High-precision Measurement of the Proton Radius with TPC

Vahe Sokhoyan

Precision Measurements and Fundamental Physics: The Proton Radius Puzzle and Beyond
Mainz, 26.07.2018

Institut für Kernphysik

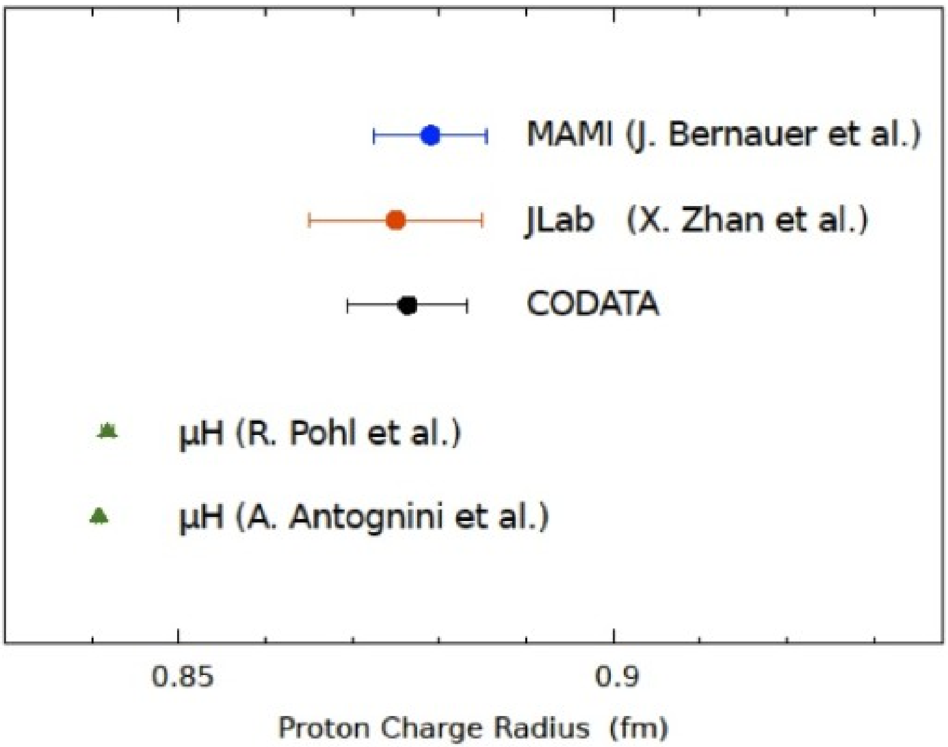
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter PRISMA

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Motivation

Main motivation: Understanding the proton radius puzzle



Significant difference between results of muonic hydrogen experiments (CREMA Collaboration, PSI) and CODATA value

- Electron scattering: validity of the Q^2 range and choice of the fitting function?
- Hadronic corrections not sufficient to explain the differences?
- Exotic particle coupling differently to electrons and muons?

More than a comparison of two numbers:

- Inconsistencies between atomic measurements
- In a more general consideration: differences between some of the measurements with electronic and muonic systems
  The solution will not come from a single experiment!

Scattering experiments

Worldwide program of scattering experiments:

- A1 Collaboration in Mainz: Initial State Radiation (ISR) experiments:
  R_{pE} = 0.810 ± 0.035 (stat) ± 0.074 (syst) fm *(M. Mihovilovič et al., Phys.Lett. B771, 194 (2017))*
  Further experiments reaching $Q^2 = 10^{-4}$ GeV^2 with improved systematics planned.

- PRad experiment at JLab: Electron scattering on a hydrogen gas jet target studied in combination with a forward calorimeter, access to $Q^2 = 10^{-4}$ GeV^2.

- ProRad Experiment at PRAE: Electron scattering at $Q^2 = 10^{-5}$- 3×10^{-4} GeV^2, detectors made of scintillating fibre planes and BGO crystals.

- ULQ^2 (Ultra-low Q^2 in Tohoku) experiment: Electron scattering at $Q^2 = 3\times10^{-4}$- 8×10^{-3} GeV^{2}with an electron spectrometer.

- MUSE Collaboration: preparing for a simultaneous measurement of the absolute cross-sections for the *ep* and *μp* elastic scattering at low momentum transfer. The electron-muon universality will be tested in the context of the measurement of the proton radius.

- New experiments with Hydrogen TPC at MAMI in the A2 Hall and at COMPASS

Working groups and infrastructure

Current composition of the working groups:

KPH, Mainz: Achim Denig, Patrik Adlarson, Marco Dehn, Peter Drexler, Andreas Thomas, Frederik Wauters, V.S., Michael Ostrick, Niklaus Berger, Oleksandr Kostikov

PNPI, Gatchina: Alexey A. Vorobyov, Alexander Vasilyev, Petr Kravtsov, Marat Vznuzdaev, Kuzma Ivshin, Alexander Solovyev, Ivan Solovyev, Alexey Dzyuba, Evgeny Maev, Alexander Inglessi, Gennady Petrov

GSI: Peter Egelhof, Oleg Kiselev

College of William and Mary: Keith Griffioen, Timothy Hayward

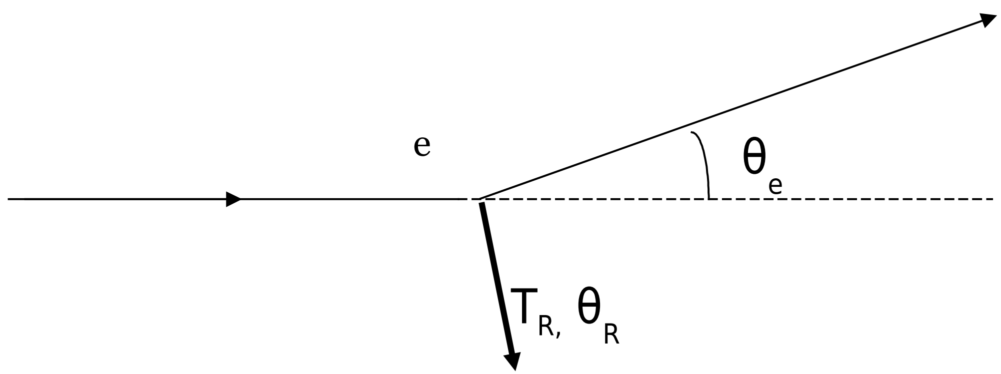
Mount Allison University: David Hornidge

Motivation

Innovative approach to the measurement of the proton radius

- Simultaneous detection of the scattered electron and recoil proton
- Lower radiative corrections
- Low transfer momentum region: 0.002 – 0.04 GeV^2
- Absolute measurements of $d\sigma/dt$ accuracy on a level of ~0.2%

(Difference between R_p=0.84 fm and R_p=0.88 fm: ~1.3% at Q^2 = 0.02 GeV^2)

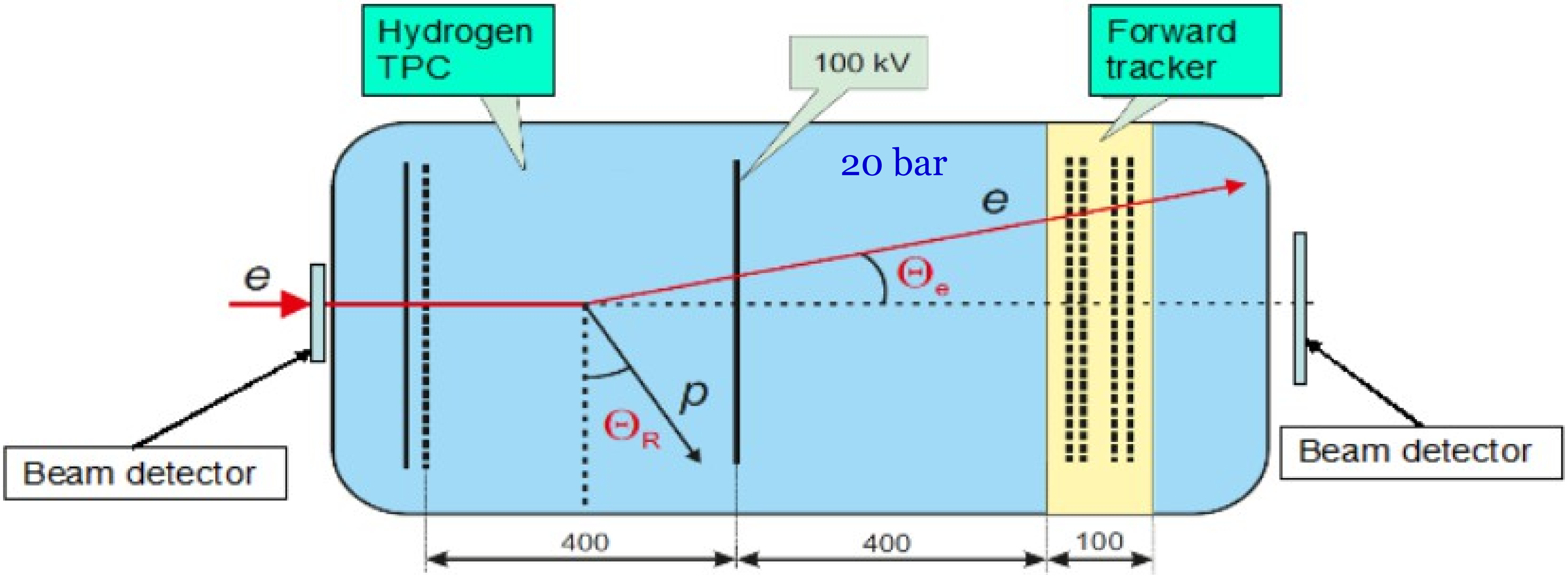


Completely different systematics compared to other experiments!

IKAR-M detector

New-generation experiments with a completely different systematics:

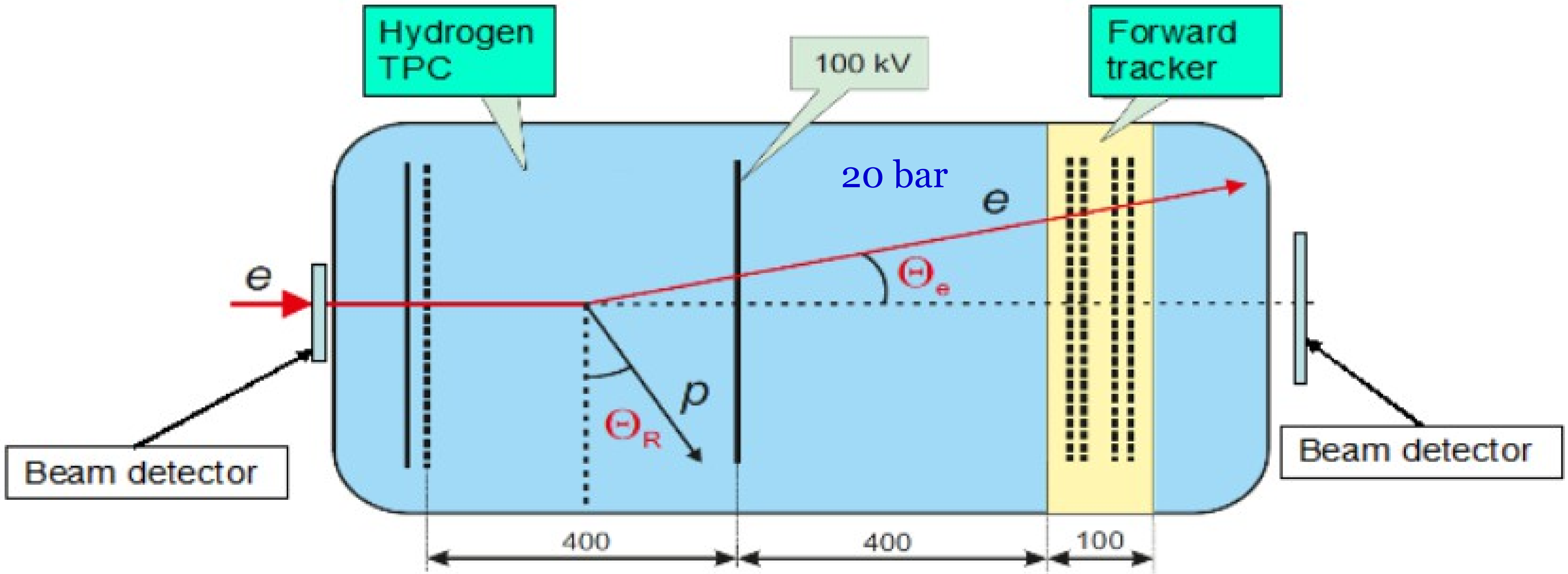
- Electron scattering with detection of both recoil proton and scattered electron
- Dilepton photoproduction (proton radius measurement, lepton universality test)



TPC&FT at MAMI beam will open avenue for various experiments:

- Experiments with electron and photon beams in A2 with accurate detection of charged particles (including recoil fragments)
- Hydrogen, deuterium, helium gas filling possible
- Longer term: transfer of technology to experiments at MESA accelerator e.g. for complementary measurement of the nucleon scalar polarizabilities (in addition to the A2 program)

IKAR-M detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

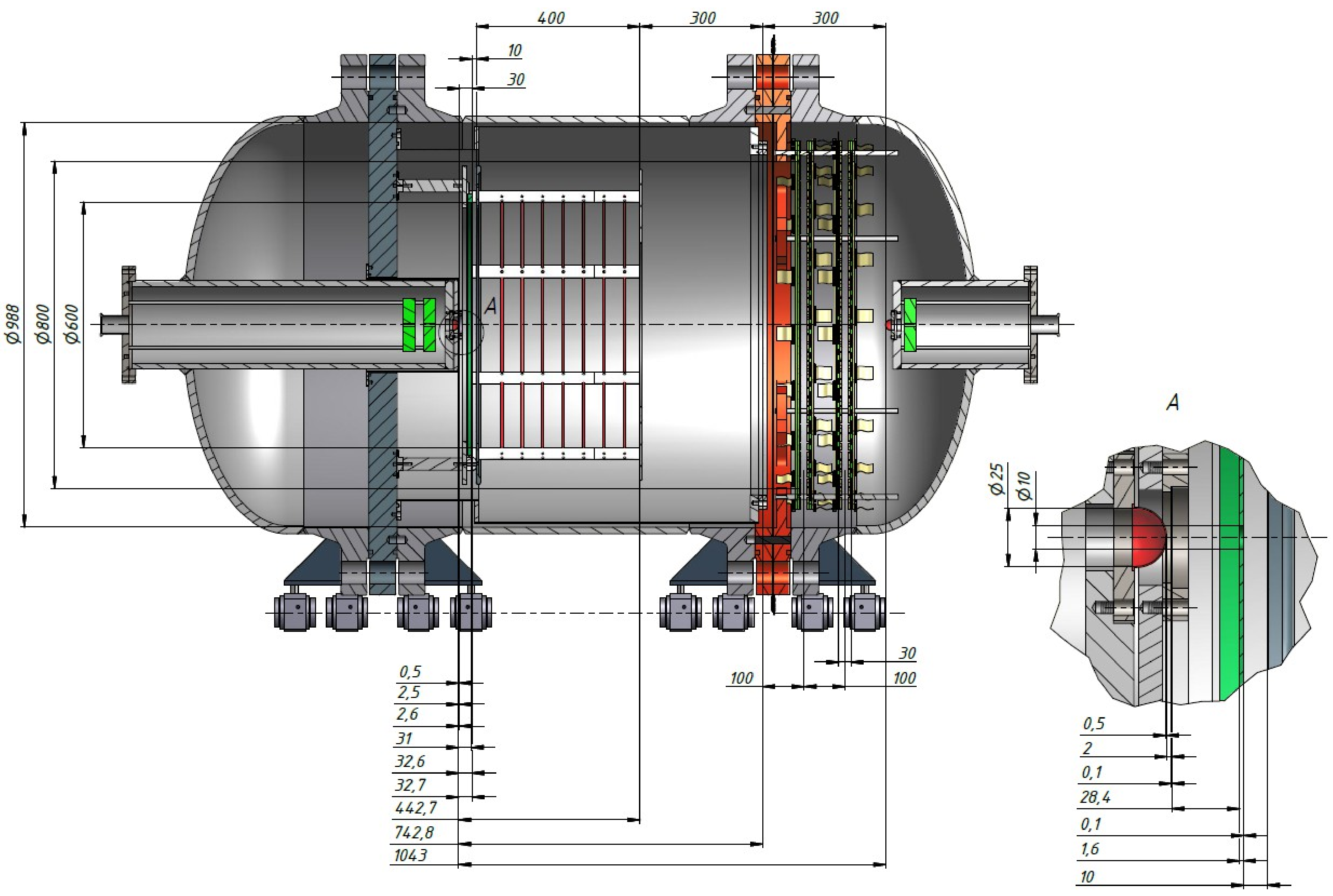
E scattering angle Θ_e

$$-t = \frac{4\varepsilon_e^2 \sin^2\frac{\vartheta}{2}}{1+\frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}}$$

$$-t = 2MT_R$$

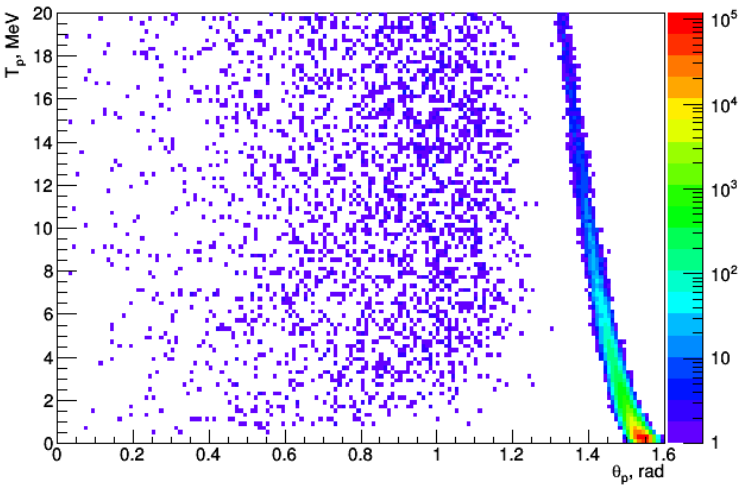
Gas pressure (bar)	4, 20
Drift distance, (mm)	300± 0.1
σ_z (μm)	150
σ_{T_p} (keV)	60
σ_{θ_p} (mrad)	10-15
$\sigma_{x/y/z}$ tracker (z TPC) (μm)	30/30/150
σ_t TPC/ tracker (ns)	40/5
θ_{max} (°)	32

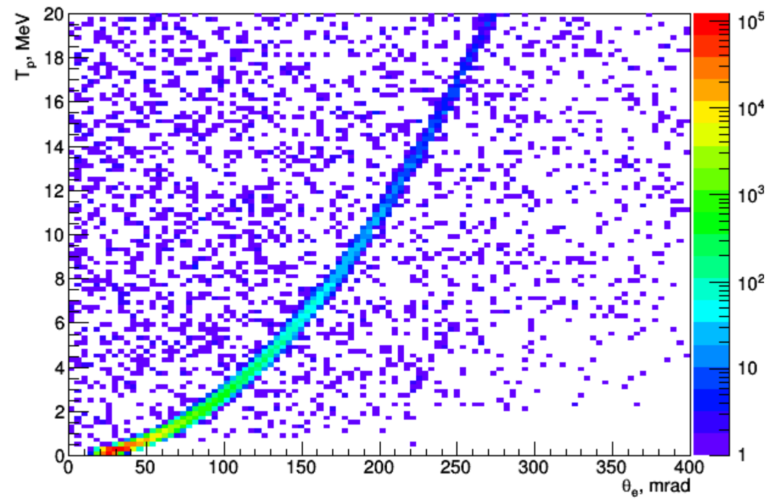
IKAR-M detector (tentative design)

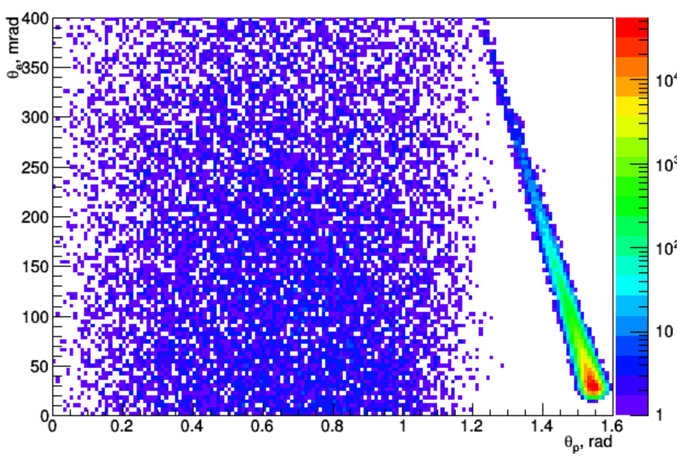


Event selection and background suppression

- Trigger: E_R > 300 keV
- Time coincidence between signals in the TPC and Forward Tracker
- Tracing back the electron trajectory: matching the Z coordinate for the vertex determined from the TPC and Forward Tracker
- Background suppression using various correlations.







