Fundamental Physics at MESA

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JG|U

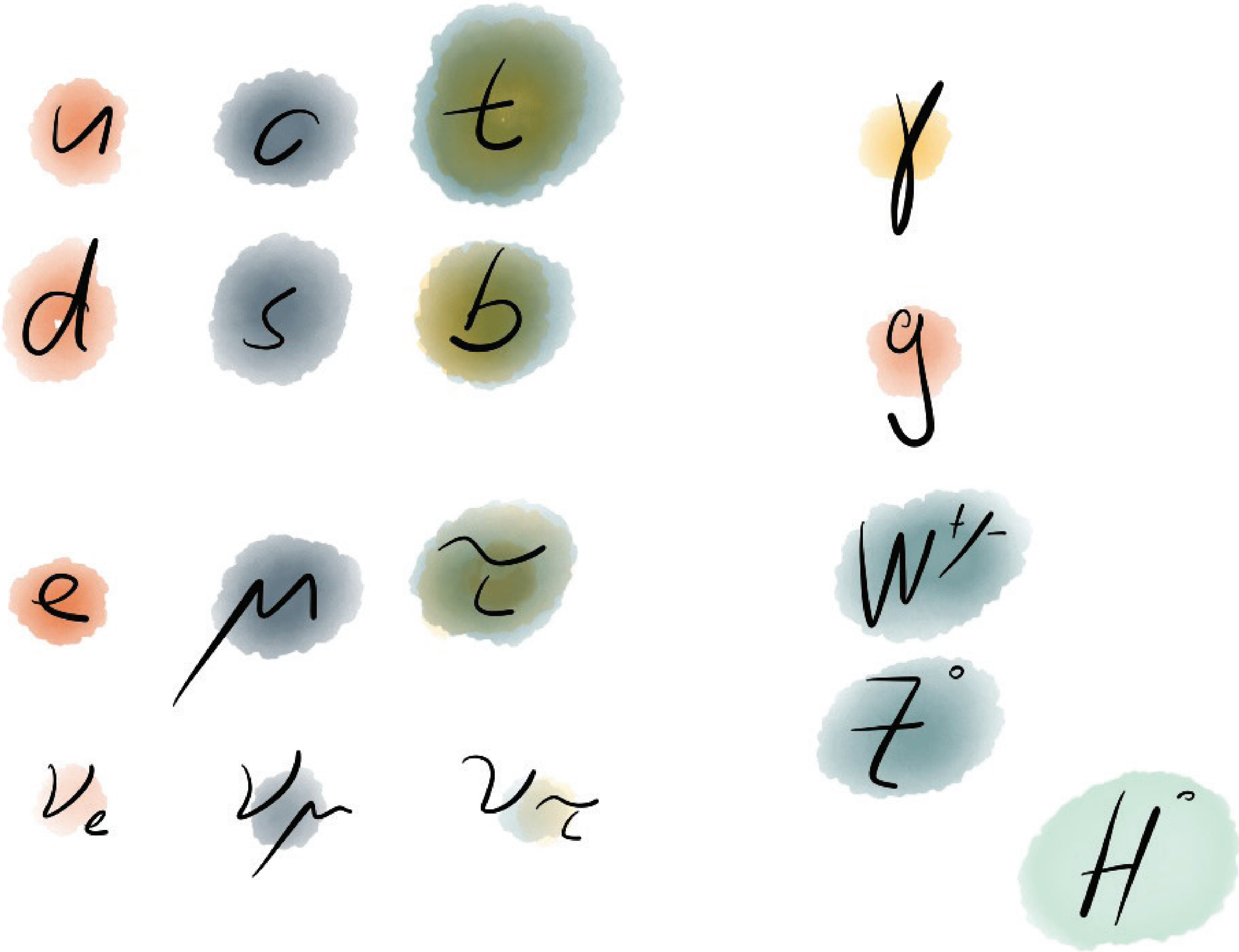
PRISMA Retreat
September 2015

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

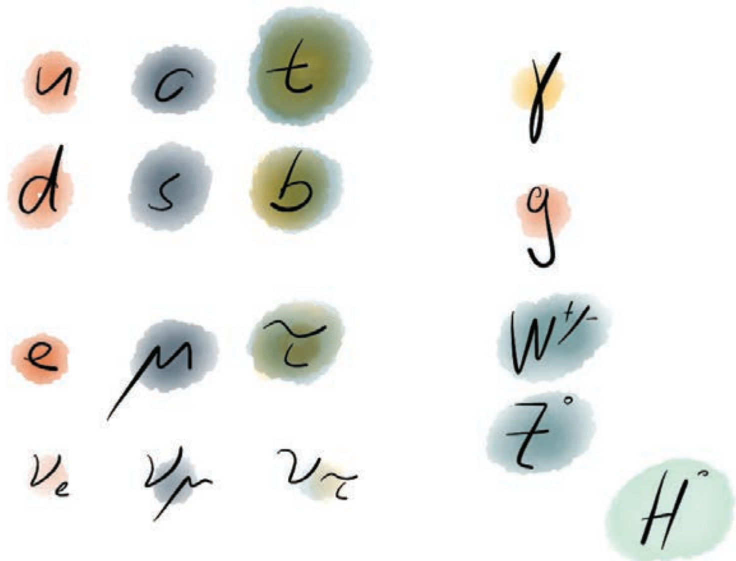
PRISMA

Particle Physics:
What are the fundamental constituents of matter and how do they interact?

The Standard Model of Elementary Particles



Hugely successful



Magnetic moment of the electron:

- Theory:

  g_e = -2.002 319 304 363 56 (154)

  (Aoyama et al., PRL 109, 111807 (2012))

- Experiment:

  g_e = - 2.002 319 304 361 53 (53)

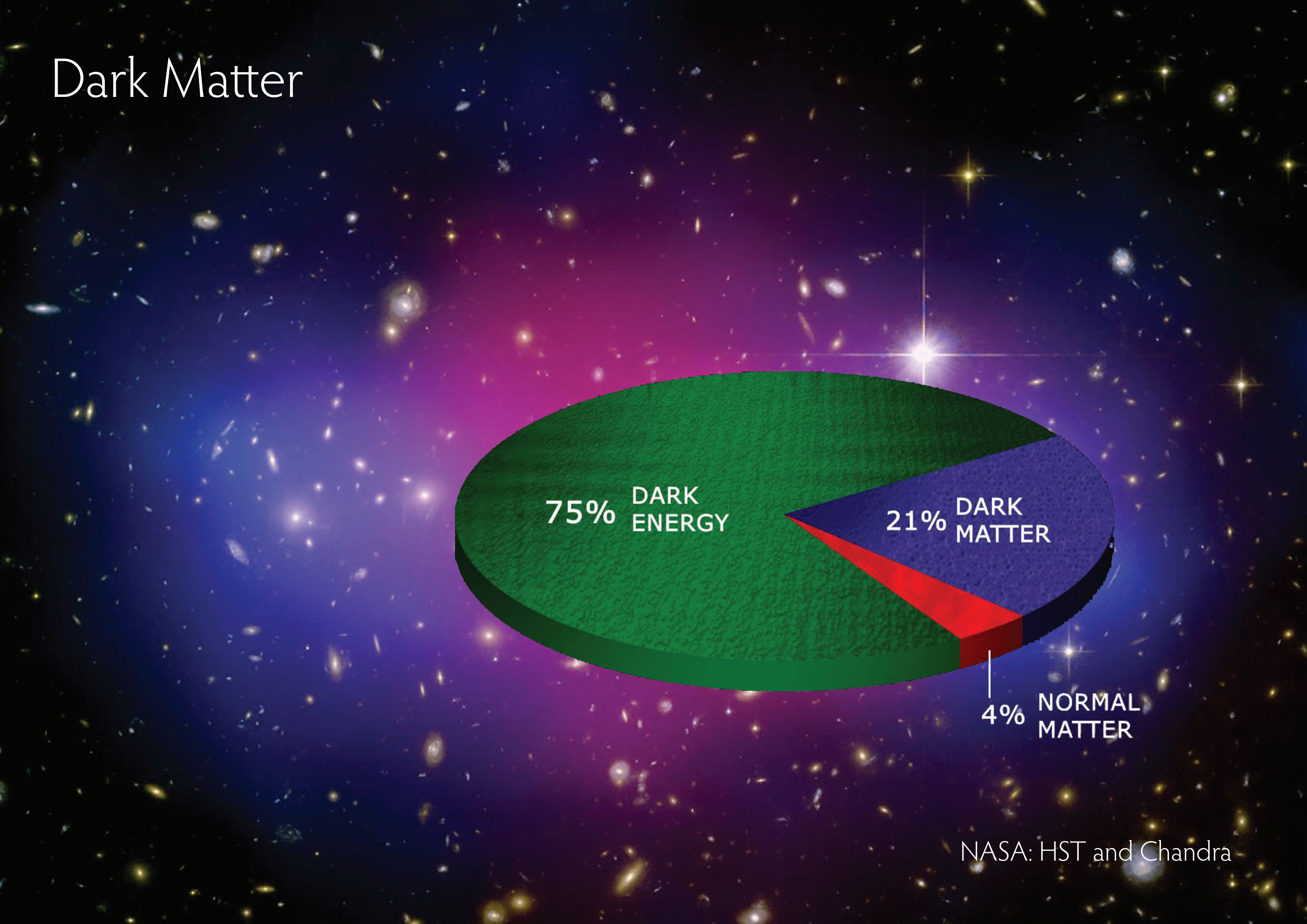
  (Hanneke et al. PRL 100, 120801 (2008))

Open Questions?

Dark Matter

NASA: HST and Chandra

Dark Matter



NASA: HST and Chandra

Matter-Antimatter Asymmetry

10'000'000'000	10'000'000'001
Antimatter	Matter

Matter-Antimatter Asymmetry

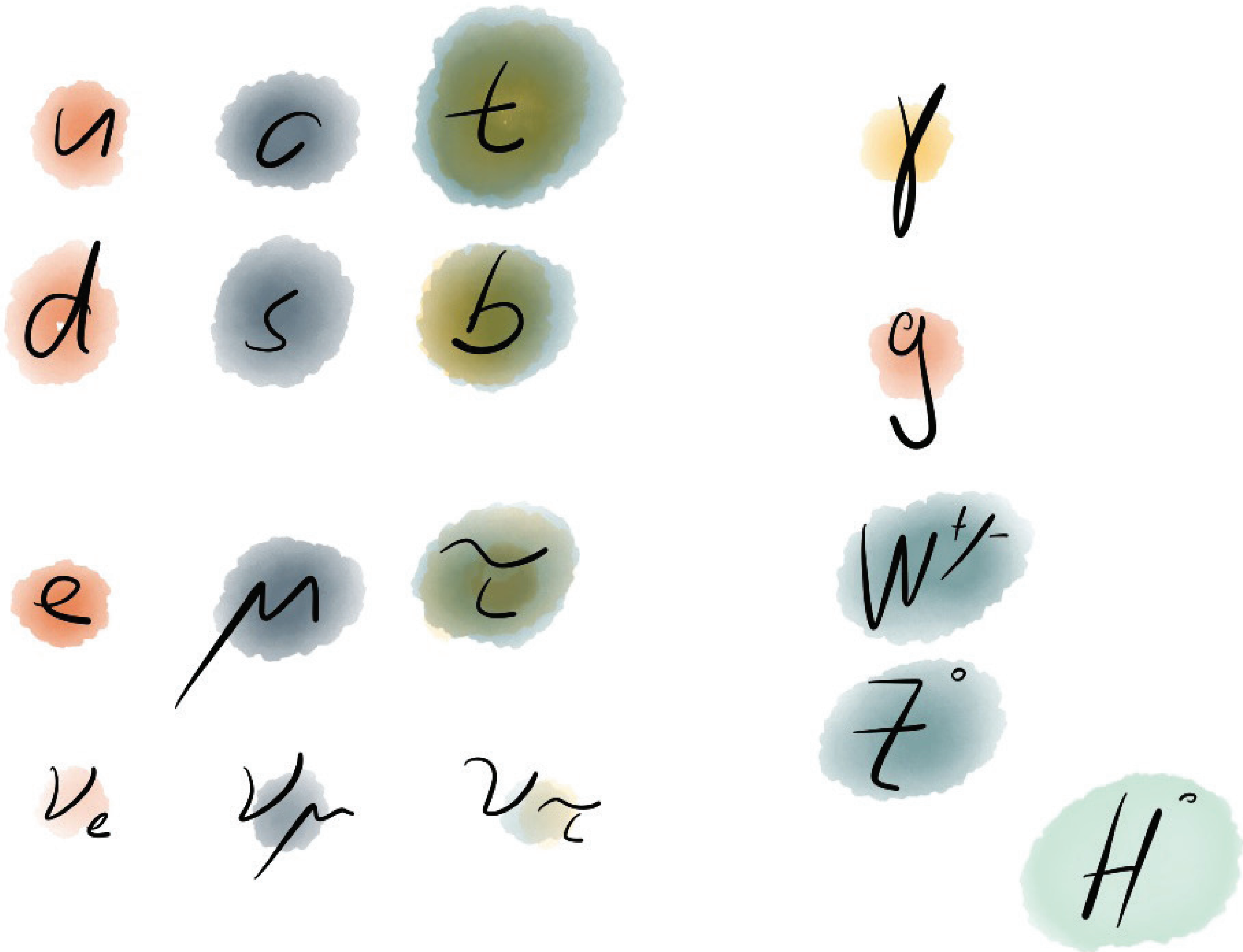
Radiation

1

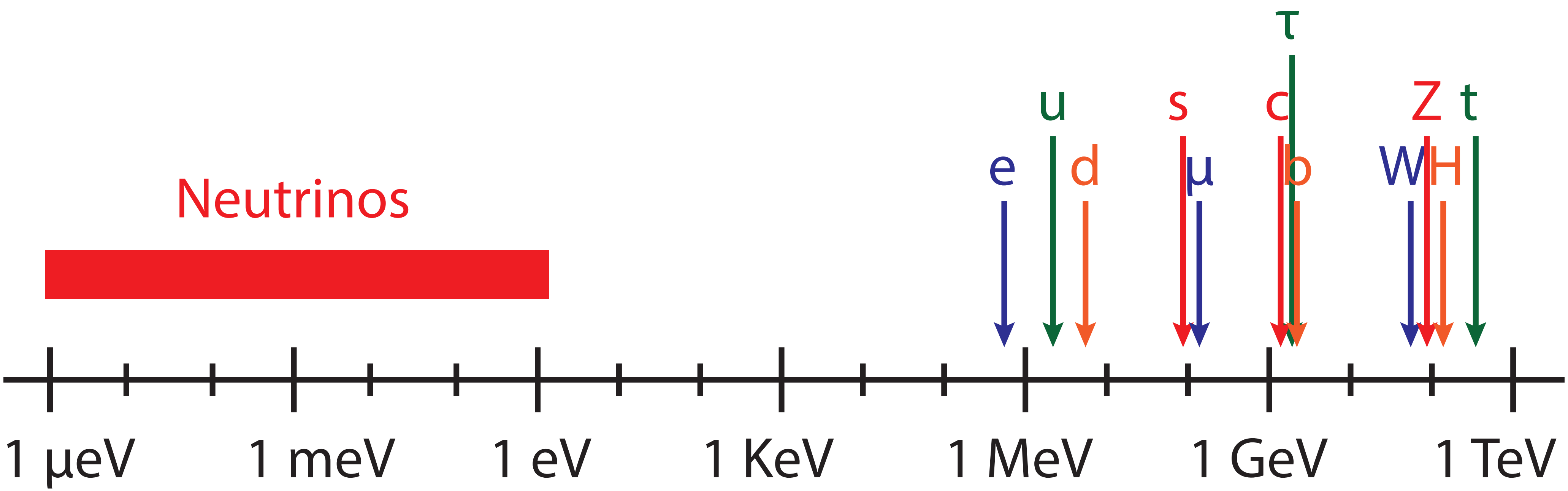
Us

Gravity

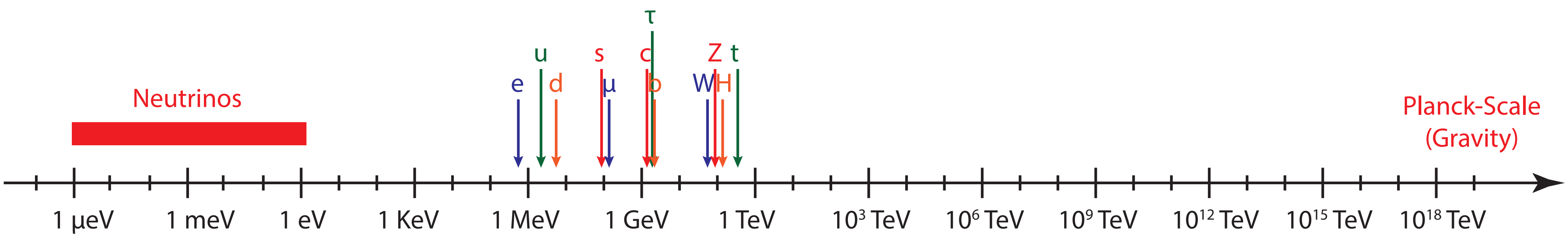
The Structure of the Standard Model



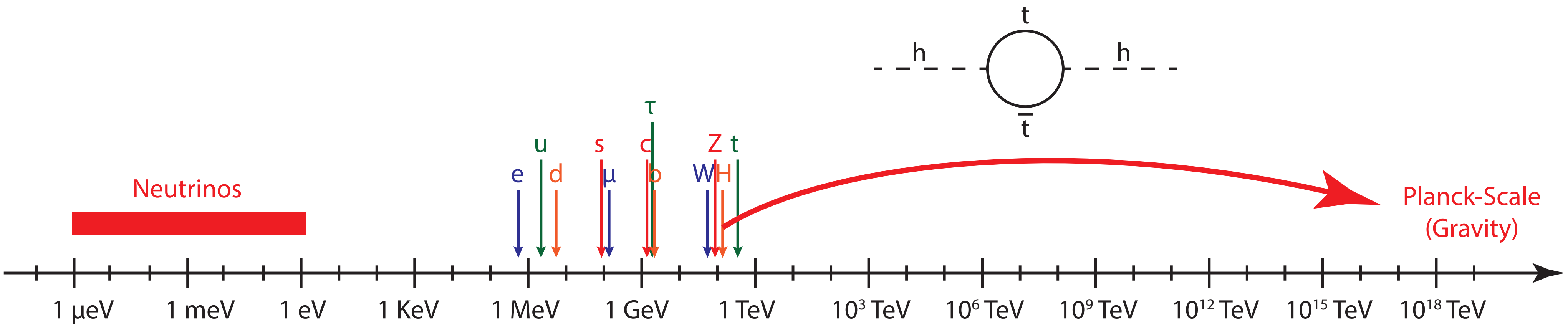
The Structure of the Standard Model



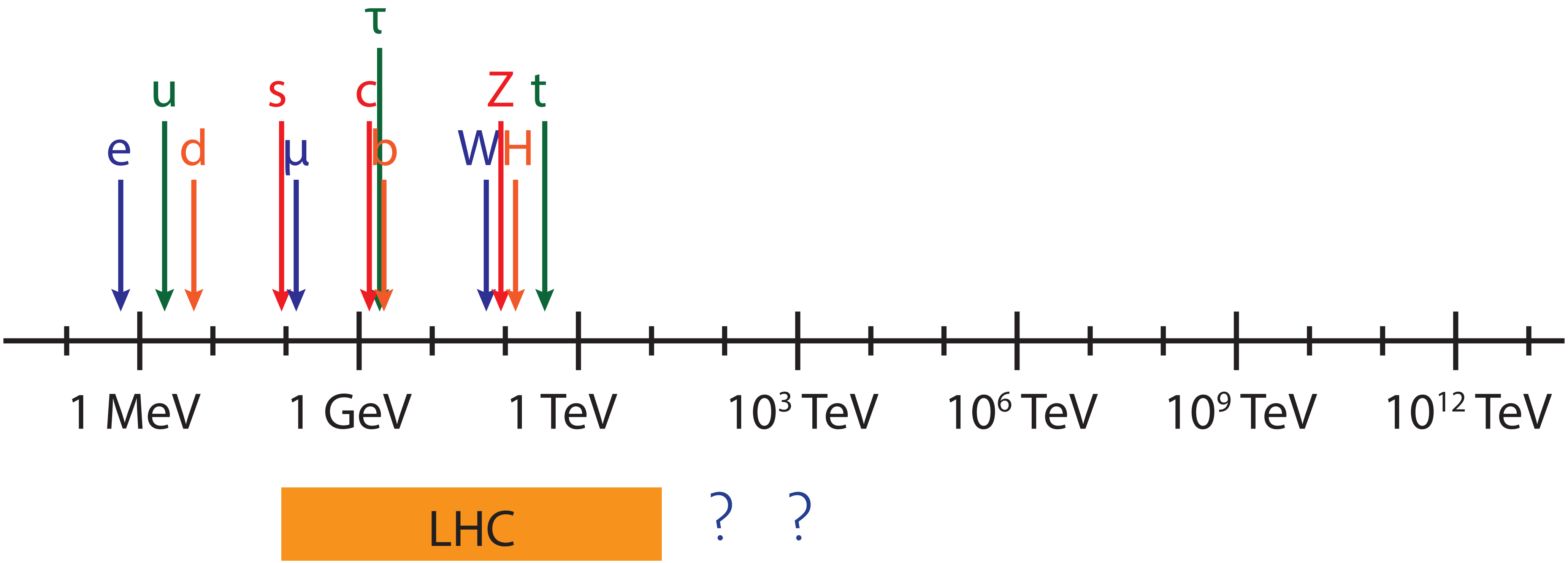
The Structure of the Standard Model



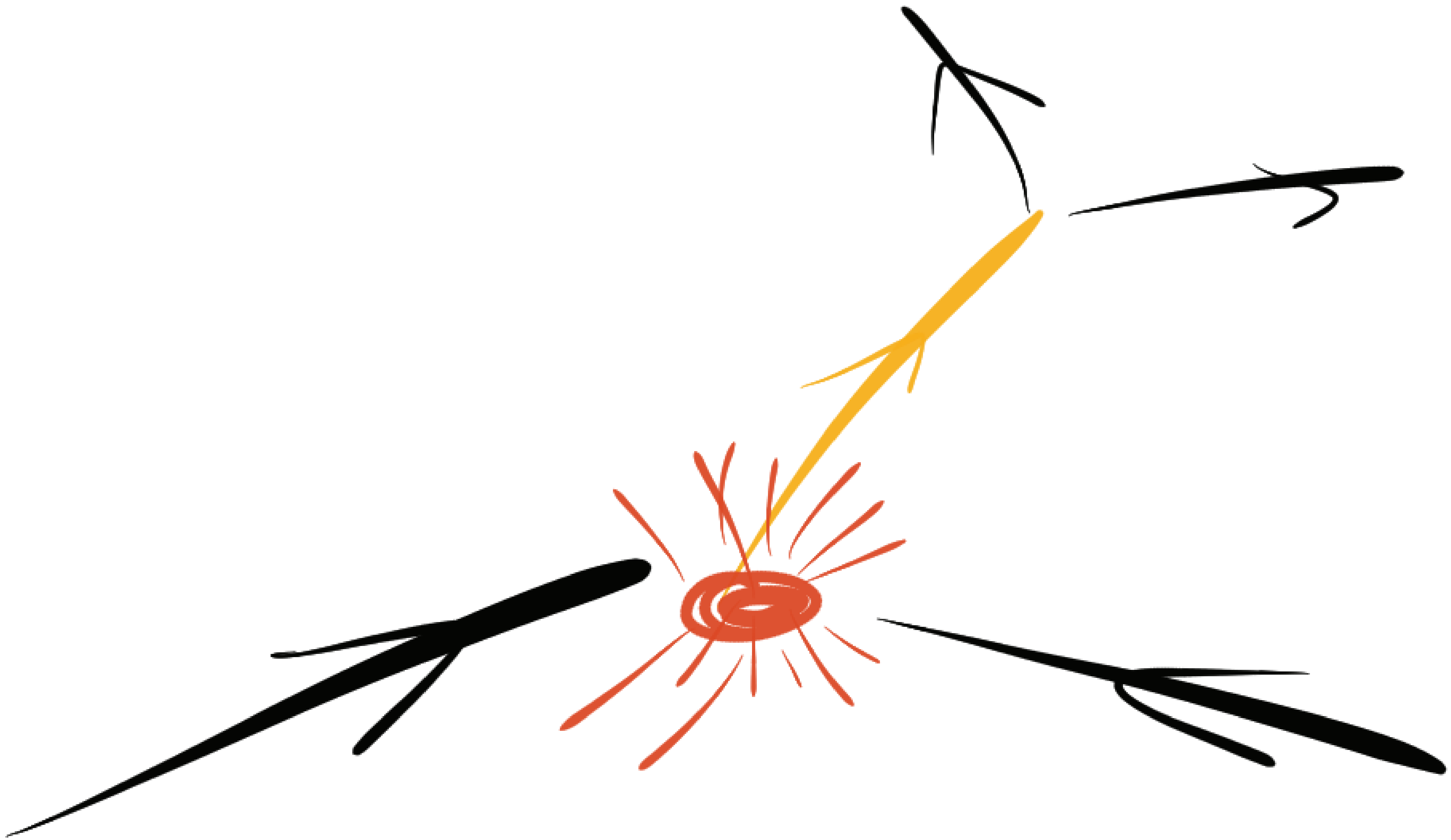
The Structure of the Standard Model



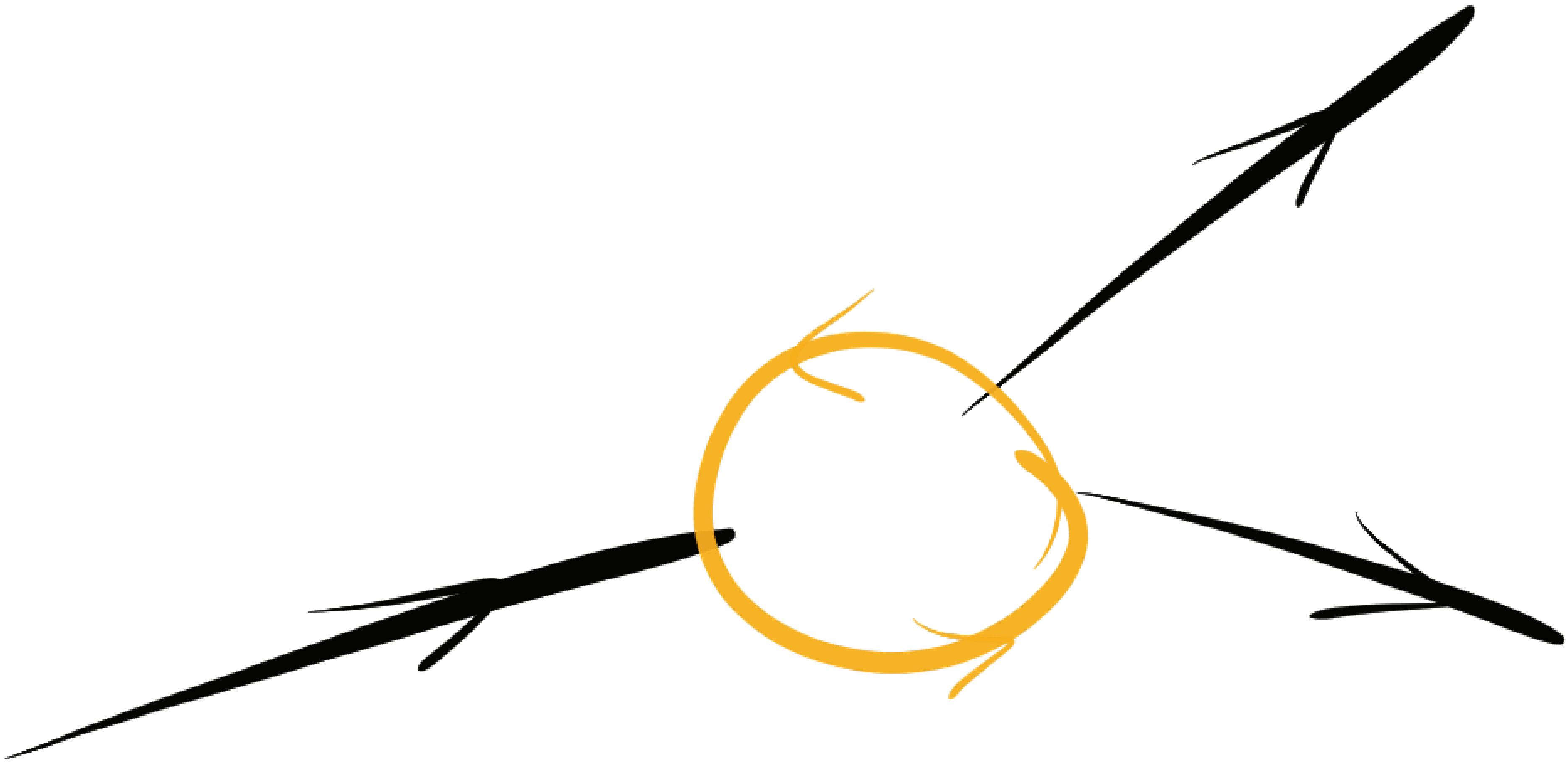
The Structure of the Standard Model



Direct production



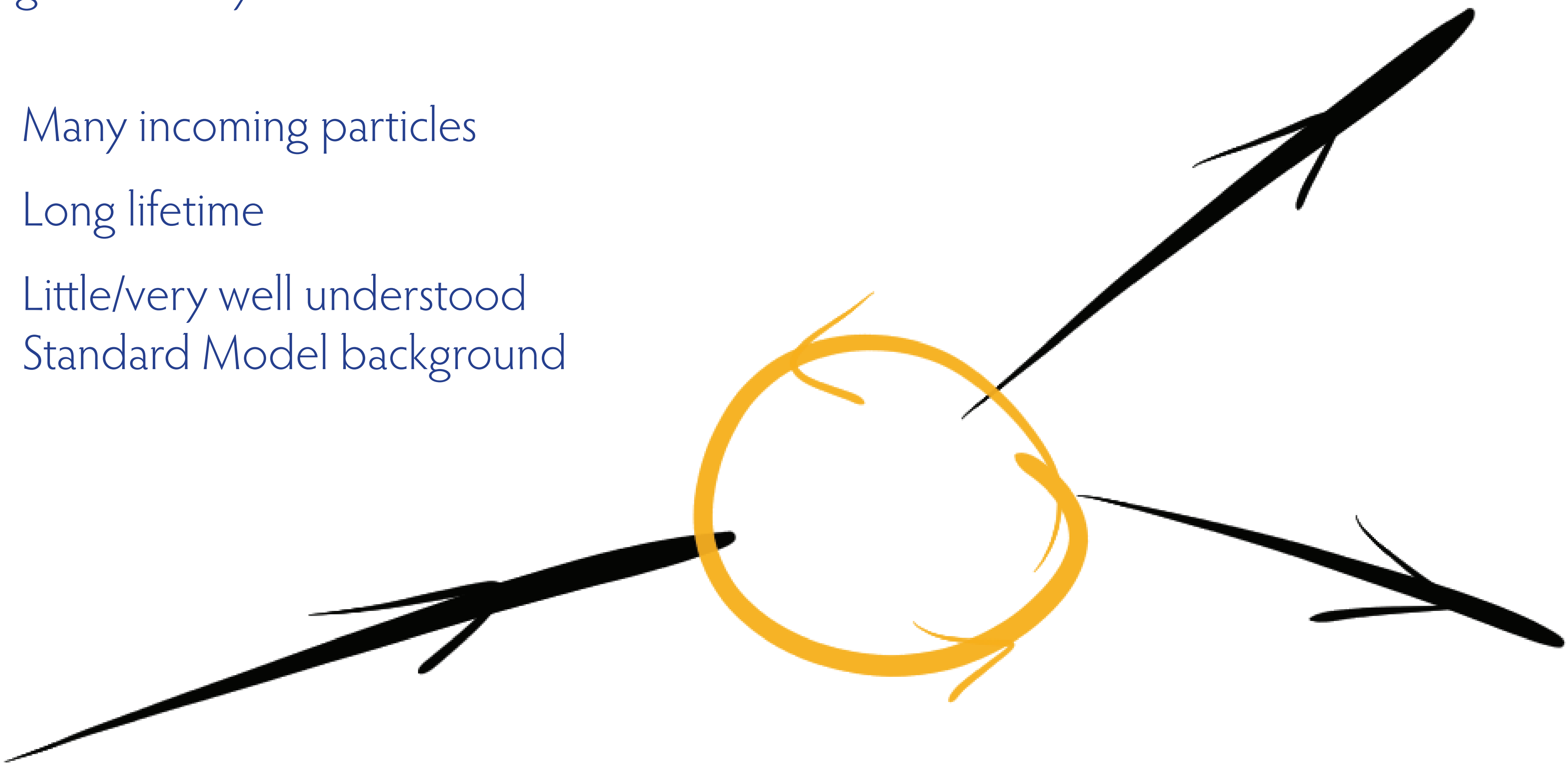
Indirect effects in quantum loops



Indirect effects in quantum loops

Large discovery reach if:

- Many incoming particles
- Long lifetime
- Little/very well understood Standard Model background



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
- Experiment II:
  Dark photons, proton radius etc. with MAGIX
- More experiments:
  Dark matter, electron electric dipole moment etc.

