Possibility of spin precession in high-field magnet

Andrea Merli[1]
[1]INFN and Università degli Studi di Milano

2nd Workshop on electromagnetic dipole moments of unstable particles

27th September 2022

Istituto Nazionale di Fisica Nucleare

European Research Council
Established by the European Commission

High-field dipole magnet

LETTER

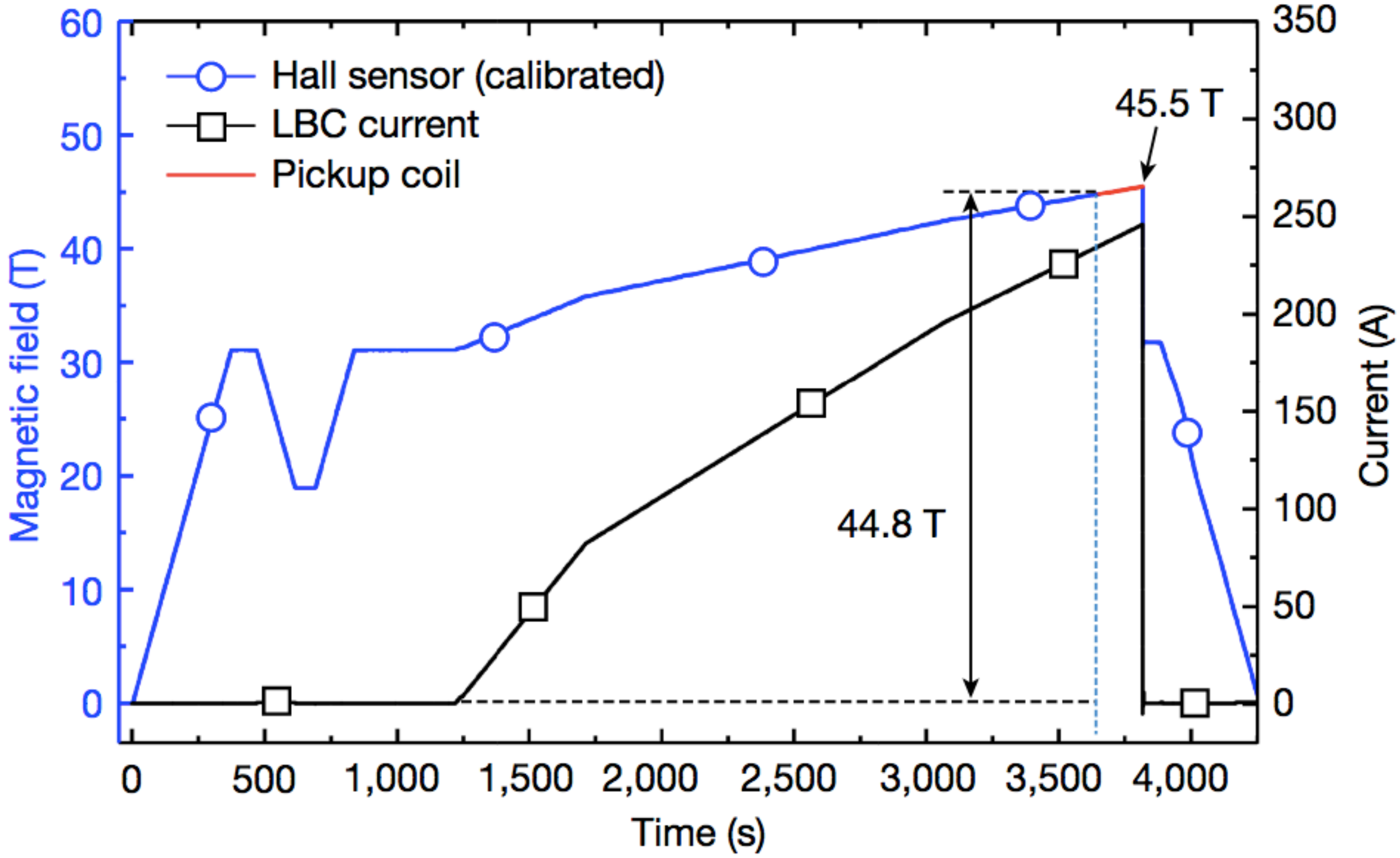
https://doi.org/10.1038/s41586-019-1293-1

45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet

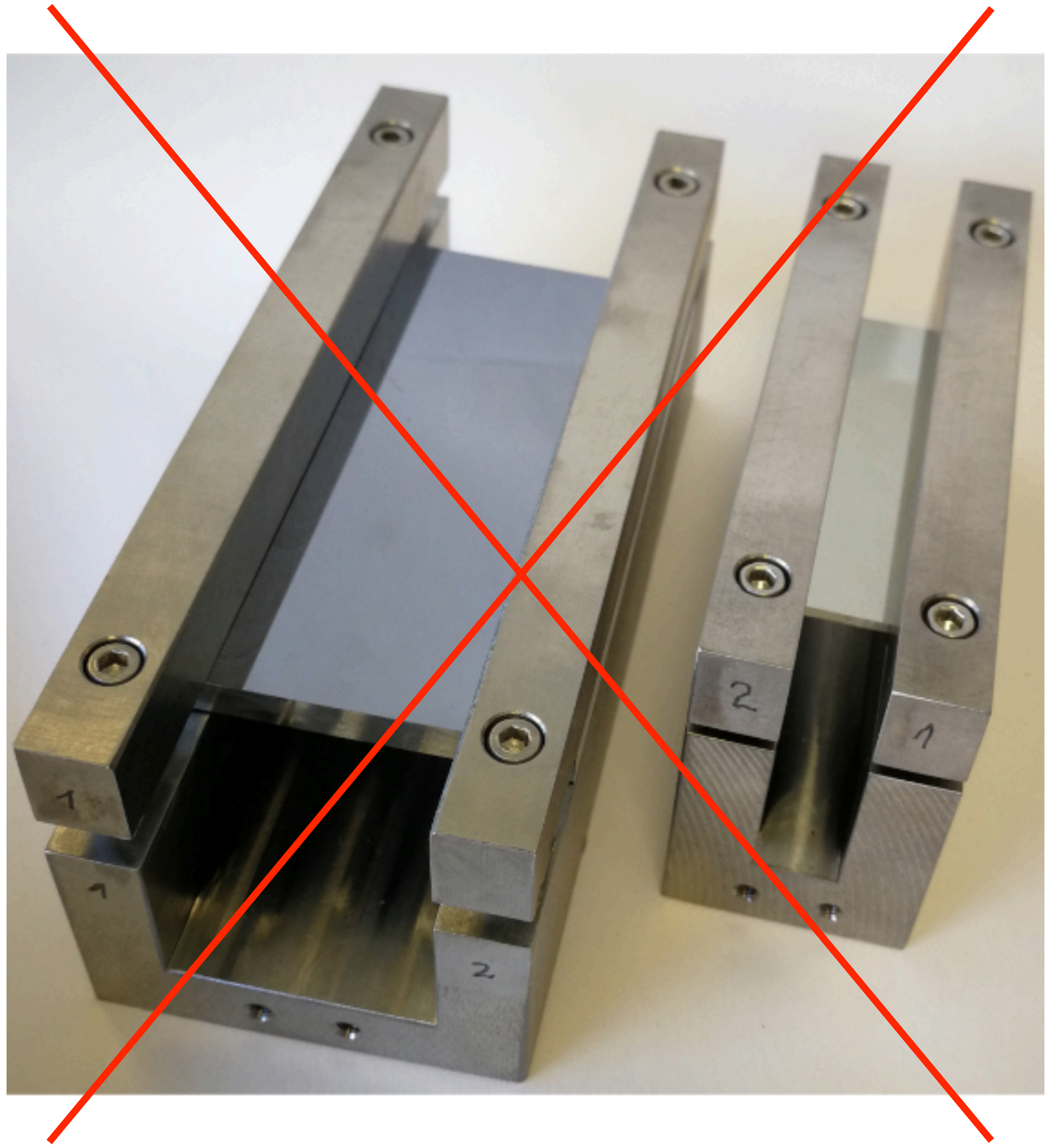
Seungyong Hahn[1,2], Kwanglok Kim[1], Kwangmin Kim[1], Xinbo Hu[1], Thomas Painter[1], Iain Dixon[1], Seokho Kim[1,3], Kabindra R. Bhattarai[1,4], So Noguchi[1,5], Jan Jaroszynski[1] & David C. Larbalestier[1,4]*

