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

Niklaus Berger for the P2 Collaboration

Institut für Kernphysik,
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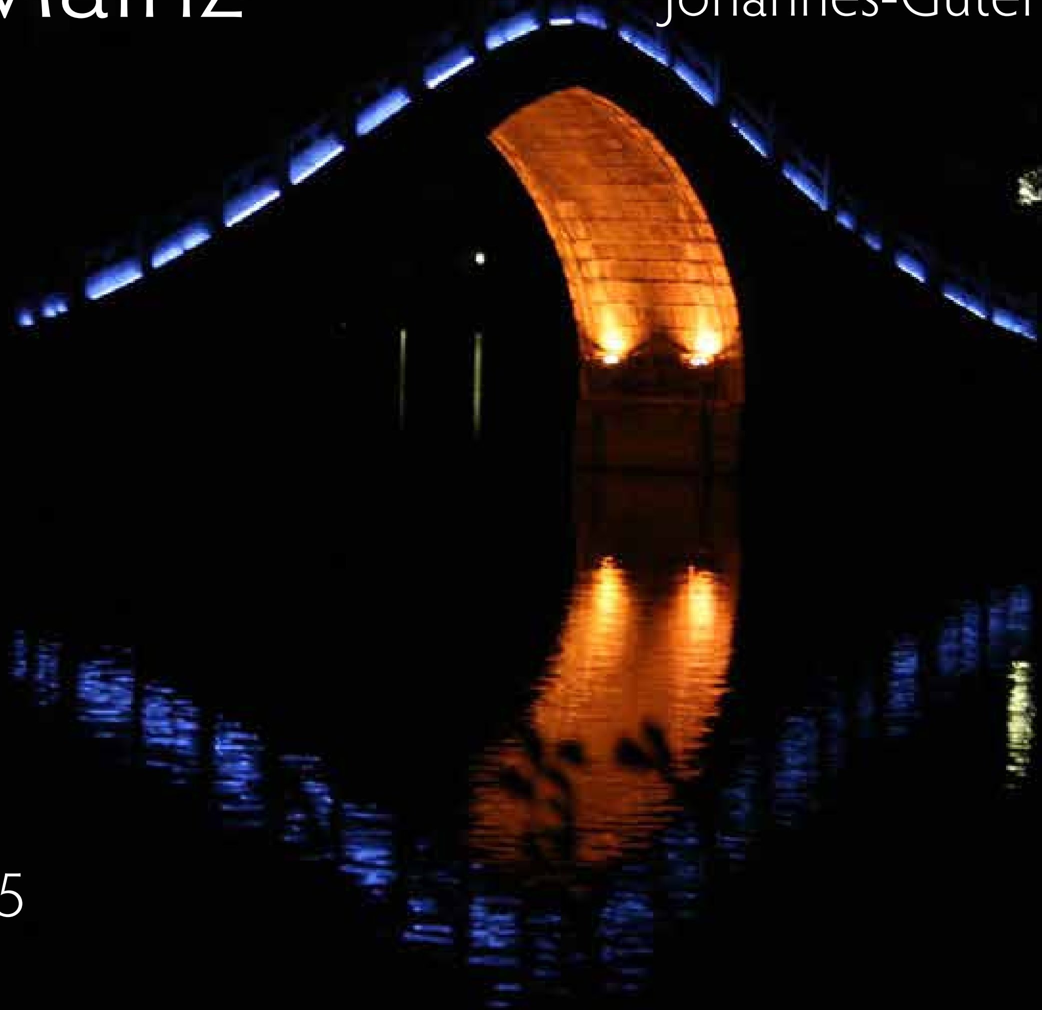


PhiPsi Hefei
September 2015

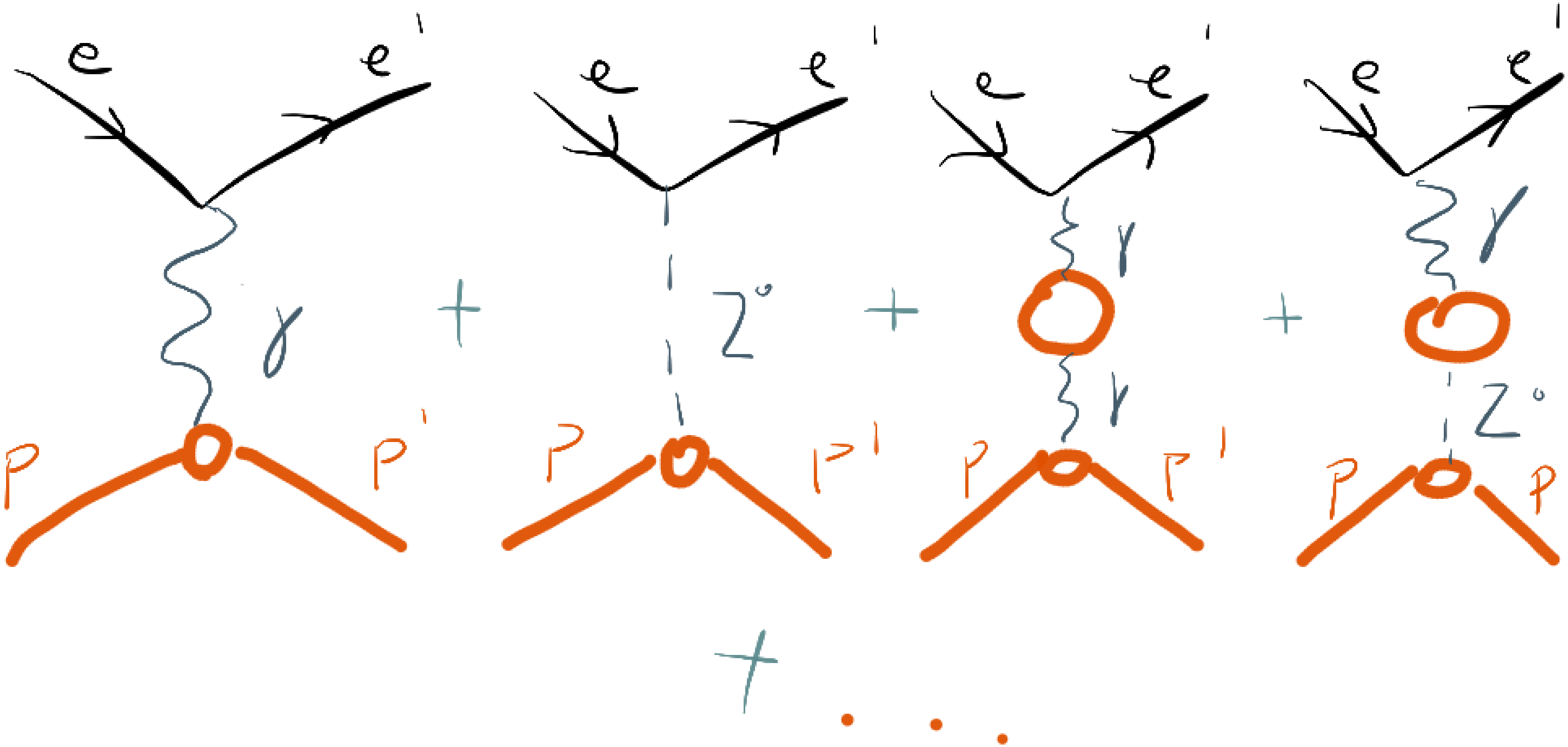
Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

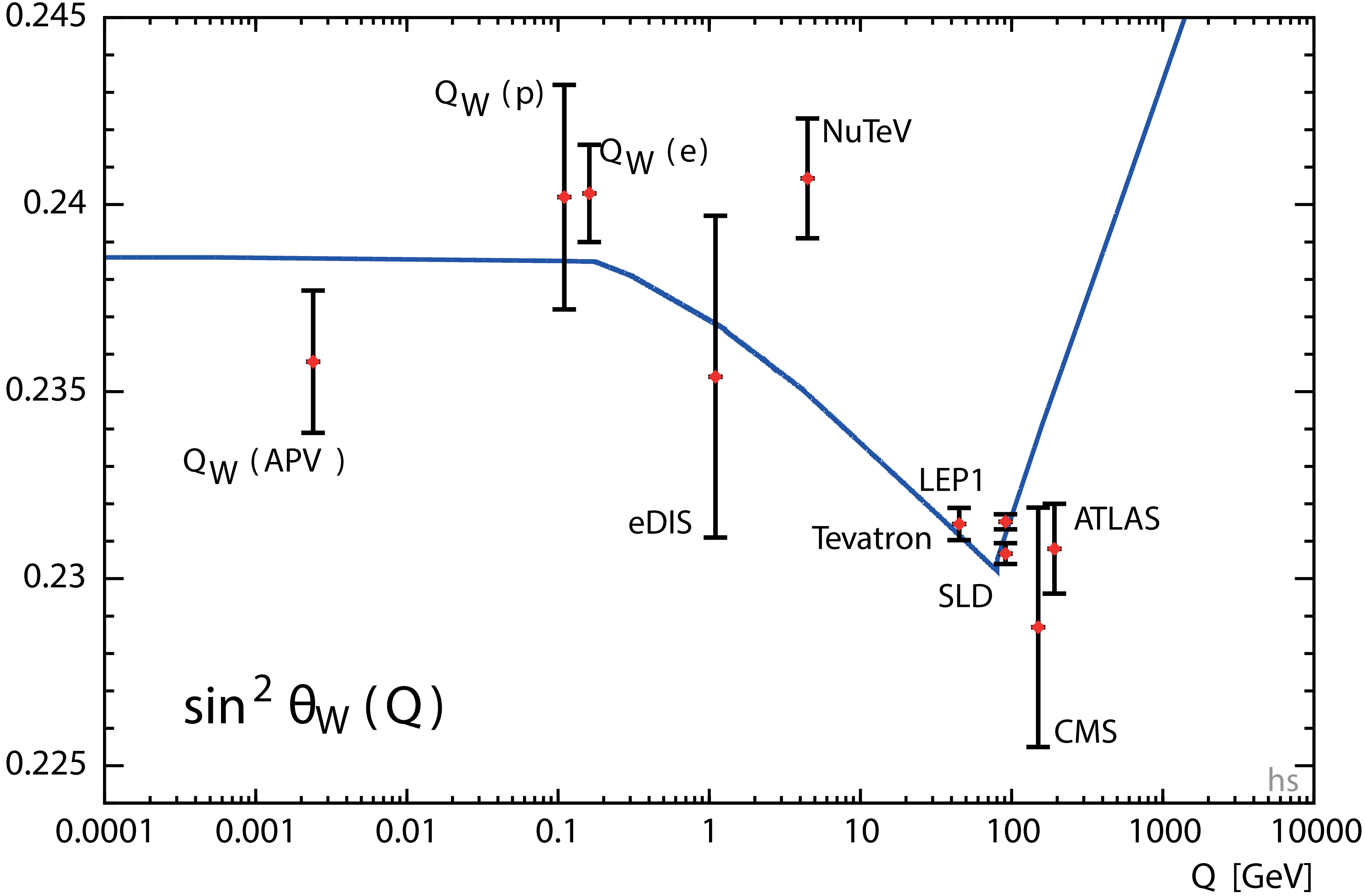
Overview

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

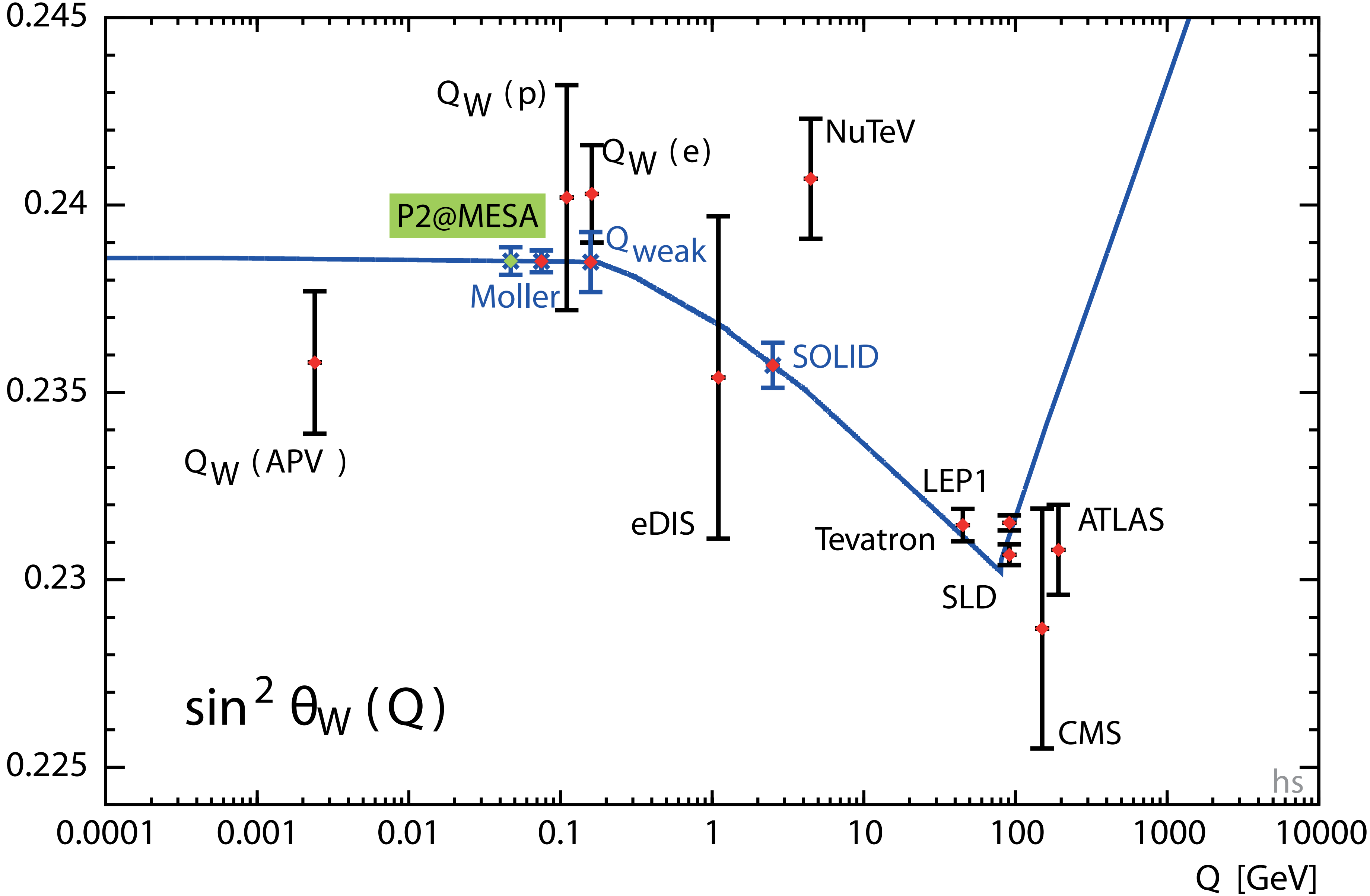
Scale dependence (running) of $\sin^2\theta_W$



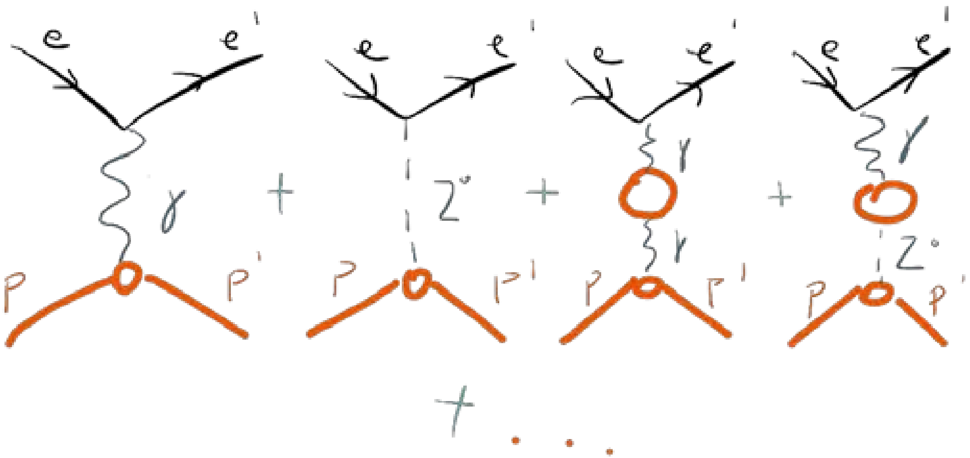
Scale dependence (running) of $\sin^2\theta_W$

