

Measuring the weak mixing angle with the P2 Experiment at MESA

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Heidelberg, December 2019

Overview

- The running weak mixing angle
- The MESA accelerator
- The P2 Experiment
- HV-MAPS based tracker for P2

See: The P2 Experiment - A future high-precision measurement of the electroweak mixing angle at low momentum transfer arXiv:1802.04759

The weak mixing angle

(also: Weinberg-angle)



Niklaus Berger – Heidelberg, December 2019 – Slide 4

The weak mixing angle

- One of the fundamental parameters of the standard model
- Electroweak symmetry breaking creates photon and Z^0
- Angle shows up both in masses and couplings (charges)

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

$$\cos \theta_W = \frac{m_W}{m_Z}$$

$$\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2}$$

Which weak mixing angle?

- The last slide is true at tree level
- But there are quantum corrections...

Two options:

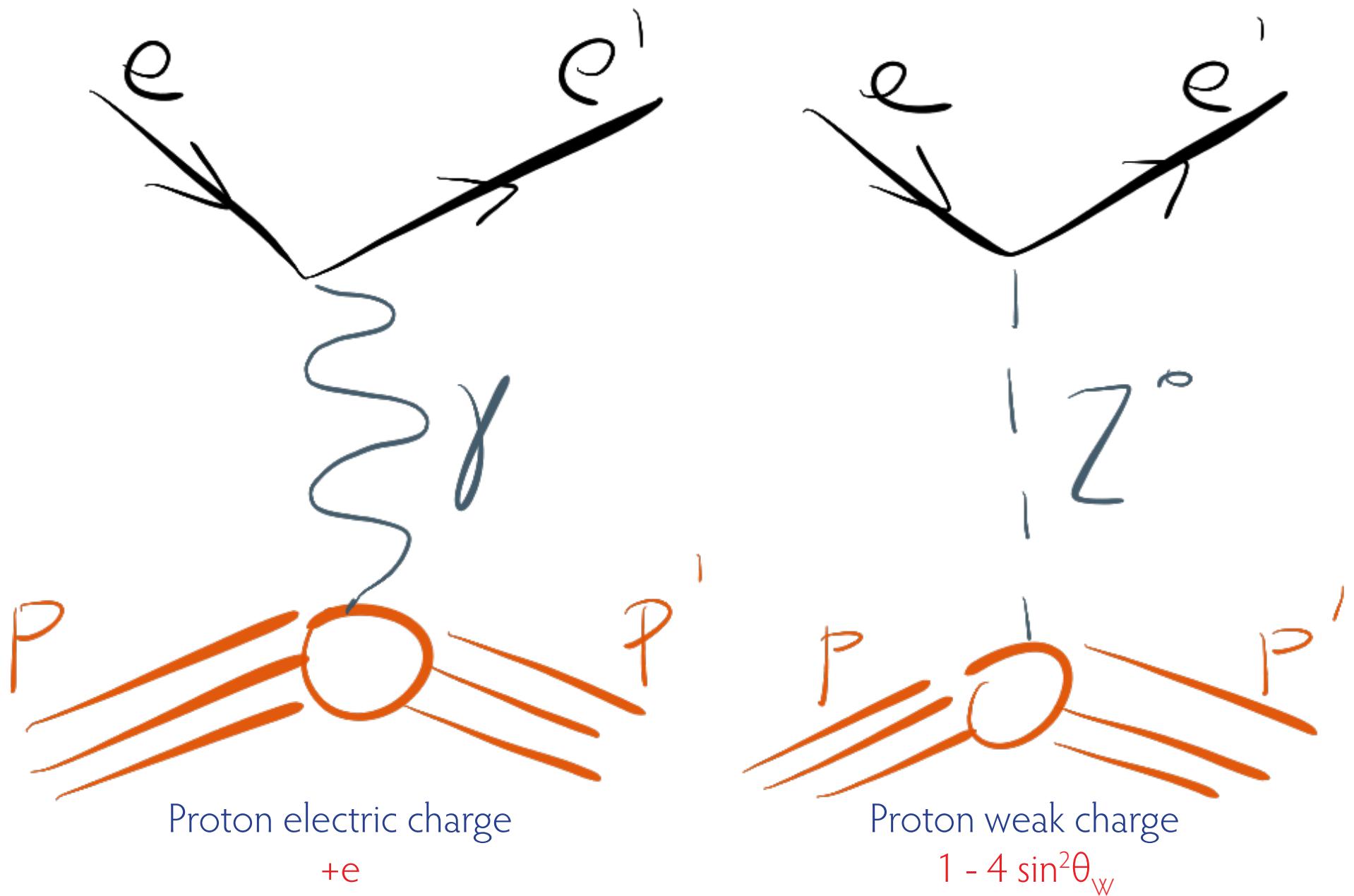
- Use the masses for the definition:
(at all orders of perturbation theory)
"On-shell scheme"
- Or use the couplings:
(which change with energy, and so does
the angle)
"MS-scheme"
- Use second option from here on

$$\cos \theta_W = \frac{m_W}{m_Z}$$

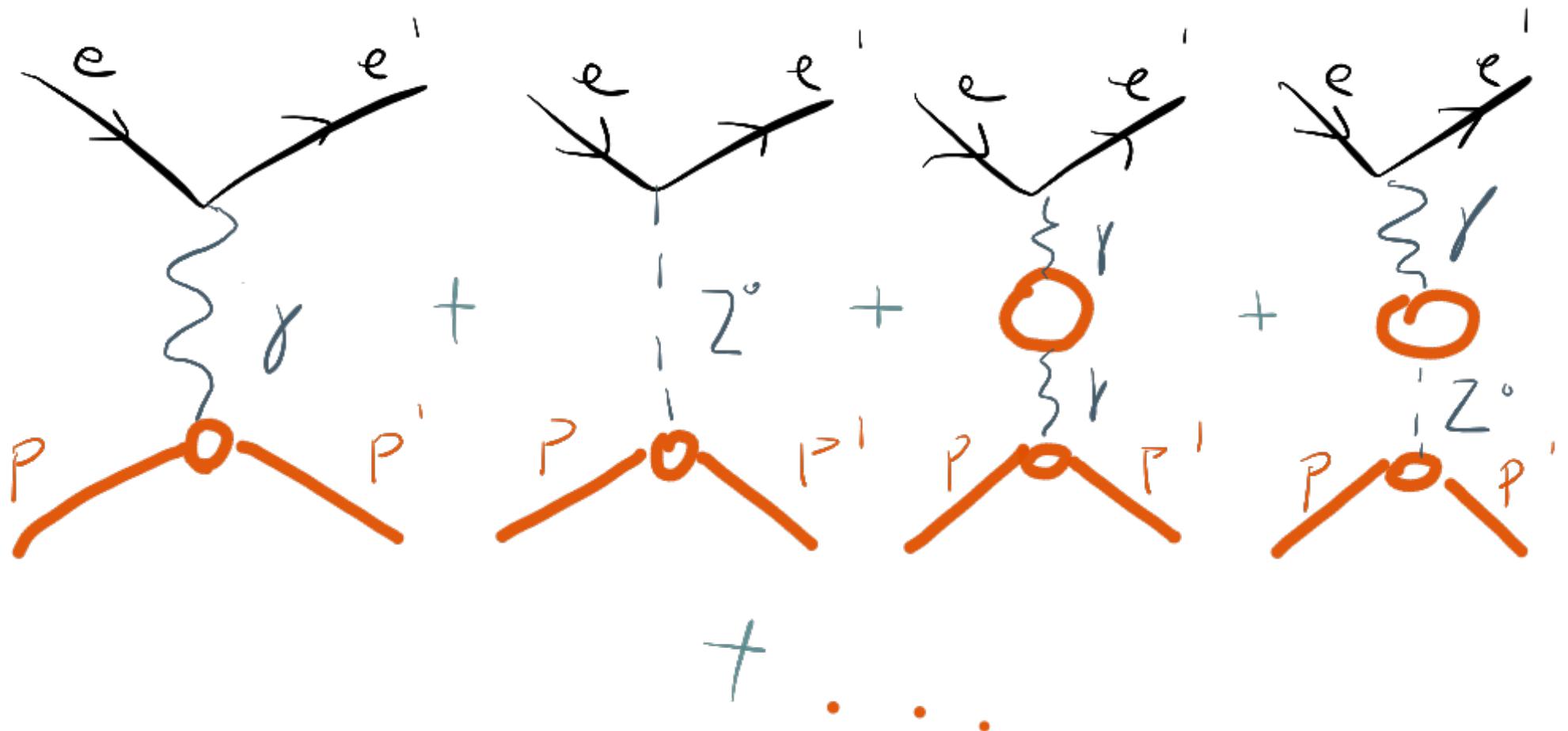
$$\sin^2 \theta_W = \frac{g'^2}{g^2+g'^2}$$

$$\sin^2 \theta_W(q^2)$$

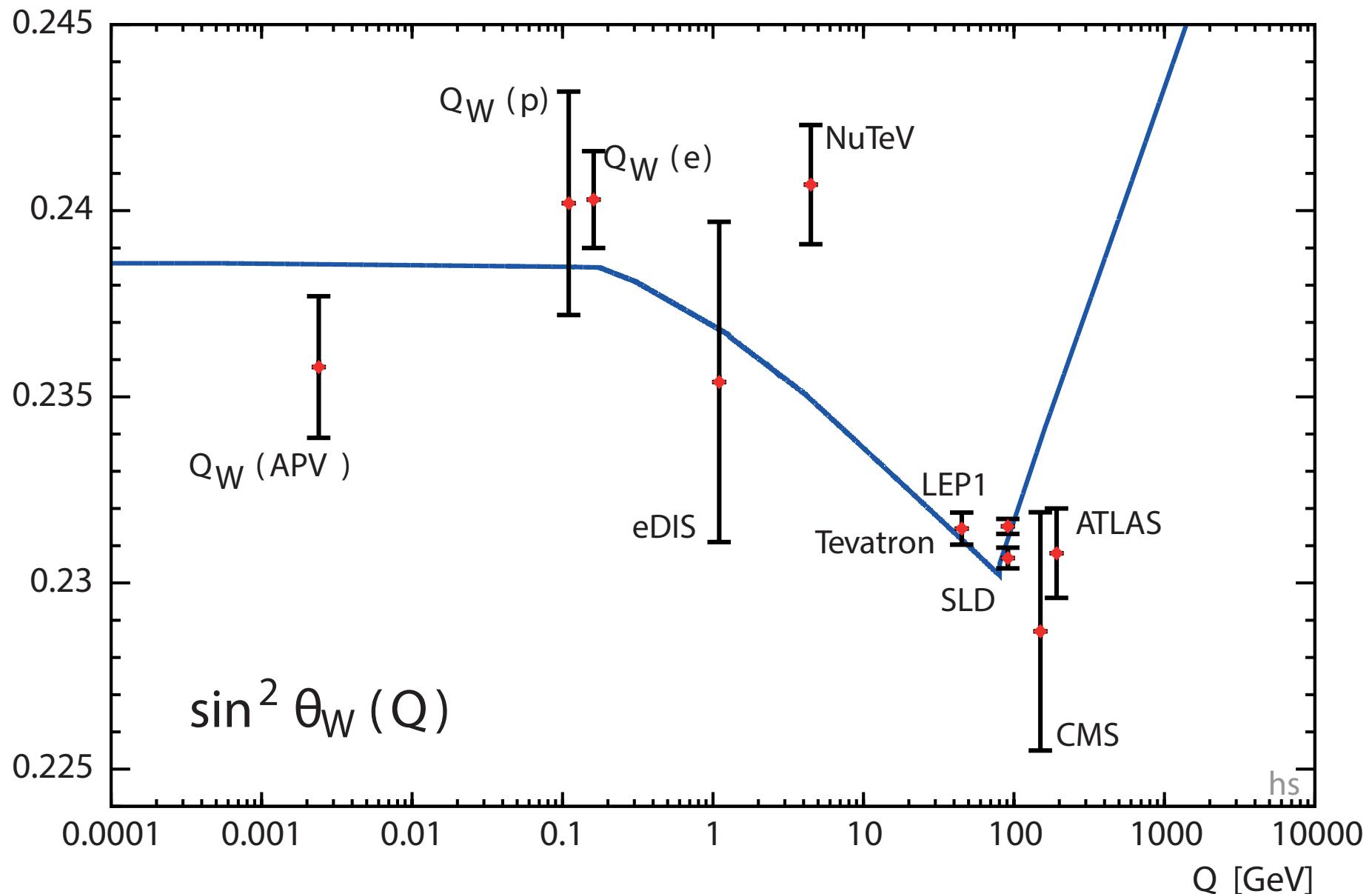
Weak mixing angle and charges



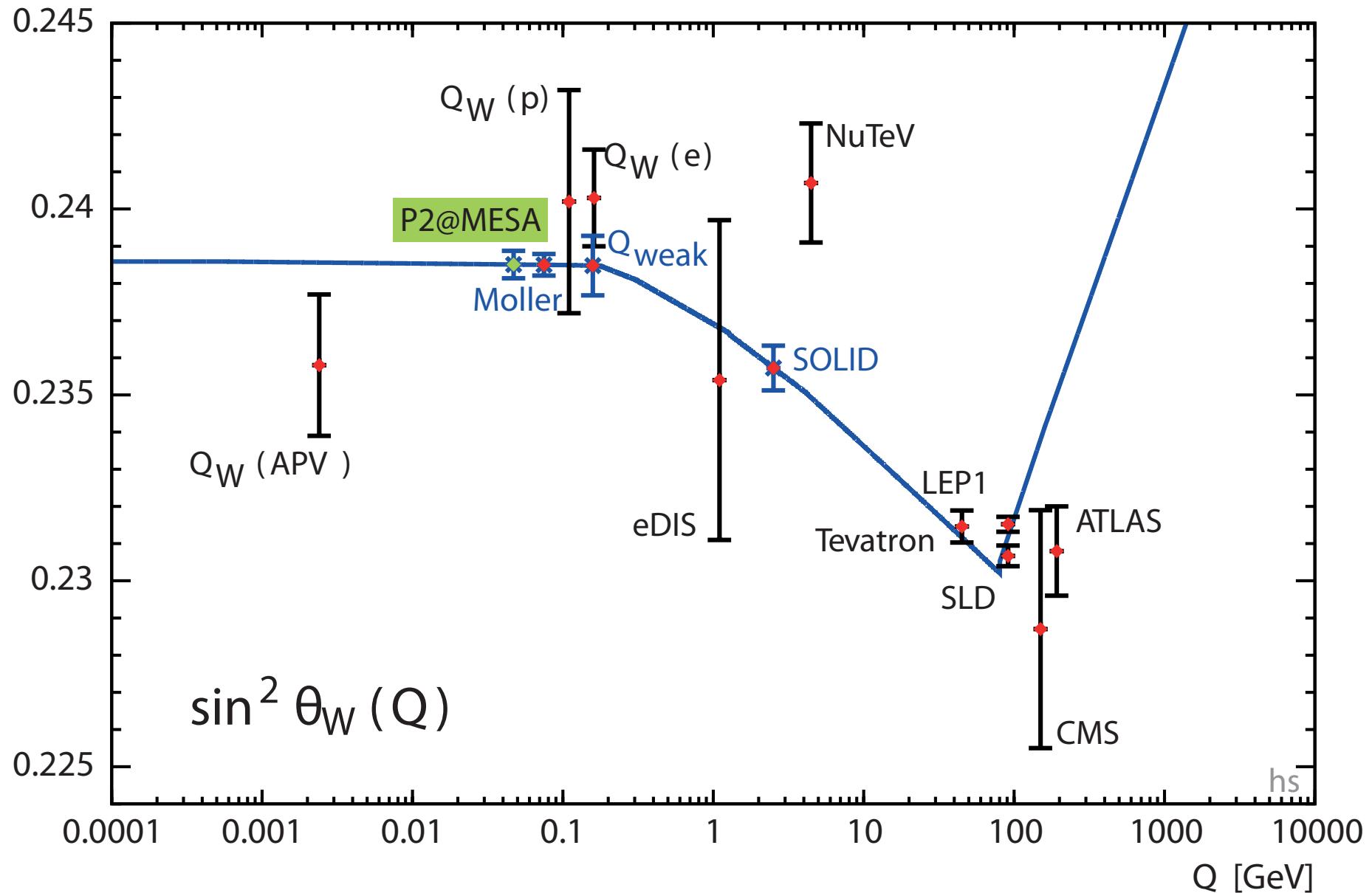
Scale dependence (running) of $\sin^2\theta_W$



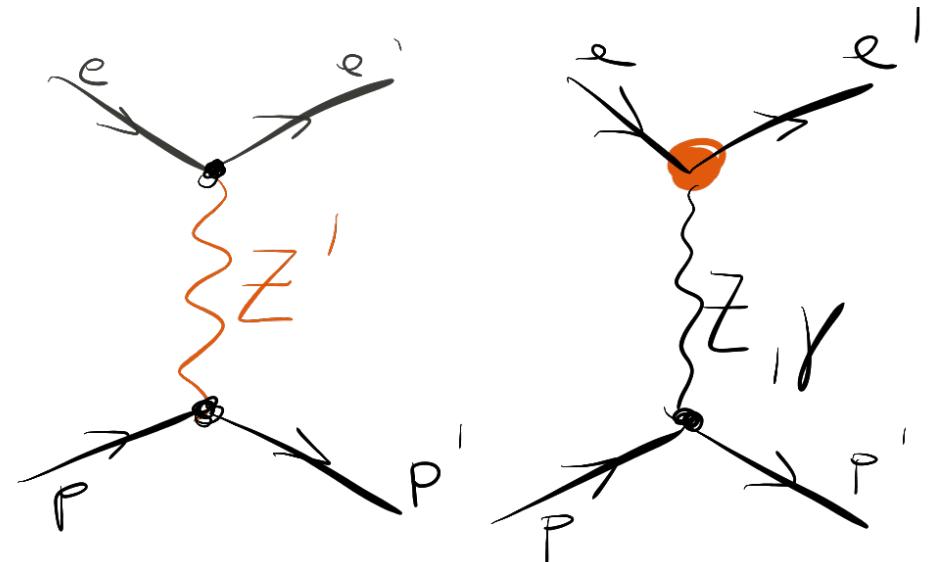
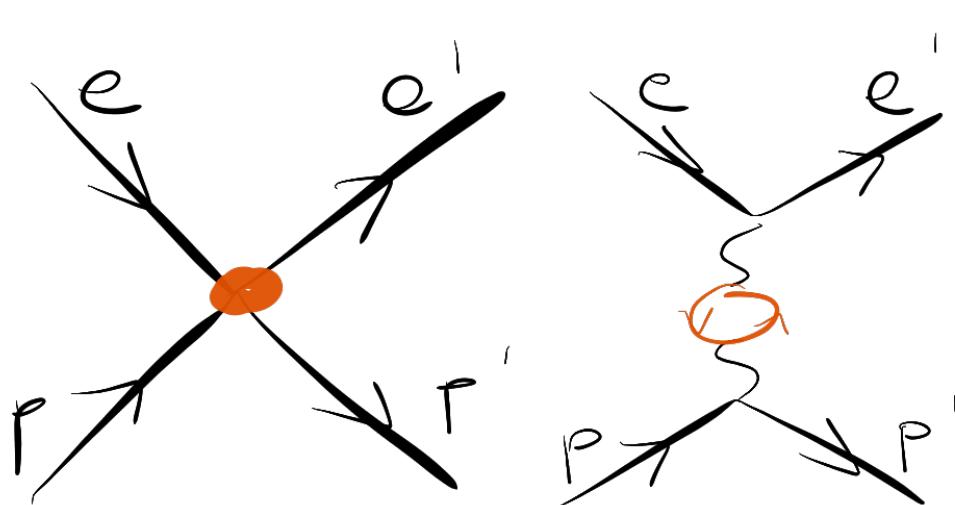
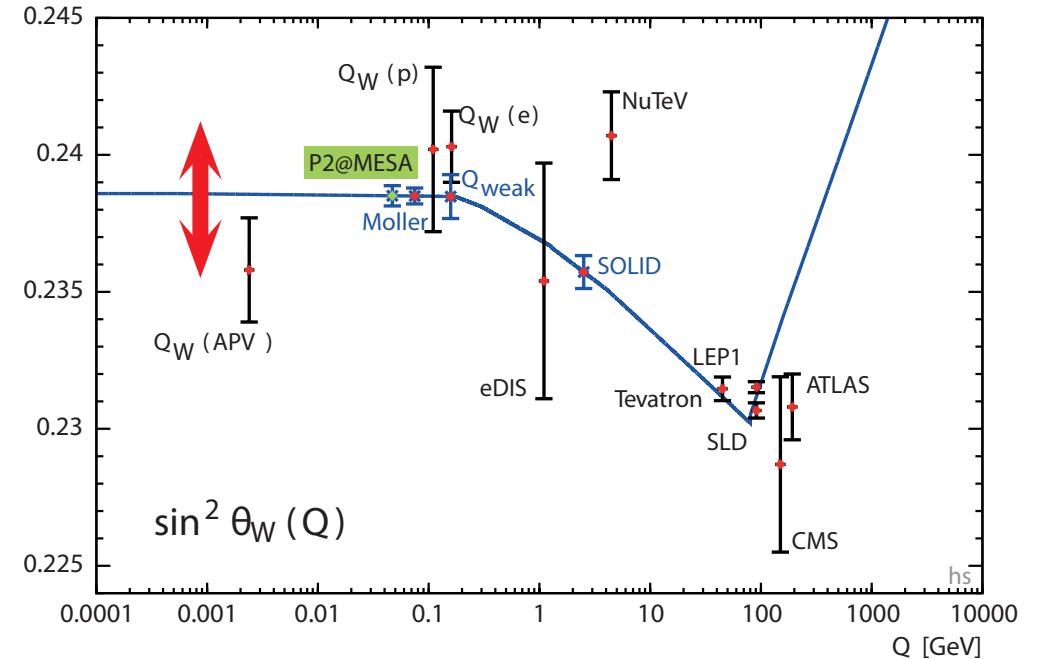
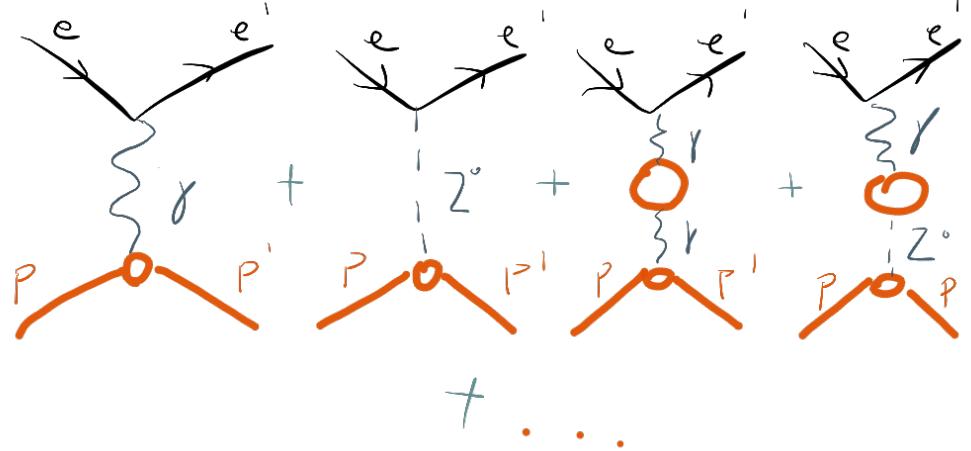
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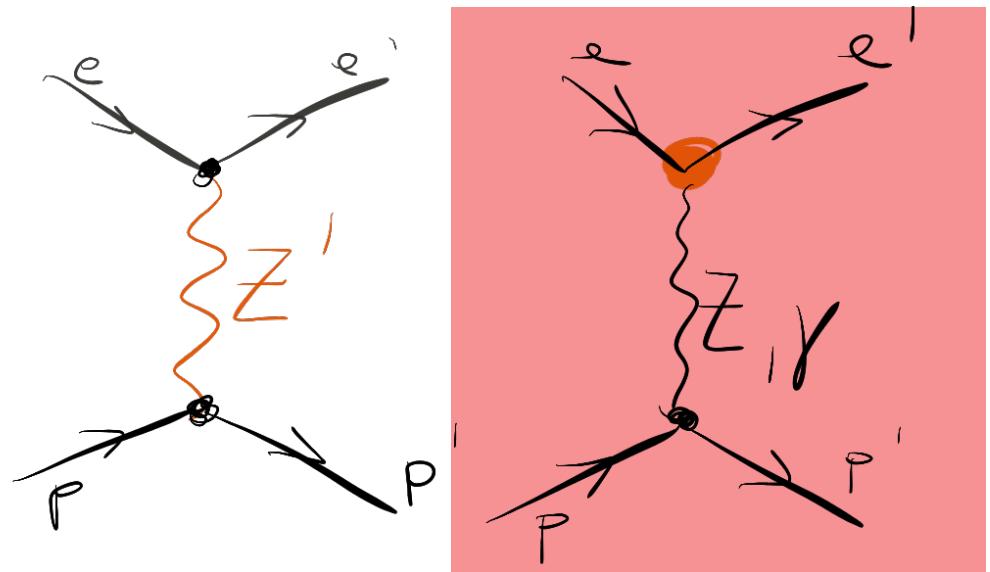
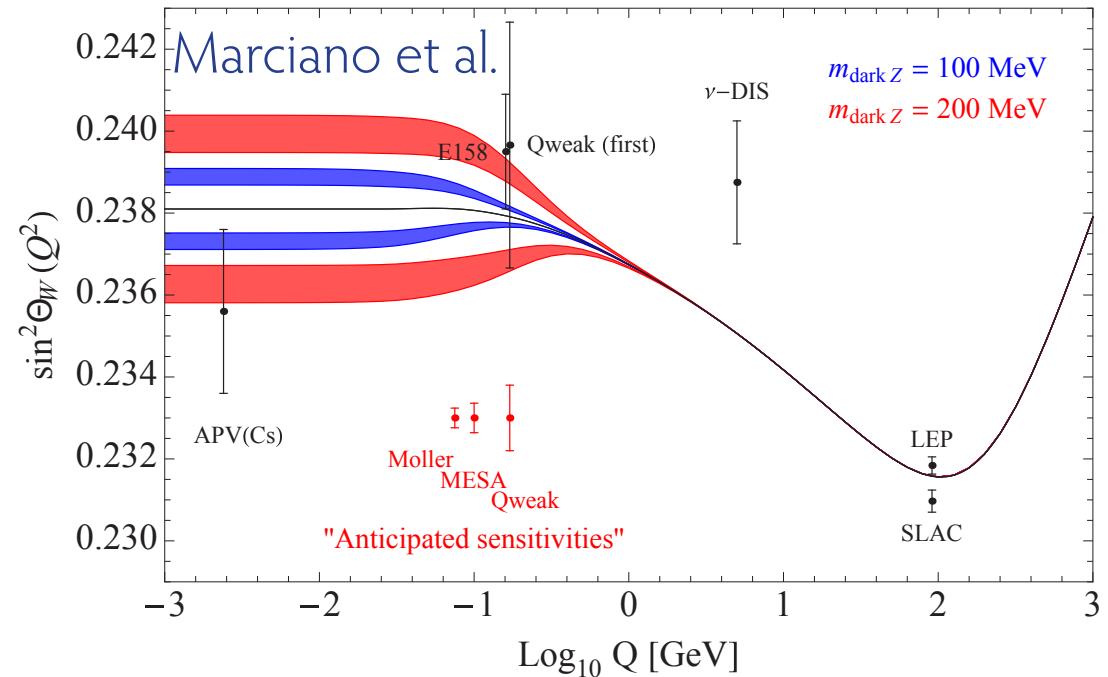
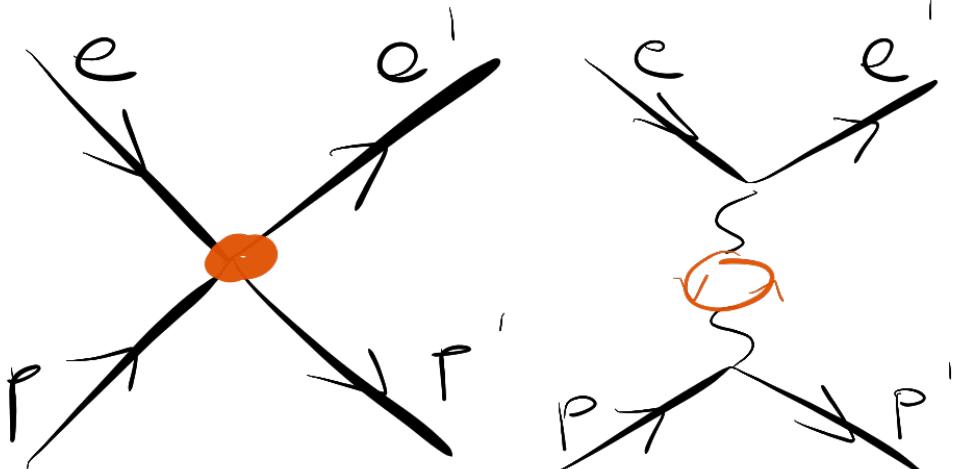
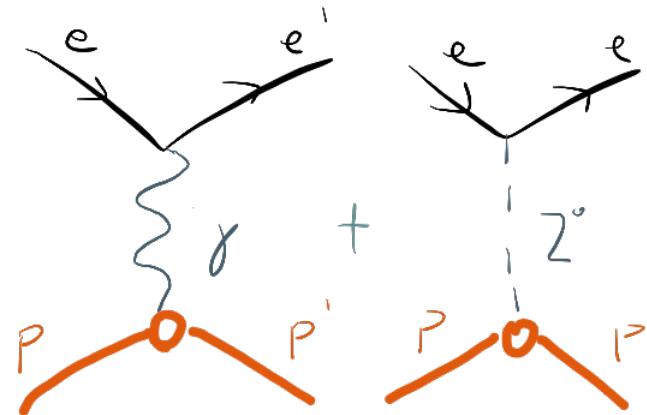
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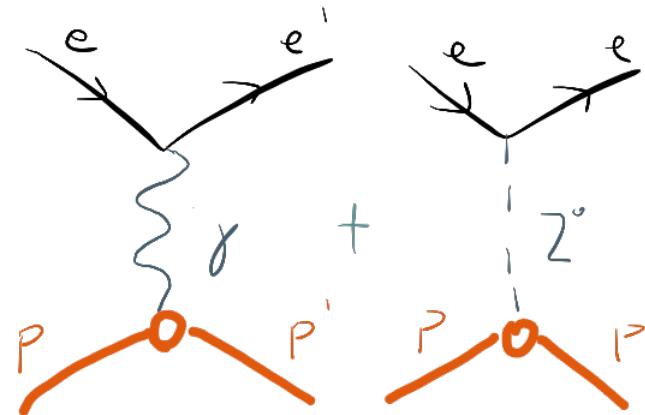
New Physics in the running



