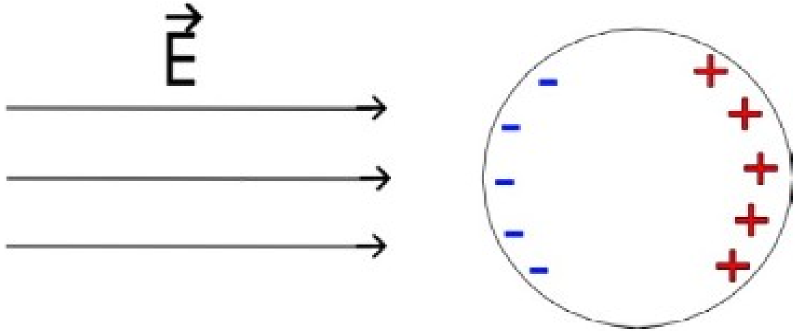
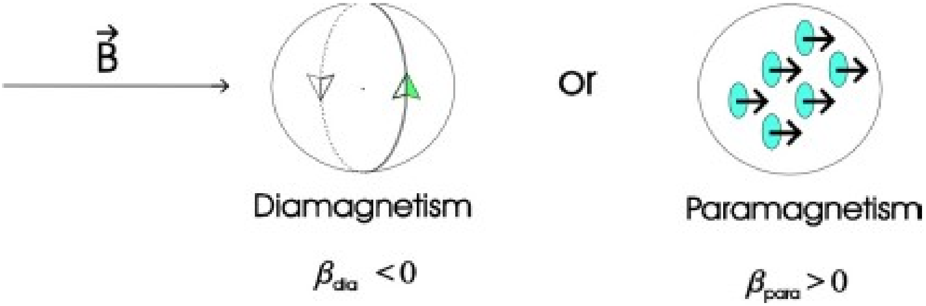
Измерение поляризуемости нейтрона. Предложение эксперимента по комптоновскому рассеянию на ядрах He3 (ускоритель MAMI, Майнц)

Scalar polarizabilities

Proton Electric Polarizability

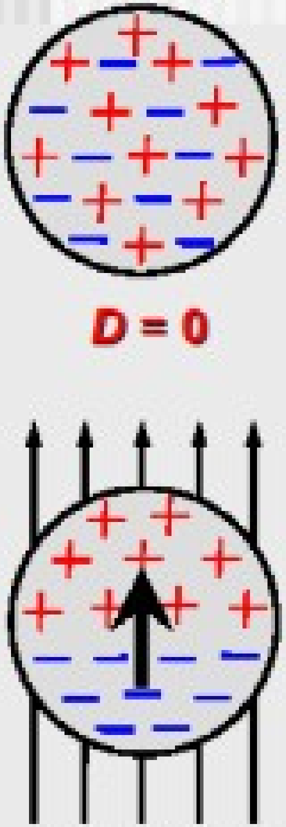


Proton Magnetic Polarizability



- Fundamental properties of the proton
- Important to atomic physics, spin polarizability measurements etc (e.g. for proton radius puzzle)

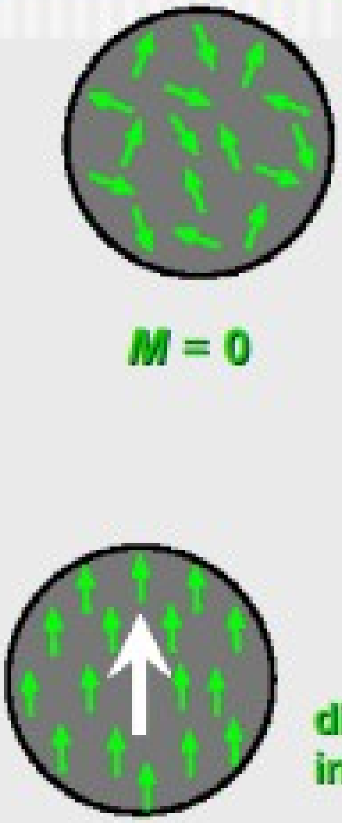
electric polarizability: separation of charge



$D = 0$

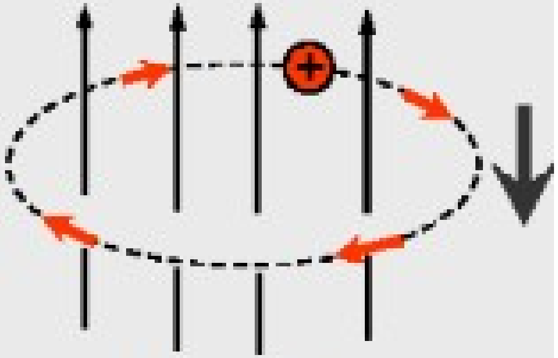
$D = \alpha E$

paramagnetic polarizability: moments align with B



$M = 0$

$M = \beta_{para} B$



$M = \beta_{dia} B$

diamagnetic polarizability: induced current opposes B

Cross section for Compton scattering at low energy

$$\left[\frac{d\sigma(E_\gamma,\theta)}{d\Omega}\right]_{\mathrm{LET}} = \left[\frac{d\sigma(E_\gamma,\theta)}{d\Omega}\right]_{\mathrm{Powell}} - \rho + \mathcal{O}(E_\gamma^4)$$

$$\rho = \frac{e^2}{4\pi m_p}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2 \frac{E_\gamma E_{\gamma'}}{(\hbar c)^2} \times$$

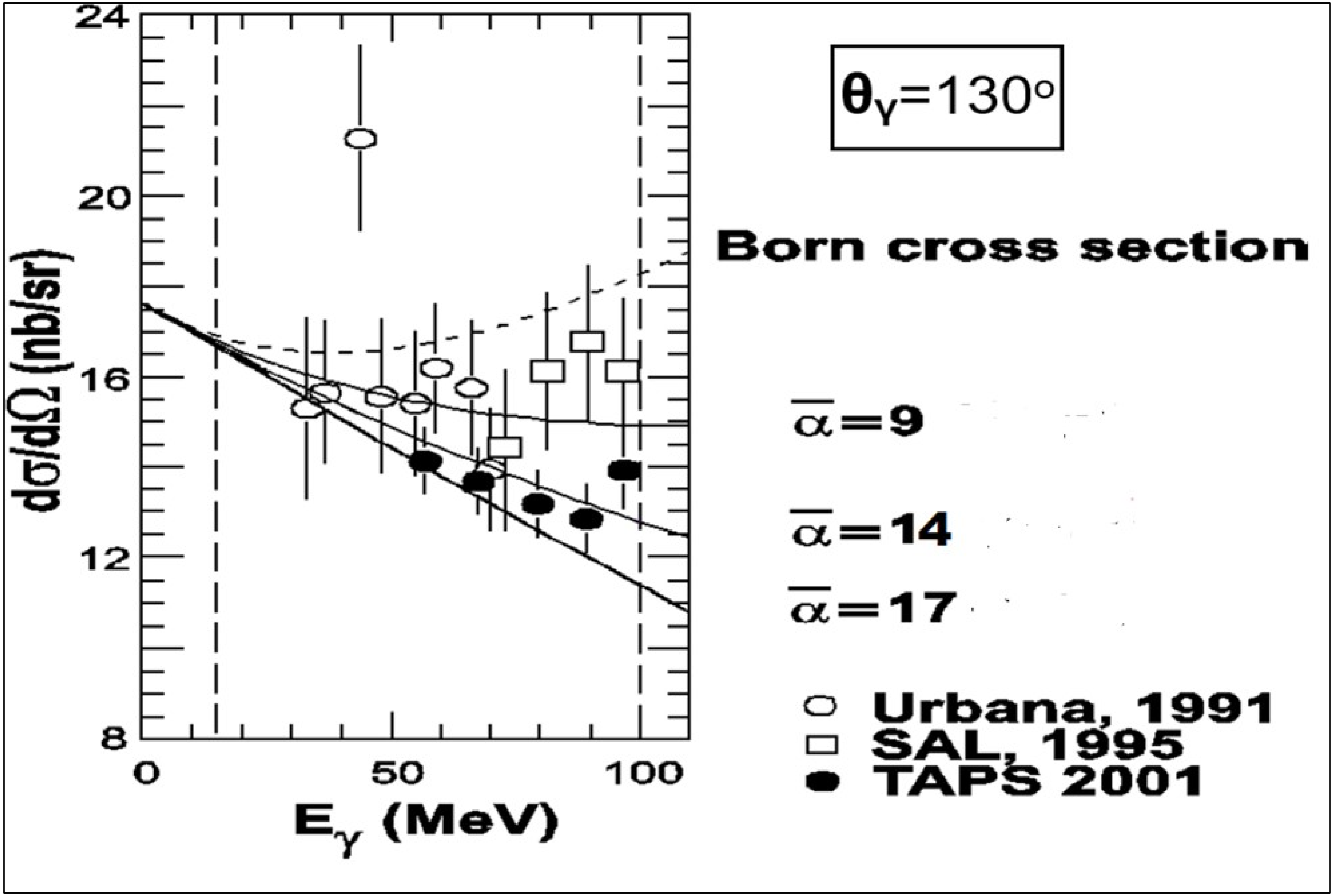
$$\times \left[\frac{\overline{\alpha}+\overline{\beta}}{2}(1+\cos\theta)^2 + \frac{\overline{\alpha}-\overline{\beta}}{2}(1-\cos\theta)^2\right]$$

