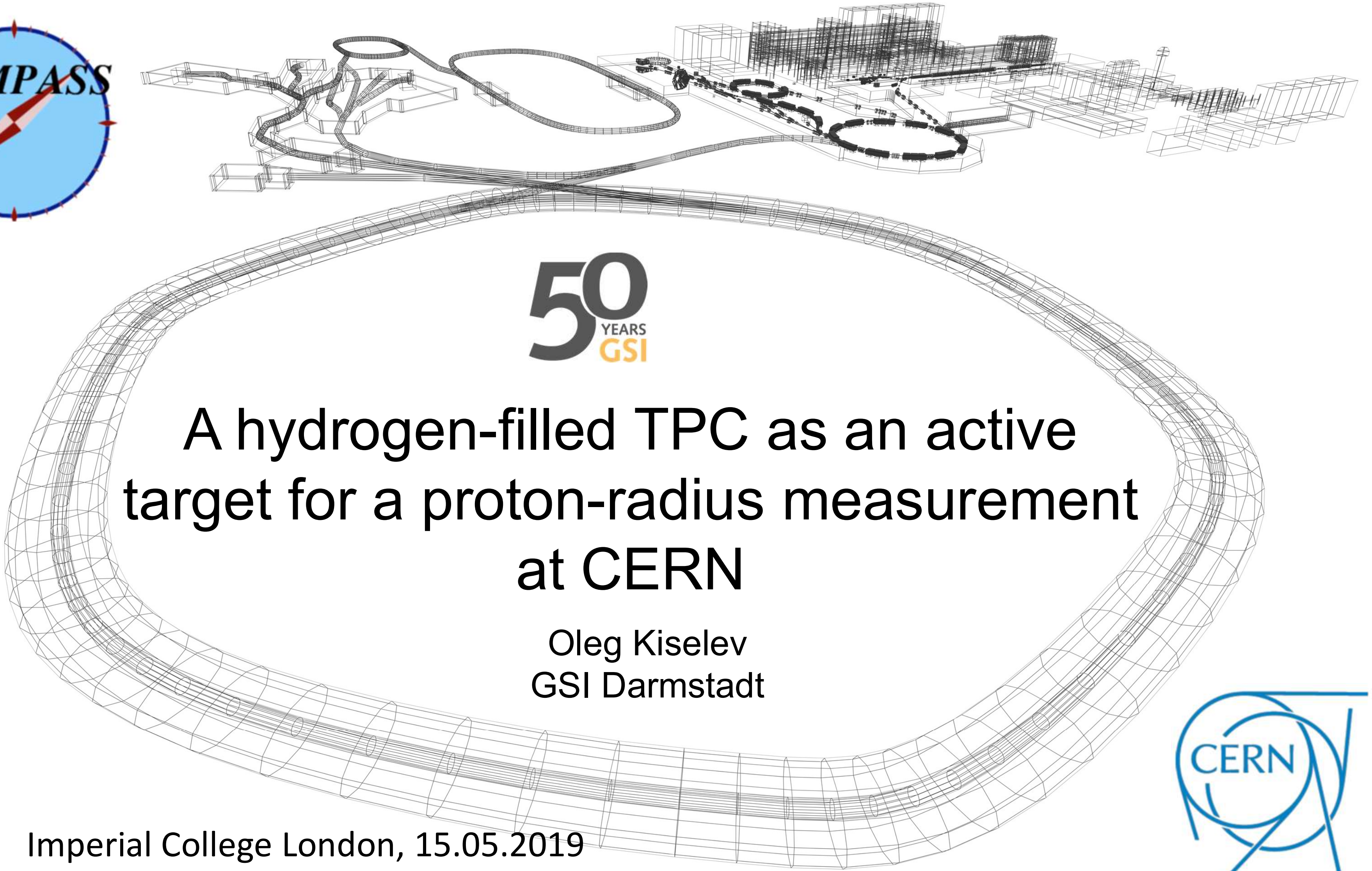
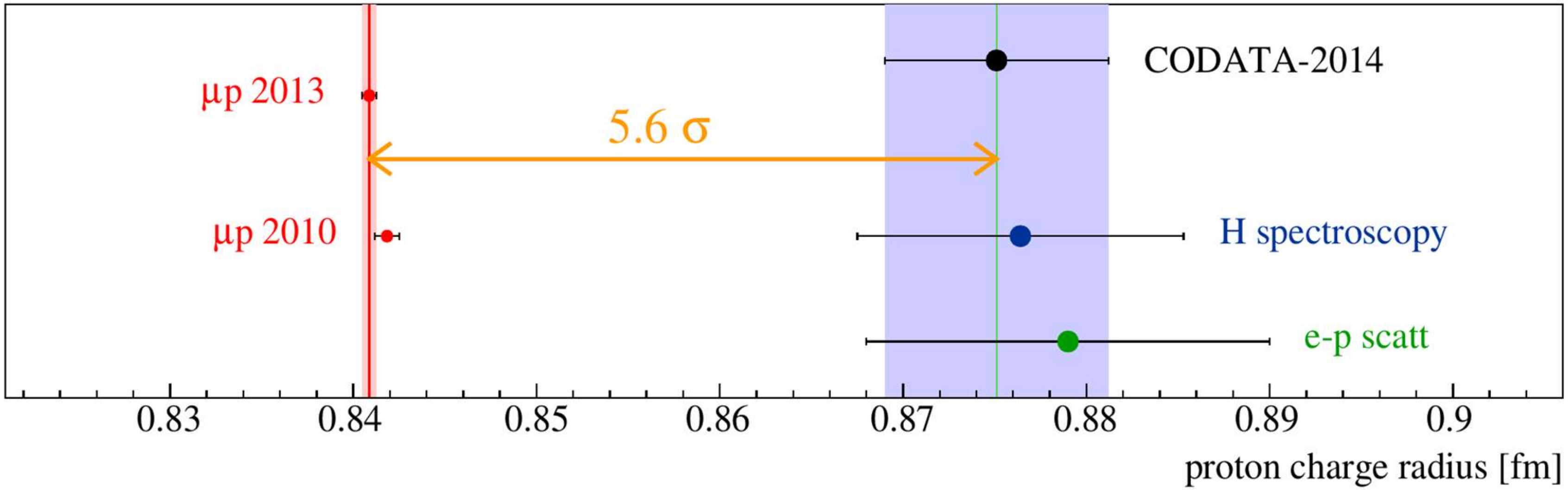


A hydrogen-filled TPC as an active target for a proton-radius measurement at CERN

Oleg Kiselev
GSI Darmstadt

Imperial College London, 15.05.2019

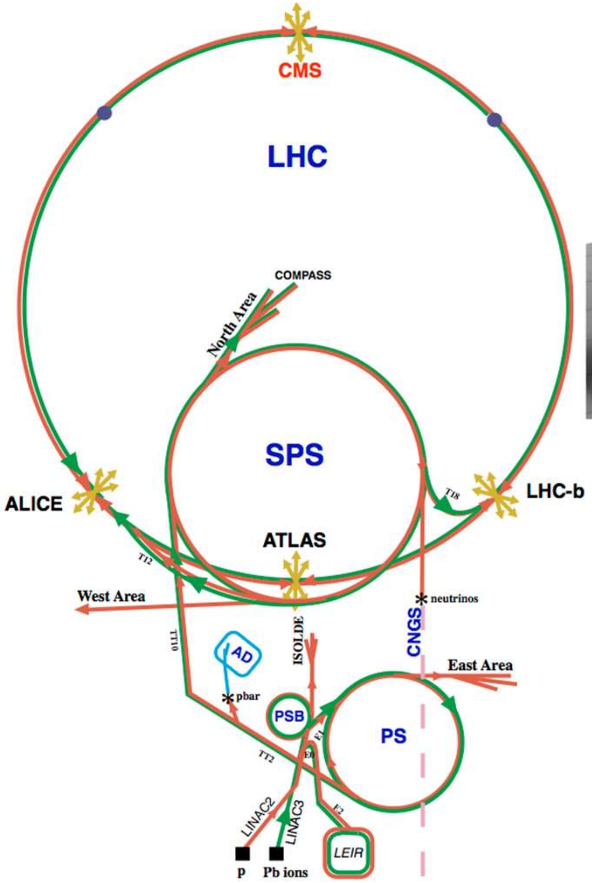
Proton radius puzzle

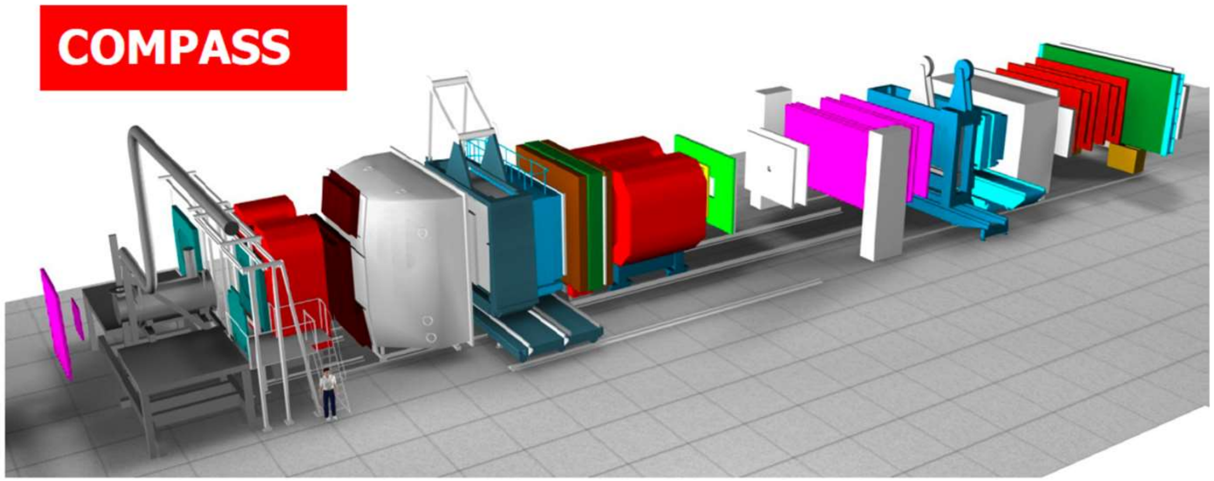


J. J. Krauth et al., 2017 [arXiv:1706.00696]

- CODATA: ep-scattering, H- and D-spectroscopy
- Too large discrepancy with muonic hydrogen experiment
- Proton radius is an important value for nuclear and particle physics

COMPASS setup



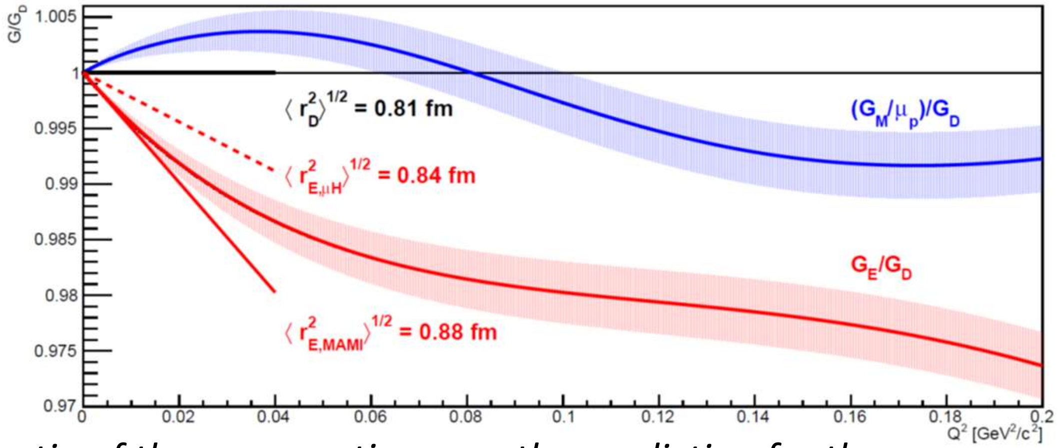


Versatile apparatus to investigate QCD:
Two-stage COMPASS spectrometer

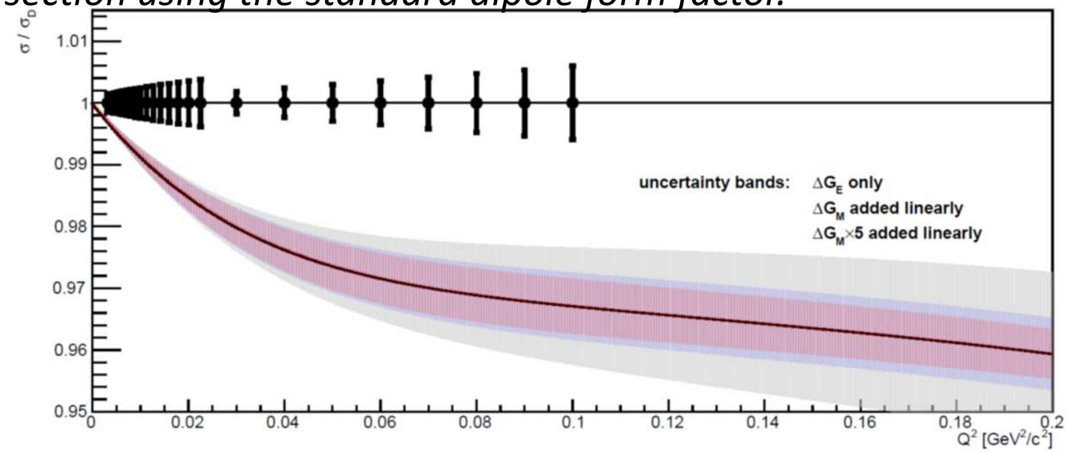
1. Muon, electron and hadron beams with momenta 20-250 GeV and intensities up to 10^8 particles per second
2. Solid-state polarised (NH3 or 6LiD), liquid hydrogen and nuclear targets
3. Powerful tracking (350 planes) and PID systems (Muon Walls, Calorimeters, RICH)

Slope of the form factor vs radius

proton form factors G_E and G_M, shown as ratio to the dipole form factor G_D



ratio of the cross section over the prediction for the cross section using the standard dipole form factor.