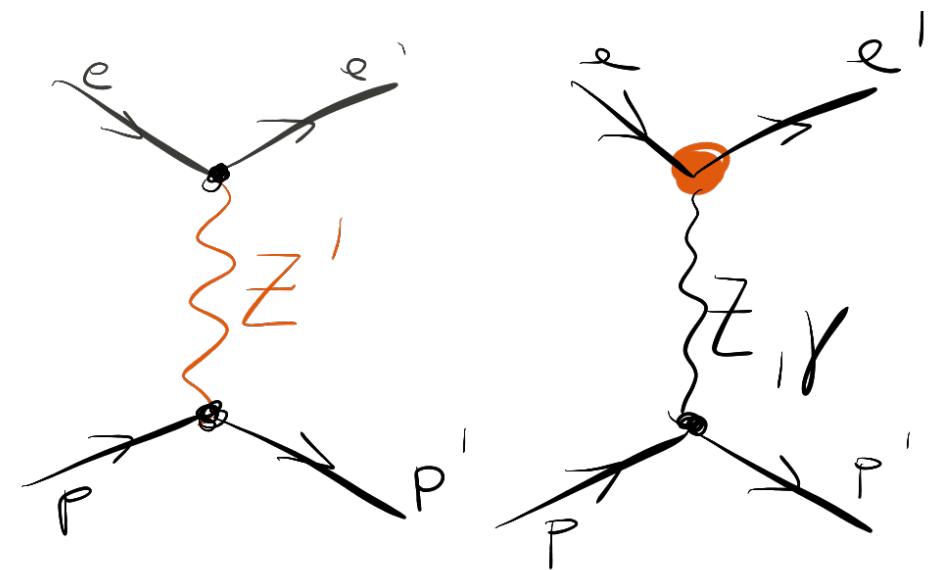
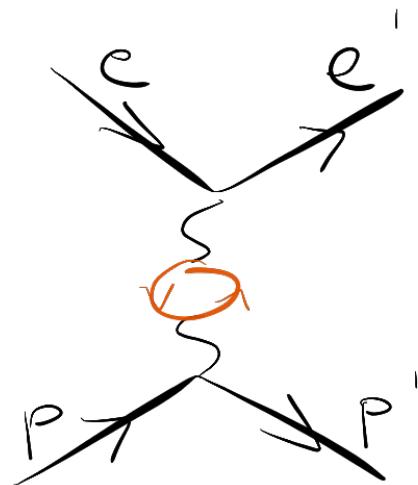
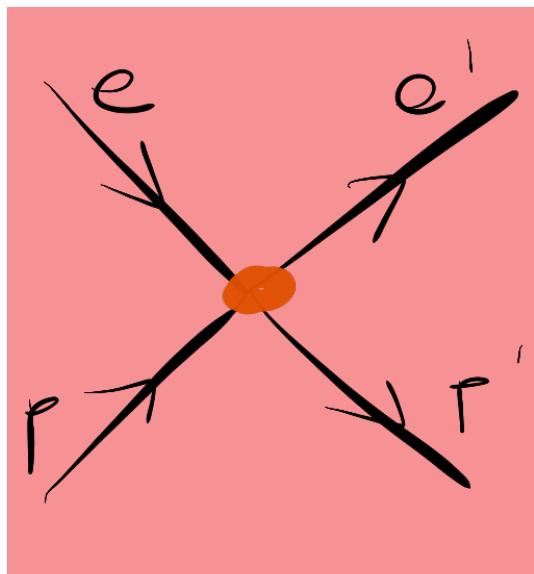
Dark Z in mixing



Contact Interactions

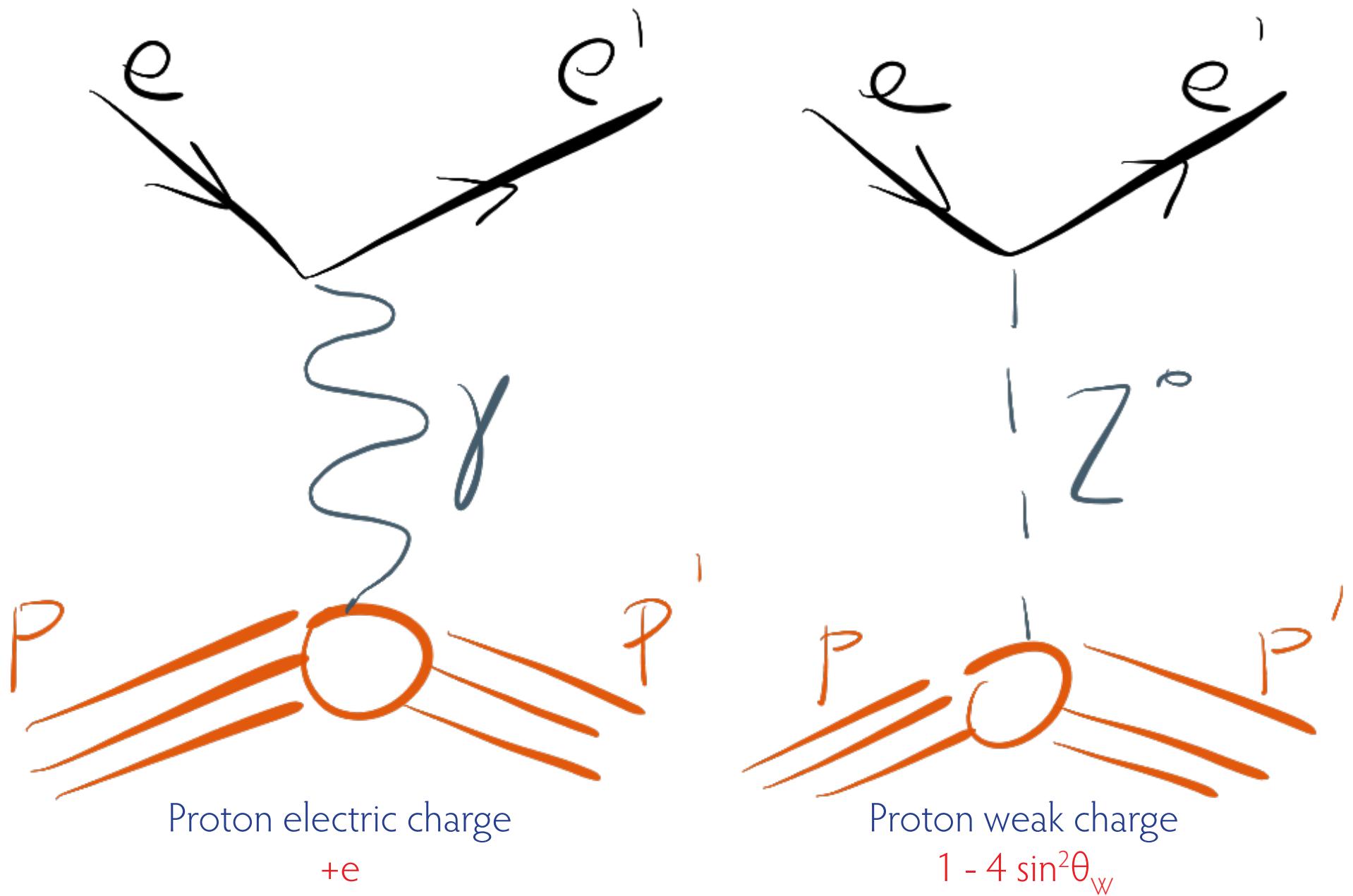


Contact interactions up to
49 TeV
(comparable to LHC at 300 fb^{-1})

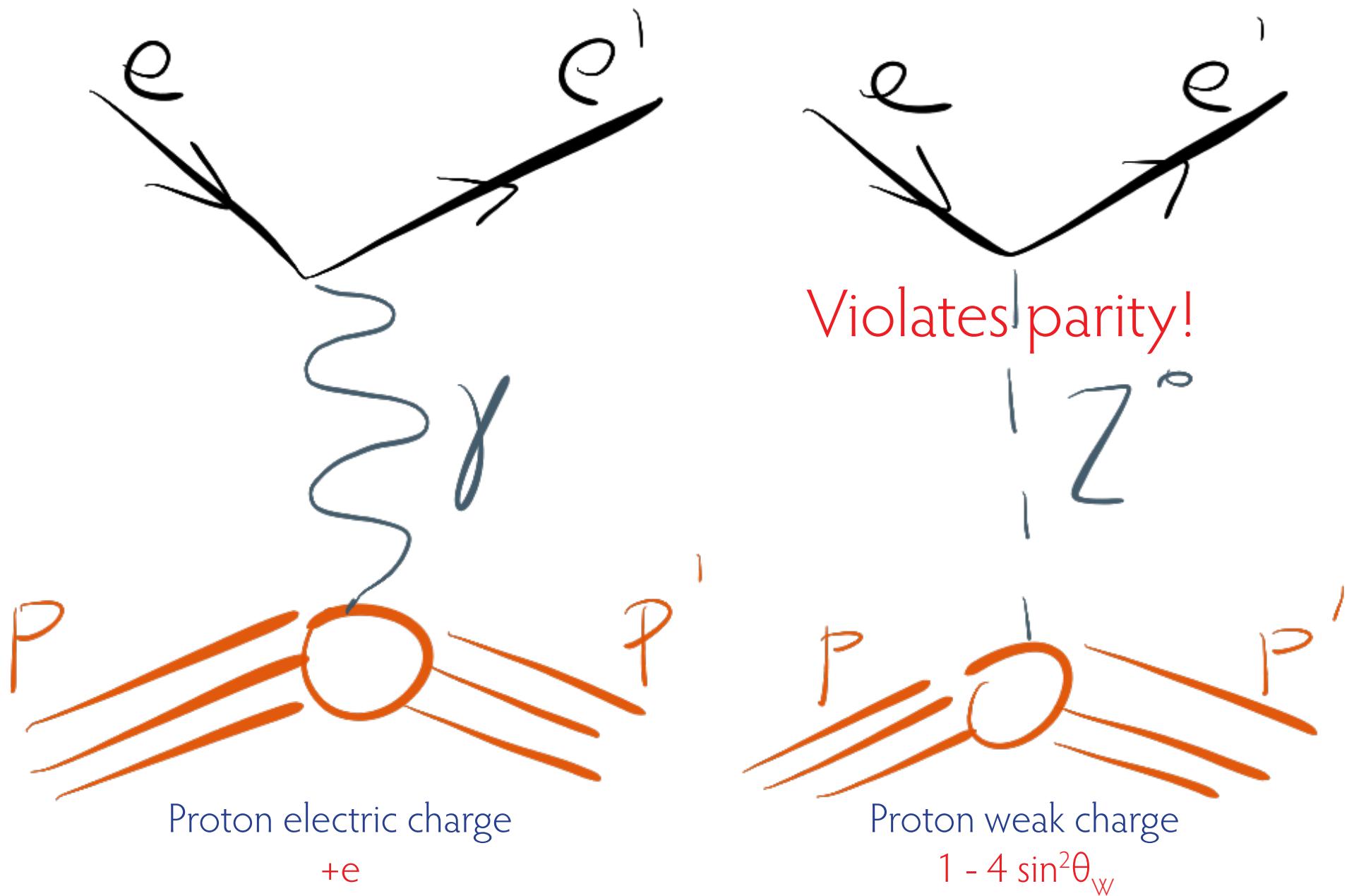


How to measure the weak charge?

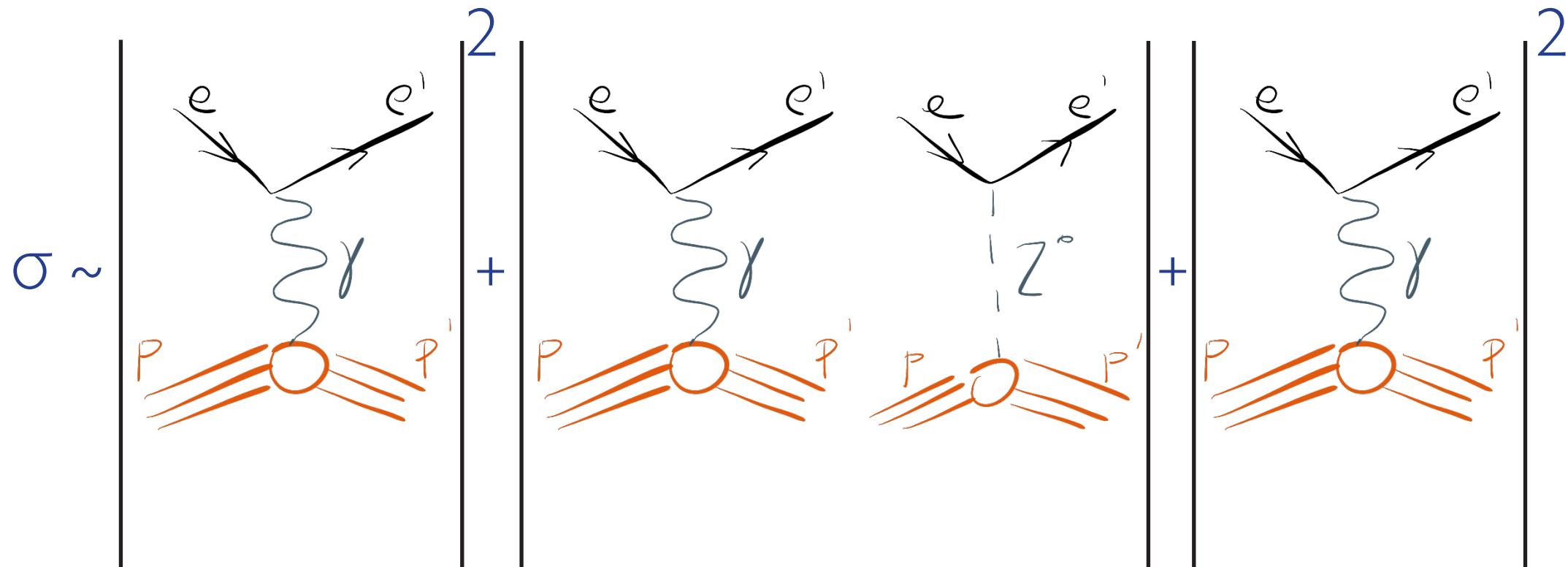
Weak mixing angle and charges



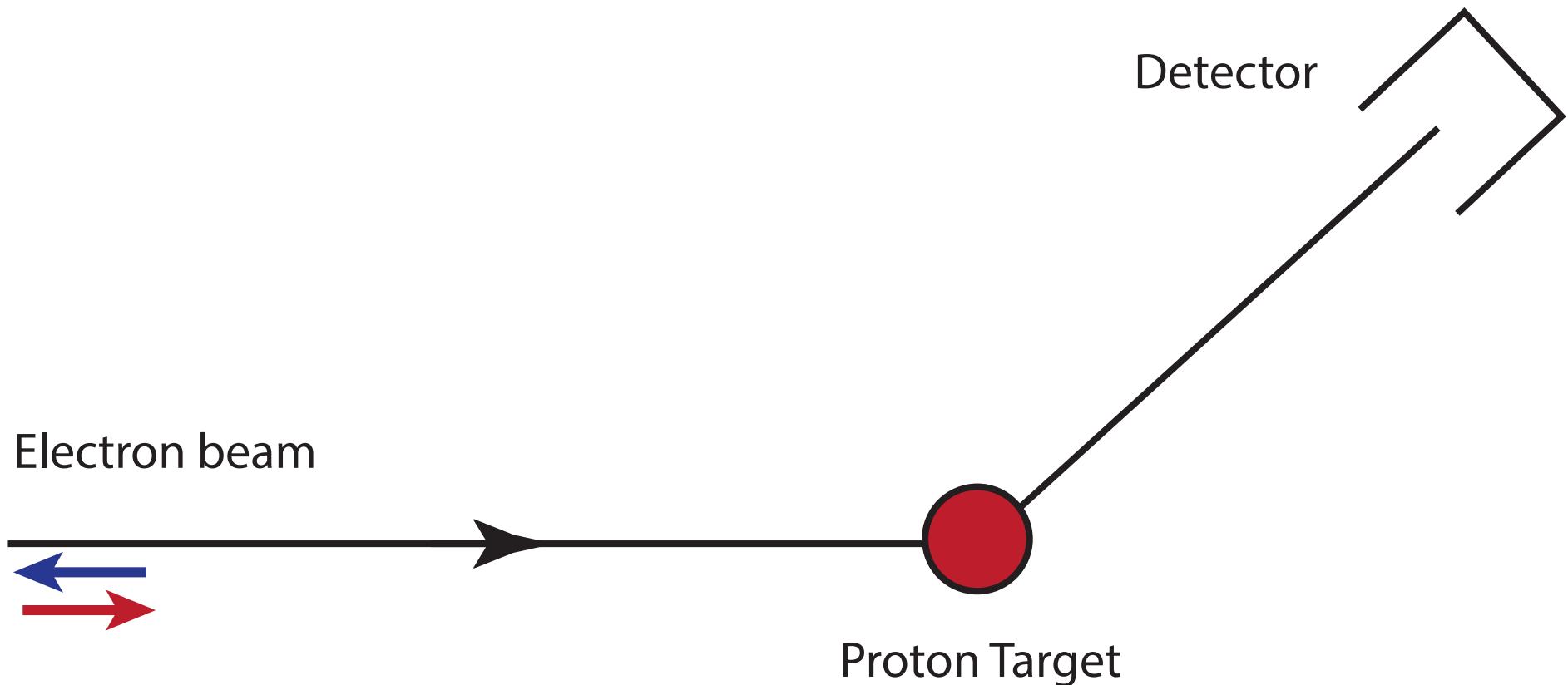
Weak mixing angle and charges



Interference

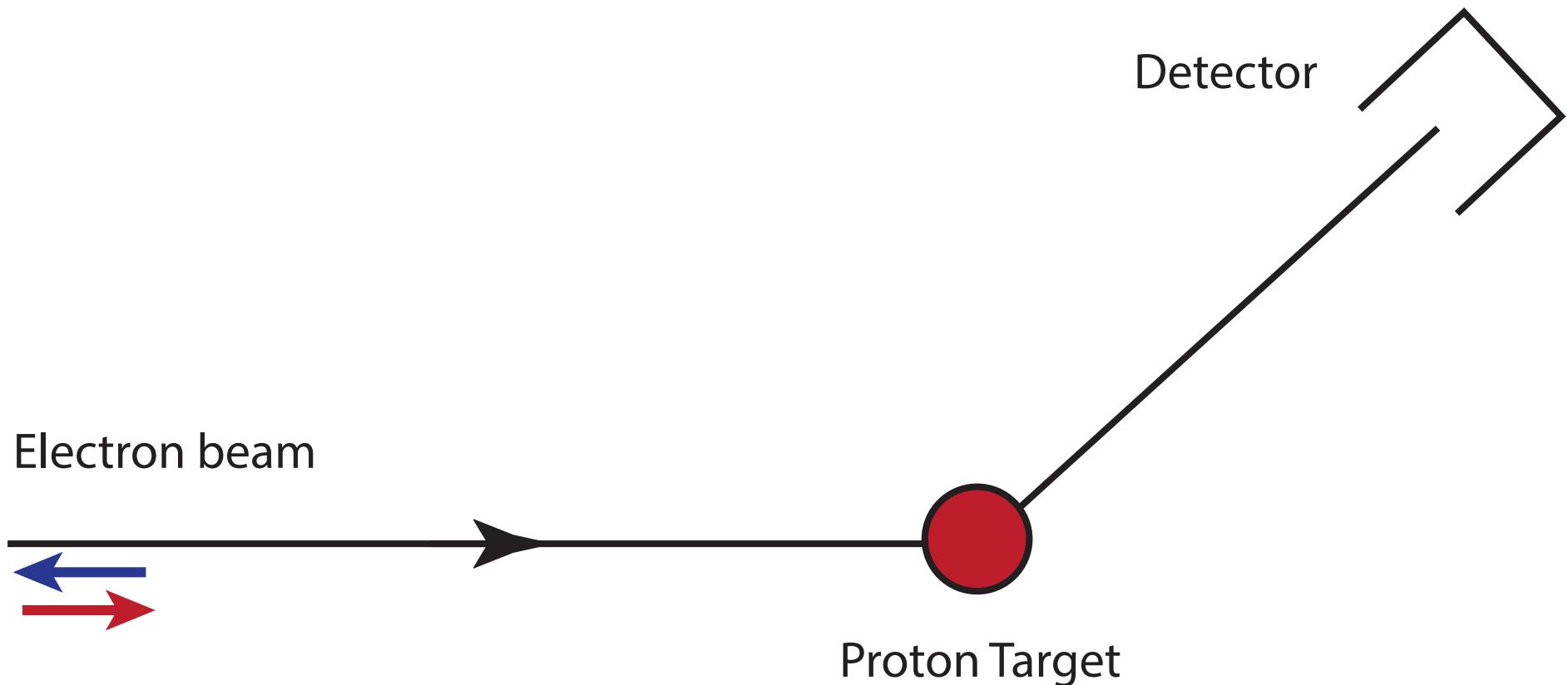


Parity violating electron scattering



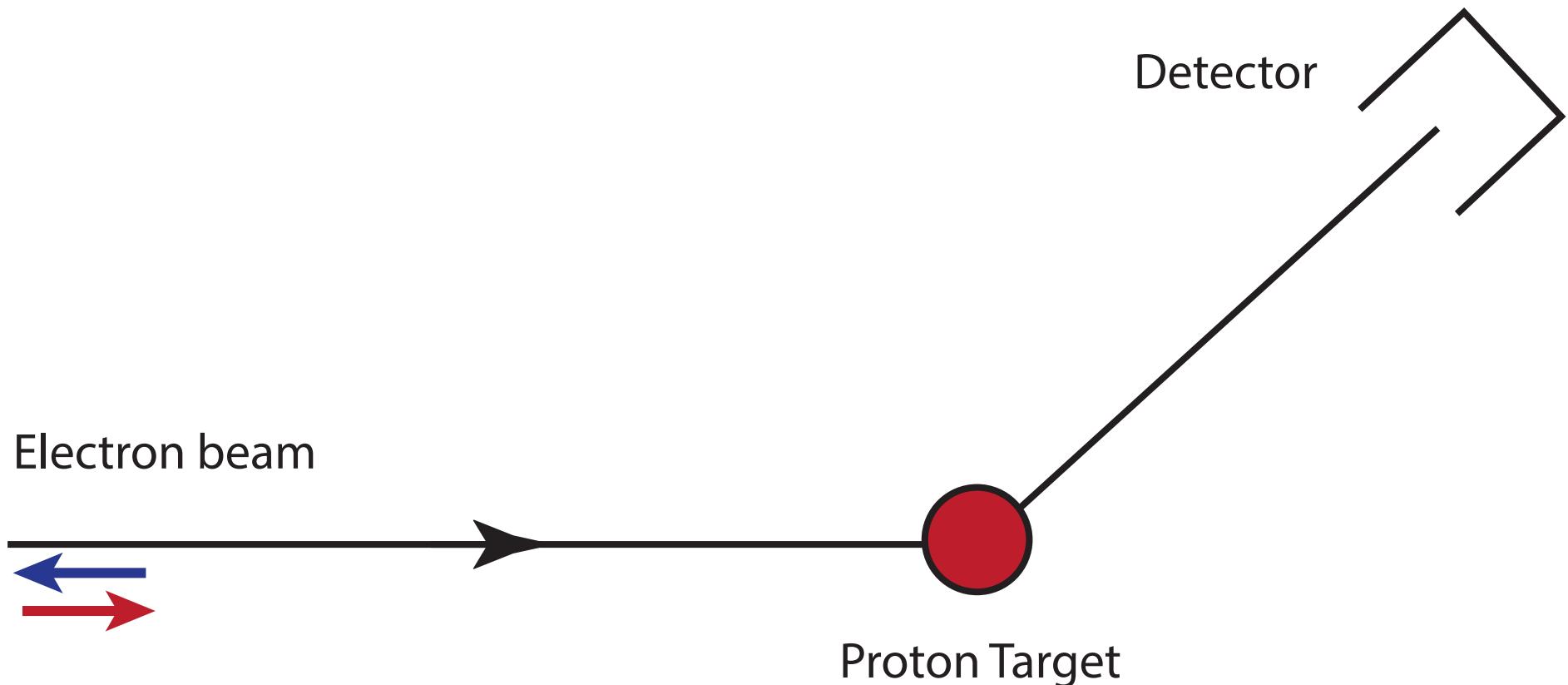
Parity violating electron scattering

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L}$$



Parity violating electron scattering

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} (Q_W - F(Q^2))$$



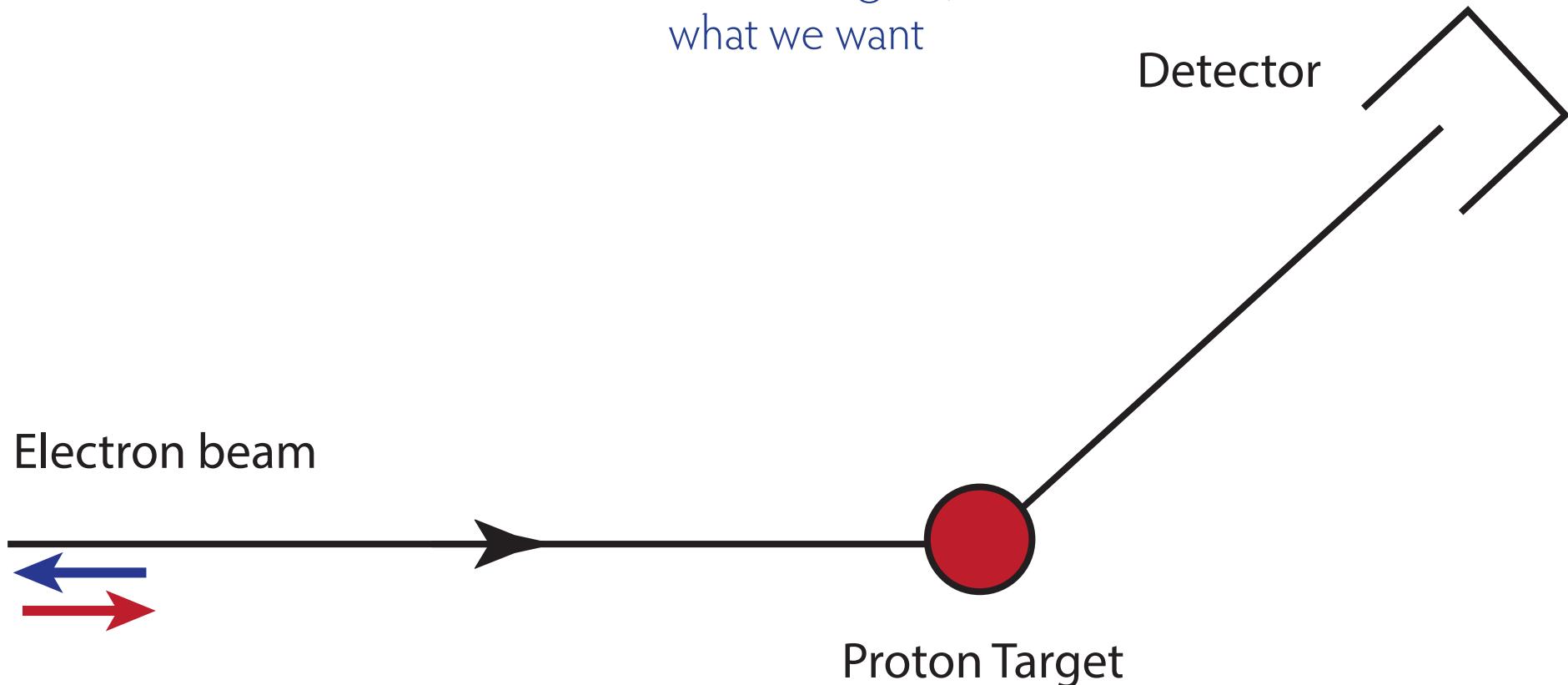
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Momentum transfer sets scale

Proton structure - small nuisance if Q^2 small

Weak charge - what we want



Parity violating electron scattering

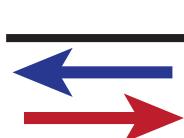
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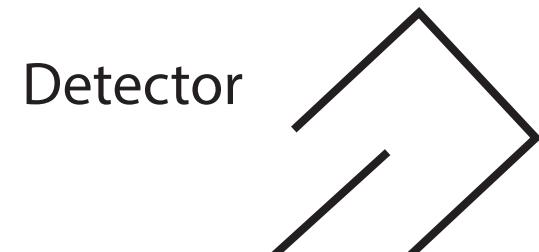
Proton structure - small nuisance if Q^2 small

$$\sin^2 \theta_W = \frac{1 - Q_W}{4}$$

Electron beam



Proton Target



Why is this difficult?

