Polarimetry for Storage Ring EDM experiments

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Friday Seminar July 1, 2016

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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.
  - $\not{C}$ and $\not{C}\not{P}$
  - 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 $\not{C}\not{P}$ in Standard Modell

Electric Dipole Moments

- Electric Dipole Moment:
  - Classical: Charge separation
  - Quantum Mechanical: $\left|\vec{d}\right\rangle = q\left|\vec{r}\right\rangle$

- Interaction of electric and magnetic dipole moments with $\vec{E}, \vec{B}$:

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

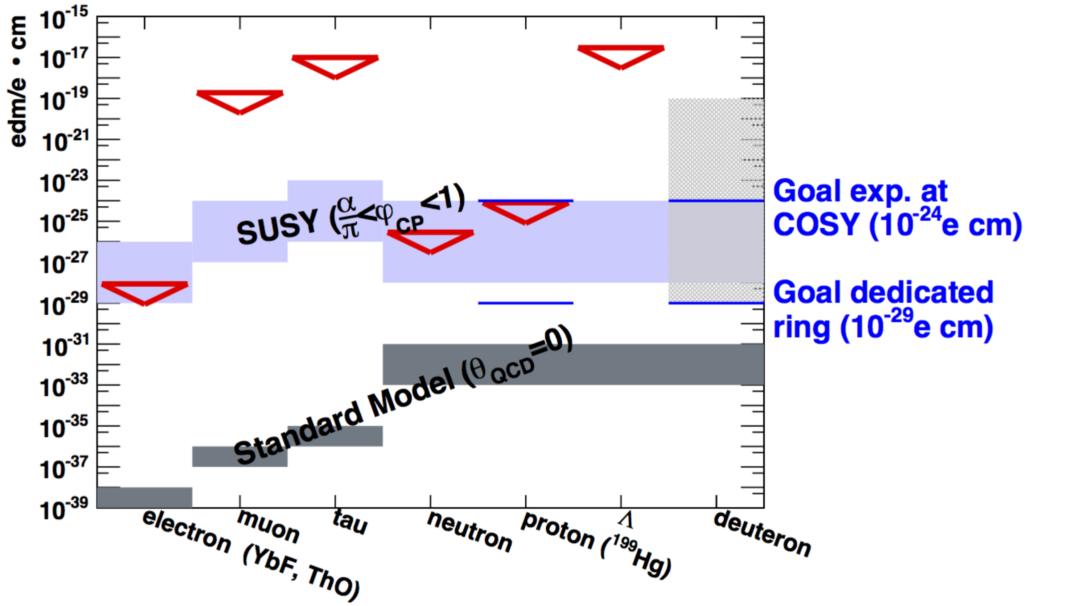
$$\vec{d} = EDM$$
$$\vec{\mu} = MDM$$
$$\vec{\mu}, \vec{d} \parallel \vec{S}$$
$$\not{\mathcal{T}} \overset{\mathcal{CPT}}{\Leftrightarrow} \not{\mathcal{CP}}$$

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

⇒Probe into the Physics of the early universe

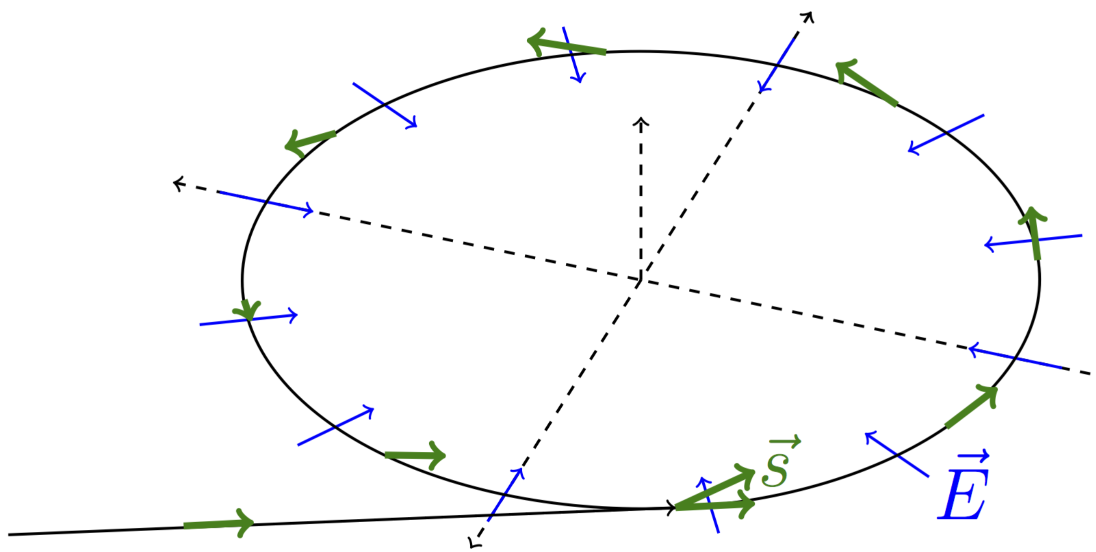
Charged particle EDMs: Current Limits and Challenges

- Most EDM searches measure EDM of neutral particles.
  - Current Limits: 10^{-17} ecm – 10^{-28} ecm
- 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



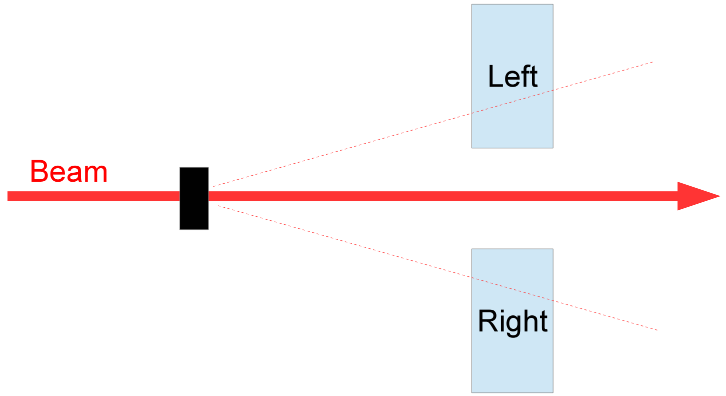
EDM searches in storage rings

- 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

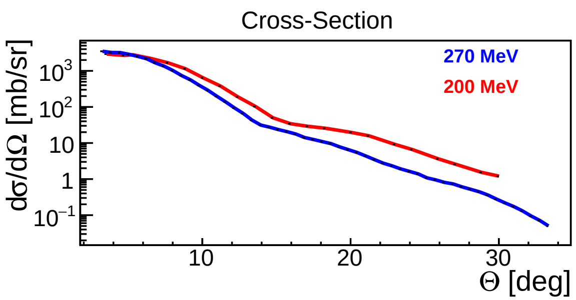


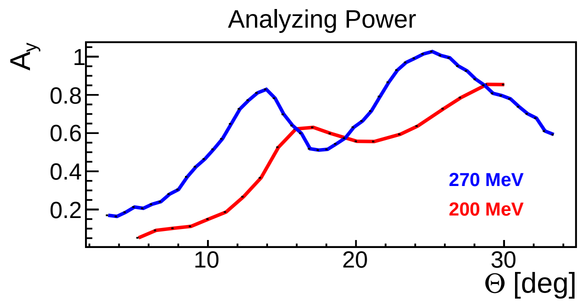
Design goals for an EDM polarimeter

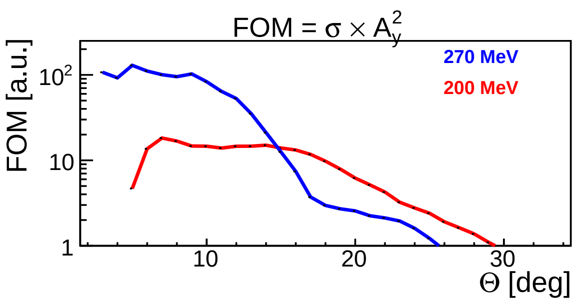
- Design goals for polarimeter:
  - Large statistical Figure-of-Merit: $\mathcal{FOM} \sim N \cdot (P_y A_y)^2$
  - Minimal influence on beam
  - Good handle on systematic effects
  - Good long term stability and reproducibility: 1 ppm per 1000 s

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

  ⇒Polarimeter needs to cover forward region
- Proton-Carbon elastic scattering also concentrated in forward region.

