Measurements of electromagnetic dipole moments of unstable particles at LHC

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on behalf the proto-collaboration for LoI

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SELDOM webpage
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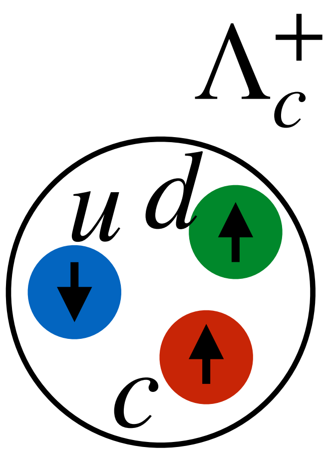
Outline

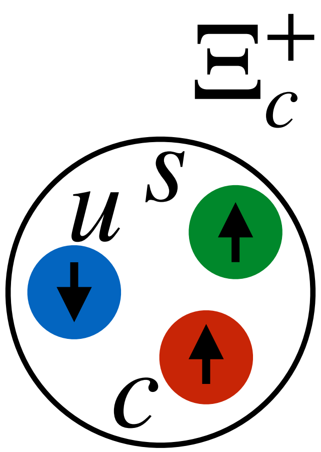
- Physics motivations
- Experimental technique
- Proposed experiment
- Physics reach
- Summary

Magnetic dipole moment of charm quark

- Spin 1/2 particle magnetic dipole moment (MDM) $\mu = \frac{g}{2}\frac{eQ}{2m}$, where g is the gyromagnetic factor. $g = 2$ for e, μ, τ (point-like), $g_p = 5.6$ for proton (substructure)

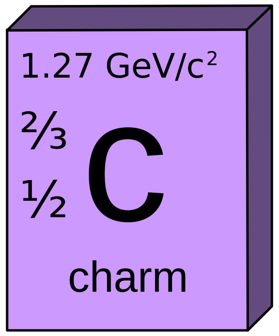


- MDM of charm baryons $\mu_{\Lambda_c^+} = \frac{g_{\Lambda_c^+}}{2}\frac{e}{2m_{\Lambda_c}^+}$ and $\mu_{\Xi_c^+} = \frac{g_{\Xi_c}^+}{2}\frac{e}{2m_{\Xi_c^+}}$



- In the quark model: $\Lambda_c^+ = [ud]c$, $\mu_{\Lambda_c^+} = \mu_c$, $\Xi_c^+ = [us]c$, $\mu_{\Xi_c^+} = \mu_c$ and $g_{\Lambda_c^+(\Xi_c^+)} = \frac{Q_c m_{\Lambda_c^+(\Xi_c+)}}{m_c} g_c \approx 0.9 g_c$

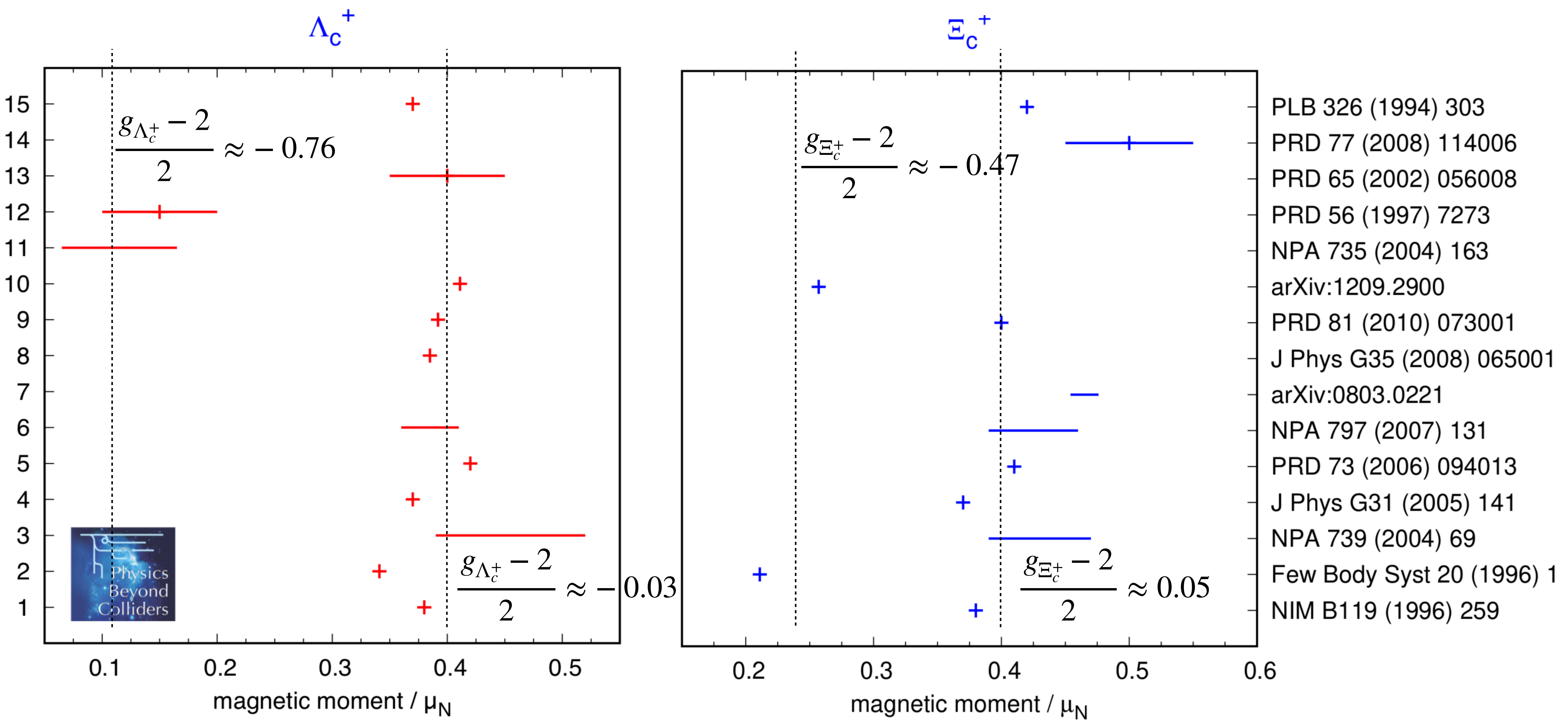
- Beyond the quark model, e.g. heavy quark effective theories, theoretical predictions $\mu_{\Lambda_c^+} = (0.34 - 0.43)\mu_N$, where μ_N is the nuclear magneton



- Determine μ_c, g_c of the charm quark from charm baryon MDM measurements. Confront experimental results with theory predictions

Theory predictions for charm baryon MDM

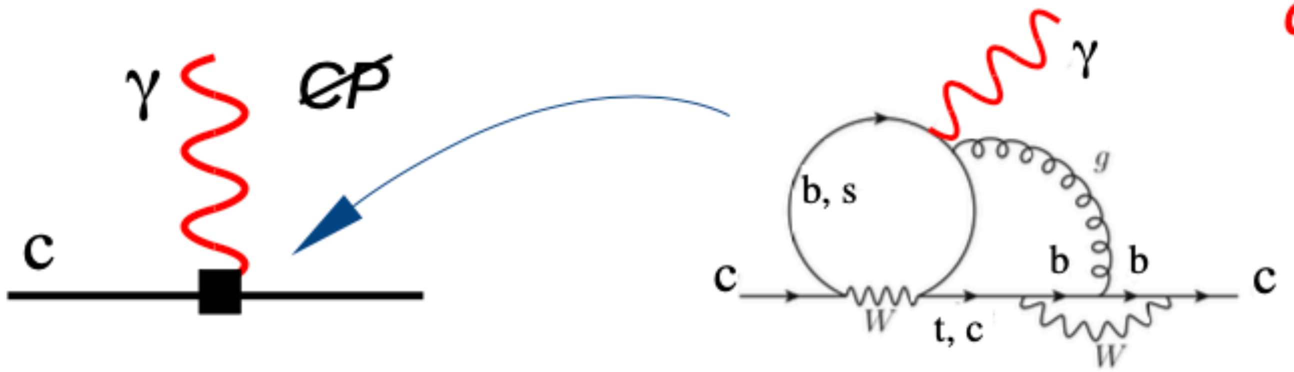
An experimental measurement at 10% precision would be useful to confront with theory predictions



CERN-PBC-REPORT-2018-008

Electric dipole moment of charm baryons

- **Electric dipole moments** (**EDM,** δ) of charm baryons are minuscule in the SM (3-loop level)
- Search for EDM as probe for physics beyond the SM



$d_c \sim 10^{-32}$ecm
negligible

Indirect limits - from J. Ruiz Vidal slides

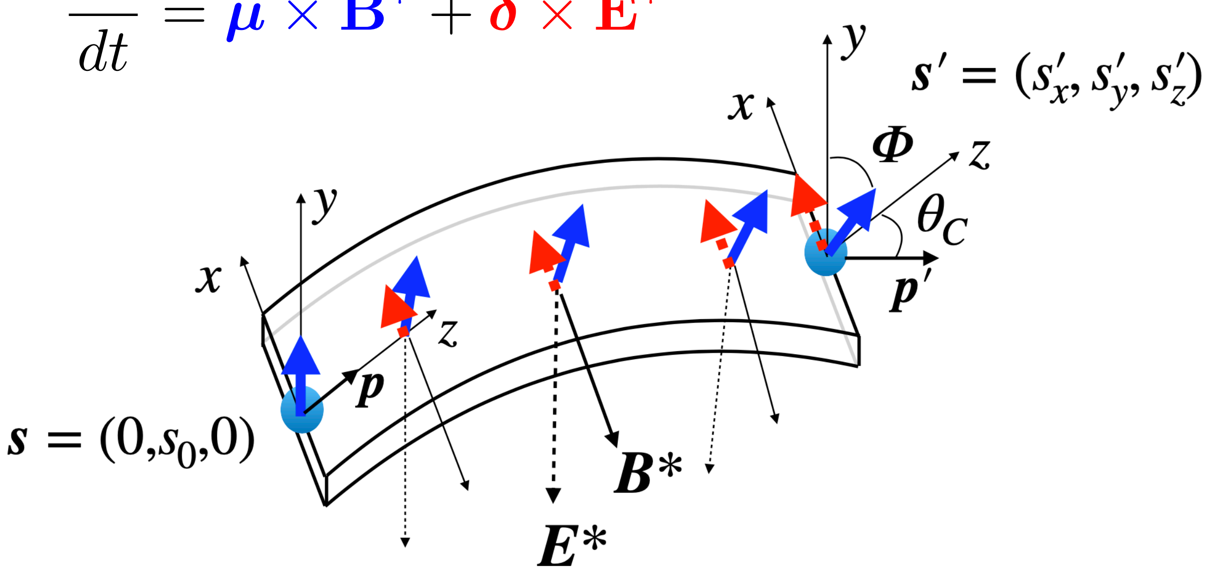
Bound	Ref.	Measurement	Method
$\lvert d_c\rvert < 8.9\times10^{-17}$ ecm	[Escribano:1993xr]	$\Gamma(Z\to c\bar{c})$	Measurement at the Z peak (LEP). Weights electic (d_c) and weak (d_c^w) dipole moments through model-dependent relations.
$\lvert d_c\rvert < 5\times10^{-17}$ ecm	[Blinov:2008mu]	$e^+e^-\to c\bar{c}$	The total cross section (from the LEP combination [ALEPH:2006bhb]) is enhanced by the charm EDM vertex $c\bar{c}\gamma$.
$\lvert d_c\rvert < 3\times10^{-16}$ ecm	[Grozin:2009jq]	electron EDM	Considers contribution of d_c into d_e through light-by-light scattering (three-loop) diagrams.
$\lvert d_c\rvert < 1\times10^{-15}$ ecm	[Grozin:2009jq]	neutron EDM	Similar approach than Ref. [Sala:2013osa] with different treatment of diverging integrals and more conservative assumptions.
$\lvert d_c\rvert < 4.4\times10^{-17}$ ecm	[Sala:2013osa]	neutron EDM	Considers contribution of d_c into d_d via $W^\pm$ loops. Expressions from Ref. [CorderoCid:2007uc].
$\lvert d_c\rvert < 3.4\times10^{-16}$ ecm	[Sala:2013osa]	BR$(B\to X_s\gamma)$	Considers contributions of d_c into the Wilson coefficient C_7.
$\lvert d_c\rvert < 1.5\times10^{-21}$ ecm	[Gisbert:2019ftm]	neutron EDM	Renormalization group mixing of d_c into $\tilde{d}_c$.
$\lvert d_c\rvert < 6\times10^{-22}$ ecm	[Ema:2022pmo]	neutron EDM	Contribution of d_c to $3g$-1γ operators, to light-quark, to neutron EDM
$\lvert d_c\rvert < 1.3\times10^{-20}$ ecm	[Ema:2022pmo]	electron EDM	Contribution of d_c to 2γ-$2g$ operators, to electron-nucleon, to paramagnetic molecule ThO

Experimental technique

- Charm baryon lifetimes is very short $\tau \approx 2 - 4 \times 10^{-13}$ s. Challenge: induce spin precession before decay
- Charm baryons from fixed-target *p*W collisions at LHC, $\sqrt{s} \approx 110\ \mathrm{GeV}$
- Exploit channeling in bent crystals at LHC: high boost $\gamma \approx 500$, flight length $\beta\gamma c\tau \approx 3 - 6\ \mathrm{cm}$, high electric field $E \approx 1\ \mathrm{GV/cm}$ between atomic planes, effective magnetic field $B \approx 500\ \mathrm{T}$

MDM μ and EDM δ precession in a bent crystal

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



PRD 103, 072003 (2021)

