Прецизионное измерение радиуса протона

Проект эксперимента

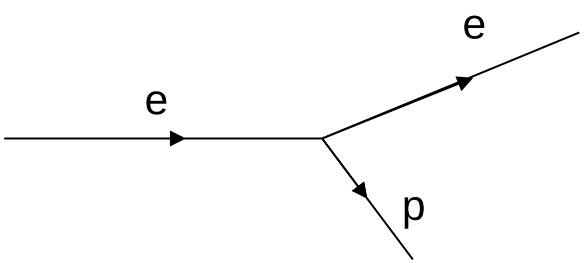
А. А. Воробьев

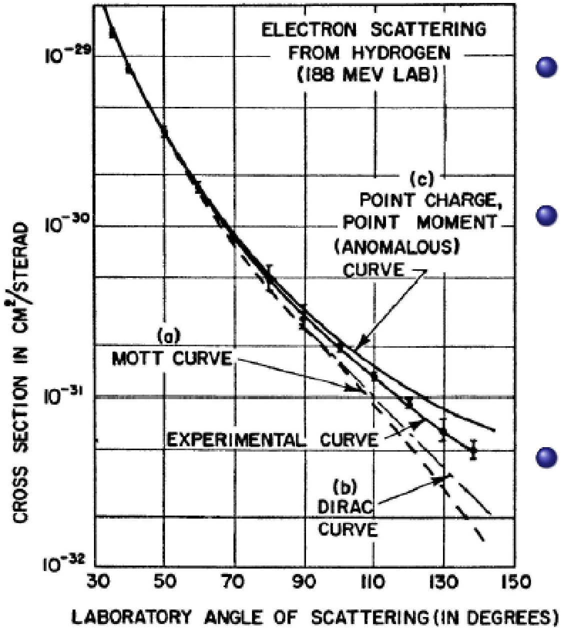
Ученый Совет ПИЯФ 18 Мая 2016

1955 Протон имеет размер !!!

Hofstadter, McAlister

Рассеяние электрона на протоне

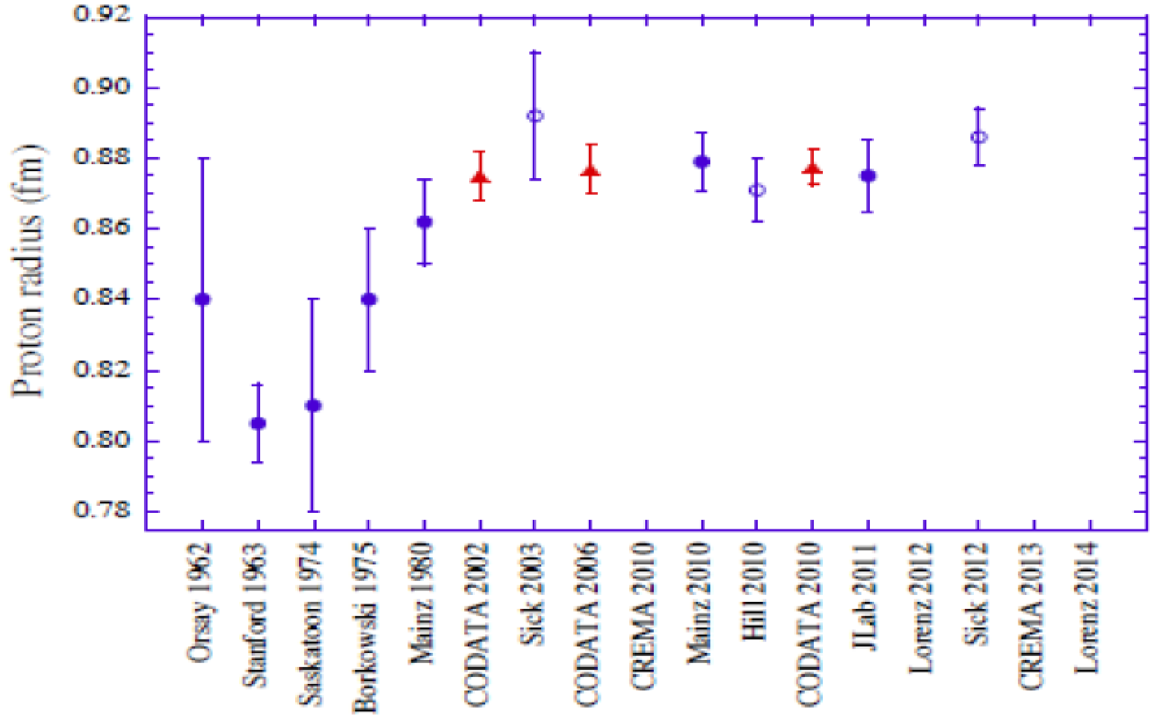




$r_p = 0.80 \pm 0.04$ fm Hofstadter et al (1958)

Нобелевская премия 1961 г.

Ep-scattering 1962-2014

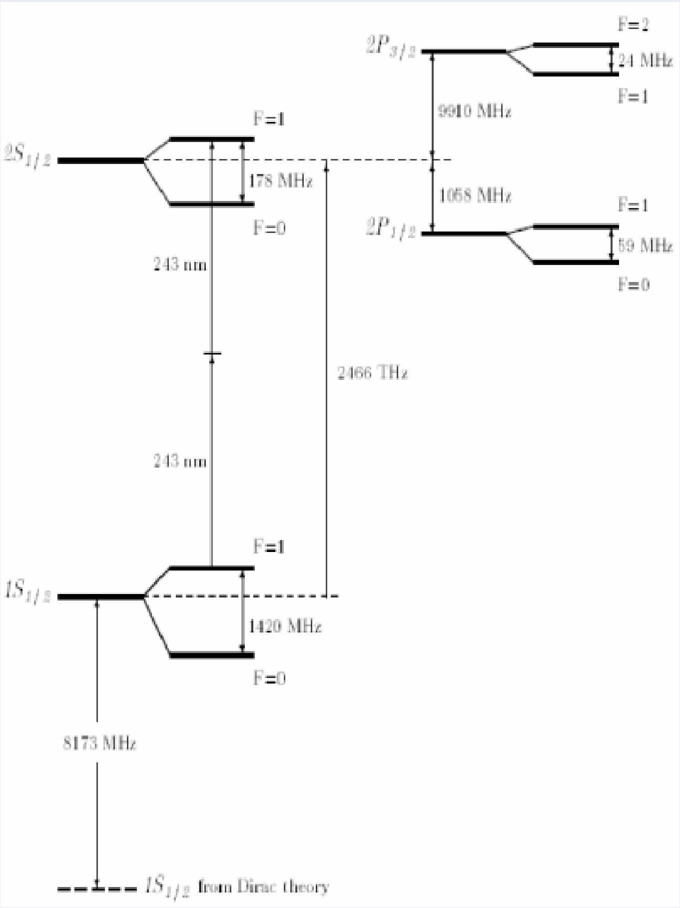


- Electron-proton scattering:
  1. $r_p = \mathbf{0.879(8)\ fm}$, *Mainz, A1 Collaboration, 2010*
  2. $r_p = \mathbf{0.875(10)\ fm}$, *JLab, Zhan et al, 2011*

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

Lamb shift in hydrogen atom (ep-atom)

Electronic Hydrogen



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

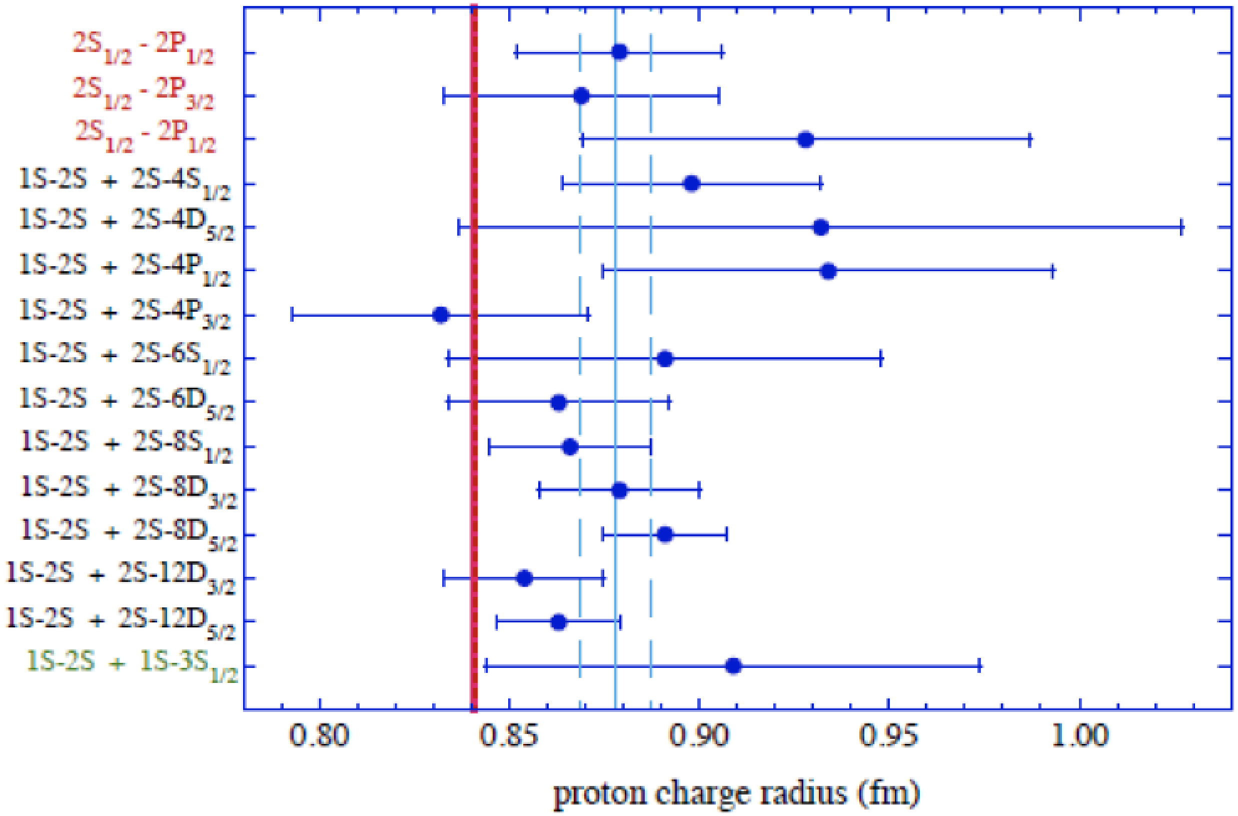
$$L_{nS} = L_{nS}^{(0)} + cr_p^2$$

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

Rydberg constant

R_∞=13.60569253(30)eV…

Lamb shift in hydrogen atom (ep-atom)



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

Ep-scattering @ ep-atom summary

Electron Data

- Electron-proton scattering:
  1. $r_p = \mathbf{0.879(8)}$ **fm**, *Mainz, A1 Collaboration, 2010*
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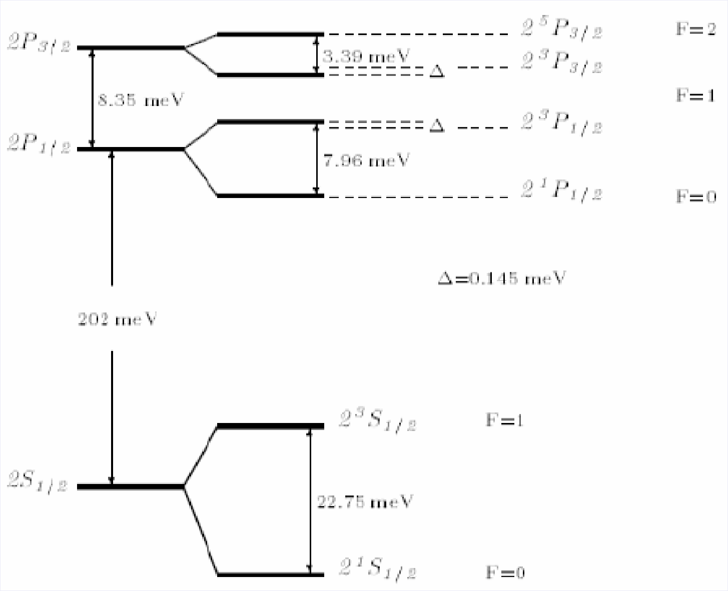
Lamb shift in muonic atom (μp-atom)

Muonic Hydrogen

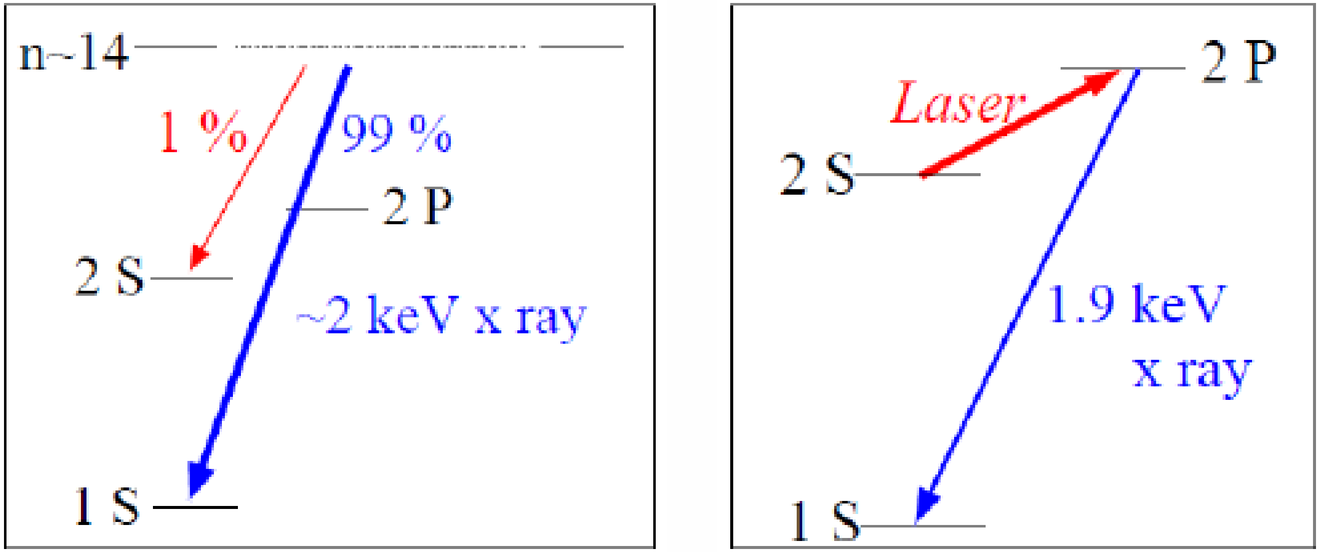


Theoretical Prediction

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

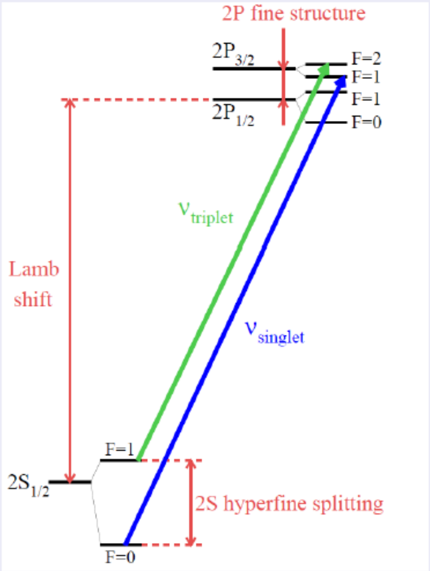
Lamb shift in muonic atom (μp-atom)

