Future experimental prospects for polarizability measurements

Measurement of Nucleon Polarizabilities with an Active Time Projection Chamber at MESA

E. Maev

on behalf of

PNPI *St. Petersburg* , IKP JGU Mainz and IKP *Darmstadt*

Cross section for Compton scattering at low energy

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

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

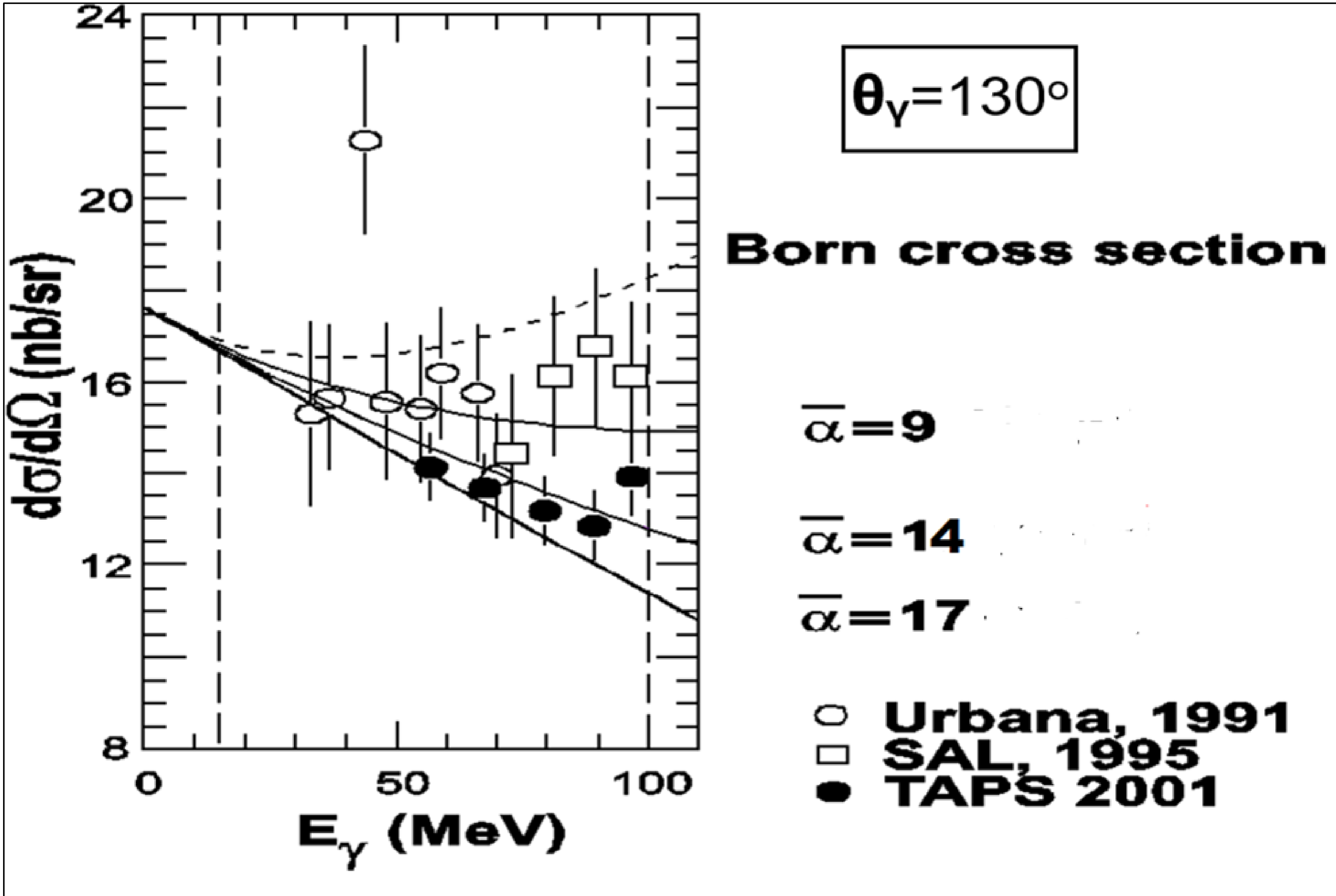
$$\times \left[\frac{\overline{\alpha}+\overline{\beta}}{2}(1+\cos\theta)^2 + \frac{\overline{\alpha}-\overline{\beta}}{2}(1-\cos\theta)^2\right]$$

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

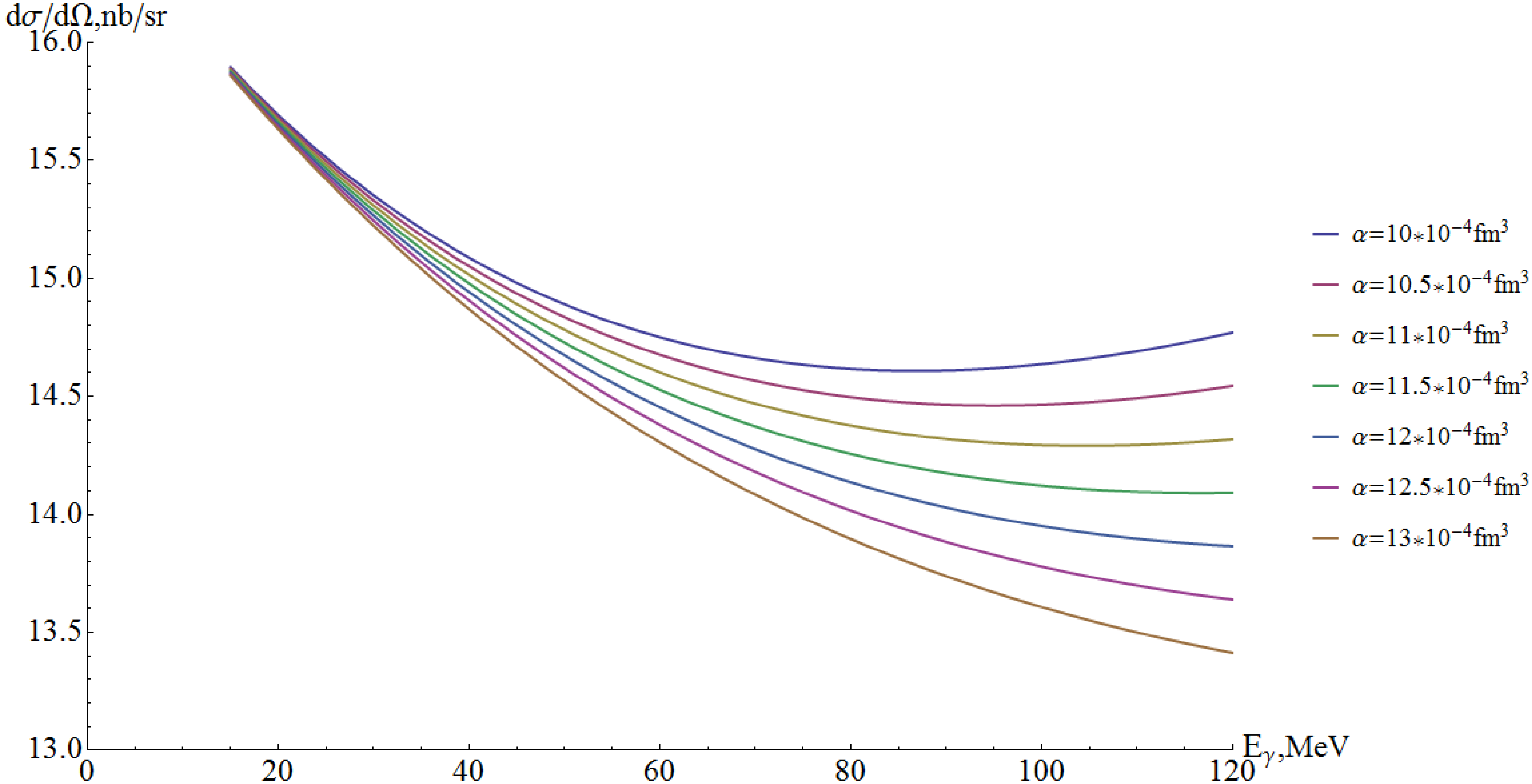
LET-formula describes the γ-p scattering with high precision at Eγ <80 MeV.

- 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.

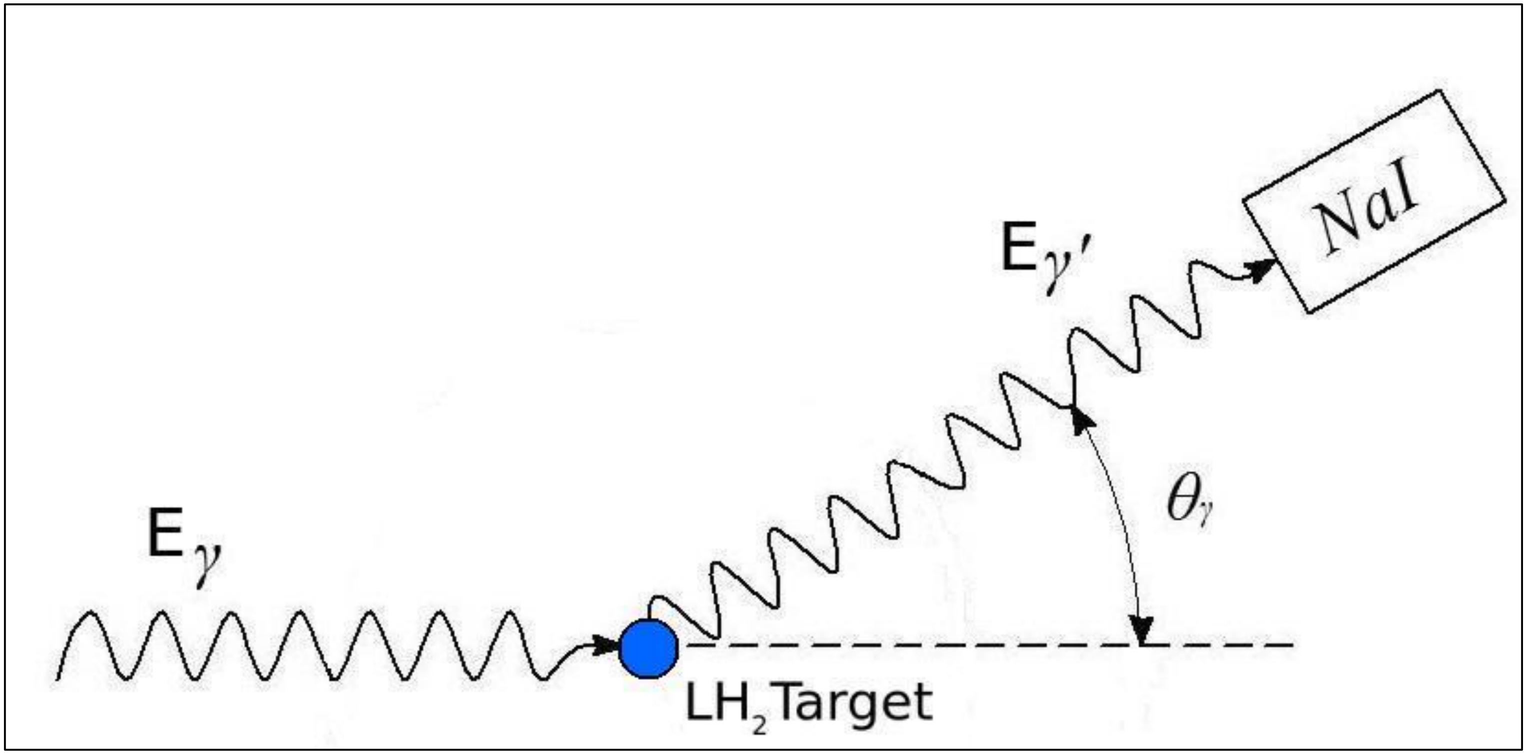
Low energy (Eγ <100 MeV) Compton scattering data



Cross section for Compton scattering ($\theta\gamma = 130°$)

