Search for strange and charm baryon EDM, and MDM measurements at LHCb

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Acknowledgements

- Special thanks to: L. M. Garcia Martin, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, J. Ruiz for helping with the preparation of the material

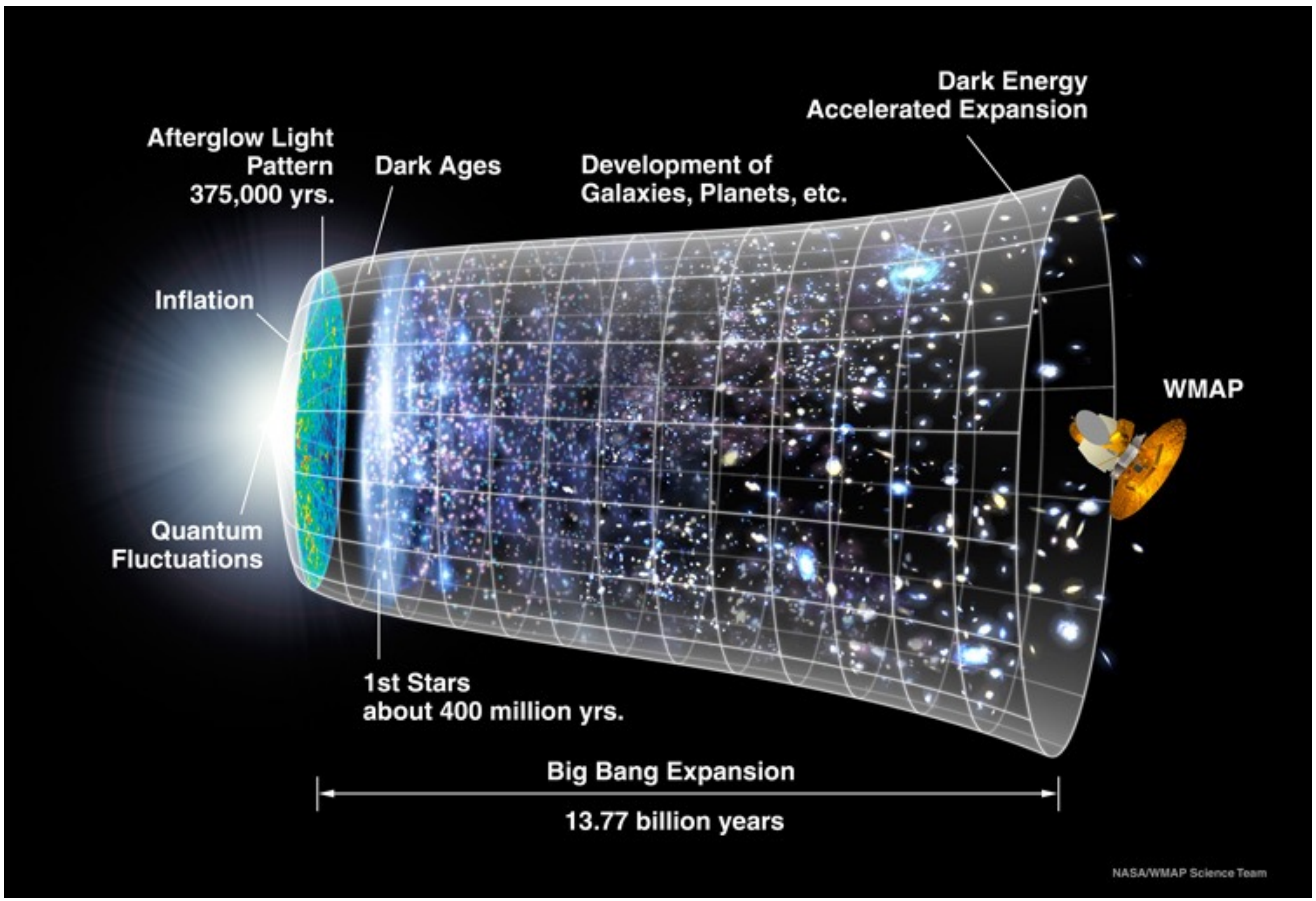
- Talk based on:
  - F.J. Botella, L. M. Garcia Martin, D. Marangotto, F. Martinez Vidal, A. Merli, N. N., A. Oyanguren, J. Ruiz Vidal, *On the search for the electric dipole moment of strange and charm baryons at LHC*, arXiv:1612.06769
  - L. Burmistrov, G. Calderini, Yu Ivanov, L. Massacrier, P. Robbe, W. Scandale, A. Stocchi, *Measurement of Short Living Baryon Magnetic Moment using Bent Crystals at SPS and LHC*, CERN-SPSC-2016-030 ; SPSC-EOI-012

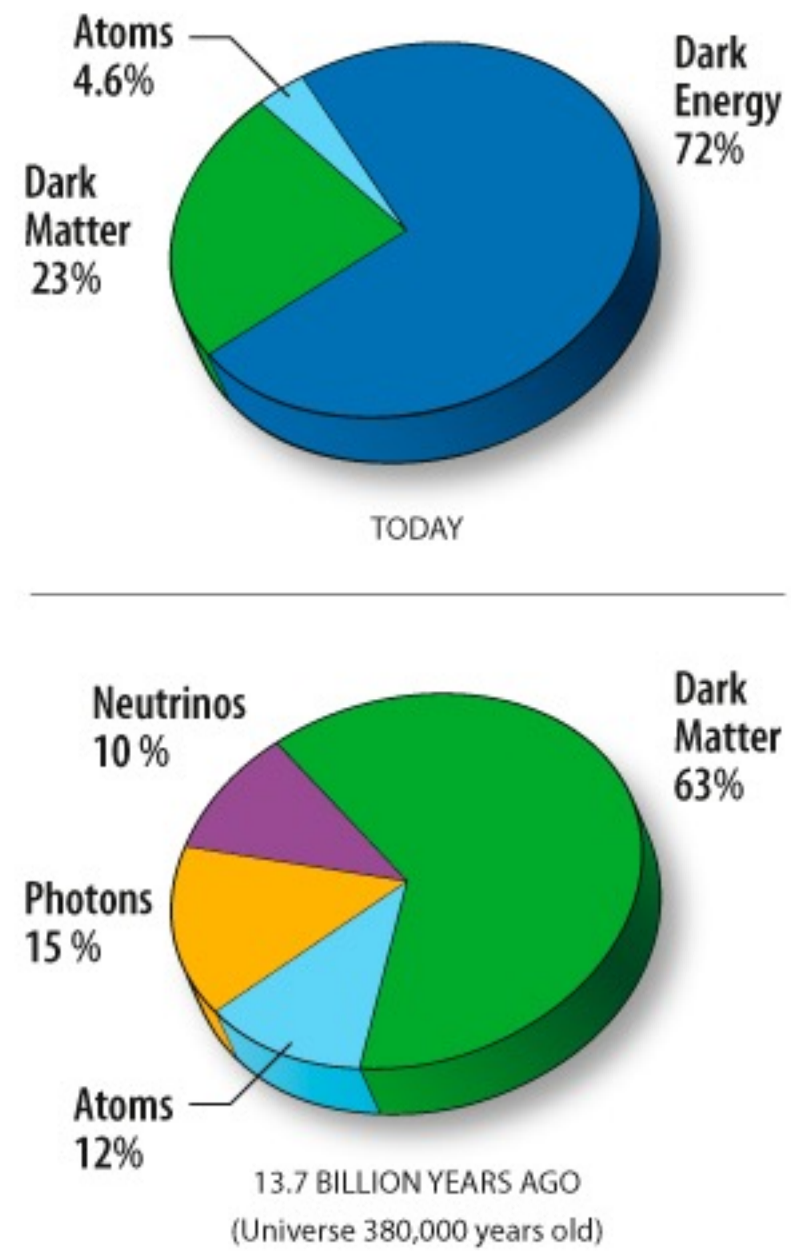
Outline

- Introduction
- Physics reach
- Expected sensitivities
- Preparatory measurements
- Summary and perspectives

Where is antimatter in the Universe?

If equal amount of matter-antimatter was produced after the Big Bang, how do we explain the absence of antimatter in the Universe today?





Matter-antimatter asymmetry and CP violation

Violation of CP symmetry (CPV), necessary condition for baryogenesis according to Sakharov conditions [1].

CPV in weak interactions via CKM mechanism in SM is too small to explain the absence of antimatter

CPV in strong interactions allowed in SM. Stringent experimental limit from neutron EDM→ "strong CP problem"

$$|\delta_n| \leq 2.9 \times 10^{-26} e \text{ cm (90\% C.L.)} \;\; \Rightarrow \theta \lesssim 10^{-10}$$

Phys.Rev.Lett.97:131801,2006

New sources of CPV expected to exist

CP mirror

[1] A. D. Sakharov, "Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe," Pisma Zh. Eksp. Teor. Fiz. 5, 32-35 (1967), JETP Lett. 5, 24-27 (1967), Sov. Phys. Usp. 34, 392-393 (1991), Usp. Fiz. Nauk 161, 61-64 (1991).

Electric dipole moment

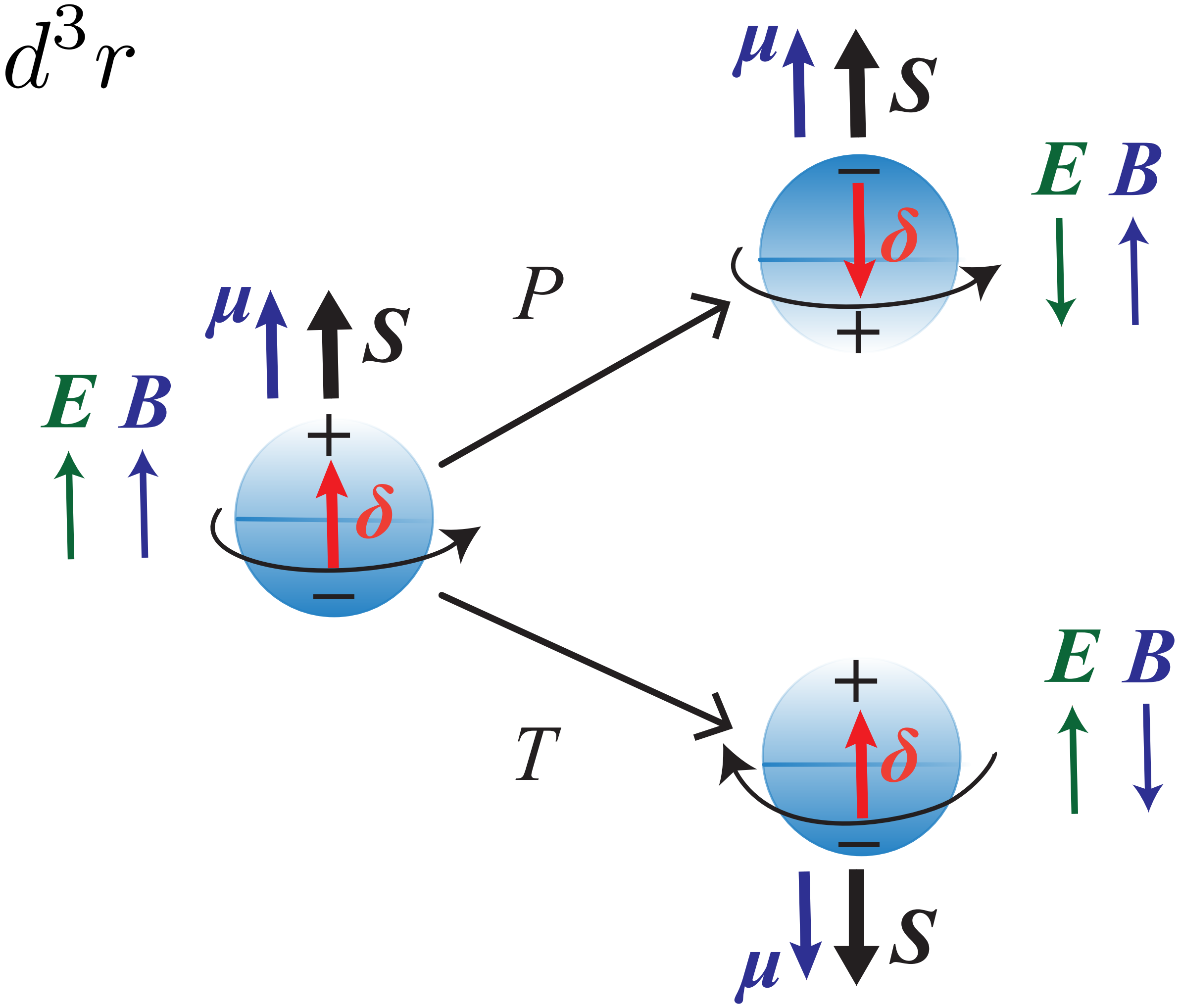
- Definition $\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$

- Quantum systems

$$\boldsymbol{\delta} = d\mu_N \frac{\boldsymbol{S}}{2} \qquad \boldsymbol{\mu} = g\mu_N \frac{\boldsymbol{S}}{2}$$

- Hamiltonian

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



Time reversal, parity: $d\mu_N \frac{\boldsymbol{S}}{2} \cdot \boldsymbol{E} \xrightarrow{T,P} -d\mu_N \frac{\boldsymbol{S}}{2} \cdot \boldsymbol{E}$

The electric dipole moment violates *T* and *P*
Thus, through CPT theorem, violates *CP*

Baryon EDM - Effective Lagrangian

- EDM coupling: $$\mathcal{L}^{\rm EDM} = -\frac{i}{2}\delta\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

- CP-odd flavour diagonal effective $\mathcal{L}$ (scale 1 GeV)

$$\mathcal{L}_{\rm eff}^{\not{P}\not{T}} = -\overline{\theta}\frac{g^2}{64\pi^2}\varepsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} \qquad \theta\text{-QCD term}$$

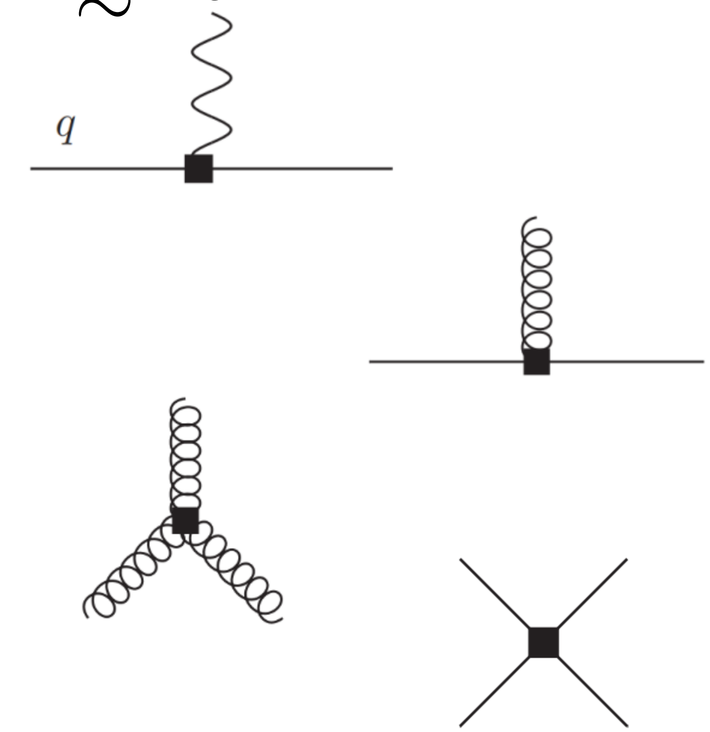
$$-\frac{1}{2}\sum_{q=u,d\ \mathbf{s,c}}(\delta_q\overline{q}i\sigma^{\mu\nu}\gamma_5 qF_{\mu\nu} \qquad \text{qEDM}$$

$$+\tilde{\delta}_q\overline{q}i\sigma^{\mu\nu}\gamma_5 t_a qG^a_{\mu\nu}) \qquad \text{qCEDM}$$

$$+\frac{d_W}{6}f_{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G_\nu^{c\rho} \qquad \text{Weinberg op.}$$

$$+\sum_{i,j,k,l=u,d\ \mathbf{s,c}} C_{ijkl}\overline{q}_i\Gamma q_j\overline{q}_k\Gamma' q_l \qquad \text{4q op.}$$