- $\sin^2\theta_W \approx 0.25$: Weak charge is tiny

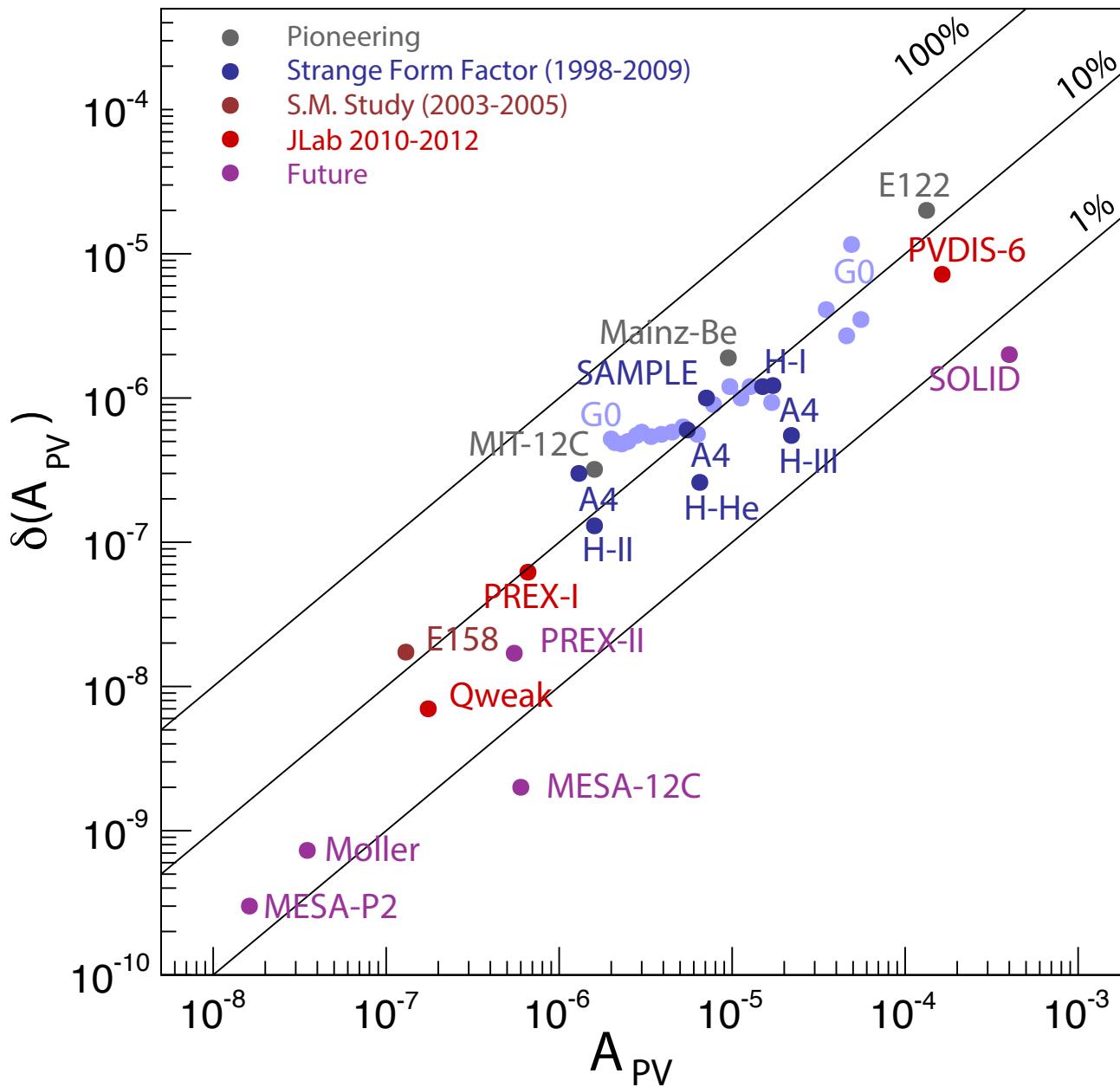
$$Q_W = 1 - 4 \sin^2 \theta_W$$

- At low Q^2 : Asymmetry is tiny (40 parts per billion):
need very large statistics

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} (Q_W - F(Q^2))$$

- We are subtracting two huge numbers from each other
(not really - switching helicity with a KHz)

PVeS Experiment Summary



How much statistics do we need?

- Want to measure $\sin^2 \theta_W$ to 0.13%

- Need Q_W at 1.5%

$$\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1 - 4 \sin^2 \theta_W}{4 \sin^2 \theta_W} \frac{\Delta Q_W}{Q_W}$$

- Essentially means 1.5% on A_{PV}

How much statistics do we need?

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- A_{PV} is 40 parts per billion

- $\delta(A_{PV})$ is 0.6 parts per billion

- N a few 10^{18}

$$\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1 - 4 \sin^2 \theta_W}{4 \sin^2 \theta_W} \frac{\Delta Q_W}{Q_W}$$

$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

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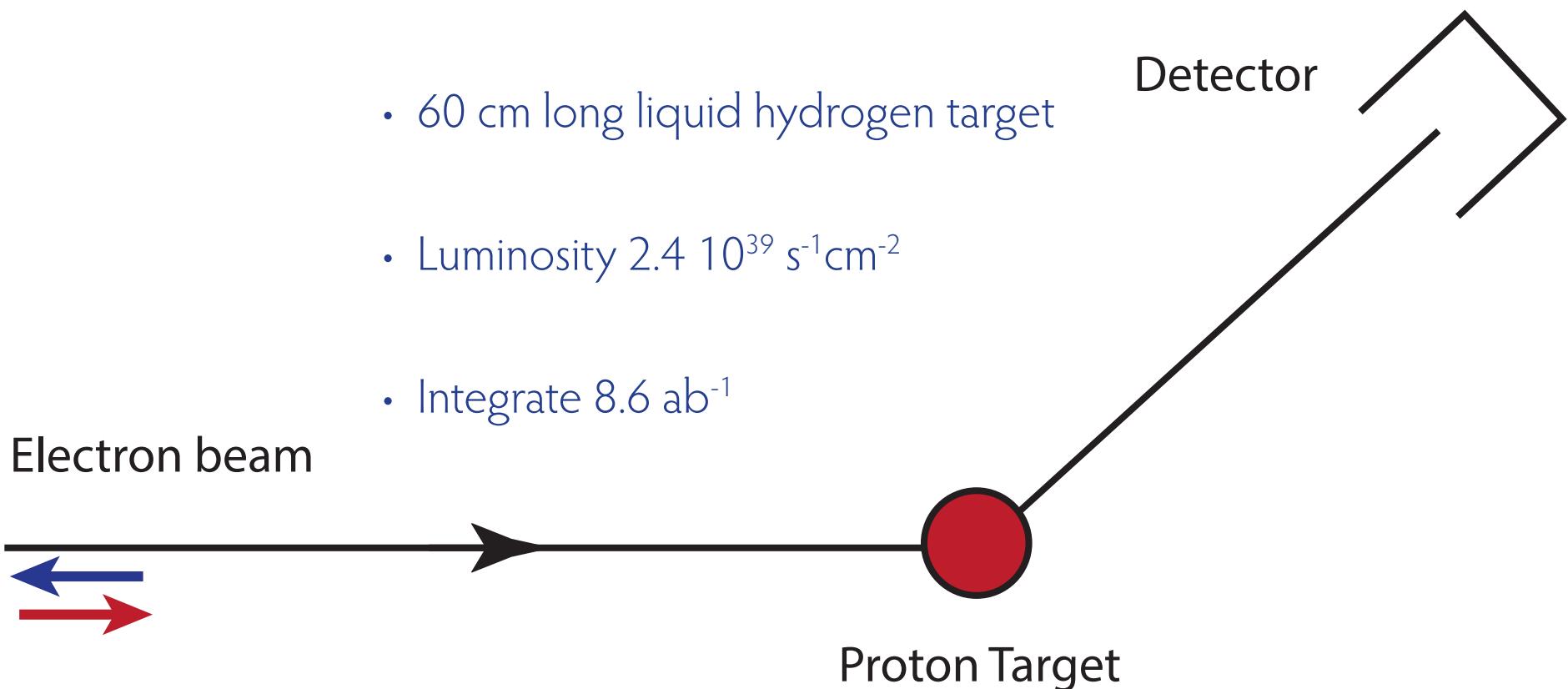
- Measure 11'000 hours (absolute maximum anyone thinks shifts are organisable)

- Need close to 10^{11} electrons/s - 100 GHz

Can we get that rate?

Yes!

- 150 μA of electron beam current
- 60 cm long liquid hydrogen target
- Luminosity $2.4 \cdot 10^{39} \text{ s}^{-1}\text{cm}^{-2}$
- Integrate 8.6 ab^{-1}



10'000 hours is *417 days 24/7* of measurements

Hard to get that amount of time at a shared
accelerator facility...

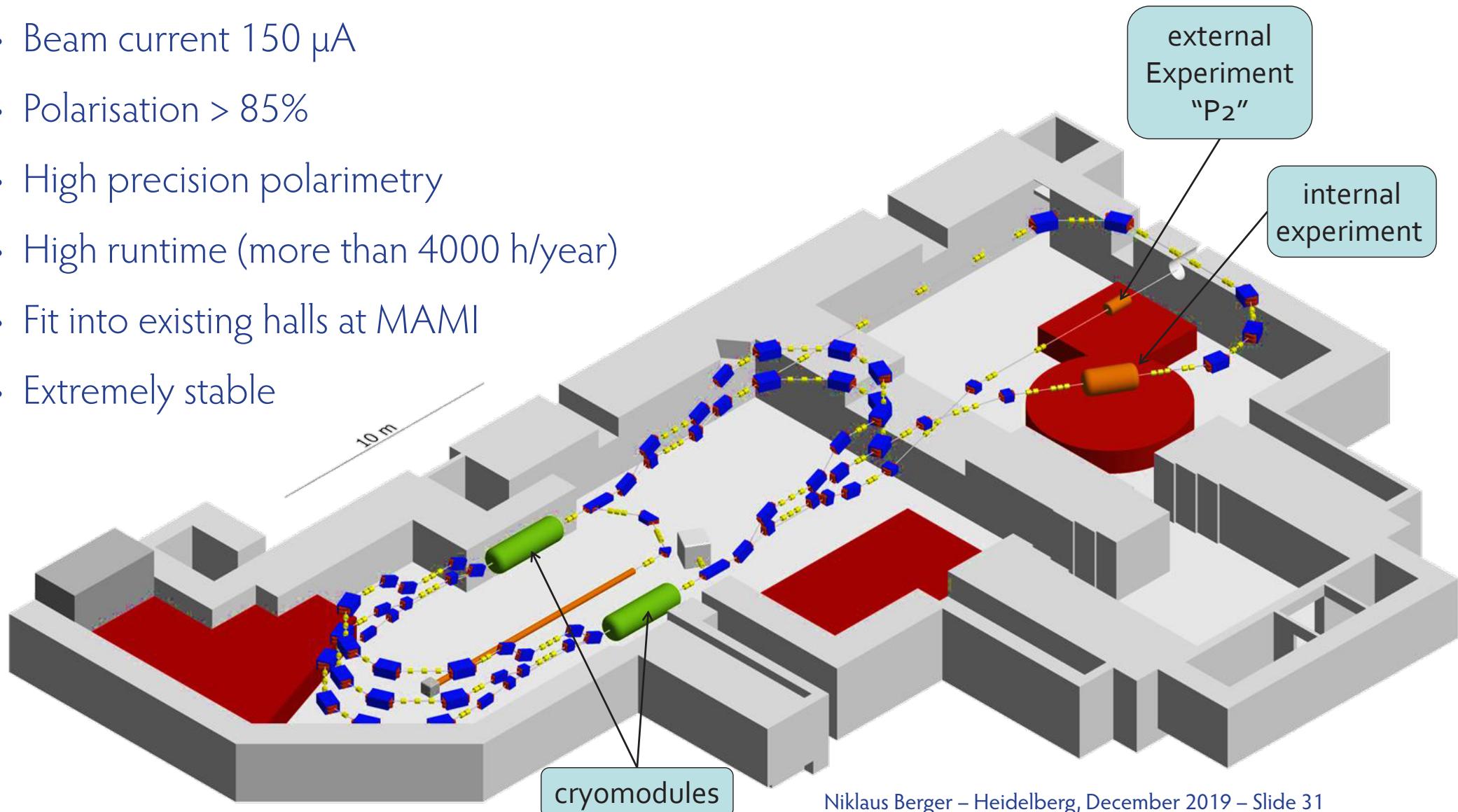
If you cannot rent it, build it:

The MESA accelerator

Mainz Energy-recovery Superconducting Accelerator

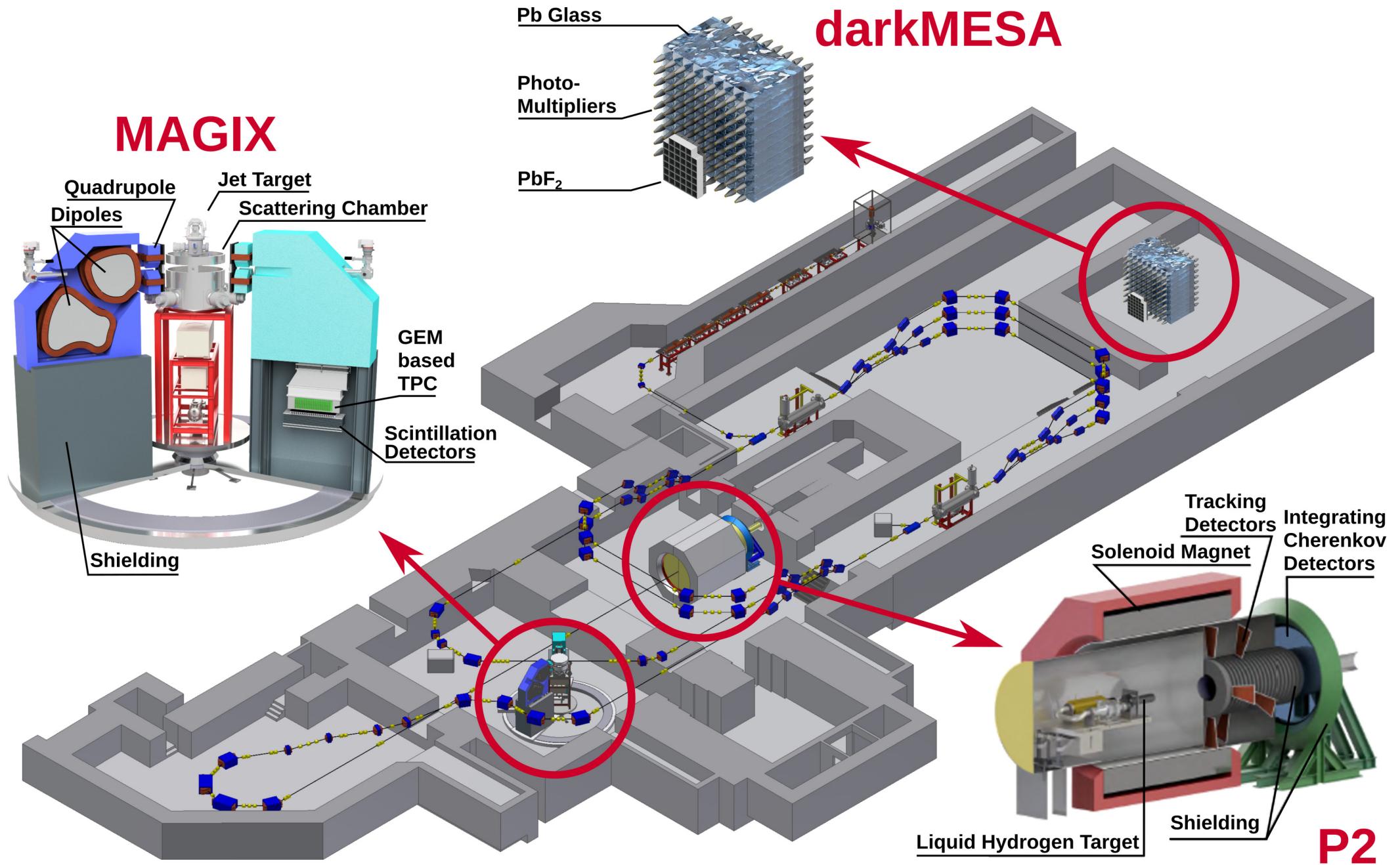
Requirements

- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry
- High runtime (more than 4000 h/year)
- Fit into existing halls at MAMI
- Extremely stable

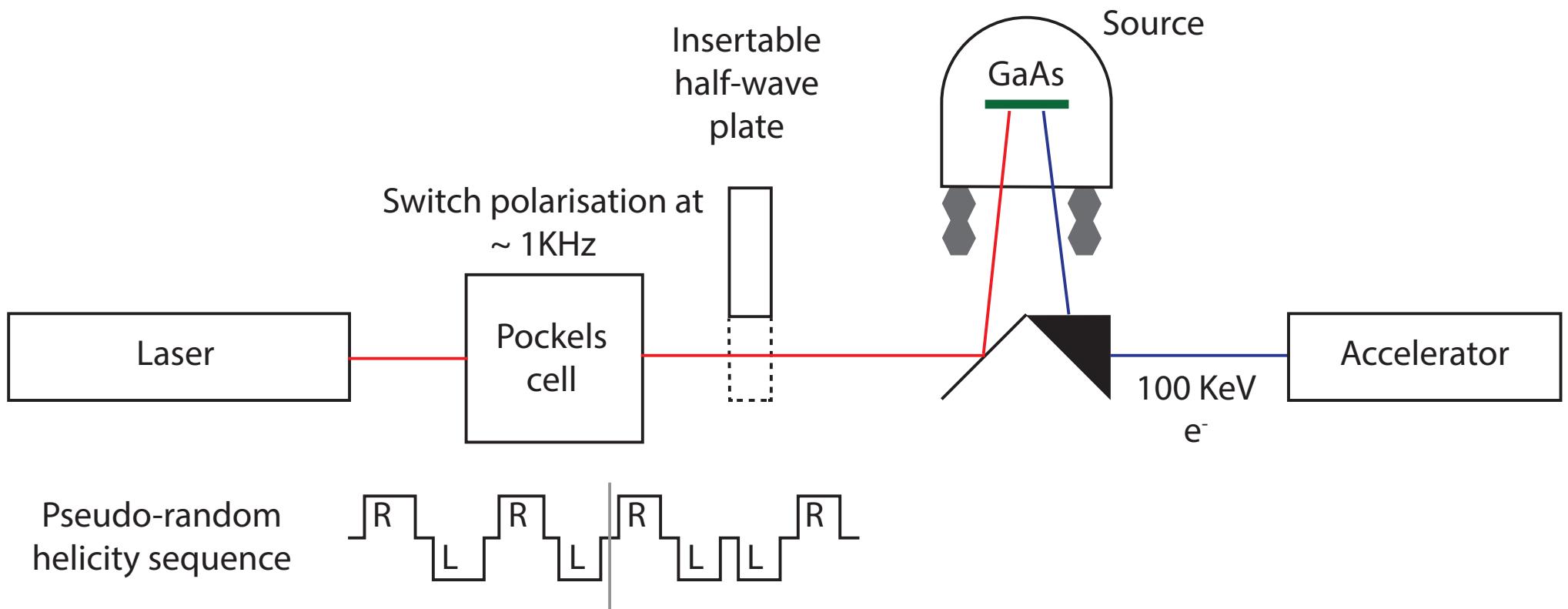


cryomodules

Mainz Energy-Recovery Superconducting Accelerator



Polarized Source and Helicity Flips



Stability Requirements

The main worry are beam fluctuations correlated with the helicity:

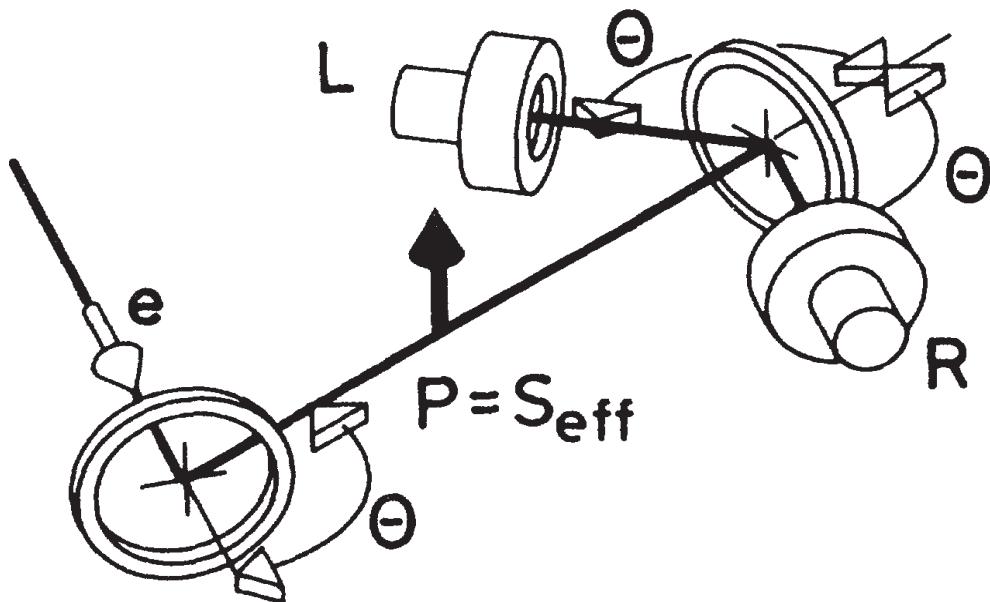
	Achieved at MAMI	$\sin^2\theta_W$ uncertainty	requirement
• Energy fluctuations:	0.04 eV	< 0.1 ppb	ok!
• Position fluctuations	3 nm	5 ppb	0.13 nm
• Angle fluctuations	0.5 nrad	3 ppb	0.06 nrad
• Intensity fluctuations	14 ppb	4 ppb	0.36 ppb

Polarimetry at MESA

Polarimetry: Double Mott Polarimeter

Mott Polarimetry:

- Measure left/right asymmetry to obtain spin polarisation
- Analysing power of foils needs to be extrapolated



Double Mott Polarimeter:

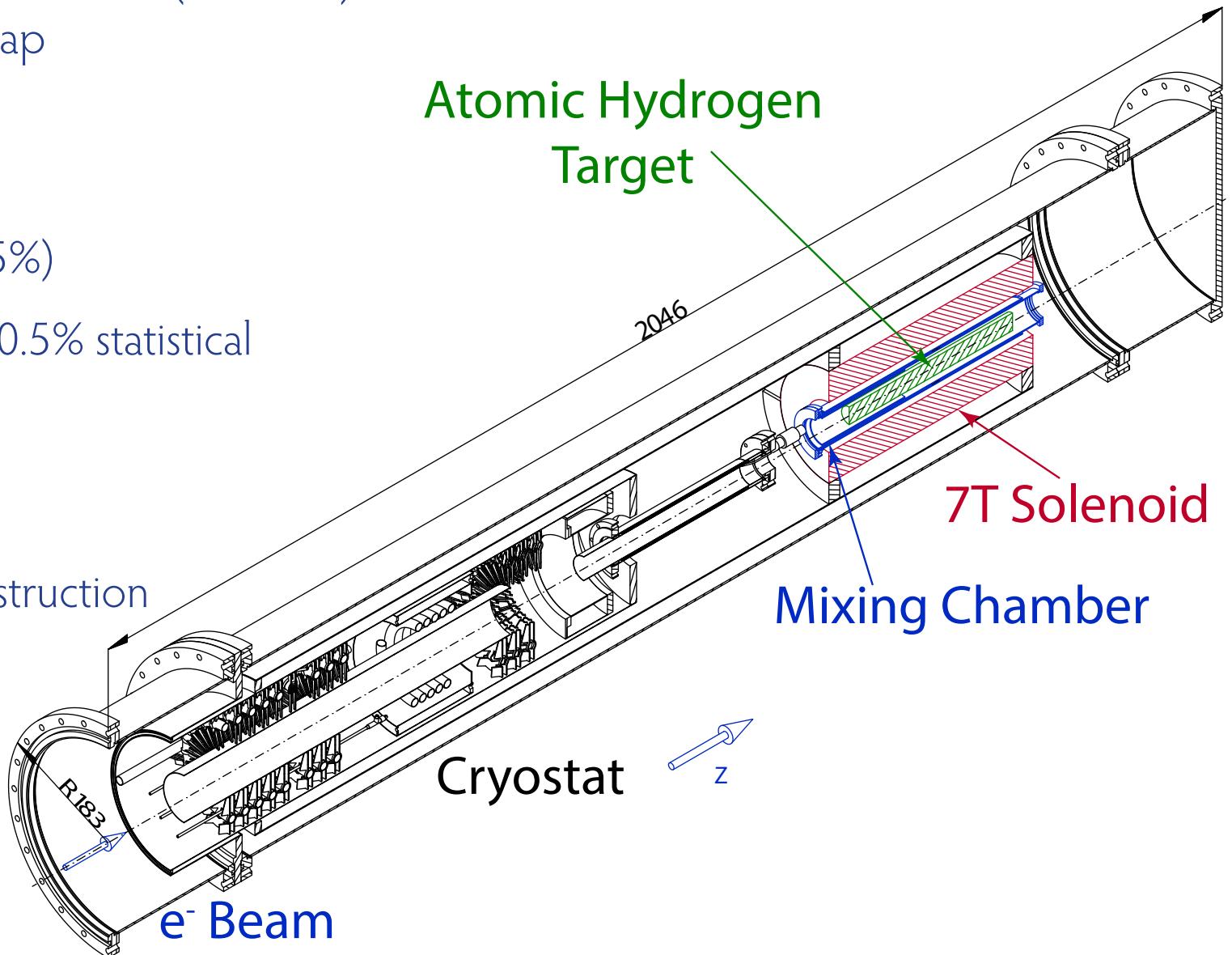
- Obtain analysing power from measurement
- Precise measurement of spin polarisation
- Invasive measurement at source

