PRISMA+

Physics at MESA

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PSI, April 2021

JG|U

PRISMA+

Overview

- The running weak mixing angle
- The MESA accelerator
- The P2 Experiment
- The MAGIX Spectrometer
- The BDX beam-dump experiment

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"

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

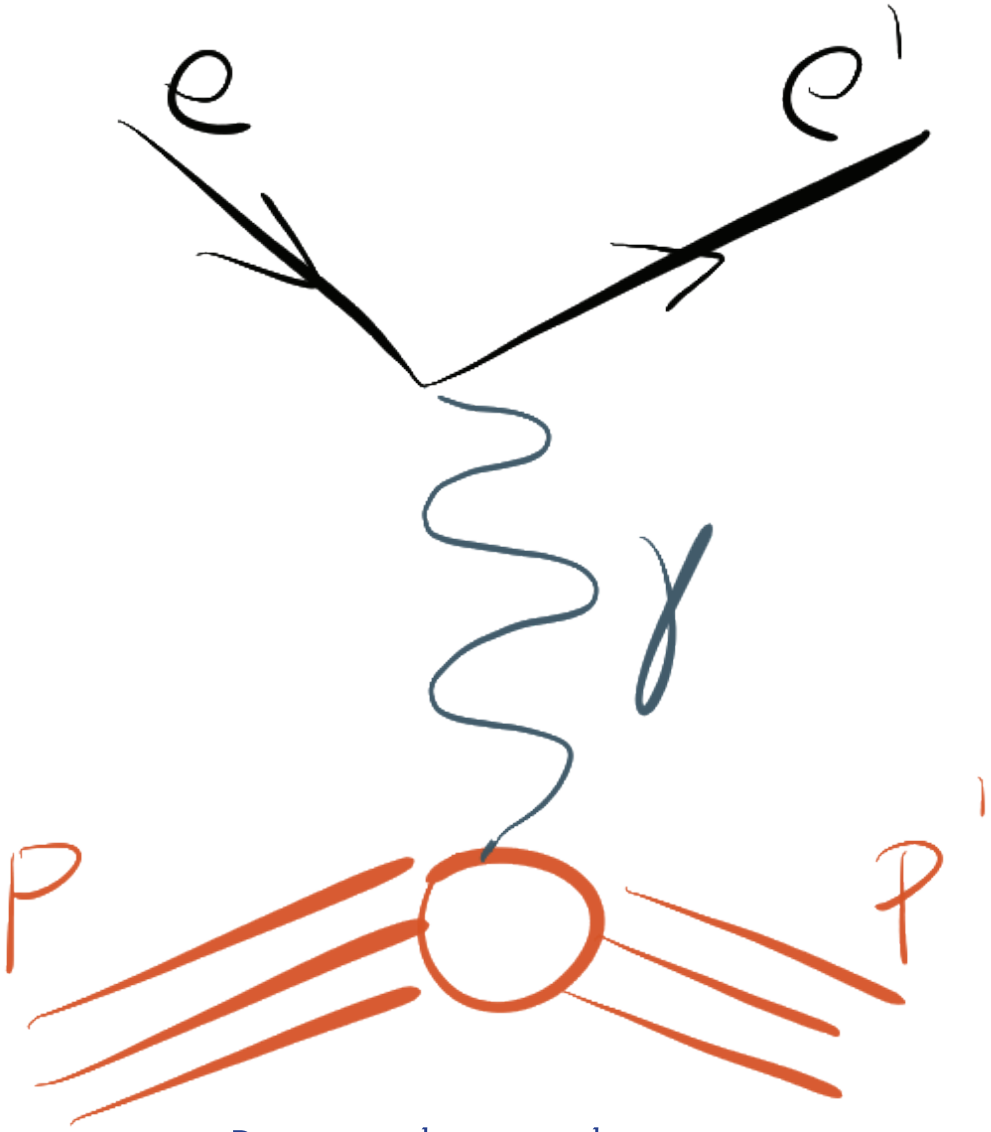
- Or use the couplings:
  (which change with energy, and so does the angle)
  "$\overline{\text{MS}}$-scheme"

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

- Use second option from here on

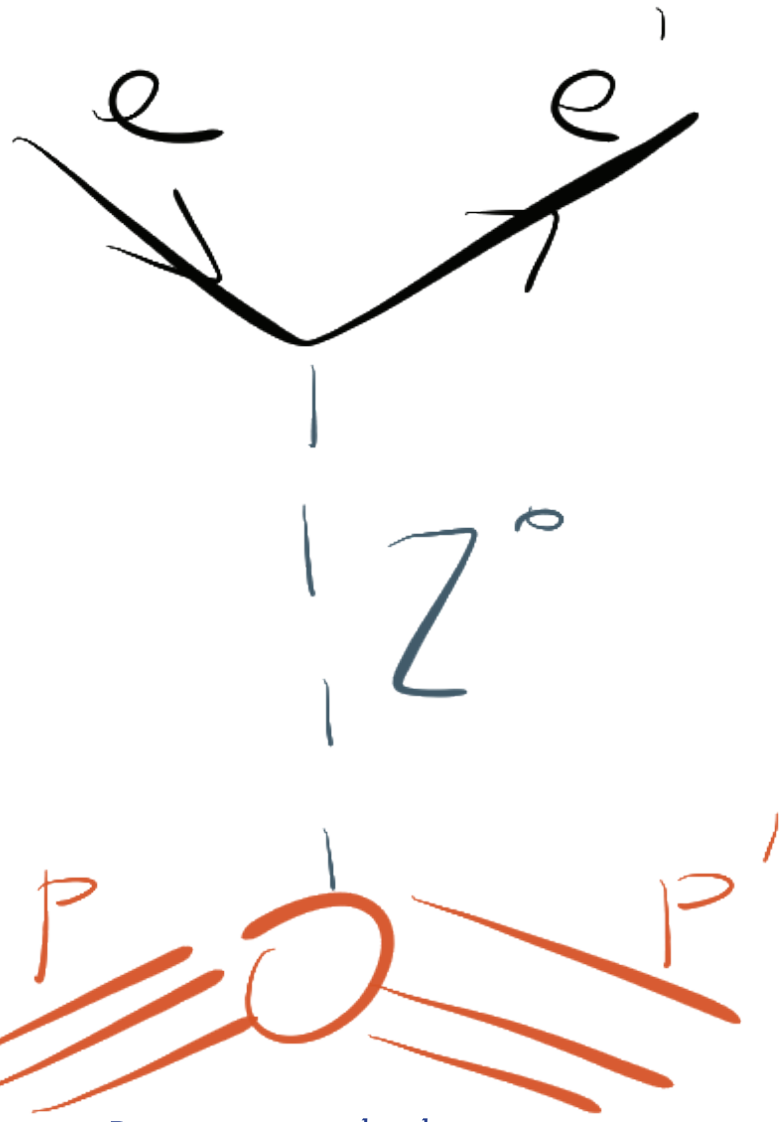
$$\sin^2\theta_W(q^2)$$

Weak mixing angle and charges



Proton electric charge

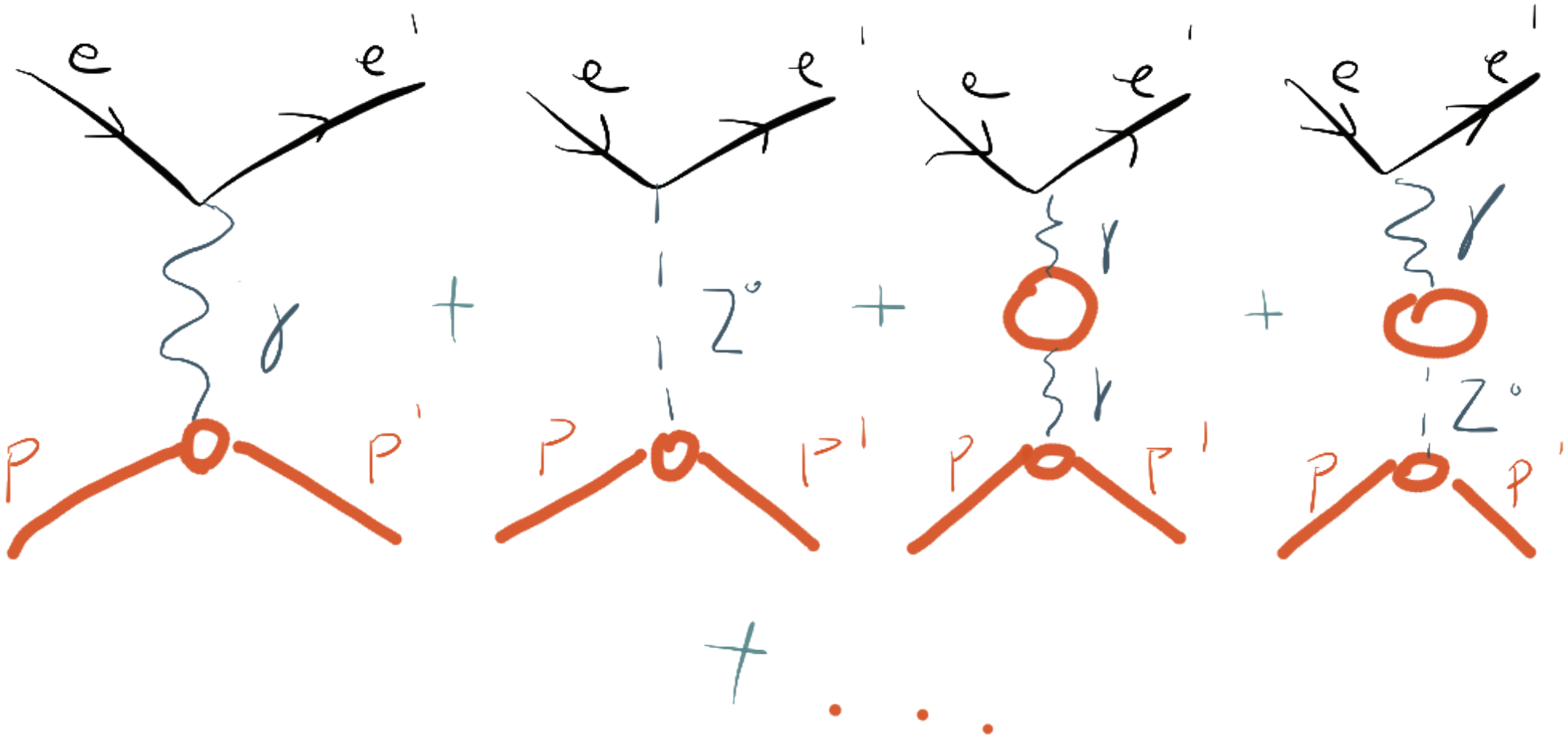
+e



Proton weak charge

$1 - 4 \sin^2\theta_W$

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



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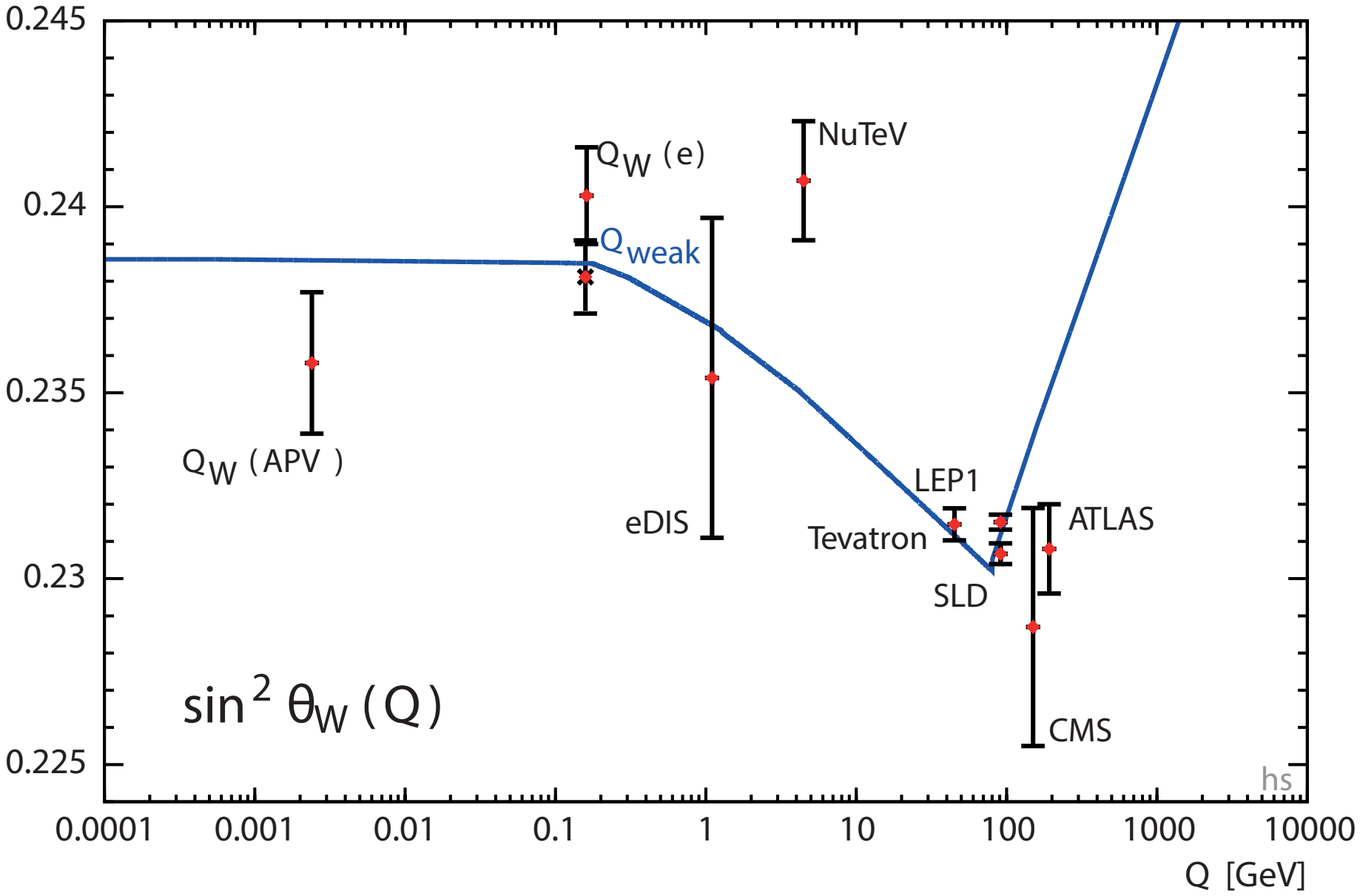

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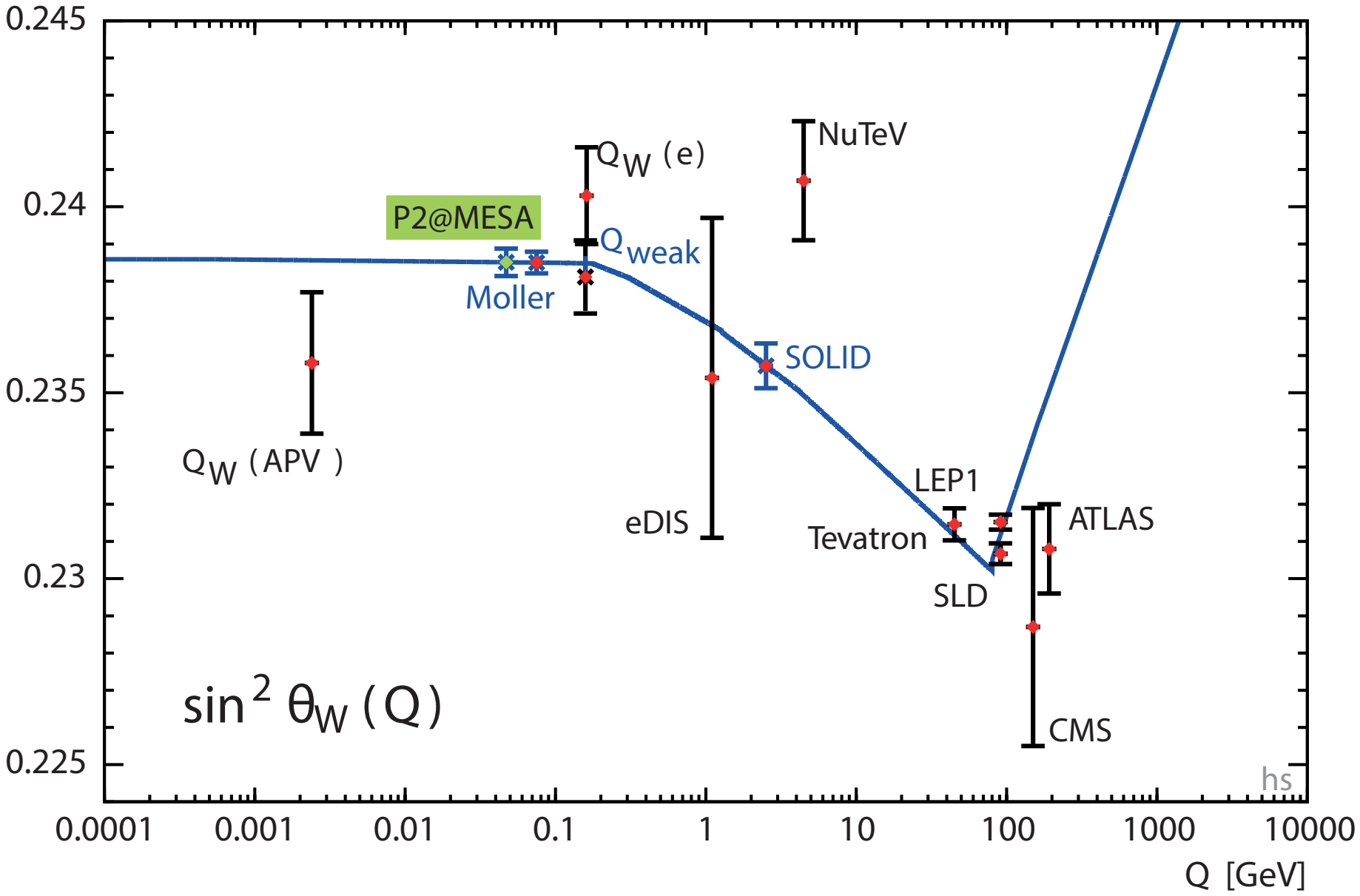
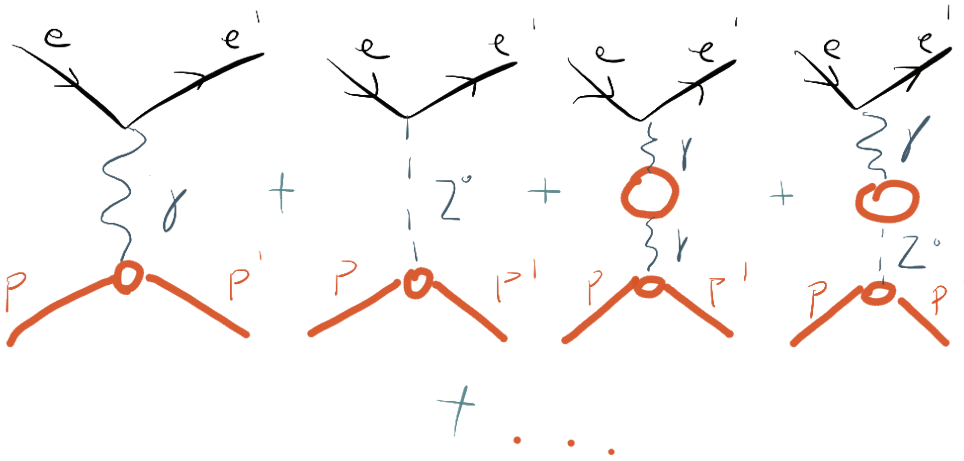
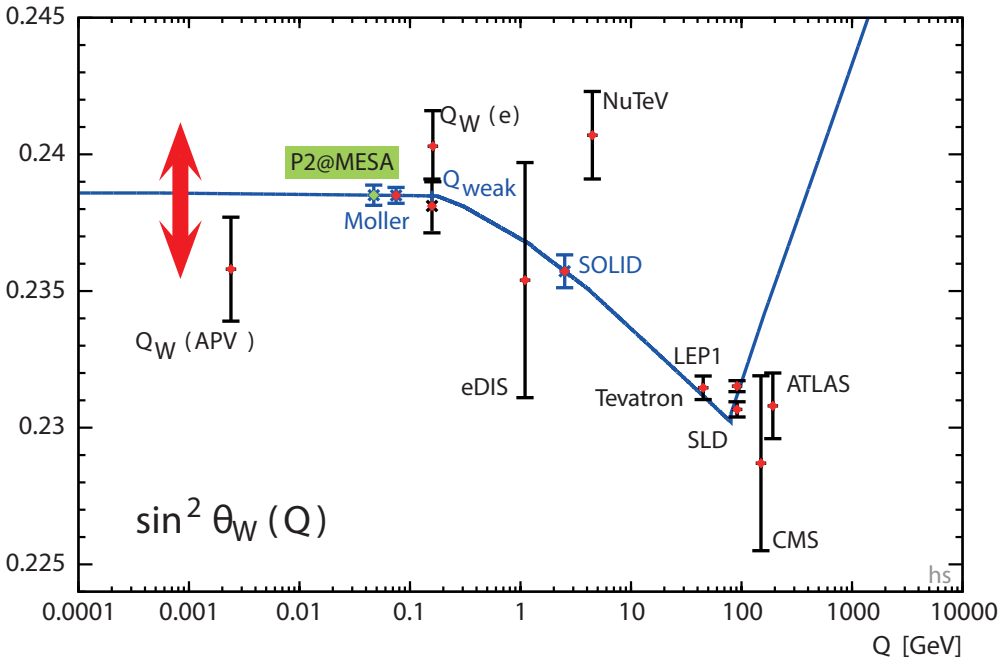
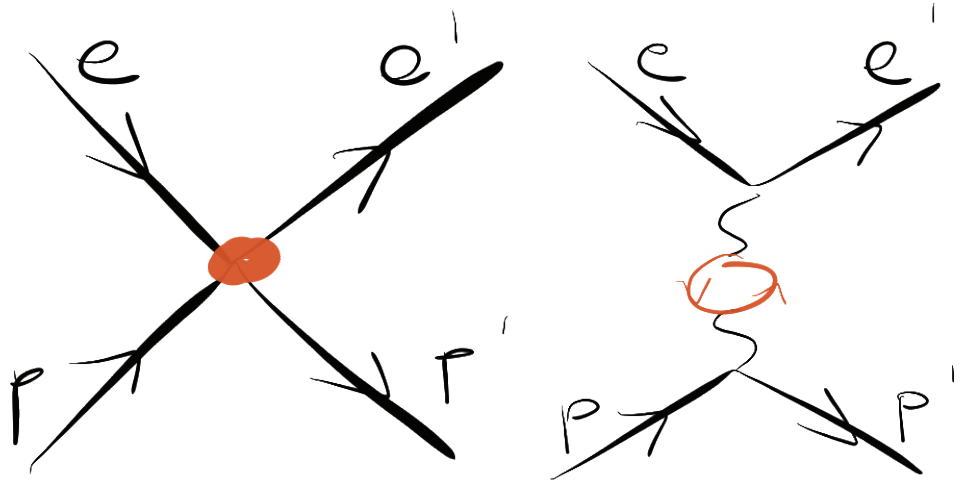
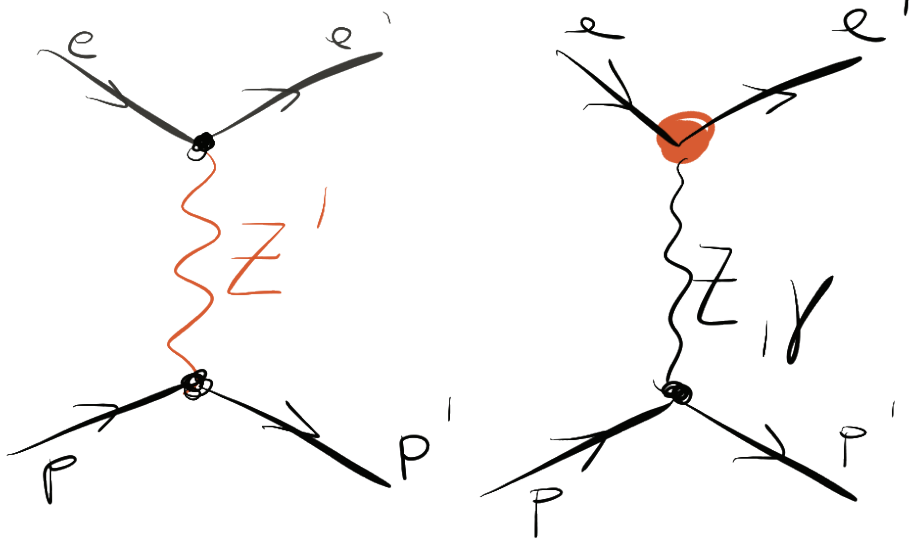


New Physics in the running

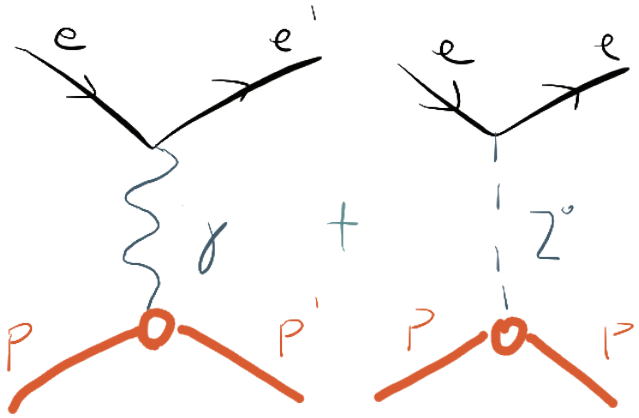


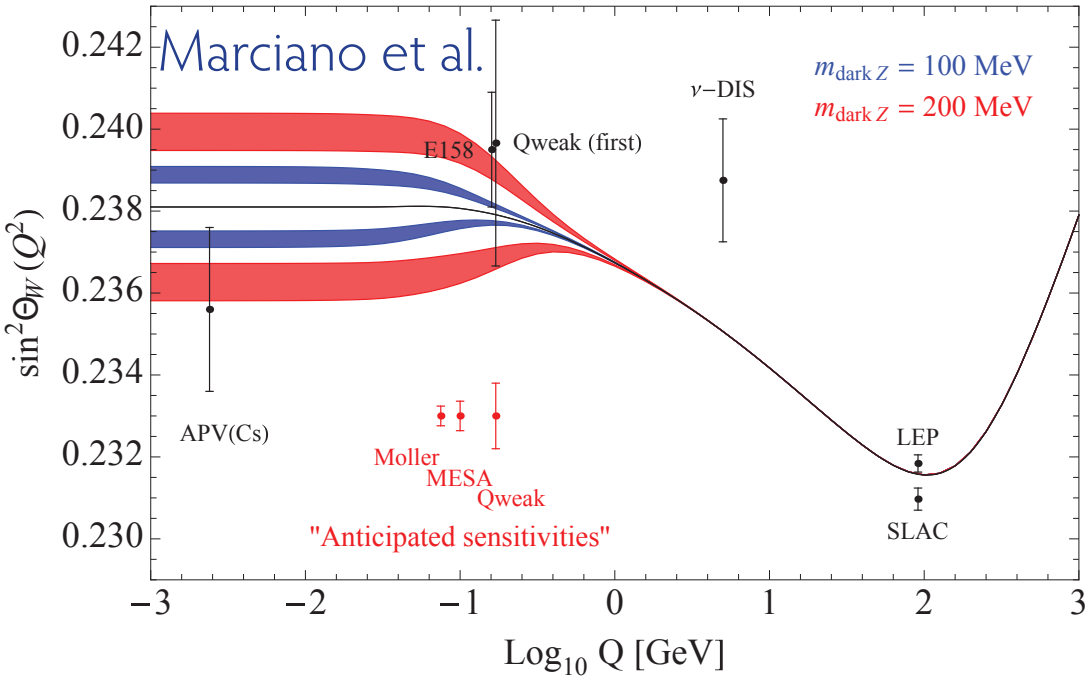


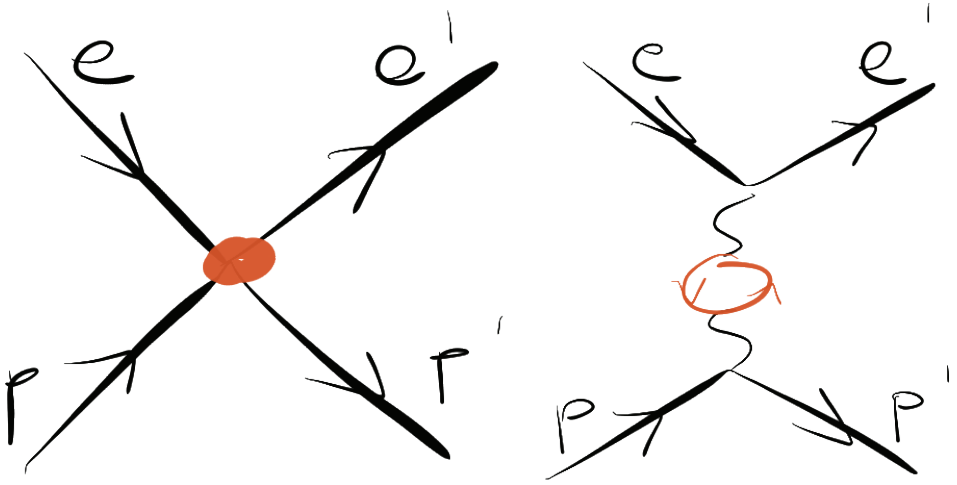


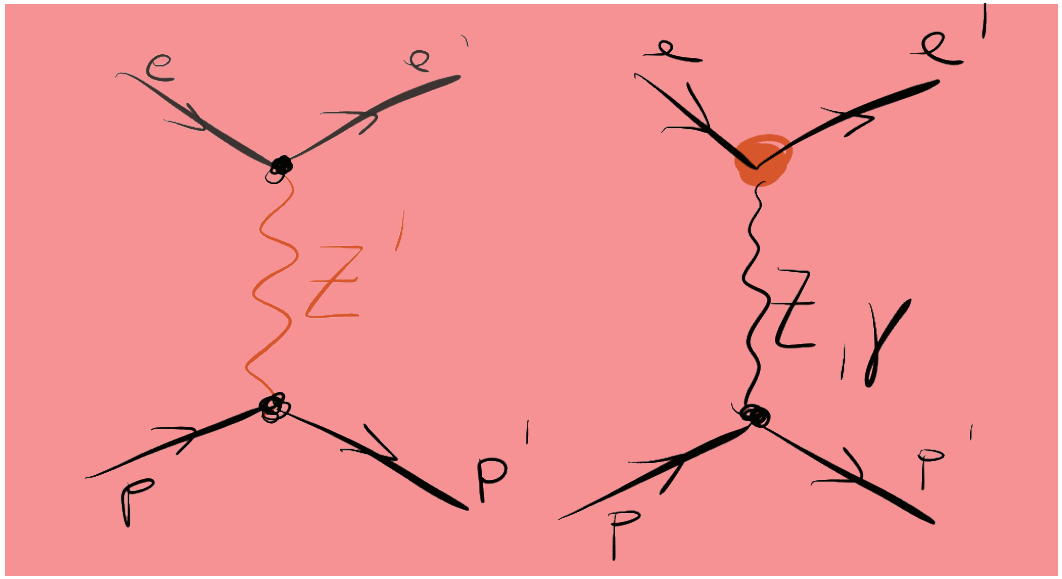


Dark Zs

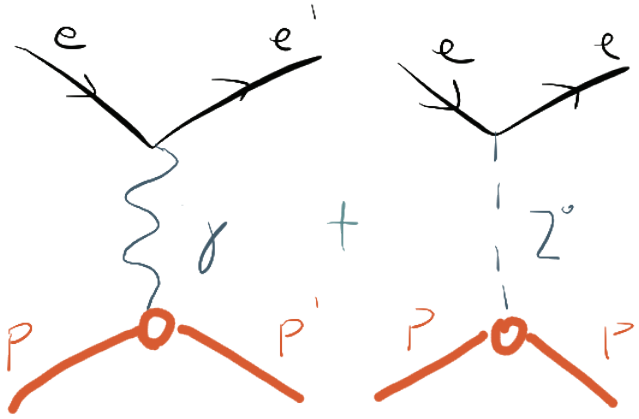

e
e'
γ
+
Z'
P
P'