Simulation for the elastic ep scattering and compared with the background reaction $ep \to ep\pi^0$ for ε_e = 720 MeV

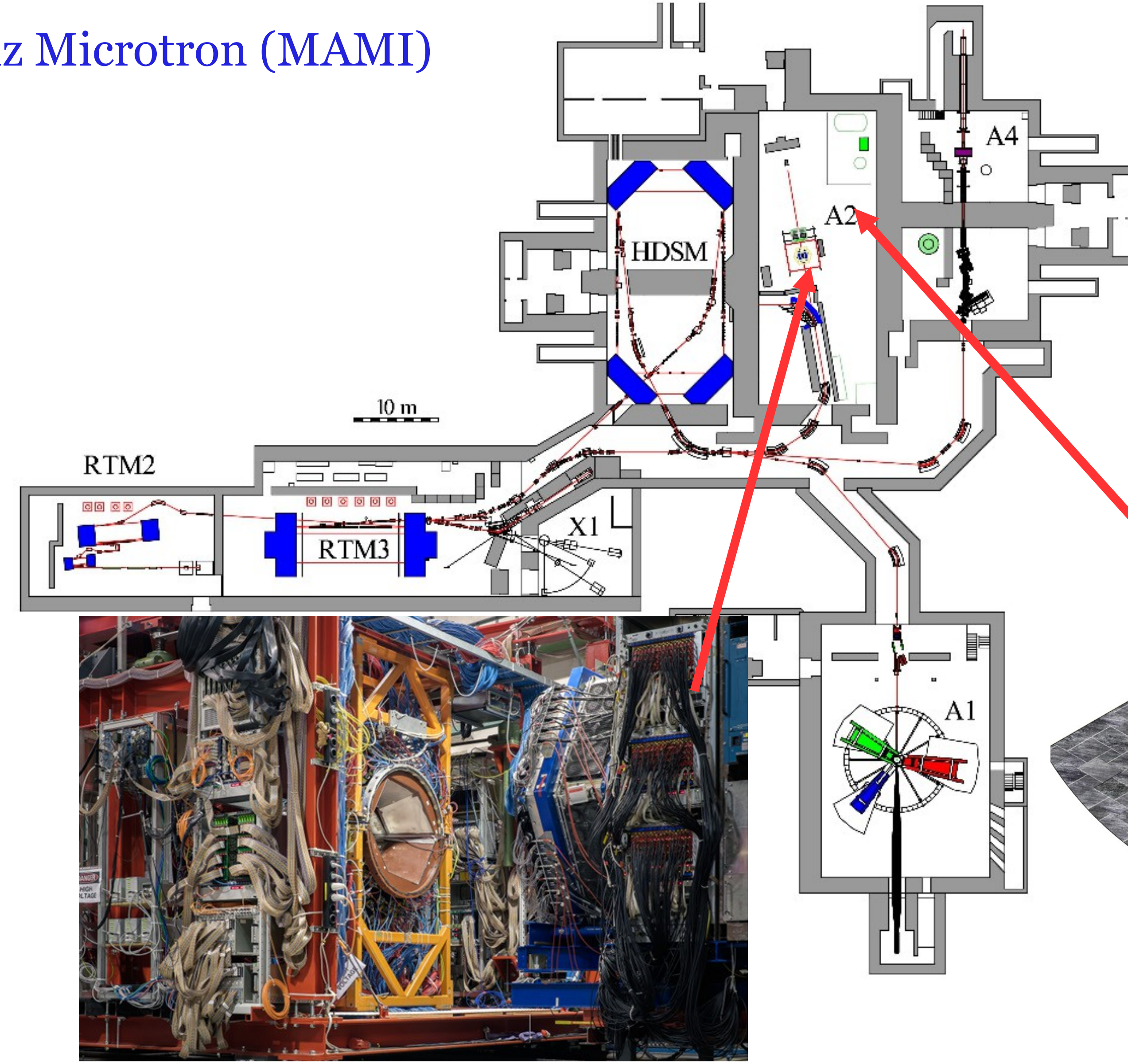
A. Dzyuba, A. Vorobyov (PNPI)

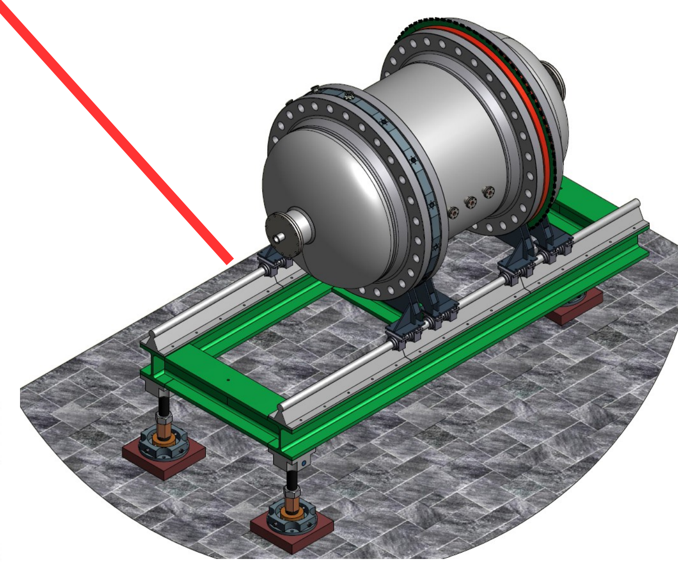
Systematic errors

1	Drift velocity, W1	0.01%
2	High Voltage, HV	0.01%
3	Temperature, K	0.015 %
4	Pressure, P	0.01%
5	H_2 density , ρ_p	0.025 %
6	Target length, L_{tag}	0.02 %
7	Number of protons in target, N_p	0.045 %
8	Number of beam electrons, N_e	0.05 %
9	Detection efficiency	0.05 %
10	Electron beam energy, ε_e	0.02 %
11	Electron scattering angle, θ_e	0.02 %
12	t-scale calibration, T_R relative	0.04 %
13	t-scale calibration, T_R absolute	0.08 %
	$d\sigma/dt$, relative	0.1%
	$d\sigma/dt$, absolute	0.2%

Mainz Microtron and the A2 Hall

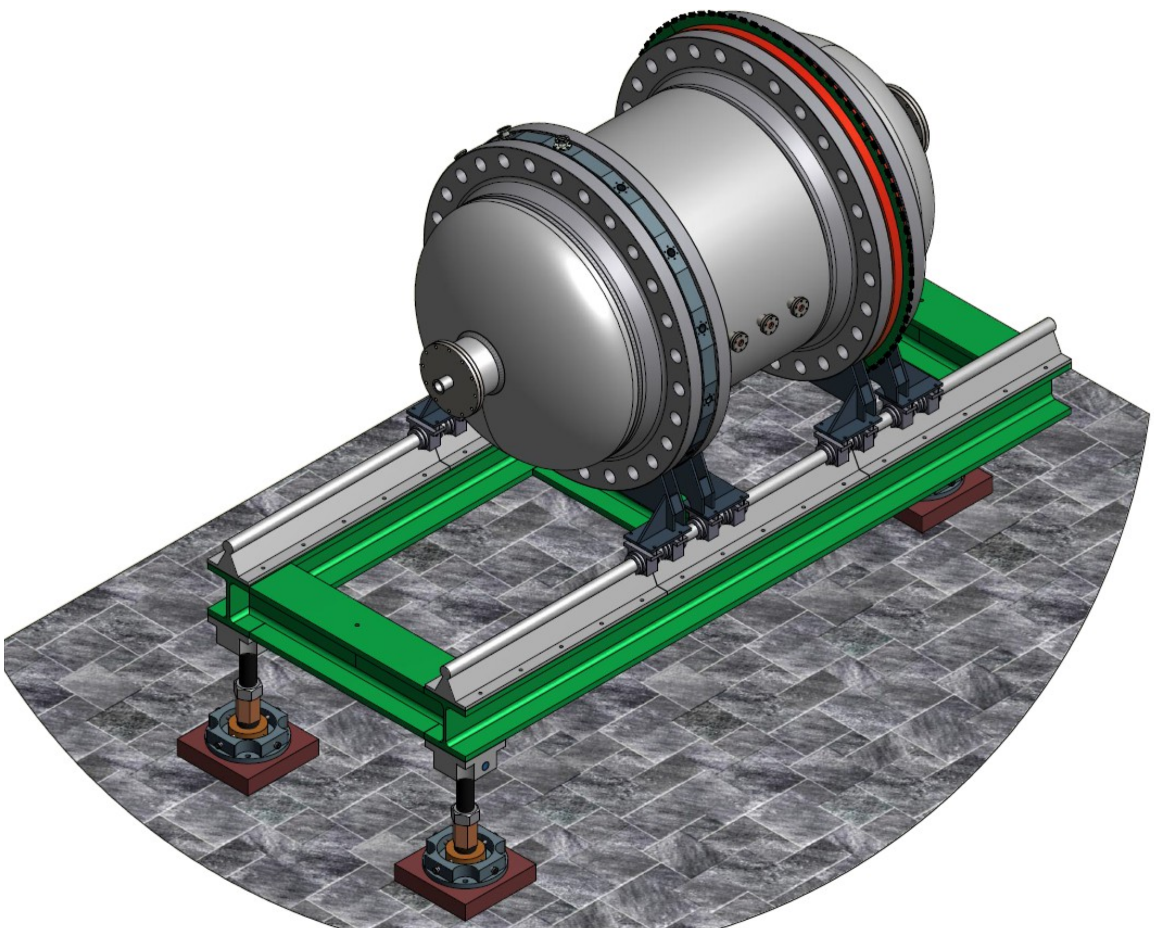
Mainz Microtron (MAMI)





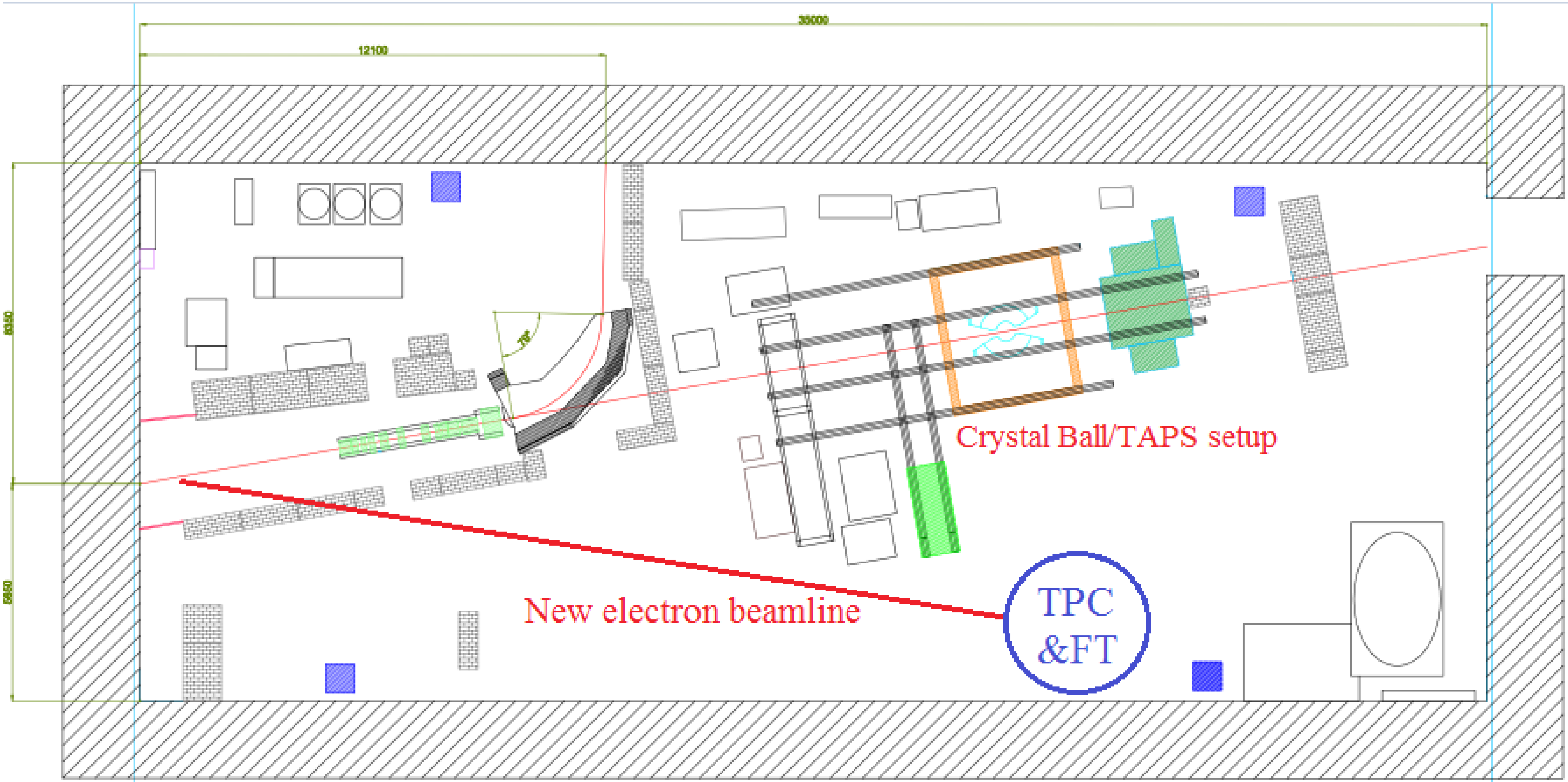
- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets
- → Electron scattering experiments with a hydrogen TPC (at 720 MeV)

IKAR-M experiment in the A2 Hall



- Total area required: 3 x 3 m
- ➔ How can the detector be used in the A2 Hall?
- ➔ How would it be possible to combine the plans of the A2 Collaboration with the proposed experiments?

Next: New electron beamline in A2

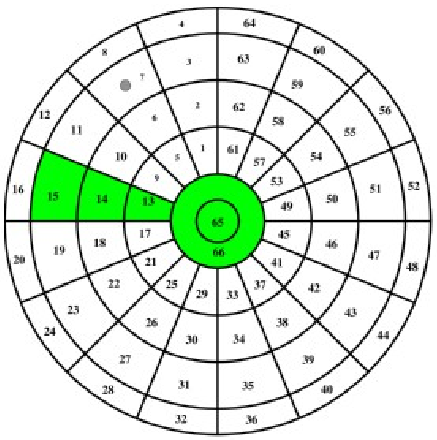


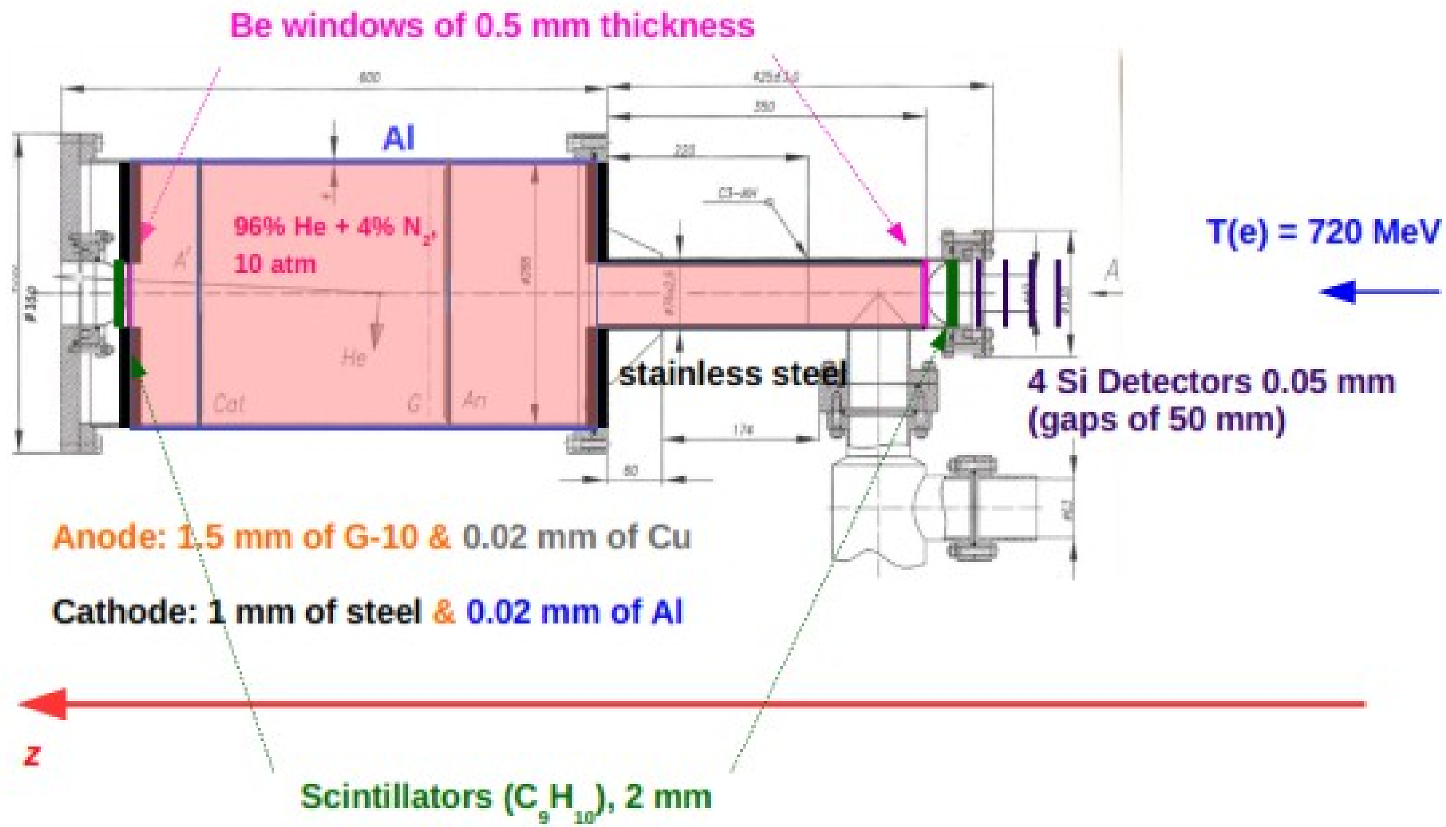
Construction of a new electron beamline in A2

- Distance ~20 m: additional dipole magnet, 3-4 quadrupole magnets, beam monitors
- Multilayer beam monitoring system for the TPC (HV-MAPS), beam scintillators
- Full support from the MAMI group + KPH Workshops

Feasibility and test experiments at MAMI

Segmented anode

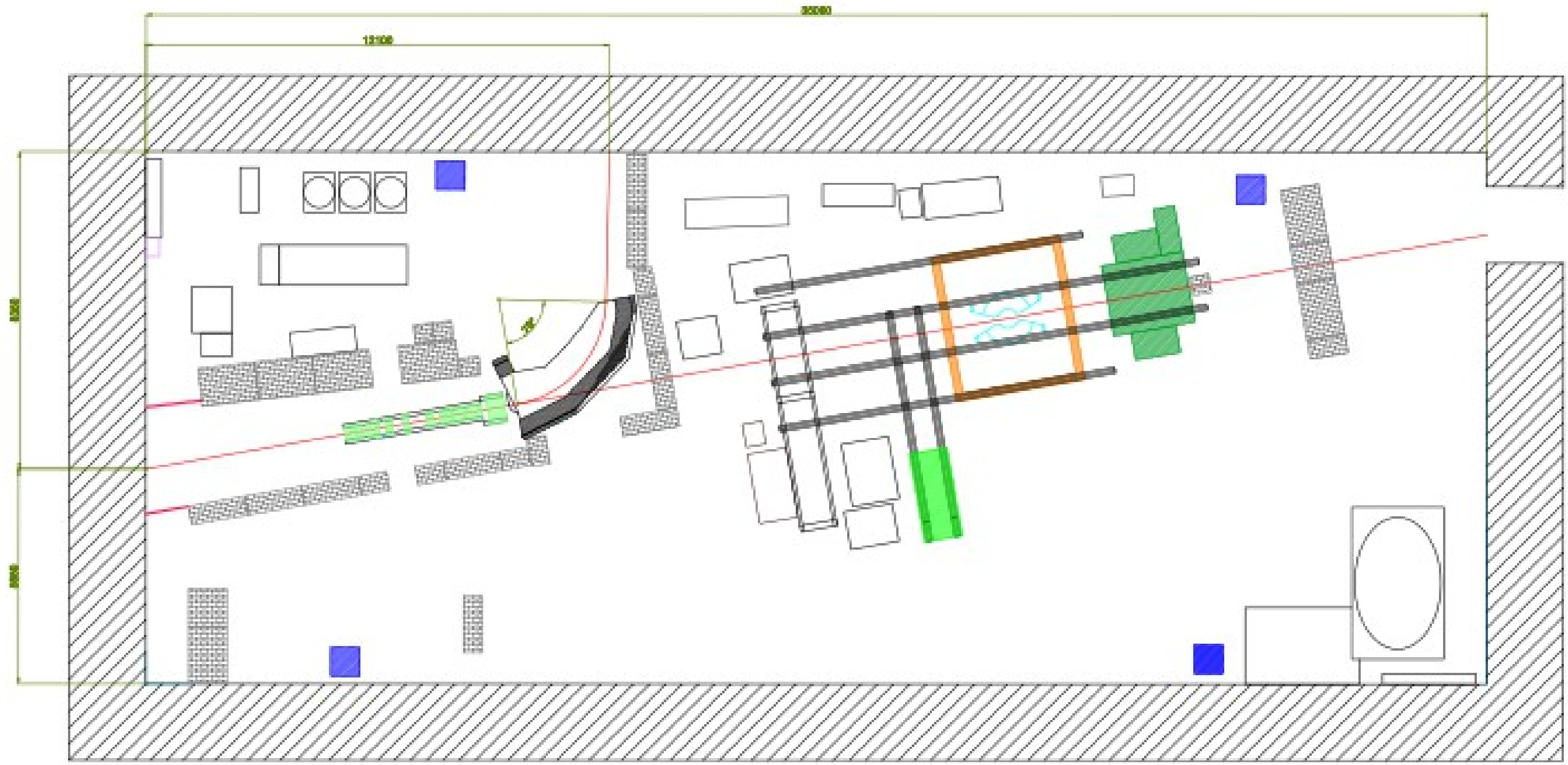




<u>Determination of the optimal run conditions for the main experiment:</u>

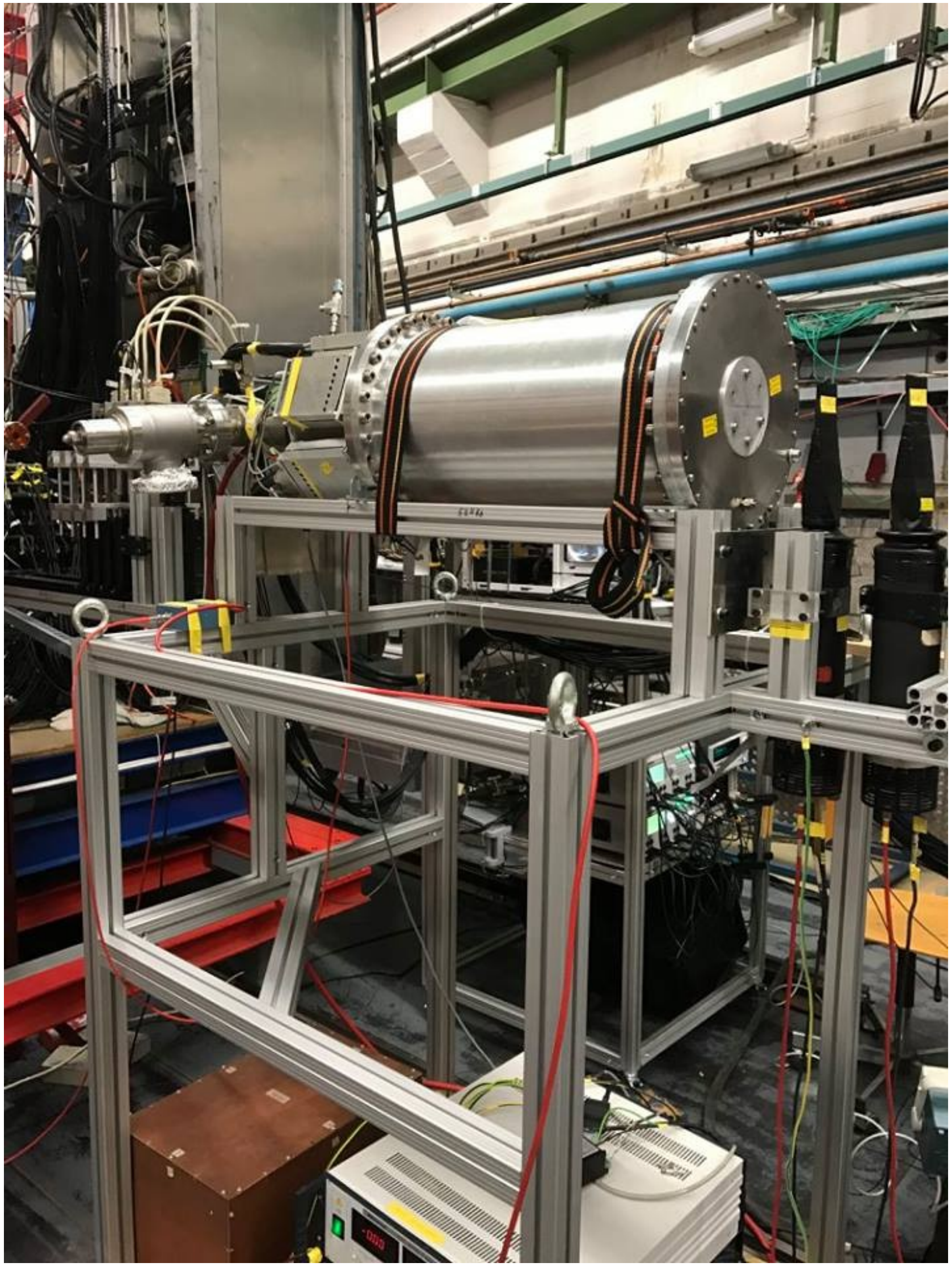
- Study of the background created by the electron beam at the intensity of 2×10^6 e/sec
- Development and test of a prototype for a beam monitoring system
- Measurement of the parameters of the low-intensity electron beam at 2×10^6 e/sec, $\sim10^4$ e/sec, and $\sim10^3$ e/sec

