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

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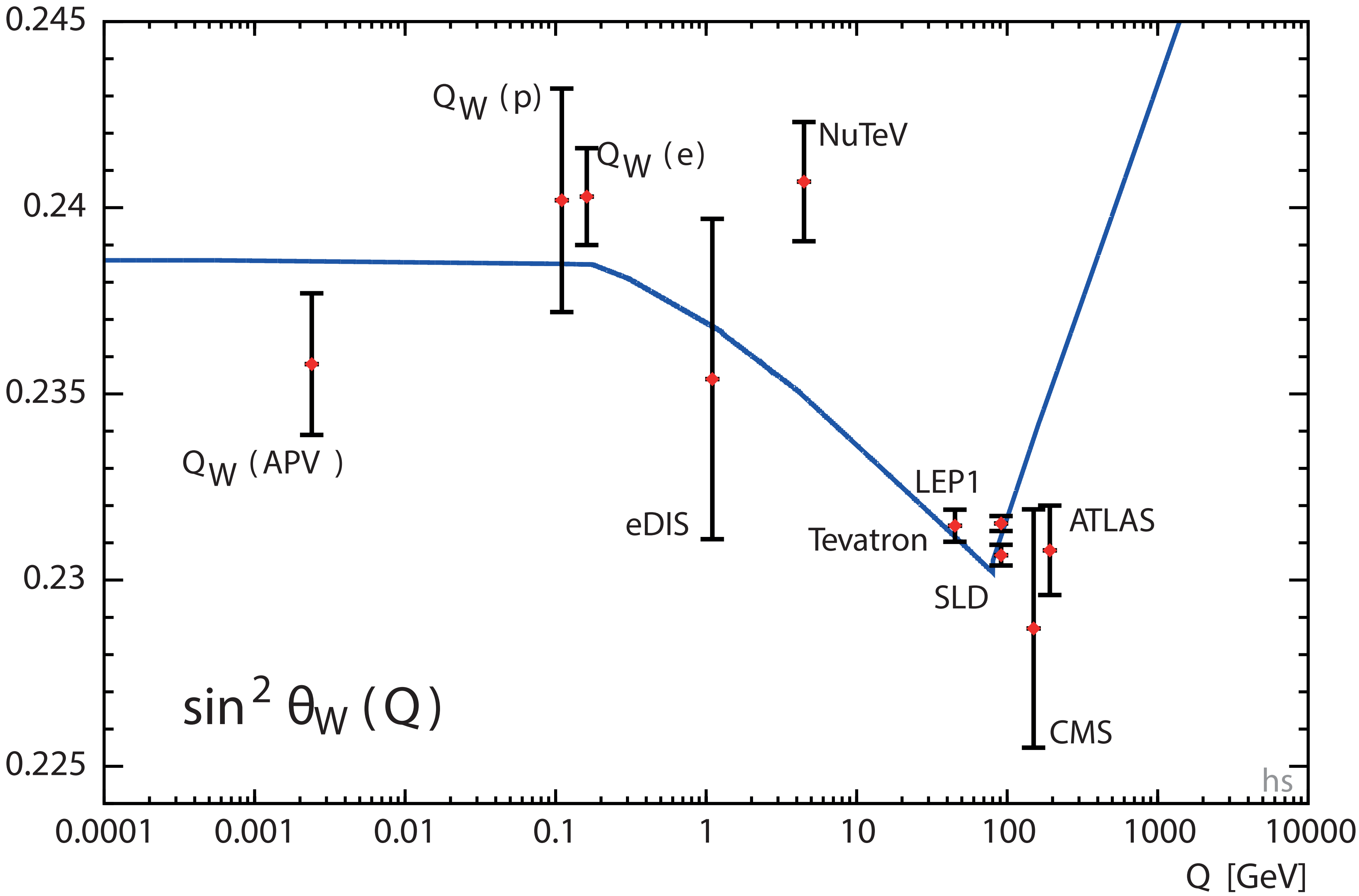
Low Energy Precision Physics
April 2016

Overview

- The Idea:
  Precision measurement of and search for new physics with the weak mixing angle
- The Method:
  Parity violating electron scattering
- The Experiment:
  The P2 spectrometer

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



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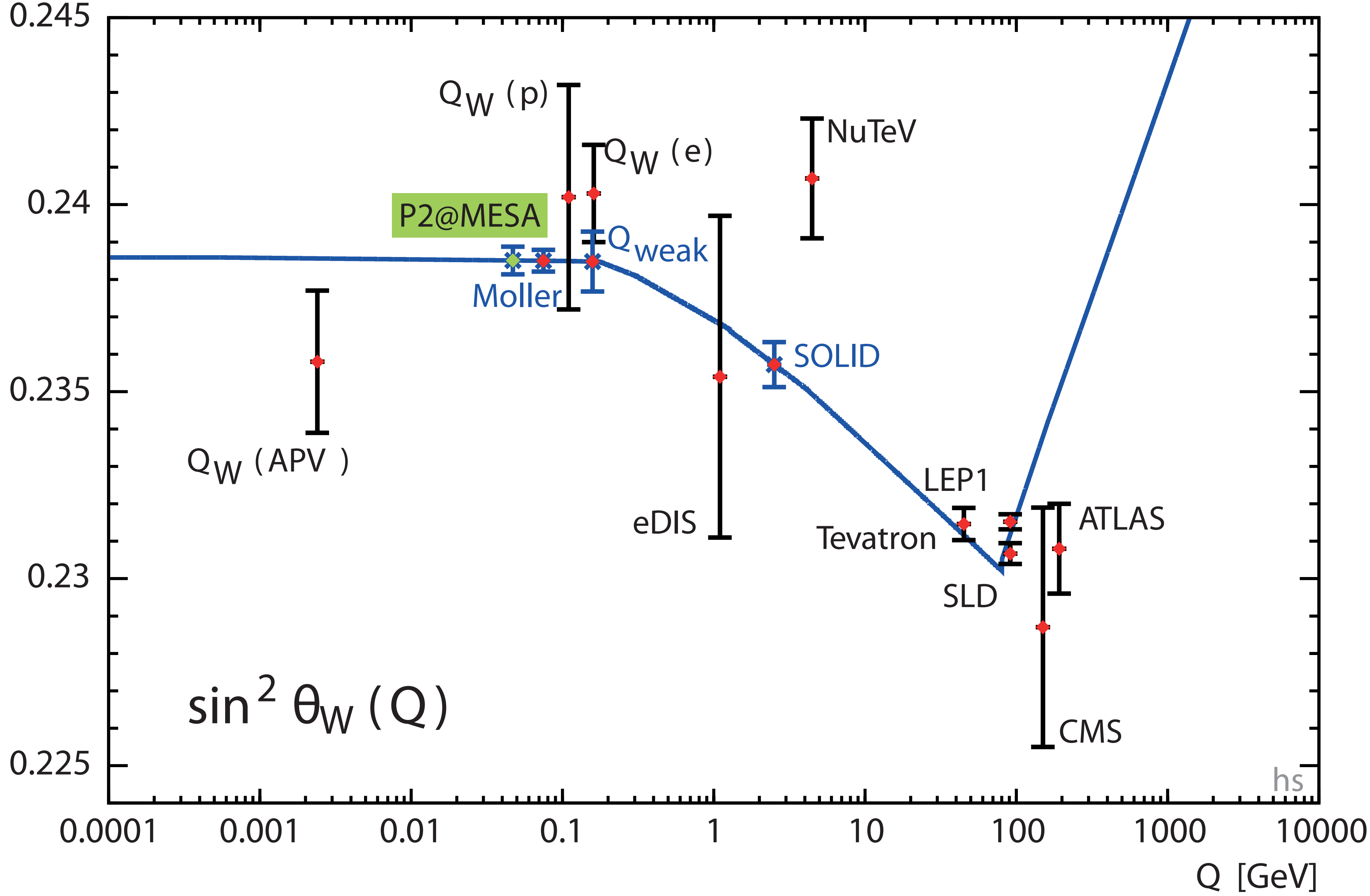
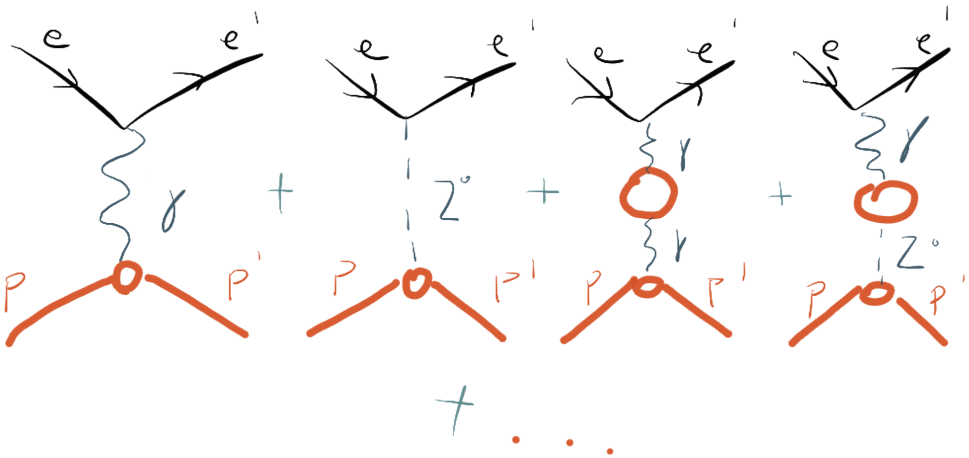
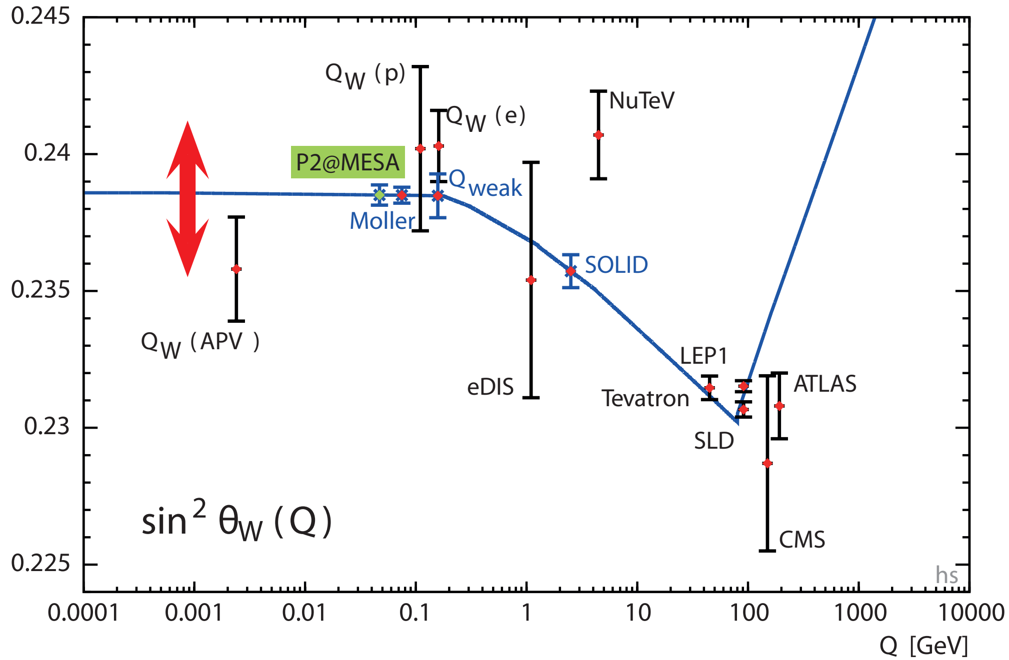
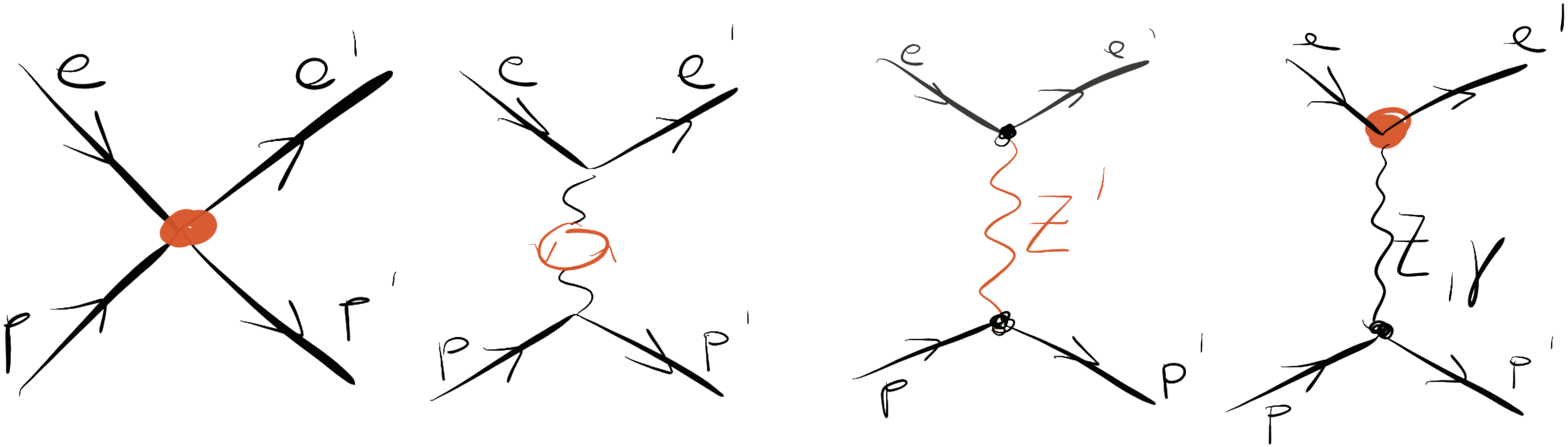