Spin-polarisation analyser

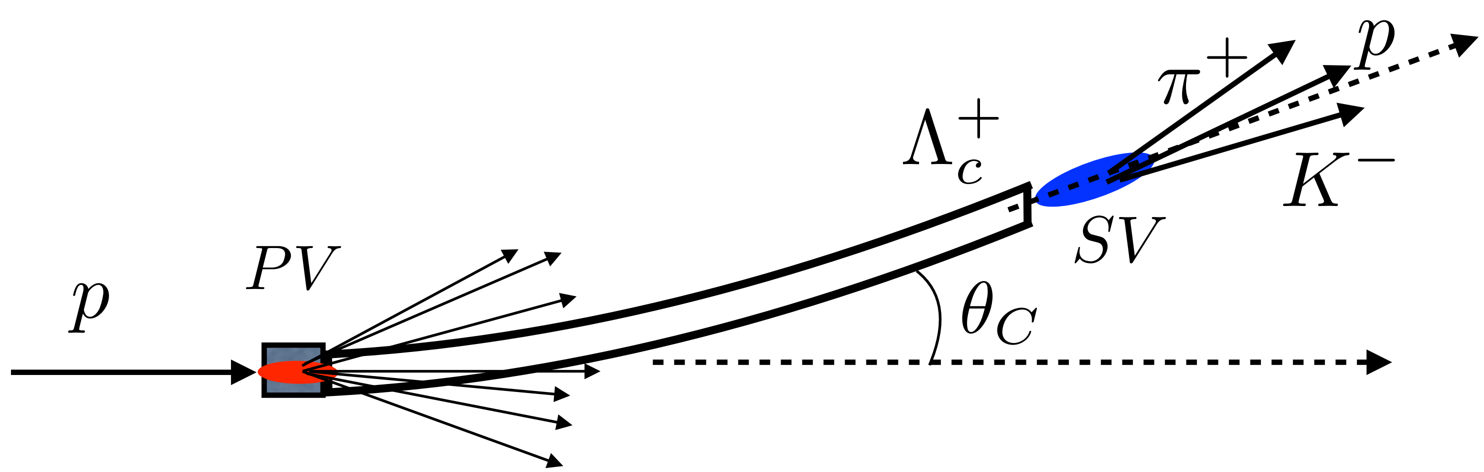
$$\frac{dN}{d\Omega'} \propto 1 + \alpha \boldsymbol{s}' \cdot \hat{\boldsymbol{k}}$$

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

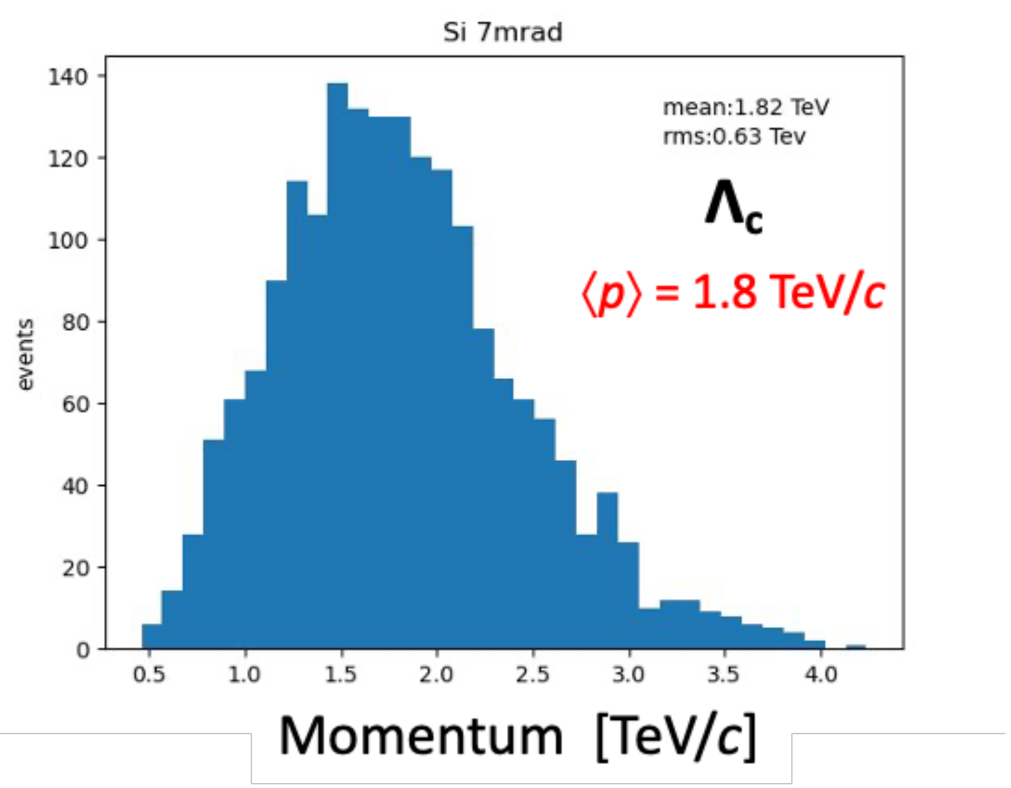
$$s'_x \approx s_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

Λ_c^+ signal event topology

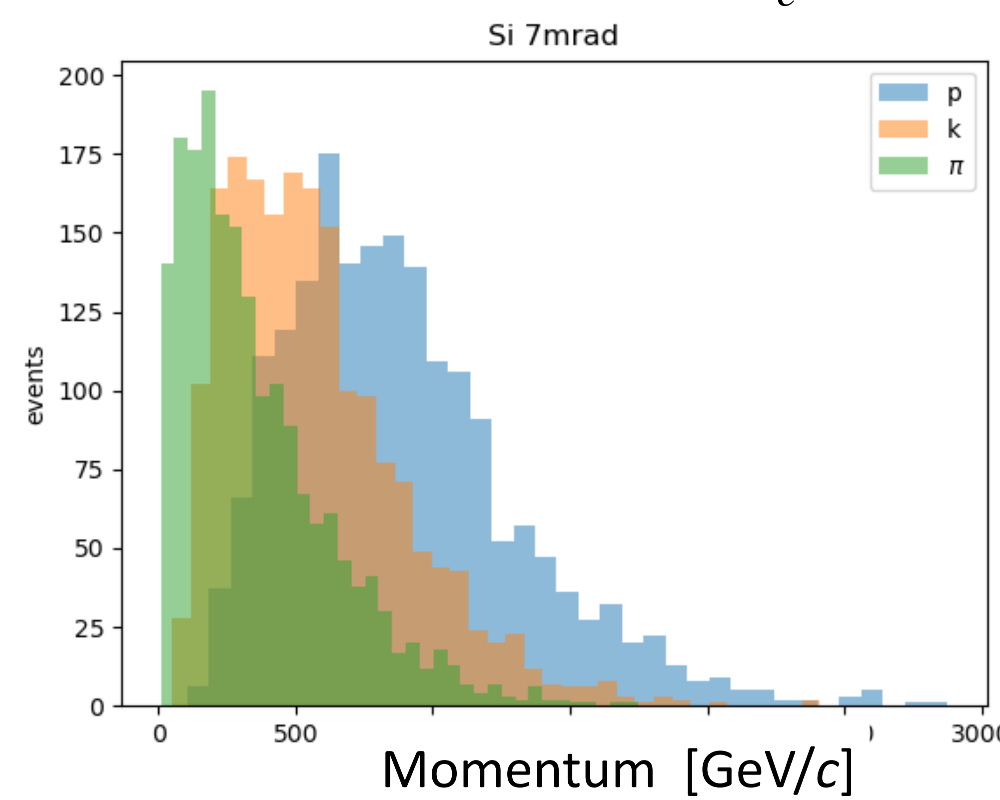
- Average momentum of 1 TeV for channeled Λ_c^+ baryons for bending angle $\theta_C = 7\ \mathrm{mrad}$



Angular distance between p and Λ_c^+



Momentum distribution of Λ_c^+ daughters



Charm baryons decays of interest

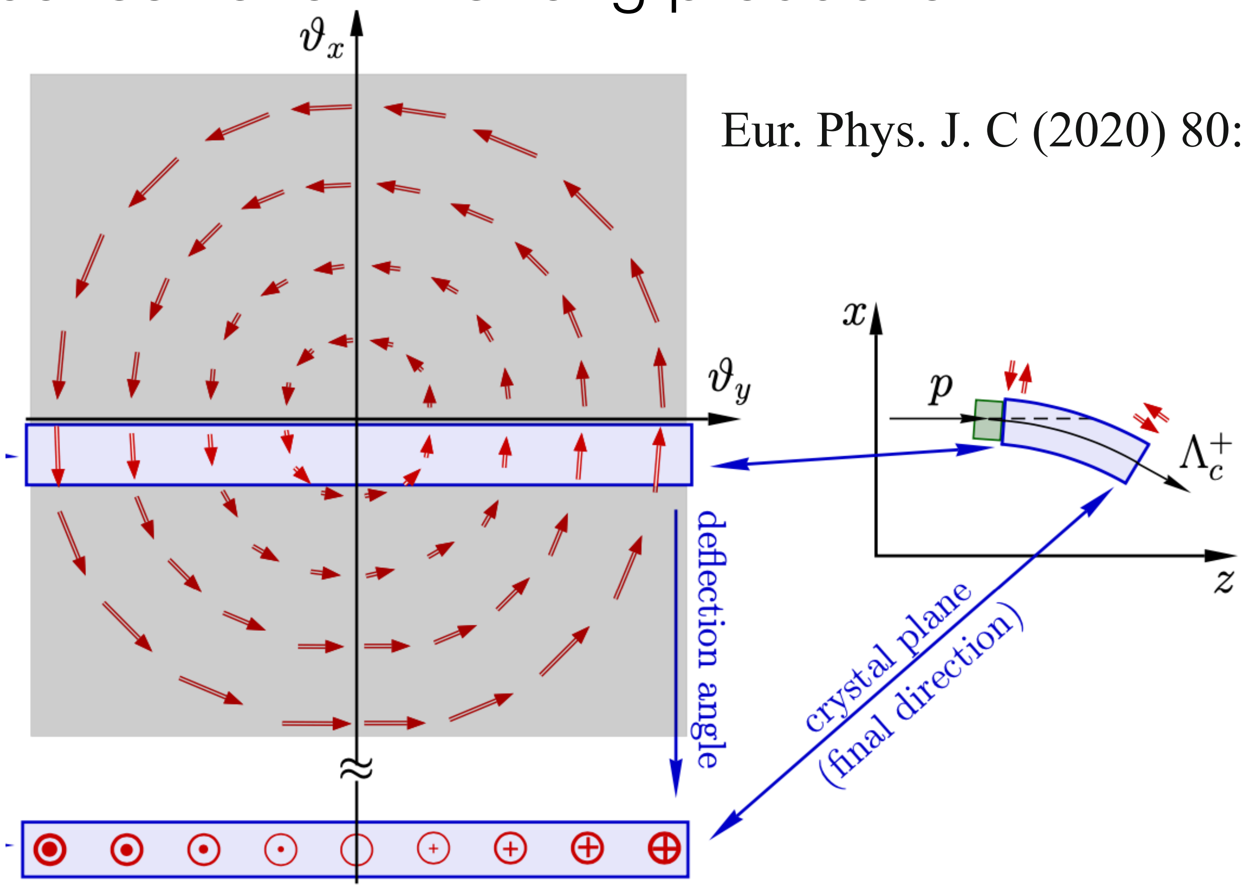
- List of Λ_c^+, Ξ_c^+ modes and corresponding branching fractions $\mathscr{B}$, reconstructibility $\epsilon_{3\text{trk}}$ and effective branching fraction $\mathscr{B}_{\text{eff}} = \mathscr{B} \cdot \epsilon_{3\text{trk}}$
- Reconstructibility of $\Sigma^+, \Sigma^-, \Xi^-$ as charged stable particles throughout the detector taken into account in $\epsilon_{3\text{trk}}$

Λ_c^+ final state	$\mathcal{B}$ (%)	$\epsilon_{3\text{trk}}$	$\mathcal{B}_{\text{eff}}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.25
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.54	2.43
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.71	1.33
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.73	0.45
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.51	0.18
pK^-K^+	0.106 ± 0.006	0.98	0.11
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.54	0.11
$pK^-\pi^+\pi^0$	4.46 ± 0.30	0.99	4.43
$\Sigma^+\pi^-\pi^+\pi^0$	3.20	0.54	1.72
$\Sigma^-\pi^+\pi^+\pi^0$	2.1 ± 0.4	0.71	1.49
$\Sigma^+[p\pi^0]\pi^-\pi^+$	2.32	0.46	1.06
$\Sigma^+[p\pi^0]K^-K^+$	0.18	0.46	0.08
$\Sigma^+[p\pi^0]\pi^-K^+$	0.11	0.46	0.05
All	...	...	20.2

Ξ_c^+ final state	$\mathcal{RB}$	$\mathcal{B}$ (%)	$\epsilon_{3\text{trk}}$	$\mathcal{B}_{\text{eff}}$ (%)
$\Xi^-\pi^+\pi^+$	1	2.86 ± 1.27	0.64	1.84
$\Sigma^+K^-\pi^+$	0.94 ± 0.10	...	0.42	1.14
$\Sigma^+\pi^-\pi^+$	0.48 ± 0.20	...	0.44	0.60
$pK^-\pi^+$	0.21 ± 0.04	...	0.99	0.60
$\Sigma^-\pi^+\pi^+$	0.18 ± 0.09	...	0.61	0.31
$\Sigma^+K^-K^+$	0.15 ± 0.06	...	0.41	0.18
$\Omega^-K^+\pi^+$	0.07 ± 0.04	...	0.42	0.08
$\Sigma^+[p\pi^0]K^-\pi^+$	0.48	...	0.57	0.79
$\Sigma^+[p\pi^0]\pi^-\pi^+$	0.25	...	0.57	0.40
$\Sigma^+[p\pi^0]K^-K^+$	0.08	...	0.59	0.13
All	...	...	...	6.1

