A fixed-target experiment to measure charm baryon dipole moments at LHC: ALADDIN

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2 University of Chinese Academy of Sciences

NSTAR workshop
2024.6.20, York, UK

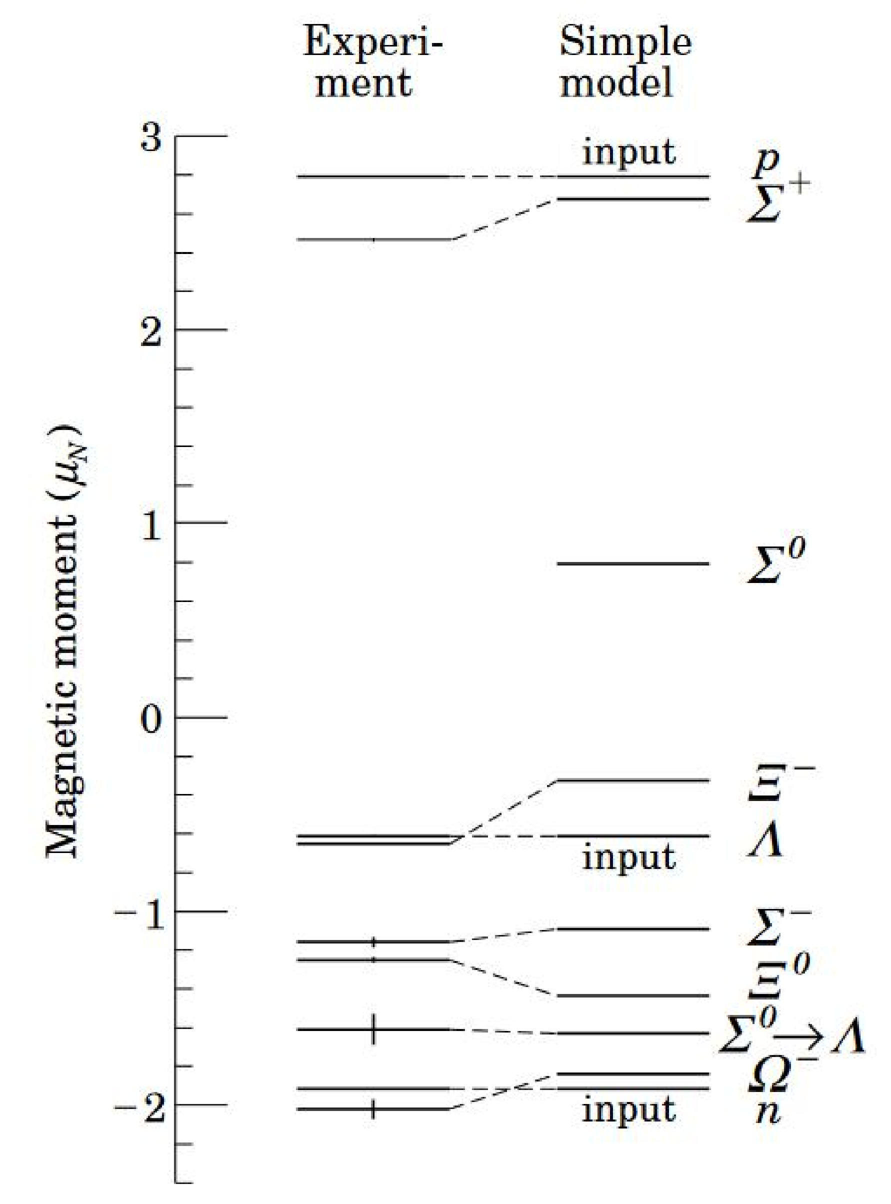
CONTENT

Part 01

Physics Potential

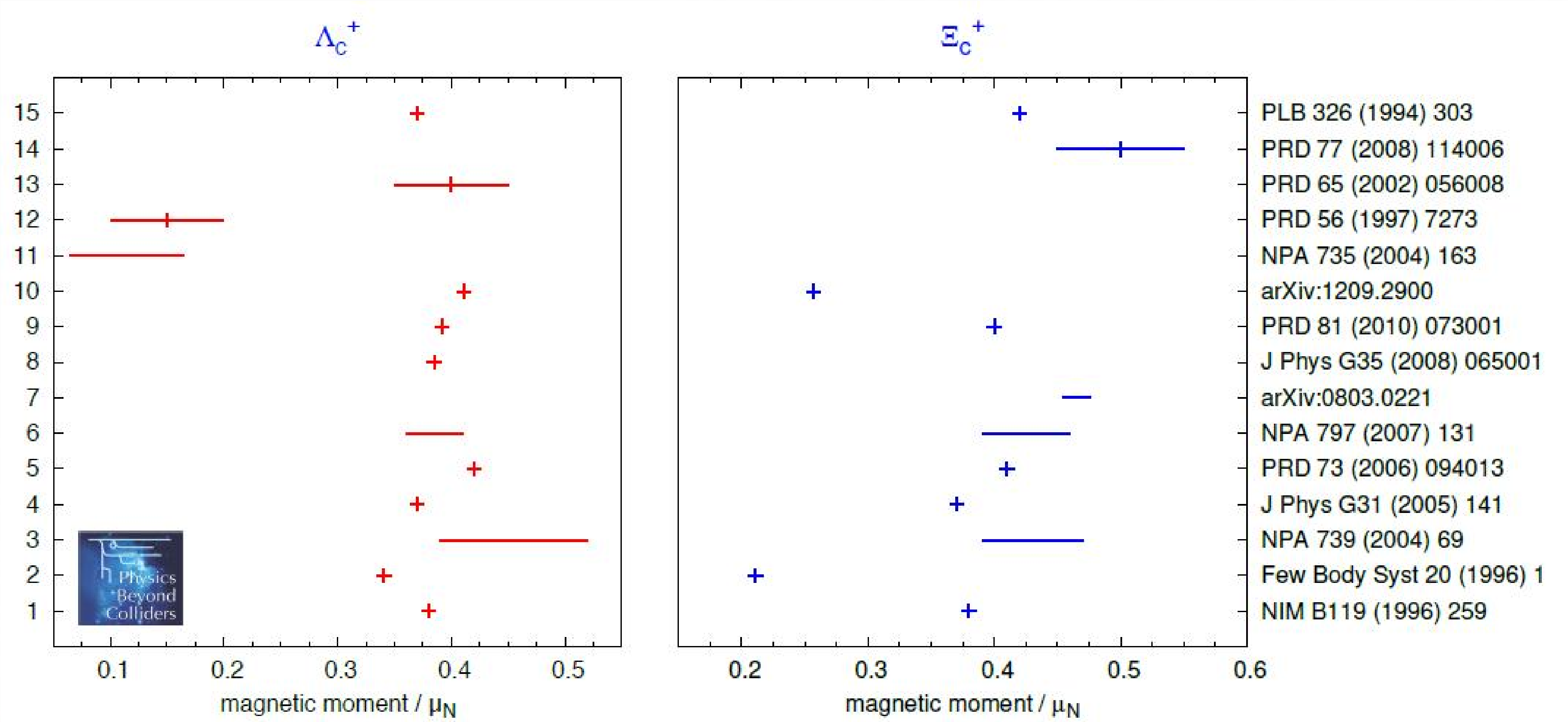
01 **Magnetic Dipole Moment**

- The magnetic moments (MDMs) of particles are among their most fundamental static properties
- MDM of baryons helps a lot to understand the internal structure
- Hadrons consisting of both light and heavy quarks play a special role in QCD: their binding is dominated by large-distance, non-perturbative dynamics, whilst the presence of a heavy quark mass brings in a simplifications due to heavy-quark symmetry



01 MDM of charmed baryons

- Theoretical predictions from different models show **a significant variation**
- The direct measurements of charm MDMs at **10% level** would help to discriminate among current theoretical models.
- Experimental proposal will trigger further theory activities in this field



A. Dainese et al. [QCD Working Group], arXiv 1901.04482 (2019)

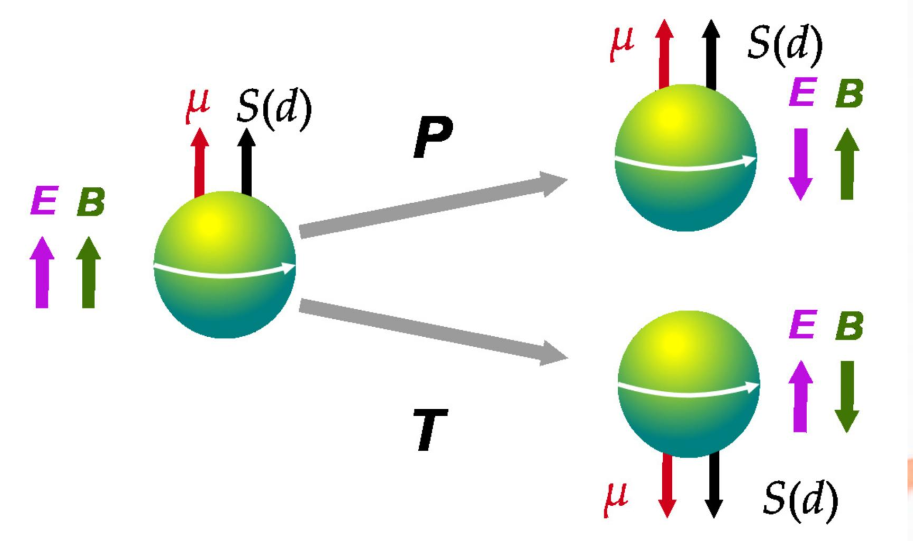
01 Electric Dipole Moment

μ: magnetic dipole moment
d: electric dipole moment
S: particle spin

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

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

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:

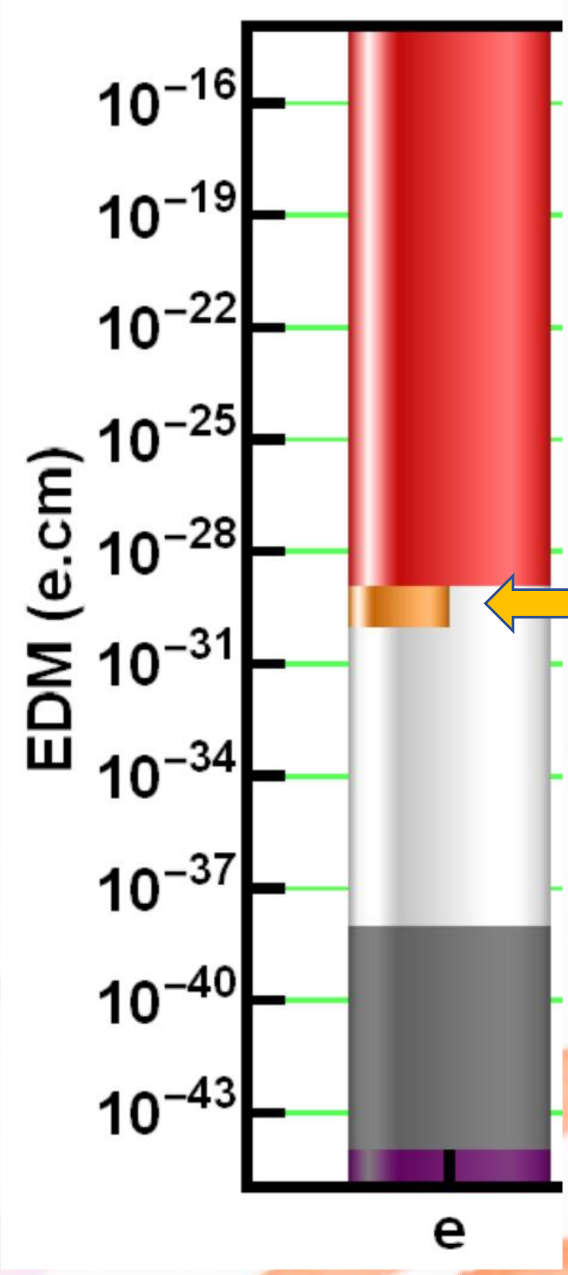
- CKM: highly suppressed by loop level (≥ 3) interaction
- QCD $\bar{\theta}$ term: main SM contributors to the EDM, $\bar{\theta} < 10^{-10}$
  - limited by neutron EDM:

$$d_n < 1.6 \times 10^{-26}\ ecm$$

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

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

01 Status of EDM Measurement



Best measurements
Limits from experimental results

Expected experimental results in the next few years

Safe BSM discovery territory

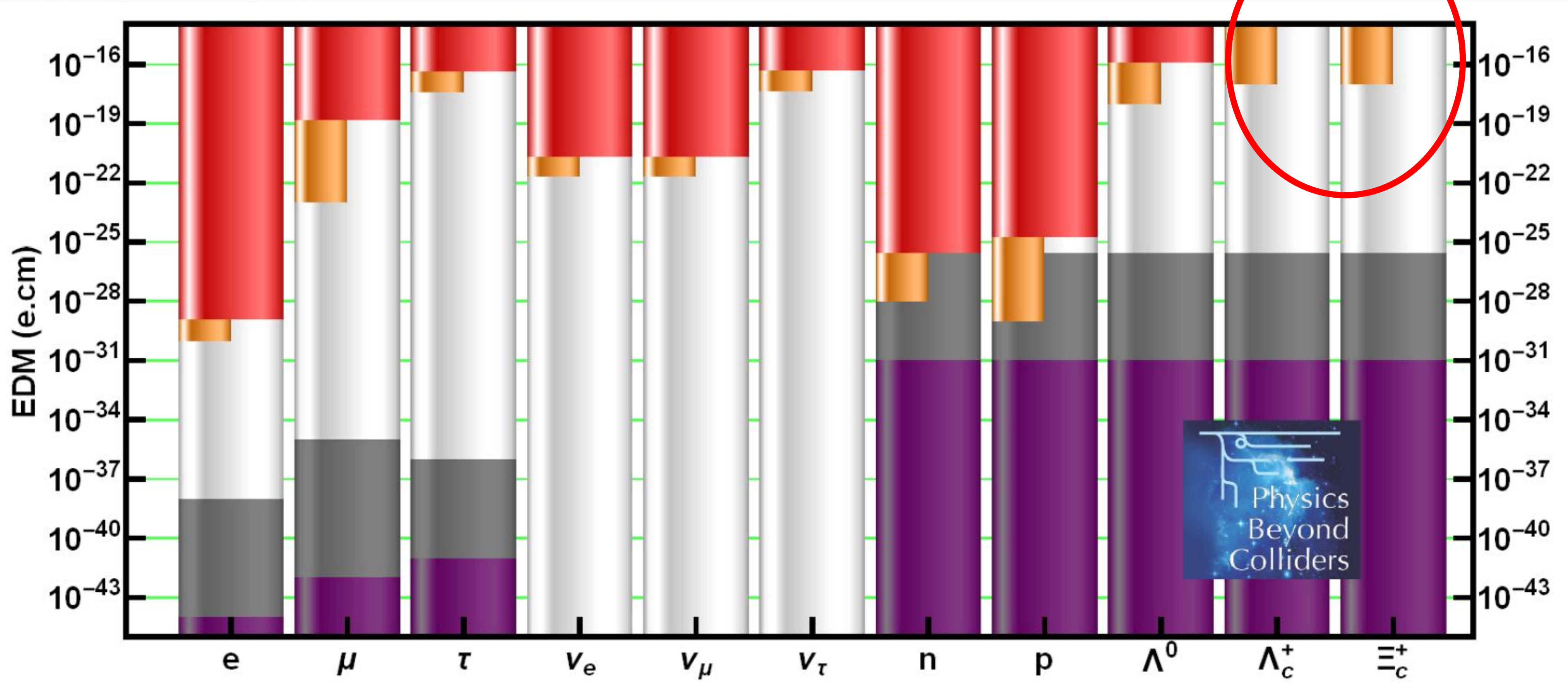
SM estimates from QCD $\bar{\theta}$ term

SM estimates from CKM

01 Status of EDM Measurement

The EDM of Λ_c and Ξ_c has never been measured !

J.Phys.G 47 (2020) 1, 010501



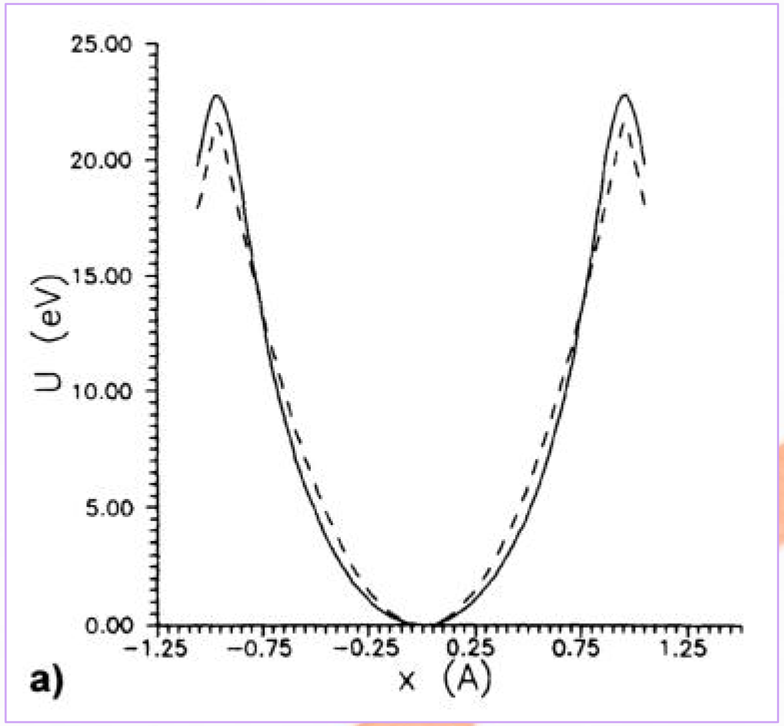
01 Channeling in a Bent Crystal

V. M. Biryukov et al., Springer-Verlag Berlin Heidelberg, 1997

To measure EDM and MDM of short-lifetime particles (~5cm) strong EM field are needed.

In bent crystal we obtain:

- Electric field E ≈ 1 GV/cm
- Effective magnetic field B ≈ 500 T



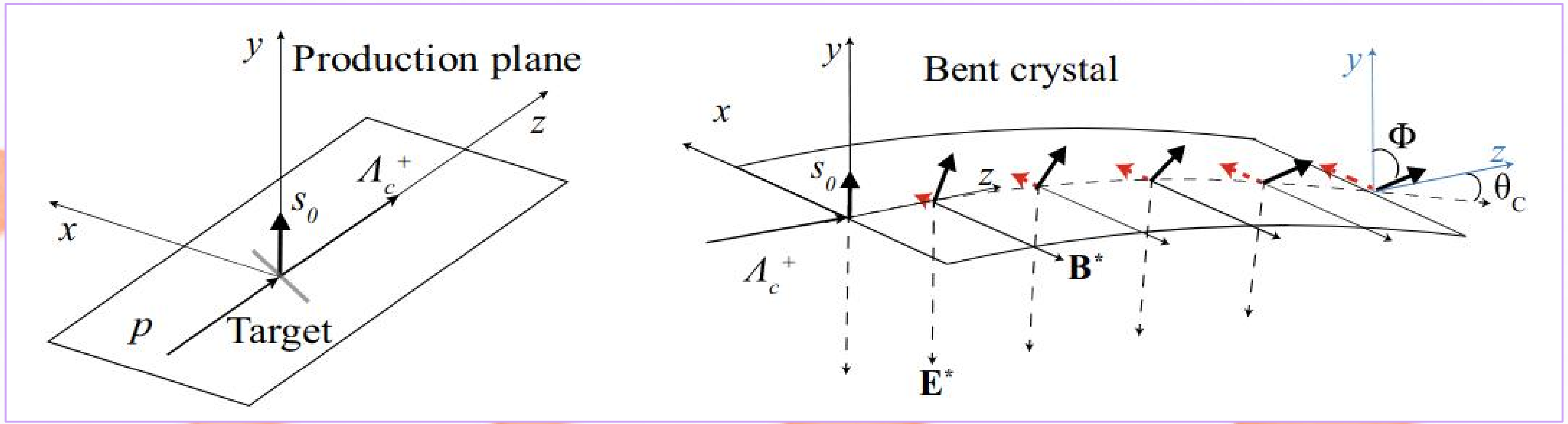
Positively charged particles are **channeled** between the atomic planes if their impact angle is small enough.

✓ Steer the particle trajectories of a given angle.

