Searching for New Physics at the intensity frontier

(at low energies with lots of particles)
Part II

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JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

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"

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

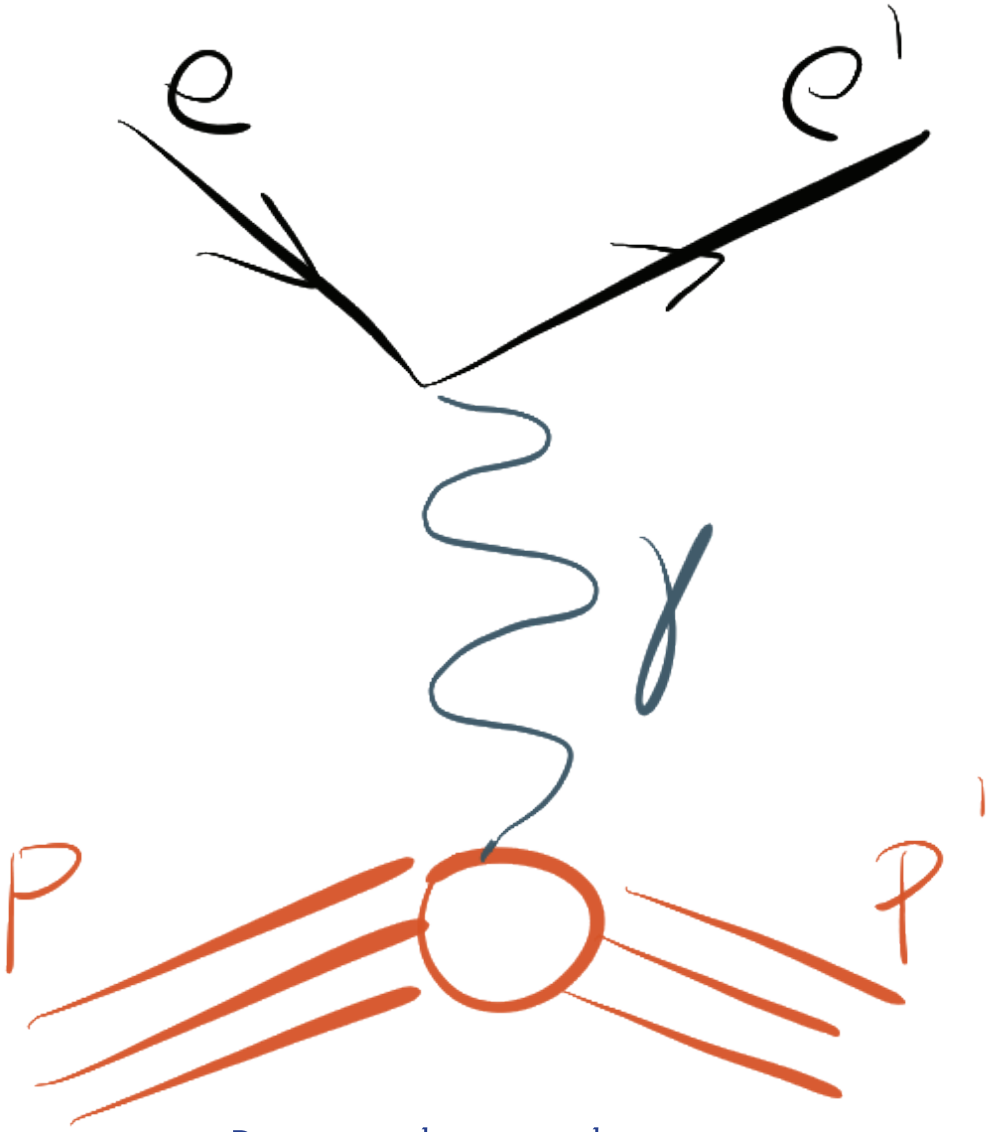
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

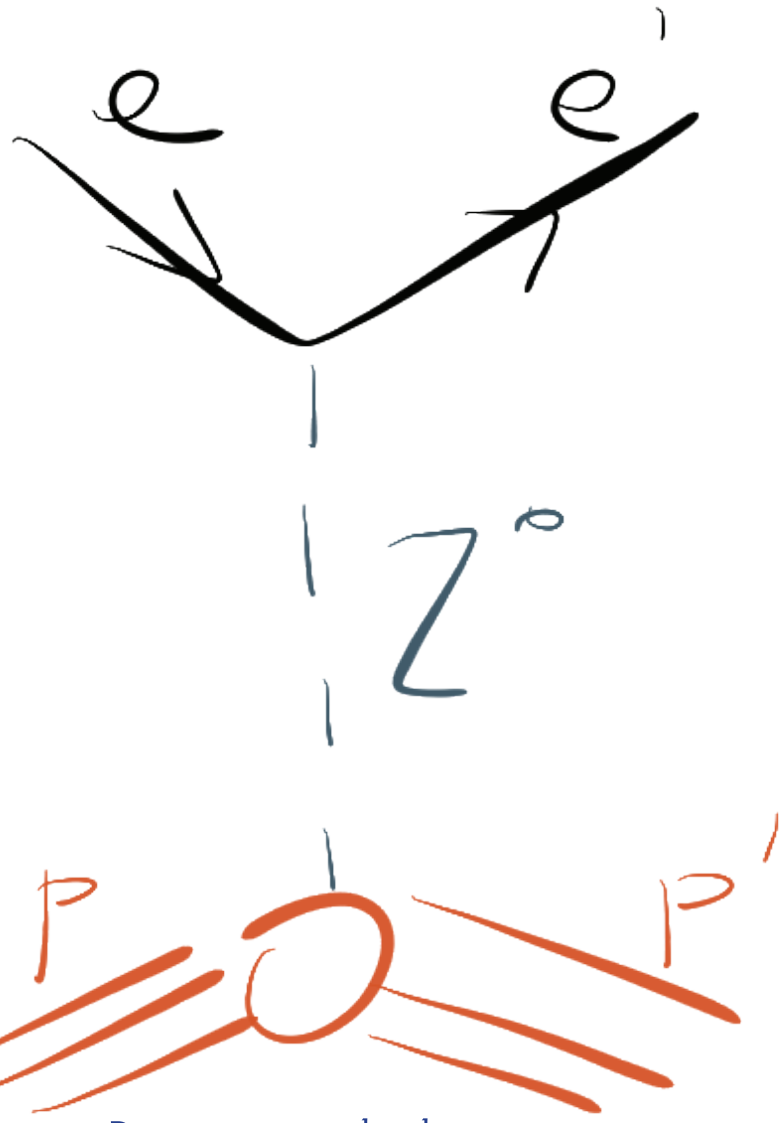
$$\sin^2\theta_W(q^2)$$

Weak mixing angle and charges



Proton electric charge

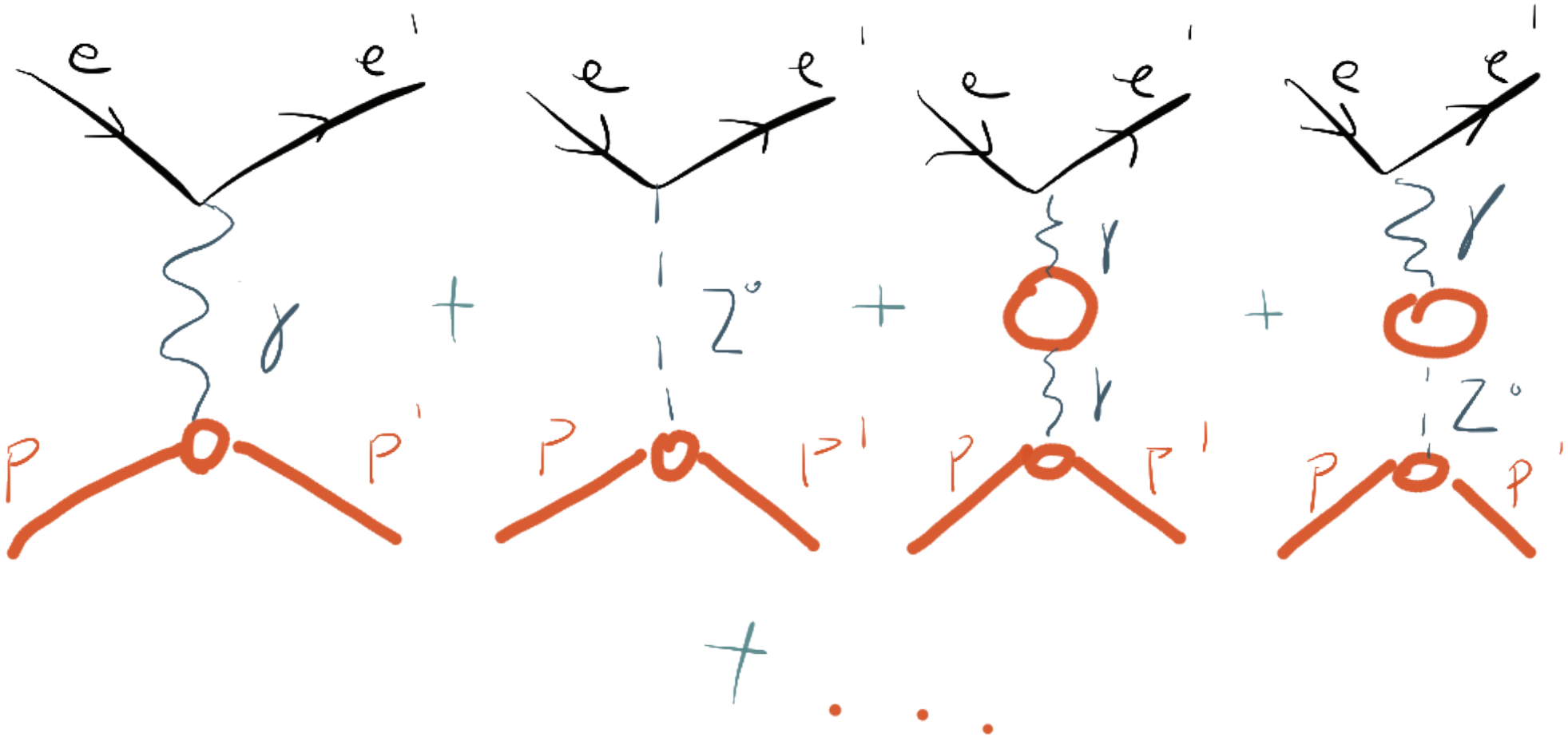
+e



Proton weak charge

$1 - 4 \sin^2\theta_W$

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



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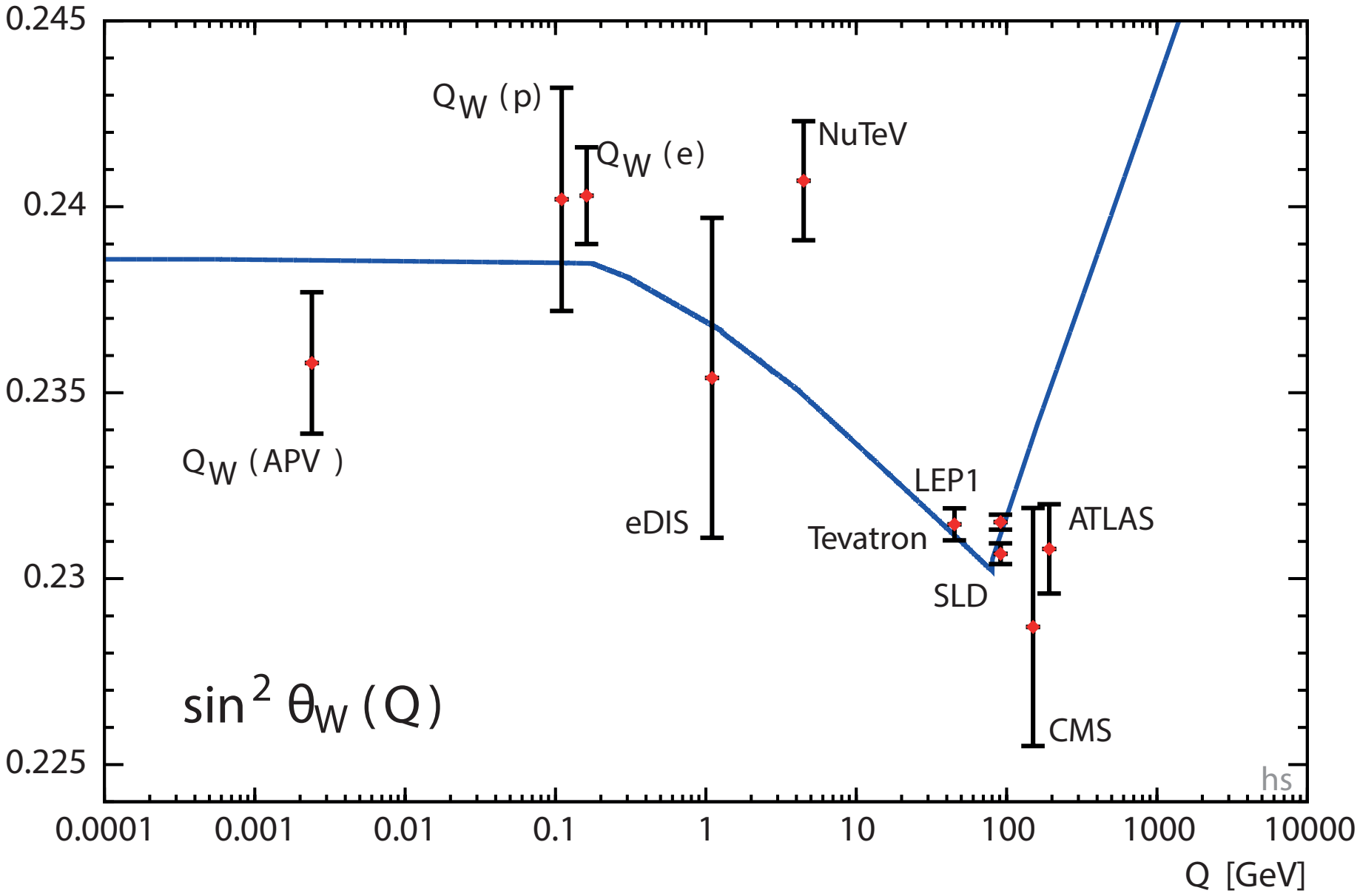

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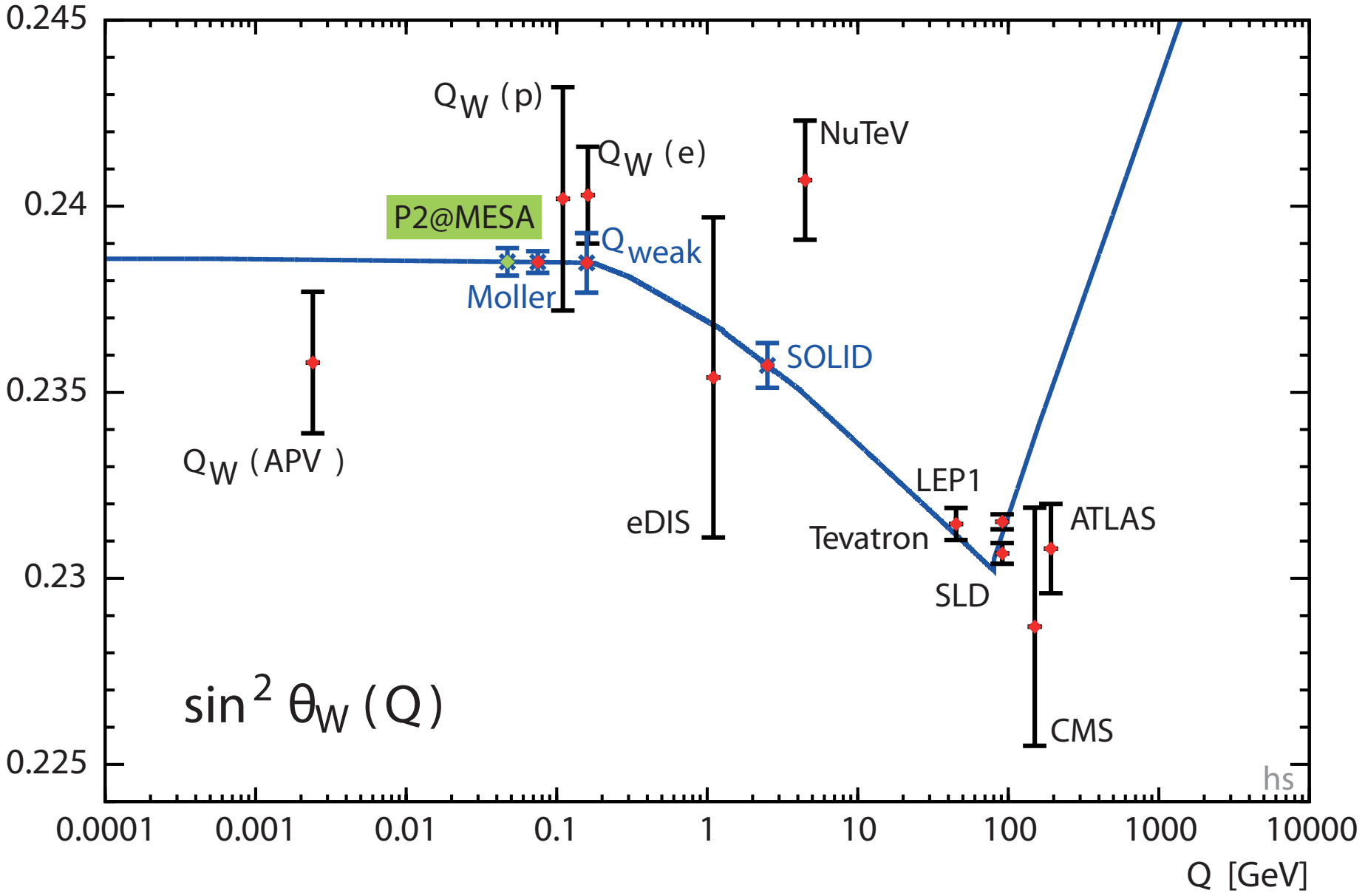
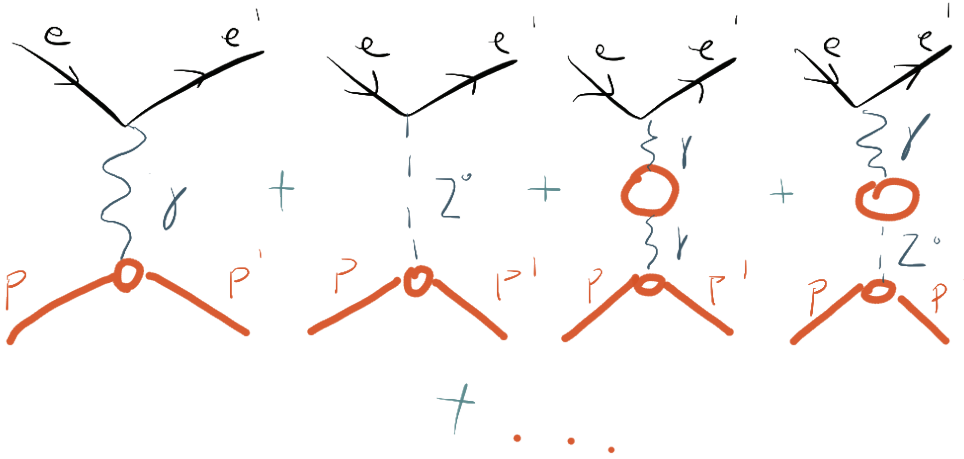
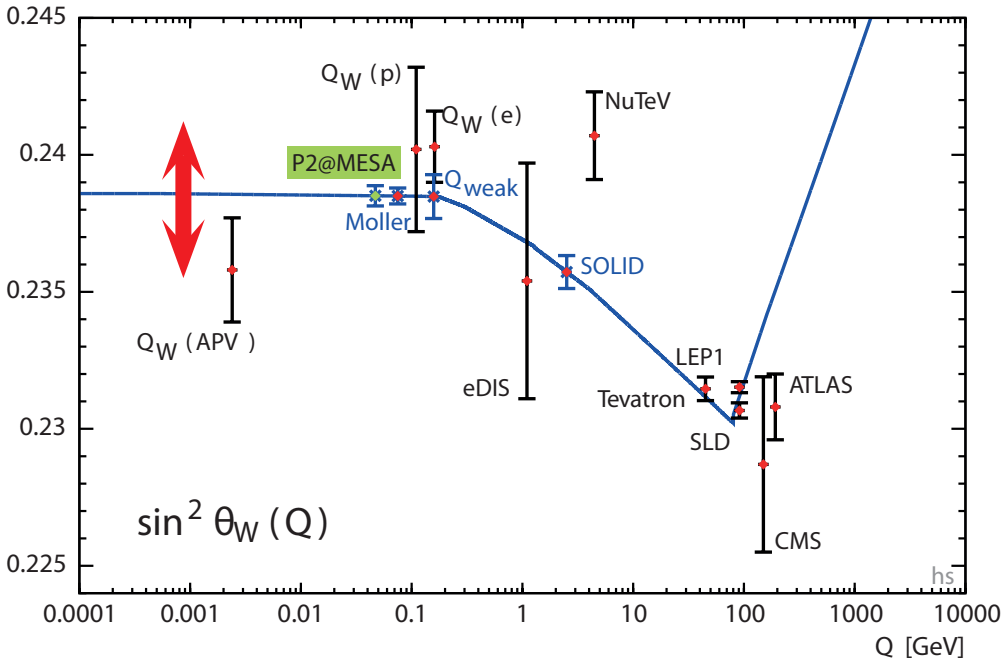
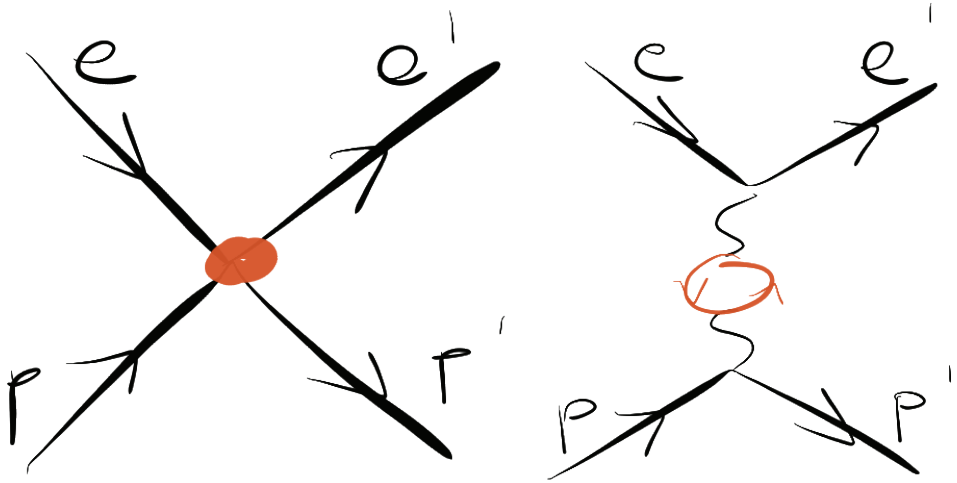
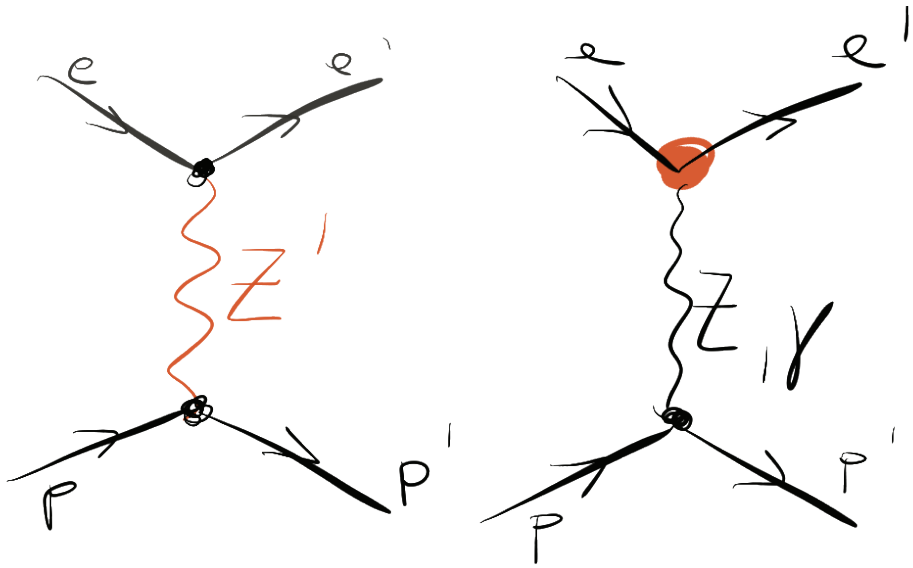


