Electron scattering in Mainz

Plans for the next decade

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EINN, Paphos, Cyprus
November 2015

Overview

- The Idea:
  Searching for new physics with the weak mixing angle
- The Machine:
  Mainz Energy-Recovery Superconducting Accelerator
- Experiment I:
  Weak mixing angle with P2

Overview

- Experiment II:
  Dark photons, proton radius etc. with MAGIX
- More experiments:
  Dark matter, electron electric dipole moment etc.
- Even more:
  Continuing program at MAMI

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"

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

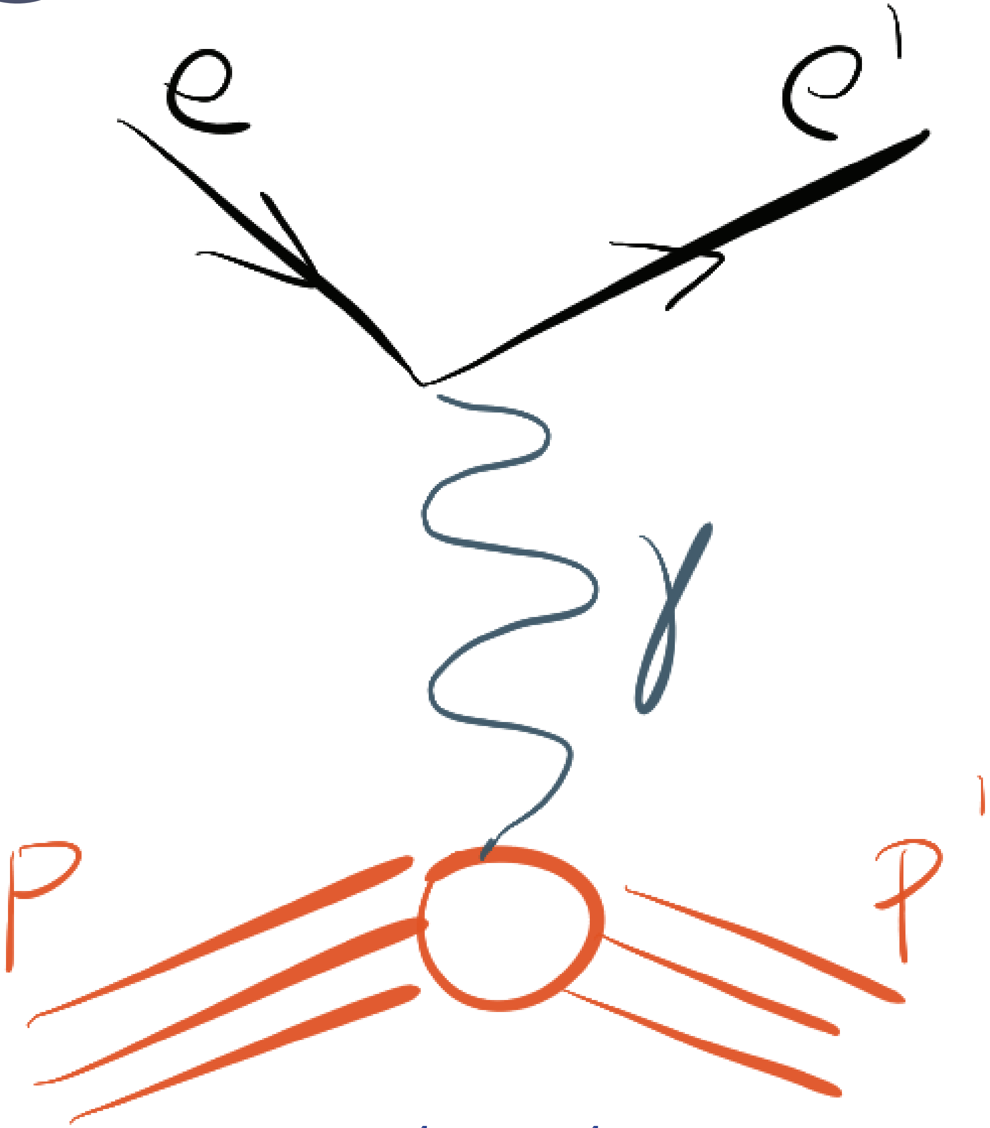
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

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

Weak mixing angle and charges



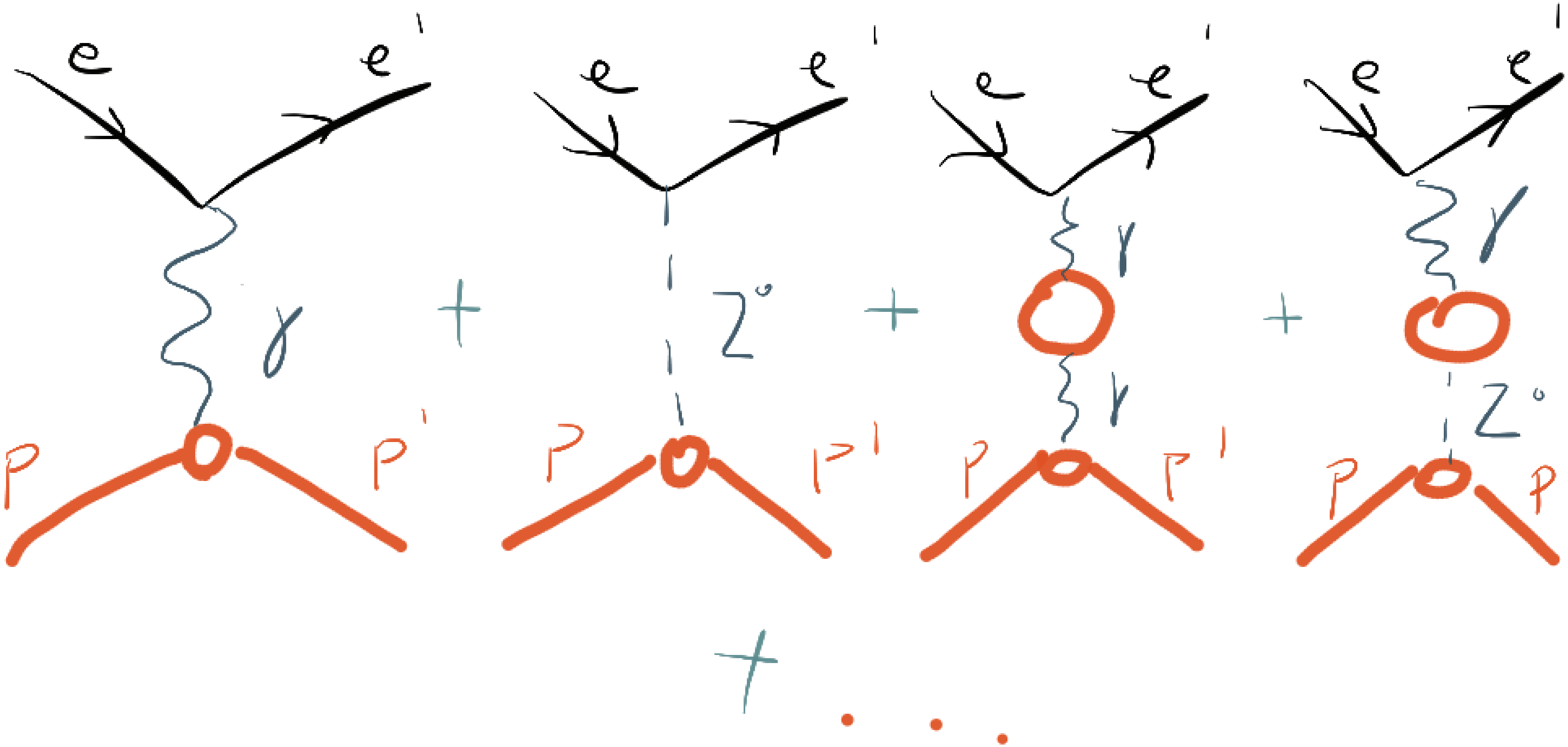
Proton electric charge

+1

Proton weak charge

$1 - 4\sin^2\theta_W$

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



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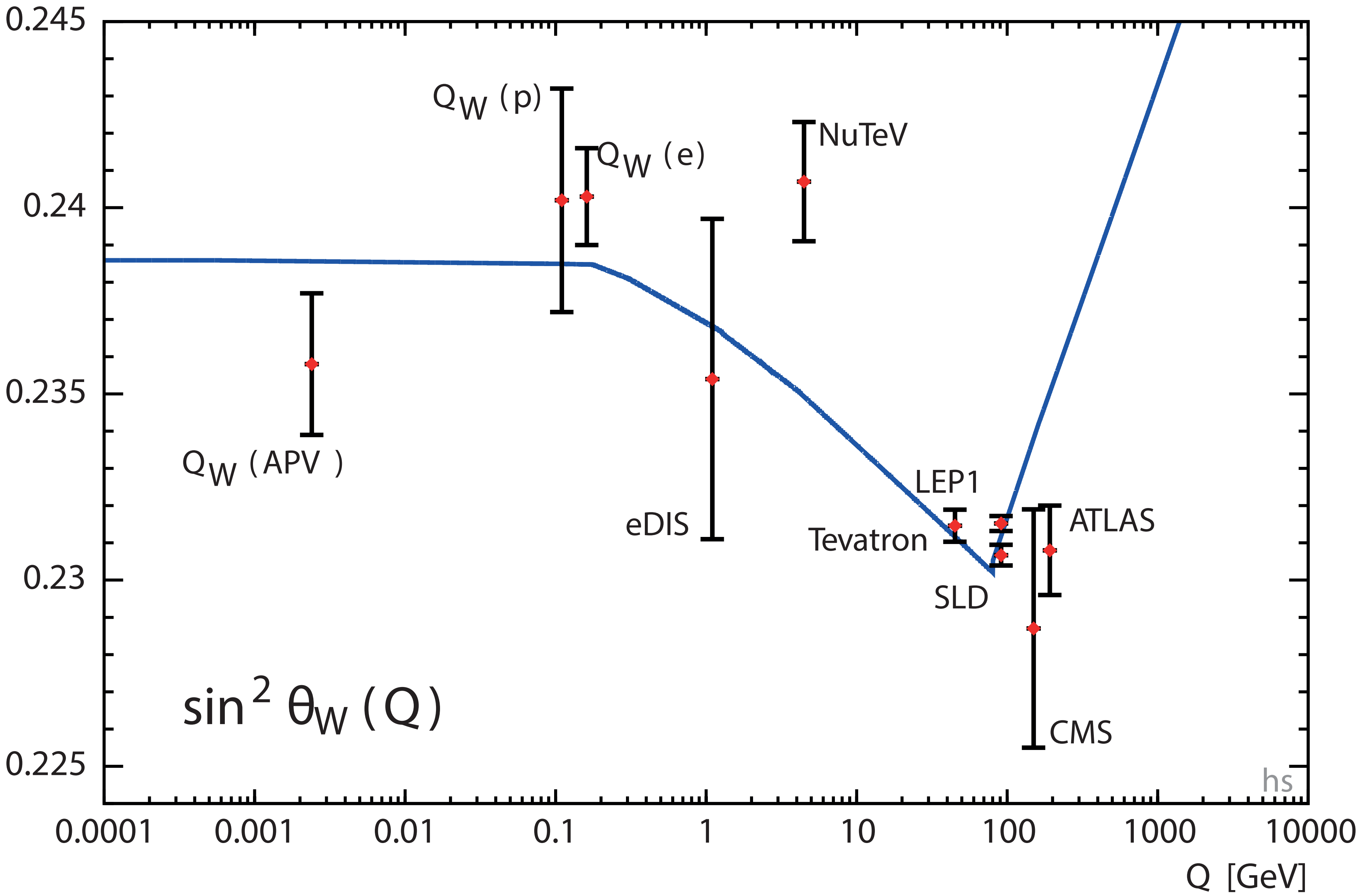
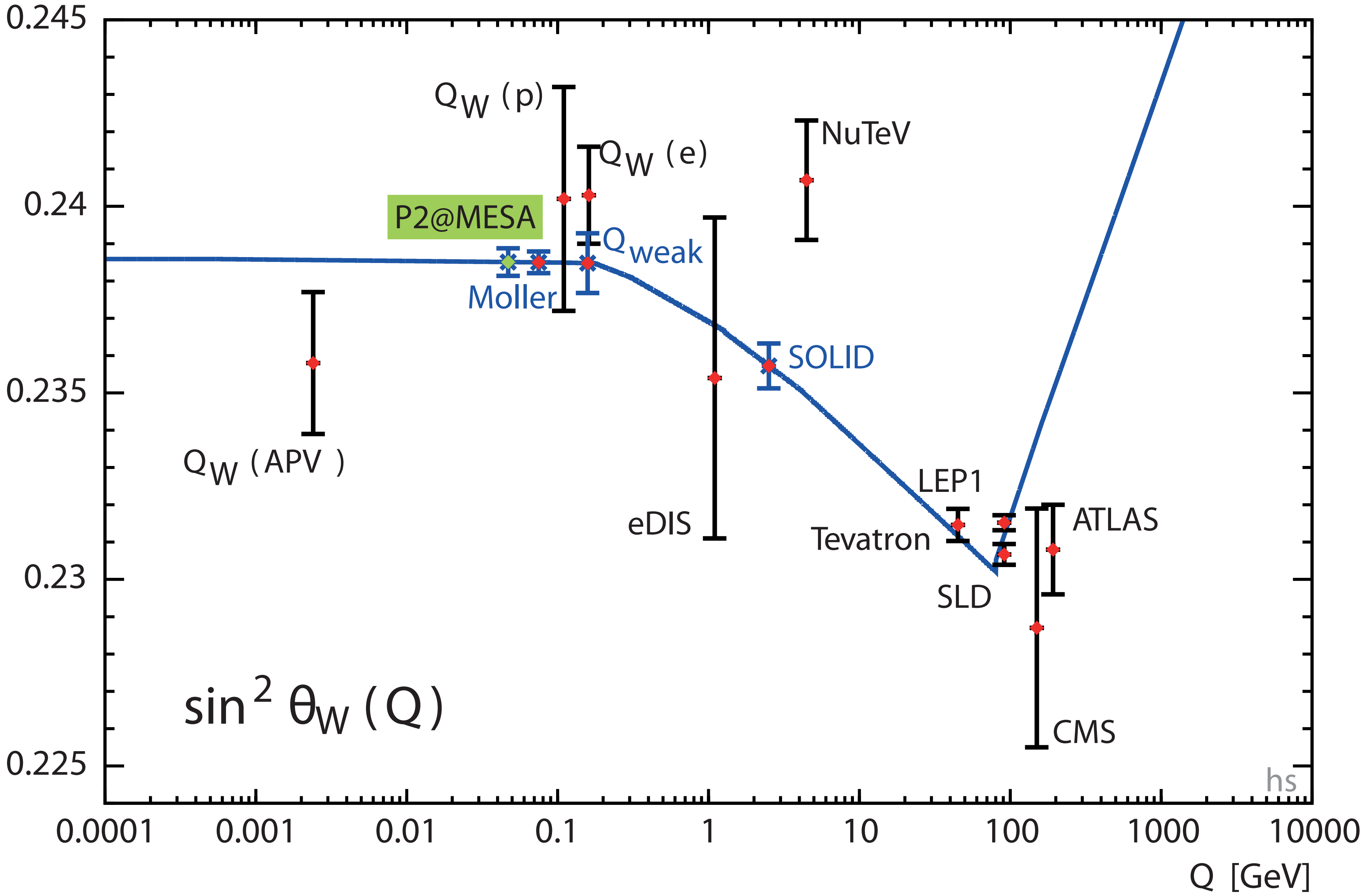
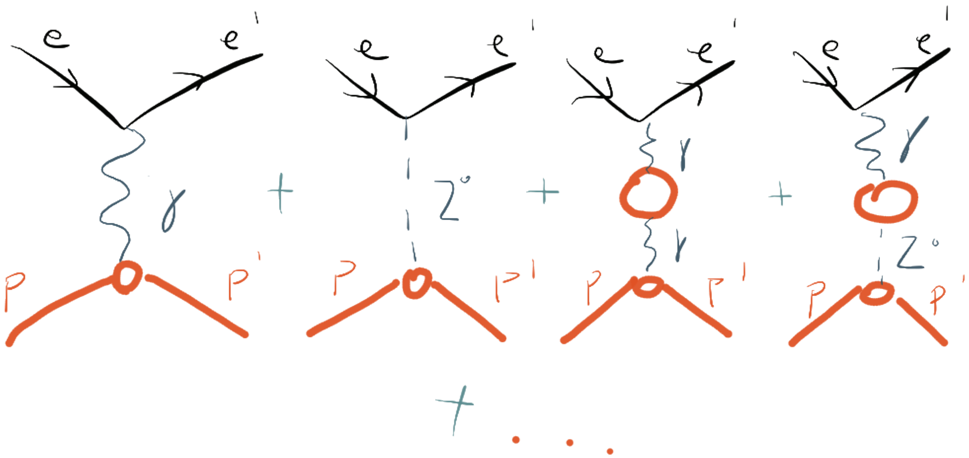
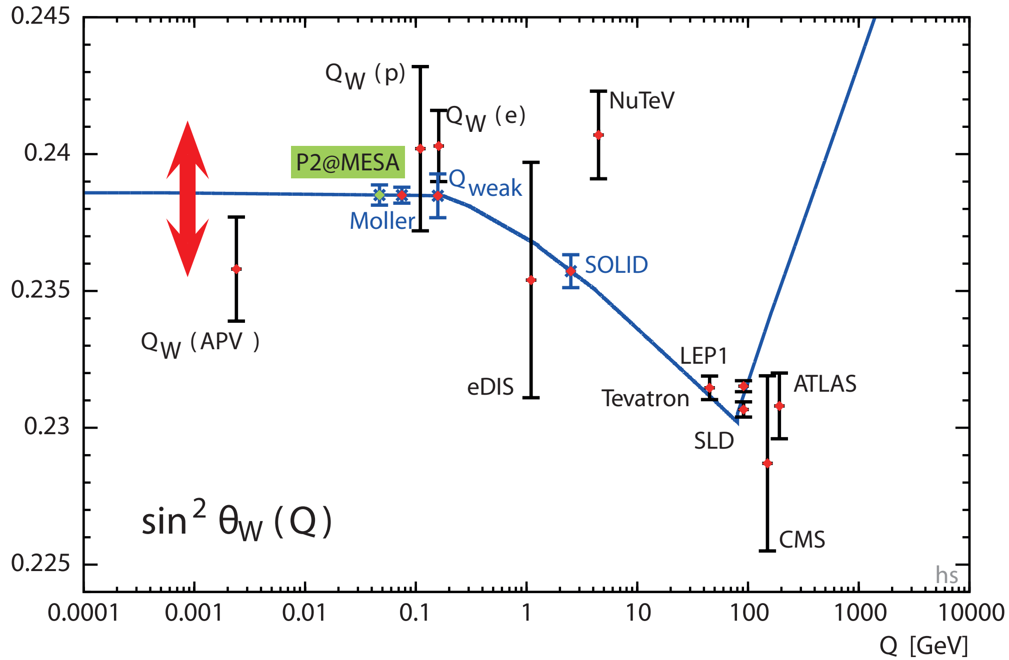


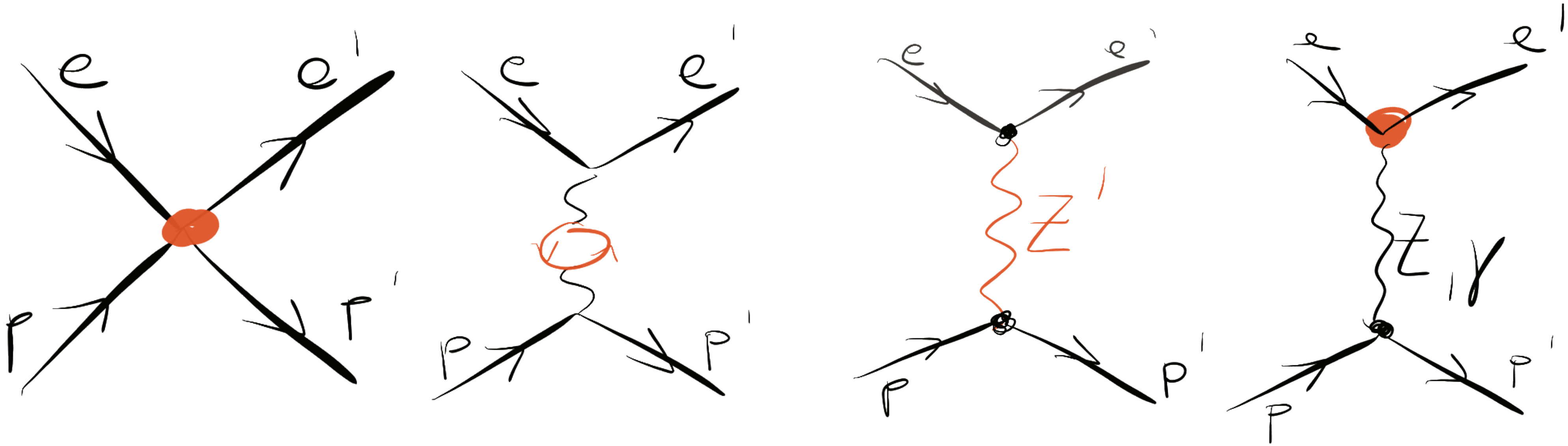
Scale dependence (running) of $\sin^2\theta_W$



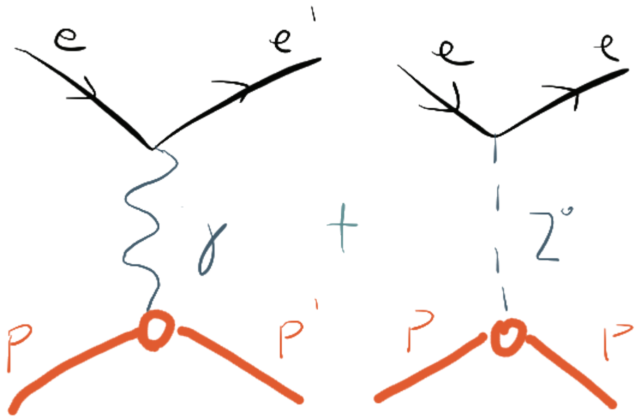
New Physics in the running

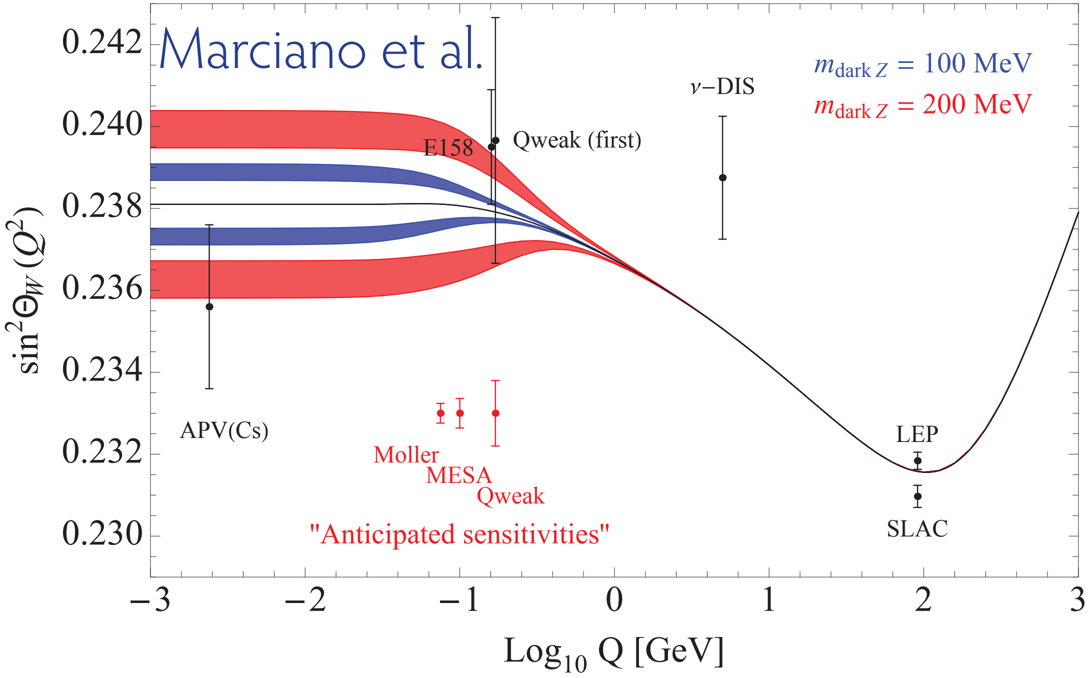


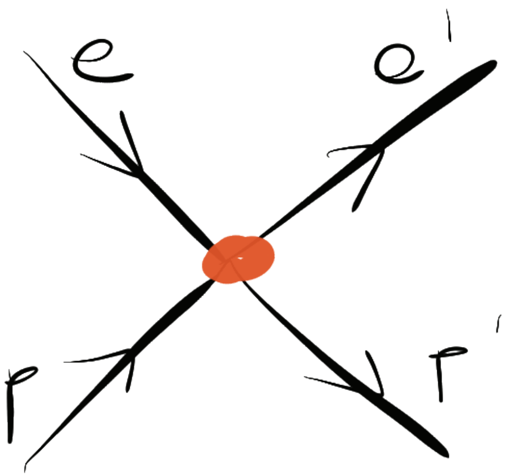


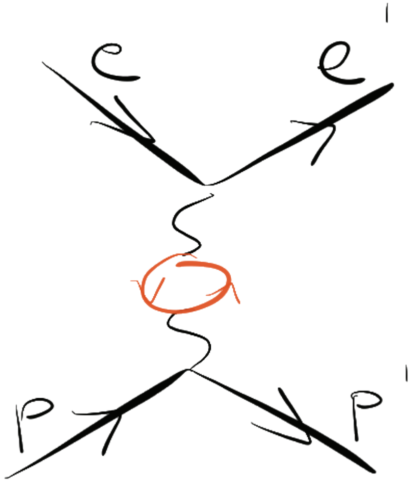


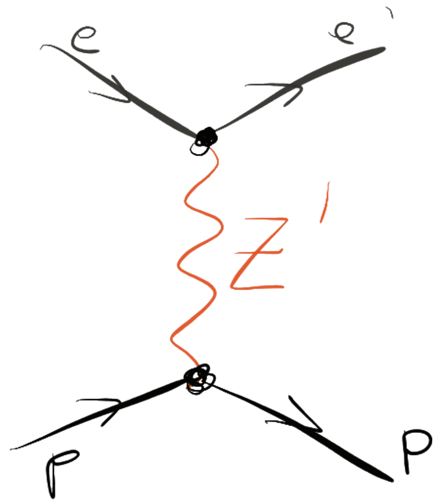
Dark Z in mixing

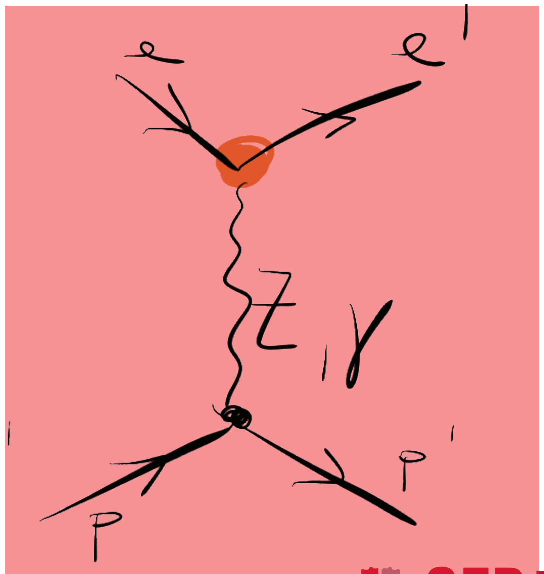




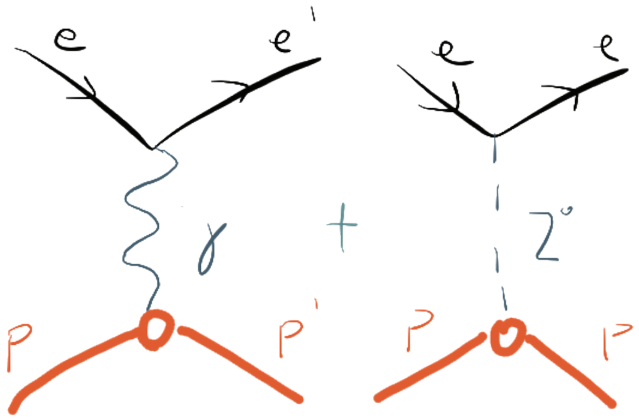








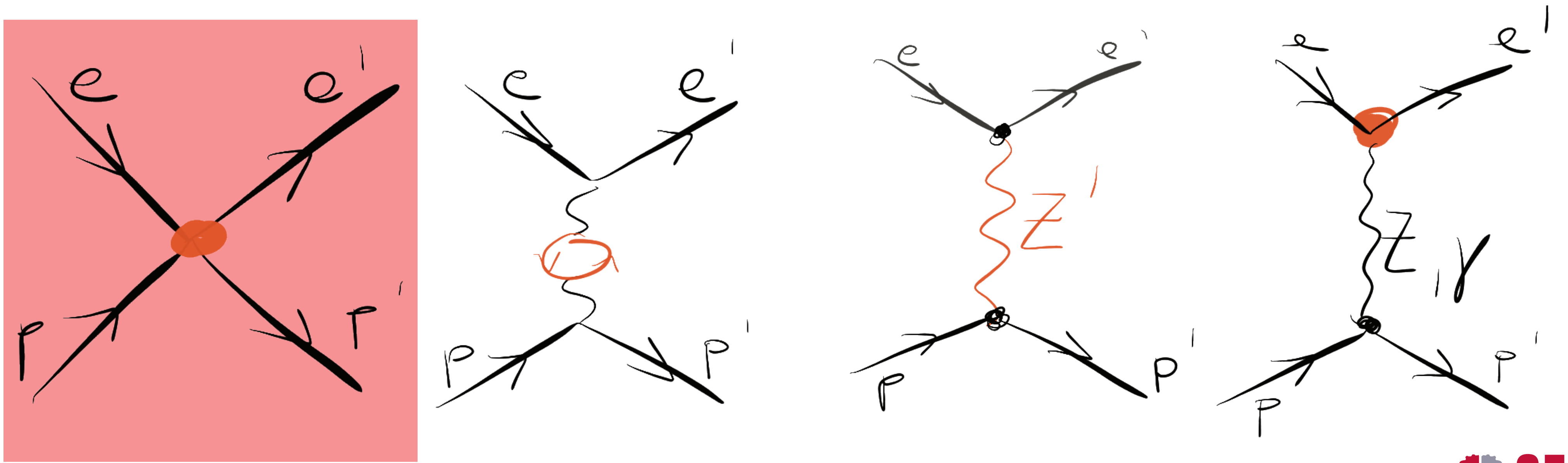
Contact Interactions



Contact interactions up to

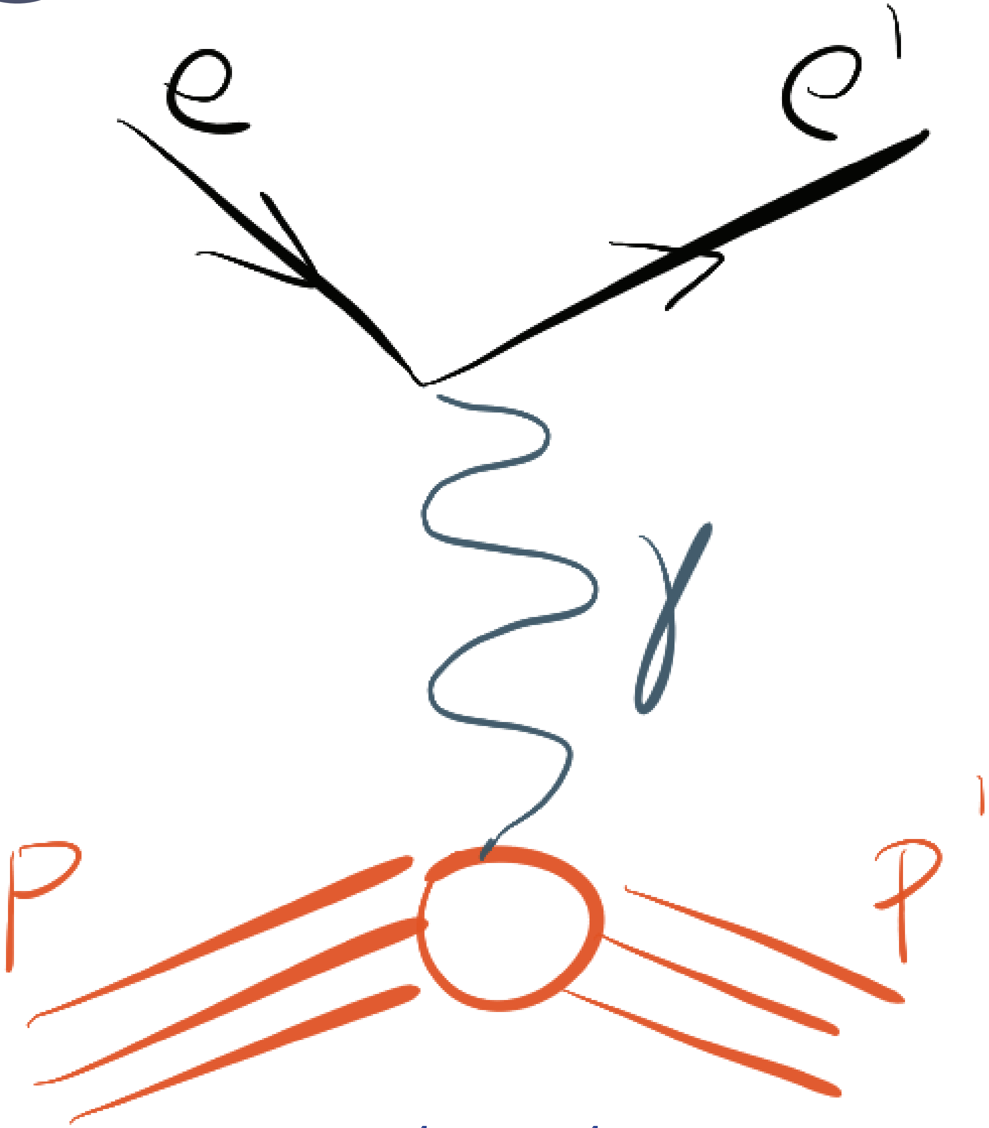
49 TeV

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



How to measure the weak charge?