High beam energy is an advantage

Muon is much heavier as electron → smaller radiative corrections

Wide Q^2 -range of 10^{-4}–10^{-2} GeV^2 to prove possible models

Experimental challenges especially for low-Q^2

With COMPASS one can measure scattering angles down to ~0.1 mrad ↔ 10^{-4} GeV^2 and muon momentum

High energy muons

opportunity for new generation experiment at M2 beam line

- scatter muon beam off proton target
- measure cross-section dependence on Q^2
- obtain combination of electric and magnetic form factor $G_E^2 + \tau G_M^2$
  - form factors cannot be separated due to high beam energy
- compared to e^- beam: smaller radiative corrections
- compared to μ beam at low energies: smaller Coulomb corrections

- for soft bremsstrahlung photon energies ($E_\gamma / E_{beam} \sim 0.01$), QED radiative corrections amount to $\sim$ 15-20% for electrons, and to $\sim$ 1.5% for muons
- important contribution to the uncertainty of elastic scattering intensities: *change* of this correction over the kinematic range of interest
- check: impact of exponantiation procedure (stricty valid only for vanishing photon energies): e^-: $2 - 4\%$, μ^-: 0.1%
- integrating the radiative tail out to large fraction of beam energy: shifts the correction to smaller values, but only *increases* the uncertainty

J. Friedrich, TUM

New Letter of Intent

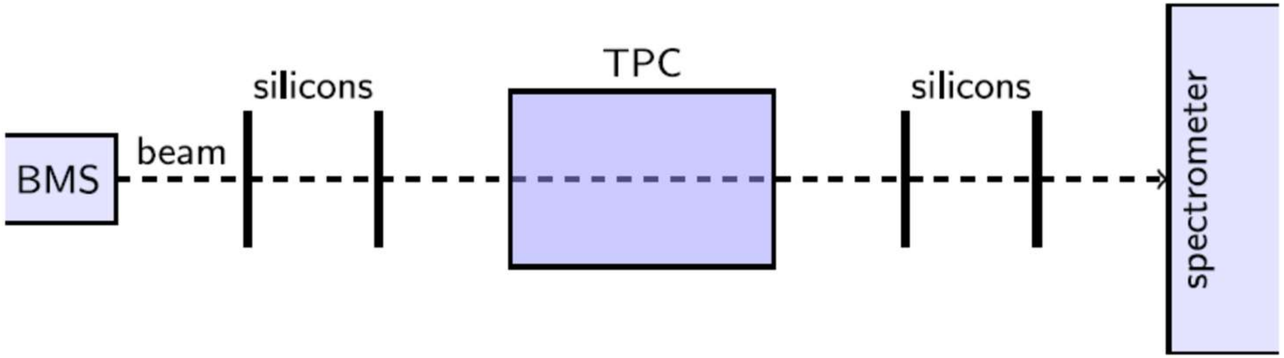
CERN-SPSC-2019-003 / SPSC-I-250
14/01/2019

A New QCD facility at the M2 beam line of the CERN SPS: COMPASS++/AMBER

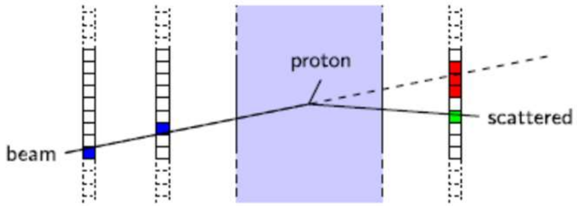
Proton radius measurement at CERN

General idea: measure the proton form factor slope using the high-energy muon beam on a high-pressure hydrogen target

In a one-year measurement, we estimate to achieve a precision of ~0.01fm on the proton radius, thus contribute to resolve the proton radius puzzle between
  0.84 fm (muonic hydrogen laser spectroscopy)
  0.88 fm (electron scattering)

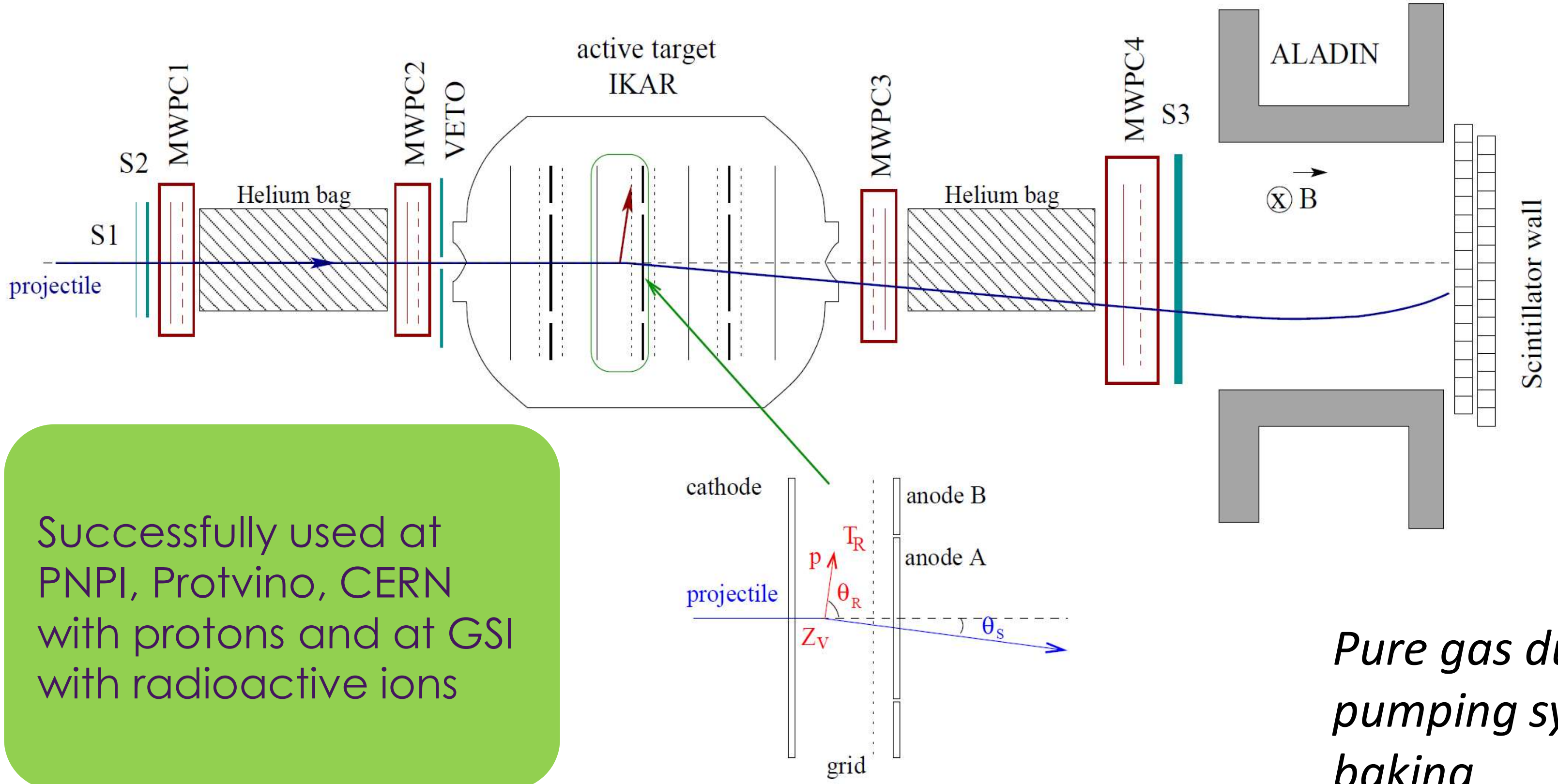


trigger concepts under study:
 triggerless readout (for 2e6…2e7/s)
 kink trigger (for Q^2 >3e-4)



Jan Friedrich

Setup with TPC/ionization chamber IKAR

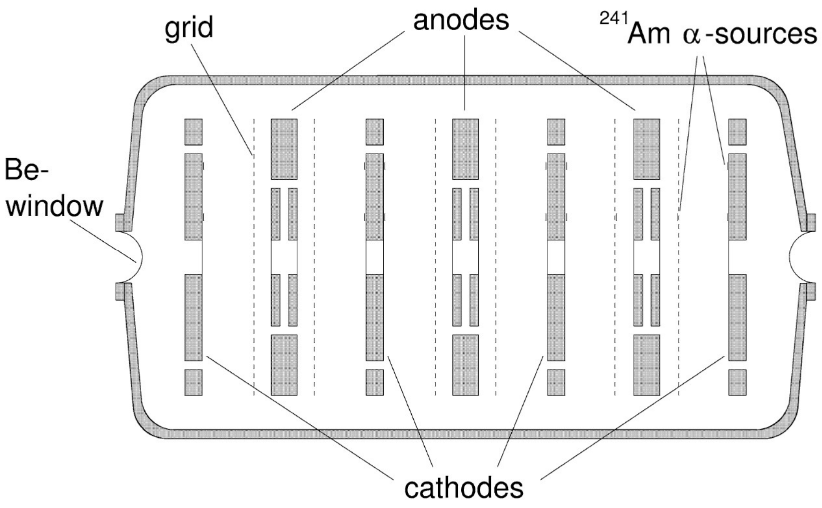


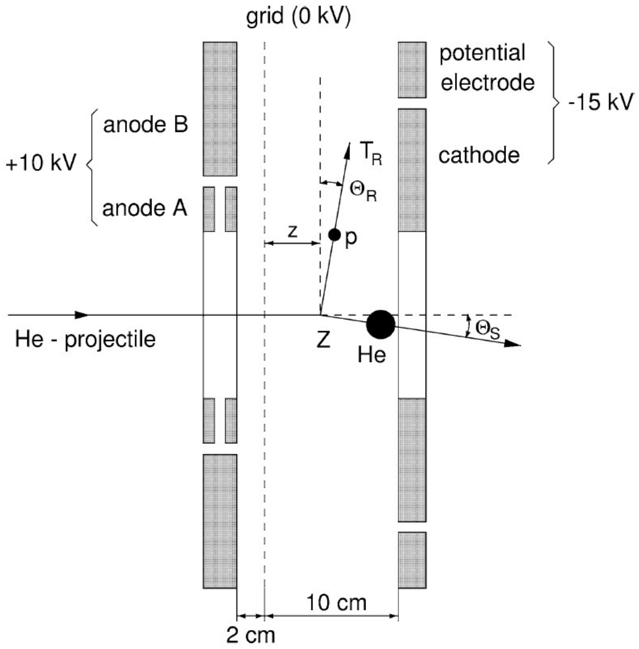
Successfully used at PNPI, Protvino, CERN with protons and at GSI with radioactive ions

Pure gas due to good pumping system and baking

“Classical” ionization chamber, built at PNPI, Gatchina
Pressure up to 10 bar
Diameter of inner anodes – 20 cm, outer – 40 cm
Normally filled with pure H_2 but D_2, He are also possible
6 independent detection modules in the same gas volume

Active target IKAR





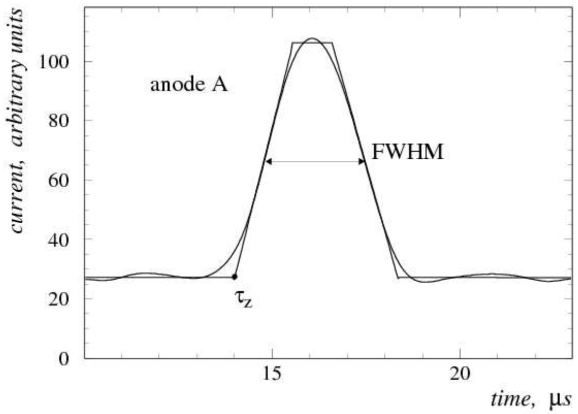
- Electrodes out of Al, 140 μm
- Be windows, 0.5 mm
- Energy and drift time measured by FADCs
- Energy resolution – 35-40 keV
- Energy threshold <100 keV
- Dynamic range for protons – 5.2 MeV