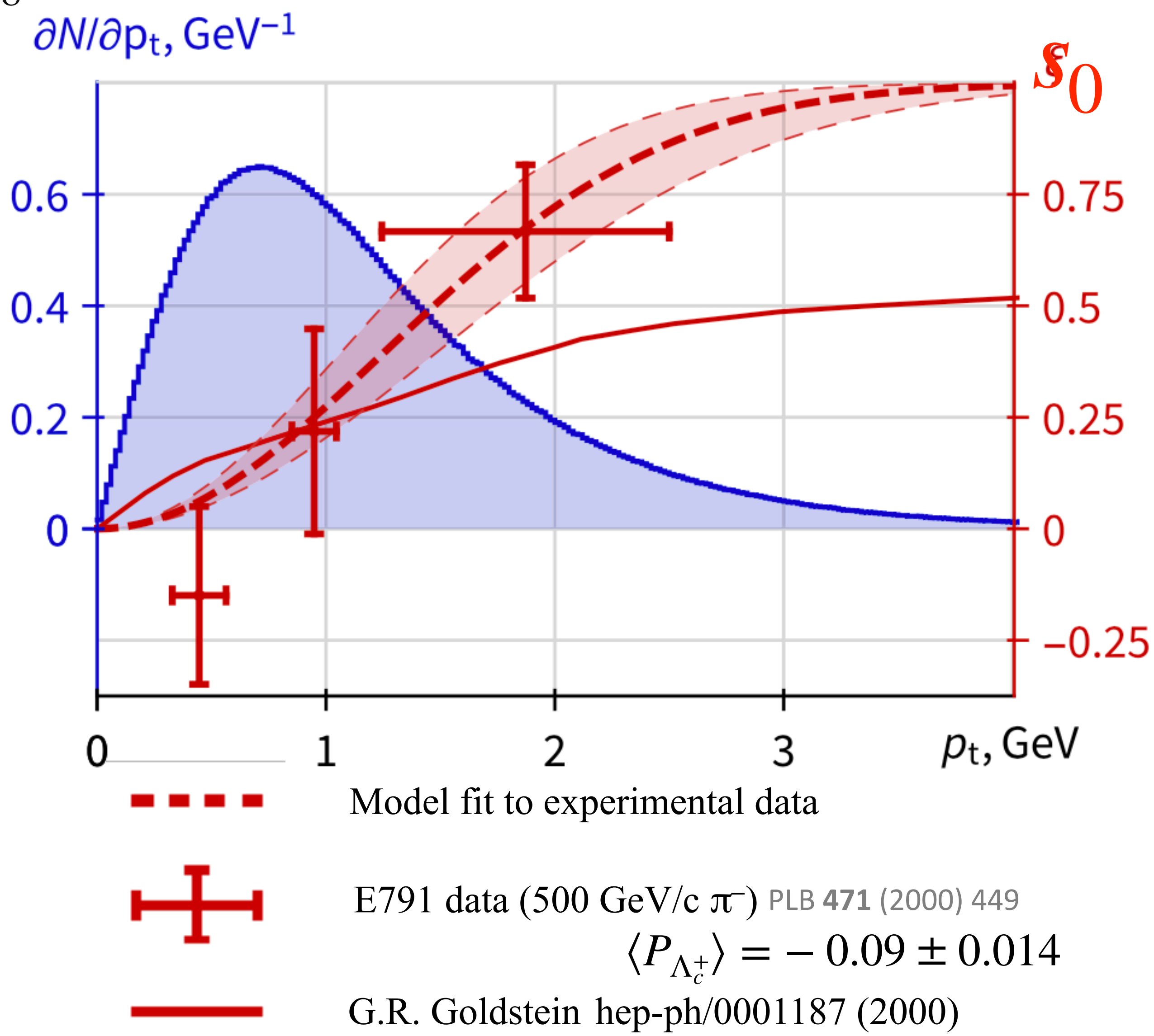
Polarisation of charm baryons

Polarisation perpendicular to production plane due to parity conservation in strong production



Eur. Phys. J. C (2020) 80:358

Sensitivity depends on baryon polarisation $\sigma_{d,g} \propto \dfrac{1}{s_0}$



Polarisation in crystal frame vs angle between p and crystal axis

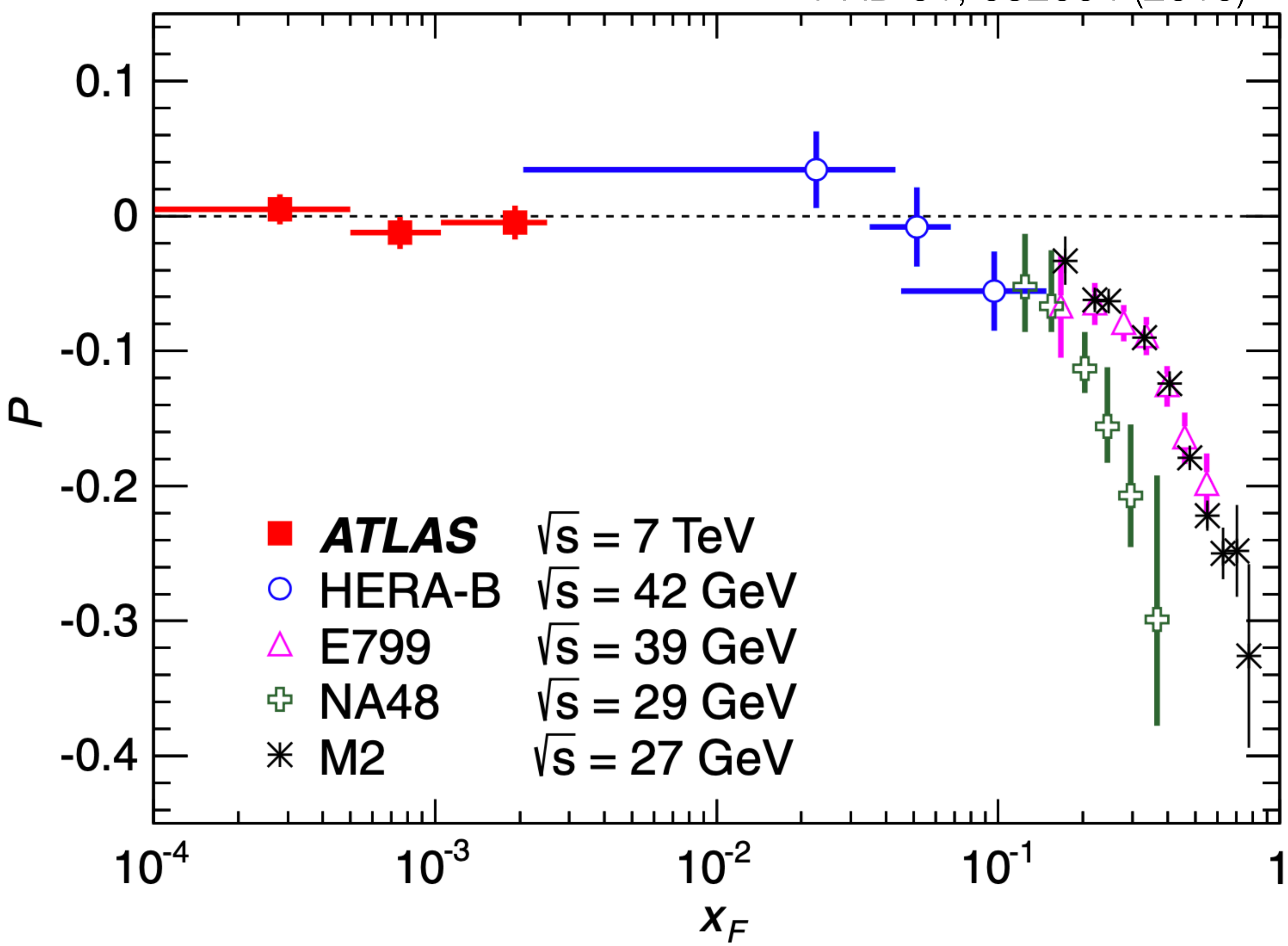
$$s_0 = (s_{0x}, s_{0y}, s_{0z}) \approx \frac{s_0(p_T)}{p_T}(-p\sin\theta_{crys}, p_{xL}, 0)$$

PRD 103, 072003 (2021)

Indications from Λ baryon polarisation

- Polarisation increases as a function of Feynman $x_F = \dfrac{p_L^*}{\max p_L^*}$
- For crystal experiment expect large positive x_F
- Work in progress to produce similar plot for Λ_c^+ with *pp* collisions and SMOG data at LHCb

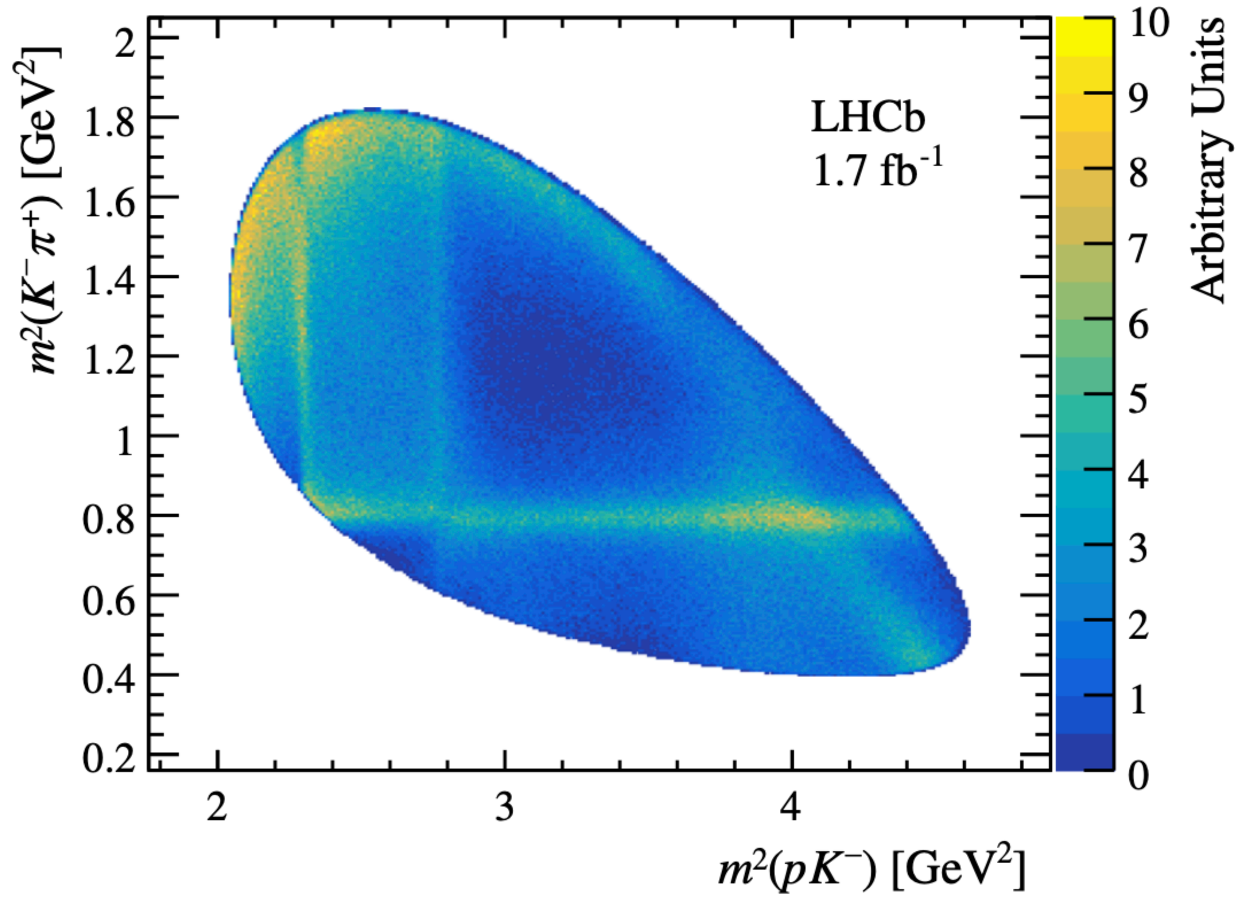
PRD 91, 032004 (2015)

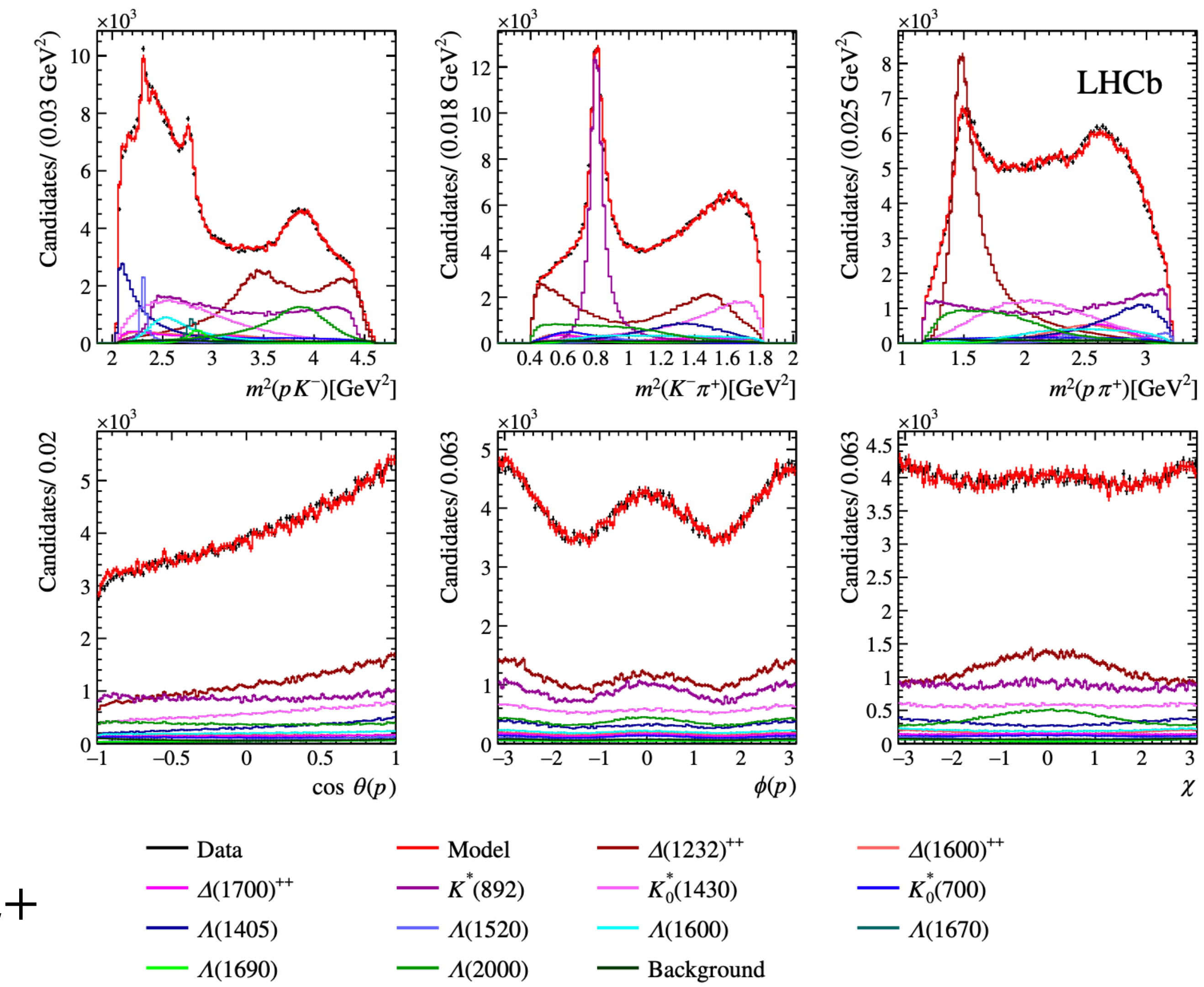


Preparatory measurements with LHCb data

PHYS. REV. D 108, 012023 (2023)

- Use 400k $\Lambda_c^+ \to pK^-\pi^+$ signal events from semileptonic beauty hadron decays to determine the **amplitude model and Λ_c^+ polarisation**





