Proposal

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

Proton radius "puzzle"

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

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

Agreement on Collaboration in Fundamental Research in Experimental Particle Physics

The main contributions of PNPI NRC KI shall consist of:

- Design and construction of a high pressure (20 bar) hydrogen ionization Time-Projection Chamber, combined with a Forward Detector for scattered electrons.
- Transportation of the detector from PNPI to INP Mainz.

INP Mainz shall provide

- Construction of a dedicated electron beamline and technical service.
- A beam monitoring detection system.
- Access to PNPI scientists for the assembly of the detector setup and for participation in experimental runs.

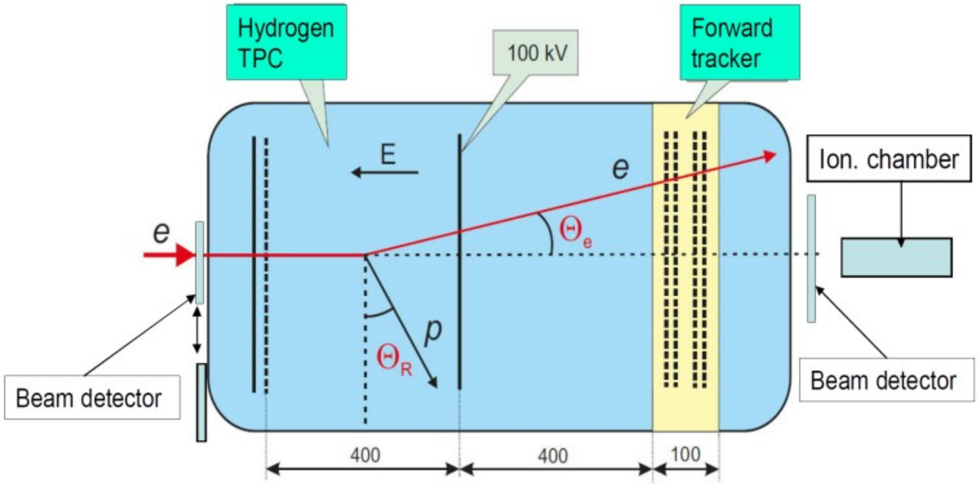
Mainz, February 25, 2017

Director of the INP Mainz
Prof. Dr. Achim Denig

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

Experimental method

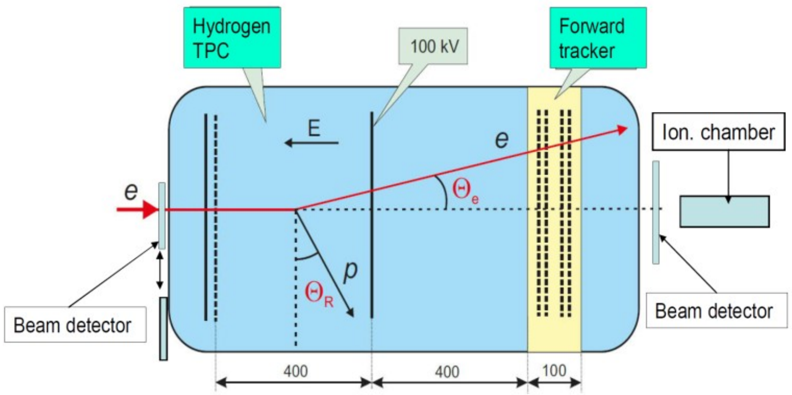
Recoiled protons and scattered electrons are detected with Hydrogen TPC and MWPC Forward Tracker.



Goals : to measure dσ/dt in the range 0.001 GeV2 <Q2< 0.04 GeV2 with 0.2% absolute precision and determine Rp with sub-percent precision.

Note that this will be the first absolute measurements of dσ/dt in *ep* scattering experiments.

Experimental method



Measured quantites

Proton energy T_R

Proton angle Θ_R

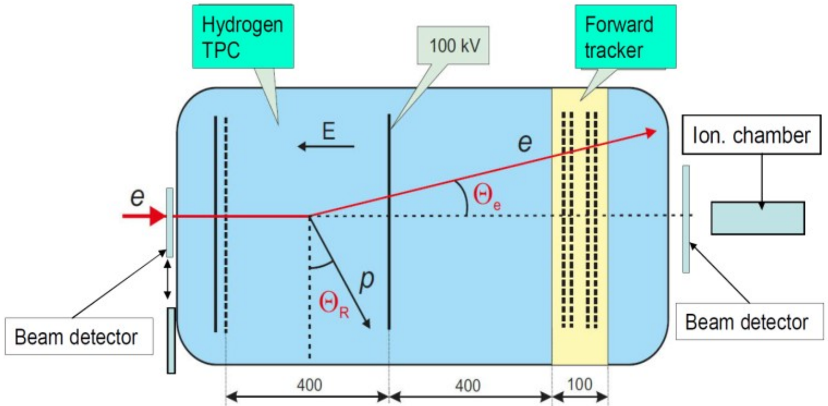
Electron angle Θ_e

* The momentum transfer Q^2 is determined by T_R : $Q^2 = 2MT_R$.
* The angle Θ_e is used for calibration of the absolute Q^2 scale;
* FT provides timing for drift time measurement.
* Correlations $T_R - \theta_e$ and $T_R - \theta_R$ eliminate the background.

* Low radiative corrections.
* Well defined H_2 target thickness without wall effects.

(Important in absolute measurement of dσ/dt).

Challenges in realizaion of the recoiled proton method



* Measurement of the electron angle θ_e to 0.04% absolute precision;
* Calibration of the T_R scale to 0.2% absolute precision;
* Super-high H_2 gas purity ~ 20 ppb;
* Linear electric field in TPC to 0.1% precision;
* Operation of the MWPCs in FT at 20 bar pressure;
* Measurement of the beam flux to 0.1 % precision;
* Safety issues in operation with the 20 bar H_2 detector.