✓ Induce a **spin precession** of the particles in a short distance

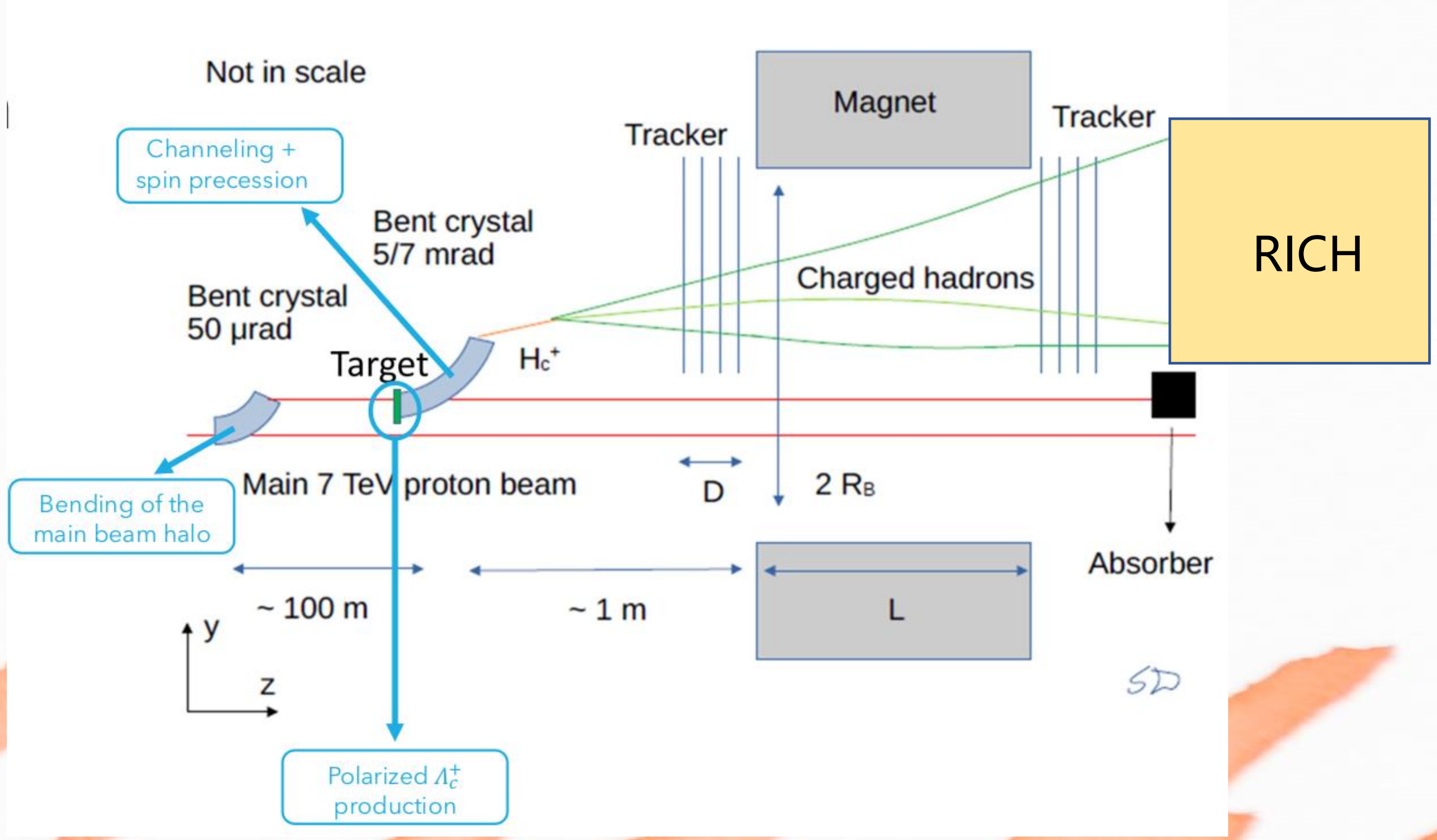
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$

$$\mathbf{s} = \begin{cases} s_x \approx s_0 \dfrac{d}{g-2}(\cos\Phi - 1) \\ s_y \approx s_0 \cos\Phi \\ s_z \approx s_0 \sin\Phi \end{cases}$$



01 Measure Dipole Moments Using Bent Crystal

Dipole Moment	Sensitivity	
	Λ_c^+	Ξ_c^+
MDM	$1.2 \times 10^{-2}\ \mu_N$	$(1.5 - 4.6) \times 10^{-16}\ e\mathrm{cm}$
EDM	$1.8 \times 10^{-2}\ \mu_N$	$3.1 \times 10^{-16}\ e\mathrm{cm}$



01 Cross Section Measurements for Charmed Hadron Production

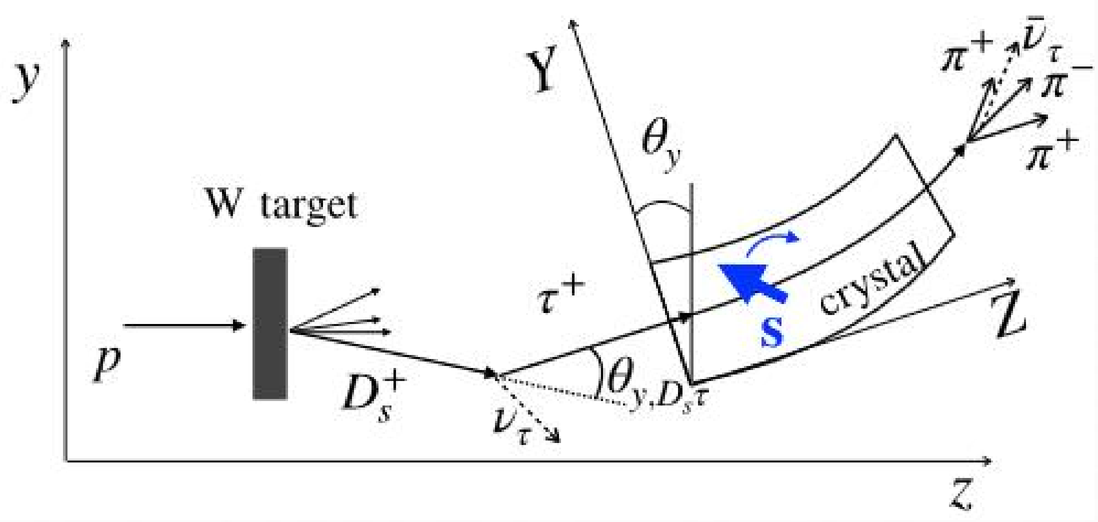
- Unique opportunity to study not only Λ_c^+ and Ξ_c^+ forward production but also to measure their cross sections and QCD polarization
- The production of D^+ and D_s^+ mesons can also be measured

	ALADDIN	SMOG
$\sqrt{s}$ (GeV)	≈ 115	≈ 115
Momentum p (GeV/c)	$\gtrsim 500$	$\lesssim 500$
Transverse momentum p_T (GeV/c)	$\lesssim 1.3$	0.2 to 1.8
Rapidity y^*	1 to 3.5	-3.5 to 0
	(very forward)	(central/backward)
Pseudorapidity η	7 to 9	2 to 5
Momentum transfer Q (GeV/c)	≈ 4	15 to 115
$\log_{10} x_B$ (Bjorken)	Down to -3.2	Down to -3
x_F (Feynman)	0.1 to 0.5, max. at 0.3	-0.5 to 0, max. at -0.1

Unique forward acceptance $\mathbf{7 < \eta < 9}$ → Worth to enlarge the physics case!

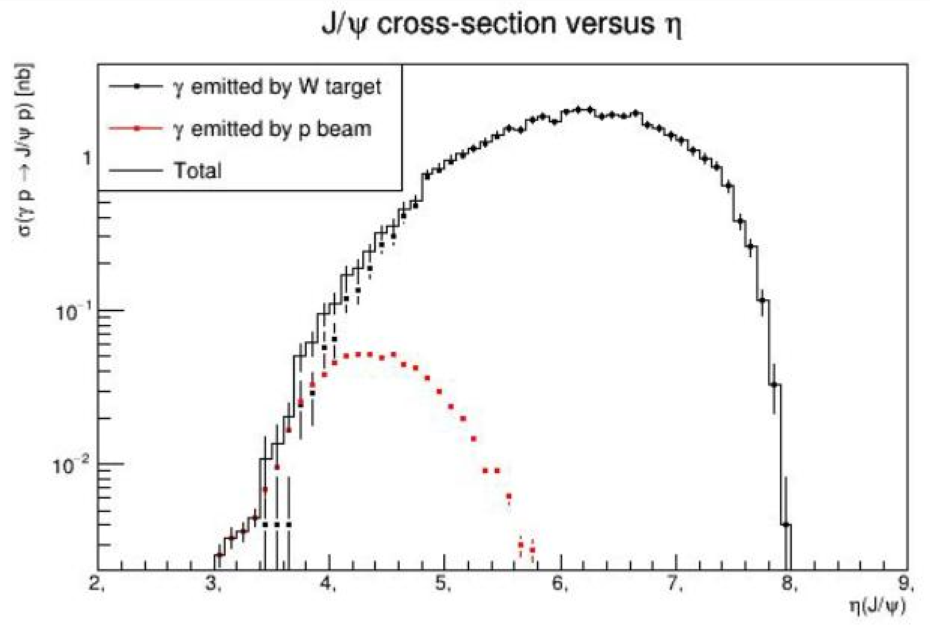
01 EDM&MDM Measurement of τ lepton

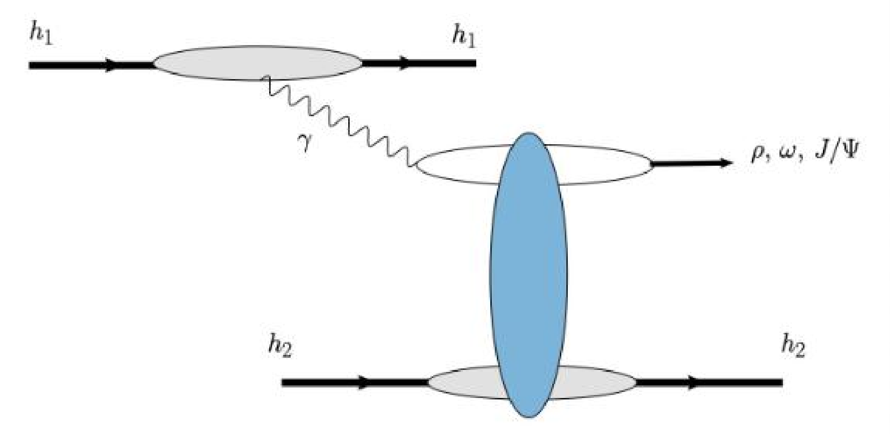
J. Fu et al. , Phys. Rev. Lett. 123 (2019) 011801
A. S. Fomin et al. J. High Energ. Phys. 03 (2019) 156



- Via $D_s^+ \to \tau^+ \nu_\tau$
- Reconstructed by 3-body decay
- Bent crystal located about 10 cm downstream the target
- $\approx 10^{17}$ PoT are needed to reach a MDM precision comparable to the SM prediction
- EDM can be measured at $10^{15}\ e\ cm$ level
- The first attempt
- An exploration of this technique will be performed

