Bent crystals report

QCD
BSM

F. Martínez Vidal, IFIC-Valencia

Contributions from:

LHC-FT Working Group, LHC Collimation Group, UA9 Collaboration,

LHCb team (L. Henry, D. Marangotto, A. Merli, N. Neri, P. Robbe, J. Ruiz Vidal, A. Stocchi)

Physics Beyond Colliders Working Group meeting

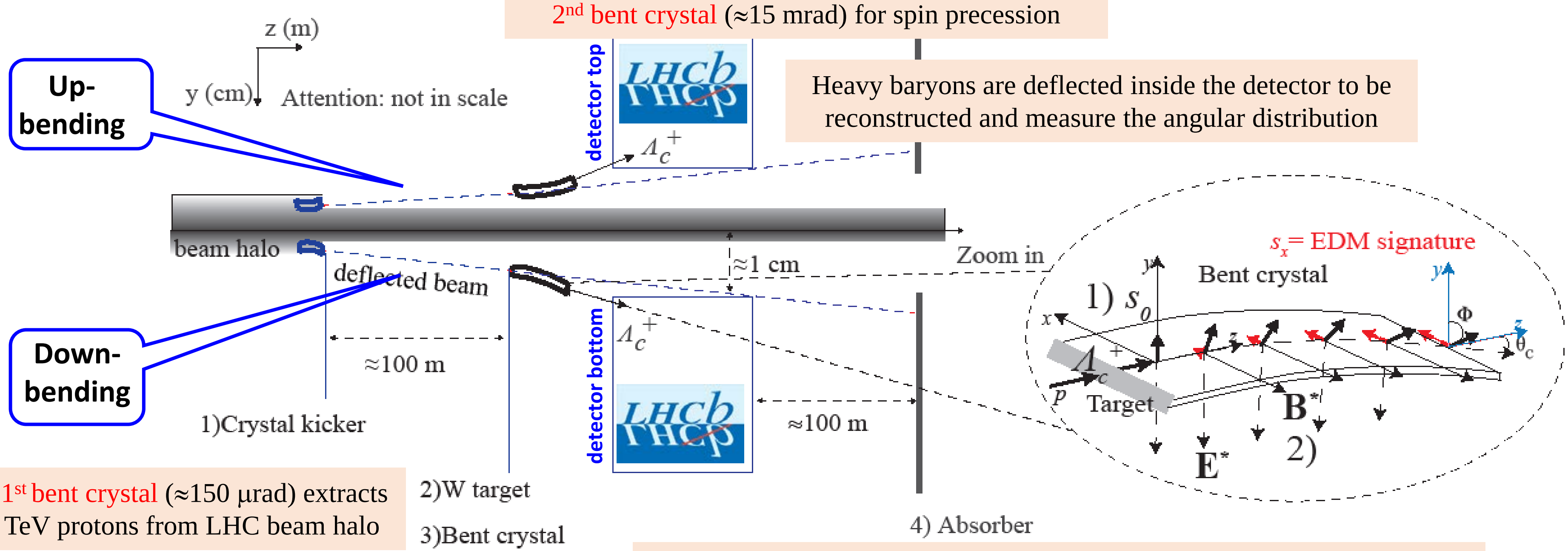
CERN, 13-14 June 2018

E. Bagli, L. Bandiera, S. Barsuk, O.A. Bezshyyko, L. Burmistrov, G. Cavoto, M. Ferro-Luzzi, A.S. Fomin, S.P. Fomin, F. Galluccio, M. Garattini, V. Guidi, A.Yu. Korchin, I.V. Kirillin, L. Henry, Y. Ivanov, L. Massacrier, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, D. Mirarchi, S. Montesano, A. Natochii, N. Neri, S. Redaelli, P. Robbe, J. Ruiz Vidal, W. Scandale, N.F. Shul'ga, A. Stocchi

Reminder of bent crystals proposal

Extracted p beam is directed on W target paired to a 2^{nd} bent crystal (≈15 mrad) for spin precession

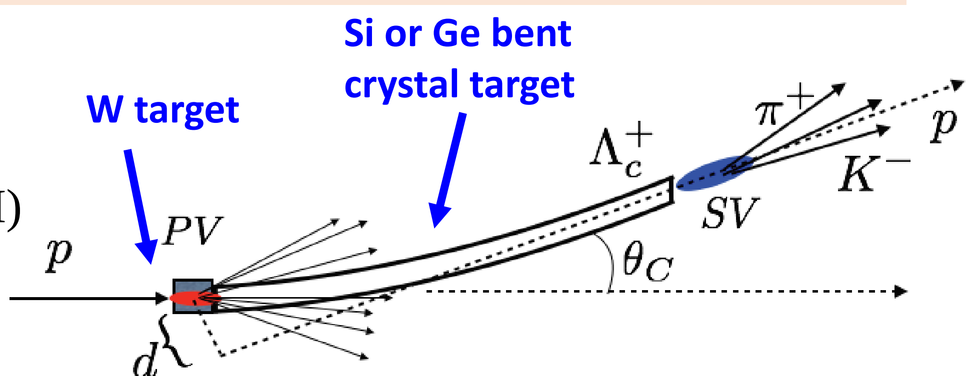
Heavy baryons are deflected inside the detector to be reconstructed and measure the angular distribution



A 1^{st} bent crystal (≈150 μrad) extracts 7 TeV protons from LHC beam halo

Non-interacting protons, non-channeling particles and most secondary interactions follow the beam pipe to be absorbed downstream the detector

- The high electric field between the crystallographic planes makes the heavy baryon spin precess, giving access to dipole moments (MDM/EDM) of heavy baryons