α and β are defined in units 10^{-4} fm^3

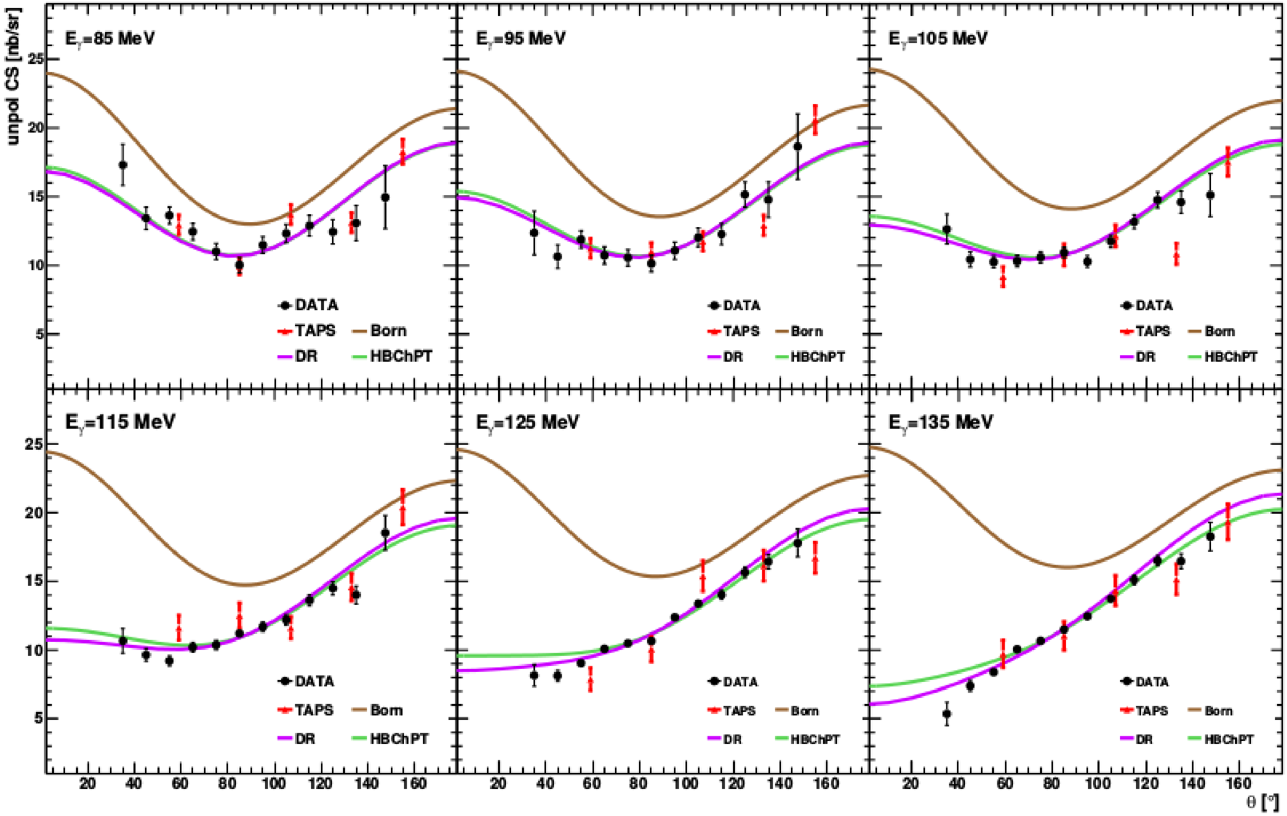
LET-formula describes the γ-p scattering with high precision at Eγ <100 MeV.

- dσ(Eγ,θγ)/dΩ (Powell) describes the γ-p scattering for point-like proton.
- Structure term ρ describes negative contribution from polarizabilities α and β.
- At θγ=90 deg, dσ(Eγ,θγ)/dΩ) sensitive to α only.
- At backward angles (e.g. θγ=130deg.), sensitive mostly to α-β.

Low energy (Eγ <100 MeV) Compton scattering data



Unpolarized Cross Section - $d\sigma/d\Omega$ - Preliminary



Work by E. Mornacchi (Ph.D. student in A2)

- Nov 2017
- Feb 2018
- Mar 2018
- Jul 2018

Big improvement over previous data

Planned precision of α_p and β_p measurements at MESA

Statistical uncertainty: $\Delta\alpha_p = 0.07$, $\Delta\beta_p = 0.12$

Systematical uncertainty: $\Delta\alpha_p = 0.11$, $\Delta\beta_p = 0.12$

Total uncertainty (in quadrature): $\Delta\alpha_p = 0.13$, $\Delta\beta_p = 0.17$

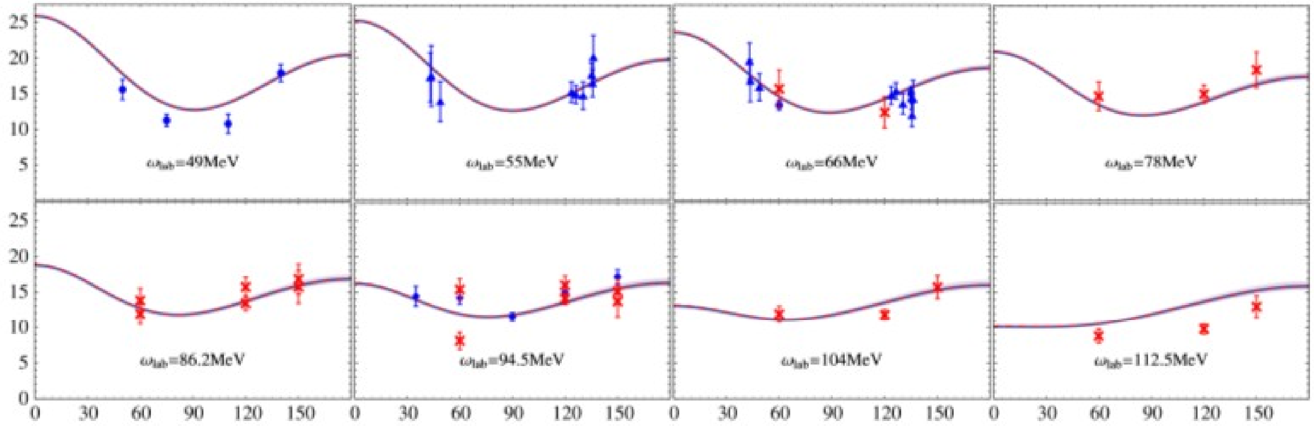
world measurements of α_p and β_p

PDG (2014) α_p=11.2 ±0.4, β_p = 2.5 ±0.4
PDG (2010) α_p=12.0 ±0.6, β_p = 1.9 ±0.5

Mainz (2001) α_p= 11.9 ±0.5 ±1.3, β_p = 1.2 ±0.7 ±0.3

Elastic Compton Scattering from Deuterium: $\gamma + d \to \gamma + d$

- Interference between proton and neutron increases sensitivity.
- Higher cross section.
- Nuclear effects are much bigger than one might naively expect!



Myers et al. PRL **113**, 262506 (2014)

Still sparse compared to proton data

$$\alpha^n_{E1} = 11.55 \pm 1.25_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.8_{\text{th}} \qquad \beta^n_{M1} = 3.65 \mp 1.25_{\text{stat}} \pm 0.2_{\Sigma} \mp 0.8_{\text{th}}$$

Deuteron target

Planned precision of α_s and β_s measurements at MESA

Statistical uncertainty: $\Delta\alpha_s = 0.07$, $\Delta\beta_s = 0.12$

Systematical uncertainty: $\Delta\alpha_s = 0.13$, $\Delta\beta_s = 0.16$

Total uncertainty (in quadrature): $\Delta\alpha_s = 0.15$, $\Delta\beta_s = 0.20$

$\alpha_s = (\alpha_p + \alpha_n)/2$, $\beta_s = (\beta_p + \beta_n)/2$ (isoscalar average)