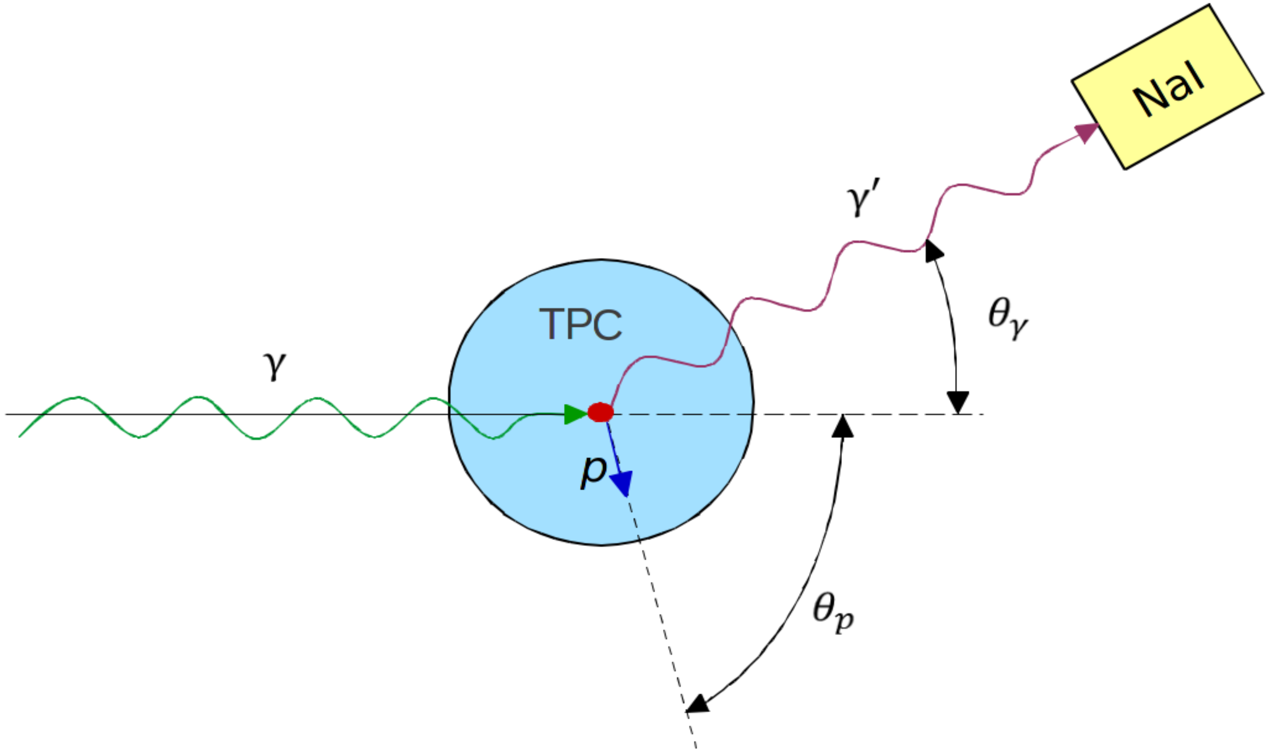


Typical tagged photon beam Copmton scattering experiment



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

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

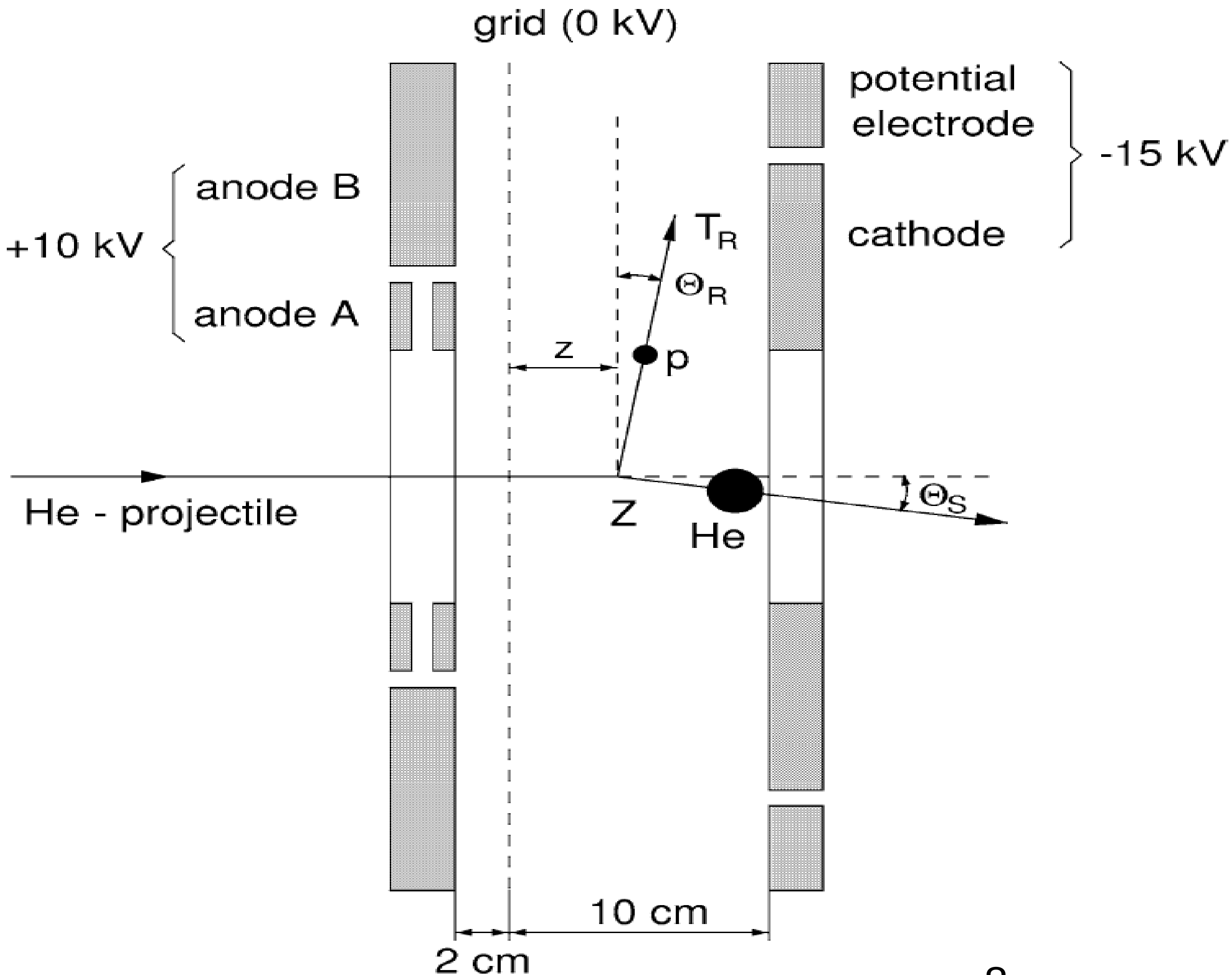
Ionization chamber (TPC) as active target

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

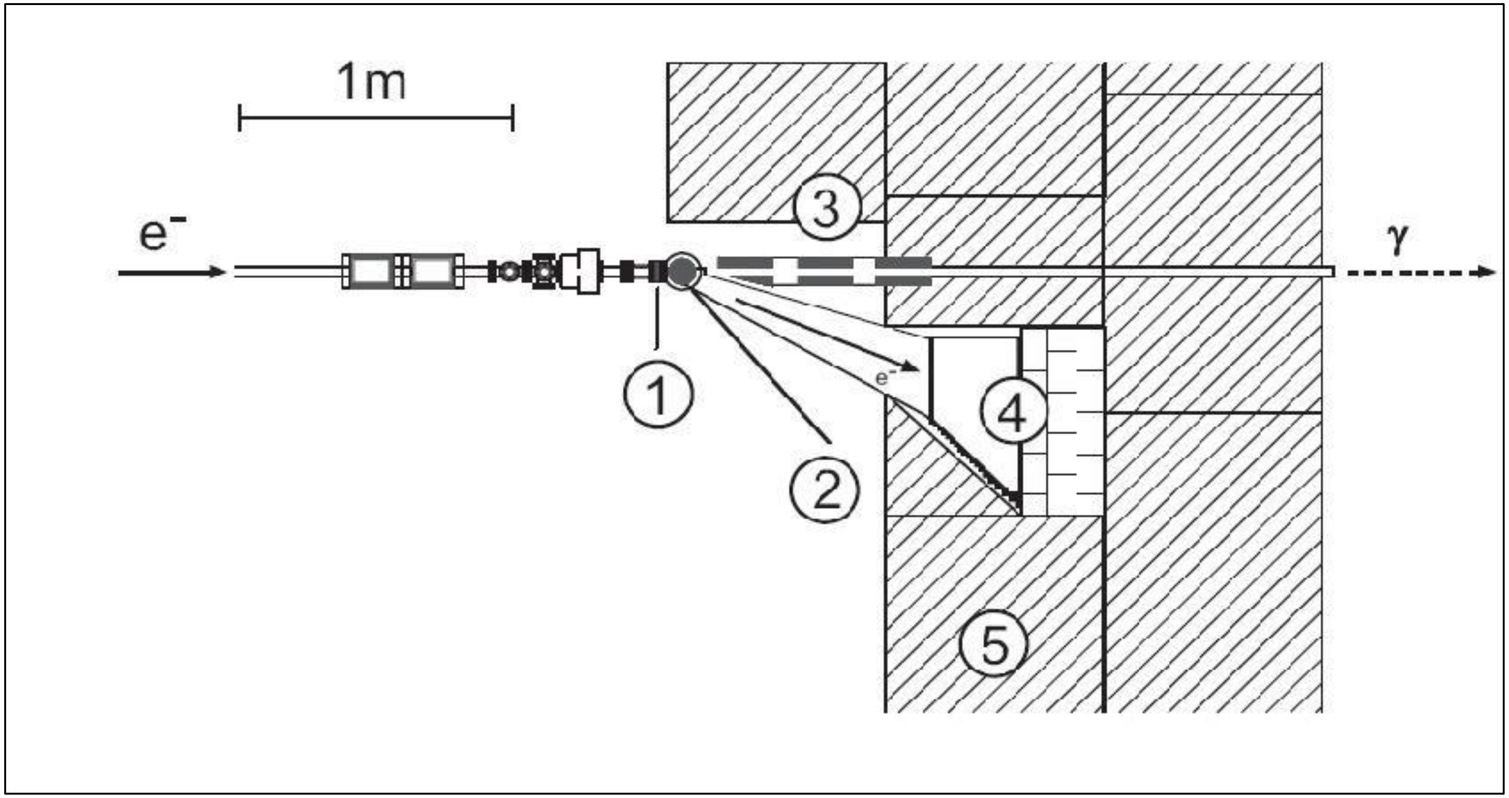
active target properties:

- Working gas - H2, D2, He3, He4 under pressure up to 200 bar;
- Registration of recoil protons in the range of 0.5 -20 MeV;
- Possibility to detect other recoils (D, H3, He3,..) ;
- Recoil proton energy resolution $\sigma \approx$ 20-30 keV;
- High (~100%) proton detection efficiency;
- Reconstruction of interaction point coordinate in direction of electrical field with resolution of $\sigma \approx$ 0.5 mm ;
- Possibility to apply effective fiducial volume cut. (no wall related background)

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

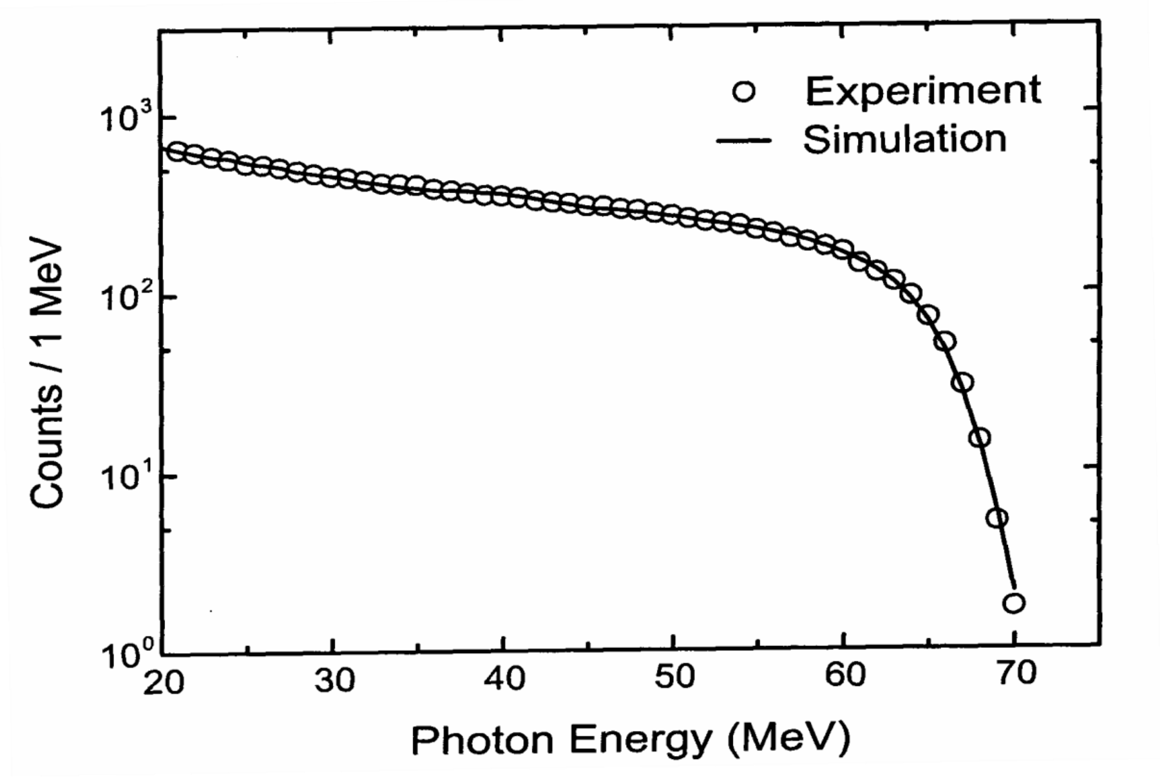


Test experiment at IKP Darmstadt. Setup of bremsstrahlung facility



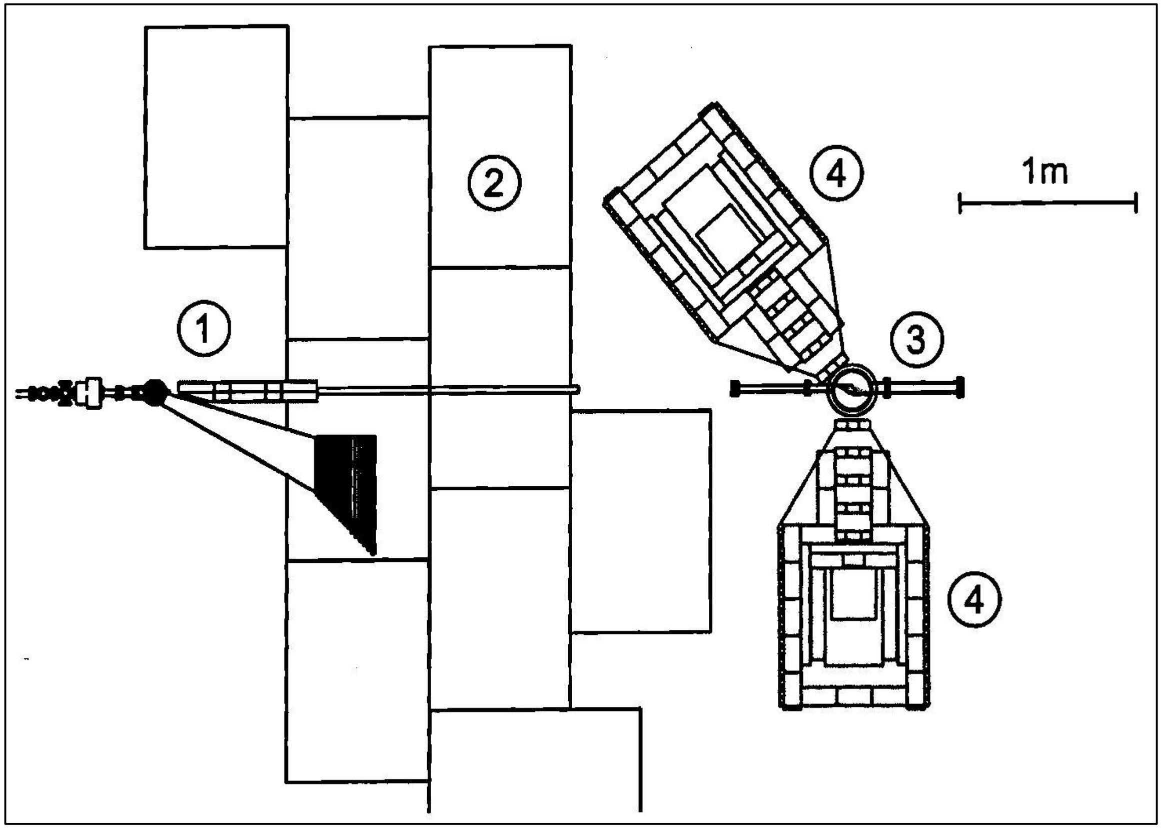
1 – bremsstrahlung converter target (0.3mm gold), **2** – cleaning magnet,
3 – **γ-** beam collimator, **4** – electron beam dump (Faraday cup), **5** – concrete shielding

Bremsstrahlung spectrum at 70MeV electron beam in IKP Darmstadt



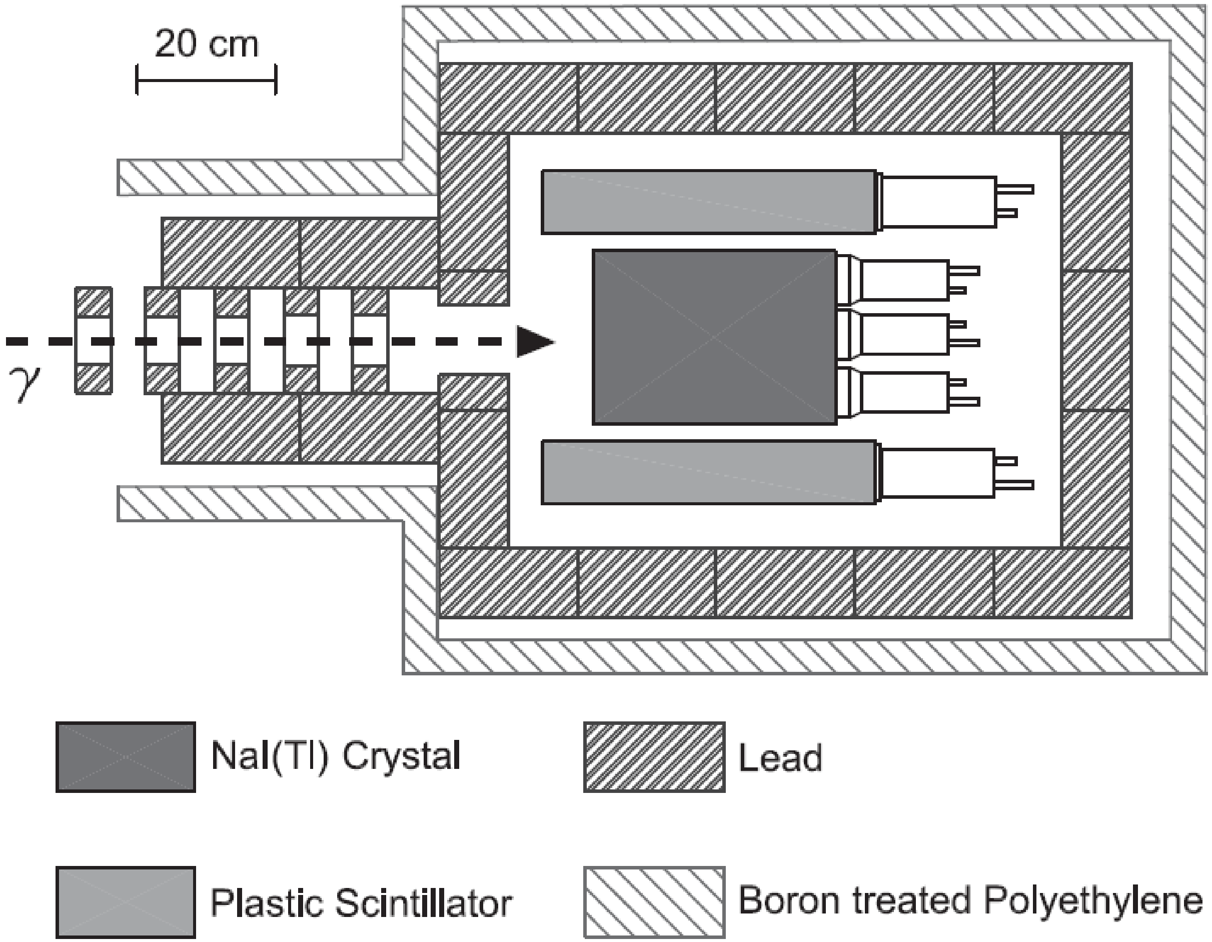
Untagged bremsstrahlung photon spectrum measured in the test experiment at S-Dalinac (IKP Darmstadt). The electron beam energy is 70 MeV. The Geant 4 routine was used for simulation of the bremsstrahlung photon spectrum.