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"

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

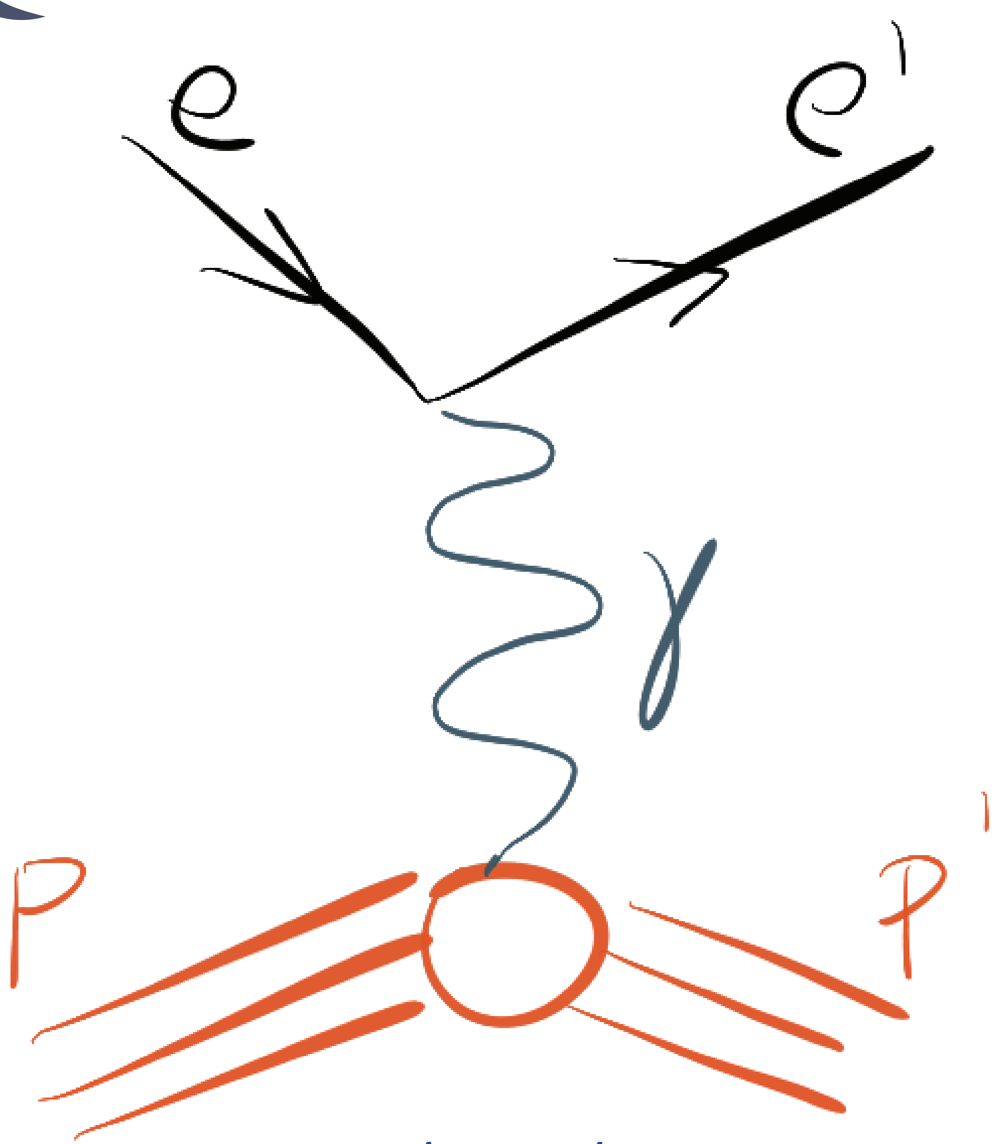
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

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

Weak mixing angle and charges



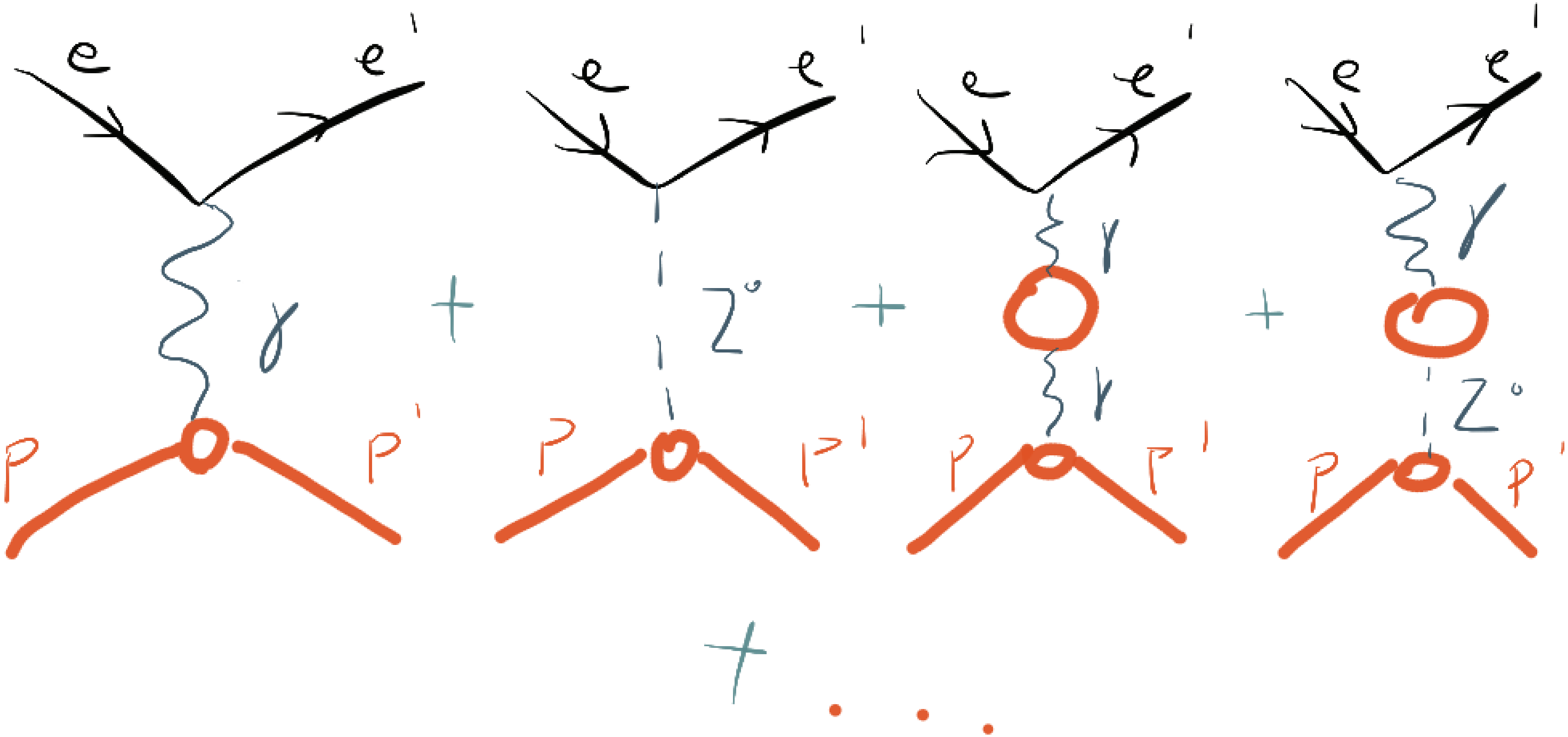
Proton electric charge

+e

Proton weak charge

$1 - 4\sin^2\theta_W$

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



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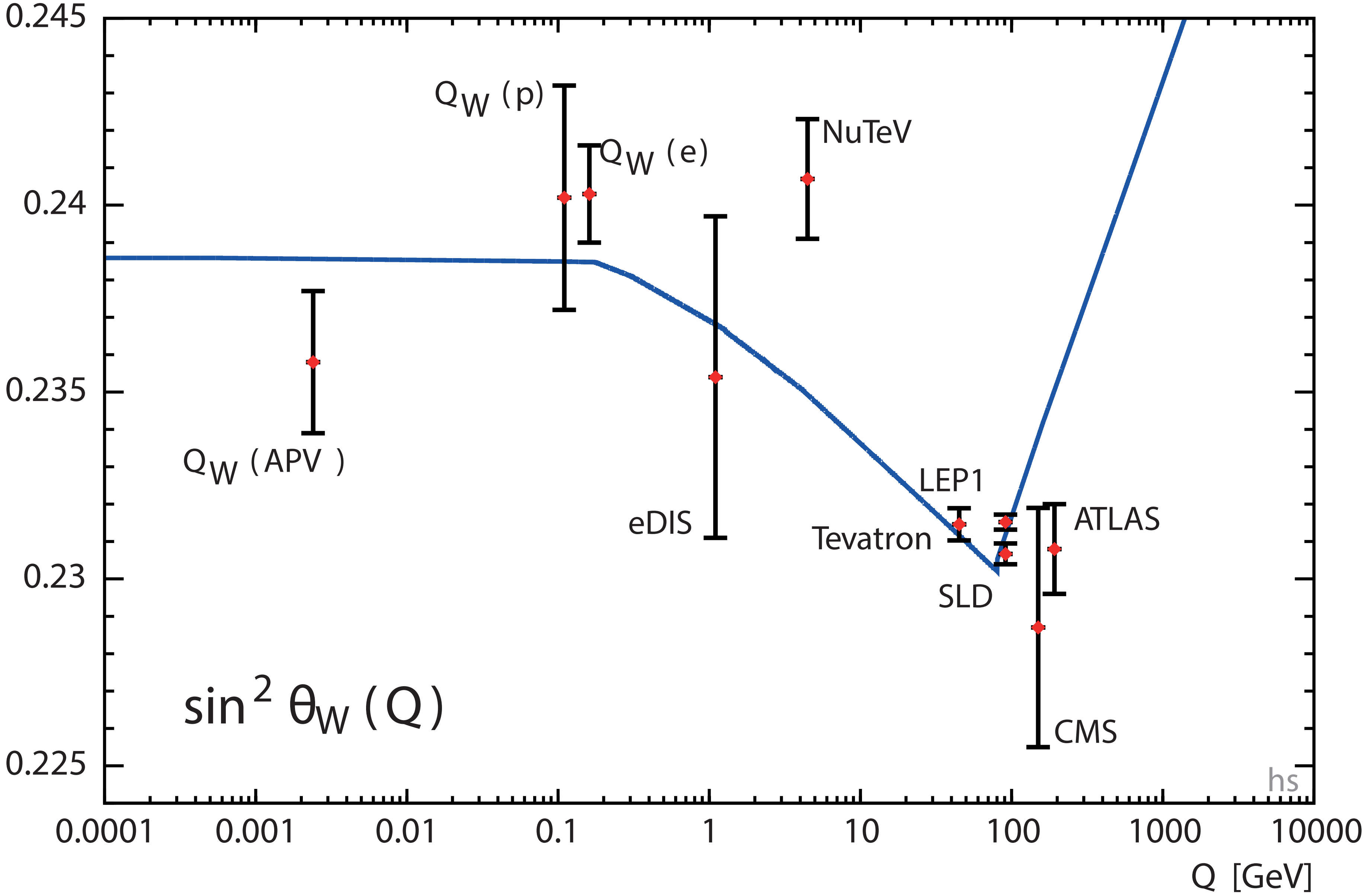

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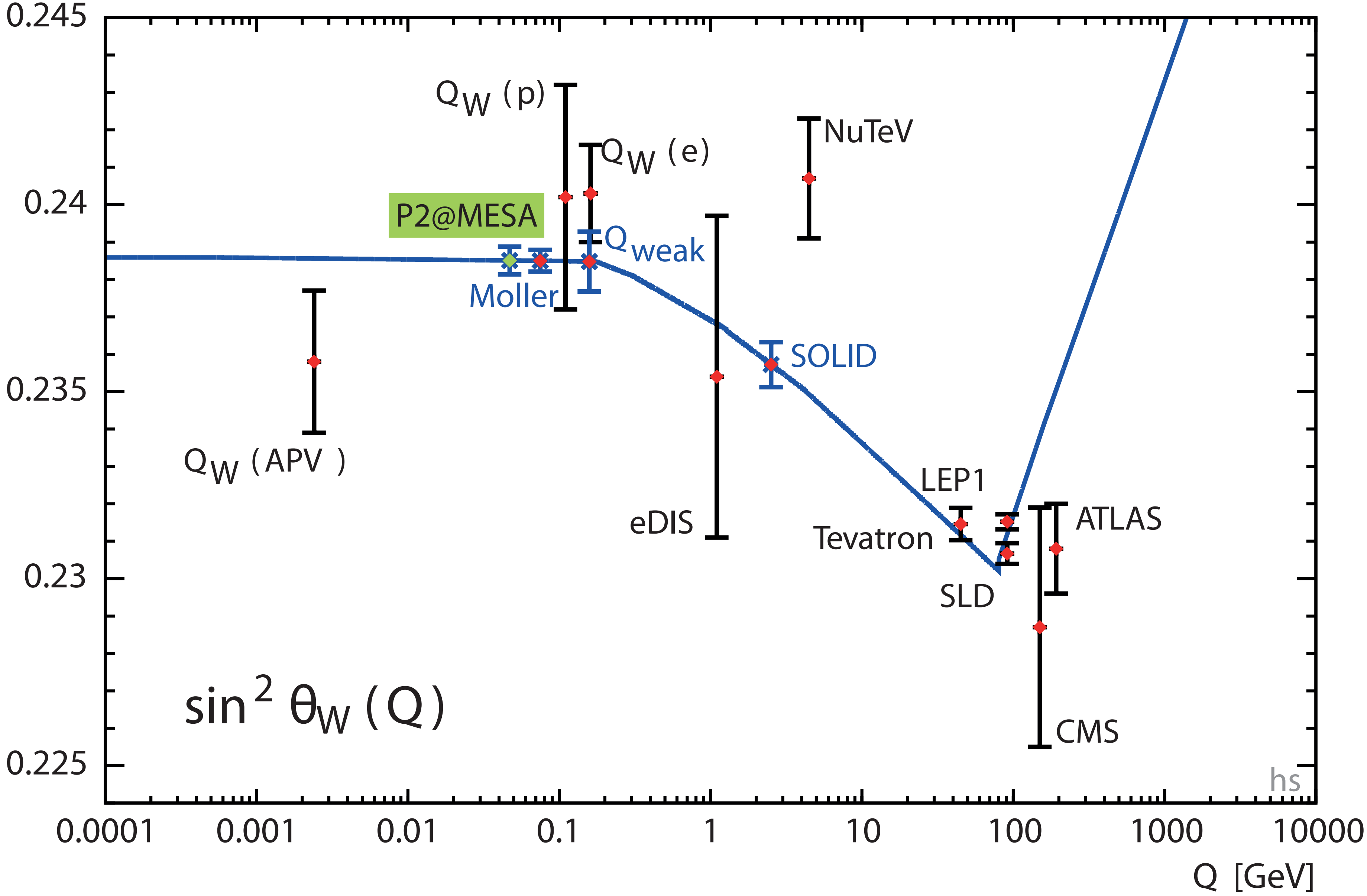
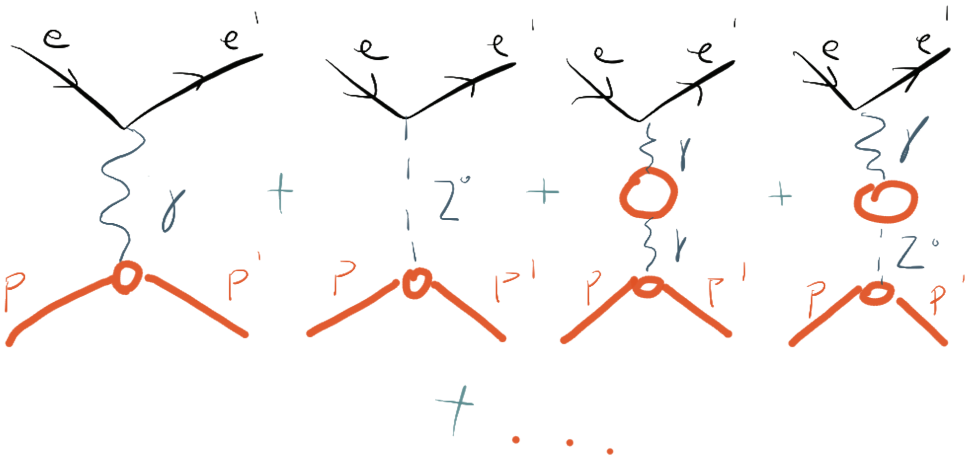
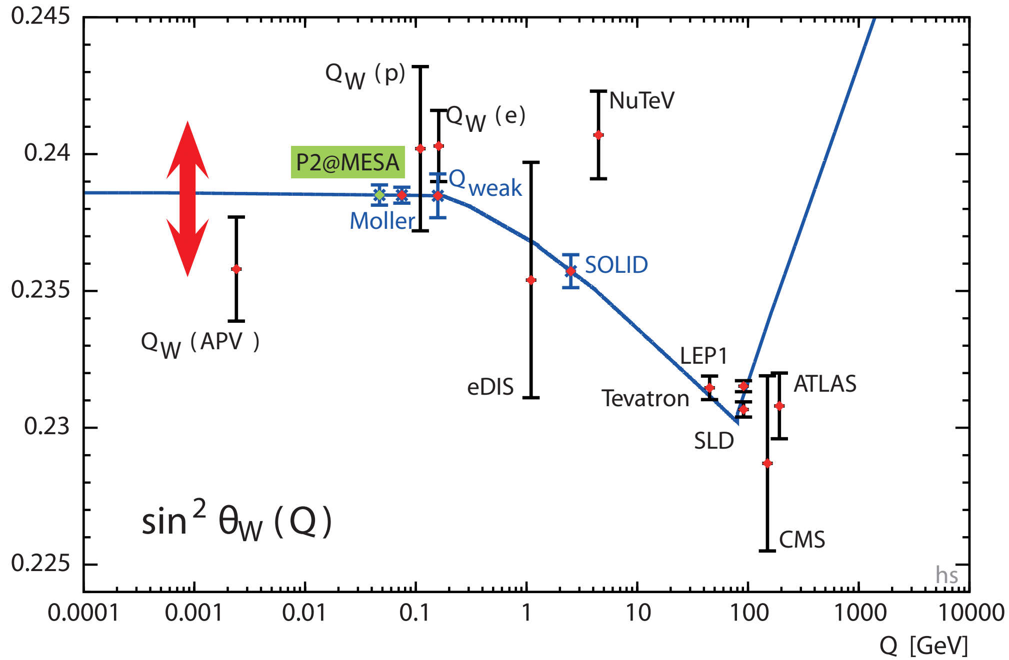
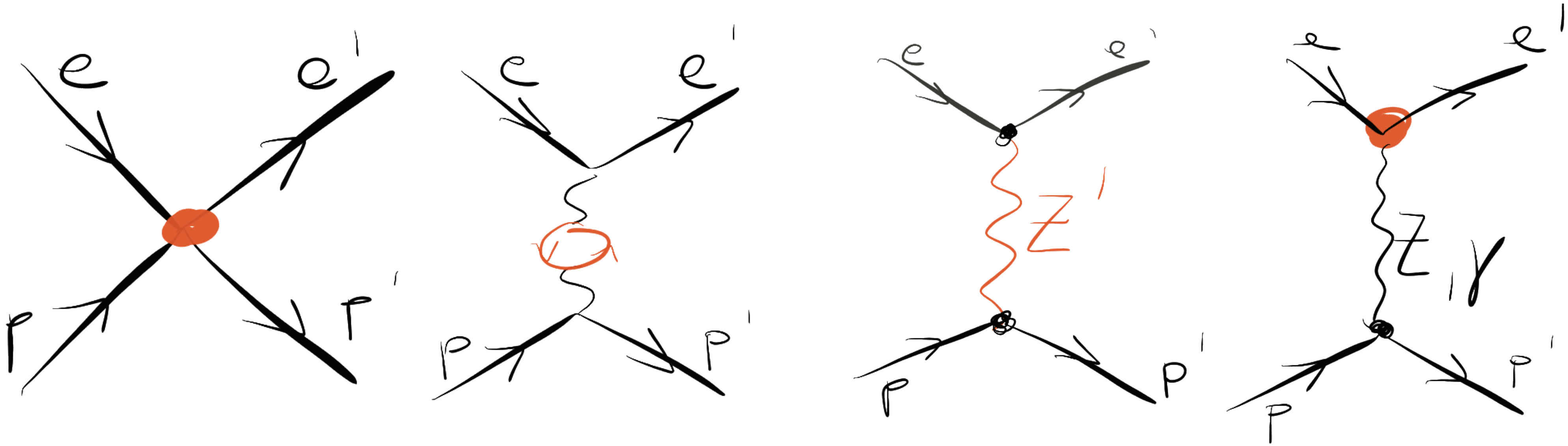


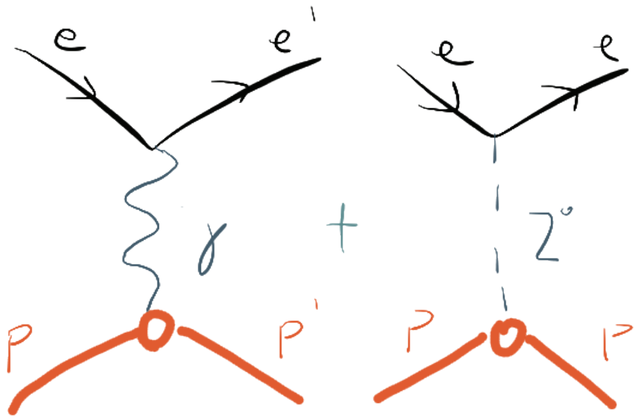
New Physics in the running

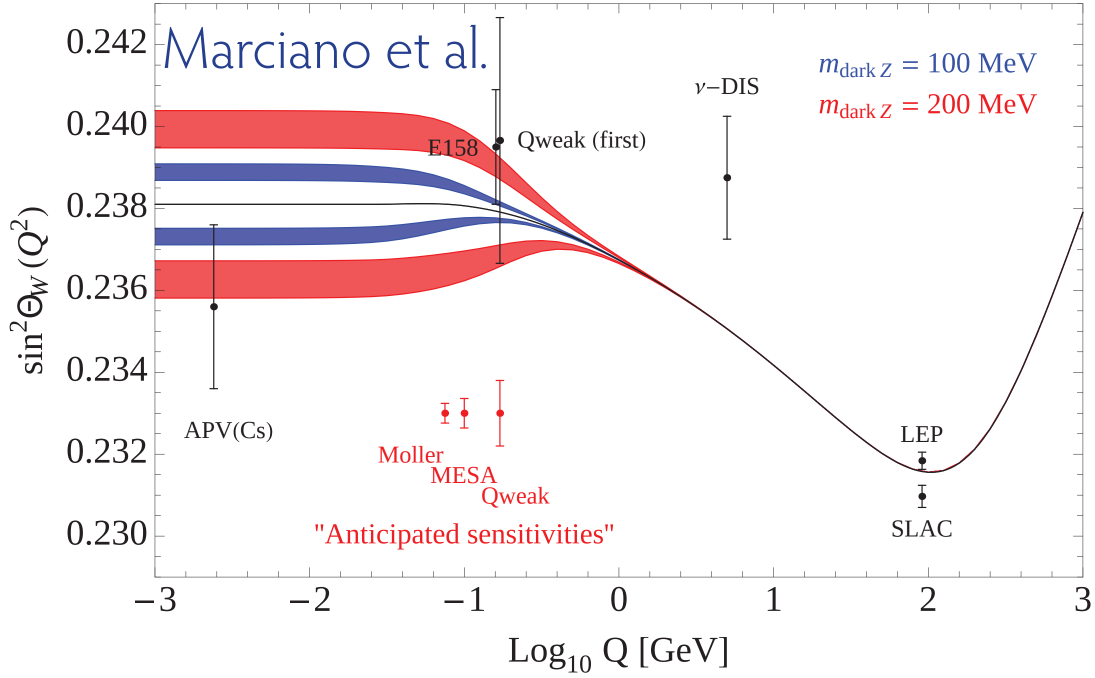


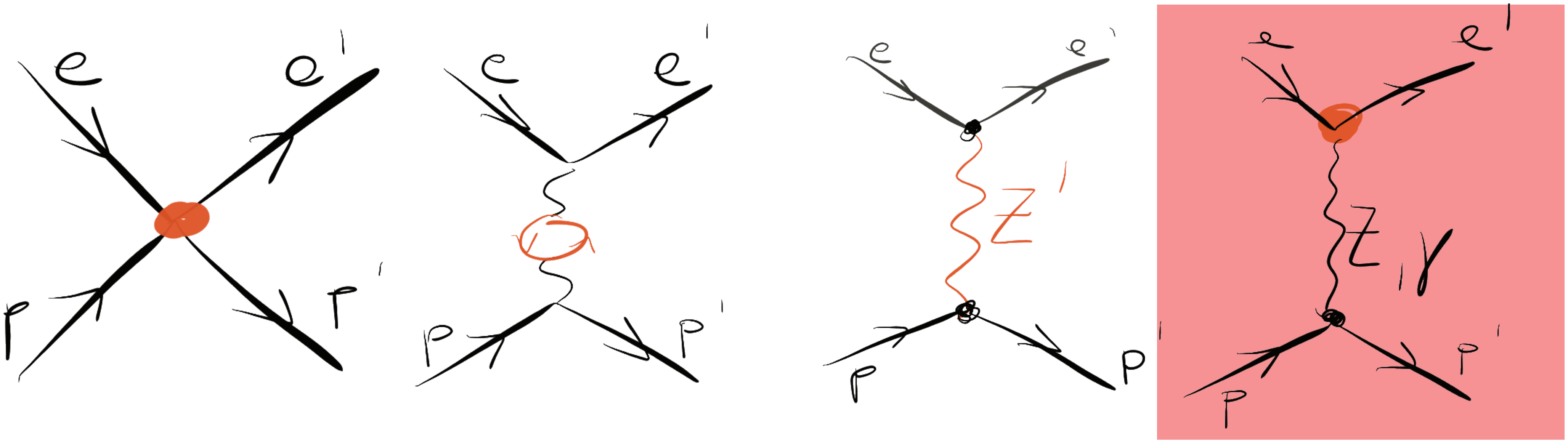




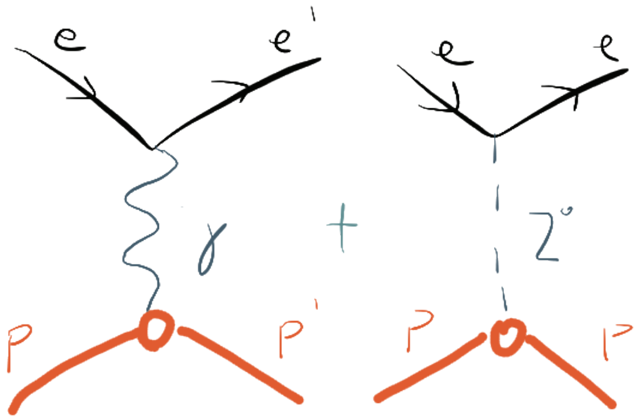
Dark Z in mixing







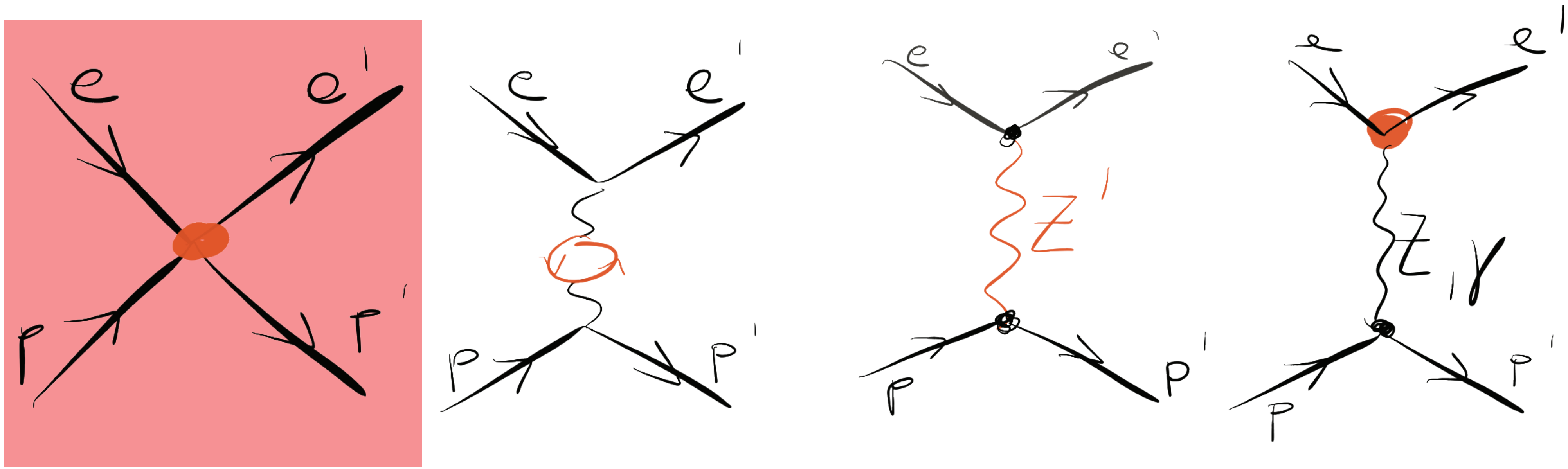
Contact Interactions



Contact interactions up to

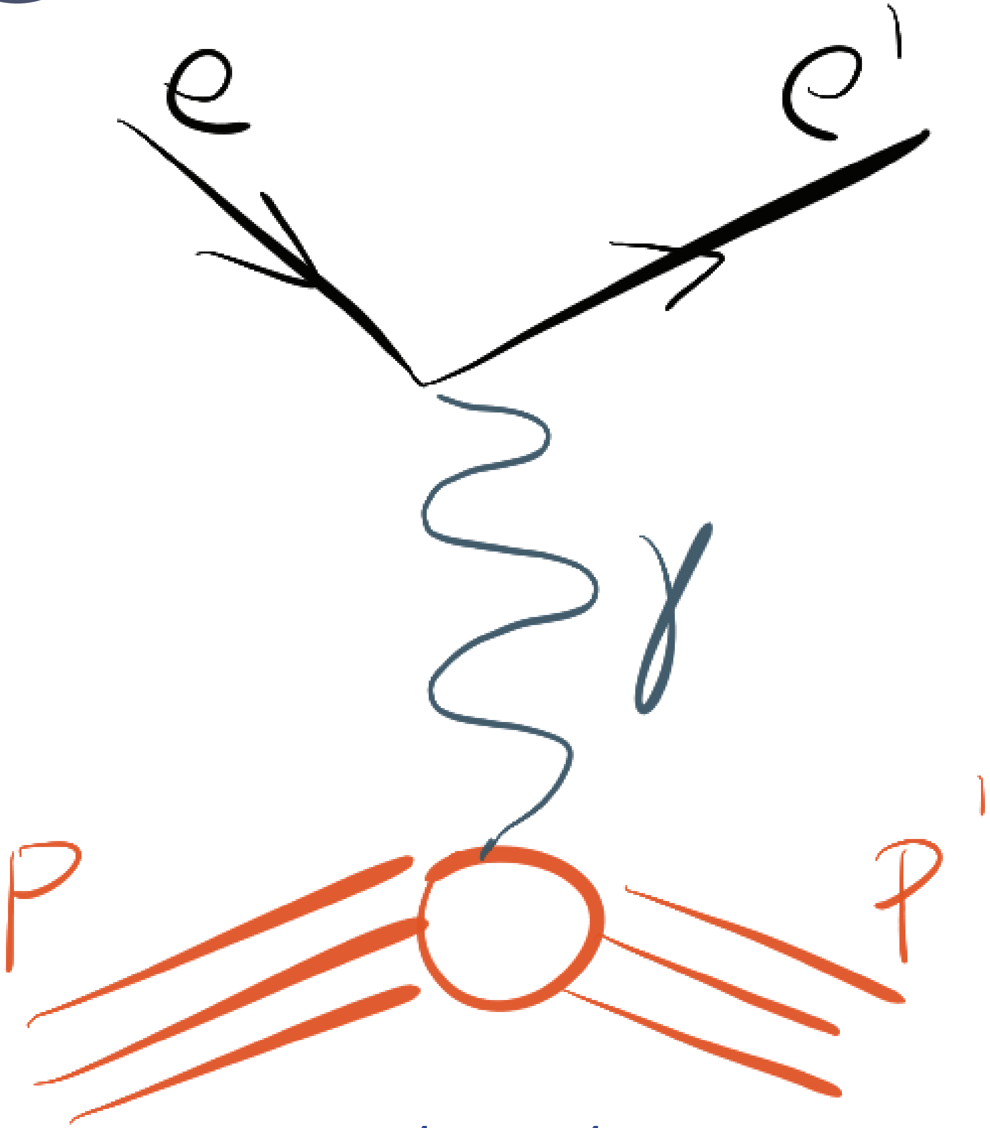
49 TeV

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



How to measure the weak charge?