01 **Photoproduction in Fixed-Target**





J/ψ photoproduction

Pentaquarks photoproduction

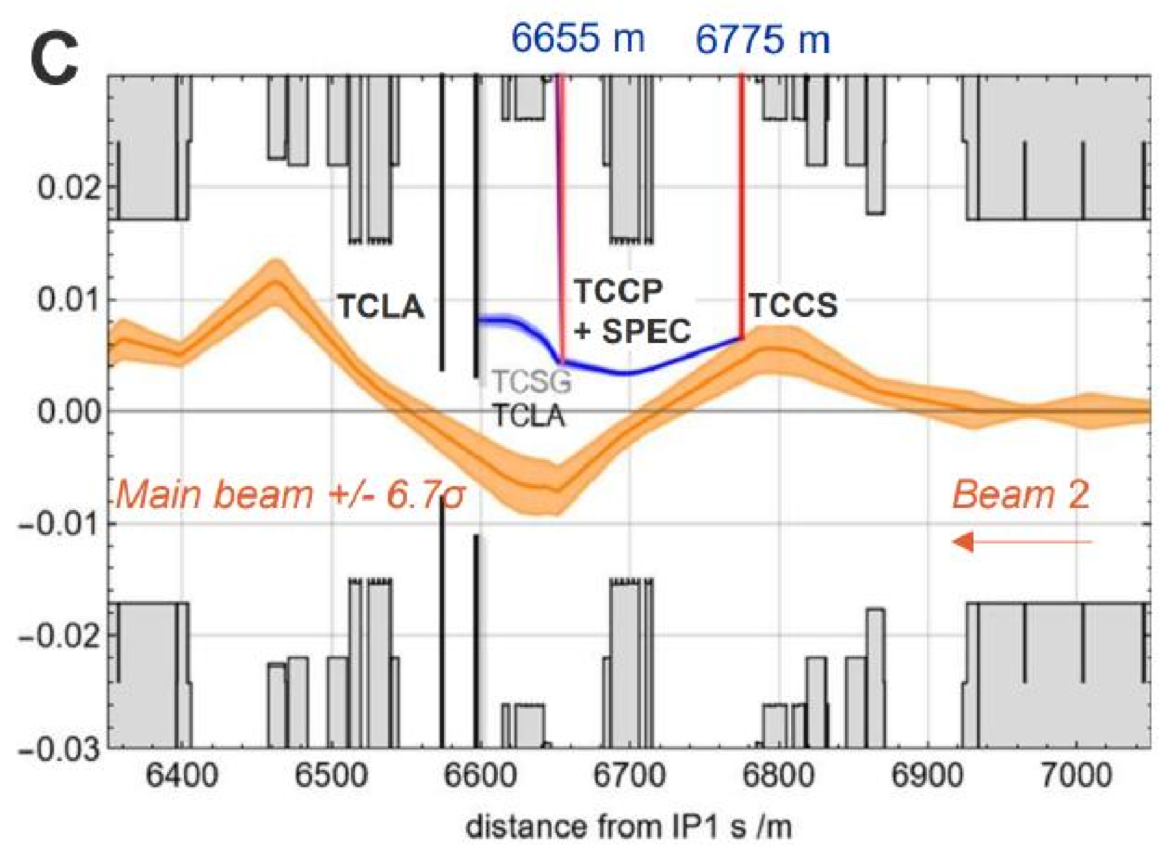
- Study the gluonic field contributions to the proton structure and proton mass
- Currently a **future possibility** (no muon detector in the baseline design).

Part 02

Experiment Proposal

02 Layout and Beam Dynamics

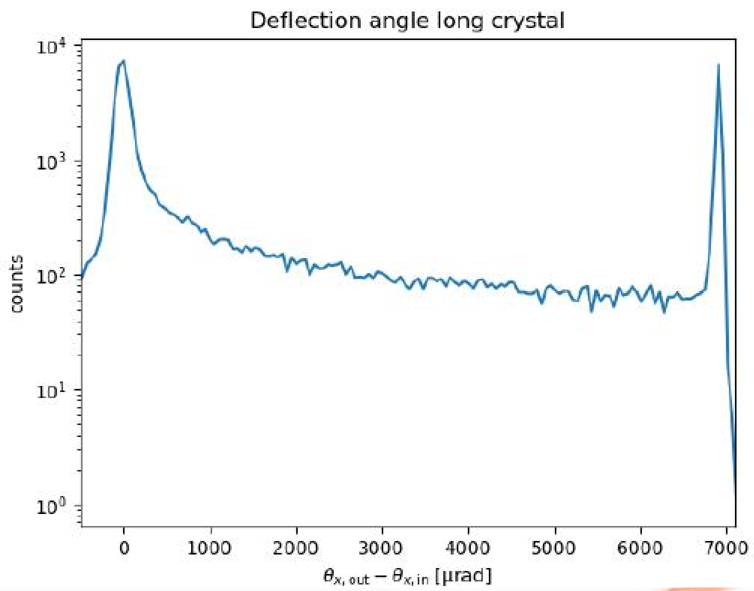
- Based on an invacuum fixed target integrated into the LHC collimation hierarchy.
- A separation from the beam core in the order of 10 mm when reaching the TCCP (The crystal for precession, which will be introduced in the next page)
- Residual of the channeled beam is absorbed safely by a set of collimators
- The kick to the main beam of LHC from the ALADDIN magnet can be corrected by the surrounding orbit corrector dipoles (existing)

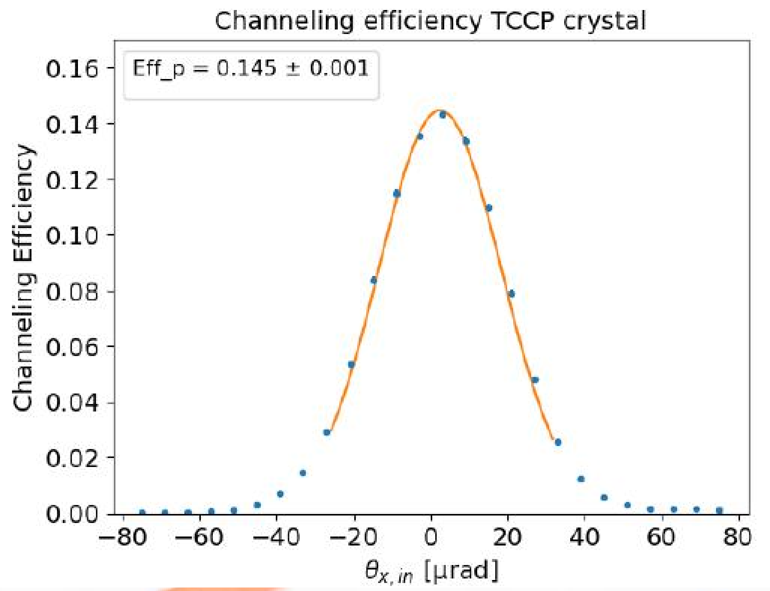


by Kay Dewhurst

02 Crystals

- Splitting Crystal (TCCS): **50 μrad** bending angle, 4 mm length
- Precession Crystal (TCCP): **7 mrad** bending angle, 7 cm length
- Tested using 180 GeV proton beam at SPS in 2023
- The channeling efficiency is measured to be **14.5%**
- The channeling efficiency in the **TeV region** will be tested in the TWOCRYST PoP in 2025

