Эксперимент ПРОТОН

Прецизионное измерение сечения упругого электрон-протонного рассеяния при малых переданных импульсах

А.Воробьев УС ОФВЭ 27.12. 2017

Эксперимент ПРОТОН

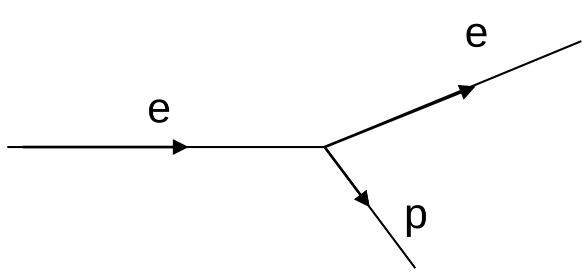
Прецизионное измерение радиуса протона

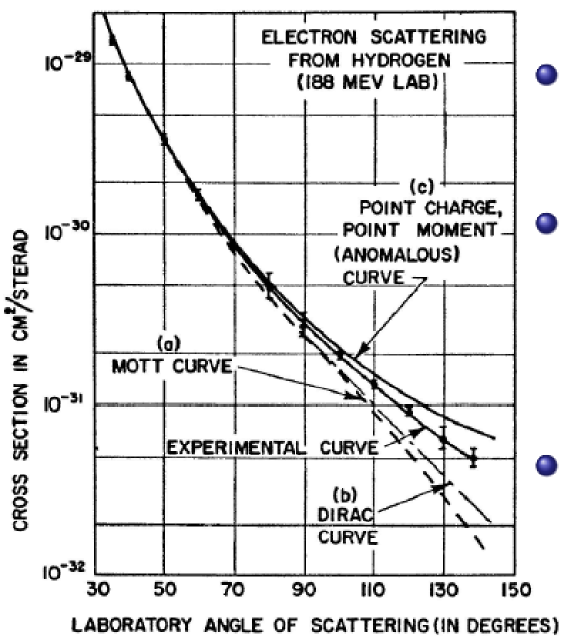
А.Воробьев УС ОФВЭ 27.12. 2017

1955 Proton is not a point-like particle !!!

Hofstadter, McAlister

Electron-proton scattering

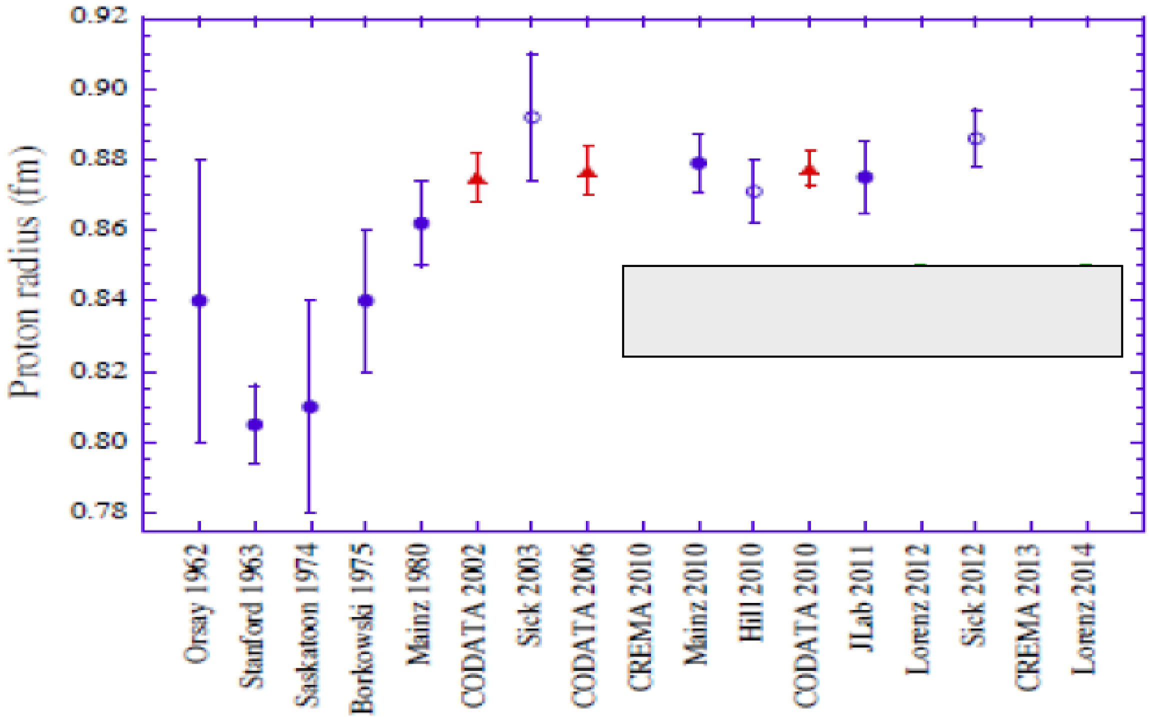




$r_p = 0.80 \pm 0.04$ fm Hofstadter et al (1958)

Nobel prize 1961 г.

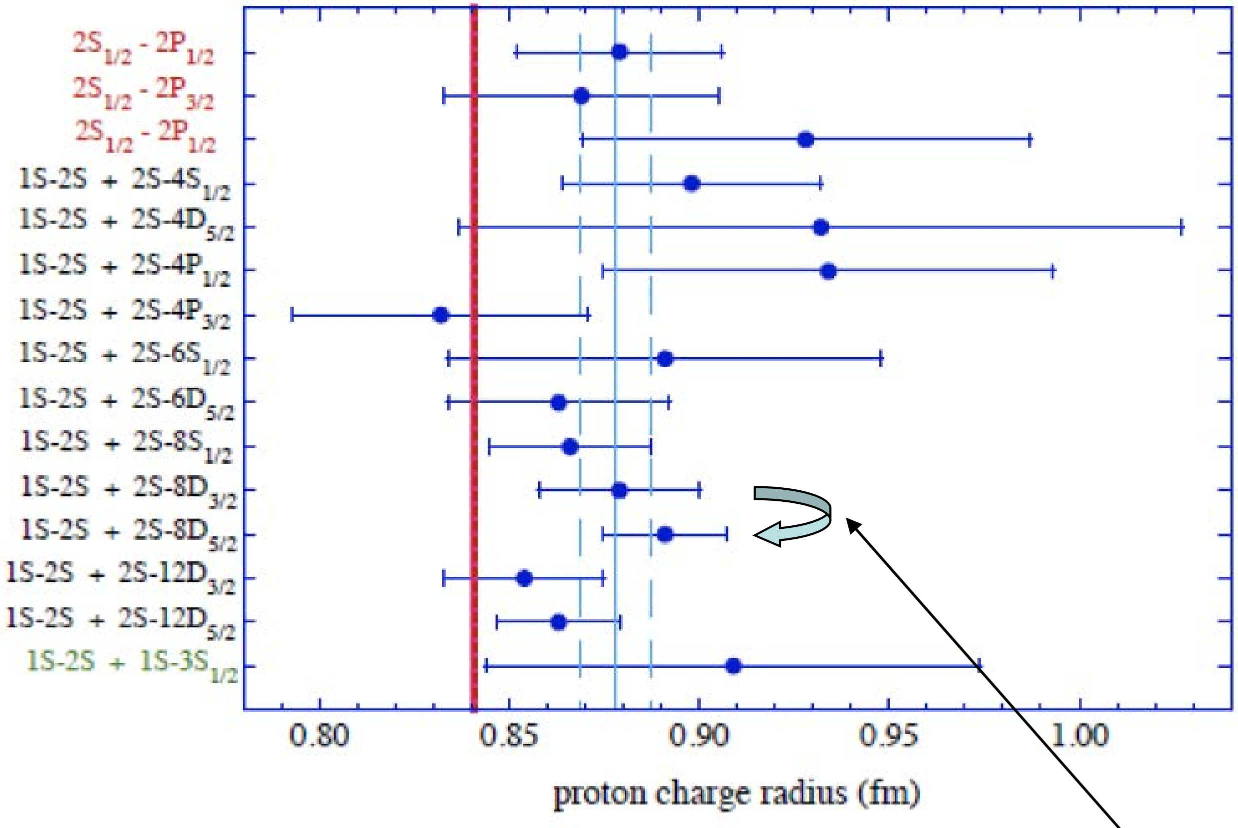
Proton radius from ep-scattering
1962-2014



- 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*

Proton radius from Lamb shift in hydrogen atom (ep-atom)



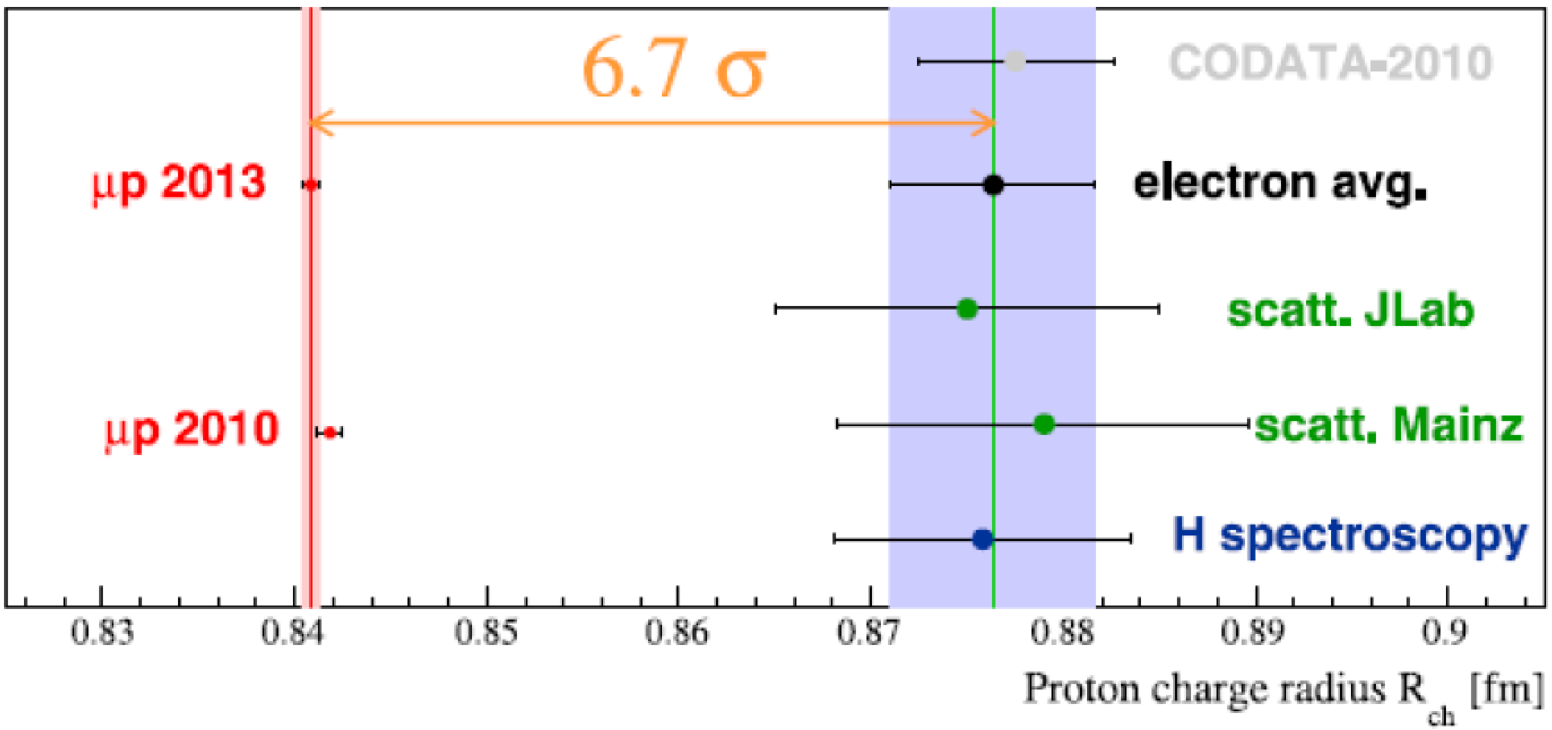
$r_p = 0.877(7)$ fm, *Garching-Paris, 2006-2011*

Proton radius 2010

Electron Data

- 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*
- $1S$ Lamb shift in *ep*: $r_p = \mathbf{0.877(7)\ fm}$, *Garching-Paris, 2006-2011*
- CODATA: $r_p = \mathbf{0.877\ 5\ (51)\ fm}$ *2010*

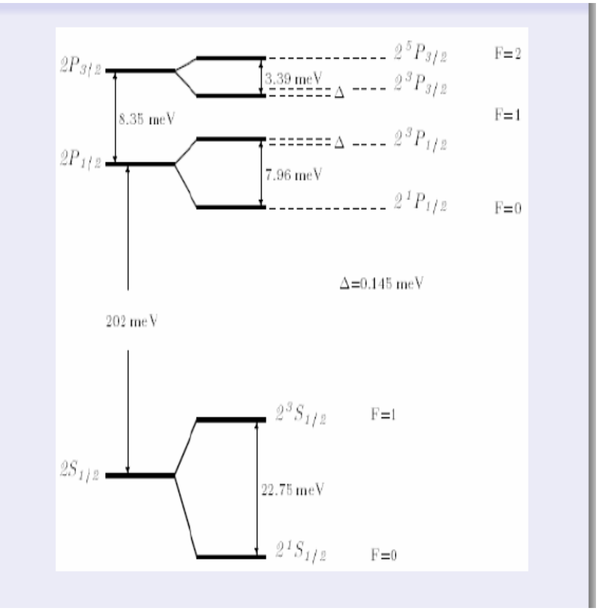
Proton radius   2015

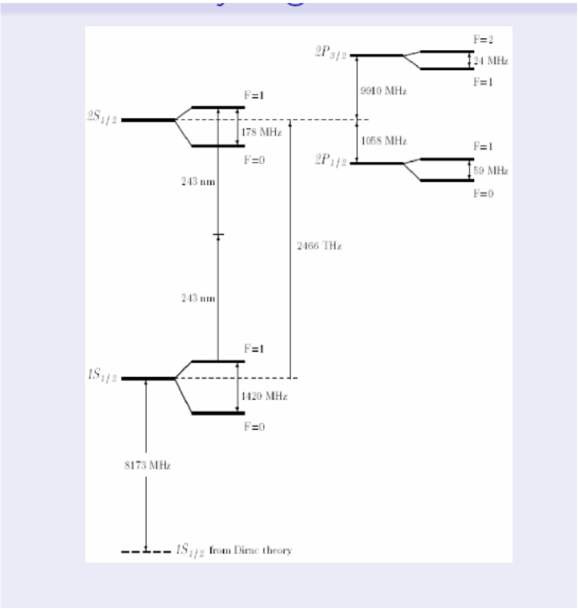


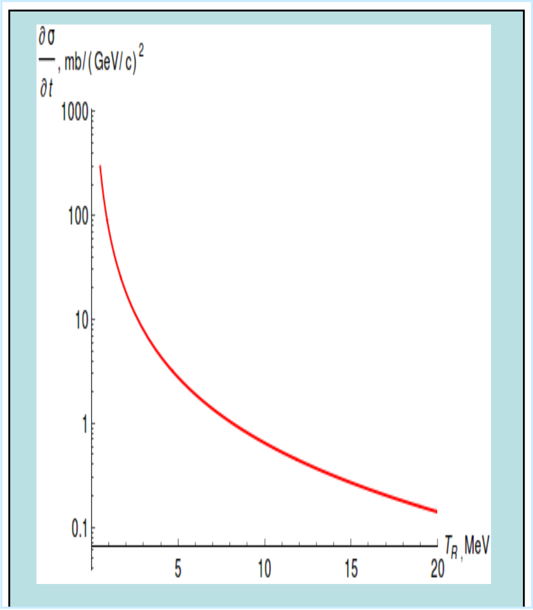
μp atom

ep atom

ep scattering







Rp = 0.8409(4)fm

Rp = 0.877(8)fm

Rp = 0.877(7)fm

Proton radius puzzle

Rp = 0.877 fm
or
Rp =0.841 fm

???

Letter of Intent for a European Proton Radius Network (EuPCR*Net*)

D. Marchand (CNRS/IPN Orsay), R. Pohl (JGU Mainz)

Proponent institutions:

- CEA Saclay/DRF/Irfu/Département de Physique Nucléaire, France; contact person: N. D'Hose,
- CNRS, France; contact persons: D. Marchand (Institut de Physique Nucléaire d'Orsay - IPN Orsay) and J.-Ph. Karr (Laboratoire Kastler Brossel - LKB),
- ETH Zurich, Switzerland; contact person: A. Antognini, P. Crivelli,
- Hebrew University, Jerusalem, Israel; contact person: G. Ron,
- Johannes Gutenberg-Universität (JGU) Mainz, Germany; contact persons: M. Ostrick, R. Pohl, M. Vanderhaeghen,
- Johann Wolfgang Goethe Universität Frankfürt, Germany; contact person: R. Grisenti,
- Jožef Stefan Institute, Ljubljana, Slovenia; contact persons: M. Mihovilovič, S. Sirca,
- LaserLaB VU Amsterdam, Vrije Universiteit, Amsterdam, Netherlands; contact person : W. Vassen,
- Max-Planck Institute of Quantum Optics (MPQ), Garching, Germany; contact persons: T.W. Hänsch, Th. Udem, S. Karshenboim,
- Technische Universität München, Garching, Germany; contact person: S. Paul,
- Universitat Autònoma de Barcelona, Spain; contact person: A. Pineda,
- University College of London, London, UK ; contact person: D. Cassidy,
- University of Warsaw, Warszawa, Polska; contact person: Krzysztof Pachucki.

Associated institutions:

- Bogoliubov Laboratory of Theoretical Physics, JINR Dubna, Russia; contact person: V. Korobov,
- George Washington University, Washington DC, USA; contact person: A. Afanasev,
- Massachusetts Institute of Technology, Cambridge, MA, USA; contact person: J. Bernauer,
- North Carolina A&T State University, Greensboro, NC, USA; contact person: A. Gasparian,
- Rutgers, The State University of New Jersey, Piscataway, NJ, USA; contact person: R. Gilman,
- **Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia; contact person: A. Vorobyov,**

- Ошибки в экспериментах

  или

  Нарушение μ-e универсальности
  ???

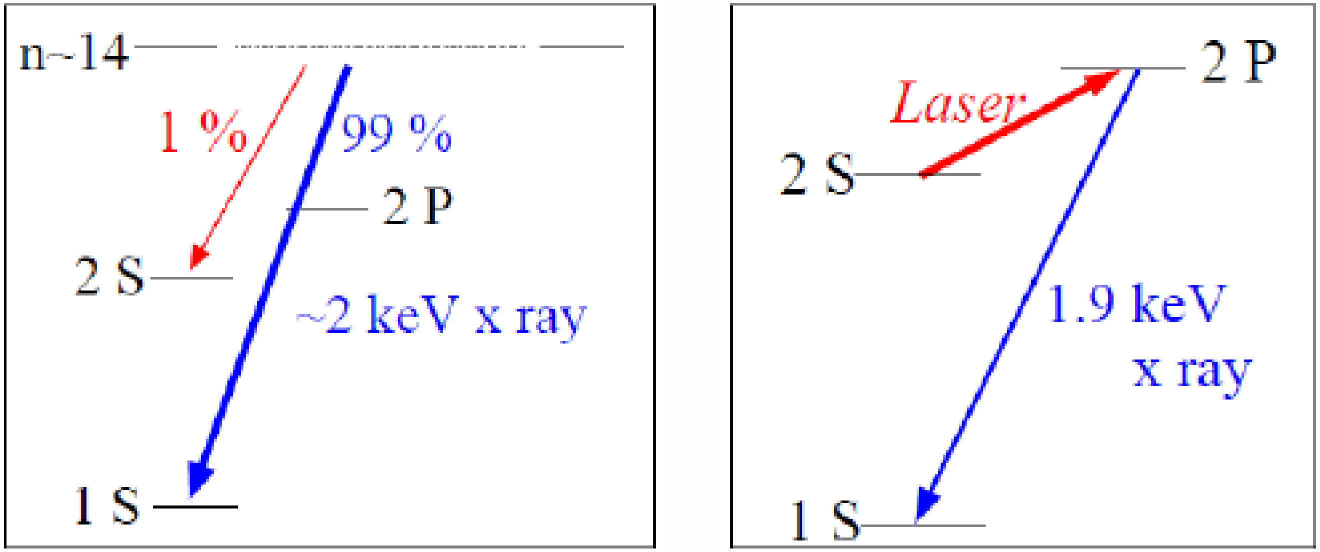
Lamb shift in muonic atom (μH-atom)

Experiment at PSI

A.Antognini et al. Science 339, 417 (2013)

Muon stop in Hydrogen gas

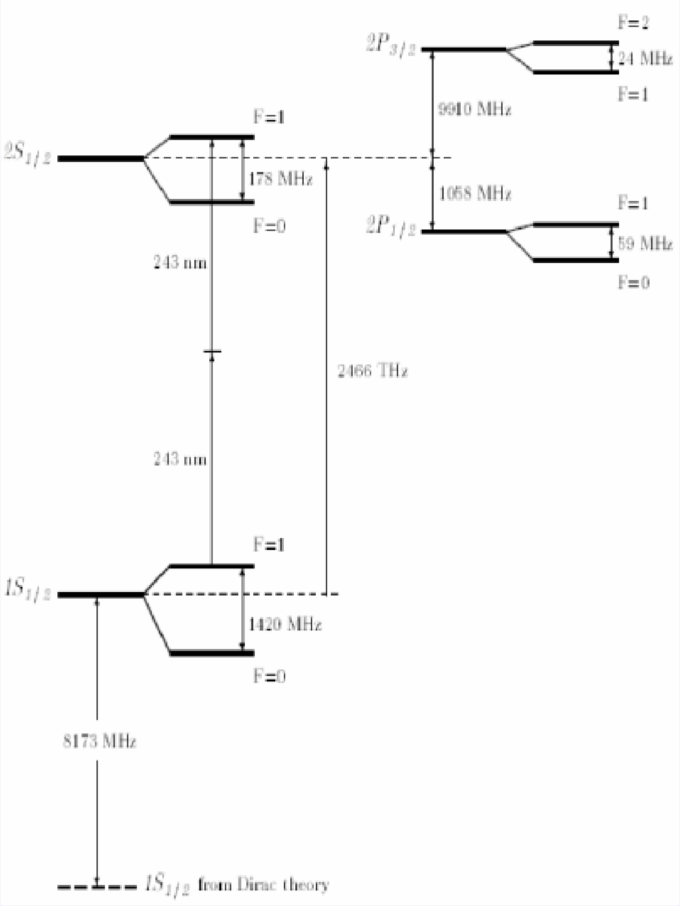
2S → 2P transfer



Rp =0.8409(4)

Proton radius from Lamb shift in hydrogen atom (eH-atom)