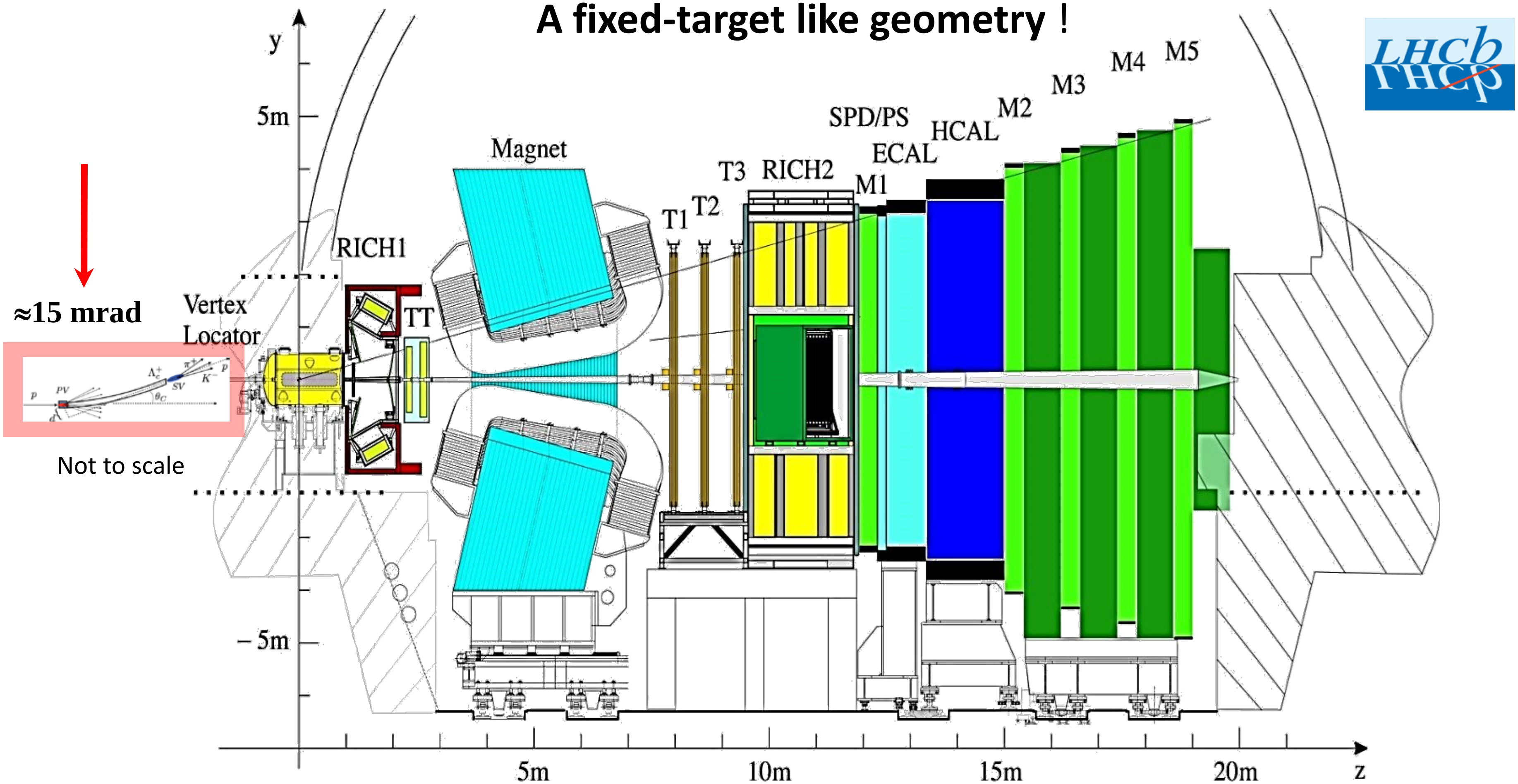


LHCb detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A30 (2015) 1530022

Single-arm forward spectrometer, optimized for b- and c-hadron physics.
The only LHC experiment fully instrumented at large η (2<η<5)

A fixed-target like geometry !



Recap of challenges and milestones

- Proof-of-principle by E761: MDM of Σ^+ from 800 GeV protons on Cu target
  - ✓ 350 GeV/*c* Σ^+, up- and down-bend Si crystals 1.6 mrad & 4.5 cm

Phys. Rev. Lett. 69 (1992) 3286

- Compatibility with LHC collimation scheme
  - ✓ Machine operation, achievable proton flux, collimation system (absorber)
  - ✓ Encouraging preliminary results by D. Mirarchi & S. Redaelli

Phys. Lett. B758 (2016) 129

- Channeling with 6.5 TeV LHC protons demonstrated by UA9 in 2016
- First UA9 test of double-crystal scheme at SPS in Fall 2017 very encouraging

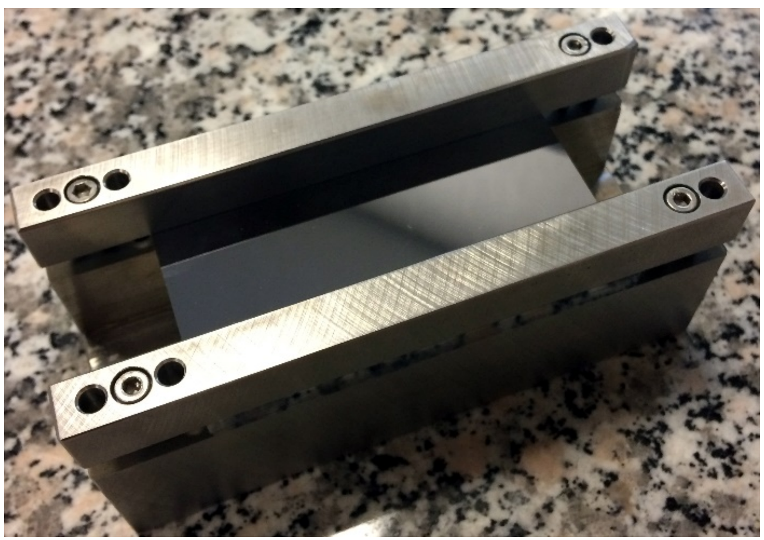
S. Redaelli's talk yesterday

Proceedings of IPAC2018, Vancouver
http://ipac2018.vrws.de/papers/tupaf043.pdf

- Feasibility of ≈15 mrad bent crystal
- Detector studies and running scheme
- Physics reach