Test experiment setup at IKP Darmstadt

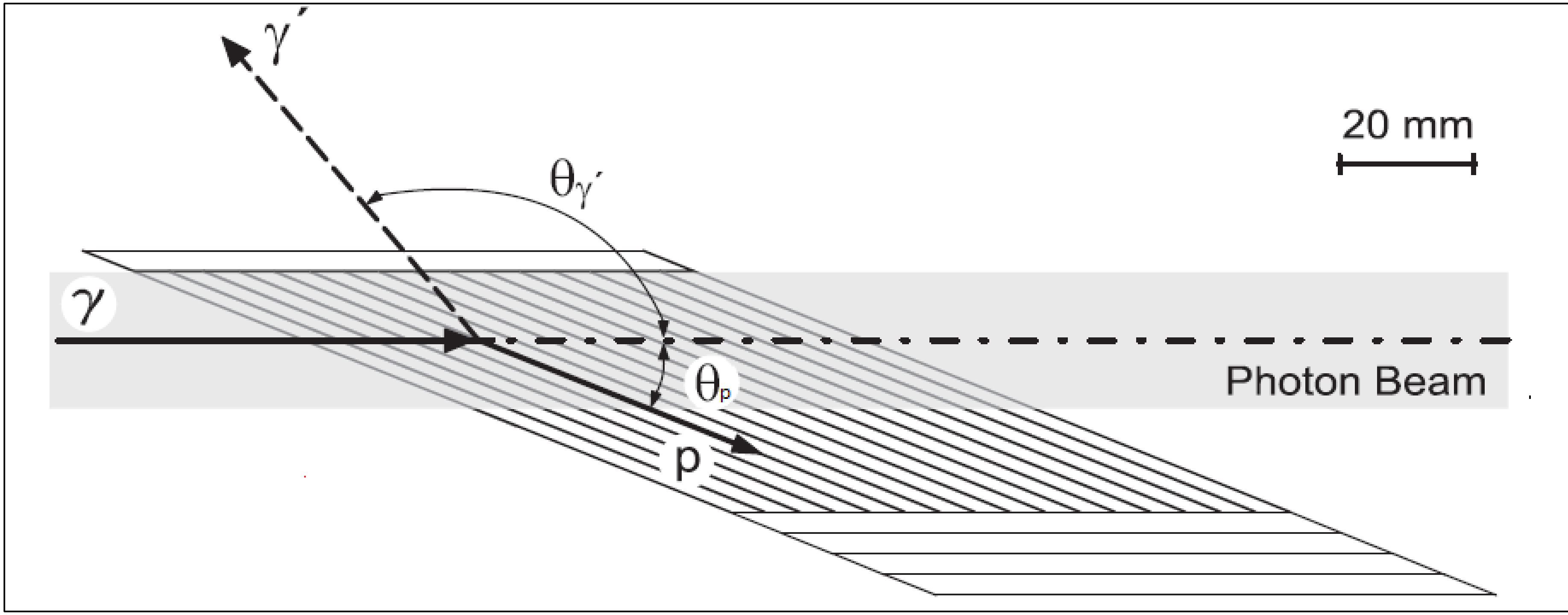


1 – bremsstrahlung facility, 2 – concrete shielding, 3 – high pressure ionization chamber (active target), 4 – γ-detectors (NaI) at θγ=130 and θγ =90 deg.

Schematic view of a 10 in x 14 in NaI(Tl) detector

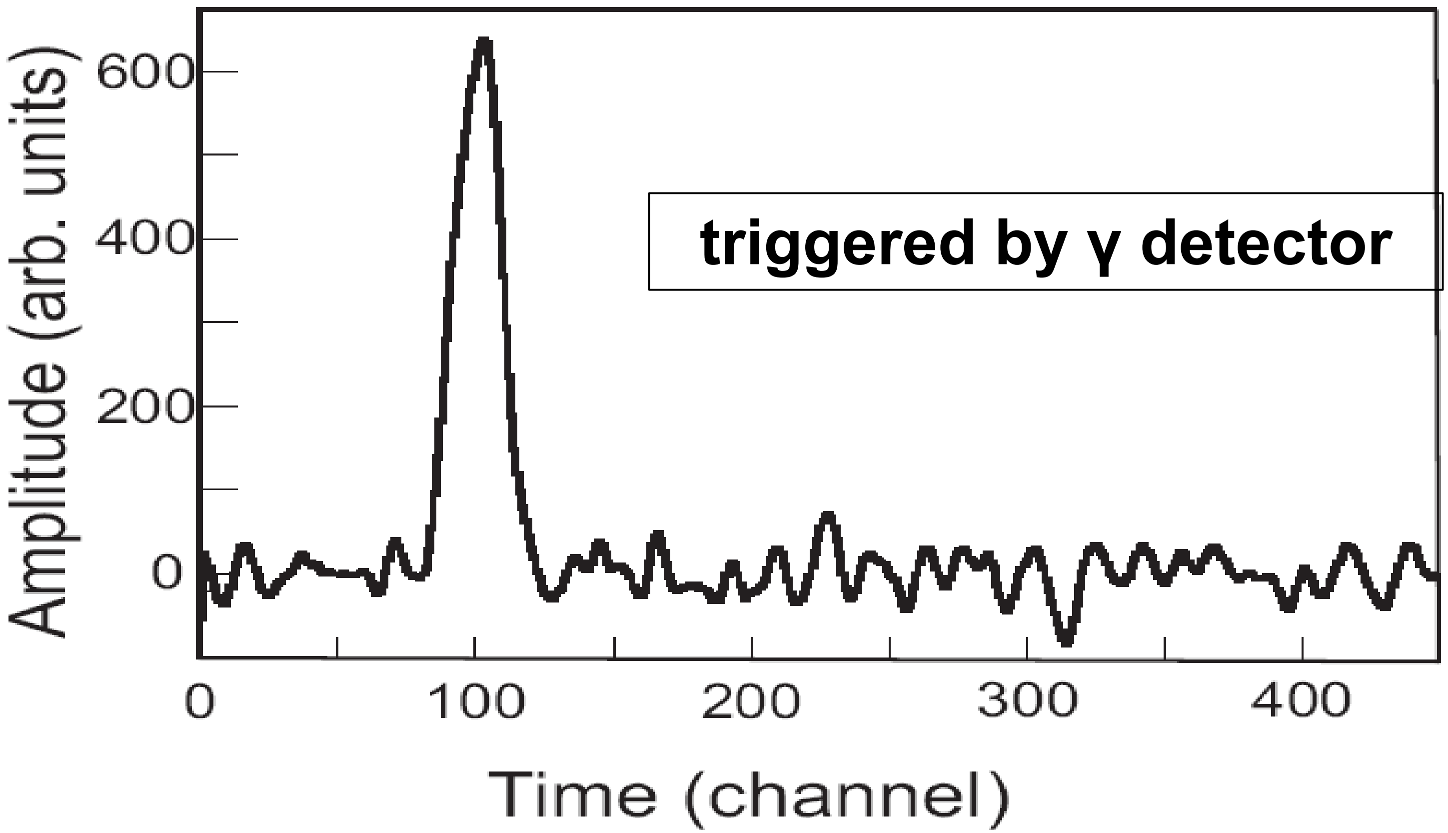


Top view on a multy-strip anode plane at θγ=130°



Multy-strip TPC anode plane for the scattering photon angle θγ=130deg. The angle of recoil proton θp =22deg, detected recoil proton energies Ep =0.5-10MeV, the ranges of protons Rp =0.2-90mm (at hydrogen pressure 75 bar, length of anodes strip is 90mm.

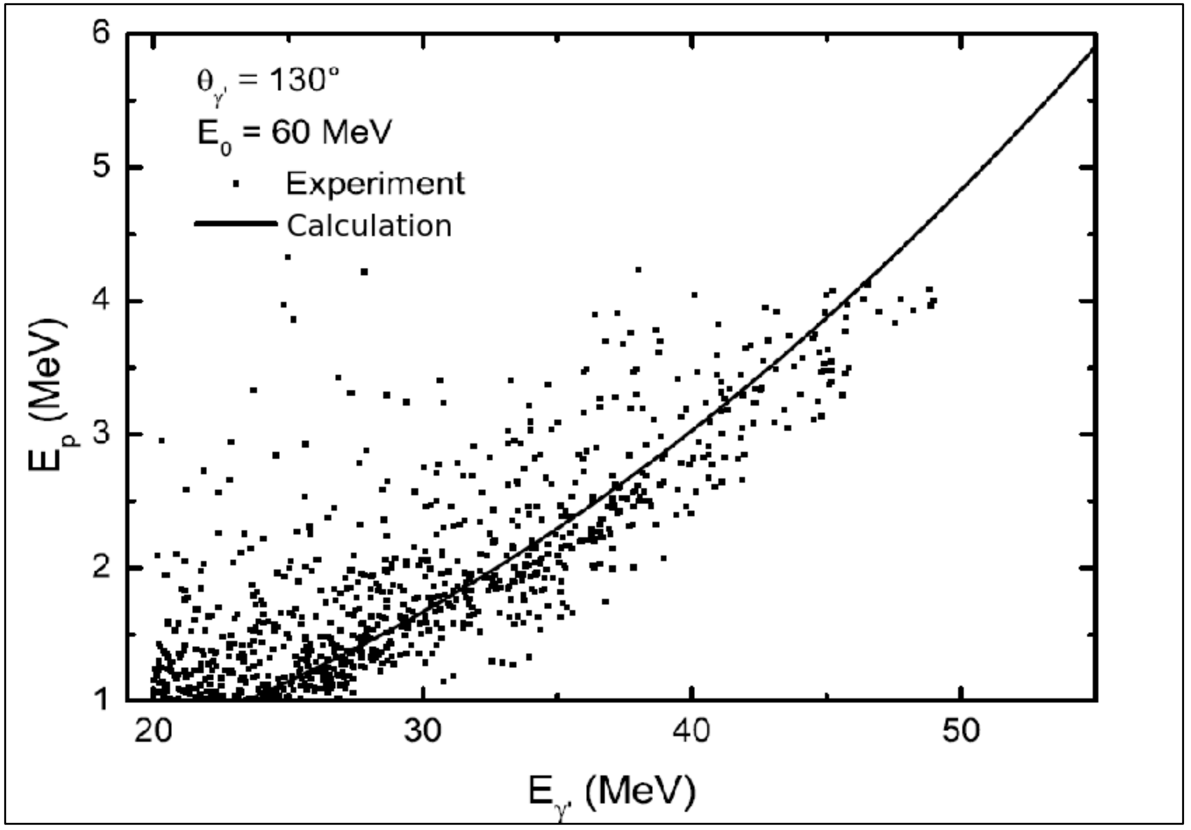
Example of a signal in TPC from 2 MeV recoil proton, registed by FADC



Signal from recoil proton on anode of TPC in **γ-p** scattering experiment at IKP

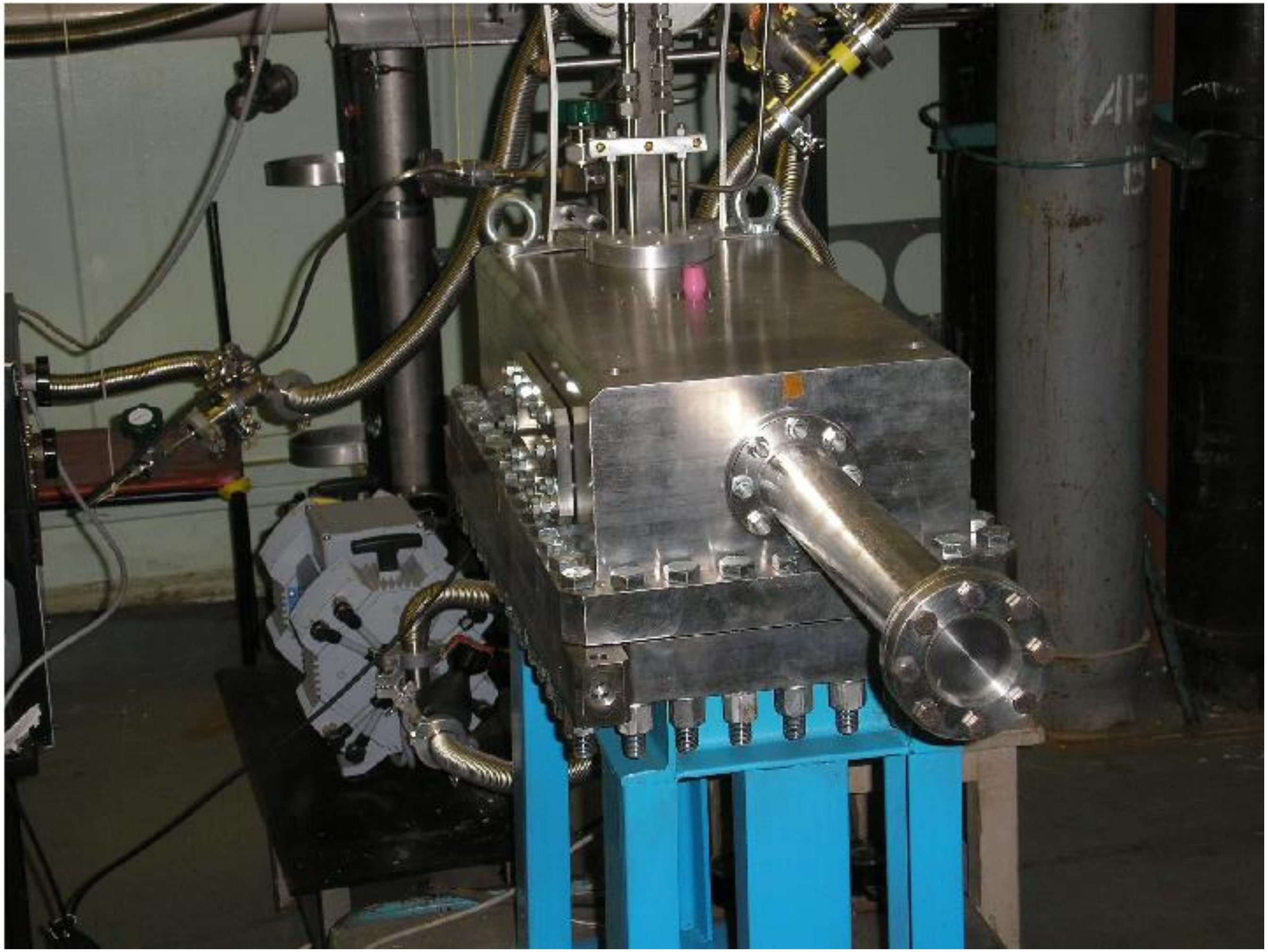
Ep- Eγ correlations.