Electronic Hydrogen



Rydberg constant

Lamb shift

$$E_{nlJ} \approx -c_{nlj}\frac{R_\infty}{n^2} + \frac{L_{nlj}}{n^3}$$

$$L_{nS} = L_{nS}^{(0)} + c r_p^2$$

$$L_{1S} = 8171.636(4) + 1.5645\langle r^2 \rangle \ \text{MHz}$$

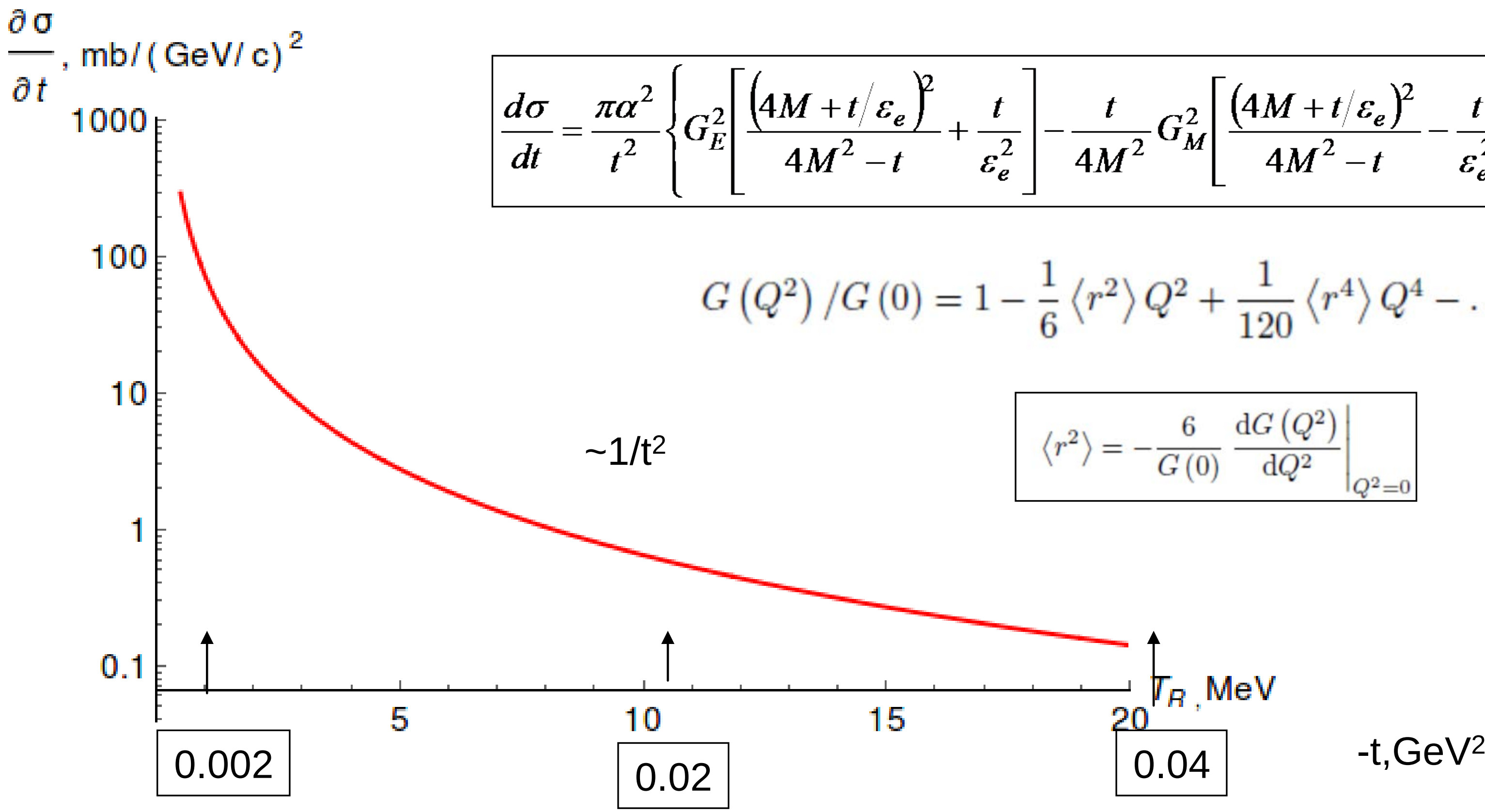
0.5% in r_p

CODATA 2014

R_∞=10973731.568508(65) m^{-1}

Change in this digit by 1 unit (10^{-12}) will change r_p by 1%

Extraction of the proton radius from ep cross sections



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

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

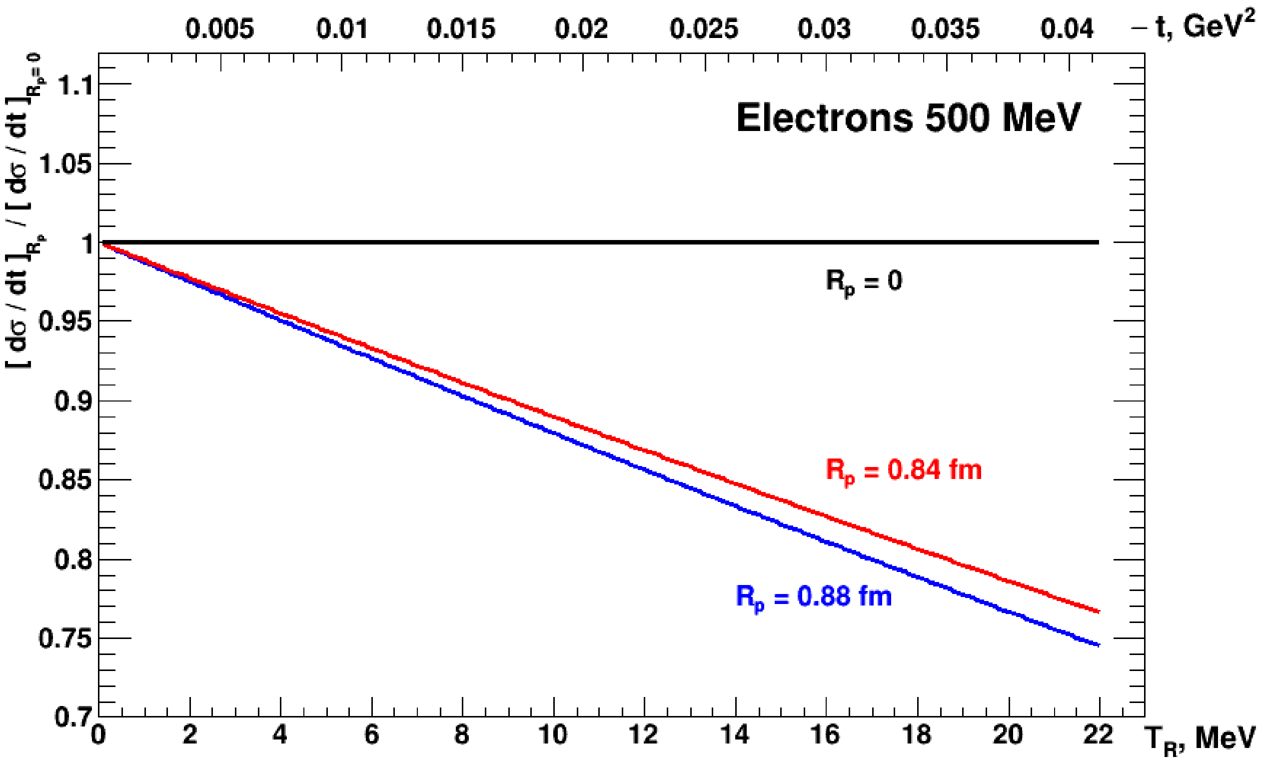
$$\left\langle r^2\right\rangle=-\frac{6}{G\left(0\right)}\left.\frac{dG\left(Q^2\right)}{dQ^2}\right|_{Q^2=0}$$

$-t = Q^2 = 2MT_R$

7

$0.001\ GeV^2 \le Q^2 \le 0.04\ GeV^2$

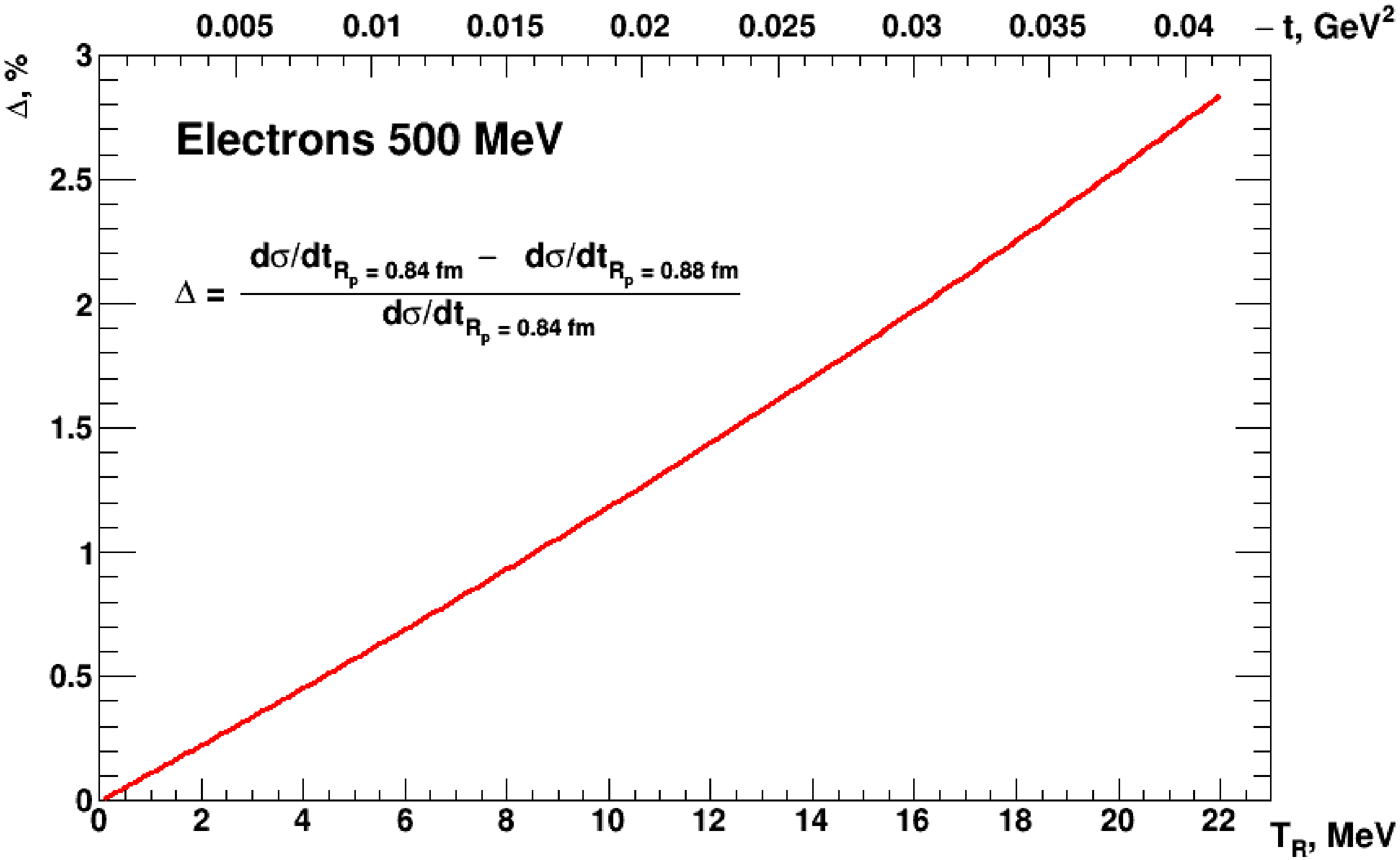
$[d\sigma/dt]_{Rp}$ / $[d\sigma/dt]_{Rp=0}$



Difference in $d\sigma/dt$ between Rp=0.84 fm and Rp=0.88 fm

is only 1.3% at Q^2 =0.02Gev^2

Sensitivity of dσ/dt to proton radius



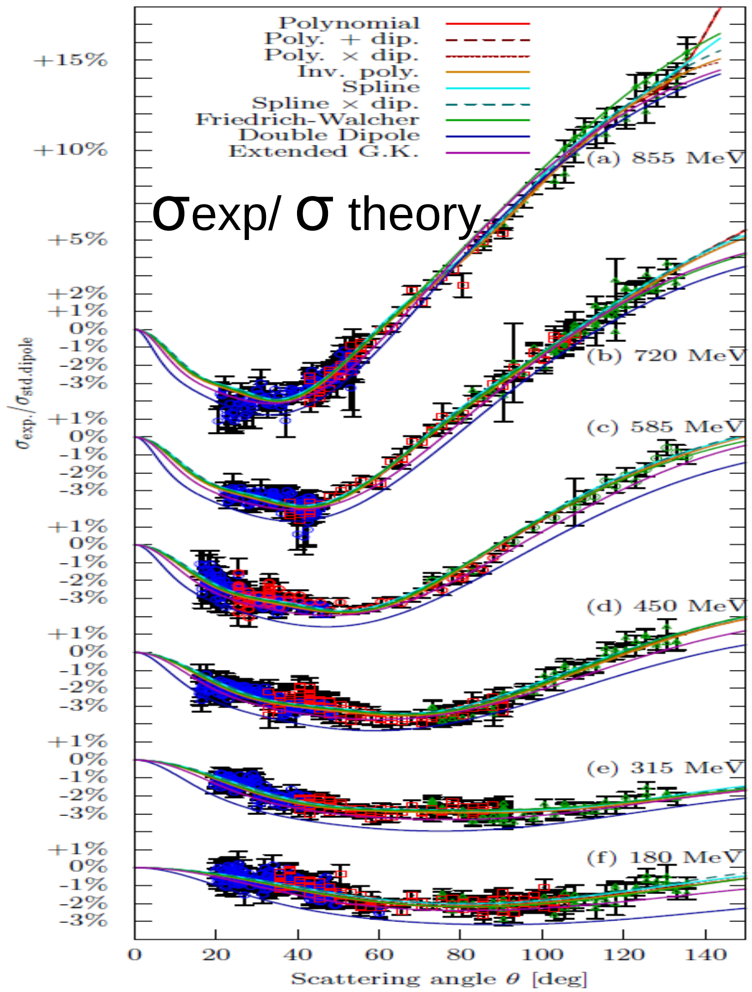
Mesurement of dσ/dt with point-to-point precision 0.1%

Requirements to the ep-scattering experiments aimed at measurements of the proton radius

- Low t-range $0.001 < -t < 0.02$ GeV^2

  larger Q2 are useful to see possible deviations from FM linear dependence on Q^2
- High t-resolution.
- ≤ 0.2% point-to-point precision in dσ/dt.
- ≤ 0.2% absolute precision in dσ/dt (highly desirable).
- Control for radiative corrections.

Most recent data on e-p scattering from experiment A1 were a subject of various analyses



$0.003 < Q^2 < 1$ GeV^2

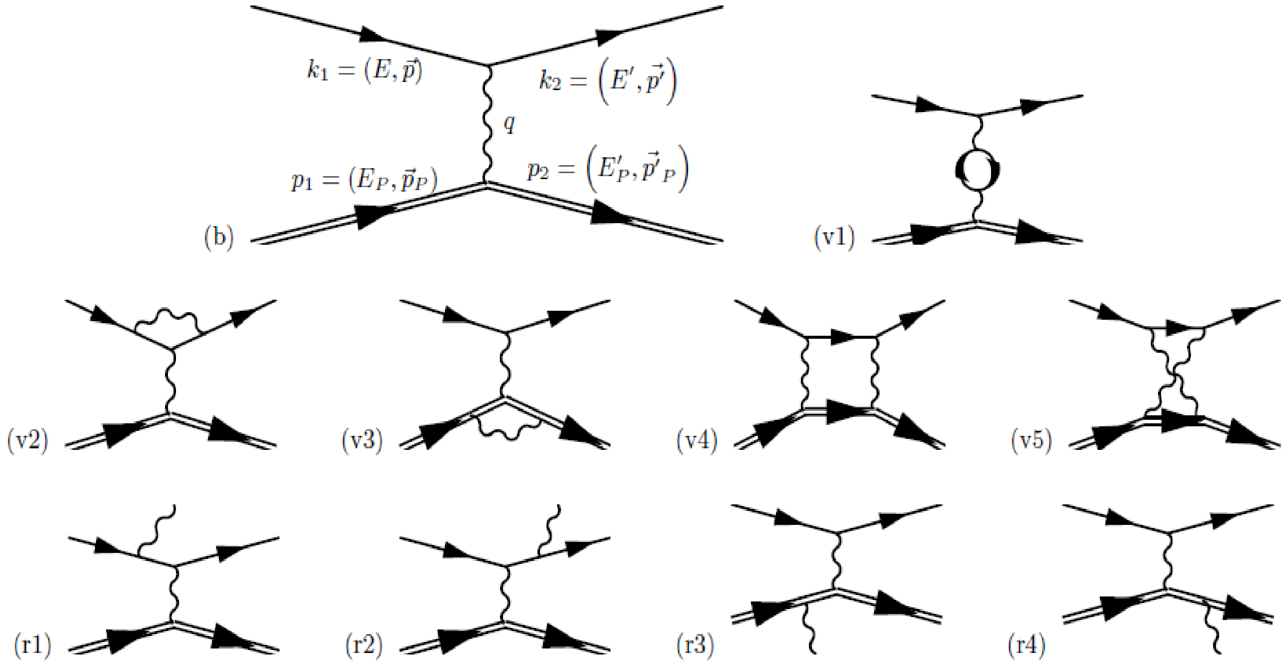
No absolue normalization

0.37% point-to-point error in σ

Large t-range analyses
$r_p \rightarrow 0.877$ fm

Radiative corrections

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



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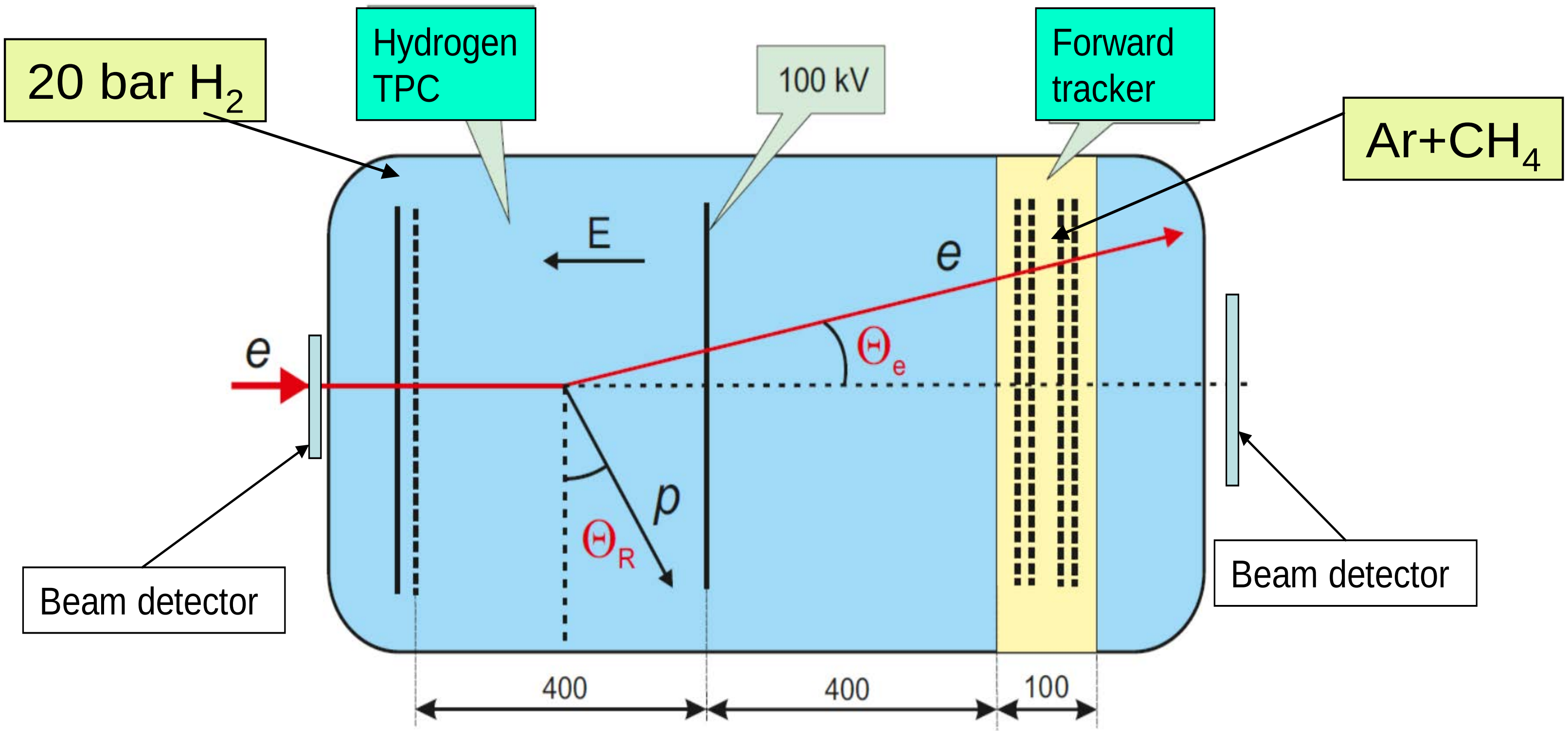
Recoiled proton @ Scattered Electron Detector



Measured quantities:

Recoil energy T_R

Recoil angle Θ_R

Vertex Z coordinate

E scattering angle Θ_e

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

$$-t = 2MT_R$$

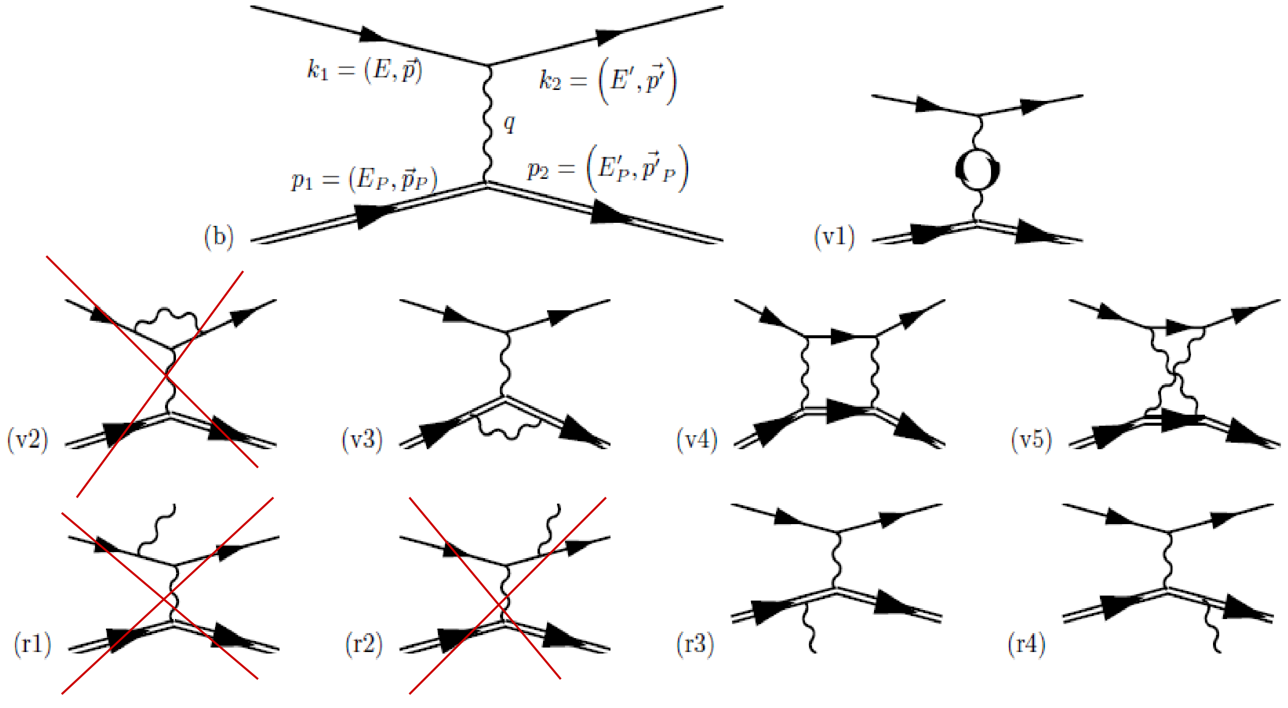
$$\sin(\theta_R) = \frac{(\varepsilon_e + M)T_R}{P_e P_R}$$

Эксперимент ПРОТОН

- t-range 0.001< -t < 0.04 GeV^2
- High t-resolution. ~100 resolved points
- 0.1% point-to-point precision in dσ/dt.
- 0.2% absolute precision in dσ/dt

Эксперимент ПРОТОН
Radiative corrections

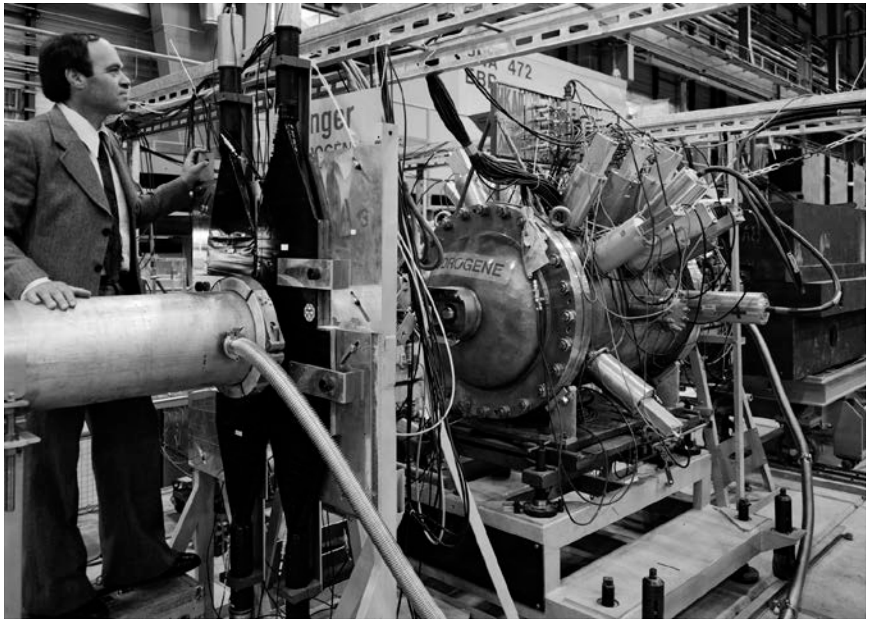
$$\left(\frac{d\sigma}{d\Omega}\right)_1 = \left(\frac{d\sigma}{d\Omega}\right)_0 (1+\delta).$$