Weak mixing angle and charges



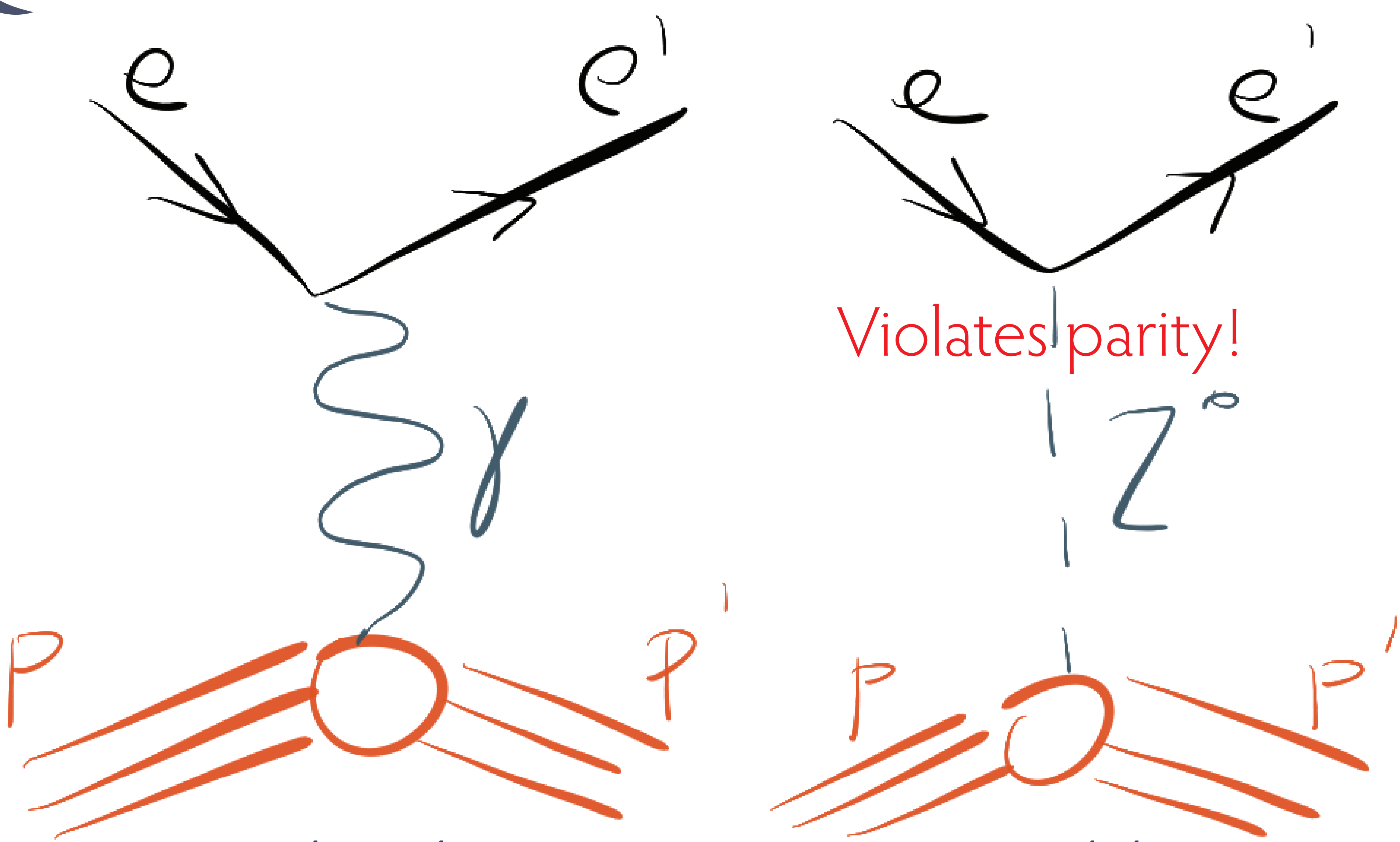
Proton electric charge

+e

Proton weak charge

$1 - 4 \sin^2\theta_W$

Weak mixing angle and charges



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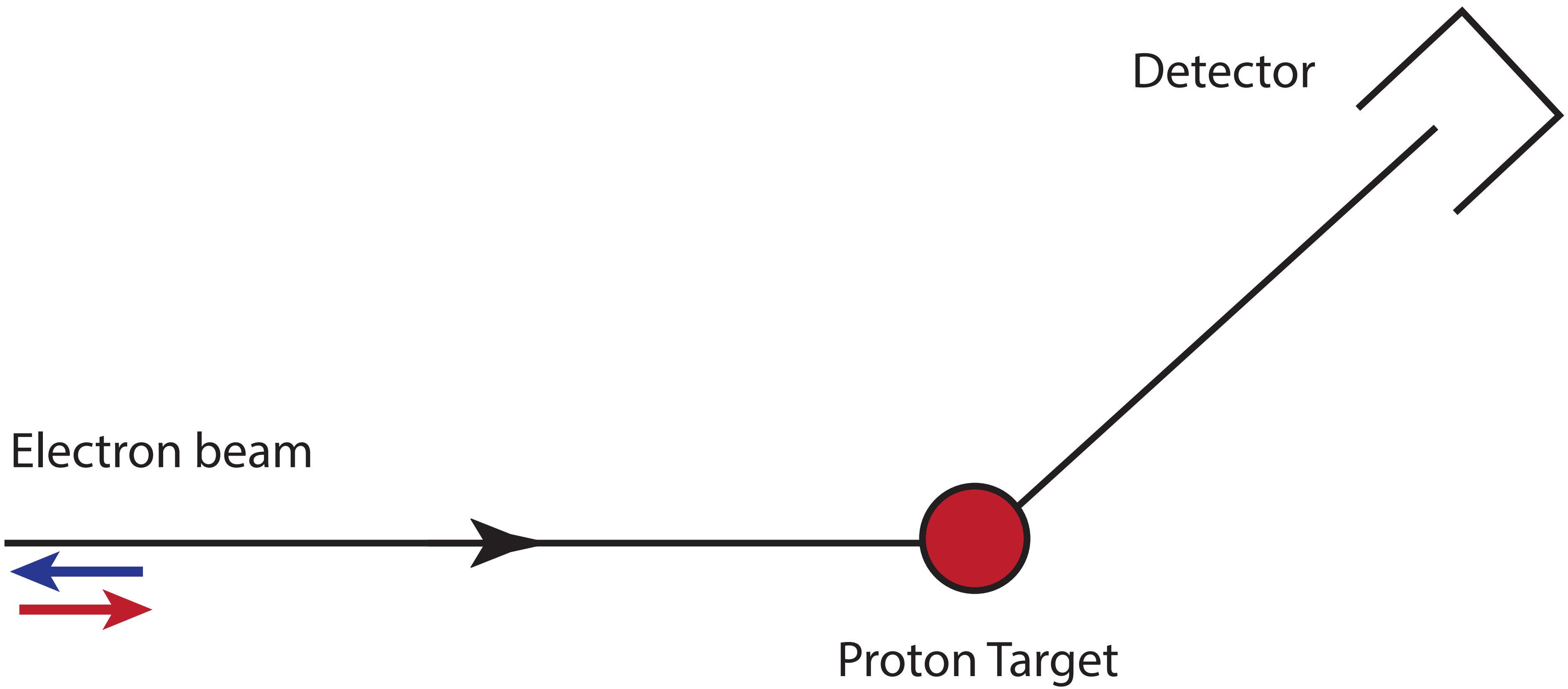
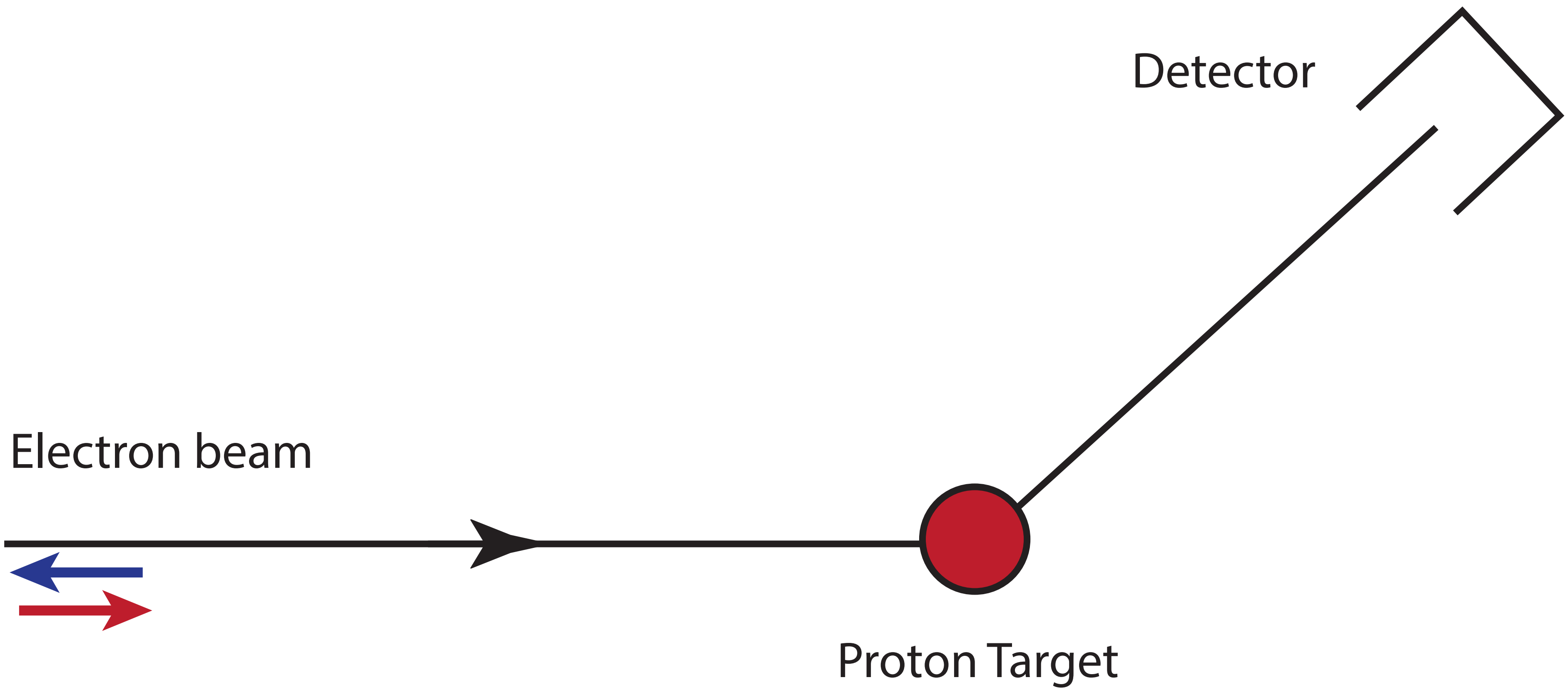
Parity violating electron scattering



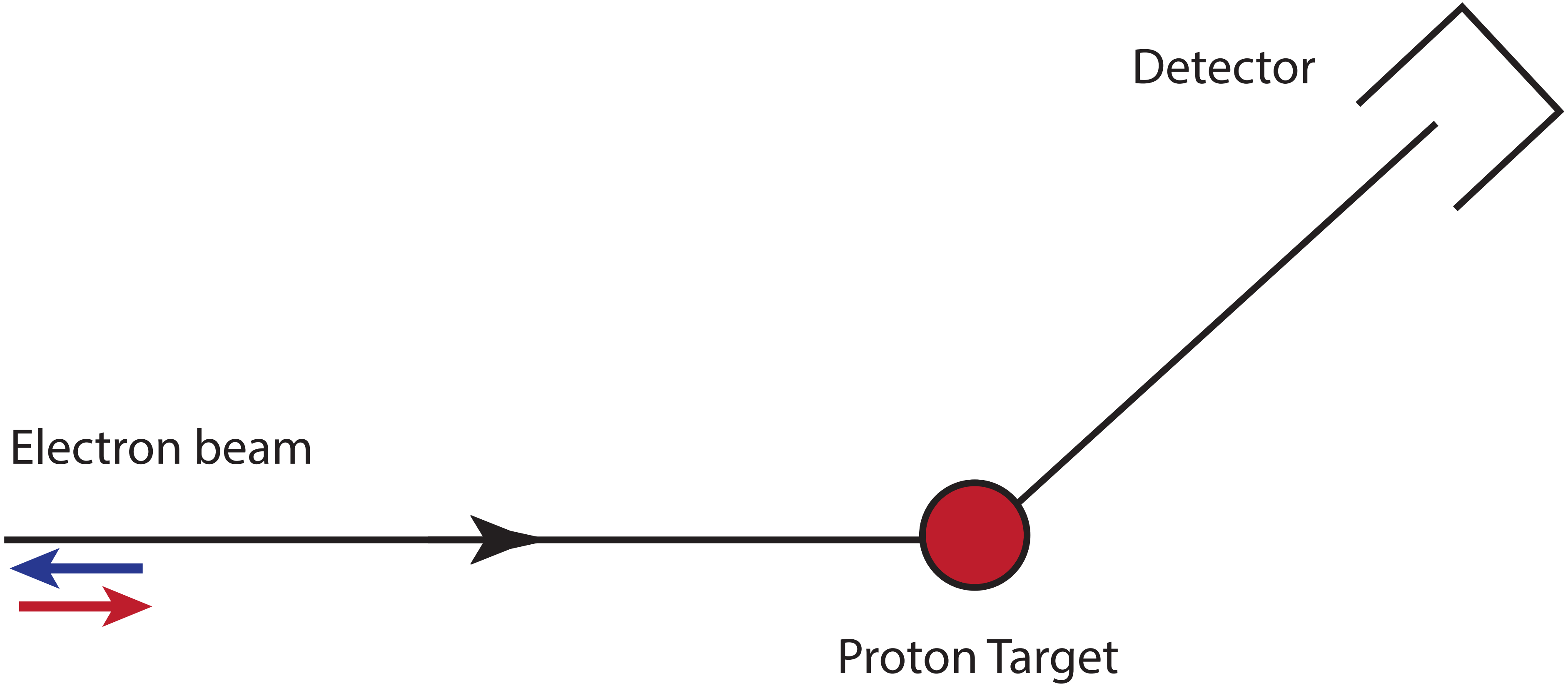
Parity violating electron scattering

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



Parity violating electron scattering

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



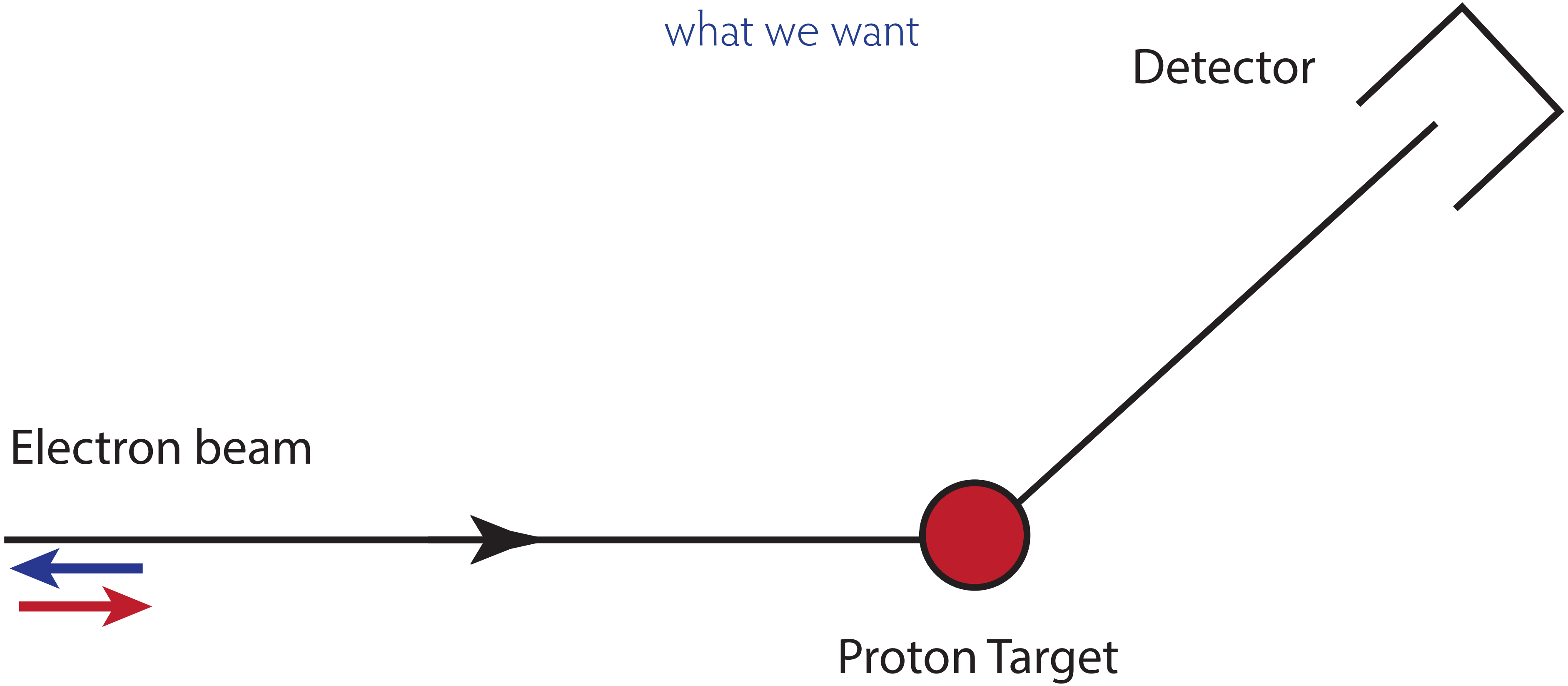
Parity violating electron scattering

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



Why is this difficult?

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

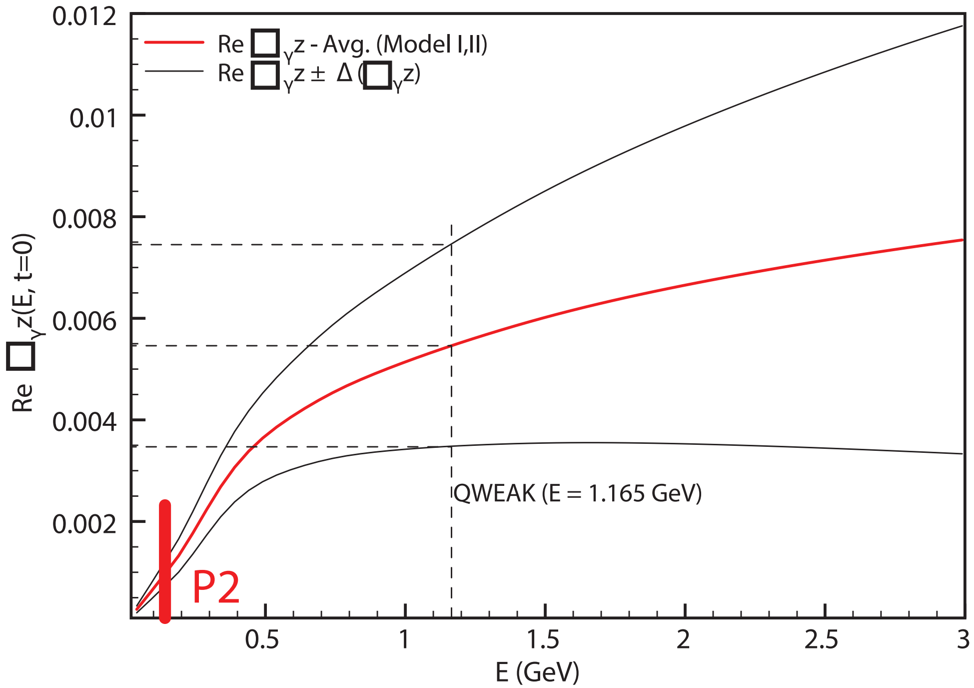
$$Q_W = 1 - 4\sin^2\theta_W$$

- At low Q^2: Asymmetry is tiny (40 parts per billion): need very large statistics

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

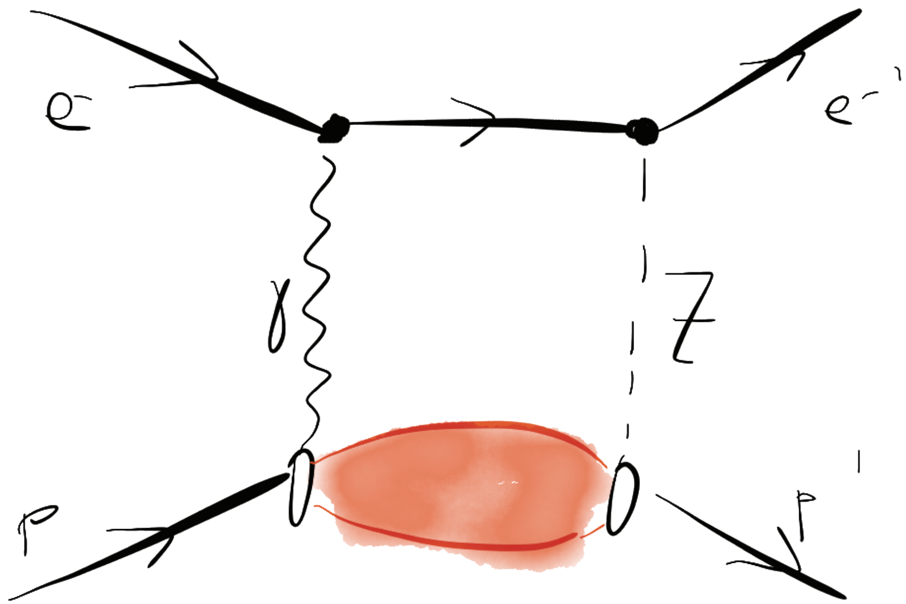
- We are subtracting two huge numbers from each other (not really - switching helicity with a few KHz)

γ-Z box graphs

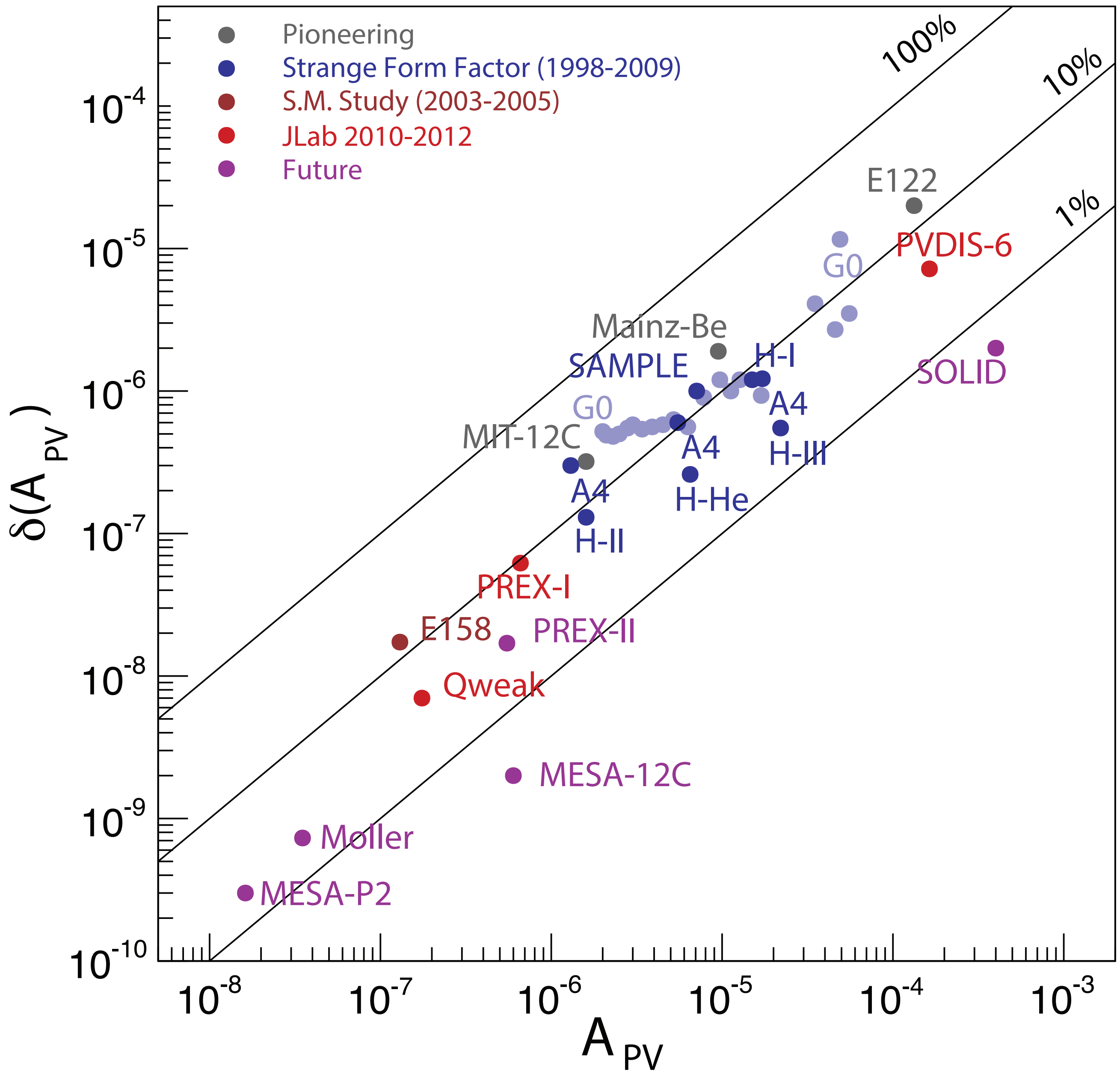


[Gorchstein, Horowitz, Ramsey-Musolf 2011]

- 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%
- 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

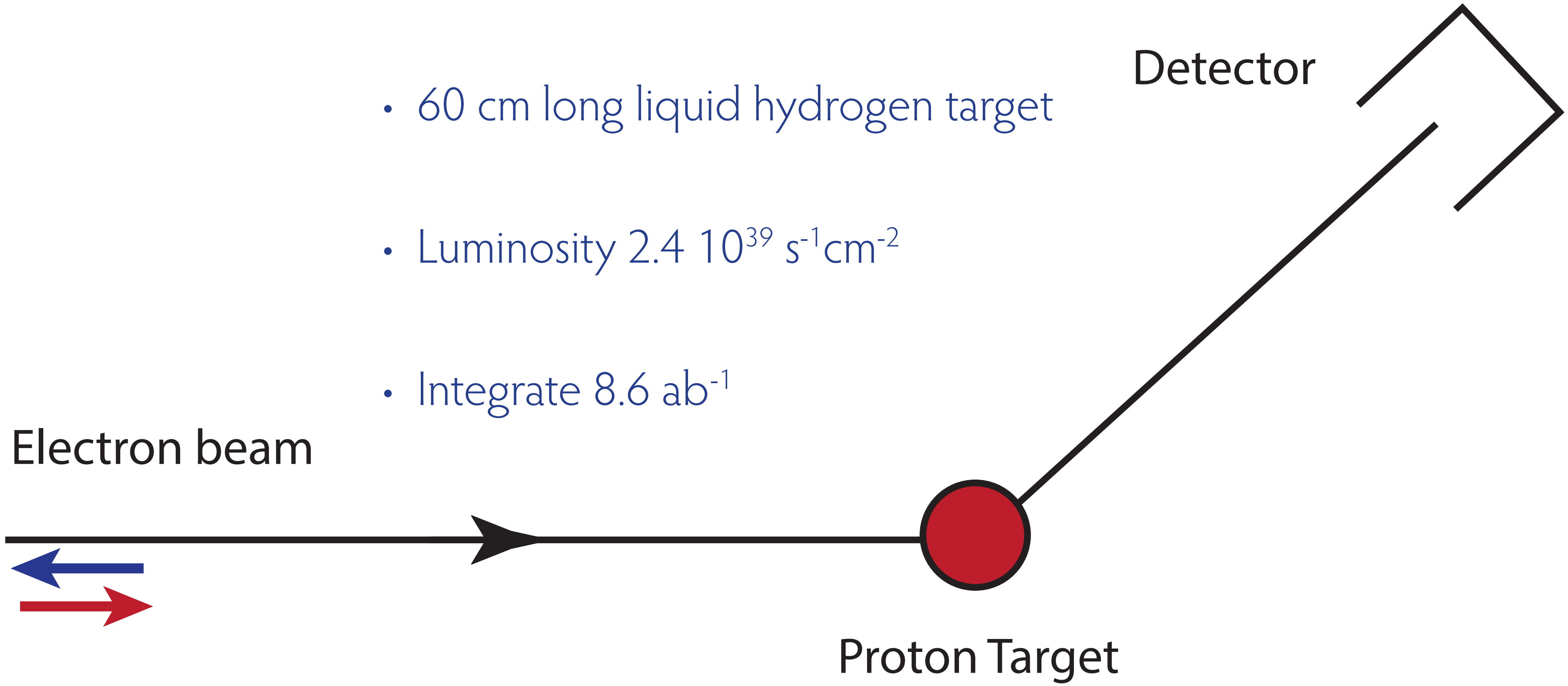
$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1-4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\Delta Q_W}{Q_W}$$

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

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 $8.6\ ab^{-1}$

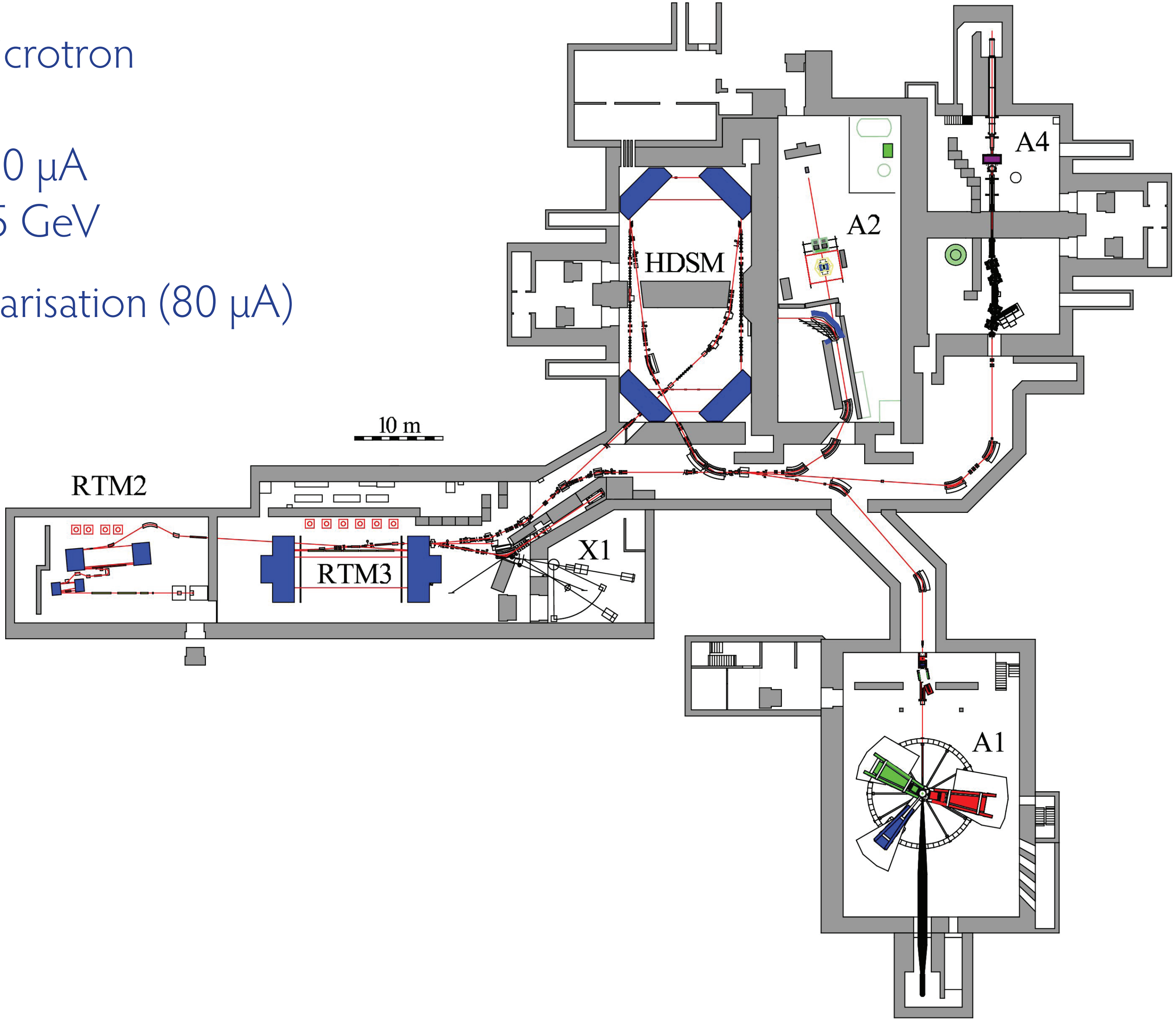


MAMI in Mainz

Mainz Microtron

Up to 100 µA
Up to 1.5 GeV

80 % polarisation (80 µA)