Not enough statistics !!

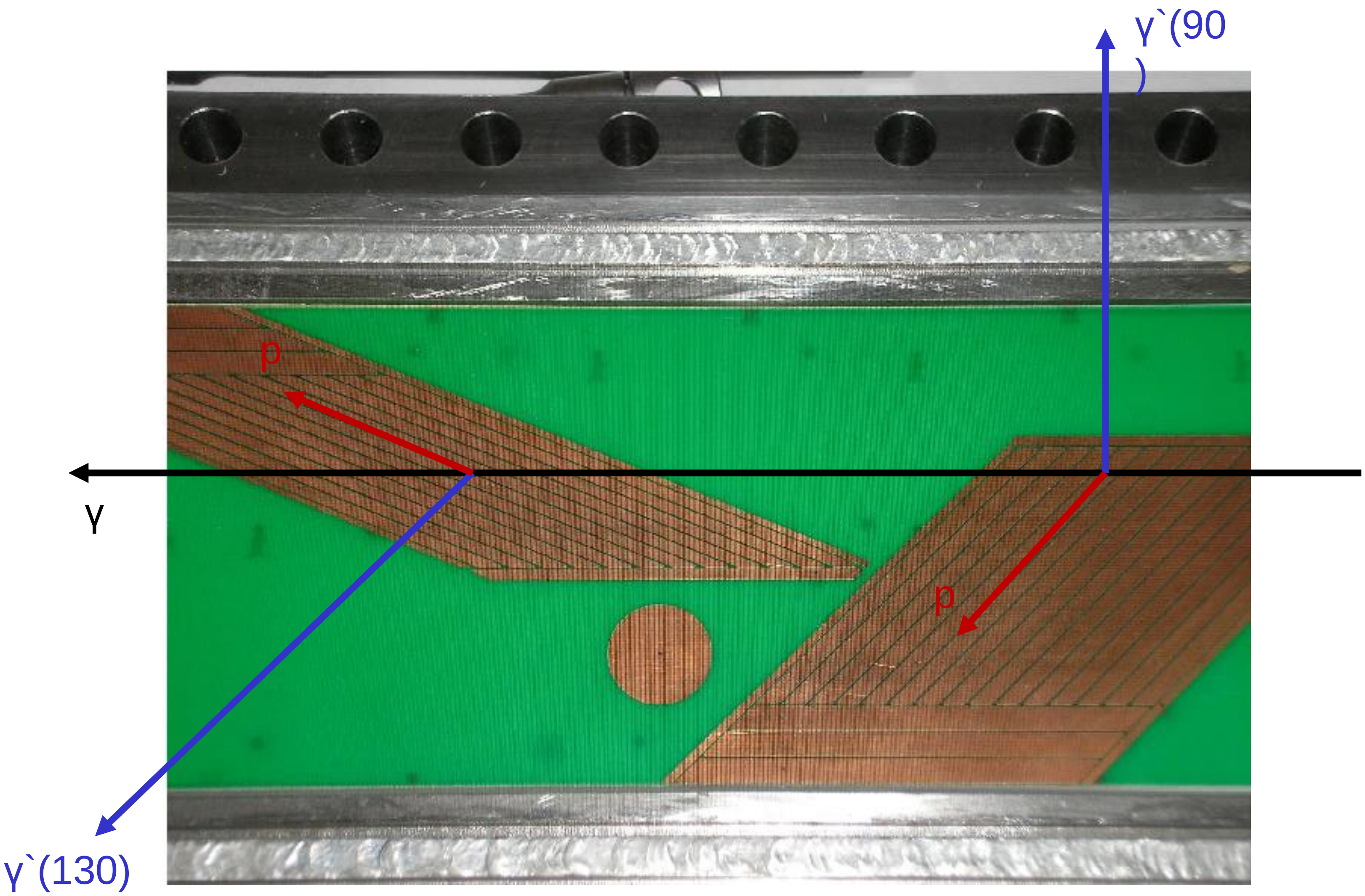


Ep- Eγ correlations in γ-p scattering experiment at IKP at electron beam energy 60MeV and θγ=130deg. The calculation is pure kinematic correlation.

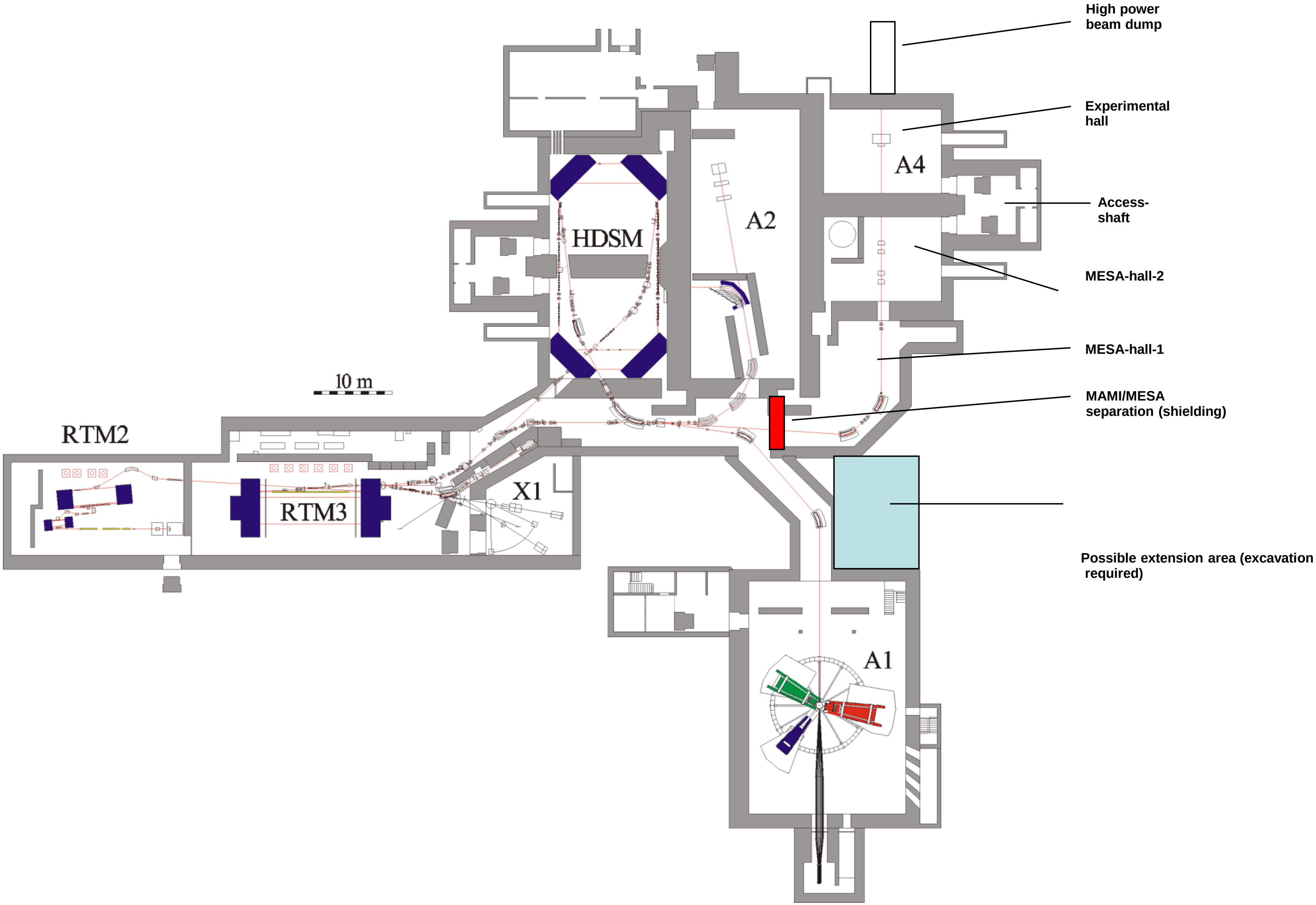
Newly fabricated TPC for Compton scattering experiments



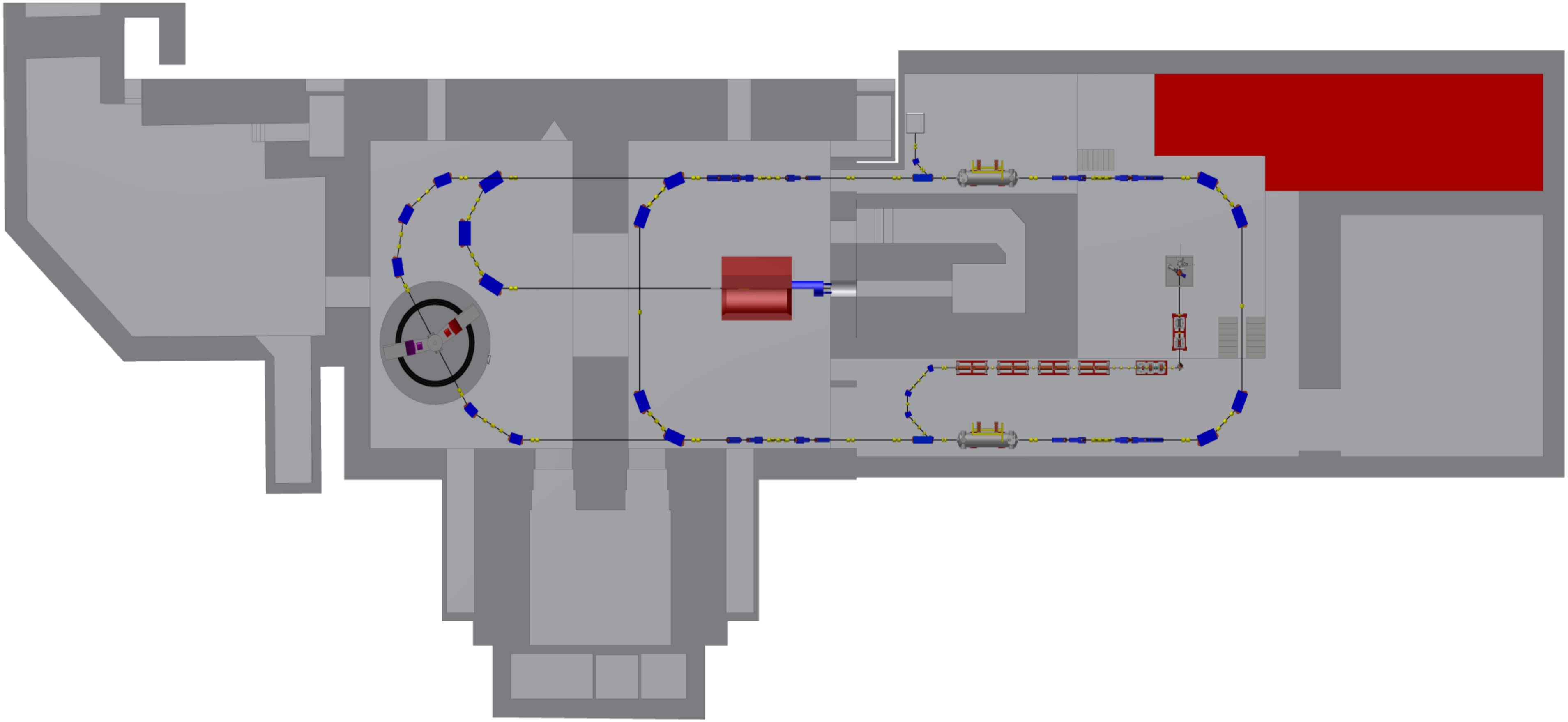
The anode plane of new TPC for simultaneously measurements of Compton scattering at two photon scattering angles θγ=90 and θγ=130 deg.



MAMI and MESA



MESA (Mainz Energy Recovering Super Conducting Accelerator)



MESA parameter set for stage-1 (stage-2).
ERL--energy recovery mode, EB- external beam mode.

Beam Energy ERL/EB [MeV]	105/155 (105/205)
Operating mode	1300 MHz, c.w.
Bunch charge EB/ERL [pC] /[μA]	0.115/0.77 (0.115/7.7) 150μA/1000μA(150μA/10mA)
Norm. Emittance EB/ERL [μm]	0.2/<1 (0.2/<1)
Beam polarization (EB-mode only)	> 0.85
Beam recirculations	2 (3)

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 (2010)	$\alpha_p = 12.0 \pm 0.6$,	$\beta_p = 1.9 \pm 0.5$
PDG (2014)	$\alpha_p = 11.2 \pm 0.4$,	$\beta_p = 2.5 \pm 0.4$
PDG (2018)	$\alpha_p = 11.2 \pm 0.4$,	$\beta_p = 2.5 \pm 0.4$

Mainz (2001) $\alpha_p = 11.9 \pm 0.5 \pm 1.3$, $\beta_p = 1.2 \pm 0.7 \pm 0.3$

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

PDG (2018) $\alpha_n = 11.8 \pm 1.1$, $\beta_n = 3.7 \pm 1.2$

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

Counting rate estimation at MESA

- electron beam **$E_e = 110$ MeV, $I_e = 50\mu A$**

- bremsstralung target convertor *0.3 mm Au (≈0.1 rad. length)*
- bremsstrahlung photon beam $E\gamma$ =20-100MeV , $I\gamma = 2x10^{11}\ s^{-1}$
  at $E\gamma$ =60MeV, $I\gamma \sim 2x10^{9}\ MeV^{-1}s^{-1}$
- γ- beam spot at active target (TPC) $1x2\ cm^{-2}$
- H2 active target density (20 cm, 75 bar) $8x10^{22} cm^{-2}$
- γ-spectrometer $E\gamma \sim$ 20-100 MeV, $\theta\gamma$ = 90 and 130 deg.
  $\Delta\Omega$=0.025sr. $\delta E\gamma / E\gamma$ =4%
- recoil proton detection $Ep \sim$ 0.5-10 MeV θp = 44 and 22 deg.
  δ (Ep)=30-40 KeV

Expected count rate 5 s-1

500 hours of data taking corresponds to 8 000 000 γp events

PNPI fabricated a new IC with the relevant electronics

Main parameters of the new IC:

1) Anode and cathode dimensions:
width – 15 cm, length (along the beam direction) –20cm, the cathode-grid distance of 26 mm, the anode-grid distance of 1.3 mm, two segmented of the anode planes: 20 strips of 3 mm width.
2) Filling gas: H_2, D_2, He3, He4.
3) Pressure: 50-100 bar.
4) Total volume of ionization chamber -6 litres