Some physics aspects of the PRES experiment

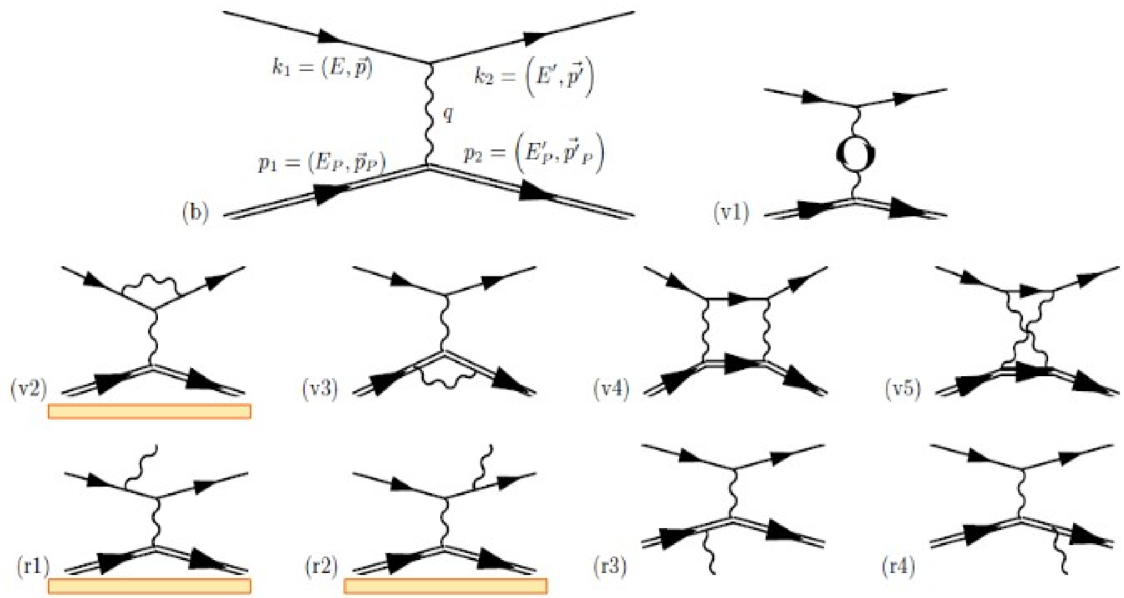
I. Radiative corrections ;

II. Measurements of the recoiled proton range in TPC, applications in the PRES and AMBER experiments;

III. Study of systematics errors in reconstruction of the proton radius.

Radiative corrections

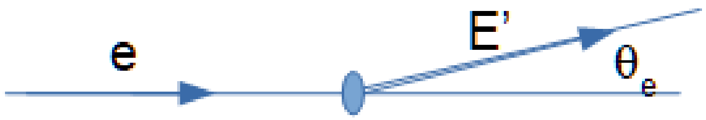
$$\left(\frac{d\sigma}{d\Omega}\right)_1 = \left(\frac{d\sigma}{d\Omega}\right)_0 (1+\delta).$$

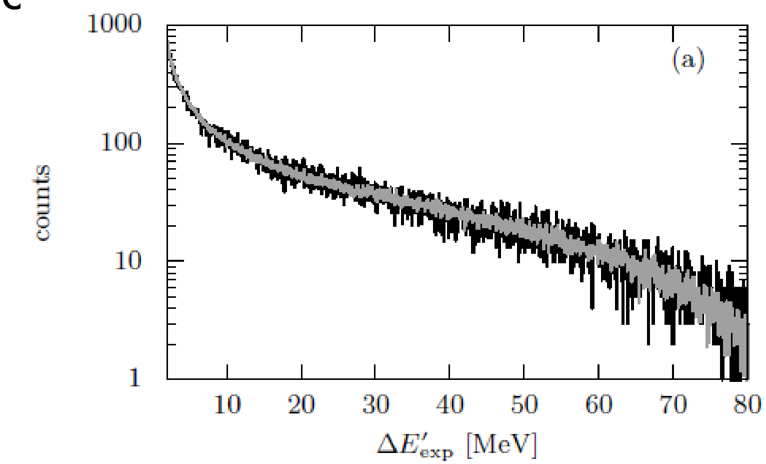


The RC corrections due to real and virtual photon emission (r1 + r2 + v2) were dominating corrections in all previous *ep* scattering experiments

A1 experiment

(as an example)

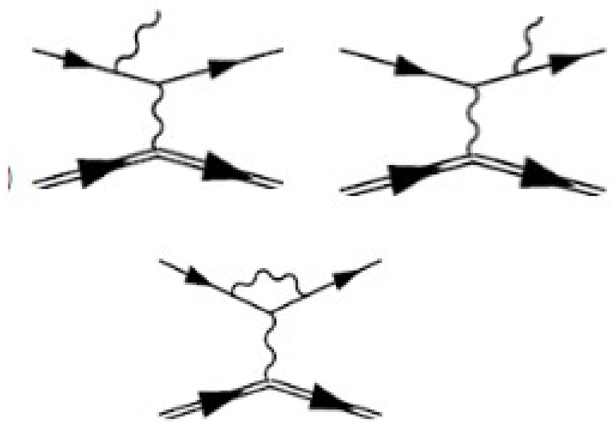




Jan.C.Bernauer

Partial cancellation of the radiative corrections δ_V and δ_R

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

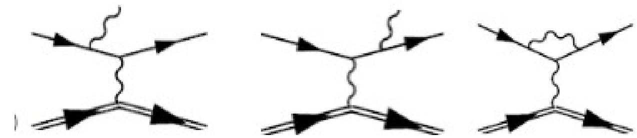


Q^2 Gev^2	$\delta_V + \delta_R(1)$	$\delta_R(2)$ $\Delta E/E=0.1$
0.0001	1.6%	-6.3%
0.002	2.65%	-9.58%
0.02	3.43%	-12%
0.04	3.69%	- 12.76

The RC are of the order 10% , depending on experimental cuts

Cancellation of radiative corrections to $d\sigma/dt$ in the recoiled proton *ep* scattering experiment

V.S.Fadin , R.E. Gerasimov Physics. Letters B 795(2019) 172-1176



$$\delta^e_{hard} = \frac{\alpha}{\pi}\left[2\left(\ln\frac{Q^2}{m^2} - 1\right)\ln\frac{E_l}{\omega_0} - \frac{3}{2}\ln\frac{Q^2}{m^2} + 2\right].$$

0.34

$$\delta^e_{vertex+soft} = \frac{\alpha}{\pi}\left[-\left(\ln\left(\frac{Q^2}{m^2}\right) - 1\right)\ln\left(\frac{E_l E_l'}{\omega_0^2}\right) + \frac{3}{2}\ln\left(\frac{Q^2}{m^2}\right) - 2\right.$$
$$\left. - \frac{1}{2}\ln^2\left(\frac{E_l}{E_l'}\right) + \mathrm{Li}_2\left(1 - \frac{Q^2}{4E_l E_l'}\right) - \frac{\pi^2}{6}\right],$$

