Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter

PRISMA

Measuring the weak mixing angle with the P2 Experiment at MESA

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JG|U

SFB 1044

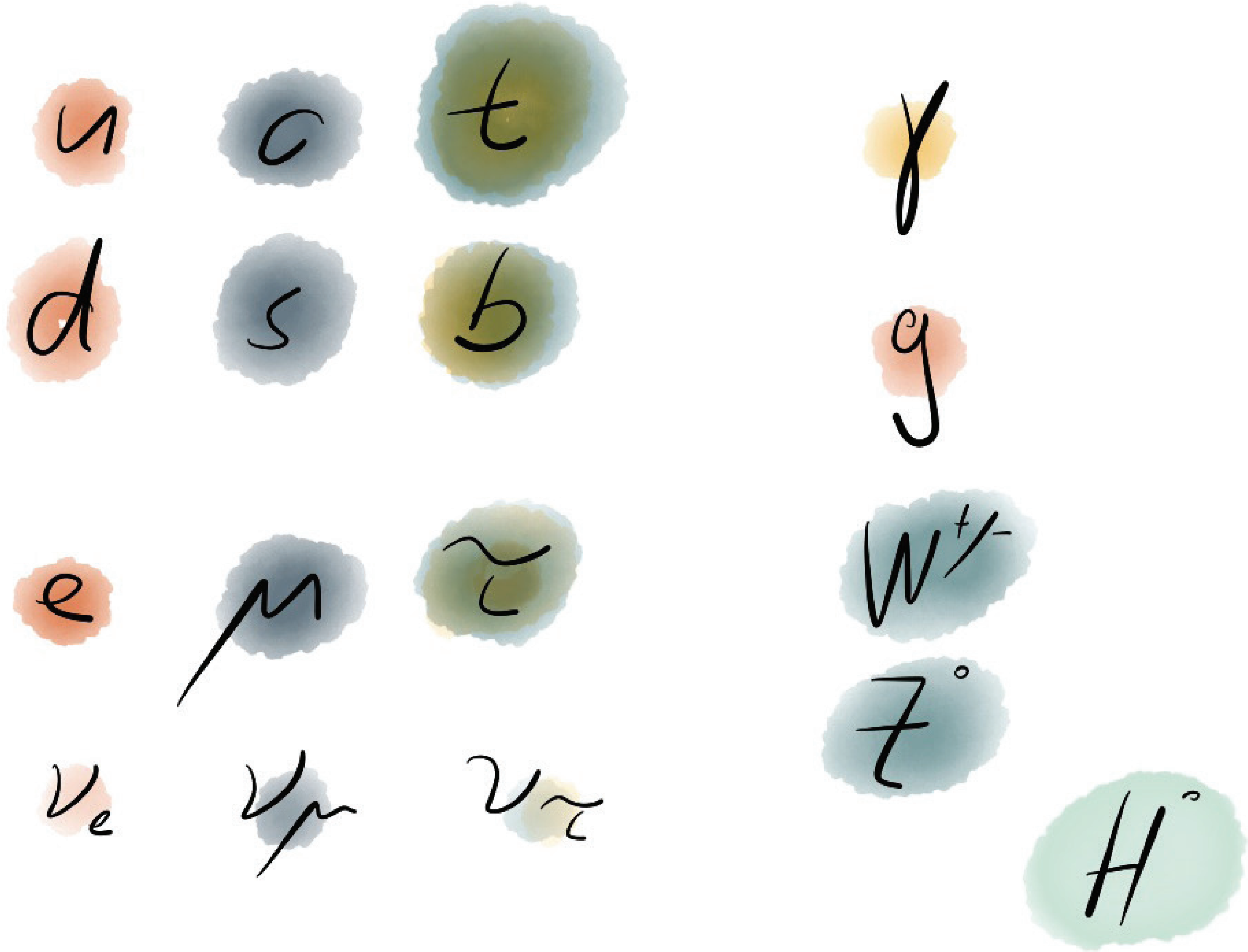
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Overview

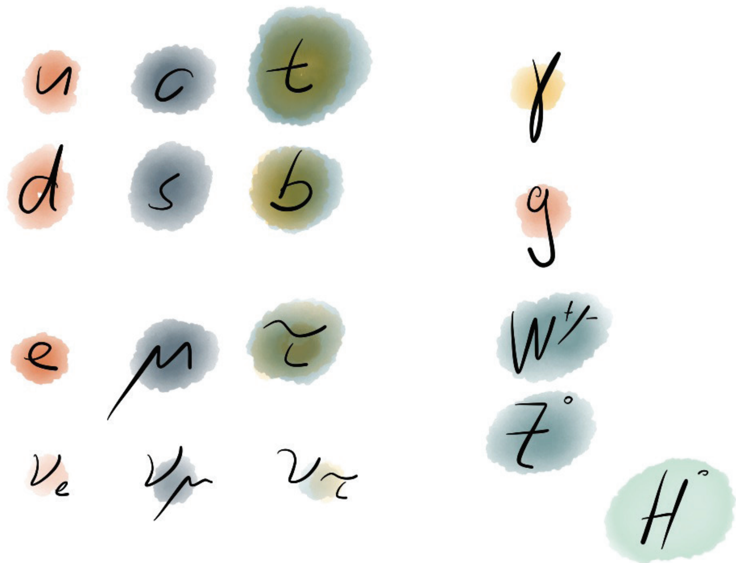
- Searching for new physics at the intensity frontier
- The running weak mixing angle
- The MESA accelerator
- The P2 Experiment

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

The Standard Model of Elementary Particles



Hugely successful



Magnetic moment of the electron:

- Theory:

  g_e = -2.002 319 304 363 56 (154)

  (Aoyama et al., PRL 109, 111807 (2012))

- Experiment:

  g_e = - 2.002 319 304 361 53 (53)

  (Hanneke et al. PRL 100, 120801 (2008))

Open Questions?

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Gravity, Dark Matter, Dark Energy, Matter-Antimatter-Asymmetry, Hierarchy Problem, Flavour,...

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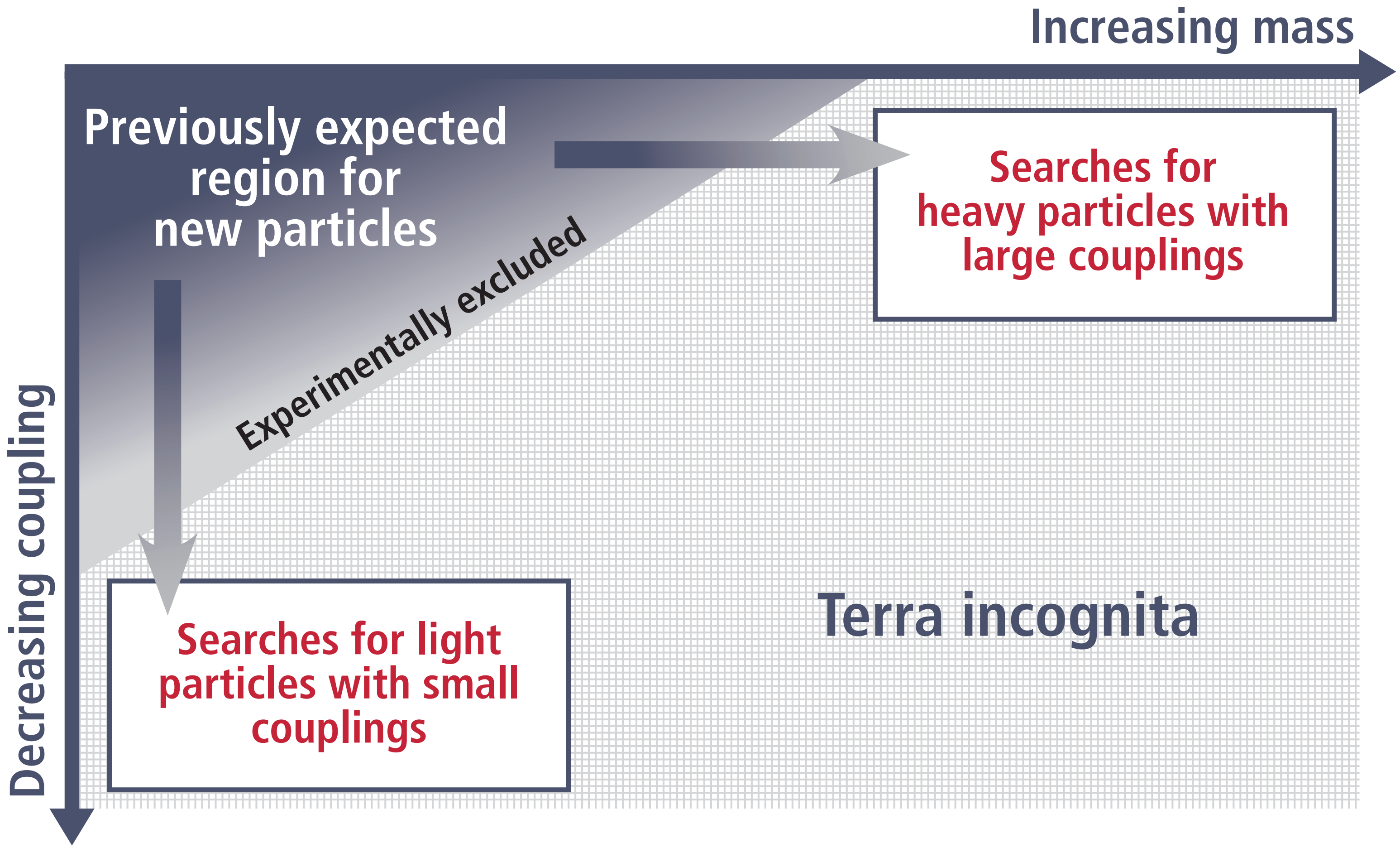
Gravity, Dark Matter, Dark Energy, Matter-Antimatter-Asymmetry, Hierarchy Problem, Flavour,...

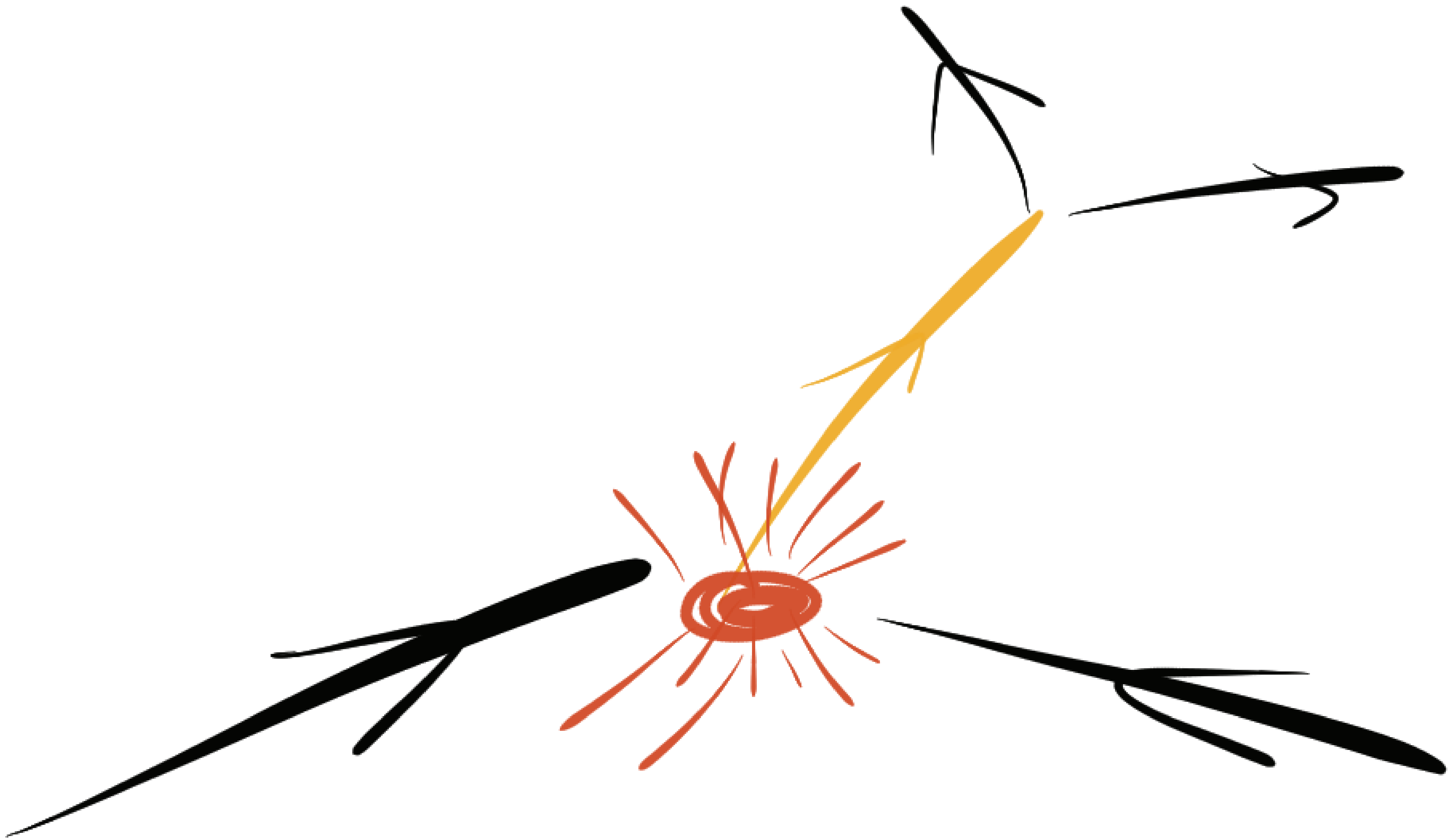
There has to be more...

Where is the new physics?

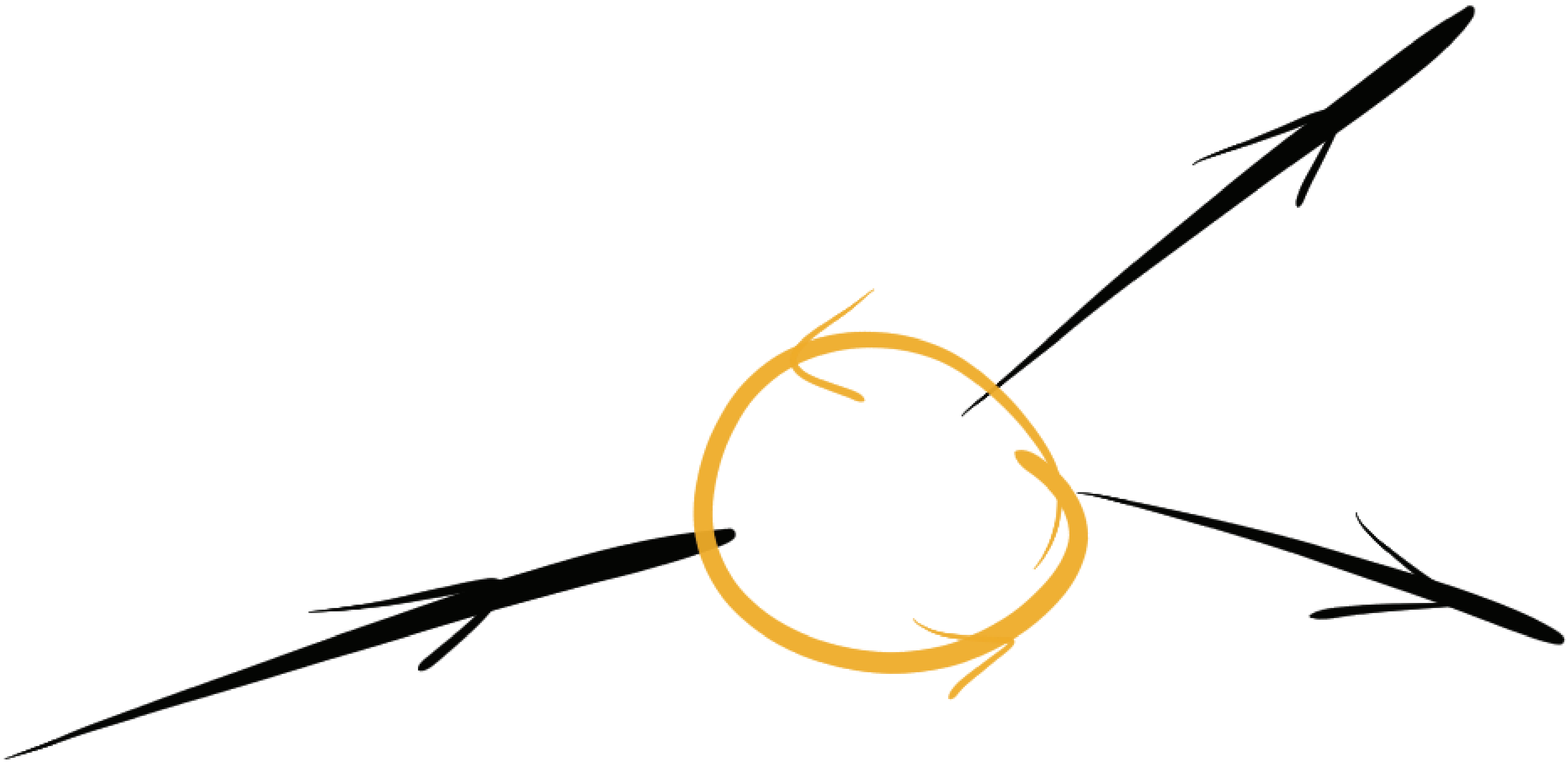
- Not where we already looked...
- Could be at very high energies
- or at very weak couplings



Direct production



Indirect effects in quantum loops



The weak mixing angle

(also: Weinberg-angle)

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"

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

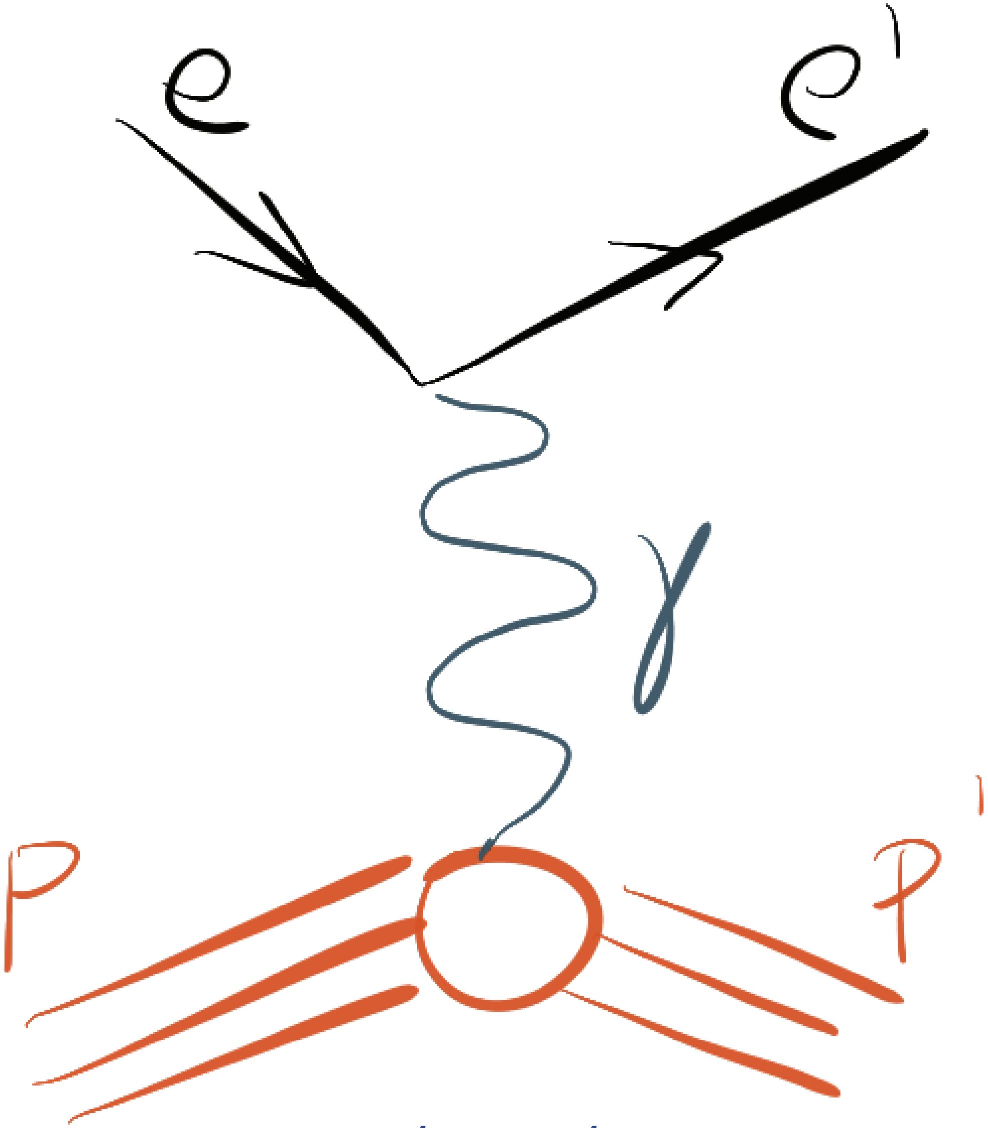
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

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

Weak mixing angle and charges



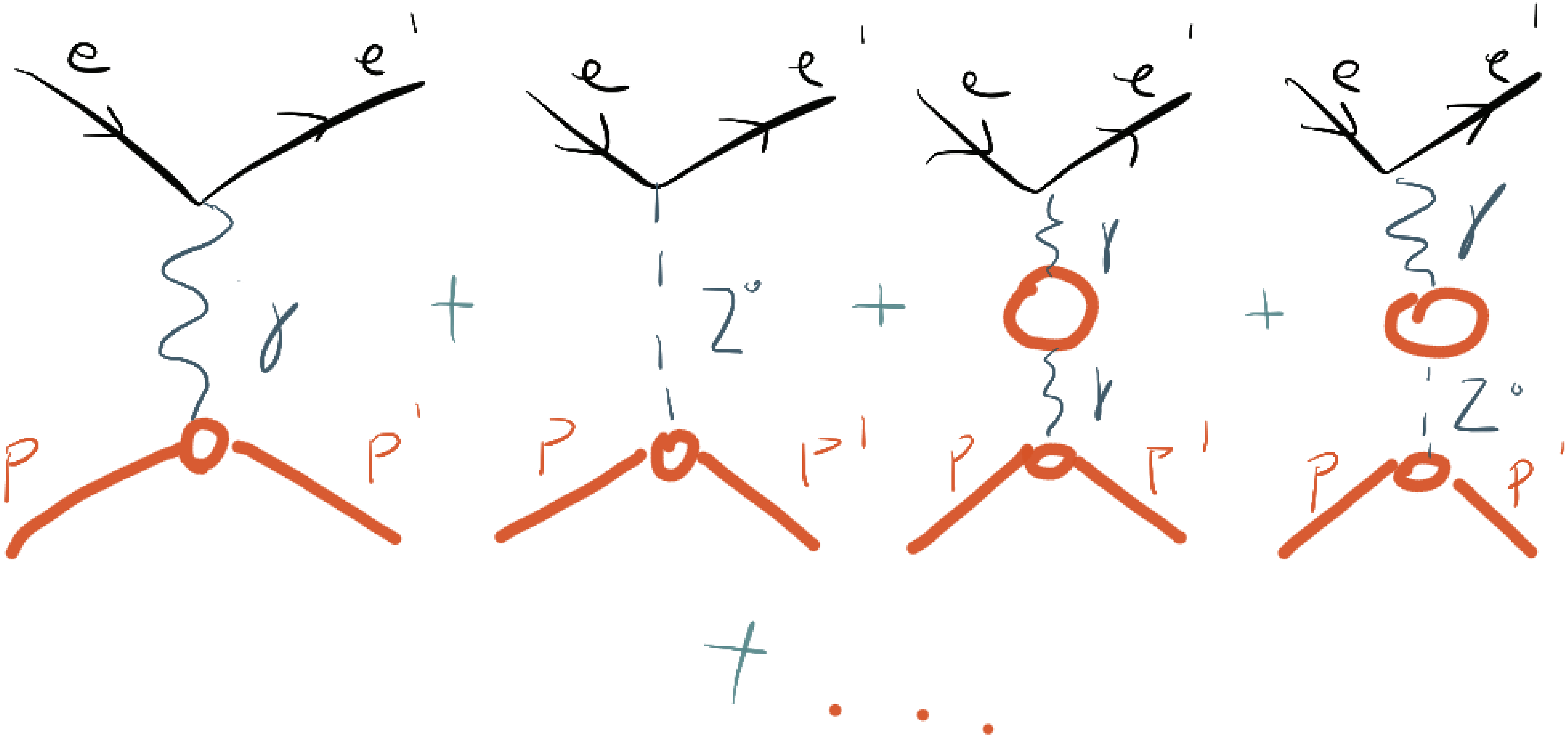
Proton electric charge

+e

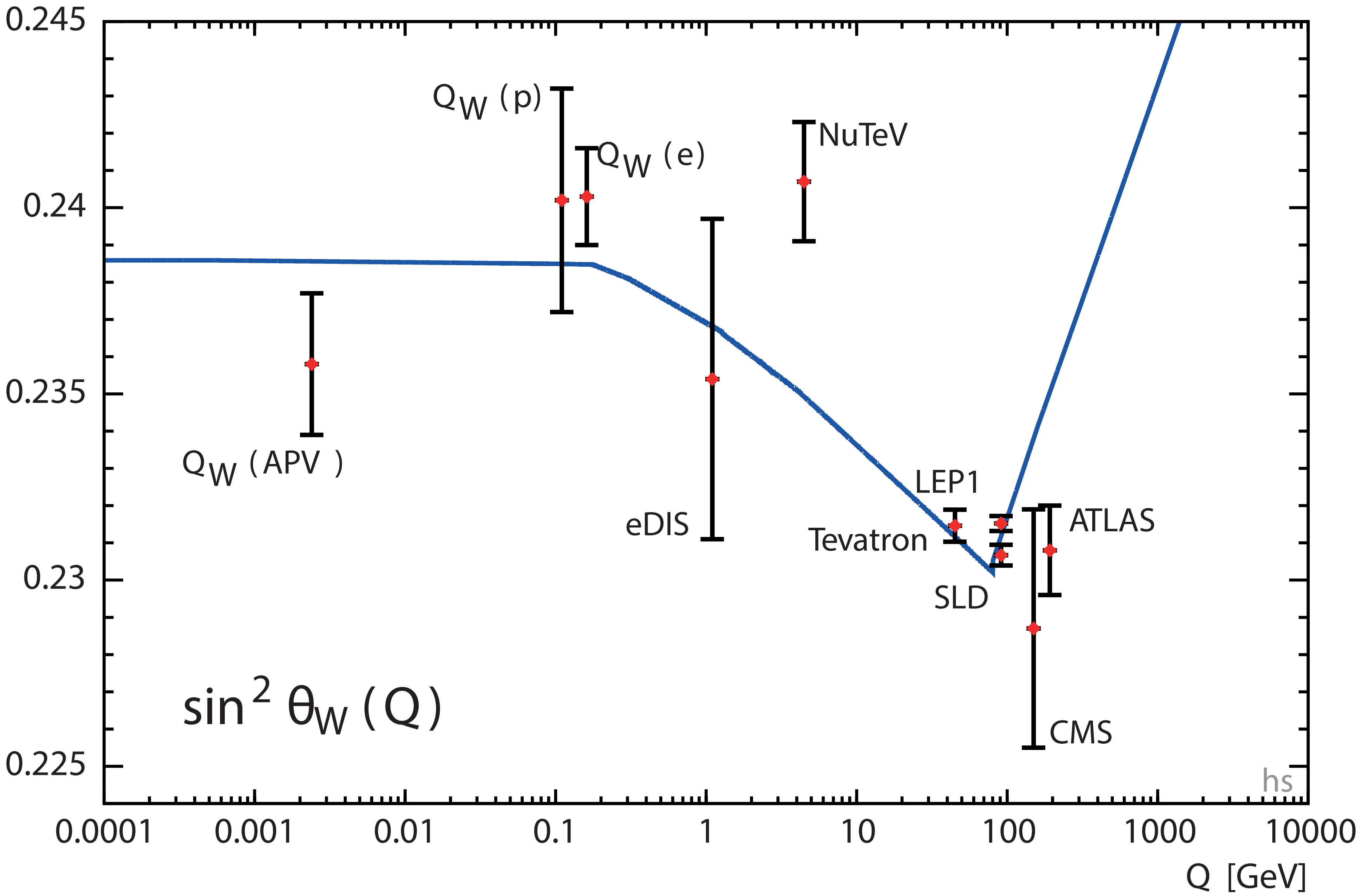
Proton weak charge

$1 - 4 \sin^2\theta_W$

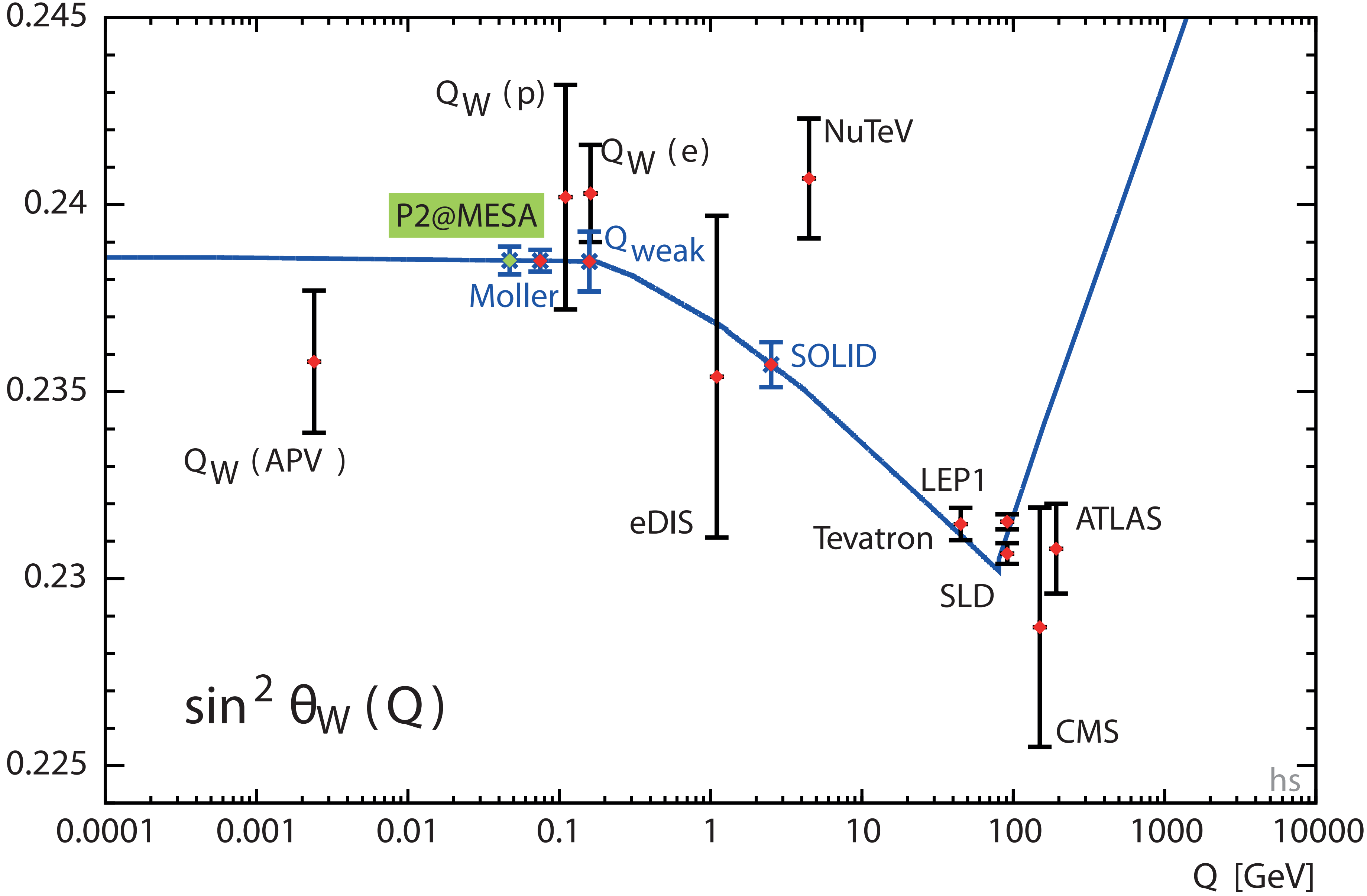
Scale dependence (running) of $\sin^2\theta_W$