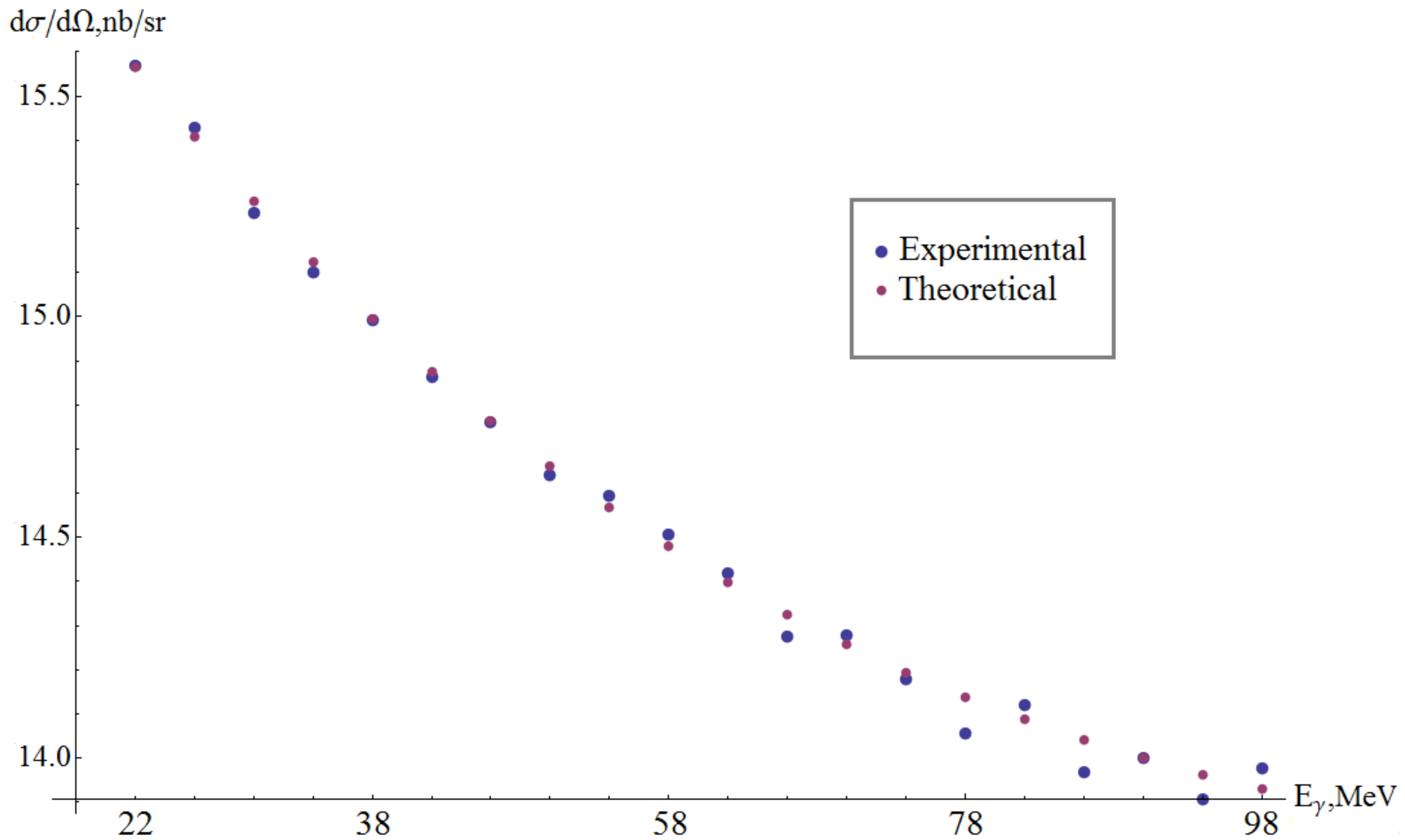
Conclusion

We propose a coincidence method to precisely measure differential cross section of γp Compton scattering using untagged bremsstrahlung photon beam ($E\gamma$ <100 MeV) of the MESA facility (under construction). The experiment aims at high precision of proton and neutron polarizability measurements.

Virtues of proposed method:

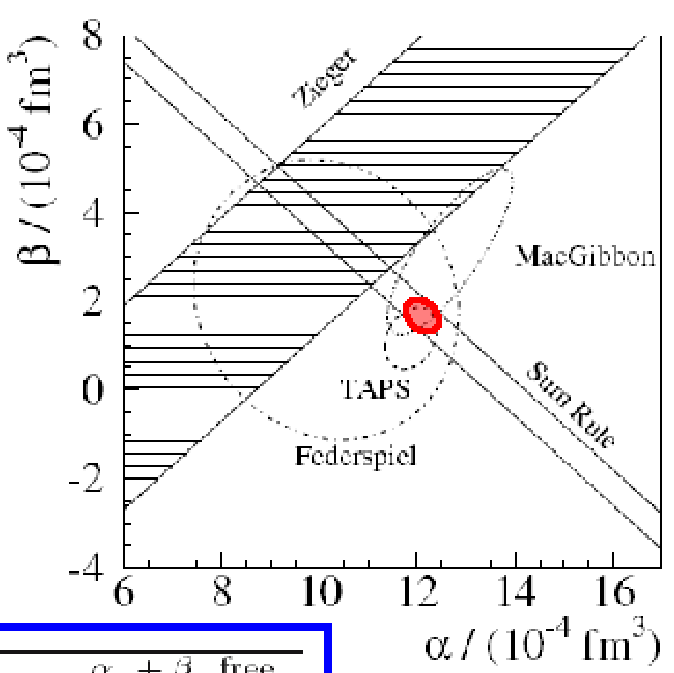
1. The measurements can be performed at a rather low photon energy allowing for the data analysis to be performed in a model-independent way.
2. The experimental data can be normalized to the theoretical value of $d\sigma(E\gamma,\theta\gamma)/d\Omega$ at the primary photon energy of 20-30 MeV where the contribution from polarizability terms is small.
3. The method provides effective background rejection due to strong correlation between the kinematic variables of the scattered photon and the recoil proton (or recoil deuteron) in the case of elastic scattering.
4. Count rate of Compton scattering events substantially larger than in the tagged photon experiments

Supporting slides



dσ/dΩ,nb/sr
15.5
15.0
14.5
14.0
22
38
58
78
98
Eγ,MeV
Experimental
Theoretical

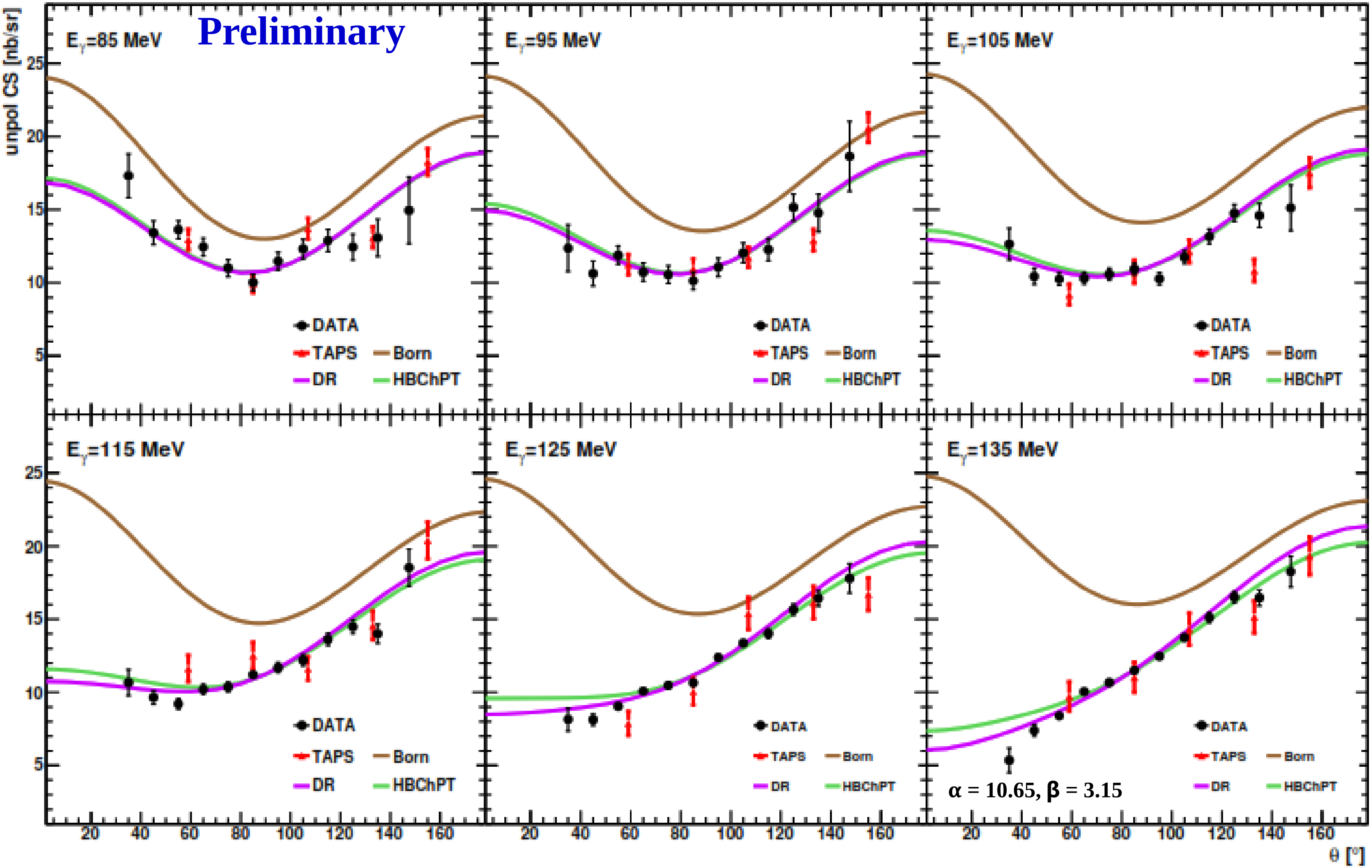
Proton Polarizability



Data		$\alpha_p + \beta_p$ fixed	$\alpha_p + \beta_p$ free
TAPS	α_p	$12.1 \pm 0.4 \mp 1.0$	$11.9 \pm 0.5 \mp 1.3$
Olmos de Leon	β_p	$1.6 \pm 0.4 \pm 0.8$	$1.2 \pm 0.7 \pm 0.3$
MacGibbon	α_p	$11.9 \pm 0.5 \mp 0.8$	$12.6 \pm 1.2 \mp 1.3$
[4]	β_p	$1.9 \pm 0.5 \pm 0.8$	$3.0 \pm 1.8 \pm 0.1$
Federspiel	α_p	$10.8 \pm 2.2 \mp 1.3$	$10.1 \pm 2.6 \mp 2.0$
[3]	β_p	$3.0 \pm 2.2 \pm 1.3$	$2.0 \pm 3.3 \pm 0.3$
Zieger	$\alpha_p - \beta_p$	$6.4 \pm 2.3 \pm 1.9$	
[6]			
Global	α_p	$12.1 \pm 0.3 \mp 0.4$	$11.9 \pm 0.5 \mp 0.5$
fit	β_p	$1.6 \pm 0.4 \pm 0.4$	$1.5 \pm 0.6 \pm 0.2$

Olmos de Leon EPJ 01

New experiment: unpolarized cross section below pion threshold



Significant improvement compared to all previous measurements!

Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]

Summary of Neutron Results

- Neutron scattering
  - Schmiedmayer (91)

$$\alpha_n = 12.6 \pm 1.5(\text{stat}) \pm 2.0(\text{syst})$$

- Quasi-free Compton scattering
  - Kossert (03)

$$\alpha_n = 12.5 \pm 1.8(\text{stat}) \,^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$$

$$\beta_n = 2.7 \mp 1.8(\text{stat}) \,^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model})$$

- Elastic Compton scattering
  - data from Lucas (94), Hornidge (00), Lundin (03)
  - global fit by Hildebrandt (05)

$$\alpha_n = 11.6 \pm 1.5\ (\text{stat}) \pm 0.6\ (\text{Baldin})$$

$$\beta_n = 3.6 \mp 1.5\ (\text{stat}) \mp 0.6\ (\text{Baldin})$$

We can do better . . .

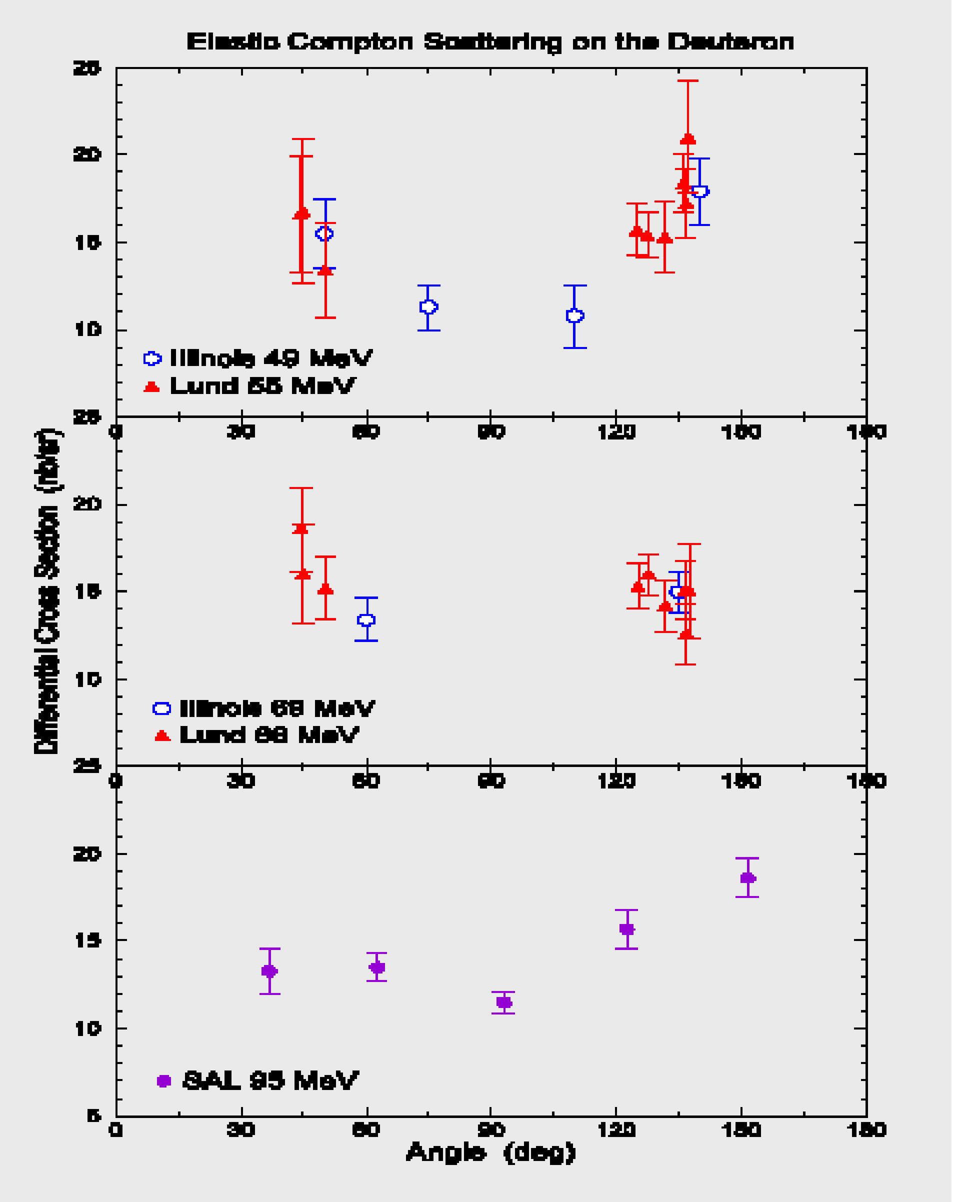
Coherent DCS

Three data sets:

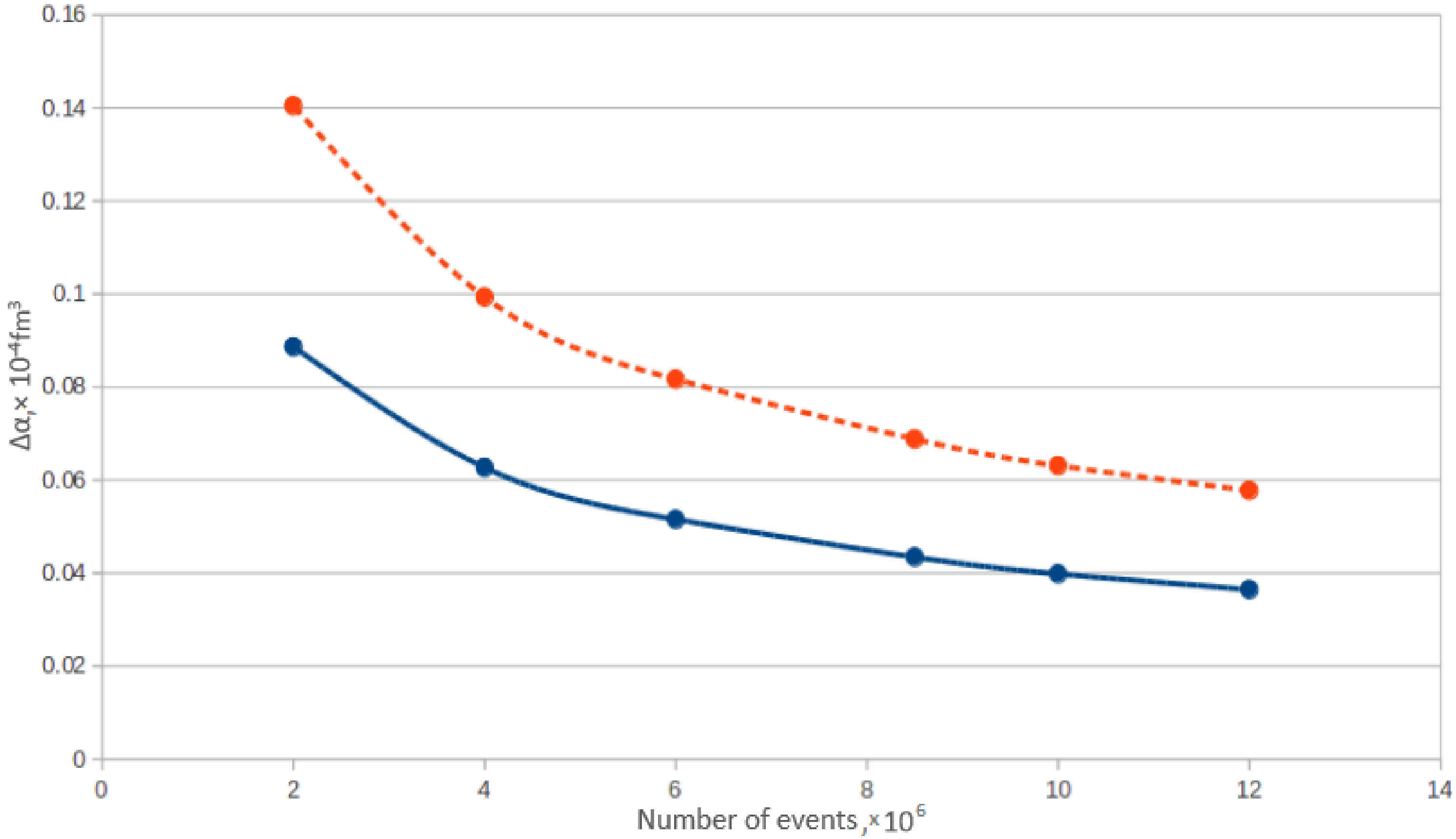
- E ~ 50,70 MeV (Illinois, Lund)
- E = 95 MeV (SAL)

"Issues" with current data:

- Large statistical uncertainties (commonly > 7%)
- Wide energy bins (ΔE is 6 - 20 MeV)
- Limited kinematic coverage



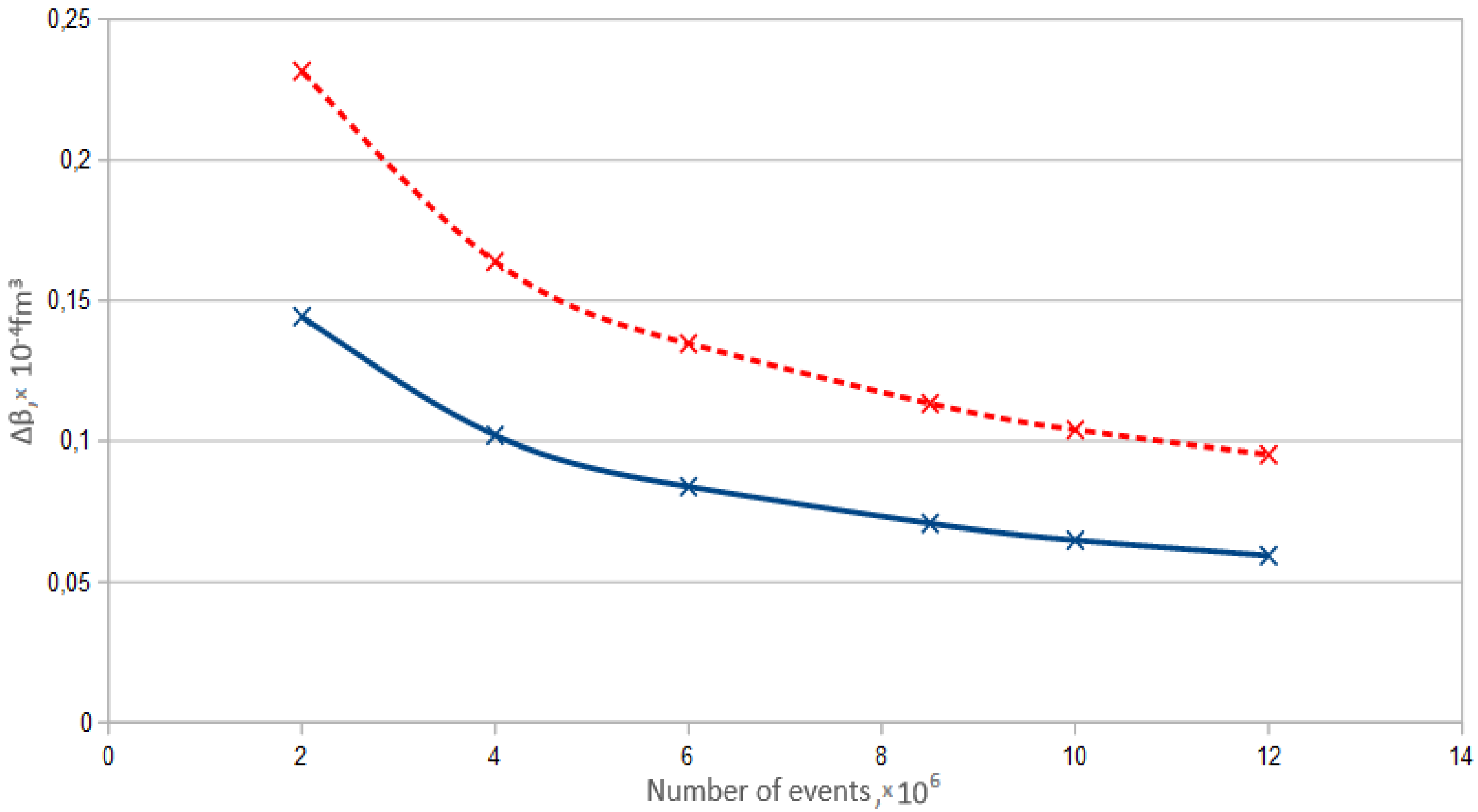
Statistical errors in determination α



___ absolute measurement - only two (α and β) free parameters

___ with additional two (for each θγ) normalization parameters

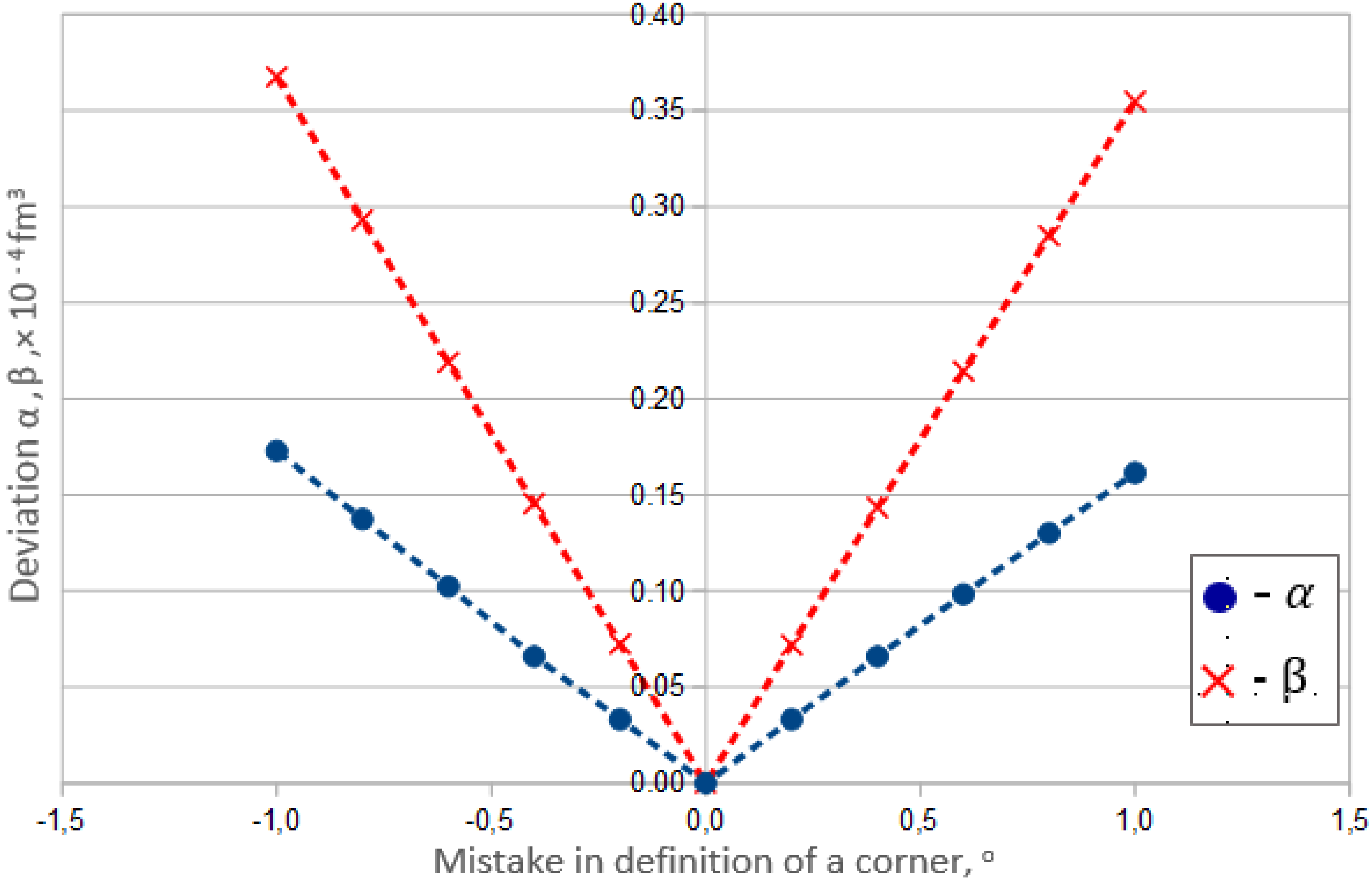
Statistical errors in determination β



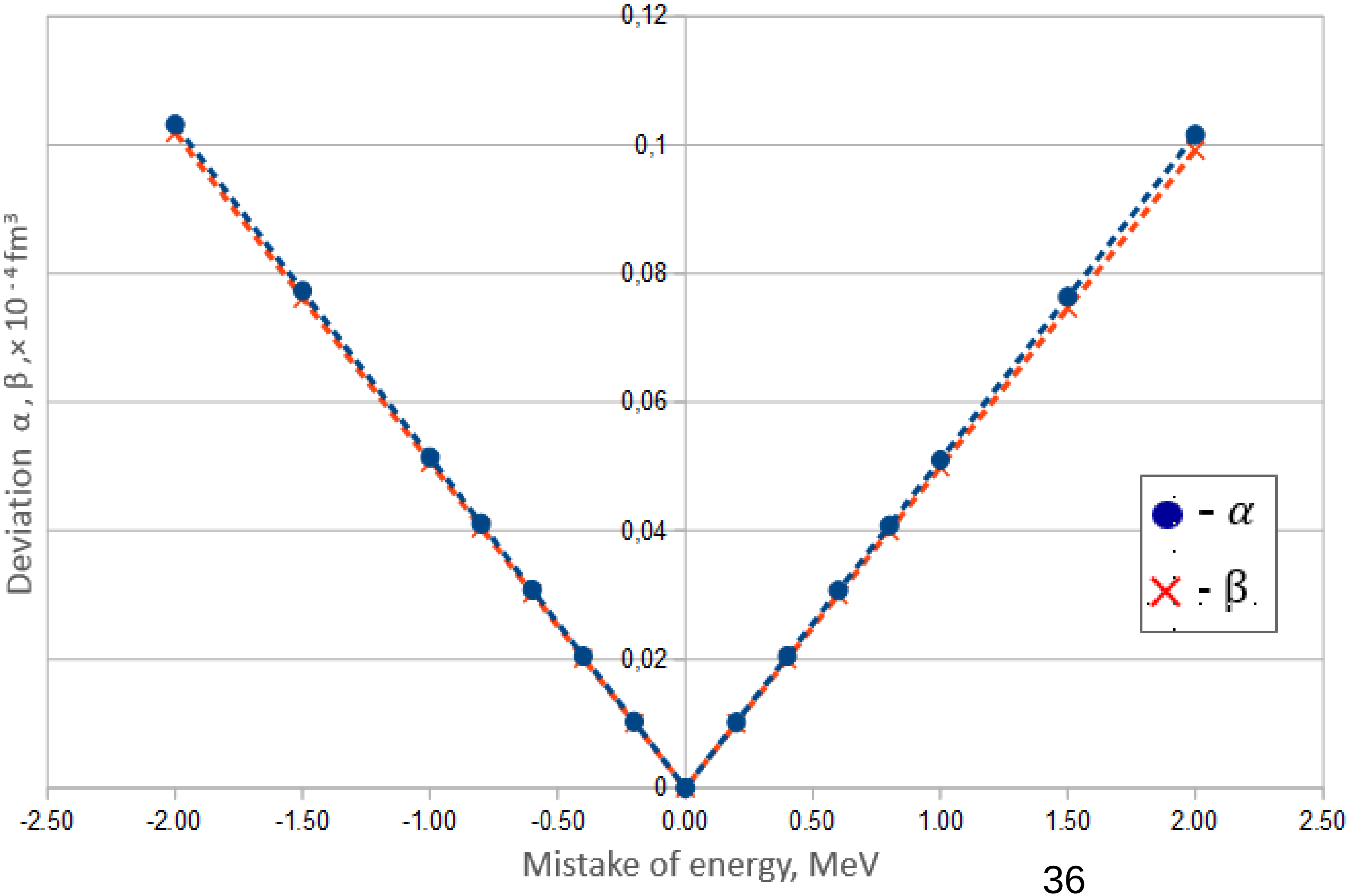
___ absolute measurement - only two (α and β) free parameters