<u>Pulse shape analysis</u>

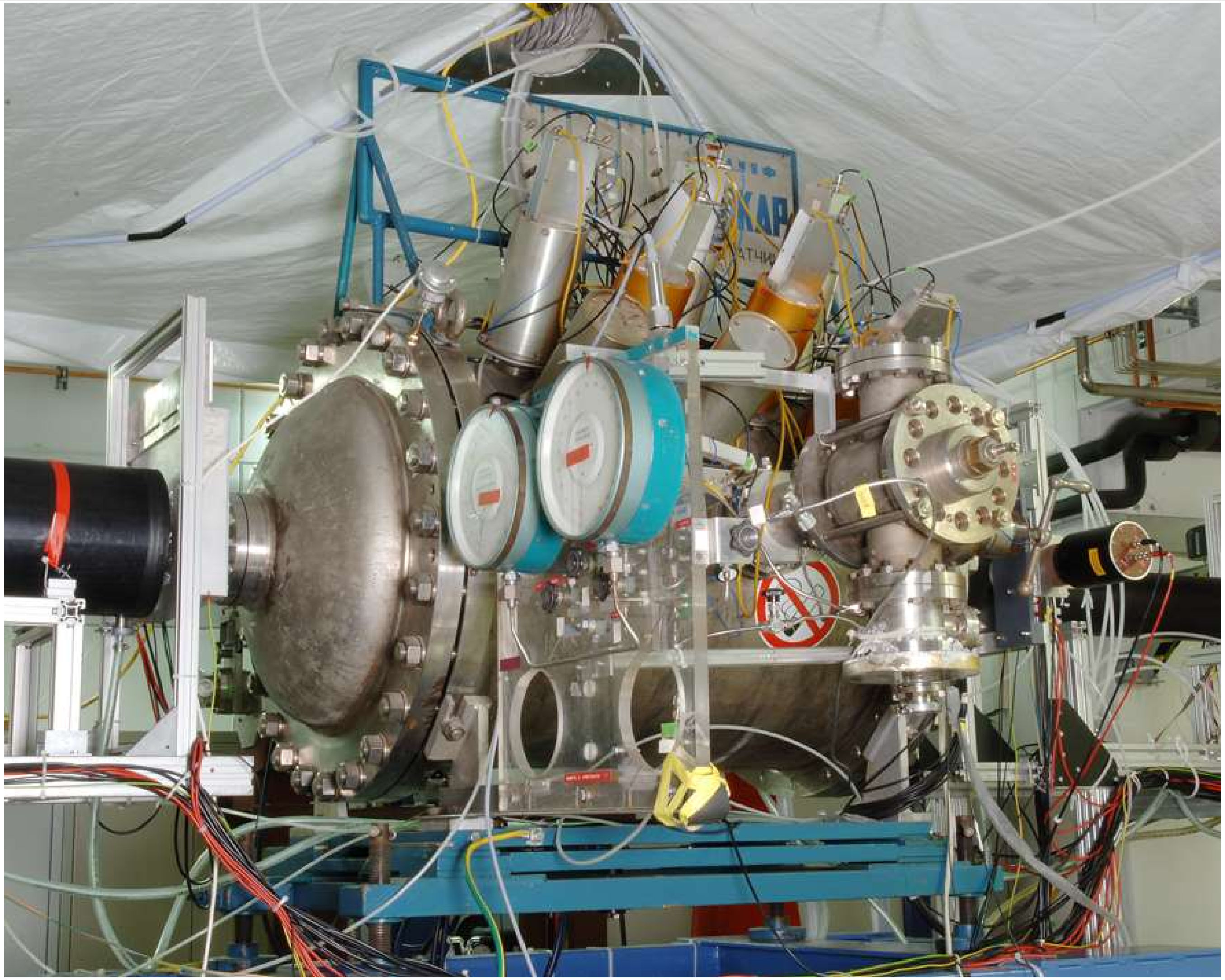
integral - recoil energy T_R

risetime - recoil angle Θ_R ($\delta\Theta_{R\ FWHM} < 0.6°$)

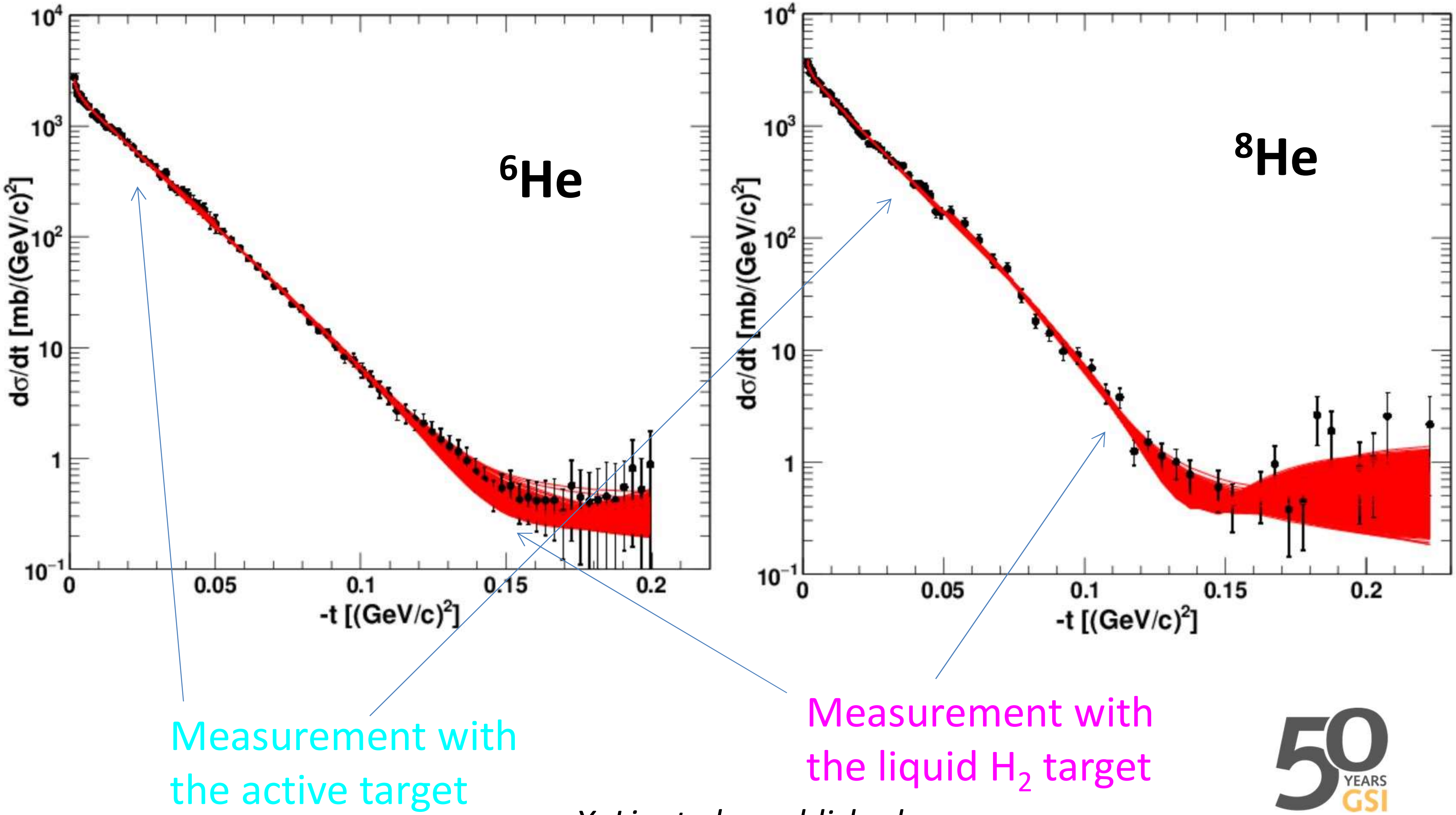
start - vertex point Z_V ($\delta z_{FWHM} < 110\ \mu m$)



IKAR at GSI, Darmstadt

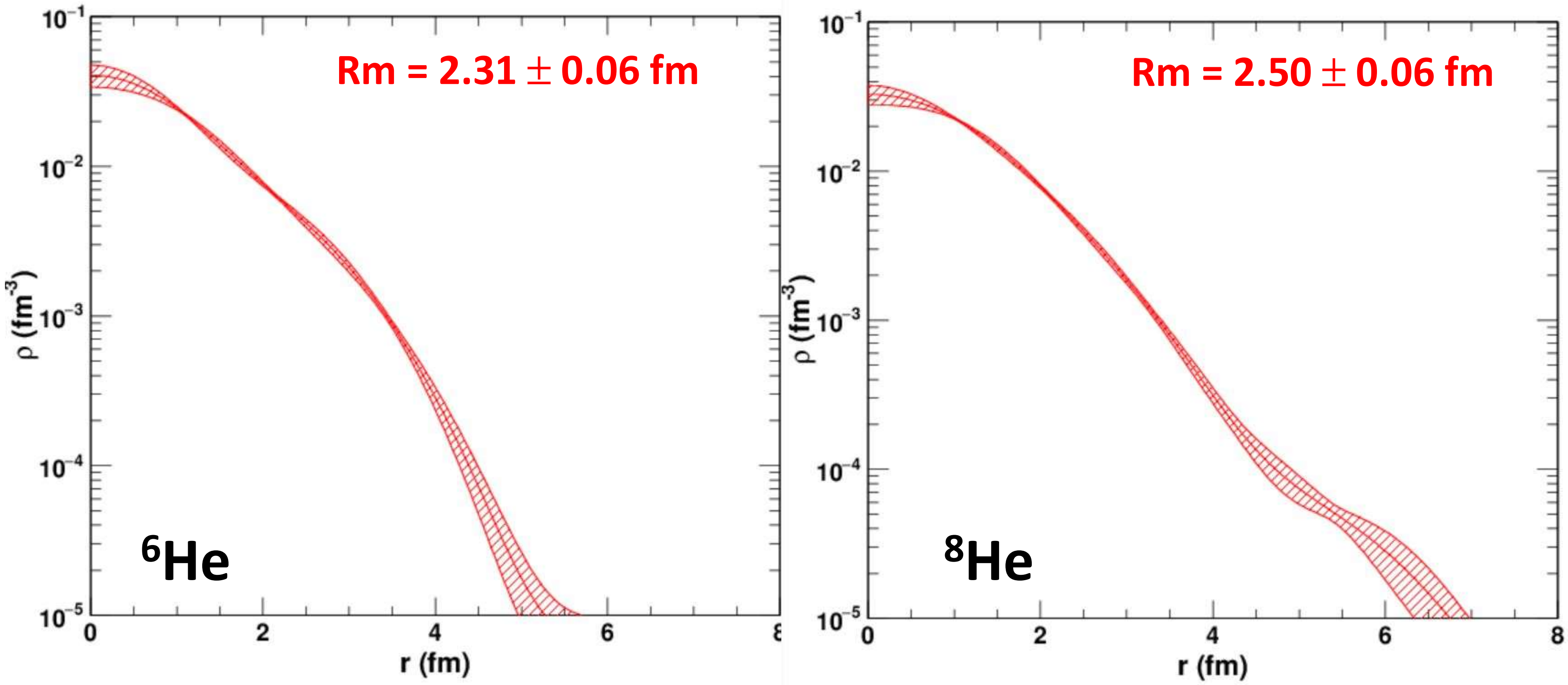


SOG fits of $p^{6,8}He$ elastic scattering data



X. Liu, to be published

SOG analysis - matter density distributions of ^6He and ^8He



2.44 ± 0.07 fm (^{6}He) and 2.50 ± 0.08 fm (^{8}He) from L. Chung et al., Phys. Rev. C 92, 034608 (2015). (full data set)

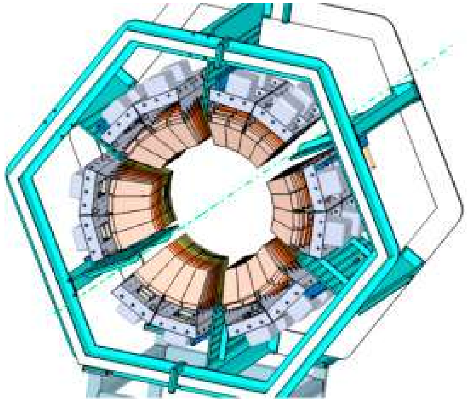
2.30 ± 0.07 fm (^{6}He) and 2.45 ± 0.07 fm (^{8}He) from G.D. Alkhazov et al., Phys. Rev. Lett. 78, 2313 (1997). (low-t data set)

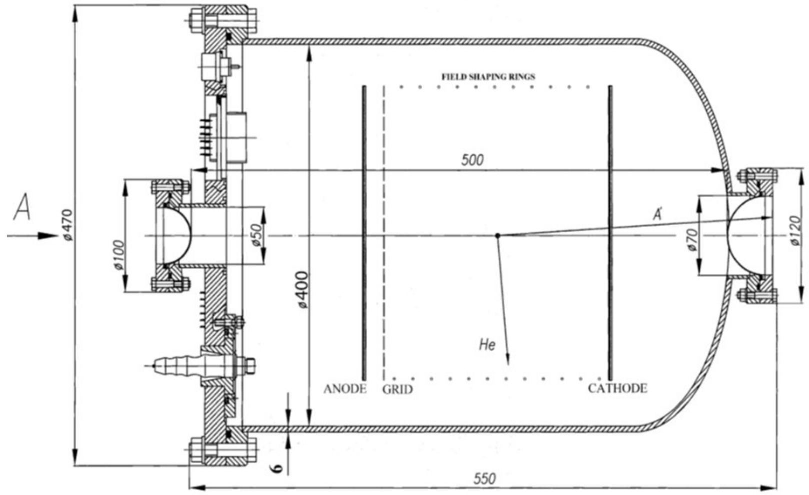
SOG analysis provides similar value of R_m as phenomenological analysis within errors but it is model independent