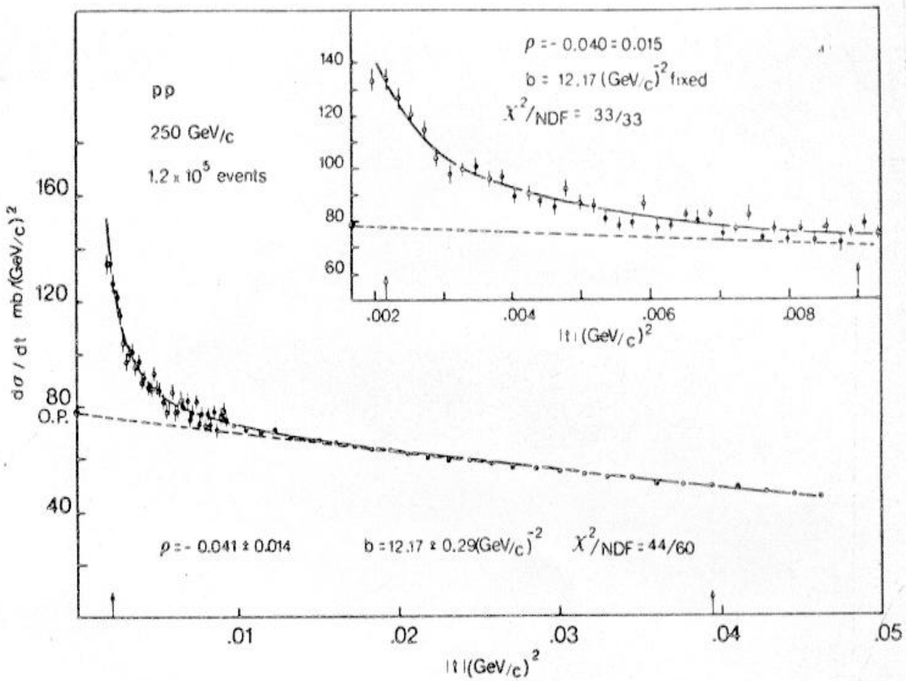
Absolute normalization of dσ/dt with ≤ 0.2% precision

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

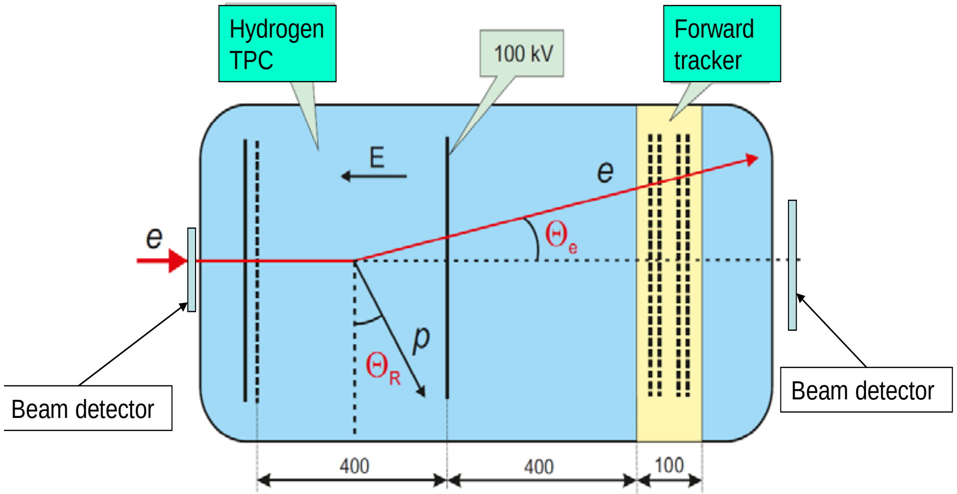


Recoiled proton detector ICAR at CERN



H$_2$ 10 bar TPC

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

Electron scattering angle with 0.02 % absolute precision

Systematical 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%**

Микротрон MAMI идеальный ускоритель для нашего эксперимента

- **MAMI Specifications**
- Beam energy 720 MeV
- Energy spread < 20 keV (1σ)
- Absolute energy ±< 150 keV (1 σ)
- Duty factor 100%

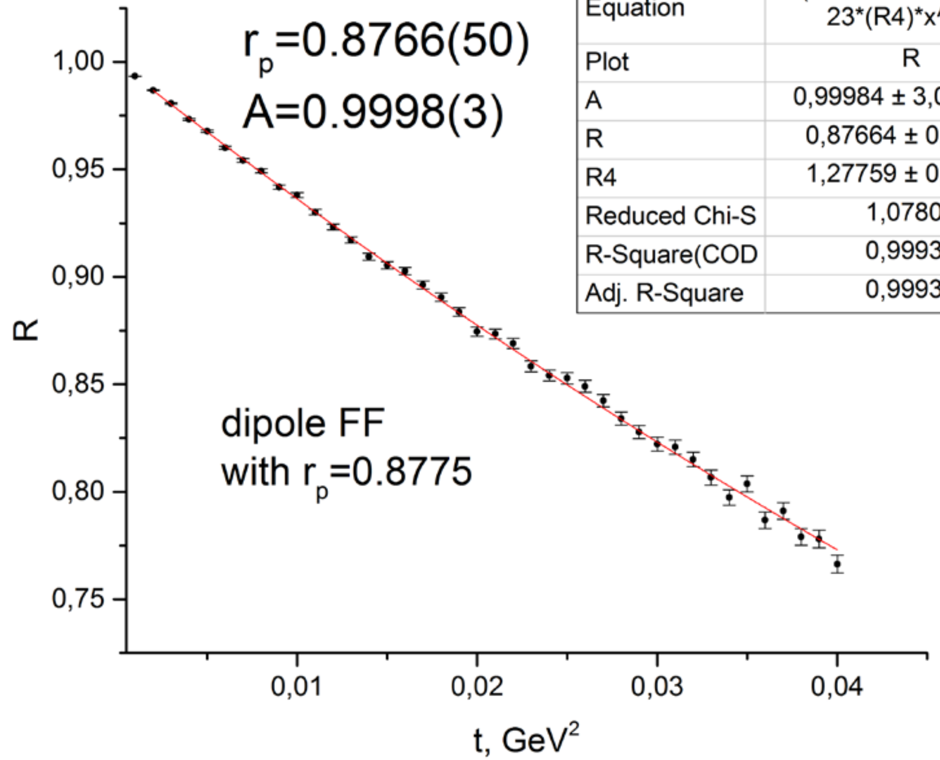
- **Electron Beam Specifications**
- Beam intensity (main run) 2x10^6 e/sec
- Beam intensity for calibration 10^4 e/sec and 10^3 e/sec
- Beam divergence ≤ 0.5 mrad
- Beam size ≤ 0.2 мм

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

Статус эксперимента

- Ноябрь 2016

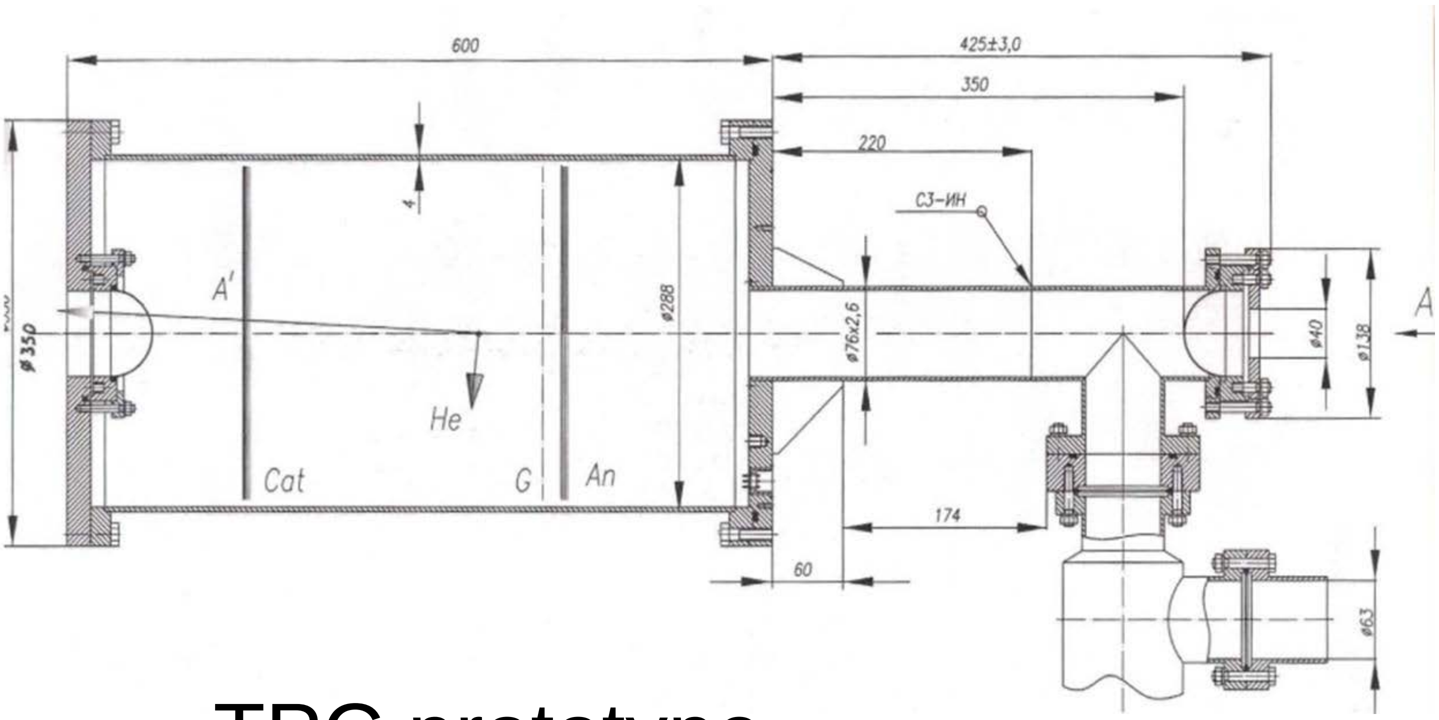
  PAC_MAMI одобрил LOI.
- Февраль 2017

  Соглашение PNPI_INP Mainz.
- Сентябрь 2017

  Test run на MAMI.
- Ноябрь 2017

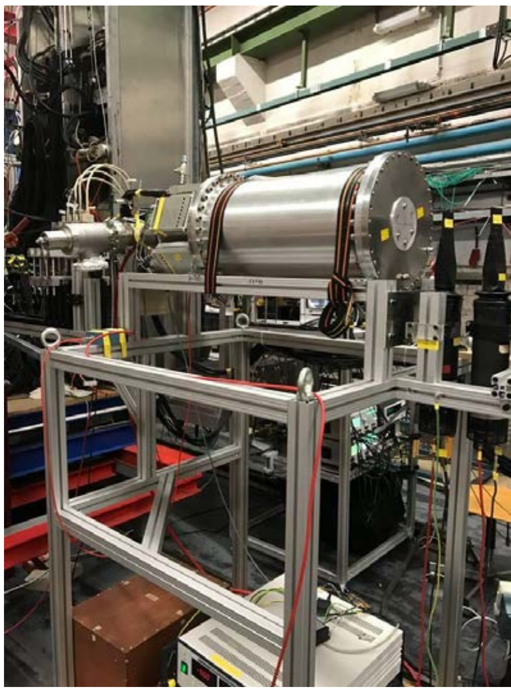
  PAC_MAMI одобрил Proposal.

Test run at MAMI



TPC prototype

Test run at MAMI



The ACTAR2 setup downstream of the Cristal Ball/Taps setup.

Participants in the test run and data analysis

- **Mainz**: Patrik Adlarson, Marco Dehn, Peter Drexler, Andreas Thomas, Frederik Wauters, Vahe Sokhoyan, Achim Denig, Michael Ostrick, Niklaus Berger, Oleksandr Kostikov Maik, Biroth,Edoardo Mornacchi, Jurgen Ahrens.
- **PNPI**: 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

План подготовки эксперимента

- Сентябрь 2018

  Test run на MAMI

- Июнь 2019

  Завершение создания установки

  Транспортировка в Майнц

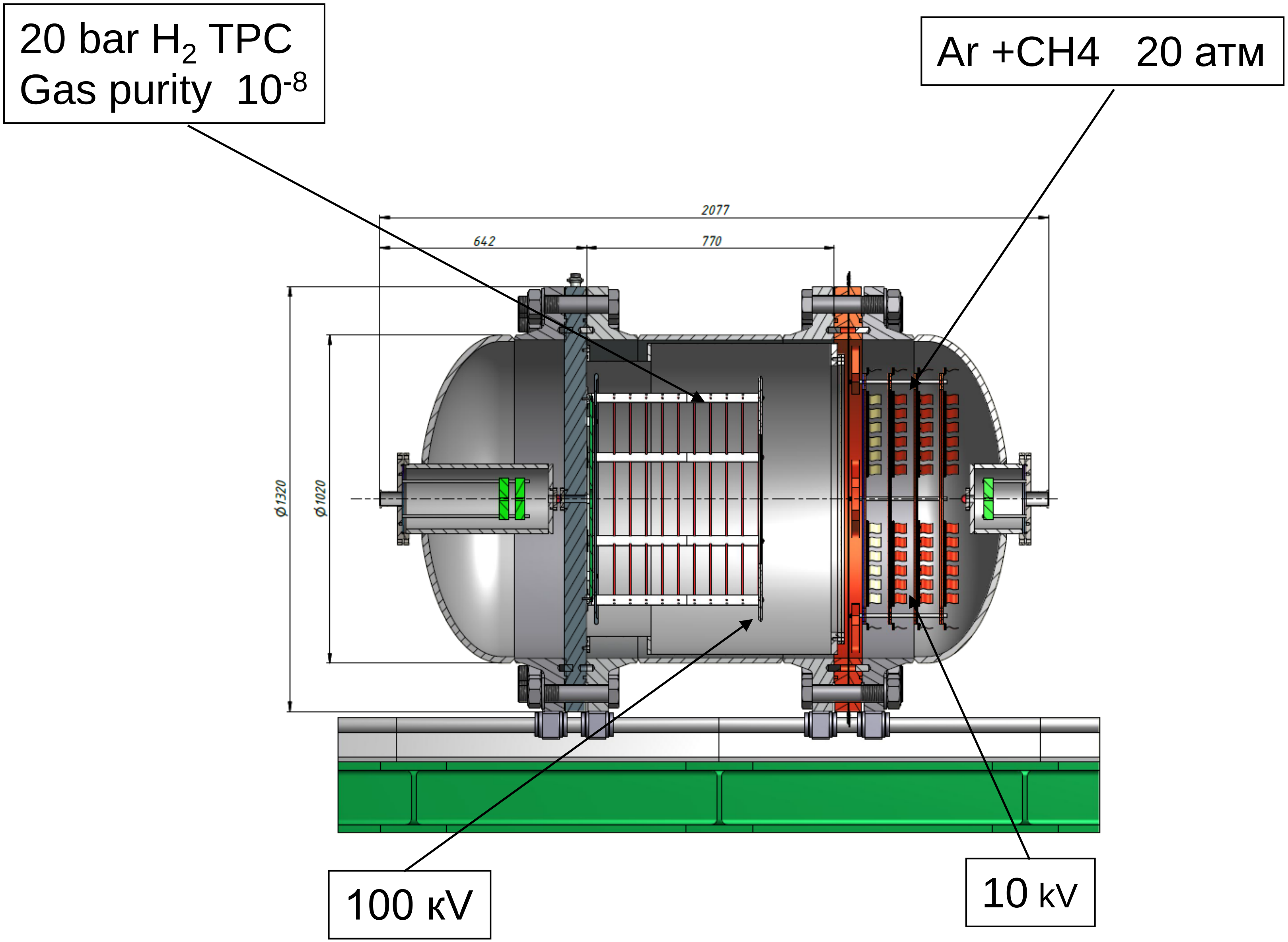
- Ноябрь 2019

  Пробный рабочий сеанс

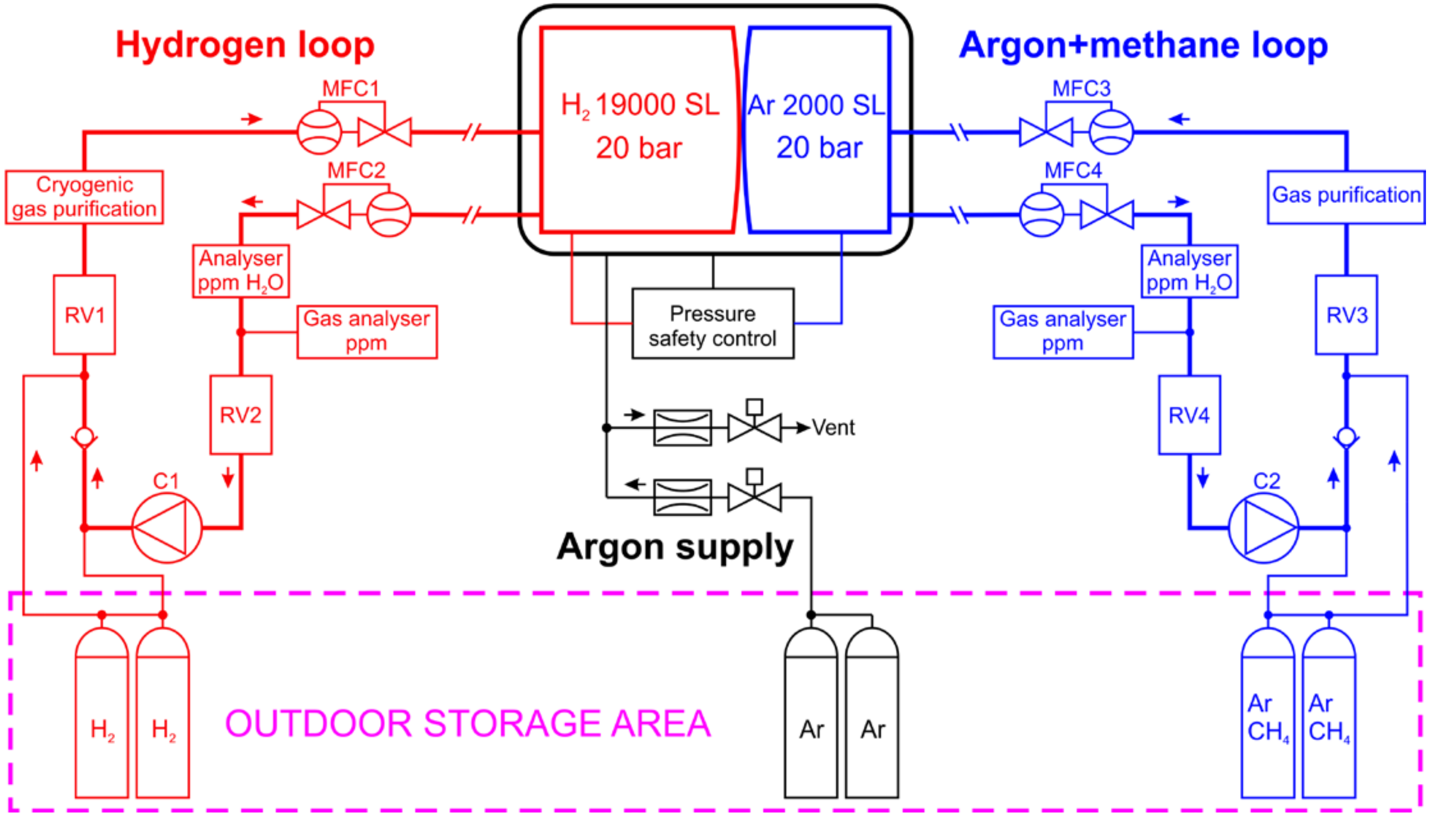
- 2020

  Физические измерения

ИКАР -М


20 bar H_2 TPC
Gas purity 10^{-8}
Ar +CH4   20 атм
2077
642
770
Ø1320
Ø1020
100 кV
10 кV

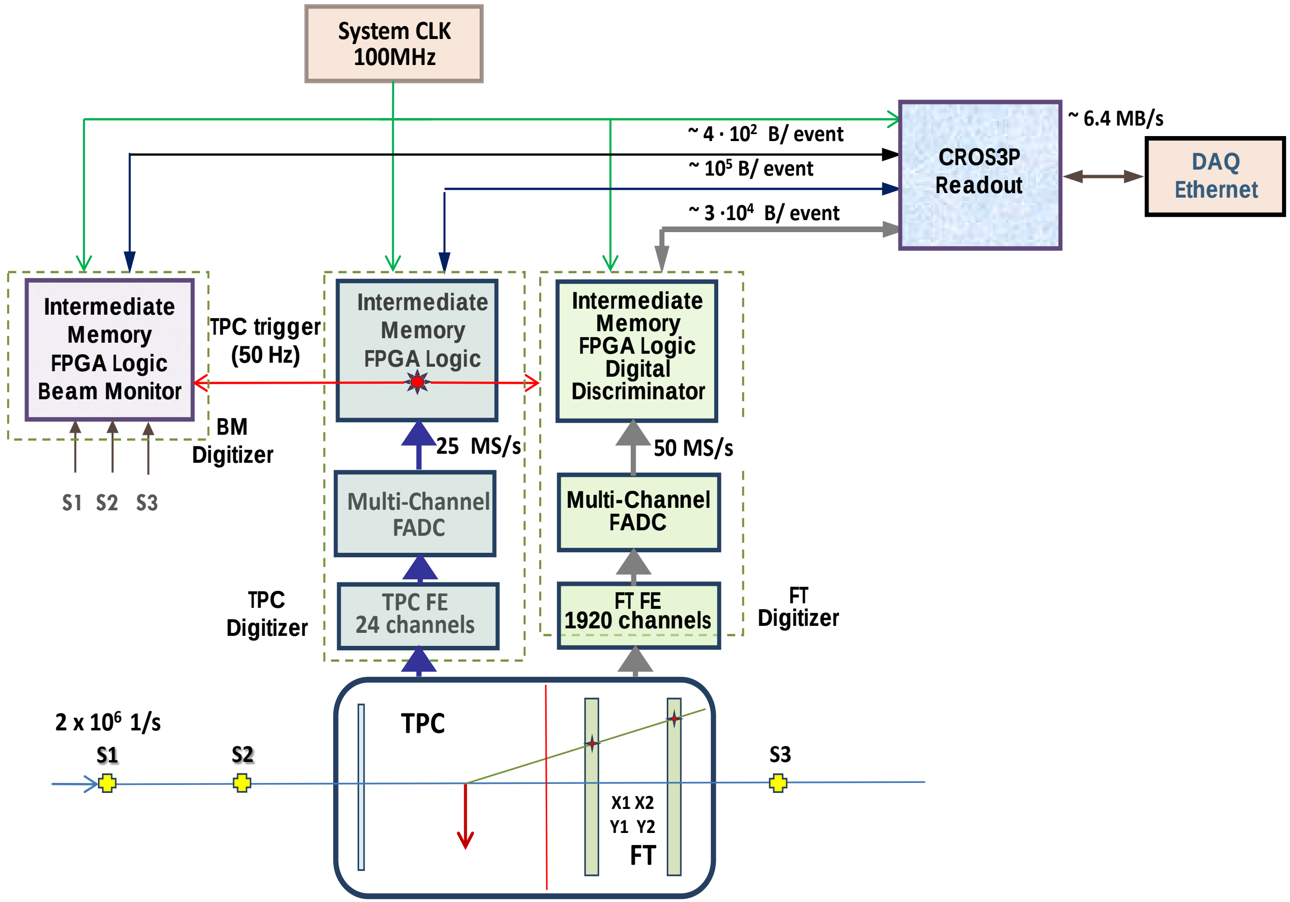
Gas system



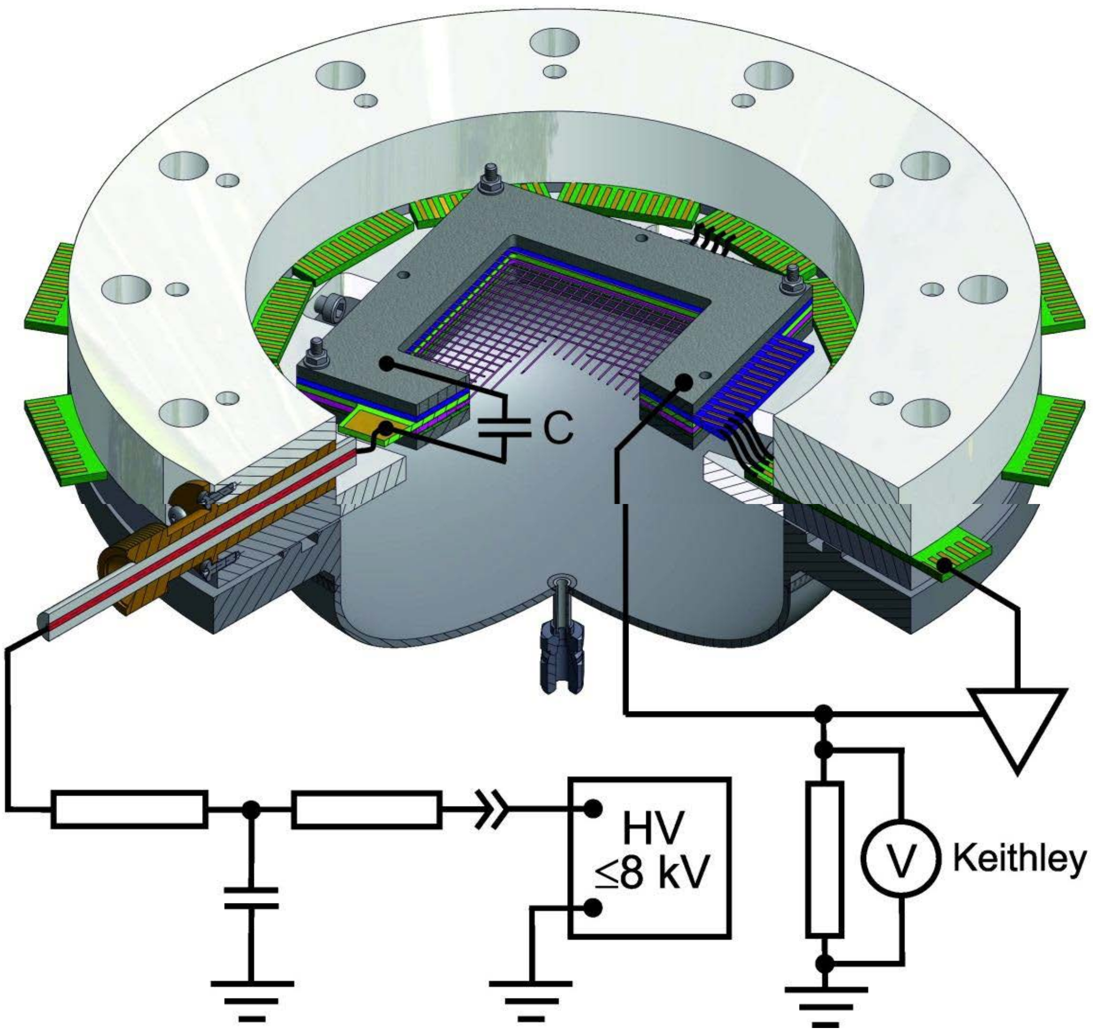
Hydrogen loop
Argon+methane loop
MFC1
MFC2
MFC3
MFC4
H2 19000 SL
20 bar
Ar 2000 SL
20 bar
Cryogenic gas purification
Gas purification
Analyser ppm H2O
Analyser ppm H2O
Gas analyser ppm
Gas analyser ppm
Pressure safety control
RV1
RV2
RV3
RV4
C1
C2
Vent
Argon supply
H2
H2
OUTDOOR STORAGE AREA
Ar
Ar
Ar CH4
Ar CH4

DAQ system

TPC self-trigger. Continious data flow. No dead time.