Weak mixing angle and charges



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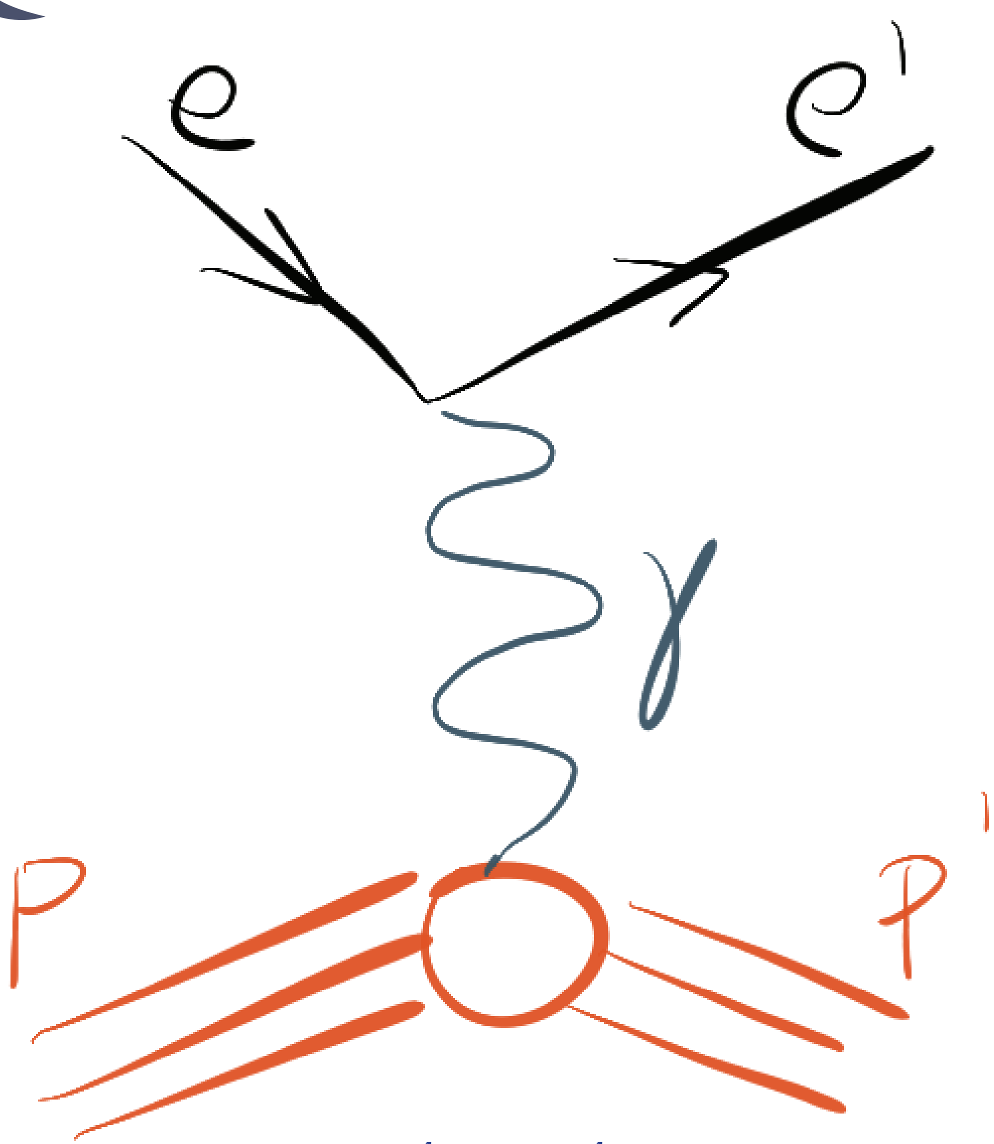
Weak mixing angle and charges



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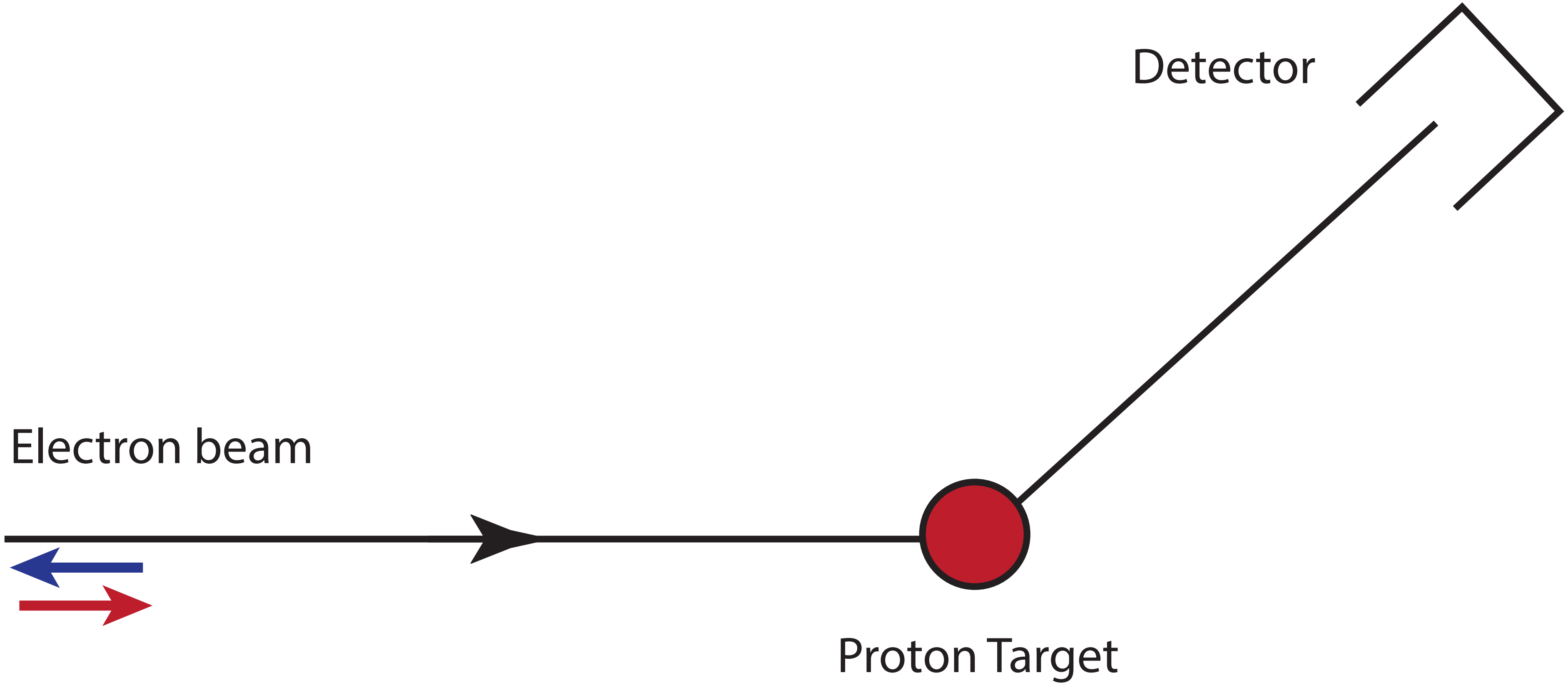
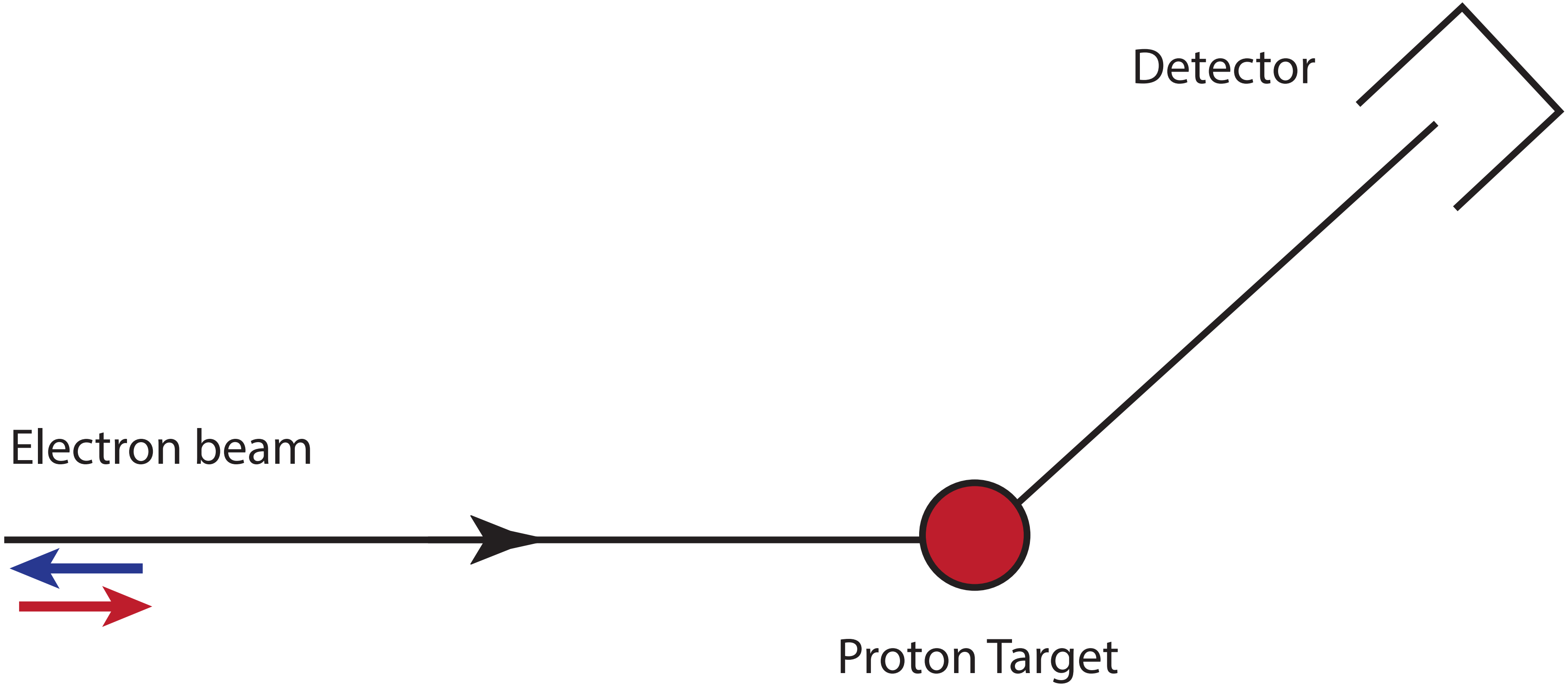
Parity violating electron scattering



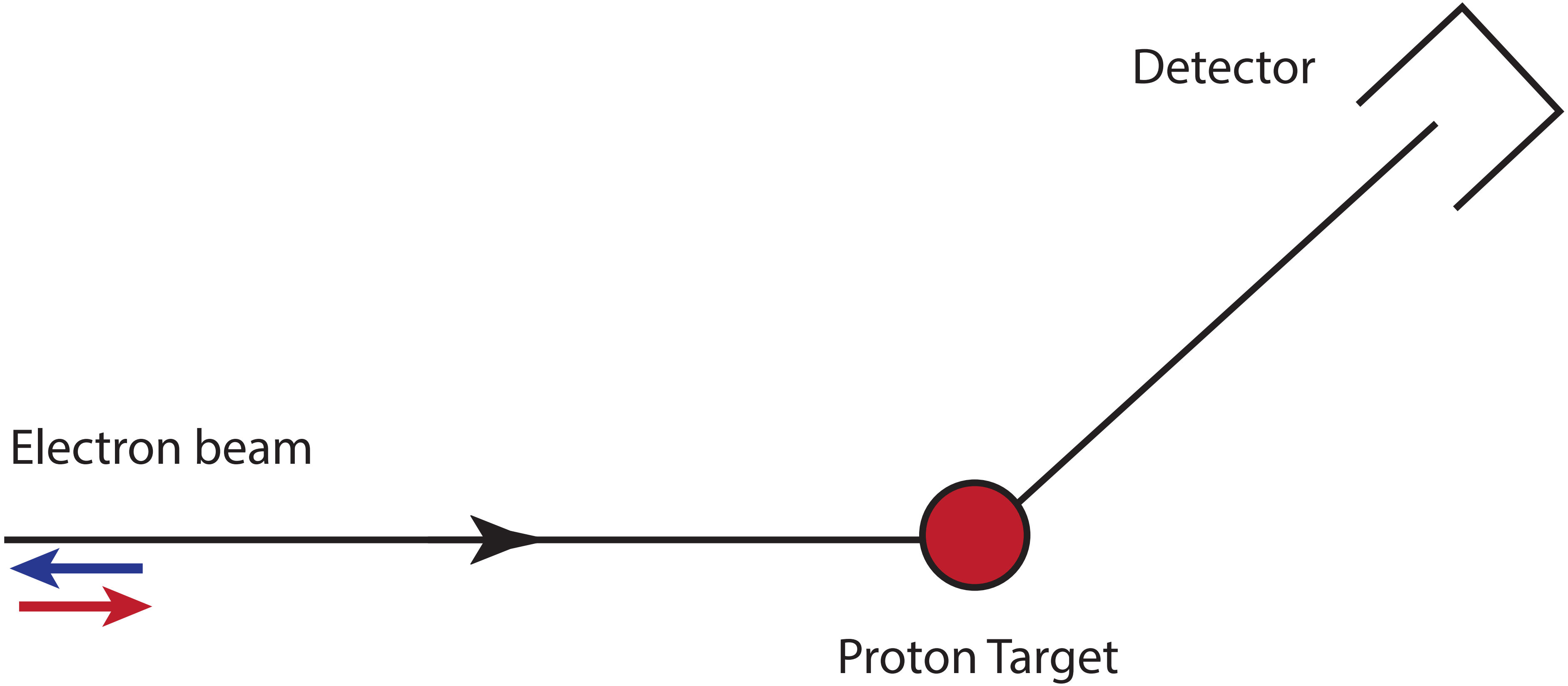
Parity violating electron scattering

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



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

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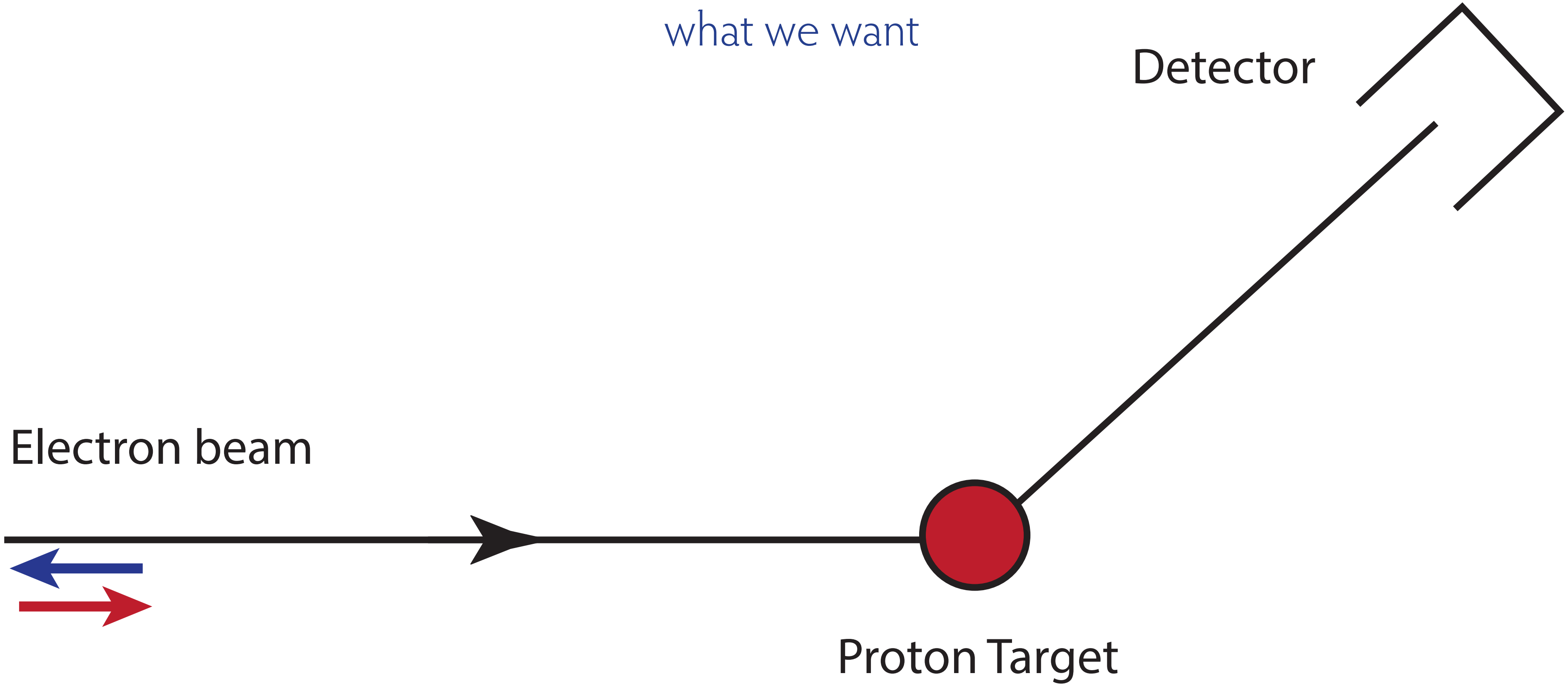
Weak charge - what we want



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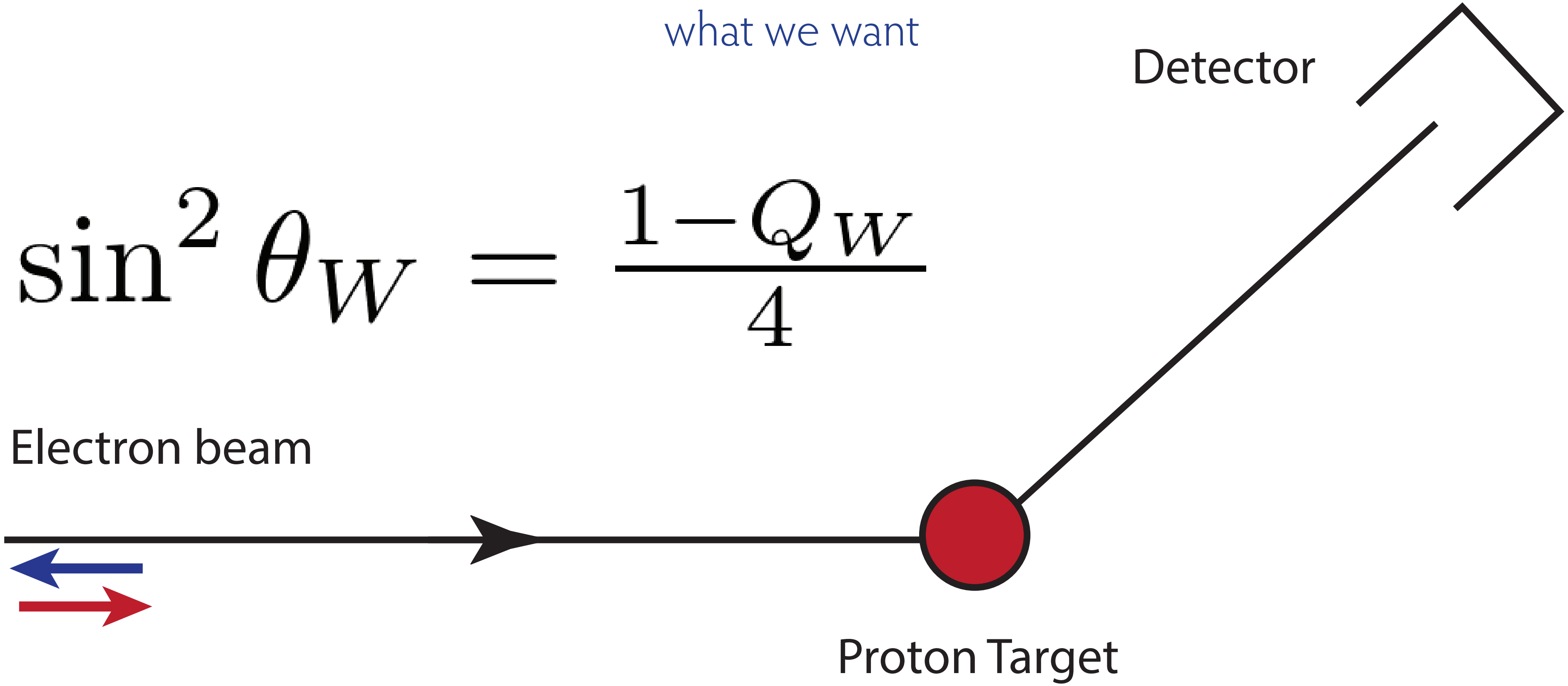
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

Weak charge - what we want

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



Why is this difficult?

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

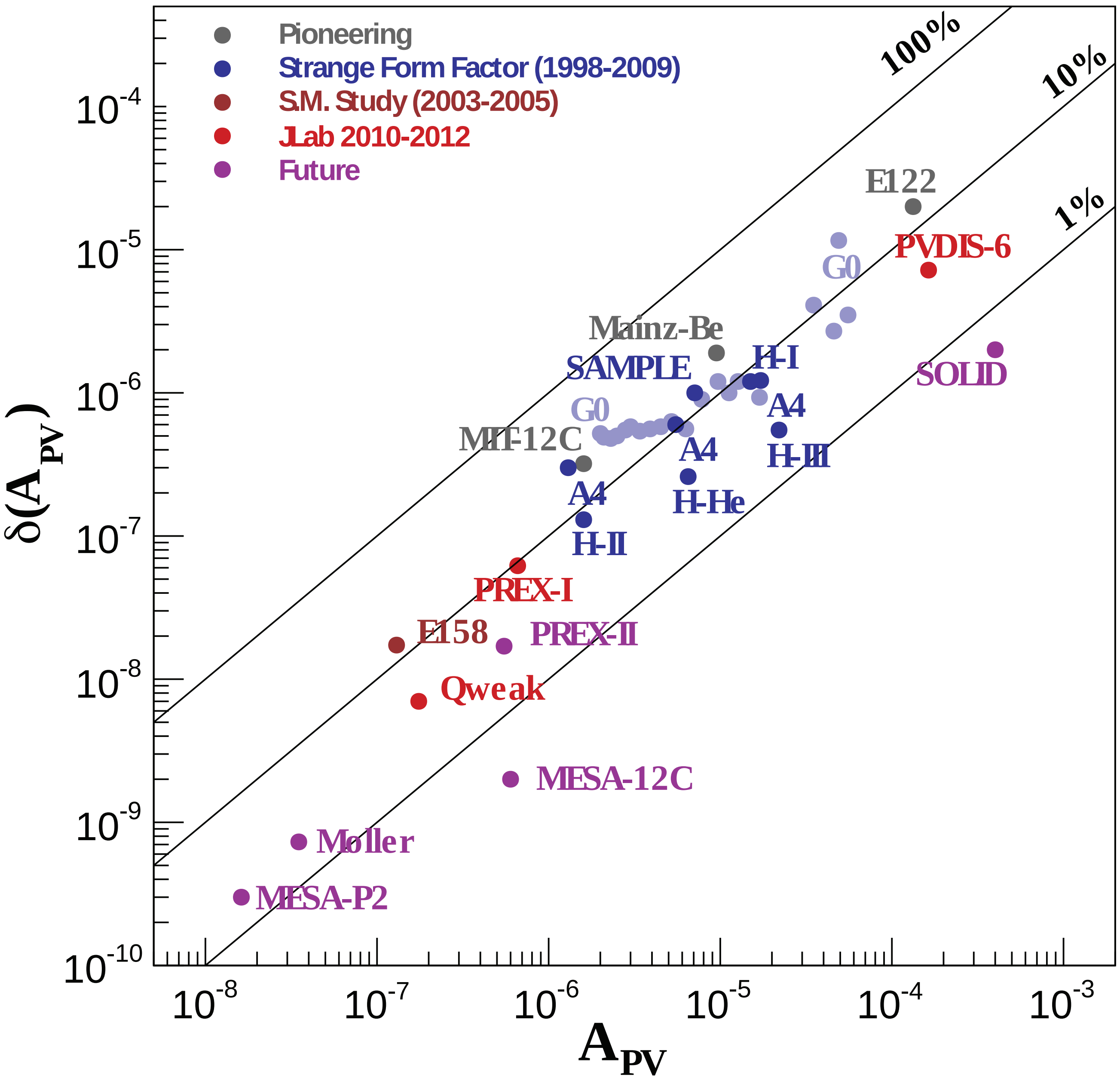
$$Q_W = 1 - 4\sin^2\theta_W$$

- 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%
- 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

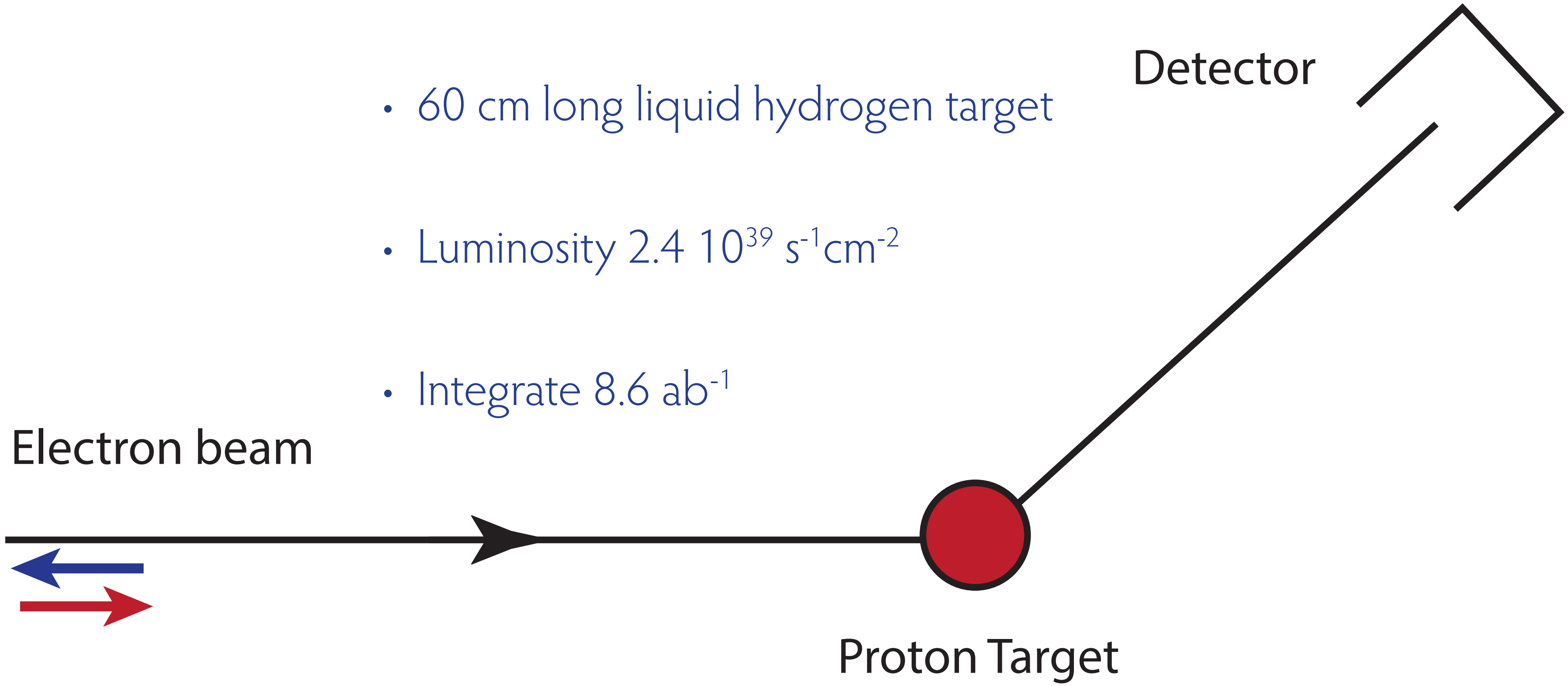
$$\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1-4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\Delta Q_W}{Q_W}$$

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

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}



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

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

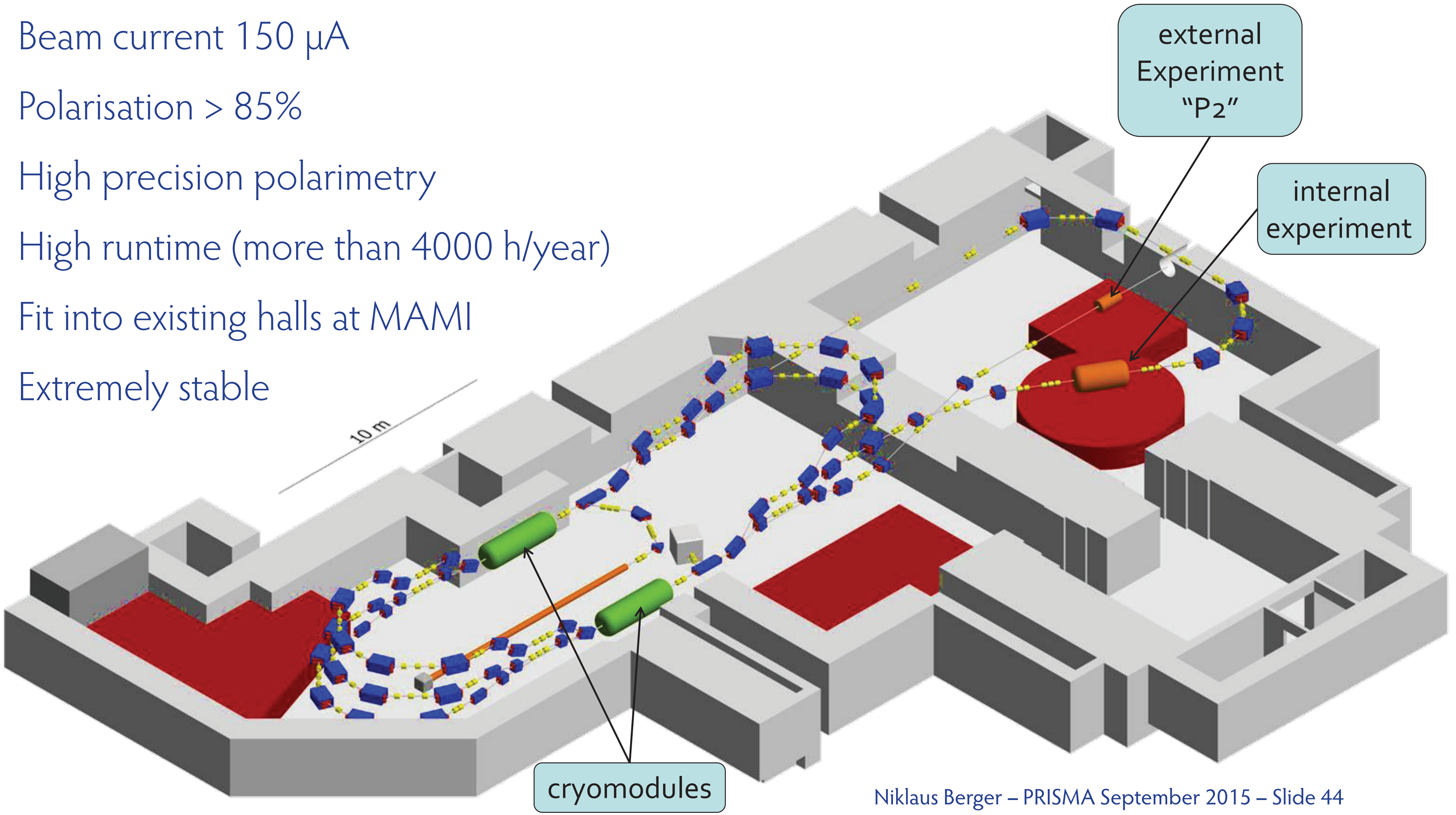
If you cannot rent it, build it:

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

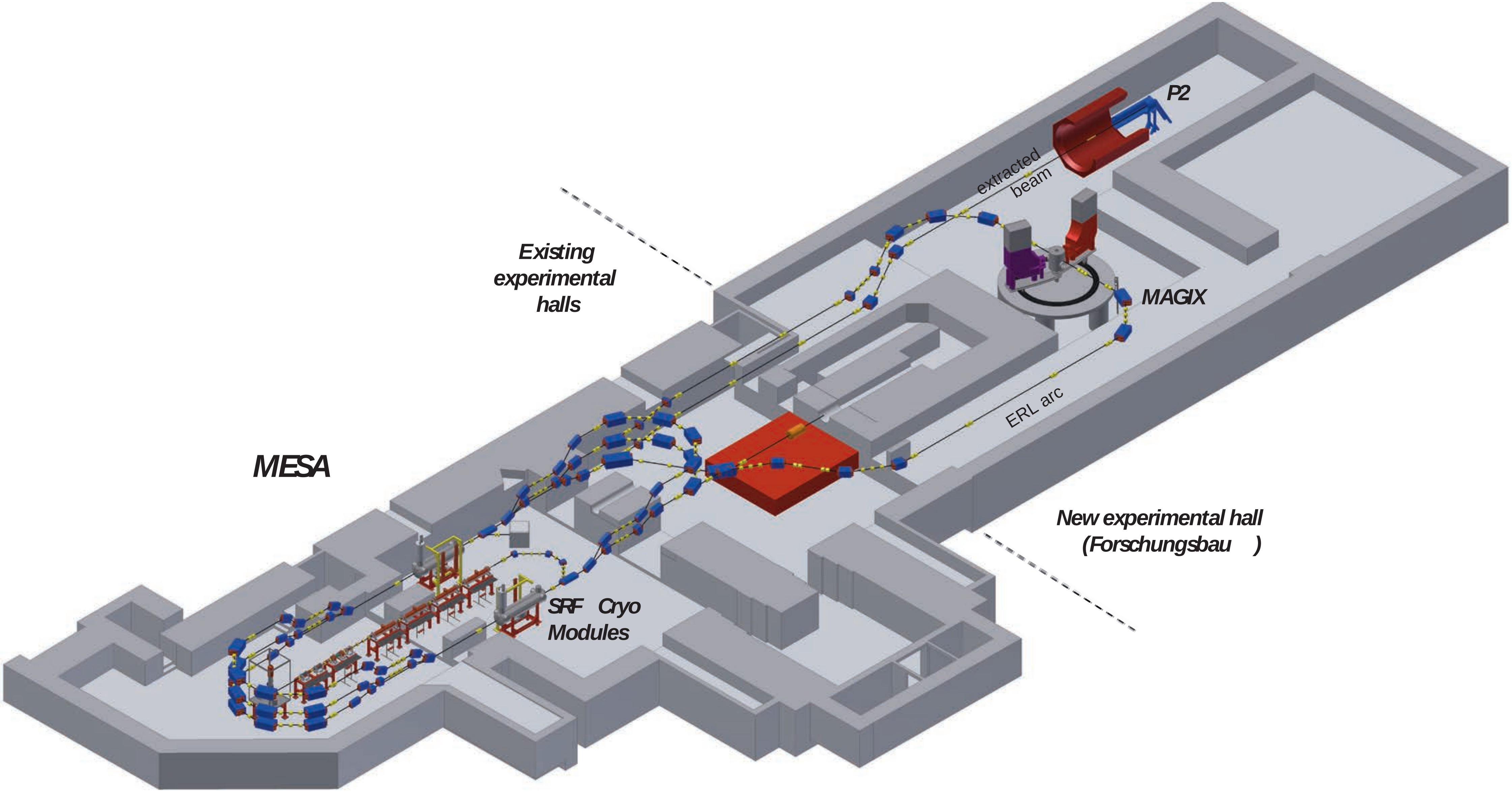


Stability Requirements

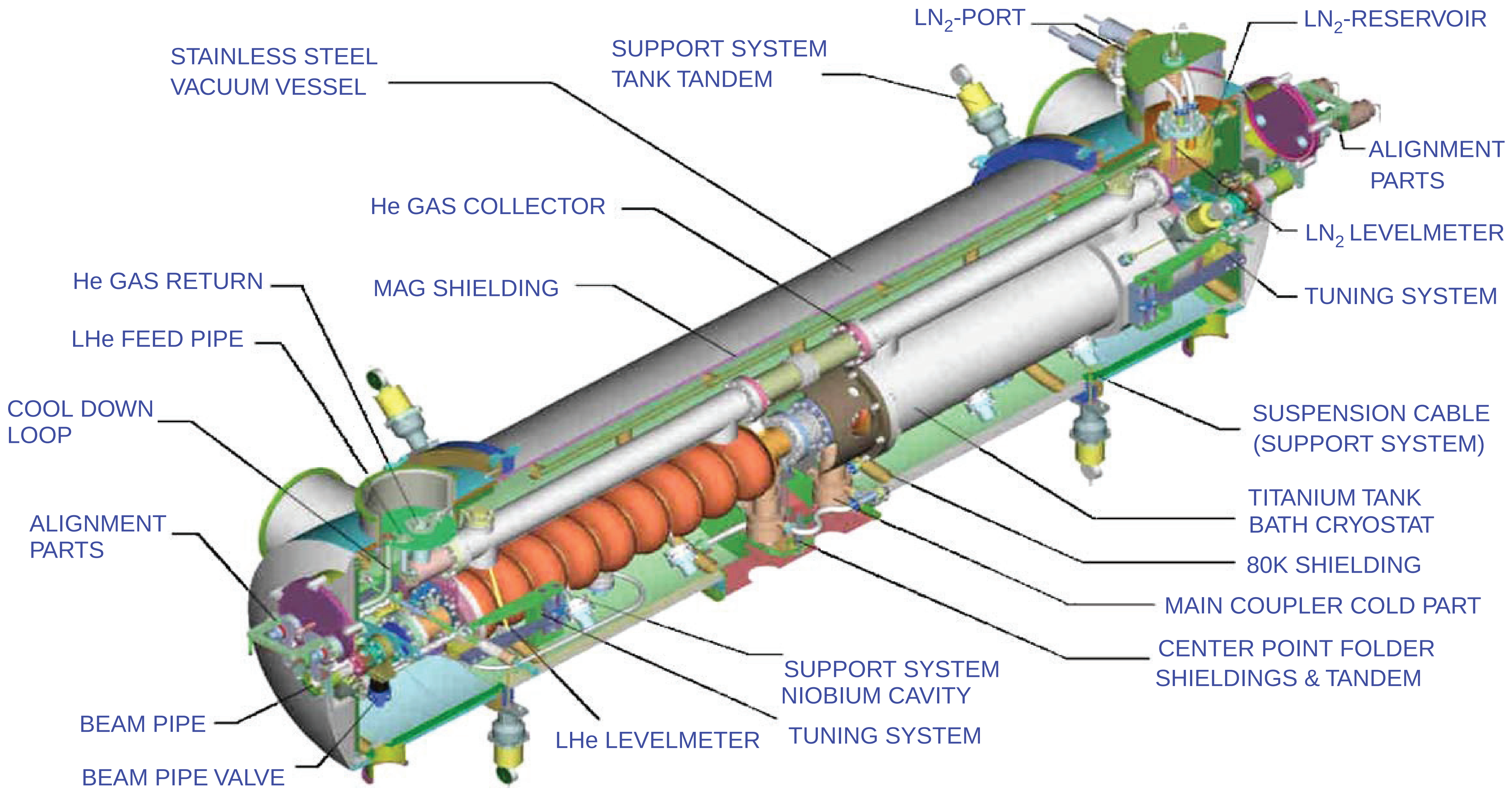
The main worry are beam fluctuations correlated with the helicity:

	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


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

Superconducting Cryomodules



Teichert et al. NIM A 557 (2006) 239

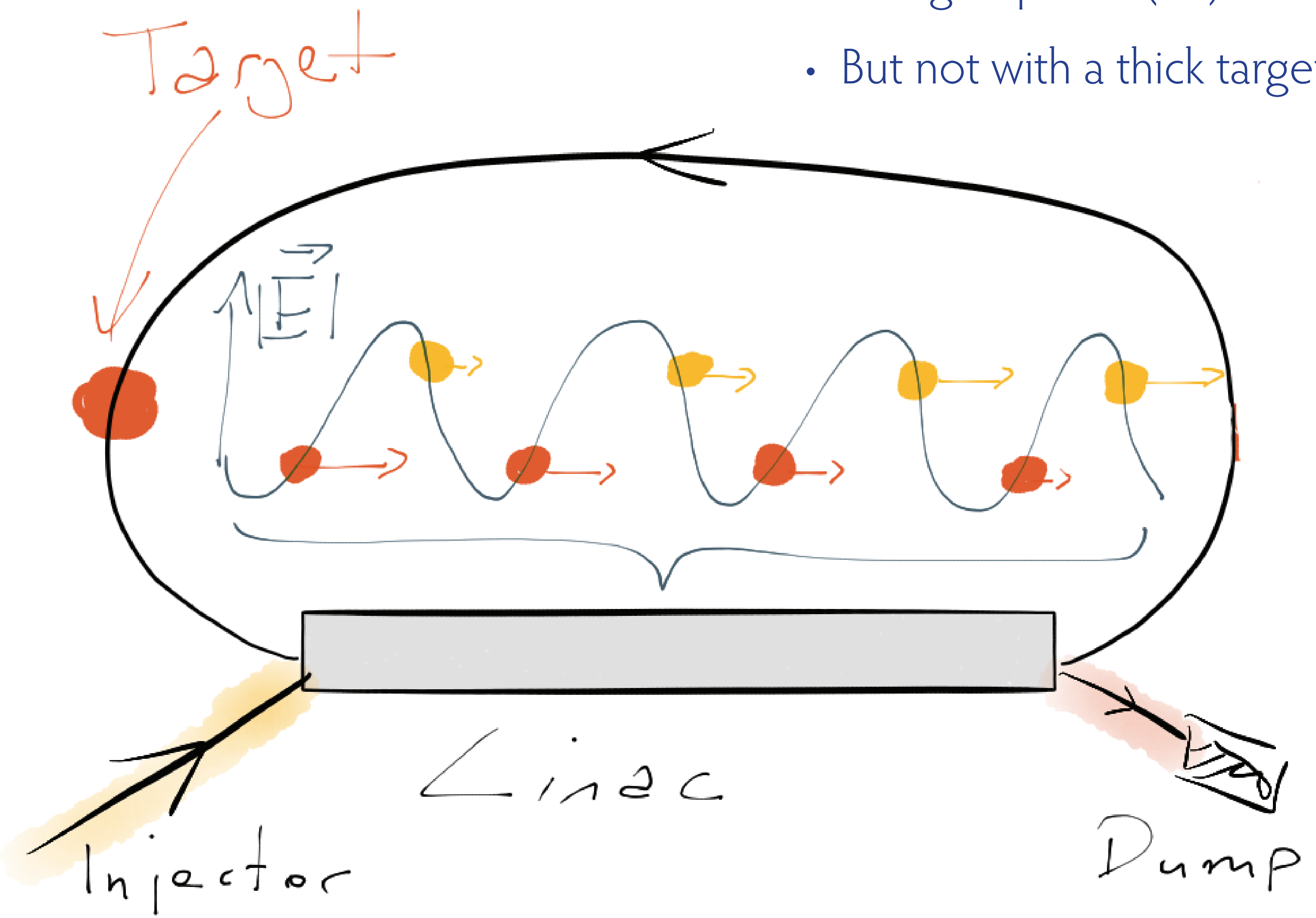
Energy recovery

Can we go to higher beam currents?

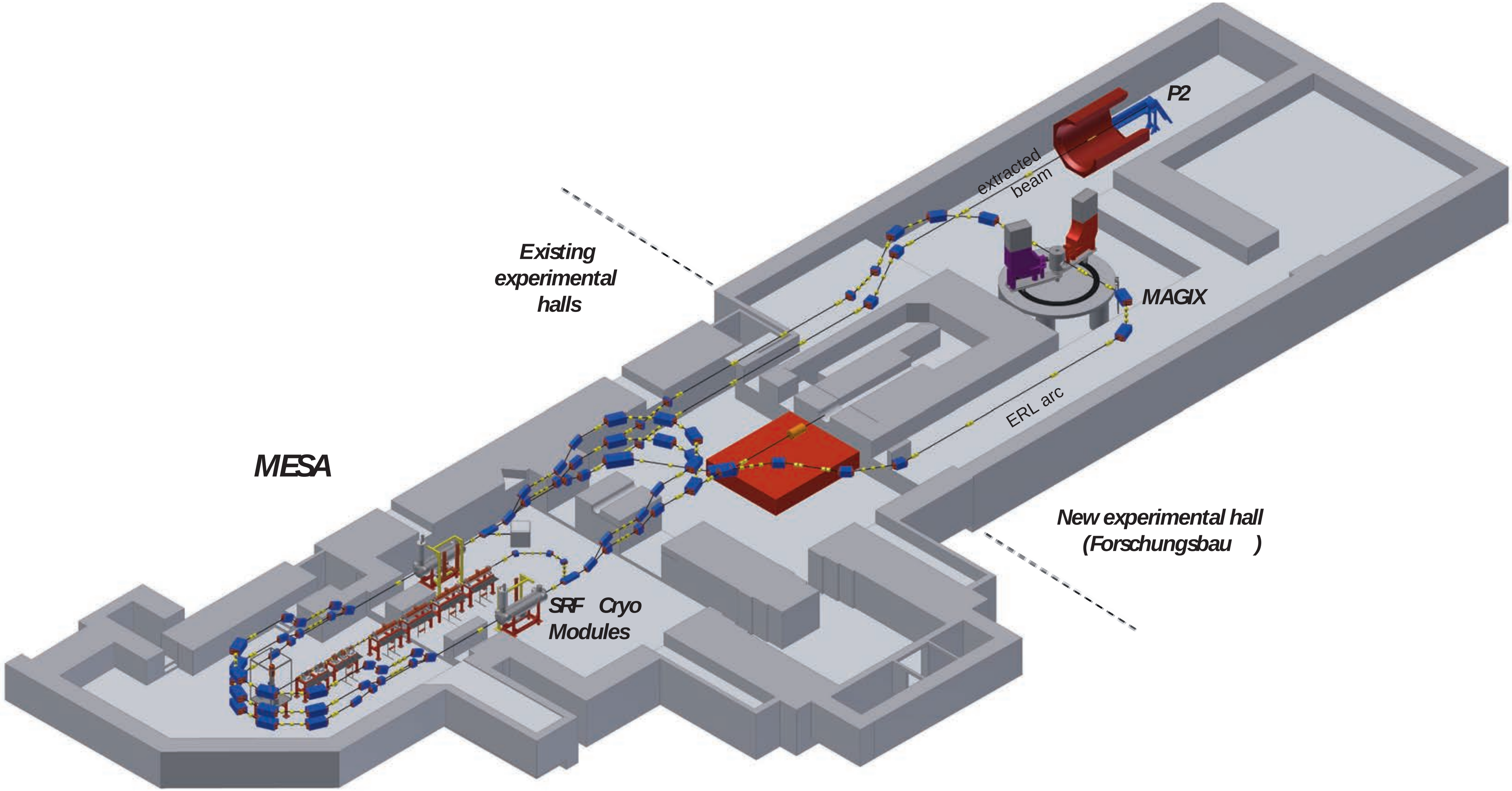
- In principle yes...
- But power is expensive
- Why dump electrons?

Energy recovery

- Put energy back into field!
- Can go up to 1 (10) mA beam current
- But not with a thick target



MESA


P2
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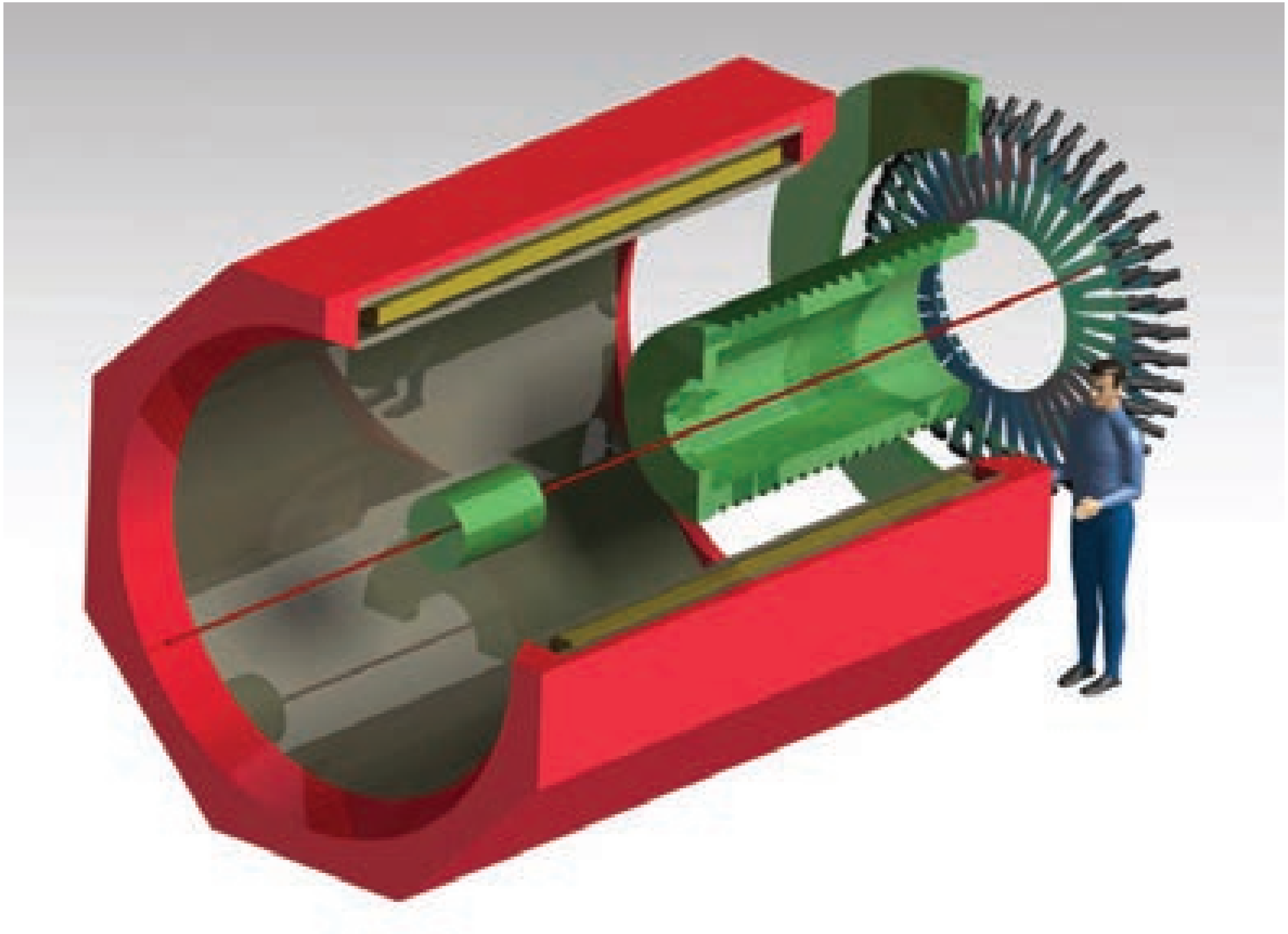
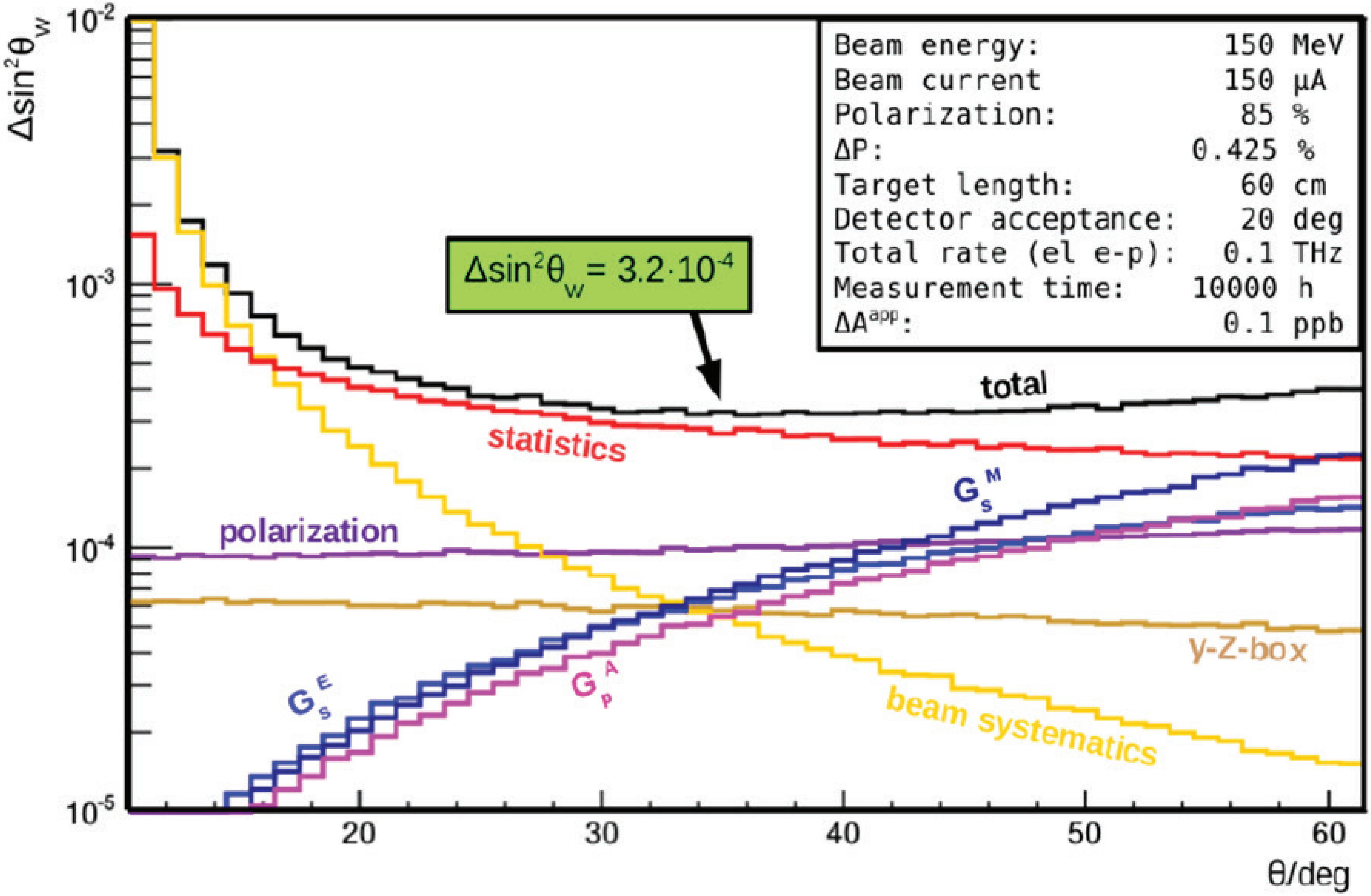
P2:

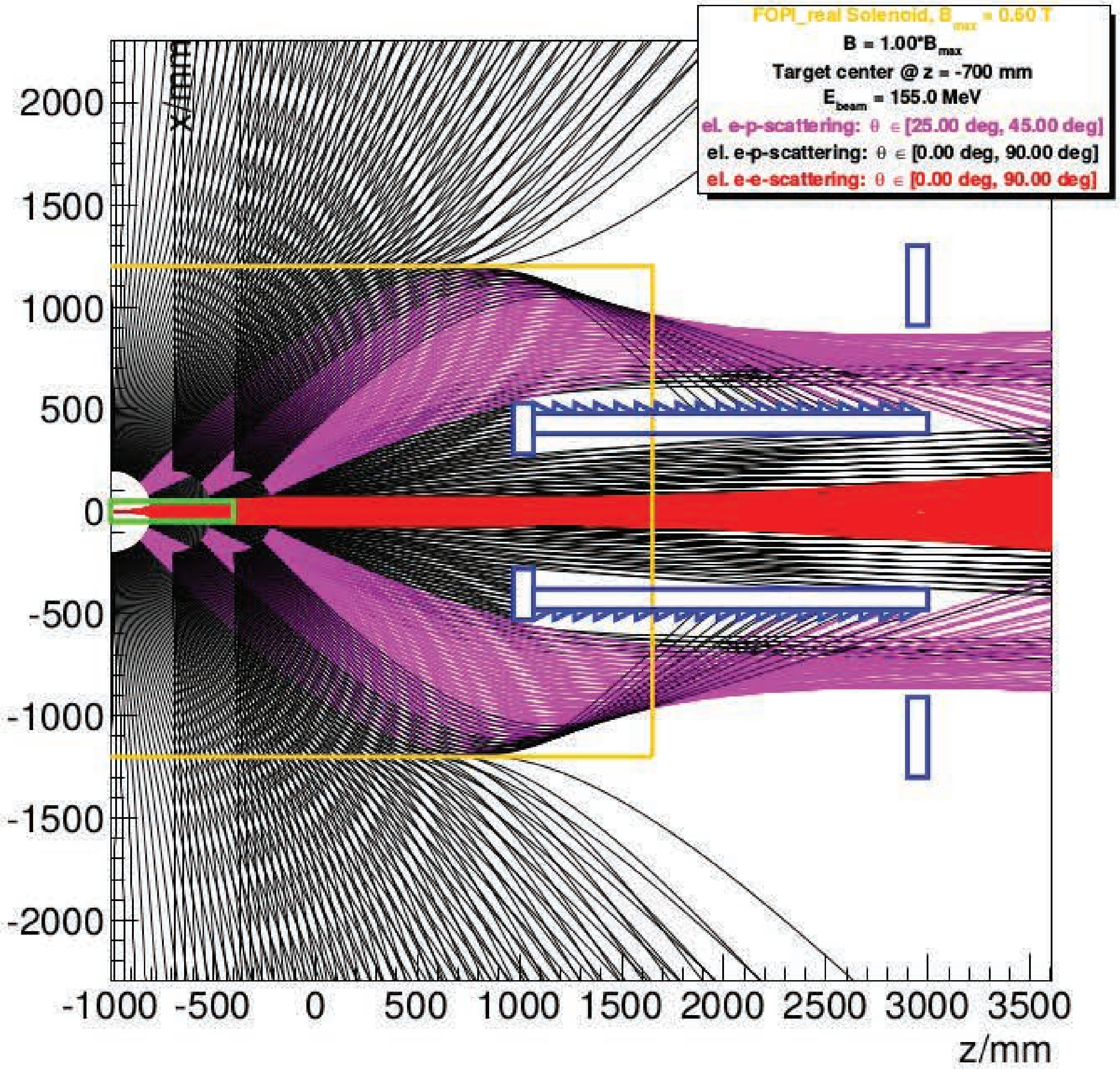
How to detect 100 GHz of (the right) electrons…



Choice of scattering angle



Solenoid spectrometer



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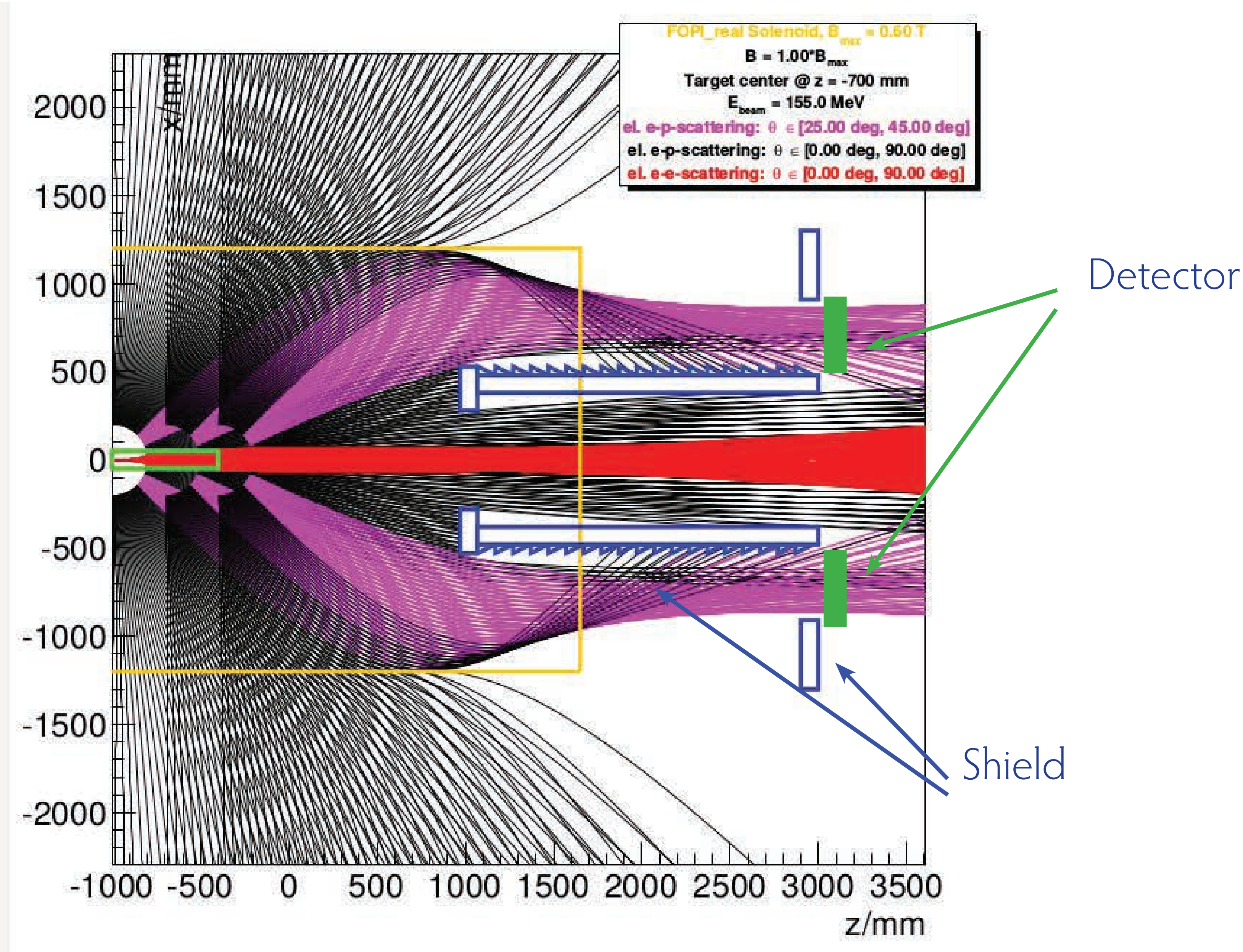
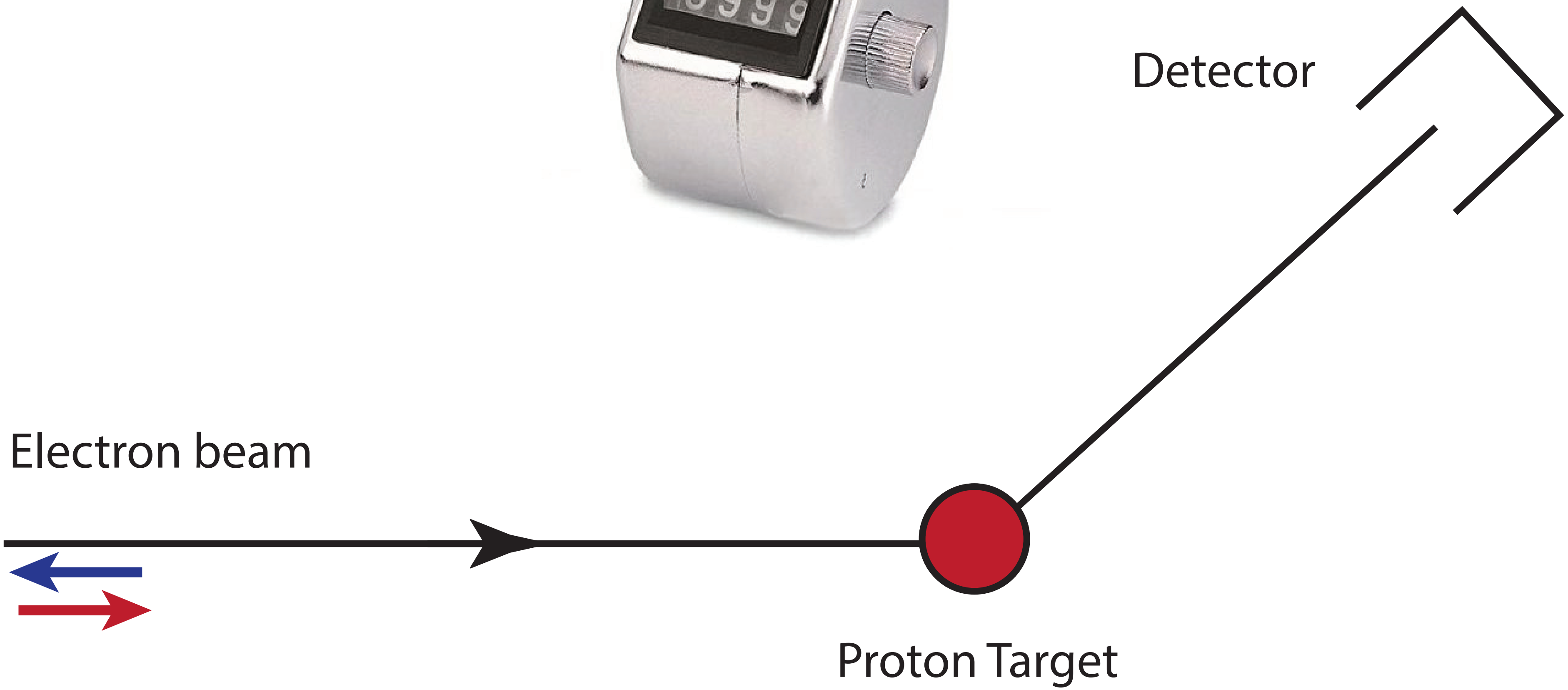
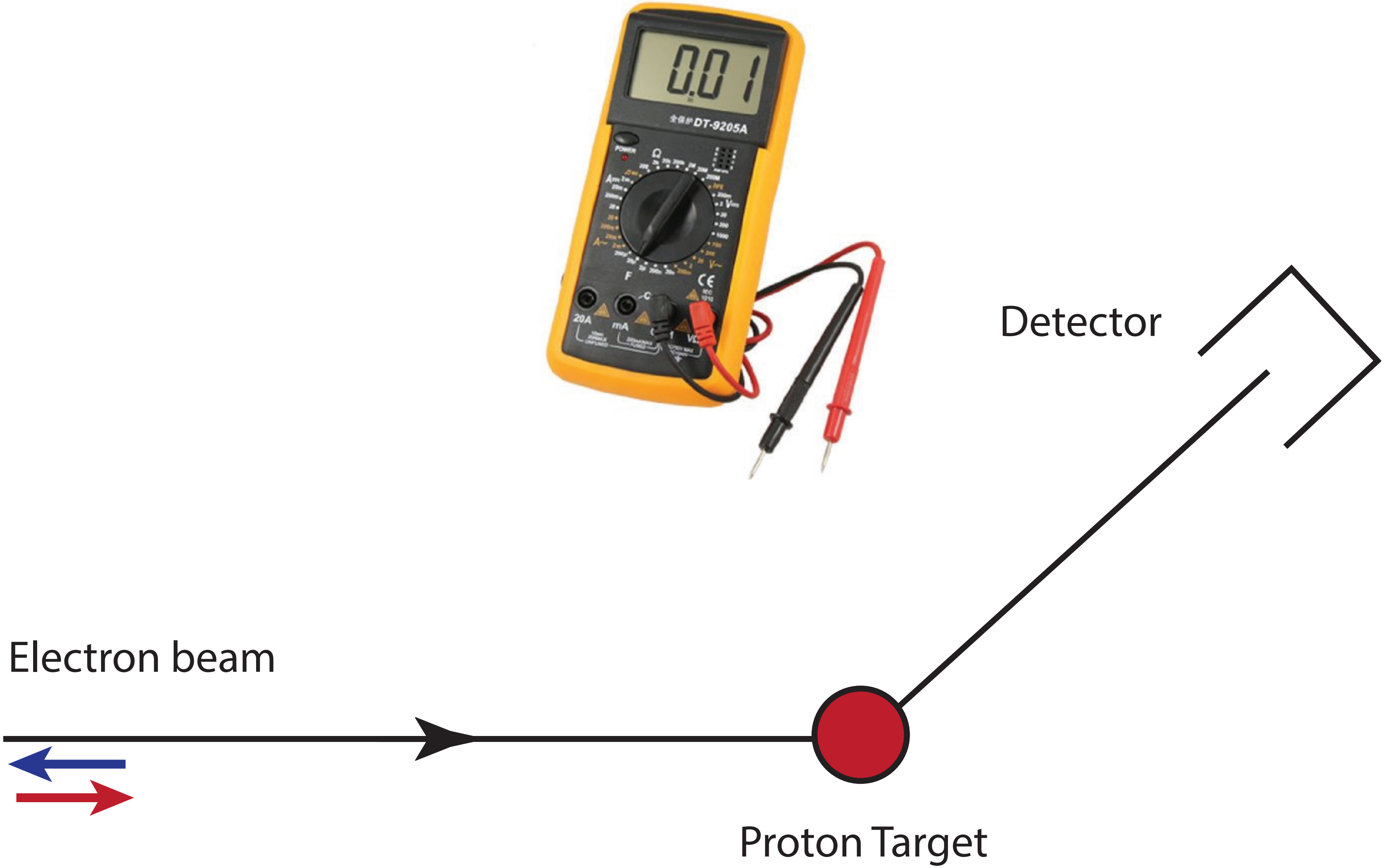


