New experiments with an active TPC detector at A2

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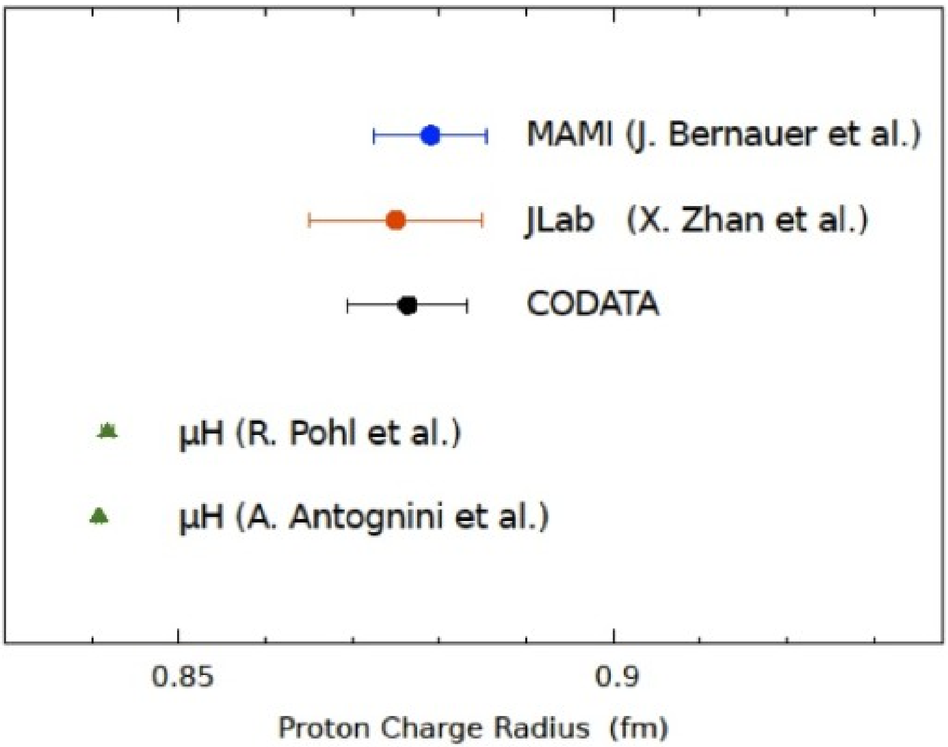
Bonn, 21.03.2017

Motivation

Main motivation: Understading 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 electronic and muonic systems
- Differences observed for the deuteron, but not for helium isotopes
- 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
  Accessing Q^2 below values defined by the experimental kinematics:
  $R_{pE} = 0.810 \pm 0.035$ (stat) $\pm$ 0.074 (syst) fm *(M. Mihovilovič et al., arXiv:1612.06707, 2016)*
  Further experiments reaching $Q^2 = 10^{-4}$ GeV^2 with improved systematics planned.

- PRad experiment at Jlab:
  Similar goals with the new experiments in Mainz (A2 Hall), but very different systematics: Electron scattering on a hydrogen gas jet target studied in combination with a forward calorimeter, access to $Q^2 = 10^{-4}$ GeV^2.

- 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.

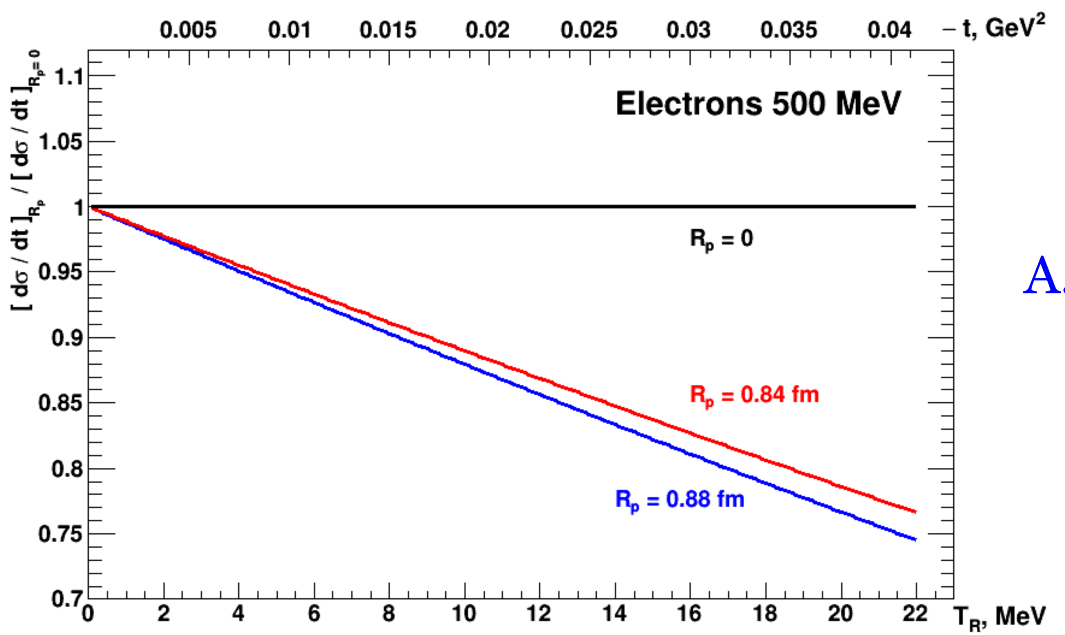
- New experiments at MAMI (A2 Hall): Accessing proton radius with dilepton photoproduction at with a Hydrogen Time Projection Chamber combined with Forward tracking detector (IKAR-M).

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 – 0.02 (0.04) GeV^2
- High resolution in Q^2 (~100 resolved points)
- Absolute measurements of $d\sigma/dt$ accuracy on a level of ~0.2%

Completely different systematics compared to other experiments



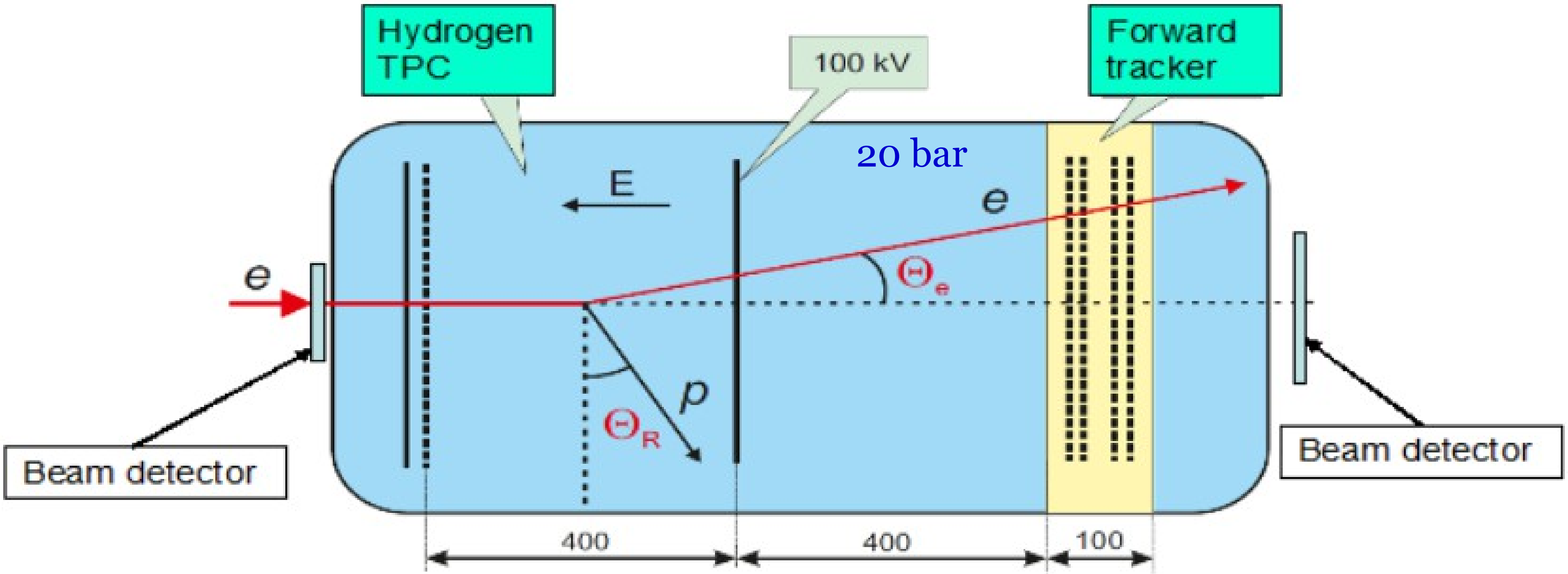
A. Vorobyov (PNPI)

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

IKAR-M detector

New-generation experiments with a completely different systematics:

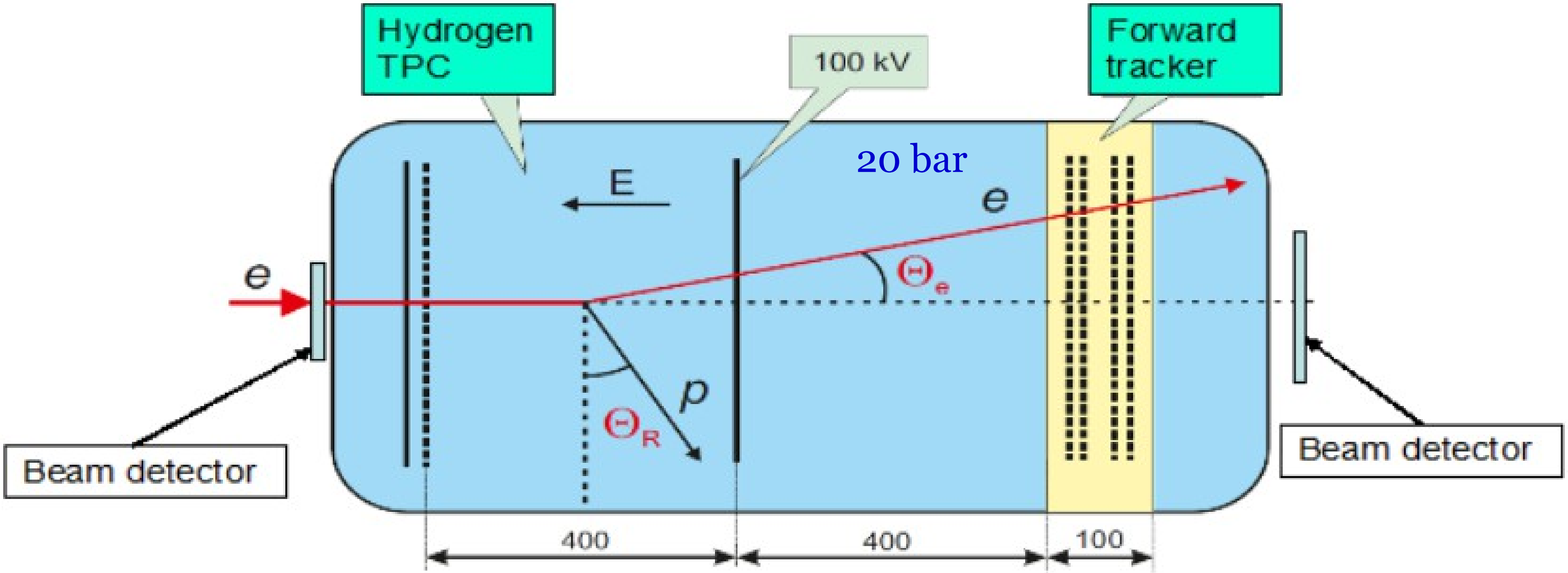
- Electron scattering with detection of both recoil proton and scattered electron
- Dilepton photoproduction (proton radius measurement, lepton universality test)



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: trasfer of technology to experiments at MESA accelerator e.g. for complementary measurement of the nucleon scalar polarizabilities *(current program in A2 will be presented by Edoardo Mornacchi, next session)*

IKAR-M detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

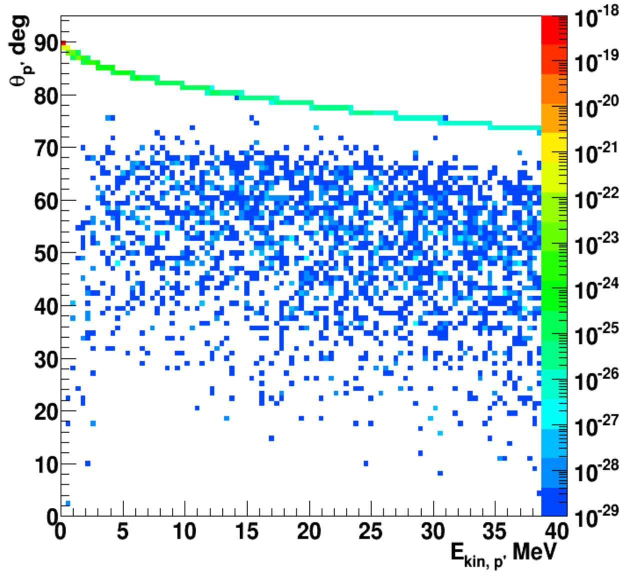
E scattering angle Θ_e

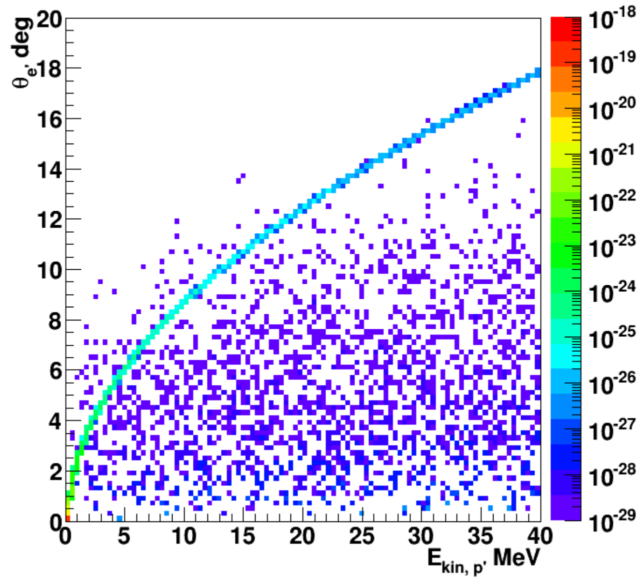
$$-t = \frac{4\varepsilon_e^2 \sin^2 \frac{\vartheta}{2}}{1 + \frac{2\varepsilon_e}{M} \sin^2 \frac{\vartheta}{2}}$$

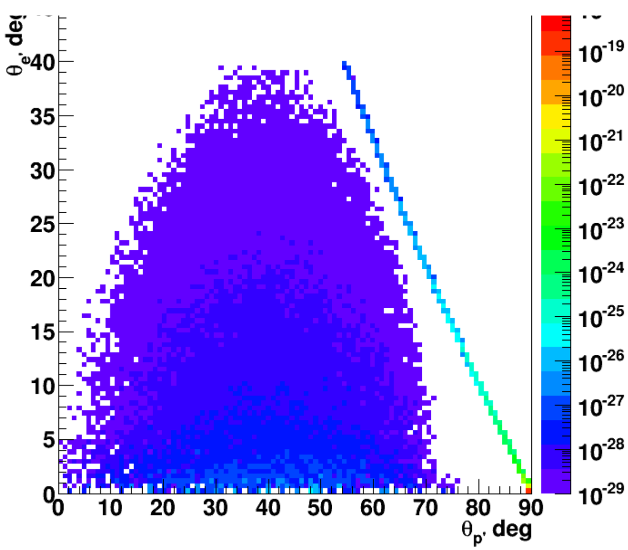
$$-t = 2MT_R$$

Gas	H_2, D_2, He_3, He_4, CH_4
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

Background suppression







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Background suppression:

Correlations: $(\Theta_e;T_R)$, $(\theta_R;\ T_R)$, and $(\theta_e;\ \theta_R)$ plots calculated for the elastic ep scattering and for the background reaction $ep \rightarrow ep\pi^0$ for $\varepsilon_e = 900$ MeV