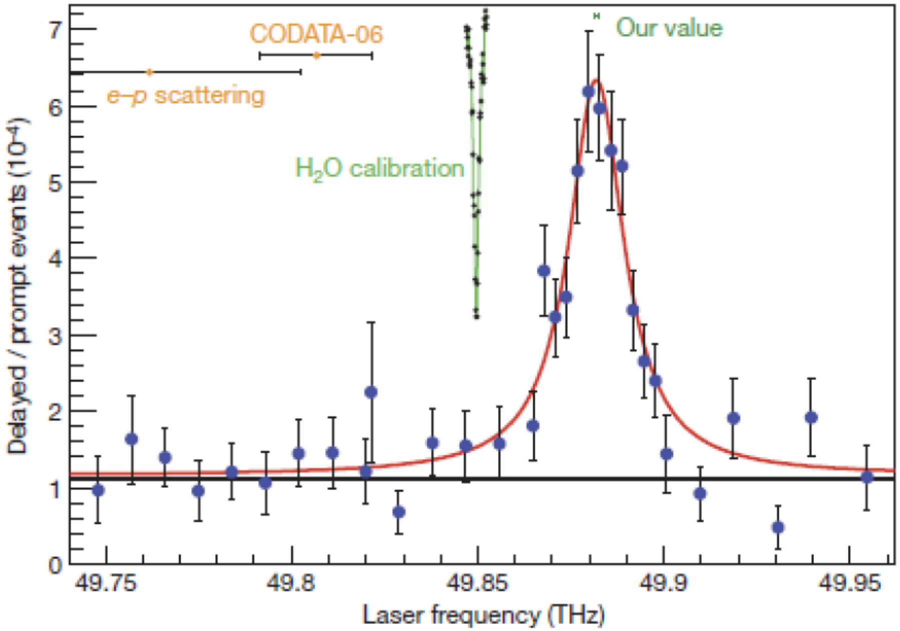
Experiment at PSI   2013



Lamb shift in muonic atom (μp-atom)

Experiment at PSI 2013



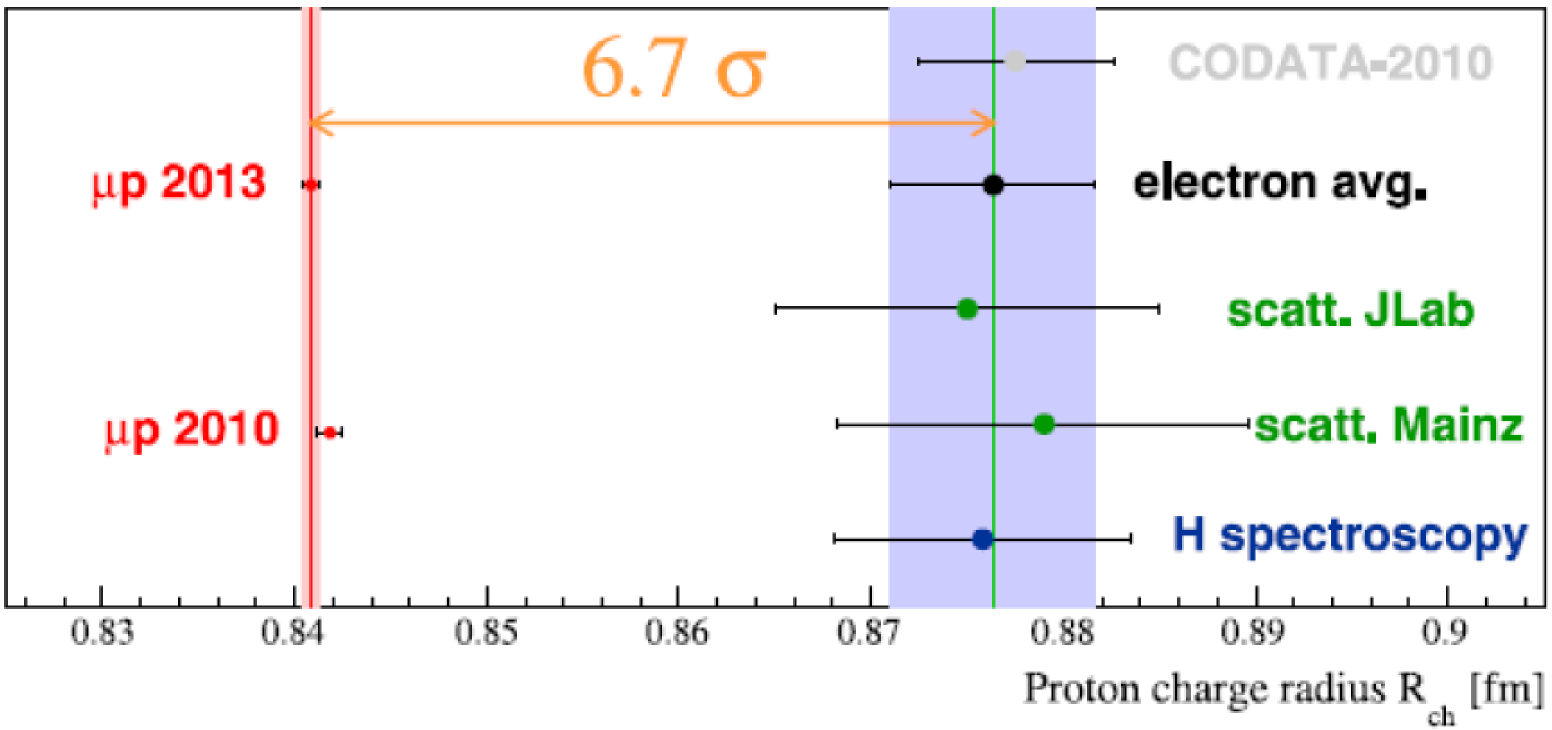


- $\Delta E_L^{exp} = \Delta E(2P_{1/2} - 2S1/2) = 202.3706\ (23)$ meV,

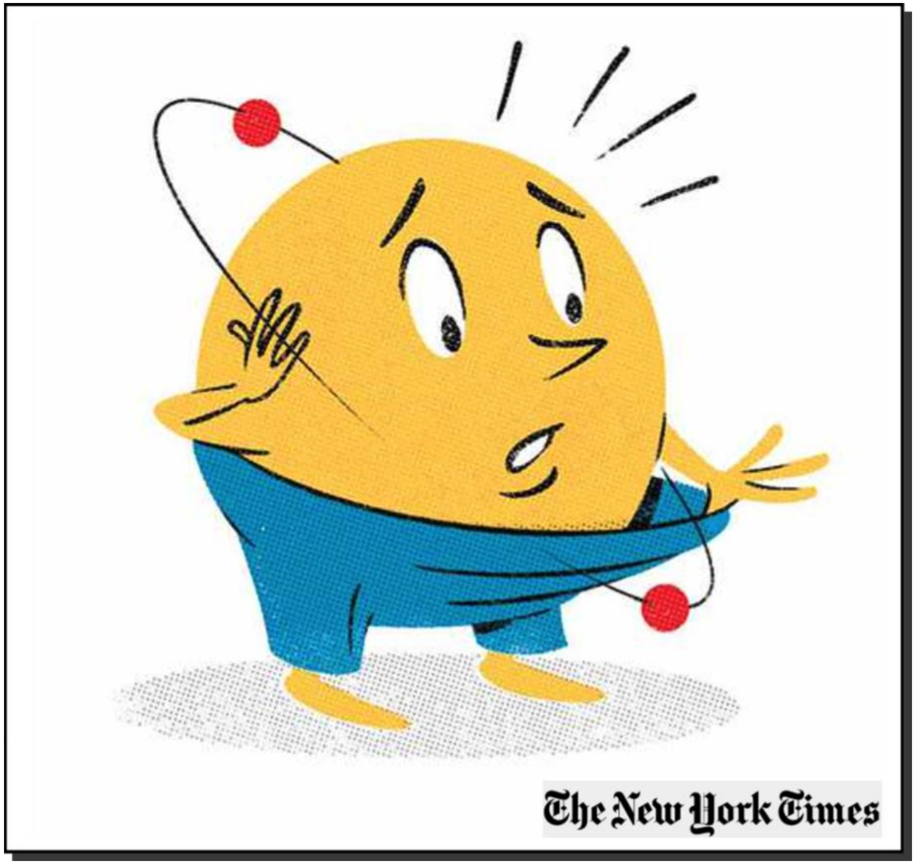
- $\Delta E_L^{th} = 202.042\ (5)$ meV for $r_p = 0.877\ 5\ (51)$ fm
- **Discrepancy:** $\Delta = E_{exp} - E_{th} = 0.33\ (6)$ meV

$\boxed{\text{Rp} = 0.8409(4)}$

Proton charge radius status 2016



Proton radius puzzle

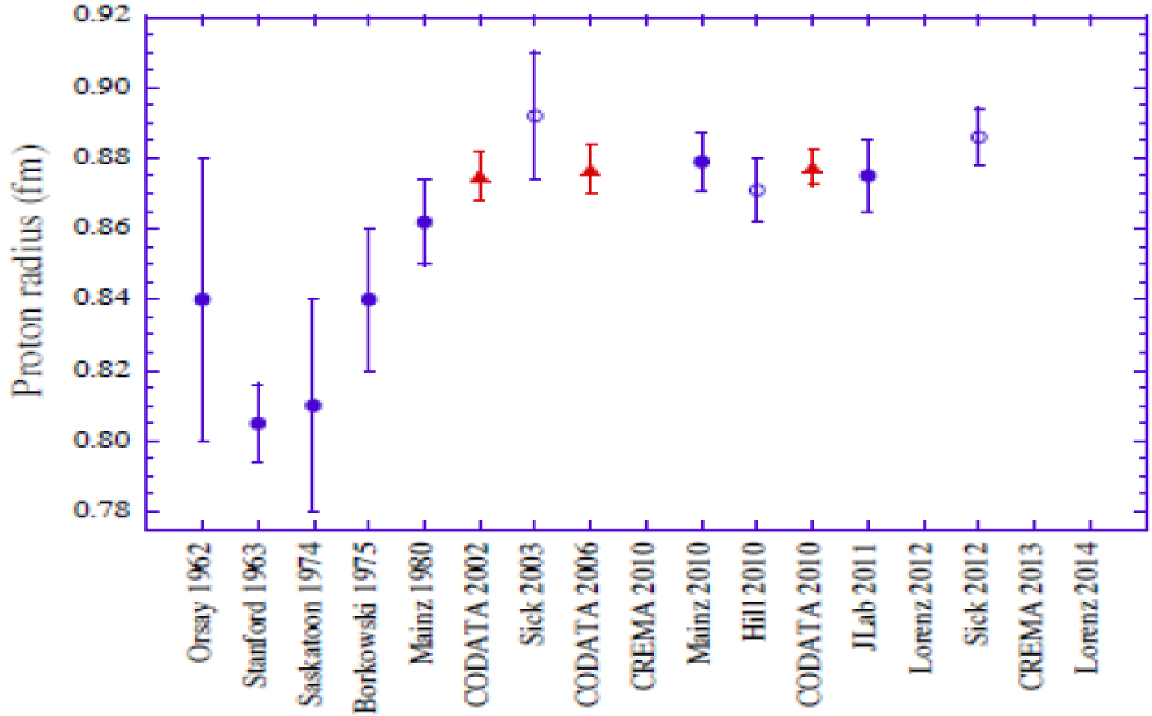


Rp = 0.877 fm
or
Rp =0.841 fm
???

Возможные объяснения

- Ошибки в экспериментах
- Нарушение лептонной универсальности (новая физика)

