University of Chinese Academy of Sciences

Search for the electromagnetic dipole moments of the short-lived particles

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第二届重味物理前沿论坛研讨会

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Outline

- Introduction
- Λ EDM and MDM measurement at LHCb
- Hyperon EDM measurement at BESIII
- Charm baryon EDM and MDM measurement at ALADDIN

Electric and Magnetic Dipole Moments

- Definition in the ensemble of particles: $\mathrm{n}, \Lambda, \Lambda_c^+, \tau^+$

EDM: $\boldsymbol{\delta} = d\mu_B\, \boldsymbol{s}/2$

MDM: $\boldsymbol{\mu} = g\mu_B\, \boldsymbol{s}/2$

Spin polarization vector:

$\boldsymbol{s} = \mathrm{Tr}[\rho\boldsymbol{\sigma}] = \frac{2}{\hbar} < \widehat{\boldsymbol{S}} >$

Magneton: μ_B

Gyro-electric(magnetic) factor: $d(g)$

- Interaction with EM field

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

$$\mathcal{H} \xrightarrow{\mathrm{P,T}} \mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} \boxed{+\boldsymbol{\delta}\cdot\boldsymbol{E}}$$

Non-zero EDM is a signal of P/T, CP violation

Why EDM and MDM

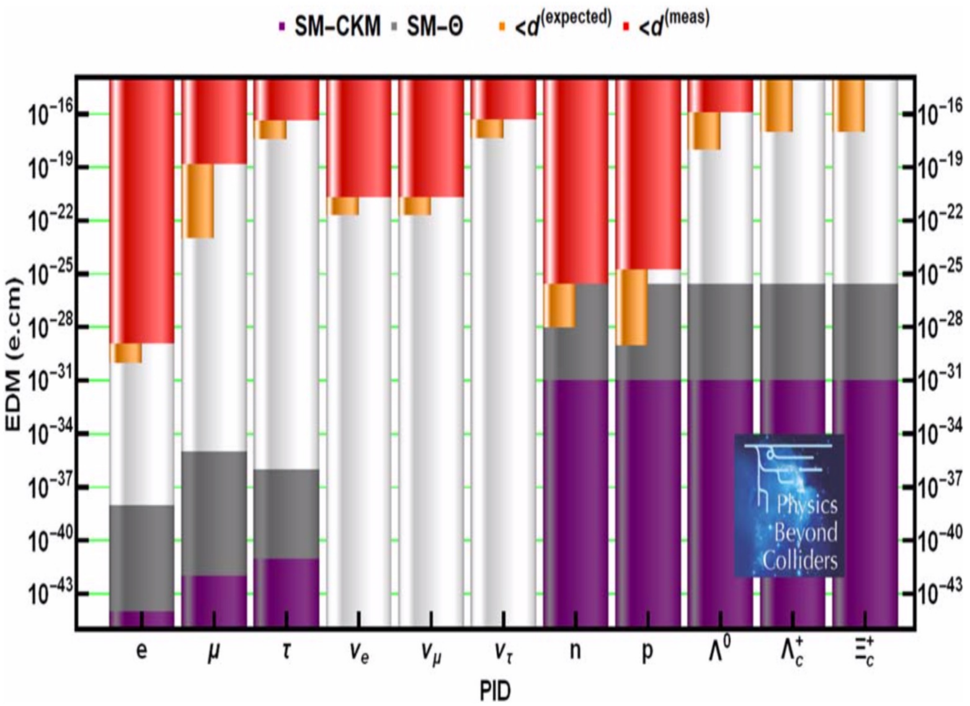
- CPV in CKM not sufficient for the missing antimatter in universe

- EDM extremely tiny in SM but can be largely enhanced by NP

- EDM for a single particle is insufficient to disentangle various sources of CPV

Lepton EDM

$$d \approx (10^{-16} e\,\mathrm{cm}) \left(\frac{v}{\Lambda}\right)^2 (\sin \phi_{\mathrm{CPV}})(y_f F)$$



- Global EDM analysis needs experimental input from various systems

Why EDM and MDM

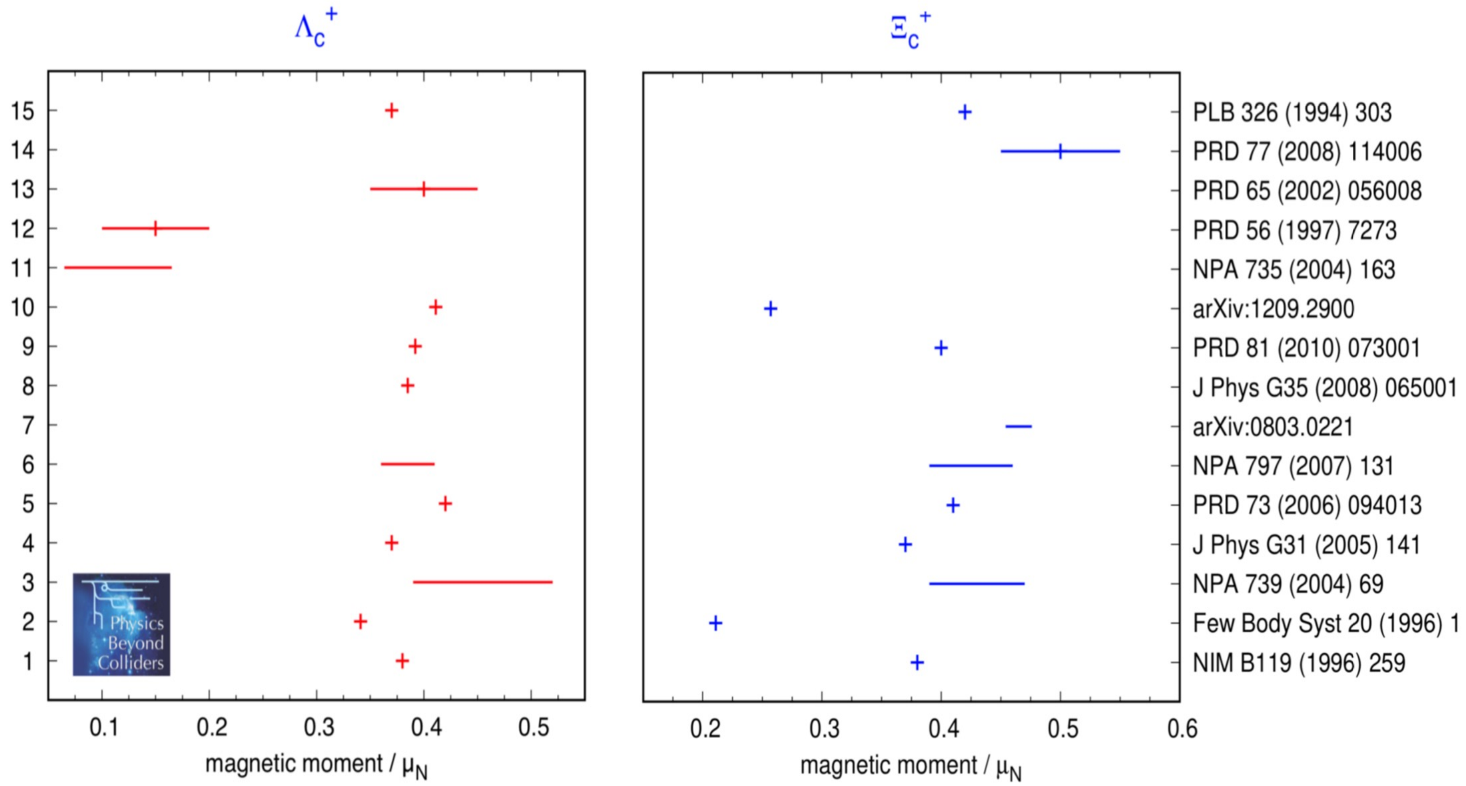
- Elementary particle: e, μ, τ

  $g = 2$ + QFT loop correction, i.e muon g-2 measurement

- Composite particle: $\Lambda, \Lambda_c^+, \Xi_c^+ \ldots$

  $g \neq 2$, depends on inner structures

  Probe for baryon structure, low-energy QCD physics, LQCD



How to access EDM and MDM

- EDM and MDM extracted from spin procession in EM field

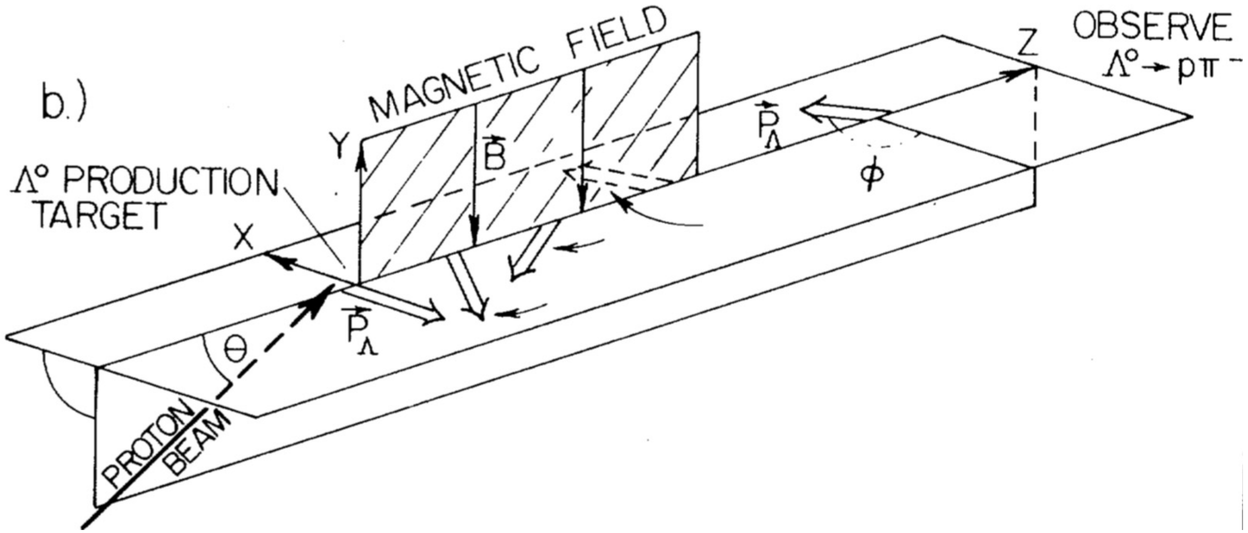
$$\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \mathbf{\Omega} \qquad \mathbf{\Omega} = \mathbf{\Omega}_{\rm MDM} + \mathbf{\Omega}_{\rm EDM} + \mathbf{\Omega}_{\rm TH}$$