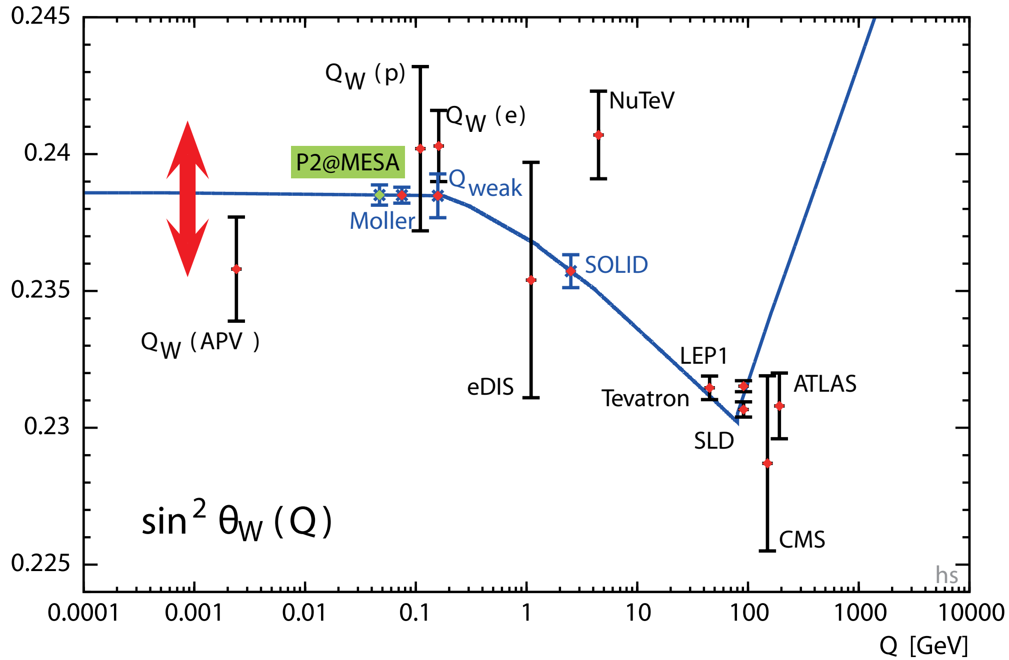


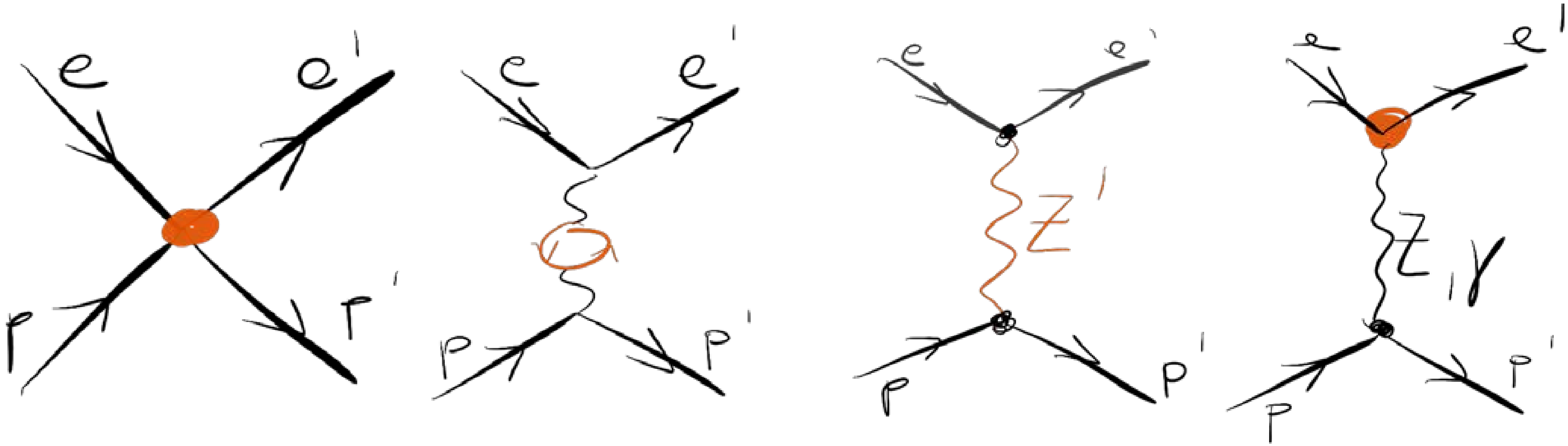
Scale dependence (running) of $\sin^2\theta_W$