Ep-scattering 1962-2014



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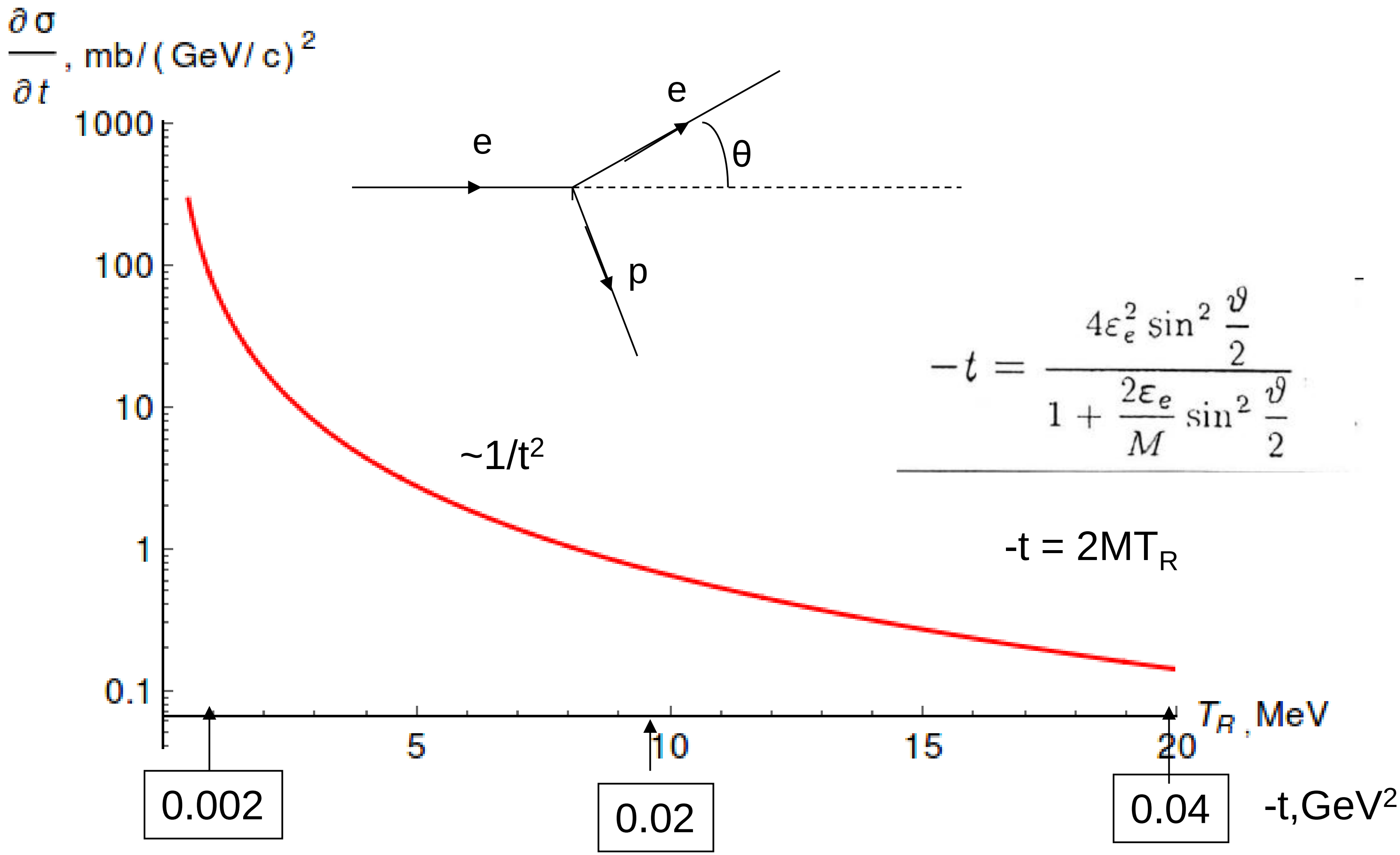
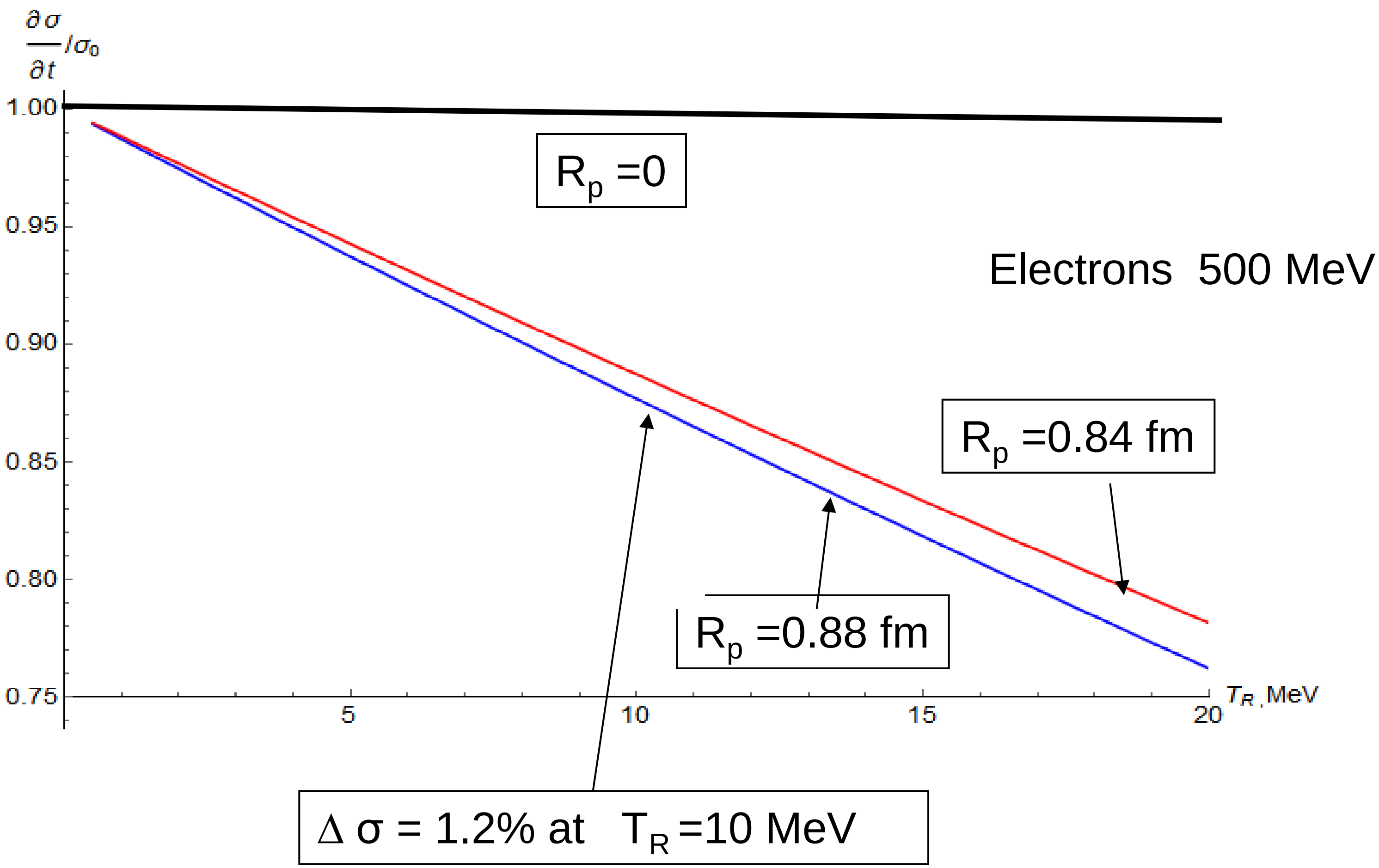
Extraction of proton radius from differential e-p cross section



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

$-t = 2MT_R$

Чему соответствует разница в радиусе протона Rp=0.84 fm and Rp=0.88 fm



Чтобы надежно различить варианты Rp=0.87 фм и Rp=0.84 фм, нужно измерить сечение в интервале $10^{-3} – 4\cdot10^{-2}$ ГэВ с абсолютной точностью 0.2%

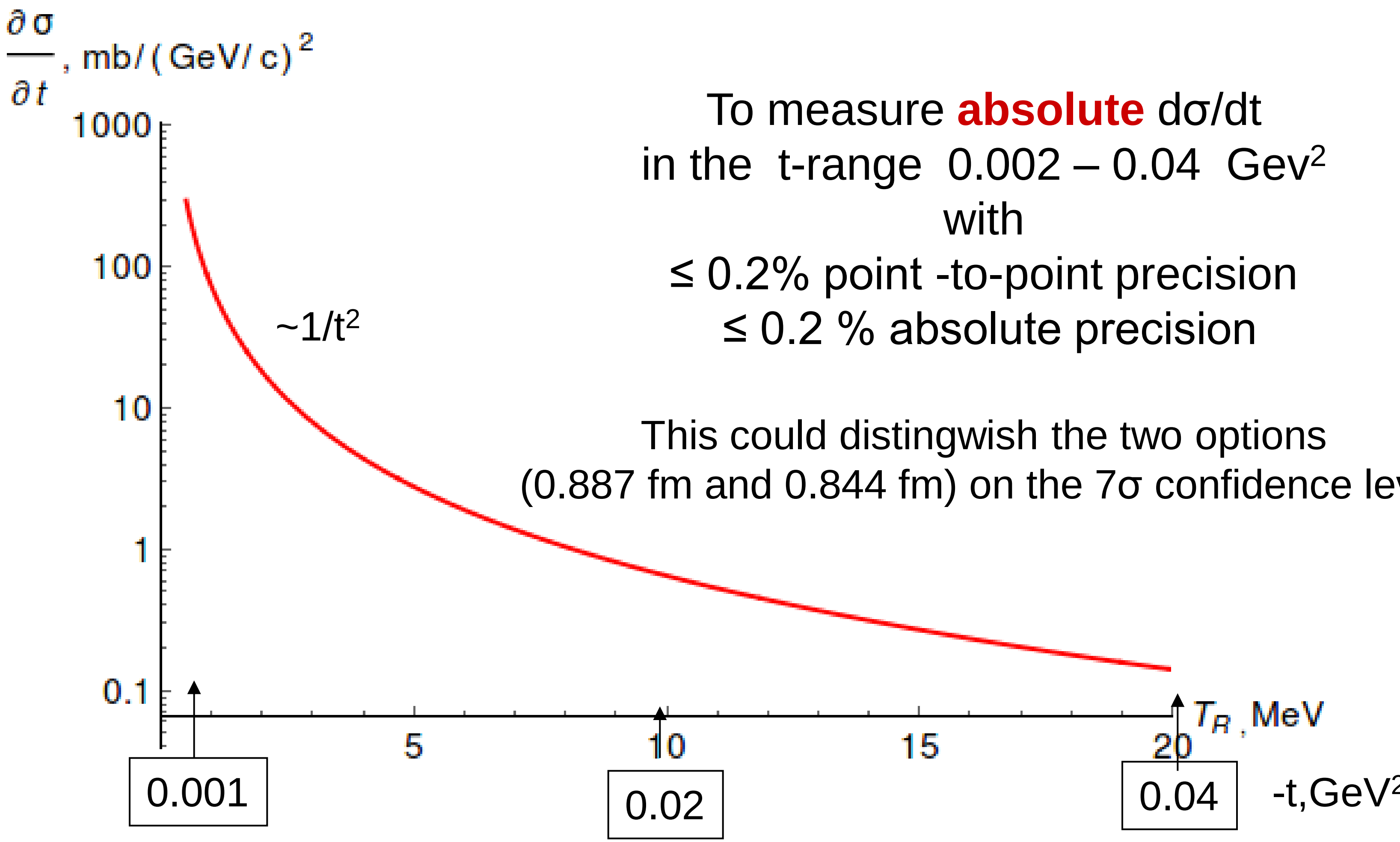
Proposal

for high precision measurements of the e-p differential cross section at small t-values with the recoiled proton detector

PMPS experiment
Precision Measurement of Proton Size

A.Vorobyev
Petersburg Nuclear Physics Institute
Mainz April 6, 2016

The main goal of the proposed experiment



To measure **absolute** dσ/dt
in the t-range 0.002 – 0.04 Gev^2
with
≤ 0.2% point -to-point precision
≤ 0.2 % absolute precision

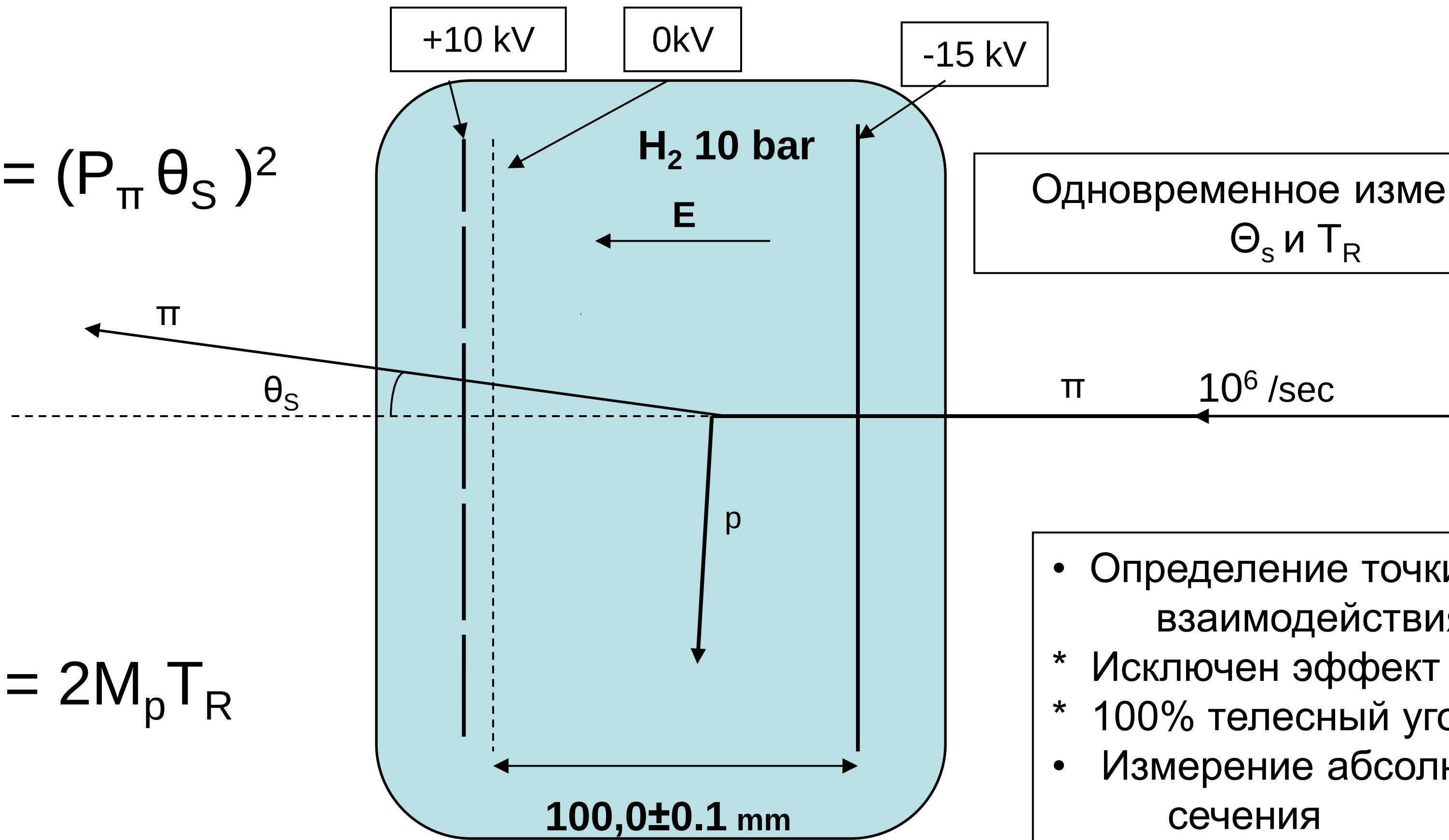
This could distingwish the two options
(0.887 fm and 0.844 fm) on the 7σ confidence level

$-t = 2MT_R$

Детектор ИКАР в экспериментах WA9/NA8 в ЦЕРН

Active target
Мишень и детектор

$-t = (P_\pi \theta_S)^2$



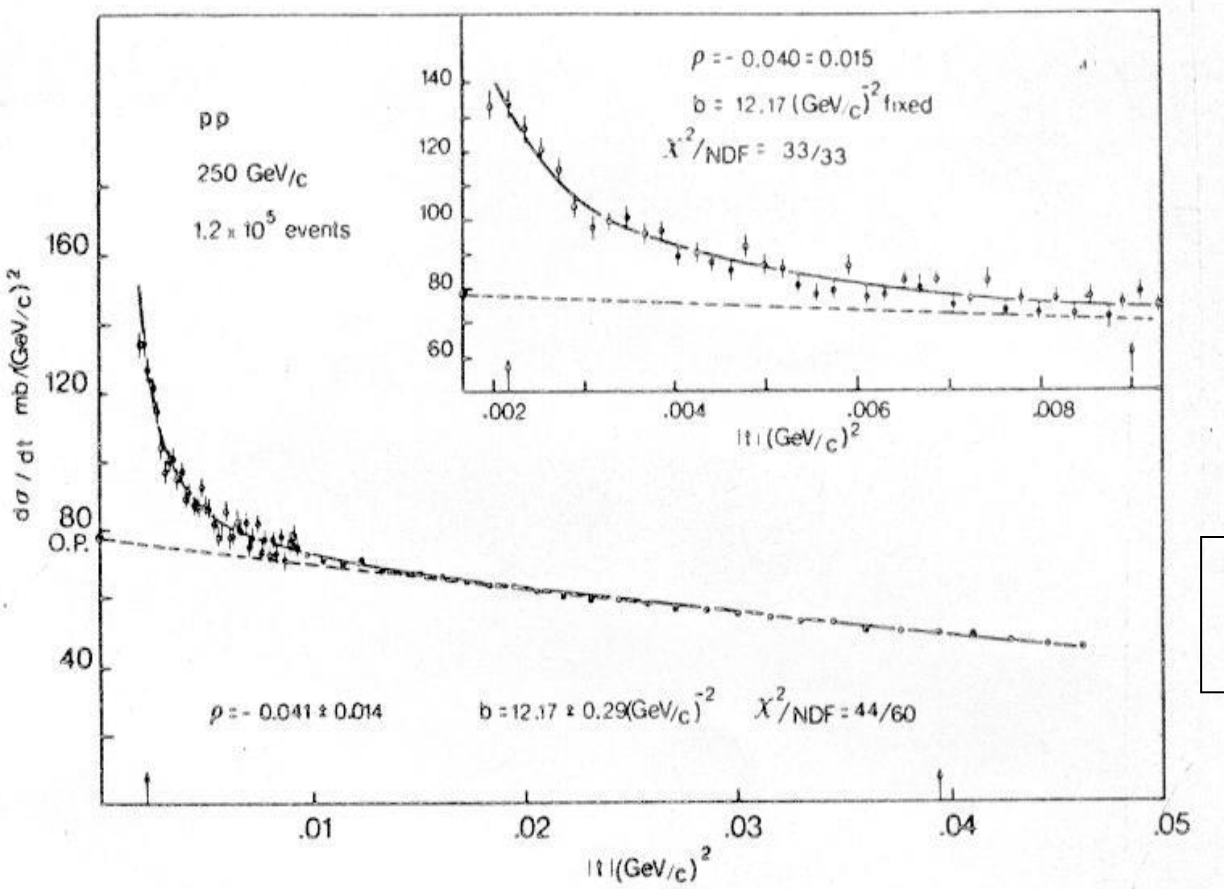
$-t = 2M_p T_R$

Одновременное измерение
Θ_s и T_R

- Определение точки взаимодействия
- * Исключен эффект стенок
- * 100% телесный угол
- Измерение абсолютного сечения

