# $\sin^2\theta_W$ with P2 in Mainz

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JG|U

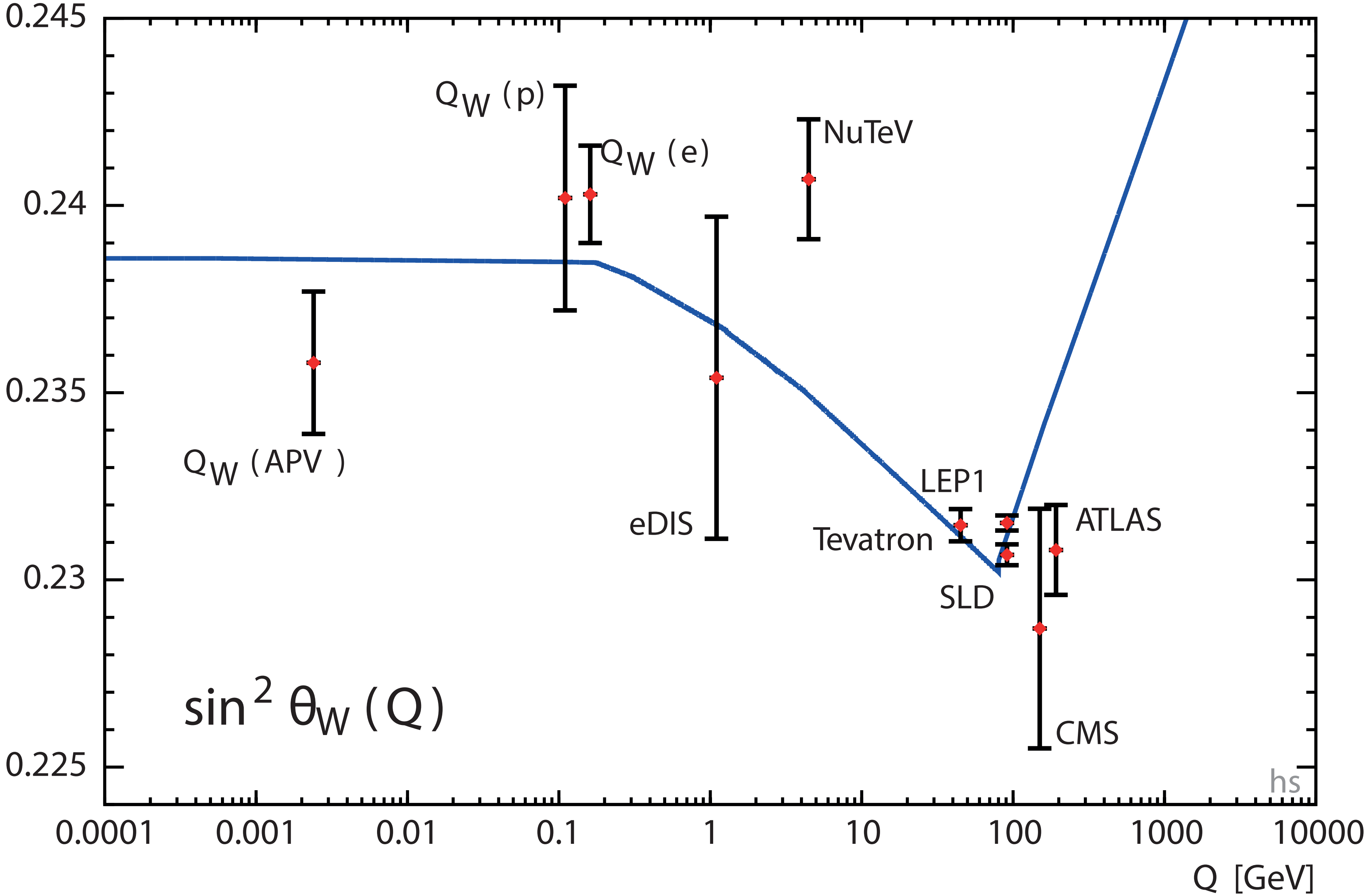
Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

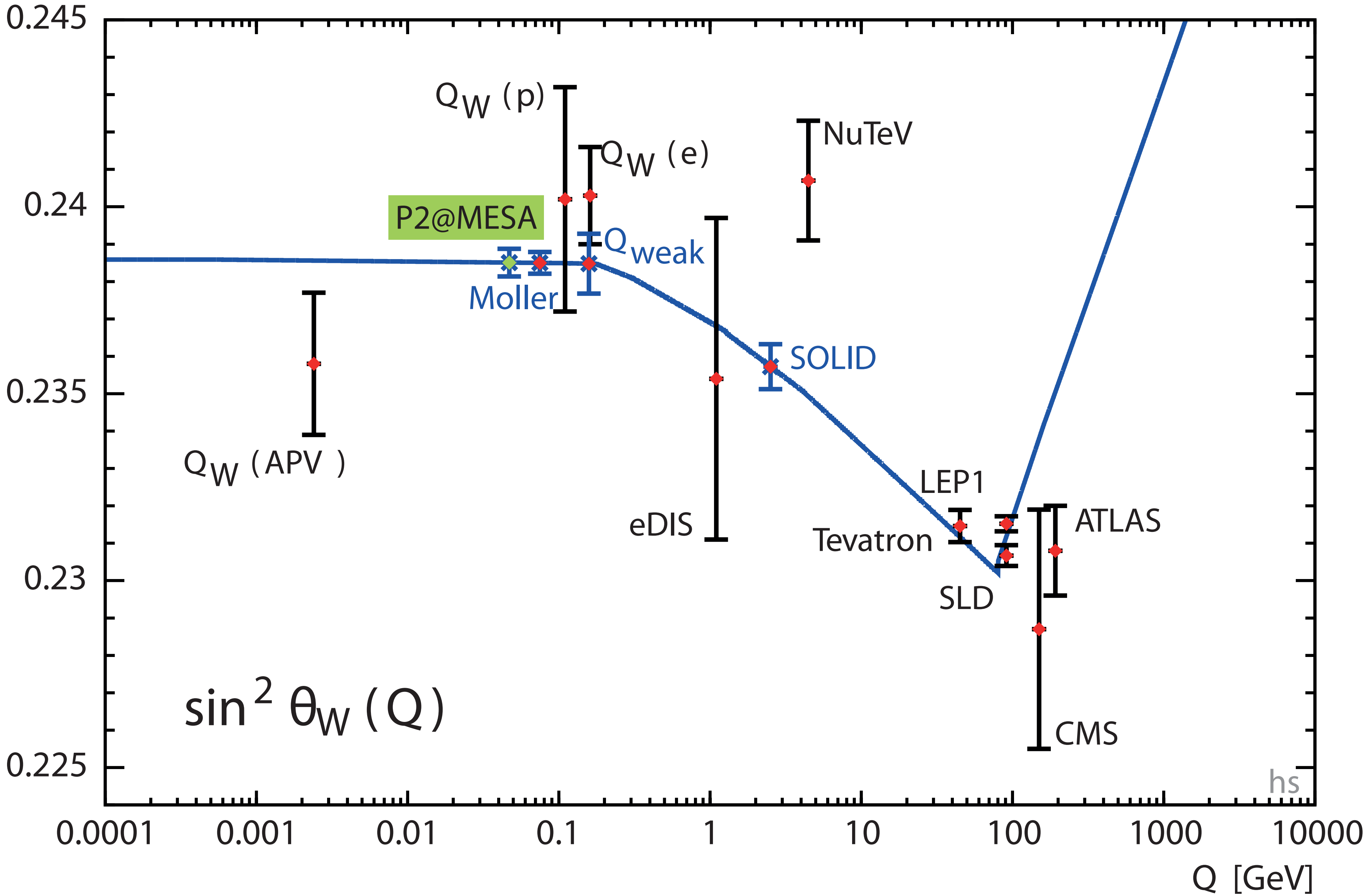
# Overview

- The Idea:
  Precision measurement of and search for new physics with the weak mixing angle
- The Machine:
  Mainz Energy-Recovery Superconducting Accelerator MESA
- The Experiment:
  Parity violating electron scattering with P2

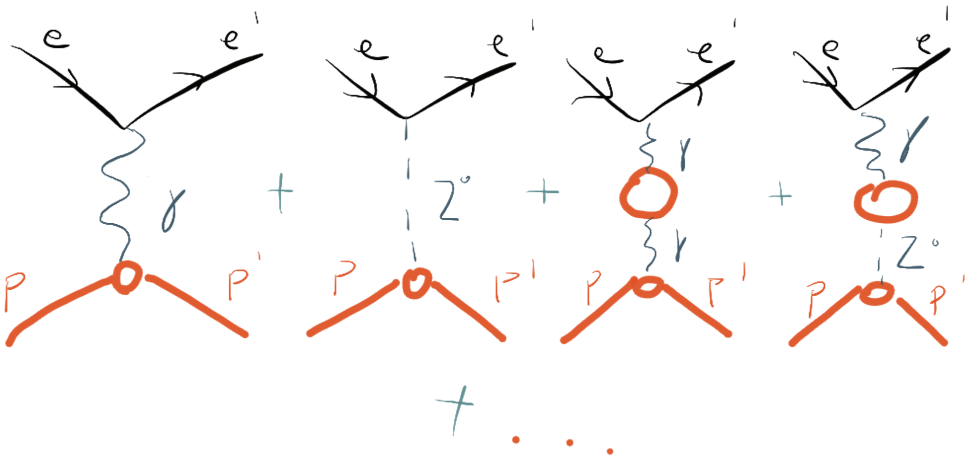
# Scale dependence (running) of $\sin^2\theta_W$

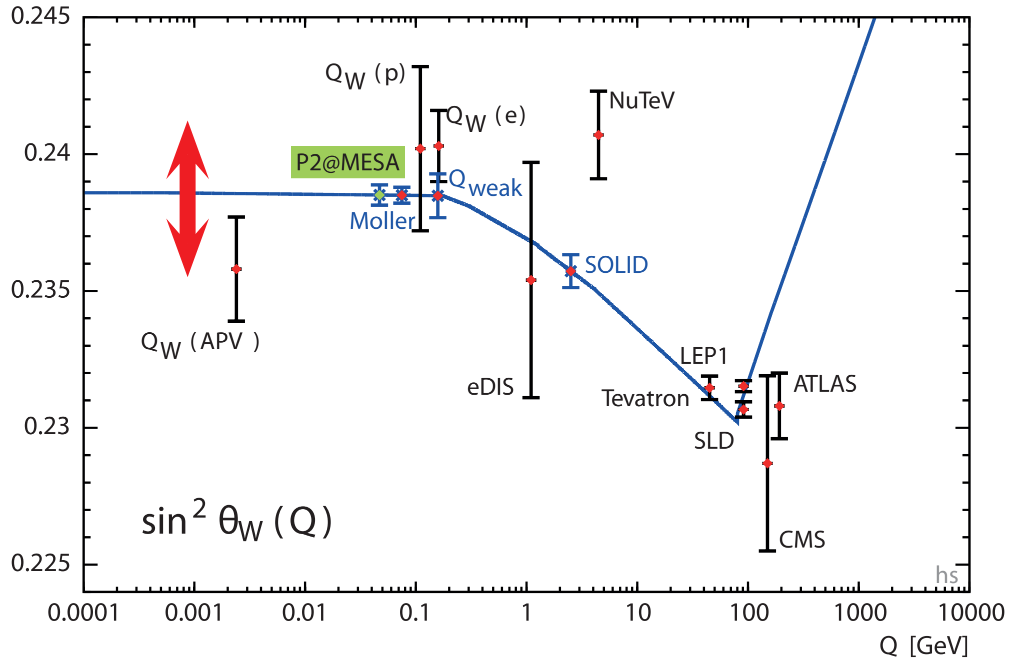


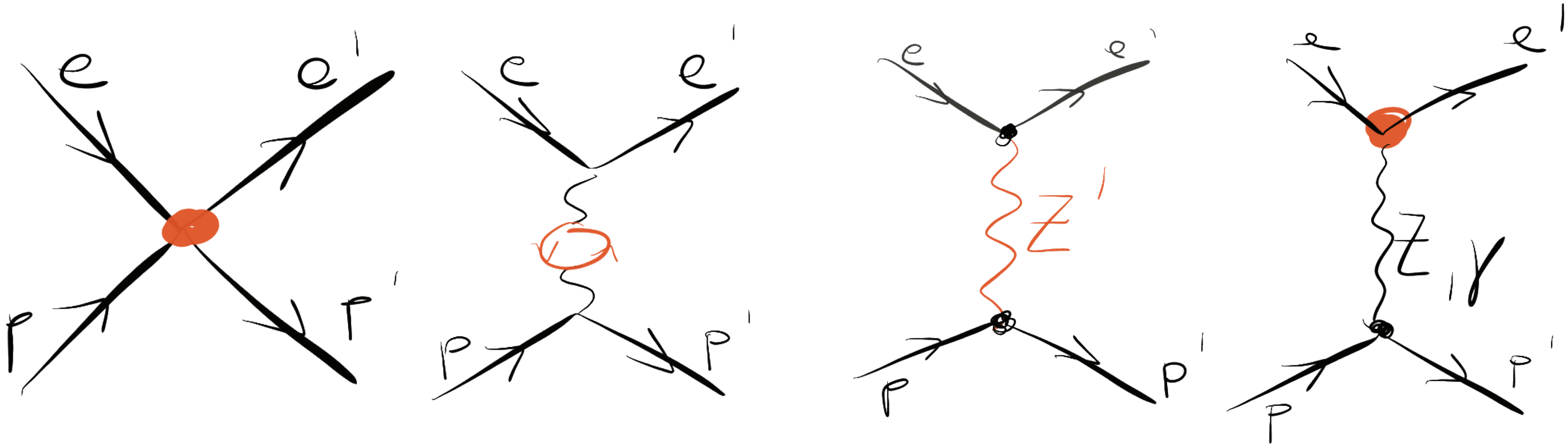
# Scale dependence (running) of $\sin^2\theta_W$



