Polarimetry for Storage Ring EDM experiments

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Motivation

Polarimeter concept

Simulation studies

R&D Beam time @ COSY: First results

Summary & Outlook

Motivation

Motivation

Where is the Antimatter in our Universe?

- Sakharov (1967): Three conditions for baryogenesis
  - At least one Baryon-number violating process.
  - $\not{\mathcal{C}}$ and $\not{\mathcal{CP}}$
  - Interactions outside of thermal equilibrium.

- Baryon number asymmetry: $\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx \begin{cases} 10^{-18} & (SM) \\ 10^{-10} & (Exp.) \end{cases}$

$\Rightarrow$Not enough $\not{\mathcal{CP}}$ in Standard Modell

Electric Dipole Moments

- Classical Electric Dipole Moment: Charge separation
- Interaction of electric and magnetic dipole moments with $\vec{E}, \vec{B}$:

$$
\begin{aligned}
\mathcal{H} &= -\mu\frac{\vec{S}}{S}\cdot\vec{B} - d\frac{\vec{S}}{S}\cdot\vec{E} \\
\mathcal{P}\colon \mathcal{H} &= -\mu\frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E} \\
\mathcal{T}\colon \mathcal{H} &= -\mu\frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E}
\end{aligned}
$$

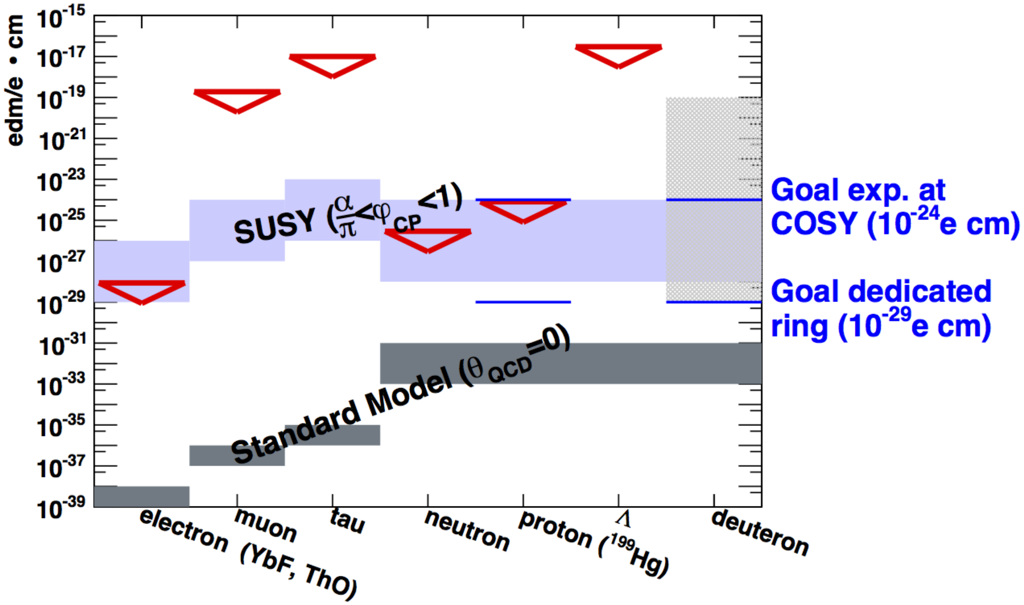
$$
\begin{gathered}
\vec{d} = EDM \\
\vec{\mu} = MDM \\
\vec{\mu}, \vec{d} \parallel \vec{S} \\
\cancel{\mathcal{T}} \overset{\mathcal{CPT}}{\Leftrightarrow} \cancel{\mathcal{CP}}
\end{gathered}
$$

⇒Electric Dipole Moments violate $\mathcal{CP}$ (assuming $\mathcal{CPT}$)

⇒Probe into the Physics of the early universe

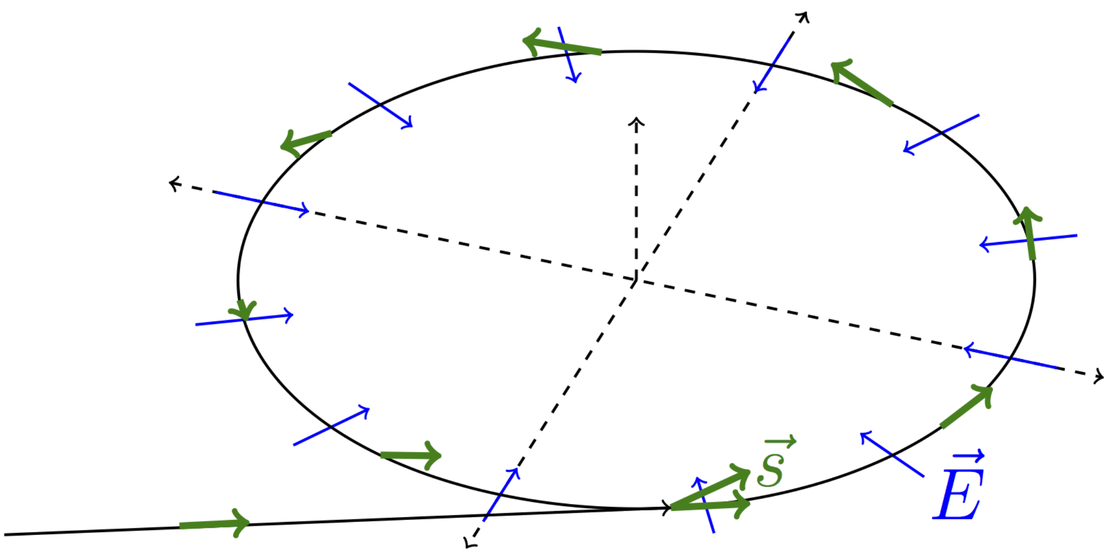
Charged particle EDMs: Current Limits and Challenges

- Most EDM searches measure EDM of neutral particles. Current Limits $10^{-17}e\text{cm} - 10^{-28}e\text{cm}$
- No direct limits for charged hadrons exist
  - Technical challenge: No trap for charged particles
    $\Rightarrow$Storage Ring needed!
- EDM search @ FZJ: p, d, ^{3}He



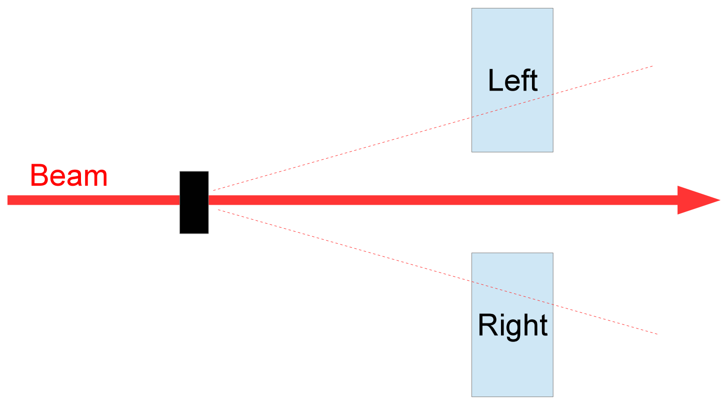
EDM searches in storage rings

- All EDM experiments measure interaction between $\vec{d}$ and $\vec{E}$:
  - $\frac{d\vec{S}}{dt} \propto d\vec{E} \times \vec{S}$
- "Frozen Spin" method: Align spin with momentum vector, wait for vertical polarization change:
  - $\frac{\Delta S_y}{\Delta t} \propto d$
- Current candidate method for EDM search implicates a buildup of polarization with time at $\Delta P = \mathcal{O}(10^{-6}/1000s)$



Nuclear scattering polarimetry

- Nuclear scattering cross section for scattering of polarized particles: $\sigma_{L,R} = \sigma_0 \cdot \left(1 \pm P_y A_y\right)$
- Measure left-right asymmetries in count rate: $P_y = \frac{1}{A_y}\frac{N_L - N_R}{N_L + N_R}$
- Up and Down counting rates may be used to control systematics

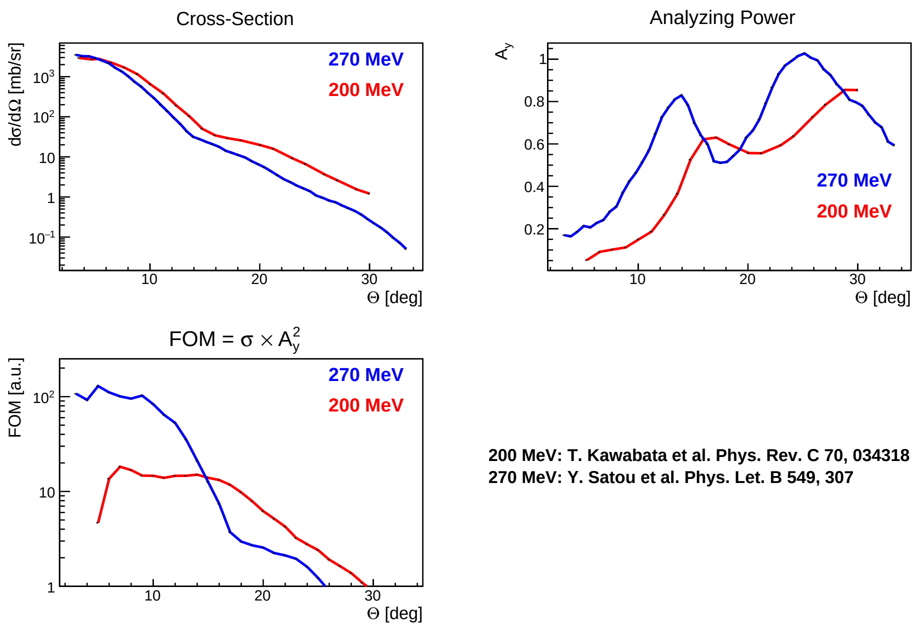


Design goals for an EDM polarimeter

- Design goals for polarimeter:
  - Large statistical Figure-of-Merit: $\mathcal{FOM} \sim N \cdot (P_y A_y)^2$
  - Minimal influence on beam
  - Good handle on systematic effects
  - Good long term stability and reproducibility: 1ppm per 1000s