$$\Omega_{\rm EDM} = \boxed{\frac{d\mu_B}{\hbar}} \left(\mathbf{E} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta} \cdot \mathbf{E})\boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{B} \right)$$

$$\mathbf{\Omega}_{\rm MDM} = \boxed{\frac{g\mu_B}{\hbar}} \left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta} \cdot \mathbf{B})\boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{E} \right)$$

- Experimental requirement
  - ✓ Sizable polarized particle source
  - ✓ Enough fight length/intense EM field for precession
  - ✓ Excellent detector for polarization measurement in the angular analysis
  - ☹ Significant challenge for short-lived particles, i.e. $\Lambda(10^{-10}\text{s})$, $\Lambda_c^+(10^{-13}\text{s})$, $\tau^+(10^{-13}\text{s})$

Λ EDM/MDM measurement at Fermilab



Phys. Rev. D23 (1981) 814

$d_\Lambda < 1.5\times10^{-16} e$ cm @ 95% C.L.

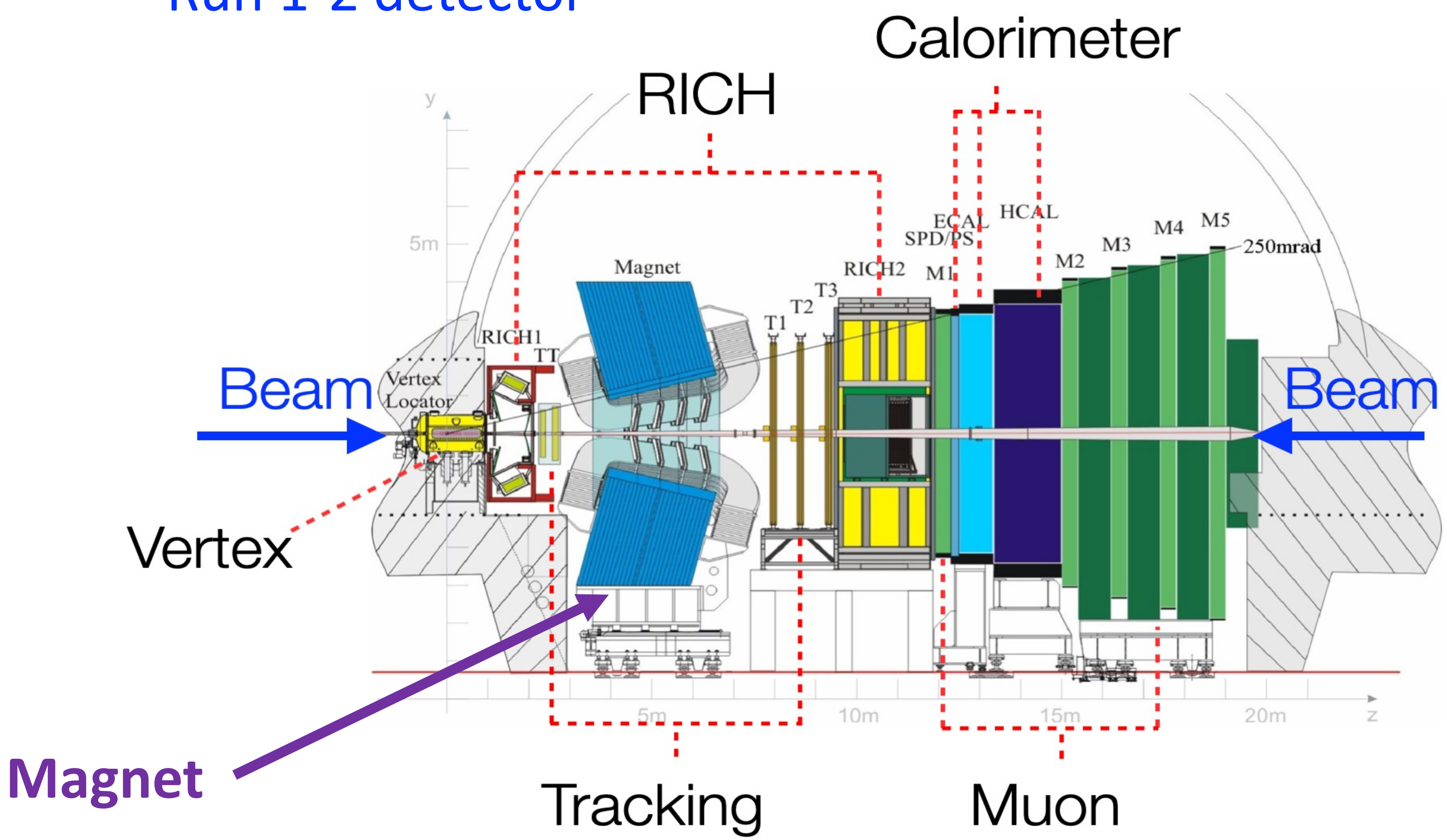
Phys. Rev. Lett. 41 (1978) 1348

$\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$

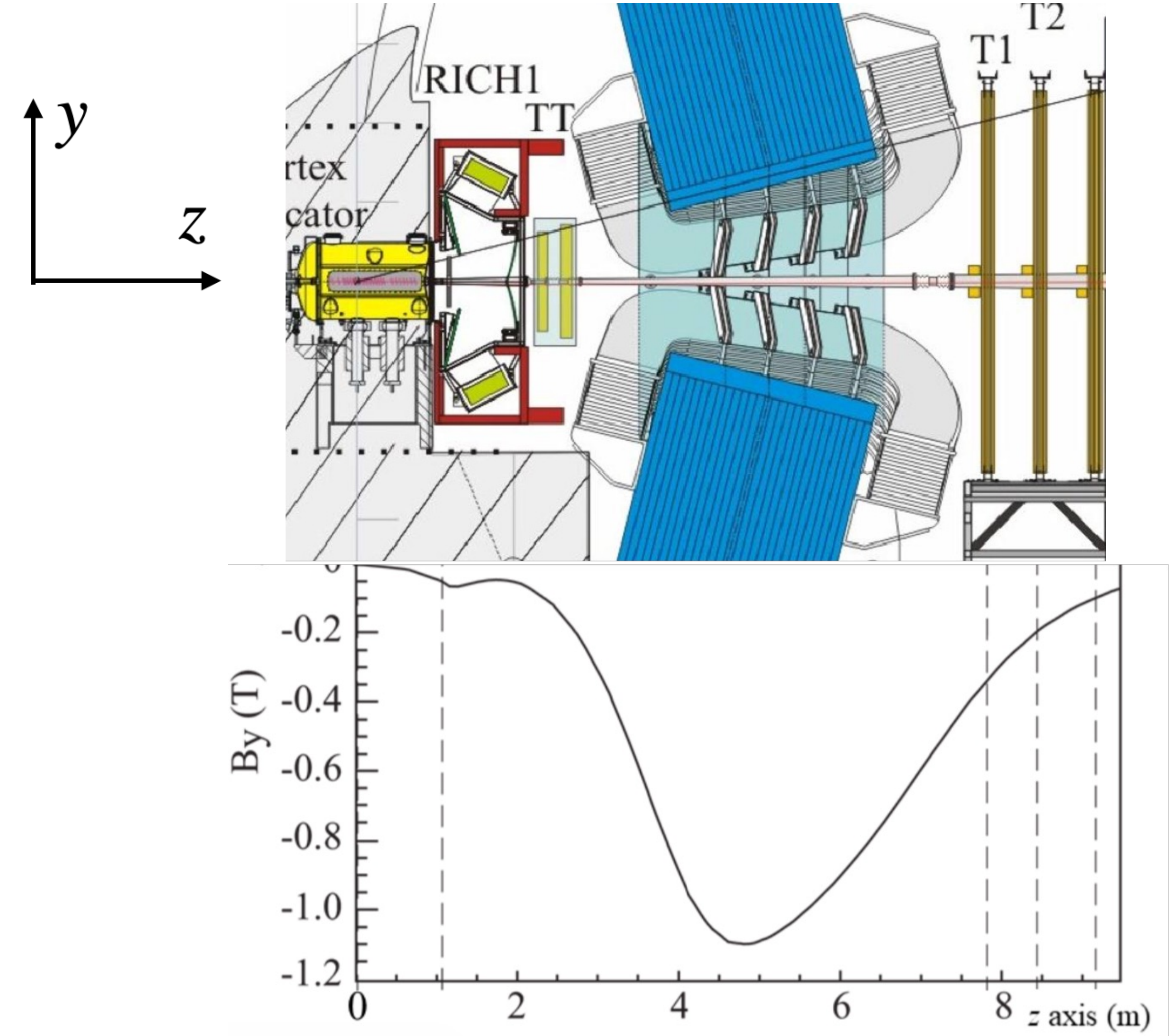
- Last direct measurement in 70's and 80's from E761@Fermilab
- Fixed-target experiment with 300GeV proton beam on Be
- Reconstructed 3×10^6 $\Lambda \to p\pi^-$ decays
- Small transverse polarization ~8%
- Magnet: 5m, 15Tm
- No measurement for $\bar{\Lambda}$, hence no CPT test via MDM