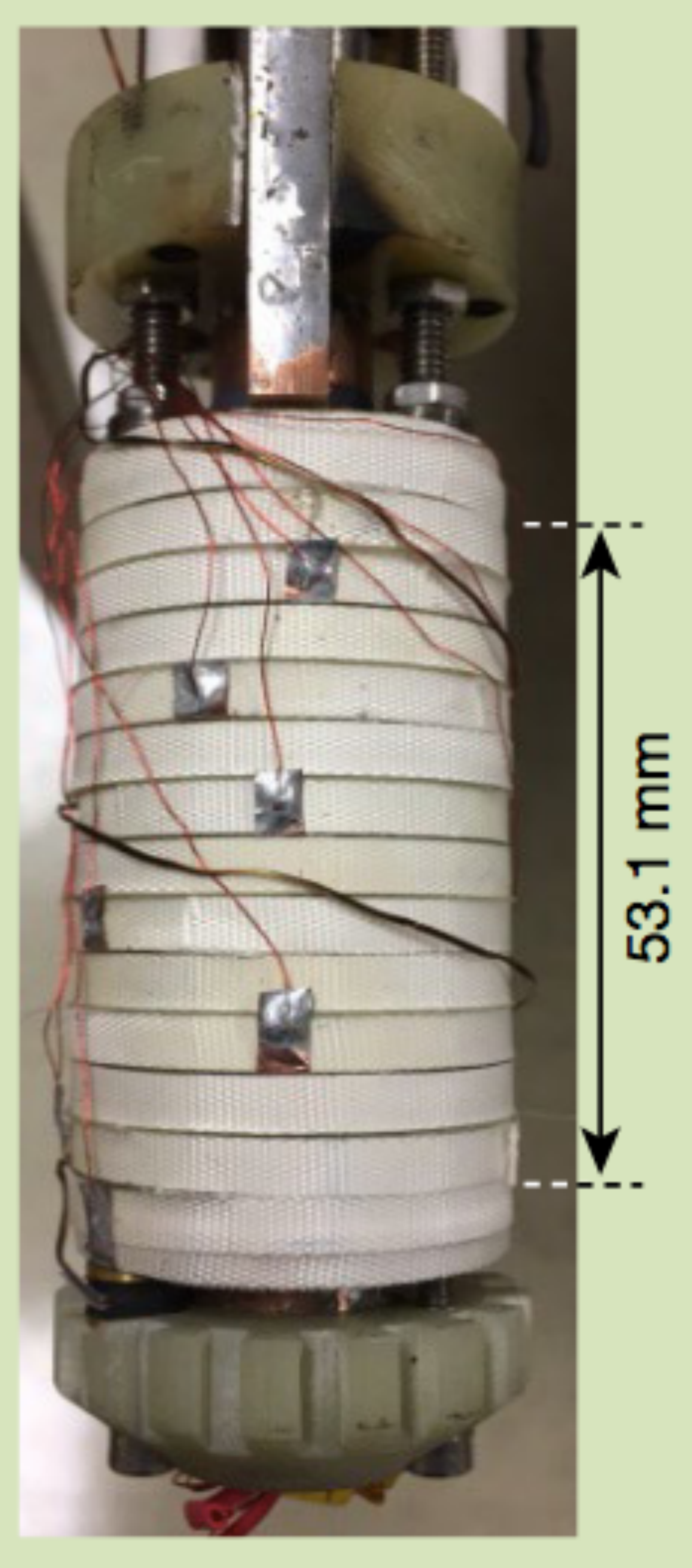
Nature 570 (2019) 496

World record for direct-current magnetic field



Could we replace the crystal with a dipole magnet?





LBC3 after 45.5-T test

Physics opportunities?

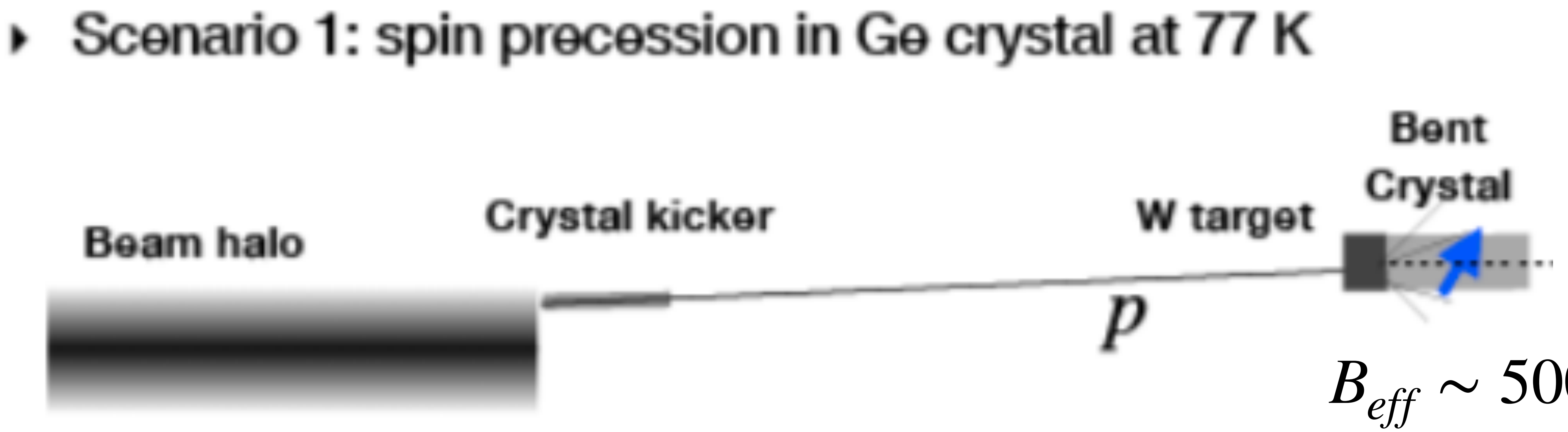
Main idea

- Uncertainty on dipole moments (DM):
- $\sigma_{DM} \propto \frac{1}{P\Phi\sqrt{N}}$

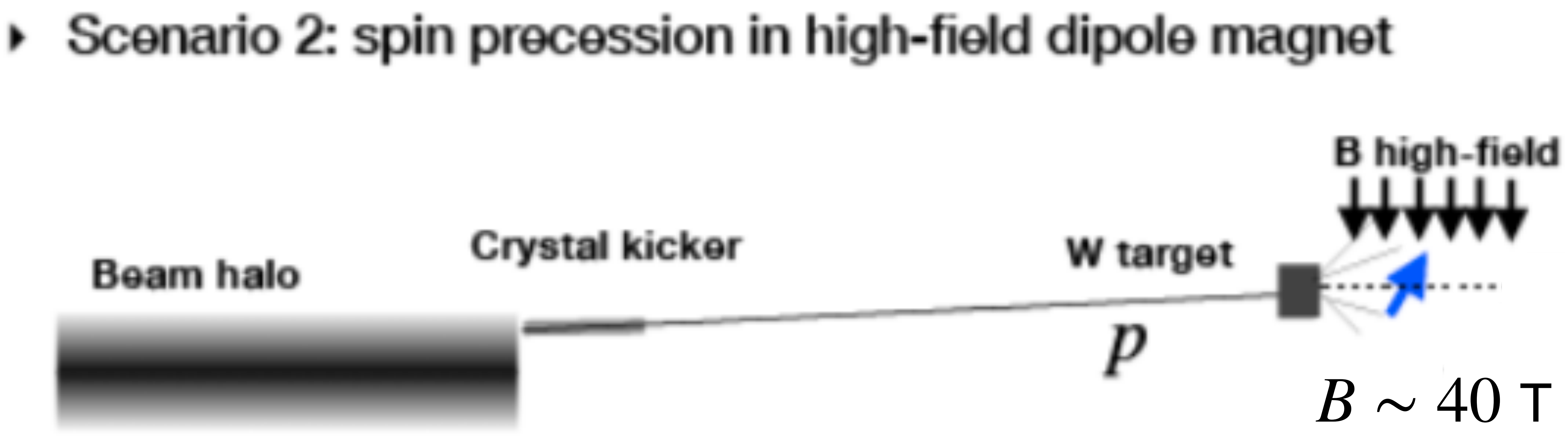
- Bent crystal (Scenario1):
  - ✓ High precession angle $\sim \mathcal{O}(0.1 - 1 \text{ rad})$
  - ✗ Low channeling efficiency $\sim 10^{-4}$
  - ✗ Induce spin precession only for positively charged particles
- High-field dipole magnet (Scenario2):
  - ✗ Low precession angle $\sim 10 - 100$ mrad
  - ✓ High channeling efficiency ~ 1
  - ✓ Induce spin precession for all fermions

- The polarisation P depends on the production mode
- The precession angle $\Phi \propto B$
- The number of reconstructed particles $N \propto \varepsilon$

