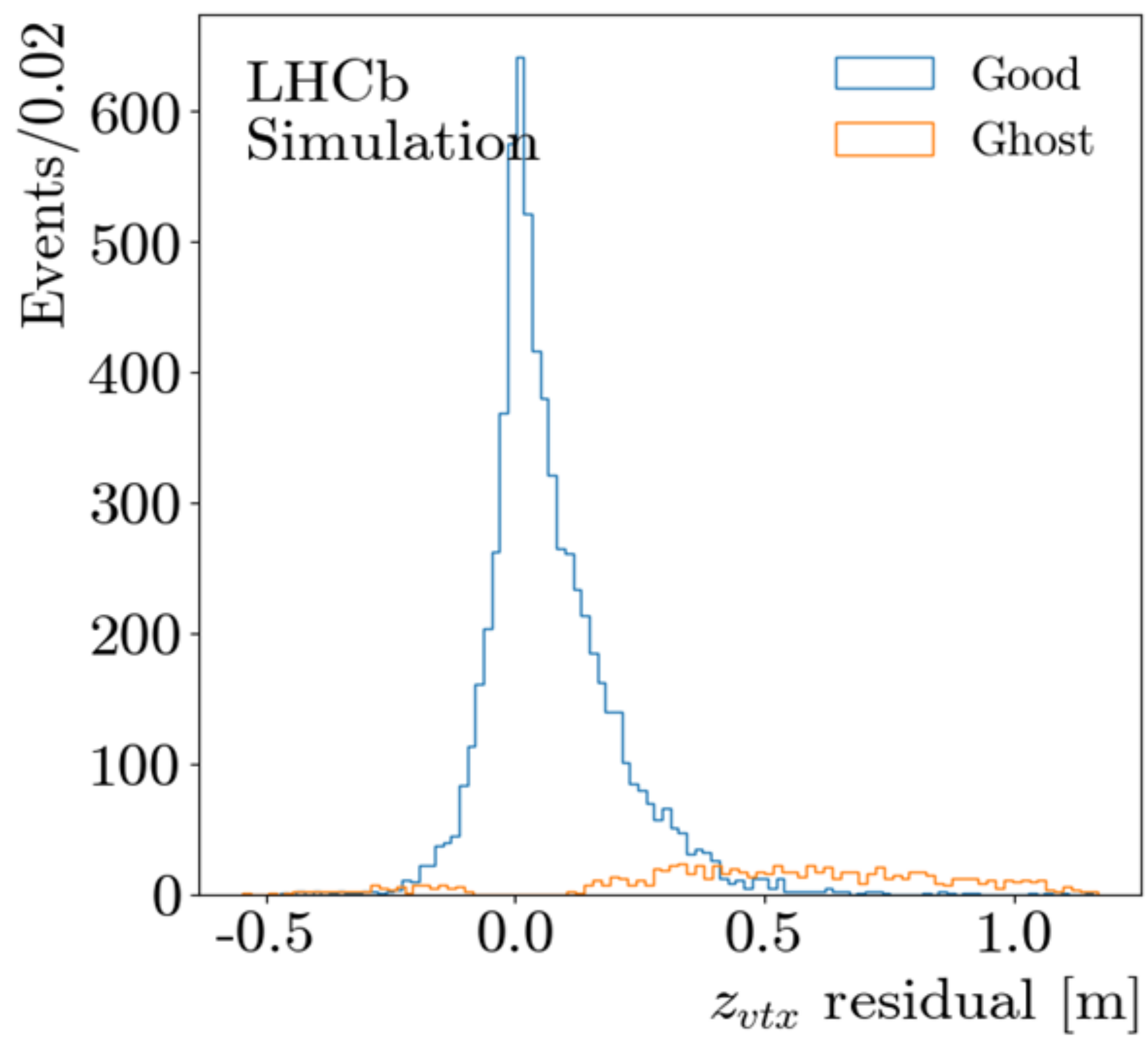
Before CatBoost selection



After CatBoost selection



Angular resolution

- Helicity angles of the protons benefit of ghost vertex rejection. Significant improvements after BDT selection