Max-lab (Lund,2014) $\alpha_s = 12.1 \pm 0.8$stat, $\beta_s = 2.4 \pm 0.8$stat

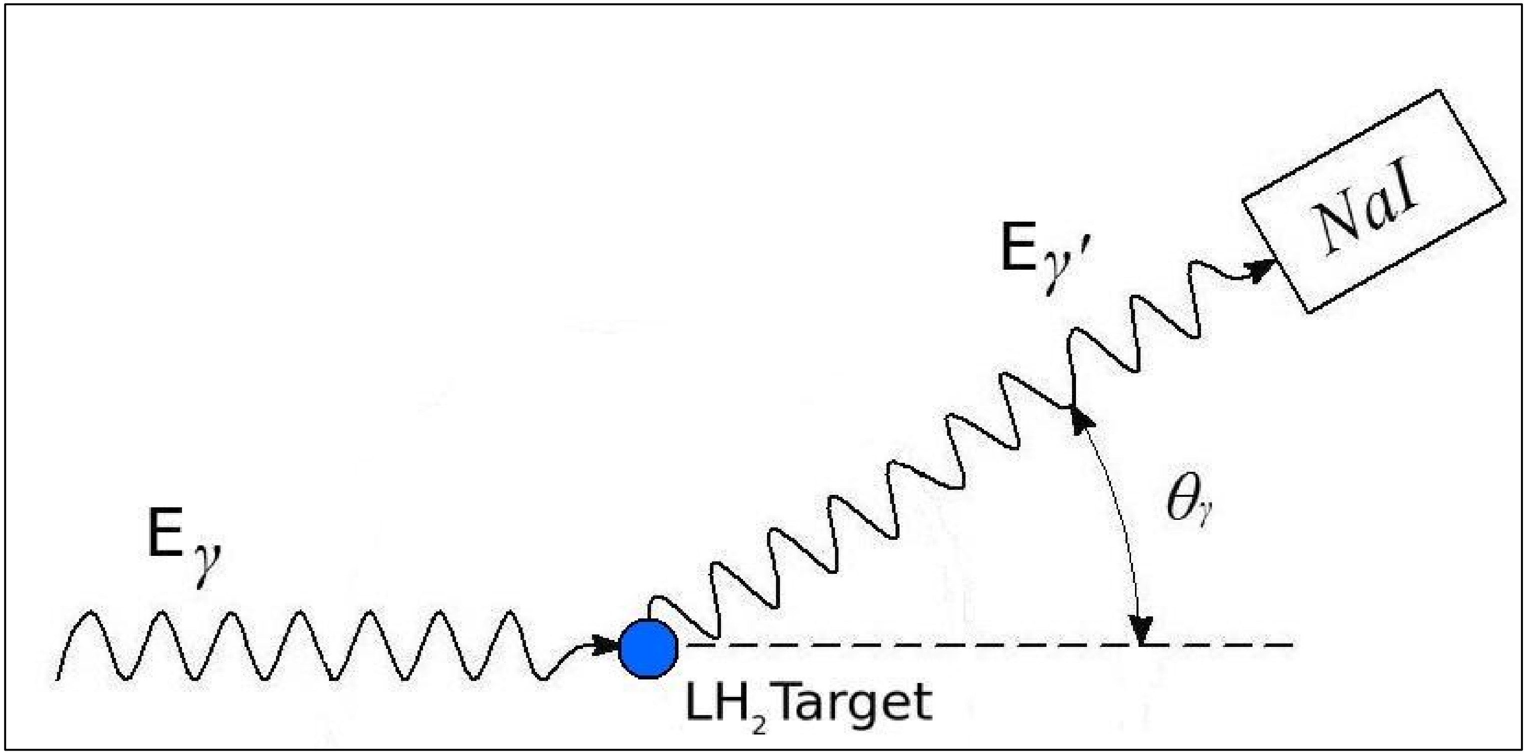
world measurements of α_n and β_n

PDG (2010) $\alpha_n = 12.5 \pm 1.7$, $\beta_n = 2.7 \pm 1.8$

PDG (2014) $\alpha_n = 11.6 \pm 1.5$, $\beta_n = 3.7 \pm 2.0$

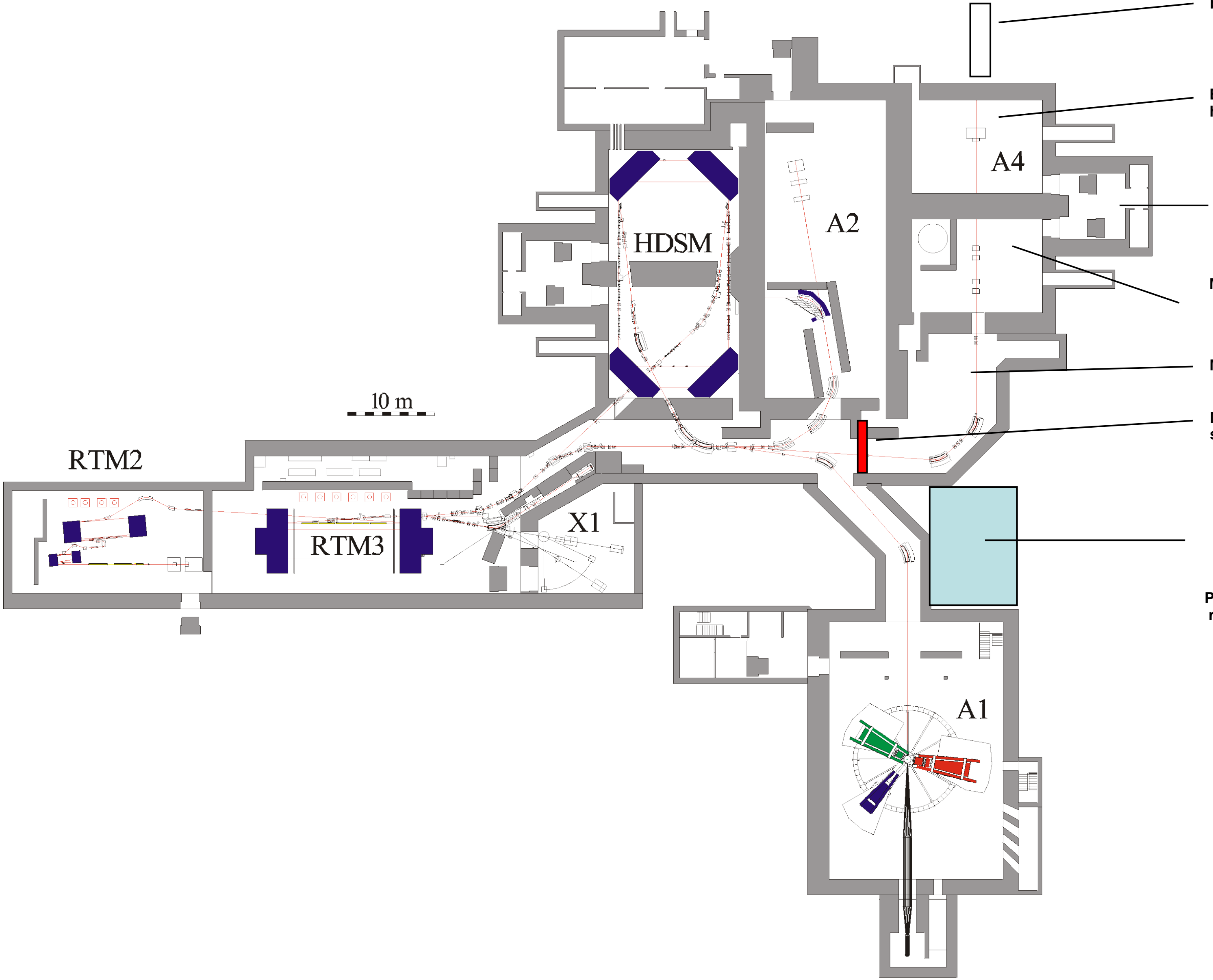
Max-lab(Lund, 2014) $\alpha_n = 11.55 \pm 1.25$stat, $\beta_n = 3.65 \pm 1.25$stat

Typical tagged photon beam Copmton scattering experiment



measured are **Eγ , Eγ’ θγ’** -kinematics reconstruction complete

MAMI and MESA



High power beam dump

Experimental hall

Access-shaft

MESA-hall-2

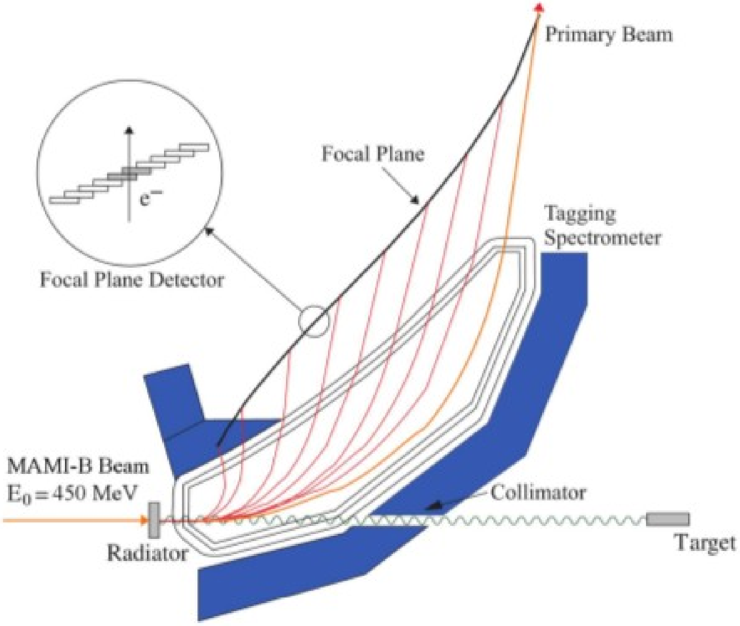
MESA-hall-1

MAMI/MESA separation (shielding)

Possible extension area (excavation required)

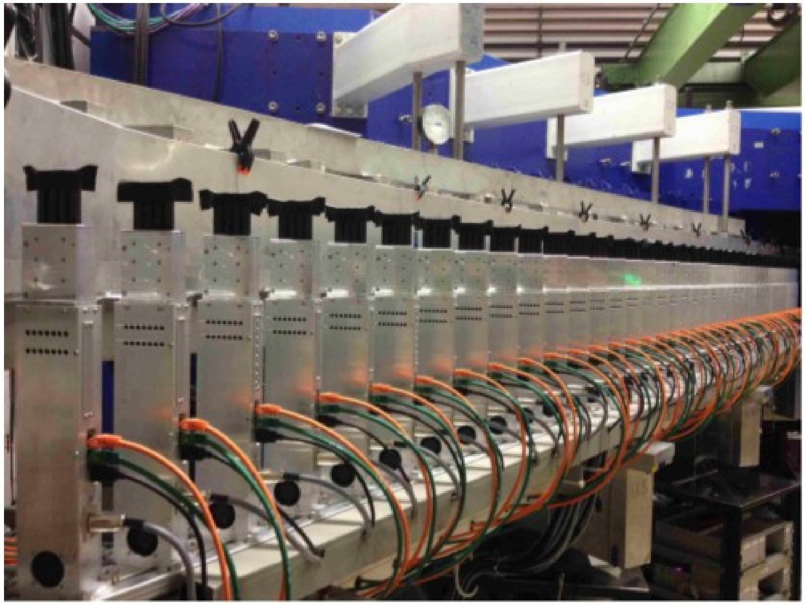
A high energy electron can produce Bremsstrahlung ('braking radiation') photons when slowed down by a material.