Marciano et al.
$m_{\text{dark }Z}$ = 100 MeV
$m_{\text{dark }Z}$ = 200 MeV
ν–DIS
E158
Qweak (first)
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC
$\sin^2\Theta_W(Q^2)$
Log_{10} Q [GeV]
0.242
0.240
0.238
0.236
0.234
0.232
0.230
−3
−2
−1
0
1
2
3

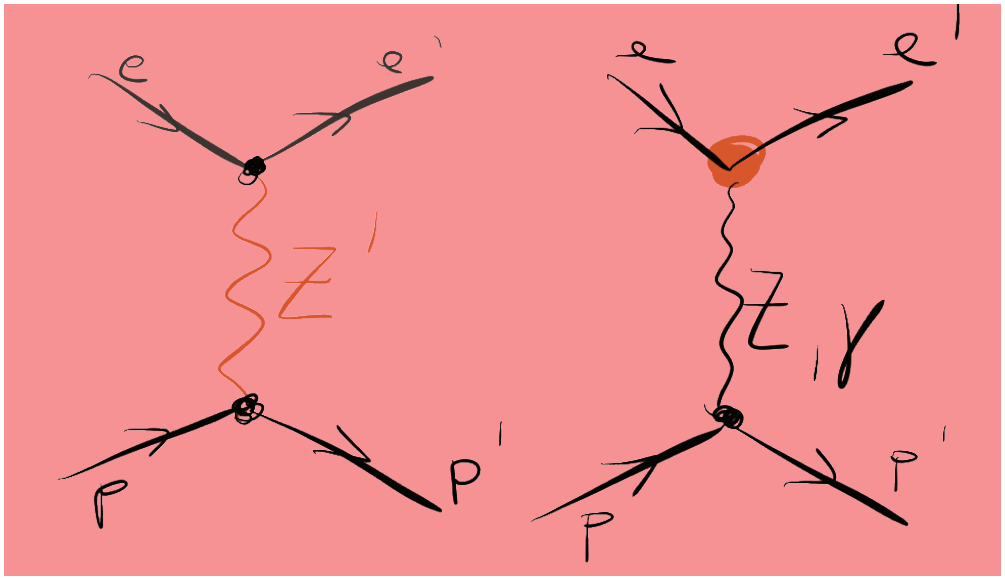

e
e'
P
P'

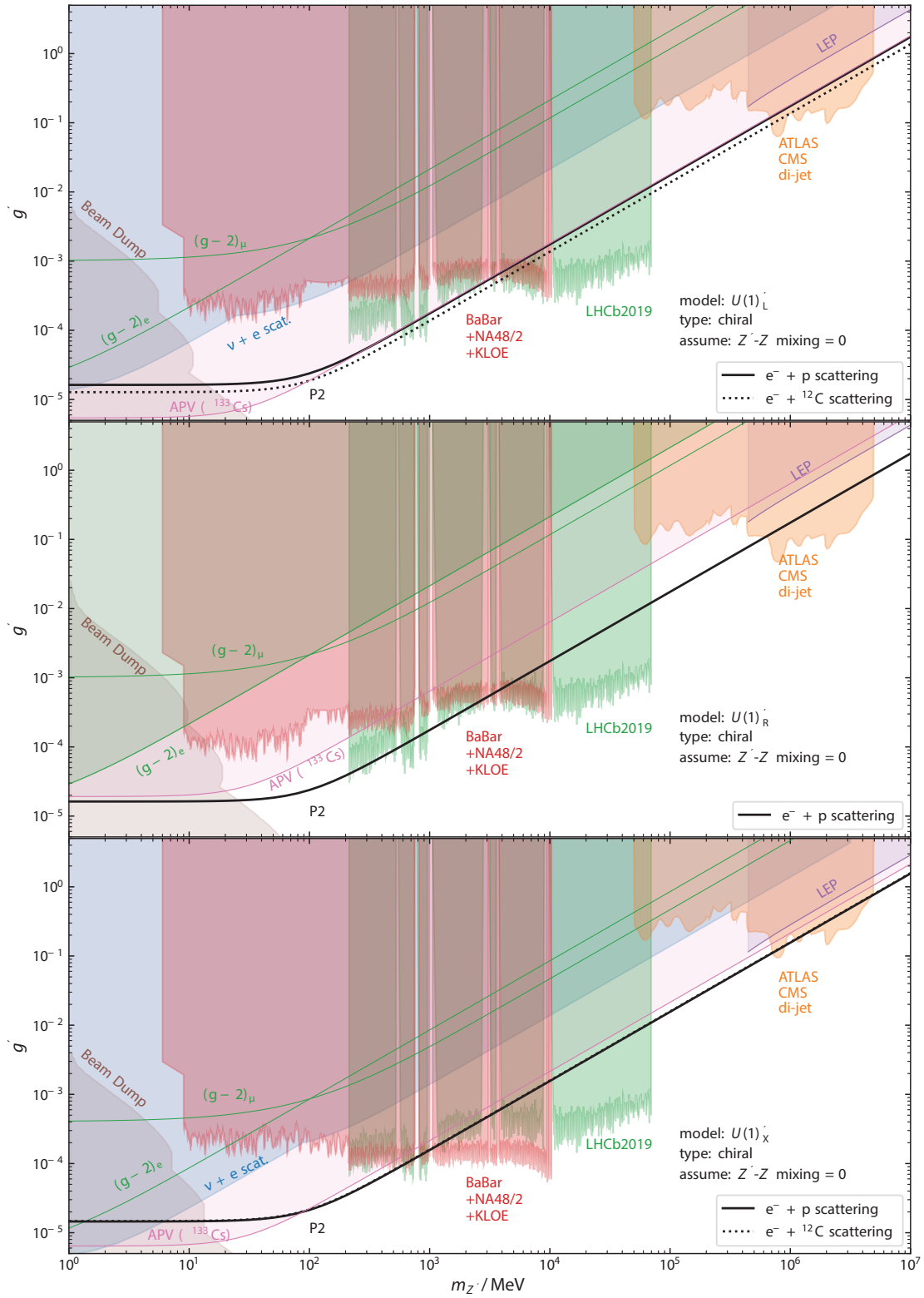

e
e'
Z'
P
P'
γ

Dark Zs

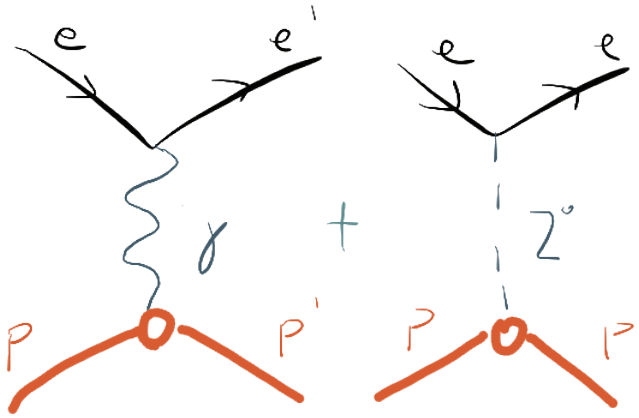


Bhupal Dev, Rodejohann, Xu, Zhang,
arXiv:2103.09067





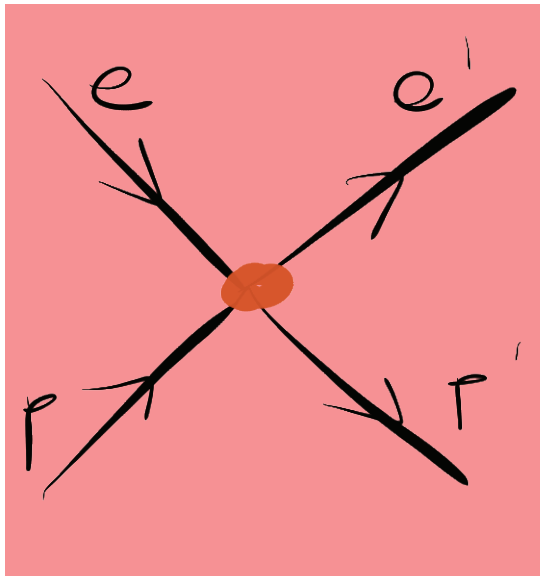
Contact Interactions

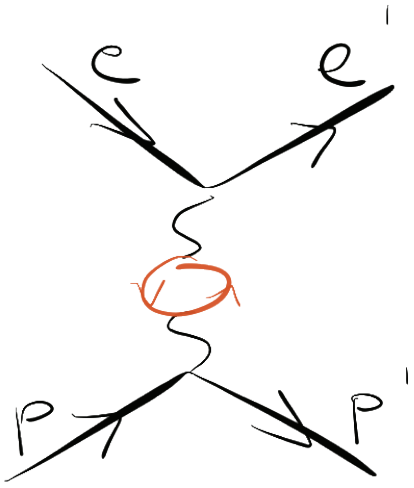


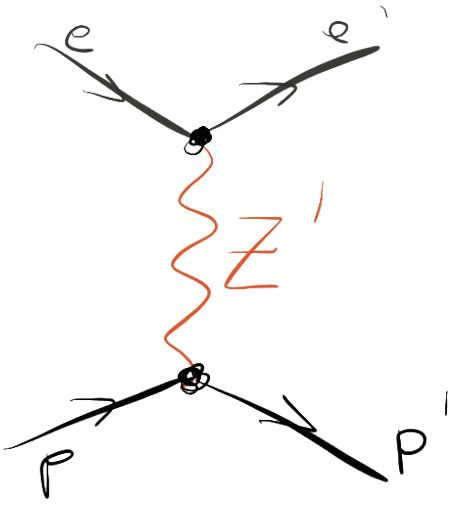
Contact interactions up to

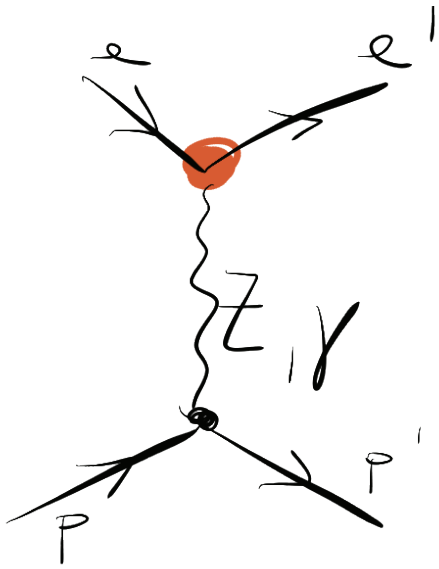
49 TeV

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



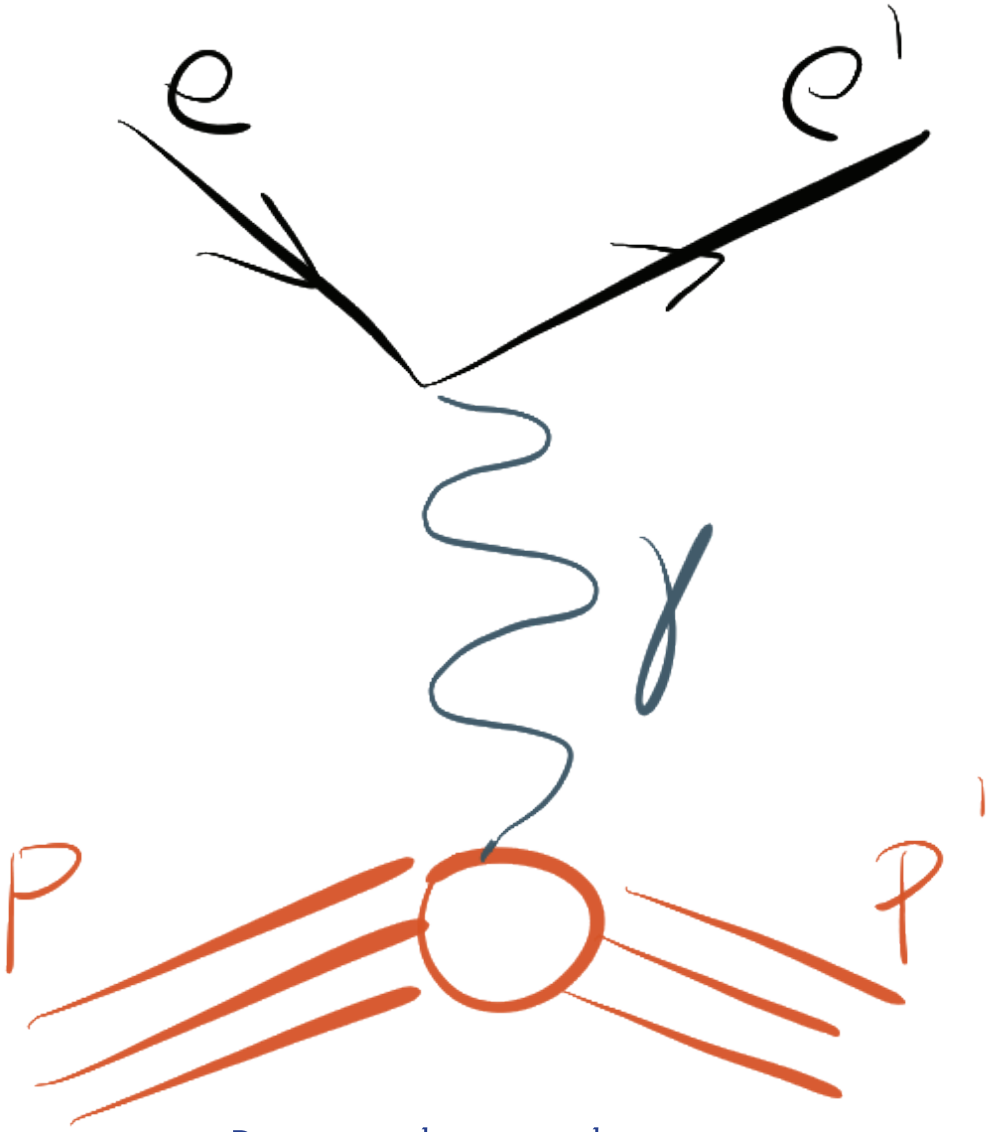






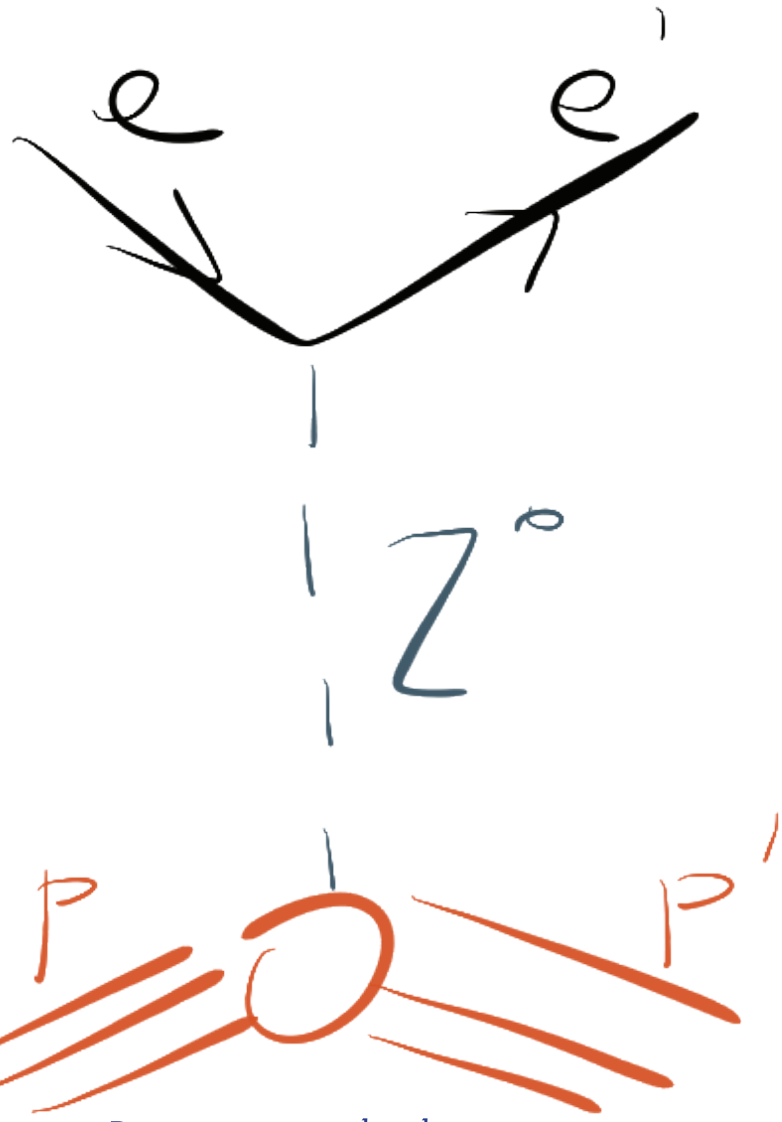
How to measure the weak charge?

Weak mixing angle and charges



Proton electric charge

+e



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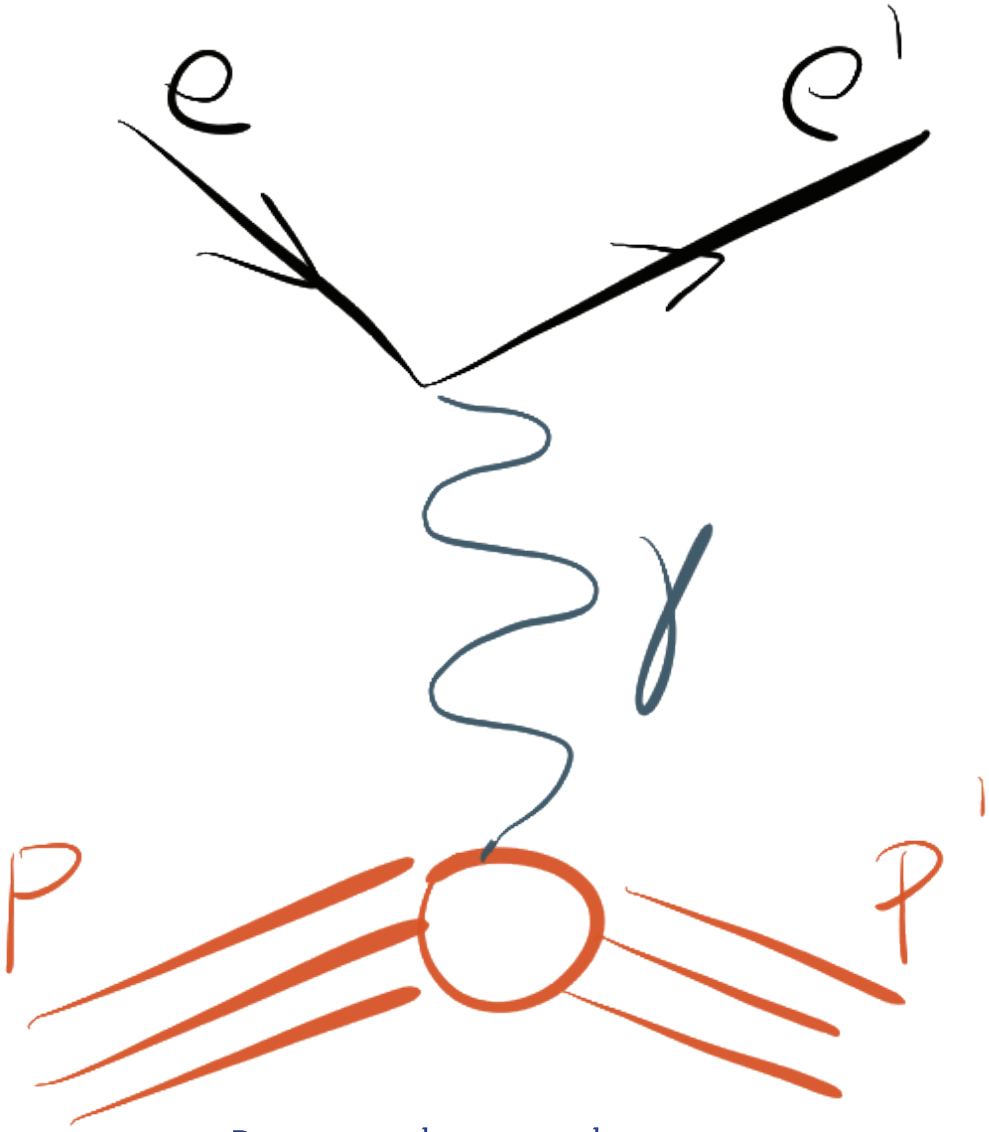

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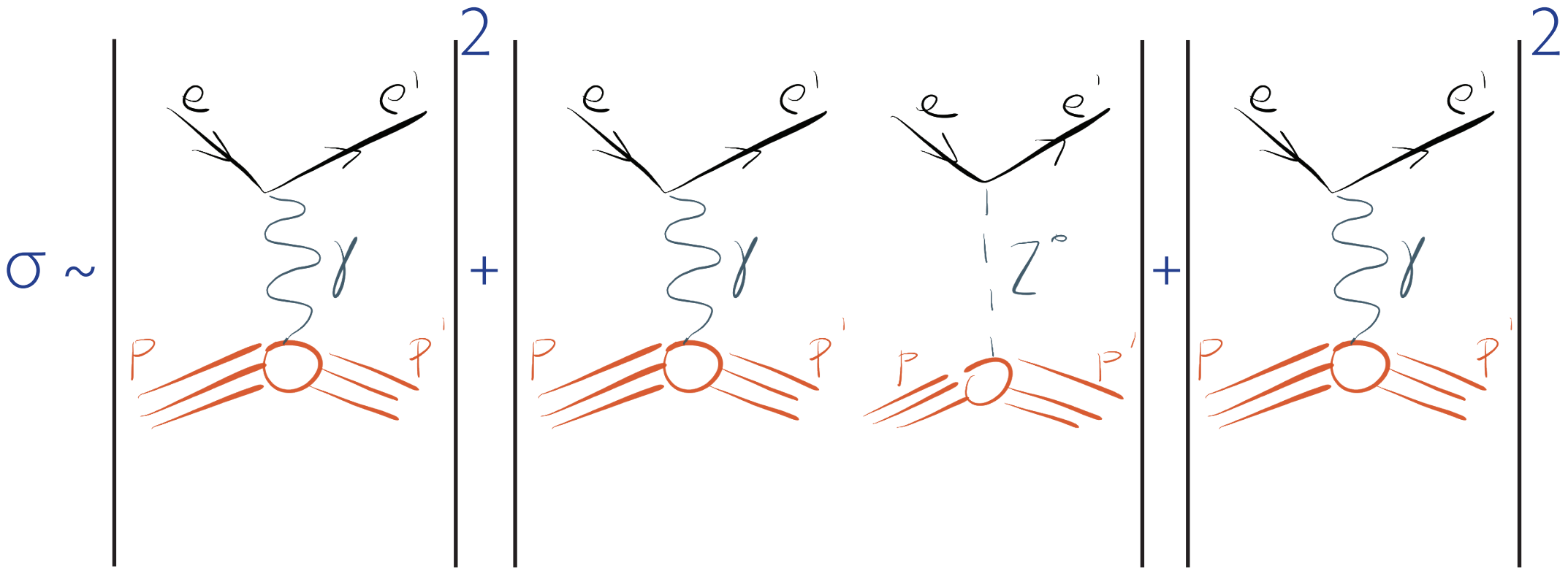
+e

Violates parity!