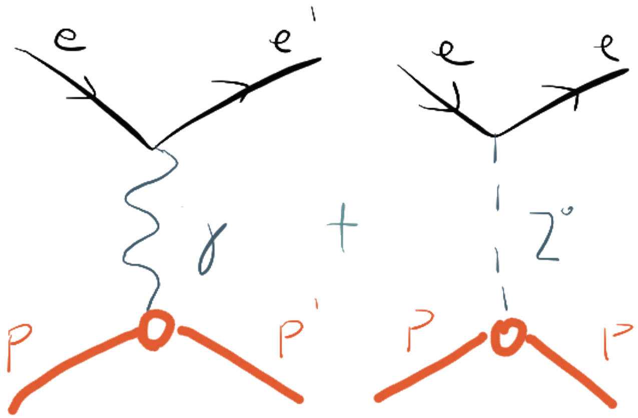
# New Physics in the running

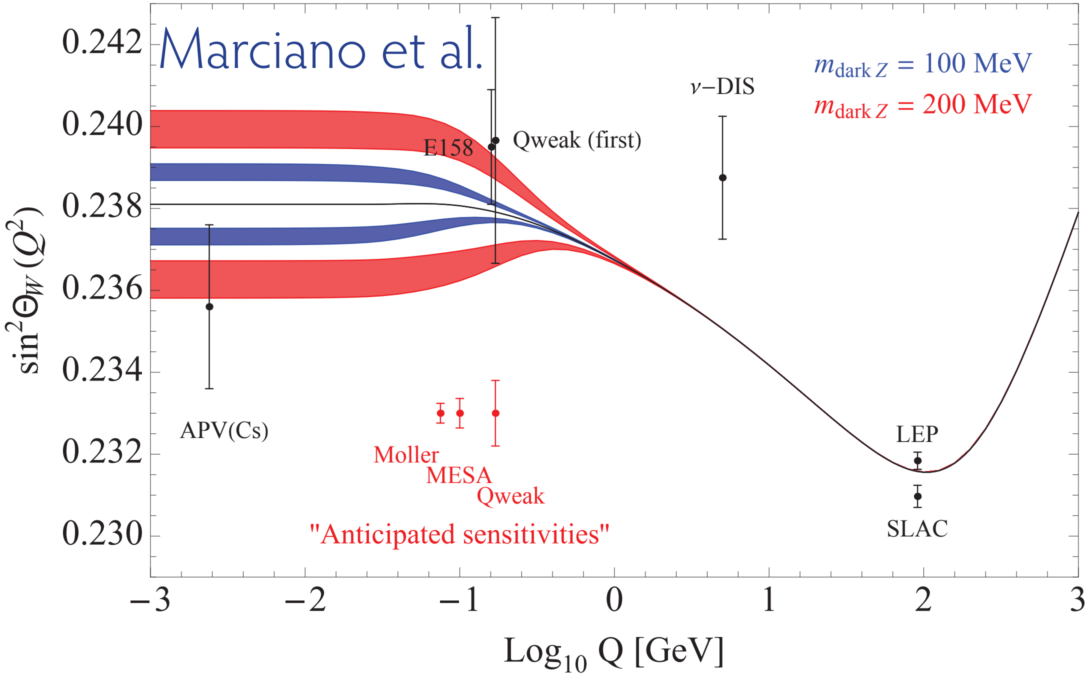


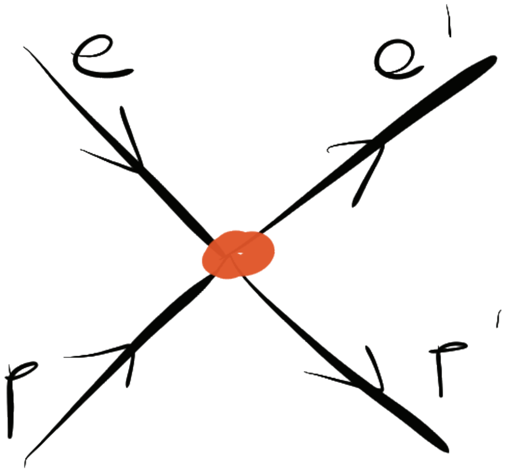



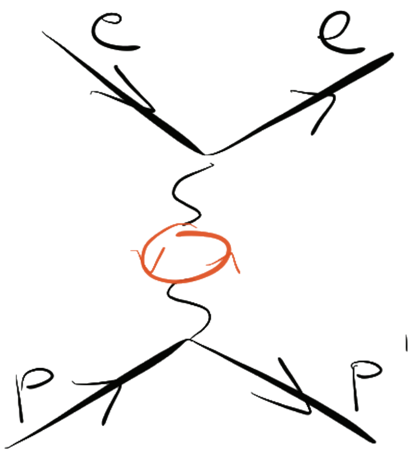



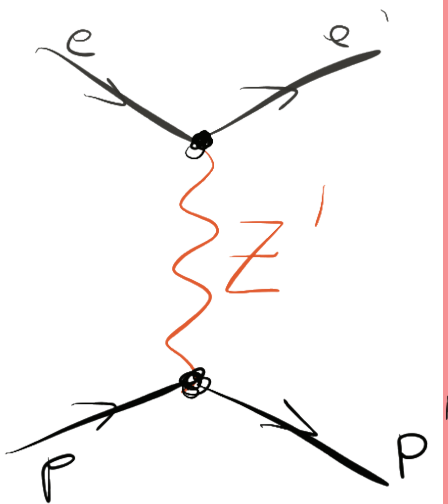
# Dark Z in mixing

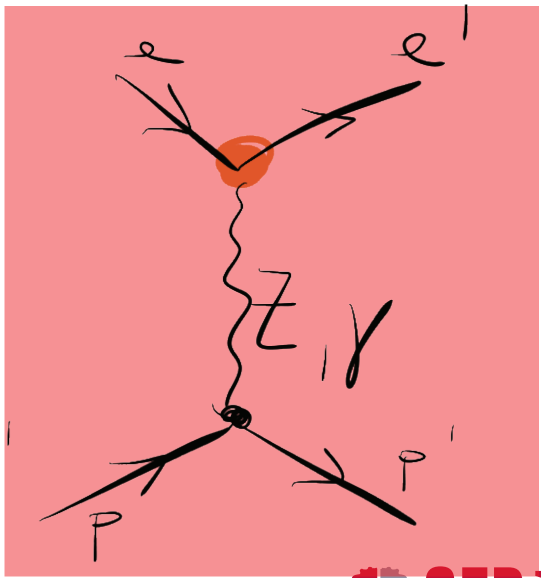




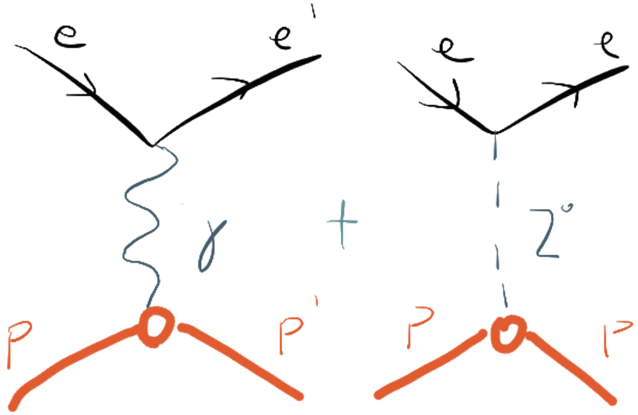









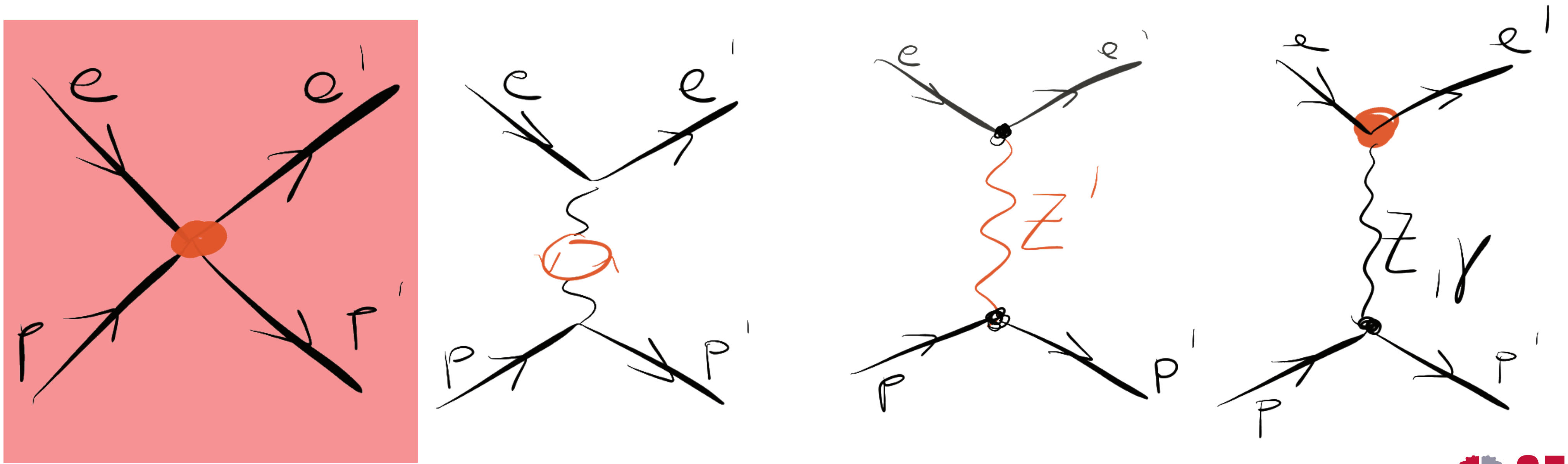
# Contact Interactions




Contact interactions up to

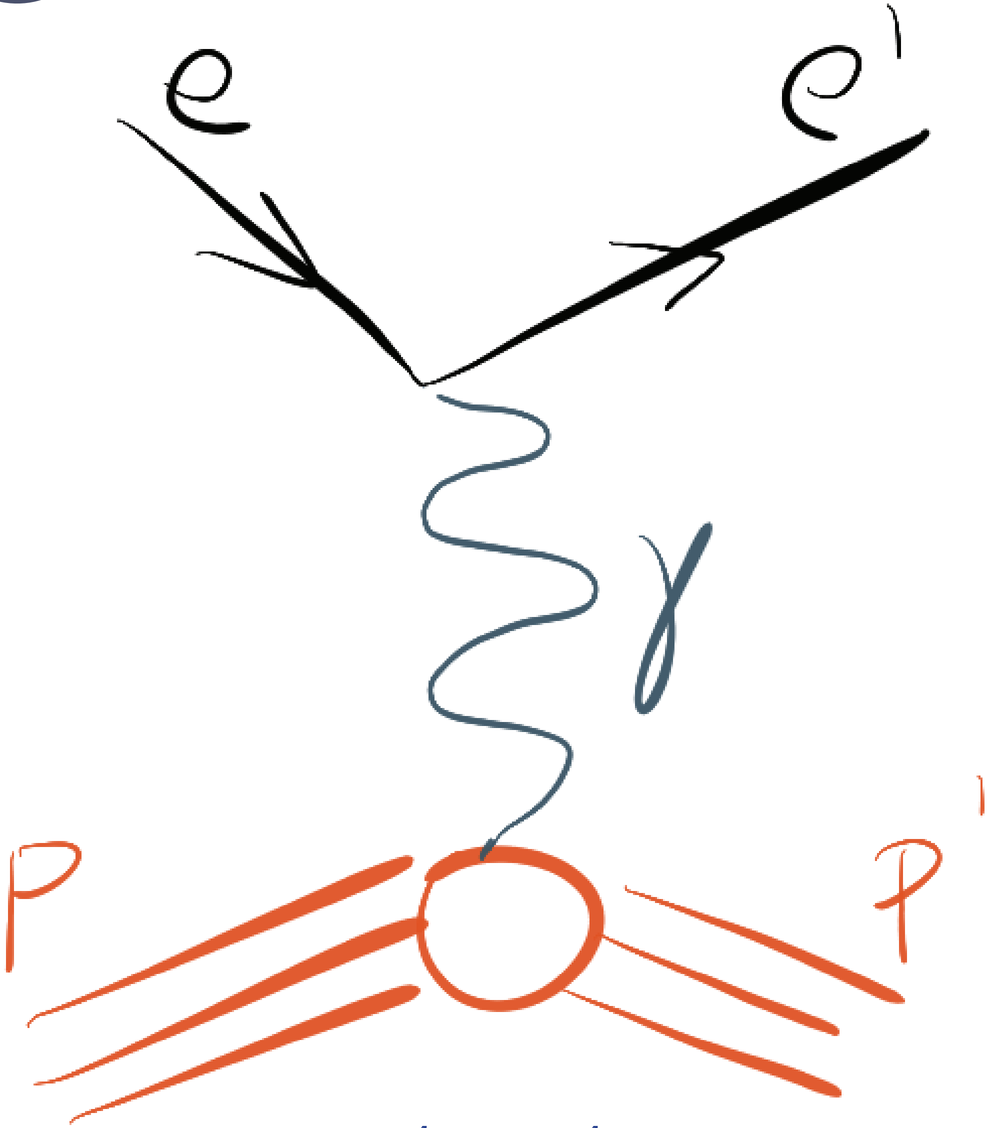
**49 TeV**

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



# Measuring the weak charge

# Weak mixing angle and charges



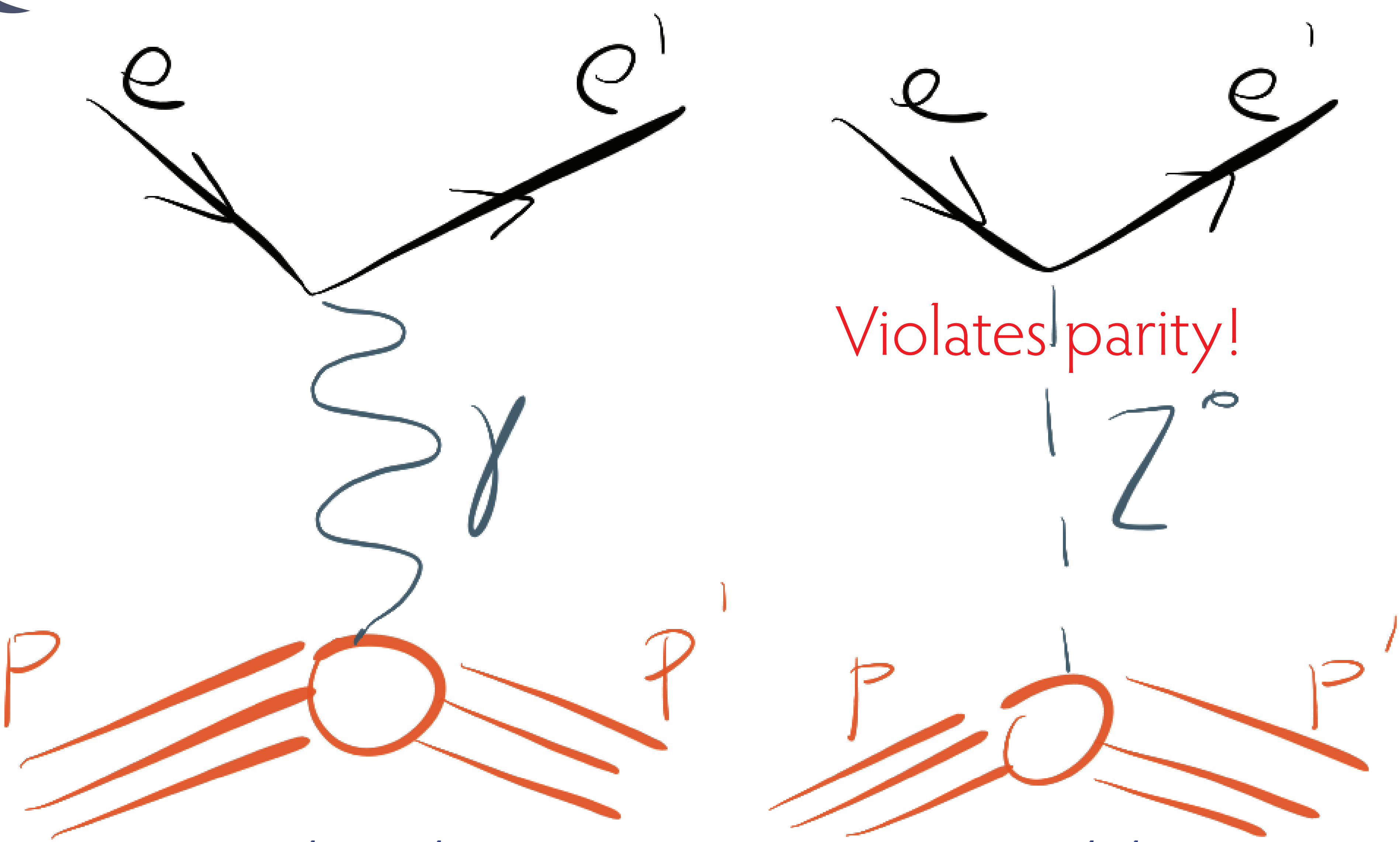

Proton electric charge

+1


Proton weak charge

$1 - 4 \sin^2\theta_W$

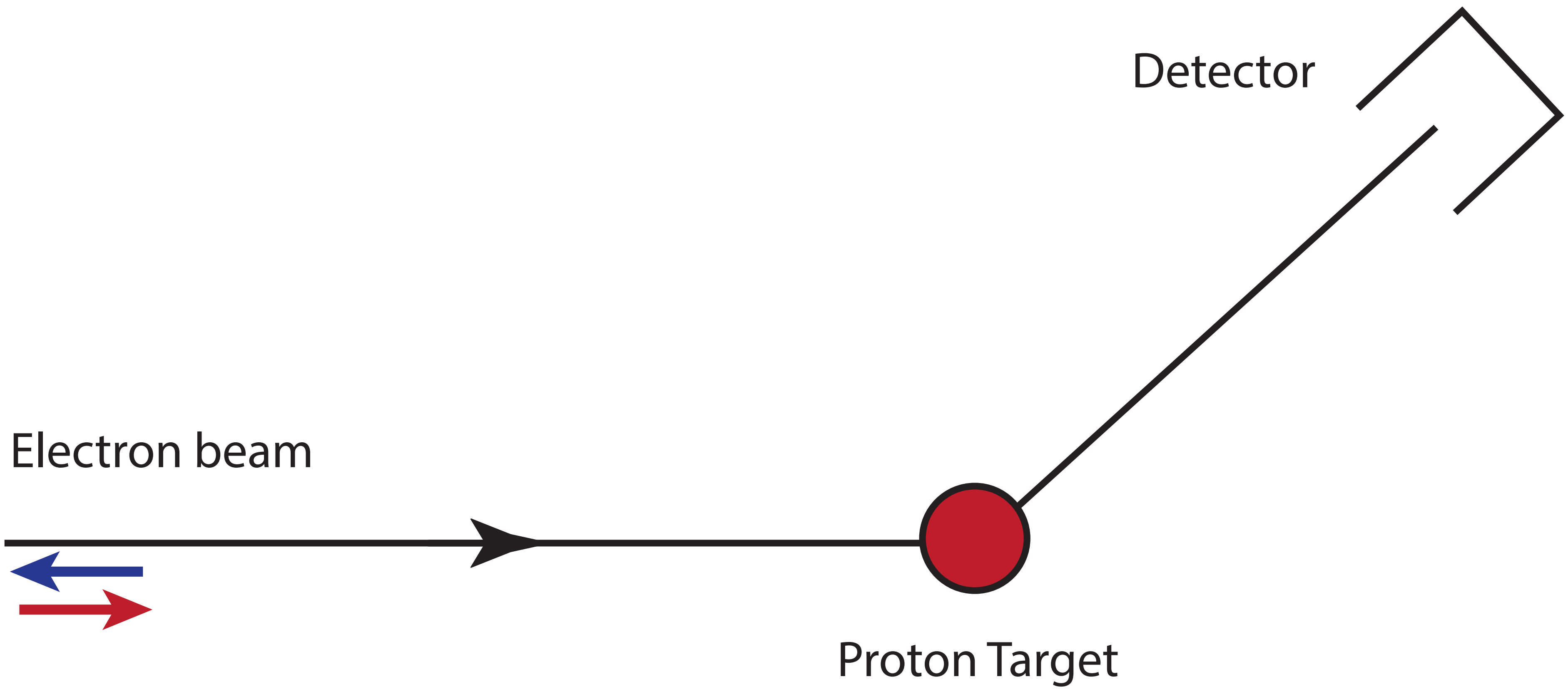
# Weak mixing angle and charges




Proton electric charge
+1

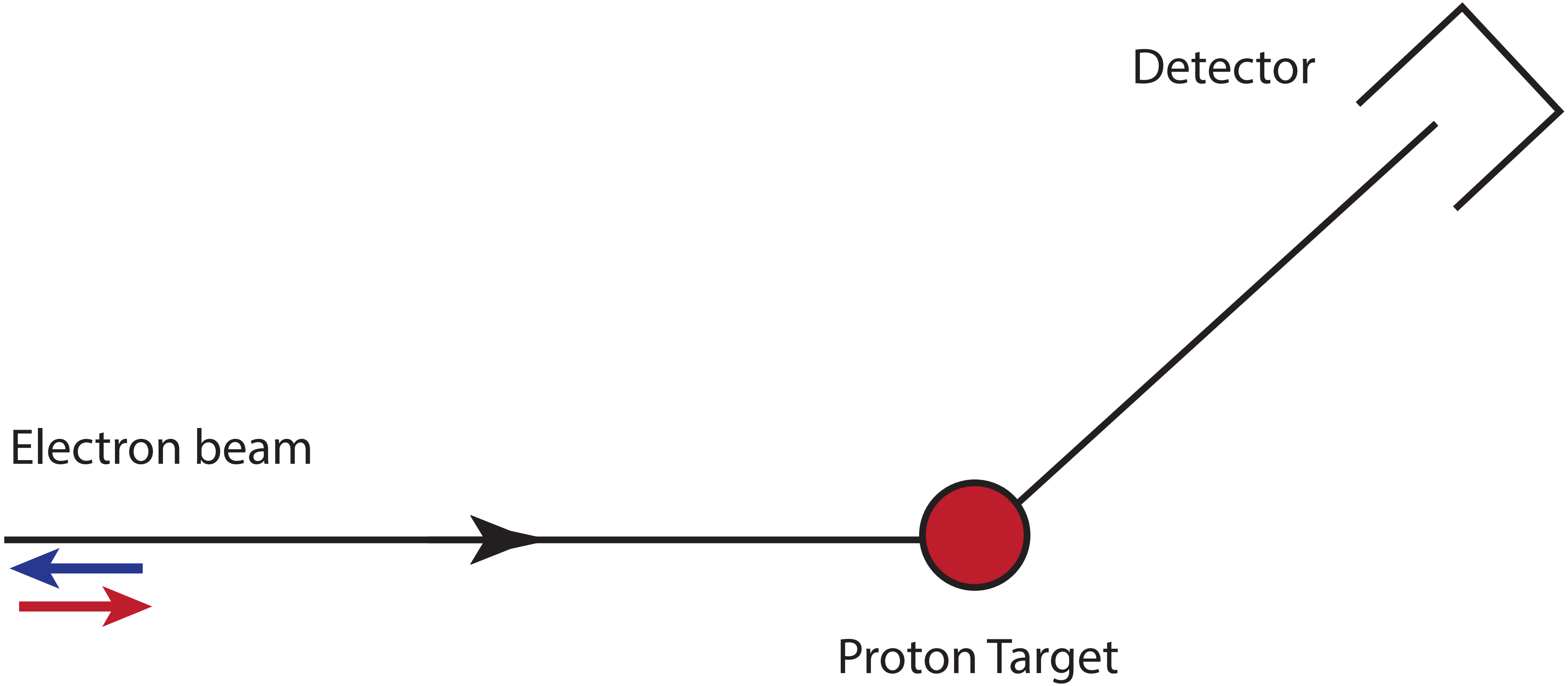
Proton weak charge
$1 - 4\sin^2\theta_W$