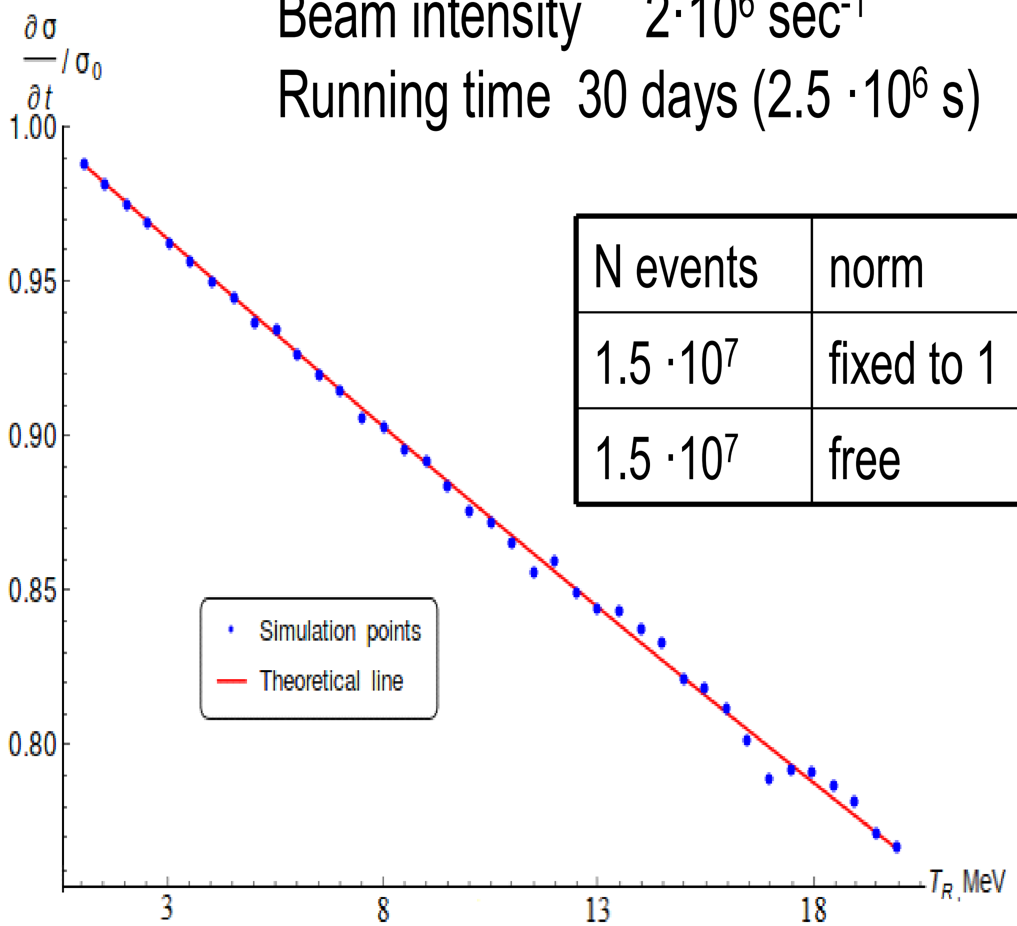
Statistical accuracy

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

P =20bar L =35cm

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

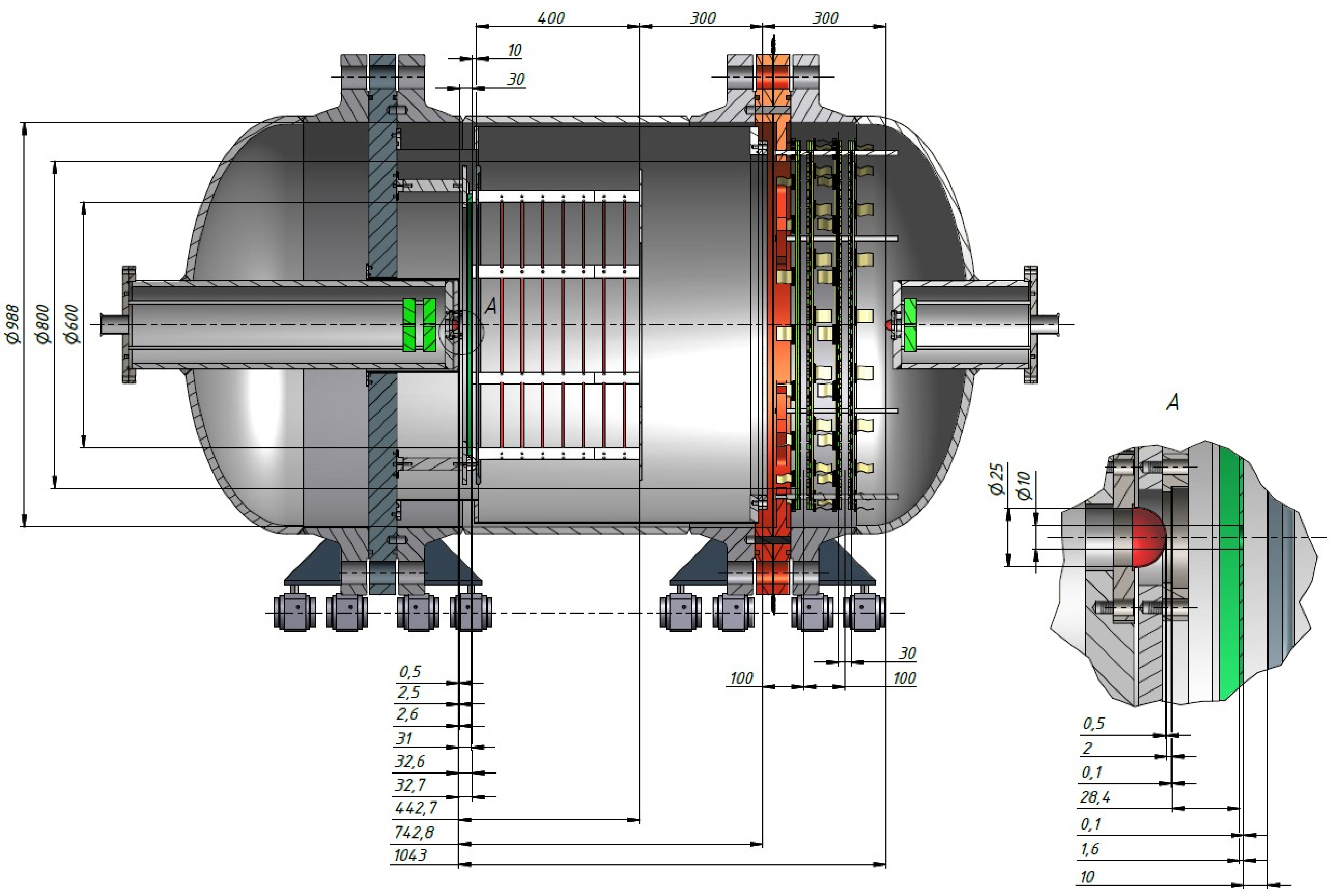
Running time 30 days ($2.5 \cdot 10^6$ s)



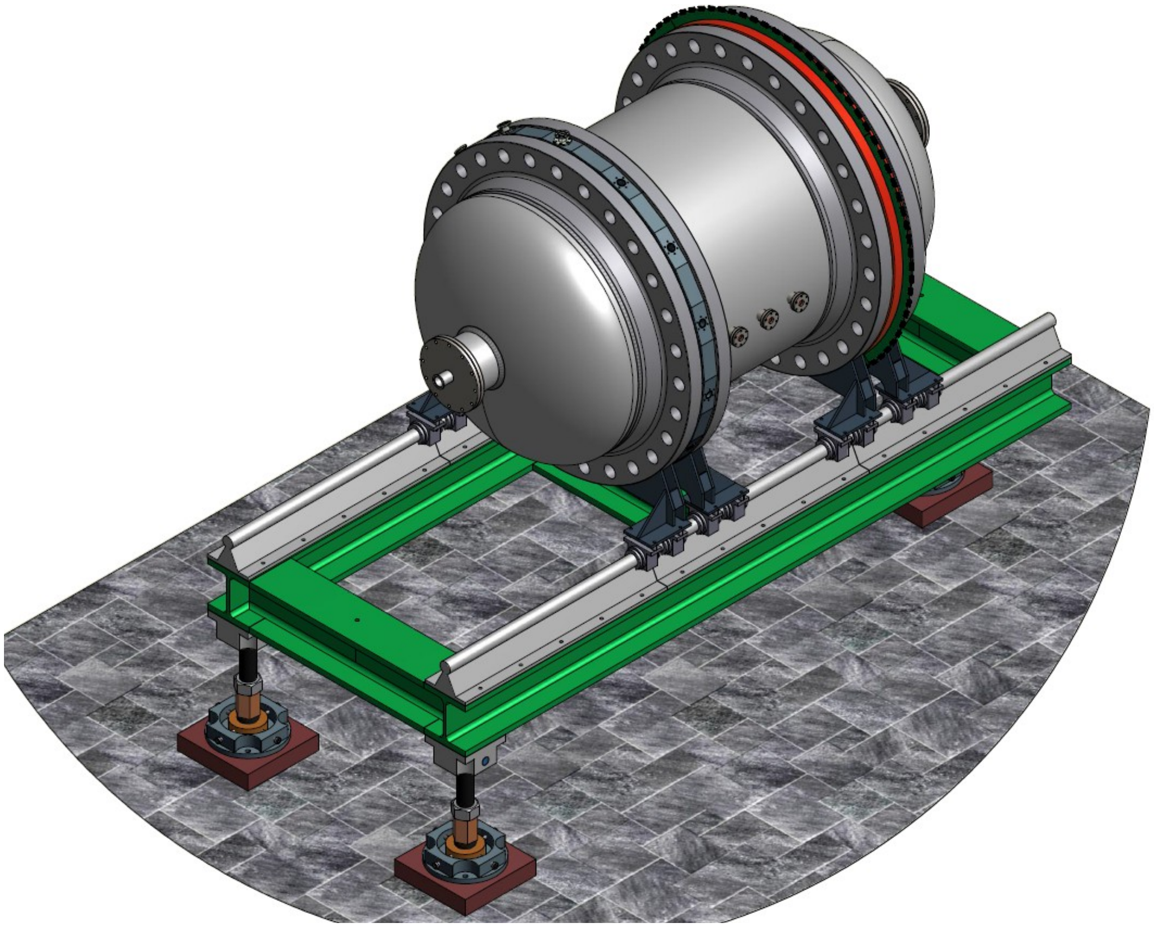
N events	norm	t-scale	σ(Rp)
$1.5 \cdot 10^7$	fixed to 1	fixed	± 0.002 fm
$1.5 \cdot 10^7$	free	fixed	± 0.003 fm

A. Vorobyov (PNPI)

IKAR-M detector (tentative design)

