Proposal

to perform an experiment at MAMI

High Precision Measurement of the ep elastic cross section at small Q^2

Contact person for the Experiment:
Alexey Vorobyev, Petersburg Nuclear Physics Institute

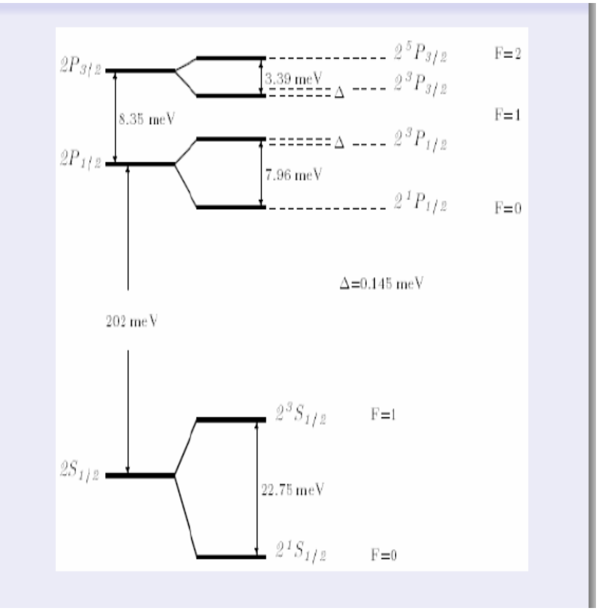
Mainz contact person: Achim Denig,
Institute for Nuclear Physics, JGU Mainz

A.Vorobyev PAC meeting November 17 2016

Motivation

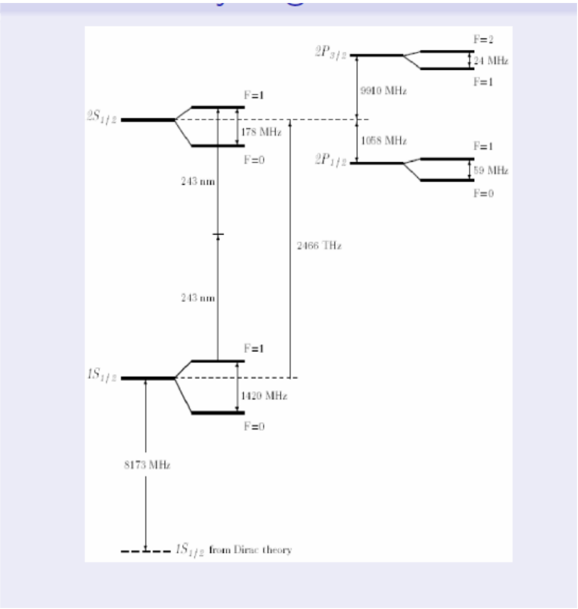
Proton radius puzzle

μp atom



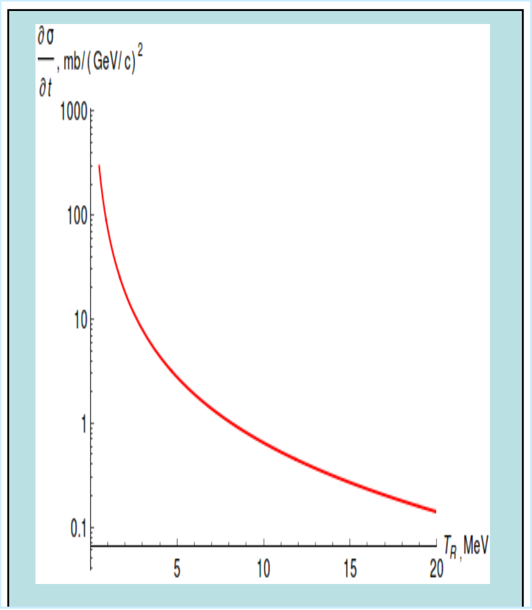
Rp = 0.8409(4)fm

ep atom



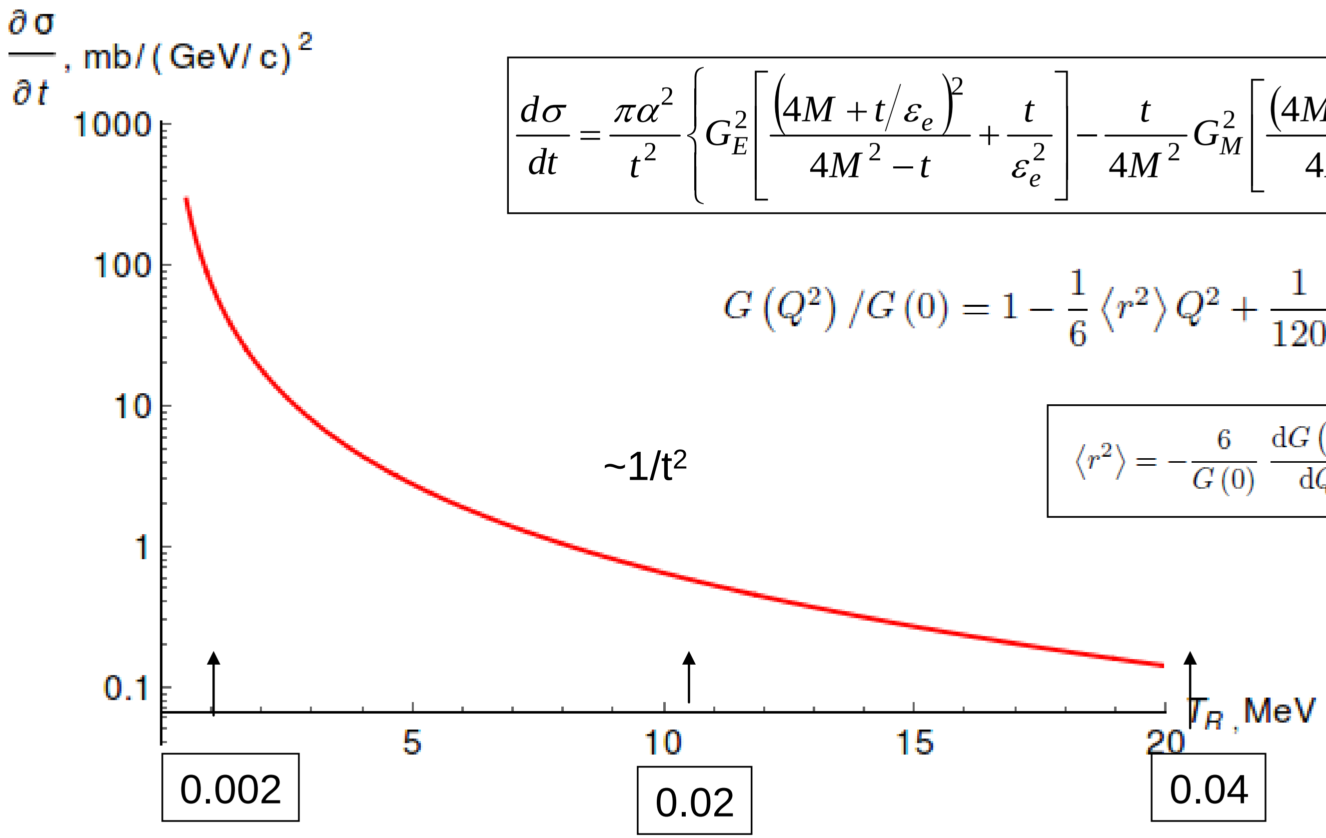
Rp = 0.877(8)fm

ep scattering



Rp = 0.877(7)fm

Extraction of proton radius from e-p cross section



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

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

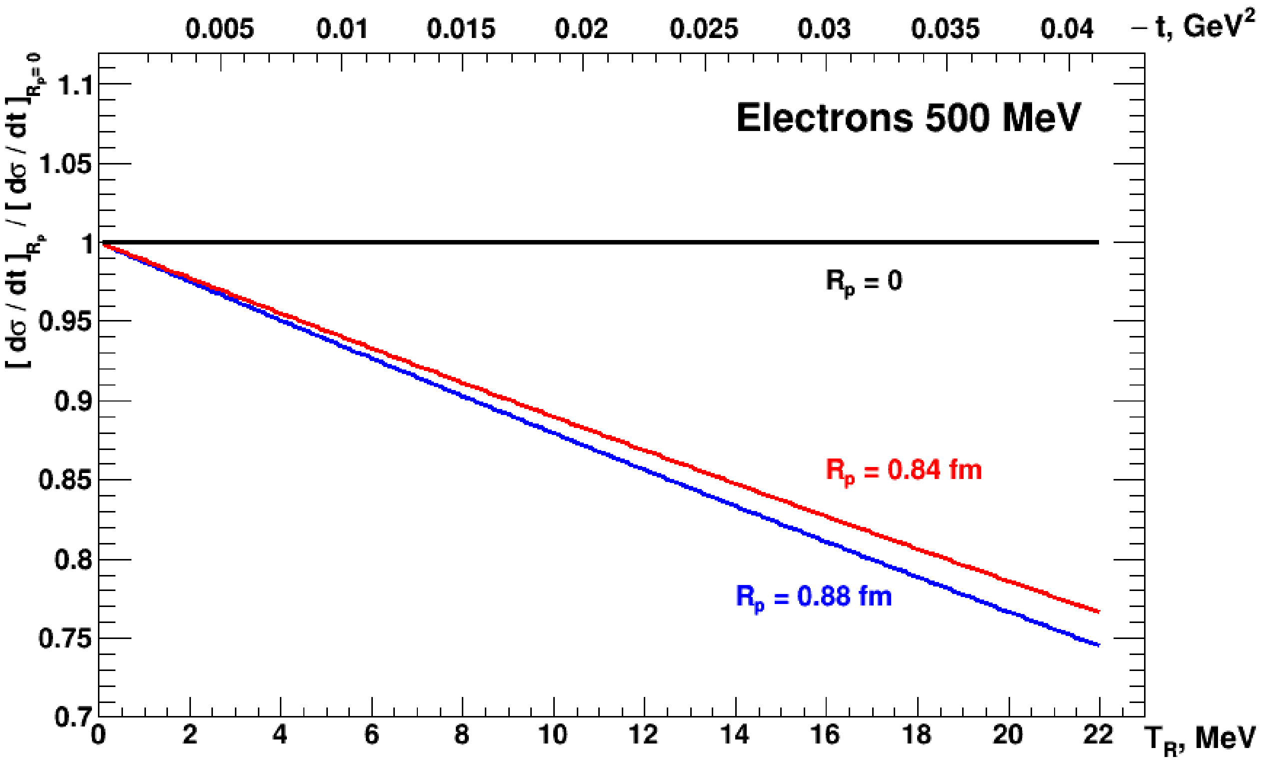
$$\left\langle r^2\right\rangle=-\frac{6}{G\left(0\right)}\left.\frac{\mathrm{d}G\left(Q^2\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

$-t=Q^2=2MT_R$

7

The measurements of dσ/dt should be at $Q^2 \leq 0.02$ GeV^2

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

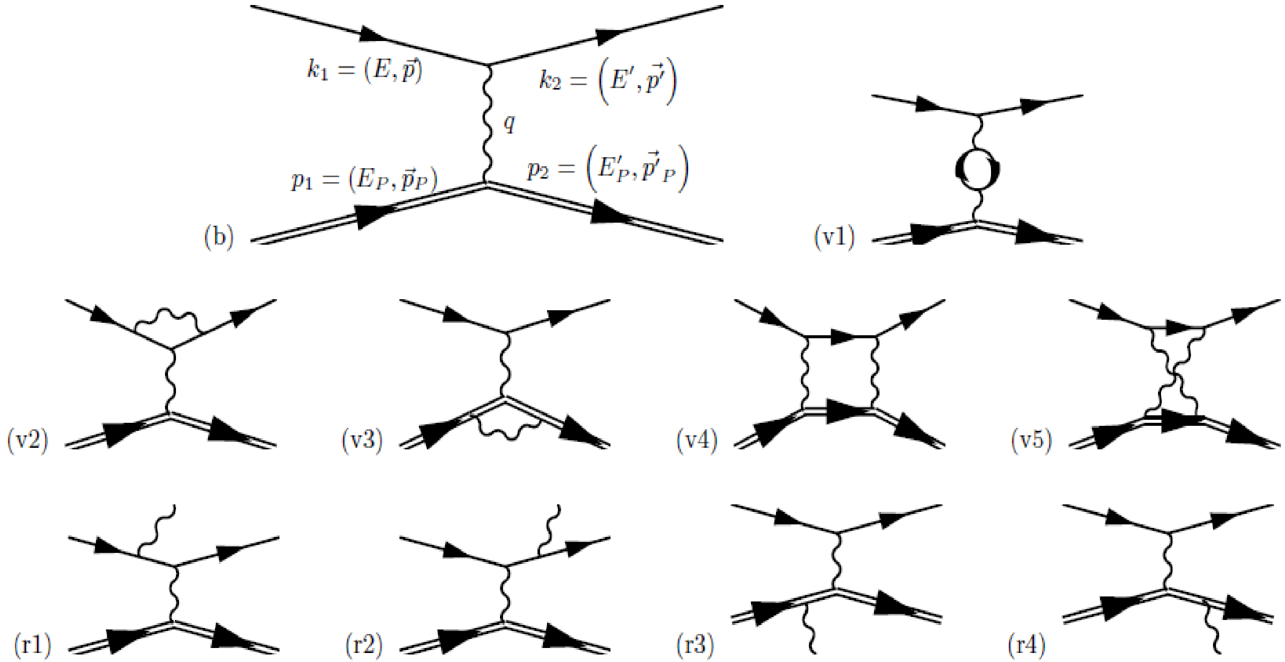


Difference in dσ/dt between Rp=0.84 fm and Rp=0.88 fm
is only 1.3% at Q^2 =0.02Gev^2