X. Liu, to be published

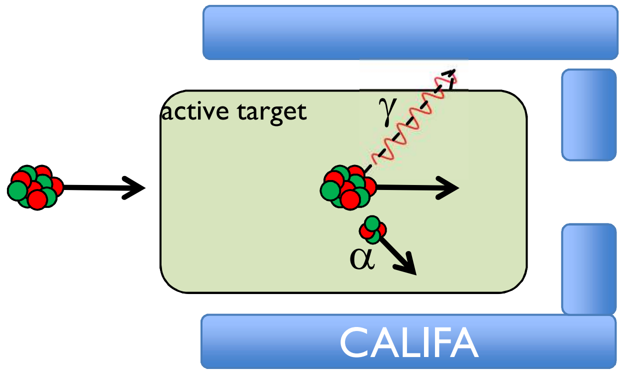
TPC ACTAF2 inside calorimeter CALIFA, R3B/FAIR

- Investigation of low-lying dipole strength in inelastic α scattering
- Experiments on stable nuclei show significant difference to (γ,γ')
- Extension to unstable nuclei in inverse kinematics



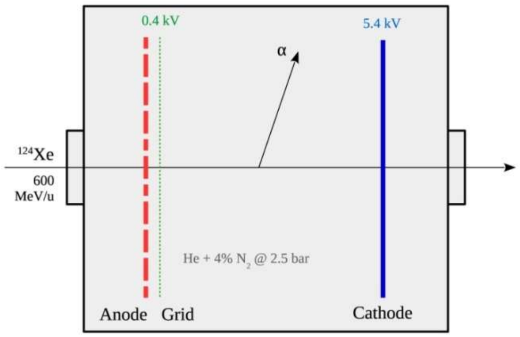


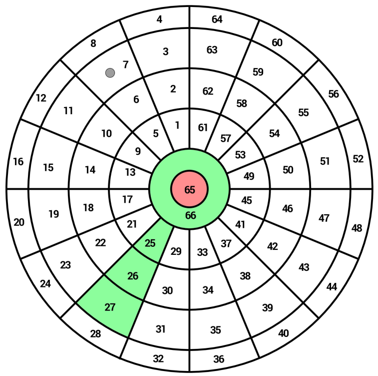
Gas pressure up to 10 bar
Volume ~40 l
Can be filled with He, H_2, D_2

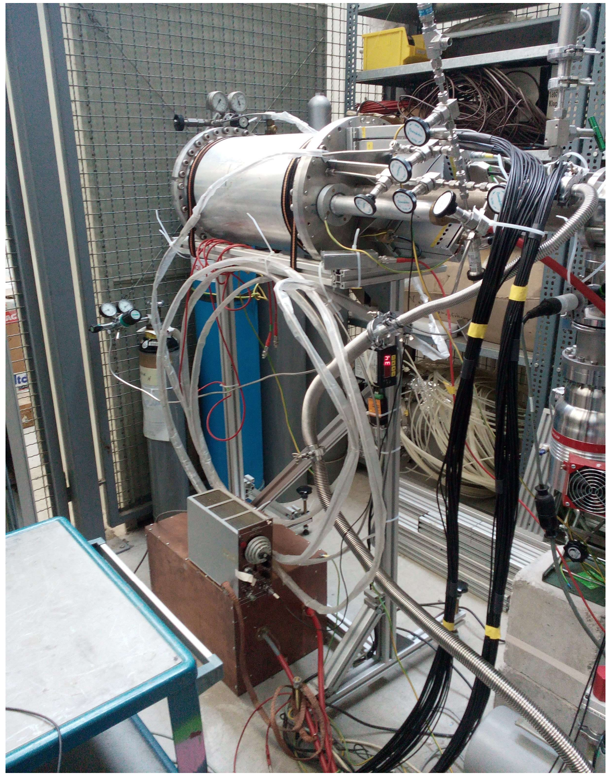


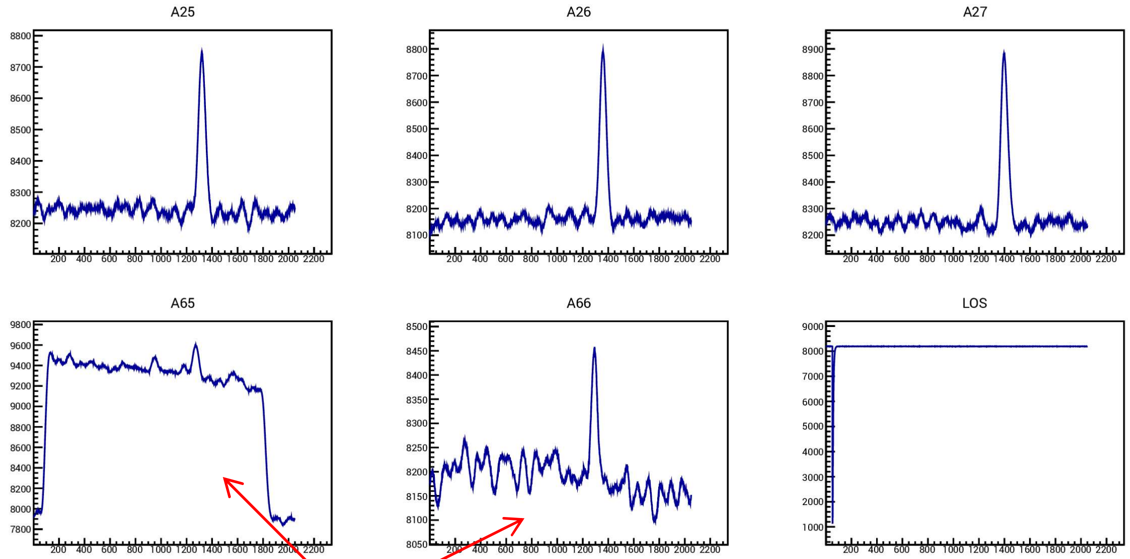
- Coincident determination of excitation and decay energy
- Allows selection of decay channel
- Clean separation of E1 excitation in $(\alpha,\alpha'\gamma)$ experiments