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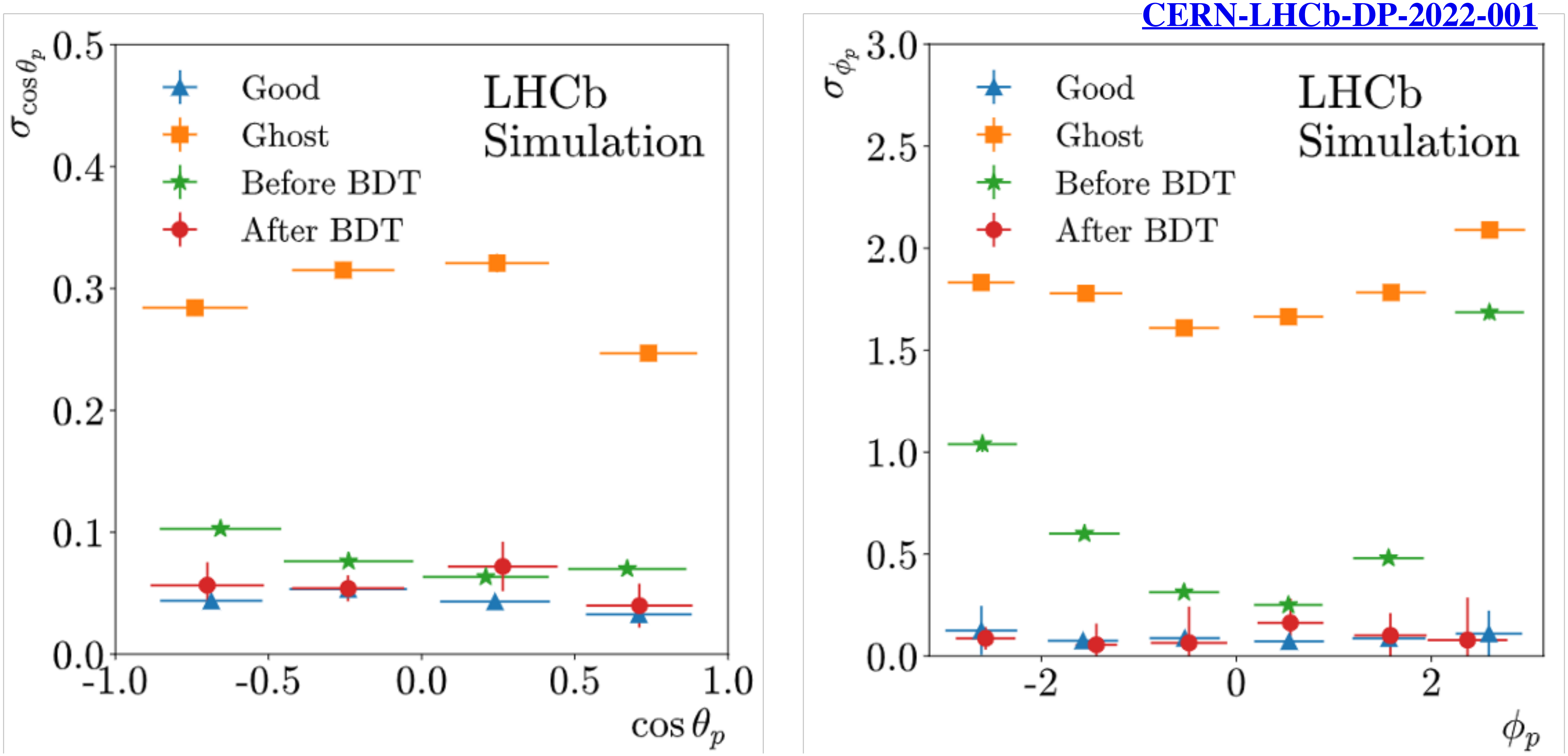

Vertex resolution

- Ghost vertex has quite large impact on vertex resolution
- Significant improvement after BDT selection