  ⇒Possibility for multi-purpose polarimeter

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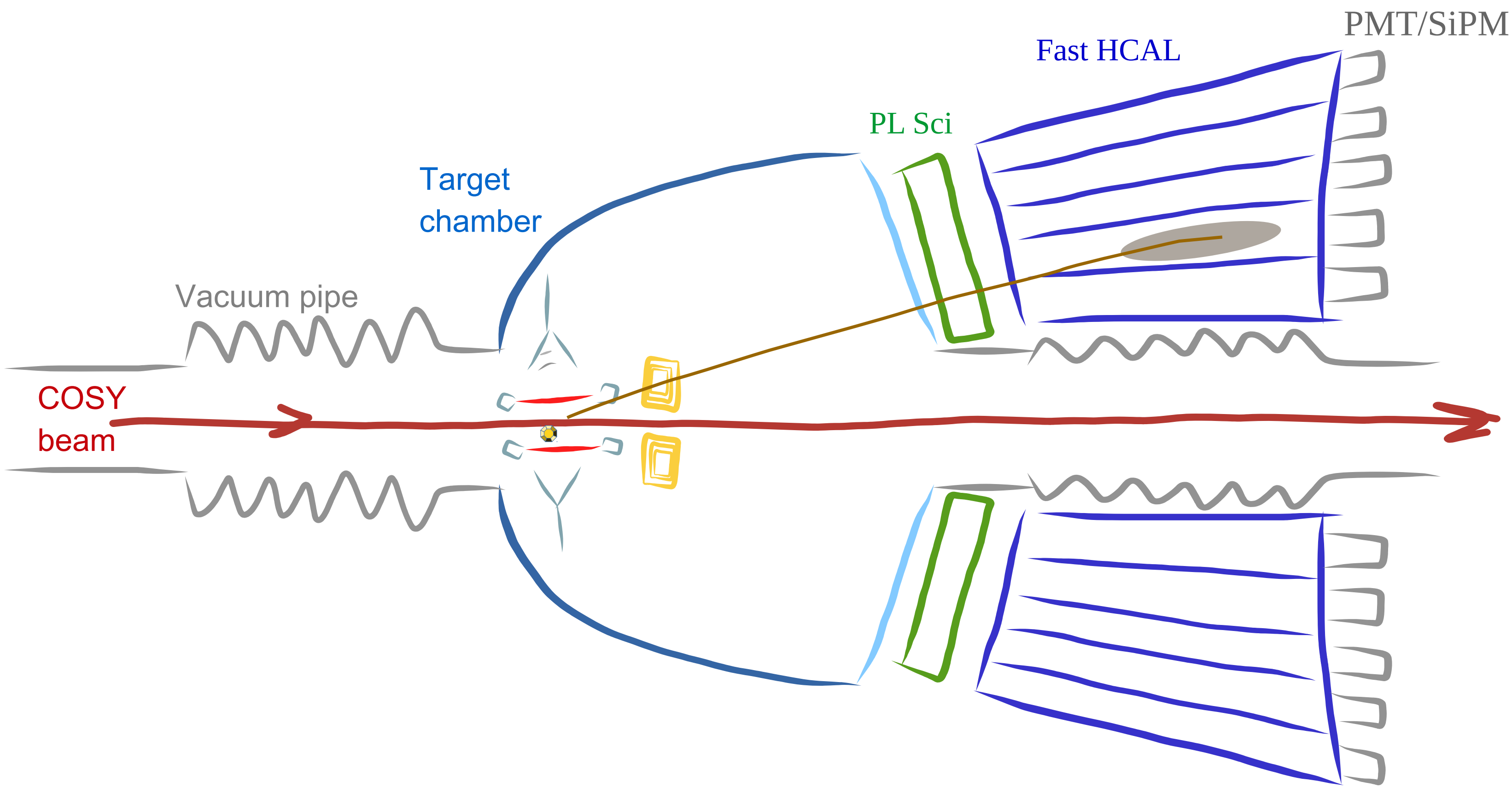
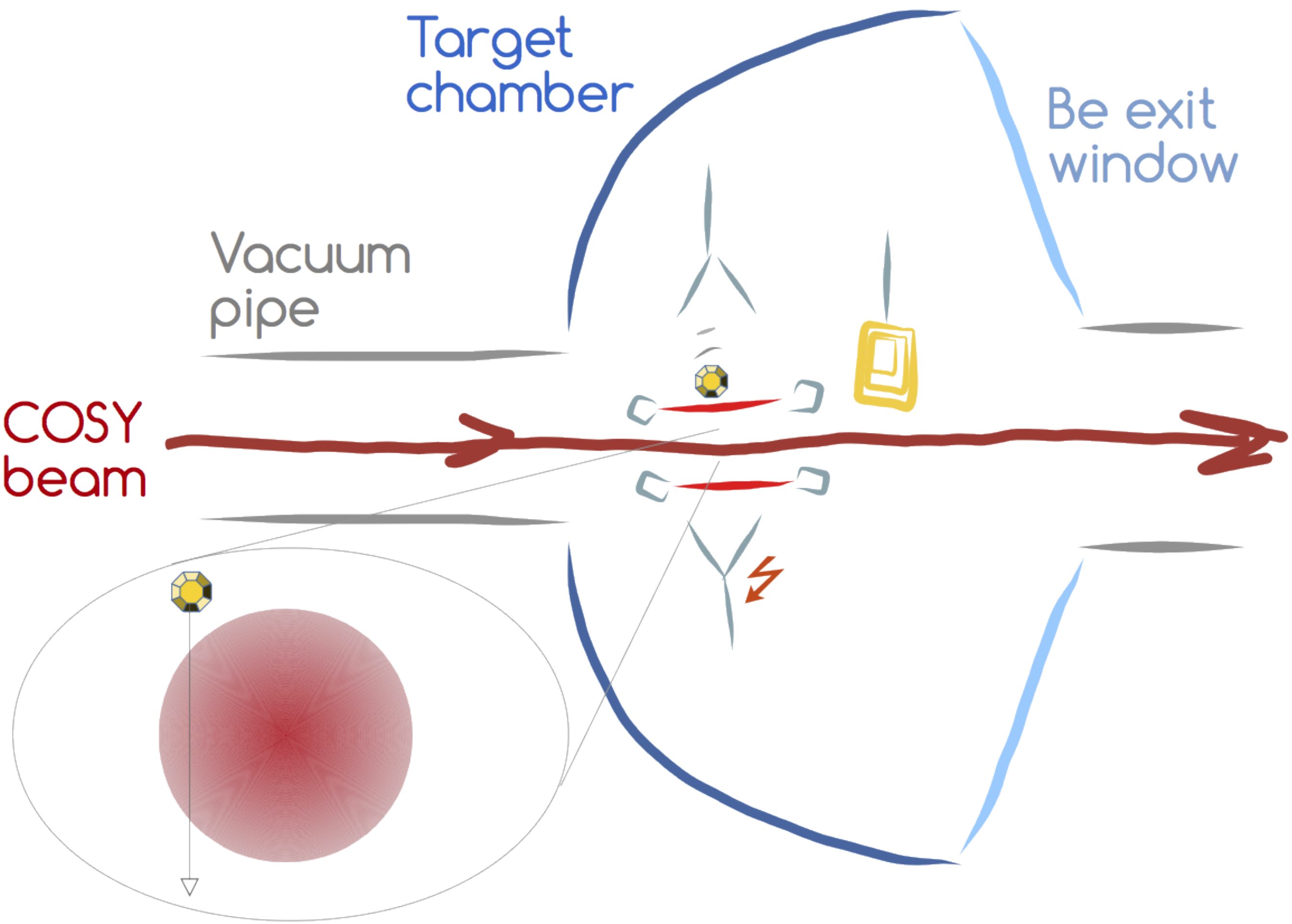
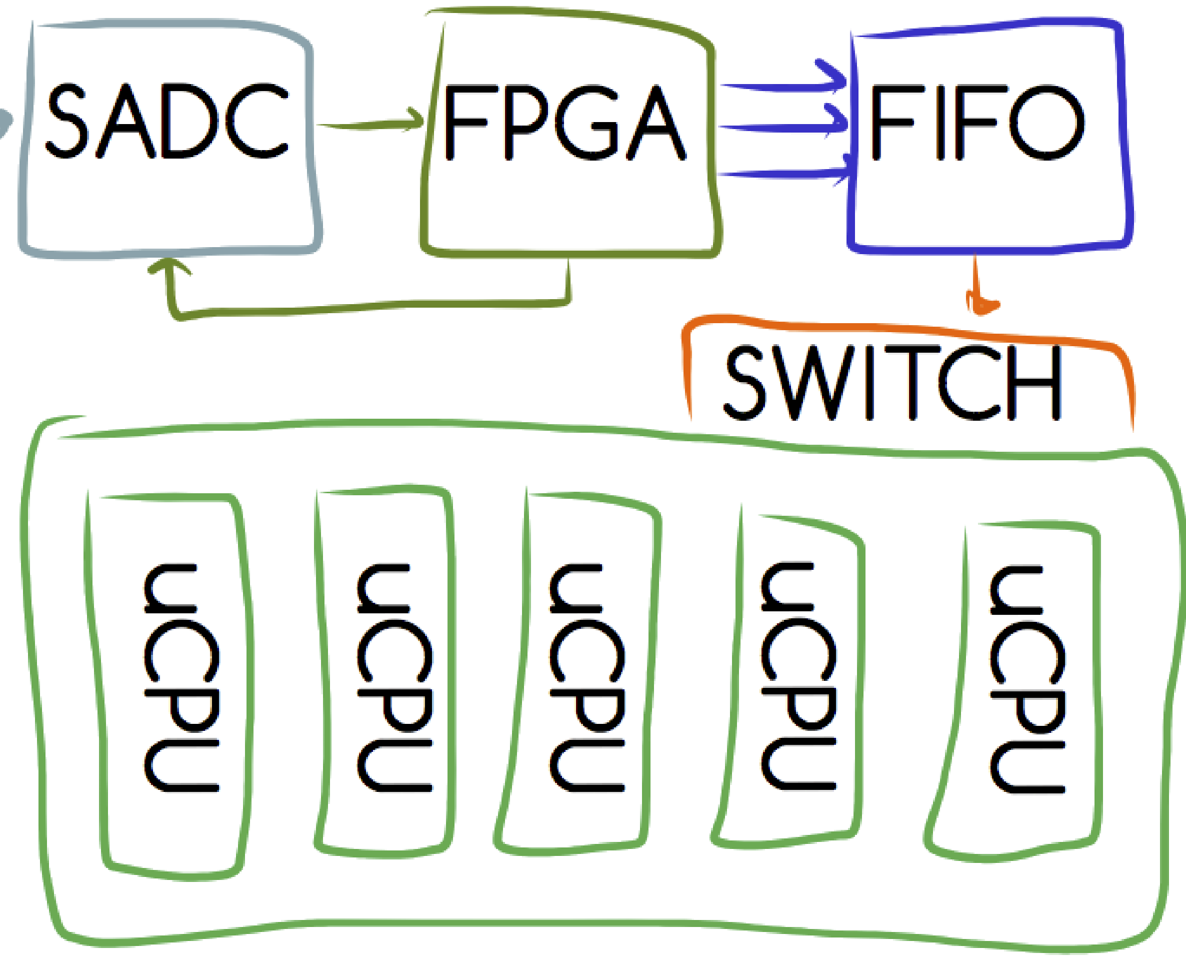
Detector concept