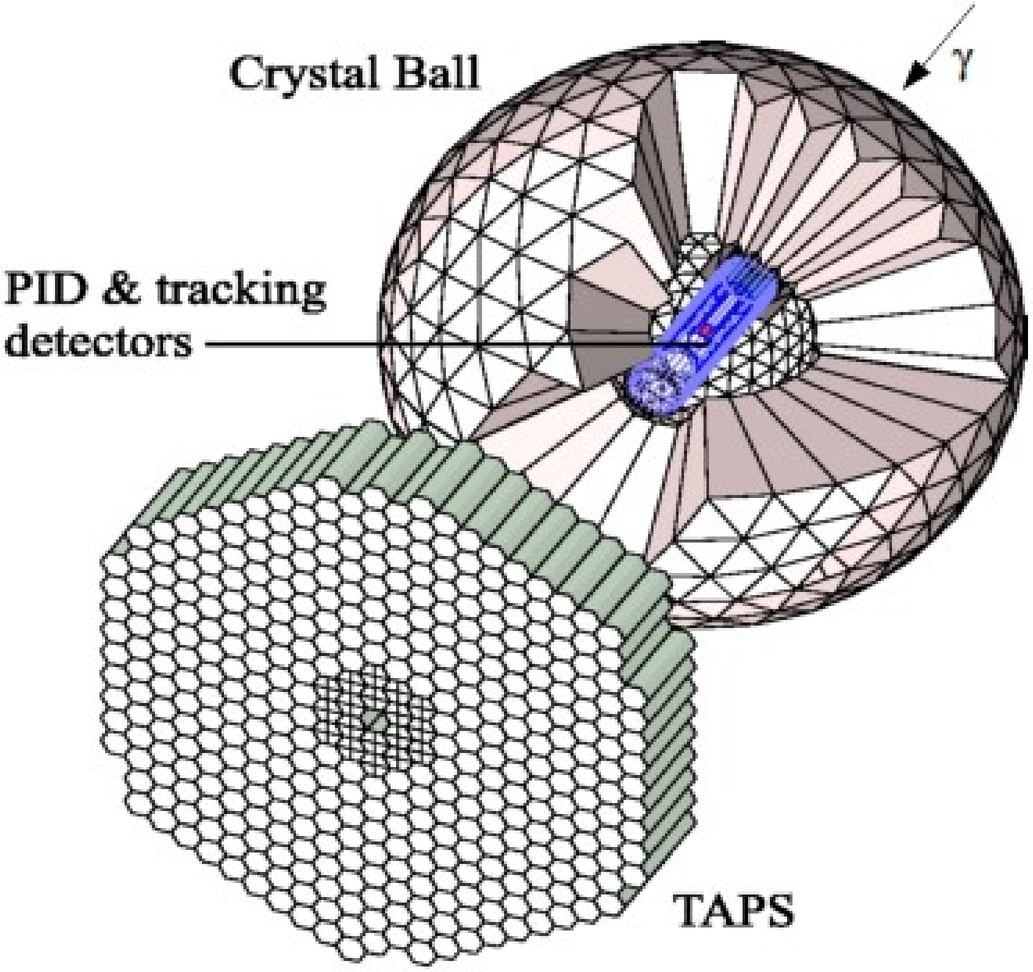
- Longitudinally polarized electrons produce circularly polarized photons (helicity transfer).
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).
- Residual electron paths bent in a spectrometer magnet.



A high energy electron can produce Bremsstrahlung (‘braking radiation’) photons when slowed down by a material.

- Longitudinally polarized electrons produce circularly polarized photons (helicity transfer).
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).
- Residual electron paths bent in a spectrometer magnet.
- Detector array determines the e^- energy, and ‘tags’ the photon energy by energy conservation.





Crystal Ball:

672 NaI(Tl) crystals
93,3% of total solid angle
Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma}=\frac{2\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta)=2^\circ\ldots3^\circ$$

Δt = 2.5 ns FWHM

$$\sigma(\phi)=\frac{2^\circ\ldots3^\circ}{\sin(\theta)}$$

TAPS:

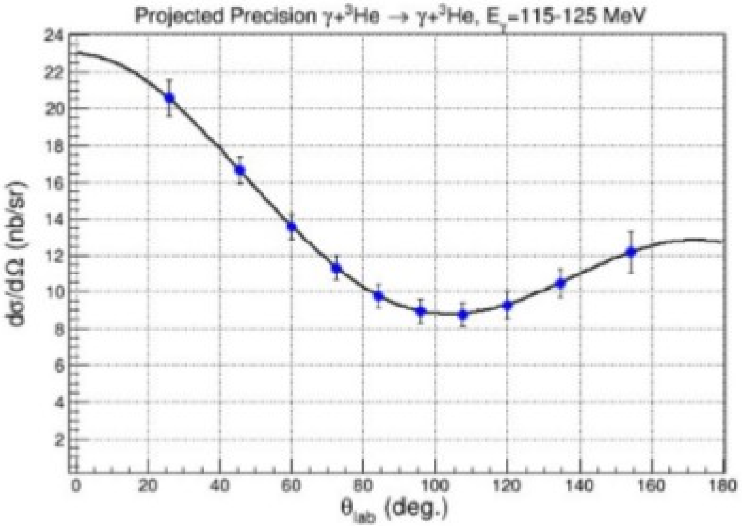
Up to 510 BaF_2 crystals
Polar acceptance: 4-20°

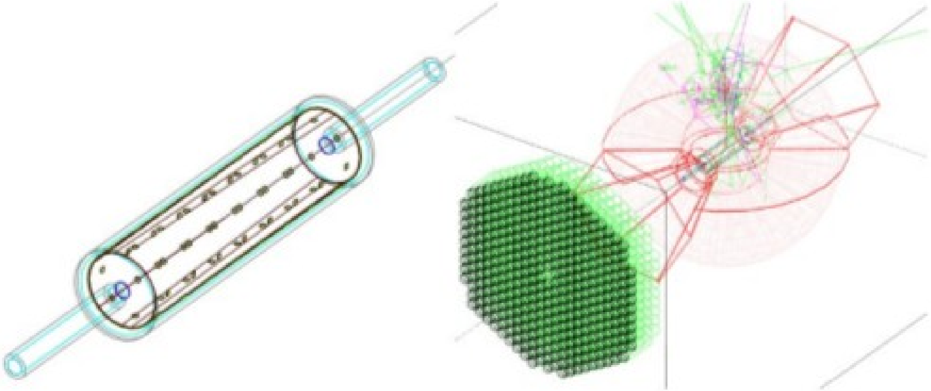
Δt = 0.5 ns FWHM

$$\frac{\sigma}{E_\gamma}=\frac{0{,}79\%}{\sqrt{E_\gamma/GeV}}+1{,}8\%$$

Neutron polarizabilities

- Neutron polarizabilities: deuteron or helium targets
- No data on ^{3}He available (recoil detection needed!) but theory exists
- Data on ^{4}He taken recently by the A2 Collaboration with detection of the photon in the final state aiming for improvement of the existing database
- Theory needed to extract polarizabilities is under development for ^{4}He





PAC proposal for ^{3}He/^{4}He: J. Annand et al.
(rating A from PAC – scintillation principle for the active target)
and PAC proposal (2020) : P. Martel et al. → improvement in PDG uncertainties for the neutron polarizabilities by factor of 2!)

Background Reactions

$\gamma + d \rightarrow \gamma + d$

- $\gamma + p + n$ (quasi-free)
- $p + n$ (breakup)

Min $\Delta E_B = 2.2$ MeV

- Unresolvable
- Need theory help
  - Provide Elastic plus Quasi-free
  - Already in progress for HIγS data

$\gamma + {}^3\mathrm{He} \rightarrow \gamma + {}^3\mathrm{He}$

- $\gamma + p + d$ (quasi-free)
- $p + d$ (breakup)
- $p + p + n$ (breakup)

Min $\Delta E_B = 4.5$ MeV

- Unresolvable
- Need active He target
  - Recoiling energy
  - Event vertex?
  - Track with TPC?

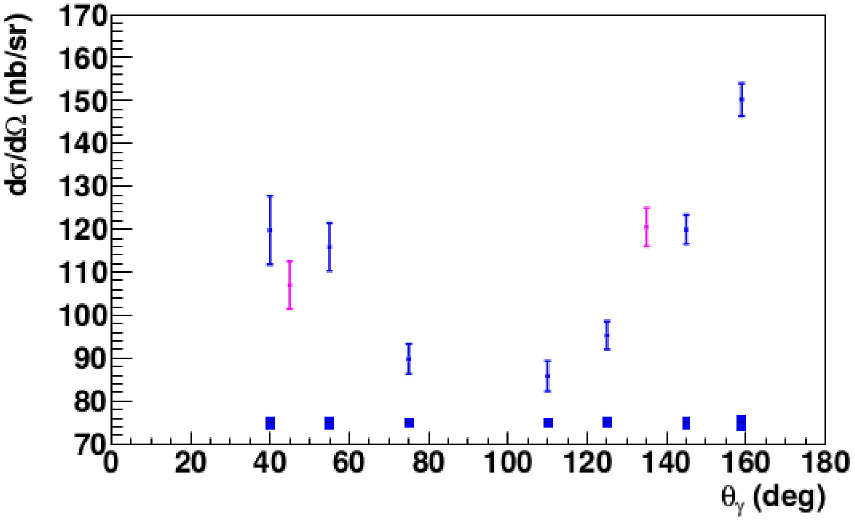
$\gamma + {}^4\mathrm{He} \rightarrow \gamma + {}^4\mathrm{He}$

- $\gamma + n + {}^3\mathrm{He}$ (quasi-free)
- $\gamma + p + t$ (quasi-free)
- $n + {}^3\mathrm{He}$ (breakup)
- $p + t$ (breakup)
- $p + n + d$ (breakup)
- $p + p + n + n$ (breakup)
- $d + d$ (breakup)

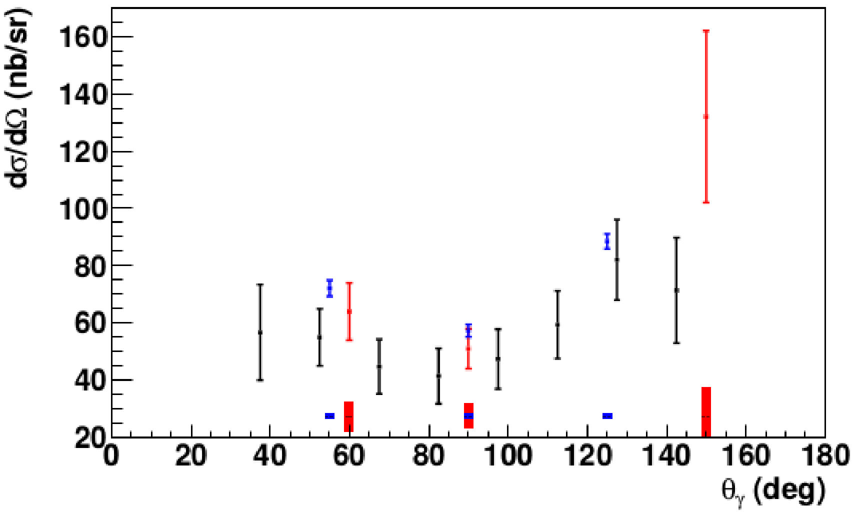
Min $\Delta E_B = 20$ MeV

- Resolvable!