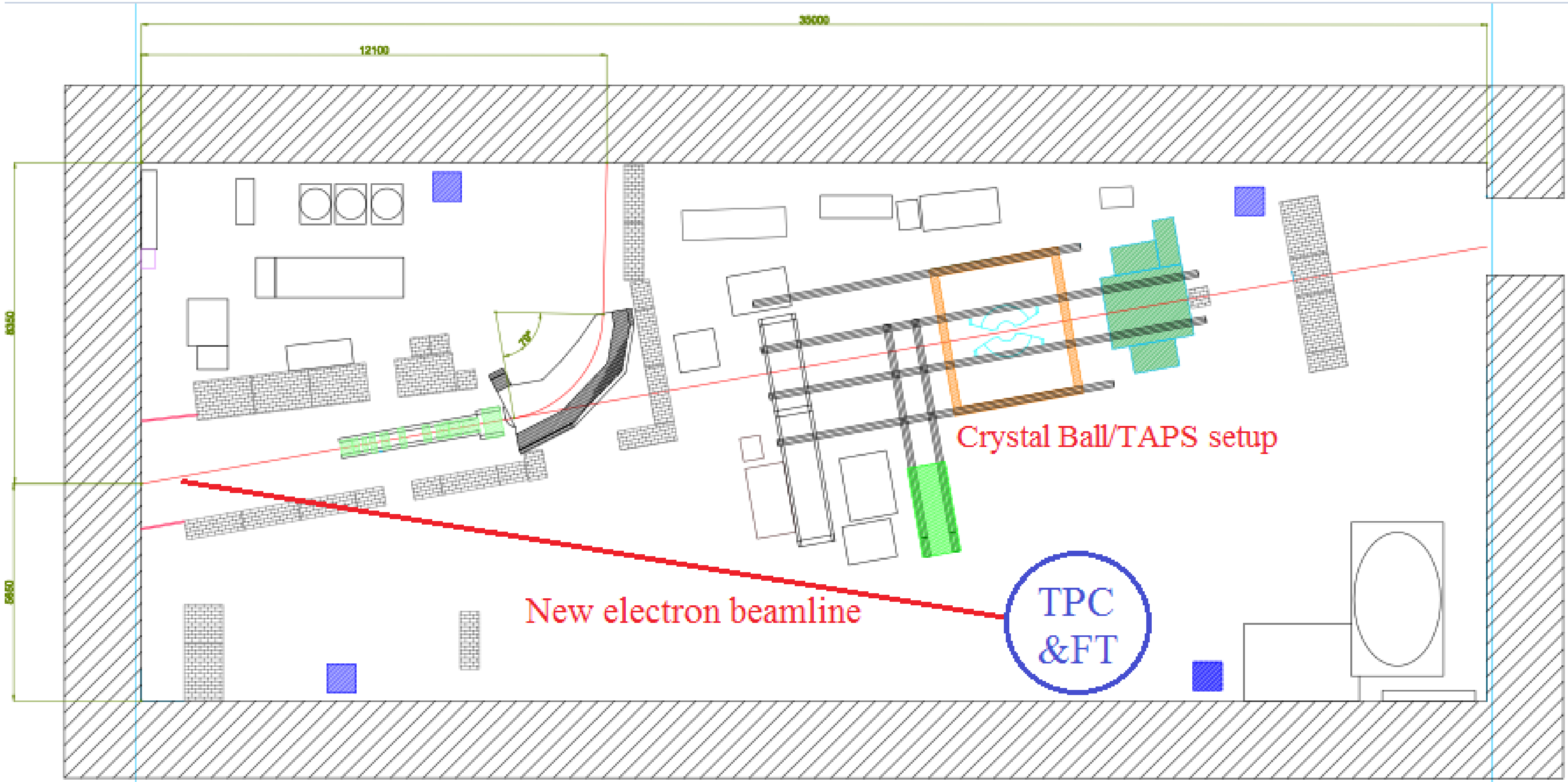


IKAR-M experiment in the A2 Hall



- 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?

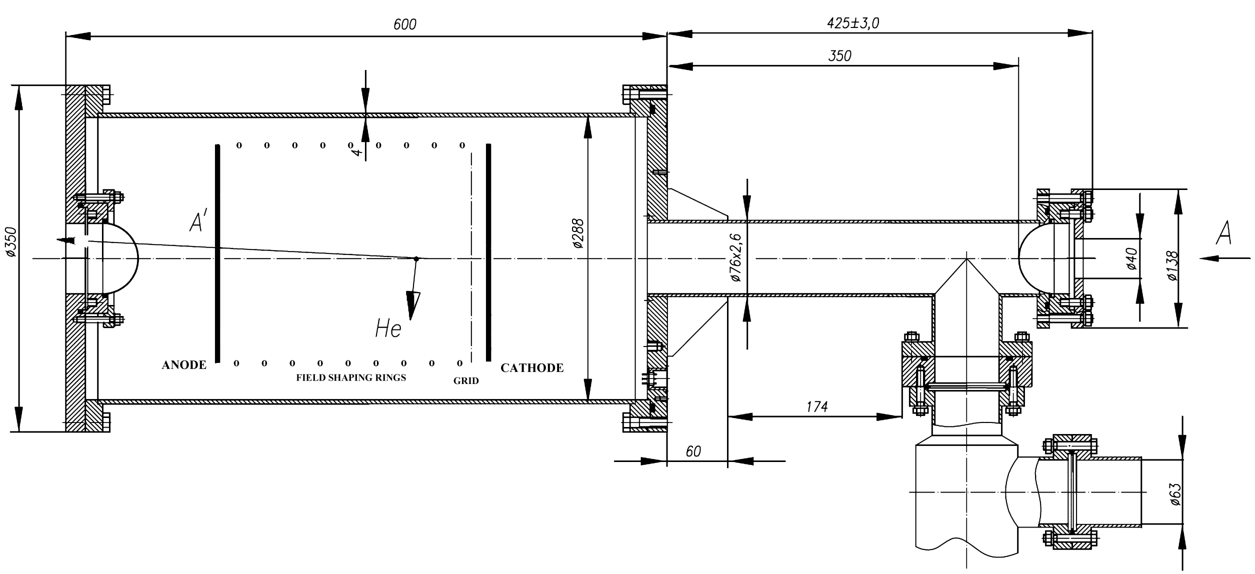
New electron beamline in A2



Solution: 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)
- Full support from the MAMI group + KPH Workshops

Test setup and beam monitoring system



<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
- Measurement of the flux of charged particles created by the electron beam in the forward direction (covered by the FT detector).
- 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

- Visits of 5 PNPI scientists (05.04.2017 – 30.04.2017)
- Preparation of space: 4x4 m (Modulator Hall: Next to the A2 counting room)
- **Transportation of the test TPC from GSI to Mainz at 12.04.2017**
- **Preliminary schedule for the test run: 14.08.2017 - 04.09.2017**

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 detection 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

Practical steps

- Two Letters of Intent (LOI) were presented to the MAMI PAC (2016). Planning and preparation of new experiments was supported by the PAC and the preparation of full proposals was encouraged.

Funding:

KPH:

- Submitted a DFG application within the DFG-RFBR Call (2018-2020)
- Module Eigene Stelle (Temporary position for principal investigators)
- 2 PhD positions (Beamline construction and preparation of the beam monitoring detector system)
- Requested support for the construction of the new beamline and beam detectors

PNPI:

- Submitted an application to RFBR within the DFG-RFBR Call (2018-2020)
- PNPI invests ~500 kEUR in the construction of the IKAR-M detector (core funding)
- Working group of 8 people at PNPI

Working groups and infrastructure

Current composition of the working groups:

Direct contribution of the local KPH group to the project: Dr. Patrik Adlarson, Dr. Marco Dehn, Dr. Andreas Thomas, V.S., Dr. Frederik Wauters, Dr. Andreas Thomas, V.S., Prof. Dr. Achim Denig, Prof. Dr. Michael Ostrick, Prof. Dr. Niklaus Berger.
Expertise and support from: Prof. Dr. Marc Vanderhaeghen, Dr. Vladimir Pascalutsa, Priv.-Doz. Dr. Harald Merkel, Dr. Michael Otto Distler, MAMI accelerator group.

Partners within the joint DFG-RFBR Call (PNPI, Gathina, Russia): Prof. Dr. Alexey A. Vorobyov, Dr. Vasilyev Alexander, Dr. Kravtsov Petr, Dr. Vznuzdaev Marat, Ivshin Kuzma, Solovyev Alexander, Solovyev Ivan, Dr. Kravchenko Polina, Dr. Dziuba Alexey, Dr. Maev Evgeny

Partners from external institutions: Prof. Dr. Peter Egelhof (GSI and University of Mainz), Prof. Dr. Keith Griffioen (College of William and Mary), Timothy Hayward (College of William and Mary), Dr. Oleg Kiselev (GSI), Dr. Magnus Wolke (Uppsala University).

Available equipment and infrastructure: Quadrupole magnets, prototypes of the beam monitoring system. Availability and support from Mechanical, Vacuum, and Electronics Workshops at the KPH

Summary and Outlook

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

- Agreement signed between KPH Mainz and PNPI (2017-2020)

- Submitted common DFG-RFBR (2018-2020) application
  - Construction of a new electron beamline in the A2 Hall (KPH)
  - Constructon of the beam monitoring detector system for IKAR-M (KPH)
  - Construction of the IKAR-M detector (PNPI)

Short term plans:
- Test TPC will be moved toMainz in April
- Test run in August-September

- Two LOI presented to the PAC 2016
  - Preparation of a full proposal

Summary and Outlook

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Thank you for your attention!