Polarimeter concept

Reaction choice



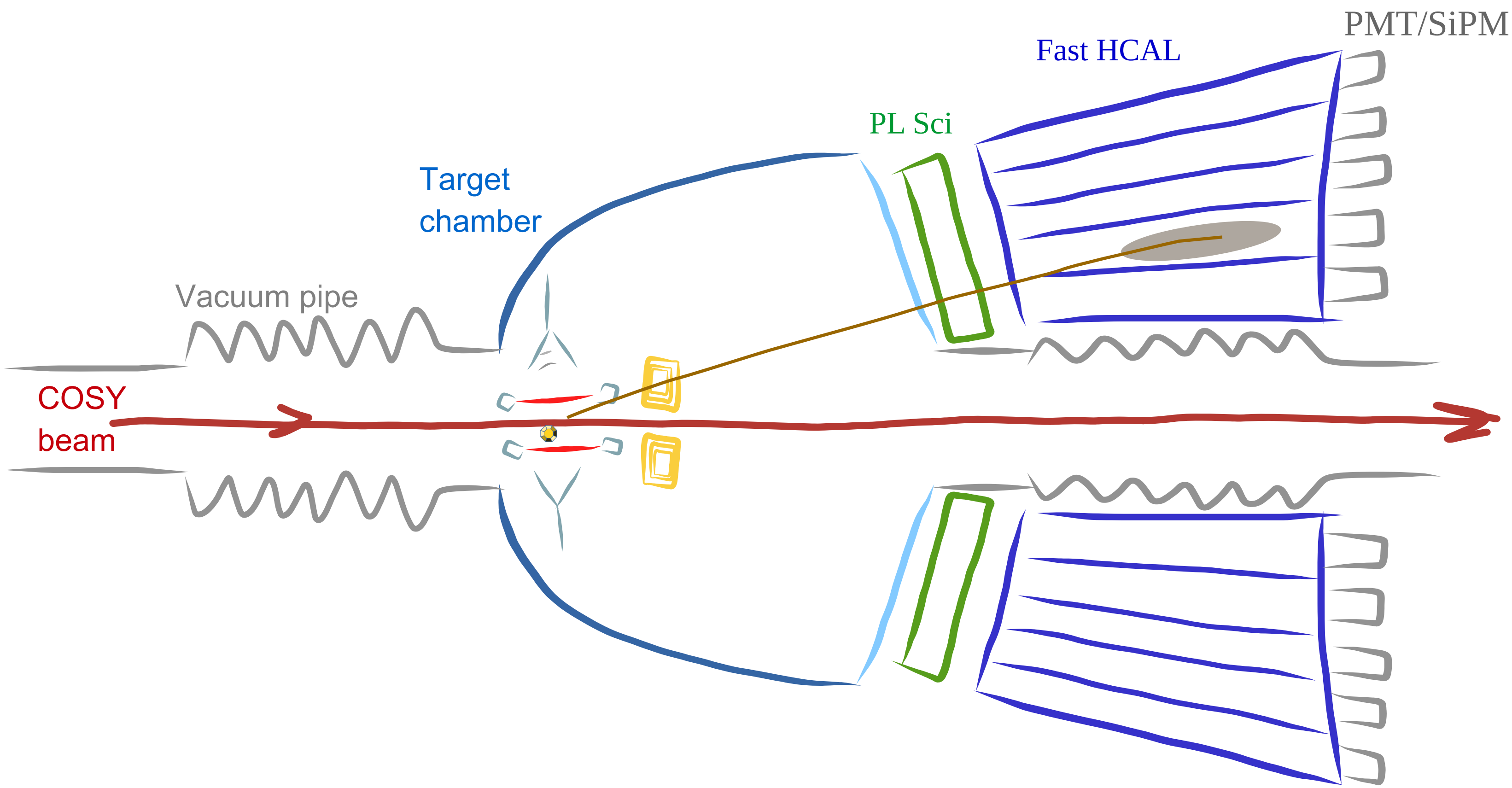
200 MeV: T. Kawabata et al. Phys. Rev. C 70, 034318
270 MeV: Y. Satou et al. Phys. Let. B 549, 307

- Carbon is the current material of choice
- $\mathcal{FOM}$ concentrated in forward region

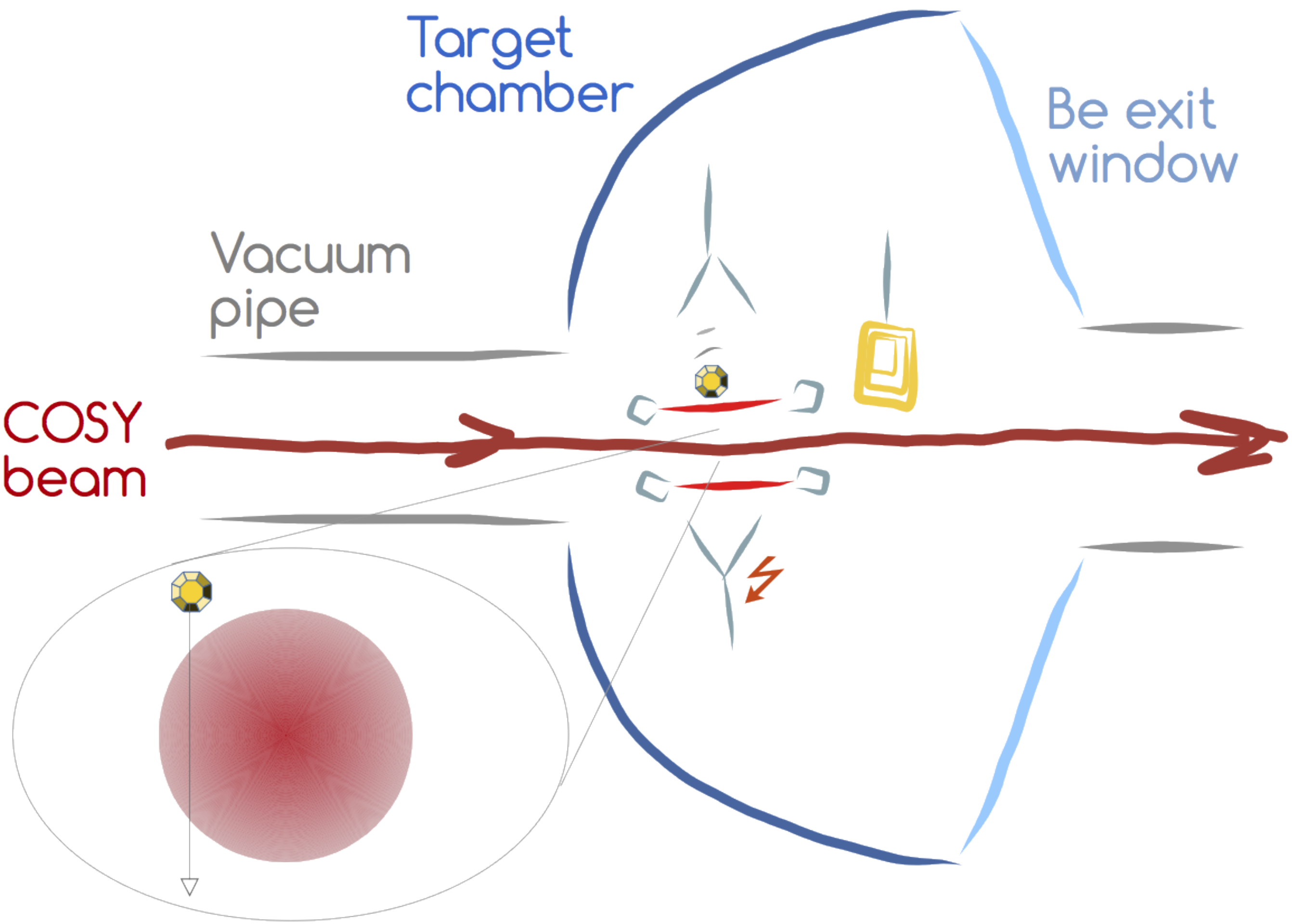
  $\Rightarrow$Polarimeter needs to cover forward region
- Proton-Carbon elastic scattering also concentrated in forward region.