Bent crystals R&D

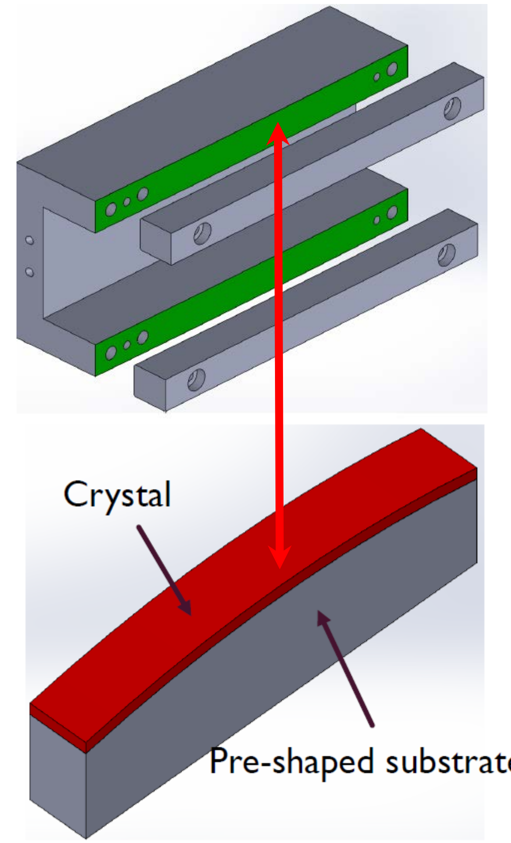
- R&D ongoing at INFN-Ferrara & PNPI/IHEP for large bending angle, ≈15 mrad, mainly determined by downstream tracker acceptance
  - ✓ Cannot use anticlastic deformation
  - ✓ Need special bending techniques with very precisely machined (~100 nm) holder to maintain uniform deformation
  - ✓ First prototypes produced. First test beam results will be available soon



Courtesy of A. Mazzolari, INFN-Ferrara

Sample tested on May 22, 2018 at H8 external line of the SPS in the frame of the UA9 Collaboration.