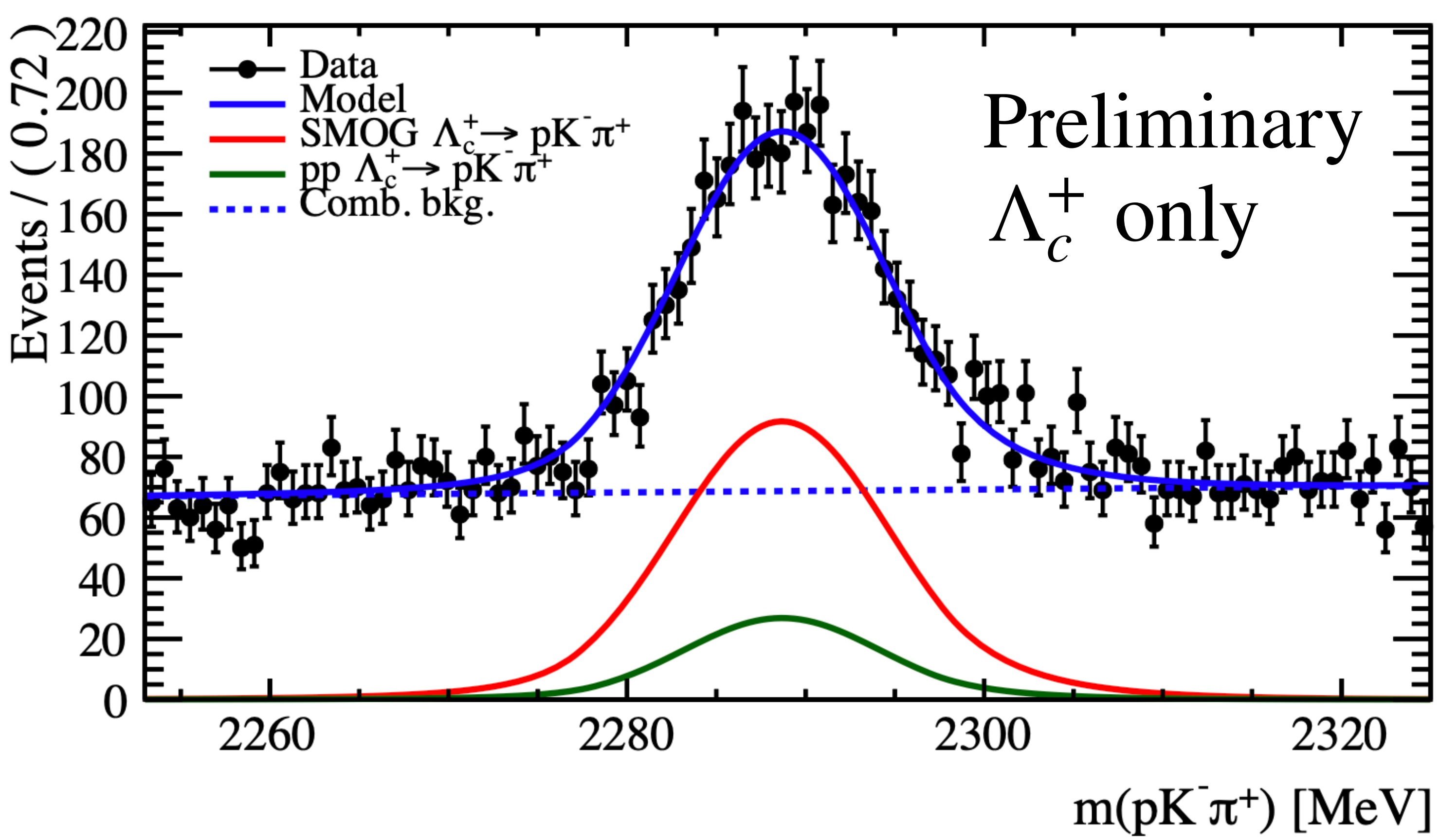
Similar analysis in progress for $\Xi_c^+ \to pK^-\pi^+$

- Large sensitivity to polarisation. $\Lambda_c^+ \to pK^-\pi^+$ **best probe for polarisation measurements** of Λ_c^+ produced in fixed-target collisions

Polarisation in p-Ne collisions with LHCb SMOG

- Λ_c^+ polarisation in pW at $\sqrt{s} \approx 110$ GeV is unknown. Measure Λ_c^+ polarisation in LHCb SMOG p-Ne collisions at $\sqrt{s} = 68.6$ GeV
- More than 10^{23} PoT: 3k $\Lambda_c^+ + \overline{\Lambda}_c^-$ signal yield with $\Lambda_c^+ \to pK^-\pi^+$. Analysis is ongoing, expect 10% uncertainty on polarisation
- Large improvements in Run3 with SMOG2, x1000 increase in signal yield

LHCb-PUB-2018-015

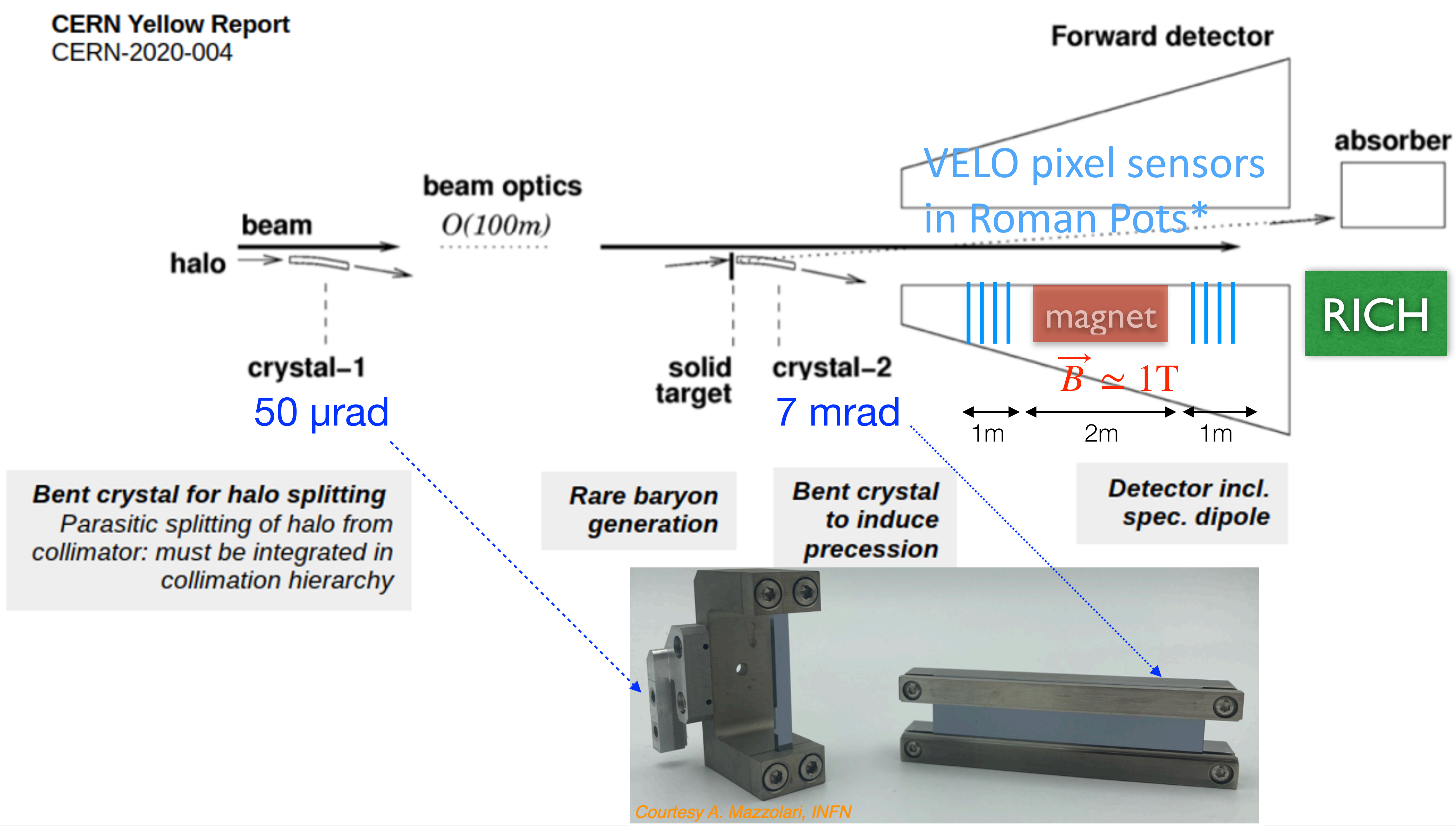


Use decay amplitude model from PRD 108, 012023 (2023)

Fix decay model parameters from high statistics Λ_c^+ sample and fit directly for polarisation

Double-crystal setup: Crystal based EDM/MDM measurement

See next talk by Pascal Hermes (CERN-BE) for the proof-of-principle experiment at LHC



** dedicated experiment solution shown here*

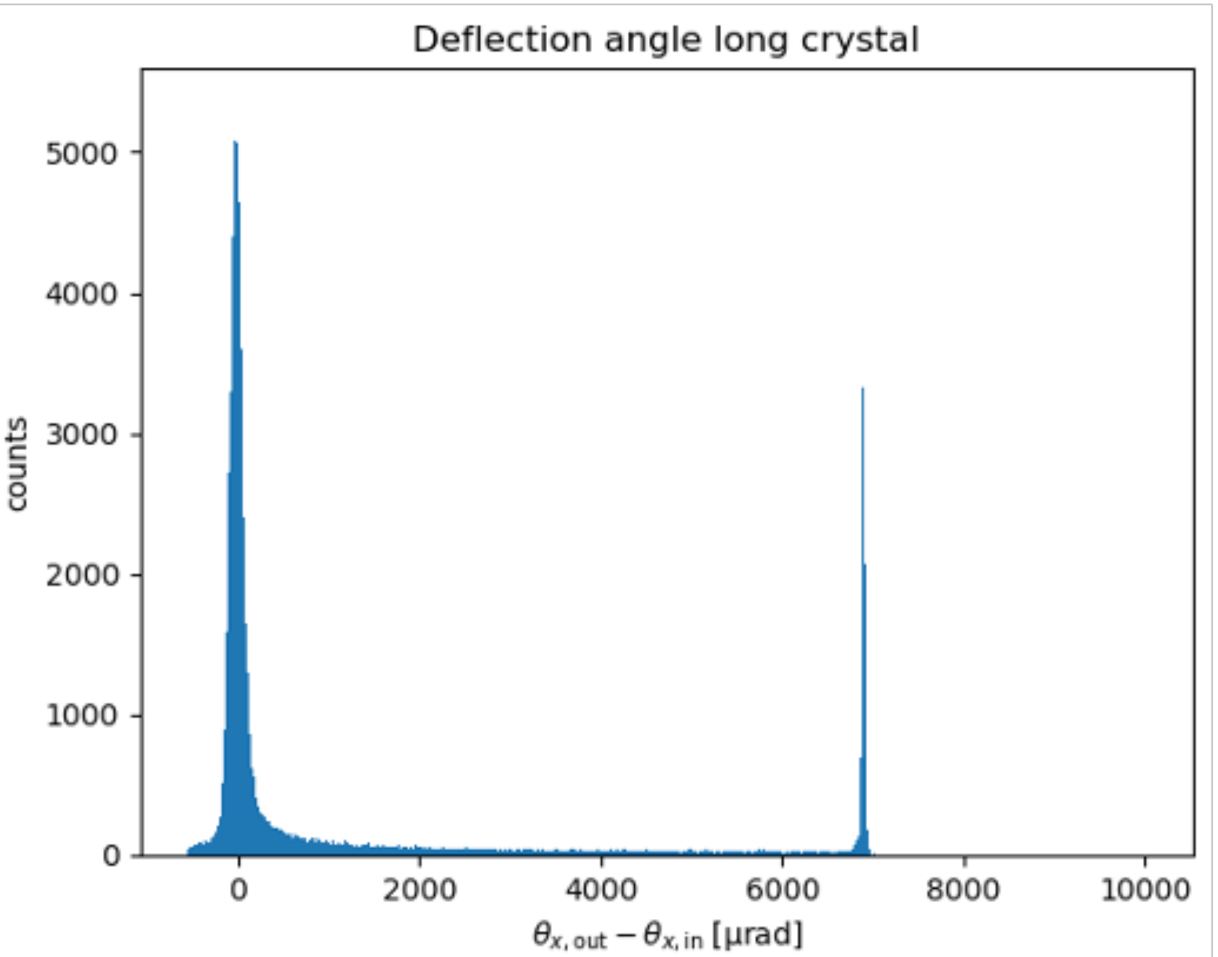
- Operational scenario is transparent to high intensity proton operations
- Solid PoP to validate relevant aspects for such an experiment: **TWOCRYST**
- **LoI** in preparation for the LHCC review

IR3 Double Crystal Test Stand Proposal | LHC Machine Committee (LMC #467) 7

Bent crystals

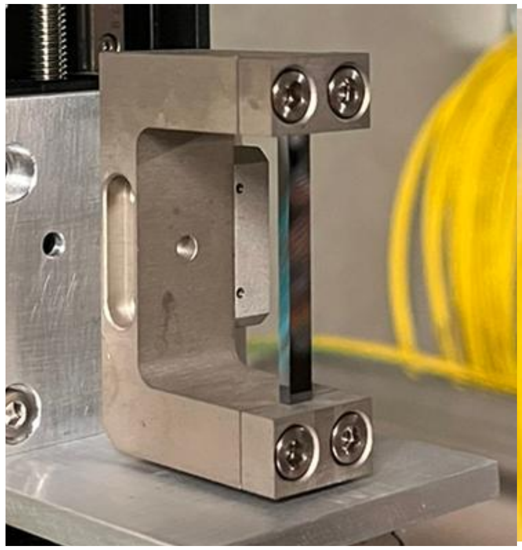
- Bent crystals produced at INFN Ferrara and characterised at SPS H8 with INFN Milano Bicocca/Insubria telescope using 180 GeV/c positive hadron beam (Aug 2023)
- Paper in preparation