[Gellrich and Kessler, Phys.Rev.A. 43, 204 (1991)]

Polarimetry: Hydro-Møller Polarimeter

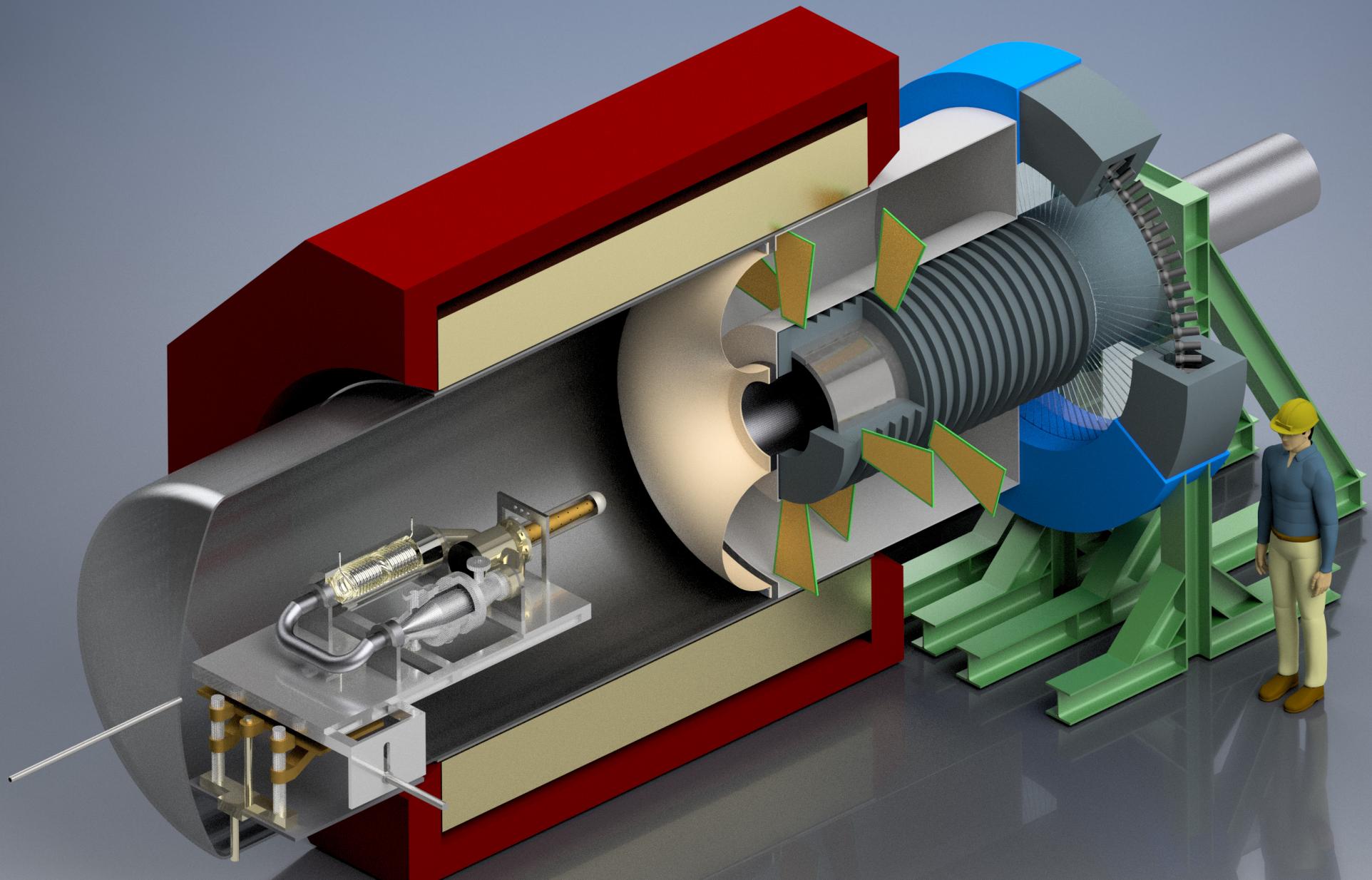
Møller scattering from polarized (8 T field)
atomic hydrogen in a trap

- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy
- Cryostat under construction in Mainz
- Also needs a detector...

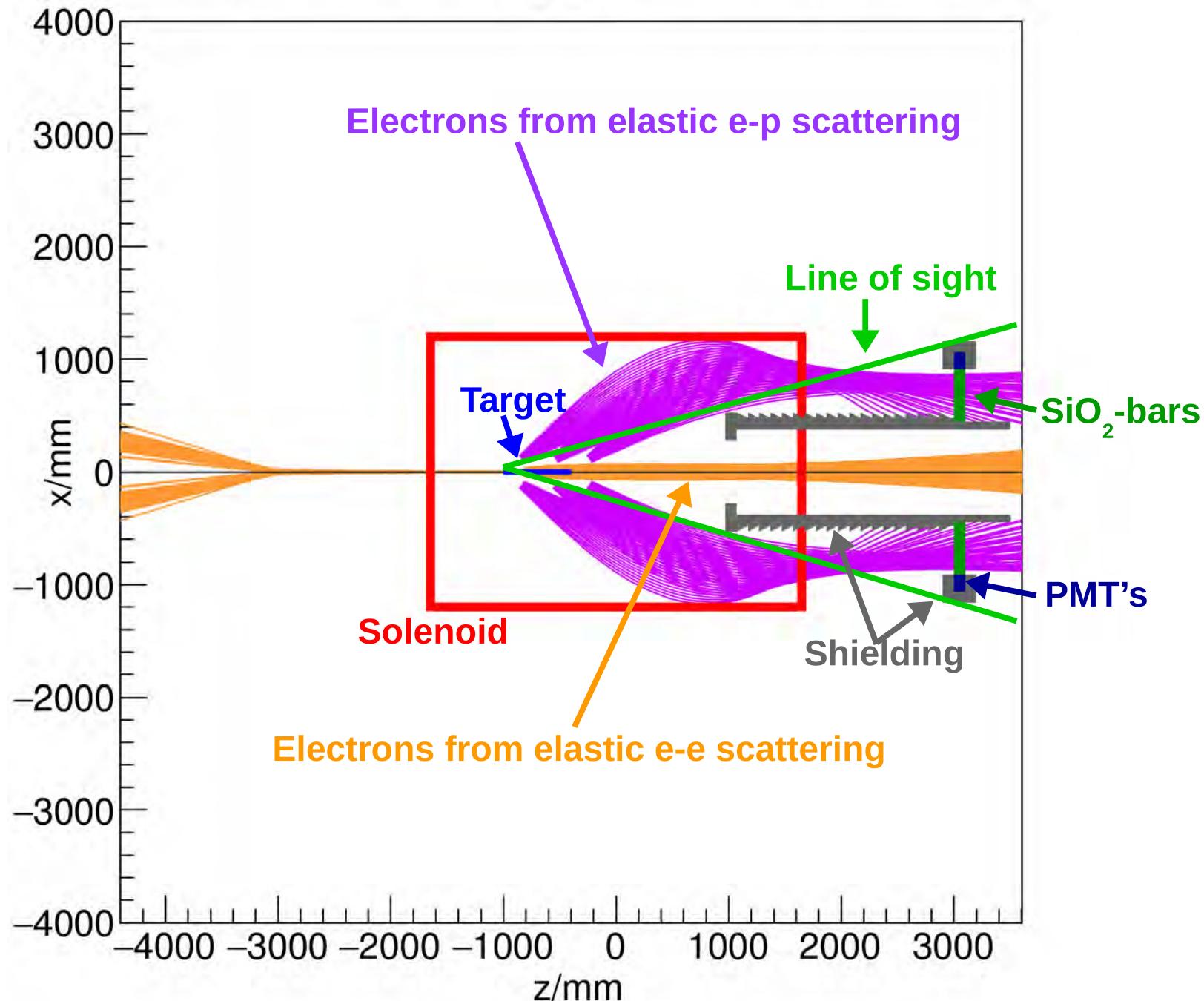


P2:

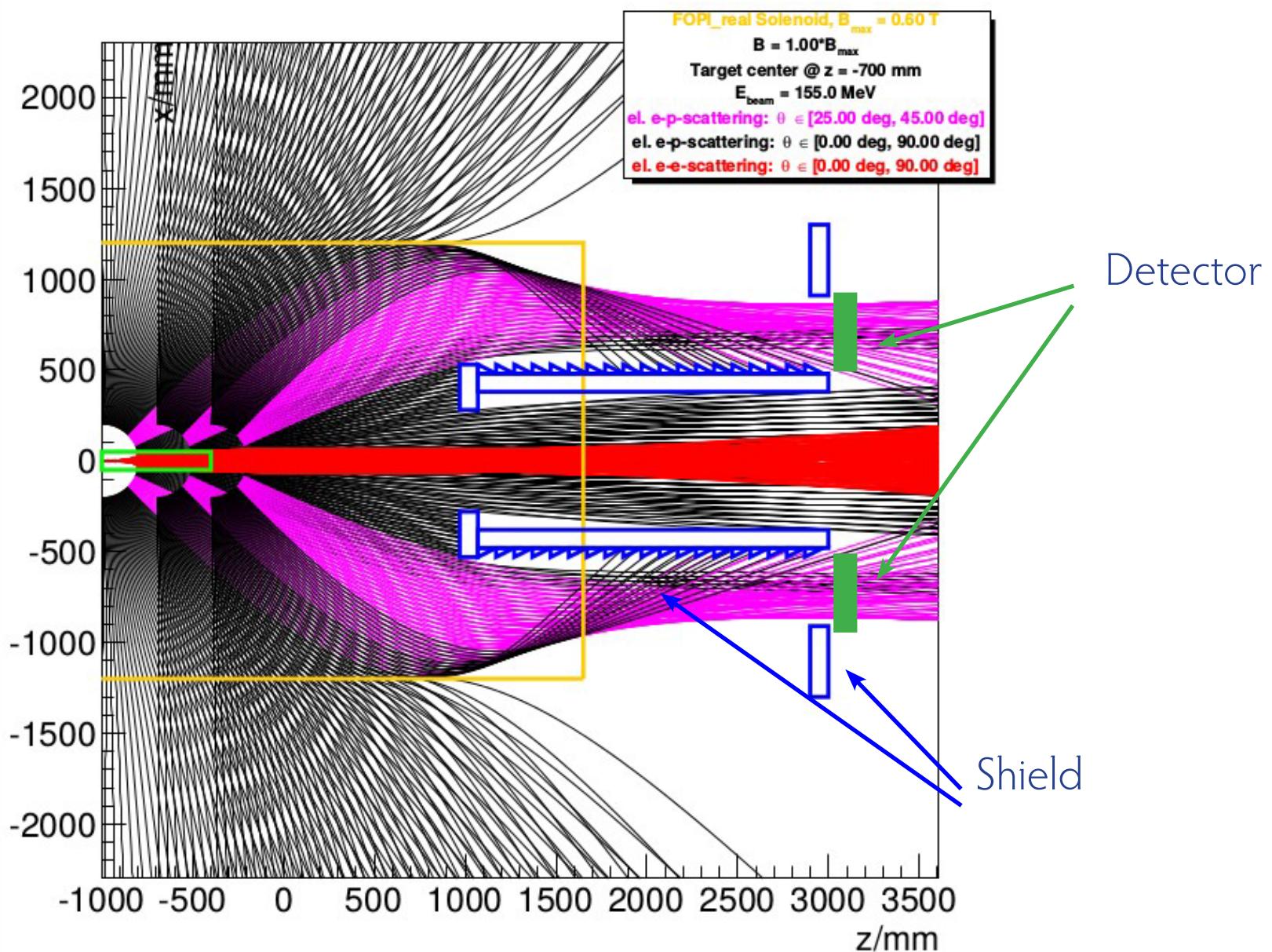
How to detect 100 GHz of (the right) electrons...