JG|U

SFB 1044

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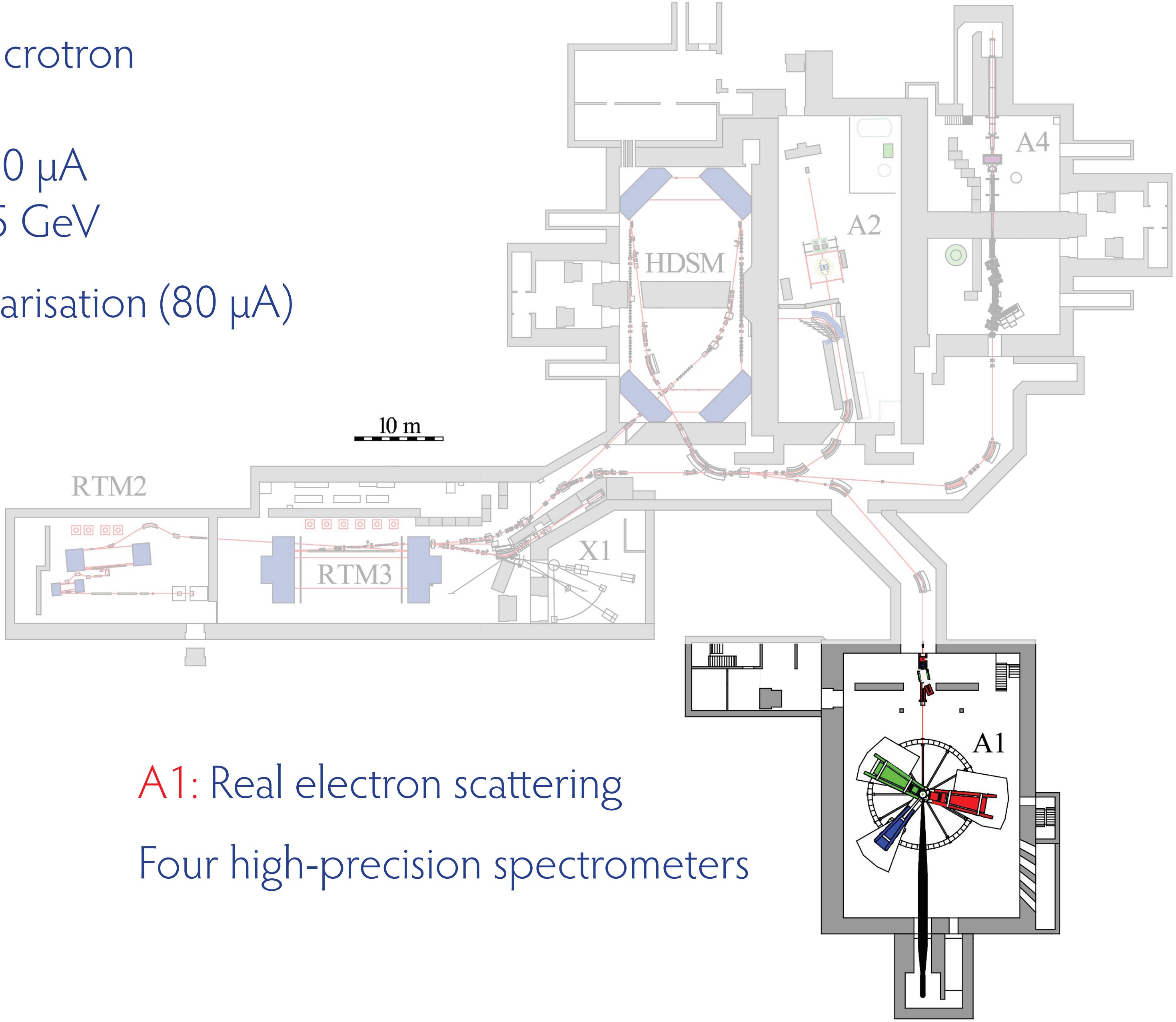

A1: Real electron scattering

Four high-precision spectrometers

MAMI in Mainz

Mainz Microtron

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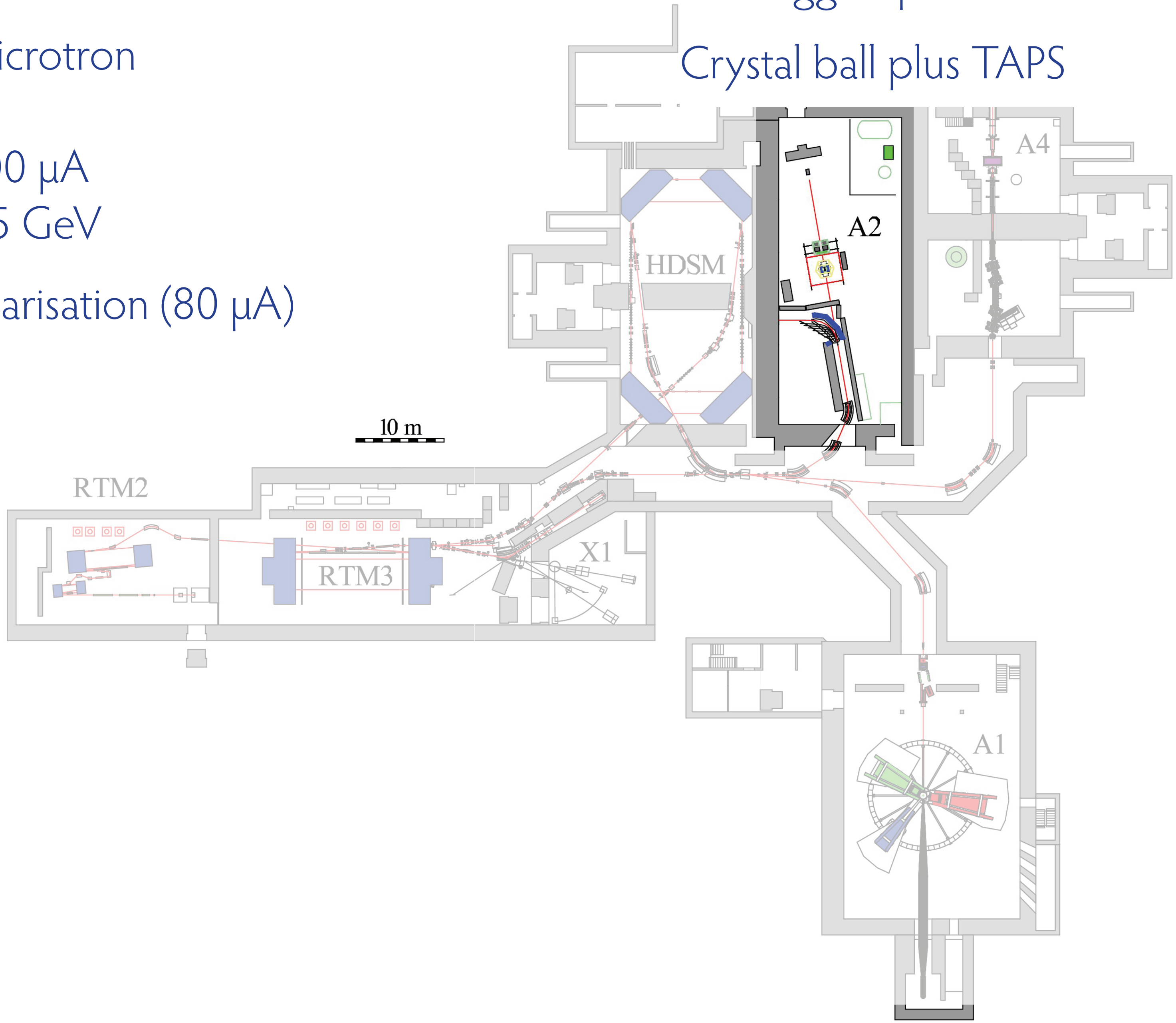
Up to 1.5 GeV

80 % polarisation (80 μA)

A2: Tagged photon beam

Crystal ball plus TAPS



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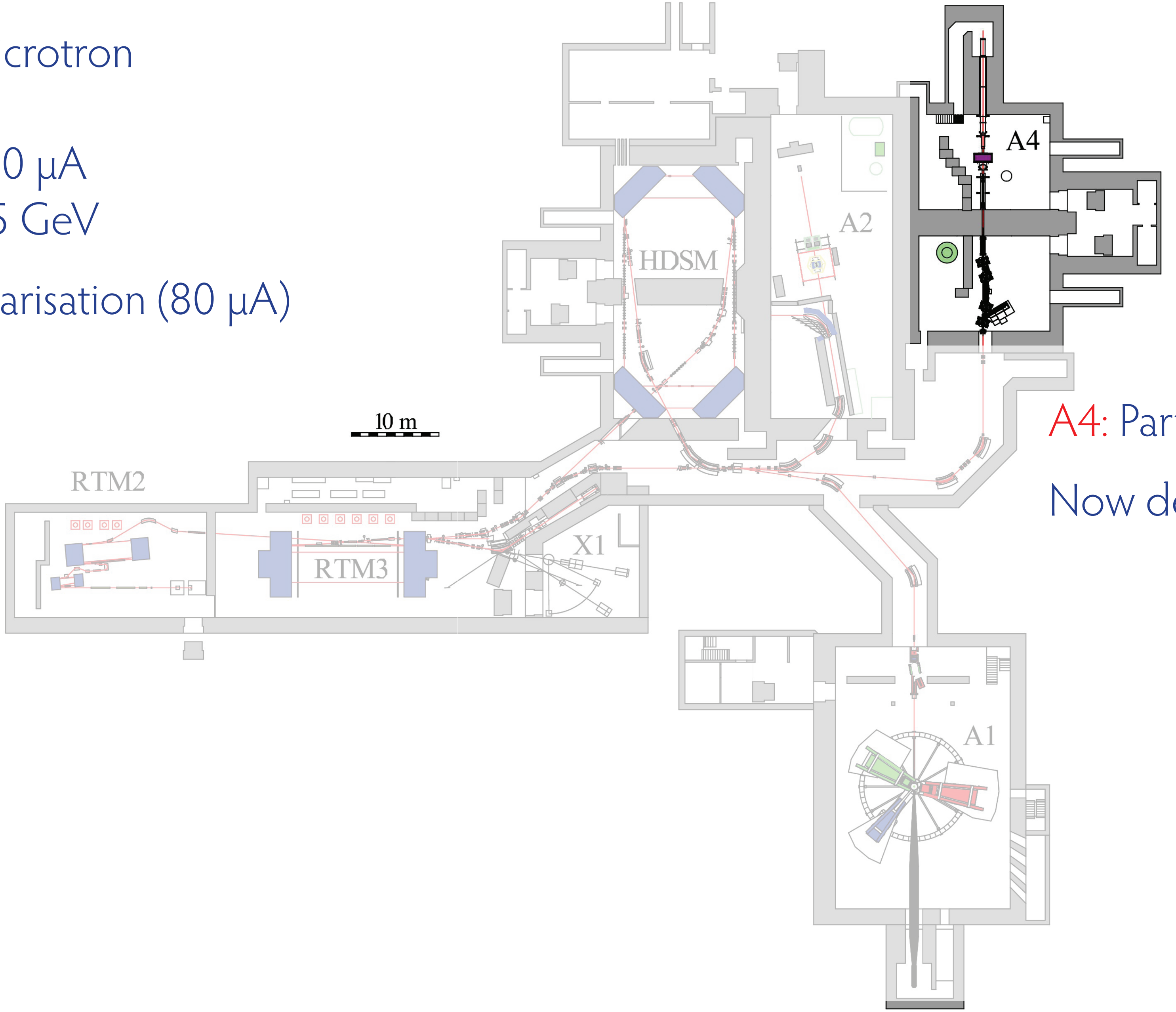


A4: Parity violation

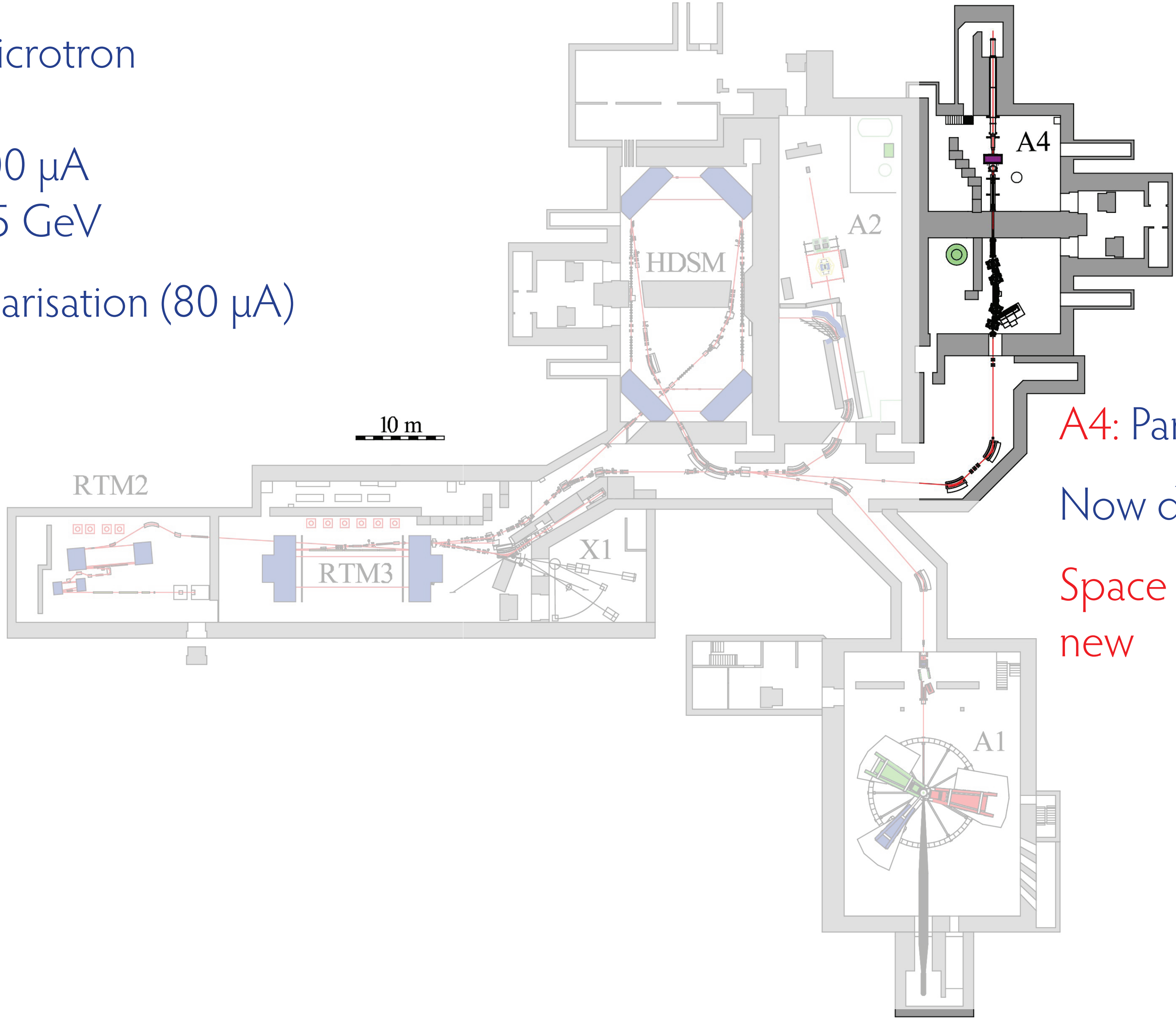
Now decommissioned

MAMI in Mainz

Mainz Microtron

Up to 100 μA
Up to 1.5 GeV

80 % polarisation (80 μA)



A4: Parity violation

Now decommissioned

Space for something new

10'000 hours is 417 days 24/7 of measurements

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

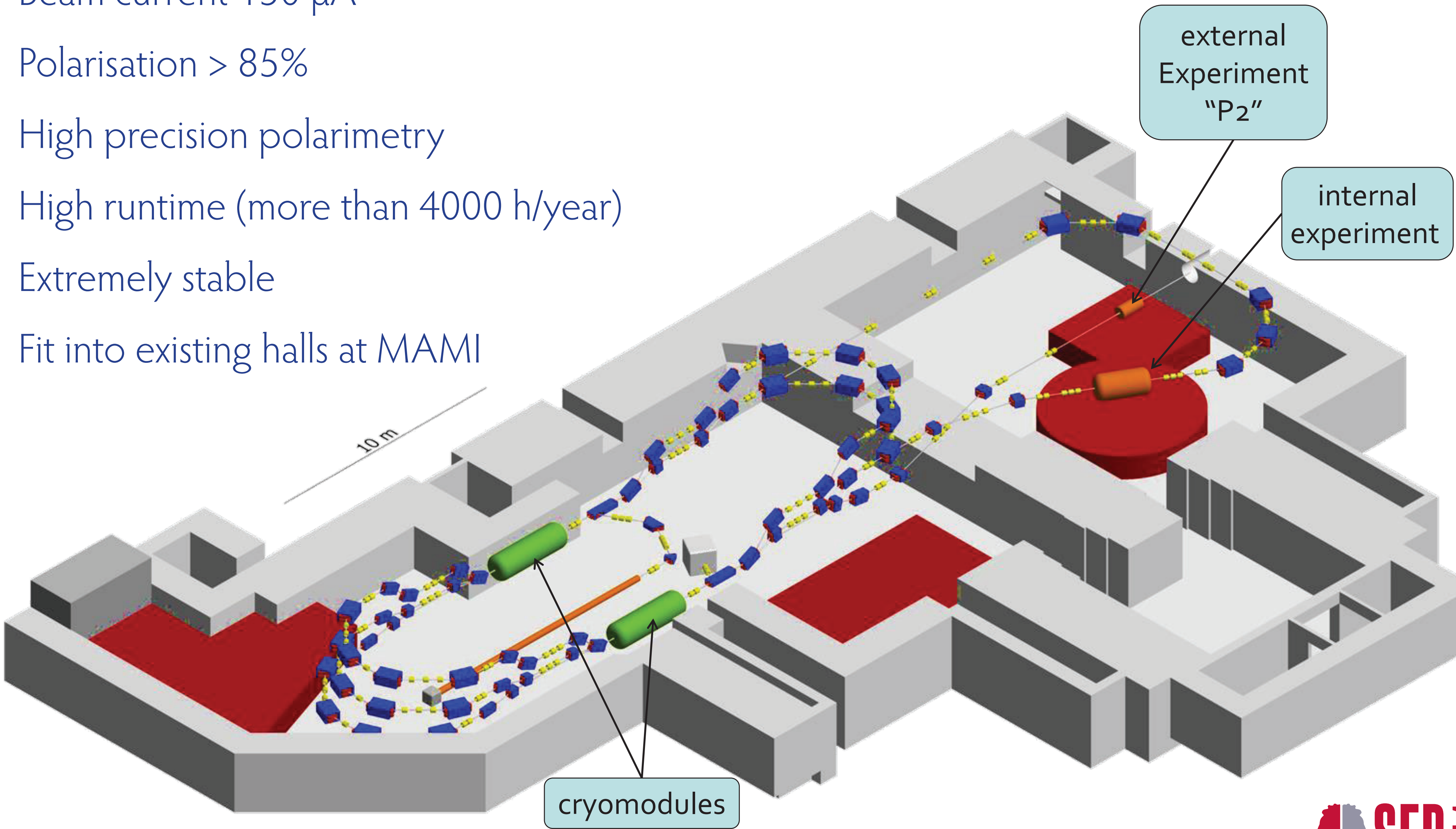
If you cannot rent it, build it:

The MESA accelerator

Mainz Energy-recovery Superconducting Accelerator

Requirements

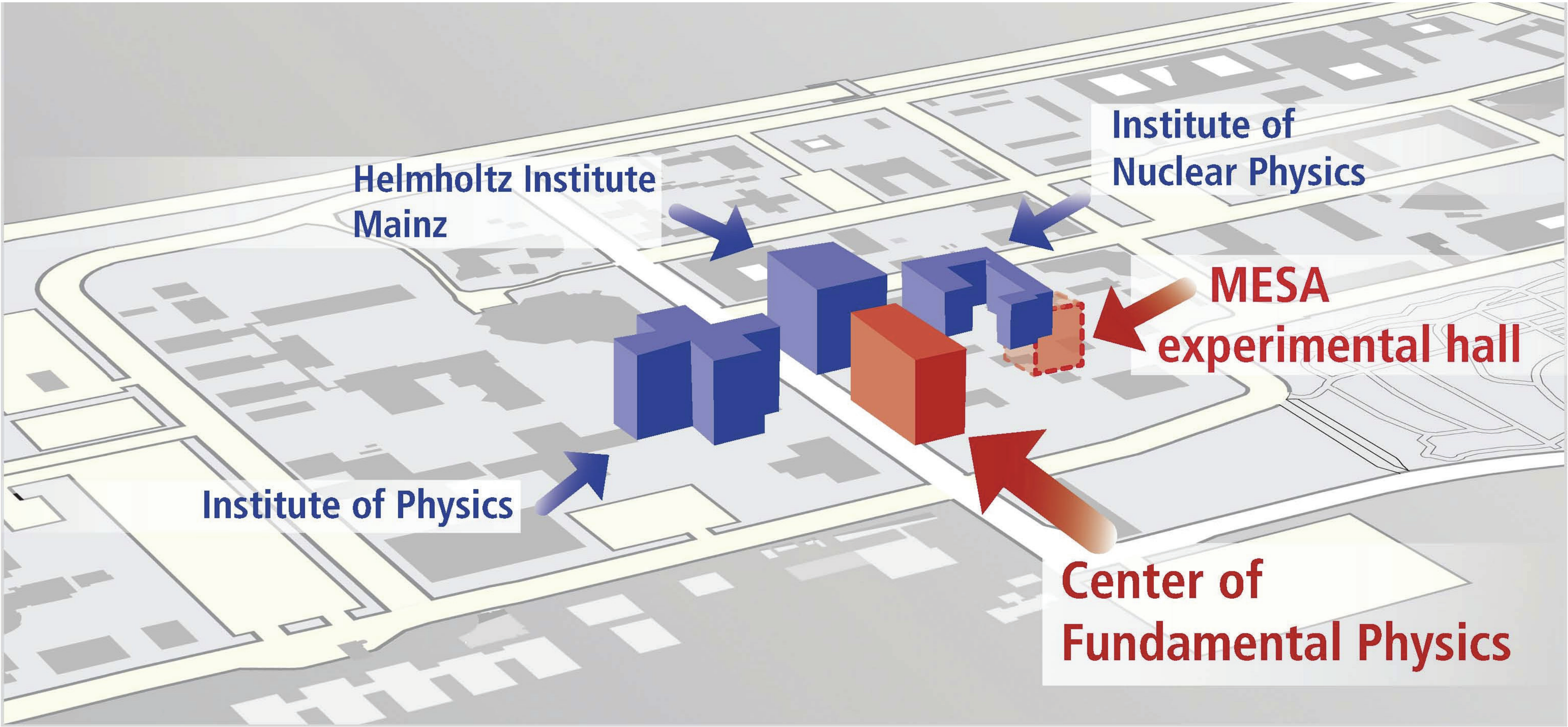
- Beam current 150 µA
- Polarisation > 85%
- High precision polarimetry
- High runtime (more than 4000 h/year)
- Extremely stable
- Fit into existing halls at MAMI



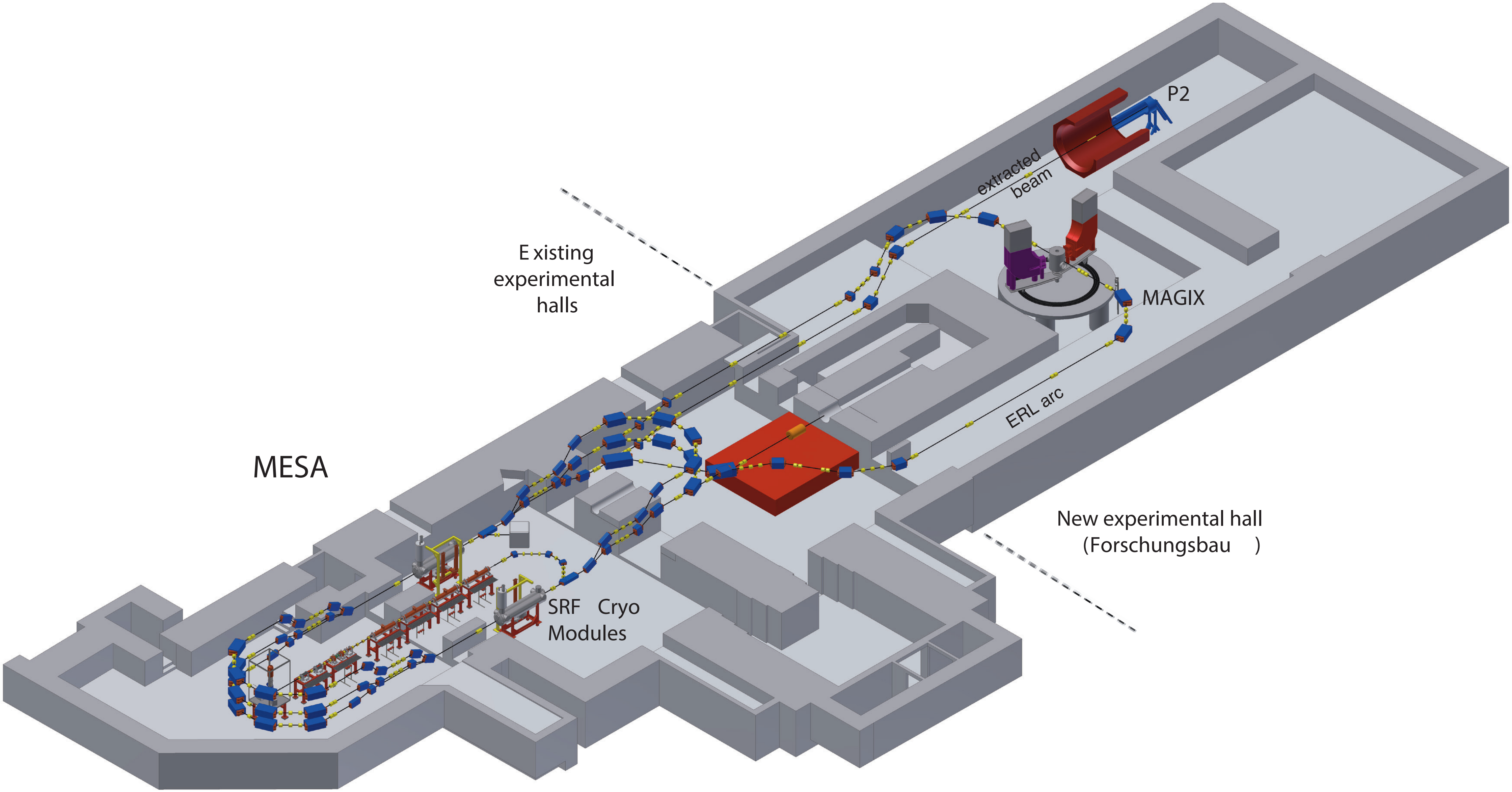
More space: Centre of Fundamental Physics

Research building recently funded:

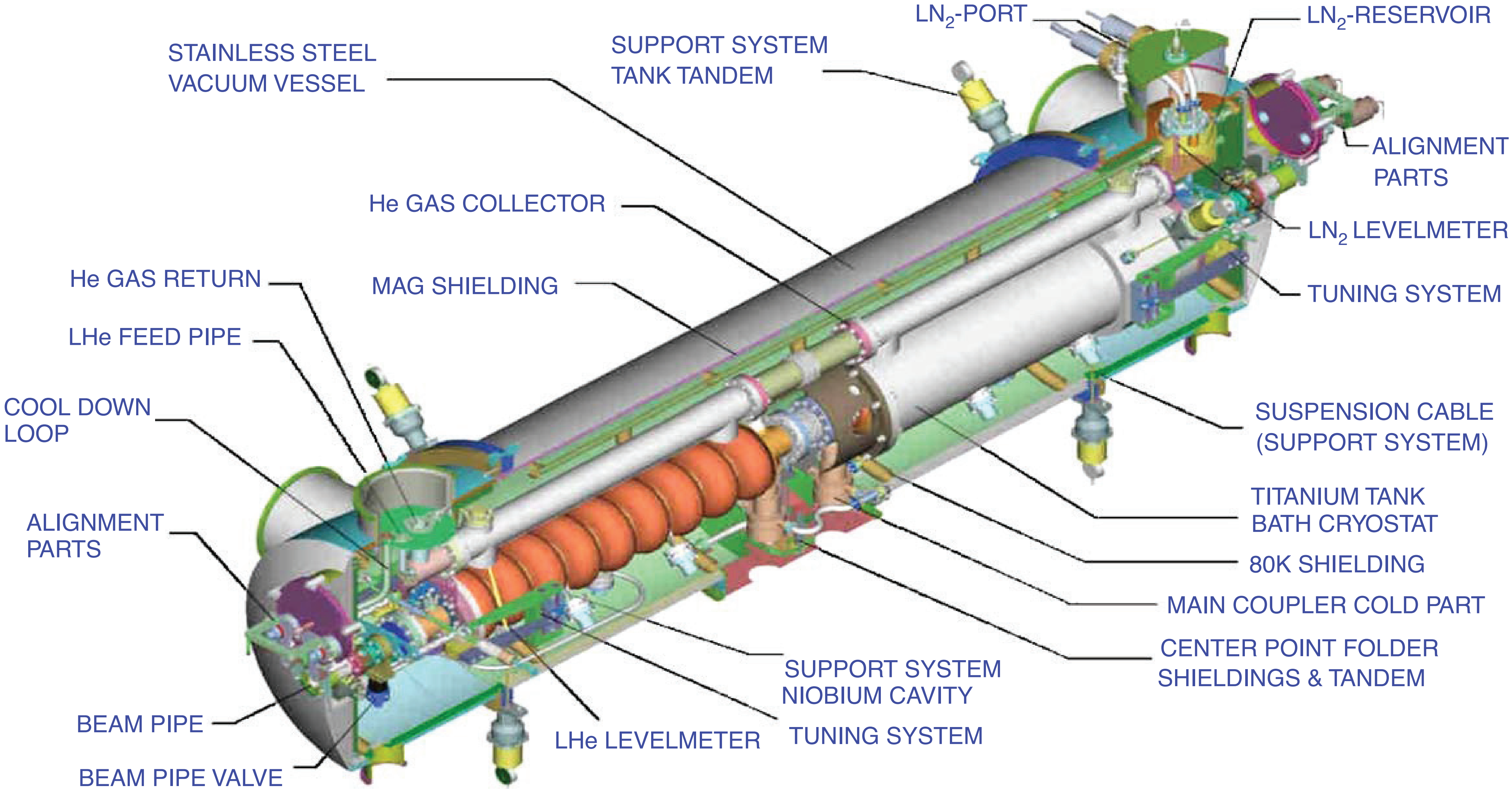
- Lab and office building
- Experimental hall for MESA