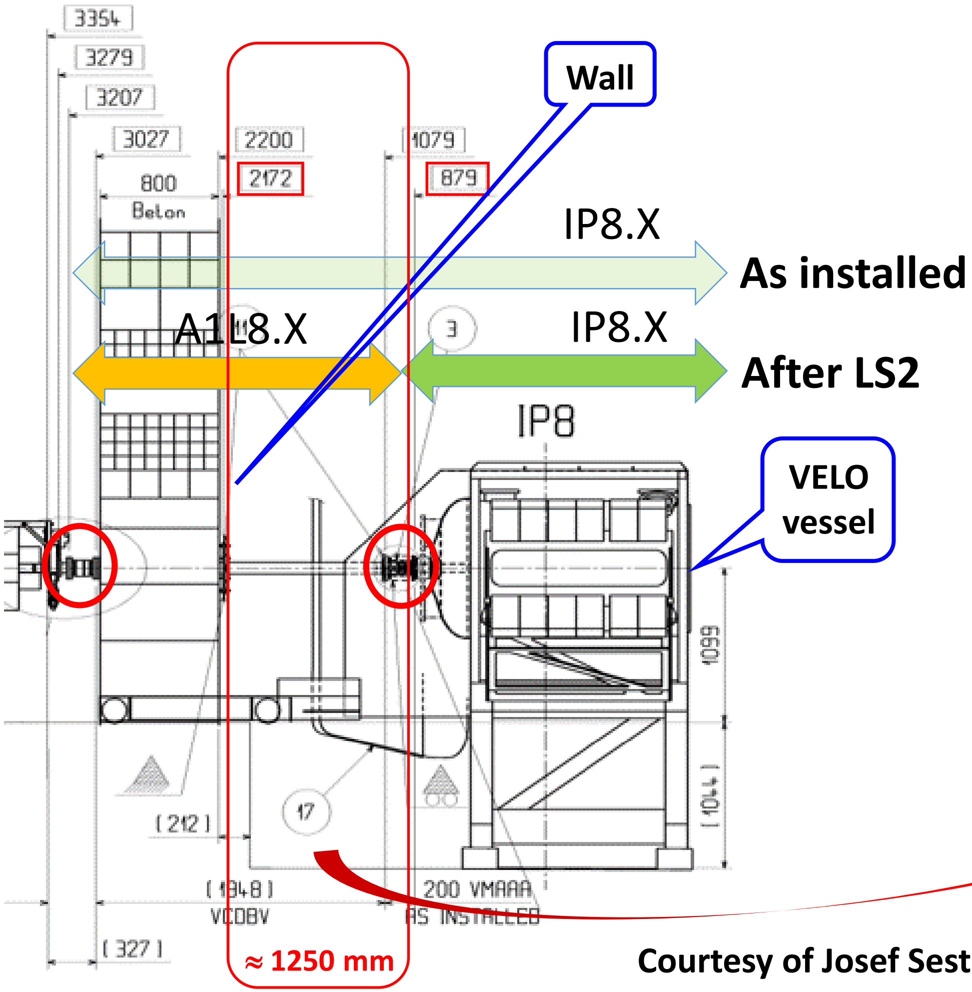
Bending angle is ≈ 12 mrad



Additional vacuum sector upstream VELO

See also G. Graziani's talk today

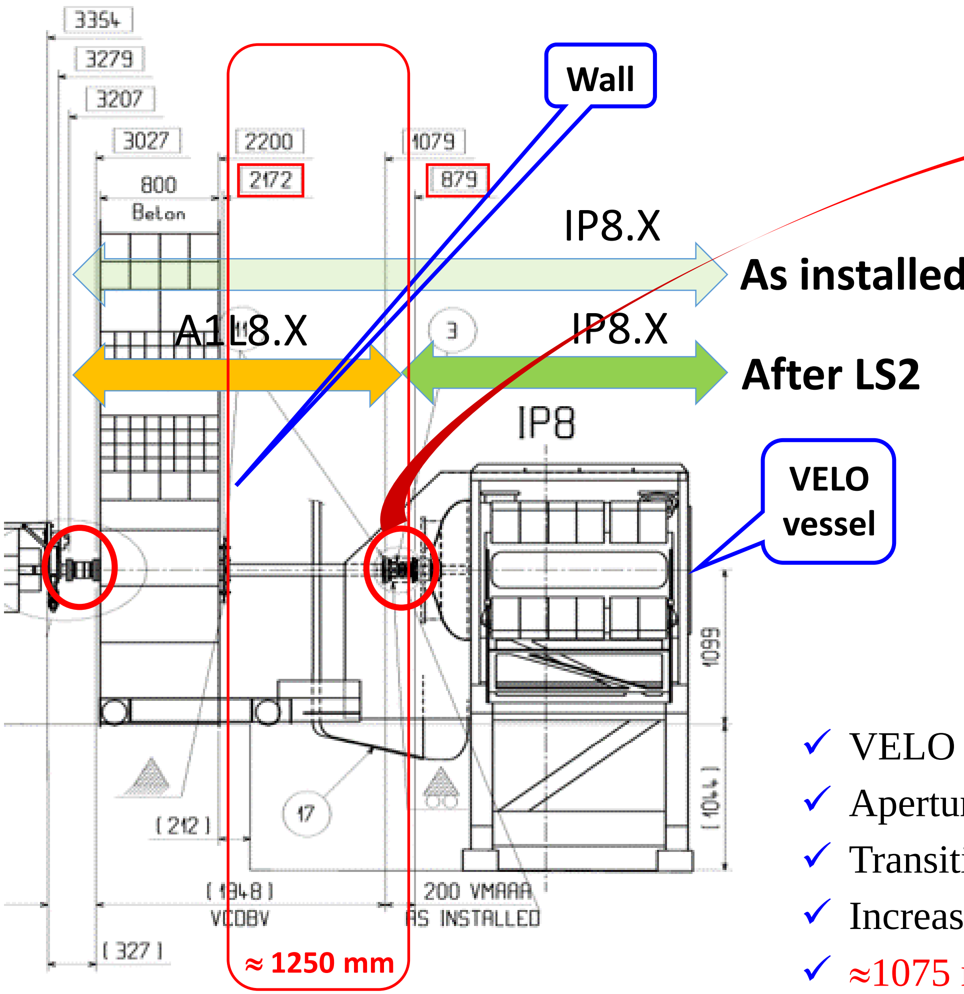
- To allow installation/maintenance of required instrumentation without breaking the VELO beam vacuum, there is the plan to install a new vacuum valve in LS2

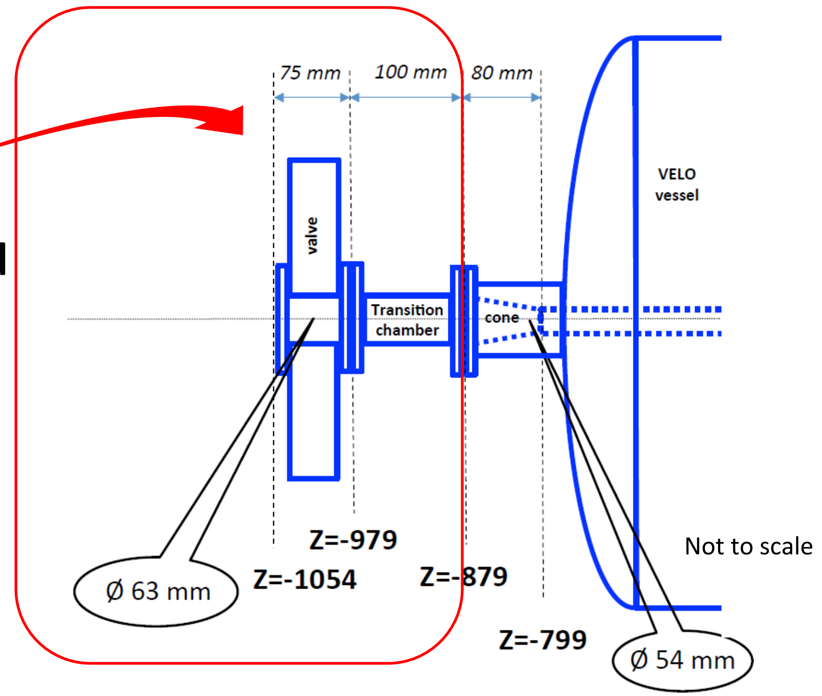


Courtesy of Josef Sestak, CERN

Additional vacuum sector upstream VELO

- To allow installation/maintenance of required instrumentation without breaking the VELO beam vacuum, there is the plan to install a new vacuum in LS2

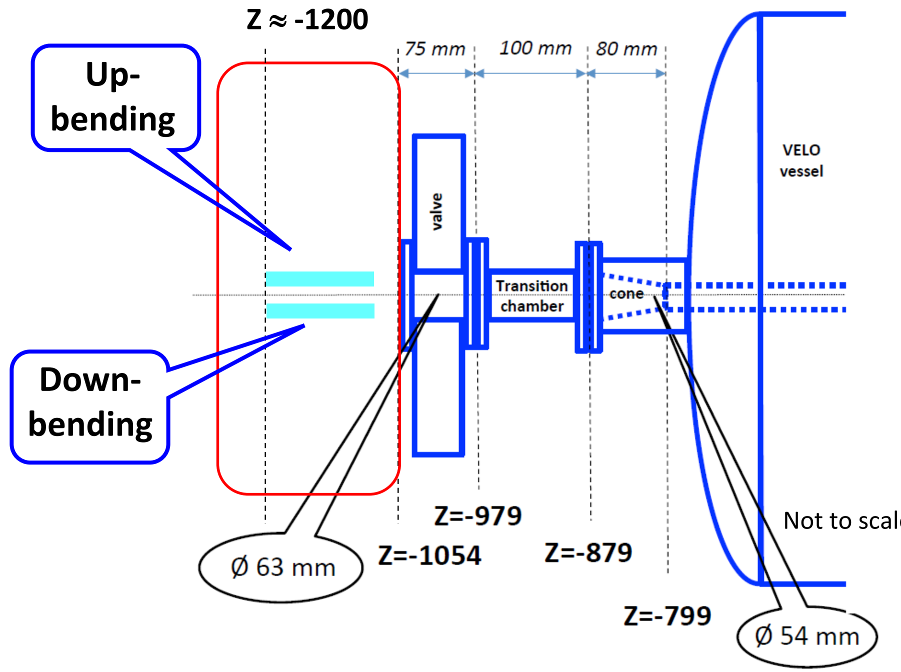




- ✓ VELO aperture ∅ 80 mm, reduced to ∅ 54 mm towards IP
- ✓ Aperture ∅ 63 mm for LHC compatibility
- ✓ Transition chamber with RF screen for ∅ compensation
- ✓ Increases ambient dose (but not dramatically)
- ✓ ≈1075 mm left for instrumentation