B magnetic field
ε efficiency



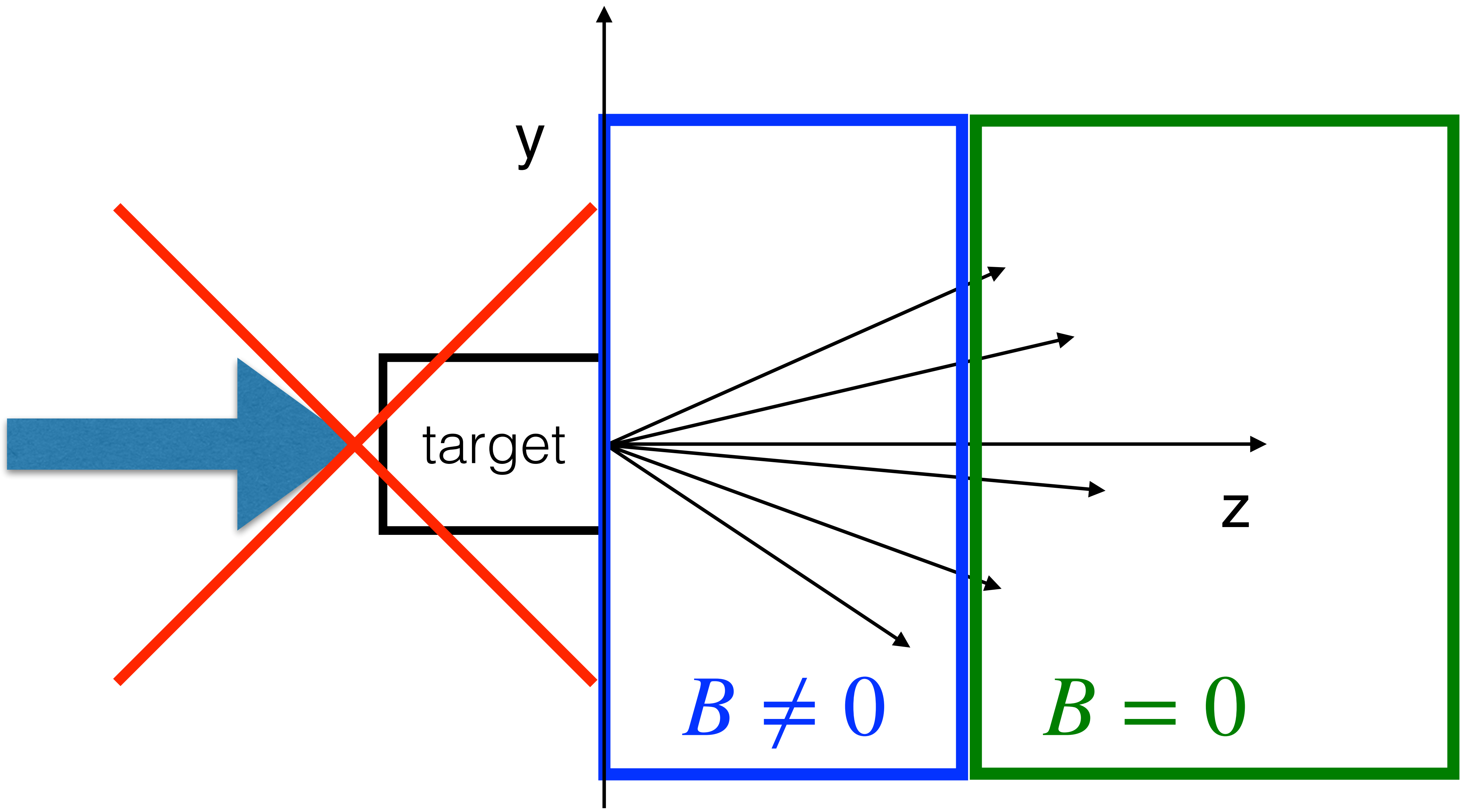
$B_{eff} \sim 500$ T



$B \sim 40$ T

Simulation

- The target is the same as the crystal setup, factored out and not simulated here
- Since beam spot << vertical dimensions, all the particles are supposed to be produced at (0,0,0)

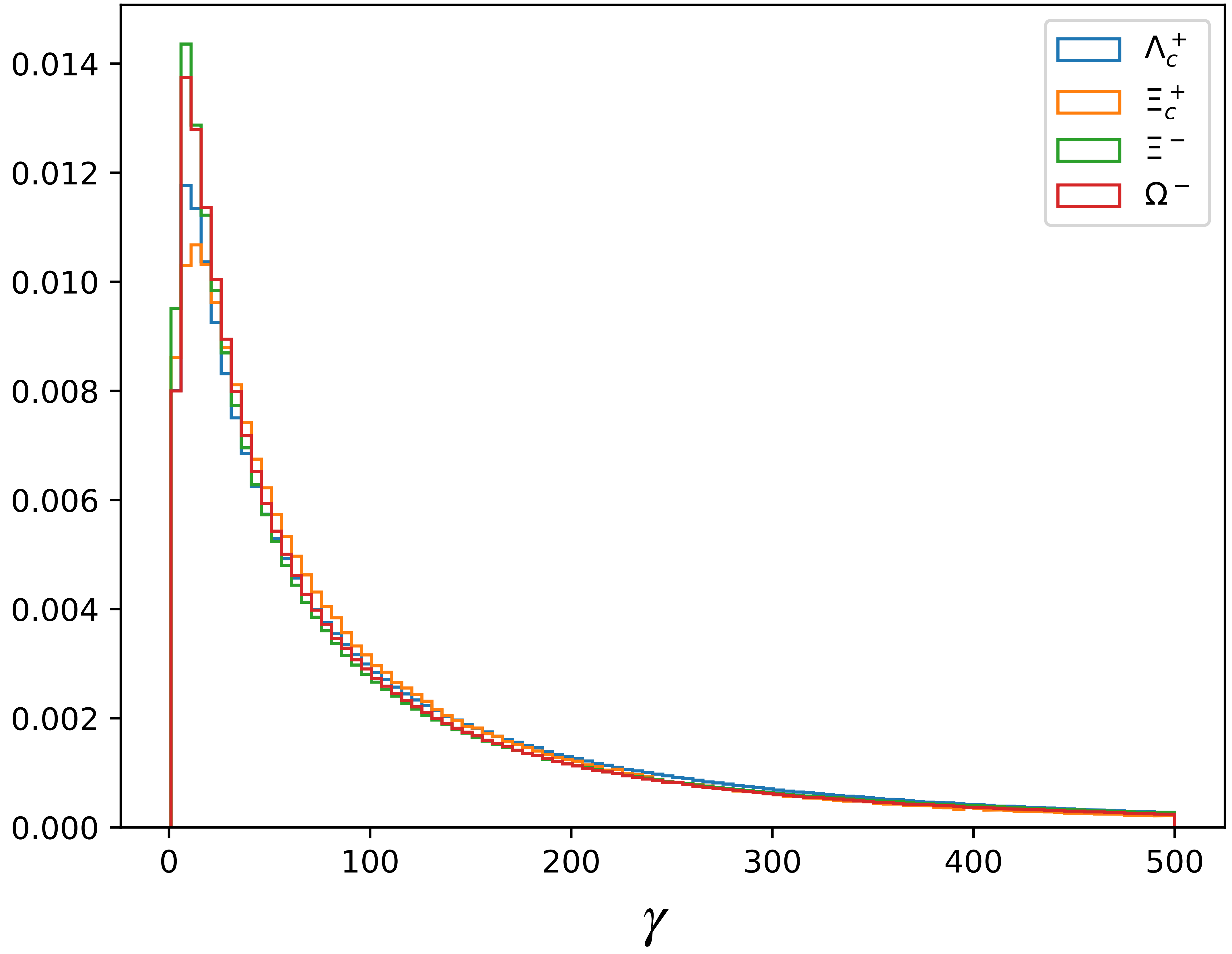


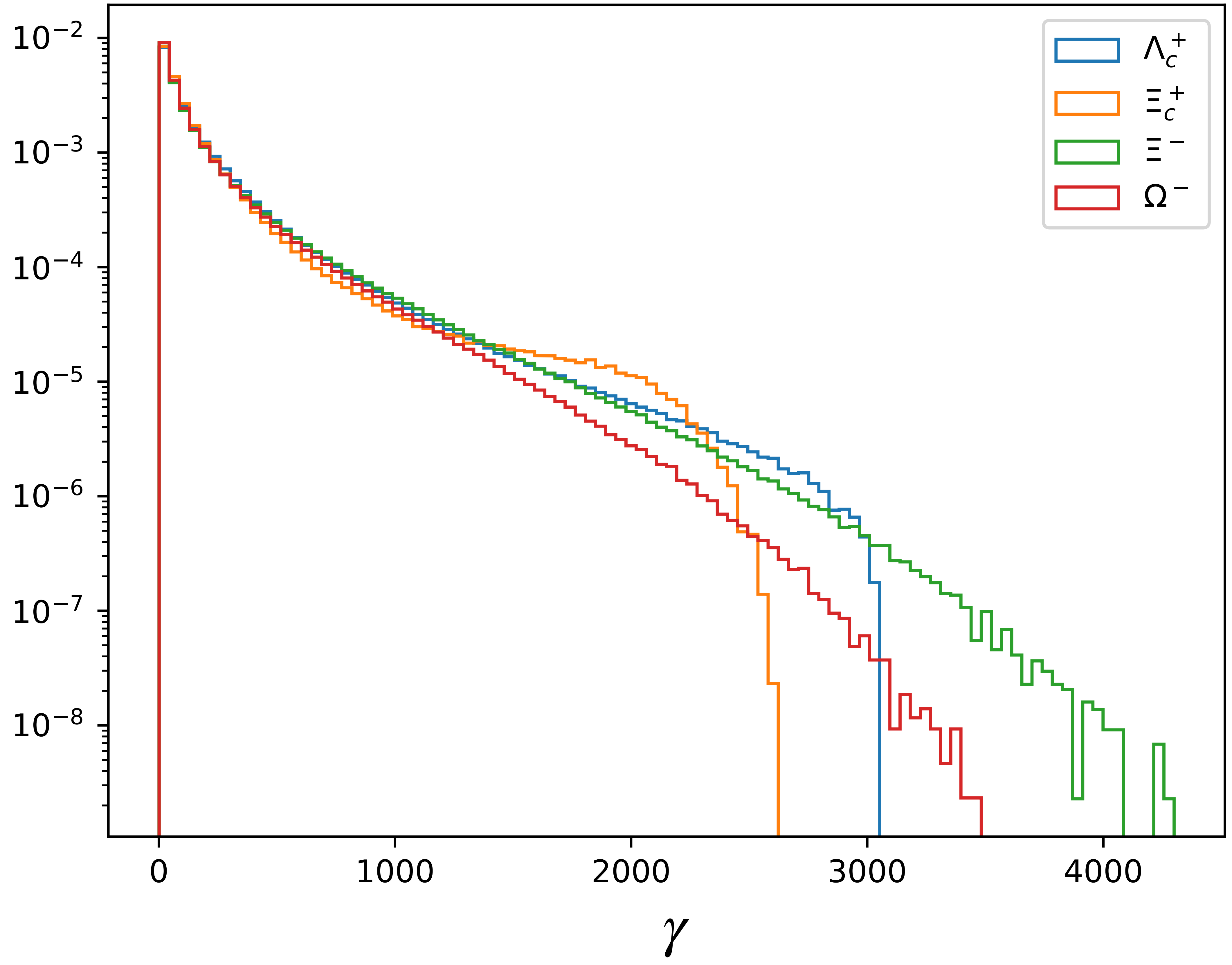
$$
\begin{cases}
\dfrac{d\vec{x}}{dt} = \vec{\beta} c \\
\dfrac{dE}{dt} = cq\vec{E} \cdot \vec{\beta} \\
\dfrac{d(\vec{p}c)}{dt} = cq\left(\vec{E} + c\vec{\beta} \times \vec{B}\right) \\
\dfrac{d\vec{s}}{dt} = \vec{s} \times \left(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM} + \vec{\Omega}_{TH}\right)
\end{cases}
$$