MESA


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

Superconducting Cryomodules: Ordered



Teichert et al. NIM A 557 (2006) 239

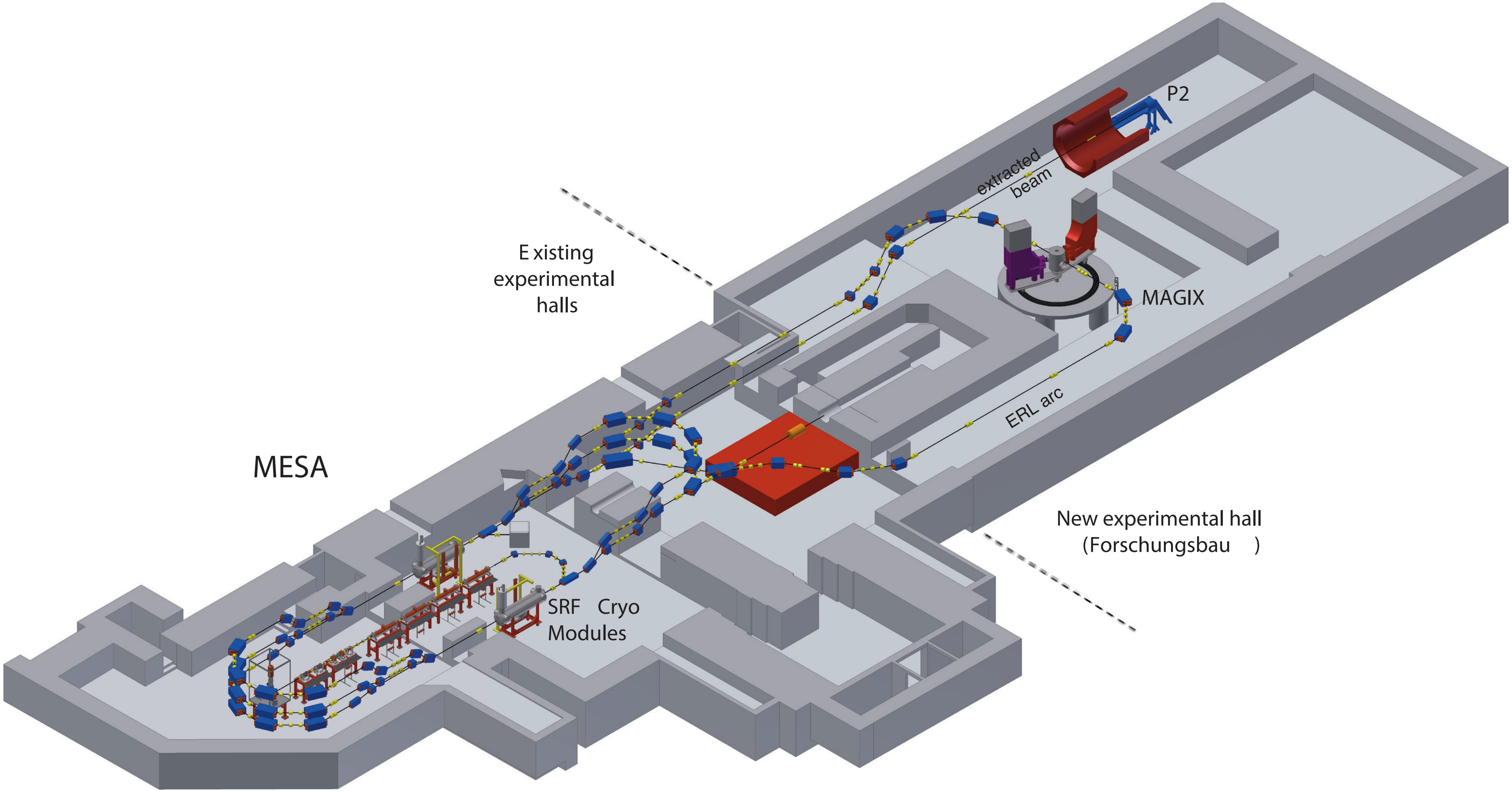
Stability Requirements

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

Now testing upgraded stabilization at MAMI

MESA


P2
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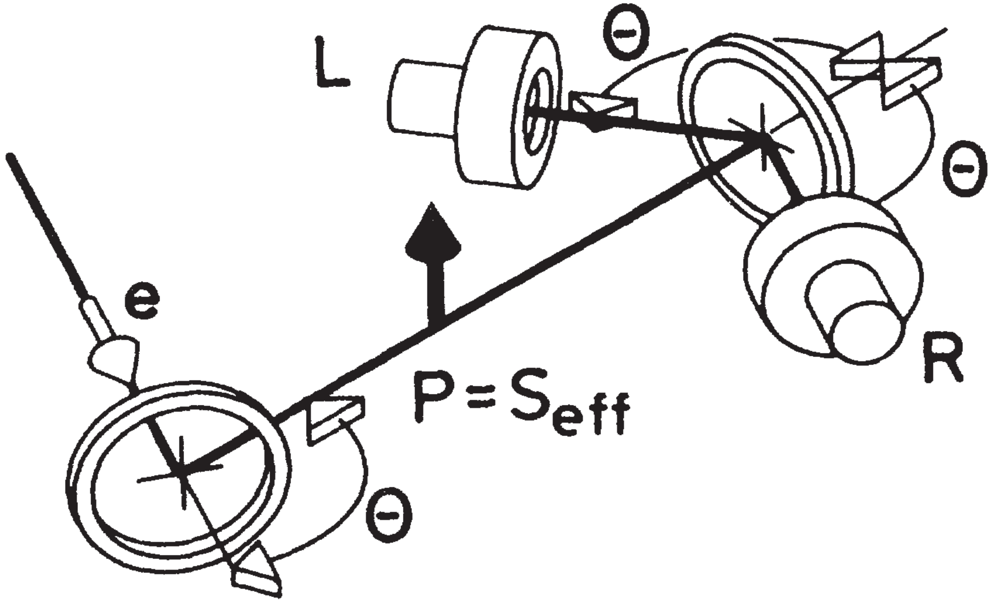
SRF Cryo Modules

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:

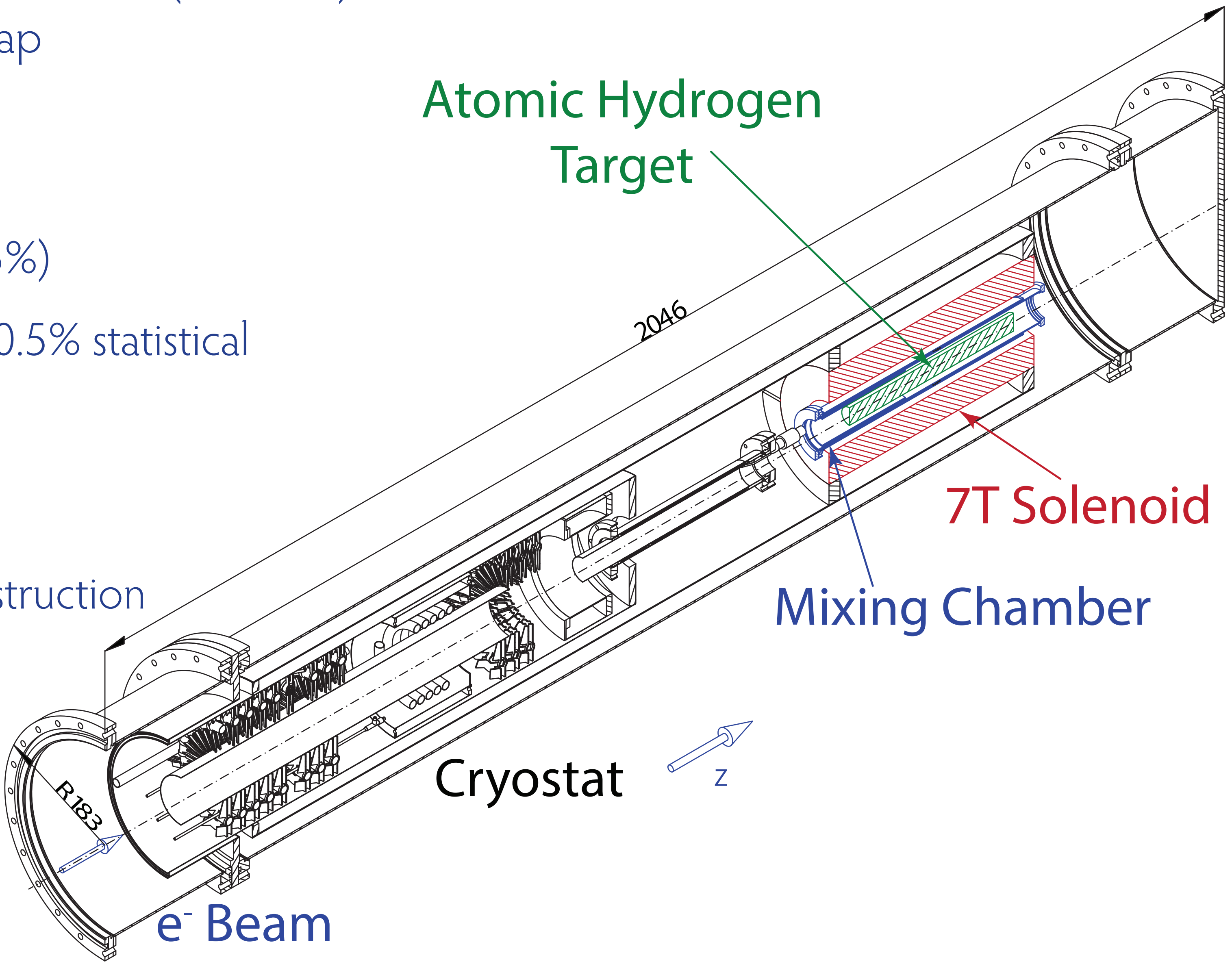
- Obtain analysing power from measurement
- Precise measurement of spin polarisation
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

Møller scattering from polarized (7 T field) atomic hydrogen in a trap

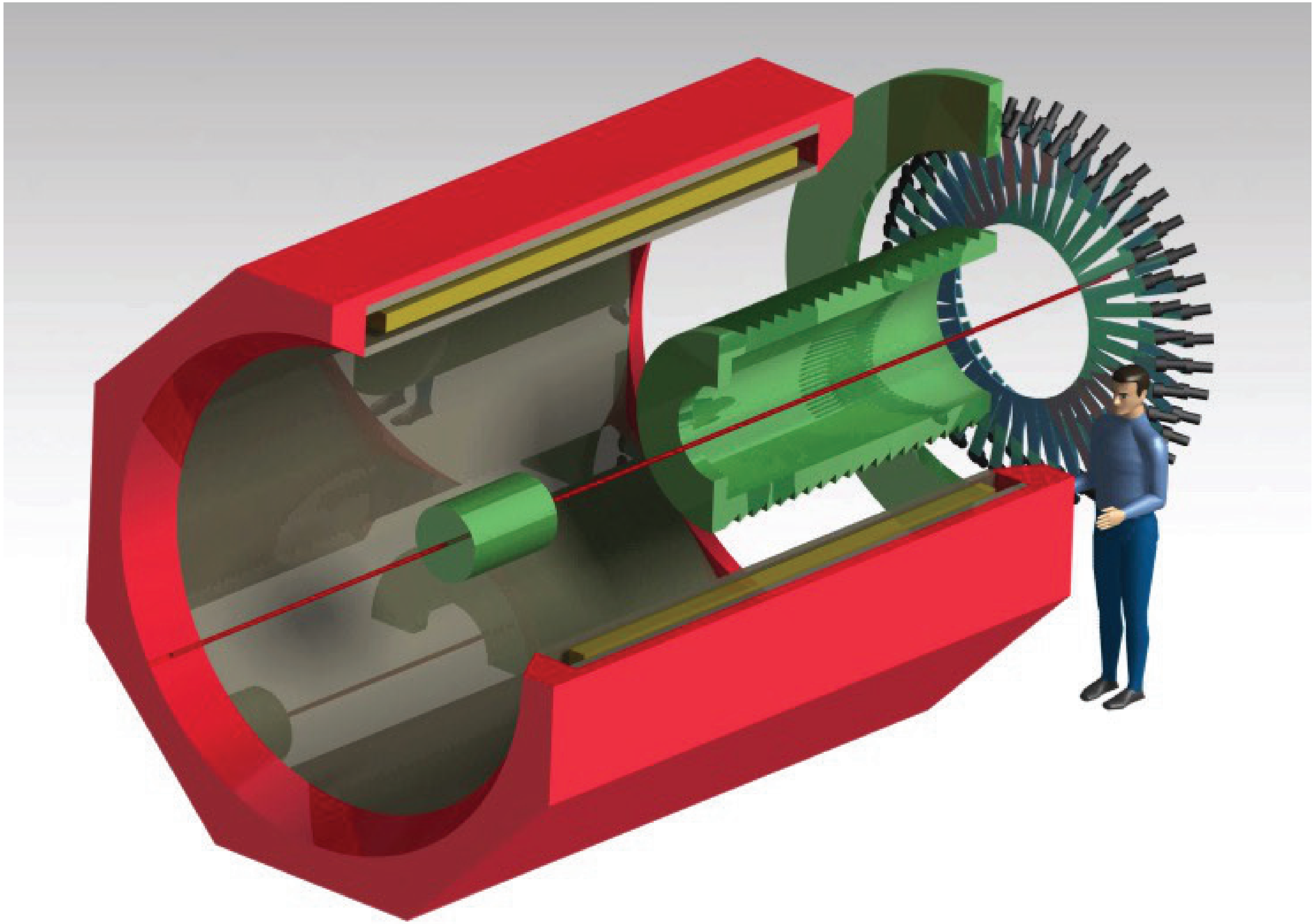
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

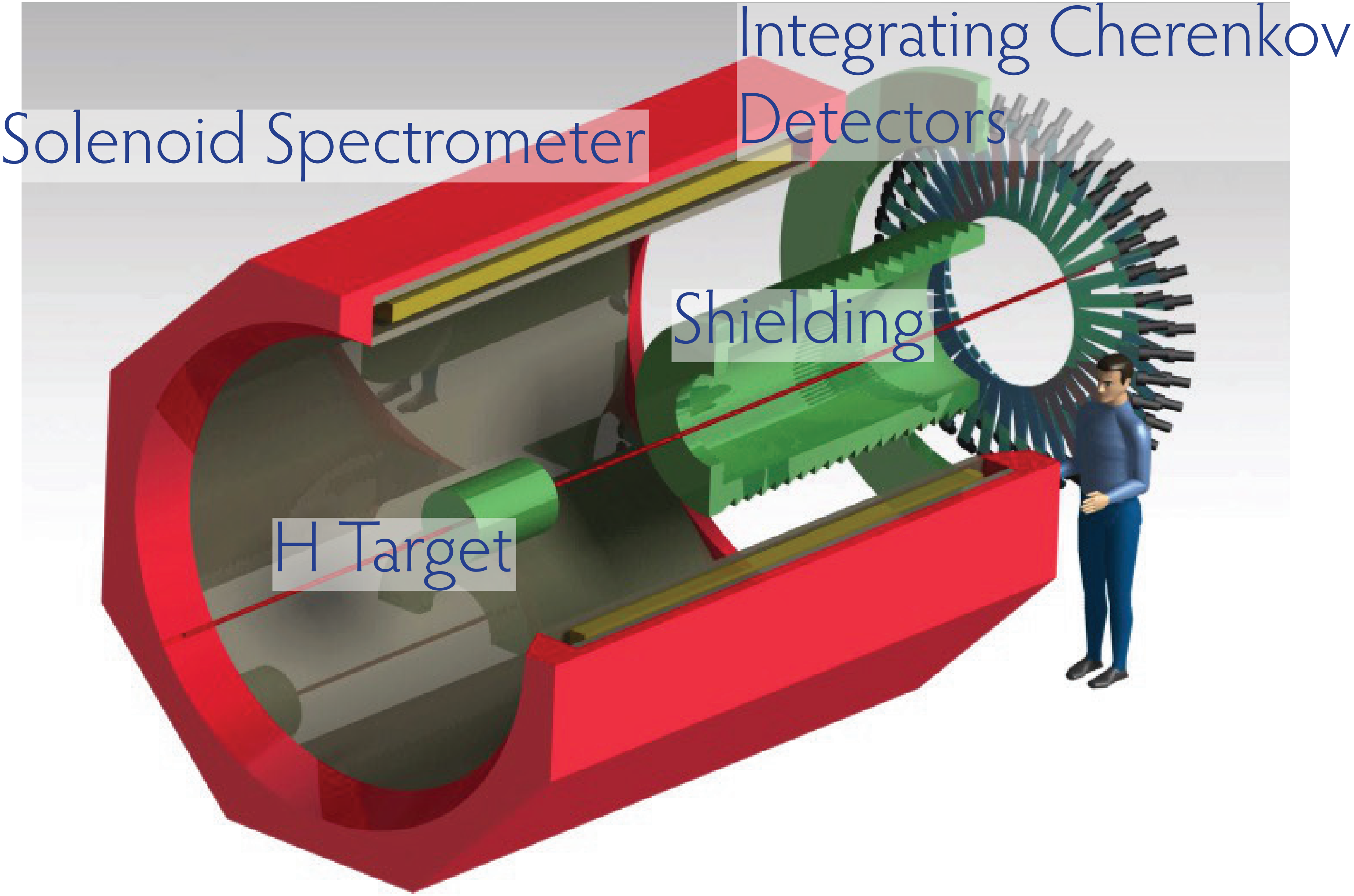
- Cryostat under construction in Mainz



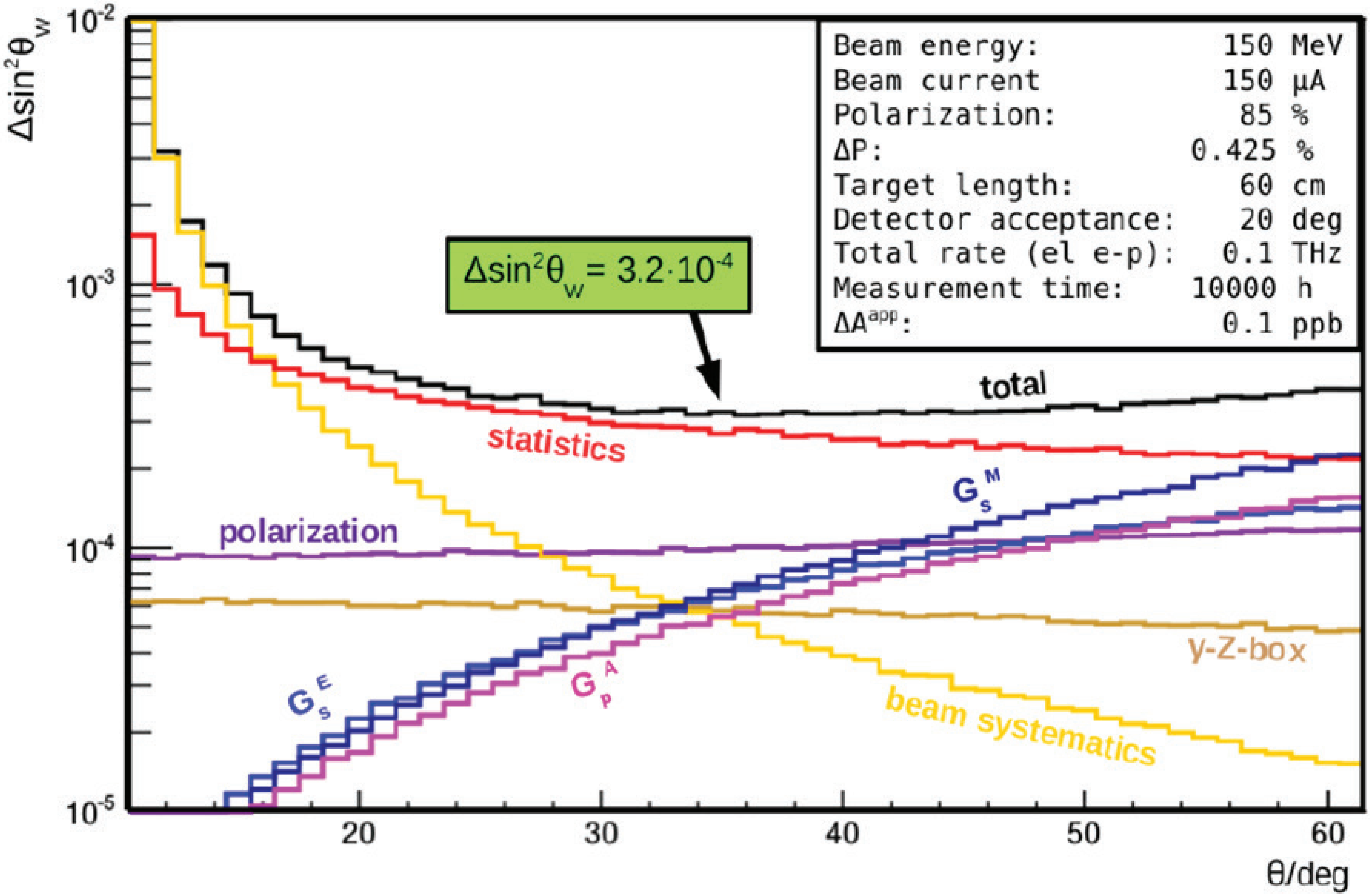
P2:

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

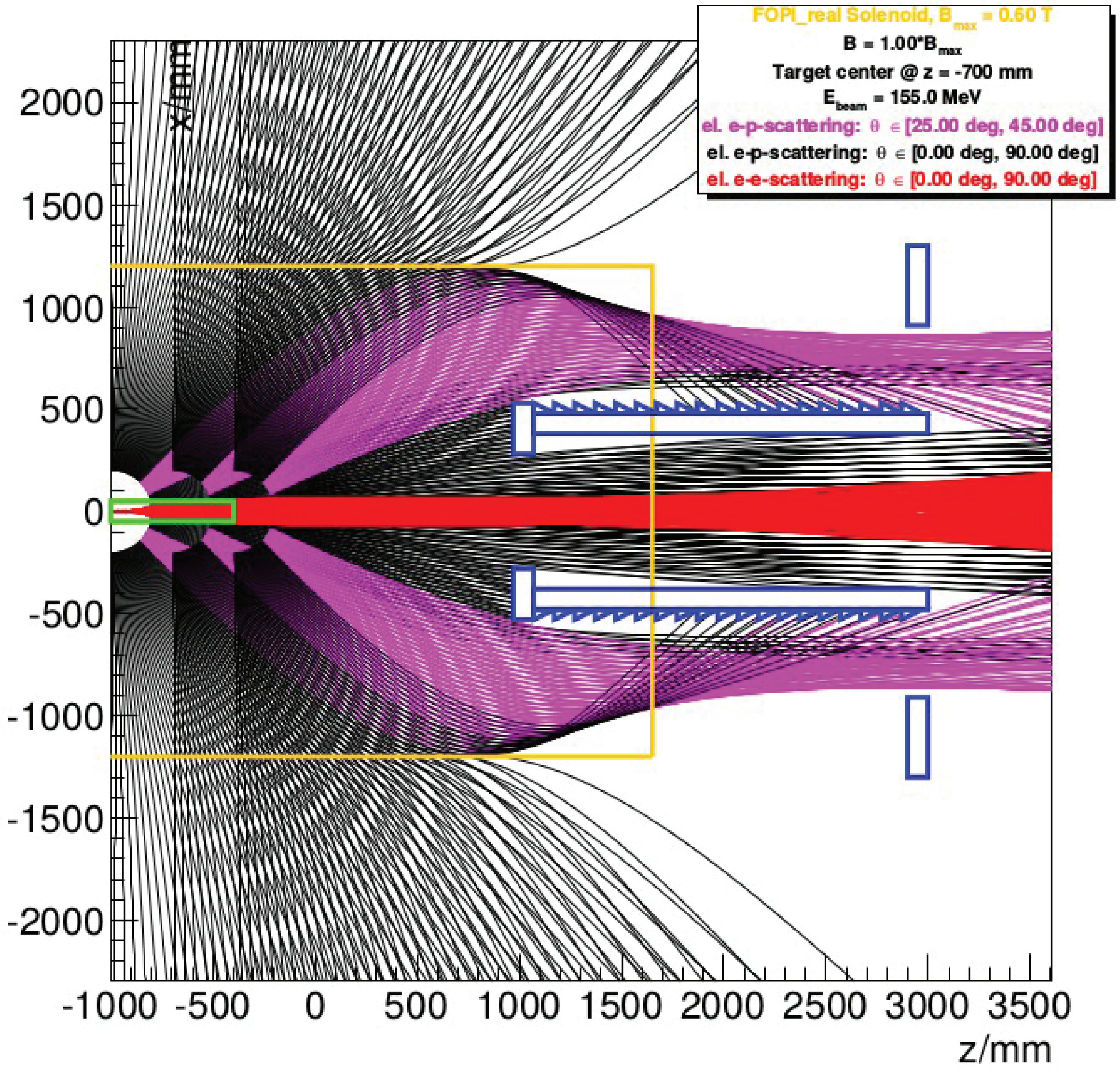



Integrating Cherenkov Detectors
Solenoid Spectrometer
Shielding
H Target

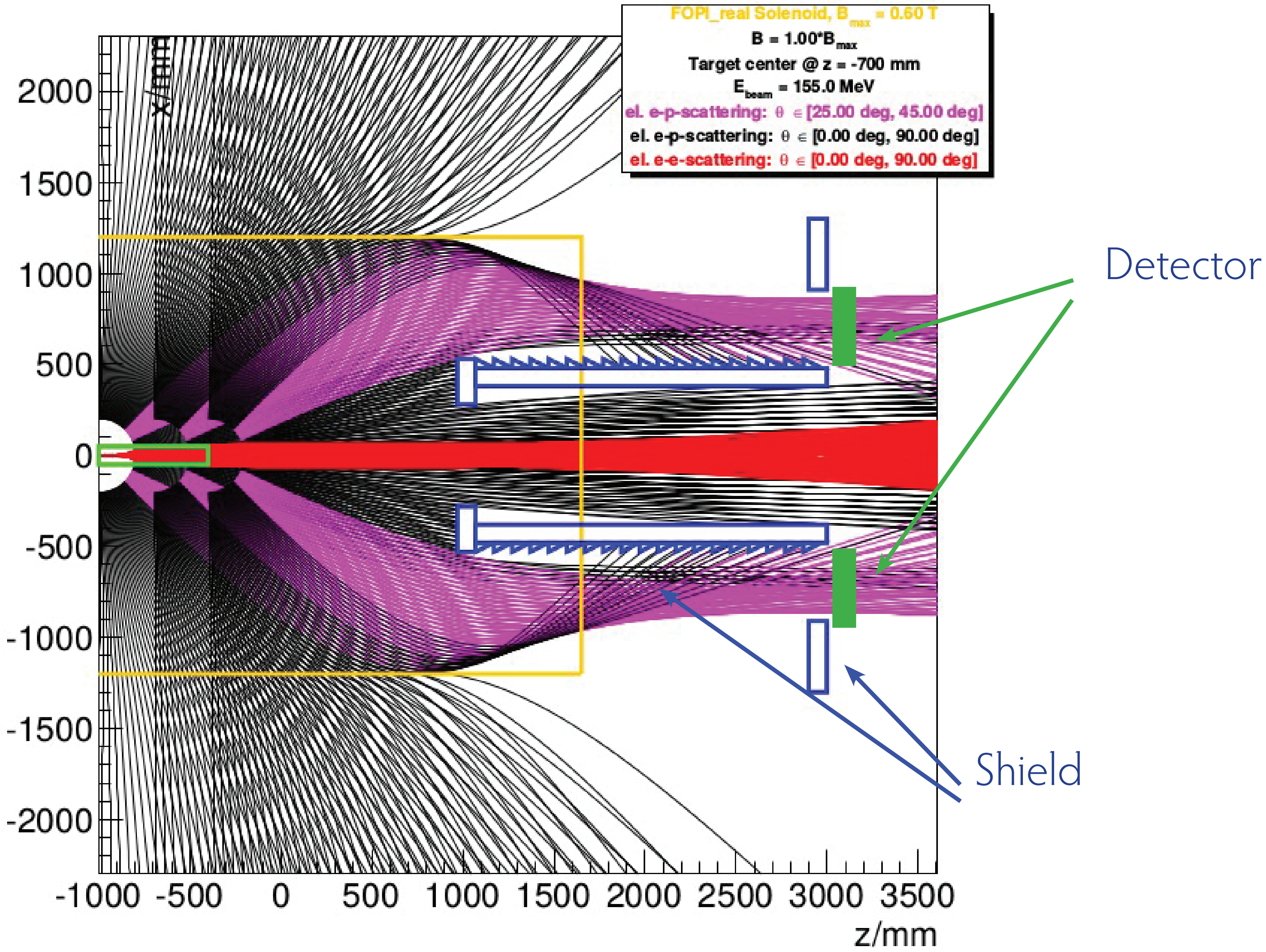
Choice of scattering angle



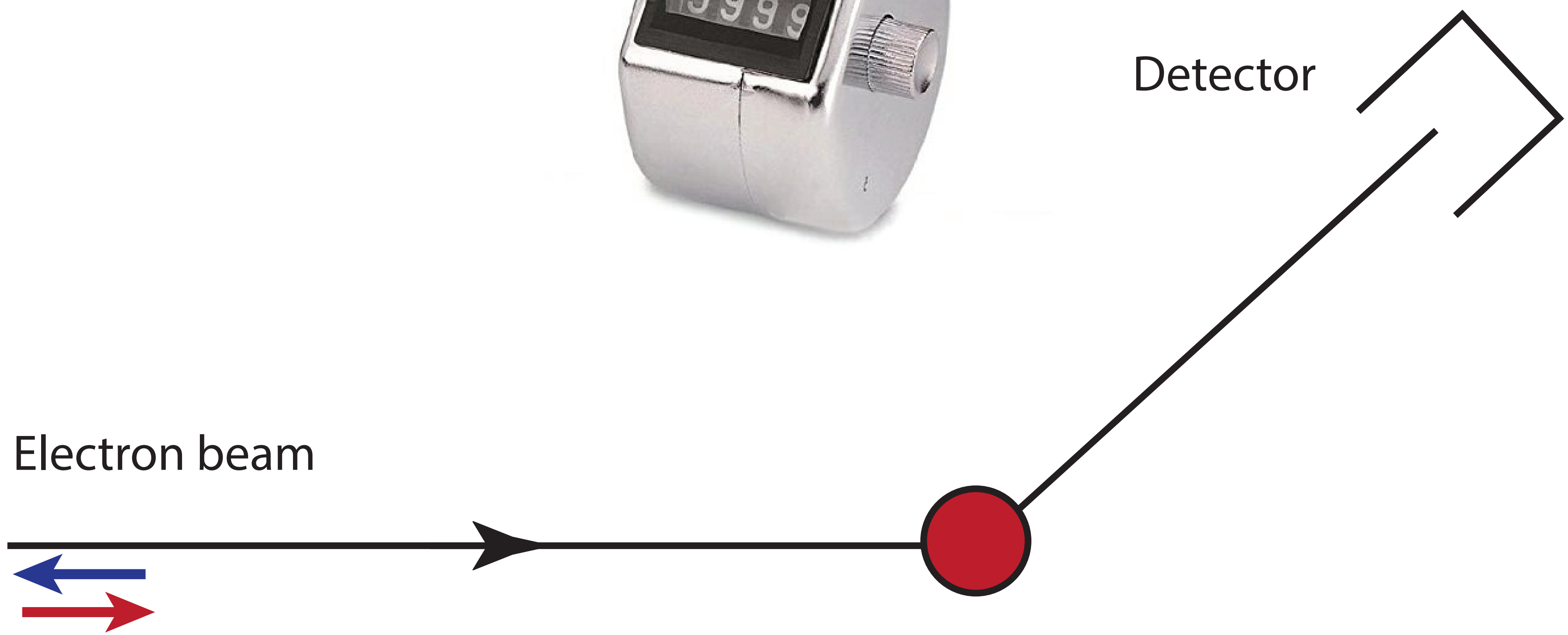
Solenoid spectrometer



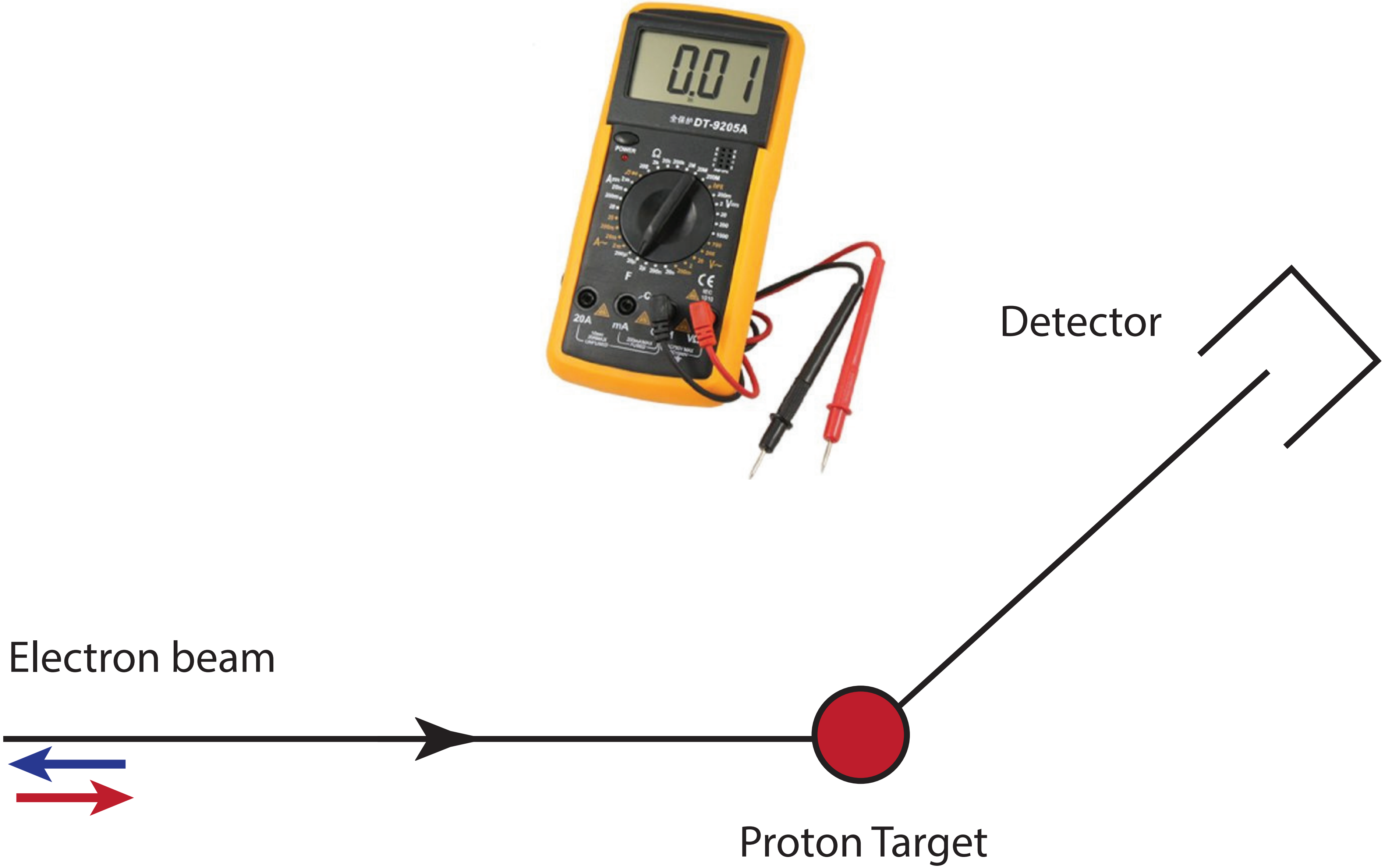
Solenoid spectrometer



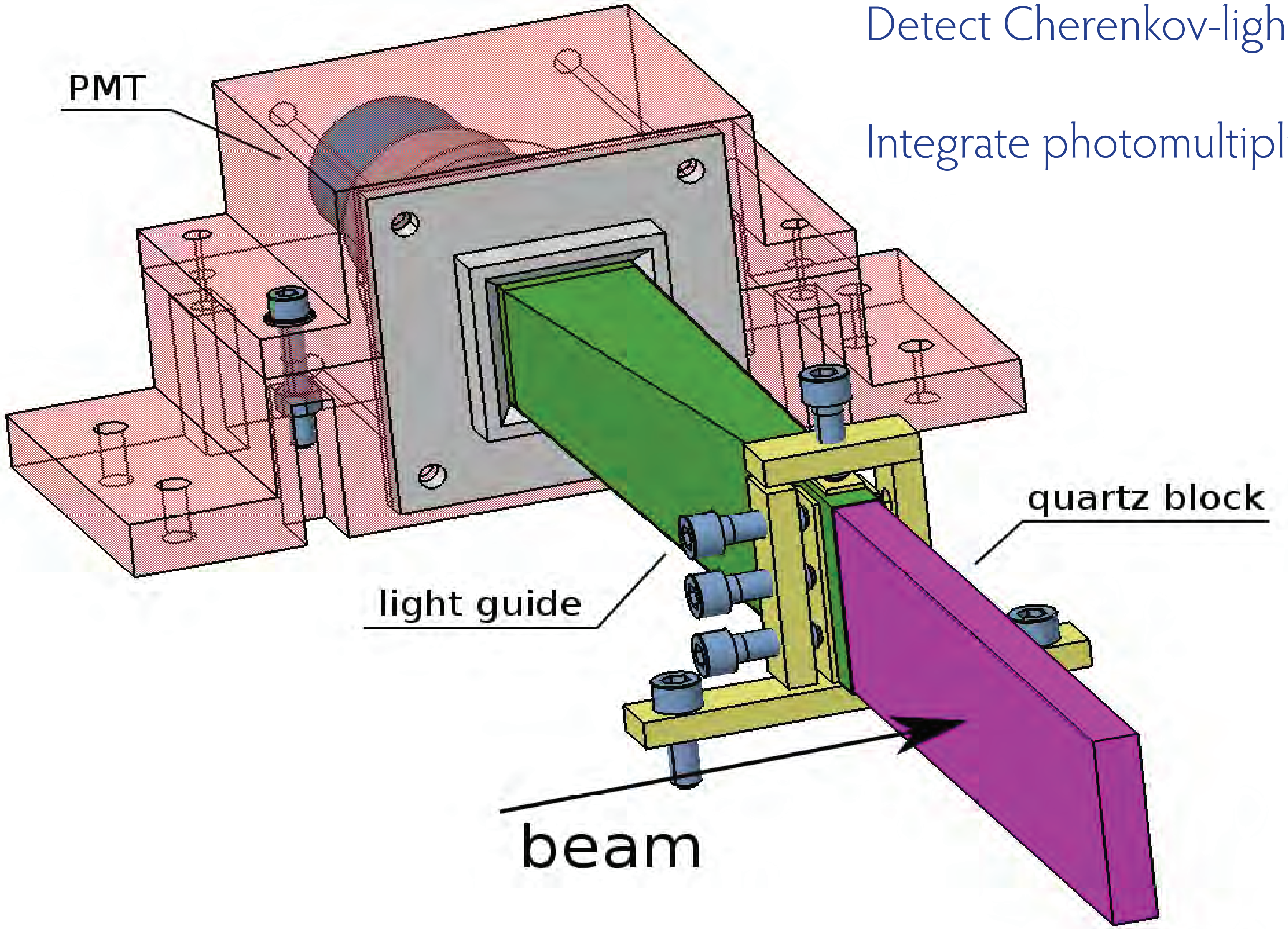
Counting detectors



Integrating detectors



Quartz-Bars & Photomultipliers



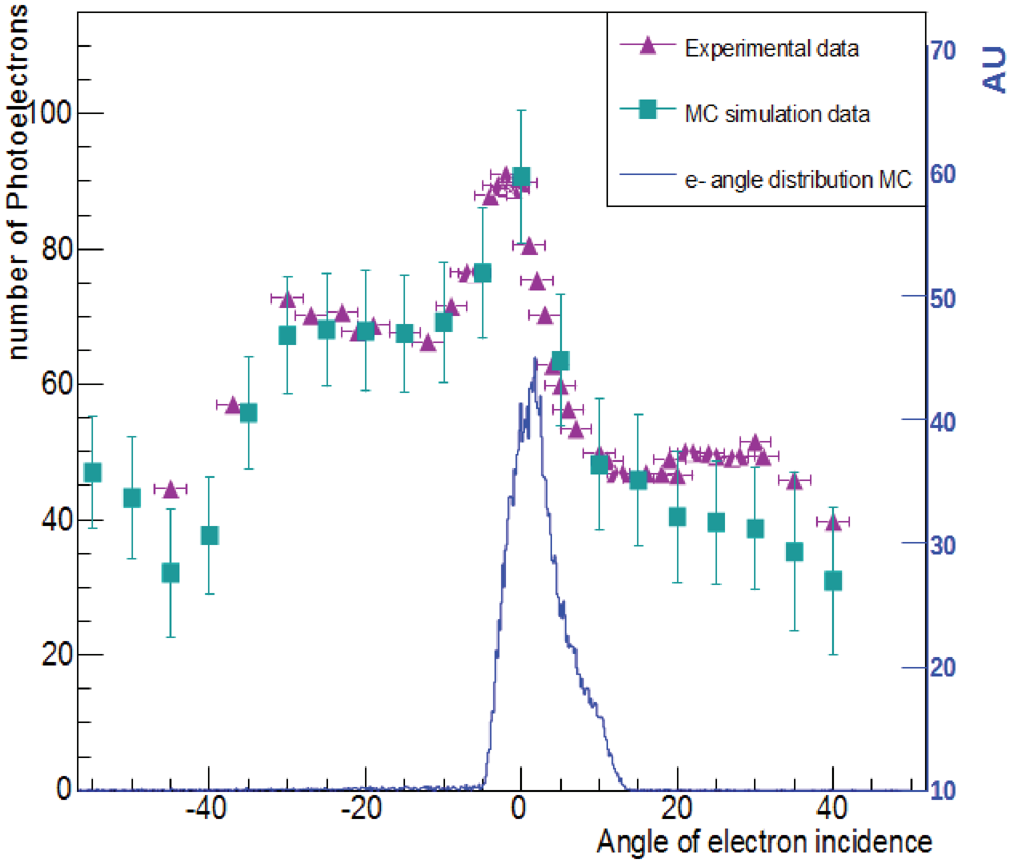
Detect Cherenkov-light created by electrons

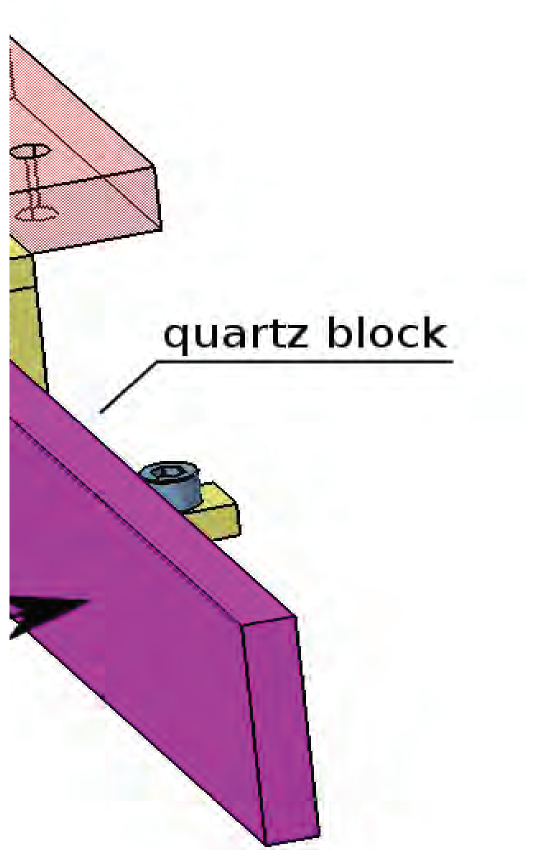
Integrate photomultiplier current

Quartz-Bars & Photomultipliers

Detect Cherenkov-light created by electrons

Integrate photomultiplier current



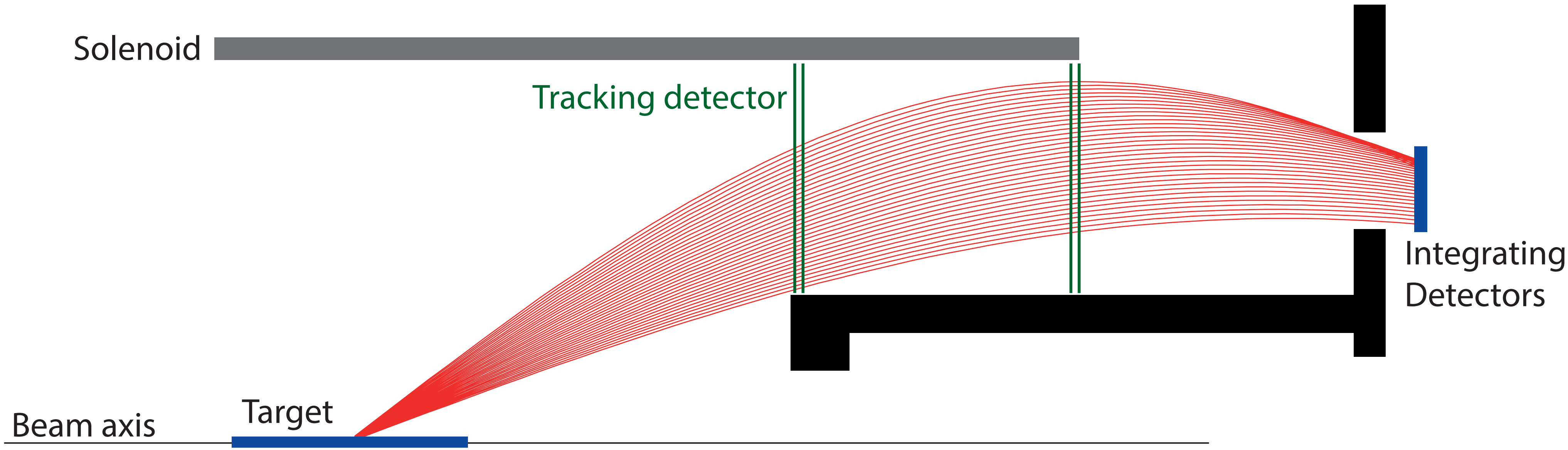


Measuring Q^2:

Tracking a
lot of low momentum particles

Tracker requirement

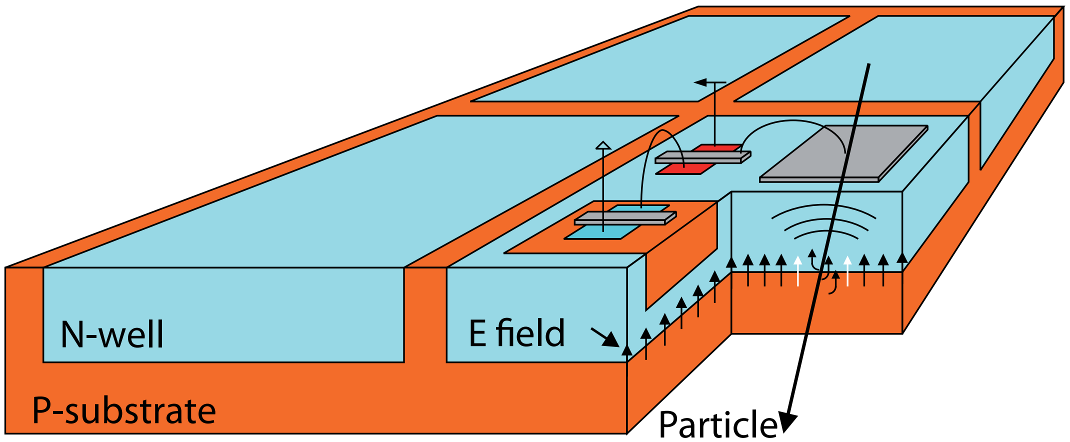
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS



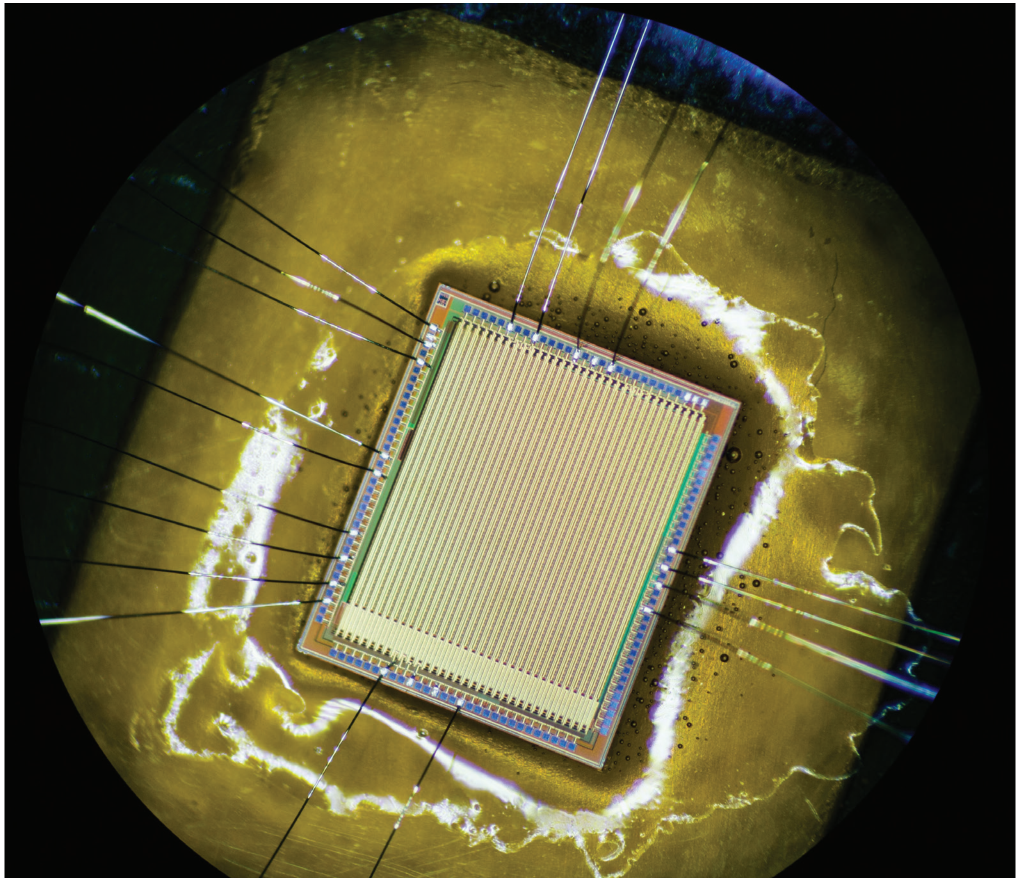
High voltage monolithic active pixel sensors - Ivan Perić

- 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

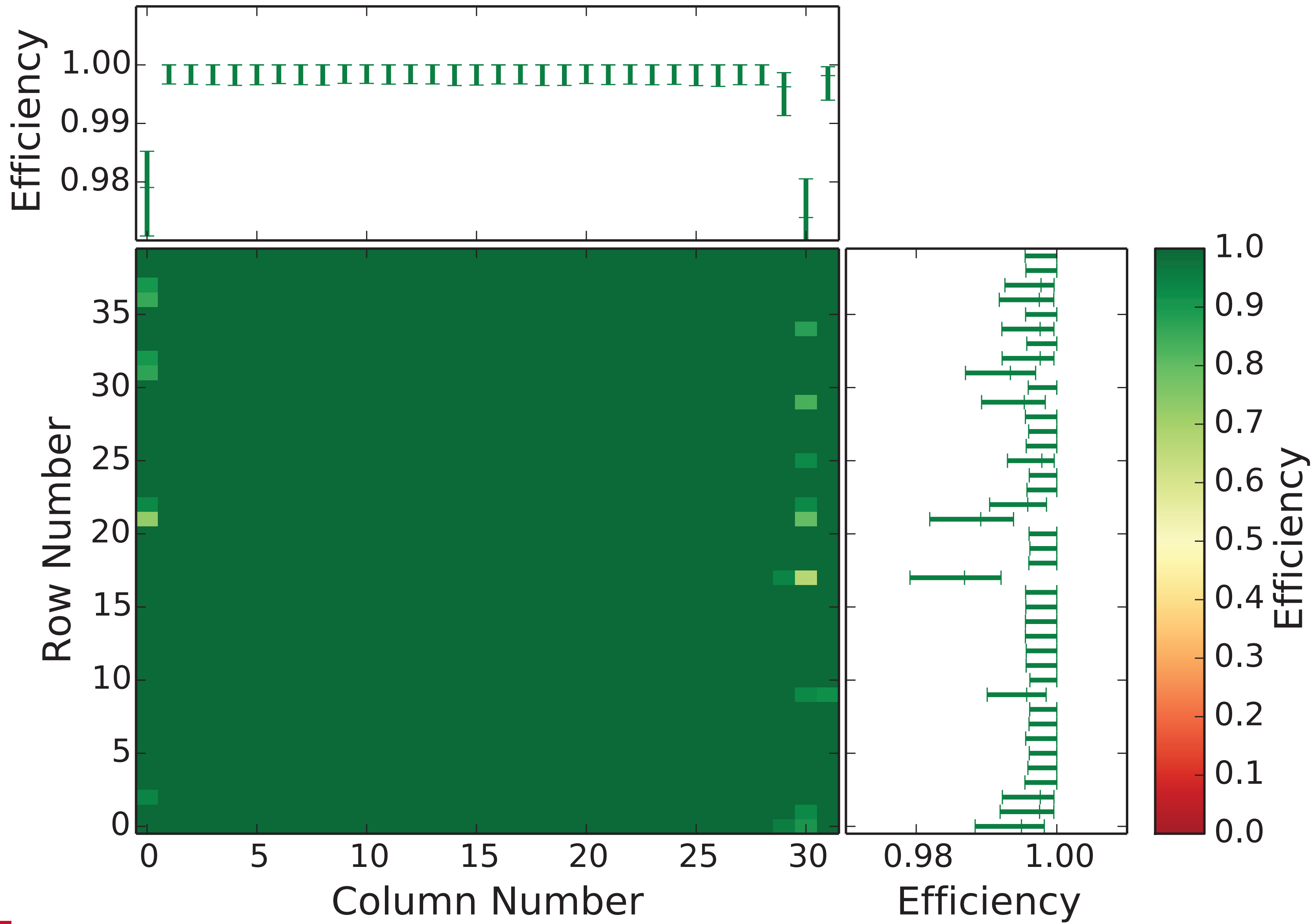
HV-MAPS chips: AMS 180 nm HV-CMOS



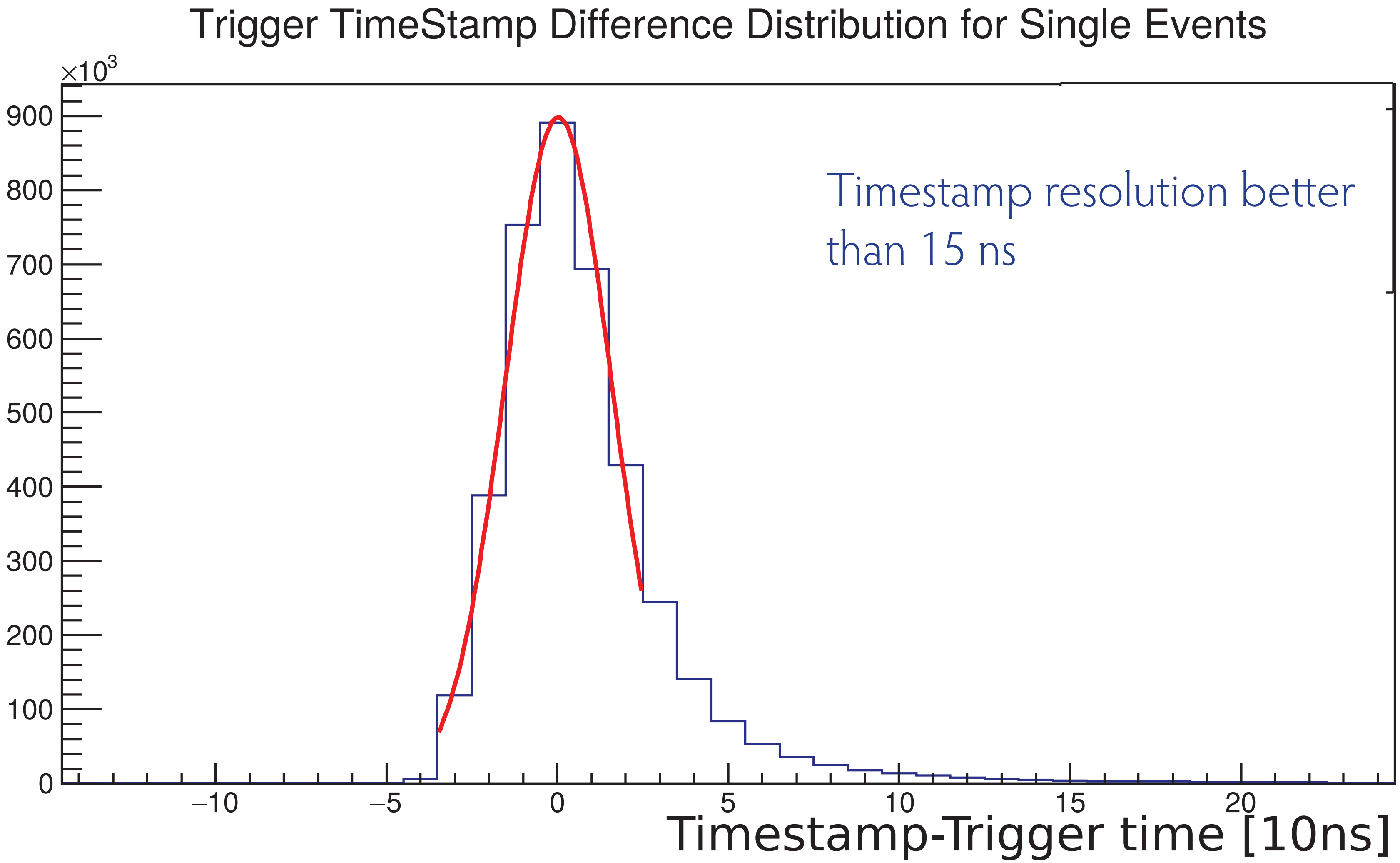
- Developed for Mu3e
- 5 generations of prototypes
- Current generation:
  MUPIX7
  40 x 32 pixels
  80 x 103 µm pixel size
  9.4 mm^2 active area
- MUPIX7 has all features of final sensor
- Left to do: Scale to 2 x 2 cm^2

Efficiency

Hit efficiency above 99% without tuning

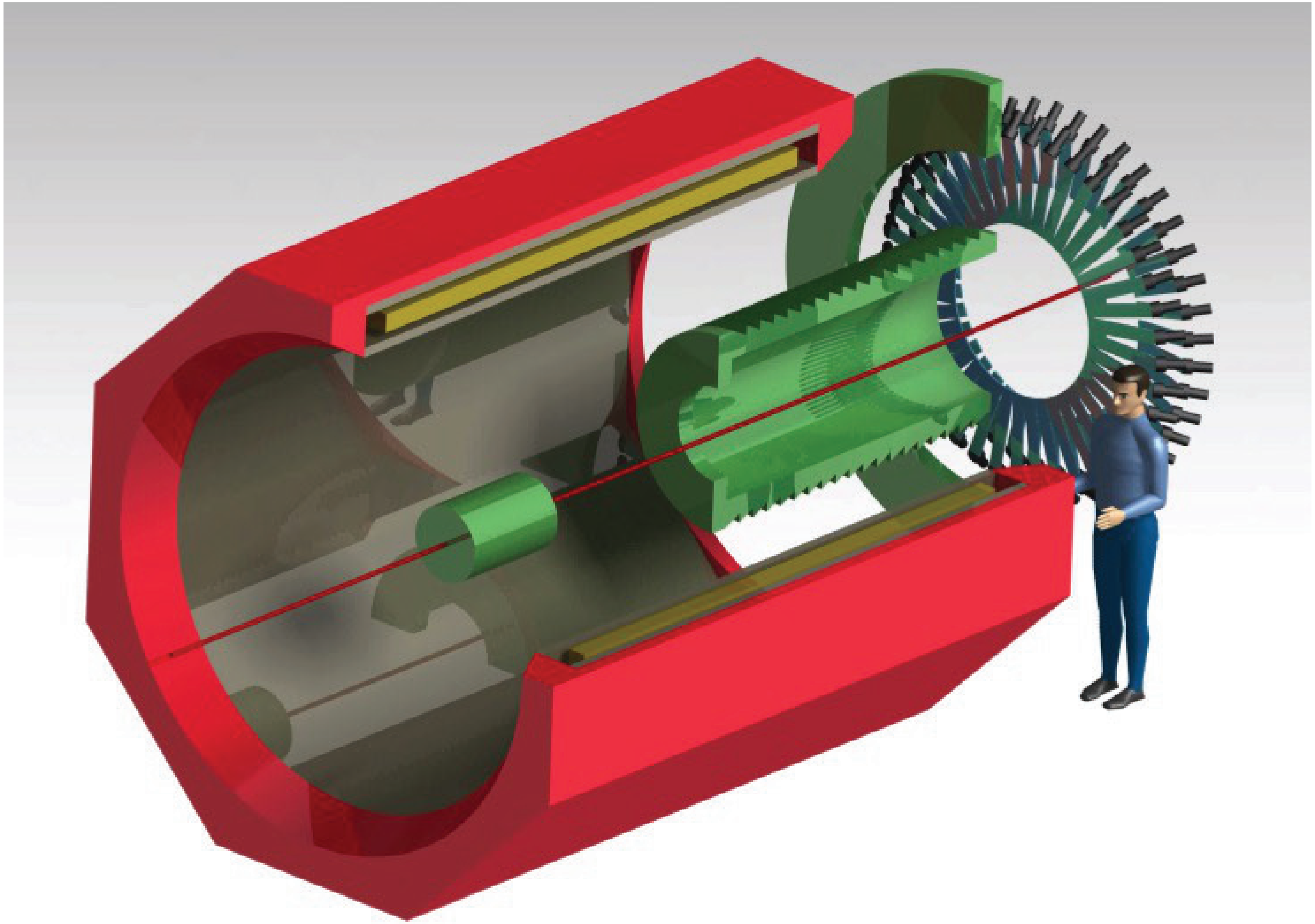


Time resolution



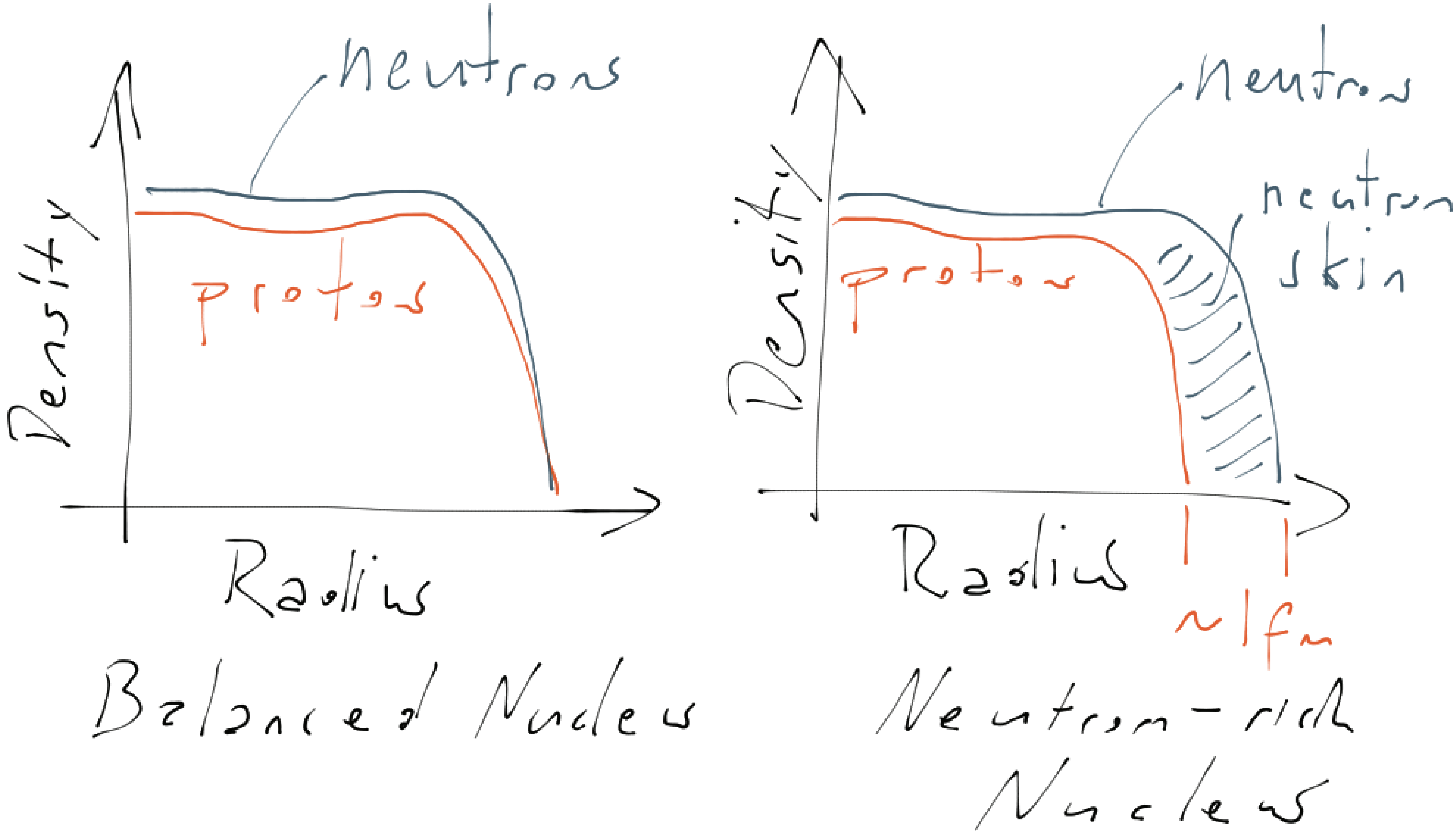
Timestamp resolution better than 15 ns

P2



Neutron Skins: Concettina Sfienti on Tuesday

Where are the neutrons in the nucleus?