Mesurement of dσ/dt with point-to-point precision ≤ 0.2%

Radiative corrections

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



Absolute normalization of dσ/dt with ≤ 0.2% precision

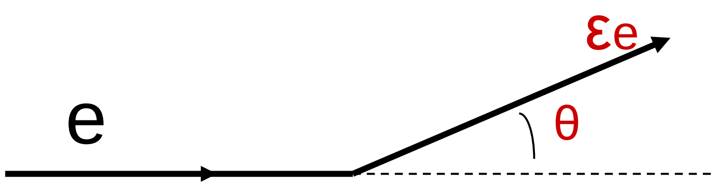
Requirements to new generation measurements of proton radius in ep scattering experiments

- Low transfer momentum region,

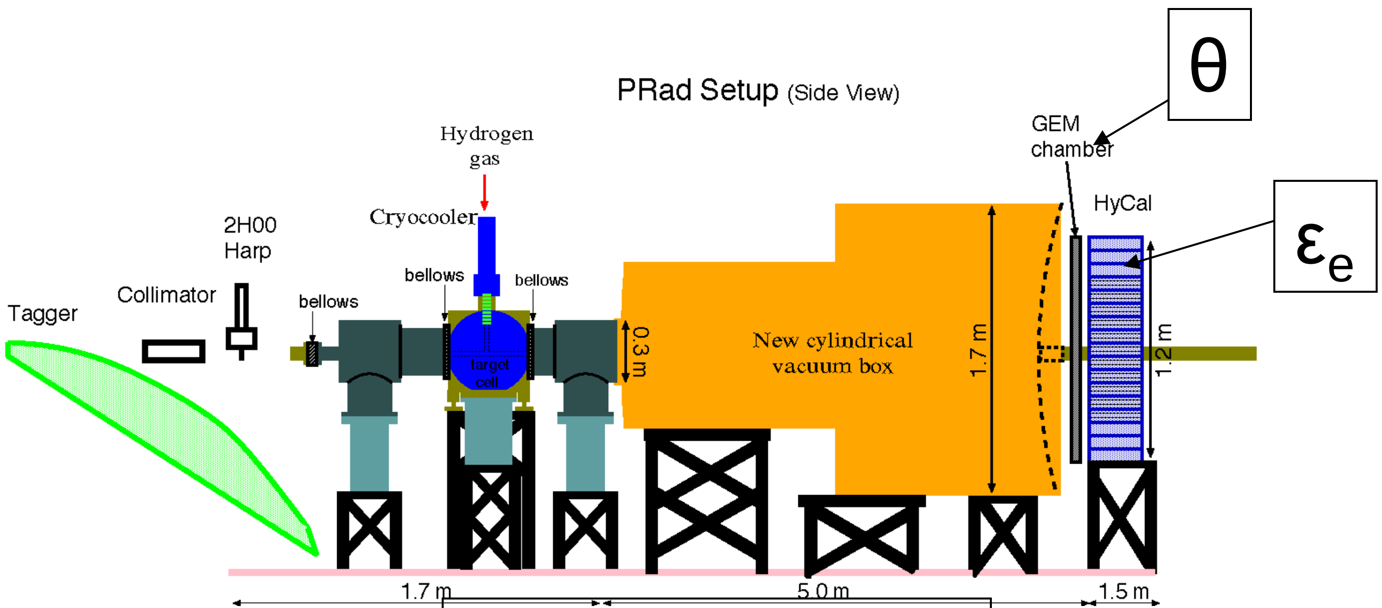
  $0.001\ GeV^2 \leq Q^2 \leq 0.02 GeV^2$
- High resolution in Q^2;
- Point-to-point precision $\leq 0.2\%$
- Absolute normalization of $\leq 0.2\%$

Experiment PRad (Proton Radius)

Jefferson Lab



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



$2x10^{-4} \leq Q^2 \leq 10^{-1}$ Gev^2

Absolute normalization via ee-scattering

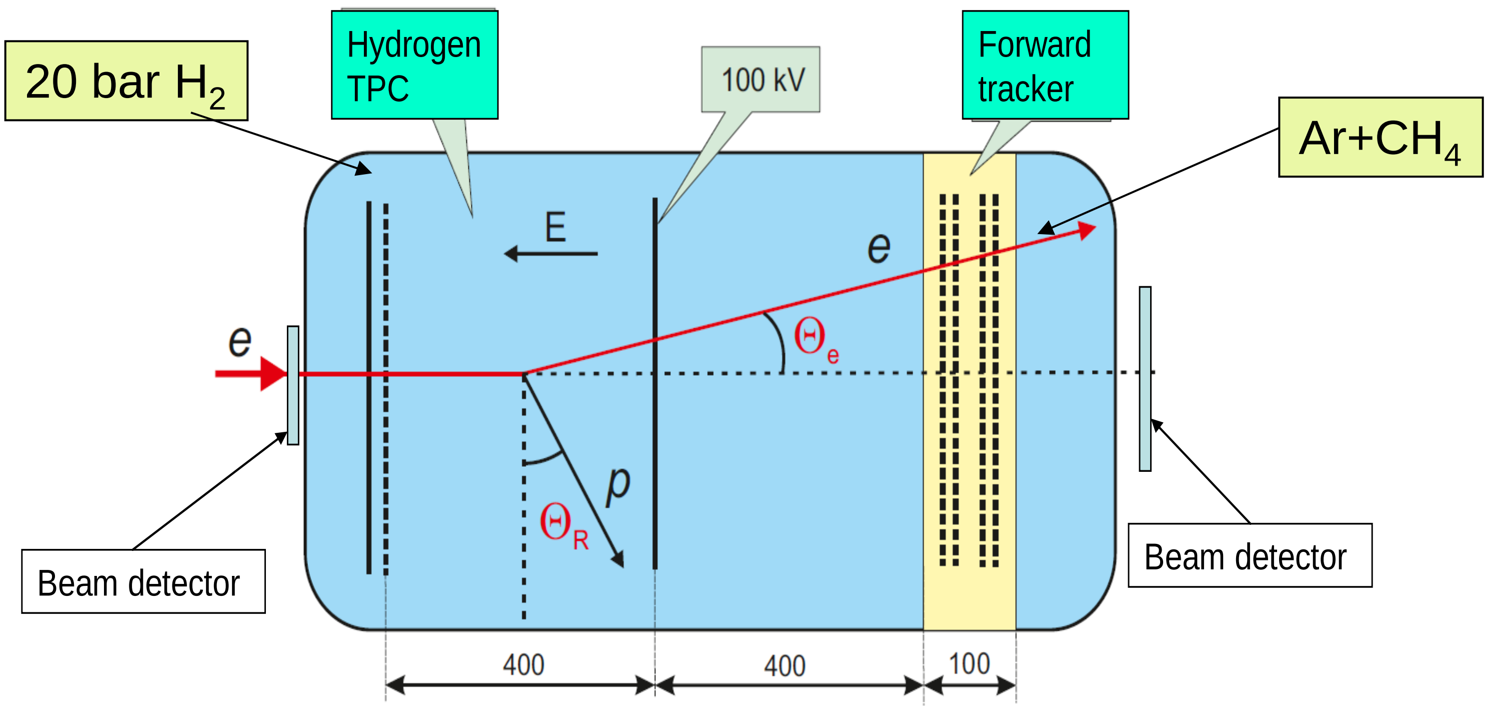
Goals of the proposed experiment

- Measurement of dσ/dt in the Q^2 range 0.002 – 0.02 (0.04) Gev^2;
- High resolution in Q^2 (~100 resolved points);
- 0.1% point -to-point precision in dσ/dt ;
- 0.2 % absolute precision in dσ/dt .

This allows to measure the proton radius with ± 0.005 fm precision
and distingush the two options (0.877 fm and 0.841 fm)
on a 7σ confidence level

In comparison with PRad experiment:
Different systematical errors. Much lower Radiative corrections.
These two experiments will be complementary to each other.

Recoiled proton @ Scattered Electron Detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

E scattering angle Θ_e

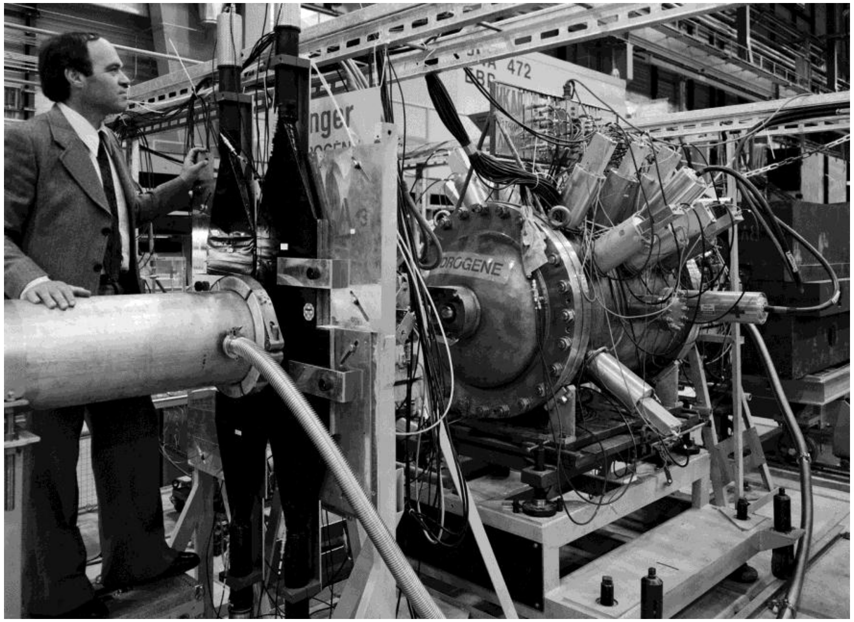
$$-t = \frac{4\varepsilon_e^2 \sin^2 \frac{\vartheta}{2}}{1 + \frac{2\varepsilon_e}{M} \sin^2 \frac{\vartheta}{2}}$$

$$-t = 2MT_R$$

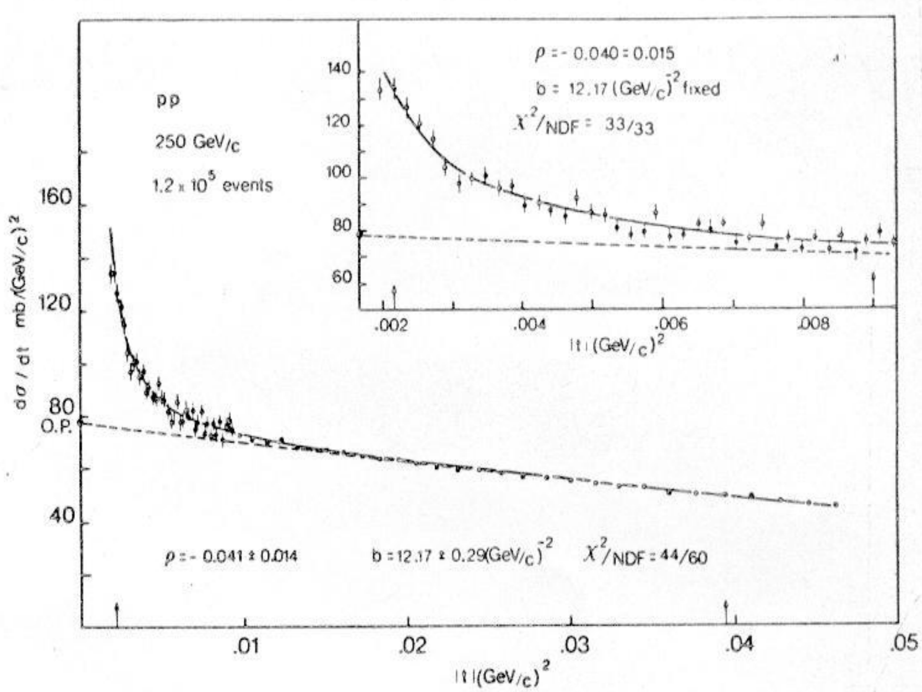
$$\sin(q_R) = \frac{(e_e + M)T_R}{P_e P_R}$$

The proposed experiment is based on
the recoiled proton detection method
which was used in WA9 and NA8 experiments
at CERN to measure small angle pp- and πp- scattering.

Nuclear Physics B217 (1983) 285-335



Recoiled proton detector ICAR at CERI



H_2 10 bar TPC

If compared with WA9/NA8 experiments

- Higher pressure from 10 bar to 20 bar
- Larger diameter from 400 mm to 600 mm
- Higher precision in $d\sigma/dt$ measurements

  relative and absolute factor of 5.