Proposed measurement at LHCb

Run 1-2 detector



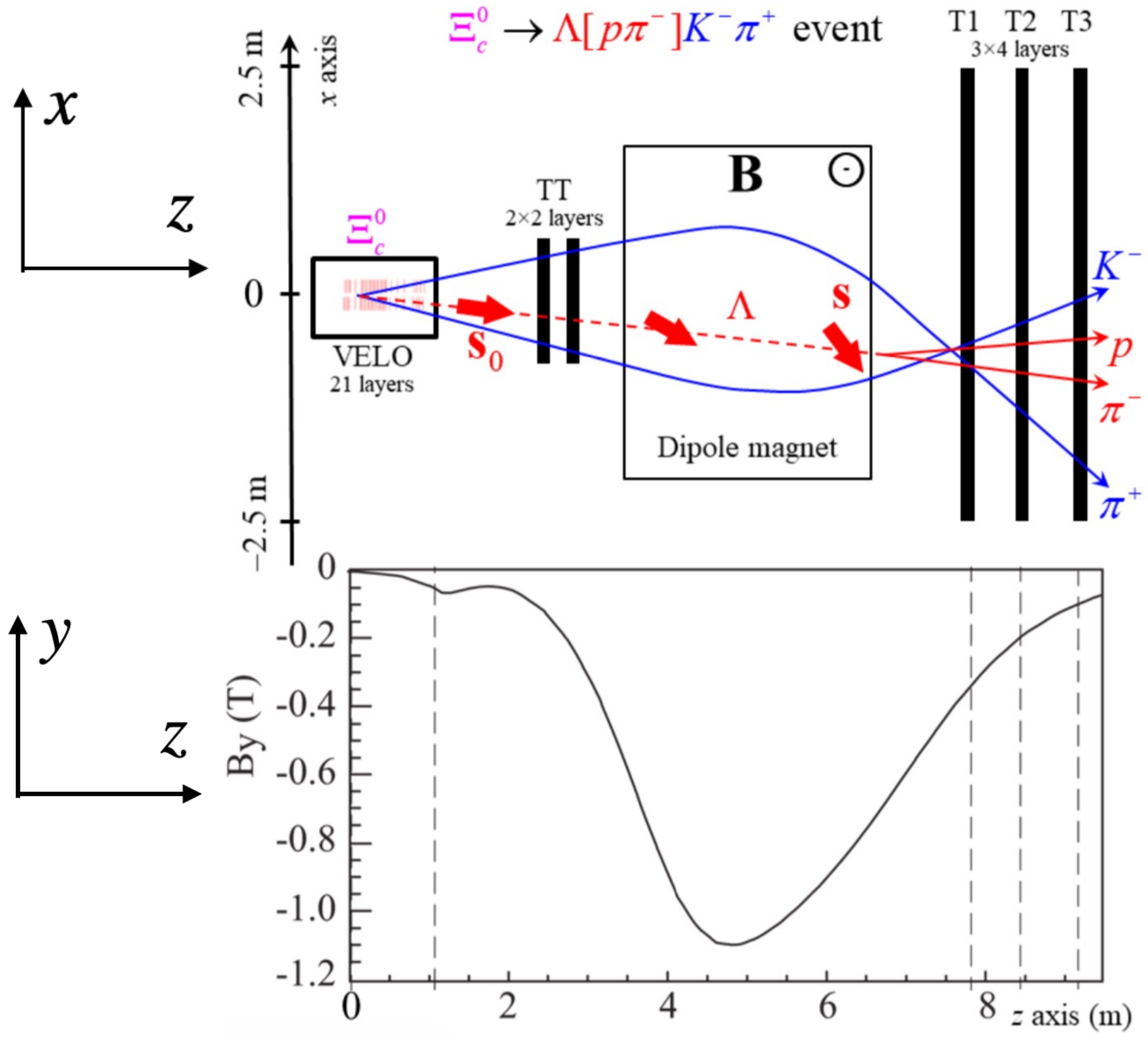
Proposed measurement at LHCb



- Acceptance:
  hor. ± 300 mrad, ver. ± 250mrad
- Measured B field values stable within $\sigma = \pm 0.07$gauss
- $\int Bdl$=4 Tm

Proposed measurement at LHCb

EPJC77(2017)181



- Consider c bayron decays to charged final particles
- Sensitivity with $50fb^{-1}$ at LHCb

  $\delta(\Lambda) < 1.3\times10^{-18}e$ cm

  first $\overline{\Lambda}$ MDM measurement at similar precision
- Challenging: Λ decay reconstruction after magnet

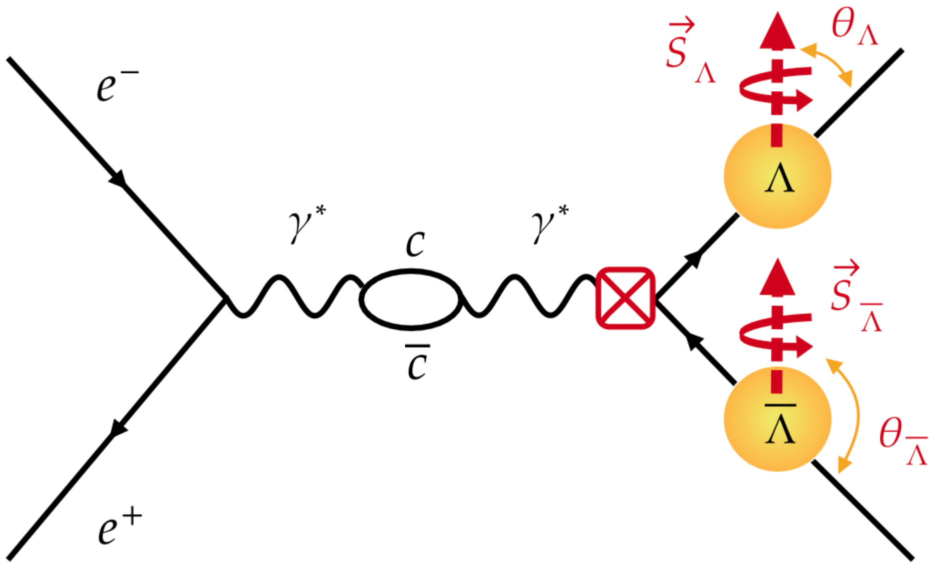
Indirect access to EDM

PHYSICAL REVIEW D VOLUME 47, NUMBER 5 1 MARCH 1993

CP violation in $J/\psi \to \Lambda\bar{\Lambda}$

Xiao-Gang He, J. P. Ma, and Bruce McKellar
Research Center for High Energy Physics, School of Physics, University of Melbourne, Parkville, Victoria 3052 Australia
(Received 19 November 1992)

We study CP violation in $J/\psi \to \Lambda\bar{\Lambda}$ decay. This decay provides a good place to look for CP violation. Some observables are very sensitive to the Λ electric dipole moment d_Λ and therefore can be used to improve the experimental upper bound on d_Λ. CP violations in the lepton pair decays of J/ψ and Υ are also discussed.