Beamline construction



Replaced the photon beamline in the A2 Hall with a temporary electron beamline

Test setup



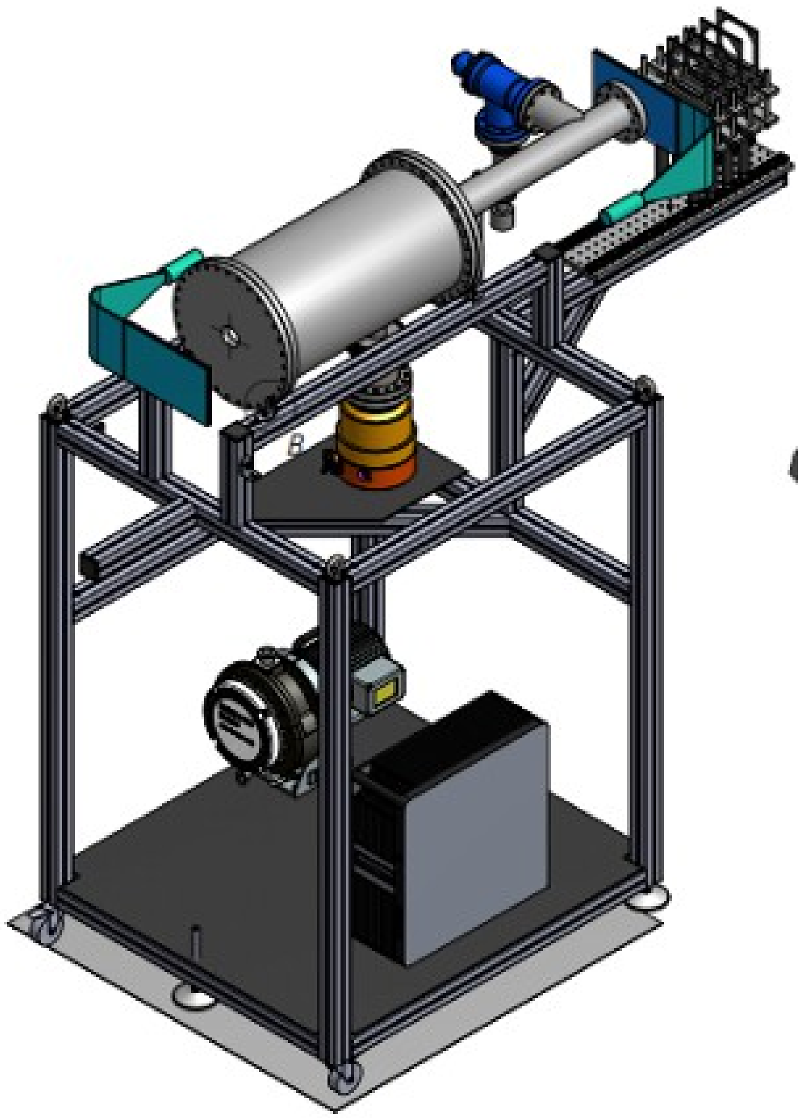
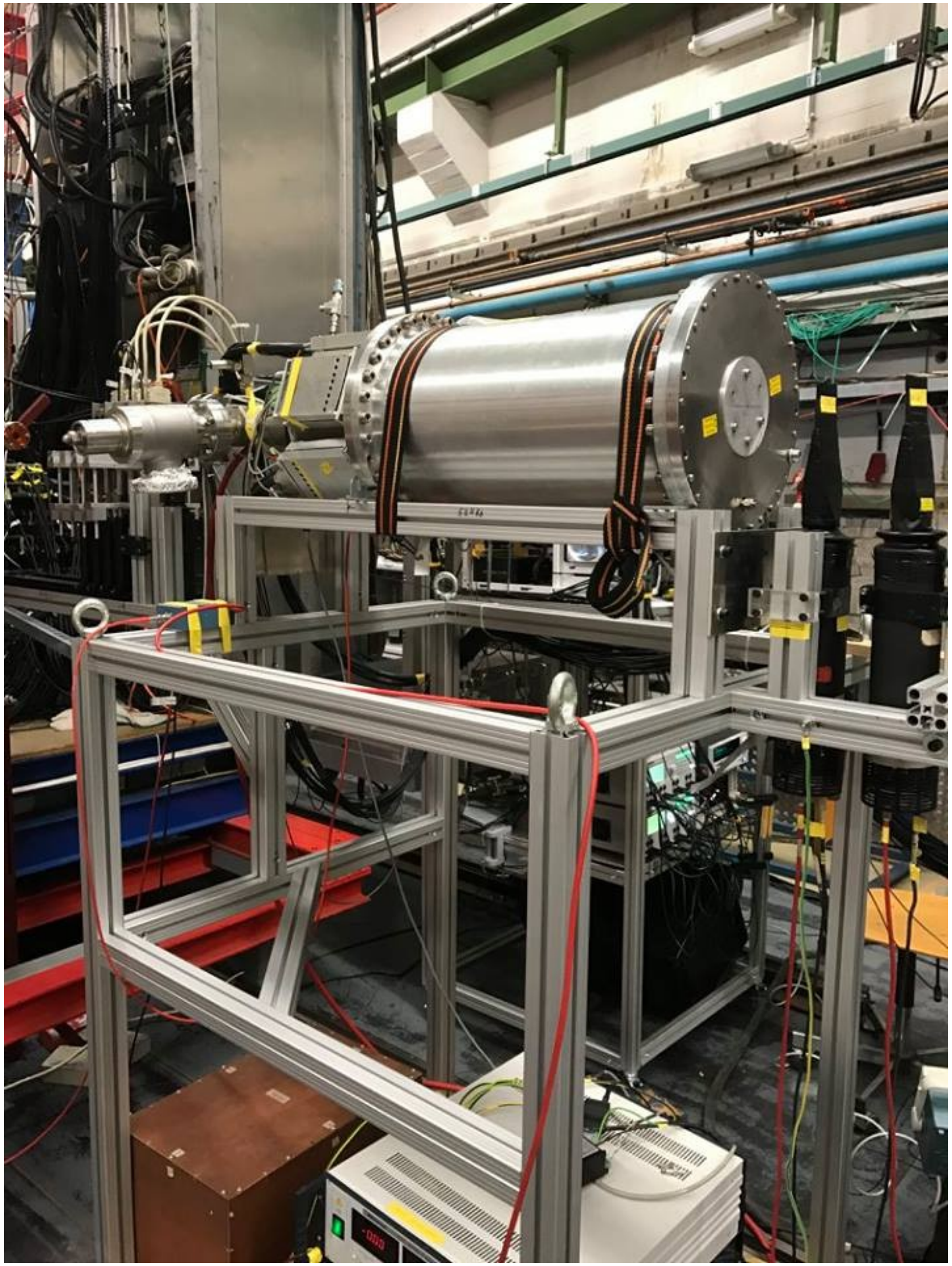


Figure from Marat Vznuzdaev (PNPI)

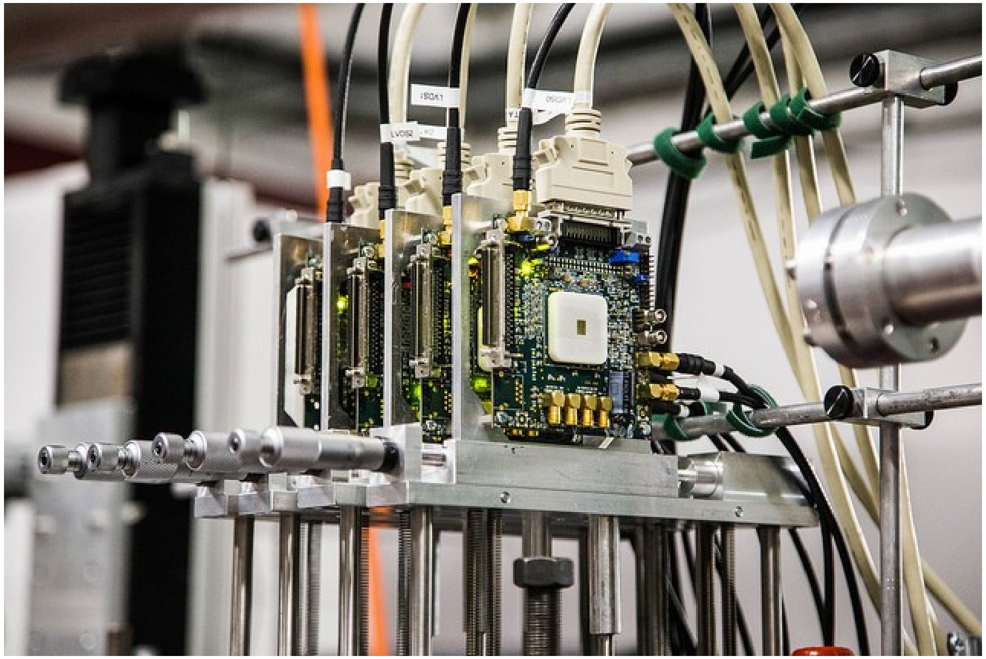
Test setup



- TPC mounted on the electron beamline Helium + 4.3% Nitrogen at 10 bar

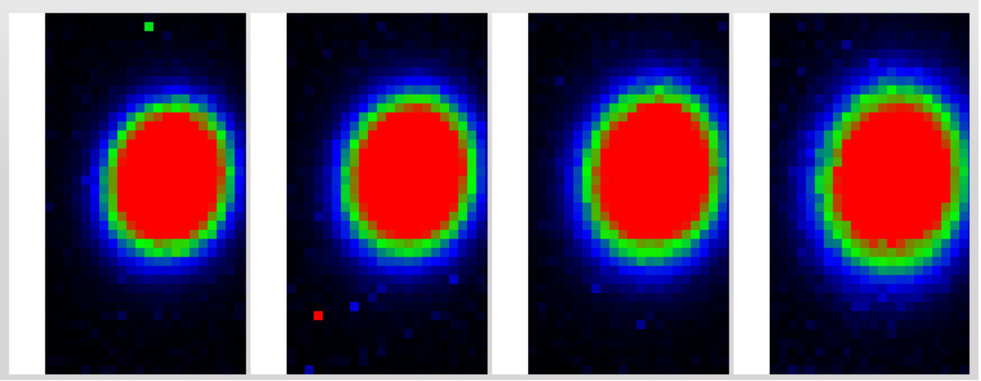
- Upstream and downstream scintillator counters (2mm thick, 55x55 mm) + 4-layer pixel detector (HV-MAPS, 3x3 mm)

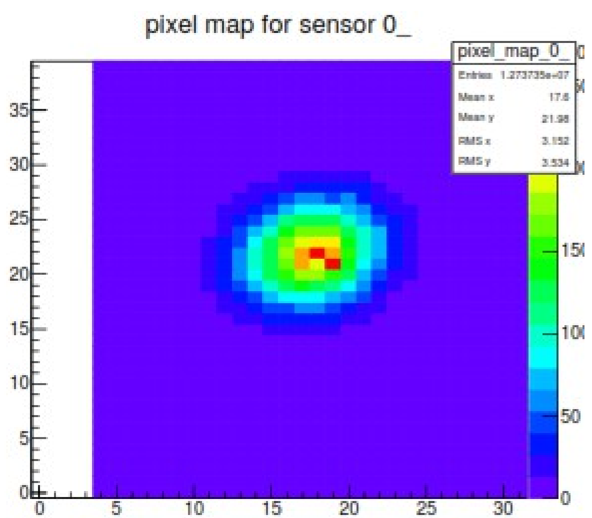
Test setup and beam monitoring system

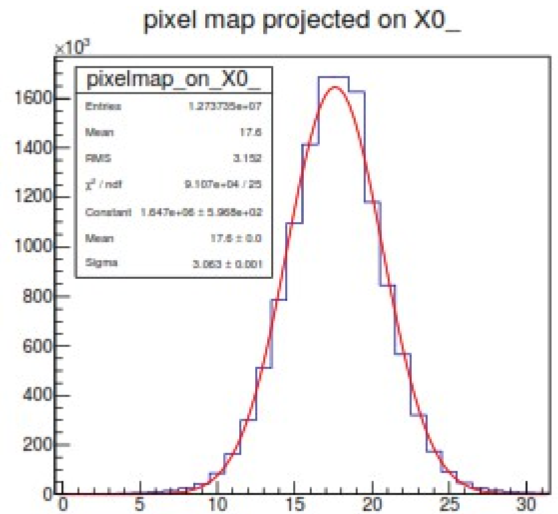


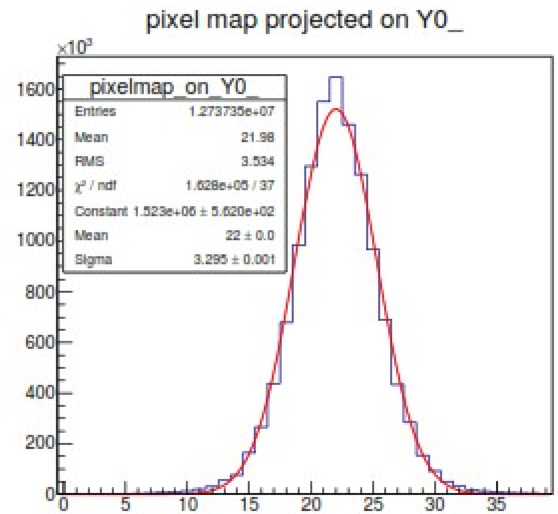
4-layer HV-MAPS pixel detector (3x3 mm)

Monitoring the beam position, reconstruction of electron tracks, and determination of the electron flux





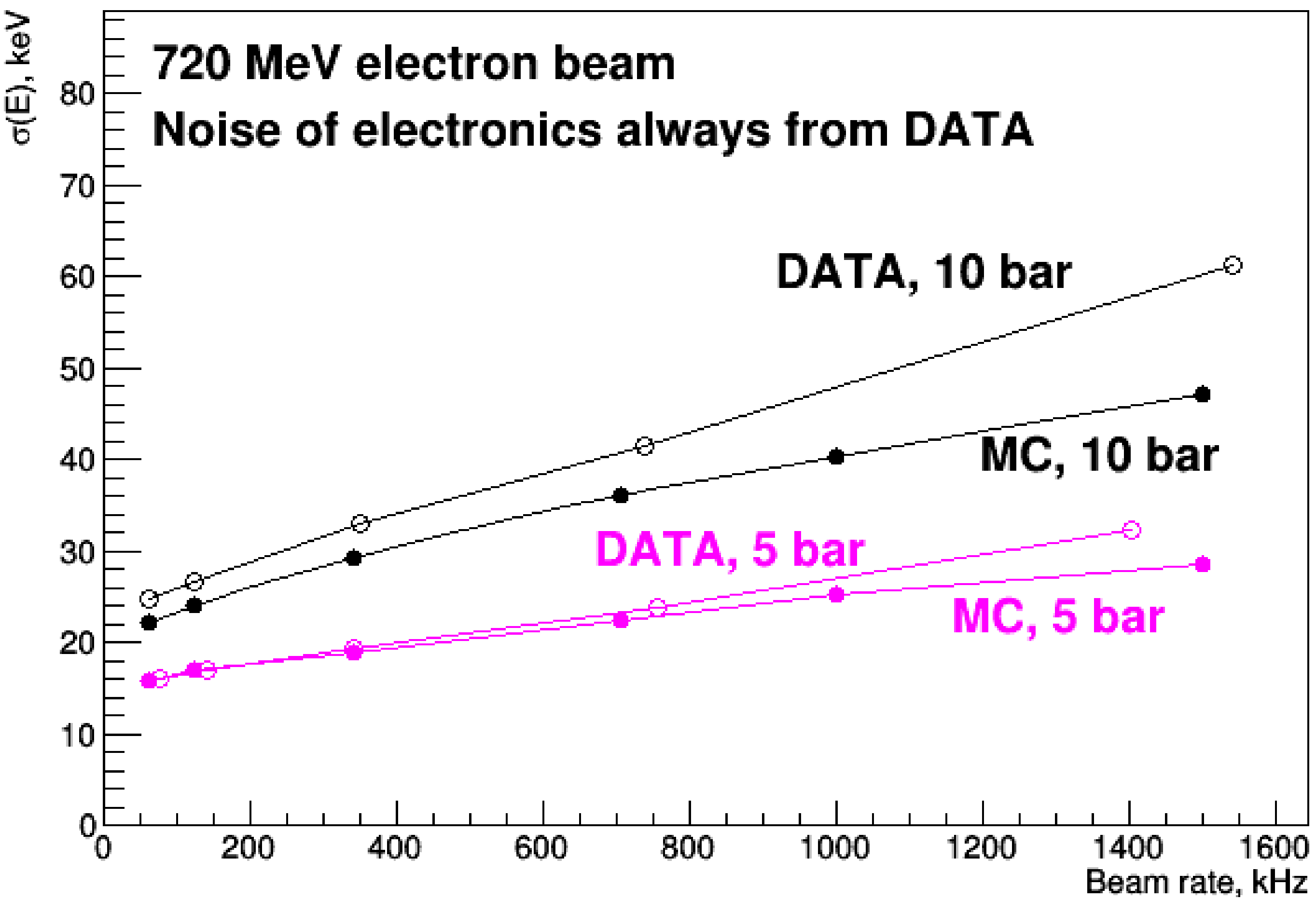




Alexey Tyukin, Frederik Wauters (KPH)

Noise from the electron beam

Beam ionization noise at the central pad

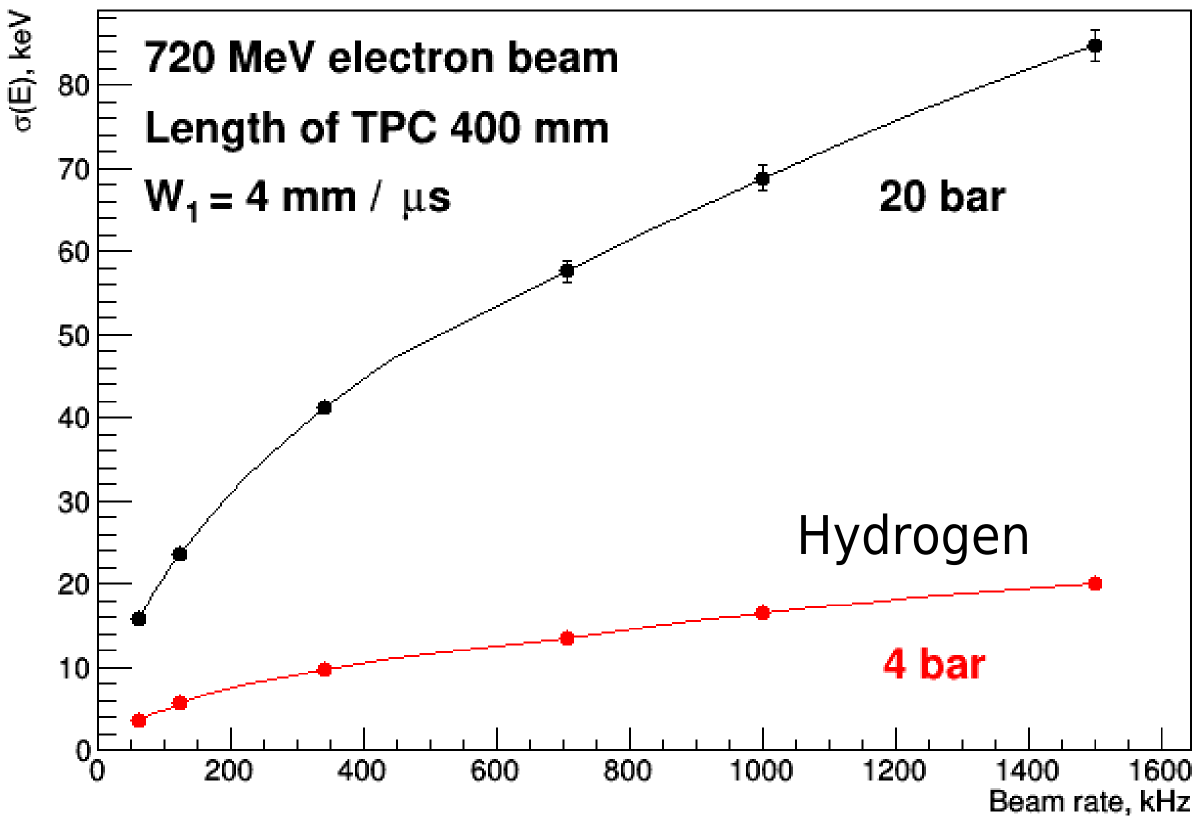


- The beam noise is nearly proportional to the gas pressure
- Measurements are in reasonable agreement with MC
- The beam noise in hydrogen is expected to be smaller than that in the He+4%N_2 mixture by ~ 20%

(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Noise from the electron beam (predictions)

Beam ionization noise at the central pad



Expected TPC energy resolution in the main experiment at 2 MHz beam rate

90 keV at the central pad, 20-30 keV at the other pads at 20 bar
30 keV at the central pad, 20-30 keV at the other pads at 4 bar

(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Main conclusions from the test run

- MAMI electron beam has excellent quality for this experiment
- The beam ionization noise in the central pad is in reasonable agreement with Monte Carlo simulation

Self triggering mode:
Any signal in the anode exceeding 300 keV
Rates:

- ~4 Hz including ~ 1Hz from elastic *e*He scattering at 10 bar with 1.6 MHz beam
- Very low background in the TPC except the central pad
- The low background allows to use TPC in the self-triggering mode

(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Agreement between KPH and PNPI (2017-2020)

Official agreement signed between KPH (Mainz) and PNPI (Gatchina)

Contribution of the KPH group:

- Construction of a dedicated electron beamline (calculations and hardware production) + technical service
- Preparation of a beam monitoring system and integration of this system into the TPC&FT readout system
- Simulations and data analysis

Contribution of the PNPI group:

- Design and construction of a high pressure (20 bar) hydrogen TPC combined with a forward tracker for scattered electrons
- Transportation of these detectors from PNPI to KPH Mainz
- Simulations, DAQ, data analysis

Status and next steps

Preparation of experiments with the IKAR-M (TPC&FT) in the A2 Hall:

- Contribution to understanding the proton radius puzzle
- Innovative approach with detection of both recoil proton and scattered electron
- Experiments possible with electron or photon beams and light nuclei

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Practical steps:

- Agreement signed between KPH Mainz and PNPI (2017-2020)
- Full proposal presented to PAC 2017 (A. Vorobyov, PNPI and A. Denig, KPH)
  → recommendation to proceed with the full program
- Successful test run: high quality electron beam in the A2 Hall and very low background contamination in the TPC

→ TPC operation feasible with an electron beam in the A2 Hall

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- ➔ First test with a complete setup in the end of 2019, the main experiment in 2020

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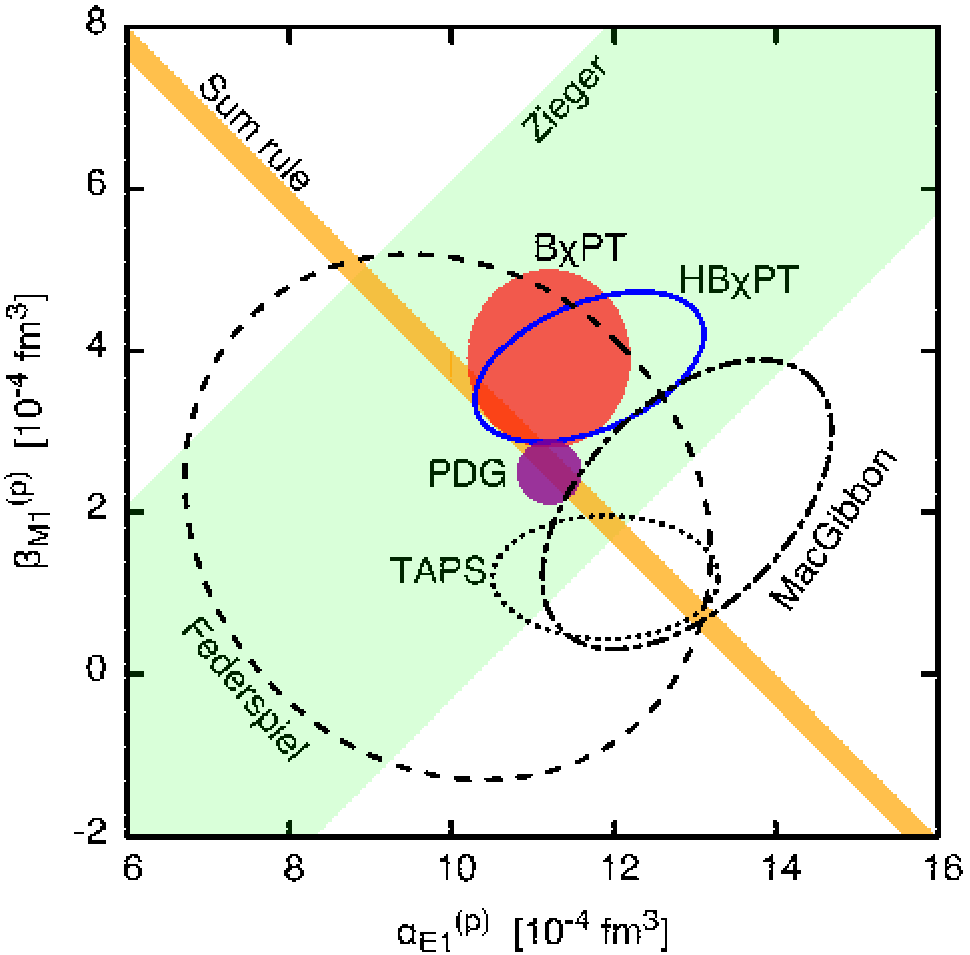
Proton radius program in Mainz:

- ➔ ISR Radiation measurements
- ➔ Measurements with a gas jet target in A1
- ➔ In the future: Measurements with a jet target at MESA

Scalar polarizabilities of the proton (A2 Collaboration)