Backup

Patrik Adlarson

CREMA deuteron charge radius

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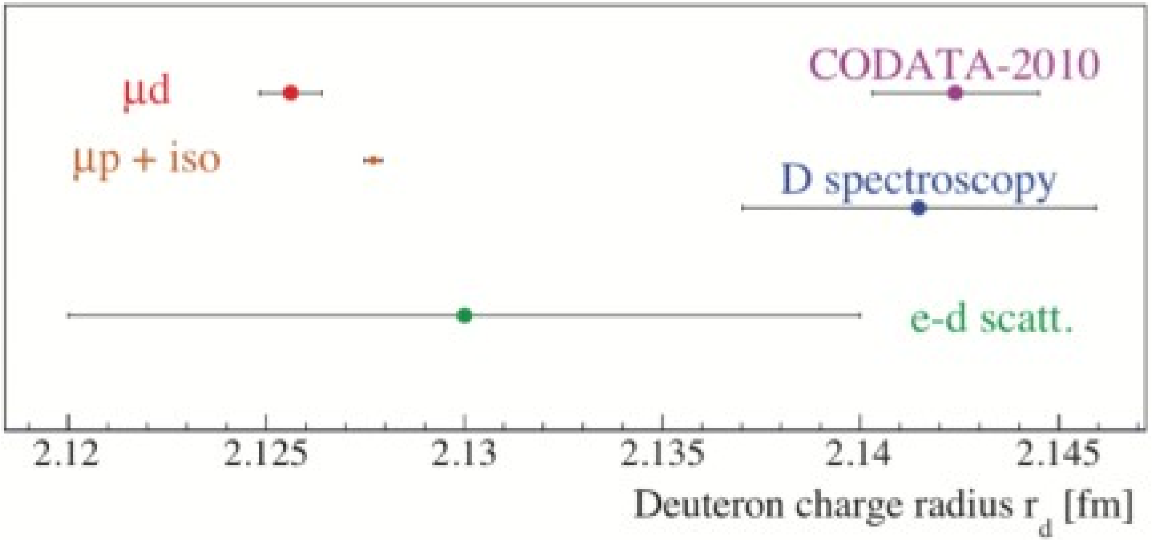


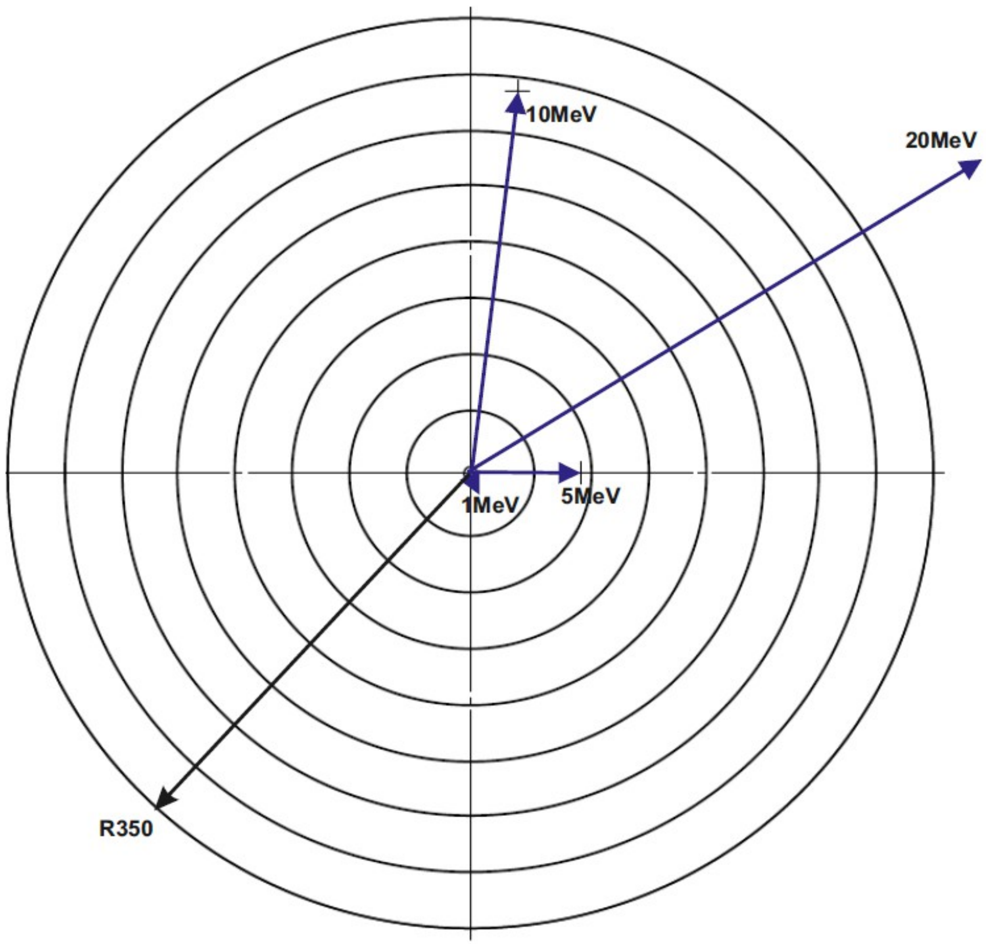
Randolf Pohl et al. CREMA collaboration. Science, 353(6300):669, August 2016.

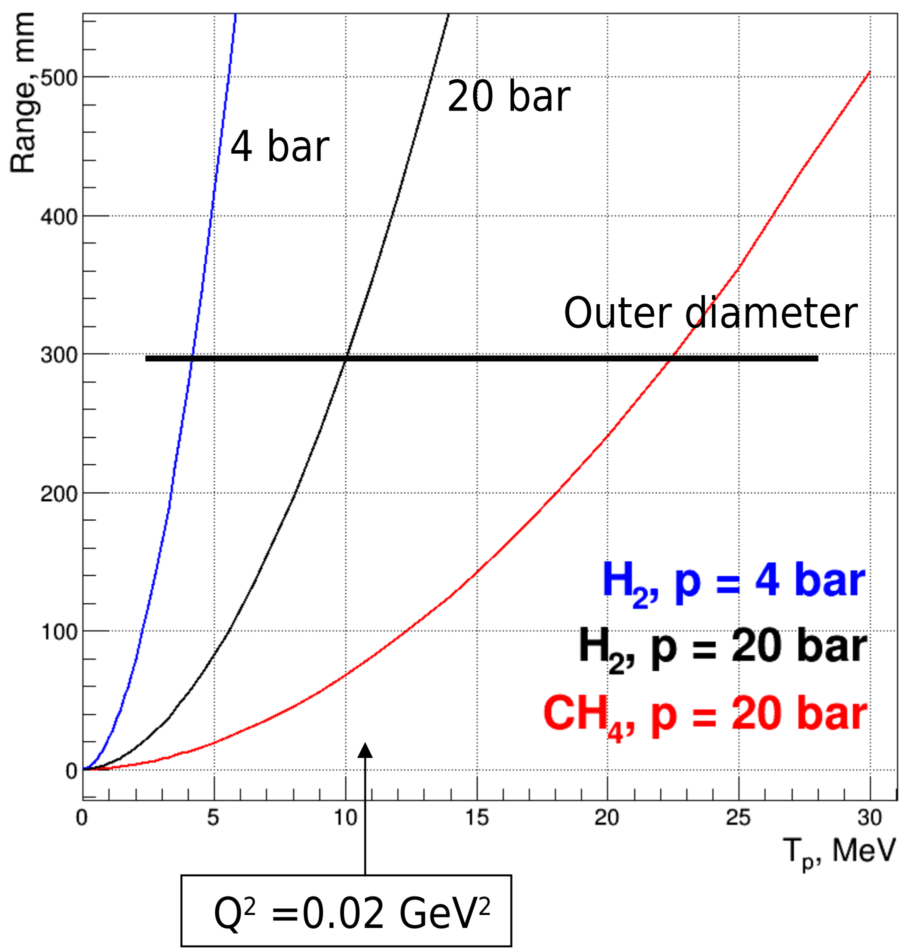
Very recently CREMA made their muonic deuterium official. Two ways to extract the deuteron radius. Both favor low deuteron radius

