Direct probe of τ dipole moments with bent crystals

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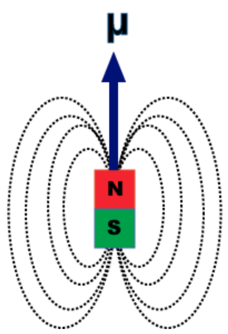
A.S. Fomin (LAL, KIPT, CERN), A. Yu Korchin (KIPT, KhNU), A. Stocchi, S. Barsuk, P. Robbe (LAL), *Feasibility of τ-lepton electromagnetic dipole moments measurement using bent crystal at the LHC,* [arXiv:1810.06699] **(2018),** JHEP 1903 **(2019)** 156 [inSPIRE]

INTRODUCTION: Magnetic dipole moment (MDM) of short-living particles



$$\vec{\mu} = \frac{g}{2}\frac{e}{m}\vec{S}, \qquad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

$|g| = 2$ → a point-like Dirac particle

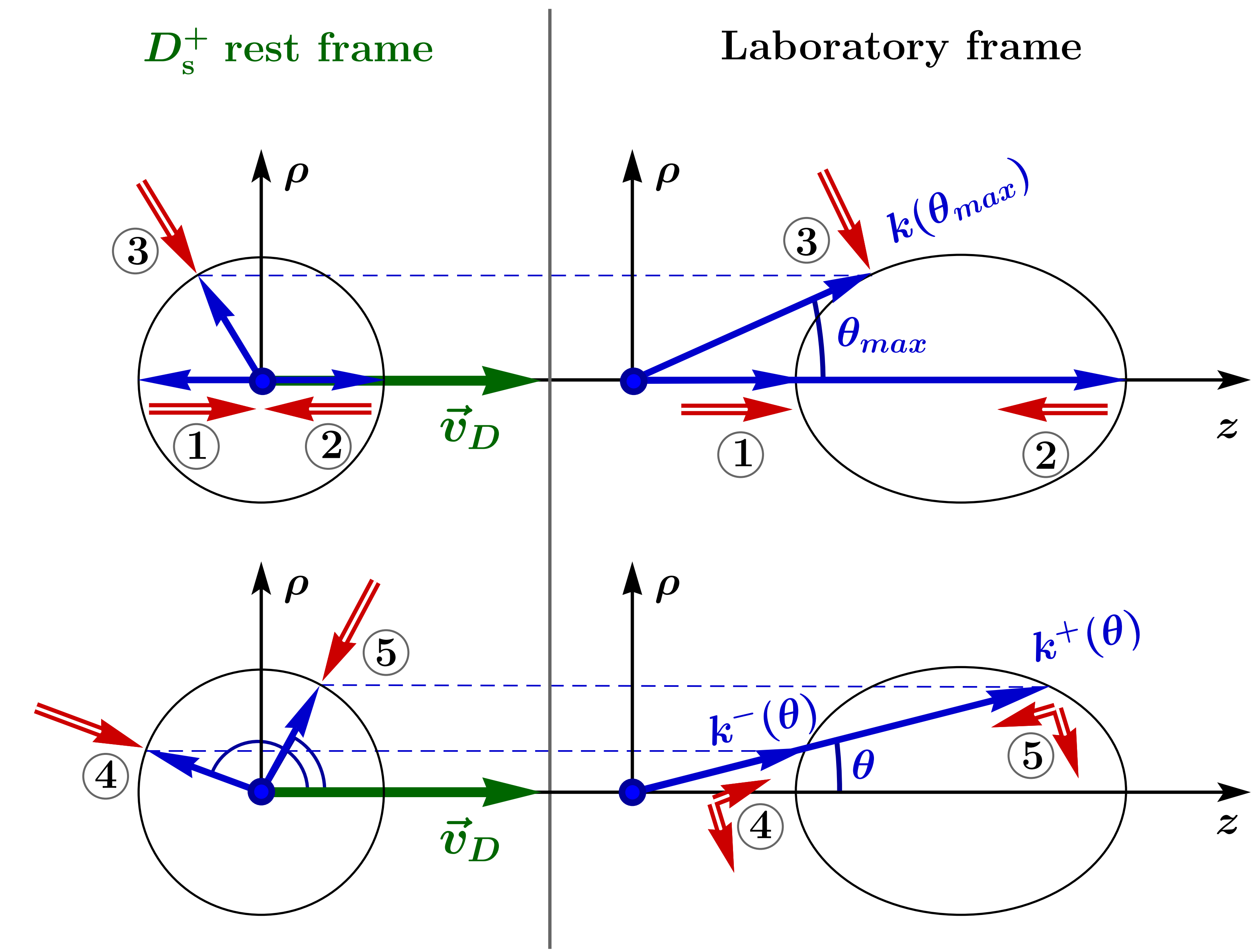
$|g| \approx 2$ → a radiative corrections

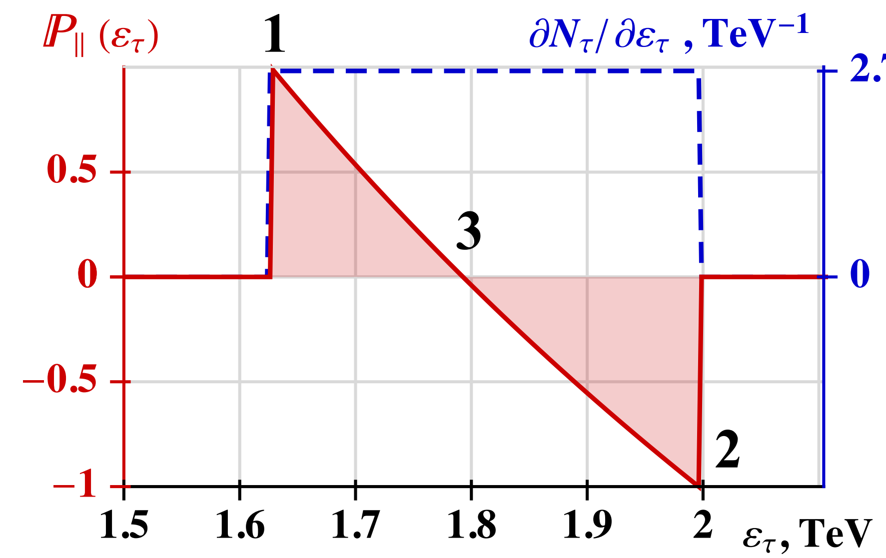
$|g| \not\approx 2$ → a composite structure or NP

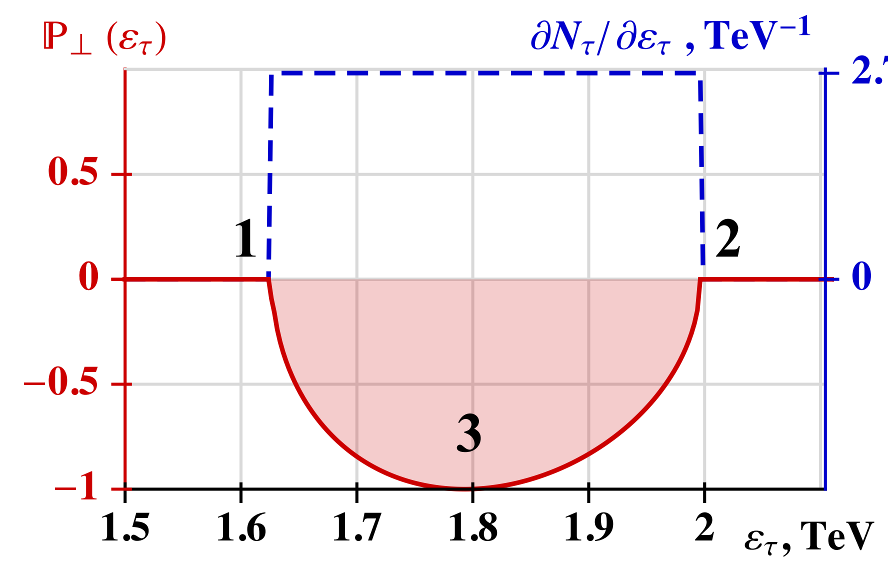
Particle	cτ	*g*-factor		Comments	Experiment
e^-		– 2.002 319 304 361 82 (52)	exp.	most accurate determinations of α	Harvard 2008
μ^-	659 m	– 2.002 331 8361 (10)	theor.	SM prediction	
		– 2.002 331 8418 (13)	exp.	3.4 σ deviation	BNL: E821 2006
τ^-	87 μm	– 2.002 354 42 (10)	theor.	SM prediction	
		– 2.036 (34)	exp.	$\sigma\,(e^+e^- \to e^+e^-\,\tau^+\tau^-)$	LEP2: DELPHI 2004
		– 2.002 (6)	*exp.*	*assuming EDM$_\tau$ = 0*	*from LEP and SLD 2000*
		no direct measurement	exp.	Proposed in arxiv:1810.06699	
p		+ 5.585 694 702 (17)	exp.		
n		– 3.826 085 45 (90)	exp.		
Σ^+	2.4 cm	+ 6.233 (25)	exp.	world-average value	
		+ 6.1 $(12)_{stat}$ $(10)_{syst}$	exp.	using Bent Crystals	Fermilab 1990
Λ_c^+	60 μm	+ 1.90 (15)	theor.	assuming $g_c \approx 2$	
		not measured	exp.	Feasibility studies at LHC	