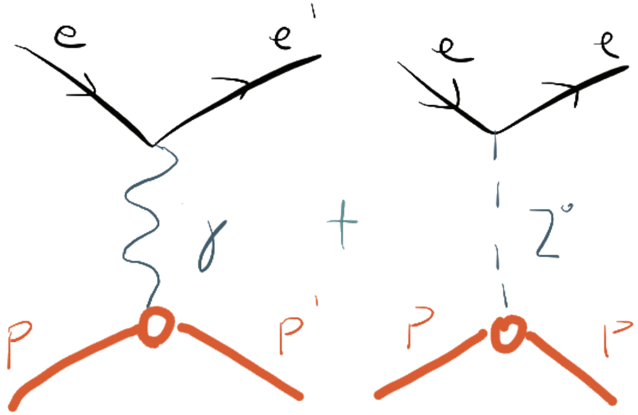
New Physics in the running

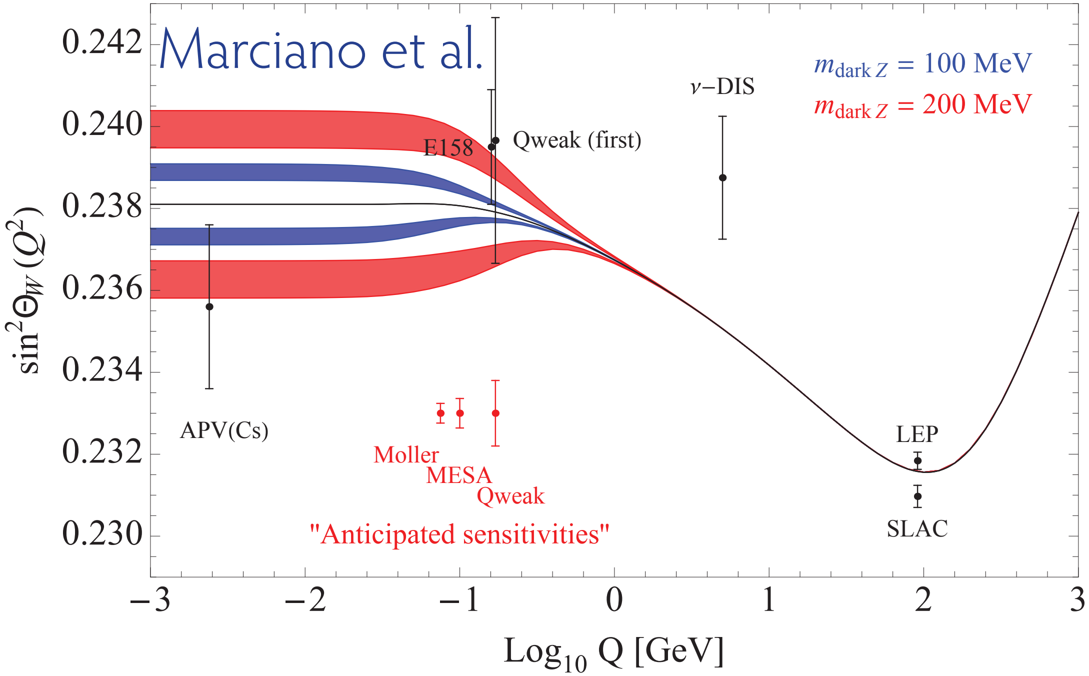


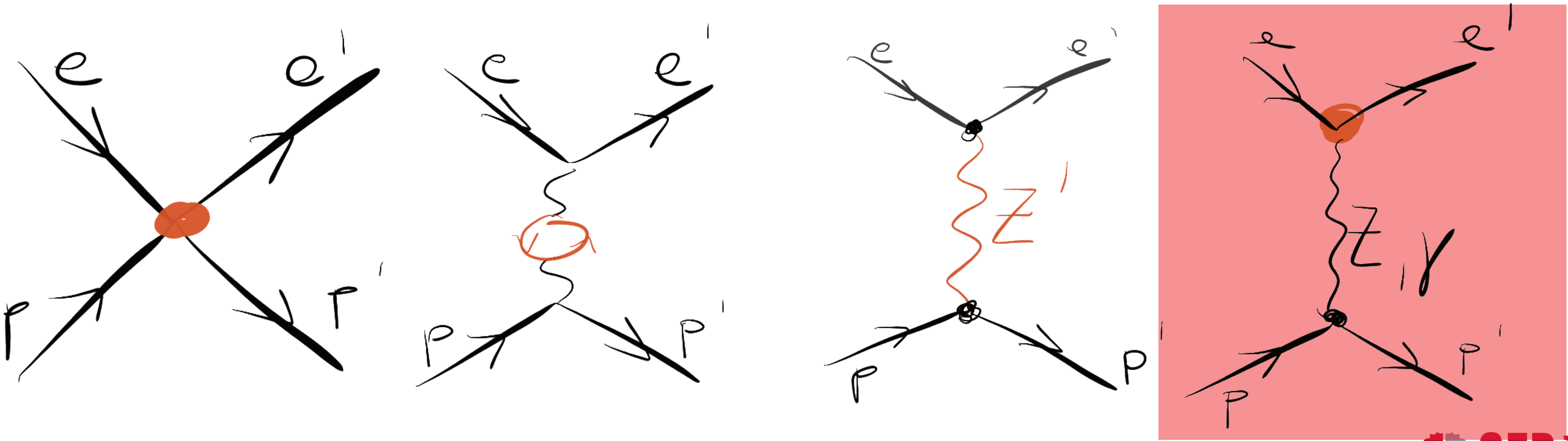




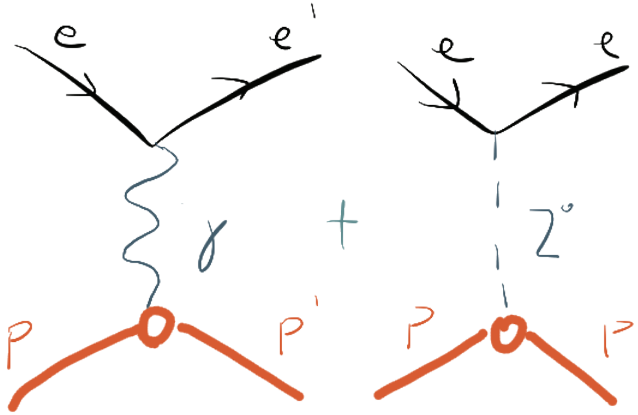
Dark Z in mixing







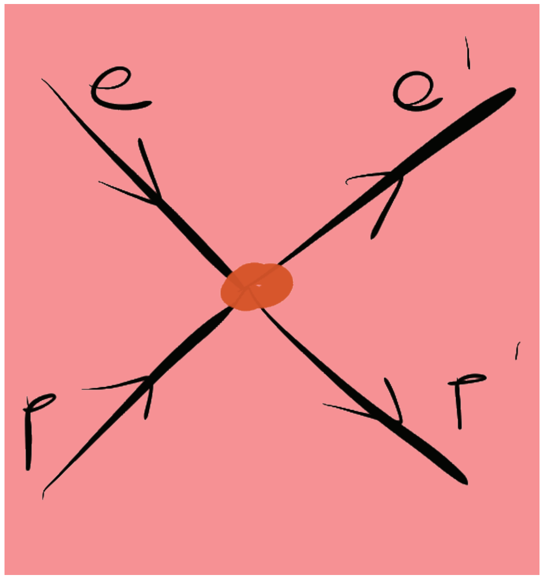
Contact Interactions

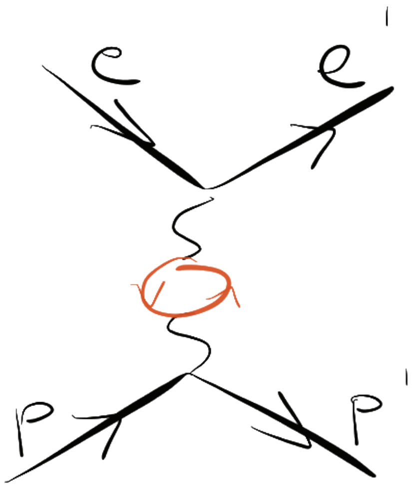


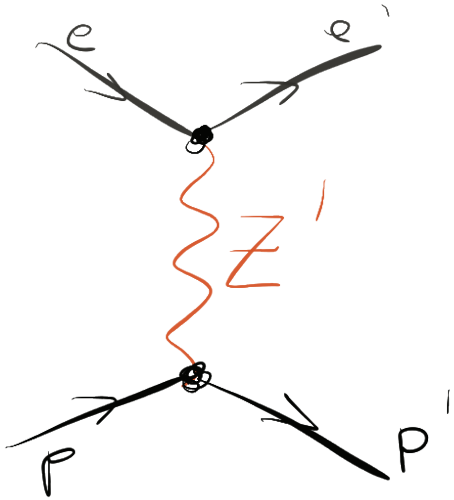
Contact interactions up to

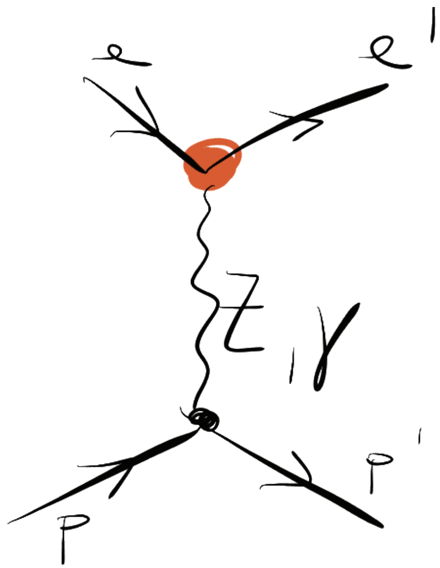
49 TeV

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



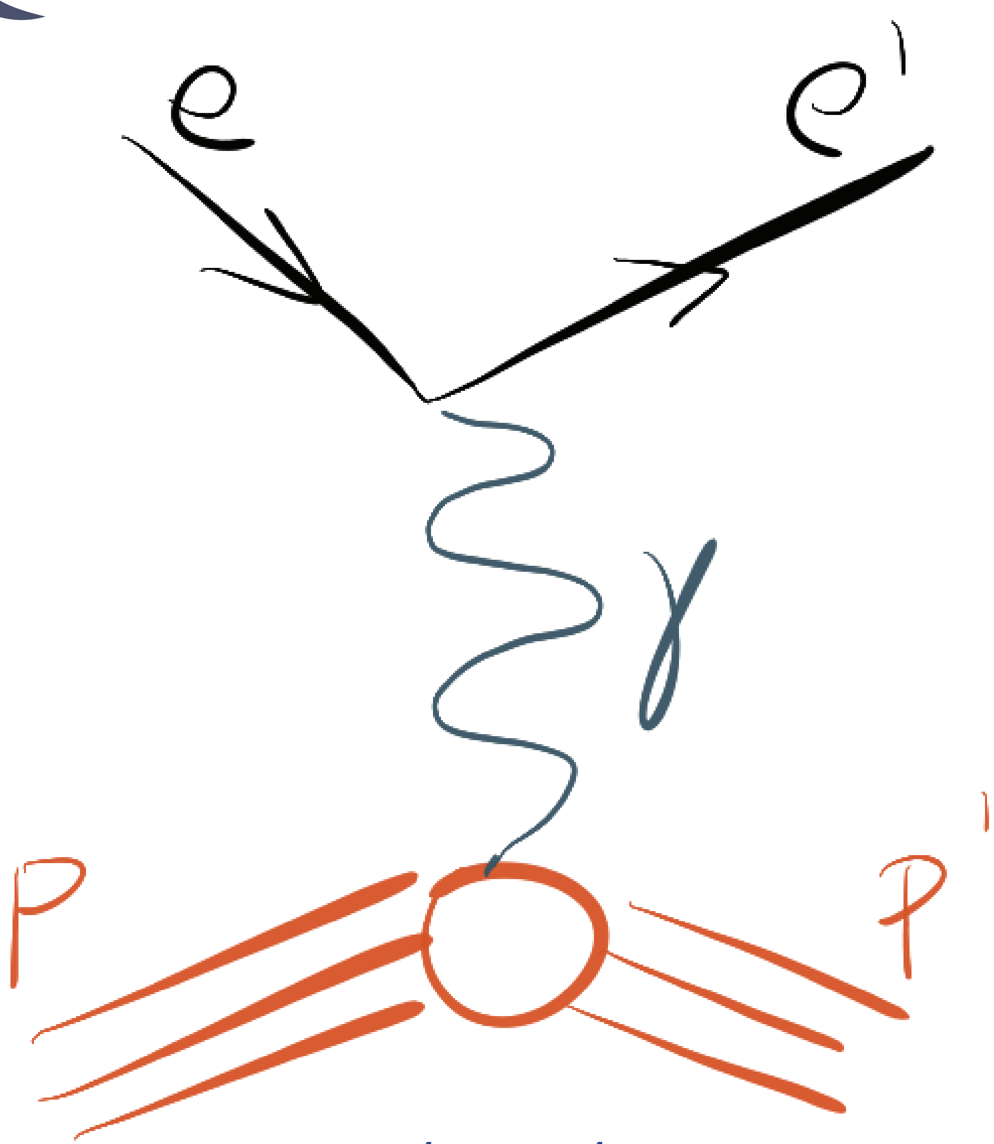






Measuring the weak charge

Weak mixing angle and charges



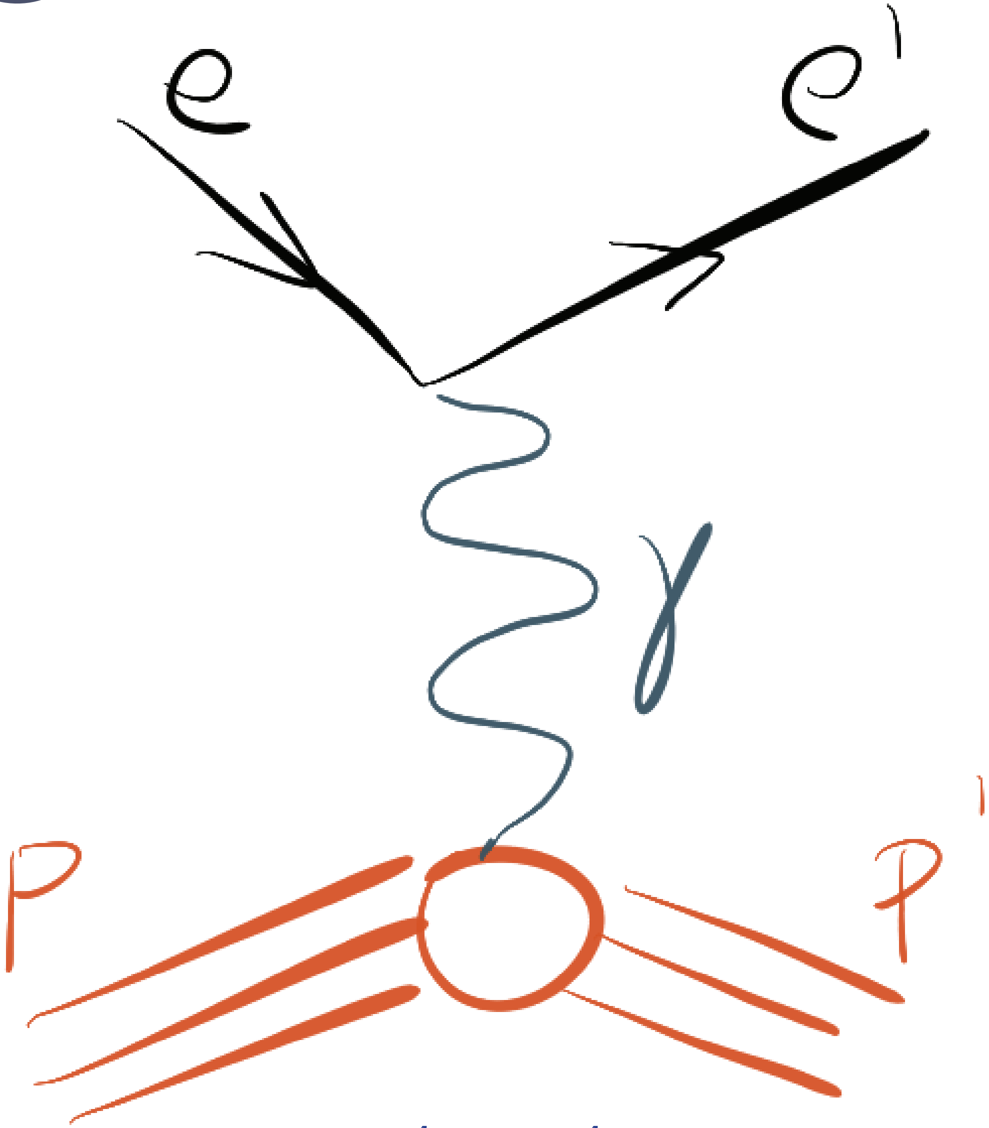
Proton electric charge

+1

Proton weak charge

$1 - 4\sin^2\theta_W$

Weak mixing angle and charges



Proton electric charge

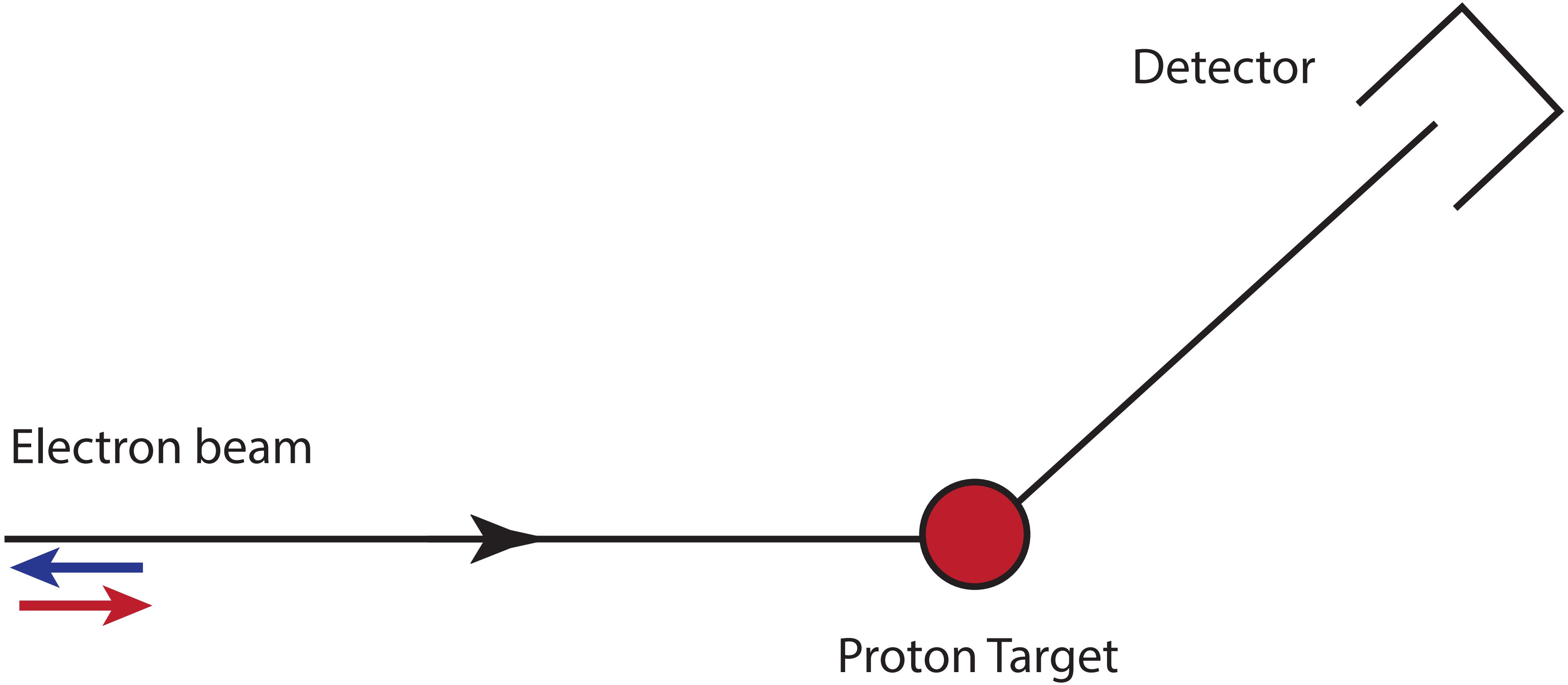
+1

Violates parity!