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

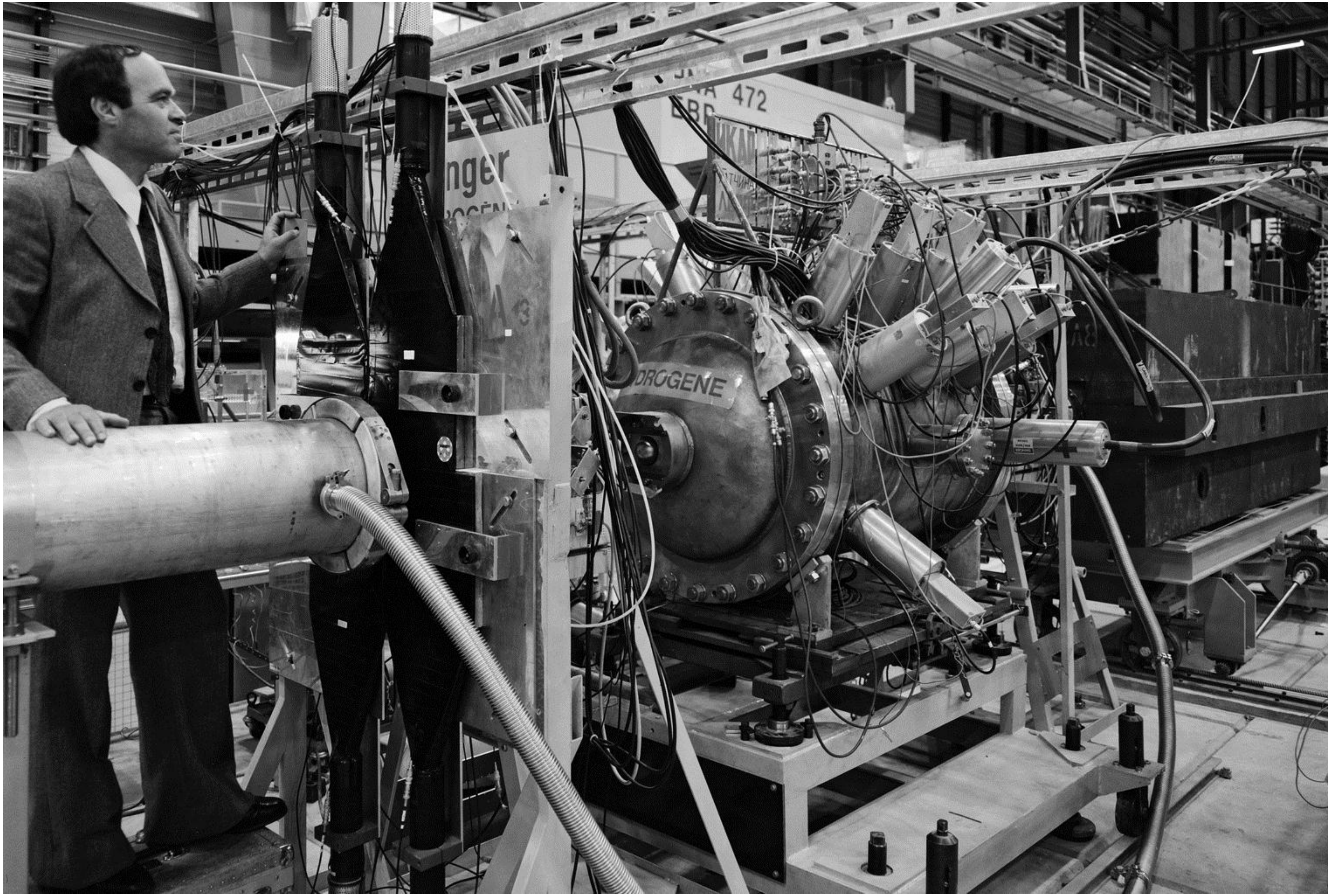
Nuclear Physics B217 (1983) 285-335



ρ= ReA(0)/ImA(0)
b = dσ/dt(t=0)

0.4% T_R-scale calibration

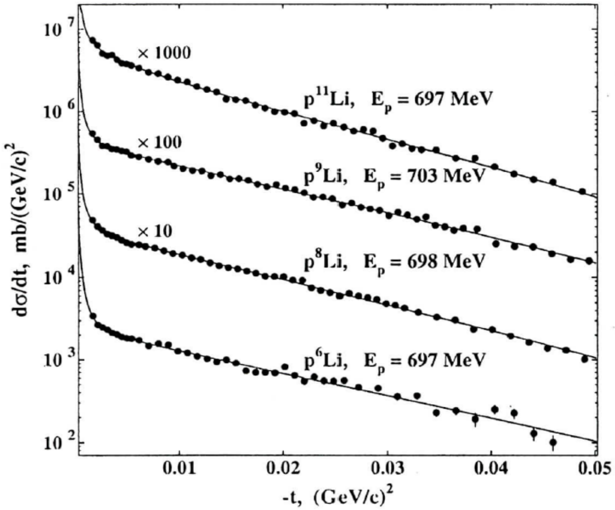
1% absolute precision in dσ/dt

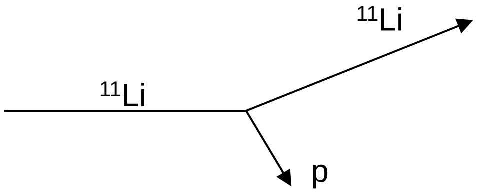


Детектор ИКАР в ЦЕРН

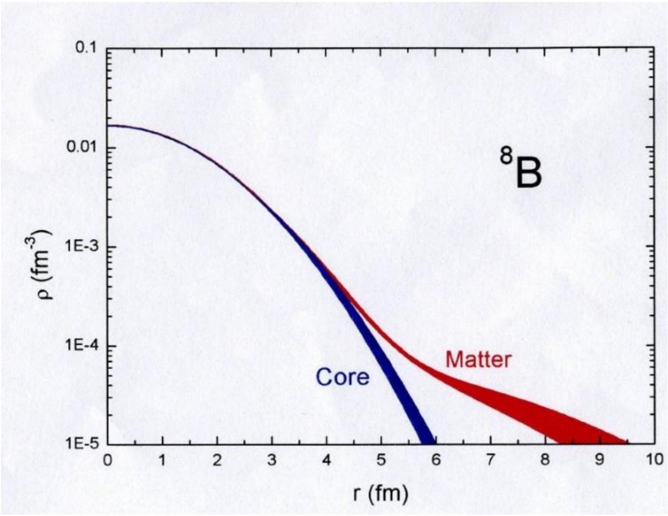
Рассеяние экзотических ядер на протоне

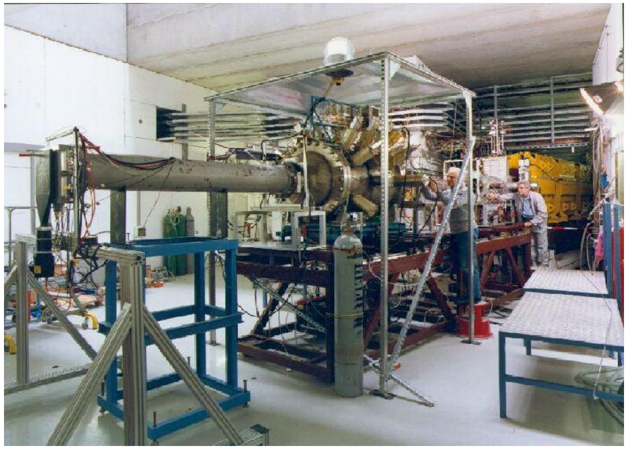
Nuclear Physics A766 (2006)1-24





^{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.

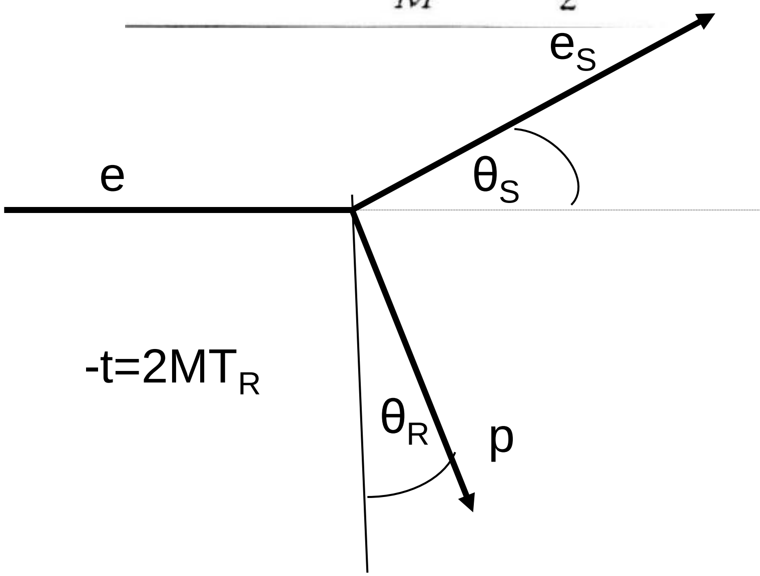




IKAR in GSI

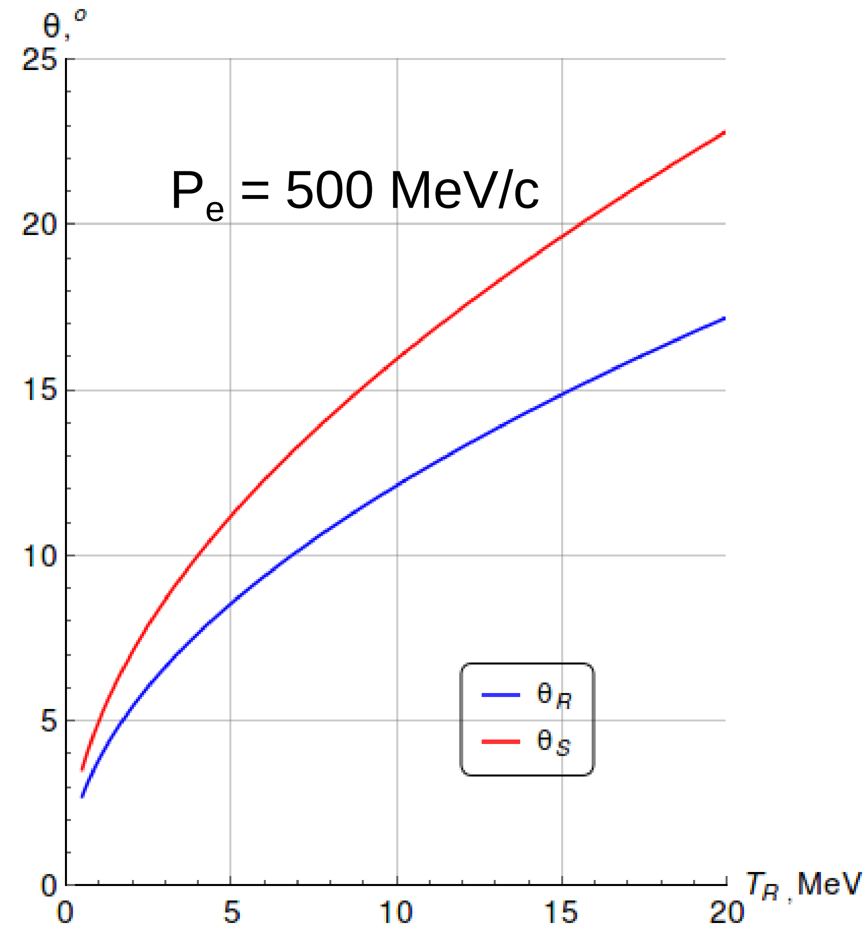
Проблема больших углов рассеяния

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

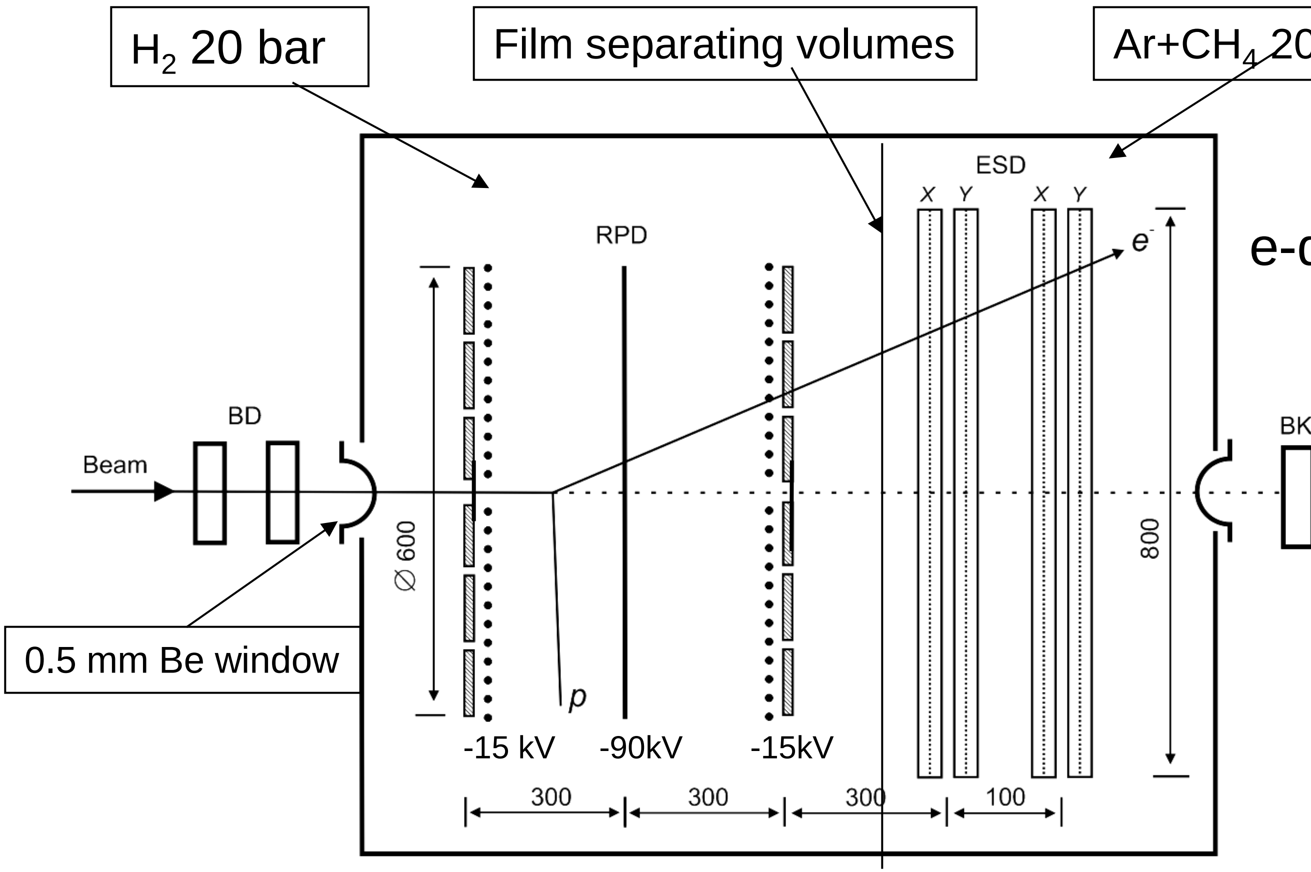


$-t=2MT_R$

$\mathrm{Sin}(\theta_R) = (\varepsilon_e+M)T_R\,/(P_eP_R)$



Combined recoiled proton @ scattering electron detector



e-detection coordinates

$\sigma X = \sigma Y = 30 \mu m$

$\sigma(\theta_S) \leq 5 \cdot 10^{-4}$

Scattering point coordinates

$\sigma X = \sigma Y = 30 \mu m$ (determined by beam telescope)