Some advantages of the recoil method in measurements of the ep elastic scattering cross sections

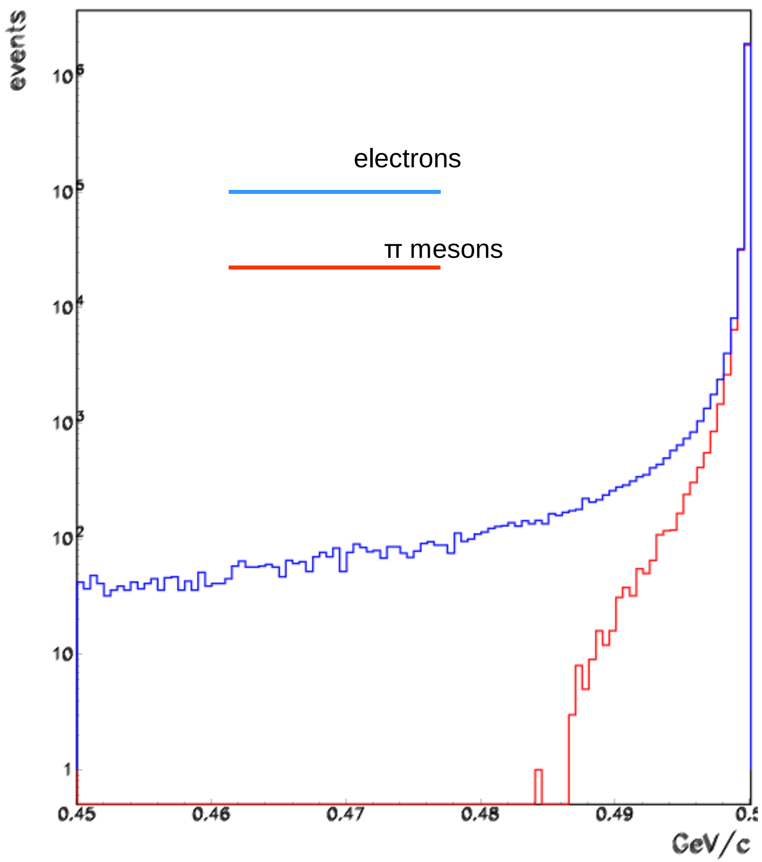
- High resolution in low Q^2-region;
- Direct measurement of Q^2 ($Q^2 = 2MT_R$) independently on the electron energy.

- No wall effects;
- Well determined gas target length;
- Close to 100% detection efficiency (under control):
- Precision absolute measurement of $d\sigma/dt$.

- Much smaller radiative corrections.

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

500 MeV/c



$-t = 2MT_R$

T_R determines dσ/dt with very little dependence on the electron energy losses before the coliision

$d\sigma_t/\sigma_t$ = +0.005 dP/P T_R =1MeV,

$d\sigma_t/\sigma_t$ = +0.05 dP/P T_R=10MeV

σ_t =dσ/dt

Radiative corrections

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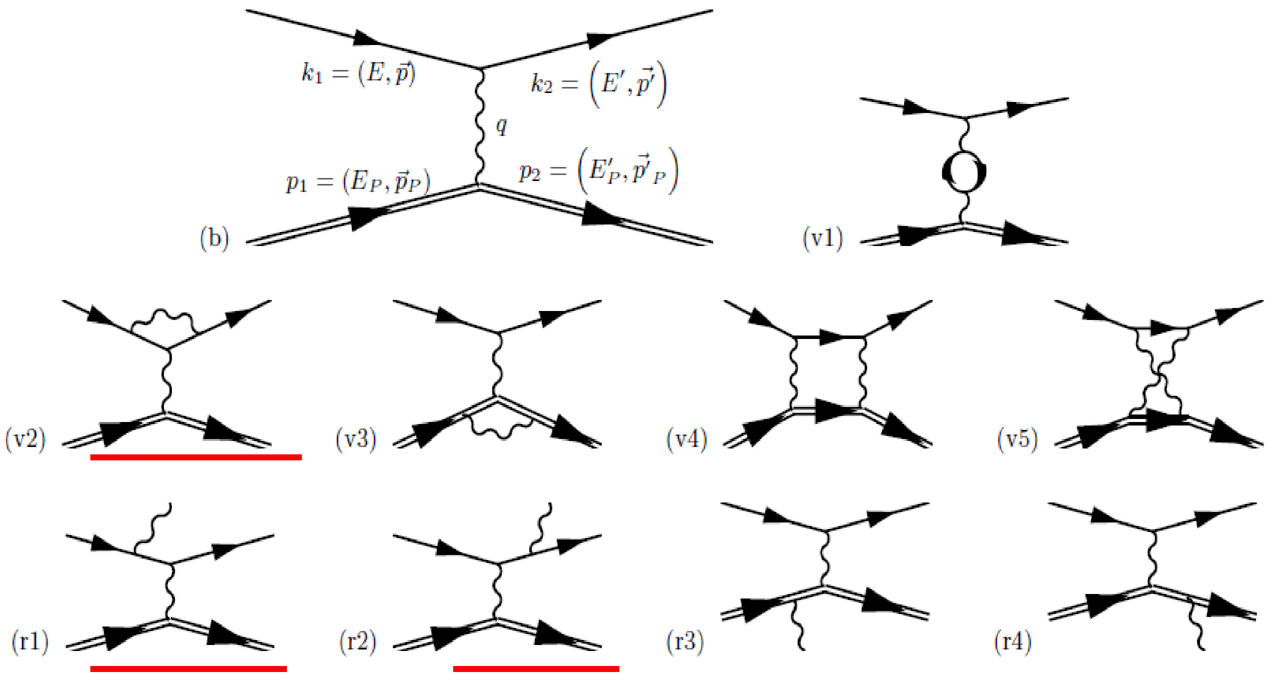
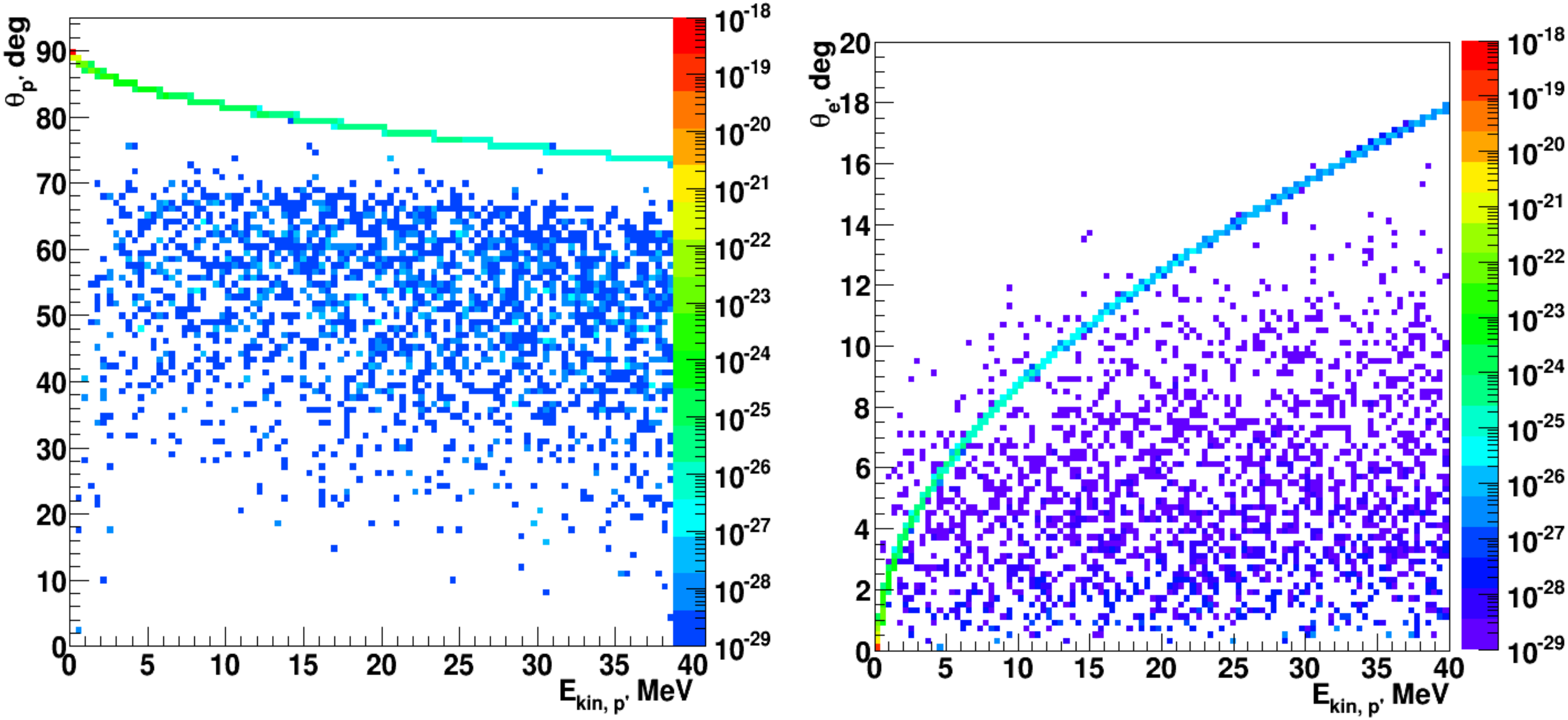


Experts on RC A.Arbuzov and A. Gramolin (group of V.Fadin) agreed to calculate the radiative corrections for our experiment

MC calculated θ_e -- T_R and $\theta_R - T_R$ plots calculated for the elastic ep scattering and for the background reaction $ep \rightarrow ep\pi^0$ for ε_e=900 MeV.



Main experimental problem

High precision calibration of the recoiled proton energy scale.

In our experiment this calibration will be done with 0.04 % precision via the T_R- θ_e correlation relying on high precision (0.02%) linear scale of the Forward Tracker.

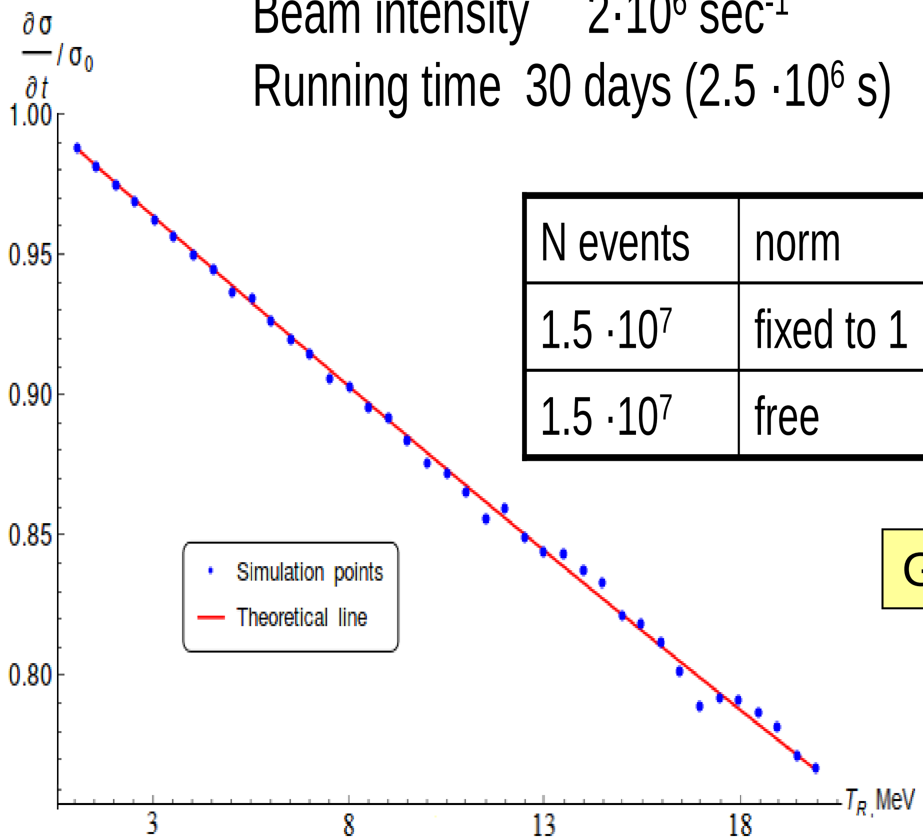
Statistics and beam time

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)