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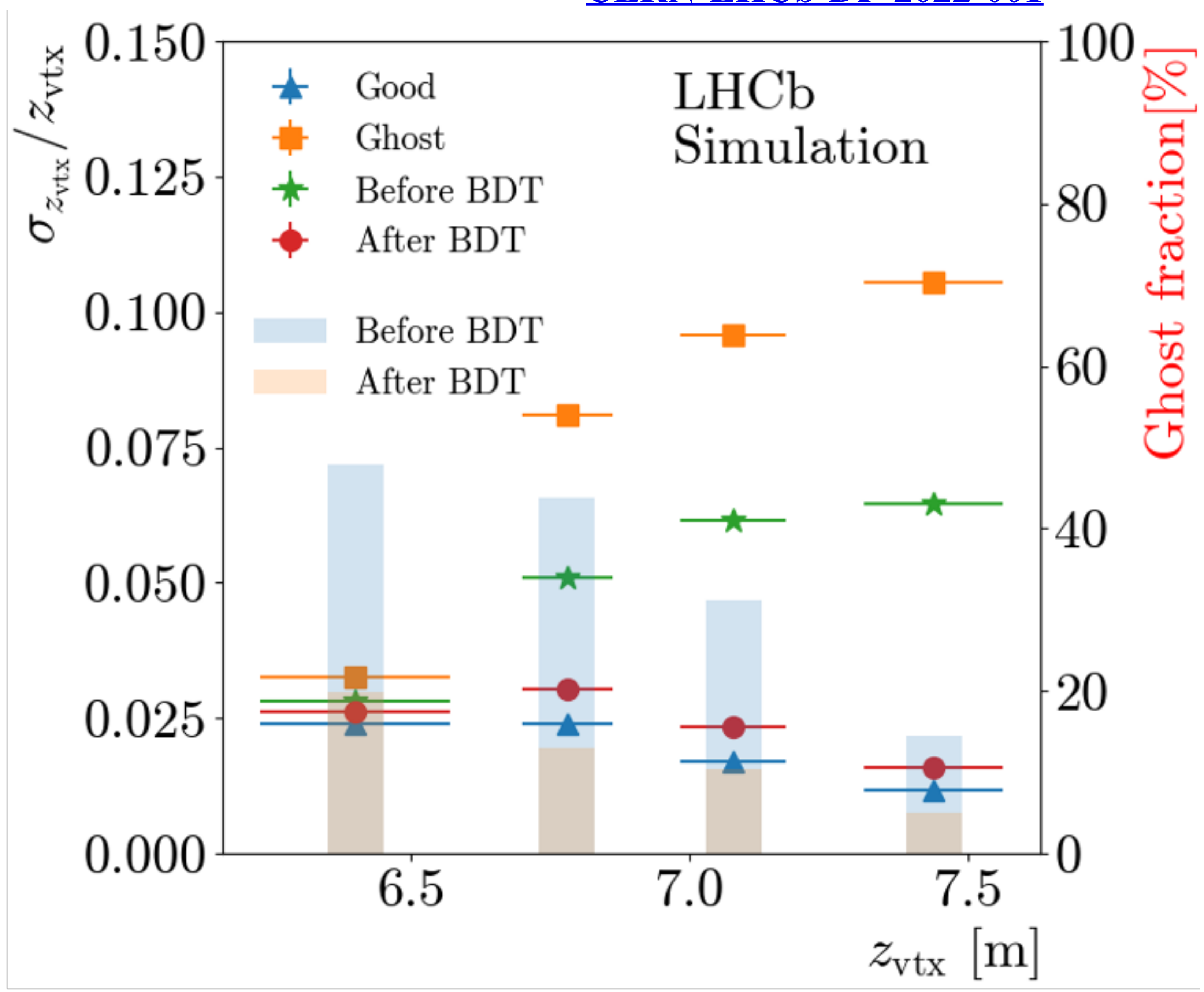
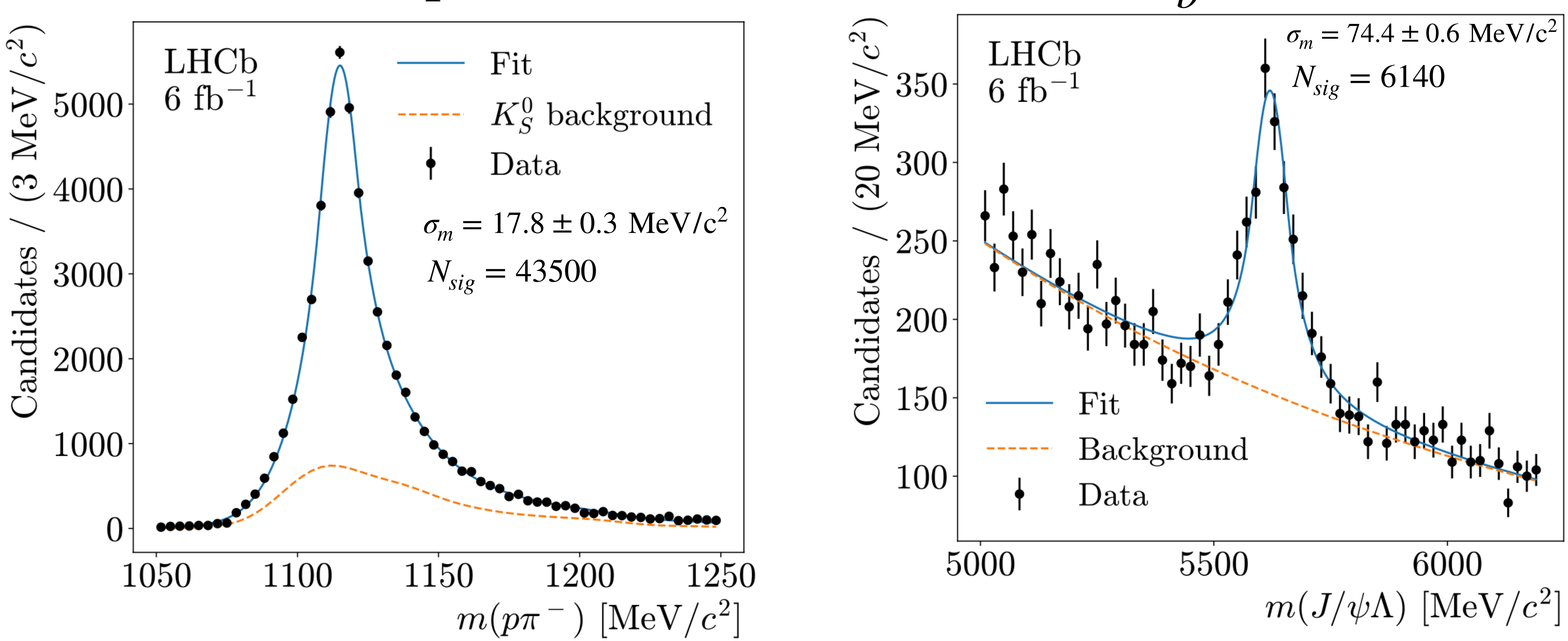