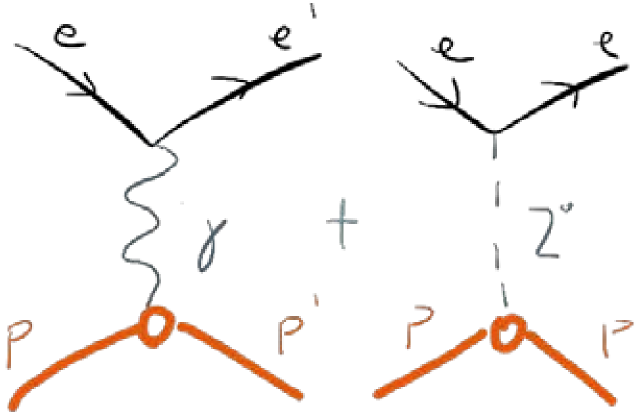
New Physics in the running

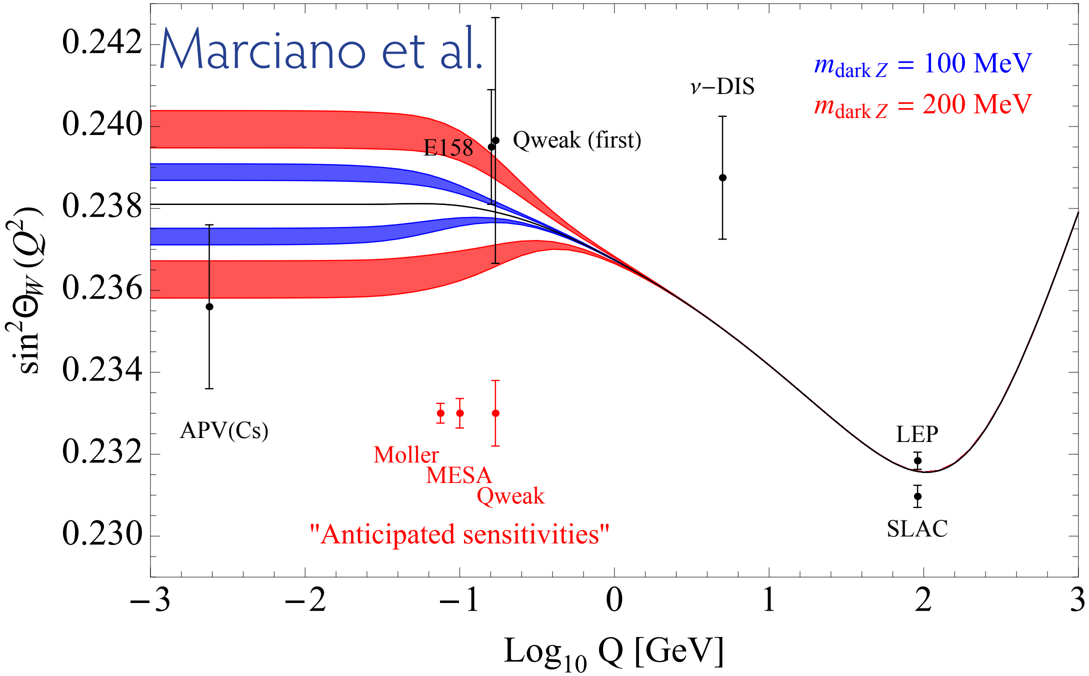


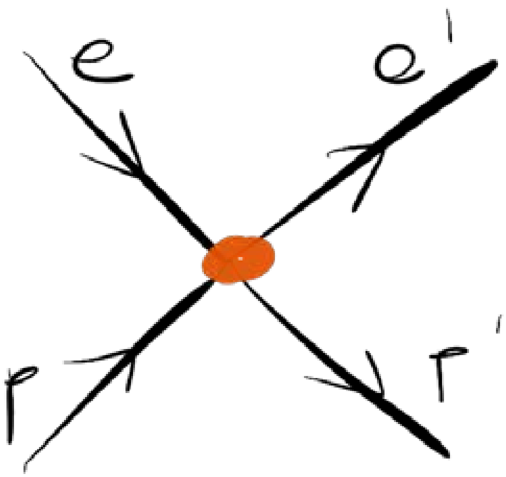


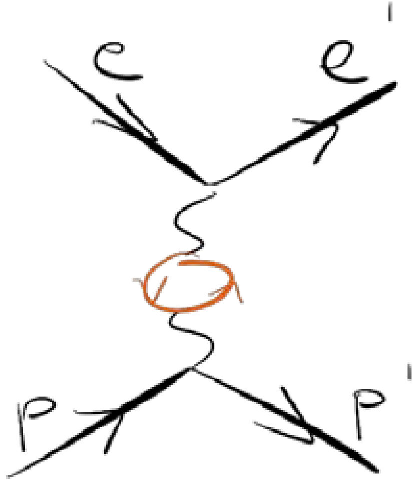


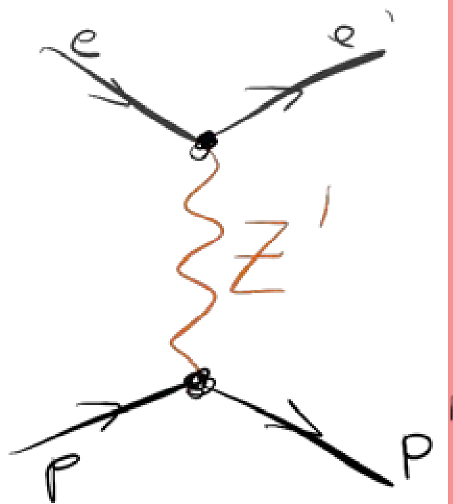
Dark Z in mixing

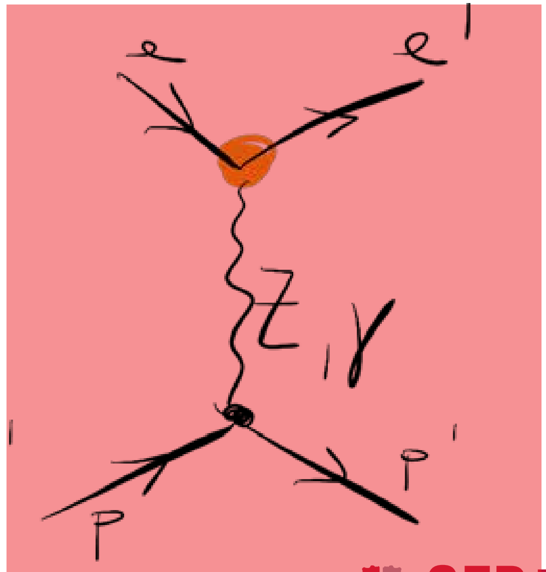




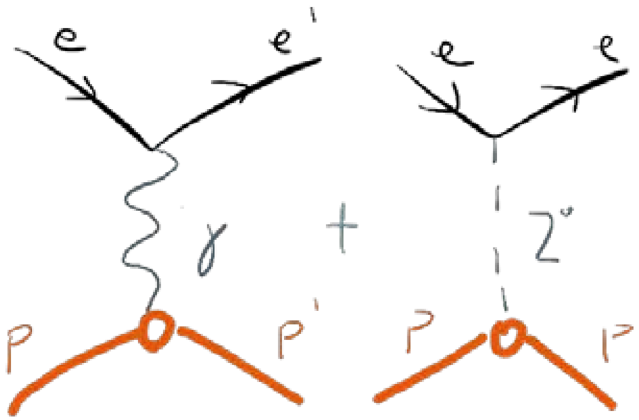








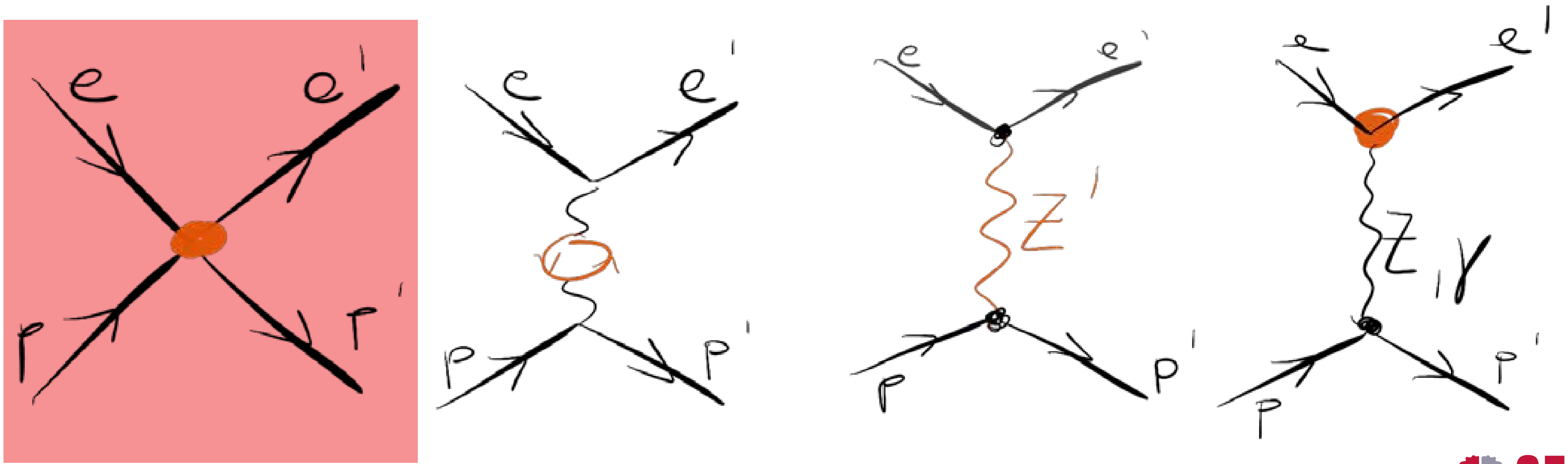
Contact Interactions



Contact interactions up to

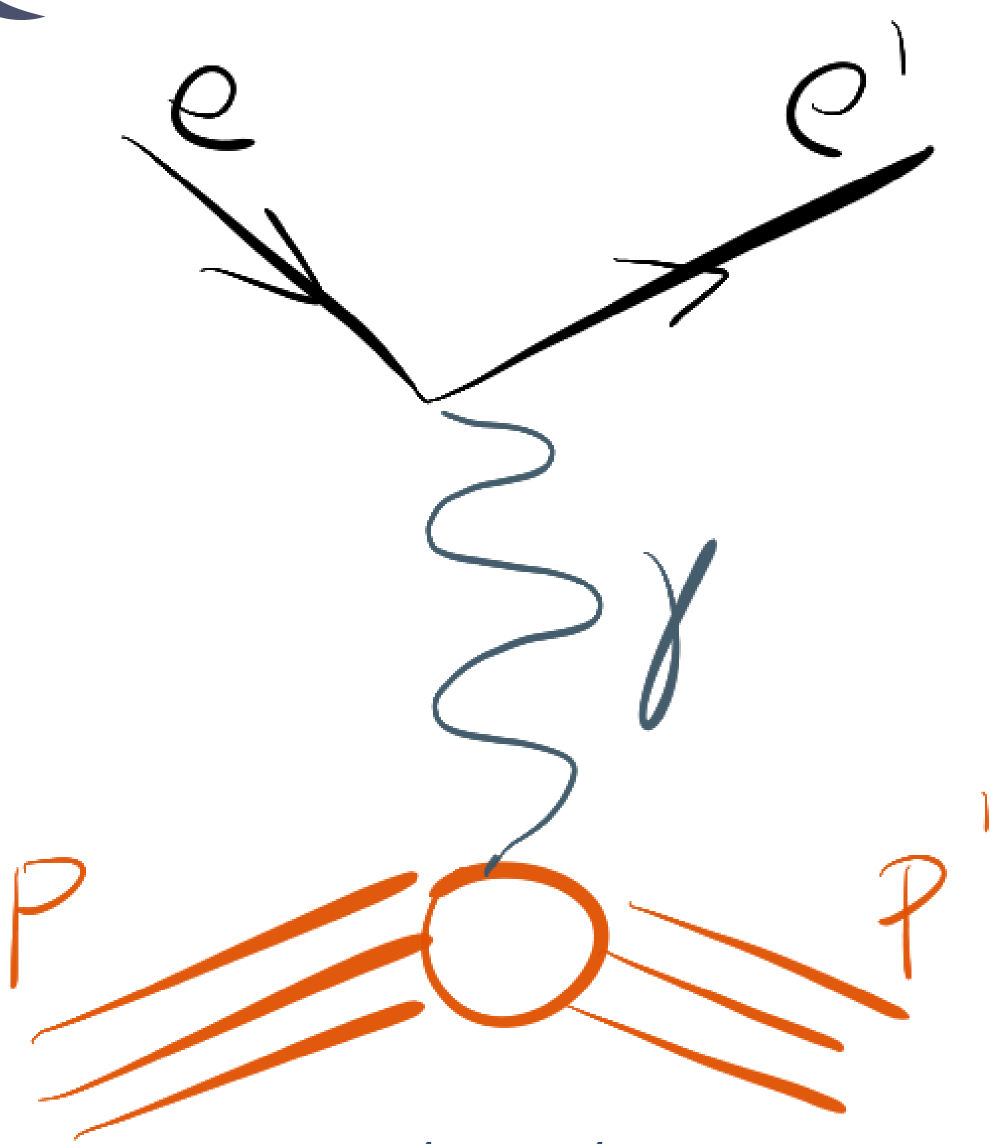
49 TeV

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



Measuring the weak charge

Weak mixing angle and charges



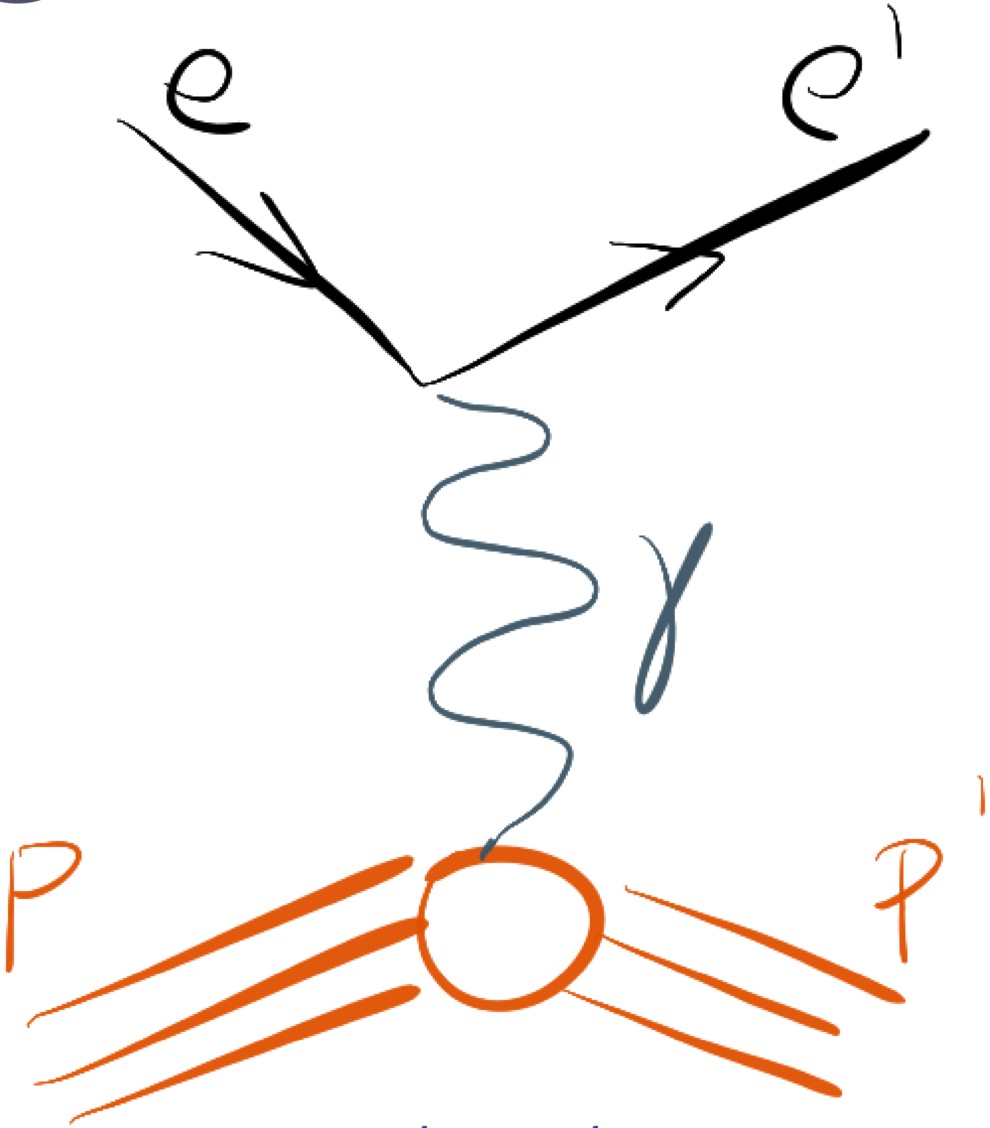
Proton electric charge

+1

Proton weak charge

$1 - 4\sin^2\theta_W$

Weak mixing angle and charges



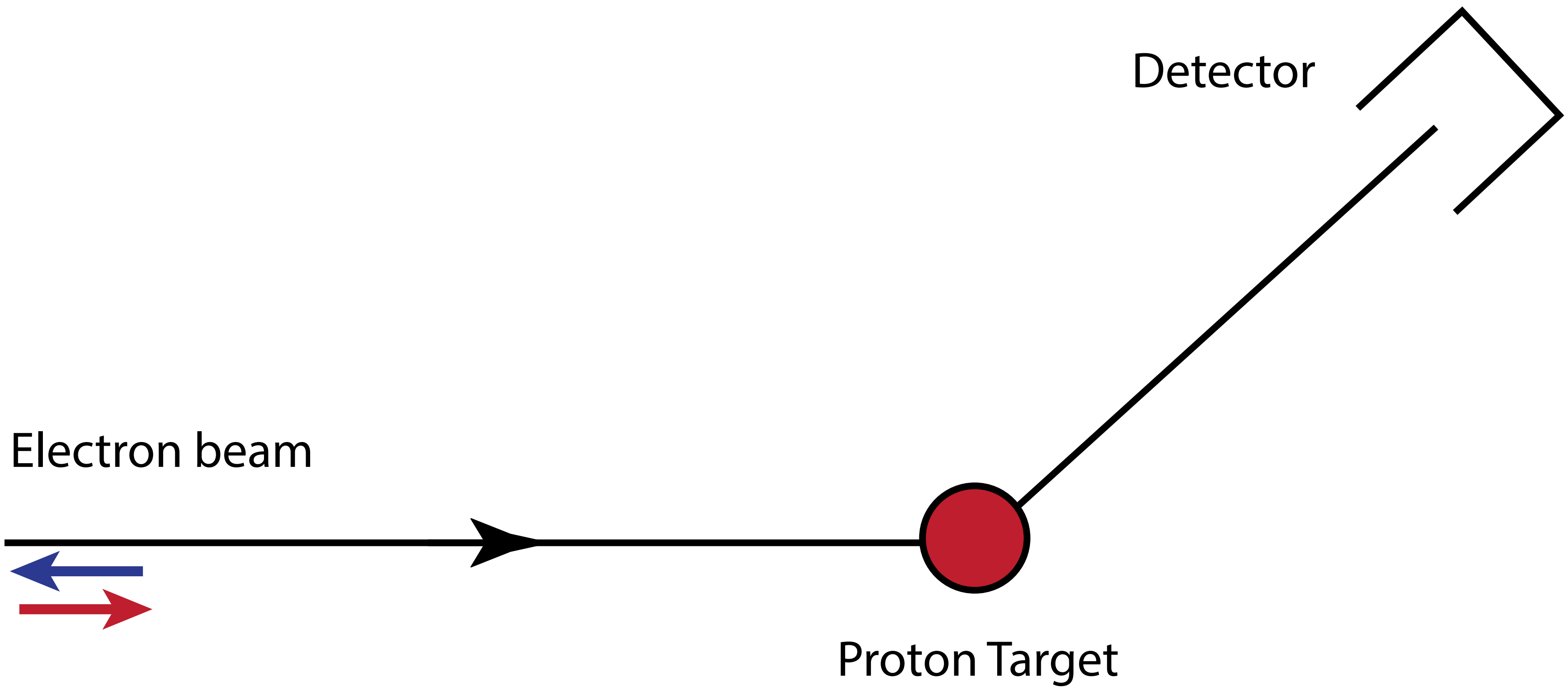
Proton electric charge

+e

Proton weak charge

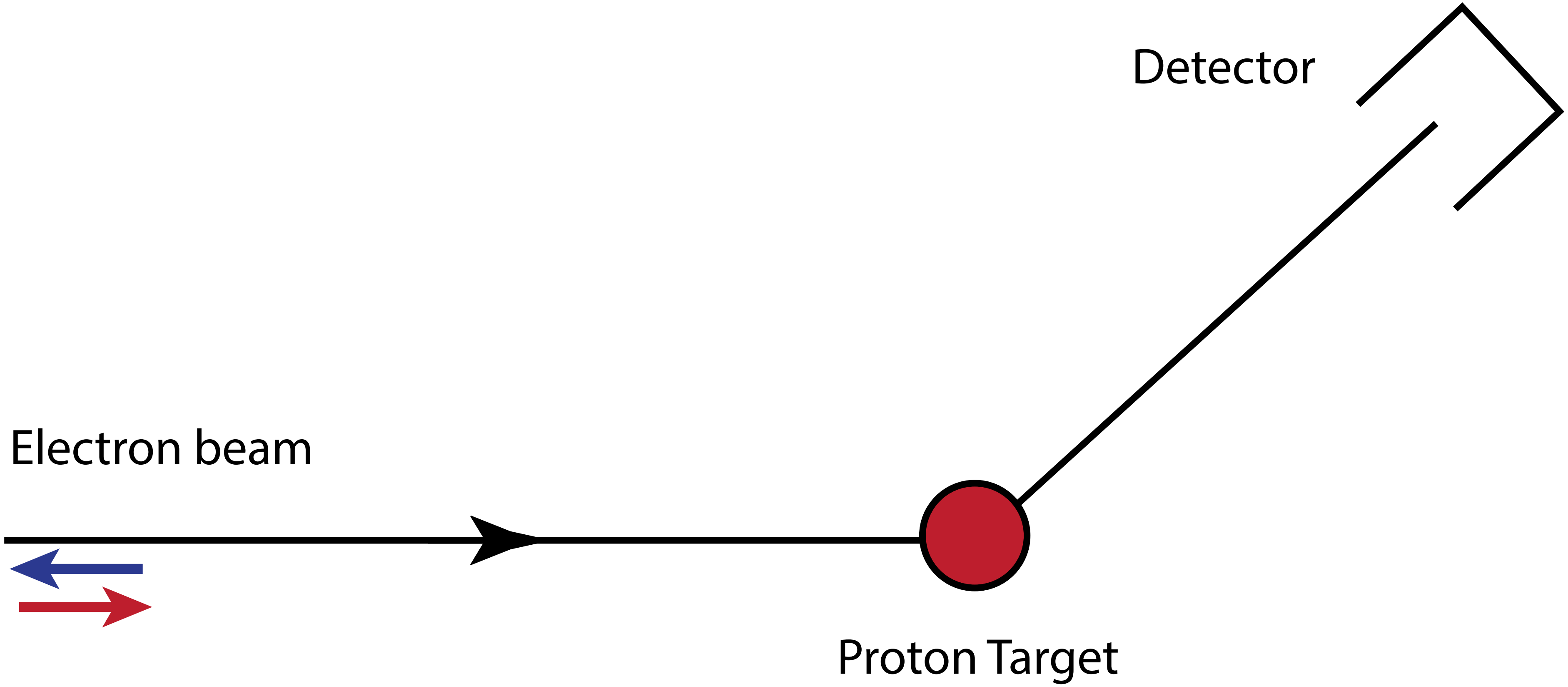
$1 - 4 \sin^2\theta_W$

Parity violating electron scattering



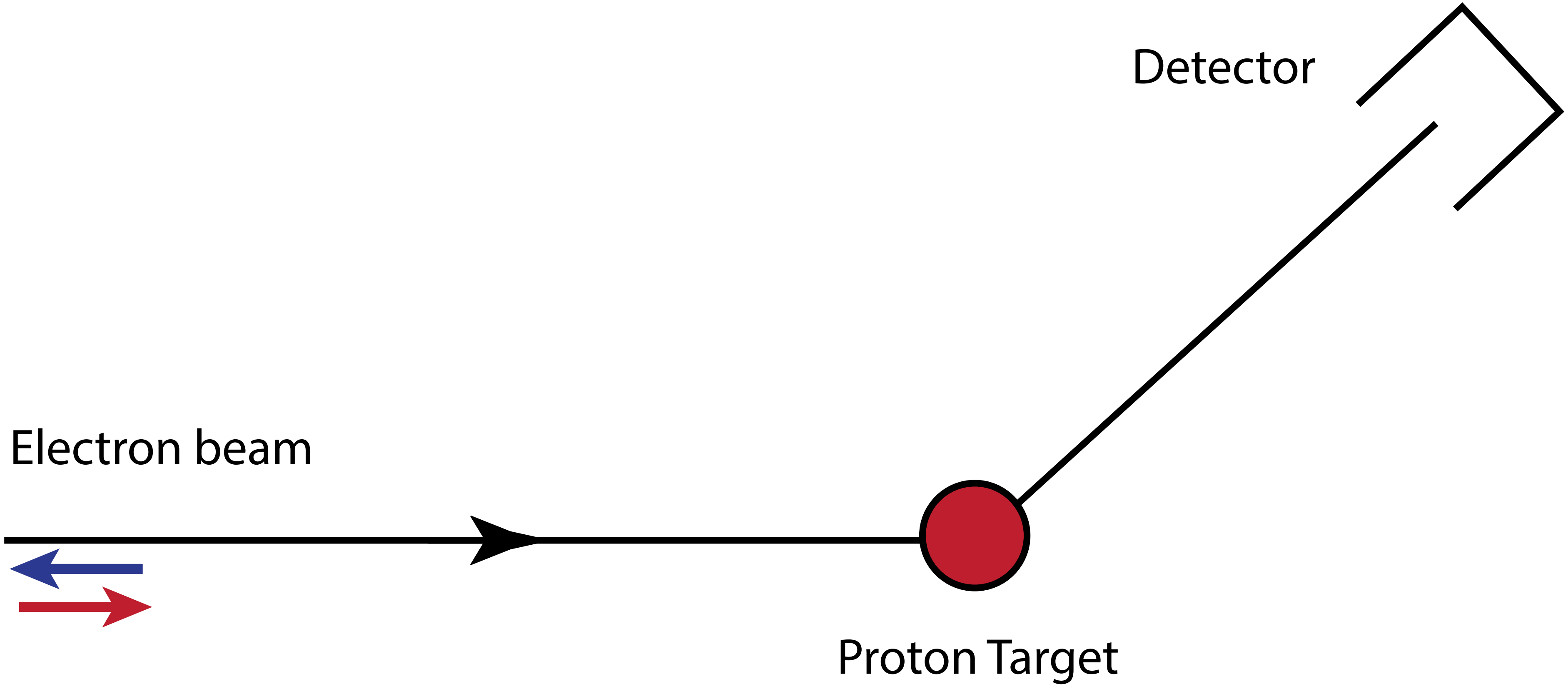
Parity violating electron scattering

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



Parity violating electron scattering

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



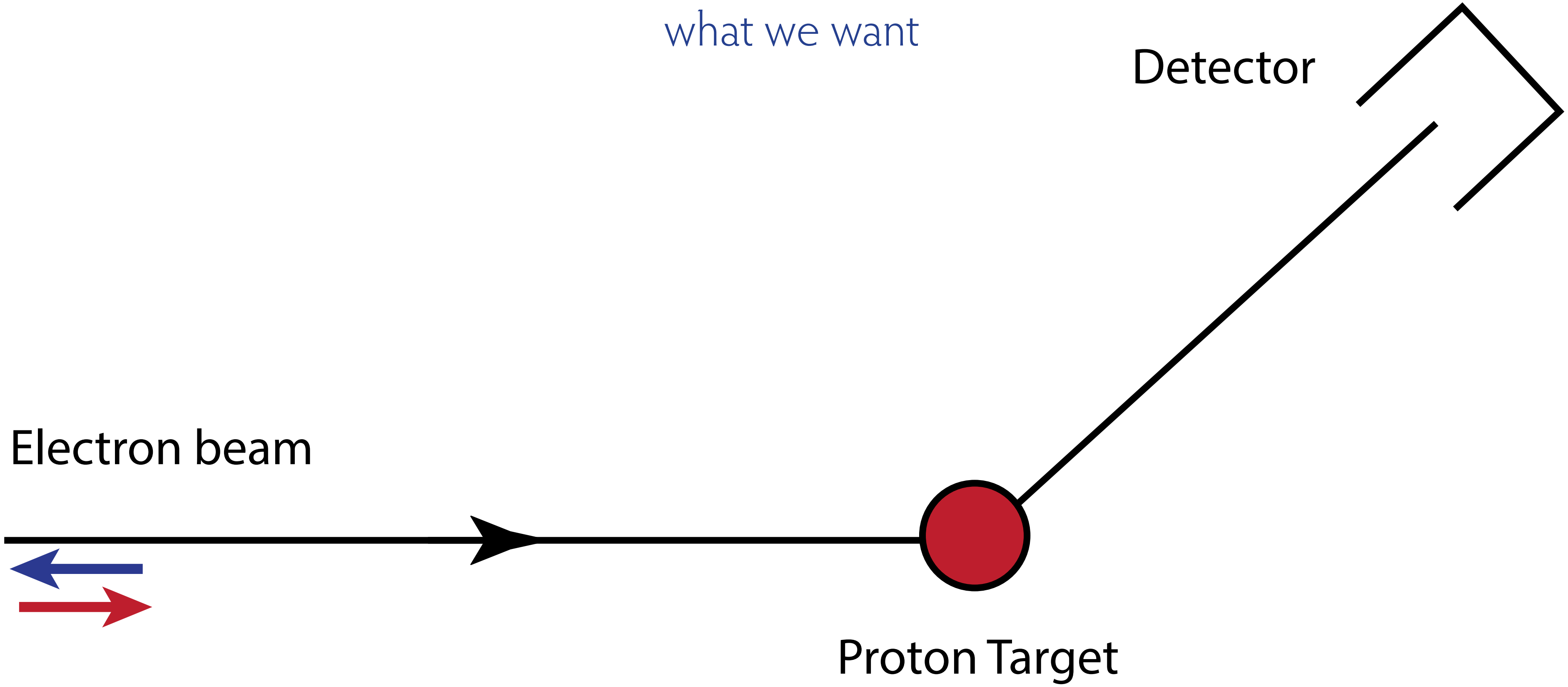
Parity violating electron scattering

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

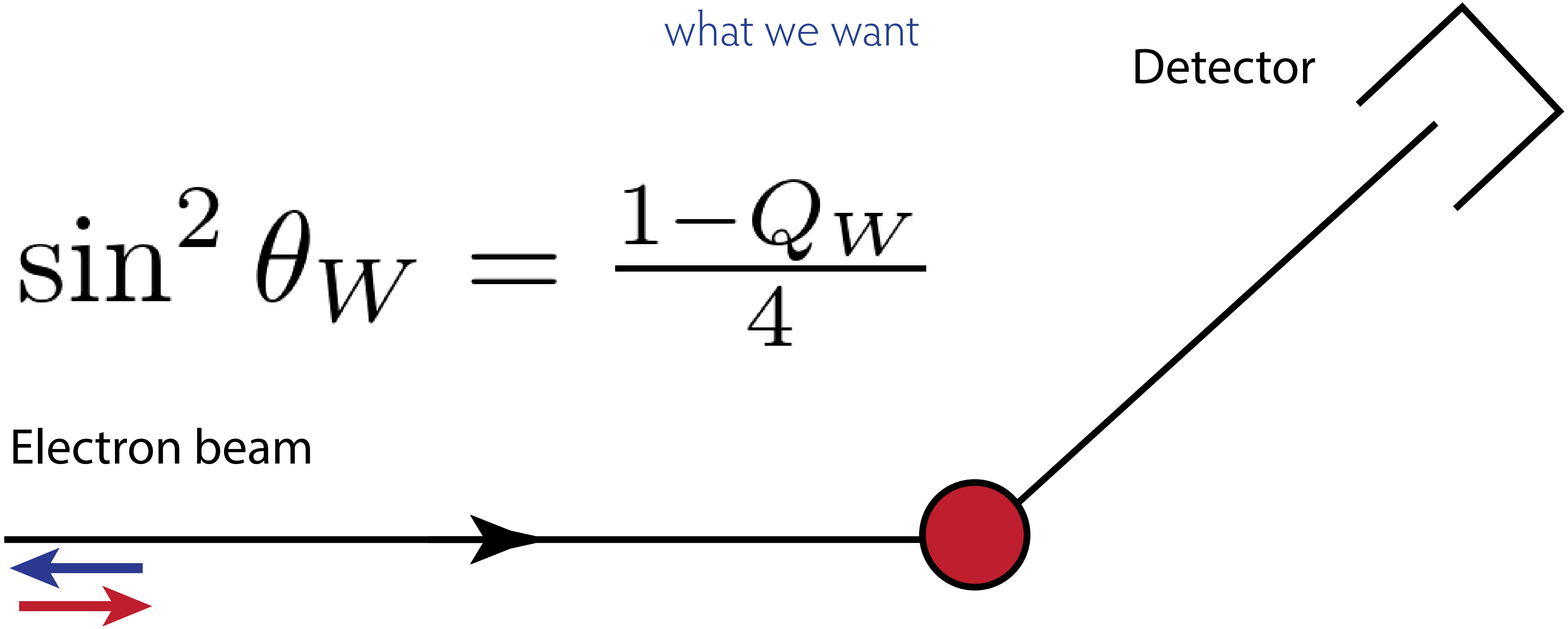
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