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 introducing new experimental data?
- 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
- Important for atomic physics, determination of spin polarizabilities, **and proton radius determination from muonic hydrogen**

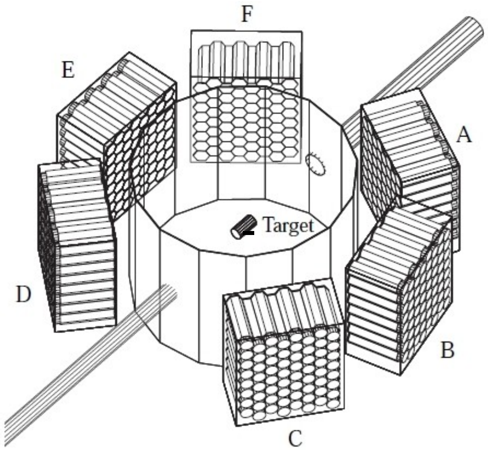
New single data set with small statistical and systematic errors

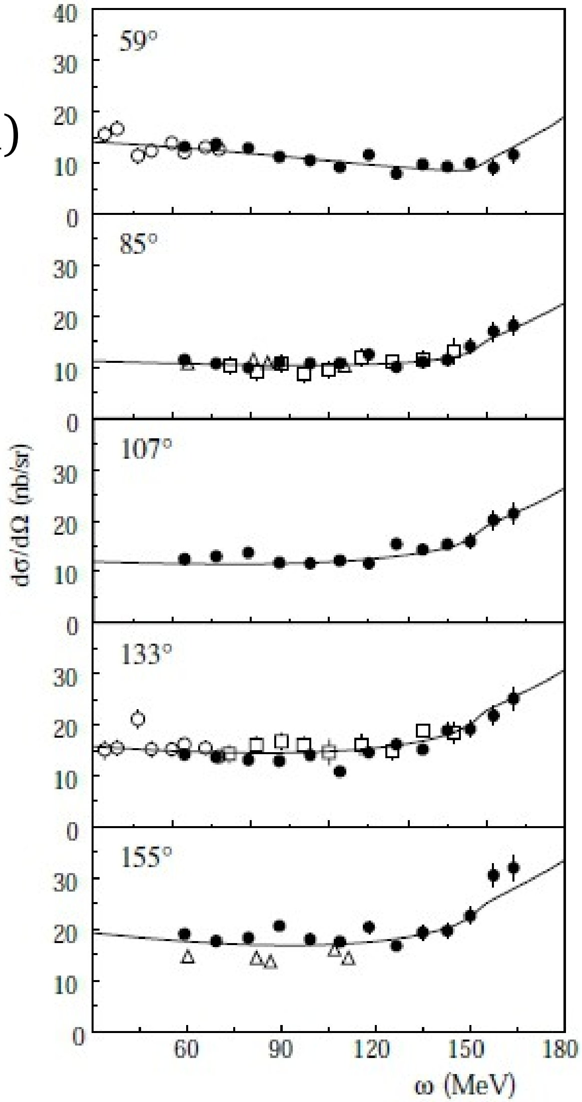
Compton scattering on the proton: Existing data

- Highest statistics data set:

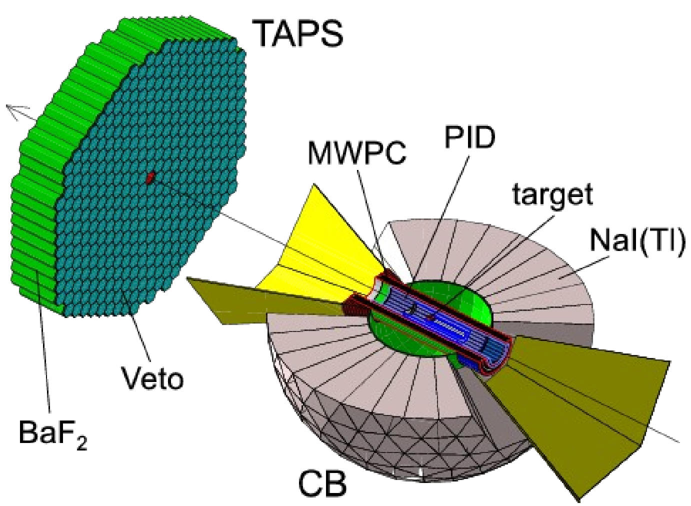
V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 1/3 acceptance of CB System!



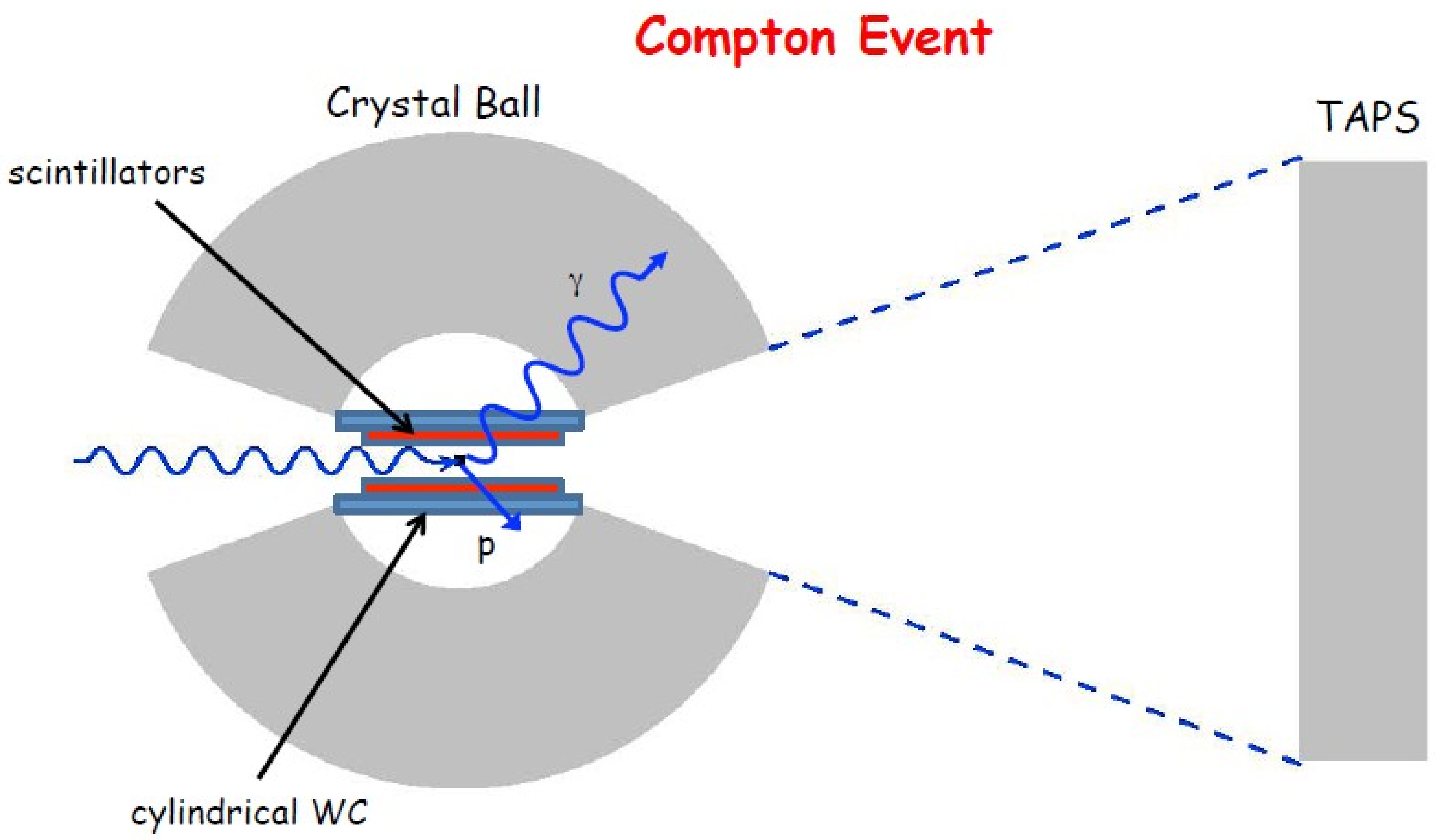


Crystal Ball/TAPS: Nearly 4π coverage



Triangles: P.S. Baranov et al., Phys. Lett. B 52, 22 (1974); P.S. Baranov et al., Sov. J. Nucl. Phys. 21, 355 (1975)
Open circles: F.J. Federspiel et al., Phys. Rev. Lett. 67, 1511 (1991)
Squares B.E. MacGibbon et al., Phys. Rev. C 52, 2097 (1995)
Curve: R.A. Arndt et al., Phys. Rev. C 53, 430 (1996)

Compton scattering



(Figure from Rory Miskimen)

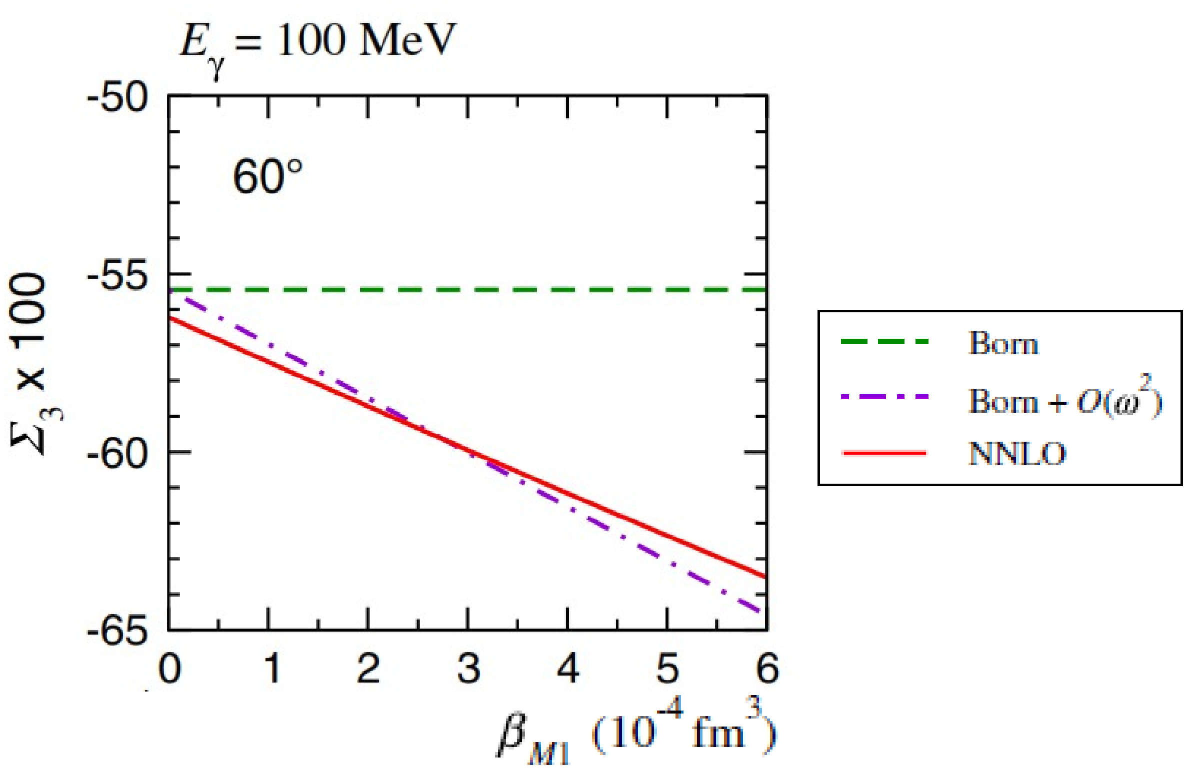
Beam asymmetry for Compton scattering

At low energies, the measurement of the beam asymmetry, Σ_3 is an alternative way to extract β_{M1} (N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)])

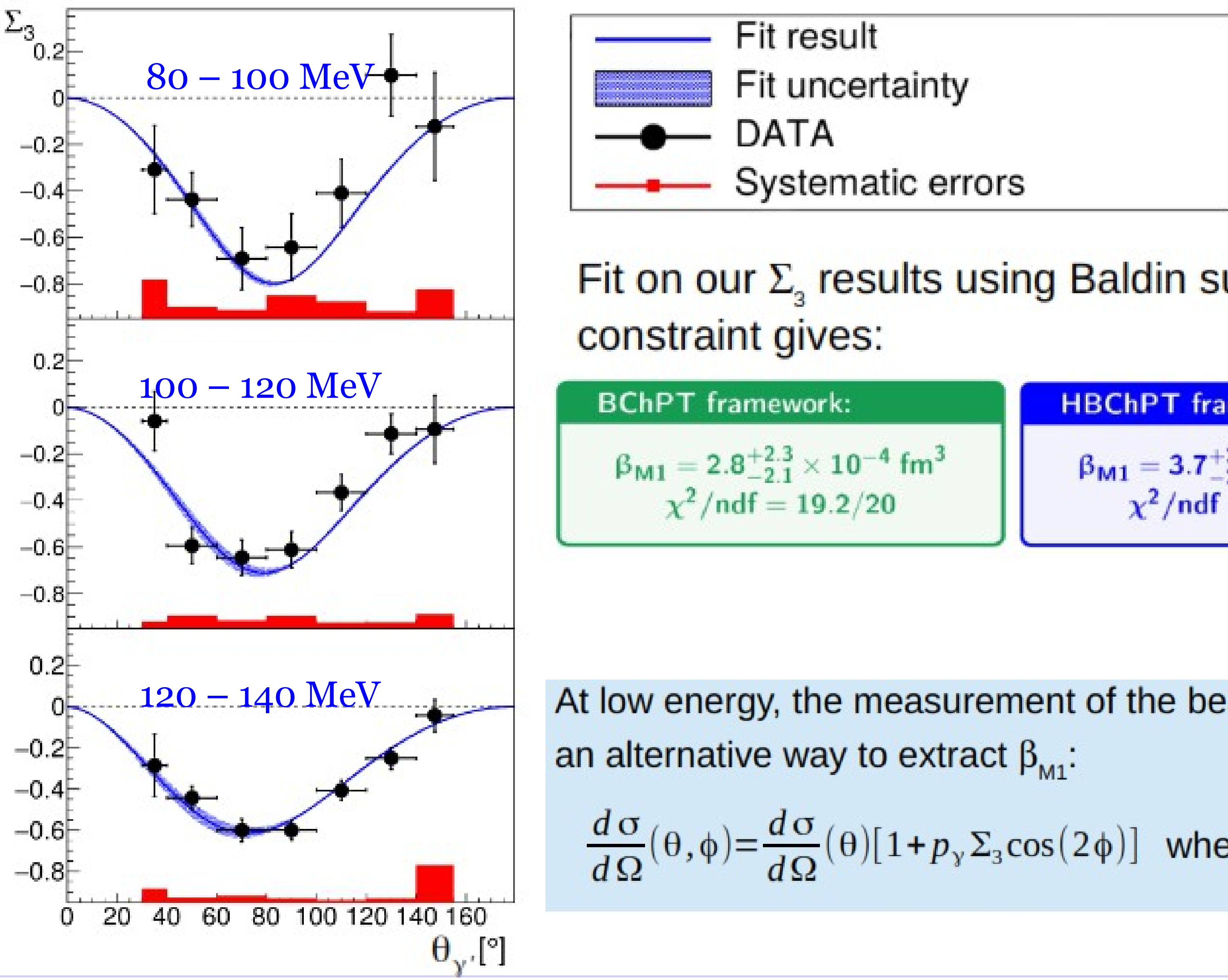
- Measurements with linearly polarized photons and liquid hydrogen target

$$\Sigma_3 \equiv \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}$$

$$\sigma_{pol} = \sigma_{unpol}(1 \pm \delta_l \, \Sigma_3 \cos 2\phi)$$



First measurement of Σ_3 below pion threshold



Fit on our Σ_3 results using Baldin sum rule constraint gives:

BChPT framework:

$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 19.2/20$

HBChPT framework:

$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 17.1/20$

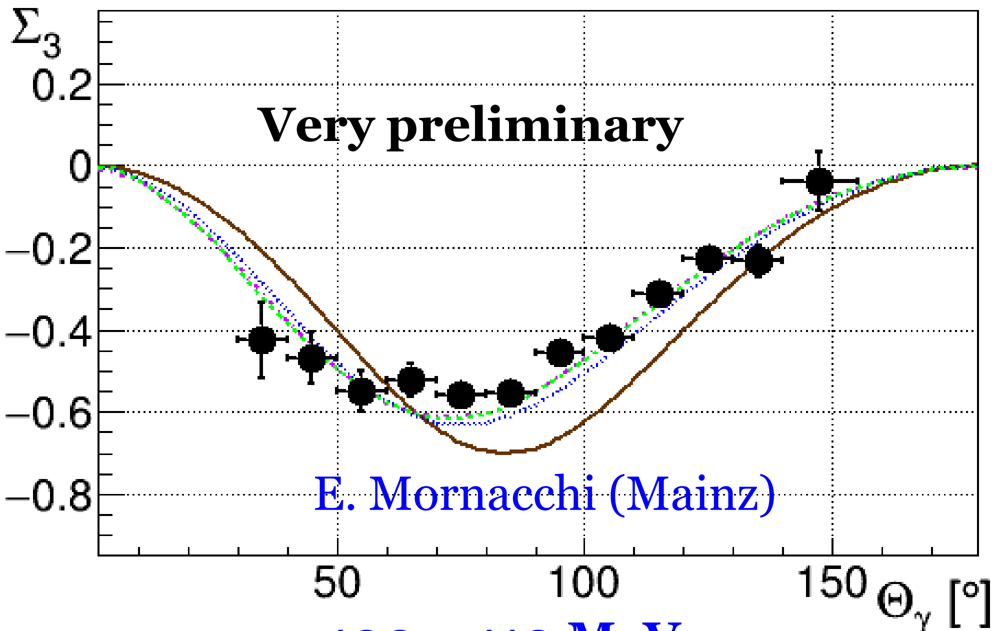
At low energy, the measurement of the beam asymmetry Σ_3 provides an alternative way to extract β_{M1}:

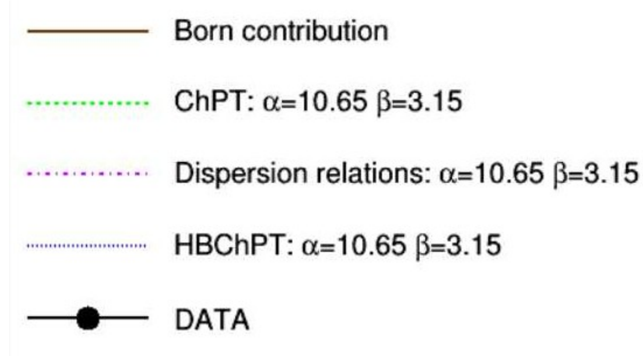
$$\frac{d\sigma}{d\Omega}(\theta,\phi)=\frac{d\sigma}{d\Omega}(\theta)[1+p_\gamma\Sigma_3\cos(2\phi)] \quad \text{where} \quad \Sigma_3=\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

V. S., E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina,Eur.Phys.J. A53 (2017) no.1, 14

New data high-quality set from the A2 Collaboration

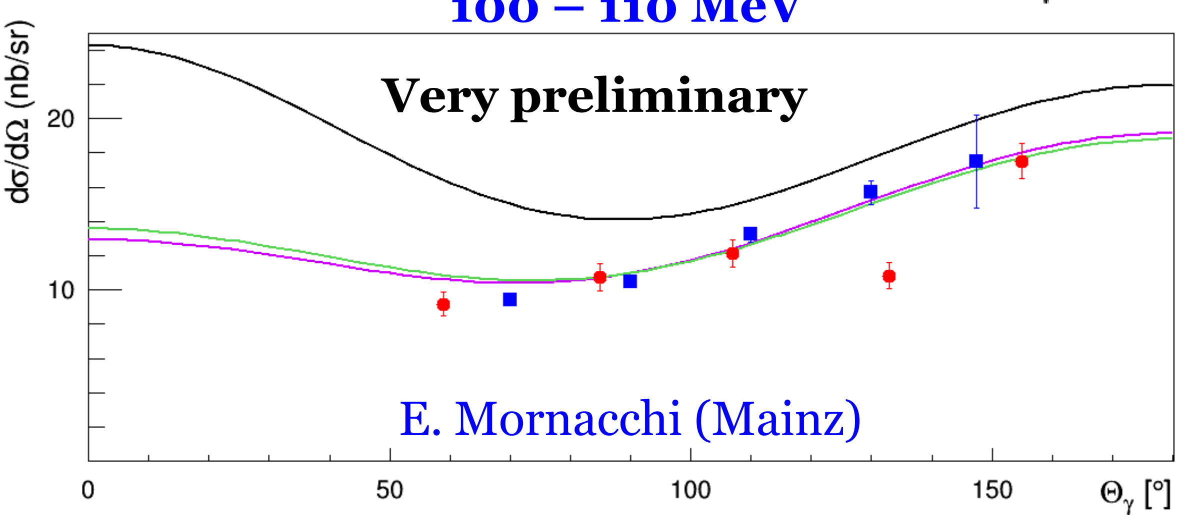
120 – 140 MeV

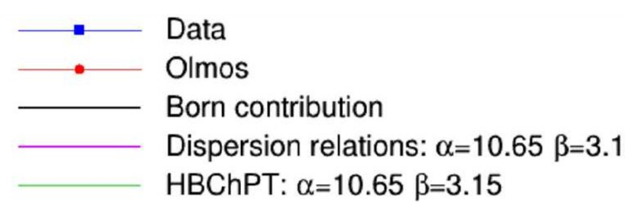




Data analysis ongoing:
Only ~60% of the available statistics

100 – 110 MeV





MAMI PAC (2016):
E.J. Downie, D. Hornidge,
P. Martel, V.S.

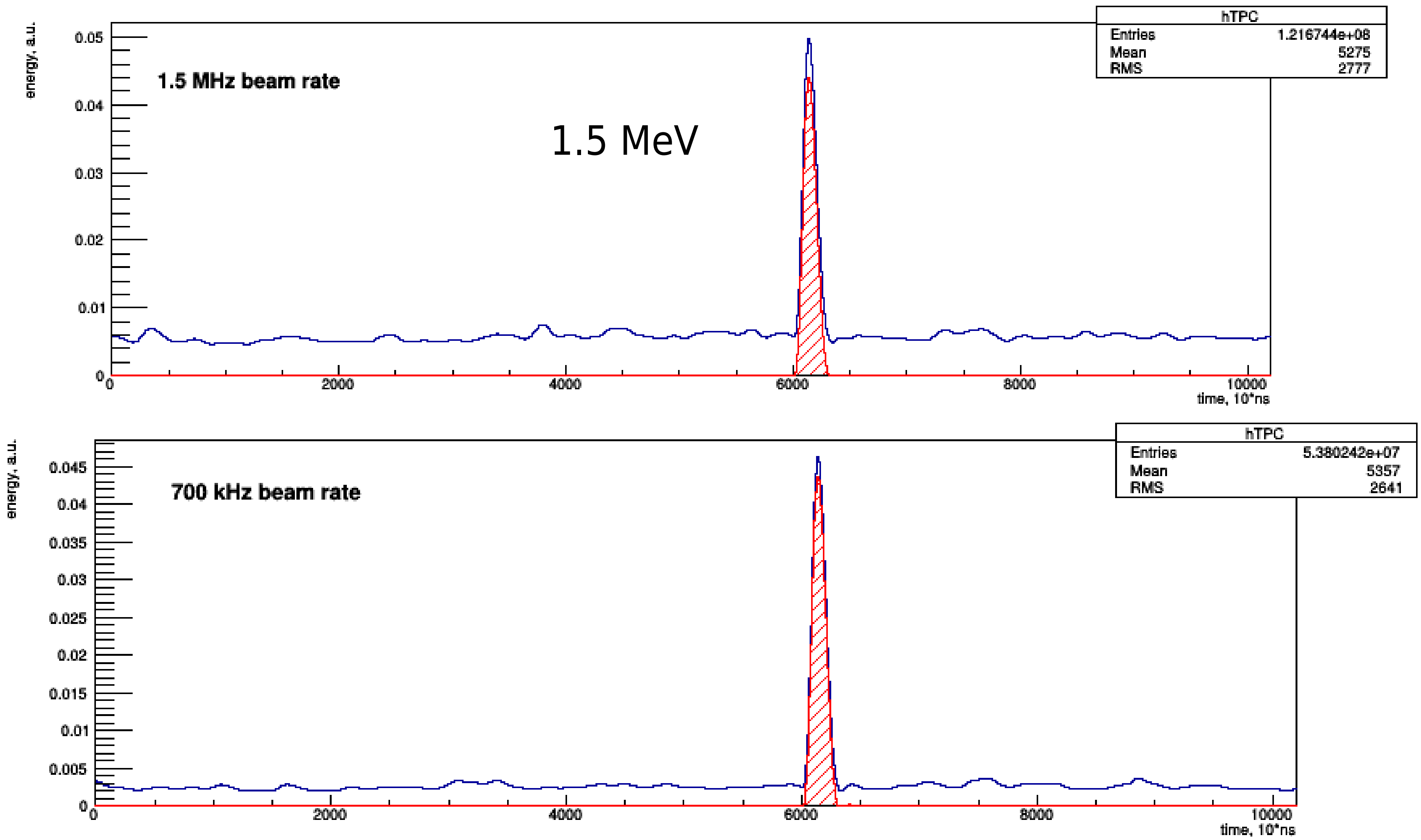
- Highest statistics data set on Compton scattering below pion threshold!
- ➔ Proton scalar polarizabilities will be extracted with unprecedented precision
- ➔ New contribution to the determination of the proton radius in muonic hydrogen

Thank you for your attention!