For E_l =720 MeV
Q^2 = 0.04 GeV^2

$4 \cdot 10^{-4}$

$\Pi^2/6$ ¬ 0.02

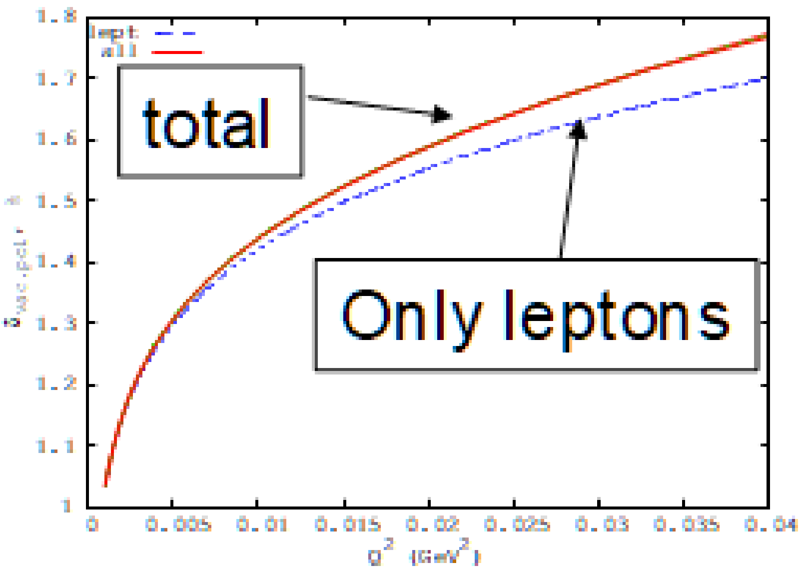
Final correction for the sum of the real and virtual photon emission

$$\delta^e_{\text{vertex +soft}} + \delta^e_{\text{hard}} \leq 0.36/\,137\,\pi = 8.4\cdot 10^{-4}$$

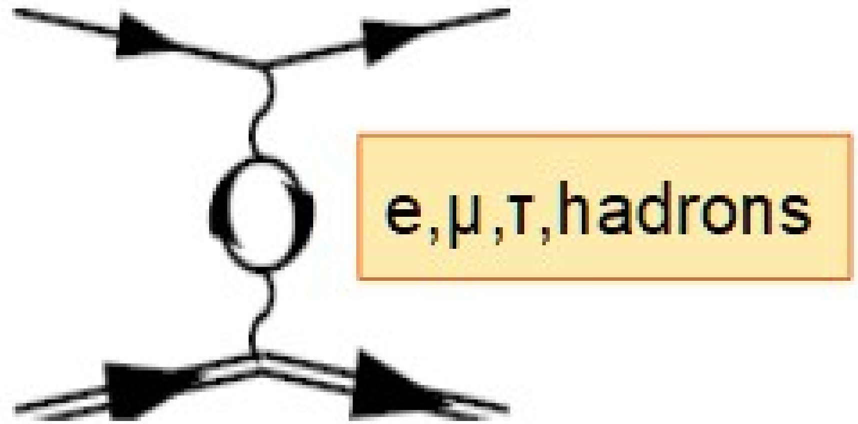
This correction does not depend on ω_0 (!!!)

Q^2 GeV^2	δreal + δvertex
0.04	$8.4\cdot 10^{-4}$
0.001	$5.8\cdot 10^{-4}$

Vacuum polarization is the largest RC in this method



A.Arbuzov



The polarization vacuum correction is calculated with very high precision.

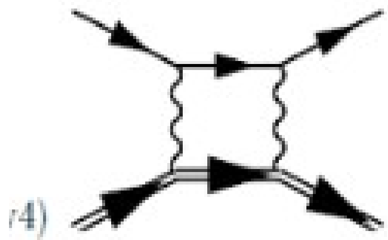
An example: δ_{VP} = **1.61546 (28) %** **for Q^2 = 0.022 GeV^2**

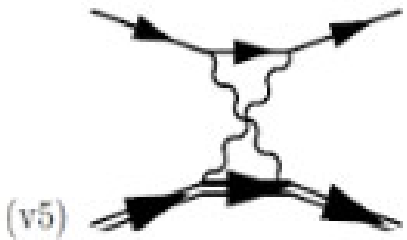
Radiative corrections due to two photon exchange

The elastic part is well calculated. It is around 0.3% in the Q^2 range $0.1<Q^2< 0.1$ (Kobushkin 1010.4808).

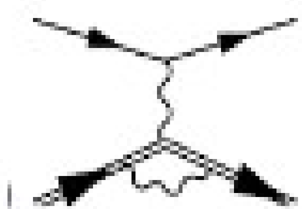
The inelastic part is more uncertain. It was calculated on the basis of dispersion relations for our Q^2 region by M.Ryskin

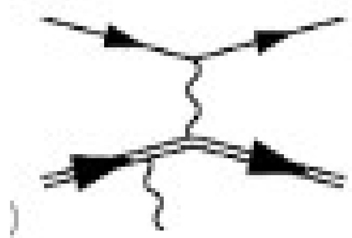
0.01 GeV^2	0.025 %
0.02	0.046 %
0.04	0.081 %
0.06	0.11 %