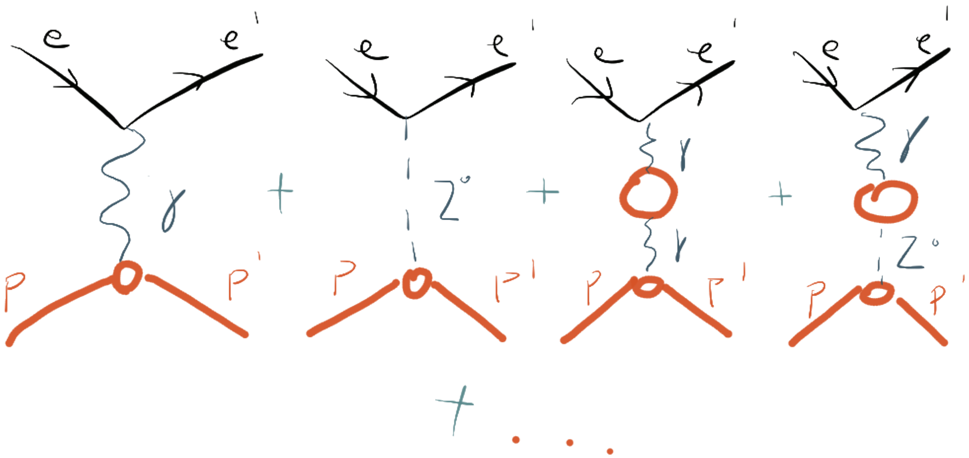
Scale dependence (running) of $\sin^2\theta_W$

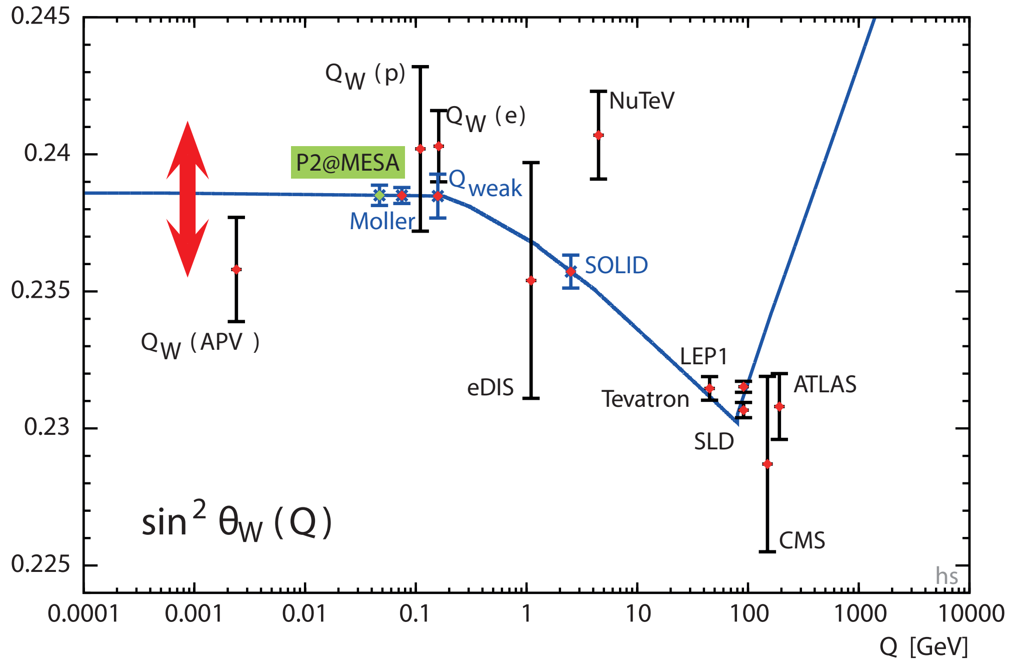


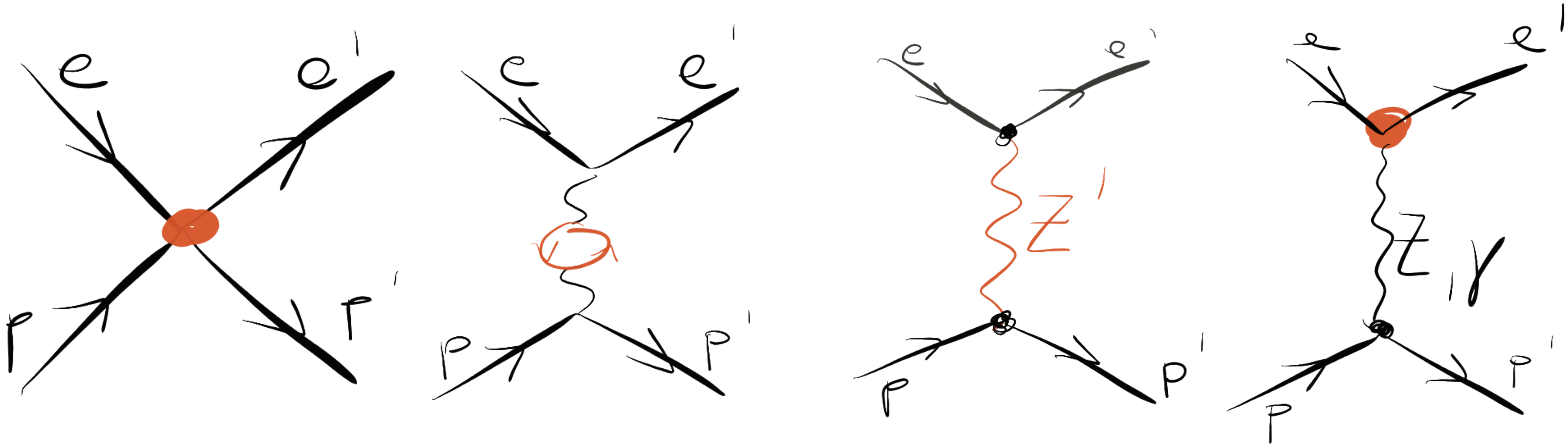
Scale dependence (running) of $\sin^2\theta_W$



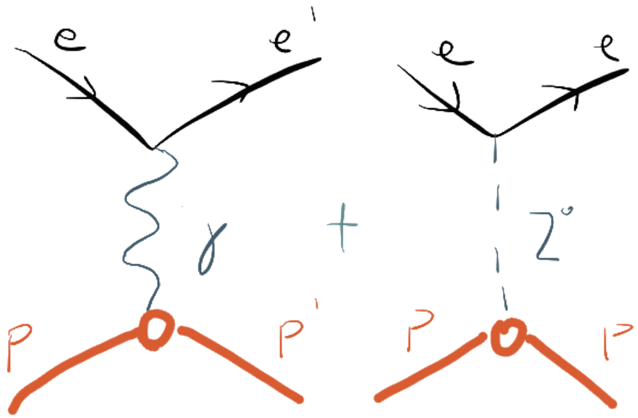
New Physics in the running

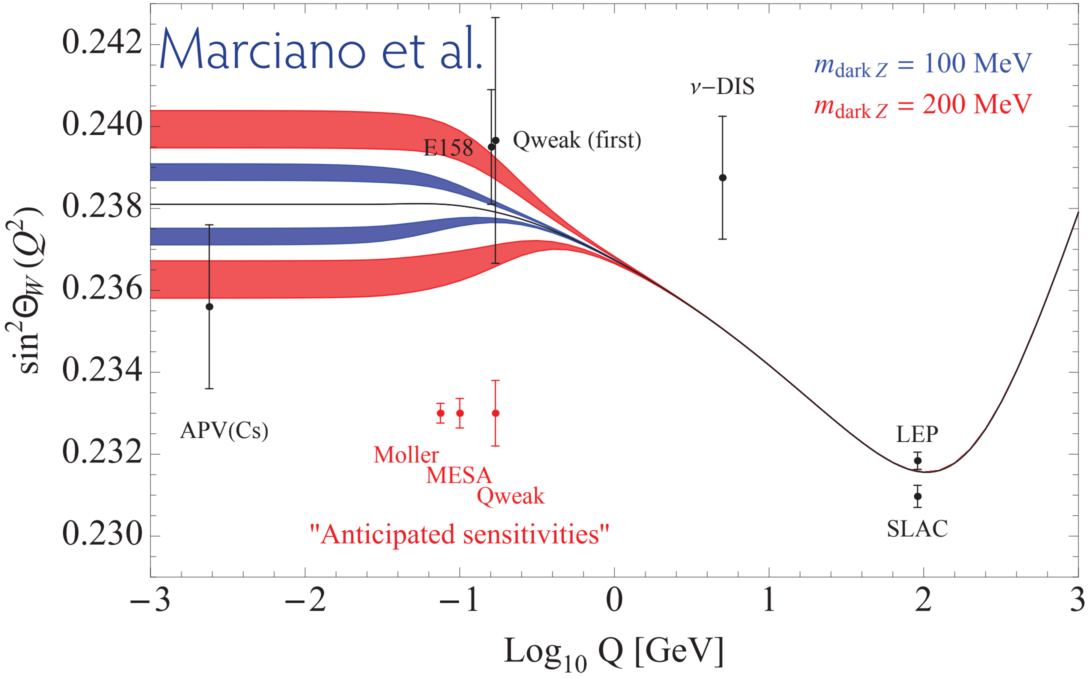


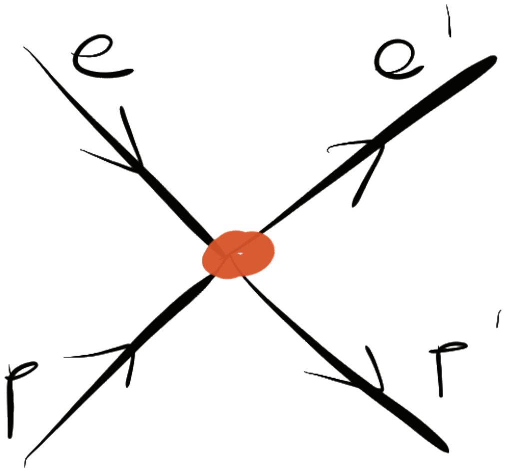


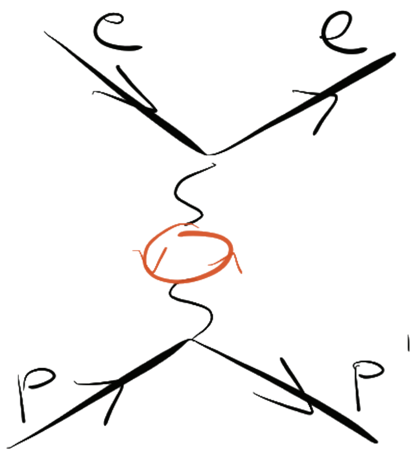


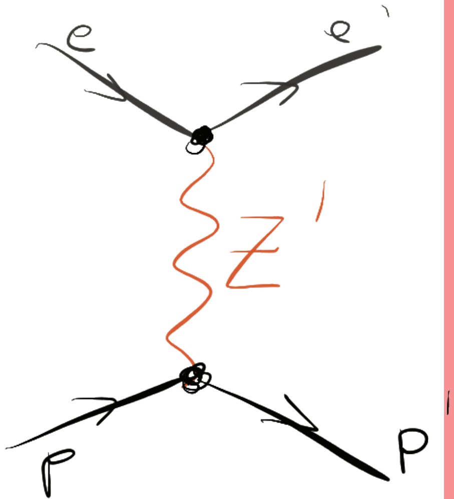
Dark Z in mixing

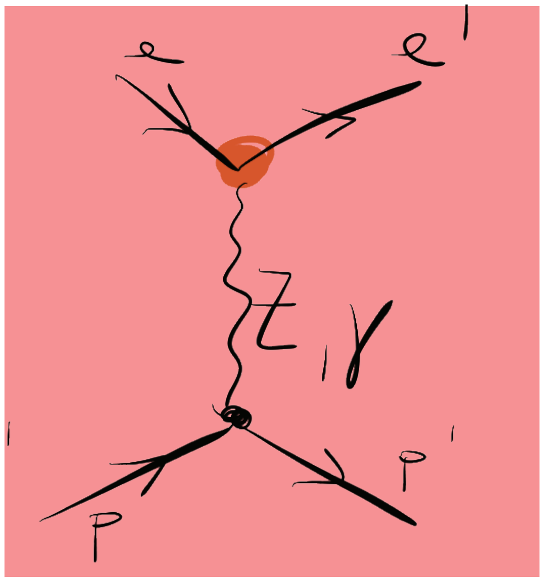




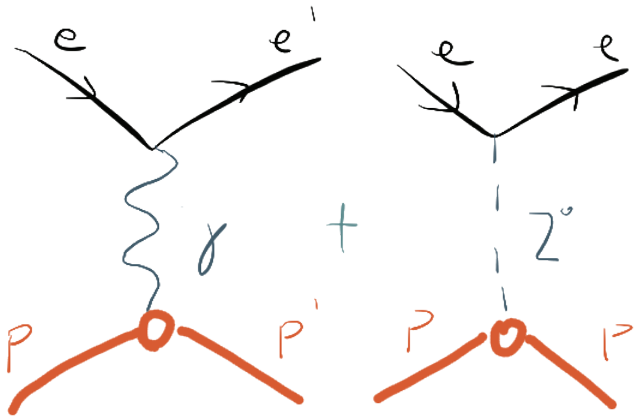








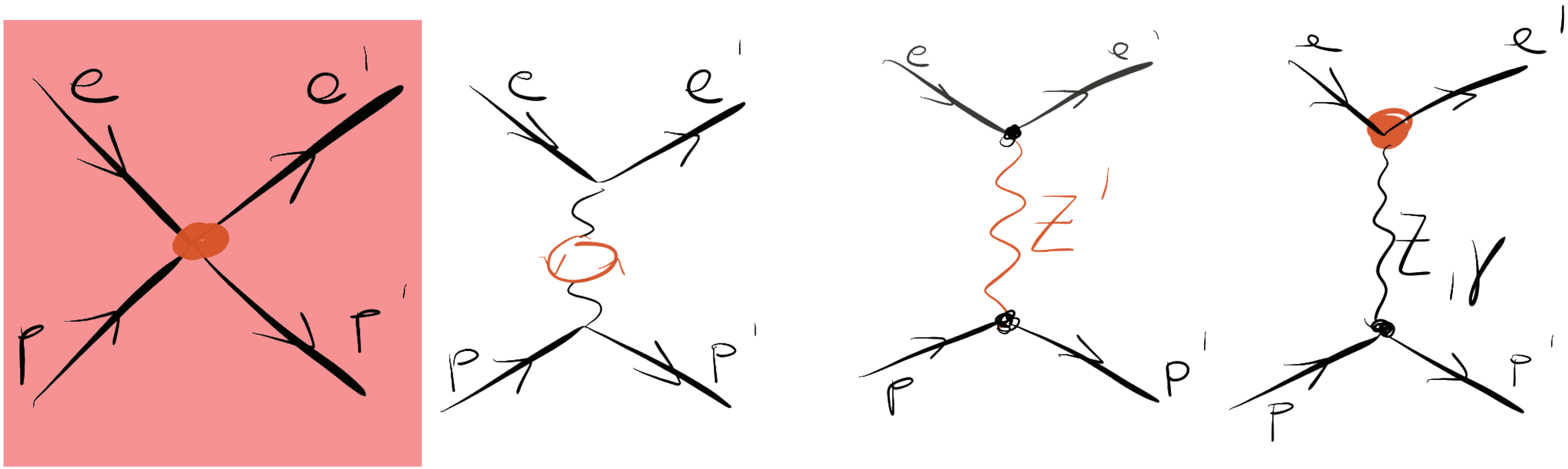
Contact Interactions



Contact interactions up to

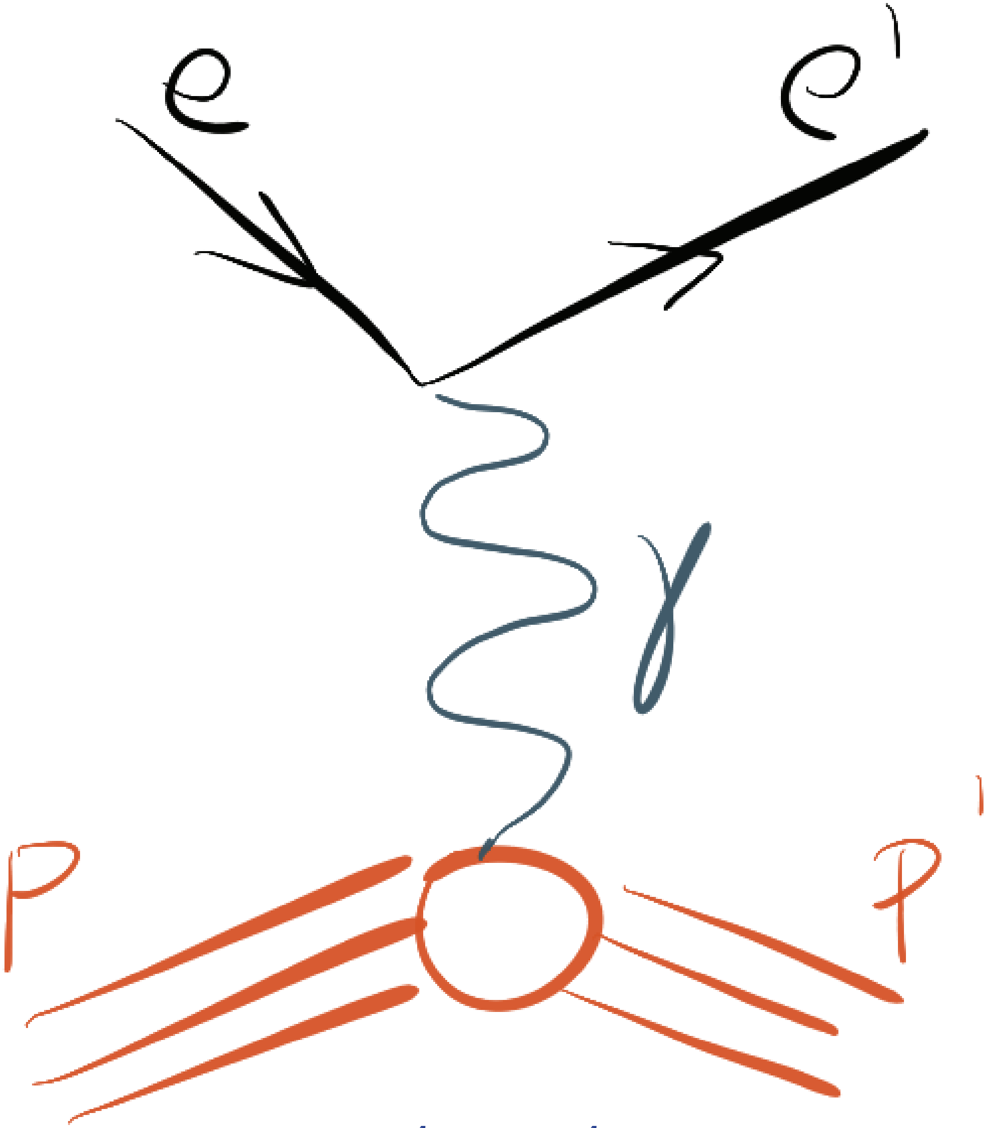
49 TeV

(comparable to LHC at 300 fb^{-1})



How to measure the weak charge?

Weak mixing angle and charges



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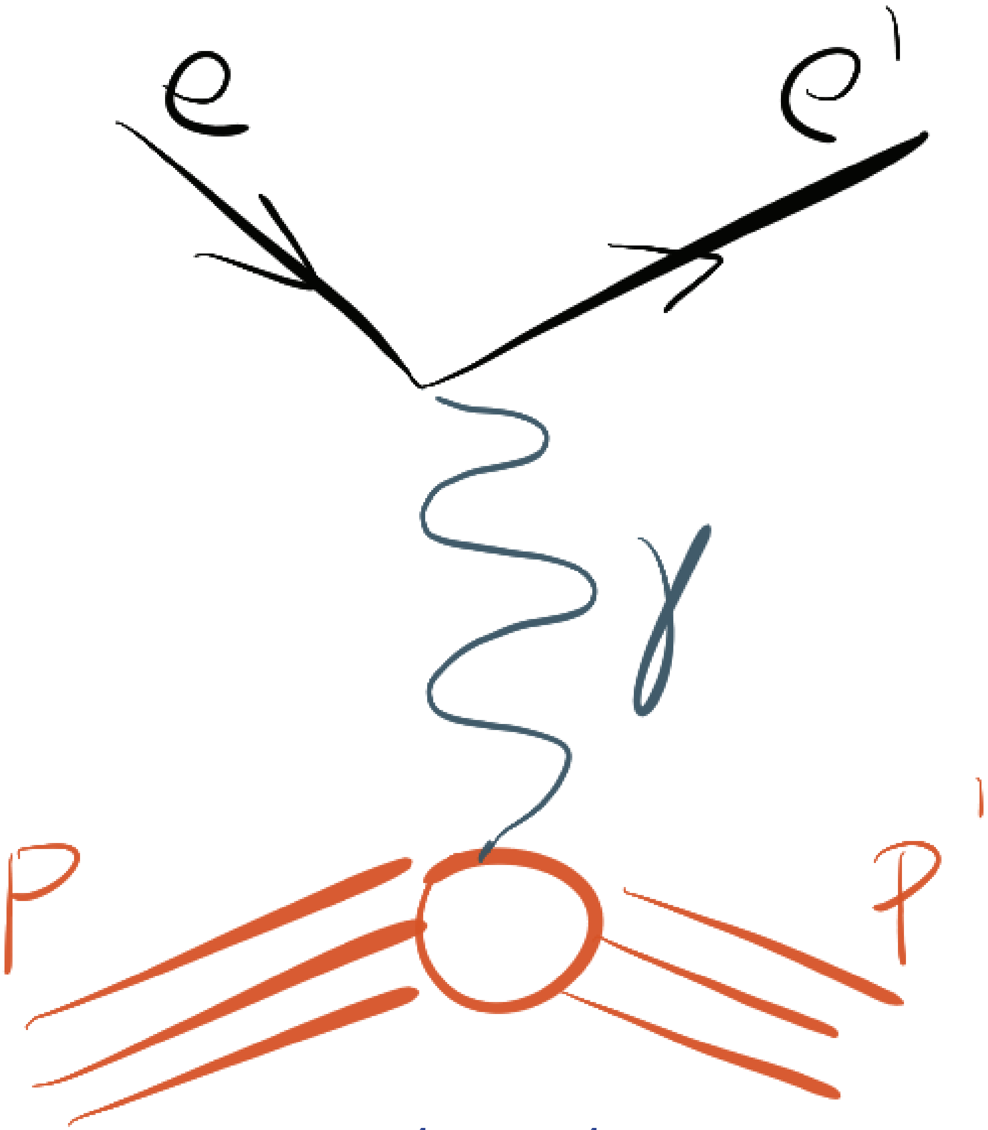
Weak mixing angle and charges



Proton electric charge

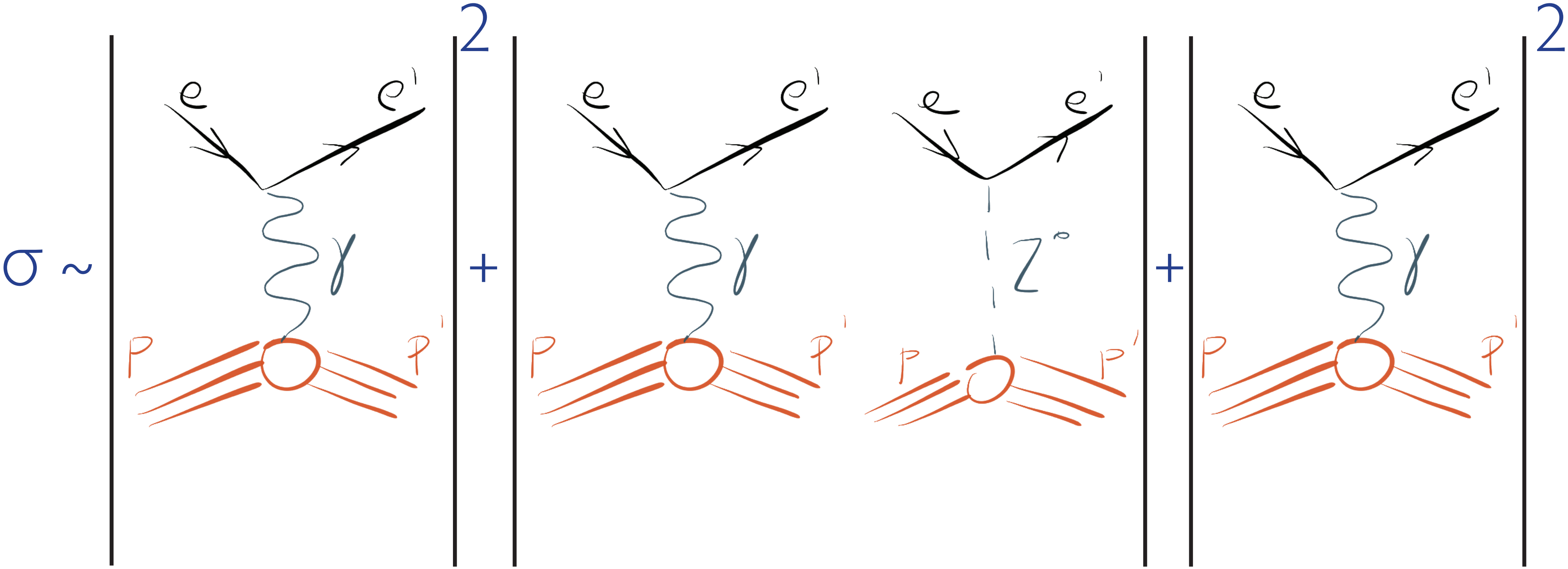
+e

Violates parity!