$\Lambda_b^0 \to J/\psi\Lambda$ reconstruction on data

- Reconstructed Λ decays between 6.0 - 7.6 m from the IP. Exploiting existing dimuon trigger on Run 1-2 data
- Λ baryon dipole moment measurement in progress

$\Lambda \to p\pi^-$ $\qquad\qquad$ $\Lambda_b^0 \to J/\psi\Lambda$



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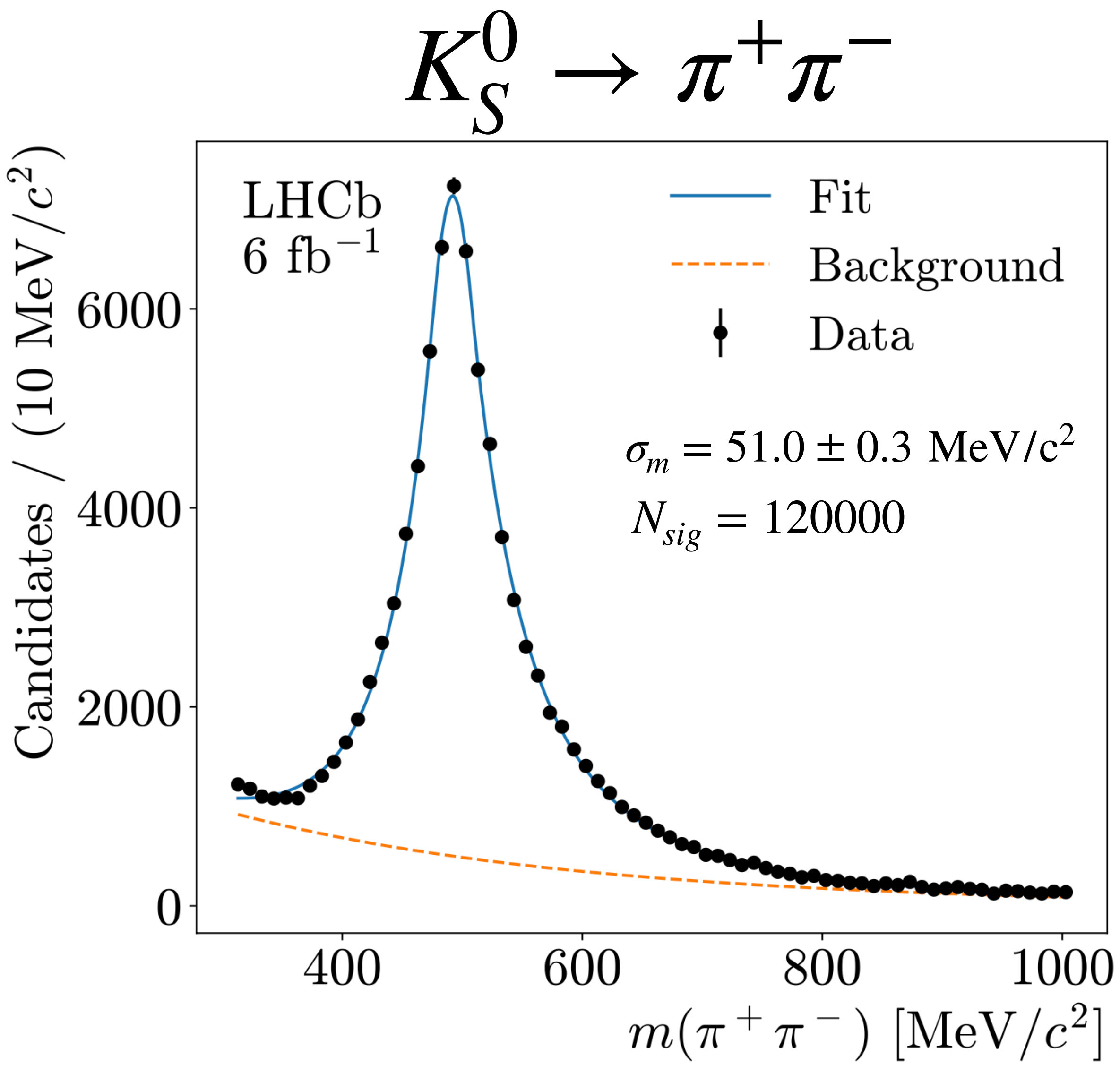
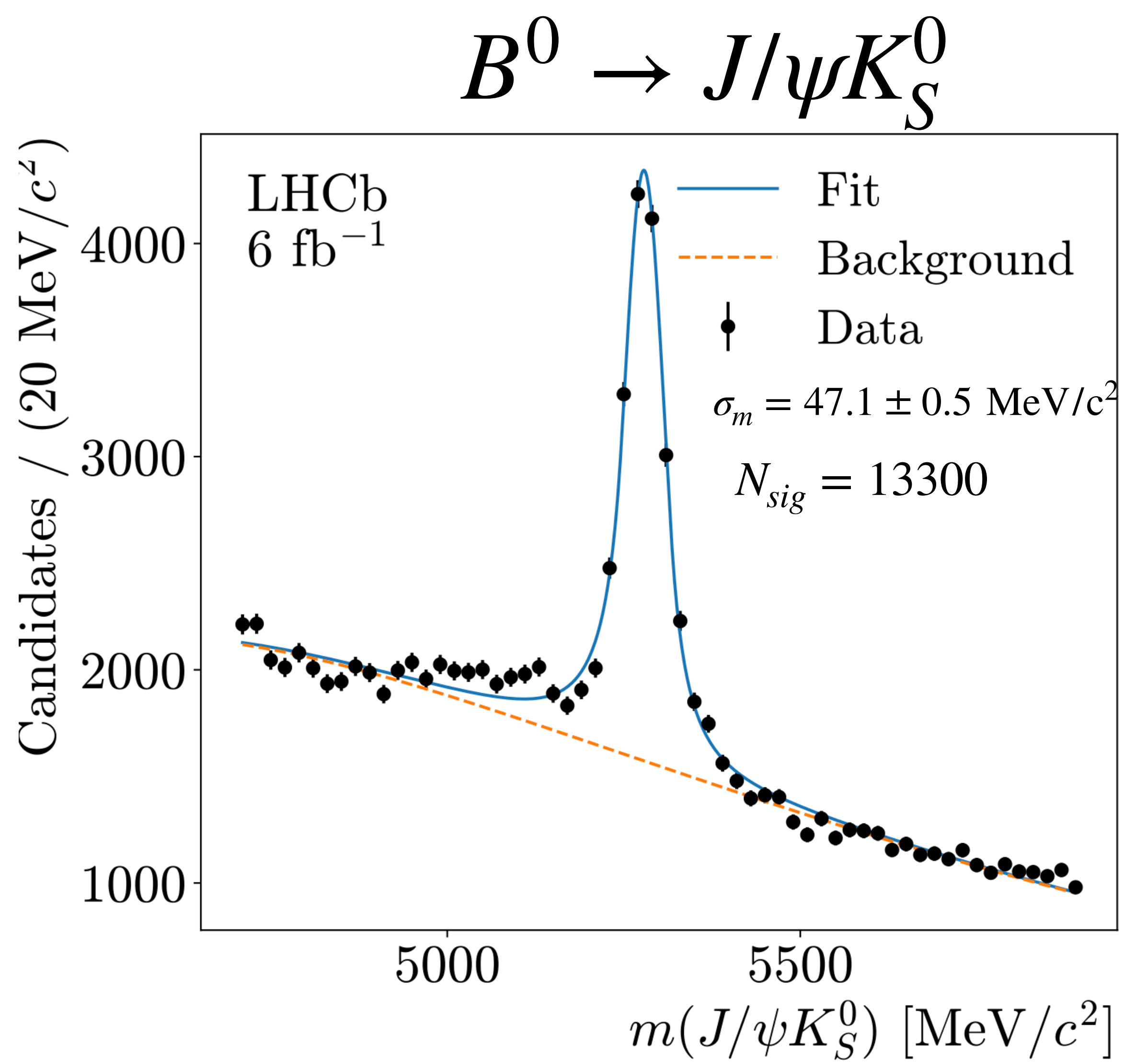
$B^0 \to J/\psi K^0_S$ reconstruction on data