# Parity violating electron scattering



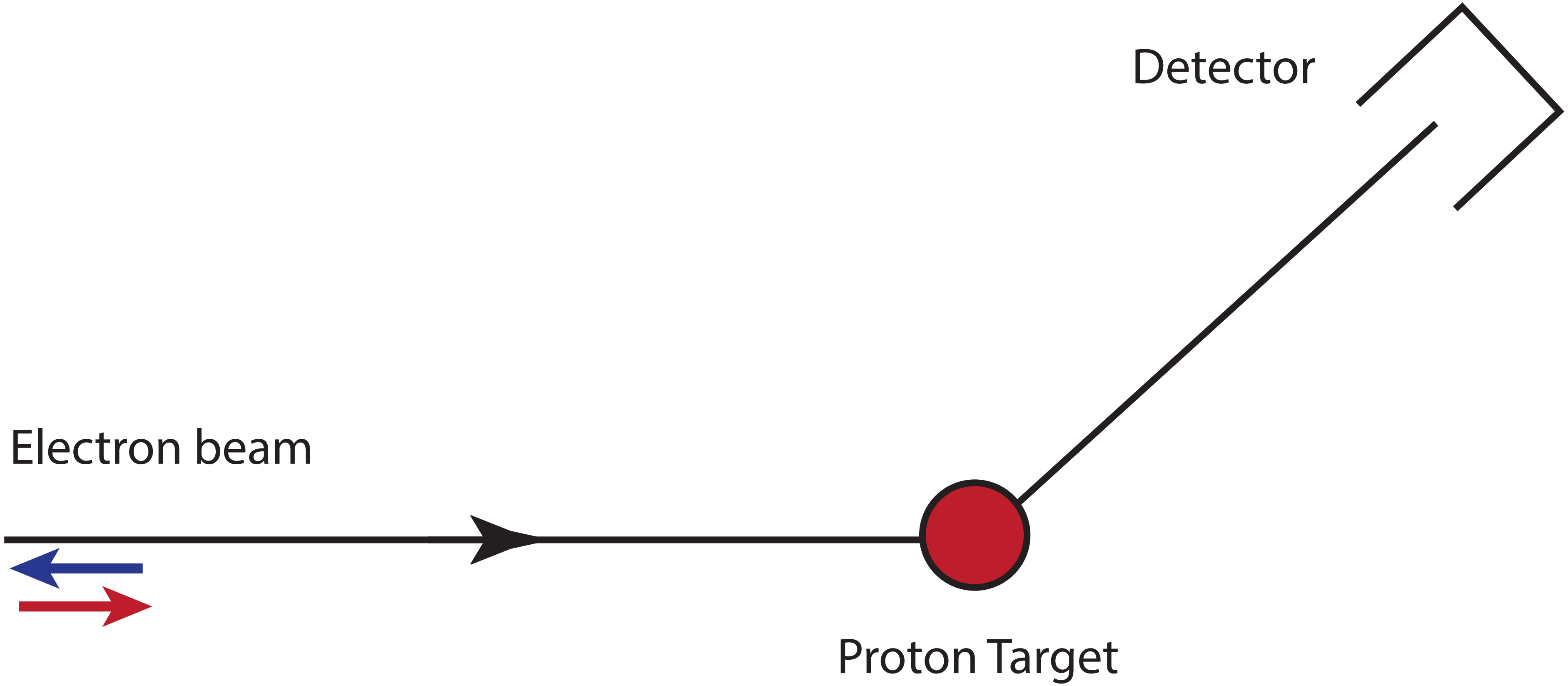
# Parity violating electron scattering

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



# Parity violating electron scattering

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



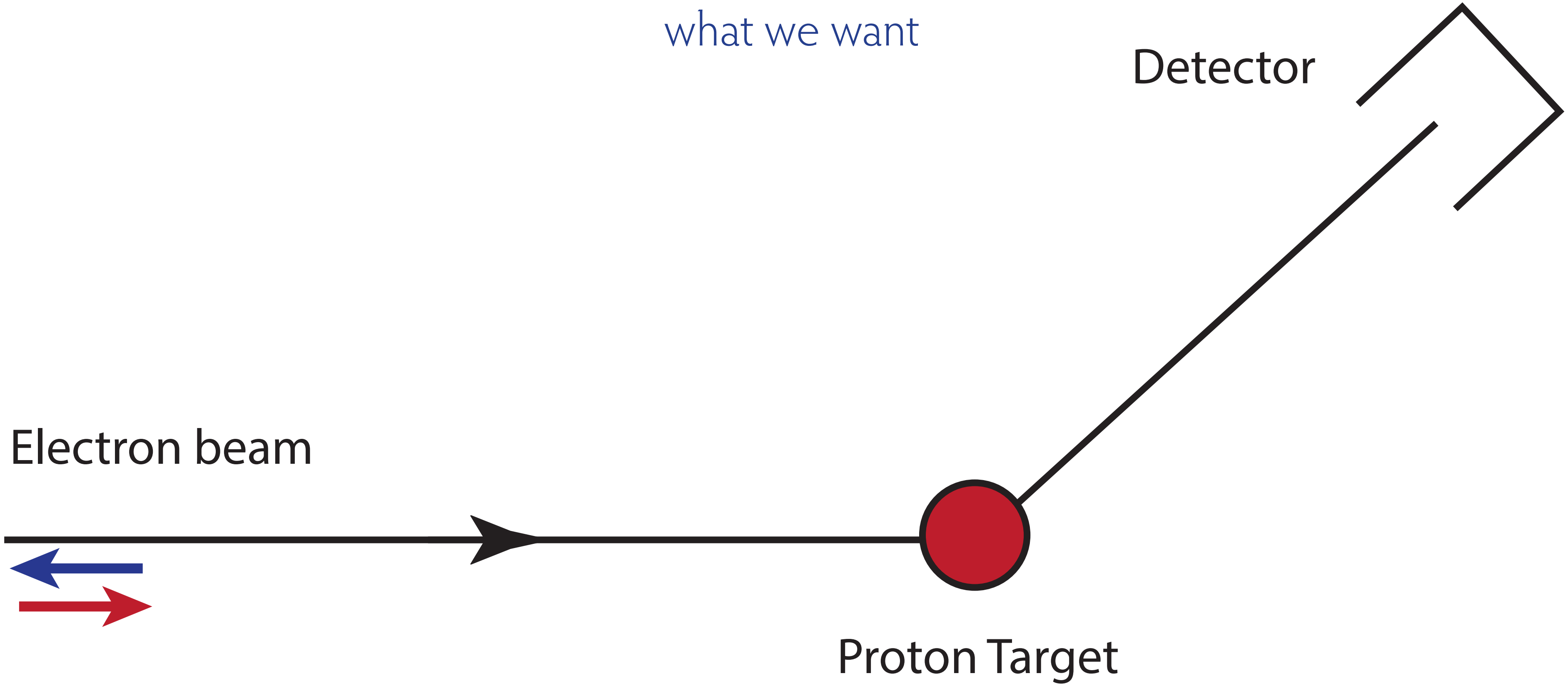
# Parity violating electron scattering

Momentum transfer sets scale

Proton structure - small nuisance if $Q^2$ small

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

Weak charge - what we want



# Parity violating electron scattering

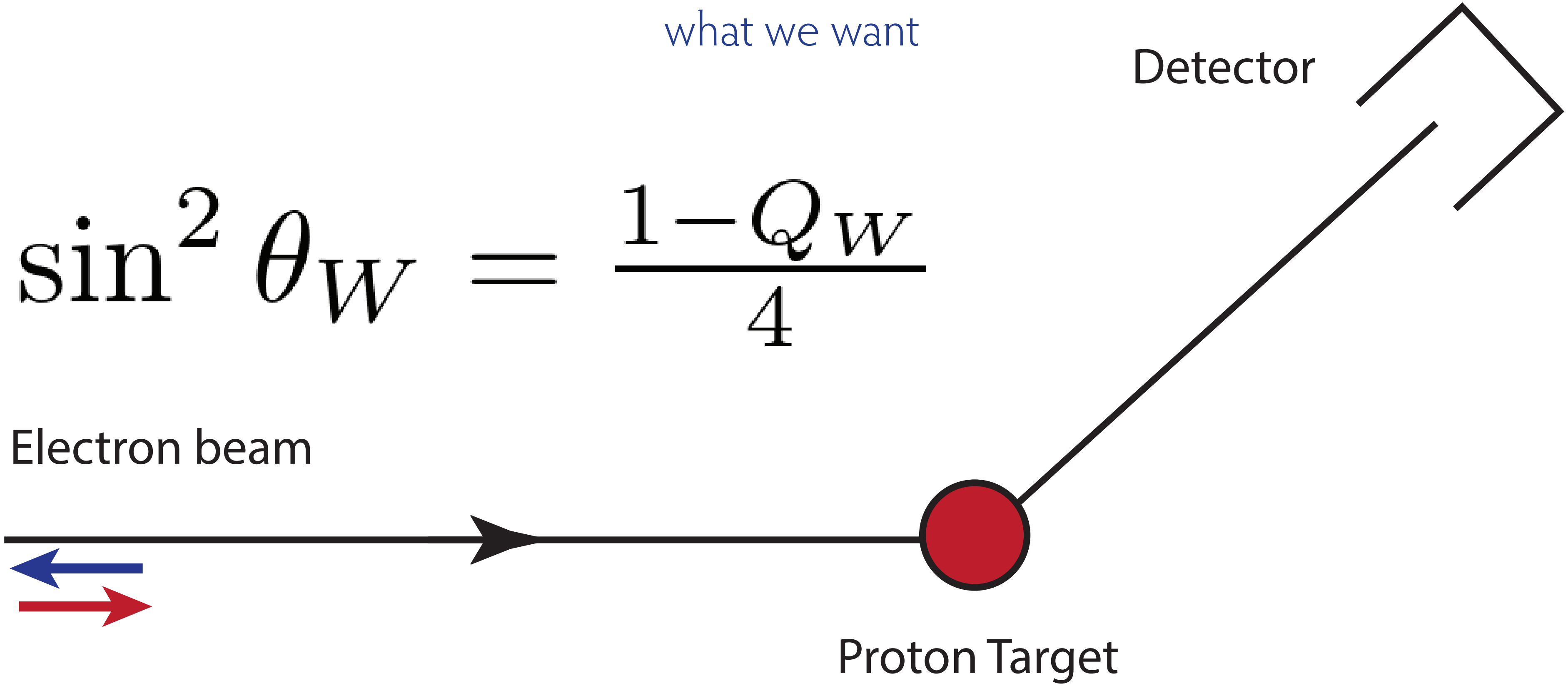
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

Momentum transfer sets scale → $Q^2$

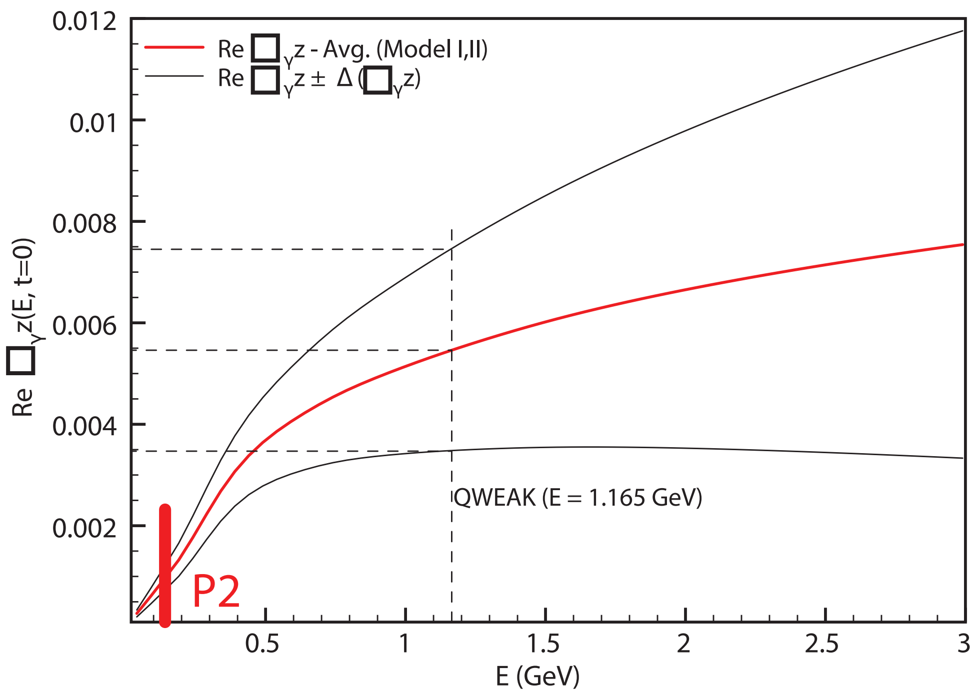
Proton structure - small nuisance if $Q^2$ small → $F(Q^2)$

Weak charge - what we want → $Q_W$

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

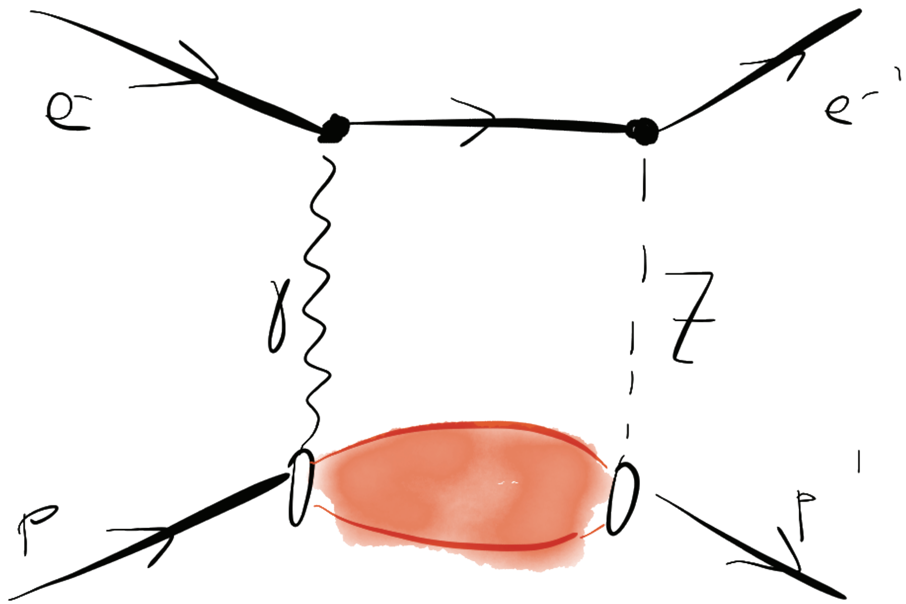


# γ-Z box graphs




[Gorchstein, Horowitz, Ramsey-Musolf 2011]

- Large uncertainty due to hadronic uncertainty
- Uncertainty rises with beam energy