New Physics in the running

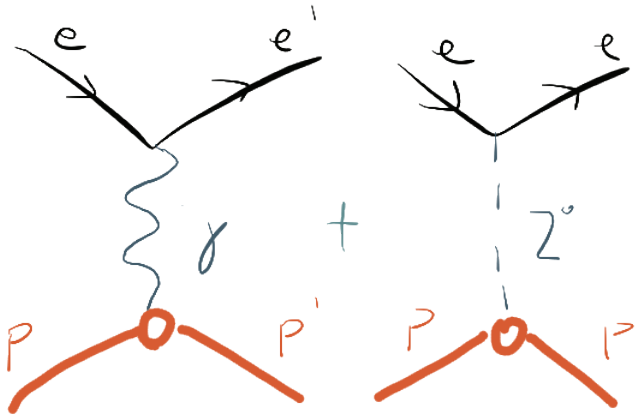


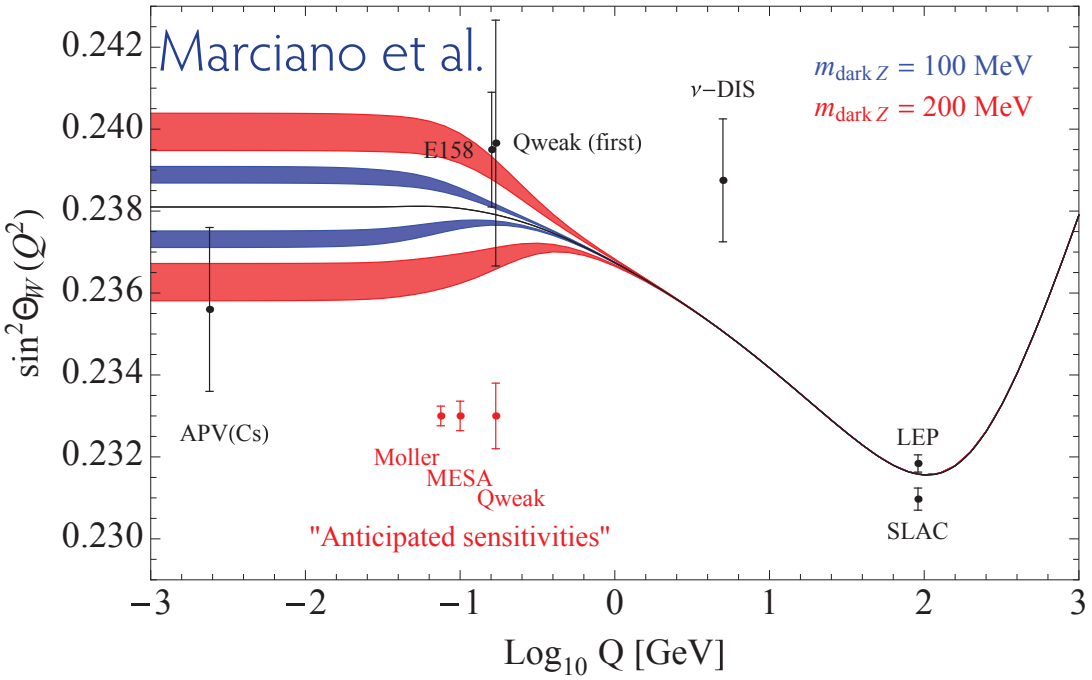


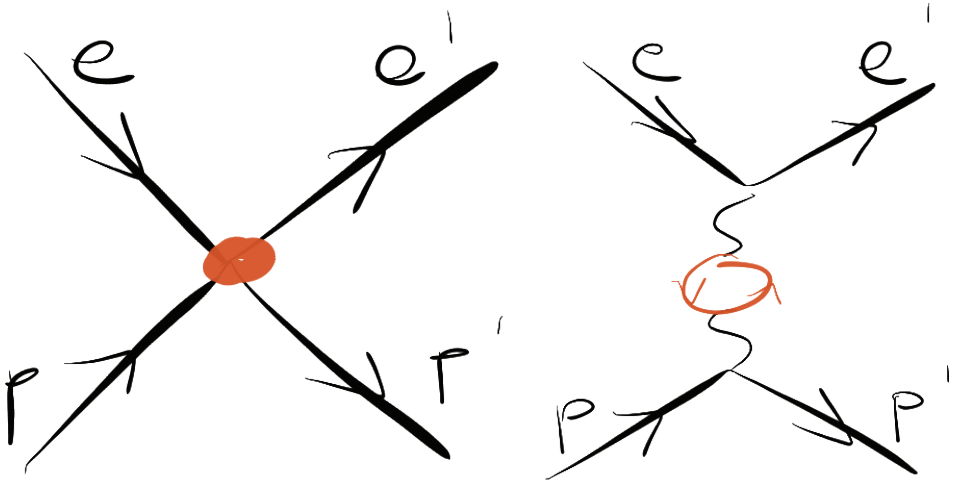


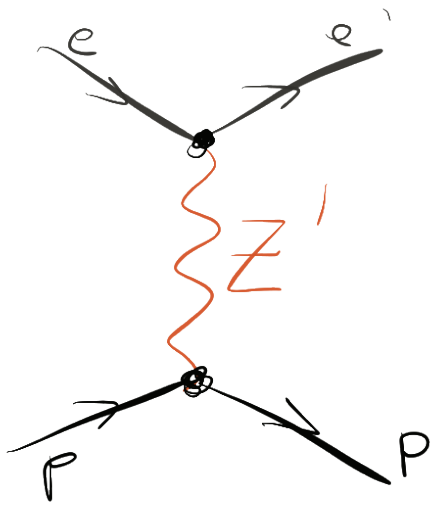


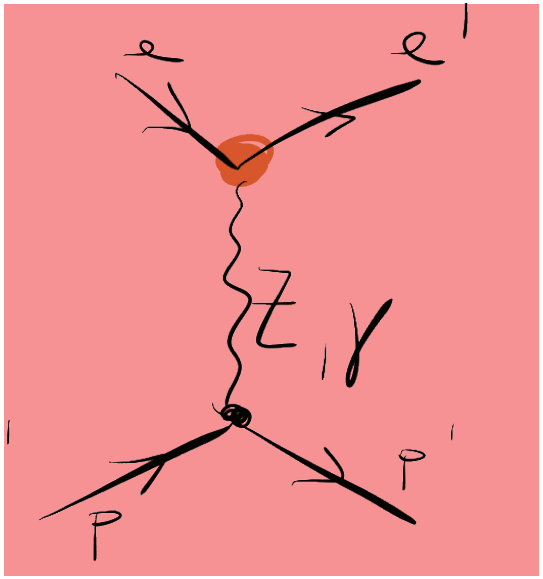
Dark Z in mixing



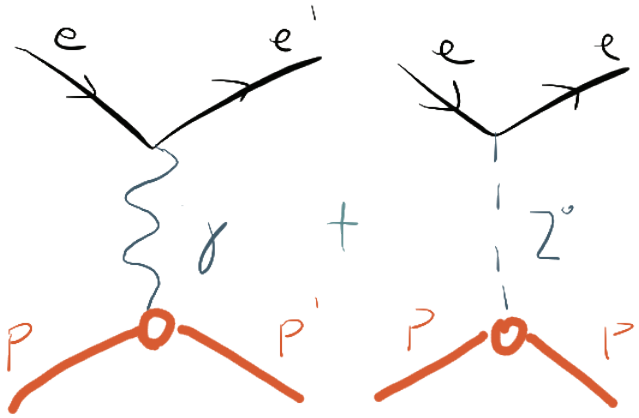








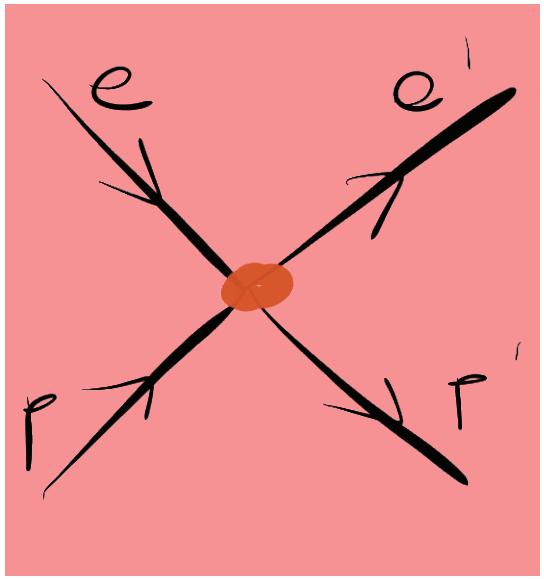
Contact Interactions

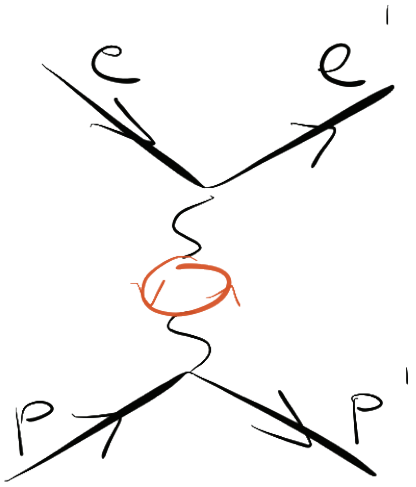


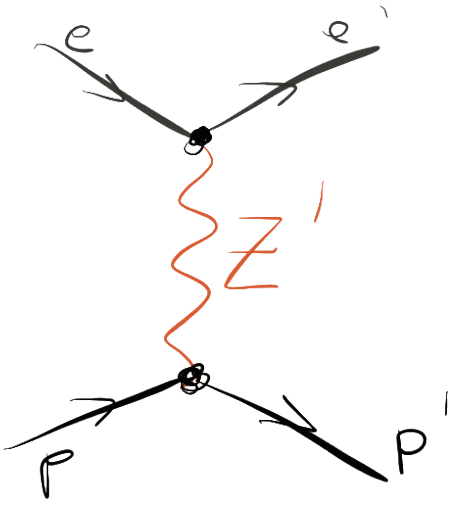
Contact interactions up to

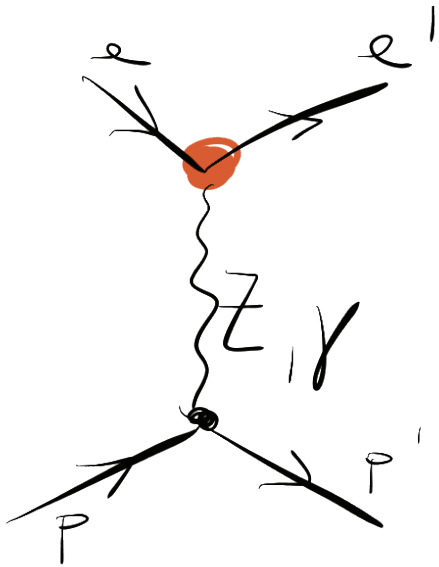
49 TeV

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



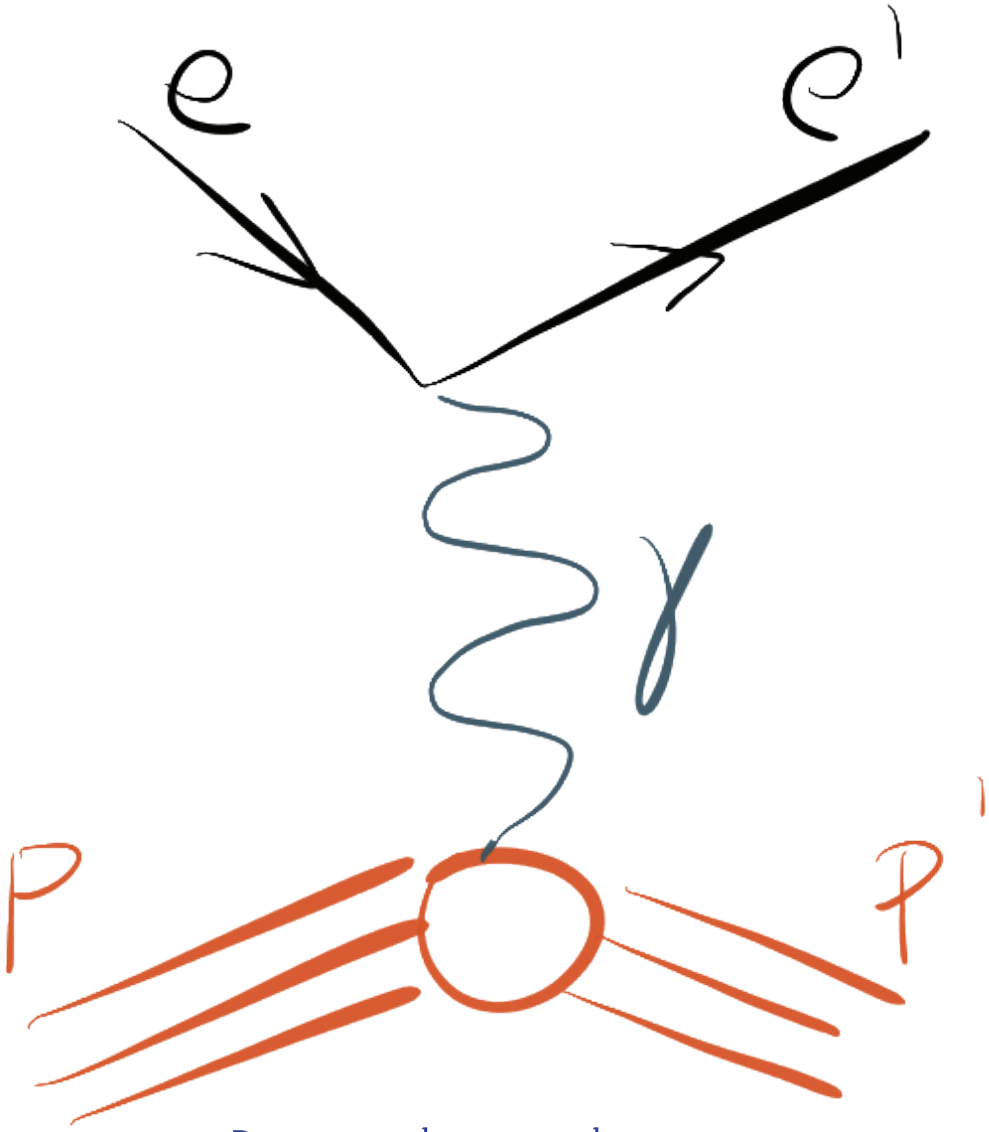






How to measure the weak charge?

Weak mixing angle and charges



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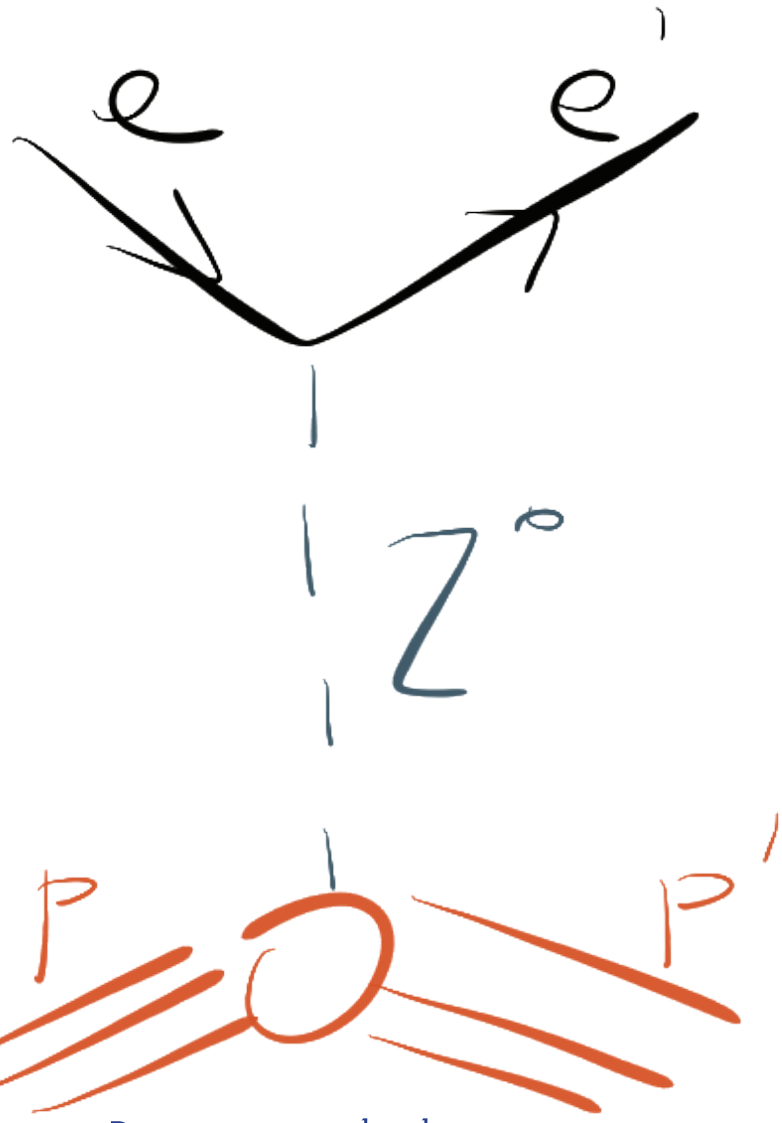

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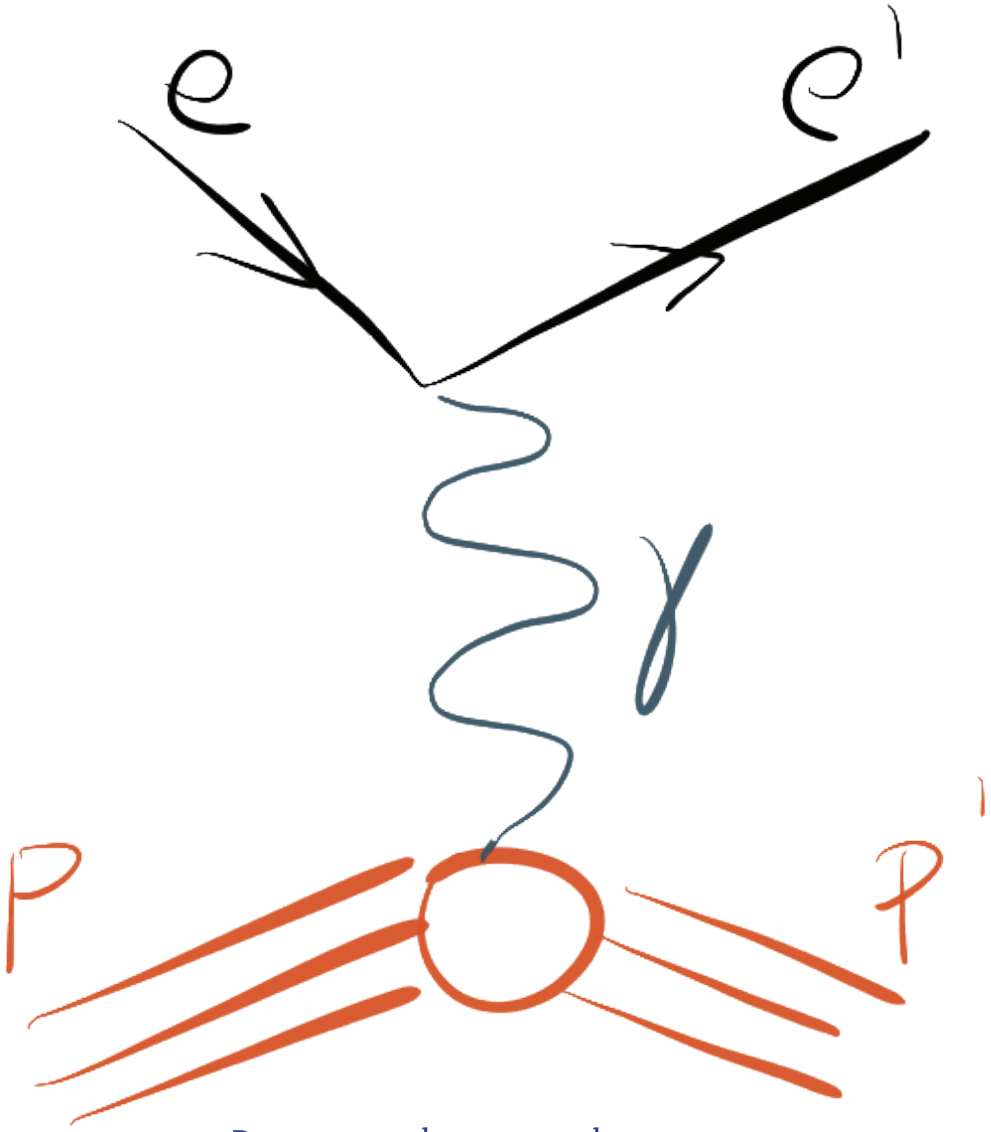


Proton electric charge

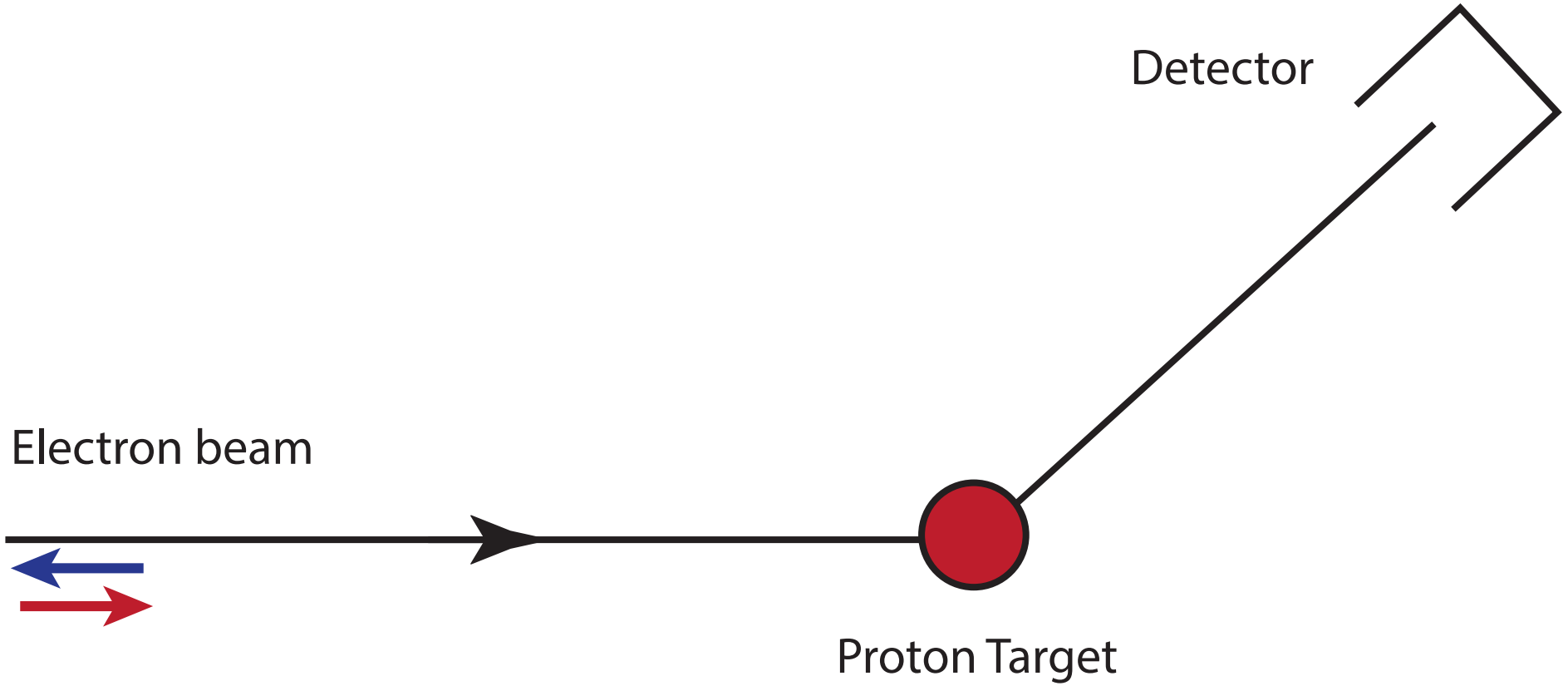
+e

Violates parity!