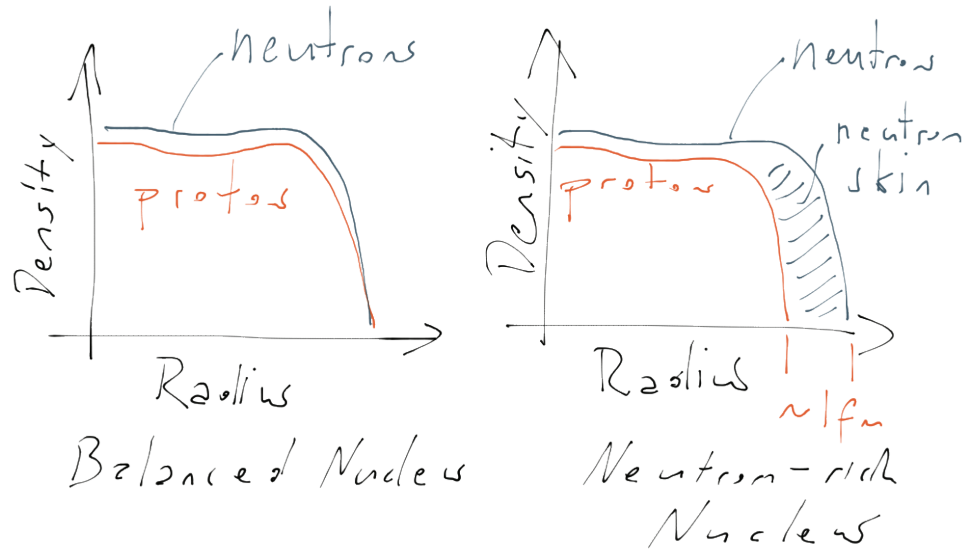


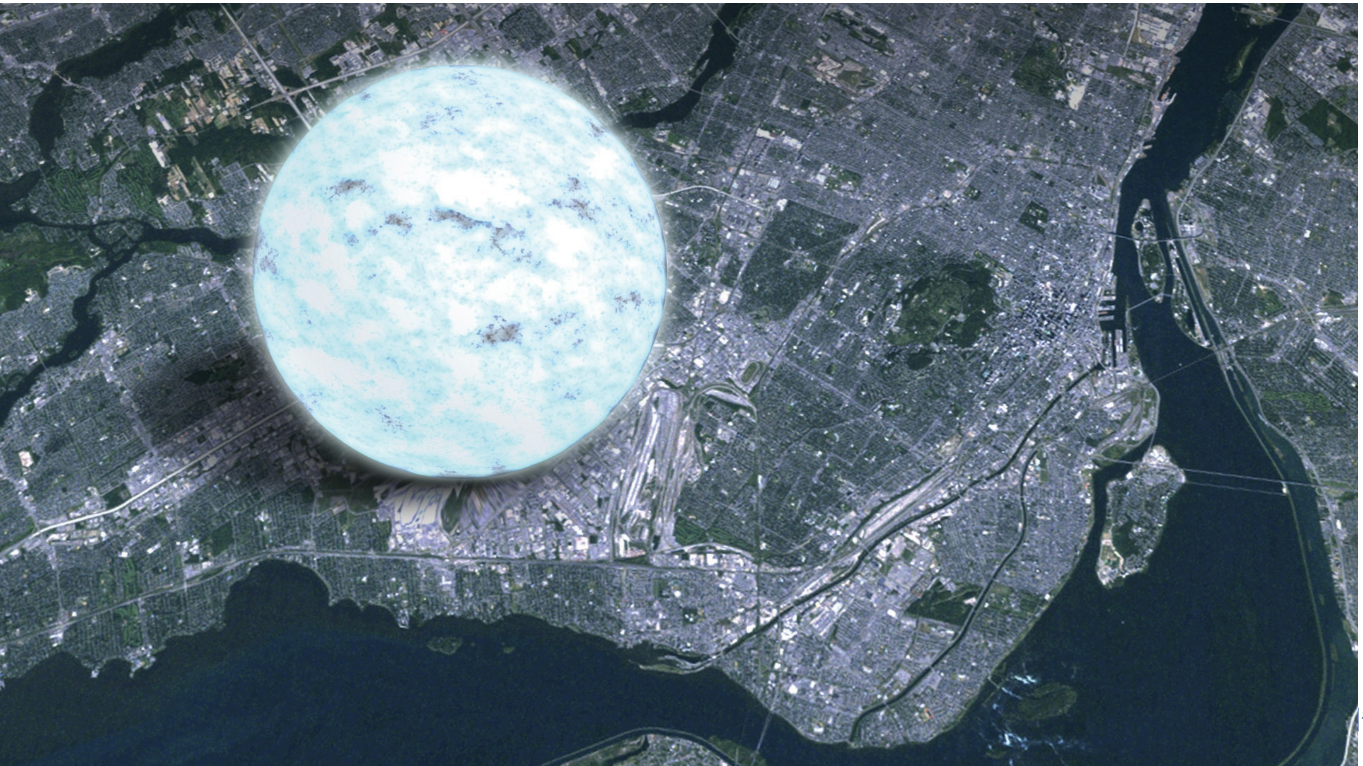
Neutron Skins

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

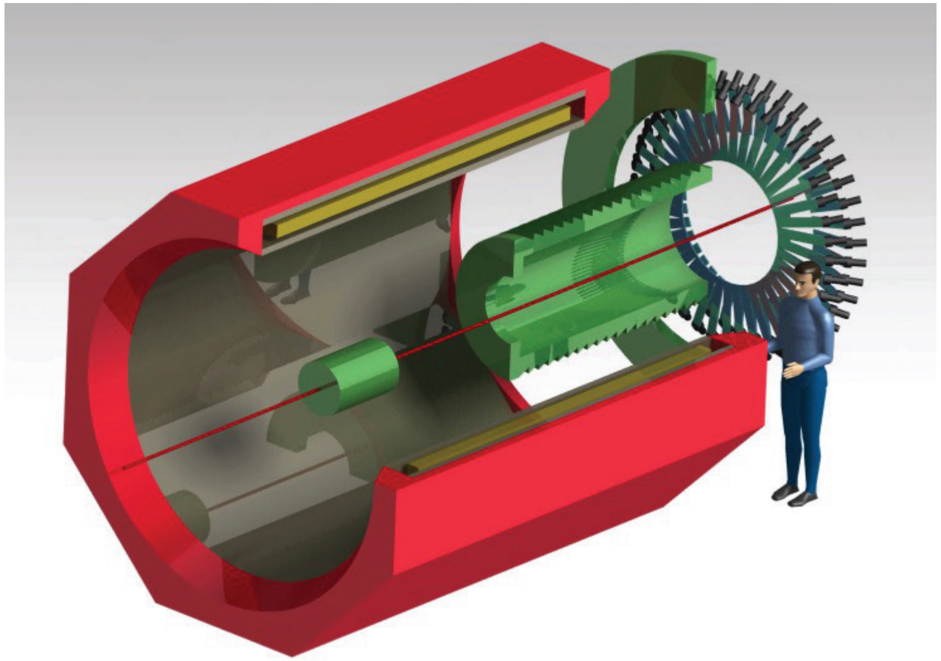




SFB 1044

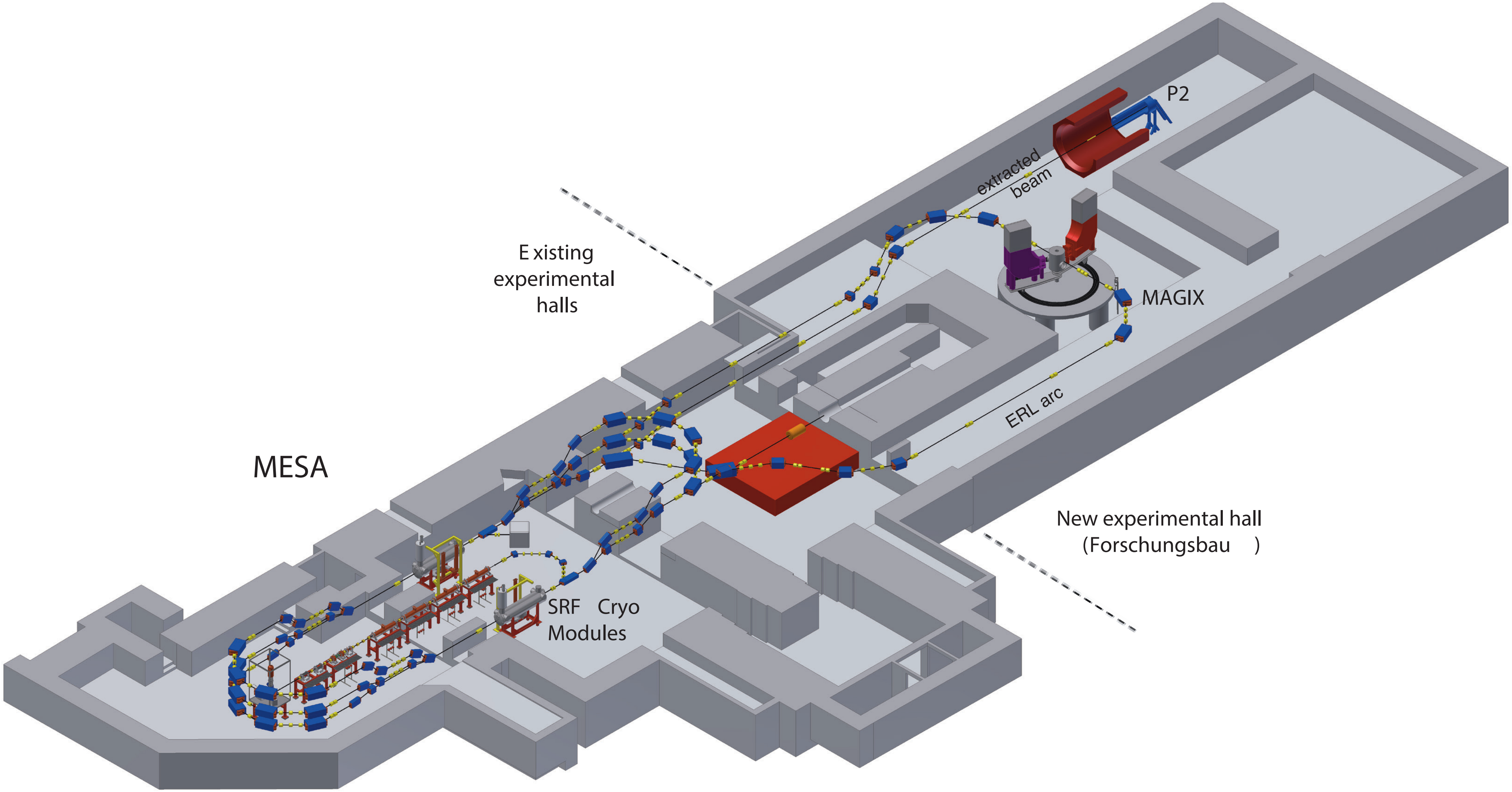
How to see the neutrons?

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



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

MESA



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

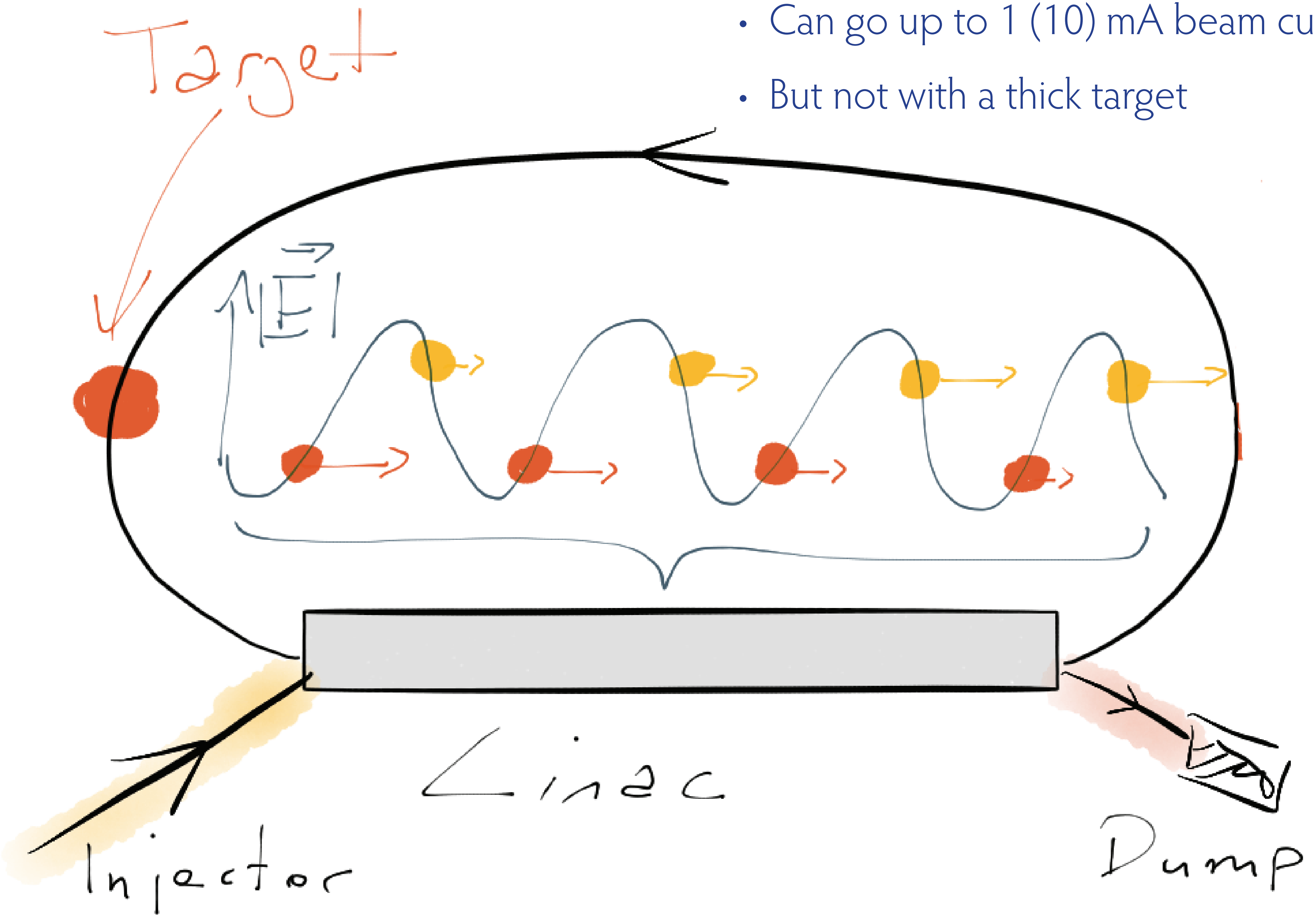
Energy recovery

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

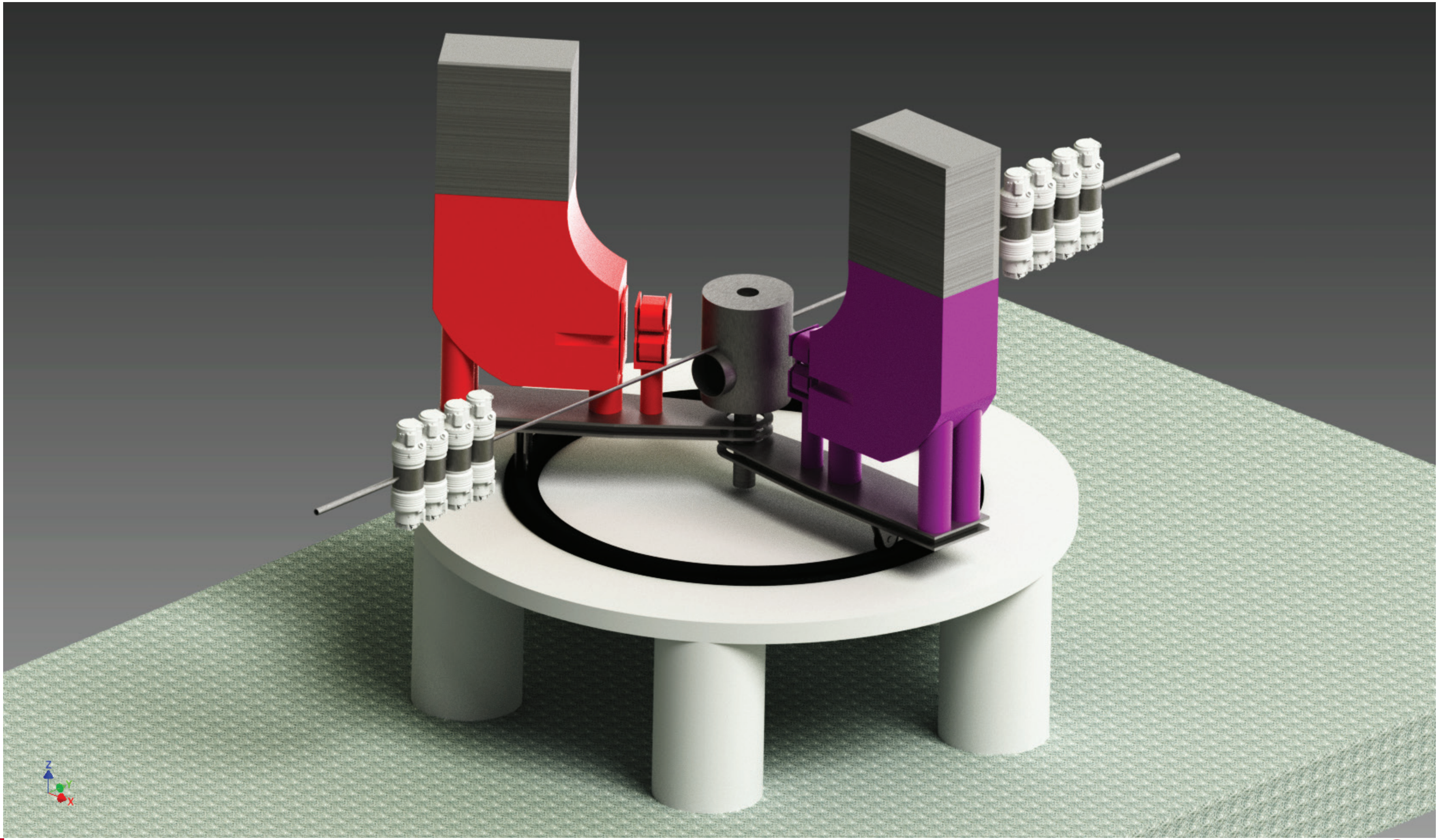


High current, high resolution:

MAGIX

Mesa Gas Internal Target Experiment

MAGIX Spectrometer



Requirements

Energy recovery: We want the beam back

- Energy loss less than 10^{-3}
- As little scattering as possible

No target window

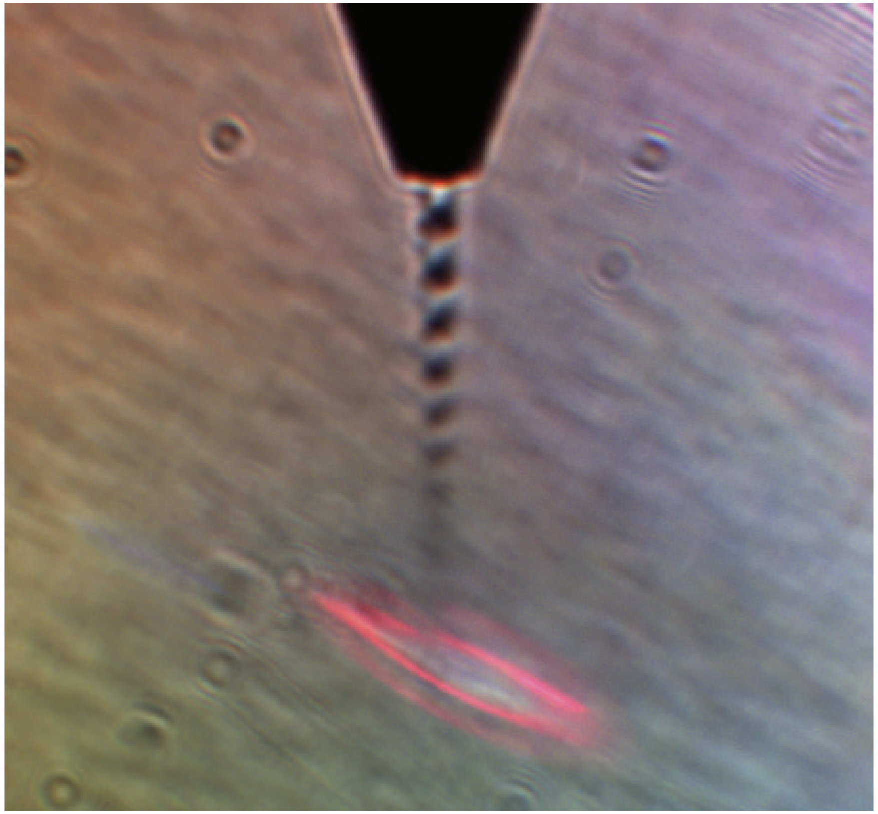
High resolution spectrometer

- No beam interactions in target window
- As little scattering as possible

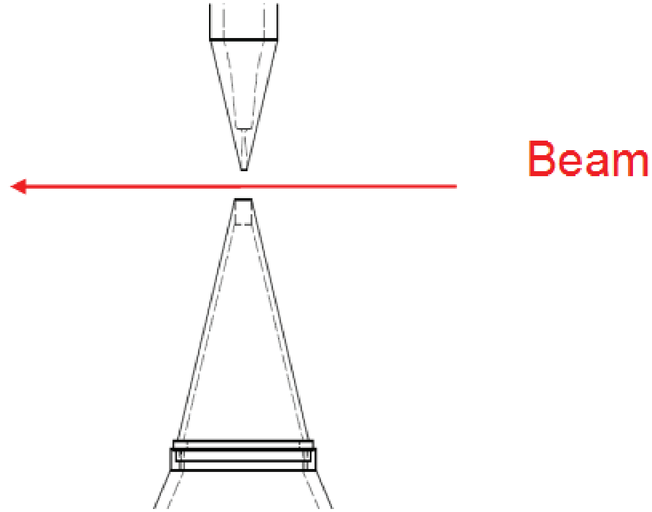
Thin walls, thin detectors

Extremely intense beam: Do not need very high acceptance

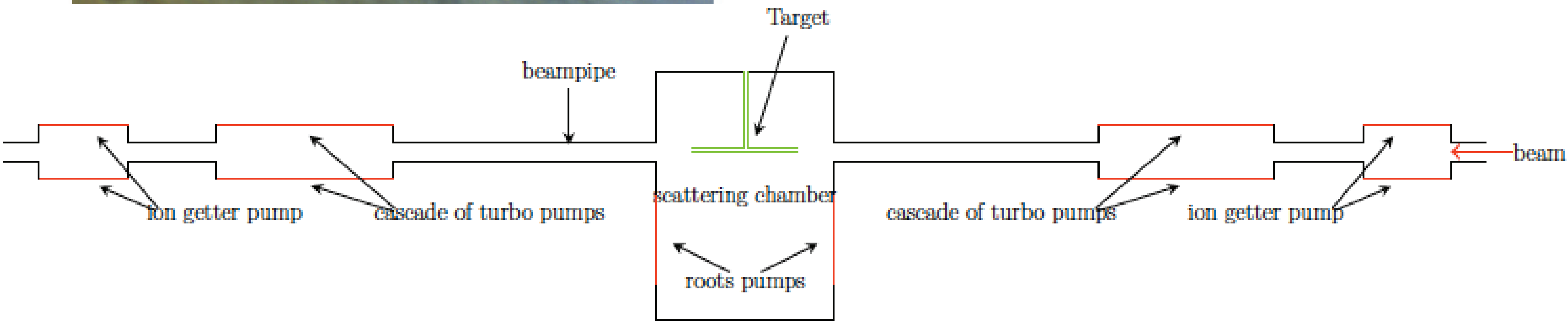
Internal gas target



- Inject gas directly into the beam pipe

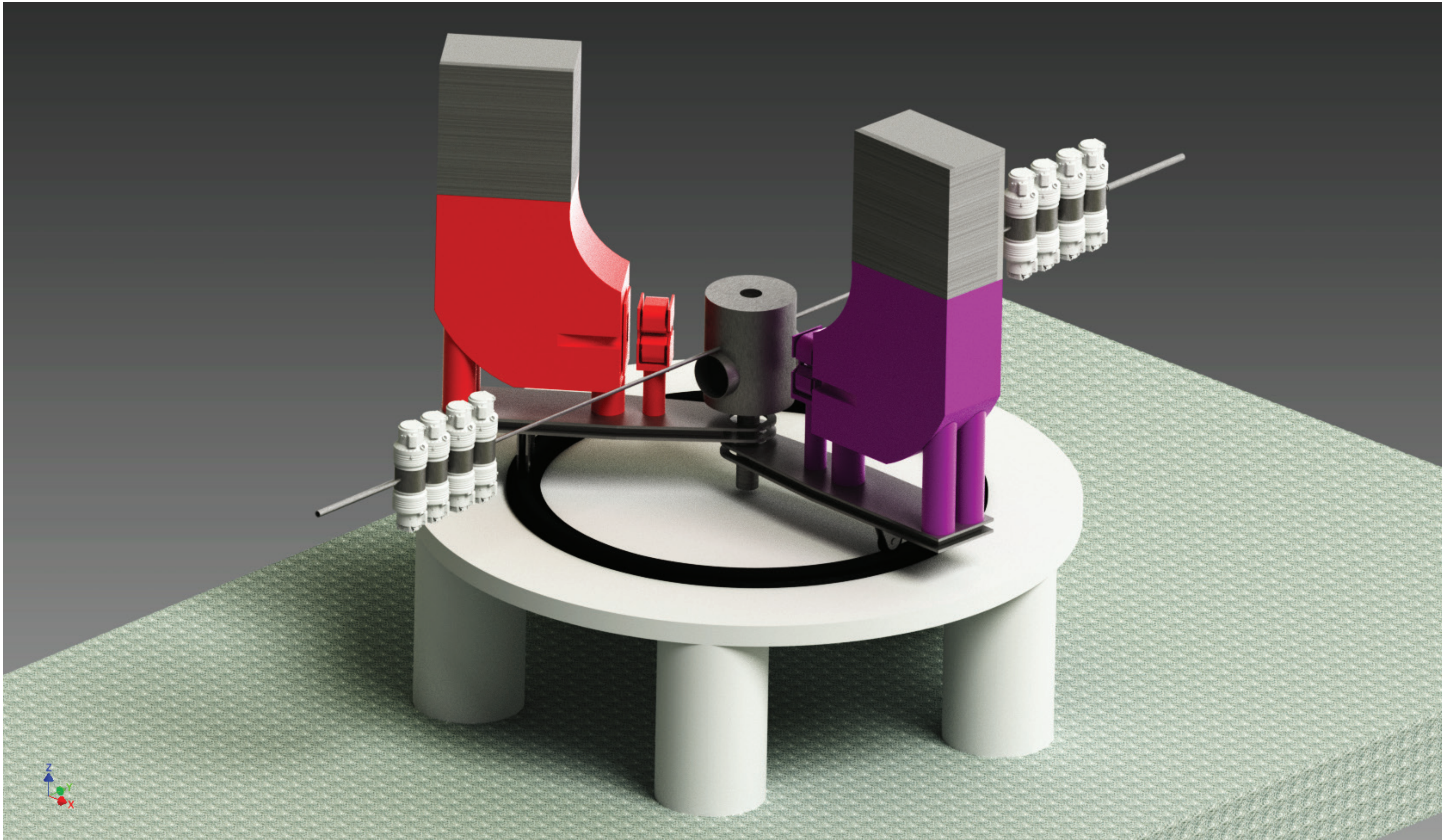


- Differential pumping to keep beam vacuum



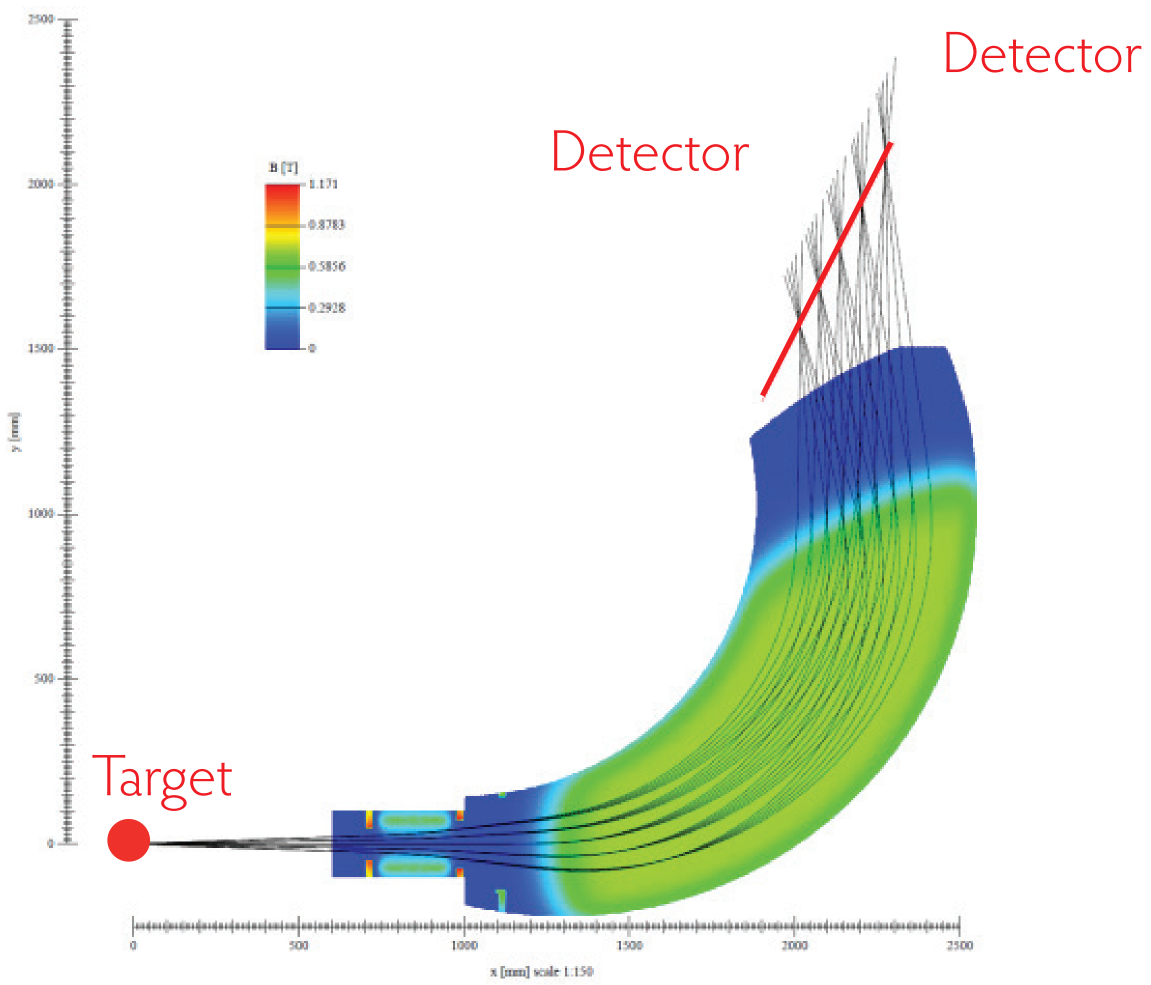
TARDIS

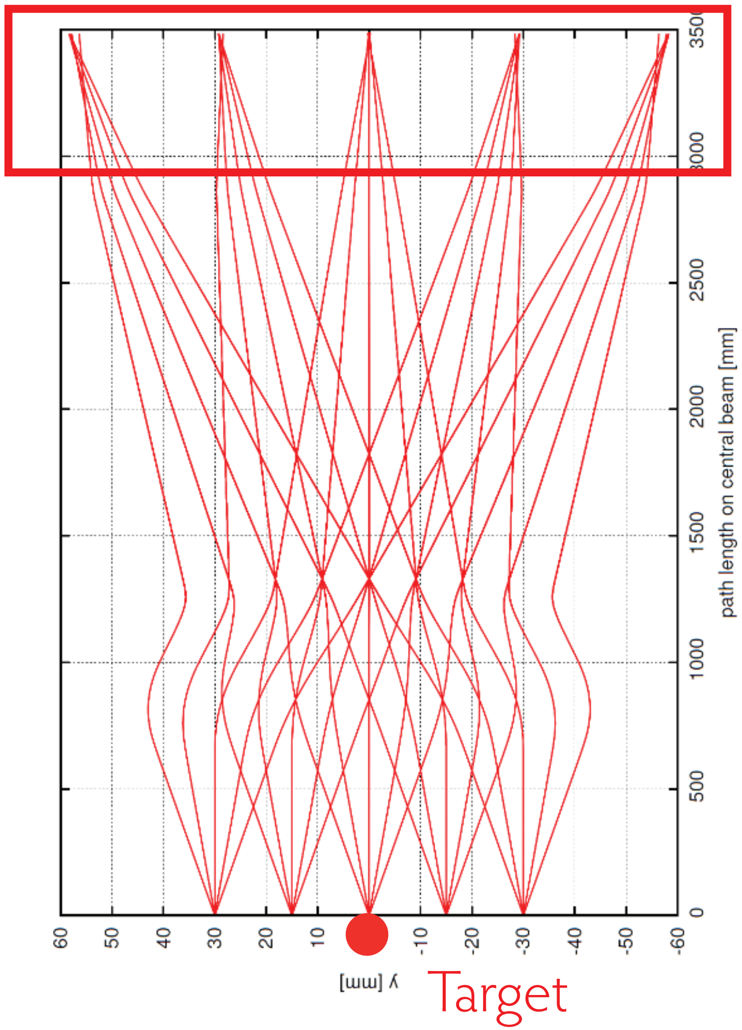
Twin-arm dipole spectrometer



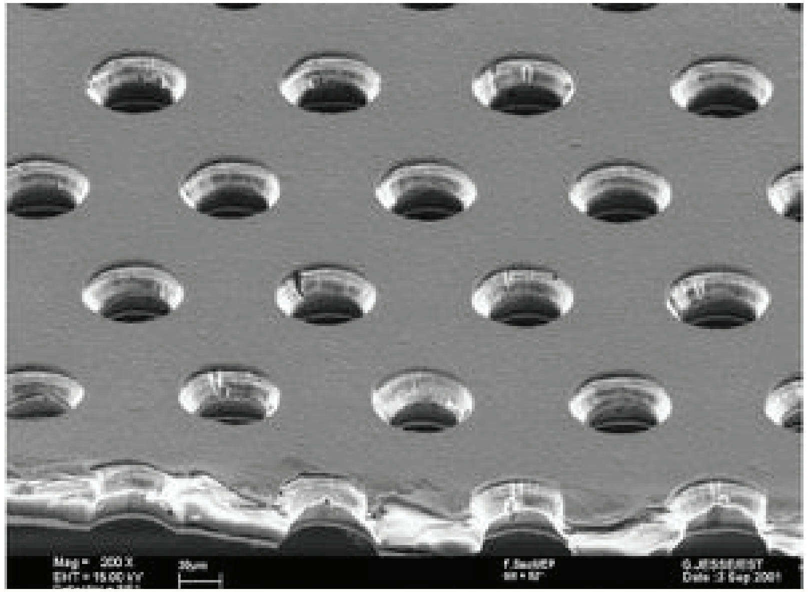
TARDIS

- Image momentum to position
- 10^{-4} momentum resolution for 50 μm position resolution
- Image angle to position