- Definition of $\vec{\Omega}_{MDM}$, $\vec{\Omega}_{EDM}$ and $\vec{\Omega}_{TH}$ is given in EPJC 77 (2017) 181

Generation of particles

- Generated different baryon species in pp fixed-target collisions with Pythia (7 TeV proton + p at rest)
- Extremely long processing time for b-baryons: assume same γ as given by c-baryons, $\Lambda_c^+ \rightarrow \Lambda_b^0$, $\Xi_c^+ \rightarrow \overline{\Xi}_b^+$





- From ~100 GeV to multi-TeV energies

Yoke aperture

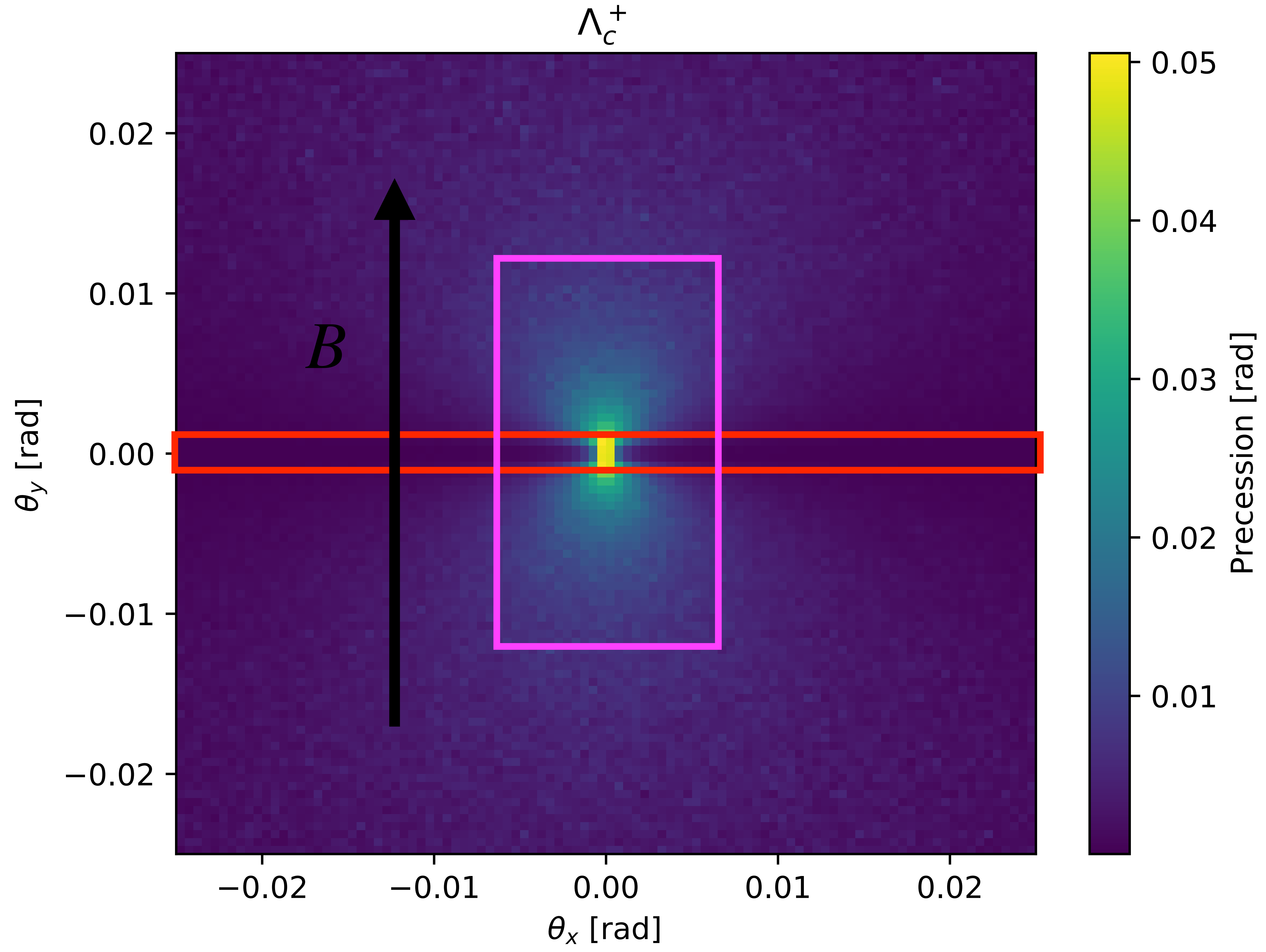
- No precession for the baryons emitted in the $\theta_y = 0$ plane (horizontal) due to spin parallel to B

Parity conservation
the spin is perpendicular to the production plane

$$\frac{s_0}{|s_0|} = \frac{\vec{p}_{\Lambda_c^+} \times \vec{p}_{BEAM}}{|\vec{p}_{\Lambda_c^+} \times \vec{p}_{BEAM}|}$$