Radiative corrections due to photon emission by the proton

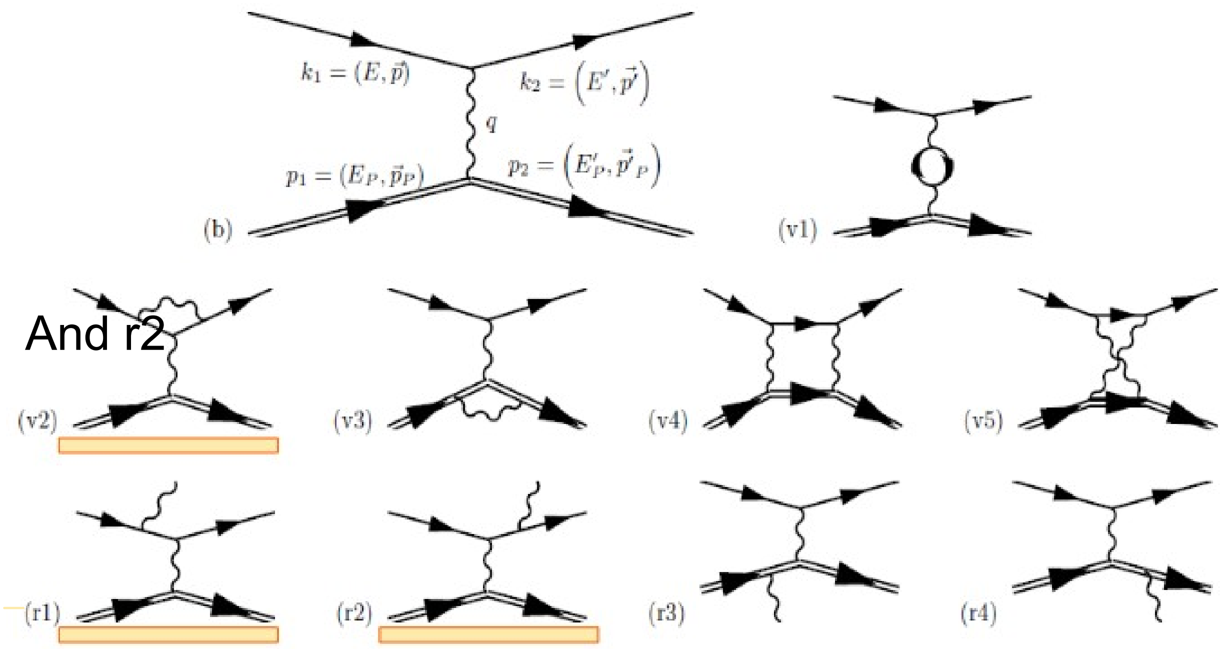




These corrections are very small and calculatable.
In addition, the mutual cancellaton works also in this case.

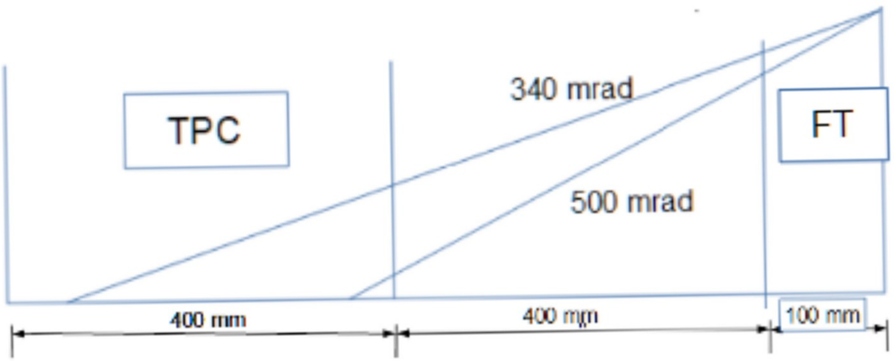
Radiative corrections
(in conclusion)

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



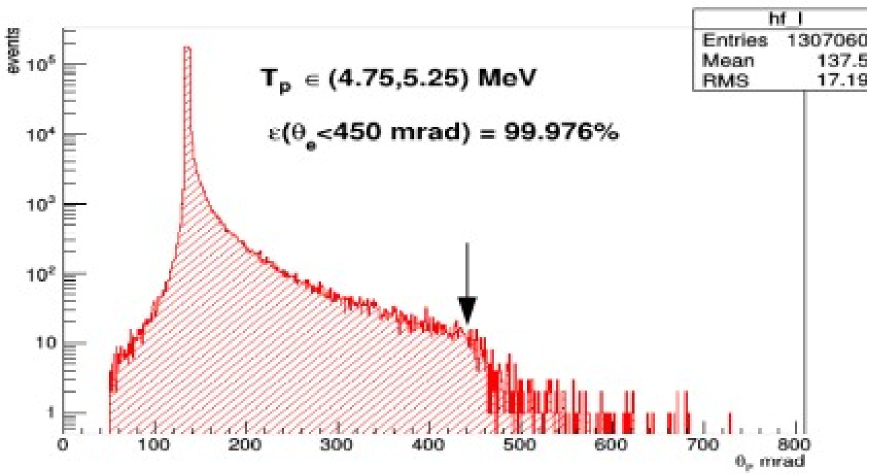
The cancellation of contributions to the radiative corrections due to v2, r1, and r2 diagrams is a nice feature of the recoiled proton method

Cancellation of the RC corrections requires full acceptance in registration of the scattered electrons



Acceptance of TPC_FT detector

Angular distribution of the electrons corresponding to $T_R = 5 \pm 0.25$ Mev calculated with the ESEPP generator for $E_e = 720$ MeV



Scattered electrons beyond 450 mrad

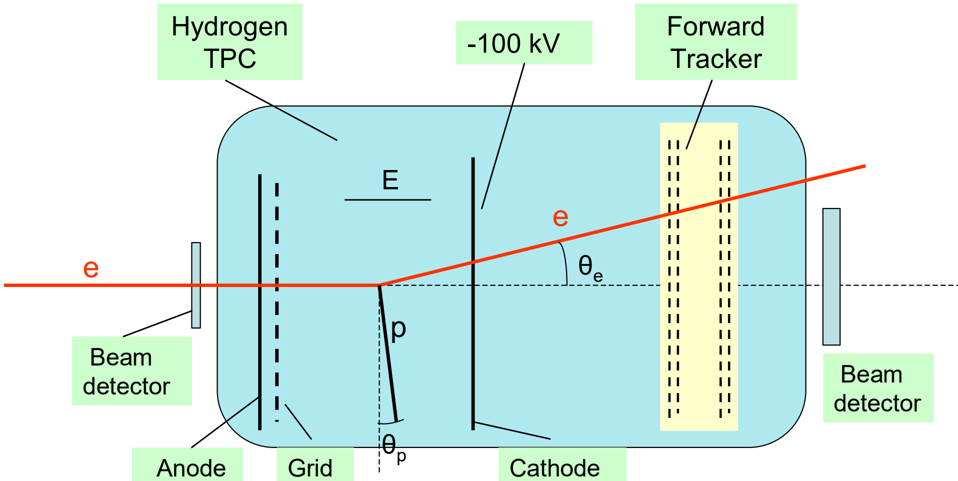
1MeV	0.004%
5MeV	0.02%
10 MeV	0.3%
15 MeV	0.5%
20 MeV	0.9%