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

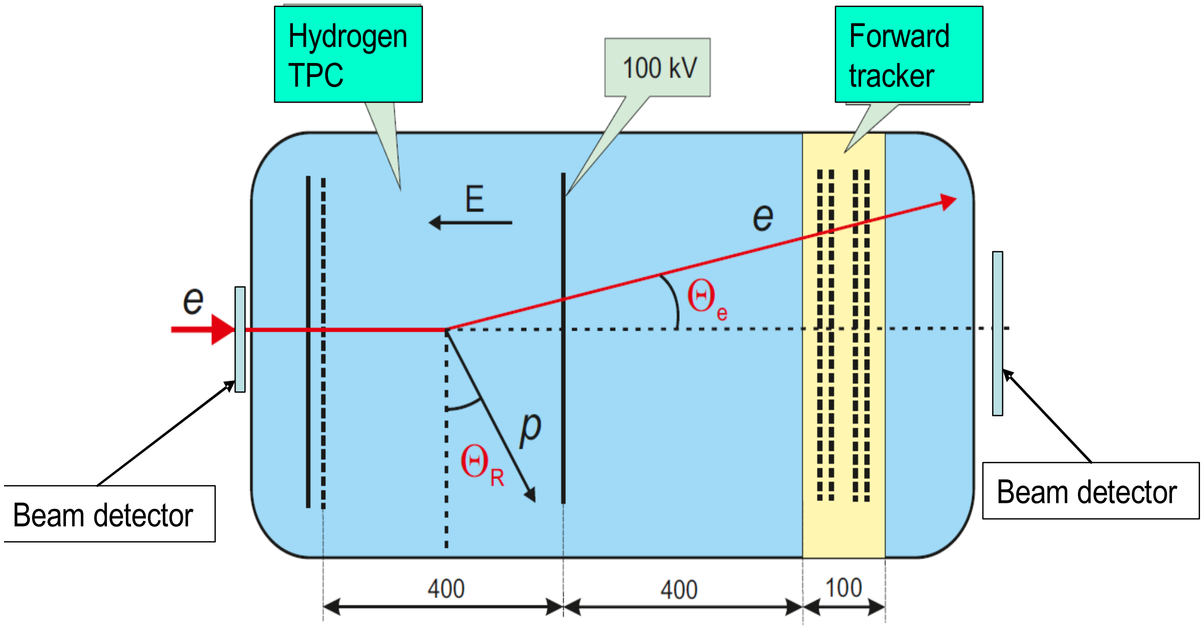
Hydrogen Time Projection Chamber





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

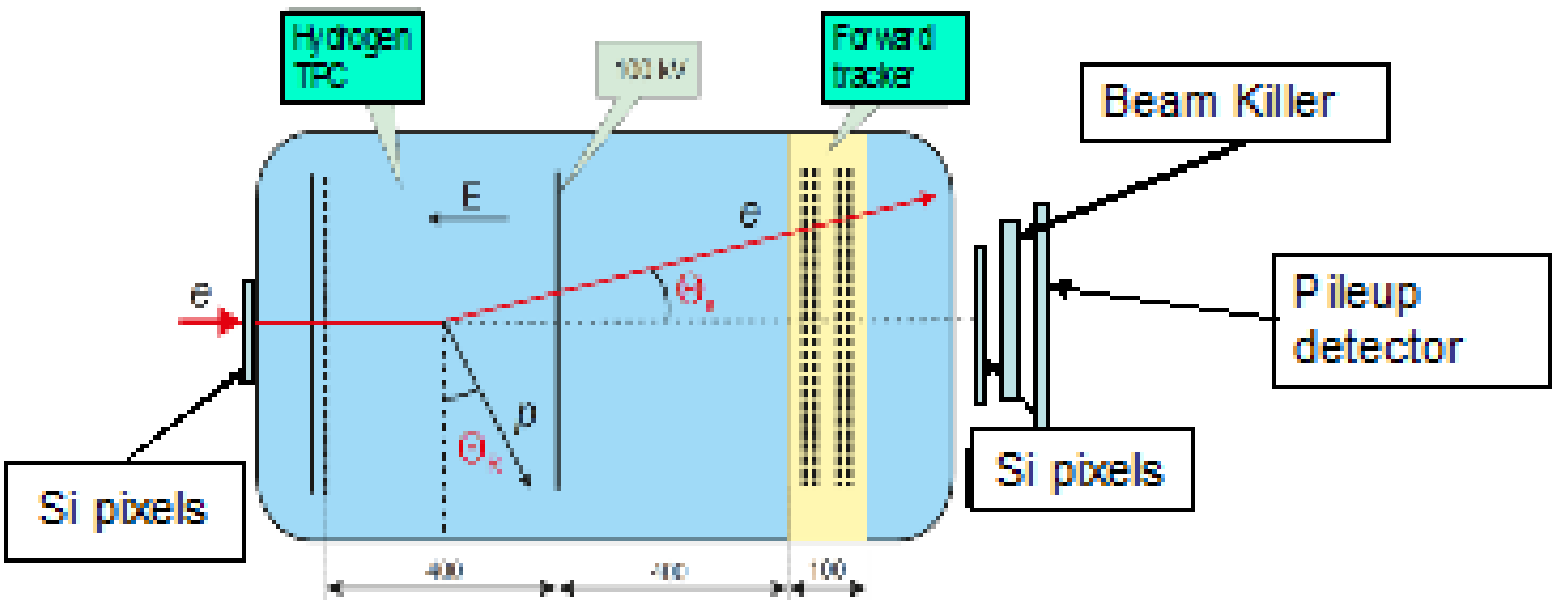
Forward Tracker



Two pairs of Cathode Strip Chambers X1/Y1 and X2/Y2.
Size: 600mm x 600 mm.
Strip width: 2mm.
Spatial resolution: 30 μm.
Time resolution : 5 ns.

Linear scale with 0.02 % absolute precision

Beam Detectors



Measured quantities:

Recoil energy T_R

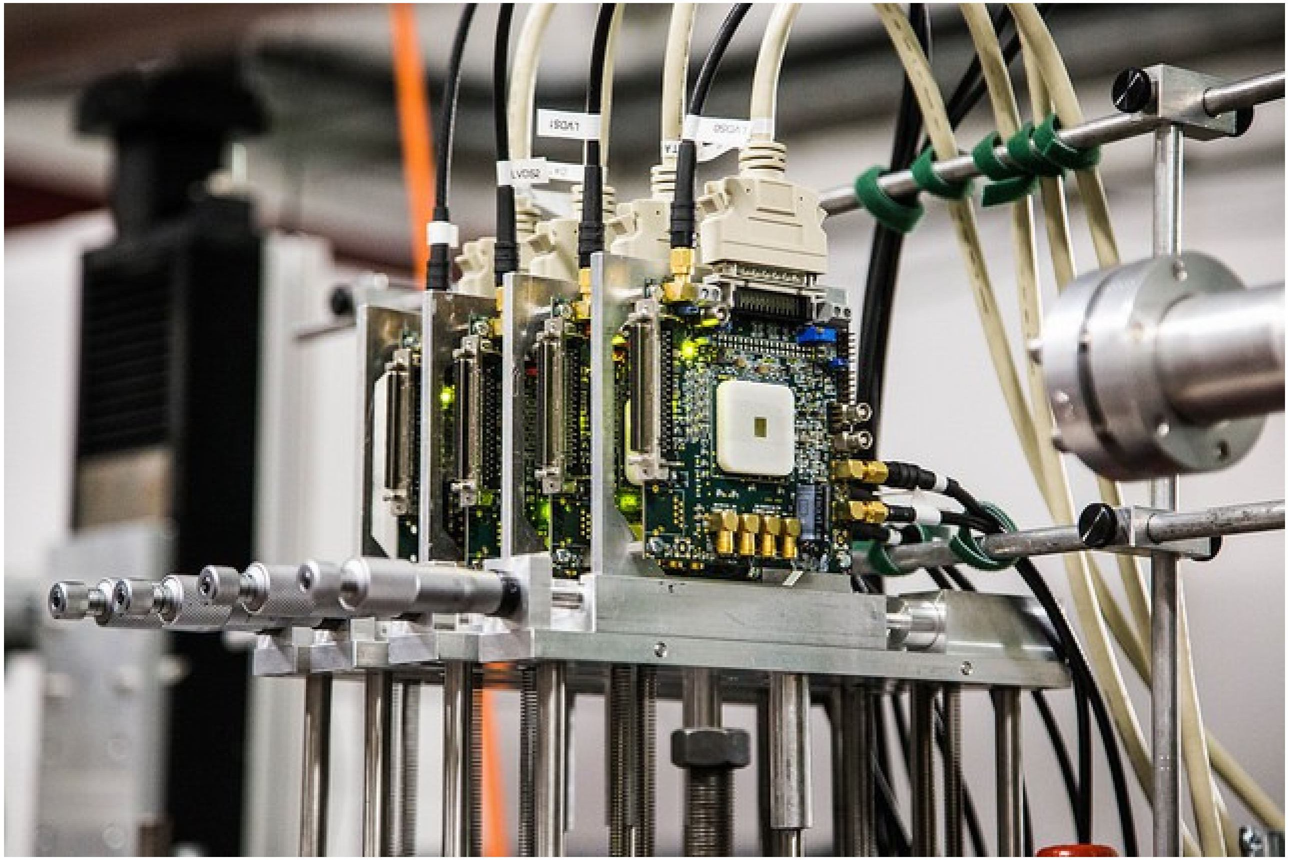
Si-pixels 3x3 mm: Input trajectory $\sigma_X = \sigma_Y = 30\ \mu m$ Time resolution 10 ns

Beam Killer: SC counter 1 ns resolution

Pileup detector: SC counter 0.1 ns resolution

Beam intensity 2 x 10^6 electrons/sec

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

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

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

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.