^{124}Xe(α,α') measurement with ACTAF2





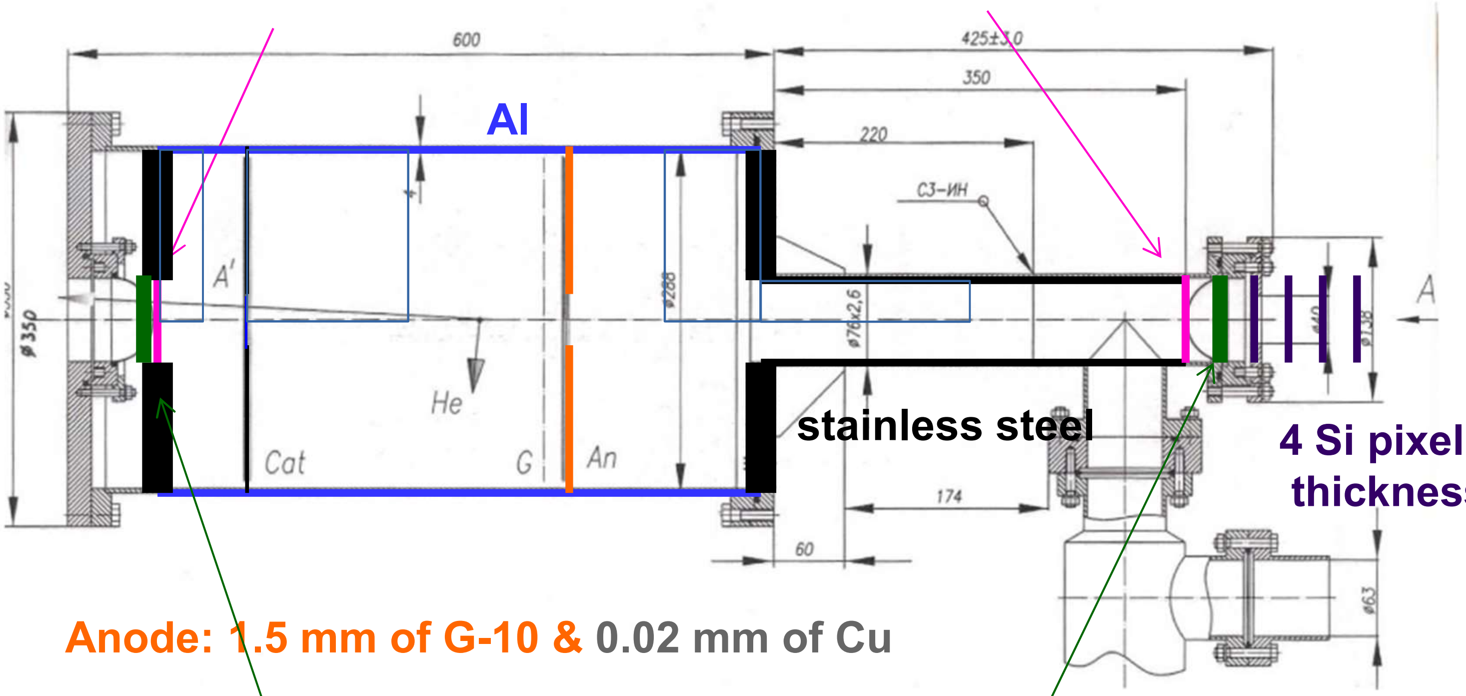




Beam electrodes

ACTAF2/R3B prototype – beam test at MAMI, 2017

Be windows of 0.5 mm thickness



T(e) = 720 MeV

4 Si pixel detectors, thickness 50 μm

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

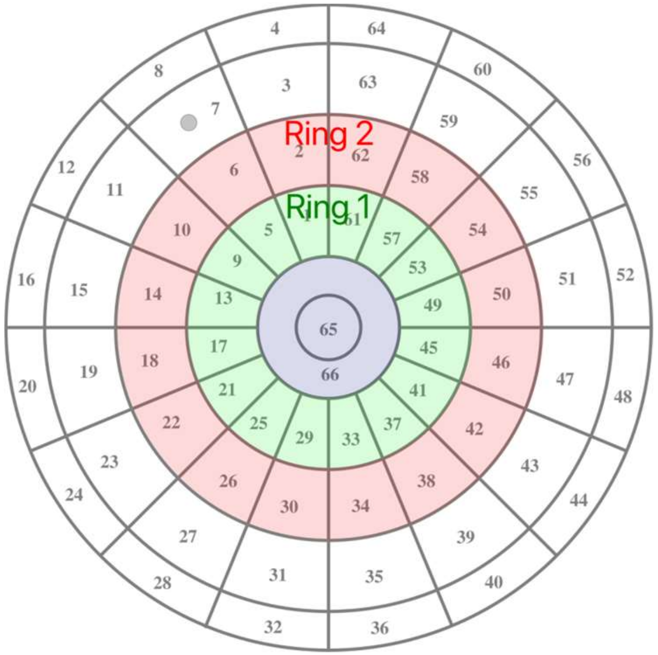
Cathode: 1 mm of steel & 0.02 mm of Al

Gas - 96% He + 4% N_2 in 2017 and 100% H_2 in 2019, pressure 10 atm

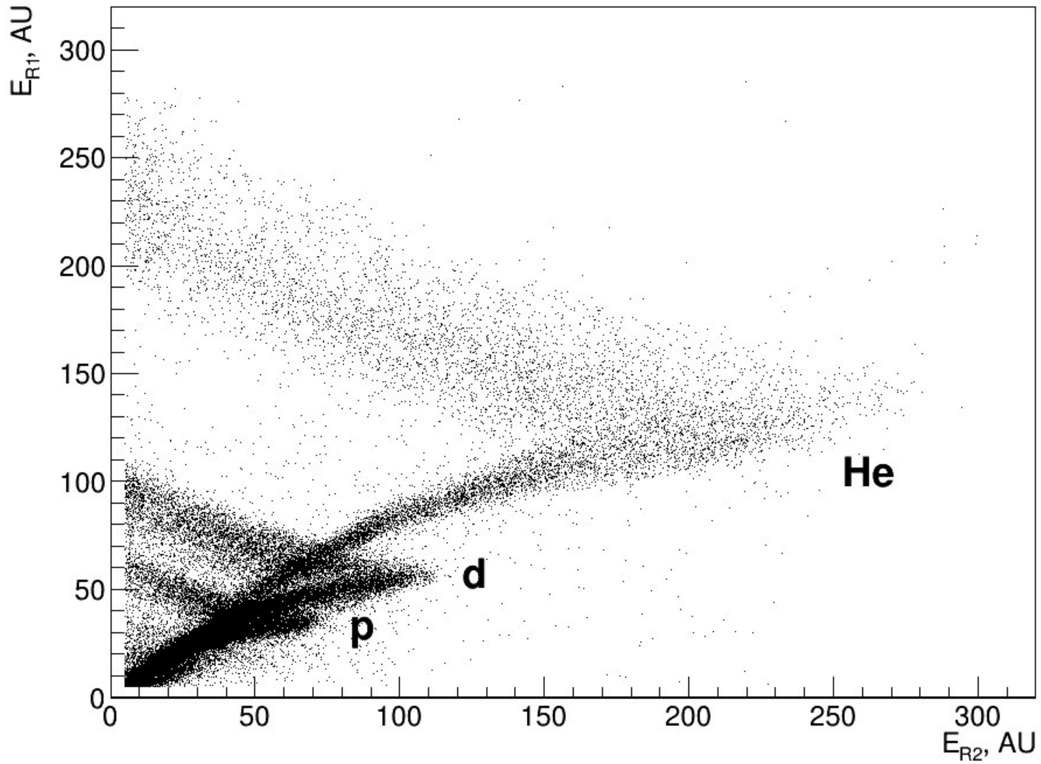
z

Scintillators, 2 mm

E-p scattering, energy correlations



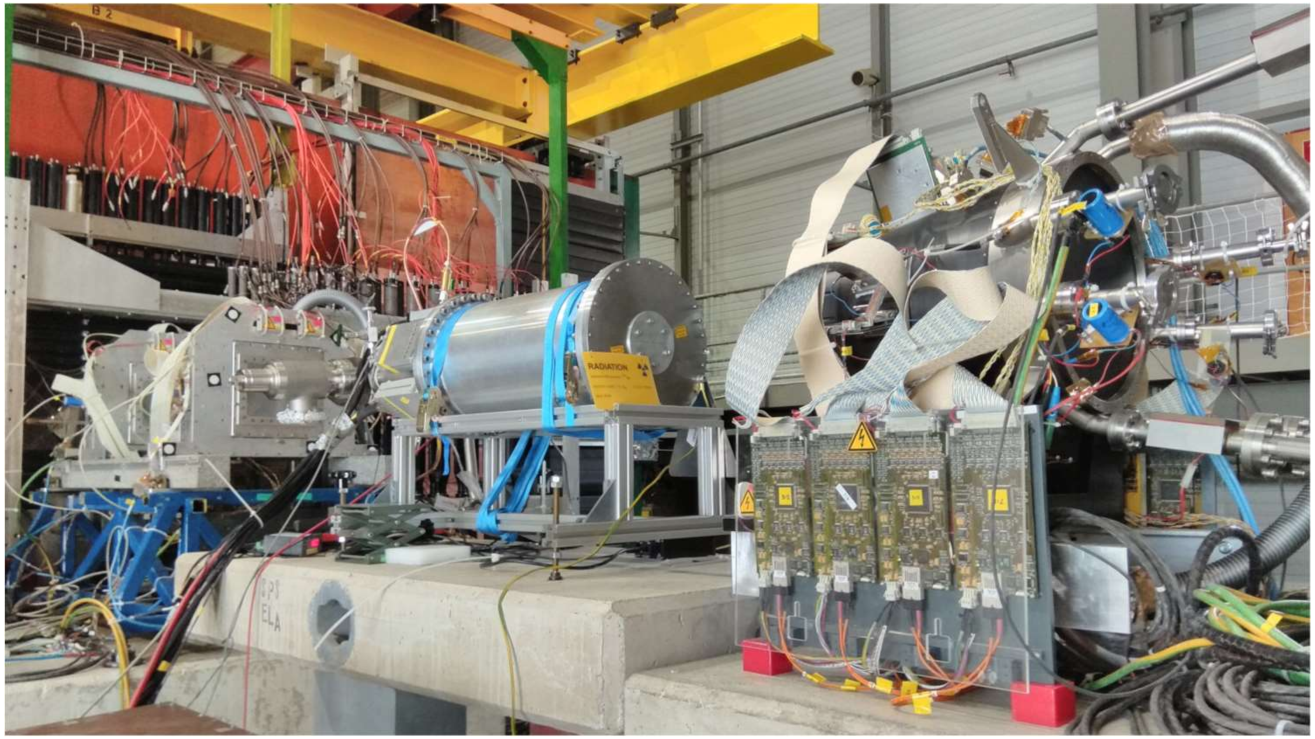
Energies on anode rings 1 and 2



1 AU = 22 keV

Energies correspond to those calculated by SRIM

Test run at COMPASS/CERN, μ-p scattering



ACTAF2 TPC between 4 tracking stations

Tracking via 70x40 mm Si microstrip detectors

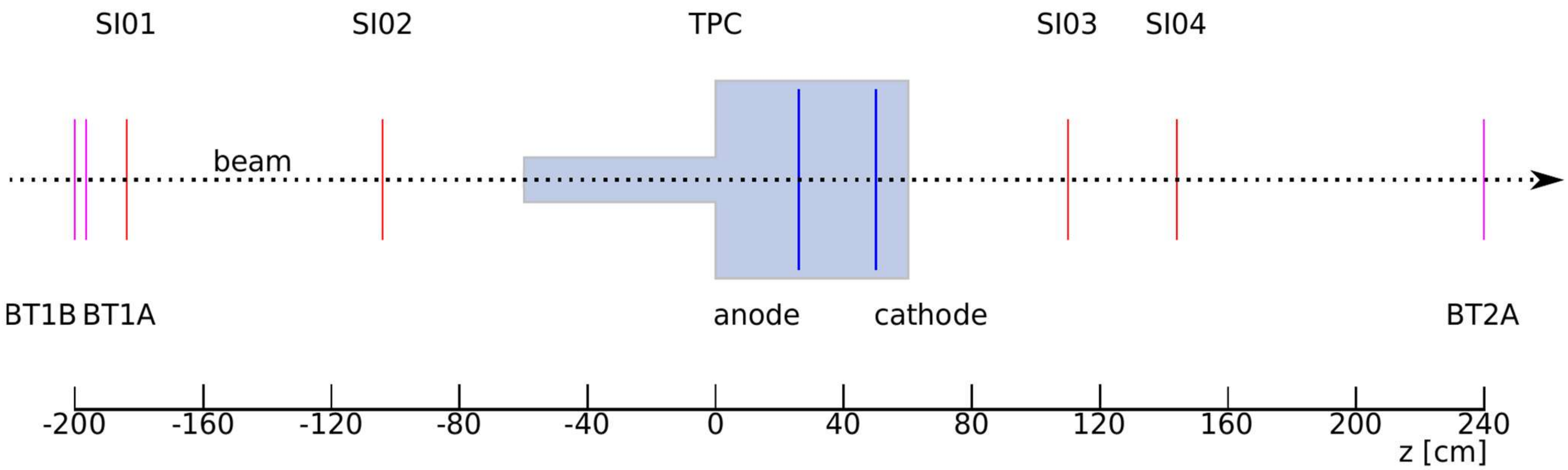
Muon rate – up to 2 MHz

E_{μ} = 190 GeV

Wide beam (RMS ≈ 20 cm)

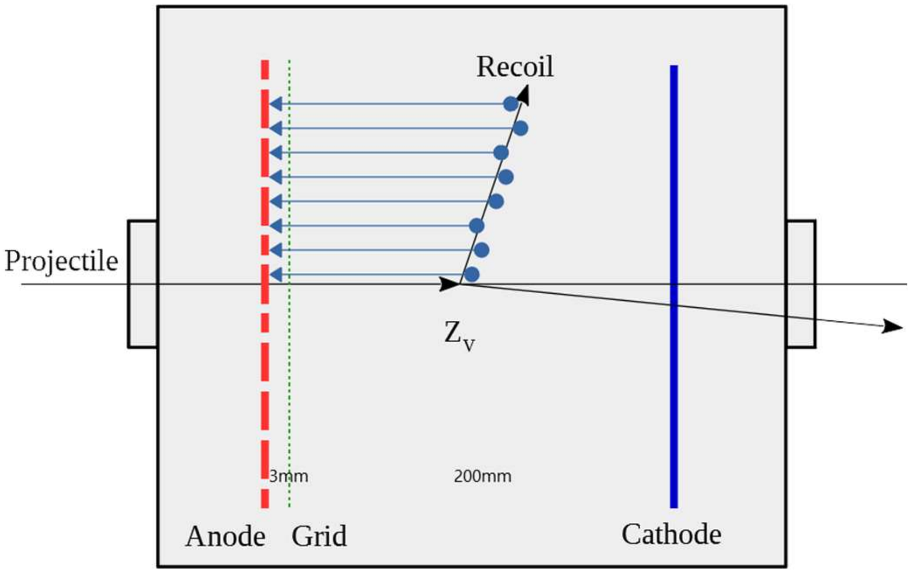
Duty cycle: ~20% (spill — 5 s)

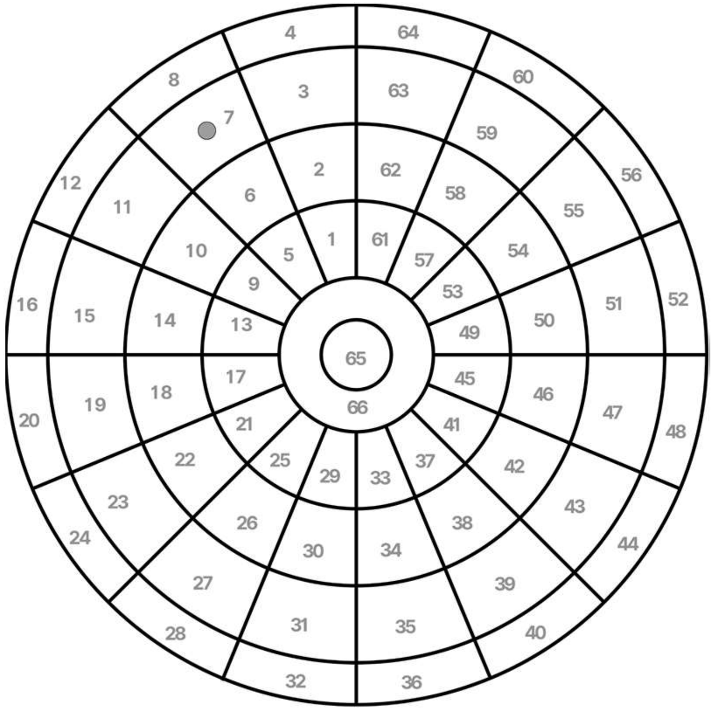
Scheme of feasibility test run, COMPASS/CERN, 2018



- Beam rate and background studies
- TPC performance with broad beam
- Recoil identification
- Correlation between TPC and tracking system
- TPC and the rest of the detectors use different DAQ, timestamped
- Short baseline limits $Q^2 \sim 3\times10^{-3}$ GeV^2

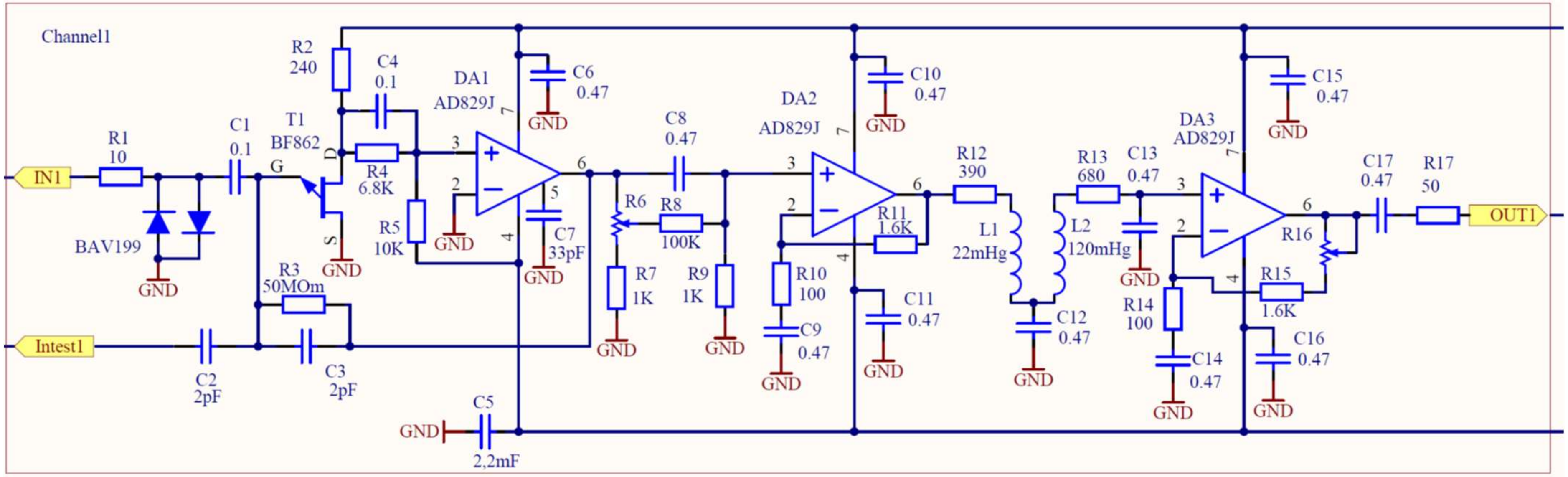
TPC parameters, April 2018, CERN





- Gas: H_2 (purity 6.0)
- p = 1, 4, 8 bar
- L_{CG} = 200 mm
- V_C = 18 kV
- V_G = 1 kV
- $t_{CG} \approx 60\ \mu s$

Preamplifier - shaper



- Low noise preamplifier
- Best available operational amplifier (AD891) for this setup
- Signal shaping for better signal/noise
- 16-ch boards