$\theta \lesssim 10^{-10}$ from nEDM

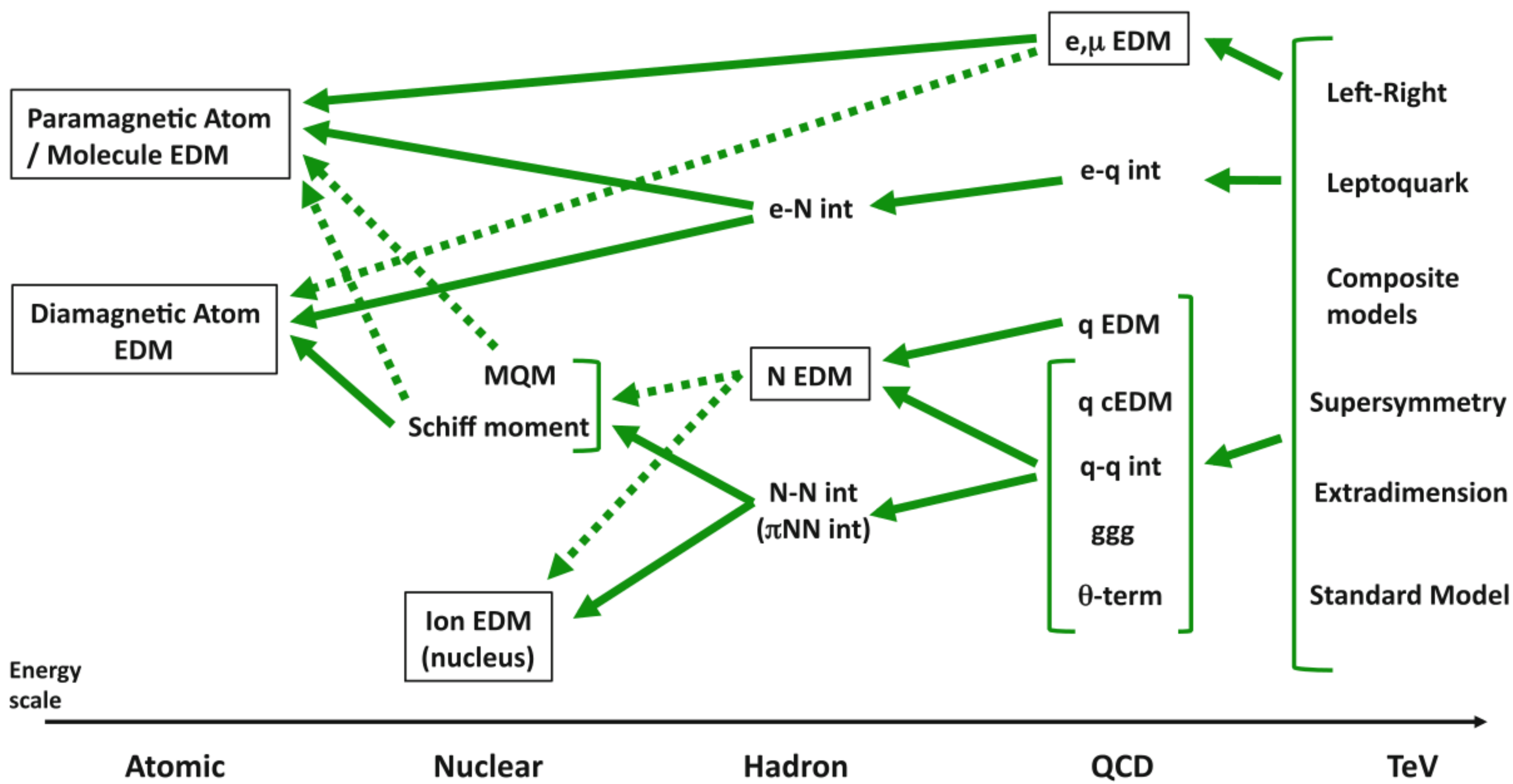


- Negligibly small contribution from SM

- Background free search for new physics

EDM contributions and observables

- Significant EDM enhancements are possible in theories beyond the SM
- EDM searches in different systems are complementary. Fundamental particles bring cleanest information

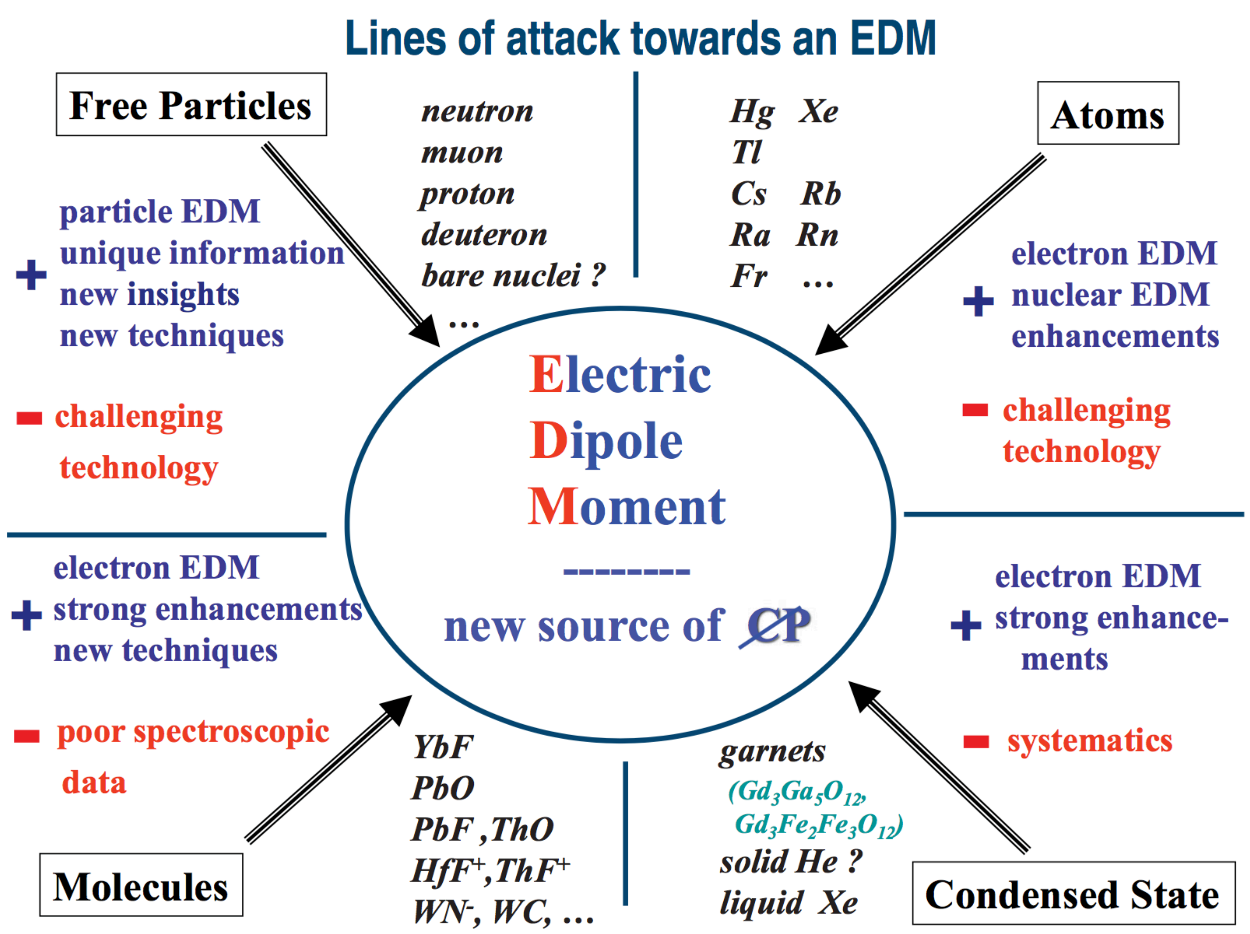


N. Yamanaka. Springer Theses (2014) DOI: 10.1007/978-4-431-54544-6

Current limits on EDM

- Intense EDM program is ongoing worldwide and new experiments are planned
- Possibility to contribute at LHCb searching for strange (Λ) and (first time) charm baryon (Λ_c^+, Ξ_c^+) EDM

Particle	Limit/Measurement [e cm]	SM limit [factor to go]
e	$<1.05 \times 10^{-27}$	10^{11}
μ	$<1.8 \times 10^{-19}$	10^{8}
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$	10^{7}
n	$<2.9 \times 10^{-26}$	10^{4}
p	$<0.54 \times 10^{-23}$	10^{6}
Λ^0	$(-3.0 \pm 7.4) \times 10^{-17}$	10^{11}
$\nu_{e,\mu}$	$<2 \times 10^{-21}$	
ν_τ	$<5.2 \times 10^{-17}$	
Hg-atom	$<3.1 \times 10^{-29}$	$\leq 10^{4}$



Ann. Phys. (Berlin) 525, No. 8–9 (2013)

Charm and strange baryon MDM

- Experimental anchor points for test of low-energy QCD models, related to non-perturbative QCD dynamics
  - discriminate among proposed models, which predict significantly different strange/charm MDM values
- Test of quark substructure: an anomalous MDM would be a sign for strange/charm quark substructure
- Measurement of MDM of particle and antiparticle would allow a test of *CPT* symmetry

I.J. Kim, Nucl. Phys B 229 (1983) 251-268

V.V. Baublis et al., NIMB 90 (1994) 112-118

Search for Λ and Λ_C^+, Ξ_C^+ baryon EDM at LHCb

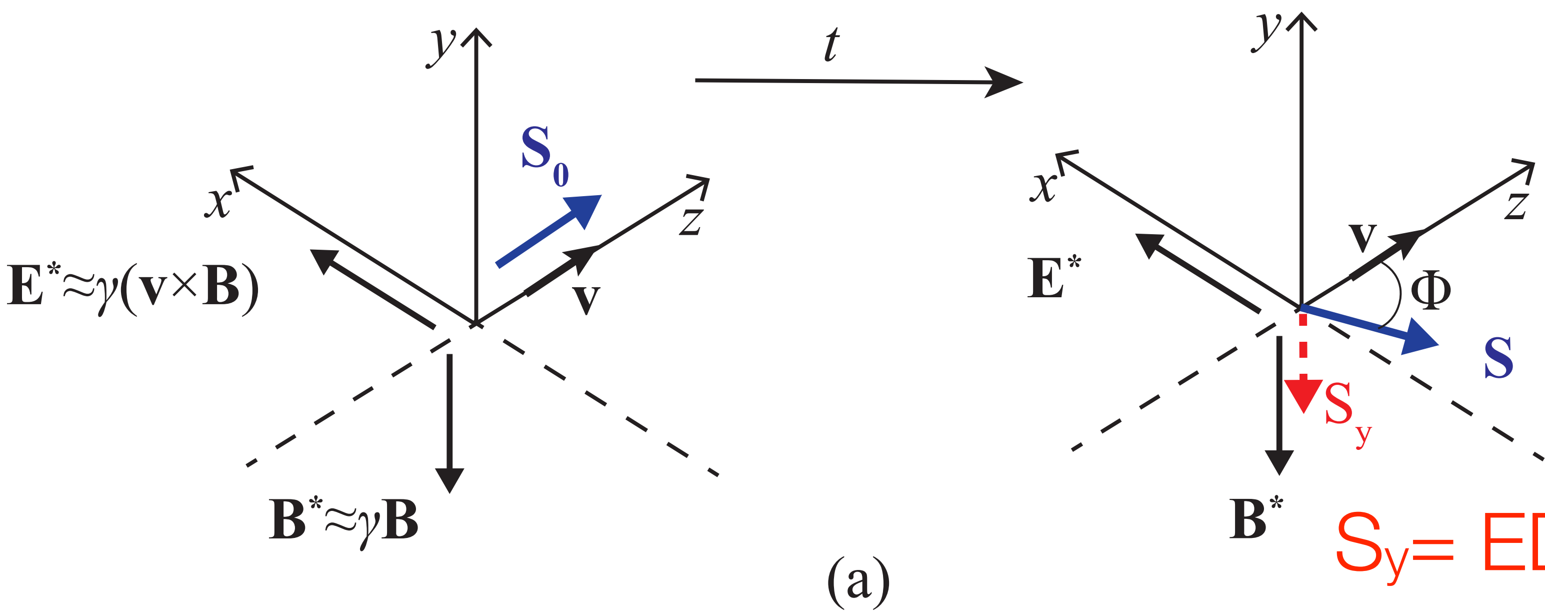
- Extract EDM, MDM information from spin precession in electromagnetic field
  - complicated for unstable particles: precession has to happen before the decay
- Unique possibility at LHCb:

arXiv:1612.06769

  - large amount of polarized baryons produced with large Lorentz boost
  - long-lived Λ precess in LHCb dipole magnet
  - short- lived *channeled* Λ_C^+, Ξ_C^+ precess in the intense electric field between crystal atomic planes
  - good reconstruction efficiency for *s* and *c*-hadrons

Spin precession for Λ baryon

- Λ precesses in the LHCb dipole magnet
- Spin-precession angle $\Phi \approx \frac{gD_y\mu}{\beta\hbar c} \approx 45^\circ$ and $D_y \approx 4\mathrm{Tm}$



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

S_y= EDM signature

- Angular analysis of Λ→pπ⁻ to extract EDM and MDM from the change of spin-polarization after the magnet

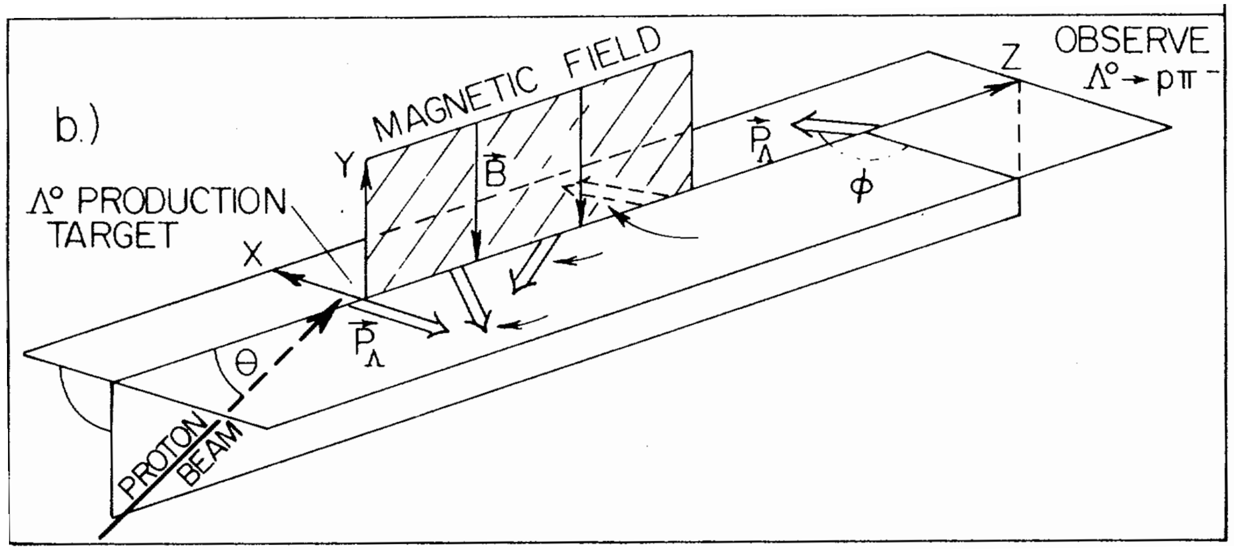
$$\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s} \cdot \hat{\mathbf{k}}$$