PRD 103 (2021) 072003

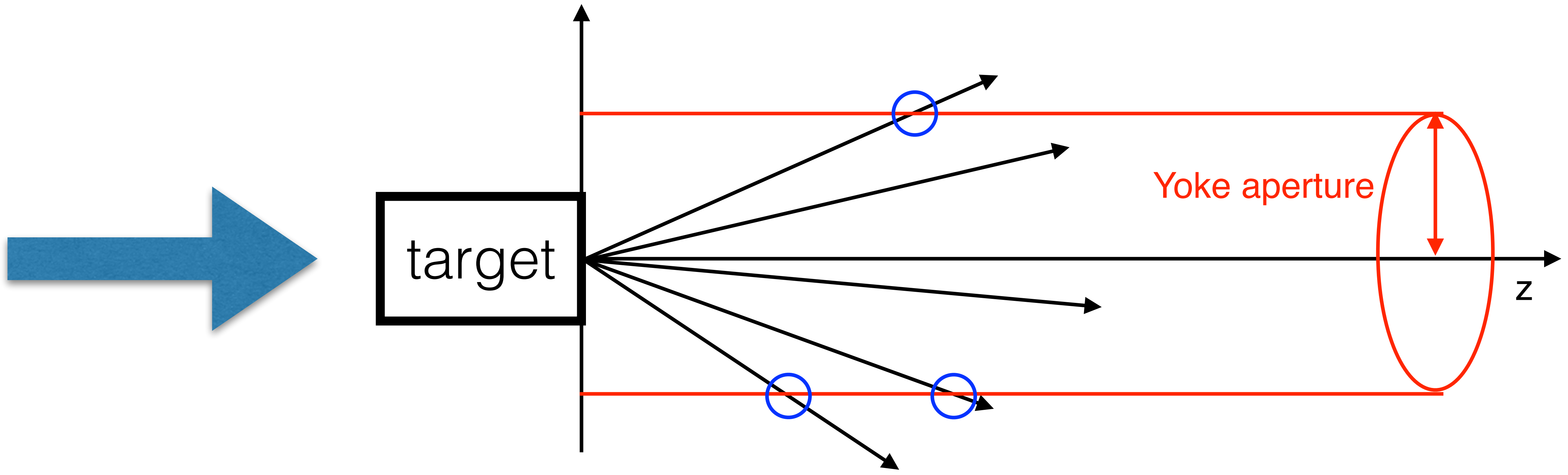
$$|s_0| = -0.9(1 - e^{-0.4p_T^2})$$

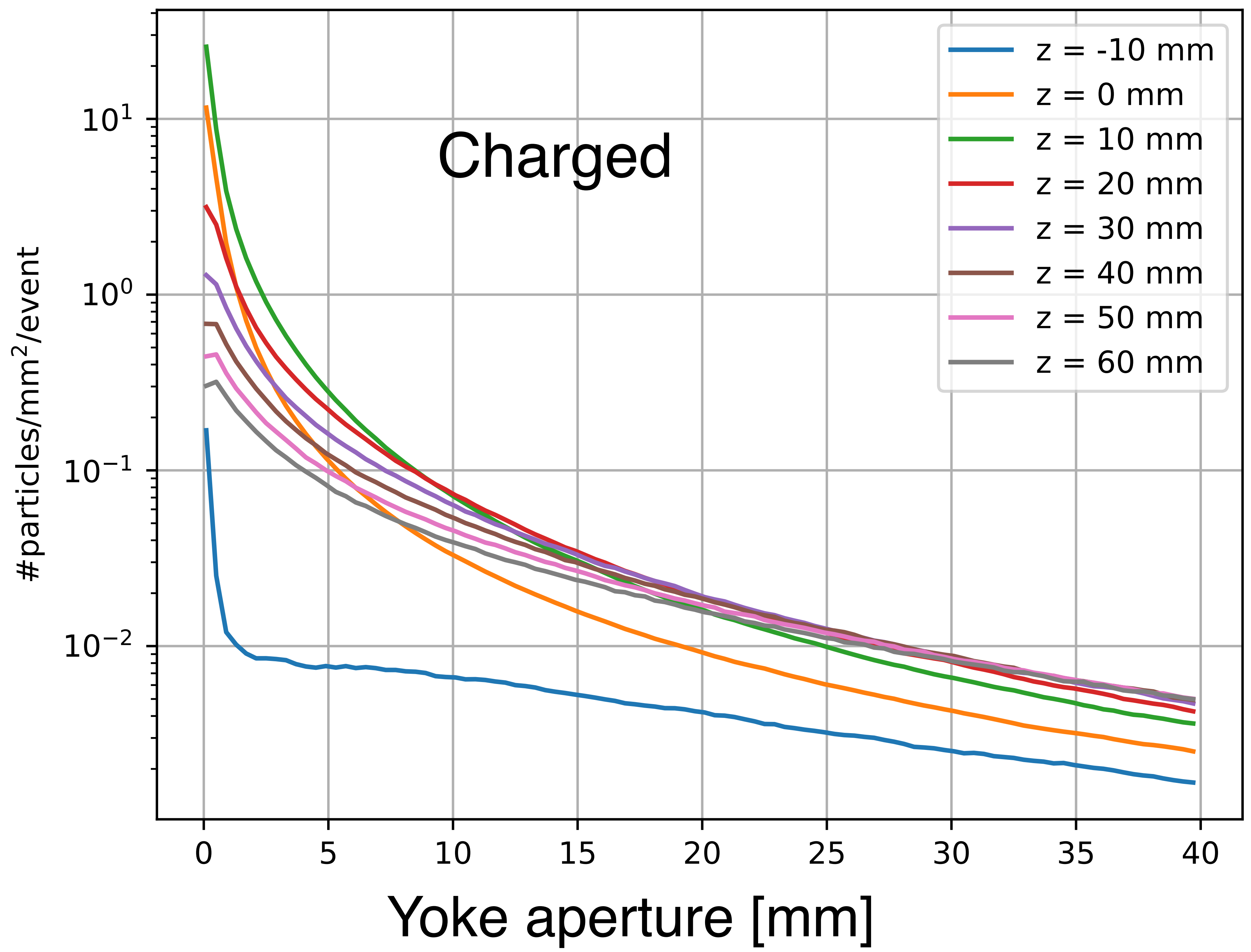


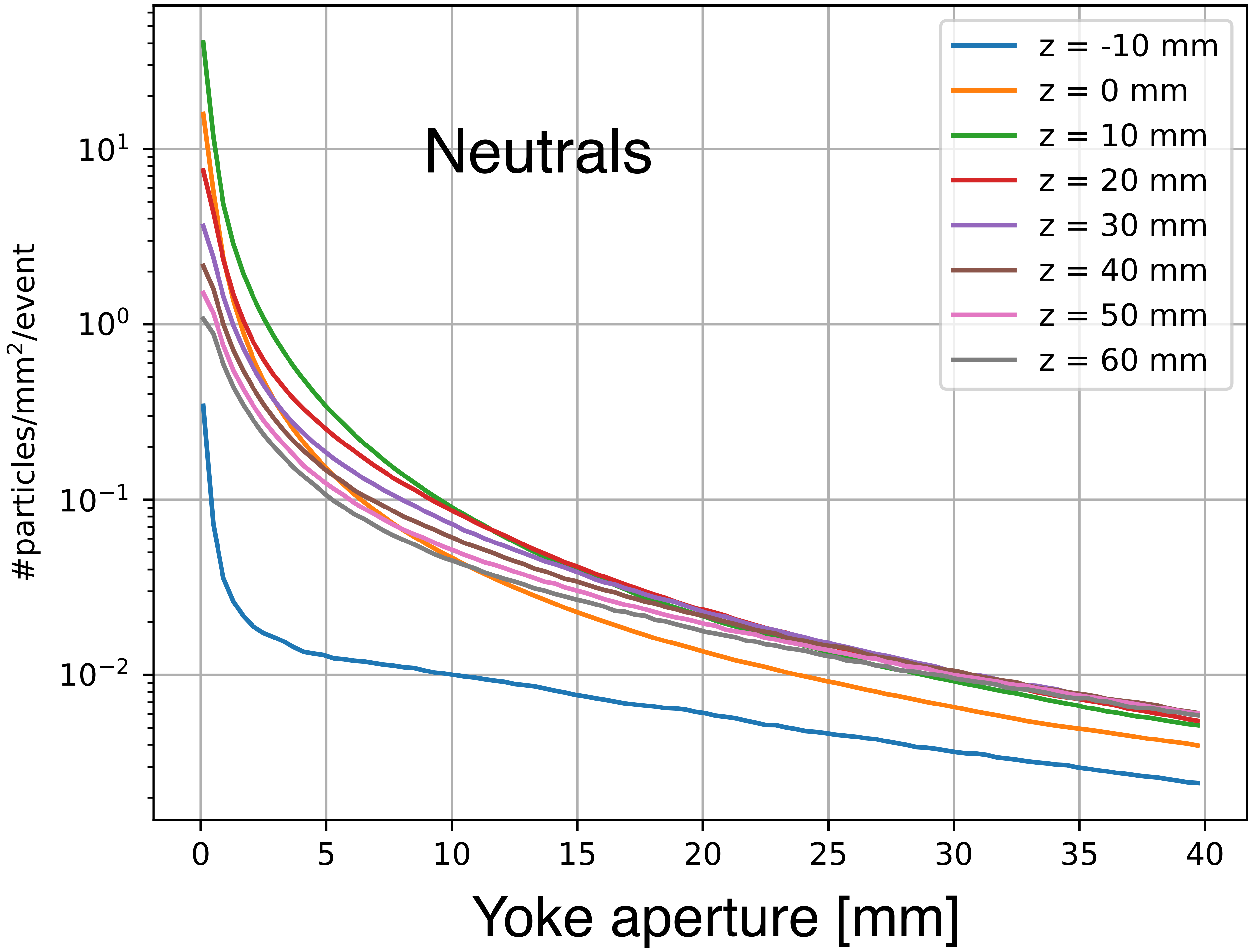
- Aperture magnet yoke preferably in the direction of the magnetic field
- Aperture radius ~ 0.02 rad in 20 cm = 0.4 cm
- The detector has to cover the forward region - pseudorapidity $\eta \sim 7$ $\theta \sim 0.001$ rad —> challenging

Magnet occupancy

- High particle flux could interfere with the operations of the magnet
- Higher yoke aperture, lower the flux, higher the cost
- Need to find a balance