erc SELDOM



Si, 7 mrad, 70 mm

Si, 50 μrad, 4 mm



Si, 7 mrad, 70 mm

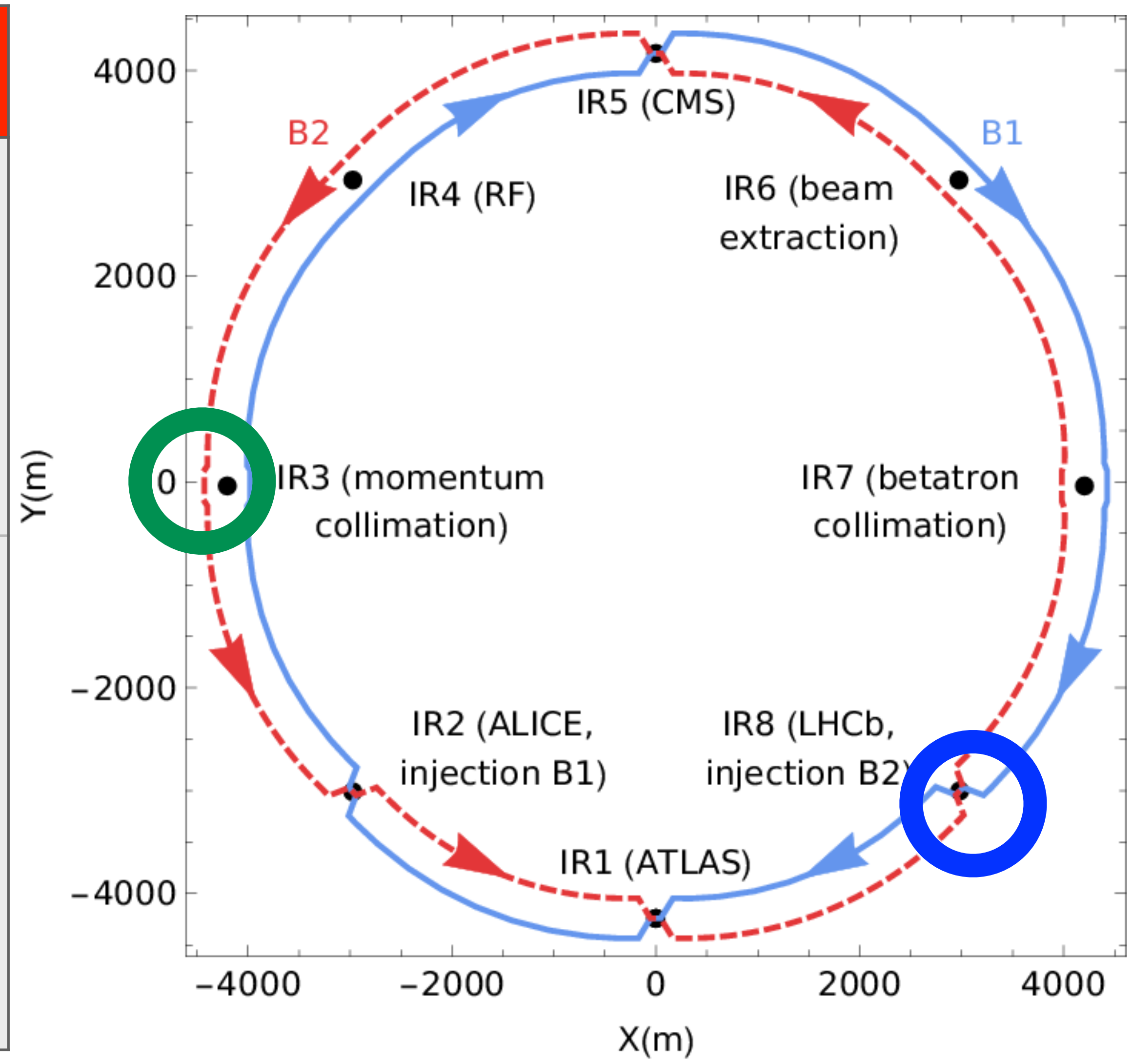
Acknowledgments: A. Mazzolari

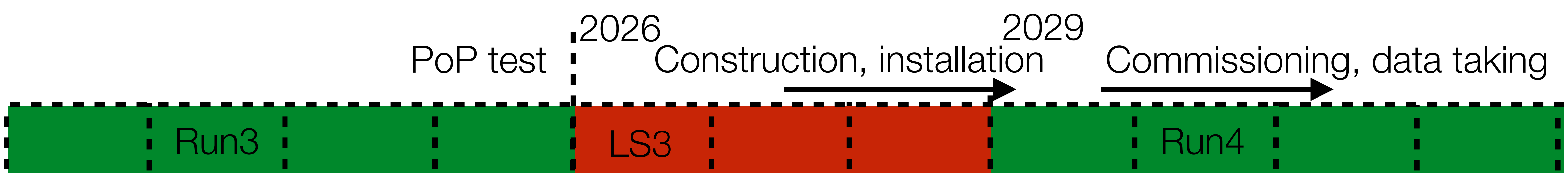
- Tested in lab for thermal stability and characterisation with X-rays
- Channeling efficiency measurements: 61.0% (50 μrad), 15.7% (7 mrad)

Proposed experiment at LHC

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

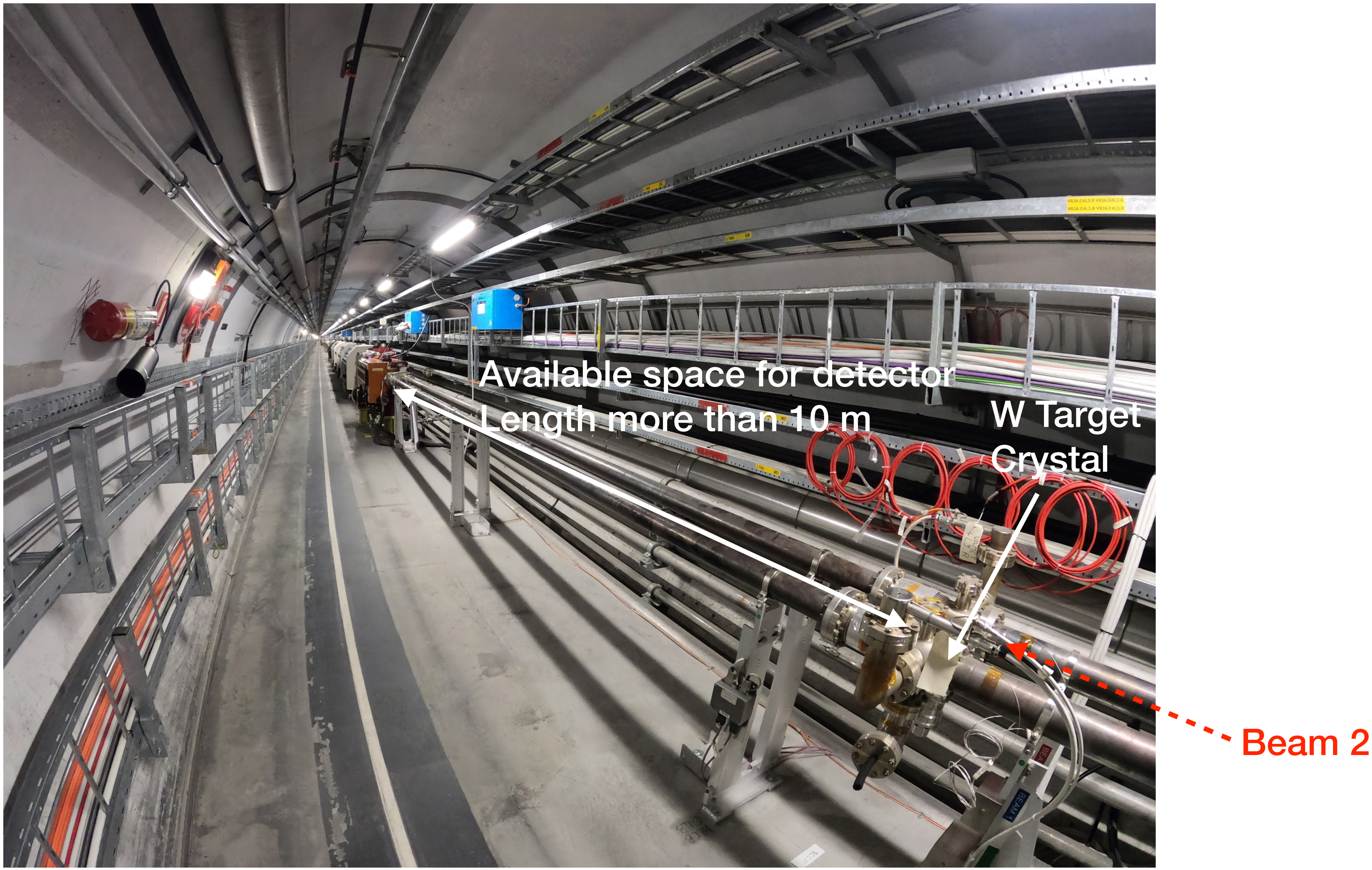
	Pro	Cons
IR3	**Optimal experiment and detector. PID information**	More resources needed. New detector, services (long cables, cooling)
LHCb	Use existing tracking detector and infrastructure. Experimental area	No PID for p>100 GeV. Potential interference with LHCb core program





LHC IR3: space identified for the experiment

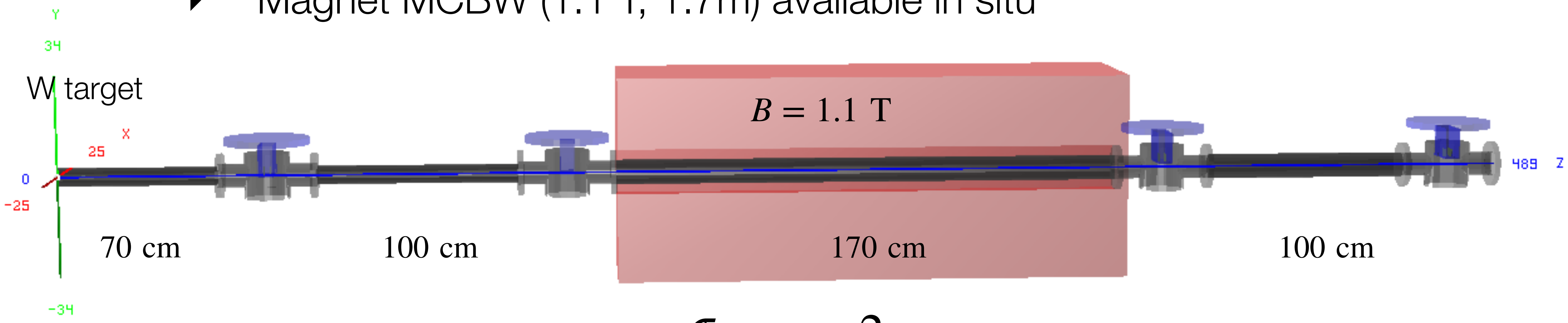
- Region for TWOCRYST PoP also suitable for the experiment <u>video</u>



Spectrometer in very forward region

** dedicated experiment solution shown here*

- VELO pixel sensors housed in Roman Pots. Acceptance $\eta > 5$
- 4 tracking stations: 2 upstream + 2 downstream of the magnet
- Magnet MCBW (1.1 T, 1.7m) available in situ

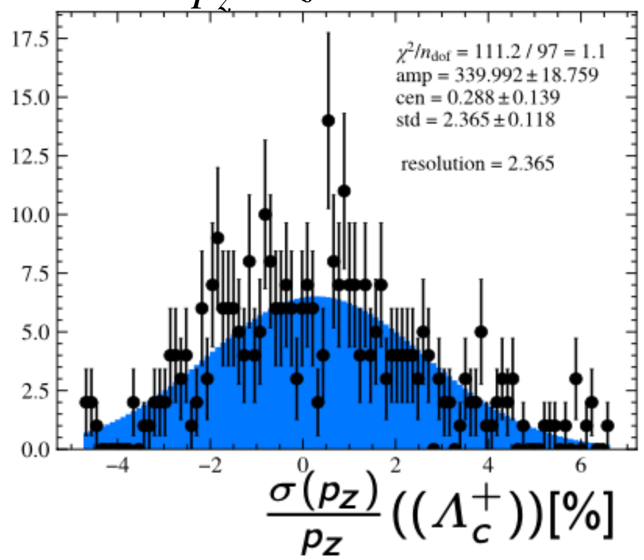


- Momentum resolution $\frac{\sigma_p}{p} \approx \frac{2p}{0.3BLD}\sigma_x = 2\,\%$ with $p = 500$ GeV, $BL = 1.9$ Tm, $D = 100$ cm, $\sigma_x = 10\ \mu m$
- Track angle resolution $\sigma_\theta \approx \sqrt{2}\sigma_x / D = 14\ \mu\text{rad}$
- Impact parameter resolution $\sigma_{x,y} \approx 20\ \mu\text{m}$

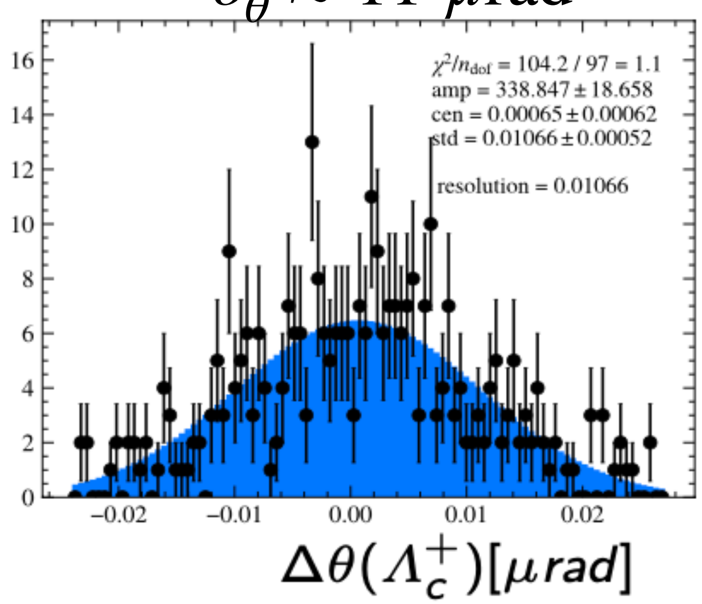
Spectrometer performance

- Good resolutions for signal $\Lambda_c^+ \to pK^-\pi^+$ decays
- Acceptance for signal decays 70% (with modifications to current RP and/or beam pipe geometry)