Initial polarisation of τ lepton

$$D_s^+ \to \tau^+ \, \nu_\tau$$







$$\theta_{max} \approx \frac{0.1025}{\gamma_D} \quad (\gamma_\tau \gg 1)$$

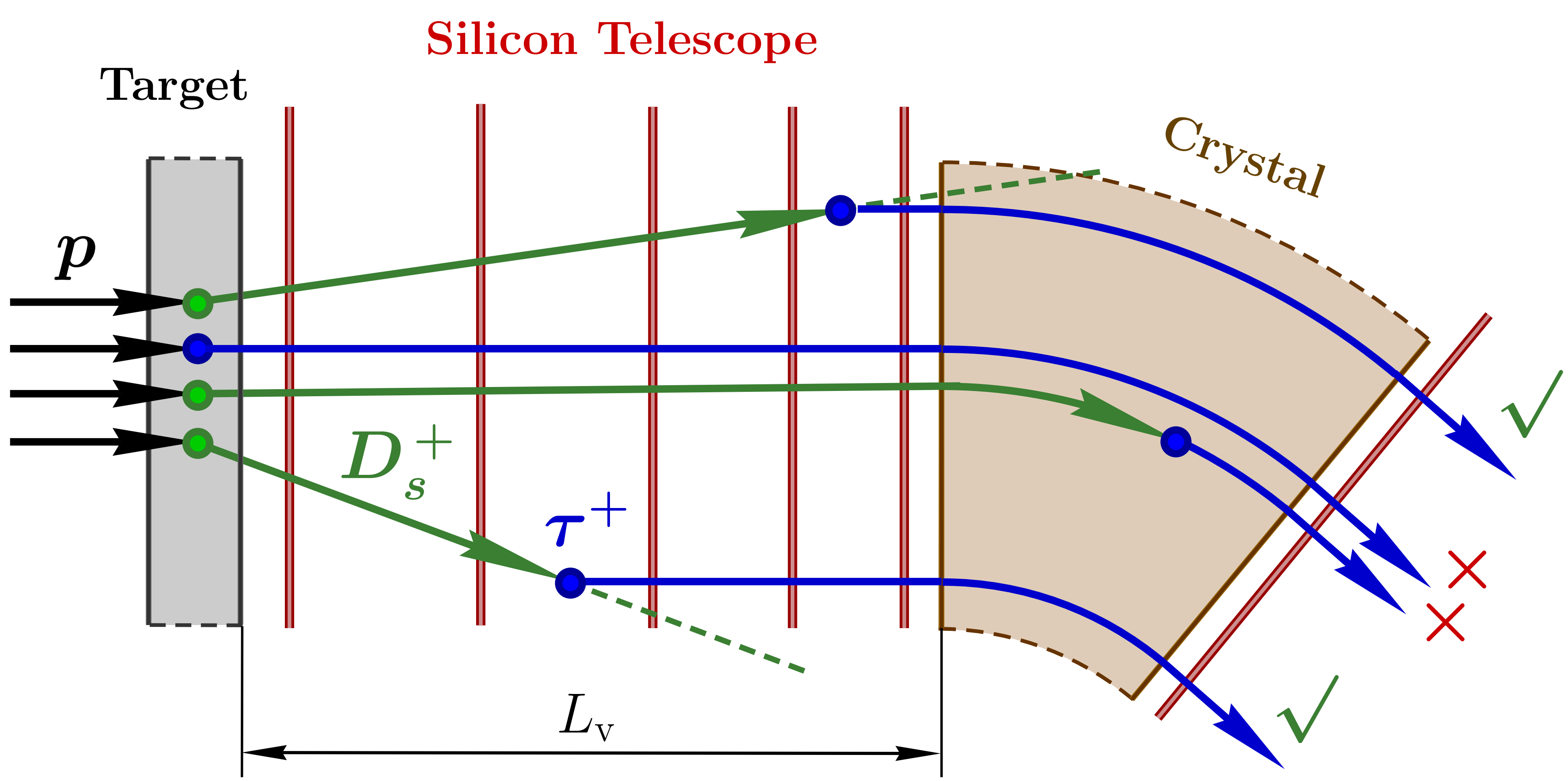
$$|\vec{P}_\perp| = \frac{m_\tau p_D}{M_D k_\tau^*} \sin\theta,$$

$$\theta_{max}(E_D = 2\,\text{TeV}) \approx 100\,\mu rad$$

$$\vec{P}_\parallel^2 = 1 - \vec{P}_\perp^2$$

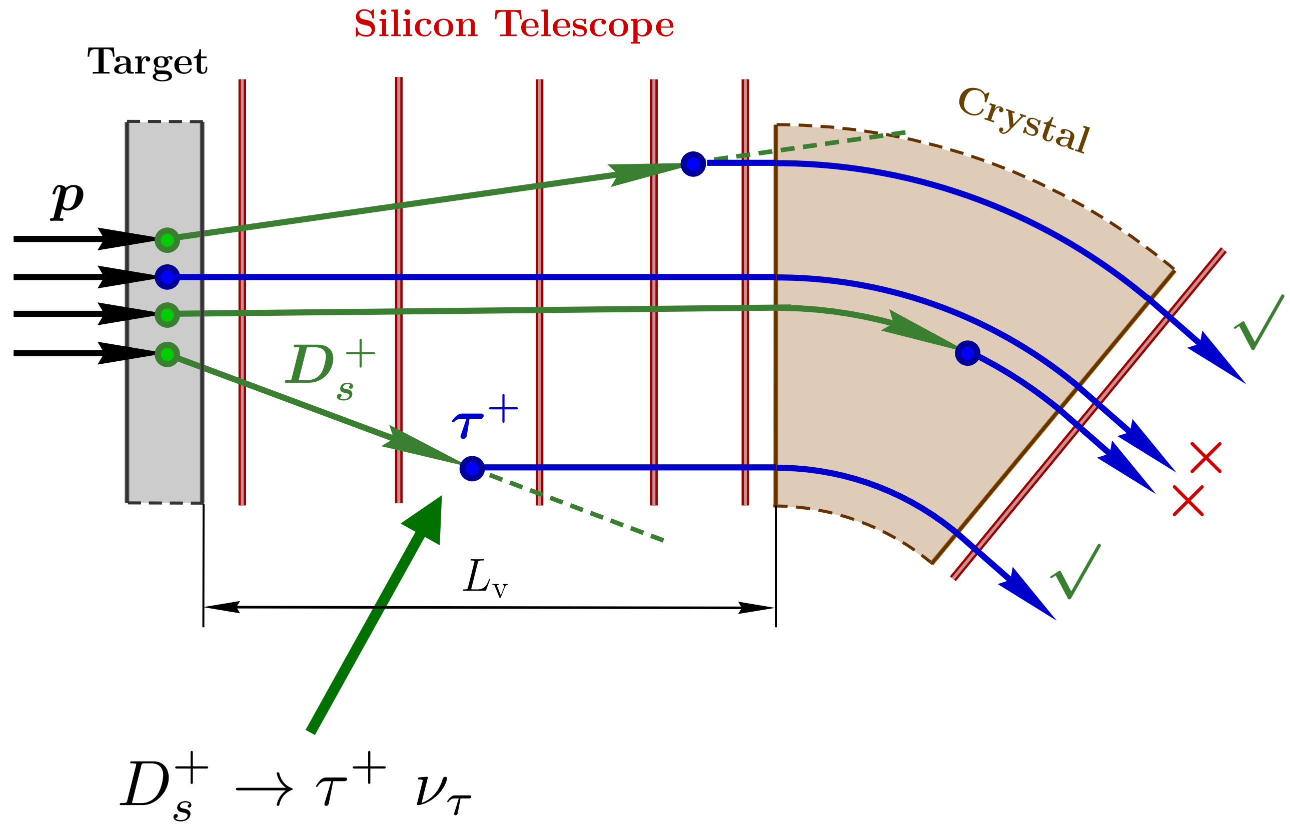
$$\vec{P}_\perp(\theta, 0) \approx -\vec{P}_\perp(\theta, \pi).$$