Proton weak charge

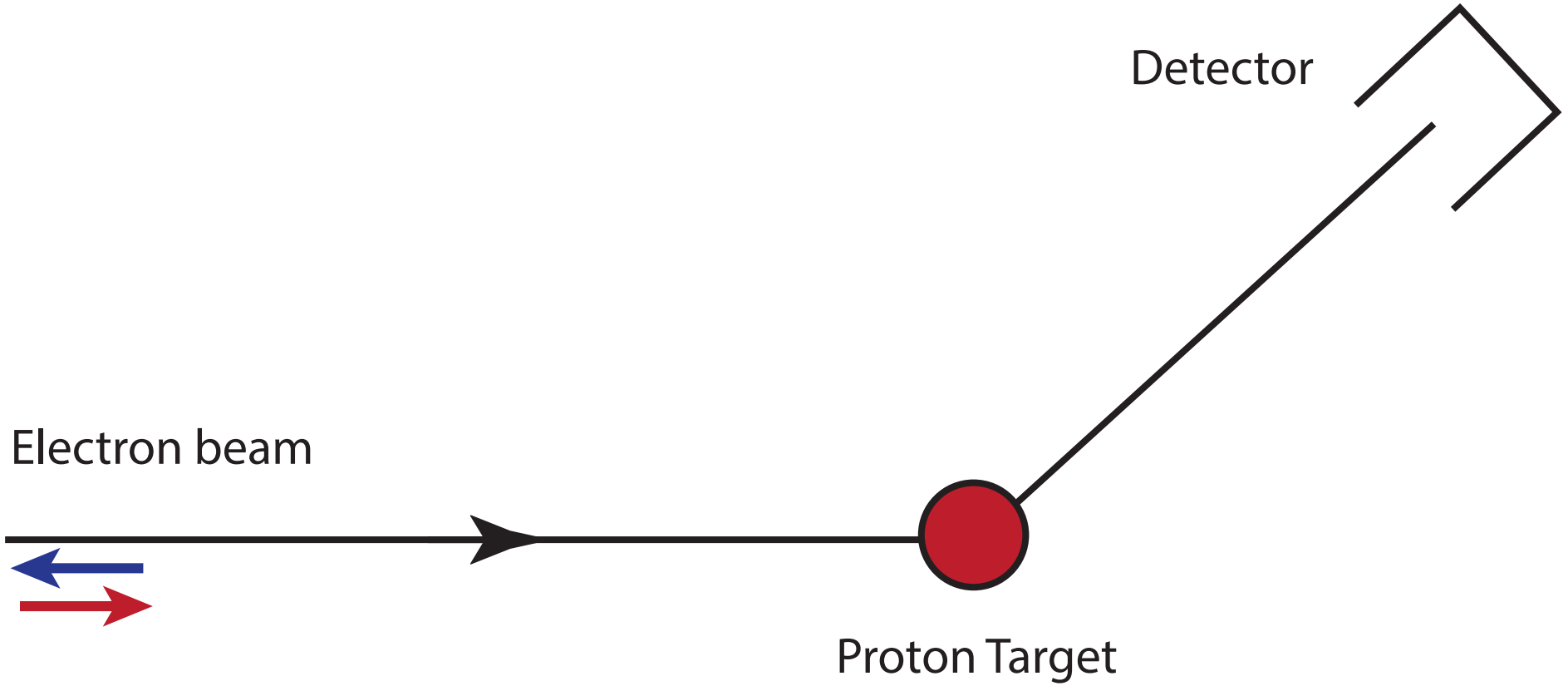
$1 - 4 \sin^2\theta_W$

Parity violating electron scattering



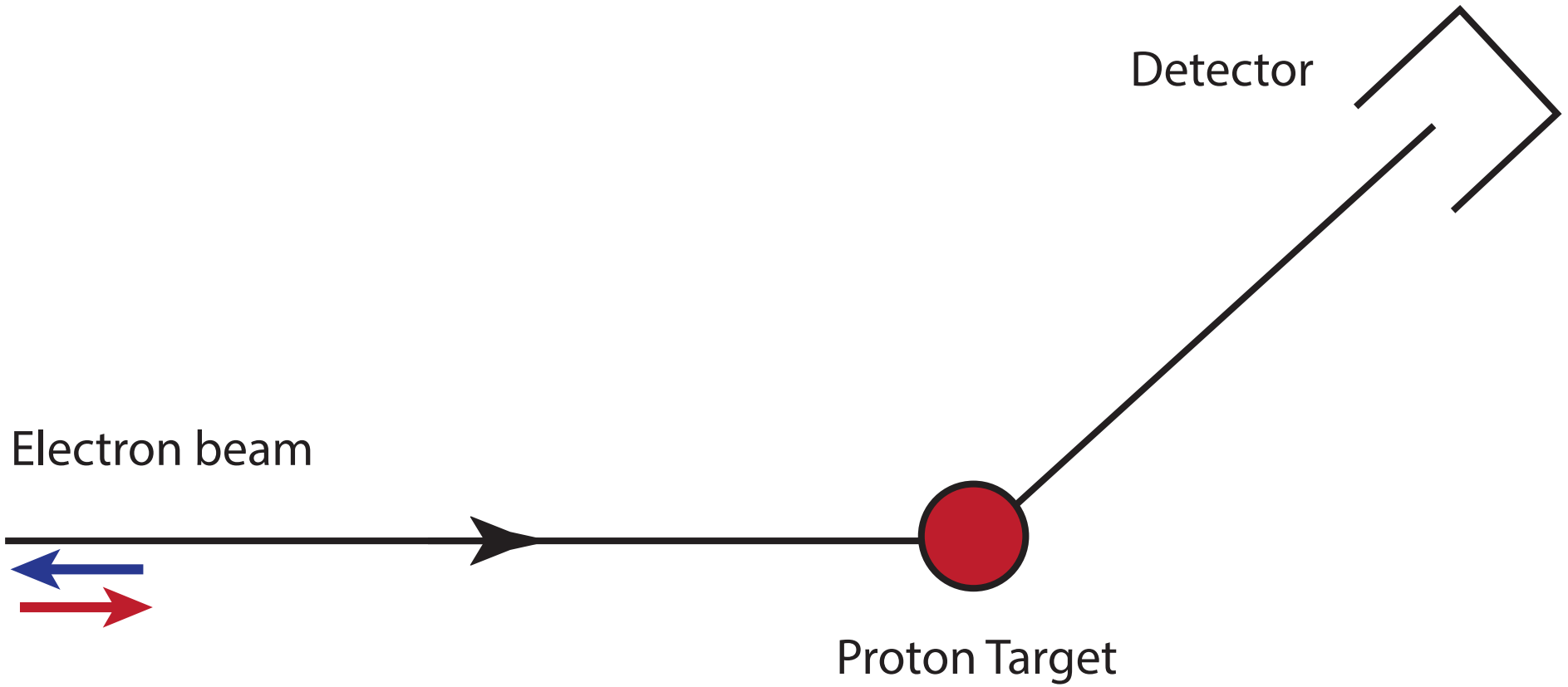
Parity violating electron scattering

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



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

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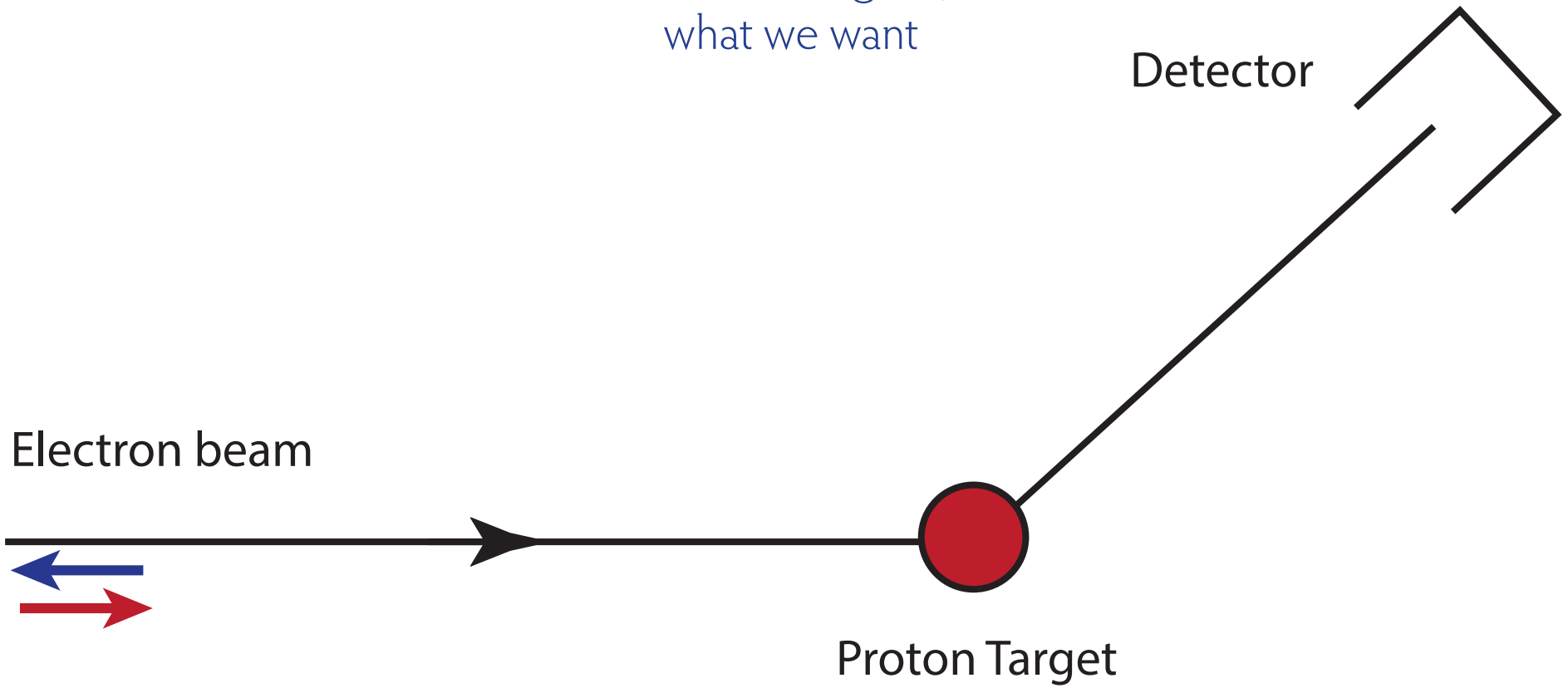
Weak charge - what we want



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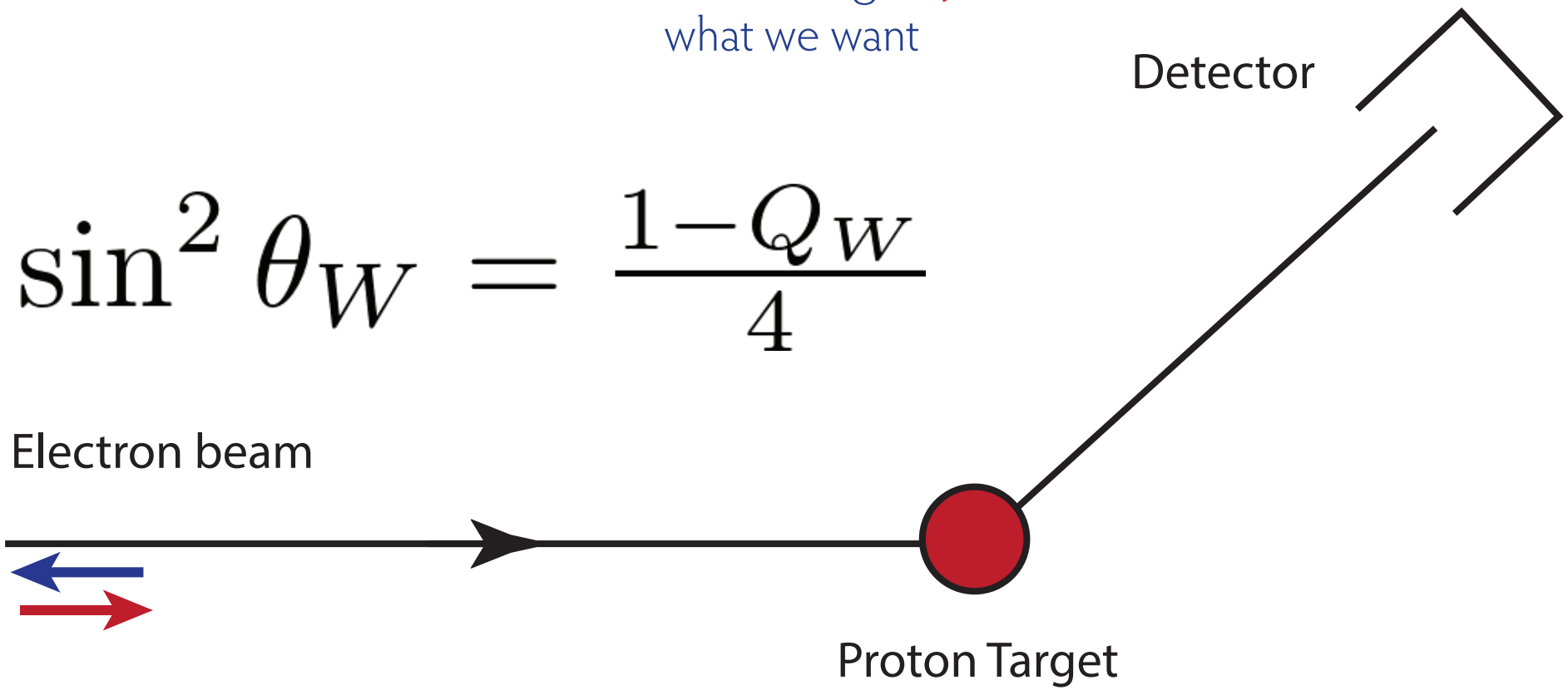
Weak charge - what we want

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



Why is this difficult?

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

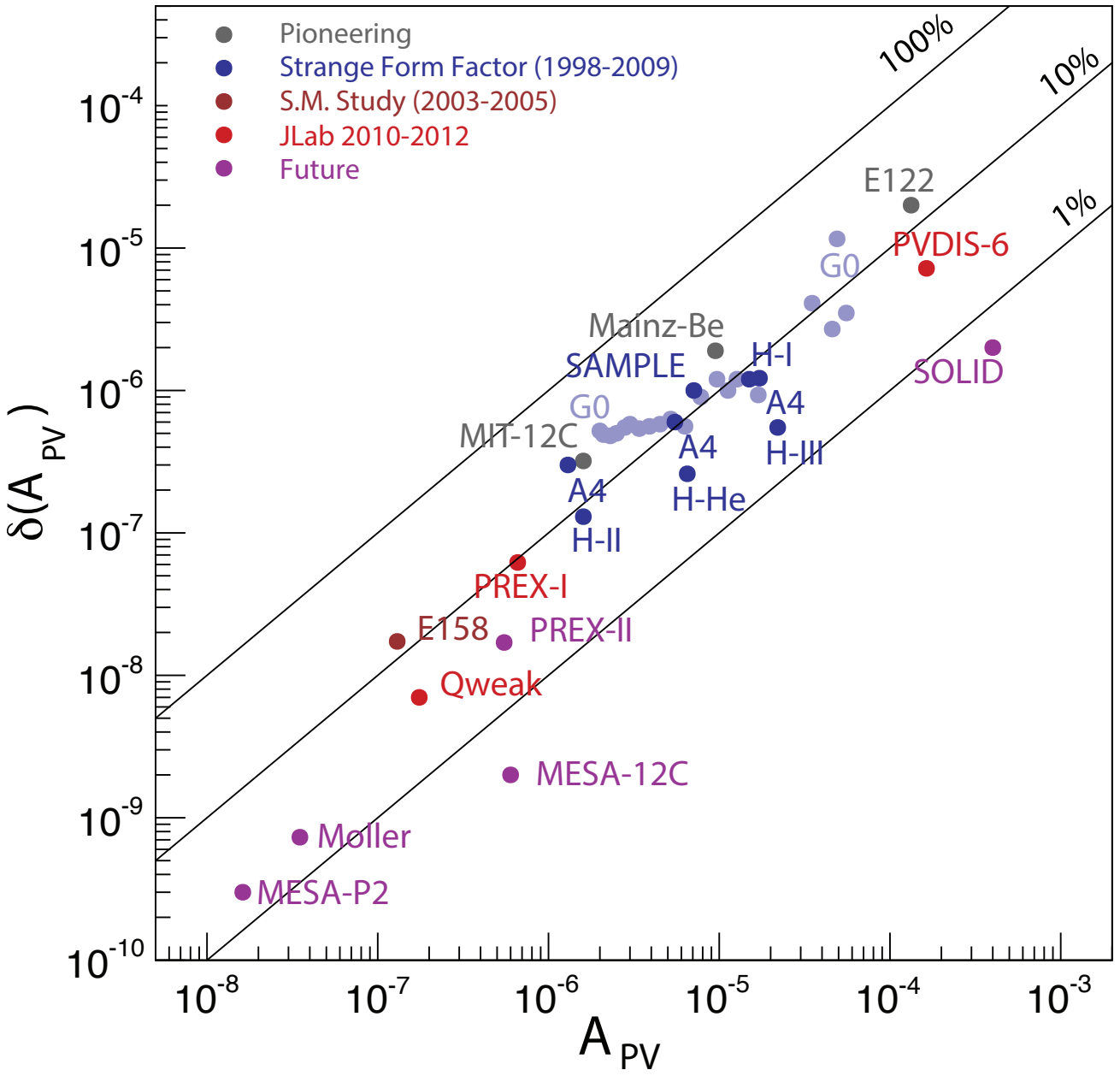
$$Q_W = 1 - 4\sin^2\theta_W$$

- 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 few 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}
- A_{PV} is 40 parts per billion
- $\delta(A_{PV})$ is 0.6 parts per billion

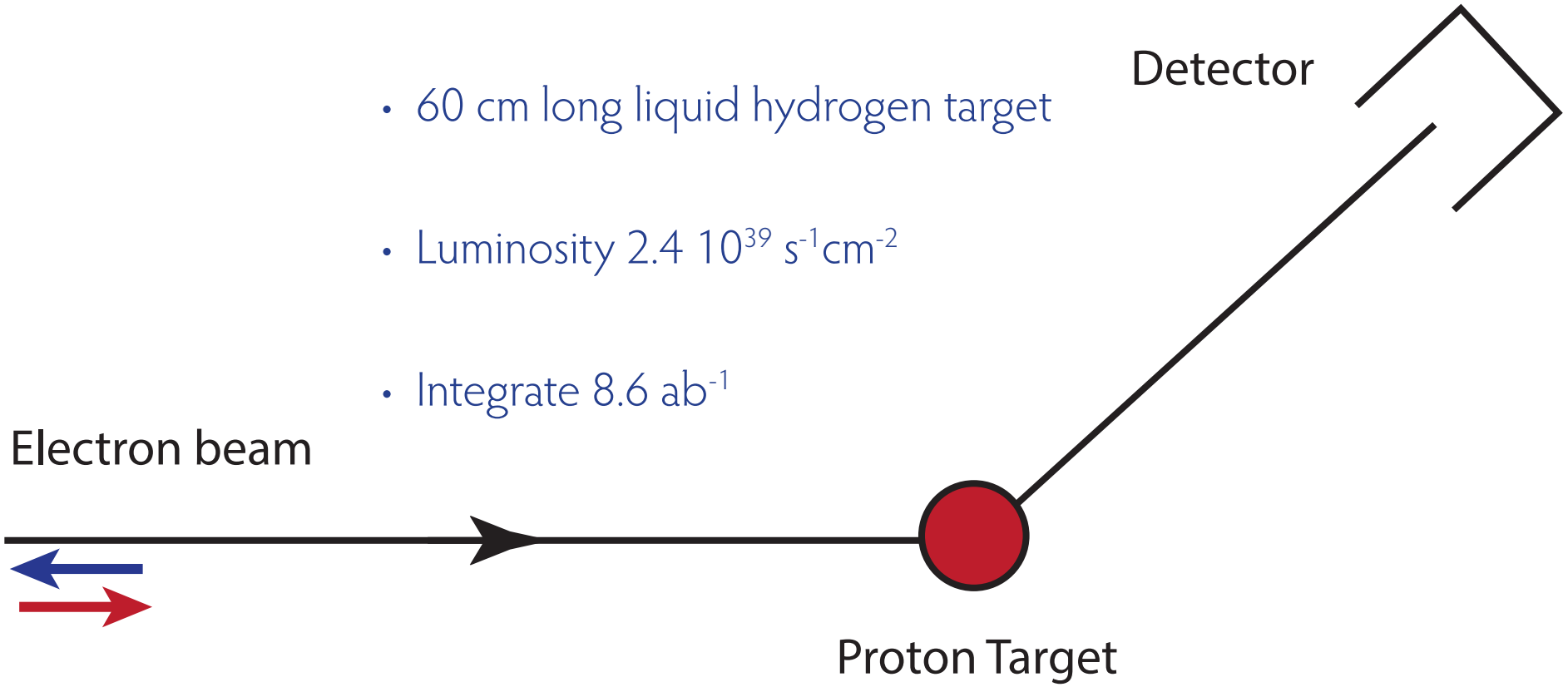
$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

- 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

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...