Forward Tracker



Участники эксперимента ПРОТОН

- А,Васильев
- М,Взнуздаев
- П.Кравцов
- К.Ившин
- А.Соловьев
- И.Соловьев

П.Неустроев
В.Головцов
Э.Спириденков
Л.Уваров
Г.Петров
В.Яцюра

А.Дзюба
А.Инглесси
Е.Маев
С.Белостоцкий
В.Саранцев

Г.Гаврилов
Б.Бочин
В.Грачев
С.Микиртычьянц

Спасибо   за внимание

Lepton scattering:

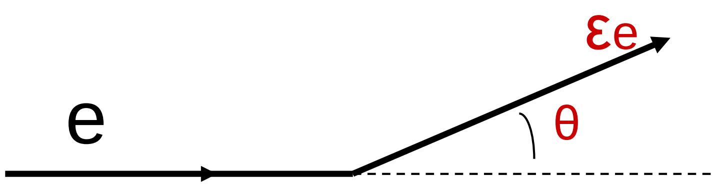
. In this context, an intensive experimental program will be performed at Mainz: a **new e-p scattering experiment, based on Initial State Radiation,** will reach Q2 values down to a few 10-4 (GeV/c)2, the MAGIX experiment relying on MESA (Mainz Electron-recovering Superconductiong Accelerator) which is based on an intense polarized beam, a polarized target and two high resolution magnetic spectrometers. MAGIX will provide a precise measurement of the proton charge and the magnetic radii.

Another experiment at Mainz will take advantage of the active Time Projection Chamber (TPC) designed by the team of A. Vorobyov (PNPI) to detect low-energy recoil protons. So as the COMPASS (Common Muon and Proton Apparatus for Structure and Spectroscopy, CERN) collaboration which proposed very recently to exploit its high energy muon beam to measure muon proton elastic scattering at very low Q2 down to 10-4 (GeV/c)2 relying on an hydrogen gas target inside a TPC (same design as the one used in Mainz) and an active scintillator fiber to complete the standard set-up. The advantages of such an experiment are the reduction of radiative corrections, of low multiple scattering effects and easy charge flips to measure both mu+ and mu- scattering.

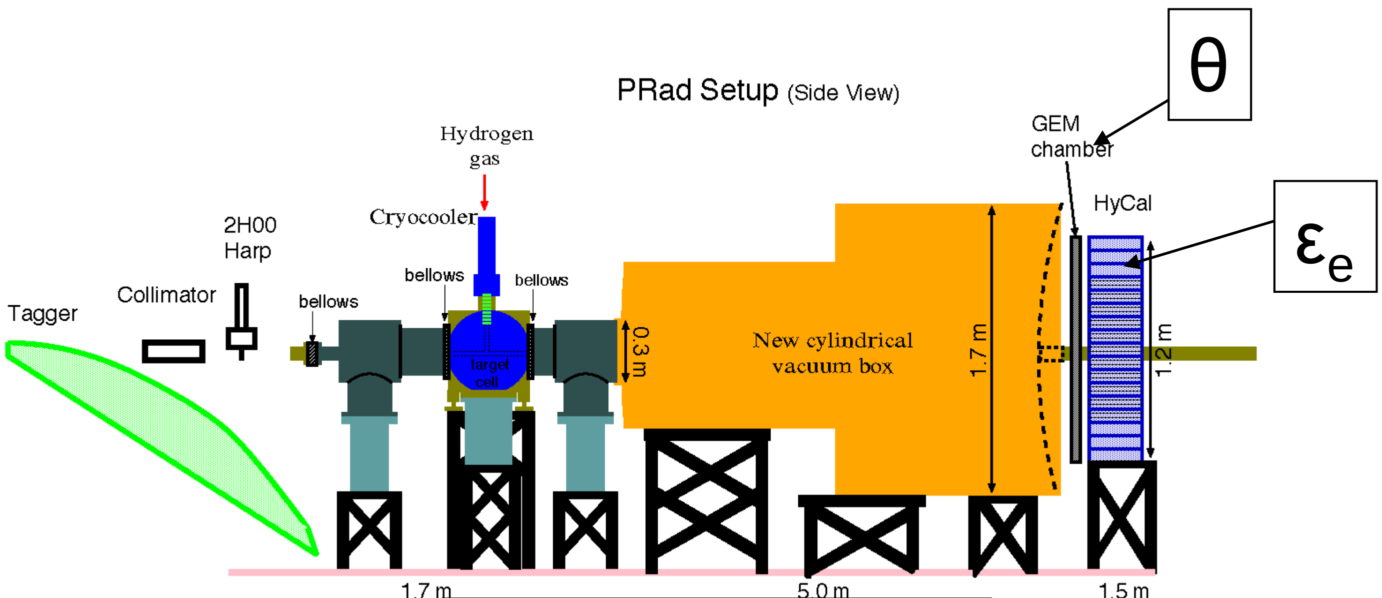
Furthermore, an international collaboration, lead by G. Ron from Israel, **proposed the MUon proton Scattering Experiment (MUSE) at PSI (Switzerland)** whose goal is to perform by 2019 electron and muon elastic scatterings simultaneously with both beam polarities. These measurements will test universality of leptons and will provide a measurement of the effect of the two-photon exchange. Besides, by 2020, the ProRad e-p elastic scattering experiment which will be held at the Platform for Research and Applications with Electrons (PRAE) in Orsay (France) aims to go down to a Q2 value of a few 10-5 (GeV/c)2 relying on a high performance pulsed electron beam of energy ranging from 30 to 70 MeV.

Experiment PRad (Proton Radius)

Jefferson Lab



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



$2\times10^{-4} \leq Q^2 \leq 10^{-1}$ Gev^2

Absolute normalization via ee-scattering

Agreement on Collaboration in Fundamental Research in Experimental Particle Physics

between PNPI NRC KI and INP Mainz

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

INP Mainz : electron beam

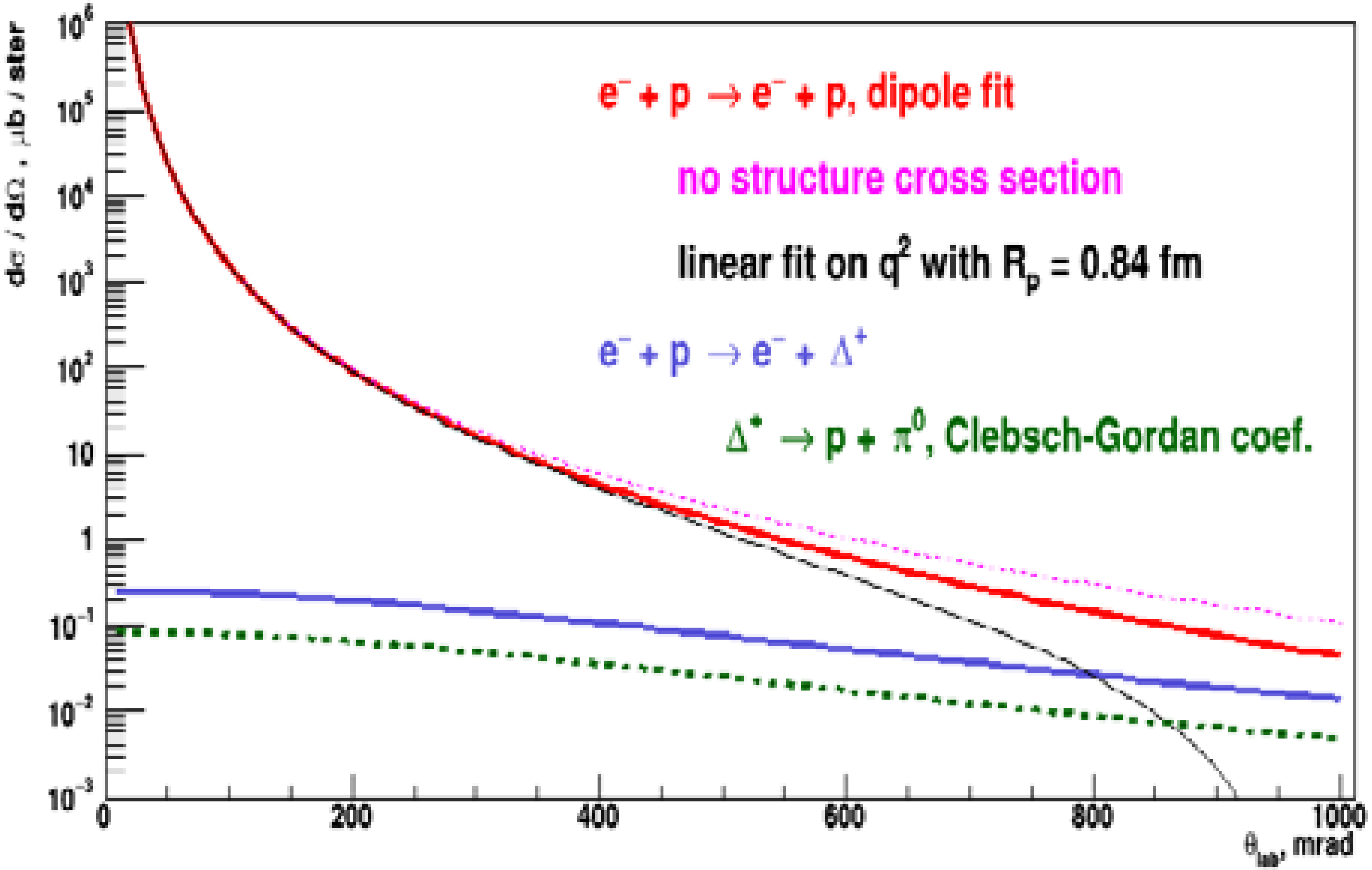
PNPI : PC@FT detector

Director of the INP Mainzf
Prof. Dr. Achim Denig

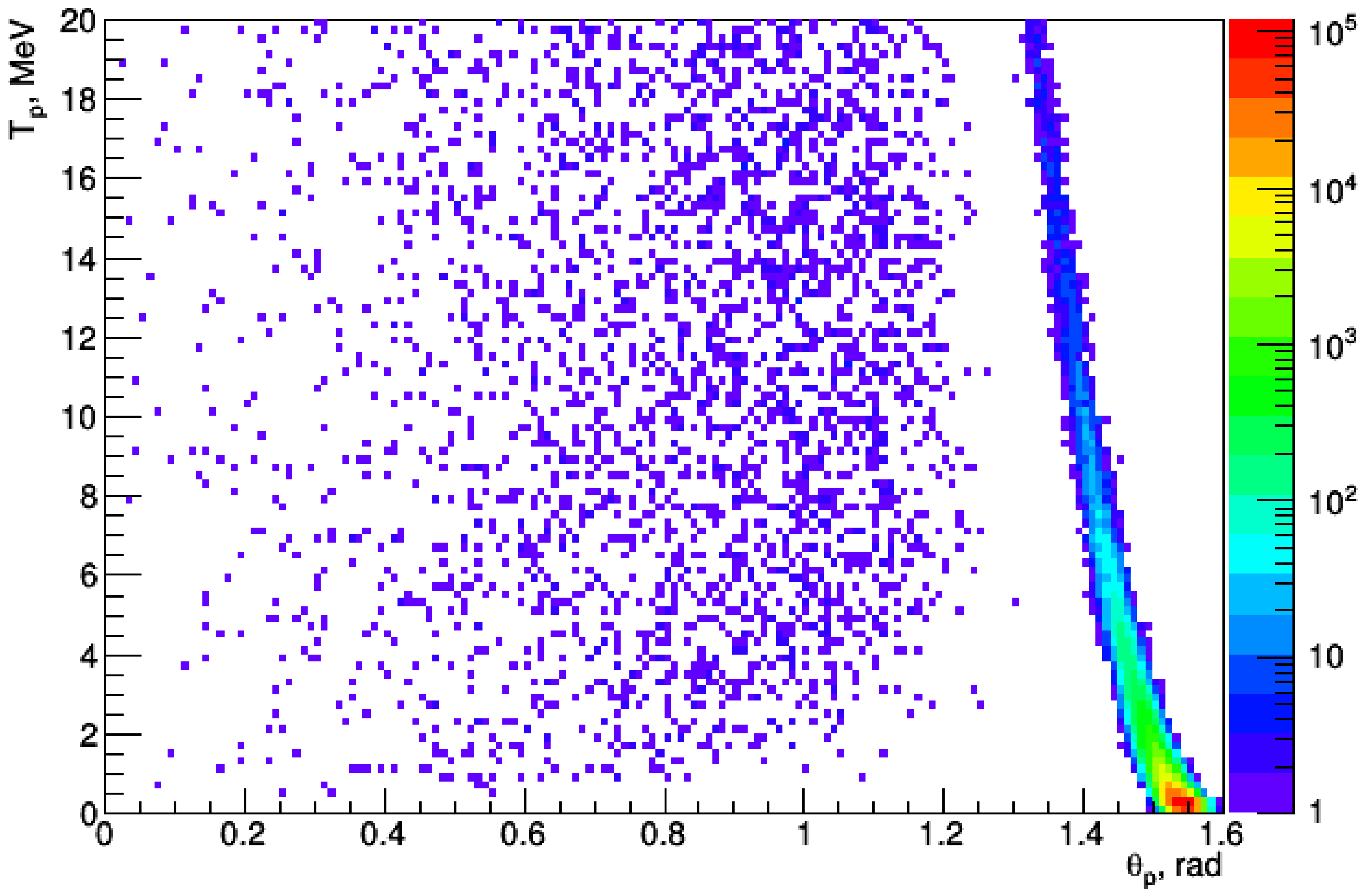
Director o f the PNPI NRC KI
Prof. Dr.Sc. Denis Yu. Minkin

February 27, 2017

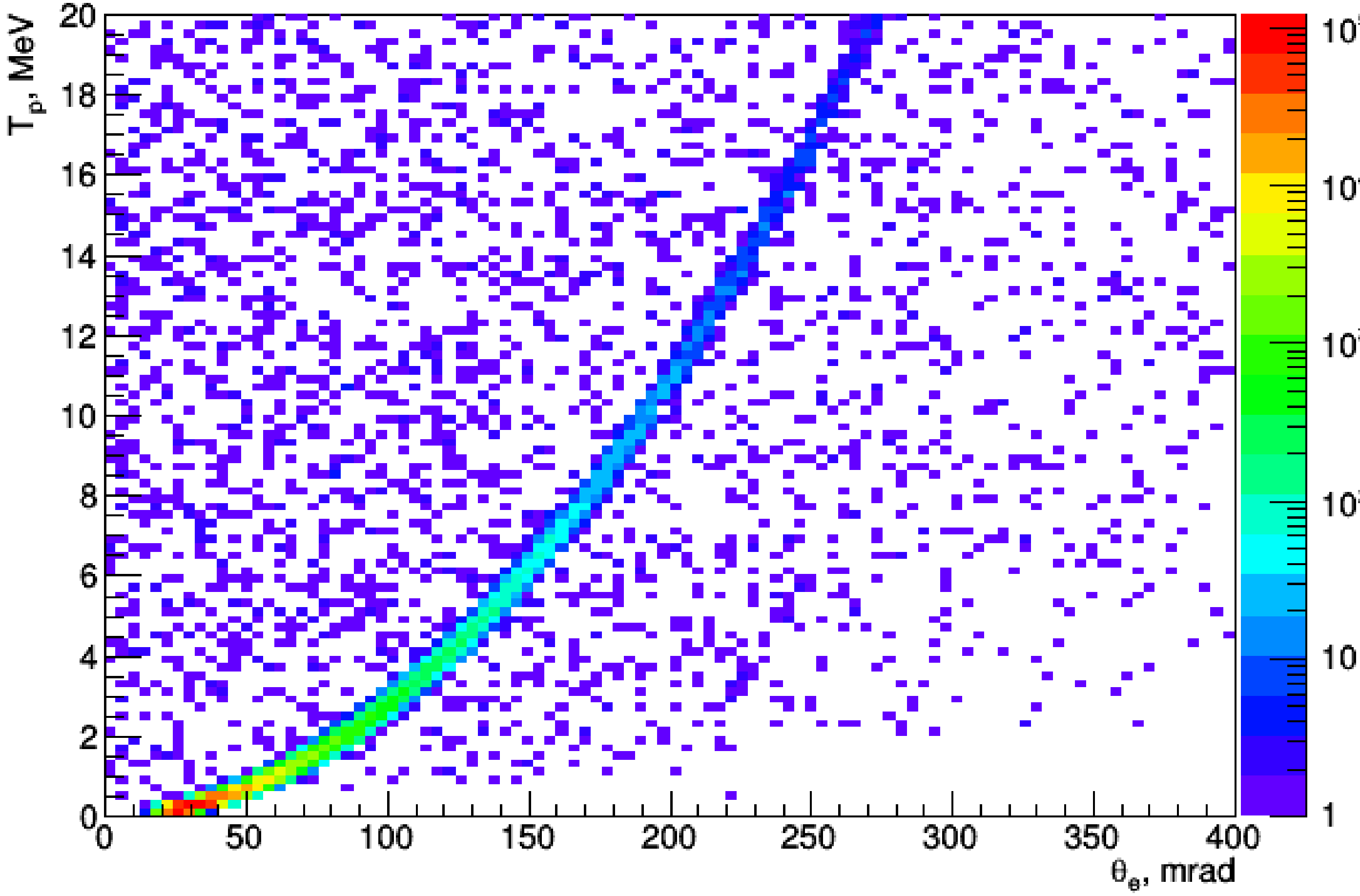
Elimination of the background reactions



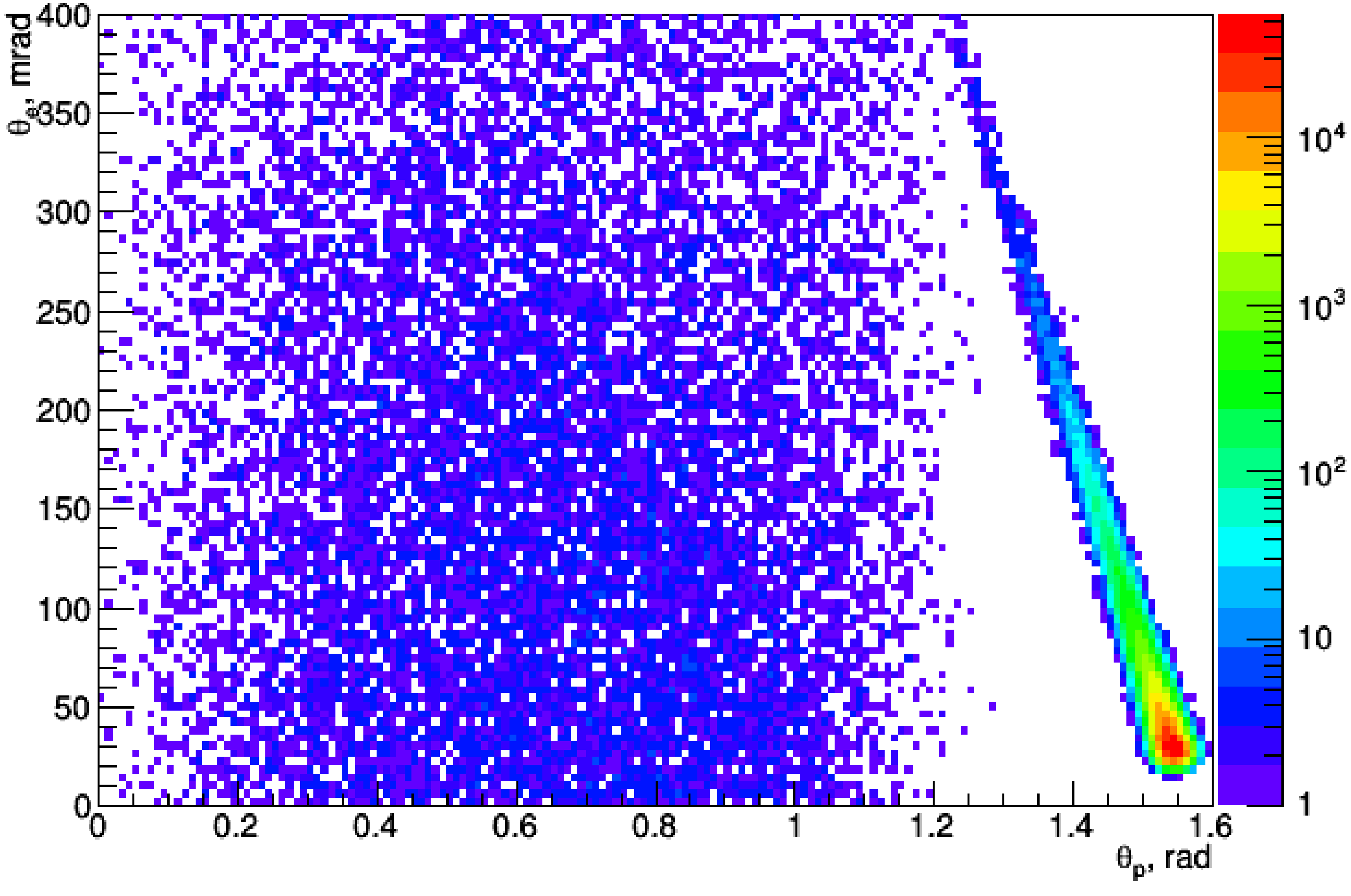
Proton energy- proton angle correlation



Proton energy- electron angle correlation



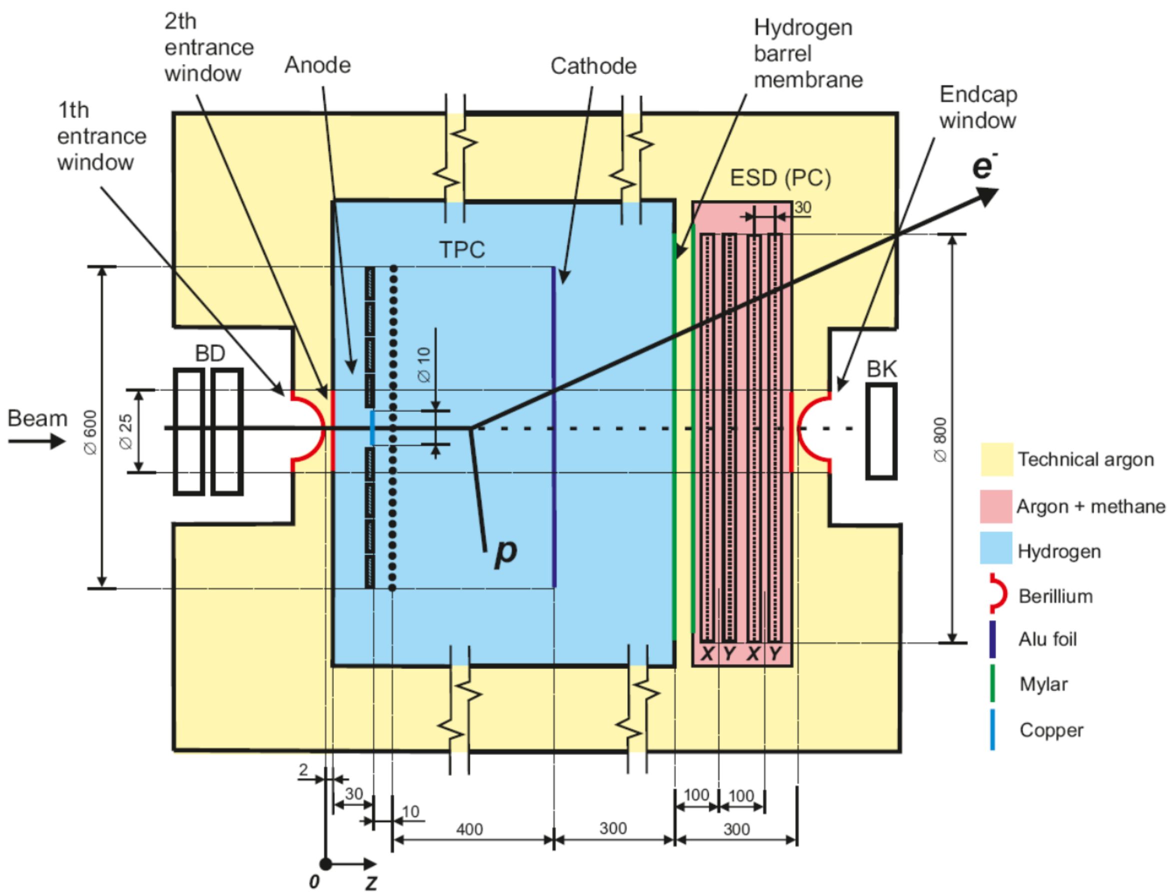
Proton angle- electron angle correlation