α = 0.642 ± 0.013 decay asymmetry parameter

k unit vector of proton momentum direction in Λ helicity frame

Current Λ baryon EDM limit

- Limit on Λ EDM from E761 fixed-target experiment:
  - Transversal polarization ≈8%
  - Signal yield $3 \cdot 10^6$
  - $\delta_\Lambda < 1.5 \cdot 10^{-16} e$ cm (95% C.L.)
  - $\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$



Phys. Rev. Lett. 41 (1978) 1348

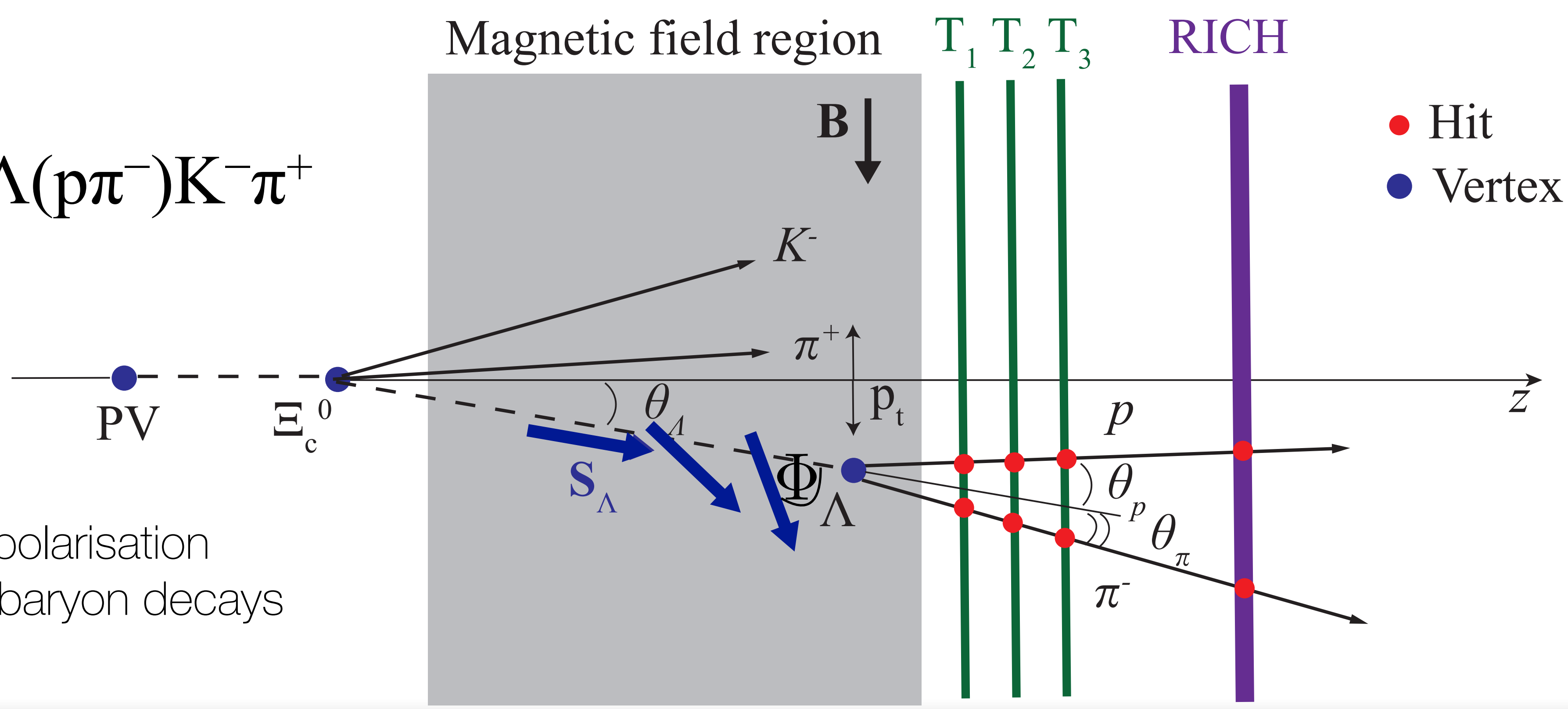
Phys. Rev. D23 (1981) 814

- Experimental setup similar to LHCb, pros/cons:
  - select large sample of Λ baryons from weak charm baryon decays with large longitudinal polarization 😎`(cool)`
  - reconstruction of Λ baryons decaying at the end of the magnetic field region is a challenge 🤓`(nerdy)`

Reconstruction of long-lived Λ baryons

- Reconstruction of Λ baryons at the end of the magnet is challenging: poor momentum and Λ vertex resolution
- Information from T stations and RICH only
- Strategy: use exclusive charm decays, e.g. $\Xi_c^0 \rightarrow \Lambda(p\pi^-)K^-\pi^+$ and exploit kinematic constraints
- According to preliminary simulations is doable but requires "ad-hoc" trigger/reconstruction algorithms

$\Xi_c^0 \rightarrow \Lambda(p\pi^-)K^-\pi^+$

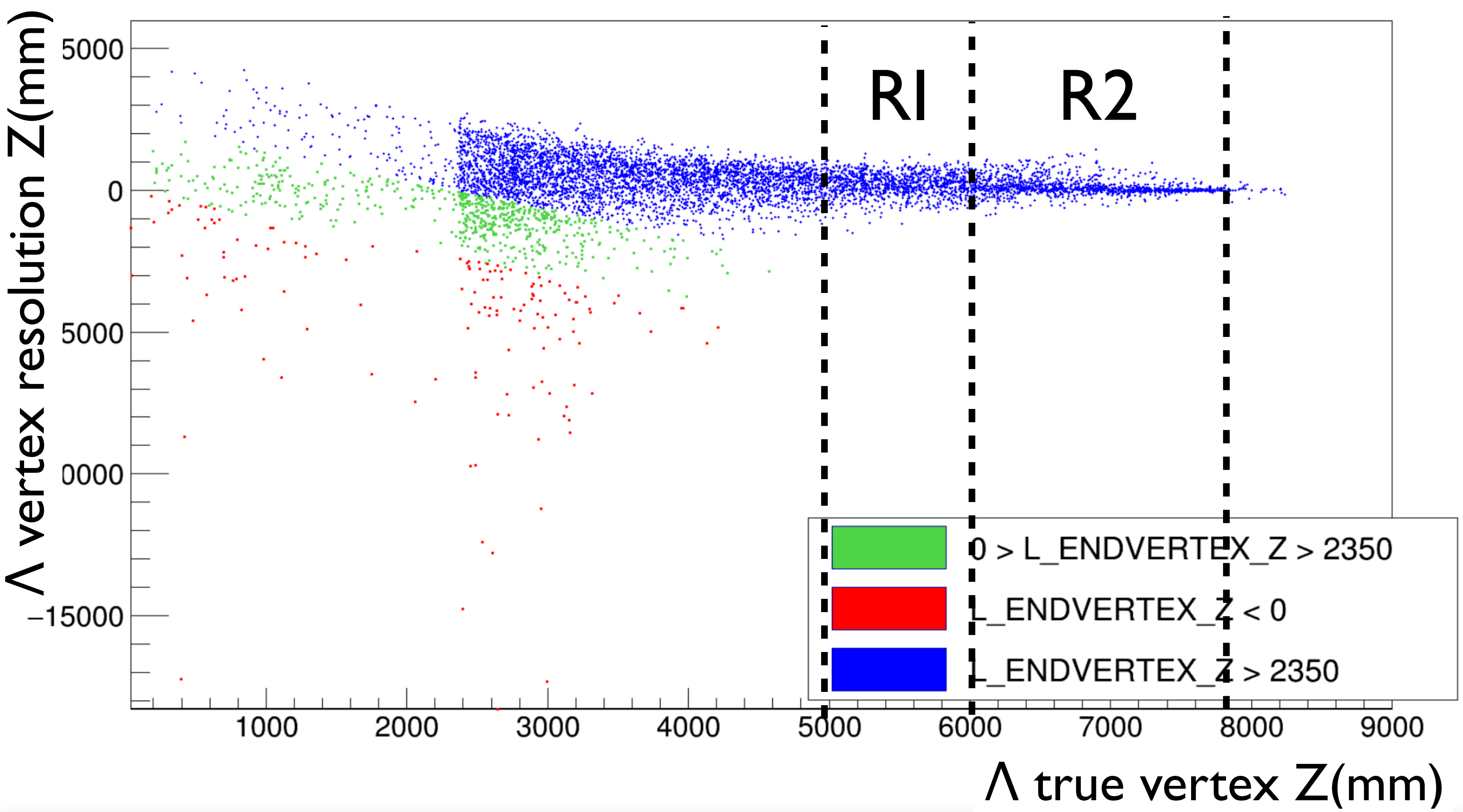


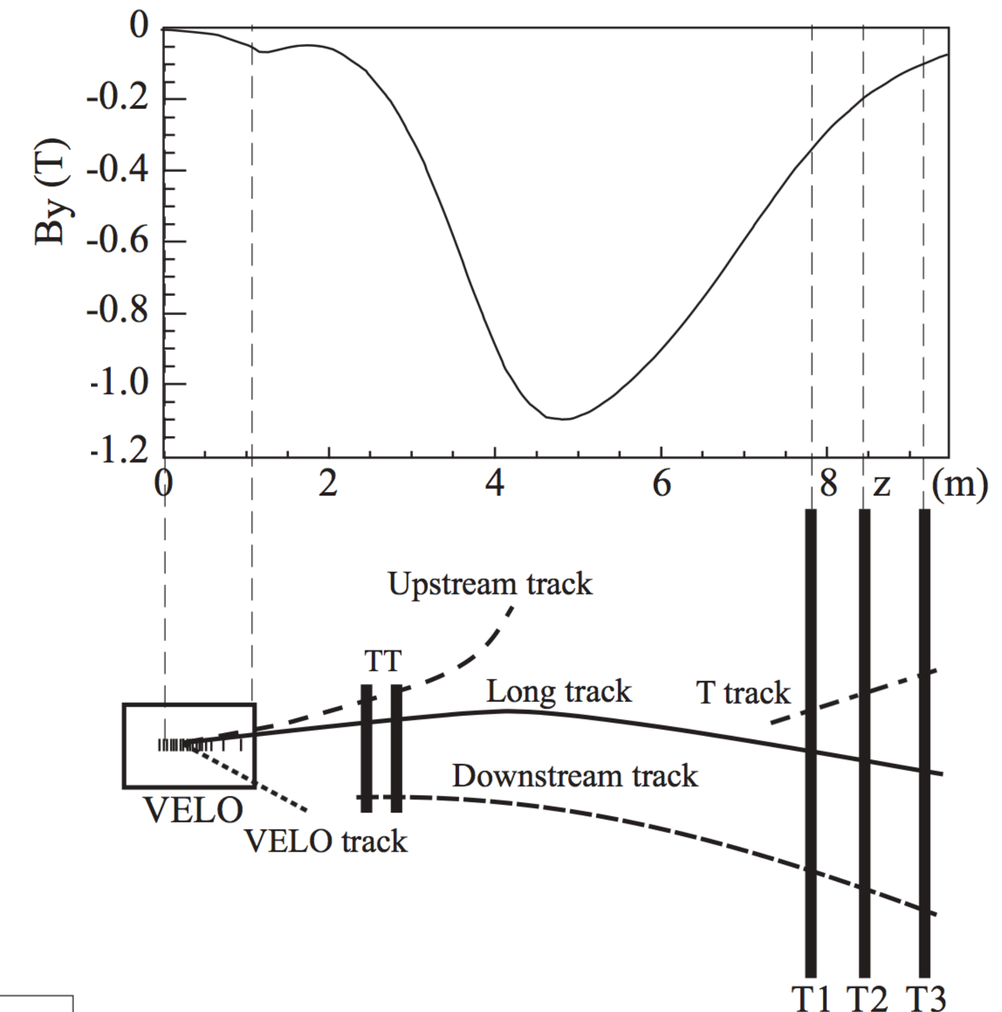
Λ longitudinal polarisation
from weak charm baryon decays

Λ baryon vertex resolution

- In R1 vertex z resolution ≈40 cm (40/550≈7%), in R2 ≈30 cm (30/700≈4%)
- vertex x, y resolution ≈2cm