  $\Rightarrow$Possibility for multi-purpose polarimeter

Detector concept



Target concept



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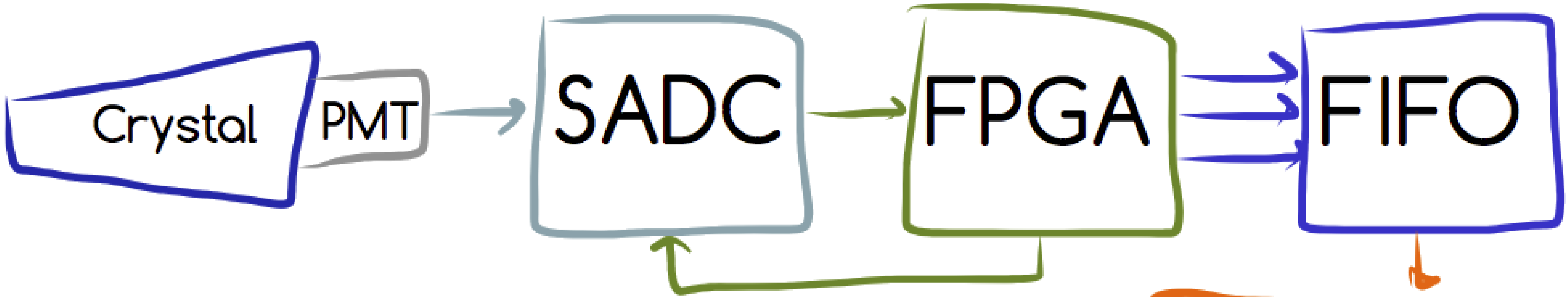
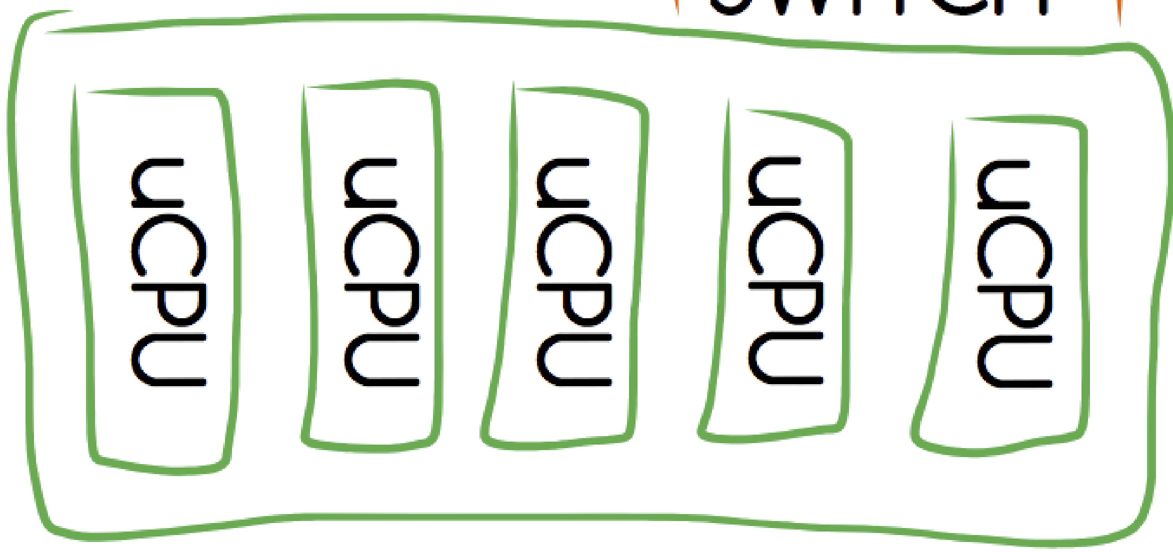
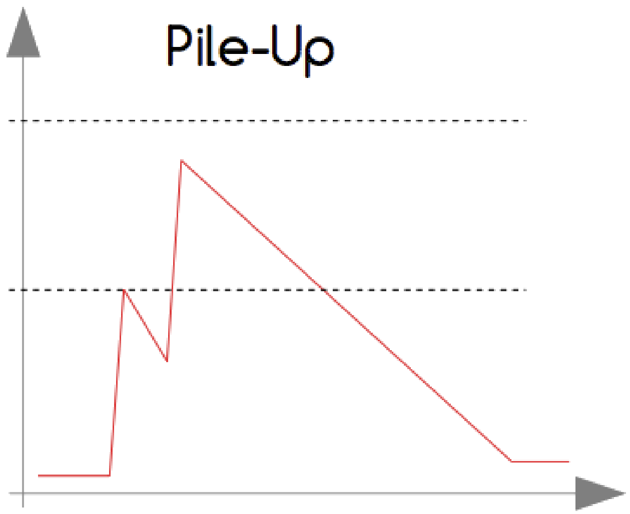
Readout concept



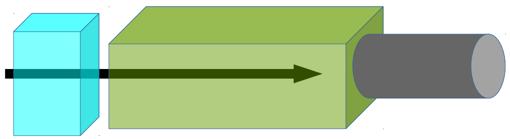




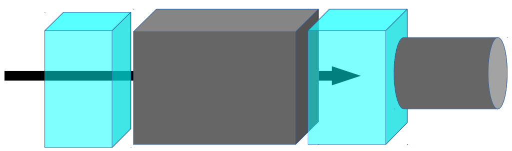
Simulation studies

HCal Candidate Materials: LYSO/Plastic Scintillator

Pl. + LYSO

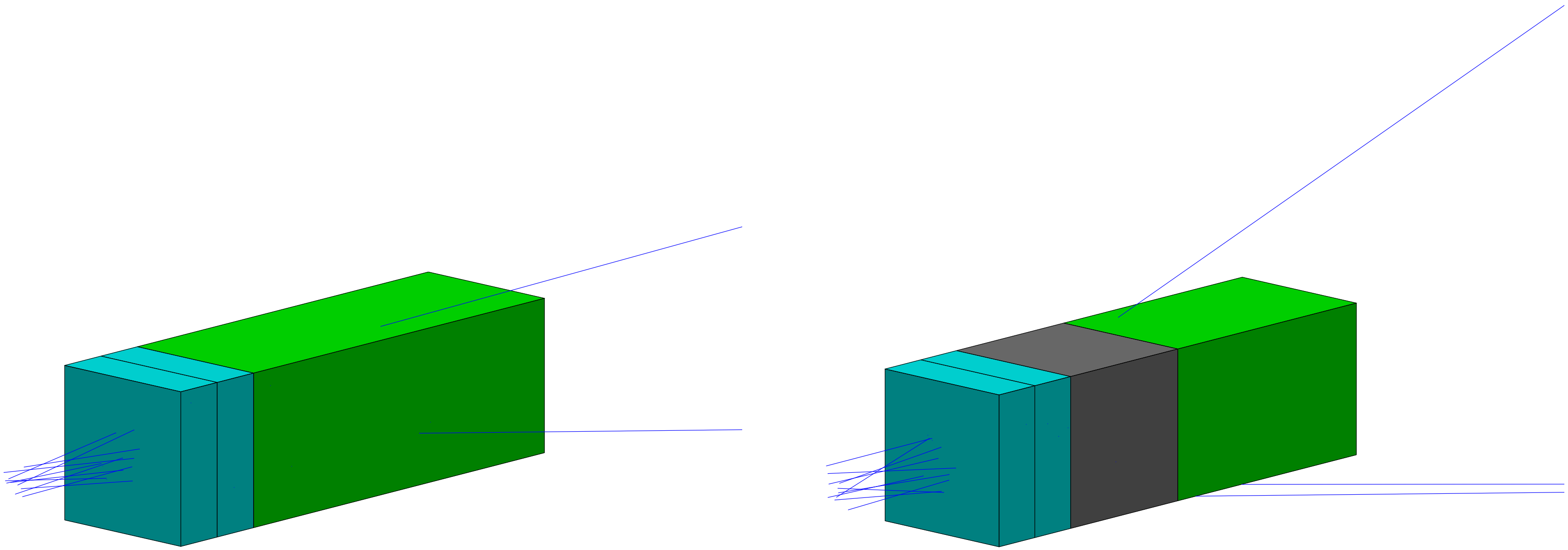


Pl. +W/Fe + Pl.



	LYSO	Plastic
Stopping power	+	-
Speed	+	+
Energy resolution	+	-
Cost	-	+

First step: Detector element dimensions



- Open Questions:
  - Optimal calorimeter element size?
  - Absorber Thickness?
  - Monolithic or Sandwich?
  - Plastic or LYSO?

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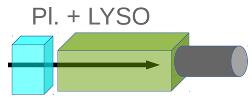
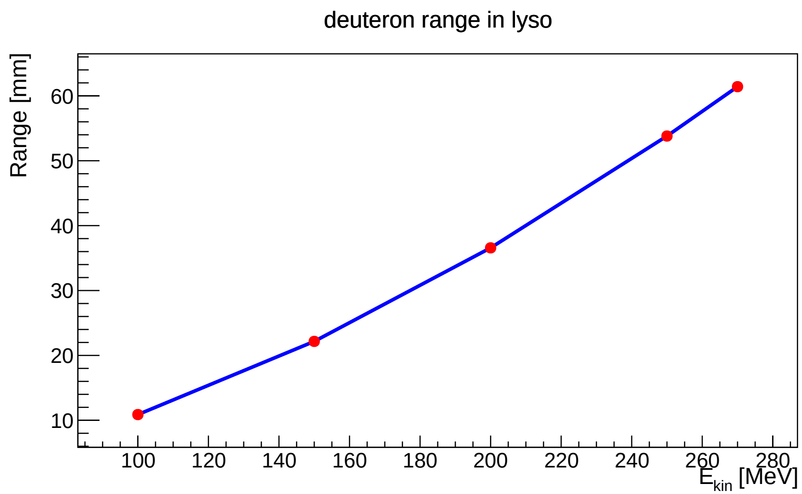
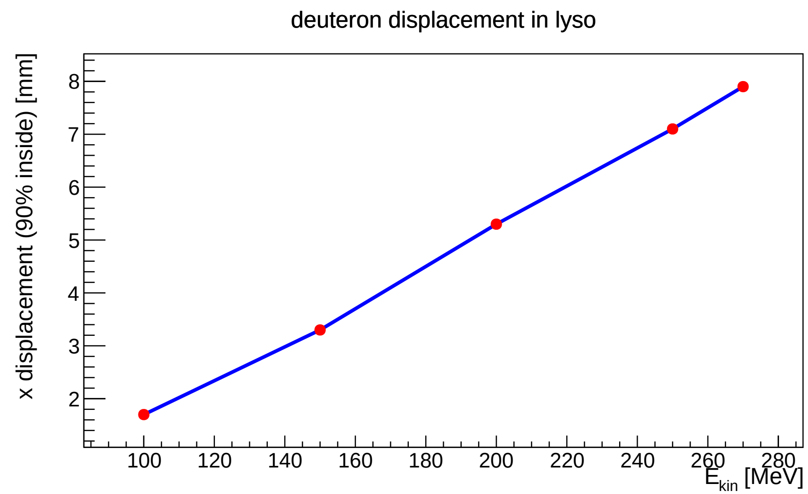
Detector dimensions - LYSO