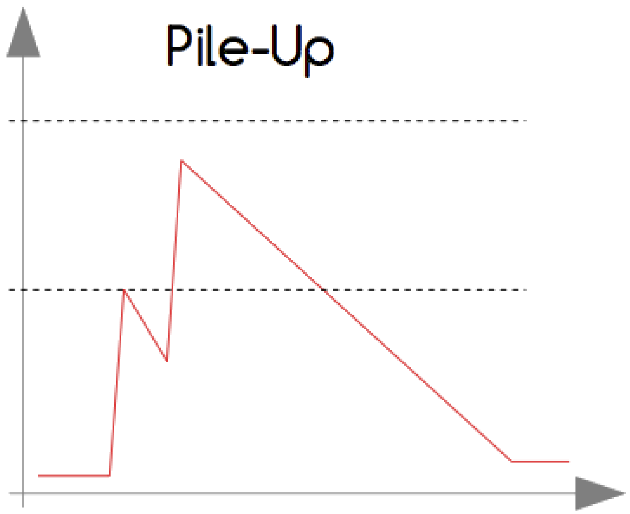


Target concept



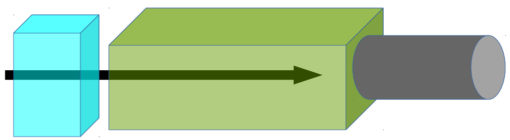
Readout concept

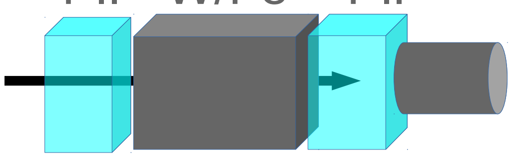




Simulation studies

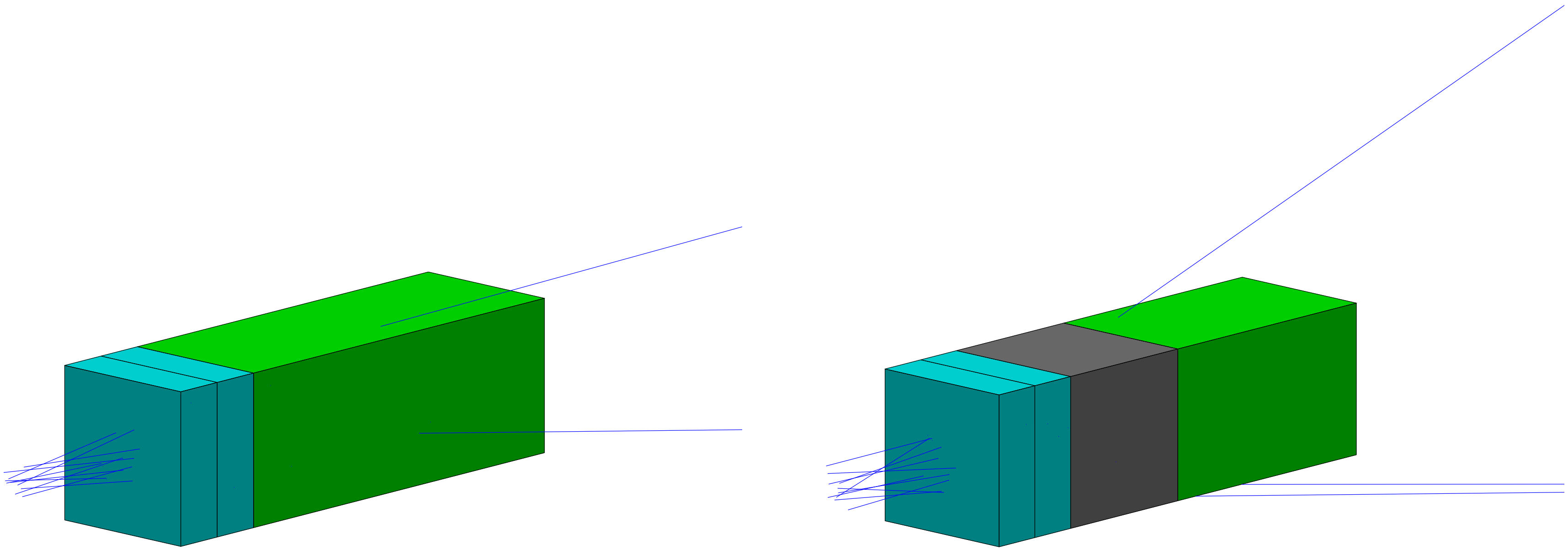
HCal Candidate Materials: LYSO/Plastic Scintillator





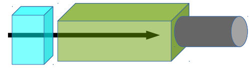
	LYSO	Plastic
Stopping power	+	-
Speed	+	+
Energy resolution	+	-
Cost	-	+

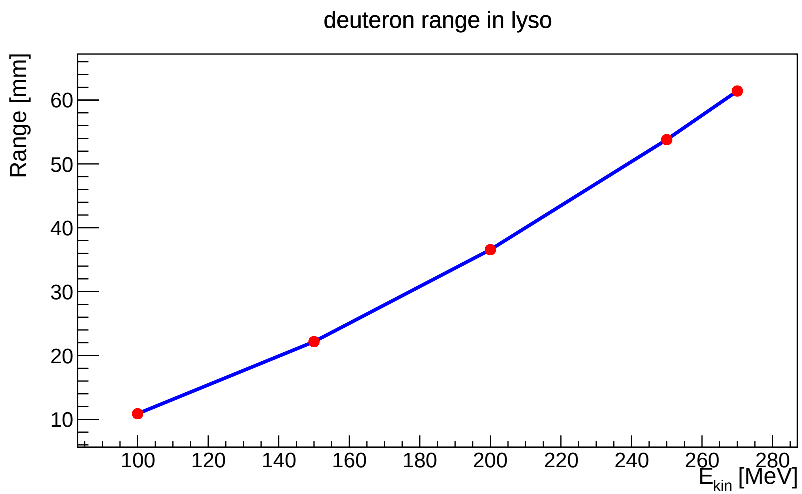
First step: Detector element dimensions

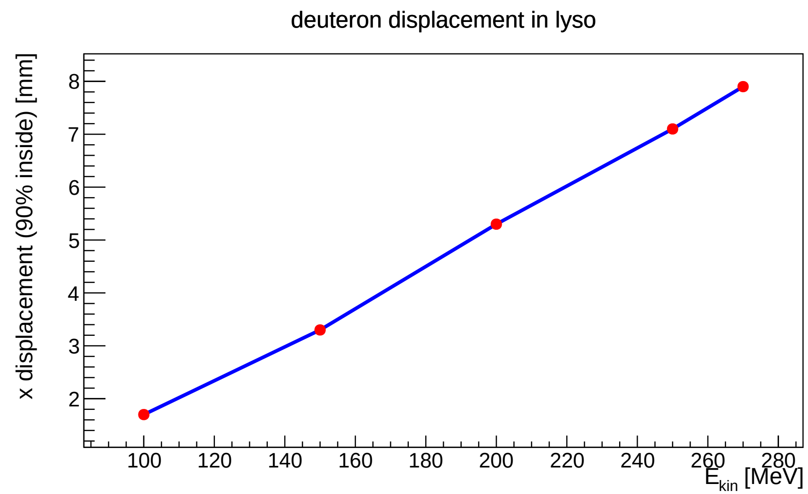


- Open Questions:
  - Optimal calorimeter element size?
  - Absorber Thickness?
  - Monolithic or Sandwich?
  - Plastic or LYSO?