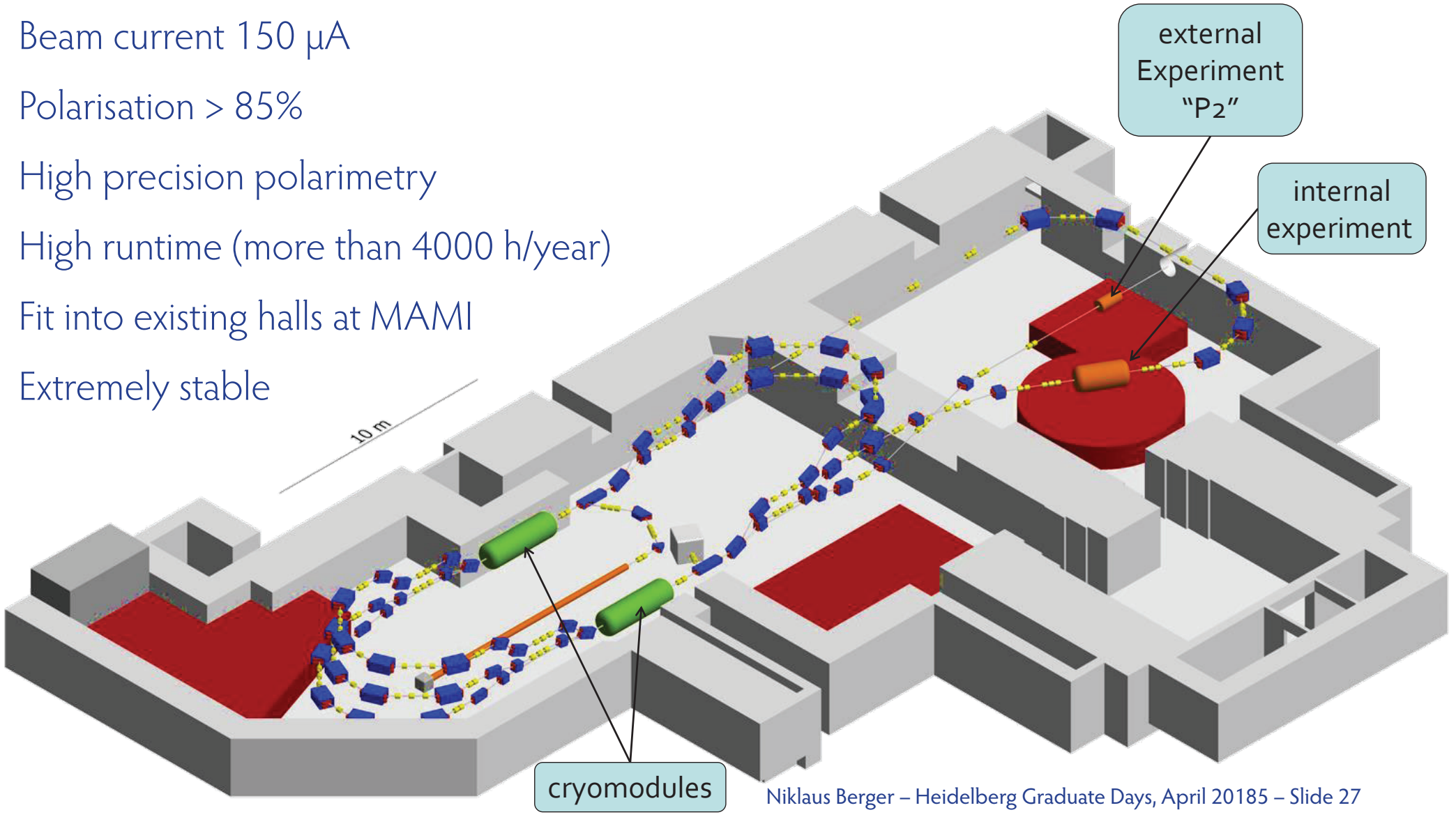
If you cannot rent it, build it:

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

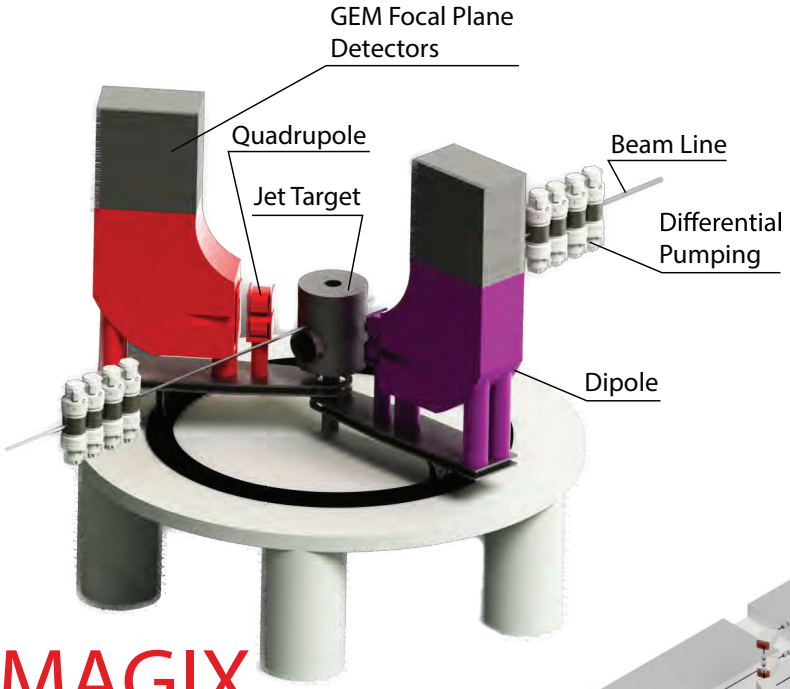


Stability Requirements

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

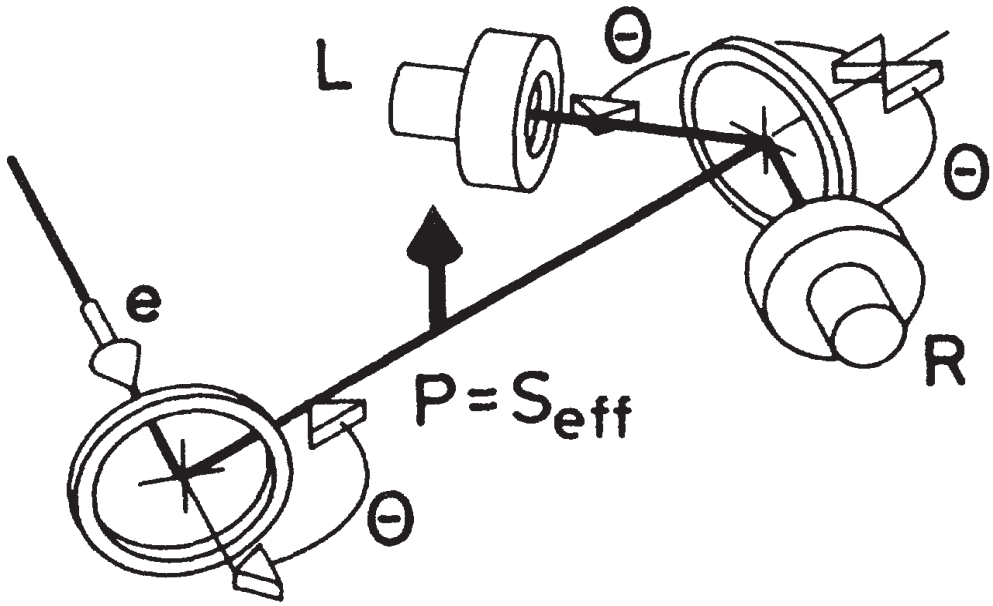
MESA



MAGIX

P2

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

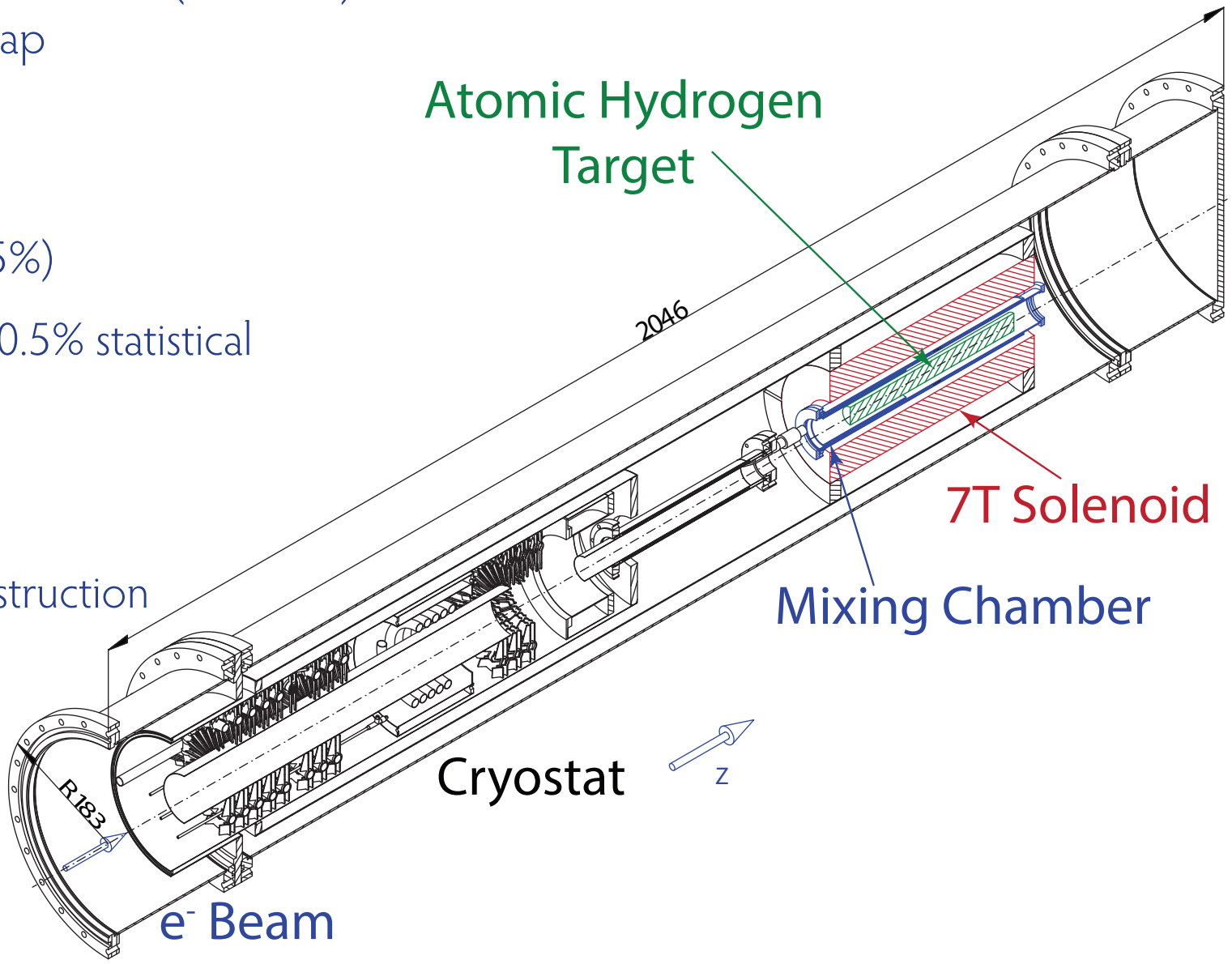
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

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

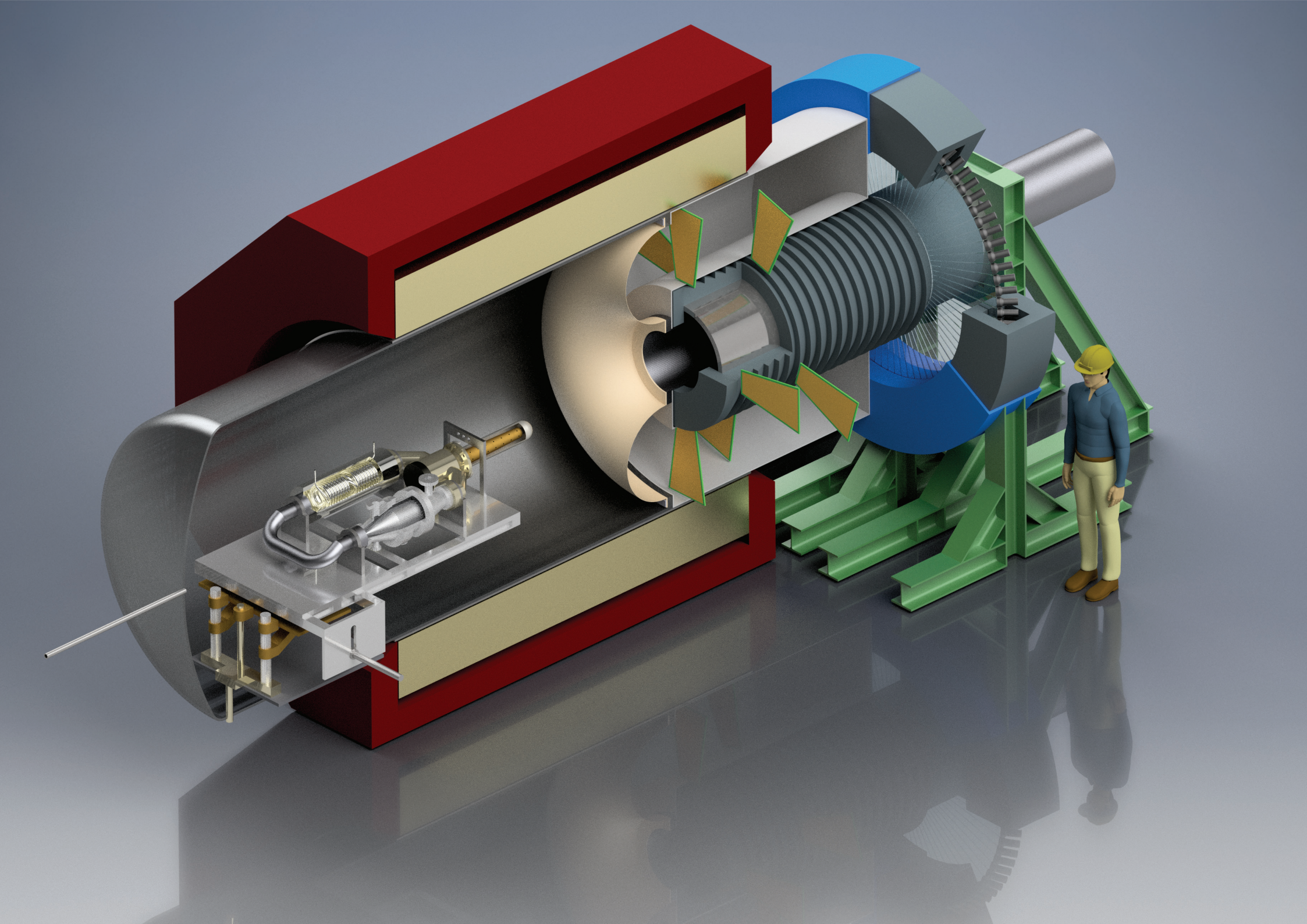
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

- Cryostat under construction in Mainz



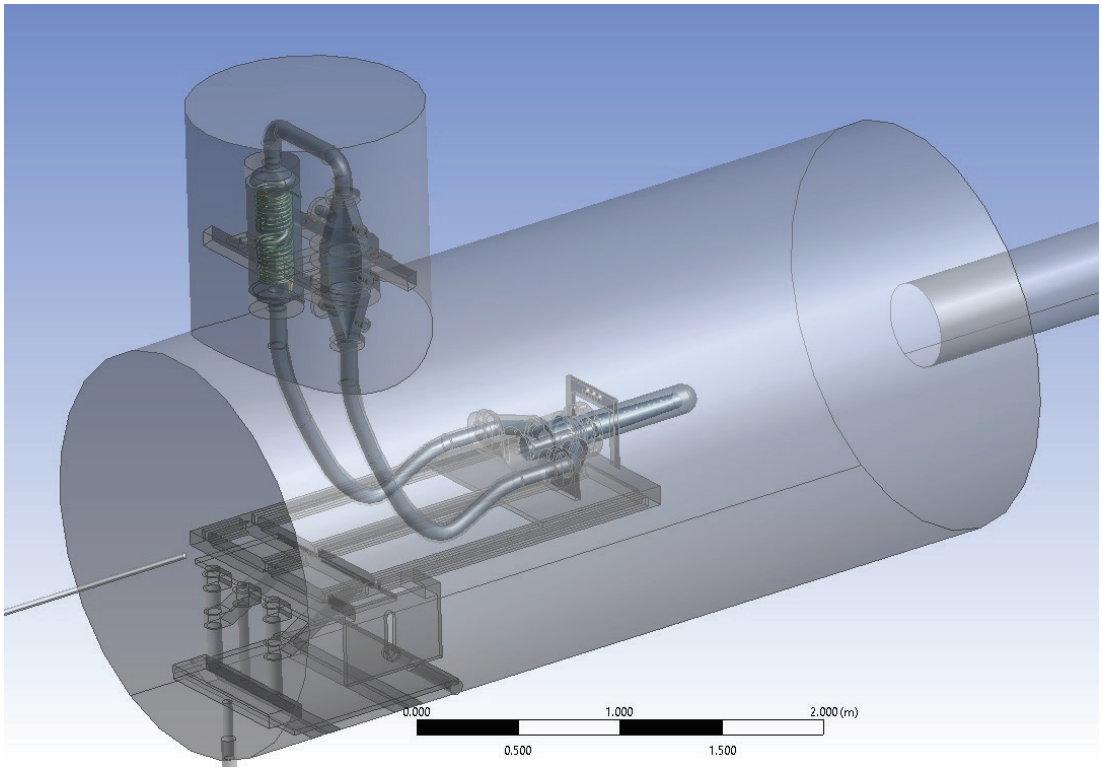
P2:

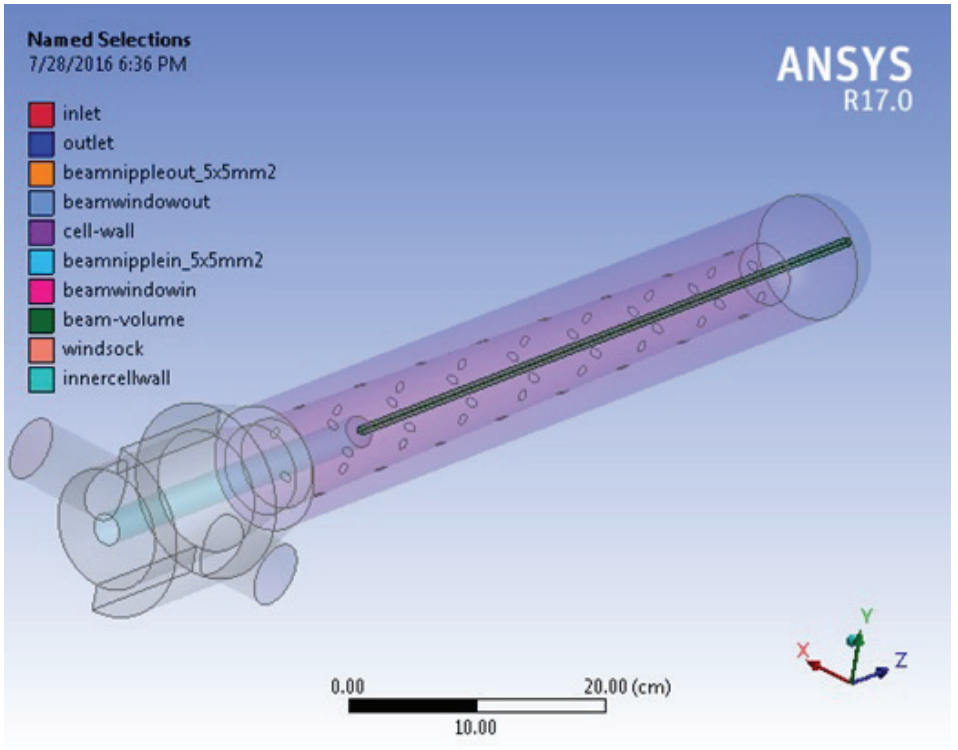
How to detect 100 GHz of (the right) electrons...