Impact of valve

- Setup at ≈ 0.4 cm from beam center, installed on retractable goniometer inside roman pot upstream the valve, ≈ −1.2 m from pp IP (W)
- Additional material (aperture) and slightly more displaced upstream
- No sizeable increase of detector occupancies



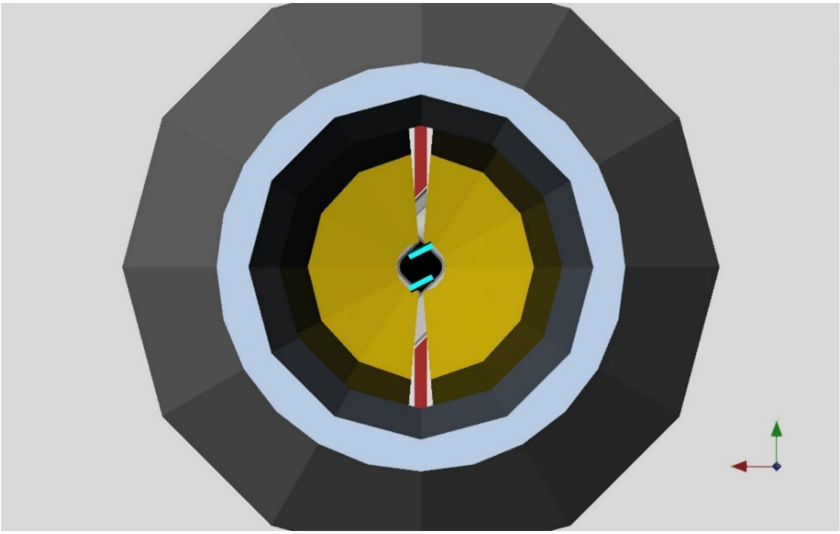
- No impact on detector performance. For $\Lambda_c^+ \to pK^-\pi^+$:
  - ✓ Reconstruction efficiency ≈ 35%
  - ✓ Resolutions: angular ≈ 25 μrad, mass ≈ 15 MeV, vertex ~ 9 mm z (≈ 100 μm in xy)
- Clean signal signature (bkg rejection at 10^{-7} level and efficiency ~80%)
  - ✓ p>≈ 0.8 TeV, polar angle (defined by bending), invariant mass
  - ✓ Compensates relatively low vertex resolution from upstream configuration

Unchanged

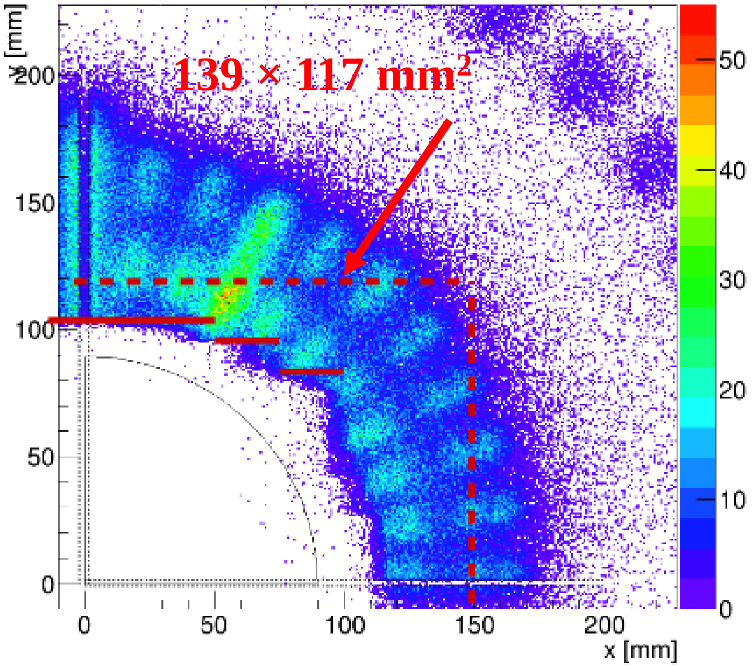
Impact of updated detector geometry

- New beam hole geometry for upgraded downstream tracker (SciFi)
  - ✓ Previous was crenelled, increasing with *z*
  - ✓ New is a rectangle, stable with *z* → expect to lose particles in T1

- Crystals rotated with $\phi \approx (9/10)\pi/2$ to recover & maximize detector acceptance



Downstream view of the up- and down-bent crystals



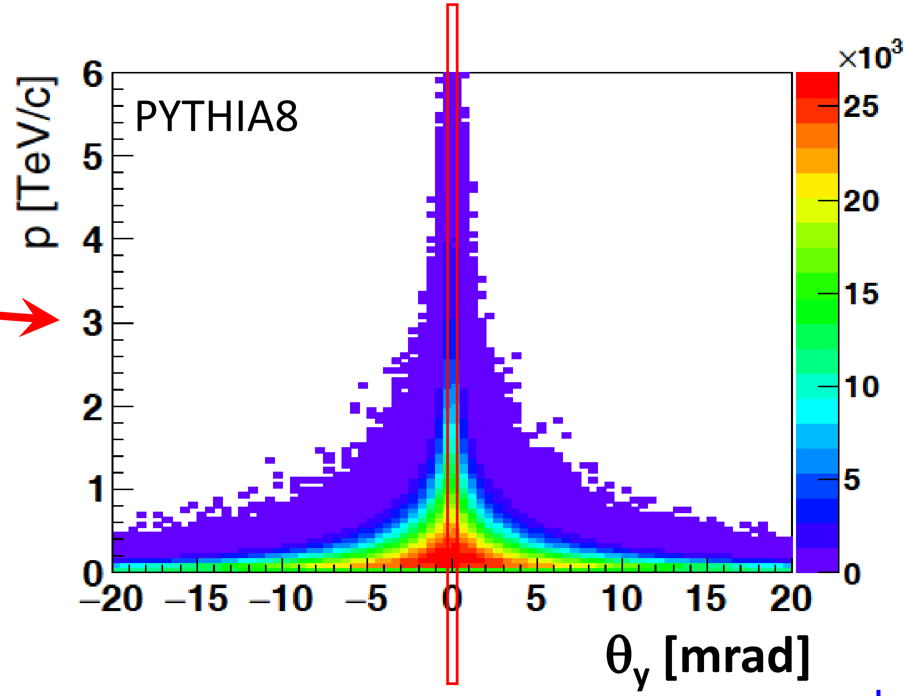
Transverse positions of reconstructed tracks for different azimuth configurations (spots are collimated because of generation). Crenelling is visible

2^{nd} goniometer specs

- Goniometer for 2^{nd} (long-bent) crystal will require a compact design
- What about its angular resolution?