Detector dimensions - LYSO

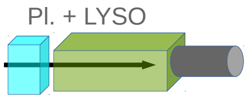


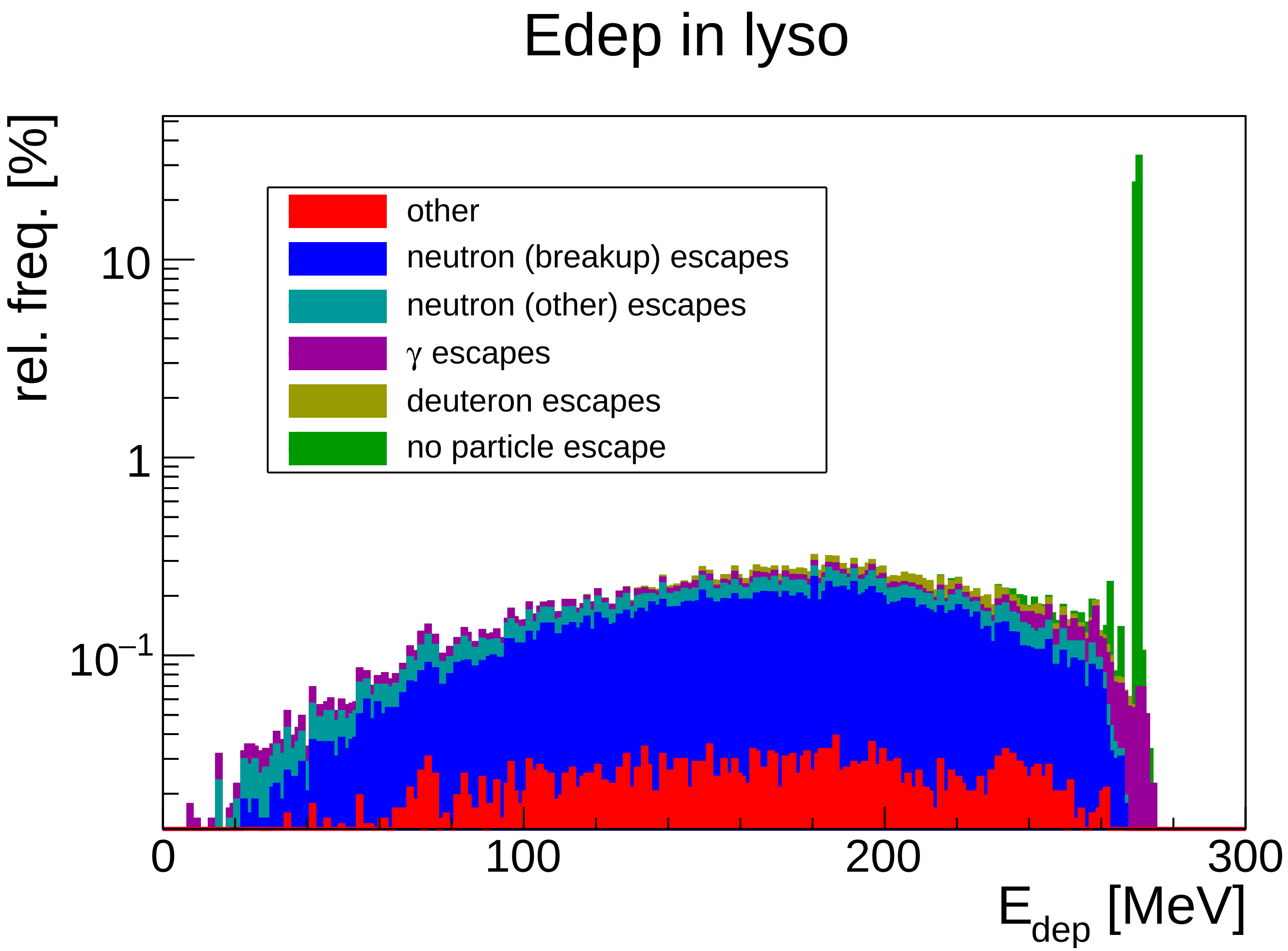




- To get lateral and longitudinal range of deuteron in detector element:
  - Shoot particle gun into front face, determine x_f, y_f, z_f of endpoint of primary track
  - Longitudinal range: Gaussian fit
  - Lateral width: $\int_{-x0}^{x0} dN/dx = 90\% \cdot N_{tot}$
- Chosen detector size of $3 \times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