# 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

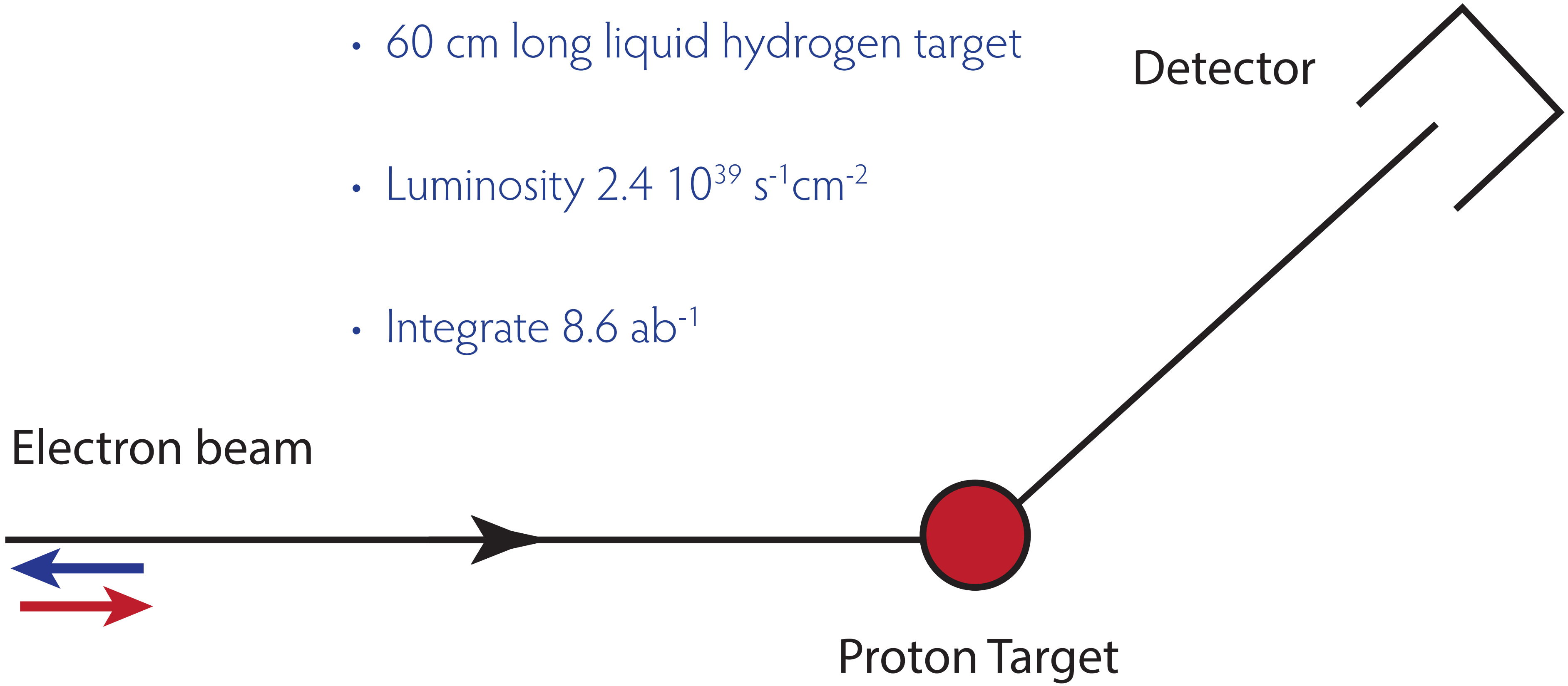
$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

- 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...

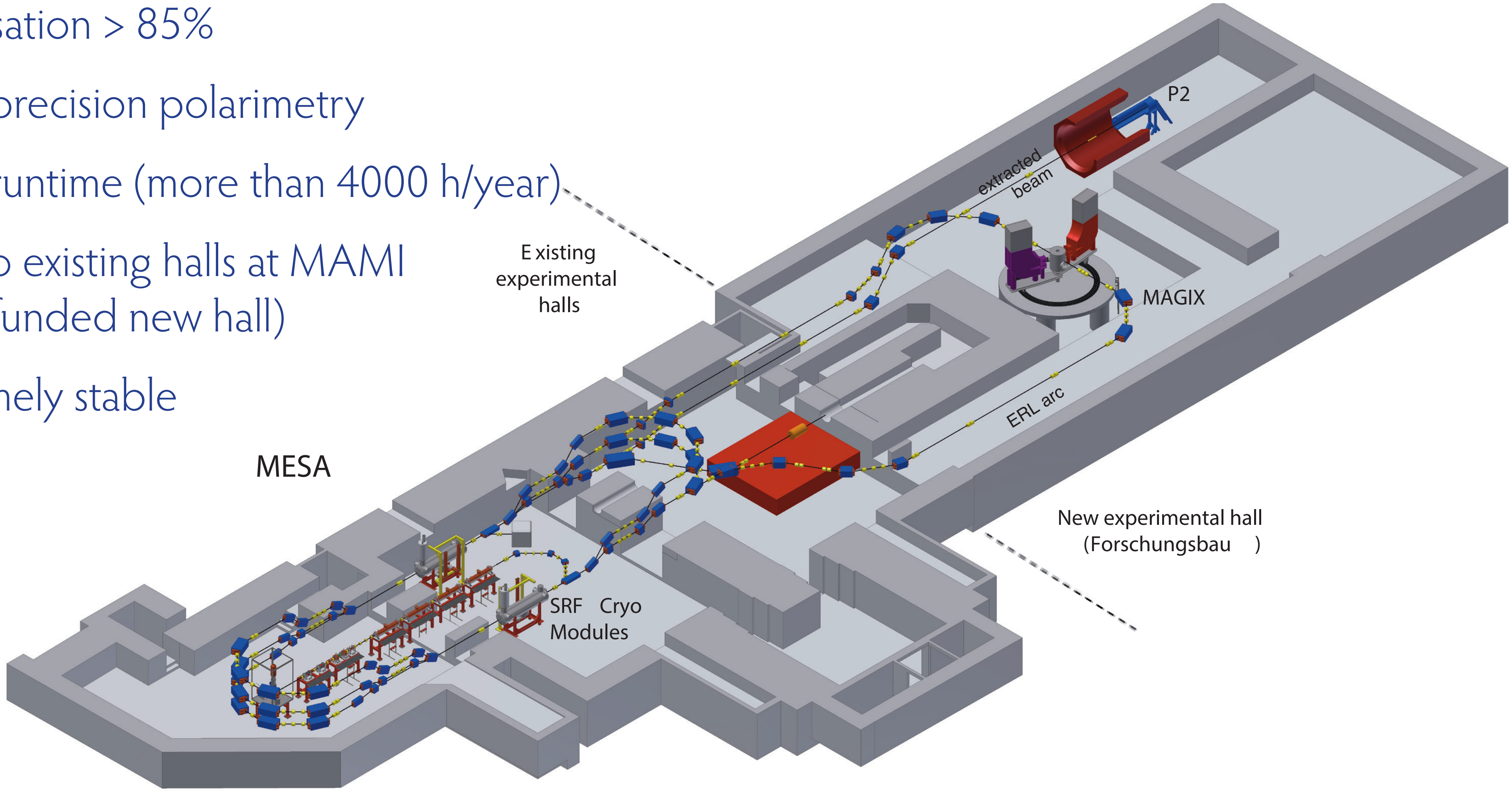
If you cannot rent it, build it:

# 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 (plus funded new hall)
- Extremely stable



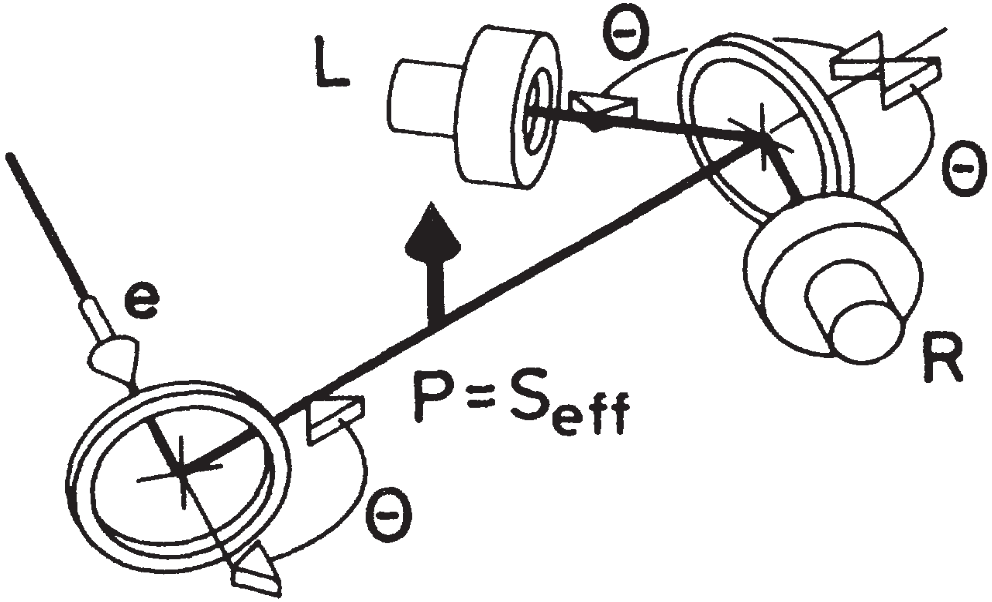
# Stability Requirements

The main worry are beam fluctuations correlated with the helicity:

| | Achieved at MAMI | $A_{PV}$ 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 |

Currently testing beam monitoring and feedback at MAMI

# Polarimetry: Double Mott Polarimeter




[Gellerich 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

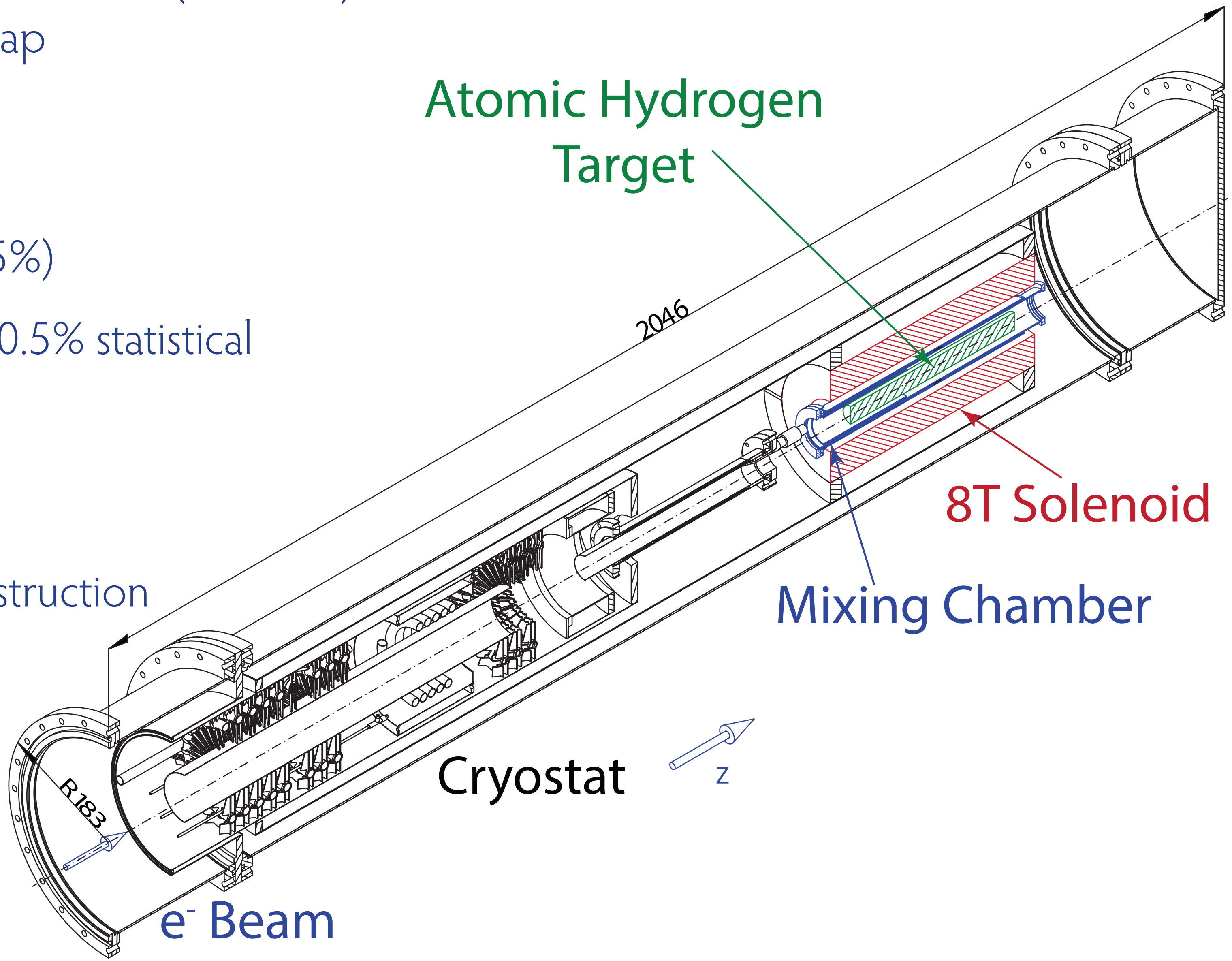
- Invasive measurement at source

# Polarimetry: Hydro-Møller Polarimeter

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

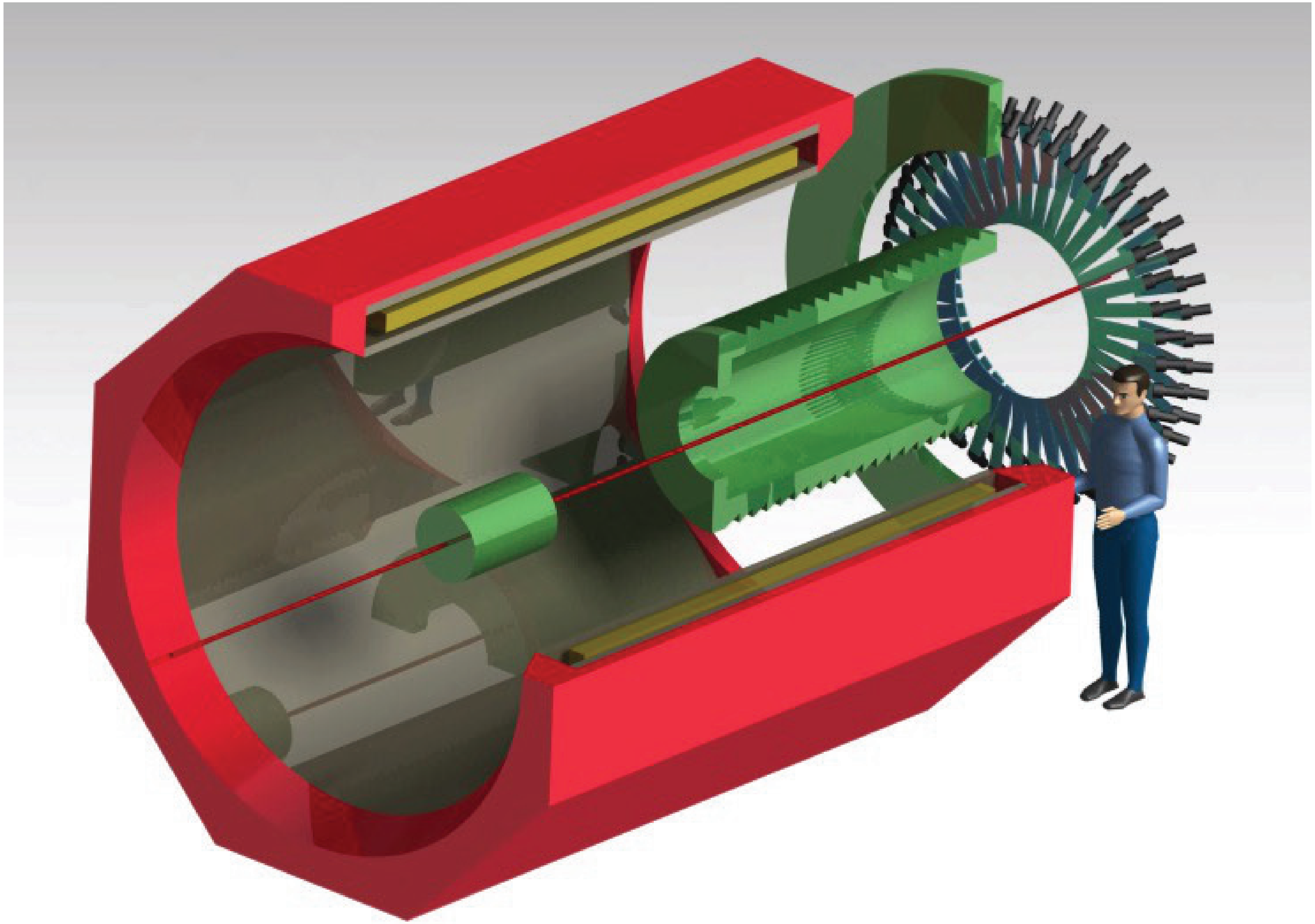
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