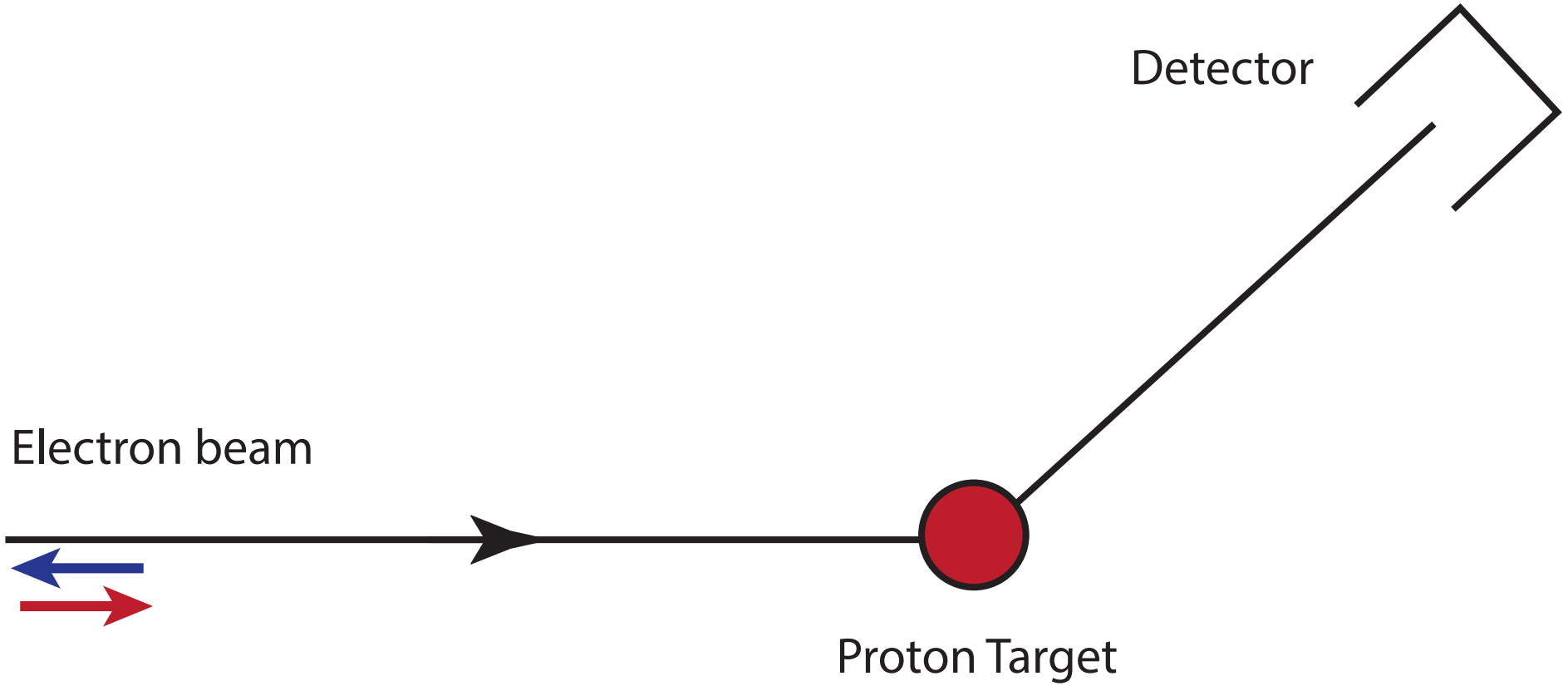
Proton weak charge

$1 - 4 \sin^2\theta_W$

Interference

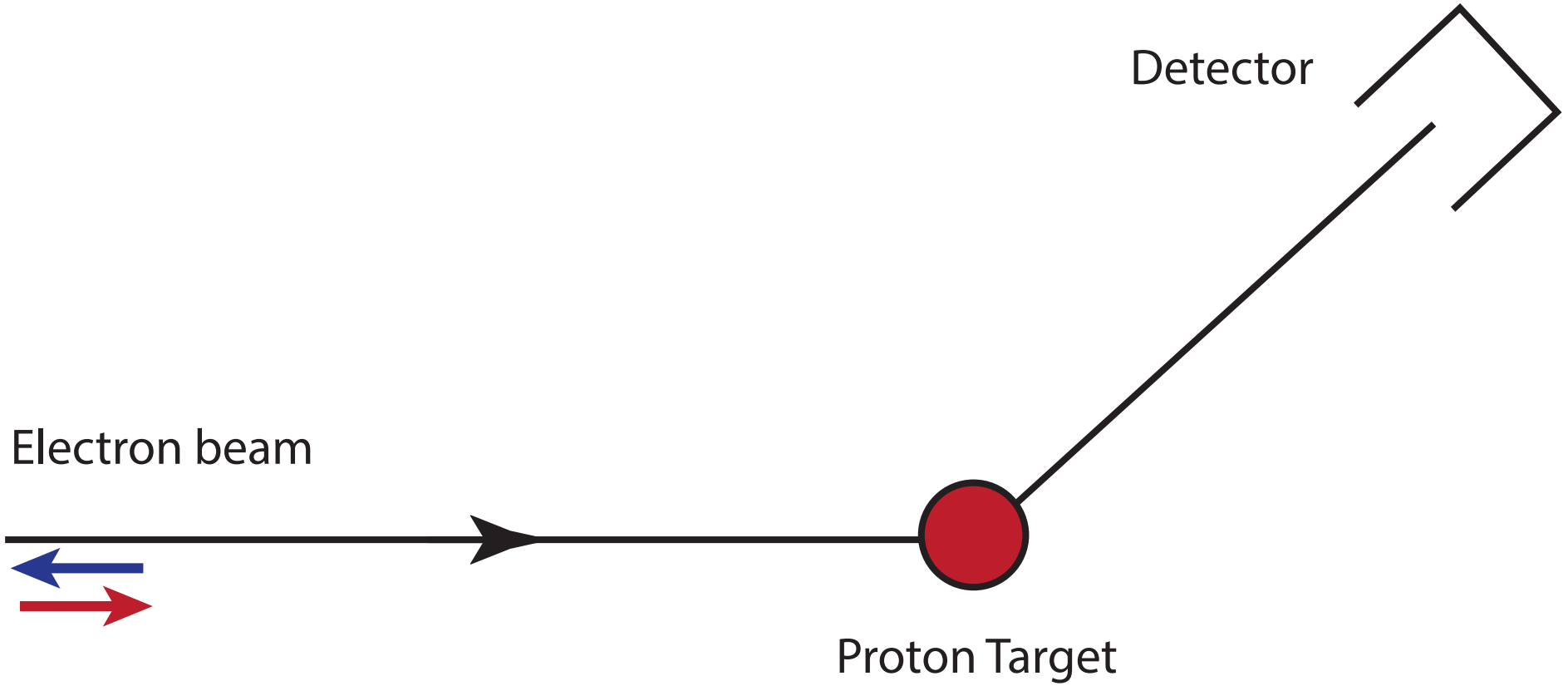


Parity violating electron scattering



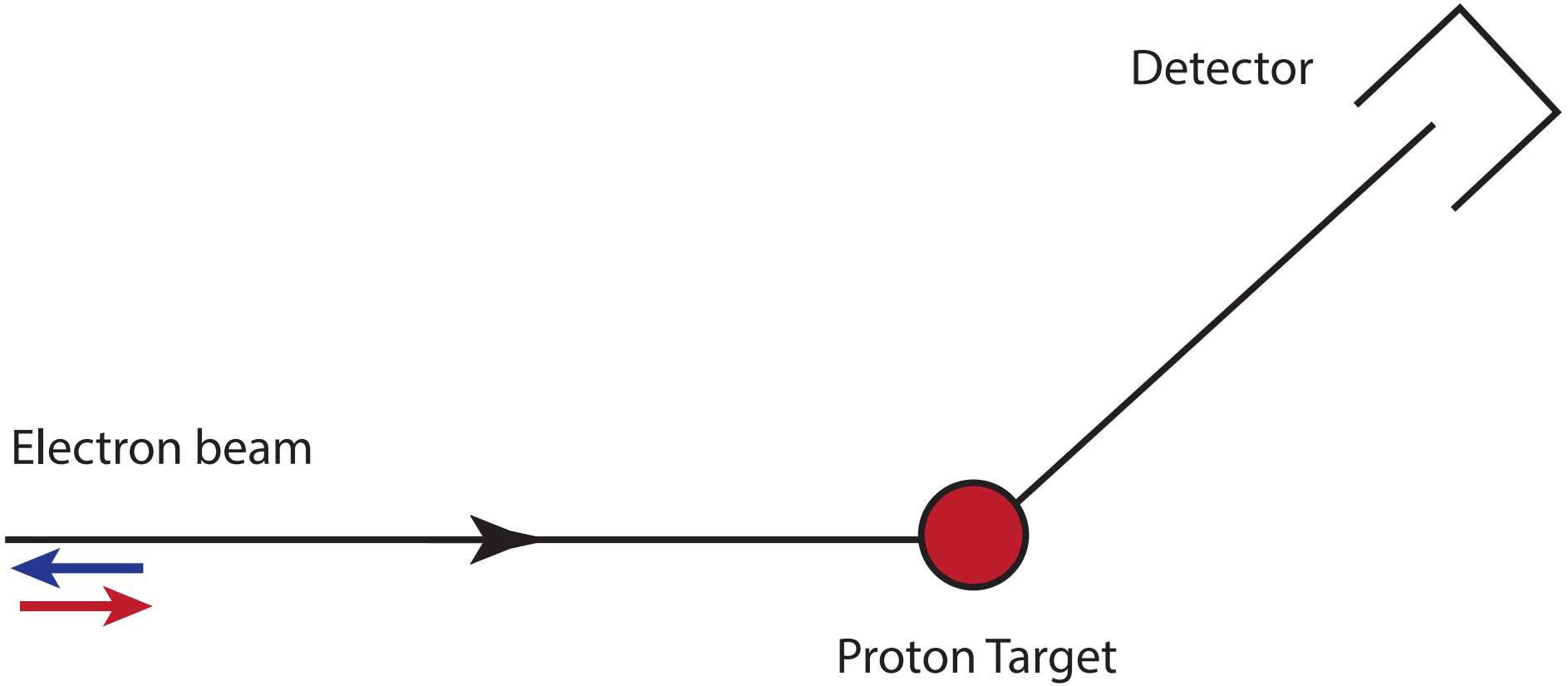
Parity violating electron scattering

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



Parity violating electron scattering

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



Parity violating electron scattering

Momentum transfer sets scale

Proton structure - small nuisance if Q^2 small

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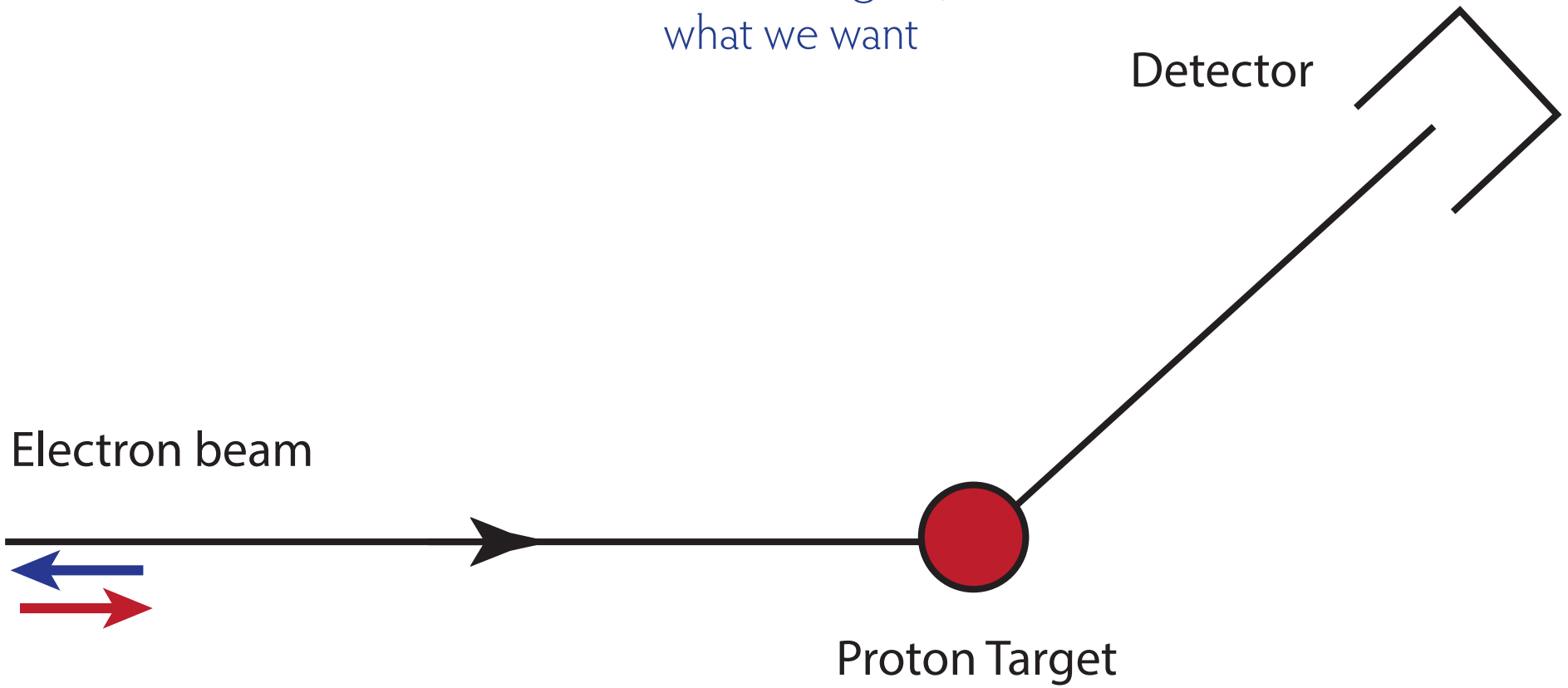
Weak charge - what we want



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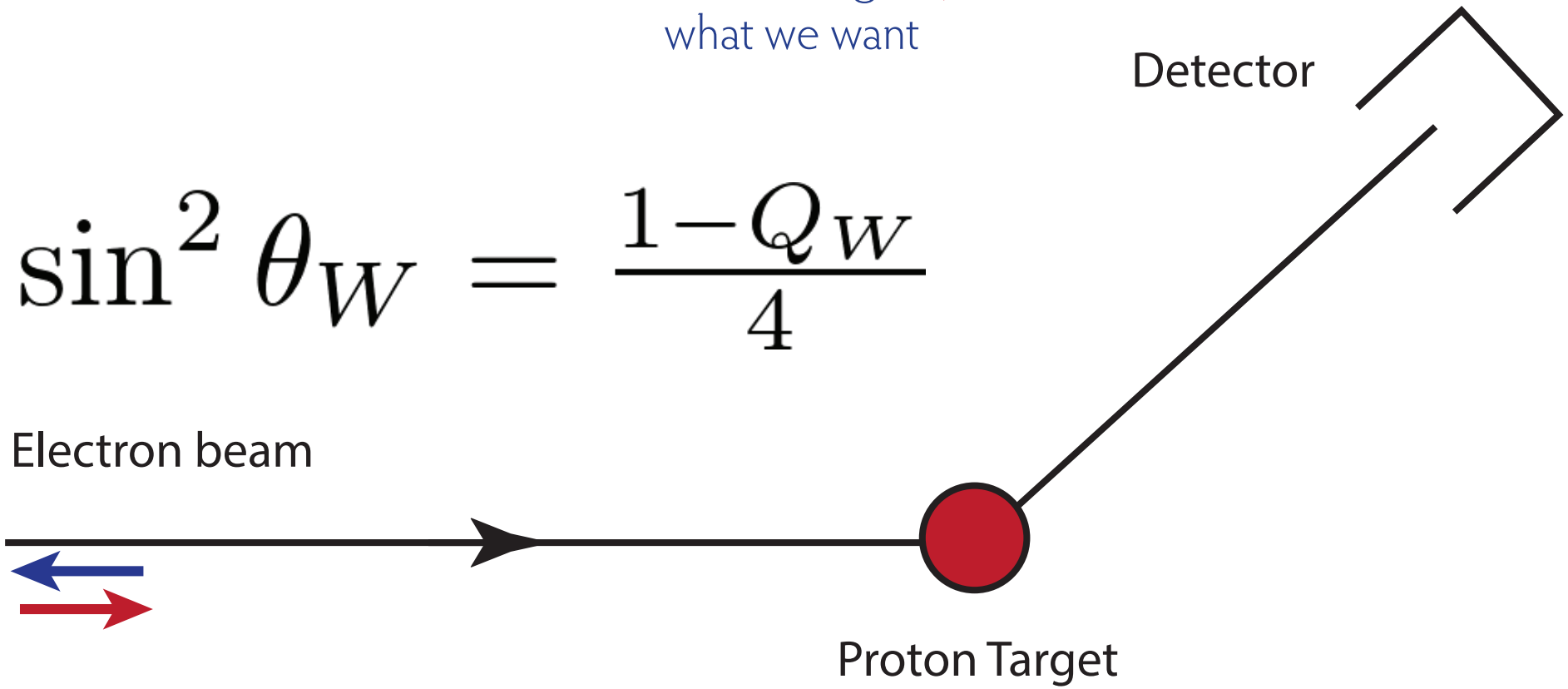
Weak charge - what we want

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



Why is this difficult?

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

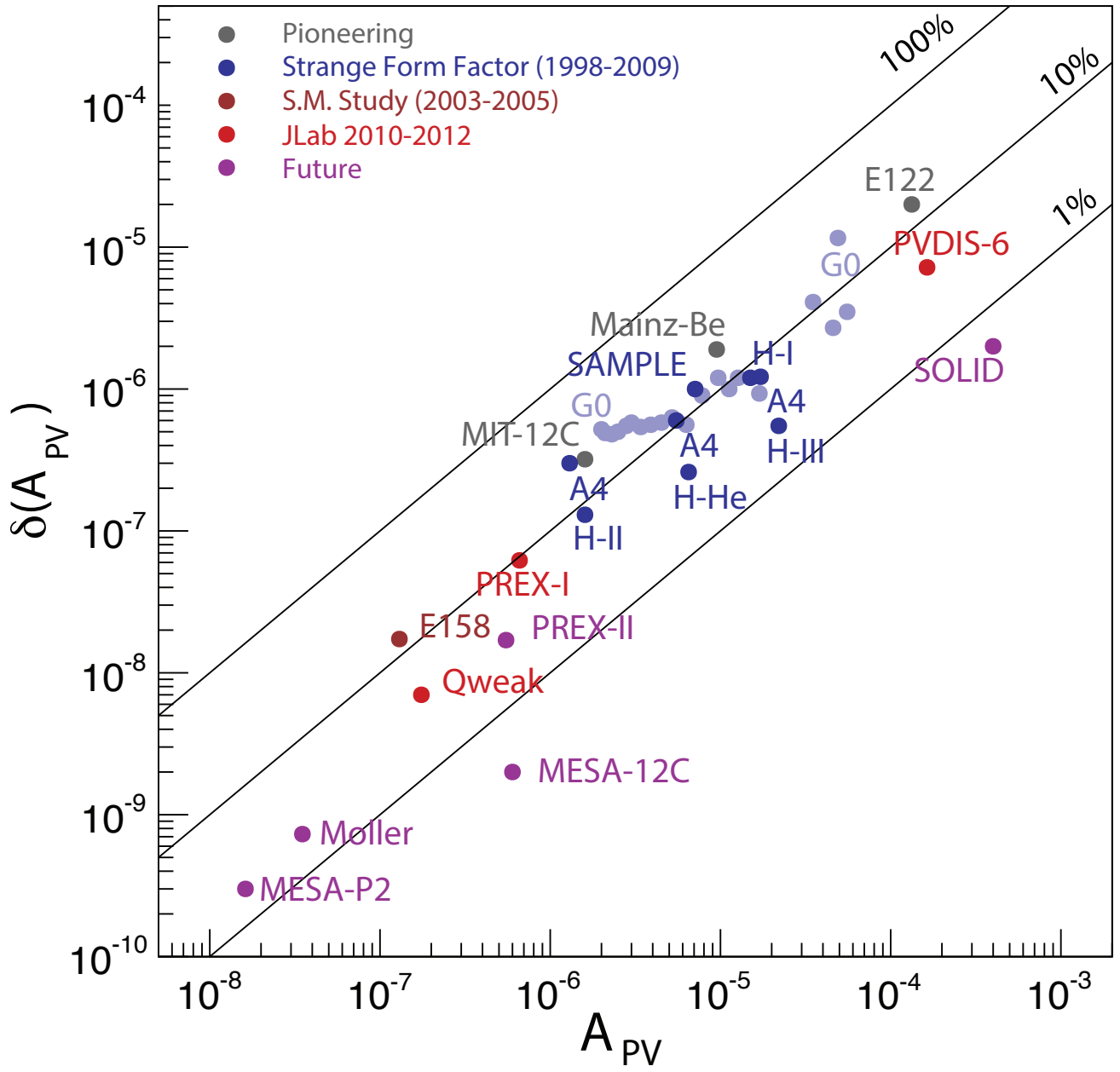
$$Q_W = 1 - 4\sin^2\theta_W$$

- 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

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}

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

How much statistics do we need?

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- A_{PV} is 40 parts per billion
- $\delta(A_{PV})$ is 0.6 parts per billion
- N a few 10^{18}

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

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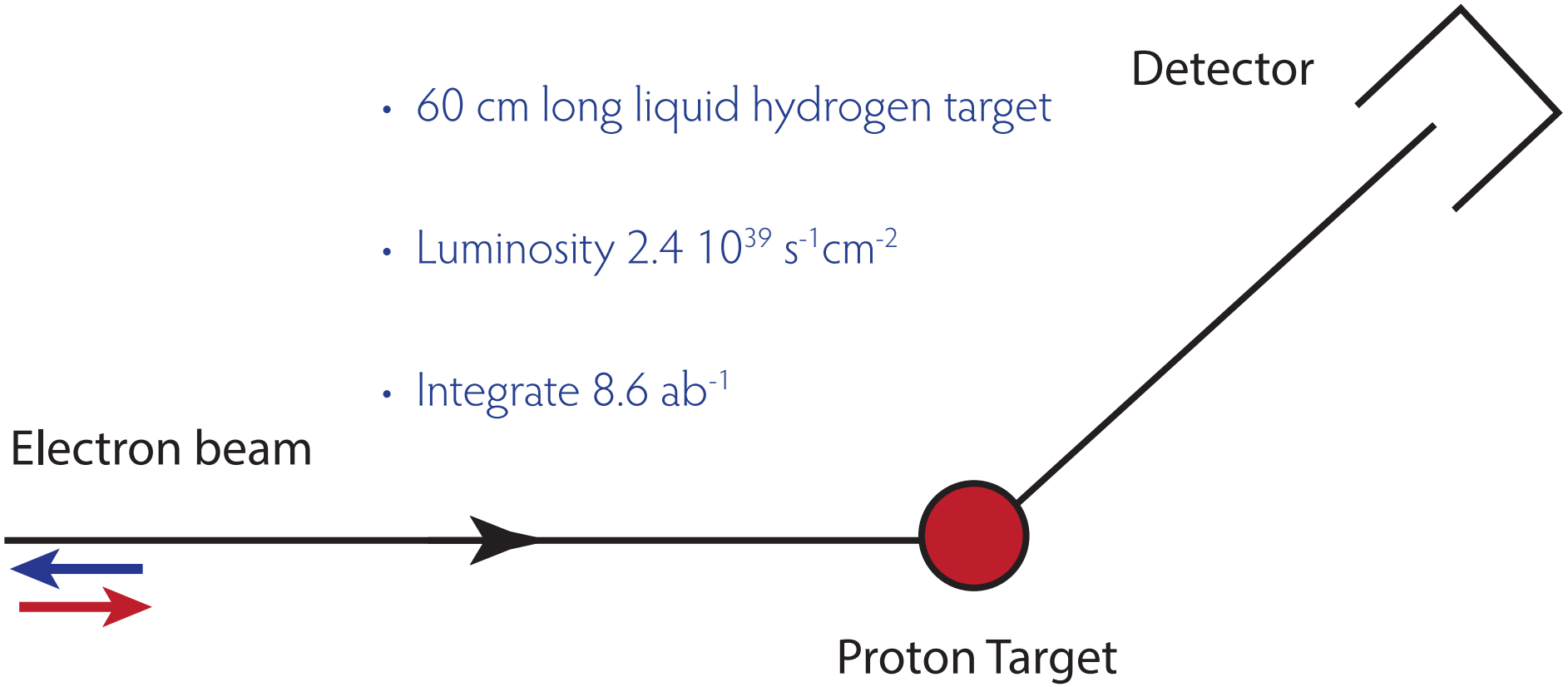
$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

- N a few 10^{18}
- Measure 11'000 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}



11'000 hours is 458 days 24/7 of measurements

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

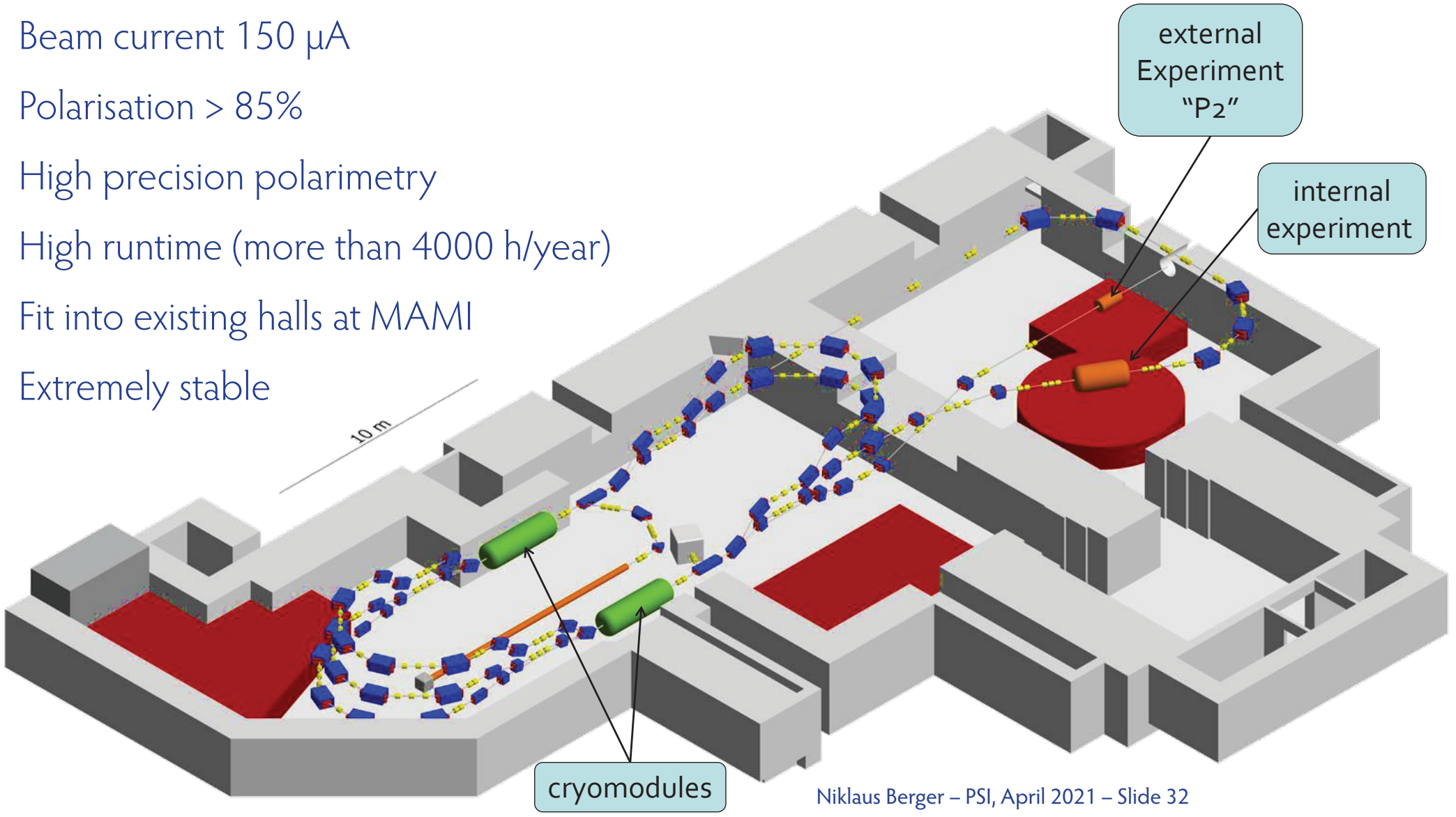
If you cannot rent it, build it:

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



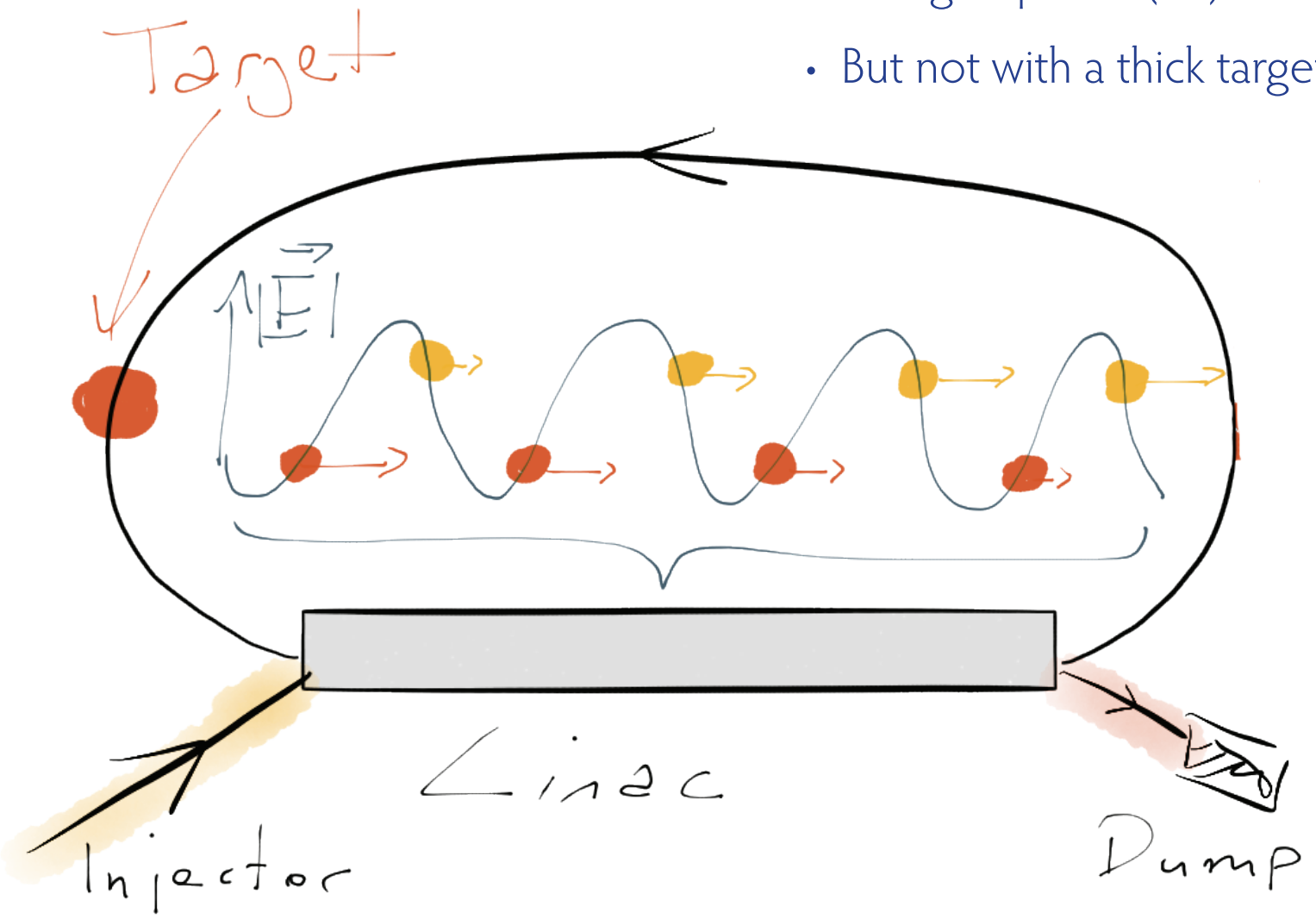
Energy recovery

Can we go to higher beam currents?

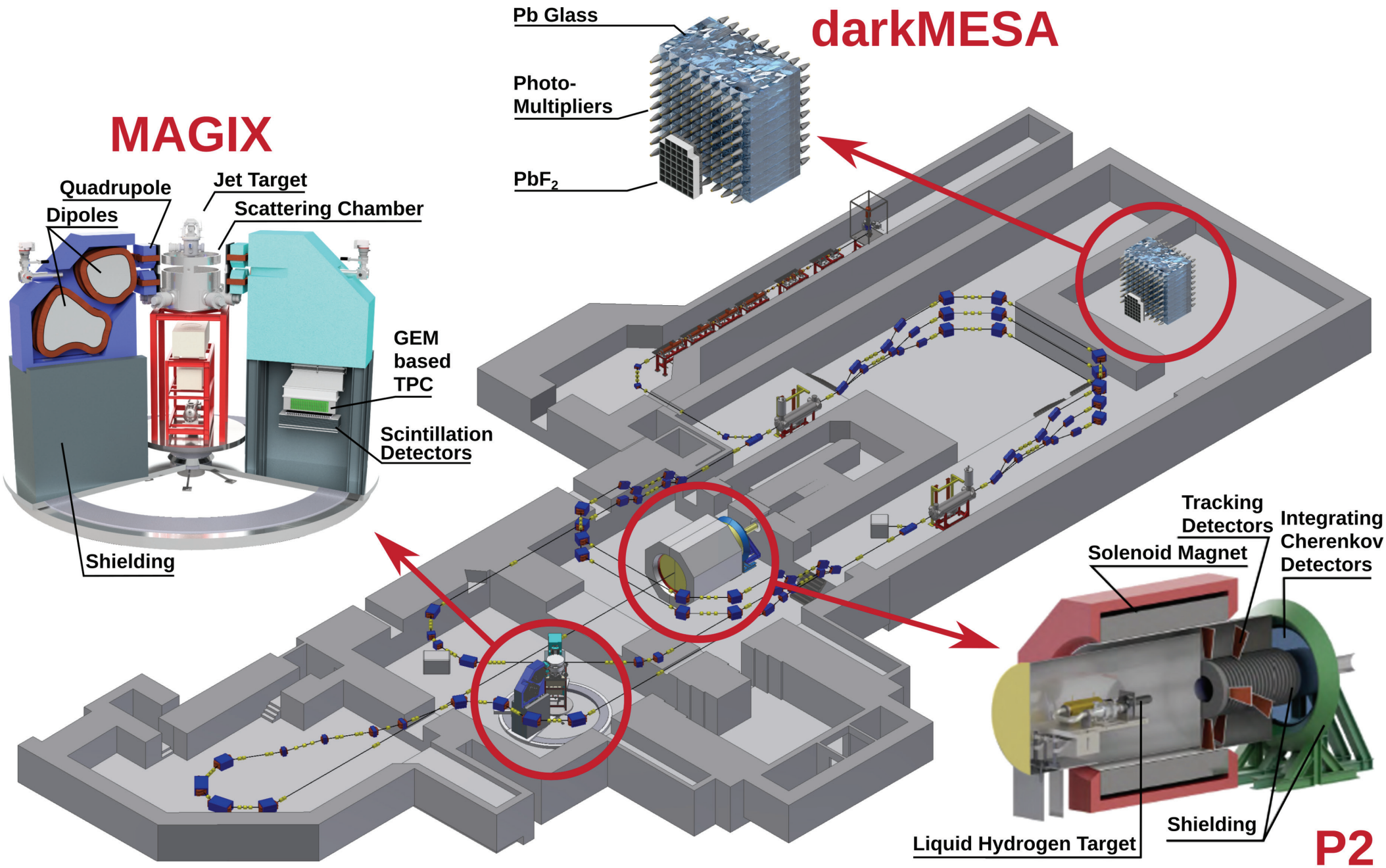
- In principle yes...
- But power is expensive
- Why dump electrons?