Phys. Lett. B758 (2016) 129

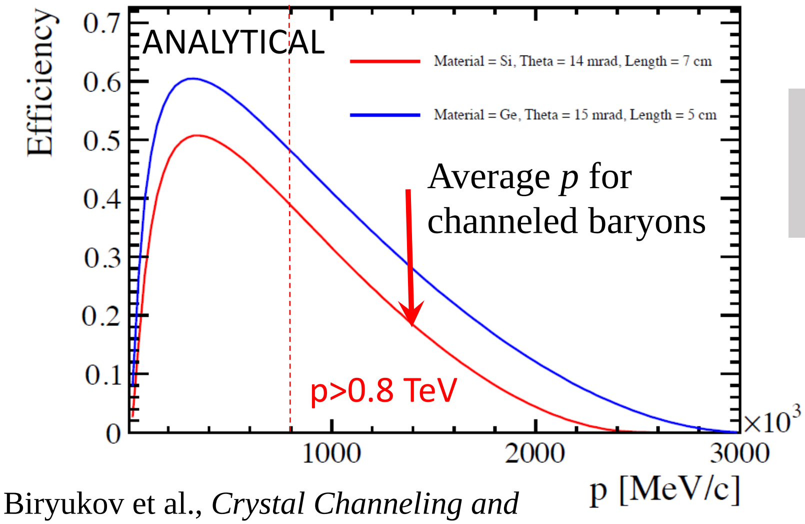
- For the 1^{st} crystal (proton extraction), it has to be ~sub-μrad, determined by small proton beam divergence and Lindhard angle at 7 TeV (≈2 μrad)
- For he 2^{nd} crystal, ~100 μrad would be enough, as heavy baryons are produced with an angular divergence $\propto 1/\gamma$, ≈1 mrad
- Trapping efficiency (Lindhard angle) ~10^{-3}, dominates overall channeling efficiency (trapping+dechanneling+decay flight): ≈1.2×10^{-5} (Si), 4.6×10^{-5} (Ge)



Signal events (within ≈ 6-7 μrad)

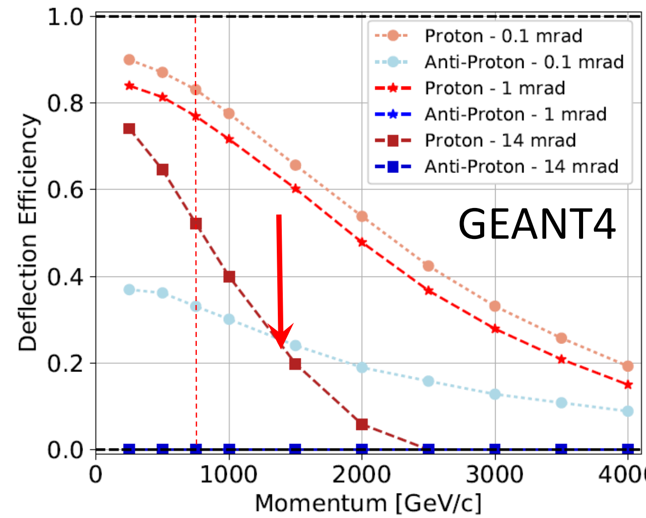
Dechanneling efficiency simulation

- Ongoing effort (within LHC-FT WG) to understand discrepancies between Geant4 and SixTrack codes for bending efficiency in the range 1-500 GeV for cm-long bent crystals

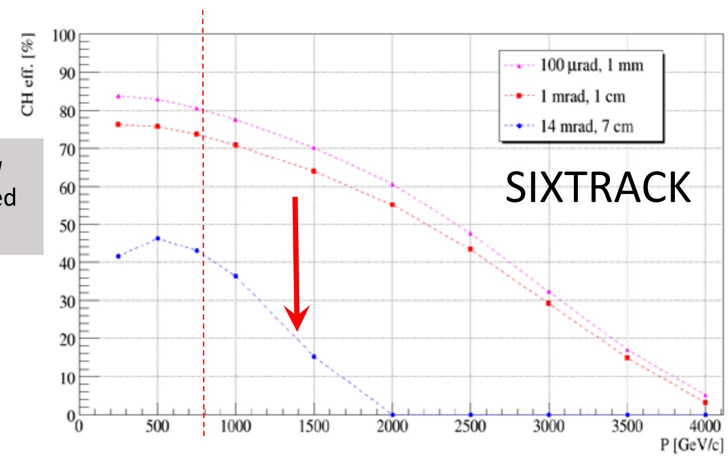


Biryukov et al., *Crystal Channeling and Its Application at High-Energy Accelerators*, Springer (1997)

E. Bagli at the Physics Beyond Colliders, LHC fixed target WG, CERN, 5th June 2018



D. Mirarchi, S. Redaelli, "*Update on crystal channeling simulations*", at the Physics Beyond Colliders, LHC fixed target WG, CERN, 24th April 2018