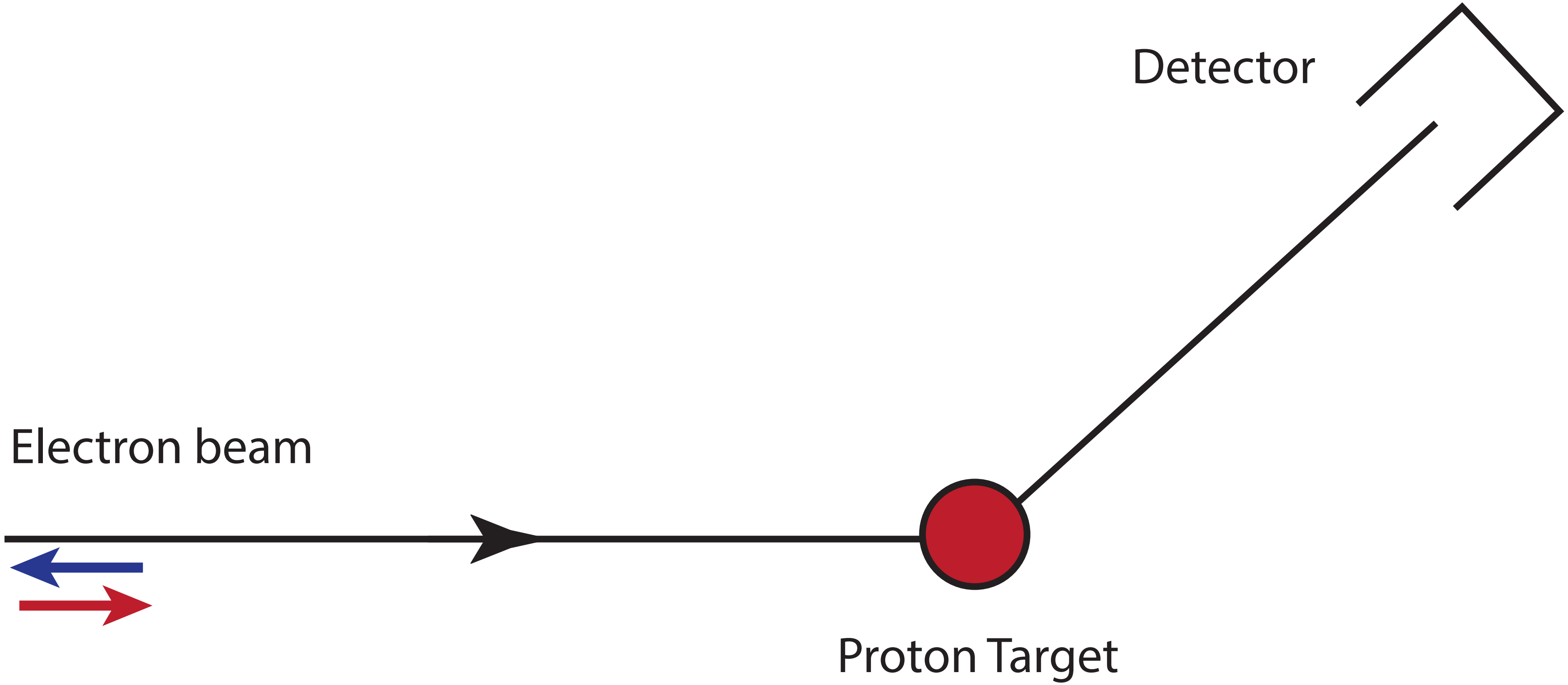
Proton weak charge

$1 - 4\sin^2\theta_W$

Interference

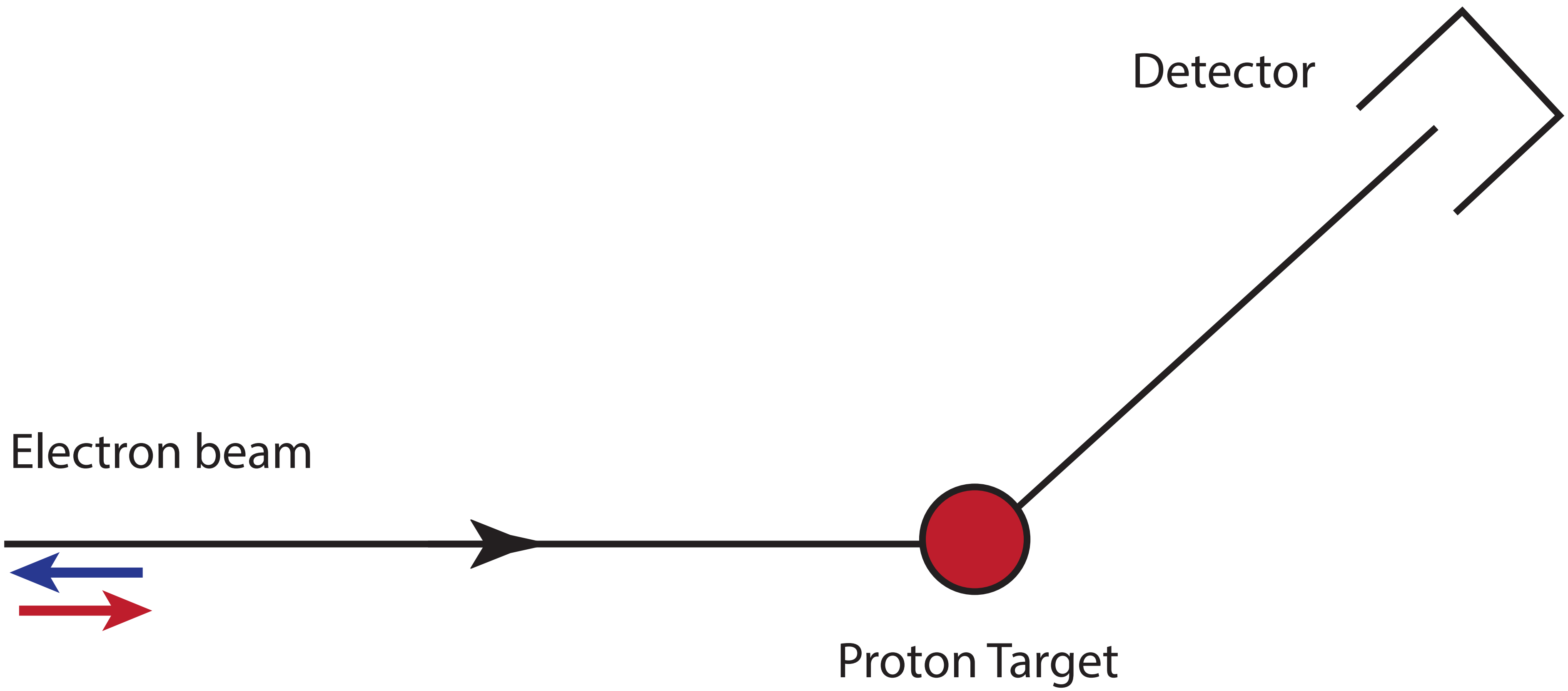


Parity violating electron scattering



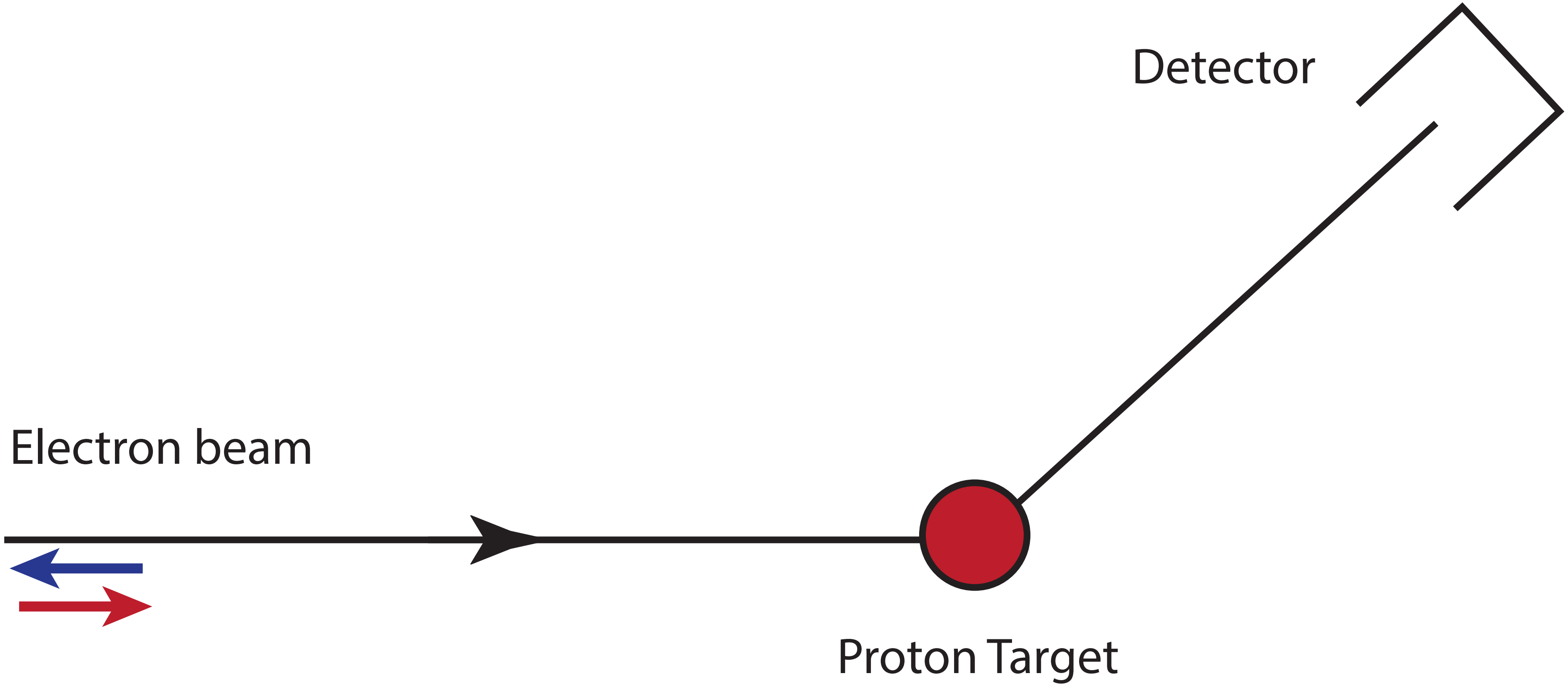
Parity violating electron scattering

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



Parity violating electron scattering

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



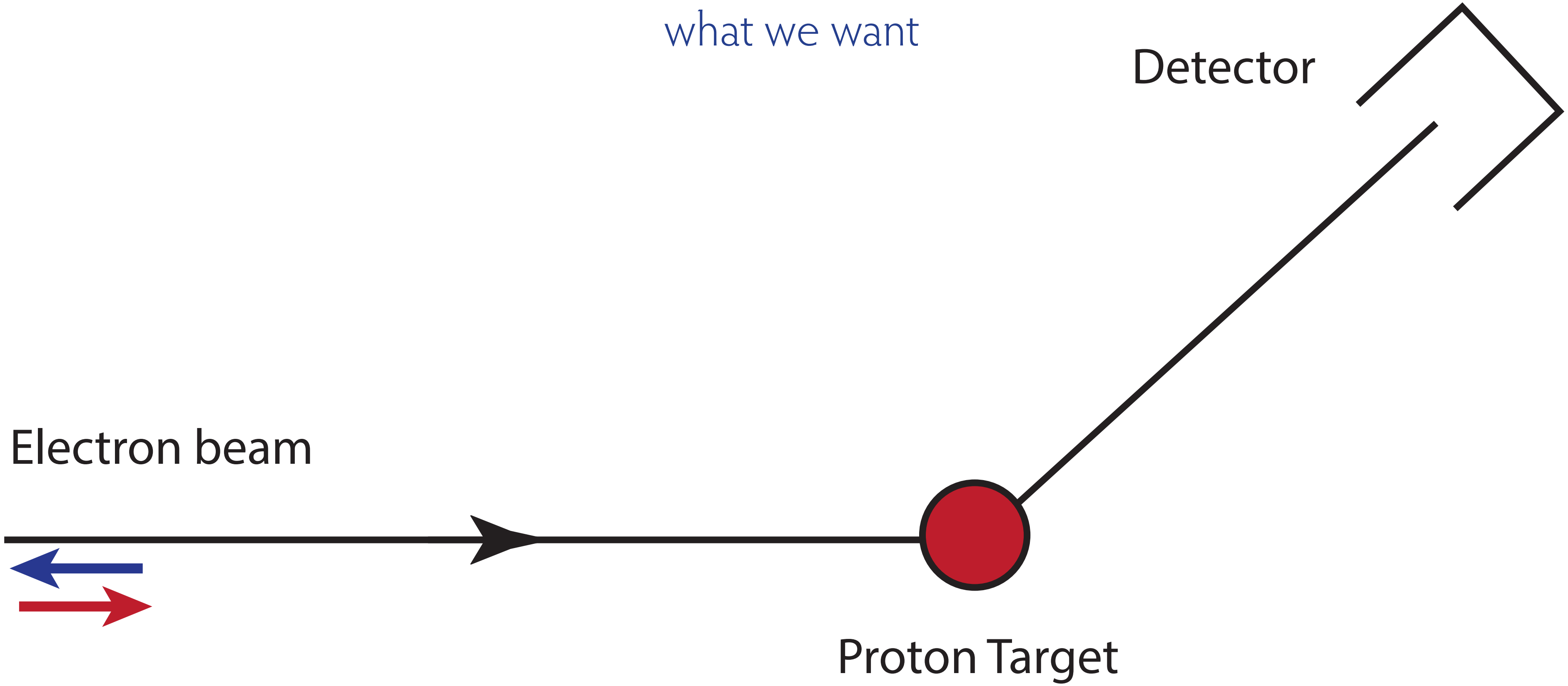
Parity violating electron scattering

Momentum transfer sets scale

Proton structure - small nuisance if Q^2 small

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

Weak charge - what we want



Parity violating electron scattering

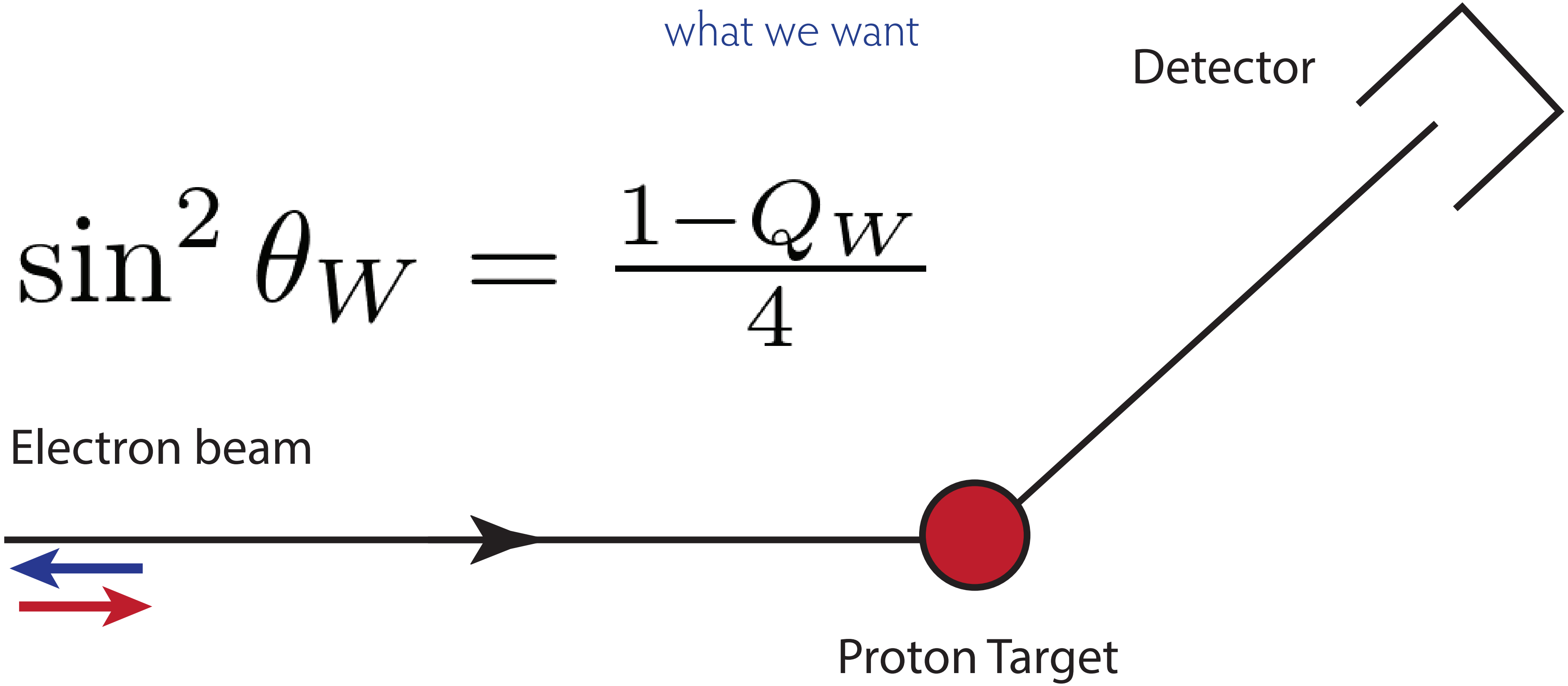
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

Momentum transfer sets scale → Q^2

Proton structure - small nuisance if Q^2 small → $F(Q^2)$

Weak charge - what we want → Q_W

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



Why is this difficult?

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

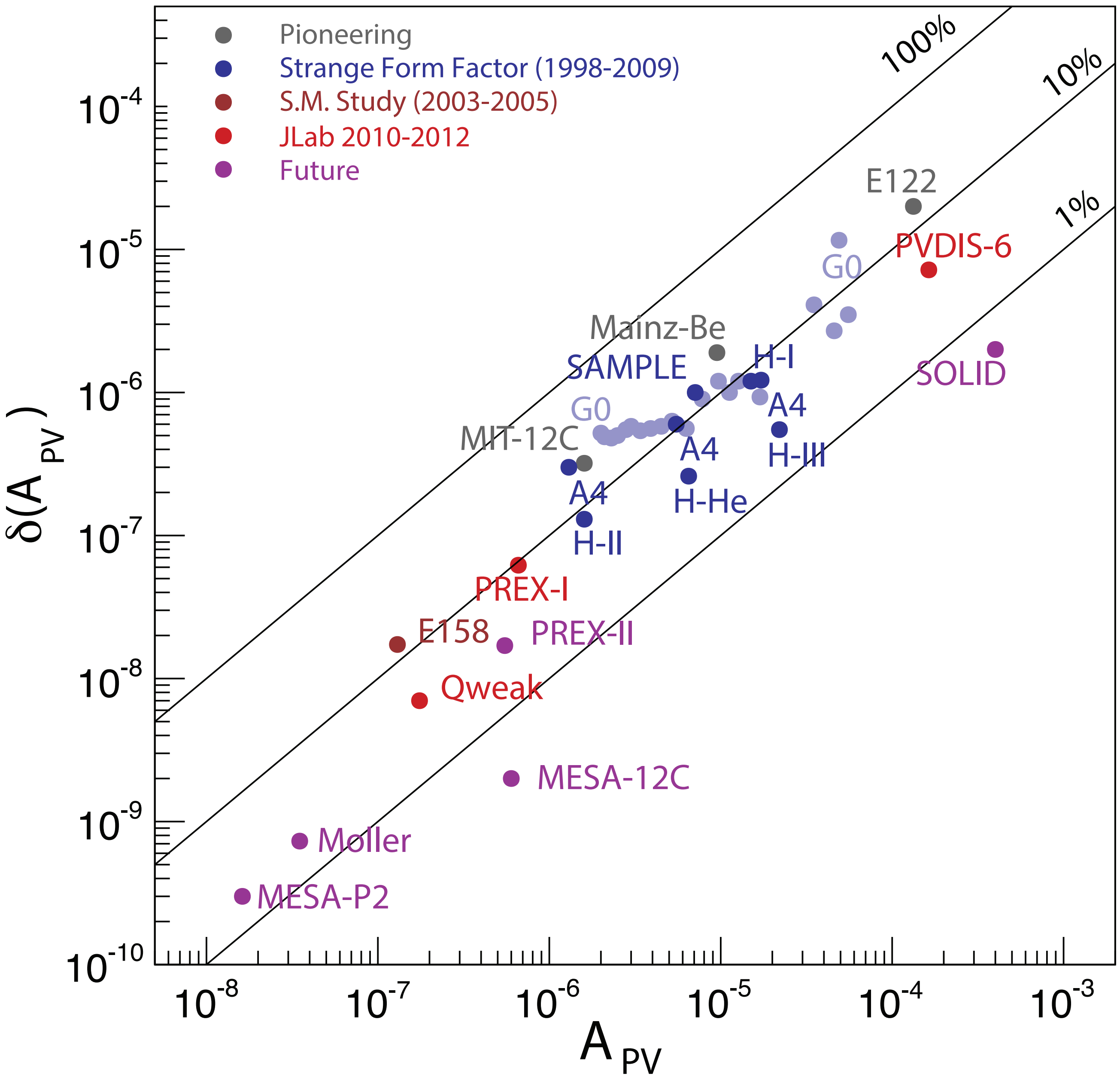
$$Q_W = 1 - 4\sin^2\theta_W$$

- 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%

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

- Need Q_W at 1.5%
- Essentially means 1.5% on A_{PV}

How much statistics do we need?

- Want to measure $\sin^2\theta_W$ to 0.13%
- Need Q_W at 1.5%
- Essentially means 1.5% on A_{PV}
- A_{PV} is 40 parts per billion
- $\delta(A_{PV})$ is 0.6 parts per billion
- N a few 10^{18}

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

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

How much statistics do we need?

- Want to measure $\sin^2\theta_W$ to 0.13%
- Need Q_W at 1.5%
- Essentially means 1.5% on A_{PV}
- A_{PV} is 40 parts per billion
- $\delta(A_{PV})$ is 0.6 parts per billion
- N a few 10^{18}
- Measure 10'000 hours (absolute maximum anyone thinks shifts are organisable)
- Need close to 10^{11} electrons/s - 100 GHz

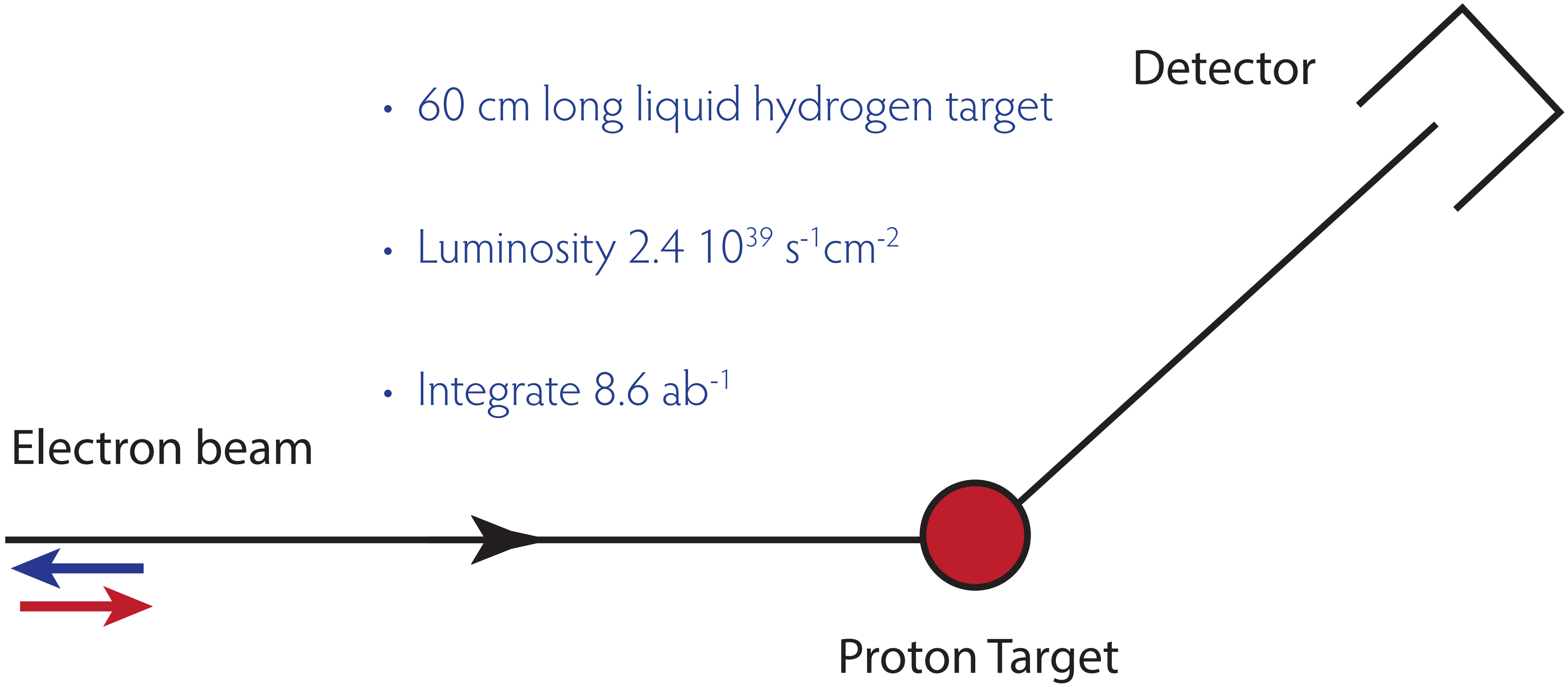
$$\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1-4\sin^2 \theta_W}{4\sin^2 \theta_W} \frac{\Delta Q_W}{Q_W}$$

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

Can we get that rate?

Yes!

- 150 μA of electron beam current
- 60 cm long liquid hydrogen target
- Luminosity 2.4 10^{39} $s^{-1}cm^{-2}$
- 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...