- Reconstructed K^0_S decays between 6.0 - 7.6 m from the IP as control sample





CERN-LHCb-DP-2022-001

Plans for Run 3 (2022-2025, 50 fb^{-1})

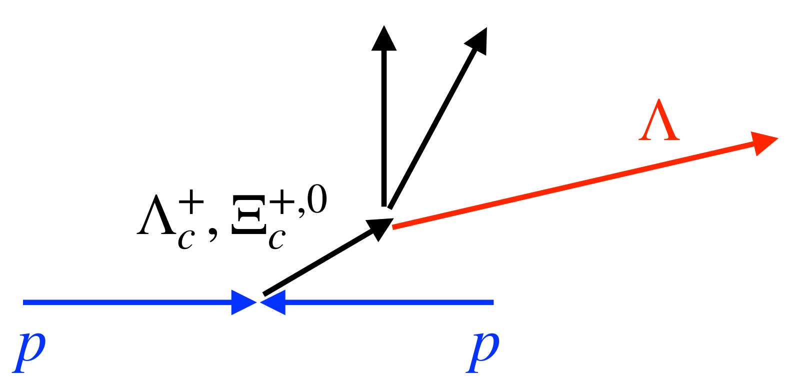
- New software trigger of Upgrade I detector allows to reconstruct Λ from charm decays. Expected several orders of magnitude increase in yield with respect to $\Lambda_b^0 \to J/\psi\Lambda$

- Developed new charm (and beauty) hadron trigger lines for Λ decays

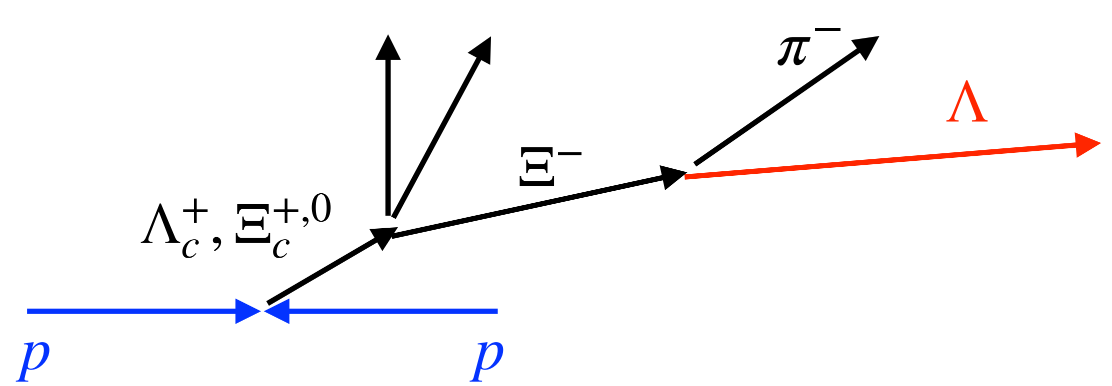
Eur. Phys. J. C **77** (2017) 181

SL events	$N_\Lambda/\mathrm{fb}^{-1}$ ($\times 10^{10}$)	LL events, $\Xi^- \to \Lambda\pi^-$	$N_\Lambda/\mathrm{fb}^{-1}$ ($\times 10^{10}$)
$\Xi_c^0 \to \Lambda K^-\pi^+$	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]

"Short-lived" category



"Long-lived" category



Sensitivity on MDM/EDM

- For initial longitudinal polarisation $\mathbf{s}_0 = s_0\hat{z}$
- Spin rotation after LHCb magnet (B field)

$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin \Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin \Phi \\ s_z = s_0 \cos \Phi \end{cases}$$

$$\Phi \approx \frac{g\mu_B BL}{\beta\hbar c} \approx \frac{\pi}{4} \qquad BL \approx 4 \text{ T m}$$