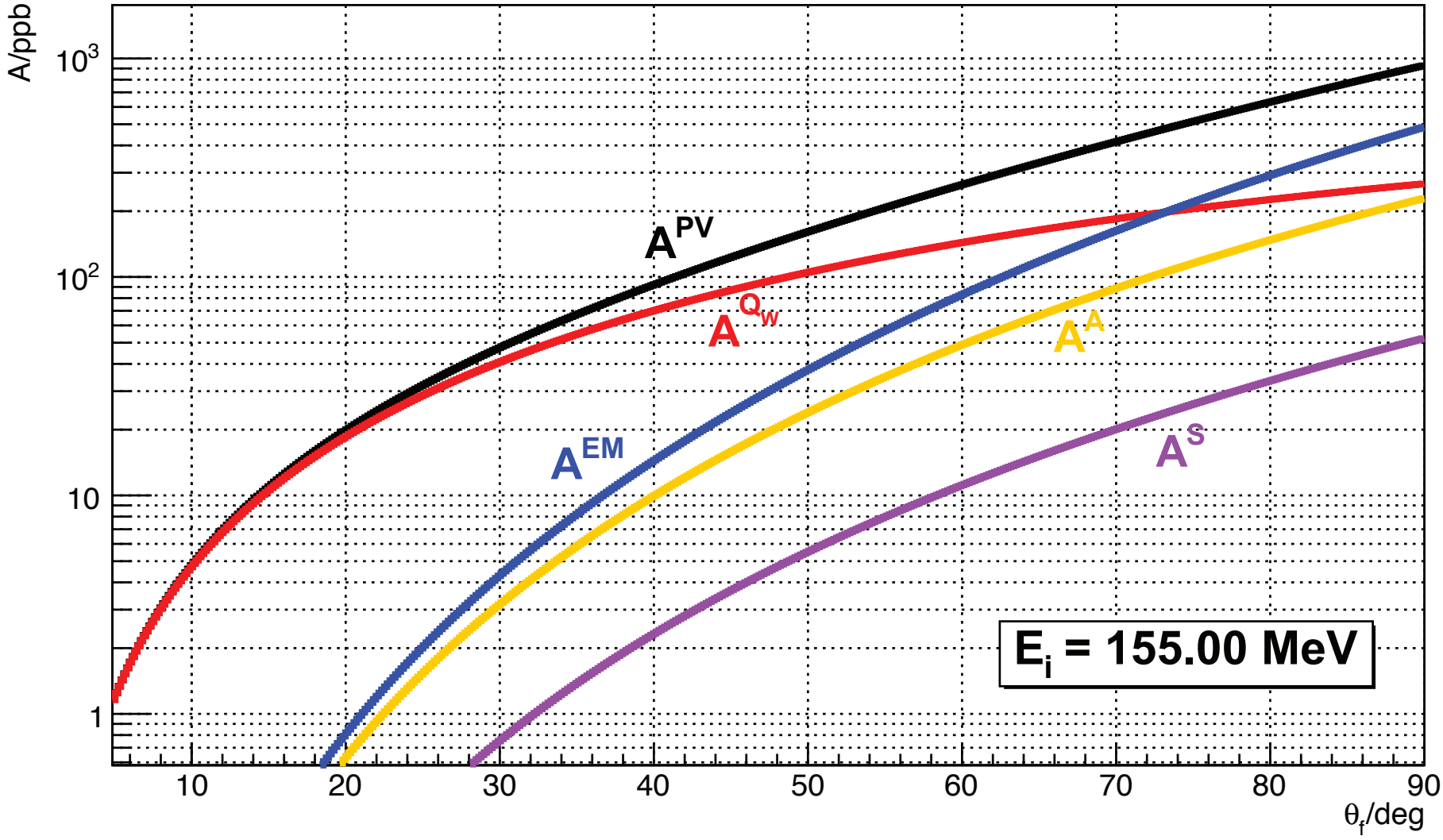
Target

- 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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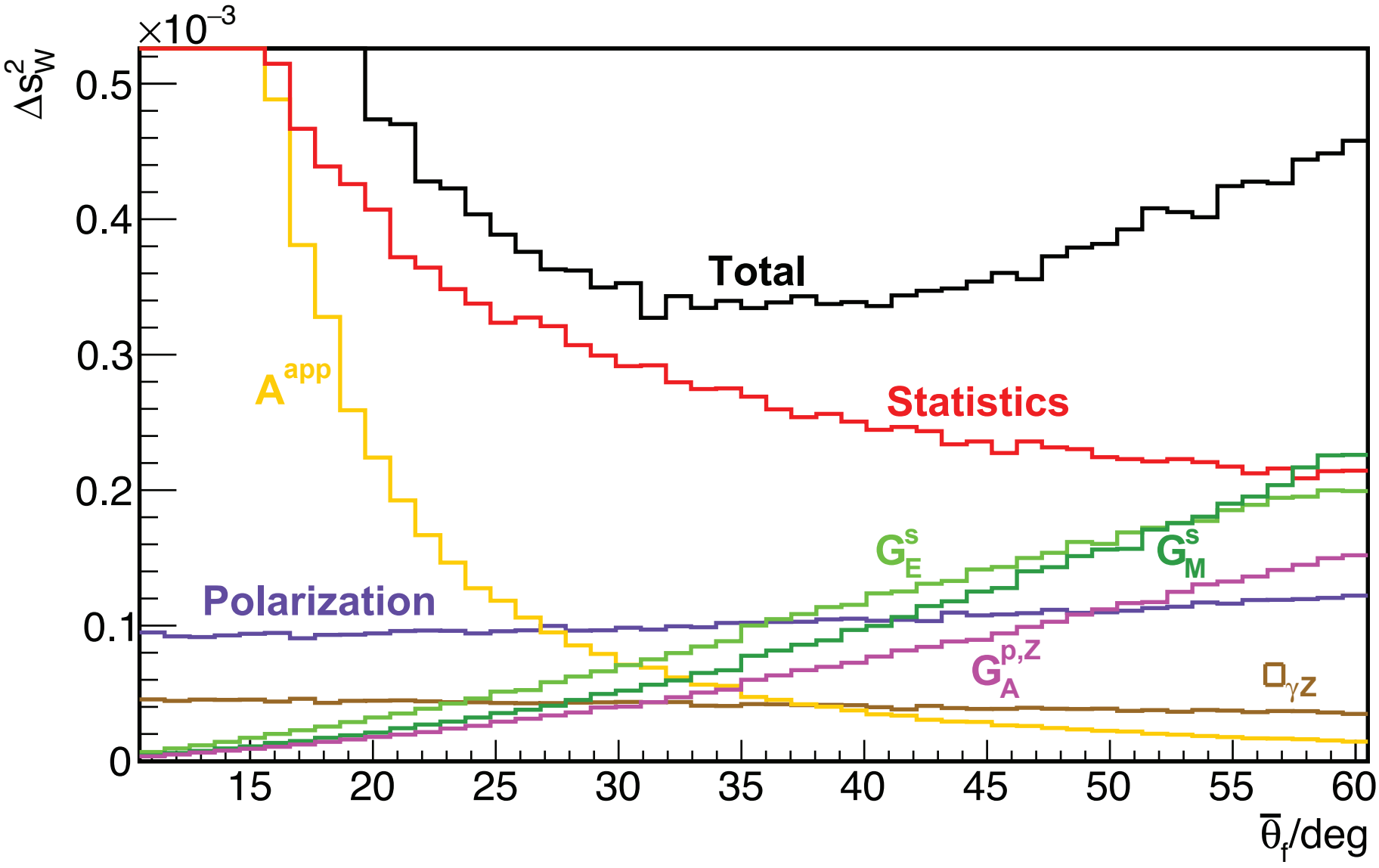
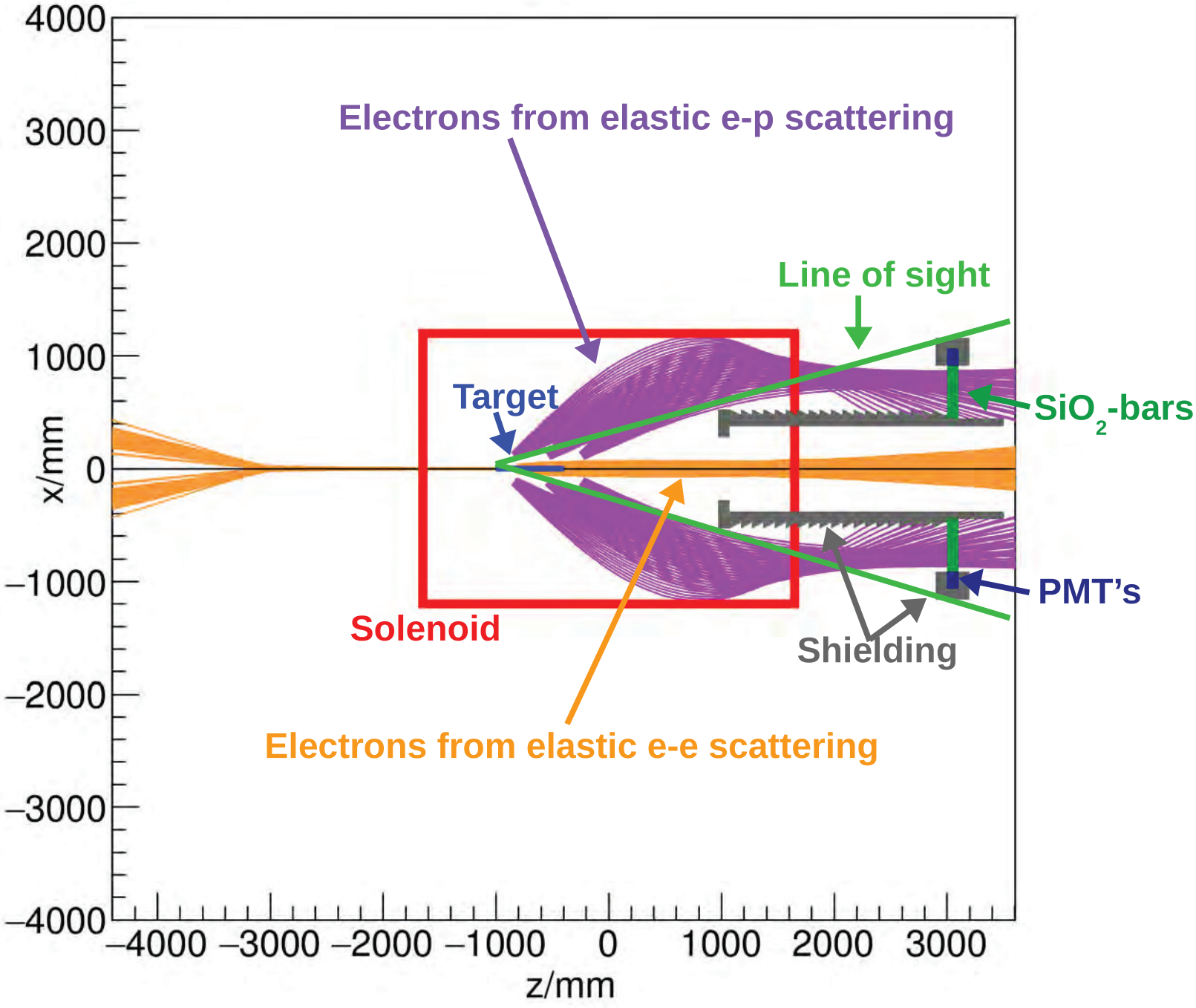


Solenoid spectrometer



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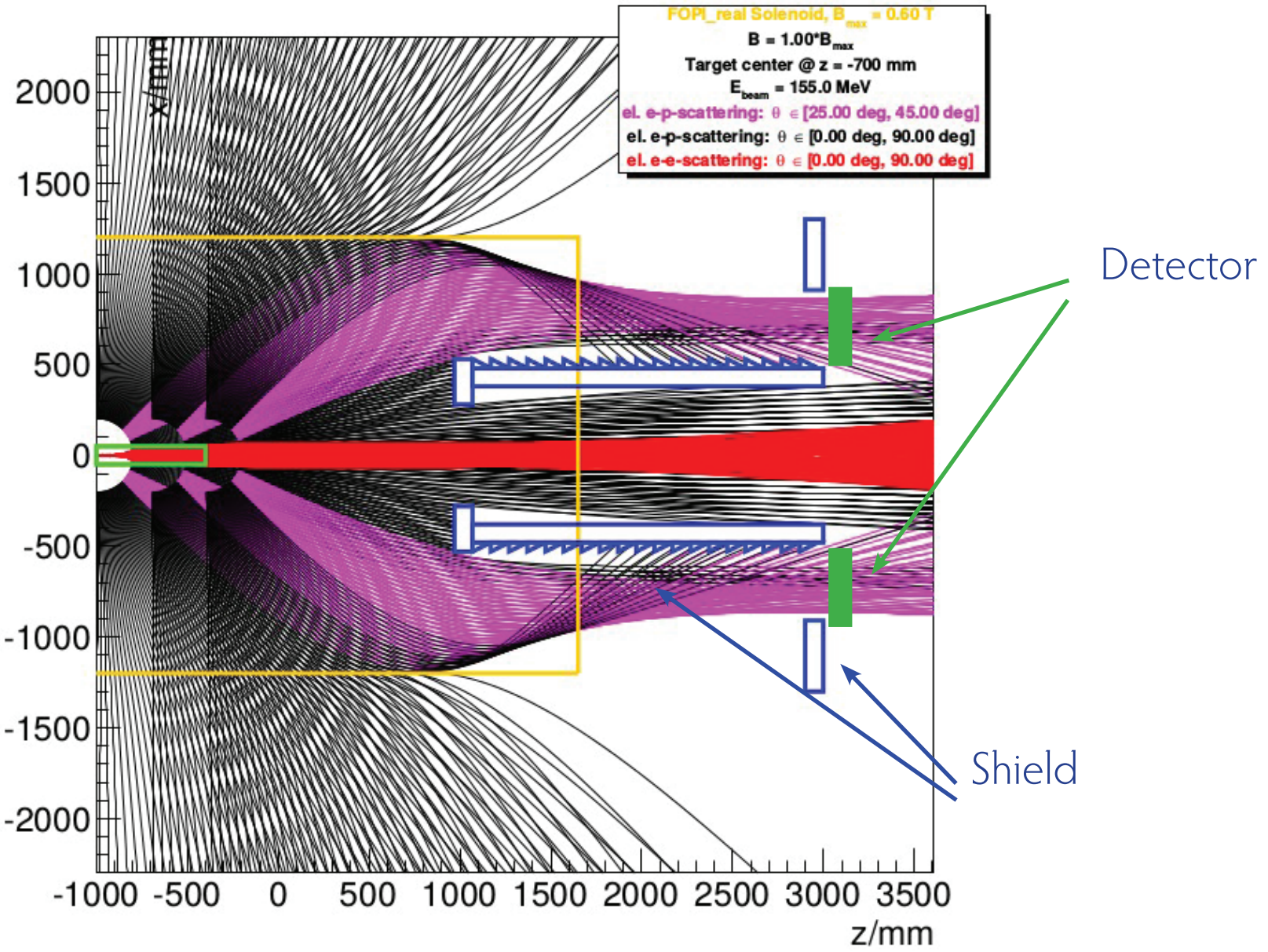
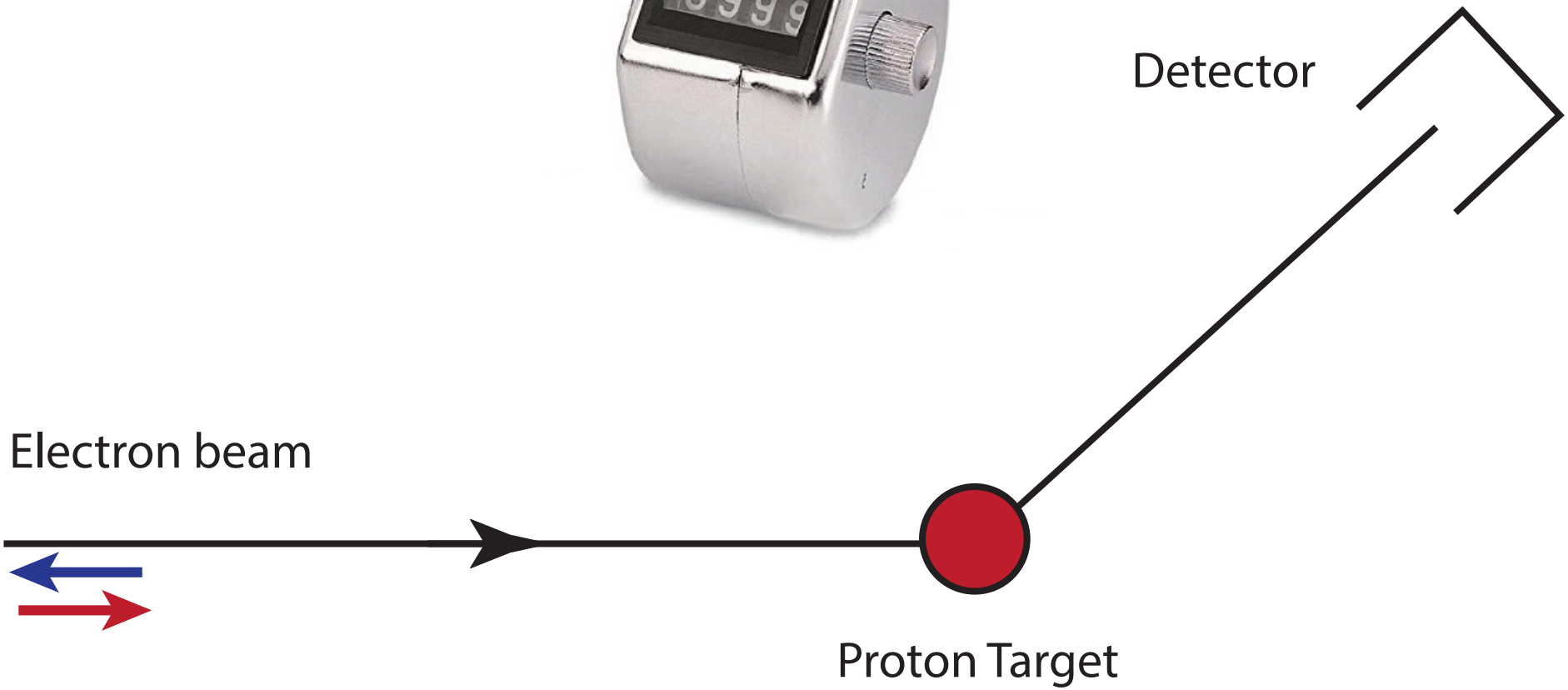
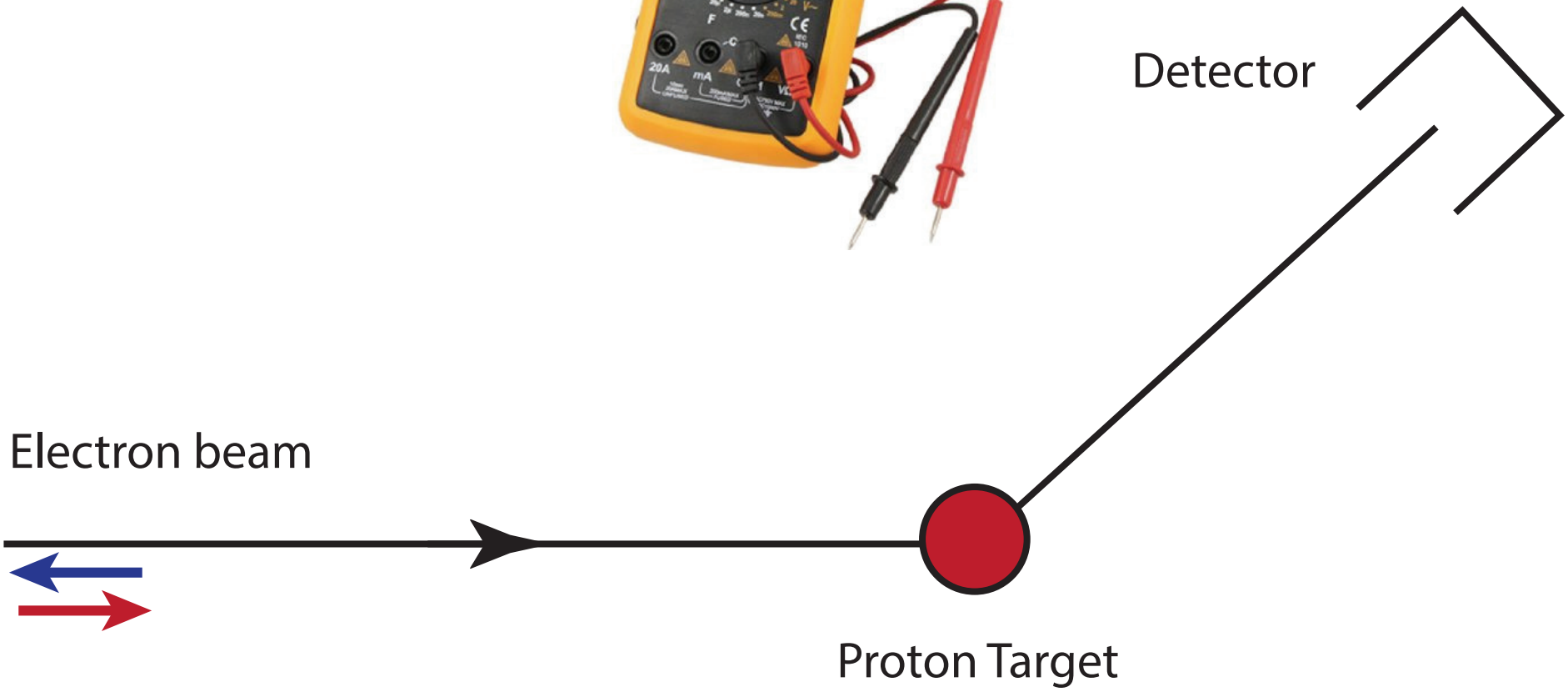