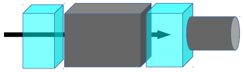
Detector response - LYSO

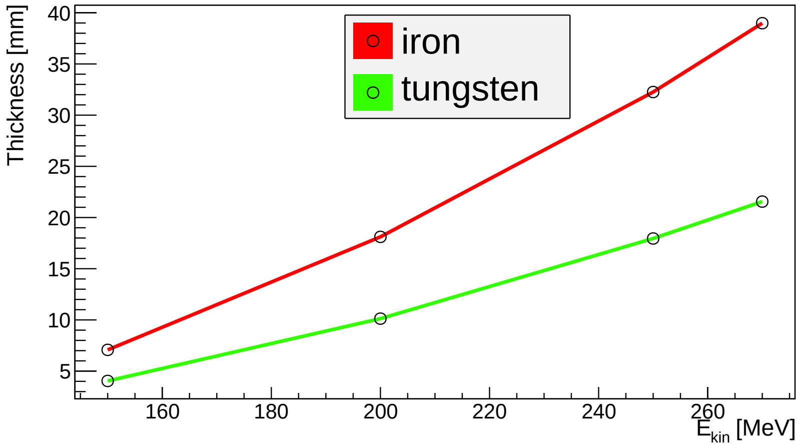


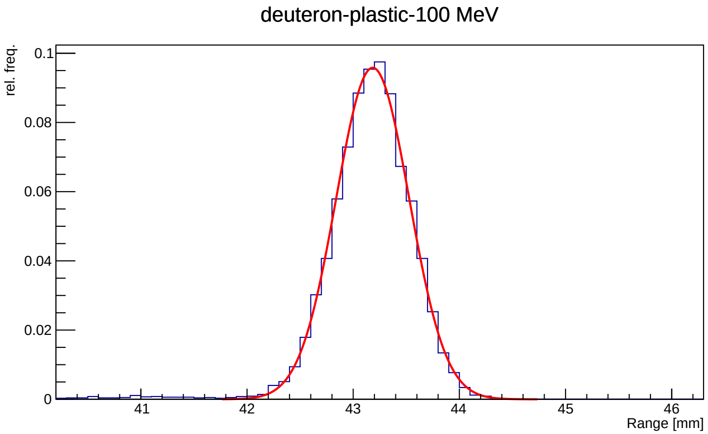


- Breakup in detector element causes distortion of energy spectrum

Detector dimensions - Plastic

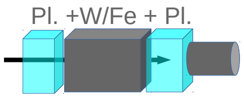


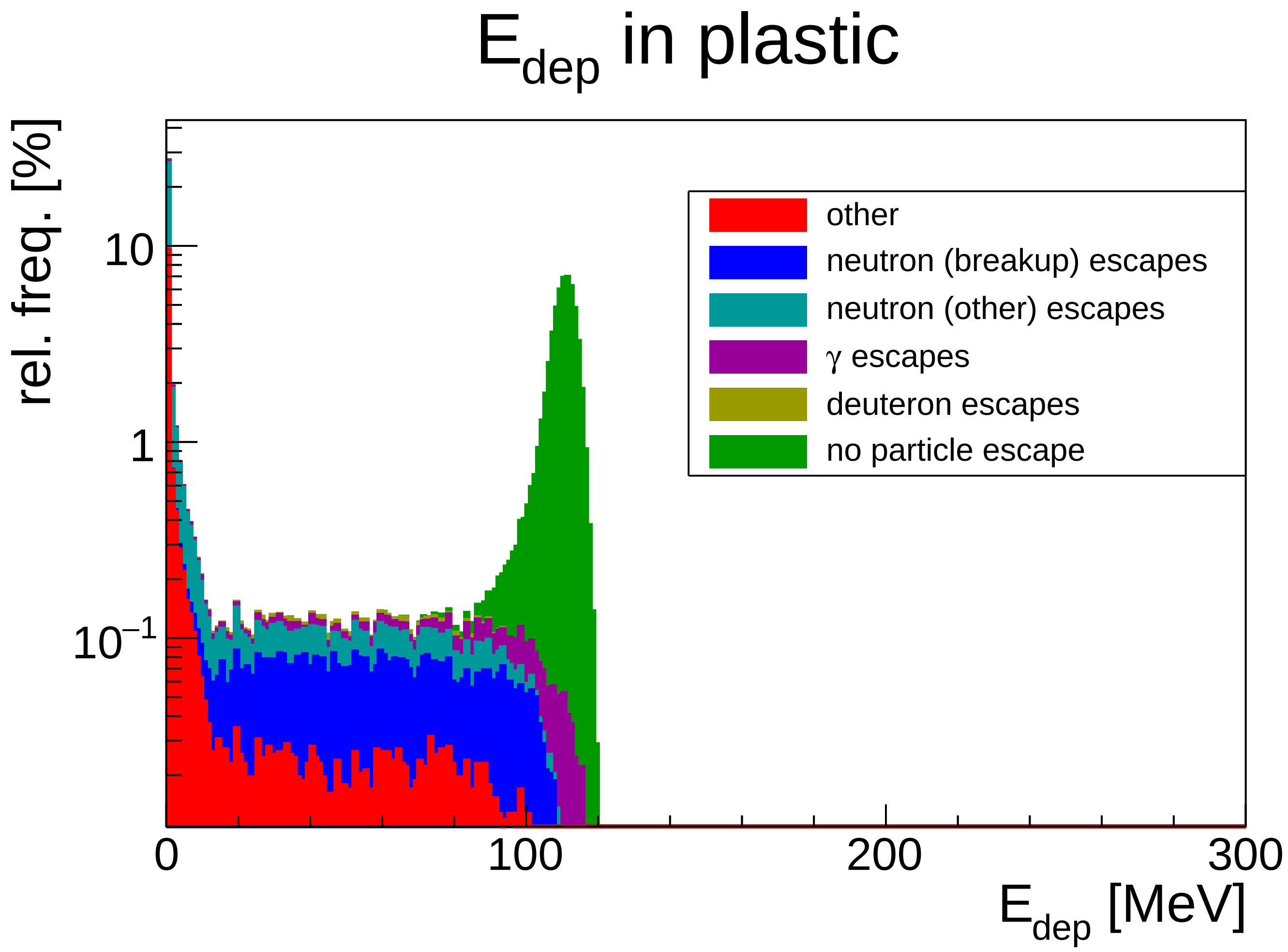




- Use absorber to suppress proton background and reduce length of plastic detector
- Arbitrarily chosen 100 MeV entry energy @ 270 MeV beam energy as working point for plastic scintillator
  - Iron thickness ca. 50 mm
  - Pl. scintillator thickness ca. 50 mm

Detector response - Plastic





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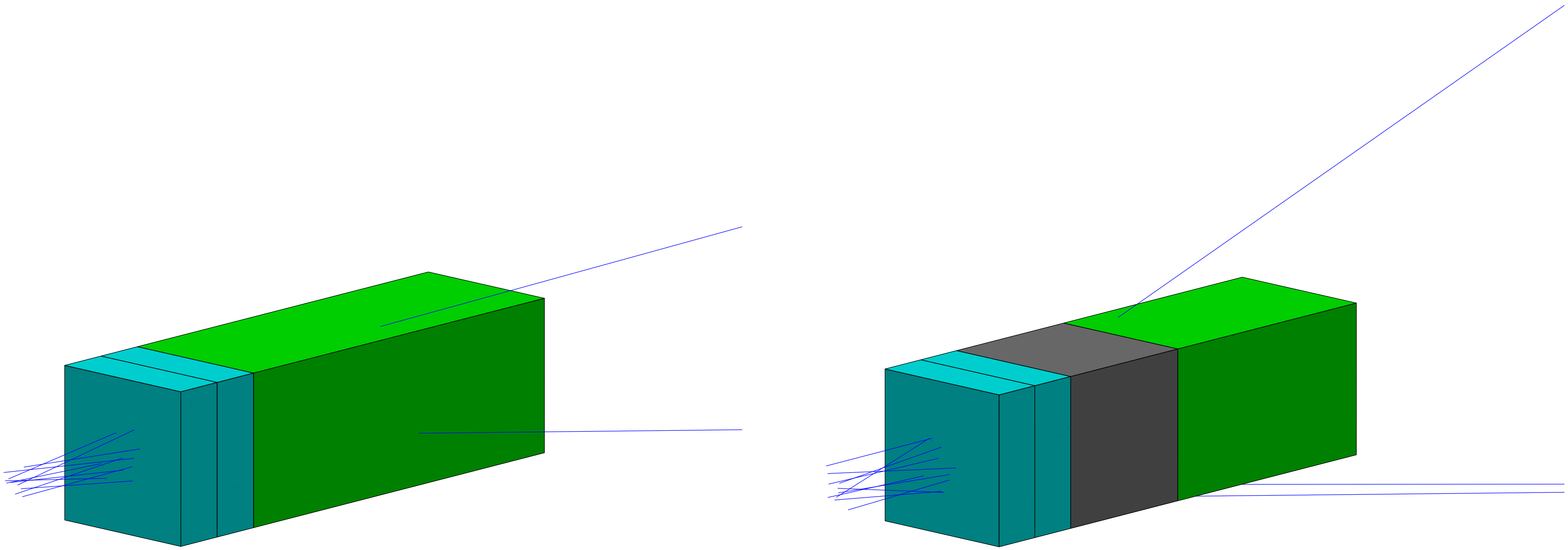
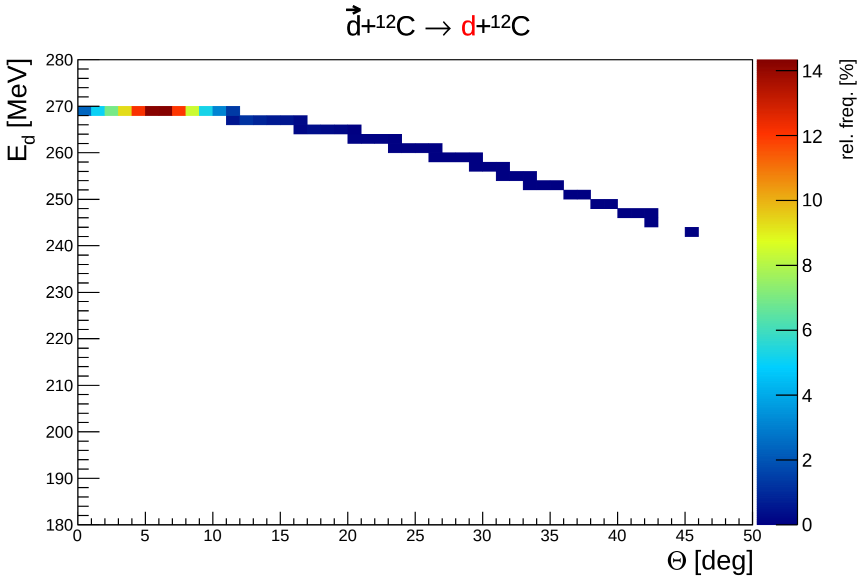
Next step(s): Monolithic or sandwich detector?

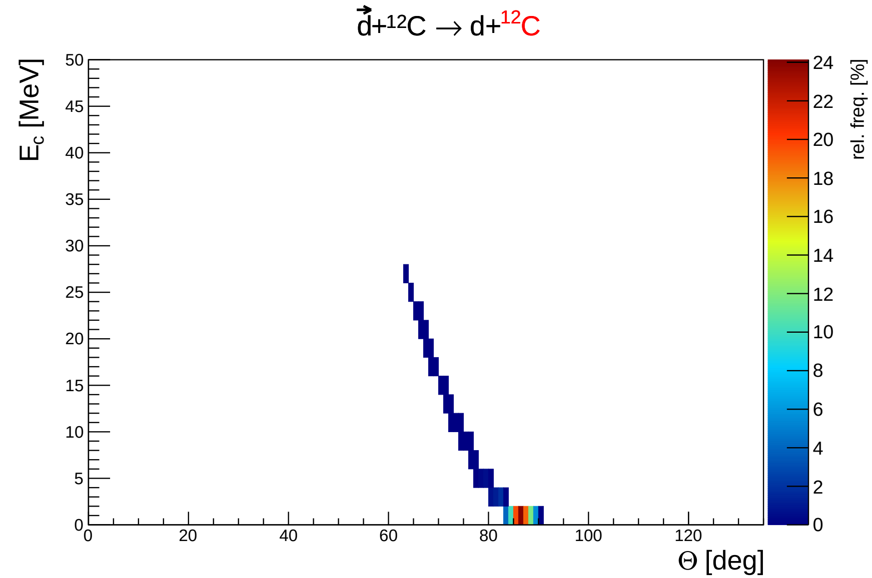


- Generated 100k events each at $T_d = 270\,\text{MeV}, 5^\circ < \Theta < 20^\circ$, $0^\circ < \phi < 360^\circ$
  - Signal: $^{12}C(\vec{d}, d)^{12}C, \sigma \approx 84\,\text{mb}, < A_y > \approx 0.32$
  - Background: $^{12}C(\vec{d}, pn)^{12}C, \sigma \approx 121\,\text{mb}, < A_y > \approx -0.09$