Backup

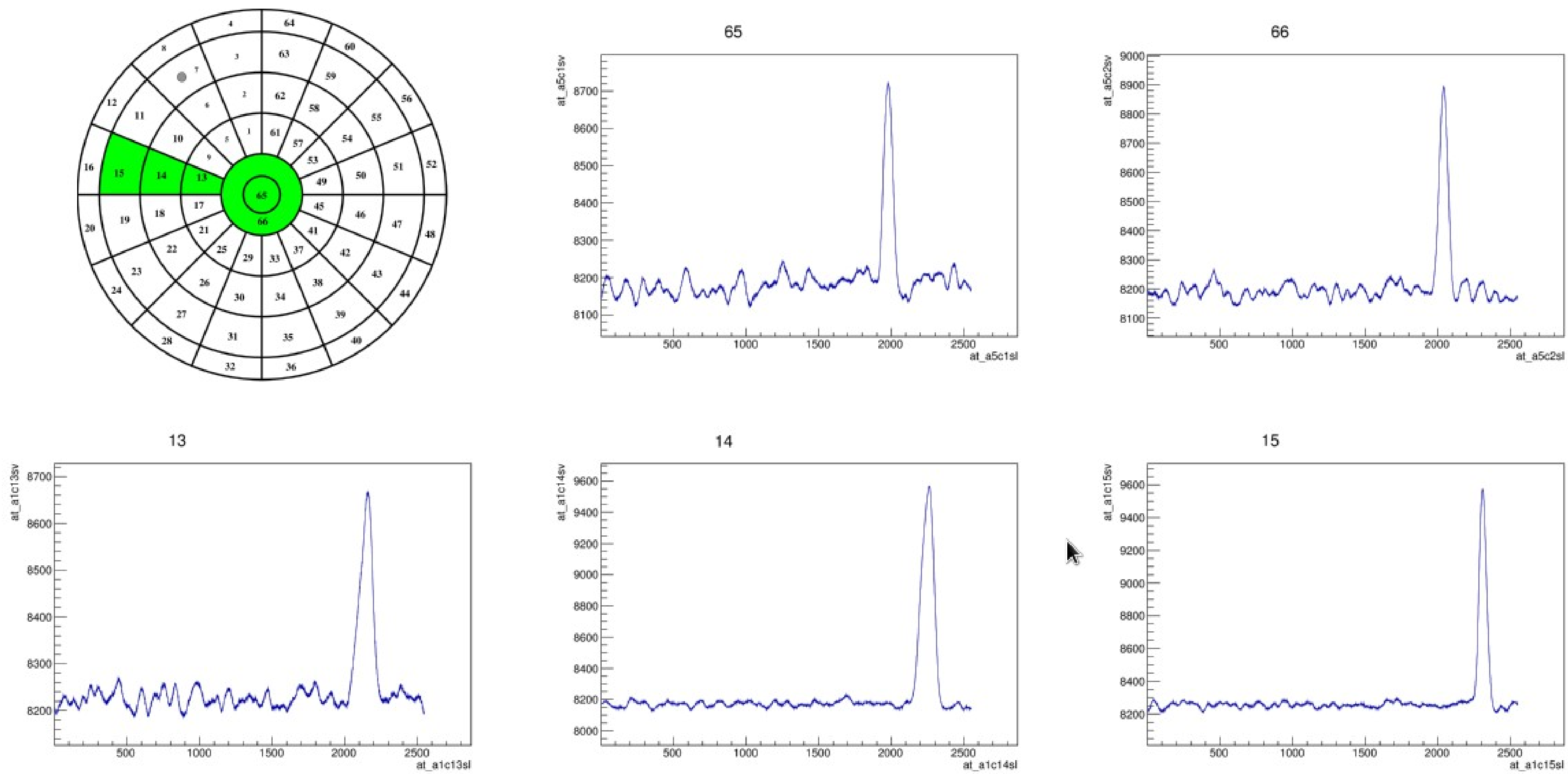
Beam ionization noise in the TPC

Central pad



(Alexey Dzyuba, Alexey Vorobyov, PNPI)

Example recoil track in the TPC



Signals in the TPC clearly identified!

(Alexander Inglessi, PNPI)

Patrik Adlarson

CREMA deuteron charge radius

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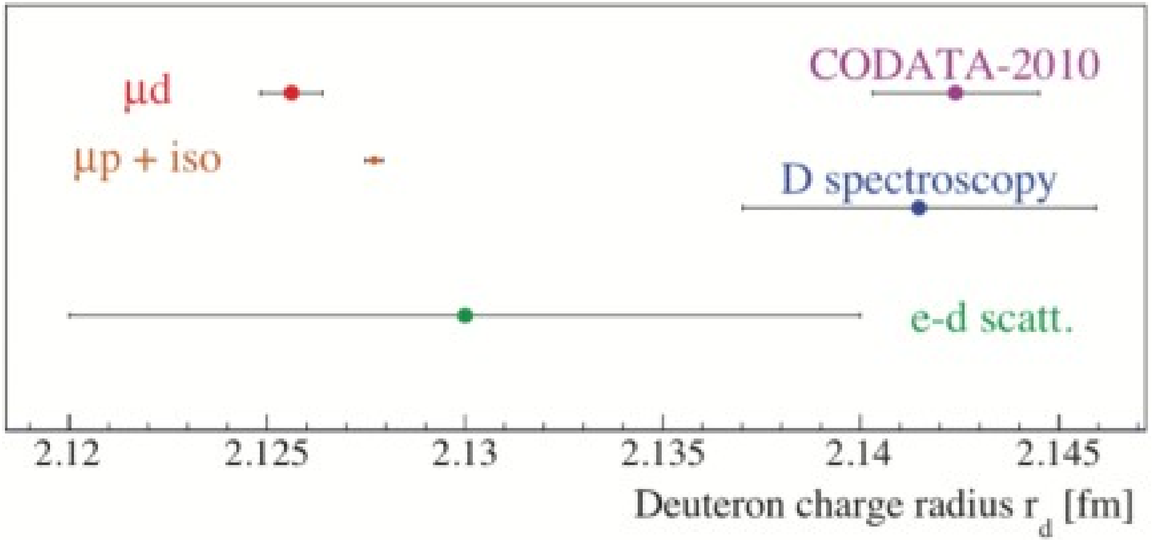


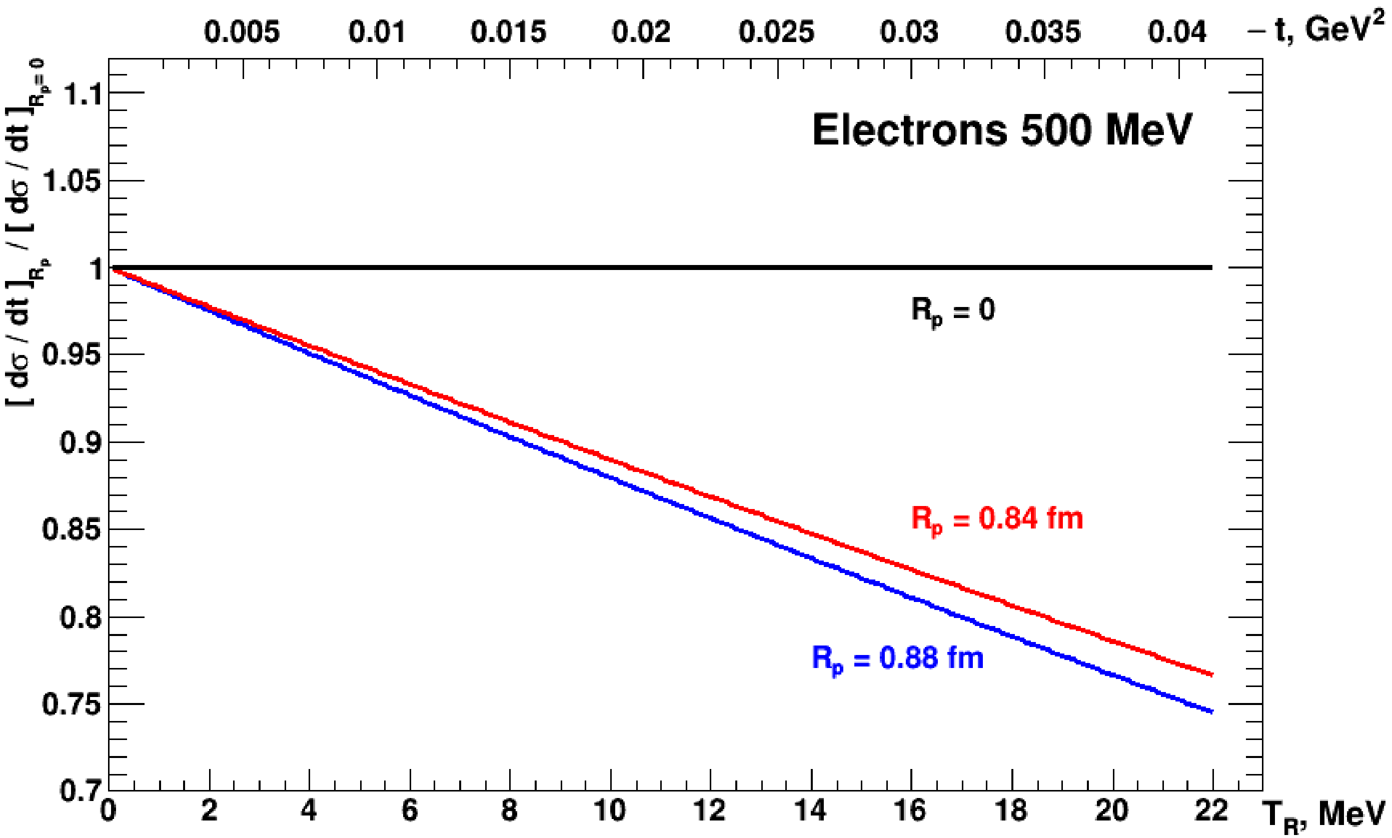
Randolf Pohl et al. CREMA collaboration. Science, 353(6300):669, August 2016.

Very recently CREMA made their muonic deuterium official. Two ways to extract the deuteron radius. Both favor low deuteron radius

Similar discrepancy compared to e-deuteron, 7.5σ, only 2.6σ off when taking the muonic proton + isotope shift

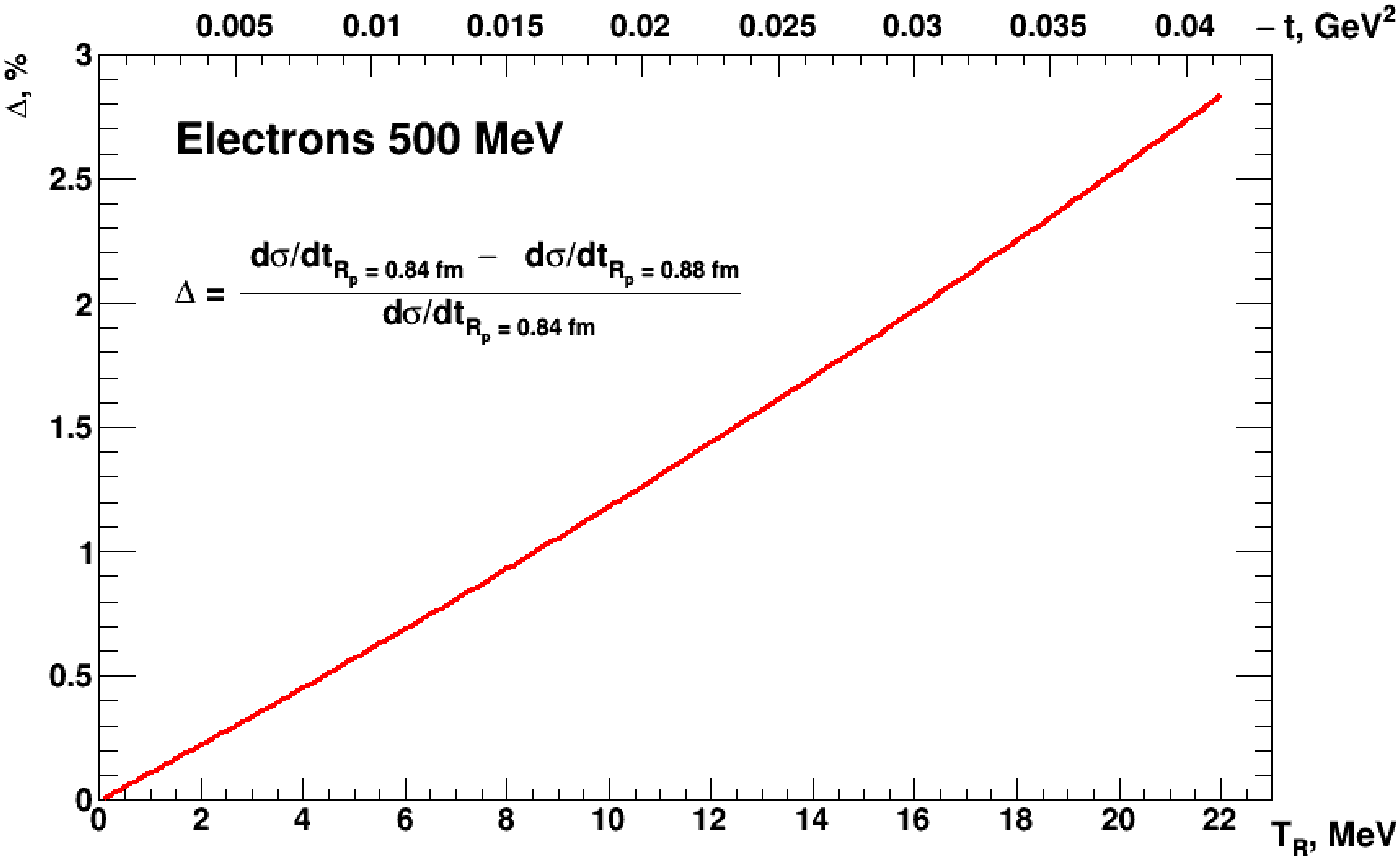
Charge radius puzzle became charge radii puzzle

$[d\sigma/dt]_{Rp}$ / $[d\sigma/dt]_{Rp=0}$



Difference in dσ/dt between Rp=0.84 fm and Rp=0.88 fm
is only 1.3% at Q^2 =0.02Gev²

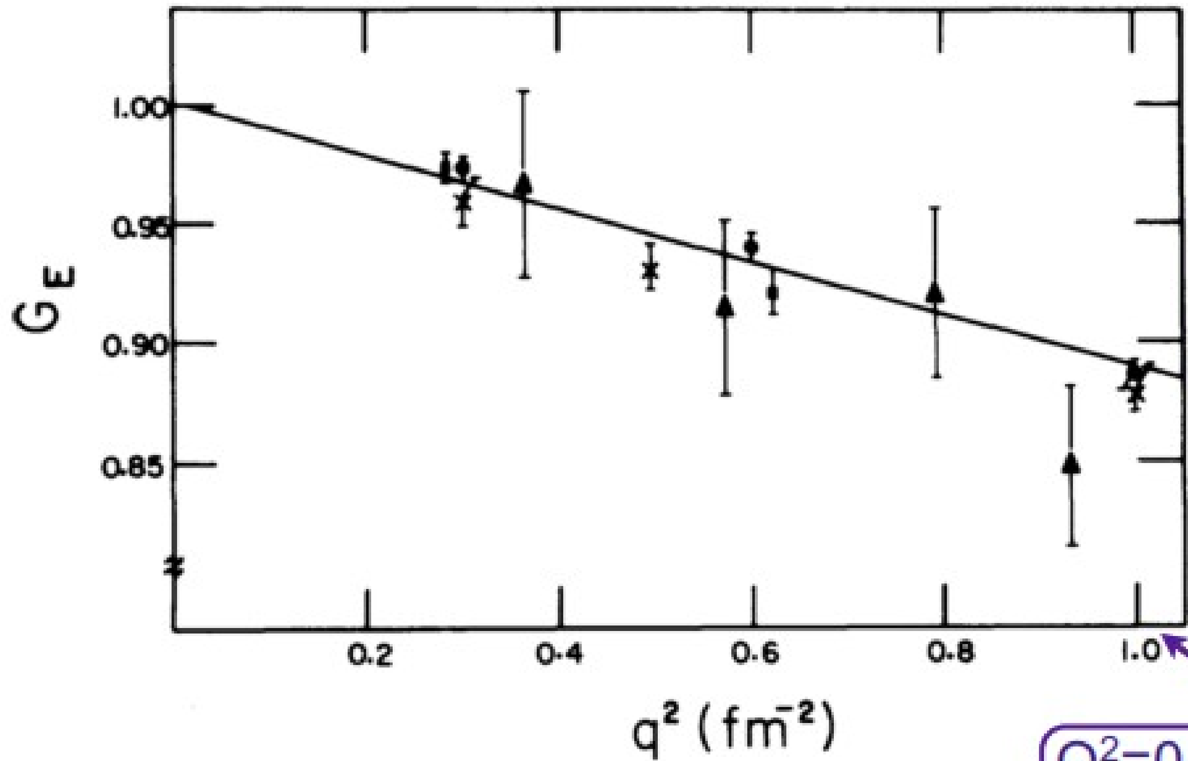
Sensitivity of dσ/dt to proton radius



Mesurement of dσ/dt with point-to-point precision 0.1%

Backup

Low Q^2 G_E in 1974



r_E = 0.810(40) fm

Q^2=0.0389 GeV^2

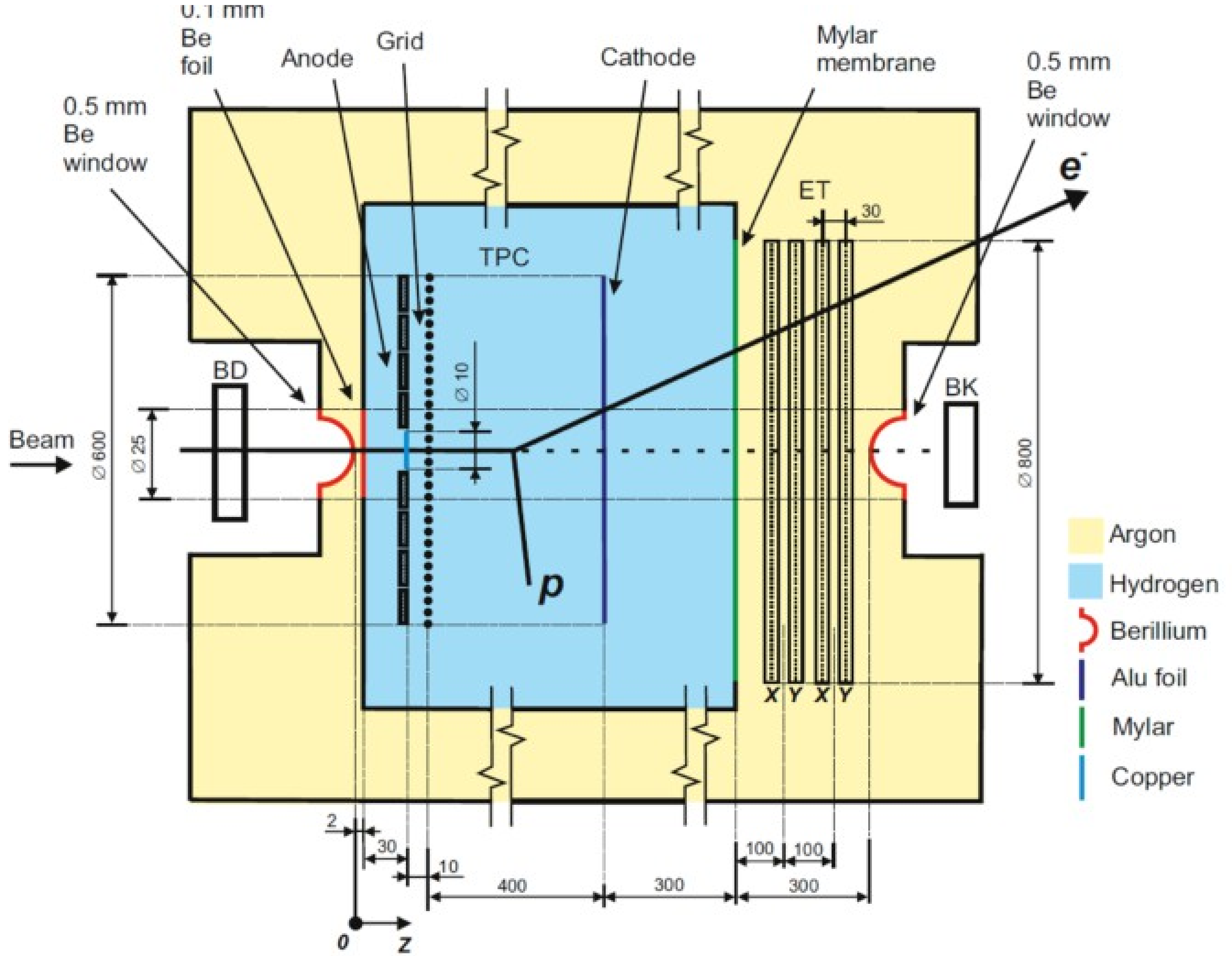
Fit to $G_E(Q^2)=a_0+a_1Q^2+a_2Q^4$

Saskatoon 1974

factor we deduce an rms charge radius for the proton of 0.81 ± 0.04 fm, which is in agreement with the generally accepted value of 0.805 ± 0.011 fm,[5]

Murphy PRC9(74)2125

Backup



A. Vorobyov (PNPI)

Backup

The ep elastic scattering cross sections are given by the following expression:

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{t^2}\left\{G_E^2\left[\frac{\left(4M + t/\varepsilon_e\right)^2}{4M^2 - t} + \frac{t}{\varepsilon_e^2}\right] - \frac{t}{4M^2}G_M^2\left[\frac{\left(4M + t/\varepsilon_e\right)^2}{4M^2 - t} - \frac{t}{\varepsilon_e^2}\right]\right\} \tag{1}$$

where $t = -Q^2$, $\alpha = 1/137$, ε_e - initial electron energy, M – proton mass, G_E – electric form factor and G_M – magnetic form factor.