Proton weak charge

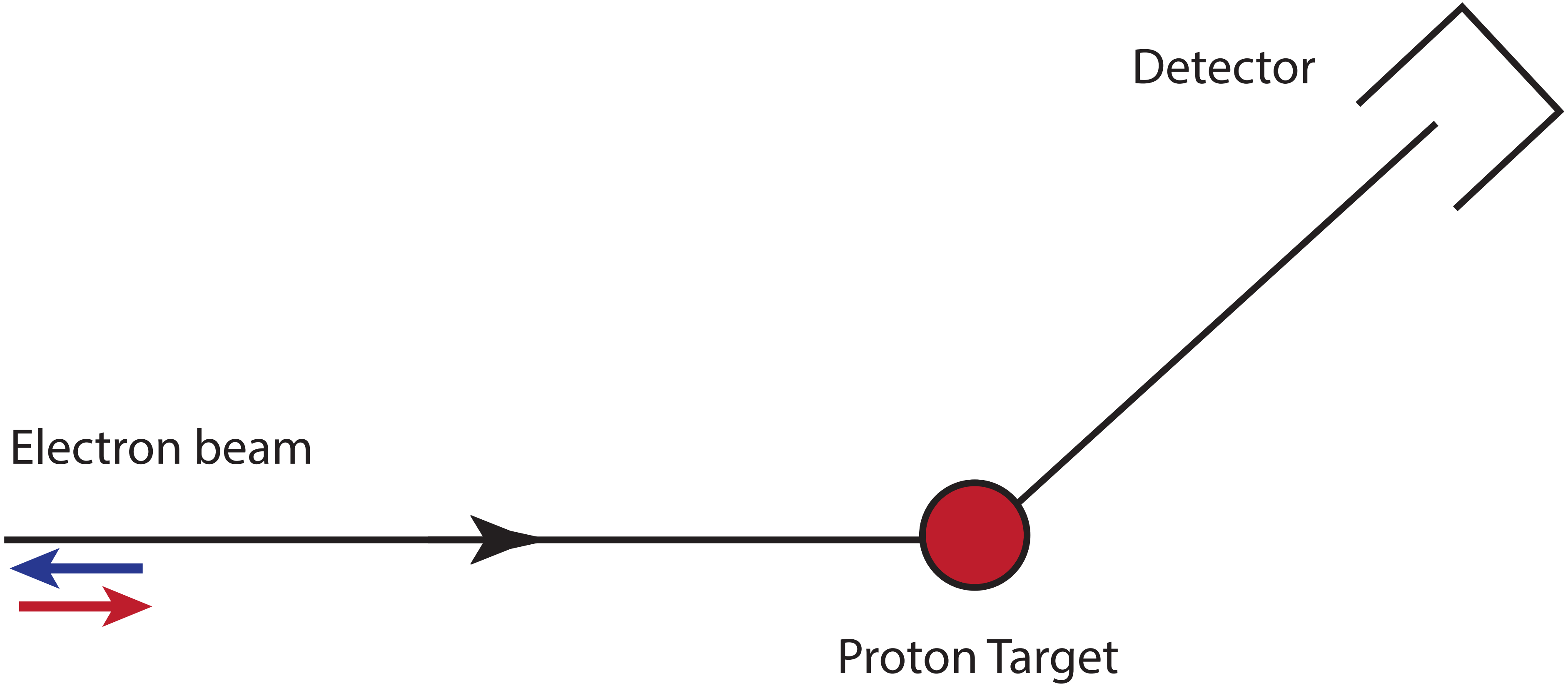
$1 - 4 \sin^2\theta_W$

Parity violating electron scattering



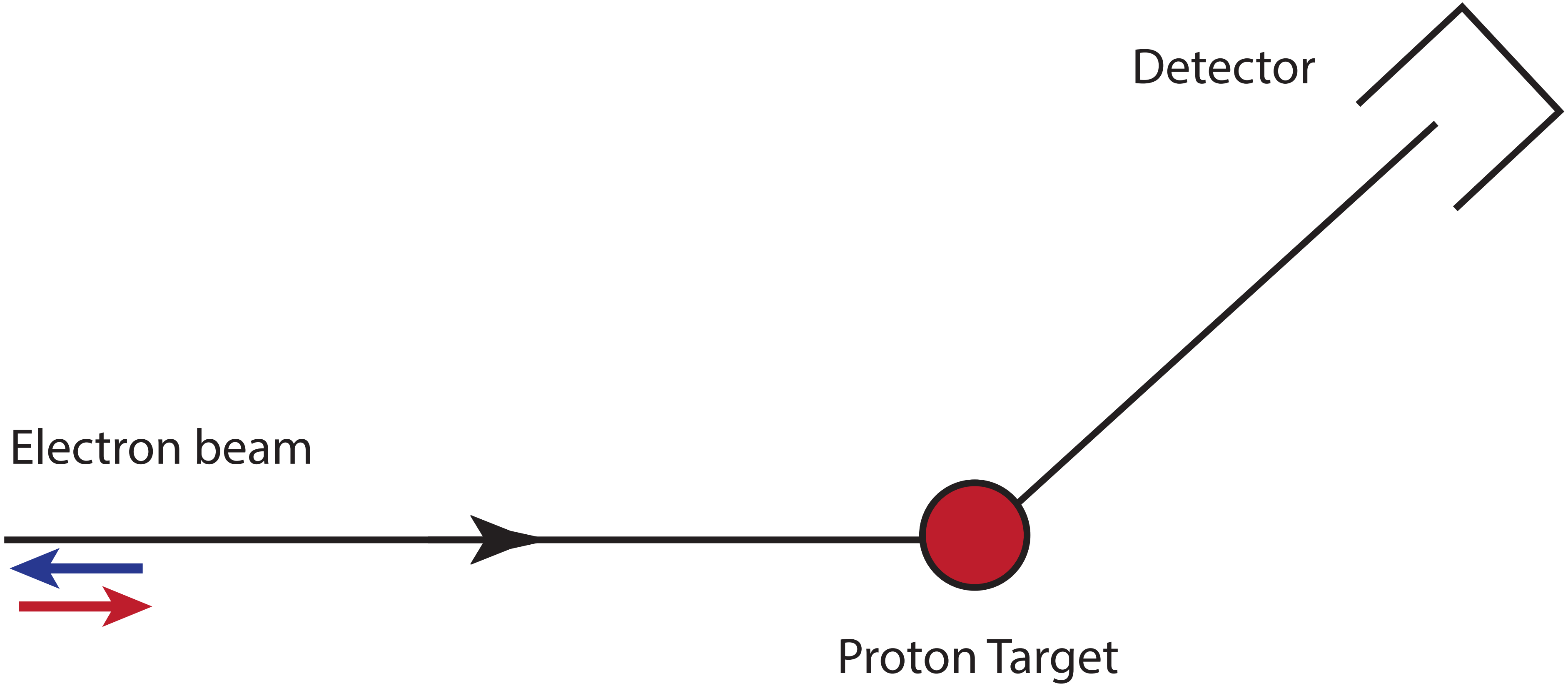
Parity violating electron scattering

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



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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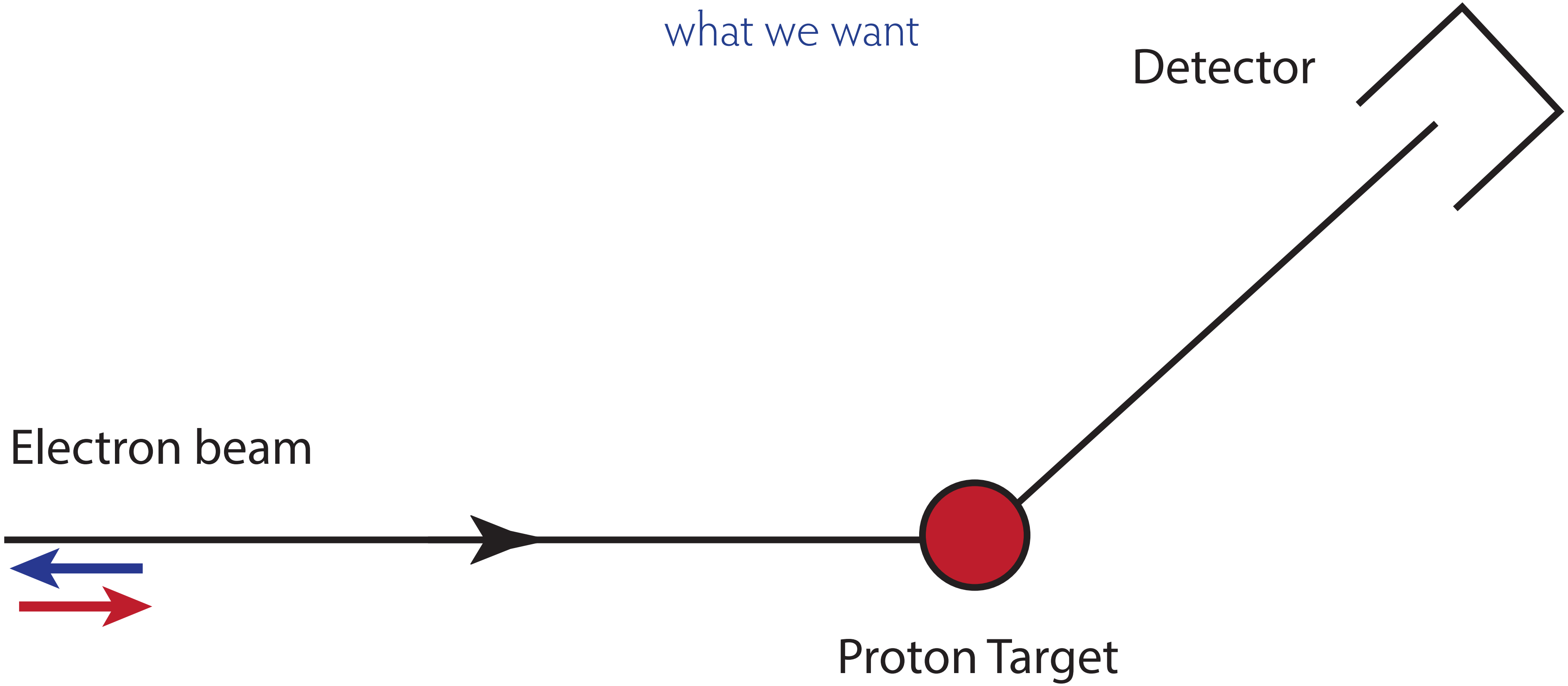
Weak charge - what we want



Parity violating electron scattering

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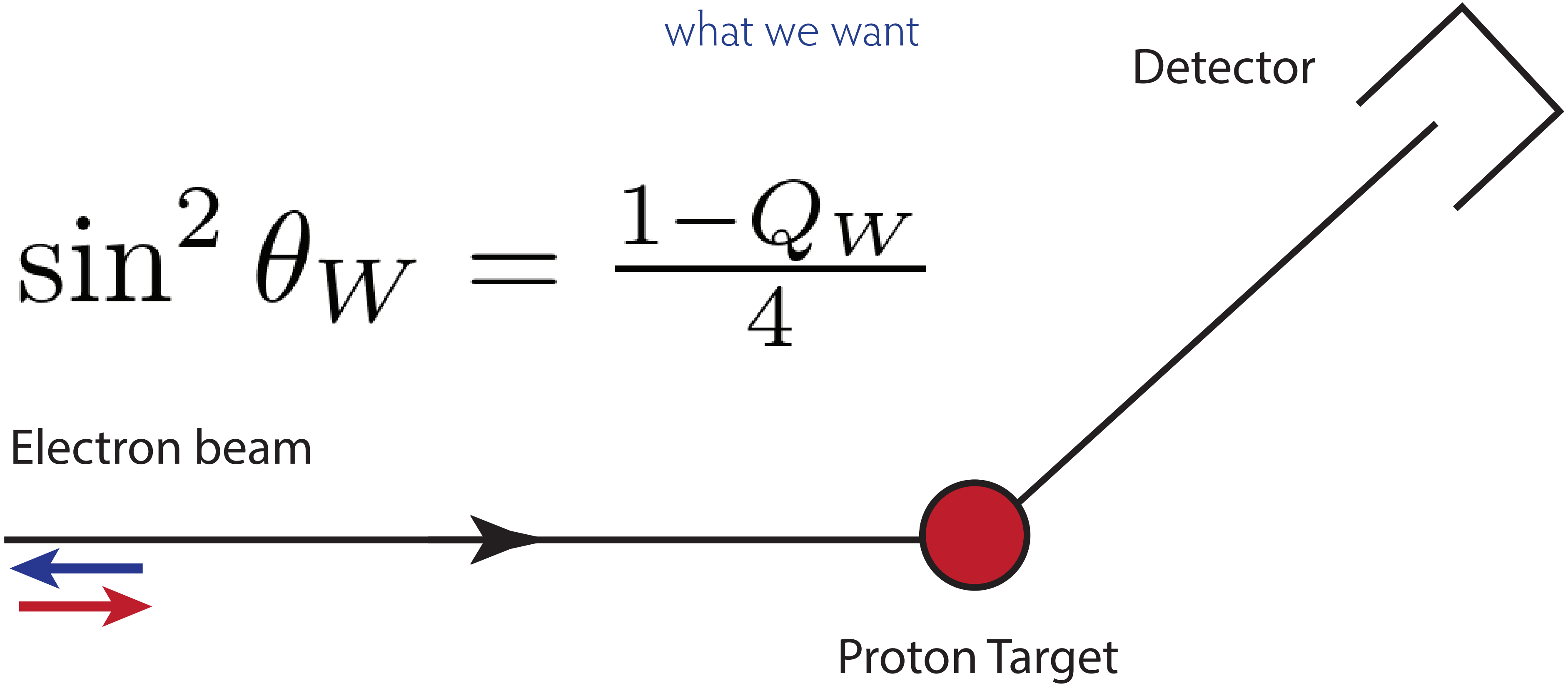
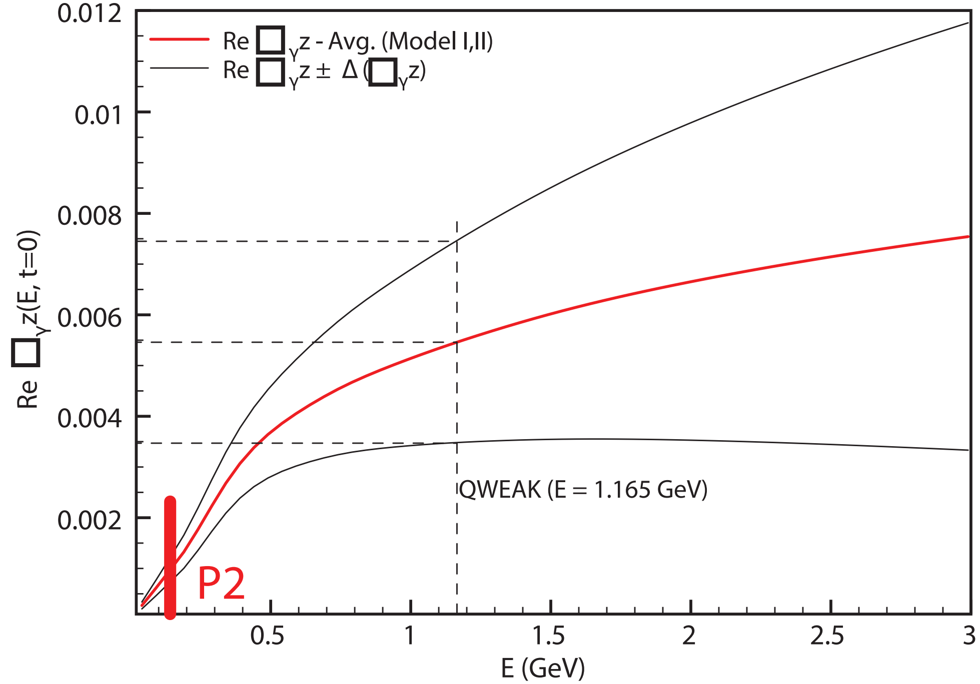
Weak charge - what we want

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

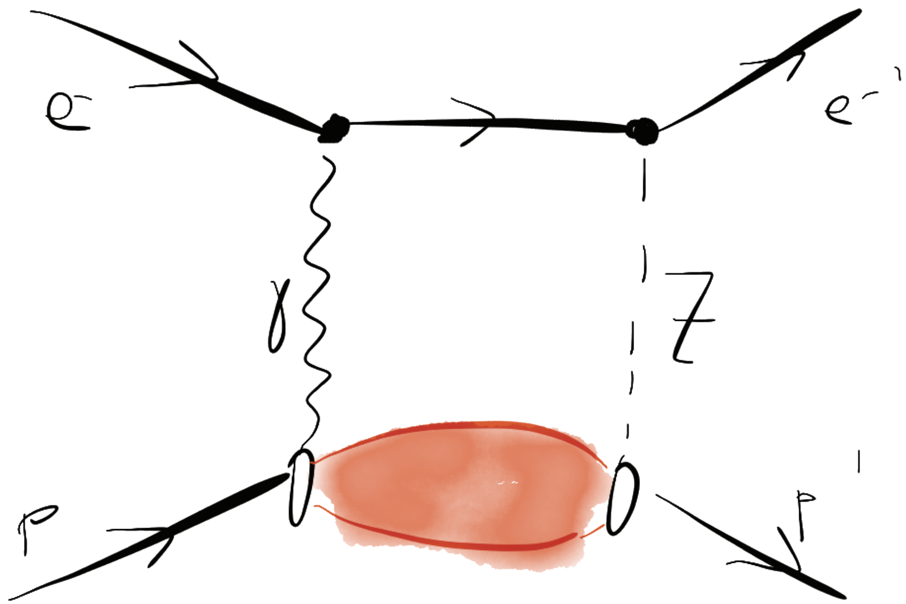


γ-Z box graphs



[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

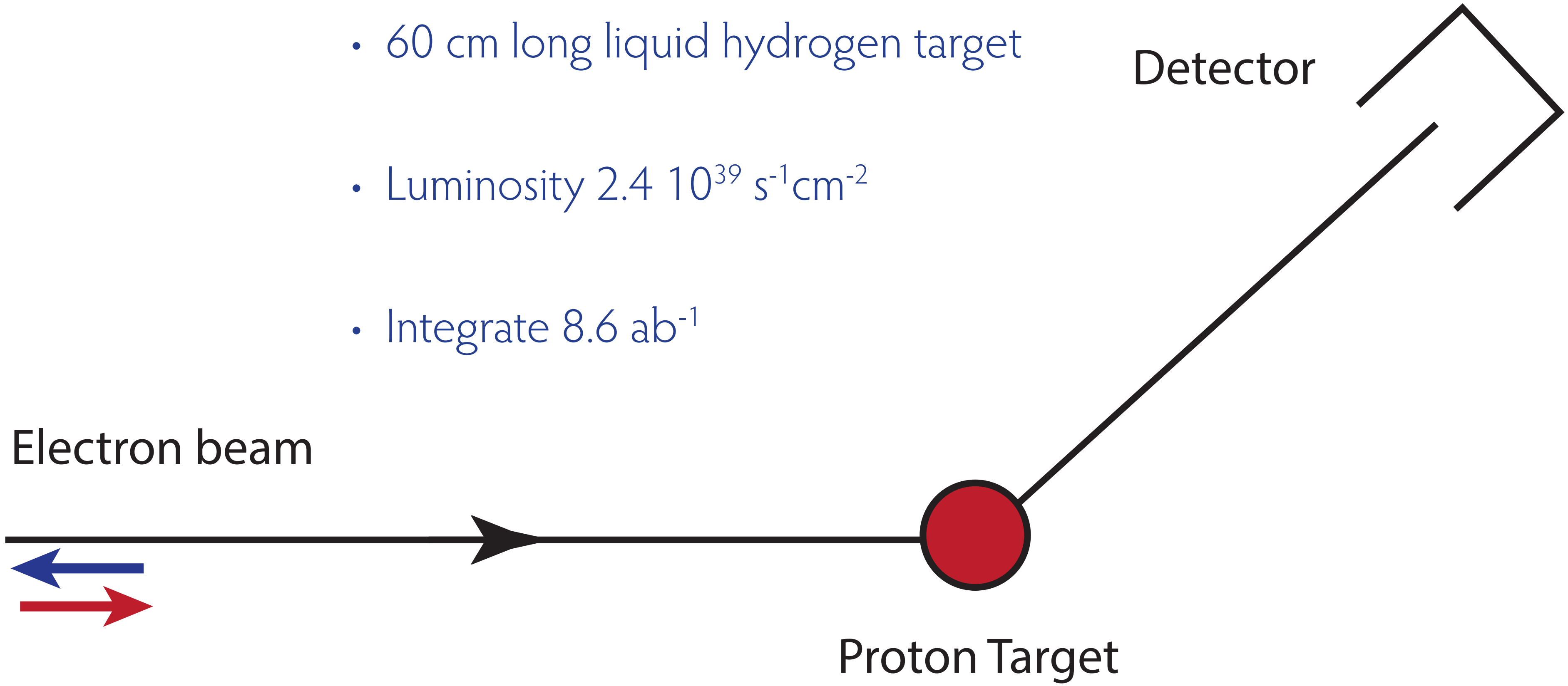
$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