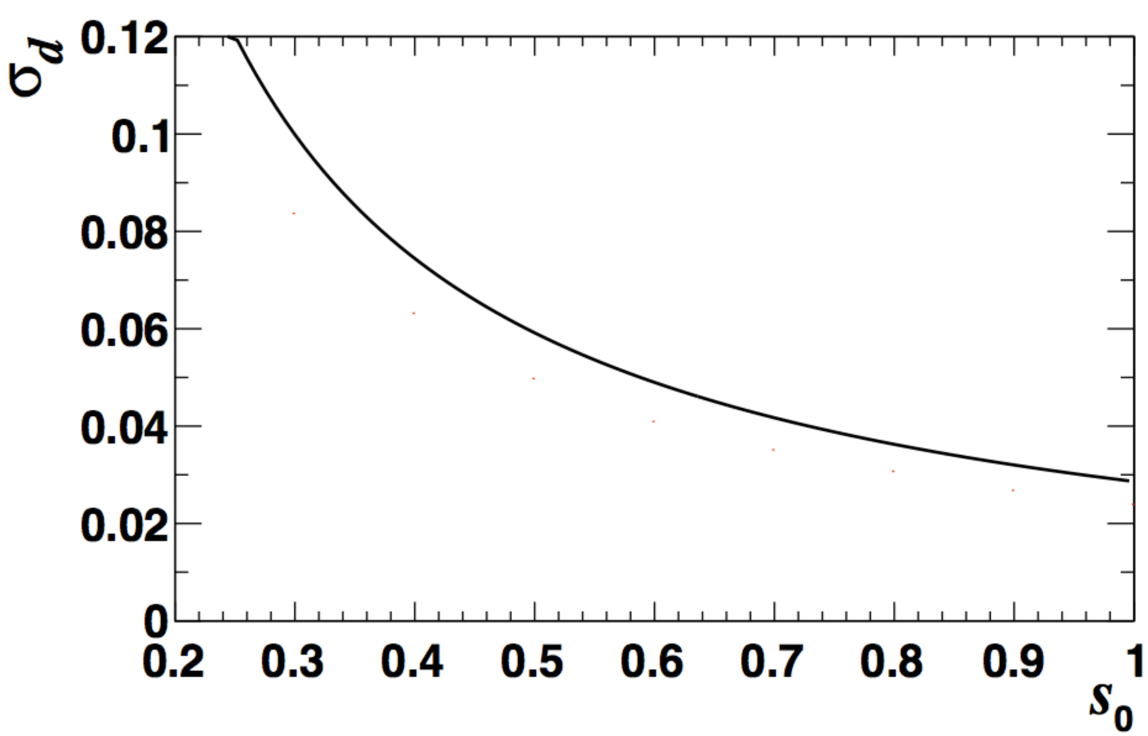
from A. Merli, L. M. Garcia Martin

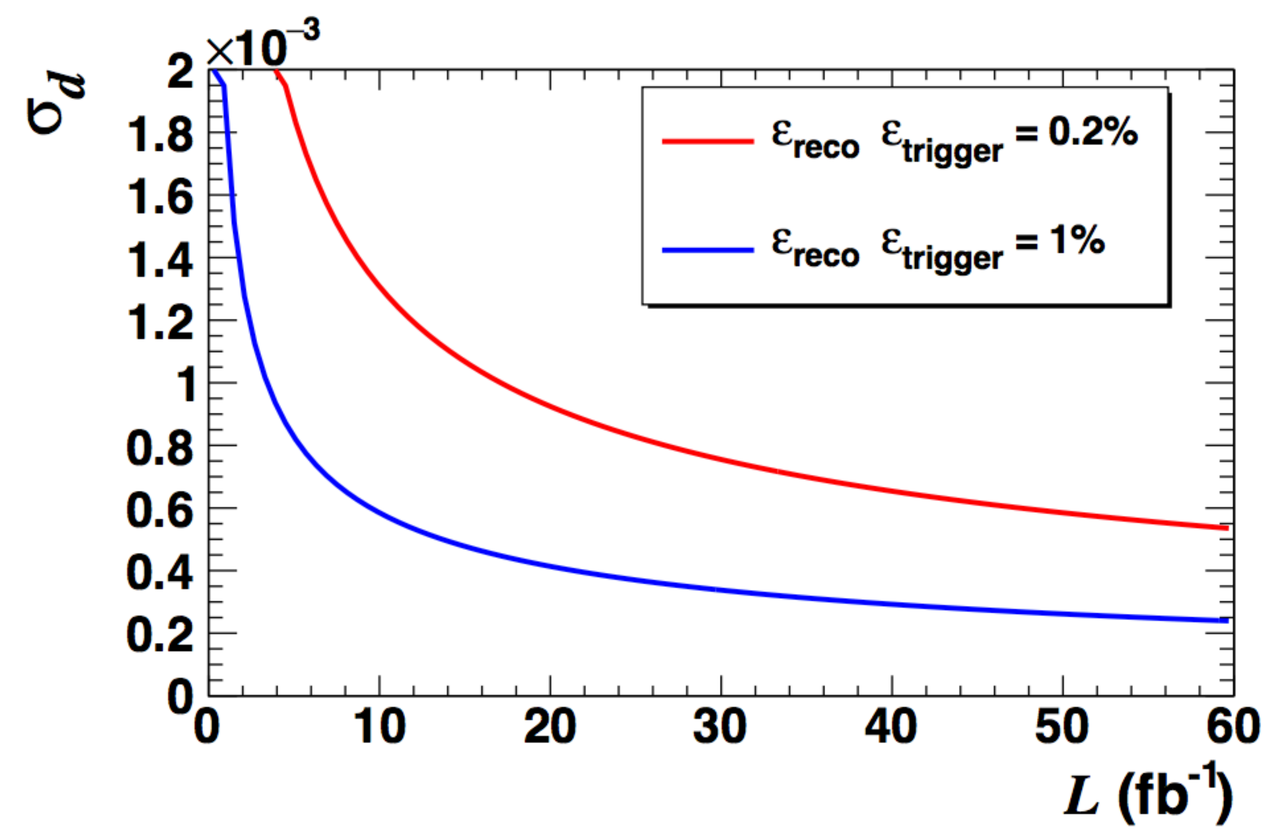




Sensitivity to Λ EDM

- Uncertainty ∝ $1/(S_0\sqrt{N})$, S_0=initial polarization
- Sensitivity to EDM at LHCb. Considering only events from *pp* collisions at ≈14 TeV





- Can achieve 2 orders of magnitude improved sensitivity
- Λ and anti-Λ baryon MDM provide a test of *CPT* symmetry at per-mille level

Current charm baryon EDM limit

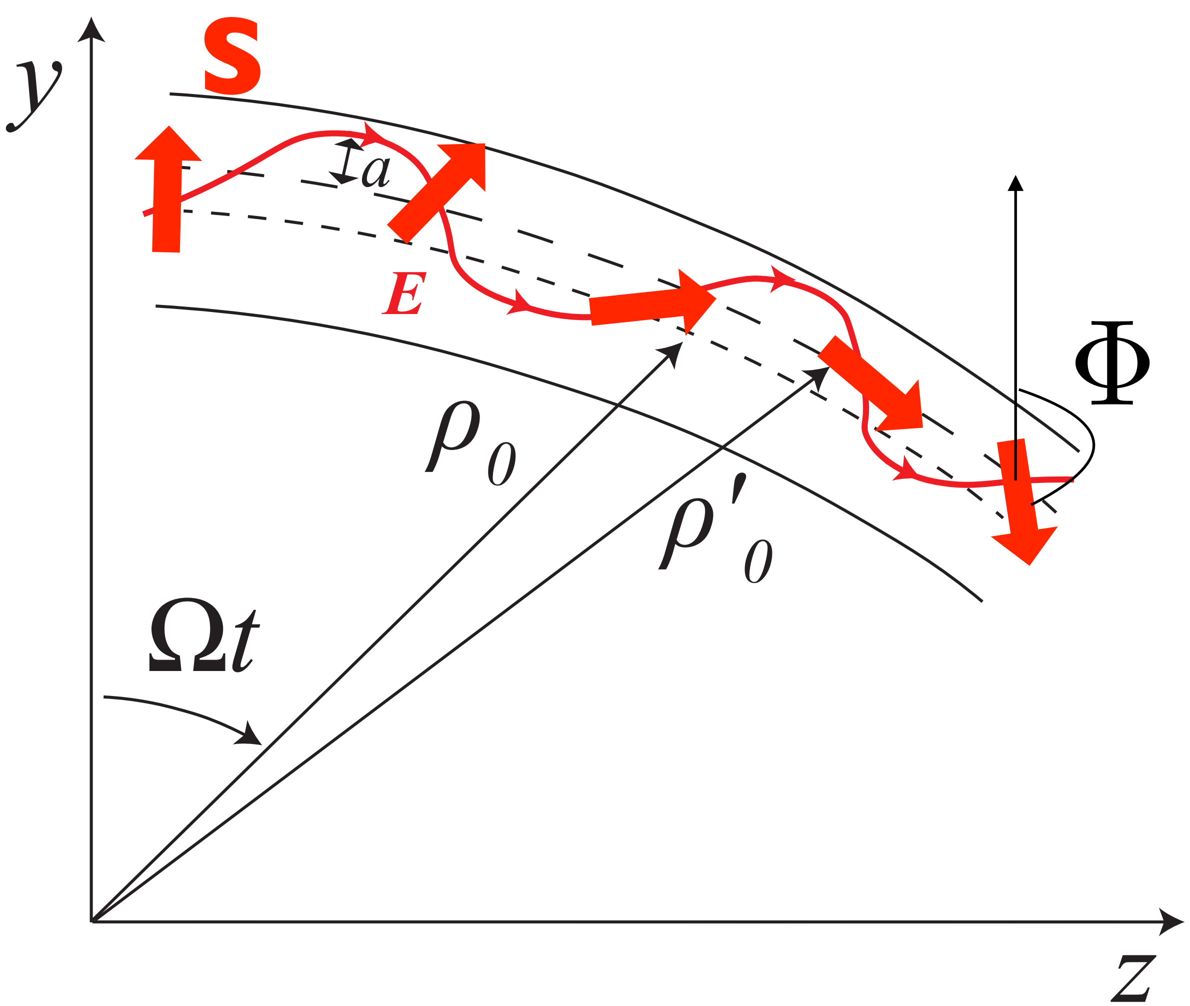
- No experimental measurements exist both for charm MDM and EDM
- Charm quark EDM indirect limits from F. Sala, JHEP 1403 (2014) 061
  - $|\boldsymbol{\delta_c}| \lesssim 4.4 \cdot 10^{-17} e\ \mathrm{cm}$ from neutron EDM limit
  - $|\boldsymbol{\delta_c}| \lesssim 3.4 \cdot 10^{-16} e\ \mathrm{cm}$ from charm dipole contribution to C_7 Wilson coefficient in $BR(B \to X_s \gamma)$
- Charm quark EDM upper limit is relevant for models allowing non-negligible flavour violation in the up-quark sector
  - stronger constraints than from ΔA_{CP}

Search for Λ_c^+, Ξ_c^+ baryon EDM at LHCb

- Charm baryons are short-lived

$$\tau(\Lambda_c^+) \approx 10^{-13}\mathrm{s} \ll \tau(\Lambda) \approx 10^{-10}\mathrm{s} \quad (\mathrm{B}\approx 1\mathrm{T})$$

- Required very high magnetic field $\approx 10^3$T to induce measurable spin-precession $\Rightarrow$ crystal channeling

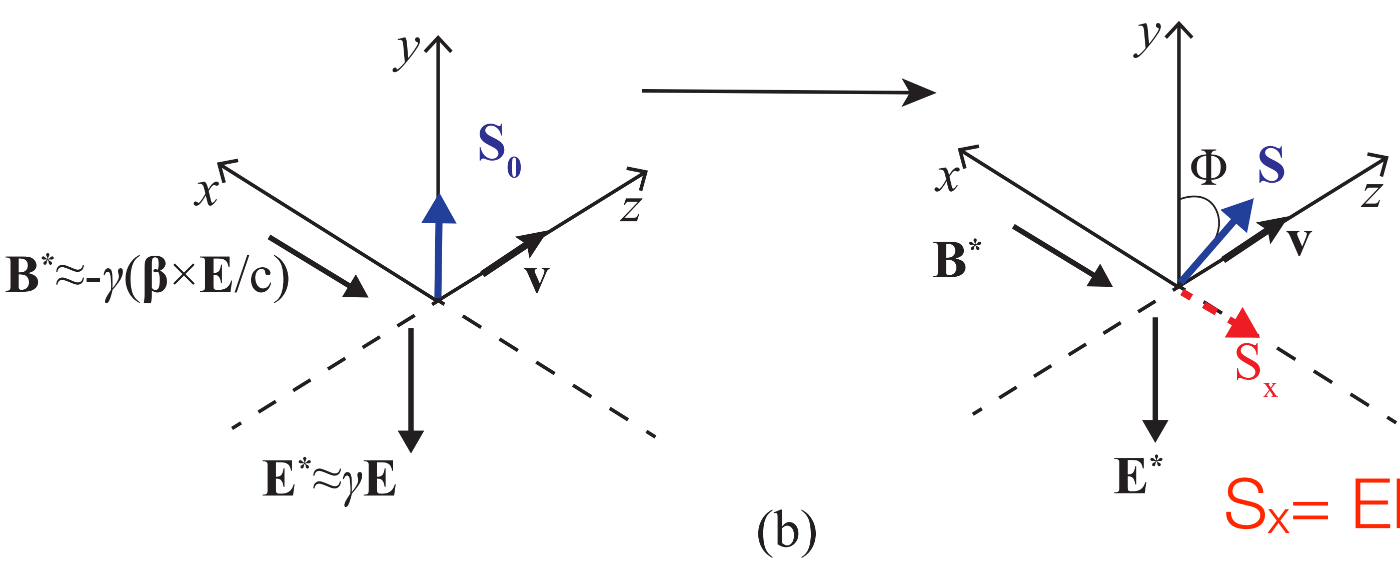


- Effective magnetic field seen by particles channeled in crystal atomic planes is of the order of 10^3T
- Positively-charged particles are bent and precess

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

Charm baryon EDM and MDM

- Electric field in the crystal channel is not uniform. T-BMT equation integrated in presence of field gradients and non-zero EDM $\boxed{\text{arXiv:1612.06769}}$
- For ultra-relativistic particles in bent crystal we obtain



Sx= EDM signature

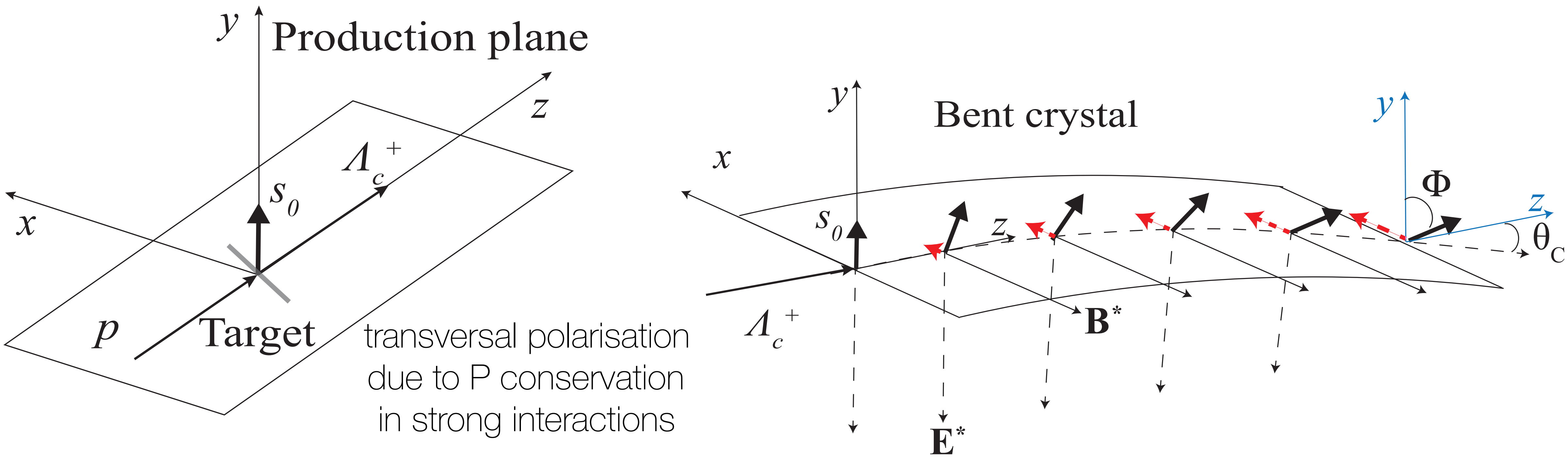
$$\mathbf{s} = \begin{cases} s_x \approx s_0 \dfrac{d}{g-2}(\cos\Phi - 1) \\ s_y \approx s_0 \cos\Phi \\ s_z \approx s_0 \sin\Phi \end{cases}$$

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

- From angular analysis of Λ_c^+, Ξ_c^+ decay products extract spin-polarization after the crystal and EDM, MDM information

Search for Λ_c^+, Ξ_c^+ baryon EDM at LHCb

- Fixed-target experiment for charm MDM measurement proposed in L. Burmistrov et al., CERN-SPSC-2016-030
- EDM can be searched for using identical experimental setup



- Experimental setup: fixed-target+bent crystal in LHC beam pipe. Impinging protons extracted from LHC beam halo using bent crystals ≈100 m upstream of the target
- Feasibility proved by UA9 experiment