___ with additional two (for each θγ) normalization parameters

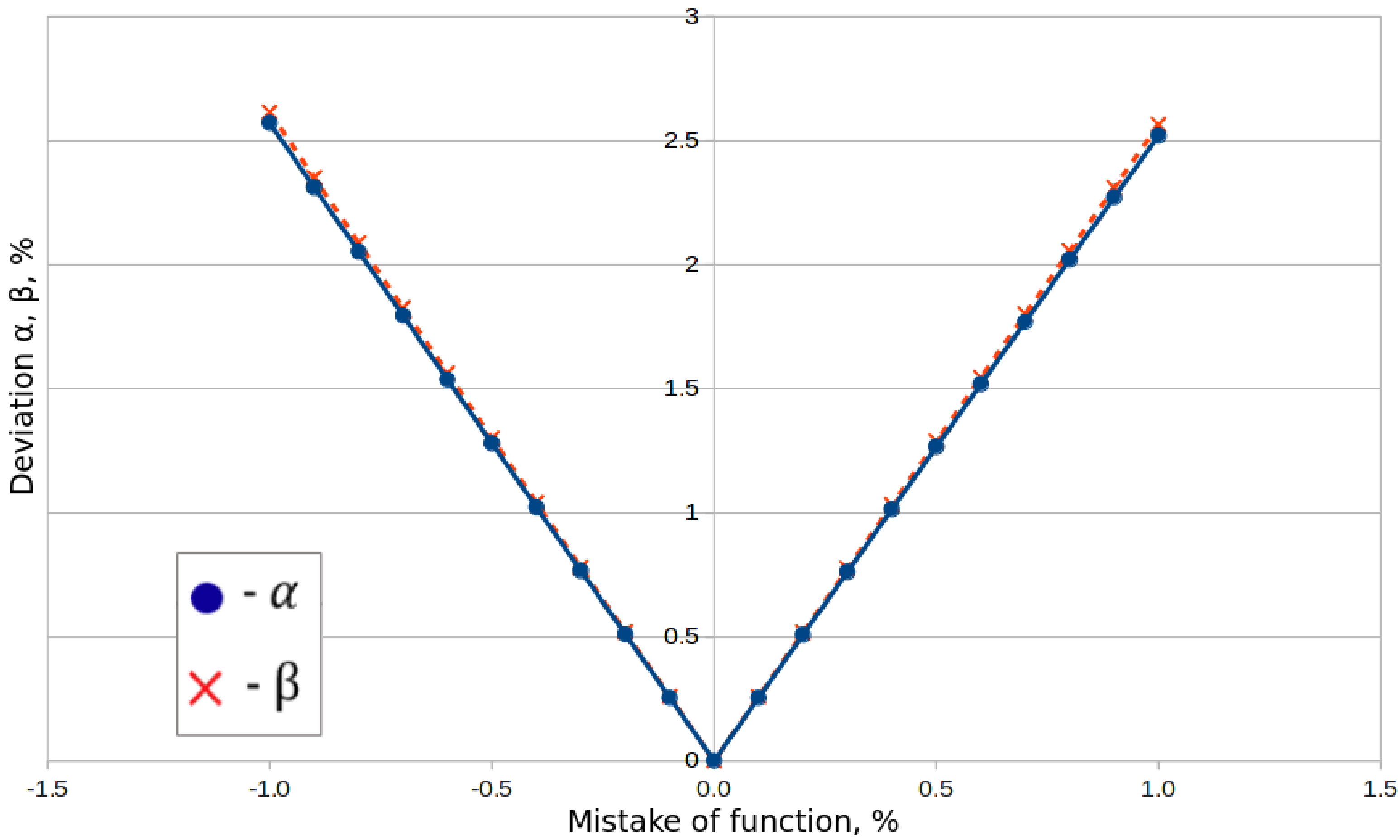
Systematical errors (θγ) in determination of α and β



Systematical errors (Eγ) in determination of α and β

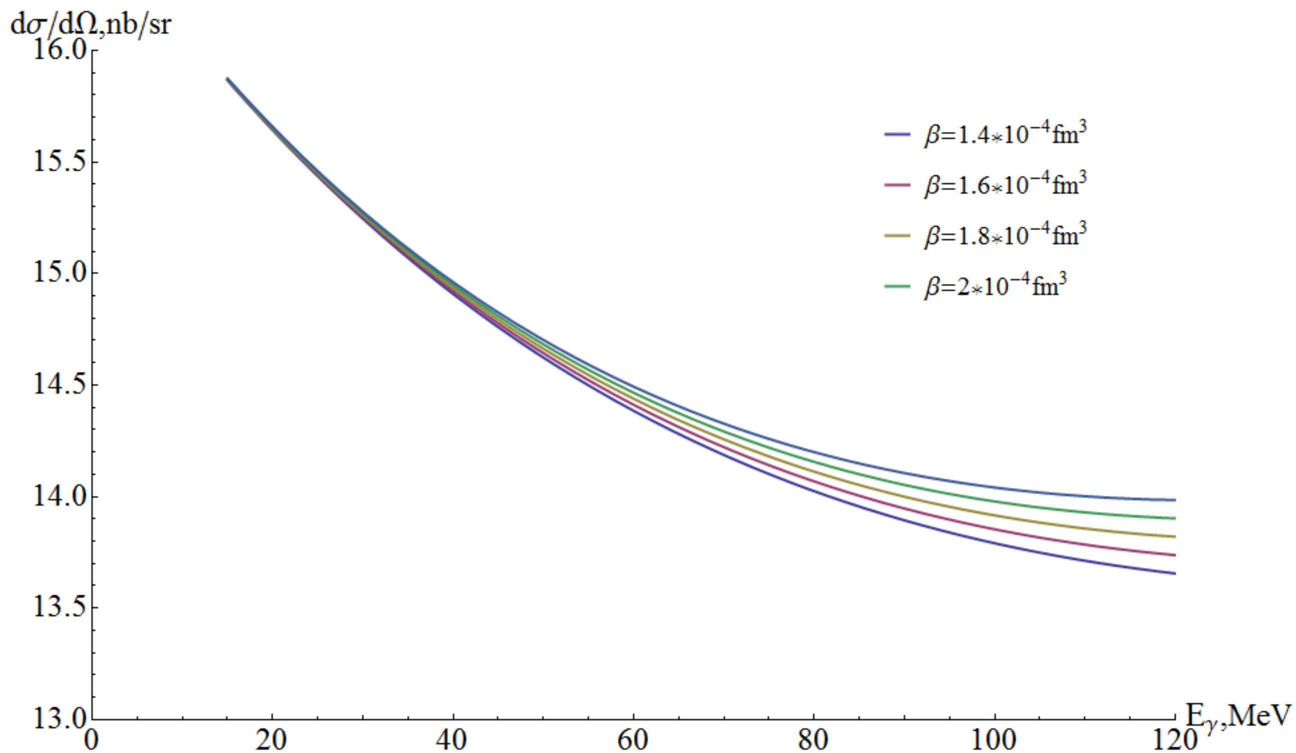


Systematical errors (Nγ) in determination of α and β

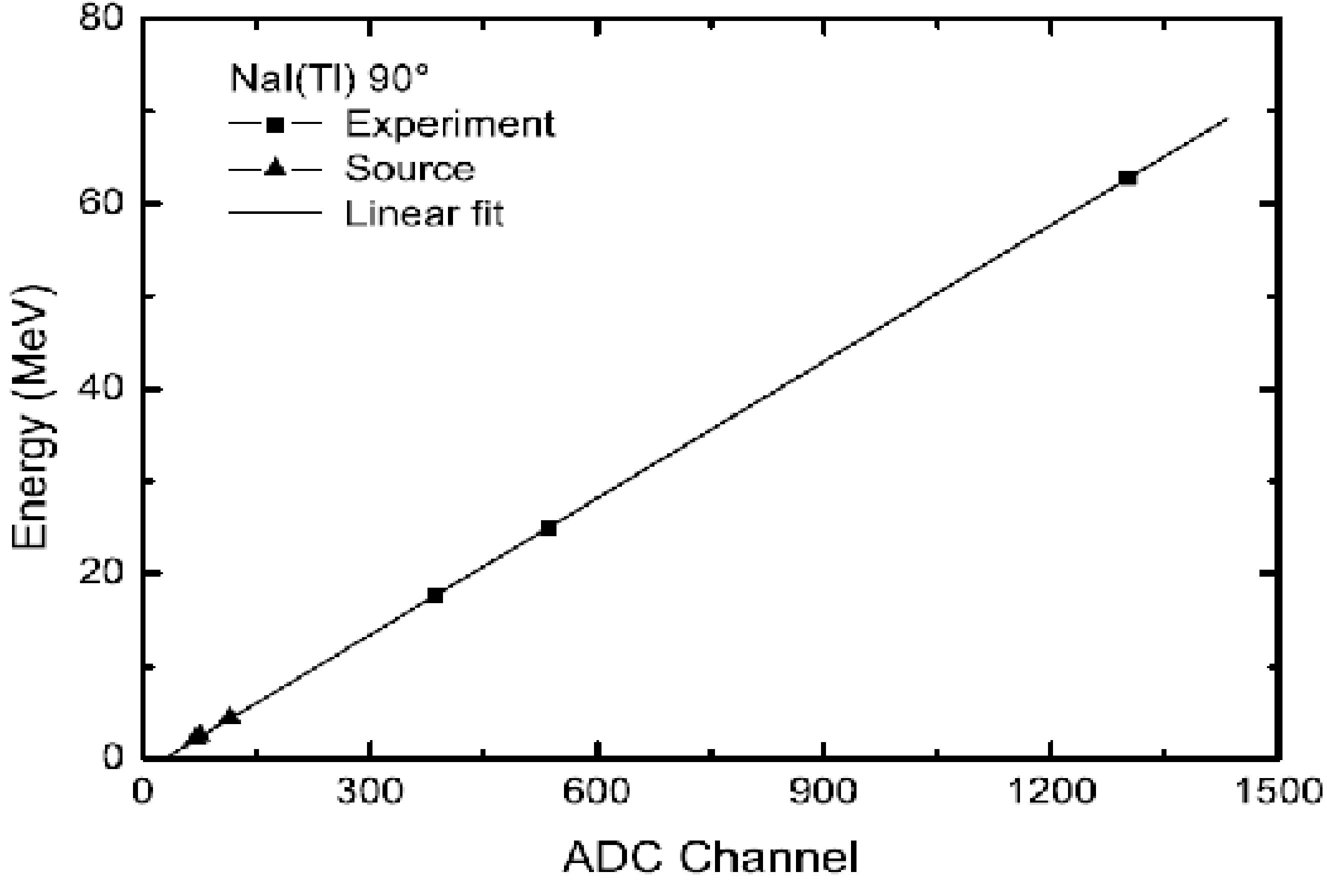


The energy dependence of incident photon beam:

$N\gamma(E\gamma) = F(x) = 1/[x(1+\Delta x)]$, $x = E\gamma/E\gamma max$, $E\gamma max = 100$ MeV

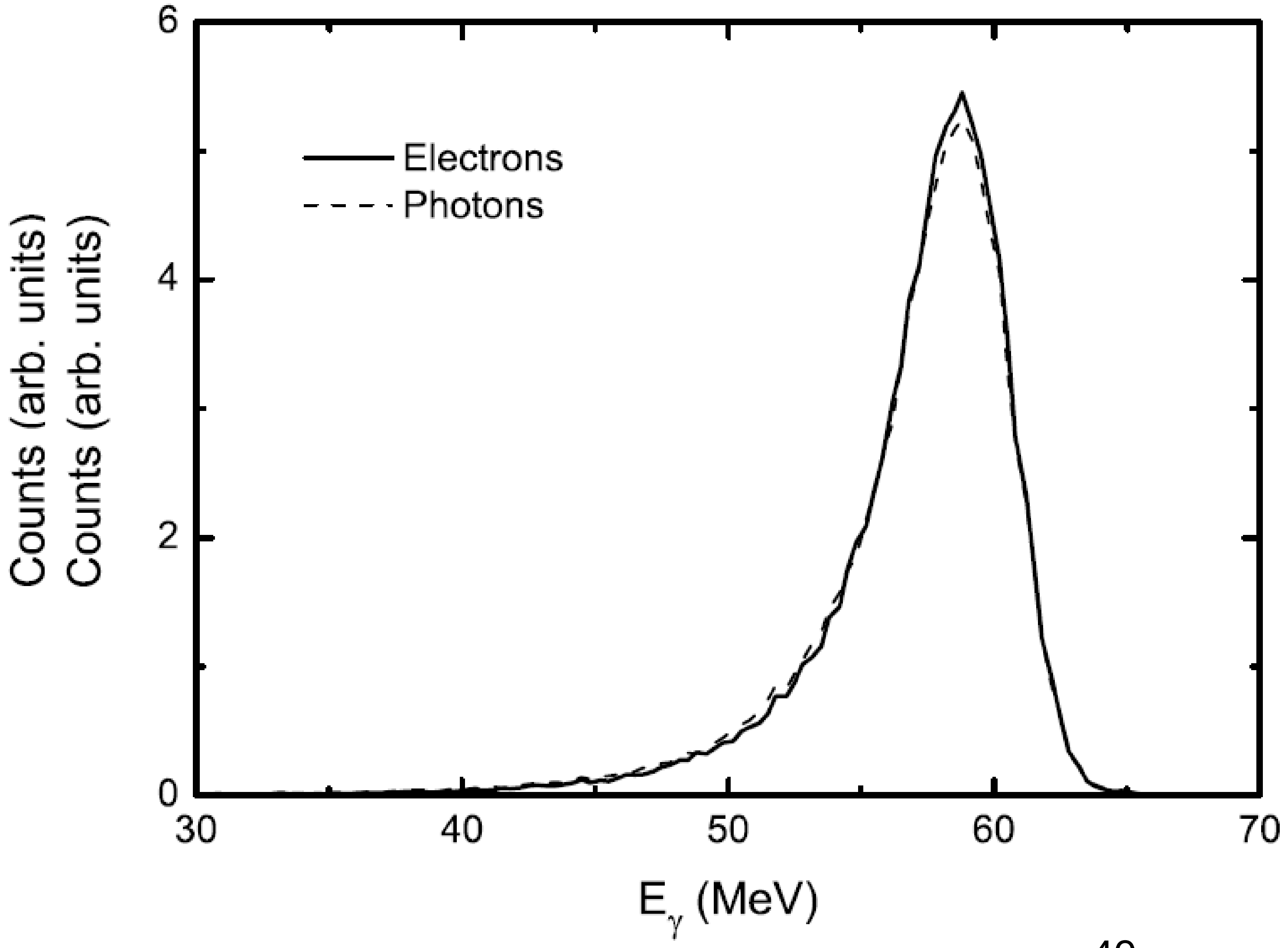

dσ/dΩ,nb/sr
16.0
15.5
15.0
14.5
14.0
13.5
13.0
0
20
40
60
80
100
120
E_γ,MeV
β=1.4∗10^-4fm^3
β=1.6∗10^-4fm^3
β=1.8∗10^-4fm^3
β=2∗10^-4fm^3