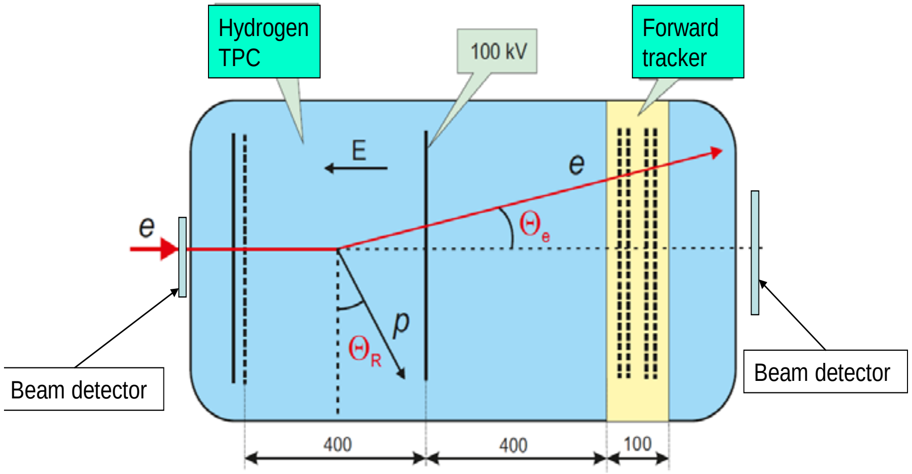
Gas system

Three different gases Hydrogen, Ar + 1%CH4, Ar in one vessel

Gas pressure from 4 atm to 20 atm.
Absolute precision and stability 0.01%

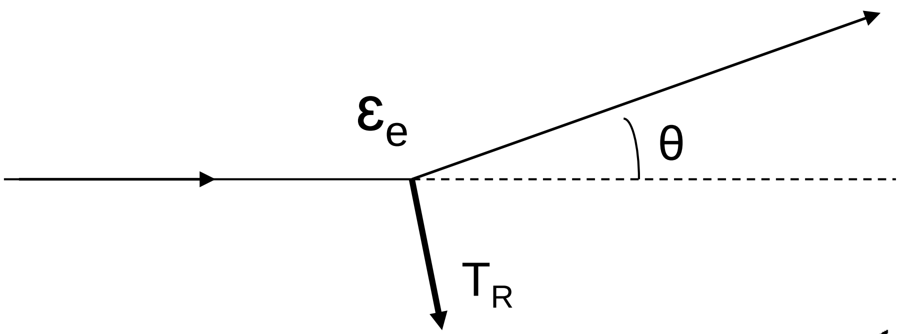


Beam monitoring



Absolute beam rate monitoring	**0.05 %**

-t scale self-calibration

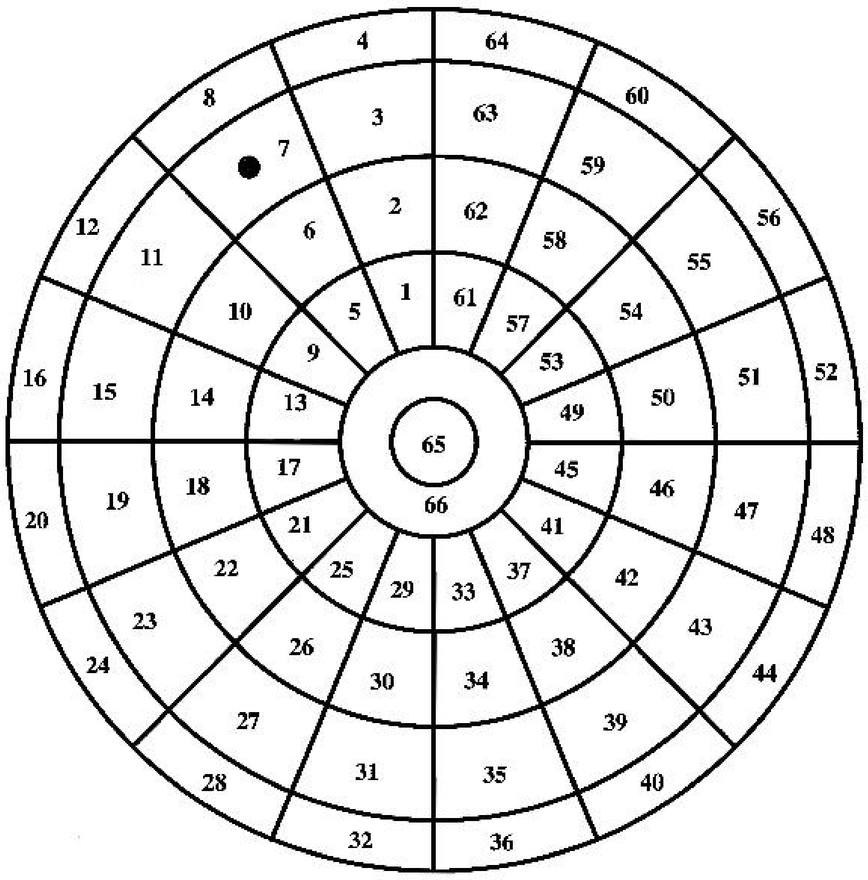


Absolute electron angle	**0.02%**
T_R-scale calibration, relative	**0.04 %**
Absolute electron energy	**0.02%**
T_R-scale calibration, absolute	**0.08%**

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

$$-t = 2MT_R$$

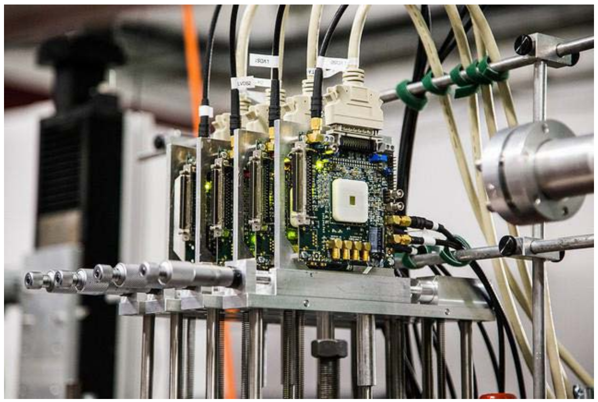
Anode segmentation in ACTAR2

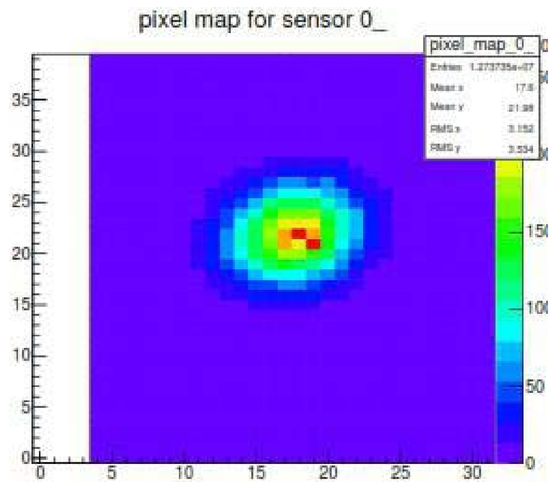


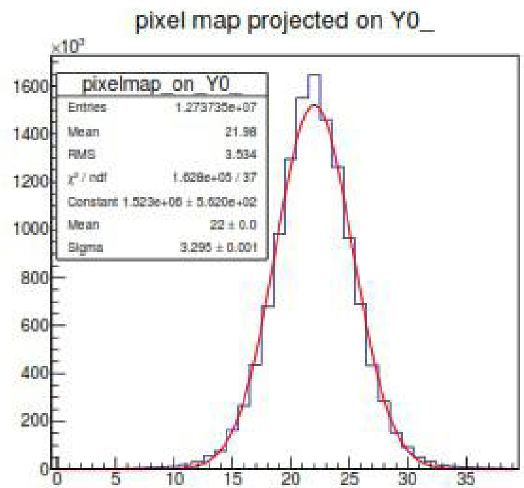
. *66 pads in total. The central pad is 20 mm in diameter*

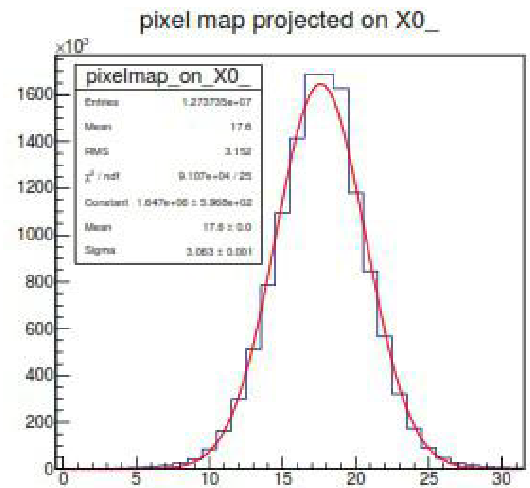
Read out with FADC from each pad

Pixel detectors and electron beam parameters









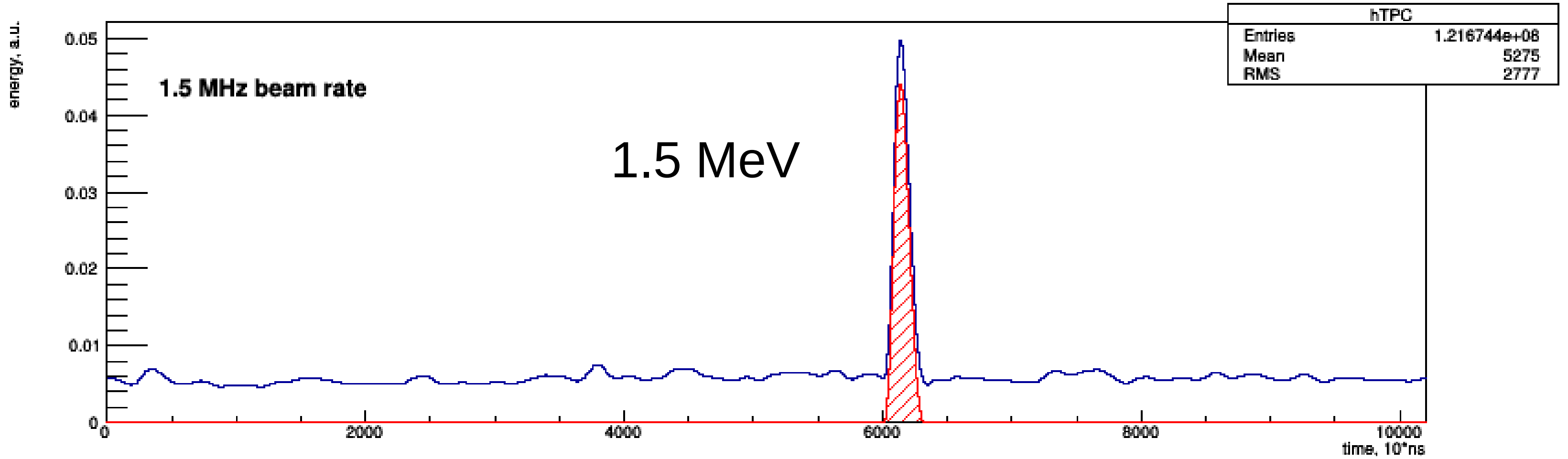
Beam telescope - four planes of 80 μm x100 μm pixels

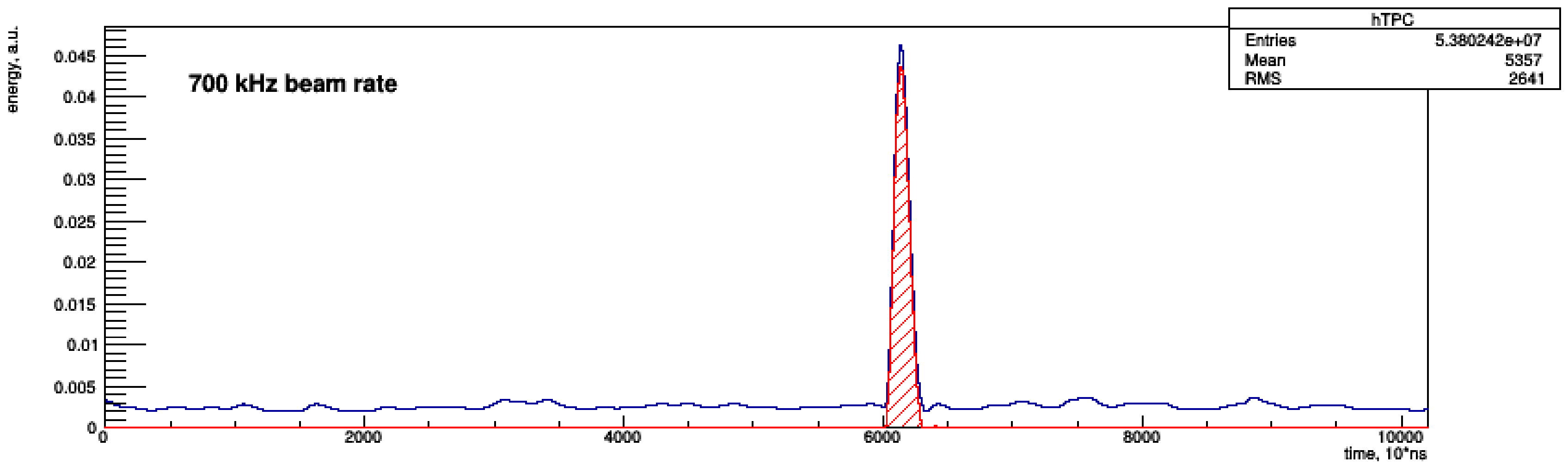
Measured beam parameters

• Beam size :	250µm (sigma)	OK
• Beam divergence:	1 mrad	~ OK
• Beam intensity:	$2x10^6$ - 10^3 e/sec	OK
• Intensity stability		OK
• Beam spot pozition stability		Satsfactory

to be under control during the run

Beam ionization noise in TPC
The central pad



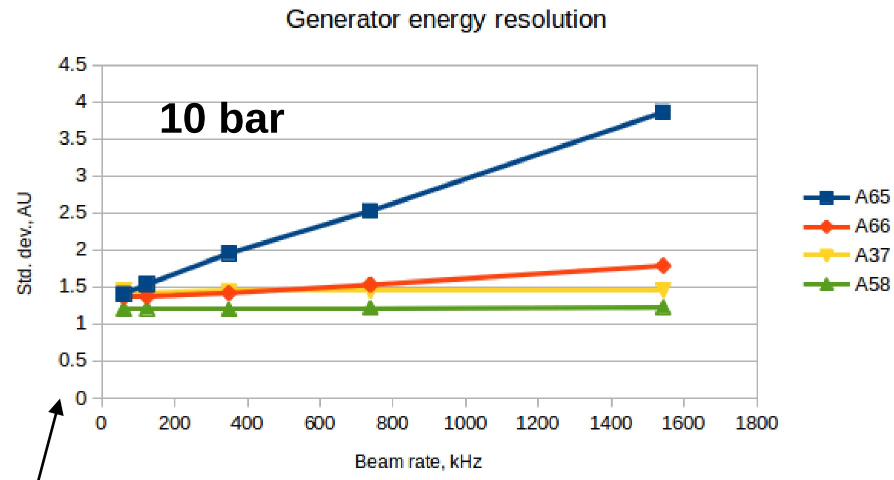


Measured pulse generator resolution

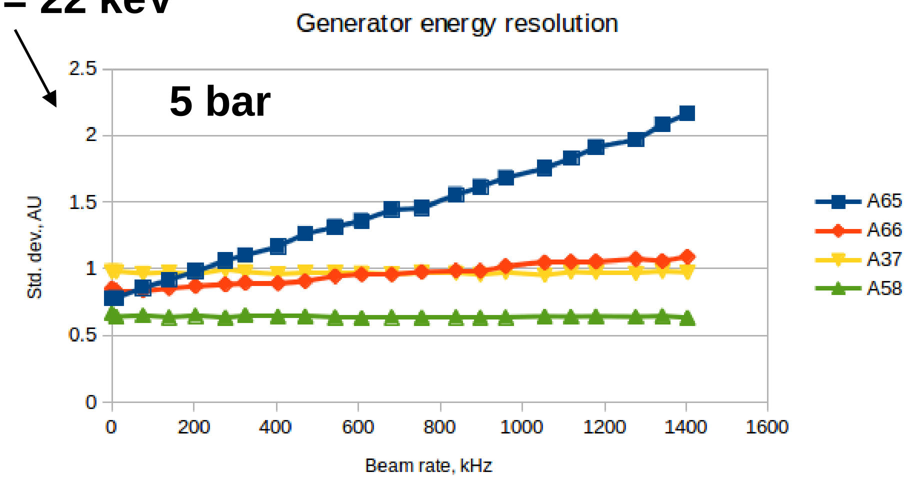
– **Sizeble effect only for centrlal anode (A65);**