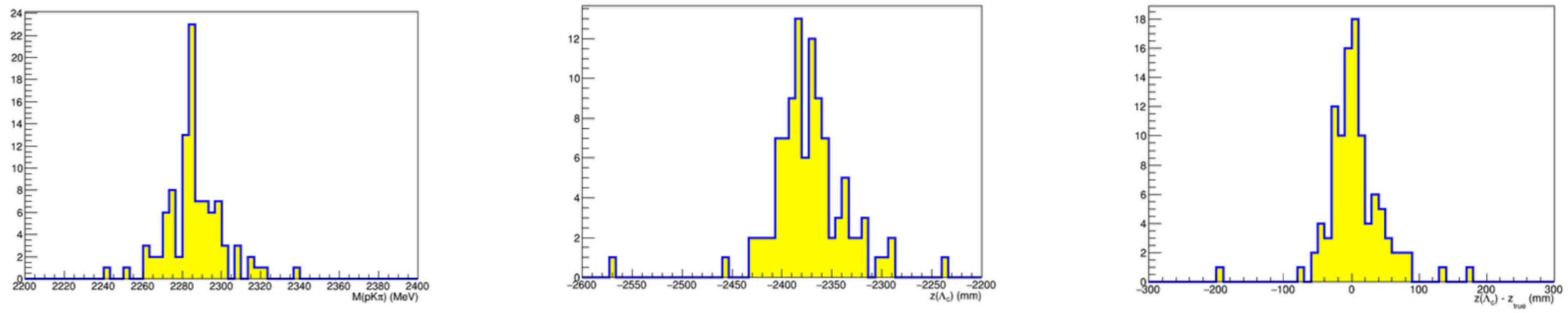
Physics Letters B 758 (2016) 129–133

Patrick Robbe's talk

Simulation studies

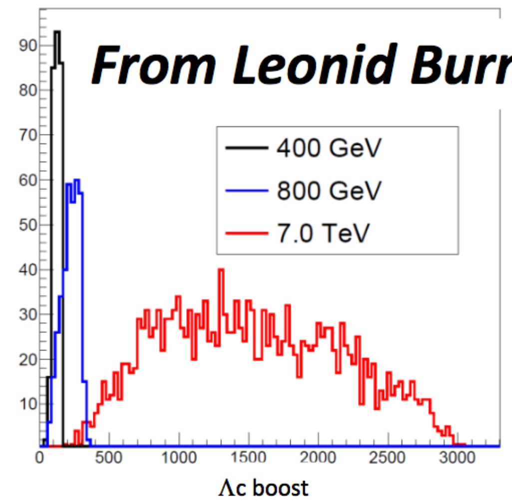
- Full **LHCb** detector simulation
- Generate 15000 $\Lambda_c \to p\,K\,\pi$ at the crystal position (x=0.945mm , y=4mm , z=-2379mm)
- $p(\Lambda_c)$ = 100 GeV

From Patrick Robbe



- Mass resolution: 14 MeV
- **z decay position resolution: 18mm**
- **Efficiency: 1.5% !**

From Leonid Burmistrov

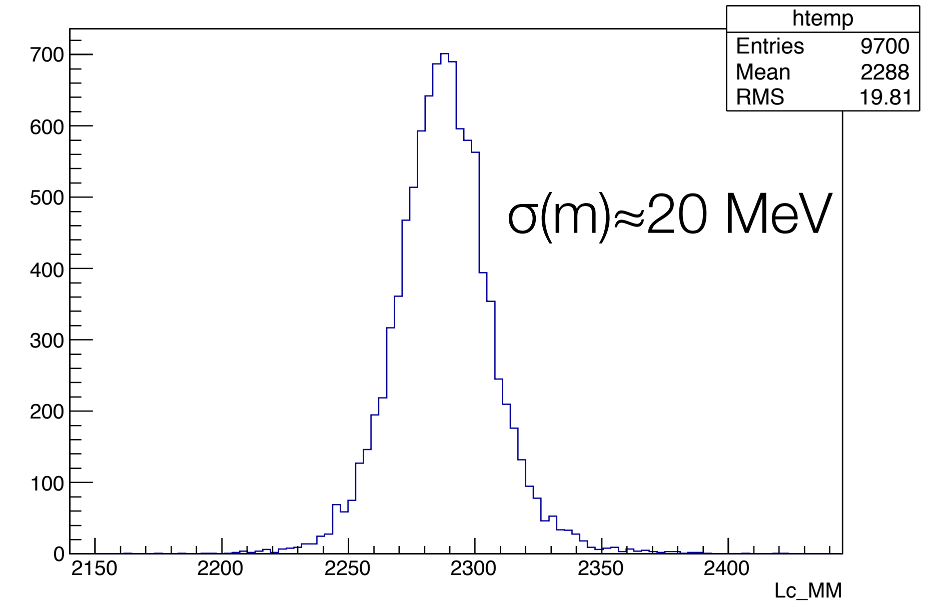


The particles selected after the crystal are
- -2.5m from the interaction point in z
- at extremely large momentum

Not ideal for resolution and efficiency !

11

- $p(\Lambda_c)$=1 TeV



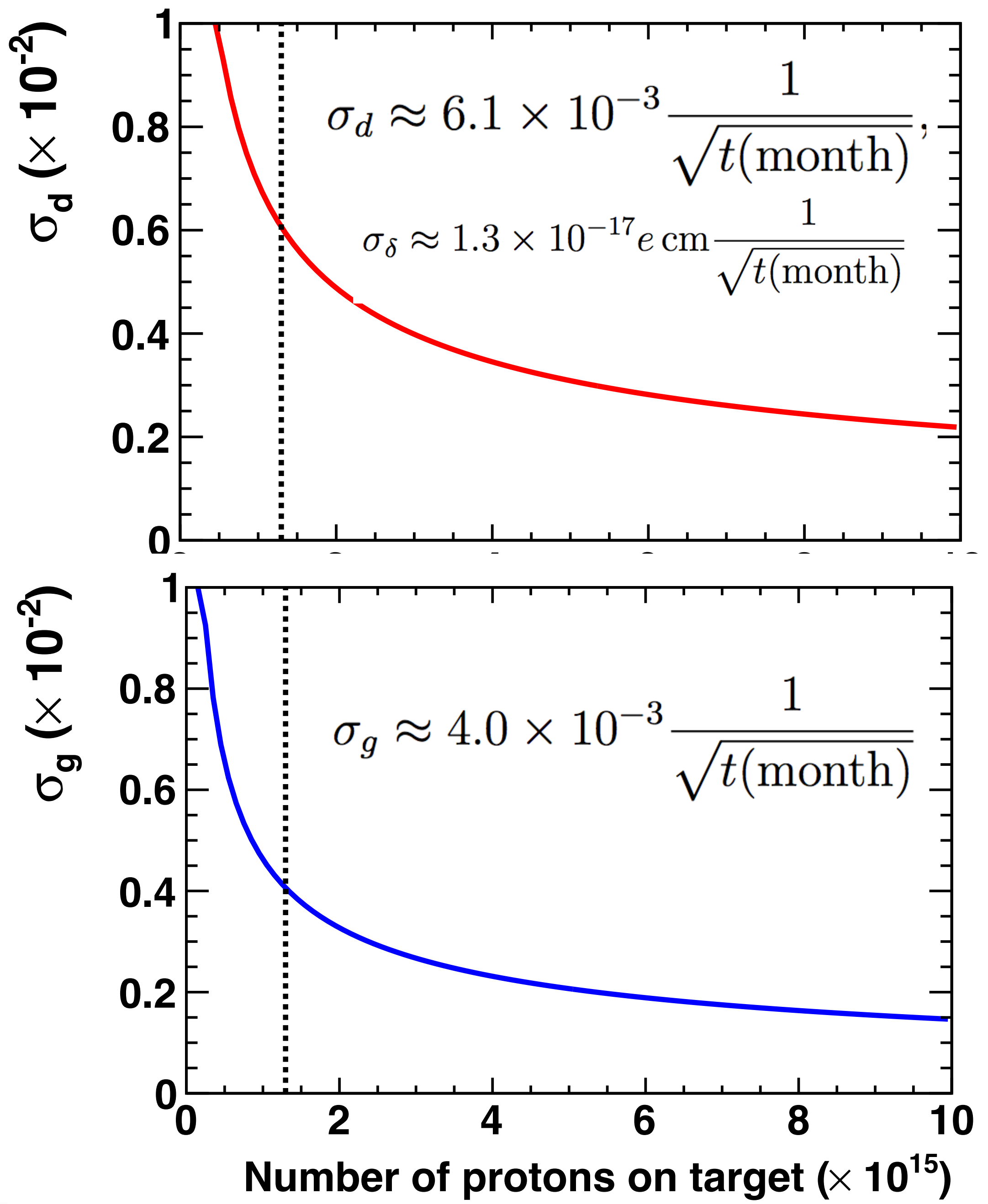
from Andrea Merli

Charm EDM expected sensitivity

- Flux 5 10^8 p/s, 5mm thick W target

arXiv:1612.06769

- Good sensitivity in 1 month, using $\Lambda_c^+ \to \Delta^{++}K^-$ decays



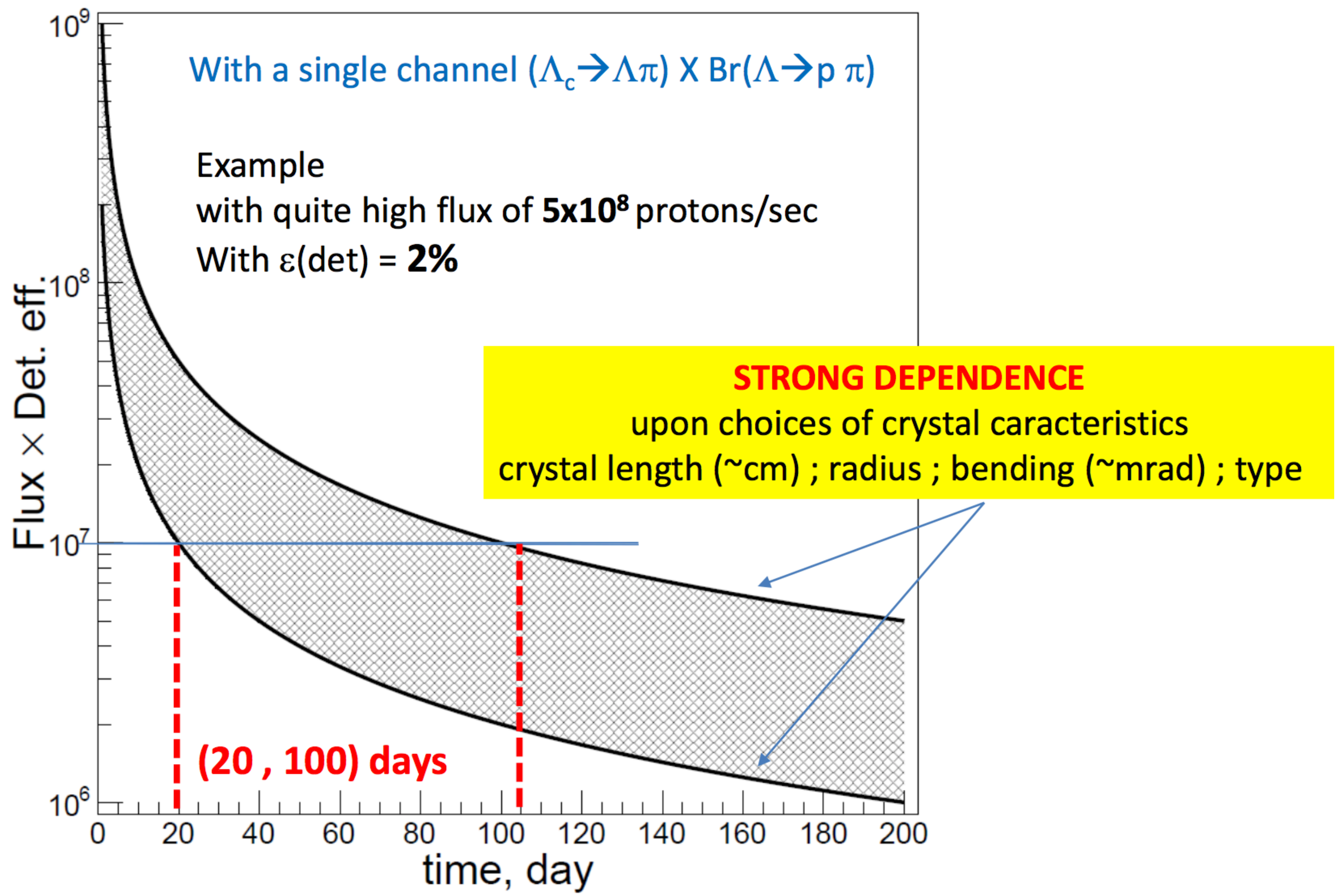
Estimated values for sensitivity studies

Definition	Quantity	Value	Unit
Proton flux on target	F	5×10^8	proton/s
Avogadro number	N_A	6.022×10^{23}	atoms/mol
Target density (W)	ρ	19.25	g/cm^3
Target thickness	T	0.5	cm
Atomic mass (W)	A_T	183.84	g/mol
Atomic mass number (W)	A_N	183.84	
pp cross-section to Λ_c^+	$\sigma(pp \to \Lambda_c^+ X)$	18.2	μb
Branching fraction [38]	$\mathcal{B}(\Lambda_c^+ \to \Delta^{++}K^-)$	1.09%	
	$\mathcal{B}(\Lambda_c^+ \to \Lambda(p\pi^-)\pi^+)$	0.83%	
Λ_c^+ boost	γ	10^3	
Crystal length	L	10	cm
Crystal radius	ρ_0	10	m
Channeling efficiency	ε_{CH}	10^{-3}	
Decay flight efficiency	$\varepsilon_{\text{DF}}(\Lambda_c^+)$	19%	
	$\varepsilon_{\text{DF}}(\Xi_c^+)$	47%	
Detector efficiency	$\varepsilon_{\text{det}}(\Lambda_c^+ \to pK^-\pi^+)$	5.4%	
	$\varepsilon_{\text{det}}(\Lambda_c^+ \to \Lambda(p\pi^-)\pi^+)$	10^{-3}	
Λ_c^+ polarization	s_0	0.6	
α parameter	$\alpha_{\Lambda\pi^+}$	-0.91	
	$\alpha_{\Delta^{++}K^-}$	-0.67	
MDM anomaly	$(g-2)/2$	0.3	

MDM sensitivity using $\Lambda_c^+ \rightarrow \Lambda(p\pi^-)\pi^+$

- Long-lived Λ more difficult to reconstruct, $\alpha_{\Lambda\pi} = -0.91 \pm 0.15$

Example. To have a precision on $g \pm 0.1$



From Leonid Burmistrov

R&D for long bent crystals

For more details see presentation at conference Channeling 2016: A. Mazzolari

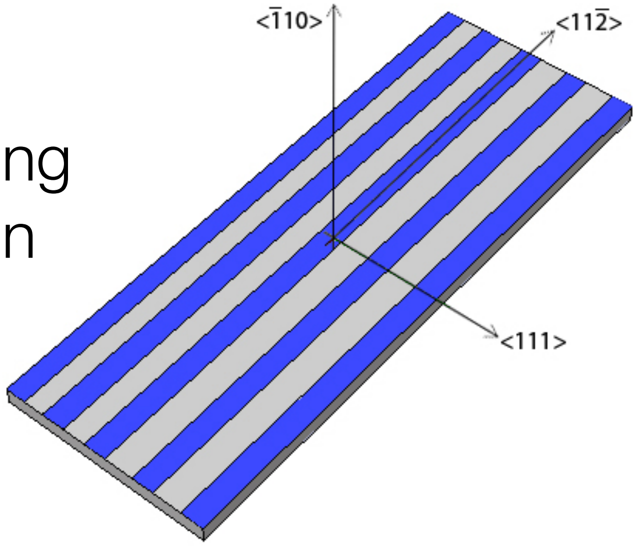
- R&D ongoing at INFN Ferrara for long crystal production following two different approaches:

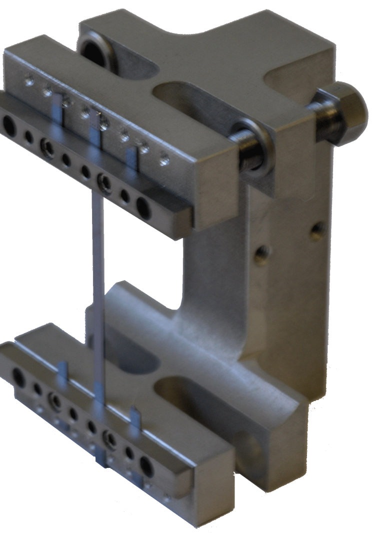
1) Anticlastic deformation

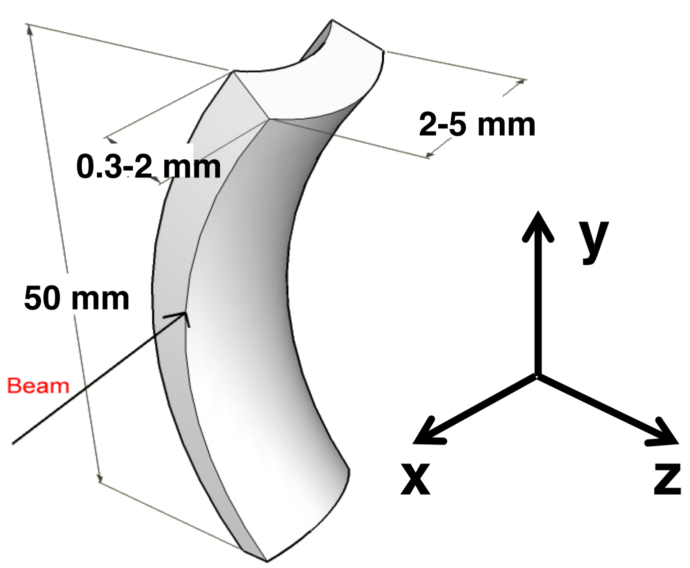
- Bending of the crystal exploits anticlastic deformation
- A mechanical bending device is needed

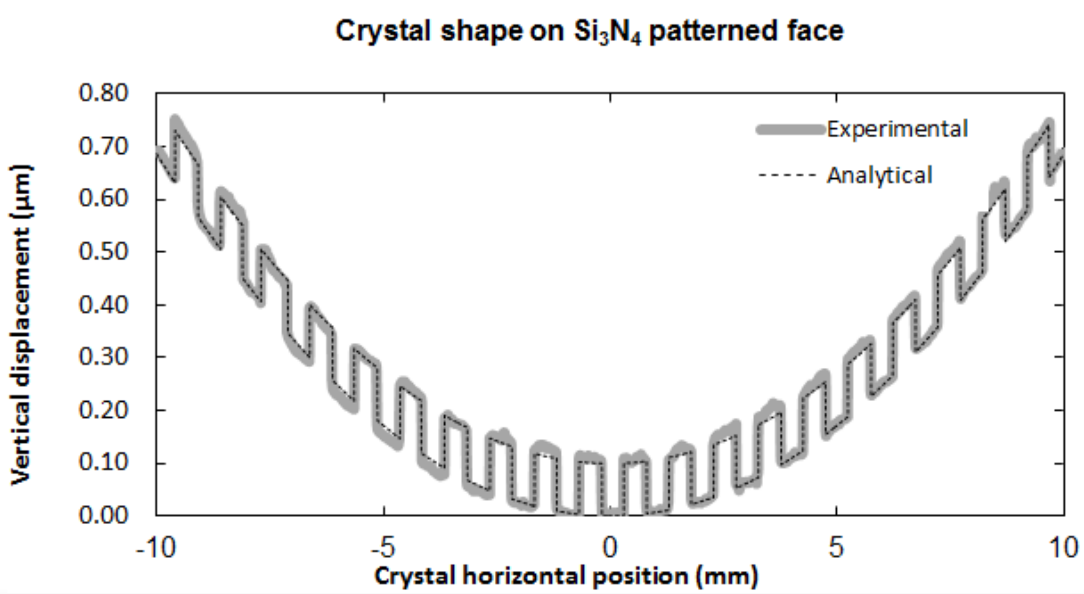
2) Self bent crystals

- Curvature generated by deposition and patterning of a thin (100 nm) silicon nitride layer









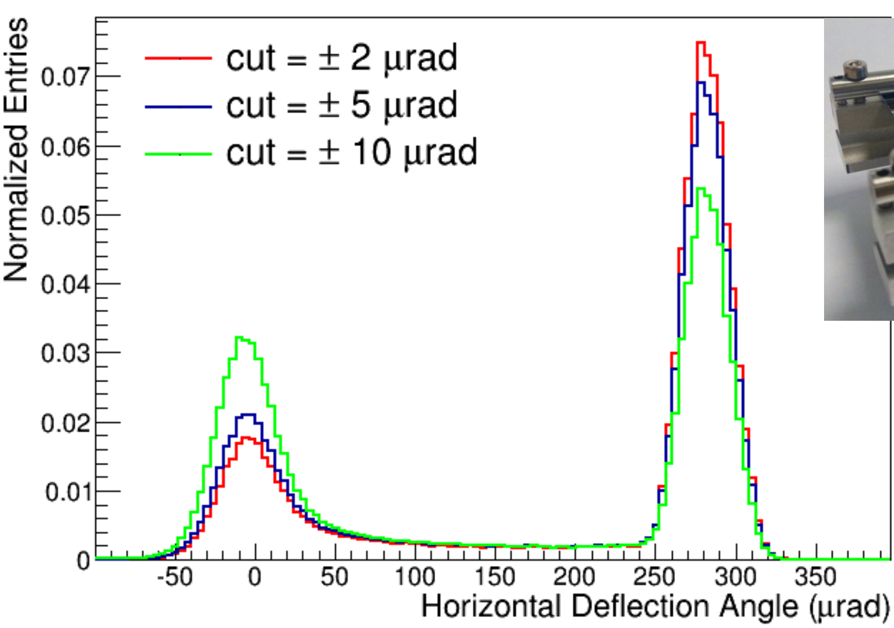
Preliminary results are very encouraging

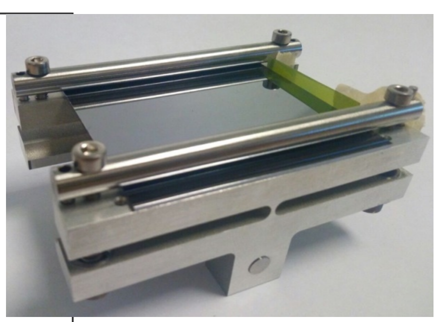
For more details see presentation at conference Channeling 2016: A. Mazzolari

1) Anticlastic deformation

Parameter	PL03	PL02	PL02-B
Plane	(111)	(110)	(110)
Thickness (z)	56.8±0.1 mm	23.8±0.1 mm	23.8±0.1 mm
Height (y)	55 mm	55 mm	55 mm
Width (x)	1 mm	1 mm	1 mm
Bending angle (μrad)	(322.6±1.0)	~ 300	~ 1900

L = 5.7 cm
Bending angle ~ 0.3 mrad

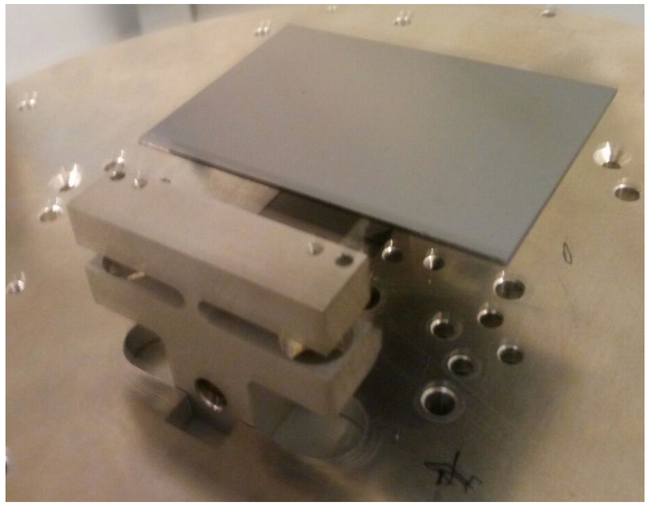


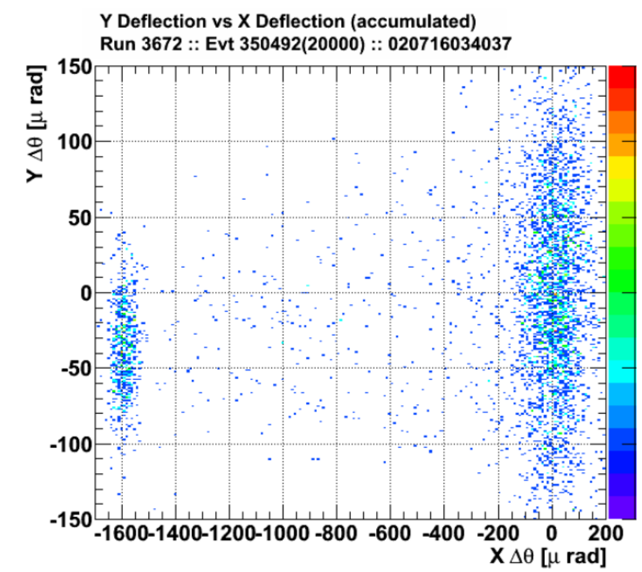


2) Self bent crystals

Characterization	Value
Crystal thickness along the beam	55±0.1 mm
Crystal transverse thickness	1 mm
Crystal height	55 mm
Channeling plane	(110)
Channeling axis	<111>

L = 5.5 cm
Bending angle ~ 1.6 mrad





Preparatory measurements for EDM searches

- We can already start a program of measurements at LHCb that are preparatory for the EDM search:
  - polarization of Λ baryons originated from weak charm decays, e.g. $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$, $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^- \pi^+$
  - $\sigma(pp \rightarrow \Lambda_c^+ X)$ and $\sigma(pp \rightarrow \Xi_c^+ X)$ cross sections and polarization at $\sqrt{s} \approx 115$ GeV, using p-gas SMOG data
  - Amplitude analysis of $\Lambda_c^+, \Xi_c^+ \rightarrow$ 3-body decays, e.g. $\Lambda_c^+, \Xi_c^+ \rightarrow p K^- \pi^+$, $\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$, $\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$ for determination of baryon polarization, using *pp* collision data at $\sqrt{s} \approx 14$ TeV

Summary

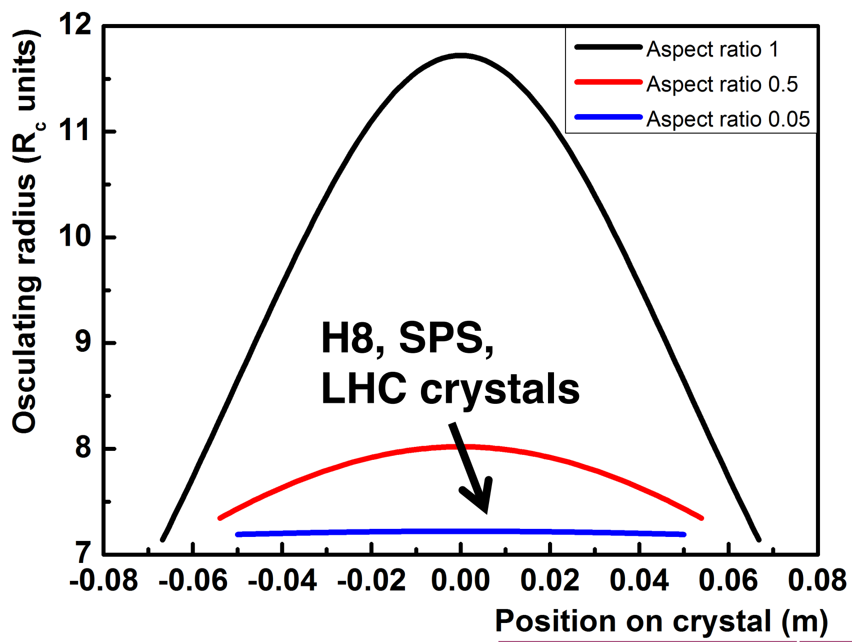
- Interesting possibility to contribute to the EDM research program at LHCb:
  - two orders of magnitude improved sensitivity to Λ baryon EDM: $\sigma_\delta \approx 10^{-18} e \text{ cm at } 50 fb^{-1}$
  - precise measurements of Λ and anti-Λ baryon MDM for a test of *CPT* symmetry at per-mille level
  - first search for Λ_c^+, Ξ_c^+ charm baryon EDM and first MDM measurement: $\sigma_\delta \approx 1.3 \times 10^{-17} e\,\text{cm} \frac{1}{\sqrt{t(\text{month})}}$ $\sigma_g \approx 4.0 \times 10^{-3} \frac{1}{\sqrt{t(\text{month})}}$
- Several challenges:
  - reconstruction of Λ baryons decaying at the end of the magnet using T stations and RICH info
  - fixed-target experiment with bent crystals for charm baryons

Results and perspectives

- Preliminary results:
  - Λ reconstruction is doable exploiting kinematic constraints of exclusive weak charm baryon decays
  - high energy Λ_c^+, Ξ_c^+ (1 TeV) can be reconstructed by LHCb detector
  - UA9 using bent crystals in the LHC beam pipe deflected the beam halo with good efficiency
  - R&D on long crystals is ongoing and preliminary results are very encouraging
- EDM studies being summarised in a note to circulate within LHCb collaboration
- Considering to produce a “CDR document” for MDM/EDM charm baryon experiment

Backup slides

Crystal bending
-anticlastic deformation-



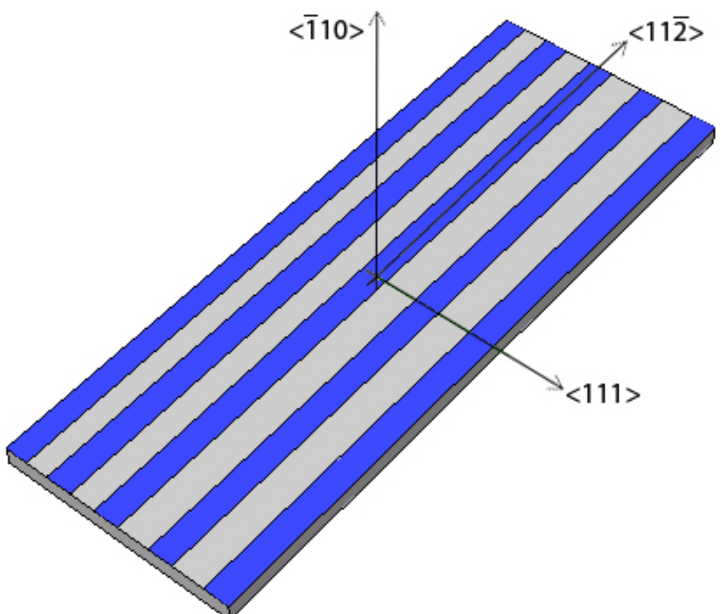
We consider a crystal with thickness along the beam of ~100 mm. Bending angle 1 mrad
We increase aspect ratio →

- Compact crystal along the vertical direction
- Decrease of deformation uniformity
- Stronger bending
- Exploting anticlastic requires pretty high deformations.