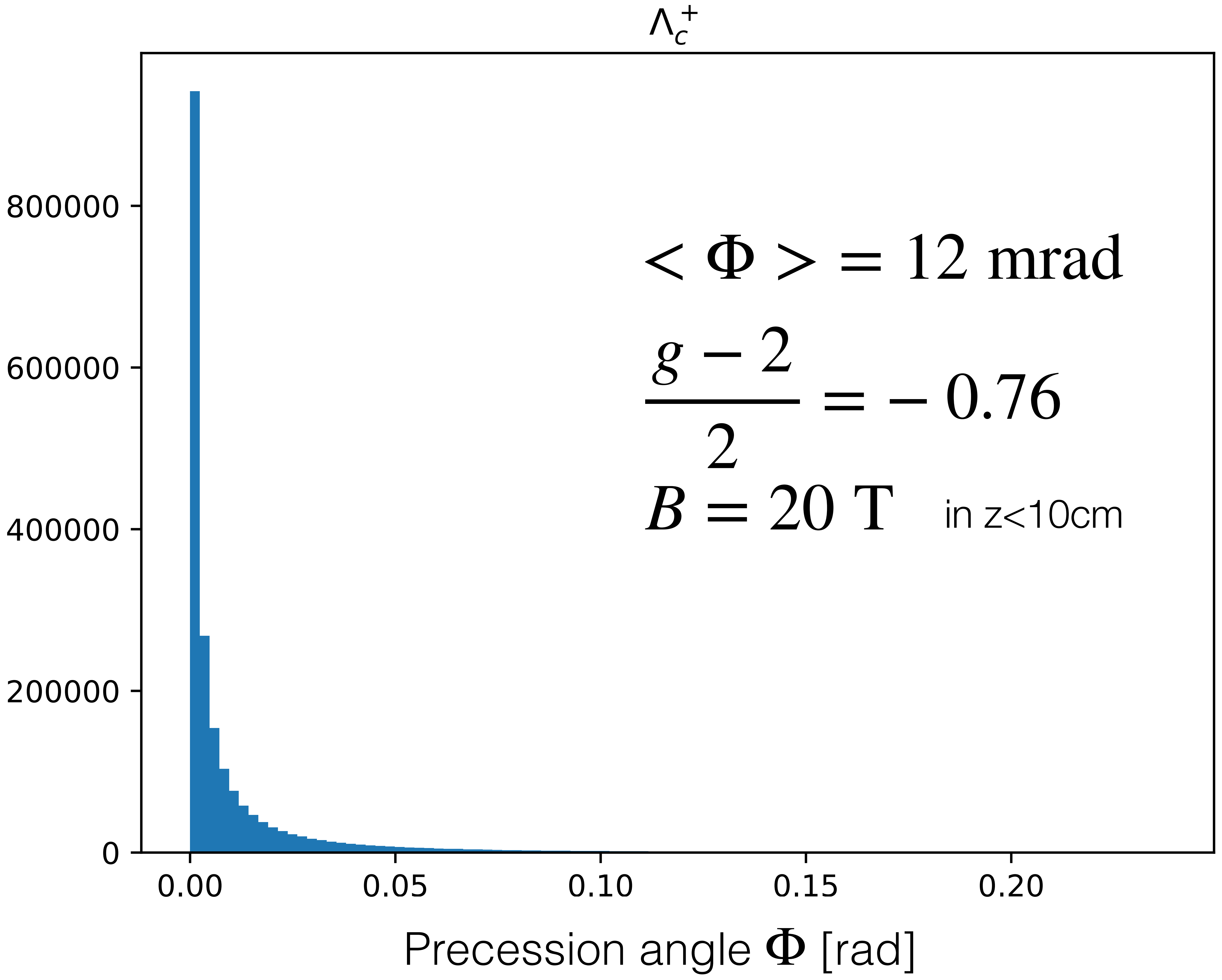


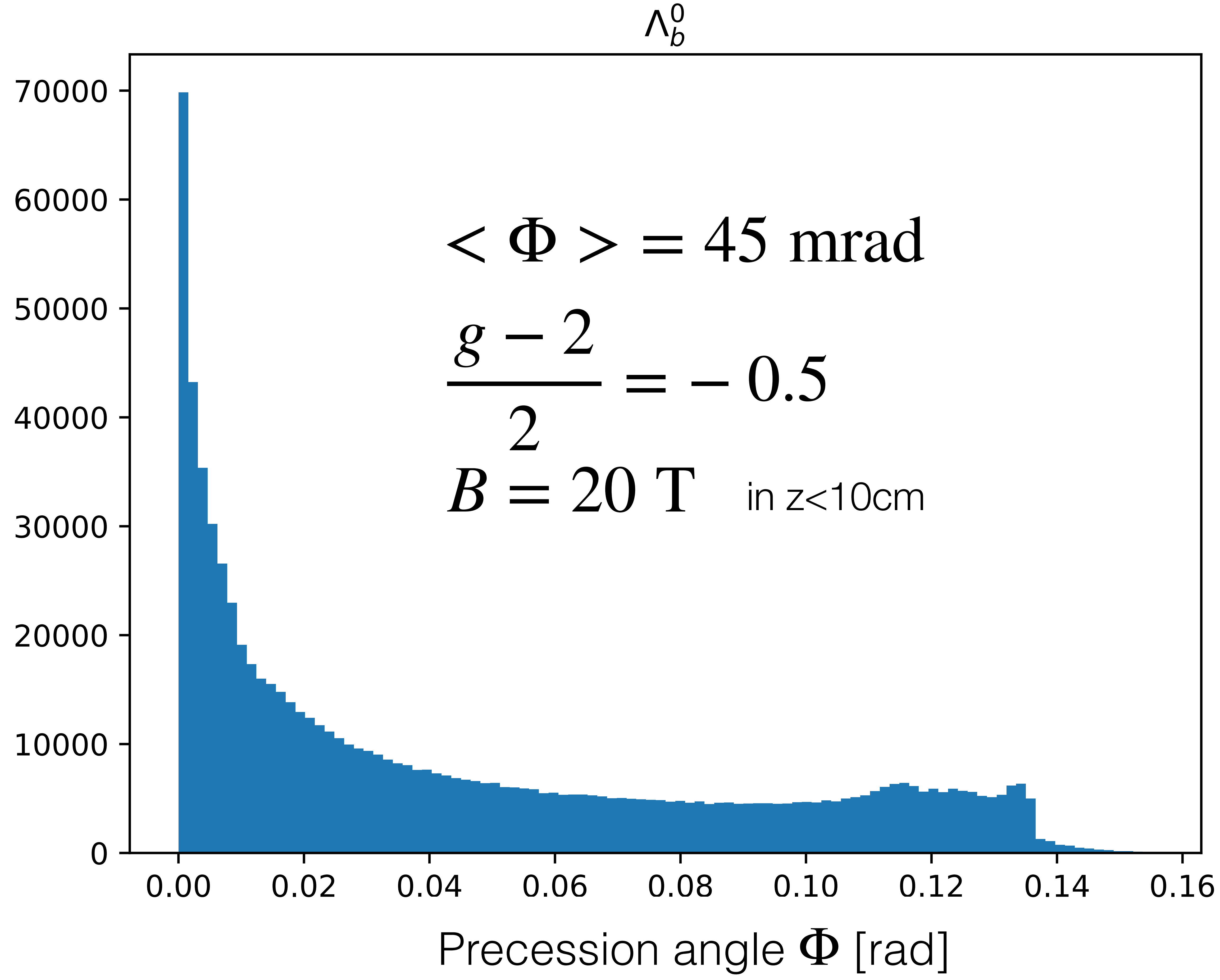




Expected precession angles for Λ_c^+ and Λ_b^0

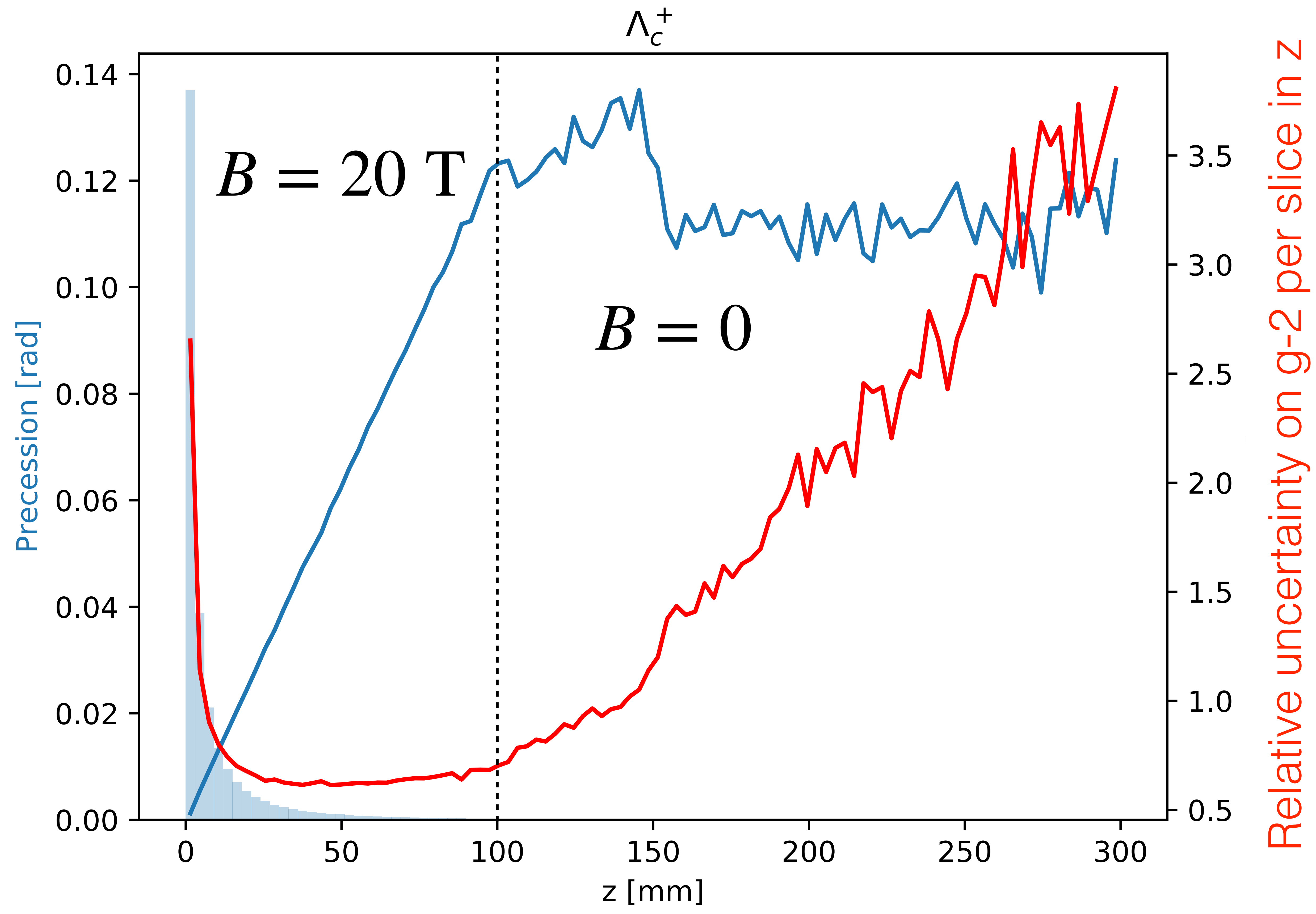
- $< \Phi > \ll 1$ rad (with crystals)