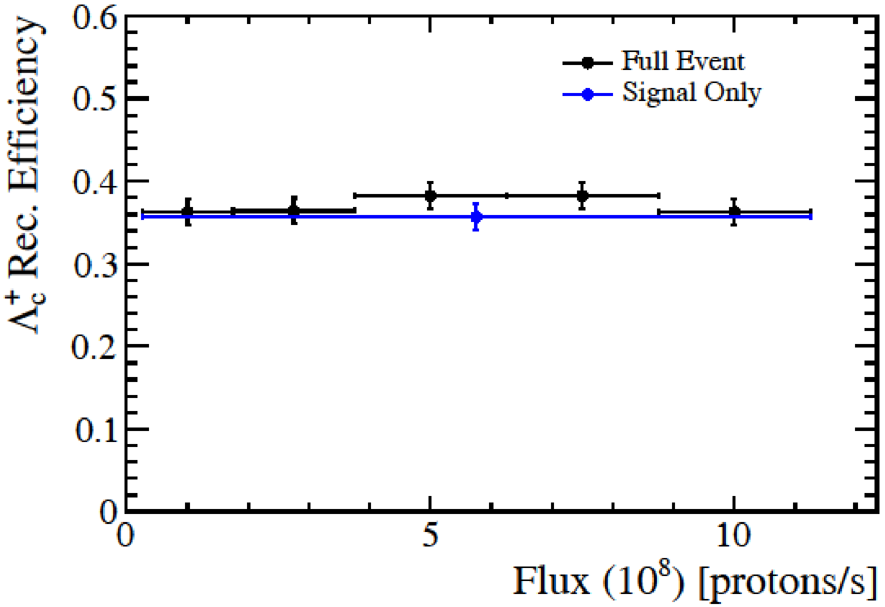
Working Hypothesis:

The dechanneling due to the interaction with valence electrons may be underestimated by the Geant4 simulation (multiple scattering)

Detector running scheme

- Reconstruction efficiency and resolutions stable up to 10^9 p/s

  $\Rightarrow$ **Room to tune flux, thickness and operation**



- $\approx 2\times10^{14}$ protons on 2.0 cm thick W target could be reached with

Parallel detector running	**Dedicated detector running**
Flux 10^7 p/s	Flux 10^8 p/s
Pileup $\nu\approx0.13$ (W+Ge)	Pileup $\nu\approx1.3$
10% occupancy	2 weeks/year
3 years	3 years
$\approx3\times10^4$ reco'd $\Lambda_c^+\to pK^-\pi^+$	$\approx3\times10^4$ reco'd $\Lambda_c^+\to pK^-\pi^+$

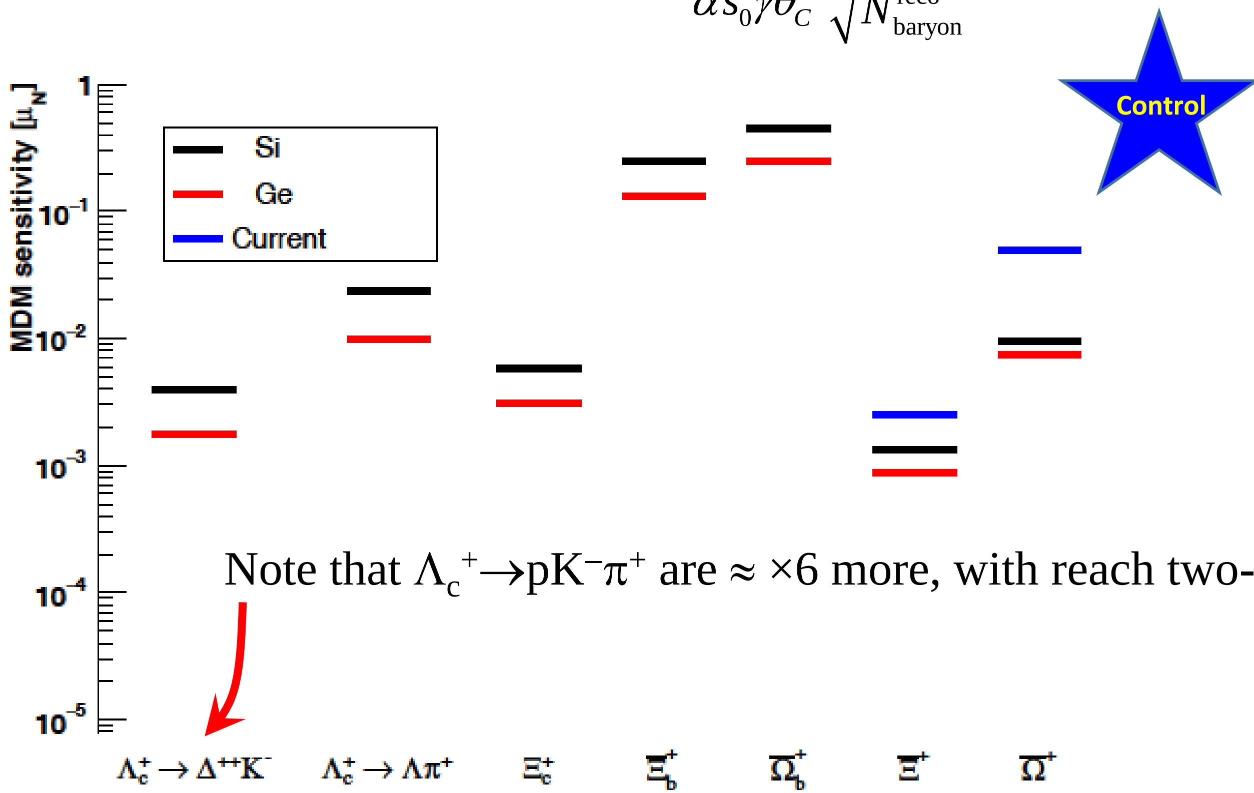
[$\nu\approx$ 7.6 in pp collisions]

Sensitivity

≈2×10^14 PoT on 2 cm W target

- Sensitivity reach for charm baryons:
  - ✓ **~10^{-3}-10^{-2} μ_N** for **MDM**

$$\sigma_g \approx \frac{2}{\alpha s_0 \gamma \theta_C} \frac{1}{\sqrt{N^{\rm reco}_{\rm baryon}}}$$



Note that $\Lambda_c^+ \to pK^-\pi^+$ are ≈ ×6 more, with reach two-resonant structure

  - ✓ **~10^{-17}-10^{-18} e cm** for **EDM**

$$\sigma_d \approx \frac{g-2}{\alpha s_0 (\cos\Phi - 1)} \frac{1}{\sqrt{N^{\rm reco}_{\rm baryon}}}$$