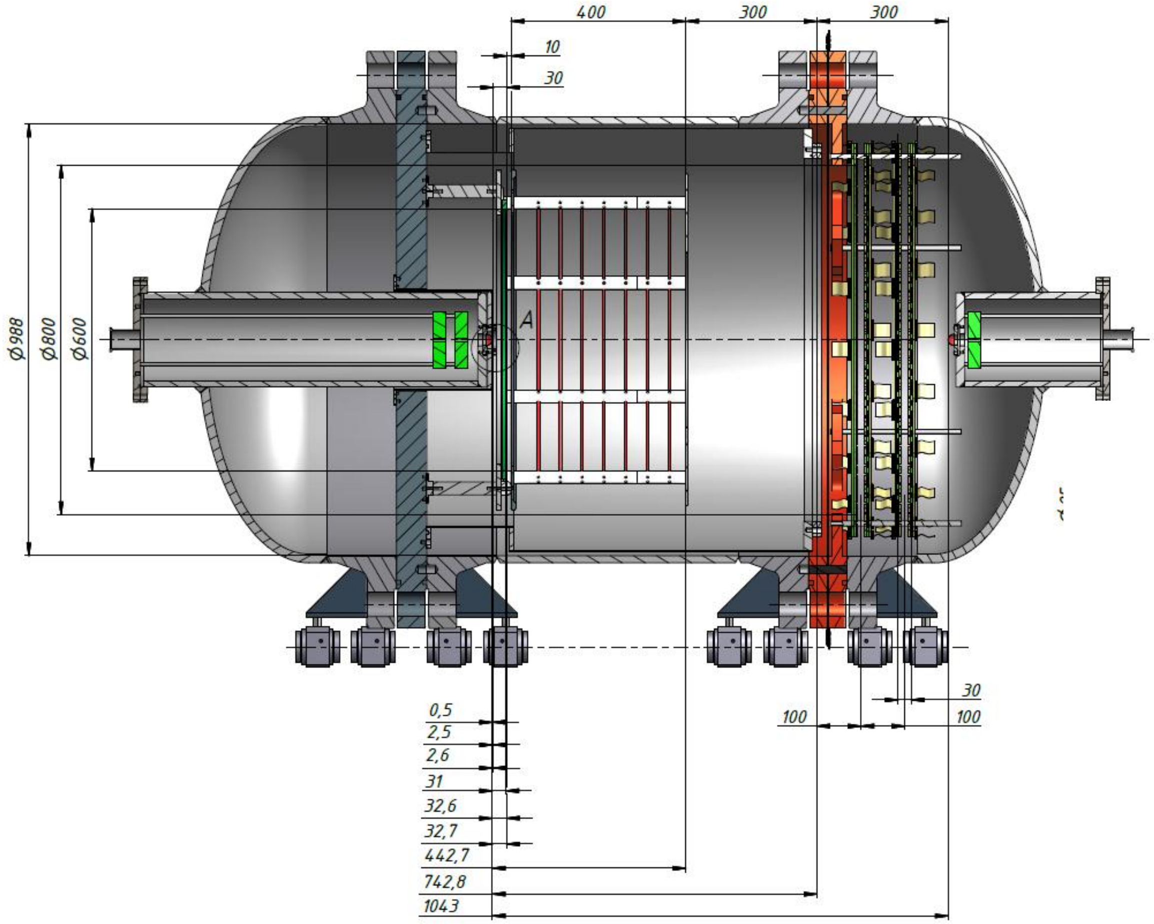
N events	norm	t-scale	σ(Rp)
$1.5 \cdot 10^7$	fixed to 1	fixed	± 0.002 fm
$1.5 \cdot 10^7$	free	fixed	± 0.003 fm

Goal : σ(Rp) ≤ 0.005 fm

The systemetic errors entering the measured dσ/dt

		Syst. Error %	comments
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	Sum of errors 3 and 4
6	Target length, L_{tag}	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	Clean Tr0 free of pileups
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 errors 11 and 10
	dσ/dt , relative	0.1	0.08% from error 12
	dσ/dt , absolute	0.2	0.16% from err.13 plus errors 7,8,9

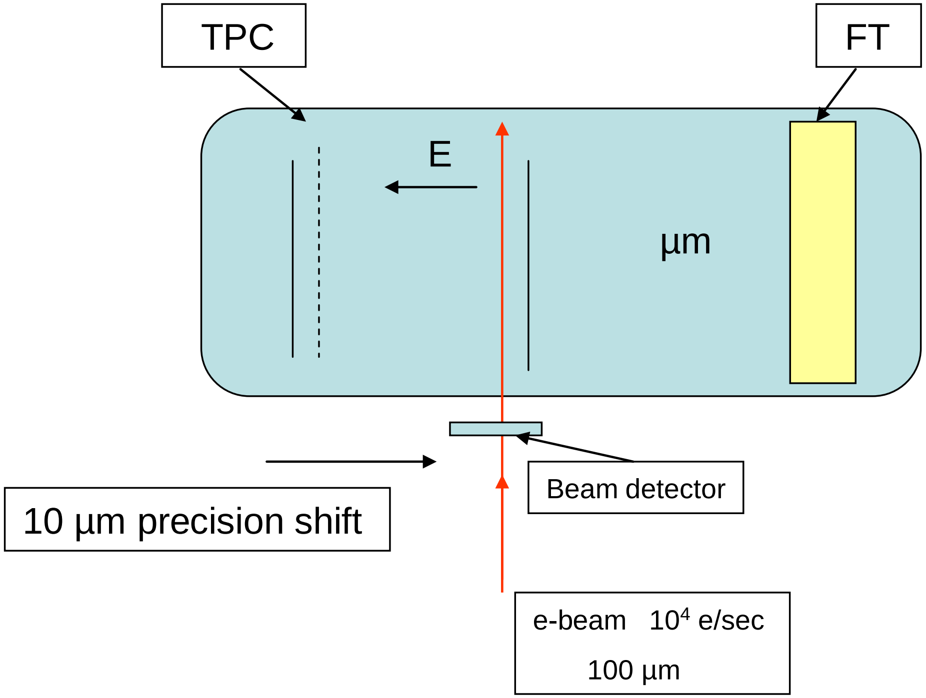
Tentative design of the TPC& FT detector



MAMI and beam specifications

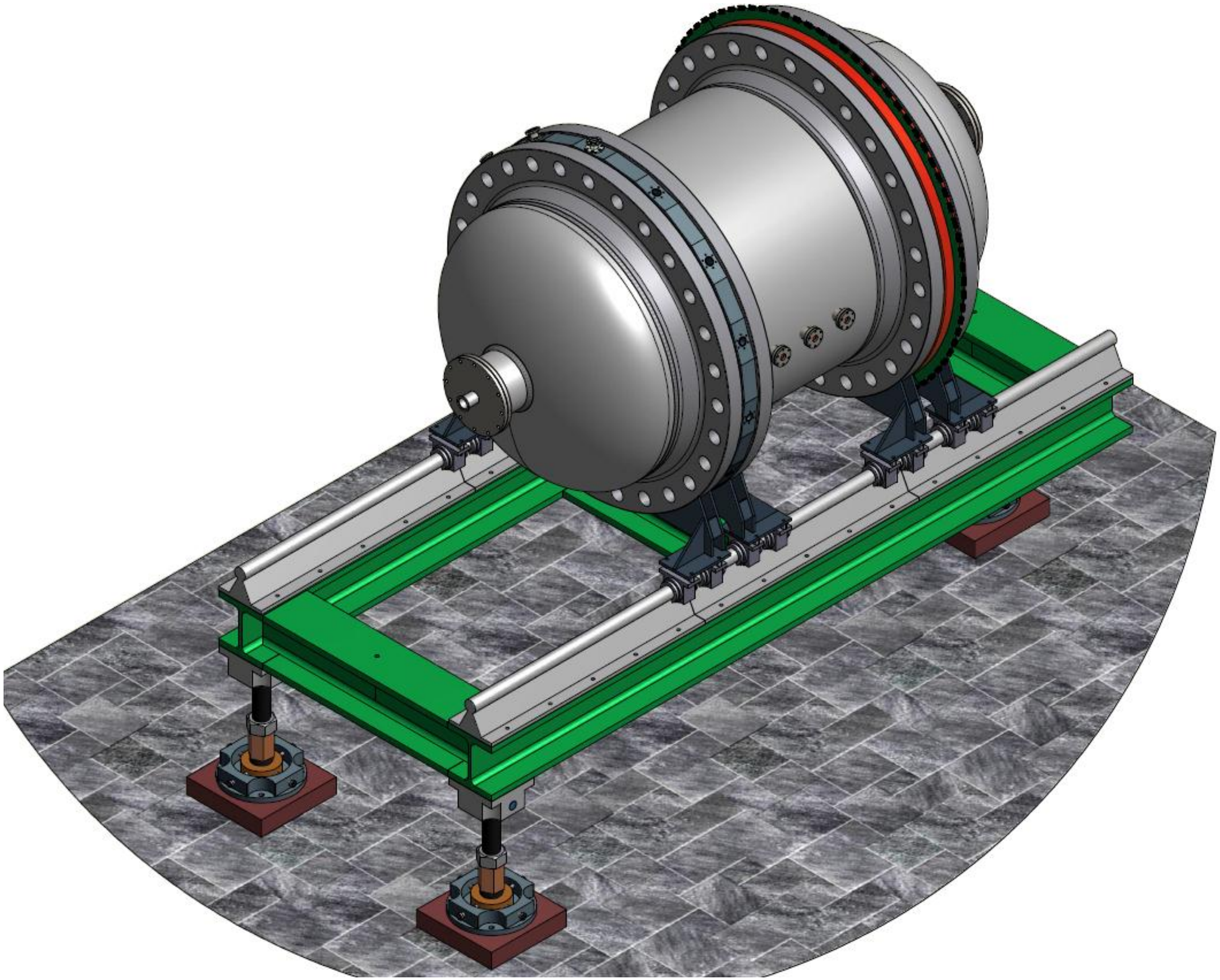
- **MAMI Specifications**
- Beam energy 500 MeV, 720 MeV
- Energy spread < 20 keV (1σ)
- Energy shift < 20 keV (1σ)
- Absolute energy ≤ ±150 keV (1 σ)
- **Electron Beam Specifications**
- Beam intensity (main run) 2x10^6 e/sec
  Beam intensity for calibration 10^4 e/sec and 10^3 e/sec
- Beam divergency ≤ 0.5 mrad
- Beam size ≤ 100 μm

Drift velocity measurement

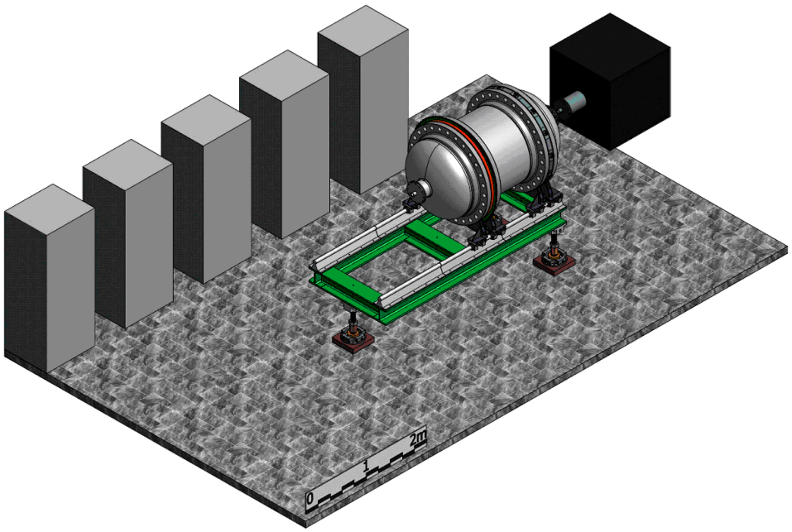


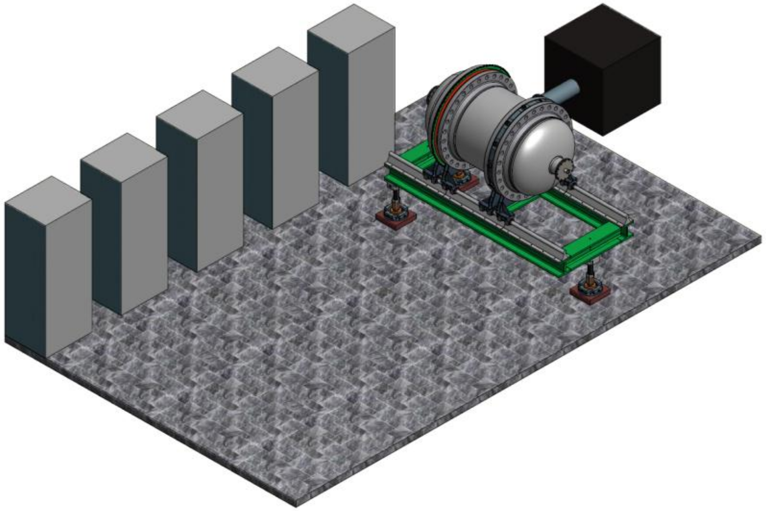
Precision in W measurements 0.01%

The TPC&FT detector on a movable platform.



Experimental layout for the physics run (Left panel) and for drift velocity measurements (Right panel).





The space for TPC platform 3m x 3m.