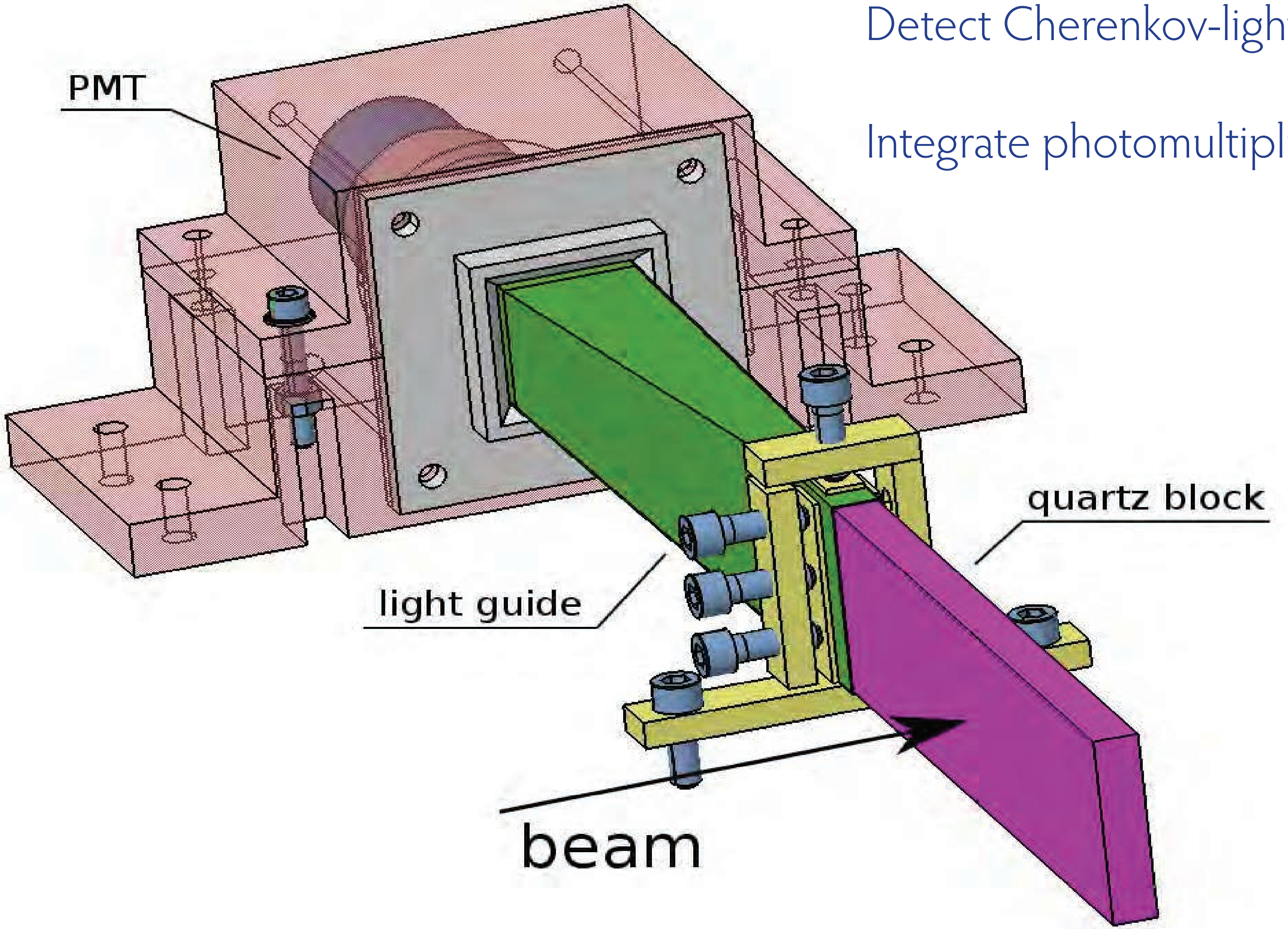
Counting detectors



Integrating detectors



Quartz-Bars & Photomultipliers



Detect Cherenkov-light created by electrons

Integrate photomultiplier current

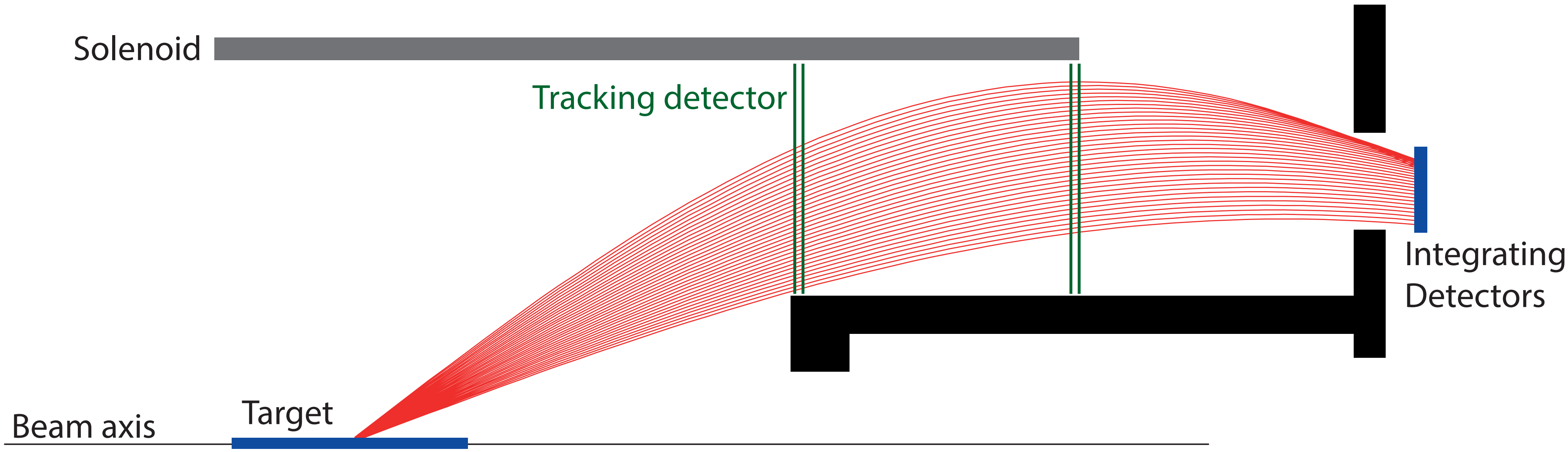
Measuring Q^2:

Tracking a

lot of low momentum particles

Tracker requirement

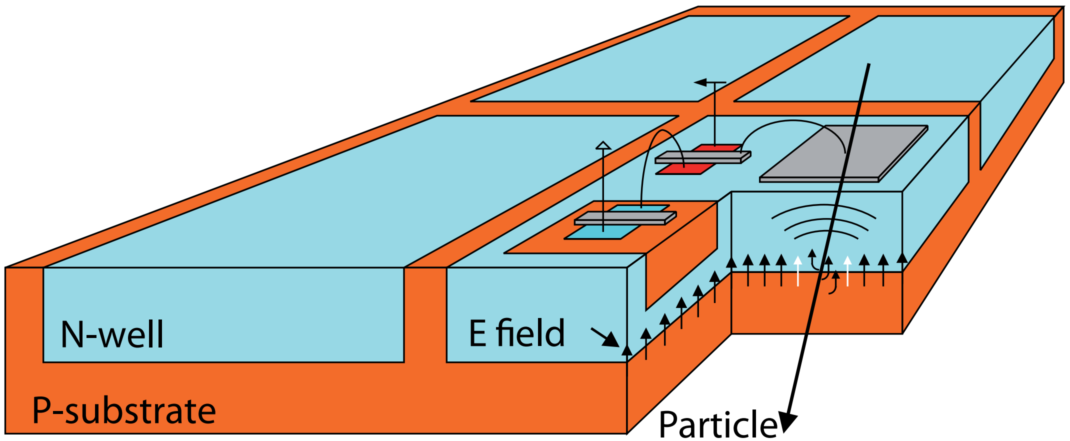
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

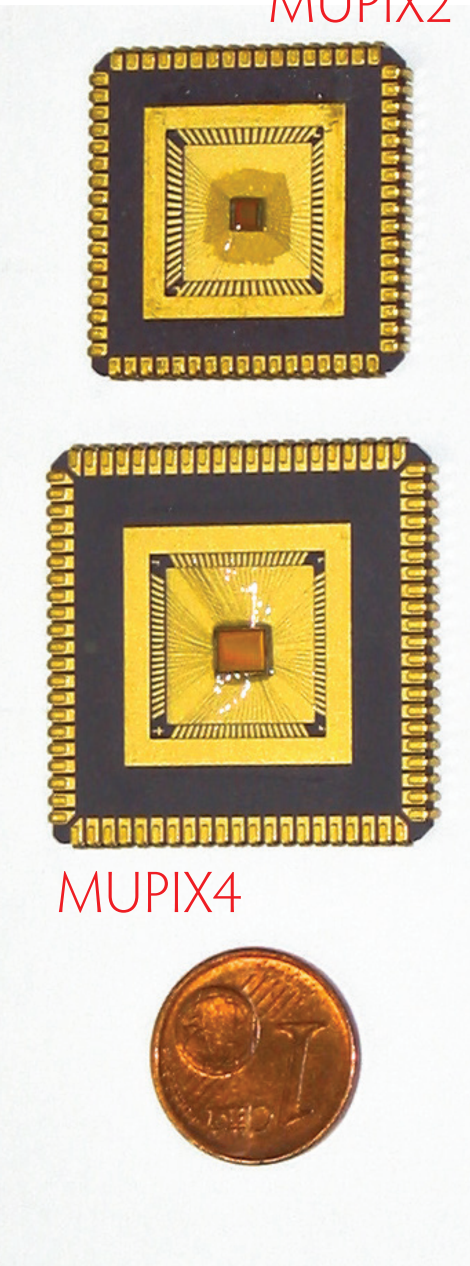


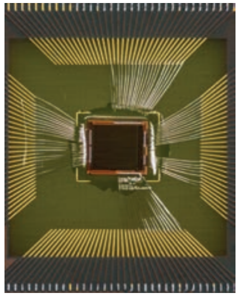
High voltage monolithic active pixel sensors - Ivan Perić

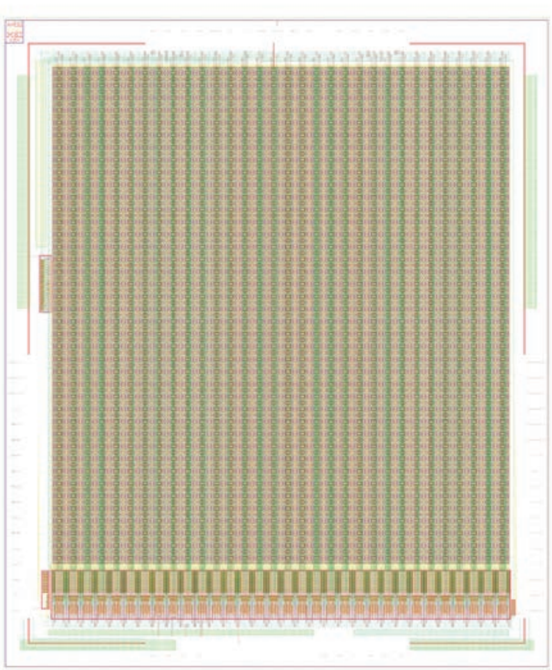
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 µm
- Logic on chip: Output are zero-suppressed hit addresses and timestamps

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

The MUPIX chip prototypes



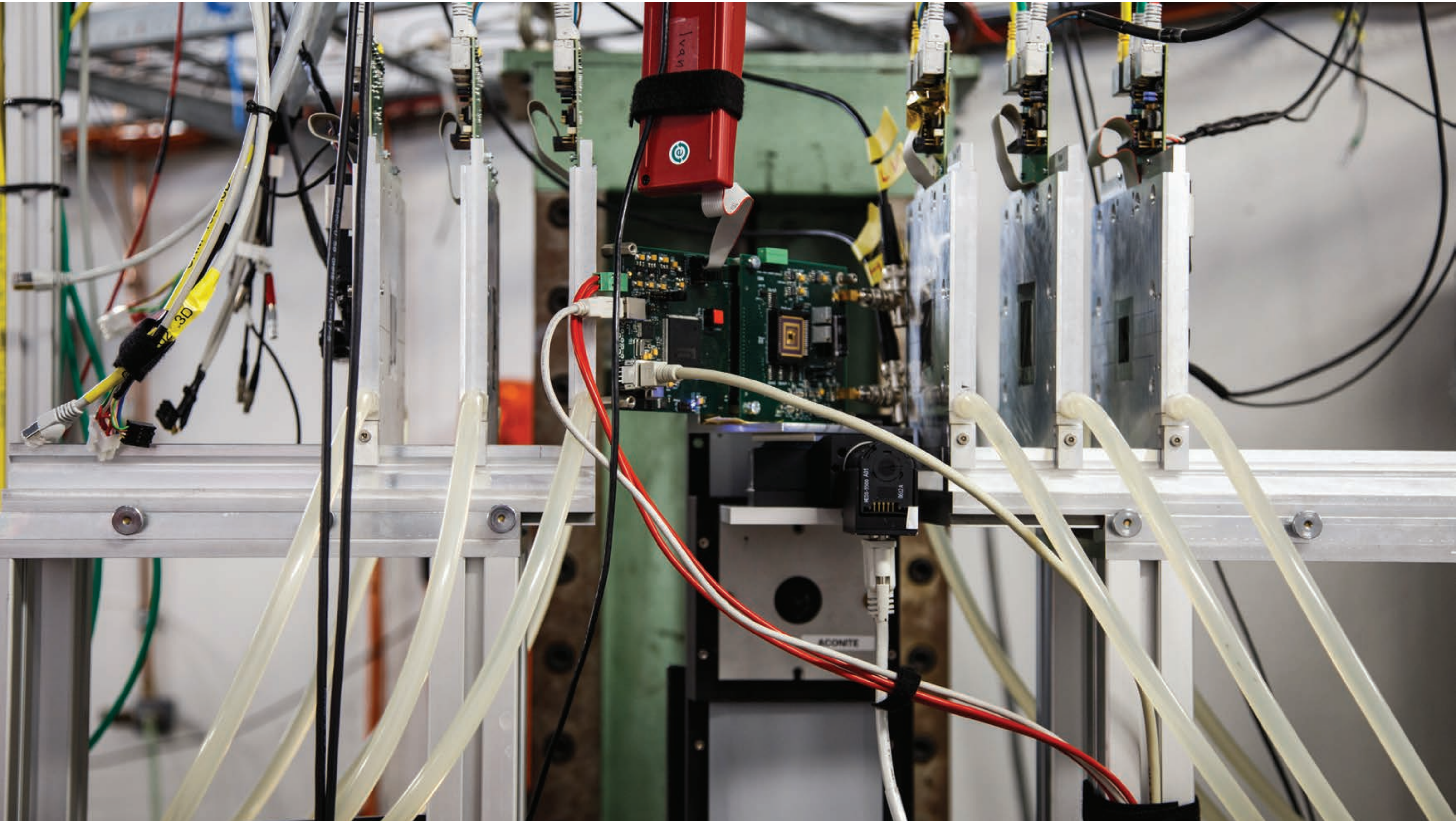

MUPIX6



HV-MAPS chips: AMS 180 nm HV-CMOS

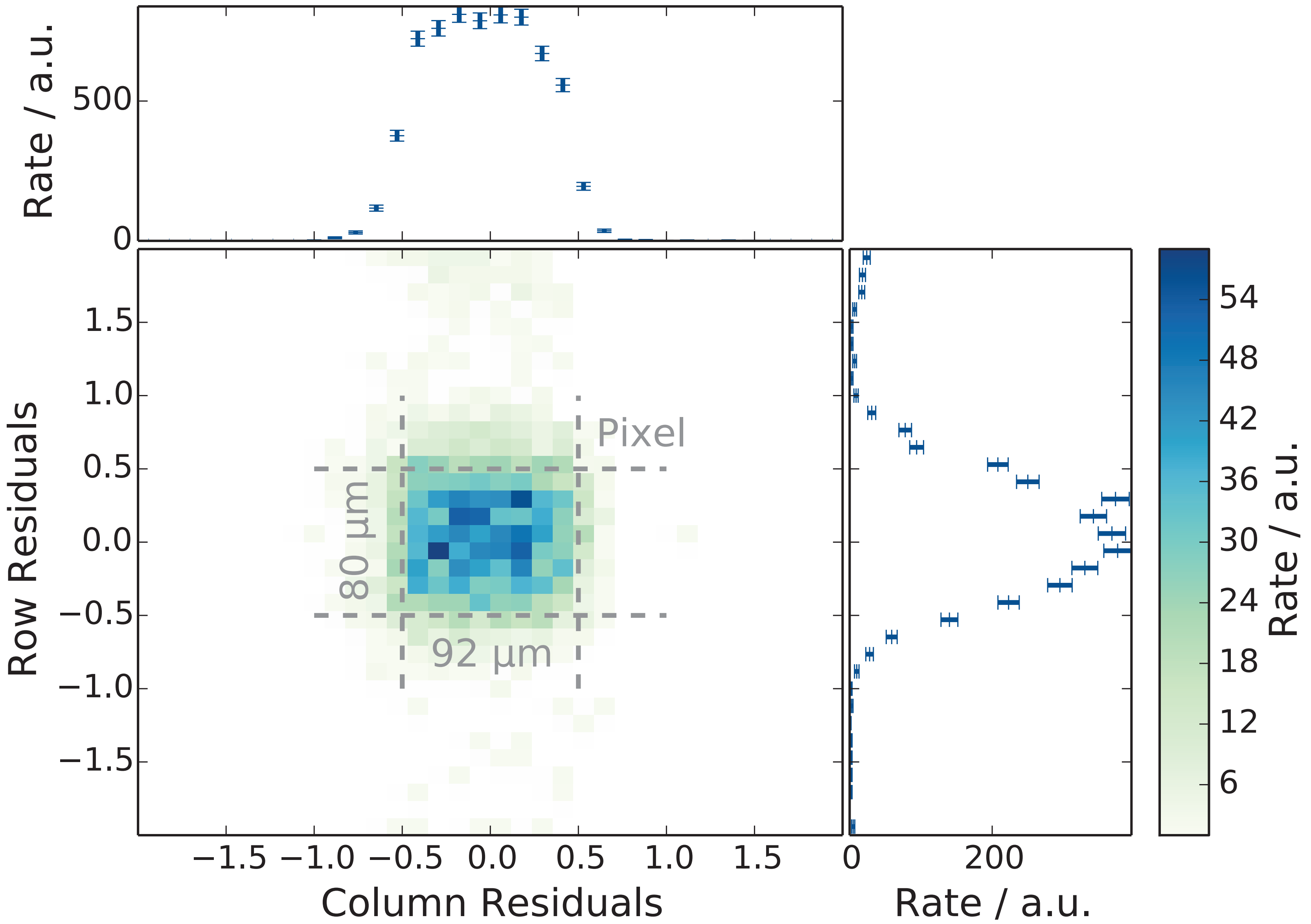
- 5 generations of prototypes
- Current generation:
  MUPIX7
  40 x 32 pixels
  80 x 103 μm pixel size
  9.4 mm^2 active area
- MUPIX7 has all features of final sensor
- Left to do: Scale to 2 x 2 cm^2

Test beam at DESY



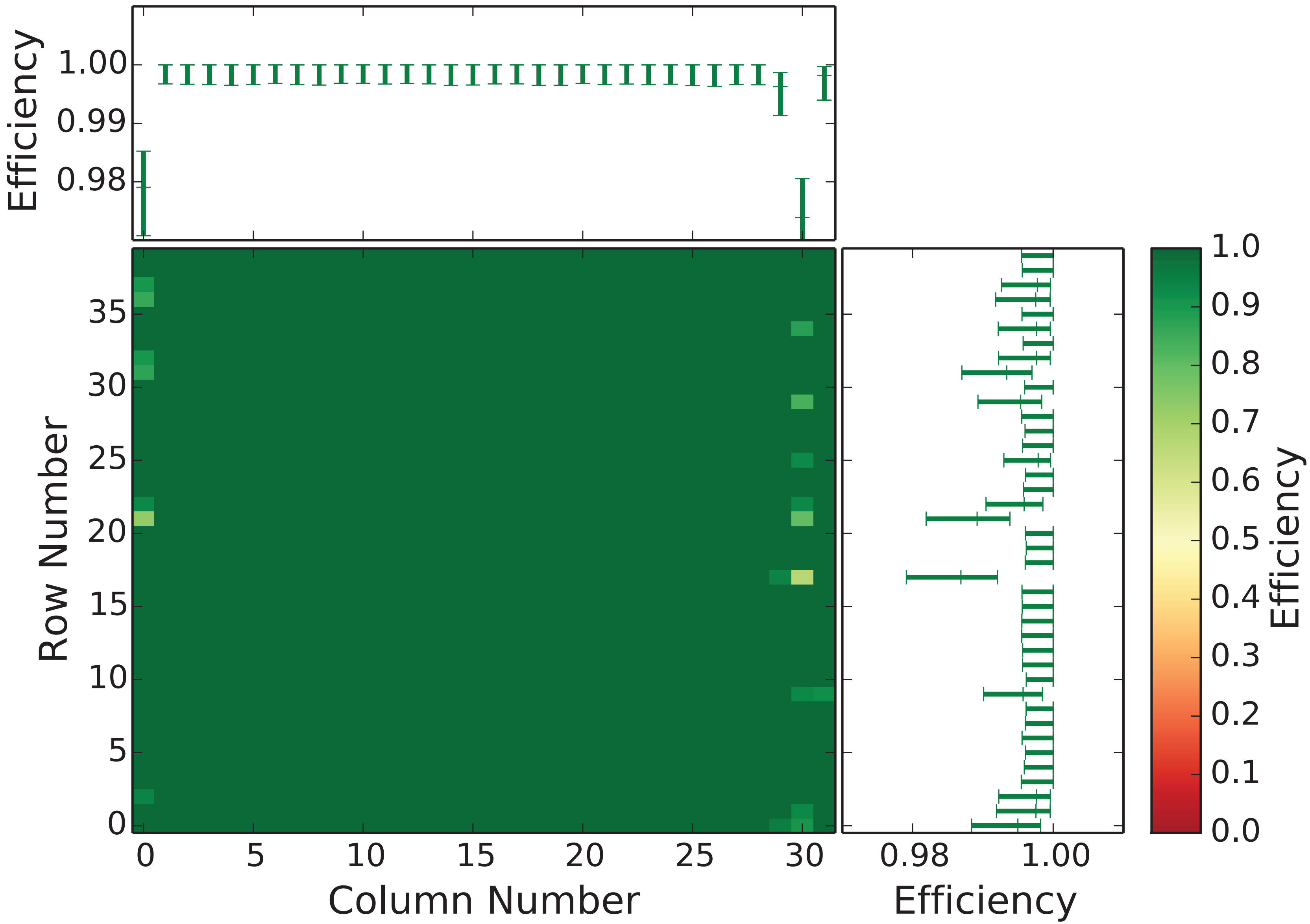
Position Resolution

Position resolution given by pixel size

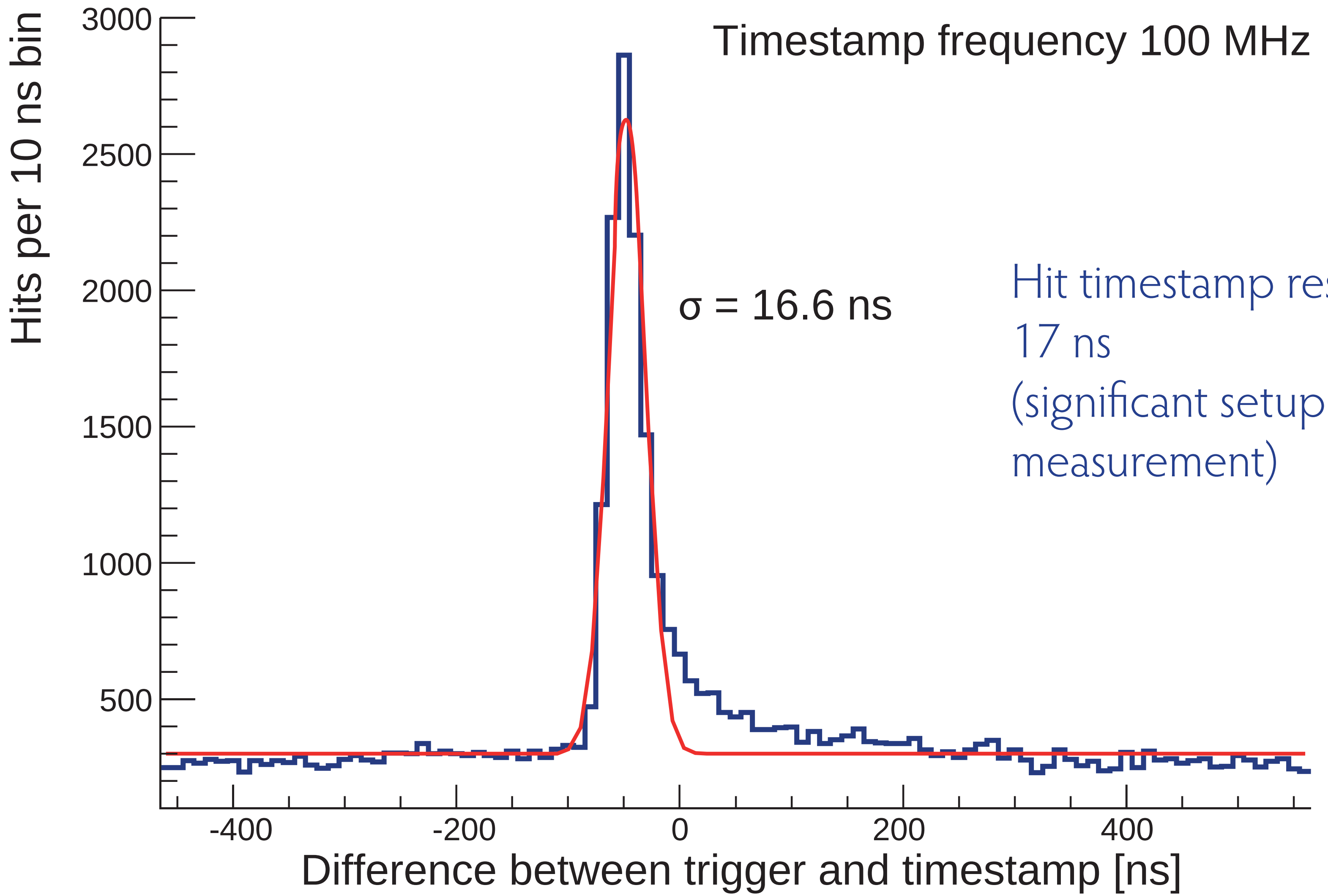


Efficiency

Hit efficiency above 99% without tuning



Time resolution

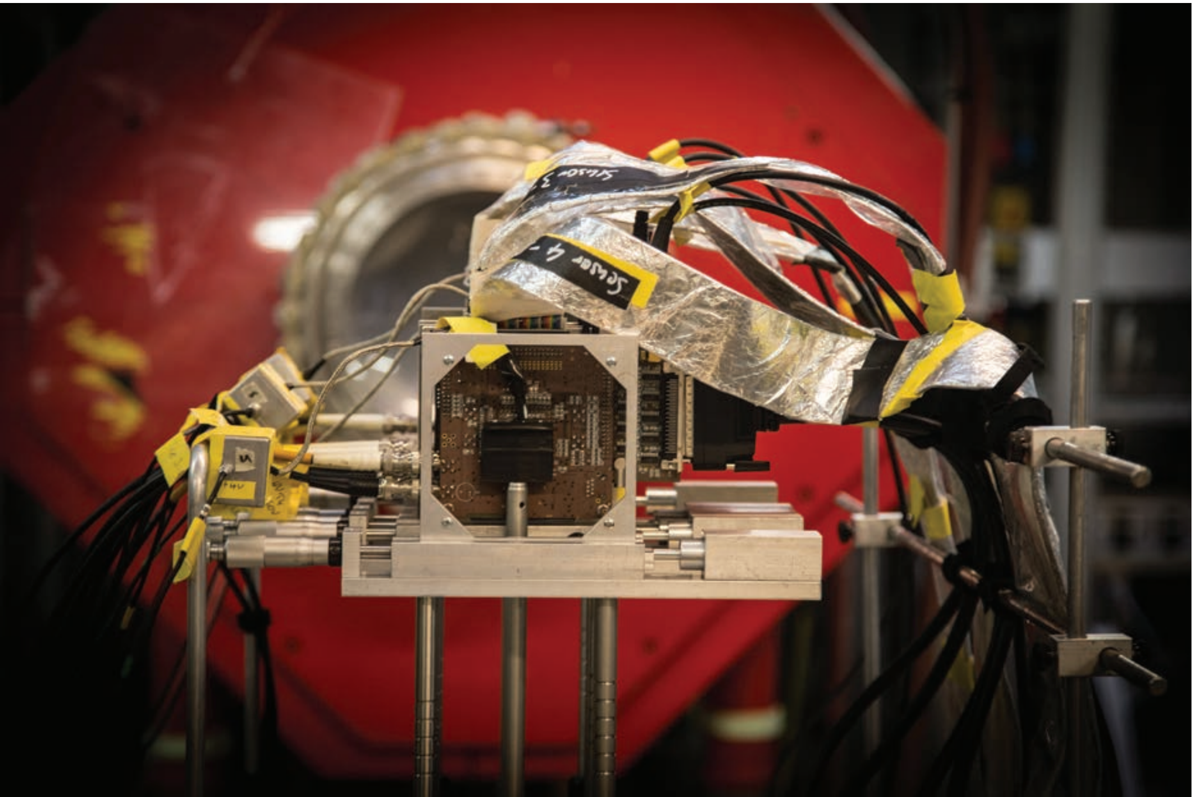


Hit timestamp resolution better than 17 ns
(significant setup contribution in the measurement)