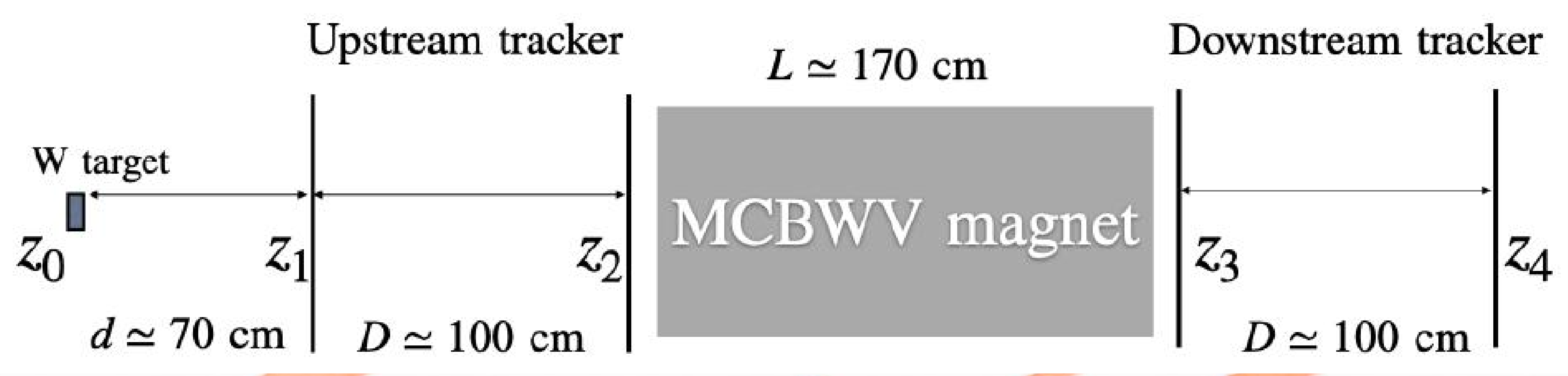




by Sara Cesare

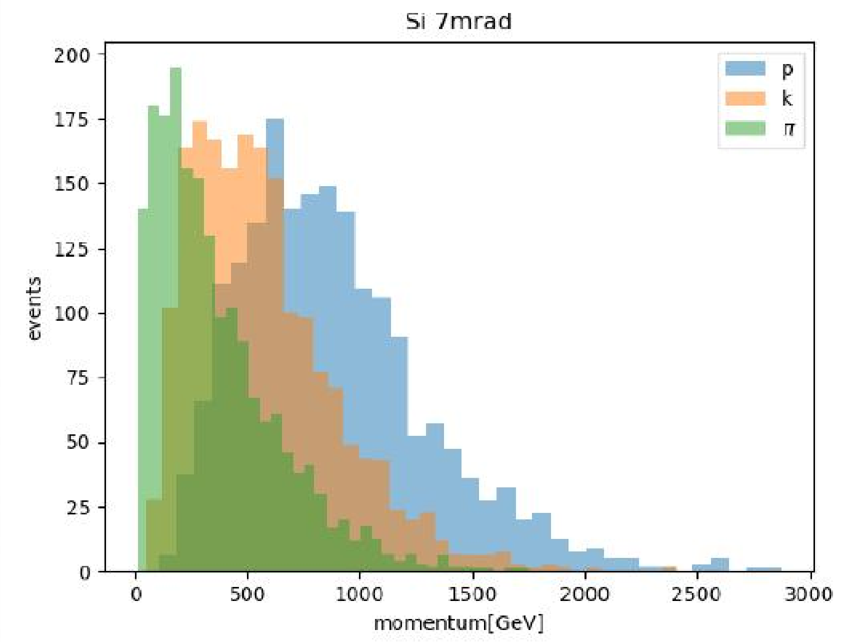
02 Spectrometer

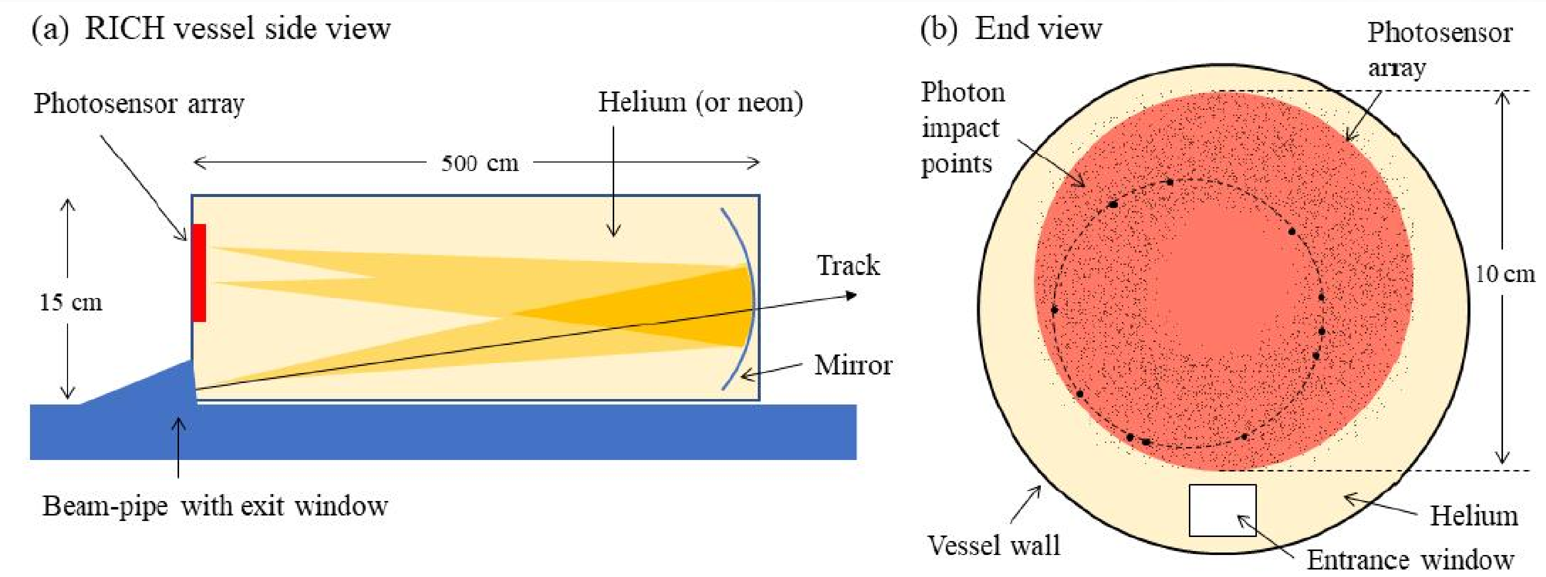
- 4 tracker stations, of which each has 2 tiles of pixel detector, are assembled inside Roman Pot to keep the vacuum
- Occupancy: **250 MHz/cm²** and **30 MHz/cm²** for the upstream and downstream stations
- Two options for the tracker
  - ✓ VELO hybrid sensors of the LHCb upgrade I (upstream and downstream)
  - ✓ Silicon strip sensor for LHCb UT (downstream)
- MCBWV magnet provide **1.1 T** magnetic field

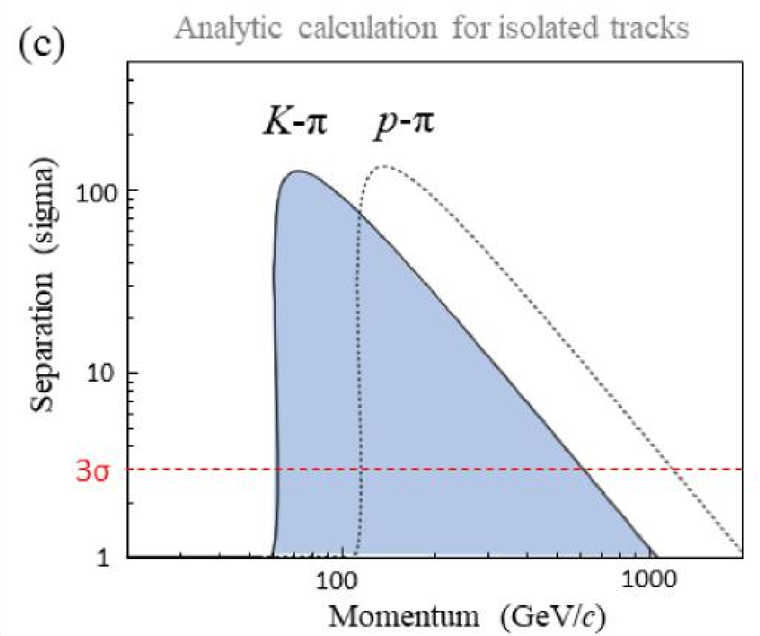


02 **RICH**

- Consider the requirement to identify particles within **super high momentum range (~TeV)**
- **Helium** gas: n=1.000035
- Provide the separation of different particles up to 1 TeV/c
- About 12 Cherenkov photons per track
- SiPM for the photon readout



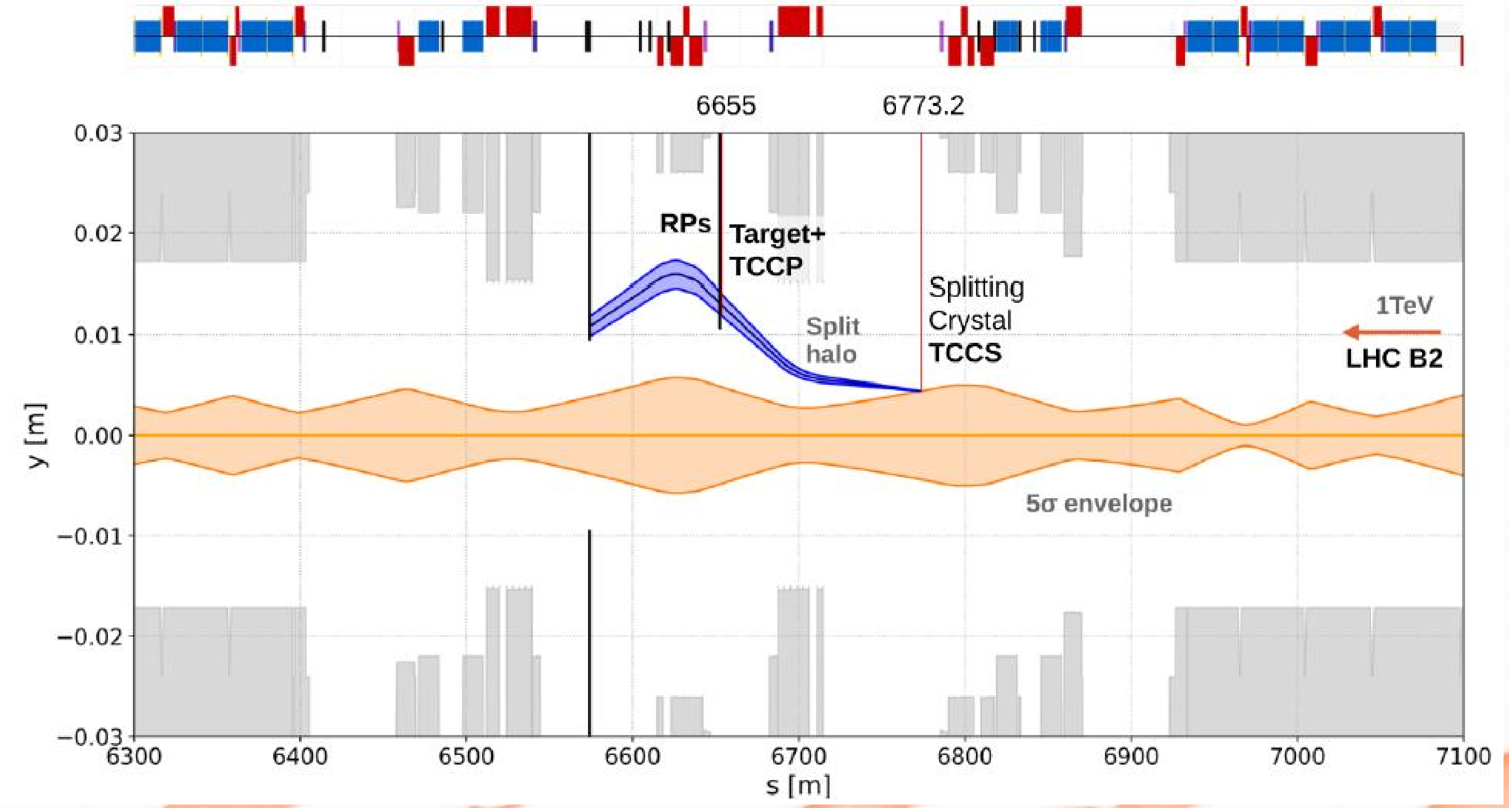




02

TWOCRYST: Proof-of-Principle at LHC

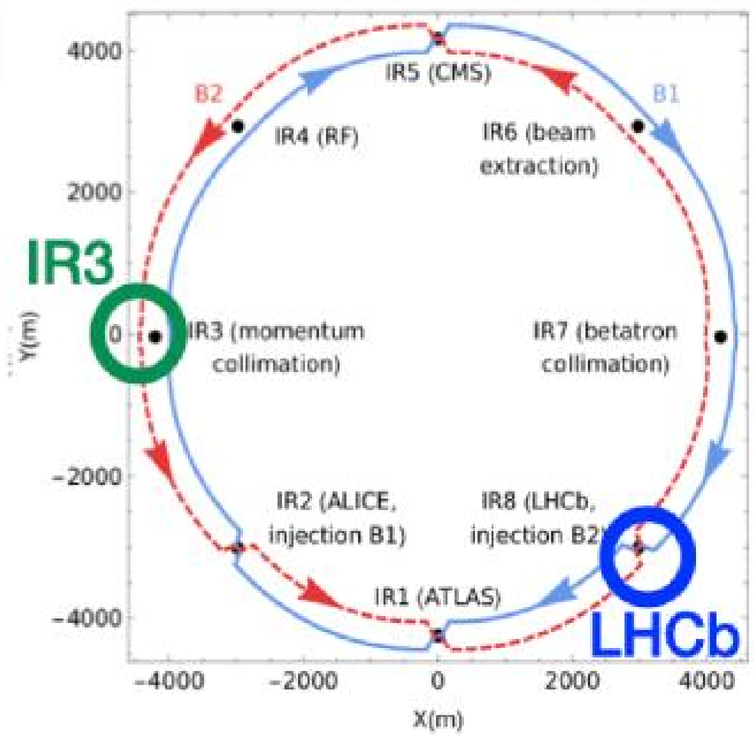
- Proof-of-principle setup to be operated in **2025**
- With TCCS and TCCP, W target, trackers, and a scintillation counter for charged particles
- Channeling efficiency will be measured at **450 GeV, 1 TeV and 3 TeV**
- Demonstration of operational feasibility
- To obtain the occupancy and estimate potential background of the spectrometer and RICH
- Verifying the simulation result