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

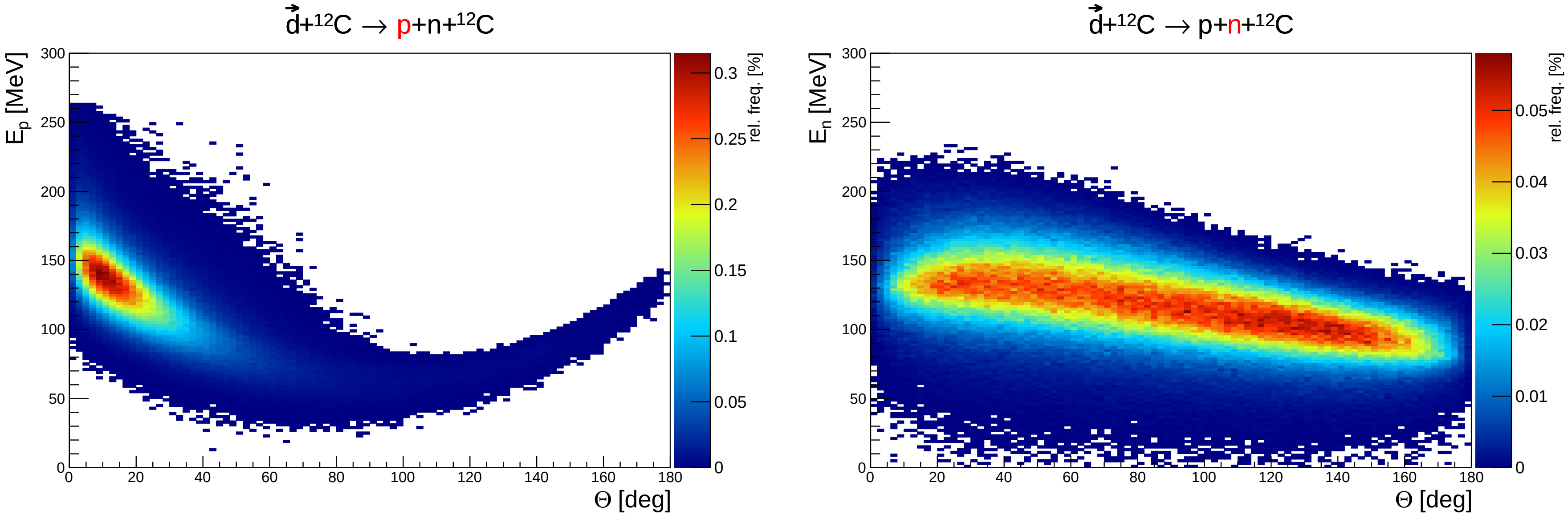
Signal and Background generation





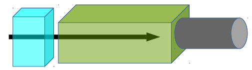
- Using data-driven model for signal and background
- Elastically scattered deuterons retain almost complete beam energy
- Contribution of recoil carbons negligible

Signal and Background generation (cont'd)

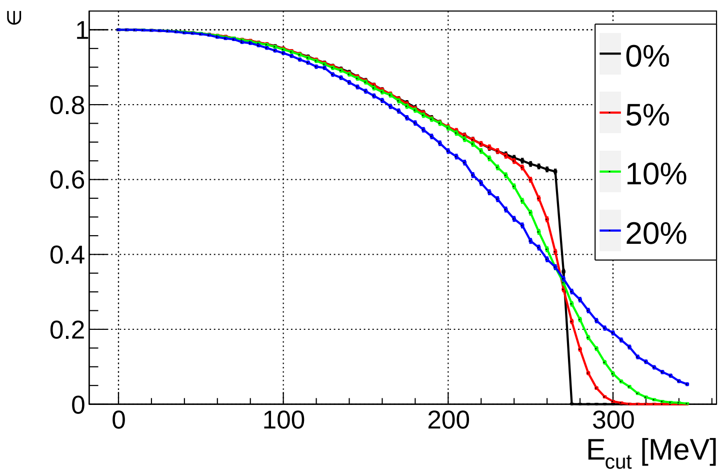


- Break-up has almost no analyzing power, so discard it
- Protons and neutrons from break-up are energetically well separated from signal
  ⇒But: Break-up in target is not distinguishable from break-up in detector!
- No reliable model for inelastic reactions available
  - Qualitative experiments show: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

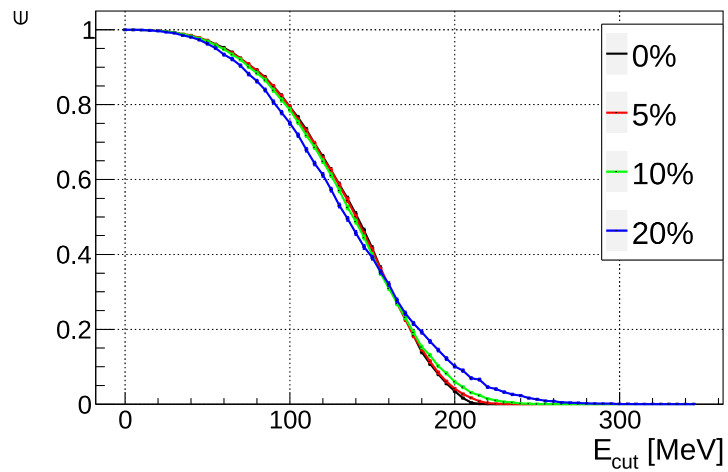
Detection efficiencies (lyso)



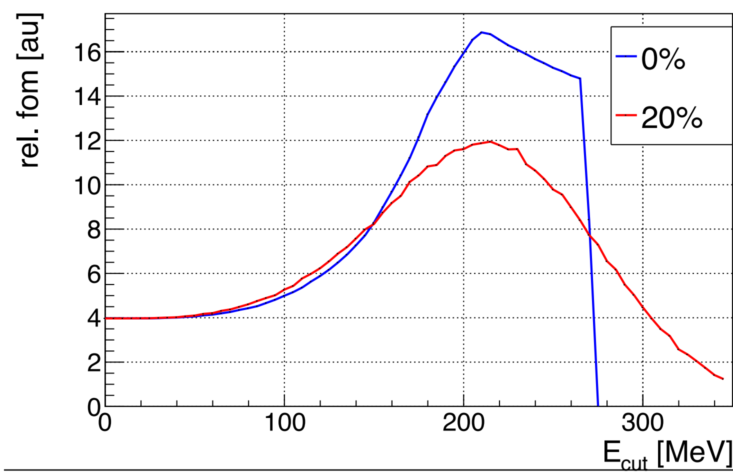
dcelastic detection efficiency in lyso



dcbreakup detection efficiency in lyso



relative fom in lyso



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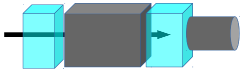
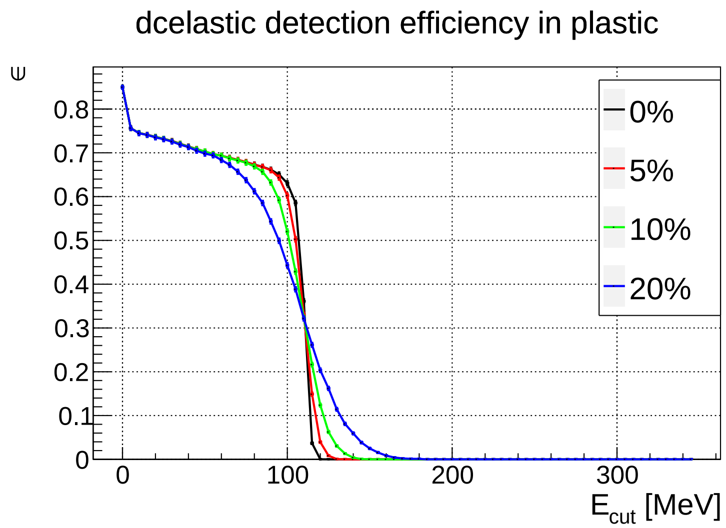
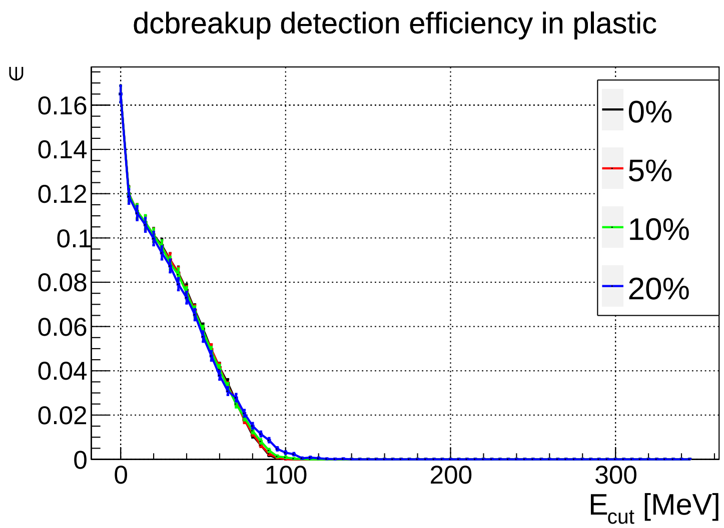
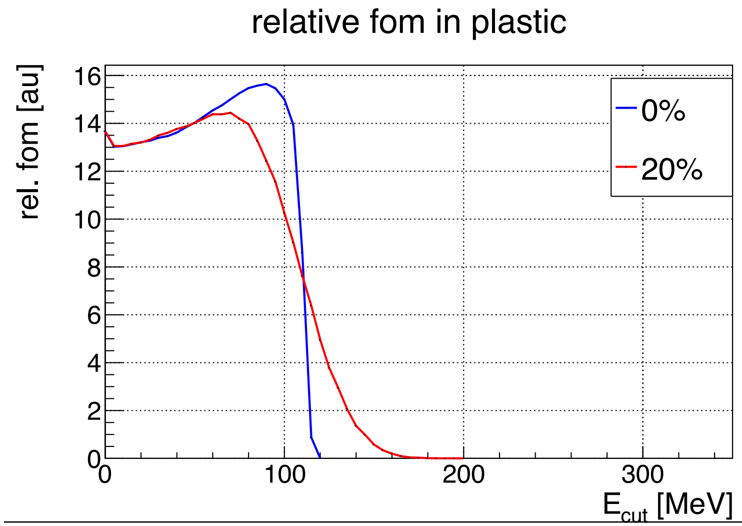
Detection efficiencies (plastic)