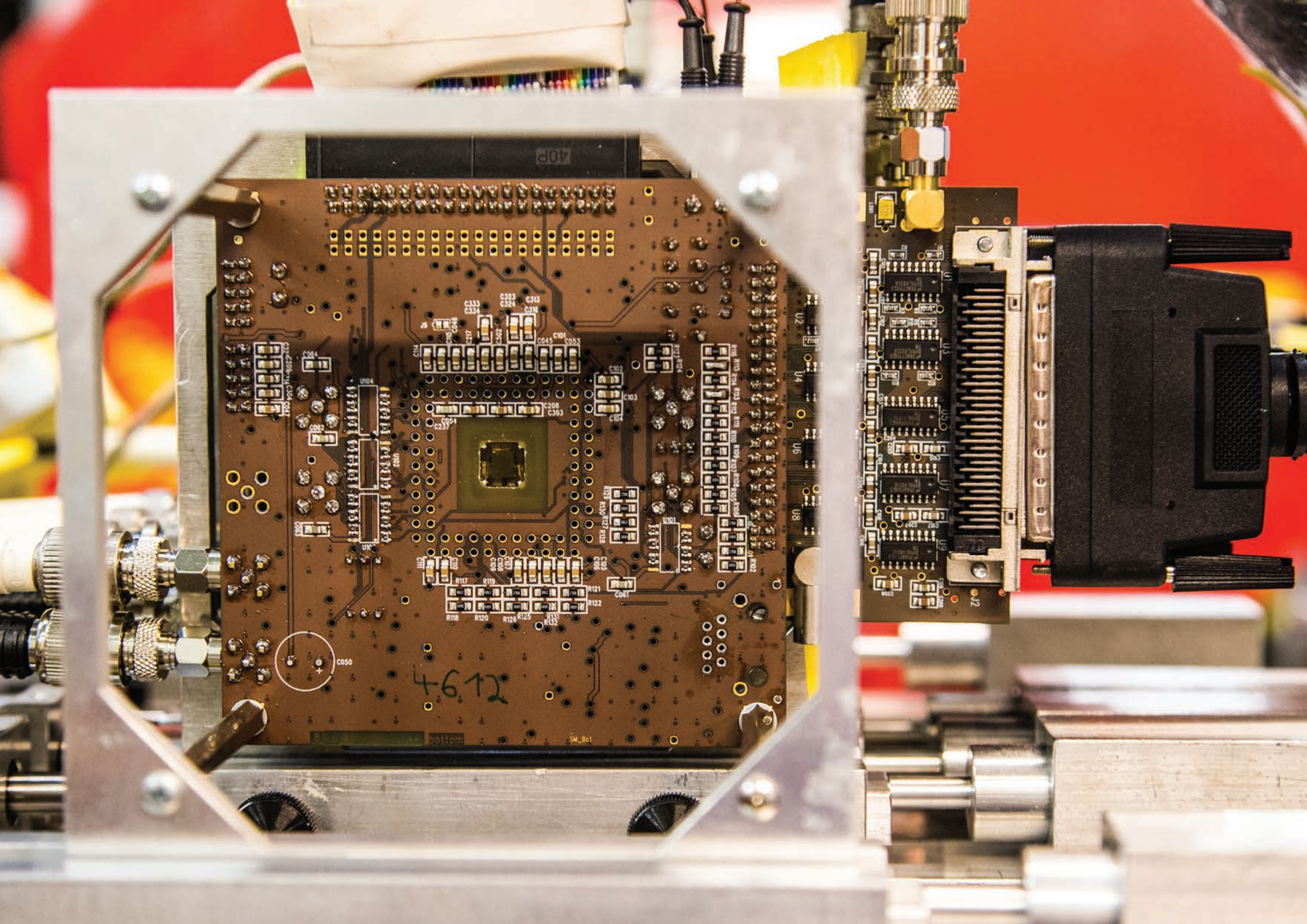
Mupix Telescope

Built our own pixel telescope

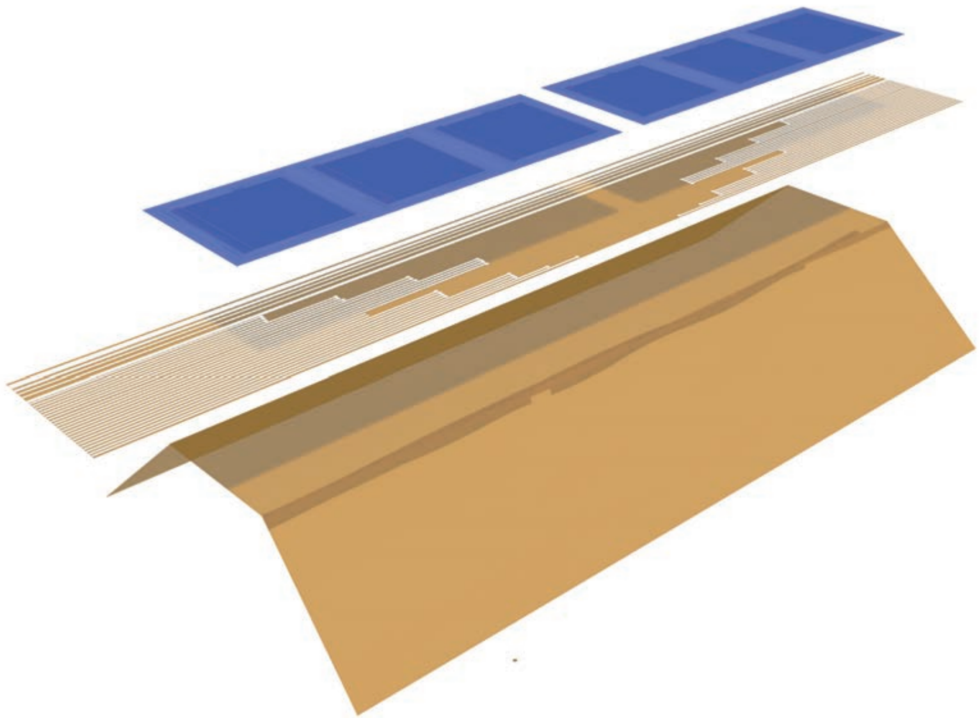
- Four planes of thin Mupix sensors
- Fast readout into PCIe FPGA cards
- Currently about 1 MHz hits/plane possible
- Tested at DESY, PSI and MAMI



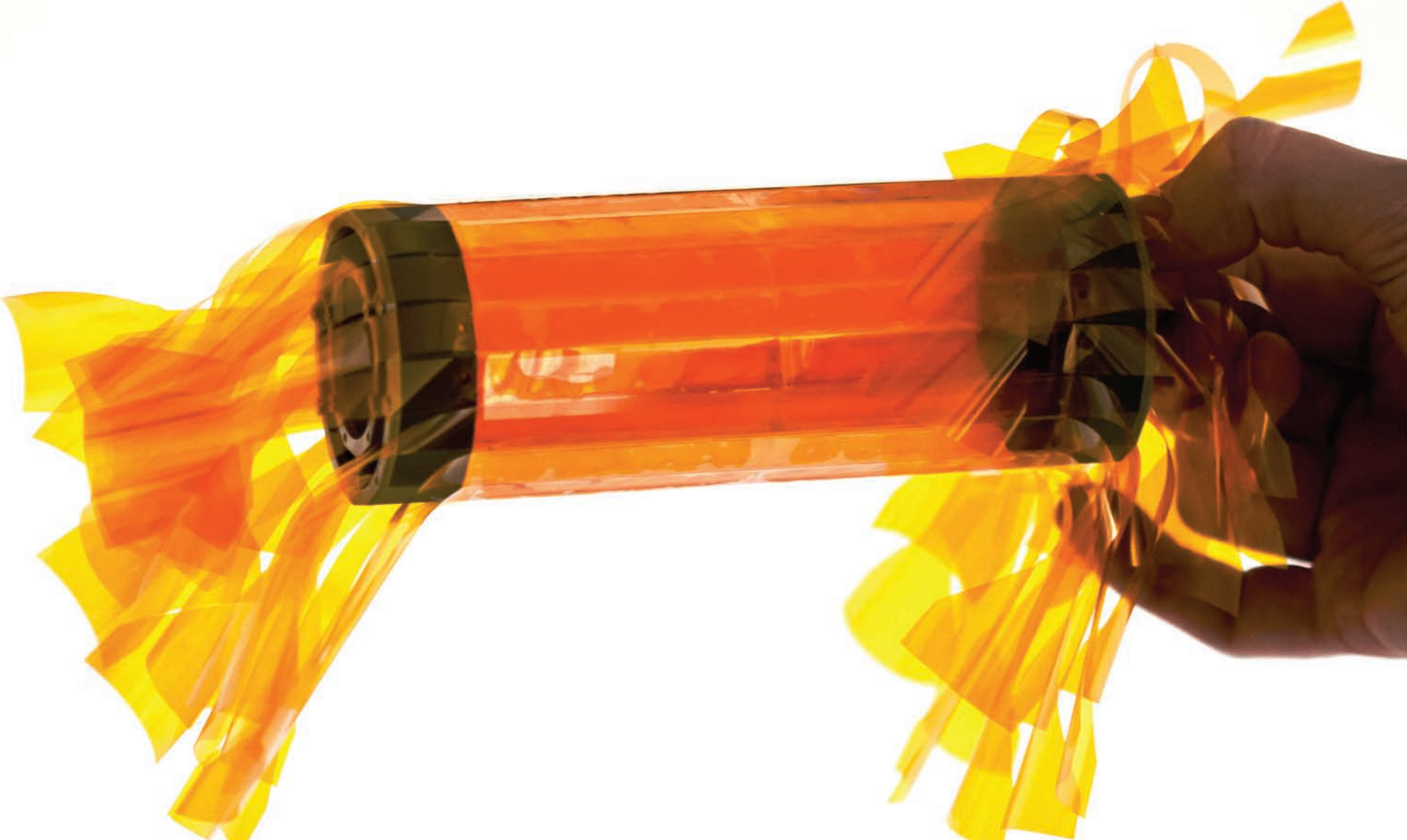

-HV
+HV
Tile 3


40P
4612
bottom

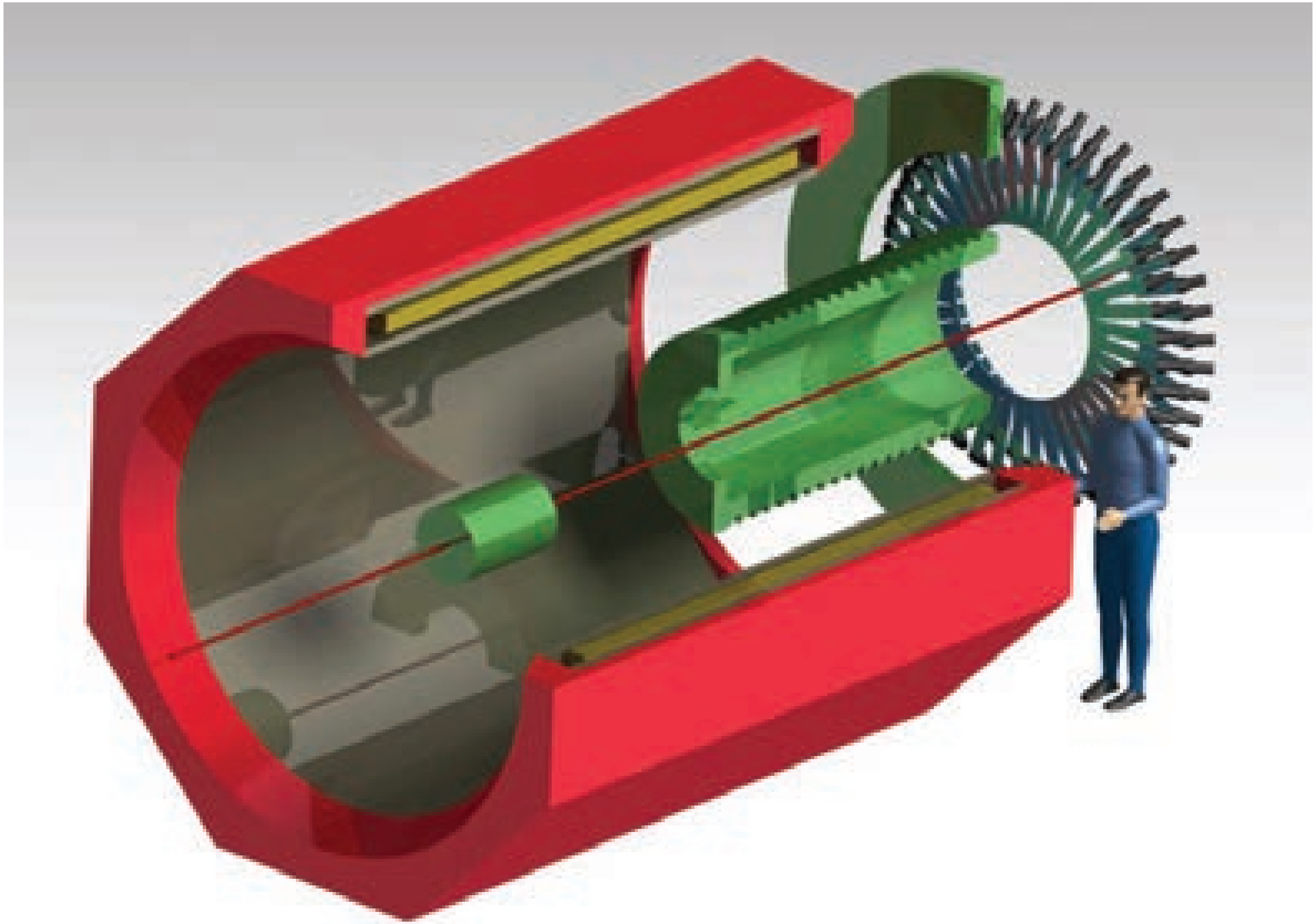
Mechanics



- 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

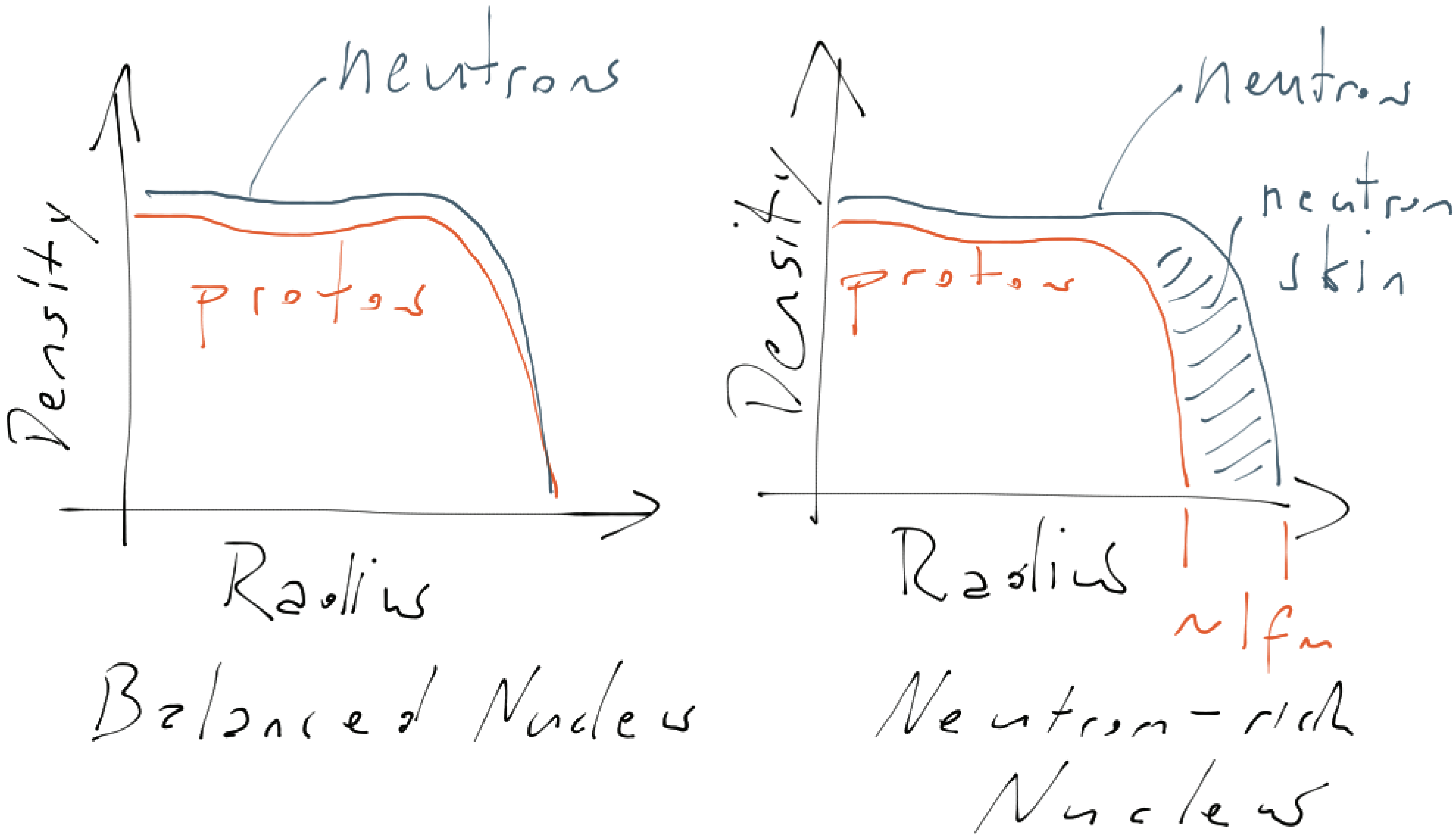


P2



Neutron Skins

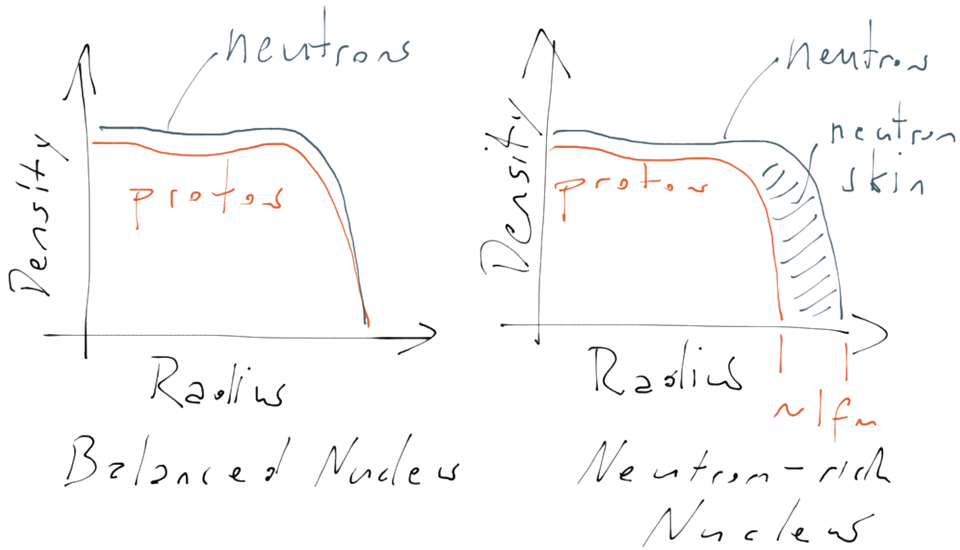
Where are the neutrons in the nucleus?

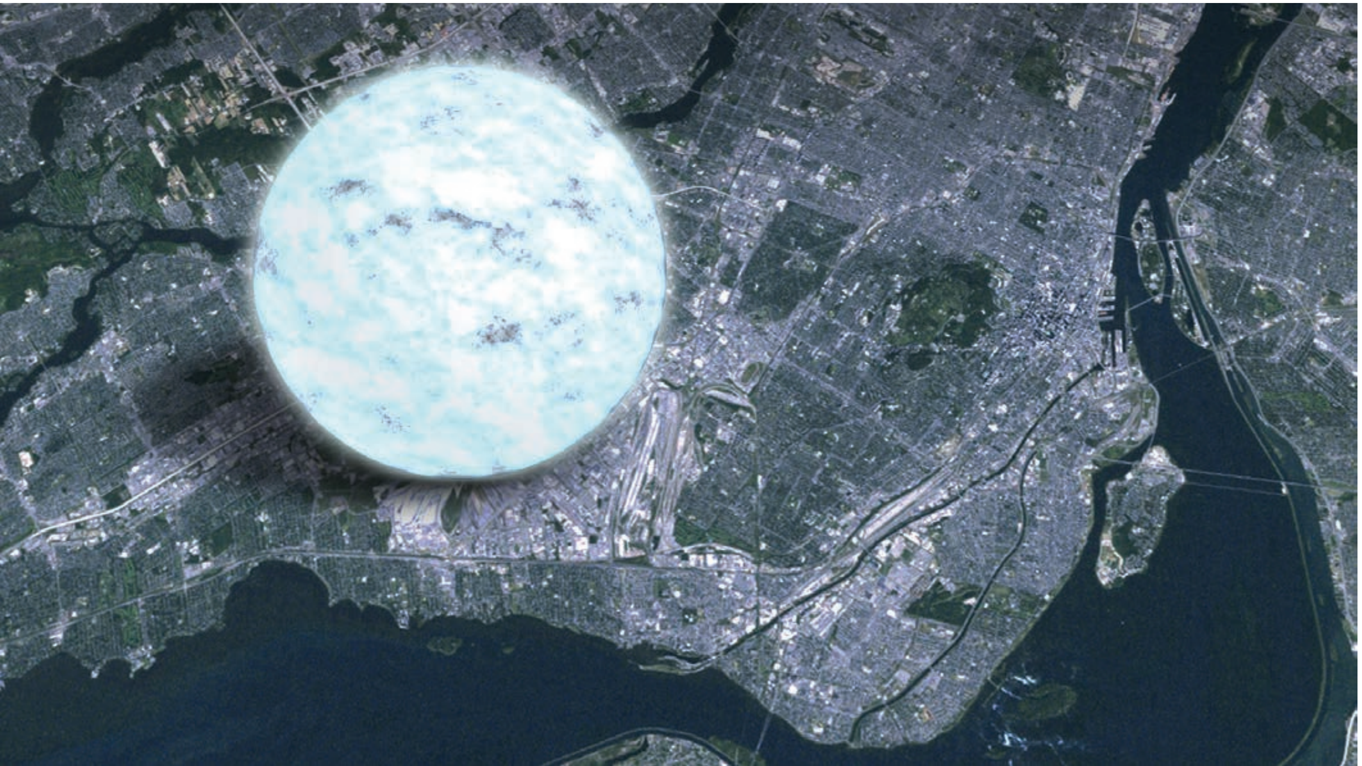


Neutron Skins

Where are the neutrons in the nucleus?

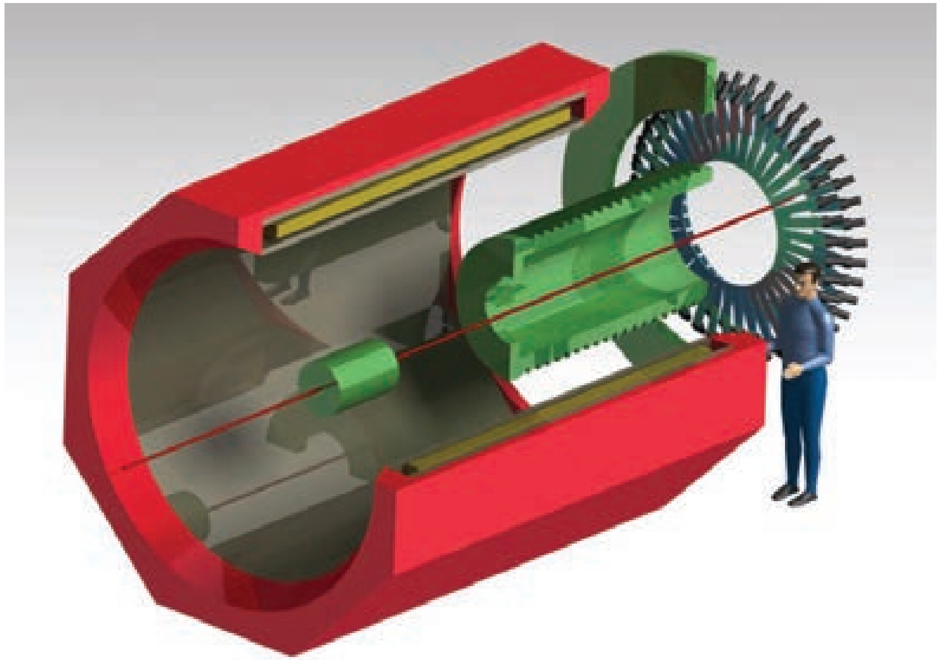
- Gives access to the equation of state of neutron matter
- Tells us how big/small neutron stars are





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



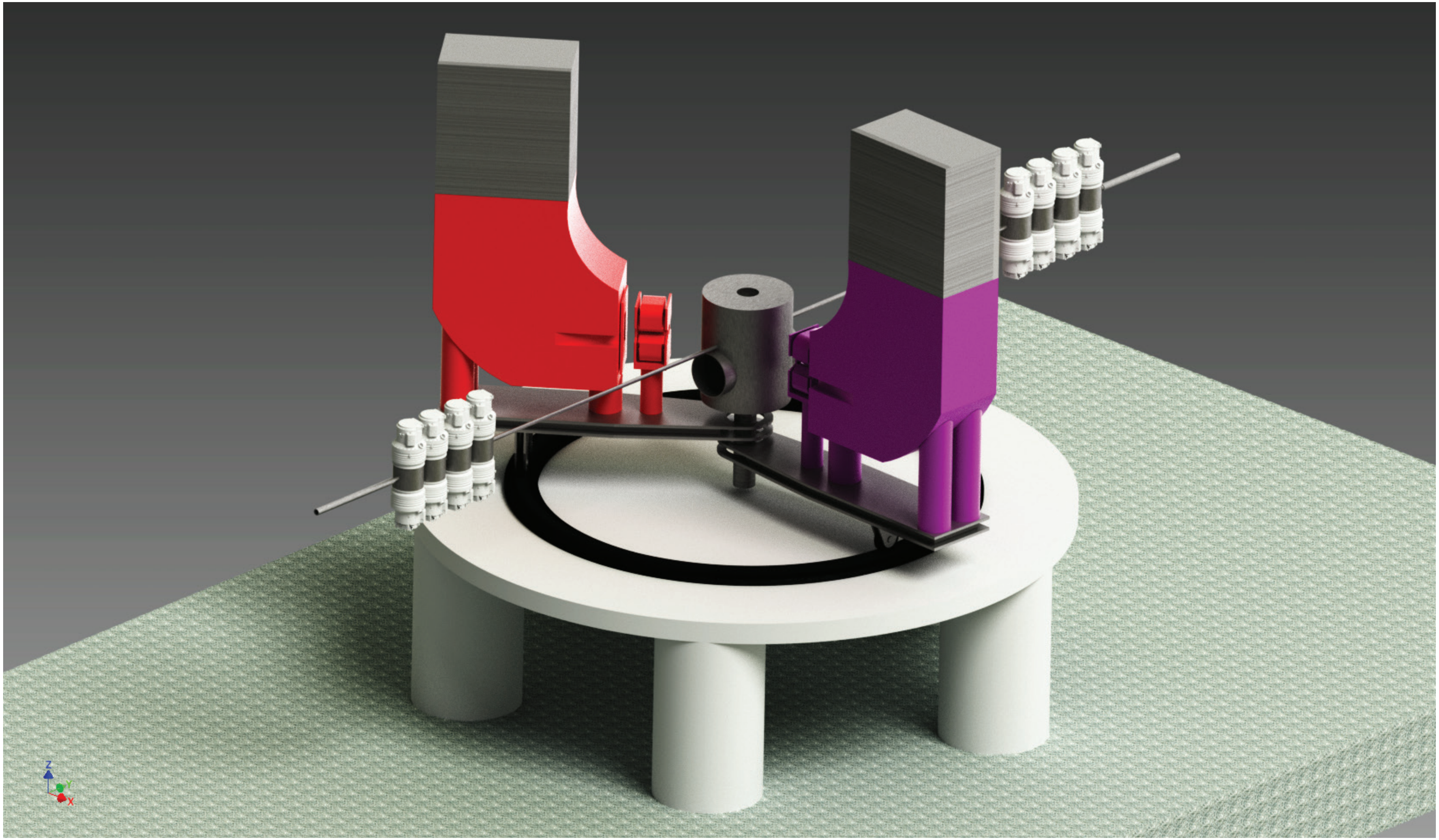
$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left(\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right)$$

And now for something different:

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

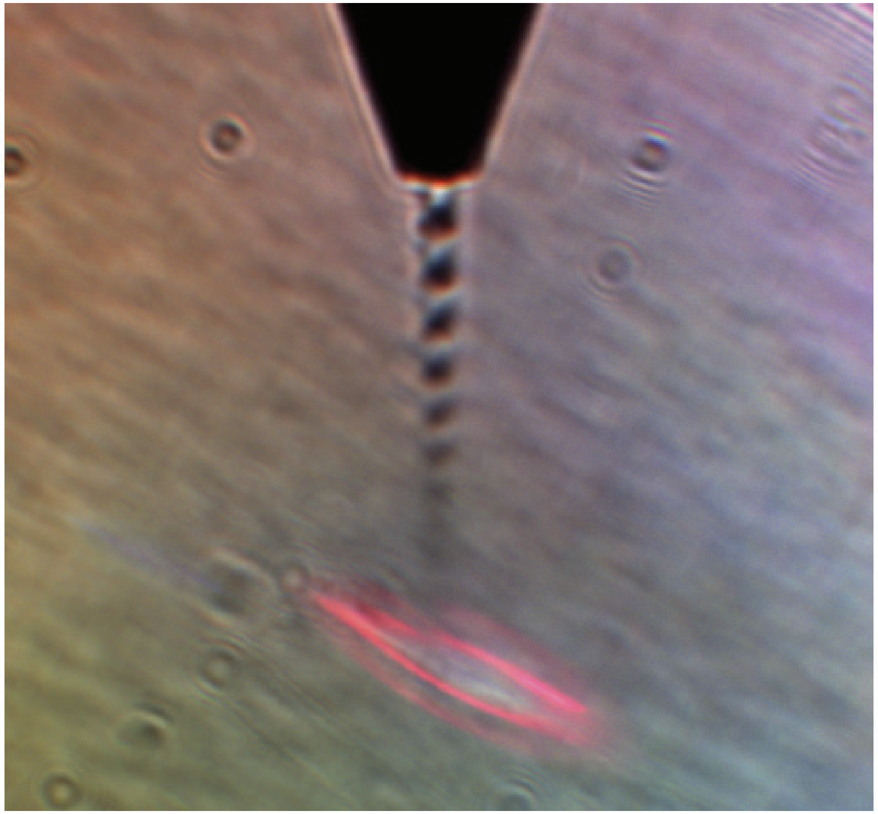
High resolution spectrometer

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

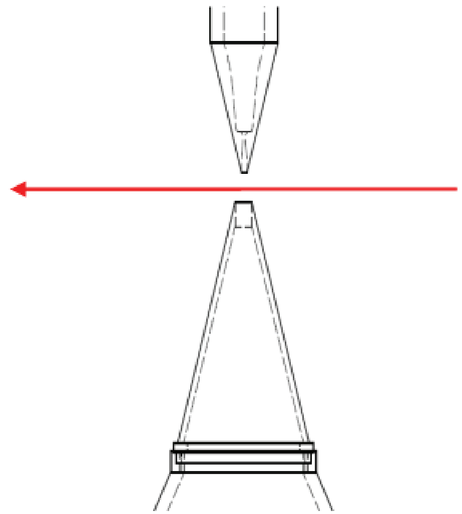
Thin walls, thin detectors

Extremely intense beam: Do not need very high acceptance

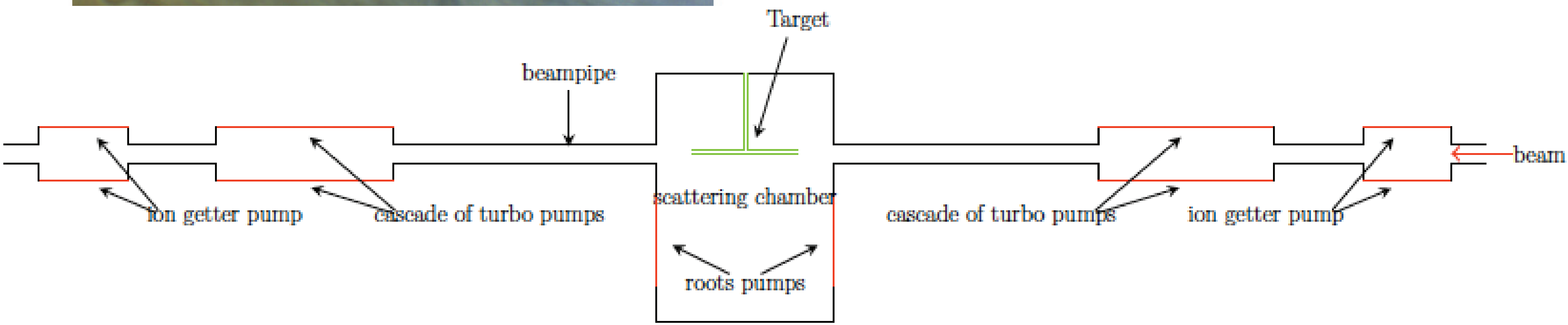
Internal gas target



- Inject gas directly into the beam pipe

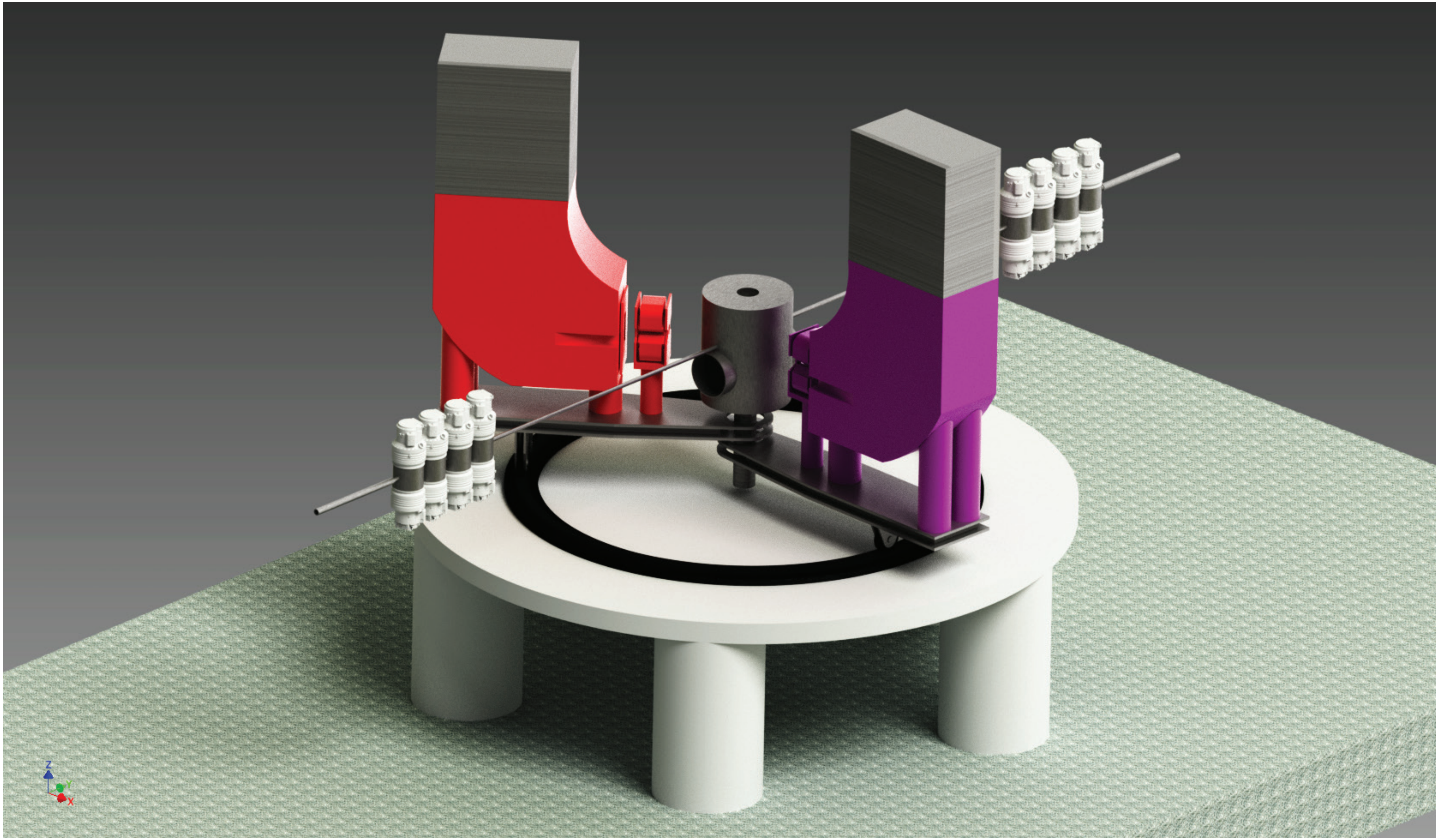


- Differential pumping to keep beam vacuum



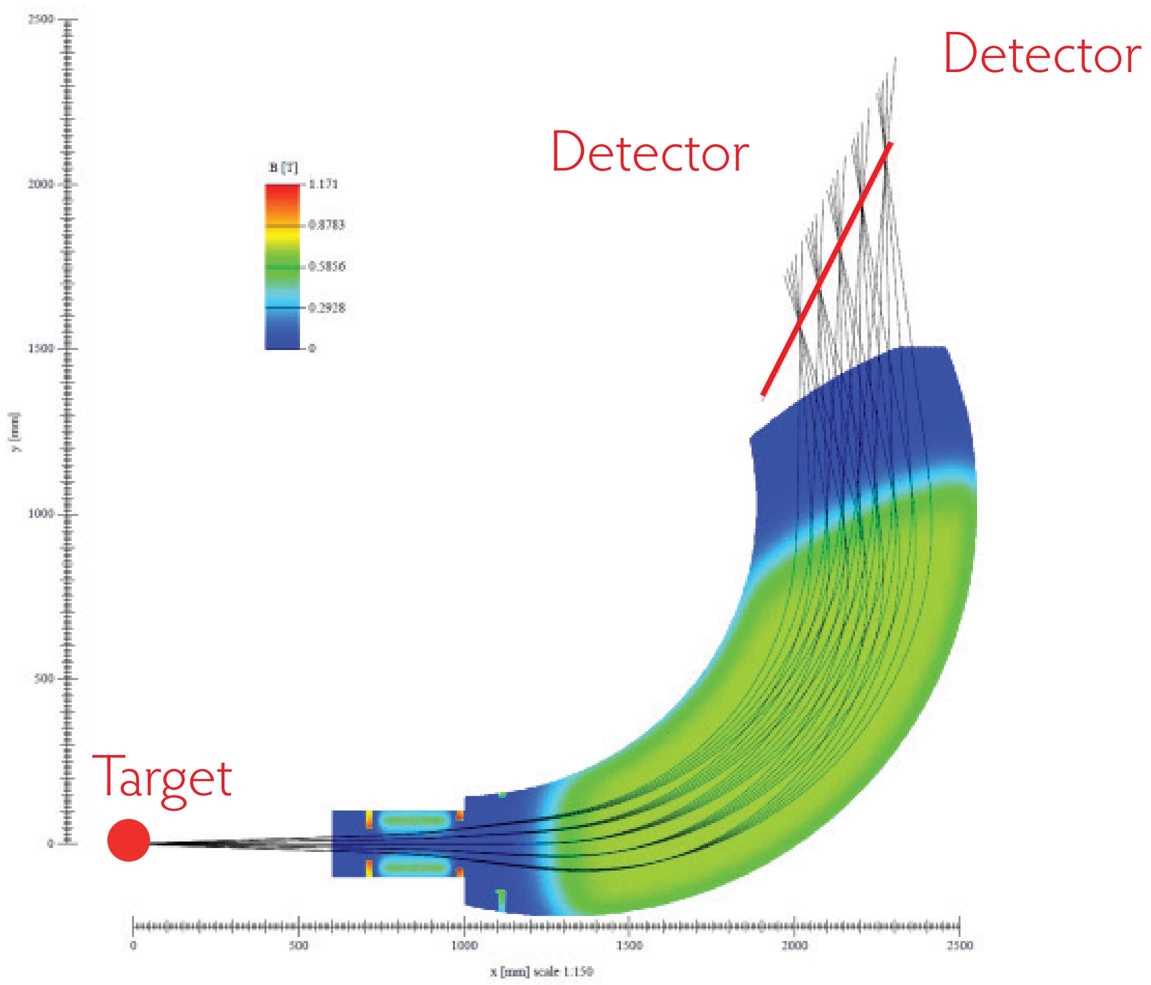
TARDIS

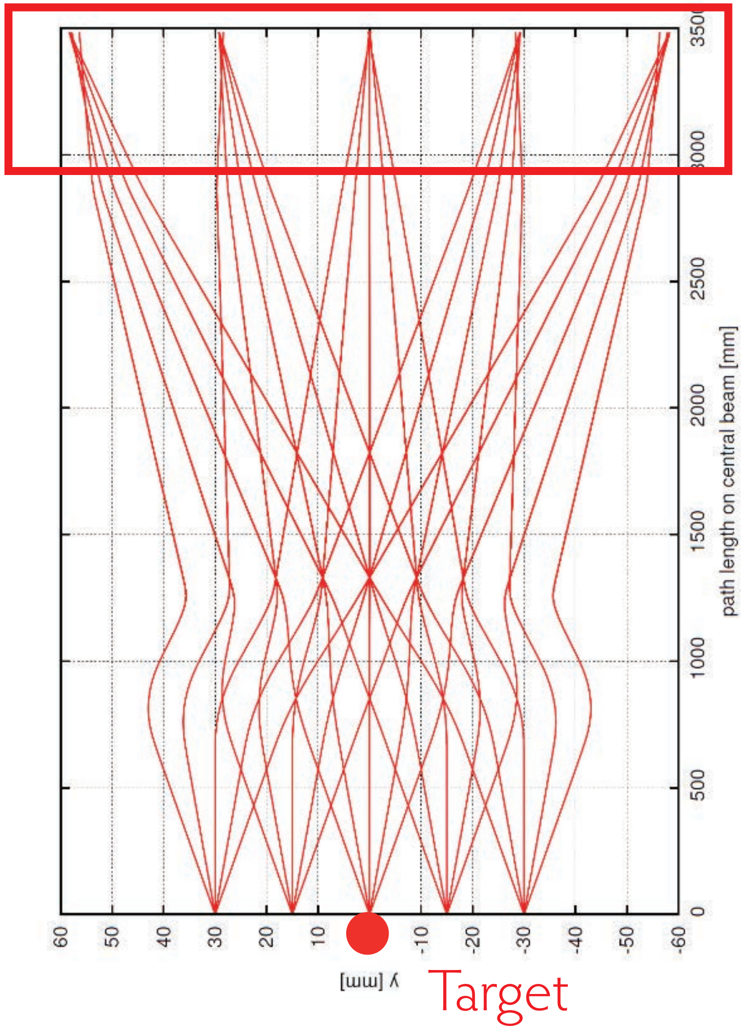
Twin-arm dipole spectrometer



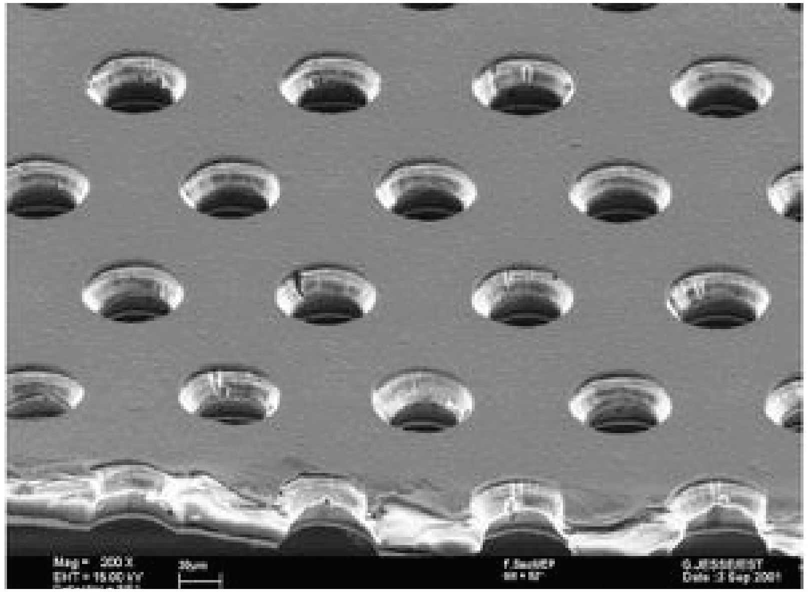
TARDIS

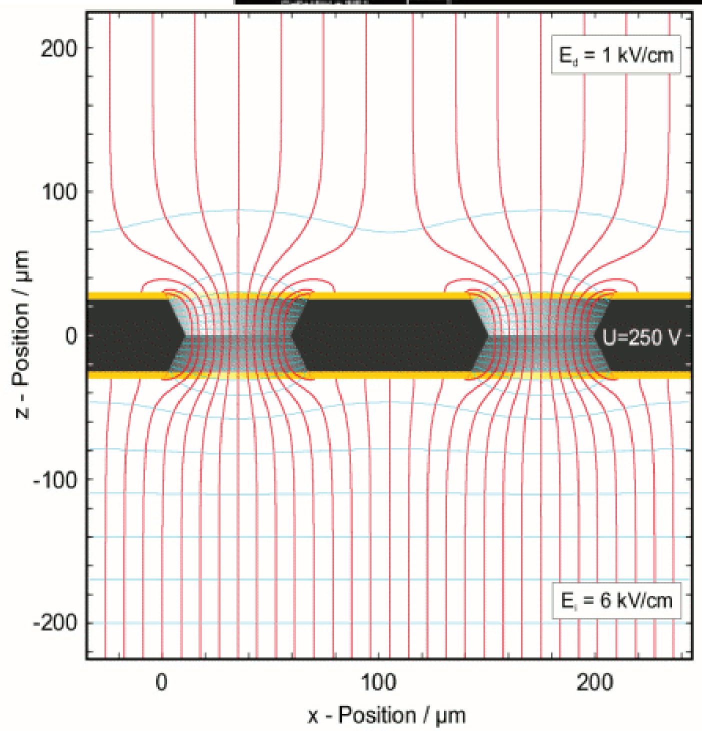
- Image momentum to position
- 10^{-4} momentum resolution for 50 µm position resolution
- Image angle to position

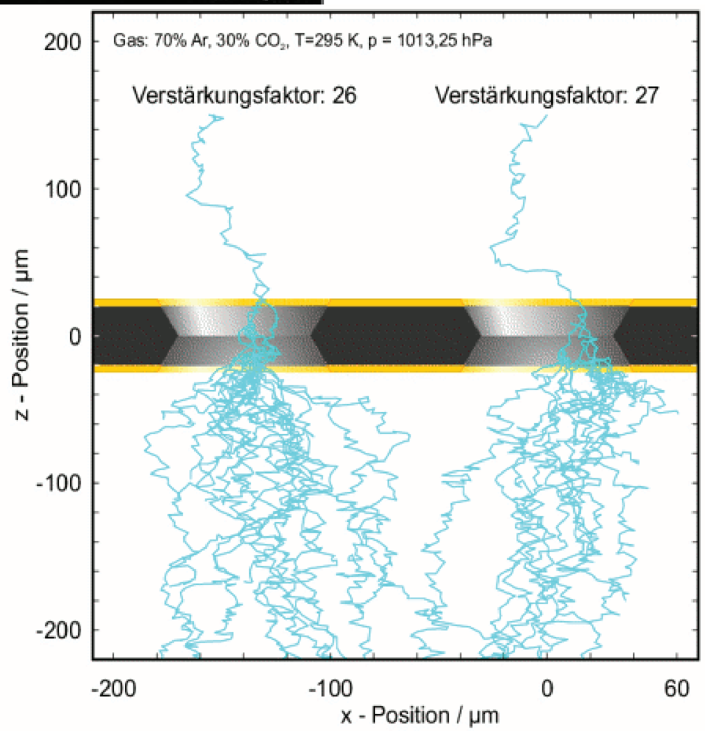




Focal plane detectors



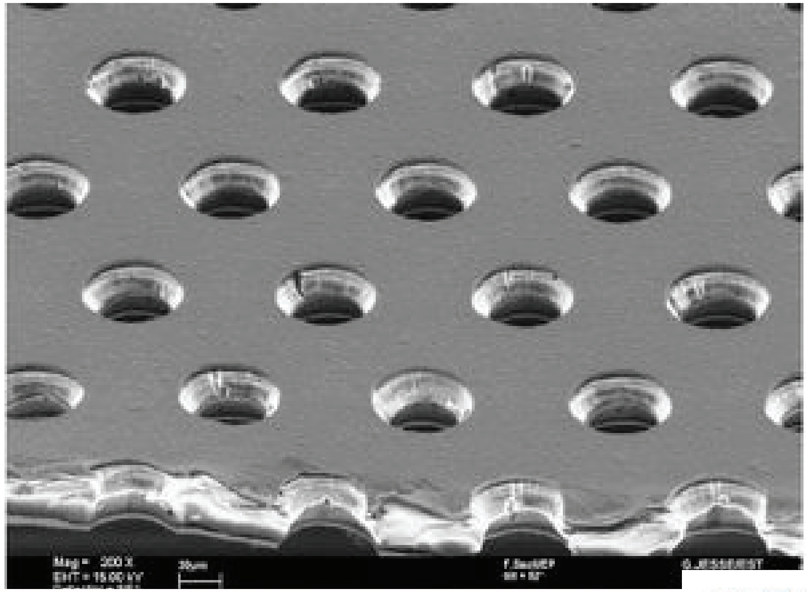




Gas Electron Multipliers (GEMs)

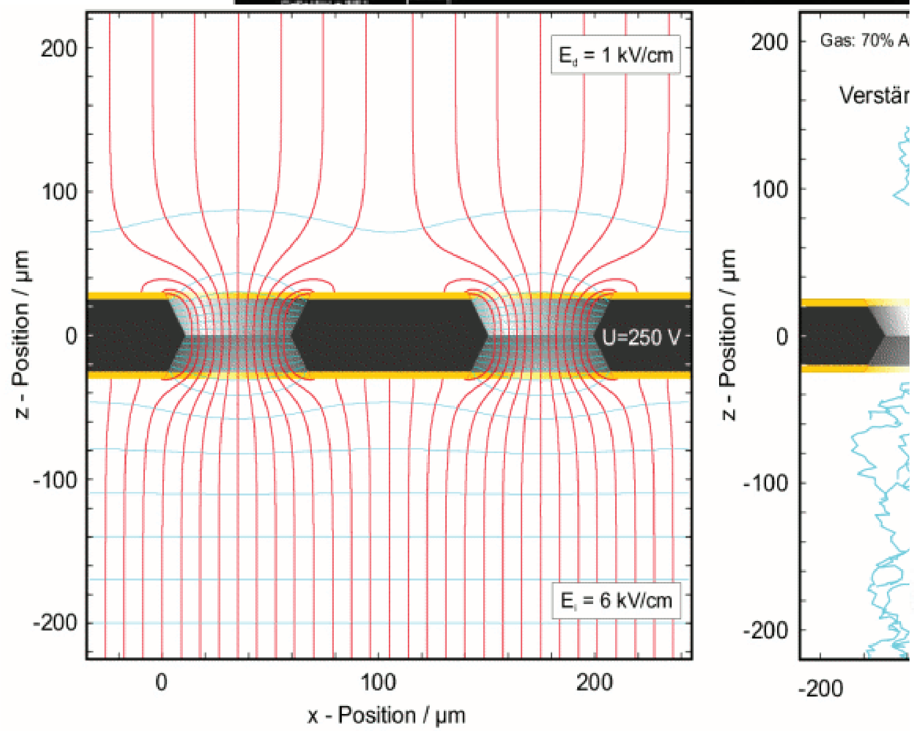
- Metalized Kapton foil with tiny holes
- Apply electric field

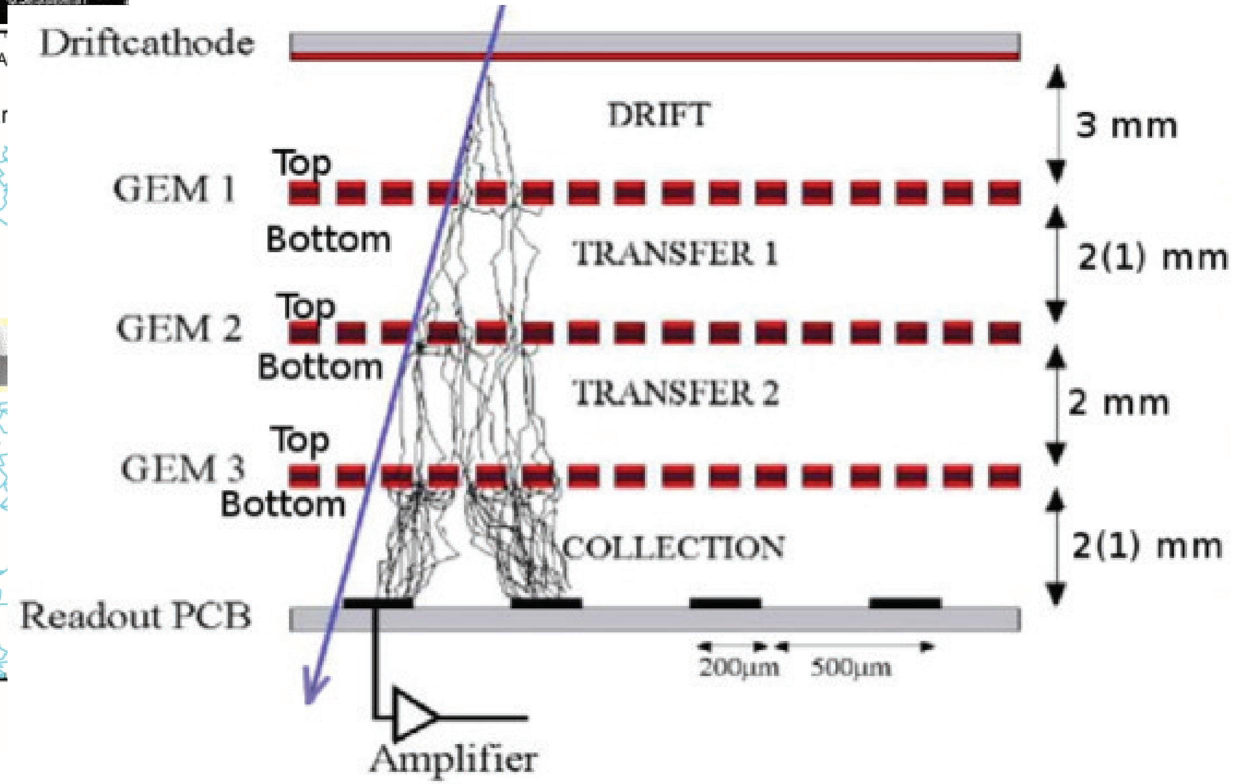
Focal plane detectors



Gas Electron Multipliers (GEMs)

- Metalized Kapton foil with tiny holes
- Apply electric field
- Stack GEMs to reduce ion back drift
- PRISMA detector lab





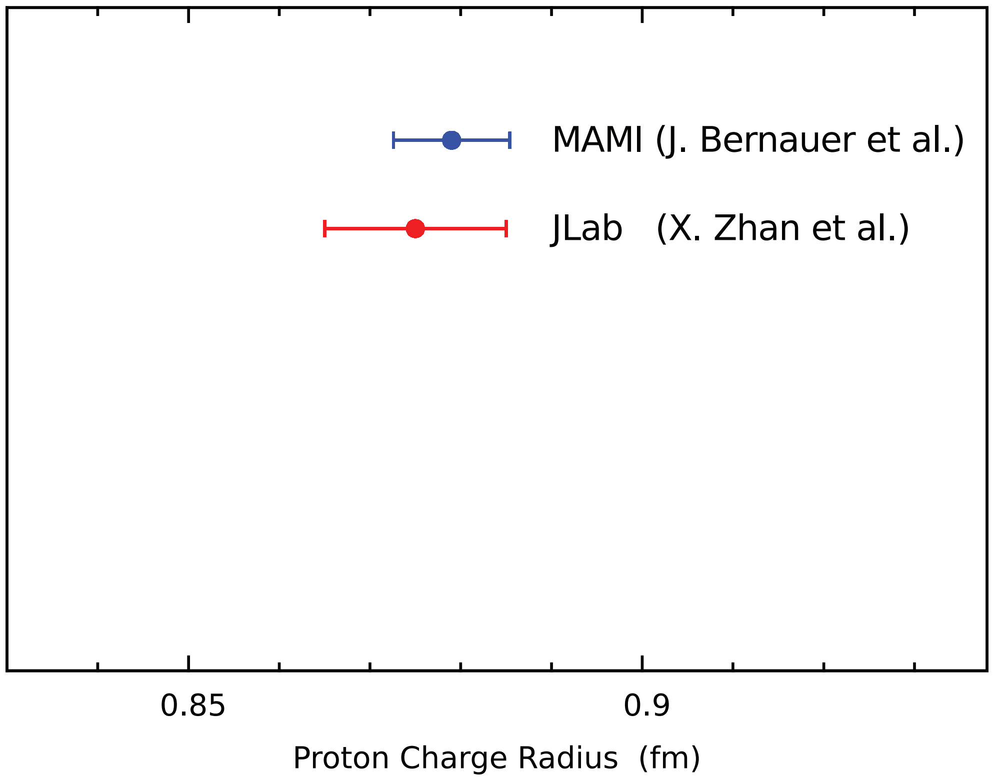
The proton, dark photons and more:

Physics at MAGIX

Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

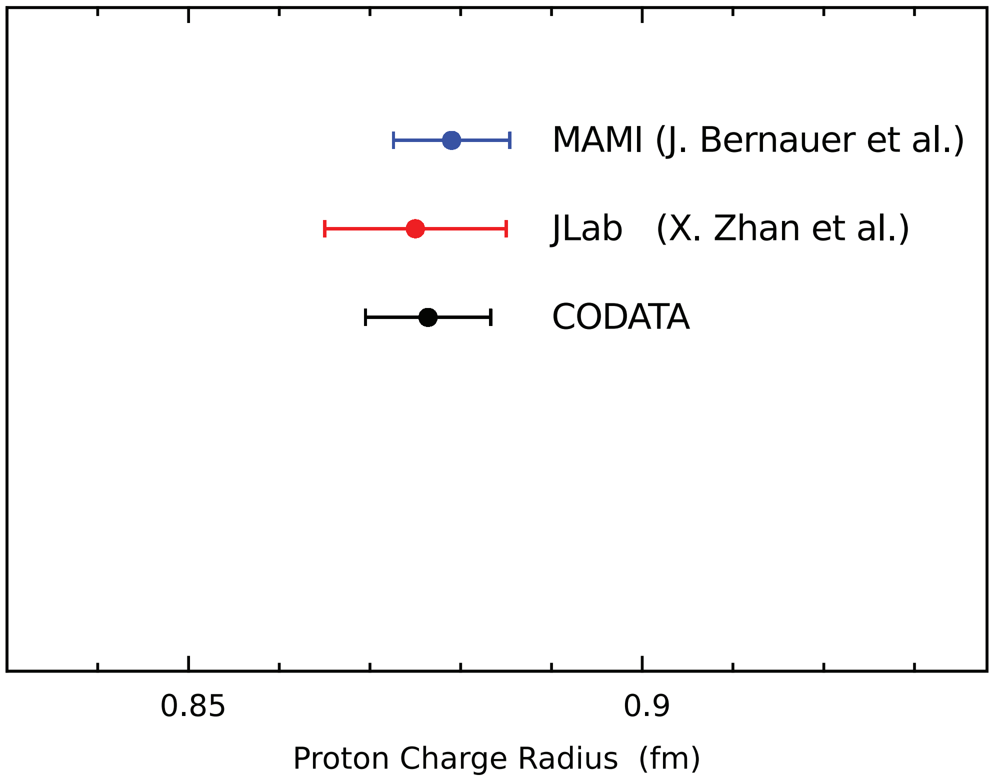
- Measure in scattering experiments (Mainz!)



Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

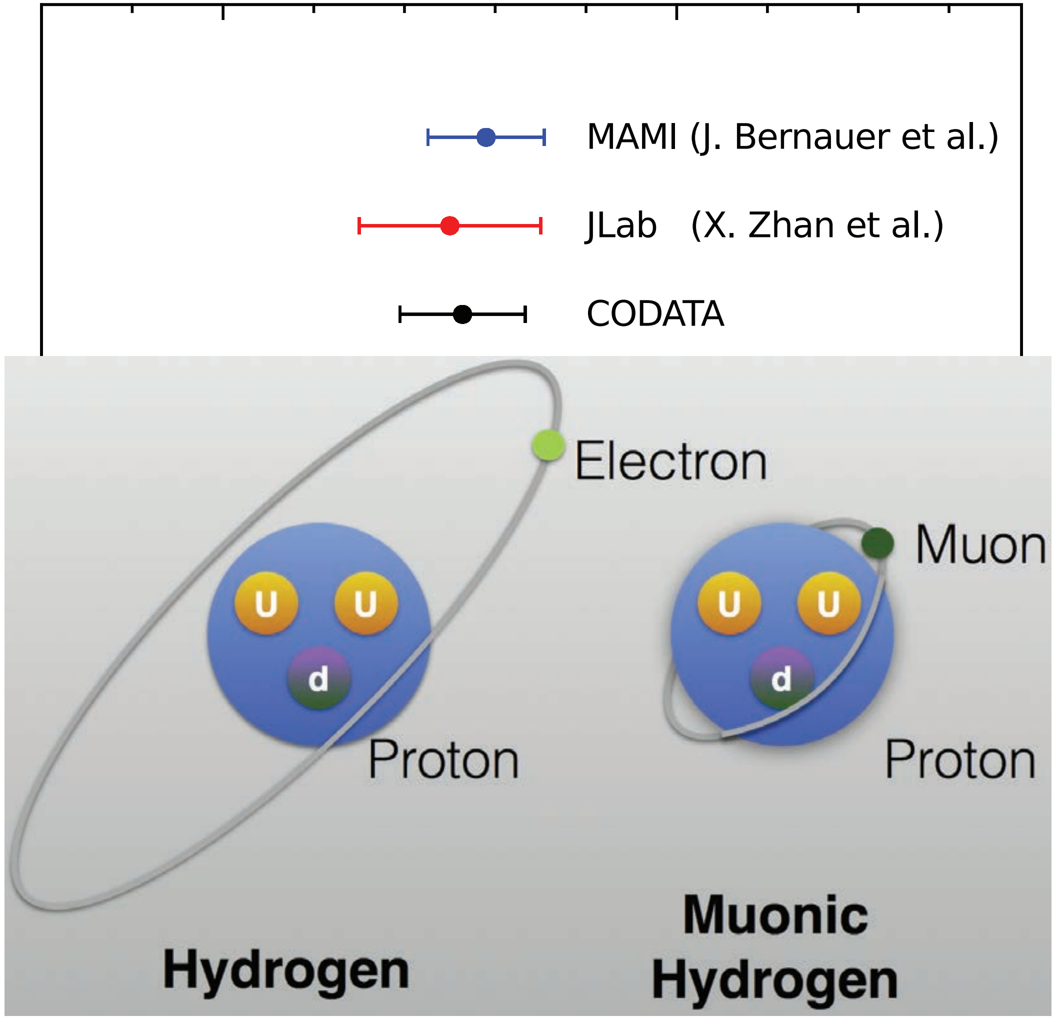
- Measure in scattering experiments (Mainz!)
- Measure in spectroscopy (Lamb-shift)



Proton Radius Puzzle

How big is a proton?
(electromagnetic charge radius)

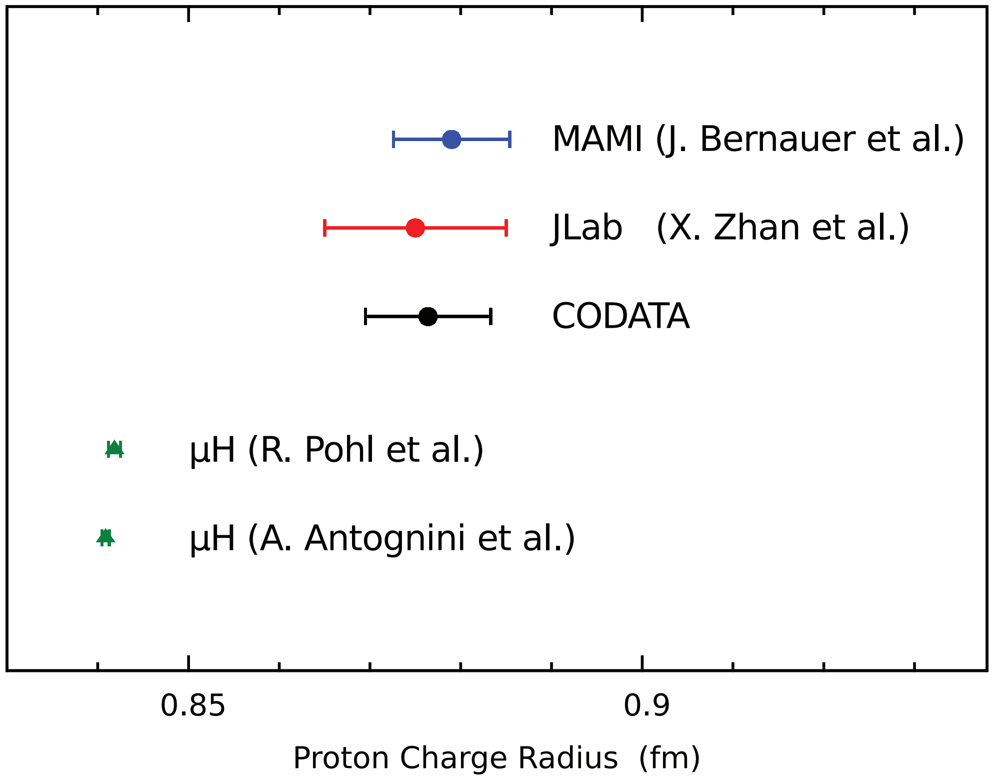
- Measure in scattering experiments (Mainz!)
- Measure in spectroscopy (Lamb-shift)
- Lamb shift is tiny - except in muonic hydrogen



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?