$$L_{c-\Lambda} = -\frac{2}{3M^2} e d_\Lambda (p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c\bar{\Lambda} i\gamma_5 \Lambda$$

$$H_T = \frac{2e}{3M^2} g_v d_\Lambda$$

measure time-like dipole form factor

X.G.He, J.P. Ma, Phys.Rev.D47(1993)1744

X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

Angular distribution

J. Fu, H.B.Li *et al*. Phys. Rev. D 108, L091301 (2023)

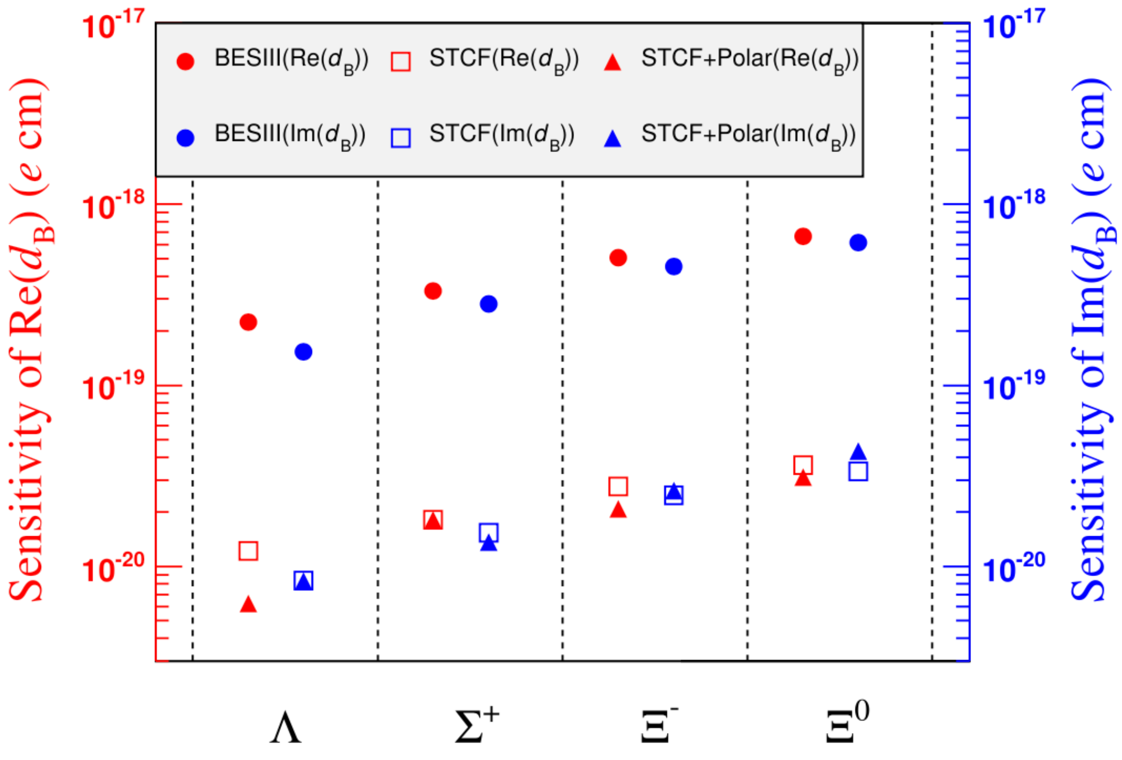
$$\frac{d\sigma}{d\Omega} \propto \sum_{[\lambda]} R(\lambda_1,\lambda_2;\lambda_1',\lambda_2')$$
$$D^{*j=1/2}_{\lambda_1,\lambda_3}(\phi_1,\theta_1) D^{j=1/2}_{\lambda_1',\lambda_3'}(\phi_1,\theta_1)\mathcal{H}^*_{\lambda_3}\mathcal{H}_{\lambda_3'}$$
$$D^{*j=1/2}_{\lambda_2,\lambda_4}(\phi_2,\theta_2) D^{j=1/2}_{\lambda_2',\lambda_4'}(\phi_2,\theta_2)\bar{\mathcal{H}}^*_{\lambda_4}\bar{\mathcal{H}}_{\lambda_4'}$$
$$D^{*j=1/2}_{\lambda_3,\lambda_5}(\phi_3,\theta_3) D^{j=1/2}_{\lambda_3',\lambda_5}(\phi_3,\theta_3)\mathcal{F}^*_{\lambda_5}\mathcal{F}_{\lambda_5}$$
$$D^{*j=1/2}_{\lambda_4,\lambda_6}(\phi_4,\theta_4) D^{j=1/2}_{\lambda_4',\lambda_6}(\phi_4,\theta_4)\bar{\mathcal{F}}^*_{\lambda_6}\bar{\mathcal{F}}_{\lambda_6}$$

$$R(\lambda_1,\lambda_2;\lambda_1',\lambda_2') \propto \sum_{m,m'} \rho_{m,m'} d^{j=1}_{m,\lambda_1-\lambda_2}(\theta) d^{j=1}_{m',\lambda_1'-\lambda_2'}(\theta) \times \mathcal{M}_{\lambda_1,\lambda_2}\mathcal{M}^*_{\lambda_1',\lambda_2'}\delta_{m,m'},$$

$$\mathcal{M}_{\lambda_1,\lambda_2} = \epsilon_\mu(\lambda_1-\lambda_2)\bar{u}(\lambda_1,p_1)(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T)v(\lambda_2,p_2).$$

- Based on previous work, we establish a full angular analysis in $e^+e^- \to J/\psi \to B\bar{B}$, B is for Λ, Σ and Ξ
- Hyperon EDM, along with CP-violating observables in hyperon decay, effective weak mixing angle and beam polarization, can be determined simultaneously

Sensitivity study



J. Fu, H.B.Li *et al*. Phys. Rev. D 108, L091301 (2023)

- Sensitivity assessed via psudoexperiments generated and fitted by using a probability density function based on the full angular distribution
- Expected yields, Form Factors and decay parameters are fixed to known values for generation
- Sensitivity at BESIII and STCF $10^{-19}\sim 10^{-21} e$ cm

Λ EDM measurement BESIII

arXiv:2506.19180

- Preserve CP symmetry with a precision of 10^{-19} e cm, a 3-order-of-magnitude improvement over E761@Fermilab

$$Re(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e\ \text{cm},$$

$$Im(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e\ \text{cm}.$$

$$-8.6 \times 10^{-19} < Re(d_\Lambda) < 3.3 \times 10^{-19}\ e\ \text{cm},$$

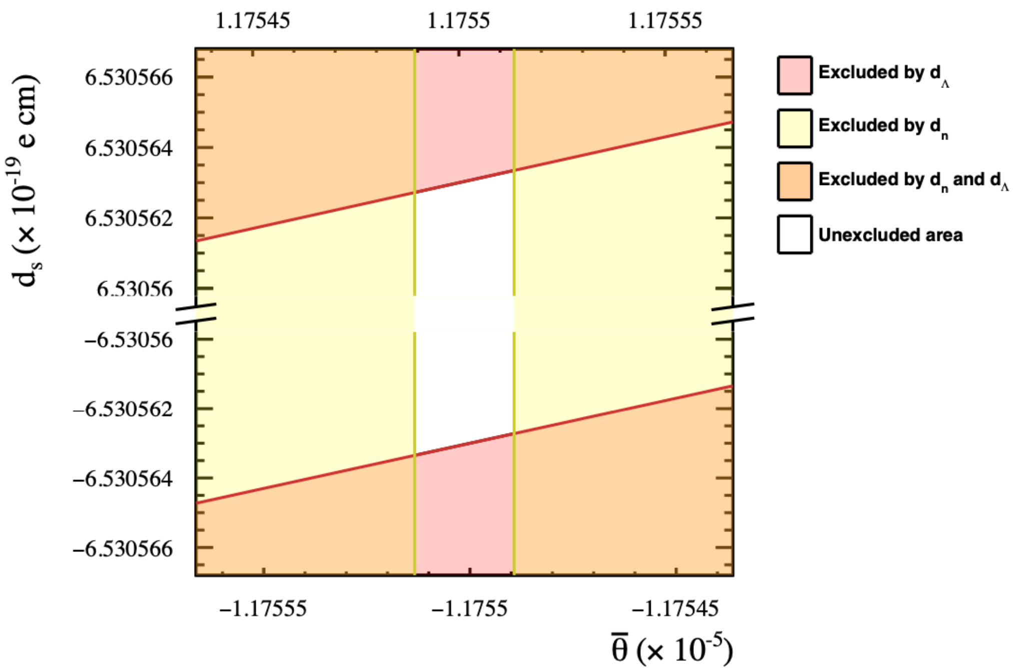
$$-2.5 \times 10^{-19} < Im(d_\Lambda) < 7.2 \times 10^{-19}\ e\ \text{cm},$$

$$|d_\Lambda| < 6.5 \times 10^{-19}\ e\ \text{cm}.$$

- Stringent constraints on fundamental parameters together with neutron EDM

$$d_n = -(1.5 \pm 0.7) \times 10^{-16}\ \bar{\theta}\ e\ \text{cm}$$
$$- (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s$$

$$d_\Lambda = (-2.6 \pm 0.4) \times 10^{-16}\ \bar{\theta}\ e\ \text{cm} + d_s$$



How to access EDM and MDM

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$$\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \mathbf{\Omega} \qquad \mathbf{\Omega} = \mathbf{\Omega}_{\mathrm{MDM}} + \mathbf{\Omega}_{\mathrm{EDM}} + \mathbf{\Omega}_{\mathrm{TH}}$$

$$\Omega_{\mathrm{EDM}} = \boxed{\frac{d\mu_B}{\hbar}} \left(\mathbf{E} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta} \cdot \mathbf{E})\boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{B} \right)$$

$$\mathbf{\Omega}_{\mathrm{MDM}} = \boxed{\frac{g\mu_B}{\hbar}} \left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta} \cdot \mathbf{B})\boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{E} \right)$$