The acceptance is > 99%. The correction can be calculated with MC and checked with the data collected at E=1000 MeV

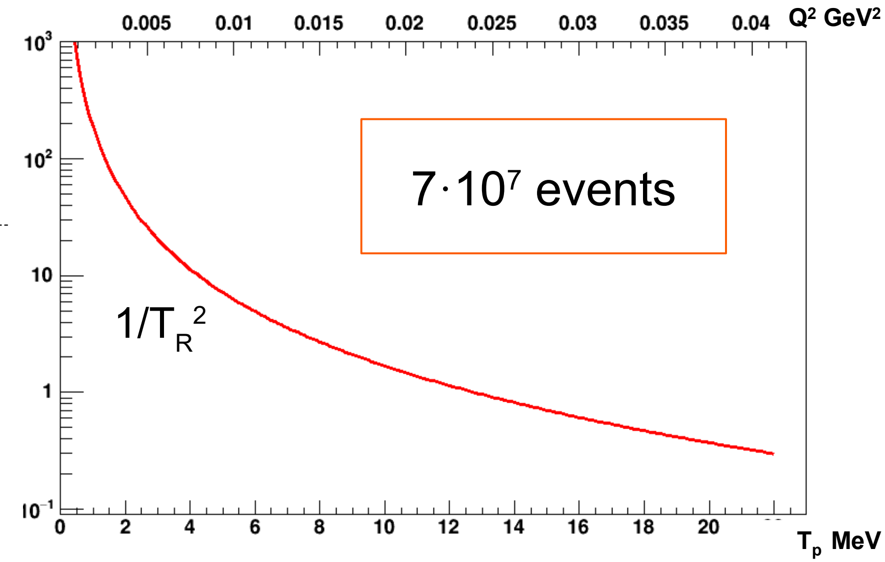
Measurement of the recoiled proton range in TPC
Applications of this method
in the PRES and AMBER experiments

Measurements of the proton range in TPC

A.Vorobyev, N.Sagidova arXiv 1912.06065



$$(P_e \theta_e)^2 = Q^2 = 2MT_R$$



PRES setup as a generator of protons of variable and well determined energy inside the H_2 target.

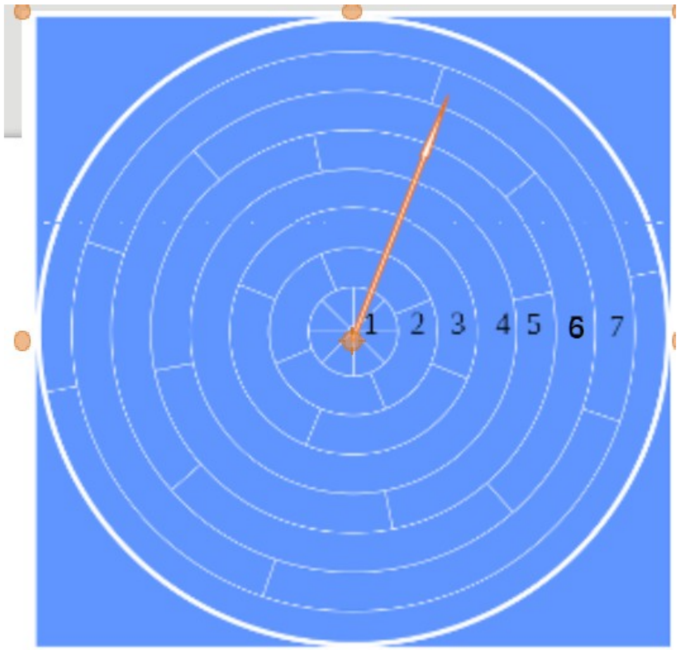
A unique possibility to measure the proton Range-Energy relation to 0.1 % precision,
At present this precision is ~3-5%.

The proton energy distribution in the PRES experiment.
70 mln events in total

Measurements of the proton range in TPC

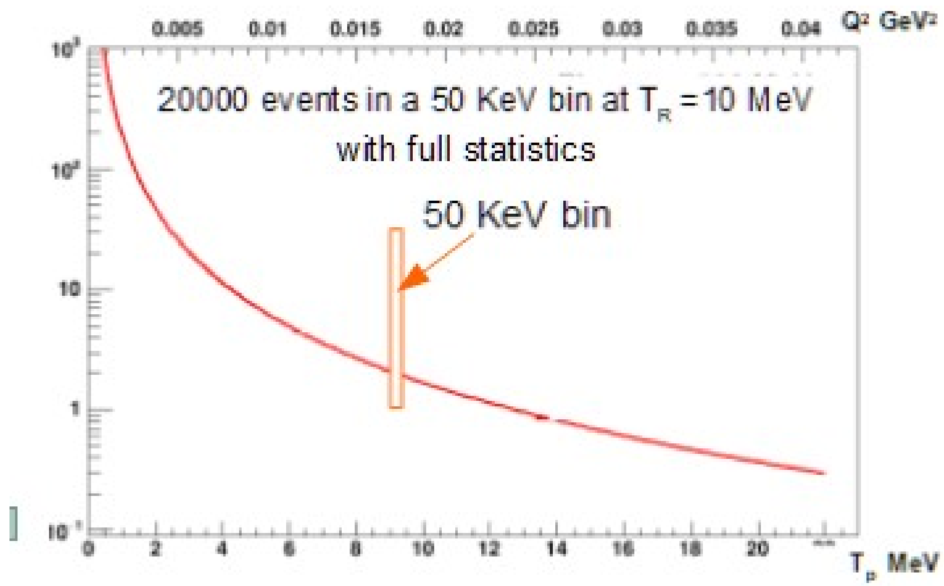
Proton range-energy relation from SRIM software package for 20 bar H_2

Energy T_p MeV	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Range $\langle R_p \rangle$ mm	5.20	17.59	36.37	61.2	91.8	127.9	169.6	216.5	268.7	326.0