– **Visible effect for the second ring (A66);**

– **Practically no effects in the other channels (A37 / A58).**

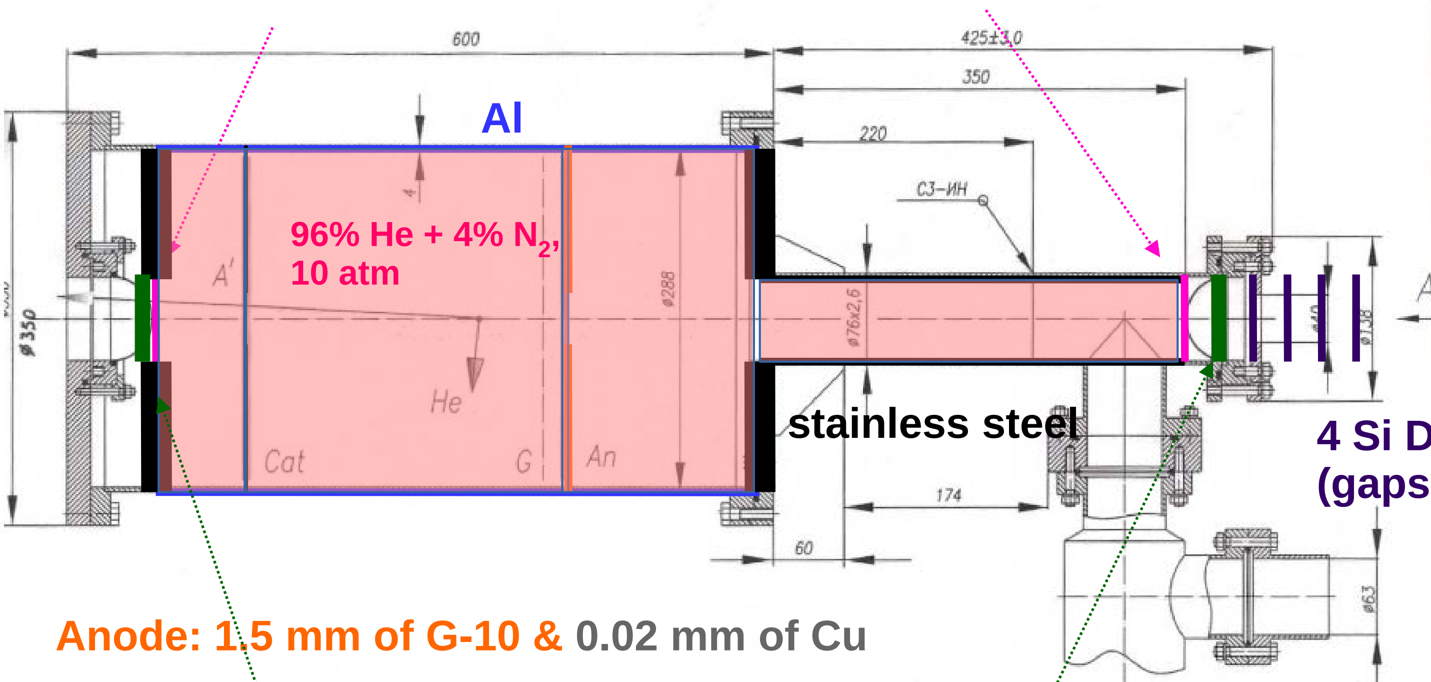


1 AU = 22 keV



TPC & GEANT4 model

Be windows of 0.5 mm thickness



T(e) = 720 MeV

4 Si Detectors 0.05 mm
(gaps of 50 mm)

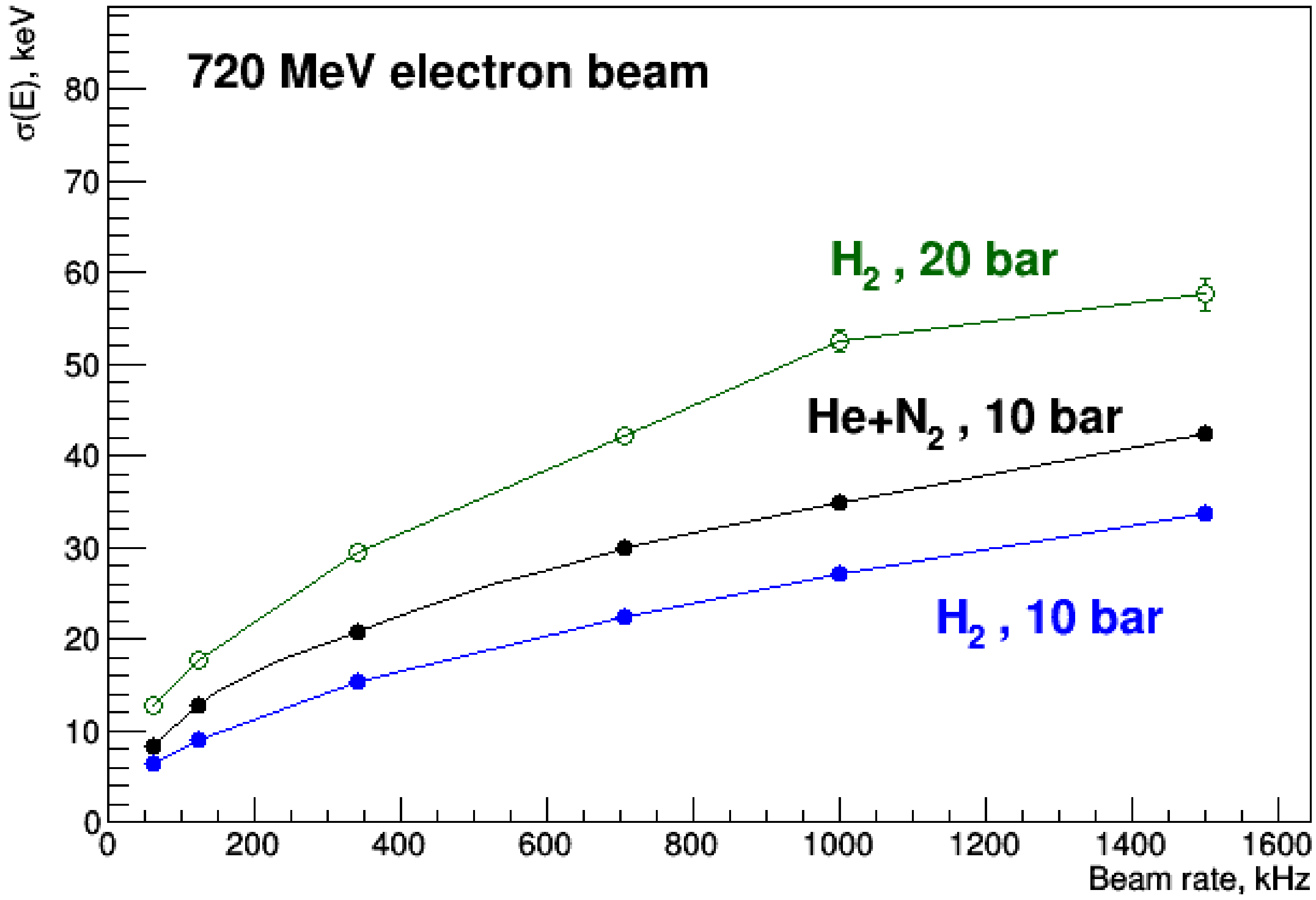
Anode: 1.5 mm of G-10 & 0.02 mm of Cu

Cathode: 1 mm of steel & 0.02 mm of Al

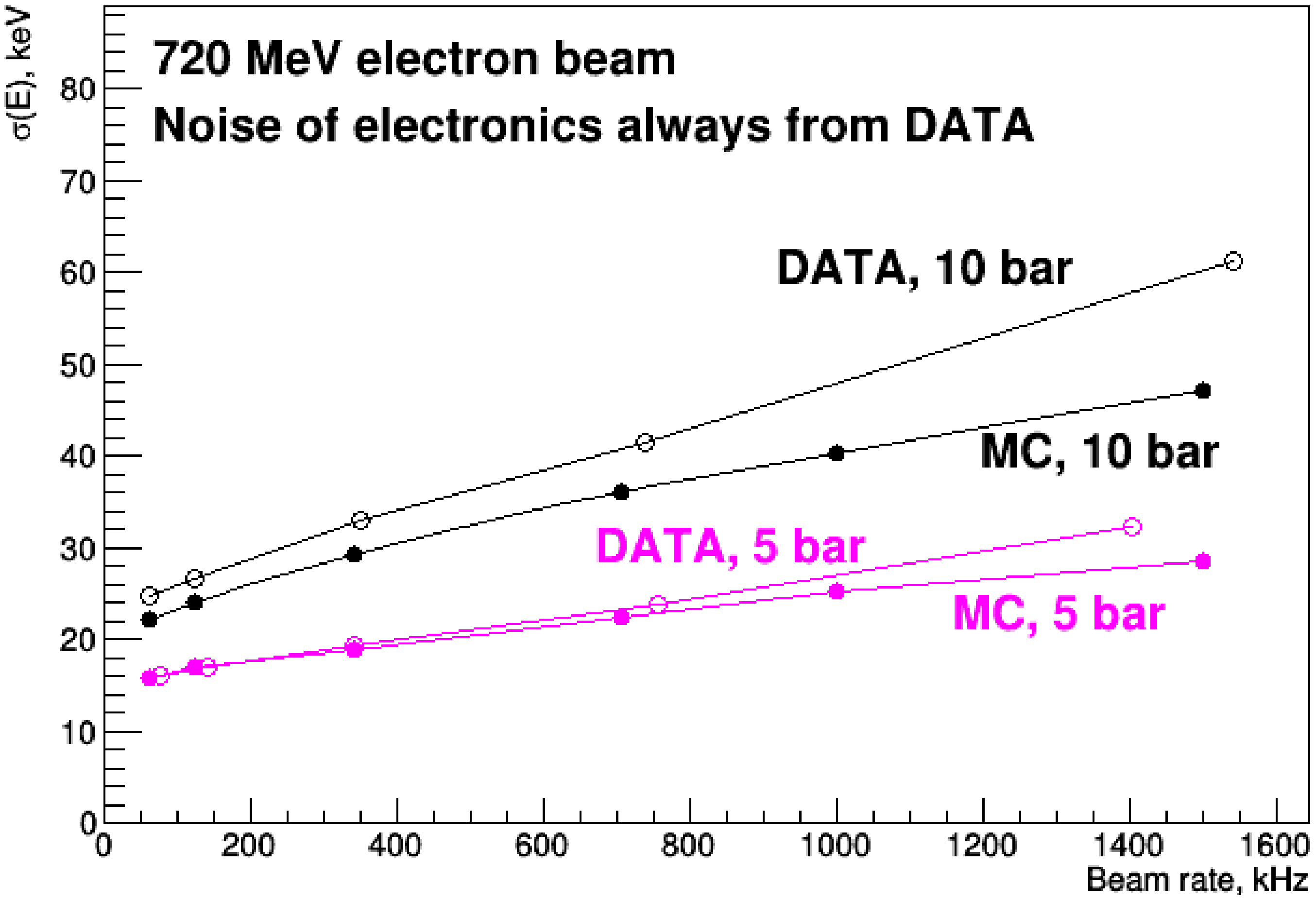
z

Scintillators (C_9H_{10}), 2 mm

Beam ionization noise
MC simulation



MC - measurements comparison

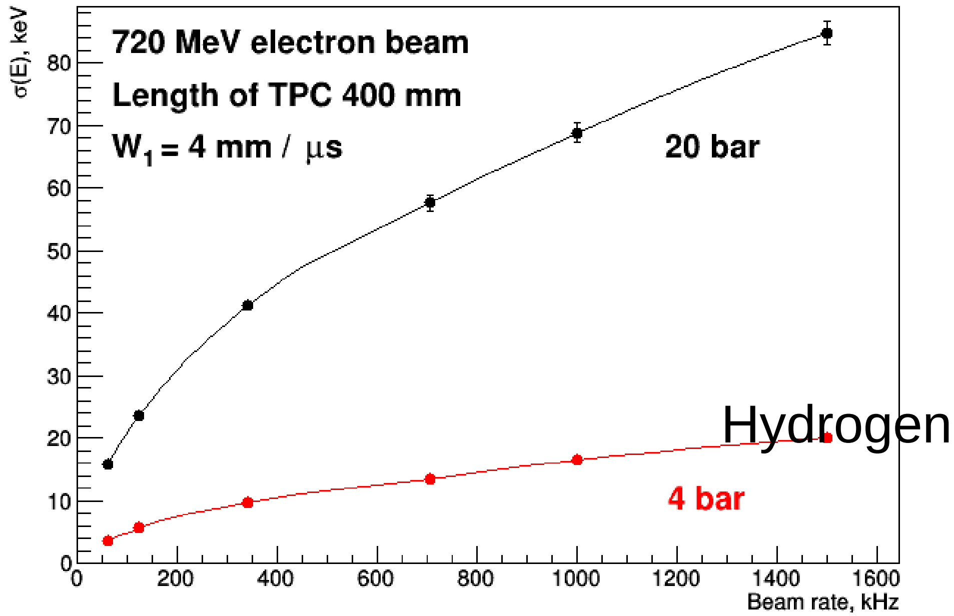


Summary on beam ionization noise studies

- The beam noise is increasing with beam rate as a root square of the beam rate;
- 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%.

Predictions for the main experiment

Beam ionization noise at the central pad



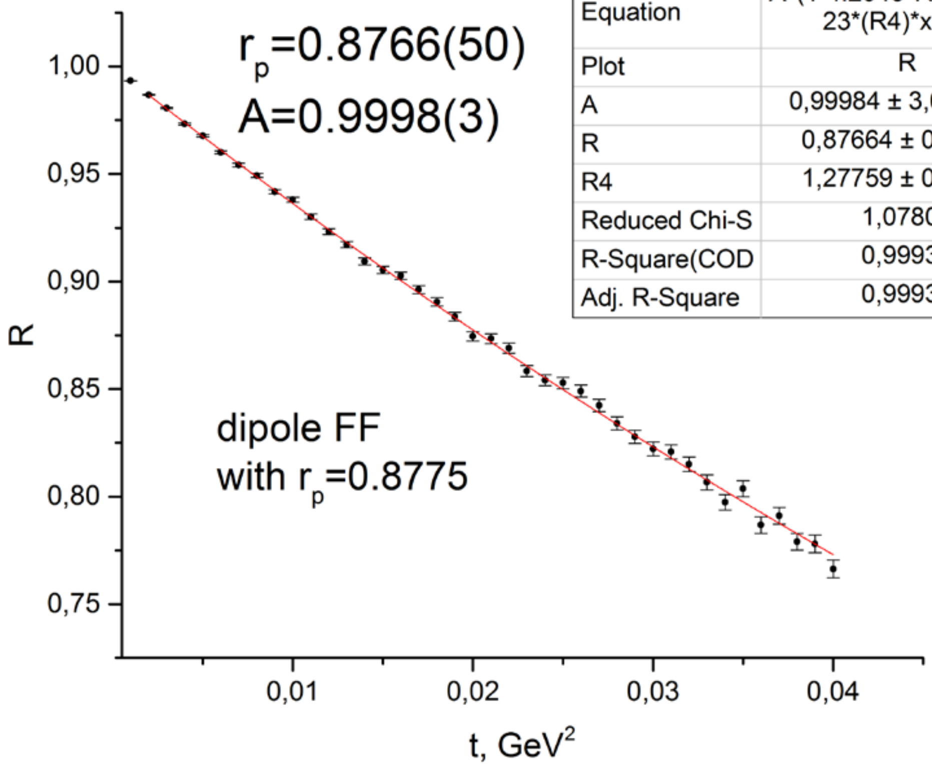
Expected TPC energy resolution in the main expt. at 2 MHz beam rate

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

Statistics

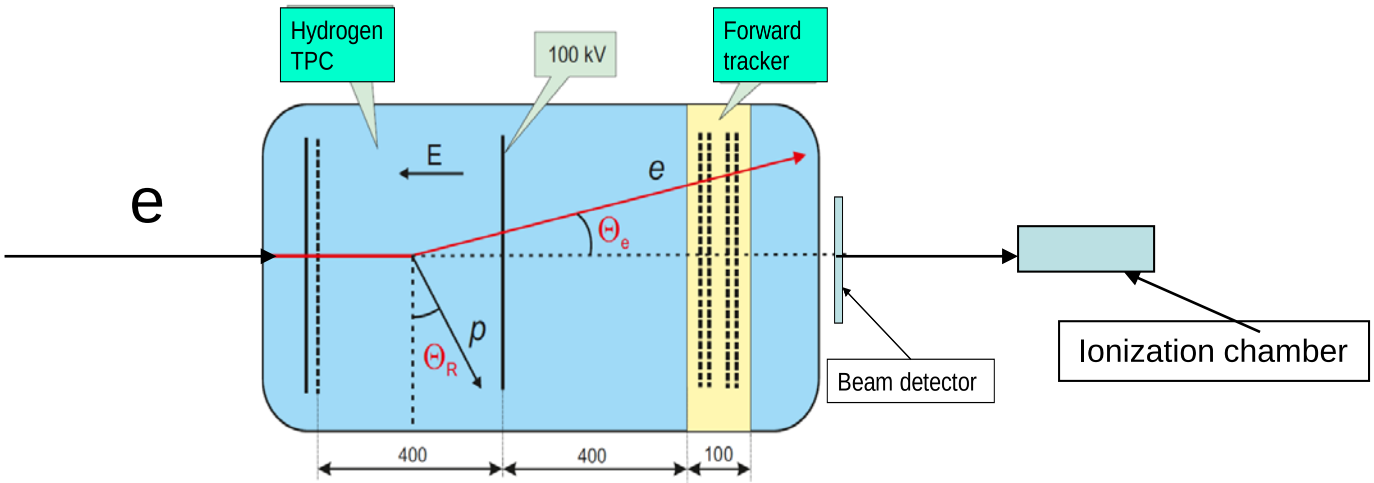
45 days $\quad$ $33\text{x}10^6$ events

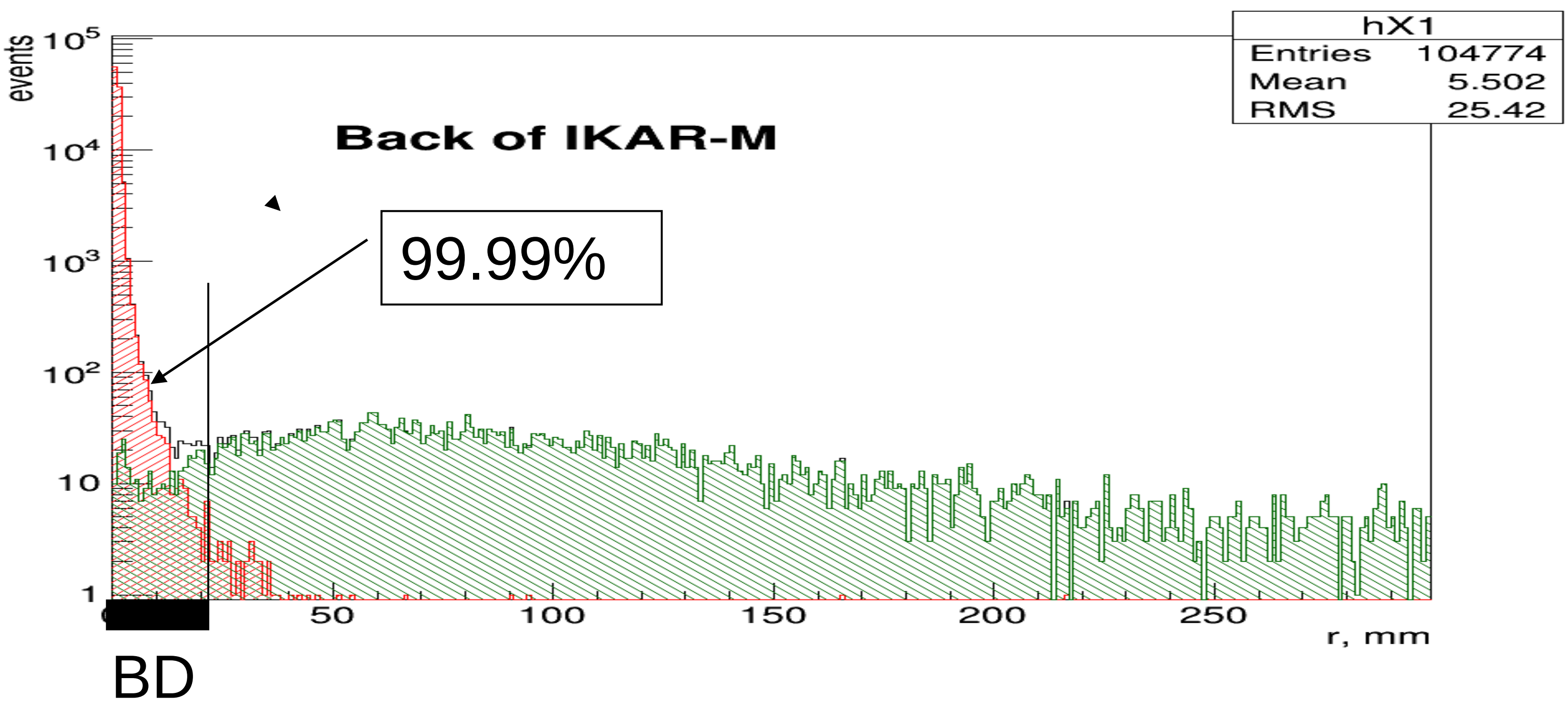
$$\frac{G(Q^2)}{G(0)} = 1 - \frac{1}{6}\langle R_p^2 \rangle Q^2 + \frac{1}{120}\langle R_p^4 \rangle Q^4 - \ldots,$$



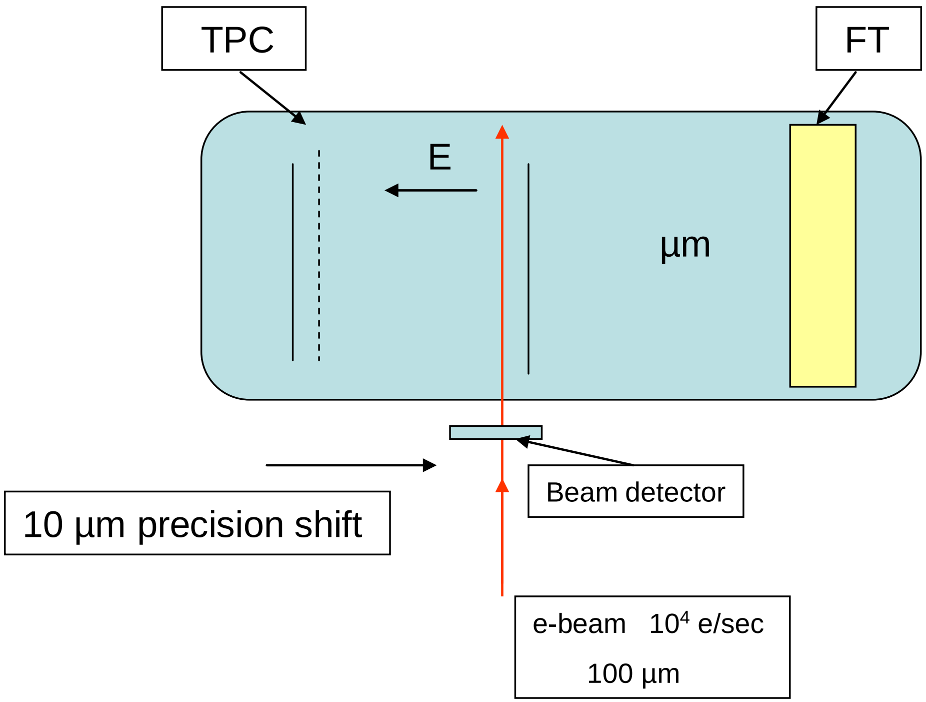
Model	polinFF (User)
Equation	A*(1-4.2943*R^2*x+5.5323*(R4)*x^2)^2
Plot	R
A	0,99984 ± 3,0008E-4
R	0,87664 ± 0,00495
R4	1,27759 ± 0,22675
Reduced Chi-S	1,07804
R-Square(COD	0,99939
Adj. R-Square	0,99936

Rp ± 0.005 fm


Hydrogen TPC
100 kV
Forward tracker
e
E
e
Θe
p
ΘR
Beam detector
Ionization chamber
400
400
100