Simulation Results

- Main cause of efficiency loss is breakup in detector
- Maximum relative FOM:

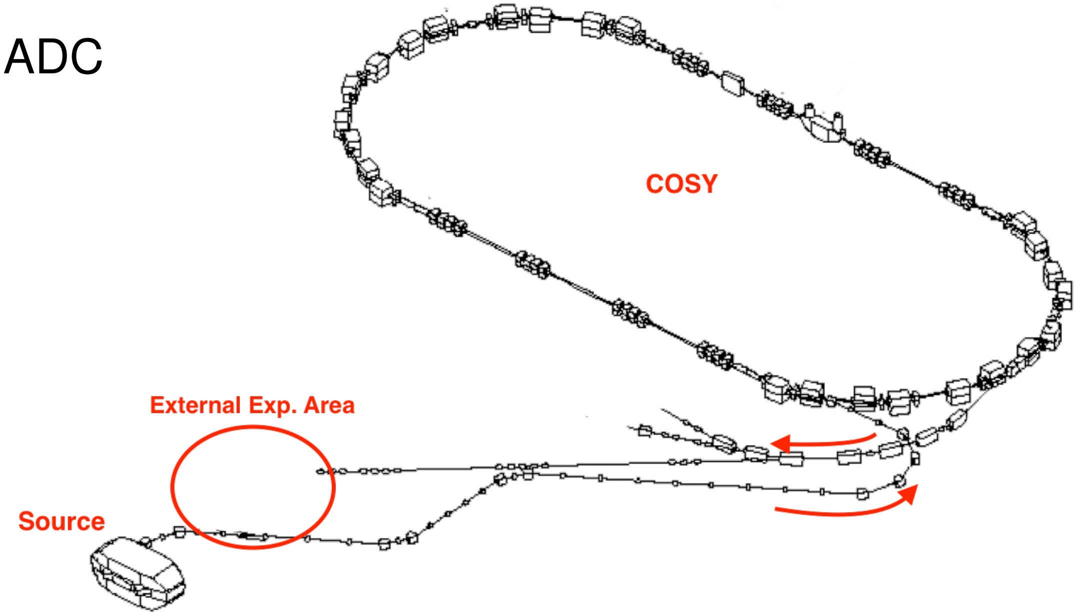
	0%	20%
Plastic	15.5	14.5
LYSO	17	12

- LYSO and plastic scintillators provide comparable performance
- Plastic scintillator performance exhibits no strong dependence on energy resolution