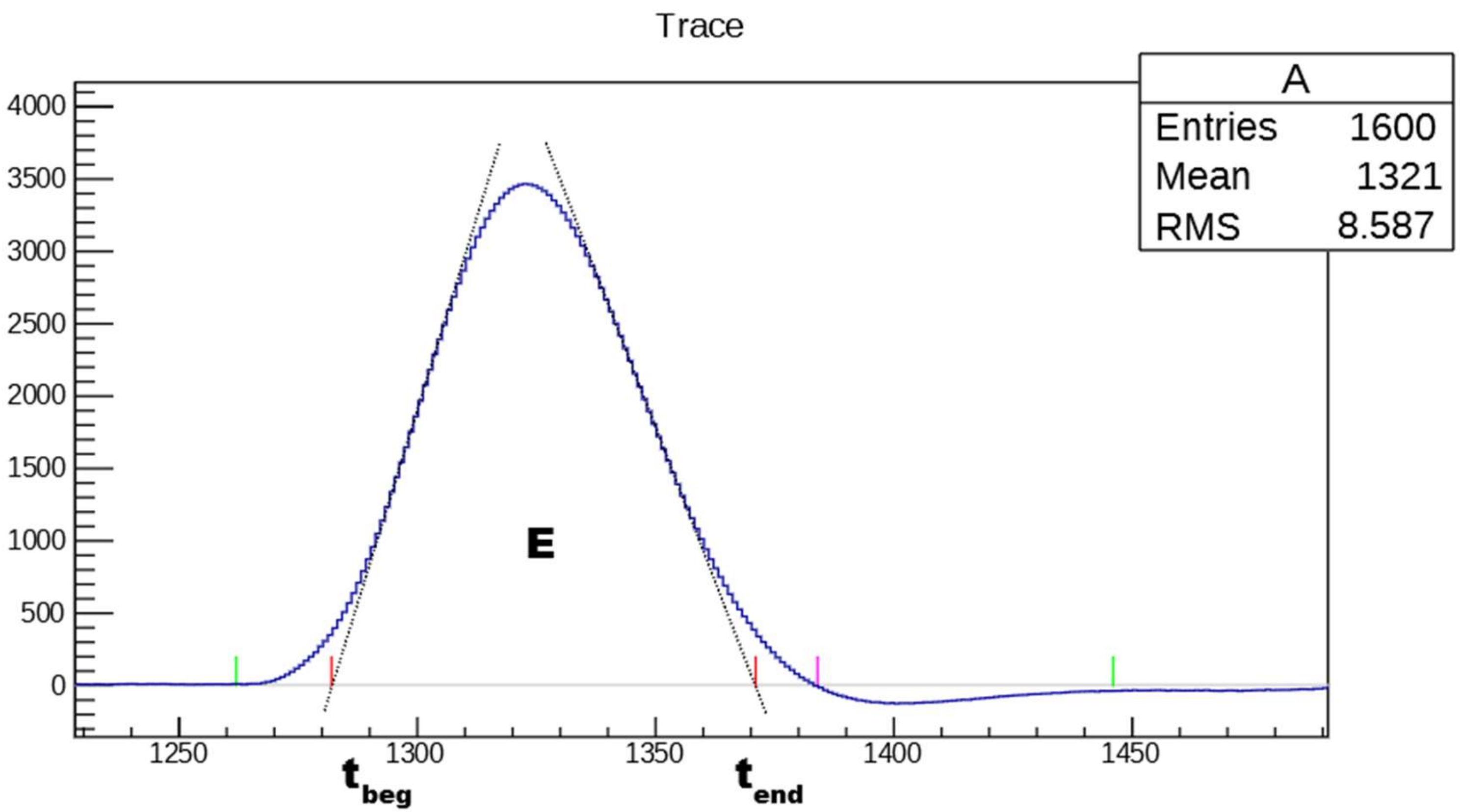
PNPI, Gatchina

No gas amplification -> very small signals

FADC/waveform digitizer

- Struck SIS3316 VME FADC
- 14 bit @ 250 MHz (we use at 25 MHz)
- 16 channels
- Range: -2,5 – +2,5 V
- Modes: external trigger or self-triggering
- Clock PLL lock
- Reading of raw ADC values or 2/4/8 points averaging
- Energy threshold via Moving Average Window (MAW)
- Readout via VME bus or optics
- Raw data readout or signal processing with imbedded FPGA

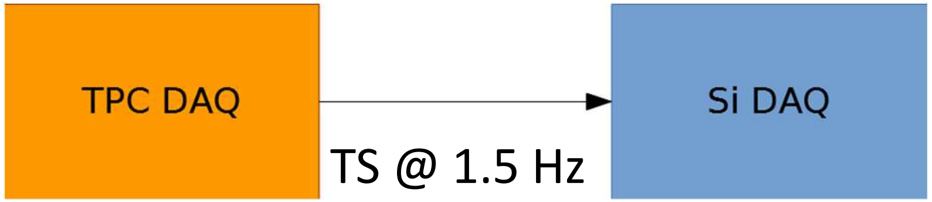
Waveforms

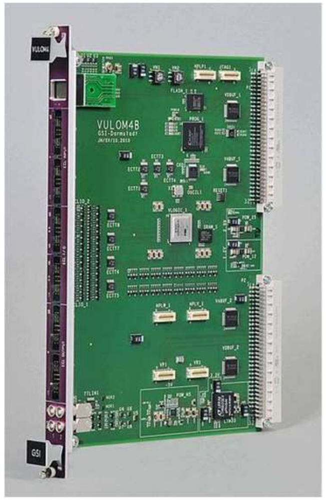


- Waveforms have all information about the noise and signal
- Amplitude, energy/integral, time of signal, pile-up can be extracted
- Principally – hardware processing (with corresponding firmware)

Timestamp/event syncronisation

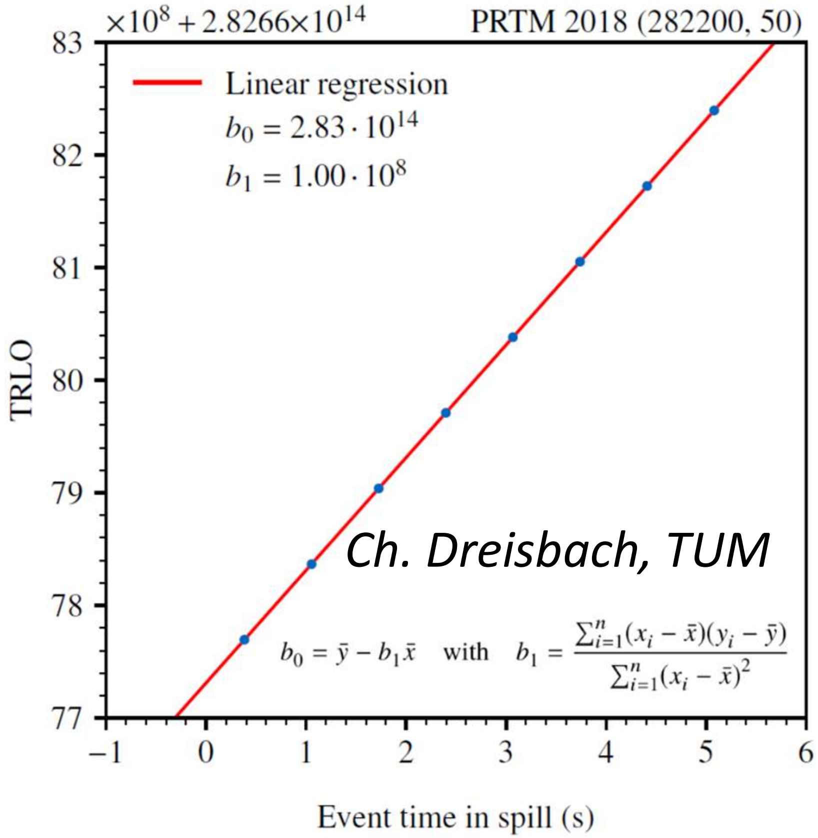
Two independent DAQs





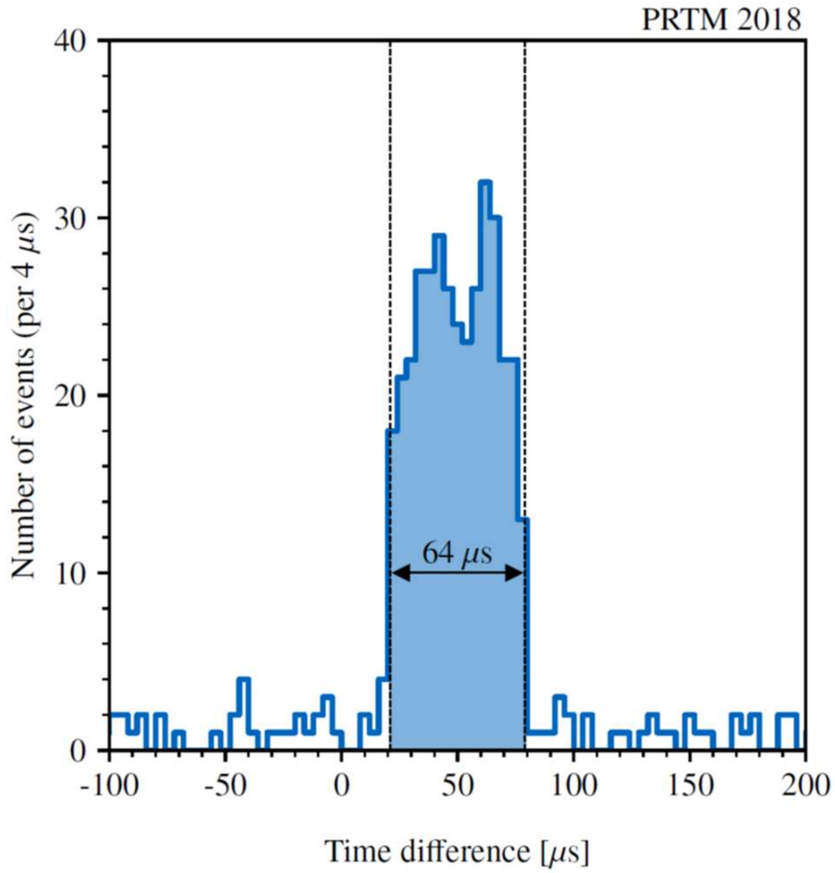
- 32 bit «watch/clock» @100 MHz
- Sending to any device, saving the timestamps
- Si DAQ – linear interpolation between the timestamps
- Offline time stamps matching between Si and TPC events

VULOM4B - logic module with FPGA



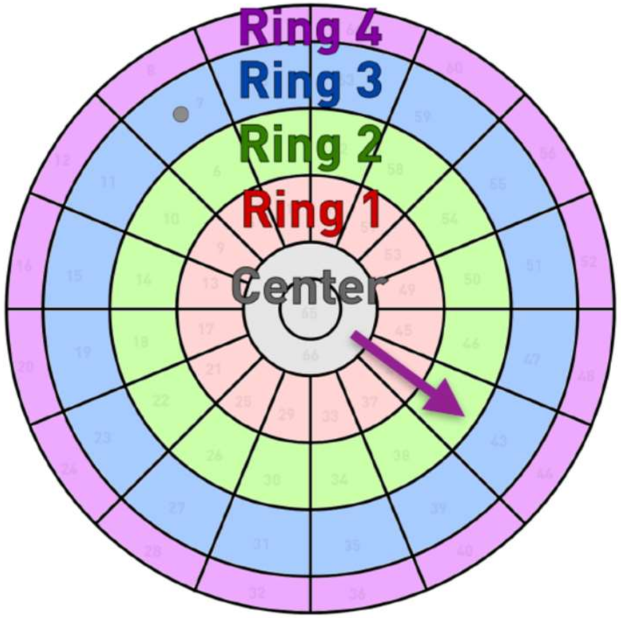
Events syncronyzed

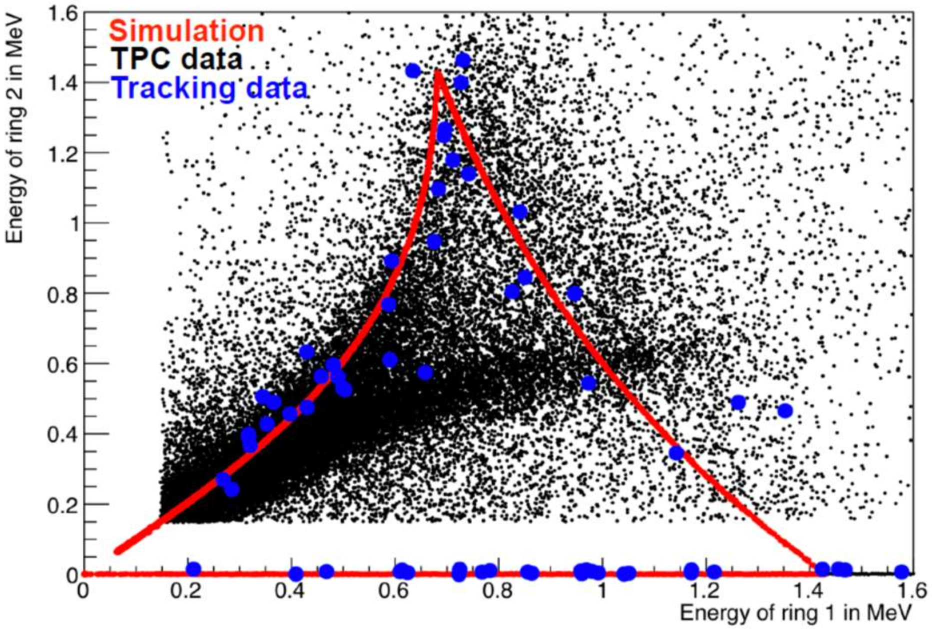
- Timestamp sync – TPC DAQ and Si/trigger DAQ
- Files recorded independently, processed and sync offline
- Width of the coincidence peak - drift time of the TPC (~64 μs)
- Primary vertex–Z correlation with the active volume of the TPC



Ch. Dreisbach, TUM

Matched events – energy correlations





Use kinematics for energy correlation

The scattering angle of the scattered muon and deposit energy in the TPC of the recoil proton can be matched.