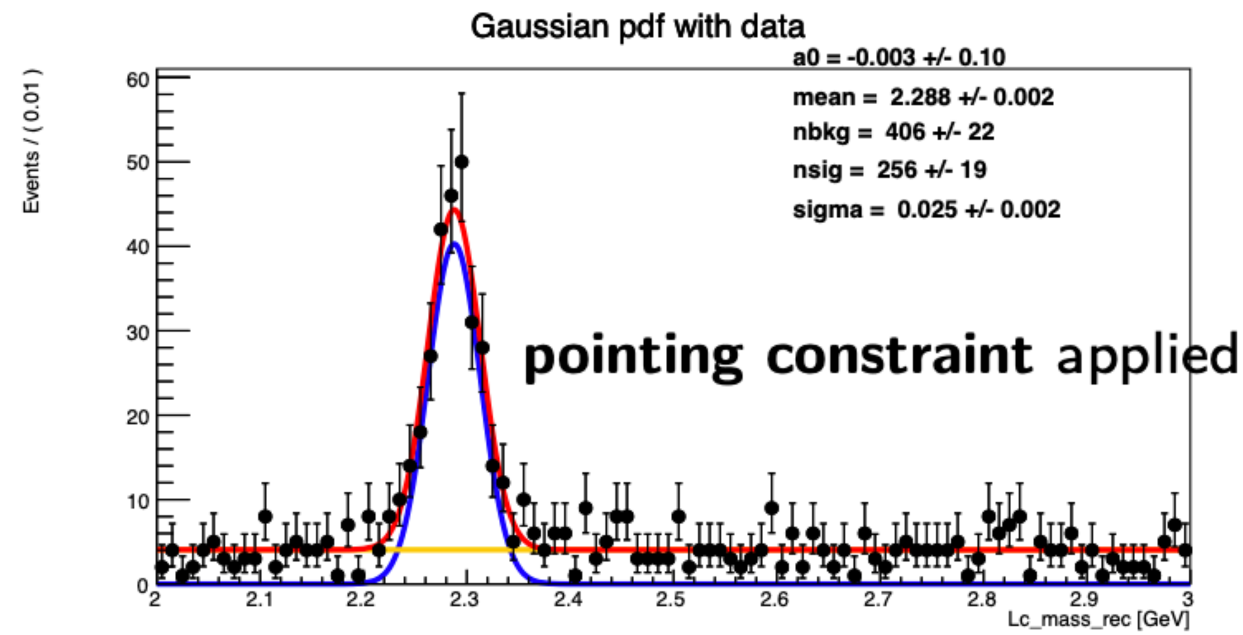
$\sigma_{p_z}/p_z \approx 2.4\,\%$



$\sigma_\theta \approx 11\ \mu\mathrm{rad}$



$\sigma_m \approx 25\ \mathrm{MeV}$



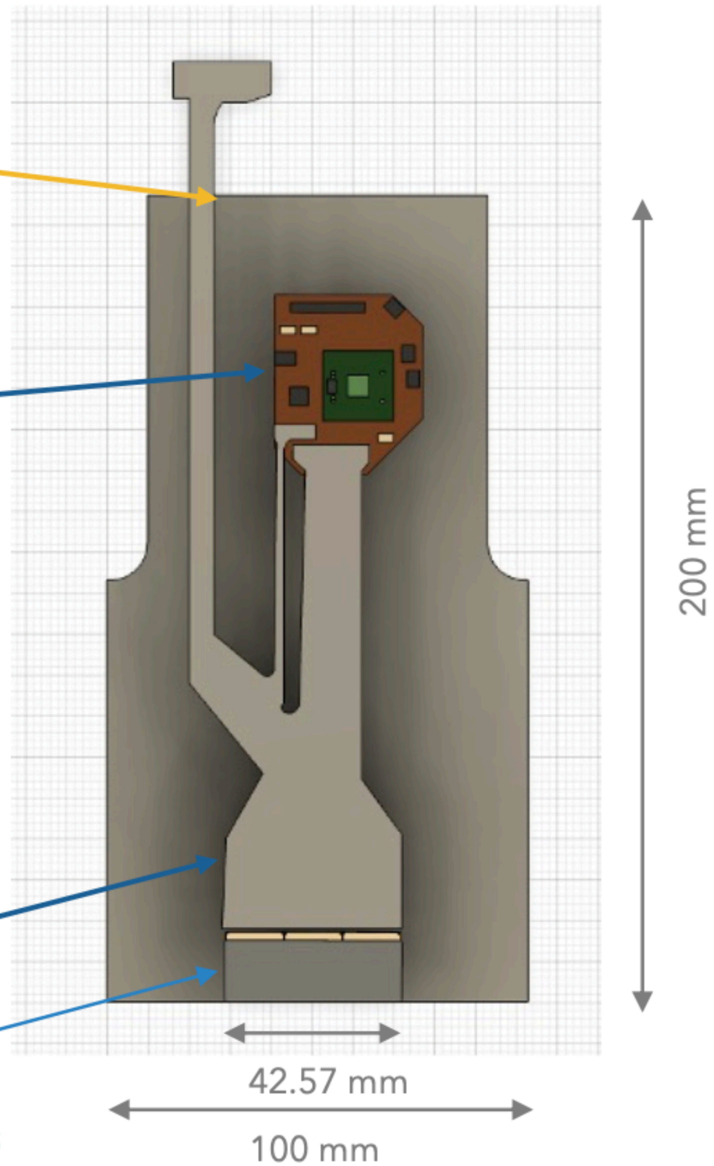
$m(pK^-\pi^+)$ [GeV]

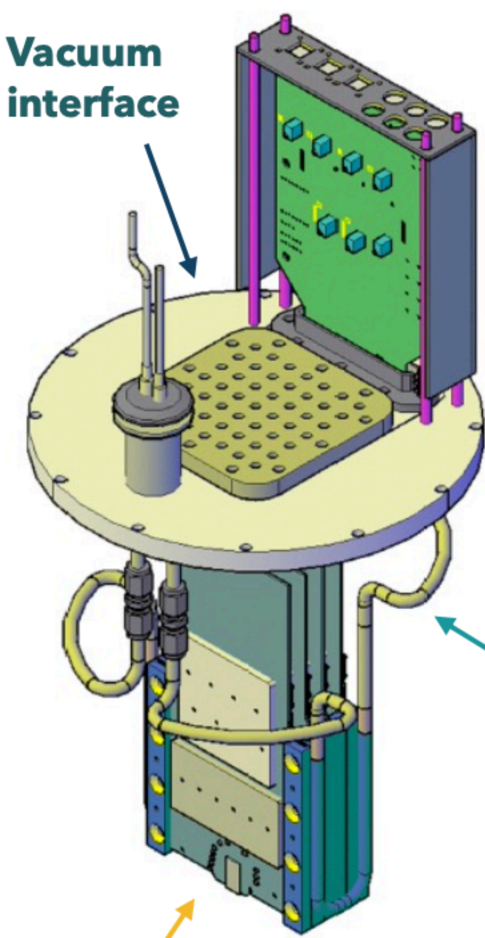
- Signal acceptance up to 90% and factor 2 improvement in momentum resolution with magnet B=4 T, L=1 m
- Potential future upgrade: compact magnet in 20K HTS technology

Pixel sensor module

** dedicated experiment solution shown here*

- Based on VELO sensors and CMS-Totem mechanics/cooling





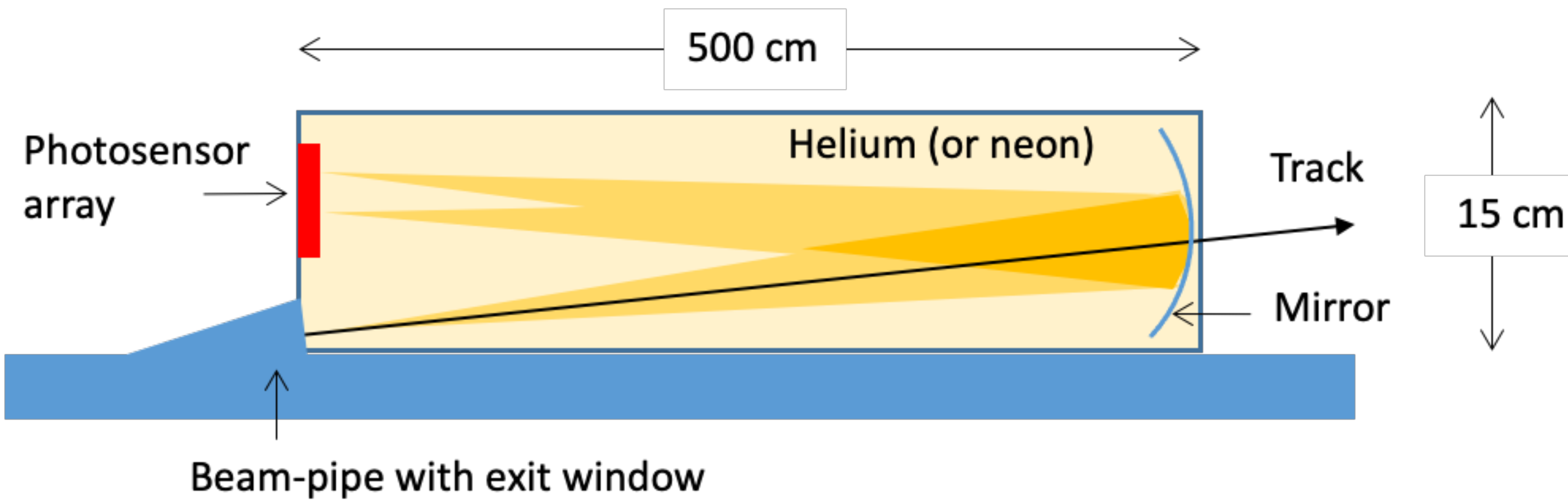
Acknowledgements: J. Buytaert, V. Coco, E. Lemos from LHCb VELO group

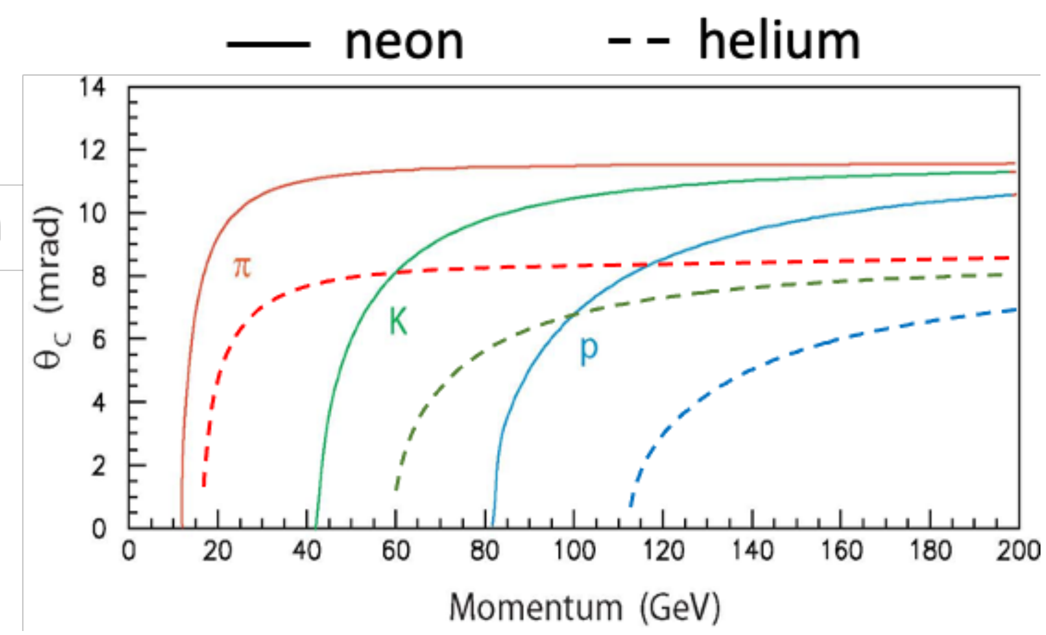
Acknowledgments: N. Turini from CMS-Totem

Particle identification with RICH up to 1 TeV

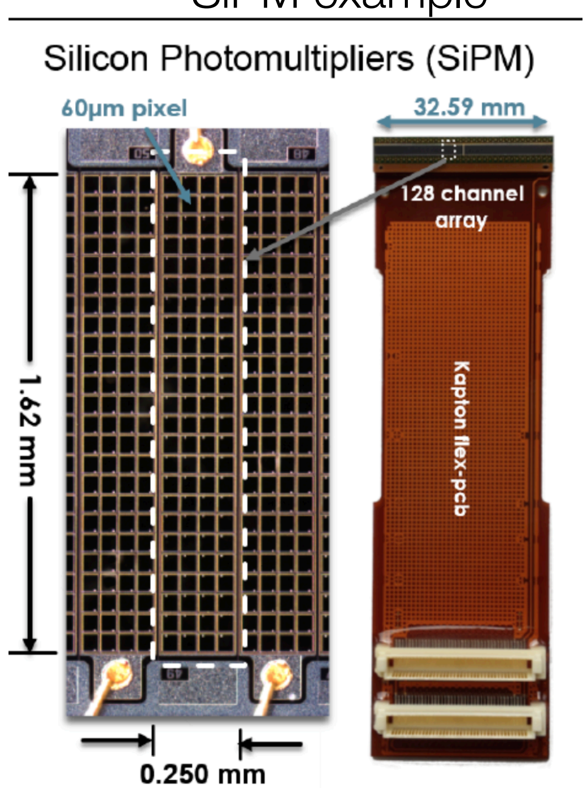
** dedicated experiment solution shown here*

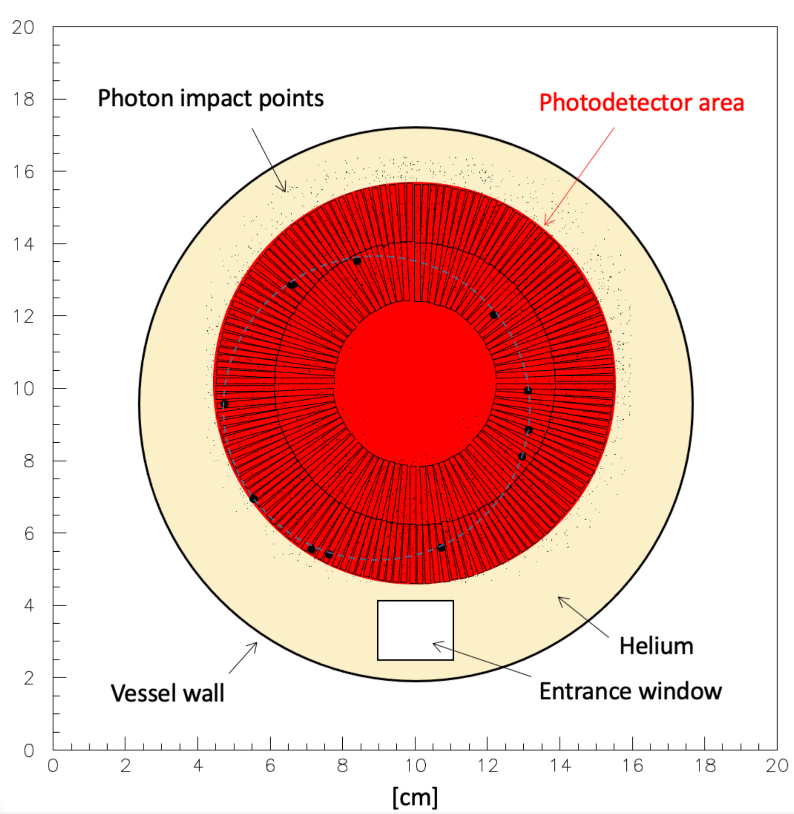
- He radiator gas n=1.000035, length 500 cm, $N_{pe} \approx 12$