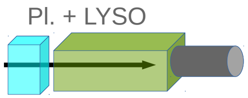


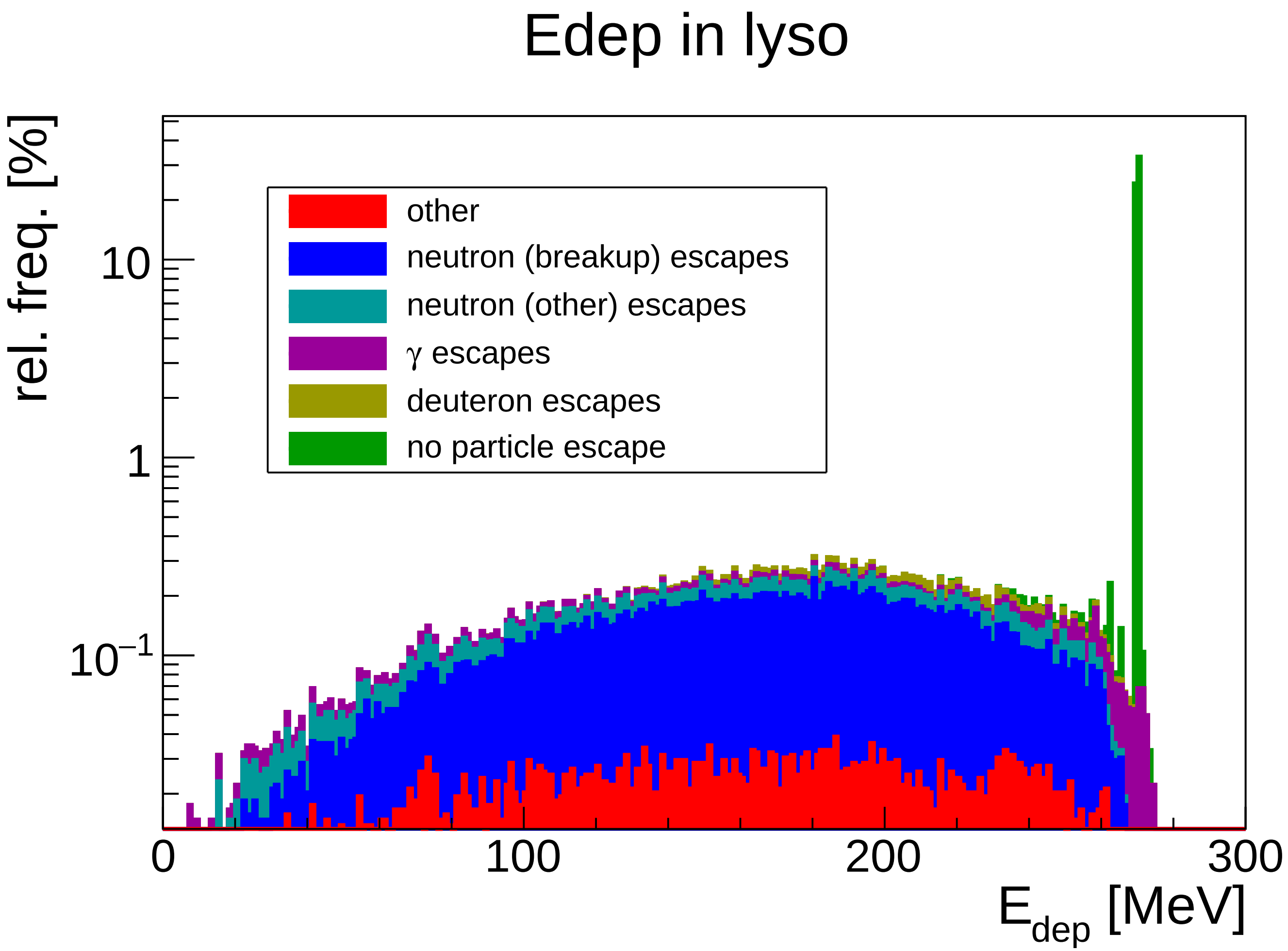




- To get lateral and longitudinal range of deuteron in detector element:
  - Shoot particle gun into front face, determine x_f, y_f, z_f of endpoint of primary track
  - Longitudinal range: Gaussian fit
  - Lateral width: $\int_{-x0}^{x0} dN/dx = 90\% \cdot N_{tot}$
- Chosen detector size of $3 \times 3 \times 10\,\mathrm{cm}^3$ as starting point for further studies