- 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

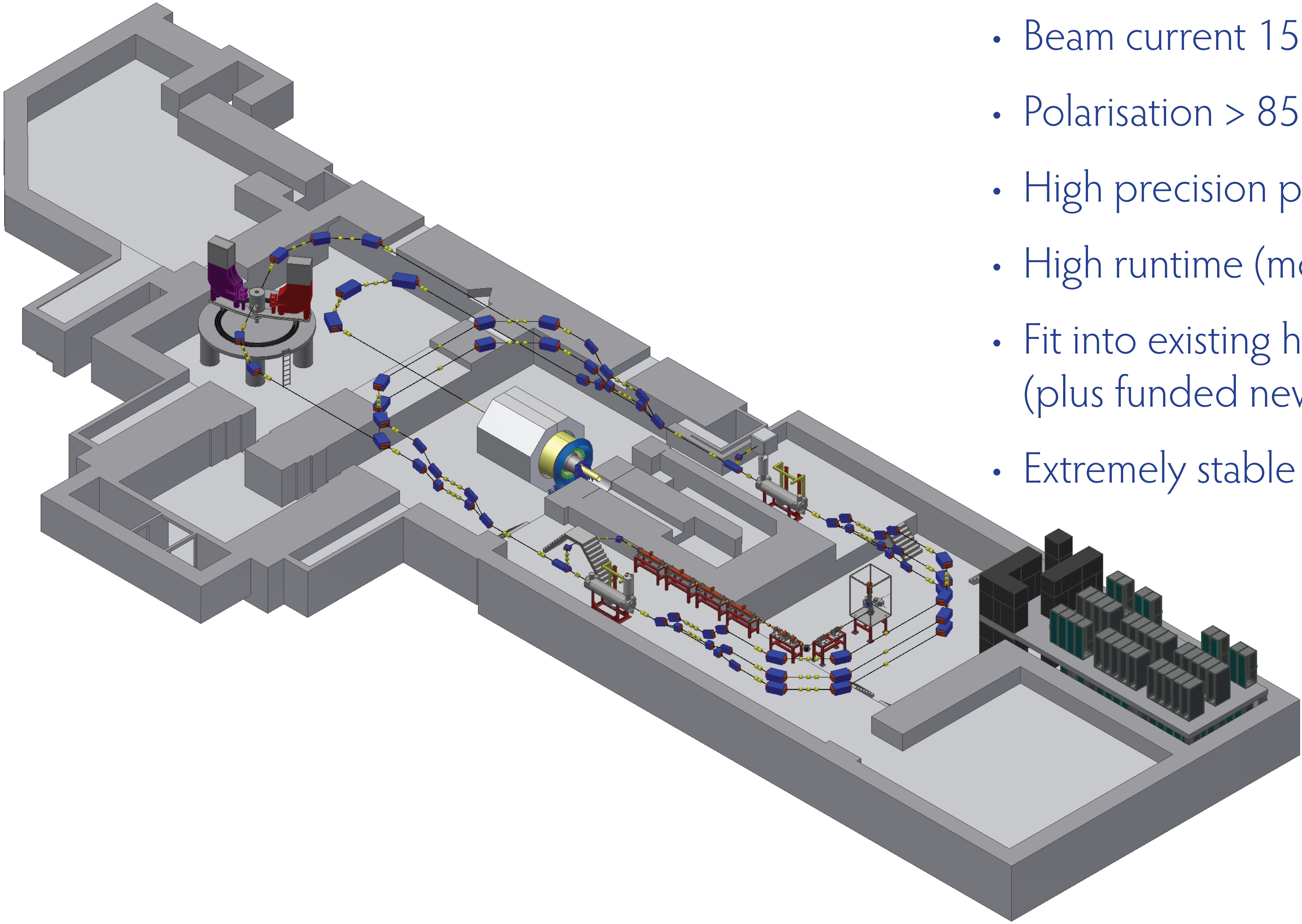
Hard to get that amount of time at a shared accelerator facility...

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

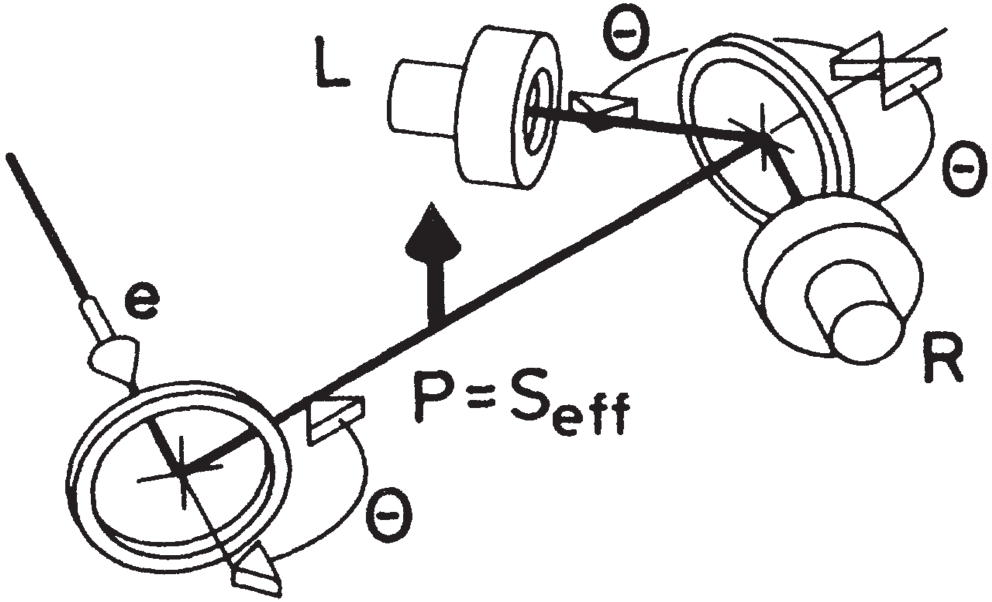
Stability Requirements

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



[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

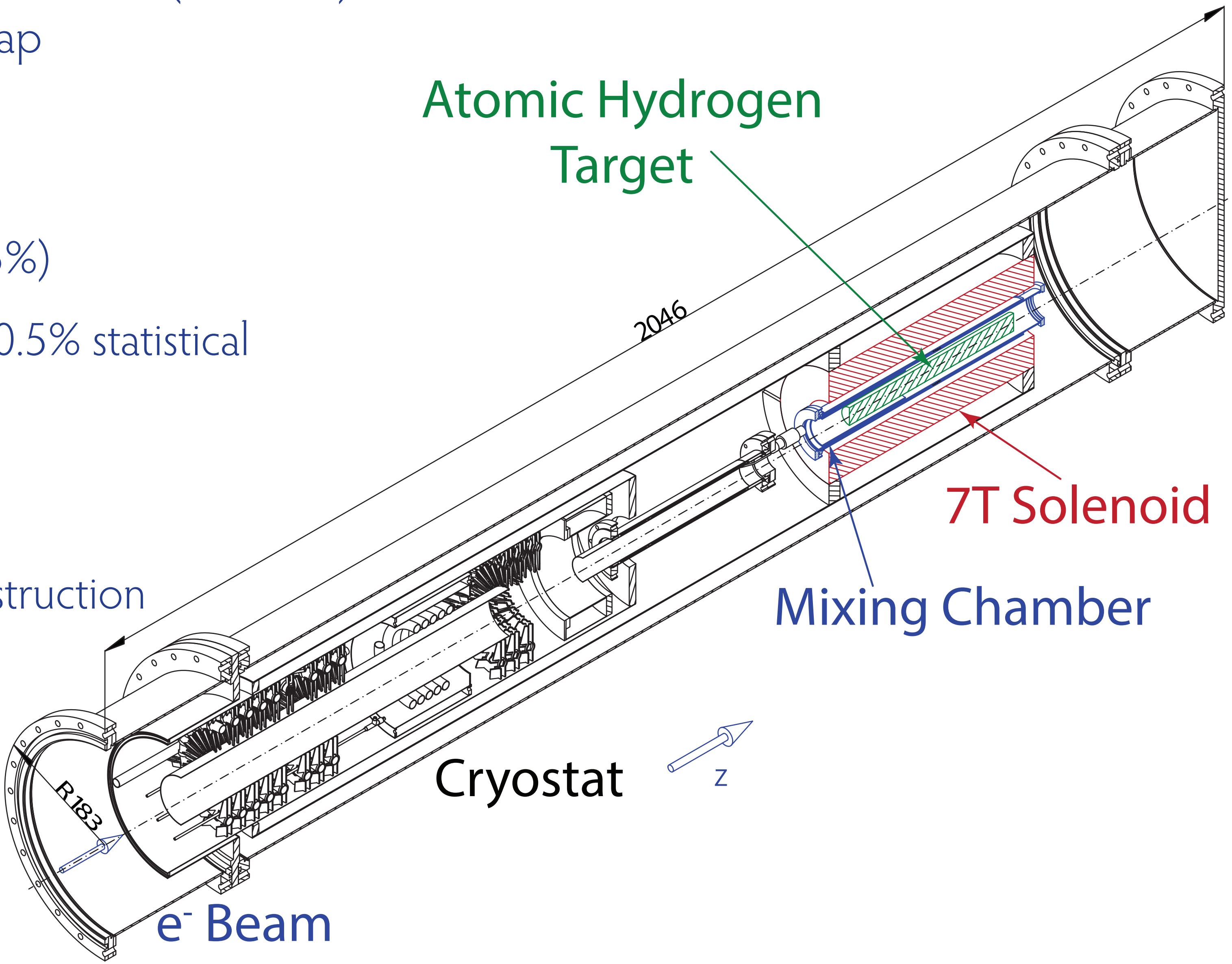
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

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

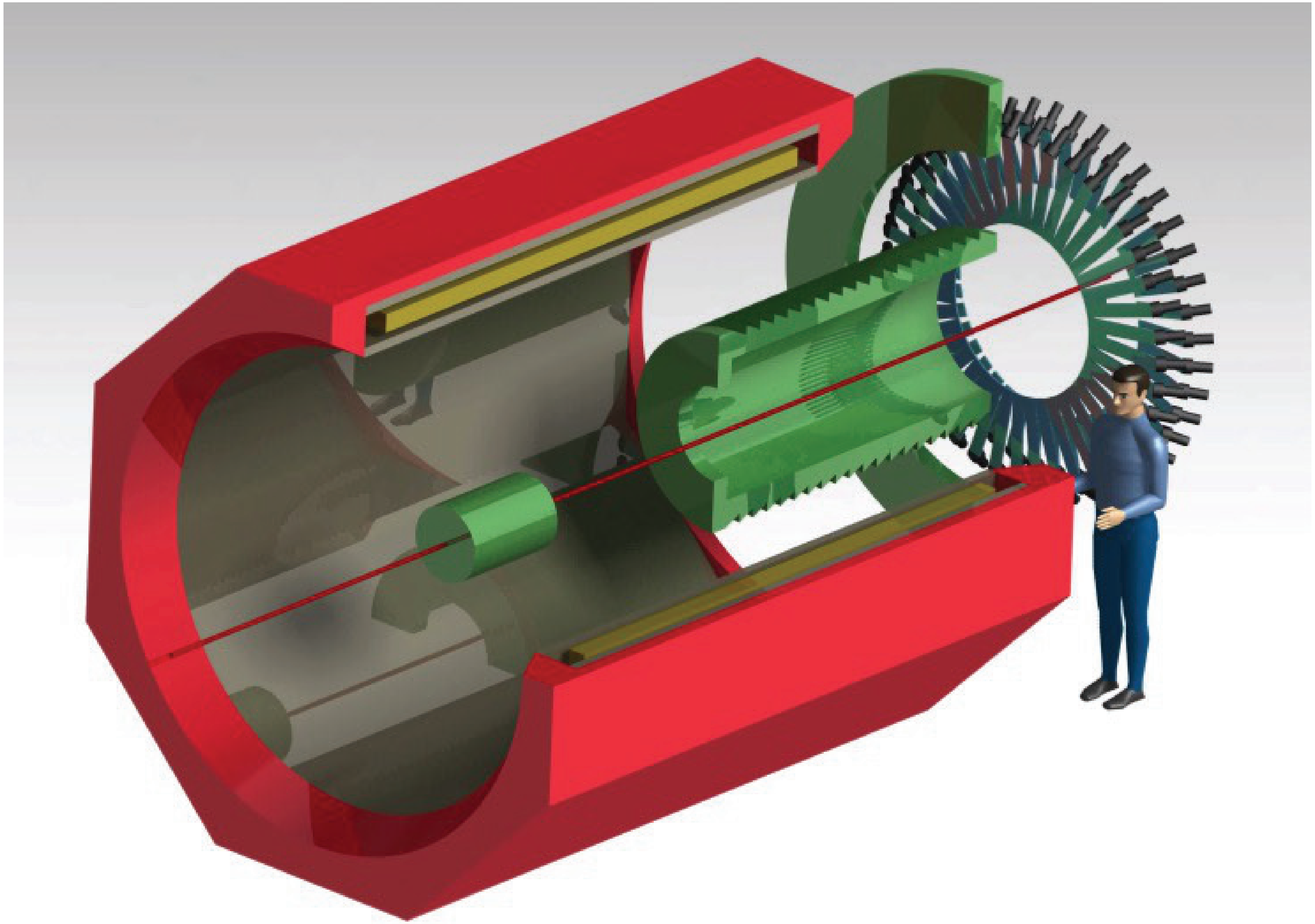
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