Spin analyser in Λ helicity frame

$$\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s} \cdot \hat{\mathbf{k}} \,,$$

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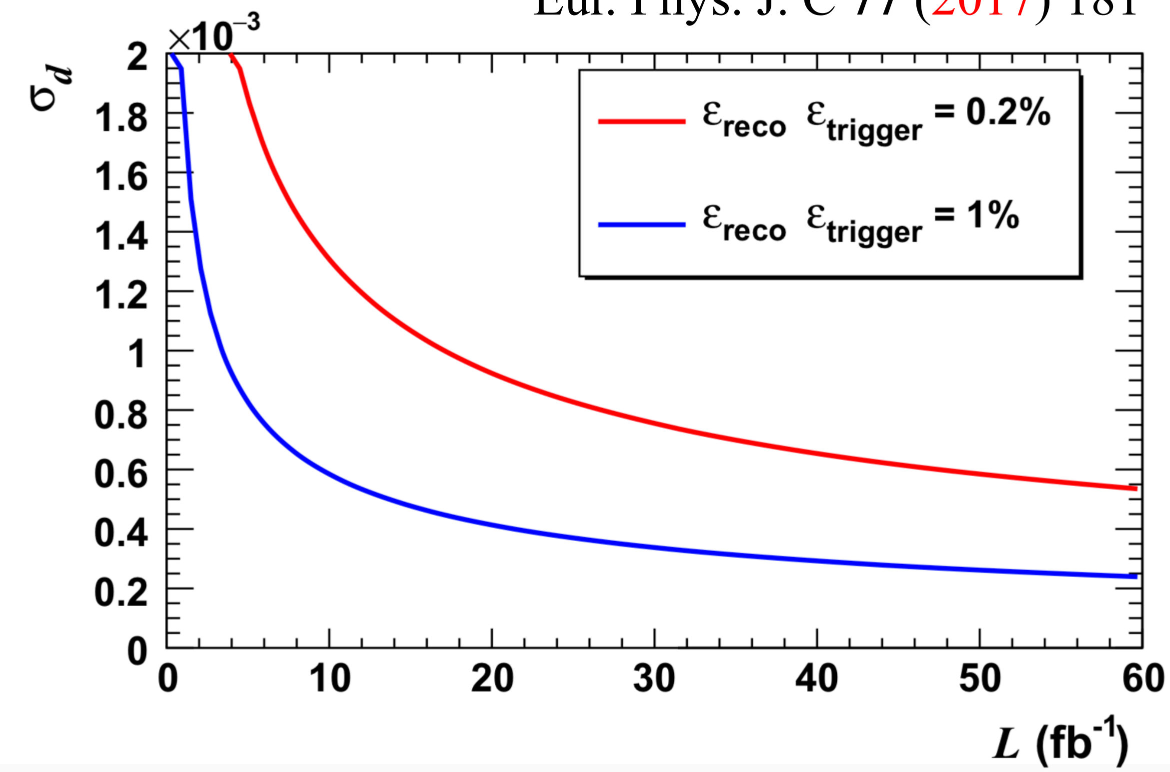


CPT test at 10^{-4} via $\Lambda/\bar{\Lambda}$ MDM

EDM limit at 10^{-18} e cm with 50 fb^{-1}

Summary

- Measurements of **MDM/EDM** of particles are sensitive to physics within and beyond the SM
- Demonstrated the possibility to measure Λ baryon MDM/EDM using the **LHCb detector** by reconstructing Λ decays after the dipole magnet. Extended the physics reach of LHCb [CERN-LHCb-DP-2022-001]
- **First measurement** at LHC of Λ **baryon MDM/EDM** is in progress, based on LHCb Run1-2 data (9 fb^{-1}) in $\Lambda_b^0 \to J/\psi\Lambda$ decays
- Interesting perspectives with LHCb upgrade detector for Run3 - Run4 (50 fb^{-1})
  - several orders of magnitude increase in yield reconstructing Λ from charm baryon decays
  - **CPT test at 10^{-4} via $\Lambda/\bar{\Lambda}$ MDM**
  - **EDM limit at 10^{-18} e cm**

Backup slides

The Λ baryon

- Quark composition uds
- Mass = 1115.683 ± 0.006 MeV
- $\tau = (2.617 \pm 0.010) \times 10^{-10}$ s
- Spin = $\frac{1}{2}$

- Λ baryon decays
  - $\Lambda \to p\pi^-$ 64%
  - $\Lambda \to n\pi^0$ 36%

- $\Lambda \to p\pi^-$ decay parameter α recently measured by BES III [1]