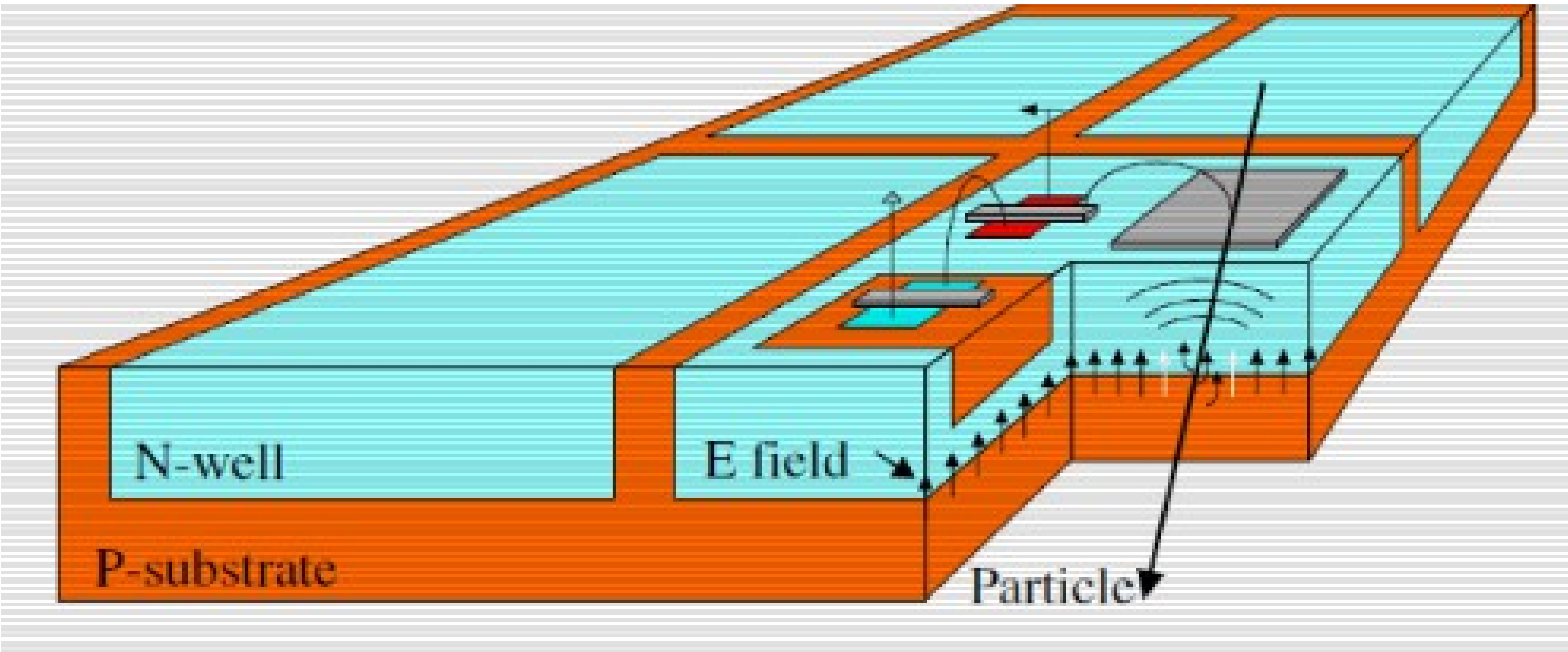
At low Q^2 the form factors can be represented by the expansions:

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

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:

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

Backup



Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

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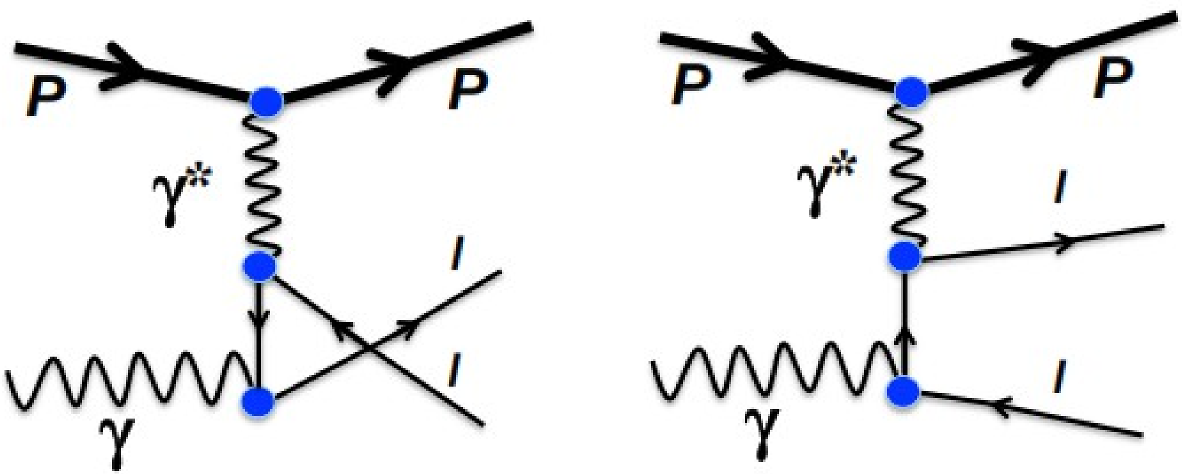

$$\frac{d\sigma^{BH}}{dt\,dM_{ll}^2} = \frac{\alpha^3}{(s-M_p^2)^2}\cdot\frac{4\beta}{t^2(M_{ll}^2-t)^4}\cdot\frac{1}{1+\tau}\times\left[C_E G_{E_p}^2 + C_M \tau G_{M_p}^2\right]$$

Invariant mass sq lepton pair

Proton mom transfer

Proton form factors

Backup (Patrik Adlarson)

Bethe–Heitler dσ/dEγ

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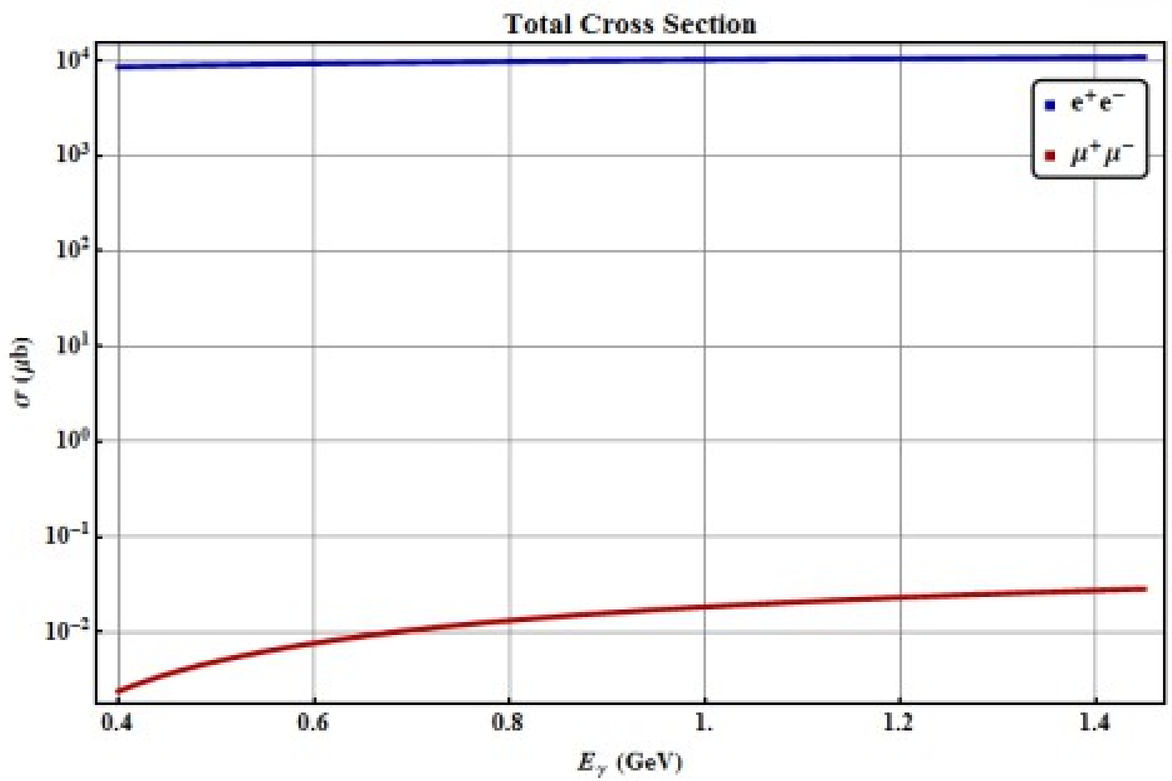
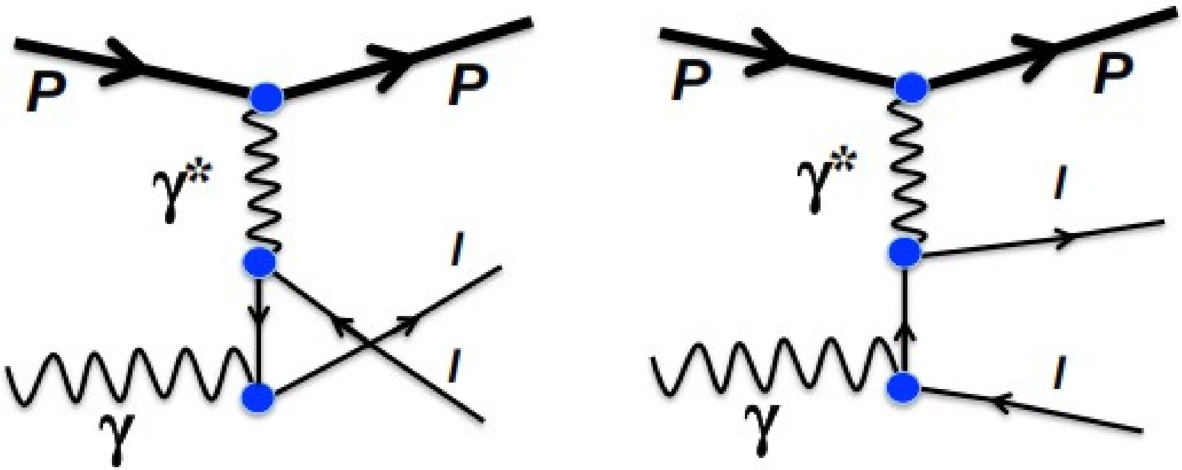