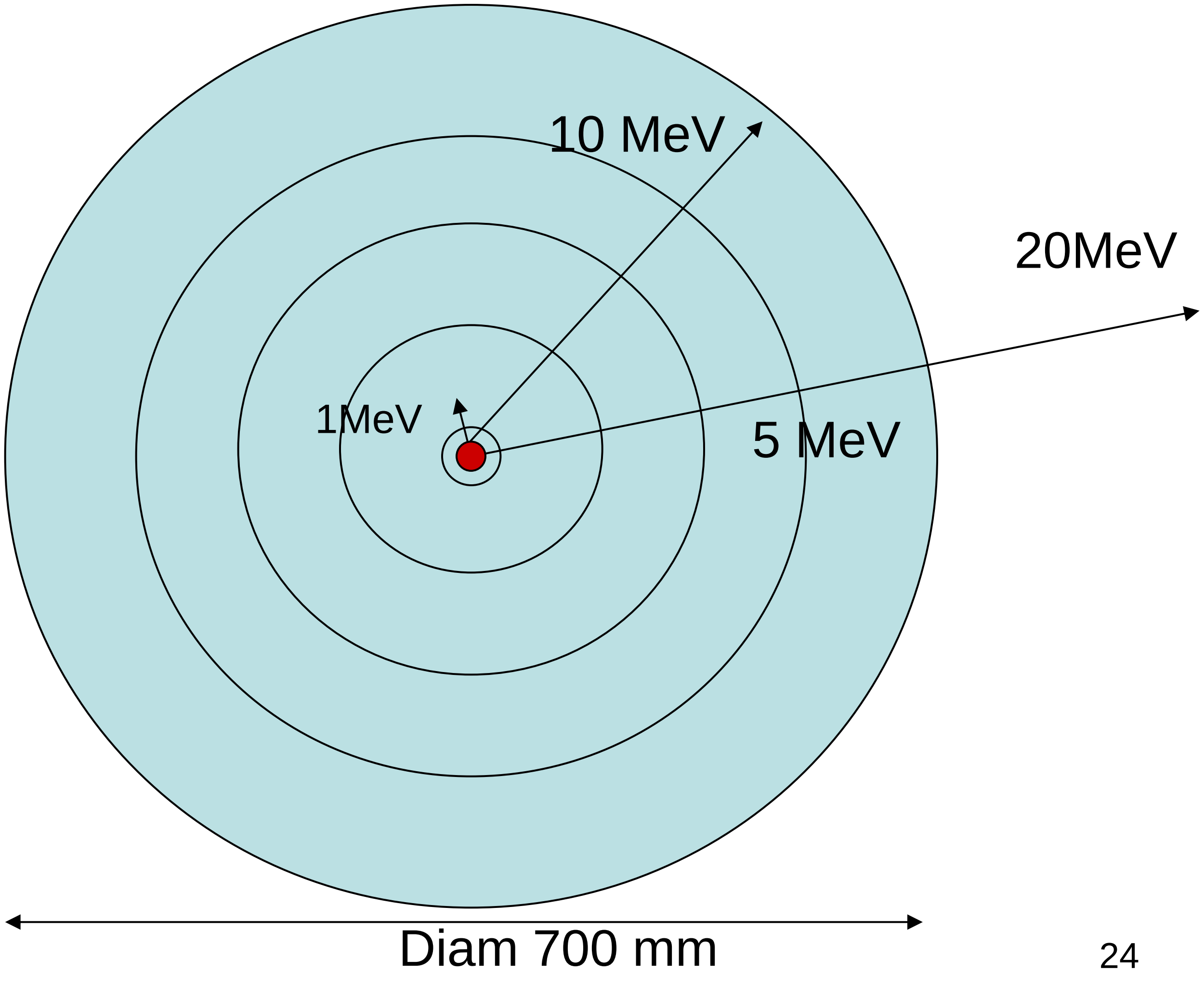
$\sigma Z = 150\ \ \mu m$ (determined by TPC)

Why 20 bar ?

To stop 10 MeV protons inside the sensitive volume.
Also, to increase counting rate.

P=20 bar

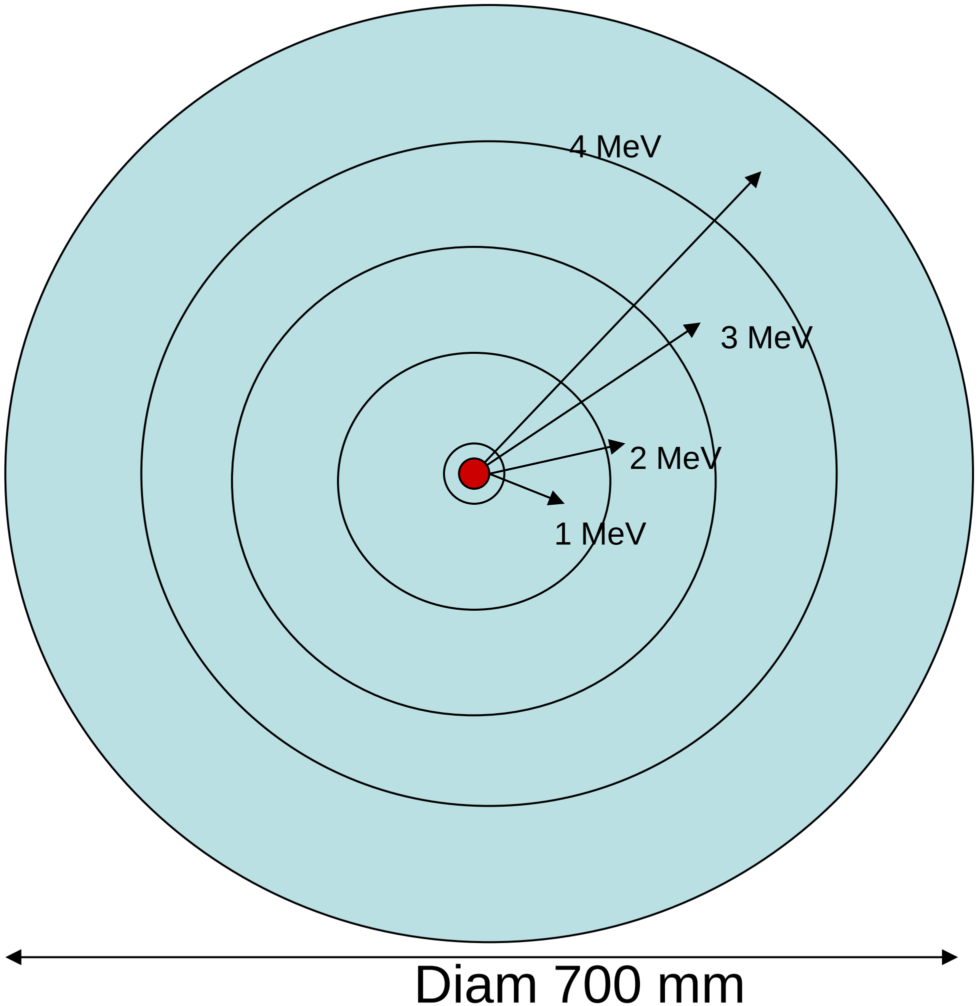
T_R MeV	R mm
1	4,7
2	16
3	33
4	55.5
5	83.5
6	116
7	154
8	196
9	244
10	296



Lower pressure can be used for measurements at the lowest t-values with better T_R resolution

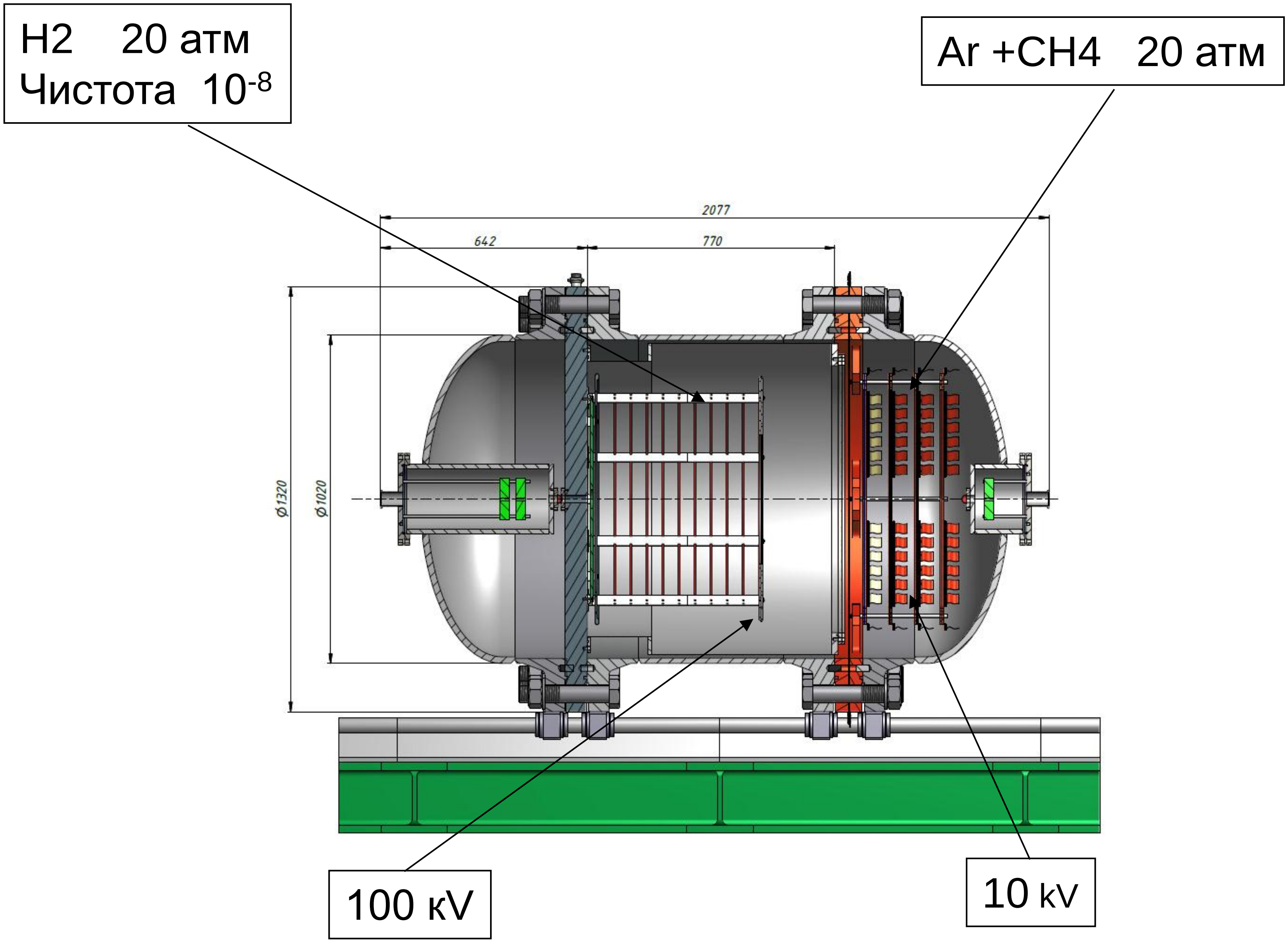
P=4 bar

T_R MeV	R mm
1	23.5
2	80
3	165
4	277

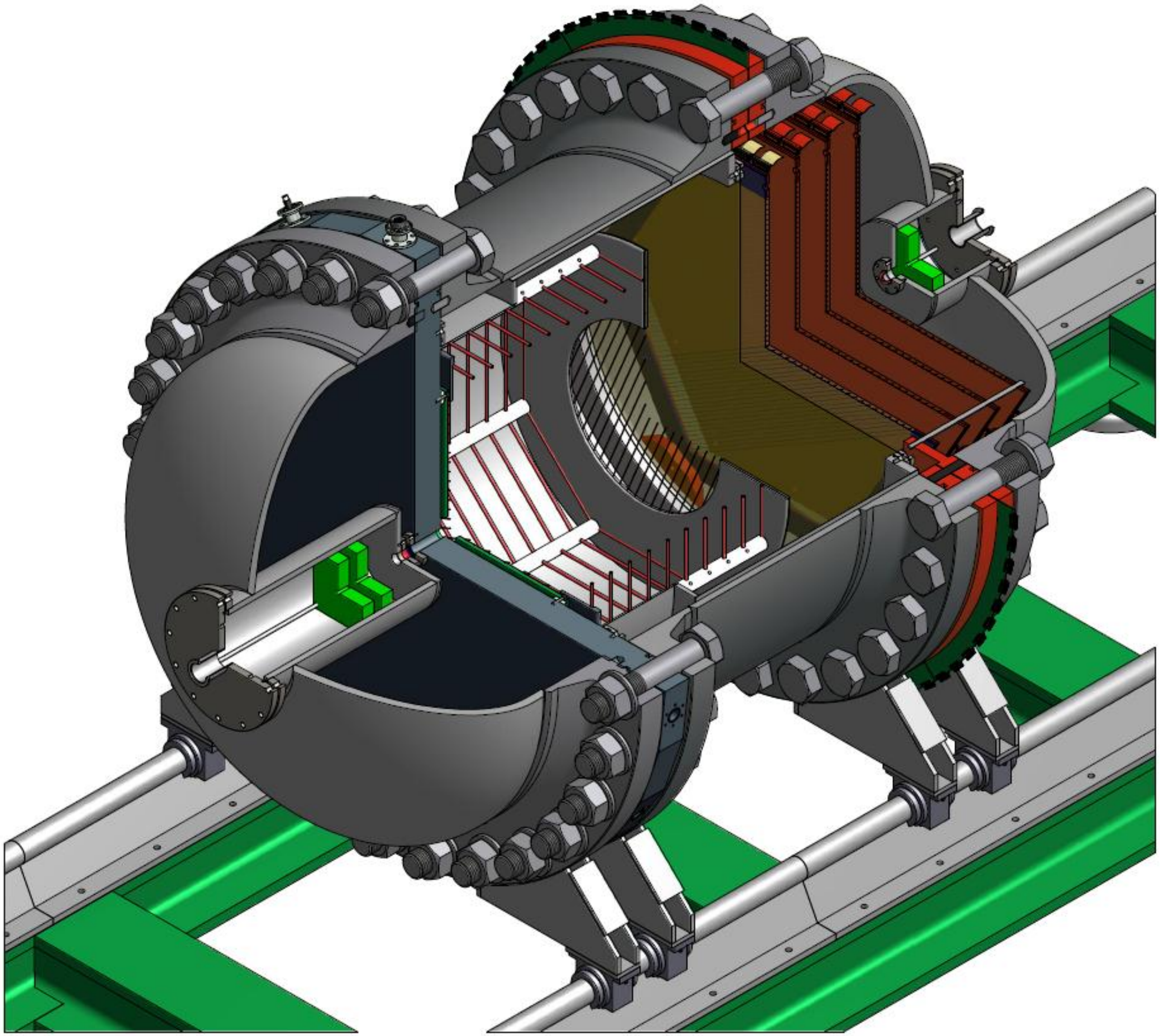


Comparison of the TPC parameters in the WA9/NA8 experiments with those in the proposed experiment