At low Q^2 the form factors can be represented by the expansions:

$$\frac{G(Q^2)}{G(0)} = 1 - \frac{1}{6}\langle R_p^2\rangle Q^2 + \frac{1}{120}\langle R_p^4\rangle Q^4 - \ldots, \tag{2}$$

The electric proton radius R_{pE} can be measured by measuring the slope of the electric form factor G_E as Q^2 goes to 0:

$$R_{pE}^2 = \left.\frac{-6 \cdot dG_E(Q^2)}{dQ^2}\right|_{Q^2 \to 0} \tag{3}$$

A. Vorobyov (PNPI)

Backup

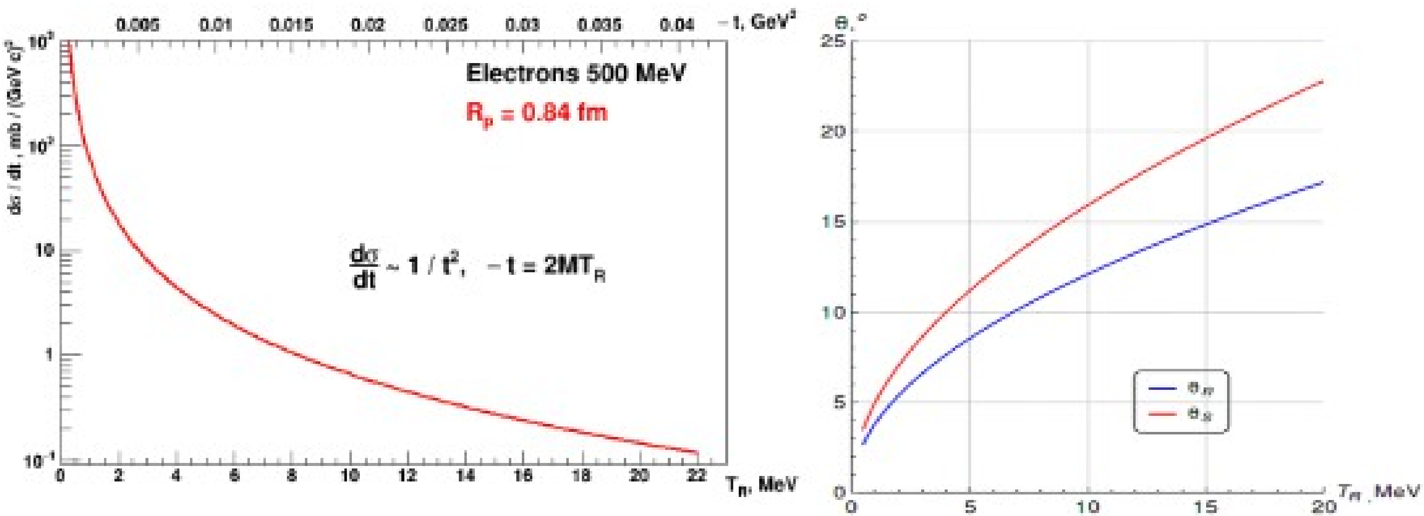


Figure 2: Left panel: differential cross section of the ep elastic scattering calculated for ε = 500 MeV with electric and magnetic form factors represented by expansion Eq. 2. Right panel: Scattering electron and recoil proton angles as function of the recoil proton energy.

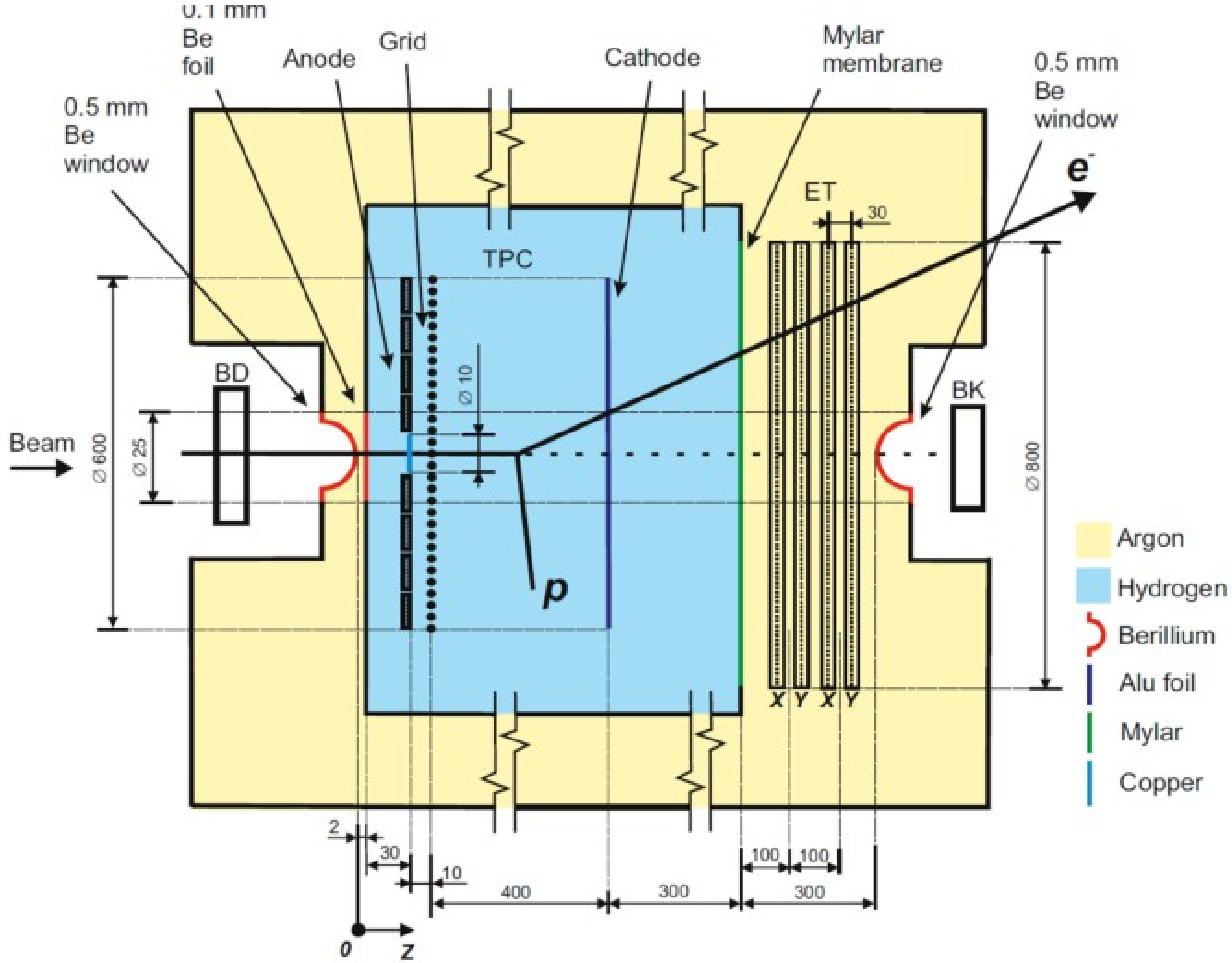
The ep elastic scattering differential cross section is given by the following expression:

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{t^2}\left\{G_E^2\left[\frac{(4M+t/\varepsilon)^2}{4M^2-t}+\frac{t}{\varepsilon^2}\right]-\frac{t}{4M^2}G_M^2\left[\frac{(4M+t/\varepsilon)^2}{4M^2-t}-\frac{t}{\varepsilon^2}\right]\right\}, \quad (1)$$

where $t = -Q^2$, $\alpha = (137)^{-1}$ – fine structure constant, ε – initial electron energy, M – proton mass, G_E and G_M -– proton electric and magnetic form factors. At the low Q^2, the form factors can be represented by the expansions

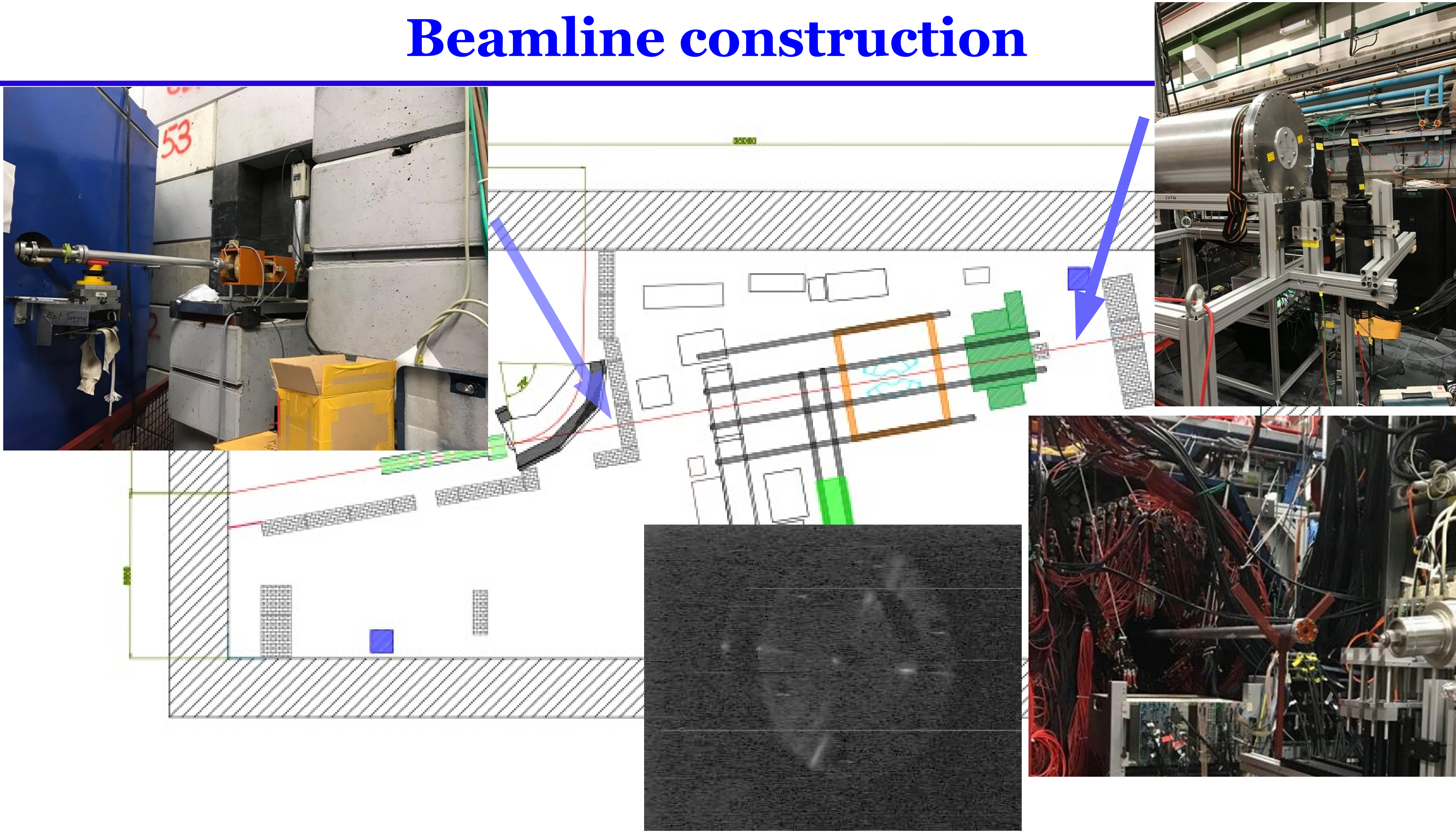
$$\frac{G_{E,M}(Q^2)}{G_{E,M}(0)} = 1 - \frac{\langle r^2_{pE,M}\rangle}{6}Q^2 + \mathcal{O}(Q^4), \quad (2)$$

Backup



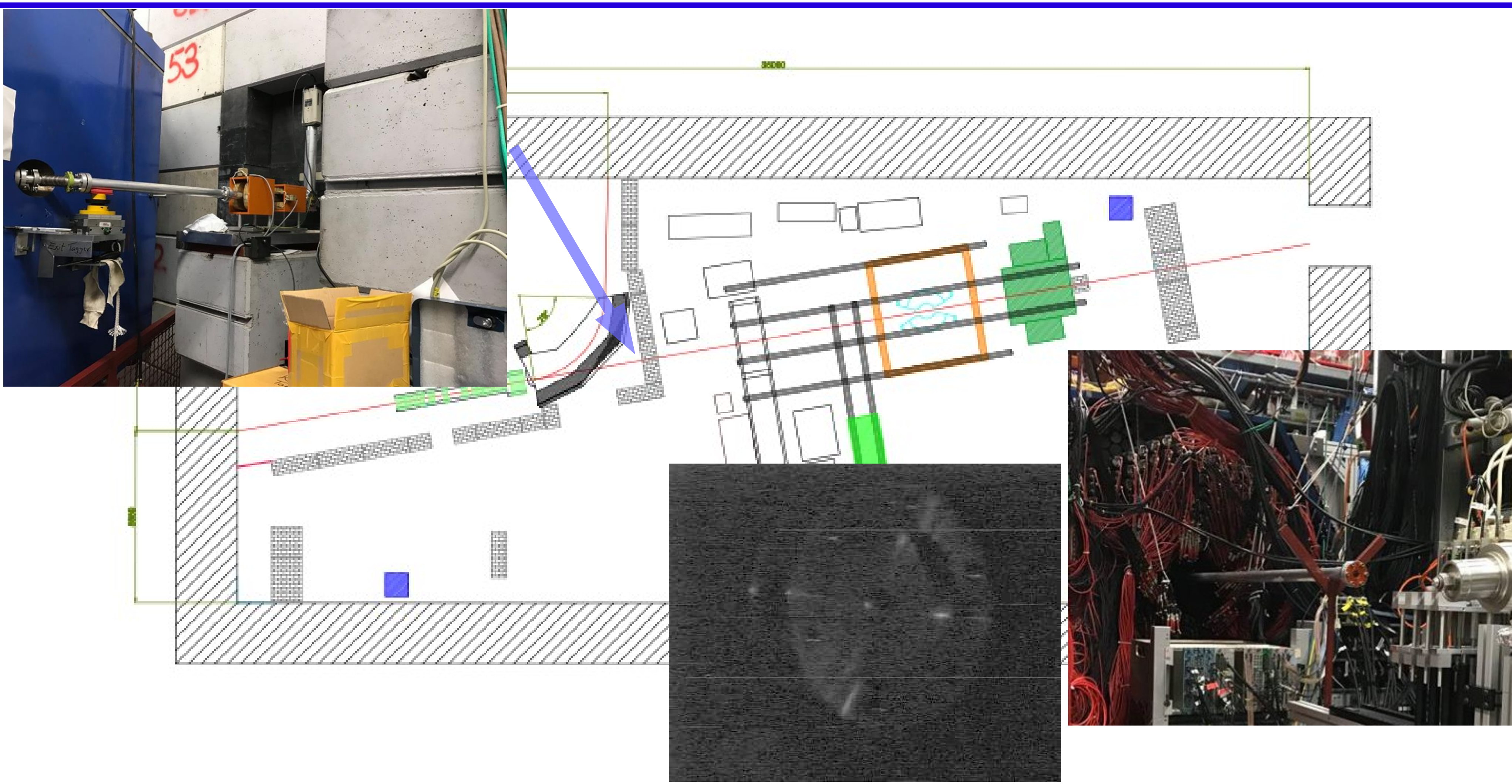
A. Vorobyov (PNPI)

Beamline construction



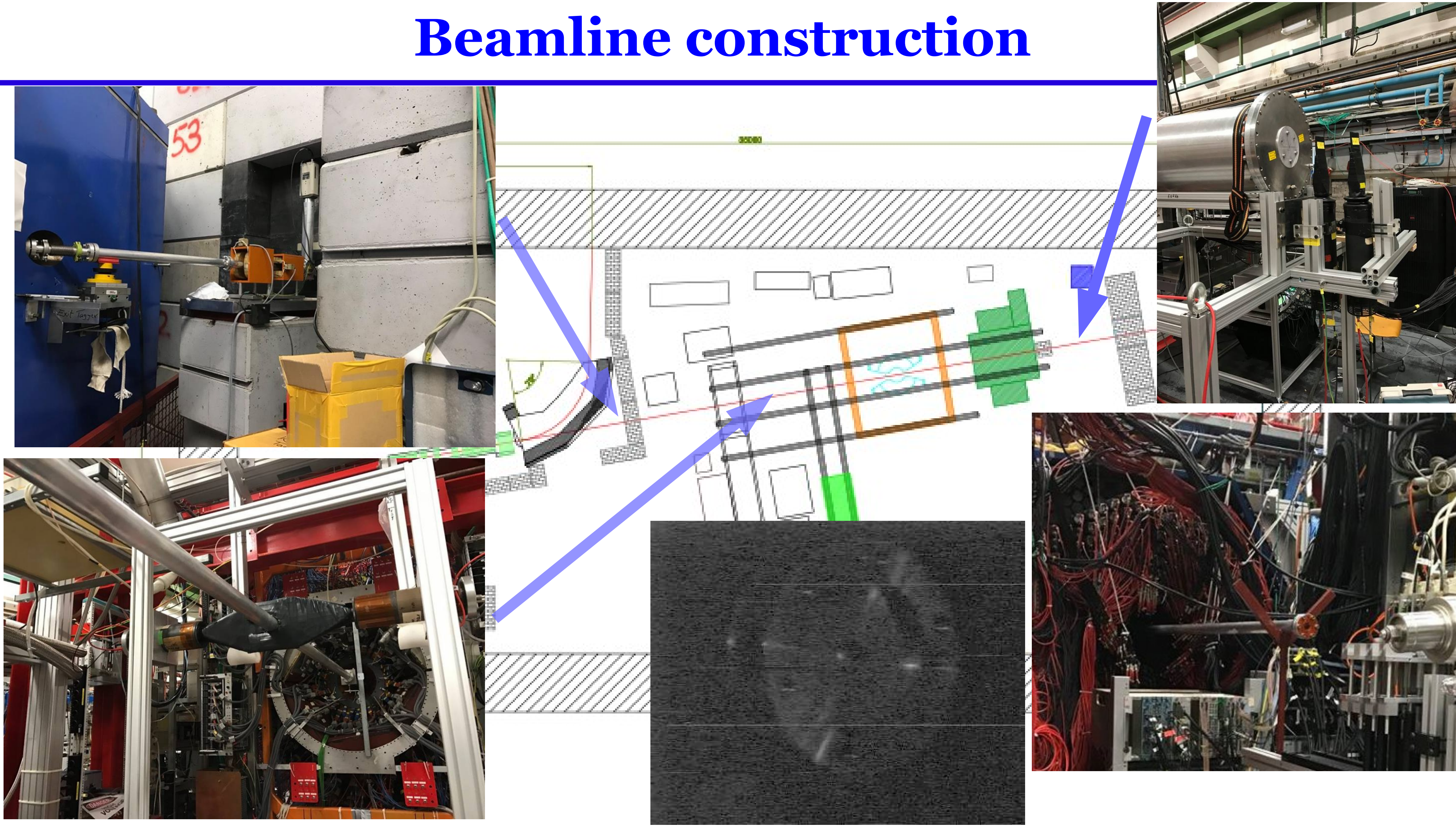
- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)
- Beam scintillators (M. Biroth, O. Kiselev, P. Drexler)

Beamline construction



- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)

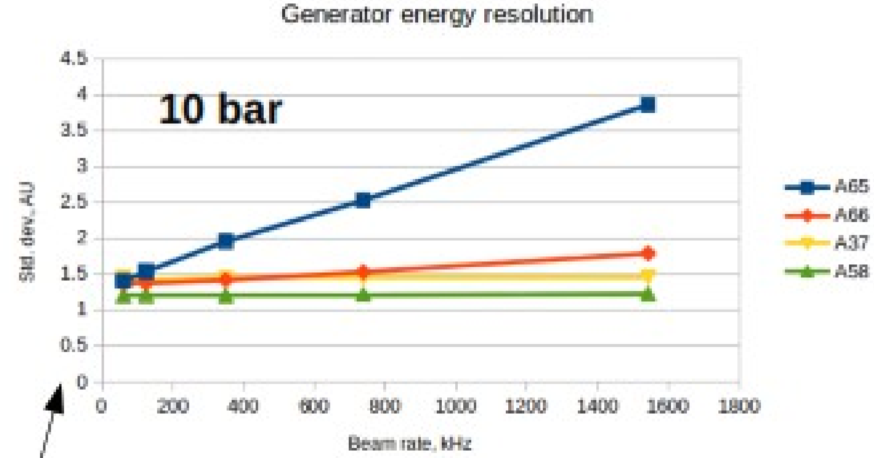
Beamline construction



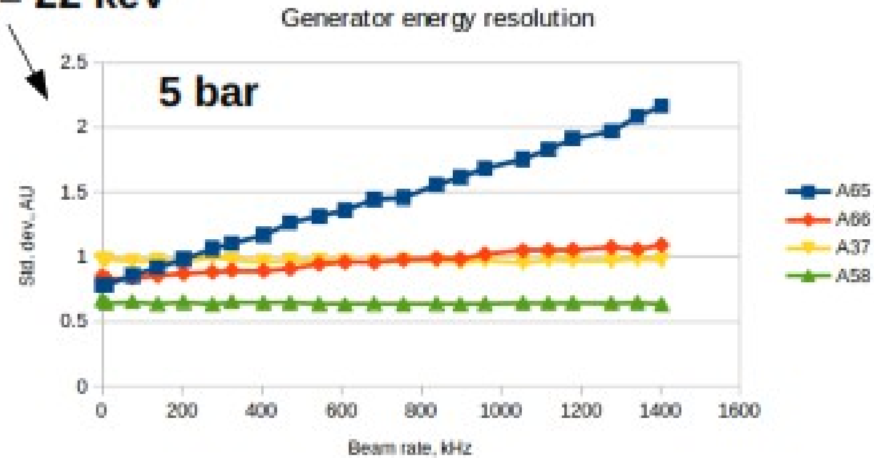
- One horizontal and one vertical steering magnets before tagger wall, luminescent screens for steering, ionization chamber connected to the interlock (M. Dehn)
- Beam scintillators (M. Biroth, O. Kiselev, P. Drexler)
- Beam telescope (F. Wauters, A. Tyukin, M. Zimmermann, N. Berger)
- PIZZA detector (P. Drexler, A. Inglessi, O. Kiselev)
- Scintillator counters before Crystal Ball (M. Biroth)

Measured pulse generator resolution

- **Sizeble effect** only for centrlal anode (A65);
- **Visible effect** for the second ring (A66);
- Practically no effects in the other channels (A37 / A58).