Five racks could be placed within 10 m from TPC.
Some space is needed outside to keep H_2 containers

Working plan

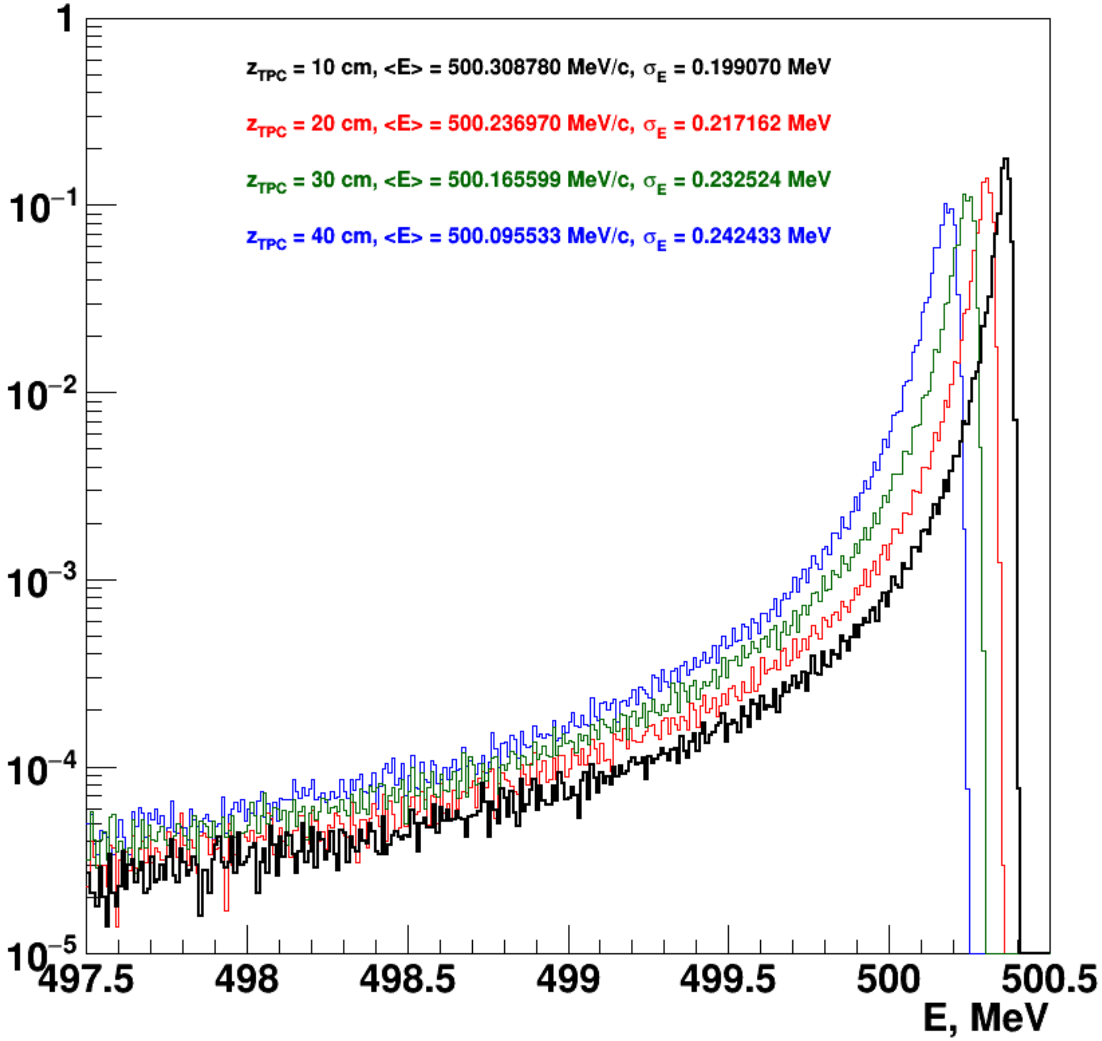
2017 Test experiment in the electron beam at MAMI with a TPC prototype now available at GSI.

Beam test equipment, TPC background

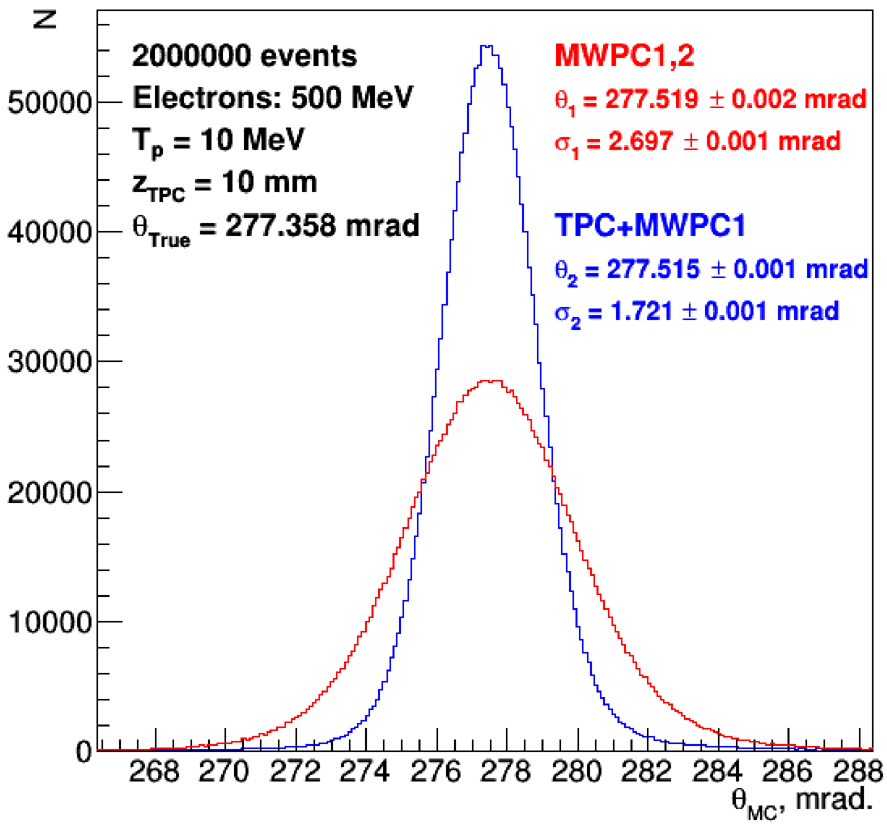
2018 Construction of the whole setup. First physics run.

Thank you for your attention

Electron energy E* in the collision point

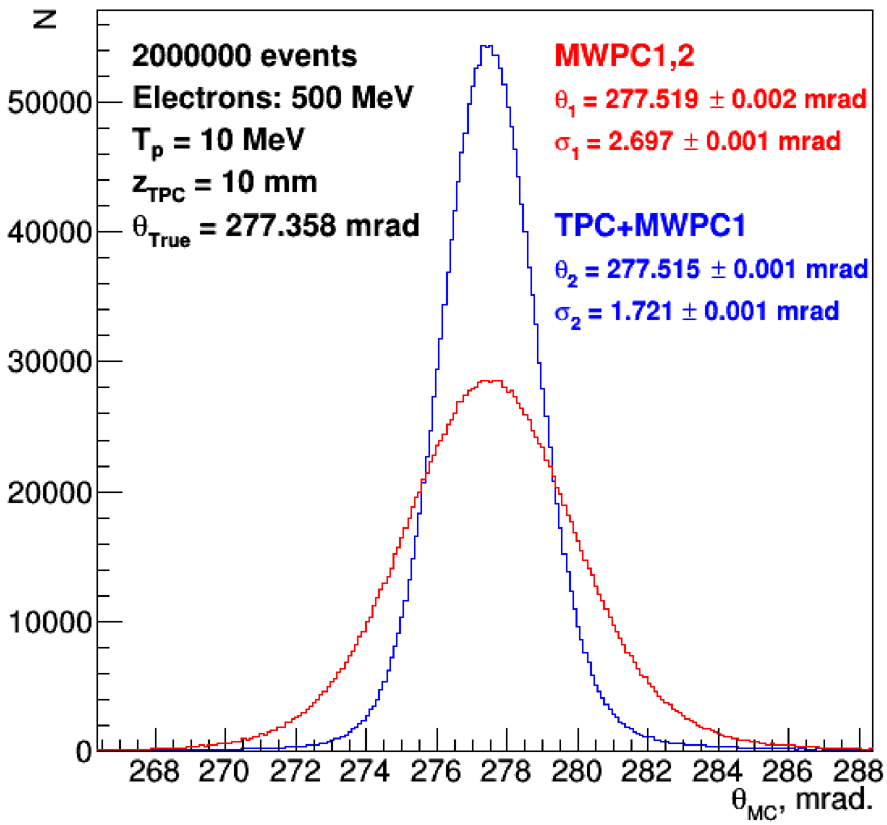


T_R scale calibration via T_R- θ_e correlation



$$T_R^*(E_0,\theta_e)/T_R = 1 + 1.2\cdot 10^{-3}$$

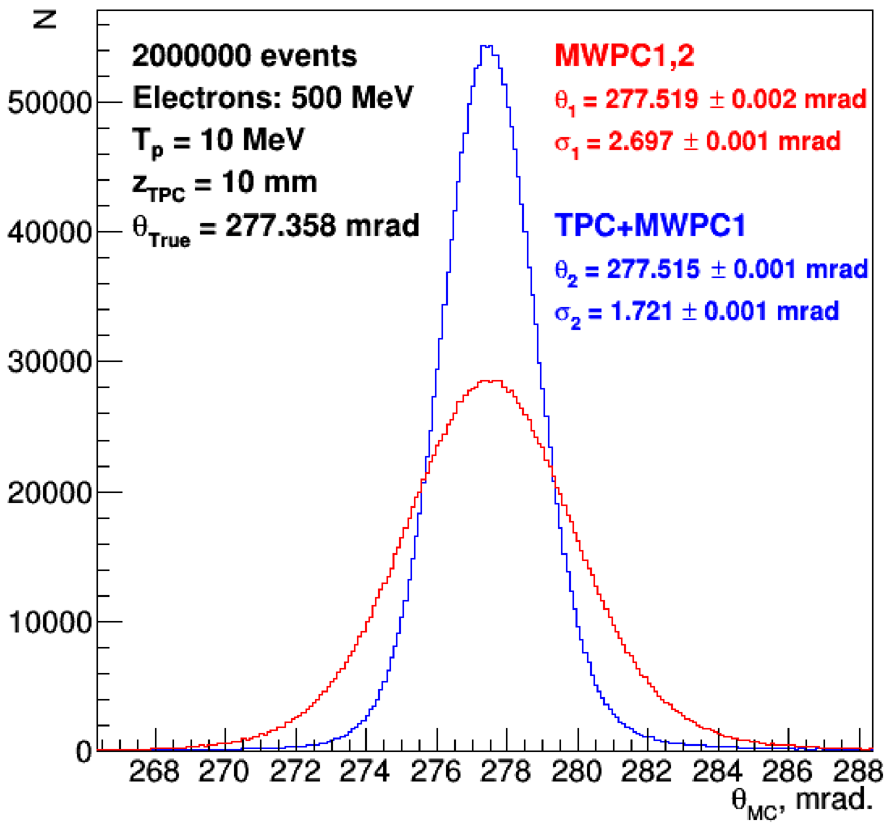
T_R scale calibration via T_R- θ_e correlation