	WA9/NA8 experiments	Proposed experiment
H_2 pressure	10 bar	20 bar, 4 bar
Drift distance, mm	100,0 ± 0.1	400,0 ± 0.1
Drift velocity,mm/200ns	1,000 ± 0,003	1,000 ± 0,001
σ(z-coordinate)	±300μm	±150μm
σ (target thickness)	0.4%	0.1%
σ (T_R)	60 KeV	40 KeV
T_R-scale calibration	0.5%	0.1%



H2 20 атм
Чистота 10^{-8}
Ar +CH4 20 атм
2077
642
770
ø1320
ø1020
100 кV
10 кV

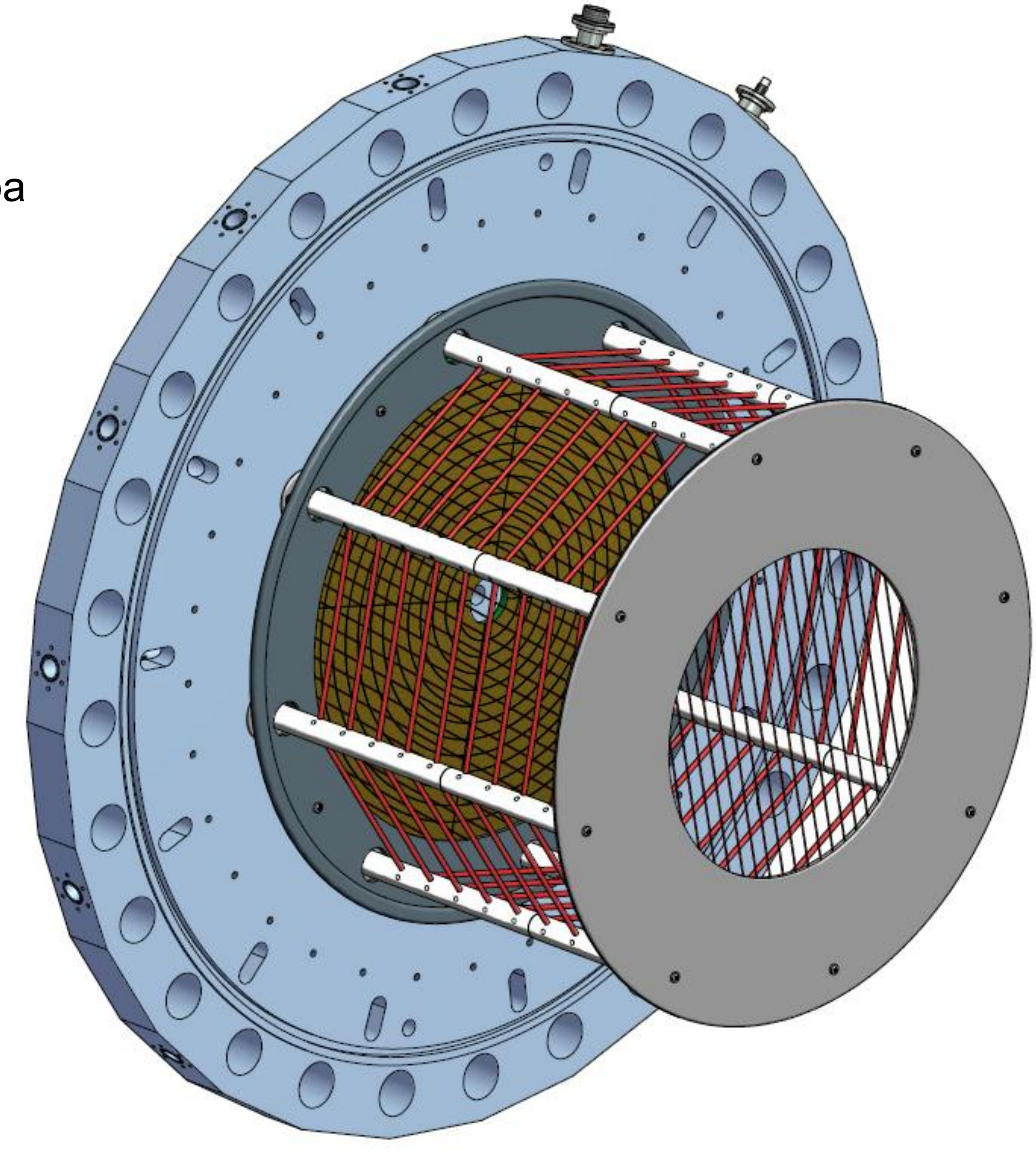


Детектор протонов отдачи

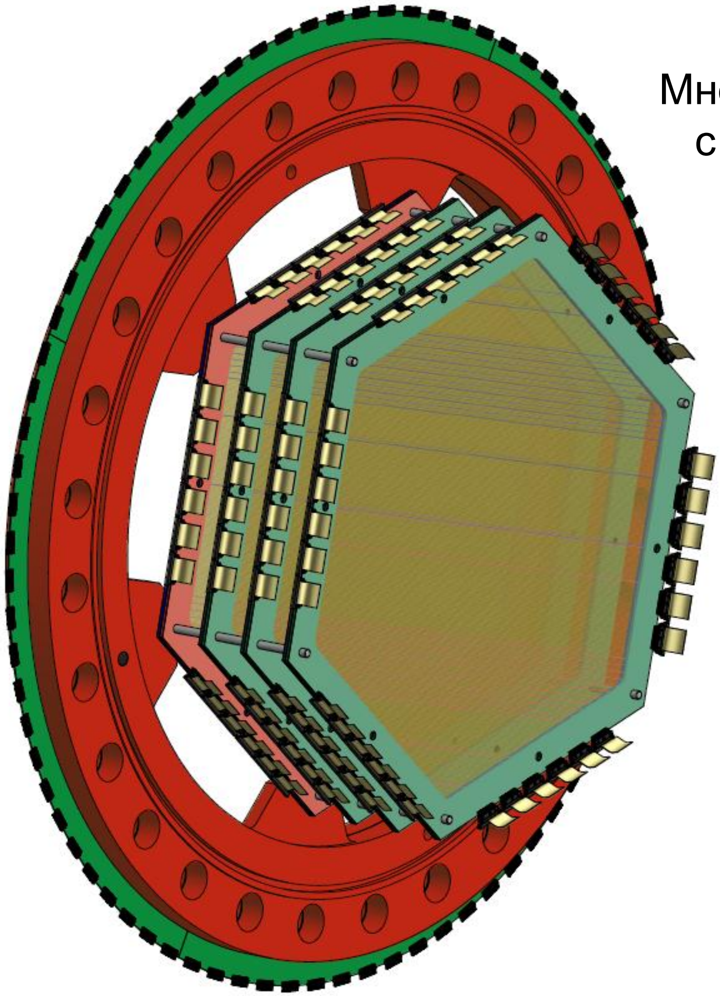
Время-проекционная камера

Диаметр   600 мм
Длина   400 мм

H2   20 атм



Детектор рассеянных электронов



Многопроволочные пропорциональные камеры с катодным съёмом информации

X-Y- X-Y плоскости

800 x 800 мм^2

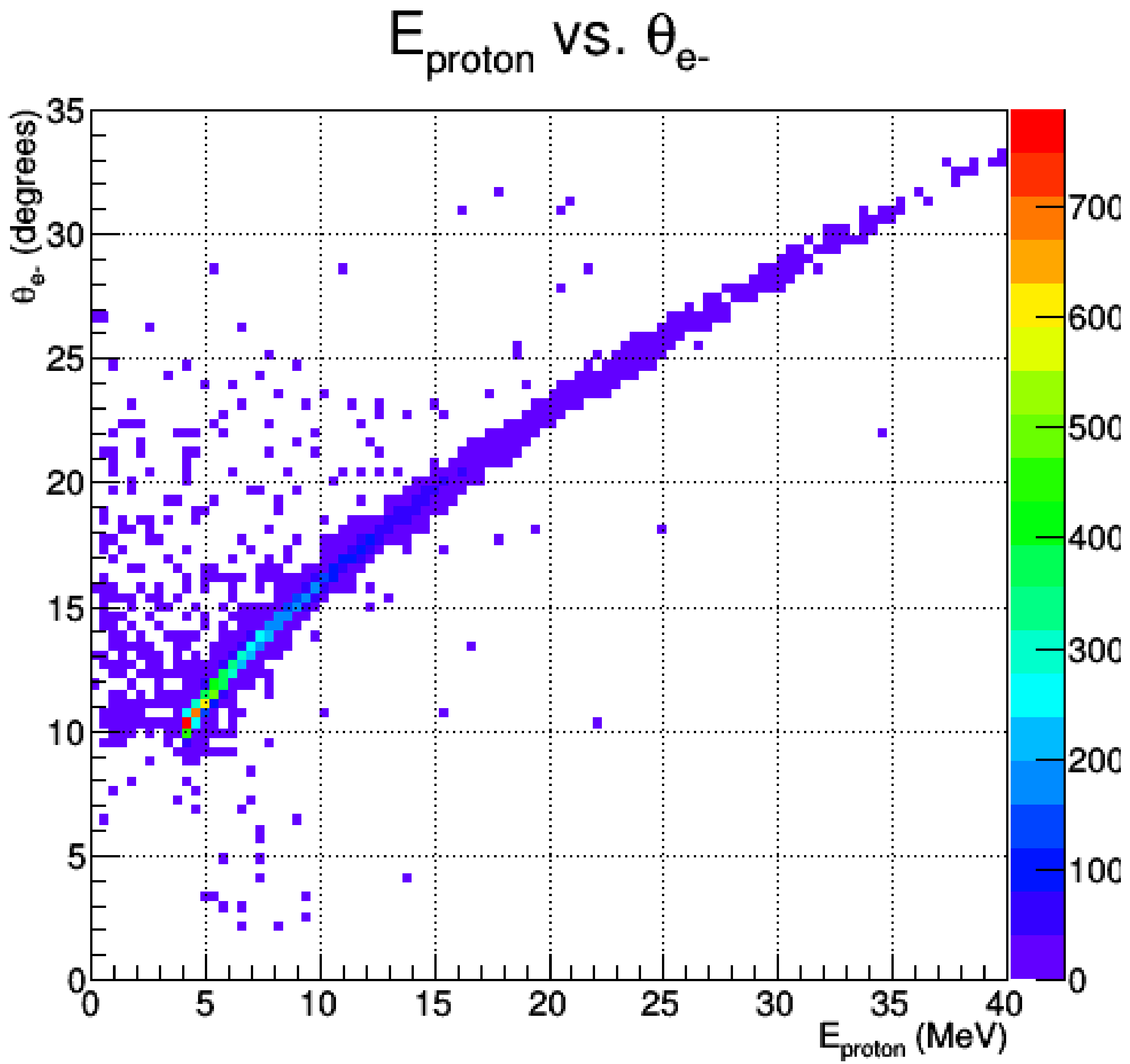
Ar + CH4 20 атм

σX =σY ≈ 20 микрон

Катодные стрипы 2 мм

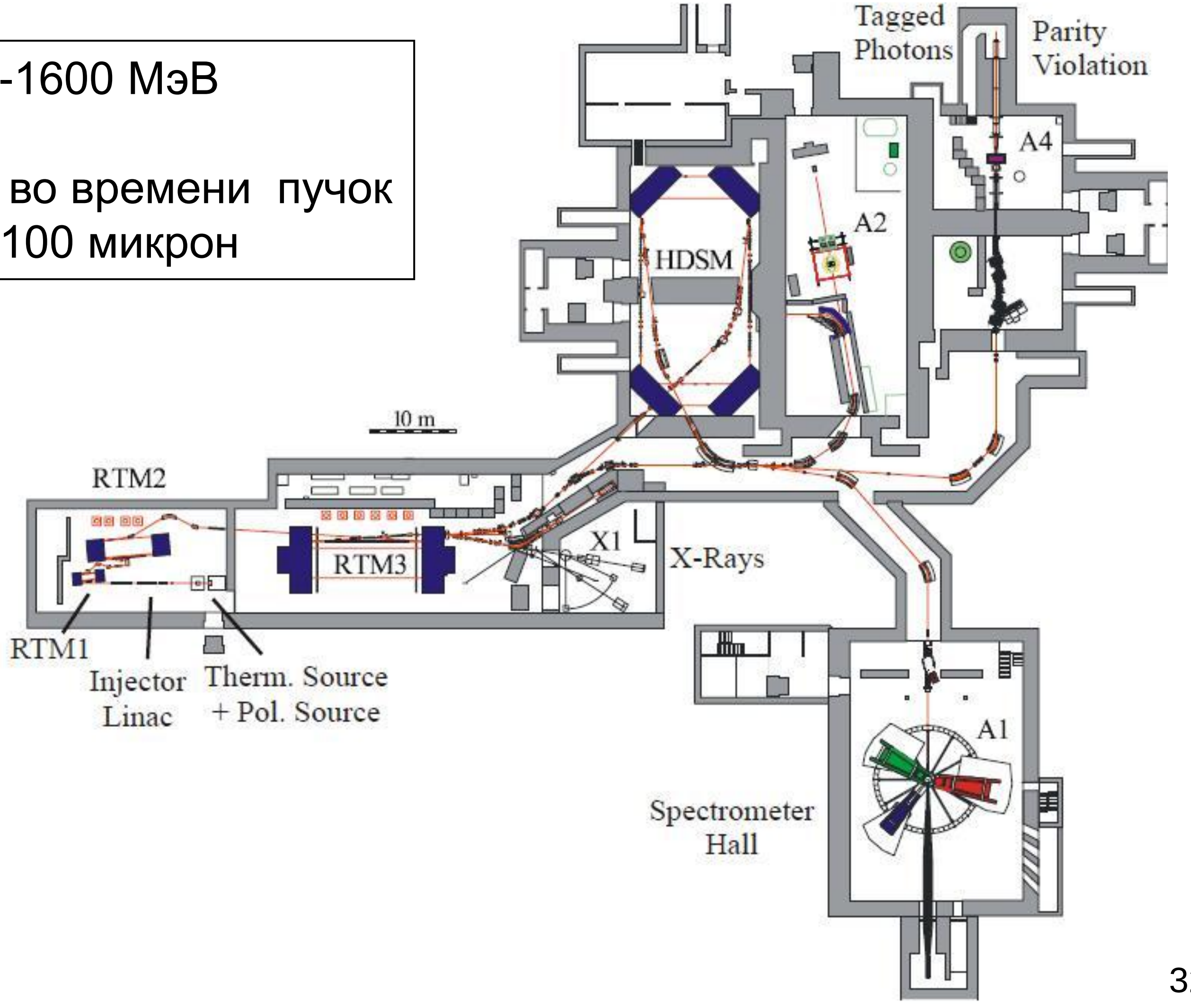
Метод: центр тяжести наведенных сигналов

Монте Карло симуляция



Ускоритель MAMI (Mainz Microtron)