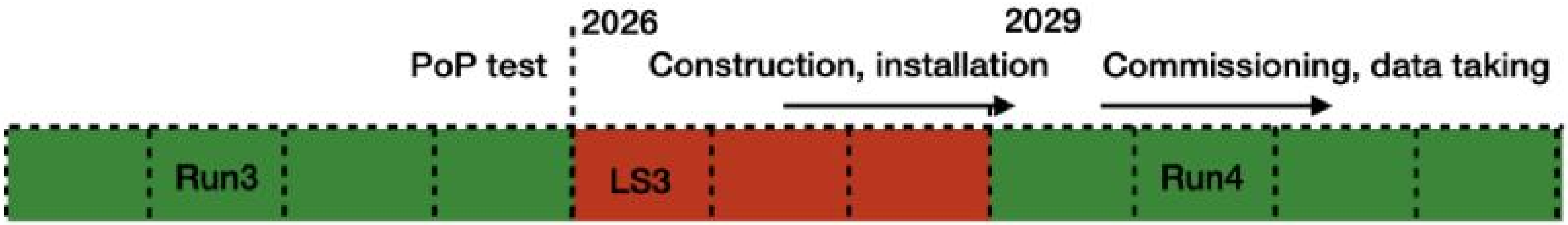


by Chiara Maccani

02 Timeline

	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



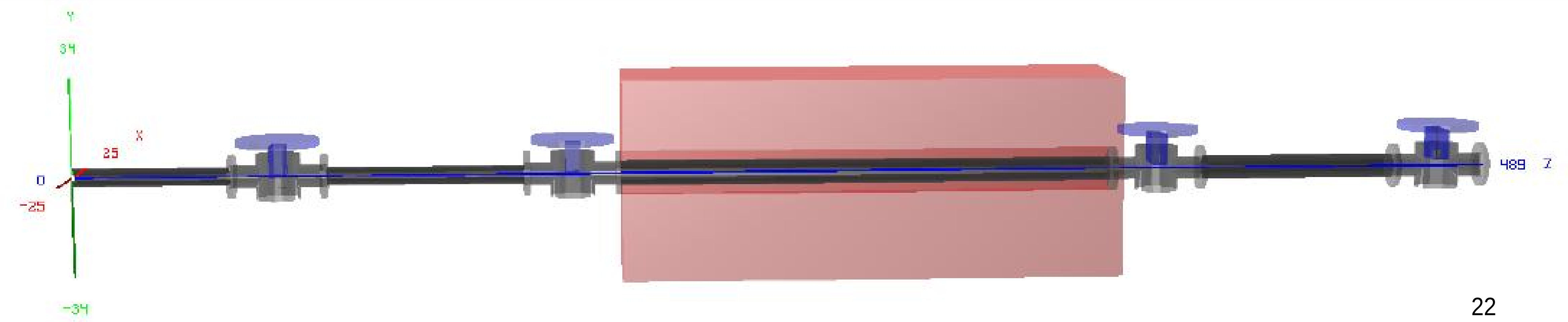


Part 03

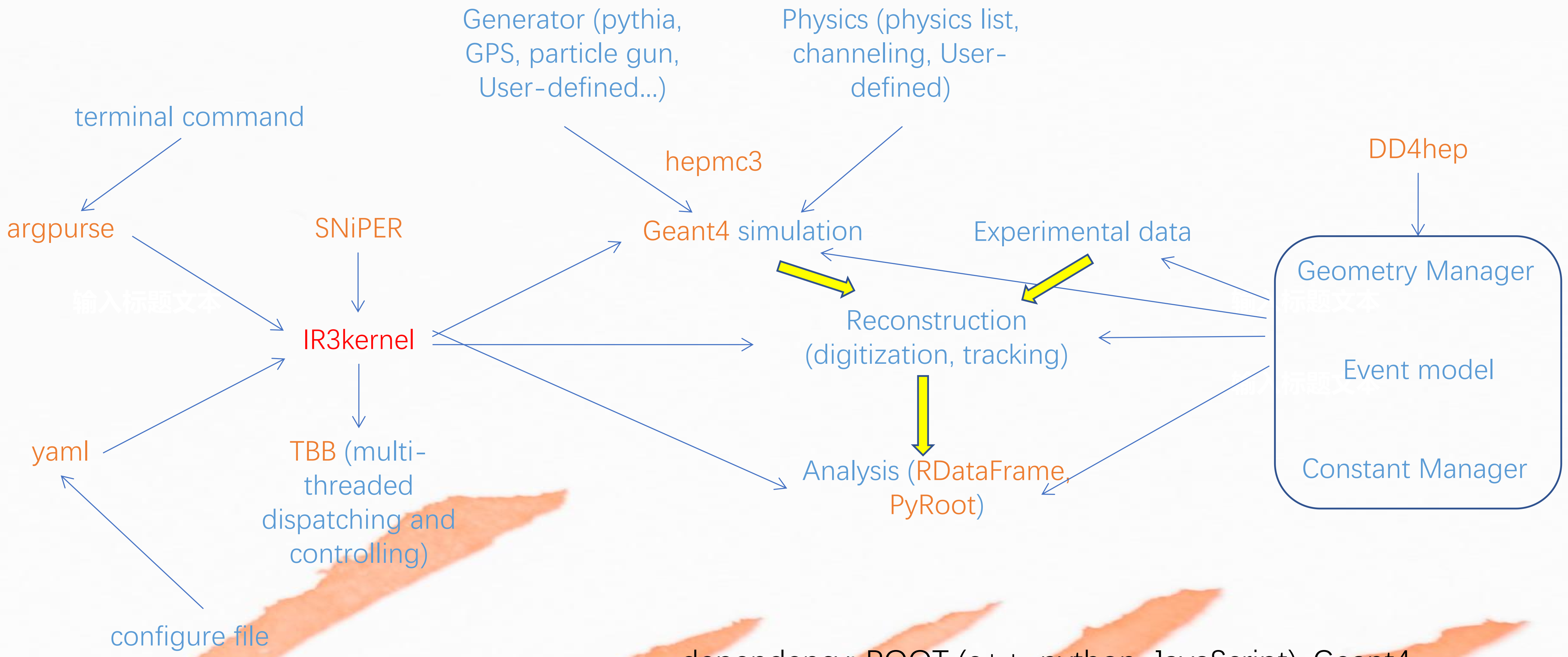
Simulation

03 Detector Layout

- W target: 2 cm long, with a transversal size of 2 mm in y and 8 mm in x
- Si crystal: 7 cm long, with same transversal size as the target, with 7 mrad of bending angle
- Beam pipe: made of Al, with default external radii of $2.1 \times 2.94\ \mathrm{cm}^2$ and a thickness of 2 mm
- Tracking stations: made of Si, 200 µm thick
- Dipole magnet (MCBWV.4L3.B2, already present at IR3): made of iron, 1.7 m long and with a magnetic field of 1.1 T. Joke dimensions are $49.4 \times 67.6\ \mathrm{cm}^2$. Bore dimensions are $5.2 \times 14\ \mathrm{cm}^2$
- Use DDG4 for the simulation and IR3ana framework for the following analysis with incorporating GenFit2, PODIO…



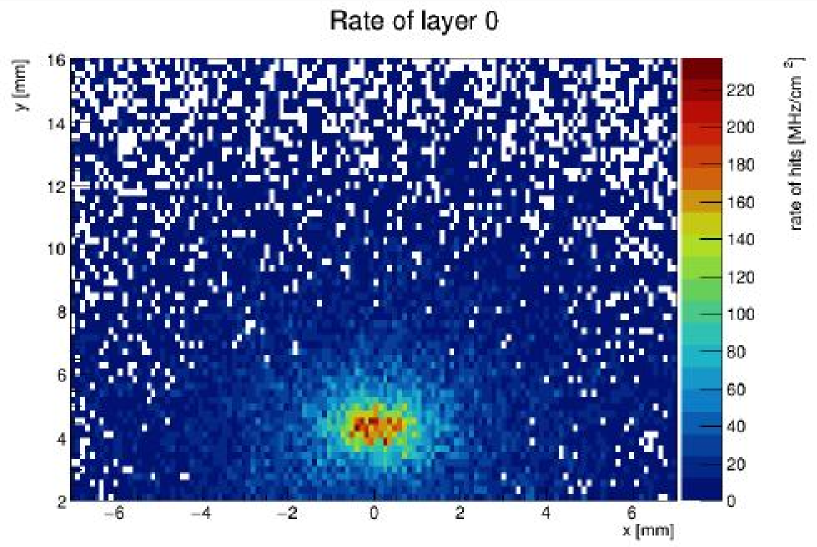
03 Software Framework for ALADDIN: IR3ana

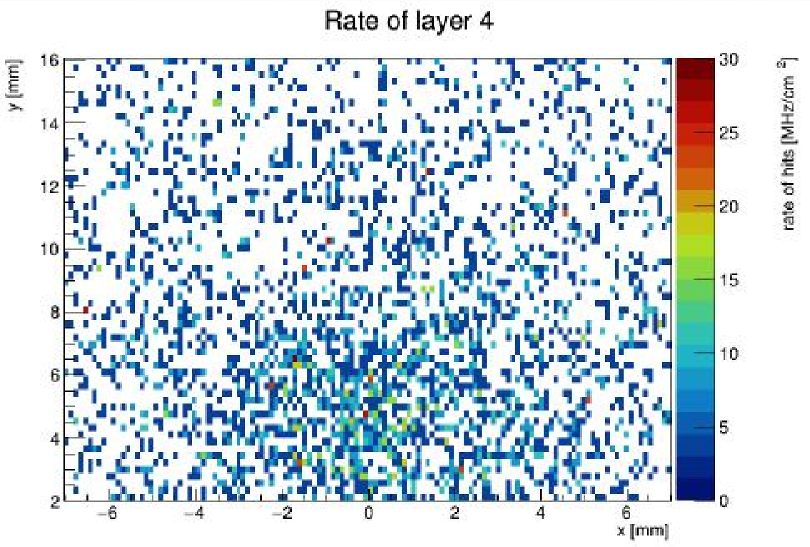


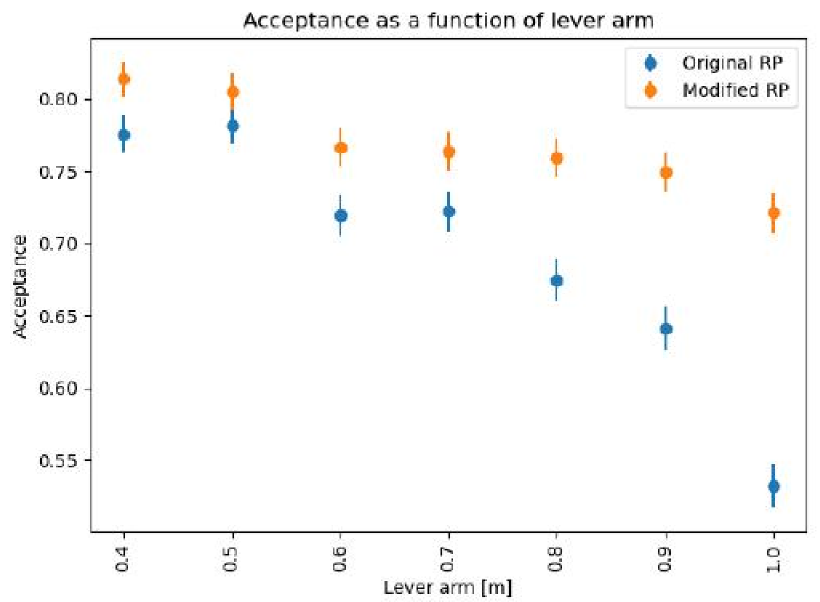
dependency: ROOT (c++, python, JavaScript), Geant4, DD4hep, PODIO, argpurse, yaml, SNiPER, Eigen3…