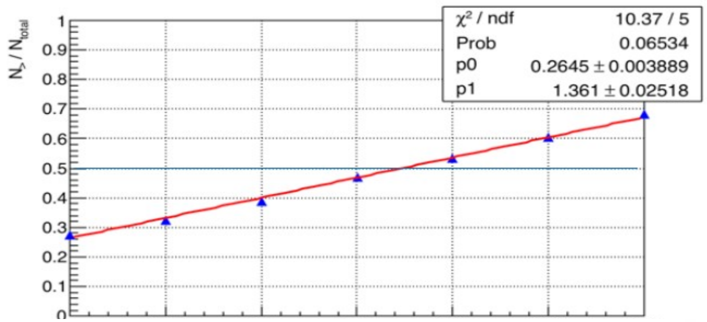
TPC anode plane. 50 μm precision In the ring radius. That is from $2 \cdot 10^{-4}$ for rings 6/7 and $5 \cdot 10^{-4}$ for rings 3/4.

$$\langle R_p \rangle = 4.82\, T_p^{\,1.83}$$

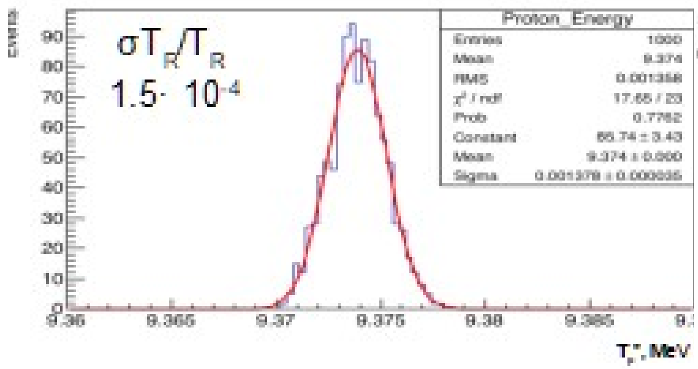


Scan with the 50 keV bin to determine T_R corresponding to the proton stop in between the rings. The number of events registered in the outer ring should be 50% of the total number. The 50/50 method.

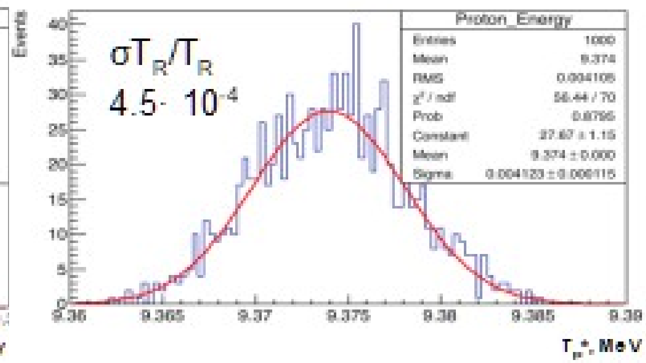
MC demonstration of determination the energy of the protons stopped in between Ring 6 and Ring 7



Scan with 50 keV bin around T_R = 9.370 MeV. 10 000 events in each bin. Linear fit.



Results from 1000 times repetition of the scanning procedure with 10 000 events in each bin,



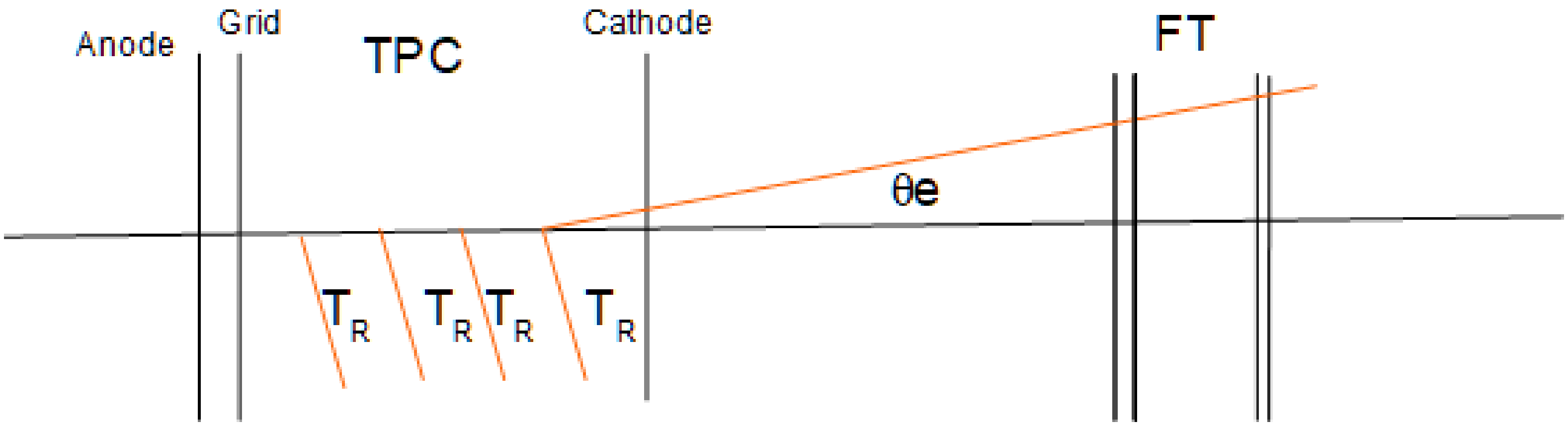
Results from 1000 times repetition of the scanning procedure with 1 000 events in each bin,

Conclusion: 10% statistics of the PRES experiment will be enough to determine the proton Range-Energy relation with 0,1% precision.

No additional measurements. Just analysis of the collected experimental data.