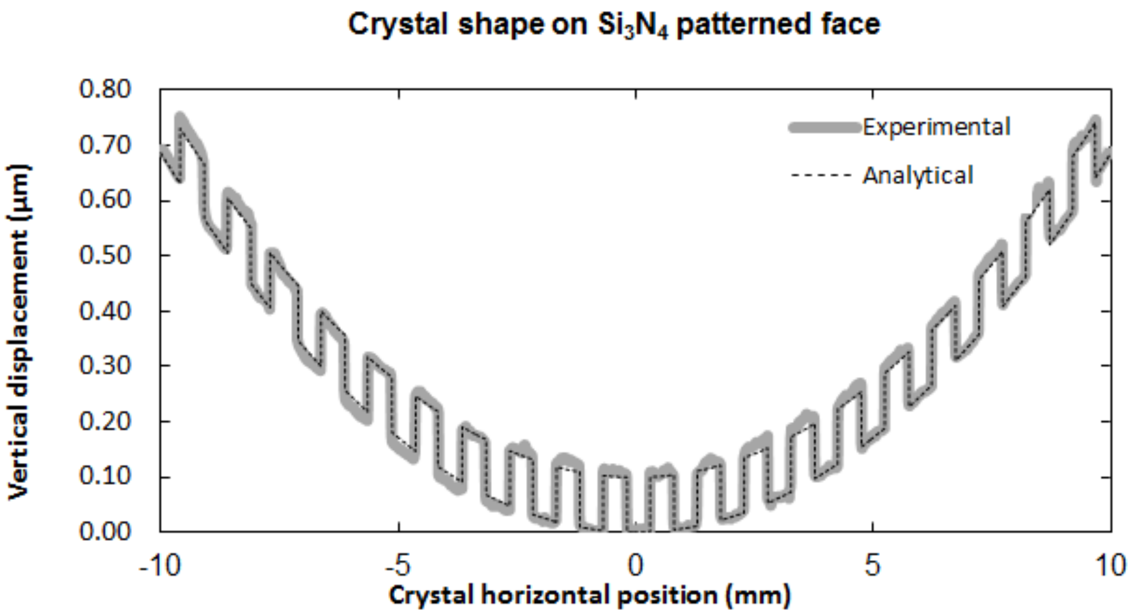
Thickness along the beam (m)	Crystal height (m)	Aspect ratio	Bending angle (urad)	Principal radius (m)
0.137	0.137	1	1000	7.79
0.11	0.22	0.5	1000	14.01
0.102	2.04	0.05	1000	17.68

For more details see presentation at conference Channeling 2016

Crystal bending
-Thin/thick film deposition-



Deposition of 100 nm thin silicon nitride and patterning

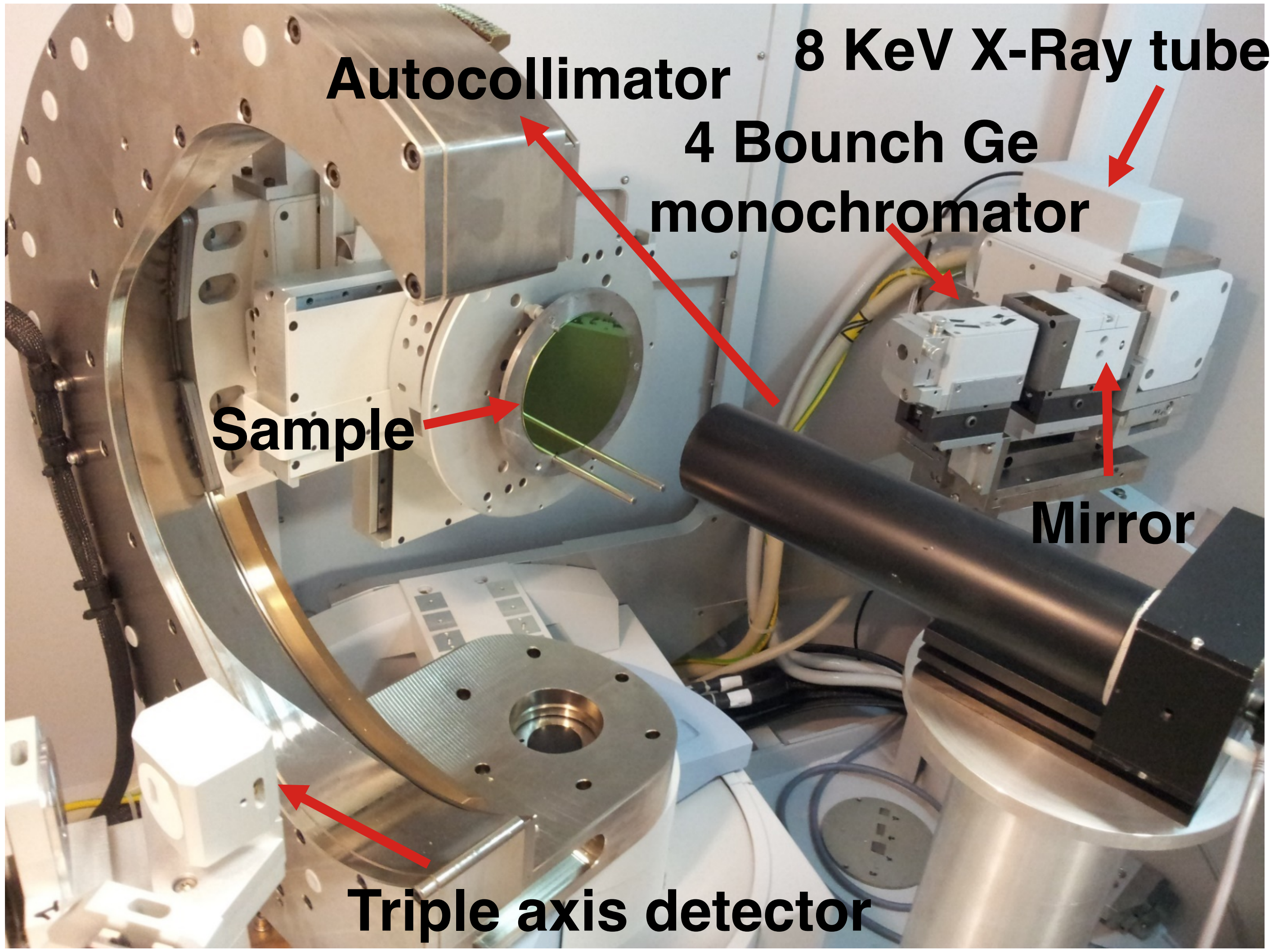


Perfect agreement between deformed and predicted crystal shape.

- lines 500 μm wide
- spacing 1000 μm

V. Guidi et al. Thin Solid Films 520 (2011) 1074

CRYSTALS MANUFACTURING AND CHARACTERIZATION



High resolution x-ray diffraction+autocollimator.

- Assestement of crystalline quality (dislocations).
- Crystal deformational state (bending angle and torsion).
- Off-axis measurement.

CRYSTALS MANUFACTURING AND CHARACTERIZATION

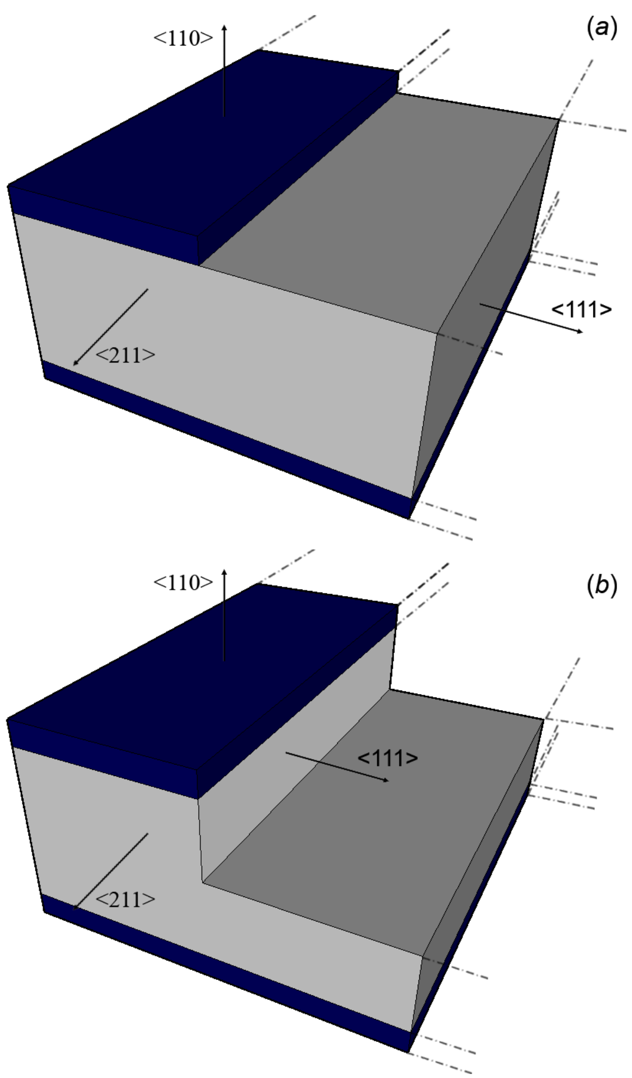
Interferometric microscope Veeco NT1100

3D reconstruction of a surface with sub-nm accuracy in the vertical direction and micrometer accuracy along lateral.

Possibility to stich over areas up to 100x100 mm^2

[For more details see presentation at conference Channeling 2016]()

Crystal manufacturing -Anisotropic etching-



Anistropic etching is a feasible way to realize sub-surface damage free crystals entirely by wet chemical methods.

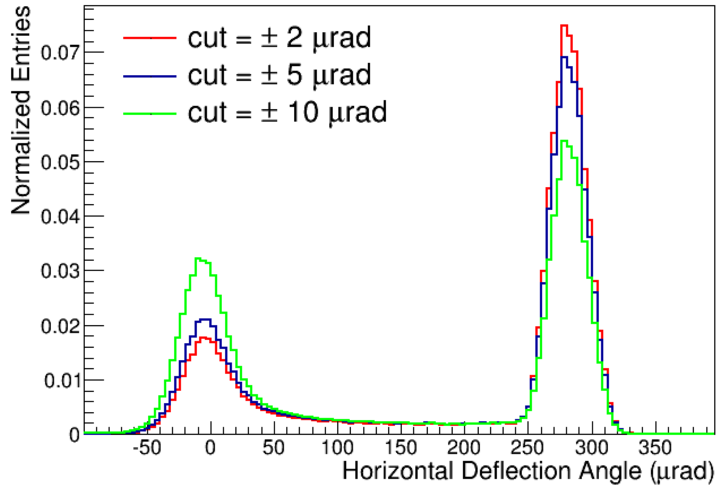
Etch rate on different silicon planes for KOH 20% at 40 deg.

(100)	(110)	(111)
7.1 ?m/h	10.7 ?m/h	Negligible

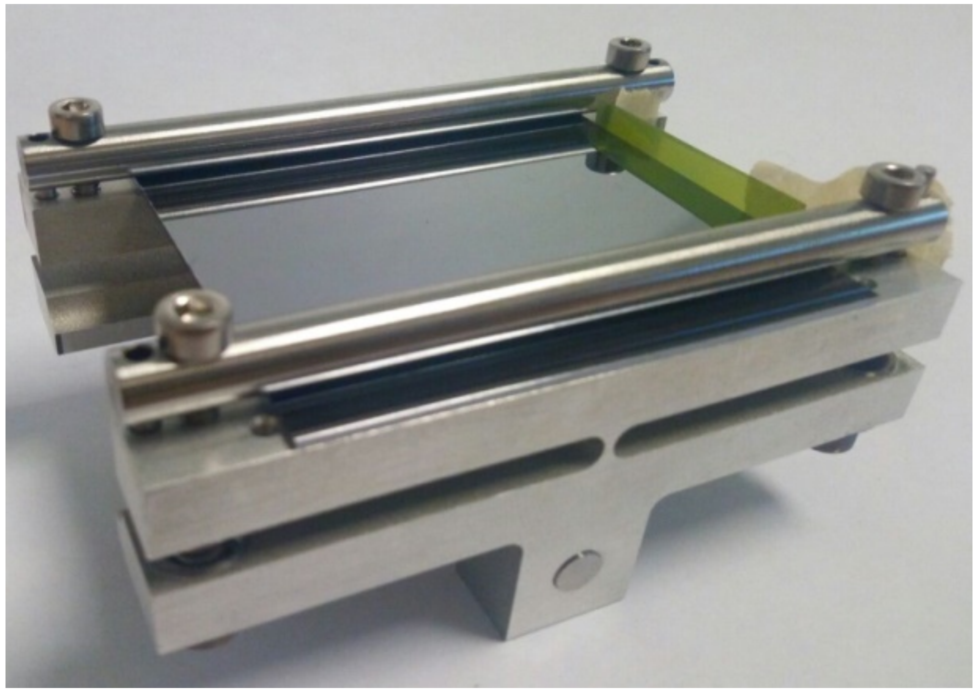
For more details see presentation at conference Channeling 2016

INFN - LONG CRYSTALS - ANTICLASTIC DEFORMATION -tested at H8 extracted beam line (2016)-

Parameter	PL03	PL02	PL02-B
Plane	(111)	(110)	(110)
Thickness (z)	56.8±0.1 mm	23.8±0.1 mm	23.8±0.1 mm
Height (y)	55 mm	55 mm	55 mm
Width (x)	1 mm	1 mm	1 mm
Bending angle (μrad)	(322.6±1.0)	~ 300	~ 1900

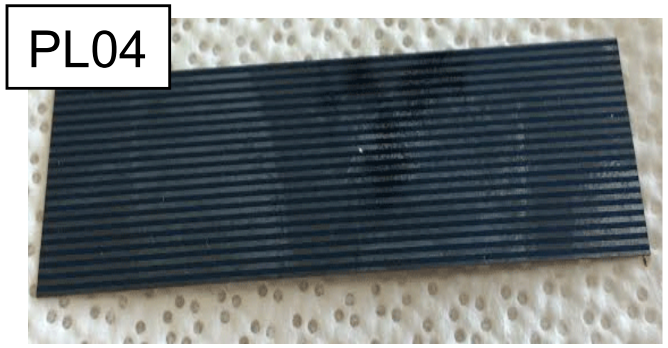


- Bending of the crystal exploits anticlastic deformation
- A mechanical bending device is needed

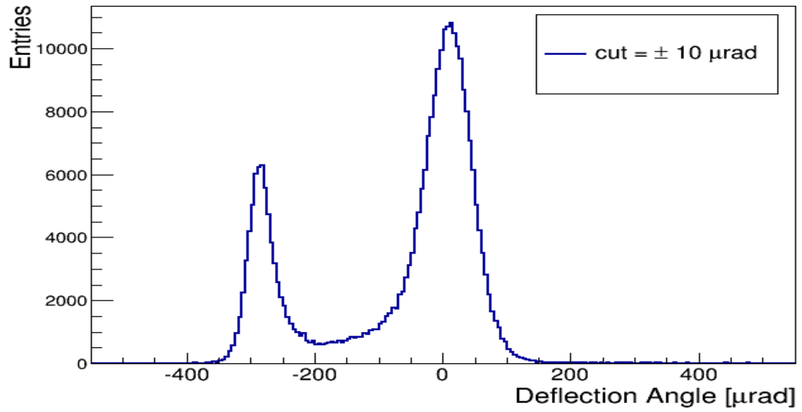


INFN - LONG CRYSTALS - SELF BENT CRYSTAL -tested at H8 extracted beam line (2016)-