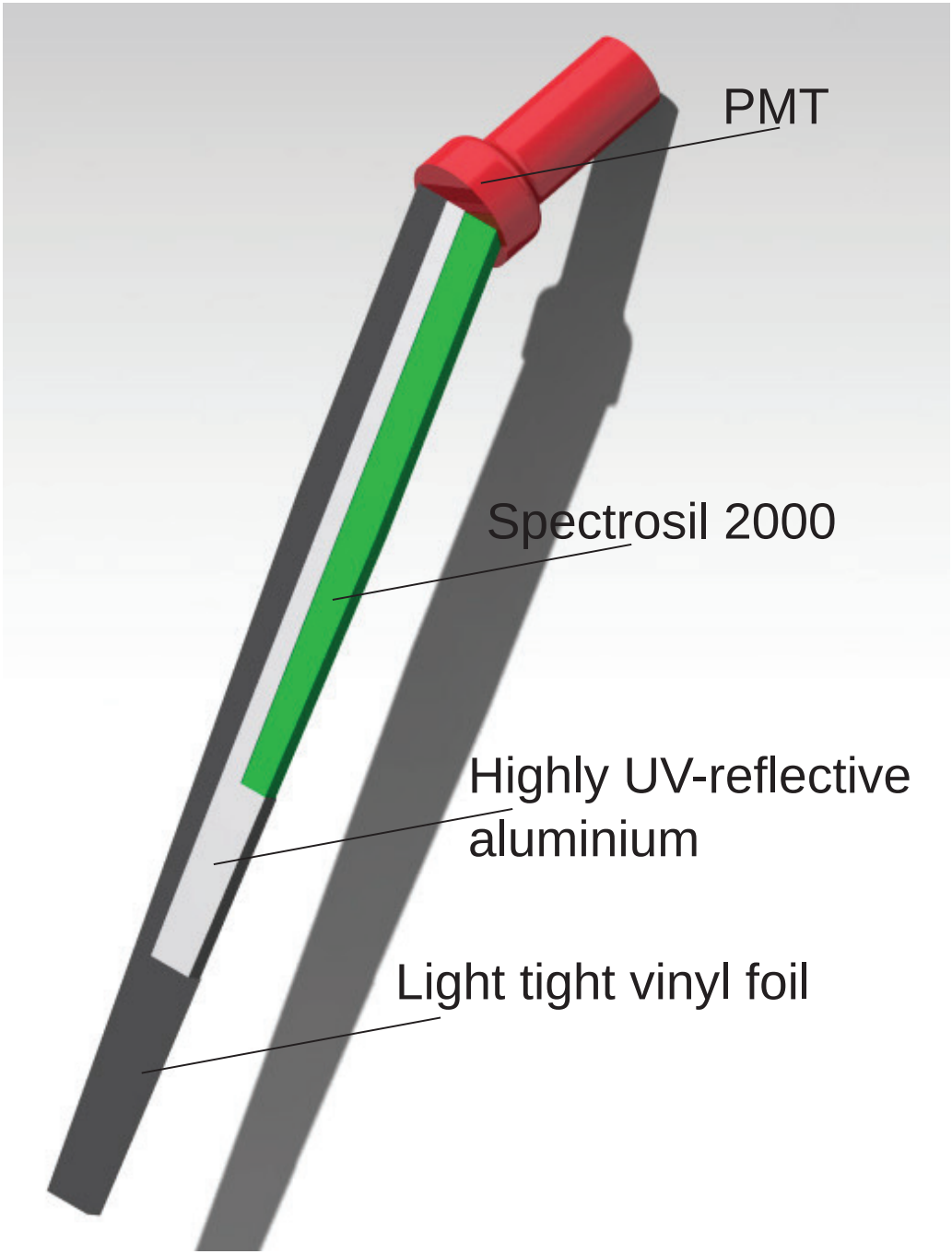
Counting detectors



Integrating detectors

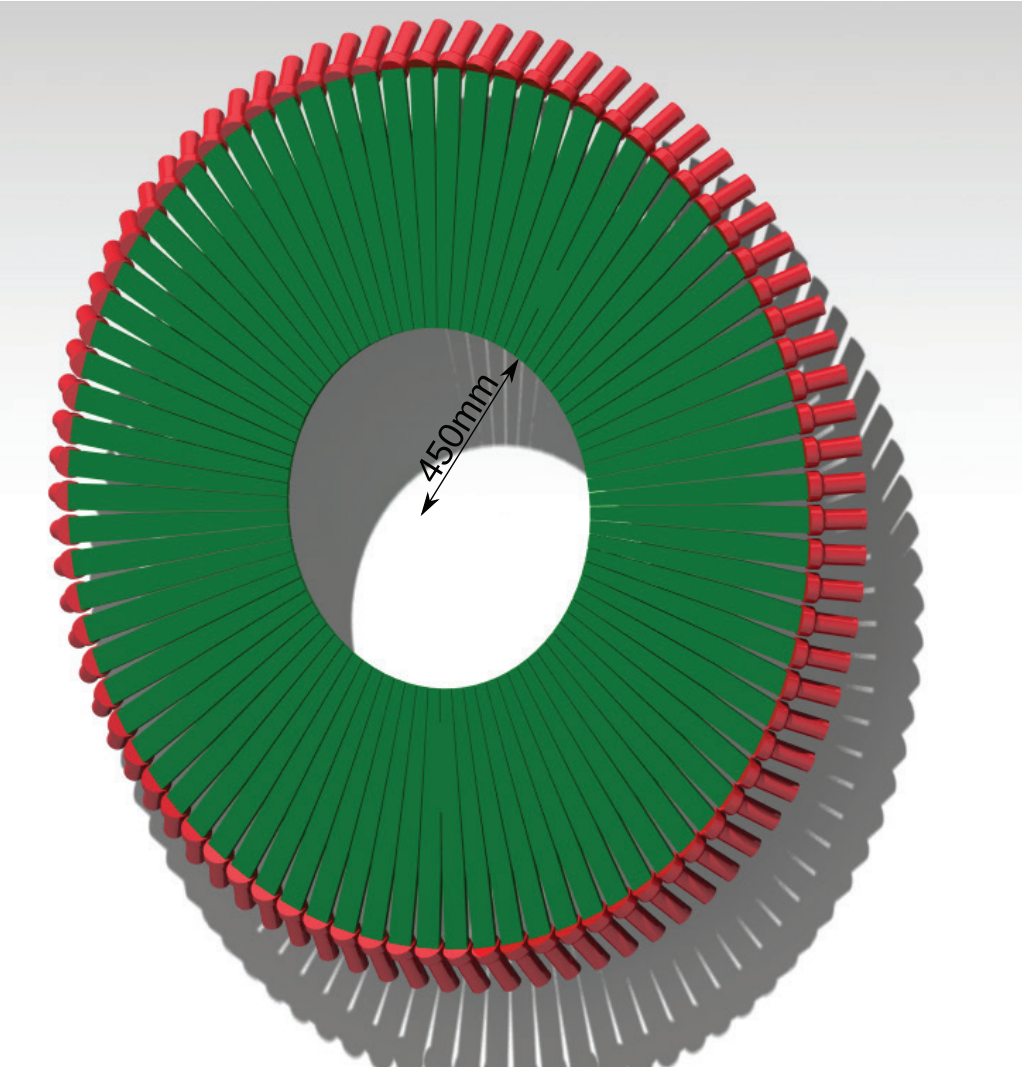


Quartz-Bars & Photomultipliers



Detect Cherenkov-light created by electrons

Integrate photomultiplier current



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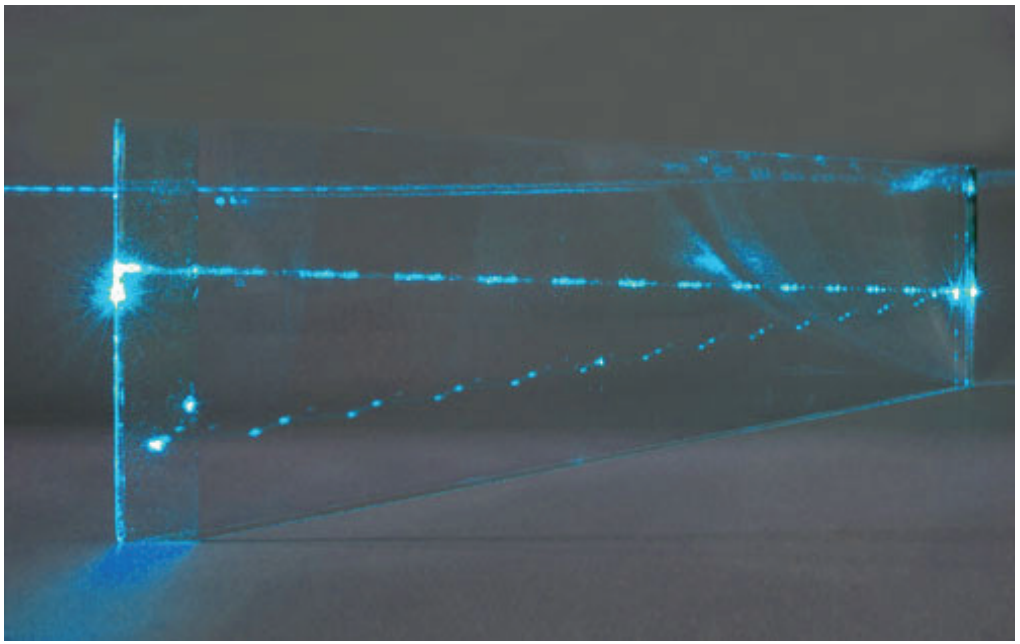
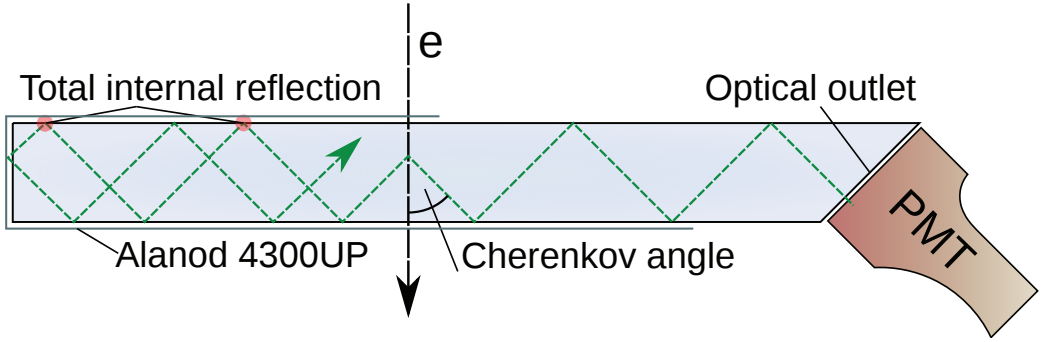
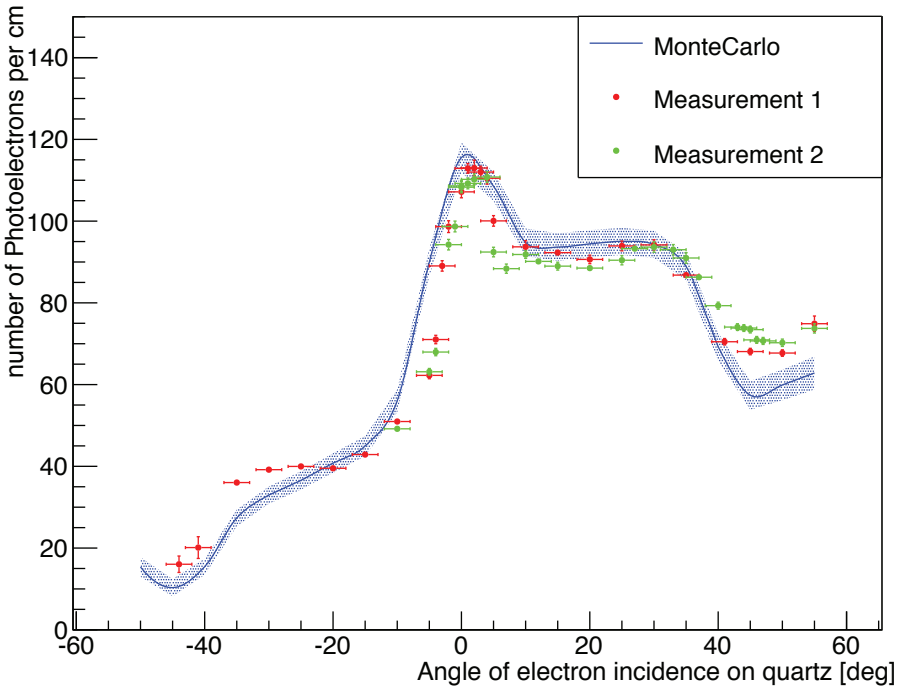




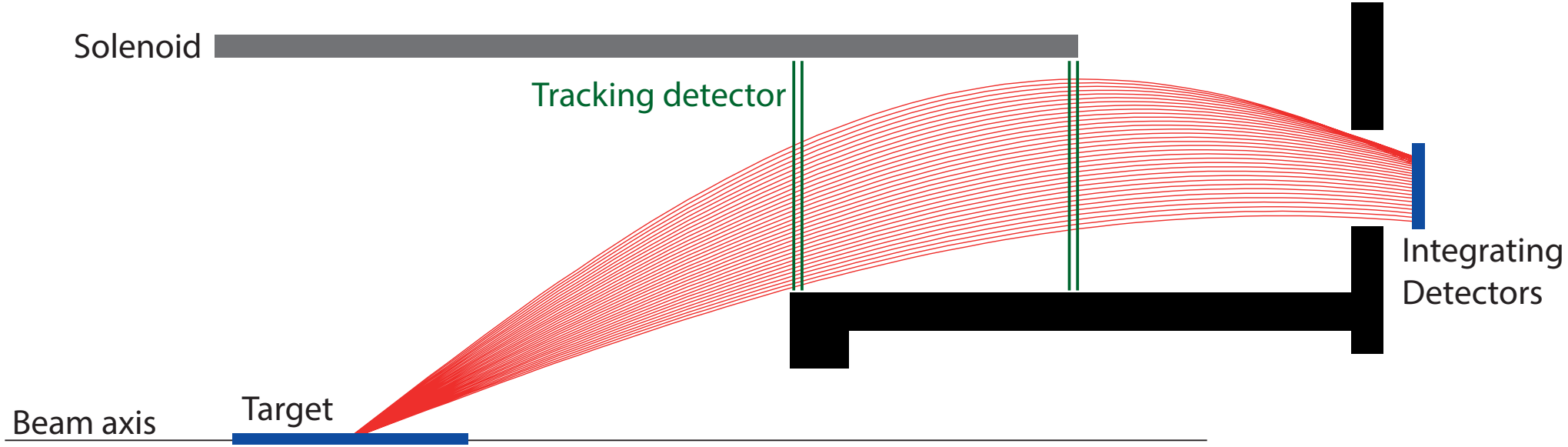


Measuring Q^2:

Tracking a
lot of low momentum particles

Tracker requirement

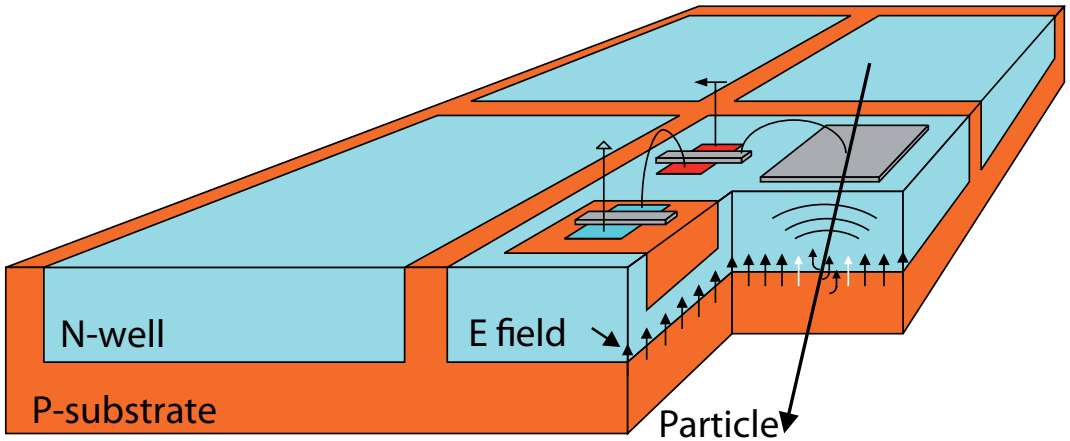
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

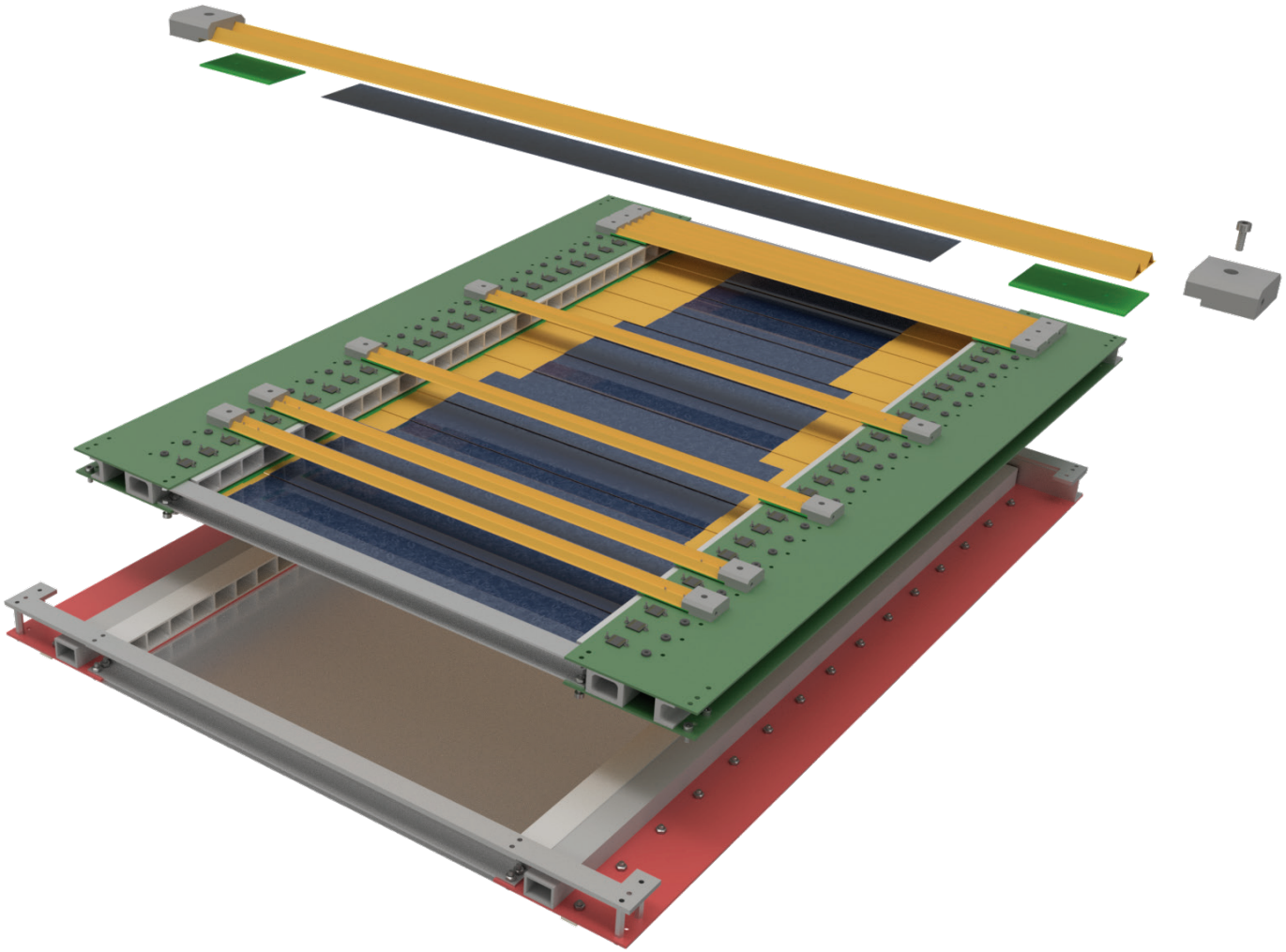


High voltage monolithic active pixel sensors - Ivan Perić (morning sessions!)

- 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

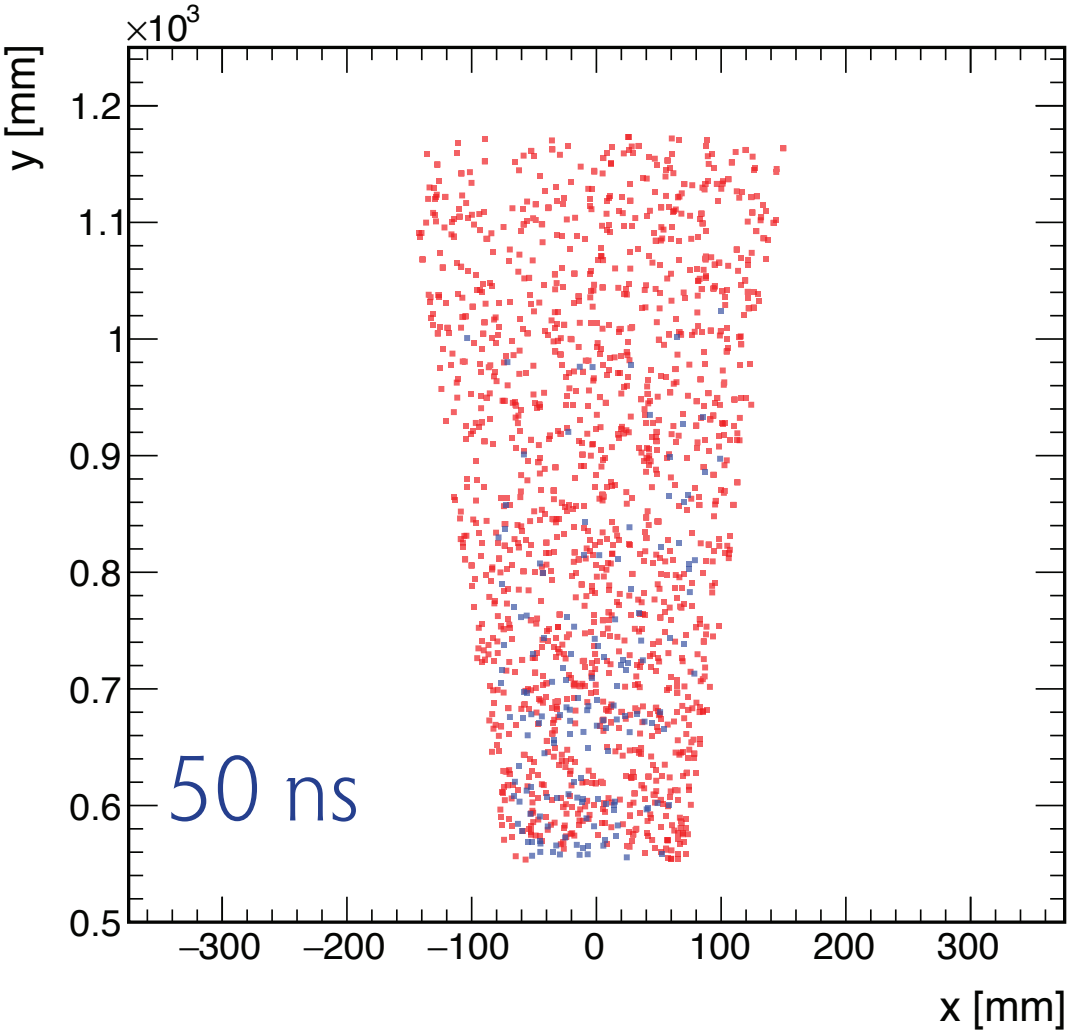
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

Mechanics



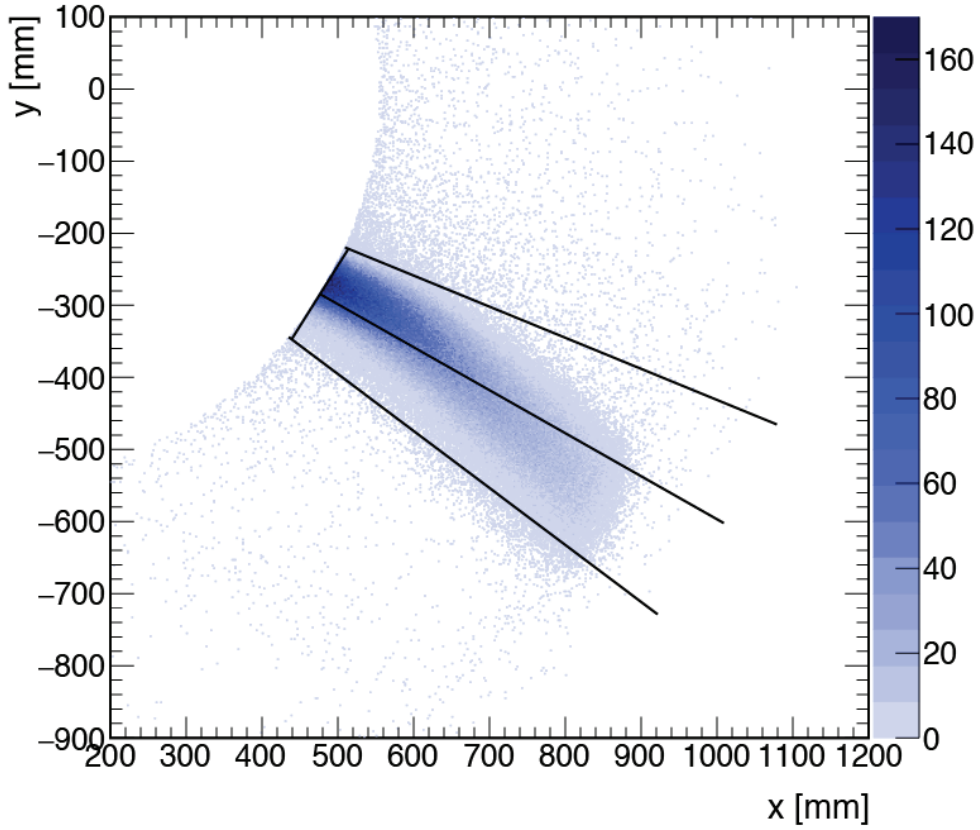
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- About 1‰ of a radiation length per layer