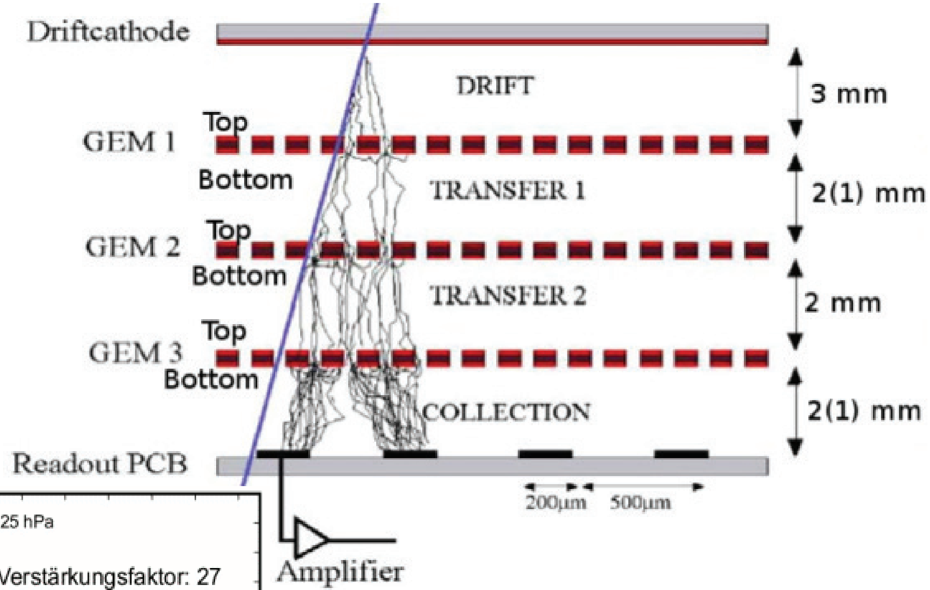


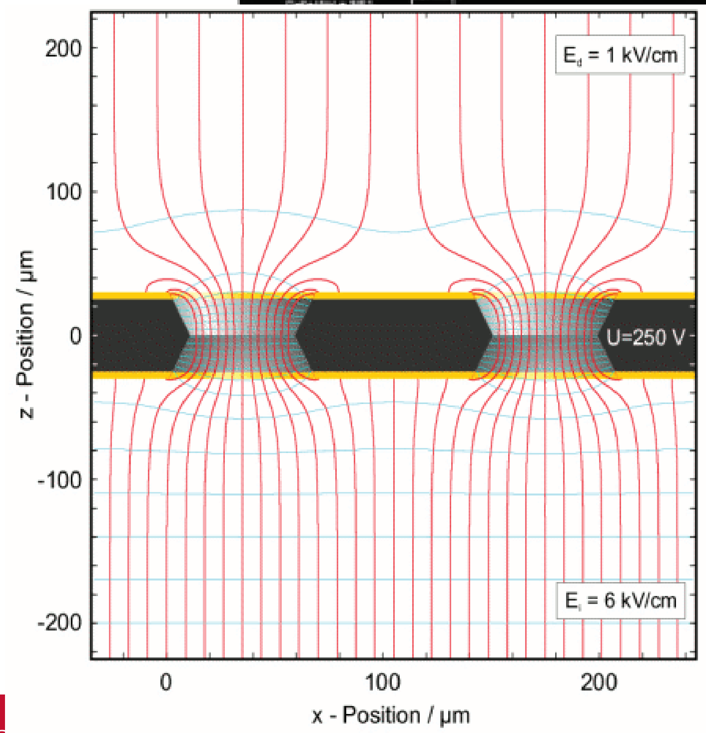


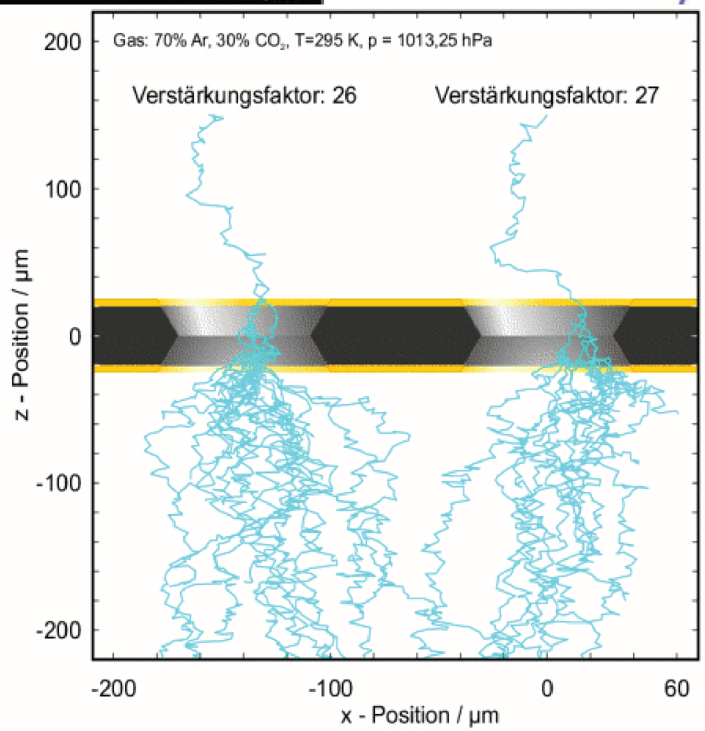
Focal plane detectors



Gas Electron Multipliers (GEMs)







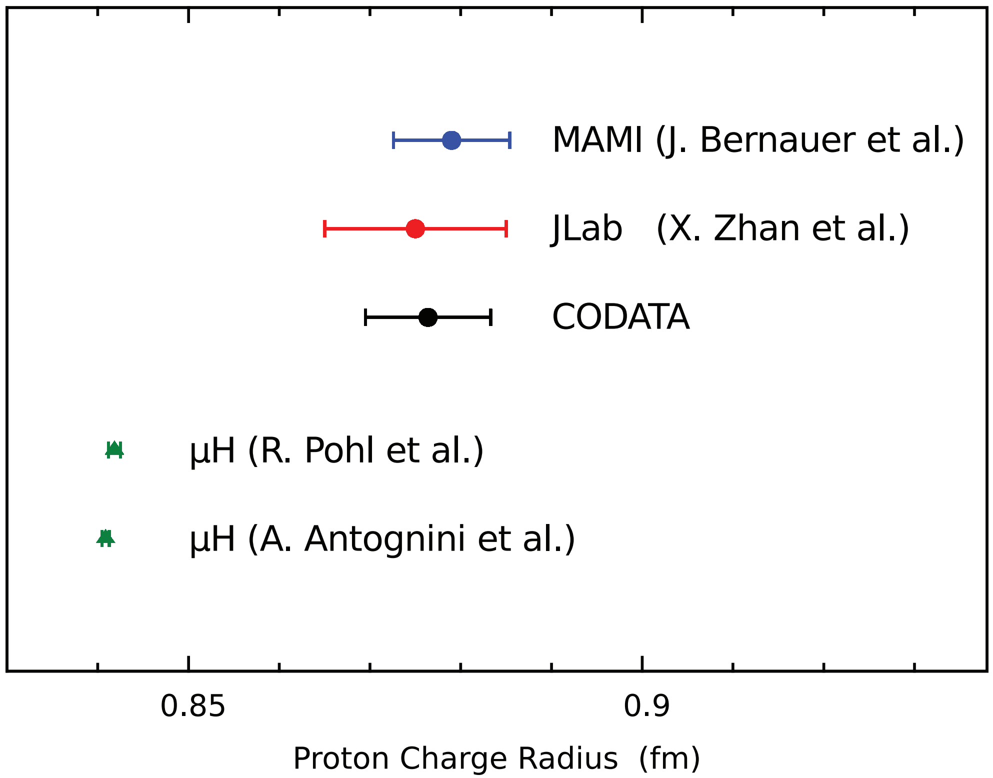
The proton, dark photons and more:

Physics at MAGIX

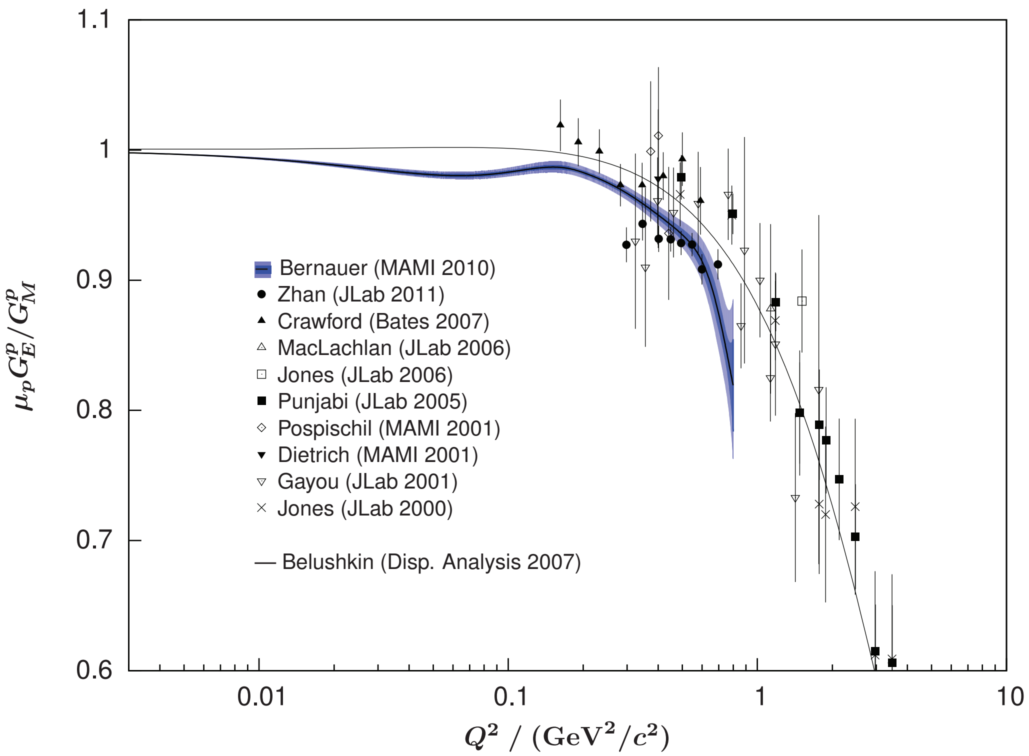
Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

- Measure in scattering experiments (Mainz!)
- Measure in spectroscopy (Lamb-shift)
- Lamb shift is tiny - except in muonic hydrogen
- Big surprise!
  4 - 7 σ discrepancy - why?

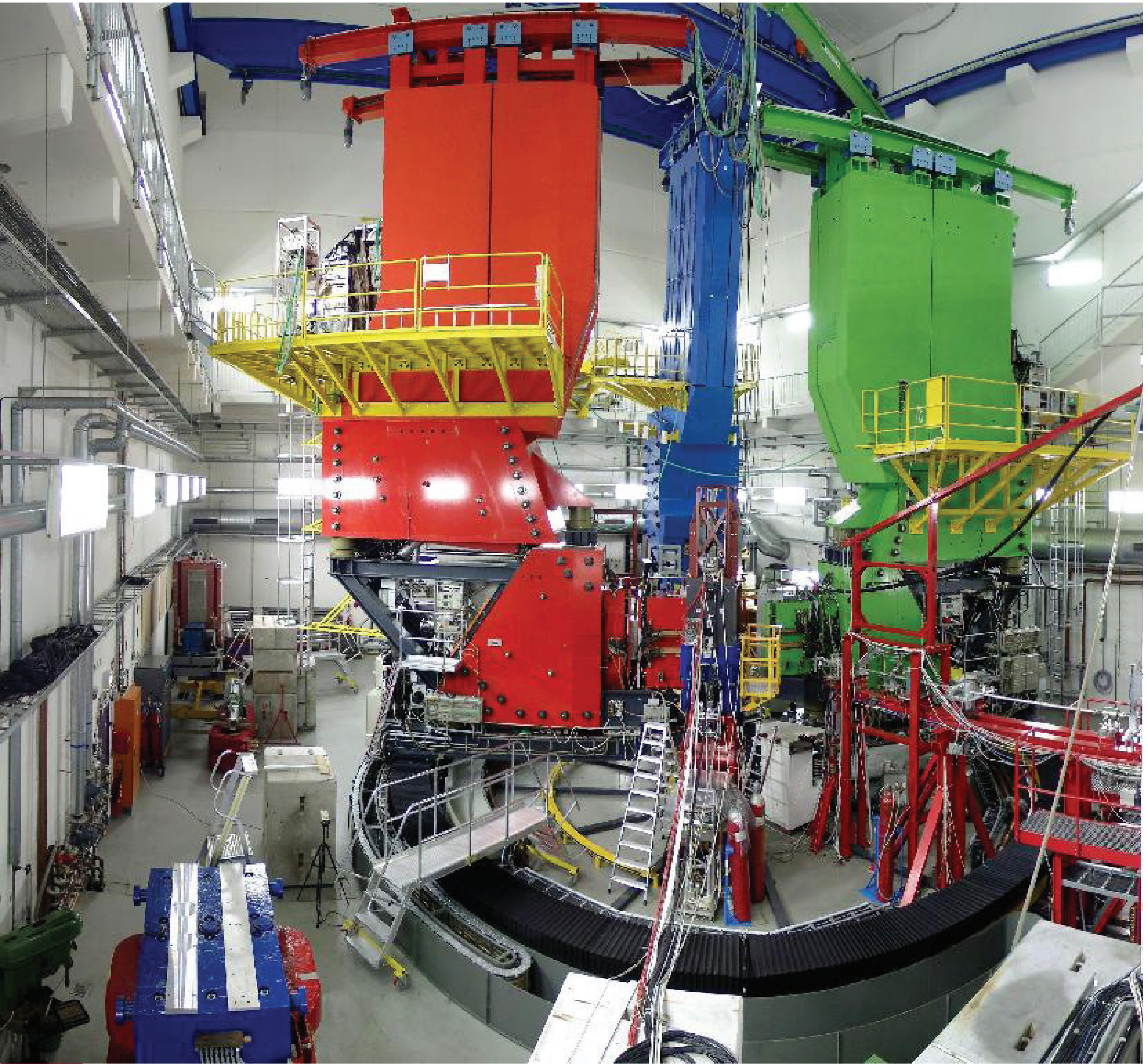


Scattering, Q² and substructure



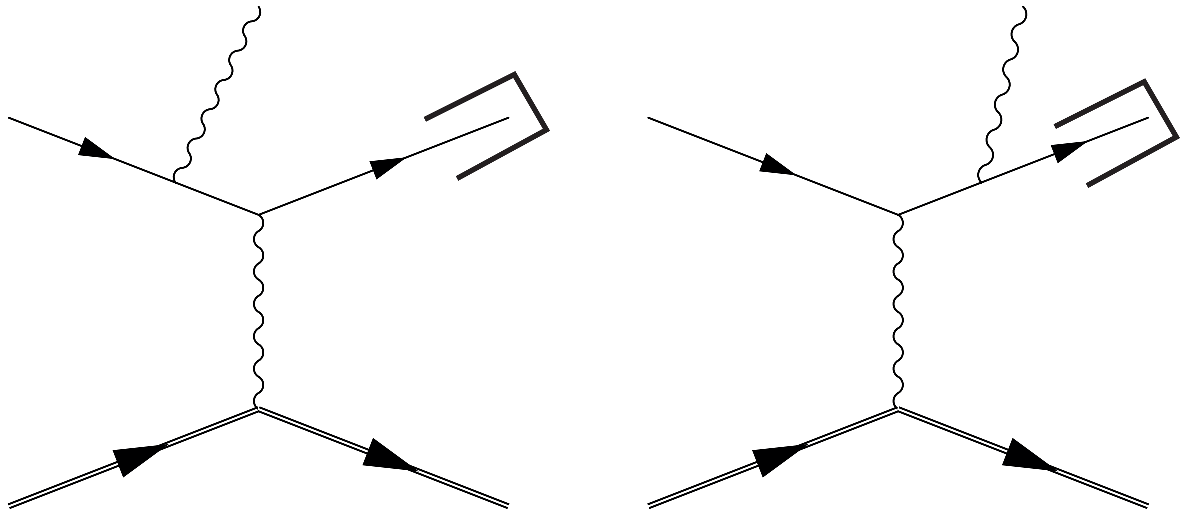
- Scattering experiments happen at finite momentum transfer Q^2
- They will see some of the proton substructure
- Charge radius is defined at $Q^2 = 0$
- Need to extrapolate: Potentially large error
- Want to measure at as small Q^2 as possible

Before MESA: A1 at MAMI - Miha Mihovilovic



- A1 measurements a pillar of scattering radius measurements
- Limited by extrapolation to $Q^2 = 0$
- How to get lower Q^2?

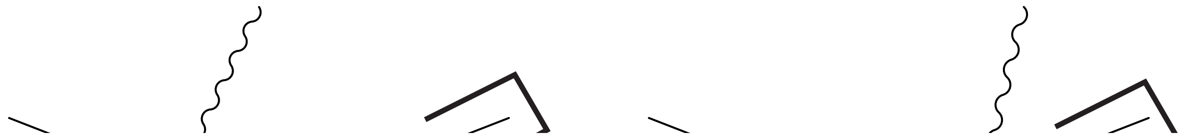
Initial state radiation at A1

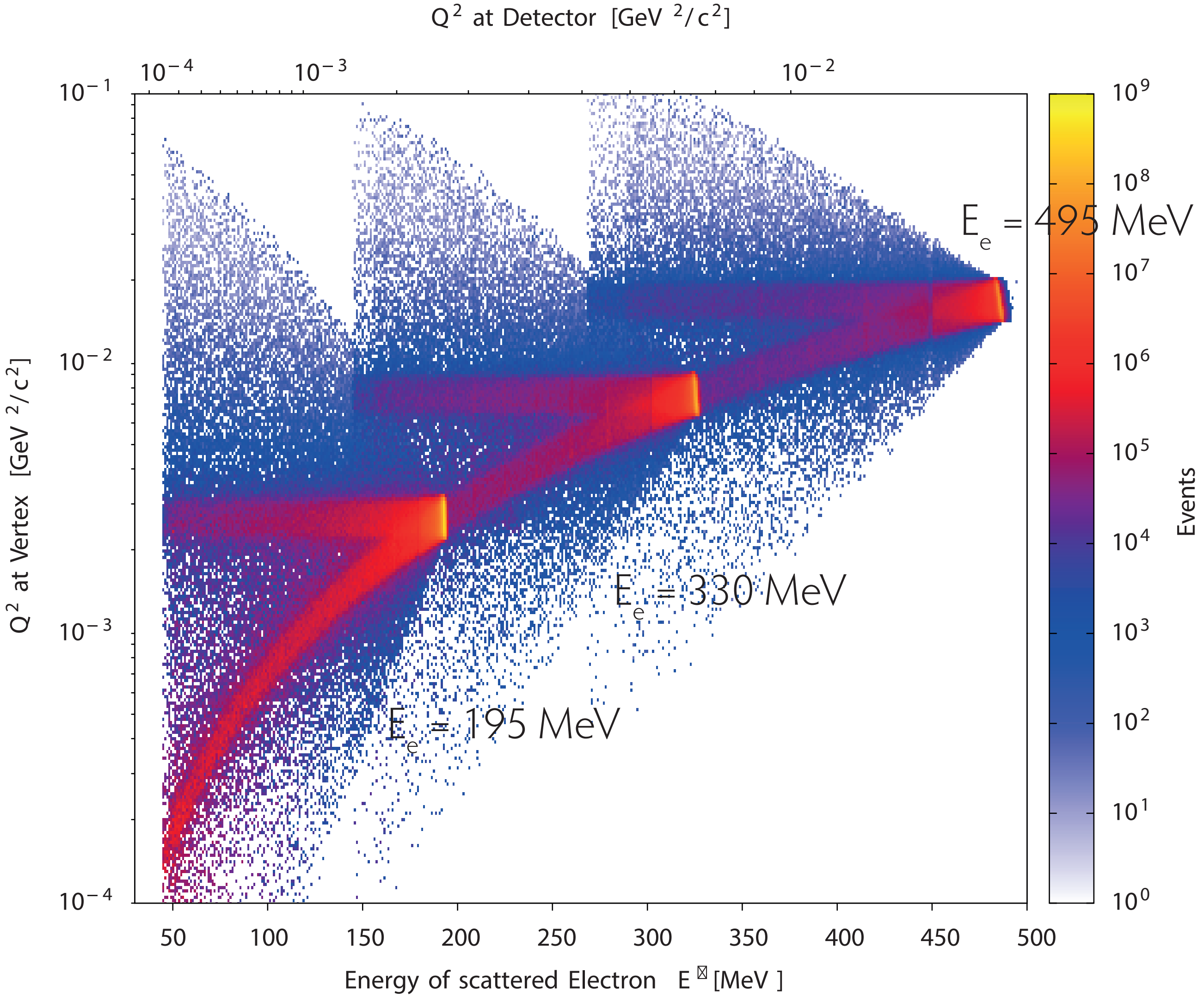


Strategy:

- Access very low Q^2 region via initial state radiation events
- Measure momentum spectrum of scattered electrons
- Needs very good understanding of radiative corrections and final state radiation

Initial state radiation at A1





Strategy:

- Access very low Q^2 region via initial state radiation events
- Measure momentum spectrum of scattered electrons
- Needs very good understanding of radiative corrections and final state radiation

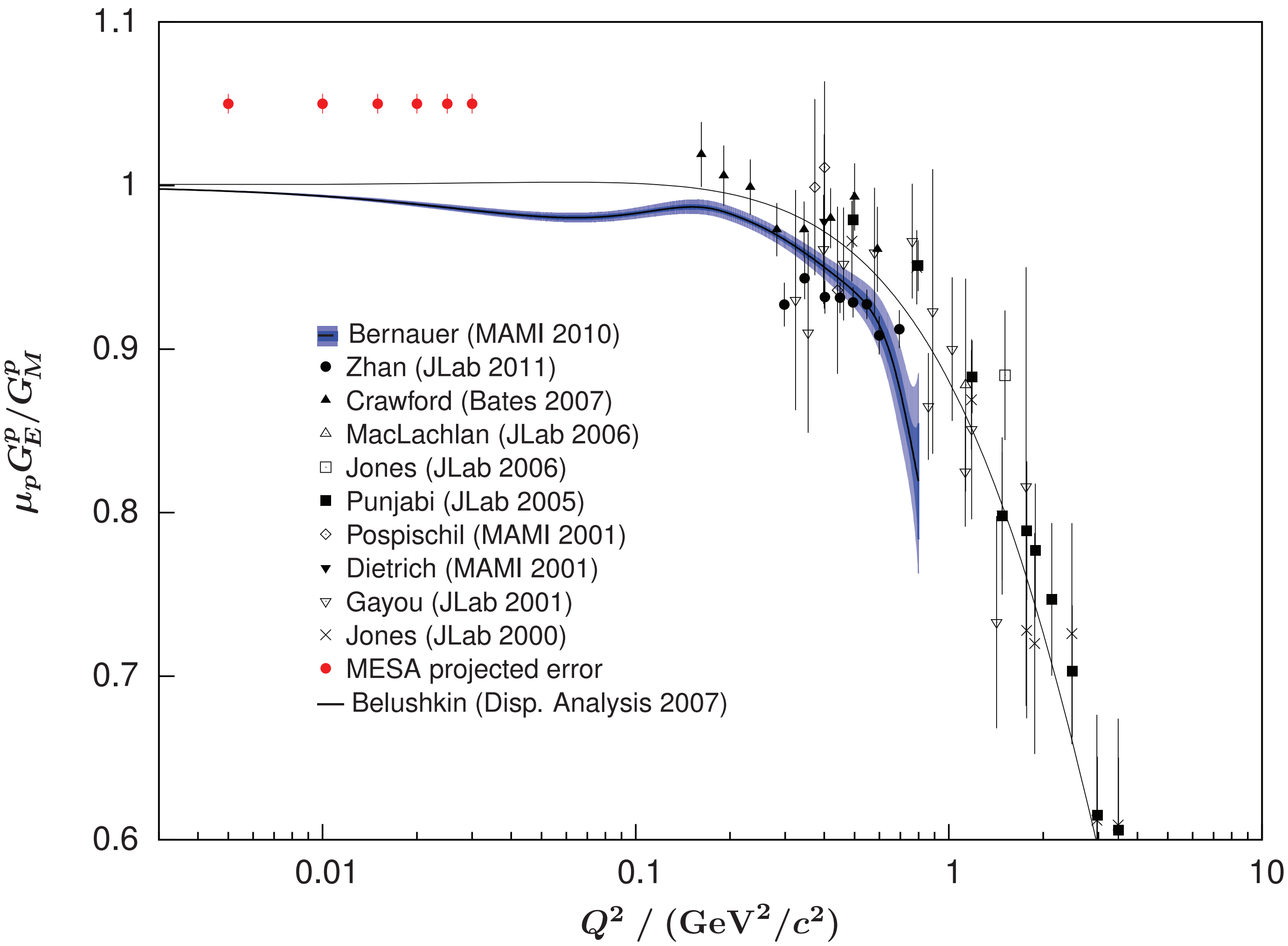
Plan:

- Gas jet target (less wall back-ground)
- Go to lower energies
- Extract proton radius