$T_R^*(E_0,\theta_e)/T_R = 1 + 1.2\cdot10^{-3}$

$T_R^*(E^*,\theta_e)/T_R = 1 + 3.8\cdot10^{-4}$

T_R scale calibration via T_R- θ_e correlation



$T_R^*(E_0,\theta_e)/T_R = 1 + 1.2\cdot10^{-3}$

$T_R^*(E^*,\theta_e)/T_R = 1 + 3.8\cdot10^{-4}$

$T_R^*(E^*,\theta_e^*)/T_R = 1 + 0.8\cdot10^{-4}$

The TPC@FT detector

can be also used

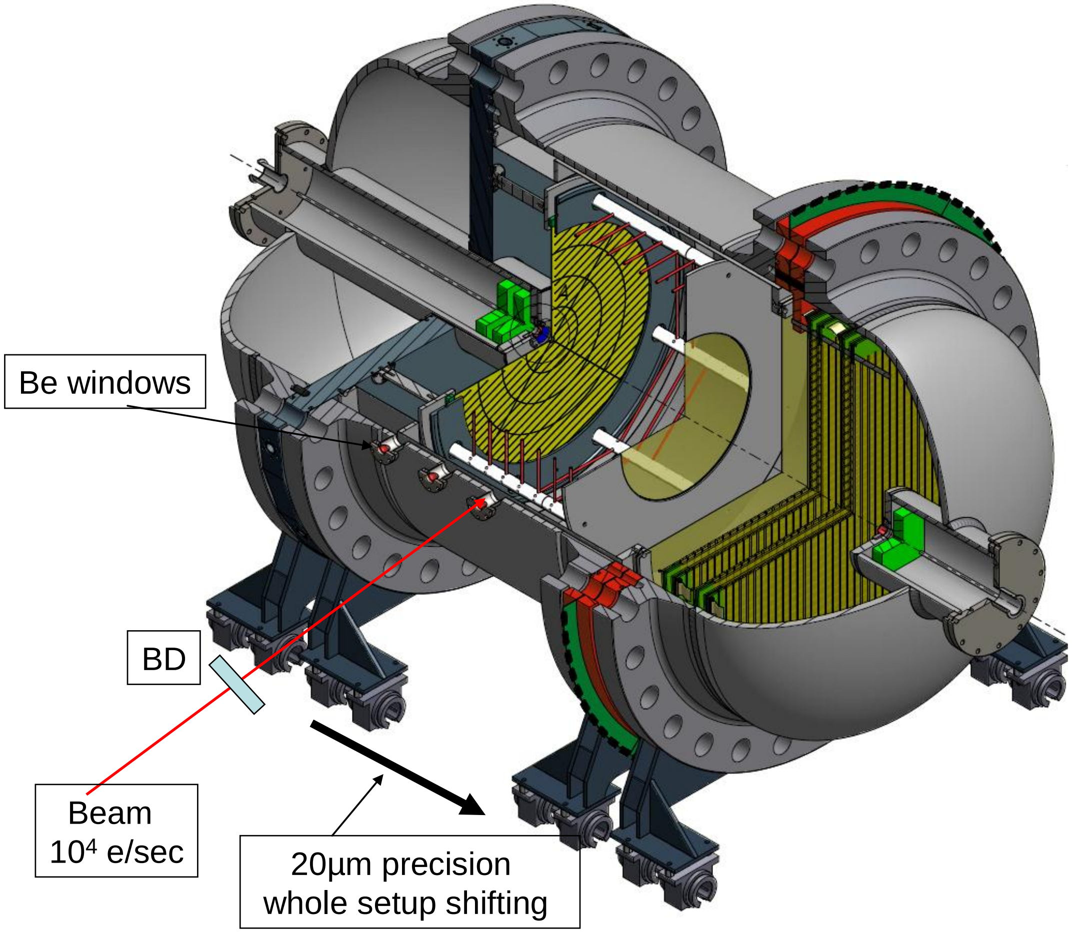
to study

e-d, He scattering

μ-p,d,He scattering

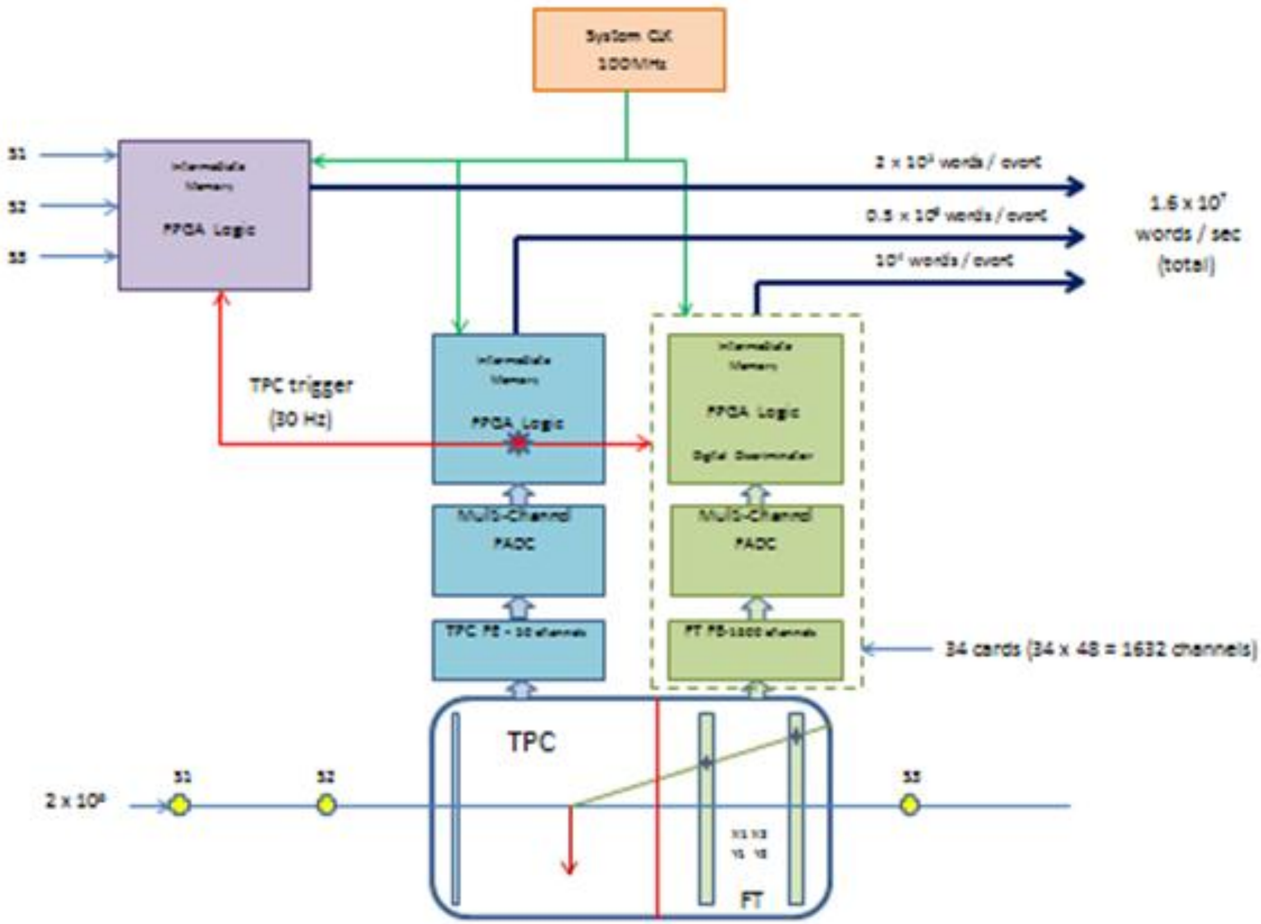
- Exotic nuclei –p,d,He scattering

Experimental layout for high precision measurement of electron drift velocity.

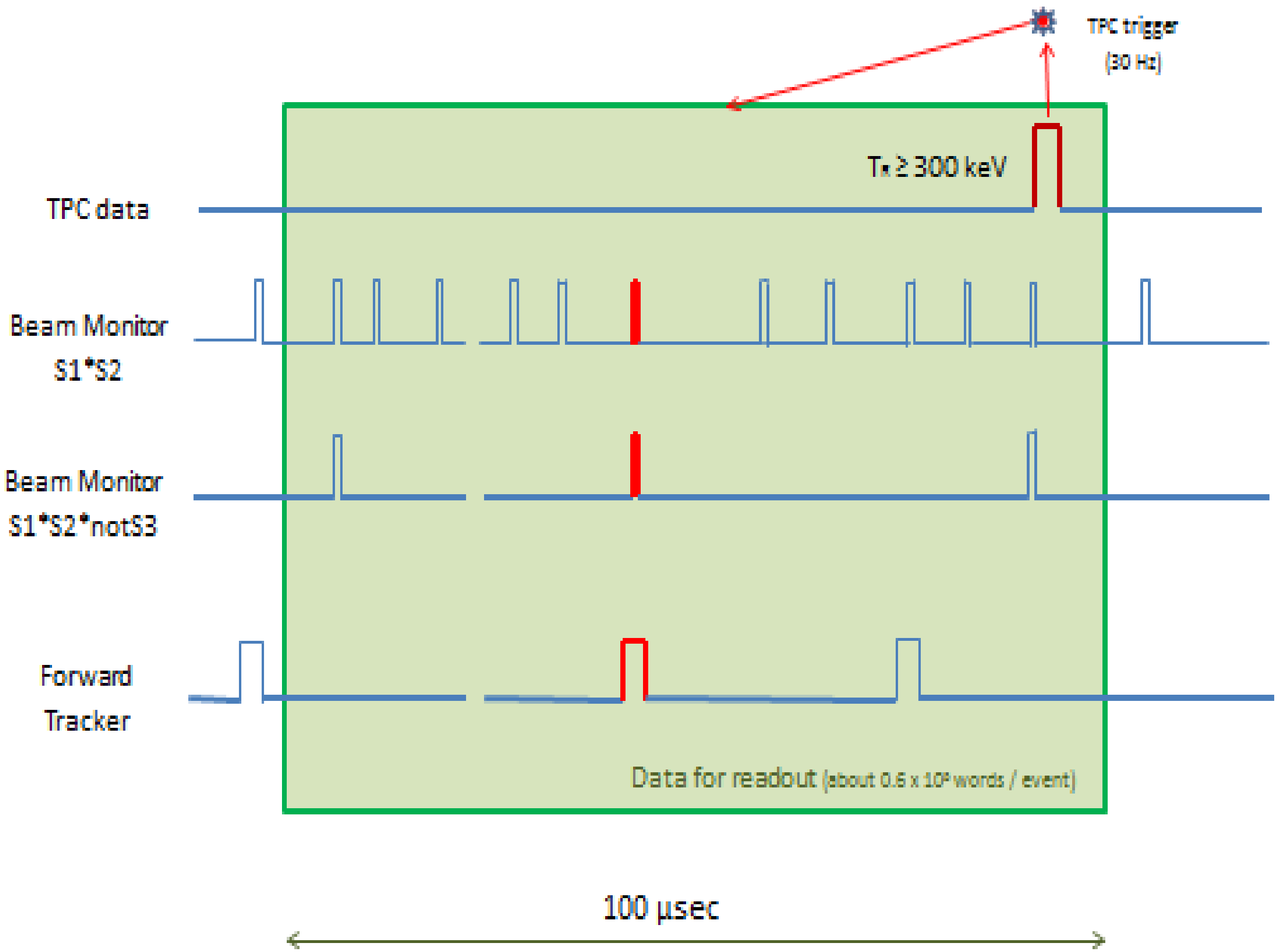


DAQ system

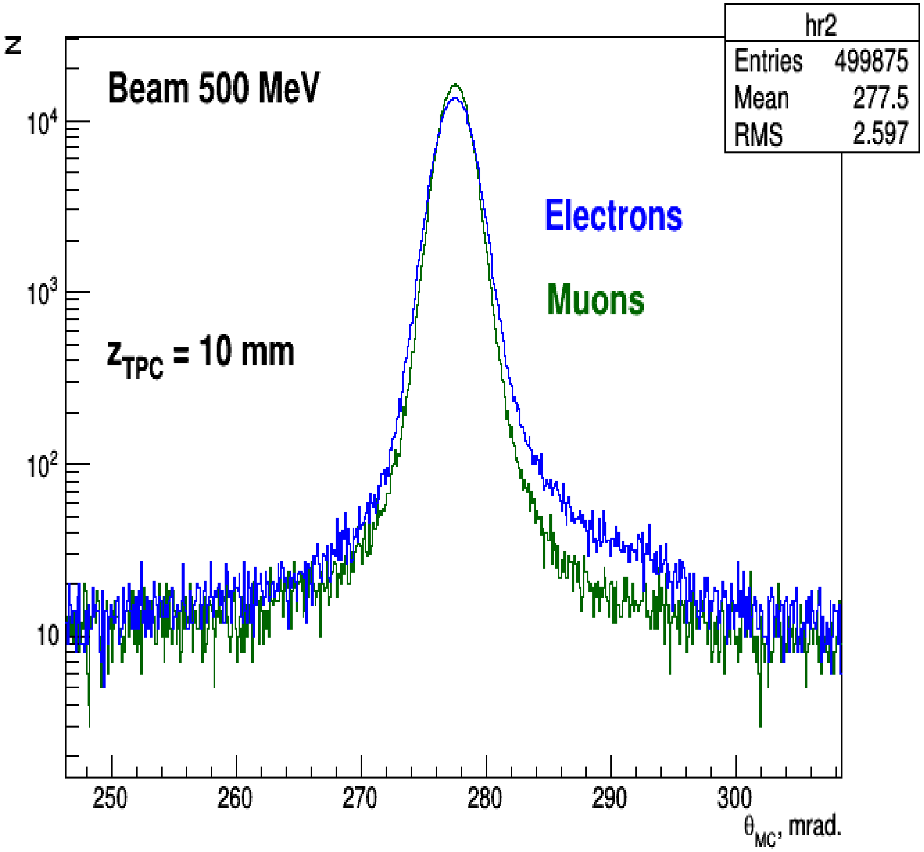
Continious data flow . 100 MHz clock. T_R trigger



All data from 100 μs interval before T_R trigger are sent to memory without introducing any dead time in data aquisition.



θ_e^* corrected for the radiation tail



θ_e = 277.514 mrad

θ_e* = 277.471 mrad

Fig. 15. Schematic view of the ACTAR2 prototype (side view).