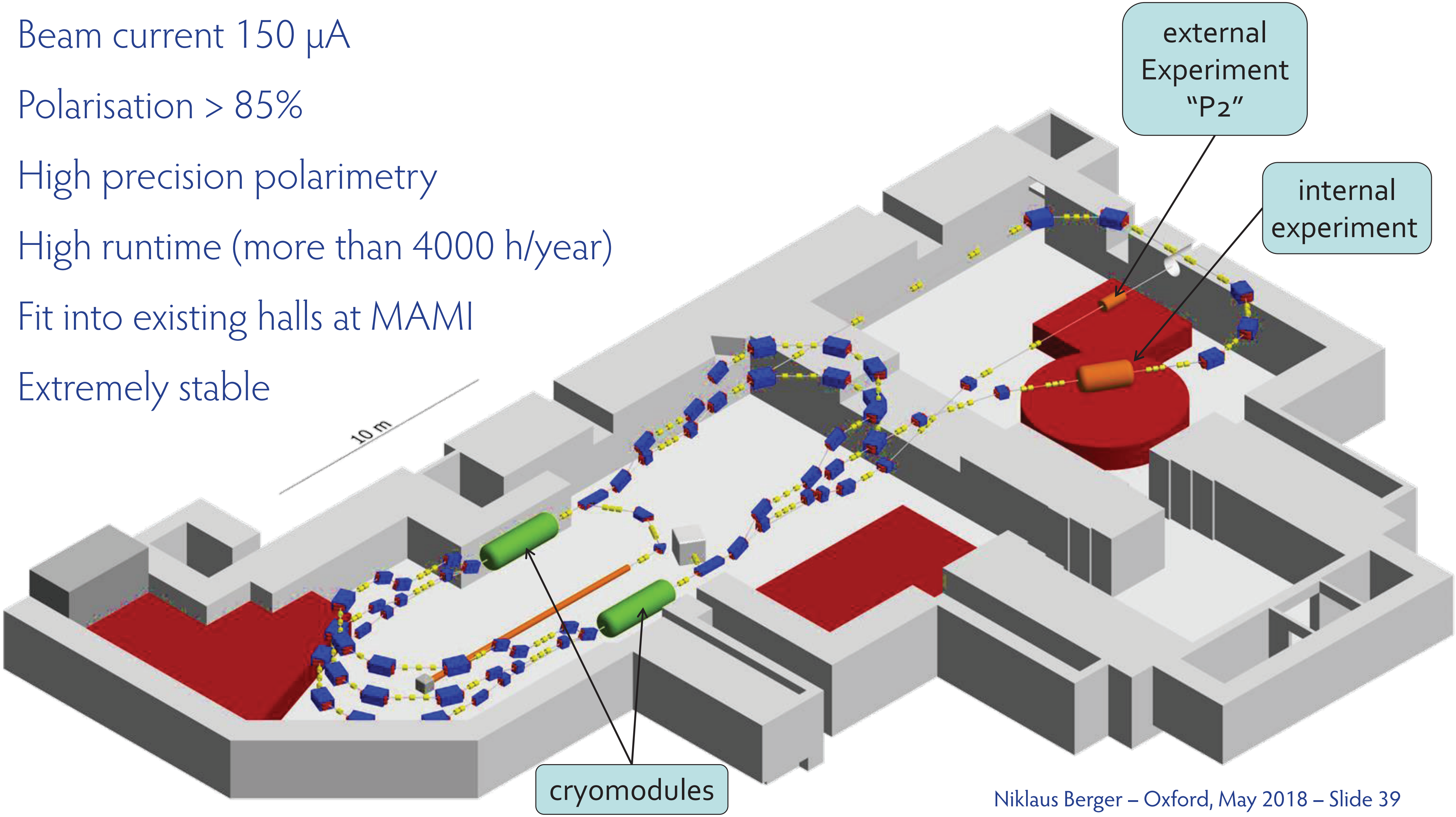
If you cannot rent it, build it:

The MESA accelerator

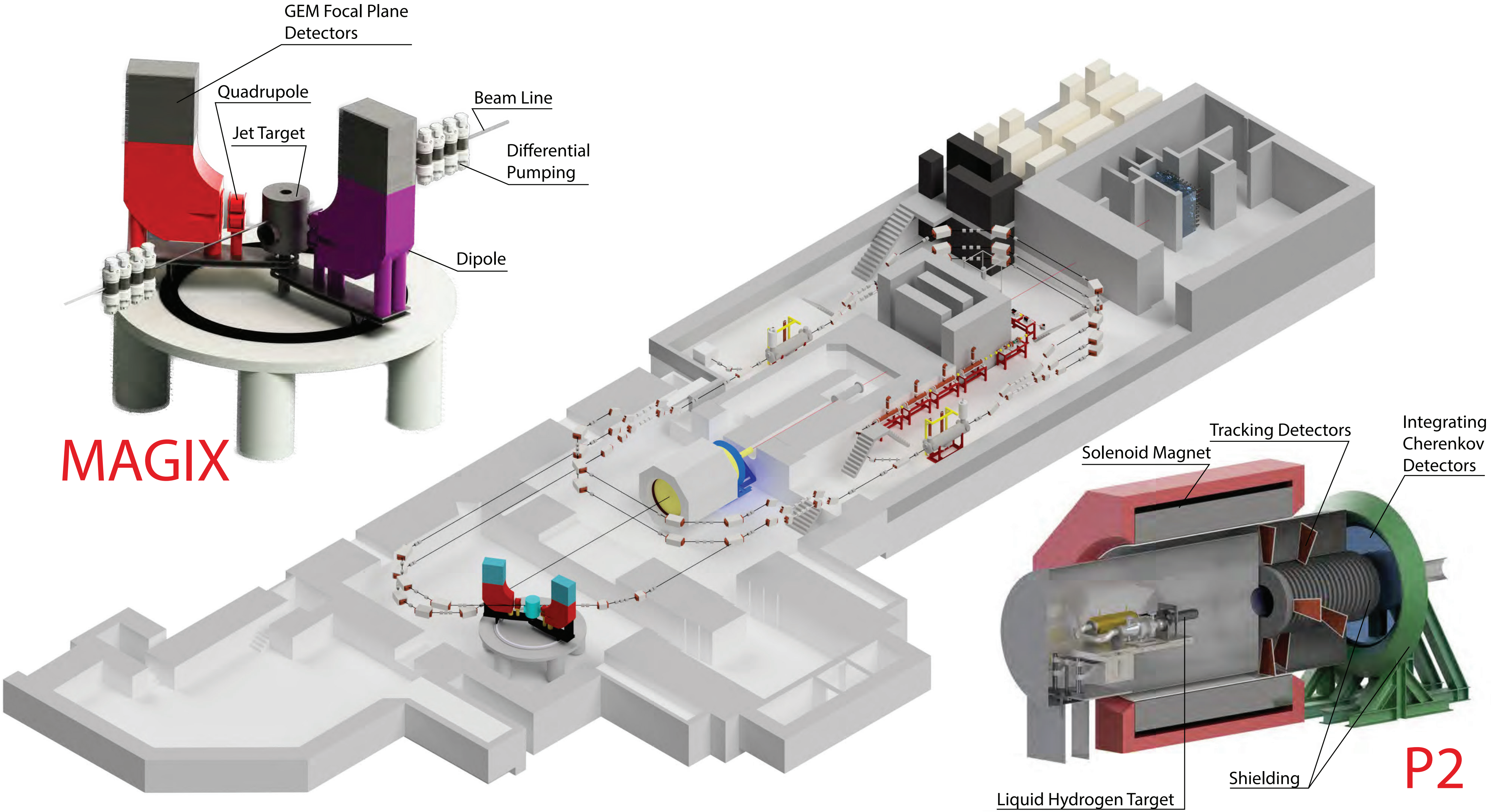
Mainz Energy-recovery Superconducting Accelerator

Requirements

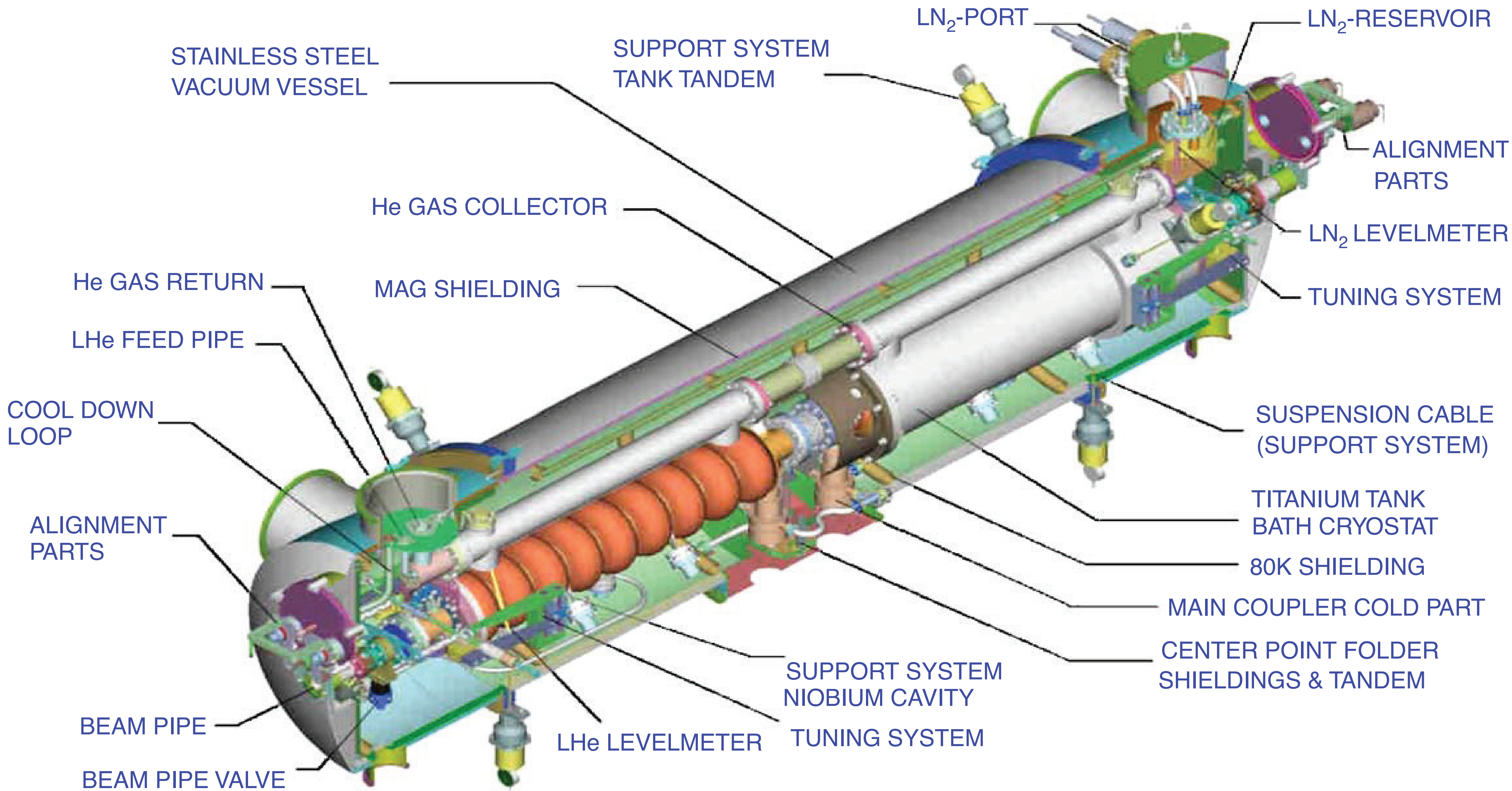
- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry
- High runtime (more than 4000 h/year)
- Fit into existing halls at MAMI
- Extremely stable



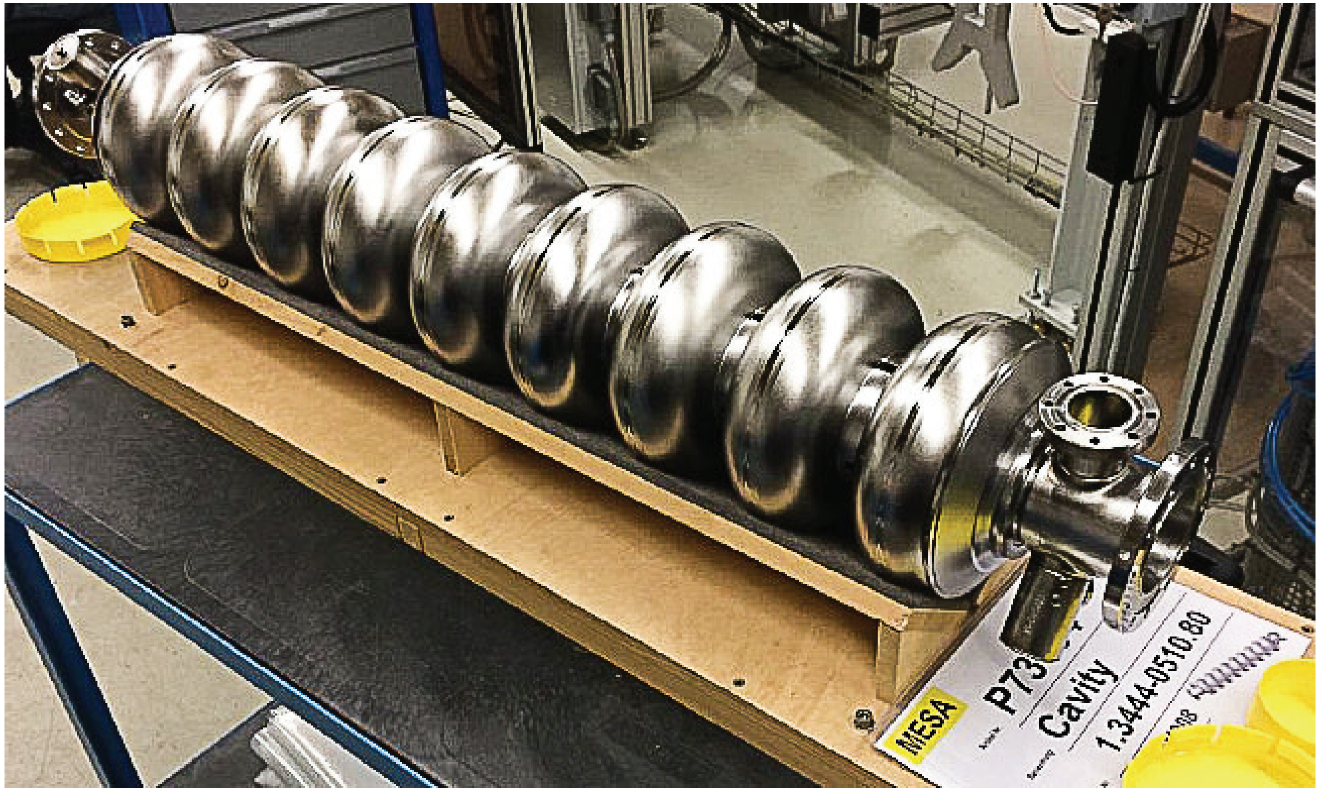
Mainz Energy-Recovery Superconducting Accelerator



Superconducting Cryomodules



Teichert et al. NIM A 557 (2006) 239


MESA
Cavity
1.3444-0510.80


research
instruments

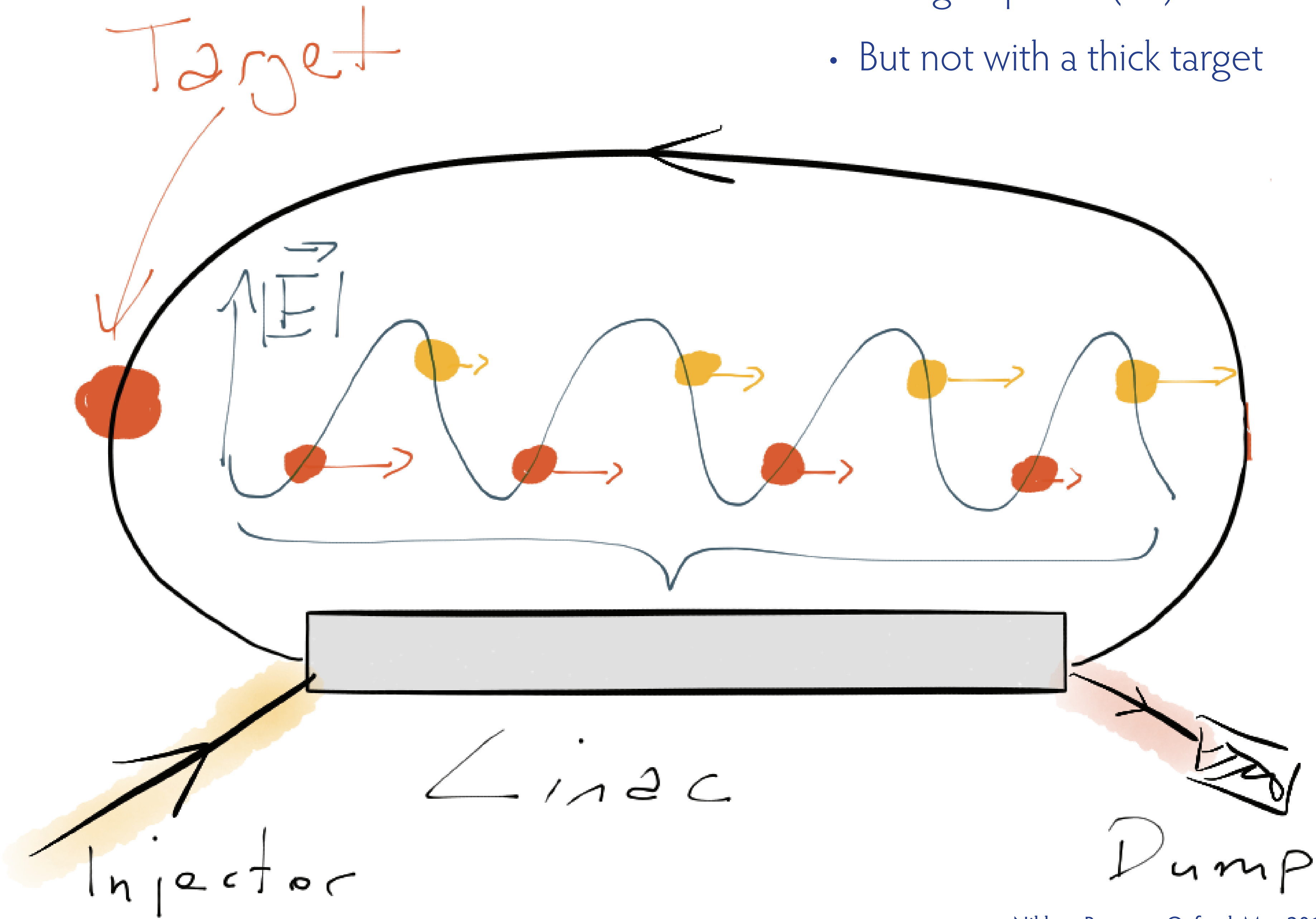
Energy recovery

Can we go to higher beam currents?

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

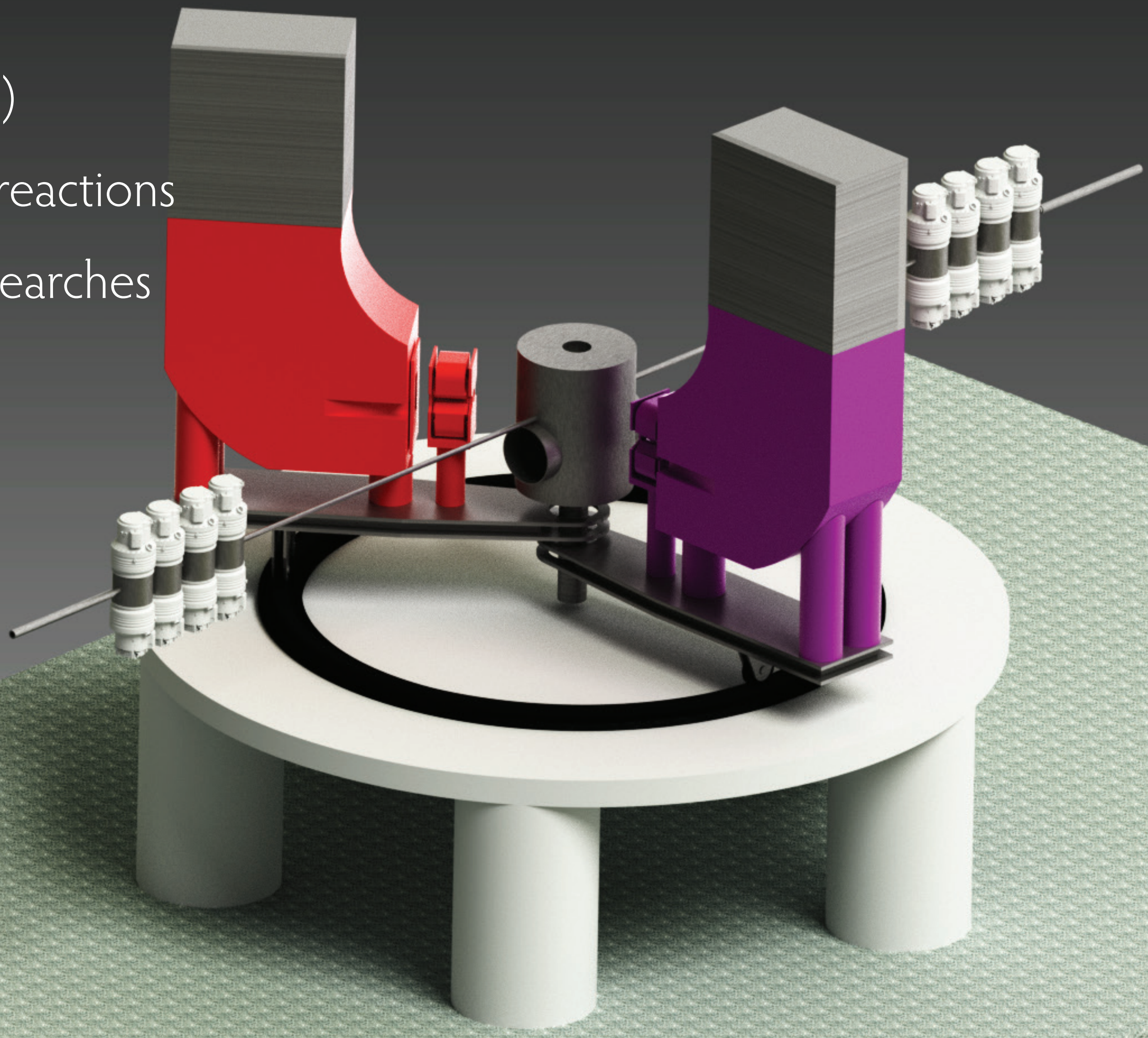
Energy recovery

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

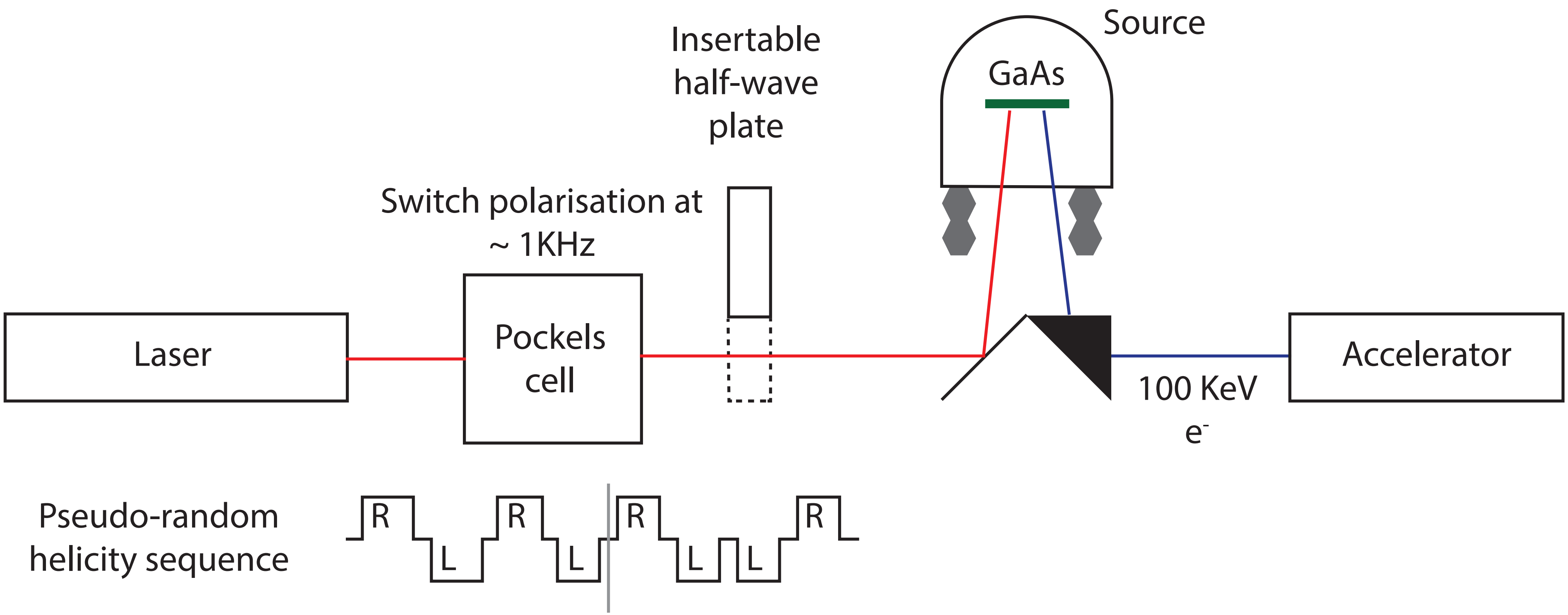


MAGIX Spectrometer

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



Polarized Source and Helicity Flips



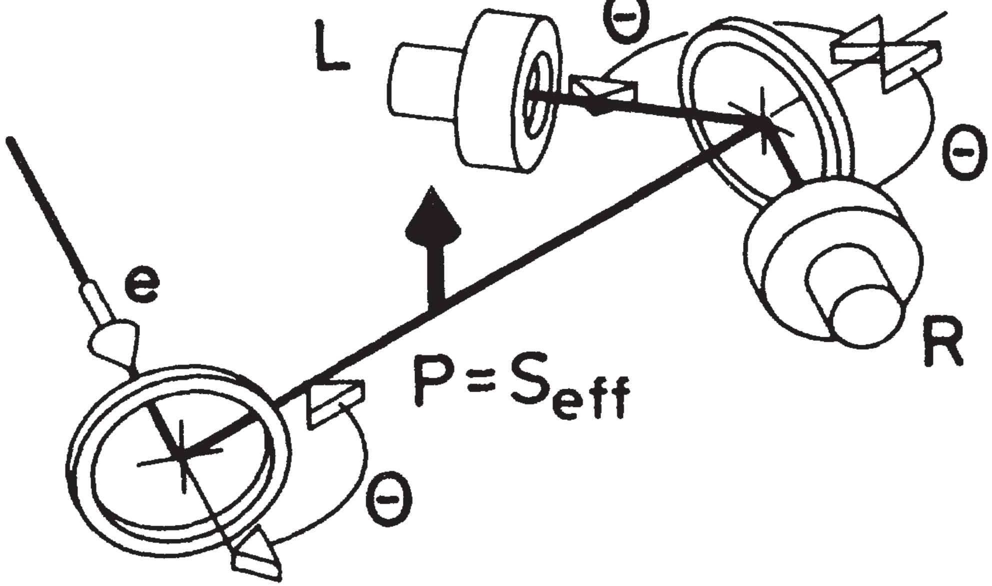
Stability Requirements

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



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

Mott Polarimertry:

- 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

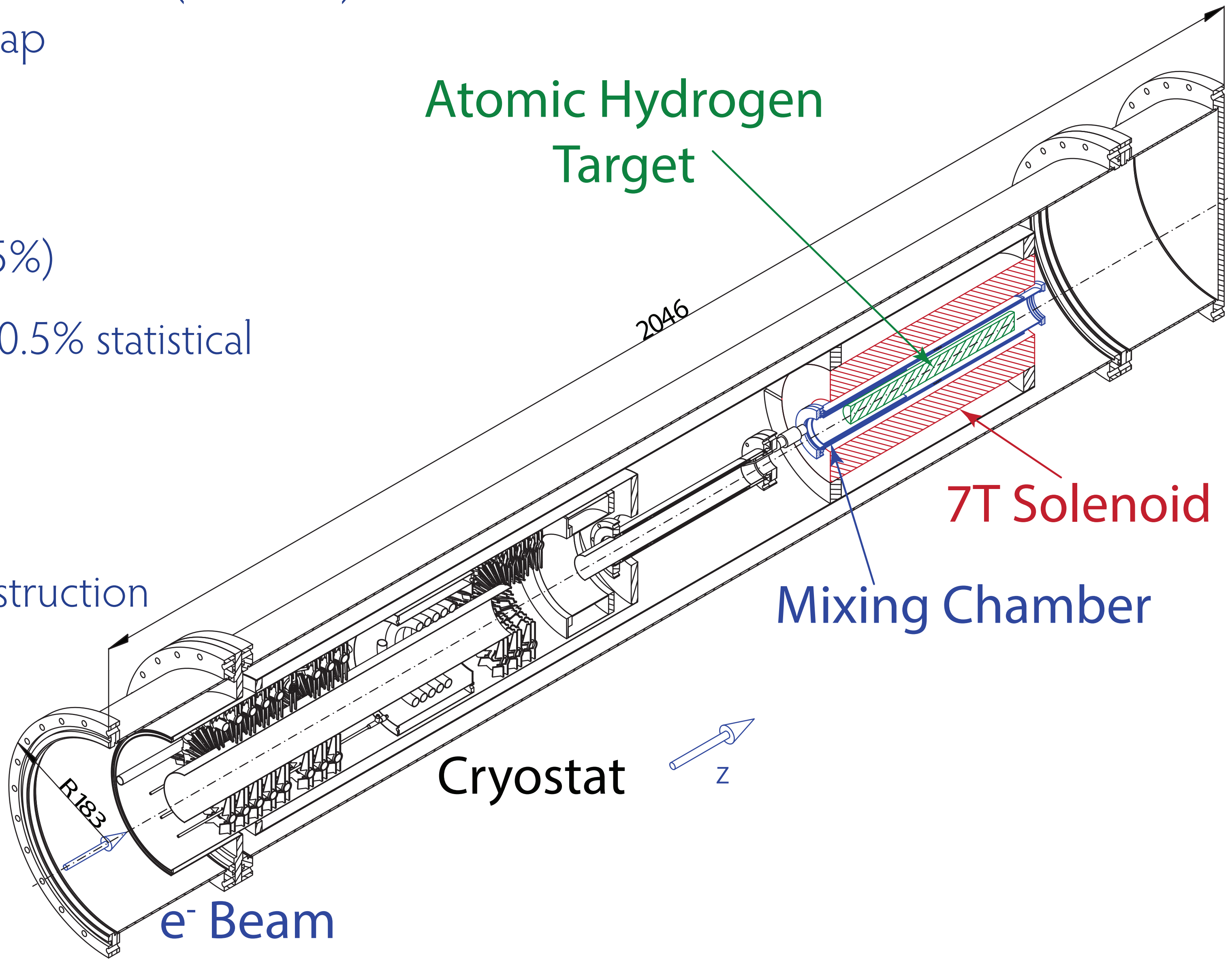
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