Momentum transfer sets scale

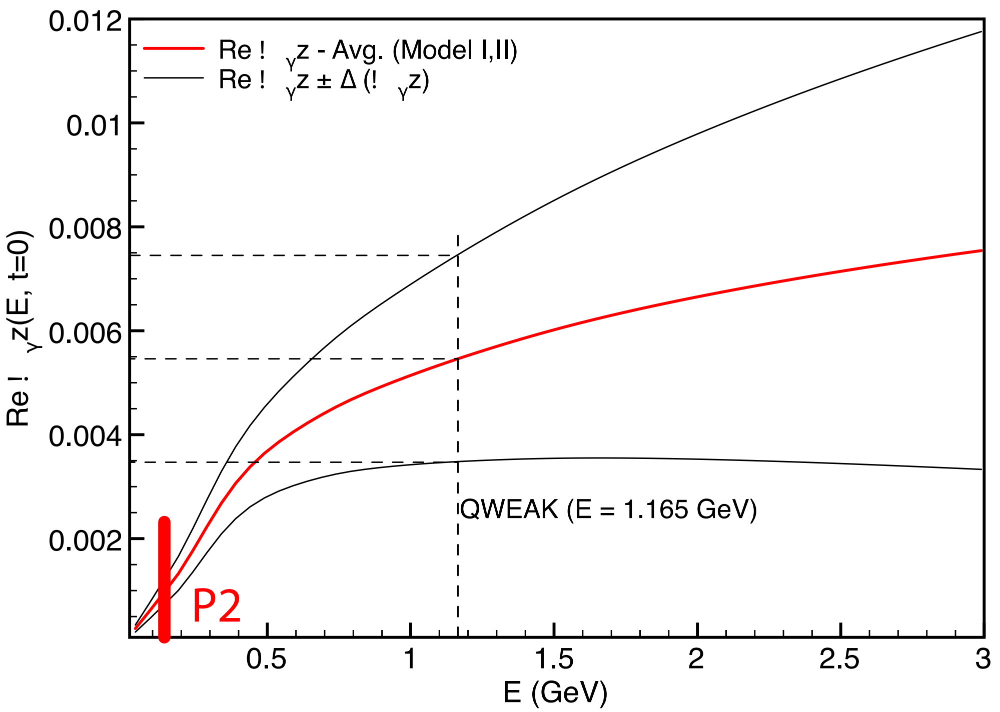
Proton structure - small nuisance if Q^2 small

Weak charge - what we want

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

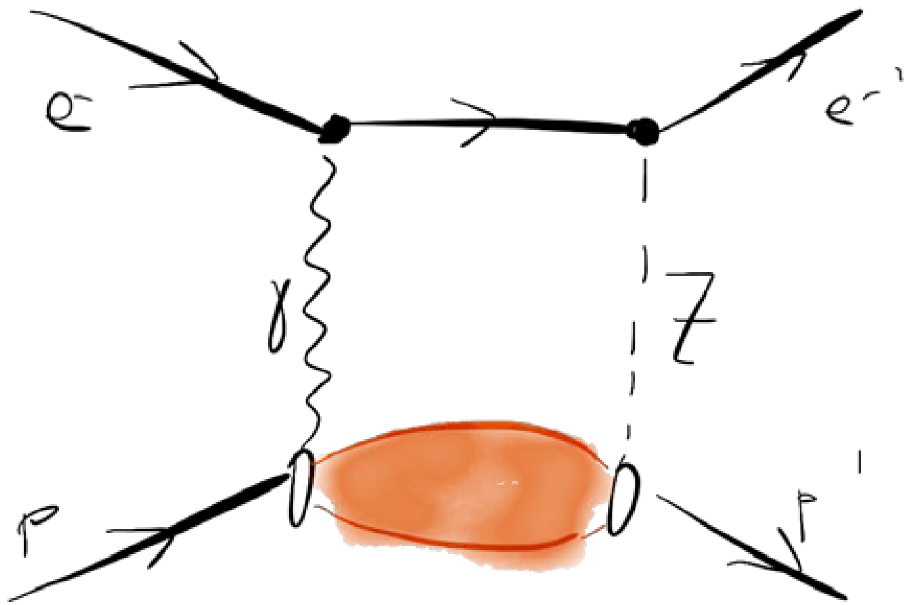


γ-Z box graphs

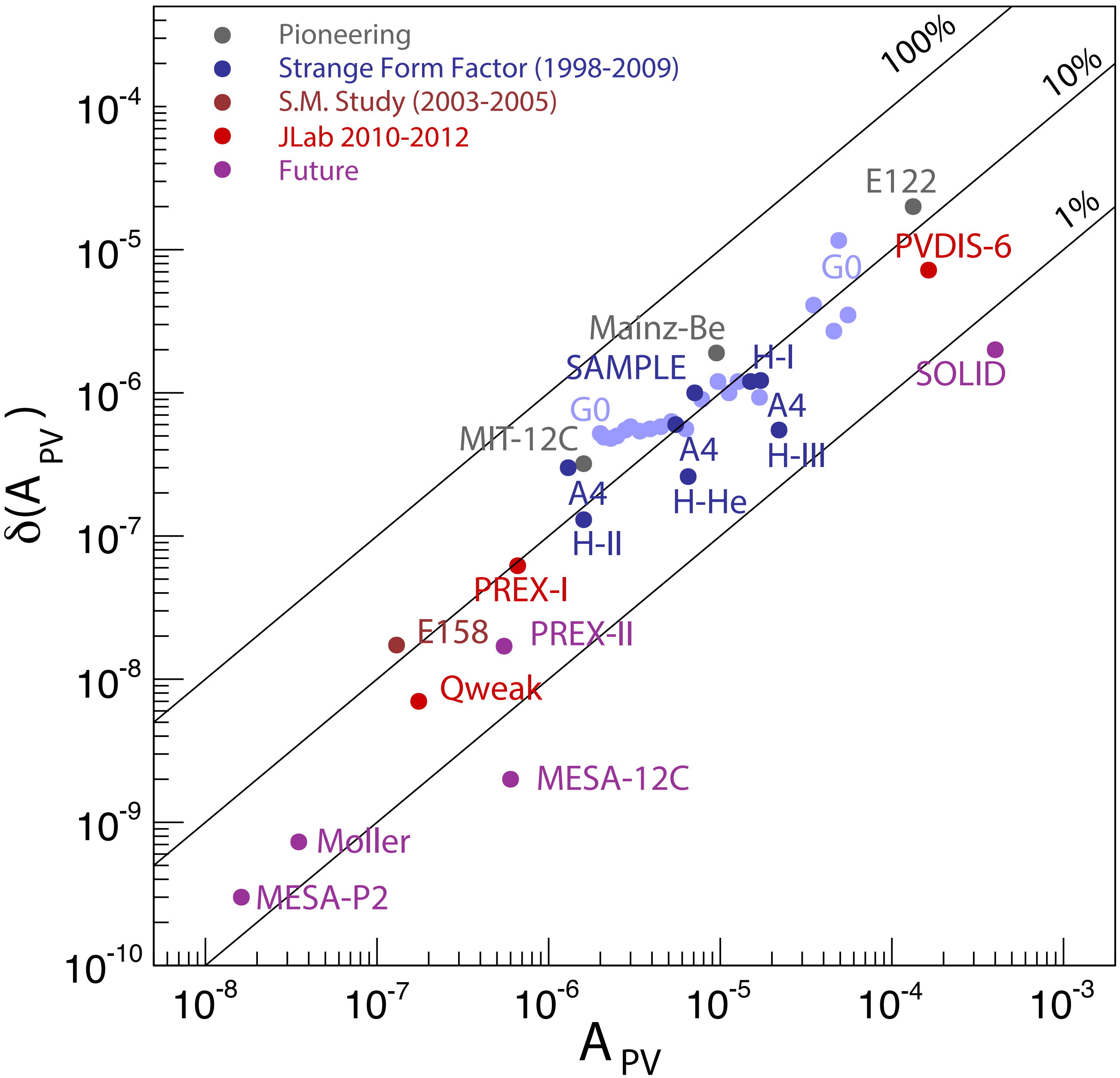


[Gorchstein, Horowitz, Ramsey-Musolf 2011]

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



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

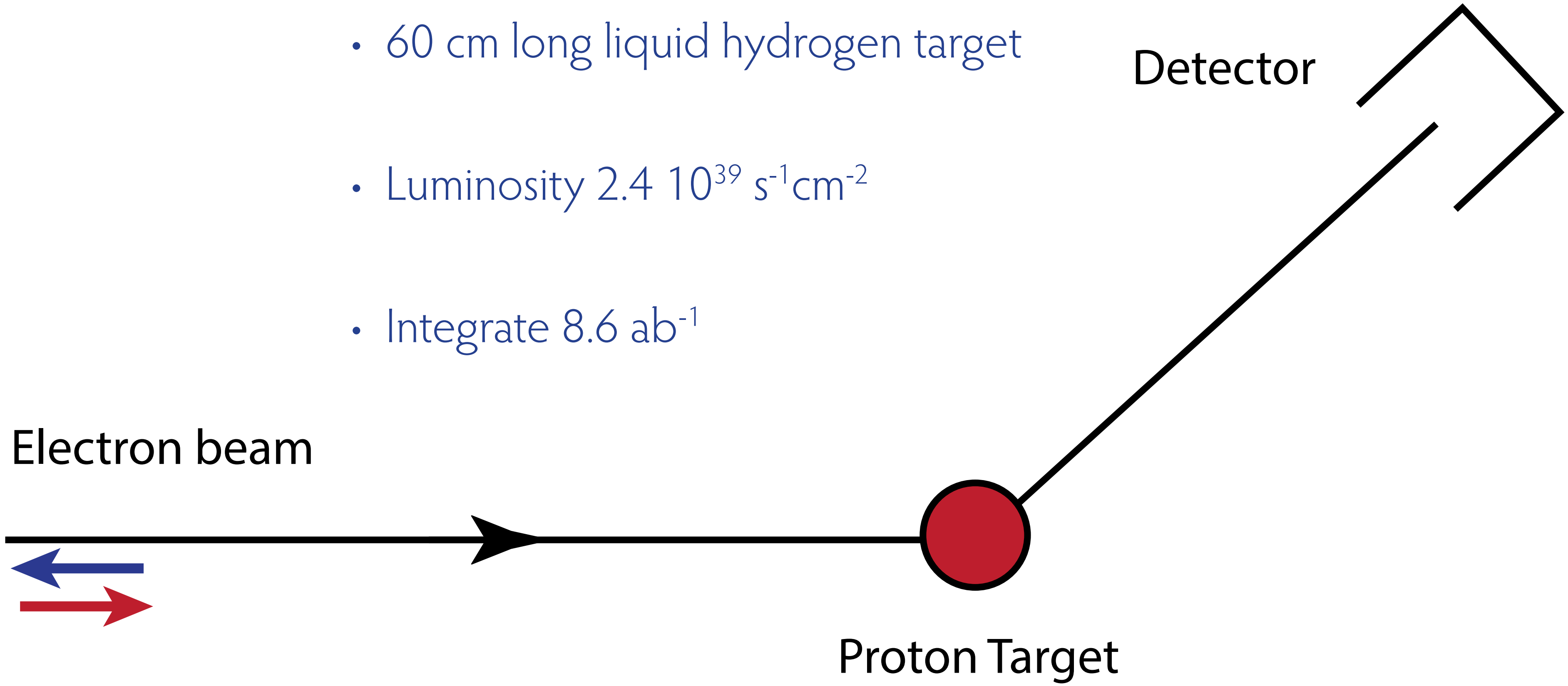
$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

- 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...

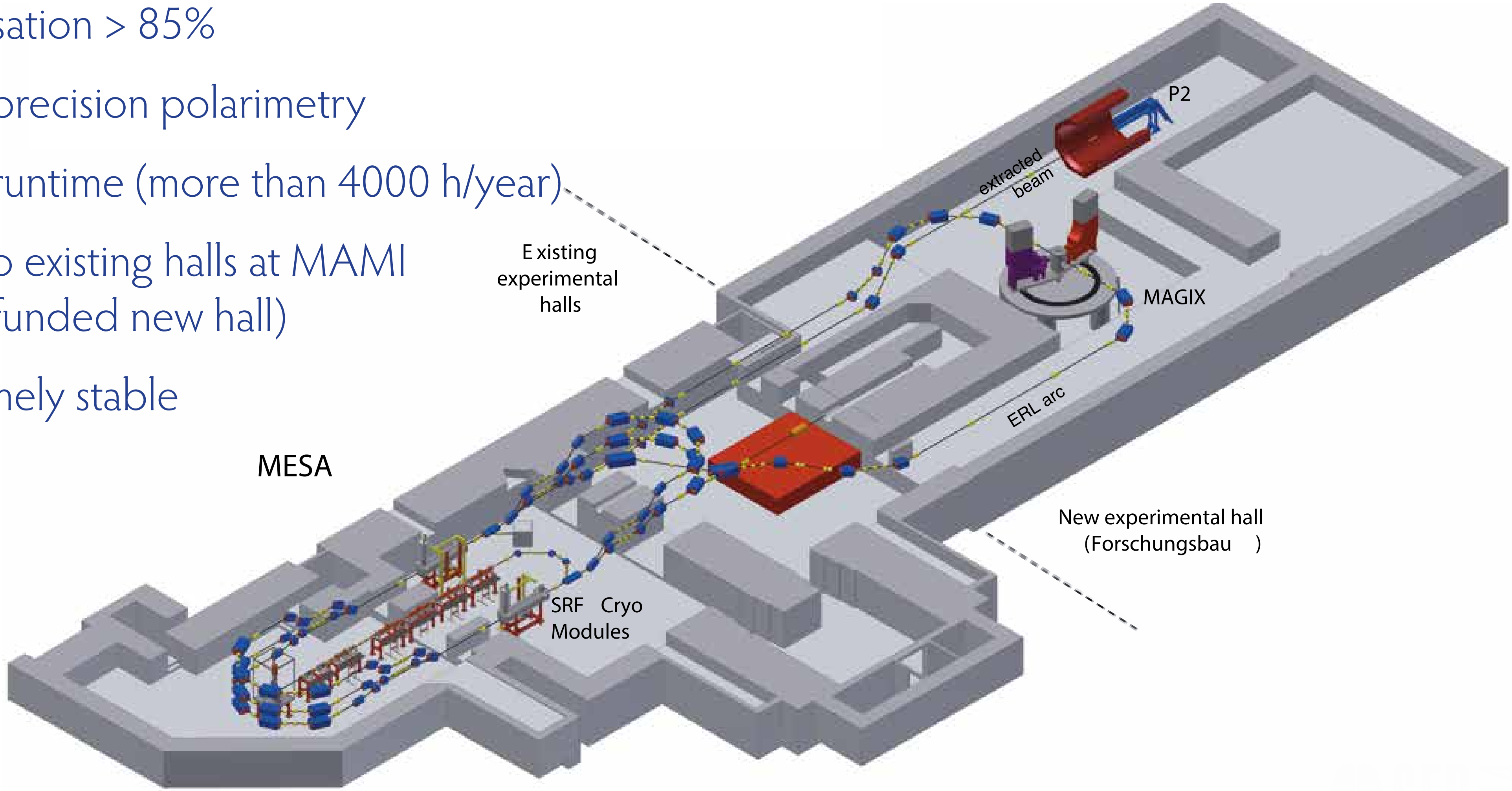
If you cannot rent it, build it:

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 (plus funded new hall)
- Extremely stable



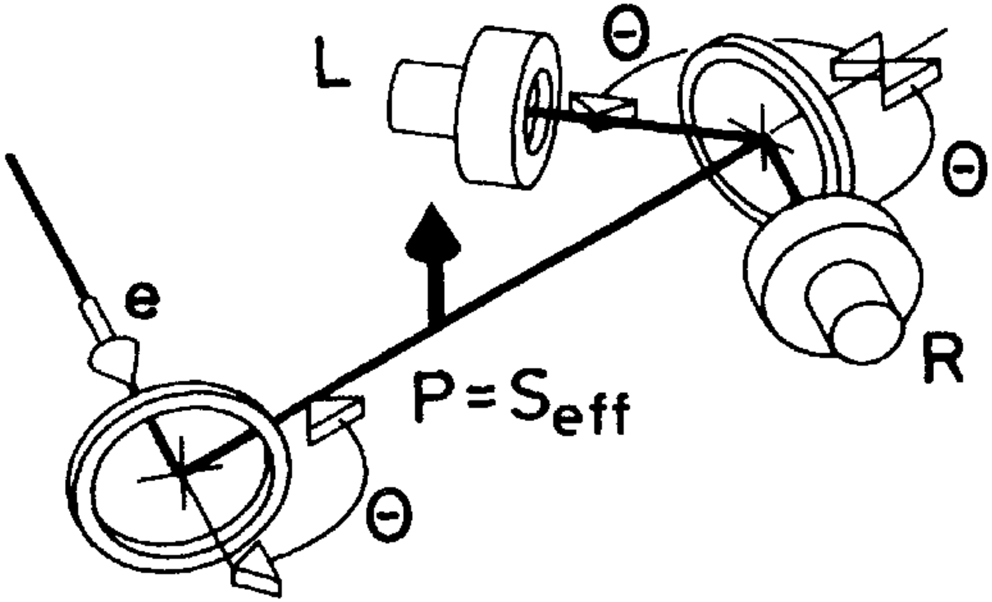
Stability Requirements

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

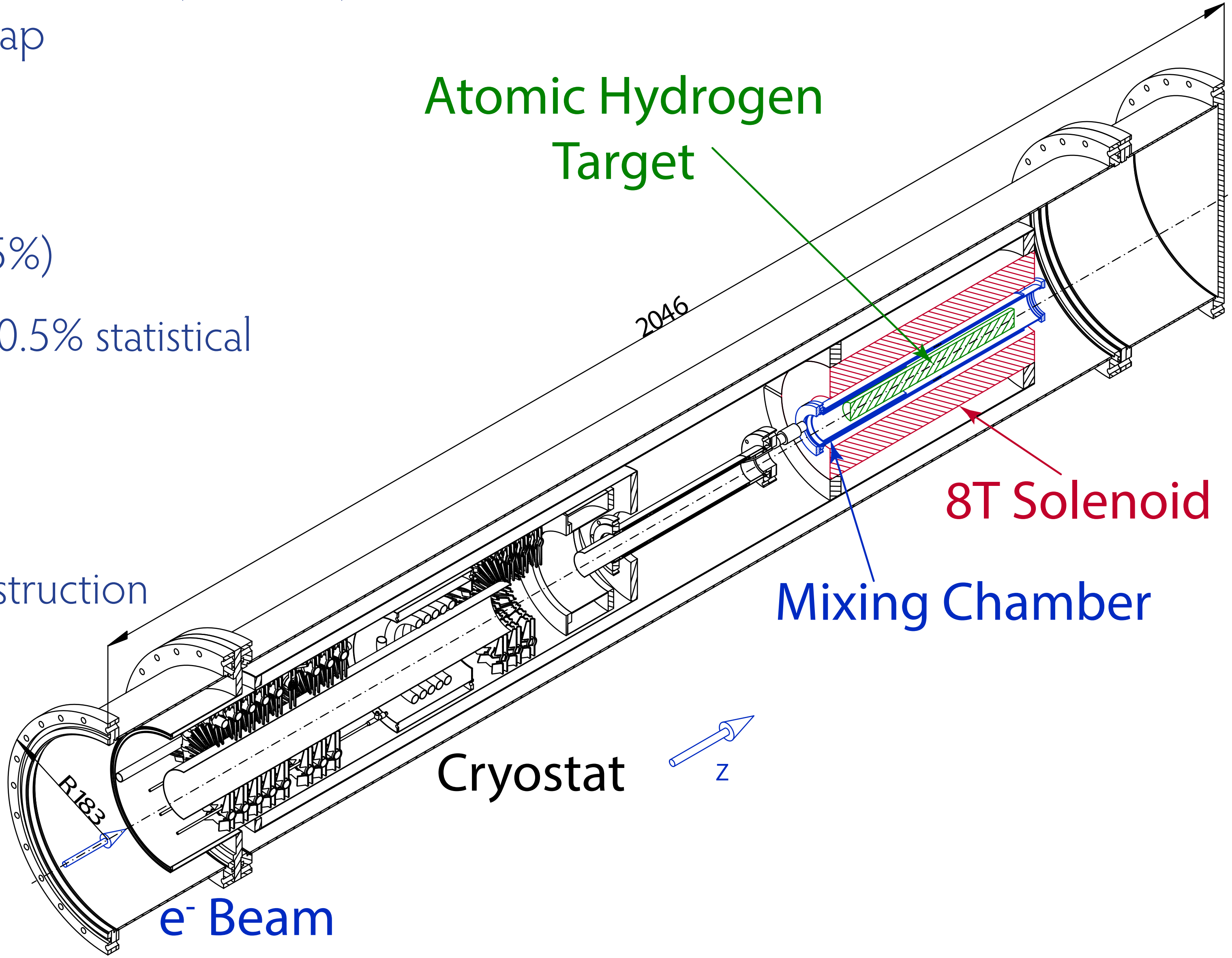
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