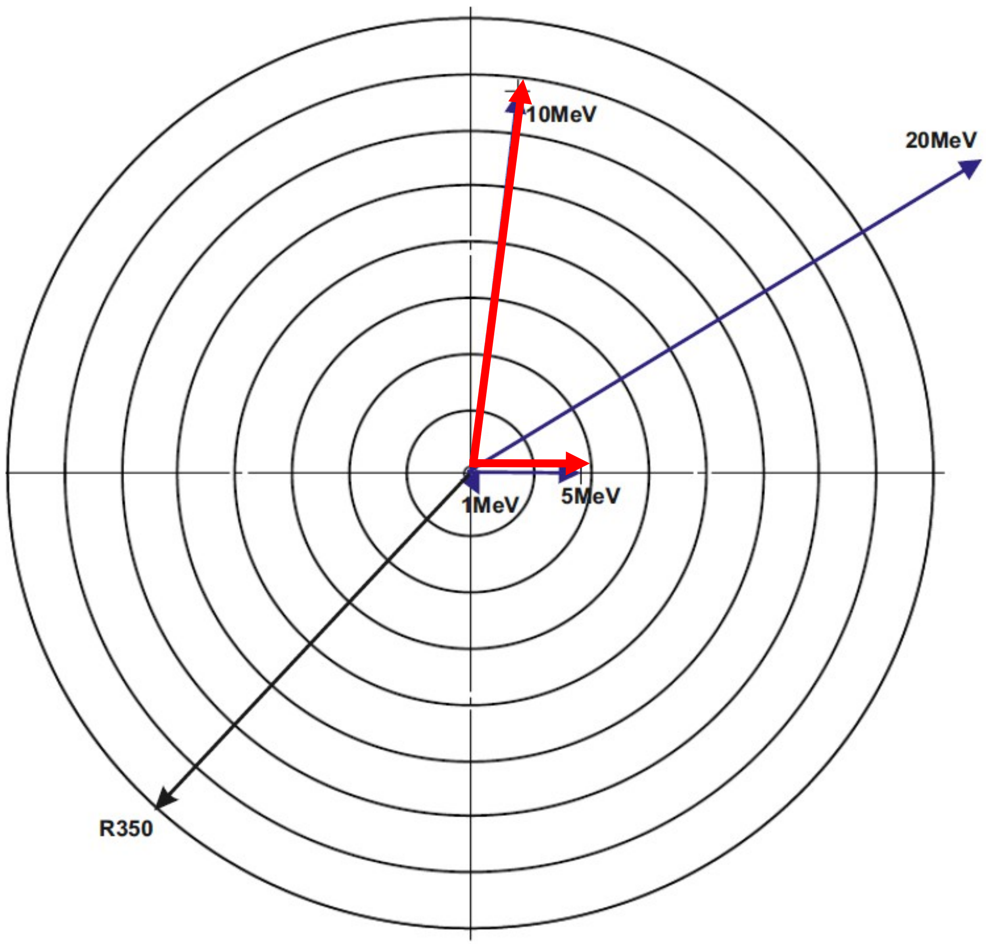


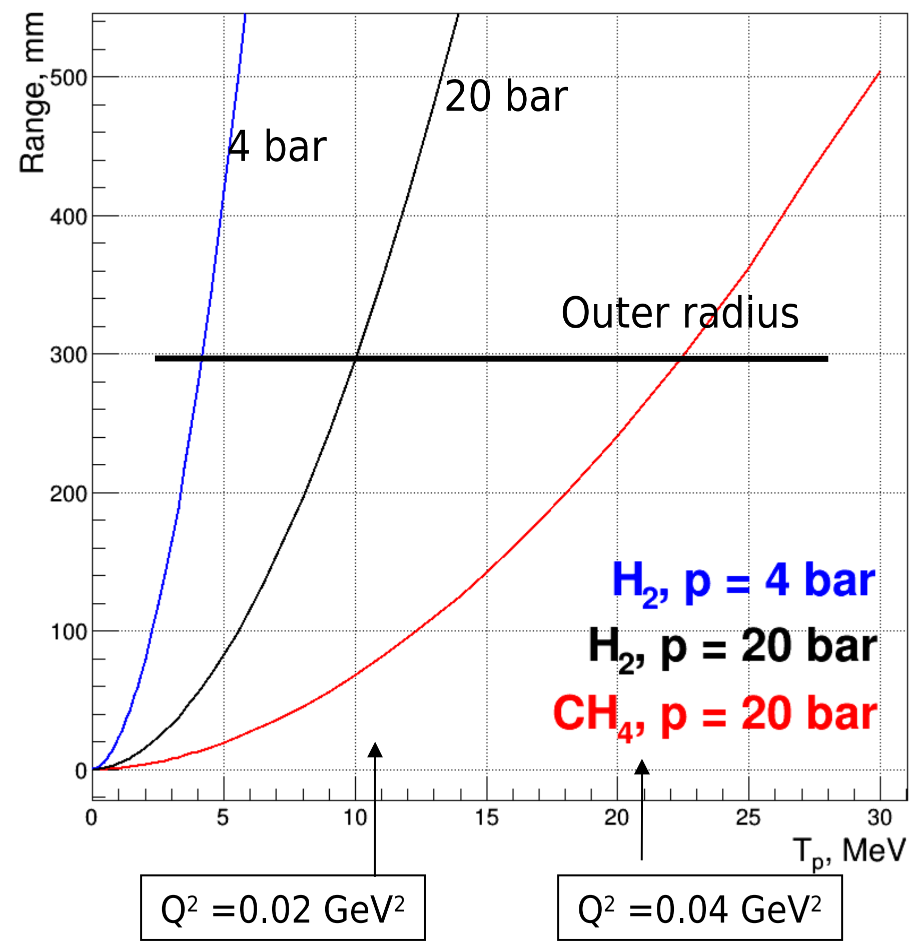
1 AU = 22 keV



TPC gas fillings

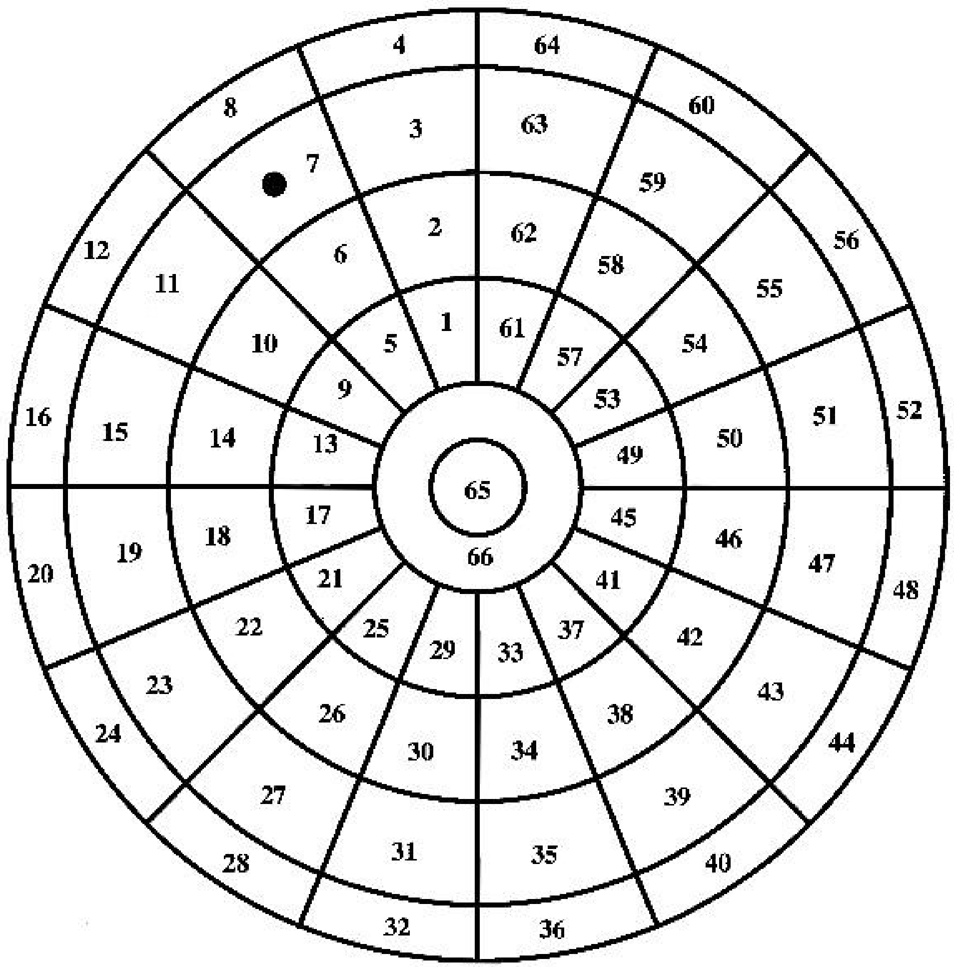
H_2 4 bar	$T_R \leq 4$ MeV
H_2 20 bar	$T_R \leq 10$ MeV
CH_4	$T_R \leq 22$ MeV





TPC anode structure: 10 mm in diameter disc surrounded by 7 rings

Anode segmentation in ACTAR2

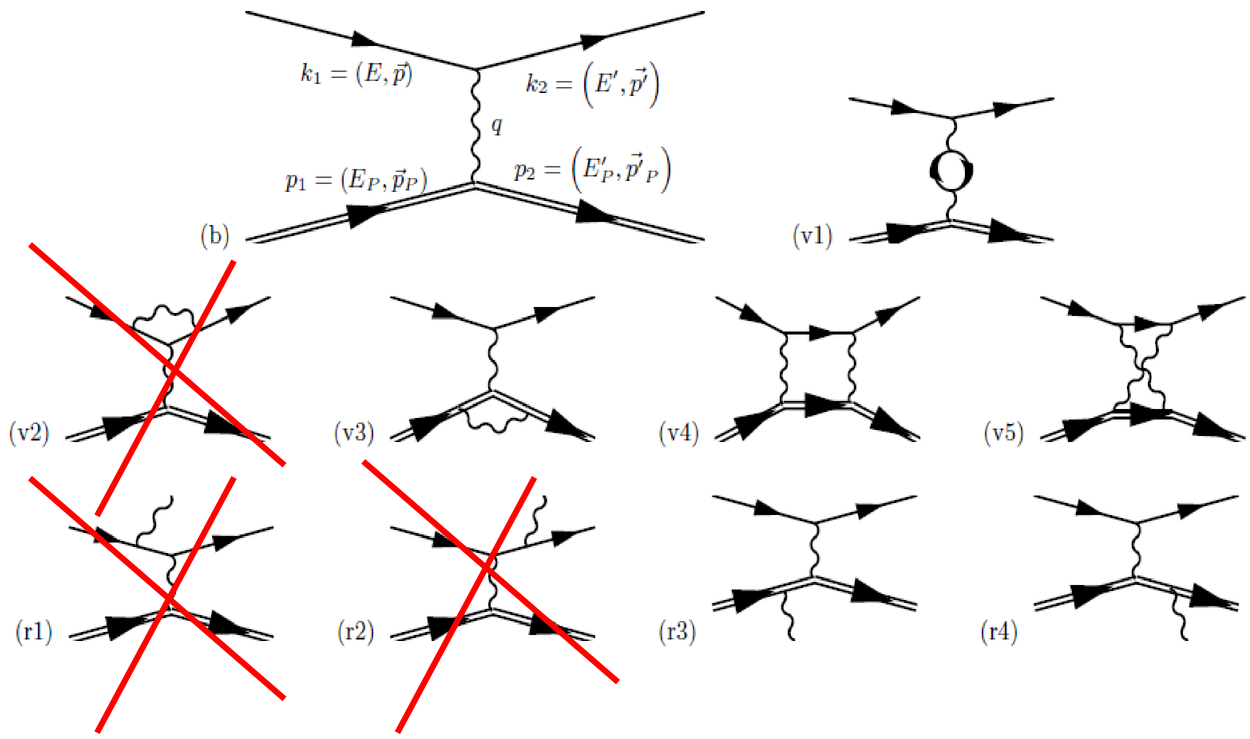


. *66 pads in total. The central pad is 20 mm in diameter*

Read out with FADC from each pad

Radiative corrections

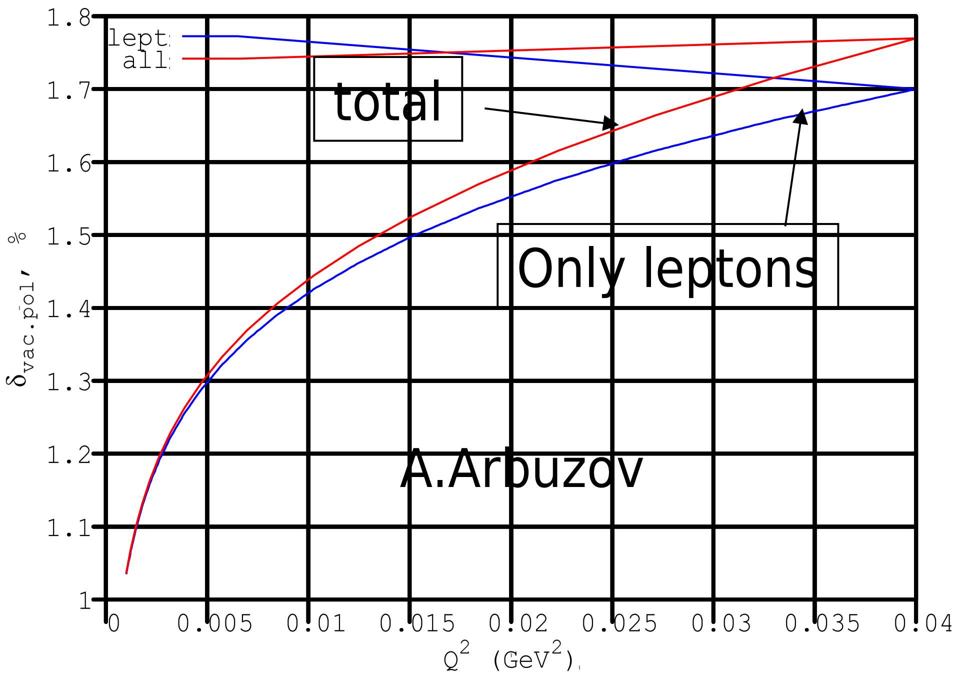
$$\left(\frac{d\sigma}{d\Omega}\right)_1 = \left(\frac{d\sigma}{d\Omega}\right)_0 (1+\delta).$$

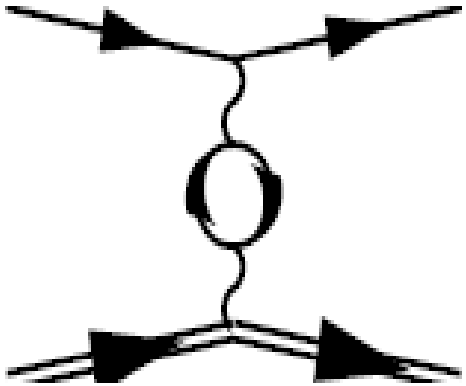


Diagrams v2, r1,r2 are self-cancelling in the recoil method.
The other RC are small and can be calculated to ≤ 0.1% precision.

Absolute measurement of dσ/dt with 0.2% precision
gives a control for the level of introduced radiative corrections.

Vacuum polarization is the largest RC in this method





Q^2=0.022 GeV^2

δ_{VP} =1.61546((28)%

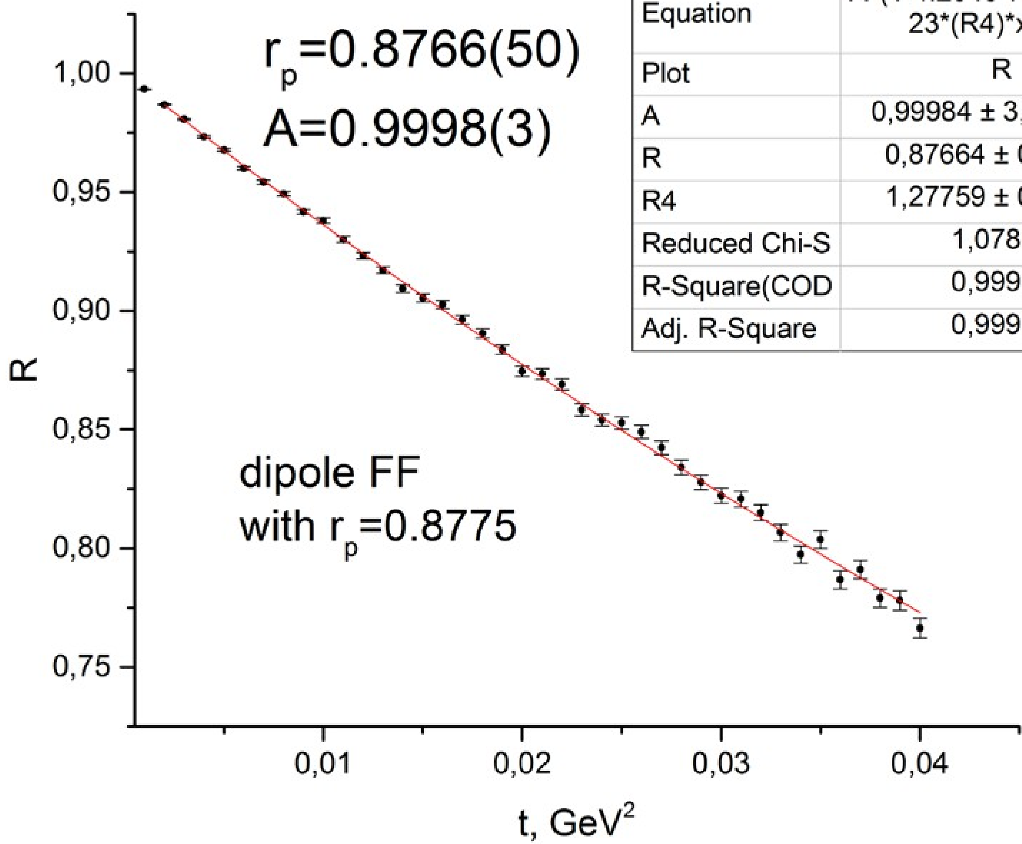
The other corrections will be calculated with the Novosibirsk ESEPP generator

Statistics

45 days 33×10^6 events

$$\frac{G(Q^2)}{G(0)} = 1 - \frac{1}{6}\langle R_p^2 \rangle Q^2 + \frac{1}{120}\langle R_p^4 \rangle Q^4 - \ldots,$$

Model	polinFF (User)
Equation	A*(1-4.2943*R^2*x+5.5323*(R4)*x^2)^2
Plot	R
A	0,99984 ± 3,0008E-4
R	0,87664 ± 0,00495
R4	1,27759 ± 0,22675
Reduced Chi-S	1,07804
R-Square(COD	0,99939
Adj. R-Square	0,99936



Rp ± 0.005 fm

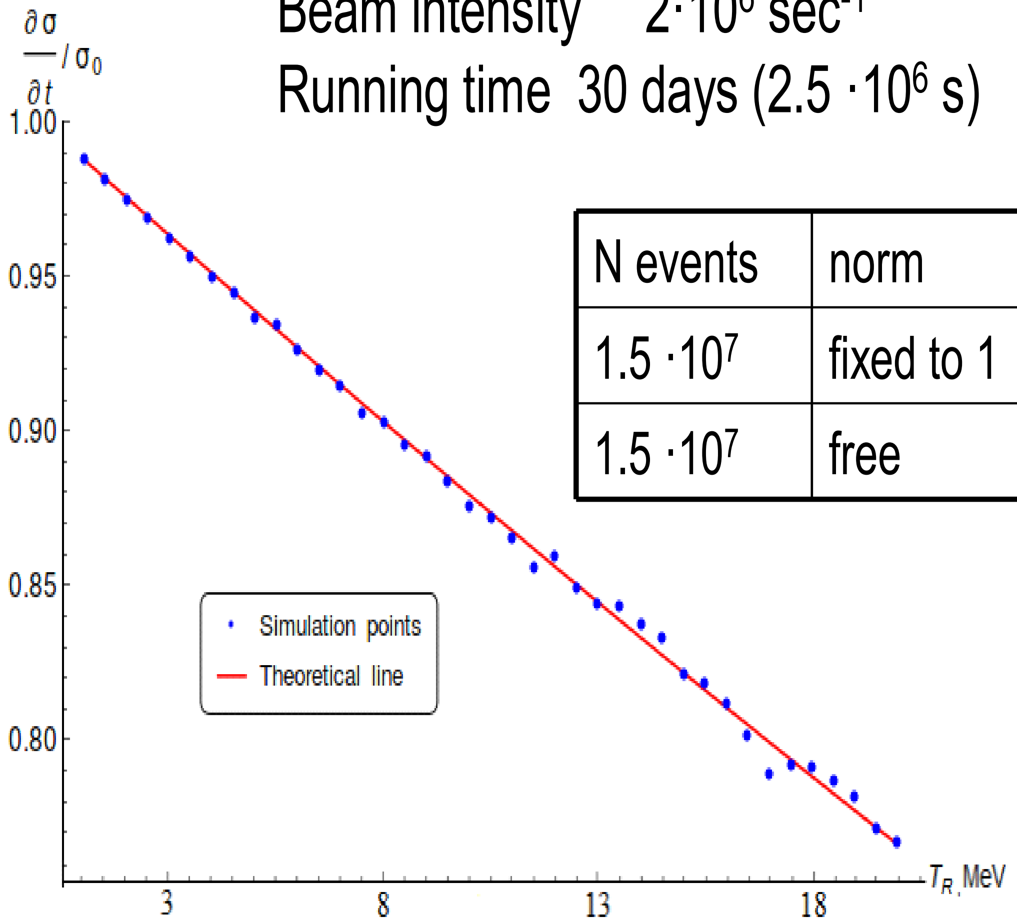
Statistical accuracy

Target thickness = $3.6 \cdot 10^{22}$ p/cm^2

P =20bar L =35cm

Beam intensity $2 \cdot 10^6$ sec^{-1}

Running time 30 days ($2.5 \cdot 10^6$ s)



N events	norm	t-scale	σ(Rp)
$1.5 \cdot 10^7$	fixed to 1	fixed	± 0.002 fm
$1.5 \cdot 10^7$	free	fixed	± 0.003 fm

A. Vorobyov (PNPI)

Run conditions and acquired data

- The main run: 10 bar pressure, electron beam intensity ~ 1.4 MHz (counted by the upstream scintillator): ~100 hours, acquired ~2000 files. ~$2.5x10^6$ events (total)

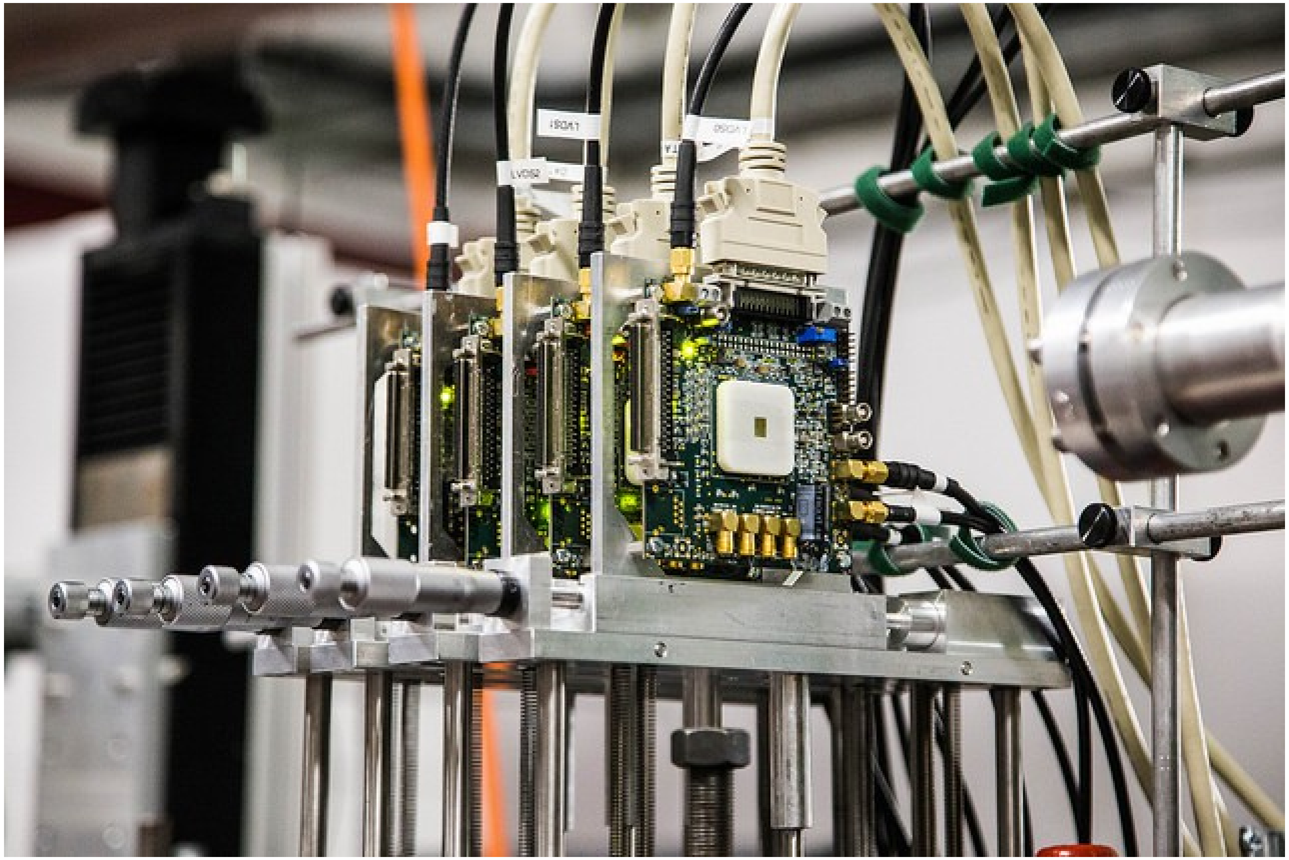
- Low intensity tests: (130kHz, 90files) and (300kHz, 150 files)

In the end of the experiment: the gas pressure in the TPC was decreased down to 5bar (HV on cathode ~9kV), beam intensity ~ 1.35 MHz, ~35 hours were collected ~ 350 files,~ $4x10^6$ events (total)

<u>See the talk of A. Dzyuba for further details and results</u>

Data:
- ~2.1 TB from the TPC and scintillators and 3.7 TB from the pixel telecsope
- Stored at GSI at two different locations and will be copied to the machines in Mainz in the near future
- Analysis and simulation steps to be discussed (Patrik Adlarson, Alexey Dzyuba, Timothy Hayward, Alexander Inglessi, V.S.)