03 Occupancy and Acceptance

- Simulation for 10^6 p/s on 2.0 cm of W target
- **Occupancy:**
  - Upstream: **250 MHz/cm²**
  - Downstream: **30 MHz/cm²**
- **Acceptance:**
  - **50%** for the dedicated design of Roman Pot
  - Can be increased to **70%** if the flange radius changes from 4 cm to 5 cm

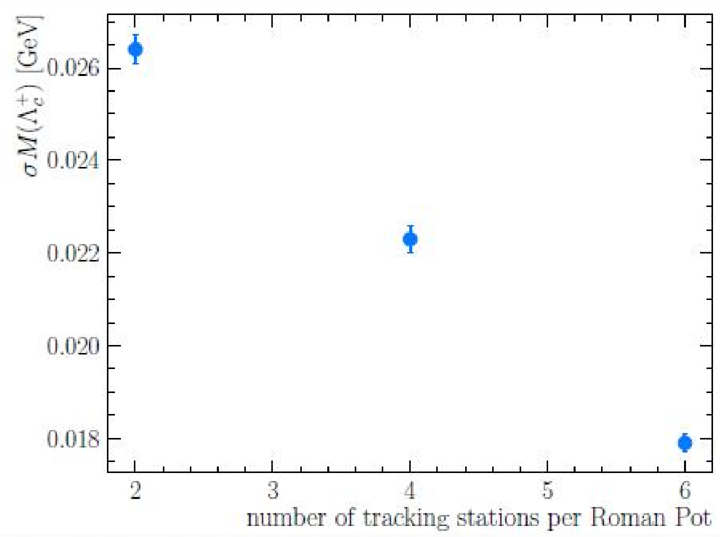


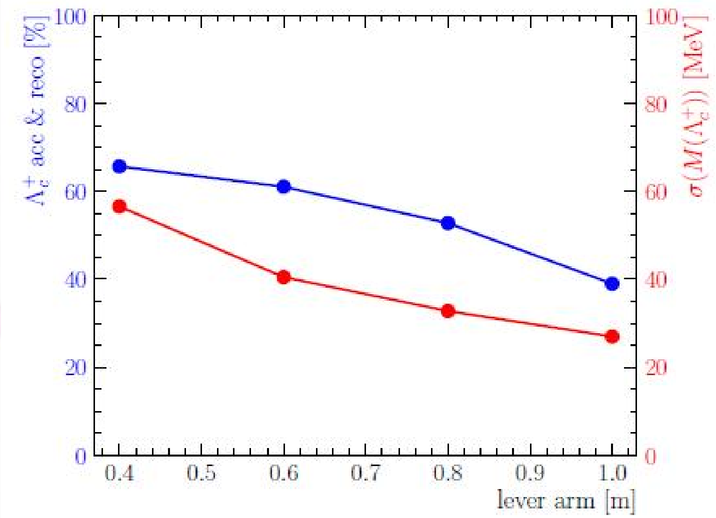


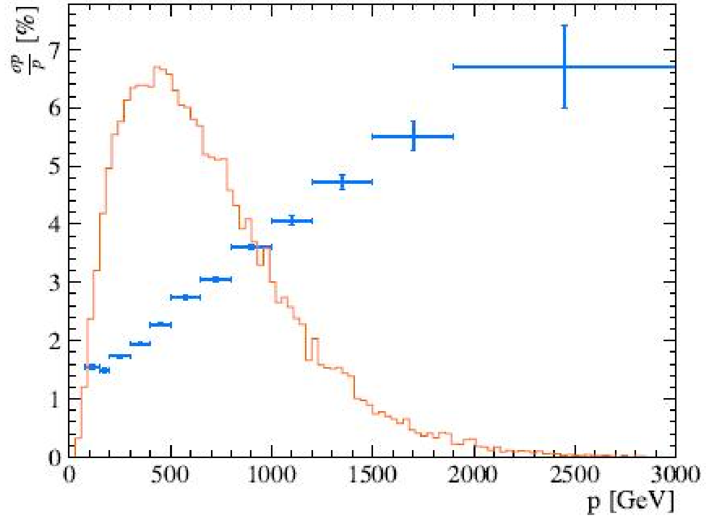


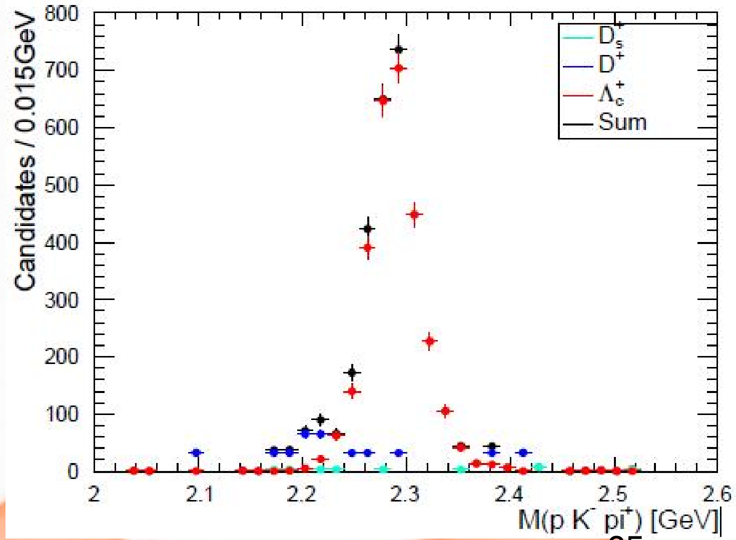
03 Reconstruction of Λ_c^+

- Momentum resolution ranges from **1.5%-7%** for charged particles as a function of momentum up to 2.5 TeV
- Λ_c^+ is reconstructed using $\Lambda_c^+ \to pK^-\pi^+$ with incorperating Kalman filtering and vertex fit
- Not use information from RICH but a simple PID by charge and momentum
- Reconstruction efficiency of Λ_c^+: **35%**
- Invariant mass resolution of Λ_c^+: **27 MeV** (can be further increased to 18 MeV if assembling 6 tiles per Roman Pot)



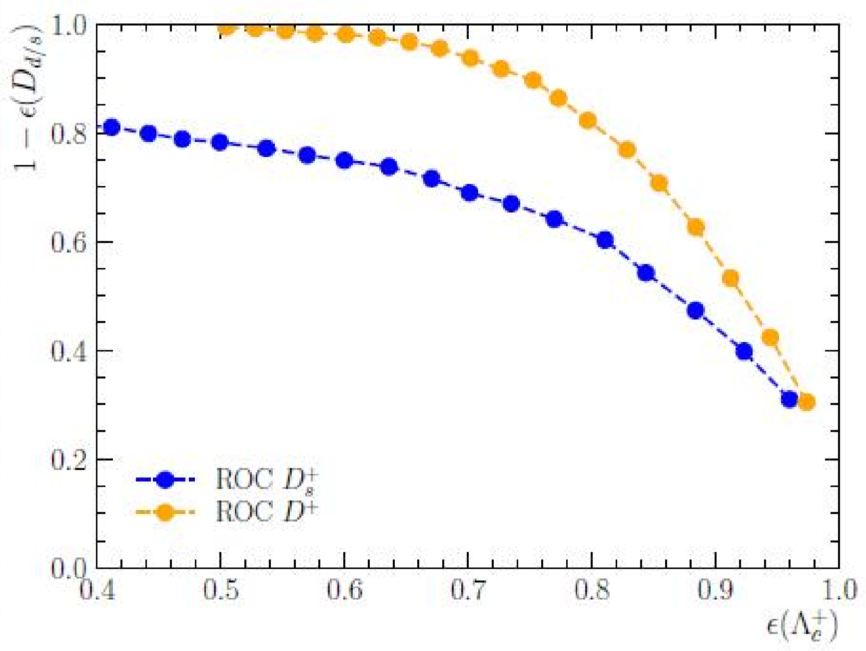


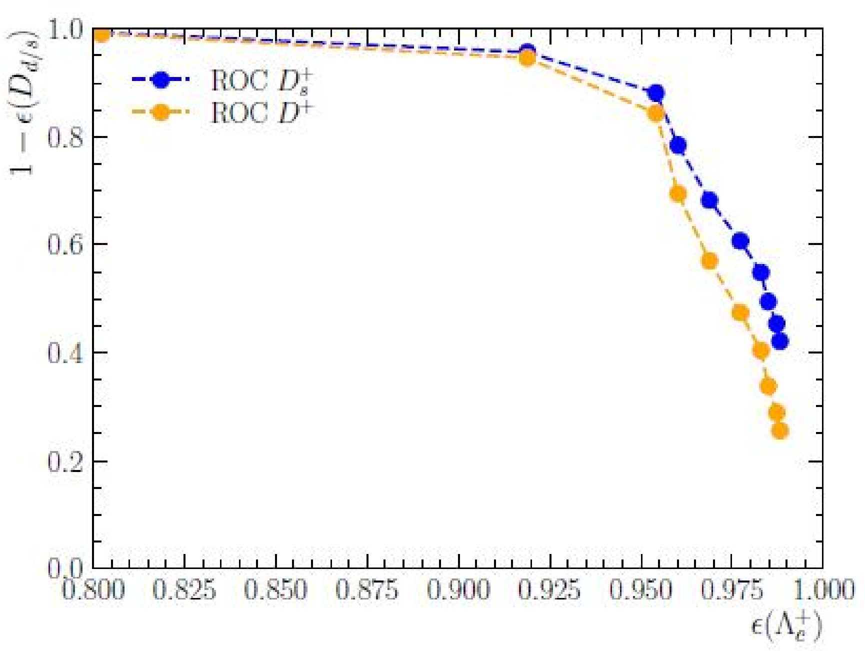




03 **Potential Background**

- $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^+K^-\pi^+$ with a π^+ or a K^+ misidentified to be proton
- Rejection by cut the mass window for D^+ and D_s^+ (without RICH information)
  - Reject less than 80% background when relative signal efficiency is 80%
- Rejection using RICH information
  - Reject 99% background when relative signal efficiency is 85%
- **RICH will significantly improve the performance**