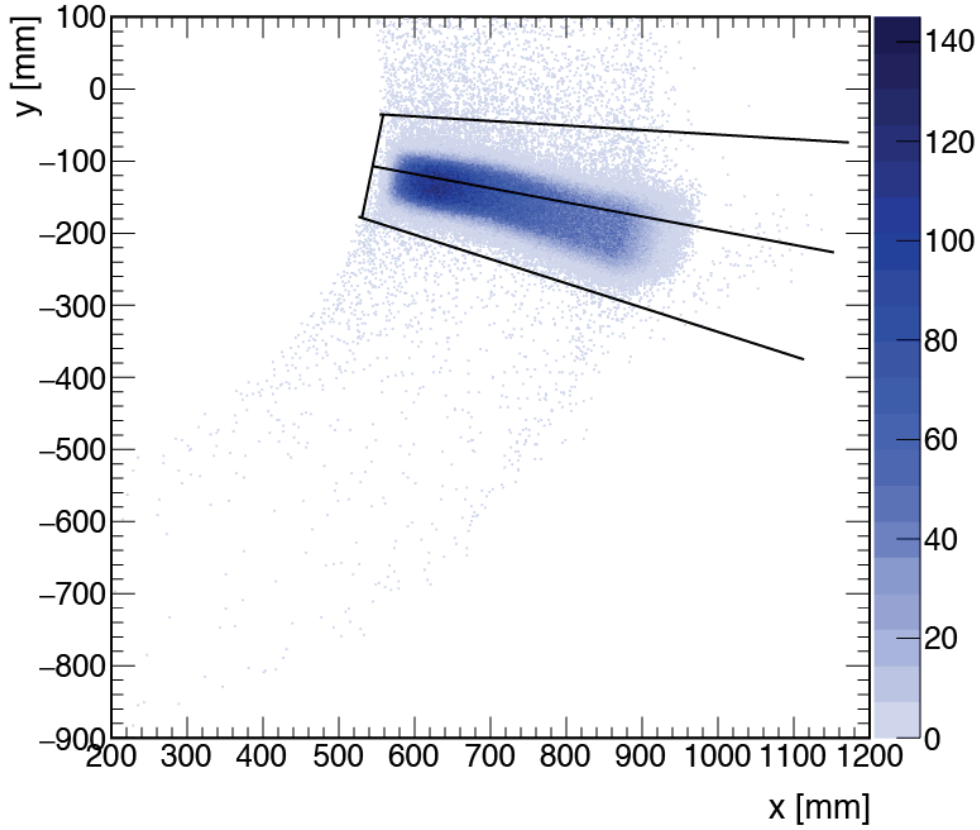
The tracking challenge



- 100 GHz electrons
- about 1000 Bremsstrahlung photons per electron

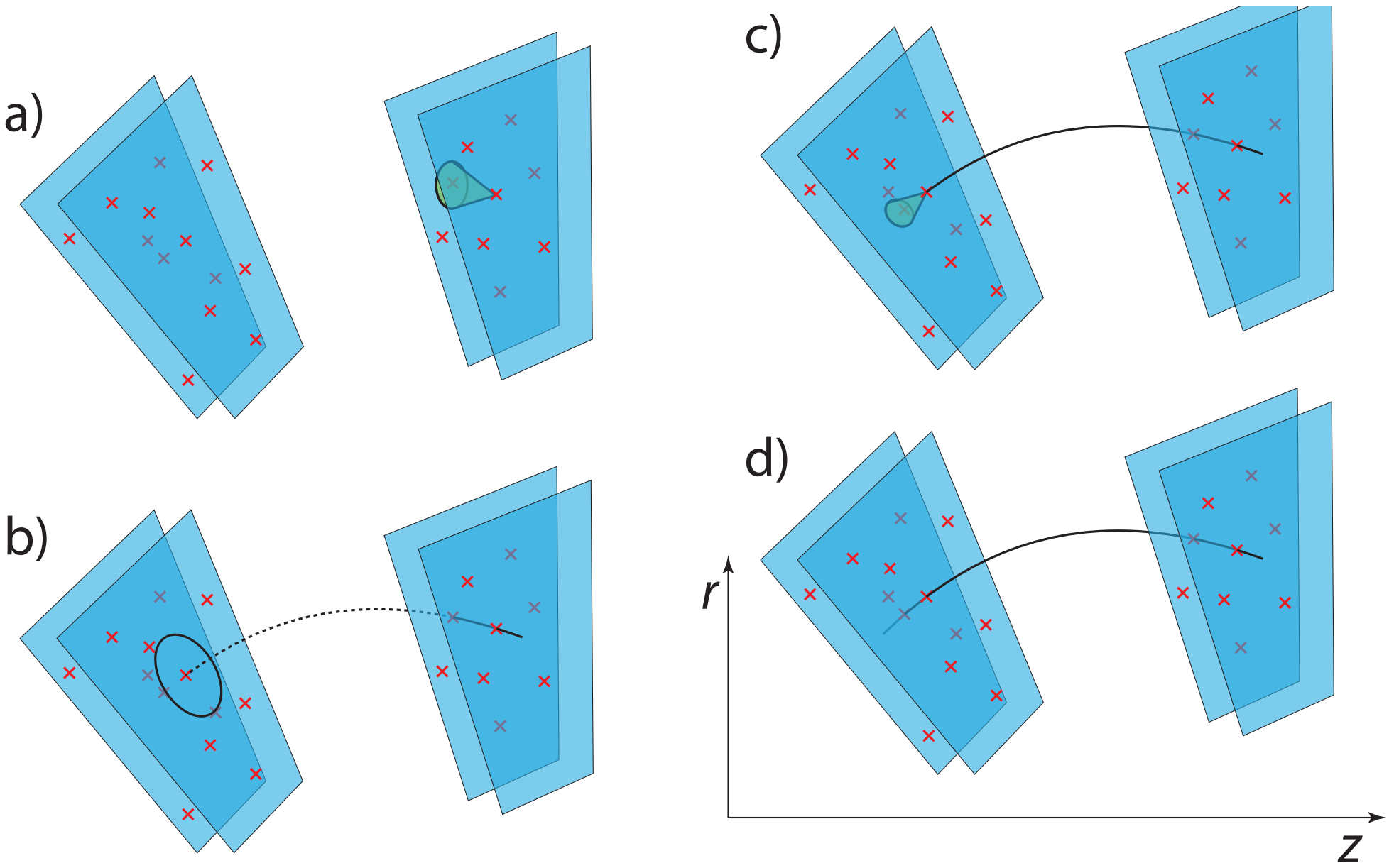
No need for full coverage



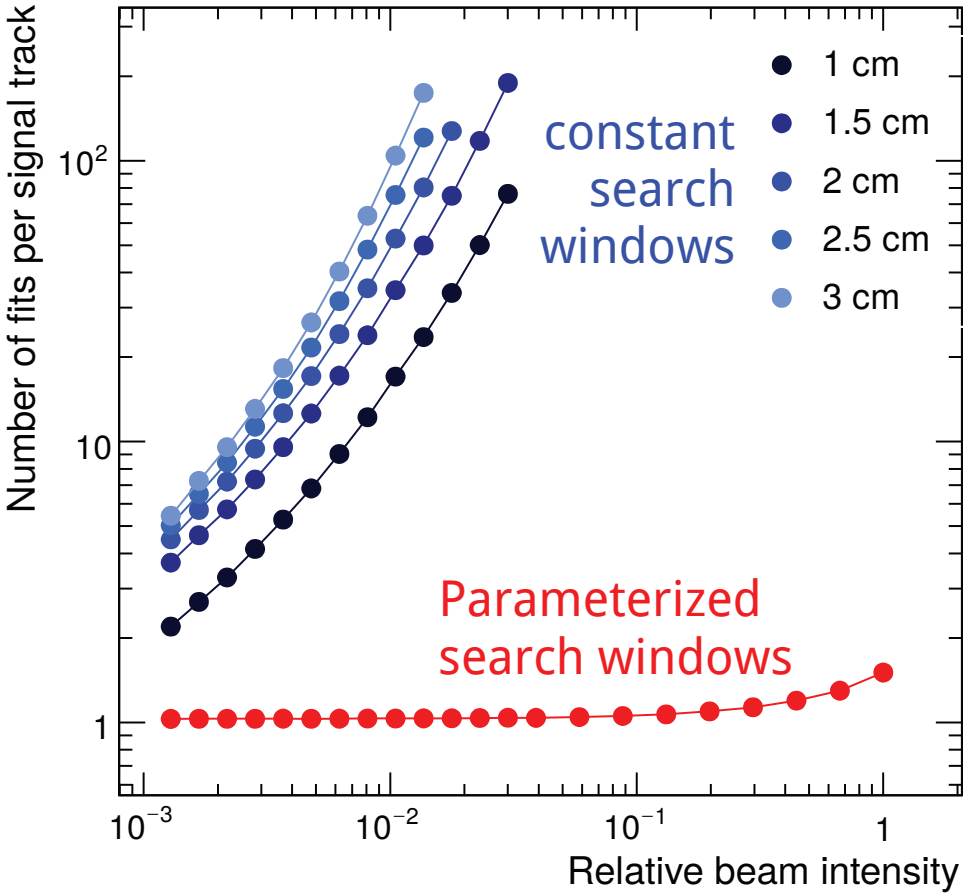


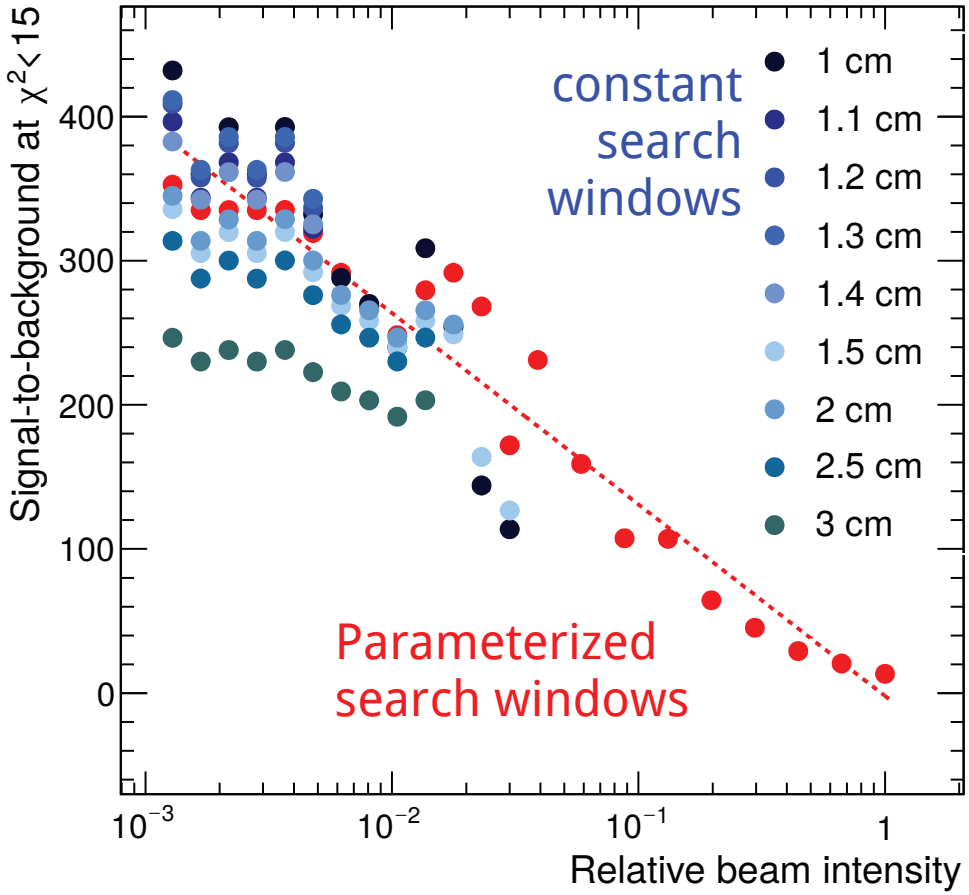
Parametrization based tracking

I. Sorokin

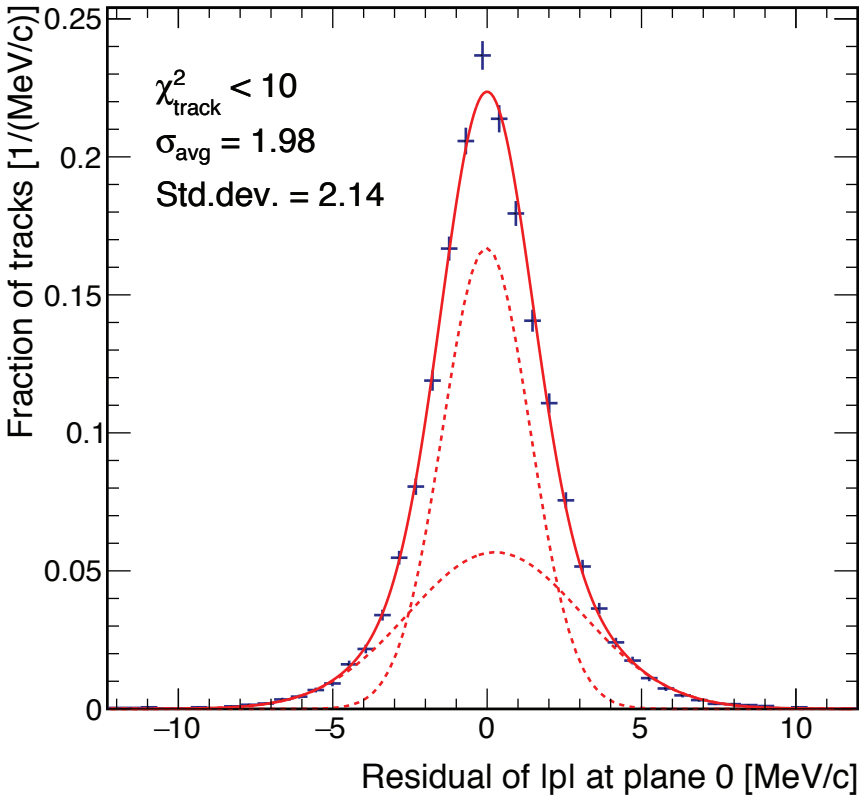


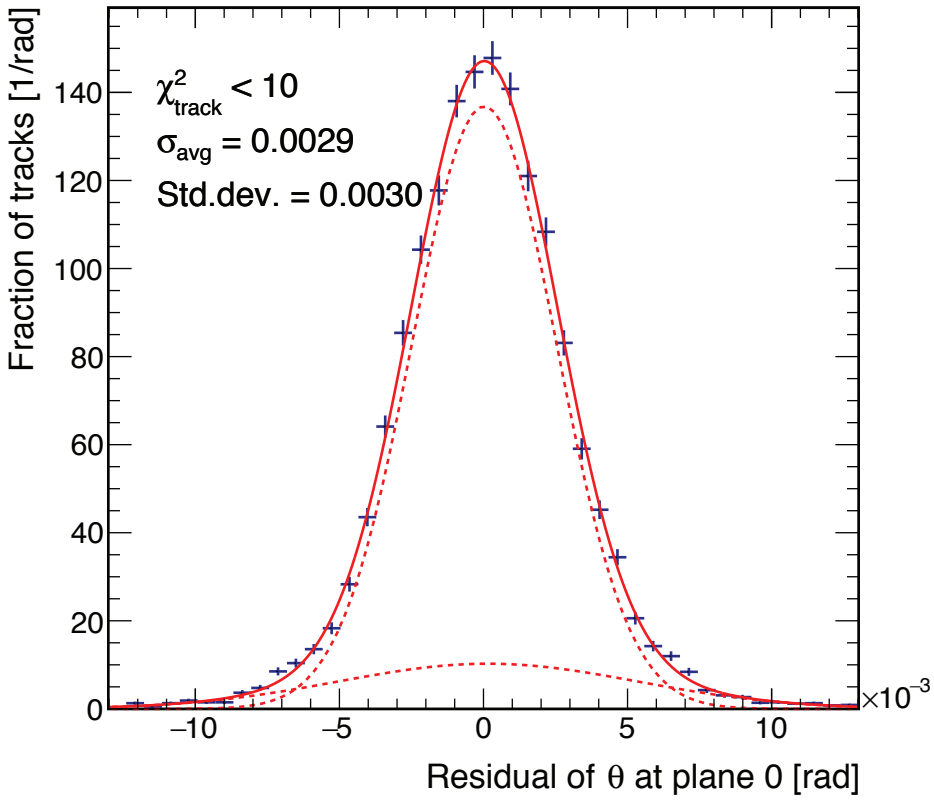
Tracking performance



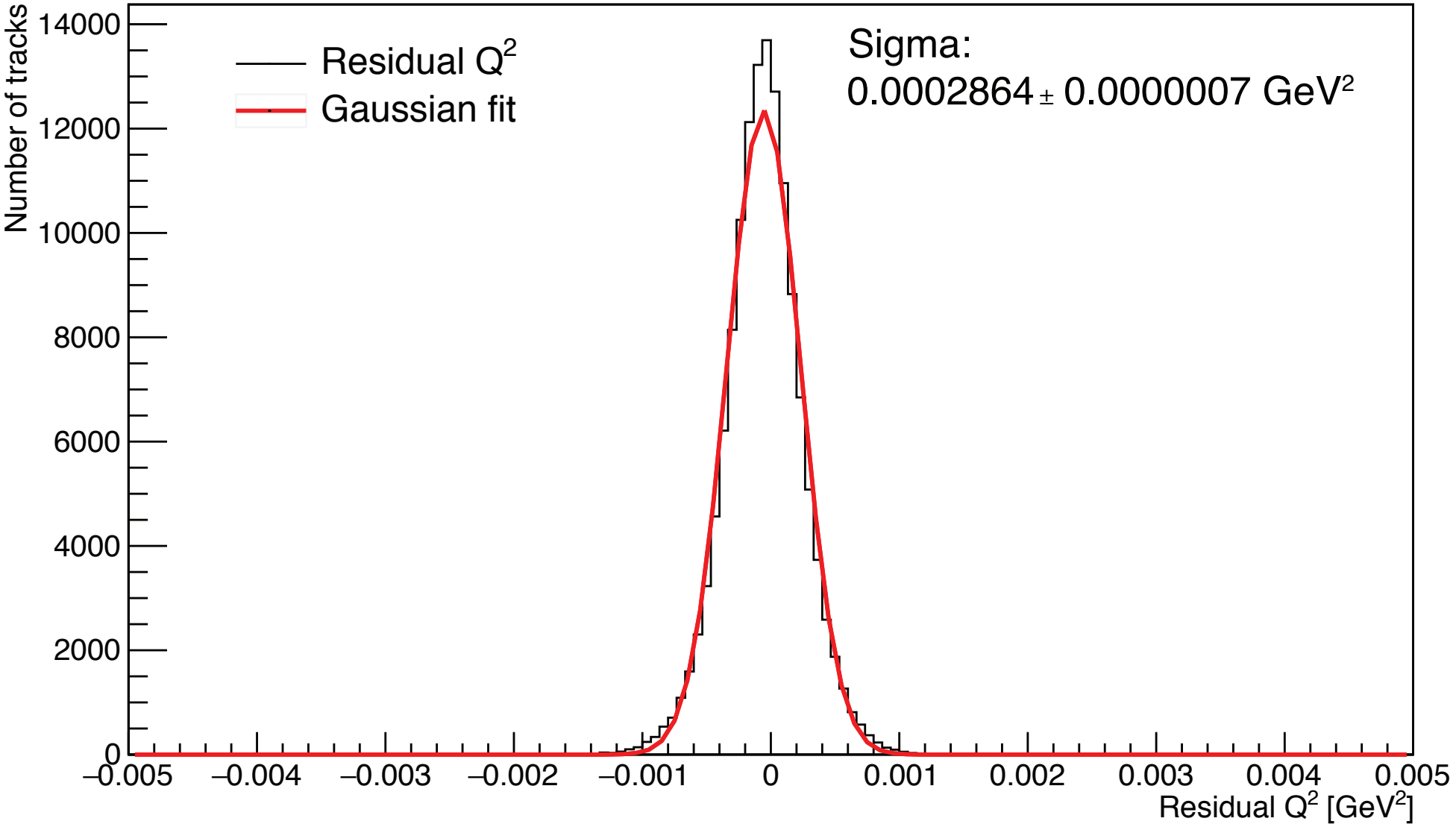


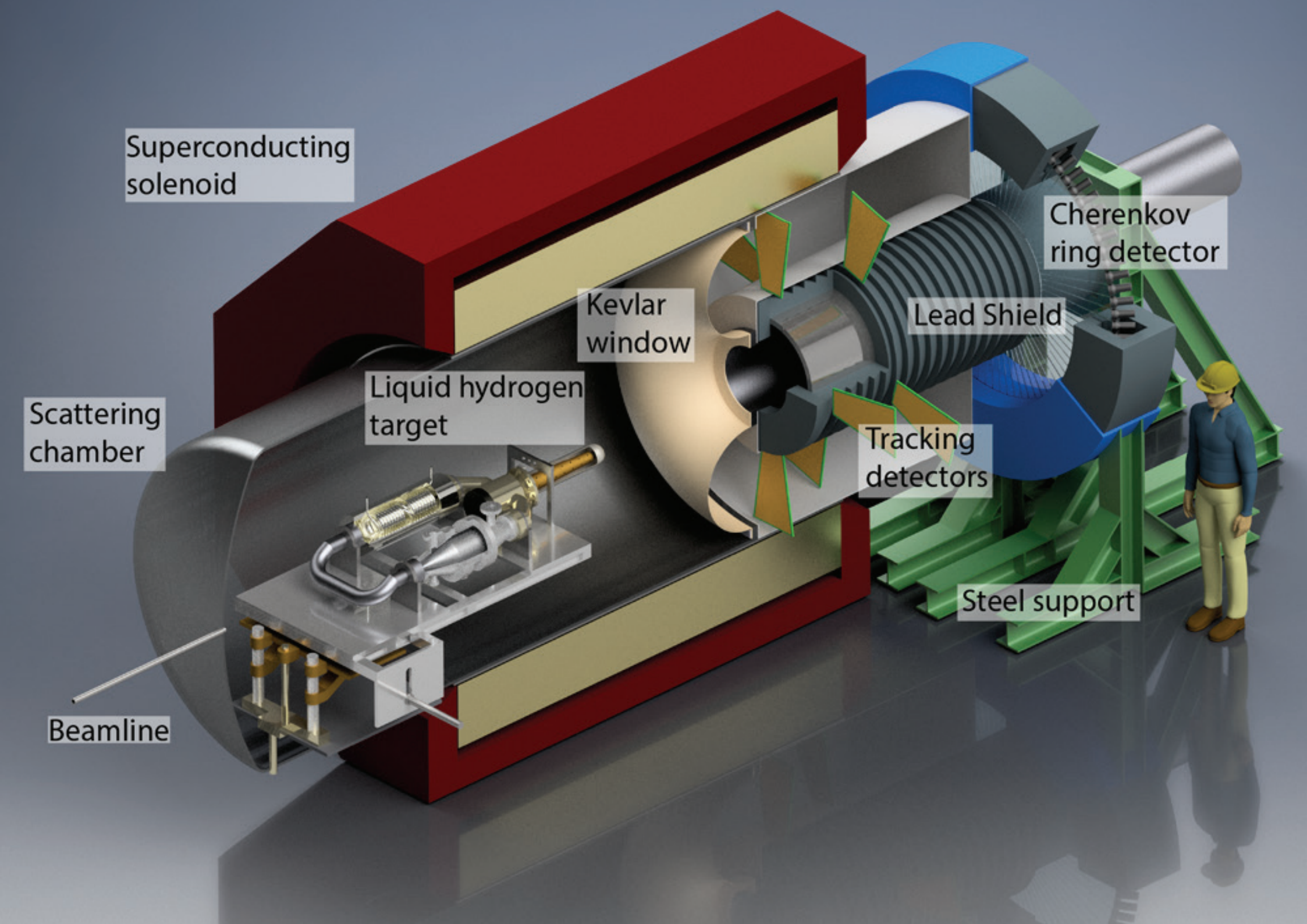
Tracking performance





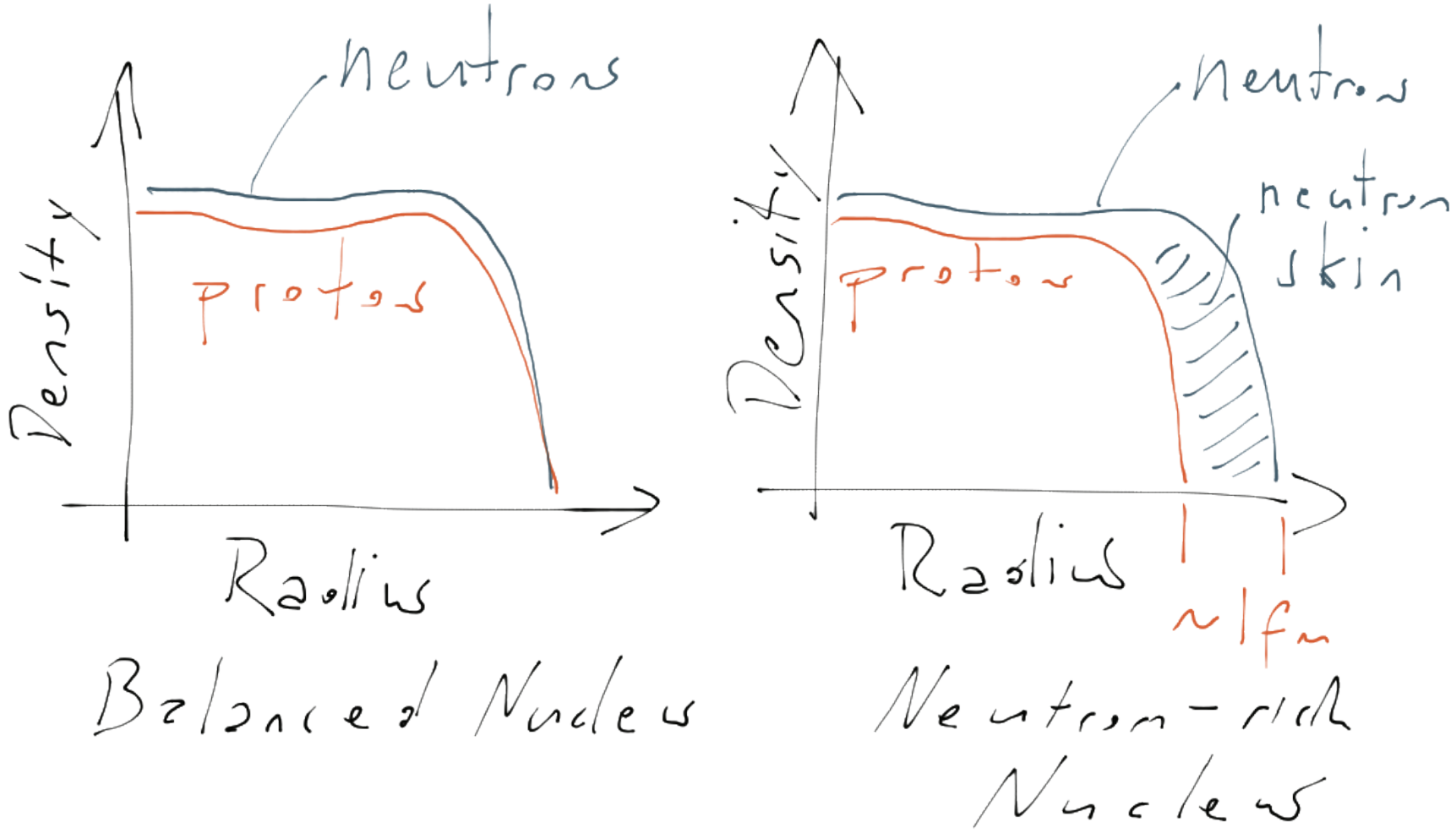
Q^2 reconstruction




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

Neutron Skins

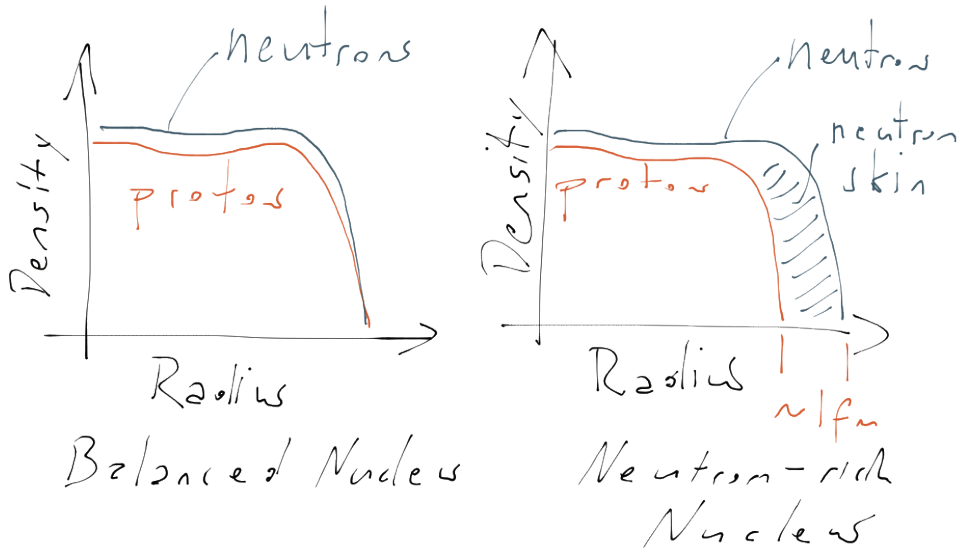
Where are the neutrons in the nucleus?