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

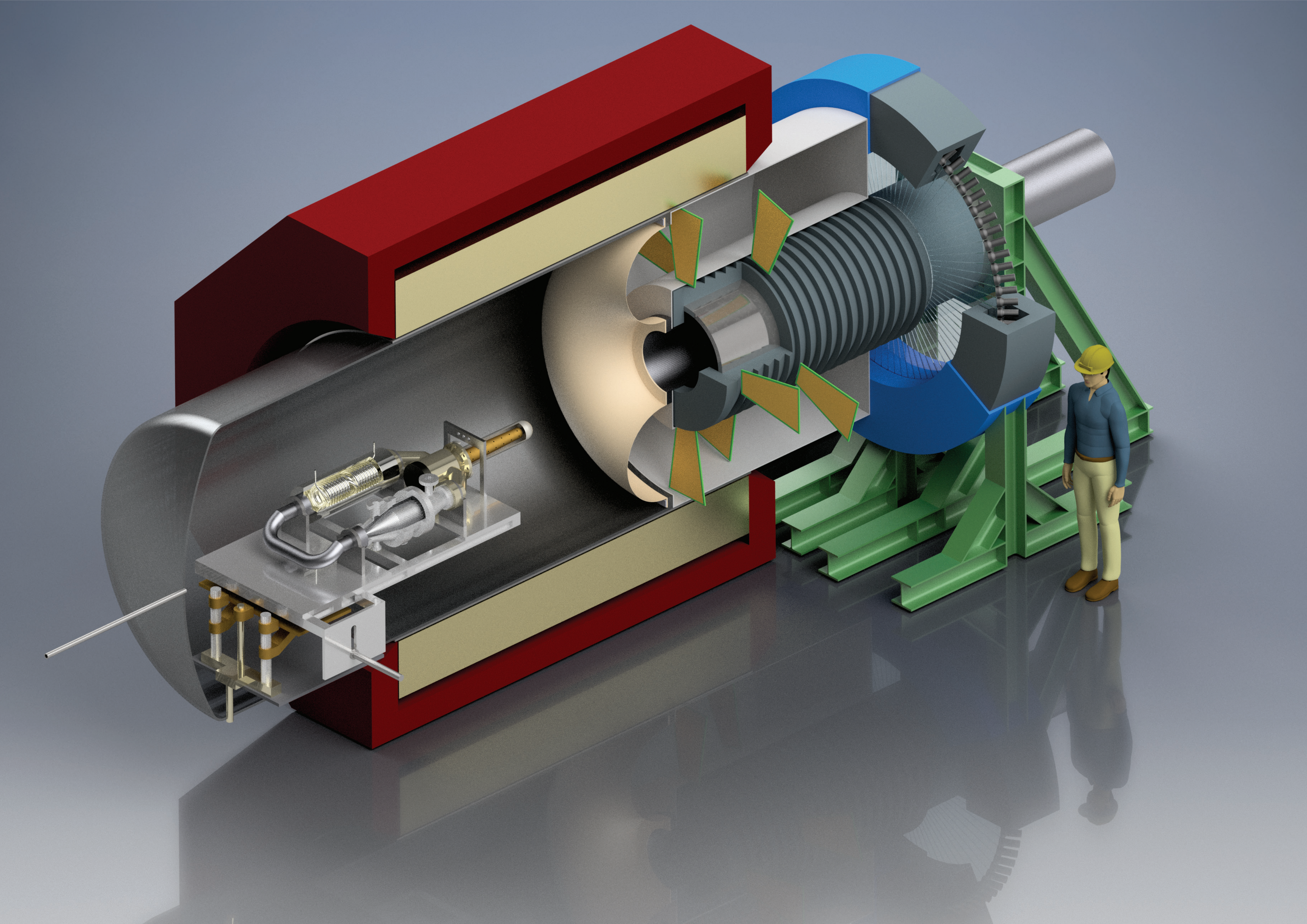
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

- Cryostat under construction in Mainz



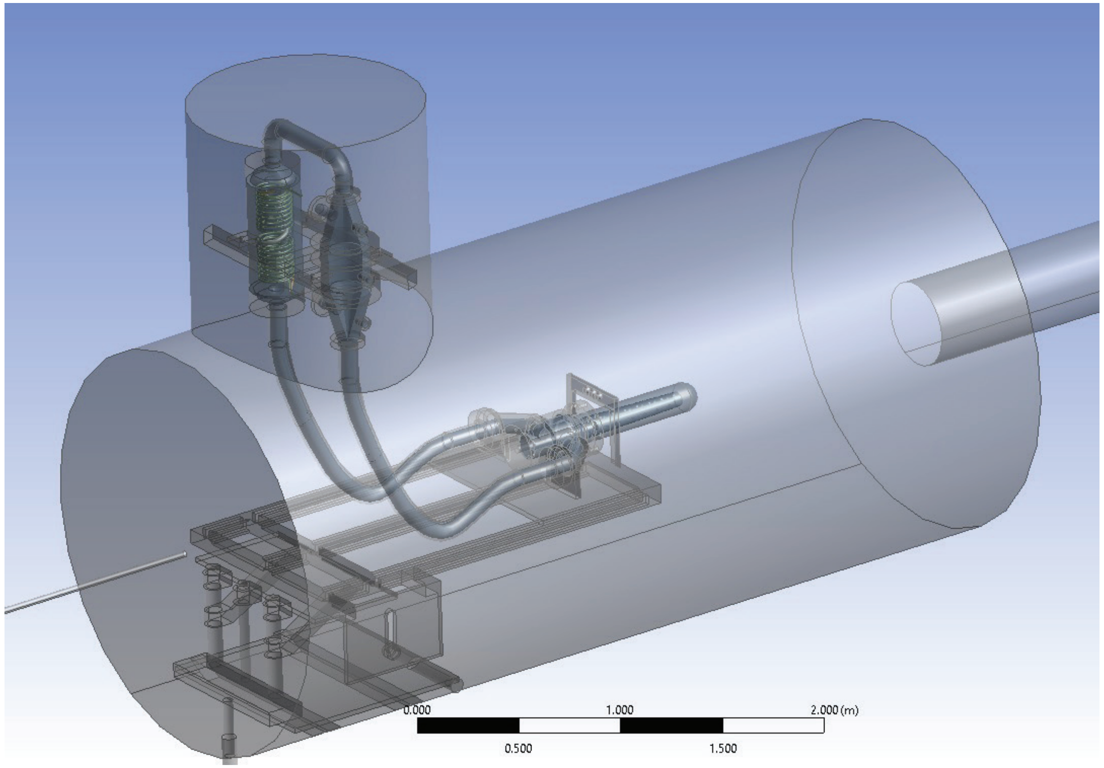
P2:

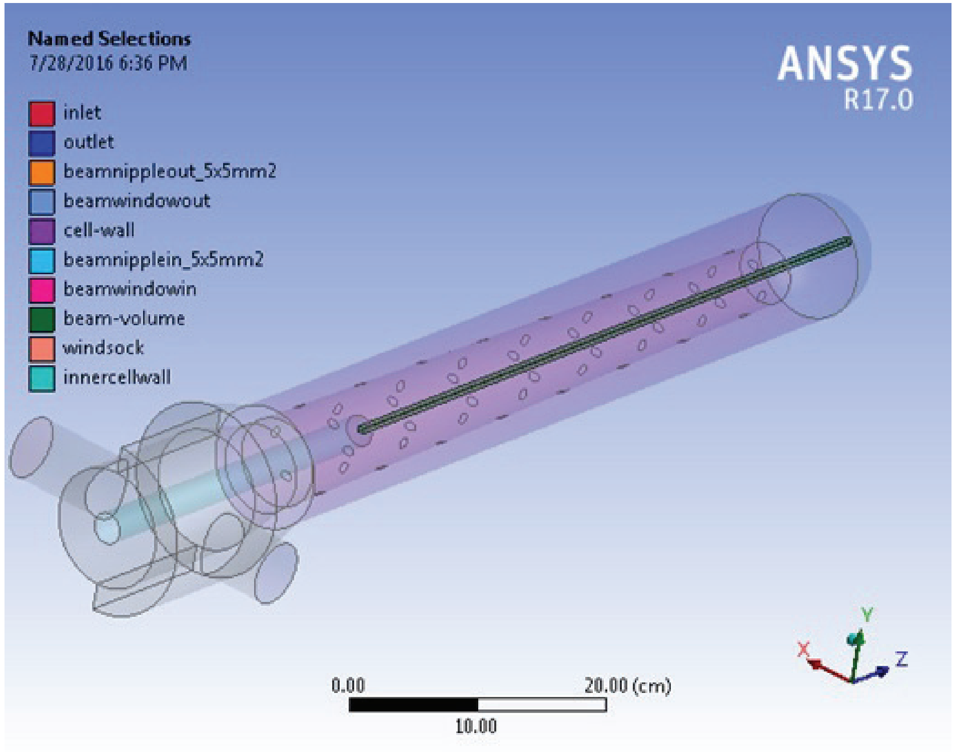
How to detect 100 GHz of (the right) electrons...



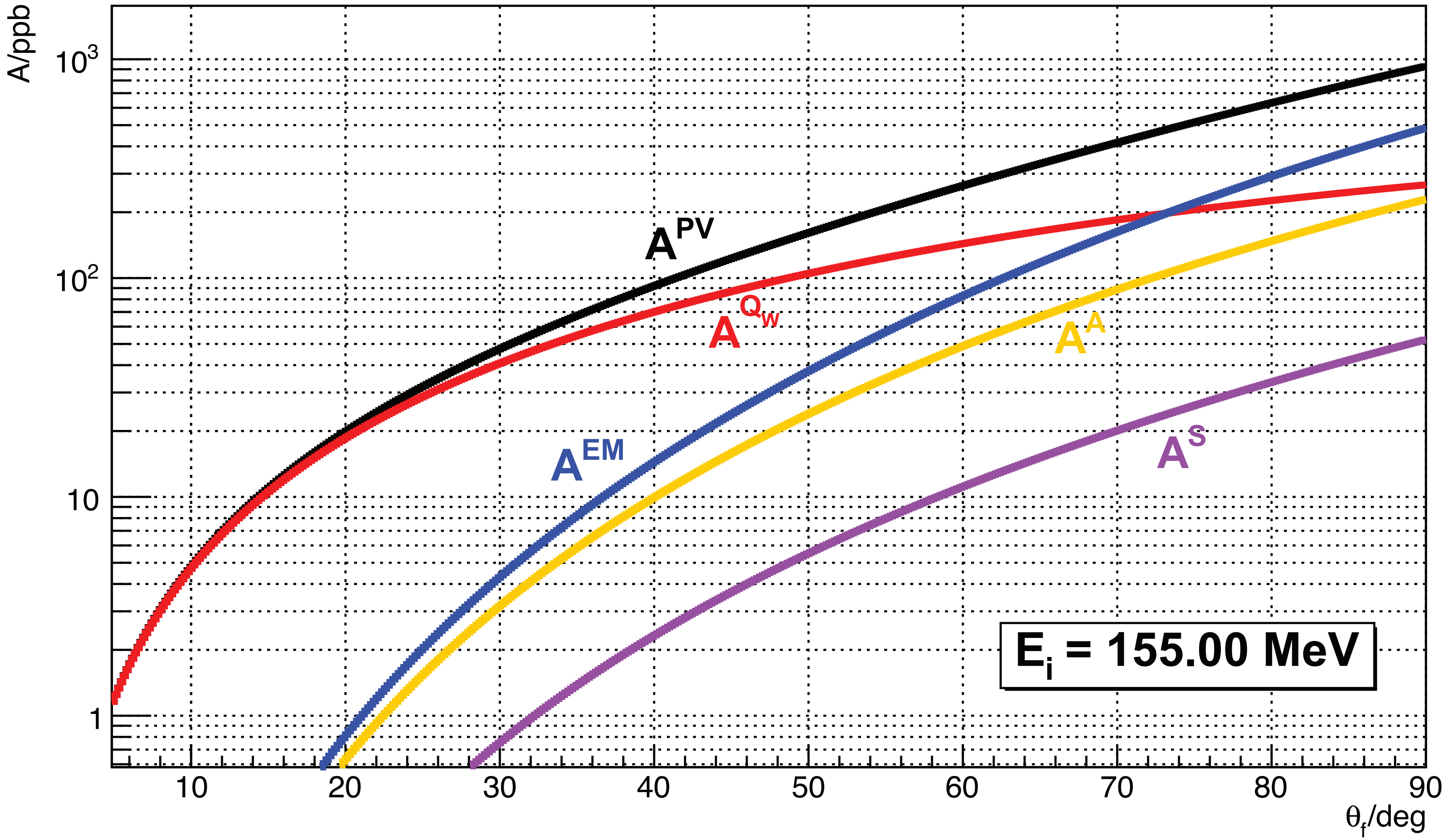
Target

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





Choice of scattering angle



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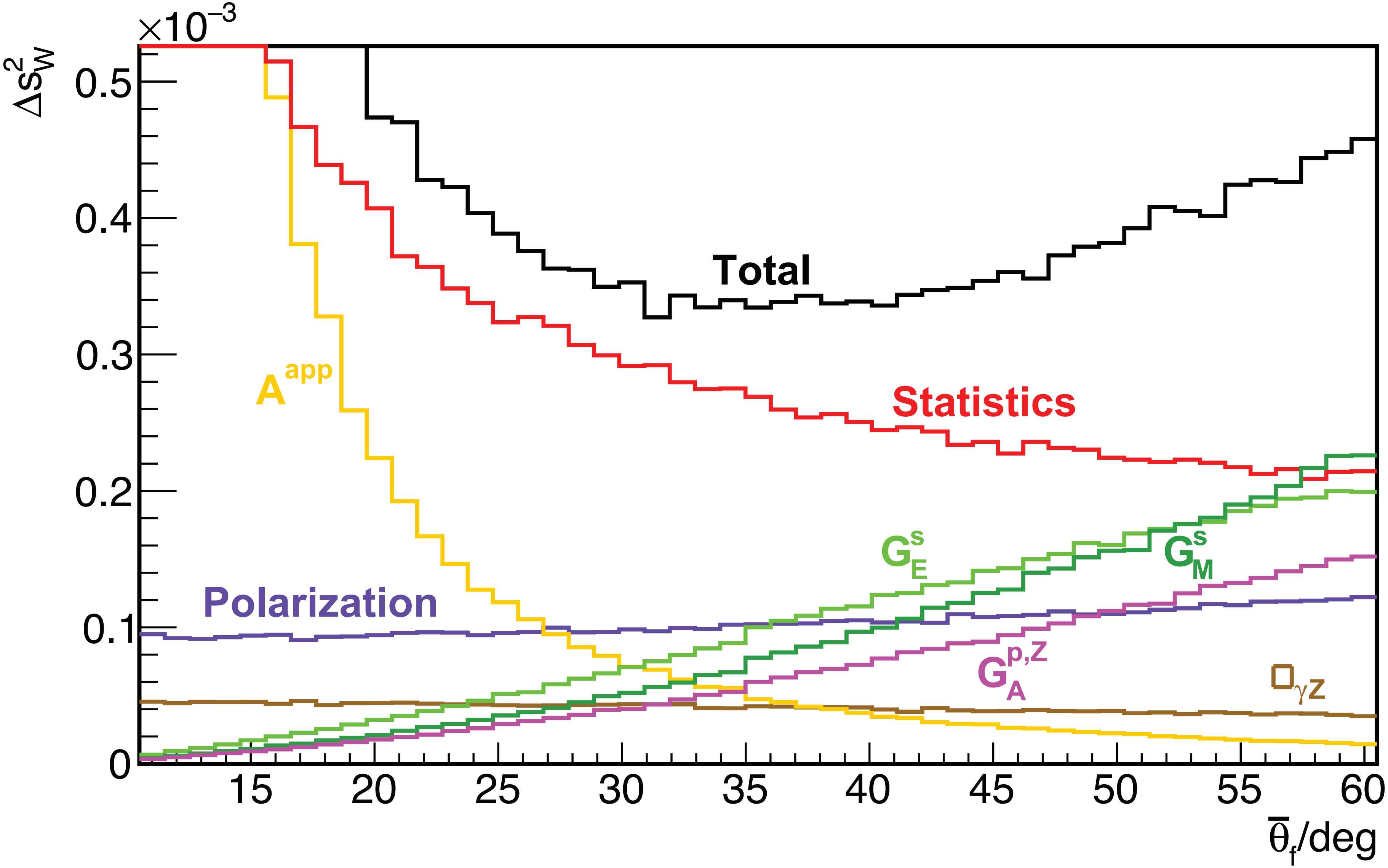
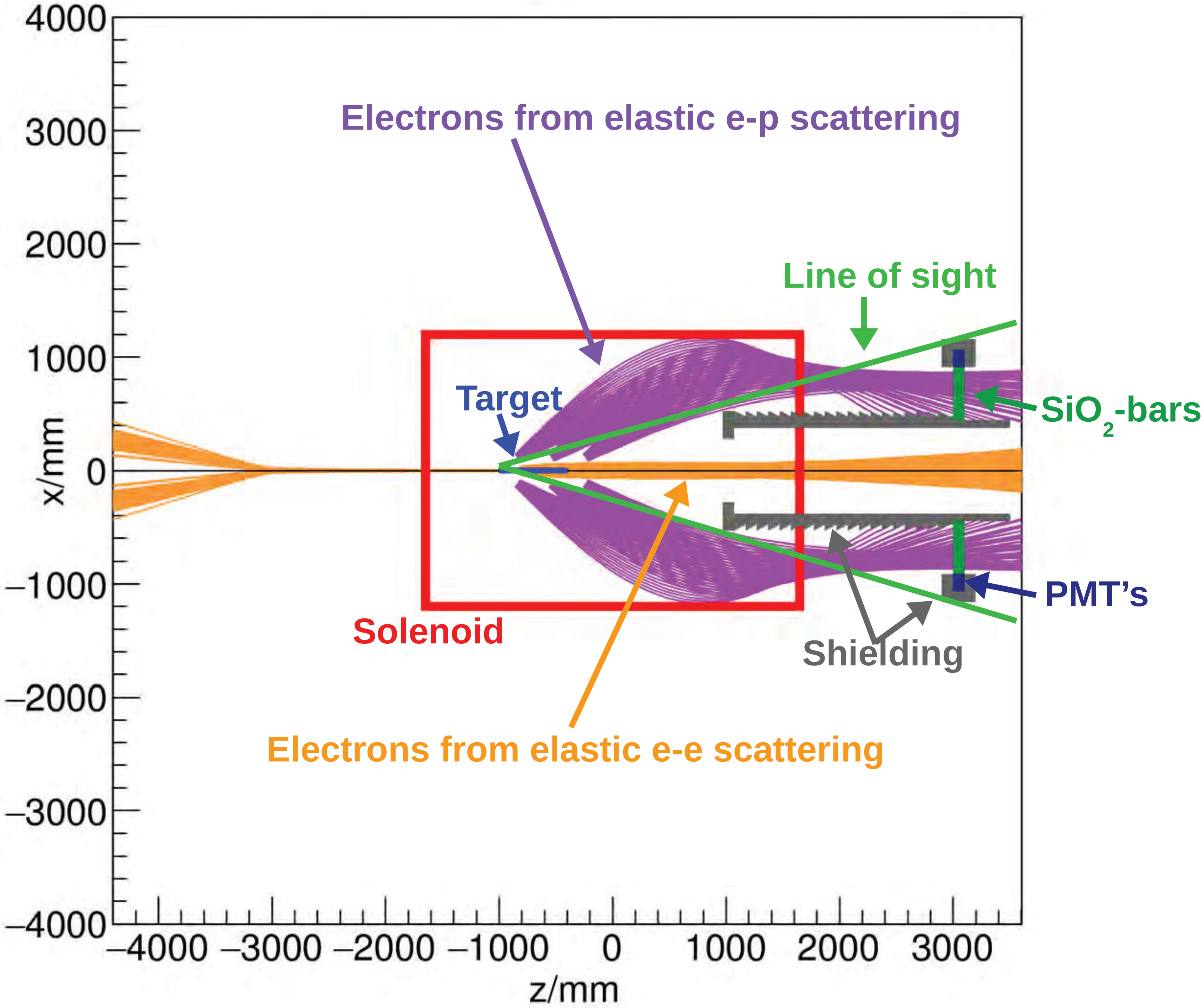


Solenoid spectrometer



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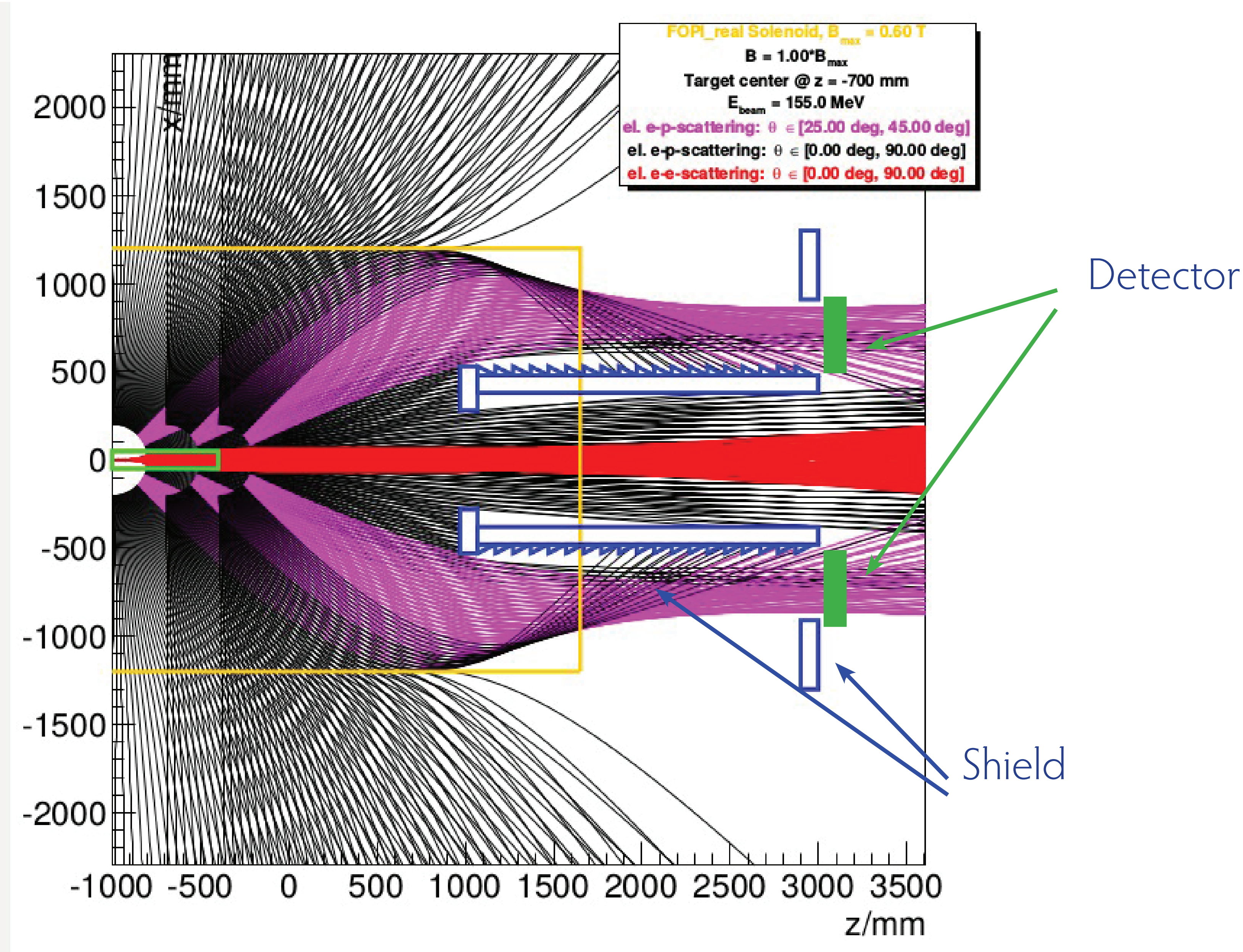
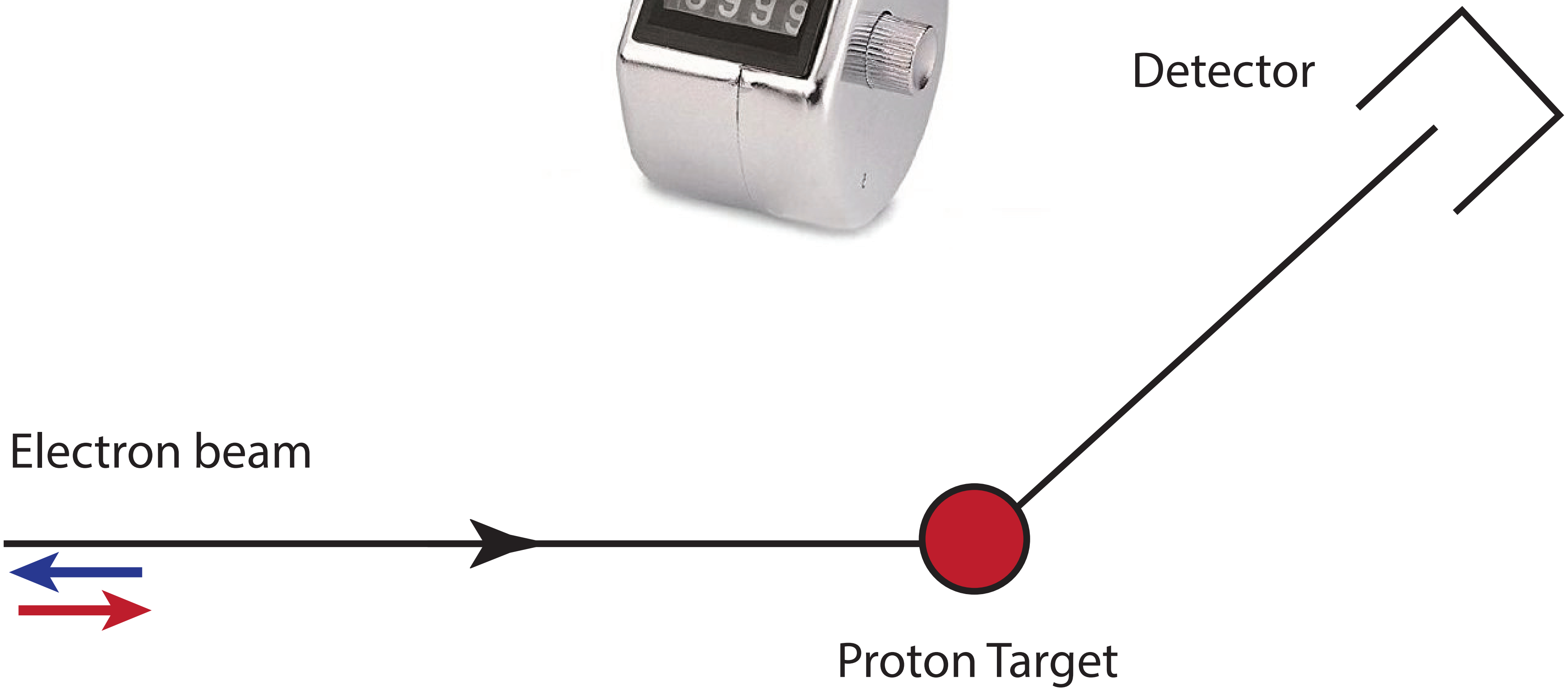
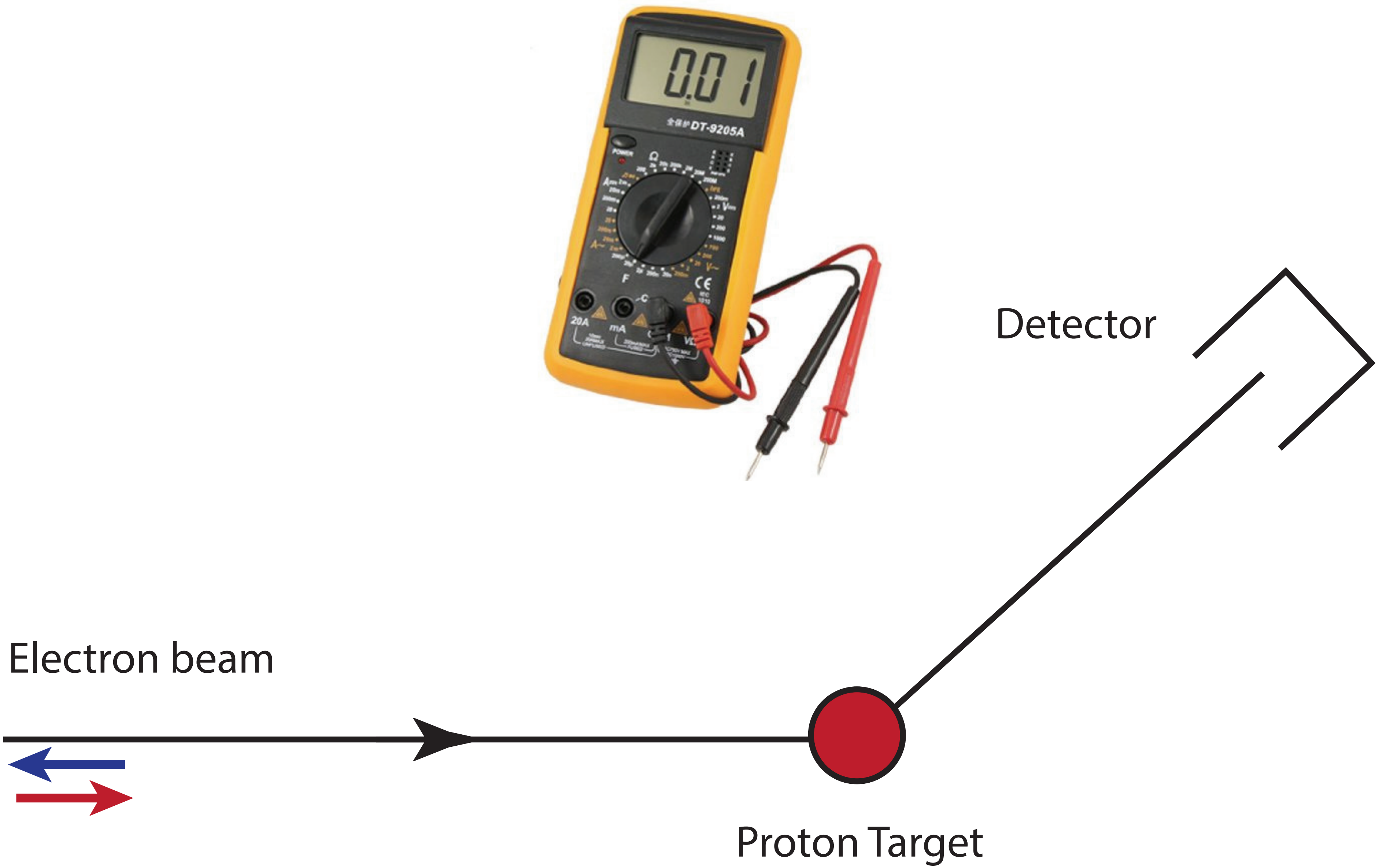