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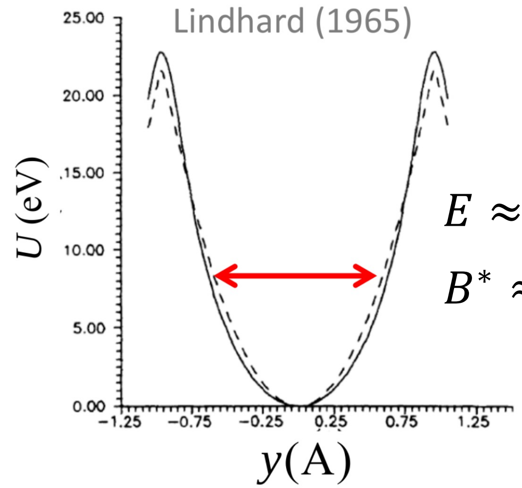
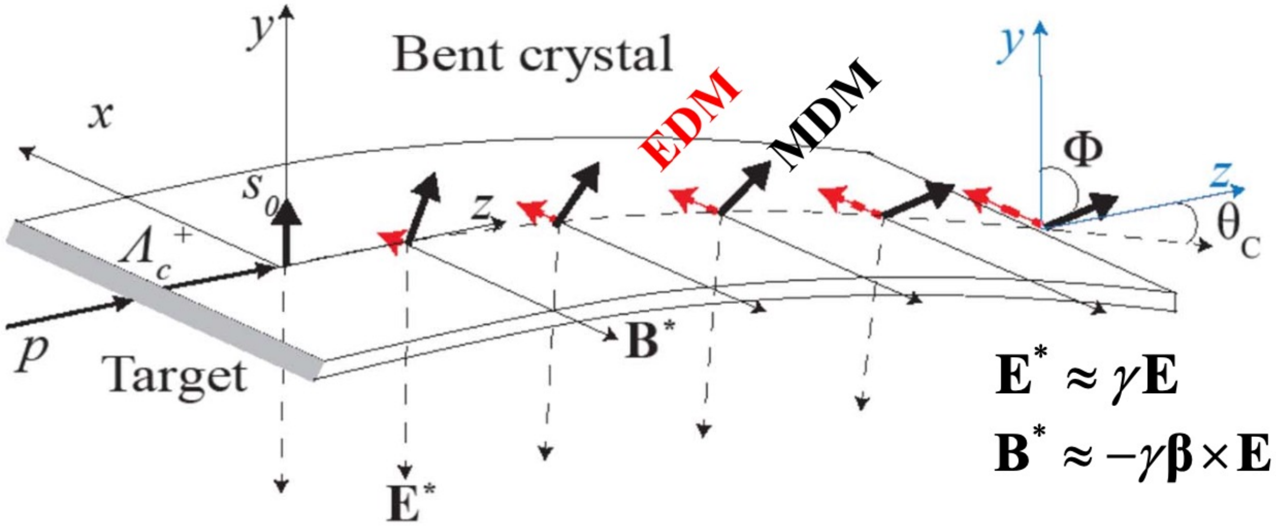
New experiment concept

- Polarized Λ_c^+ and Ξ_c^+ sources, produced from fixed-target pW collisions at LHC $\sqrt{s}$ ≈110 GeV
- Flight length: high boost $\gamma \approx 600{\sim}900 \Rightarrow \beta\gamma\tau c \approx 7{\sim}10\ cm$
- Intense EM field induced from bent crystal and spin precession by channeling effect



$E \approx 6GV/cm$

$B^* \approx 10^6$T



$\mathbf{E}^* \approx \gamma\mathbf{E}$

$\mathbf{B}^* \approx -\gamma\boldsymbol{\beta}\times\mathbf{E}/c$

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$

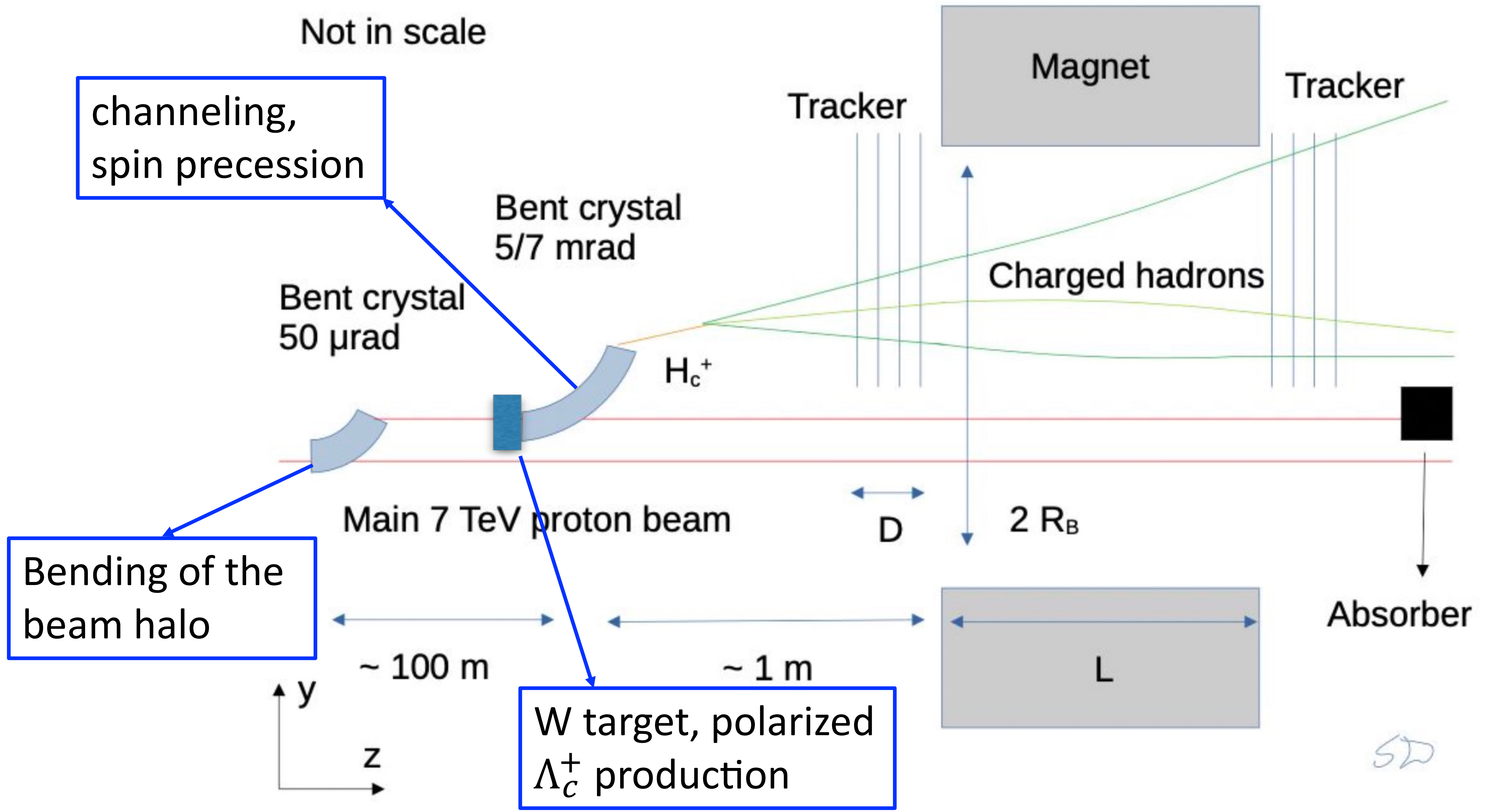
$$s'_x \approx s_0\frac{d}{g-2}[\cos\Phi - 1]$$

$\mathbf{s} = (0, s_0, 0)$ $\mathbf{s}' = (s'_x, s'_y, s'_z)$

Eur. Phys.J.C(2017)77:828

Phys.Rev.D 103, 072003 (2021)

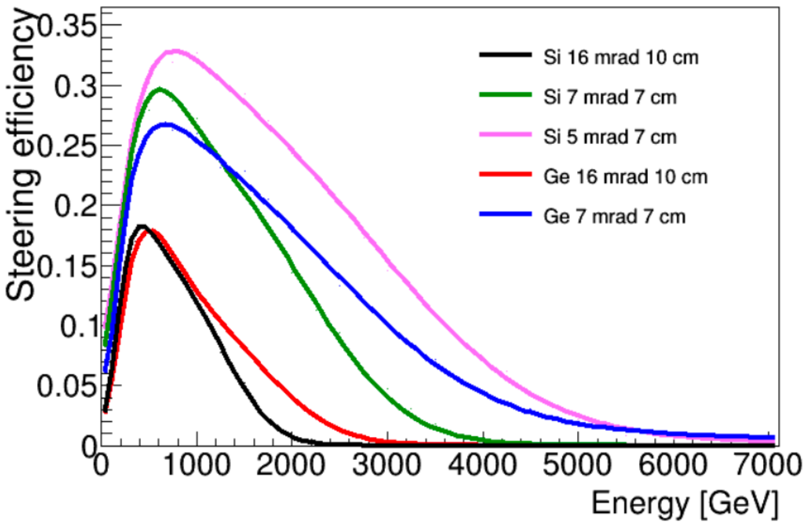
Double-crystal setup for MDM and EDM measurement