Energy recovery

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



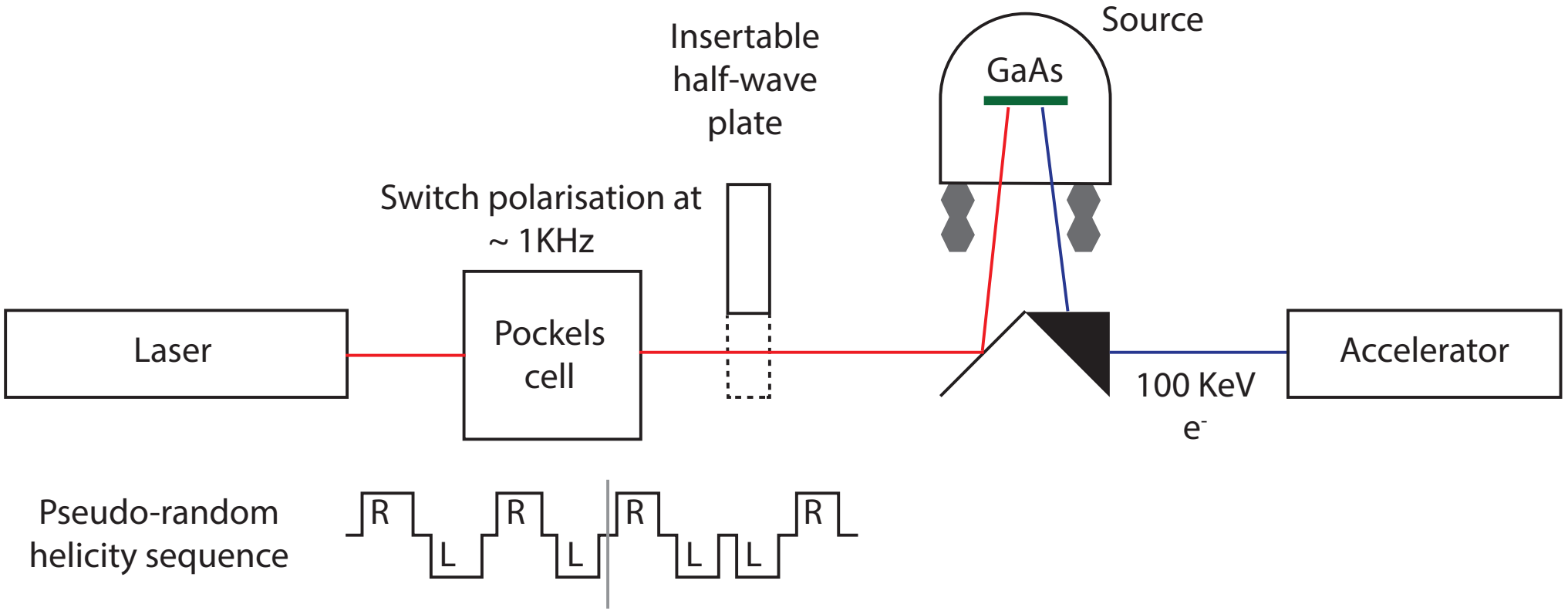
Mainz Energy-Recovery Superconducting Accelerator



Civil construction

- Start was long delayed
- Actual construction making very good progress
- Accelerator construction in 2022

Polarized Source and Helicity Flips



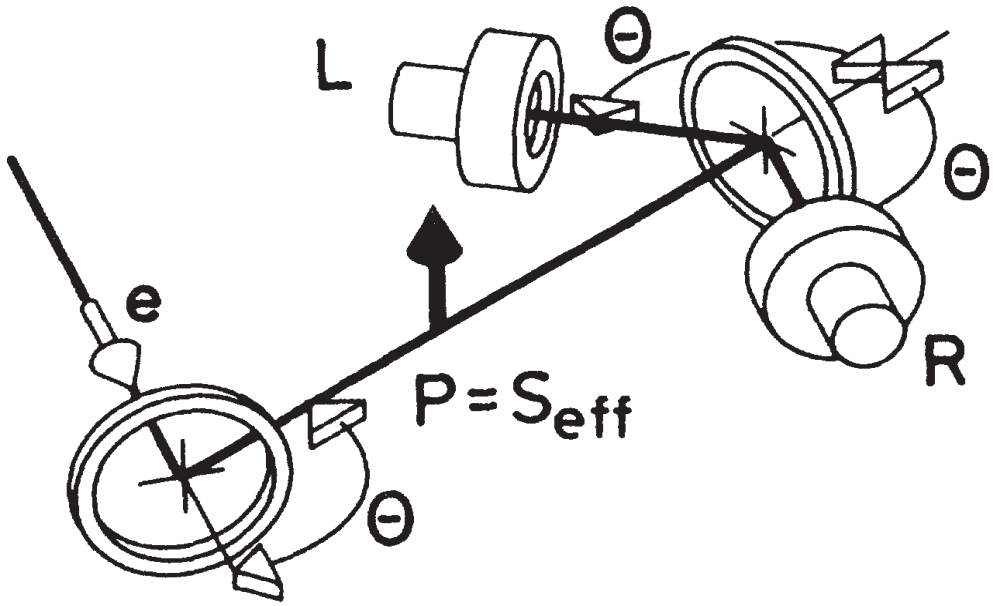
Stability Requirements

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

Polarimetry at MESA

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

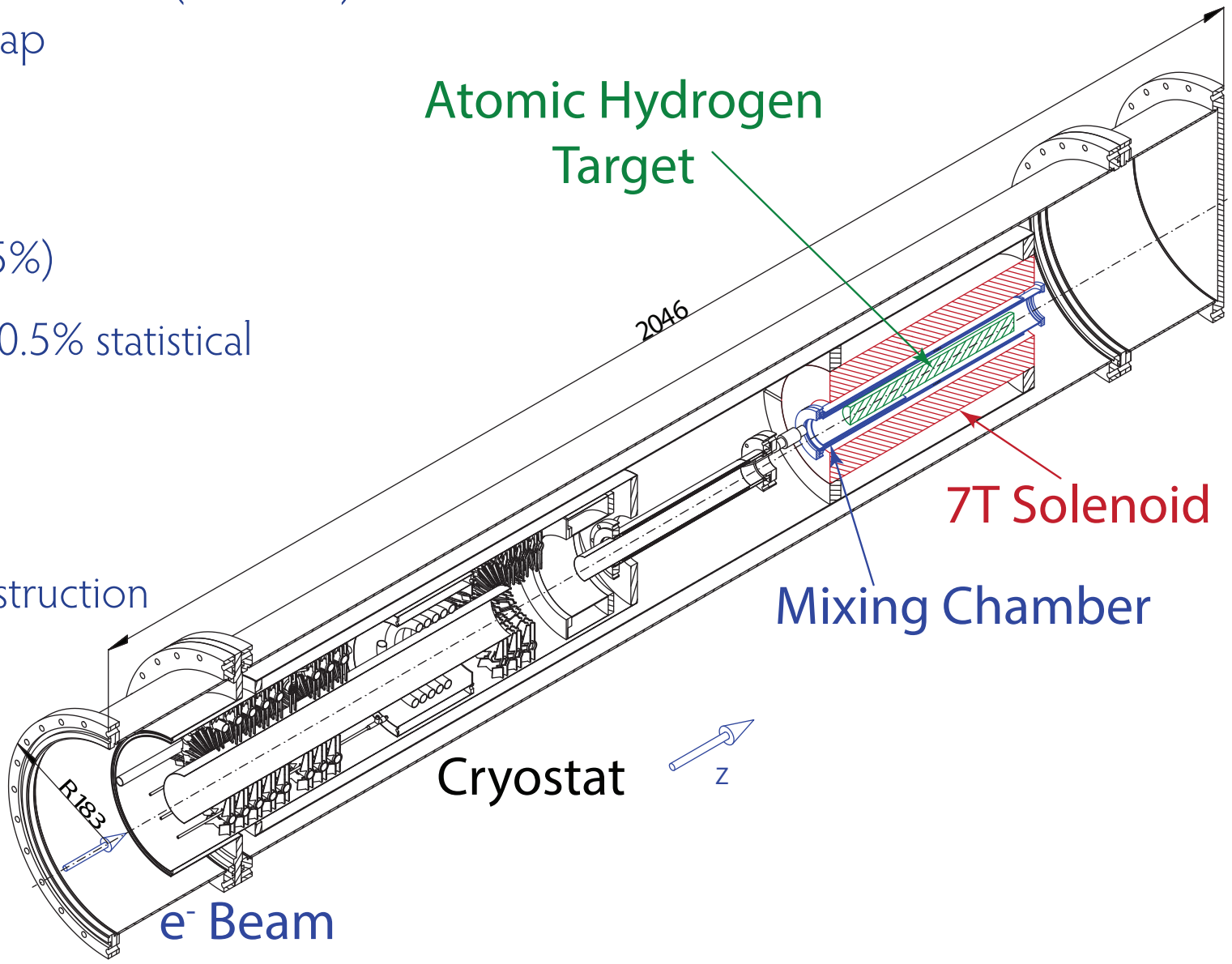
- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

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

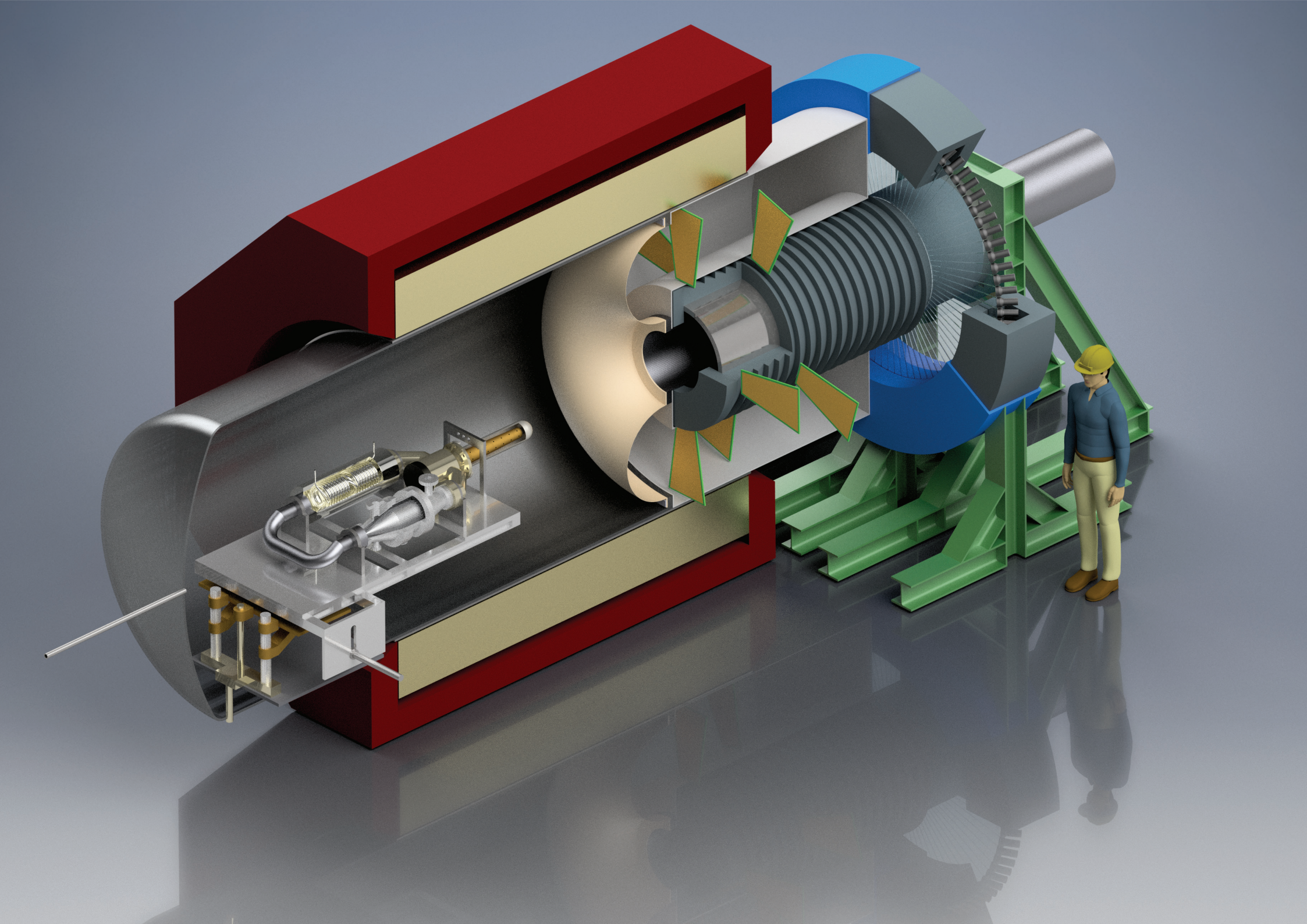
- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy

- Cryostat under construction



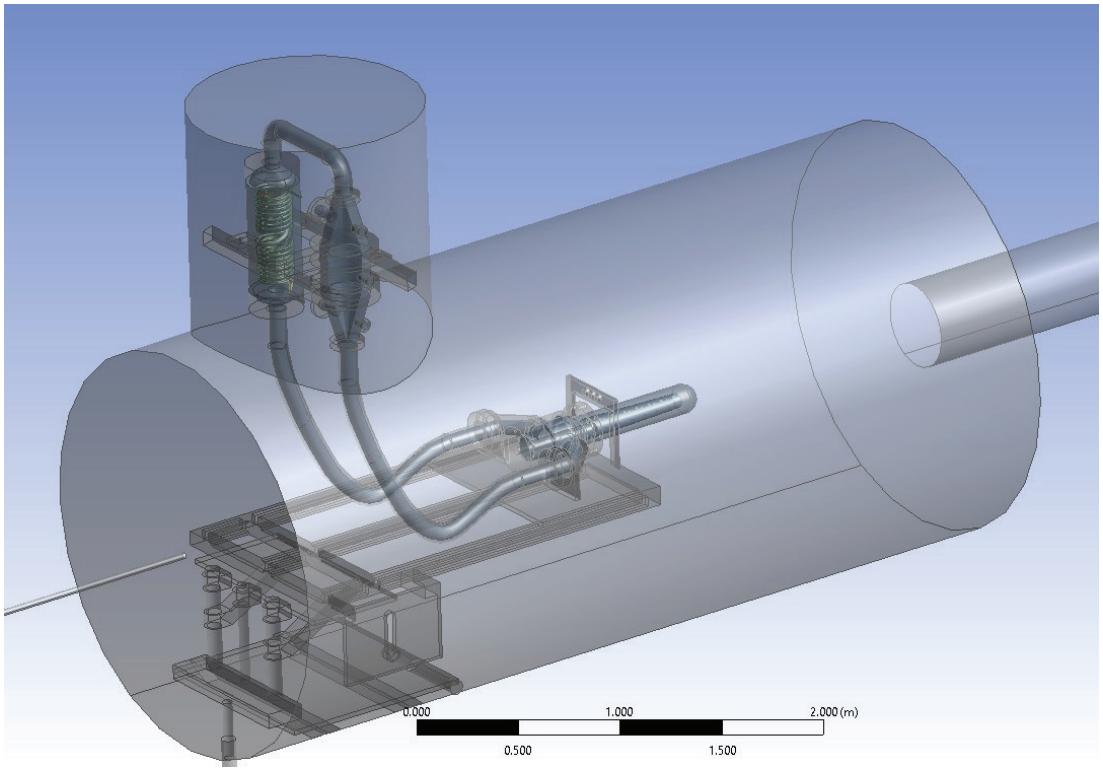
P2:

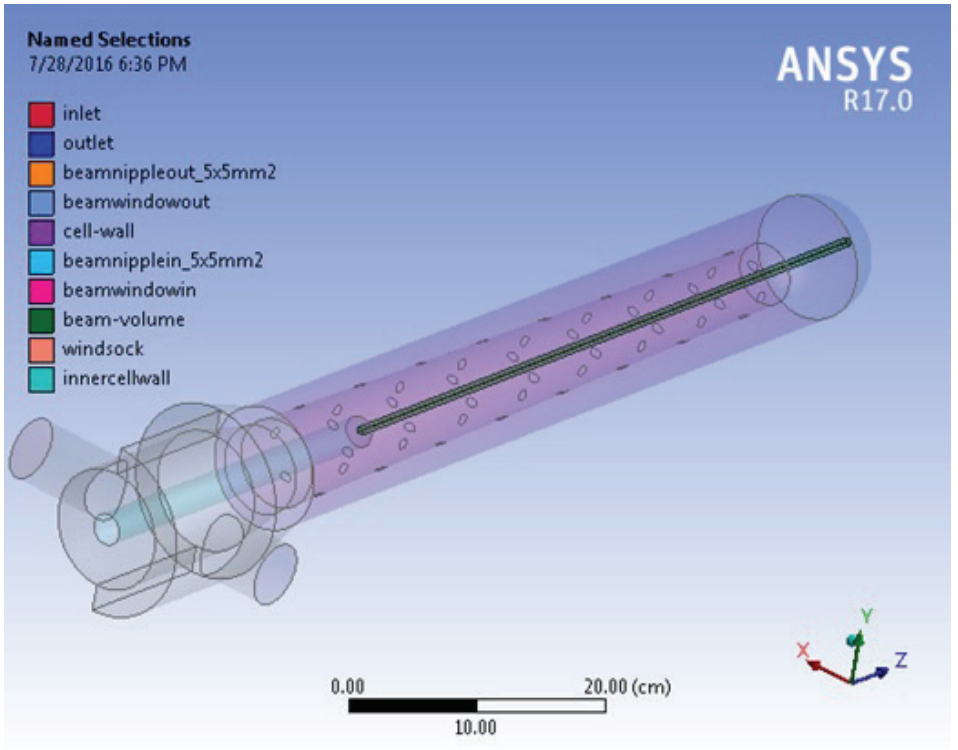
How to detect 100 GHz of (the right) electrons...



Target

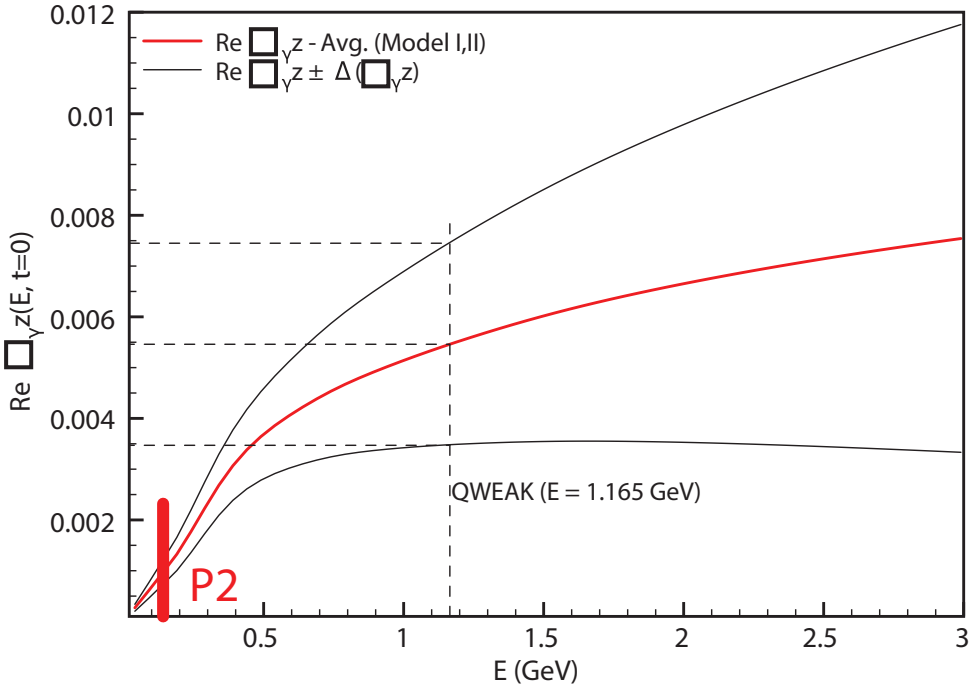
- 60 cm of liquid hydrogen
- 3.1 KW beam power deposited
- Should not boil...
- Challenging design using CFD tools (Silviu Covrig, JLab)



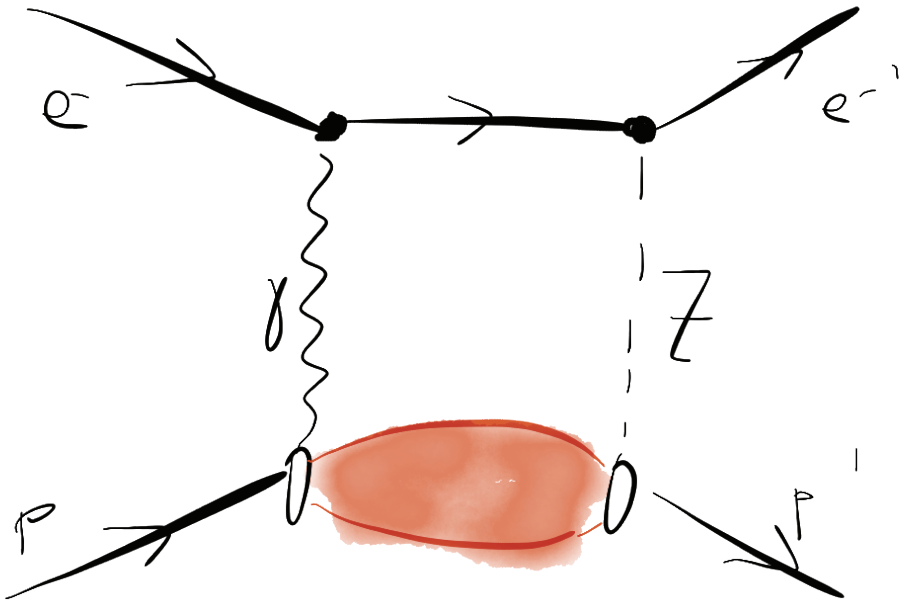


Choice of beam energy

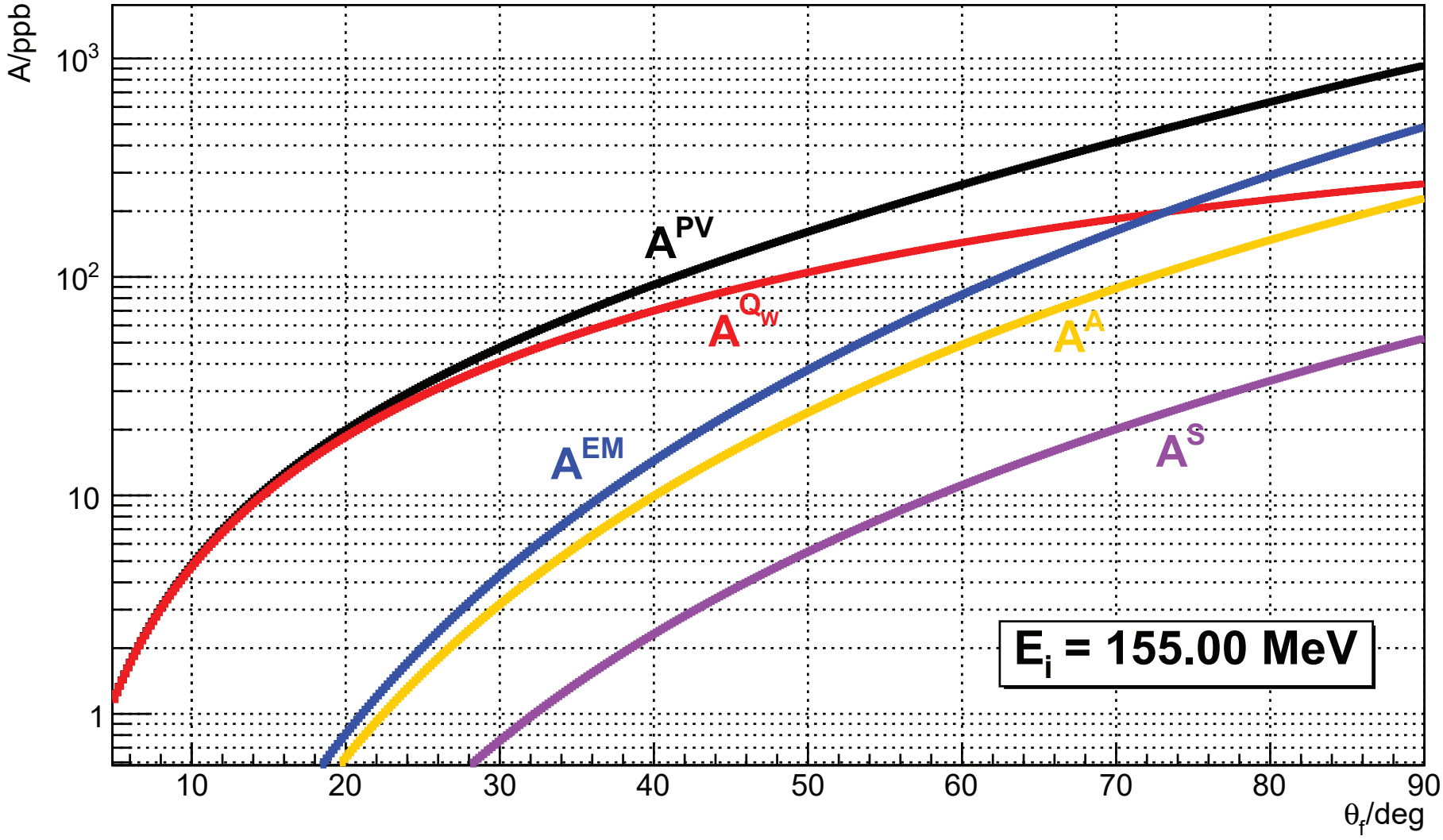
- γ-Z box graphs contribute to asymmetry
- Large uncertainty due to hadronic uncertainty
- Uncertainty rises with beam energy
- Choose small energy (155 MeV)



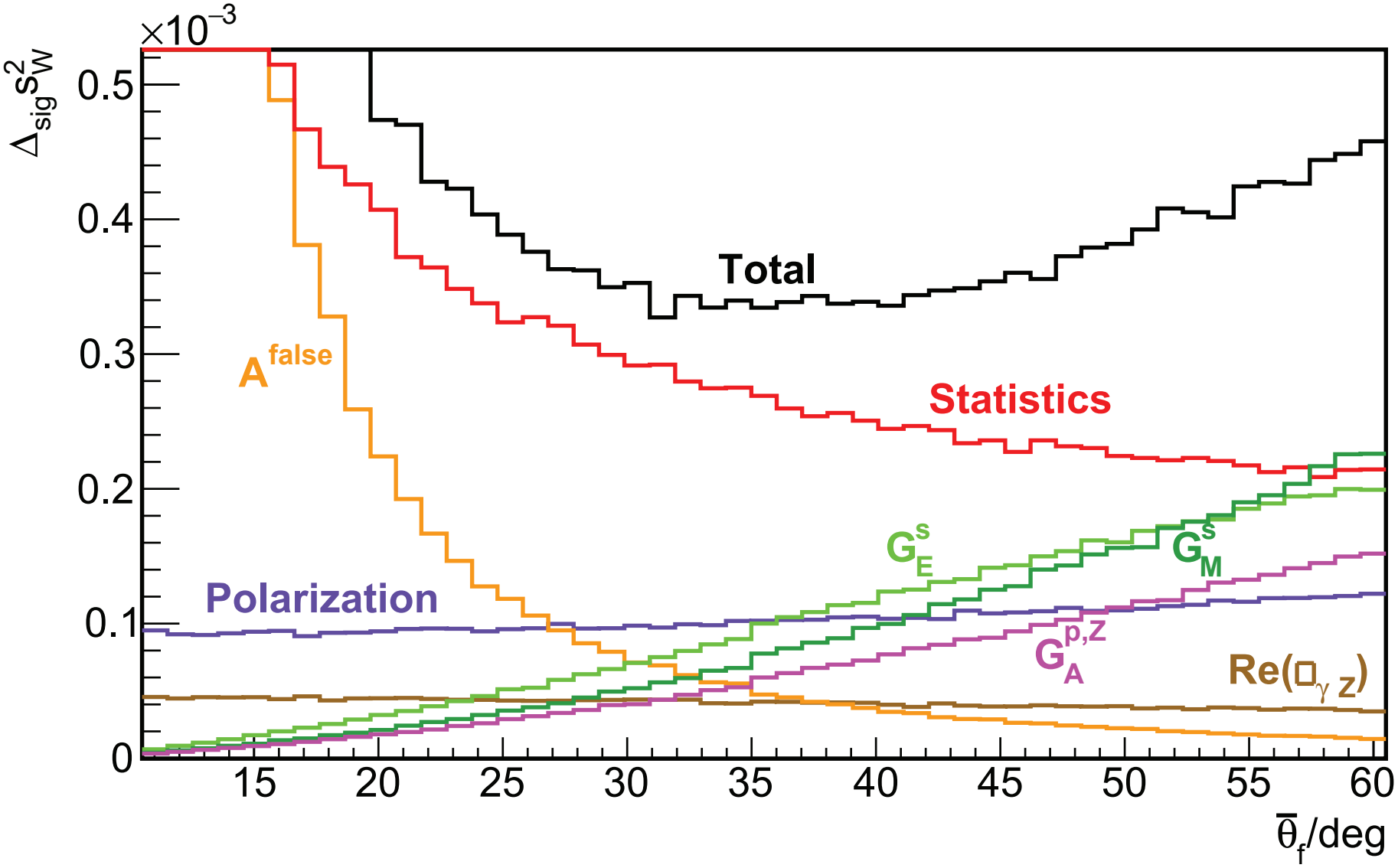
[Gorchstein, Horowitz, Ramsey-Musolf 2011]