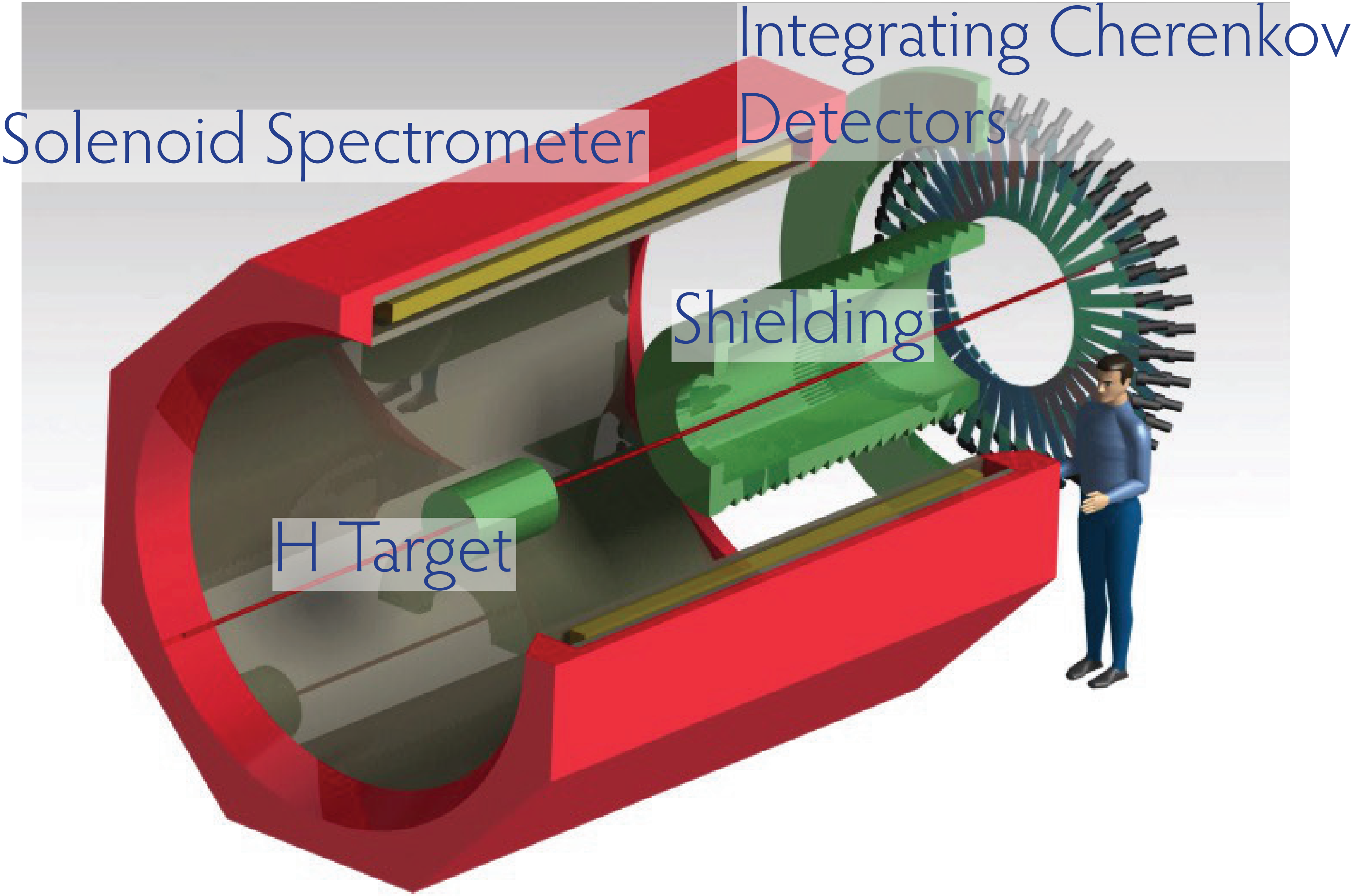
- Cryostat under construction in Mainz



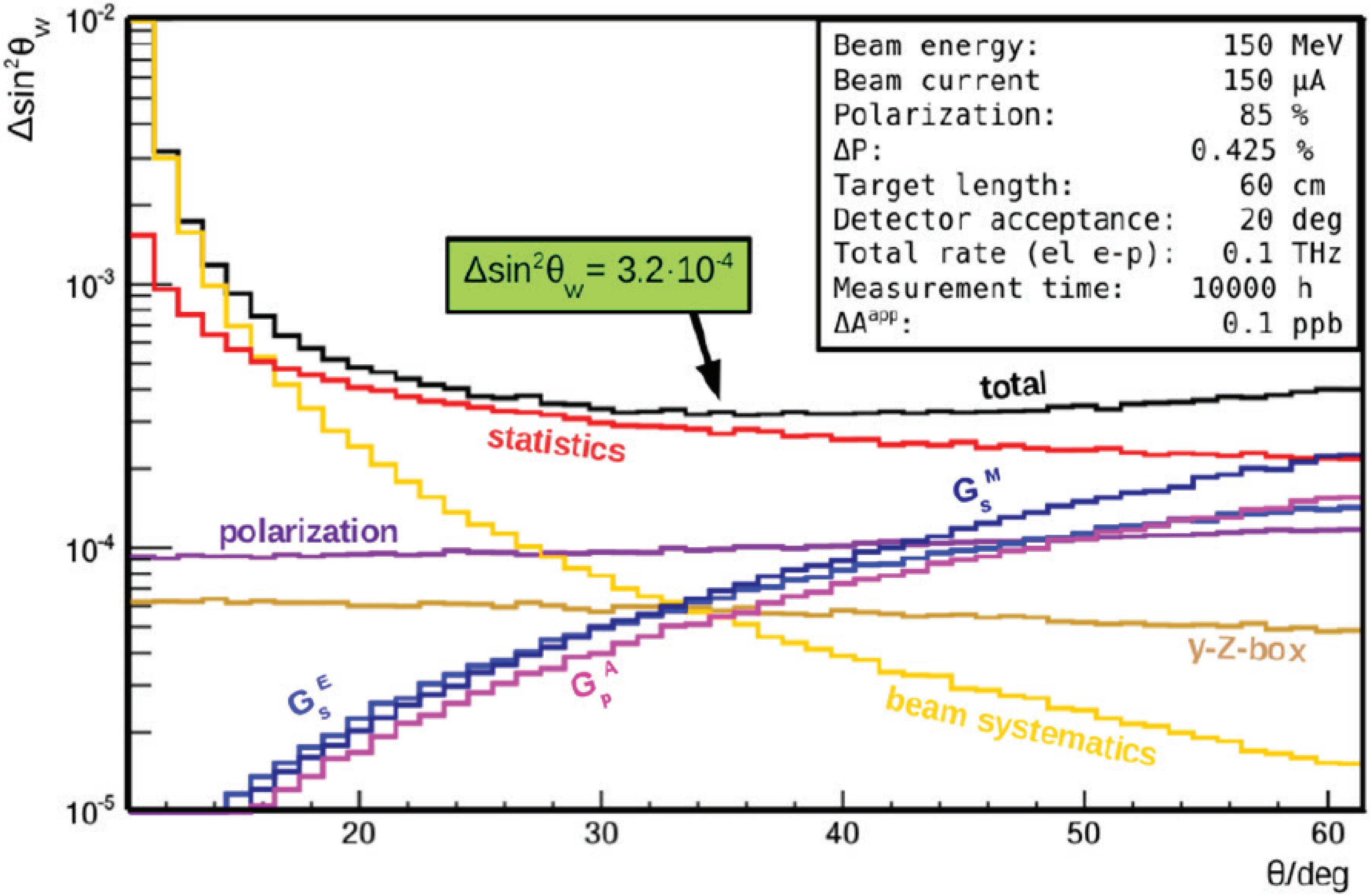
P2:

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

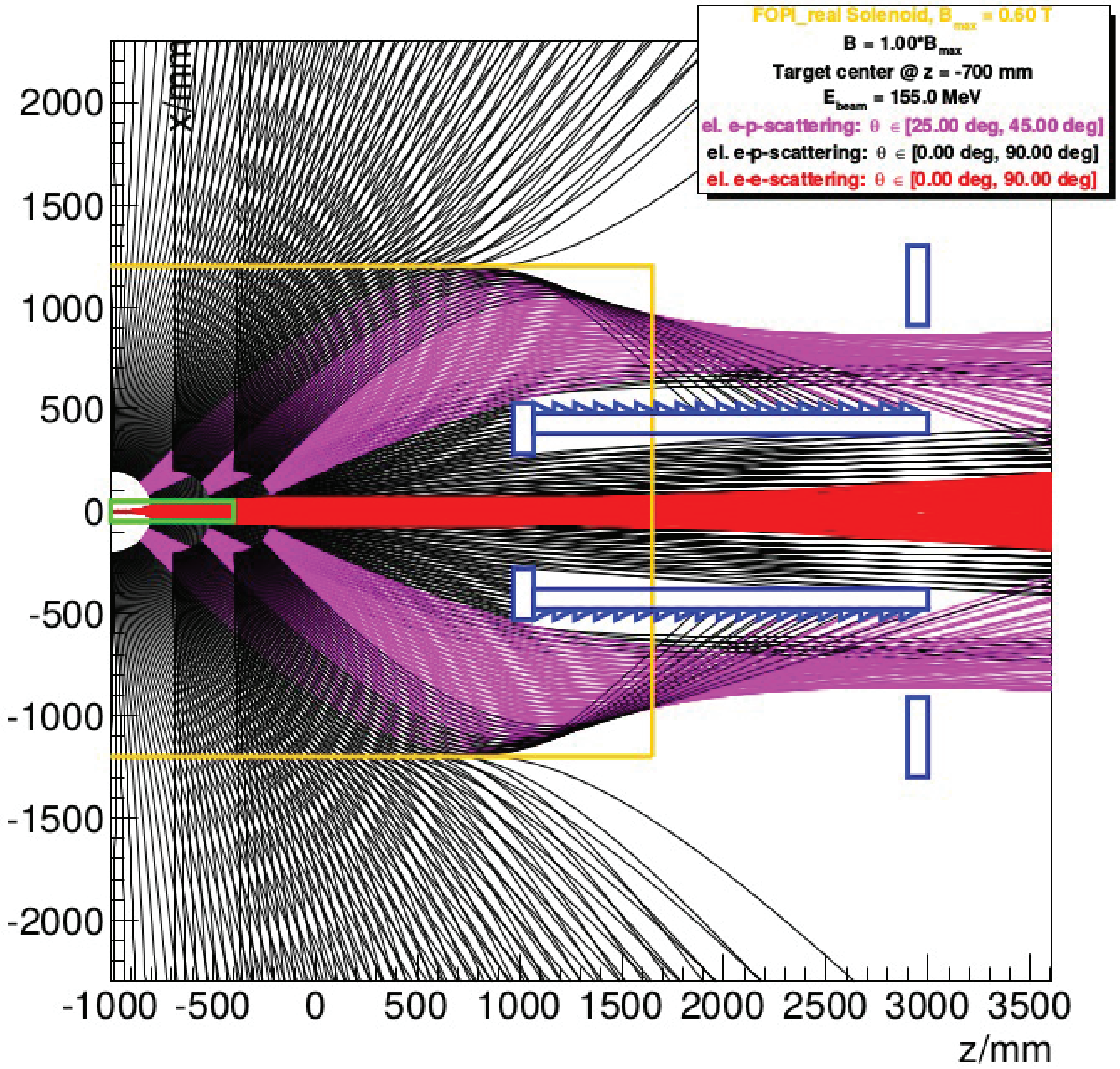



Integrating Cherenkov Detectors
Solenoid Spectrometer
Shielding
H Target

Choice of scattering angle



Solenoid spectrometer



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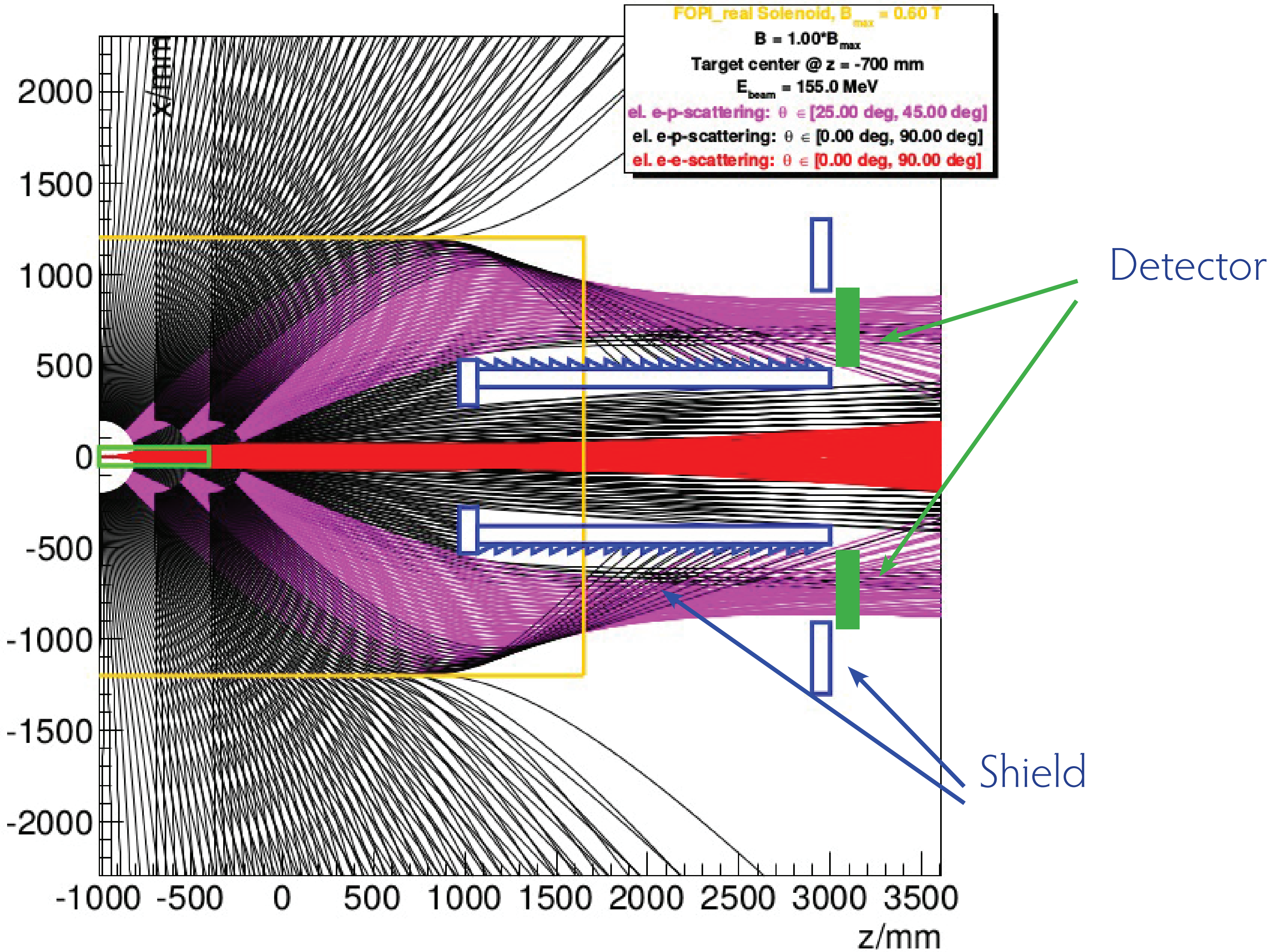
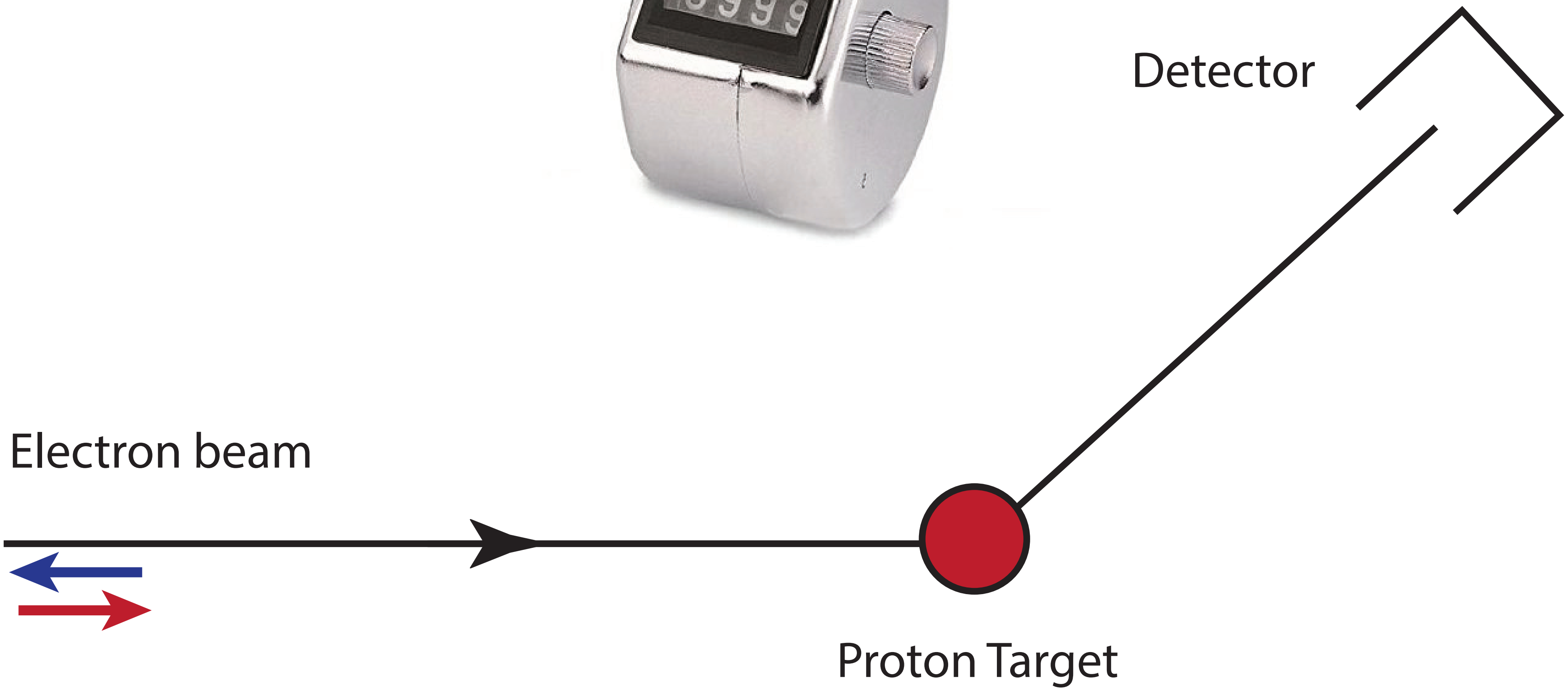
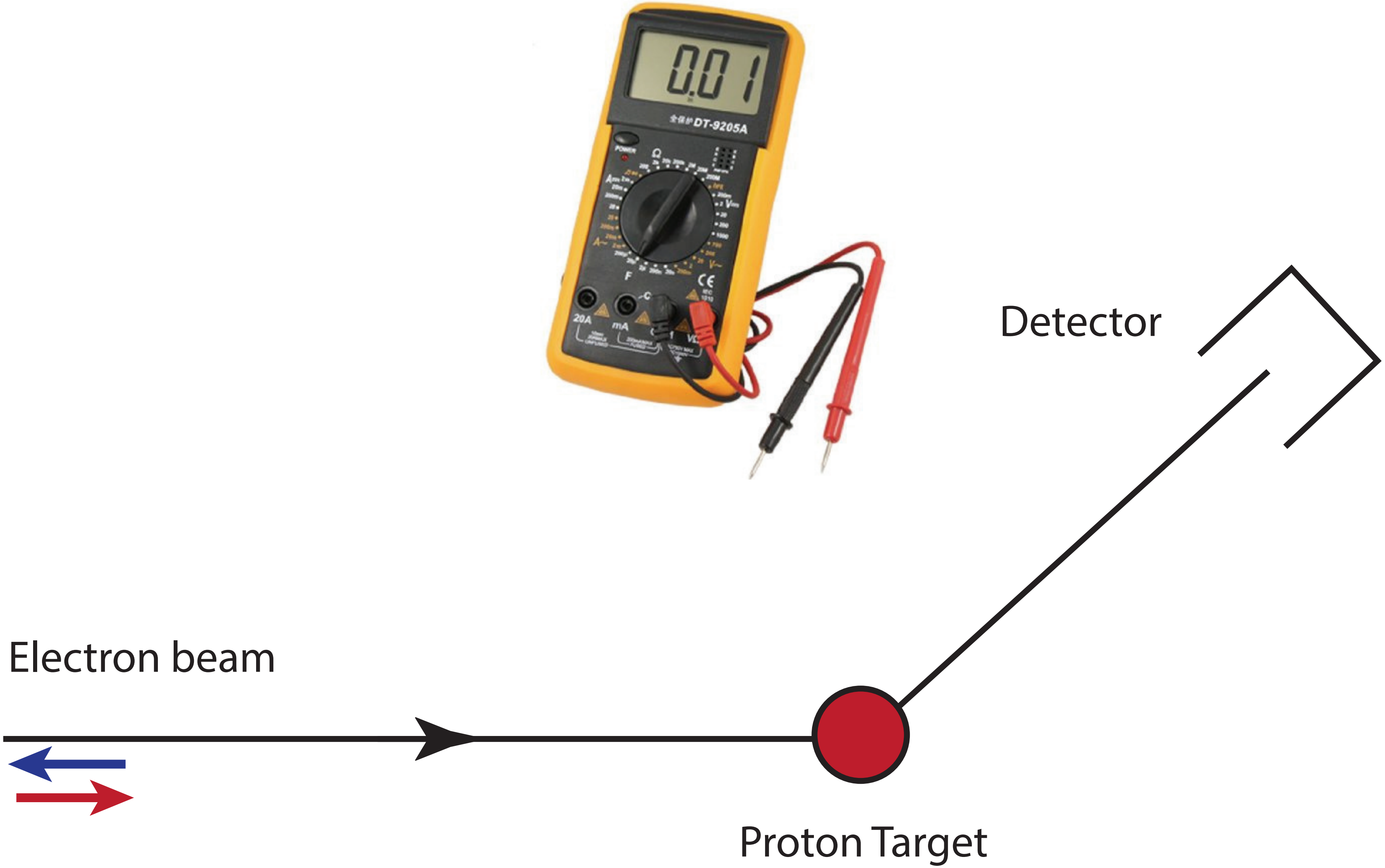