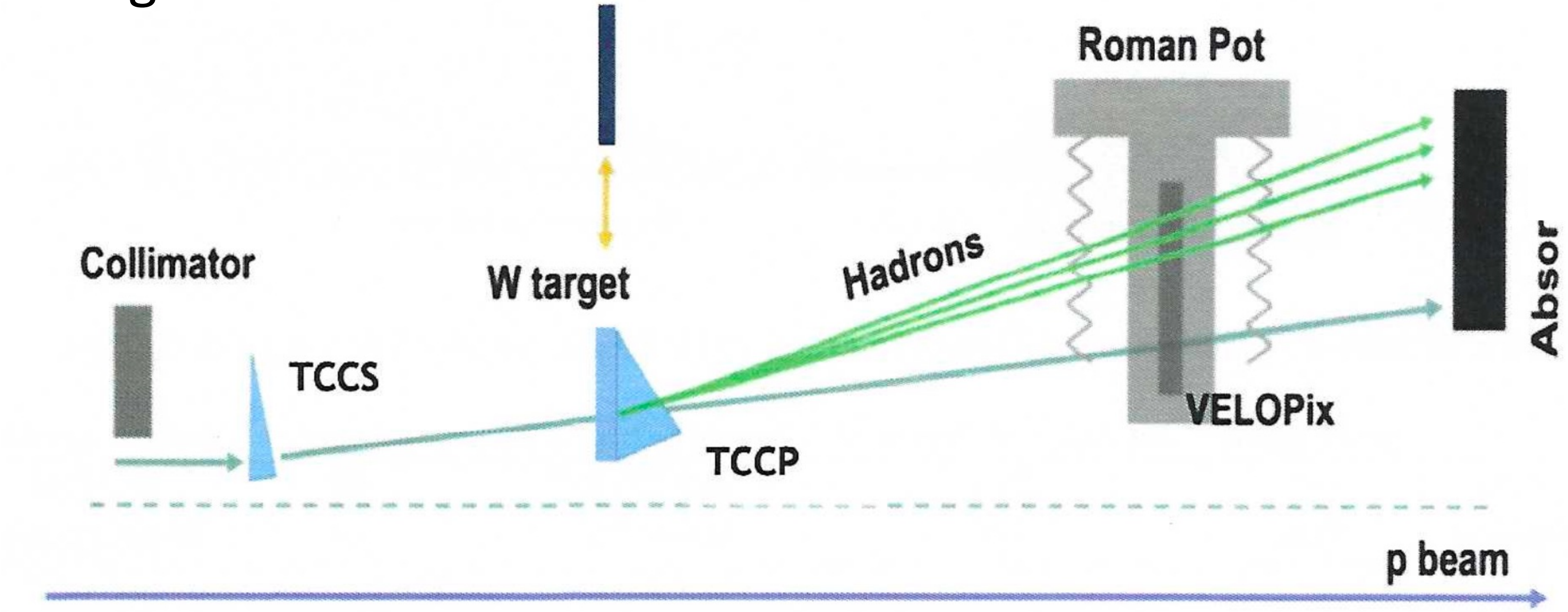


TWOCRYST: proof-of-principle test at LHC

- ❑ Validate crystal properties, channeling eff. at TeV beam
- ❑ Demonstration of operational feasibility
- ❑ Validation of achievable PoT
- ❑ Background studies for RICH detector

Channeling eff. simulation

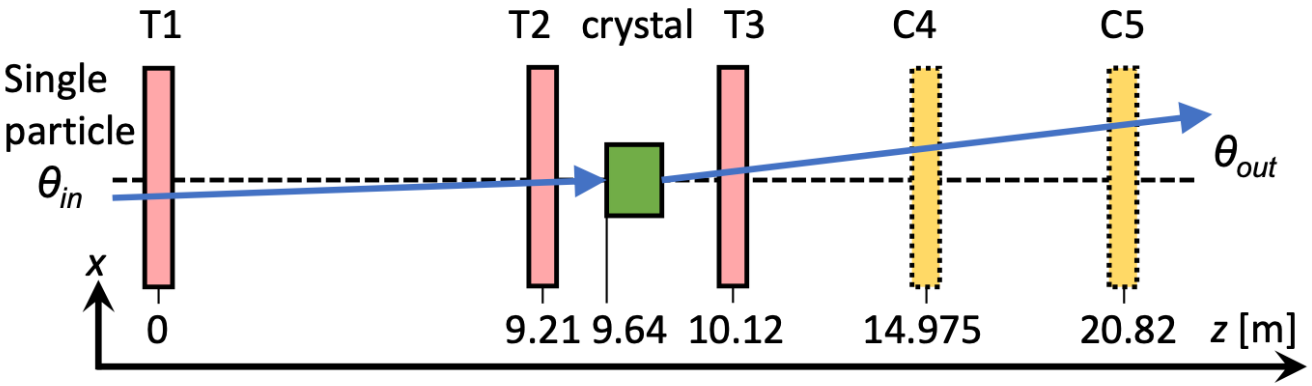




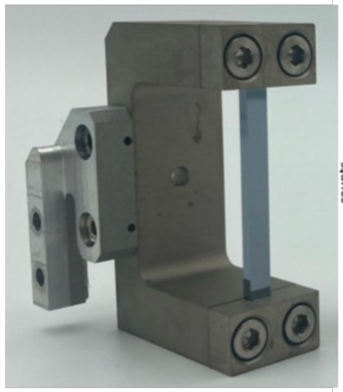
- ❑ Two silicon crystals: splitting crystal (TCCS) and precession crystal (TCCP)

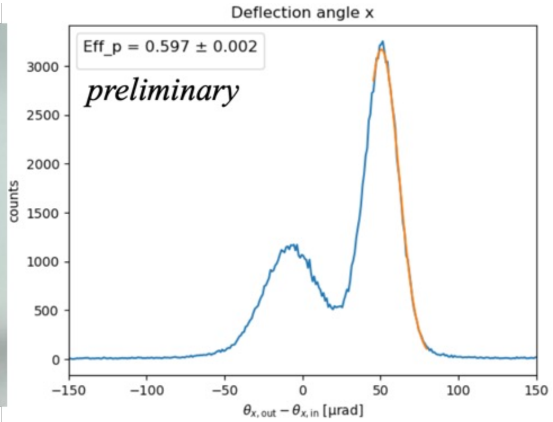
Bent crystal testbeam at CERN SPS

Tested at SPS H8 with 180GeV/c hadron beam (Aug. 2023)