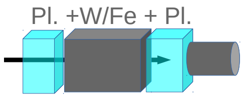
Detector response - LYSO

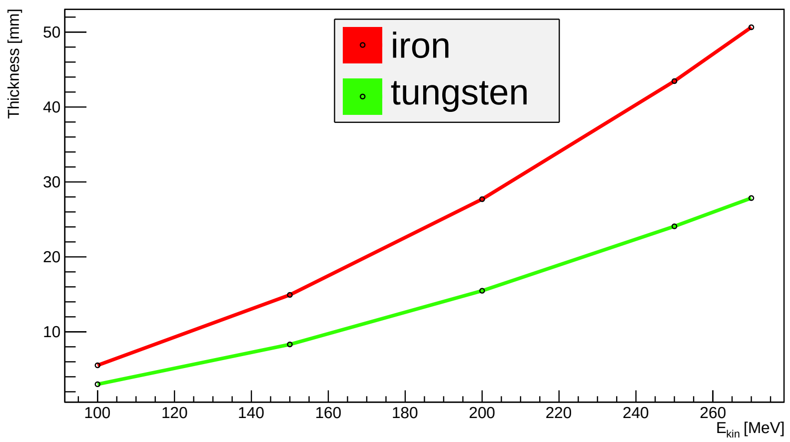


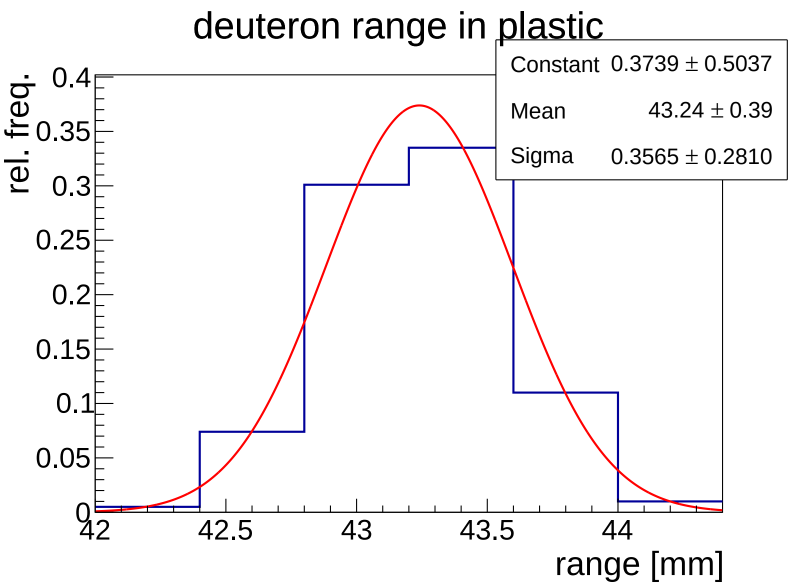


- Breakup in detector element causes distortion of energy spectrum

Detector dimensions - Plastic

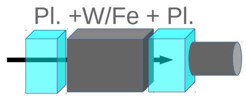


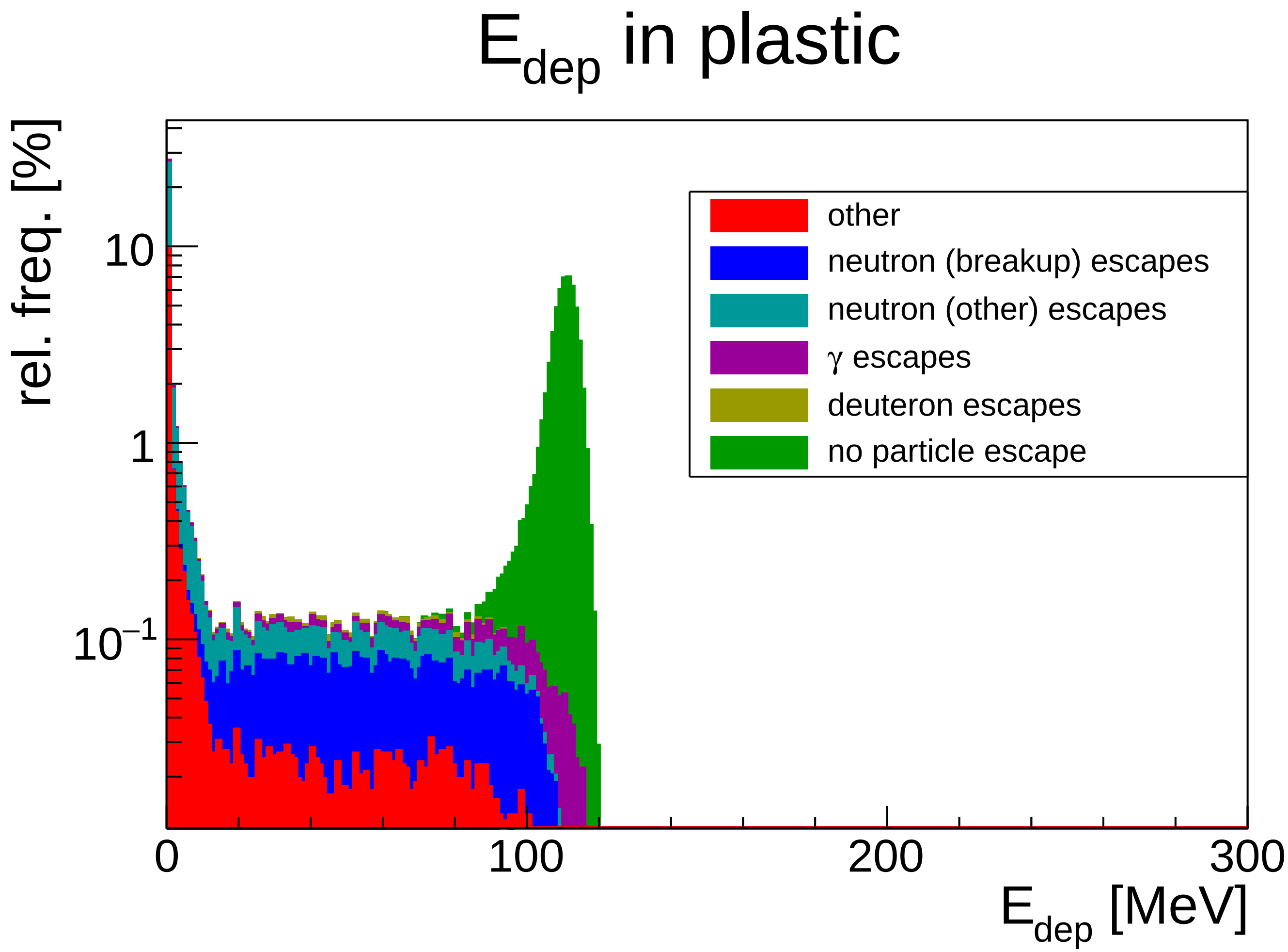




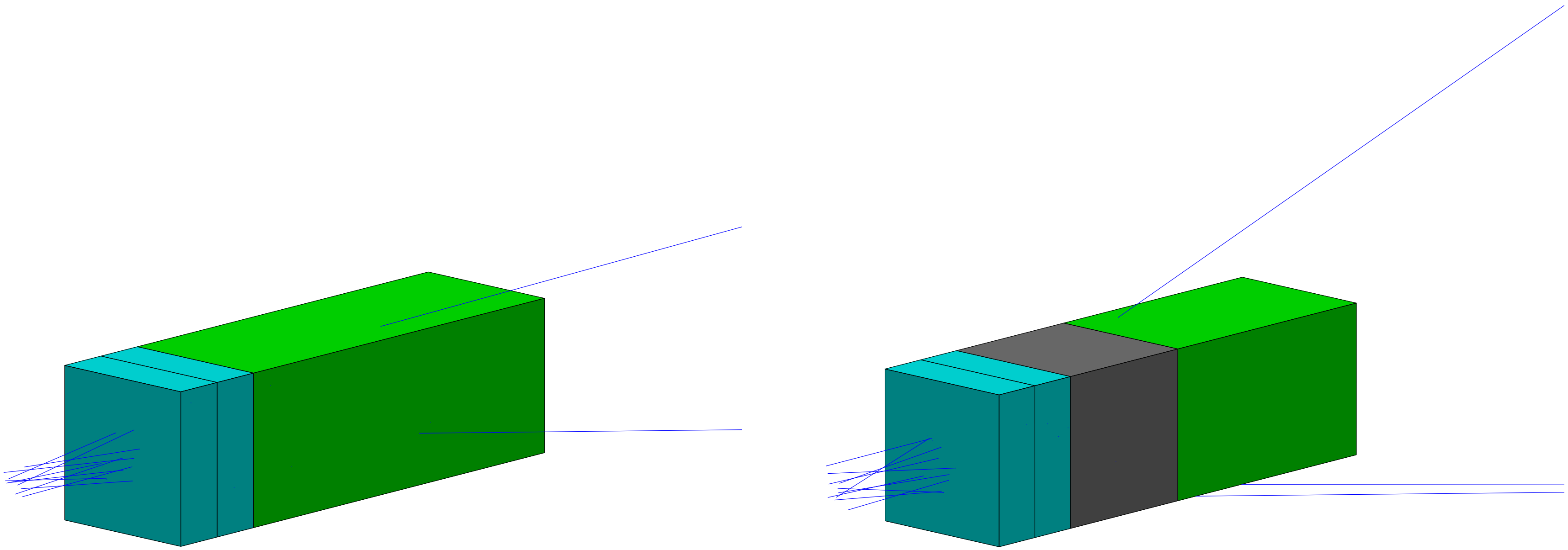
- Use absorber to suppress proton background and reduce length of plastic detector
- Arbitrarily chosen 100 MeV entry energy @ 270 MeV beam energy as working point for plastic scintillator
  - Iron thickness ca. 50 mm
  - Pl. scintillator thickness ca. 50 mm

Detector response - Plastic





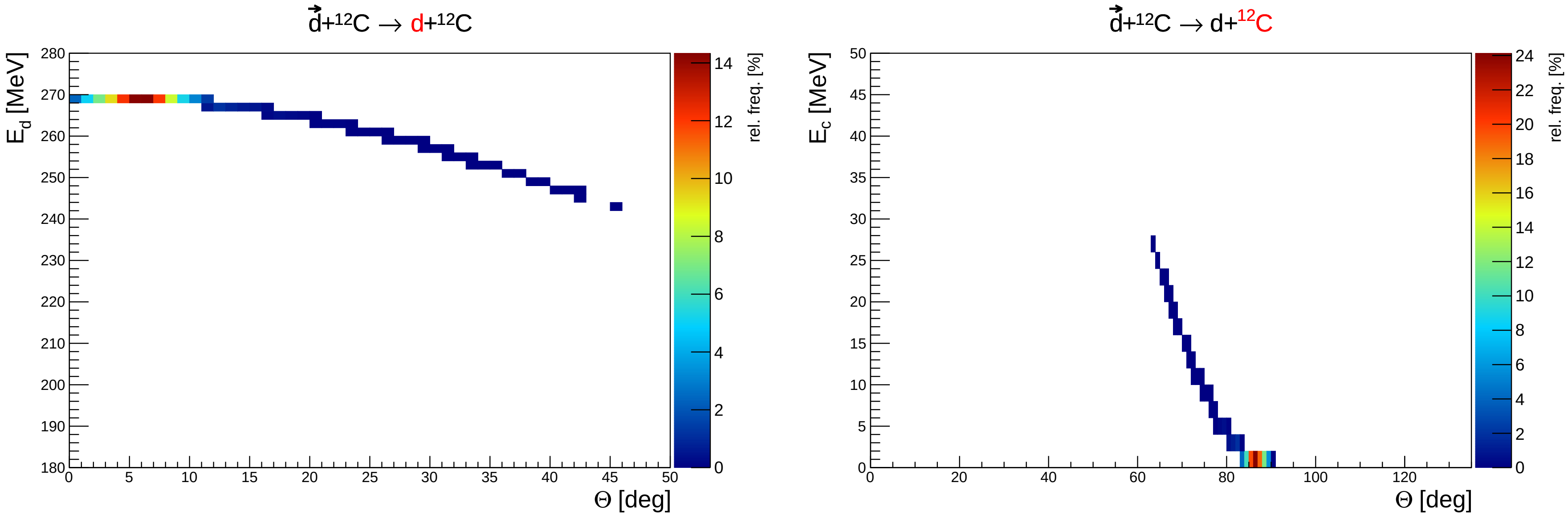
Next step(s): Monolithic or sandwich detector?



- Generated 100k events each at $T_d = 270\,\mathrm{MeV}, 5^\circ < \Theta < 20^\circ$, $0^\circ < \phi < 360^\circ$
  - Signal: $^{12}C(\vec{d}, d)^{12}C$,$\sigma_{el} \approx X\,\mathrm{mb}$,$< A_y >\approx$
  - Background: $^{12}C(\vec{d}, pn)^{12}C$,$\sigma_{el} \approx X\,\mathrm{mb}$,$< A_y >\approx$

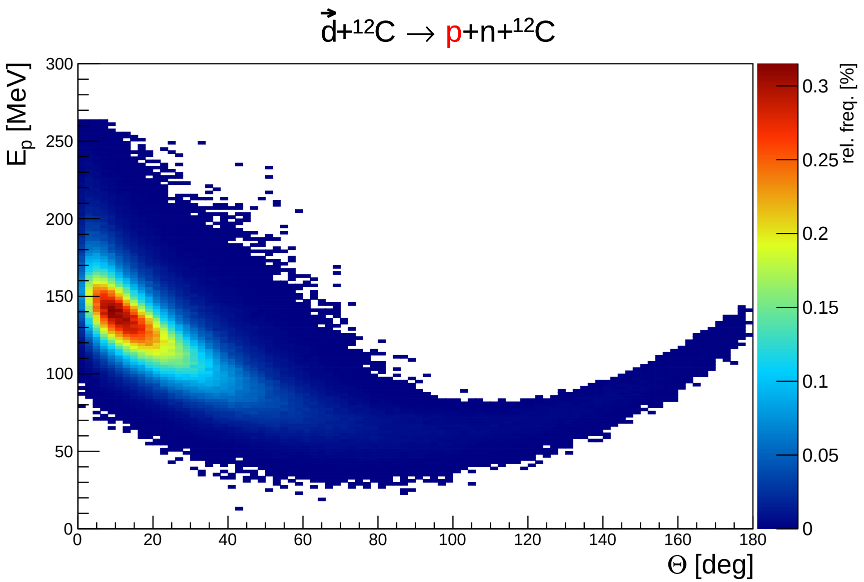
- $\mathcal{FOM} \propto \sigma_{eff} \times < A_{y,eff} >^2$