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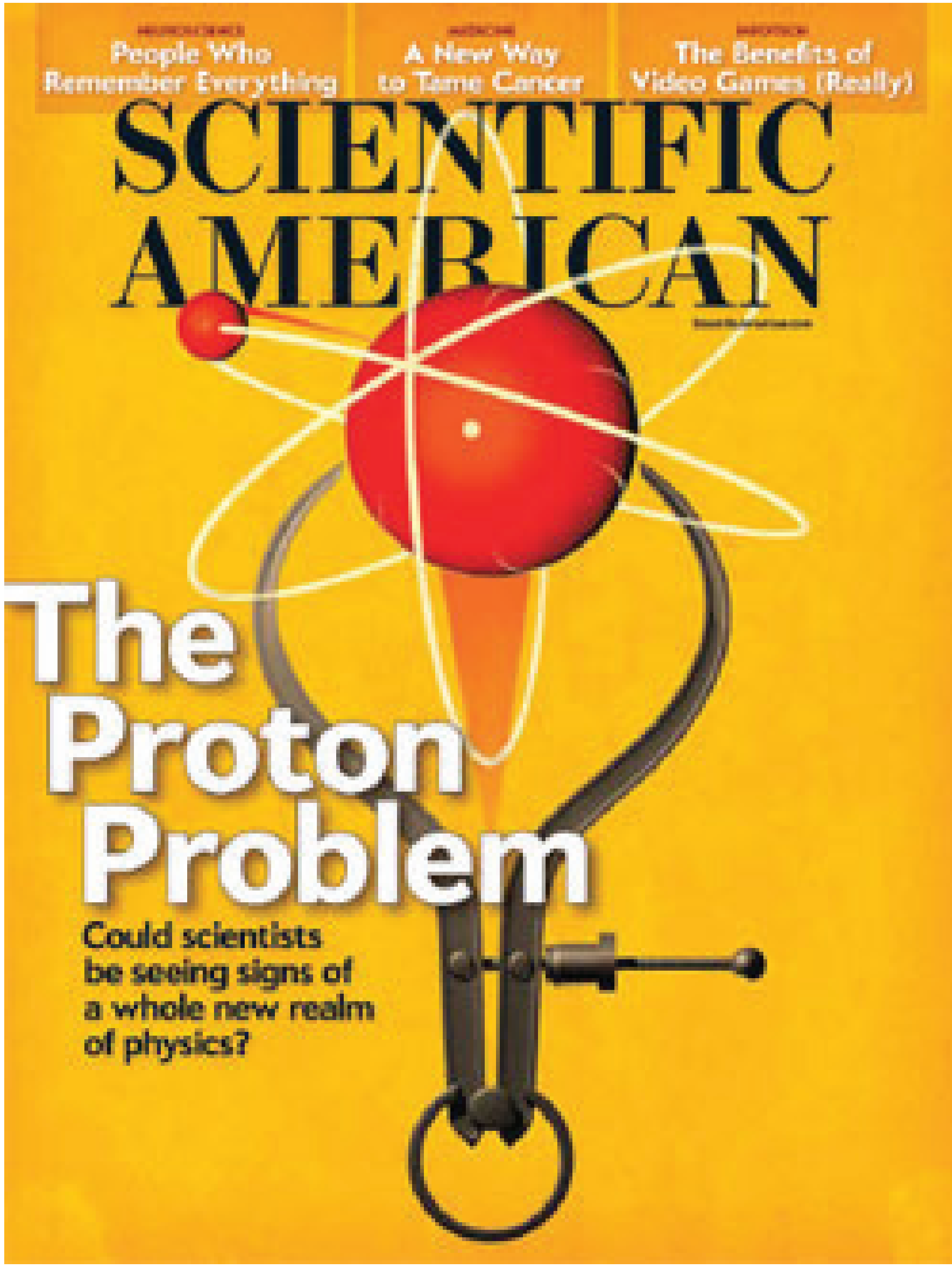
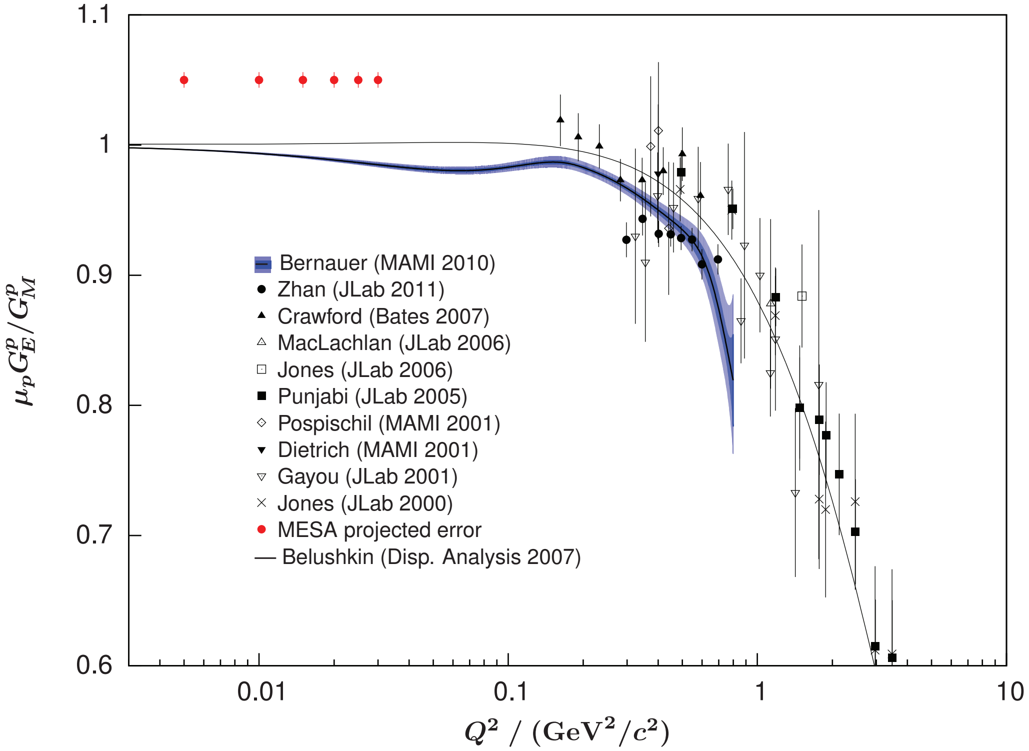
nature
OIL SPILLS
There's more to come
PLAGIARISM
It's worse than you think
CHIMPANZEES
The battle for survival
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent
NATUREJOBS
Reseachers for hire



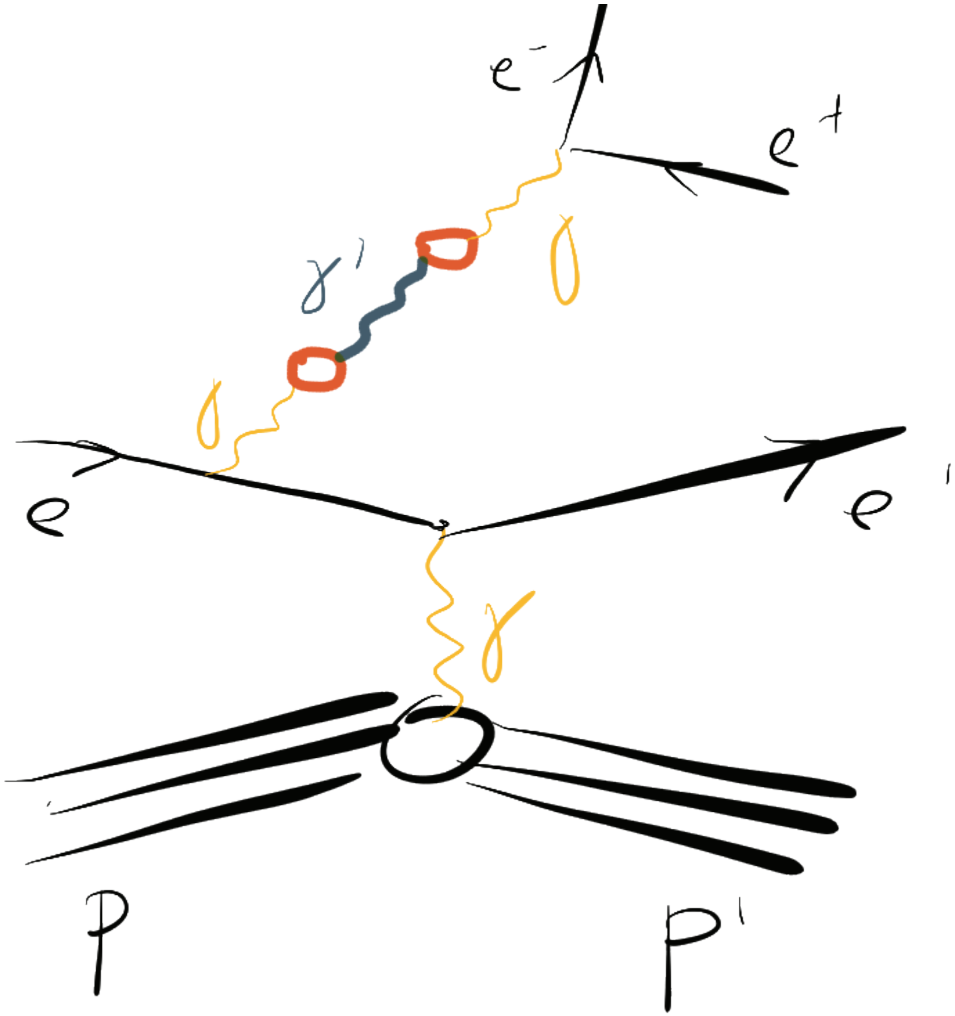
People Who Remember Everything
A New Way to Tame Cancer
The Benefits of Video Games (Really)
SCIENTIFIC AMERICAN
The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?

Scattering, Q^2 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

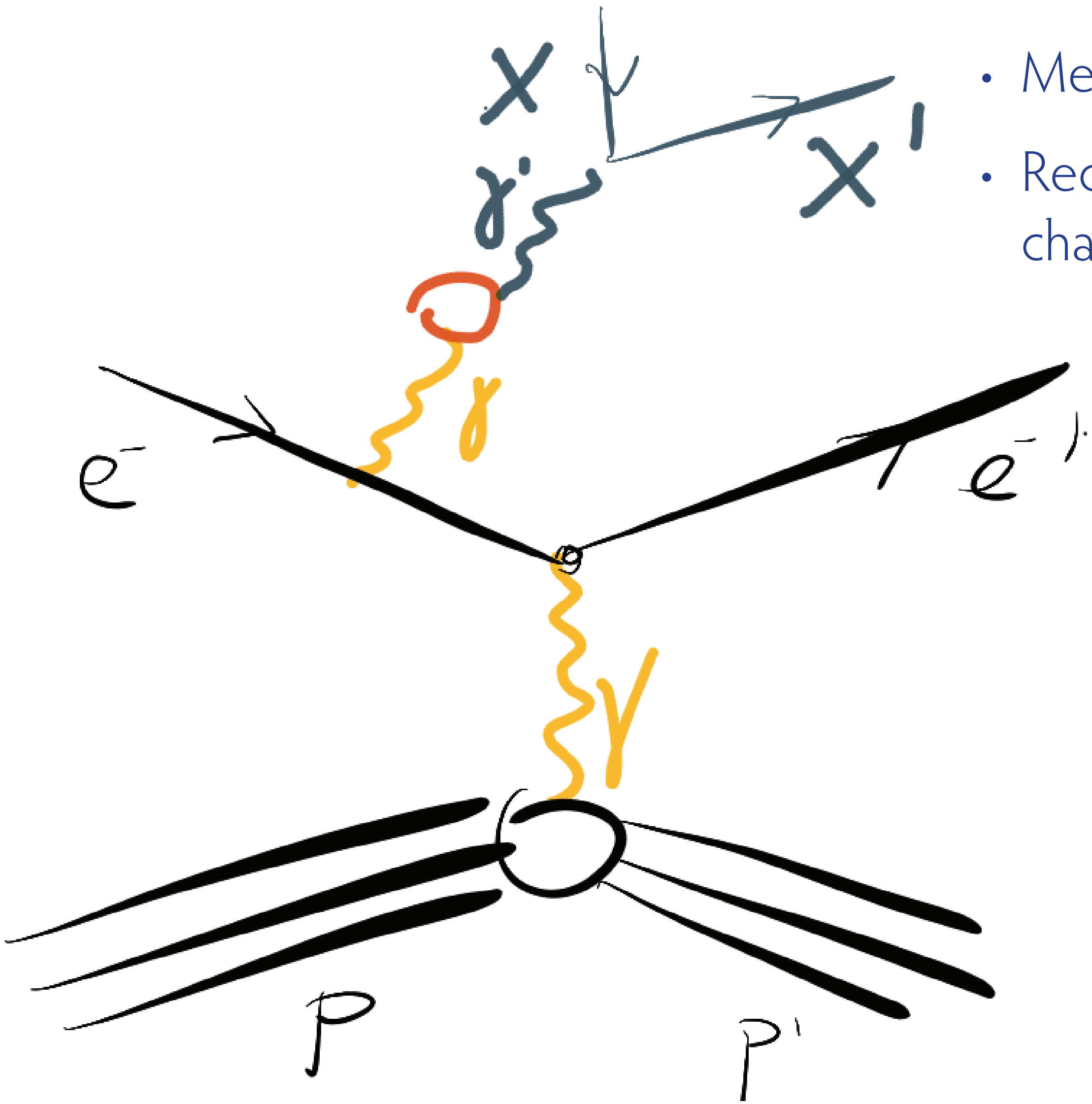
Dark photons



There is dark matter out there…

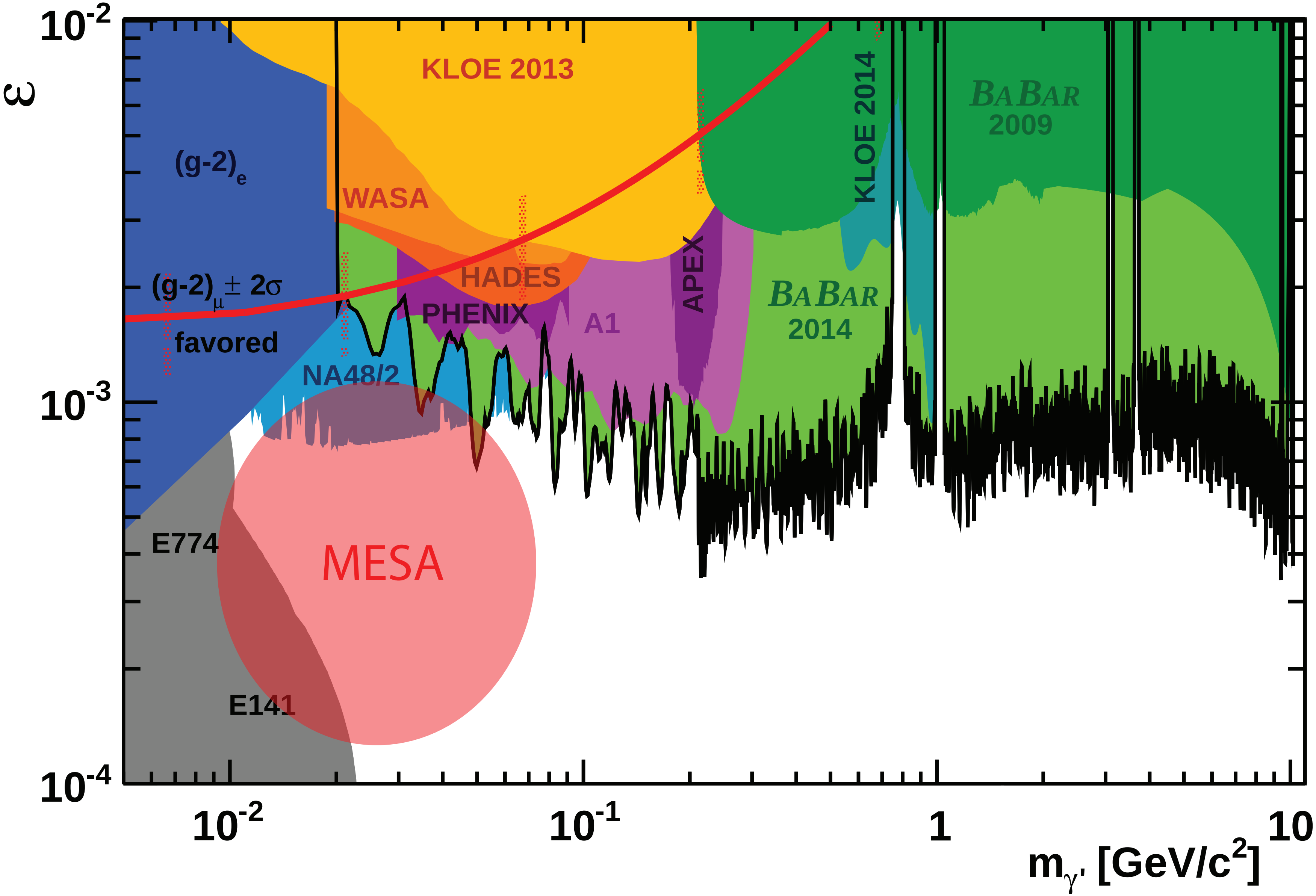
- There could be additional U(1) gauge symmetries with an exchange particle (dark photon, mass $m_{\gamma'}$)
- It could mix with the photon via heavy fermions (mixing parameter ε)
- It would then show up as a bump in the e^+e^- spectrum

Invisible dark photons



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

Dark photons



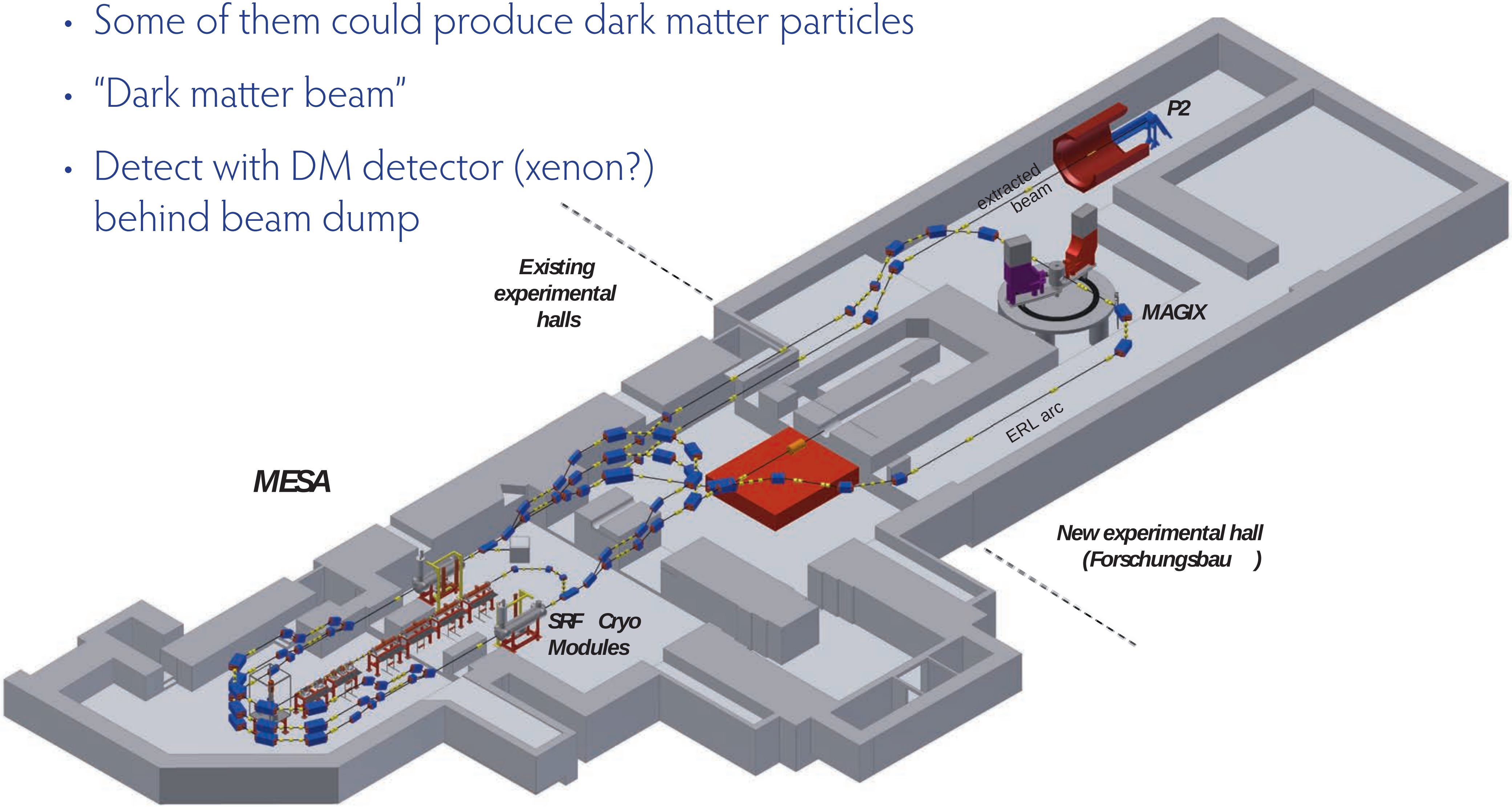
Dark Matter with the Beam Dump

BDX

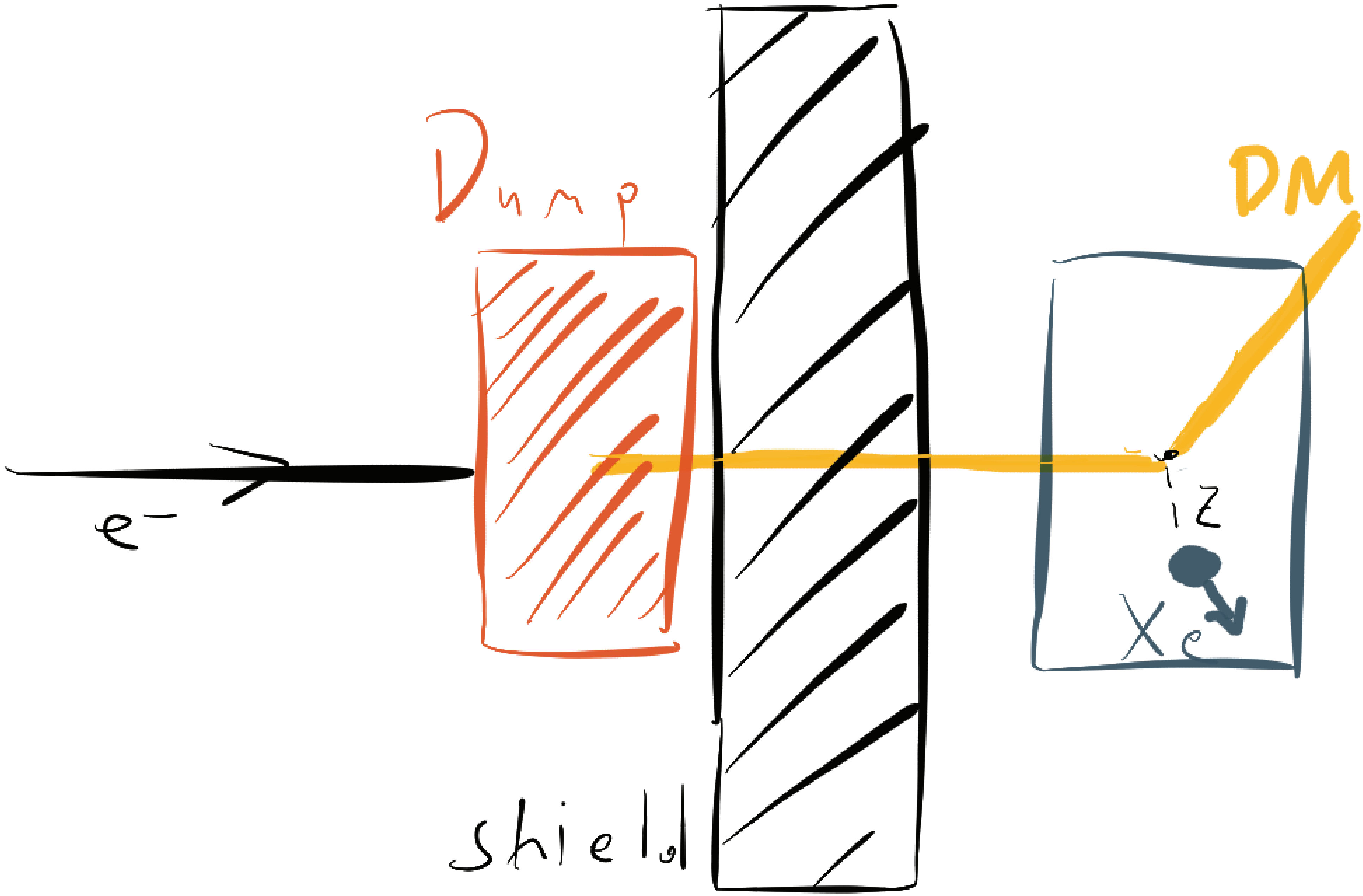
Search for dark matter

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



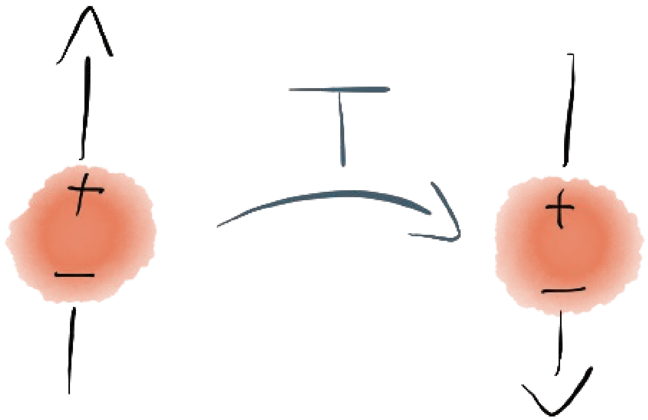
Beam dump dark matter

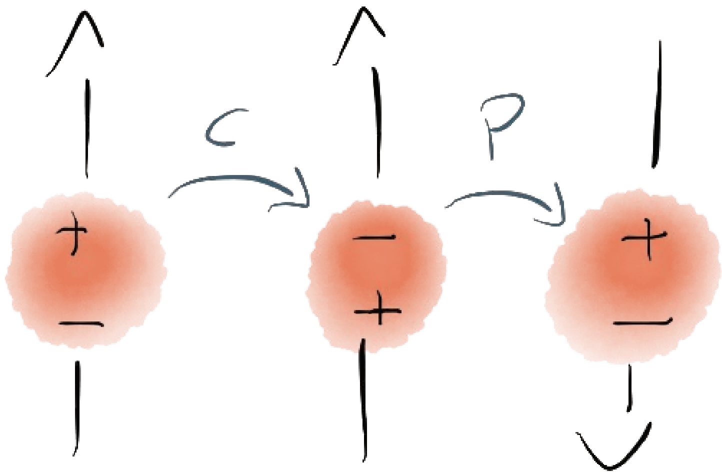


And one more:

Electric dipole moment of electrons

Electric Dipole Moments





- 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

Sakharov Criteria

Matter-Antimatter Asymmetry

Antimatter	Matter
10'000'000'000	10'000'000'001

Necessary conditions to create baryon asymmetry:

- Baryon number violation
- C and CP violation
- Out of thermal equilibrium

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)

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

Magnetic dipole

Electric dipole

Precession in a storage ring

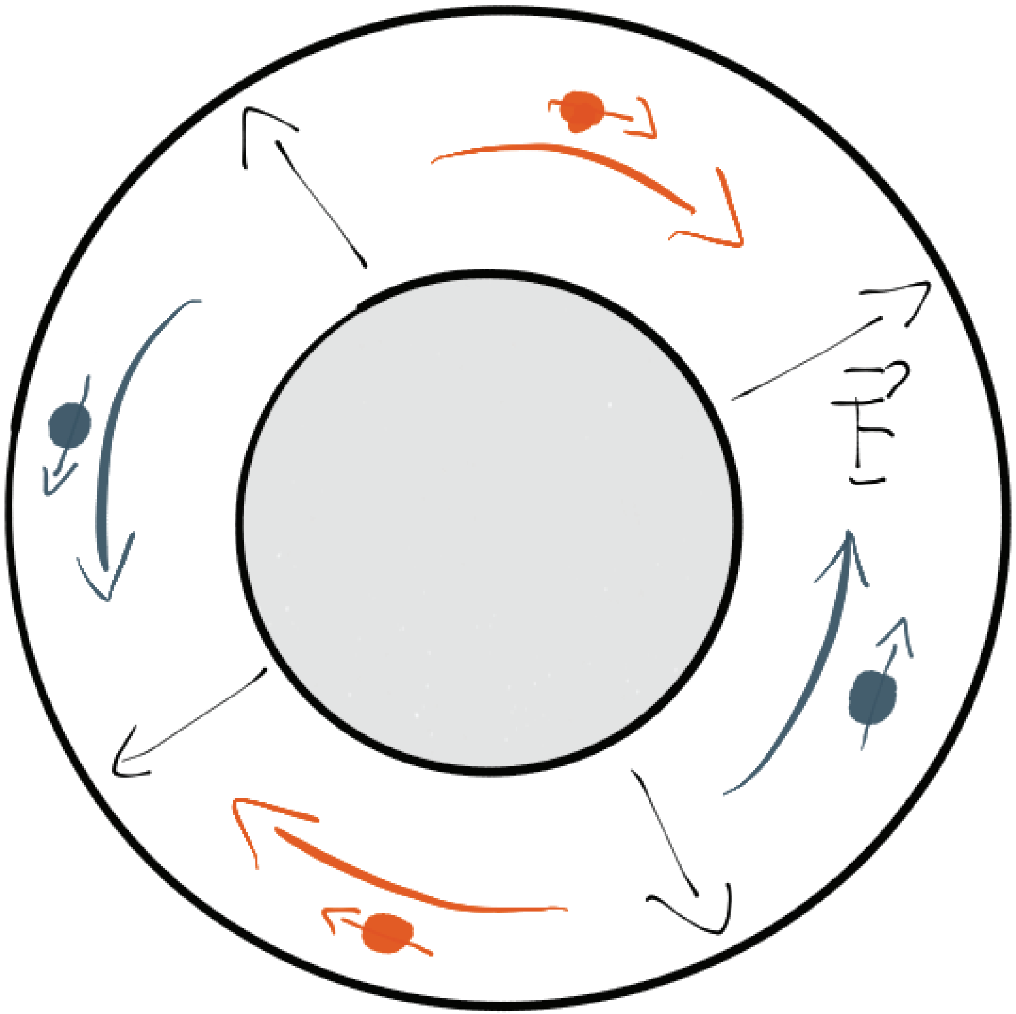
- No magnetic field!
- Magic momentum!

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

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

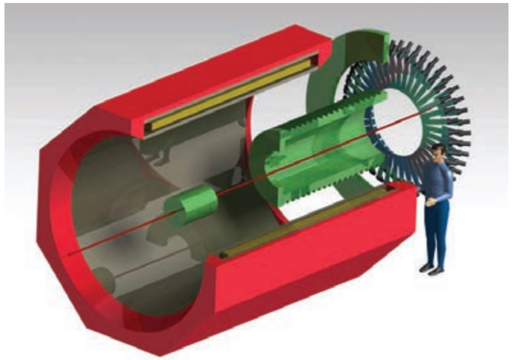
$$|d_e| < 8.7 \times 10^{-29} e \cdot \mathrm{cm} \;\; (\mathrm{ThO})$$

ACME collaboration,
Science 343, 269 (2104)

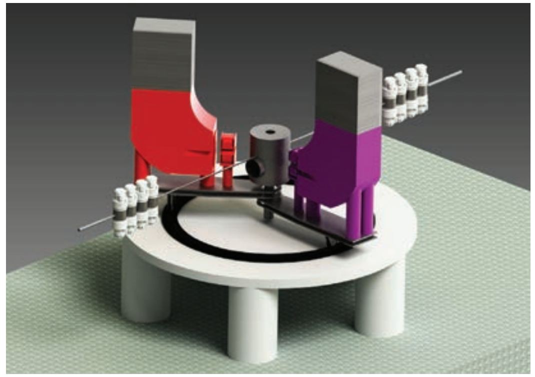
- Need very low magnetic field
- Good control of electric field
- Very hard to compete with molecules for limits ...
- ... but only option for a precise measurement ...
- ... and a pathfinder for the proton EDM (Jülich, Korea...)

Summary

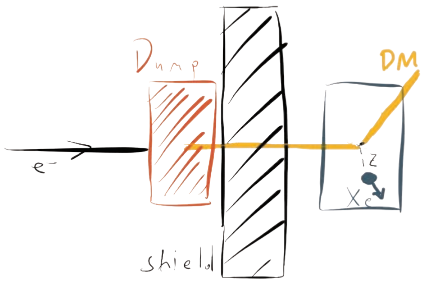
Exciting physics program at MESA:



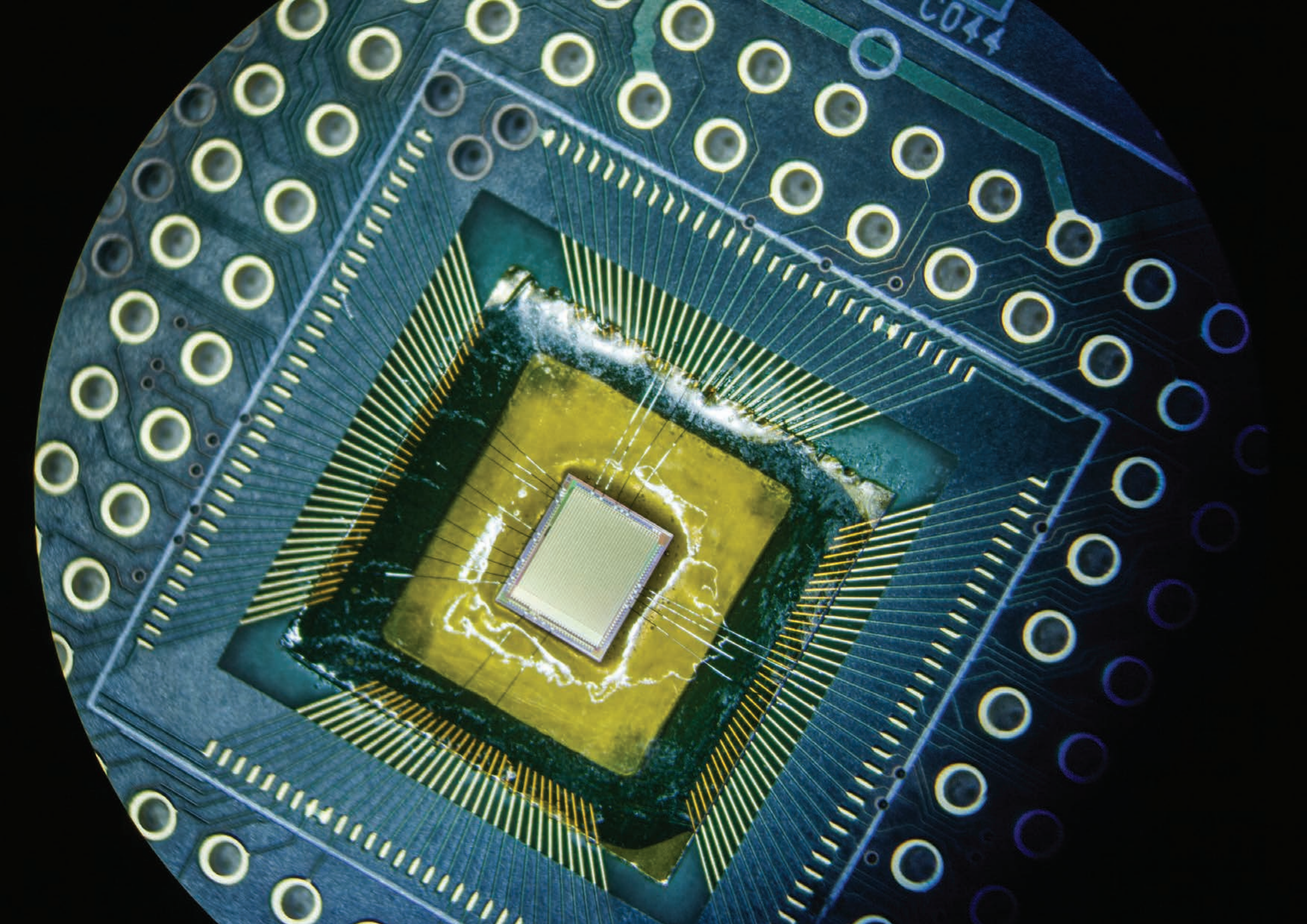
- Weak mixing angle measurement with P2
- Also gives access to neutron skins



- Proton radius, dark photon and much more with MAGIX



- Second generation of experiments:
  Beam dump dark matter and electron EDM
- Start 2019/2020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