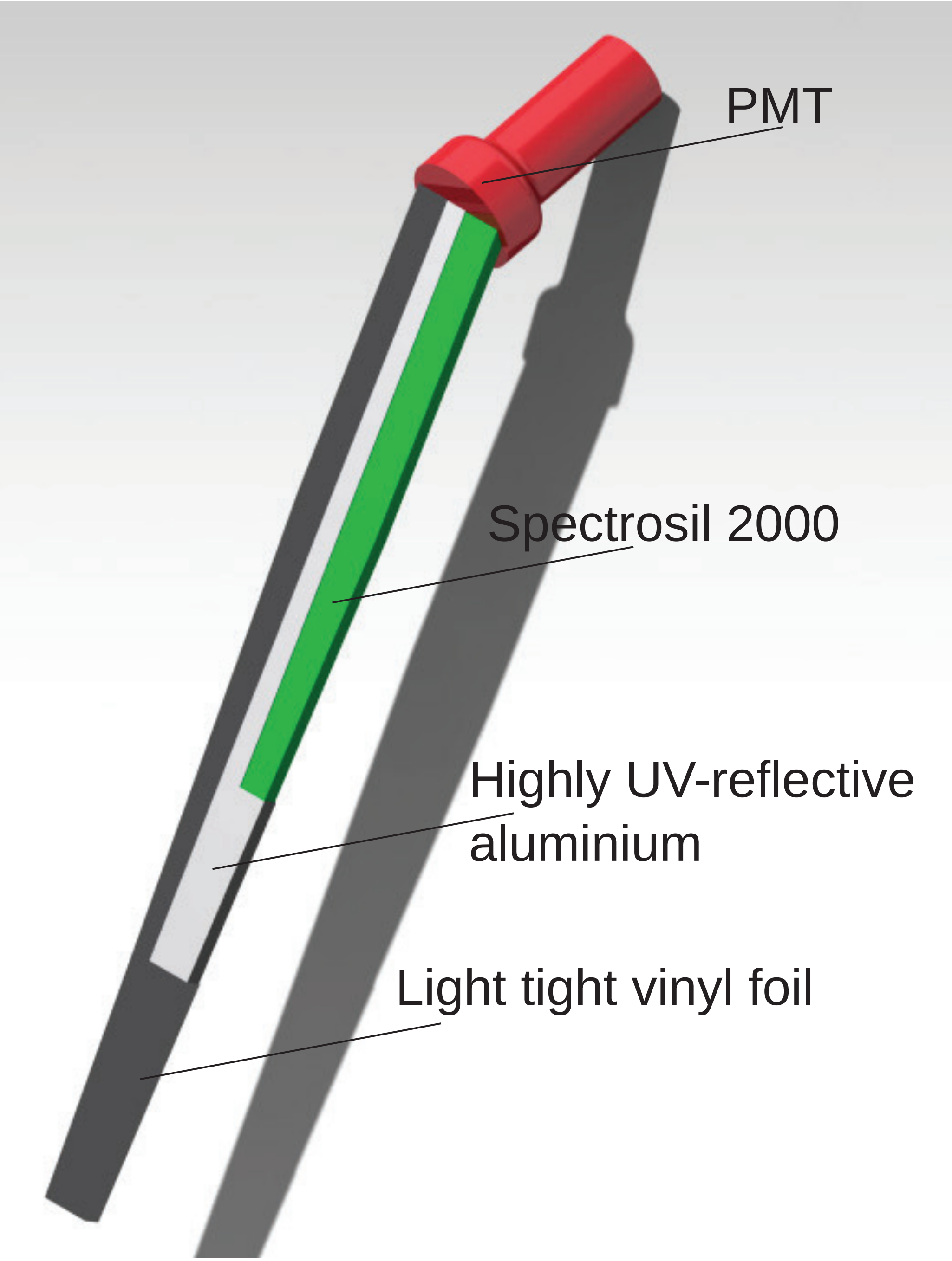
Counting detectors



Integrating detectors

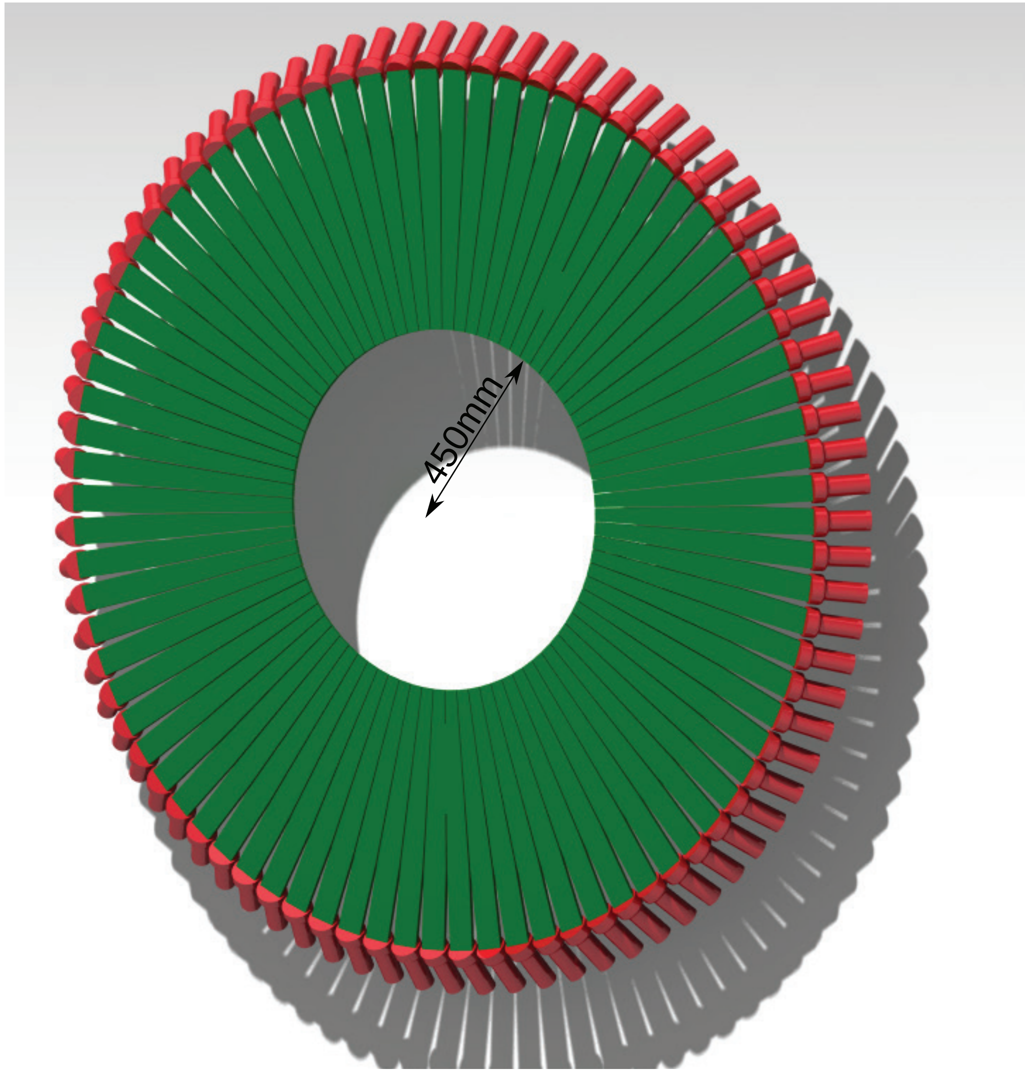


Quartz-Bars & Photomultipliers

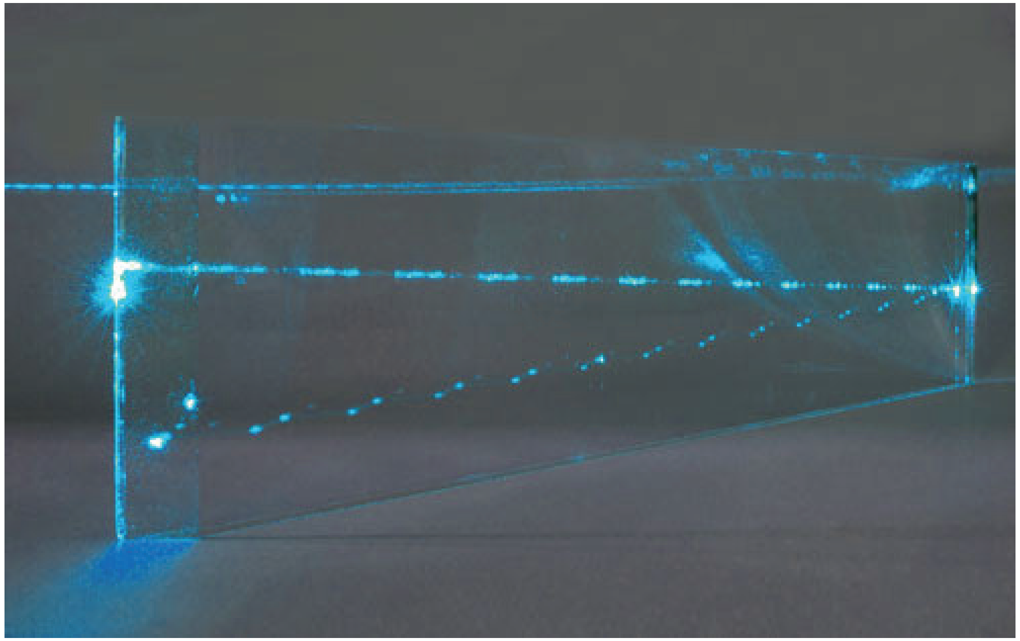


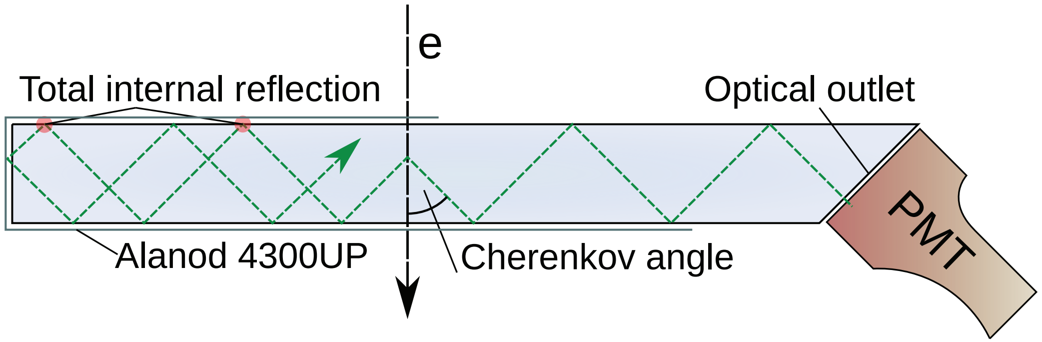
Detect Cherenkov-light created by electrons

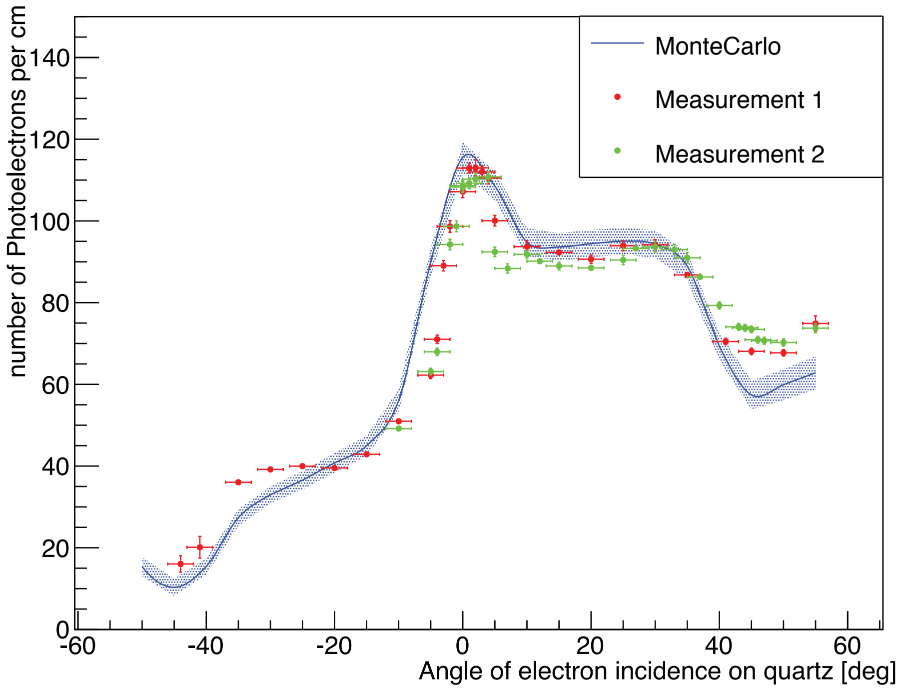
Integrate photomultiplier current



Quartz-Bars & Photomultipliers







Measuring Q^2:

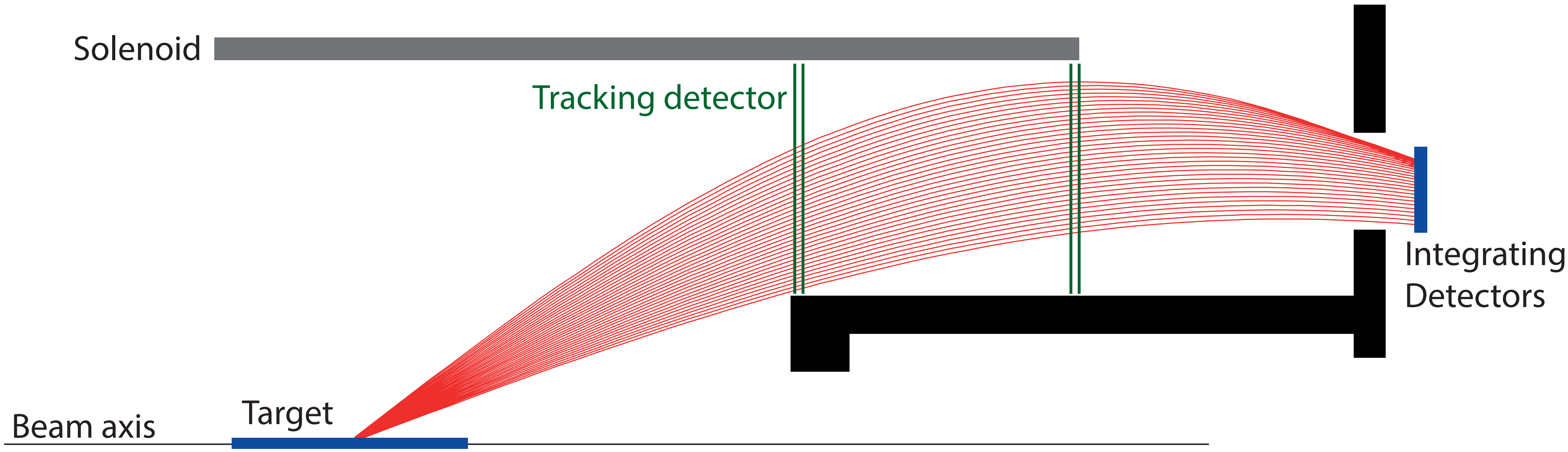
Tracking a

lot of low momentum particles

Tracker requirement

- Low momentum electrons:
  Thin detectors

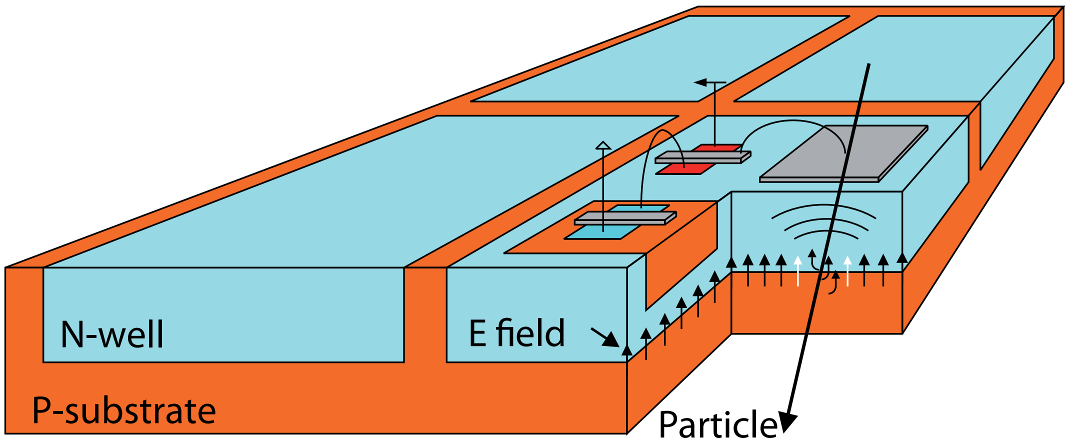
- Very high rates:
  Fast and granular detectors



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

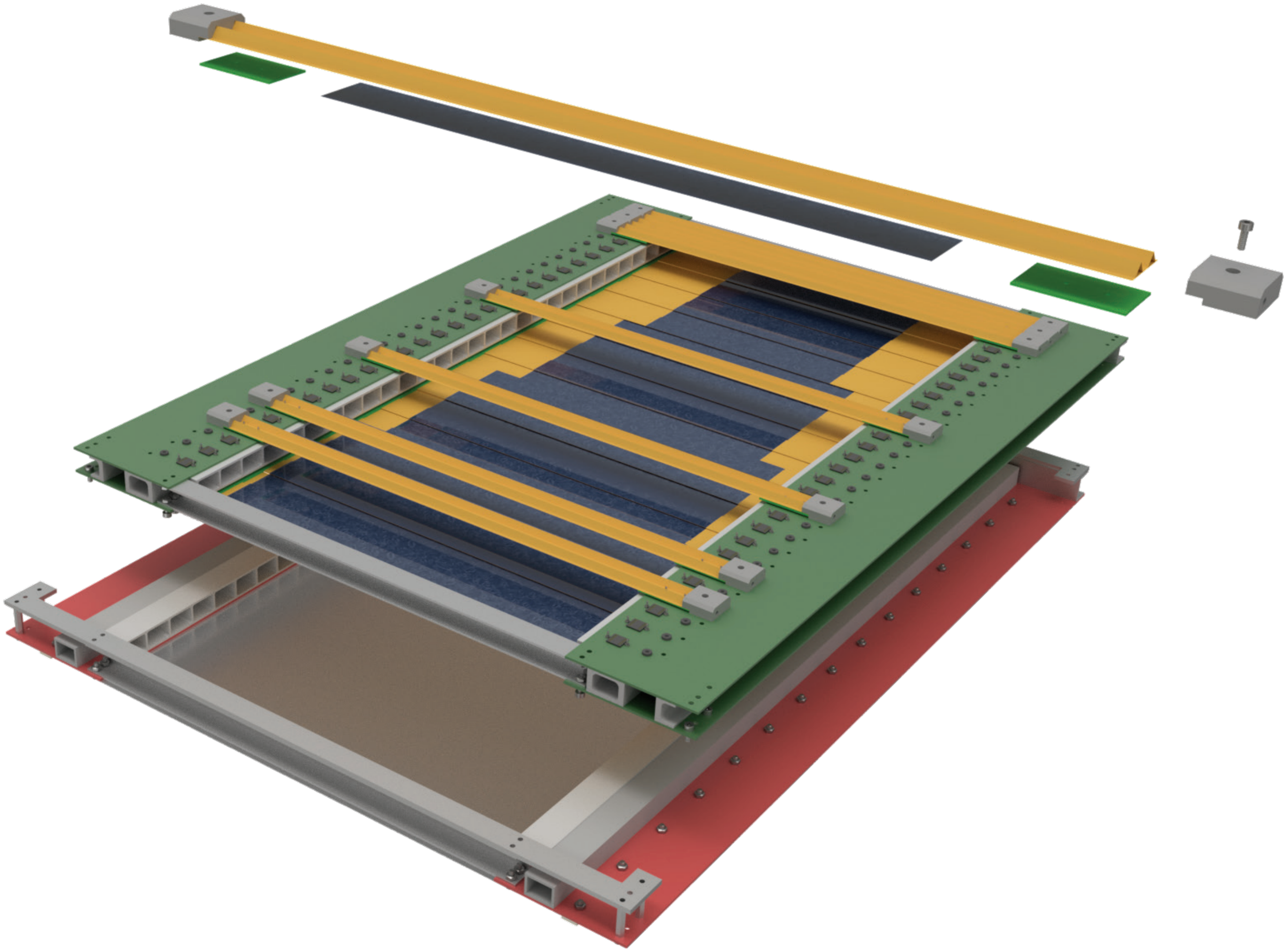


High voltage monolithic active pixel sensors - Ivan Perić (morning sessions!)

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 µm
- Logic on chip: Output are zero-suppressed hit addresses and timestamps

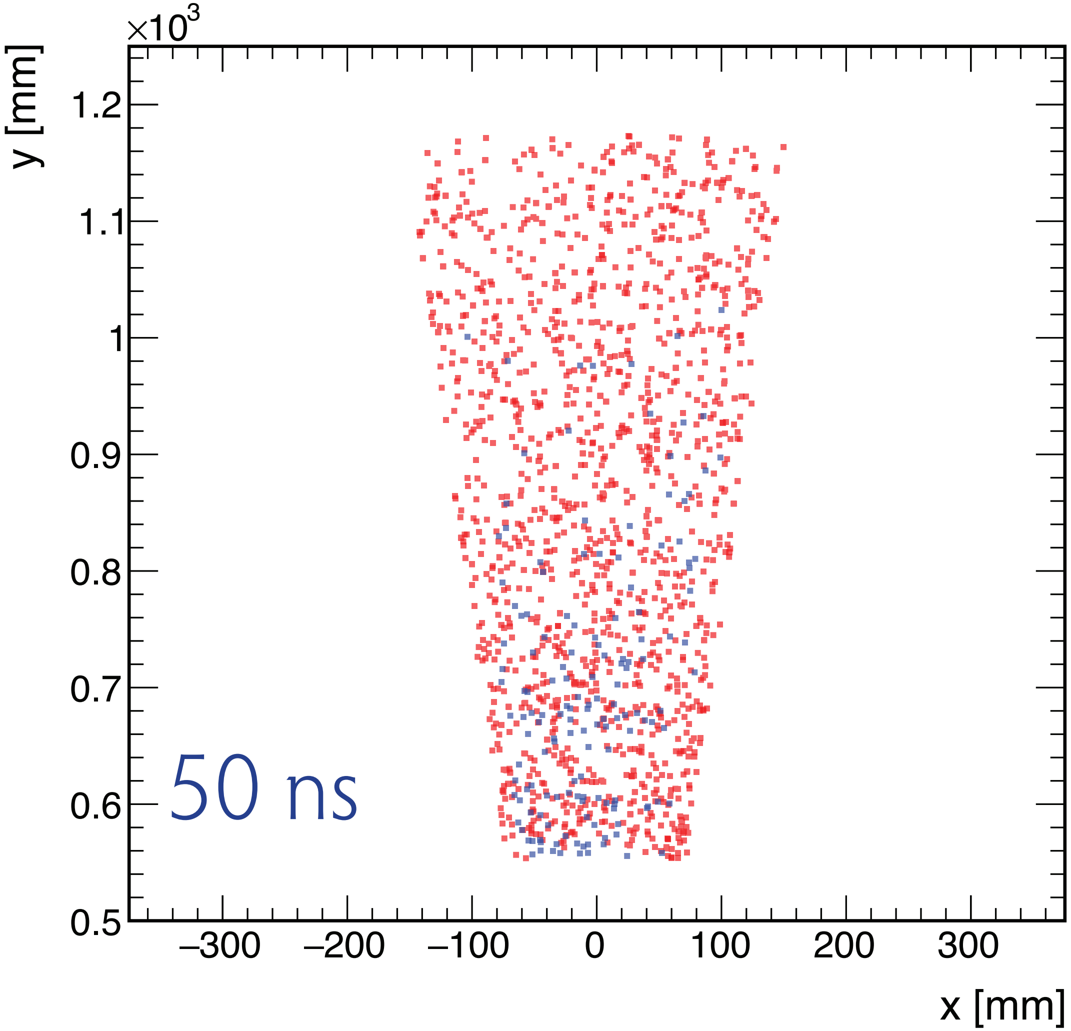
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

Mechanics



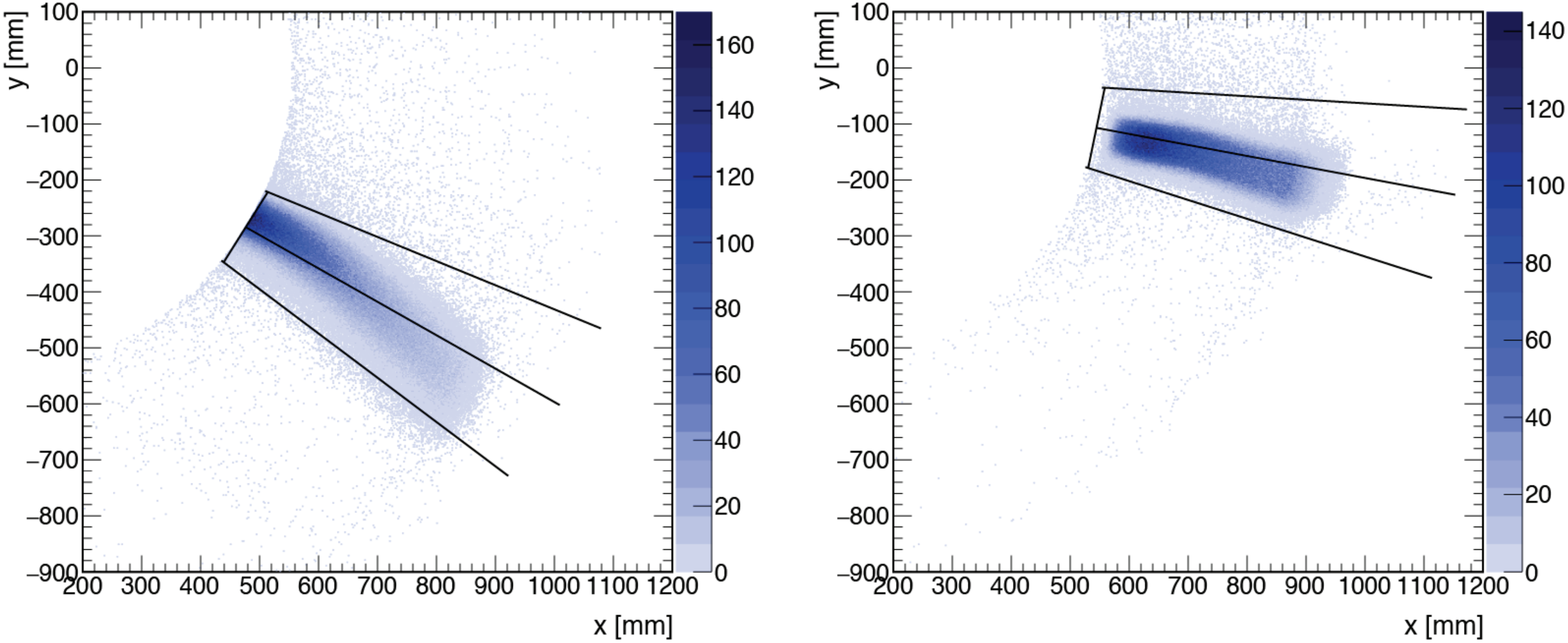
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ folds as support
- About 1‰ of a radiation length per layer