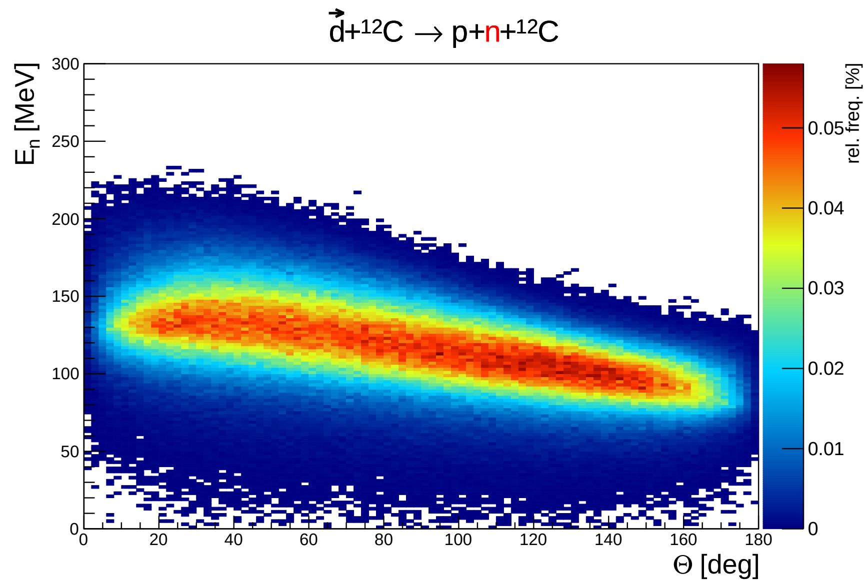
Signal and Background generation



- Using data-driven model for signal and background
- Elastically scattered deuterons retain almost complete beam energy
- Contribution of recoil carbons negligible

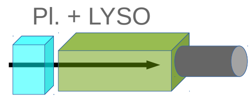
Signal and Background generation (cont'd)

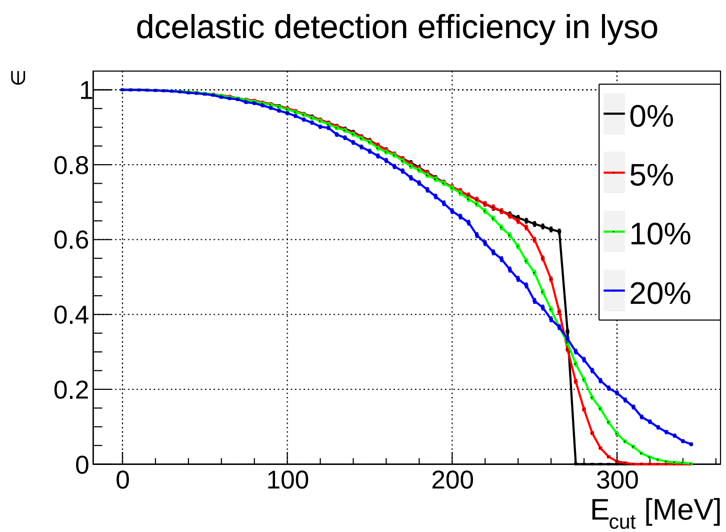


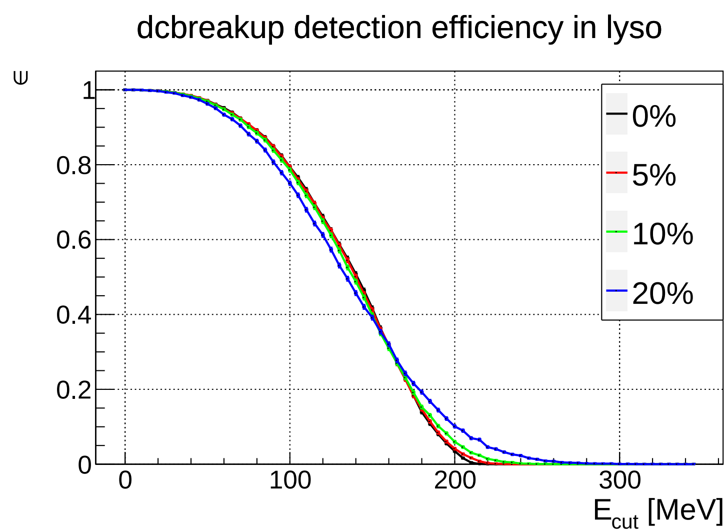


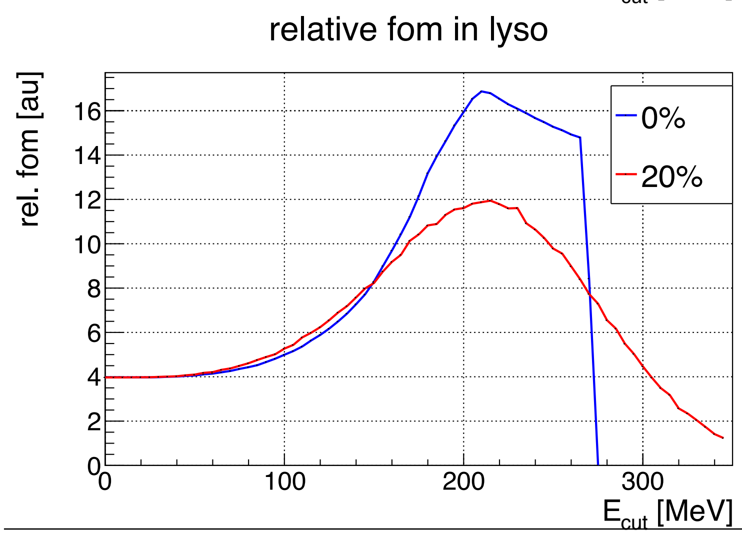
- Break-up has almost no analyzing power, so discard it
- Protons and neutrons from break-up are energetically well separated from signal
  ⇒But: Break-up in target is not distinguishable from break-up in detector!
- No reliable model for inelastic reactions available
  - Qualitative experiments show: Inelastic reactions carry some analysing power, so maybe keep these

Detection efficiencies (lyso)

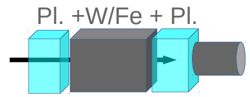




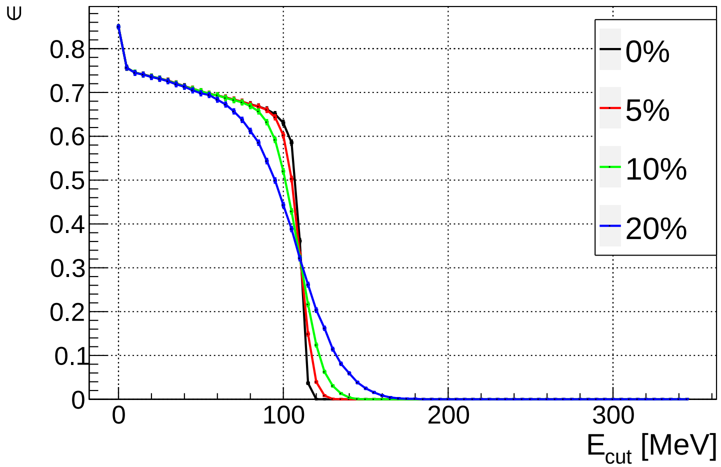




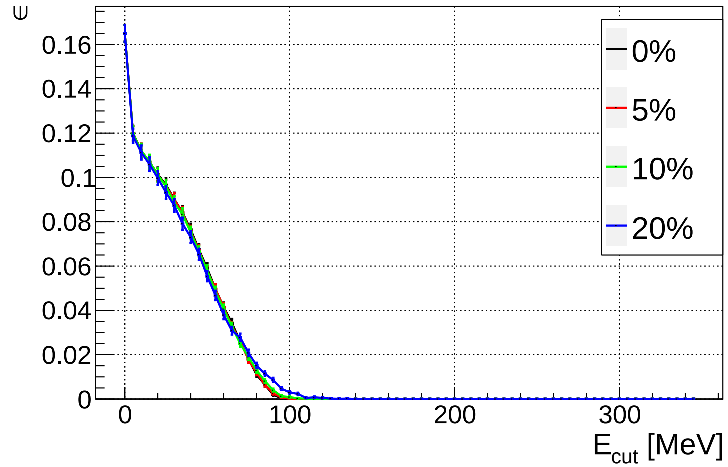
Detection efficiencies (plastic)



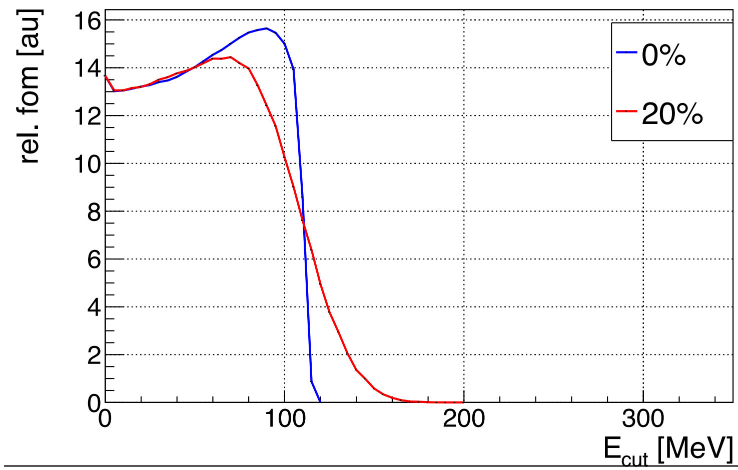
dcelastic detection efficiency in plastic



dcbreakup detection efficiency in plastic



relative fom in plastic



Simulation Results

- Main cause of efficiency loss is breakup in detector

- Maximum relative FOM:

	0%	20%
Plastic	15.5	14.5
LYSO	17	12

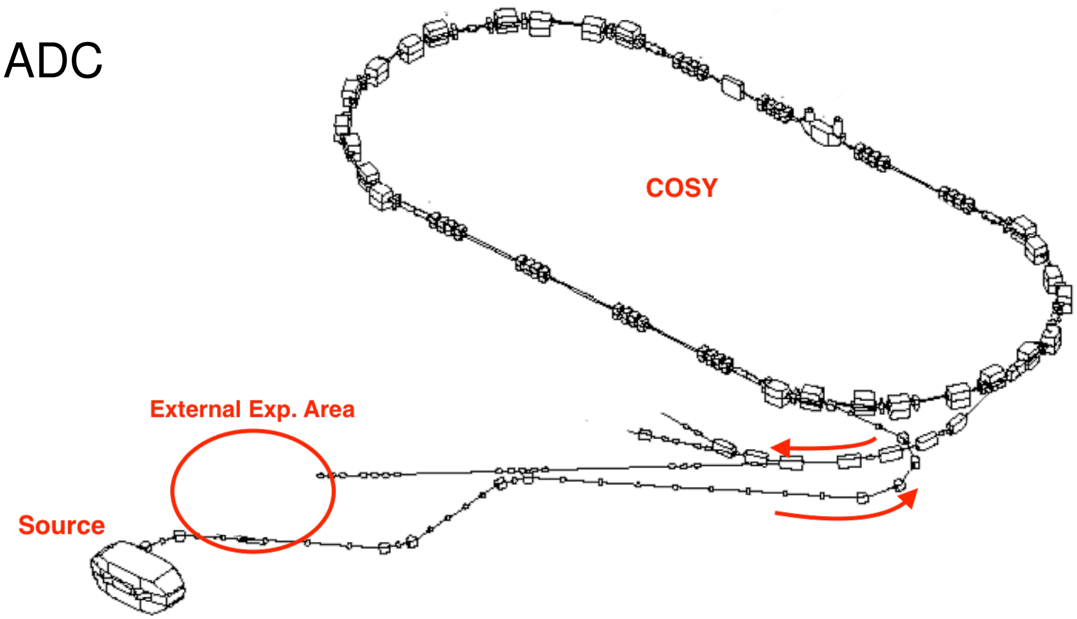
- LYSO and plastic scintillators provide comparable performance

- Plastic scintillator performance exhibits no strong dependence on energy resolution

R&D Beam time @ COSY: First results

Beam time spring 2016

- External beam at COSY in Jülich
- LYSO crystals from two different manufacturers
- PMT and Silicon Photomultiplier (SiPM)
- Unpolarized Deuteron beam @ 100MeV, 200MeV, 235MeV and 270MeV
- Struck 14 bit, 250 MS/s Flash ADC



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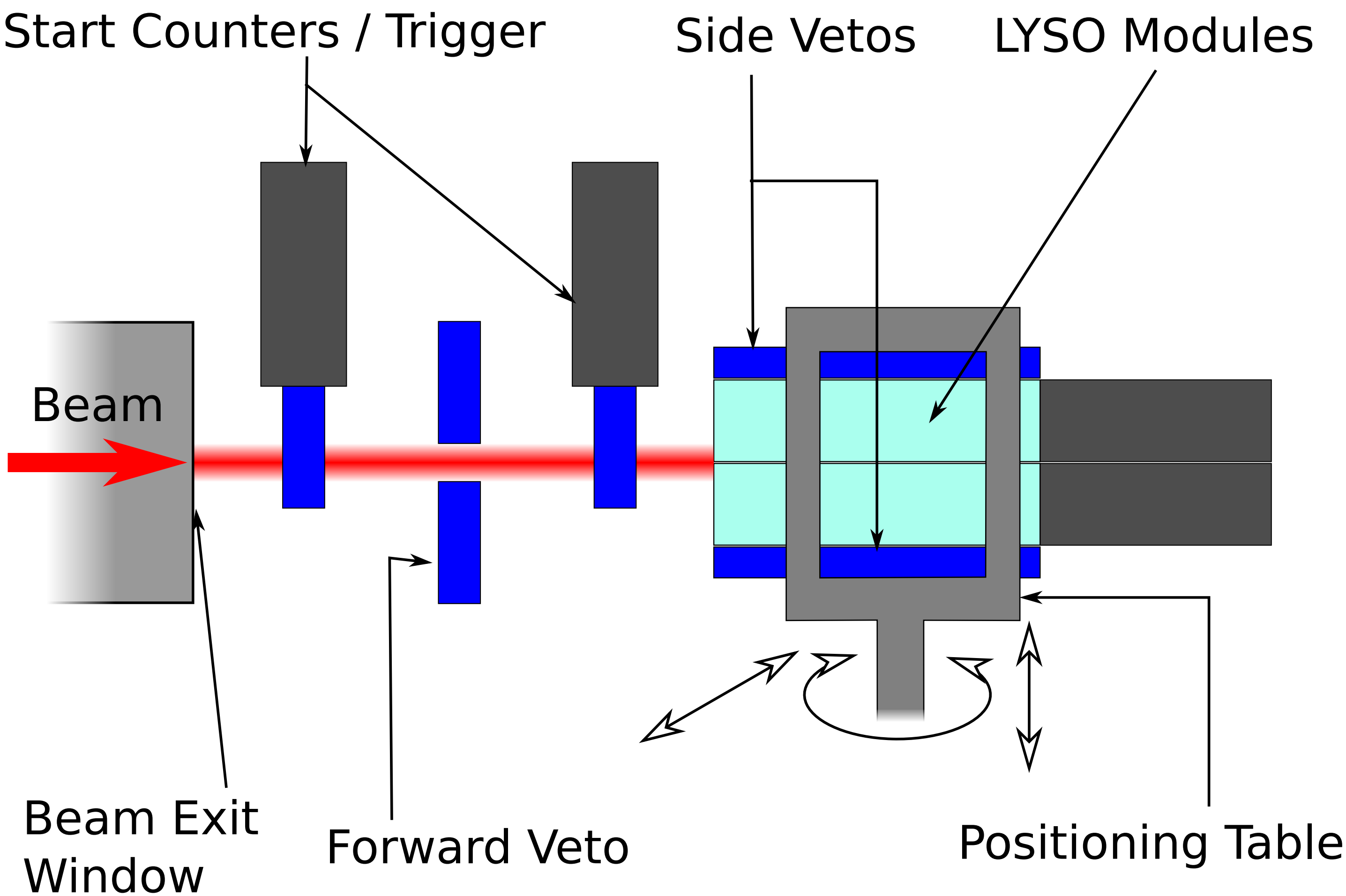
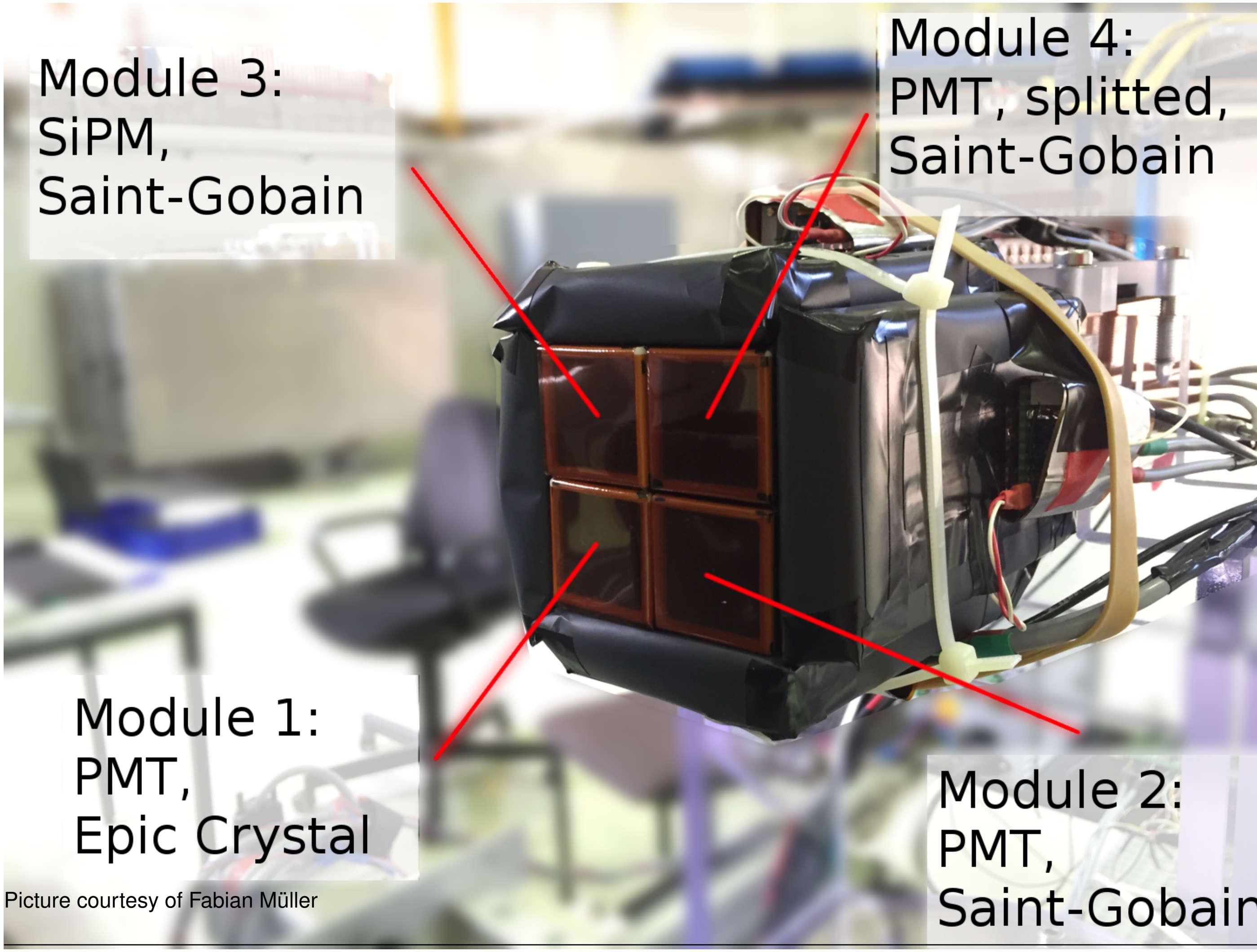
Measurement setup