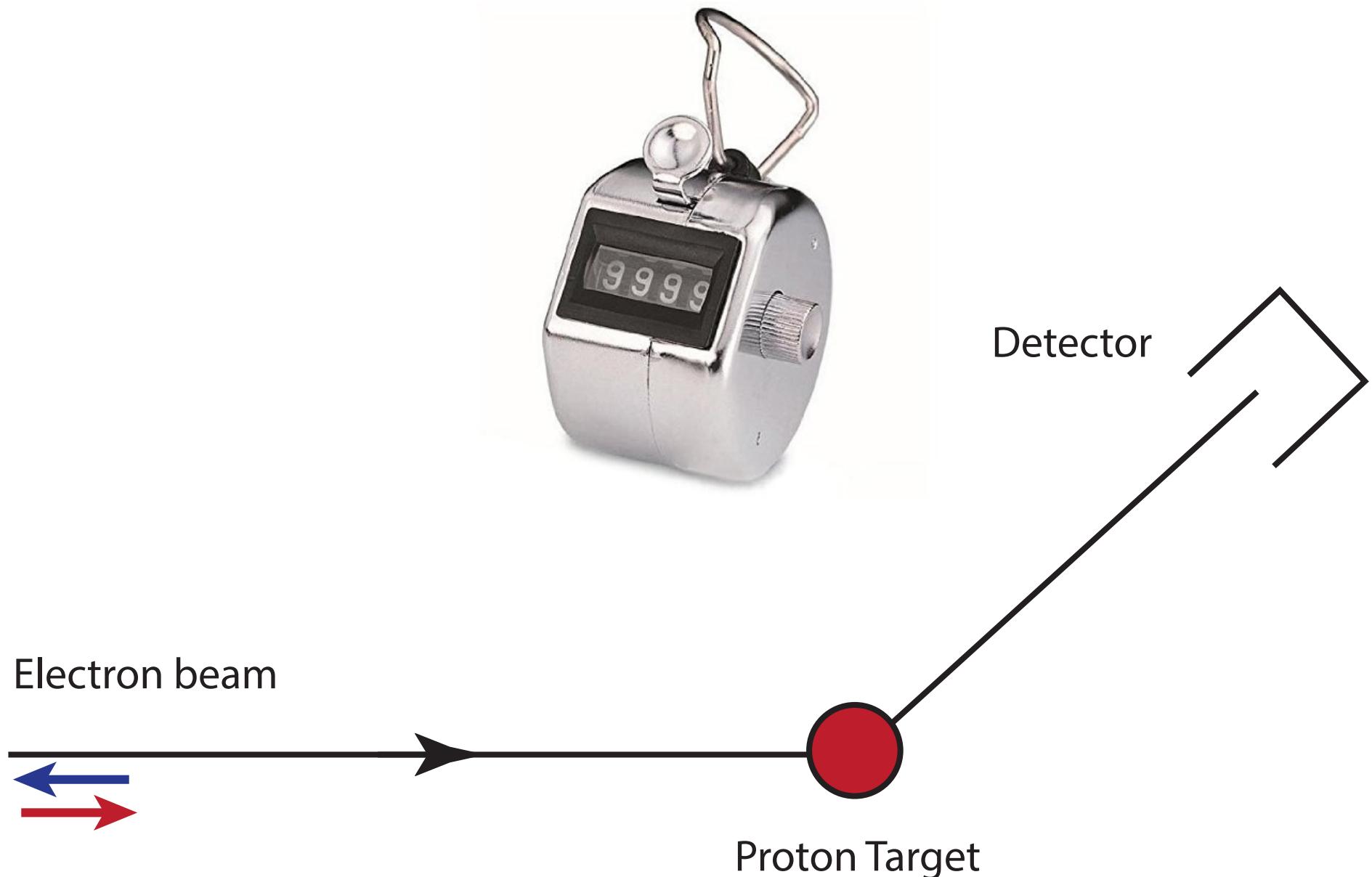
Solenoid spectrometer



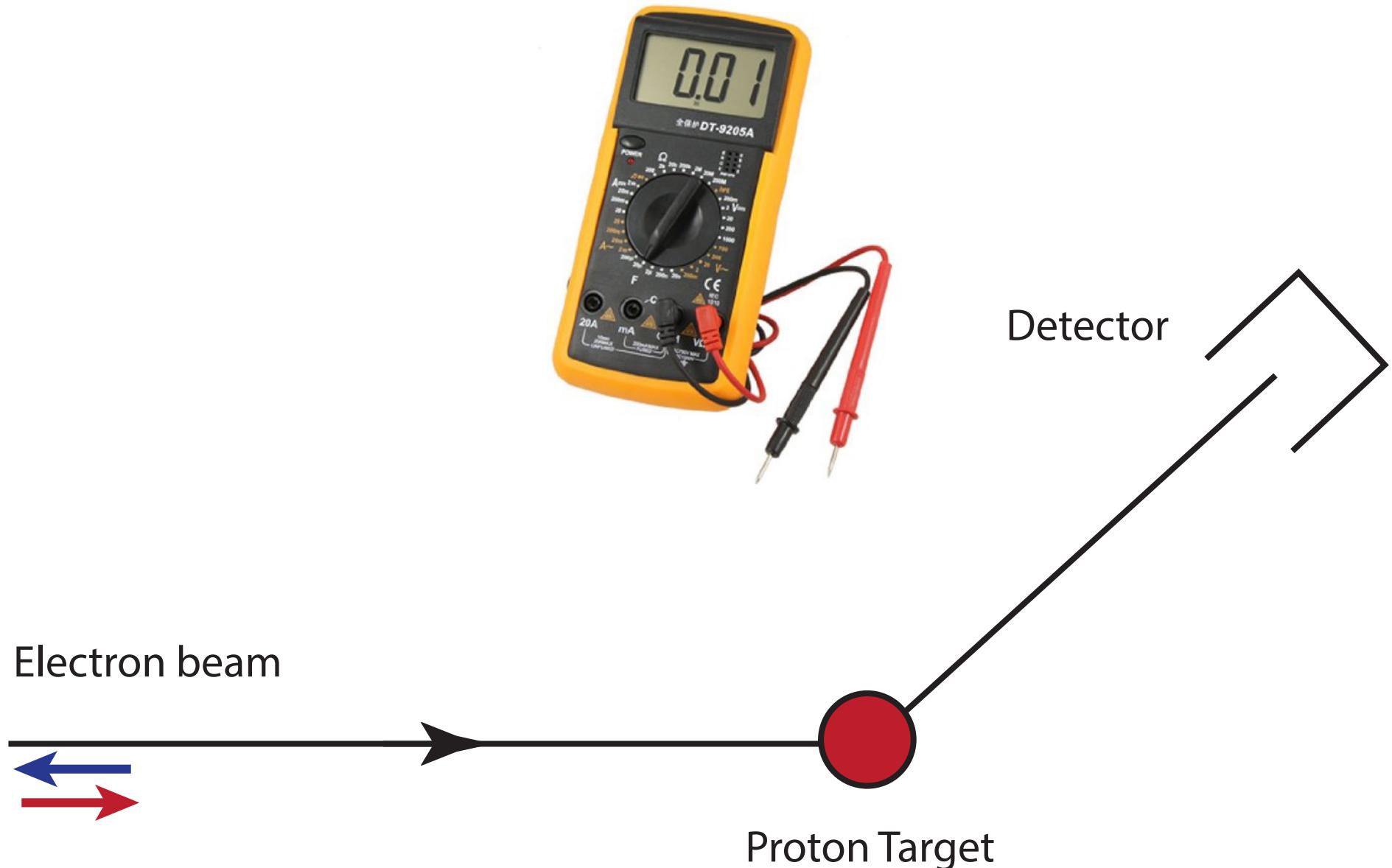
Solenoid spectrometer



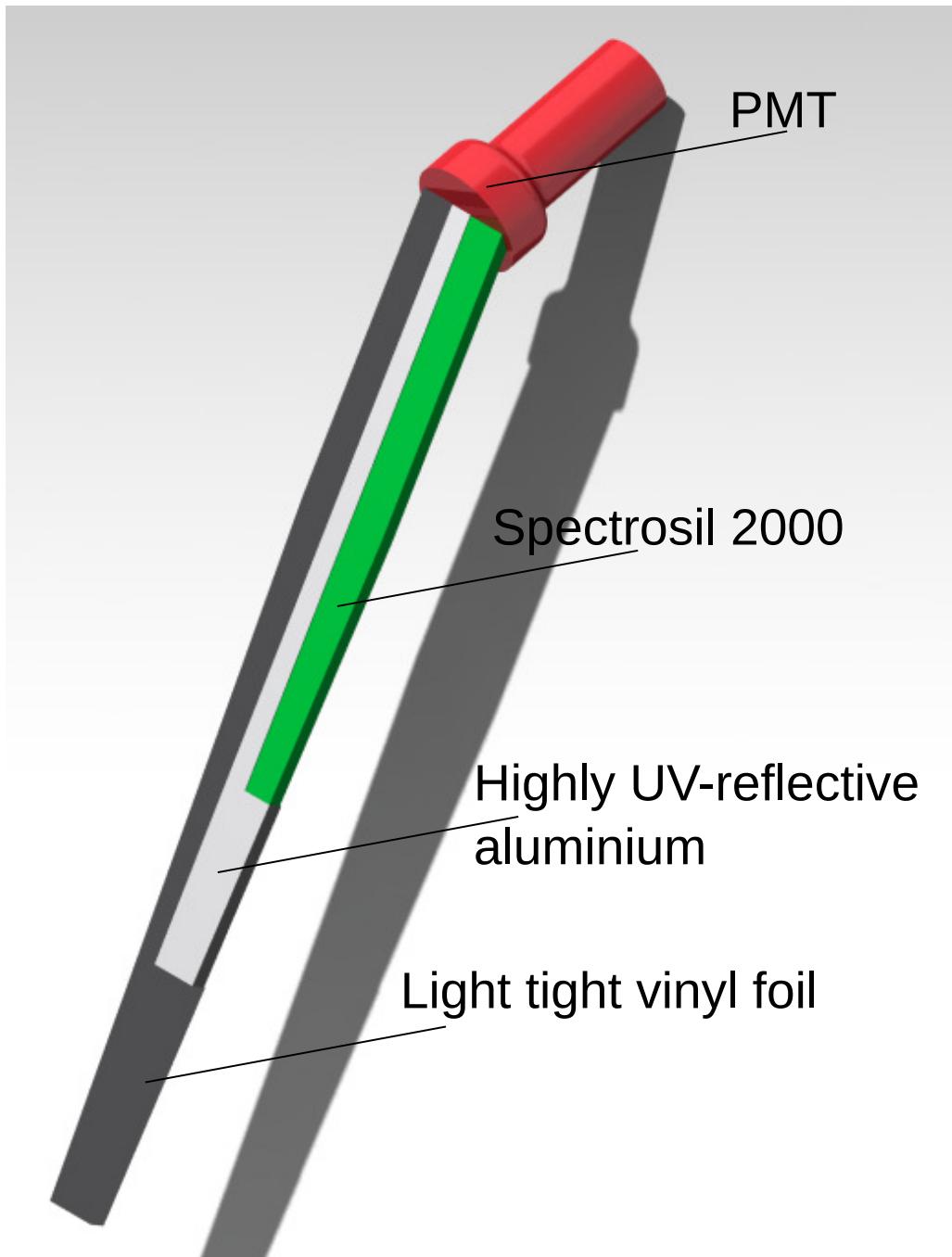
Counting detectors



Integrating detectors

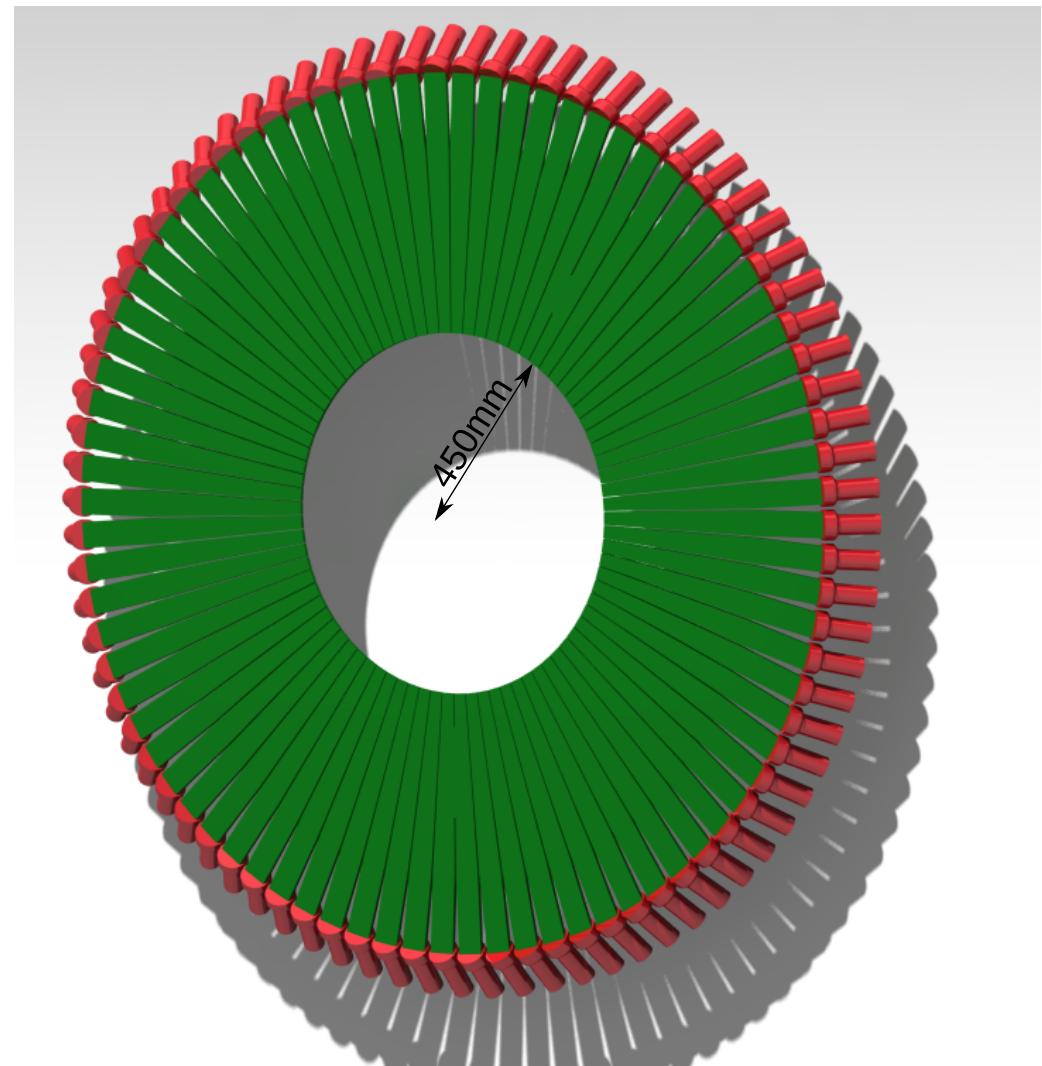


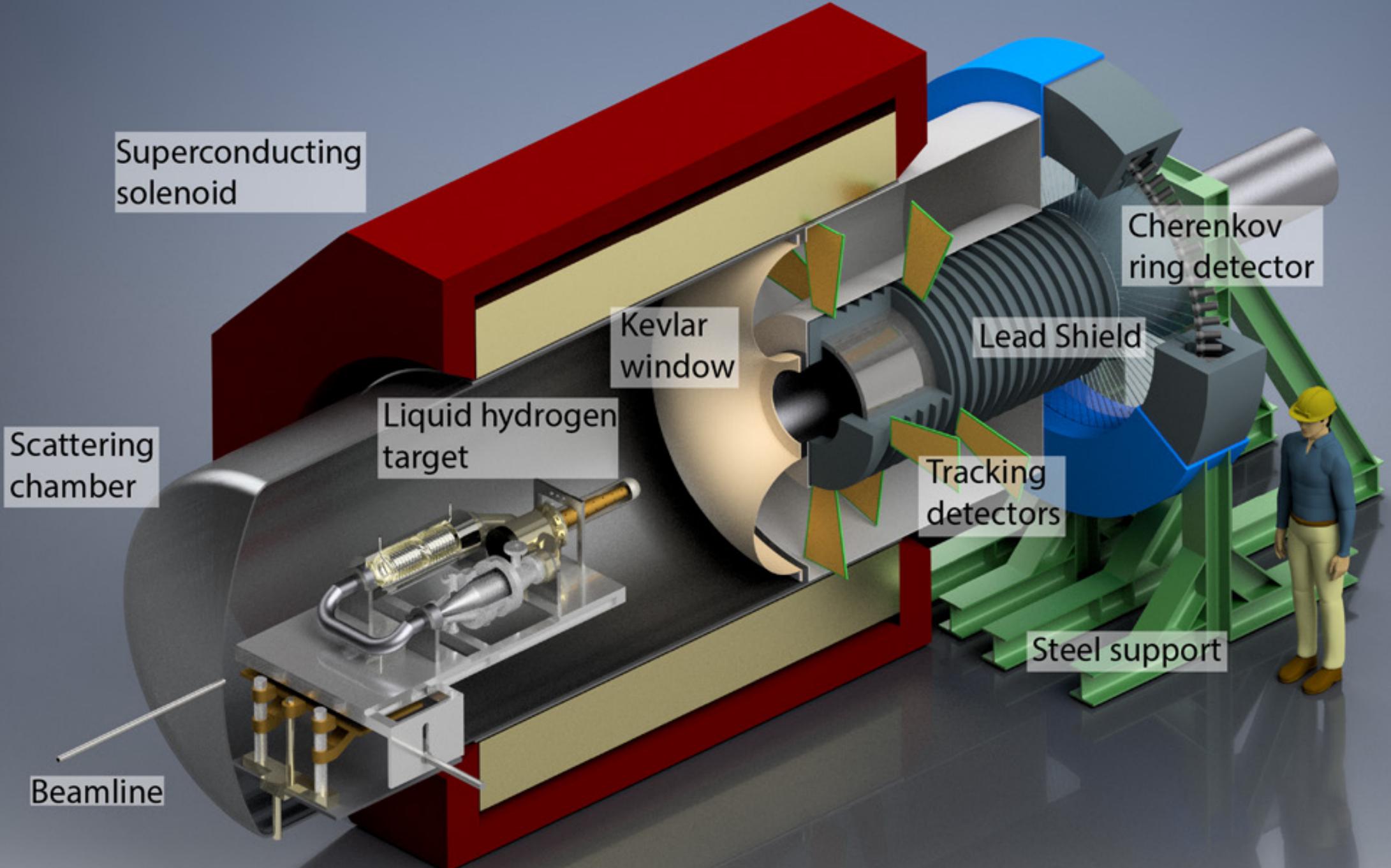
Quartz-Bars & Photomultipliers



Detect Cherenkov-light created by electrons

Integrate photomultiplier current





P2 Error budget

E_{beam}	155 MeV
$\bar{\theta}_f$	35°
$\delta\theta_f$	20°
$\langle Q^2 \rangle_{L=600 \text{ mm}, \delta\theta_f=20^\circ}$	$6 \times 10^{-3} (\text{GeV}/c)^2$
$\langle A^{\text{exp}} \rangle$	-39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	0.10 ppb (0.25 %)

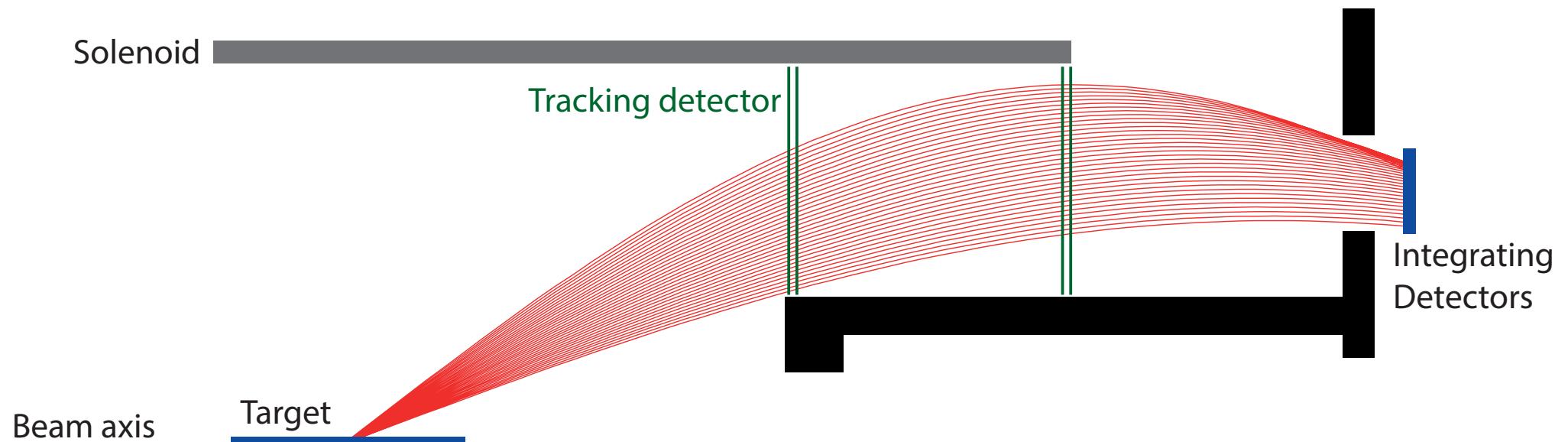
$\langle s_W^2 \rangle$	0.231 16
$(\Delta s_W^2)_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s_W^2)_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s_W^2)_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s_W^2)_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s_W^2)_{\square_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s_W^2)_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2 \rangle_{\text{Cherenkov}}$	$4.57 \times 10^{-3} (\text{GeV}/c)^2$
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	-28.77 ppb

Measuring Q^2 :

Tracking a
lot of low momentum particles

Tracker requirement

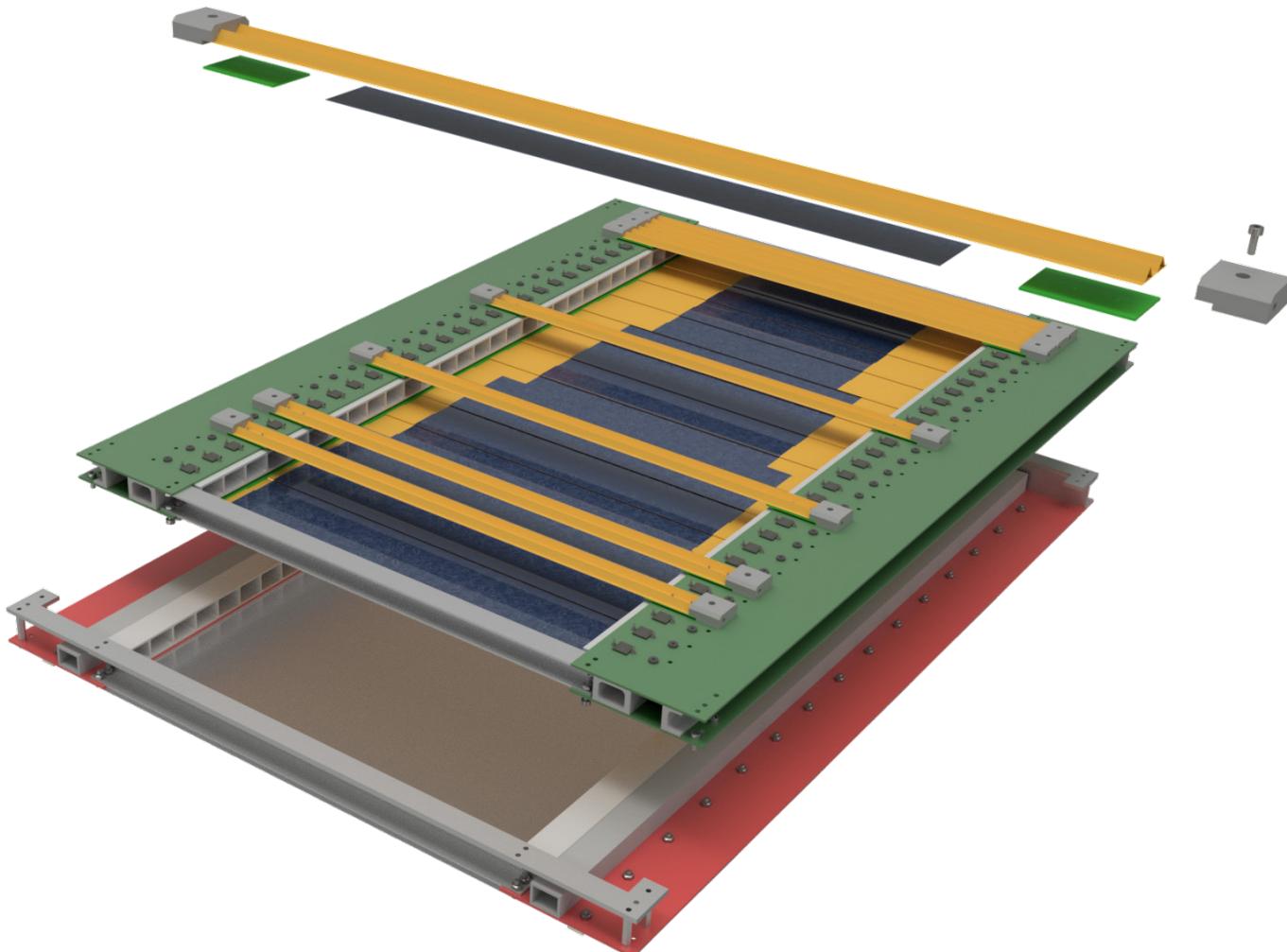
- Low momentum electrons:
Thin detectors
- Very high rates:
Fast and granular detectors



Fast, thin, cheap pixel sensors

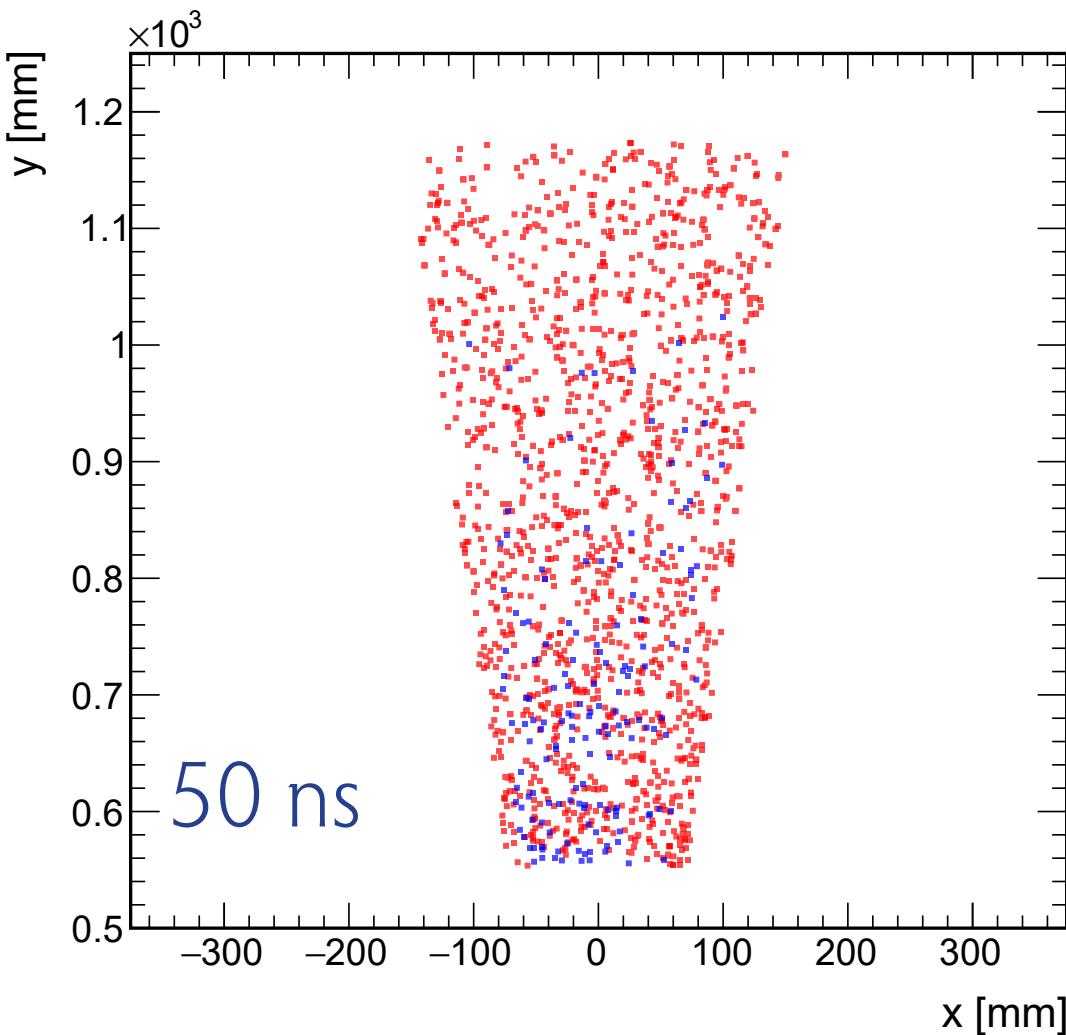
High Voltage Monolithic Active Pixel Sensors

Mechanics



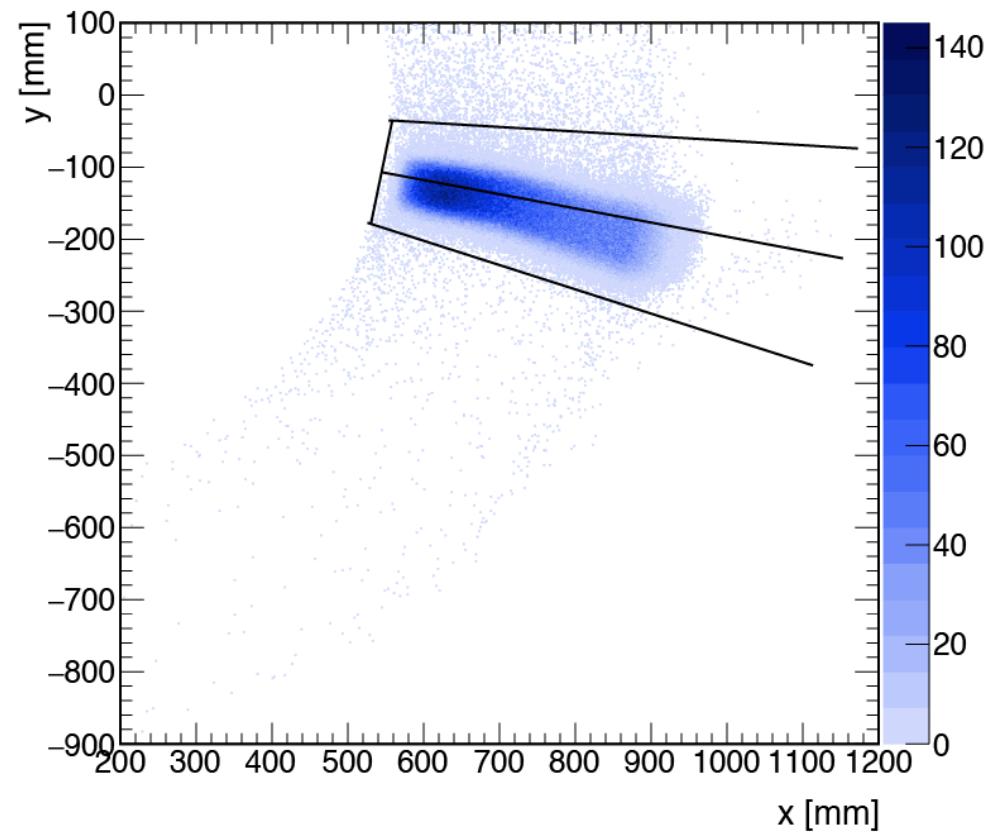
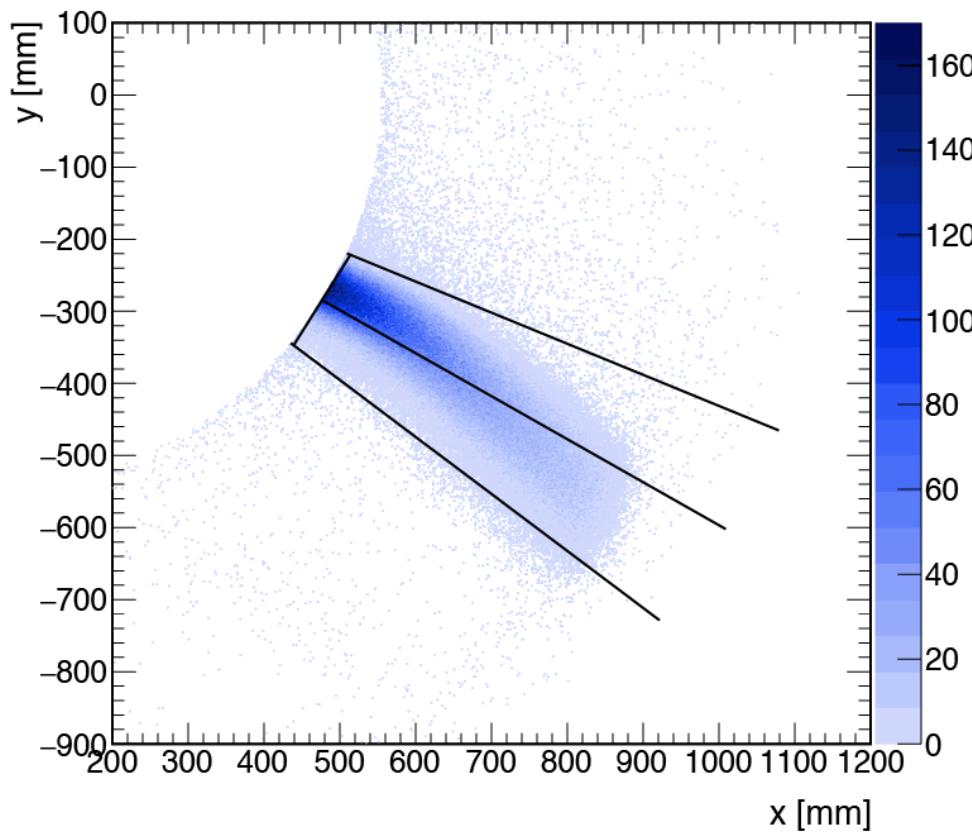
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ folds as support
- About 1% of a radiation length per layer

The tracking challenge



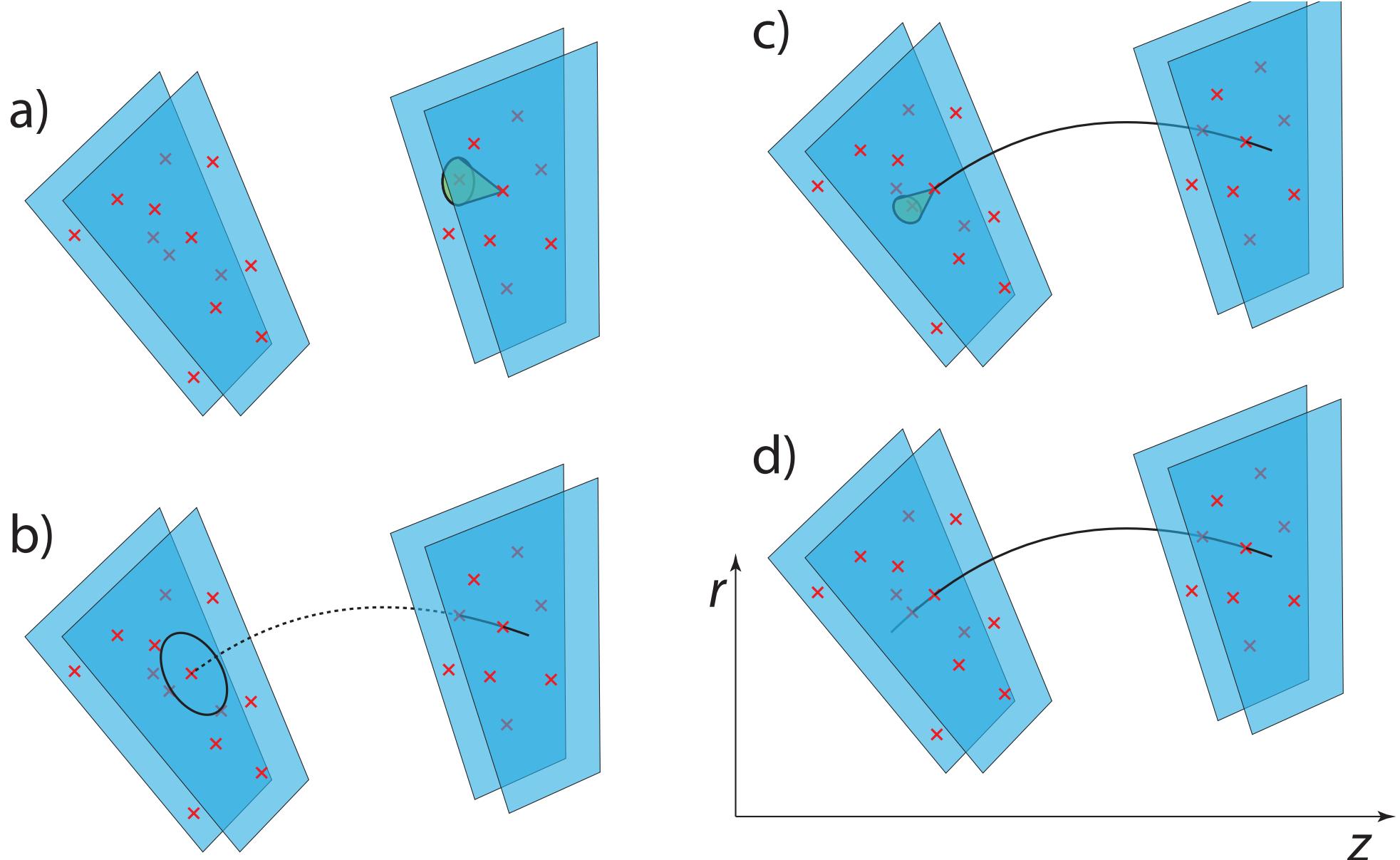
- 100 GHz electrons
- about 1000 Bremsstrahlung photons per electron

No need for full coverage

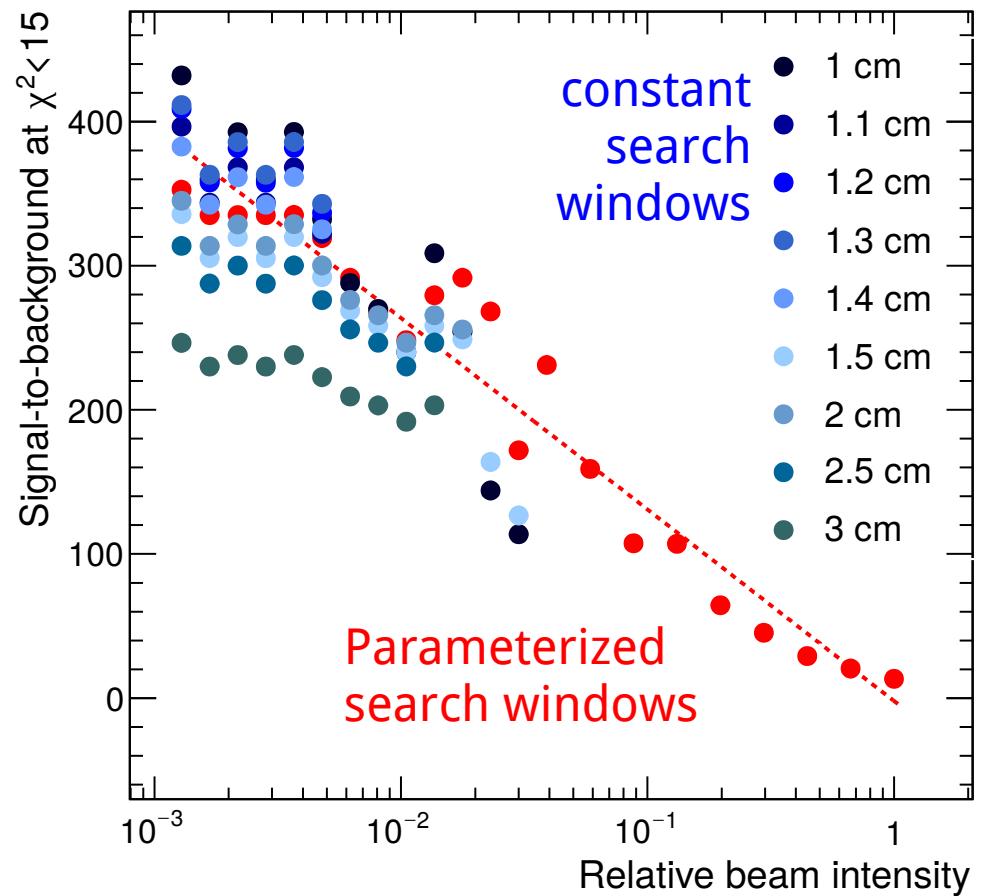
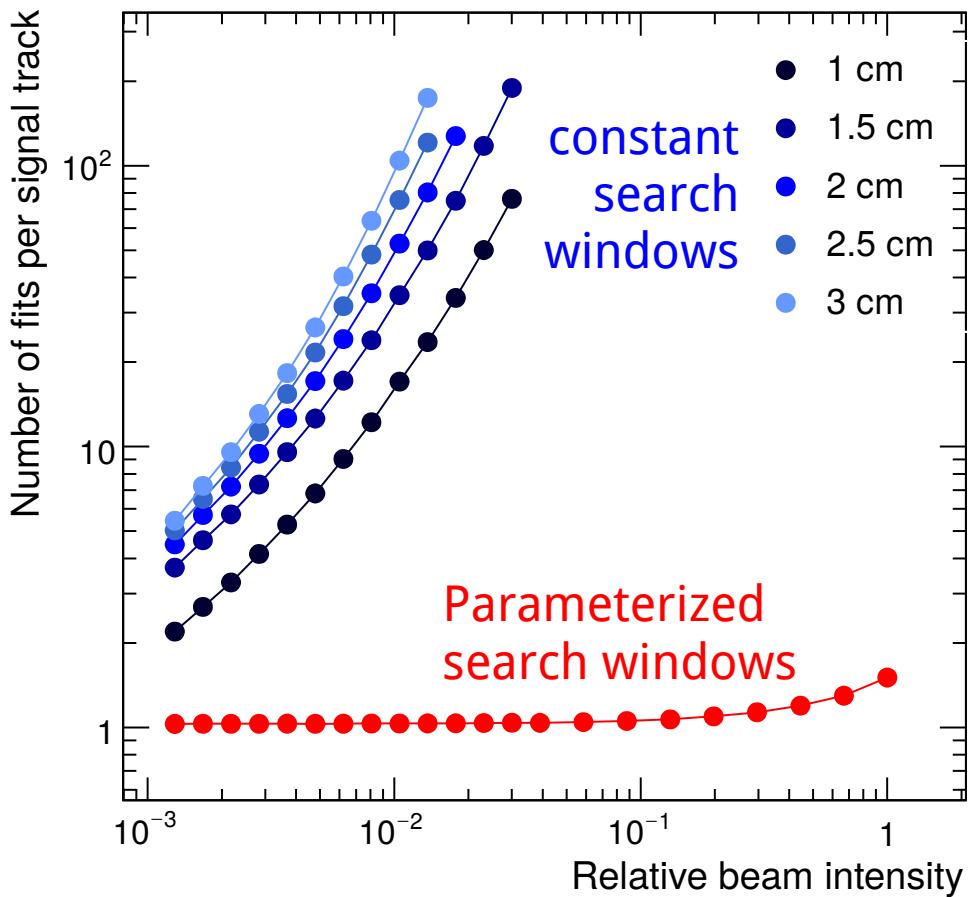