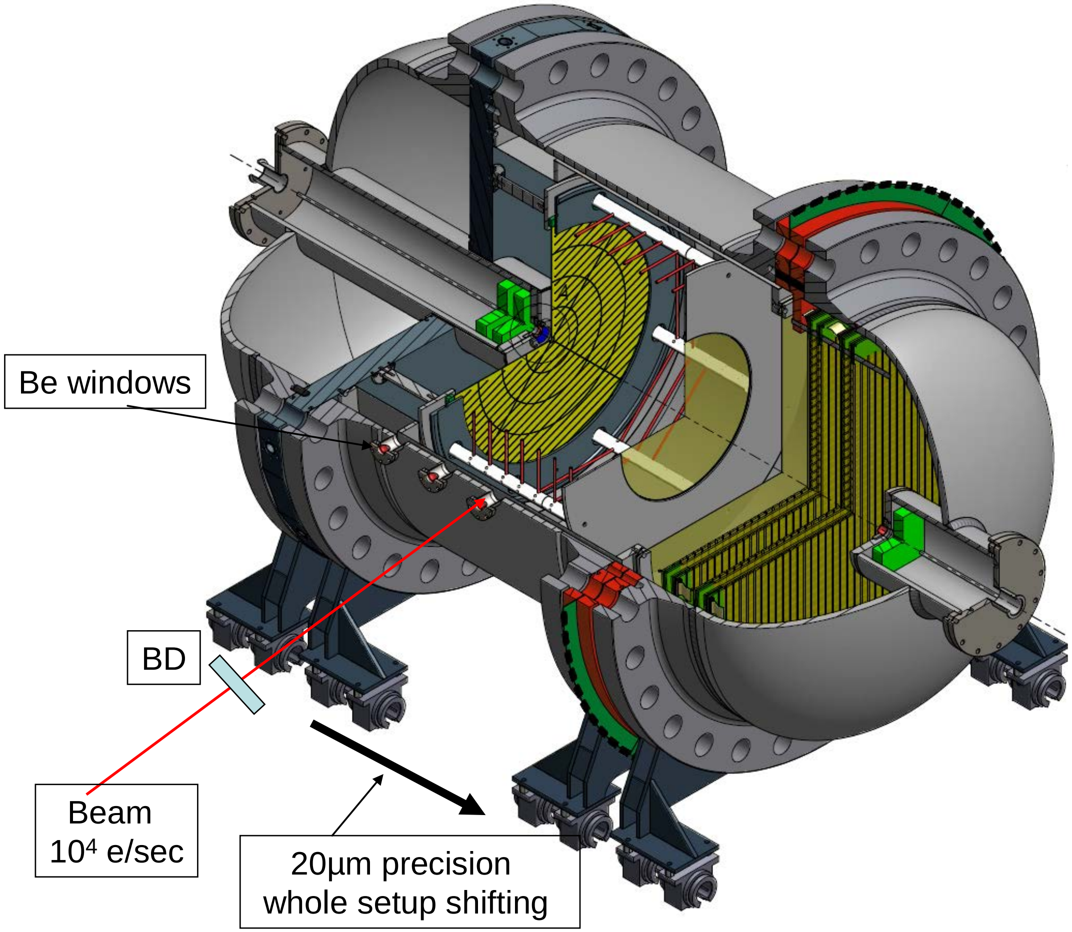

events
Back of IKAR-M
hX1
Entries 104774
Mean 5.502
RMS 25.42
99.99%
r, mm
BD

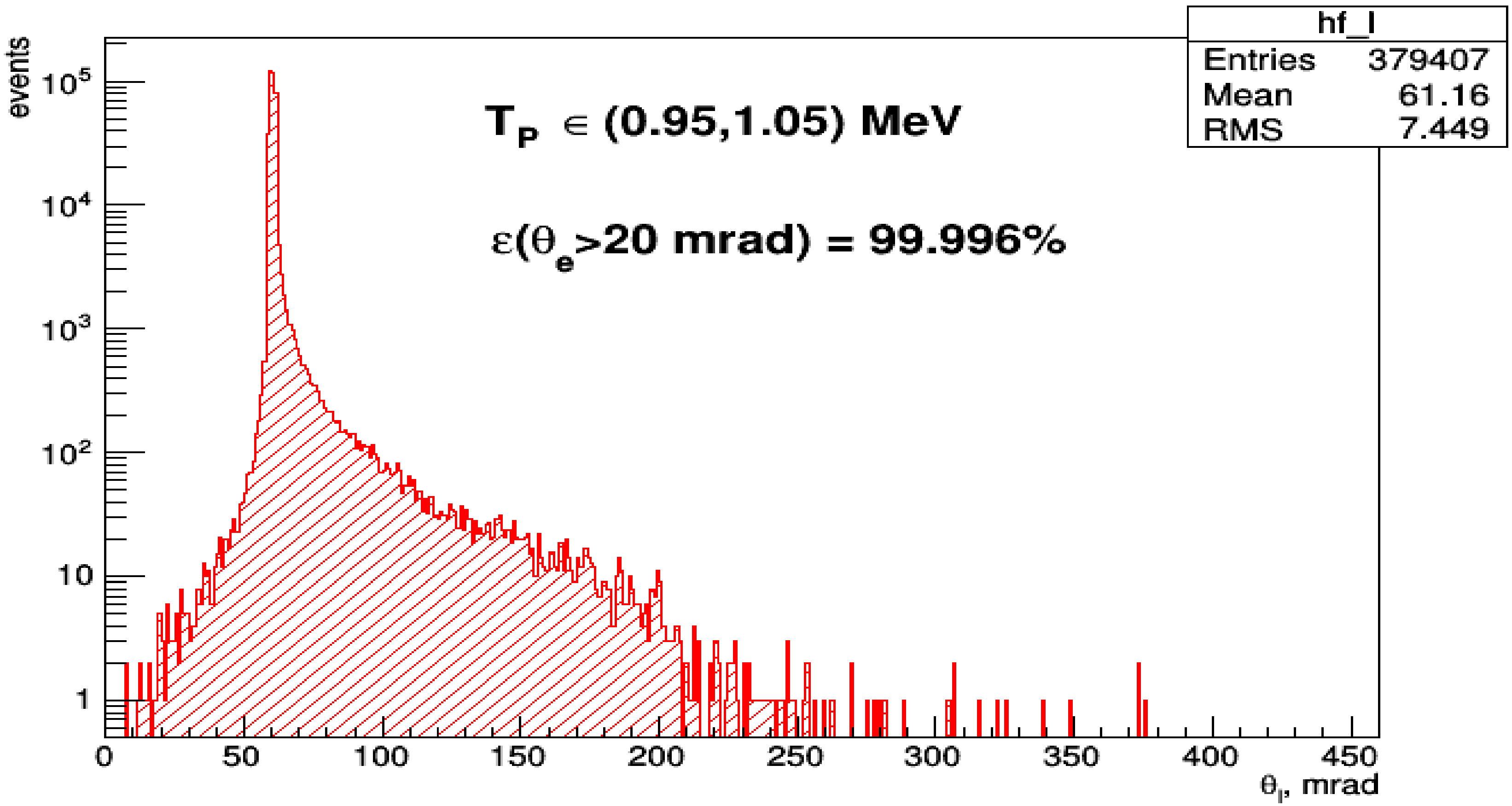
Drift velocity measurement



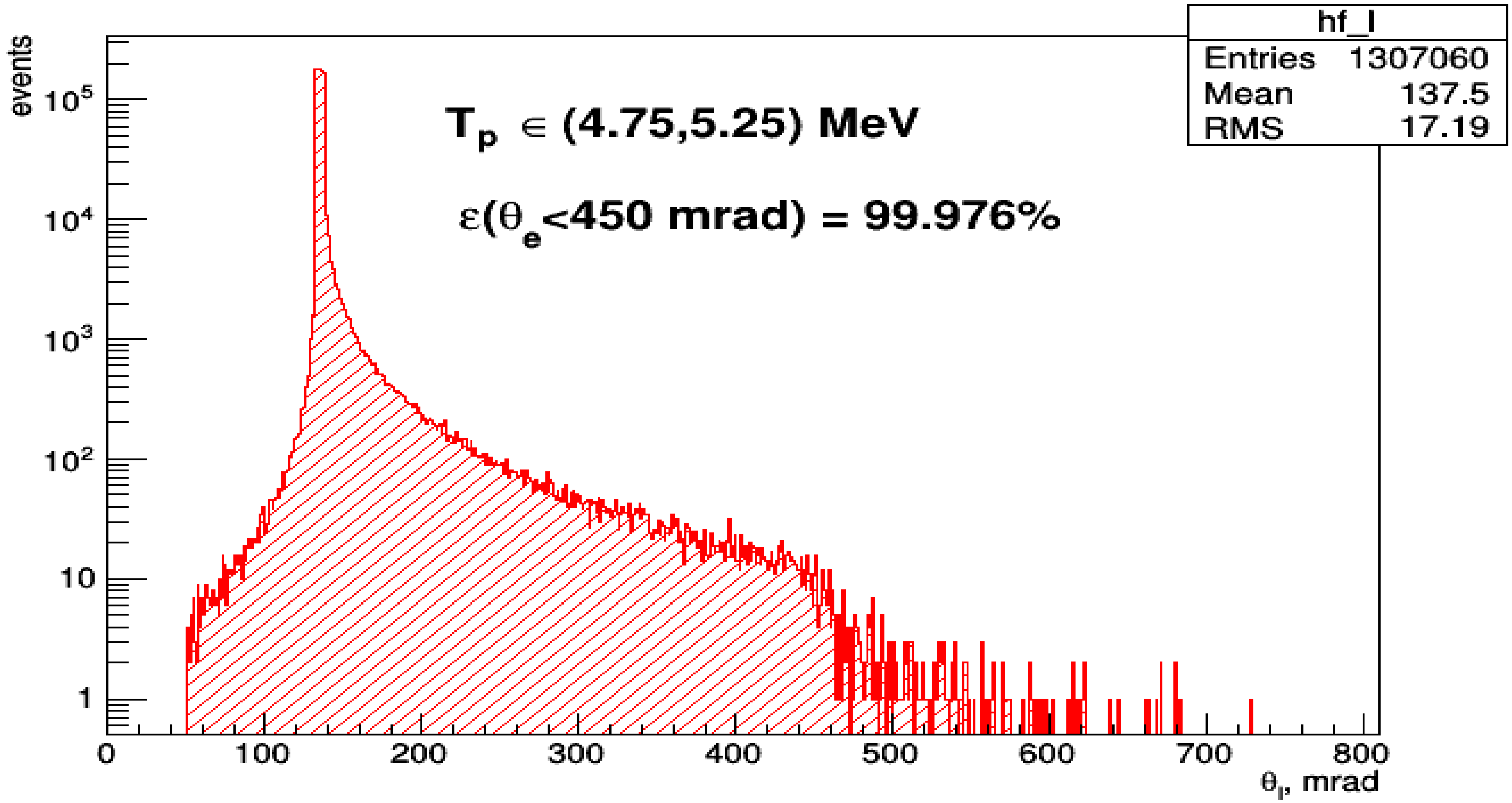
Precision in W measurements 0.01%

Experimental layout for high precision measurement of electron drift velocity.

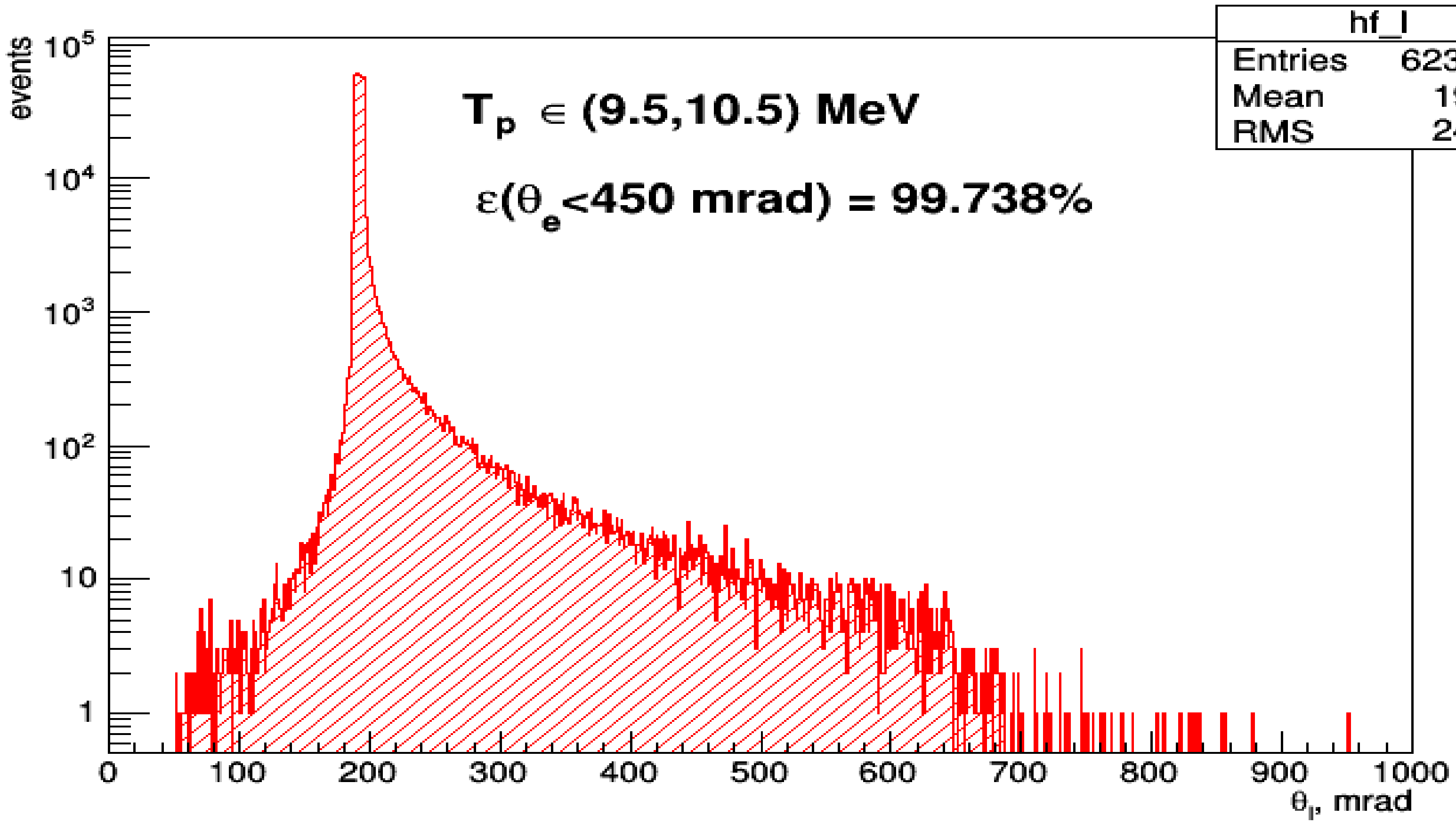




hf_l
Entries 379407
Mean 61.16
RMS 7.449
$T_P \in (0.95, 1.05)$ MeV
$\varepsilon(\theta_e > 20$ mrad$) = 99.996\%$
events
10^5
10^4
10^3
10^2
10
1
0 50 100 150 200 250 300 350 400 450
θ_l, mrad



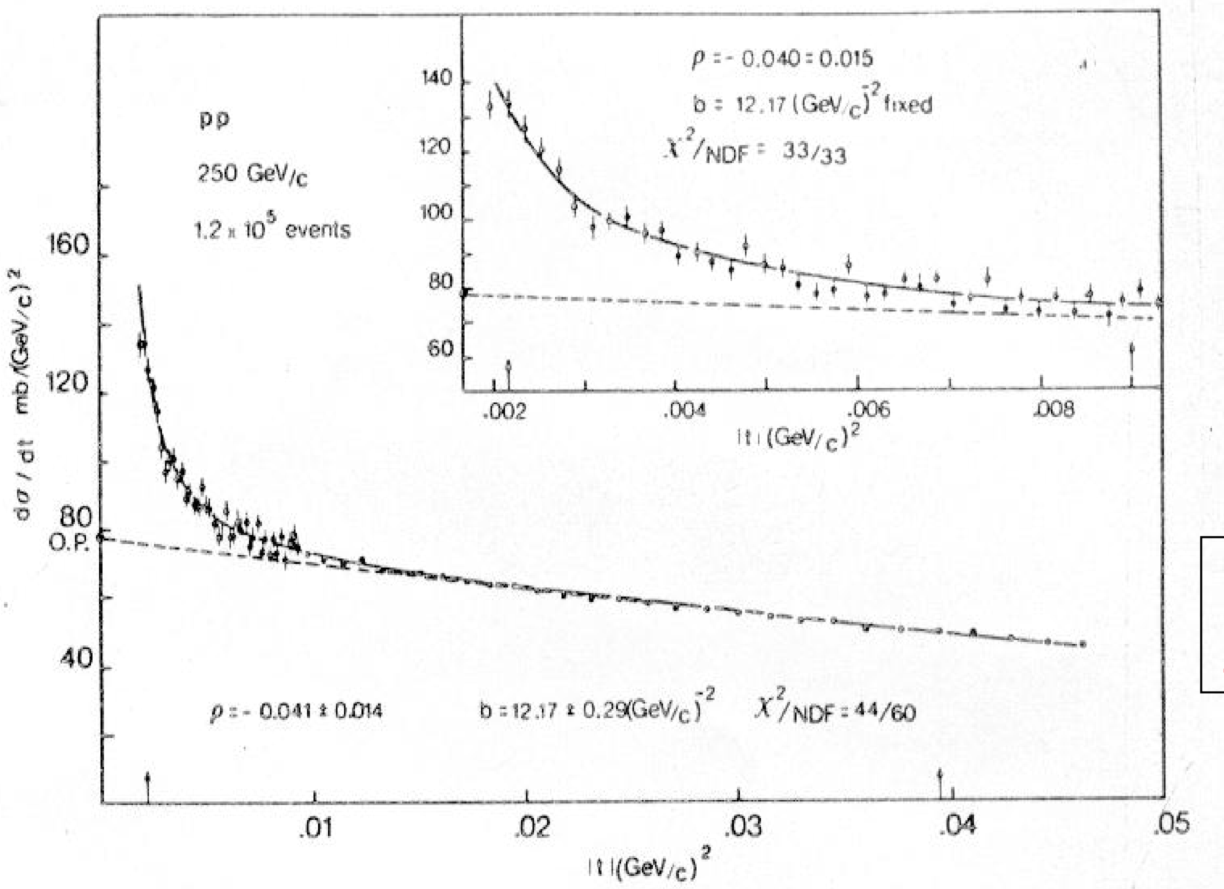
hf_l
Entries 1307060
Mean 137.5
RMS 17.19
$T_p \in (4.75,5.25)$ MeV
$\varepsilon(\theta_e<450$ mrad$) = 99.976\%$
events
10^5
10^4
10^3
10^2
10
1
0
100
200
300
400
500
600
700
800
θ_l, mrad



hf_l
Entries 623294
Mean 195.6
RMS 24.99
$T_p \in (9.5,10.5)$ MeV
$\varepsilon(\theta_e<450$ mrad$) = 99.738\%$
events
10^5
10^4
10^3
10^2
10
1
0
100
200
300
400
500
600
700
800
900
1000
θ_l, mrad

An example from cross sections of πp- and pp- scattering measured with ICAR

Nuclear Physics B217 (1983) 285-335



ρ= ReA(0)/ImA(0)
b = dσ/dt(t=0)

0.4% T_R-scale calibration

1% absolute precision in dσ/dt

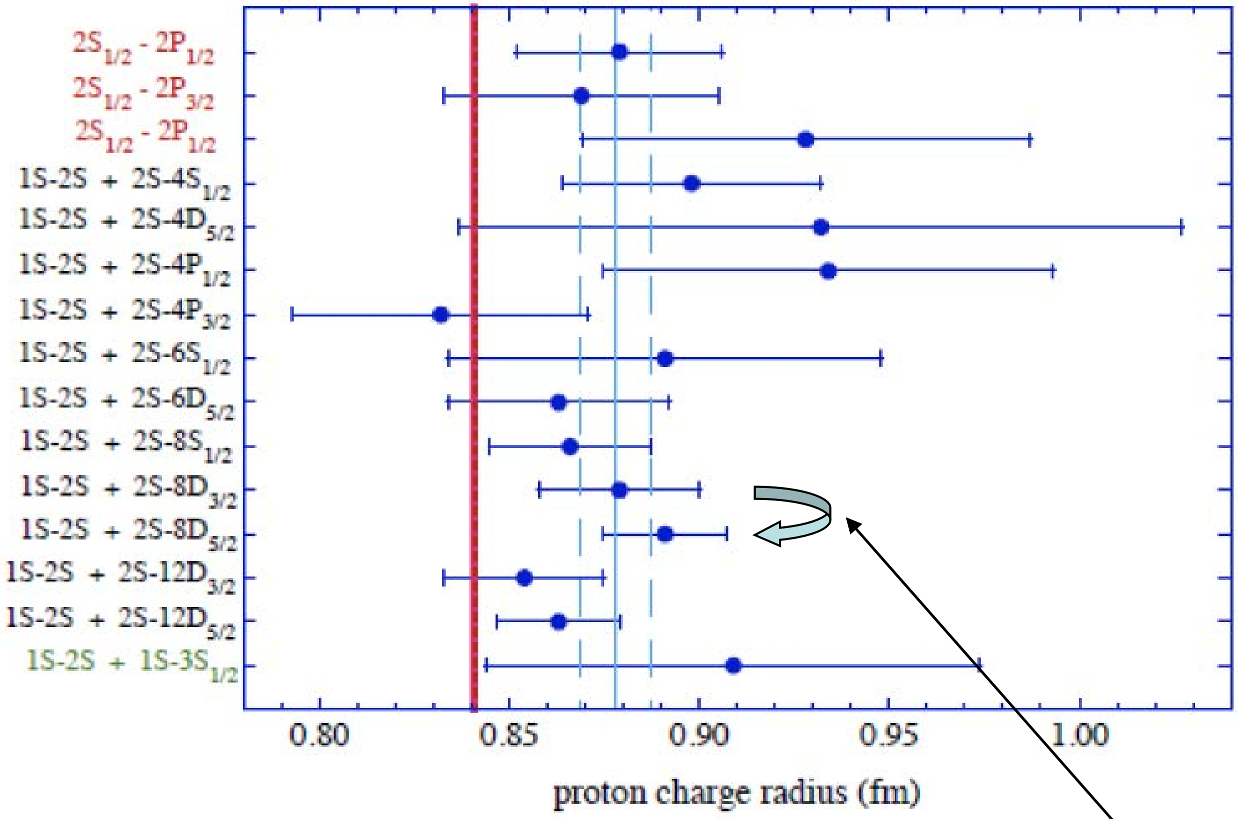
ep- scattering experiments

Main concern:

* The form factor $G_E(Q^2 \to 0)$ needed for extraction of the proton radius was obtained by extrapolation of the cross sections measured at rather large Q^2 values to $Q^2 \to 0$

* Large Radiative Corrections (~10%).
  Dependence of the RC on experimental conditions.

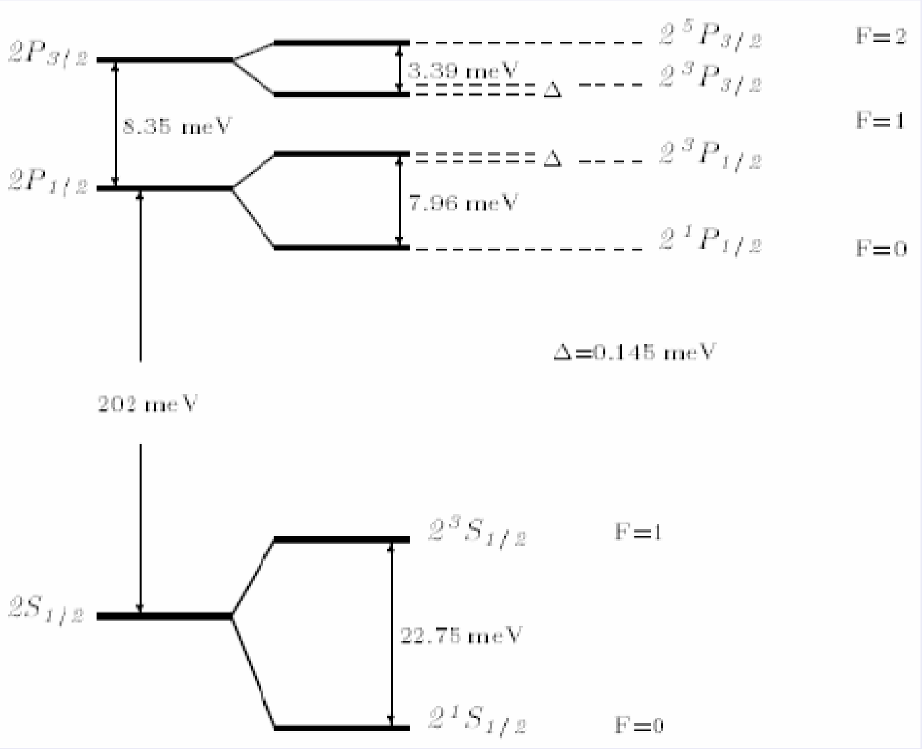
Proton radius from Lamb shift in hydrogen atom (ep-atom)



$r_p = 0.877(7)$ fm, *Garching-Paris, 2006-2011*

Lamb shift in muonic atom (μp-atom)

Muonic Hydrogen



Theoretical Prediction

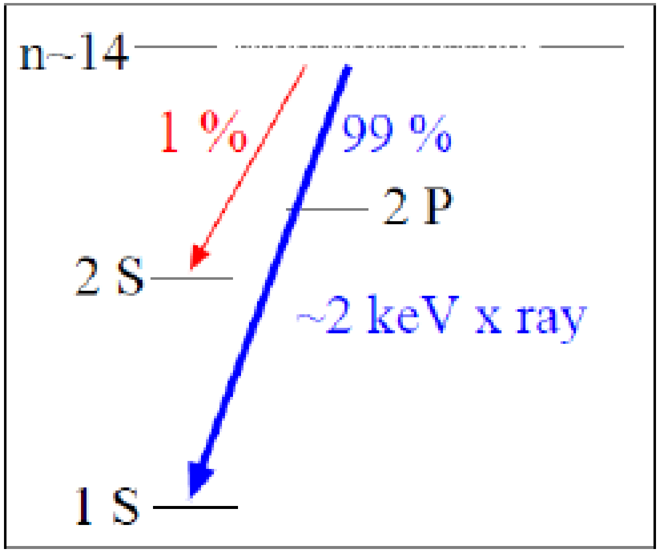
- $\Delta E_L^{th} = 206.0336\ (15) - 5.2275\ r_p^2 + \Delta E_{TPE}$ meV, $\Delta E_{TPE} = 0.0332\ (20)\ meV$

Lamb shift in muonic atom (μp-atom)

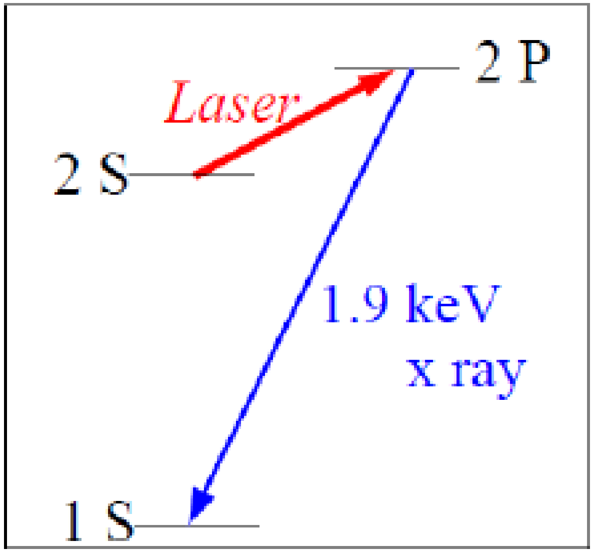
Experiment at PSI

A.Antognini et al. Science 339, 417 (2013)

Muon stop in Hydrogen gas

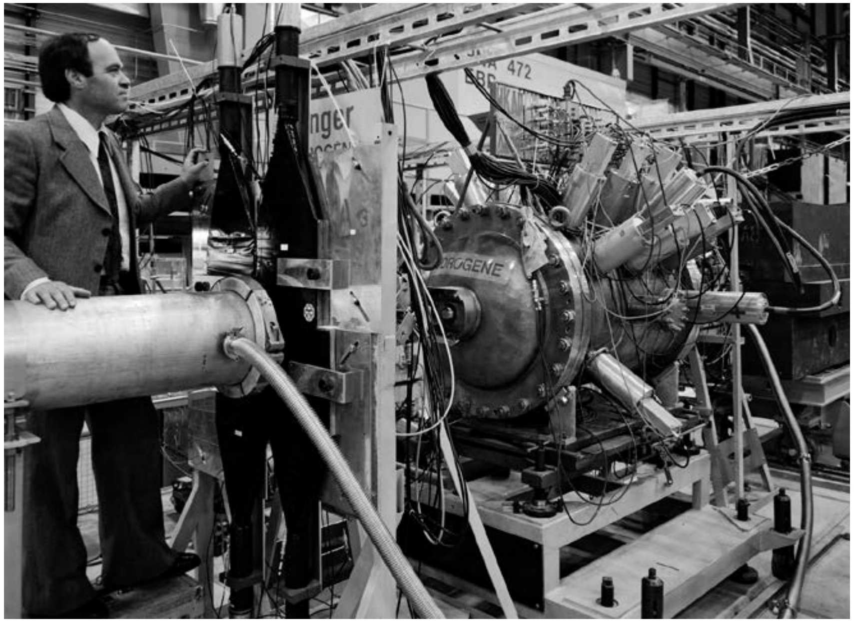


2S → 2P transfer

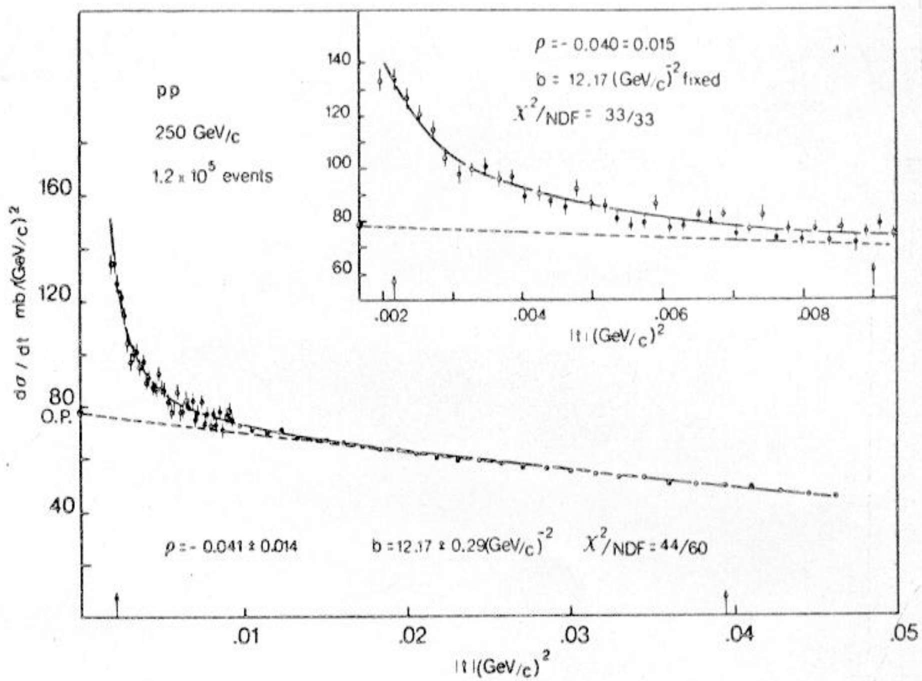


The proposed experiment is based on
the recoiled proton detection method
which was used in WA9 and NA8 experiments
at CERN to measure small angle pp- and πp- scattering.