Energy calibration of one of the NaI spectrometers

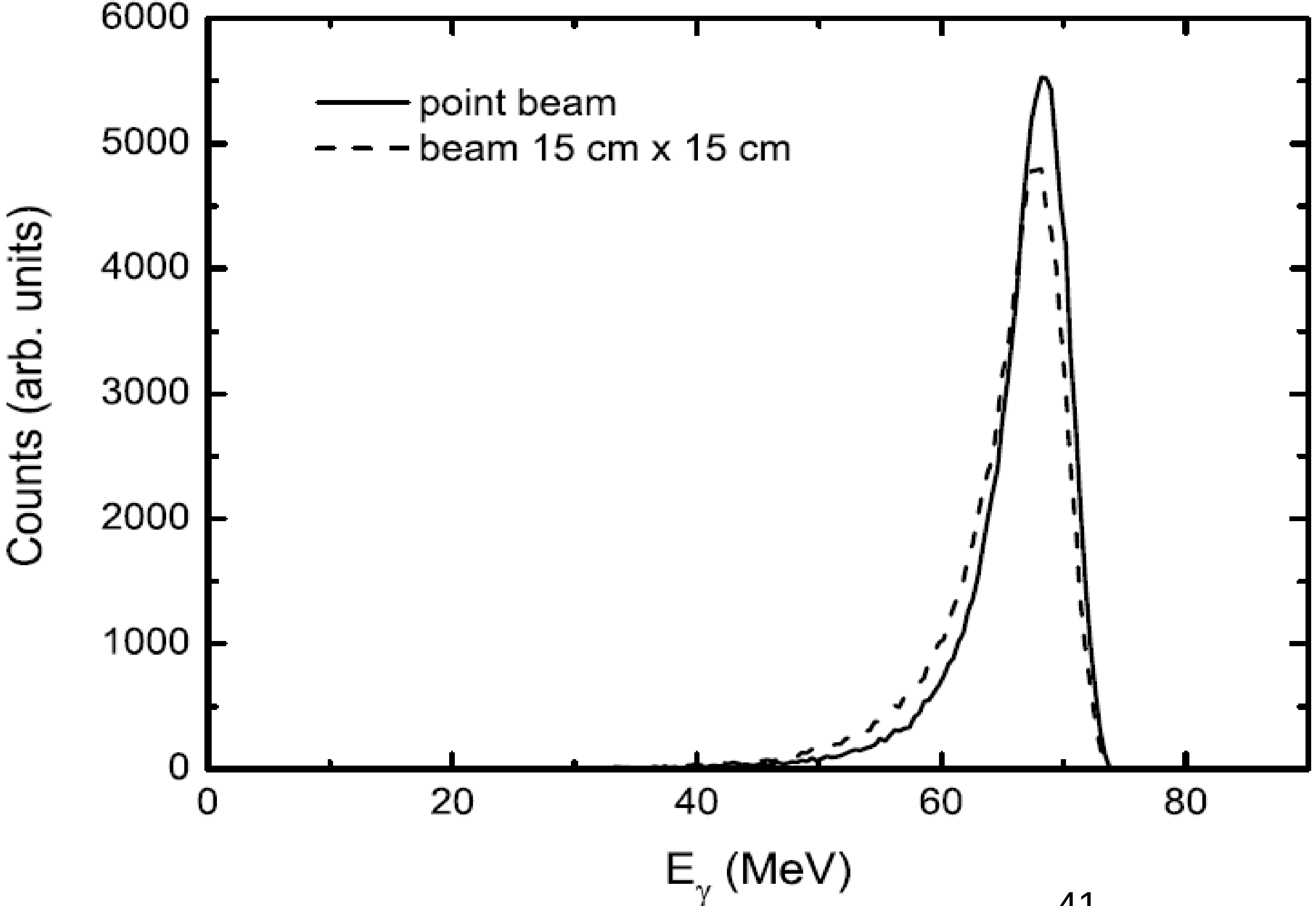


▲ – 60Co (1.3 MeV) and Am-Be (4.4 MeV) γ sources; ■ – calibration with e-A scattering

Responce function of NaI(10”x14”) detector for E=60 MeV

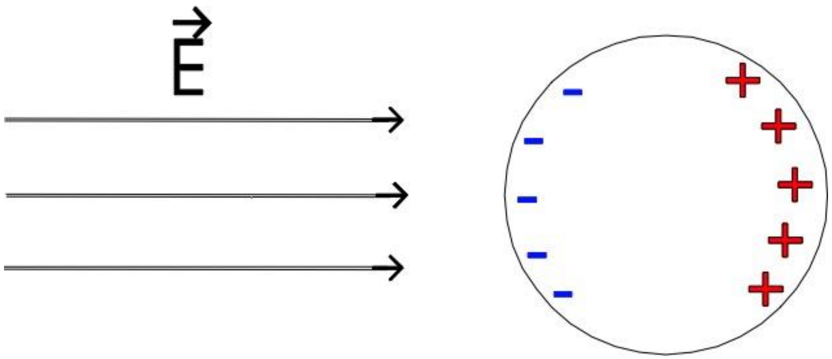


Response functions of NaI(10”x14”)detector for E=70MeV



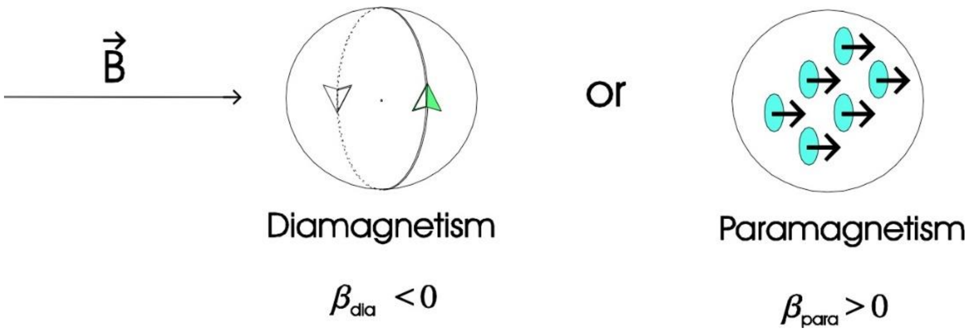
Scalar polarizabilities

Proton Electric Polarizability



- α_{E1}: electric polarizability
- Proton between charged parallel plates:
- "stretchability"

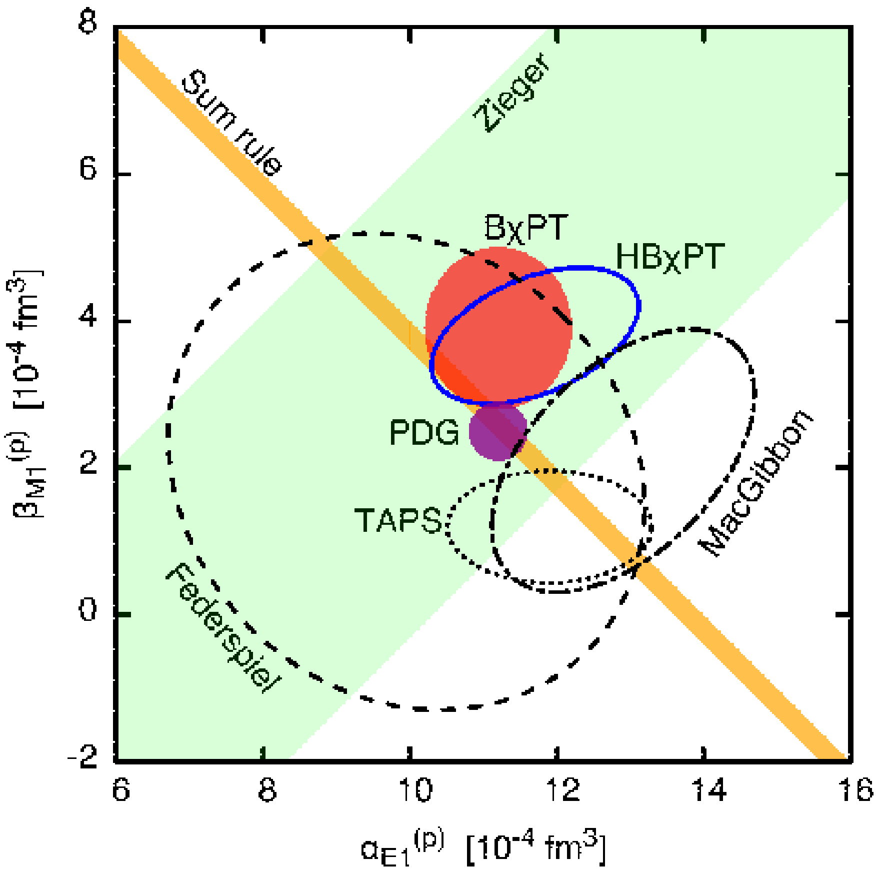
Proton Magnetic Polarizability



- β_{M1}: magnetic polarizability
- Proton between poles of a magnet:
- "alignability"

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

Scalar polarizabilities



PDG (2012) values:

$\alpha = (12.0 \pm 0.6) \times 10^{-4}$ fm^3

$\beta = (1.9 \pm 0.5) \times 10^{-4}$ fm^3

New (2014-2018) PDG values:

$\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3

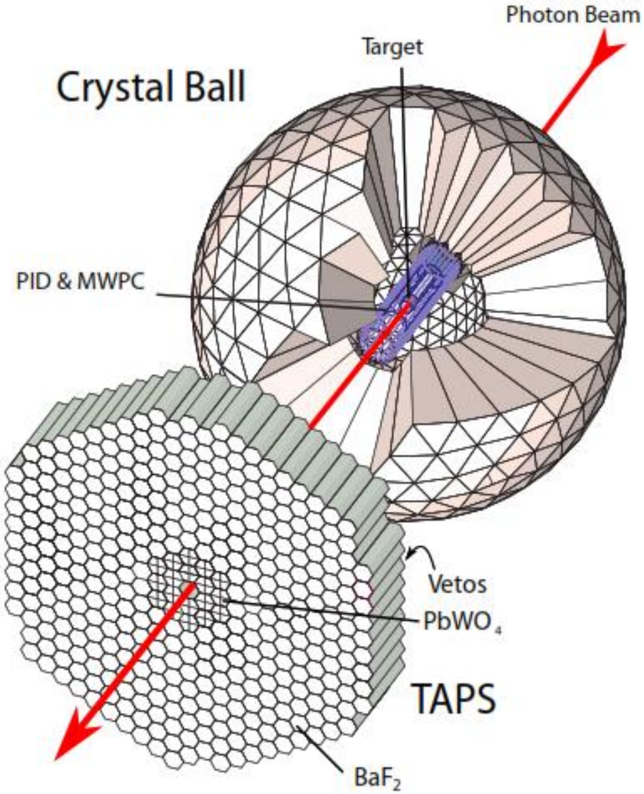
$\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3

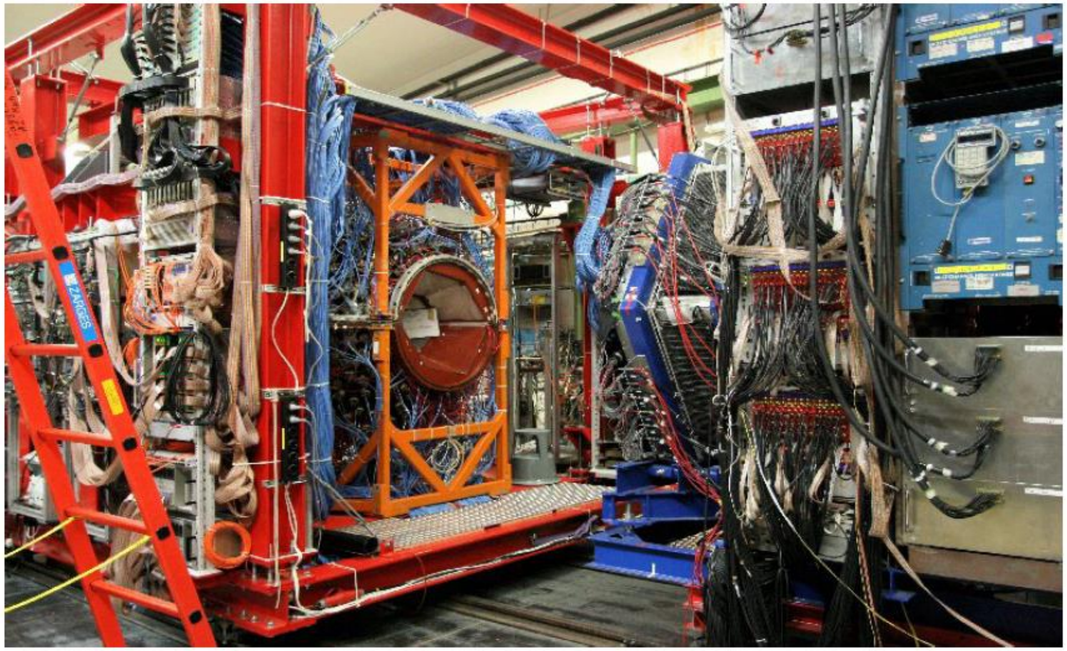
- Significant change between reviews without in
- Global database not entirely consistent

Goal: high-precision measurement of the scalar polarizabilities of the proton

- New high-precision unpolarized cross-sections
- New high-quality data on the beam asymmetry Σ_3
- New single data set with small statistical and systematic errors

Crystal Ball/TAPS experiment





Crystal Ball:

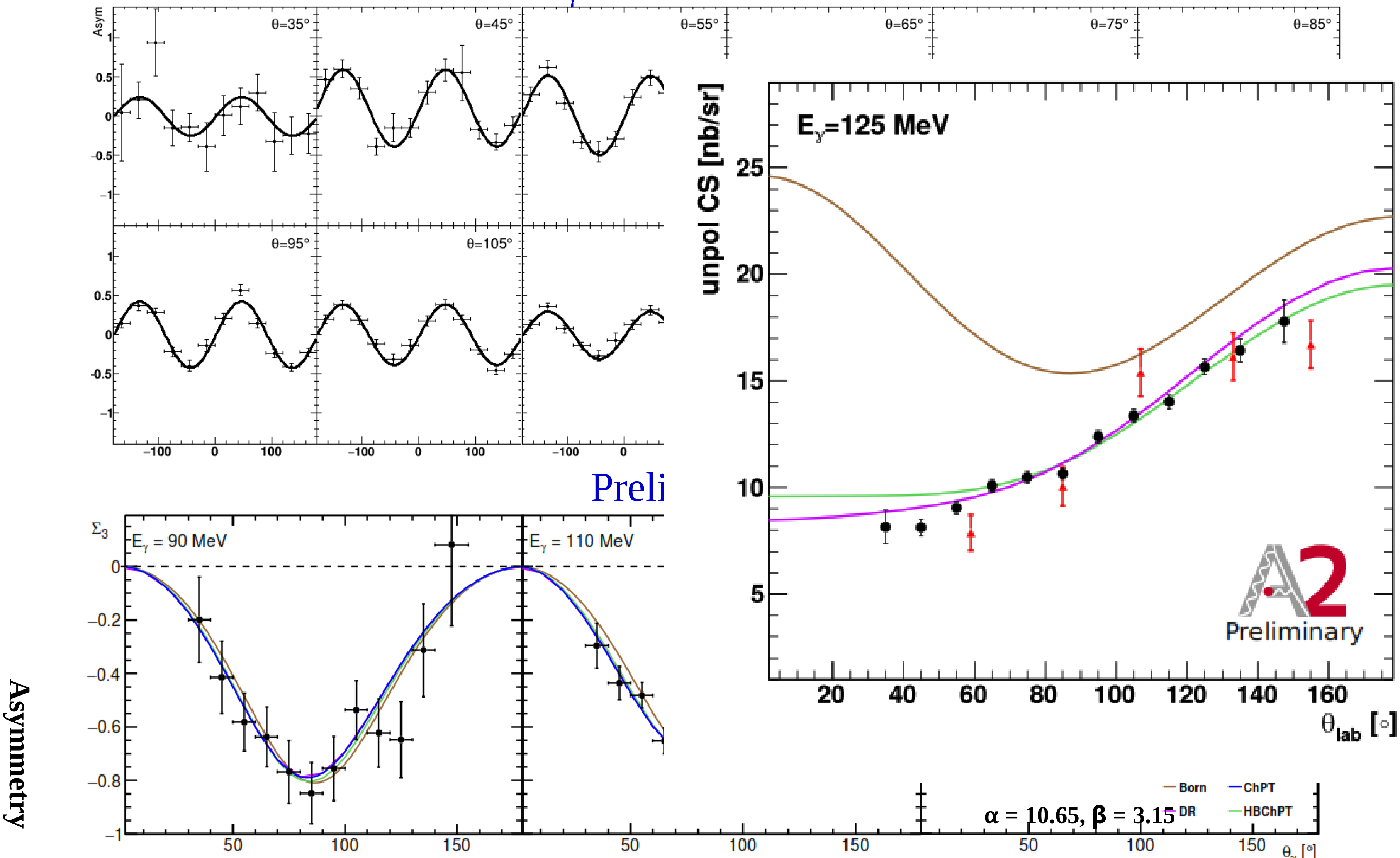
- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

TAPS:

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Detectors

New experiment: beam asymmetry below pion threshold

E_γ = 120 -140 MeV



α = 10.65, β = 3.15

Significant improvement compared to the previous measurement!

Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]