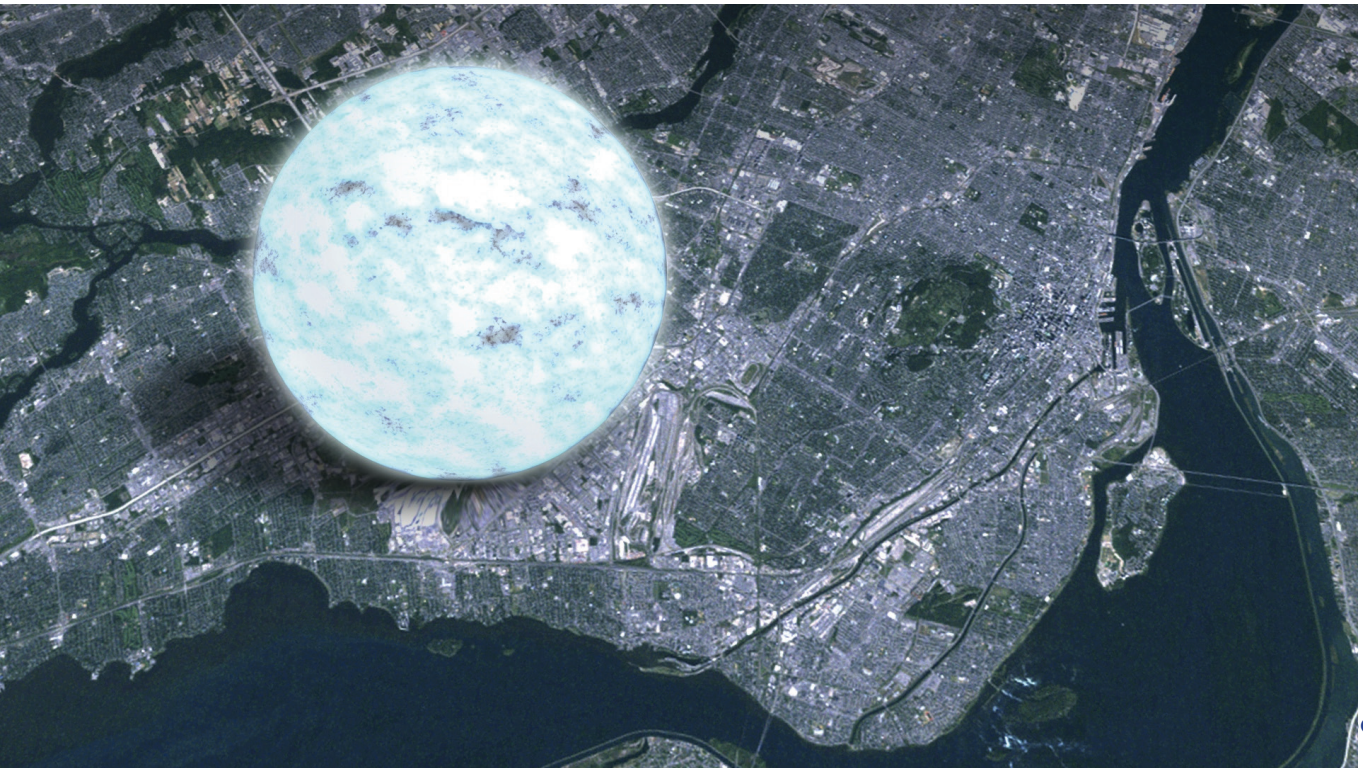


Neutron Skins

Where are the neutrons in the nucleus?

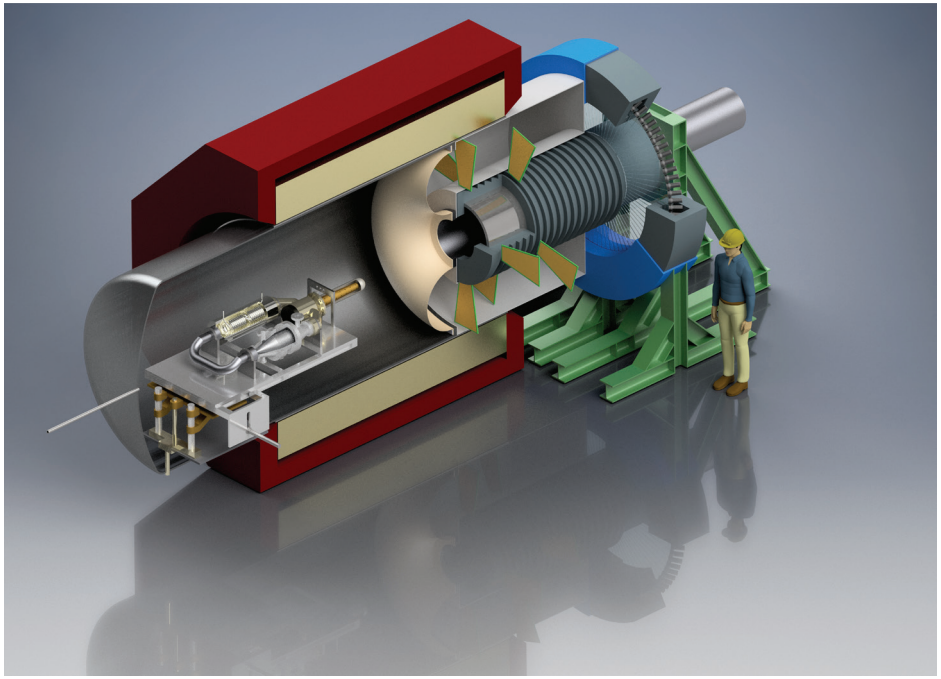
- Gives access to the equation of state of neutron matter
- Tells us how big/small neutron stars are





How to see the neutrons?

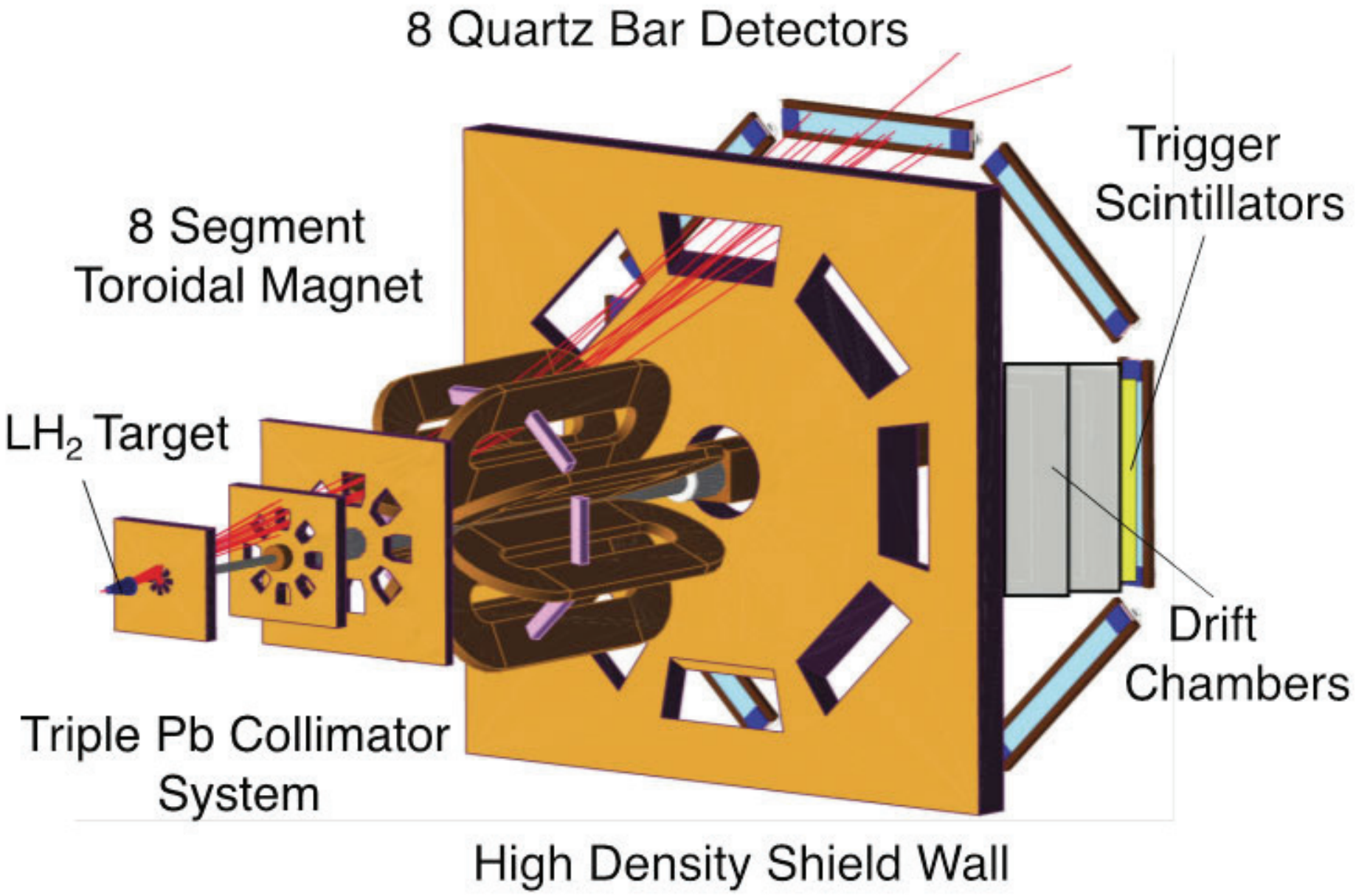
- Not charged: Photons not a good probe
- Use parity violating electron scattering:
  Proton weak charge is almost zero -
  see mostly neutrons

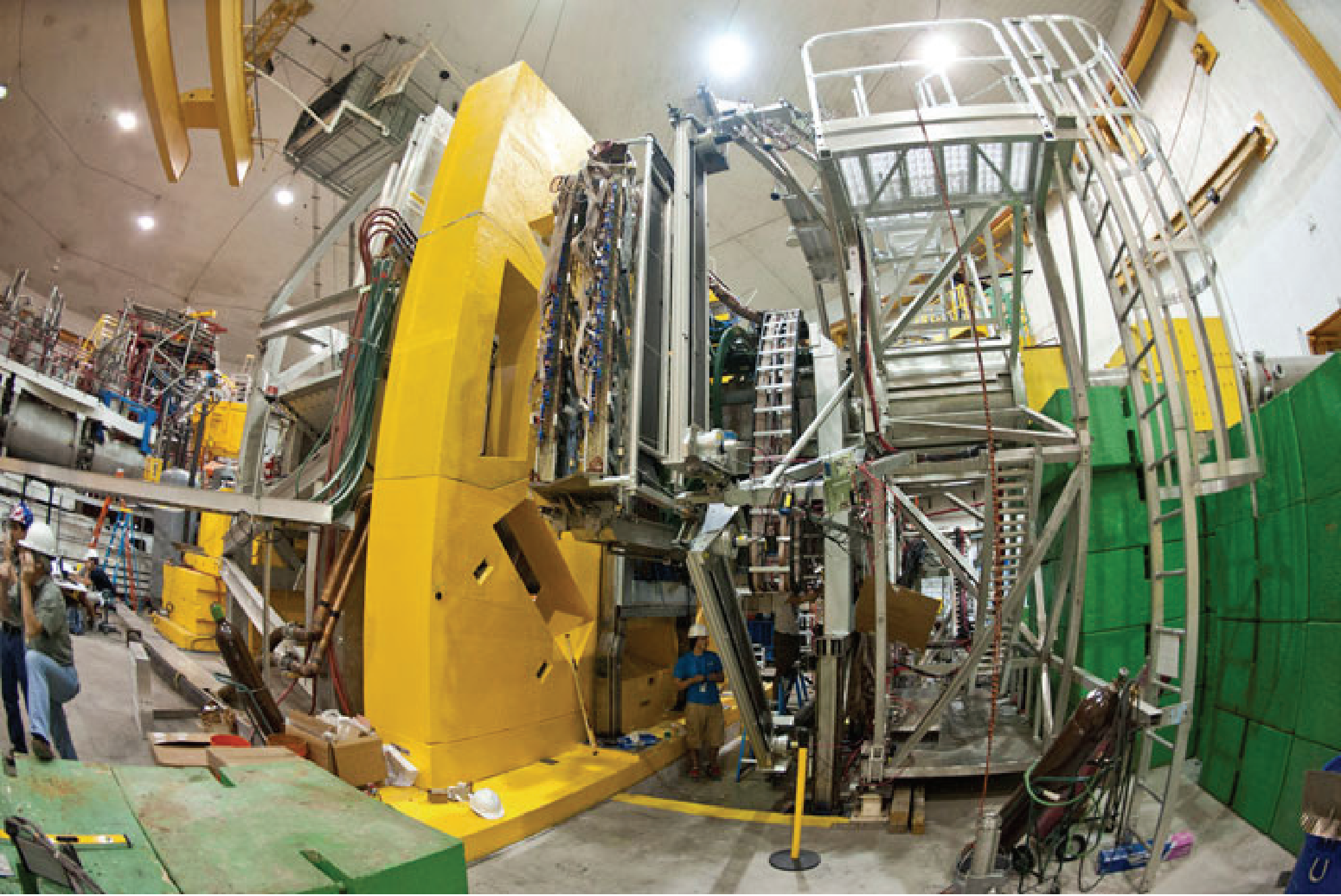


$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left(\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right)$$

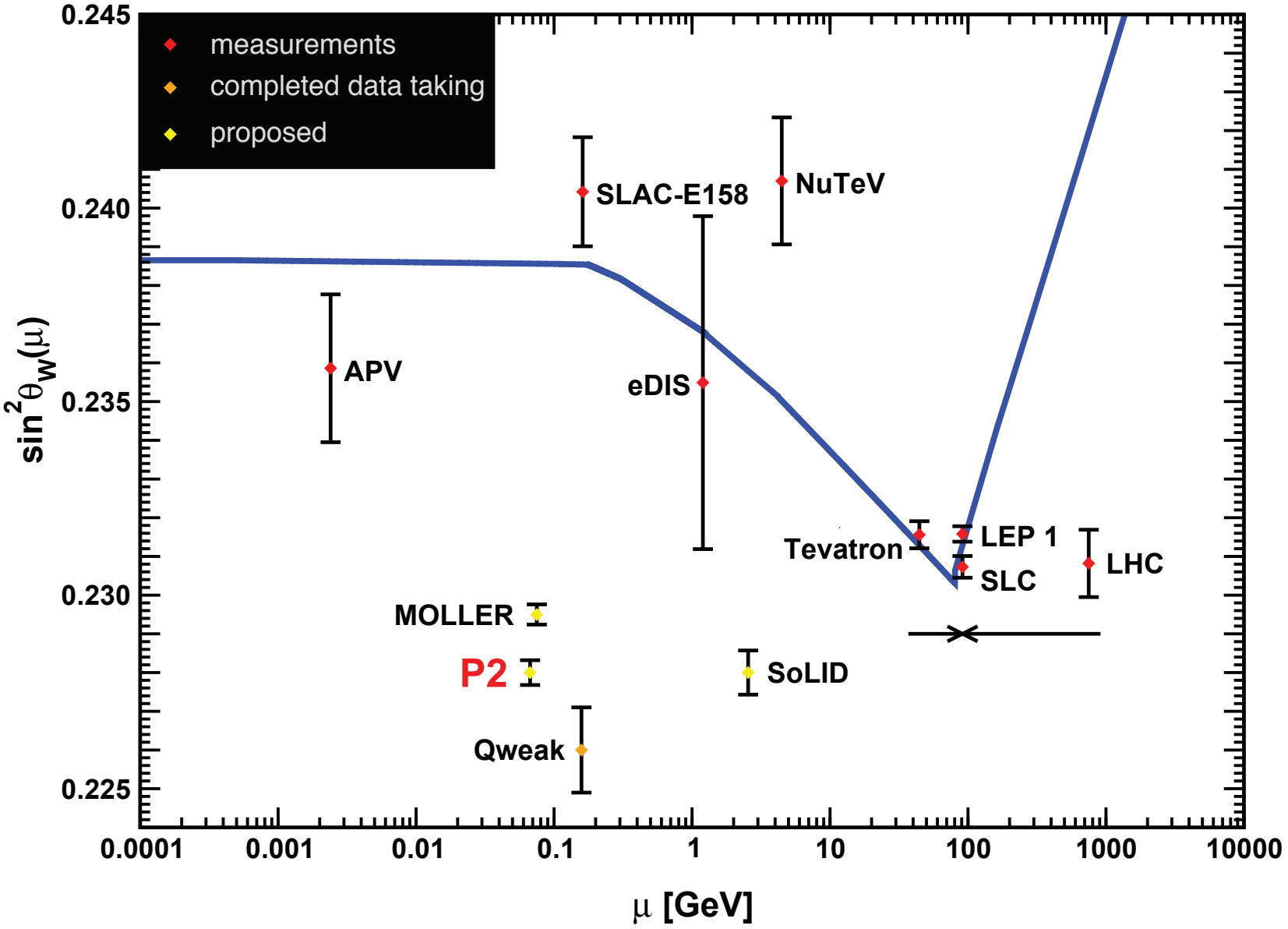
Other parity violation experiments

QWeak (JLab)

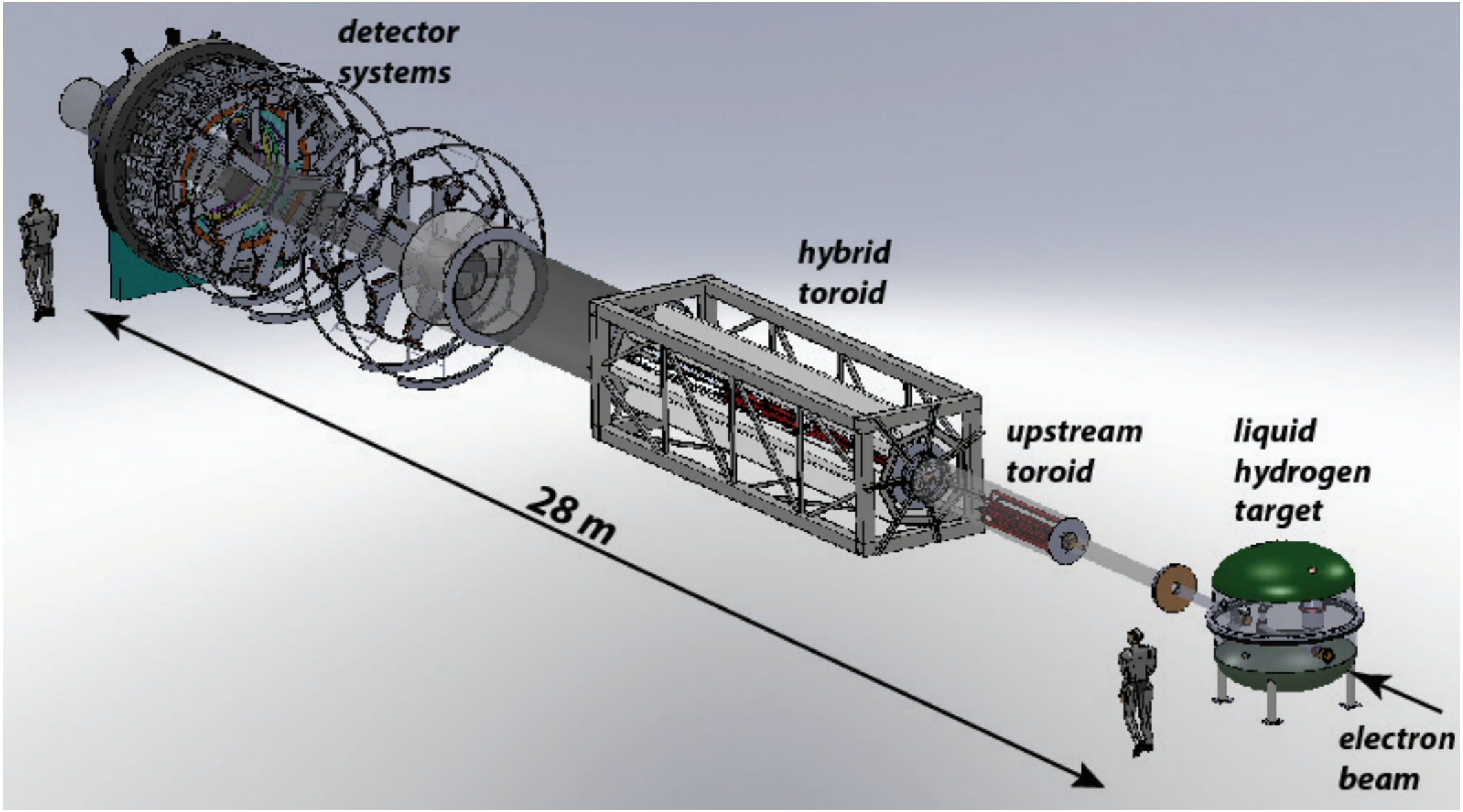

8 Quartz Bar Detectors
Trigger Scintillators
8 Segment Toroidal Magnet
LH_2 Target
Drift Chambers
Triple Pb Collimator System
High Density Shield Wall



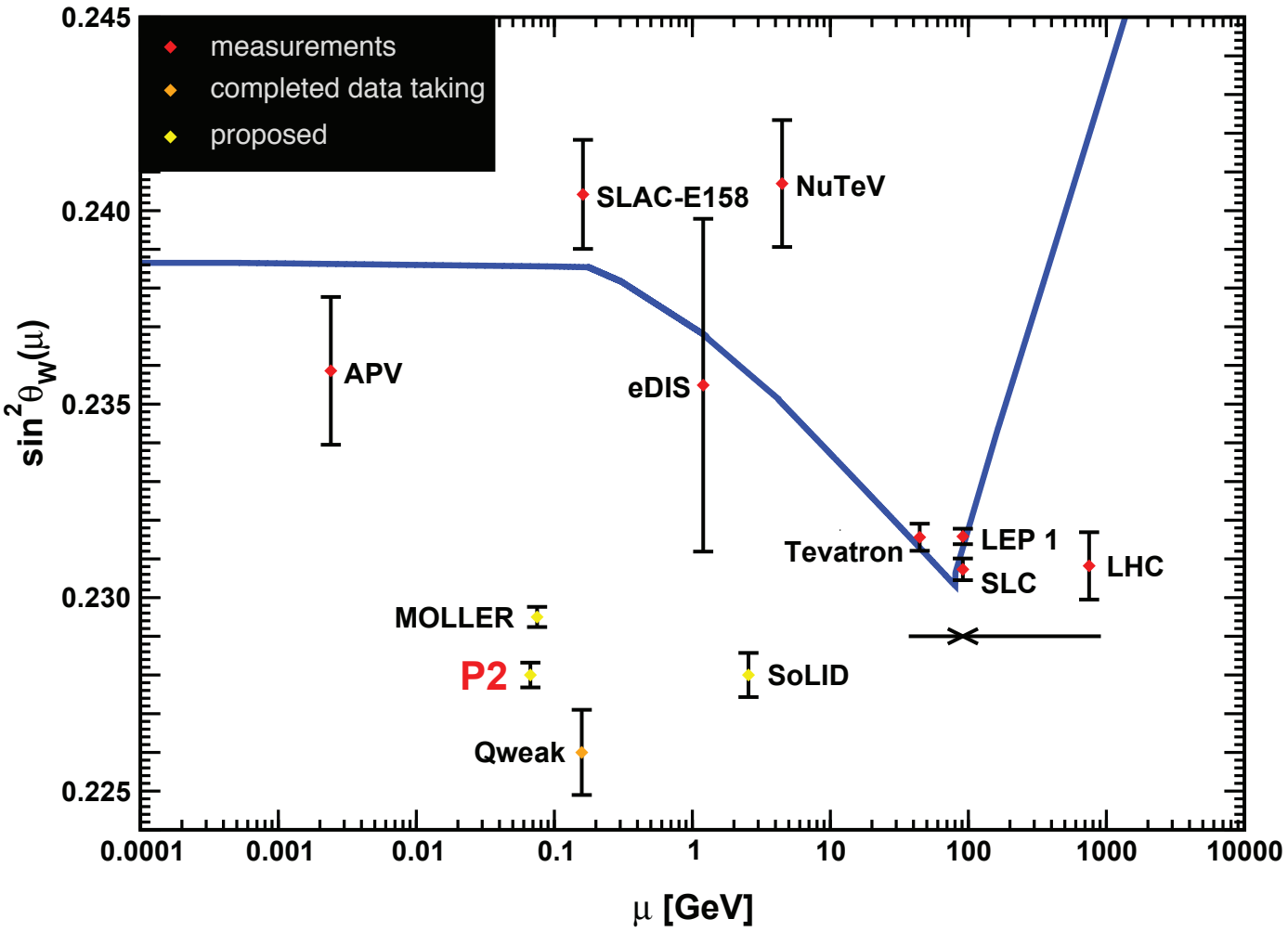
QWeak results (not)



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

End of the preceding part