Applications of the proton range method

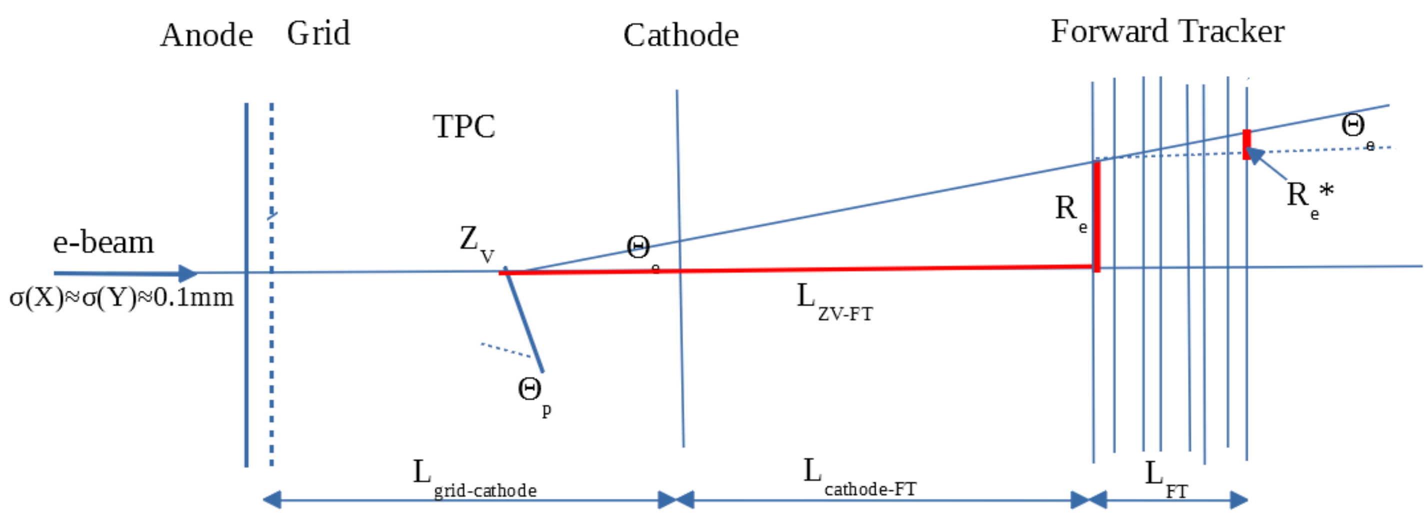
Control for electron attachment in TPC



Selection of the samples of events with equal T_R at various Z_V gives it possible to control the electron attachment to the gas impurities with 0.1 % precision .

Applications of the proton range method

Control for absolute calibration of the electron scattering angle



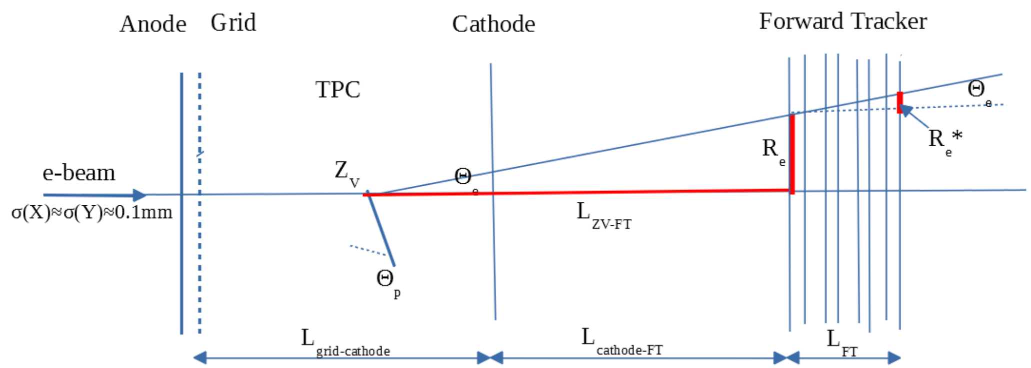
Absolute calibration of the Q^2 scale plays a decisive role in this experiment.
It relies on absolute calibrations of the beam energy ($2 \cdot 10^{-4}$ precision at MAMI) and on the electron scattering angle to be calibrated with the same precision.

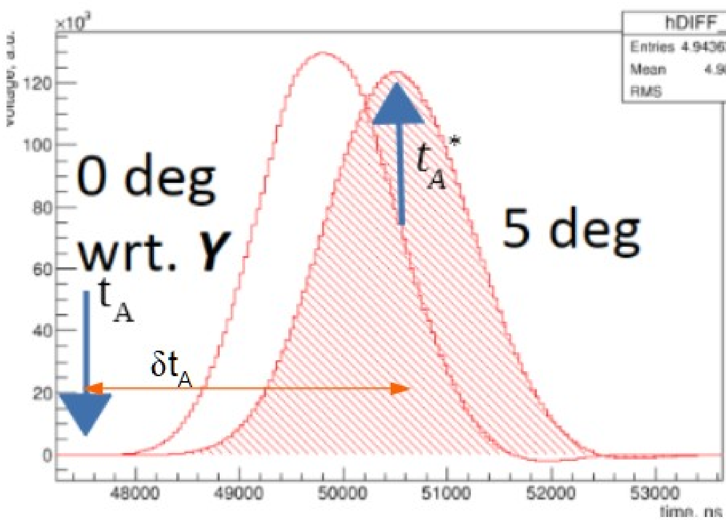
Measurements of Θ_e can be performed using two methods:

Stand_alone FT method and combined TPC_FT method

Applications of the proton range method

The combined TPC_FT method provides better angular resolution but requires high precision measurement of the Z_V position.





The measured signal arrival time t_A* has considerable delay relative to the time t_A when the first ionization electrons touch the TPC grid.

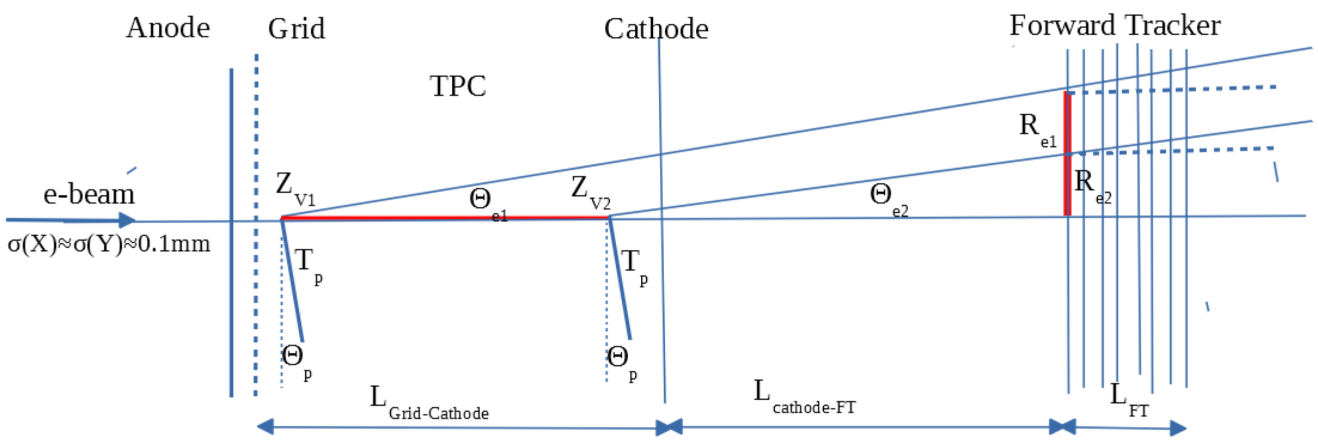
$$Z_V = (t_A - t_0 + \Delta t_A)W$$

$$\Delta t_A = 2.4 - 3.0\ \mu s$$

The delay time Δt_A should be known with ± 100 ns precision to provide $2 \cdot 10^{-4}$ precision in Z_V position. Needs for cross checks.