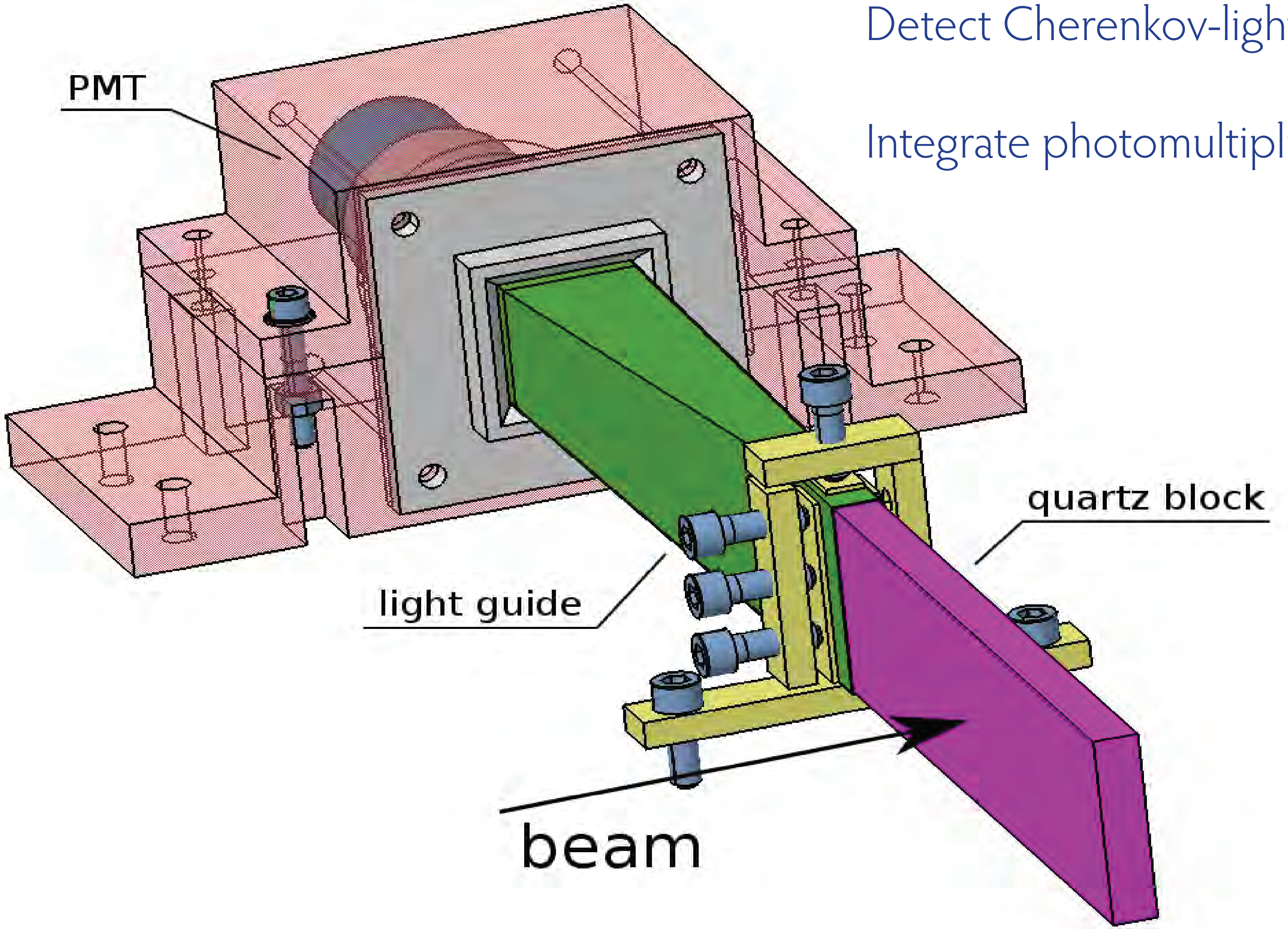
Counting detectors



Integrating detectors



Quartz-Bars & Photomultipliers



Detect Cherenkov-light created by electrons

Integrate photomultiplier current

Quartz-Bars & Photomultipliers

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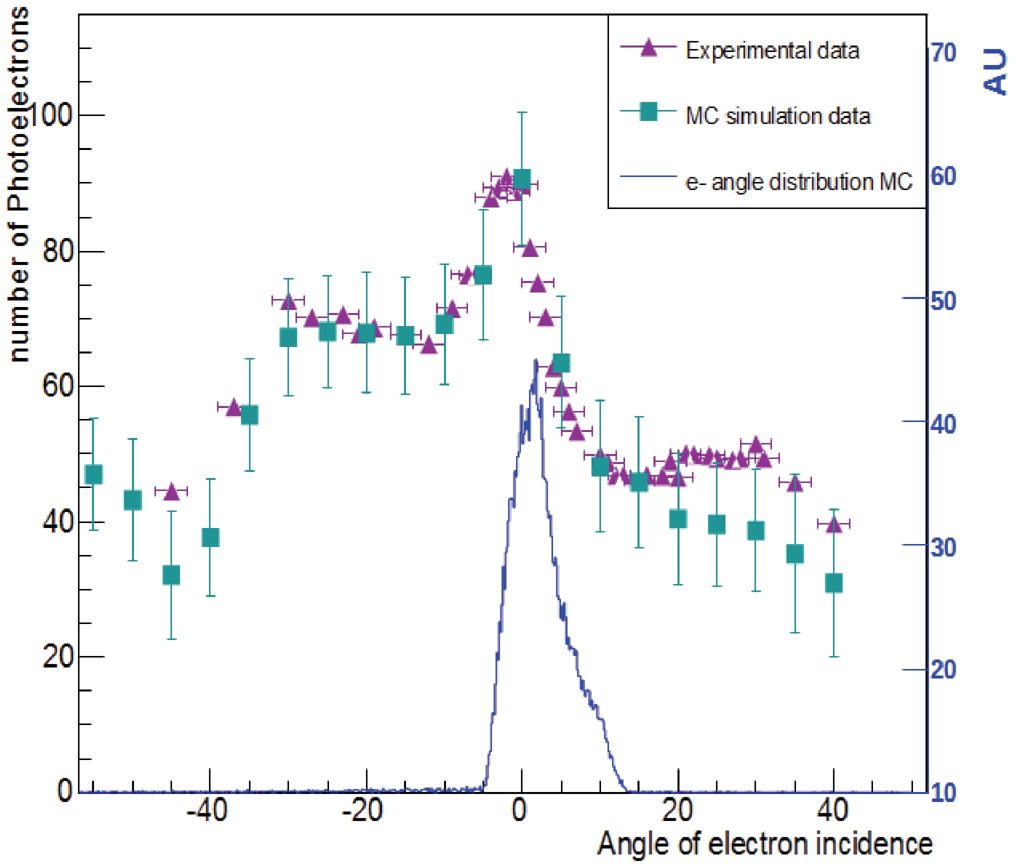
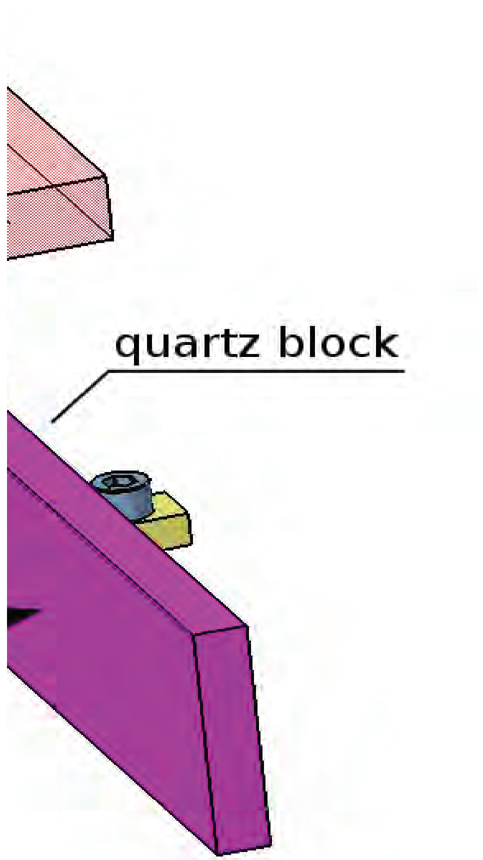
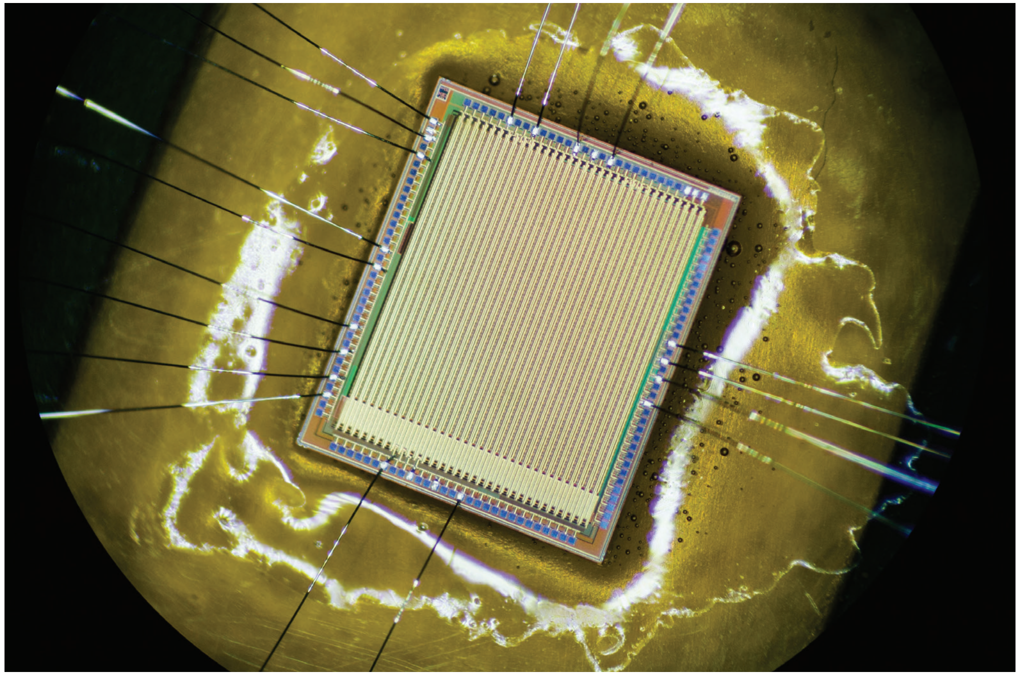
Integrate photomultiplier current

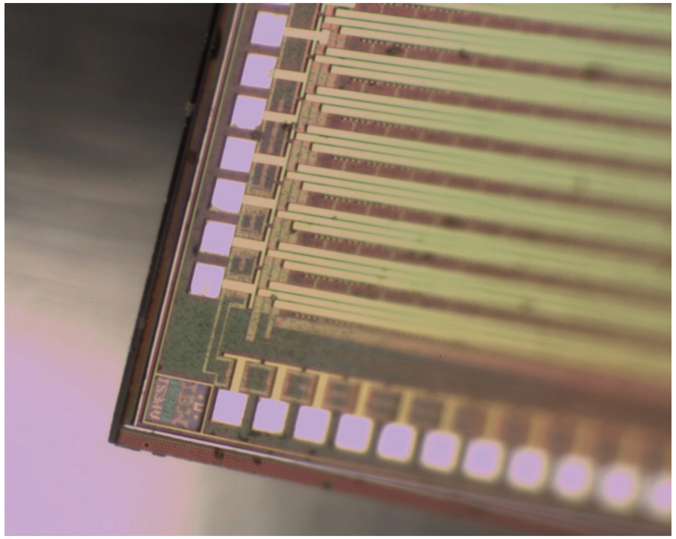




Tracking detector for Q^2 measurement

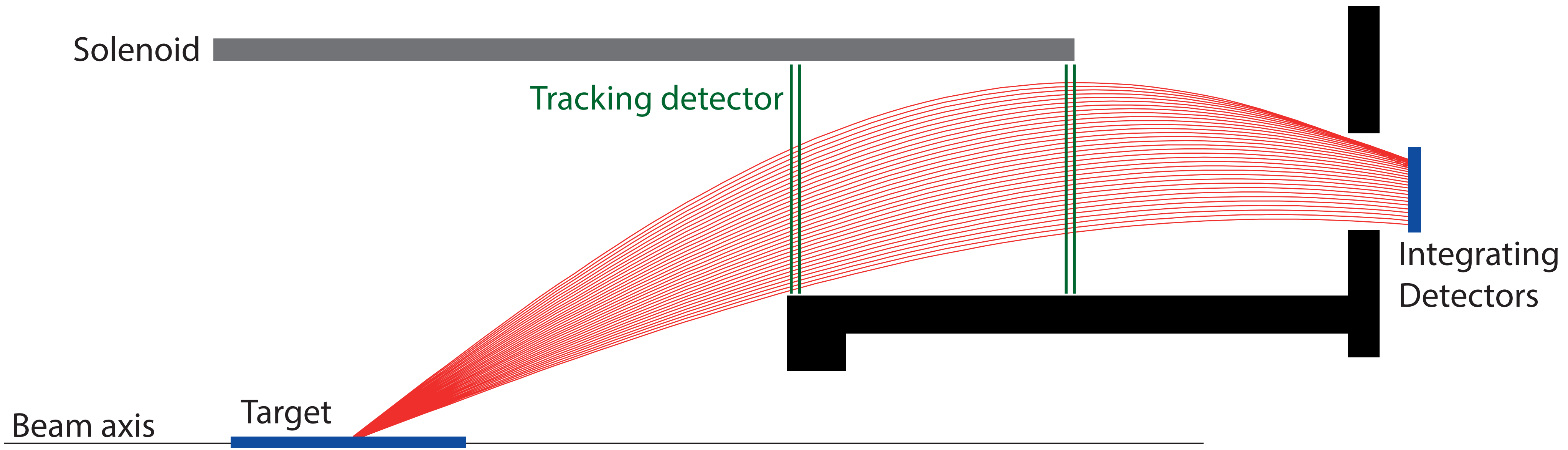
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors
- Use high-voltage monolithic active pixel sensors (HV-MAPS) thinned to 50 µm
- Last week: Beam test at MAMI, promising results





Tracking detector for Q^2 measurement

- Four layers of wedges
- Mechanical and electrical design ongoing



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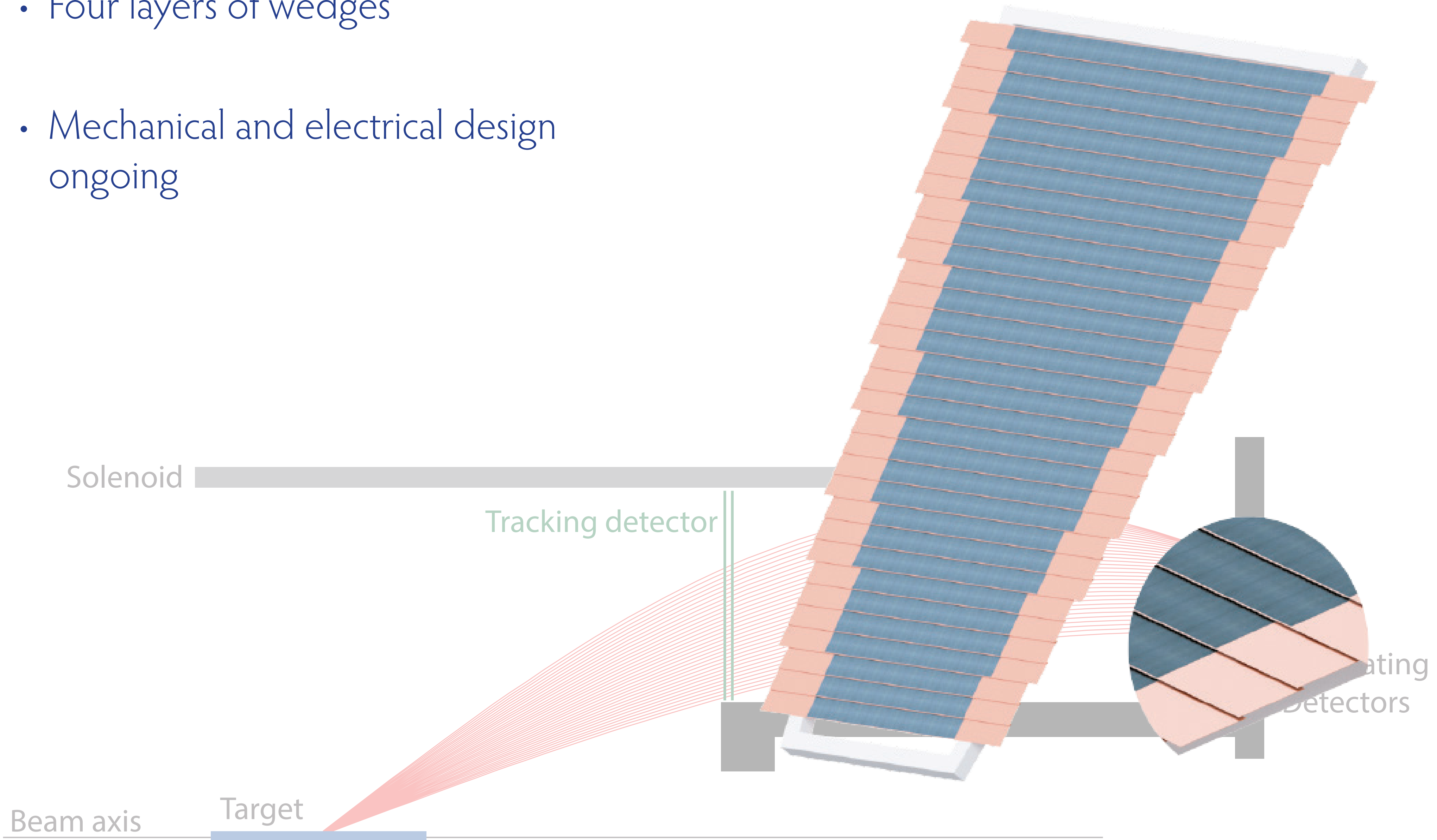
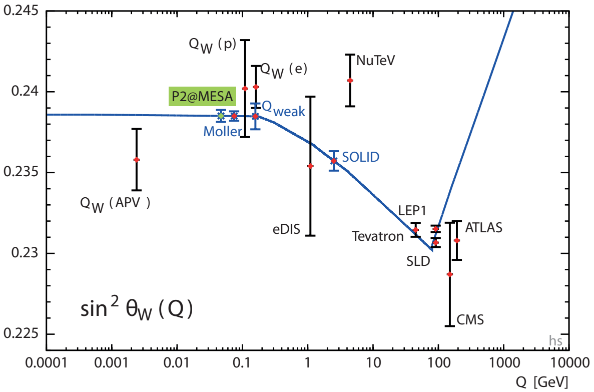
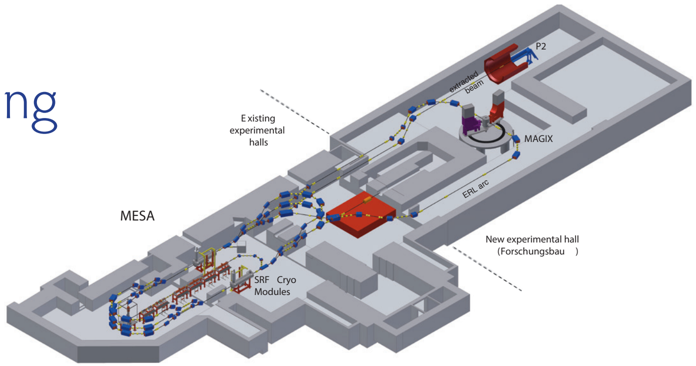
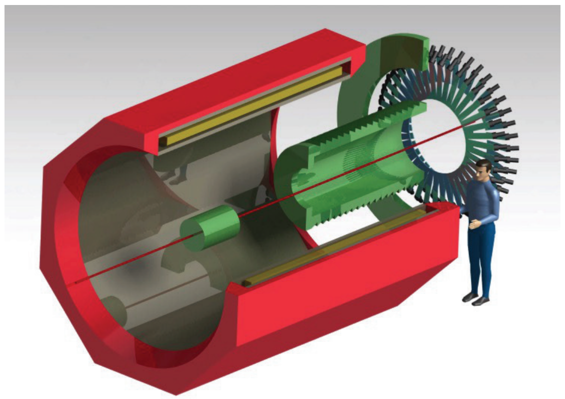