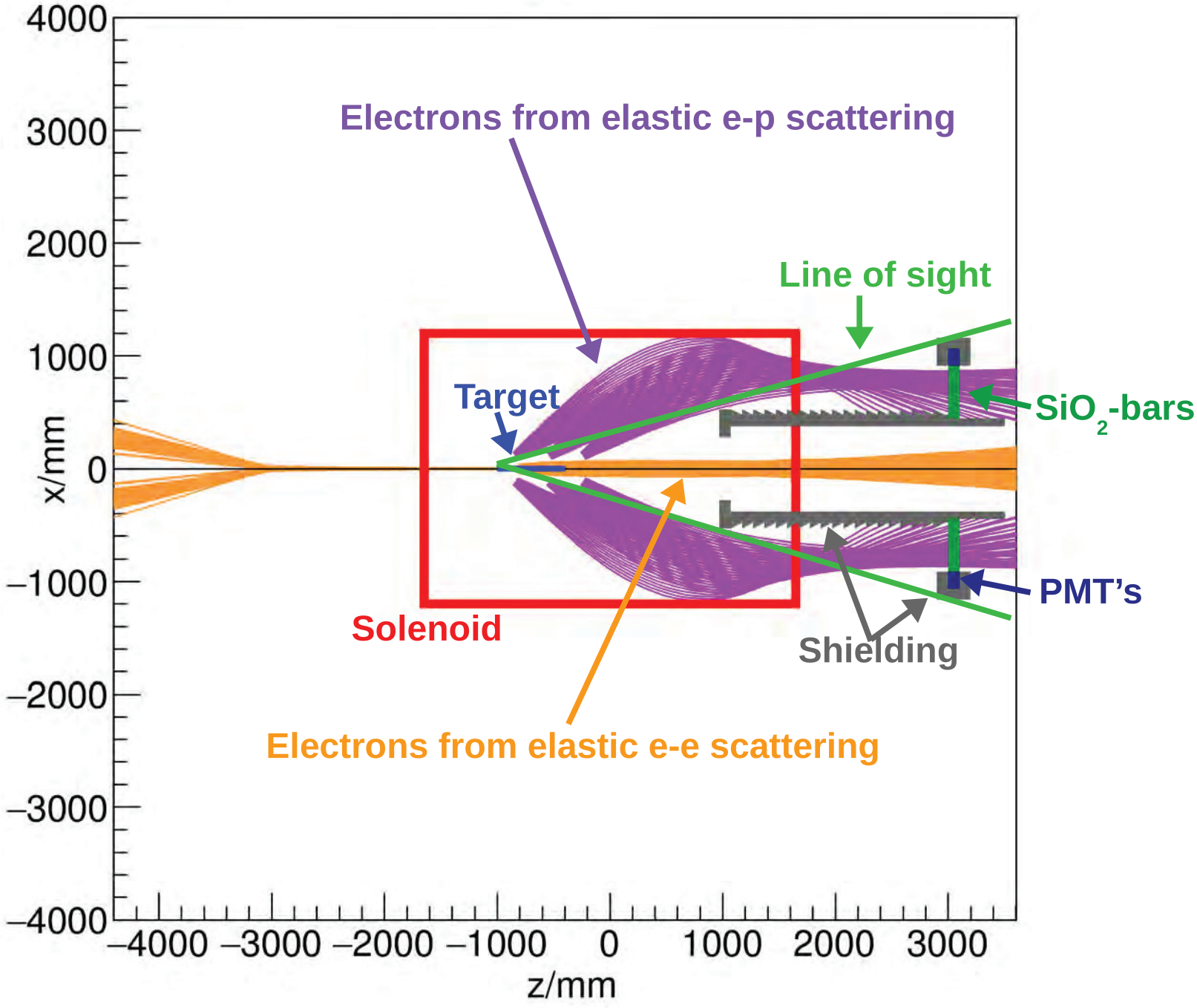
Choice of scattering angle



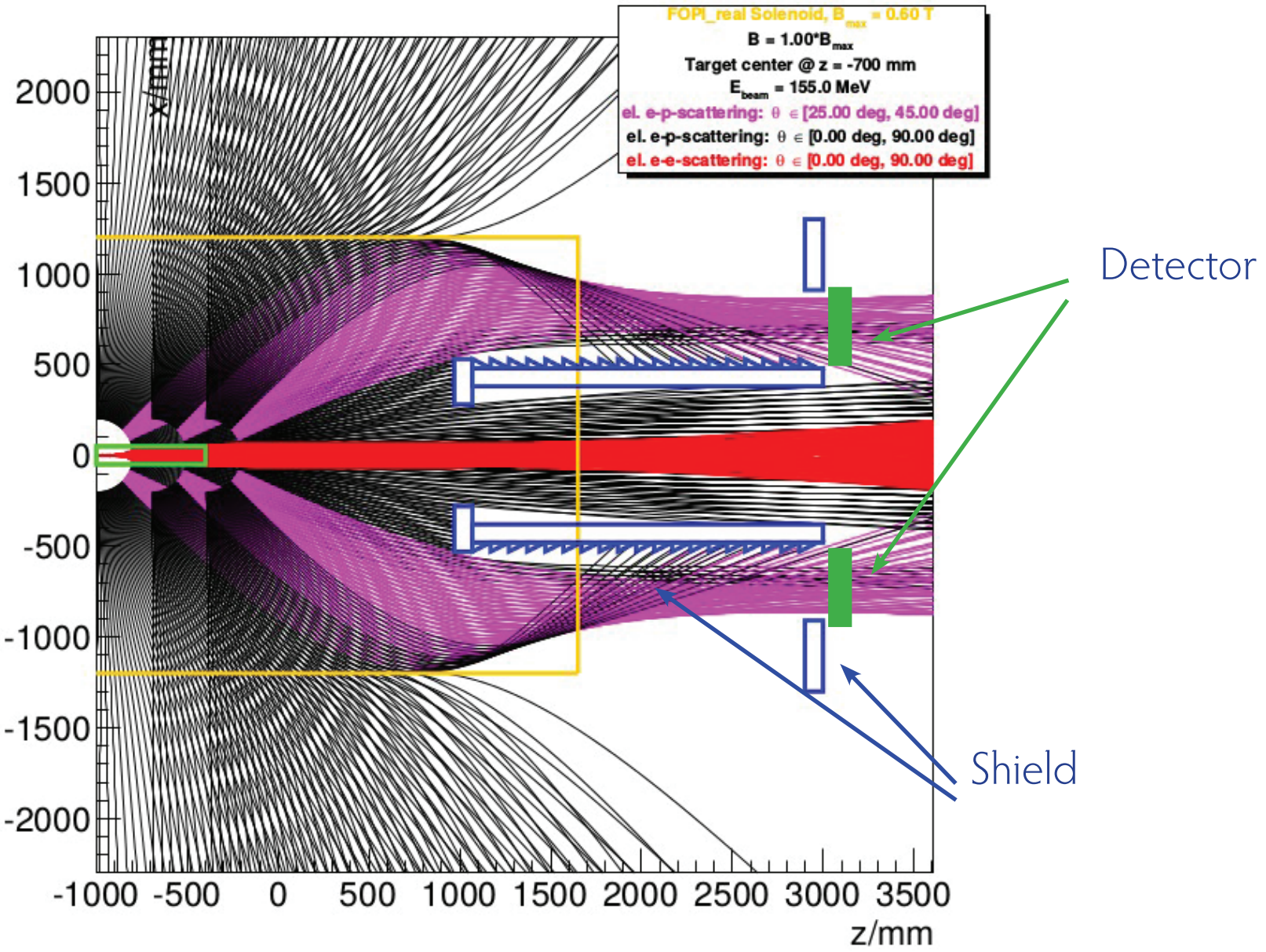
Choice of scattering angle



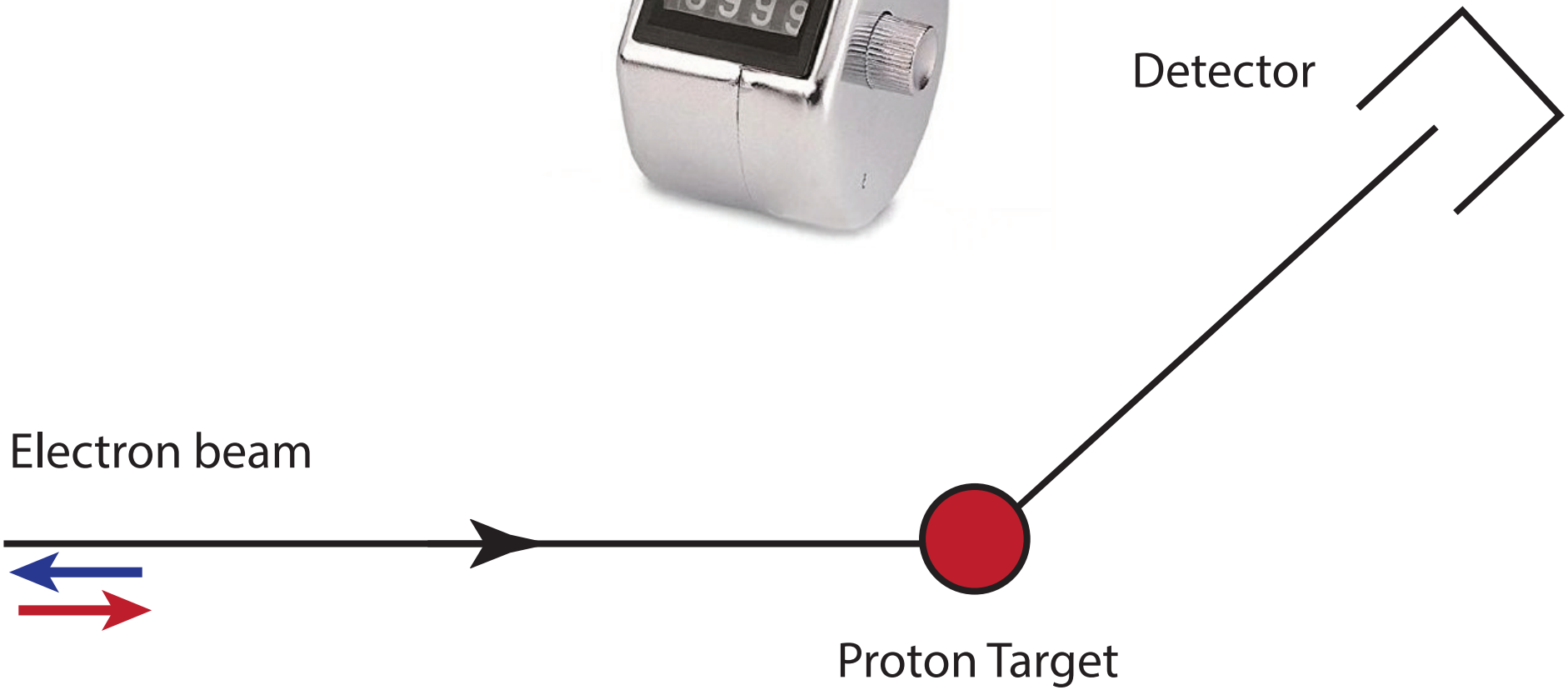
Solenoid spectrometer



Solenoid spectrometer



Counting detectors



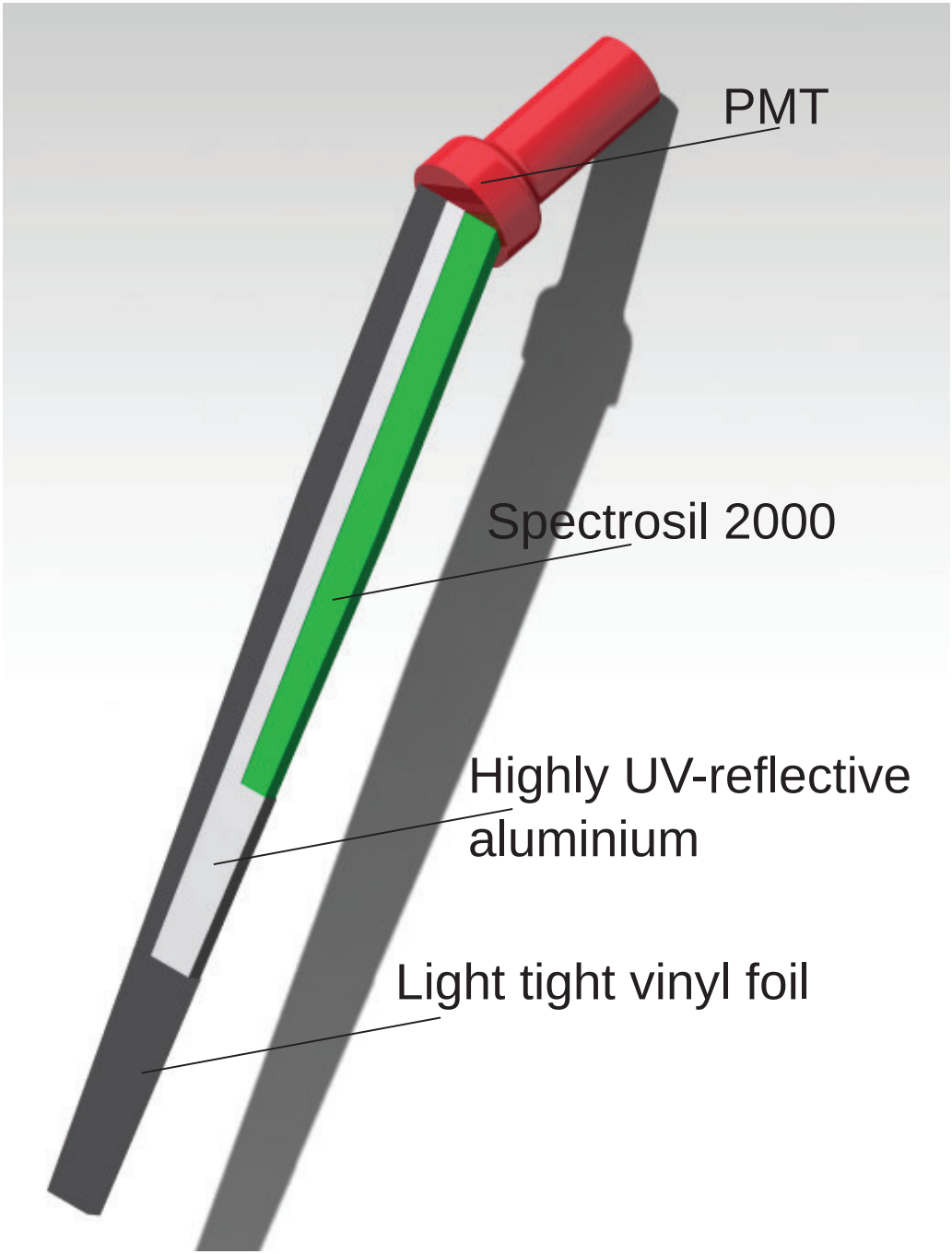
Integrating detectors

Detector

Electron beam

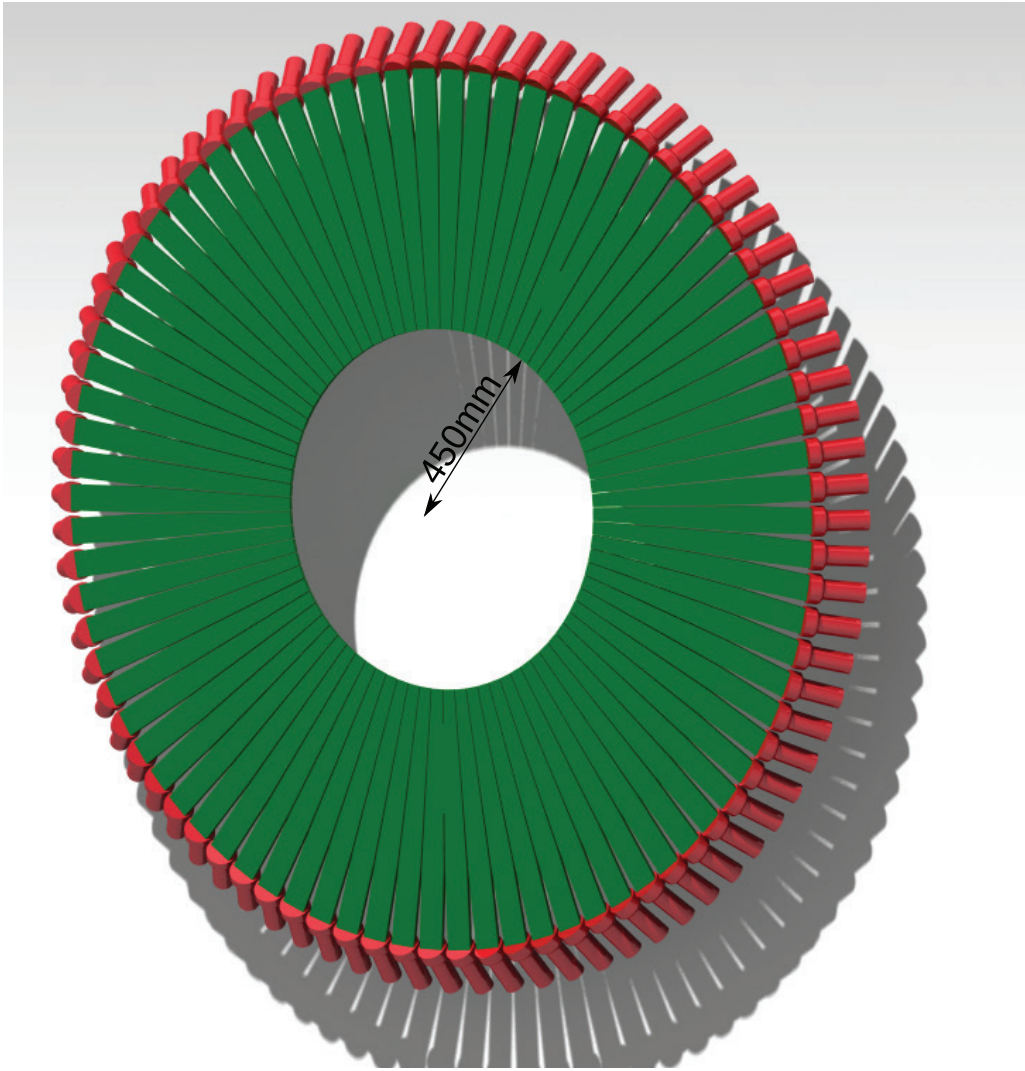
Proton Target

Quartz-Bars & Photomultipliers



Detect Cherenkov-light created by electrons

Integrate photomultiplier current

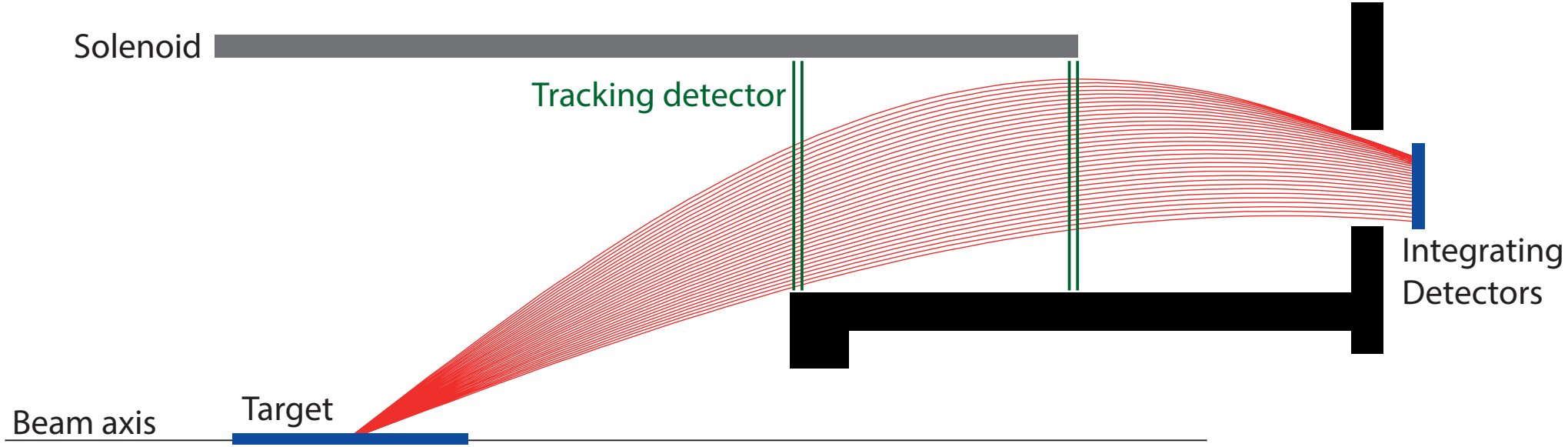


Measuring Q^2:

Tracking a
lot of low momentum particles

Tracker requirement

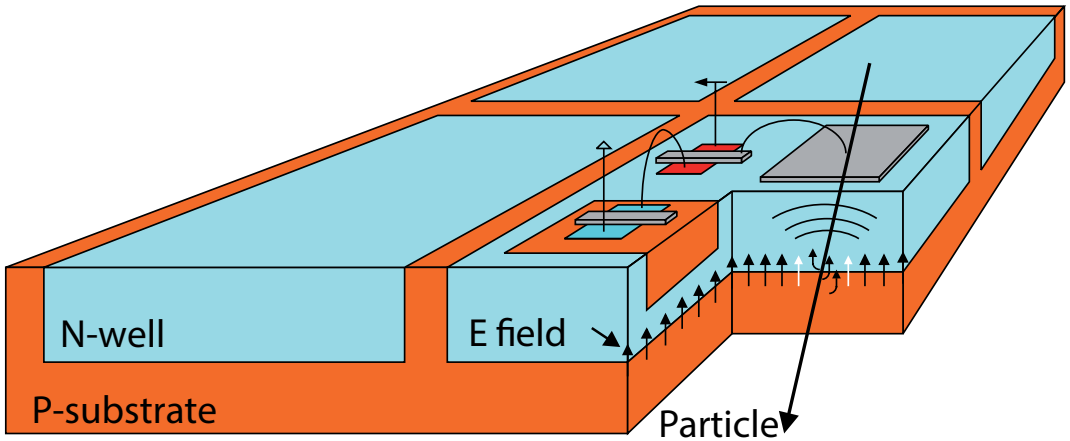
- Low momentum electrons:
  Thin detectors
- Very high rates:
  Fast and granular detectors



Fast, thin, cheap pixel sensors

High Voltage Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

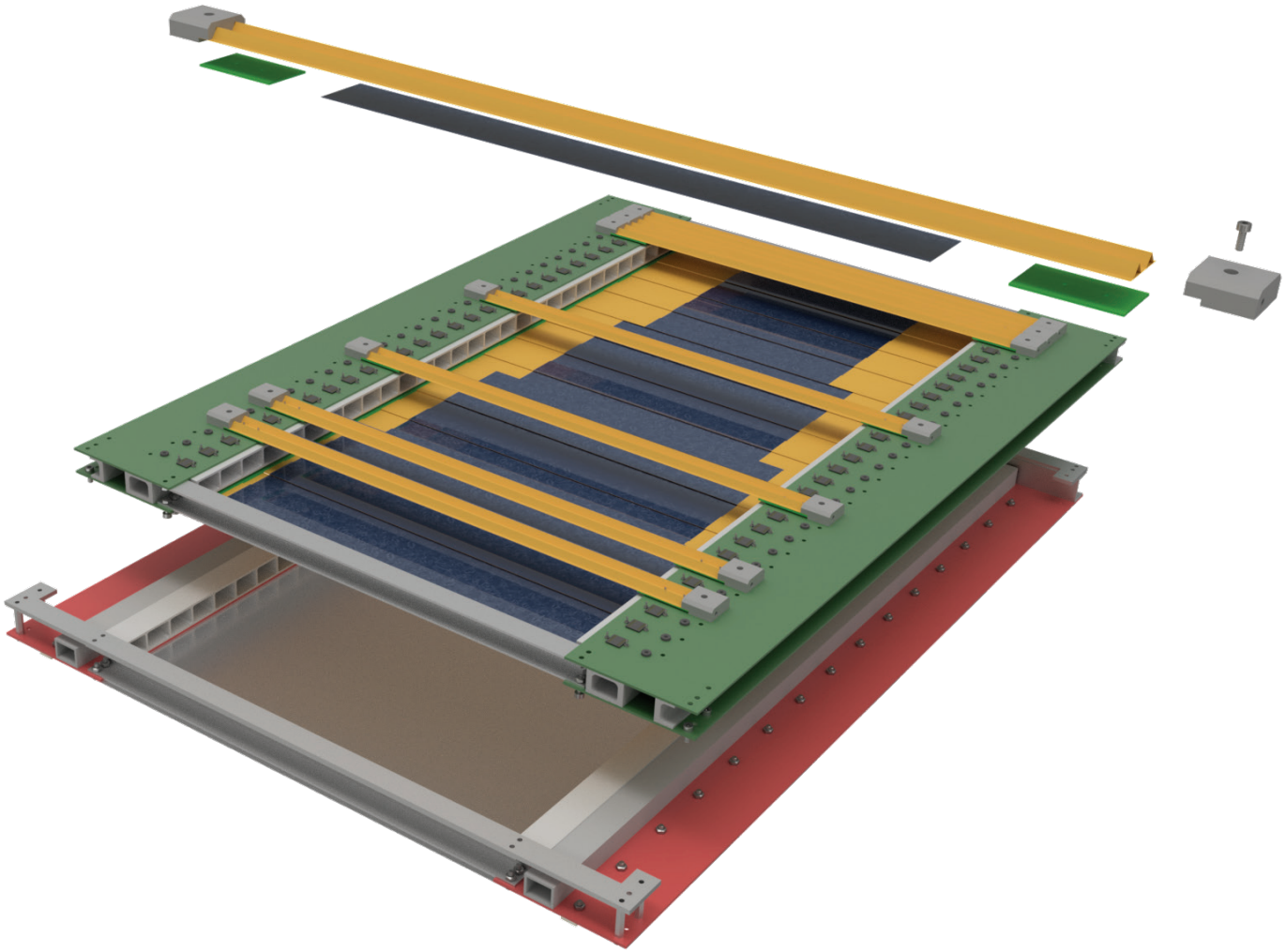


High voltage monolithic active pixel sensors - Ivan Perić (morning sessions!)

- 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

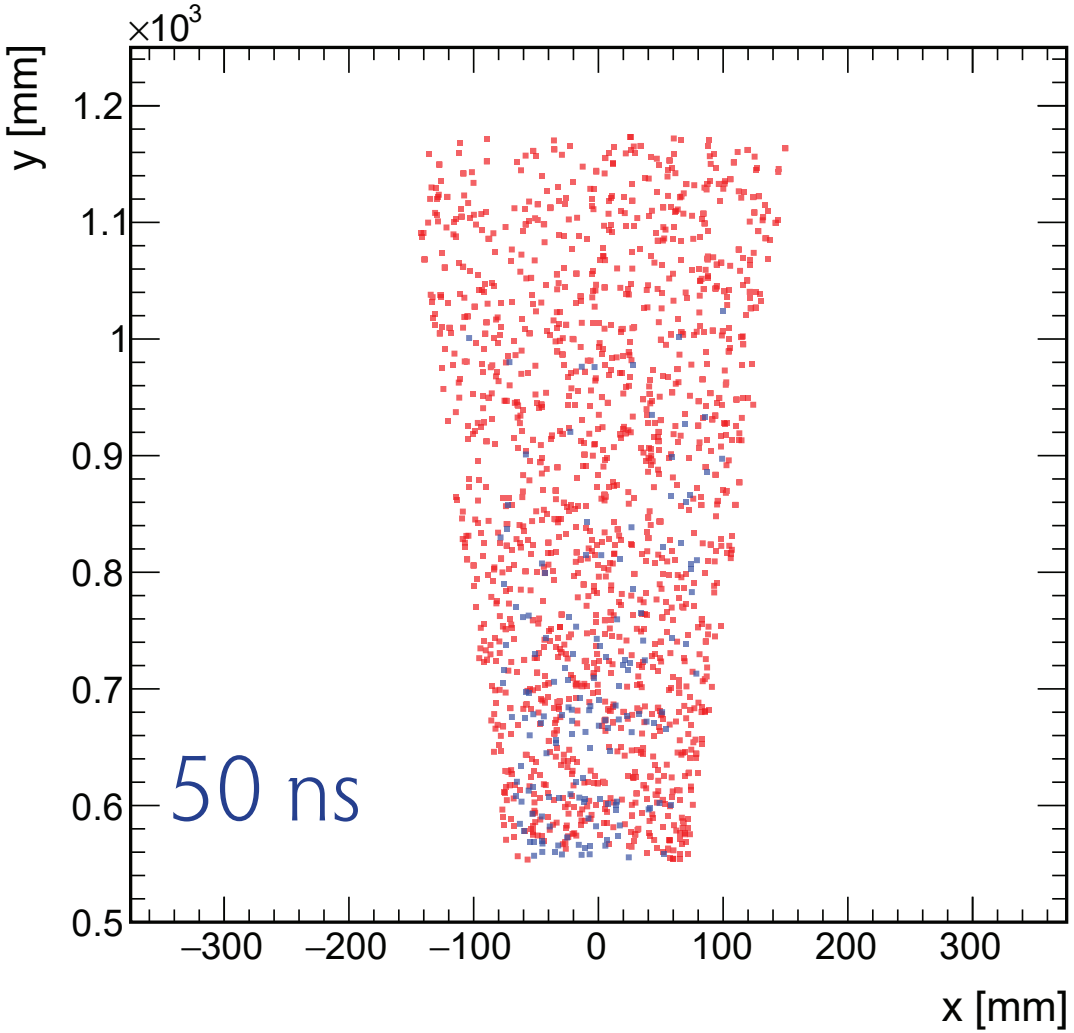
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)

Mechanics



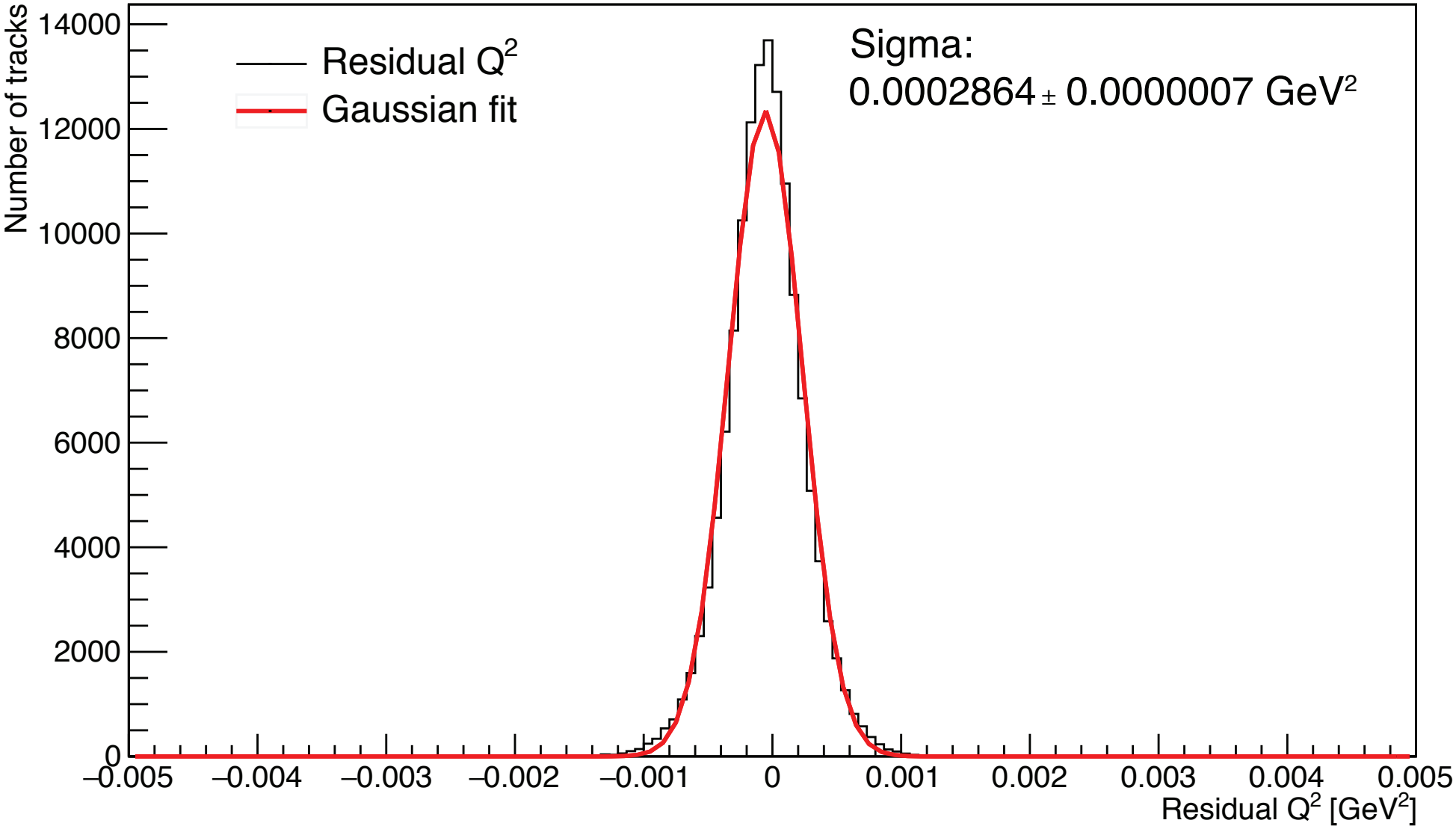
- 50 µm silicon
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ folds as support
- About 1‰ of a radiation length per layer