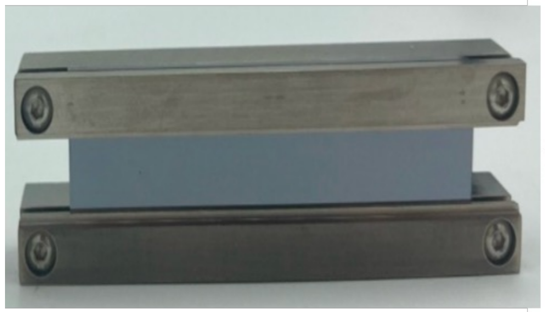


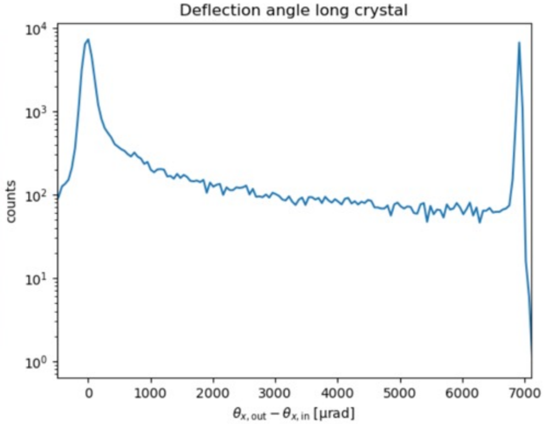
TCCS: 4mm, 50rad, channeling eff. 60%



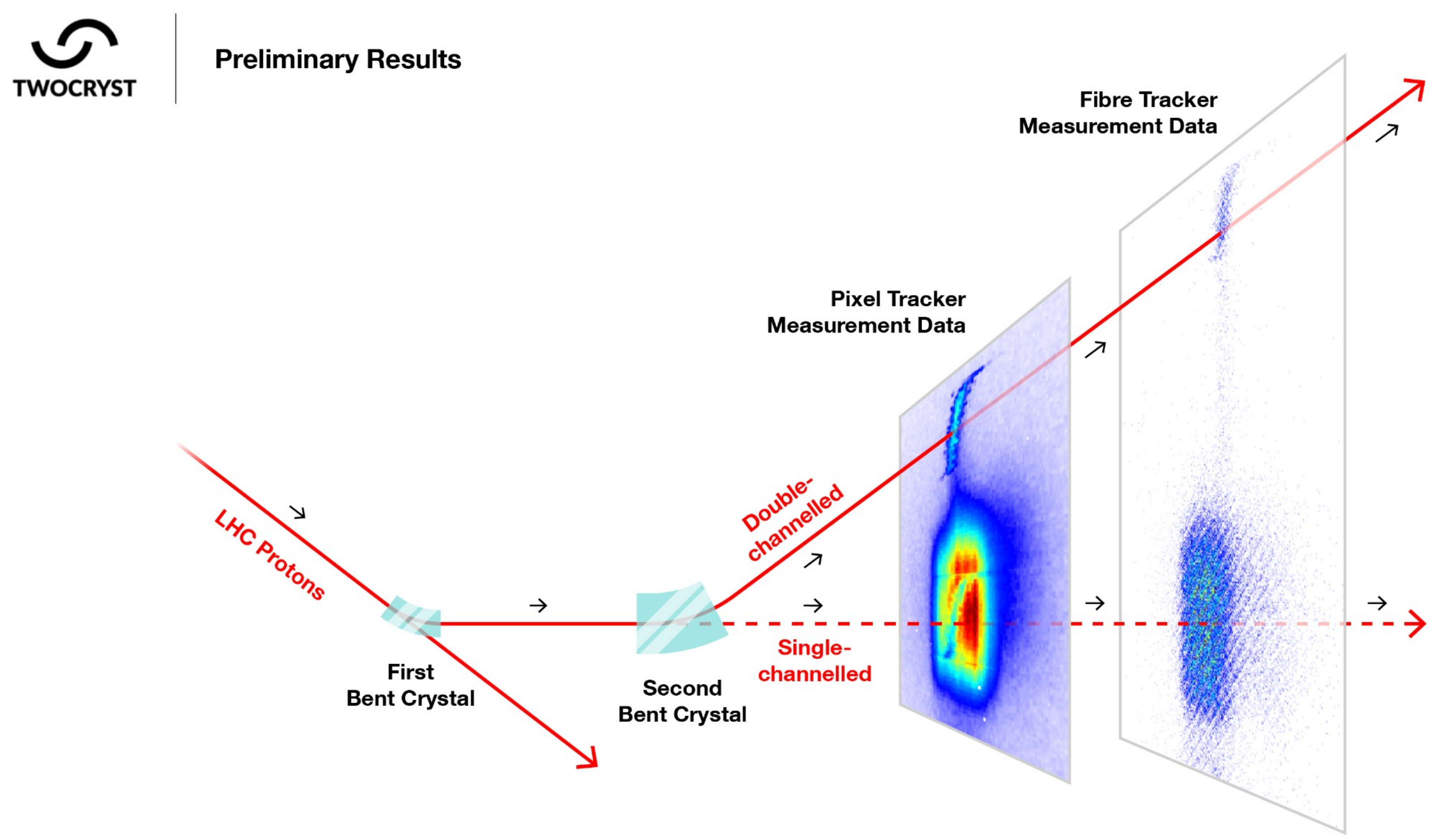


TCCP:70mm, 7mrad, channeling eff. 16%





Double crystal channeling test

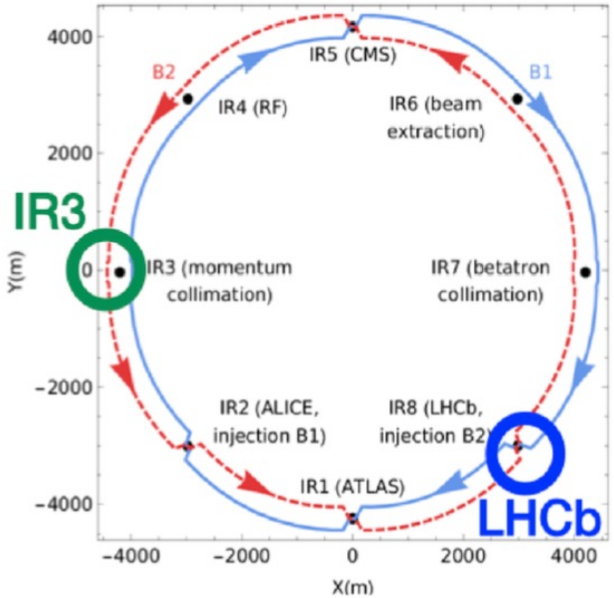


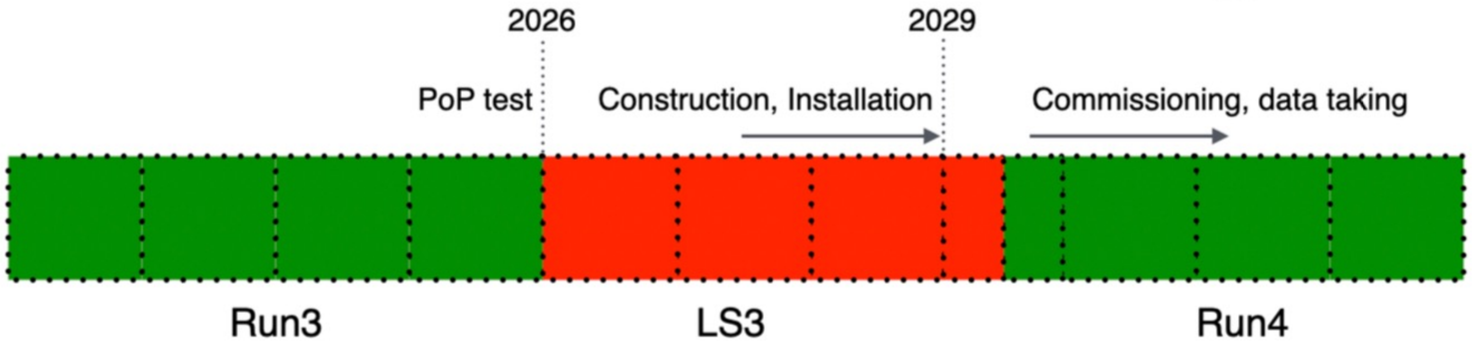
- ❑ First demonstration of double-crystal channeling at LHC, with main LHC beam at injection energy of 450 GeV (Aug. 2025)
- ❑ Further test will be for 1, 2 and 3 TeV beam

Proposed experiment at LHC and timeline

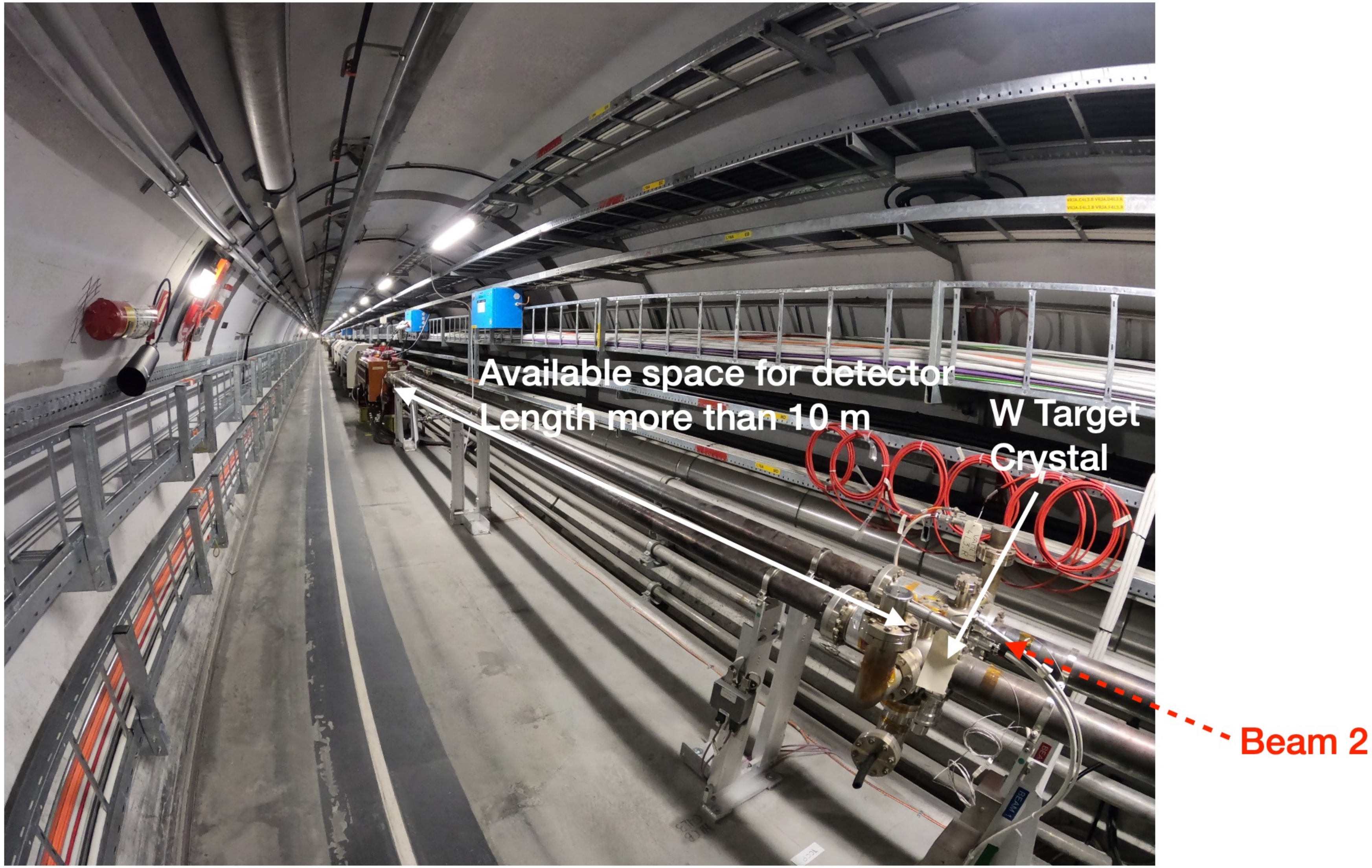
- Two alternative proposals: **i) dedicated experiment at IR3 (baseline)** ii) use LHCb detector at IP8 (fallback option)

	Pro	Cons
IR3	Optimal experiment and detector. PID information	More resources needed. New detector, services (long cables, cooling)
LHCb	Use existing tracking detector and infrastructure. Experimental area	No PID for p>100 GeV. Potential interference with LHCb core program