- $\alpha = 0757 \pm 0.011 \pm 0.008$

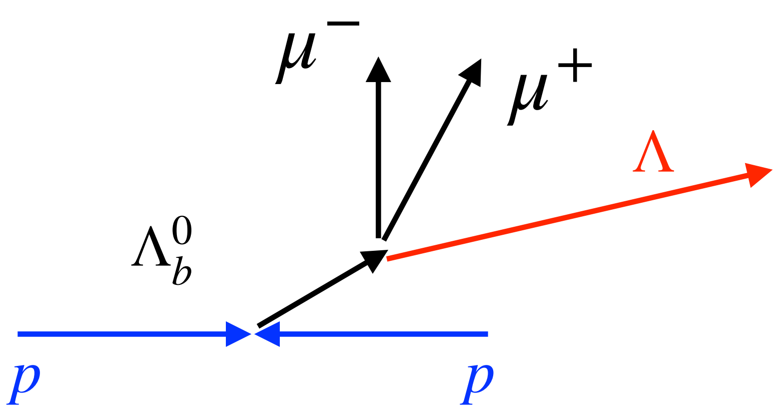
- in disagreement with previous world average (2018) [2]

$$\alpha_{\mathrm{avg}} = 0.642 \pm 0.013$$

[1] Nature Phys. 15 (2019) 631-634 [2] Particle Data Group, Review of particle physics, Phys. Rev. D98 (2018) 030001

Λ baryons from b and c hadron decays

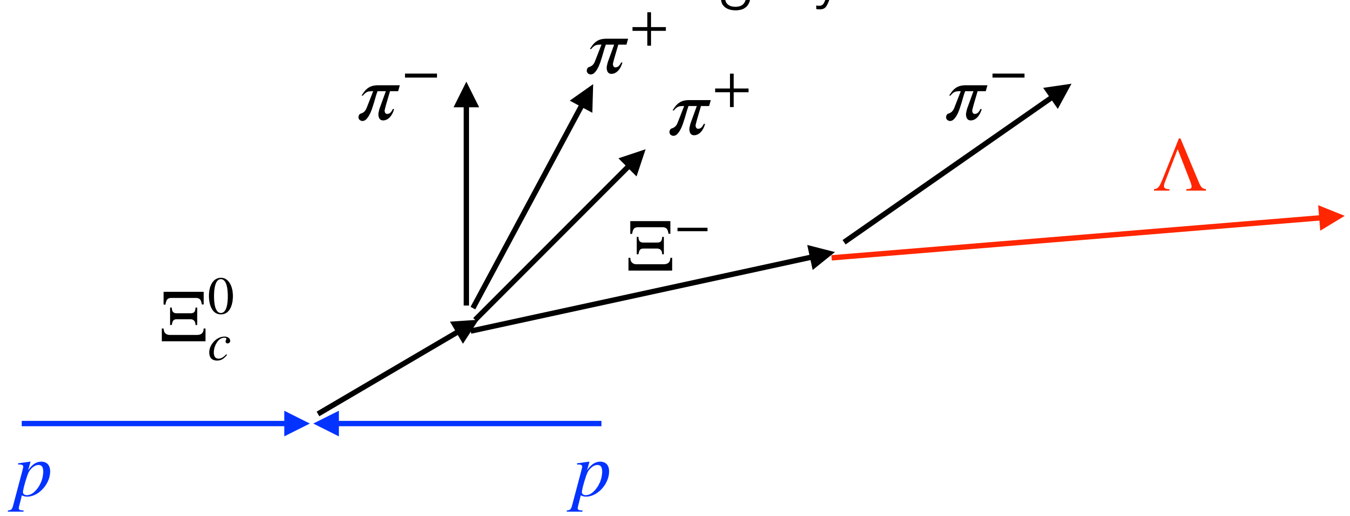
b hadron category



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

At production $N_\Lambda \approx 10^6/\mathrm{fb}^{-1}$

c hadron category



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

At production $N_\Lambda \approx 10^{11}/\mathrm{fb}^{-1}$

Not taken into account geometric acceptance, **trigger** and **reconstruction efficiencies**

Data driven momentum resolution

- From invariant mass and angular resolution to momentum resolution (simple formula for identical final particles with similar momentum, more complicated for general case)

LHCb-DP-2014-002

$$\left(\frac{\delta p}{p}\right)^2 = 2\left(\frac{\sigma_m}{m}\right)^2 - 2\left(\frac{p\,\sigma_\theta}{m\,c\,\theta}\right)^2$$

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