Parametrization based tracking

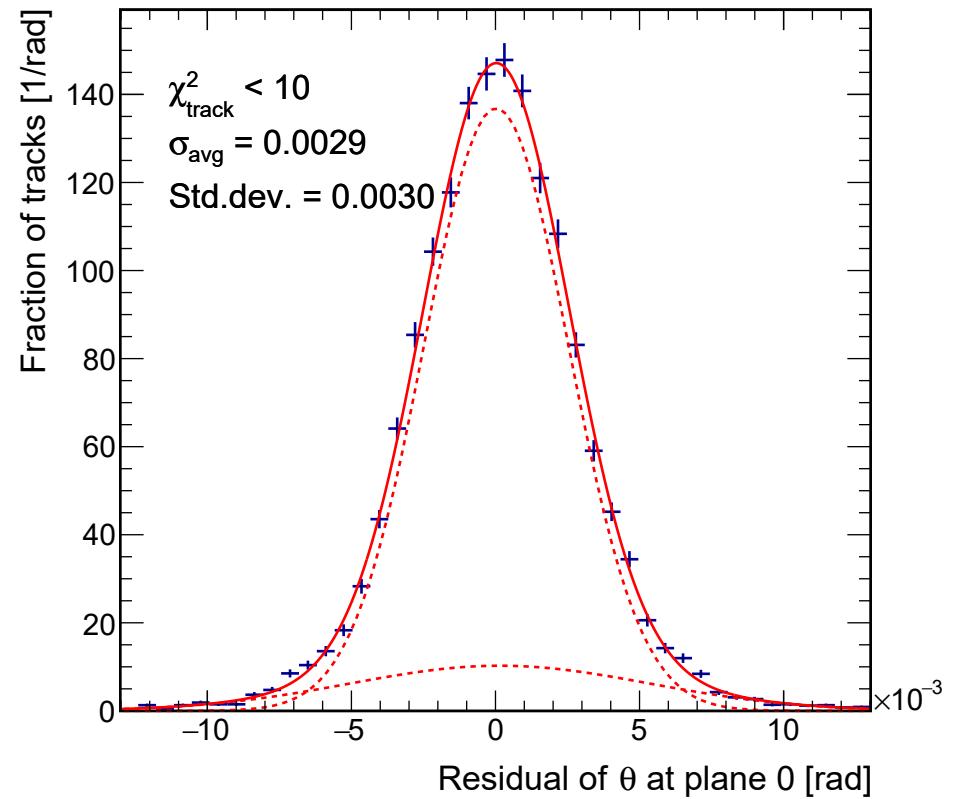
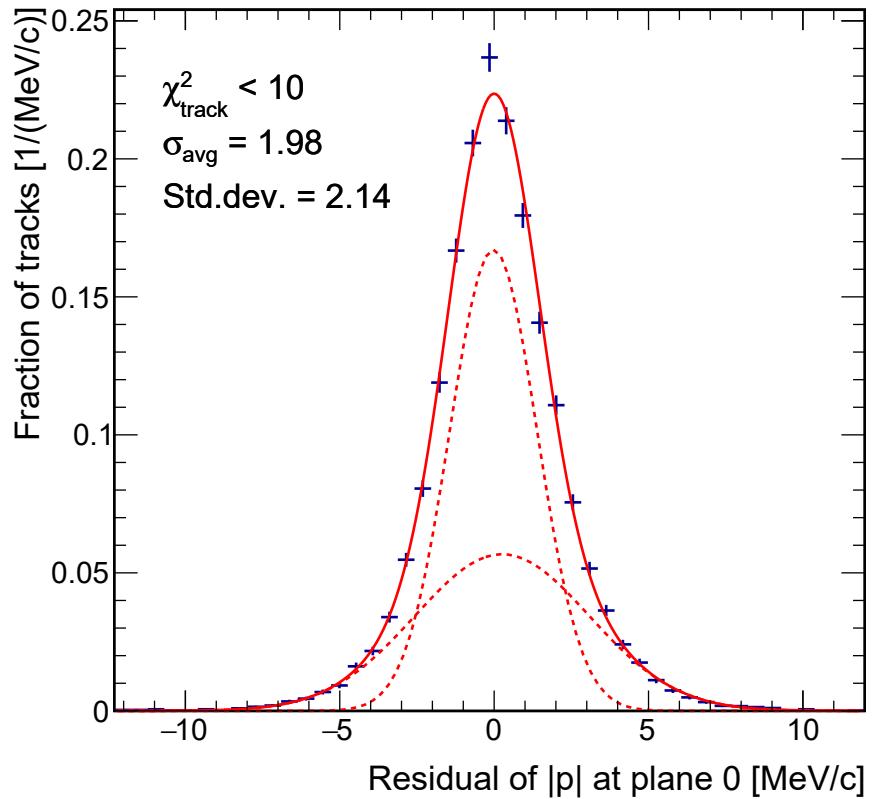
I. Sorokin



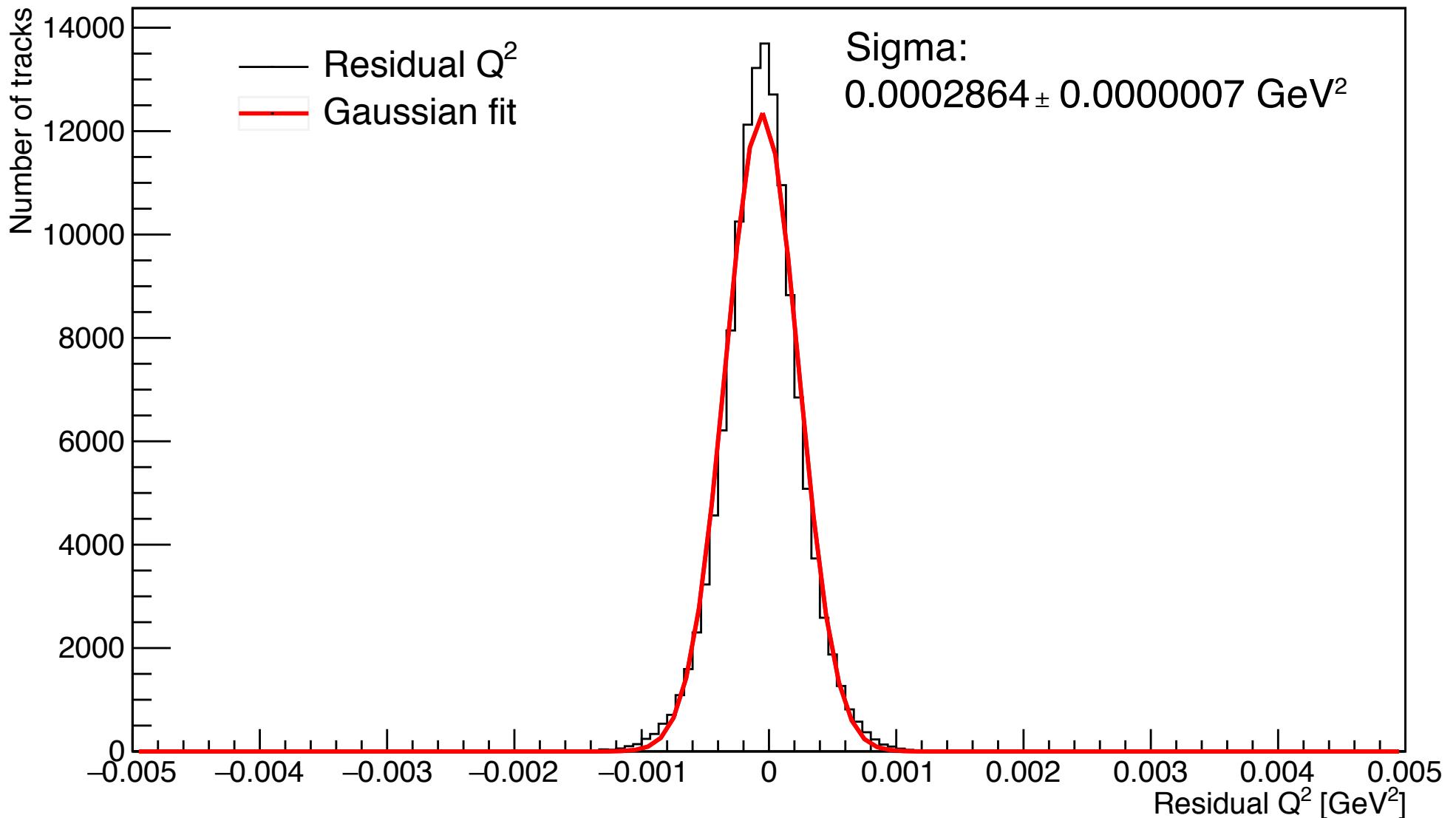
Tracking performance



Tracking performance



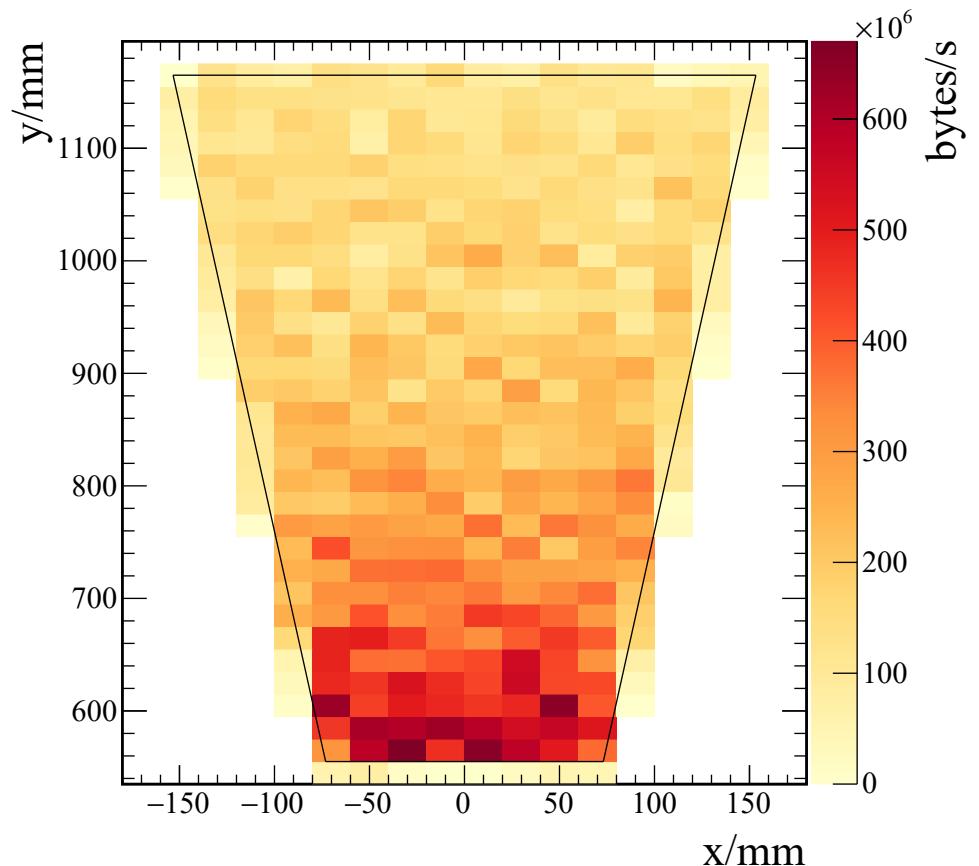
Q^2 reconstruction



Challenge I:
Very high rates

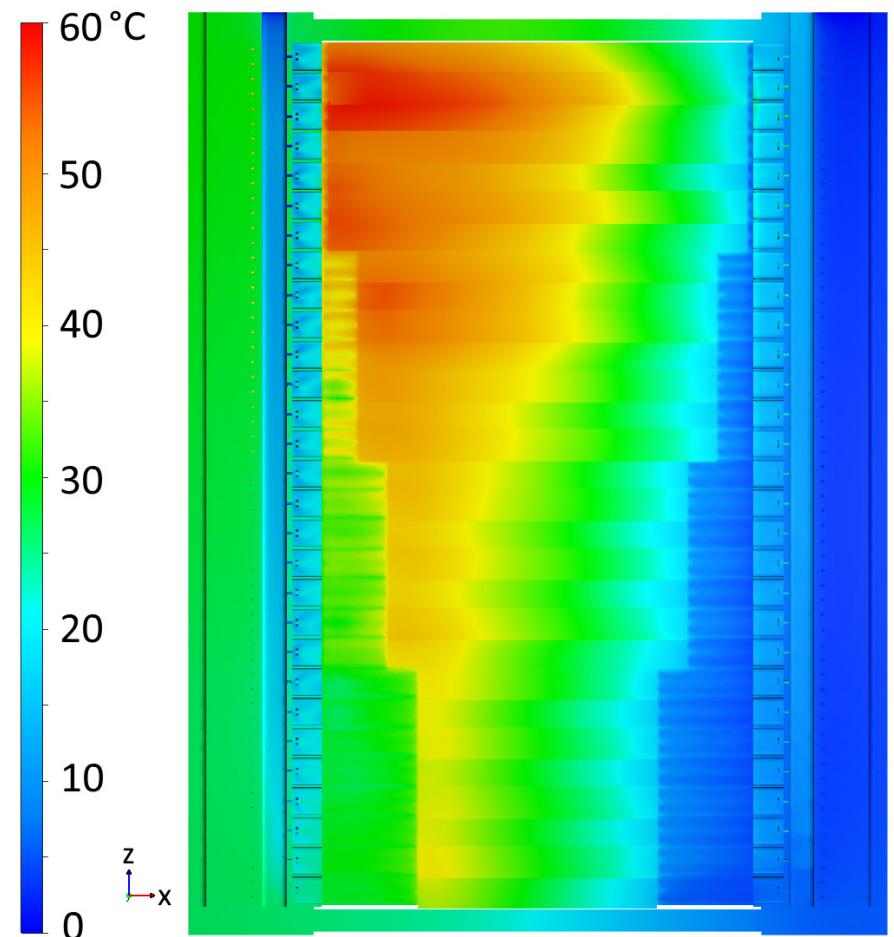
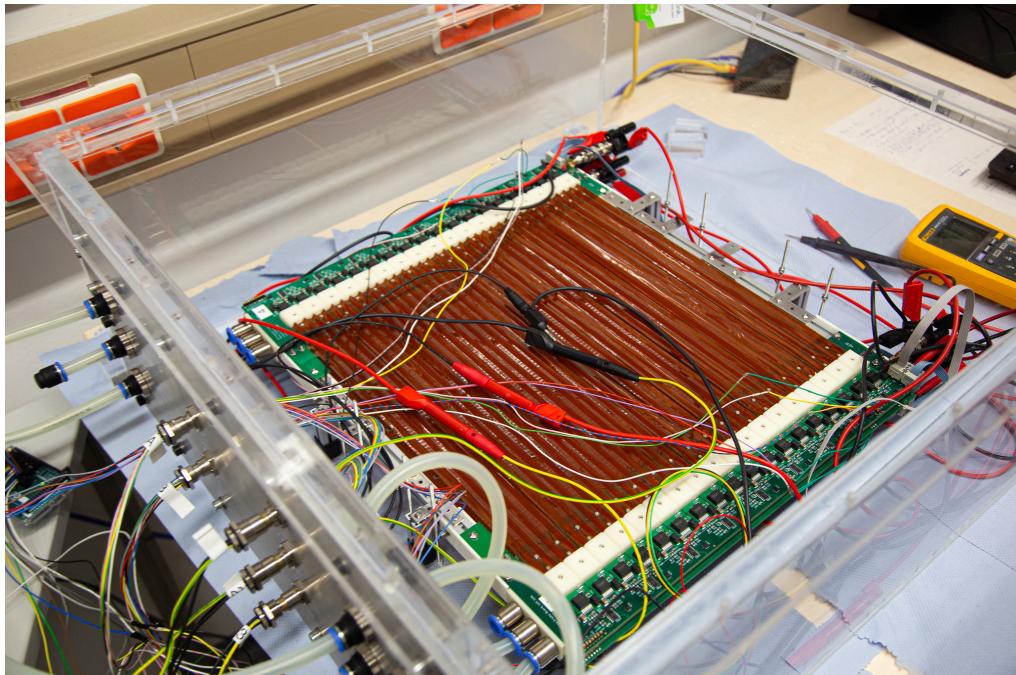
High rates

- We would like the tracker at or close to the nominal rate to study systematics
- We will probably remove the tracker for most of the 11'000 hours of running
- Need to deal with the very high instantaneous rate, but: all electrons are equal
- Gated operation to get a manageable DAQ system



Helium Gas Cooling

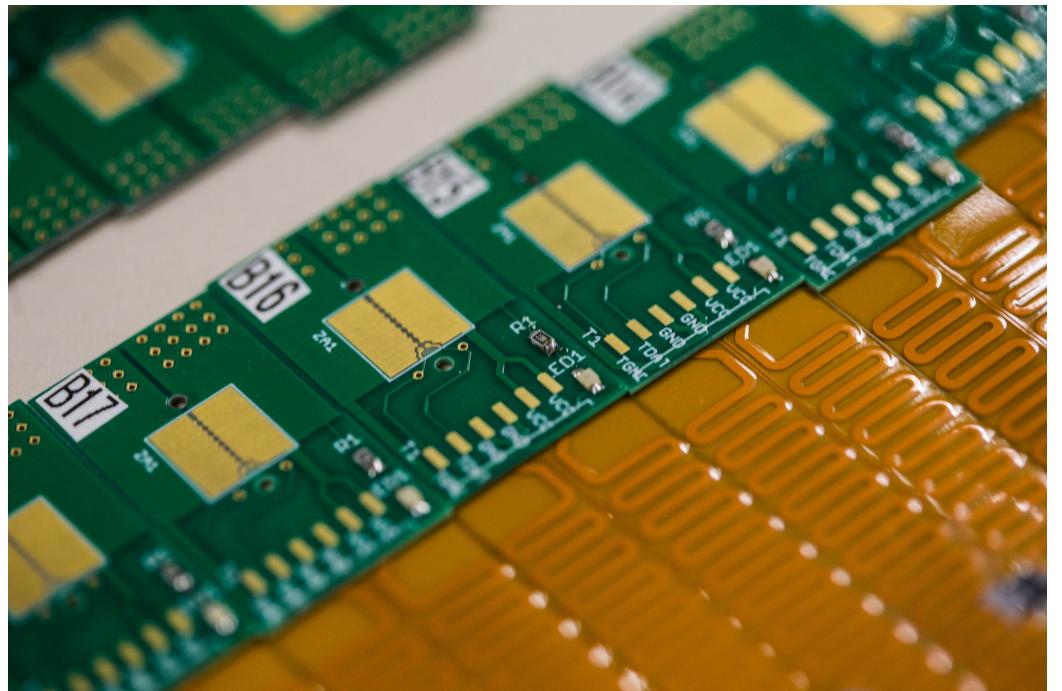
- Planning for a helium based gas cooling similar to Mu3e
- Works well in CFD simulation and in thermo-mechanical prototype
- However: Off-detector infrastructure daunting, even with the large helium plant in Mainz - other ideas are very welcome...



Challenge III: Assembly

Assembly

- We have never built a silicon detector in Mainz
- Clean room with infrastructure will come, but late for P2
- Interesting collaboration opportunities



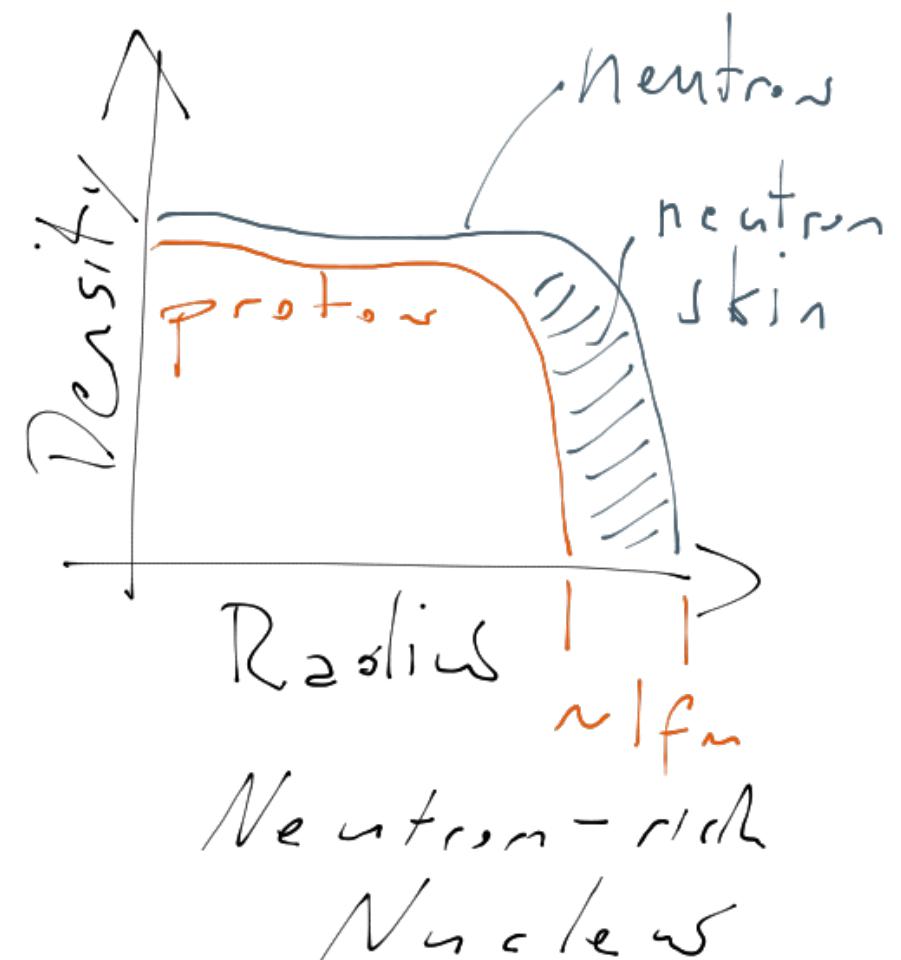
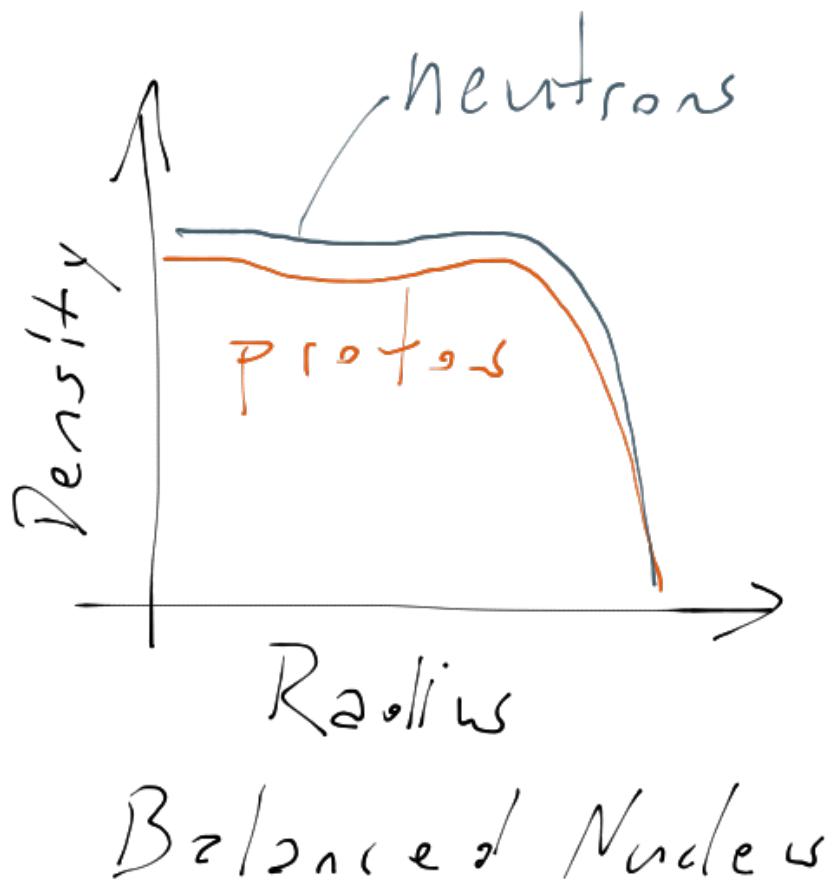
Summary

- The weak mixing angle is a fundamental parameter of the Standard Model and a good place to search for new physics
- We are building the new electron accelerator MESA in Mainz
- The P2 experiment at MESA will measure the weak mixing angle at low Q to 0.14%
- Can also study form factors and neutron skins

Can we do more?