BH-ee (blue) and BH-μμ (red) cross section as function of beam energy

Dimuon cross section increases more for increasing beam energies

Backup (Patrik Adlarson)

Bethe–Heitler (BH) process



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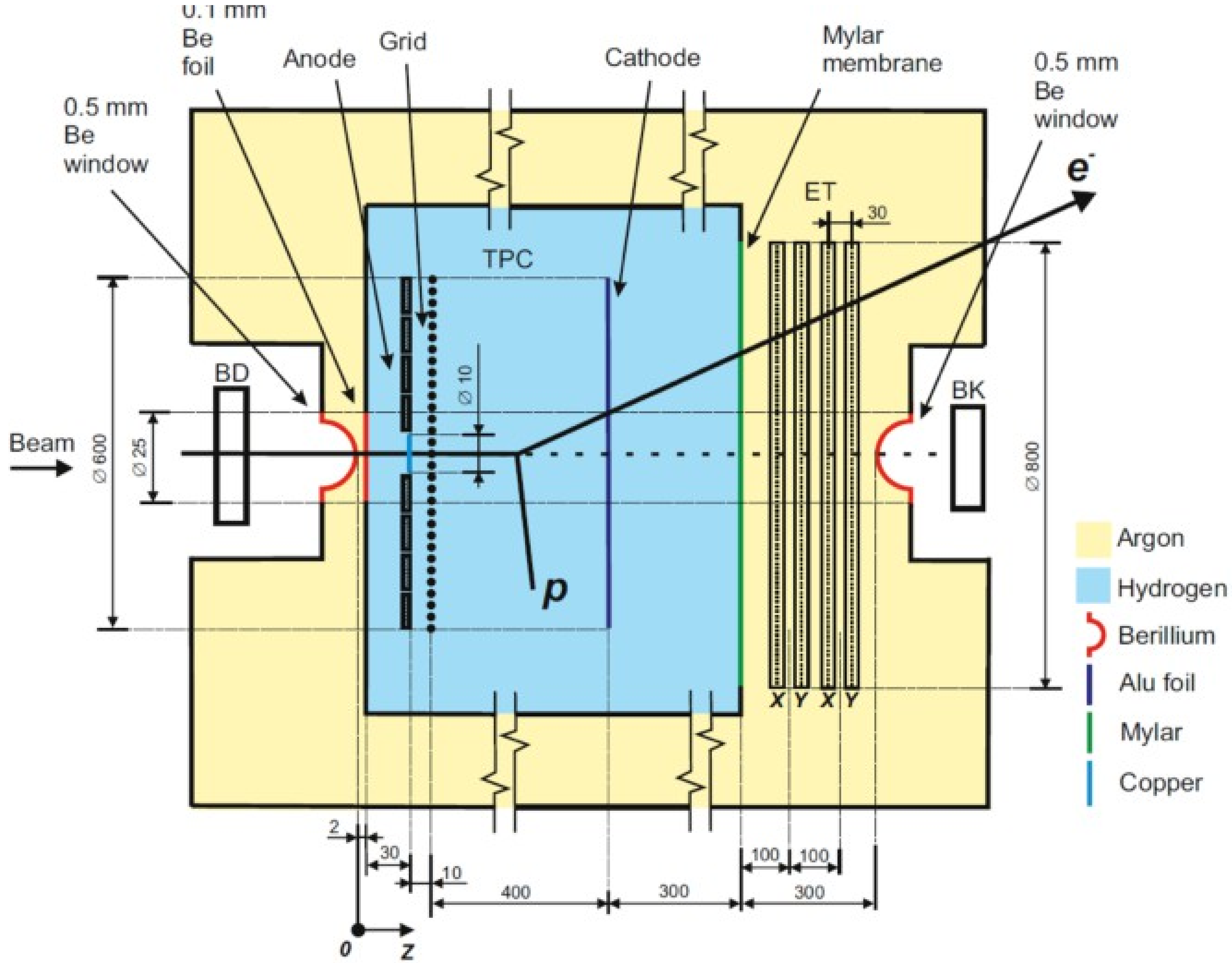
Backup



A. Vorobyov (PNPI)

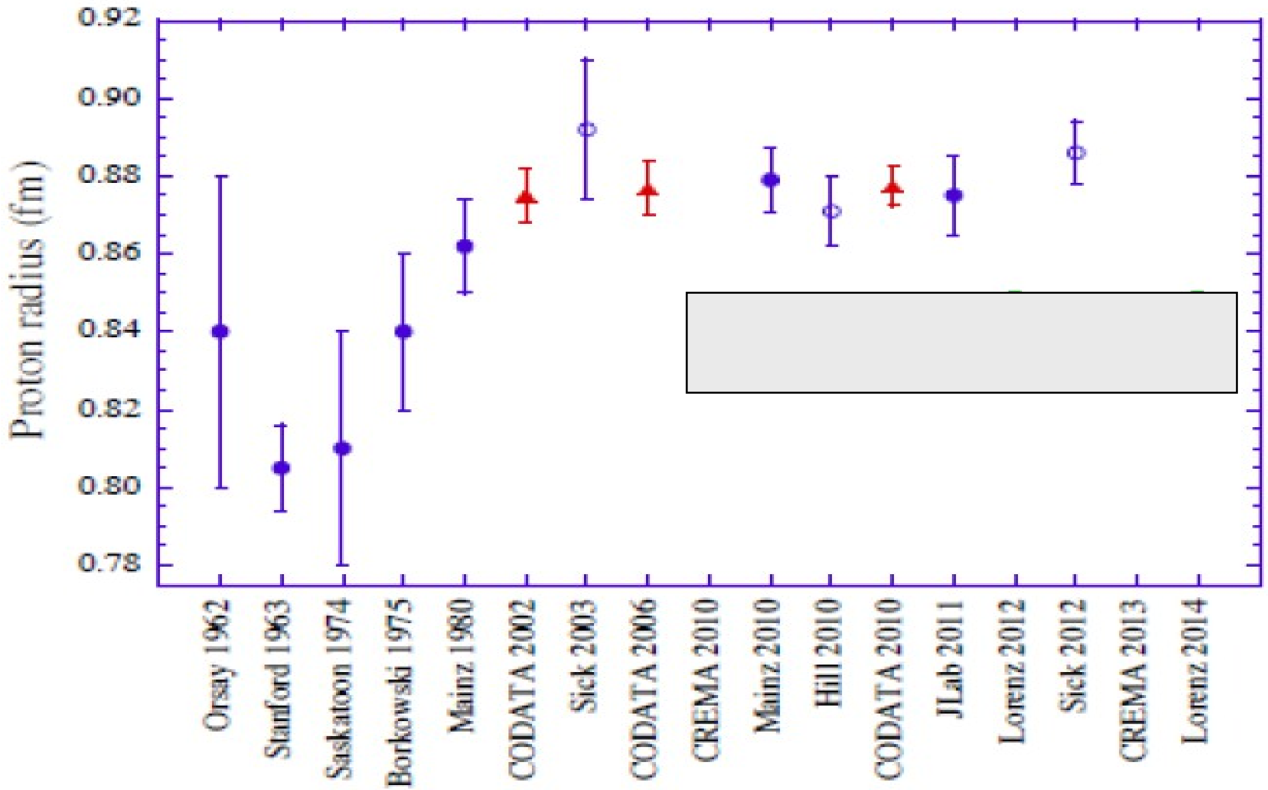
Backup

		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

Proton radius from ep-scattering
1962-2014



- Electron-proton scattering:
  1. $r_p = \mathbf{0.879(8)}$ **fm**, *Mainz, A1 Collaboration, 2010*
  2. $r_p = \mathbf{0.875(10)}$ **fm**, *JLab, Zhan et al, 2011*

- CODATA: $r_p = \mathbf{0.877\ 5\ (51)}$ **fm** *2010*

Radiative corrections

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