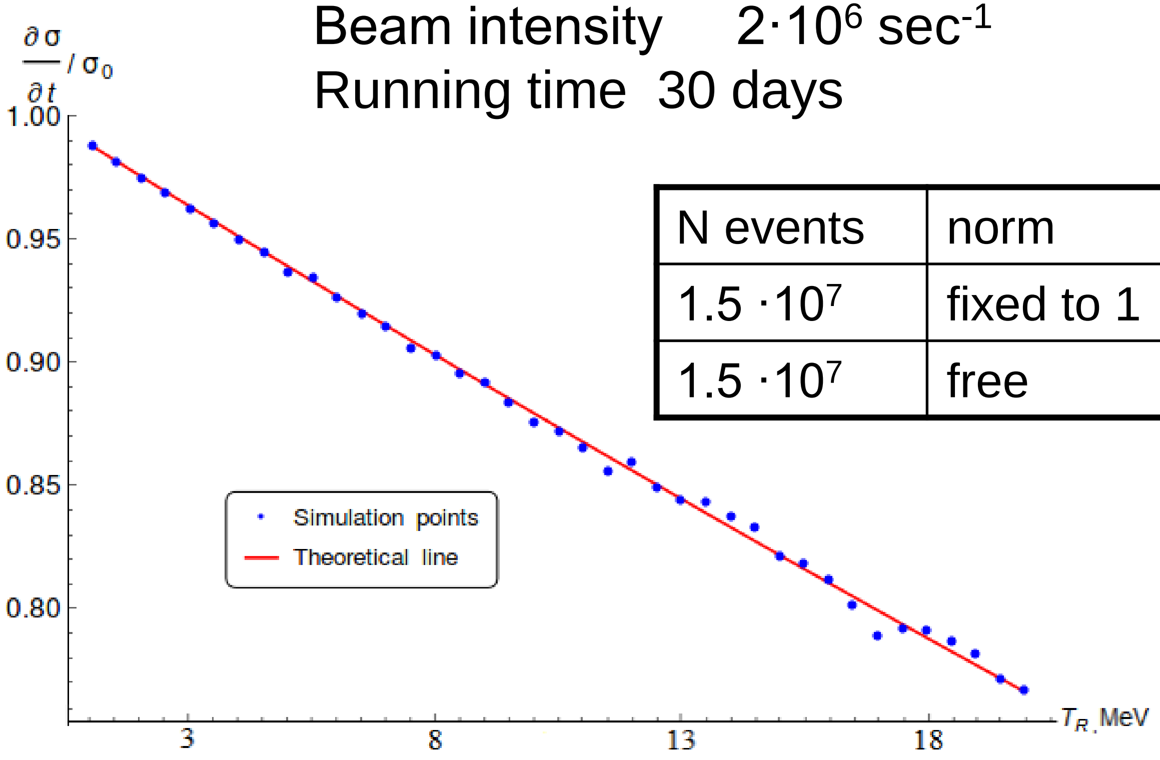
Энергия 180-1600 МэВ
$\Delta E/E = 10^{-4}$
Непрерывный во времени пучок
Размер пятна 100 микрон



Установка А1 в Майнце,
на которой получены основные данные по ep-рассеянию

Statistics and beam time

Target thickness = $5.2 \cdot 10^{22}$ p/cm^2
P =20bar L =35cm
Beam intensity $2 \cdot 10^6$ sec^{-1}
Running time 30 days



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

Предлагаемый график реализации проекта

- 2016 Разработка проекта, отработка отдельных узлов, приобретение материалов.
- 2017 Изготовление установки.
- 2018 Завершение изготовления установки, тестирование, транспортировка в МАЙНЦ, проведение тестового сеанса на пучке.

* Июнь 2016 One page letter to Mainz PAC

* 5 сент 2016 Proposal с запросом ускорительного времени на 2017 и 2018

• 2017 Test run с использованием имеющейся сейчас установки с активной мишенью для R3B

* Конец 2018 Test run с основной установкой PMPS

Оценка финансирования

2016	3 + 0.5 (командировки) млн.руб.
2017	9 + 1.5 млн. руб.
2018	6 + 2 млн. руб.
Всего	18 млн.руб.

Заключение

Реализация данного проекта позволит измерить дифференциальное сечение ep-рассеяния с относительной и абсолютной точностью 0.2%

и

определить электрический радиус протона

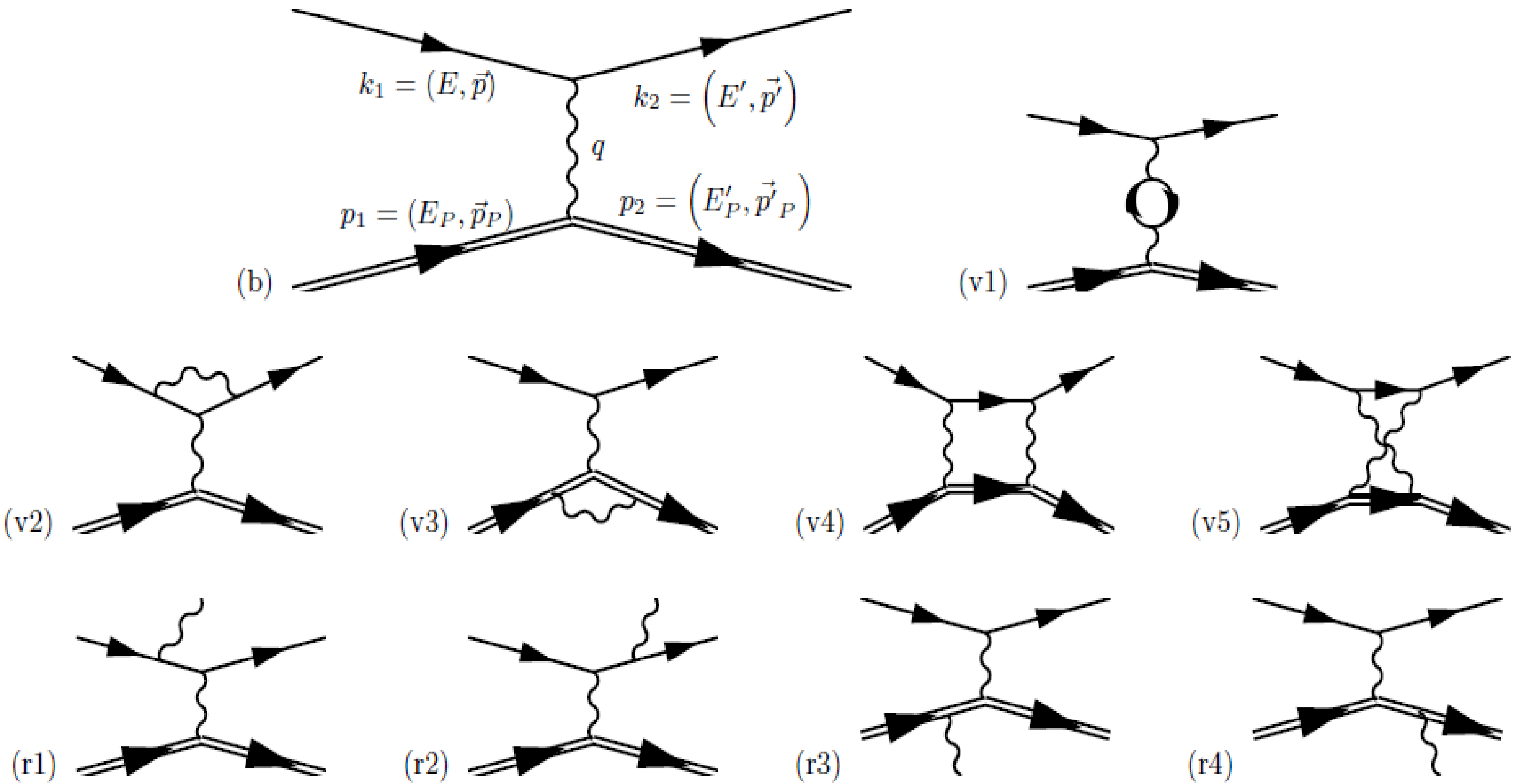
с точностью 0.5%.

Это может быть решающим фактором в понимании существующего расхождения (в 4%) между измерениями протонного радиуса мюонным и электронным методами.

Благодарю за внимание

Radiative corrections

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

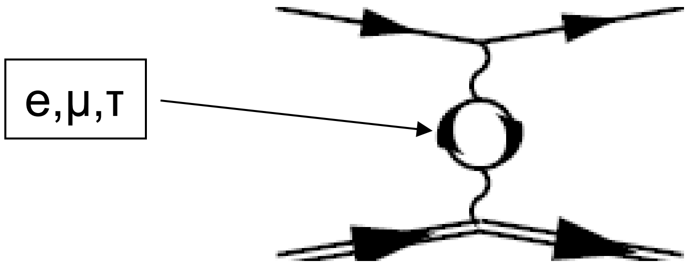


Radiative corrections

Two advantages

- Wide kinematic range, experimental cuts can be varied offline.
- Control of radiative corrections at the smallest t –values by absolute measurement of dσ/dt.

Vacuum polarization correction



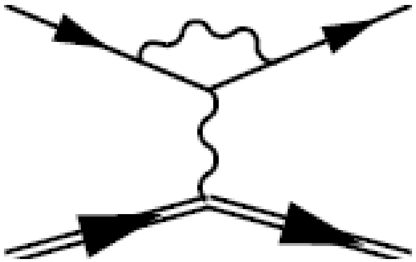
Q^2 GeV^2	e-loop	μ-loop
0.002	1.13%	
0.02	1.49%	0.048%
0.04	1.59%	

$$\delta_{\text{vac}} = \frac{\alpha}{\pi}\frac{2}{3}\left\{\left(v^2 - \frac{8}{3}\right) + v\frac{3-v^2}{2}\ln\left(\frac{v+1}{v-1}\right)\right\}, \quad (11)$$

$$\xrightarrow{Q^2 \gg m_l^2} \frac{\alpha}{\pi}\frac{2}{3}\left\{-\frac{5}{3} + \ln\left(\frac{Q^2}{m_l^2}\right)\right\}, \quad (12)$$

with $v^2 = 1 + \frac{4m_l^2}{Q^2}$, where m_l is the mass of the particle in the loop. The approximation (12) is valid for loop electrons. However, at the energy scales of this experiment and within the envisaged accuracy, the vacuum polarization via muon and tau loops has to be accounted for and must be evaluated with Eq. (11).

Electron vertex correction

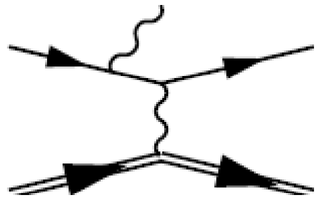
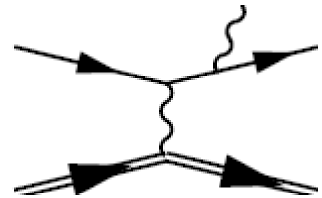


Q^2 Gev^2	δ_{vertex}
0.0001	-2.12%
0.002	-6.26%
0.02	-10.85%
0.04	-12.46%

The finite part of the electron vertex correction (v2, the infinite part cancels later on) is given in the ultrarelativistic limit by

$$\delta_{\mathrm{vertex}} = \frac{\alpha}{\pi}\left\{\frac{3}{2}\ln\left(\frac{Q^2}{m^2}\right) - 2 - \frac{1}{2}\ln^2\left(\frac{Q^2}{m^2}\right) + \frac{\pi^2}{6}\right\}. \tag{13}$$

Real photon emission by electrons

(r1)  (r2) 

ln

$$\delta_R = \frac{\alpha}{\pi}\left\{ \ln\left(\frac{(\Delta E_s)^2}{E\cdot E'}\right)\left[\left(\frac{Q^2}{m^2}\right) - 1\right] - \frac{1}{2}\ln^2\eta \right.$$
$$\left. + \frac{1}{2}\ln^2\left(\frac{Q^2}{m^2}\right) - \frac{\pi^2}{3} + \mathrm{Sp}\left(\cos^2\frac{\theta_e}{2}\right)\right\}, \qquad (14)$$

Sp(0)=0
Sp(1)= $\pi^2/6$

where $\eta = E/E'$, $\Delta E_s = \eta\cdot\Delta E'$. E' is the energy of an electron scattered elastically through an angle θ when no photon is emitted. An electron which radiates a photon has a lower energy than E'. $\Delta E'$ is the maximum difference to E' allowed by the radiative tail cut-off; it is called the cut-off energy. Details about the Spence function $\mathrm{Sp}(x)$ can be found in Appendix B of Ref. [35].

Partial mutual cancellation of δ_V and δ_R

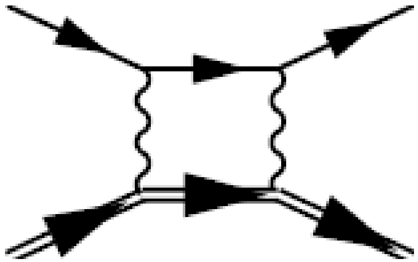
$$\delta_V + \delta_R = \delta_V + \delta_R(1) + \delta_R(2) =$$

$$= \alpha/\pi \{3/2 \ln(Q^2/m^2) - 2\} + \alpha/\pi \{\ln(\Delta E^2/EE`) \ln(Q^2/m^2)\}$$

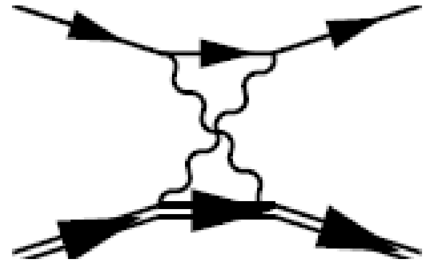
Q^2 Gev^2	**$\delta_V + \delta_R(1)$**	**$\delta_R(2)$ $\Delta E/E=0.1$**
0.0001	1.6%	-6.3%
0.002	2.65%	-9.58%
0.02	3.43%	-12%
0.04	3.69%	- 12.76

Note that $\delta_R(2)$ depends on the experimental conditions (cuts).
Hope in our experiment it will be much less and controlable
(the cuts mostly off-line)

Two Photon Exchange correction



(v5)

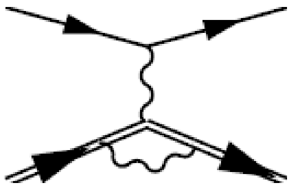


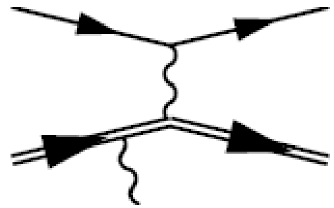
$$\delta_{\mathrm{TPE}} = -(1-\varepsilon)\, a\, \ln(b\, Q^2 + 1)$$

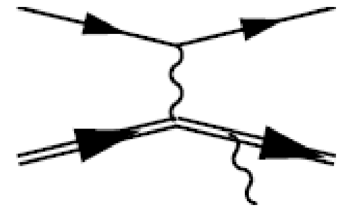
$$\varepsilon = \left(1 + 2\left(1 + \frac{Q^2}{4m_p^2}\right)\tan^2\frac{\theta}{2}\right)^{-1}.$$

example:
P_e =500 Mev, $Q^2 = 0.02$, $\theta = 16$ deg, $\varepsilon = 0.98$,
a and b were free parameters in the fits and were obtained to be $a \approx 0.1$ and $b \approx 0.4\ \mathrm{GeV}^{-2}$
Therefore $\delta_{\mathrm{TPE}} \approx 10^{-5}$ at $Q^2 = 0.02\ \mathrm{GeV}^2$