The tracking challenge



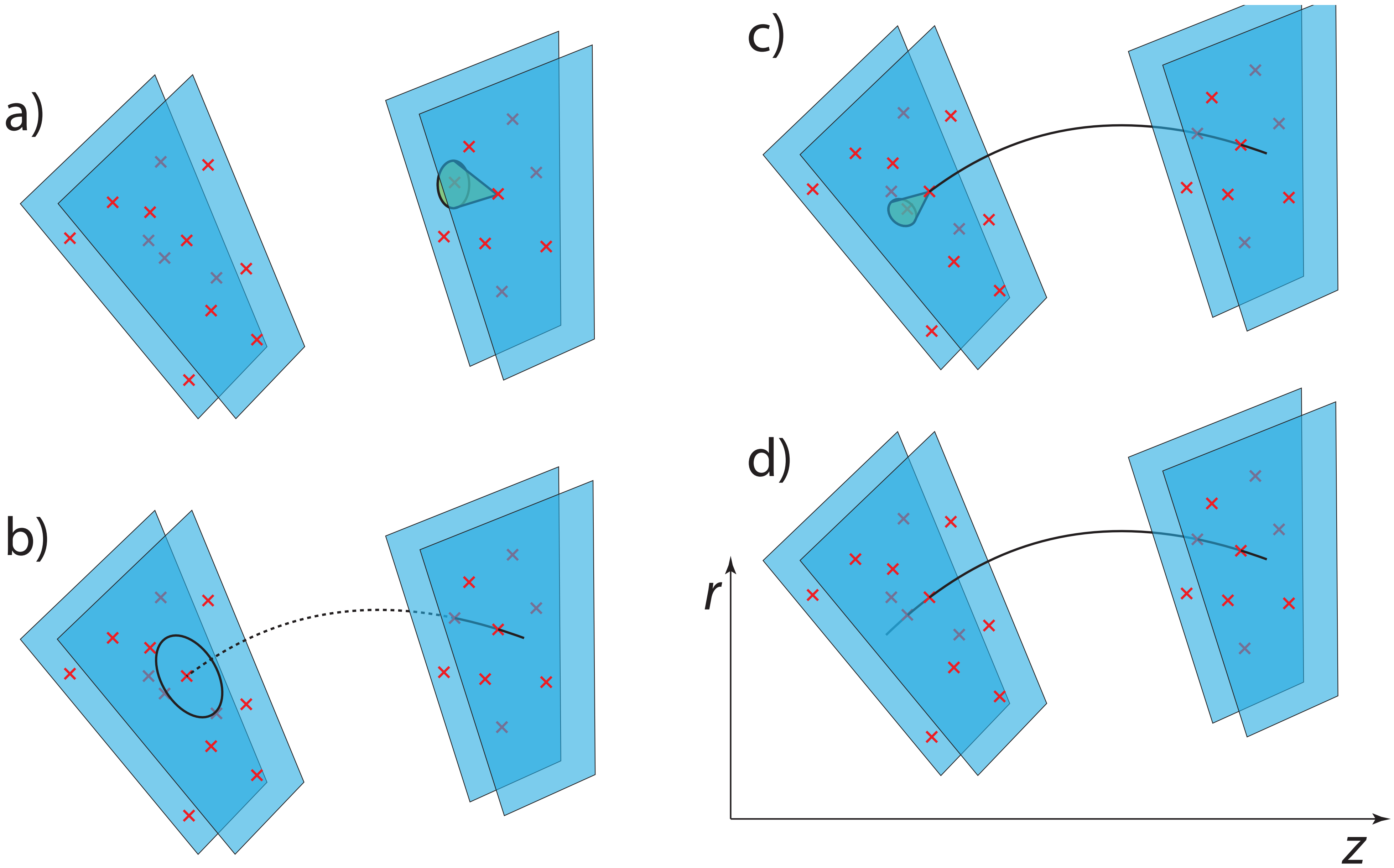
- 100 GHz electrons
- about 1000 Bremsstrahlung photons per electron

No need for full coverage

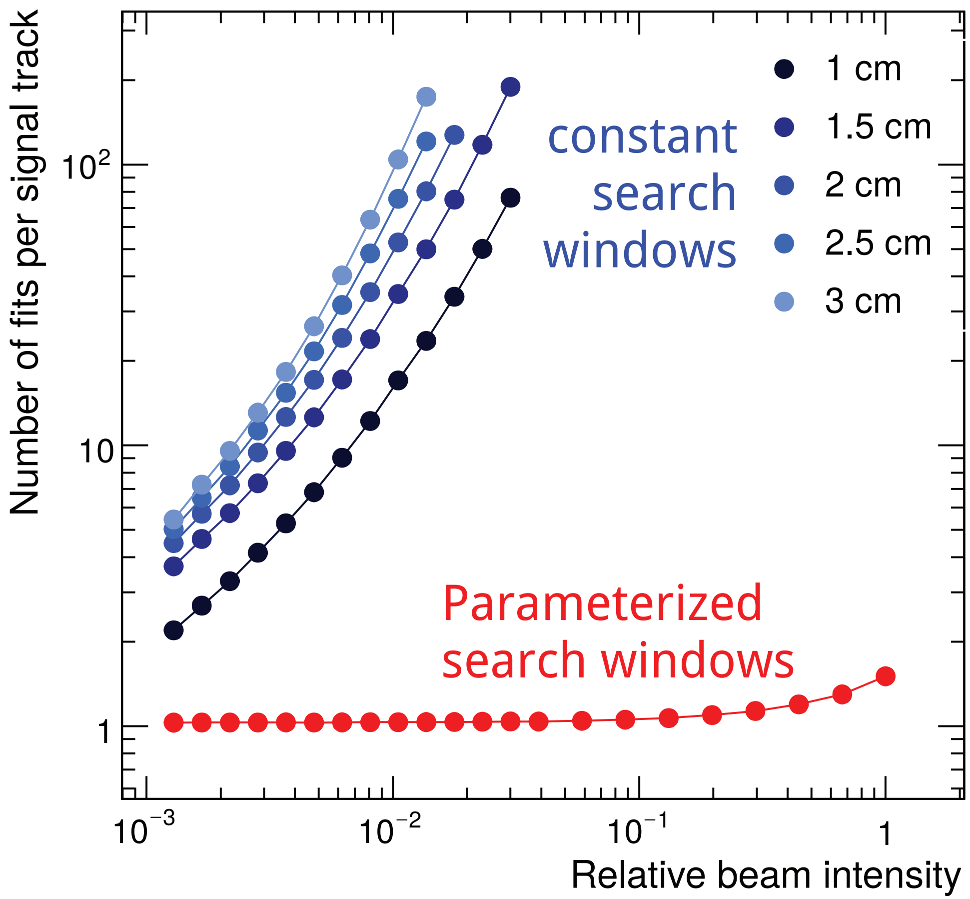


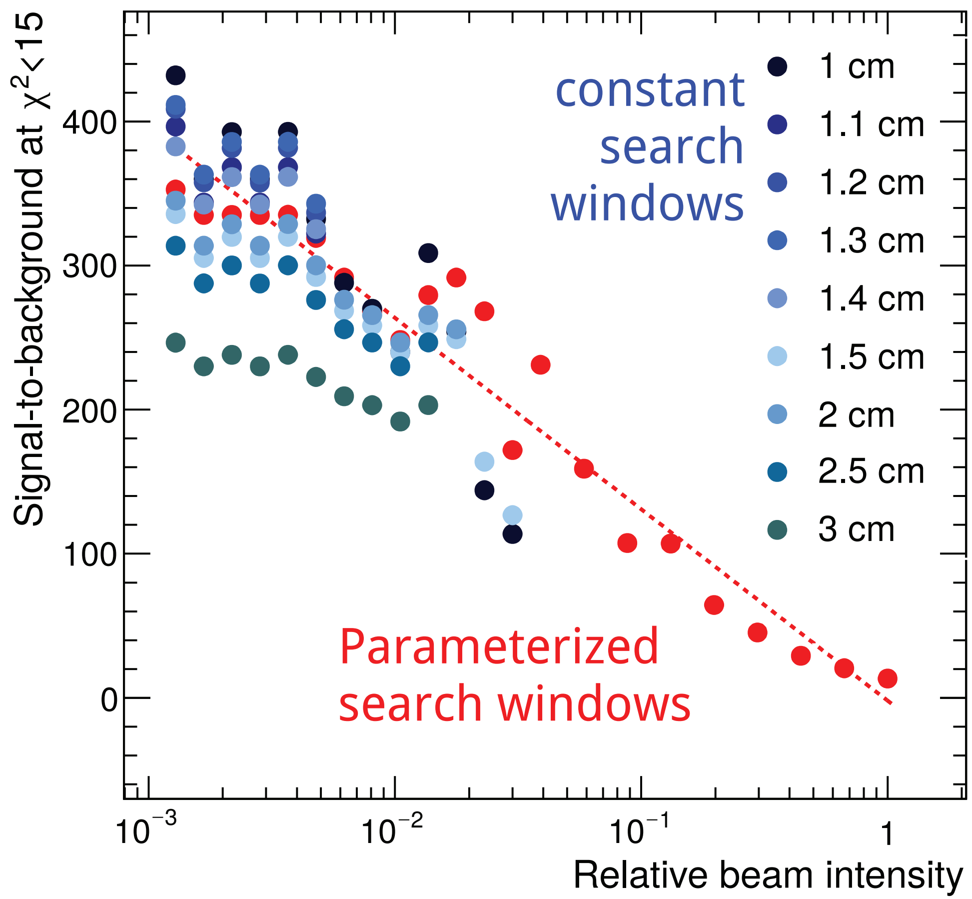
Parametrization based tracking

I. Sorokin

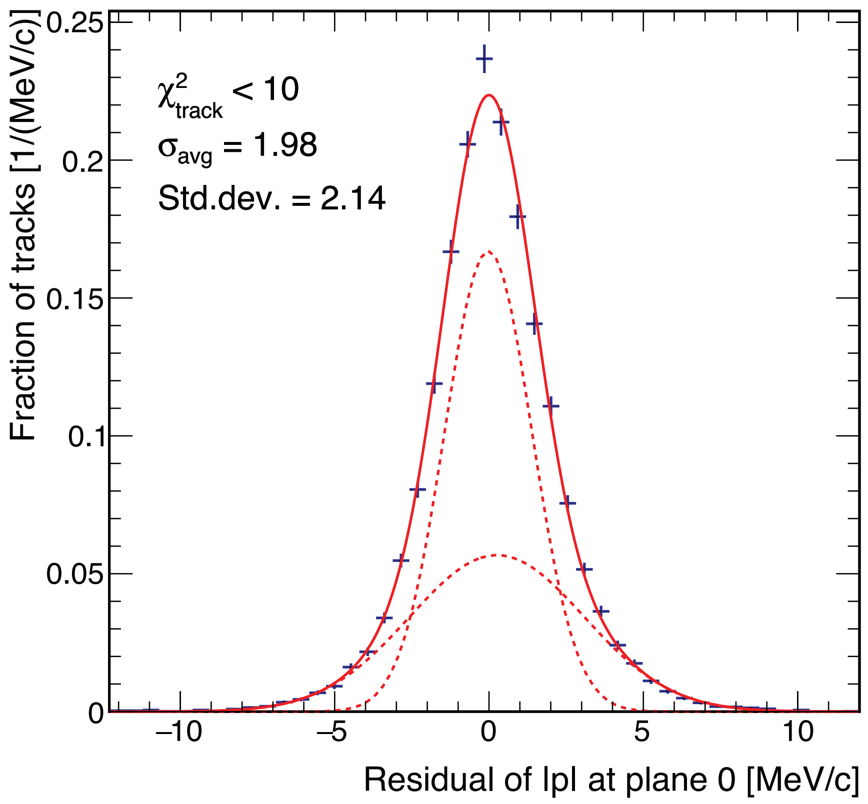


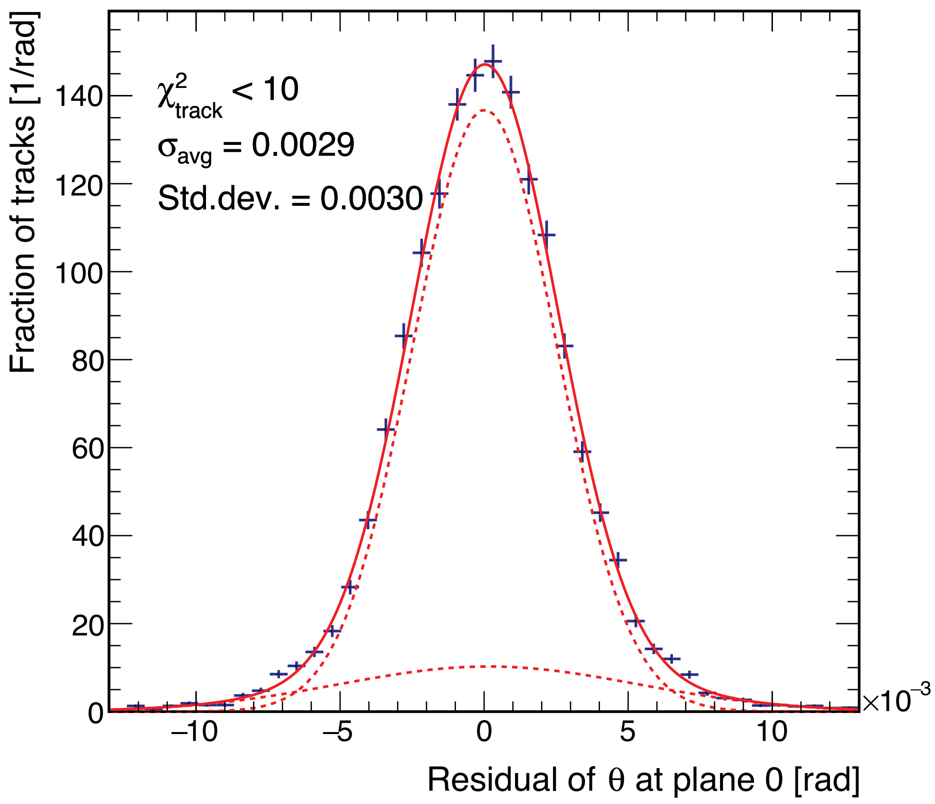
Tracking performance



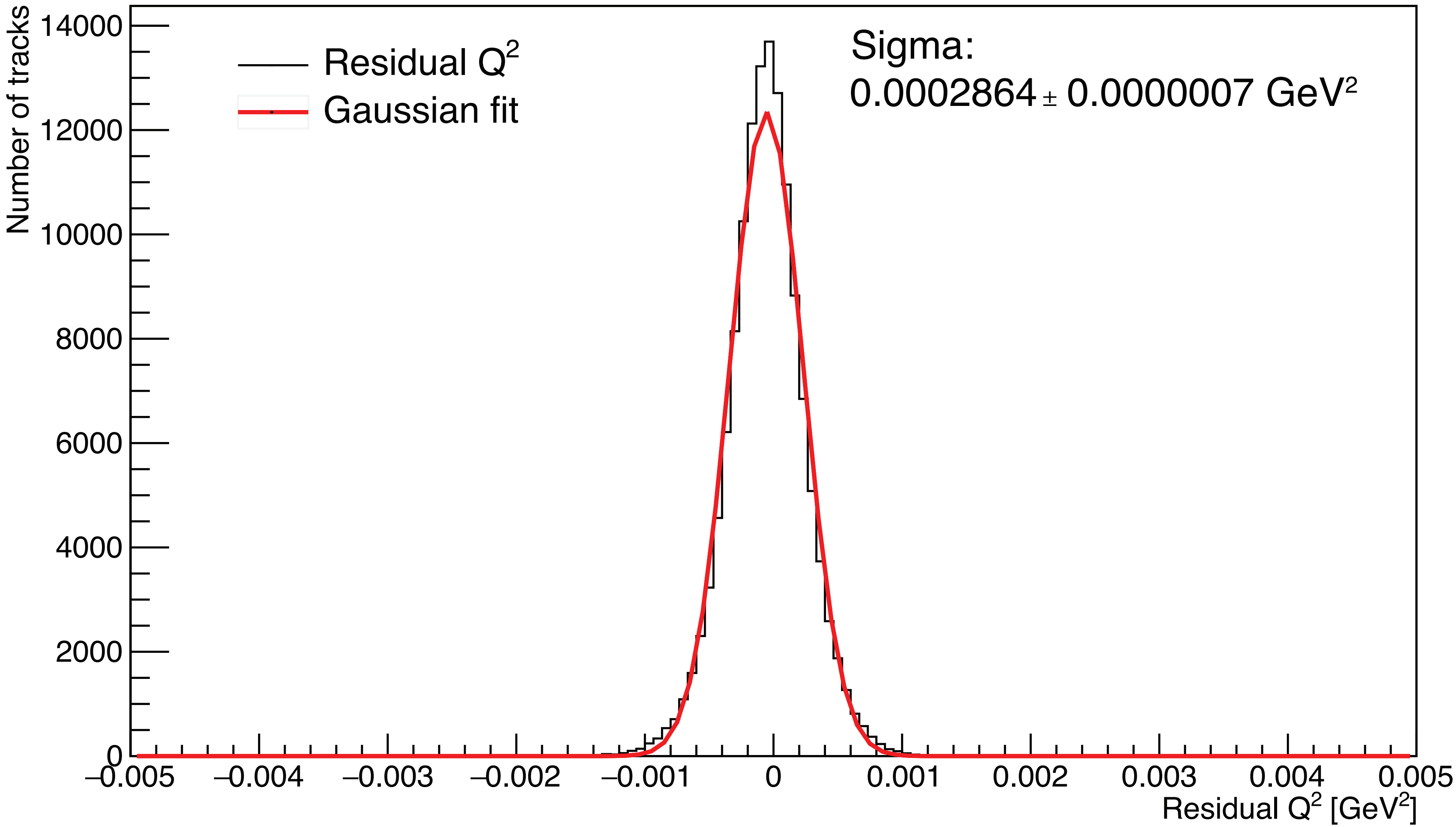


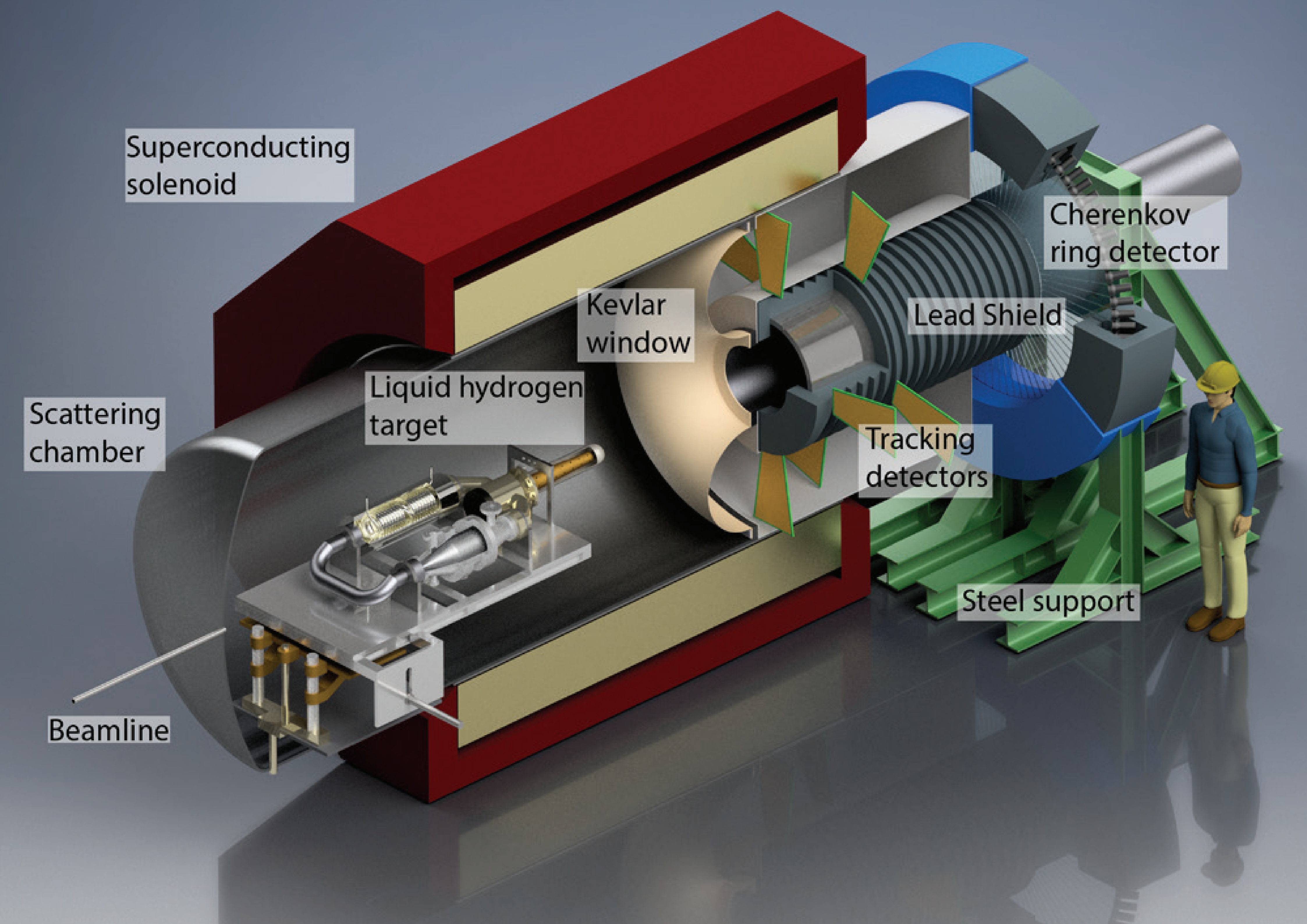
Tracking performance





Q^2 reconstruction




Superconducting solenoid
Scattering chamber
Liquid hydrogen target
Kevlar window
Cherenkov ring detector
Lead Shield
Tracking detectors
Steel support
Beamline

P2 Error budget

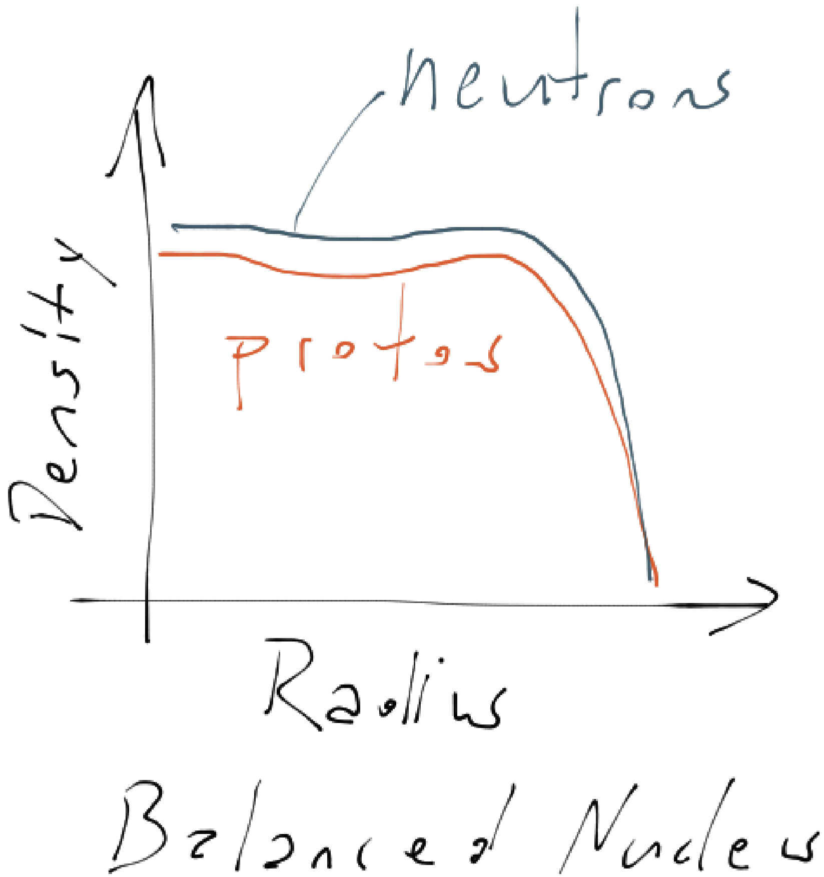
E_{beam}	155 MeV
$\bar{\theta}_{\text{f}}$	$35°$
$\delta\theta_{\text{f}}$	$20°$
$\langle Q^2\rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	$6\times10^{-3}\,(\text{GeV}/c)^2$
$\langle A^{\text{exp}}\rangle$	-39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	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 %)

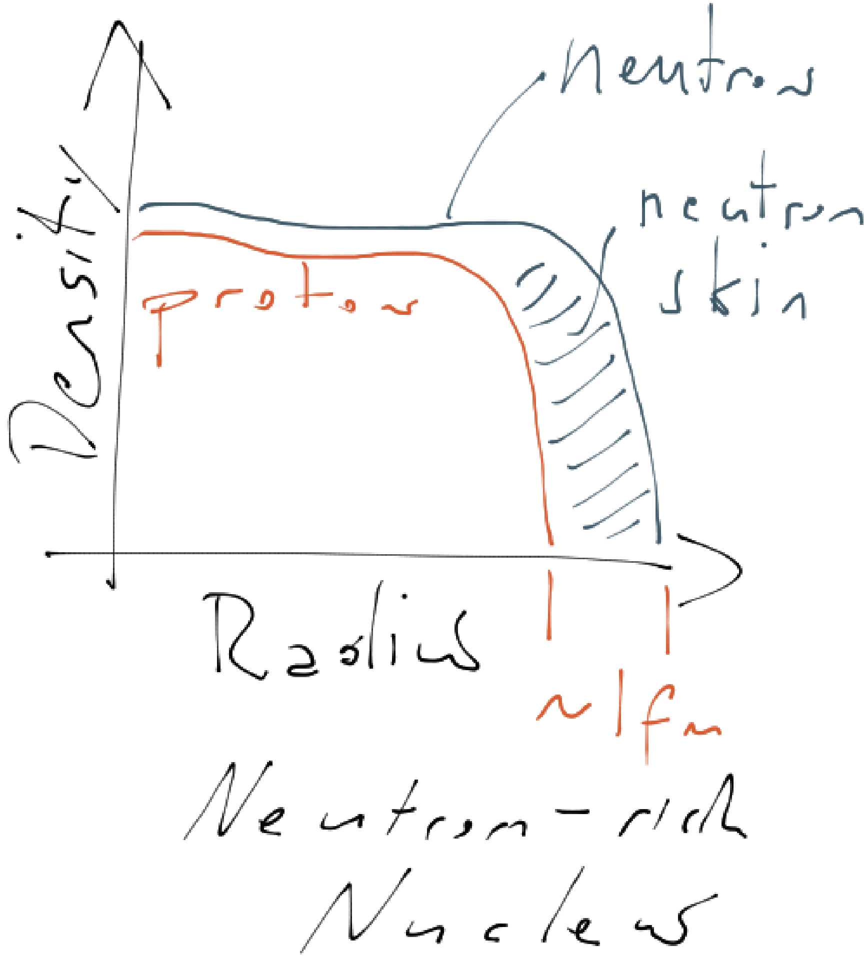
$\langle s^2_{\text{W}}\rangle$	0.231 16
$(\Delta s^2_{\text{W}})_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2\rangle_{\text{Cherenkov}}$	$4.57\times10^{-3}\,(\text{GeV}/c)^2$
$\langle A^{\text{exp}}\rangle_{\text{Cherenkov}}$	-28.77 ppb

Can we do more?

Neutron Skins

Where are the neutrons in the nucleus?