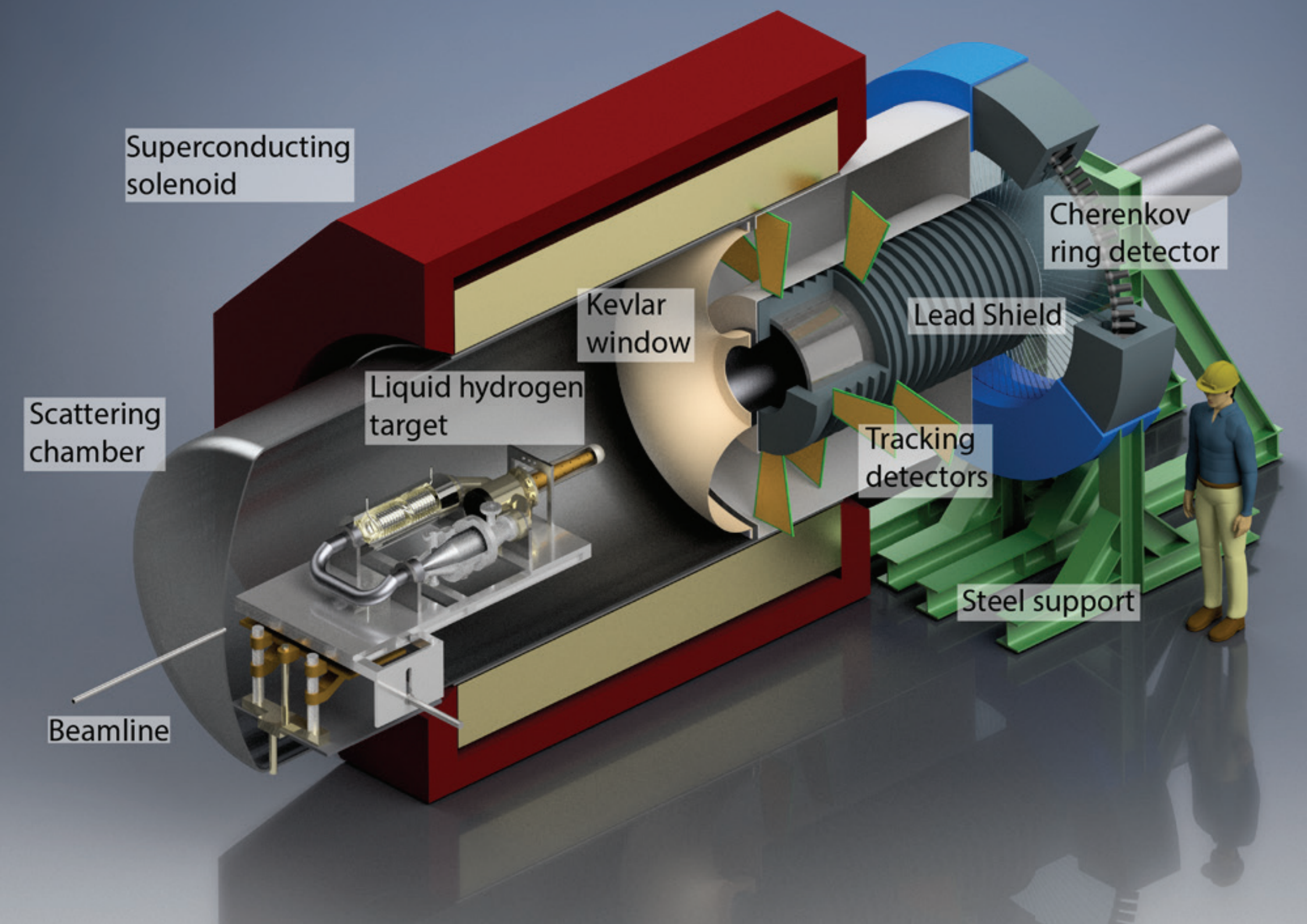
The tracking challenge



- 100 GHz electrons
- about 1000 Bremsstrahlung photons per electron

Q^2 reconstruction




Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Liquid hydrogen target
Scattering chamber
Tracking detectors
Steel support
Beamline

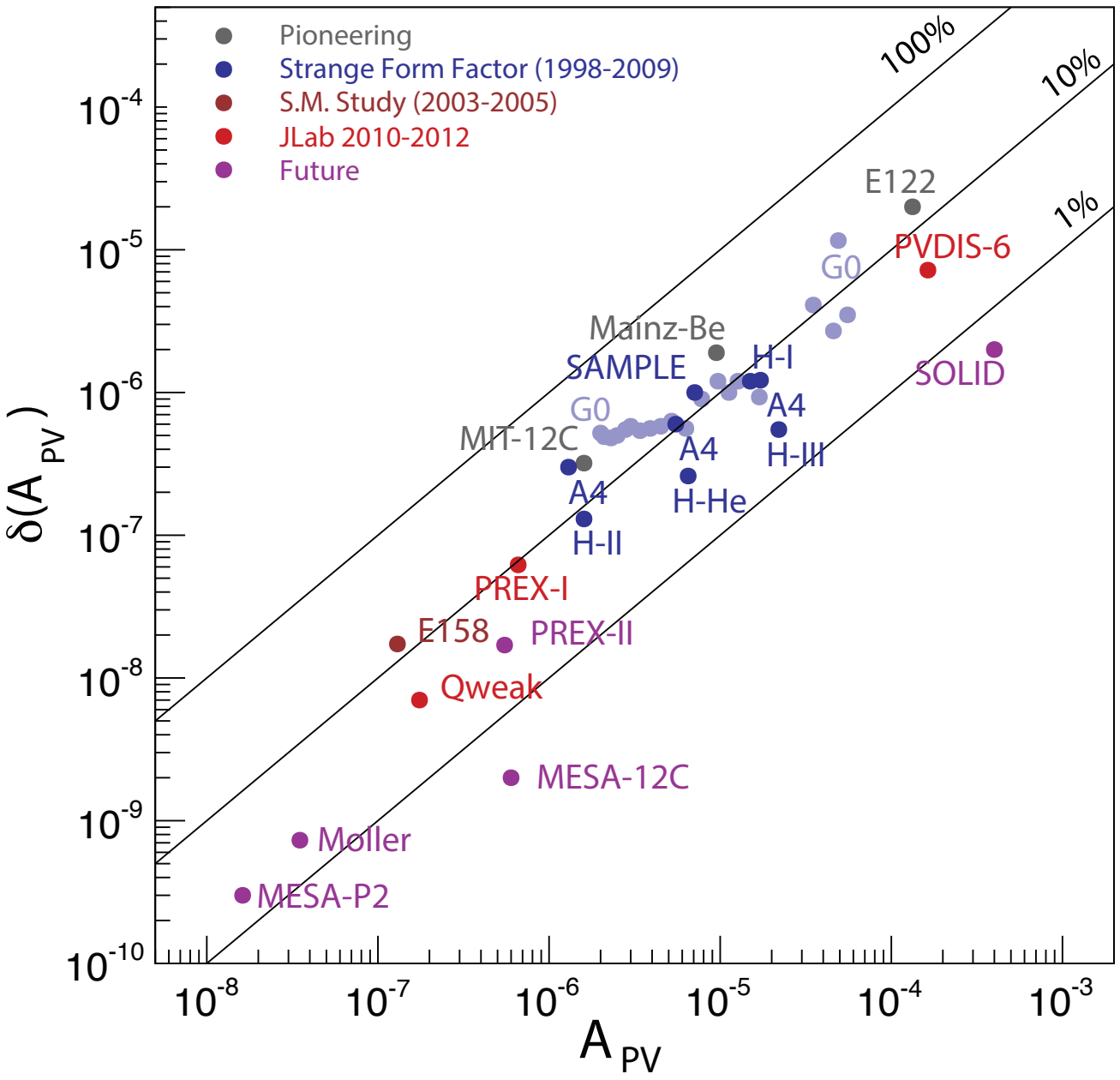
P2 Error budget

E_{beam}	155 MeV
$\bar{\theta}_{\text{f}}$	35°
$\delta\theta_{\text{f}}$	20°
$\langle Q^2 \rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	$6 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle$	−39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	0.10 ppb (0.25 %)

$\langle s^2_{\text{W}} \rangle$	0.231 16
$(\Delta s^2_{\text{W}})_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2 \rangle_{\text{Cherenkov}}$	$4.57 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	−28.77 ppb

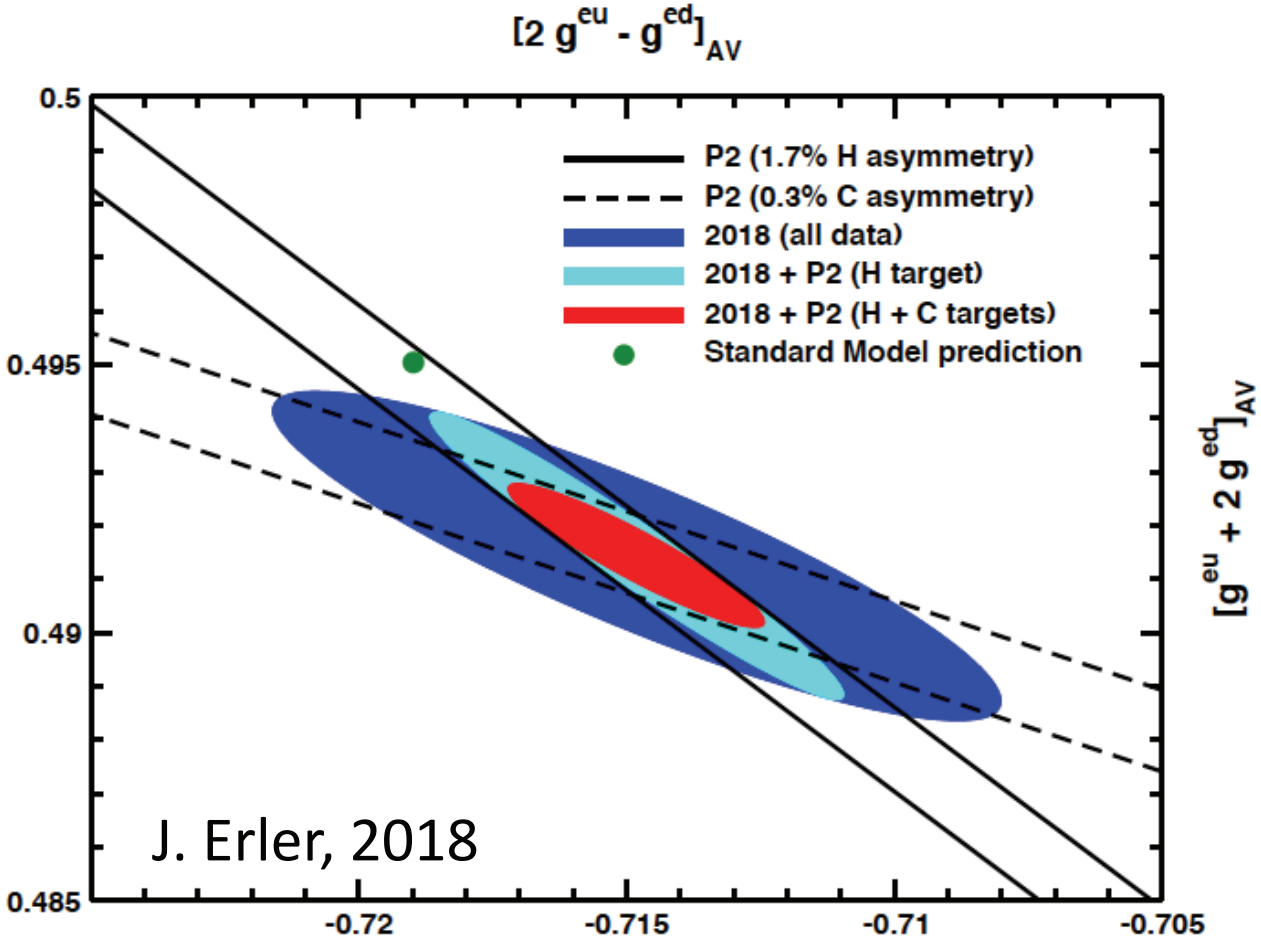
Can we do more?

Carbon



- Same with a ^{12}C target
- Much larger asymmetry
- No 1 - 4 $\sin^2\theta_W$ bonus - not competitive for $\sin^2\theta_W$ (potentially 2nd best measurement on a nucleus)
- But: New direction in isospin space
- Experimentally: Limited by polarimetry, hope to ultimately reach 0.3%
- Best measurement to date: MIT-Bates, ~25%

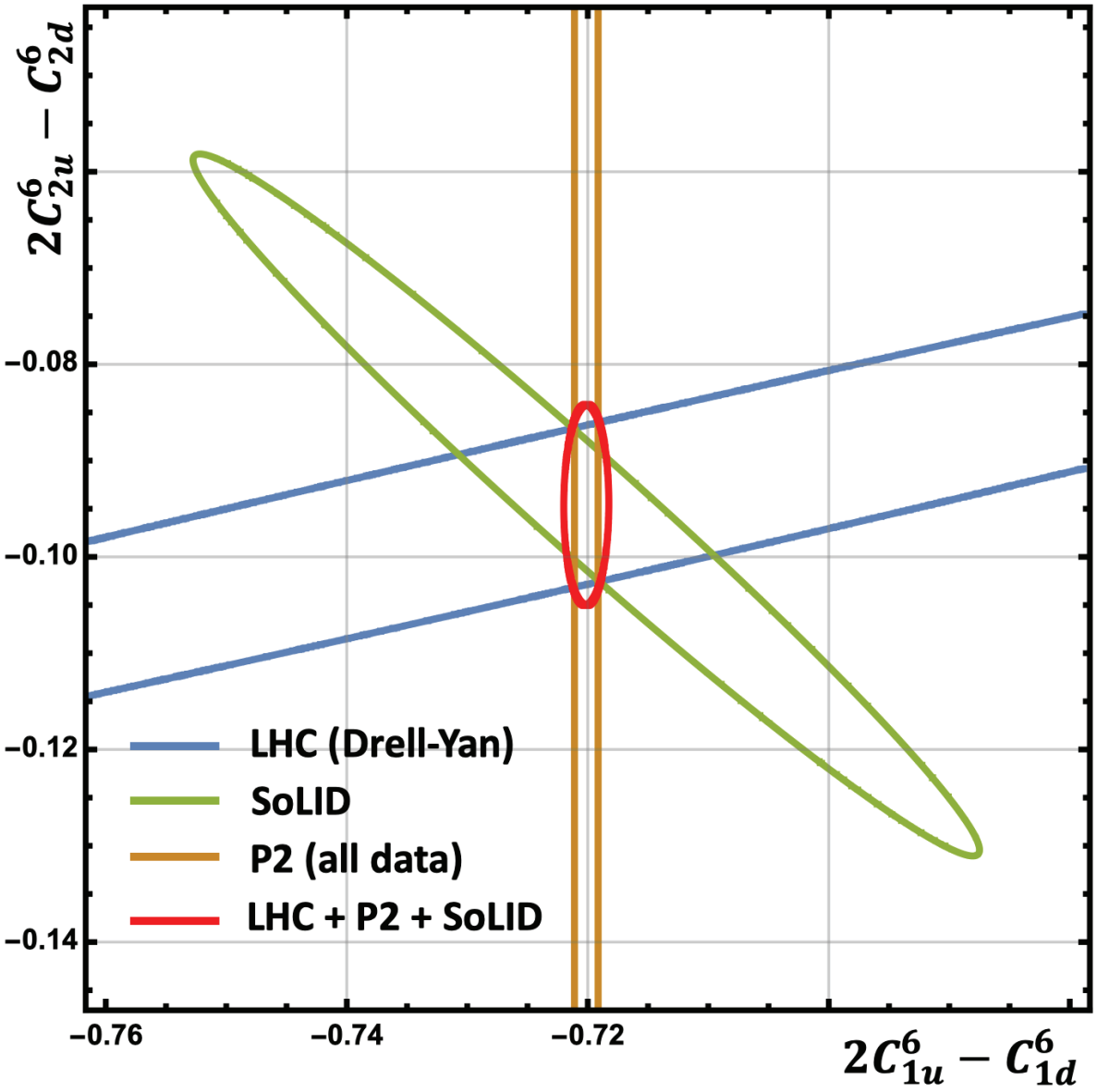
Constraints on couplings



Quark-vector electron-axial-vector couplings

- Power comes from the combination of C and H

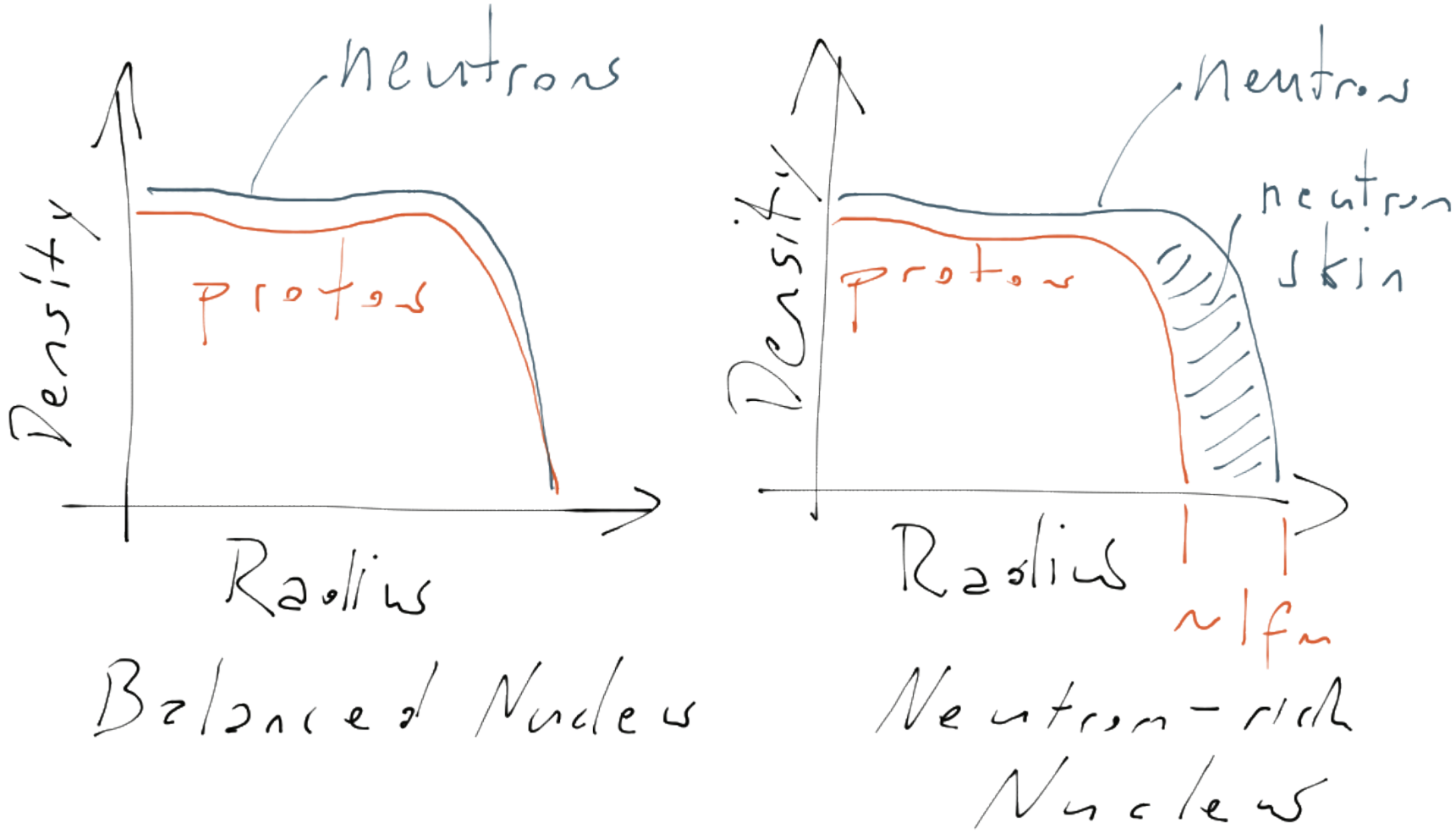
Constraints on couplings



- Power comes from the combination of C and H
- SMEFT, dimension 6 operators
- Here: All other operators set to 0
- Boughezal, Petriello, Weigand, arXiv:2104.03979

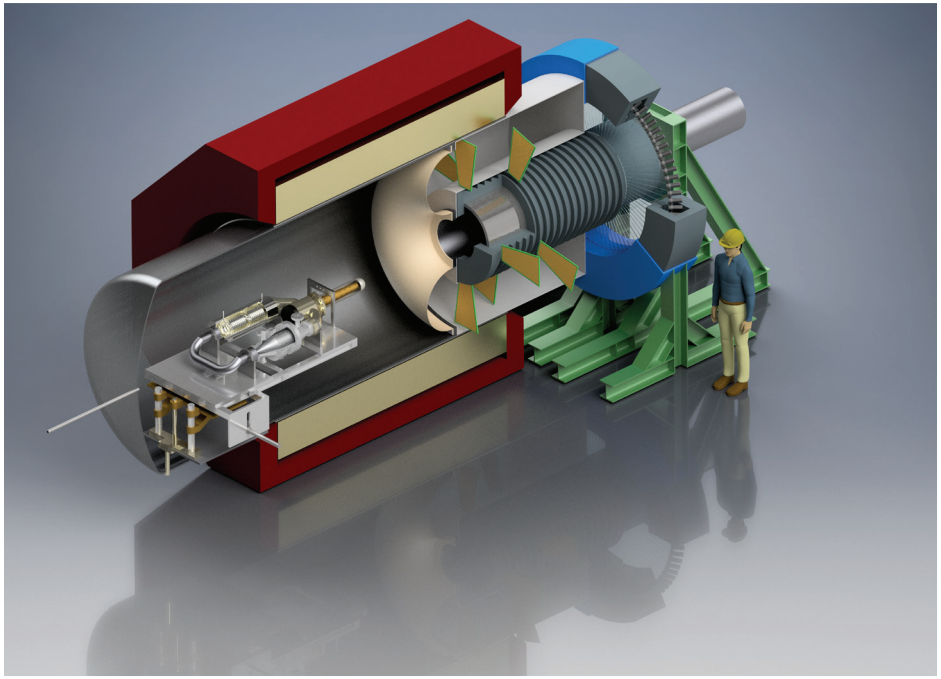
Neutron Skin of ^{208}Pb

Where are the neutrons in the nucleus?



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



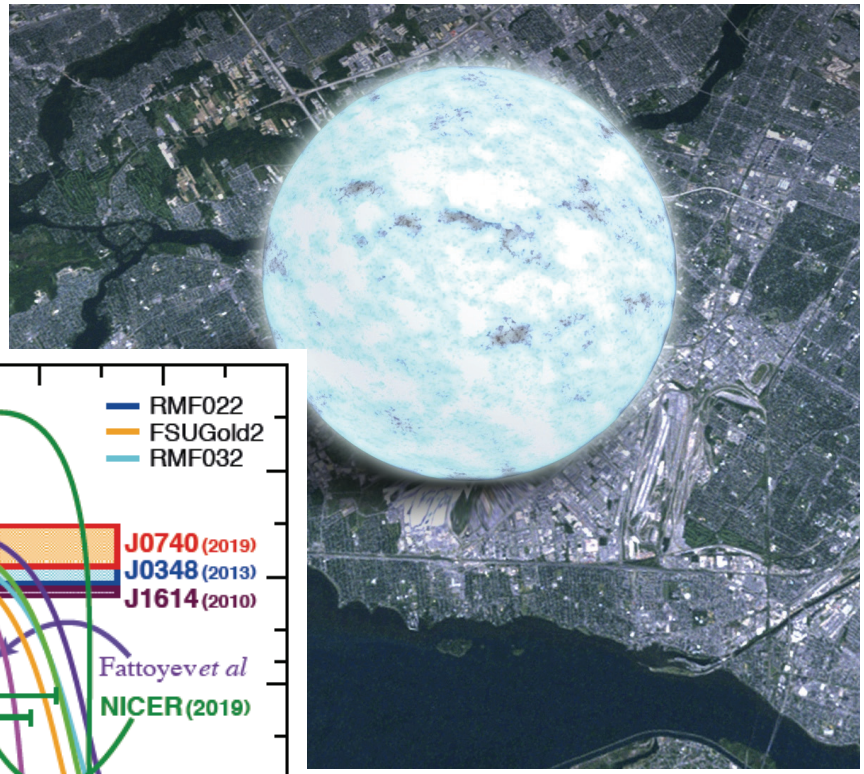
$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left(\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right)$$

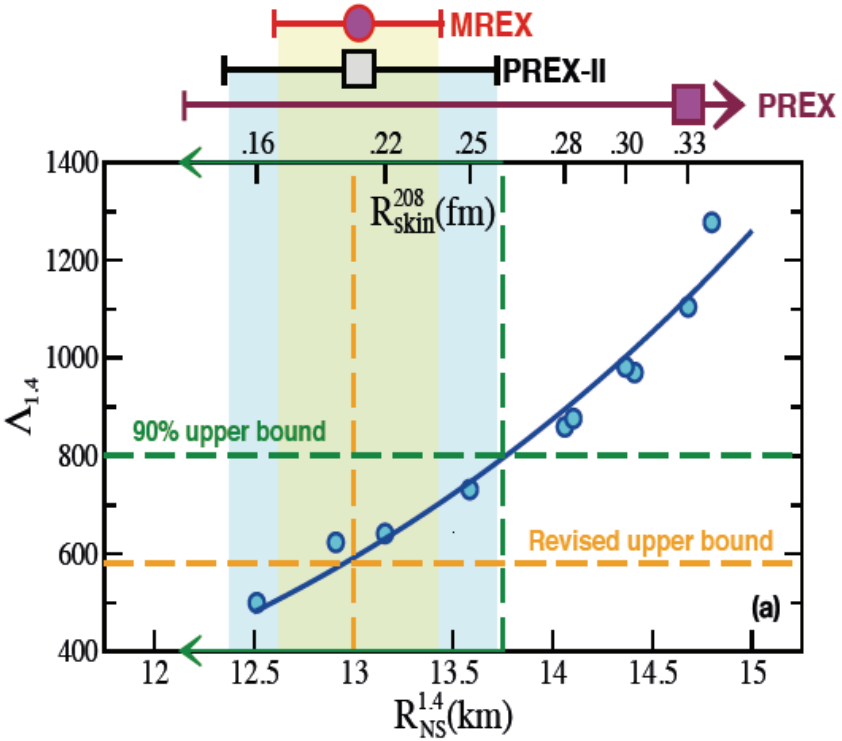
Neutron Skin of ^{208}Pb

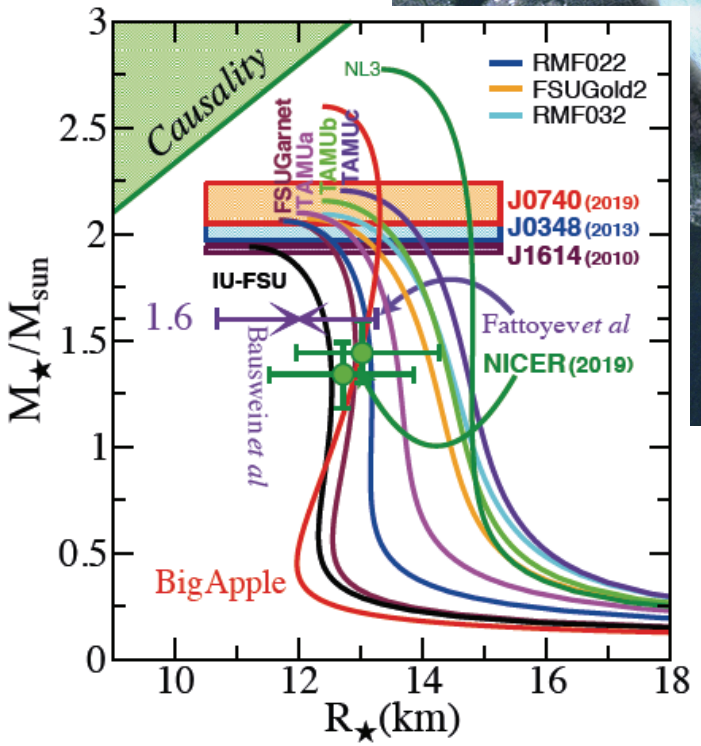
Where are the neutrons in the nucleus?