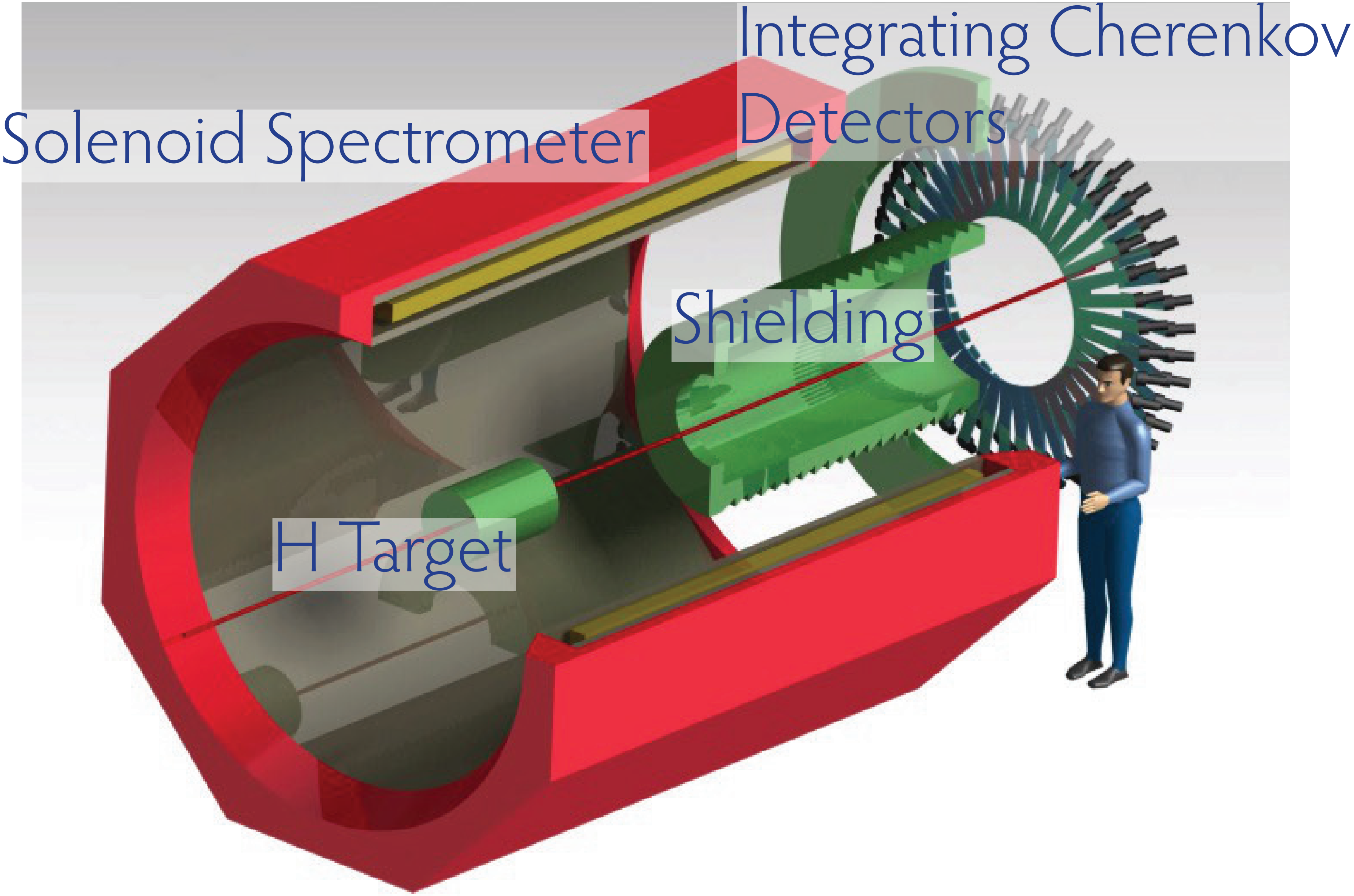
- Cryostat under construction in Mainz



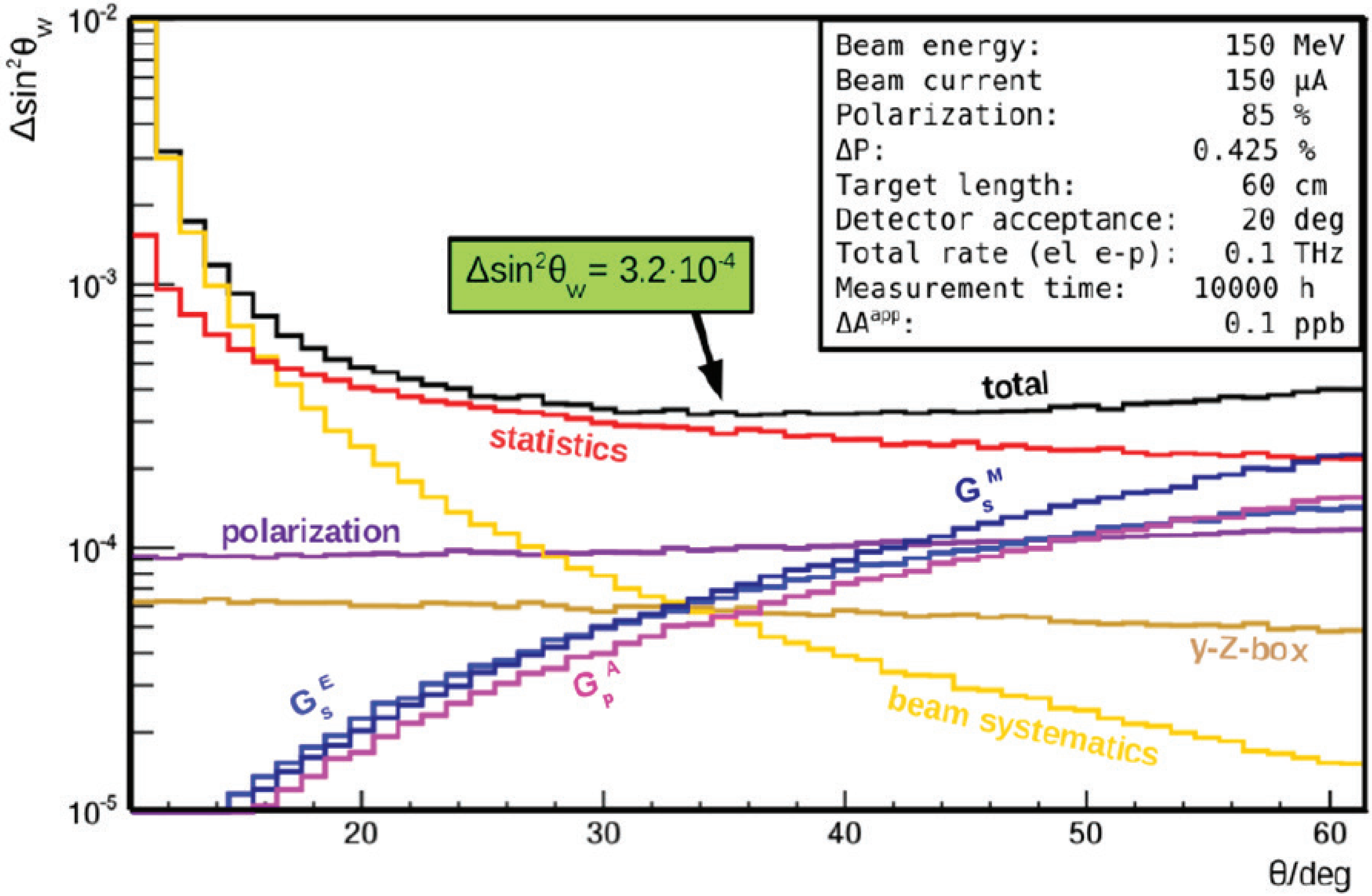
# P2:

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

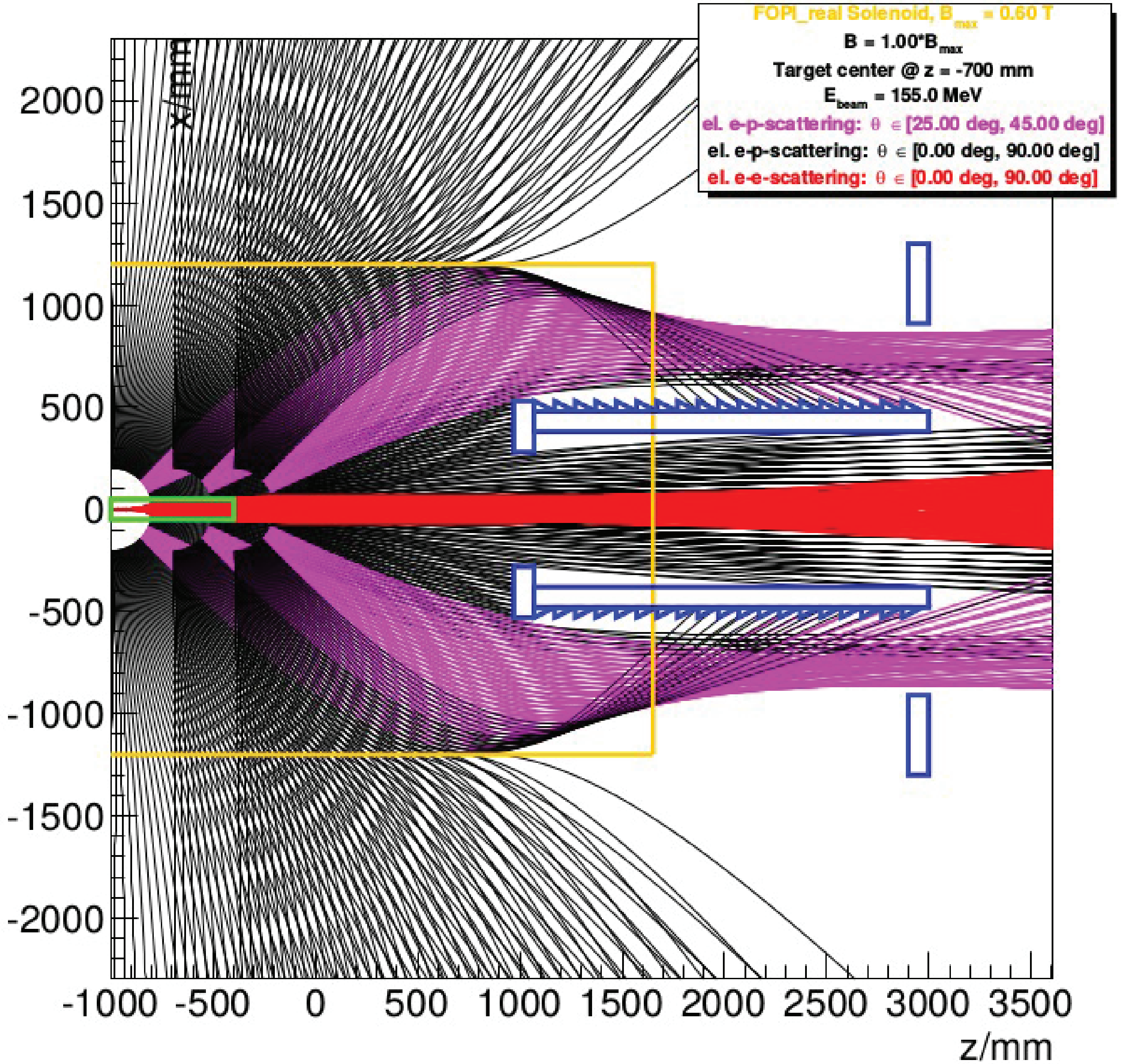



Integrating Cherenkov
Detectors
Solenoid Spectrometer
Shielding
H Target

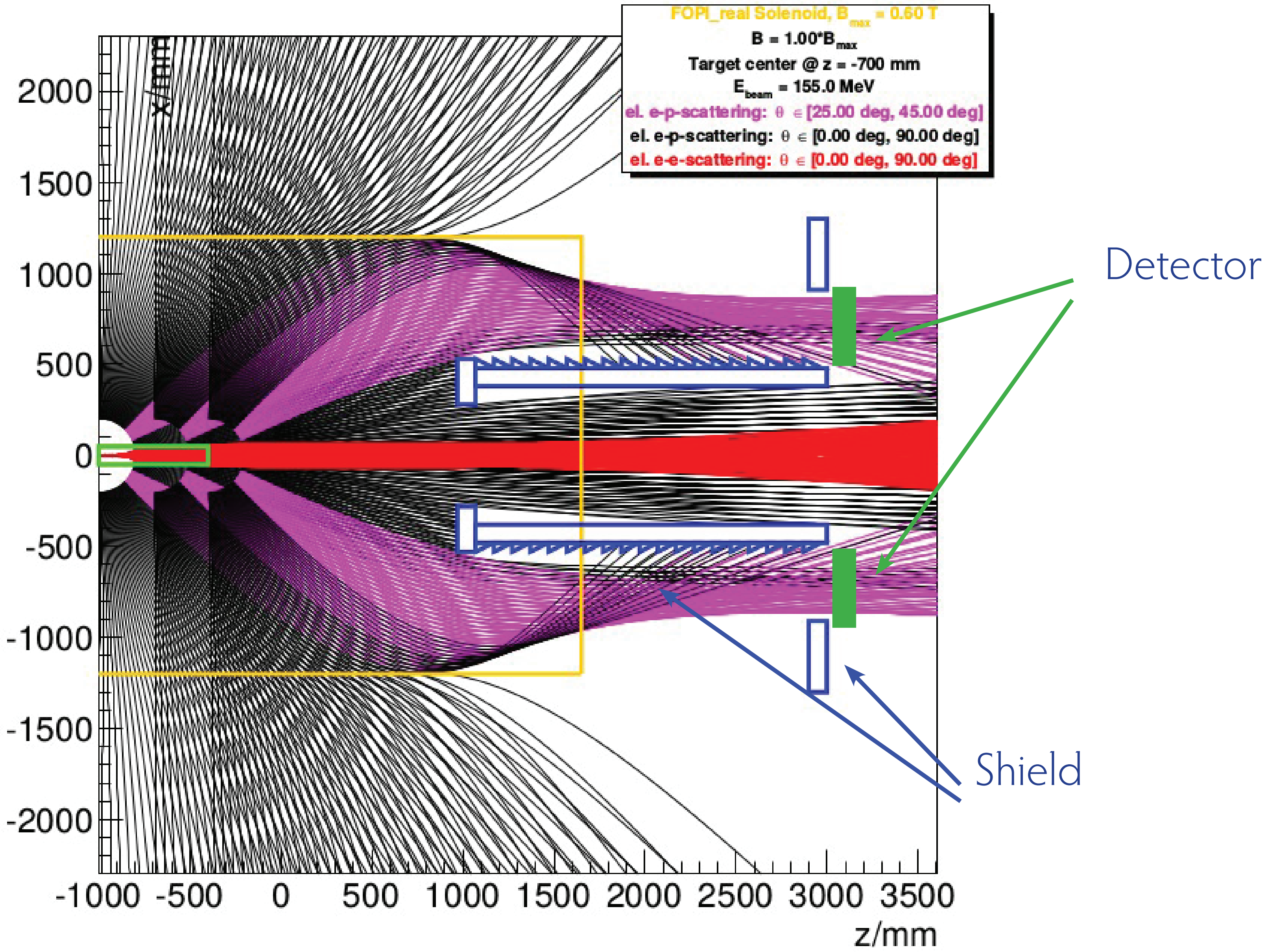
# Choice of scattering angle



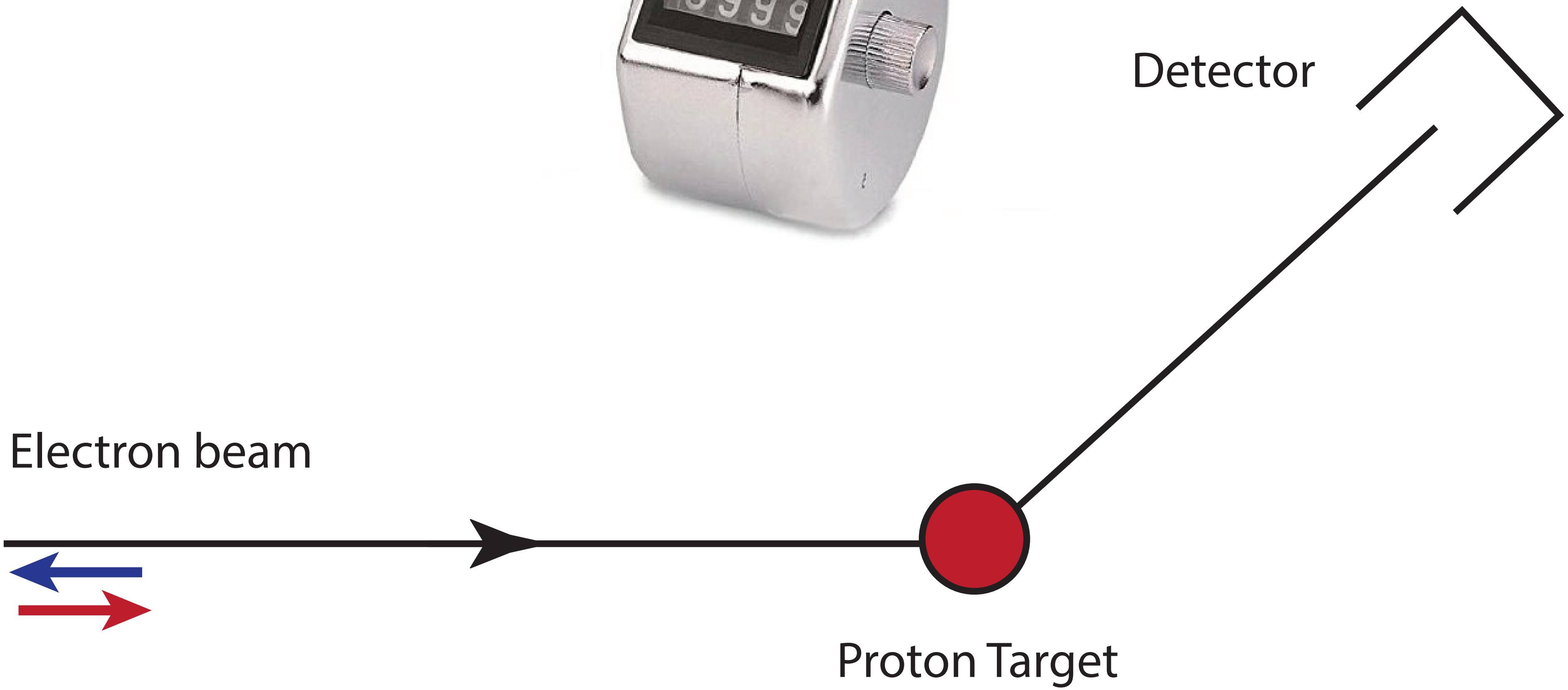
# Solenoid spectrometer



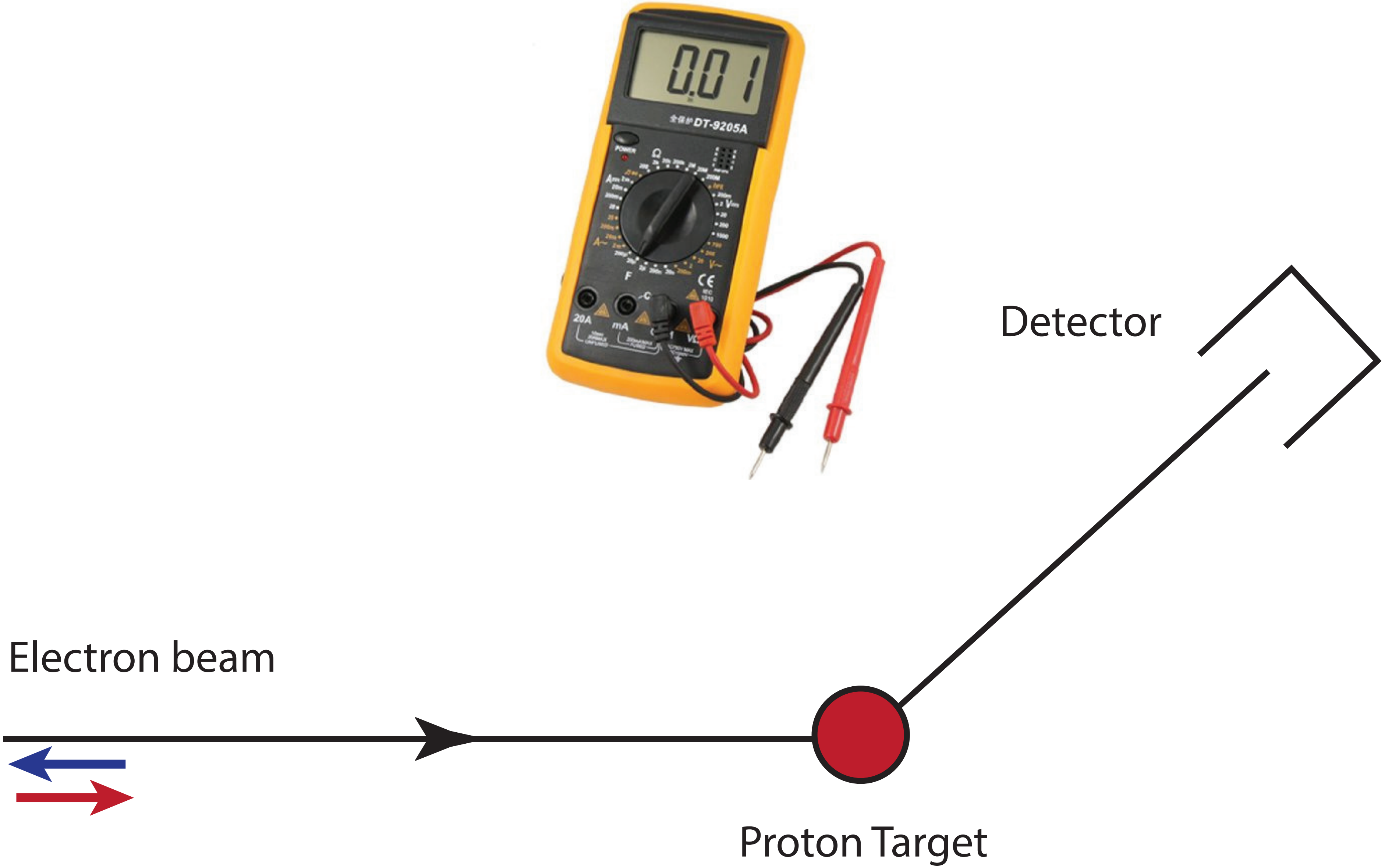
# Solenoid spectrometer



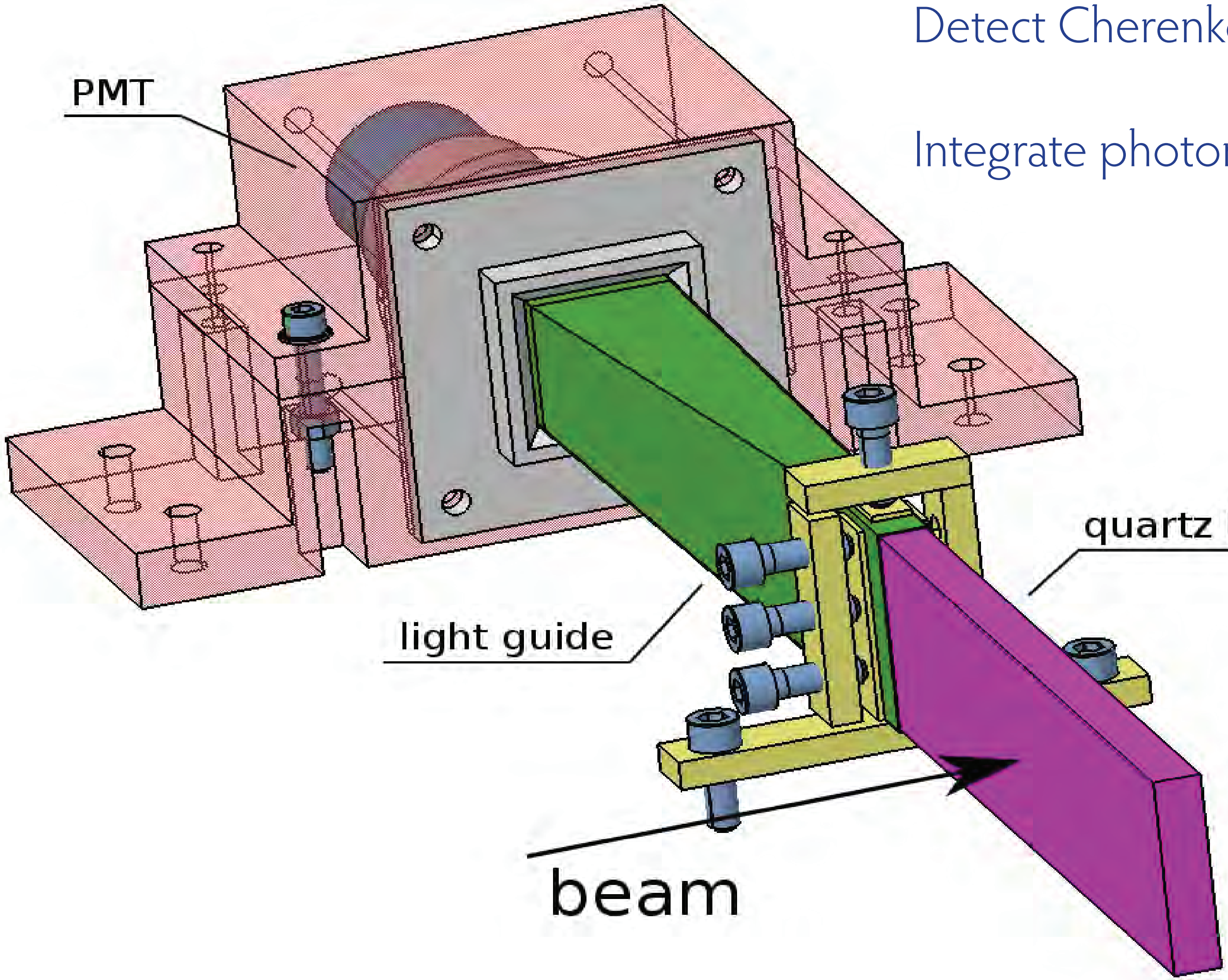
# Counting detectors



# Integrating detectors



# Quartz-Bars & Photomultipliers




Detect Cherenkov-light created by electrons

Integrate photomultiplier current

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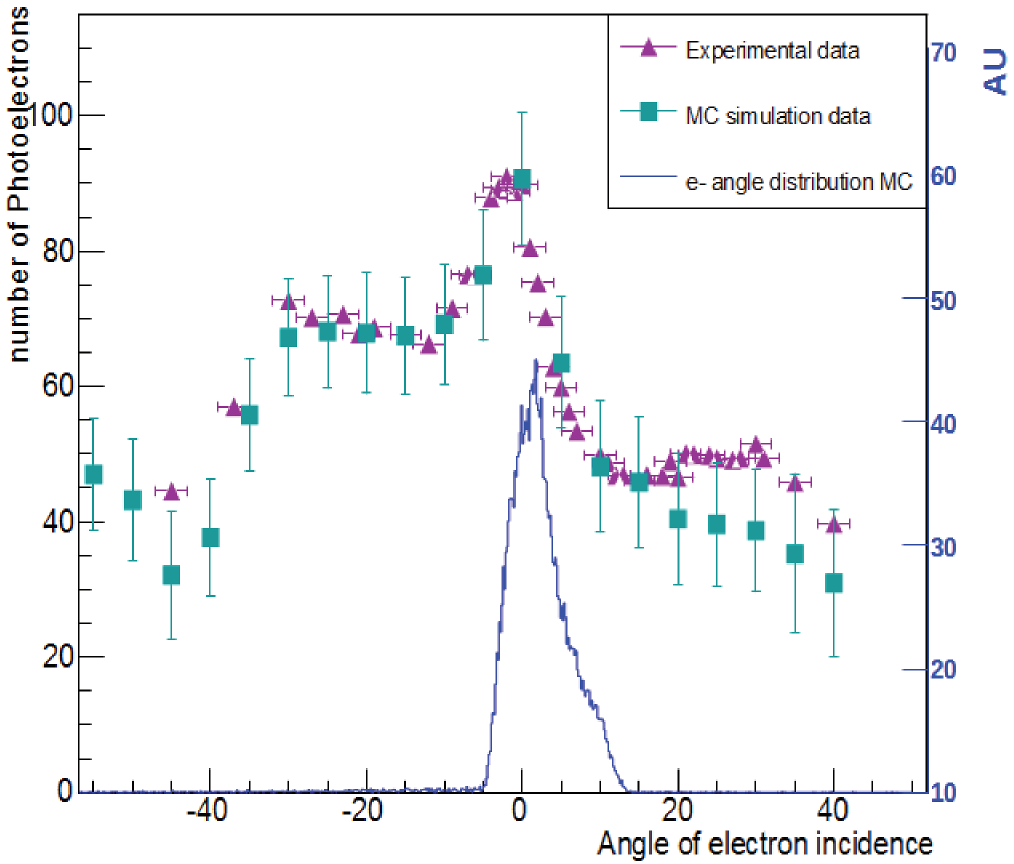
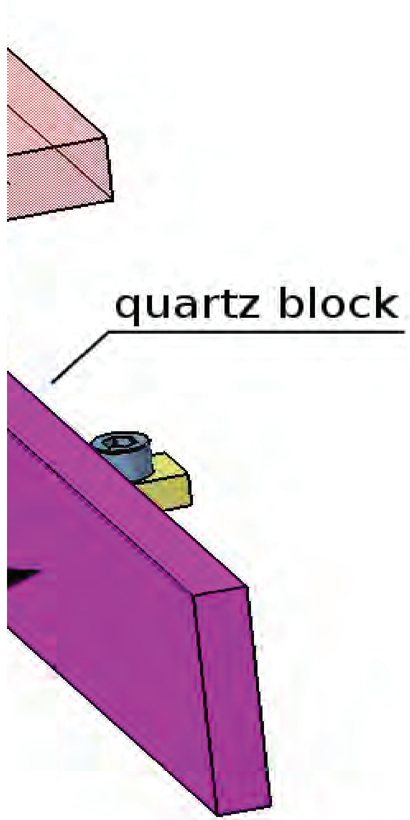
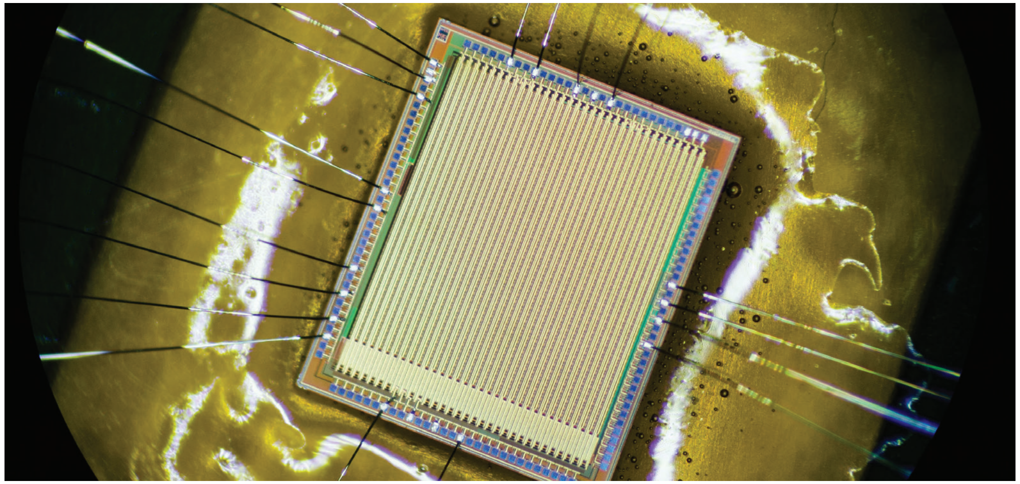


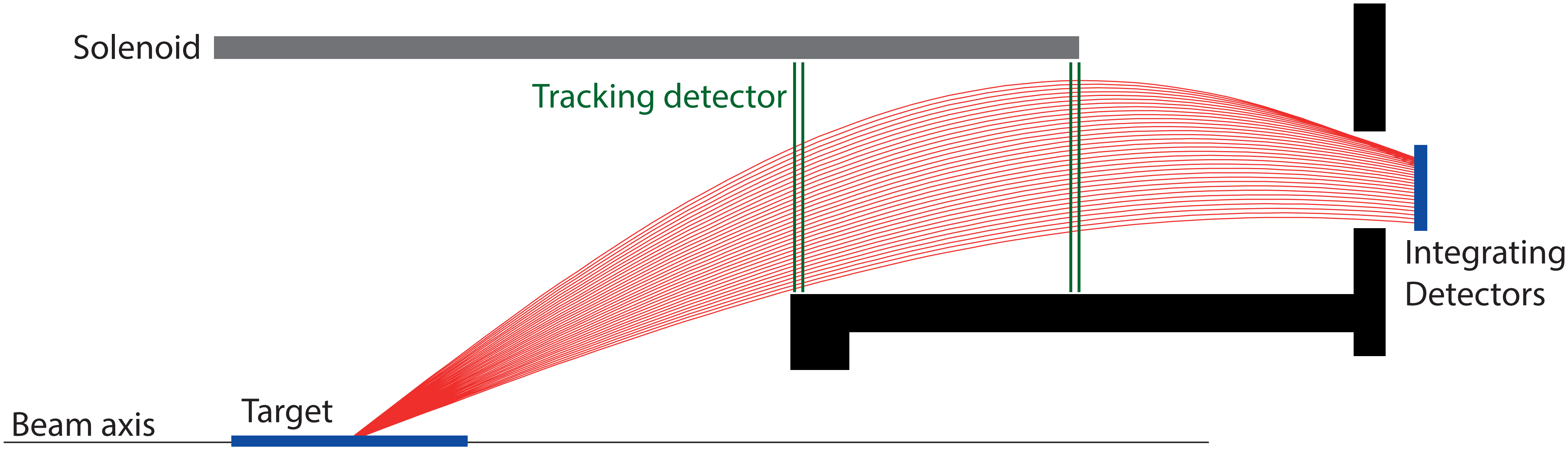



# Tracking detector for $Q^2$ measurement

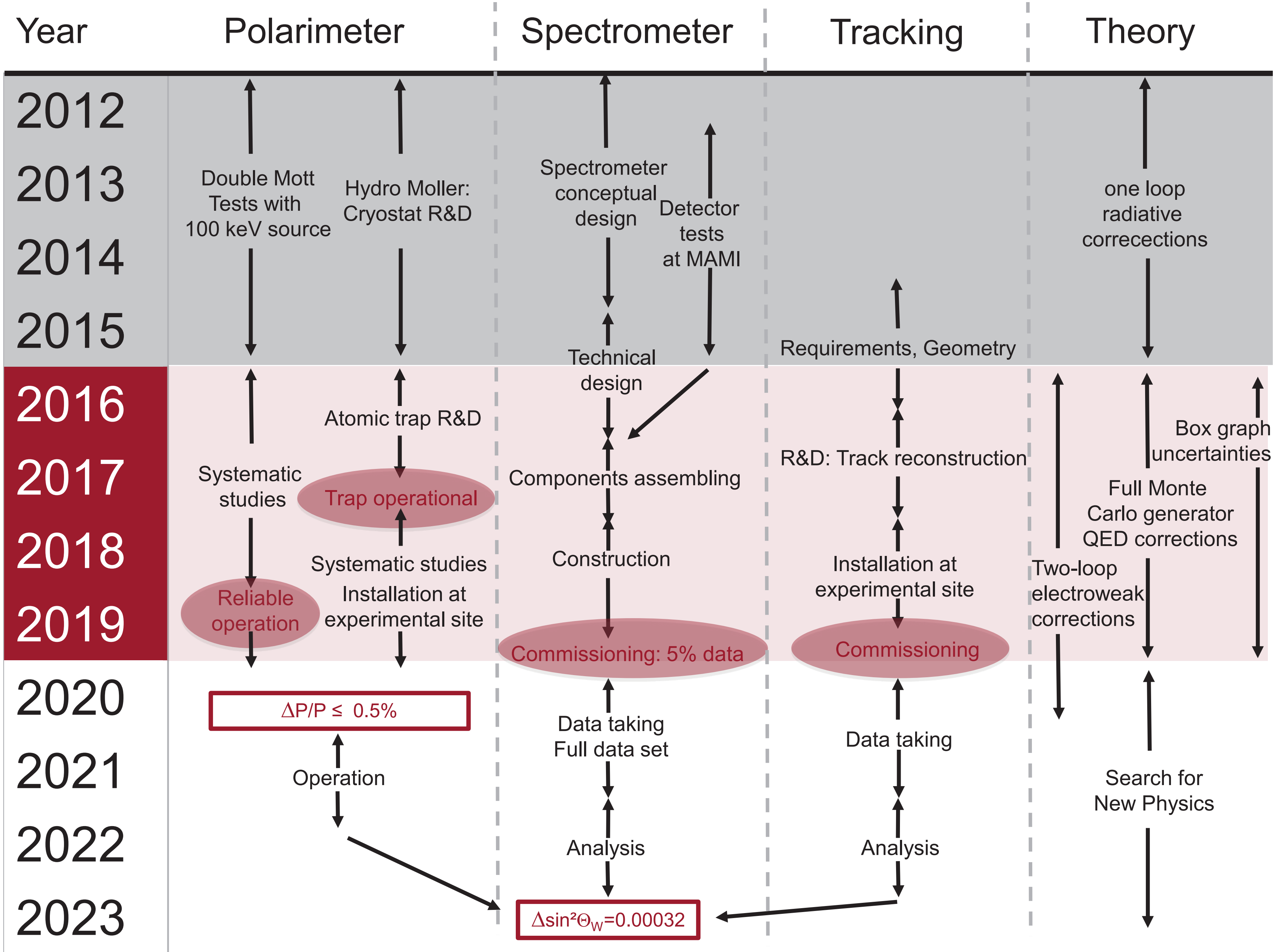
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors