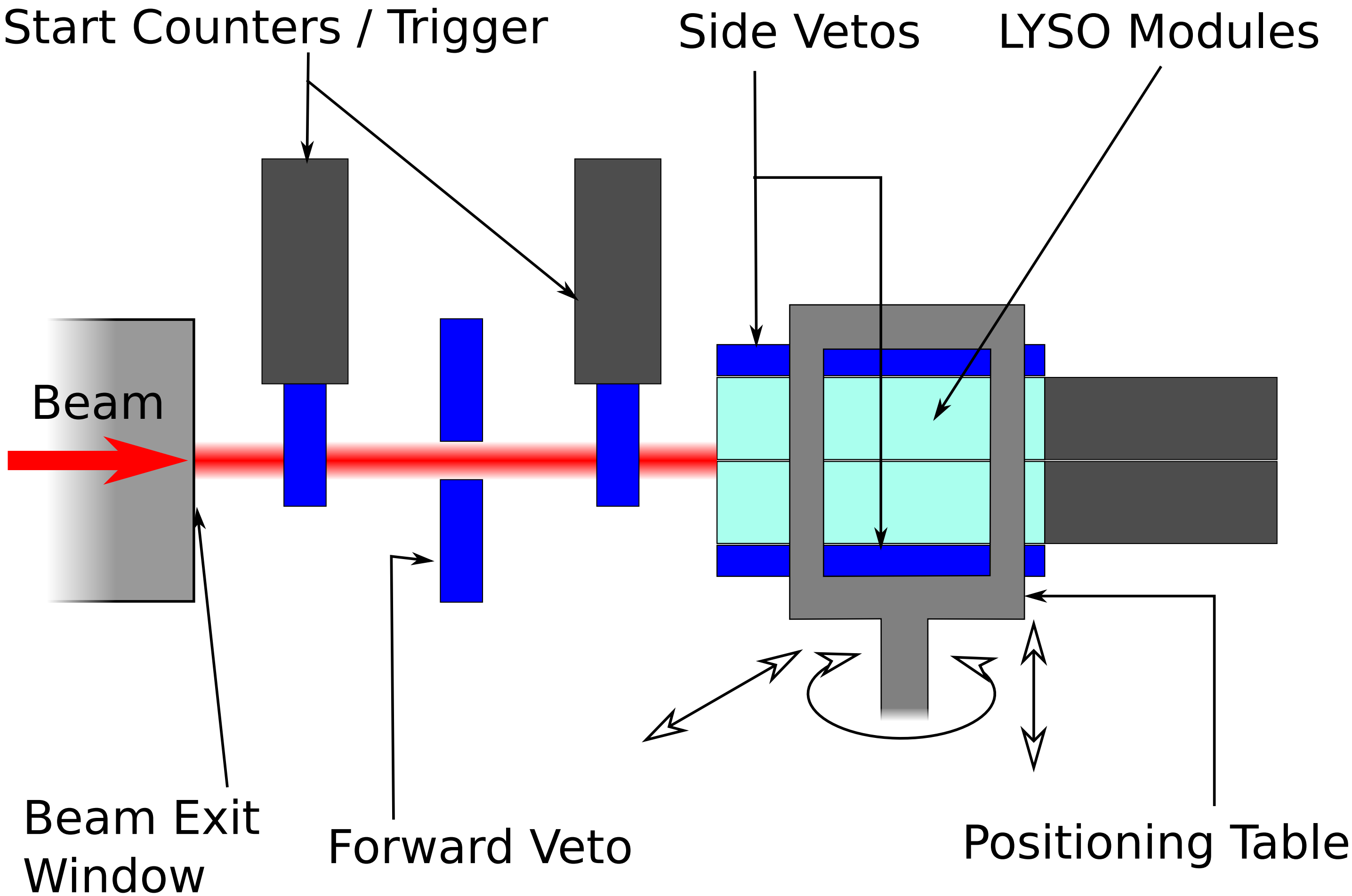
R&D Beam time @ COSY: First results

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

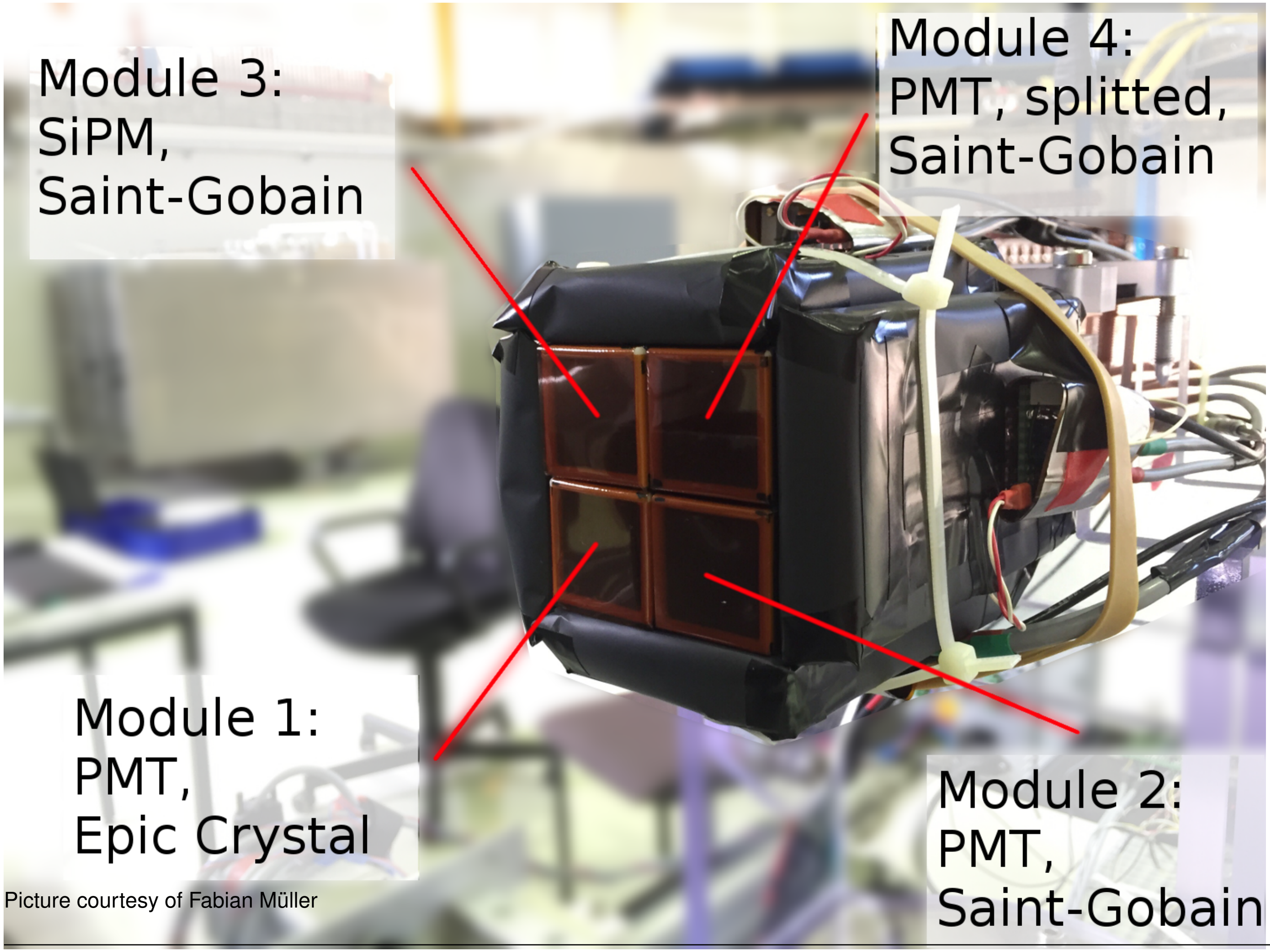


Measurement setup



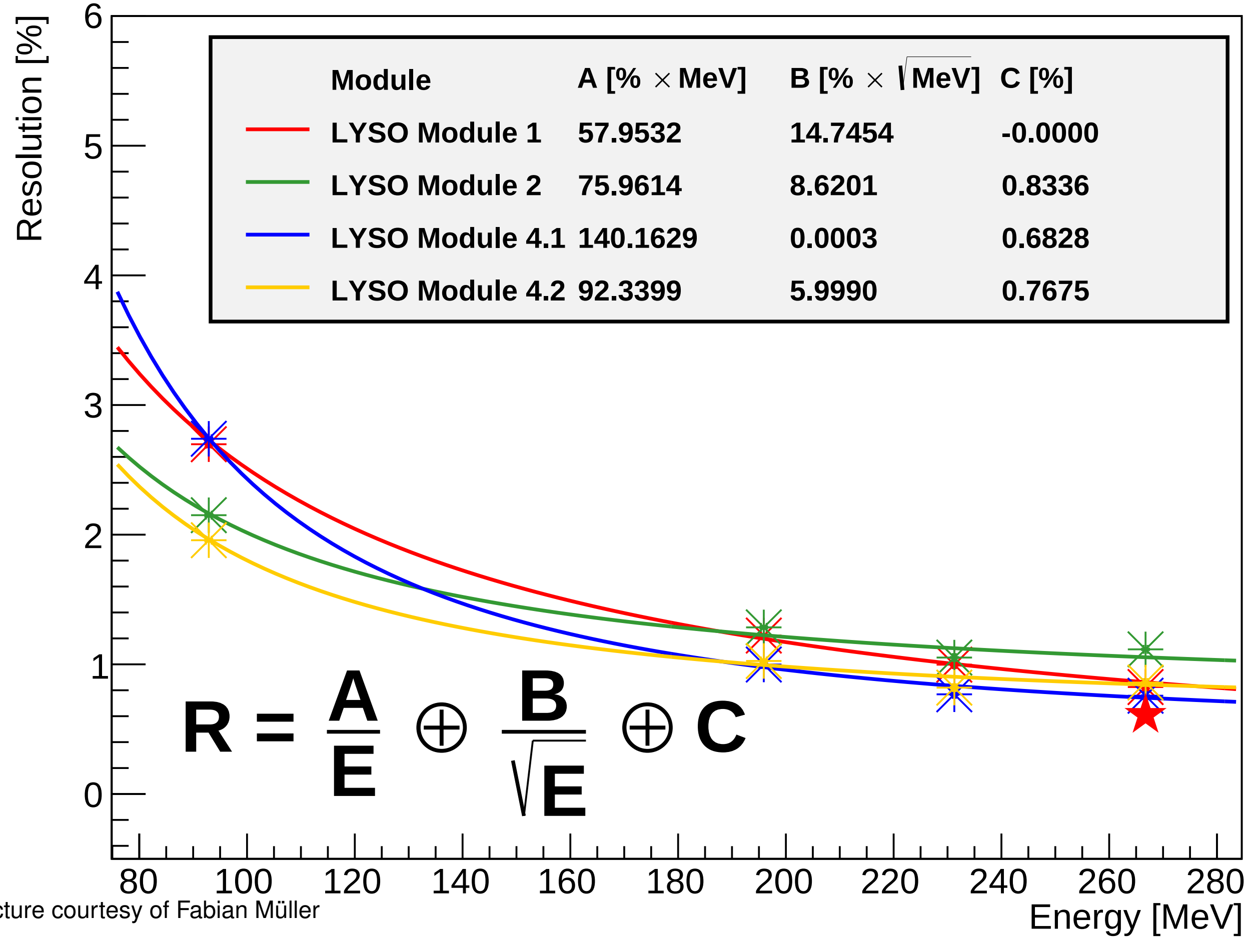
Picture courtesy of Fabian Müller

Measurement setup (cont'd)



Picture courtesy of Fabian Müller

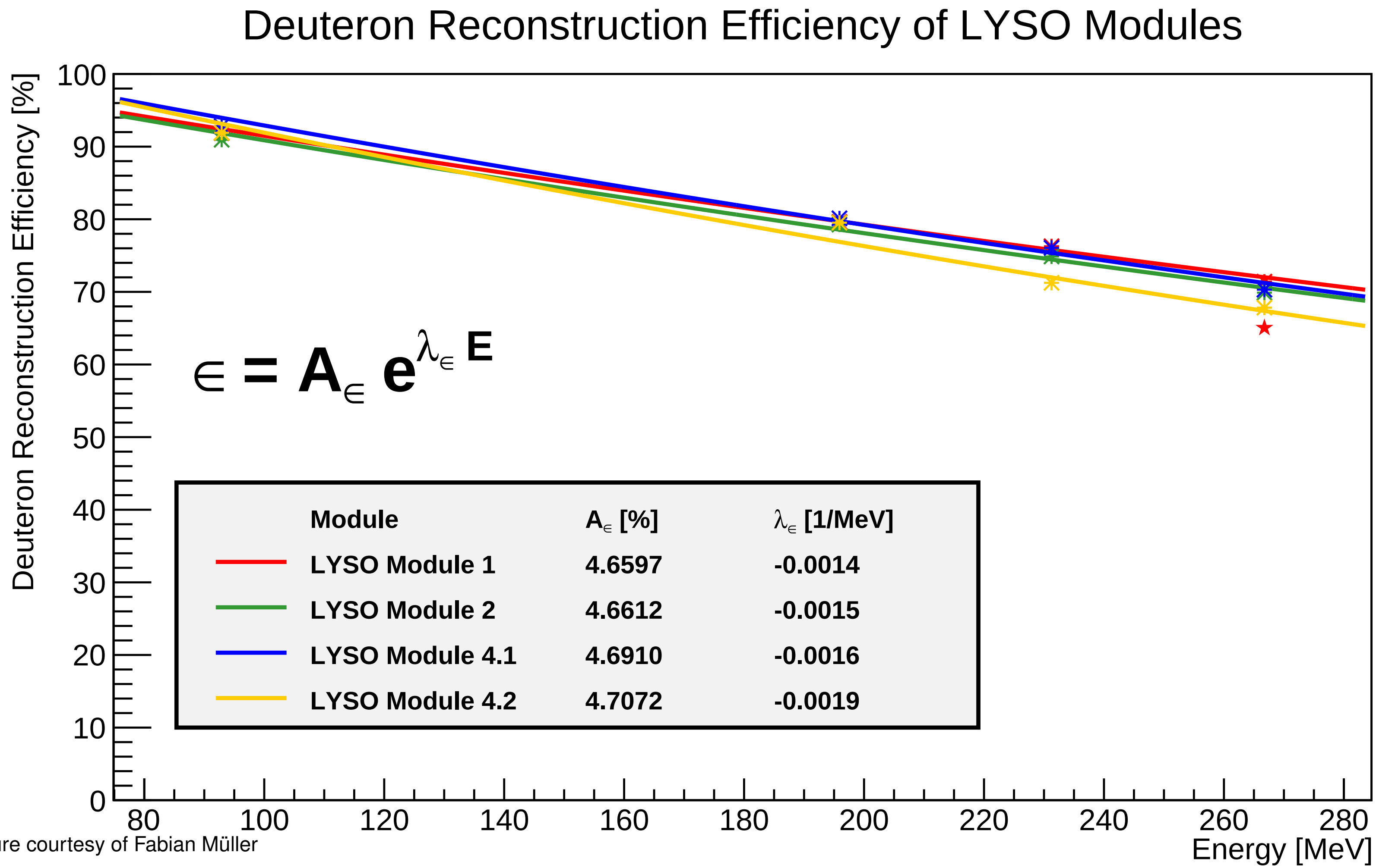
Energy resolution



$$R = \frac{A}{E} \oplus \frac{B}{\sqrt{E}} \oplus C$$

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