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

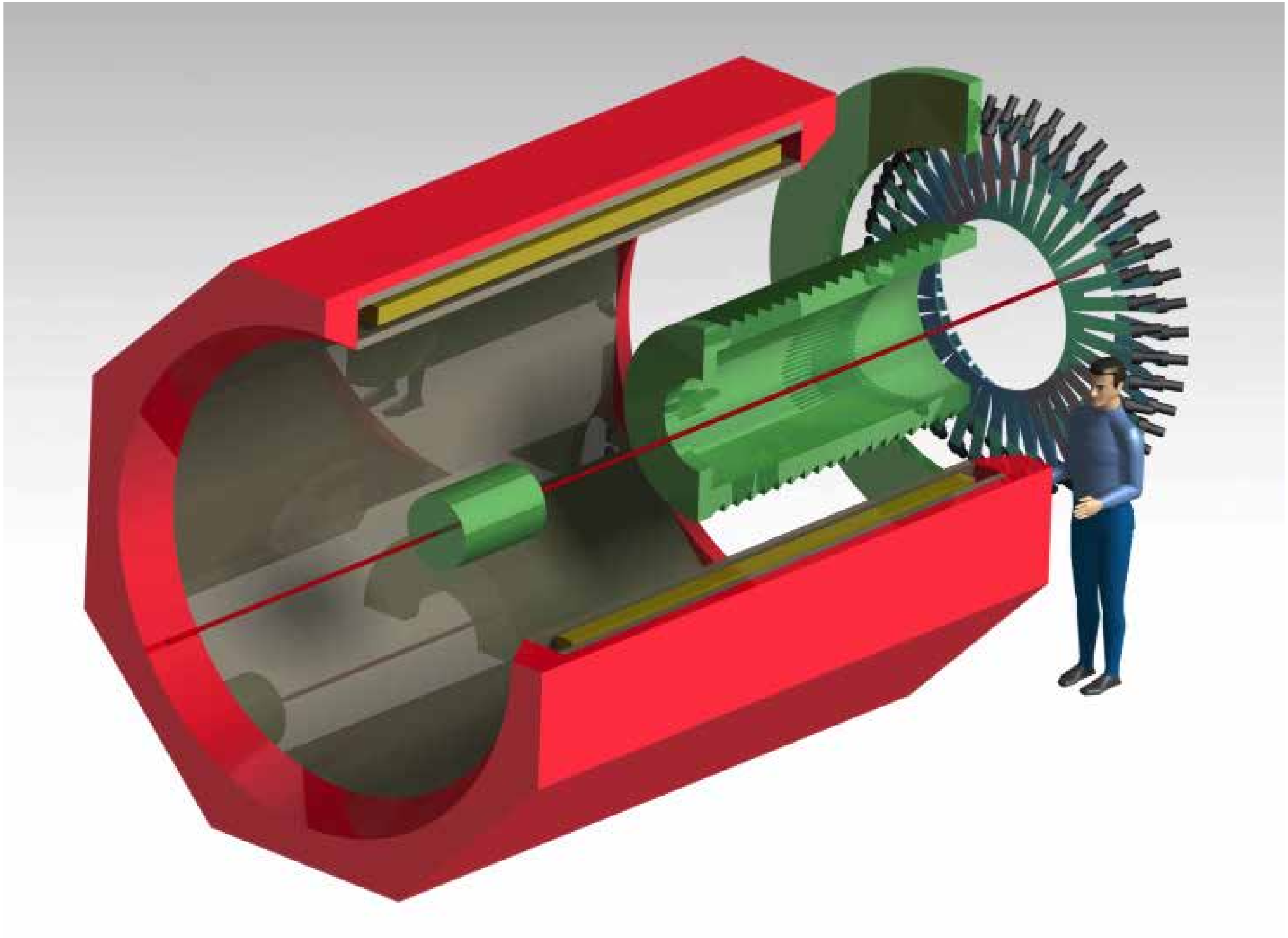
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

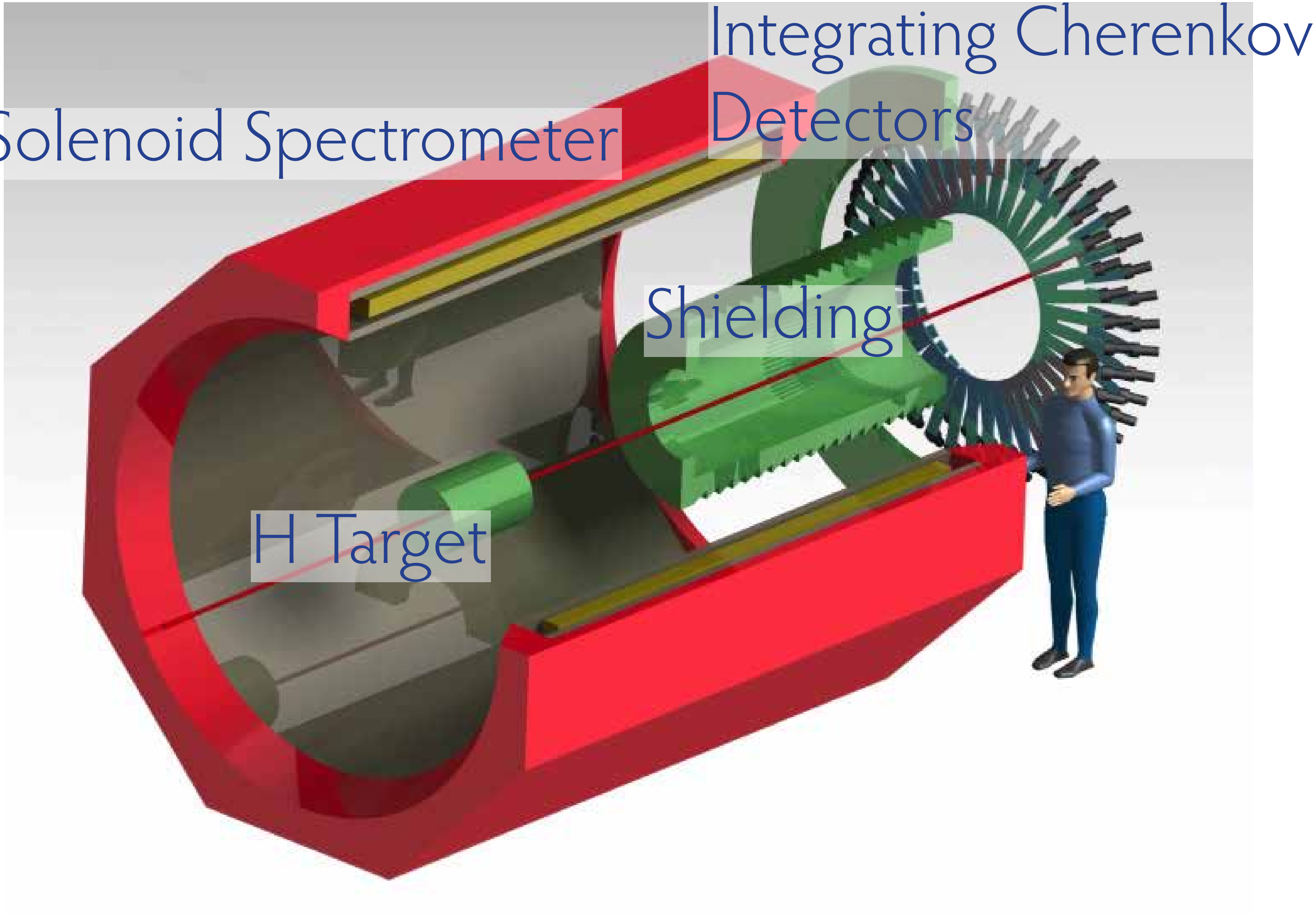
- Cryostat under construction in Mainz



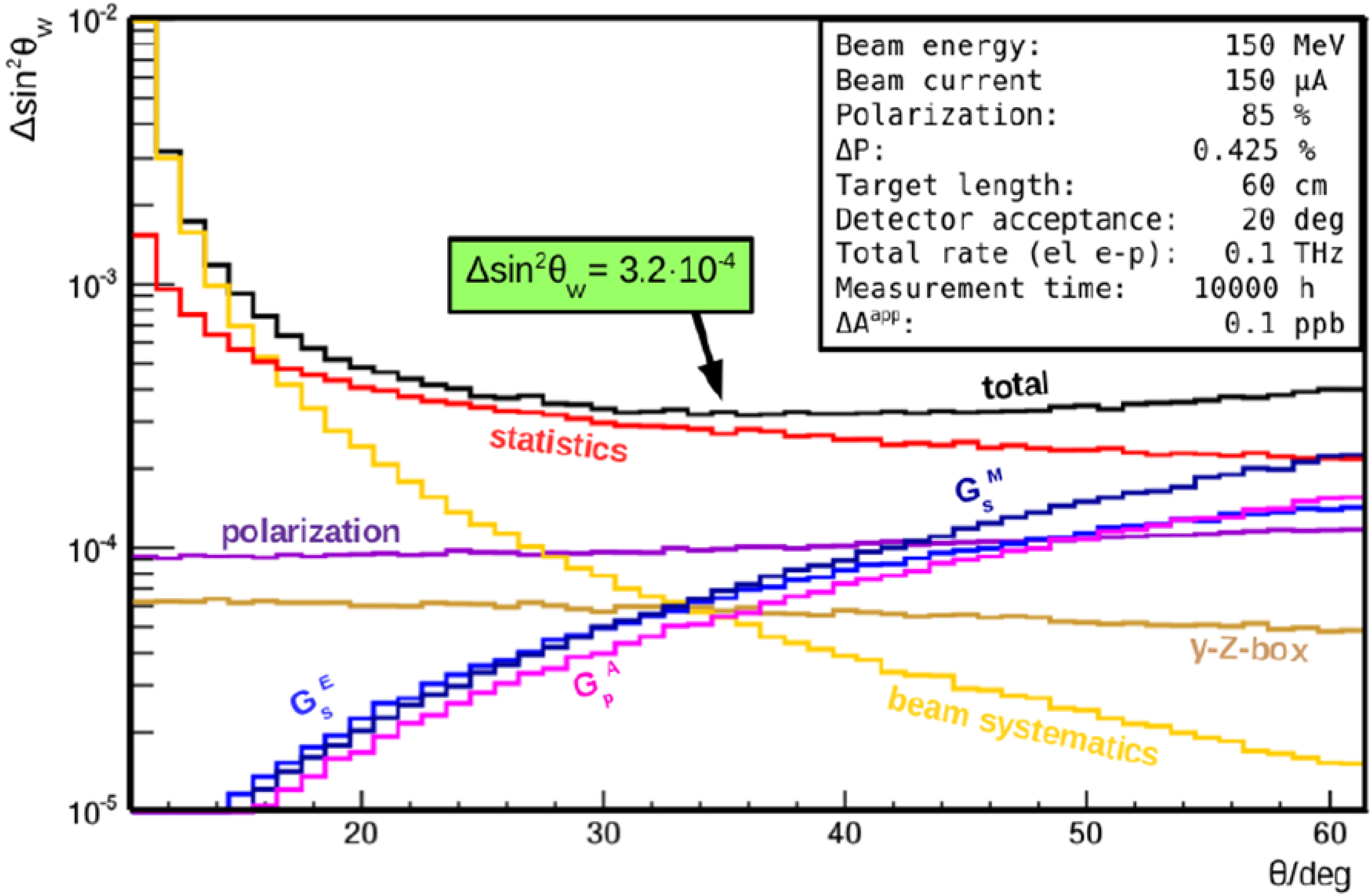
P2:

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

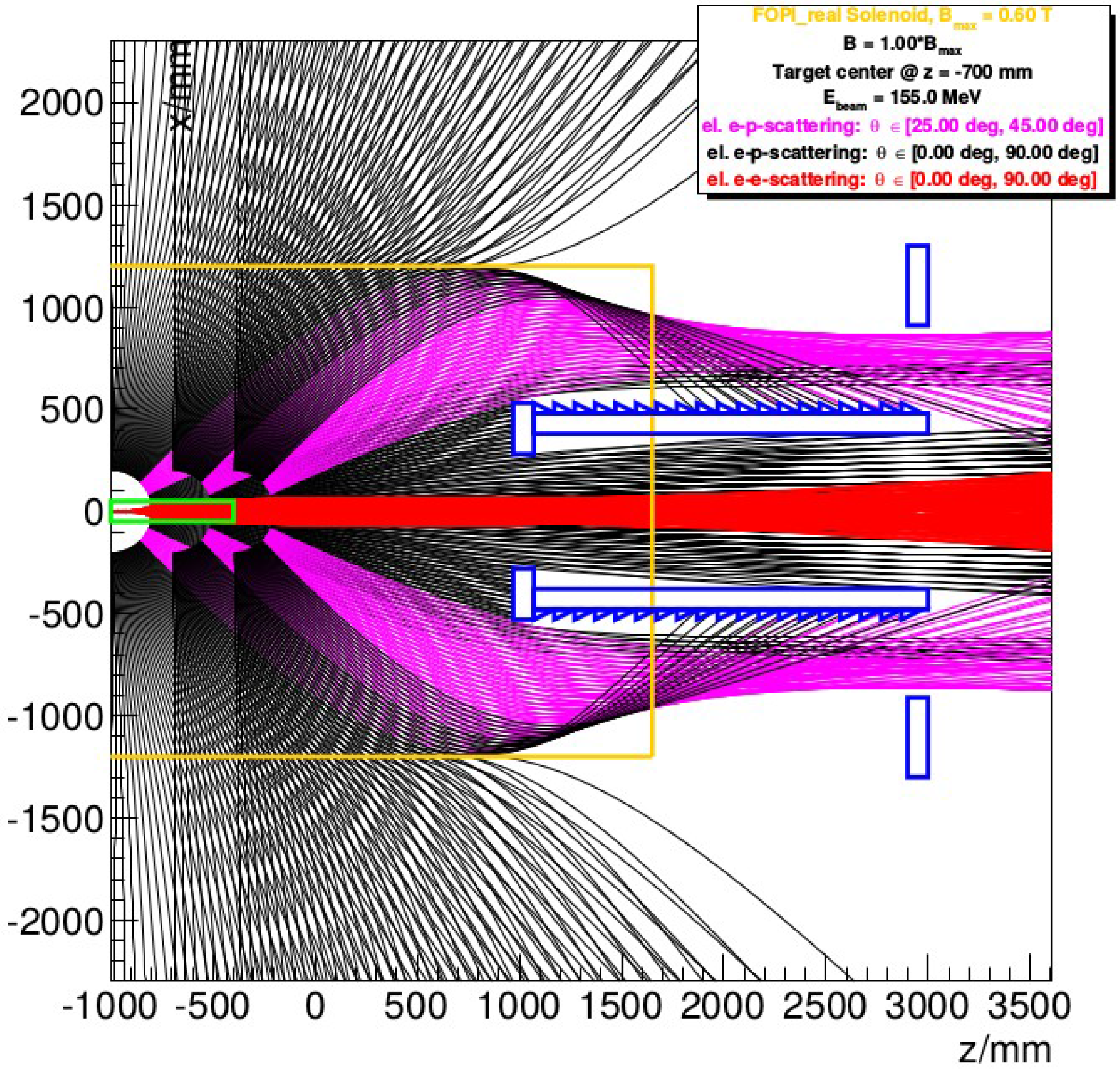



Integrating Cherenkov Detectors
Solenoid Spectrometer
Shielding
H Target

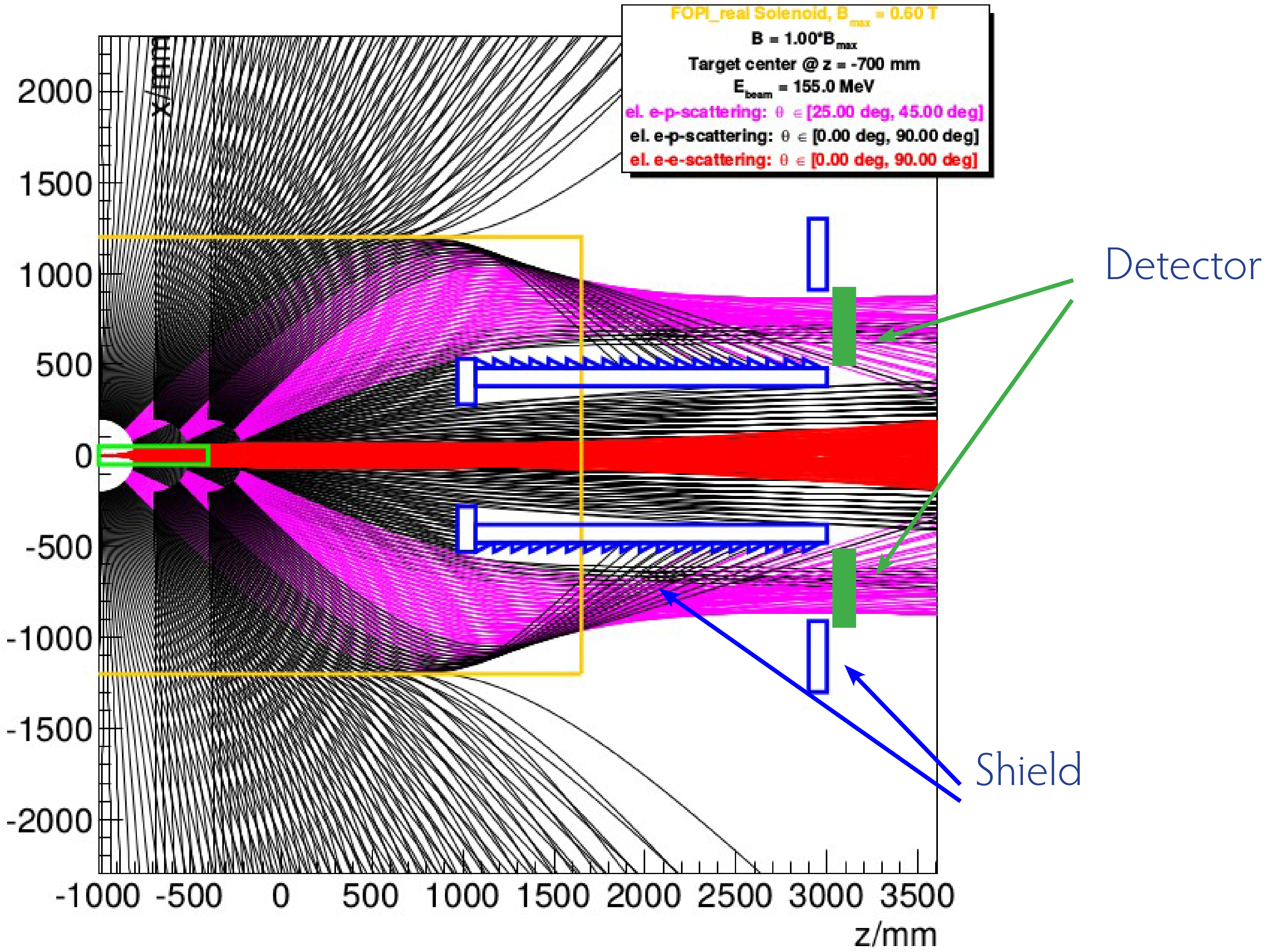
Choice of scattering angle



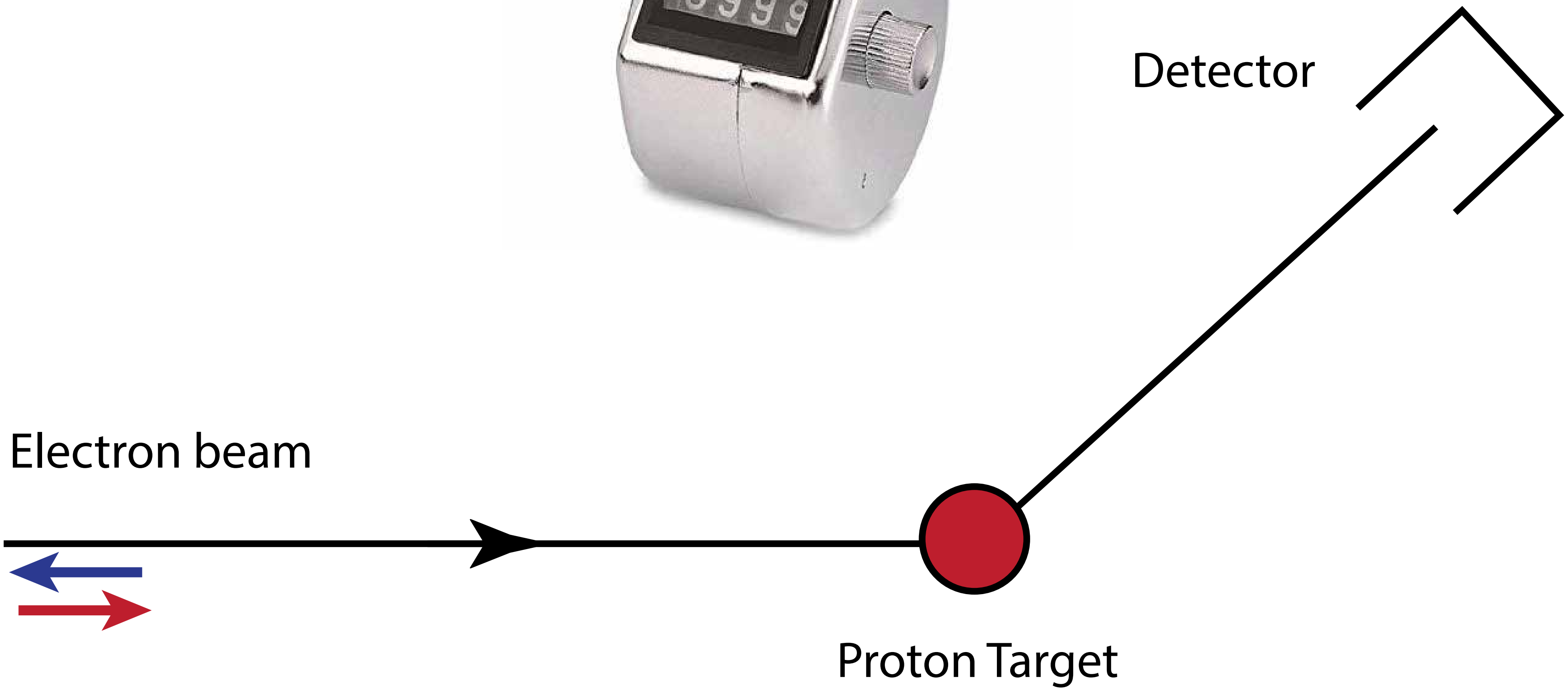
Solenoid spectrometer



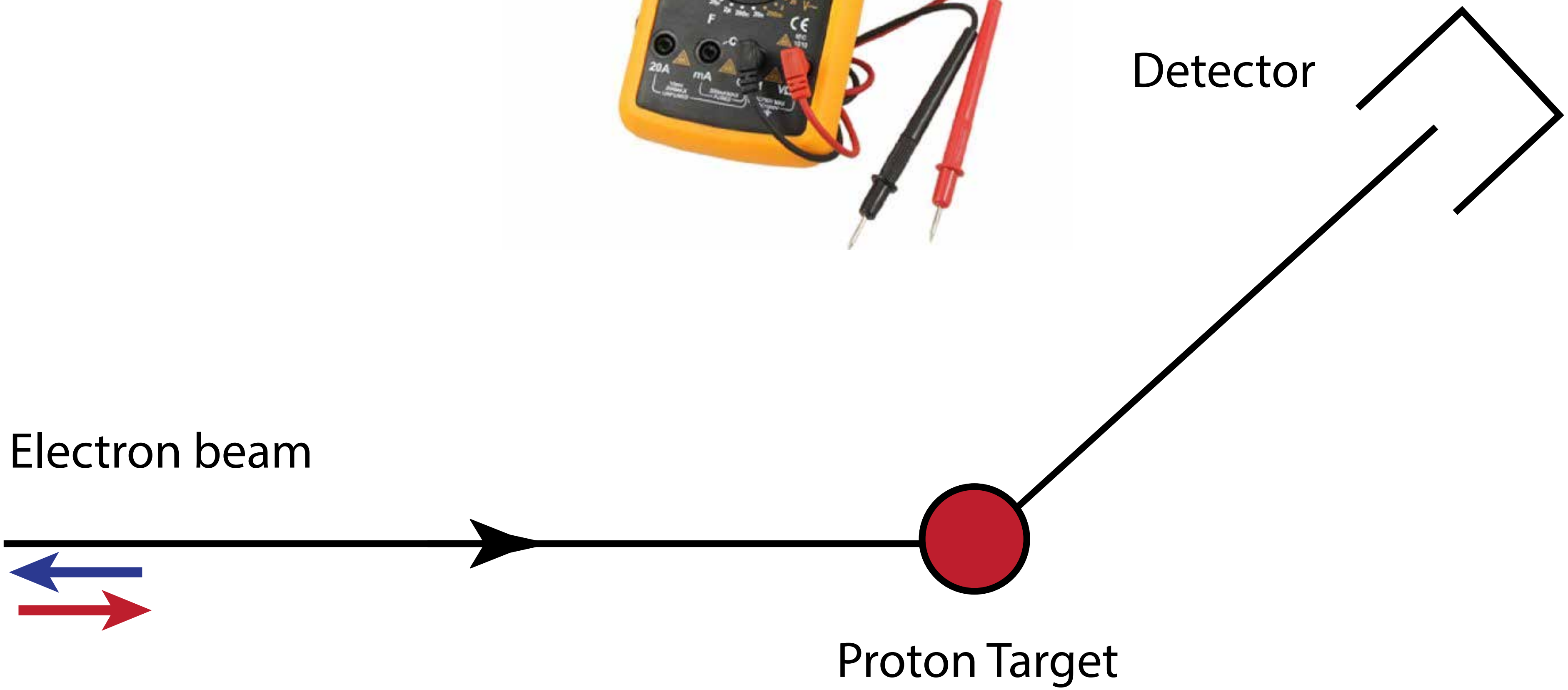
Solenoid spectrometer



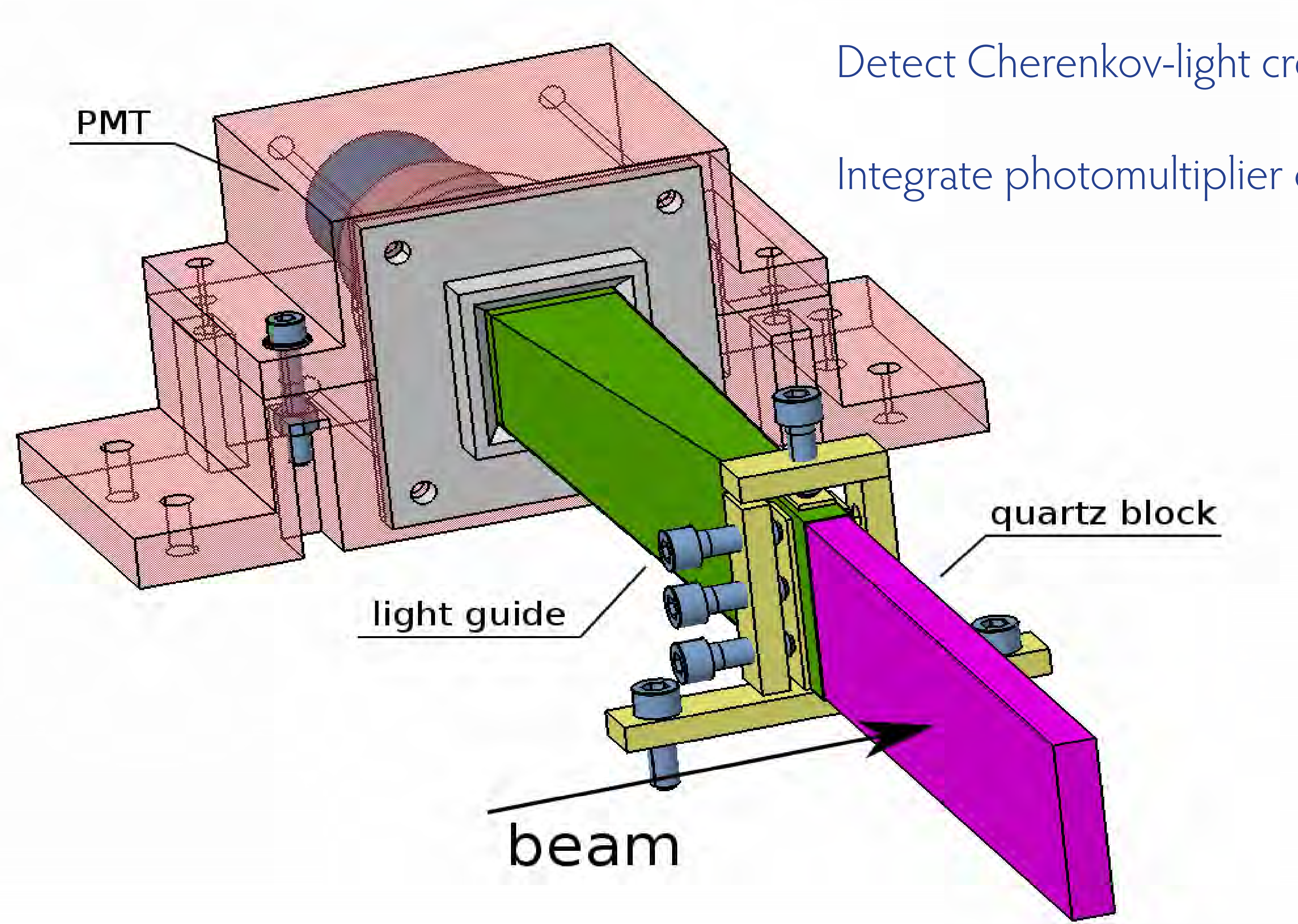
Counting detectors



Integrating detectors



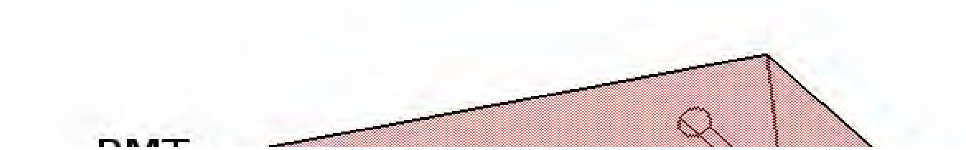
Quartz-Bars & Photomultipliers

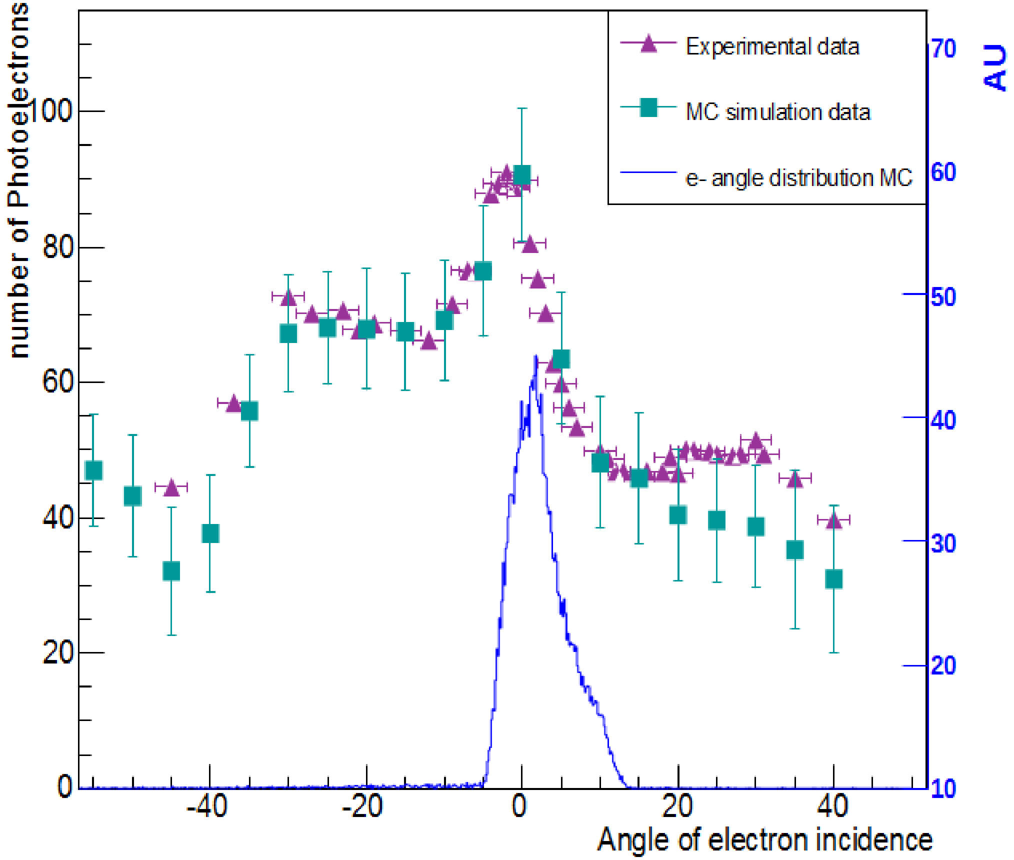


Detect Cherenkov-light created by electrons

Integrate photomultiplier current

Quartz-Bars & Photomultipliers