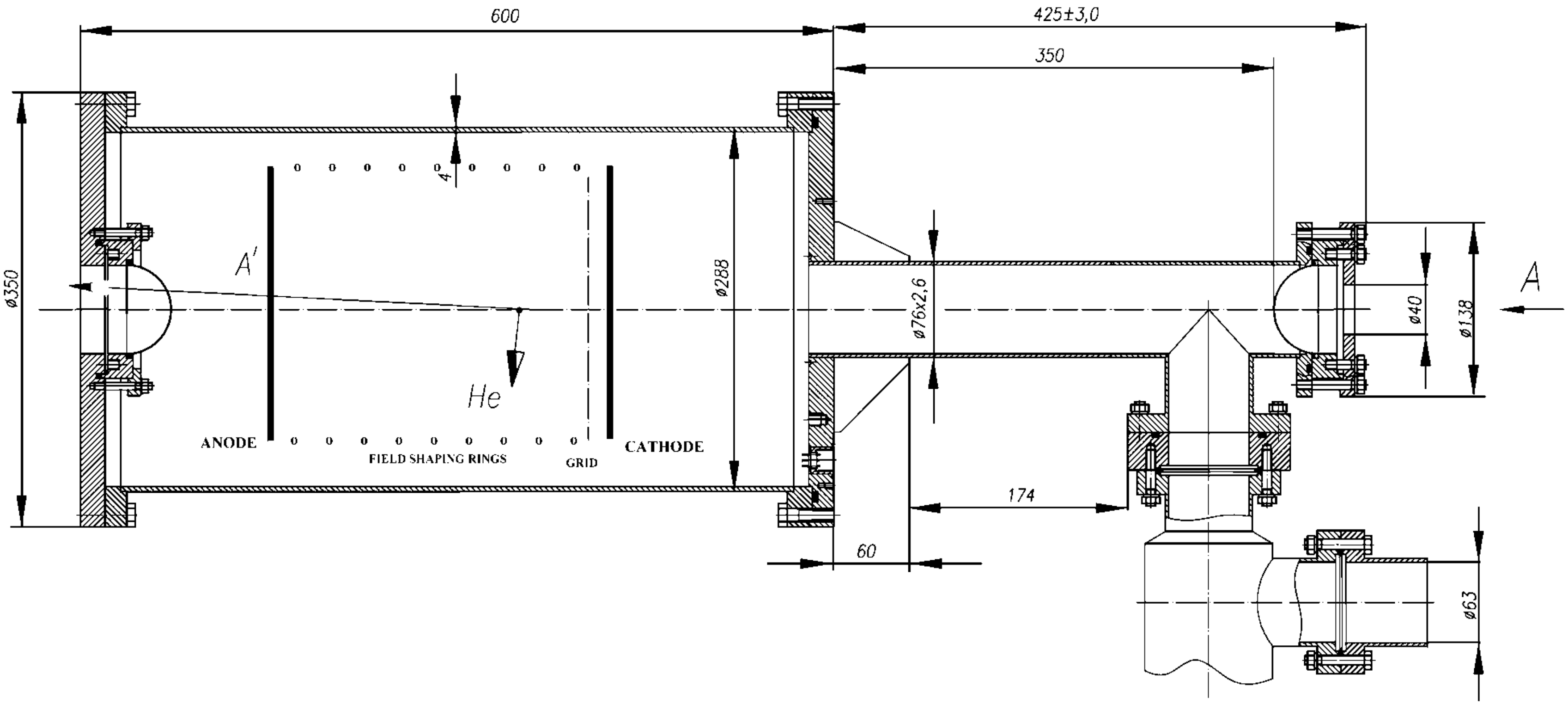
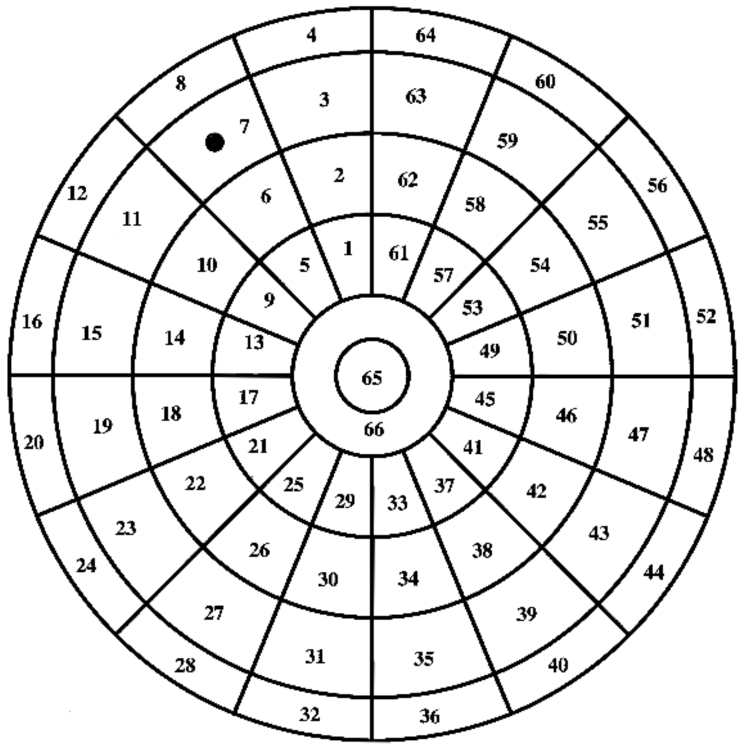
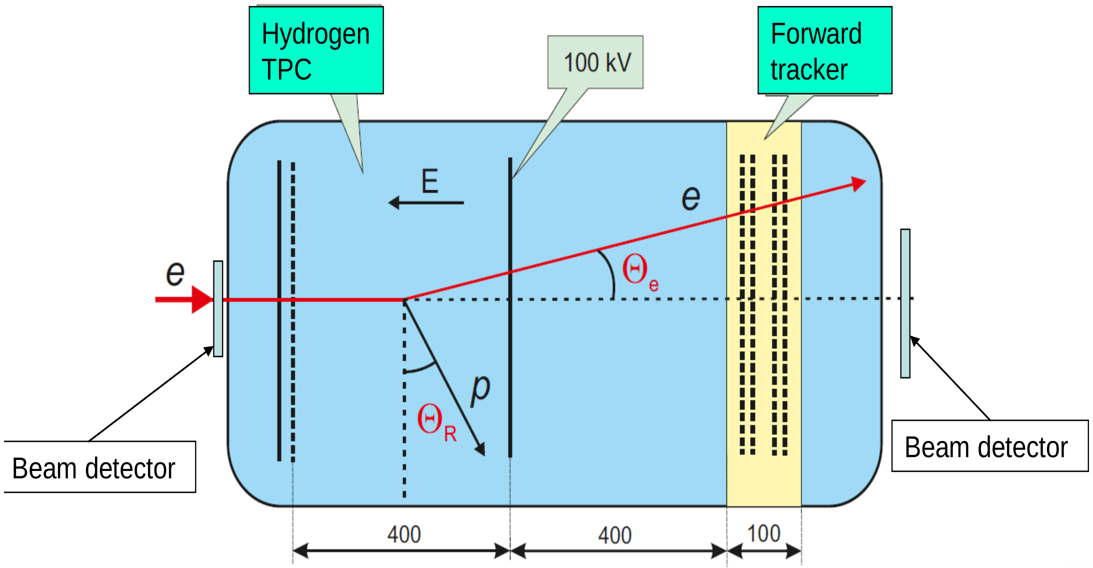
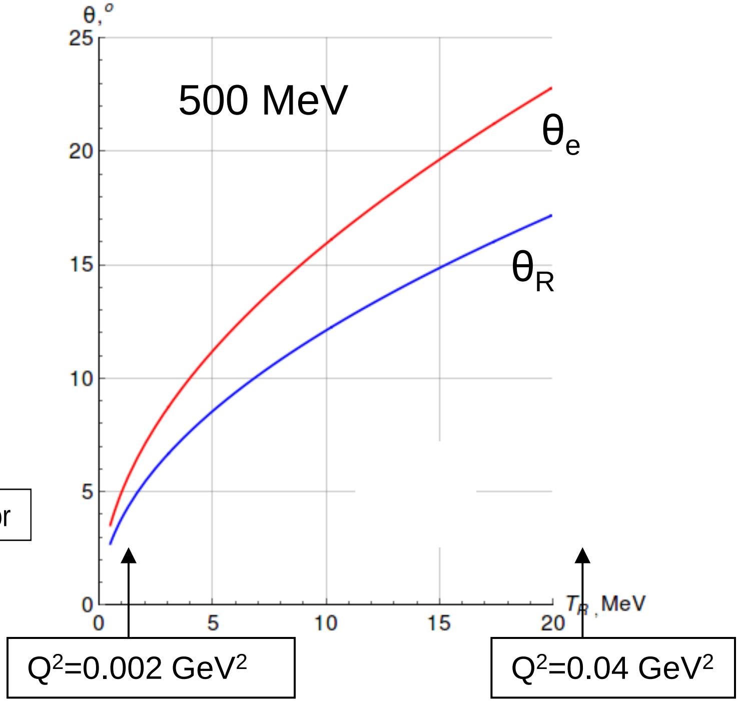


Fig.16. Layout of the ACTAR2 prototype anodes. An 241Am α-source is deposited on the cathode of the chamber opposite to the black spot on the anode number 7. The outer diameter of the anodes is 200 mm.



TPC@ FT detector



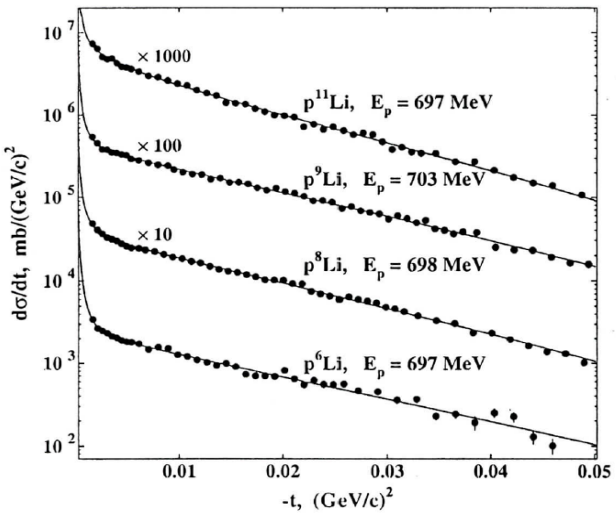


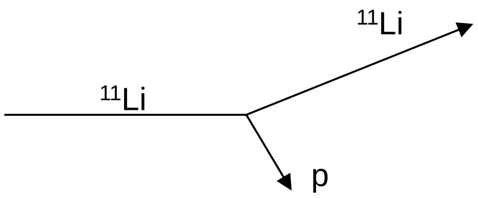
Experiment is designed for ε_e = 500 - 900 MeV
Θ_e max = 25 deg.

TPC and FT are in common body at 20 bar pressure
TPC: extra-pure H_2 , FT: Ar+CH_4

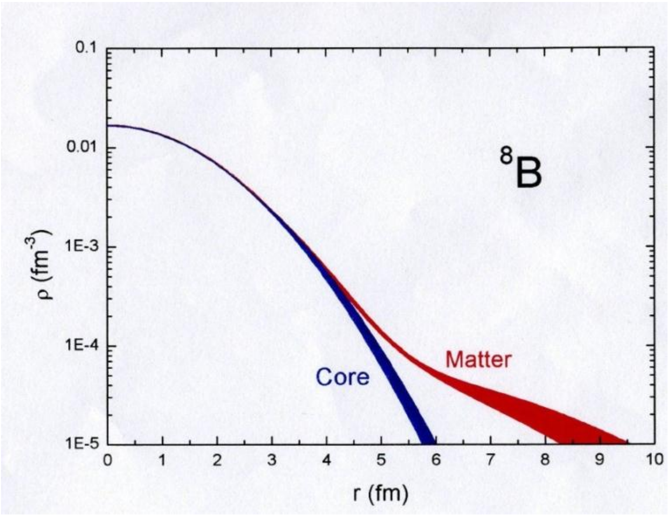
Study of elastic scattering of exotic nulei on proton