Summary



- P2 aims to measure $\sin^2\theta_W$ to 0.13%
- Parity violating electron scattering at very high rates
- Solenoid spectrometer with integrating Cherenkov detectors
- Tracking detector with thin active silicon pixel sensors
- Data taking starts with MESA





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"

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

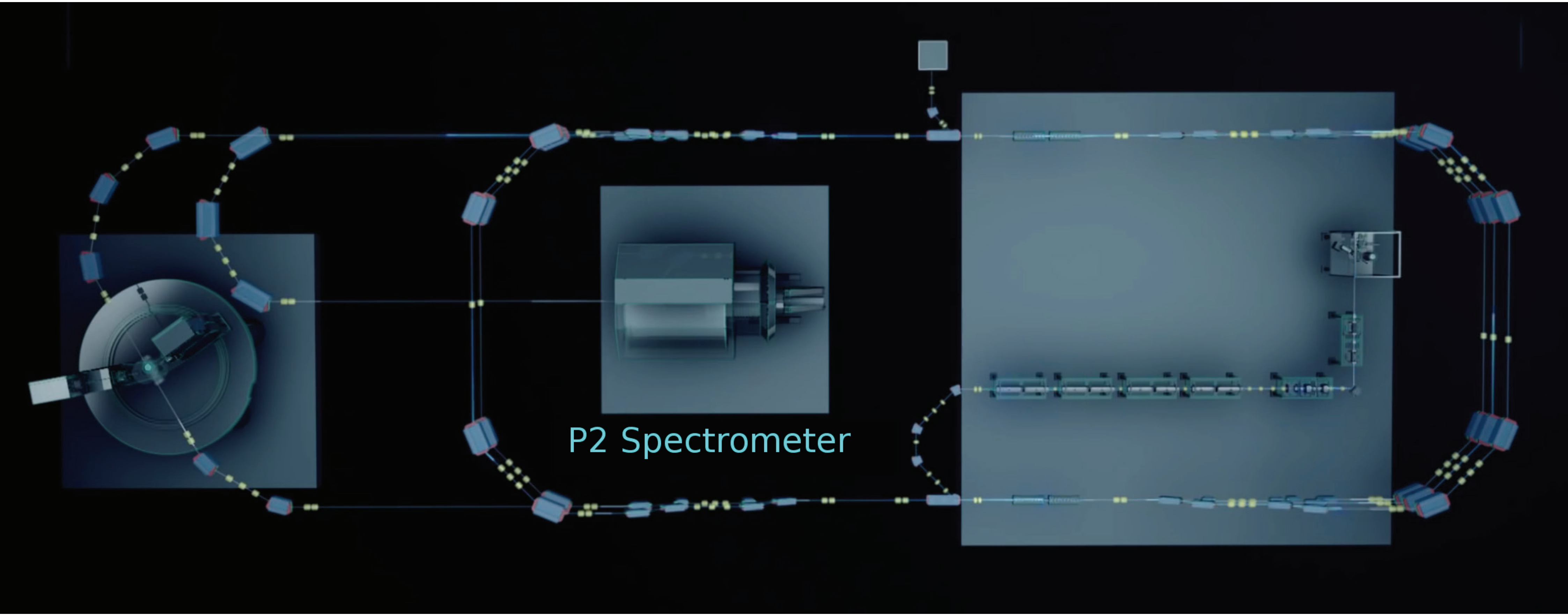
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

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

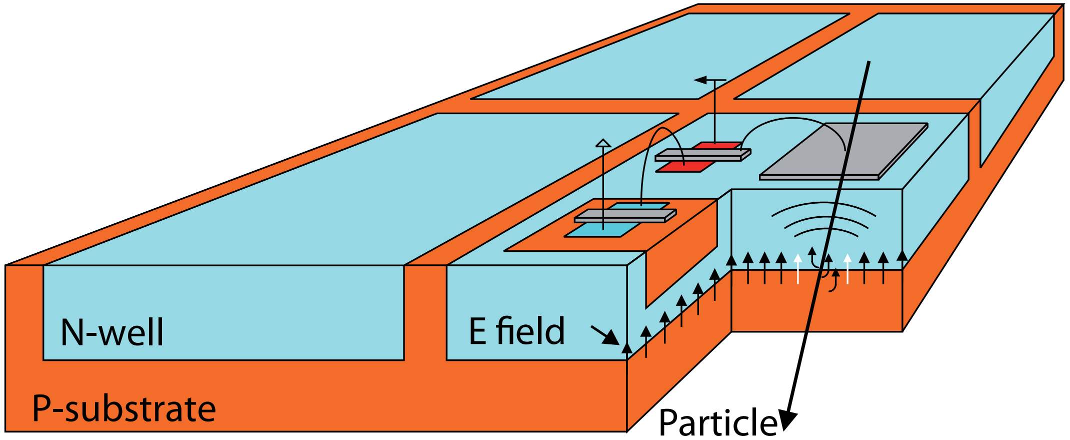
MESA



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

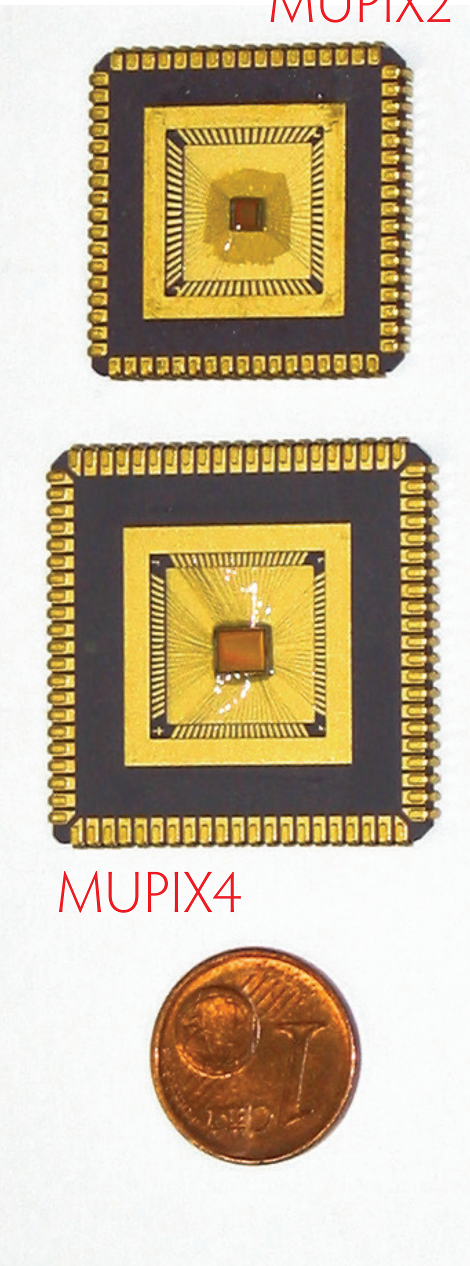


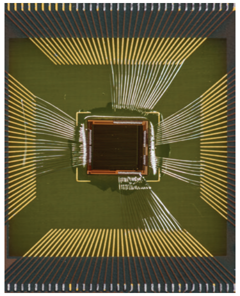
High voltage monolithic active pixel sensors - Ivan Perić

- 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

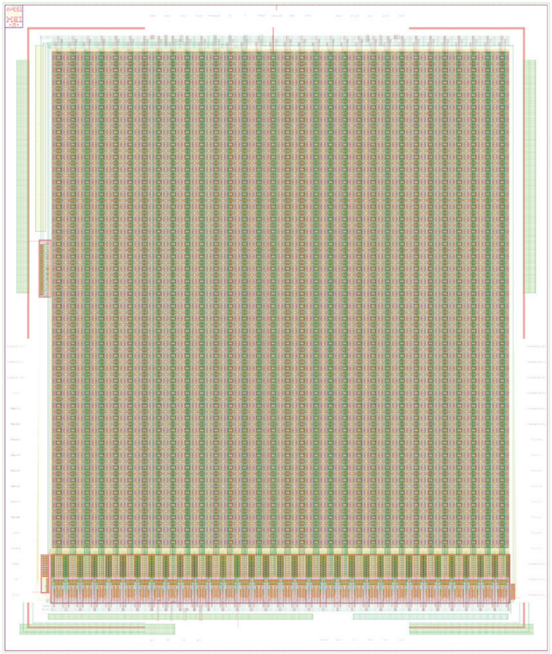
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

The MUPIX chip prototypes





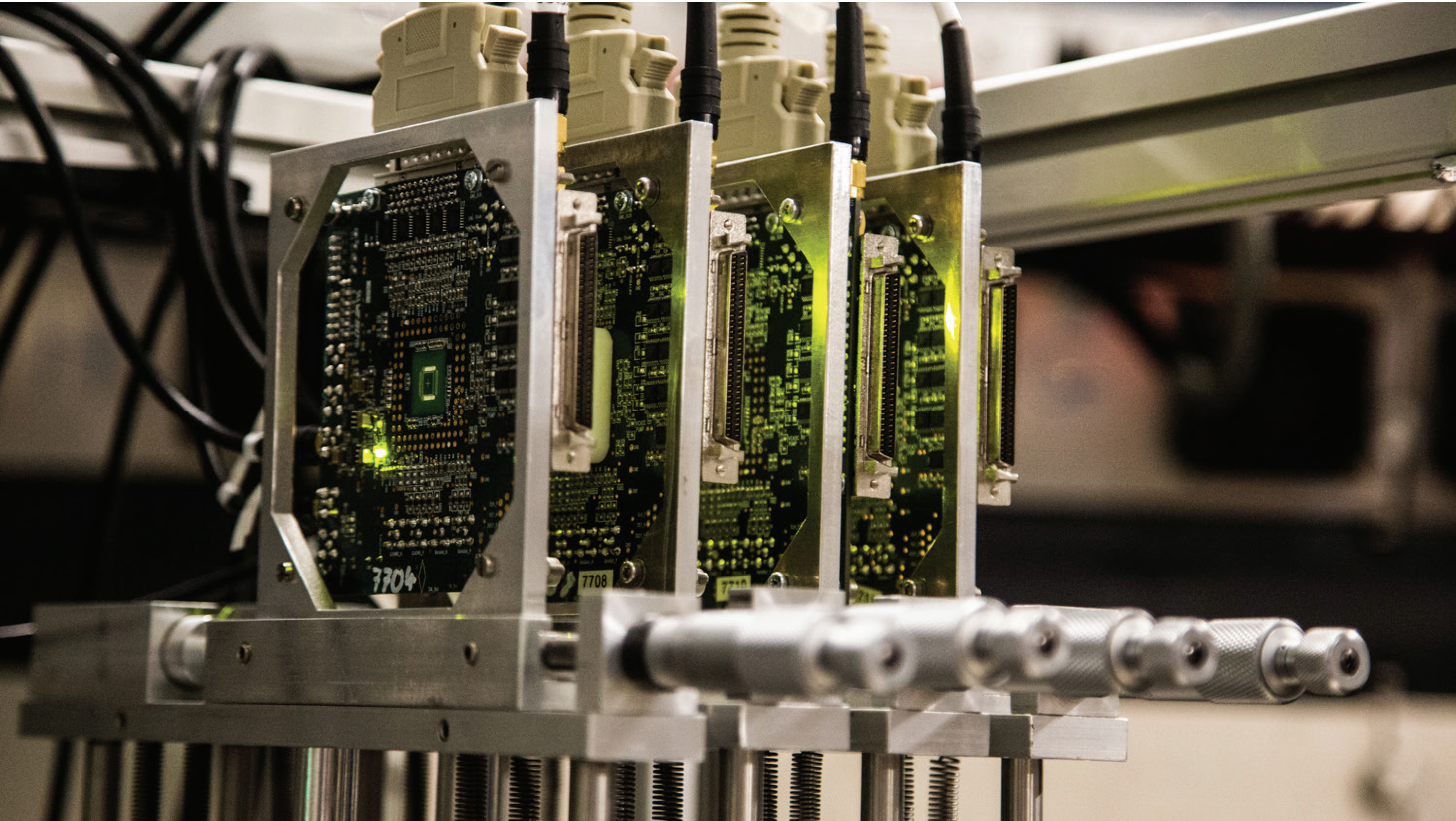
MUPIX6



HV-MAPS chips: AMS 180 nm HV-CMOS

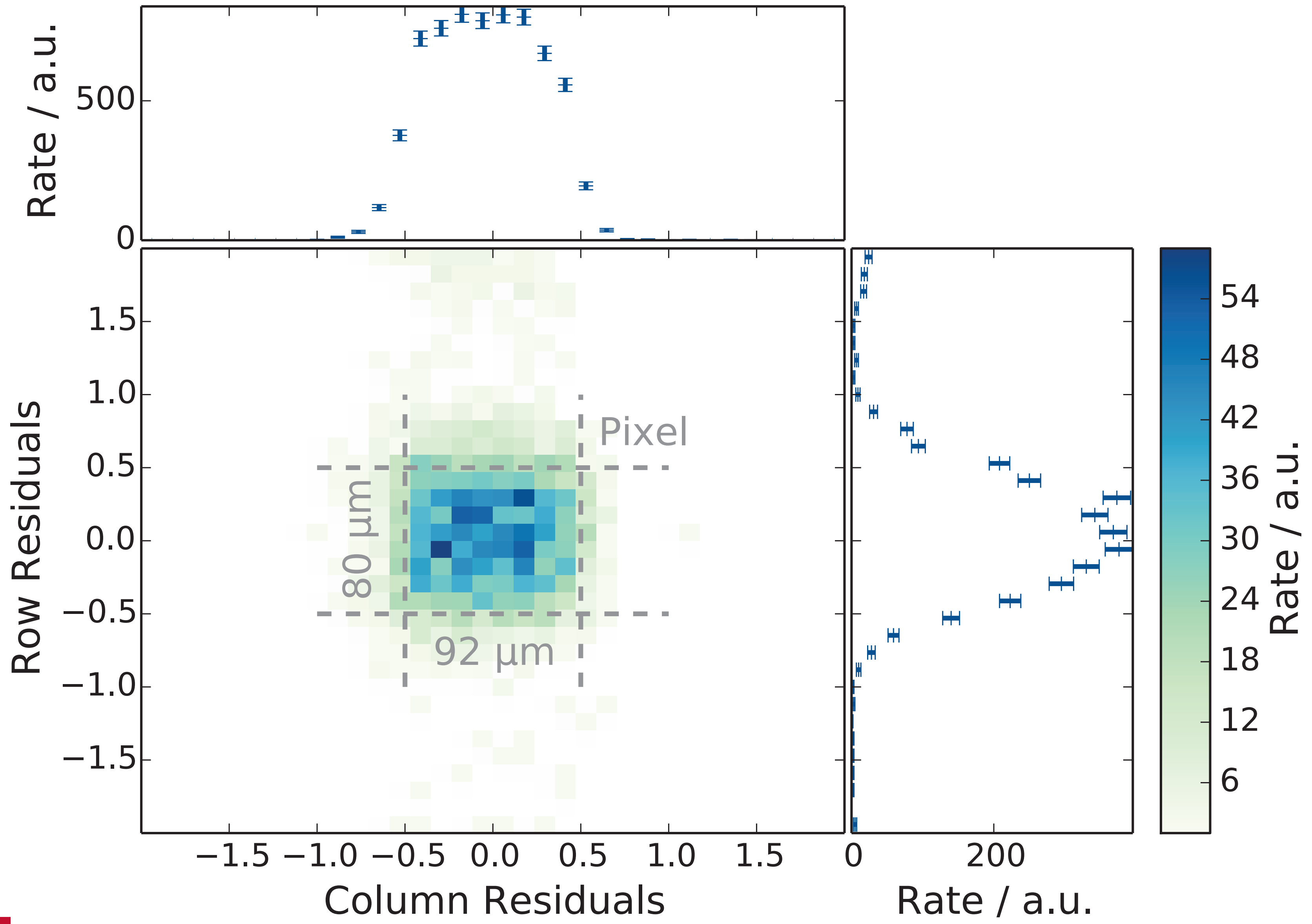
- 5 generations of prototypes
- Current generation:
  MUPIX7
  40 x 32 pixels
  80 x 103 μm pixel size
  9.4 mm^2 active area
- MUPIX7 has all features of final sensor
- Left to do: Scale to 2 x 2 cm^2