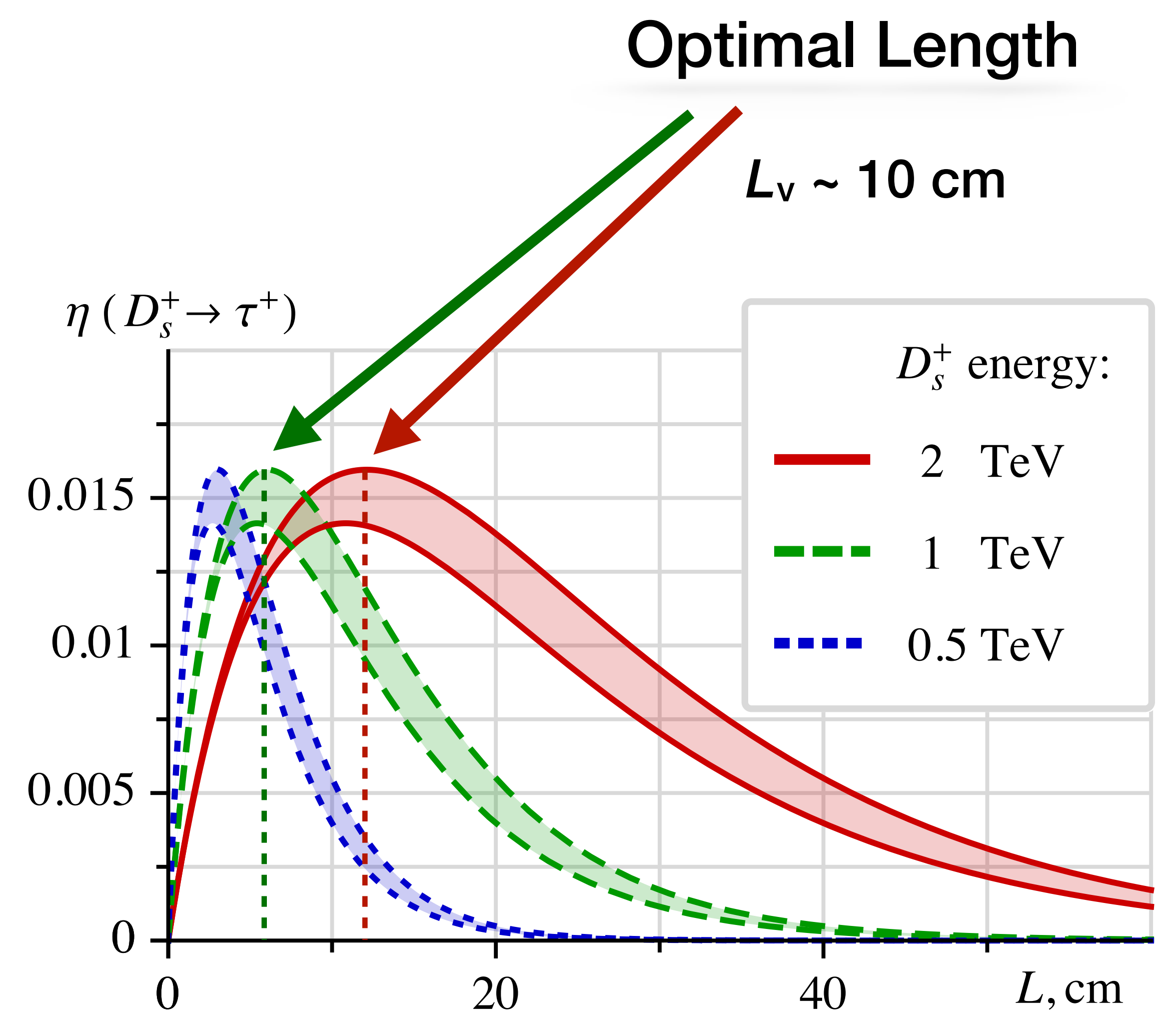
$$p\,p \to D_s^+ \ldots \to \tau^+ \ldots \to 2\pi^+\,\pi^- \ldots$$



- we need to select events: $D_s^+ \to \tau^+ \to 2\pi^+\pi^-$ out of the background: $X^+ \to 2\pi^+\pi^-$
- directions of D_s^+ and τ^+ momenta should be measured very accurately $\Delta\theta < 100\ \mu\text{rad}$

Optimal conversion length (distance between Target & Crystal)





$$\eta^*(L_v, E_D, \varepsilon_\tau^*) = Br_i \, \frac{e^{-L_v / T_D} - e^{-L_v / T_\tau}}{T_D / T_\tau - 1}$$

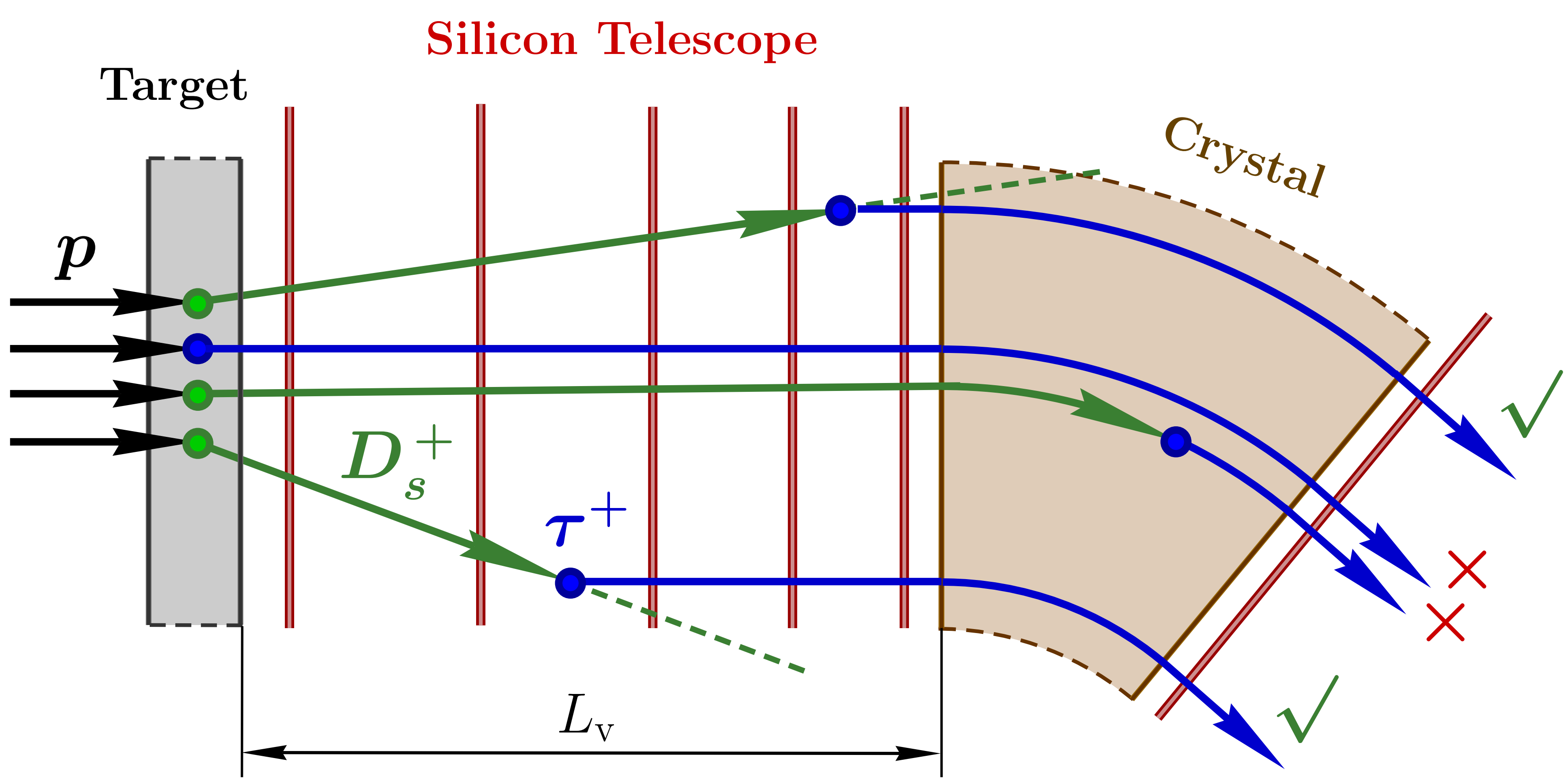
$$T_i = c\,\tau_i \gamma_i \qquad c\,\tau_D \approx 150\,\mu\text{m}$$

$$c\,\tau_\tau \approx 87\,\mu\text{m}$$

$$Br_j \approx 0.055$$

$$\eta(L_v, E_D) = \frac{\int_{\varepsilon_\tau^{min}}^{\varepsilon_\tau^{max}} d\varepsilon_\tau \, \frac{\partial N_\tau}{\partial \varepsilon_\tau} \int_0^{L_v} dx \, \frac{\partial N_{\text{prod}}}{\partial x} \, N_{\text{dec}}\,(L_v - x)}{\int_{\varepsilon_\tau^{min}}^{\varepsilon_\tau^{max}} d\varepsilon_\tau \, \frac{\partial N_\tau}{\partial \varepsilon_\tau}}$$

$$p\,p \to D_s^+ \ldots \to \tau^+ \ldots \to 2\pi^+\,\pi^- \ldots$$



- we need to select events: $D_s^+ \to \tau^+ \to 2\pi^+\pi^-$ out of the background: $X^+ \to 2\pi^+\pi^-$
- directions of D_s^+ and τ^+ momenta should be measured very accurately $\Delta\theta < 100$ μrad

Problems:
- the background overload,
- the telescope should have a very high angular resolution $\Delta\theta < 100$ μrad on a rather short base $L_v \sim 10$ cm.