Corrections with proton contributions


(v3)


(r3)


(r4)

$$\delta_1 = \frac{2\alpha}{\pi}\left\{\ln\left(\frac{4\left(\Delta E_s\right)^2}{Q^2 x}\right)\ln\eta + \mathrm{Sp}\left(1-\frac{\eta}{x}\right) - \mathrm{Sp}\left(1-\frac{1}{\eta x}\right)\right\}, \qquad (15)$$

$$\delta_2 = \frac{\alpha}{\pi}\left\{\ln\left(\frac{4\left(\Delta E_s\right)^2}{m_p^2}\right)\left(\frac{E'_P}{\left|\vec{p'}_P\right|}\ln x - 1\right) + 1 + \frac{E'_P}{\left|\vec{p'}_P\right|}\left(-\frac{1}{2}\ln^2 x - \ln x \ln\left(\frac{\rho^2}{m_P^2}\right) + \ln x - \mathrm{Sp}\left(1-\frac{1}{x^2}\right) + 2\mathrm{Sp}\left(-\frac{1}{x}\right) + \frac{\pi^2}{6}\right)\right\}, \qquad (16)$$

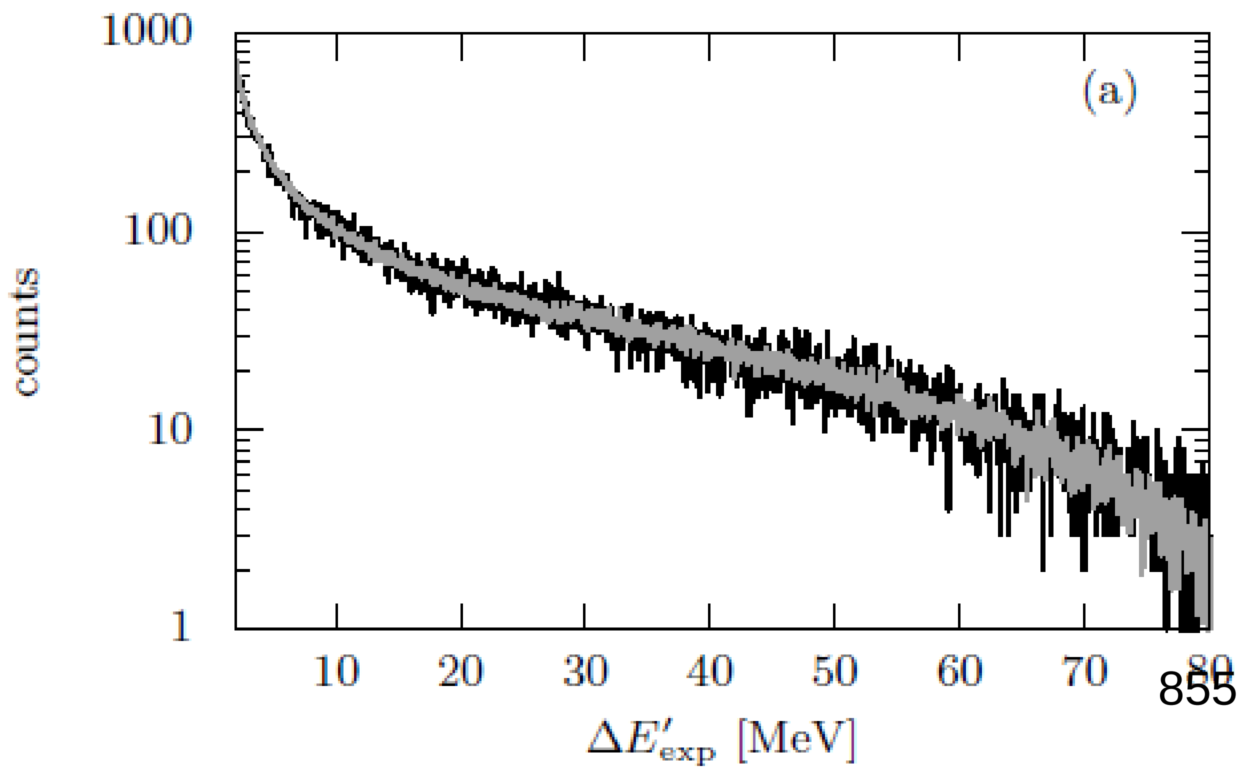
with

$$x = \frac{\left(Q+\rho\right)^2}{4m_P^2}, \qquad \rho^2 = Q^2 + 4m_P^2. \qquad (17)$$

Relatively small corrections
But to be understood

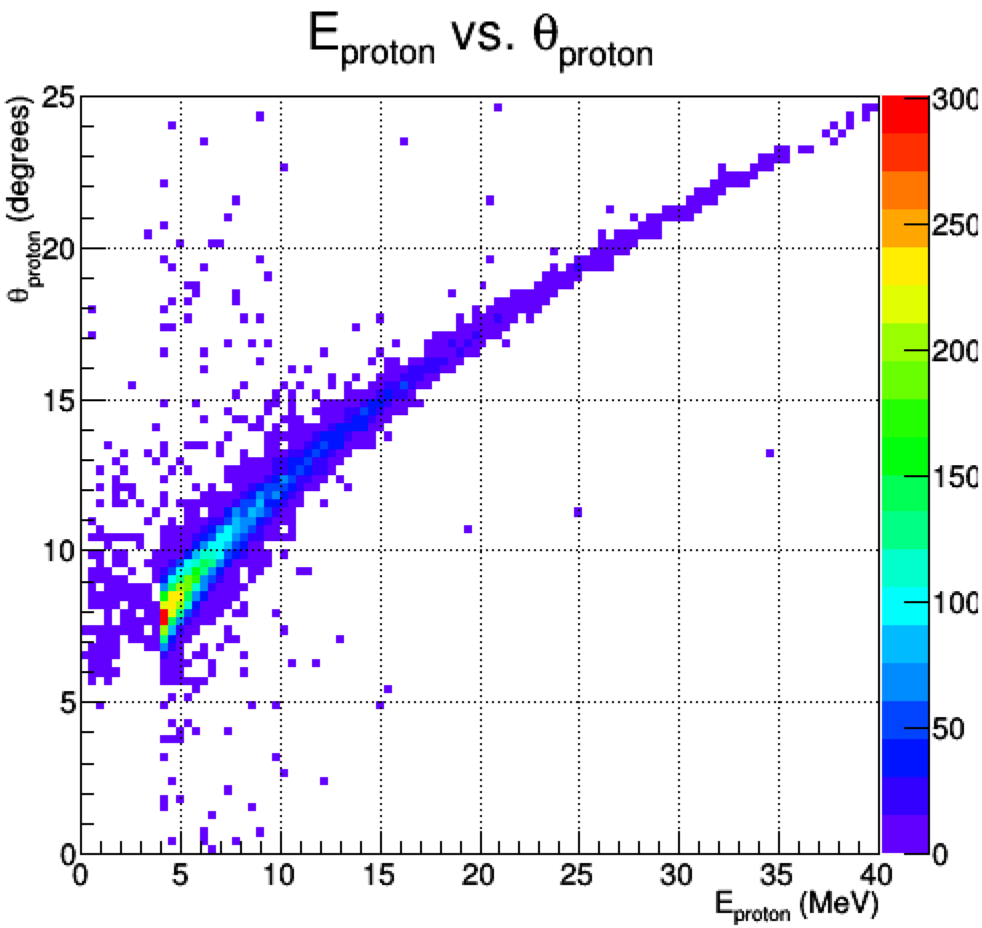
ΔEs cuts in A1

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}}(\Delta E') = \left(\frac{d\sigma}{d\Omega}\right)_{0} e^{\delta_{\mathrm{vac}}+\delta_{\mathrm{vertex}}+[\delta_R+\delta_1+\delta_2](\Delta E')}.$$



855 MeV

Монте Карло симуляция



Measurement of absolute value of beam momentum

NIM 177(1980)353-359

Gas filling
He(90%) + H_2 (10%)

Table 1
Experimental results.

Polarity	p_0 (GeV/c)	$\frac{p^* - p_0}{p_0}$ (%)	p^* (GeV/c)
–	100	+0.30 ± 0.05	100.30 ± 0.05
+	100	+0.20 ± 0.05	100.20 ± 0.05
–	150	+0.35 ± 0.12	150.52 ± 0.18
+	150	+0.35 ± 0.05	150.52 ± 0.08
–	200	+0.35 ± 0.06	200.79 ± 0.12
–	250	+0.15 ± 0.05	250.38 ± 0.13
+	250	+0.15 ± 0.07	250.38 ± 0.18
–	280	+0.23 ± 0.10	280.64 ± 0.28
–	300	–0.04 ± 0.06	299.88 ± 0.18
+	300	–0.08 ± 0.06	299.76 ± 0.18

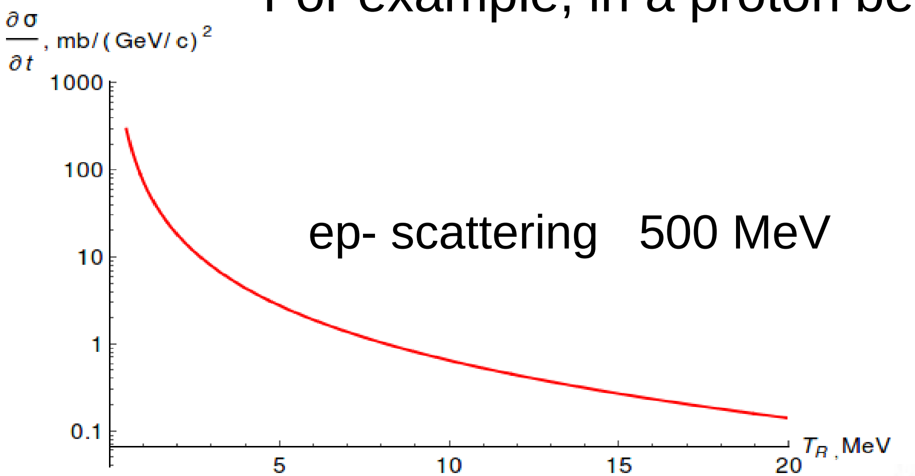
$\mathbf{(P^*\theta)^2 = 2MT_R}$

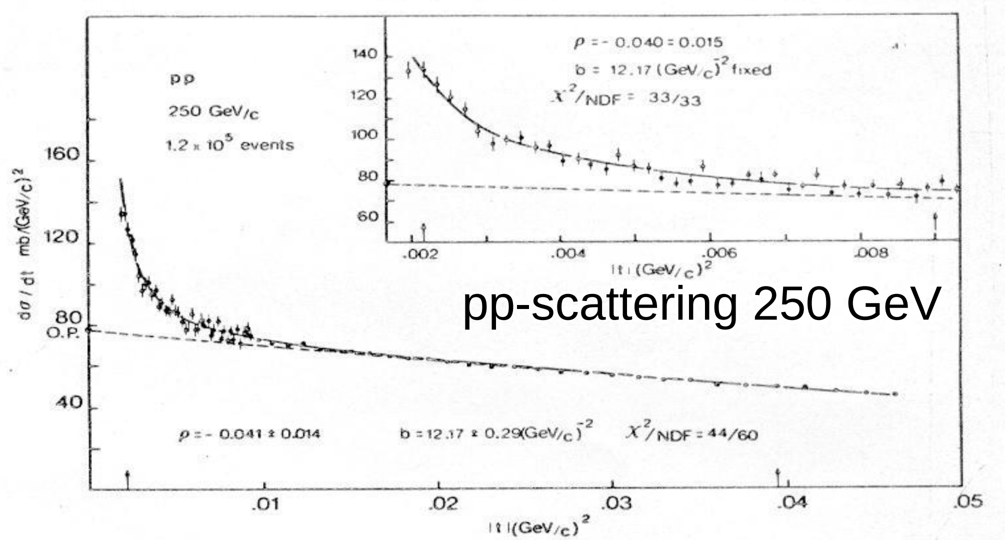
234 U Eα
4 774,6 кэВ (71,38 %

Absolute precision
σ_P= 0.05%

Possible TPC calibration in hadronic beams

For example, in a proton beam at Gatchina synchrocyclotron.





$-t = 2MT_R$

Advantages:

Flat dσ/dt.

Higher rates

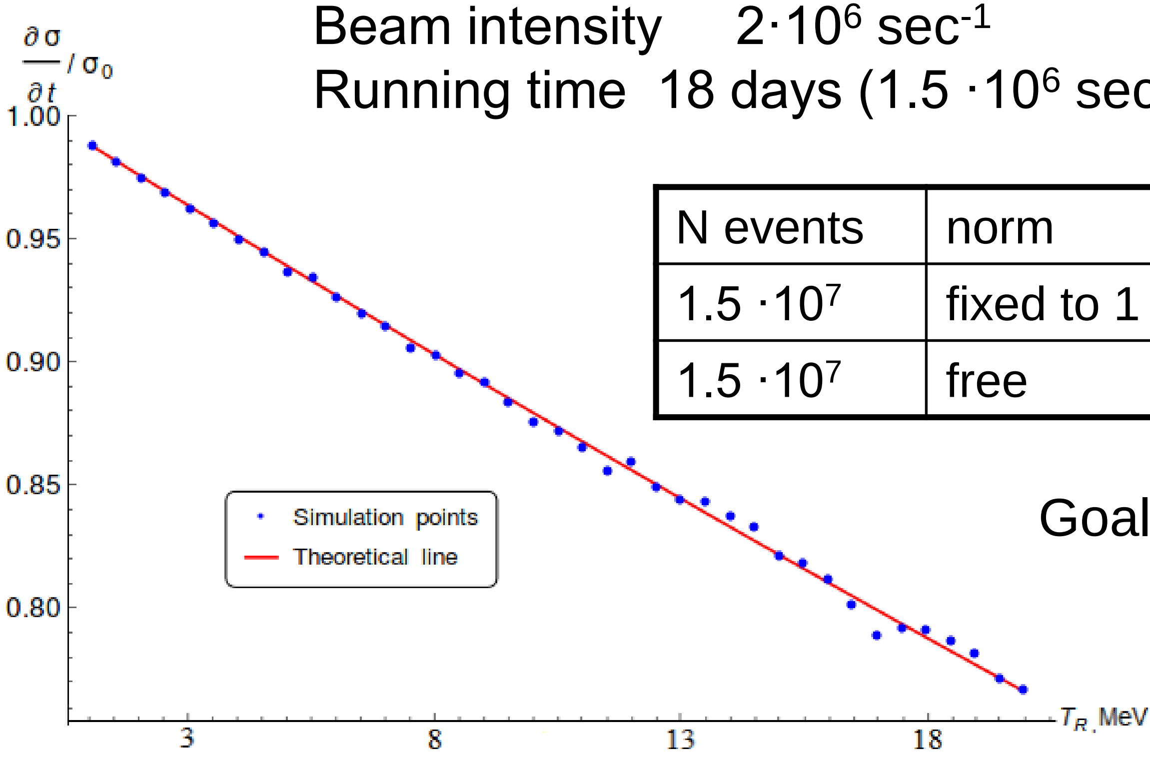
Higher precision.

Goal :

Calibration of T_R –scale to 0.1% precision

Statistics and beam time

Target thickness = $5.2 \cdot 10^{22}$ p/cm^2
P =20bar L =50cm
Beam intensity $2 \cdot 10^6$ sec^{-1}
Running time 18 days ($1.5 \cdot 10^6$ sec)



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