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

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4\sin^2(\theta_w) - \frac{F_w(Q^2)}{F_{ch}(Q^2)}\right]$$

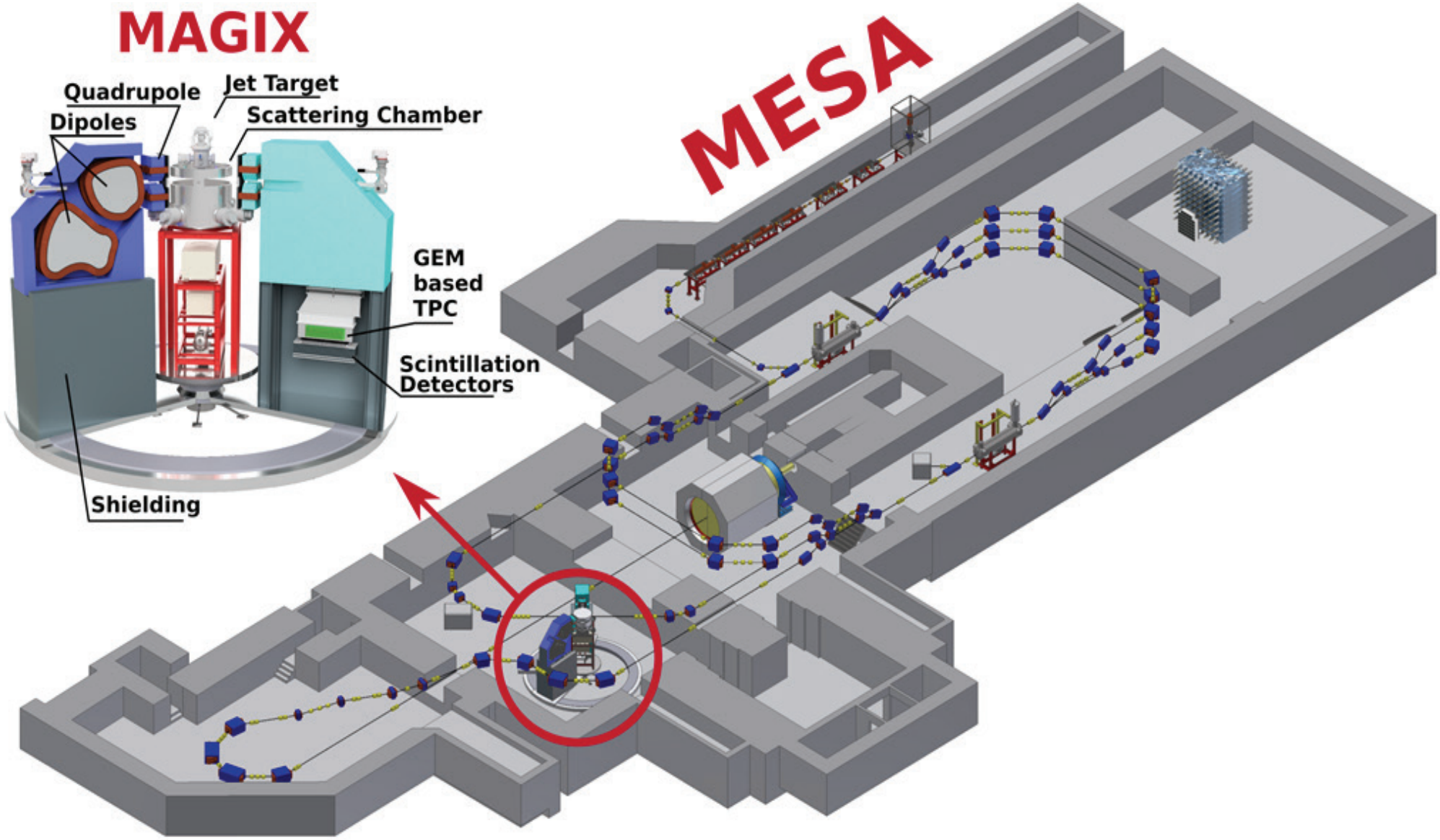






MREX

The MAGIX Spectrometers



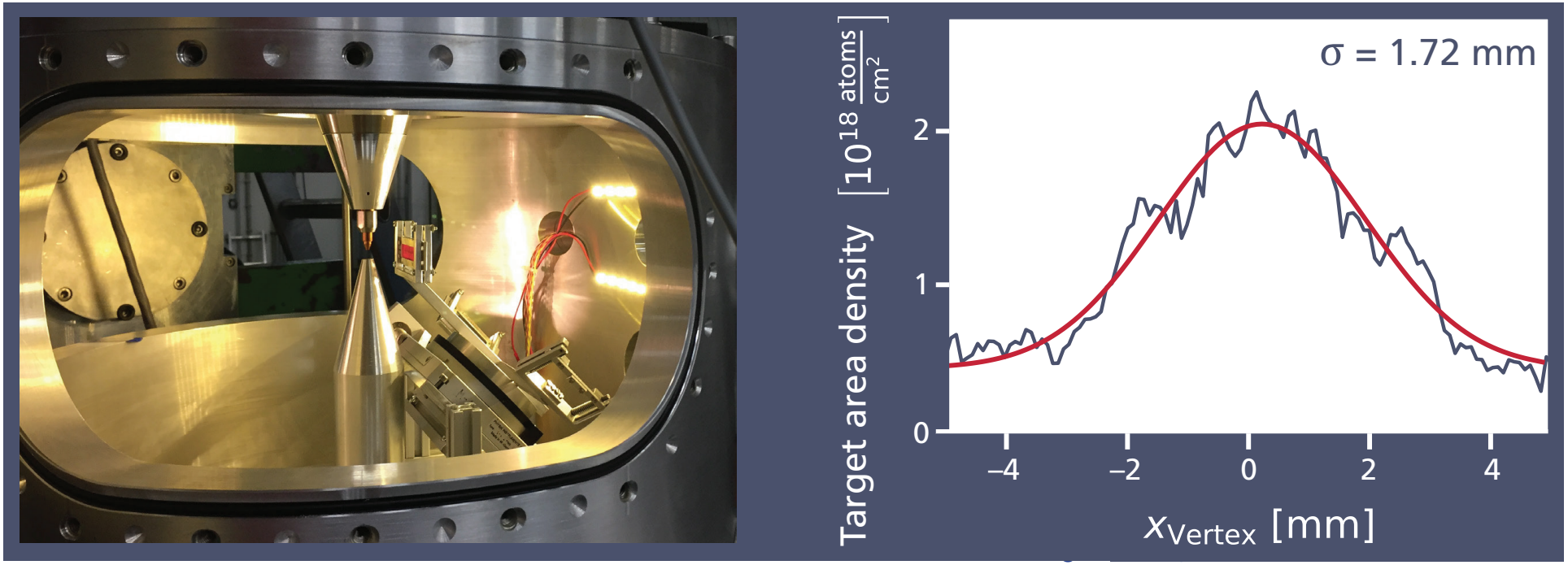
ERL mode: (un-)polarized e-beam, 30-105 MeV, 1000 µA, energy recovered in cavities

MX-EB mode: (un-)polarized e-beam, 30-105 MeV, 10 µA, small beam dump → solid state targets

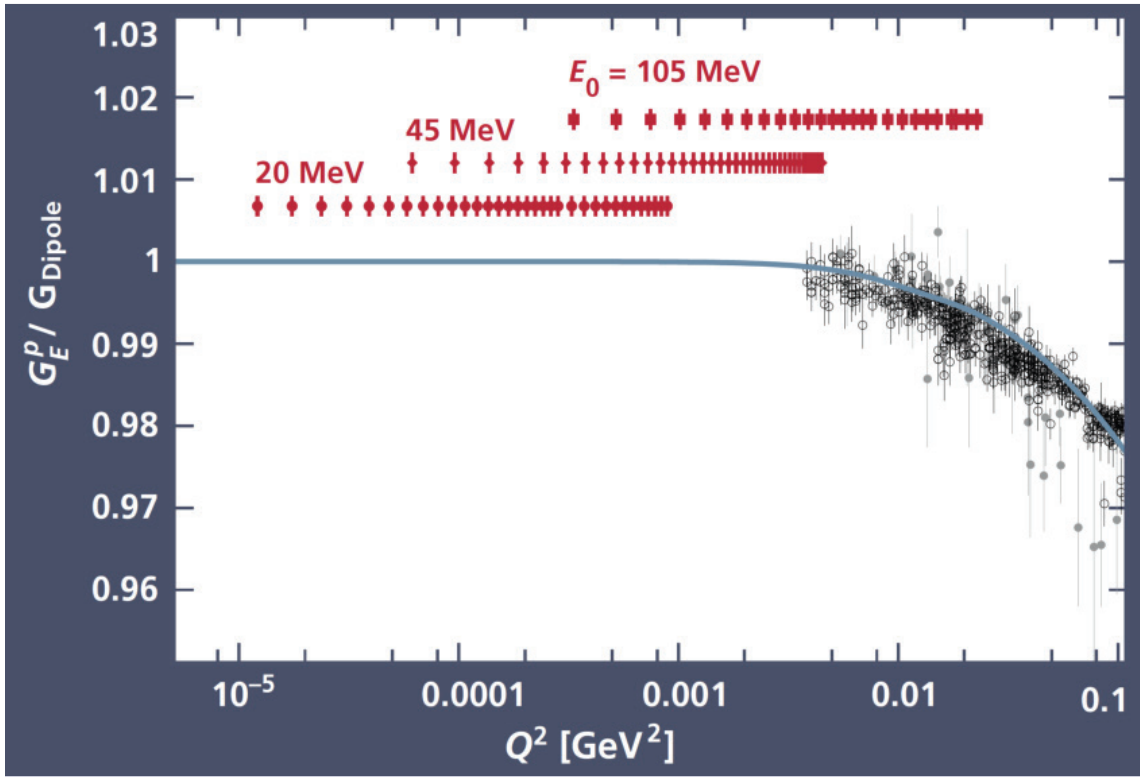
Gas Jet Target

- High resolution of spectrometers easily spoiled by scattering in the target chamber
- Worse at lower energies
- Get rid of the target chamber

- Supersonic gas stream shooting into the beam
- Catch most gas below, add differential pumping
- Group of A. Khoukaz, Uni Münster
- Tested in the A1 setup at MAMI

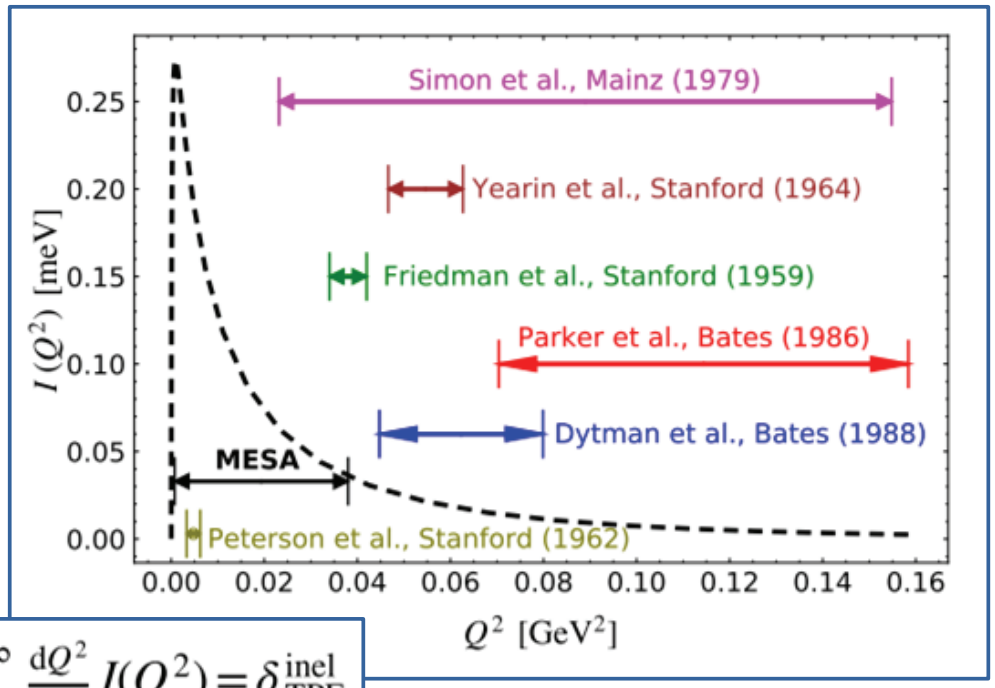


Electromagnetic form factors of the proton



- Proton radius puzzle only partially resolved
- Precision measurement over decent Q^2 range, going to small Q^2
- Forward measurement of electric form factor as an early measurement with extracted beam
- Full measurement of G_E and G_M makes use of ERL mode currents

Deuteron electrodisintegration

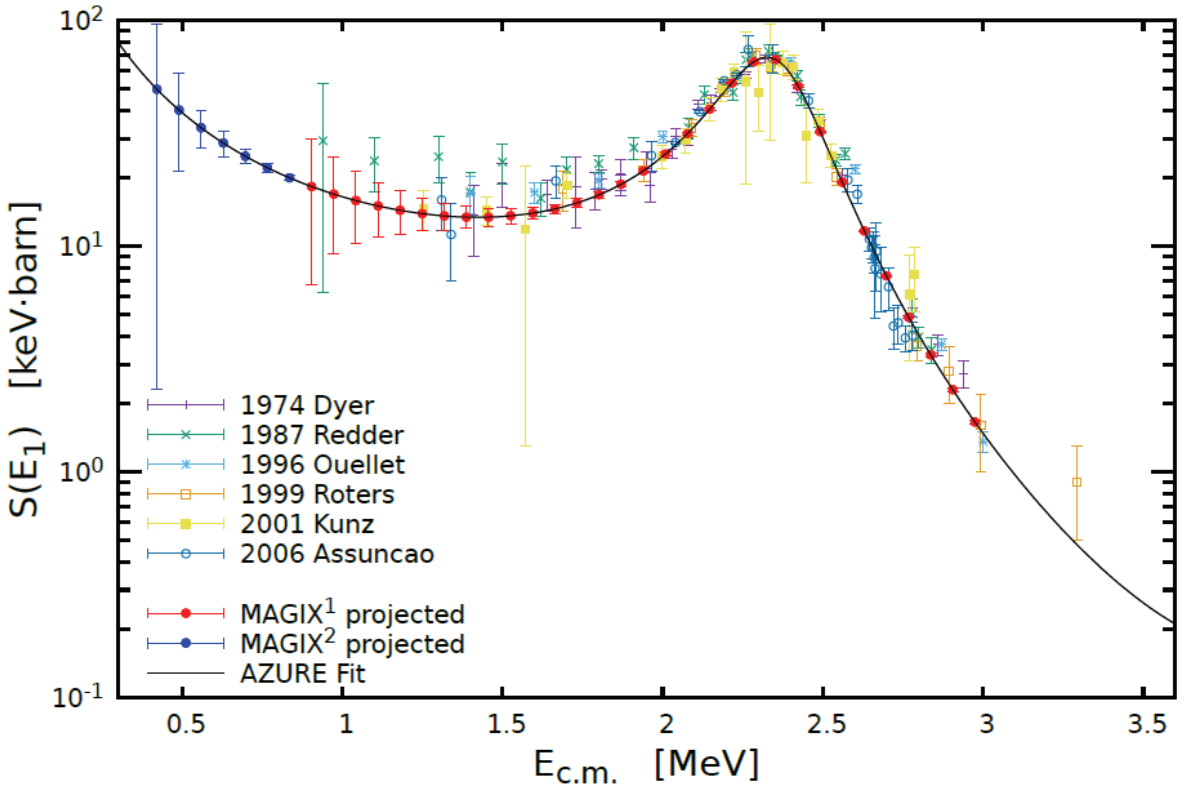


$$\int_0^\infty \frac{dQ^2}{Q^2} I(Q^2) = \delta_{\text{TPE}}^{\text{inel}}$$

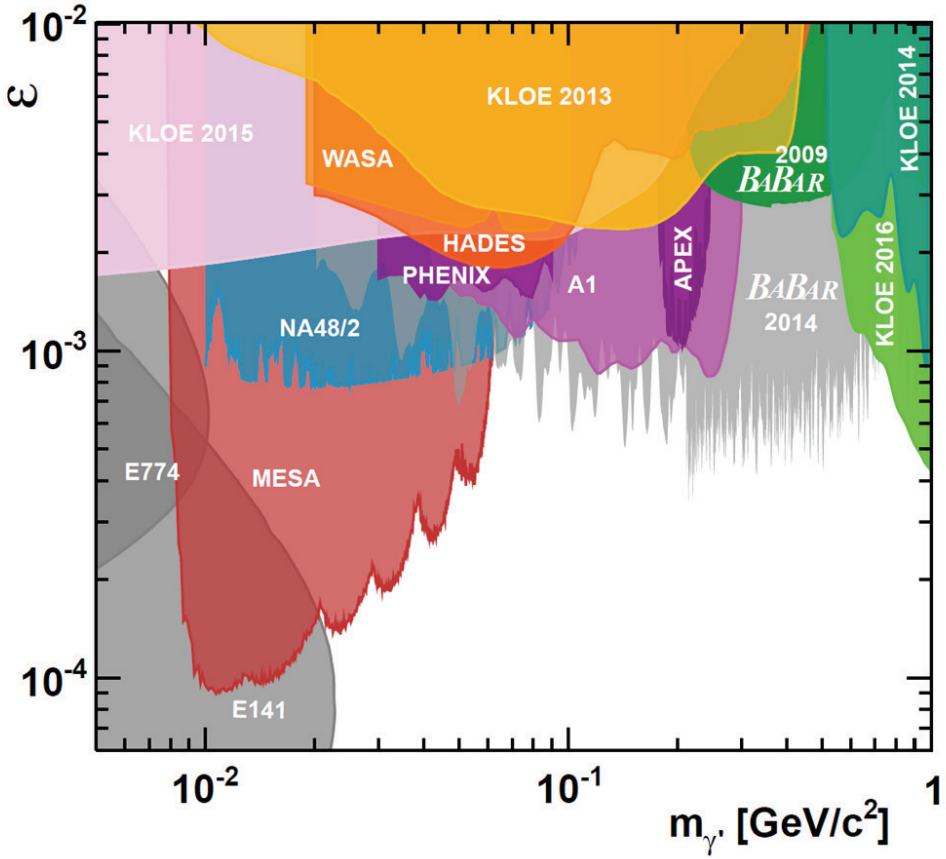
- Tests and calibrates theory needed for muonic atom calculations (two-photon exchange)
- Very relevant kinematics
- Forward measurement, as an early measurement with extracted beam

Nuclear astrophysics

- Cross-section (S-factor) of $^{12}C(\alpha,\gamma)^{16}O$ very relevant for stellar burning
- Can measure the inverse reaction $^{16}O(\gamma,\alpha)\ ^{12}C$ with MAGIX
- Spectrometer (phase I), zero-degree tagger (phase II), recoil detector
- Backgrounds need to understood
- Can be extended to further reactions:
  $^{15}N(p,\gamma)^{16}O$, $^{15}N(\alpha,\gamma)^{19}F$,
  $^{16}O(\alpha,\gamma)^{20}Ne$, $^{18}O(\alpha,\gamma)^{22}Ne$, ...

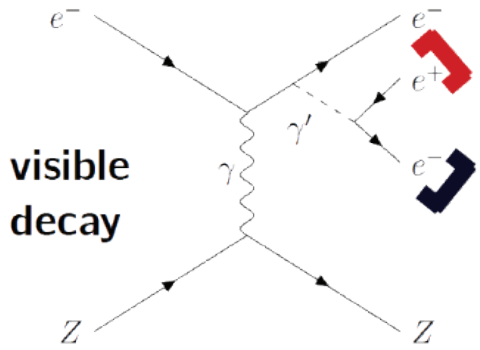


Dark Photons



Visible decay to e^+e^-

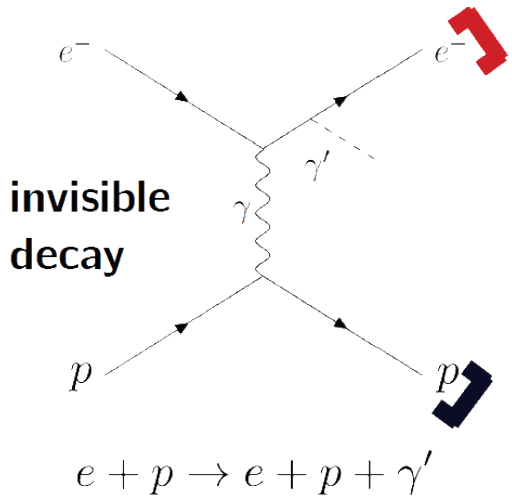
- Xenon or Argon target, high currents



$$e + Z \rightarrow e + Z + \gamma'$$
$$\hookrightarrow e^+ + e^-$$

Invisible decays

- Hydrogen target
- Recoil detector
- Limit projection on the way



$$e + p \rightarrow e + p + \gamma'$$

And more...

- Charge radius deuteron
- Charge radius ^{4}He
- Meson exchange currents and three-nucleon forces in ^{3}He /^{4}He
- Continuation of MAMI-based program electrons for neutrino physics
- Nucleus knockout reactions from light-medium nuclei
- Investigation of polarization degrees of freedom
- ...

Dark matter in the beam dump

DarkMESA

DarkMESA

- P2: Several 10^{22} electrons on target
- Dark matter χ, mediator γ'

$$Y_{Prod} \sim \epsilon^2/m_A^2$$

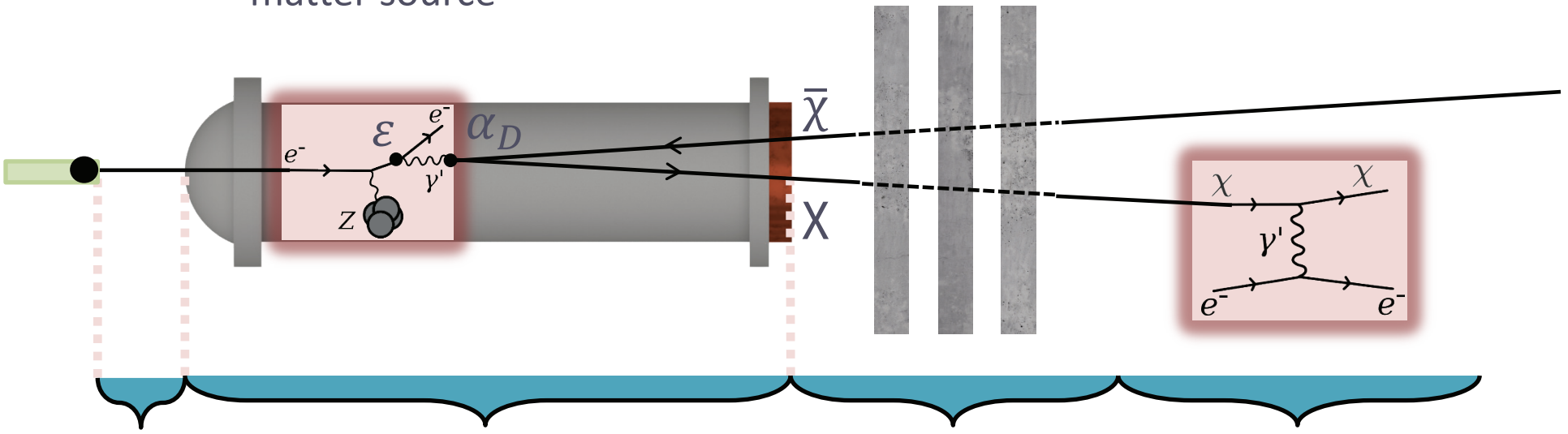
$$Y_{Det} \sim \epsilon^2 \alpha_D/m_A^2$$

P2 target

Beam dump = high energy and high intensity dark matter source

Concrete walls and air

Detector



~ 12 m

~ 2 m

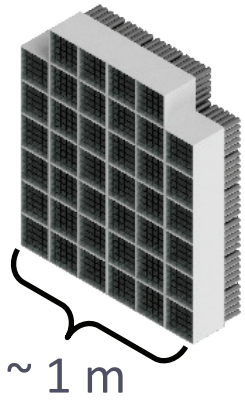
~ 23 m

2.4 m

$$Y_{TOT} \sim \epsilon^4 \alpha_D/m_A^4$$

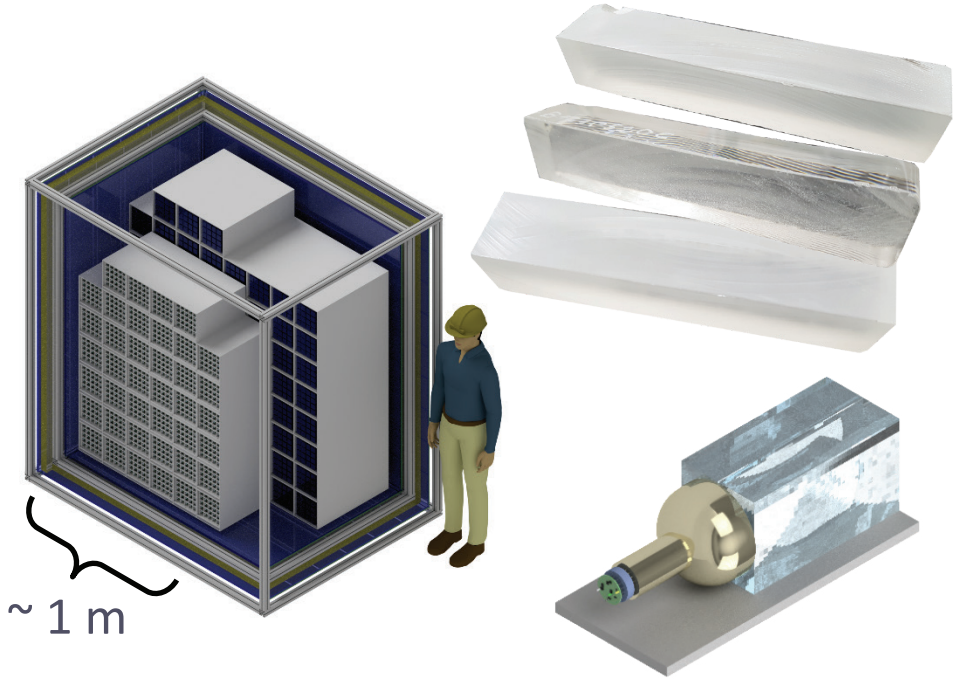
Calorimeter detector

Stage A:
PbF_2



- Use of existing PbF_2 calorimeter
- Active volume of 0.13 m^3

Stage B:
+ Pb glass



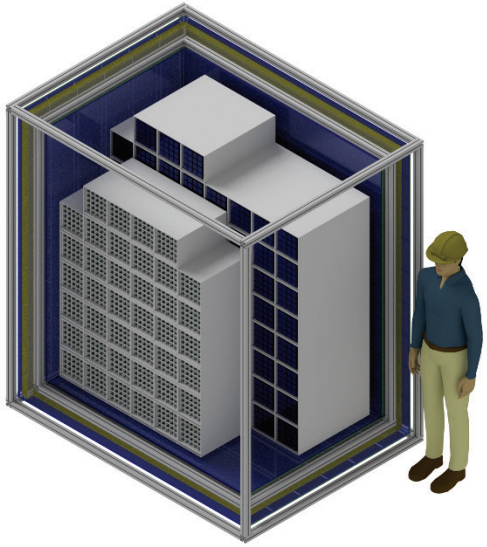
- Use of existing lead glass calorimeter
- Addition of new lead glass blocks
- Active volume of 0.6 – 1 m^3

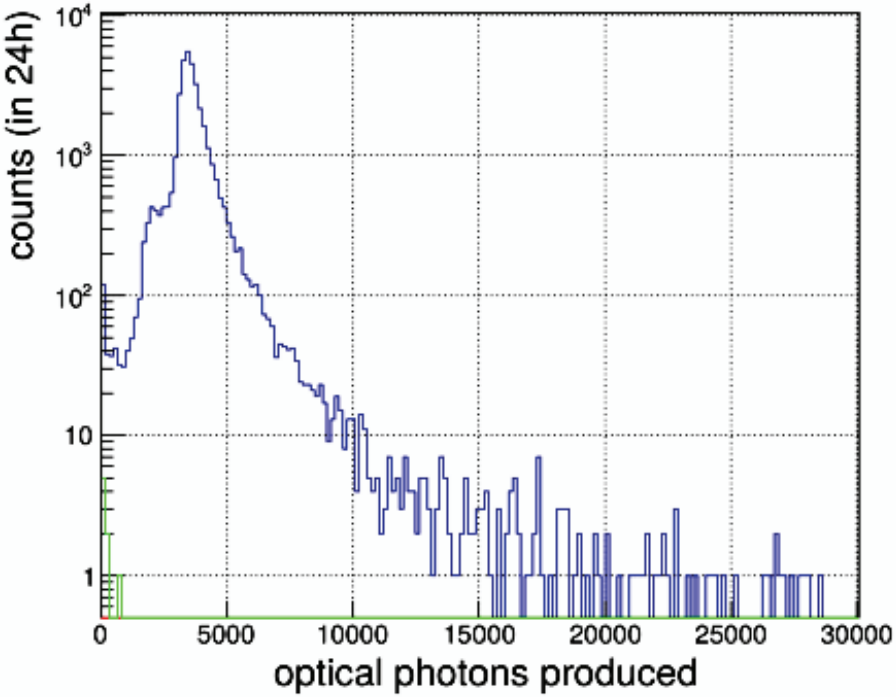
Stage C:

- Technology so far undefined
- Up to 11 m^3 volume possible

Background estimates

- Use of beam on/off information: EB time scheduling approx. 50 %
- Segmenting of detector read-out: coincidences eliminating noise
- Use of several veto layers



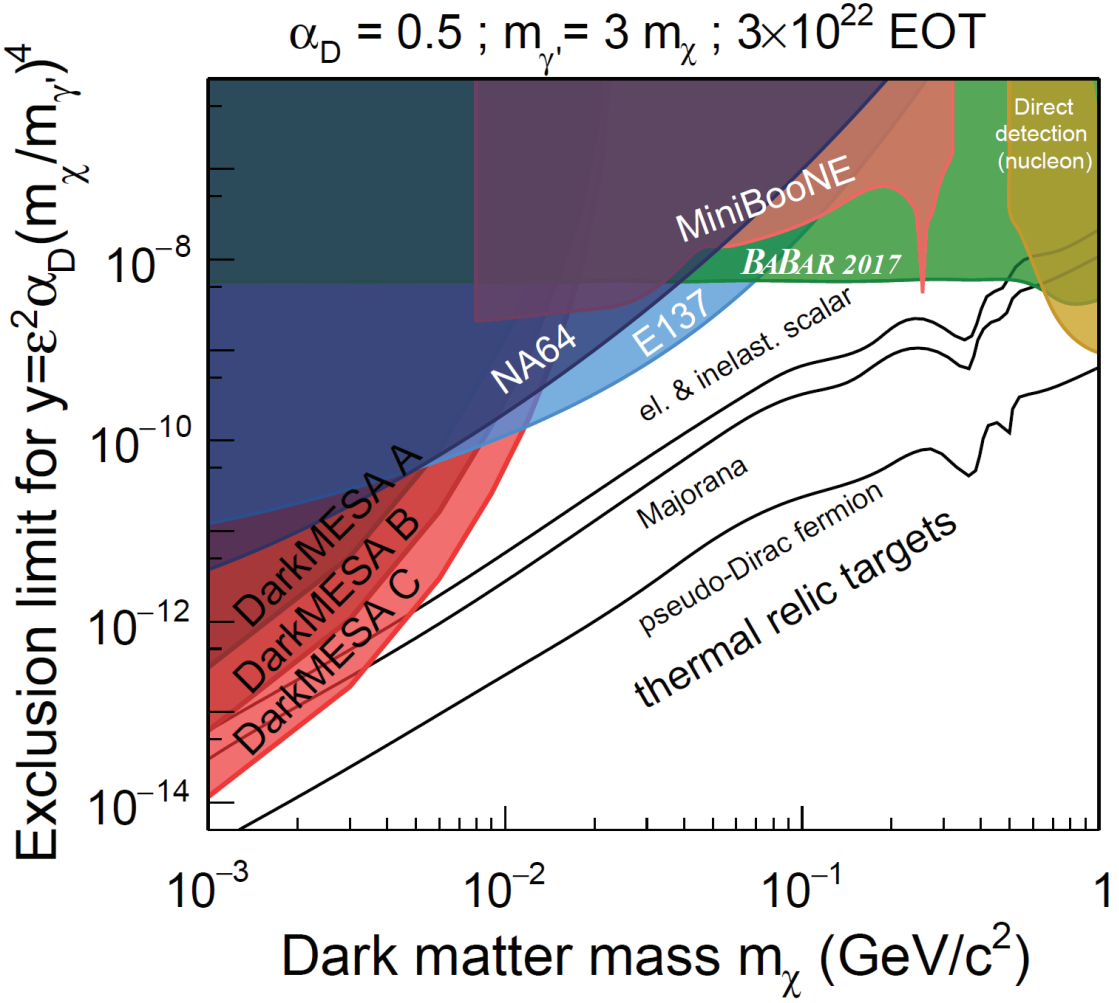


Blue: Light yield in calorimeter

Red/Green: with 1 or 2 veto hits

Veto concept reduces 24h background rate to zero events

Sensitivity



- Stage A: existing PbF2 crystals (0.13 m^3 volume)
- Stage B: lead glass calorimeter (1 m^3 volume)
- Stage C: Extrapolation (11 m^3 volume)

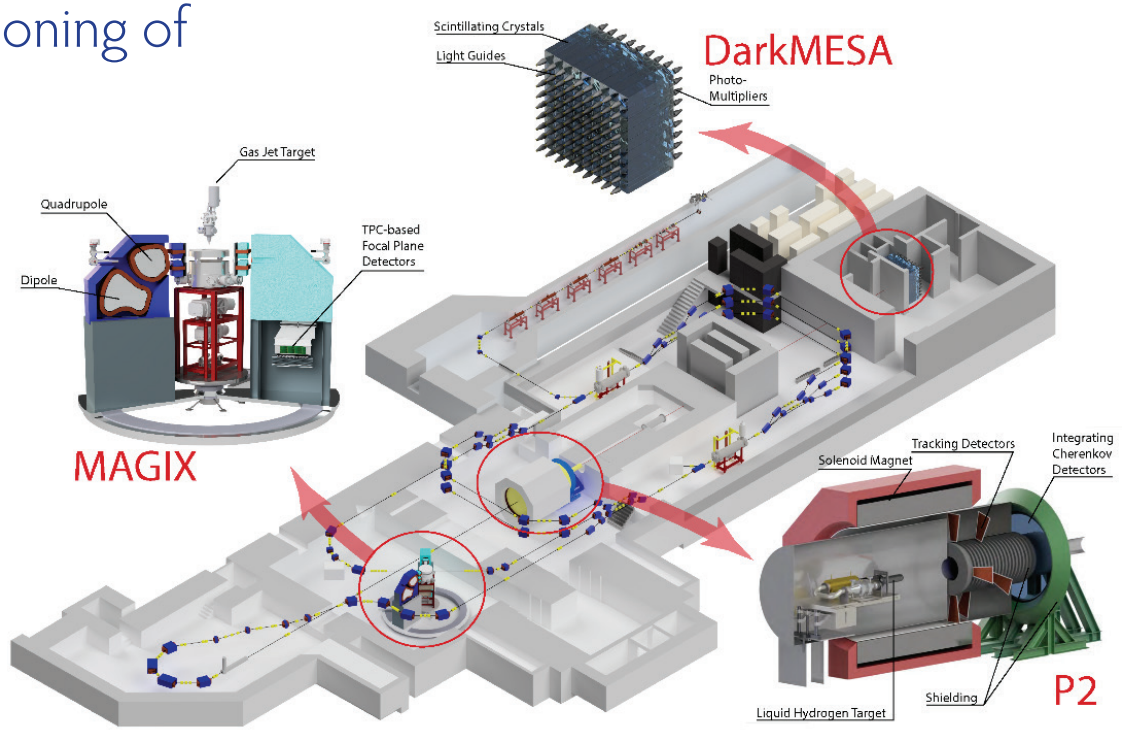
Simulation assumptions:

- Electron recoil detection
- 14 MeV energy threshold
- 90% detector efficiency
- No backgrounds

- DarkMESA has the potential to touch the thermal relic targets!