Crystal 1:

Ge: L = 3 cm R = 10 m

Si: L = 4.5 cm R = 15 m

Θ_D = 3 mrad

θ_p = 0.1 mrad

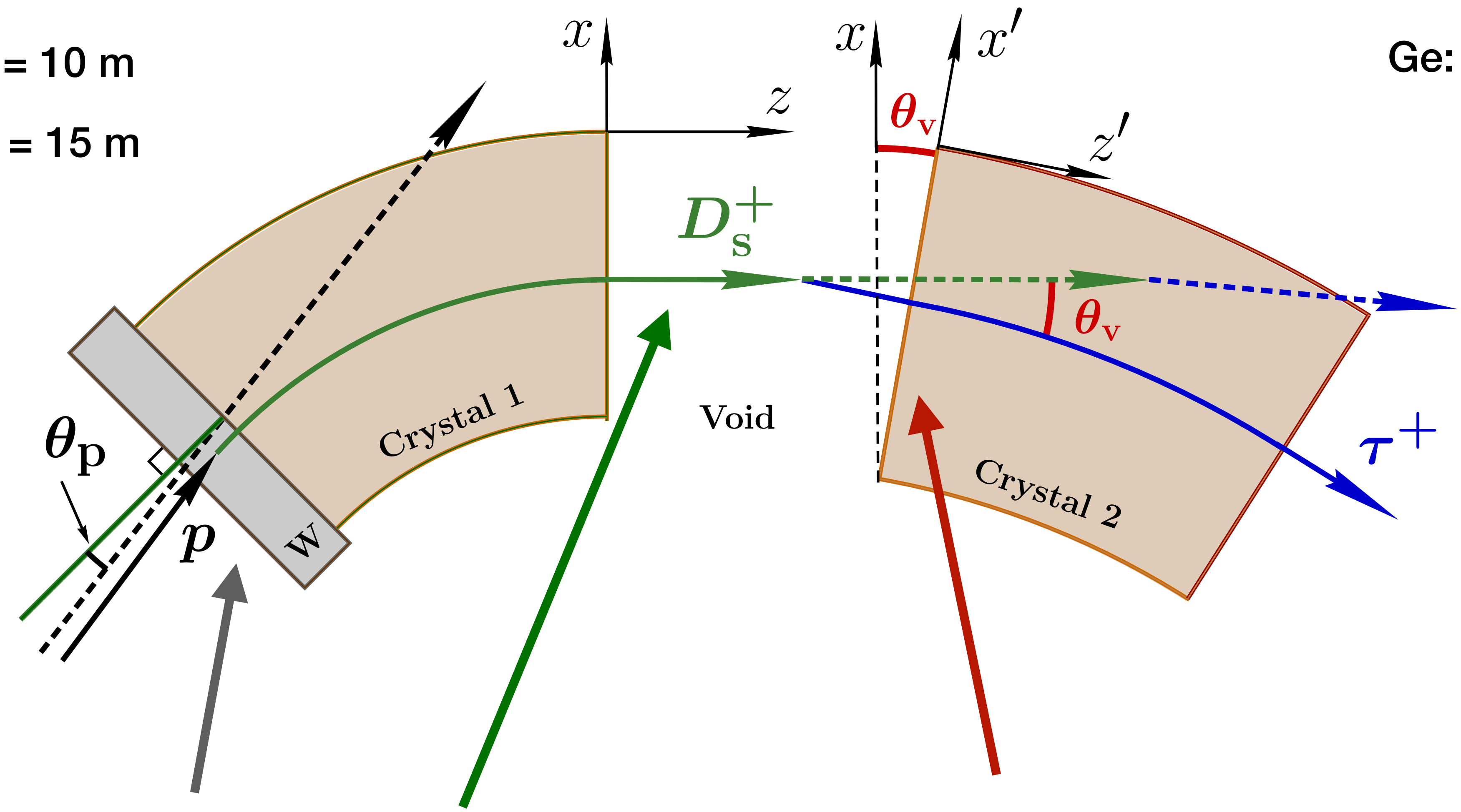
Crystal 2:

Ge: L = 10 cm R = 7 m

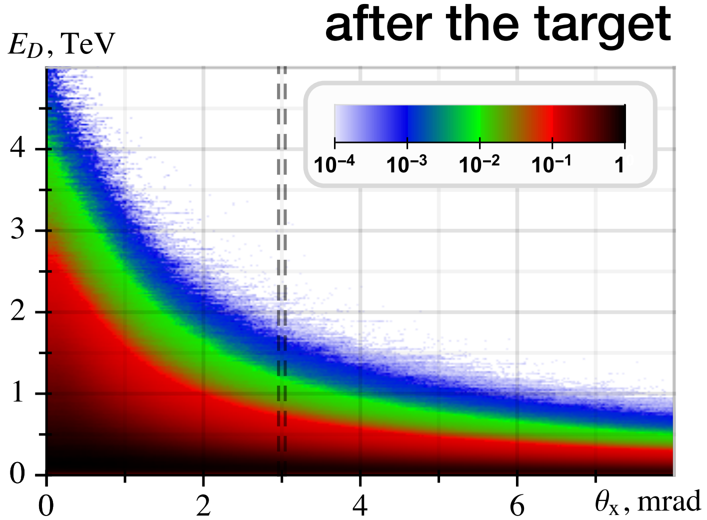
Θ_τ = 14 mrad

θ_v = 0.08 mrad

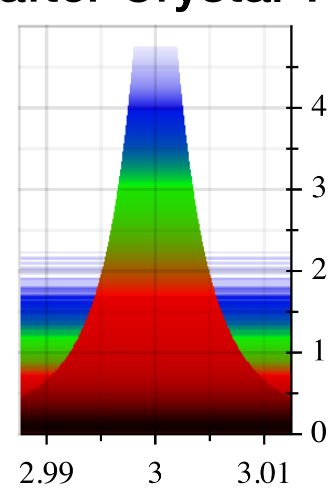
L_v = 10 cm



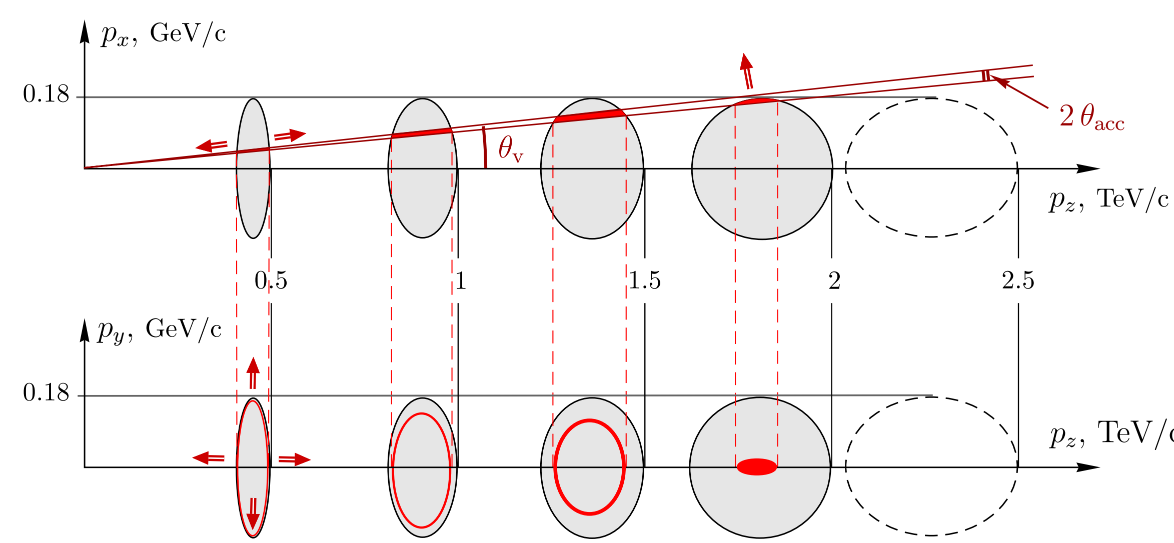
Sp.-ang. distribution of Ds after the target