SiPM example





SiPM area 100 cm², $0.5 \times 0.5\ \mathrm{mm}^2$ pixel. mm-scale SiPM pixelisation is a key goal of new DRD4 collaboration

Angular resolution: $\sigma_\theta = 42\ \mu\mathrm{rad}$ per photon (chromatic error $32\ \mu\mathrm{rad}$, emission point error $6\ \mu\mathrm{rad}$, pixel error $30\ \mu\mathrm{rad}$)

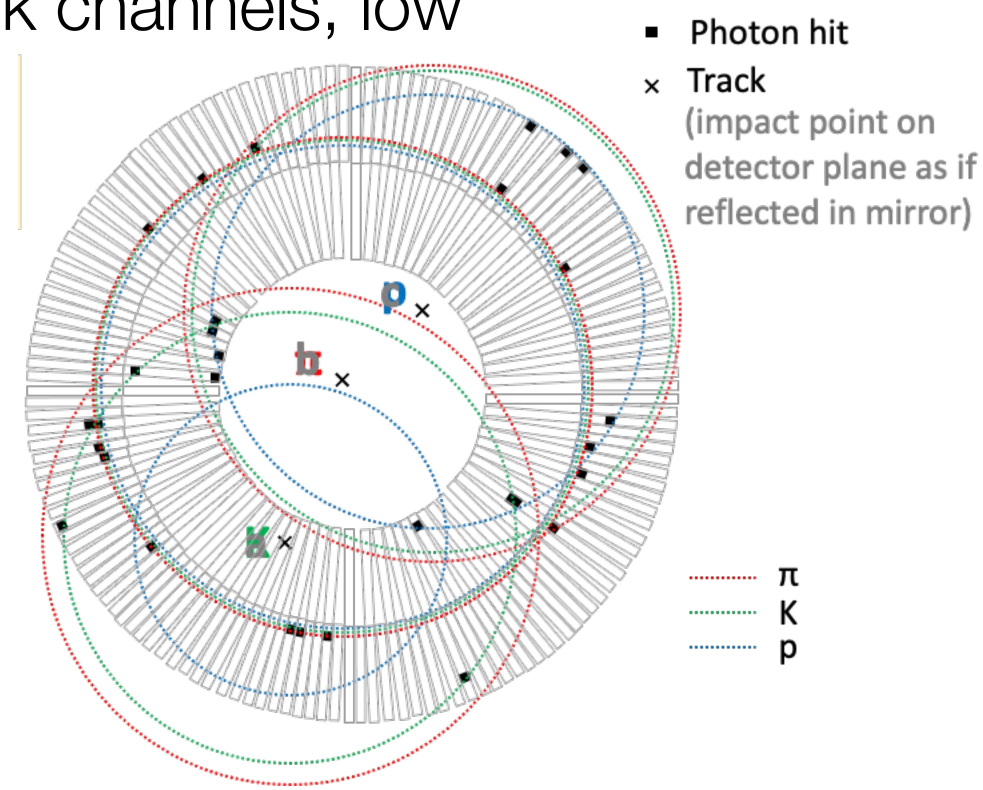
Particle identification with RICH

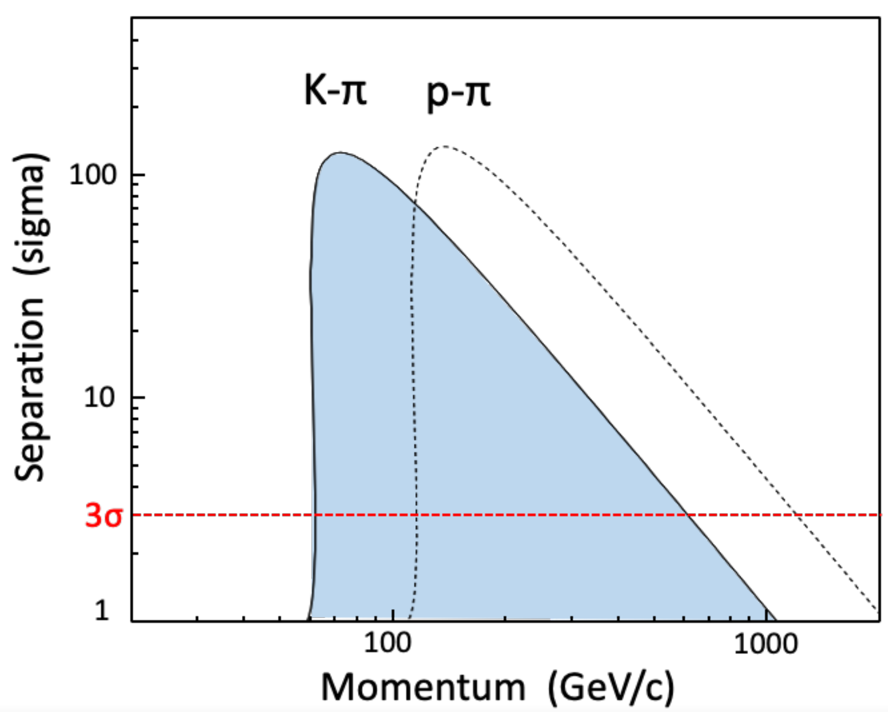
** dedicated experiment solution shown here*

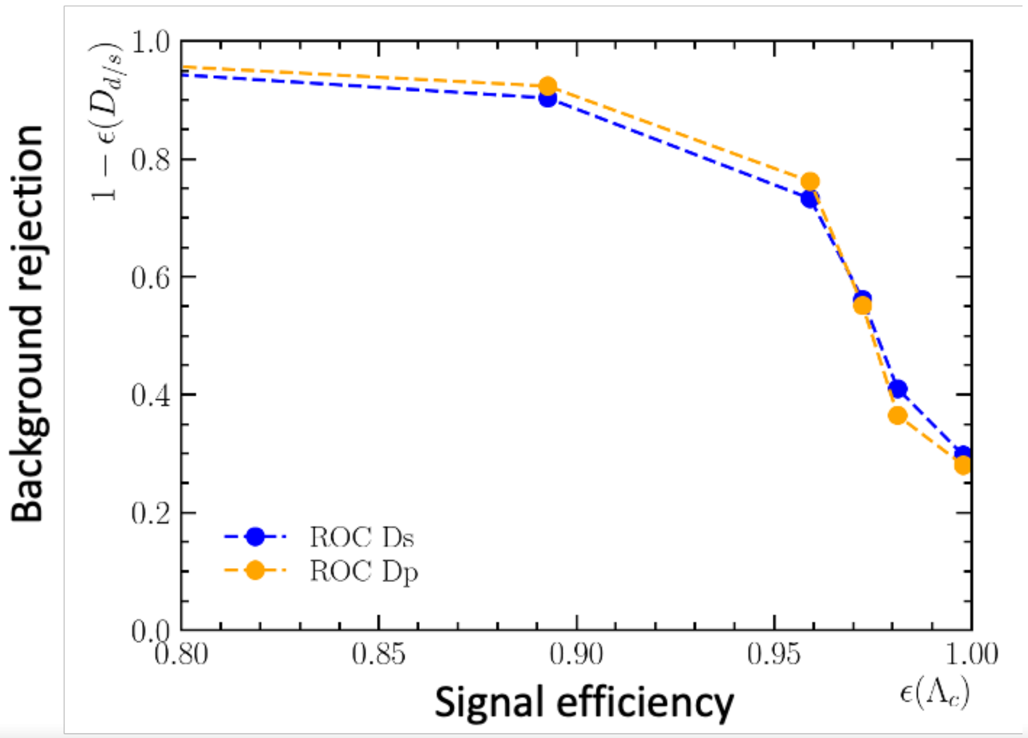
- Patter recognition: relatively easy thanks to 38k channels, low occupancy 0.1% from signal tracks

- Upper limit for 3σ K-π (p-π) separation is 610 GeV/c (1.2 TeV/c)

- Achieve 90% signal retention and 90% bkg rejection comparing $\Lambda_c^+ \rightarrow pK^-\pi^+$(signal) to $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^+K^-\pi^+$ (bkg)





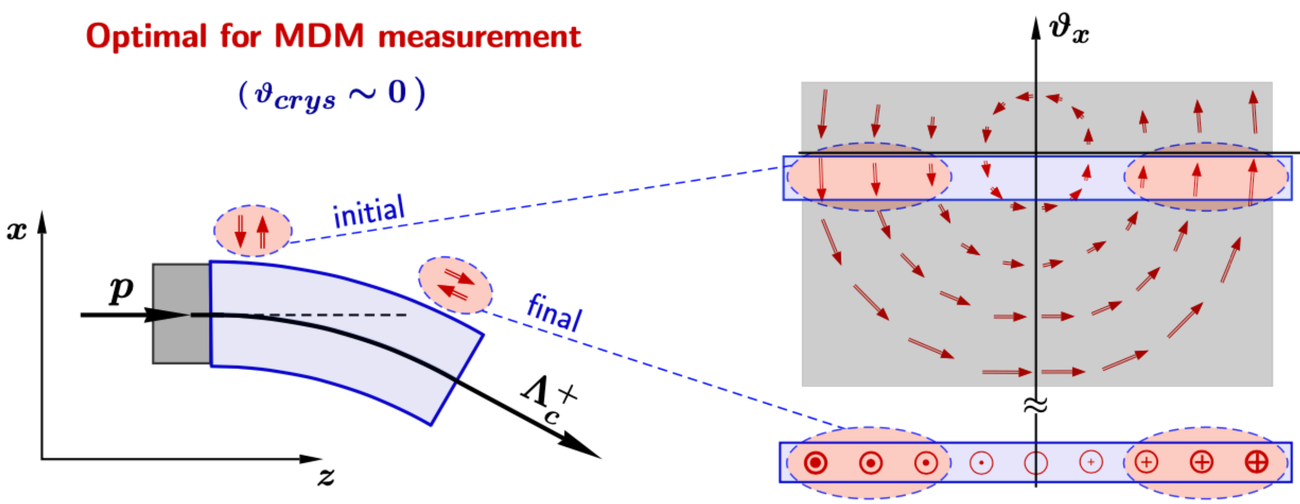


Physics reach

- **First measurements** of **charm baryon dipole moments** in 2 years data taking assuming 10^6 p/s on 2 cm W target with Λ_c^+ (Ξ_c^+) polarisation 0.22 (0.20) and use 3-body and 4-body decays
- Sensitivity on **MDM** $2 \cdot 10^{-2} \mu_N$ and **EDM** $3 \cdot 10^{-16} e$ cm with $1.4 \cdot 10^{13}$ PoT
- Exploration **of τ g-2 and EDM** (improvements are required)
- Additional physics topics: charm hadron cross-section measurements and J/ψ photo production in the very forward region at pseudorapidity $\eta > 5$

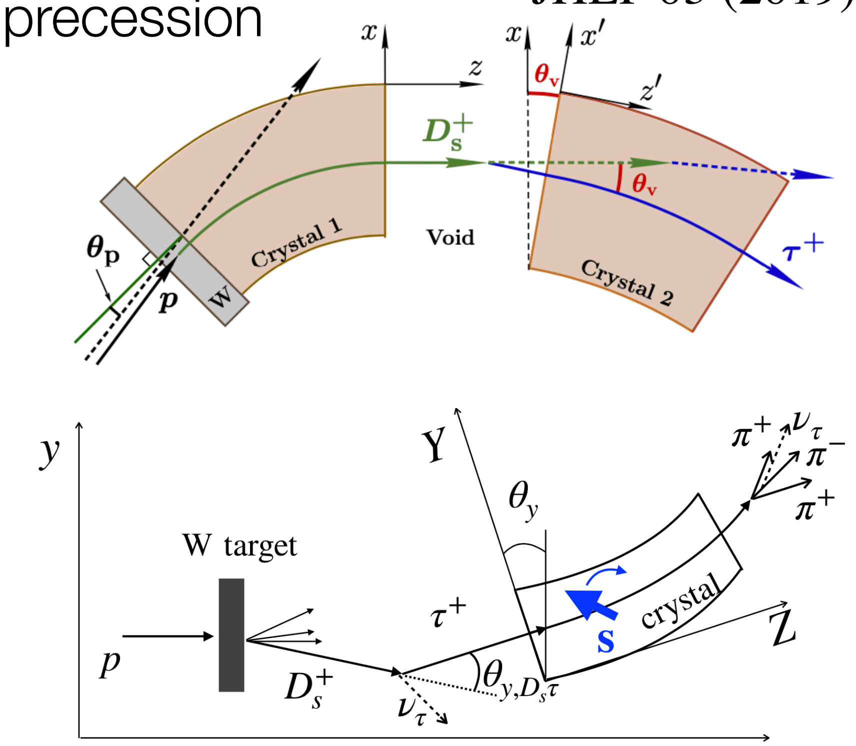
Proposed setup for Λ_c^+ precession

EPJC (2020) 80:358
PRD 103, 072003 (2021)



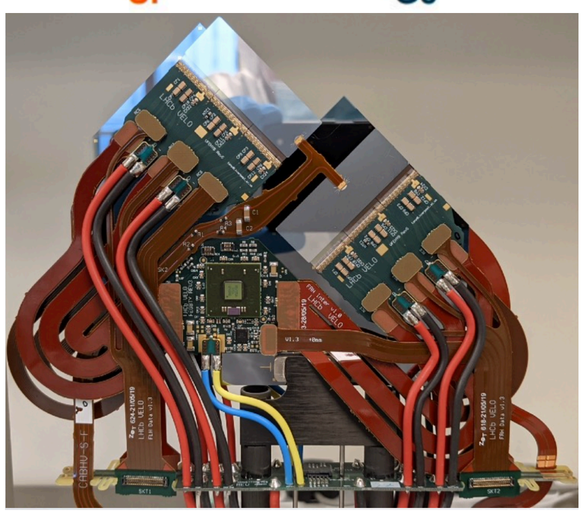
Proposed setup for τ precession

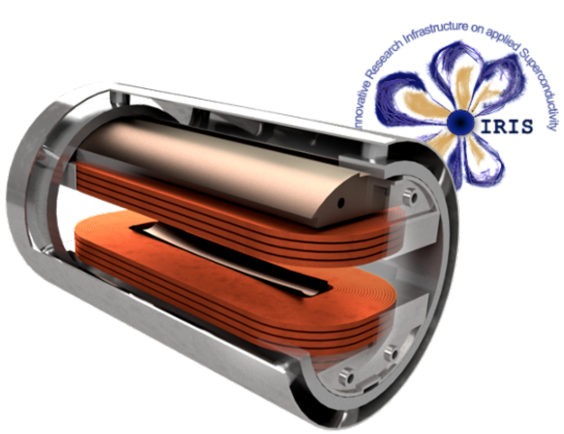
JHEP 03 (2019) 156



PRL 123, 011801 (2019)