- Energy loss correlation between single rings
- Simulation shows expected behaviour
- Consistency with Silicon data

Use kinematics measured by TPC and tracking for precise event matching

Ch. Dreisbach, TUM

Count rates during the test run

Detector	TPC	S*	S_e	Si*
Mean	16 Hz	64 kHz	640 kHz	22 kHz
Max	46 Hz	370 kHz	3.7 MHz	43 kHz

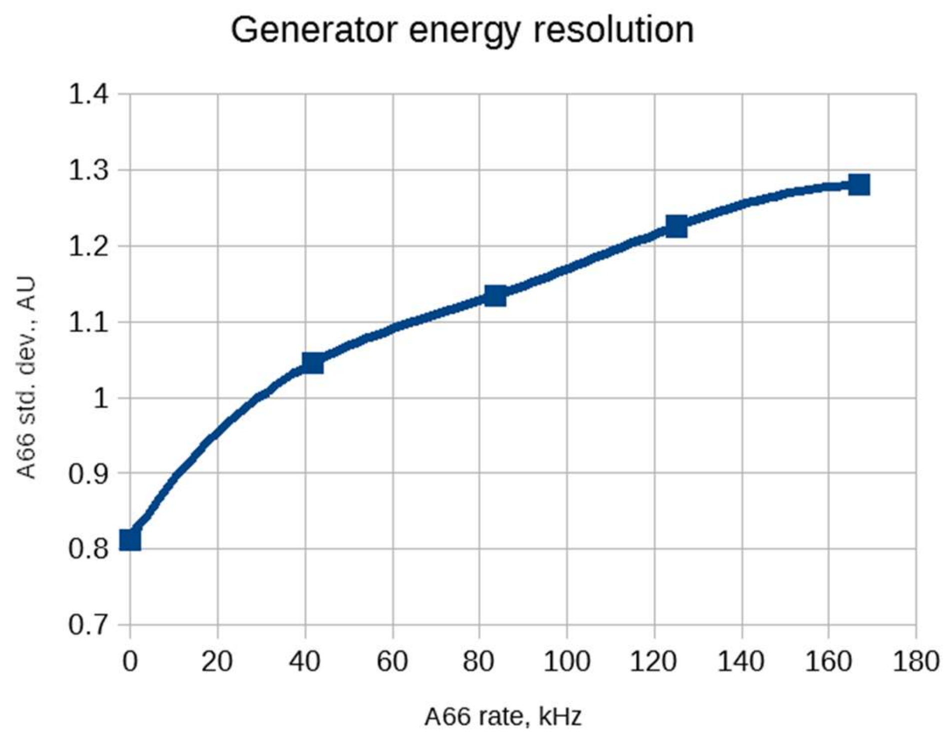
Events total: 4 600 000

With thr. 300 keV: 1 100 000 With thr. 200 keV: 3 500 000

8 bar: 4 290 000 4 bar: 310 000

- * area - 10% of full anode area of TPC
- TPC has a self-triggering, independent DAQ
- All raw waveforms were stored

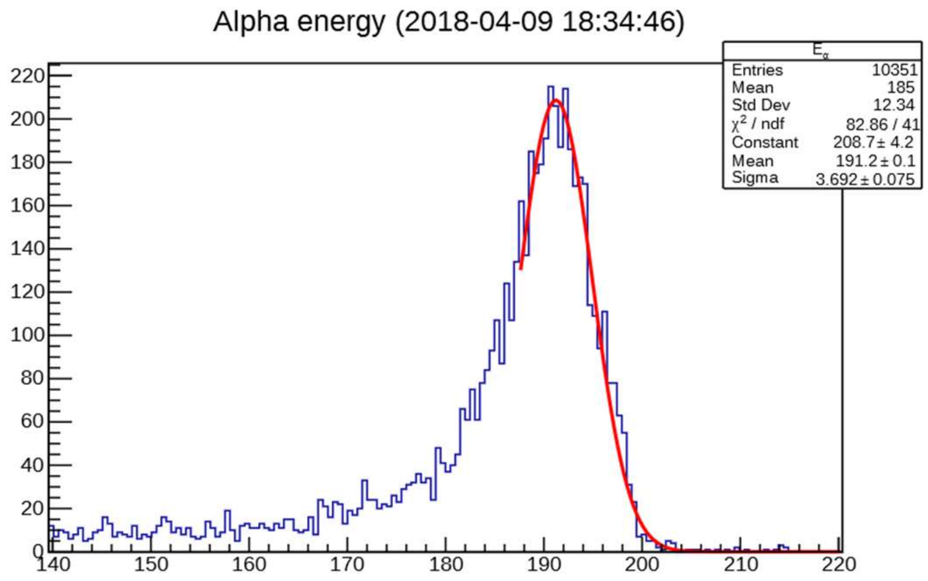
TPC energy resolution vs beam rate

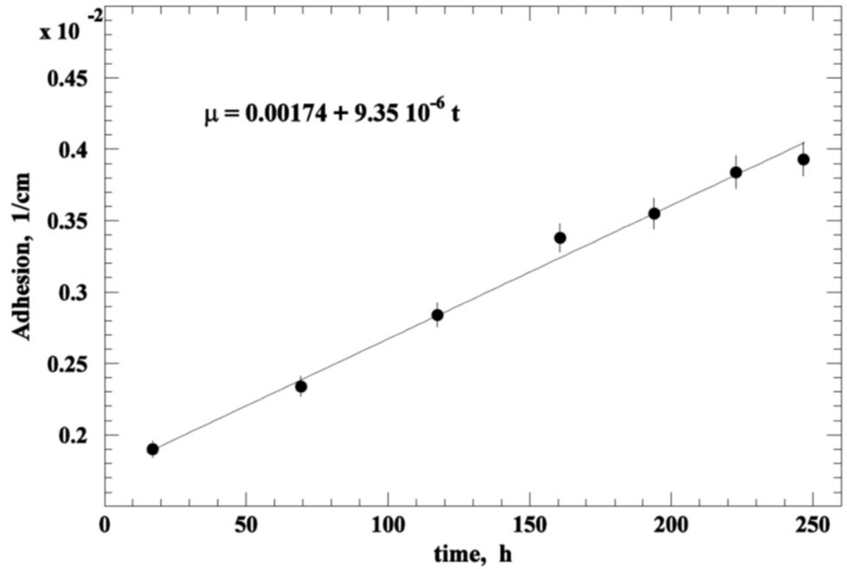


Threshold 200 keV and lower is possible

- Test pulses injected to all anodes at the same time
- Measured vs beam intensity
- Beam covered the whole TPC volume
- At 300 kHz beam rate energy resolution ~40 keV

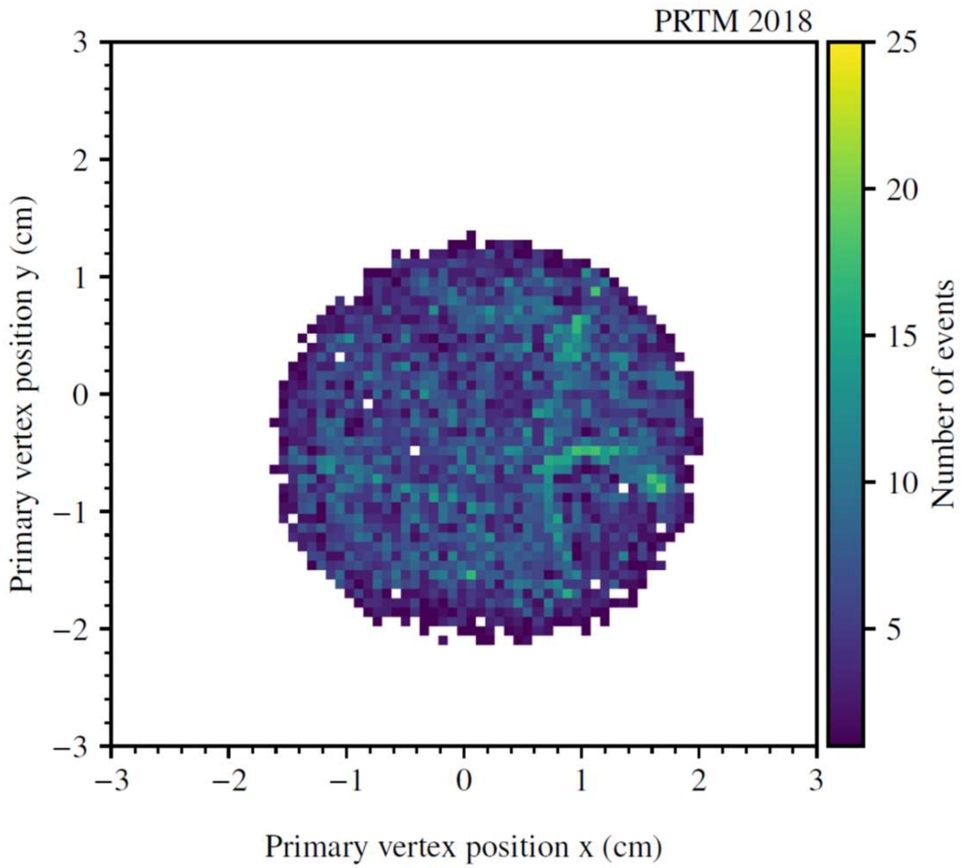
Gas quality check



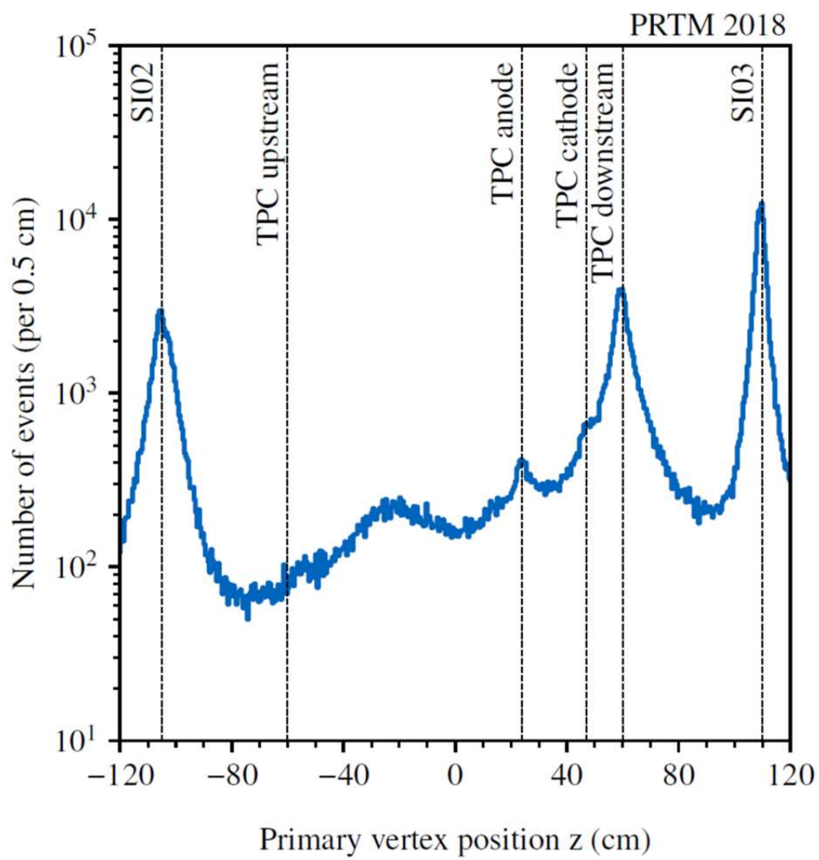


- α-spectrum measured several times per day
- Shift of the maximum ~1%/day (~1 ppm O_2)
- Refilling – once per week
- Due to good pumping and periodical baking, cleanness is fulfilled without any recirculation/purification

Vertexes from the Si tracker



All cuts applied



All cuts except z position

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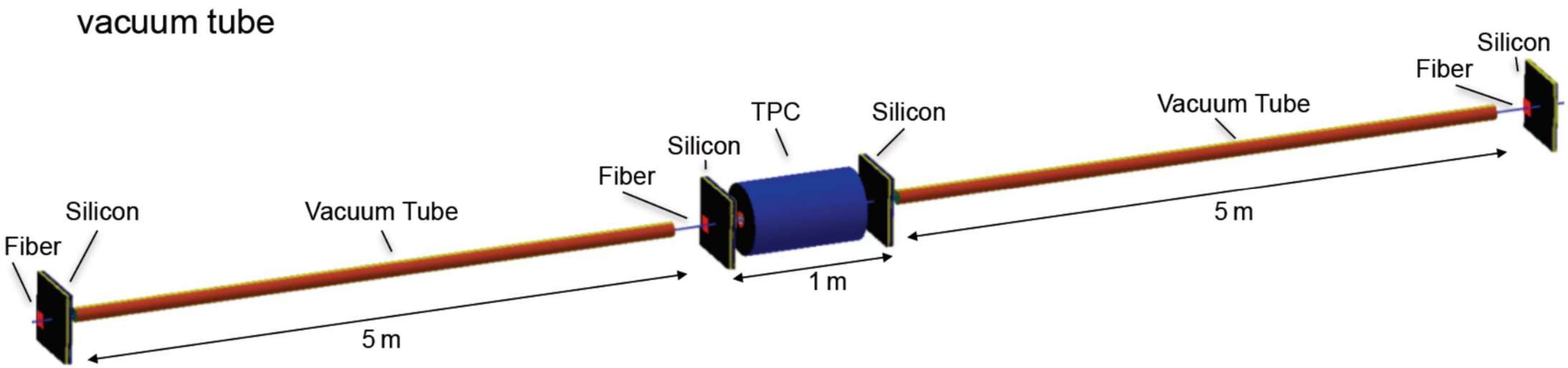
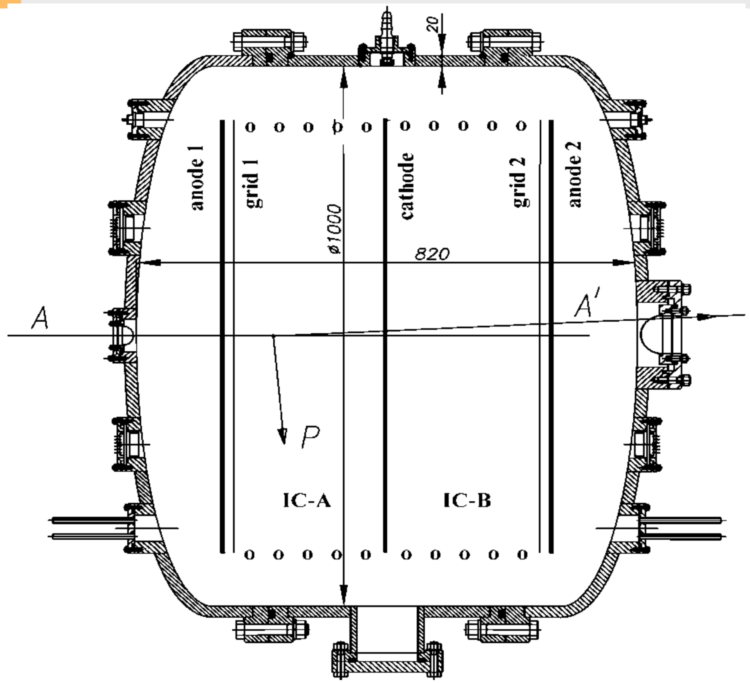
Main experiment at CERN