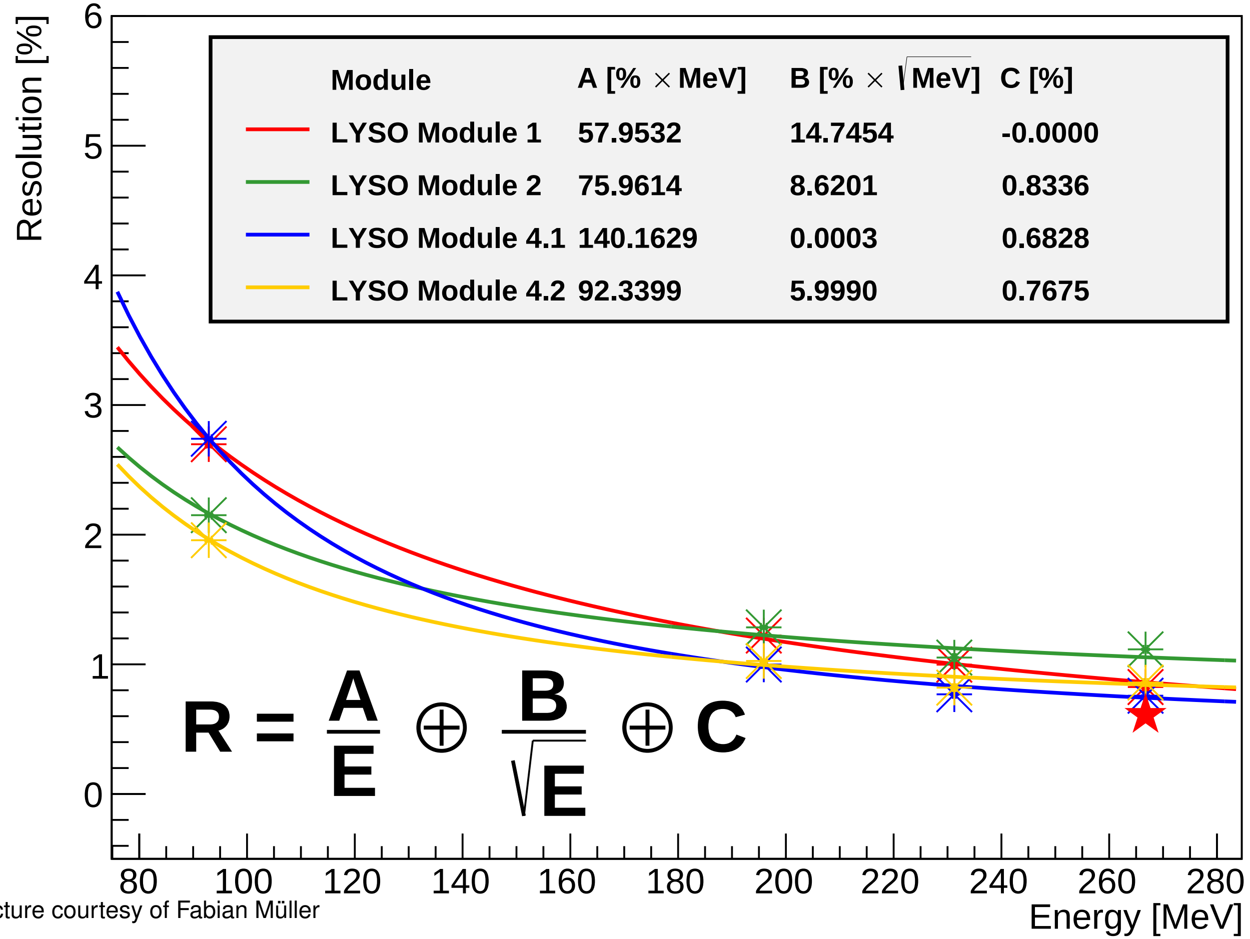


Picture courtesy of Fabian Müller

Measurement setup (cont'd)

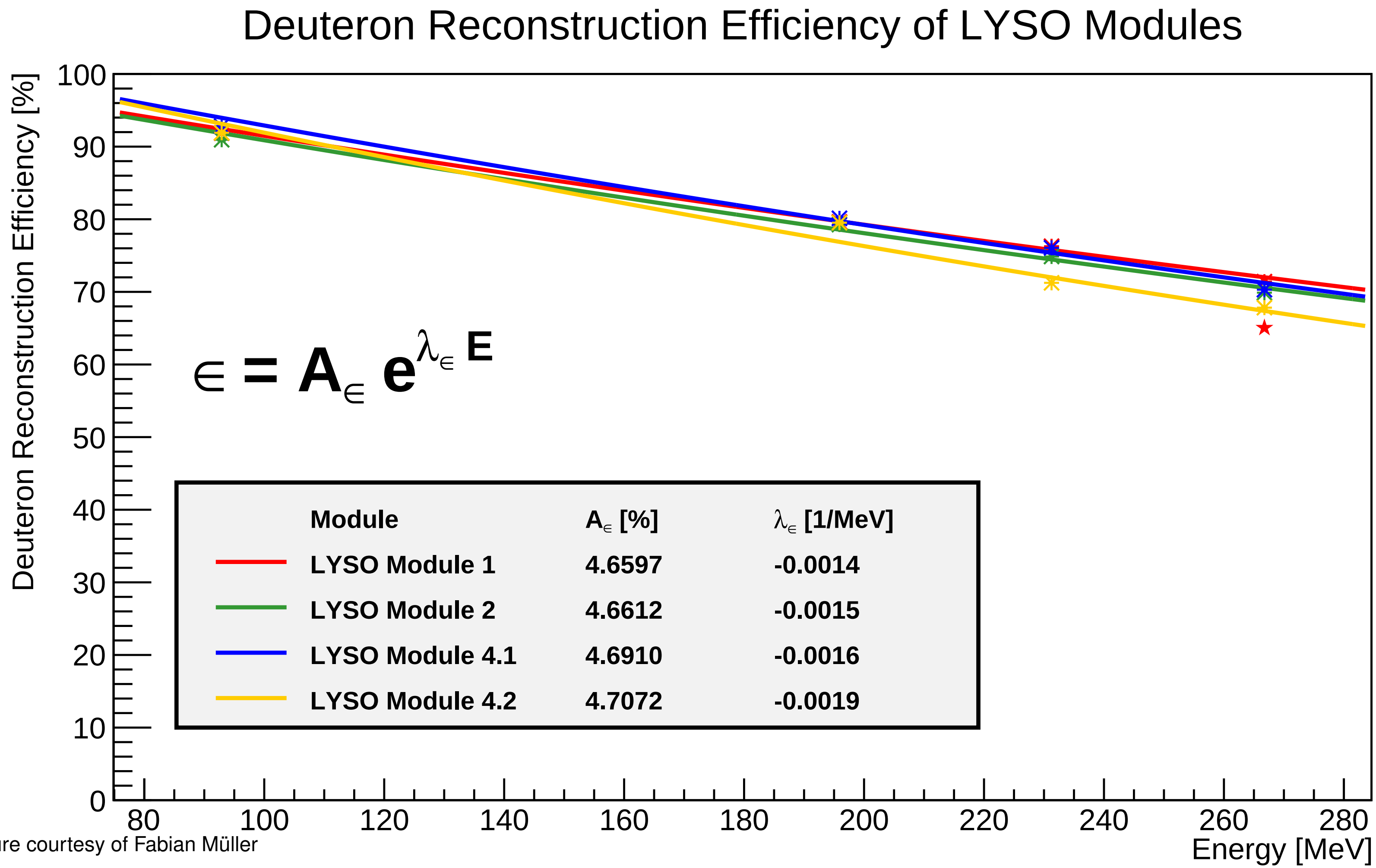


Energy resolution



Picture courtesy of Fabian Müller

Efficiency



Picture courtesy of Fabian Müller

Measurement Results

- 5 LYSO modules succesfully commissioned, PMT and SiPM readout tested
- Calibration curve exhibits considerable nonlinearity
- Energy resolution between 1% and 4%
- Deuteron reconstruction efficiency above 70%

Summary & Outlook

Summary

- We have a candidate layout for JEDI polarimeter
- Simulations suggest promising performance
- A deuteron beam with five different energies up to 270MeV was used to examine the prototype LYSO modules
- The resolution of the LYSO modules was better than 3%
- A deuteron reconstruction efficiency over 65% has been achieved in the whole energy spectrum

Outlook

- Theoretical calculations for signal and background cross sections and analyzing powers are under progress and will be included in simulation
- Next beamtime will include a greater number of crystals and test sandwich detector and polarization response
- Measurement of cross sections and analyzing powers with WASA @ COSY in preparation

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