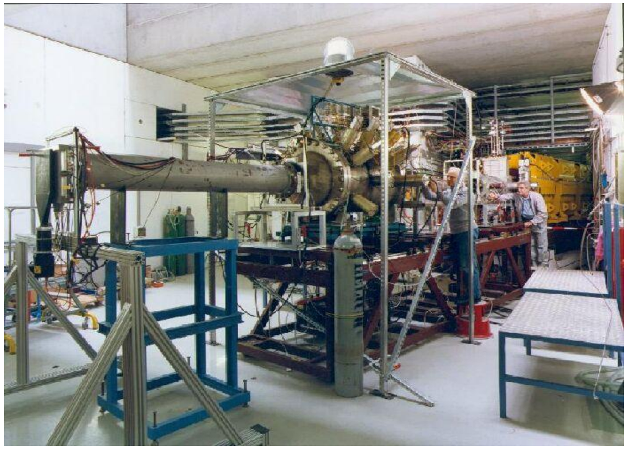
Nuclear Physics A766 (2006)1-24





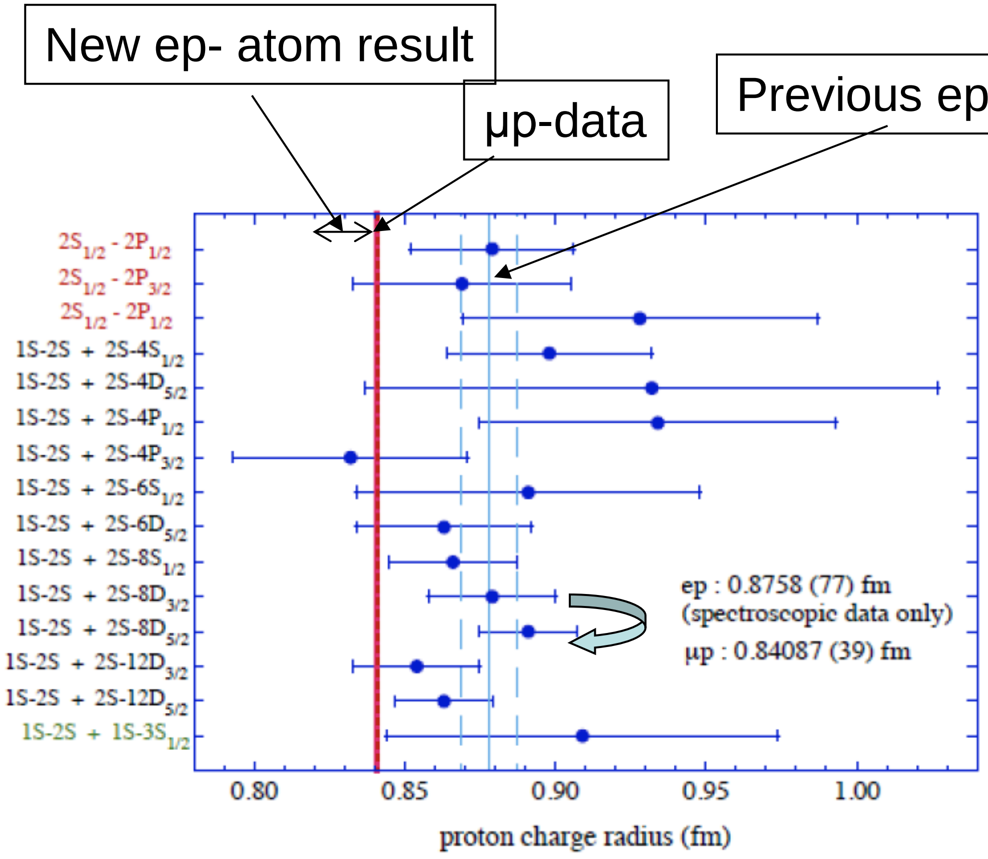
^{4}He, ^{6}He, ^{8}He
^{6}Li, ^{8}Li, ^{9}Li, ^{11}Li
^{7}Be, ^{9}Be, ^{10}Be,^{11}Be, ^{12}Be, ^{14}Be
^{8}B
^{13}C,^{14}C,^{15}C,^{17}C.





ICAR at GSI

New measurement of 2S-4P in ep-atom Garching



Previous Garching-Paris data

Rp=0.877(7)

R_∞=10973731.568508(65) m^{-1}

New Garching-Garching data

Rp= 0.830(9)

R_∞=10973731.568082(91) m-1

If compared with WA9/NA8 experiments

- Higher pressure from 10 bar to 20 bar
- Larger diameter from 200 mm to 300 mm
- Higher precision in $d\sigma/dt$ measurements

  relative and absolute factor of 5.

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- High resolution in low Q^2-region;
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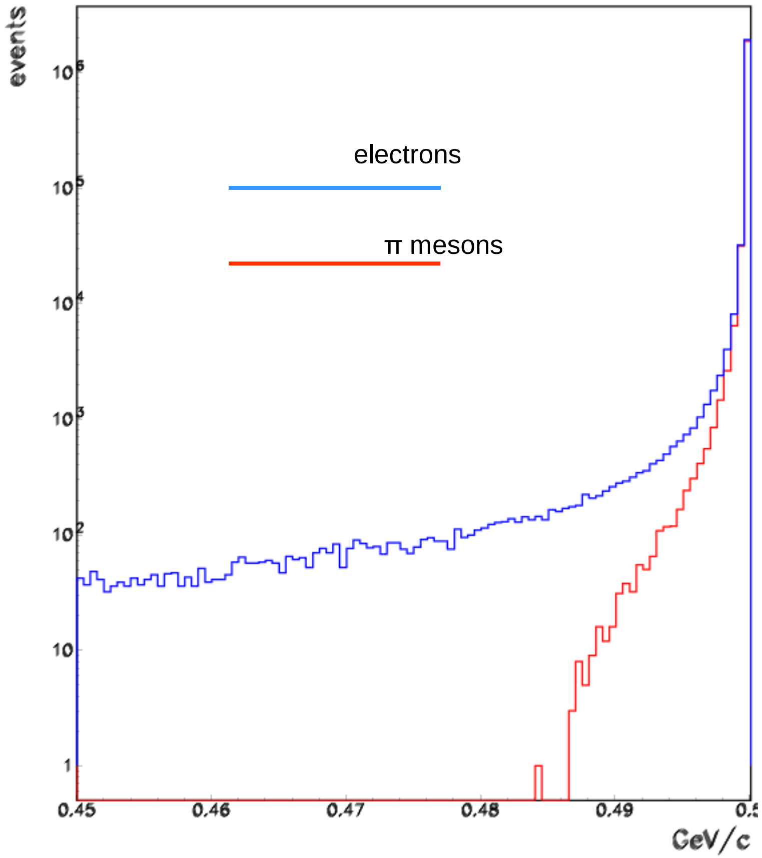
$$\frac{d\sigma}{dt}=\frac{\pi\alpha^2}{t^2}\left\{G_E^2\left[\frac{\left(4M+t/\varepsilon_e\right)^2}{4M^2-t}+\frac{t}{\varepsilon_e^2}\right]-\frac{t}{4M^2}G_M^2\left[\frac{\left(4M+t/\varepsilon_e\right)^2}{4M^2-t}-\frac{t}{\varepsilon_e^2}\right]\right\}$$

500 MeV/c



$-t = 2MT_R$

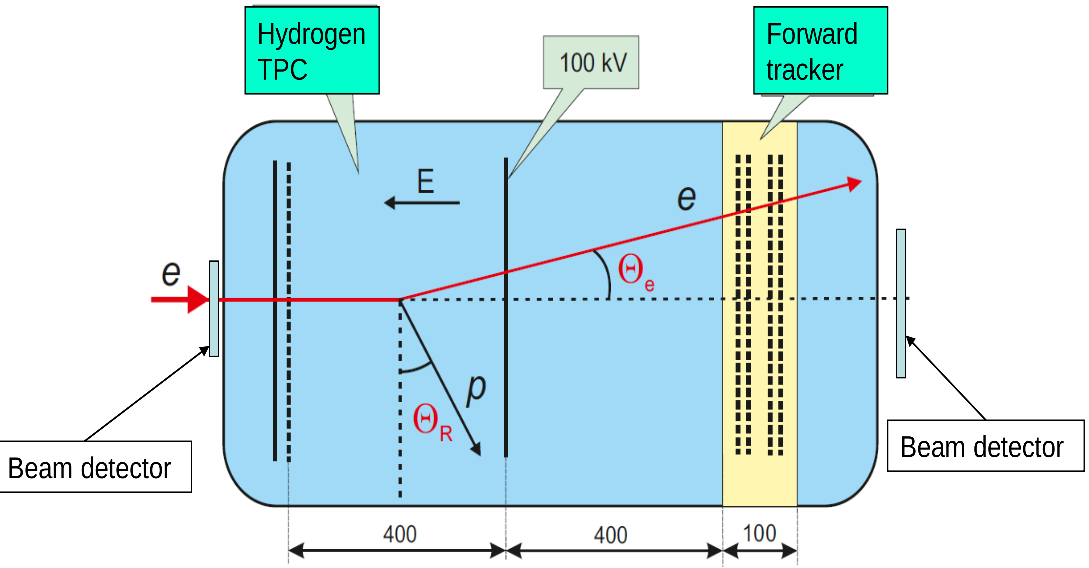
T_R determines dσ/dt with very little dependence on the electron energy losses before the coliision

Main experimental problem

High precision calibration of the recoiled proton energy scale.

In our experiment this calibration will be done with 0.04 % precision via the T_R- θ_e correlation relying on high precision (0.02%) linear scale of the Forward Tracker.

Hydrogen Time Projection Chamber



H_2 Pressure: 20 bar and 4 bar

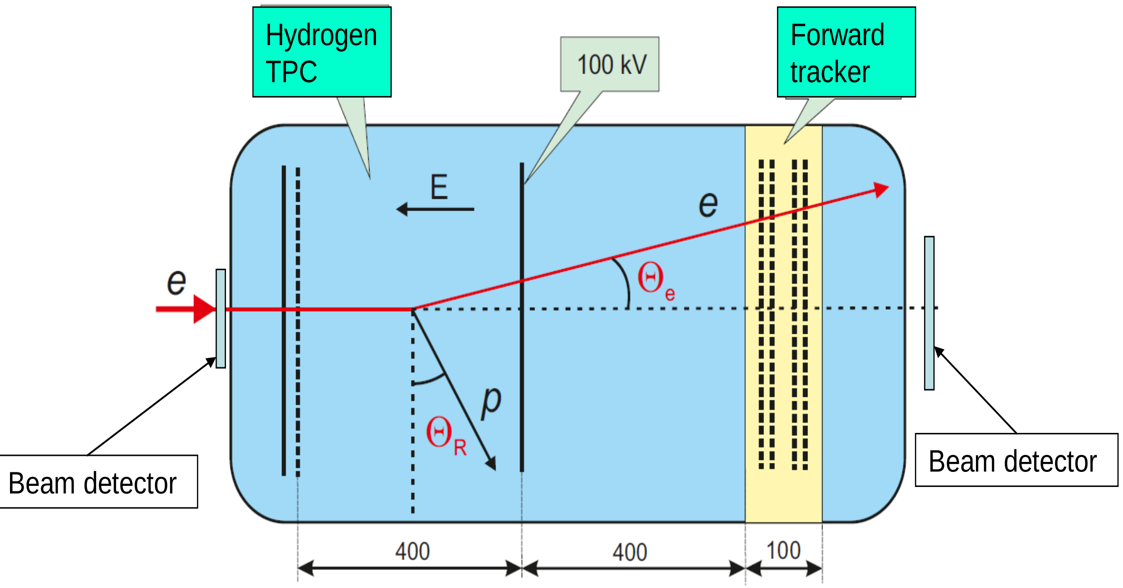
Drift velocity: 0.42 cm/μs

Max drift time 100 μs

Gas impurities <10-6

		Resolution,σ	
Recoil proton energy	T_R	**60 KeV**	1MeV ≤ T_R ≤ 10 MeV
Recoil proton angle	θ_R	**15 mrad**	Recoil range > 60 mm
Z of ep vertex	Z_V	**200 μm**	
Time arrival of TPC signals	t_{arr}	**40 ns**	

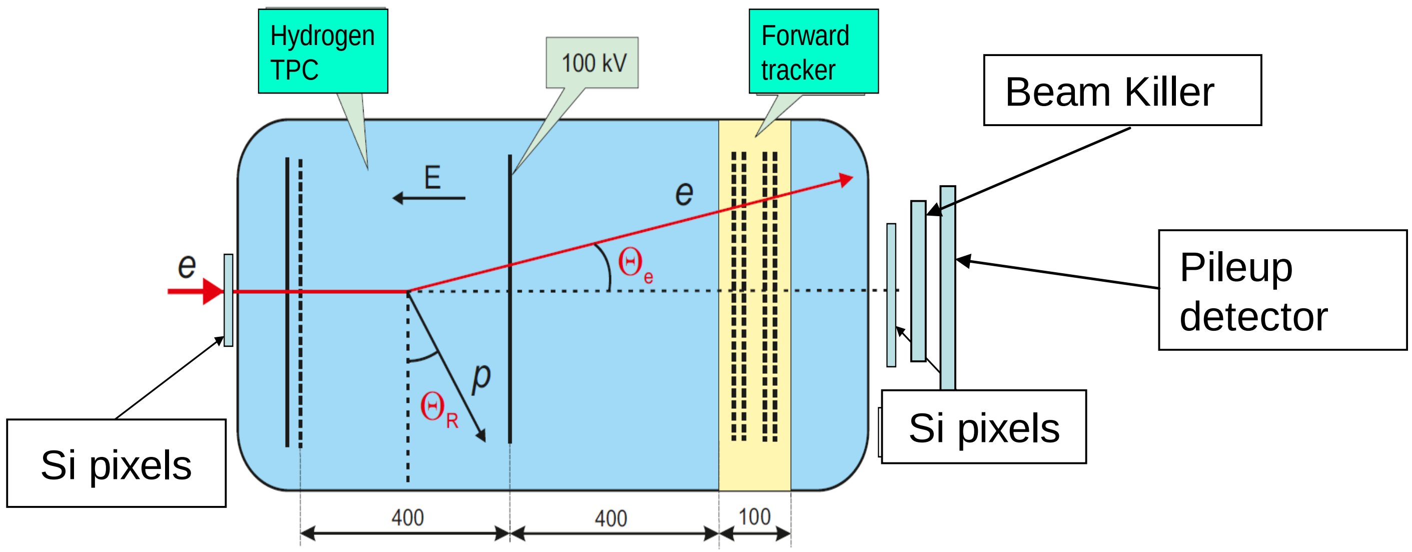
Forward Tracker



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



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