Prototype for the beam monitoring system

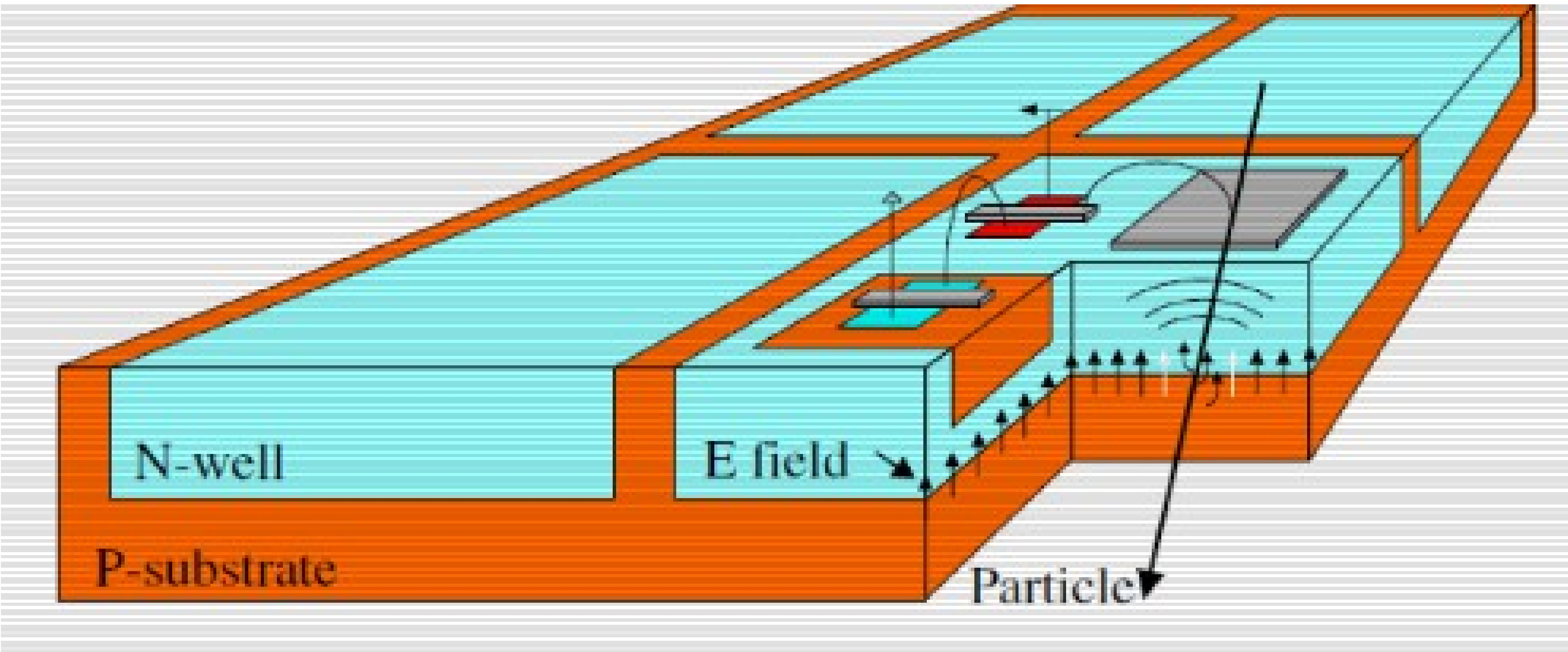


Mupix 7:

- 32 x 40 pixels of 103 um x 80 um
- 62.5 MHz timestaps
- 1.25 Gb/s readout to FPGA
- Track based alignment to better than 5 um
- 99 % efficiency per plane

(Frederik Wauters, Mainz)

Backup



Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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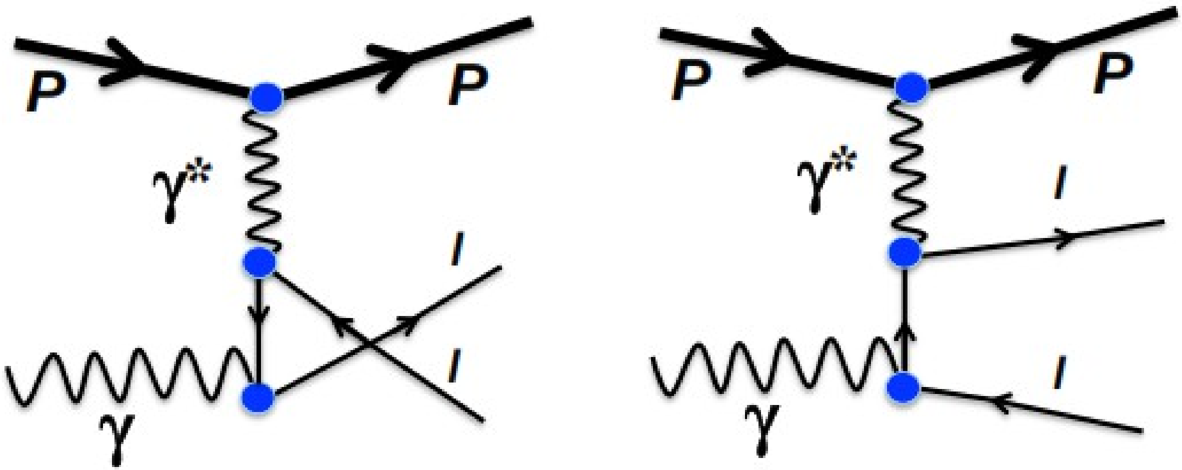

$$\frac{d\sigma^{BH}}{dt dM_{ll}^2} = \frac{\alpha^3}{(s - M_p^2)^2} \cdot \frac{4\beta}{t^2 (M_{ll}^2 - t)^4} \cdot \frac{1}{1+\tau} \times \left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2 \right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup (Patrik Adlarson)

Bethe–Heitler dσ/dEγ

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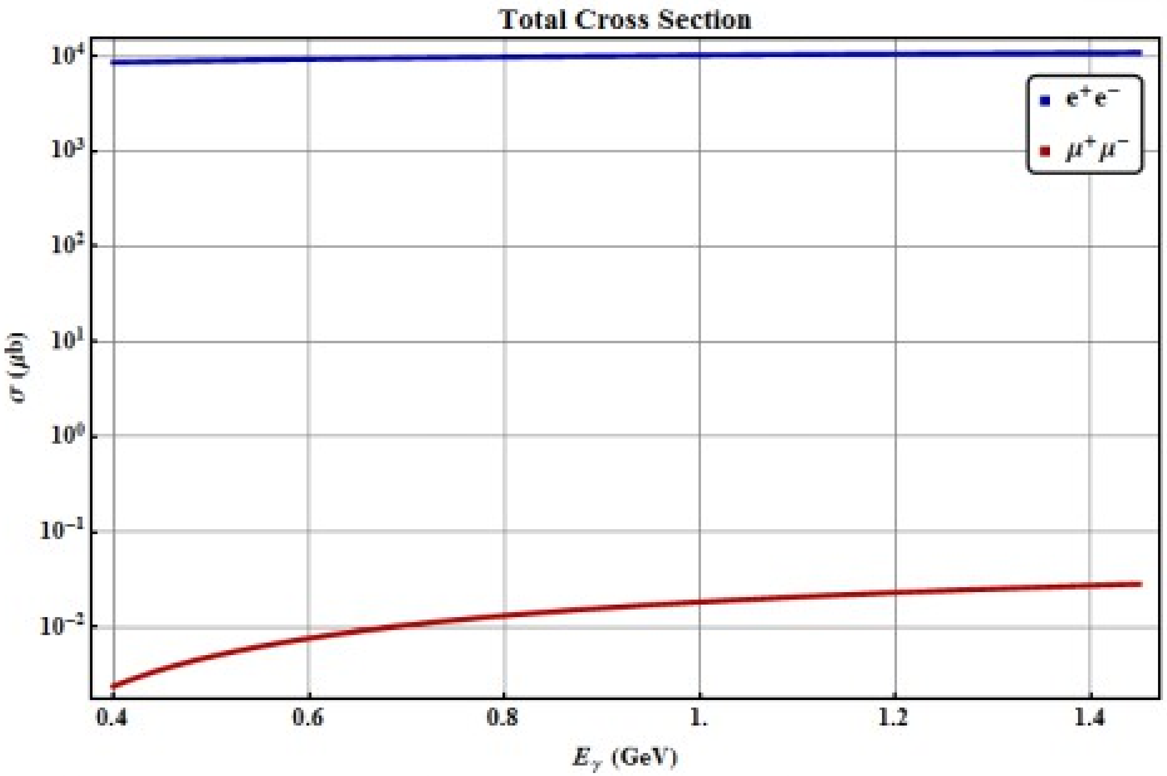


BH-ee (blue) and BH-μμ (red) cross section as function of beam energy

Dimuon cross section increases more for increasing beam energies

Backup

		Syst. Error %	comment
1	Drift velocity, W1	0.01	
2	High Voltage, HV	0.01	
3	Pressure, P	0.01	
4	Temperature, K	0.015	
5	H_2 density , ρ_p	0.025	Sum of errors 3 and 4
6	Target length, L_{targ}	0.02	
7	Number of protons in target, N_p	0.045	Sum of errors 5 and 6
8	Number of beam electrons, N_e	0.05	
9	Detection efficiency	0.05	
10	Electron beam energy, ε_e	0.02	
11	Electron scattering angle, θ_e	0.02	
12	t-scale calibration, T_R relative	0.04	Follows from error 11
13	t-scale calibration, T_R absolute	0.08	Follows from the sum of errors 11 and 10
	$d\sigma/dt$, relative	0.1	0.08 % from error 12
	$d\sigma/dt$, absolute	0.2	0.16 % from err.13 plus errors 7,8, and 9

Backup

MAMI Specifications

Beam energy	500 MeV, 720 MeV
Energy spread	< 20 keV (1σ)
Energy shift	< 20 keV (1σ)
Absolute energy	±< 150 keV (1 σ)

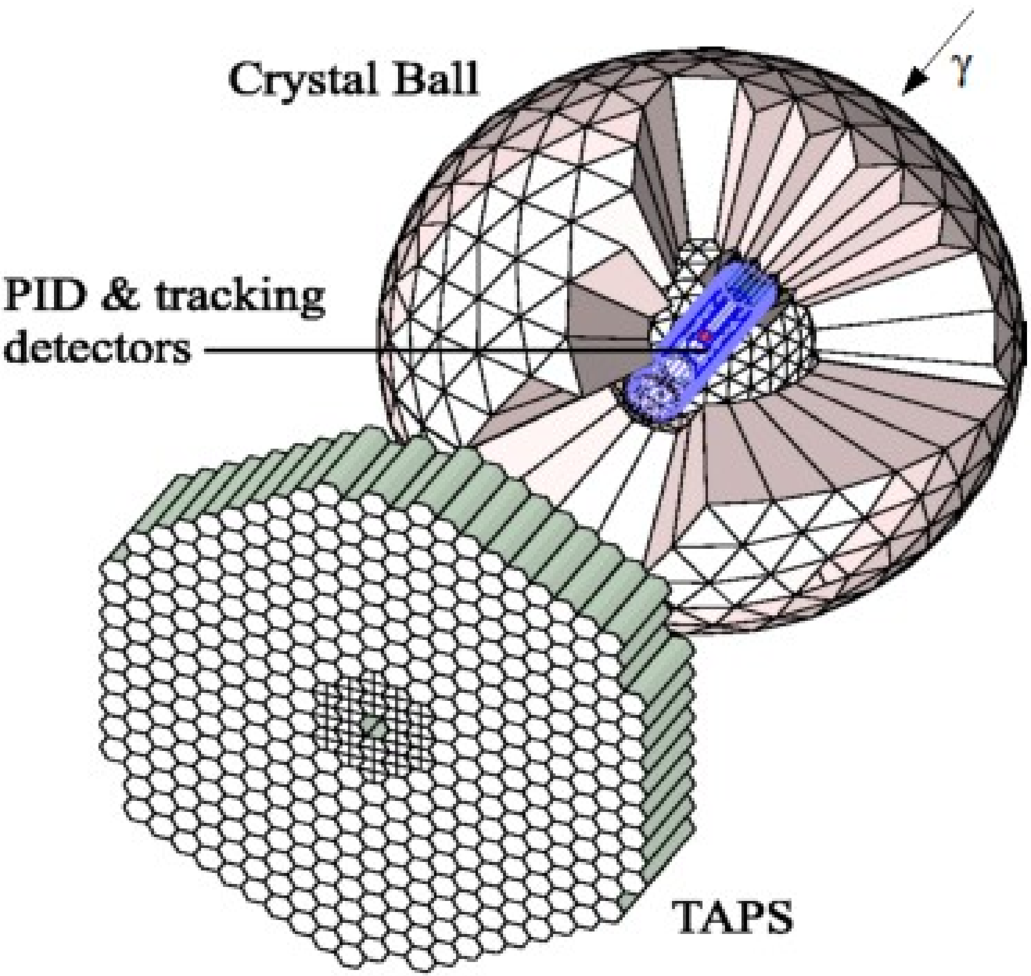
Electron Beam Specifications

Beam intensity (main run)	2x10^6 e^-/sec
Beam intensity for calibration	10^4 e^-/sec and 10^3 e^-/sec
Beam divergency	≤ 0.5 mrad
Beam size	minimal at given divergence

Beam Time Request

Test run in 2017	~ 2 weeks
First physics run in 2018	~ one month

Crystal Ball/TAPS (slide taken from M. Unverzagt)



<u>Crystal Ball:</u>
672 NaI(Tl) crystals
93,3% of total solid angle
Each crystal equipped with PMT

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

$$\Delta t = 2.5\text{ ns FWHM} \qquad \sigma(\phi)=\frac{2^\circ\ldots3^\circ}{\sin(\theta)}$$

<u>TAPS:</u>
Up to 510 BaF_2 crystals
Polar acceptance: 4-20°

$$\Delta t = 0.5\text{ ns FWHM}$$

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

Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(B)} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\, \beta_{M1} + O(\omega^4), \qquad (6)$$

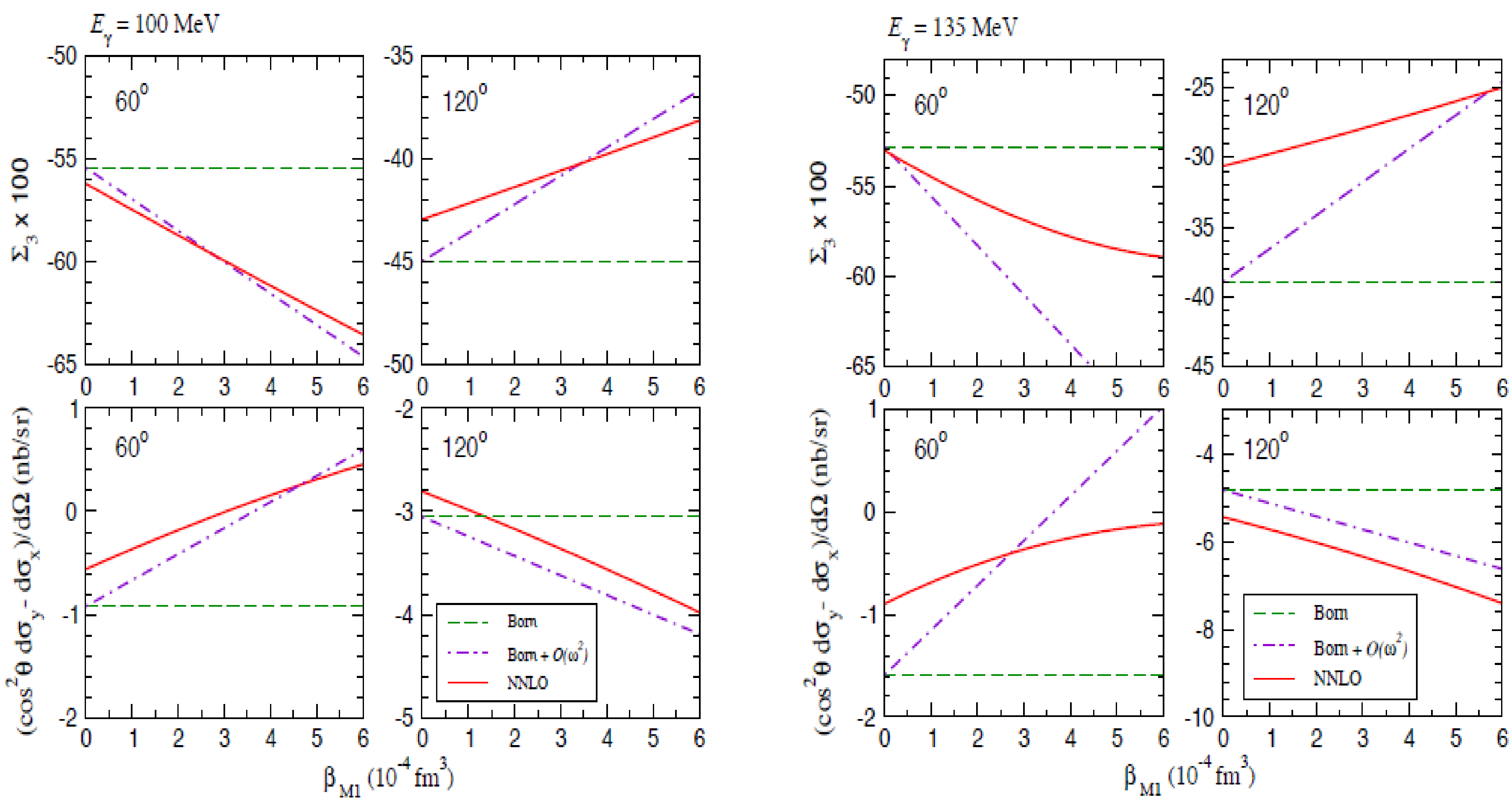
where $\Sigma_3^{(B)}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

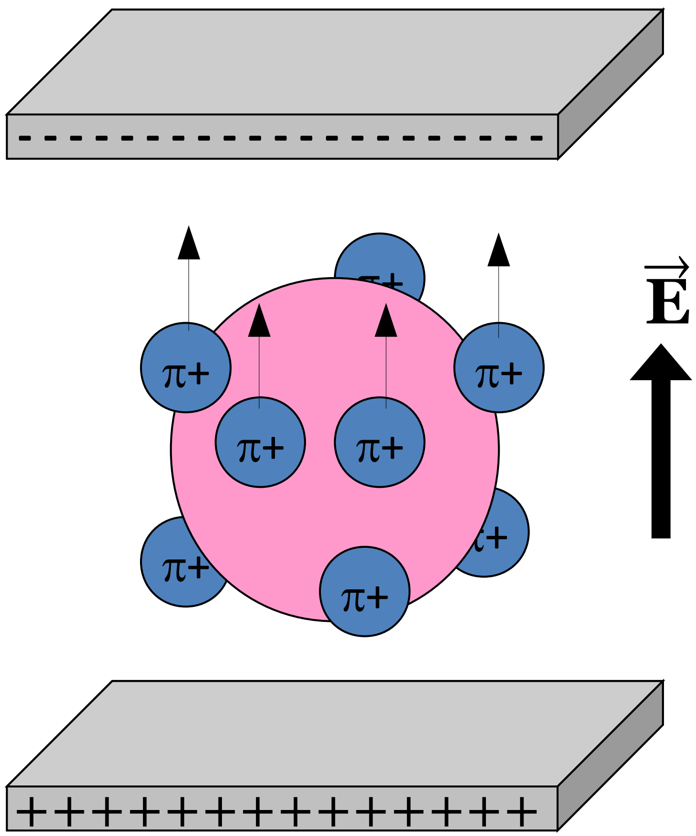
N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)]

Measurement of α and β



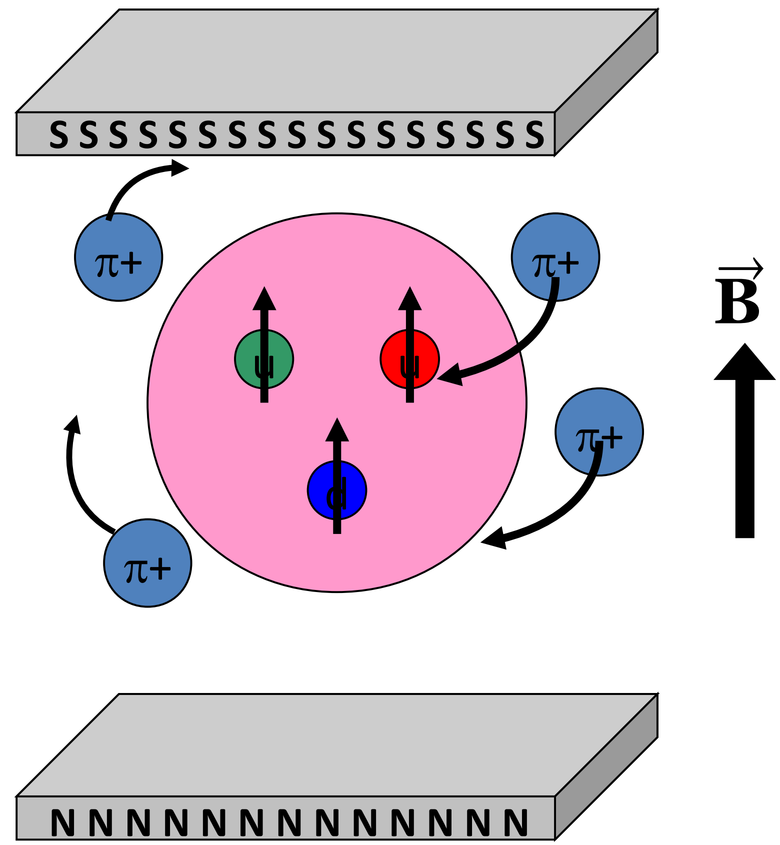
Scalar polarizabilities

Proton Electric Polarizability



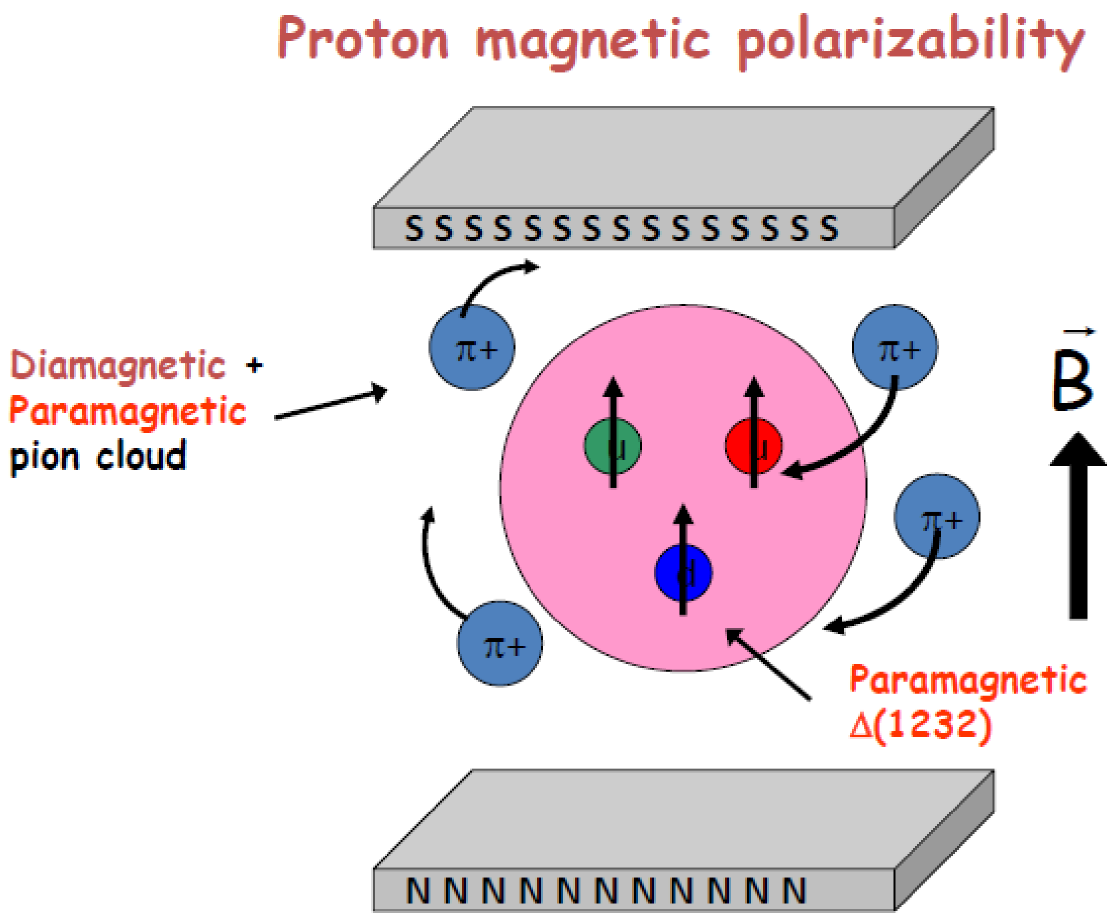
- α: electric polarizabilty
- Proton between charged parallel plates: "stretchability"

Proton Magnetic Polarizability



- β: magnetic polarizability
- Proton between poles of a magnet: "alignability"

First look in December 2012 data



Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)