- Use high-voltage monolithic active pixel sensors (HV-MAPS) thinned to 50 µm



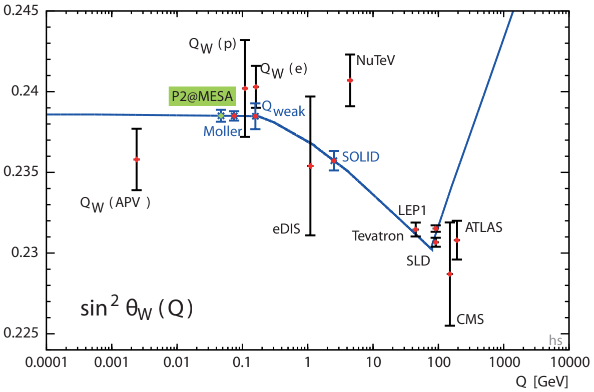


# P2 Timeline

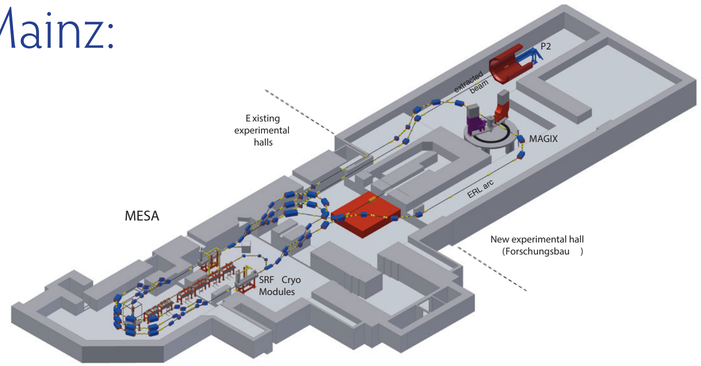


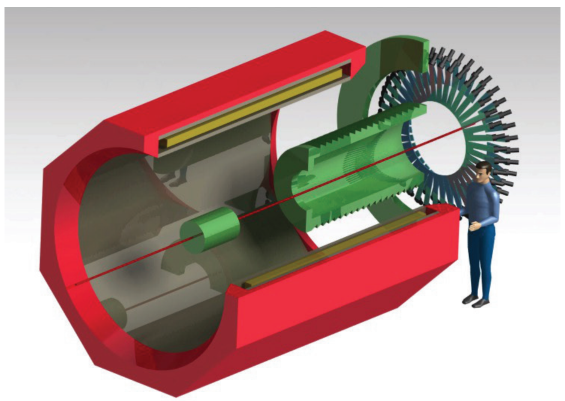
Year
Polarimeter
Spectrometer
Tracking
Theory
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Double Mott Tests with 100 keV source
Hydro Moller: Cryostat R&D
Spectrometer conceptual design
Detector tests at MAMI
one loop radiative correcections
Technical design
Requirements, Geometry
Atomic trap R&D
Systematic studies
Trap operational
Components assembling
R&D: Track reconstruction
Box graph uncertainties
Full Monte Carlo generator QED corrections
Systematic studies
Installation at experimental site
Construction
Installation at experimental site
Two-loop electroweak corrections
Reliable operation
Commissioning: 5% data
Commissioning
ΔP/P ≤ 0.5%
Operation
Data taking Full data set
Data taking
Search for New Physics
Analysis
Analysis
Δsin²Θ$_W$=0.00032

# Summary




- P2 aims to measure $\sin^2\theta_W$ to 0.13%
- Parity violating electron scattering
- New electron accelerator MESA in Mainz:
  - 150 μA of 150 MeV electrons
  - extremely stable
  - excellent polarimetry
  - wide program (→ Achim Denig)



- Solenoid spectrometer with integrating Cherenkov detectors
- Data taking starts before end of this decade

# Backup

# 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"

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

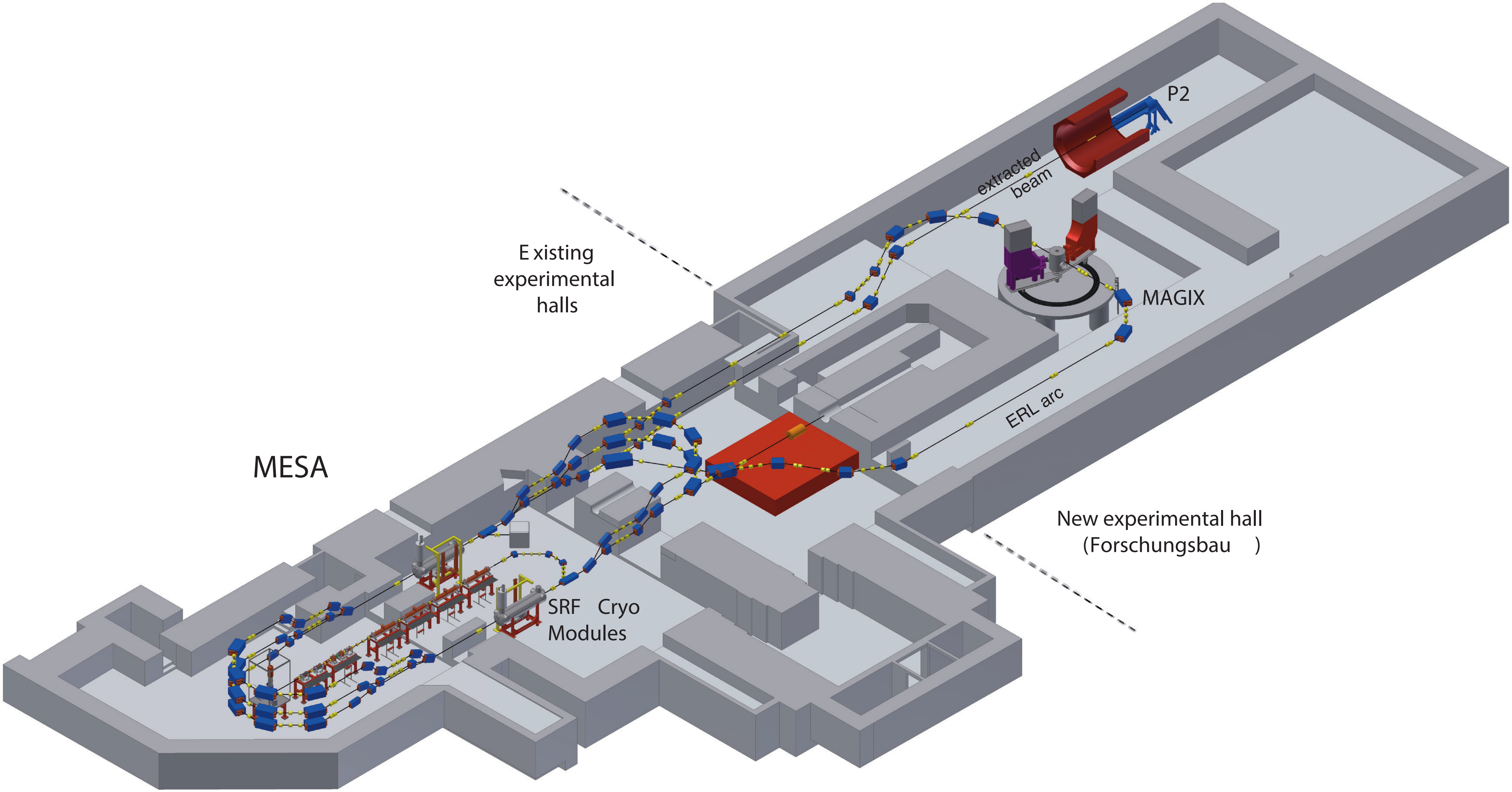
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

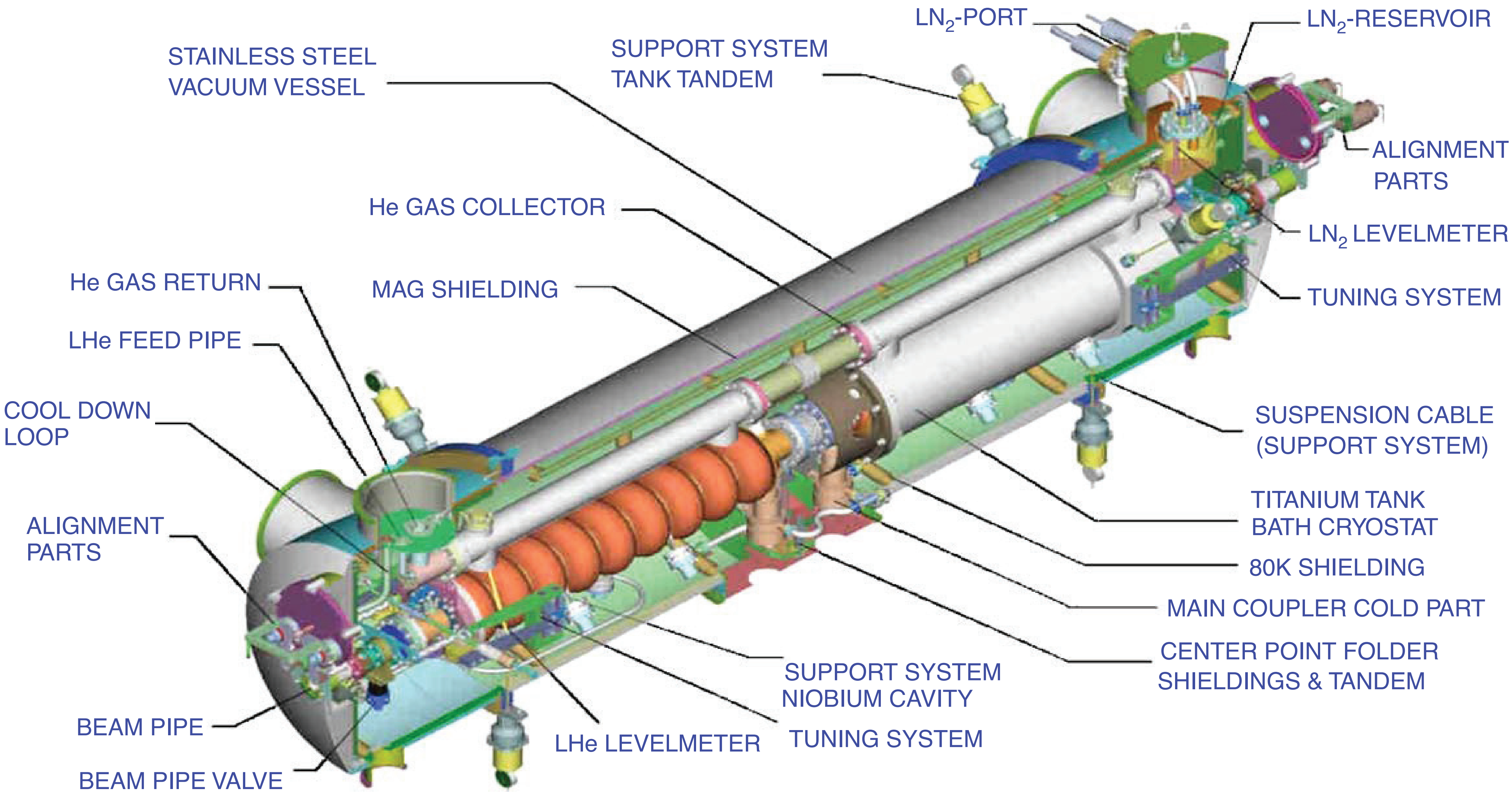
- Use second option from here on

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

# MESA


P2
extracted beam
E xisting experimental halls
MAGIX
ERL arc
MESA
New experimental hall (Forschungsbau )
SRF Cryo Modules

# Superconducting Cryomodules

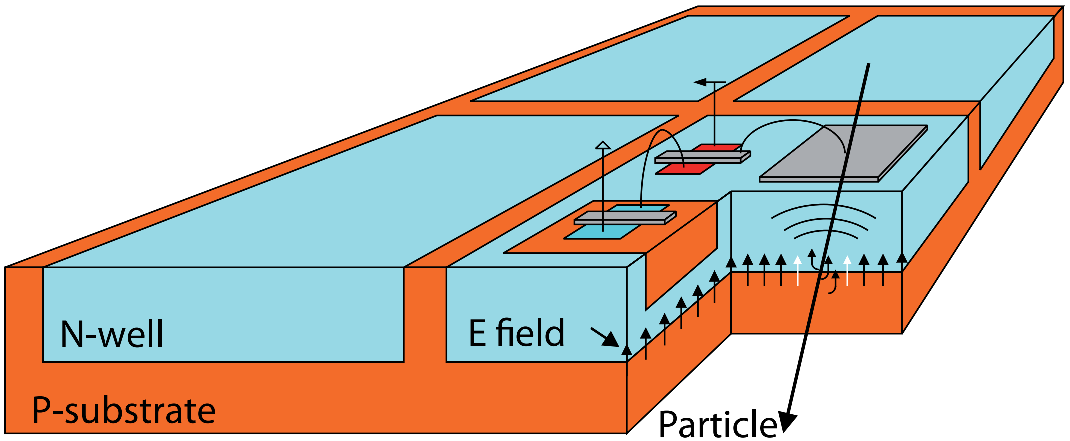



Teichert et al. NIM A 557 (2006) 239

Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

# Fast and thin sensors: HV-MAPS



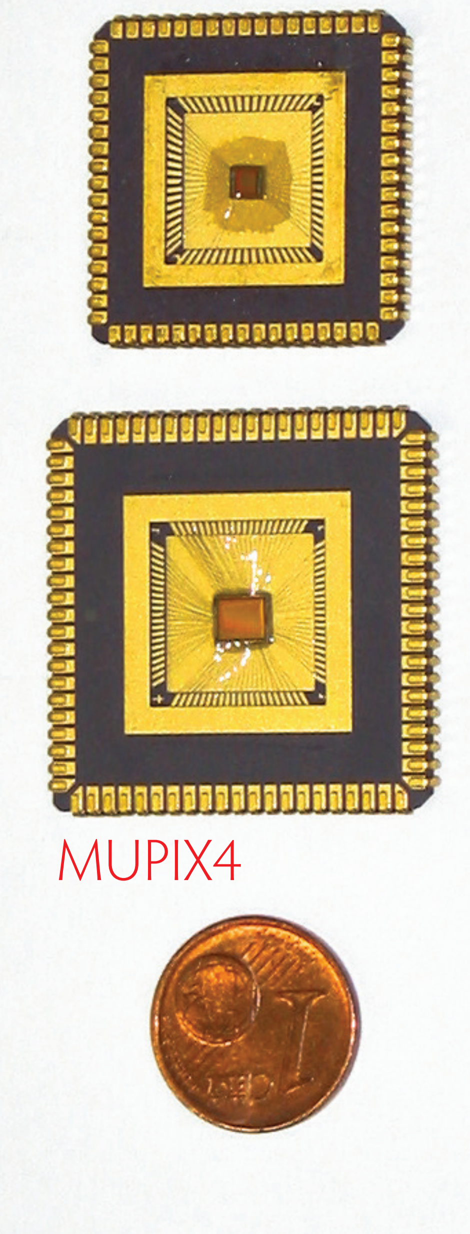

High voltage monolithic active pixel sensors - Ivan Perić

- 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

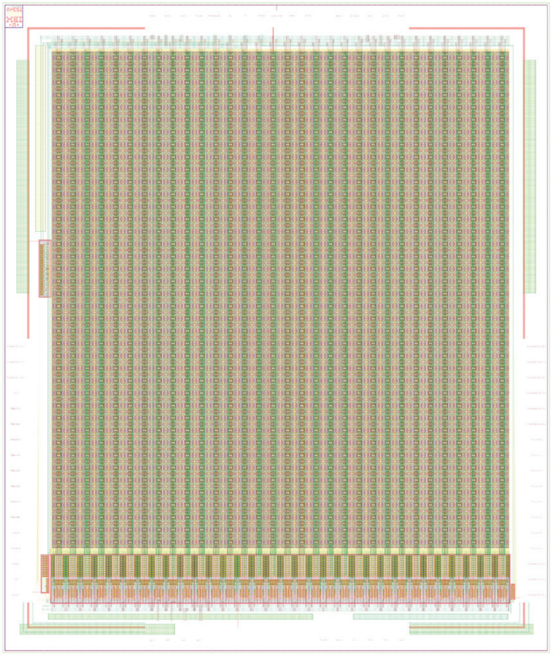
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876 )