Test beam at MAMI



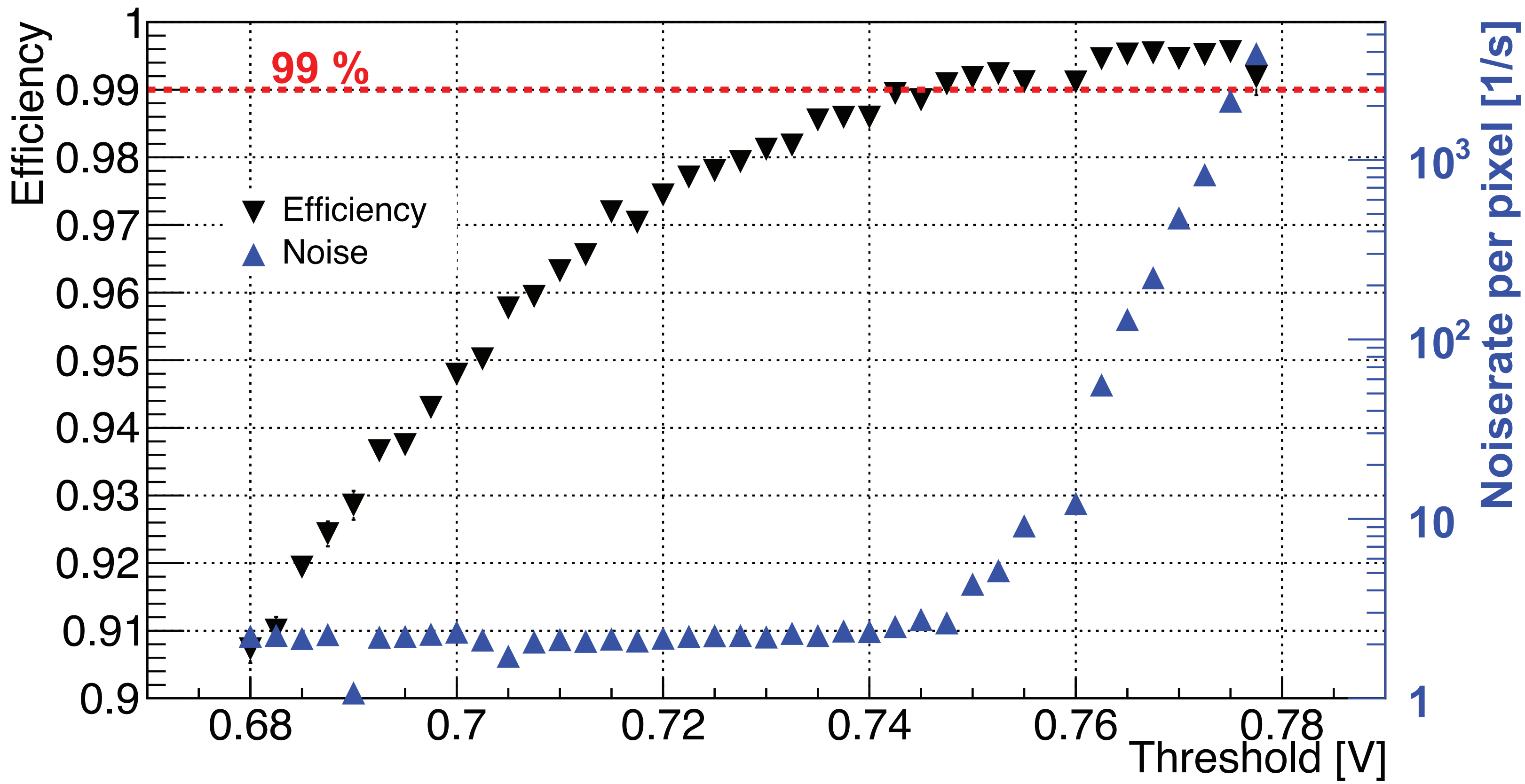
Position Resolution (measured at DESY)

Position resolution given by pixel size

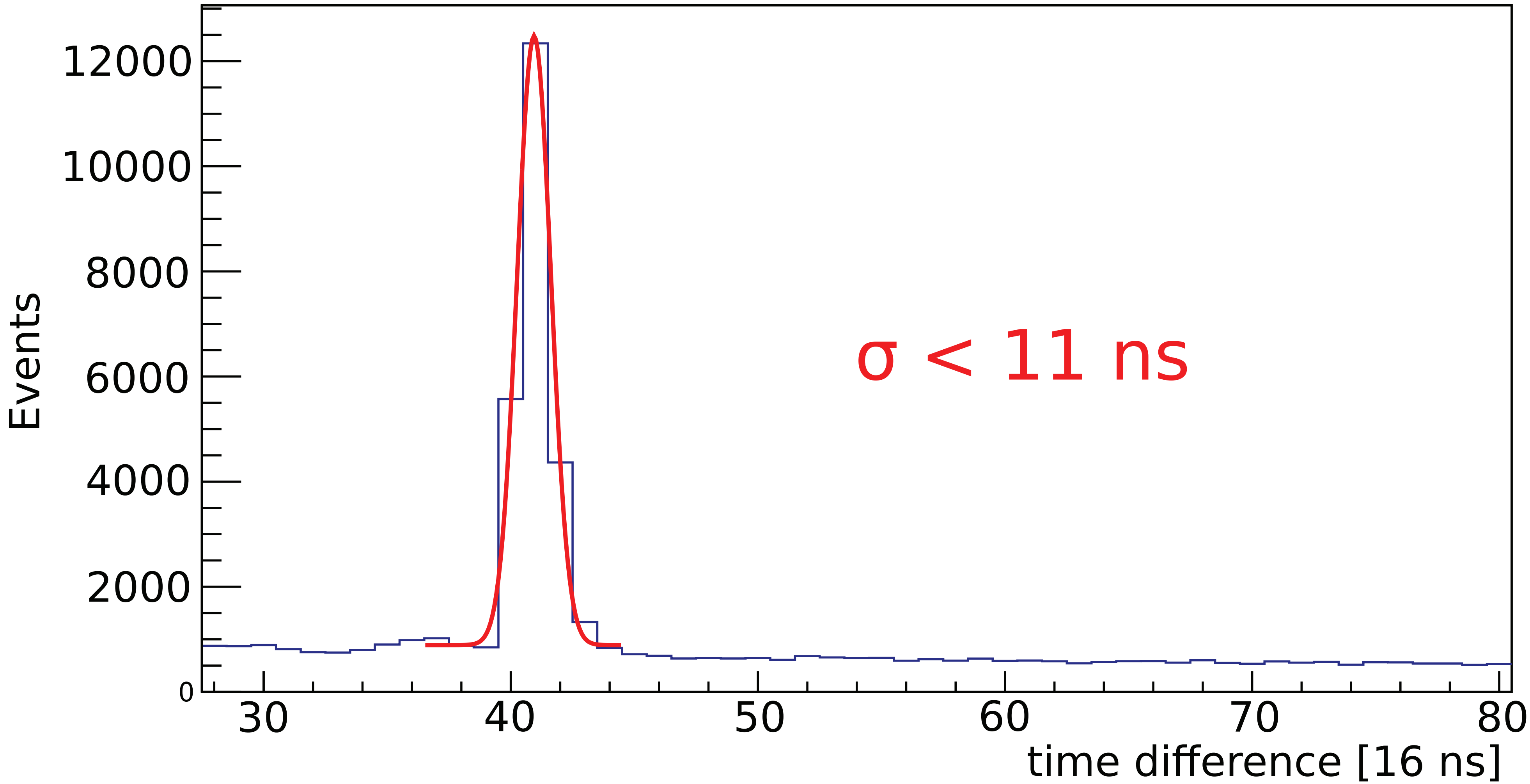


Efficiency (measured at PSI)

Hit efficiency above 99.5%

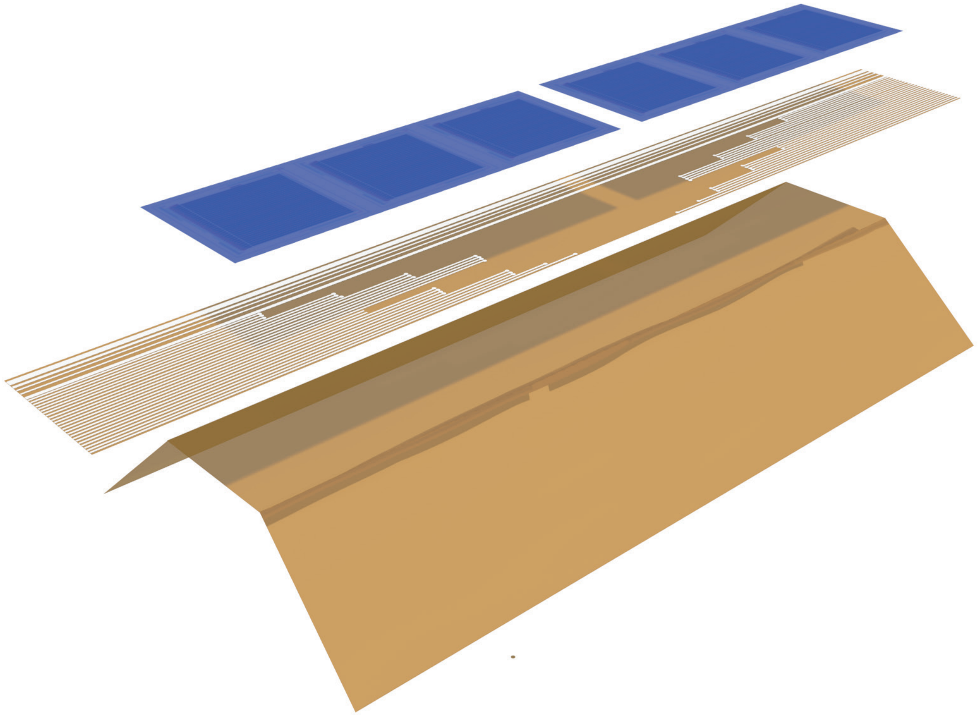


Time resolution



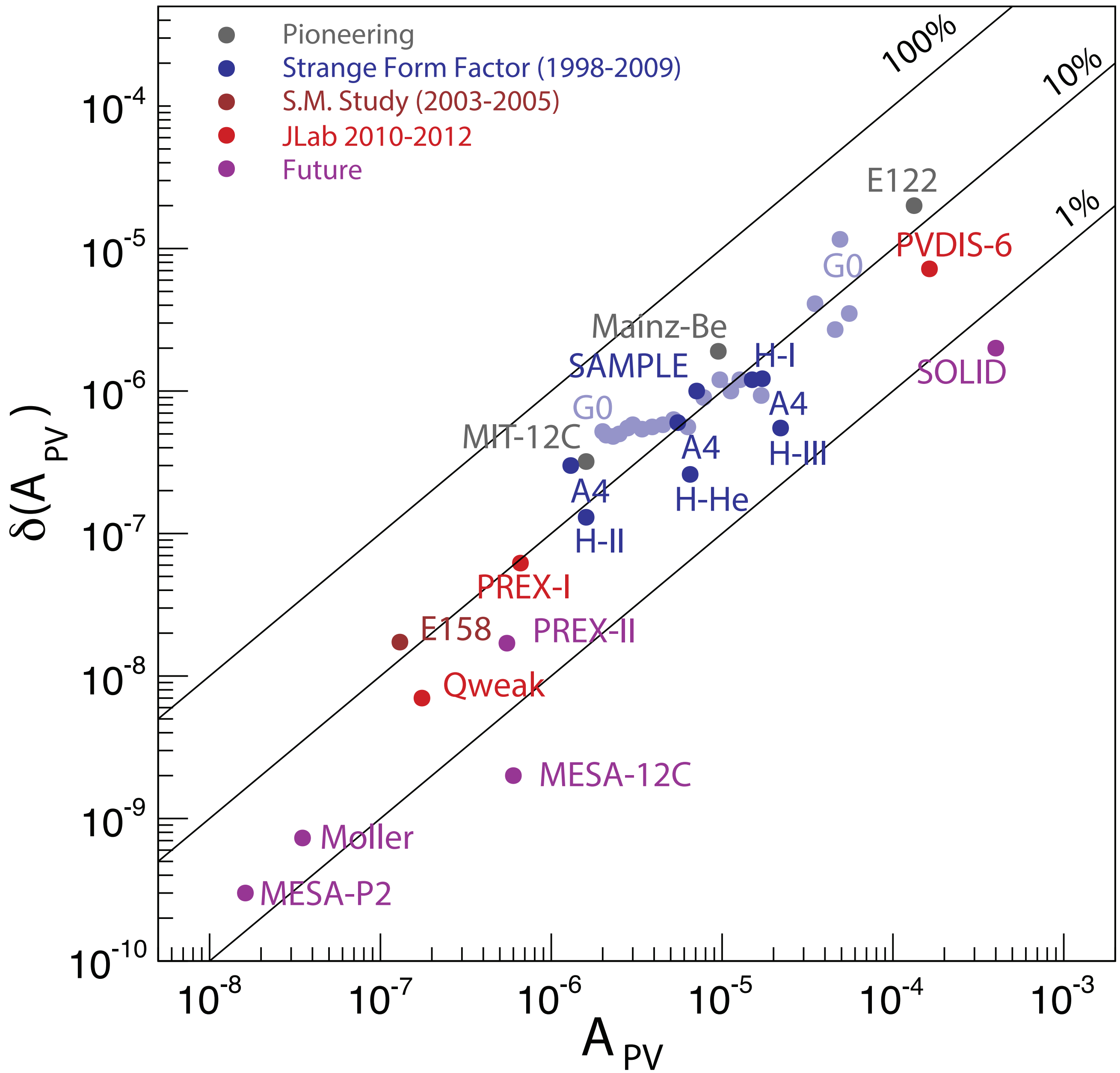
Hit timestamp resolution better than 11 ns

Mechanics

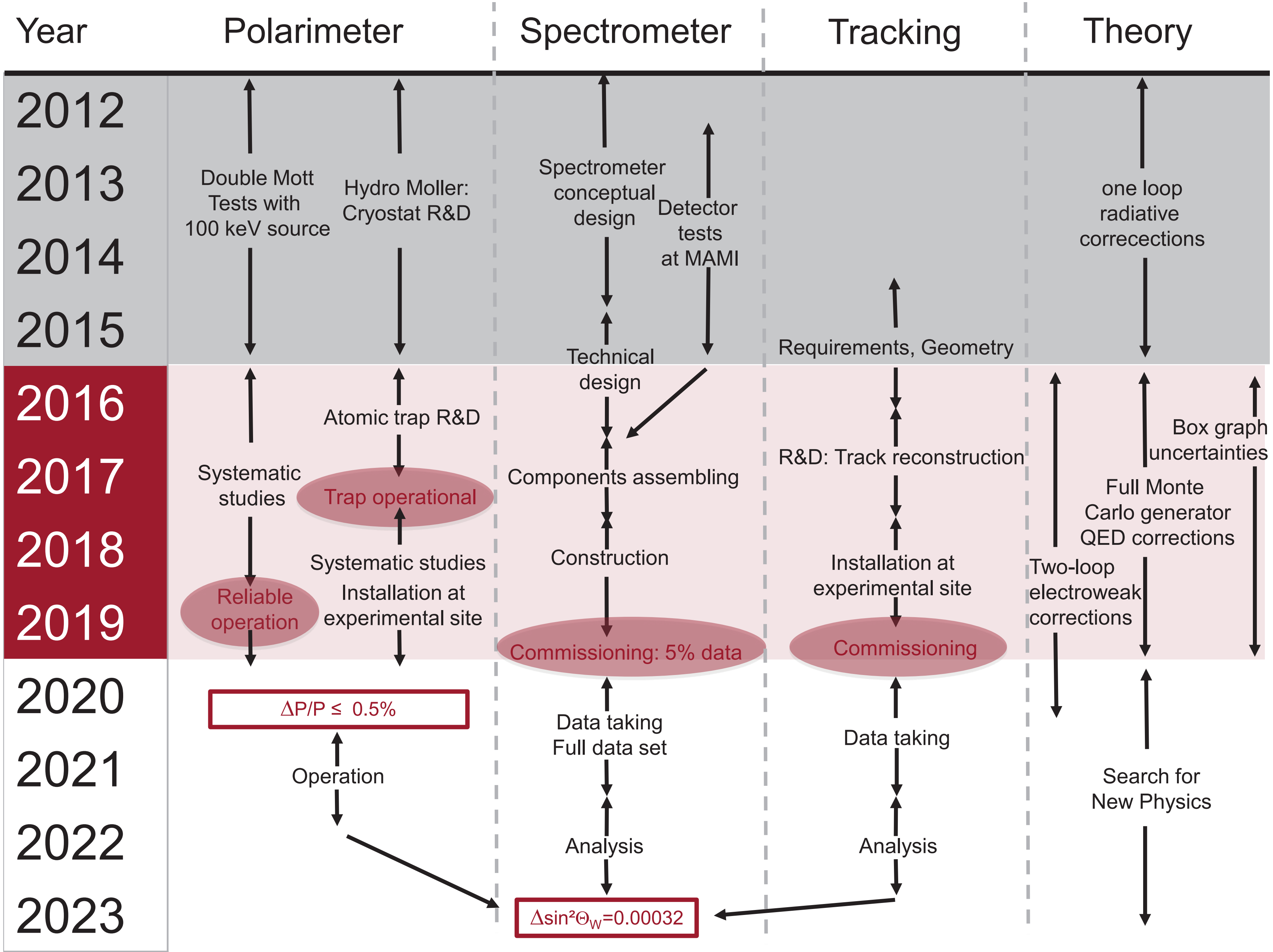


- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

PVeS Experiment Summary



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
Requirements, Geometry
Technical design
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