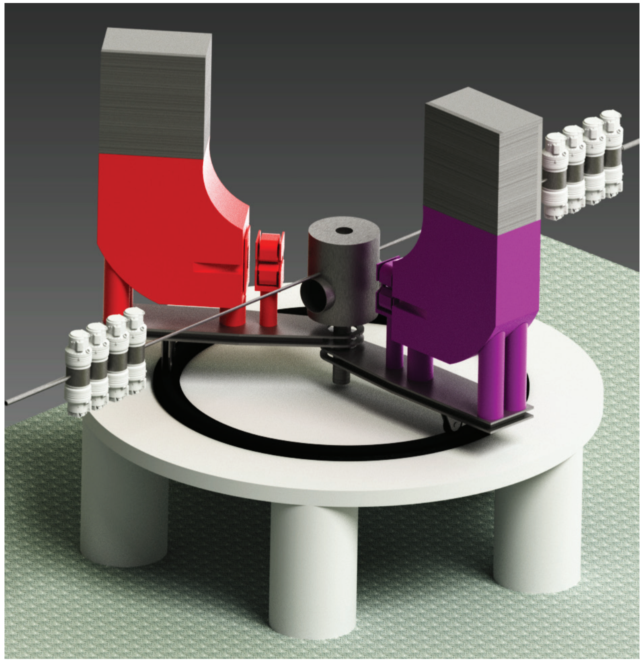
JG|U

SFB 1044

Low Q^2 with MAGIX

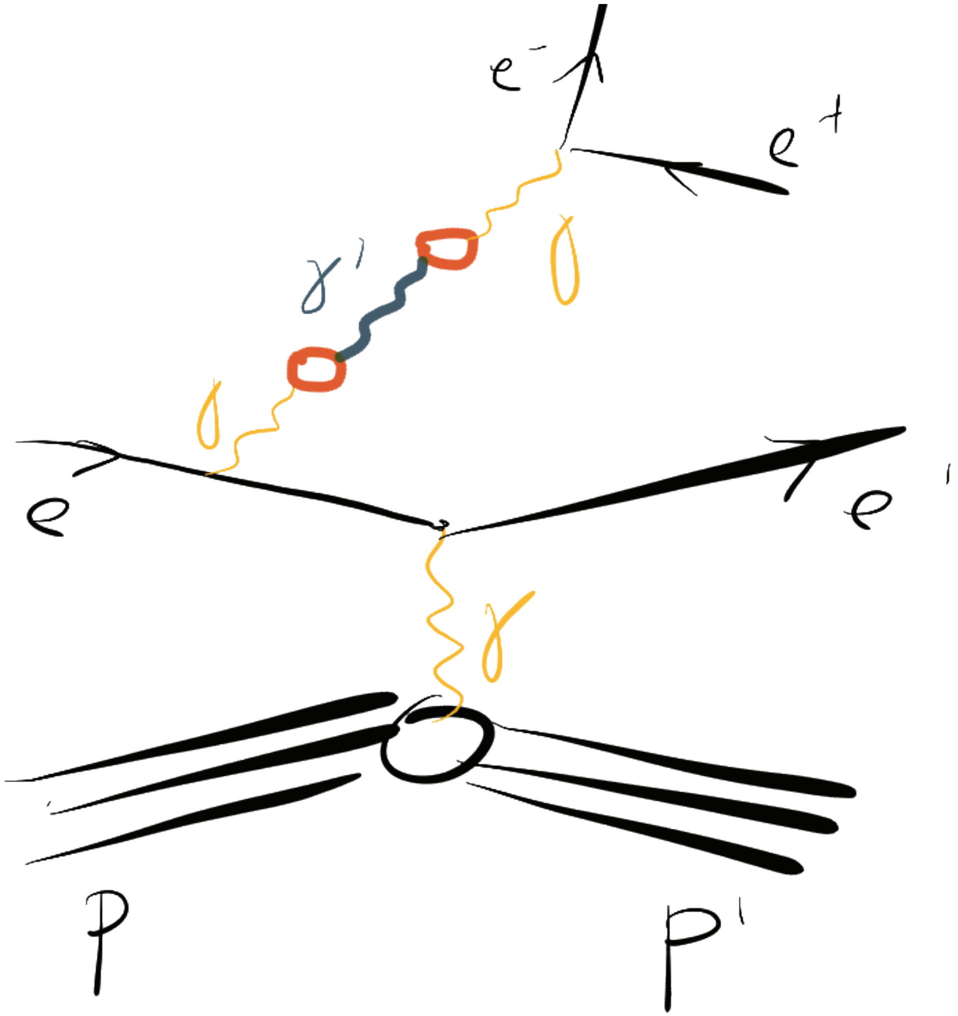


- 100 MeV beam
- Down to 14° scattering angle



Dark photons

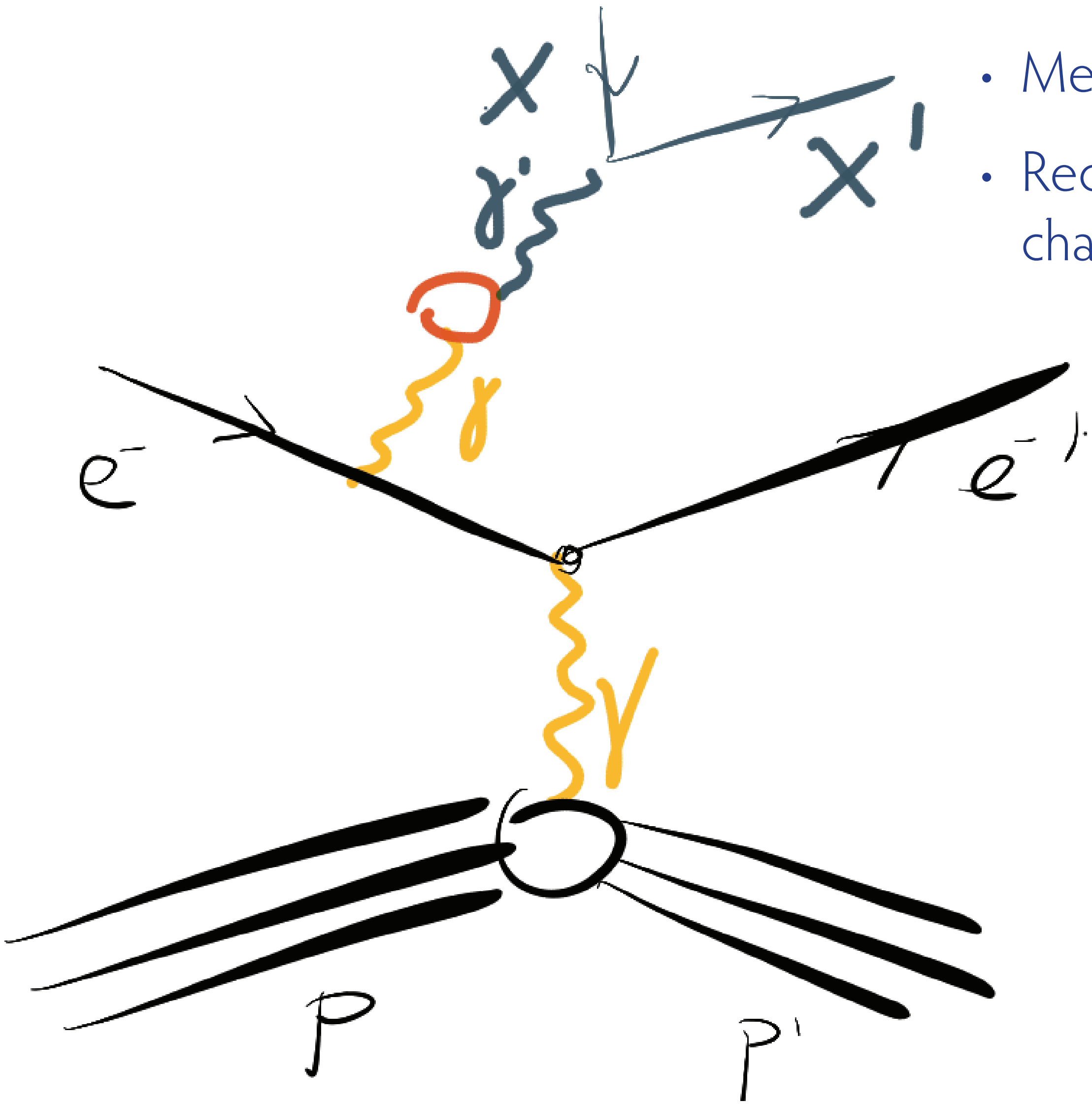
Dark photons



There is dark matter out there…

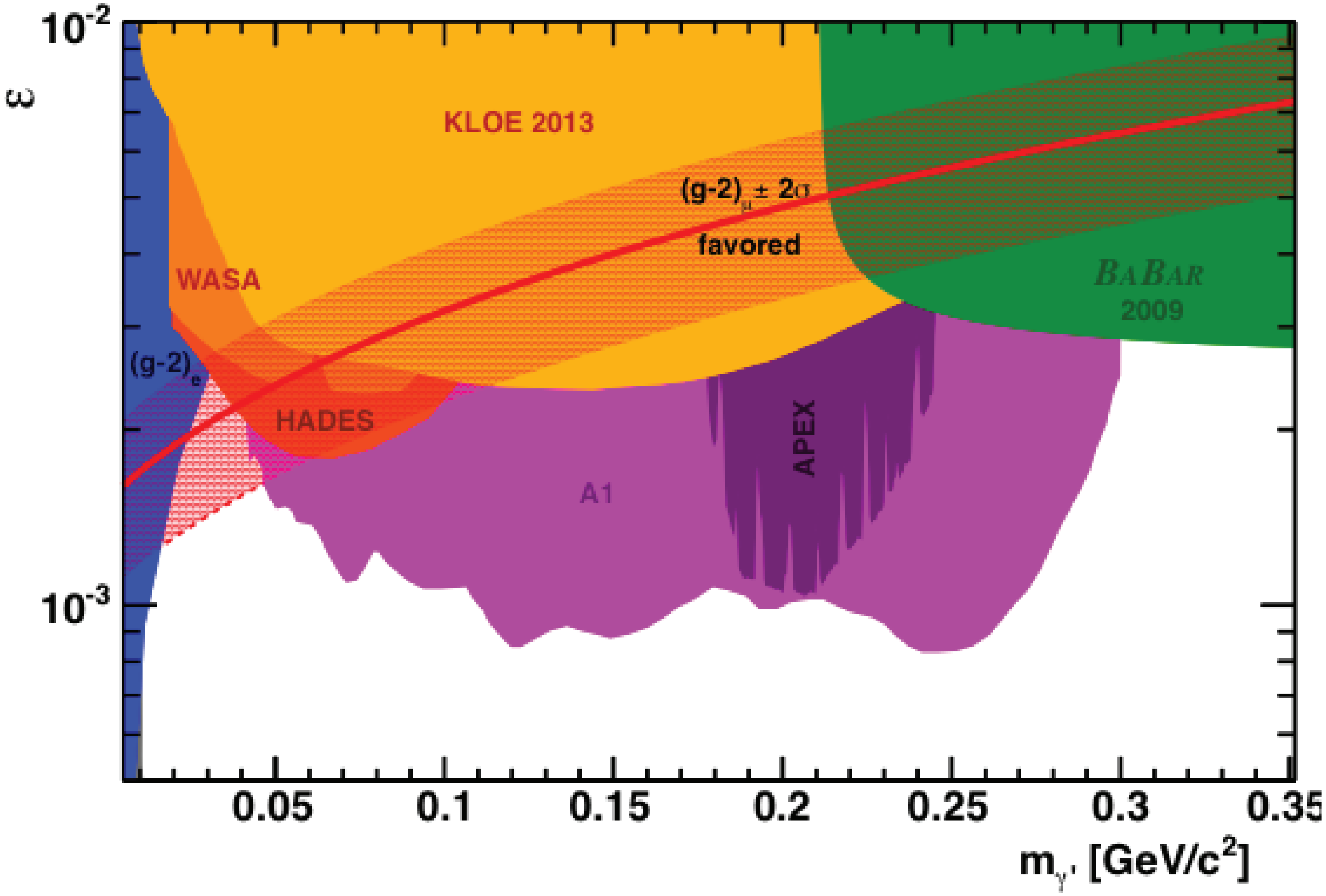
- There could be additional U(1) gauge symmetries with an exchange particle (dark photon, mass $m_{\gamma'}$)
- It could mix with the photon via heavy fermions (mixing parameter ε)
- It would then show up as a narrow bump in the e^+e^- spectrum
- It could explain the muon g-2 anomaly

Invisible dark photons



- Measurement via missing mass method
- Requires detection of low energy proton; challenging

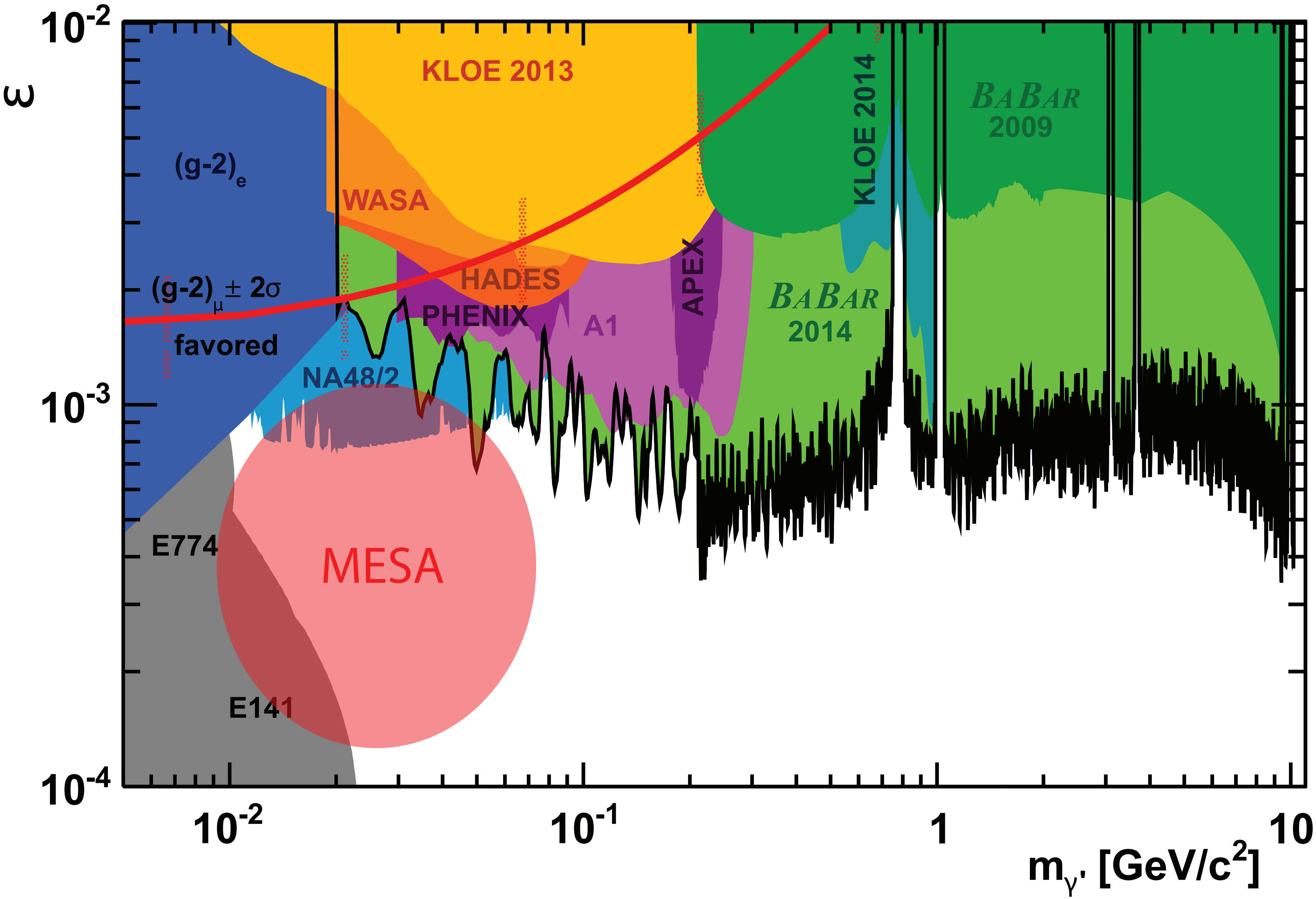
Dark photons at A1



Merkel et al. [A1] Phys.Rev.Lett. 112 (2014) 22, 221802

- E_{beam} 180-855 MeV
- 100 µA beam current
- Stack of tantalum targets
- 22 kinematic settings
- Coincidence between spectrometers for e^+e^-
- Best limits in the g-2 region at the time of publication

Dark photons at MESA/MAGIX



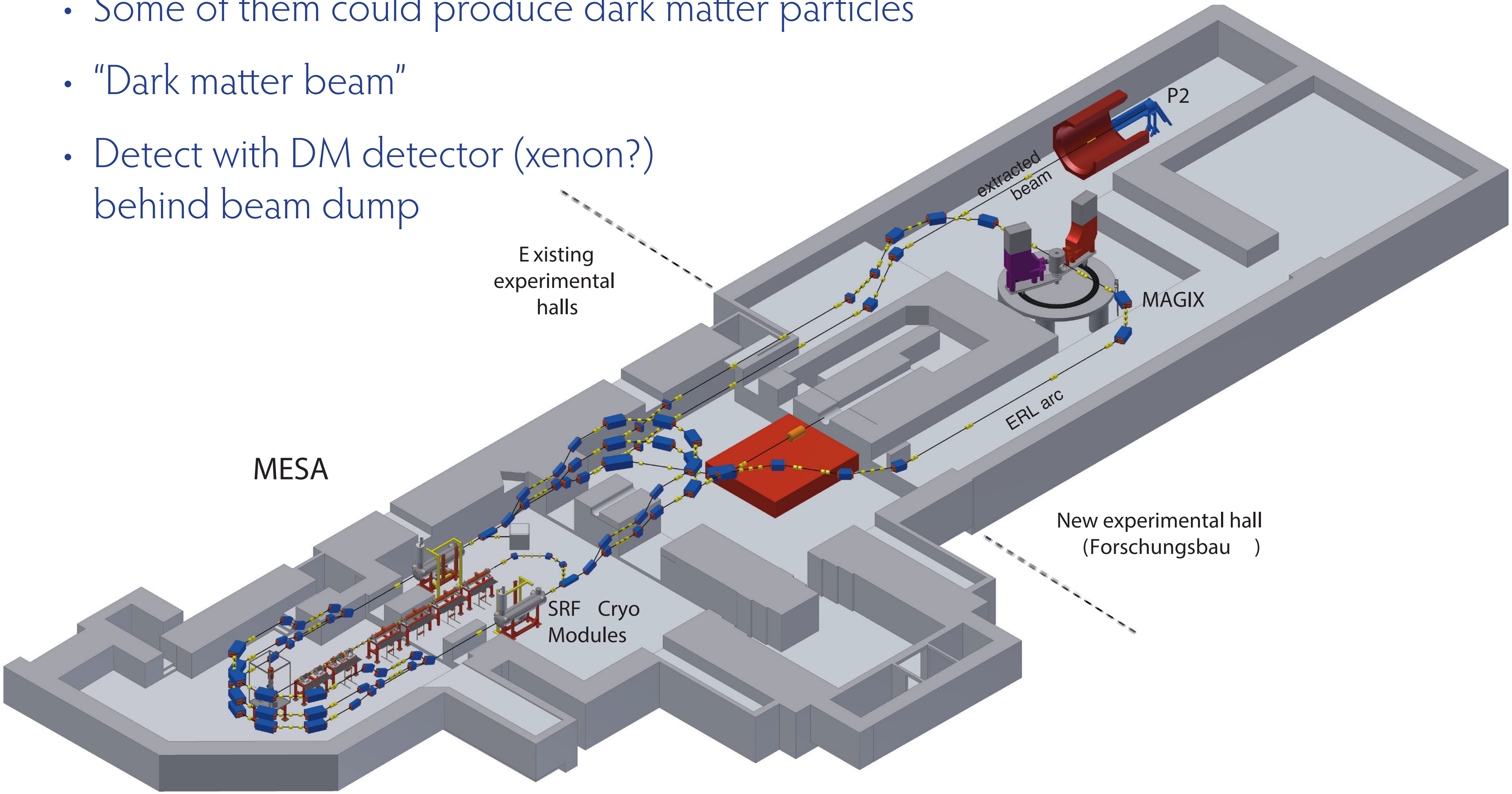
Dark Matter with the Beam Dump

BDX

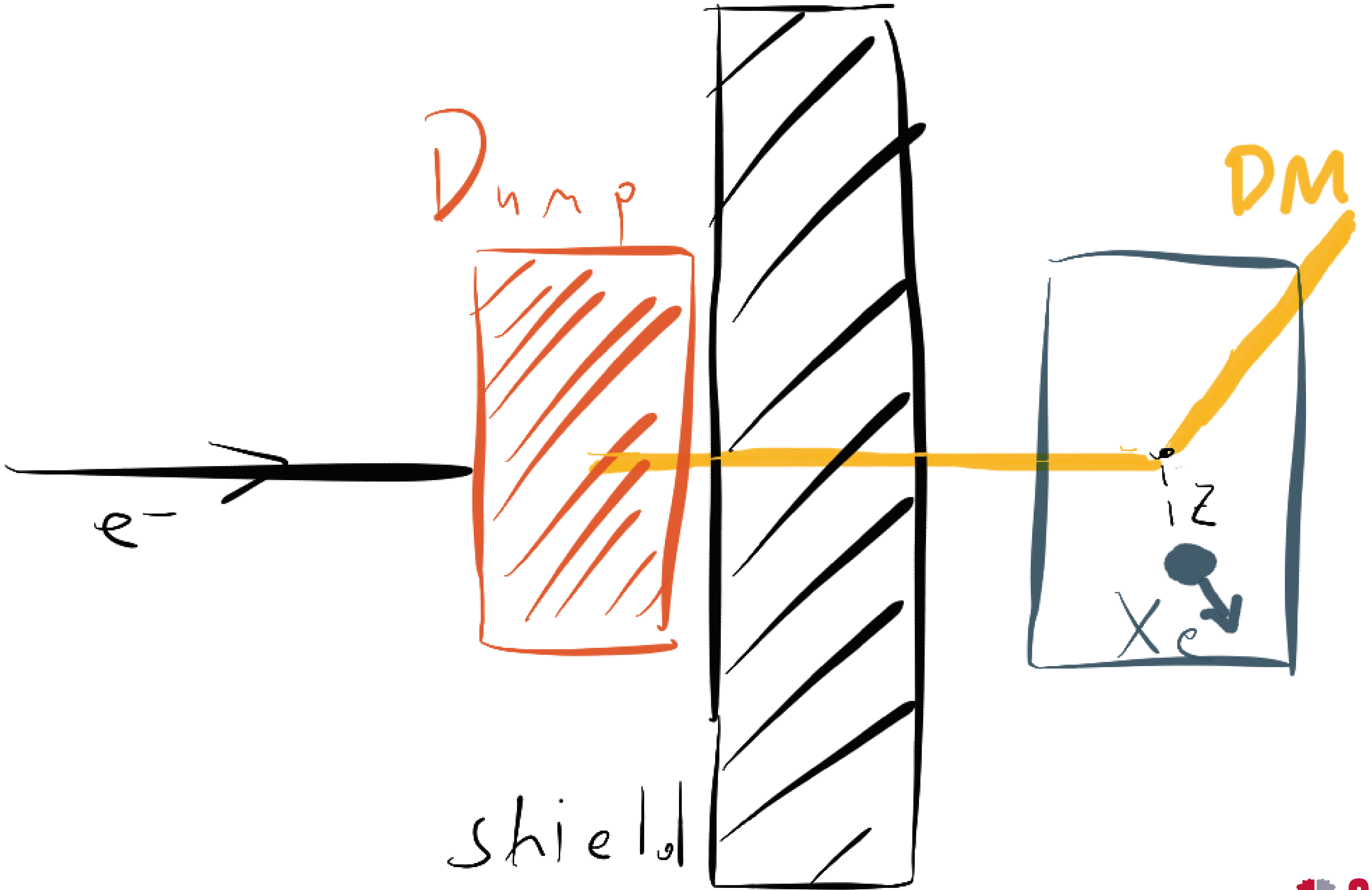
Search for dark matter

MESA: More than 10^{22} electrons hit beam dump per year

- Some of them could produce dark matter particles
- "Dark matter beam"
- Detect with DM detector (xenon?) behind beam dump

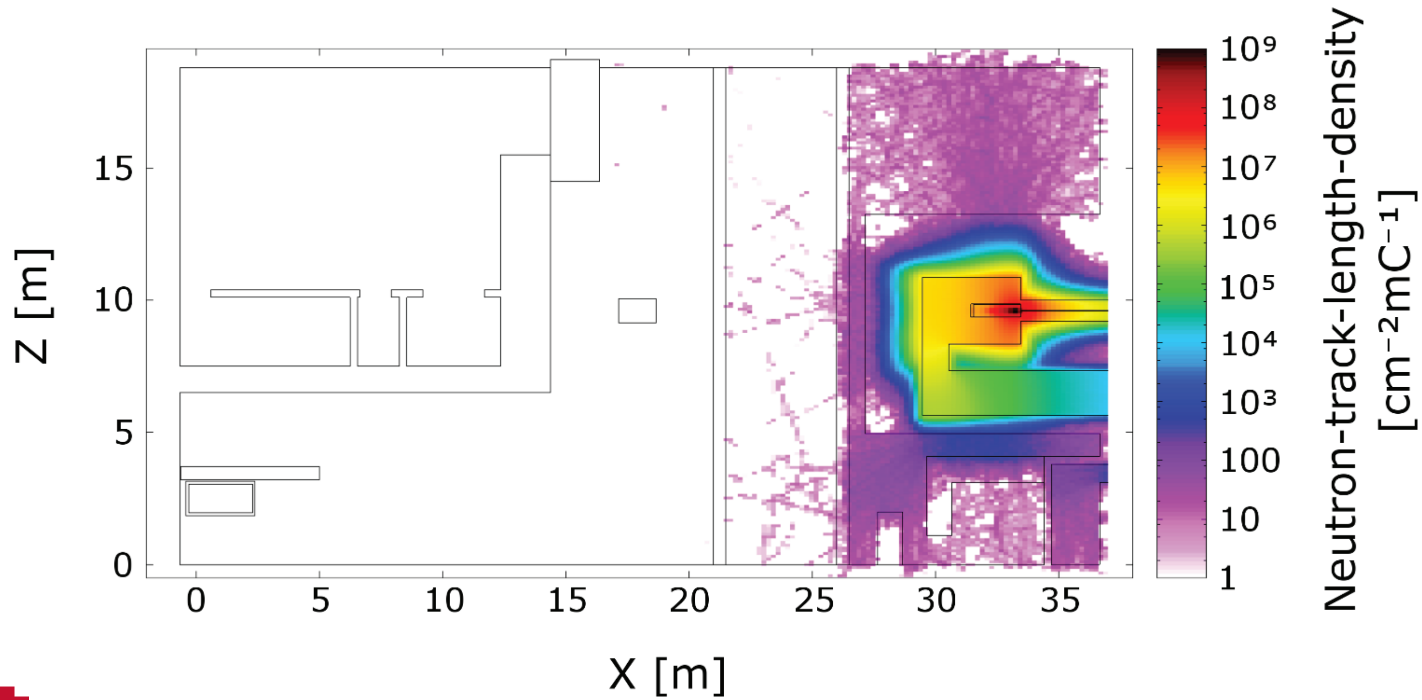


Beam dump dark matter



Beam dump dark matter

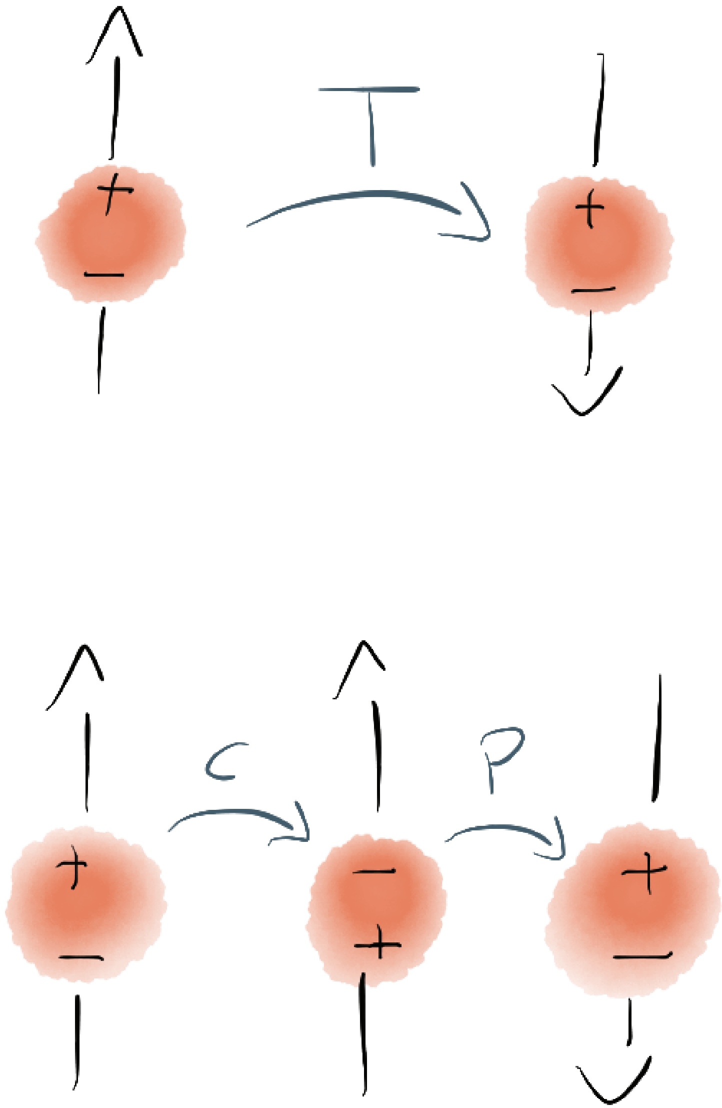
- FLUKA calculations of neutron flux behind dump look promising
- MESA operates below the pion threshold, no neutrinos produced
- Boost gives access to low mass dark matter



And one more:

Electric dipole moment of electrons

Electric Dipole Moments - Yannis Semertzidis



- An EDM of a fundamental particle violates CP and T
- Essentially 0 in the SM (tiny contribution from CKM)
- Potentially large in BSM models
- Some more CP violation needed

Dipole moments and precession

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}$$

- Spin precesses in magnetic field due to magnetic dipole moment μ
- Spin precesses in electric field due to electric dipole moment d
- μ is large, d is almost zero

Charged particle EDMs

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}$$

For neutral particles:

- Put in a "box"
- Apply large E-field
- Watch precession
- E.g.: Neutron EDM

For charged particles:

- E field leads to acceleration
- Put electron into a neutral, polar molecule (ACME, Imperial/Sussex)
- Put electron/proton/deuteron etc. in a storage ring

Precession in a storage ring

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{S}$$

- Electric and magnetic fields perpendicular to momentum

$$\vec{\Omega} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{v} \times \vec{E}) + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right)$$

Magnetic dipole　　Electric dipole

$$a = \frac{g-2}{2} \quad \vec{\mu} = 2(a+1)\frac{q}{2m}\vec{S} \quad \vec{d} = \eta\frac{q}{2m}\vec{S}$$

- How to get rid of magnetic part?

Precession in a storage ring

- No magnetic field!

(about 10 MV/m electric field)

$$\vec{\Omega} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{v}\times\vec{E}) + \frac{\eta}{2}\left(\vec{E} + \vec{v}\times\vec{B}\right)\right)$$

Magnetic dipole Electric dipole

Precession in a storage ring

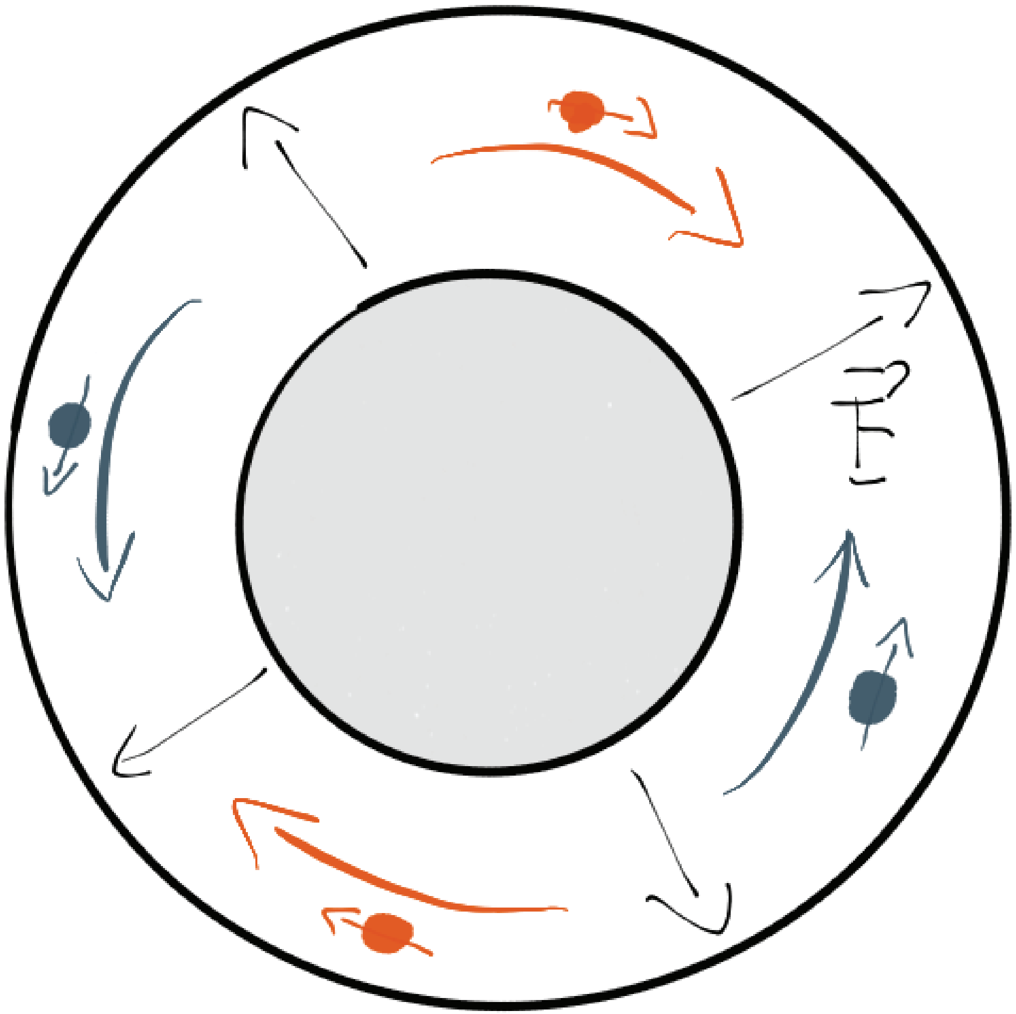
- No magnetic field!
- Magic momentum!

$$\vec{\Omega} = \frac{q}{m}\left(a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\left(\vec{v} \times \vec{E}\right) + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right)$$

Magnetic dipole — Electric dipole

- 0.7 GeV/c for protons
- 14.5 MeV for electrons

Build an electric-only storage ring



- Magic momentum
- Spin rotates with momentum vector
- EDM leads to out of plane precession
- Counter-rotating bunches help to cancel systematics

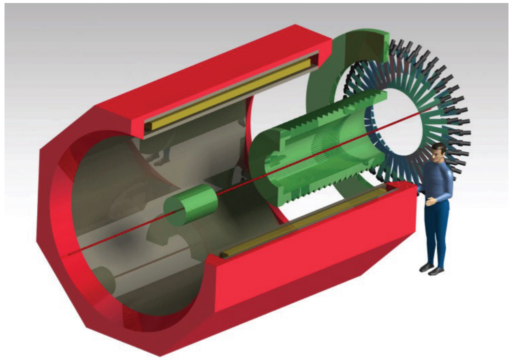
Systematics

$$|d_e| < 8.7 \times 10^{-29} e \cdot \mathrm{cm} \quad (\mathrm{ThO})$$

ACME collaboration,
Science 343, 269 (2104)

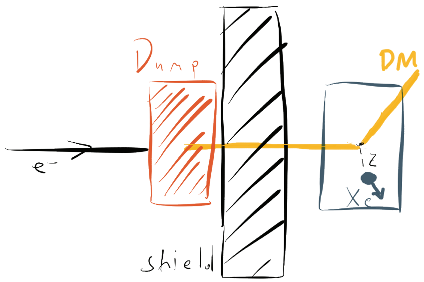
- Need very low magnetic field
- Good control of electric field
- Very hard to compete with molecules for limits ...
- ... but only option for a precise measurement ...
- ... and a pathfinder for the proton EDM (Jülich, Korea...)

Summary



Exciting physics program for electron scattering in Mainz in the next decade:

- New accelerator MESA, staring 2018/19
- Weak mixing angle measurement with P2
- Also gives access to neutron skins



- Proton radius, dark photon and much more with MAGIX
- Second generation of experiments:
  Beam dump dark matter and
  electron EDM ring (?)