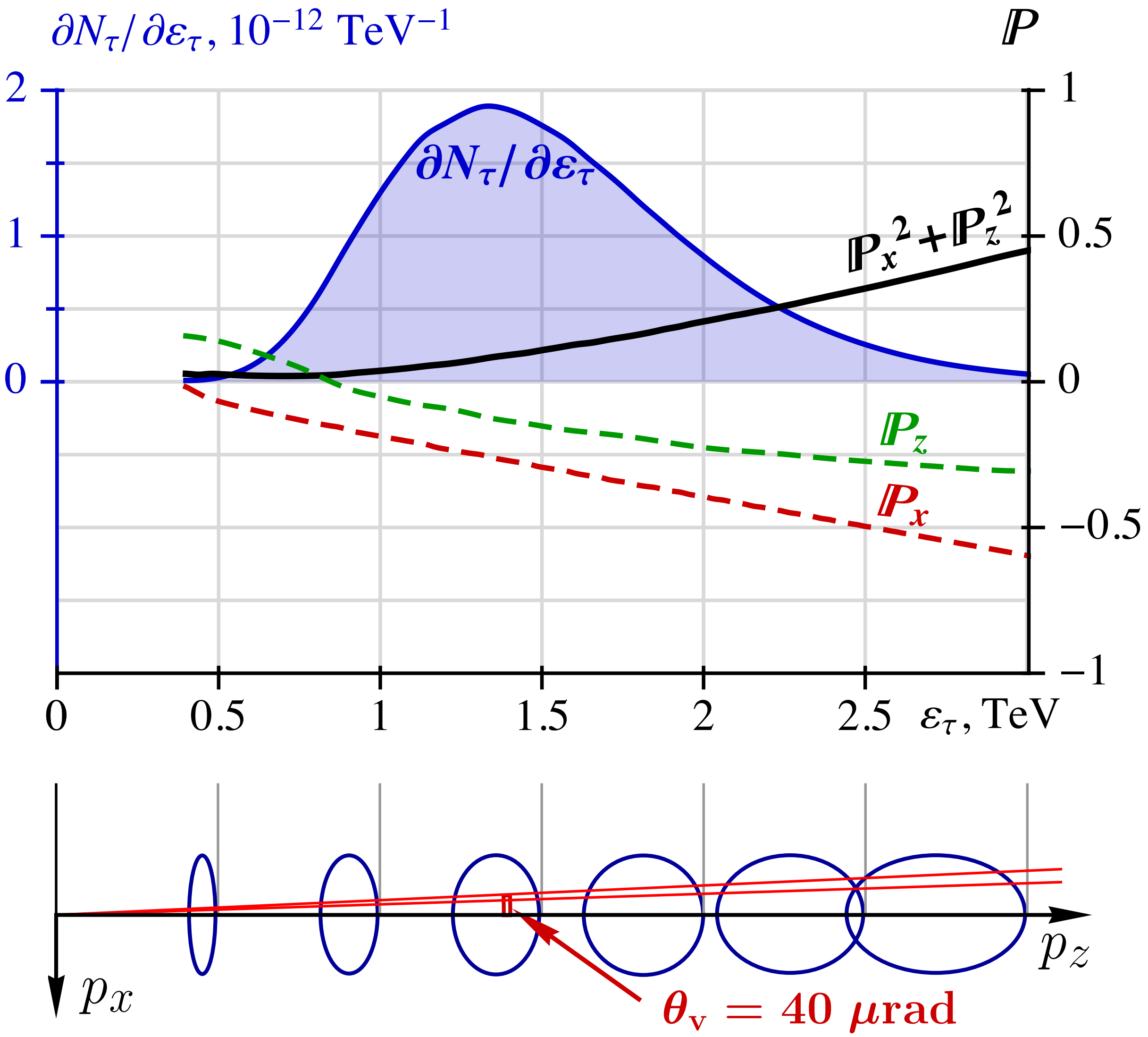


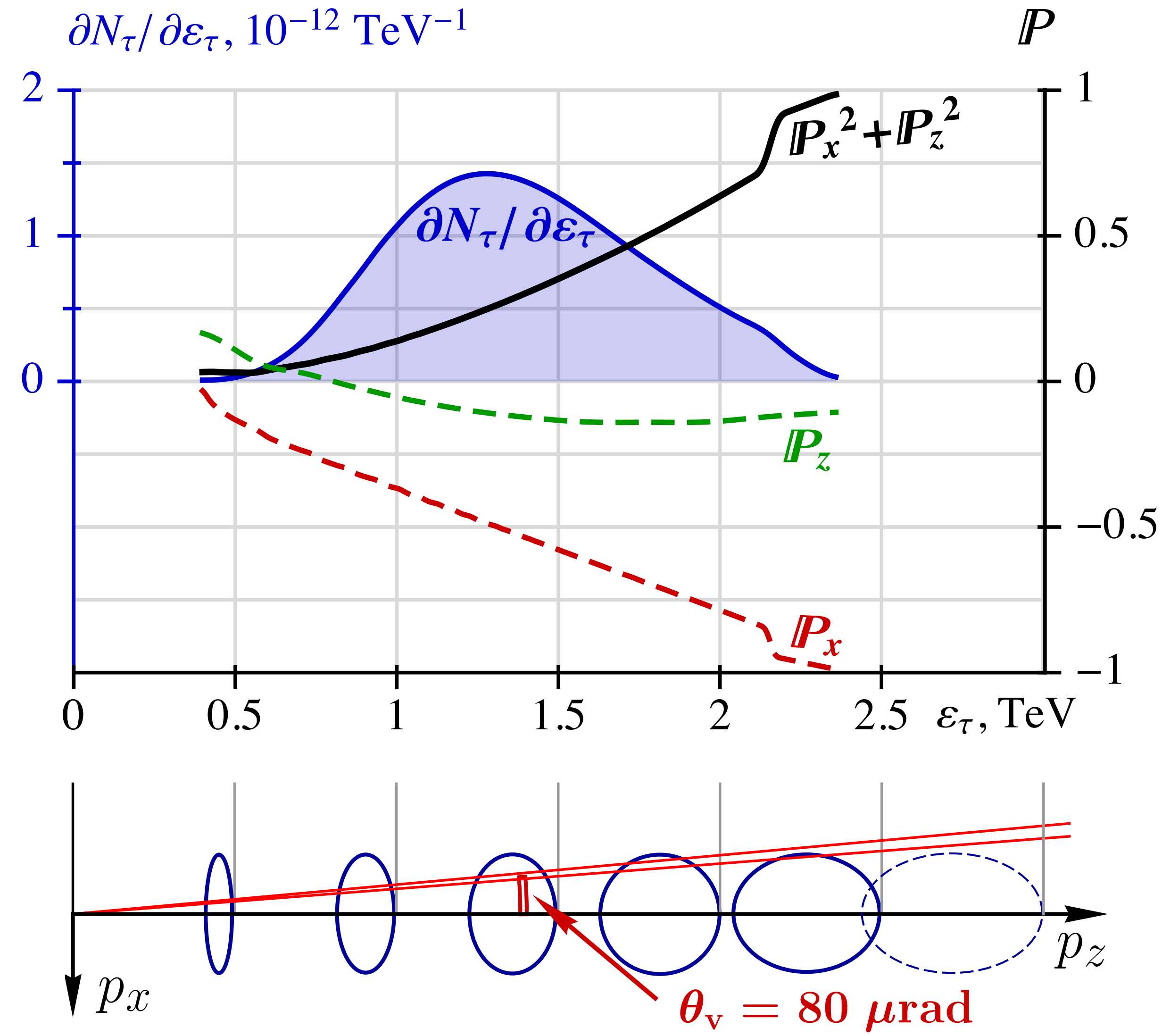
after Crystal 1



Angular collimation of τ by Crystal 2







Spectra:

$$\frac{\partial N_\tau^{\mathrm{def}}}{\partial \varepsilon_\tau} = \int_0^{\varepsilon_{\max}} dE_D \, \frac{\partial N_D}{\partial E_D} \, \eta\left(L_{\mathrm{v}}, E_D\right) \, \frac{\partial N_\tau}{\partial \varepsilon_\tau}(E_D) \, \eta_{\mathrm{coll}}(E_D, \varepsilon_\tau) \, \eta_{\mathrm{chan}}\left(\varepsilon_\tau\right)$$