# The MUPIX chip prototypes

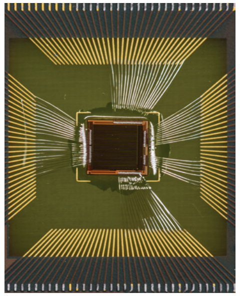
MUPIX2



MUPIX4



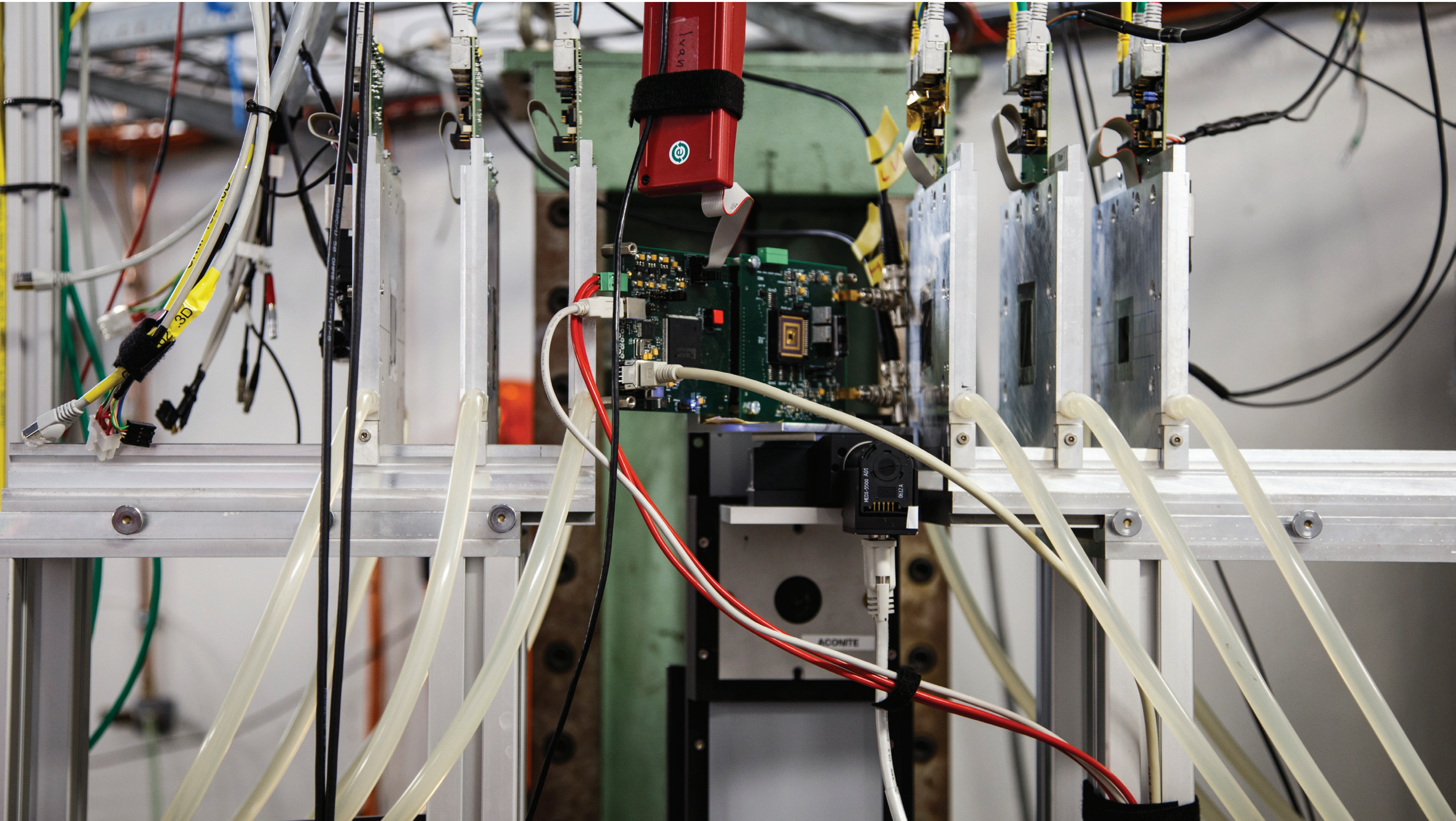
MUPIX6



HV-MAPS chips: AMS 180 nm HV-CMOS

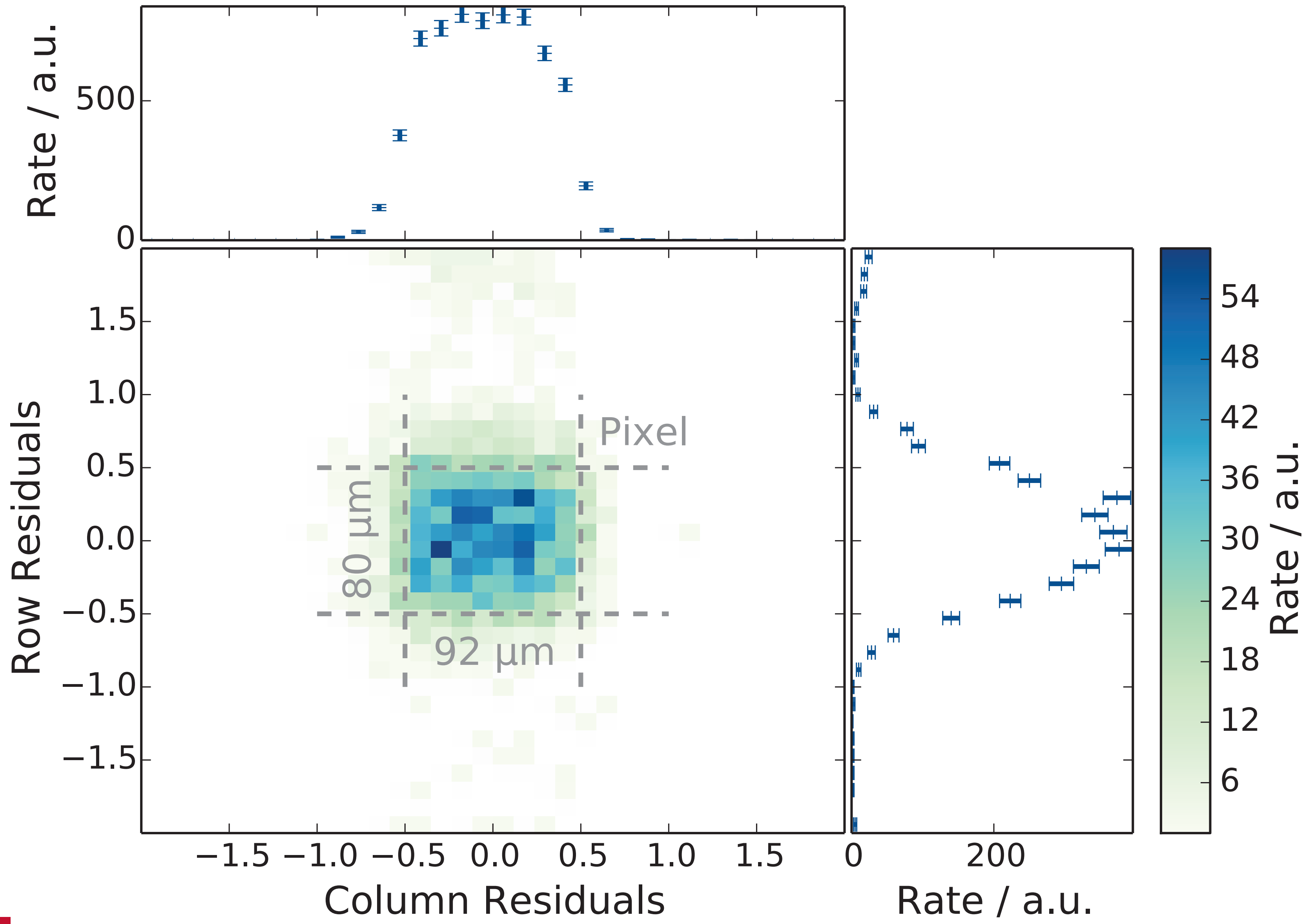
- 5 generations of prototypes
- Current generation:
  MUPIX7
  40 x 32 pixels
  80 x 103 µm pixel size
  9.4 mm$^2$ active area
- MUPIX7 has all features of final sensor
- Left to do: Scale to 2 x 2 cm$^2$

# Test beam at DESY



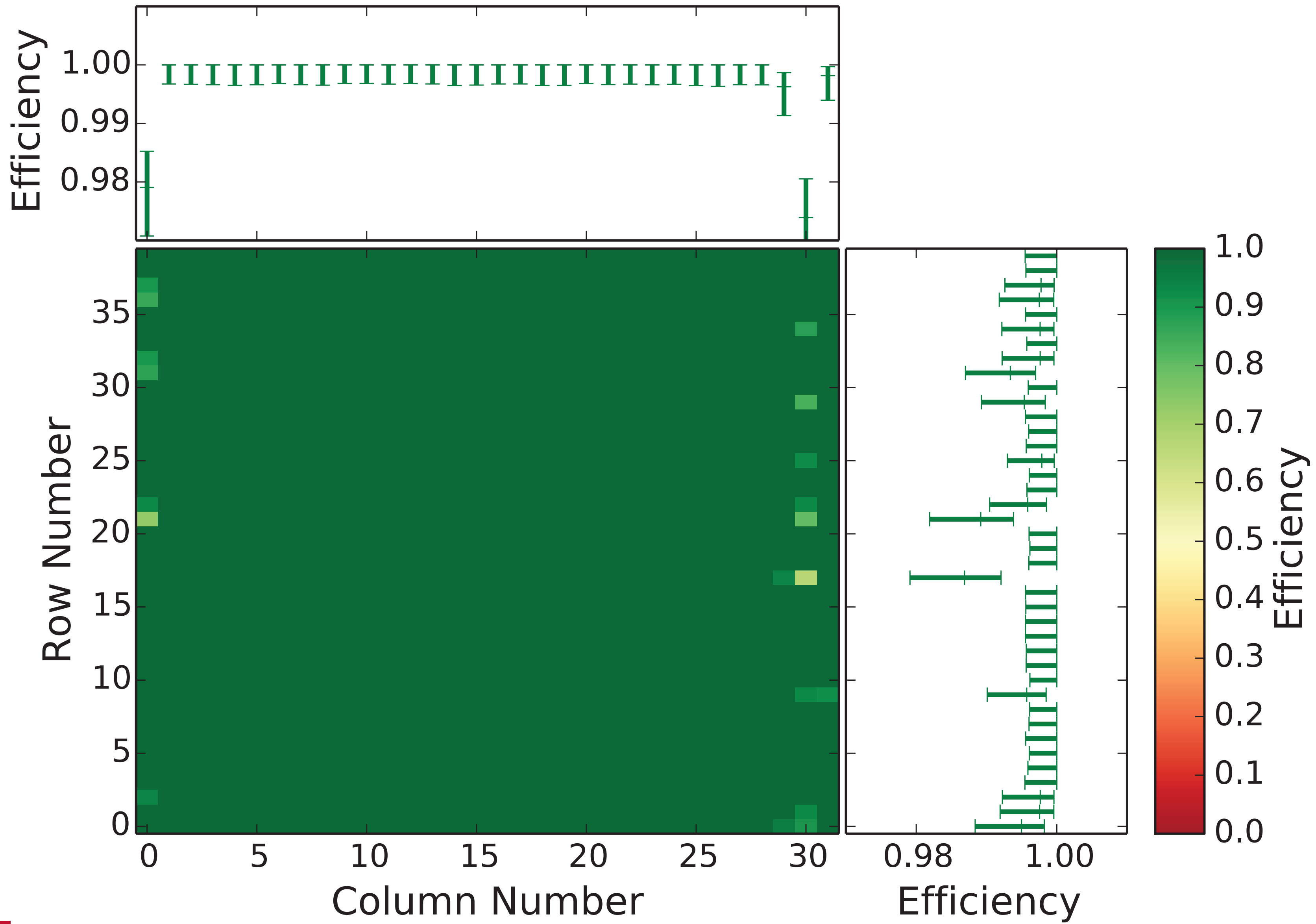
# Position Resolution

Position resolution given by pixel size

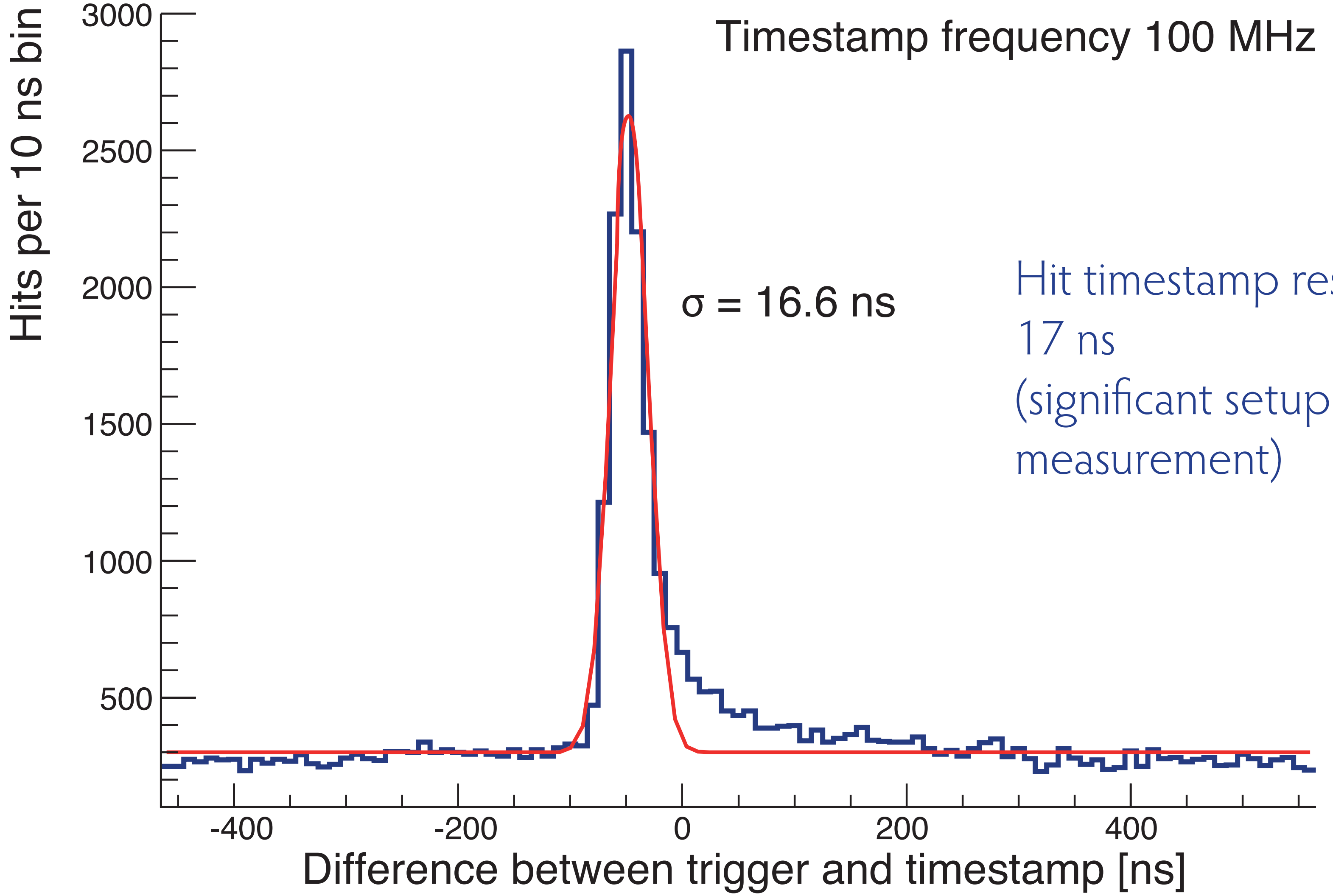


# Efficiency

Hit efficiency above 99% without tuning

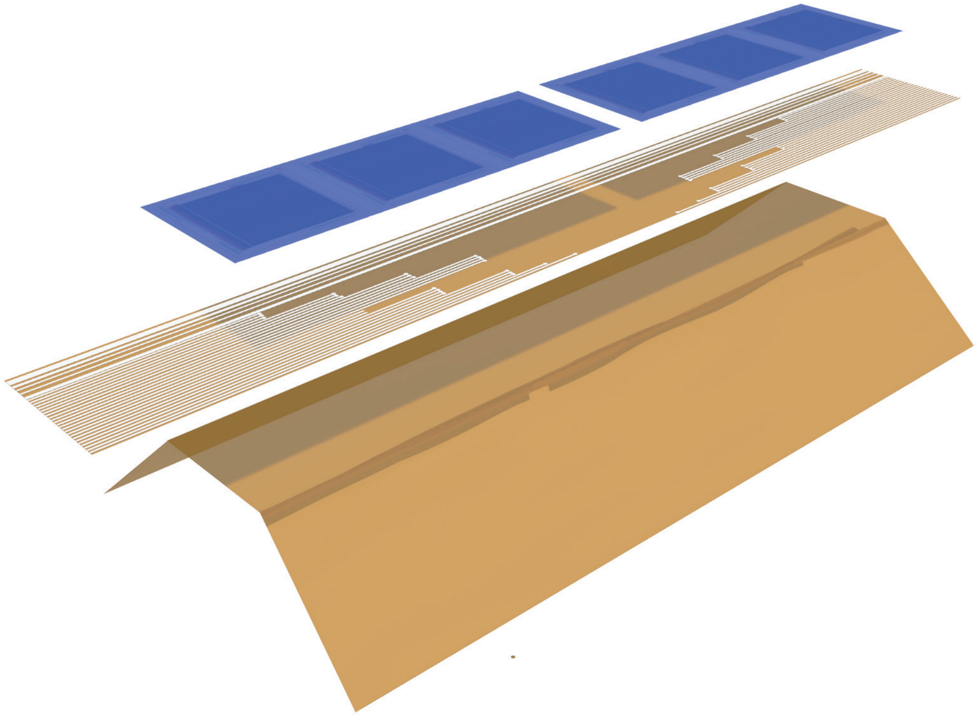


# Time resolution




Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

# Mechanics



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

# PVeS Experiment Summary