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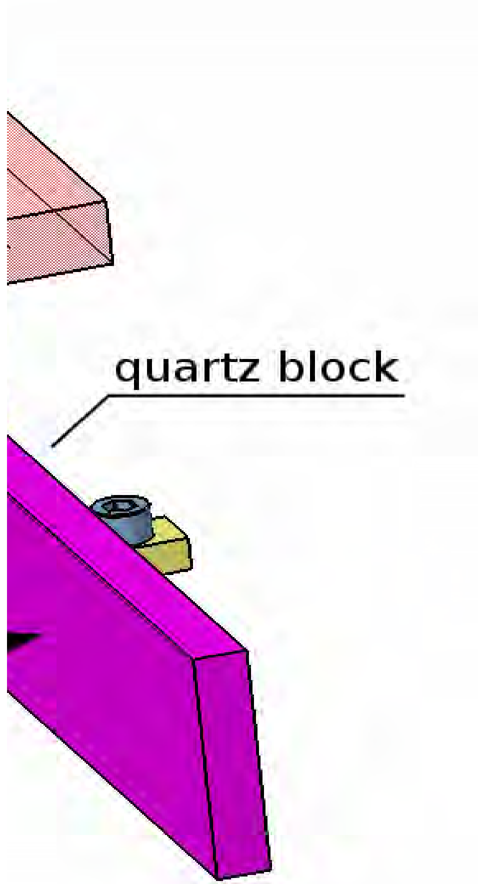
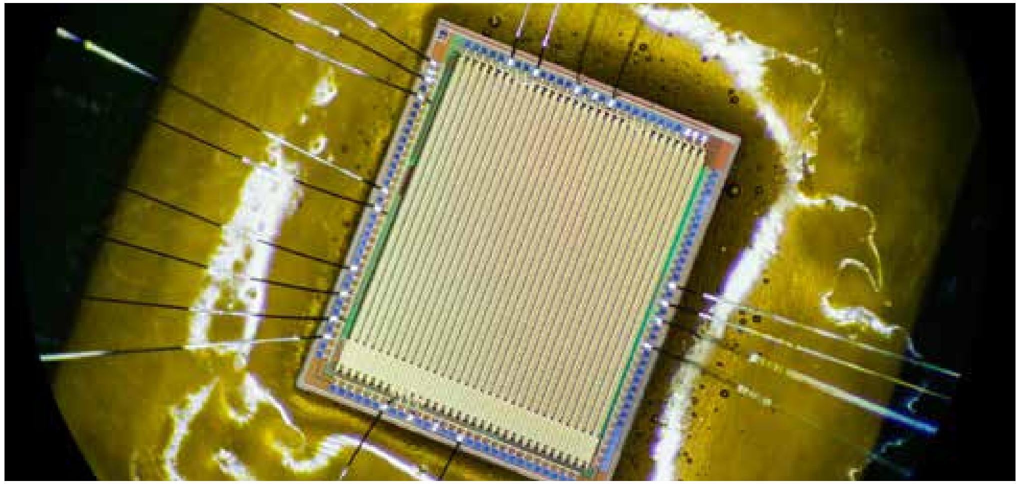
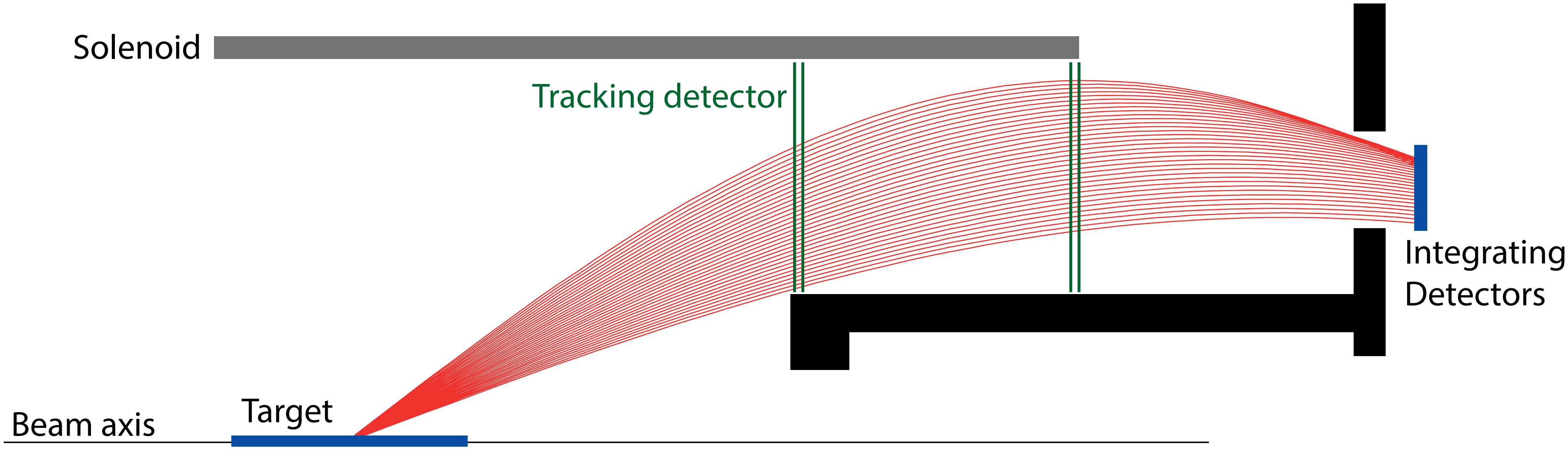


Tracking detector for Q2 measurement

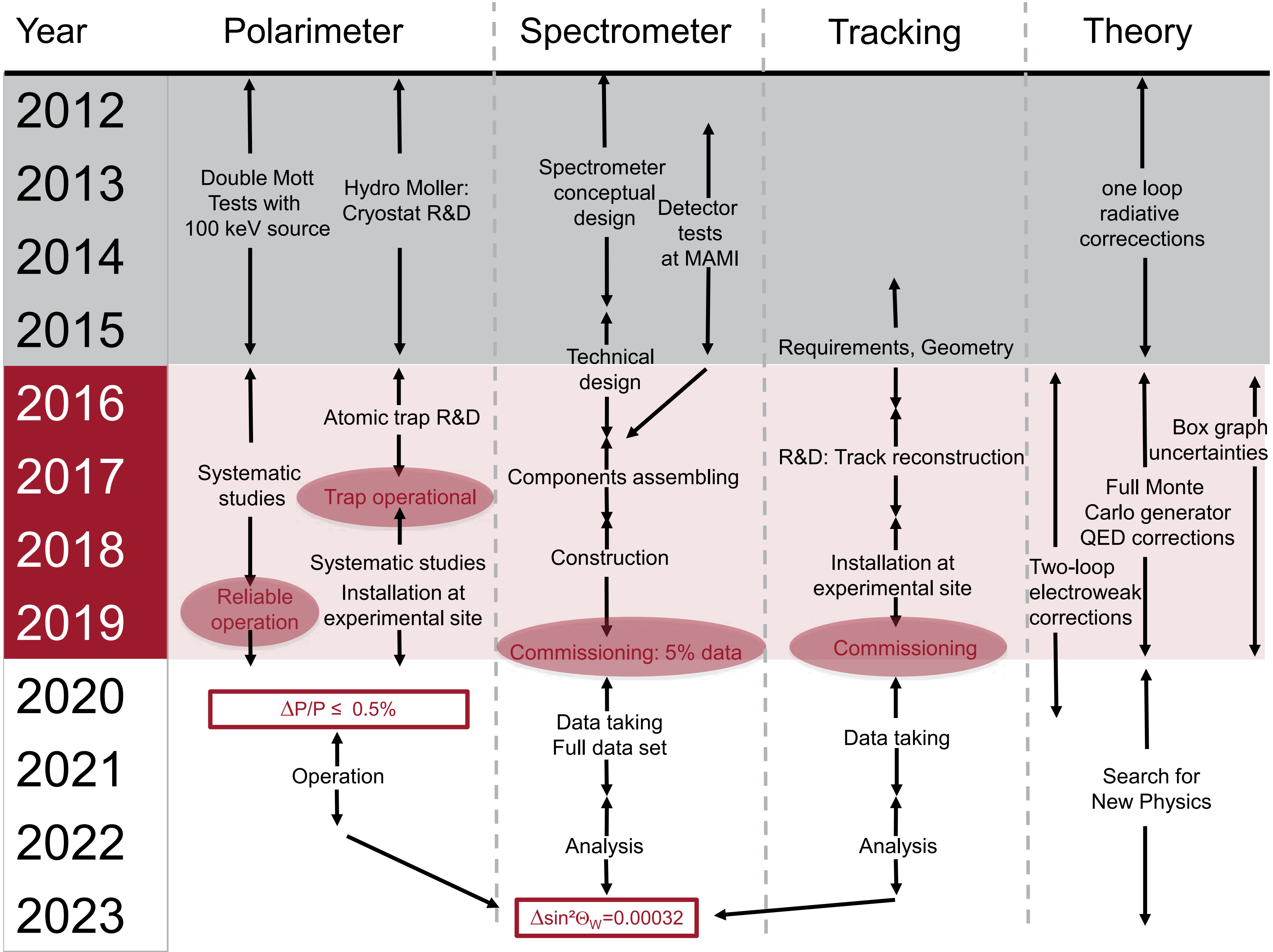
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors

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





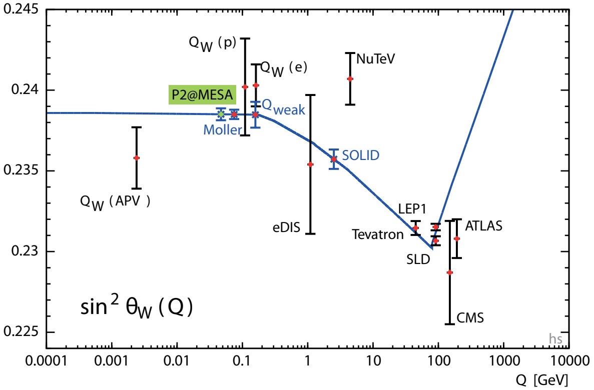
P2 Timeline



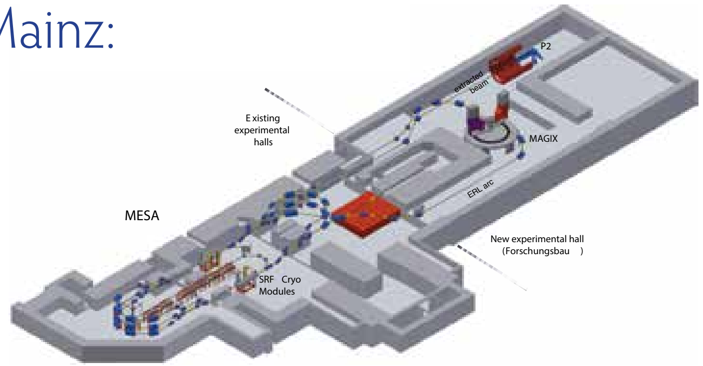
JG|U

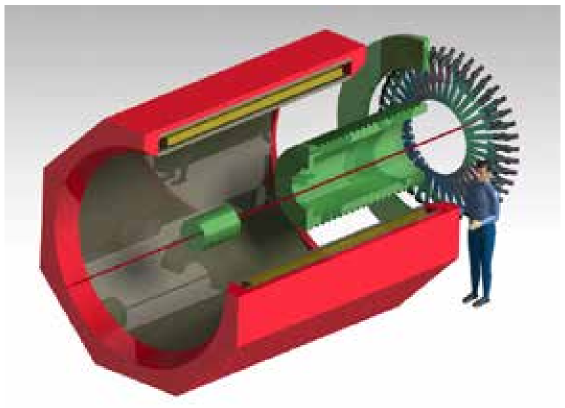
SFB 1044

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"

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

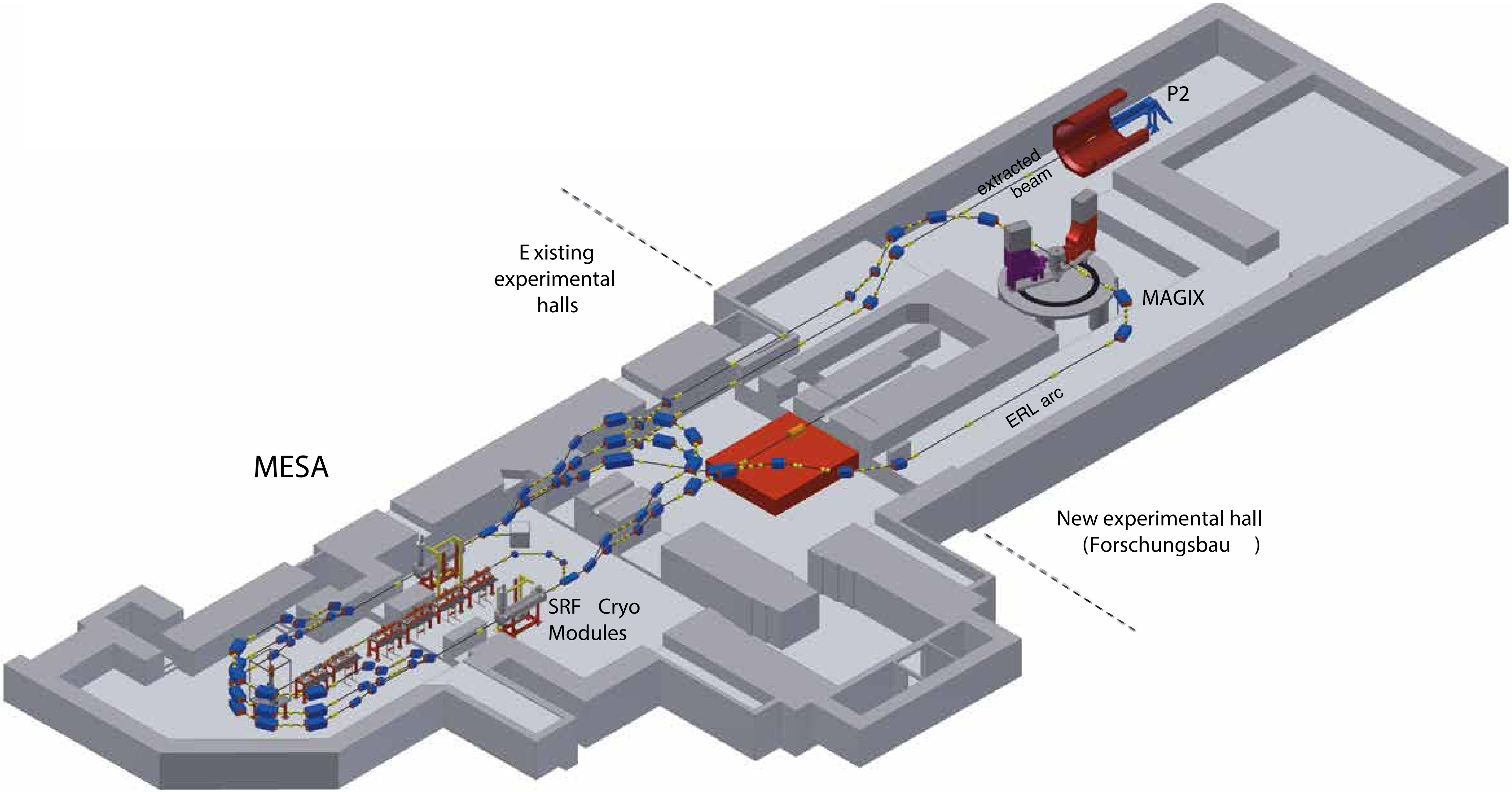
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