Neutron Skins

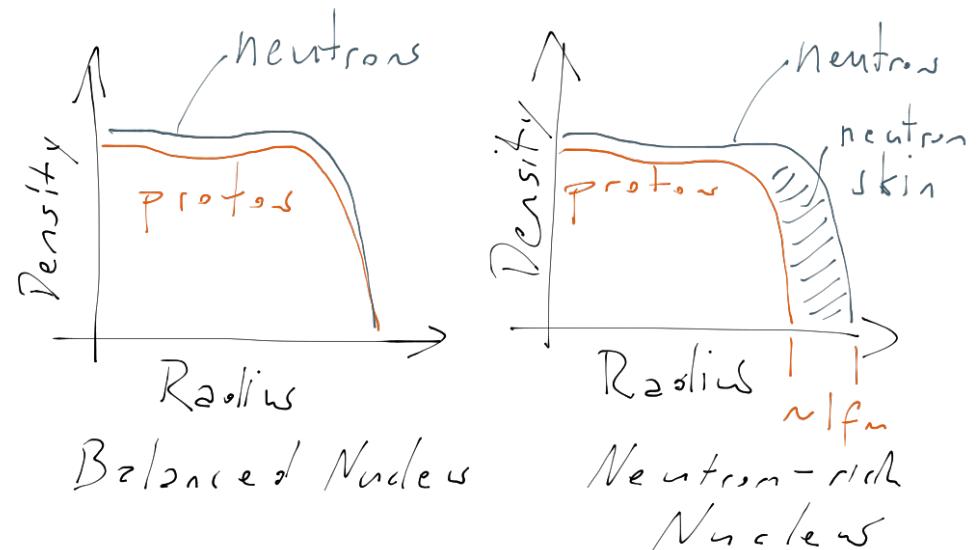
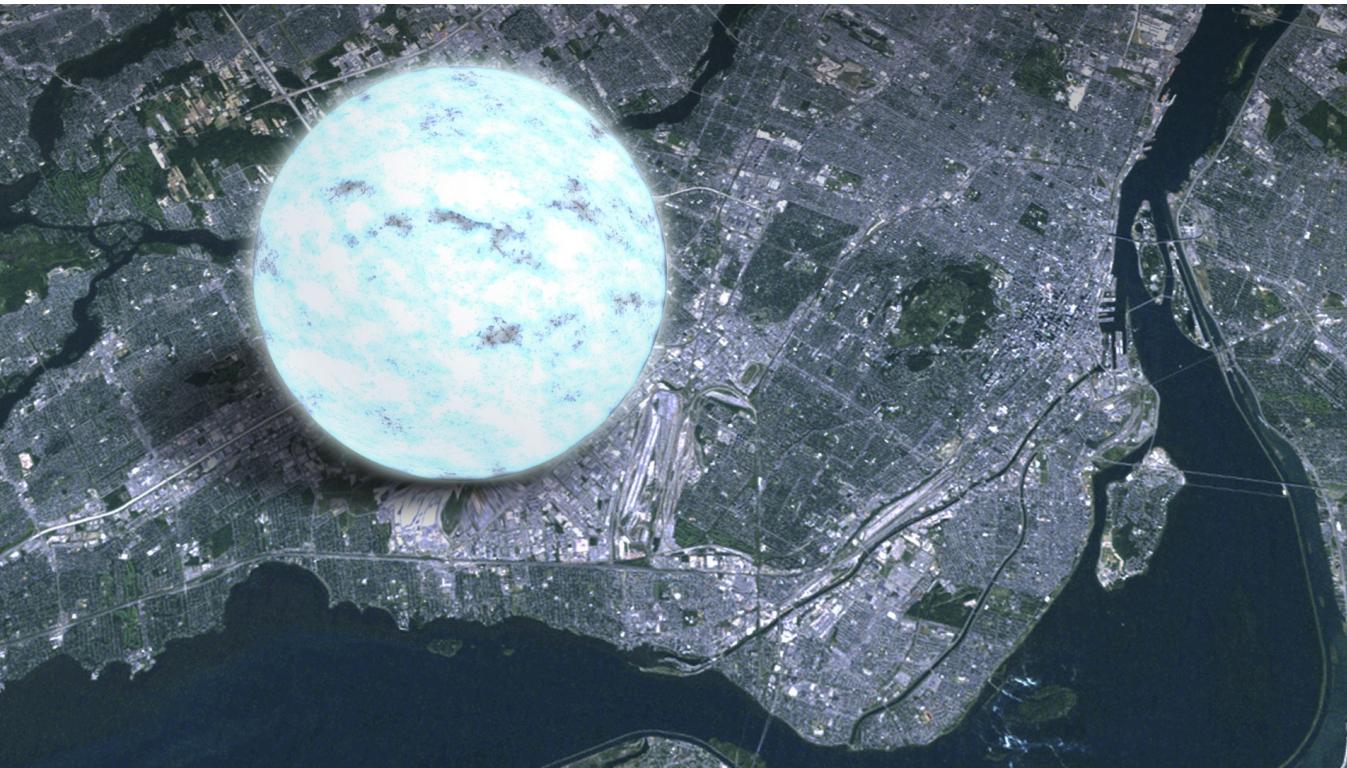
Where are the neutrons in the nucleus?



Neutron Skins

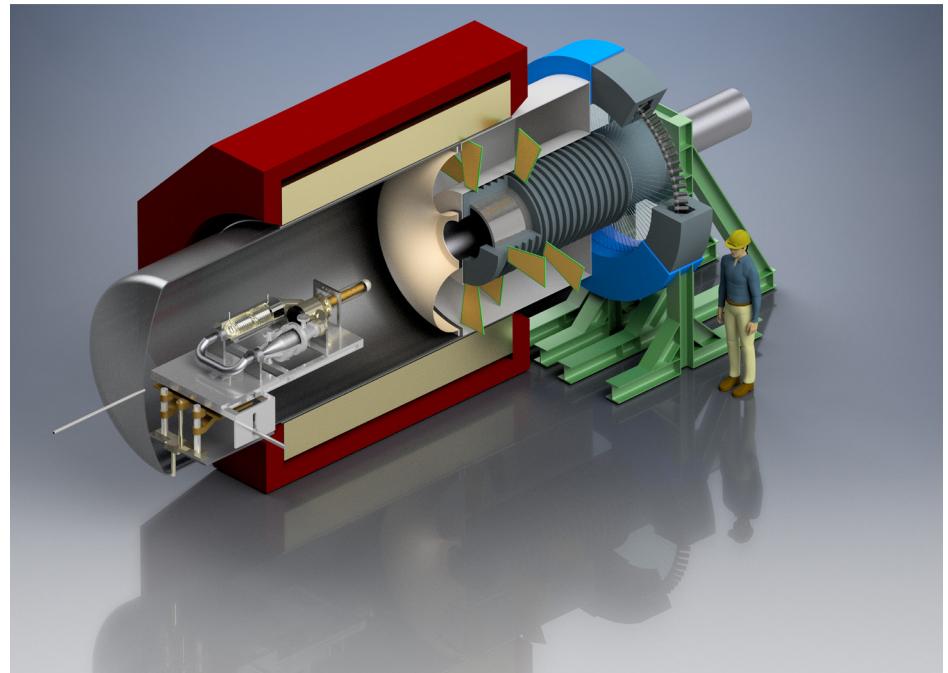
Where are the neutrons in the nucleus?

- Gives access to the equation of state of neutron matter
- Tells us how big/small neutron stars are



How to see the neutrons?

- Not charged: Photons not a good probe
- Use parity violating electron scattering:
Proton weak charge is almost zero -
see mostly neutrons

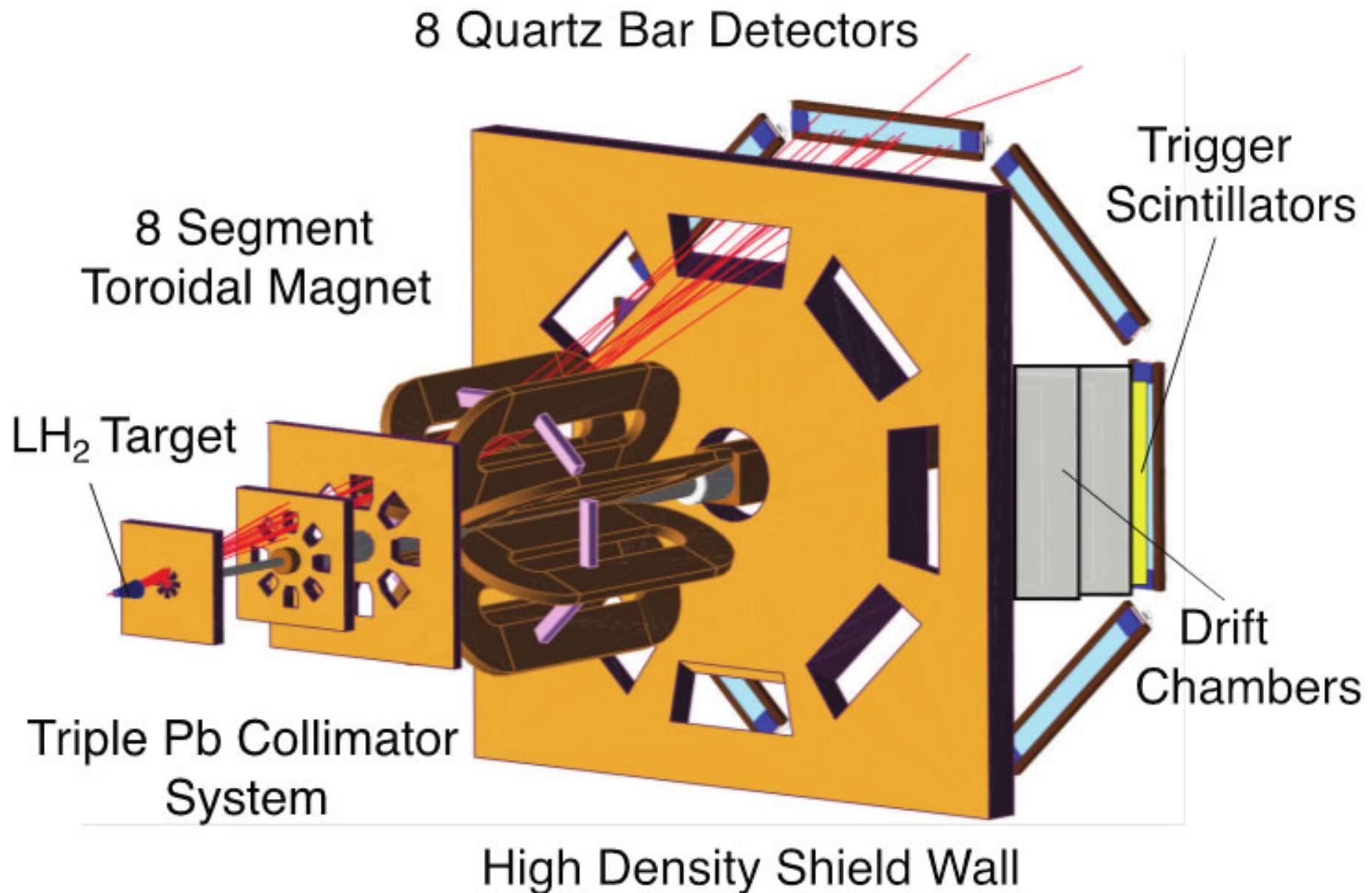


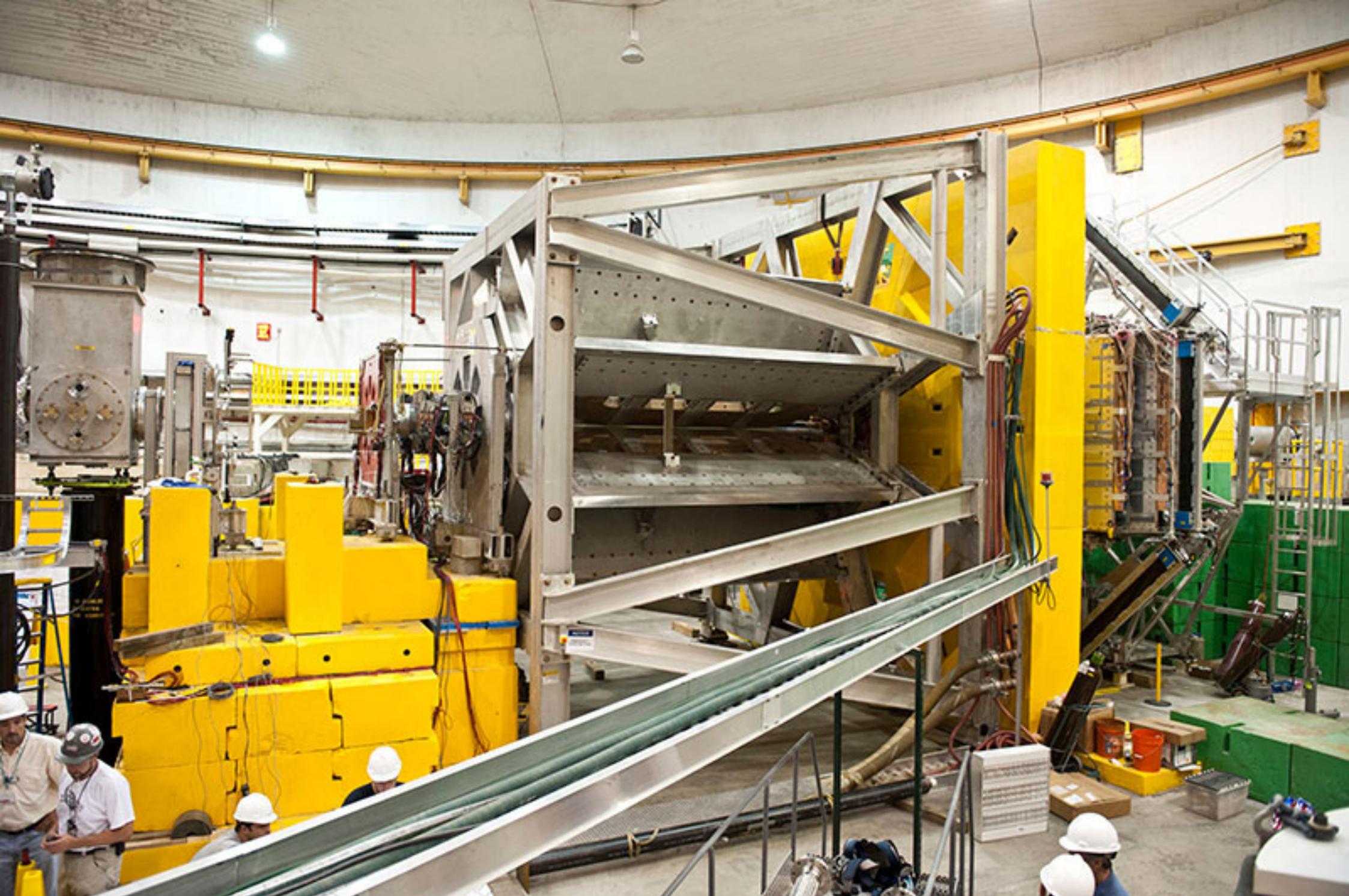
$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left(1 - 4 \sin^2 \theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right) \approx 0$$

Backup

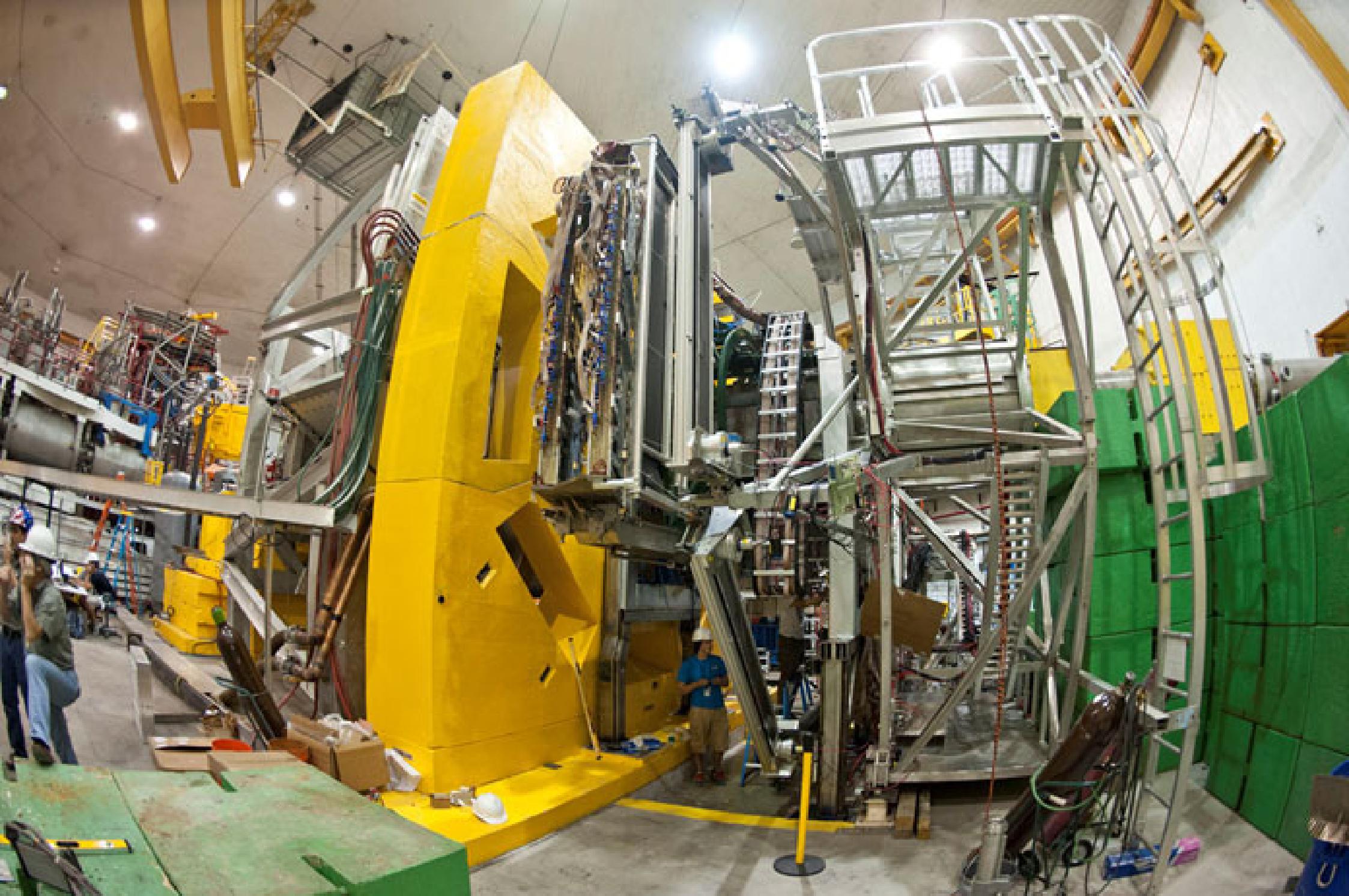
Other parity violation experiments

QWeak (JLab)



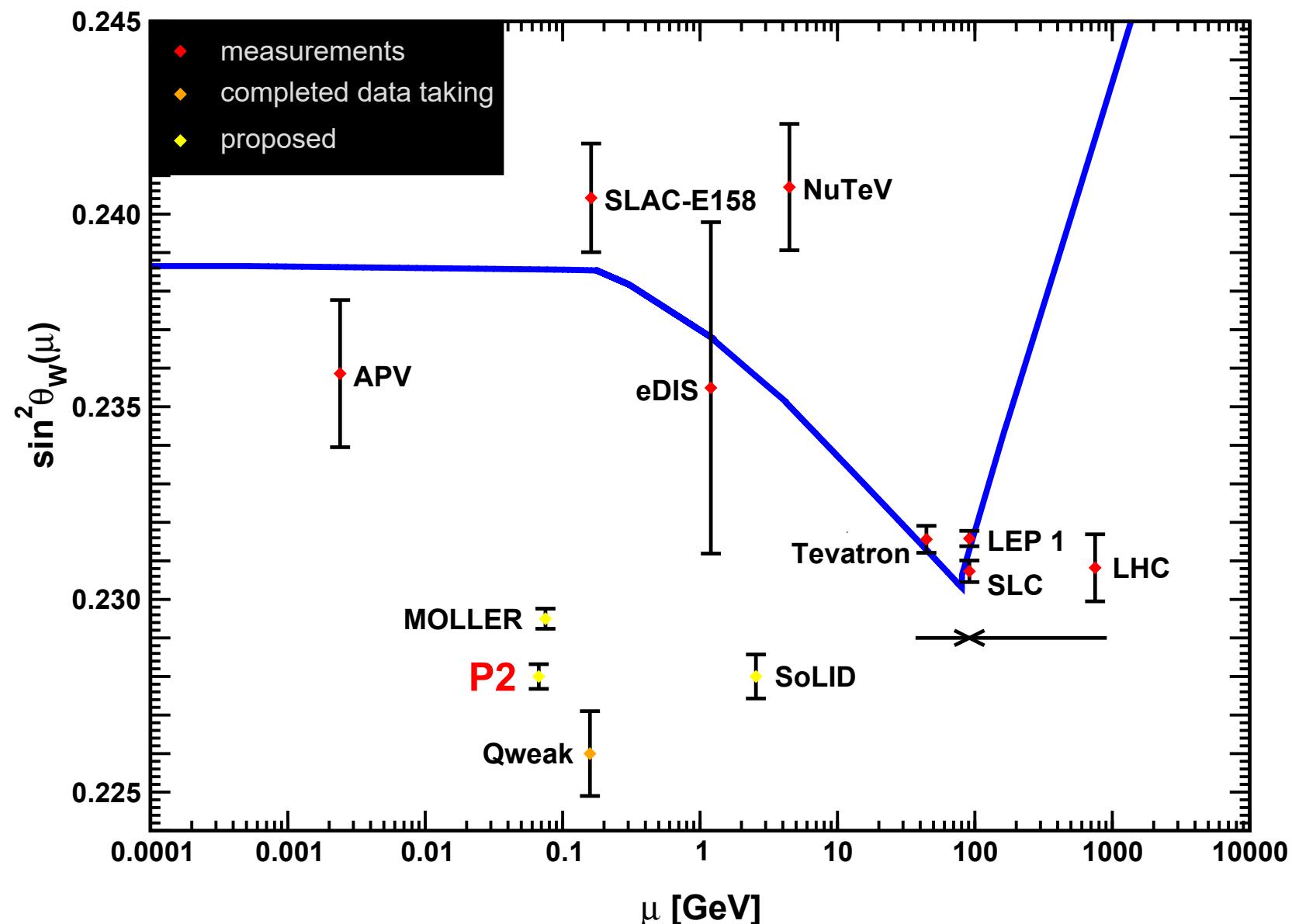


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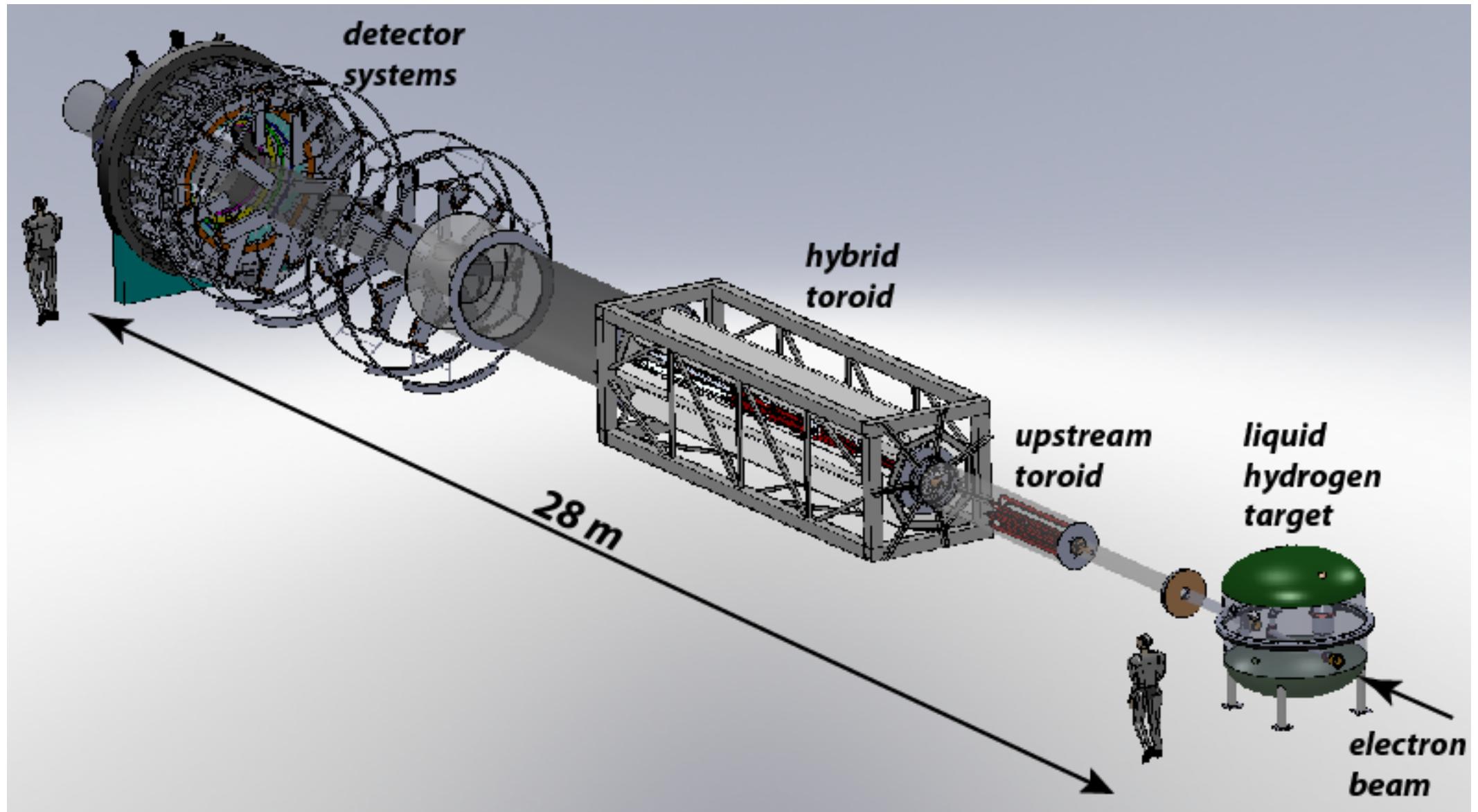


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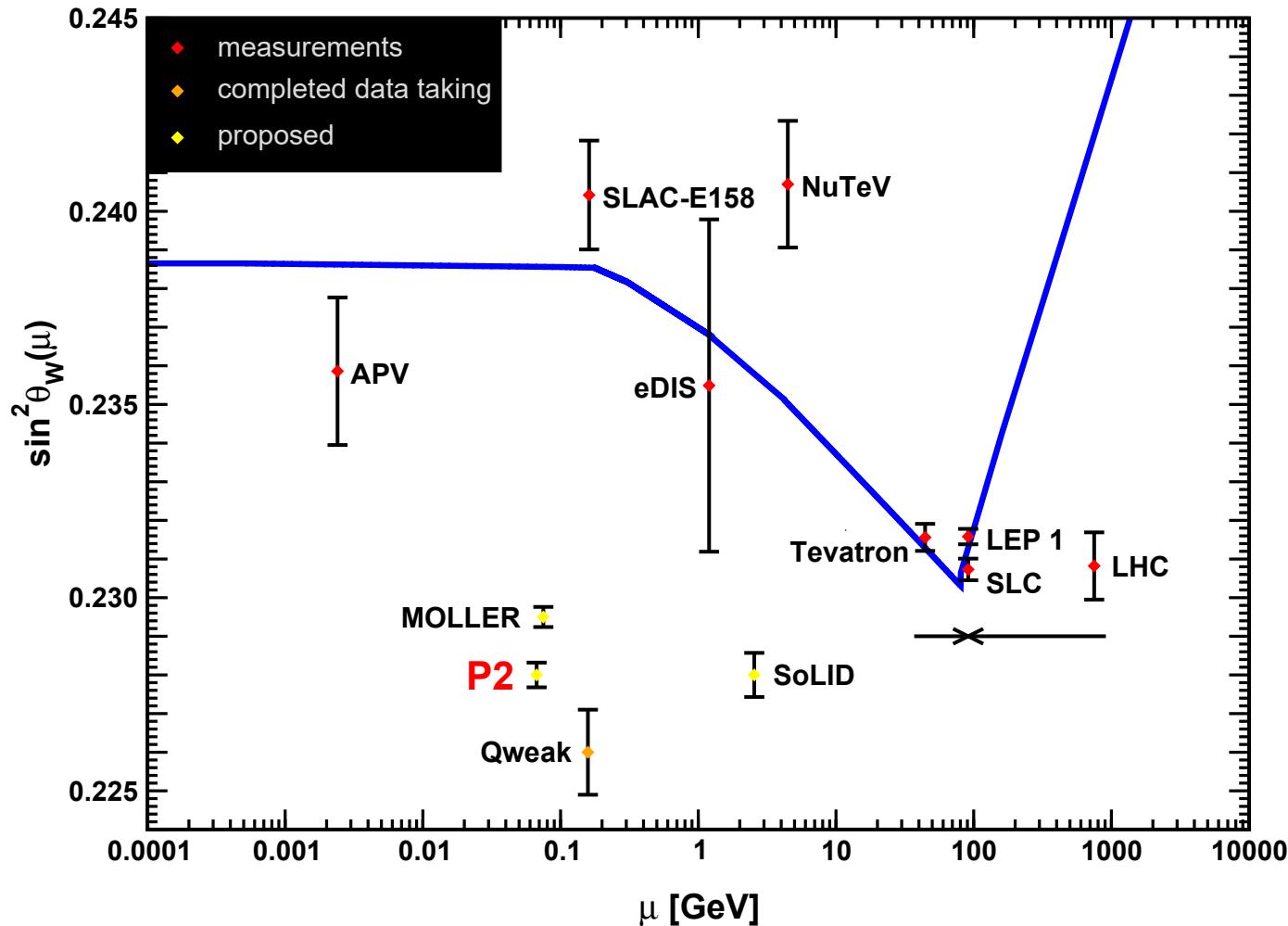
QWeak results (not)



Moller: e^-e^- scattering at JLab

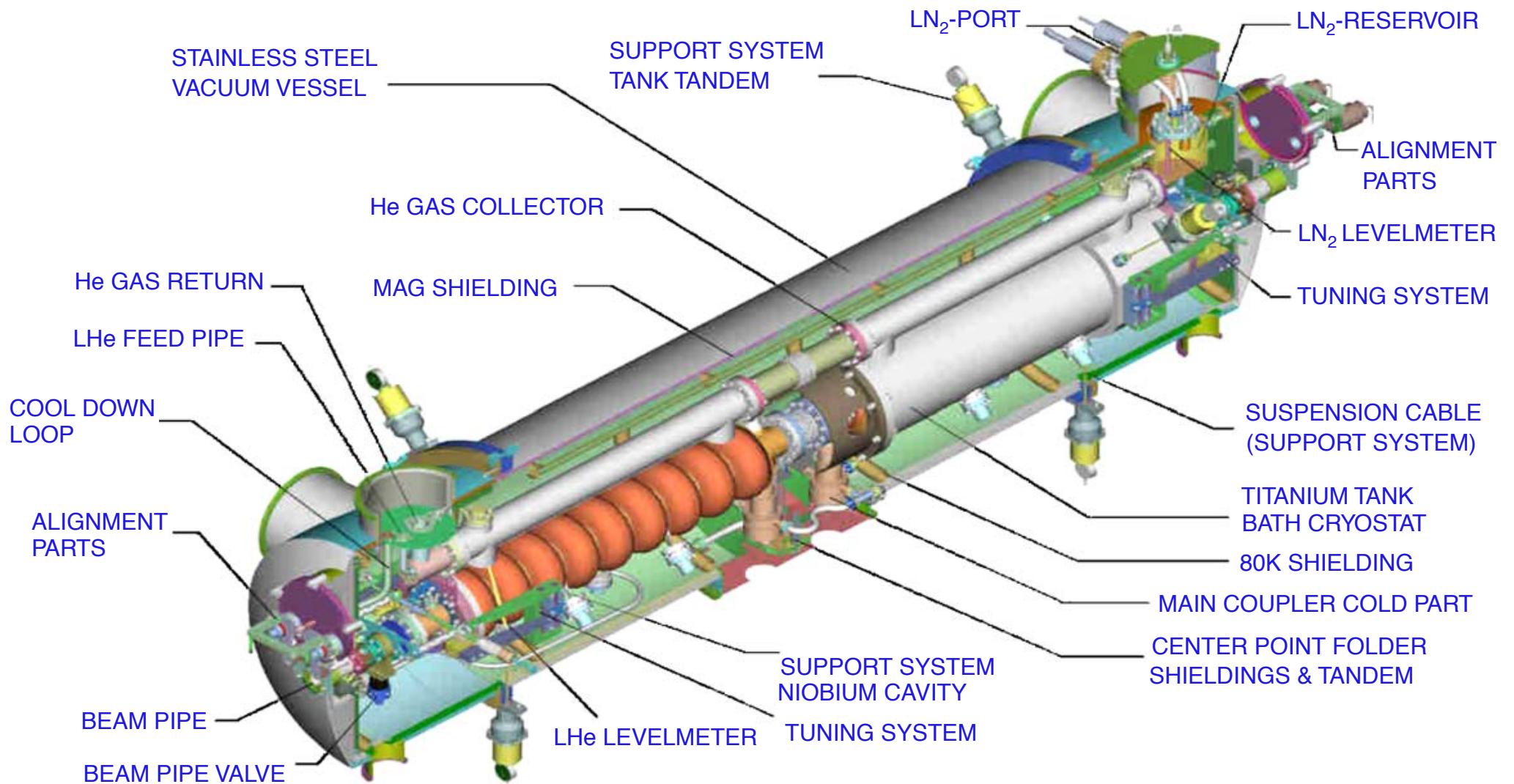


More to come...