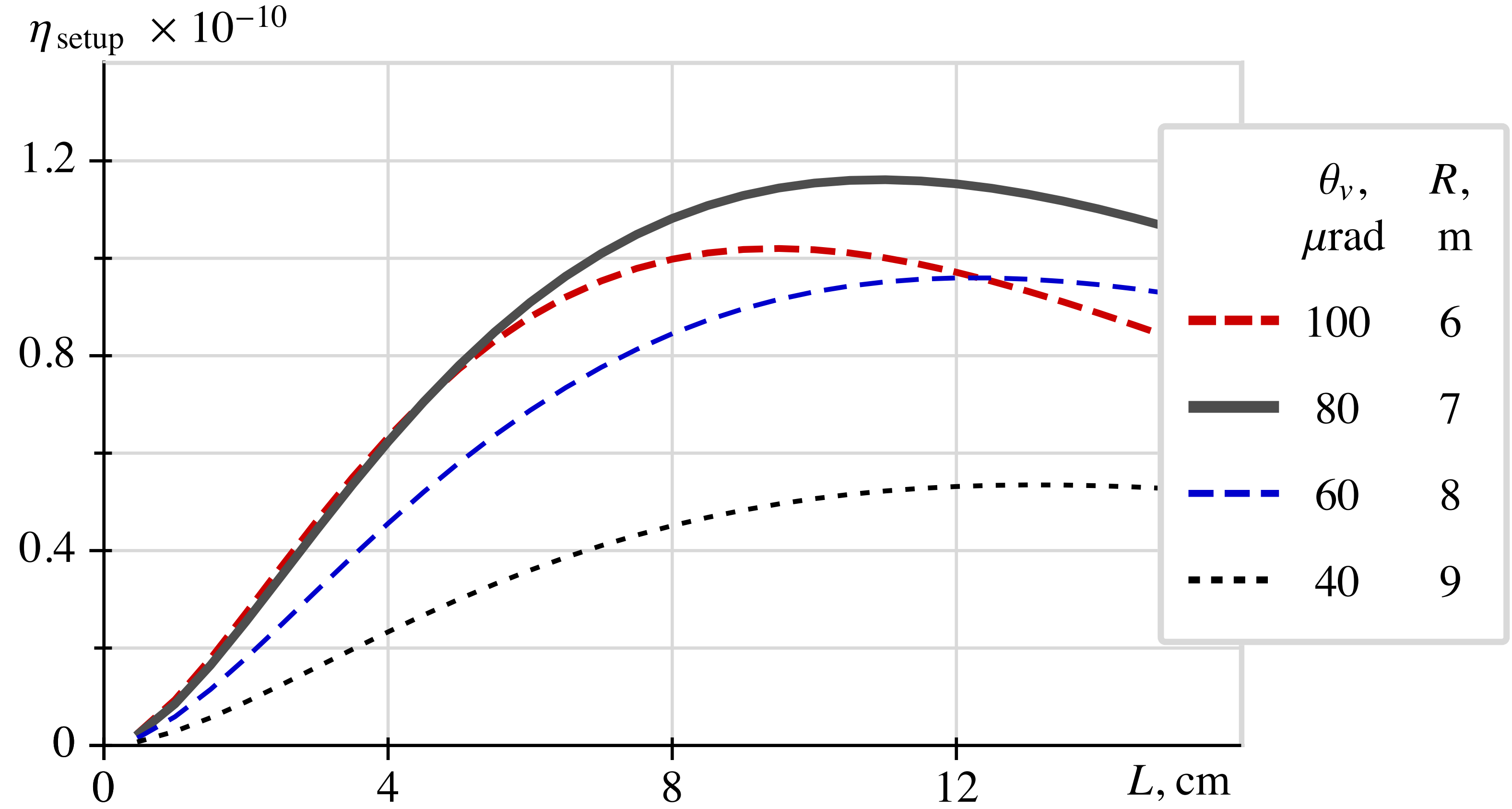
Polarisation:

$$\mathrm{P_z}(\varepsilon_\tau) = \frac{1}{\partial N_\tau^{\mathrm{def}}/\partial \varepsilon_\tau} \int dE_D \, \frac{\partial N_D}{\partial E_D} \, \frac{\partial N_\tau^{\mathrm{def}}}{\partial \varepsilon_\tau}(E_D) \, \mathrm{P_z}(E_D, \varepsilon_t)$$

$$\mathrm{P}_x(\varepsilon_\tau) = \frac{1}{\partial N_\tau^{\mathrm{def}}/\partial \varepsilon_\tau} \int dE_D \, \frac{\partial N_D}{\partial E_D} \, \frac{\partial N_\tau}{\partial \varepsilon_\tau}(E_D) \, \mathrm{P}_\perp(E_D, \varepsilon_\tau) \, \frac{1}{\pi} \int_{\phi_{min}(\varepsilon_\tau)}^{\phi_{max}(\varepsilon_\tau)} \sin\phi \, d\phi.$$

$$\Delta a_\tau = \sqrt{\frac{1}{N_p \quad \eta_{\rm det} S^2 \quad \eta_{\rm setup}}}$$

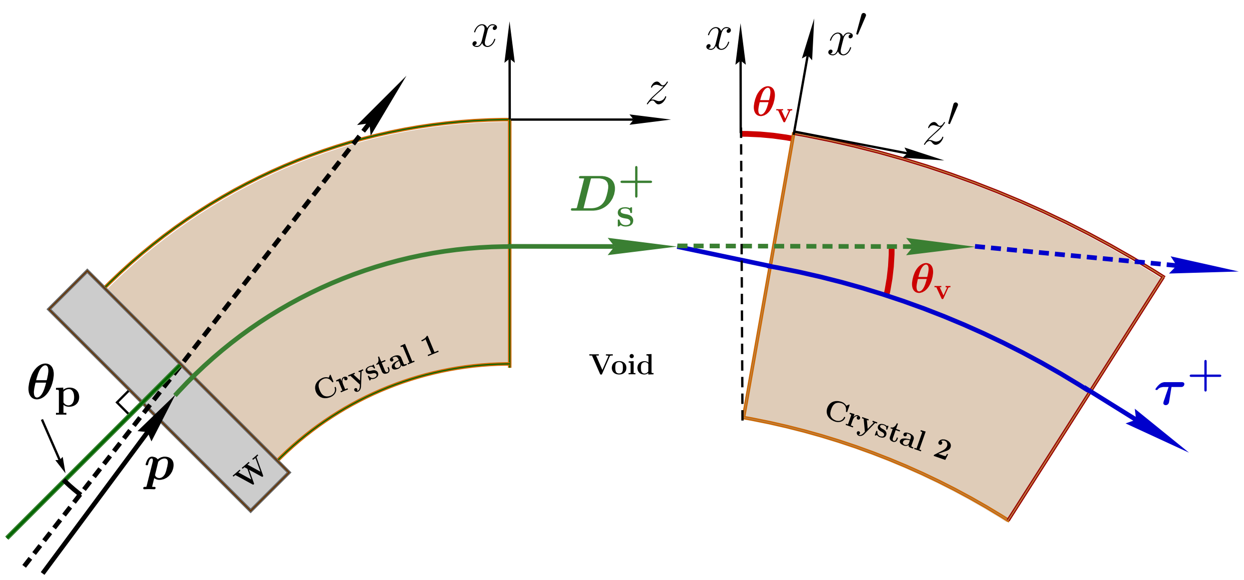
$$\eta_{\rm setup} = \Theta^2 \int d\varepsilon \, \frac{\partial N_\tau^{\rm def}}{\partial \varepsilon} \, \gamma_\tau^2 \; \mathrm{P}^2$$



N_p is the integral number of protons,

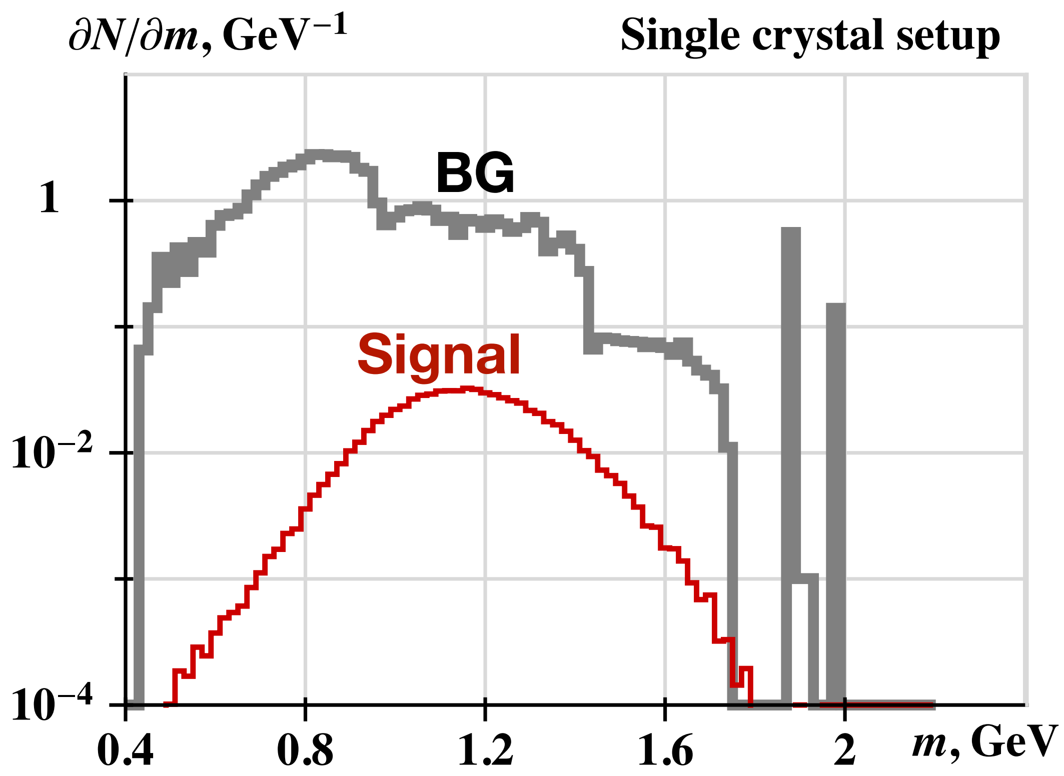
$\eta_{\rm det}$ is the detector efficiency