Nuclear Physics B217 (1983) 285-335



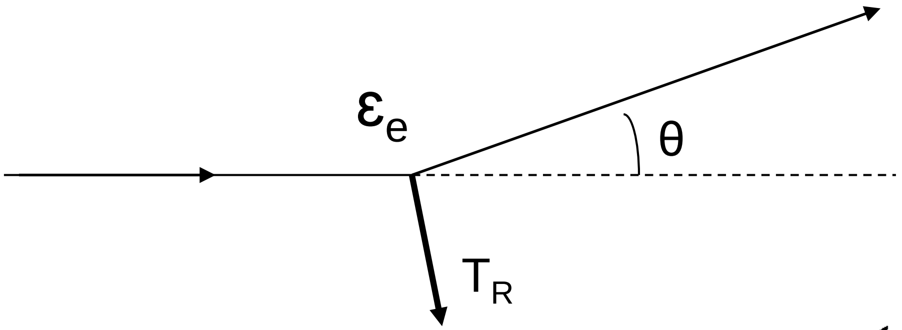
Recoiled proton detector ICAR at CERN



H_2 10 bar TPC

Q^2 scale self-calibration

-t scale self-calibration

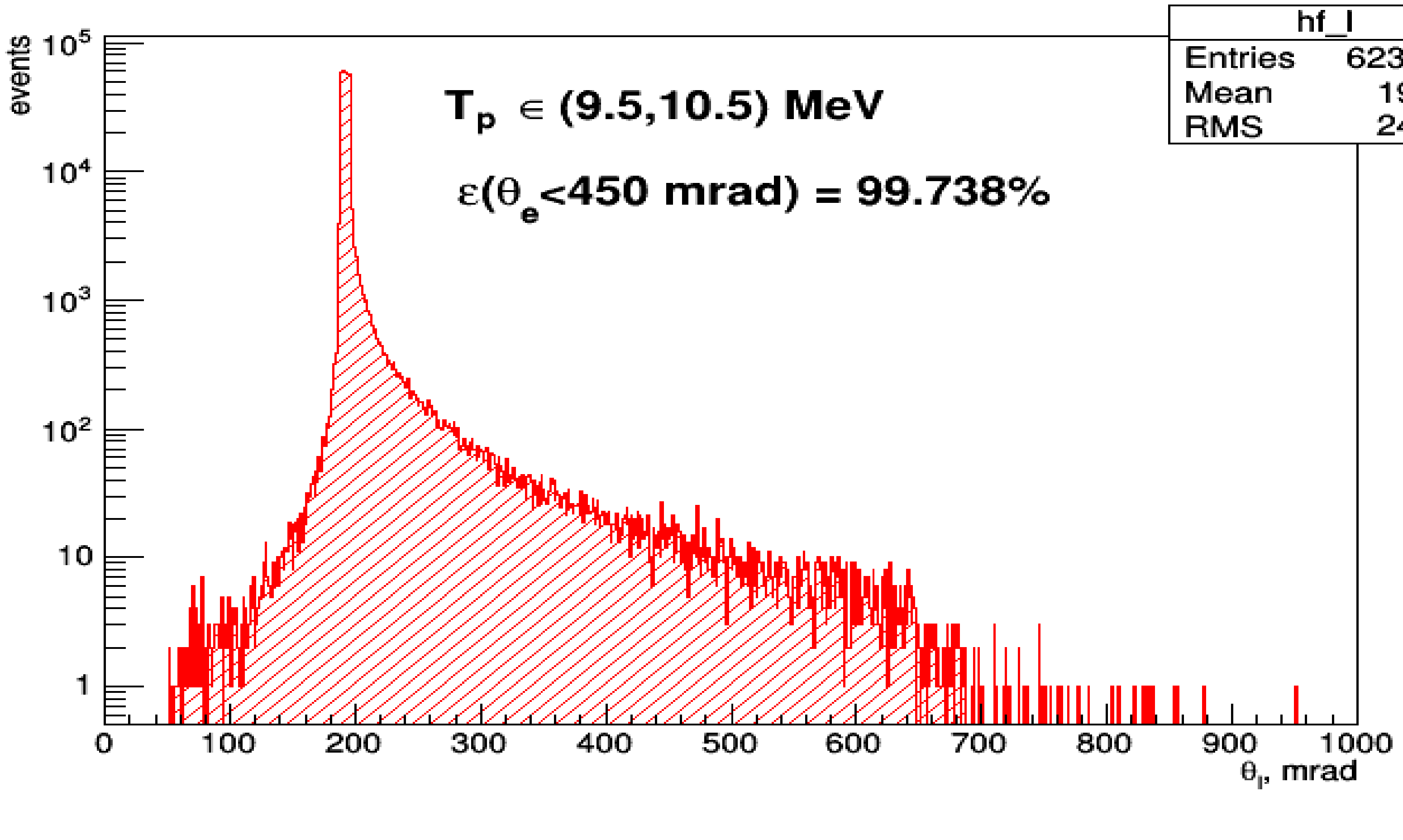


$$-t = \frac{4\varepsilon_e^2 \sin^2 \frac{\vartheta}{2}}{1 + \frac{2\varepsilon_e}{M} \sin^2 \frac{\vartheta}{2}}$$

Ɛe – electron energy in the collision point

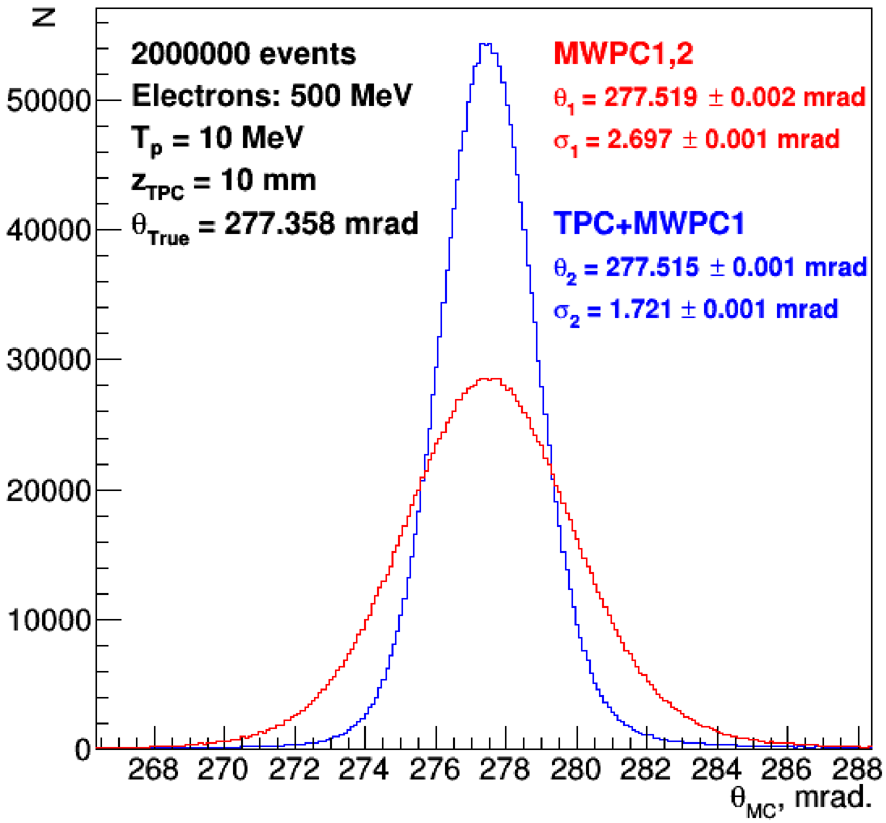
$$-t = 2MT_R$$

Electron angular distribution corresponding to a selected bin in recoil proton energy $9.5\ \mathrm{MeV} < T_R < 10.5\ \mathrm{MeV}$



T_R scale calibration via T_R- θ_e correlation

Without correction for the electron energy loss in TPC

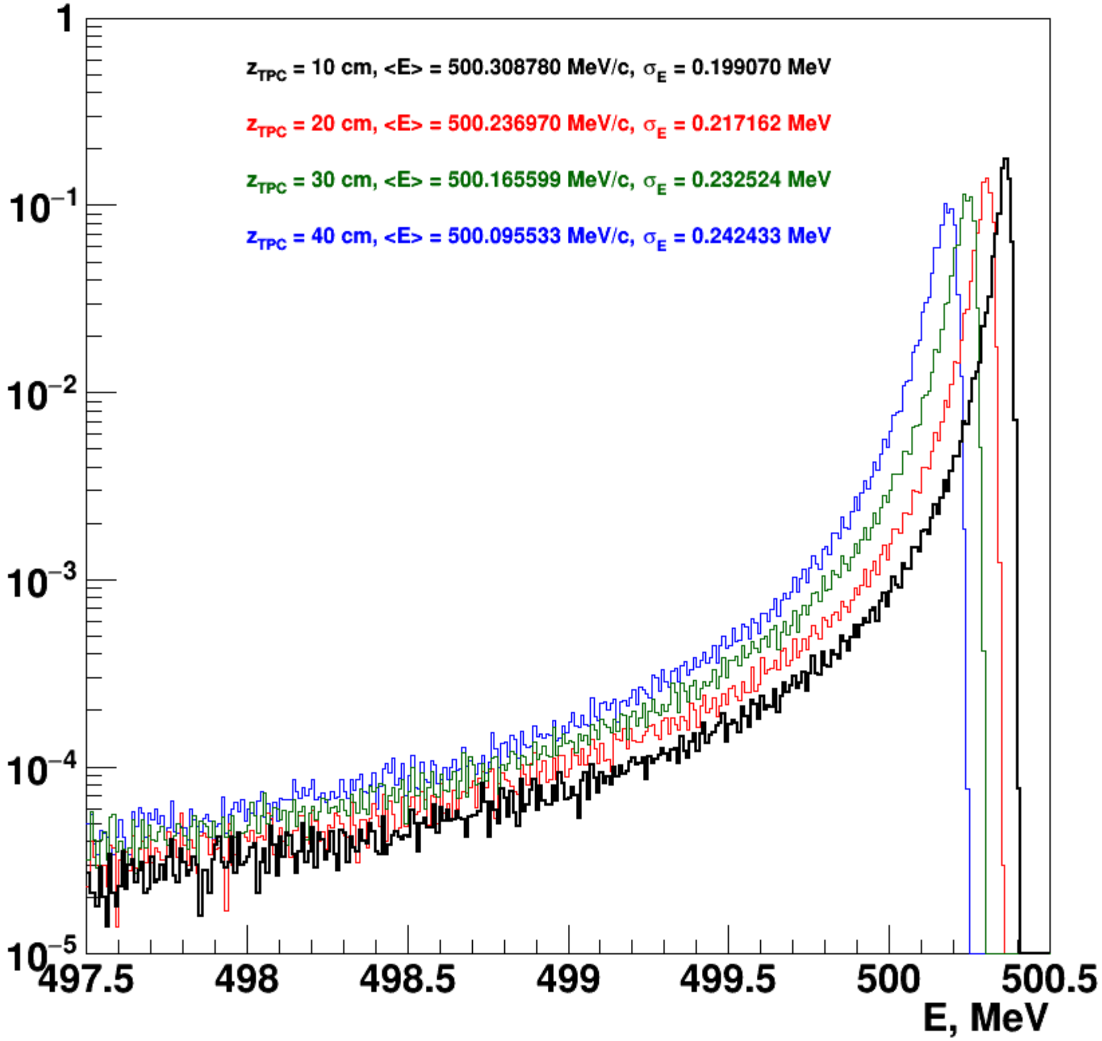


$T_R^*(E_0, \theta_e) / T_R = 1 + 1.2 \cdot 10^{-3}$

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

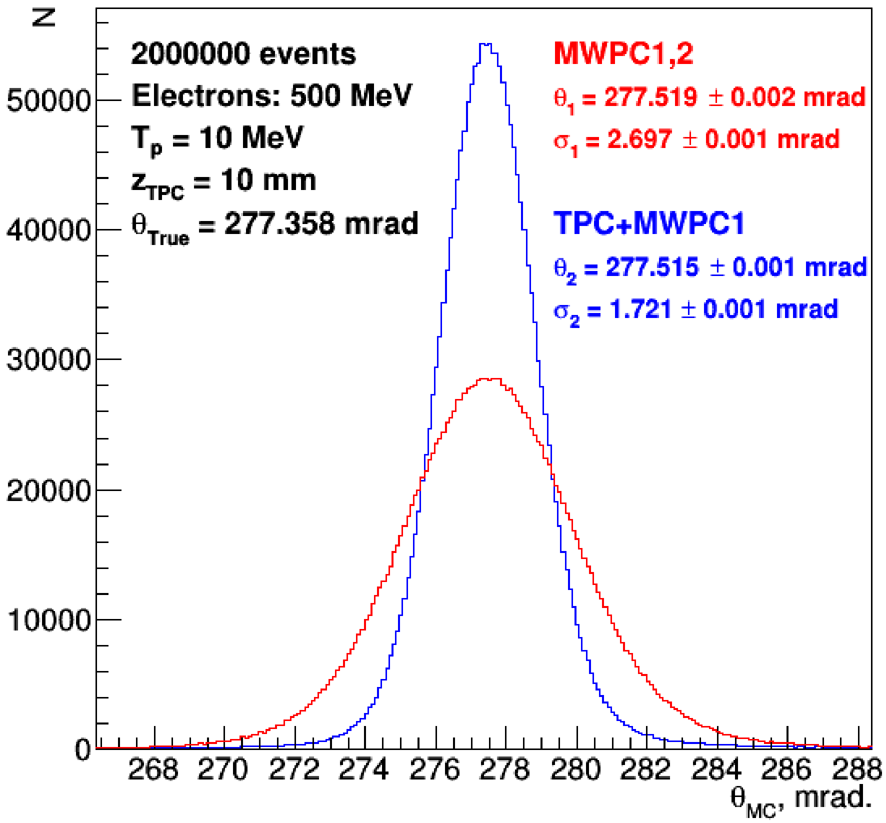
Electron energy in the collision point

GIANT4 calculation



T_R scale calibration via T_R- θ_e correlation

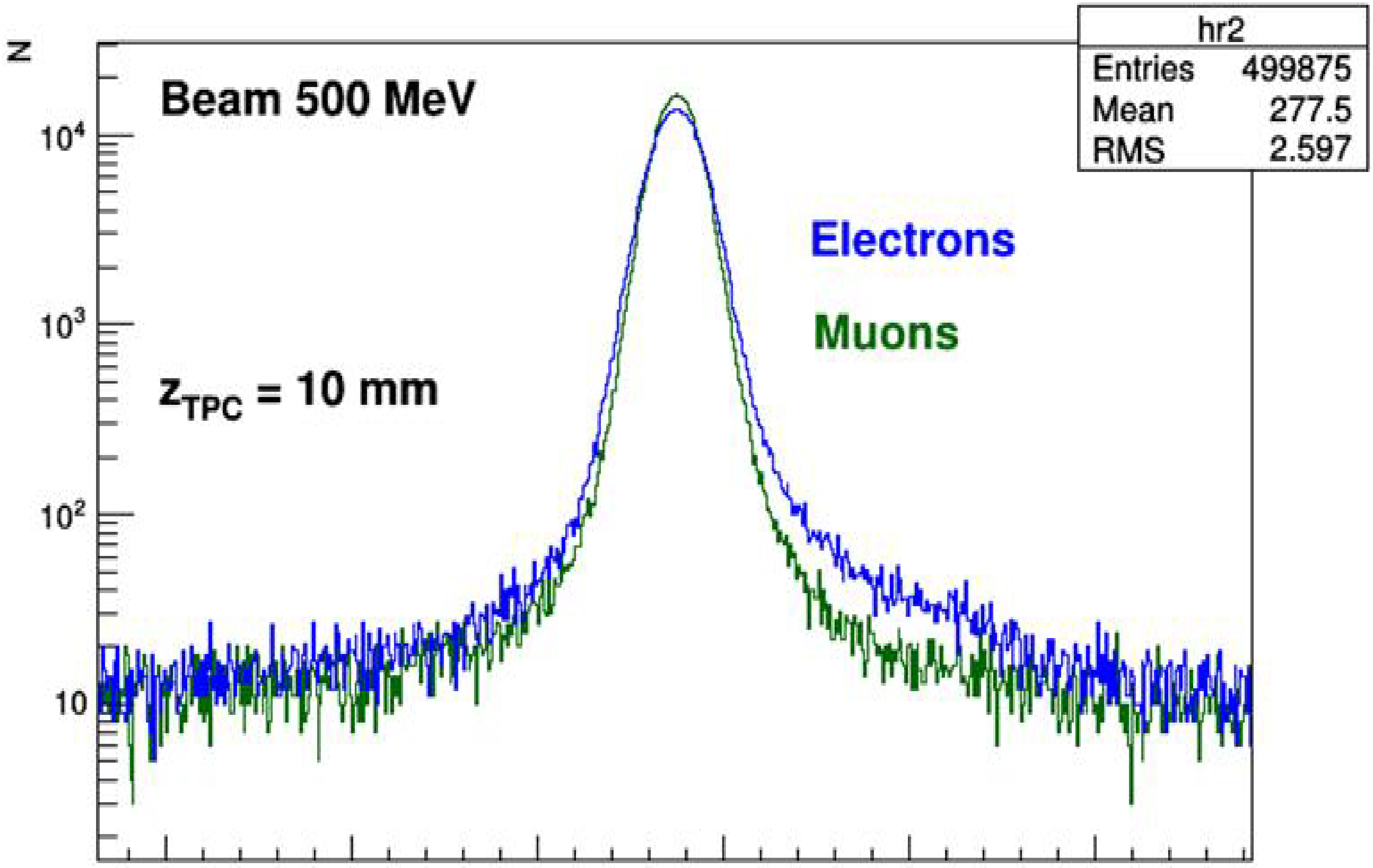
With correction for the electron energy loss in TPC



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

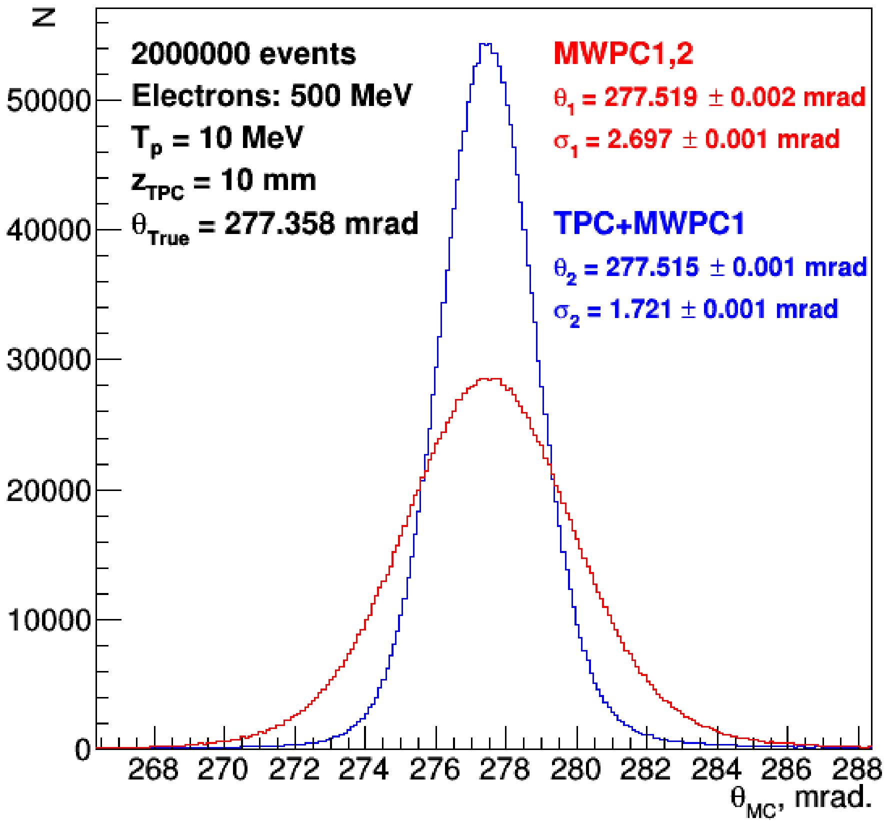
T_R*(E*,θ_e) /T_R = 1+ $3.8\cdot10^{-4}$

Peak asymmetry due to radiation tail



T_R scale calibration via T_R- θ_e correlation

With correction for the electron energy loss in TPC
and correction for asymmetry due to radiation tail



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

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

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

Letter of Intent for a European Proton Radius Network (EuPCR*Net*)

D. Marchand (CNRS/IPN Orsay), R. Pohl (JGU Mainz)

Proponent institutions:

- CEA Saclay/DRF/Irfu/Département de Physique Nucléaire, France; contact person: N. D’Hose,
- CNRS, France; contact persons: D. Marchand (Institut de Physique Nucléaire d’Orsay - IPN Orsay) and J.-Ph. Karr (Laboratoire Kastler Brossel - LKB),
- ETH Zurich, Switzerland; contact person: A. Antognini, P. Crivelli,
- Hebrew University, Jerusalem, Israel; contact person: G. Ron,
- Johannes Gutenberg-Universität (JGU) Mainz, Germany; contact persons: M. Ostrick, R. Pohl, M. Vanderhaeghen,
- Johann Wolfgang Goethe Universität Frankfürt, Germany; contact person: R. Grisenti,
- Jožef Stefan Institute, Ljubljana, Slovenia; contact persons: M. Mihovilovič, S. Sirca,
- LaserLaB VU Amsterdam, Vrije Universiteit, Amsterdam, Netherlands; contact person : W. Vassen,
- Max-Planck Institute of Quantum Optics (MPQ), Garching, Germany; contact persons: T.W. Hänsch, Th. Udem, S. Karshenboim,
- Technische Universität München, Garching, Germany; contact person: S. Paul,
- Universitat Autònoma de Barcelona, Spain; contact person: A. Pineda,
- University College of London, London, UK ; contact person: D. Cassidy,
- University of Warsaw, Warszawa, Polska; contact person: Krzysztof Pachucki.

Associated institutions:

- Bogoliubov Laboratory of Theoretical Physics, JINR Dubna, Russia; contact person: V. Korobov,
- George Washington University, Washington DC, USA; contact person: A. Afanasev,
- Massachusetts Institute of Technology, Cambridge, MA, USA; contact person: J. Bernauer,
- North Carolina A&T State University, Greensboro, NC, USA; contact person: A. Gasparian,
- Rutgers, The State University of New Jersey, Piscataway, NJ, USA; contact person: R. Gilman,
- **Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia; contact person: A. Vorobyov,**