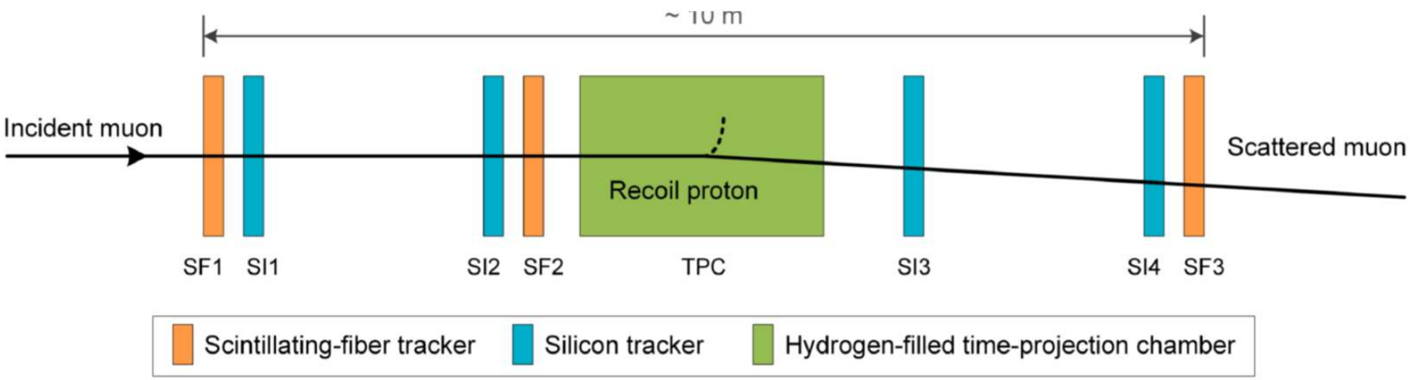
- Beam size: σ ≈ 8 mm
- Energy: 100 GeV
- Scattering angles: 0.3 – 2 mrad (Q^2 = 0.001–0.04 GeV^2/c^2)
- Base: 5 м — scattering 1.5 – 10 mm
- Si detectors Δx < 10 µm (Δθ < 2 µrad at 5 m)
- New fast electronics for the Si detectors
- Scattering trigger («kink trigger» — SciFi detector)

- **New active target: diameter — 800 мм, 20 bar H_2**

Large TPC as an active target



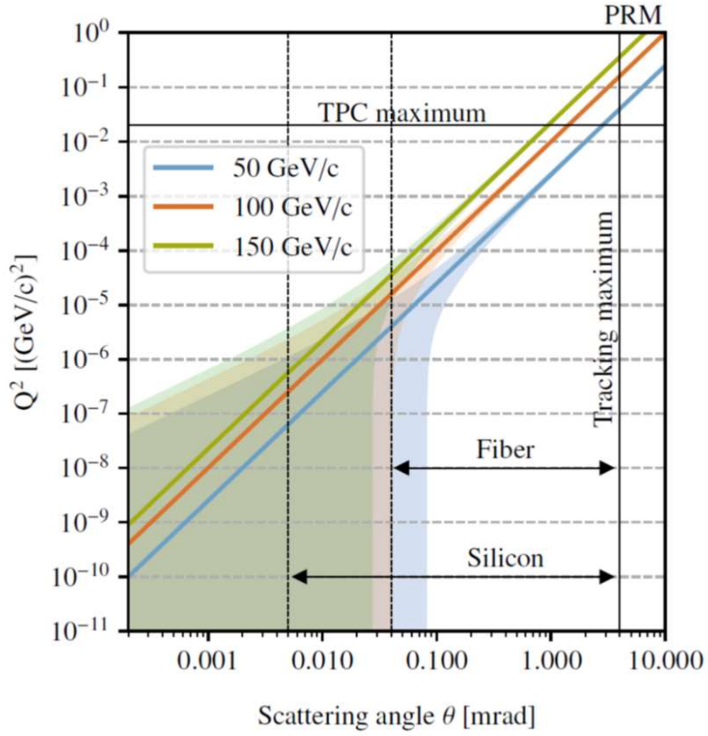
- 820 mm long, inner diameter 1000 mm
- Total volume 600 liters
- Internal surfaces electrically polished
- Gas pressure up to 20 bar
- Spherical Be beam windows
- HV up to 80 kV
- E_p = 0.5 – 20 MeV
- HV, pressure, temperature measurements with precision 0.01% → target density precision and drift velocity with precision 0.02%



Drift velocity control using UV laser (probably)

Reachable momentum transfer

Q^2	[GeV^2]	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
$\theta_{50\text{ GeV}}$	[μrad]	6.32	2.00	0.63	0.20	0.06
$\theta_{100\text{ GeV}}$	[μrad]	3.16	1.00	0.32	0.10	0.03
$\theta_{150\text{ GeV}}$	[μrad]	2.11	0.67	0.21	0.07	0.02
$\Delta Q^2_{50\text{ GeV}}$	[MeV^2]	1.25	0.40	0.13	0.04	0.01
$\Delta Q^2_{100\text{ GeV}}$	[MeV^2]	1.25	0.40	0.13	0.04	0.01
$\Delta Q^2_{150\text{ GeV}}$	[MeV^2]	1.25	0.40	0.13	0.04	0.01
$\Delta Q^2/Q^2$	[%]	1.25	3.96	12.53	39.61	125.27



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TPC minimum - $Q^2 = 10^{-3} – 10^{-4}$ GeV²/c², depending on pressure

PBC-QCD

CERN-PBC-REPORT-2018-008

Physics Beyond Colliders
QCD Working Group Report

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Plans and beam time request

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pr. H2	2022 1 year	active TPC SciFi trigger silicon veto
Hard exclusive reactions	GPD E	160	10^7	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified PT magnet
Input for DMS	$\overline{p}$ production cross-section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs Nucleon TMDs	~100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarizi-bility & pion life time	~100	$5 \cdot 10^6$	> 10	K^-	Ni	n/e 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	n/e 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Table 5: Requirements for future programs at the M2 beam line after 2021. Standard muon beams are in blue, standard hadron beams in green, and RF-separated hadron beams in red.

Summary

- Application of ionization chamber (without gas amplification) as an active target for the elastic proton scattering at high and intermediate energies is very powerful method to study the nuclear matter distribution
- Similar technique can be used for μ-p experiments aiming the measurement of the proton radius with high precision
- Test experiment at CERN in 2018 shown feasibility
- Background and event rate is measured and acceptable
- TPC can run with independent DAQ, timestamp technique is proved
- Large baseline for the Si tracker and using He/vacuum tubes is crucial
- New SciFi detectors need to be developed
- New setup can be ready for the test run in 2021 and for main run in 2022 (funding dependent)
- ***Final proposal is foreseen in June 2019***

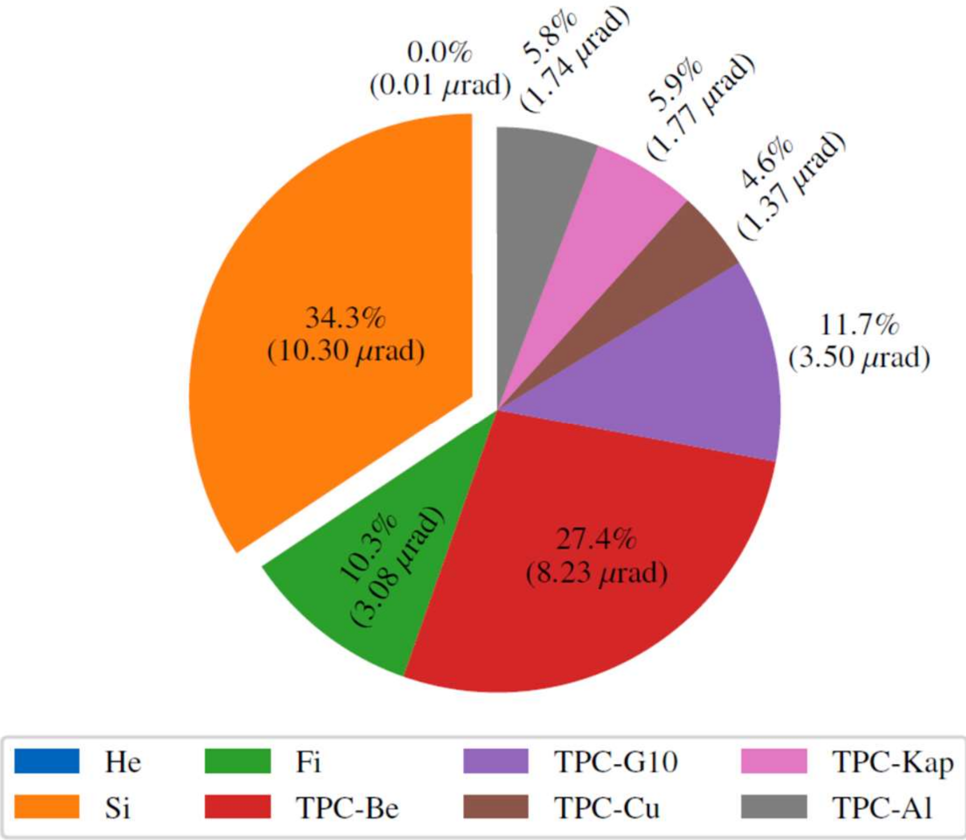
Backups

Material Budget and Multiple Scattering

Multiple scattering as lower limit

Measurable scattering angle is limited due to multiple scattering as example for a beam momentum of 100 GeV/c based on central region.

- Air: 4.5 m (3% X_0). $\Delta\theta_{MS,Air} = 1.03 \cdot 10^{-2}$ mrad
  Helium: 4.5 m (0.01 ‰ X_0) $\Delta\theta_{MS,He} = 4.89 \cdot 10^{-3}$ mrad
- Silicon: four planes with 200 µm thickness
  800 µm (Si, 0.08 ‰ X_0) $\Delta\theta_{MS,Si} = 1.03 \cdot 10^{-2}$ mrad
- Fiber: two planes with 200 µm thickness
  400 µm (Polystyr., 0.008 ‰ X_0): $\Delta\theta_{MS,Fi} = 3.08 \cdot 10^{-3}$ mrad
- TPC: two Be windows with 1 mm thickness
  2 mm (Be, 0.05 ‰ X_0): $\Delta\theta_{MS,Be} = 8.23 \cdot 10^{-3}$ mrad
- TPC: Anode with 200 µm thickness
  200 µm (G10, 0.01 ‰ X_0): $\Delta\theta_{MS,An} = 4.15 \cdot 10^{-3}$ mrad
- TPC: Cathode with 1mm thickness
  1 mm (Steel, 0.5 ‰ X_0): $\Delta\theta_{MS,Ca} = 2.88 \cdot 10^{-3}$ mrad



Proton Radius Measurement – Feedback from PBC

- physics reach of the proposed measurement acknowledged
- regarding the Q^2 range of the measurement 10^{-3} … $2x10^{-2}$ GeV^2 it is encouraged to extend this range, especially to lower values, for a better control of the „fit ambiguities“

our answer:

- yes, extending the experimental sensitivity to as-low-as possible Q^2 values (beyond 10^{-3}) is to be taken into account in the design of the set-up (will require ~10m target region for the silicon telescopes)
- low-Q^2 data points will be useful and meaningful in terms of systematics control
- the expected form factor impact on the cross-section is below 0.1% in that region, and thus of a similar size as other expected (experimental) systematic effects. Accordingly, those points are of limited use in terms of discriminating theoretical uncertainties (except for excluding unrealistic scenarios)

all in all positive feedback from PBC,
SPSC to be awaited – expected soon!

Proton range in hydrogen