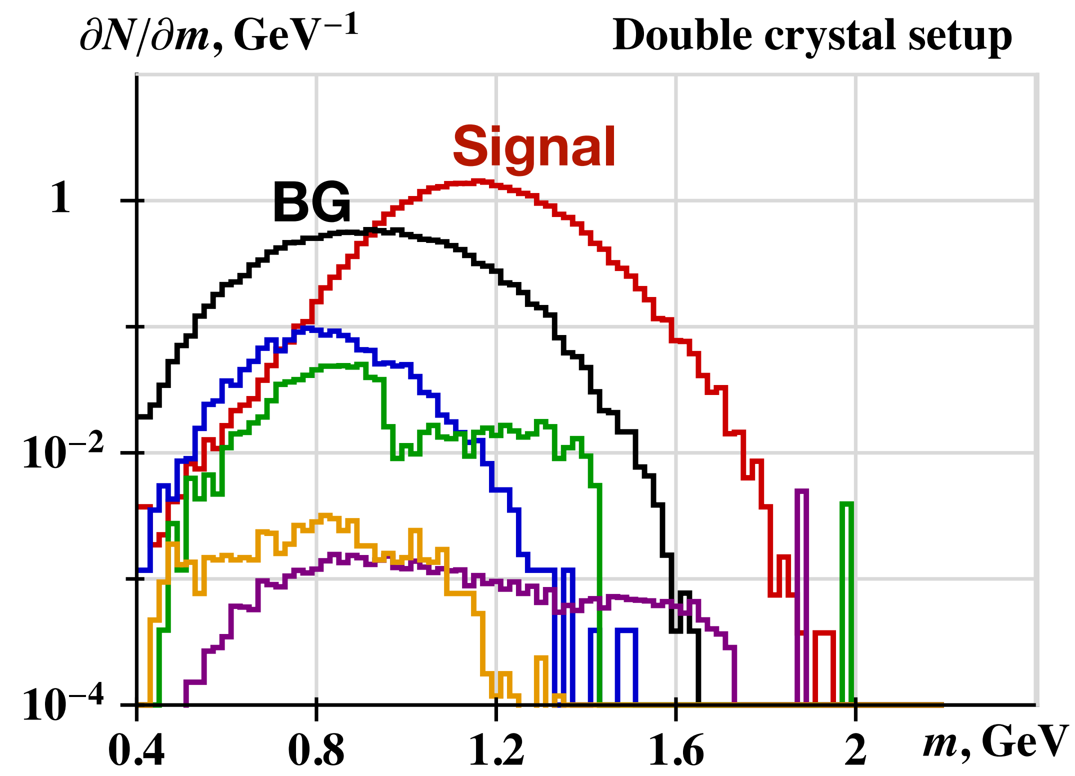
S is the sensitivity of polarisation reconstruction by the analysis of τ decay(1)



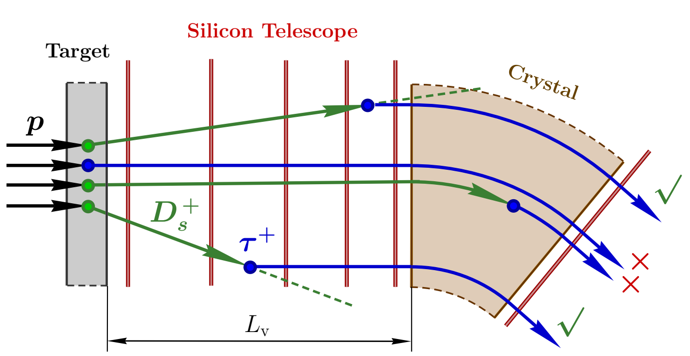
(1) J. Bernabeu et al., JHEP, 01:062, 2009

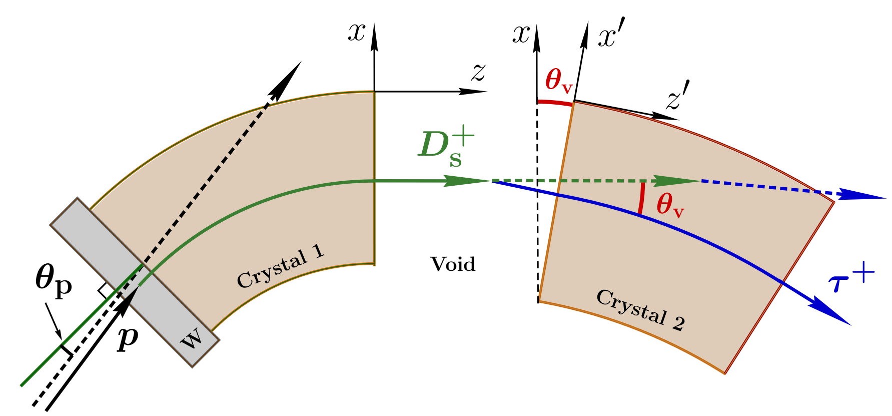
Background from other decay channels.





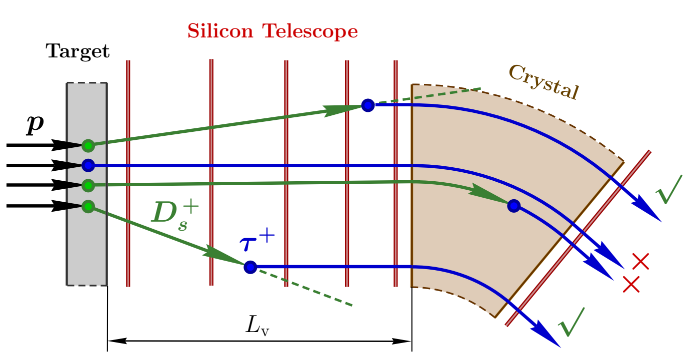
- Red: $D_s{}^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \bar{\nu}_\tau$
- Black: $D_s{}^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \pi^0 \bar{\nu}_\tau$
- Blue: $D_s{}^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \pi^0\pi^0 \bar{\nu}_\tau$
- Grey: $D_s^+, D^+, \Lambda_c^+ \to \pi^+\pi^+\pi^- X^0$
- Green: $B^+ \to D_s^+ X, \quad D_s^+ \to \pi^+\pi^+\pi^- X^0$
- Purple: $B^+ \to D^+ X, \quad D^+ \to \pi^+\pi^+\pi^- X^0$
- Orange: $B^+ \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \pi^+\pi^+\pi^- X^0$





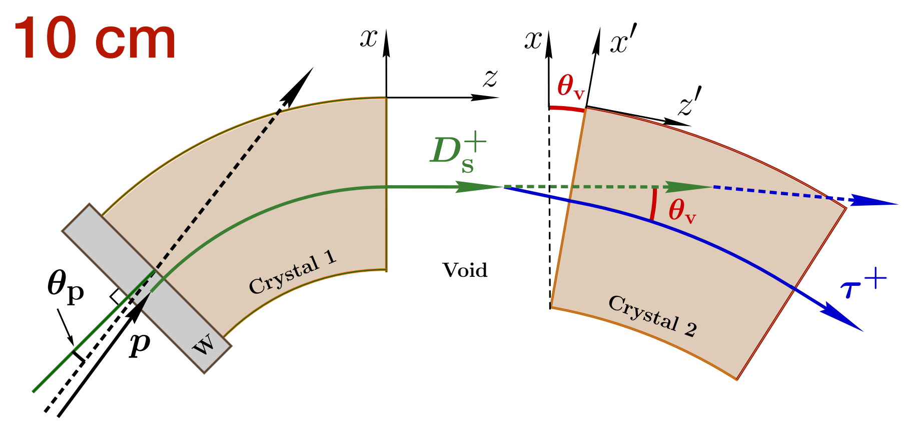
Efficiency of the measurement: current (by process) and total (per incident proton).