PL04



Parameter	PL04
Plane	(110)
Thickness (z)	20.0±0.1 mm
Height (y)	70 mm
Width (x)	0.3 mm



CUT	Deflection angle	Eff. ±3σ
±10 μrad	(-284.5±2.5) μrad	(23±1) %

- Curvature generated by deposition and patterning of a thin (100 nm) silicon nitride layer

- Mechanical bending device not needed

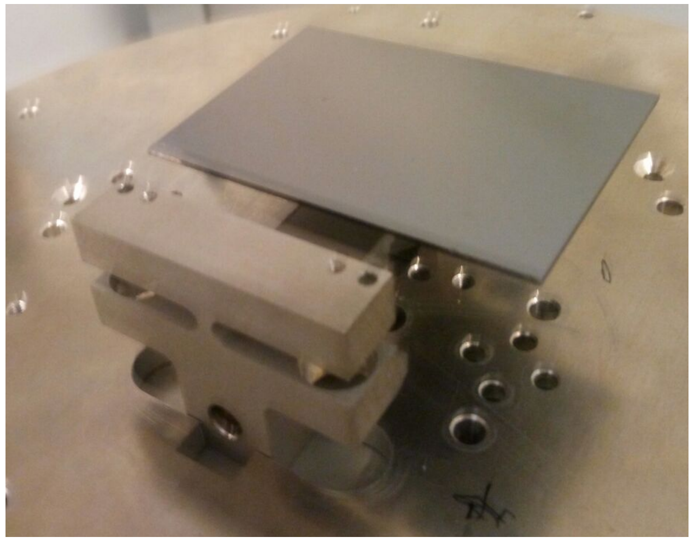
For more details see presentation at conference Channeling 2016

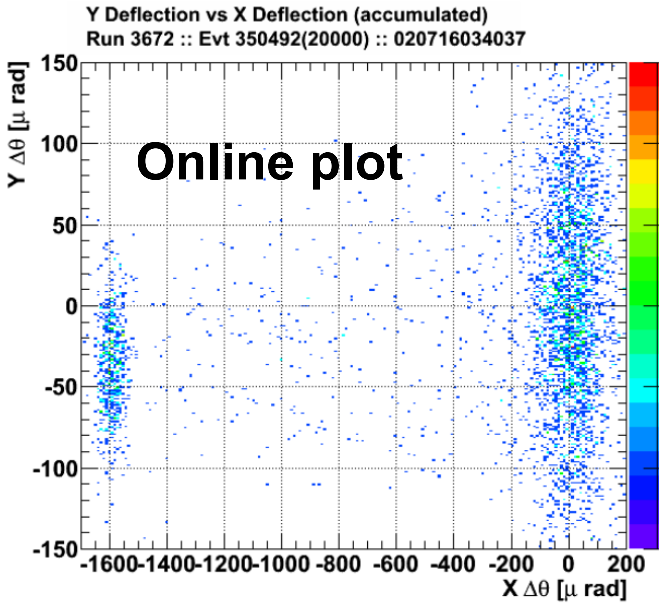
LONG CRYSTALS «PL05» - SELF BENT CRYSTAL -tested at H8 extracted beam line (2016)-

Characterization	Value
Crystal thickness along the beam	55±0.1 mm
Crystal transverse thickness	1 mm
Crystal height	55 mm
Channeling plane	(110)
Channeling axis	<111>

Bending angle ~ 1.6 mrad

- Crystal deformation occurs as a consequence of plasticitazion of one of its main surfaces
- Self standing crystal
- Mechanical bending device not needed

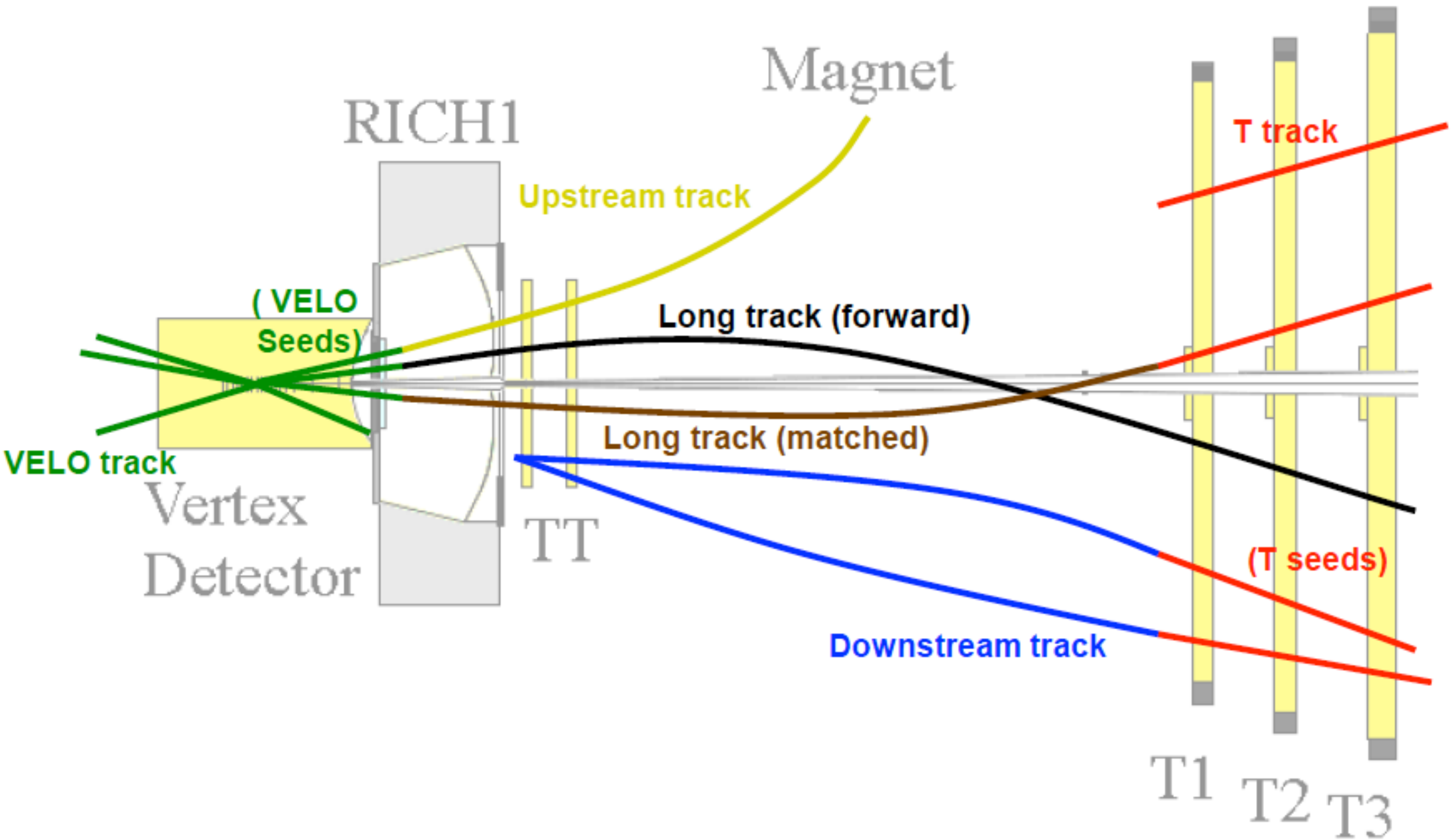




Flavour physics

- Flavour physics: study of *flavour-changing* and CP-violating phenomena of quarks and leptons
- Standard Model (SM) very successful but likely to be an effective theory
- Role of flavour physics:
  - identify symmetries and symmetry-breaking patterns beyond SM
  - indirect probe of new physics at energy scales not directly accessible at accelerators

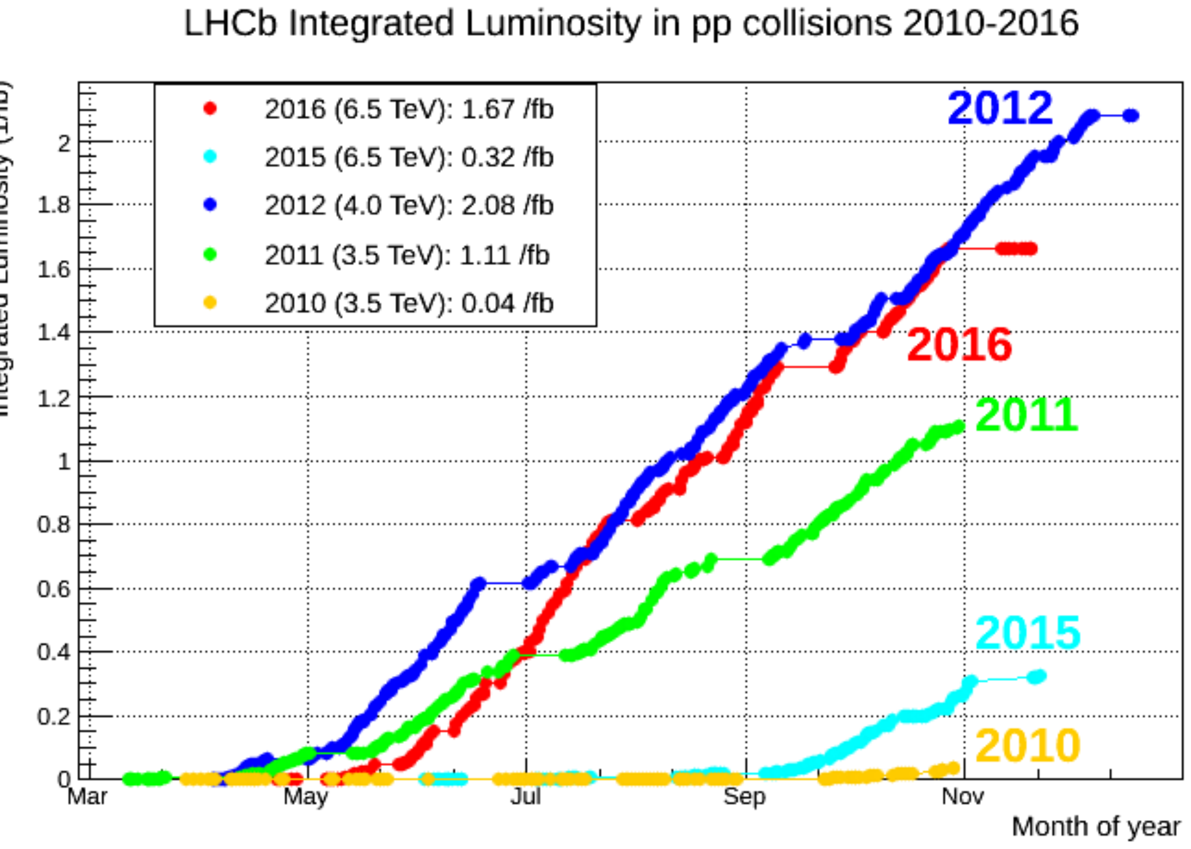
Track definitions at LHCb



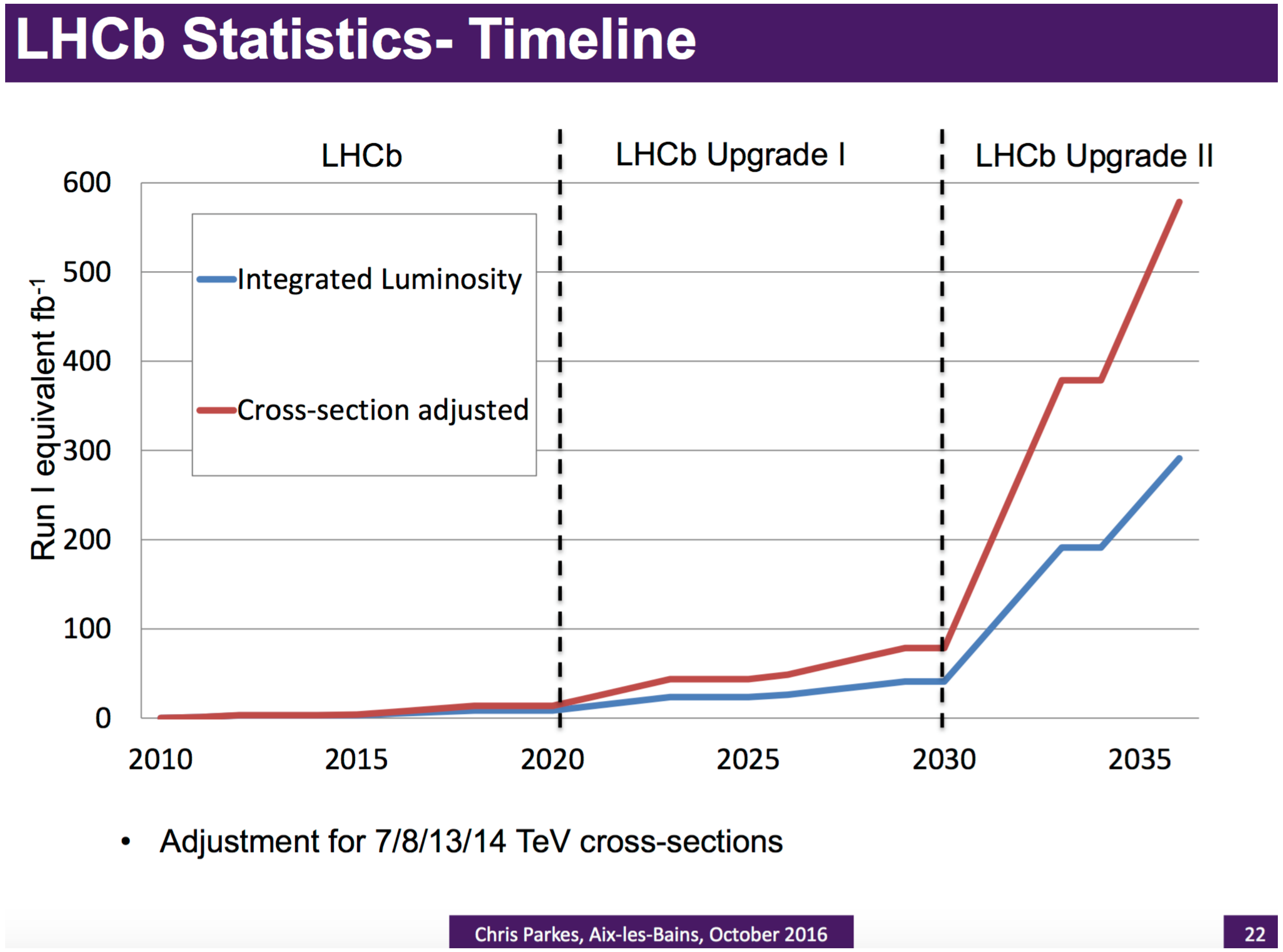
Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)

LHCb statistics and perspectives

LHCb data sample



From Chris Parkes at ECFA workshop, Oct16



- In 2016 collected almost twice *b*-baryon signal yields wrt Run1, factor 2 increase in $b\bar{b}$ cross-section from 7-8TeV to 13TeV
- Possibility to increase yields x30 Upgrade I and x200 Upgrade II