Applications of the proton range method

An alternative way to determine absolute electron scattering angle



$T_R(Z_{V1}) = T_R(V_{Z2})$ due to proton range method.

Therefore, $\Theta_{e1} = \Theta_{e2} = \Theta_e(T_R)$.

$$tg\Theta_e = (R_{e1} - R_{e2})/ (t_{A1}^* - t_{A2}^*)\ W$$

The values of W, $(R_{e1} - R_{e2})$, and $(t_{A1}^* - t_{A2}^*)$ are measured with high absolute precision.
No corrections related to time measurement or to uncertainties in the distance between TPC and FT are needed.

A very promising cross check for the measurement of the scattered electron angle with the combined TPC_FT method with ~0.04% absolute precision.

Applications of the proton range method

Interplay between the PRES and AMBER experiments

TPC in the AMBER and PRES experiment will be identical .

The high precision calibration of the absolute Q^2 scale is mandatory for successful experiments. Yet some systematics errors are inevitable.

Anode plane in PRES

Anode plane in AMBER

Comparison of the measured Q^2 values corresponding to equal proton ranges is a powerful method to make both Q^2 scales practically identical.

This makes comparison of $d\sigma/dt$ (electrons) with $d\sigma/dt$ (muons) interesting in the context of the electron-muon universality.

Proton Radius reconstruction

S. Belostotsky, N.Sagidova, A,Vorogyov arXiv: 1903.04975

MC events were generated according to the expression:

L.Landau

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

assuming:

$$G_M(Q^2) = \mu_p \cdot G_E(Q^2) = 2.793 G_E(Q^2).$$

$$G_E = 1 - \langle r_p^2 \rangle Q^2 / C_2 + \langle r_p^4 \rangle Q^4 / C_{4-} - \langle r_p^6 \rangle Q^6 / C_6 + \langle r_p^8 \rangle Q^8 / C_8$$

with $\langle r_p^2 \rangle = 0.7700\ fm^2$ $\langle r_p^4 \rangle = 2.63\ fm^4$ $\langle r_p^6 \rangle = 26\ fm^6$ $\langle r_p^8 \rangle = 374\ fm^8$

from A1 experiment.

Then the form factor G_E^2 was extracted

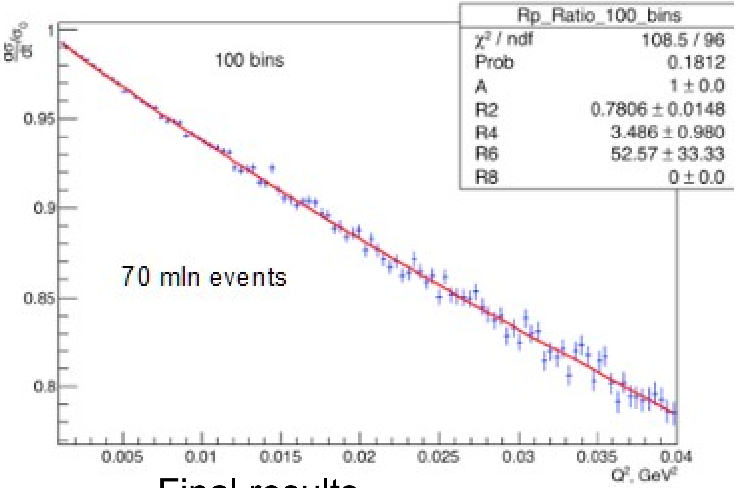
$$G_E^2(Q^2) = d\sigma/dt_{MC} / d\sigma/dt_{point}$$

and fitted with the polinomial

$$G_E = 1 - \langle r_p^2 \rangle Q^2 / C_2 + \langle r_p^4 \rangle Q^4 / C_{4-} - \langle r_p^6 \rangle Q^6 / C_6 + \langle r_p^8 \rangle Q^8 / C_8$$

with various combinations of the free parameters $\langle r^2 \rangle, \langle r^4 \rangle, \langle r^6 \rangle, \langle r^8 \rangle$.

Proton Radius reconstruction



An example of the fitting procedure

Generated	From fit
$<r^2> = 0.770\ fm^2$	0.7806 ± 0.0148
$<r^4> = 2.63\ fm^4$	3.486 ± 0.98
$<r^6> = 26\ fm^6$	52 ± 33
$<r^8> = 374\ fm^8$	0 fixed

Final results

	Free parameters	Fixed parameters	ΔR_p (stat)	ΔR_p (syst)	comments
Option1	$A < r_p^2 > < r_p^4 > < r_p^6 >$	$< r_p^8 >$	± 0.0085 fm	< 0.001fm	—-
Option2	$A < r_p^2 >< r_p^4 >$	$< r_p^6 >< r_p^8 >$	± 0.0042 fm	± 0.0025 fm < 0.001fm	$< r_p^6 >$ fromA1 $< r_p^6 >$ from[1]

With 70 mln events in the Q^2 range from 0.001 GeV_2 to 0.04 GeV^2, one can reach 0.5% statistical precision in R_p with $\leq$ 0.3% systematics errors with fixed parameters $<r_p^8>$ and $<r_p^6>$.

Reference :

J.M. Alarcon, C.Weiss, *Accurate nucleon electromagnetic form factors from dispersively improved chiral effective field theory*, ArXiv: 1803.09748 [hep-ph] Phys.Lett.B 784 (2018) 373.

	A1	Alarcon
$<r_p^2>$ fm^2	0.770	0.701-0.768
• $<r_p^4>$ fm^4	2.63	1.47-1.6
• $<r_p^6>$ fm^6	26	8.5- 9.0
• $<r_p^8>$ fm^8	374	127-130

Thank you for your attention