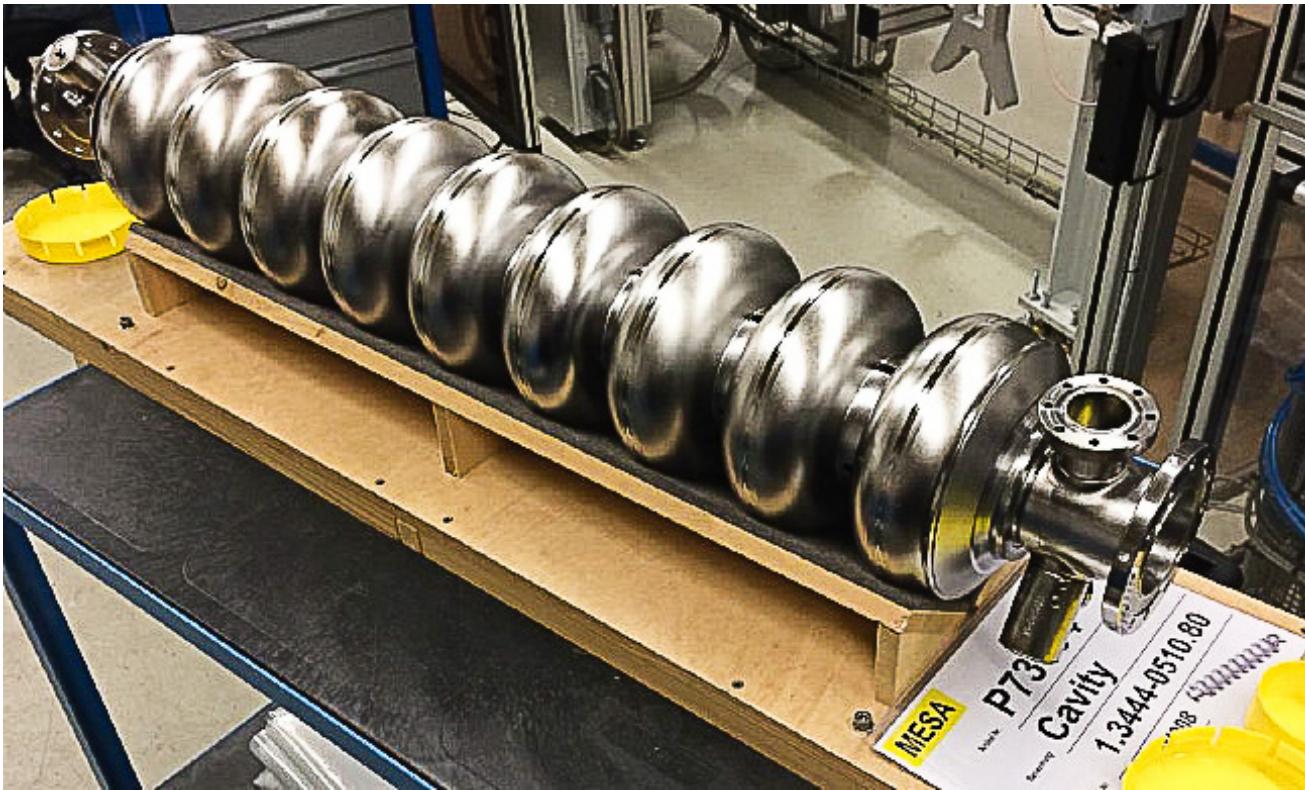


- Atomic parity violation in a single radium ion (Groningen)
- SoLID: Deep inelastic e-p scattering at JLab
- Much improved LHC measurements at the Z-pole

Superconducting Cryomodules



Teichert et al. NIM A 557 (2006) 239



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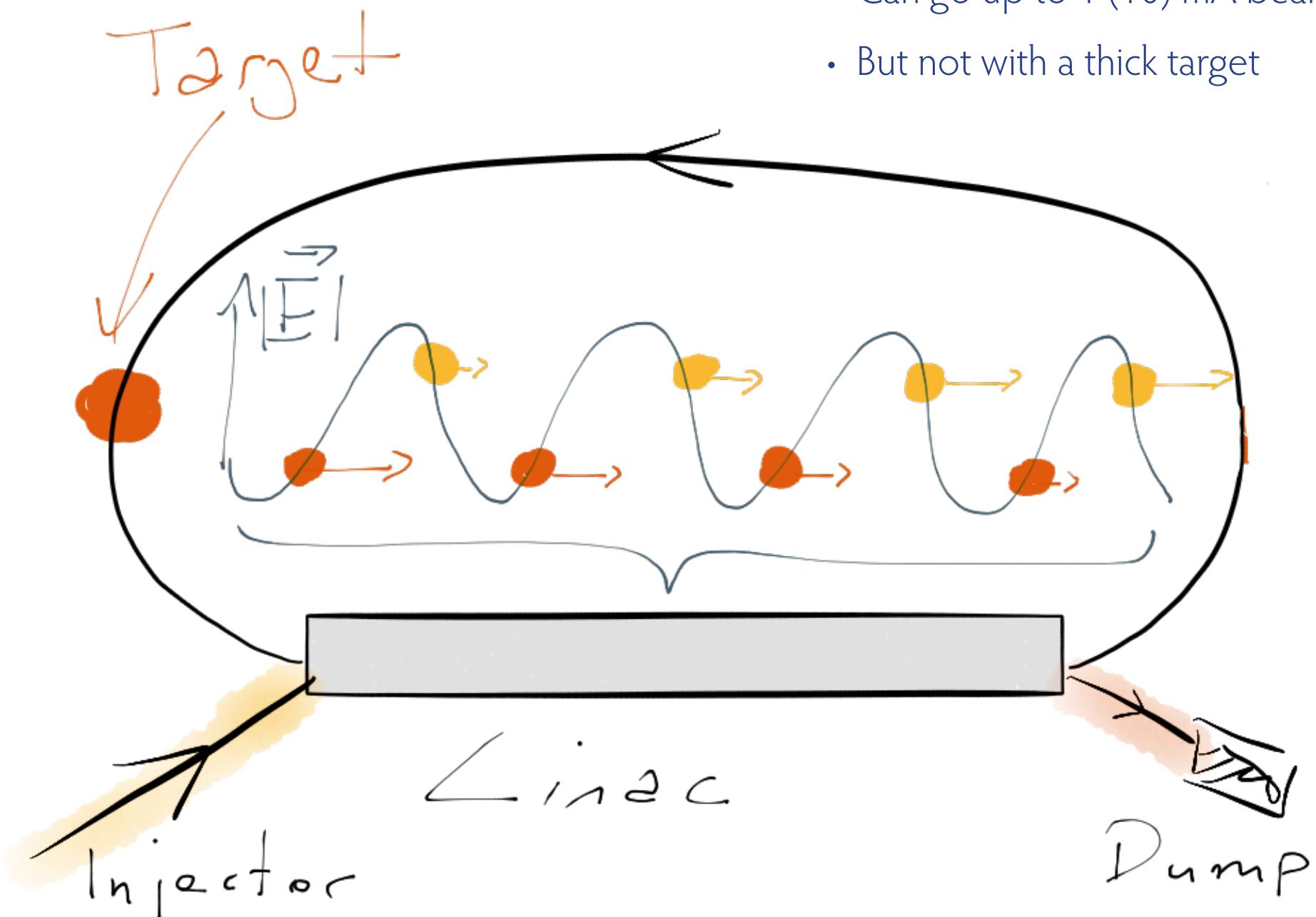
Energy recovery

Can we go to higher beam currents?

- In principle yes...
- But power is expensive
- Why dump electrons?

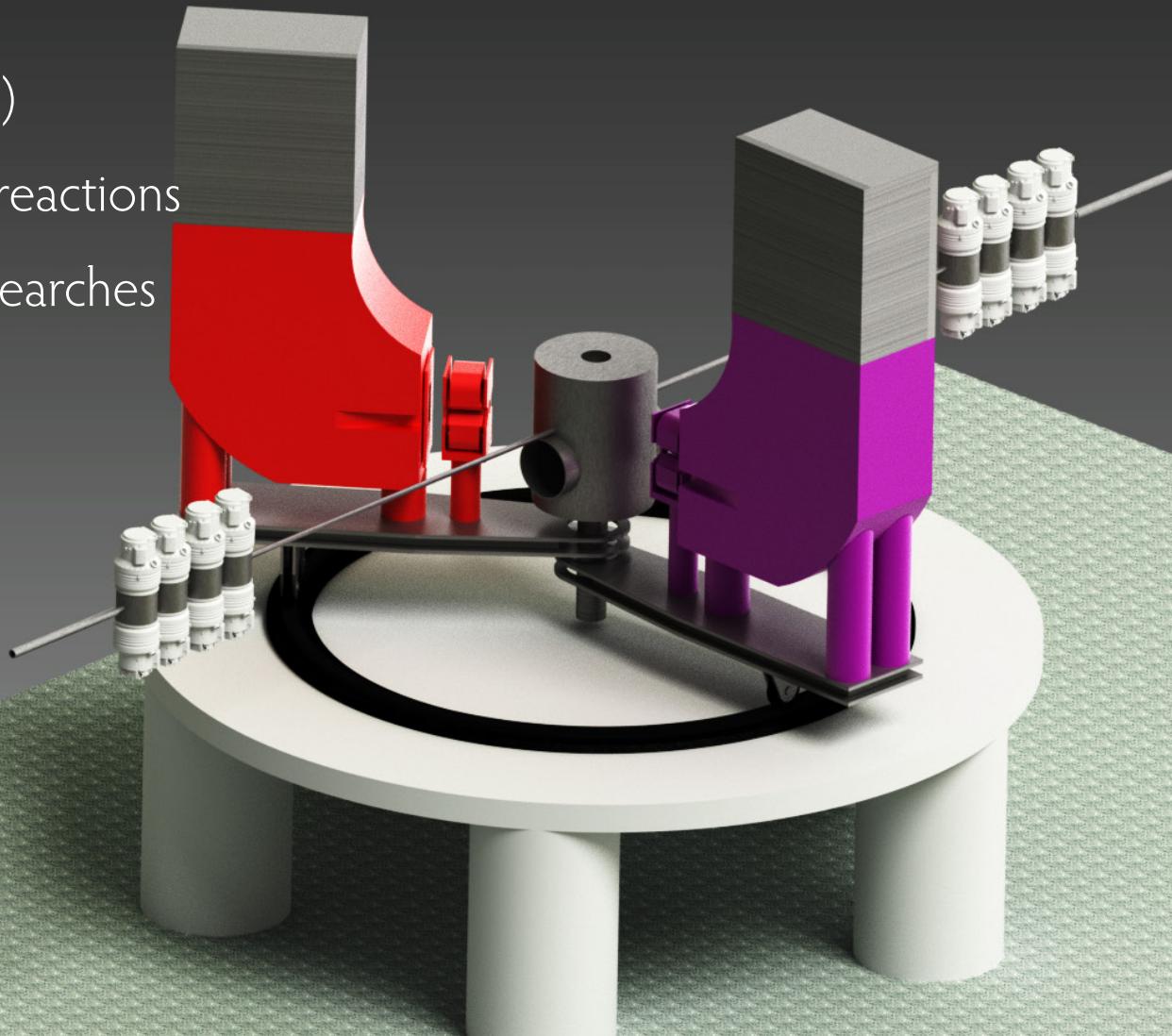
Energy recovery

- Put energy back into field!
- Can go up to 1 (10) mA beam current
- But not with a thick target

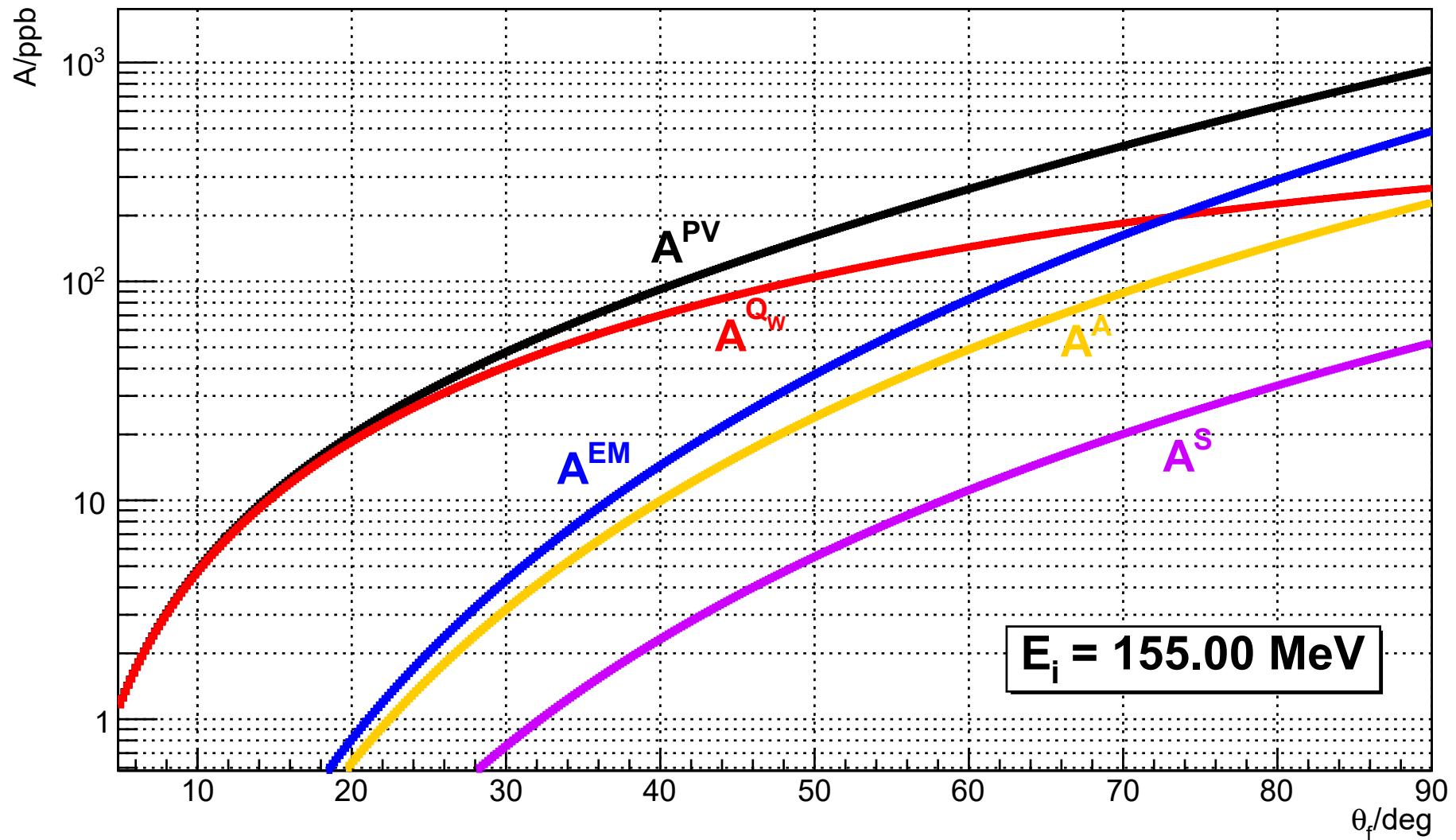


MAGIX Spectrometer

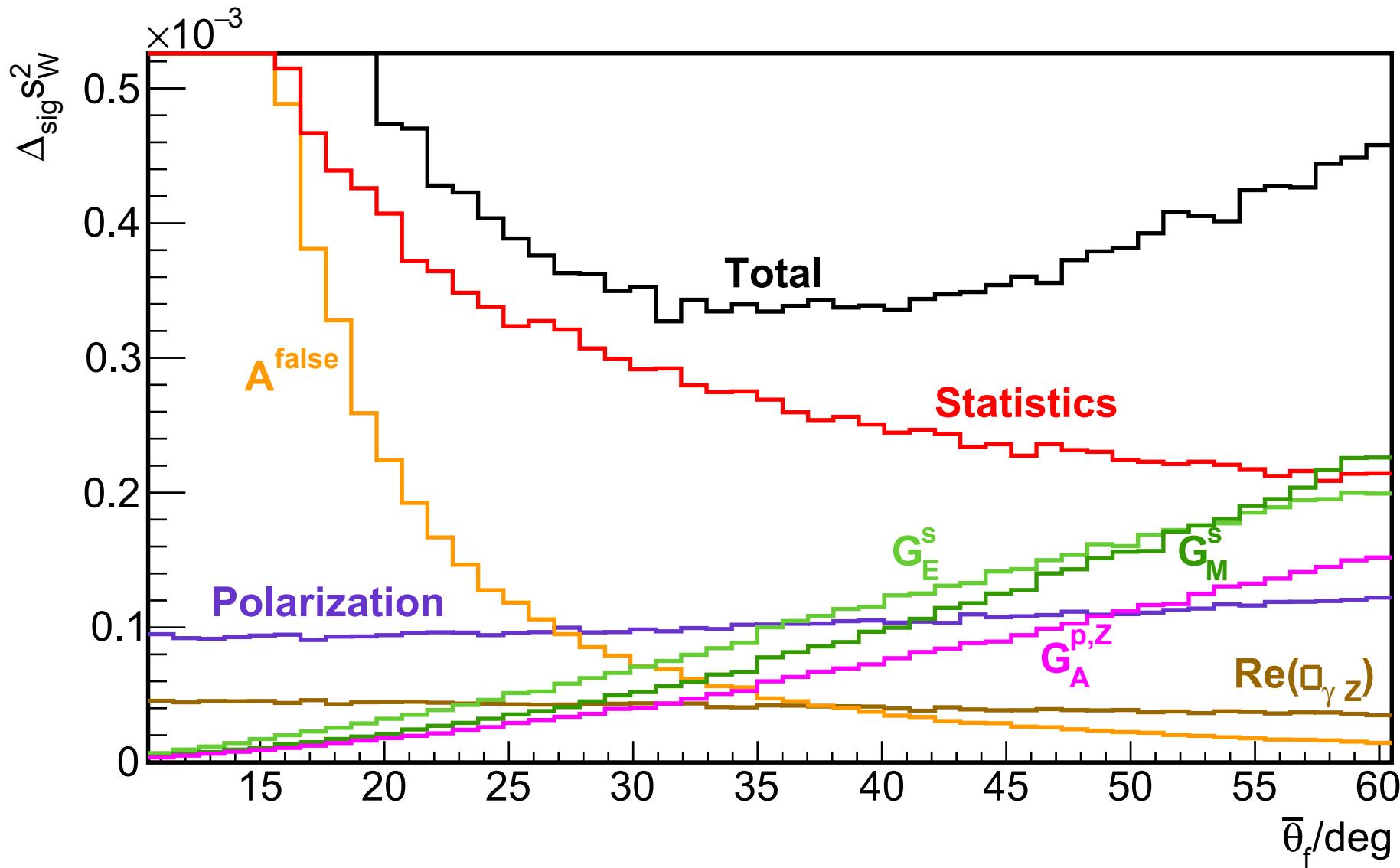
- Form factors
(proton radius)
- Astrophysical reactions
- Dark photon searches
- ...



Choice of scattering angle

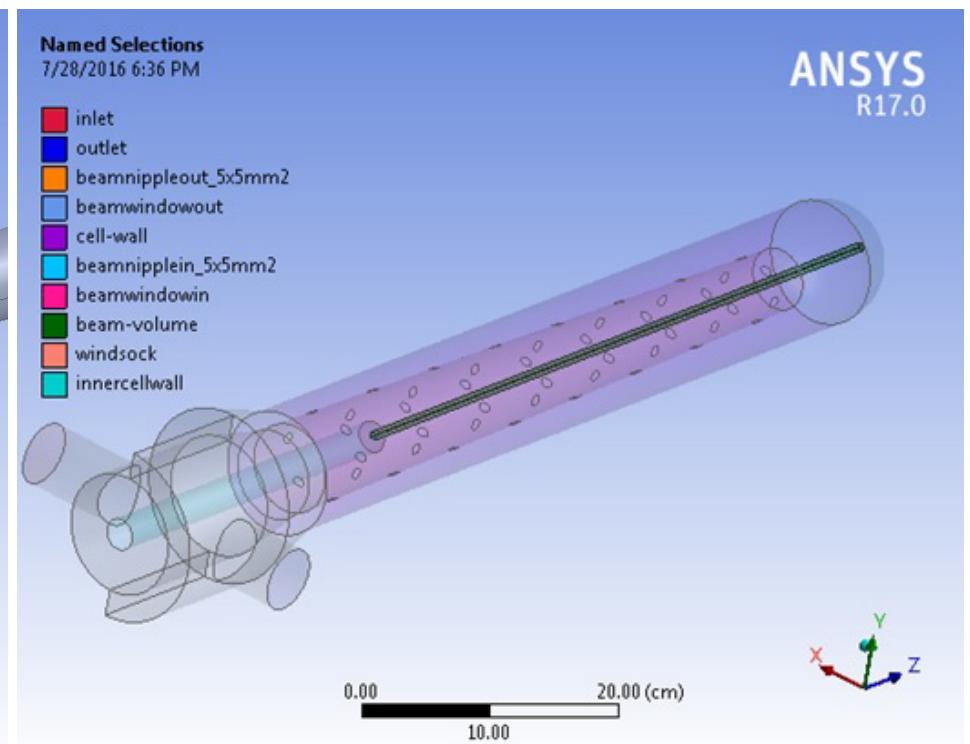
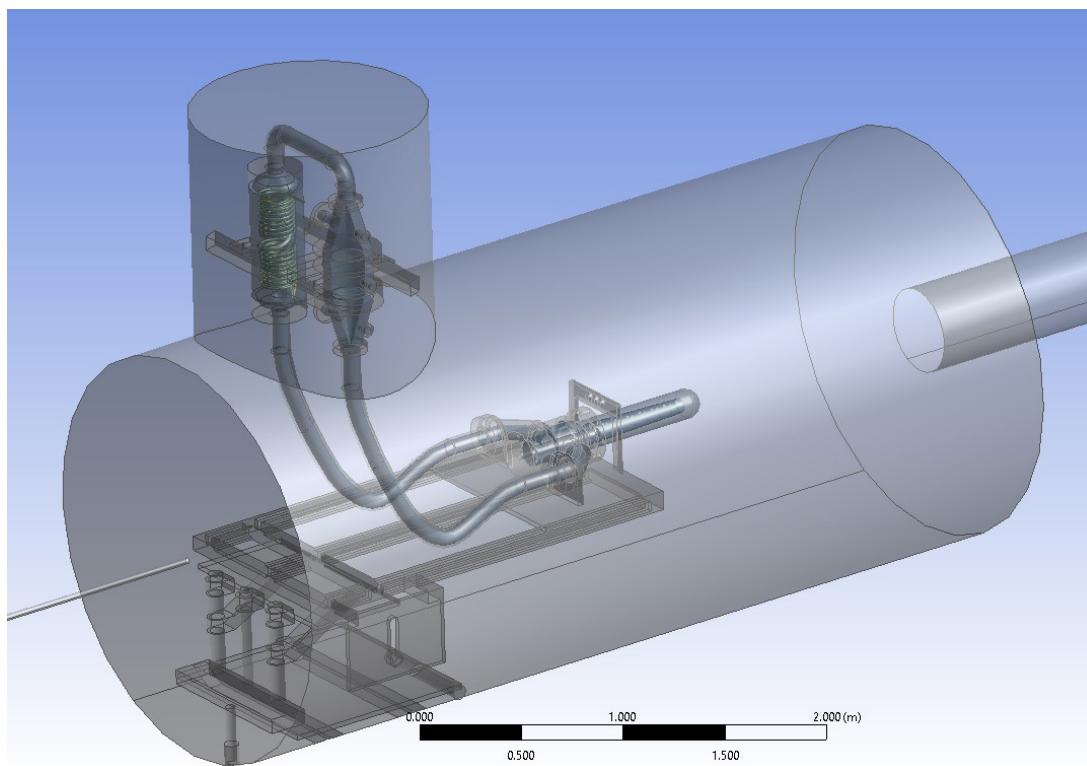


Choice of scattering angle



Target

- 60 cm of liquid hydrogen
- 3.1 KW beam power deposited
- Should not boil...
- Challenging design using CFD tools (Silviu Covrig, JLab)



Quartz-Bars & Photomultipliers