Place	process (factors)	single crystal setup		double crystal setup	
		current	total	current	total
target	$p \to D_s^+, D_s^+$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
crystal 1	D_s^+ collimation	—	—	**$0.8 \cdot 10^{-2}$**	$0.9 \cdot 10^{-6}$
crystal 1	D_s^+ deflection	—	—	**$1.3 \cdot 10^{-1}$**	$1.1 \cdot 10^{-7}$
void	$D_s^+ \to \tau^+$	**$0.5 \cdot 10^{-3}$**	$0.5 \cdot 10^{-7}$	**$1.2 \cdot 10^{-2}$**	$1.4 \cdot 10^{-9}$
crystal 2	τ^+ collimation	**$1.7 \cdot 10^{-2}$**	$0.9 \cdot 10^{-9}$	**$0.5 \cdot 10^{-1}$**	$0.7 \cdot 10^{-10}$
crystal 2	τ^+ deflection	$0.3 \cdot 10^{-1}$	$0.3 \cdot 10^{-12}$	$0.3 \cdot 10^{-1}$	$2.2 \cdot 10^{-12}$
detector	$\eta_{det} \times Br$	$0.4 \cdot 10^{-1}$	$1.3 \cdot 10^{-12}$	$0.4 \cdot 10^{-1}$	$1.0 \cdot 10^{-13}$
reconstr.	$\eta_{MDM} \sim \langle P^2 \gamma^2 \rangle$	**~ 0.5**	***$\sim 0.7 \cdot 10^{-12}$***	**~ 8**	***$\sim 0.7 \cdot 10^{-12}$***
reconstr.	$\eta_{EDM} \sim \langle P^2 \gamma^2 \rangle$	**$\sim 1.1 \cdot 10^{-4}$**	***$\sim 1.5 \cdot 10^{-16}$***	**$\sim 1.5 \cdot 10^{-3}$**	***$\sim 1.5 \cdot 10^{-16}$***



L_v = 40 cm

L_v = 10 cm

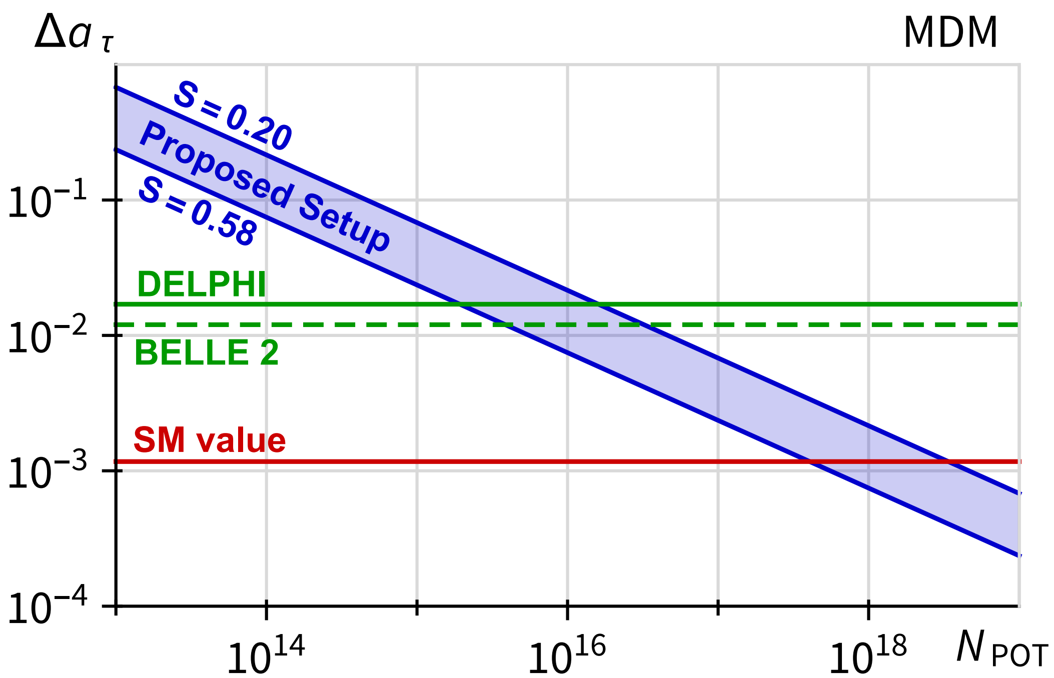


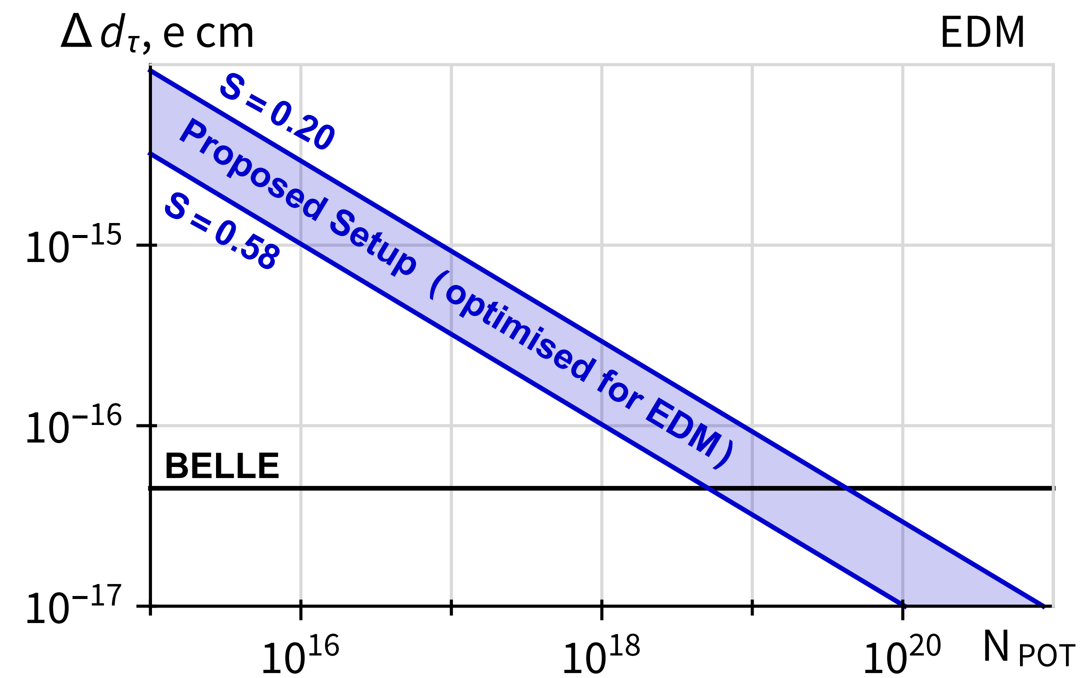
 Precision of anomalous MDM versus number of protons on target.

$$\Delta a_\tau = \sqrt{\frac{1}{N_p \ \ \eta_{\rm det} S^2 \ \ \eta_{\rm setup}}}$$

$$\eta_{\rm setup} = \Theta^2 \int d\varepsilon \, \frac{\partial N_\tau^{\rm def}}{\partial \varepsilon} \, \gamma_\tau^2 \ \ {\rm P}^2$$

$$\frac{\Delta f_\tau}{\Delta a_\tau} \approx \left| \frac{4\,\gamma\,\bar{a}_\tau}{\Theta\,(1+\gamma\bar{a}_\tau)^2} \right|$$





- Target (W)

  L_{tar} = 1 cm

- Crystal 1 (Ge)

  L_D = 3 cm,

  R_D = 10 m,

  θ_p = 100 μrad

- Crystal 2 (Ge)

  L = 10 cm,

  R = 7 m,

  θ_v = 80 μrad

- η_{det} = 50 %

— **Double Crystal Setup at LHC** $D_s^+ \rightarrow \tau^+ \nu_\tau$, $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$

— **DELPHI:** limit on aMDM from LEP2 experiment $\gamma\gamma \rightarrow \tau^+\tau^-$
J. Abdallah et al. Eur. Phys. J., C35:159–170, 2004

— **BELLE 2:** limit on aMDM expected for the BELLE 2 experiment
S. Eidelman, et al. JHEP, 03:140, 2016.

— **SM value**: aMDM value predicted by a Standard Model
S. Eidelman et al. Mod. Phys. Lett., A22:159–179, 2007.

— Belle collaboration, Search for the EDM of the τ lepton,
Phys. Lett. B 551 (2003) 16 [hep-ex/0210066].

τhank you