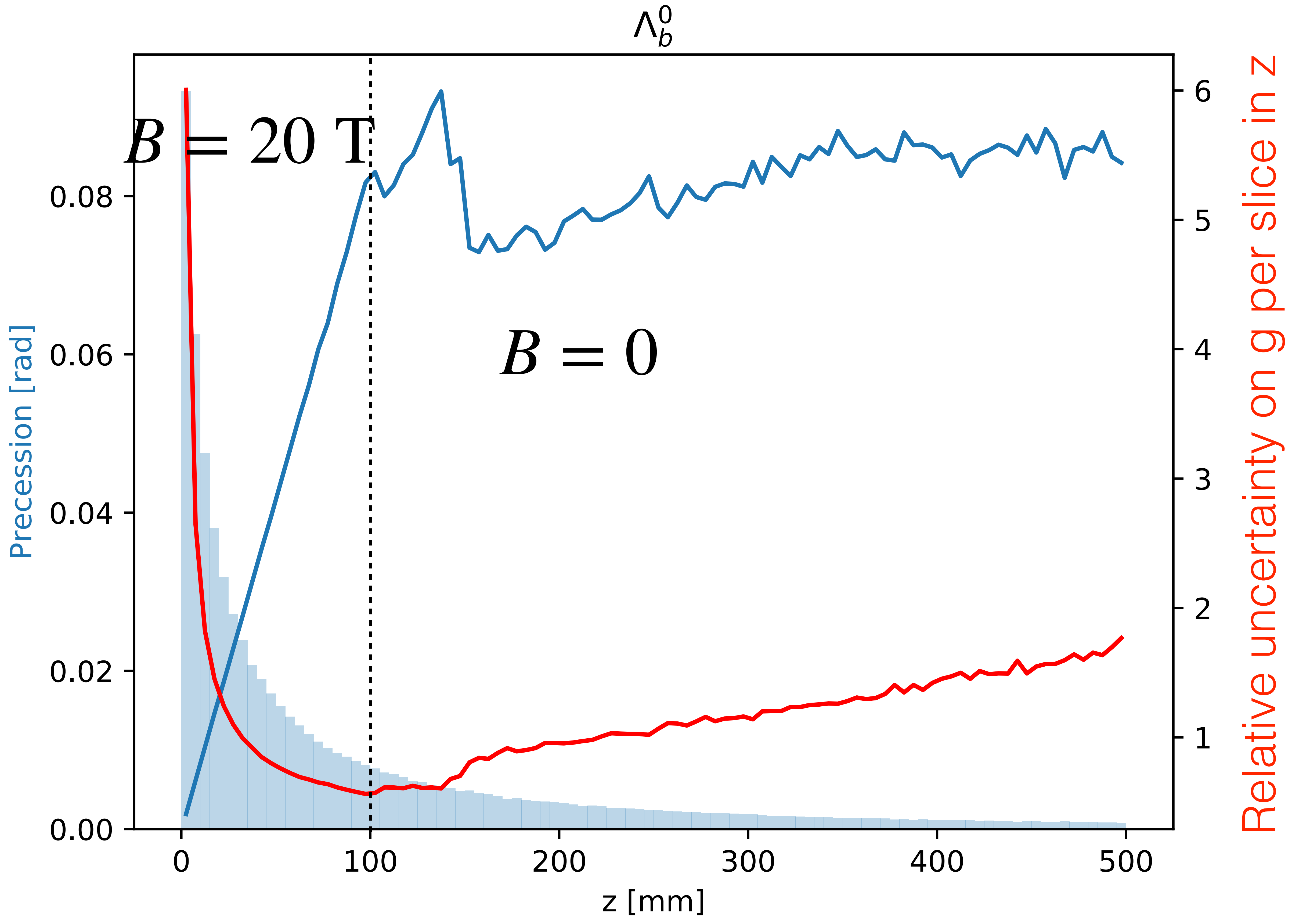




Typical decay length for Λ_c^+ and Λ_b^0

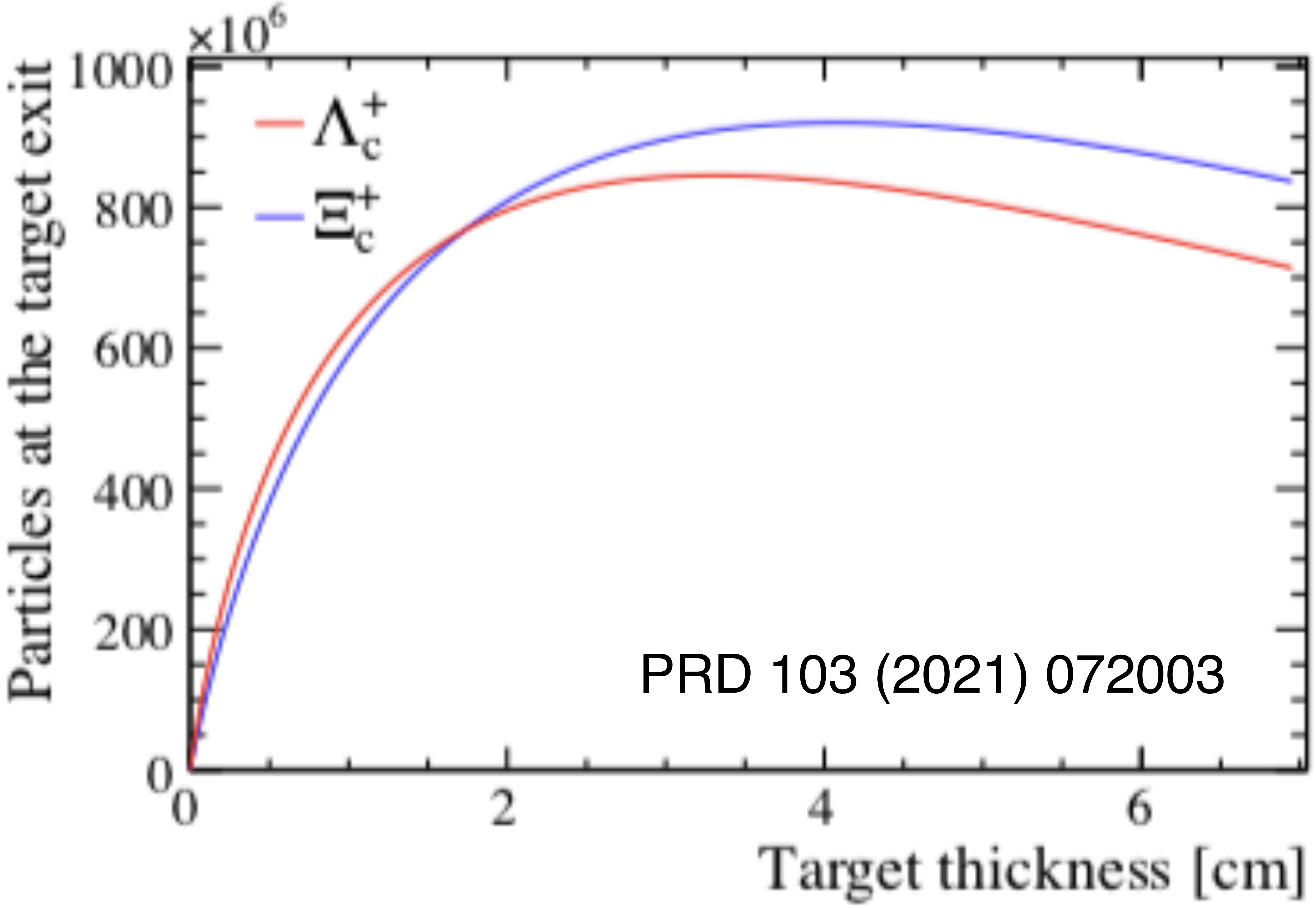
- Charm baryons decay length ~ 10 mm < b-baryons decay length ~ 70 mm