Technology





- **Machine**: beam manipulation using bent crystals
  - bent crystals: silicon (Si) with mechanical bending as baseline. Germanium (Ge) and/or anodic bonding as bending technique for potential upgrade
  - deflection of beam halo towards W target
  - goniometers for precision bent crystal positioning
- **Detector**: compact with high granularity, covers very forward region $(\eta \geq 5)$
  - LHCb VELO silicon pixel sensors inside Roman Pots (from ATLAS-ALFA)
  - RICH detector for p, K, π PID up to 1 TeV energies. SiPM pixelisation below 1 mm
- **Magnet**: compact spectrometer dipole magnet
  - warm dipole magnet already available in situ (1.9 T m) as baseline
  - Compact dipole magnet with higher field (4.0 T m) in 20K HTS technology for potential future upgrade

Proponents of the LoI (being finalised)

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With support from PBC and TWOCRYST collaborators for the machine PoP

- Series of **topical workshops**: 1st, 2nd, 3rd workshop

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Backup

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References for τ lepton and machine

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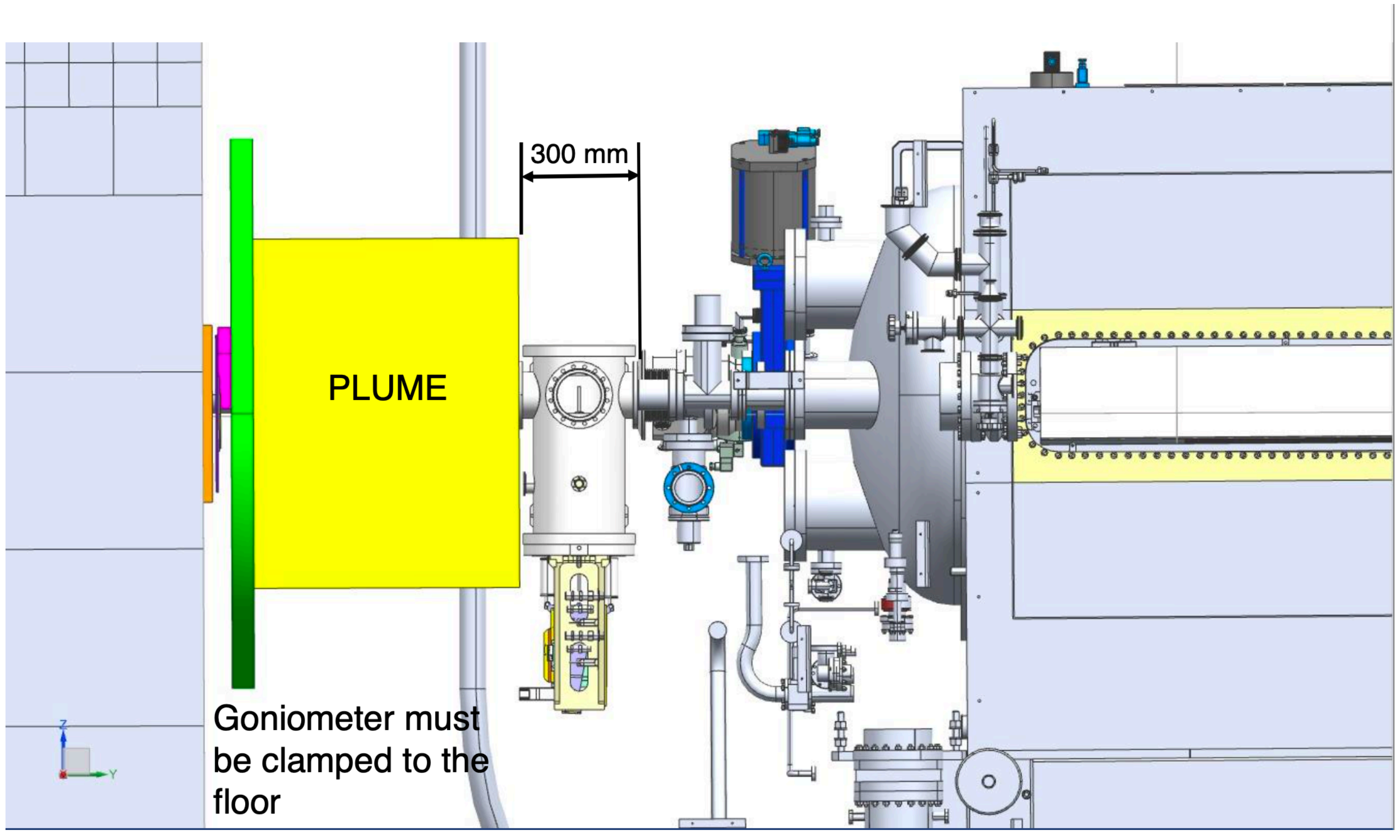
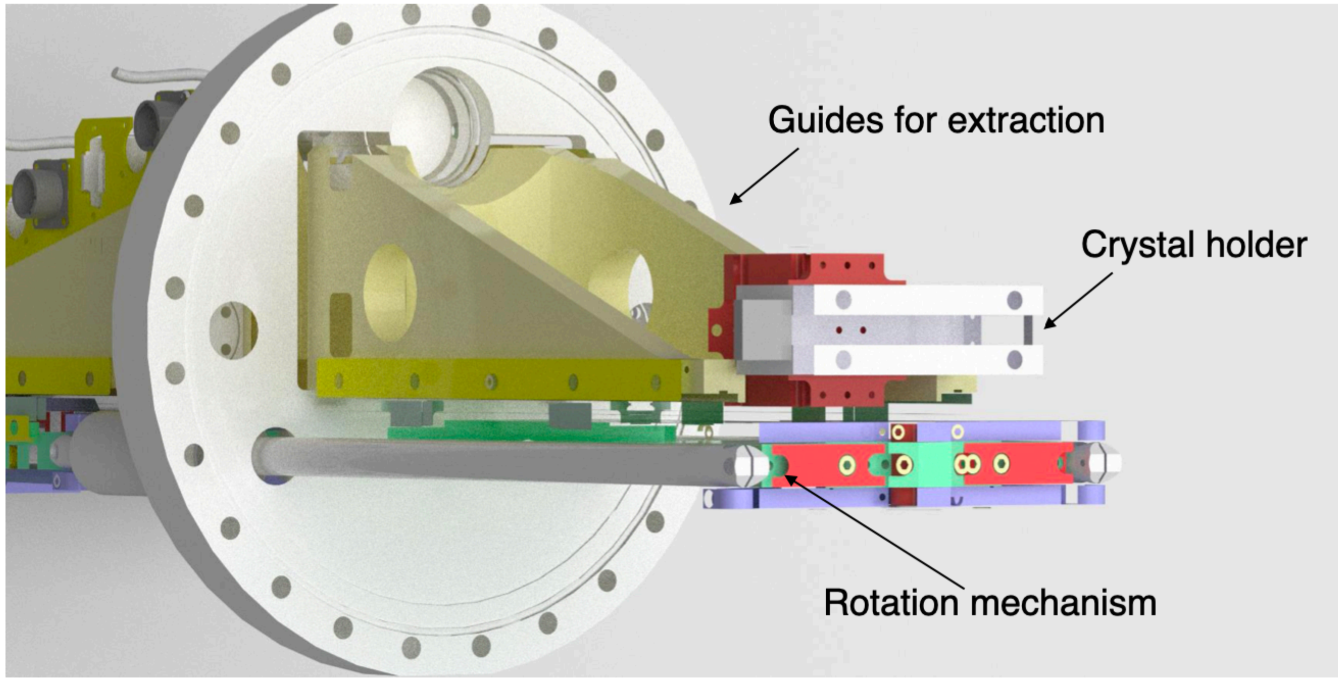
Fixed-target setup upstream of LHCb



- Goniometer for target+crystal positioned in the region upstream of the LHCb detector, close to the VELO

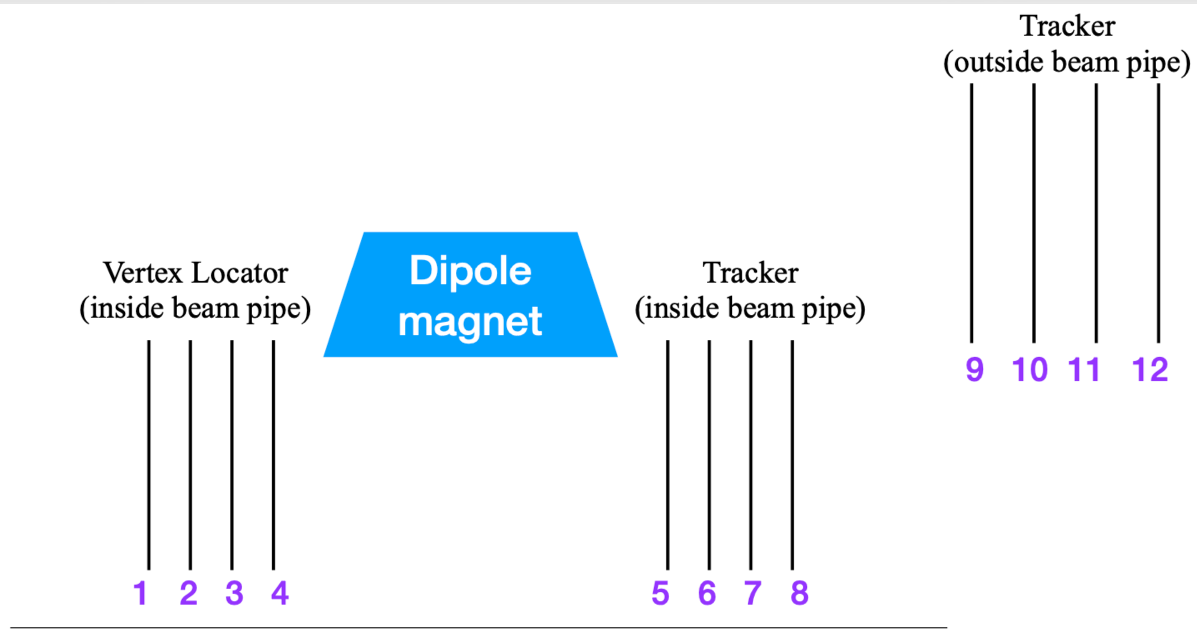
- Goniometer internal structure: compatible with operations in ultra-high vacuum

- Impedance studies ongoing



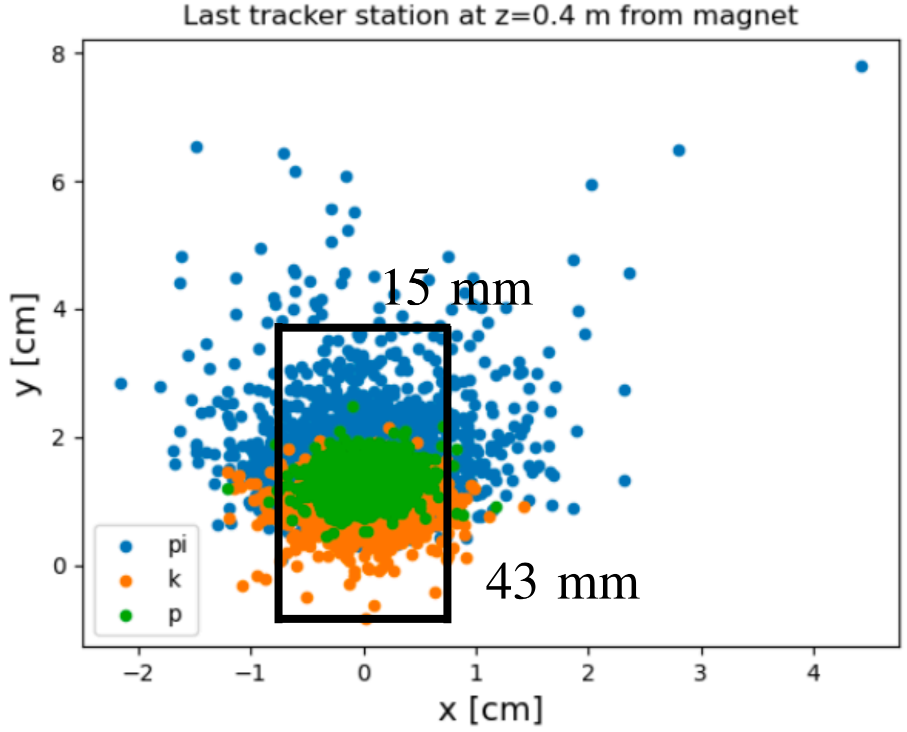
Spectrometer for a dedicated experiment at IR3

- Channeled Λ_c^+ in bent crystal are very focused in few cm²
- Preliminary simulations: with 8 **VELO tiles** + existing 1.9Tm dipole magnet in situ can build a spectrometer



Hit distribution for $\Lambda_c^+ \to pK^-\pi^+$

Area ≈ few cm². rate ≈ 100 MHz/cm²



VeloPix modules in Roman Pots

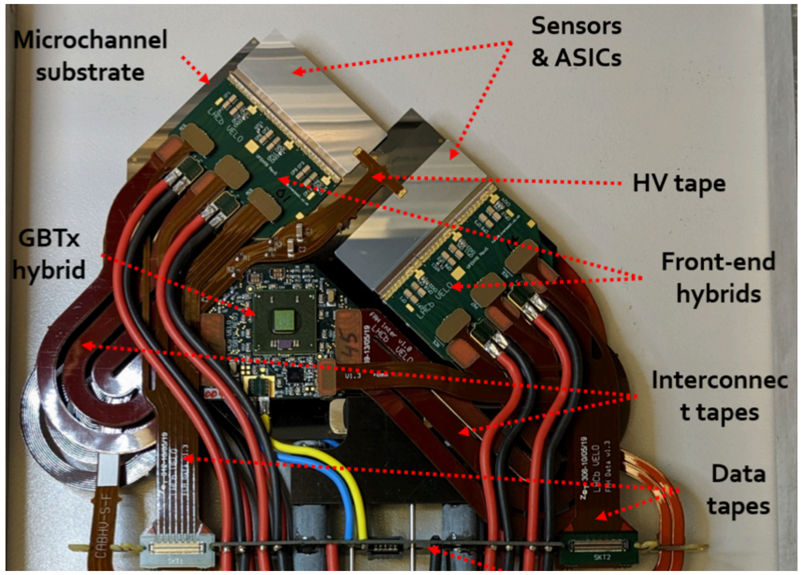
for Vertex and Tracker stations

1 cm from the beam

55x55 μm² pixel,

pixel hit rate 600 MHz/cm²,

12 μm hit resolution



LHC orbit correction dipole MCBW (1.7 m, 1.1 T) is considered for the spectrometer (Credits: Pascal Hermes, CERN)