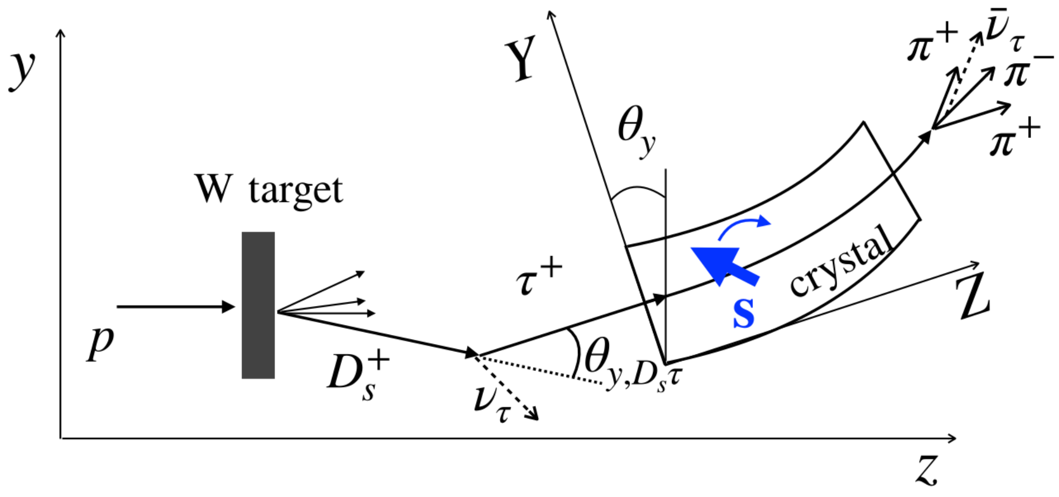
LHC IR3 venue

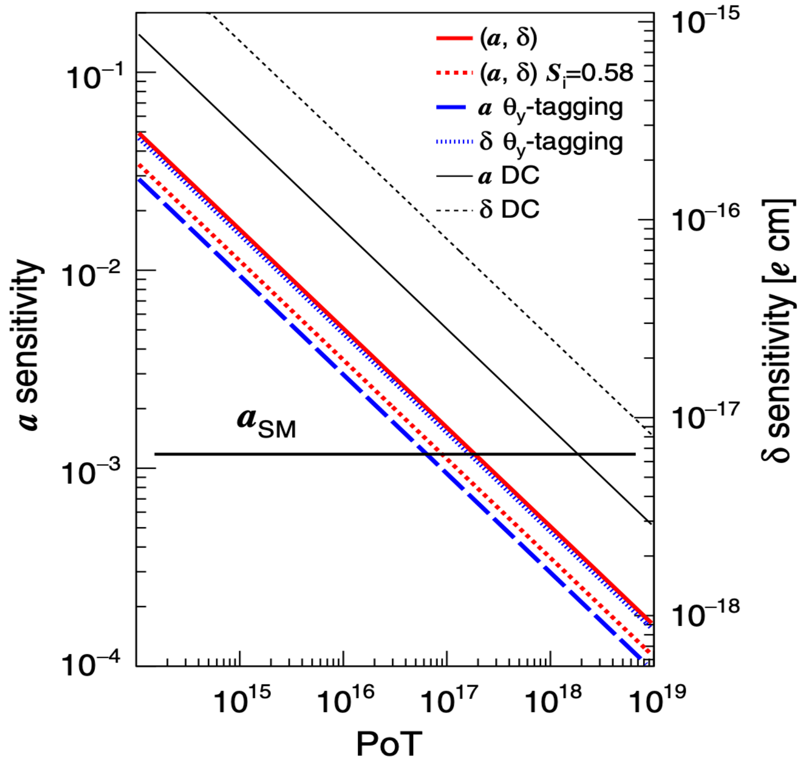


Physics reach

- First measurement of MDM and EDM of Λ_c^+ and Ξ_c^+ in 2 years data taking
  assuming 10^6 p/s, 2 cm W target, polarization ~20%
  sensitivity: $2\times10^{-2}\mu_N$ and 3×10^{-16} e cm with 1.4×10^{13} PoT
- Opportunity for Physics in the very forward region: $5 < \eta < 9$
  i.e. Cross-section of charm hadron production, QCD polarization, J/ψ photon production
- Further extended for τ EDM and g-2 (R&D required)

J. Fu *et al*. Phys. Rev. Lett. 123(2019)011801





Proponents of ALADDIN LOI and other authors

- The ALADDIN proto-collaboration, 70 scientists from 24 institute across 8 countries

K. Akiba [1], *F. Alessio* [2], *M. Benettoni* [3], *A. Bizzeti* [23,24], *F. Borgato* [3,4], *F. Bucci* [23], *R. Cardinale* [5,6], *S. Cesare* [7,8], *M. Citterio* [8], *V. Coco* [2], *S. Coelli* [8], *P. Collins* [2], *E. Dall'Occo* [9], *M. Ferro-Luzzi* [2], *A. Fomin* [21], *R. Forty* [2], *J. Fu* [10], *P. Gandini* [8], *M. Giorgi* [11,12], *J. Grabowski* [13], *S. J. Jaimes Elles* [14], *S. Jakobsen* [2], *E. Kou* [21], *G. Lamanna* [11,12], *H. B. Li* [10,16], *S. Libralon* [14], *D. Marangotto* [7,8], *F. Martinez Vidal* [14], *J. Mazorra de Cos* [14], *A. Merli* [15], *H. Miao* [10,16], *N. Neri* [7,8], *S. Neubert* [13], *A. Petrolini* [5,6], *A. Pilloni* [17], *J. Pinzino* [12], *M. Prest* [19], *P. Robbe* [21], *L. Rossi* [7,8], *J. Ruiz-Vidal* [14,22], *I. Sanderswood* [14], *A. Sergi* [5,6], *G. Simi* [3,4], *M. Sorbi* [7,8], *M. Sozzi* [11,12], *E. Spadaro Norella* [5,6], *A. Stocchi* [21], *G. Tonani* [7,8], *T. Tork* [7,8], *A. Triossi* [3,4], *N. Turini* [18,12], *E. Vallazza* [19,20], *S. Vico Gil* [14], *Z. Wang* [8], *M. Wang* [8], *T. Xing* [8], *M. Zanetti* [3,4], *F. Zangari* [7,8]

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[17] INFN Sezione di Catania, Università degli Studi di Messina, Messina, Italy
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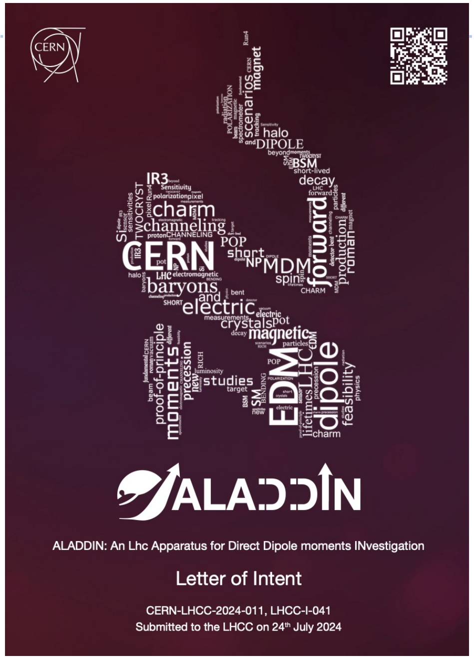
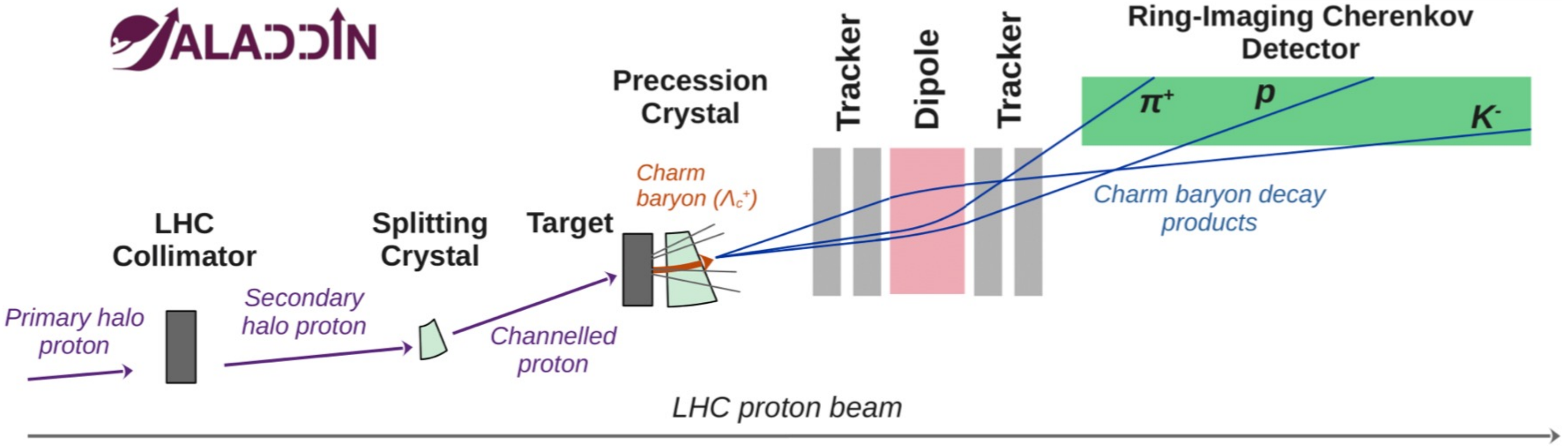


- With support from PBC and TWOCRYST collaboration



Summary

- Three-order-of-magnitude improvement in Λ EDM measurement at BESIII.

- Extensive EDM and MDM searches are ongoing at the BESIII and LHCb

- A new proposal for charm baryon and tau, presenting a challenging but unique opportunity to test SM and search for new physics

THANK YOU!