Number of events for charm baryons

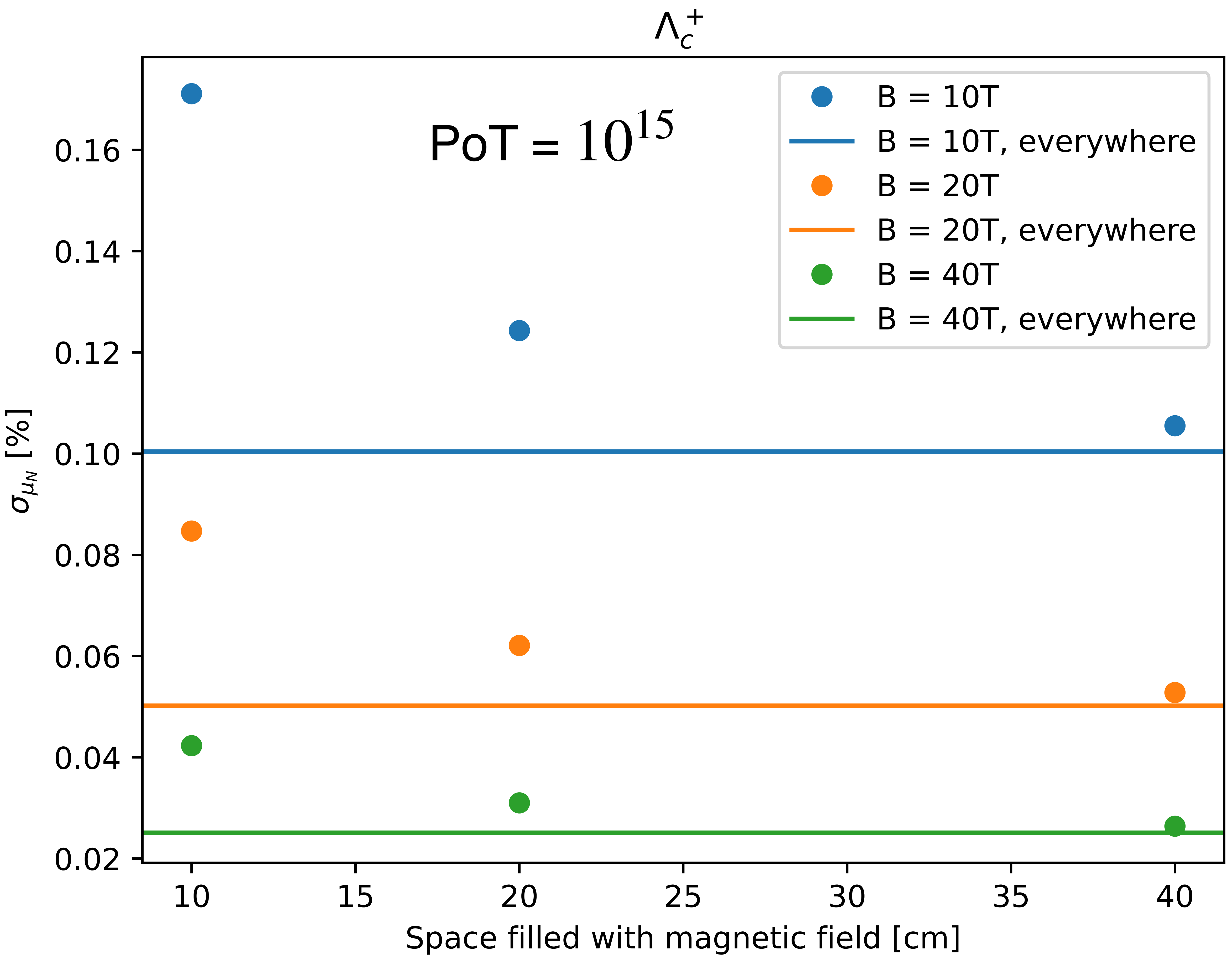
- Total number of expected Λ_c^+ signal yields = 24.6×10^6
- Assumed parameters (PRD 103 (2021) 072003):
  - Target thickness = 2cm
  - Effective branching ratio = 18.29% (sum of different decay modes)
  - Detector efficiency = 20%
  - Production cross section (Λ_c^+) = 10.6 μb/nucleon
  - PoT = 1.37E13
- Similar number of Ξ_c^+ particles



PRD 103 (2021) 072003

Sensitivity for Λ_c^+

- Sensitivity on $\mu_{\Lambda_c^+}$ at 0.05% with magnet at 20 T, x2 (3-4) better than crystal in IR3 (LHCb)
- As expected, the sensitivities are linear in B: the higher the better
- Optimal size of the magnet ~20-40 cm (compact due to the small lifetime of c-baryons)
- Unique possibility with magnet setup: measurement of negatively charged and neutral particles dipole moments
- CPT test with particle/antiparticle magnetic dipole moment

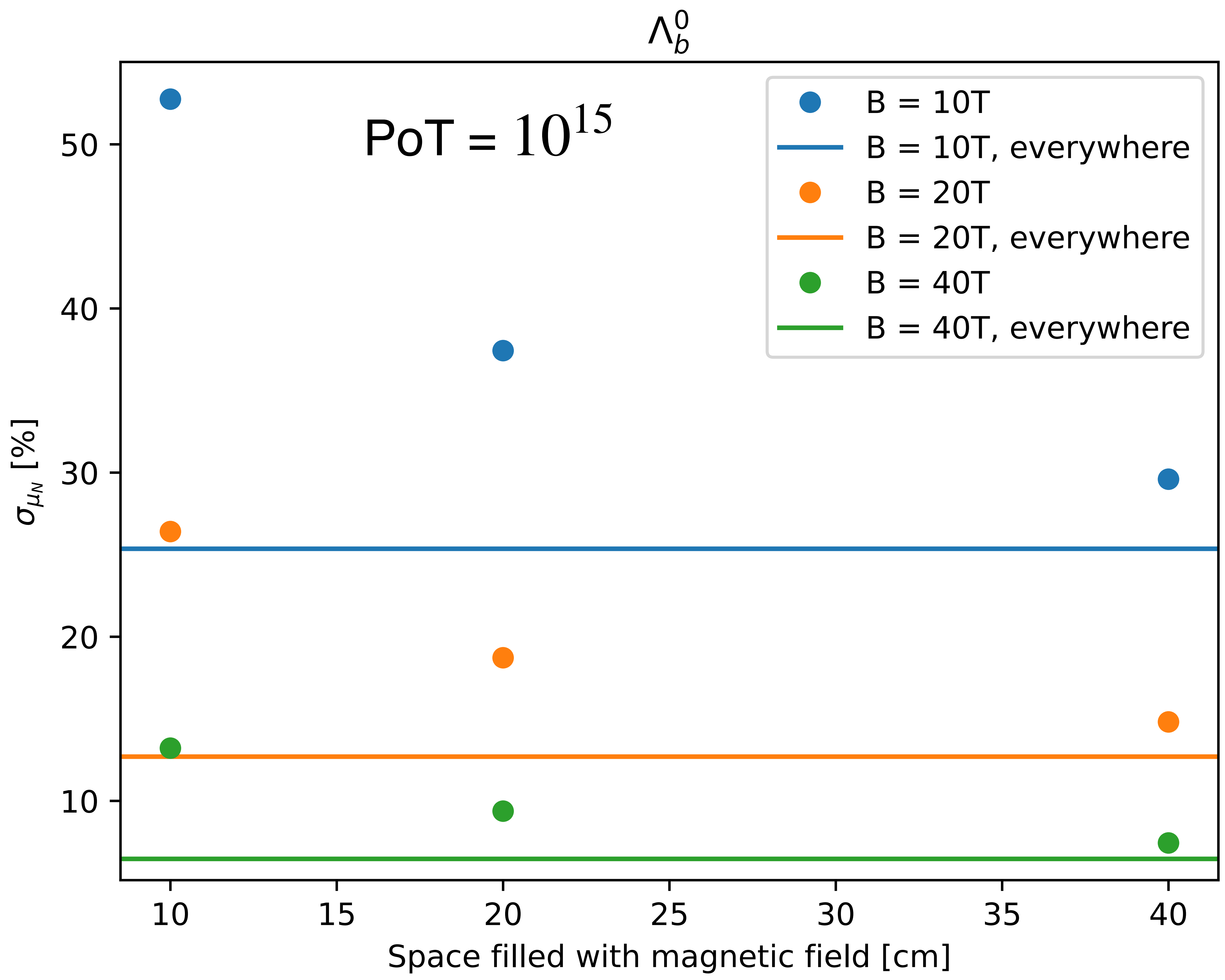


Number of events for beauty baryons

- With the magnet setup the high efficiency allow to reconstruct enough b-baryons to aim to measure their dipole moments
- Total number of expected $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK\pi)\mu\nu$ signal yields = 26.2×10^3:
  - Production cross section in fixed target collision $\sigma_{b\bar{b}} = 43.6\,\mathrm{nb}$
  - Fragmentation fraction $f_{b\rightarrow\Lambda_b} = 7\,\%$
  - Branching fraction $\mathrm{BR} = 0.68\,\%$
  - Reconstruction efficiency $\varepsilon_{det} = 12\,\%$
  - Decay asymmetry parameters $\alpha = 0.4$ (for sensitivity)
  - $\mathrm{PoT} = 10^{15}$

Sensitivity for Λ_b^0

- As expected, the sensitivities are linear in B: the higher the better
- Optimal size of the magnet $\gtrsim 40$ cm (for b-baryons)
- Aim to measure $\mu_{\Lambda_b^0}$ with sensitivity of 10%
- Unique possibility with magnet setup: measure b-baryons dipole moments: for crystal low number of yields due to low channeling efficiency
- CPT test with particle/antiparticle magnetic dipole moment



Conclusions

- The magnet setup provide higher sensitivity to dipole moments wrt crystals
- Enlarge the physics reach of dipole moments measurements to neutral, negatively charged particles, b-baryons and τ lepton (main production from $D_s^- \to \tau^- \nu$ decays)
- High-filed dipole magnet is required (technologically feasible?):
  - 20/40 T magnet field
  - Longitudinal size of ~40cm
  - Radius transversal size of 0.5/1 cm - compatible with radiation?