Baryon magnetic DMs

- Experimental anchor point for test of low-energy QCD models, related to **non-perturbative QCD** dynamics
  - ✓ heavy-light systems modern predictive tools such heavy-quark effective theory

Overview of QCD landscape, Yesterday morning

- Charm quark represents a challenge theoretically
  - ✓ It is not sufficiently heavy to be treated as bottom or top
  - ✓ It is not sufficiently light to be included in the lattice calculations

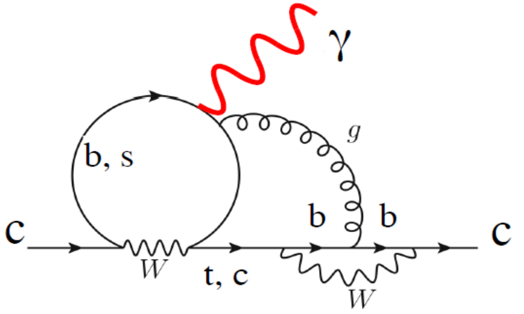
Maxim Pospelov @ LHCb review, 21/02/2018

- What is the desirable accuracy for MDM?
  - ✓ In light hadrons, most of the MDM is generated by light "valence" quarks, and it scales as $(eQ_q/m_{\text{const quark}})$ where $m_{\text{const quark}}$ is the mass of the constituent light quarks (i.e. mass of a light quark "dressed" by QCD to be ~ 300 MeV).
  - ✓ Therefore, to start seeing MDM of charm, one needs to measure to accuracy better than $m_{\text{const quark}}/m_{\text{charm}}$
  - ✓ Acceptable result: 10% measurement of the MDM

Desirable result: few% measurement of the MDM

(c.f. the MDM of the Σ [strange] baryons is measured at Fermilab at 1% level)

EDMs and BSM physics



δ_c ~10^{-32} *e* cm, SM (3-loop level)

- **'Background-free' search for BSM**
- δ ~ [some QCD ME] × SM mass scale (m_e, m_q) × (CP phase)$_{NP}/\Lambda_{NP}^2$

  ME can be fixed with some work, but we have no idea where Λ_{NP} is

Maxim Pospelov @ LHCb review, 21/02/2018

- Many possible scales for an EDM answer
  - ✓ If CP violation is broken maximally through QCD (θ ~1)

    $\delta \sim e\ \theta\ m_{up} / (4\ \pi\ f_\pi)^2 \sim \theta \times 10^{-16}$ e cm   nEDM limits $\theta < 10^{-10}$
  - ✓ If CP is *broken maximally by some "unspecified" strong interaction* at a scale Λ_{NP} ~ 1-10 TeV (EW scale) that also does not respect chiral symmetry

    $\delta \sim e\ v_{EW} / \Lambda_{NP}^2$ ~ starts at (10^{-17} - 10^{-18}) e cm

    Excluded if democratic among families, needs to emphasize charm quark
  - ✓ If perturbative: ×10^{-2}, down to (10^{-19} - 10^{-20}) e cm level and below

    E.g. some versions of SUSY reach $\delta \sim 10^{-17}$ e cm for charm
- In conclusion, achieving (10^{-17} - 10^{-18}) e cm would be a milestone showing that charmed (also beauty) EDM can probe beyond the EW scale
- Truly interesting benchmark would start at 10^{-20} e cm level

Further potential physics

- B^0_s (and perhaps D^0) mesons oscillations in baryonic matter

Suggested by Peter Filip

  - ✓ Close analogy of in-medium neutrino oscillation
  - ✓ Not observed yet for mesons, but (old) observed anomalies in K^0 oscillations

Phys. Rev. 128 (1962) 362

  - ✓ Production in metallic W, oscillation in W and dense amorphous Si/Ge crystal
  - ✓ E.g. for B^0_s, with $\gamma \approx 300$, $L = c\tau\gamma = 13.5$ cm, $L_T = cT\gamma = 3.3$ cm
  - ✓ Work needed to assess detector performance (tagging, vertexing, very limited PID) and physics reach

- Setup can also be used as a standard fixed target, reaching luminosities similar to gas targets but loosing the advantage of target types or polarized target

AFTER

Phys. Rep. 522 (2013) 239
Adv. High Energy Phys. 2015 (2015), SI

Summary

- Challenging but unique opportunity for QCD and BSM physics
- Smooth progress since Nov 2017
- Close interaction with LHC-FT Working Group
- LHCb internal review (FITPAN), 21 Feb 2018
- ERC CoG grant for EDM searches at LHCb to N. Neri (INFN-Milano)
  - ✓ Ongoing discussions to integrate with global effort

European Research Council
Established by the European Commission

- Aiming for an “experiment contribution” to PBC deliverables

More references

- E. Bagli, L. Bandiera, G. Cavoto, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, N. Neri, J. Ruiz Vidal, *Electromagnetic dipole moments of charged baryons with bent crystals at the LHC*, arXiv:1708.08483 (2017), Eur. Phys. J. C **77** (2017) 828.
- A.S. Fomin , A.Yu. Korchin, A. Stocchi, O.A. Bezshyyko, L. Burmistrov, S.P. Fomin, I.V. Kirillin, L. Massacrier , A. Natochii, P. Robbe, W. Scandale, N.F. Shul'ga, *Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals*, JHEP **1708** (2017) 120.
- V. G. Baryshevsky, *On the search for the electric dipole moment of strange and charm baryons at LHC and parity violating (P) and time reversal (T) invariance violating spin rotation and dichroism in crystal*, arXiv:1708.09799 (2017).
- L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, P. Robbe, J. Ruiz Vidal, CERN-LHCb-INT-2017-011, *Proposal to search for baryon EDMs with bent crystals at LHCb*.
- F. J. Botella, L. M. Garcia Martin, D. Marangoto, F. Martinez Vidal, A. Merli, N. Neri, A. Oyanguren, J. Ruiz Vidal, *On the search for the electric dipole moment of strange and charm baryons at LHC*, Eur. Phys. J. C **77** (2017) 181.
- V. G. Baryshevsky, *The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals*, Phys. Lett. B**757** (2016) 426.
- 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.