Previous ^{4}He Data



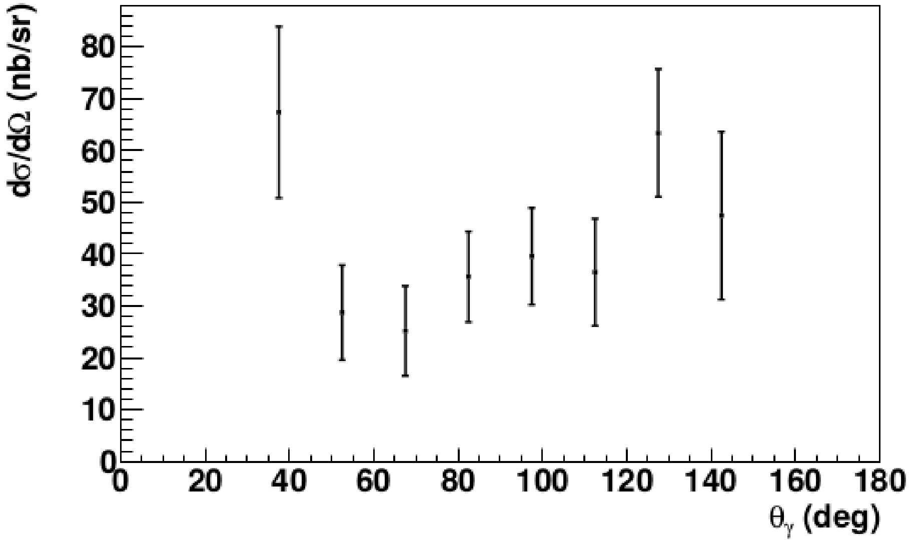
60 MeV



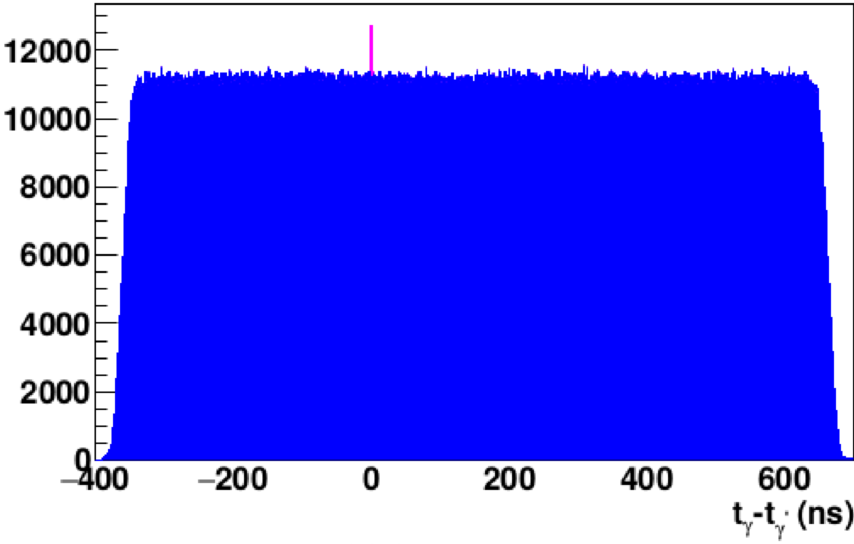
80 MeV

- Magenta points from Illinois [Wells Ph.D. Thesis (1990) unpublished]
- Red points from Lund [Fuhrberg NuclPhysA.591.1 (1995)]
- Blue points from HIγS [Sikora PhysRevC.96.055209 (2017), Li arXiv.1912.06915 (2019)]
- Black points are preliminary data (statistical) from MAMI (100 hours)

Newer ^{4}He Data



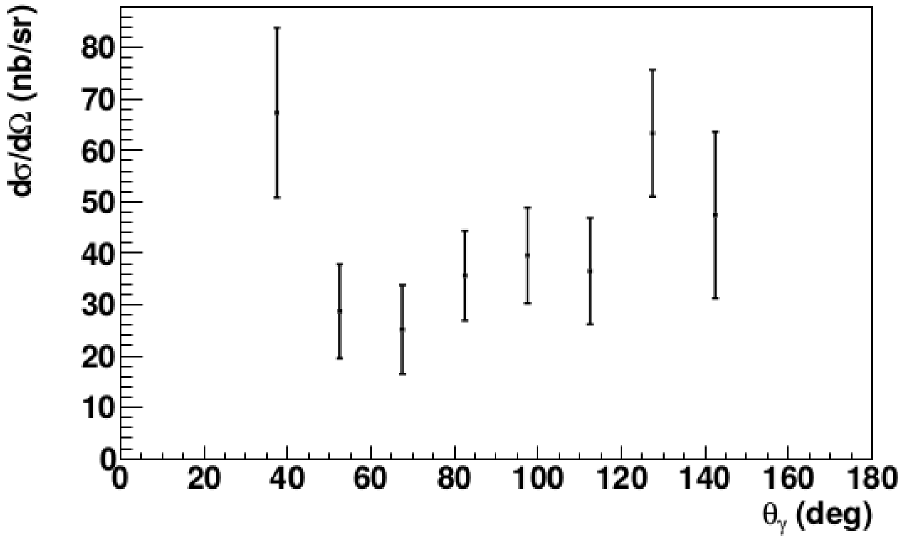
100 MeV



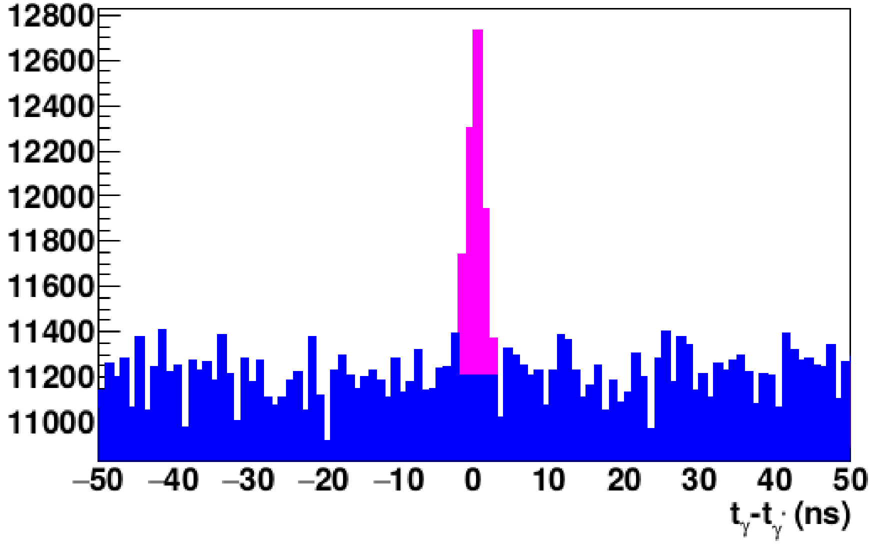
120 MeV

- Black points are preliminary data (statistical) from MAMI (100 hours)
- Still clear room for improvement (higher ϵ_{tagg}, longer run)
- Errors are larger than $\sqrt{N}$ ... Prompt correlations (P) to random coincidences (R)

Newer ^{4}He Data



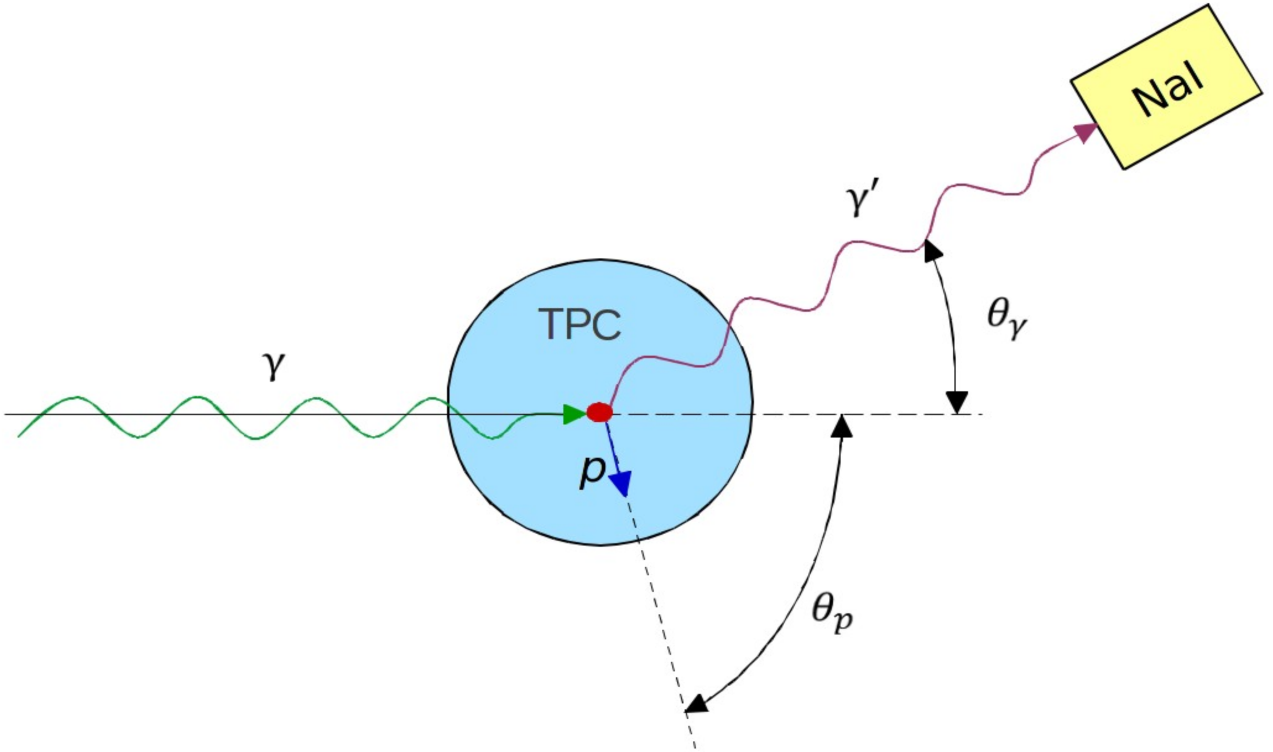
100 MeV



120 MeV

- Black points are preliminary data (statistical) from MAMI (100 hours)
- Still clear room for improvement (higher ϵ_{tagg}, longer run)
- Errors are larger than $\sqrt{N}$ . . . Prompt correlations (P) to random coincidences (R)
- $\sigma/\sigma_P = \sqrt{1 + R/P}$