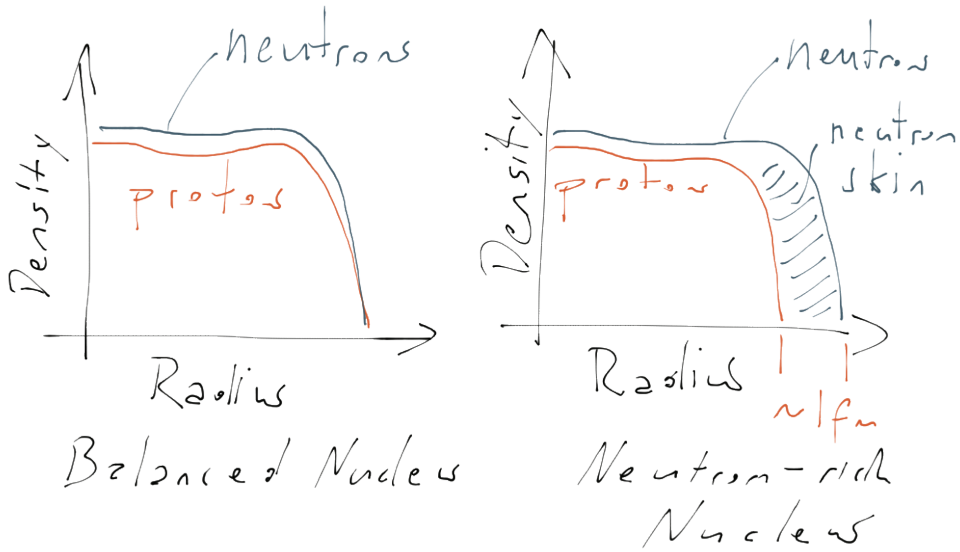


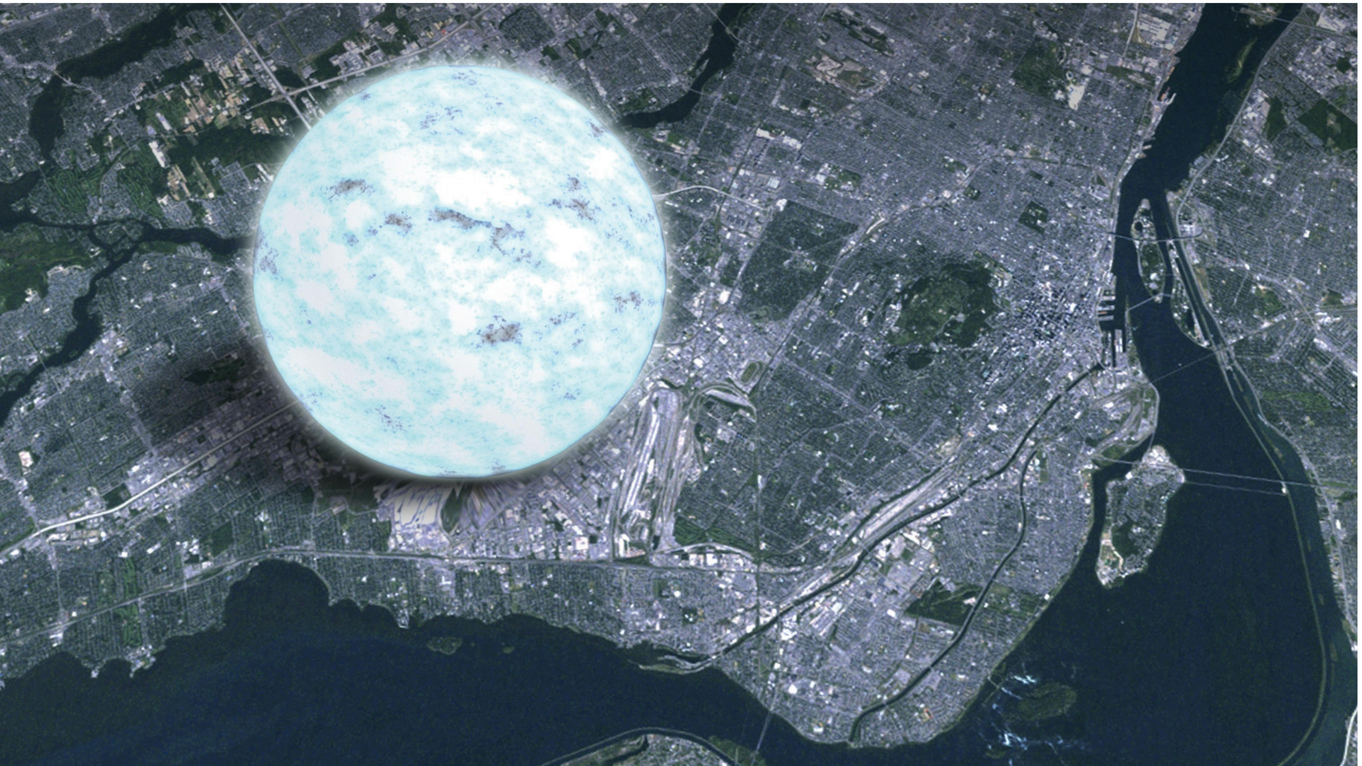


Neutron Skins

Where are the neutrons in the nucleus?

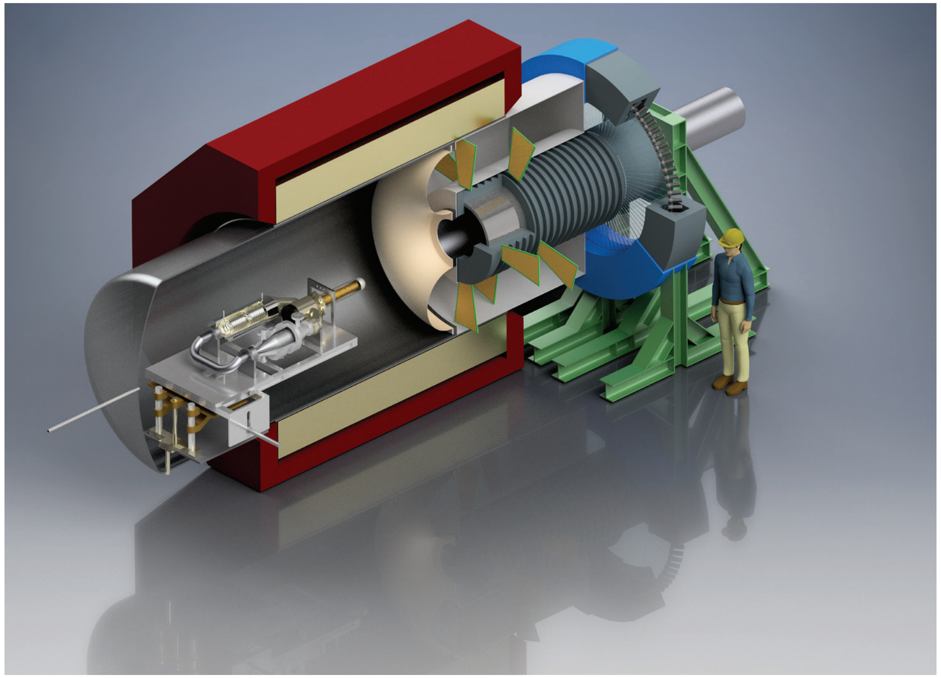
- Gives access to the equation of state of neutron matter
- Tells us how big/small neutron stars are





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



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

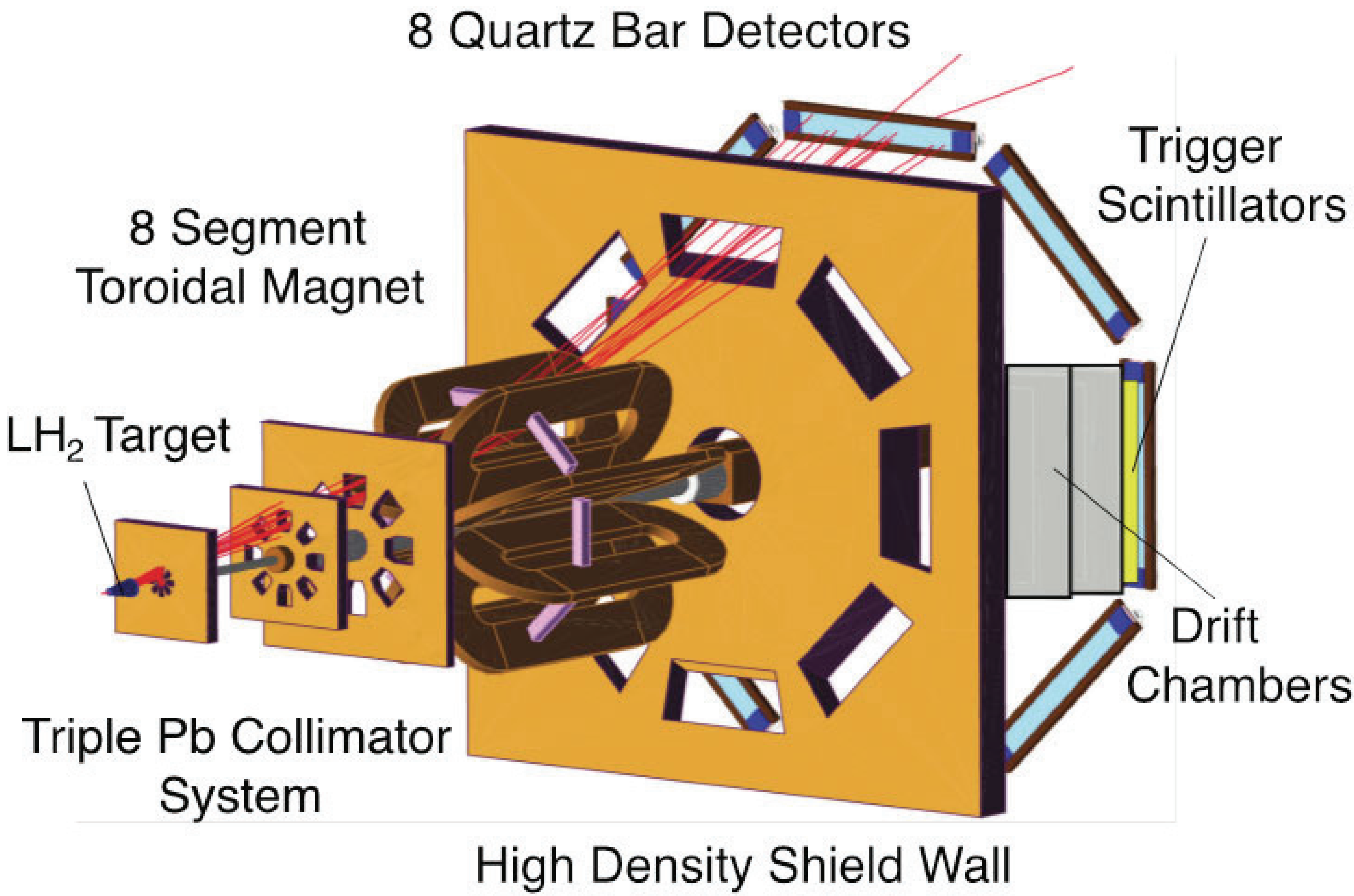
Summary

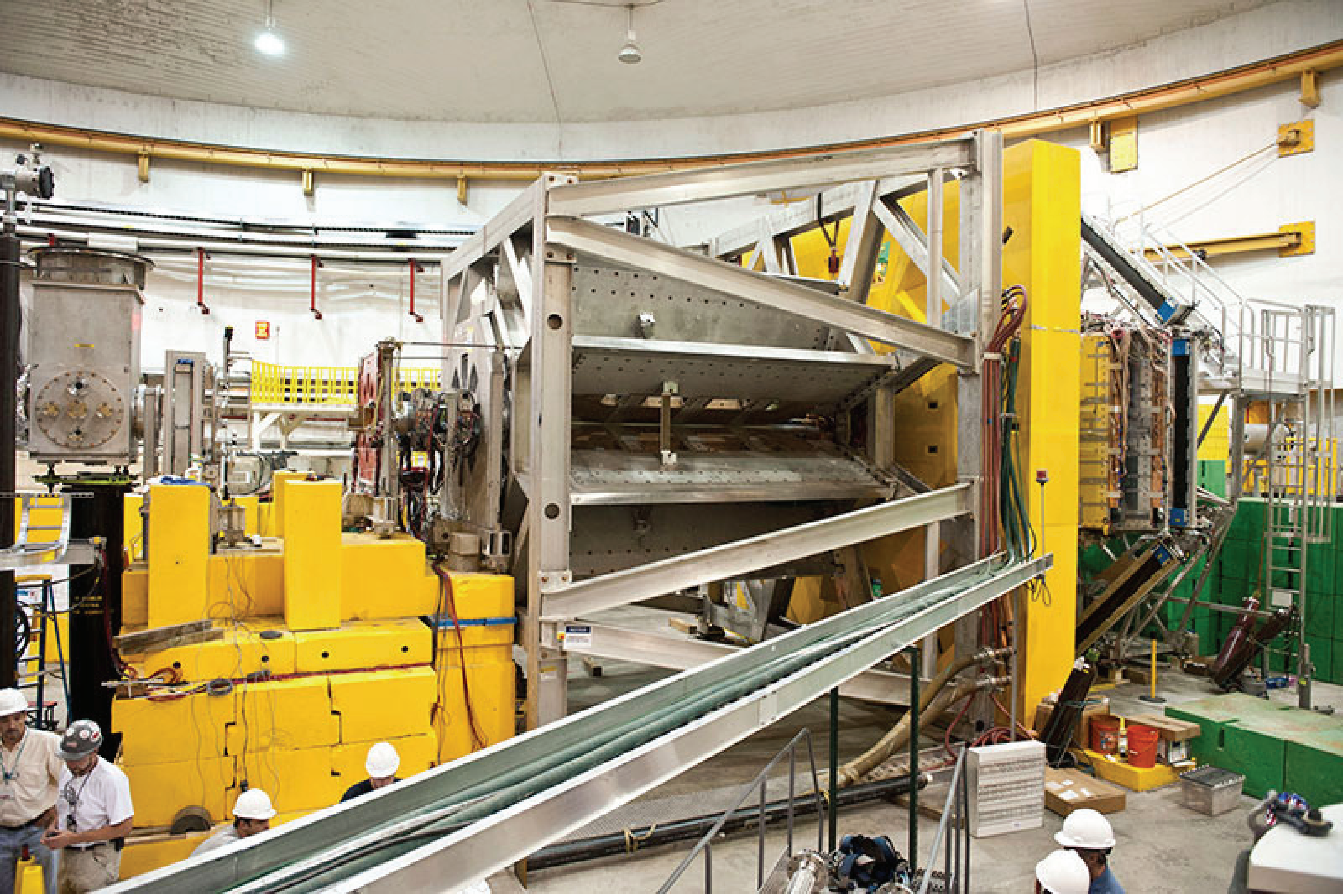
- The weak mixing angle is a fundamental parameter of the Standard Model and a good place to search for new physics
- We are building the new electron accelerator MESA in Mainz
- The P2 experiment at MESA will measure the weak mixing angle at low Q to 0.14%
- Can also study form factors and neutron skins

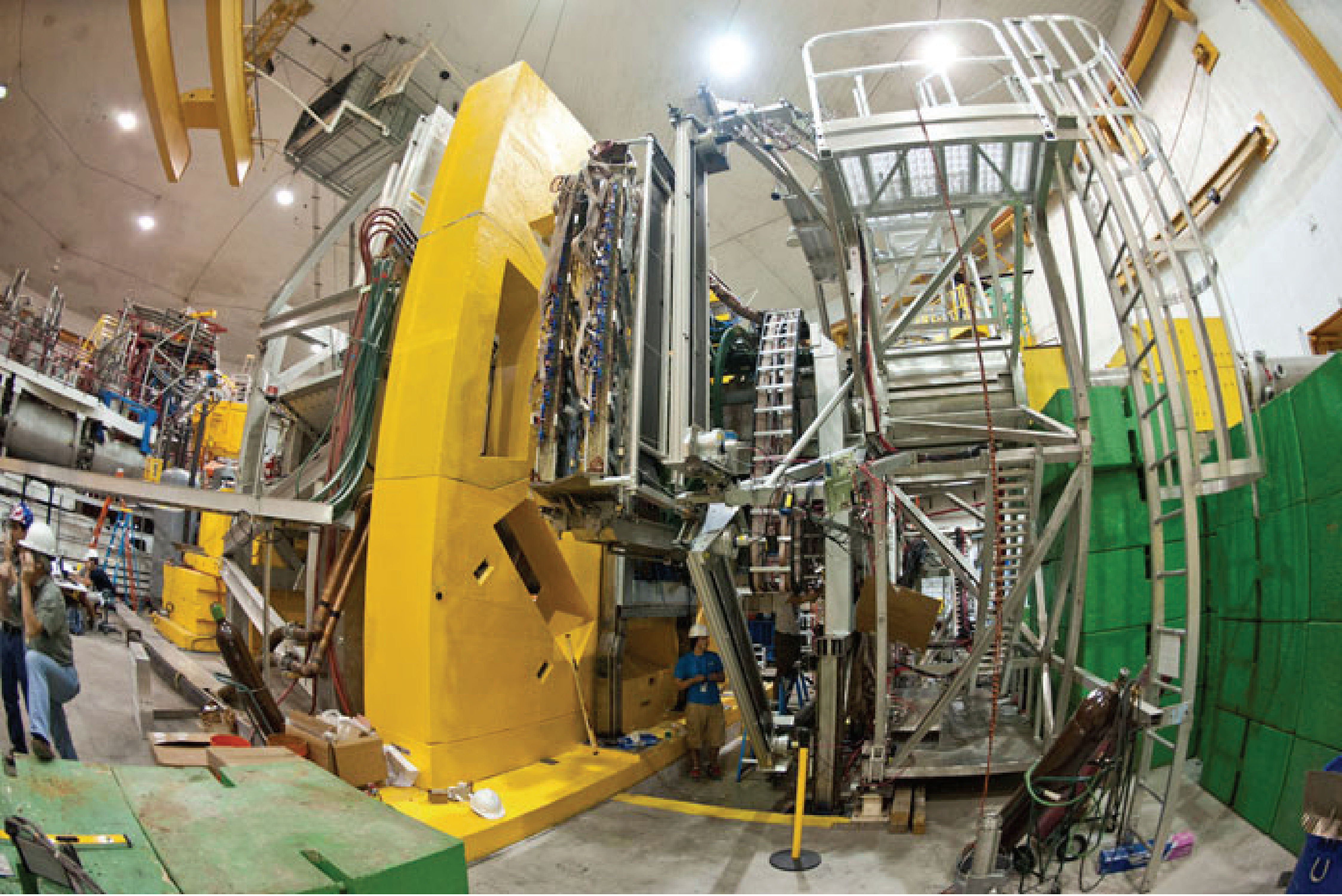
Backup

Other parity violation experiments

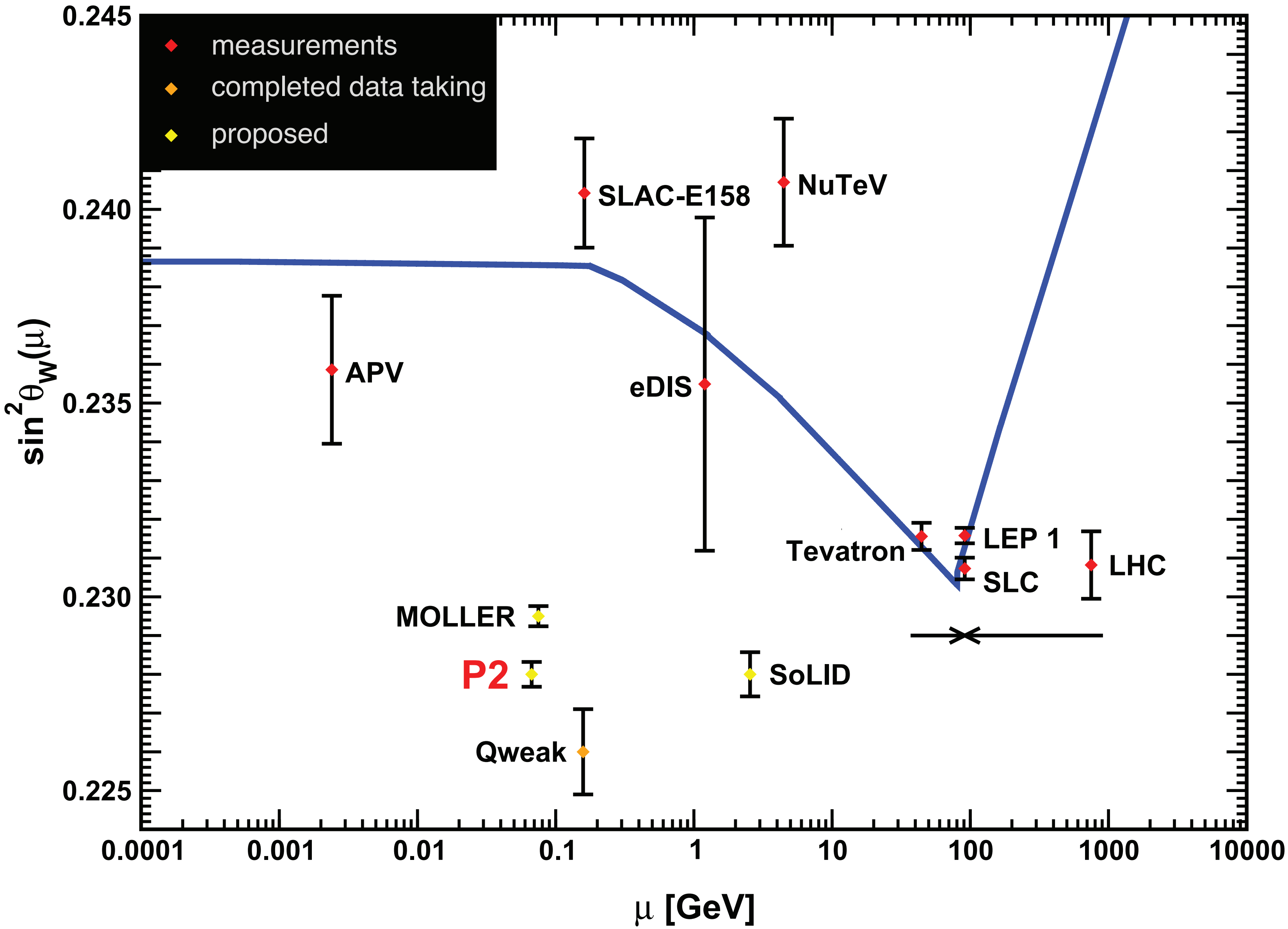
QWeak (JLab)


8 Quartz Bar Detectors
Trigger Scintillators
8 Segment Toroidal Magnet
LH$_2$ Target
Drift Chambers
Triple Pb Collimator System
High Density Shield Wall

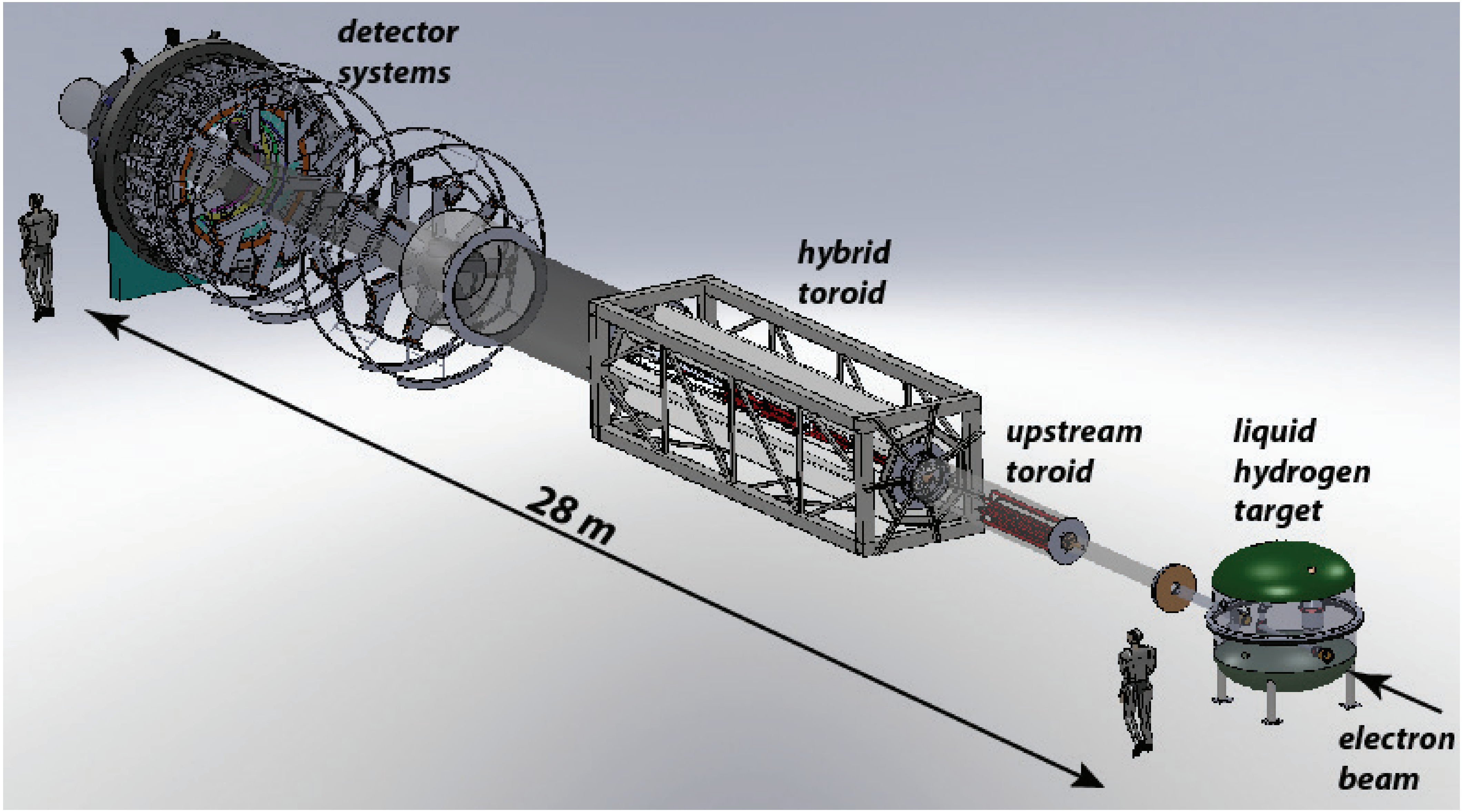




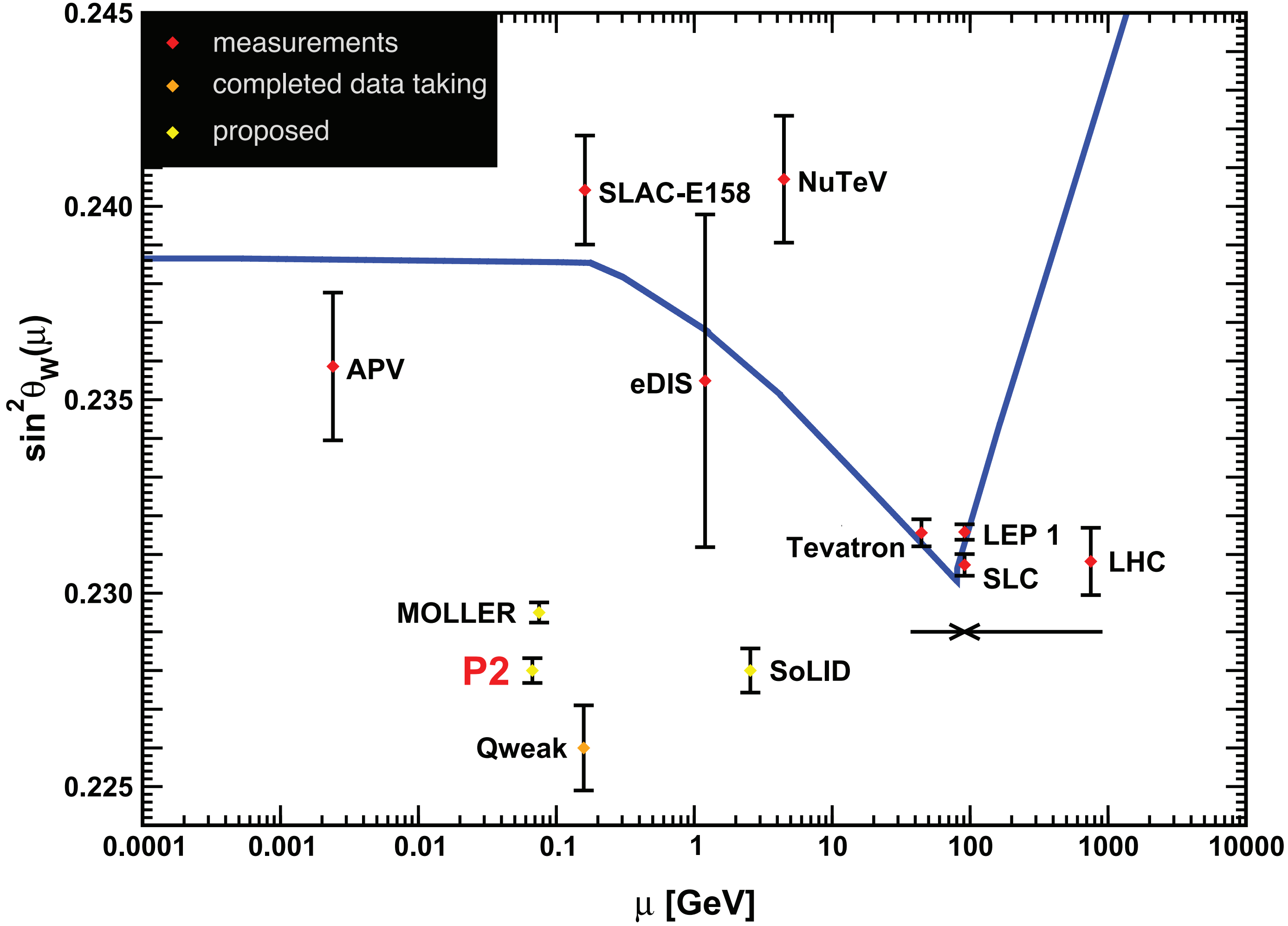
QWeak results (not)



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