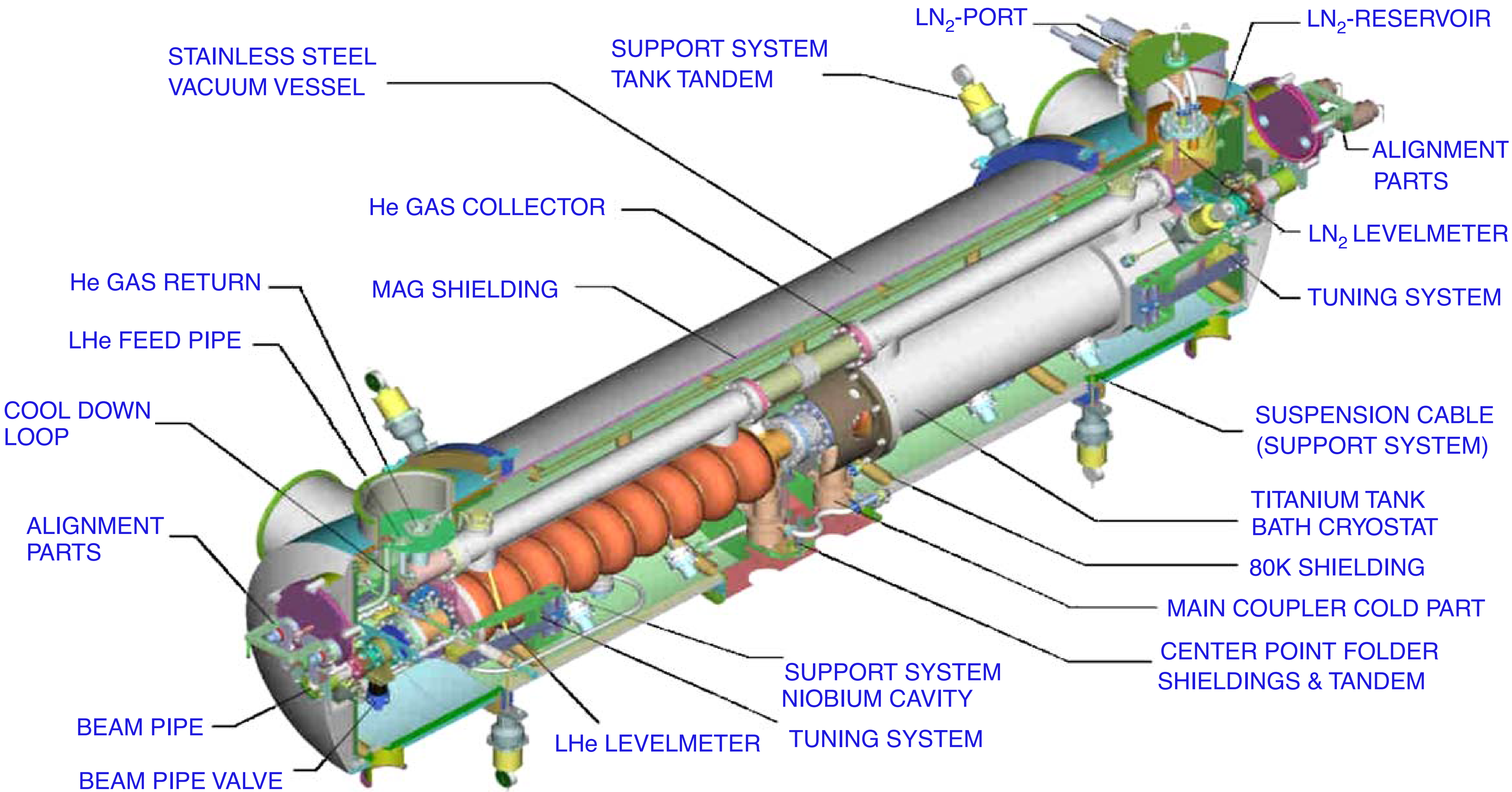
- Use second option from here on

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

MESA


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

Superconducting Cryomodules

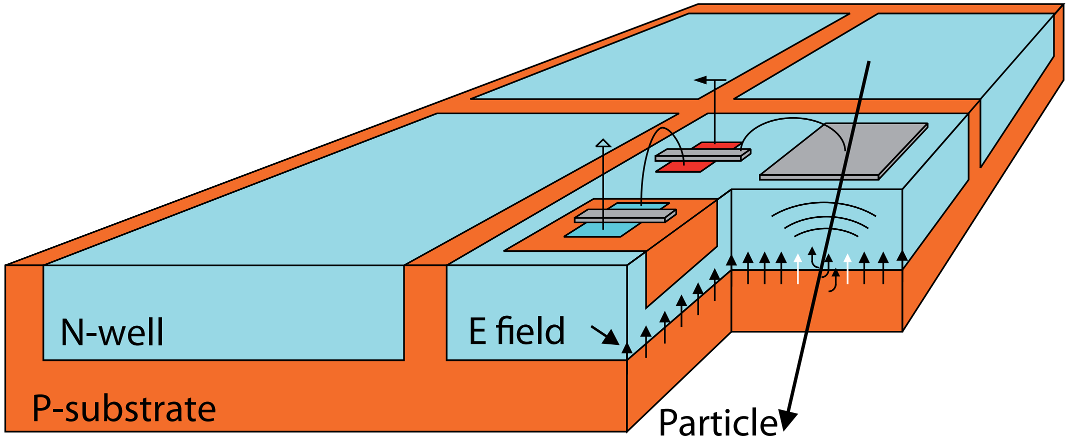


Teichert et al. NIM A 557 (2006) 239

Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

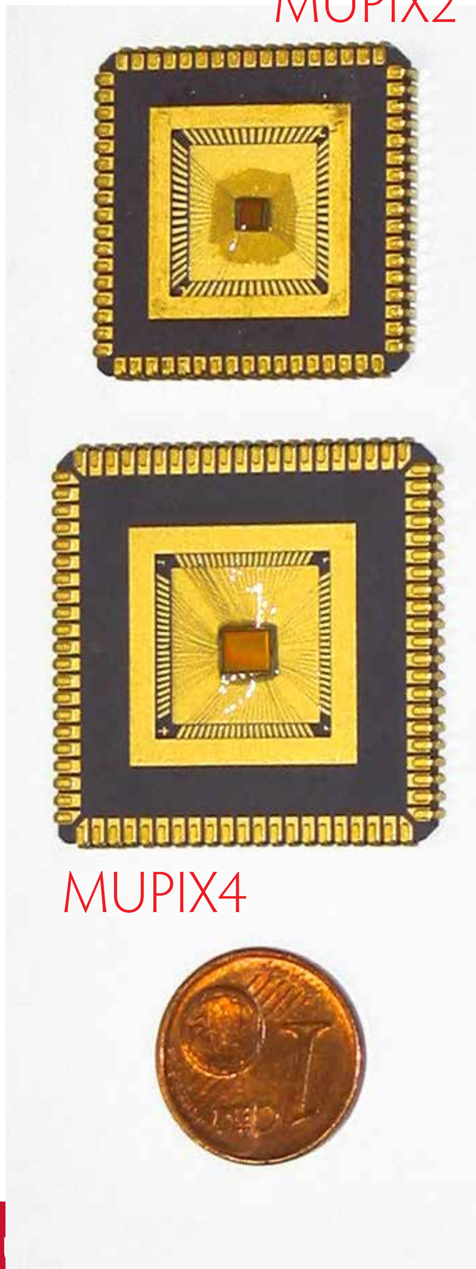


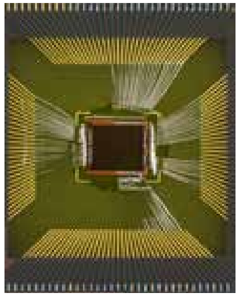
High voltage monolithic active pixel sensors - Ivan Perić

- 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

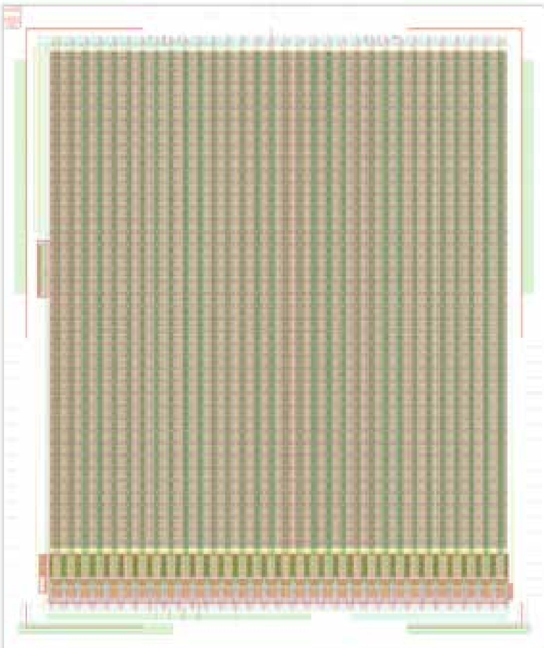
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

The MUPIX chip prototypes





MUPIX6



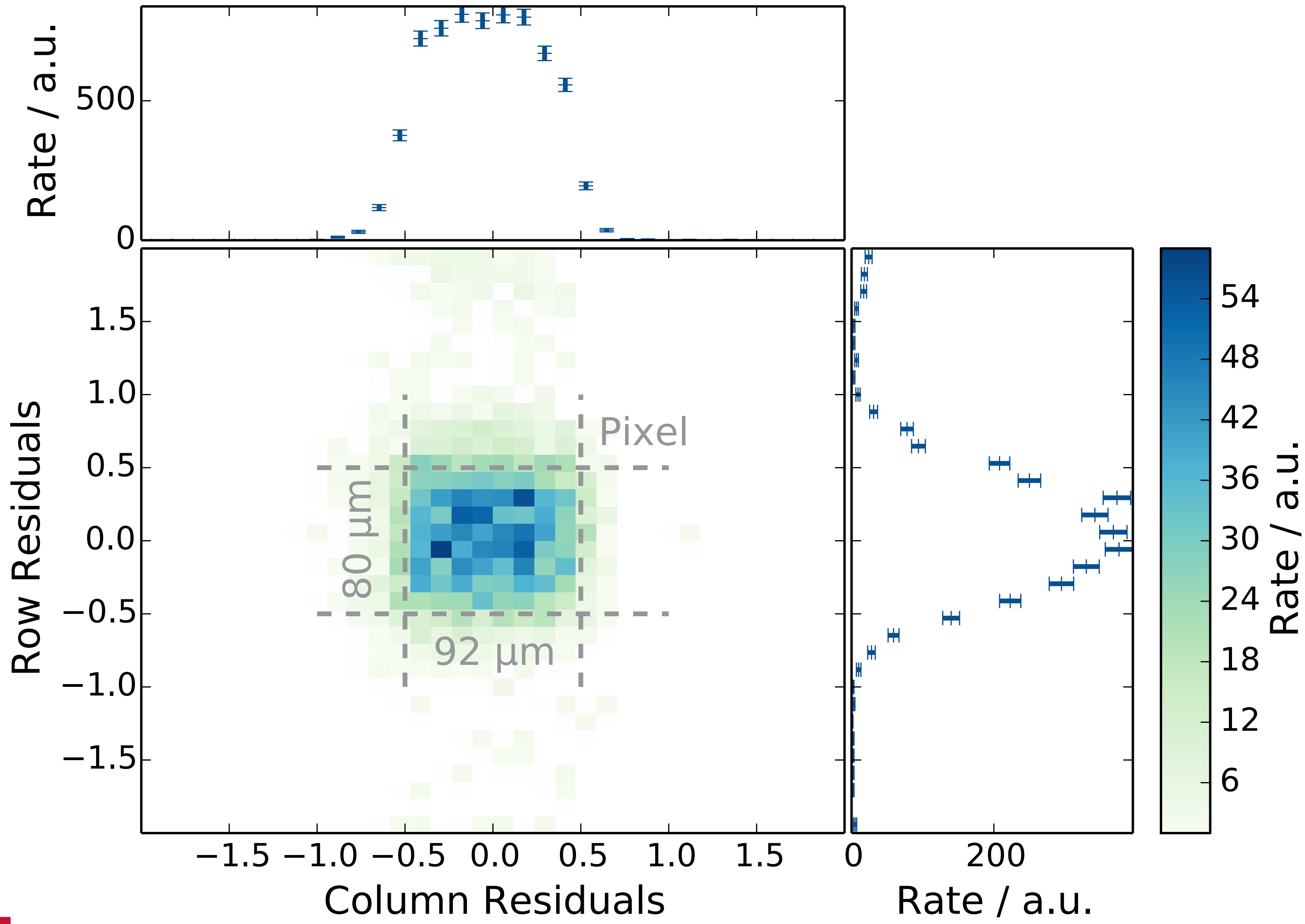
HV-MAPS chips: AMS 180 nm HV-CMOS

- 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

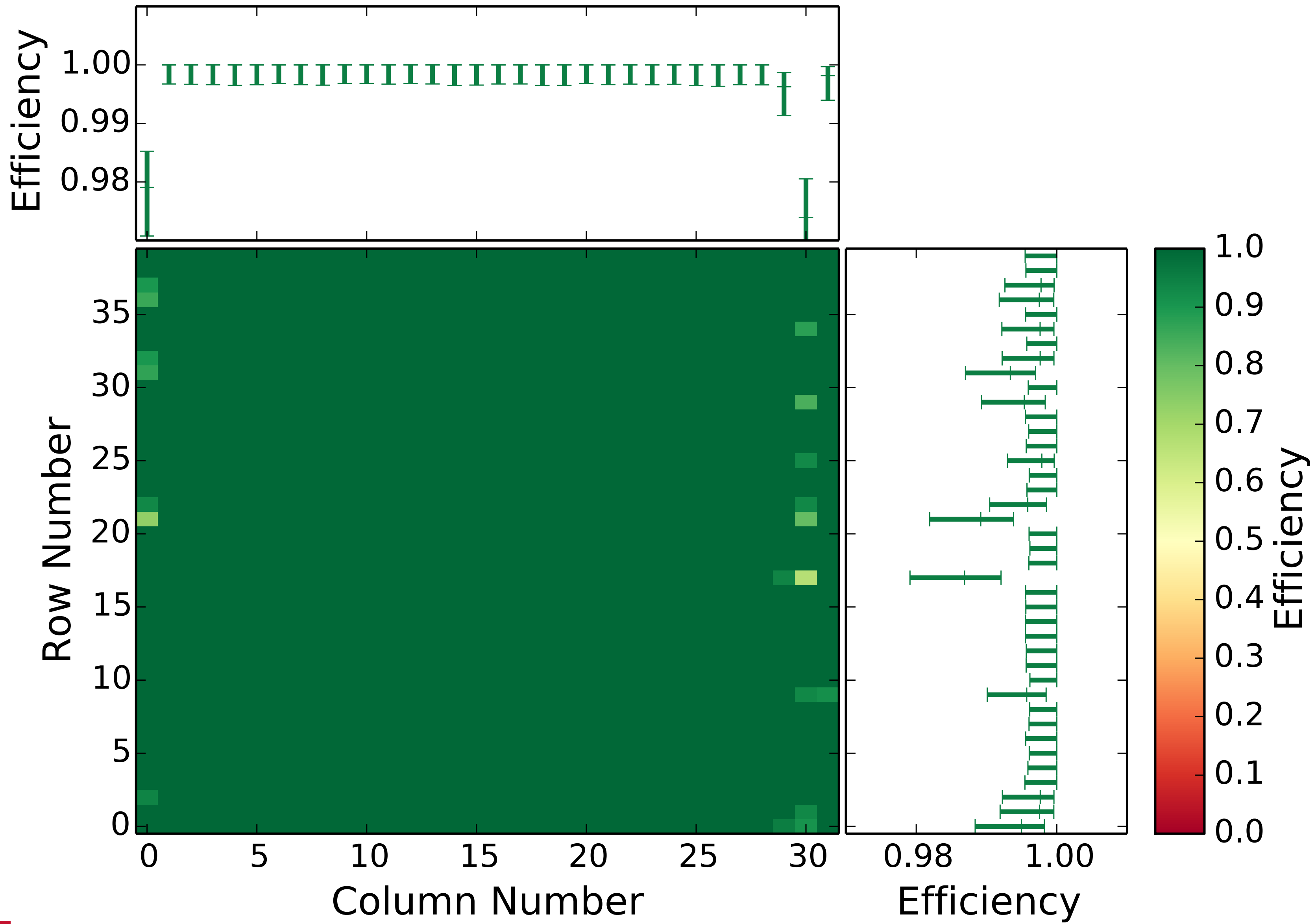
Position Resolution

Position resolution given by pixel size

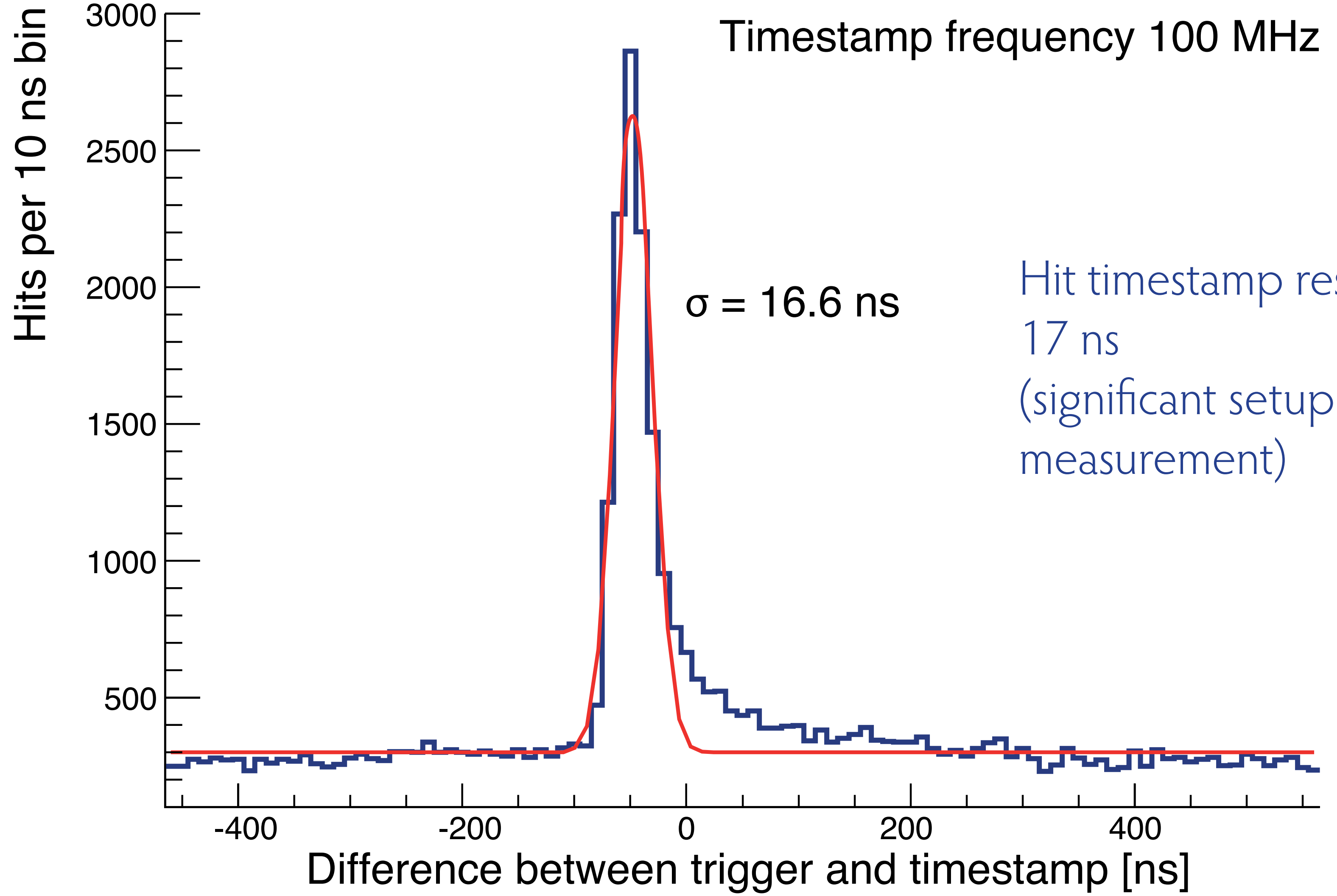


Efficiency

Hit efficiency above 99% without tuning

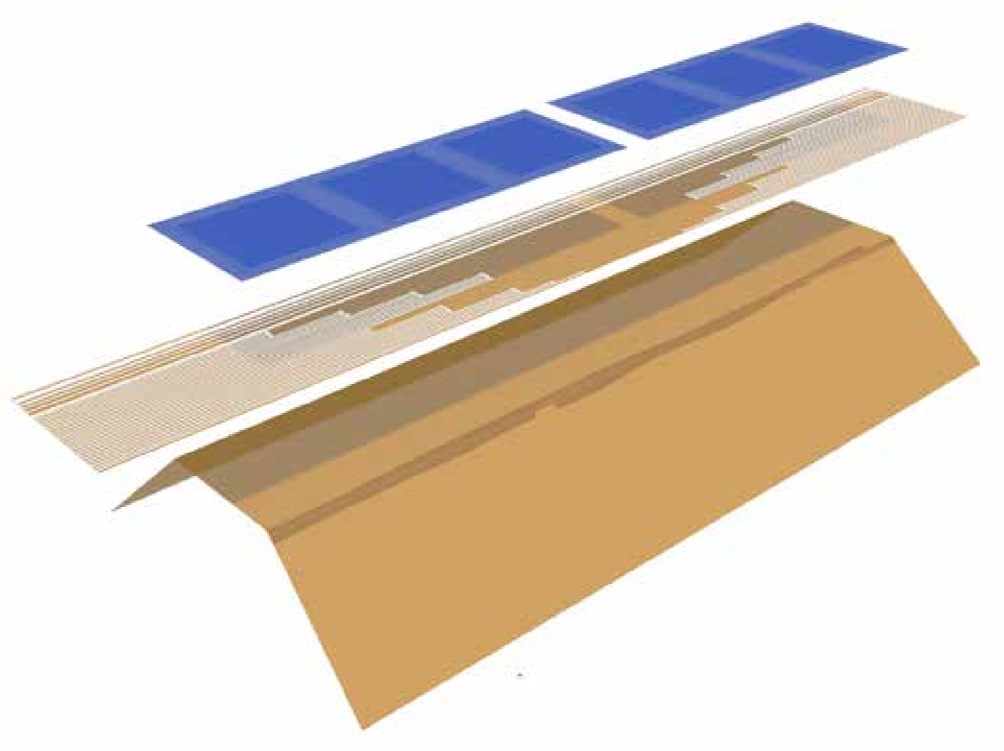


Time resolution



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