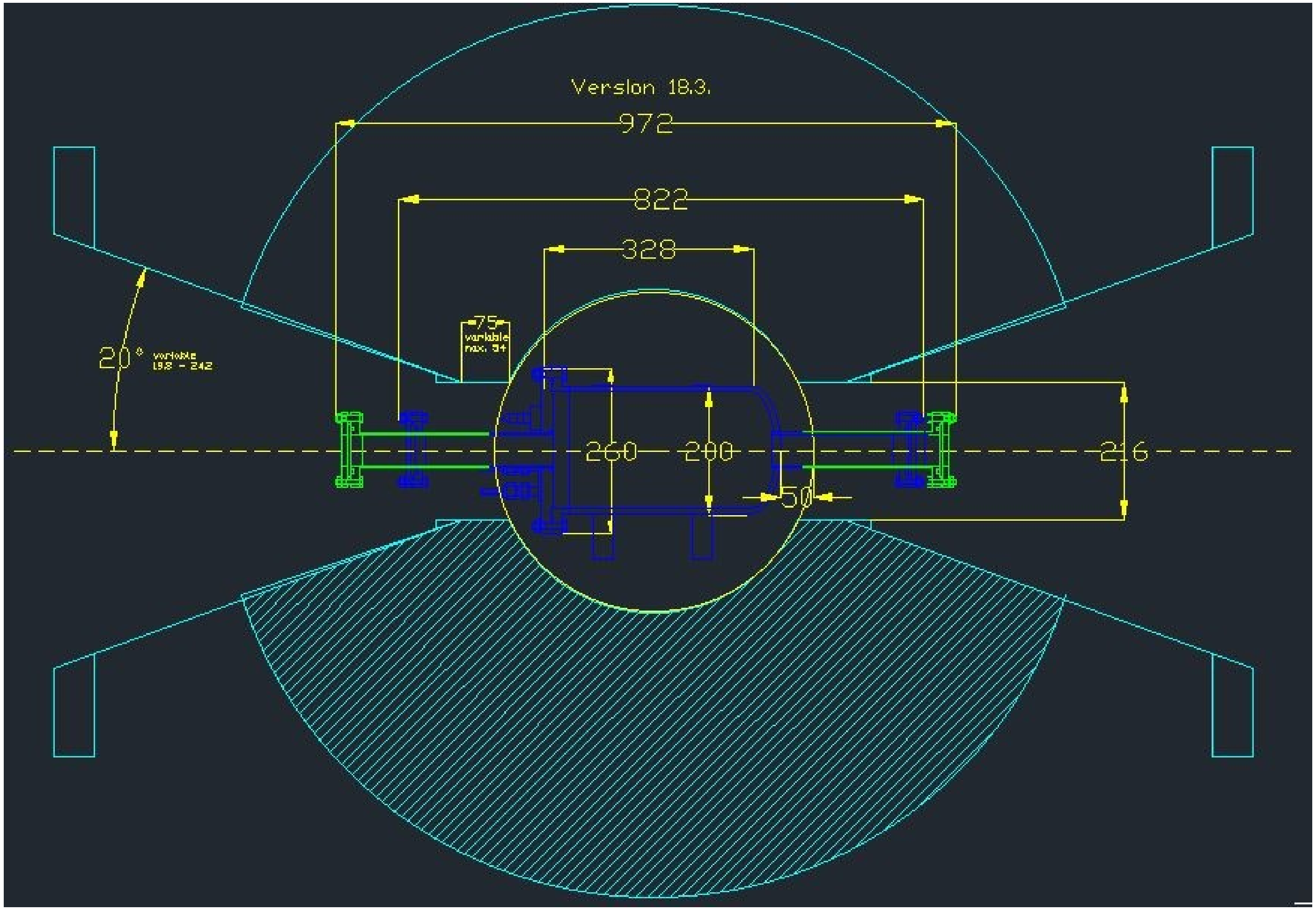
Compton scattering using γ-p coincidence technique



TPC
active target

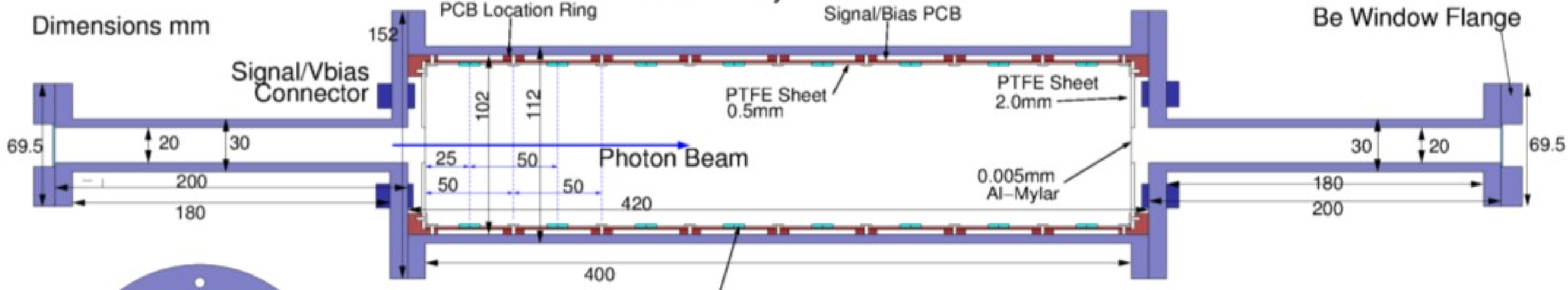
Measured are **Eγ' θγ', Ep , θp - kinematics reconstruction redundant**.

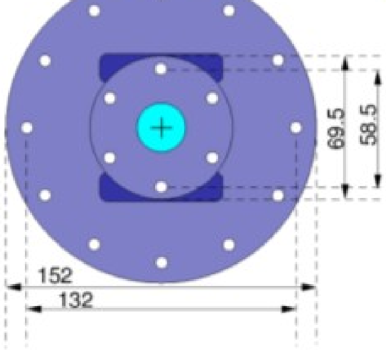
We sacrifice Eγ measurement (no tagging) thus gain essentially in counting rate. Very good background suppression due to strong γ'p kinematic correlation

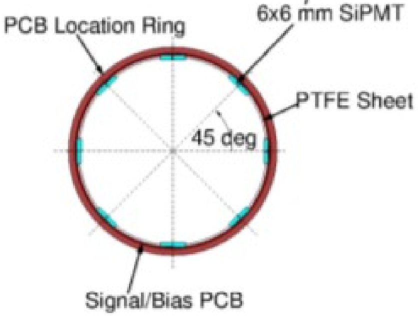

Version 18.3.
972
822
328
75
variable
max. 54
20°
variable
19.8 - 24.2
260
200
216
50

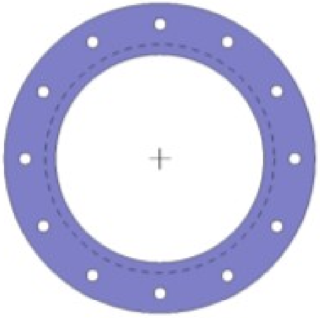
J.R.M. Annand
11th Feb. 2016
Dimensions mm