Part 04

Summary

04 Summary

- ALADDIN is a proposed fixed-target experiment to be installed at LHC IR3
- Aim to measure the MDM of Λ_c^+ and Ξ_c^+ with a relative precision better than 10% and search for the EDM with a sensitivity of $3 \times 10^{-16}\ e\ \mathrm{cm}$
- ALADDIN can also measure the heavy hadron production in the very forward region with pseudorepidity $\eta \geq 5$
- Photoproduction of J/ψ and pentaquark states are also potential physics
- The dipole moment of τ lepton may be firstly measured at ALADDIN and an exploratory study will be performed
- The TWOCRYST proof-of-principle test is scheduled at IR3 in 2025
- The detector could be installed during the LHC LS3 and start the data taking during Run4 in 2030

04

ALADDIN Collaboration and other authors

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…

THANK YOU

Han Miao (妙晗)[1,2] on behalf of ALADDIN Collaboration

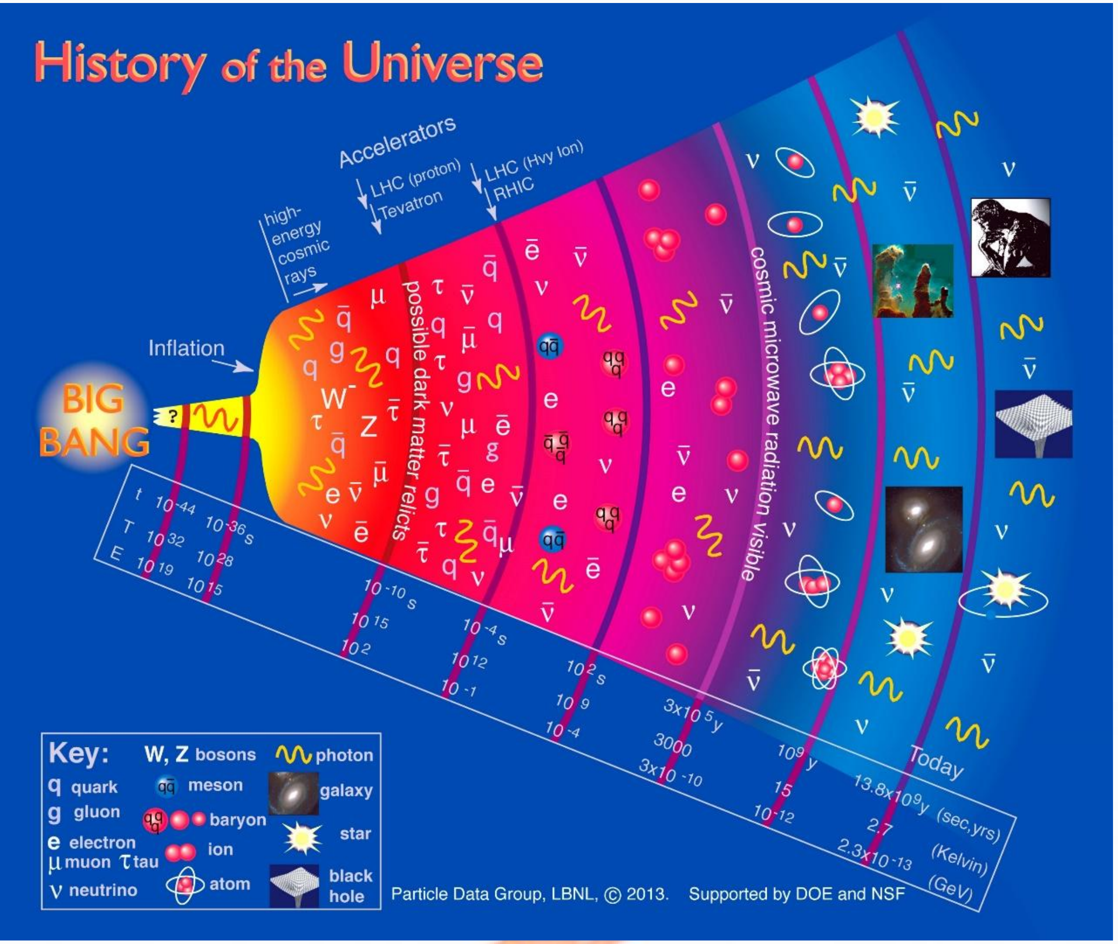
1 Institute of High Energy Physics
2 University of Chinese Academy of Sciences

NSTAR workshop
2024.6.20, York, UK

Part 00

Backup

Matter-Antimatter Asymmetry in the Universe



Big matter and anti-matter asymmetry founded in the universe!

WMAP+COBE(2012):

$$(n_B - n_{\bar{B}})/n_\gamma|_{CMB} = (6.08 \pm 0.09) \times 10^{-10}$$

Sakharov three conditions require:

C and CP symmetry violation

Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35.

CP violation has been founded at K, B, D meson system, but not enough to explain matter dominant universe.

Standard Model (SM) prediction:

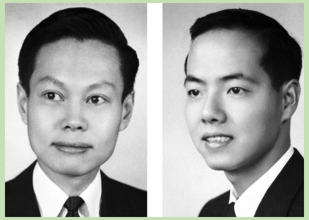
$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \sim 10^{-18} \ll 10^{-10}$$

W. Bernreuther
Lect. Notes Phys.591
(2002) 237-293

Exploring new physics is extremely important

00 A Brief History of Parity and CP Violation

Nobel Prize 1957

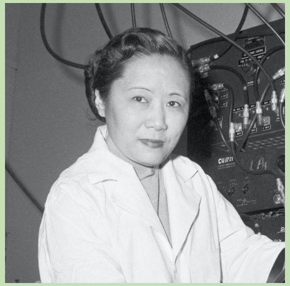


C. N. Yang T. D. Lee

$\theta - \tau$ puzzle [1]

First proposed Parity violation in weak interaction

Confirmed by



Chien-Shiung Wu

1957

No CPV founded in baryon sector!

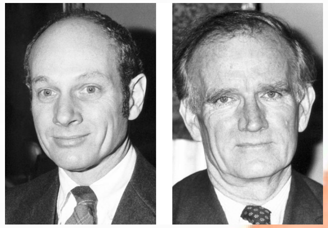
K meson *CP* violation[2]

B meson *CP* violation [3,4]

D meson *CP* violation [5]

1964

James Watson Cronin



Val Logsdon Fitch

Nobel Prize 1980

2001

Belle II

BABAR

2019

LHCb

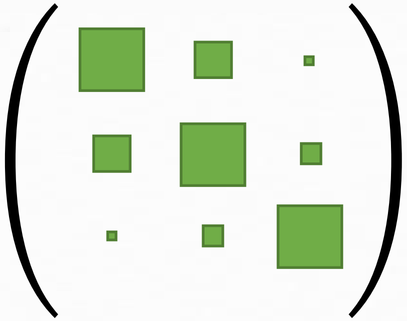
[1] Phys. Rev. 104 (1956) 254-258
[2] Phys. Rev. Lett., 1964, 13: 138-140
[3] Phys. Rev. Lett., 2001, 87: 091801
[4] Phys. Rev. Lett., 2001, 87: 091802
[5] Phys. Rev. Lett., 2019, 122(21): 211803

CPV in Standard Model

CKM mechanism:

CPV from phase δ

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$



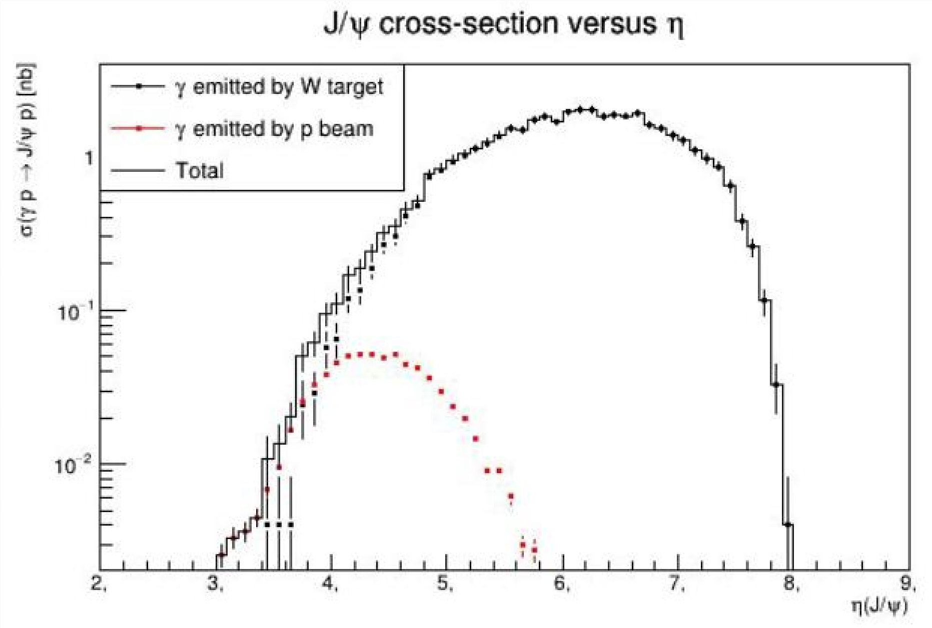
Dirac Medal 2010

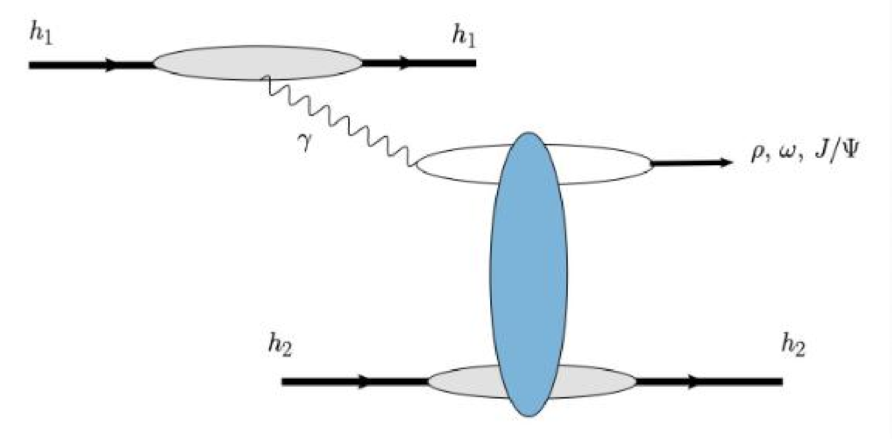
Nobel Price 2008

Strong CP

- $\bar{\theta}$ term： $\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2}\bar{\theta}\text{Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$
- Mainly through measuring the Electric Dipole Moment (EDM) of atomic nuclei, atoms, and molecular systems,
- The current most stringent constraints come from the EDM experiments of neutrons and 199Hg： $\bar{\theta} < 10^{-10}$

Photoproduction in Fixed-Target





J/ψ photoproduction

Pentaquarks photoproduction

Study the gluonic field contributions to the proton structure and proton mass