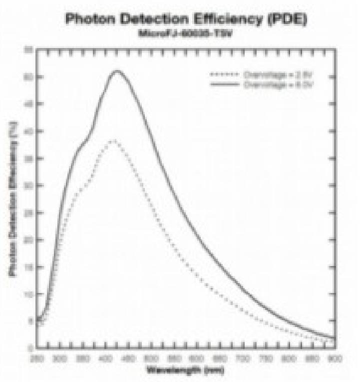
Pressure Vessel
Material Al Alloy





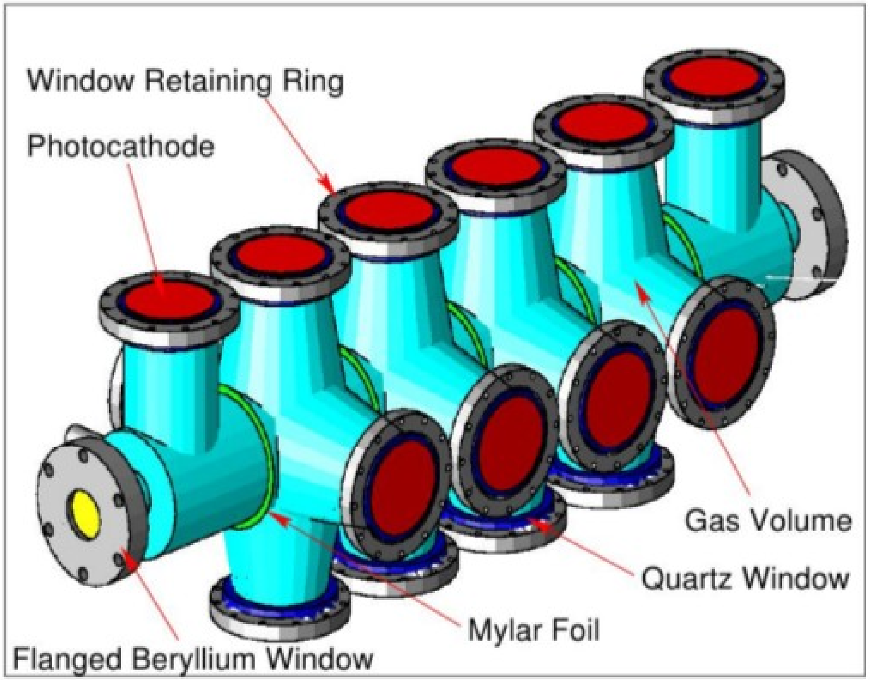


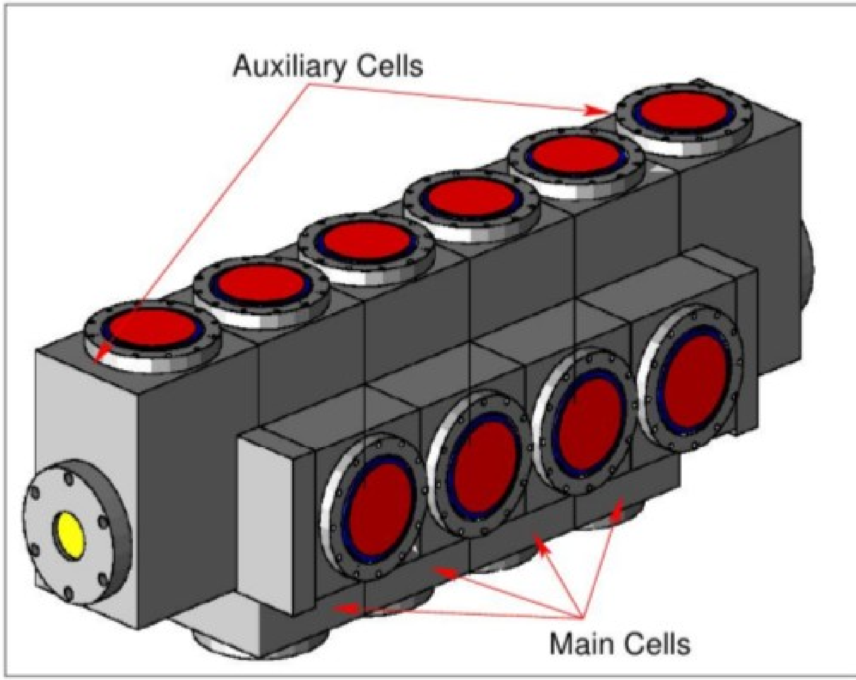




8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs

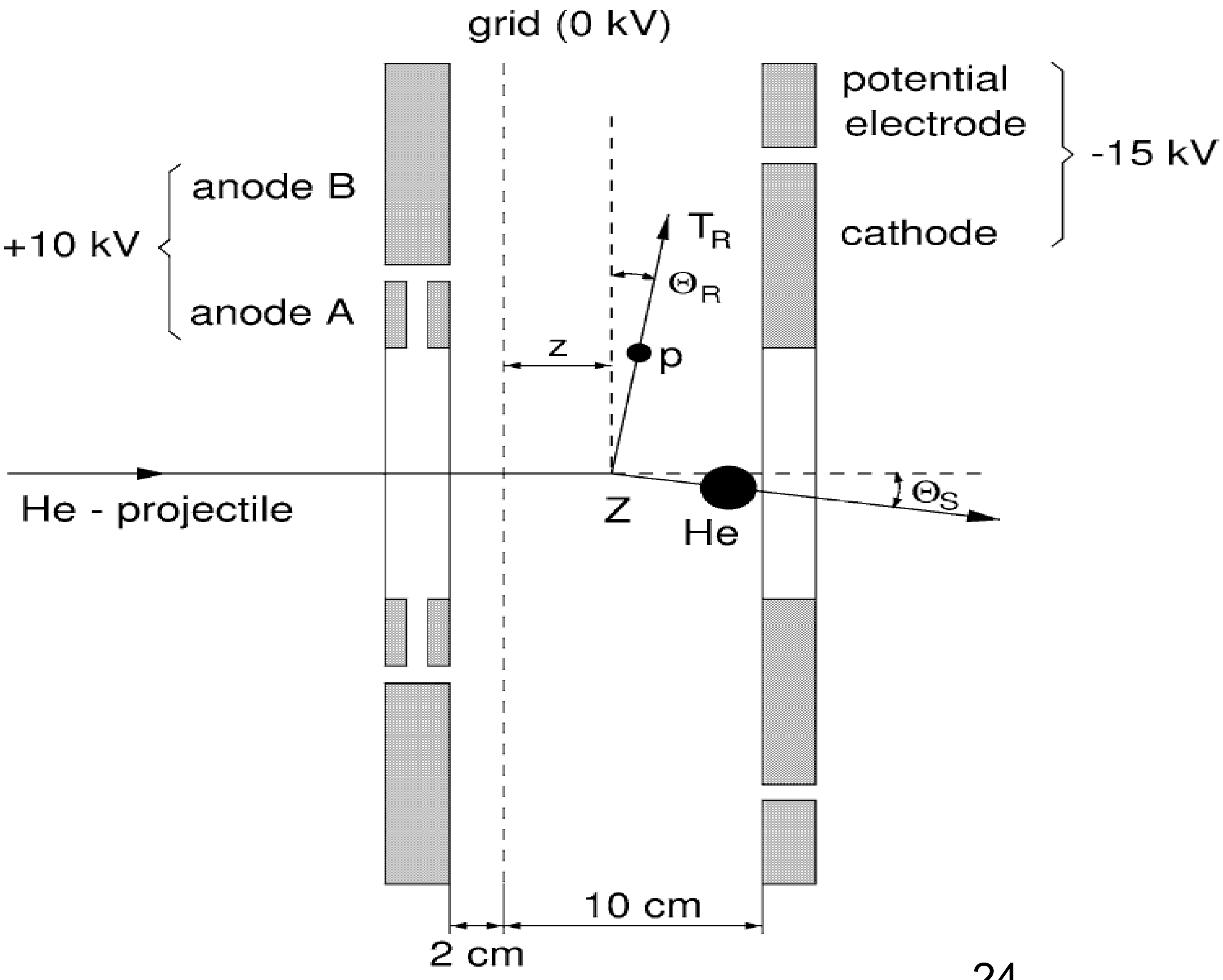
Original Active Target

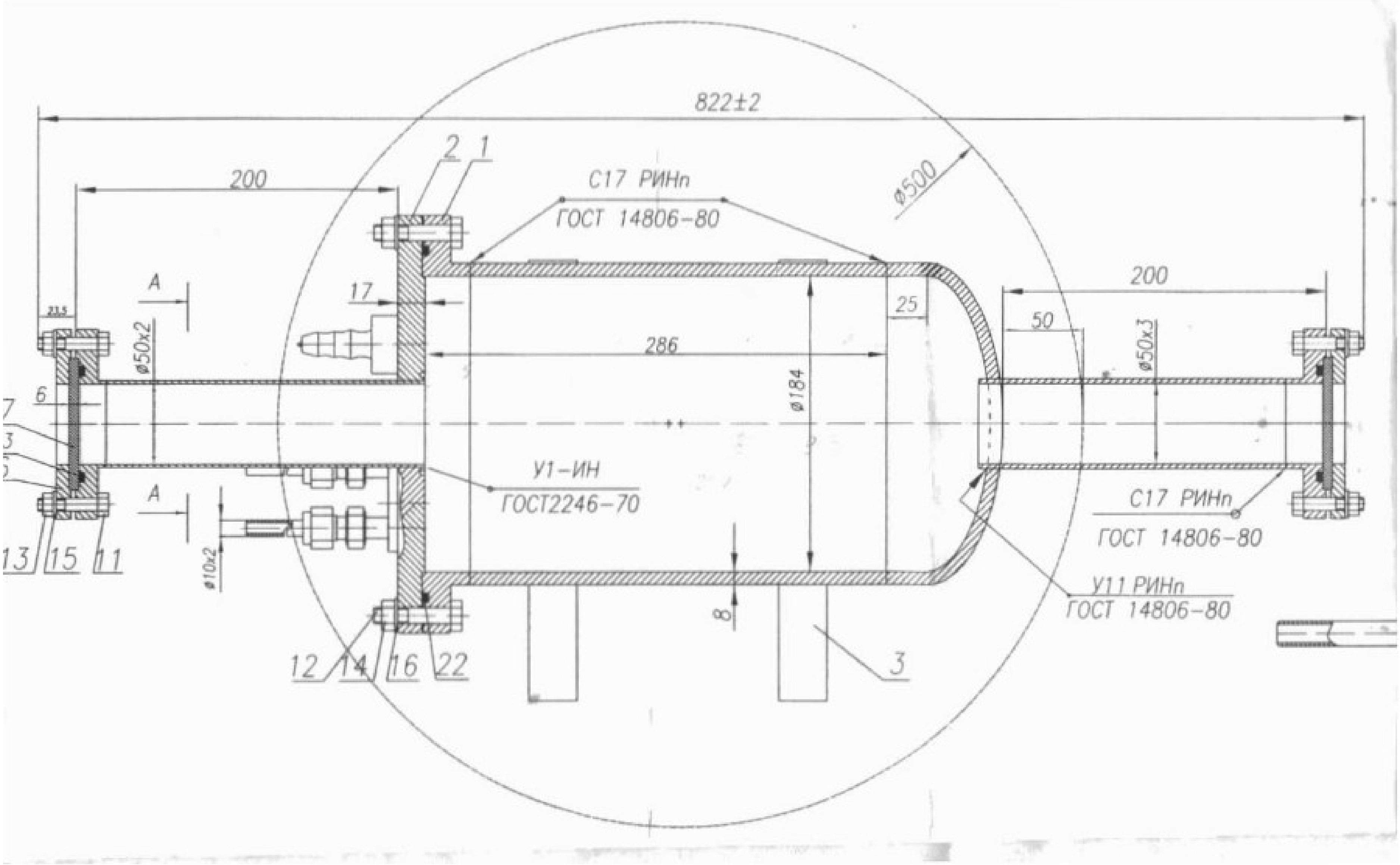




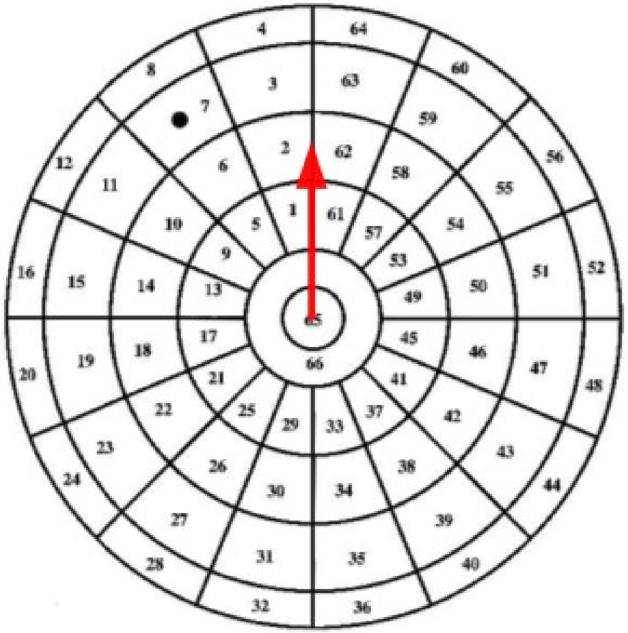
- Concerns over safety for the pressures planned
- Difficult to fit into the Crystal Ball

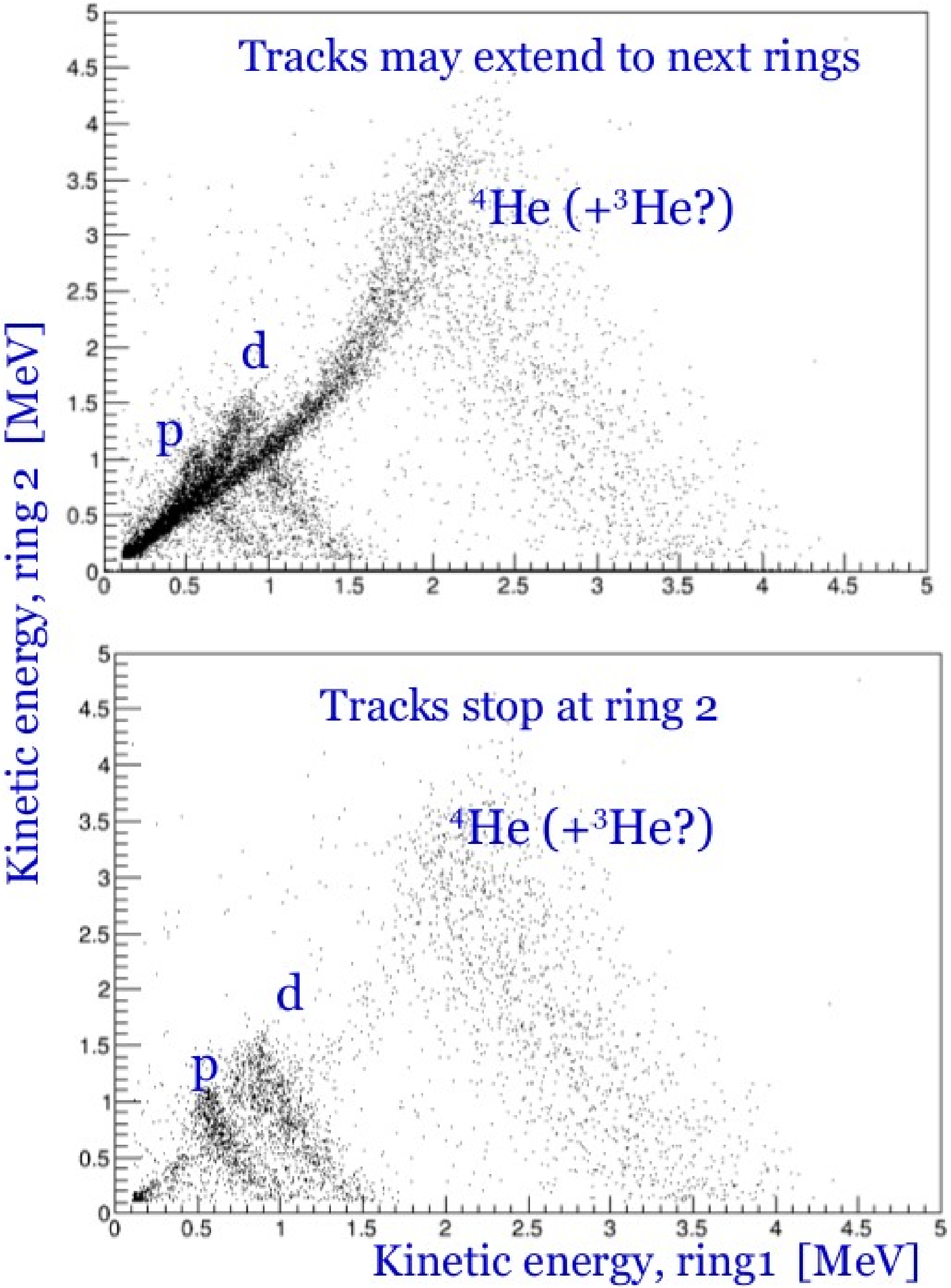
Side view of TPC IKAR for small angle elastic scattering experiment S105 at GSI

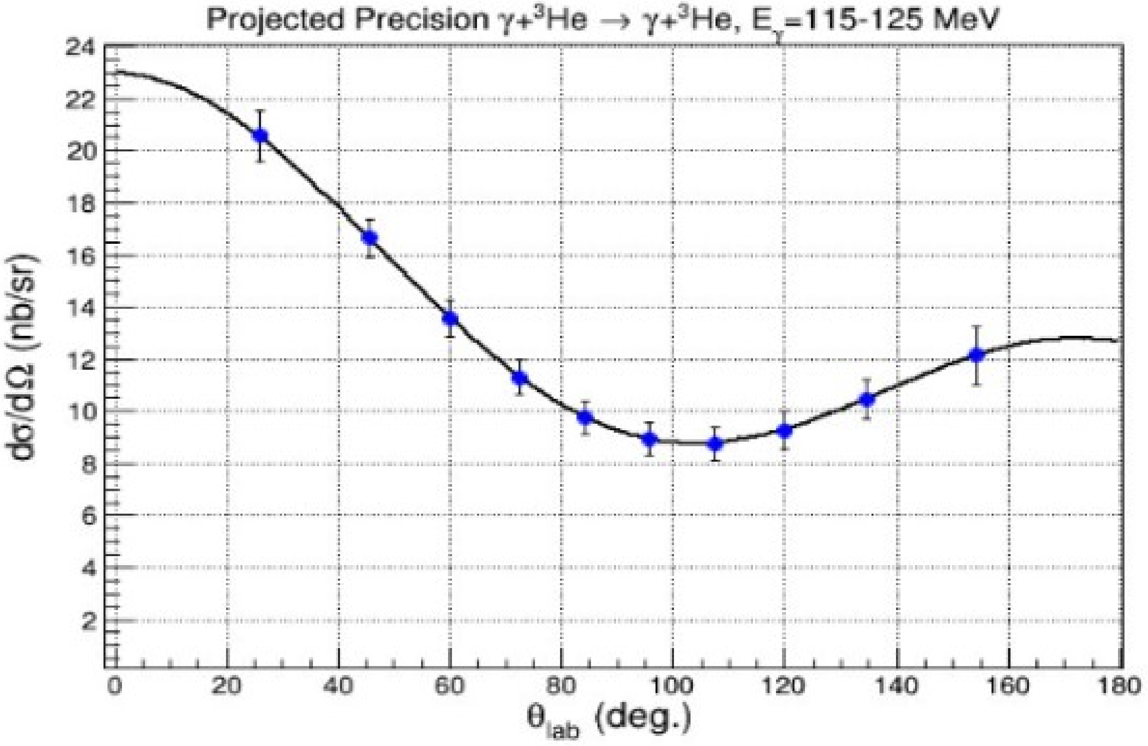



822±2
200
2
1
C17 РИНп
ГОСТ 14806-80
ø500
A
17
23,5
ø50x2
286
25
200
50
ø50x3
ø184
6
7
3
У1-ИН
ГОСТ2246-70
A
C17 РИНп
ГОСТ 14806-80
13
15
11
ø10x2
8
У11 РИНп
ГОСТ 14806-80
12
14
16
22
3

Example: Identification of recoil fragments






Projected Precision $\gamma+{}^3He \rightarrow \gamma+{}^3He$, E_γ=115-125 MeV
$d\sigma/d\Omega$ (nb/sr)
24
22
20
18
16
14
12
10
8
6
4
2
0
20
40
60
80
100
120
140
160
180
θ_{lab} (deg.)

Ionization chamber (TPC) as active target

The problem of low energy recoil detection can be solved with the help of a ionization chamber used as active target.

active target properties:

- Working gas - H2, D2, He3, He4 under pressure up to 25 bar;
- Registration of recoil particles in the range of 0.5 -20 MeV;
- Possibility to detect other recoils (p,d, H3, He3,..) ;
- Recoil particle energy resolution σ ≈ 20-30 keV;
- High (~100%) recoil detection efficiency;
- Reconstruction of interaction point coordinate in direction of electrical field with resolution of σ ≈ 0.5 mm ;
- Possibility to apply effective fiducial volume cut. (no wall related background)

Спасибо за внимание !