Outlook

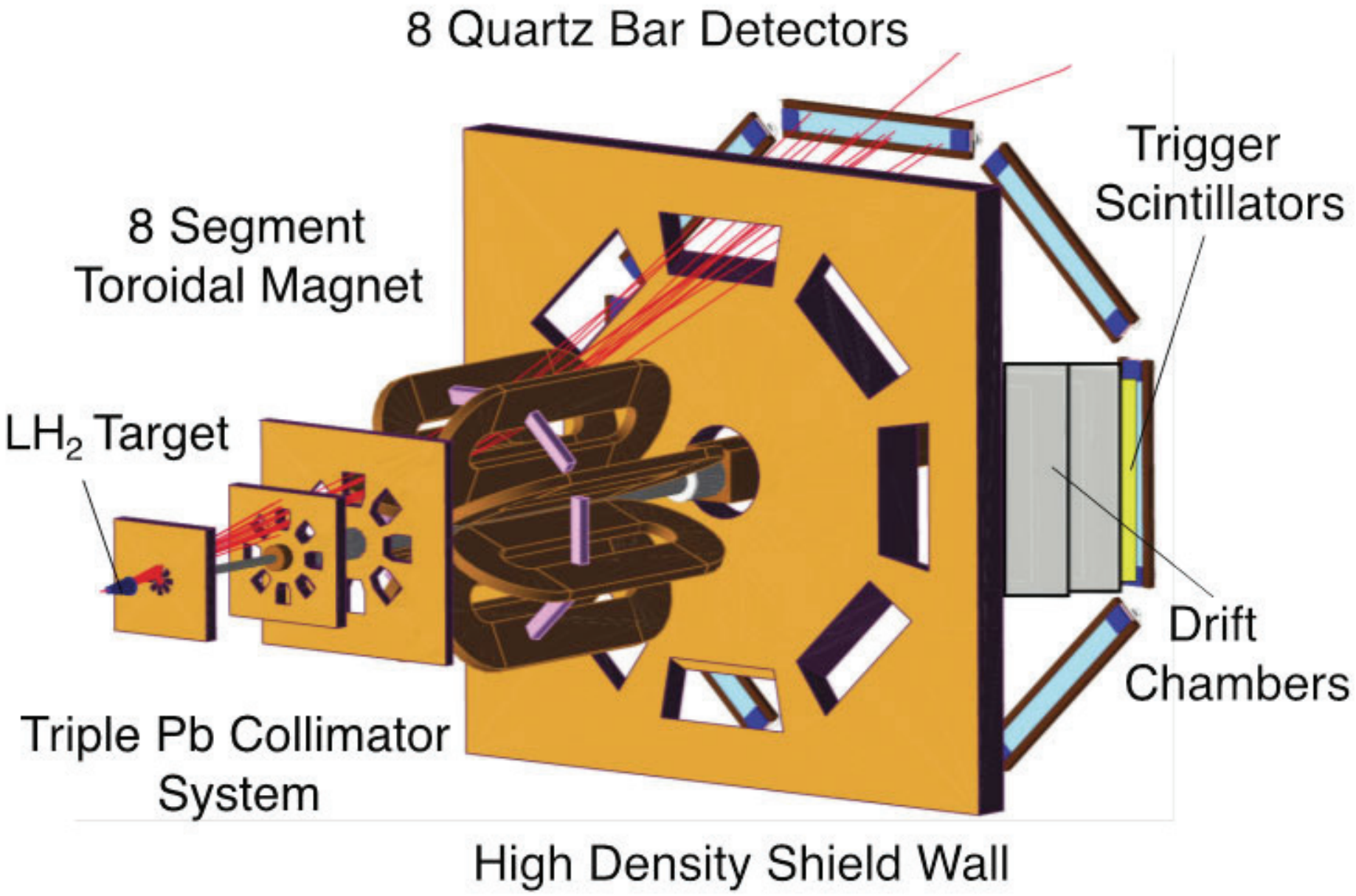
- Civil construction to finish this year
- 2022: Setting up the accelerator and experiments
  (components mostly ready and tested in existing buildings)
- 2023: Accelerator and experiment commissioning, extracted beam
- 2024: Extracted beam data taking, commissioning of energy recovery mode
- First measurements becoming available

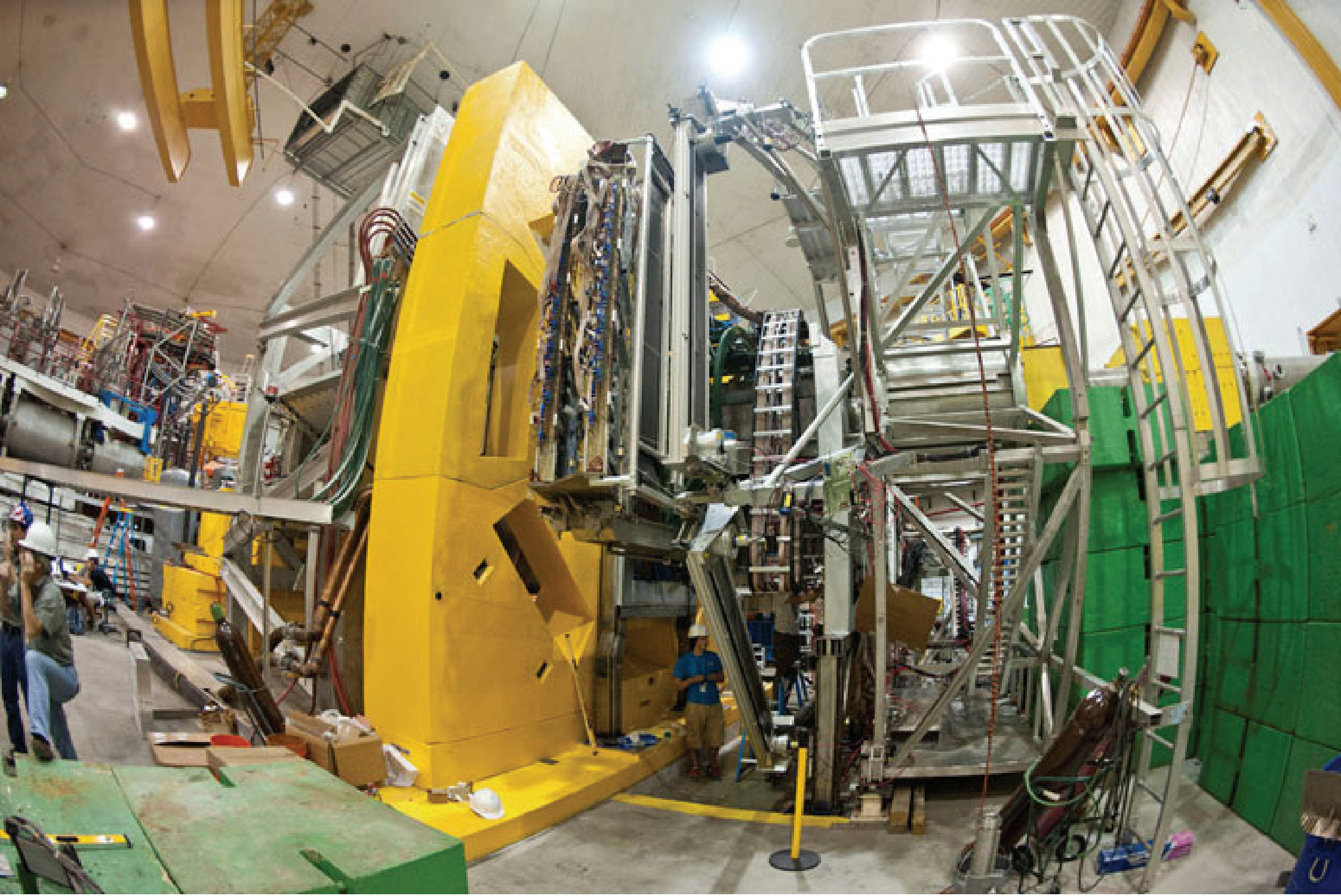


Backup

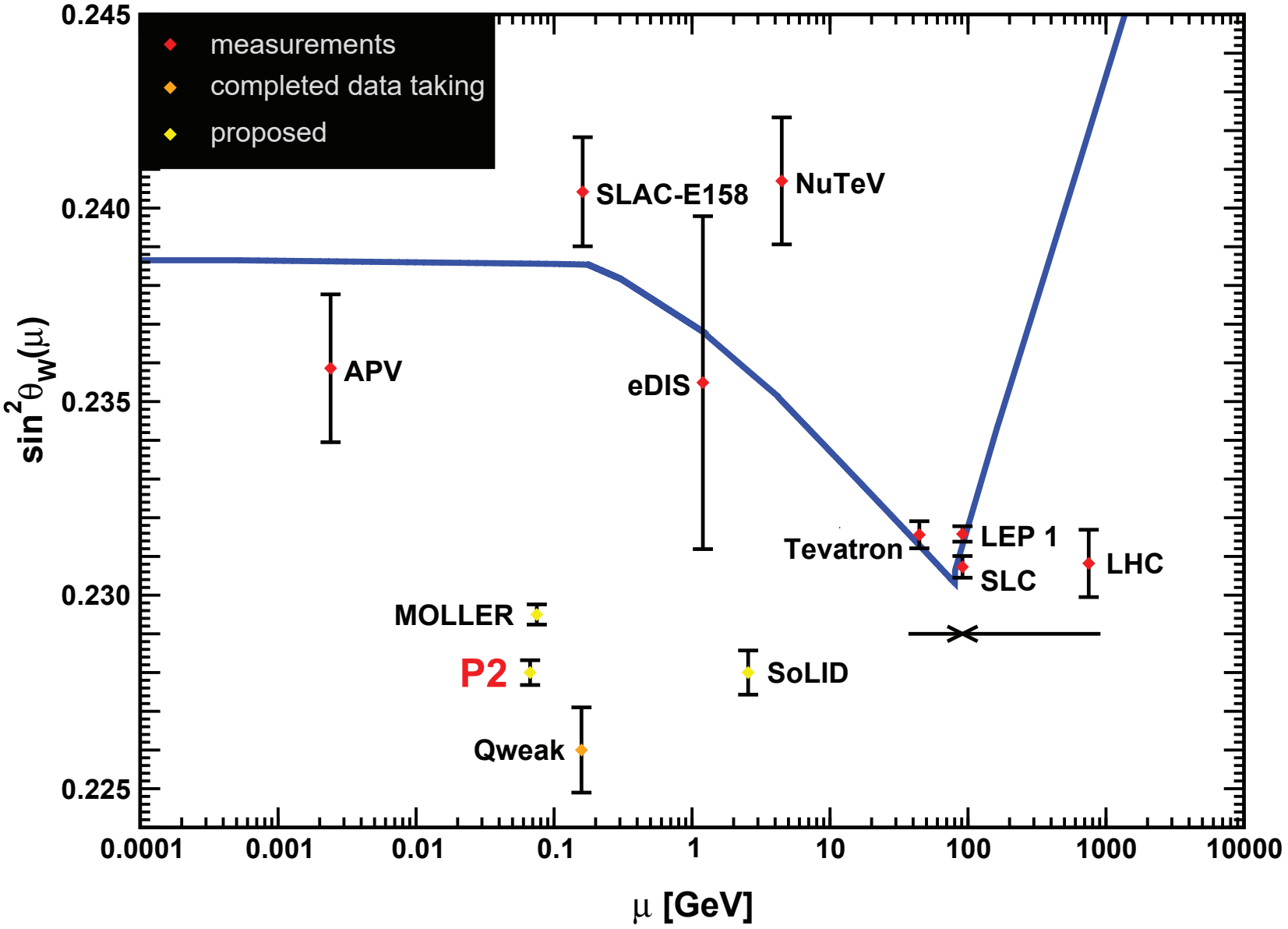
Other parity violation experiments

QWeak (JLab)

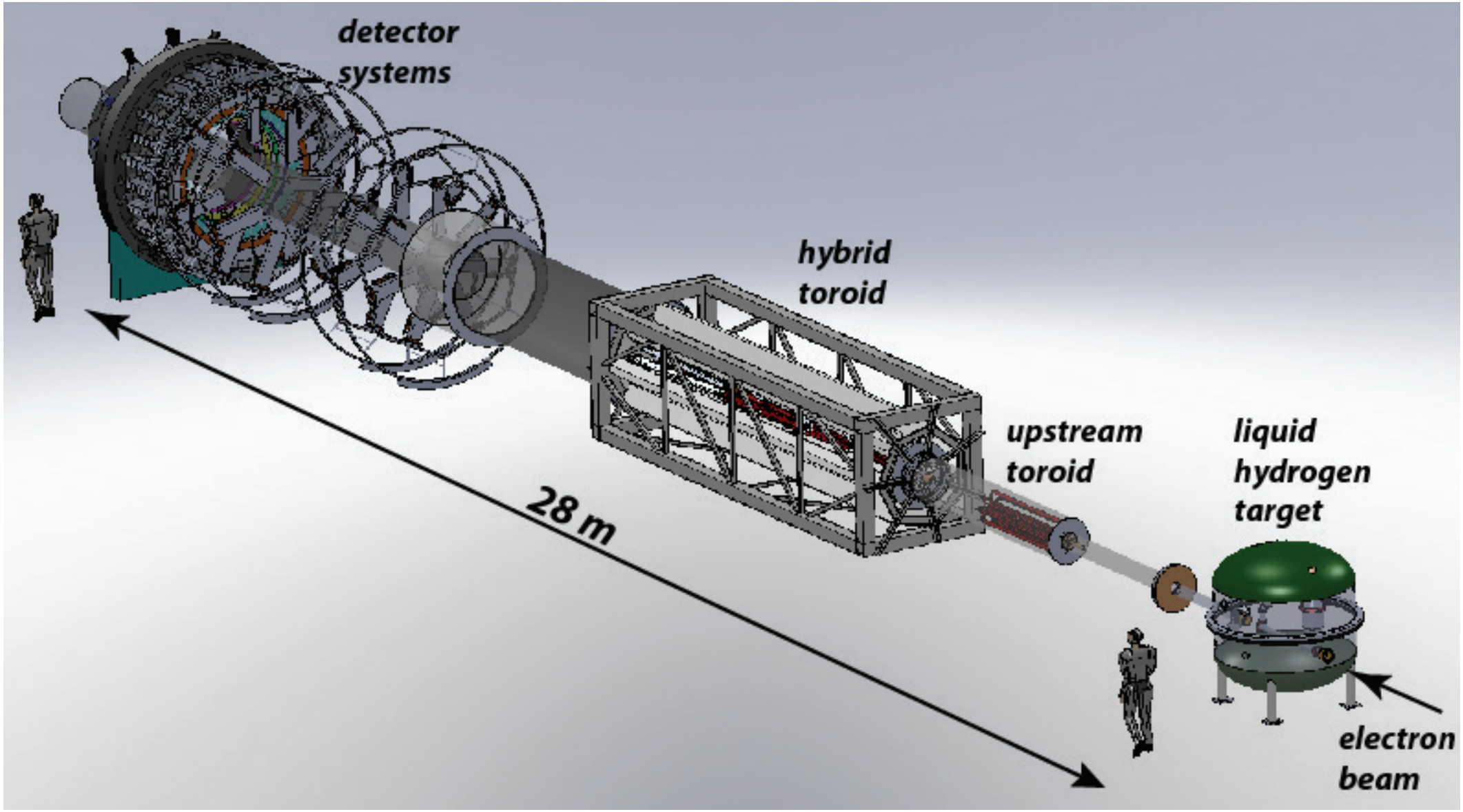

8 Quartz Bar Detectors
Trigger Scintillators
8 Segment Toroidal Magnet
LH_2 Target
Drift Chambers
Triple Pb Collimator System
High Density Shield Wall



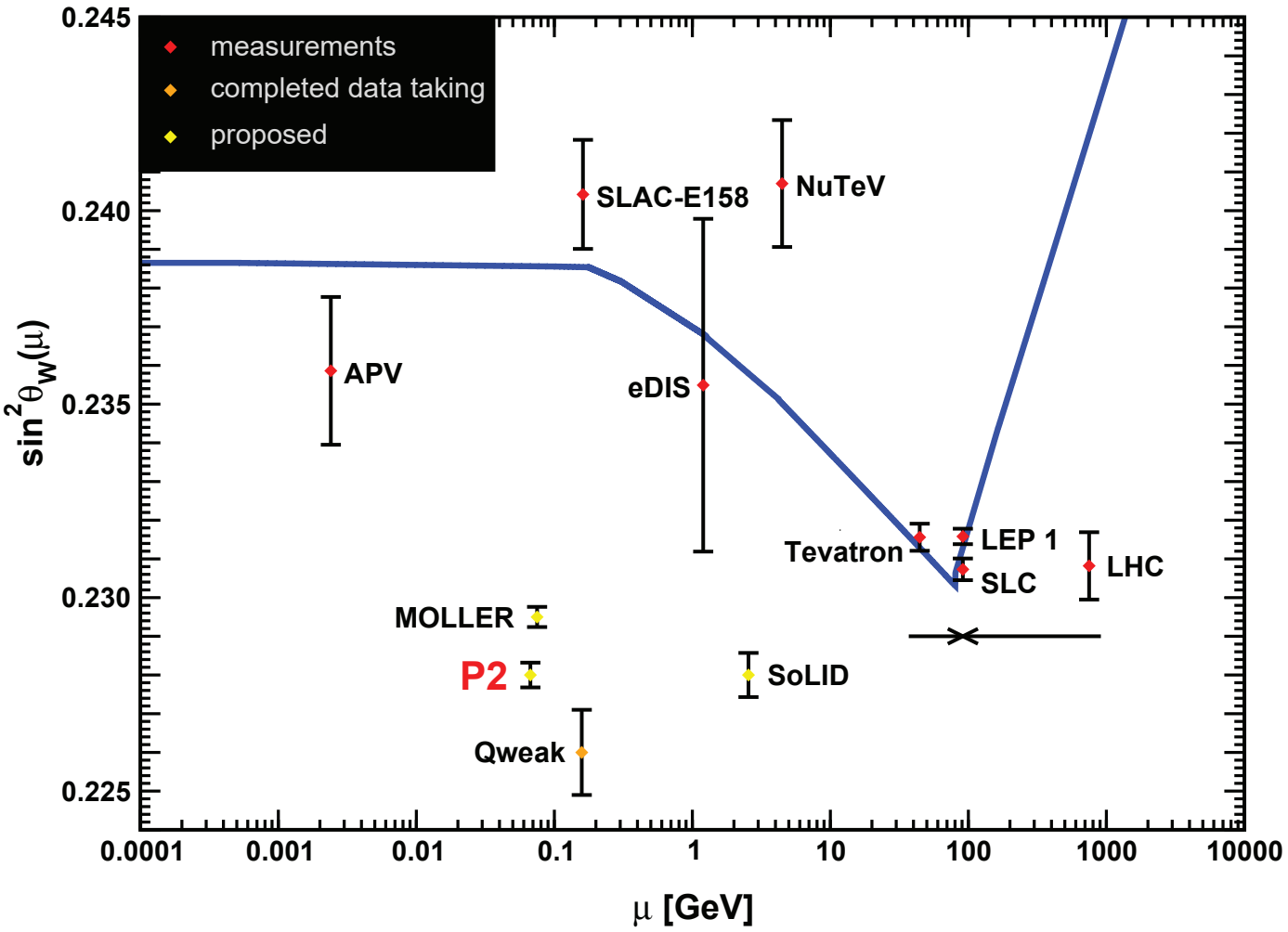
QWeak results (not)



Moller: e^-e^- scattering at JLab

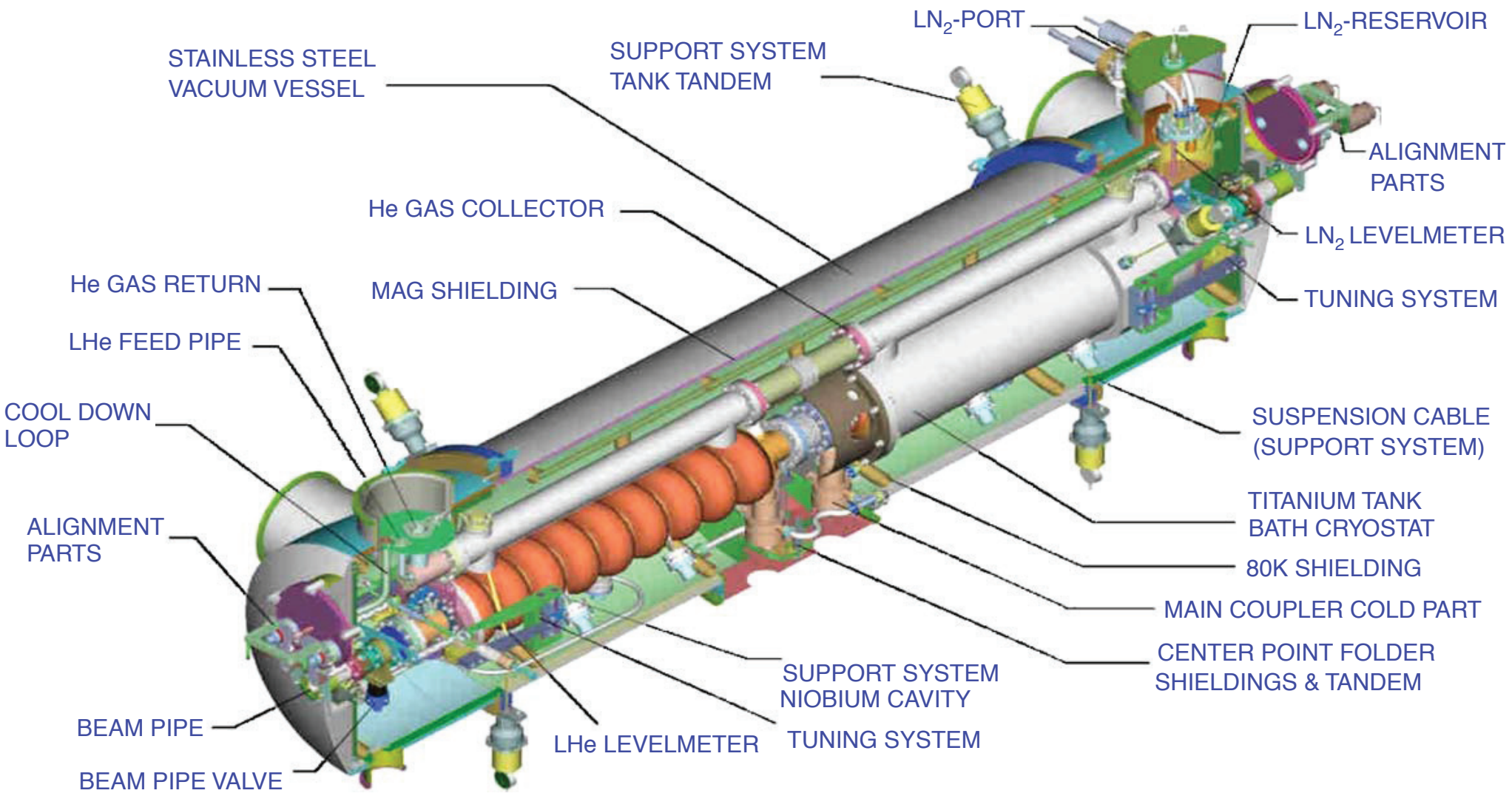


More to come...

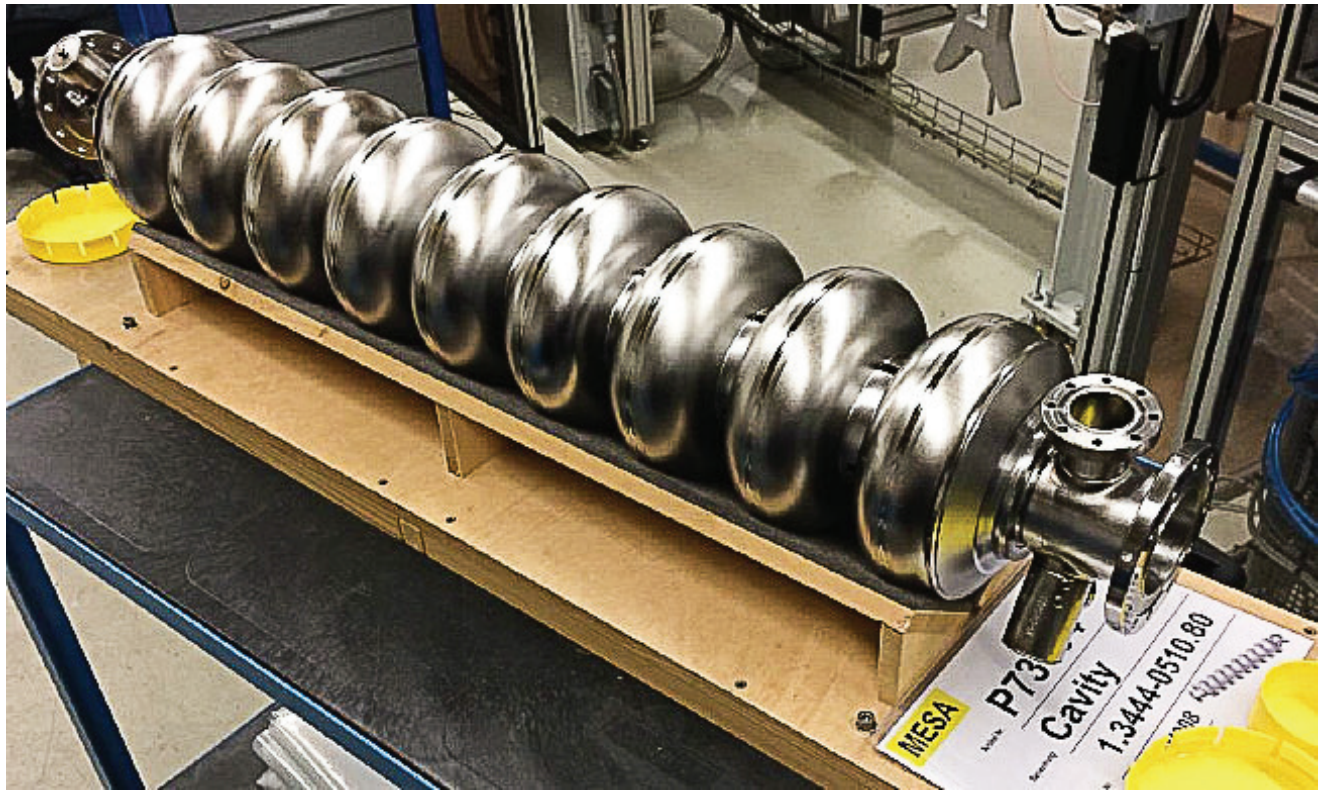


- Atomic parity violation in a single radium ion (Groningen)
- SoLID: Deep inelastic e-p scattering at JLab
- Much improved LHC measurements at the Z-pole

Superconducting Cryomodules



Teichert et al. NIM A 557 (2006) 239


MESA
Cavity
1.3444-0510.80

research
instruments

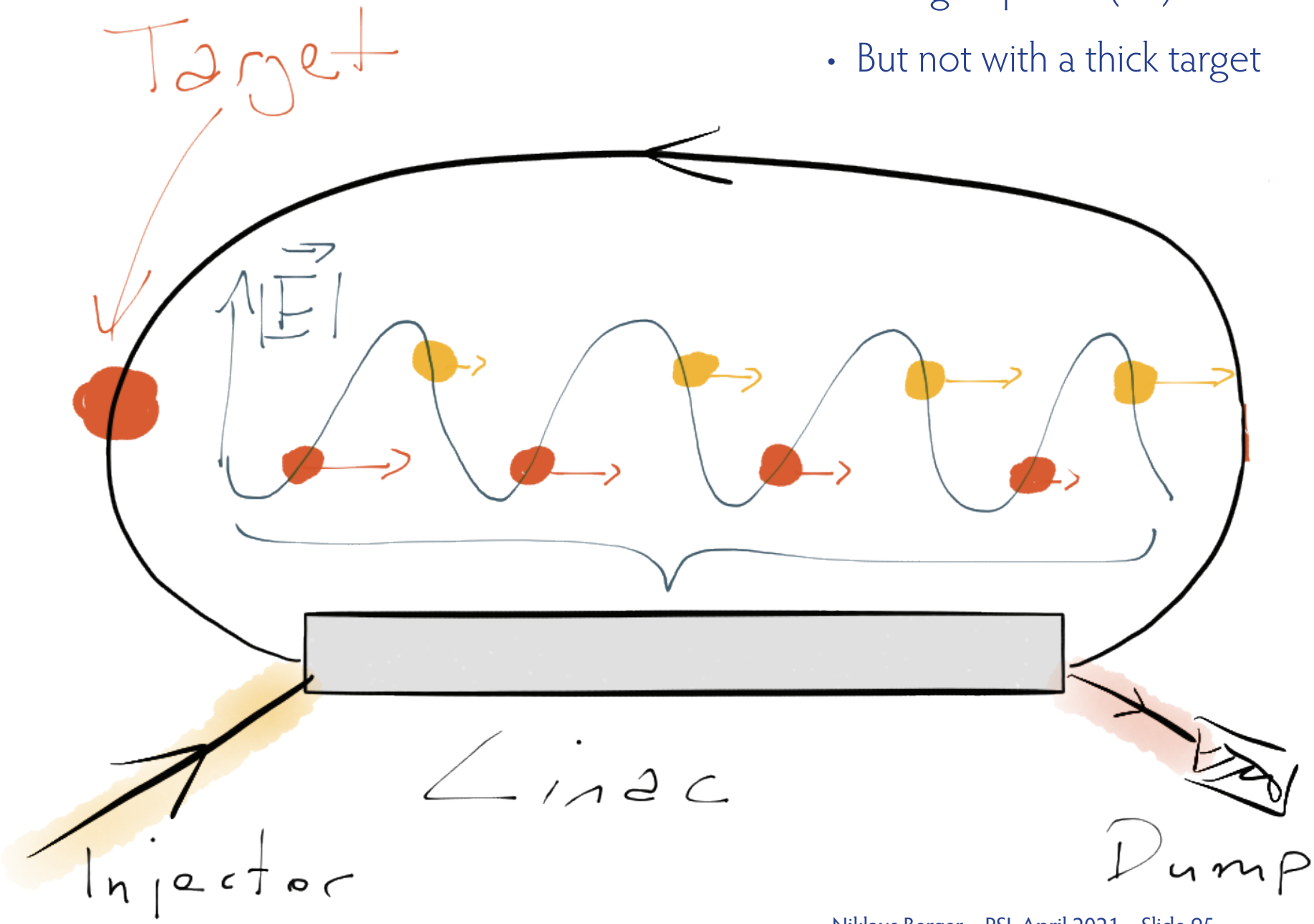
Energy recovery

Can we go to higher beam currents?

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

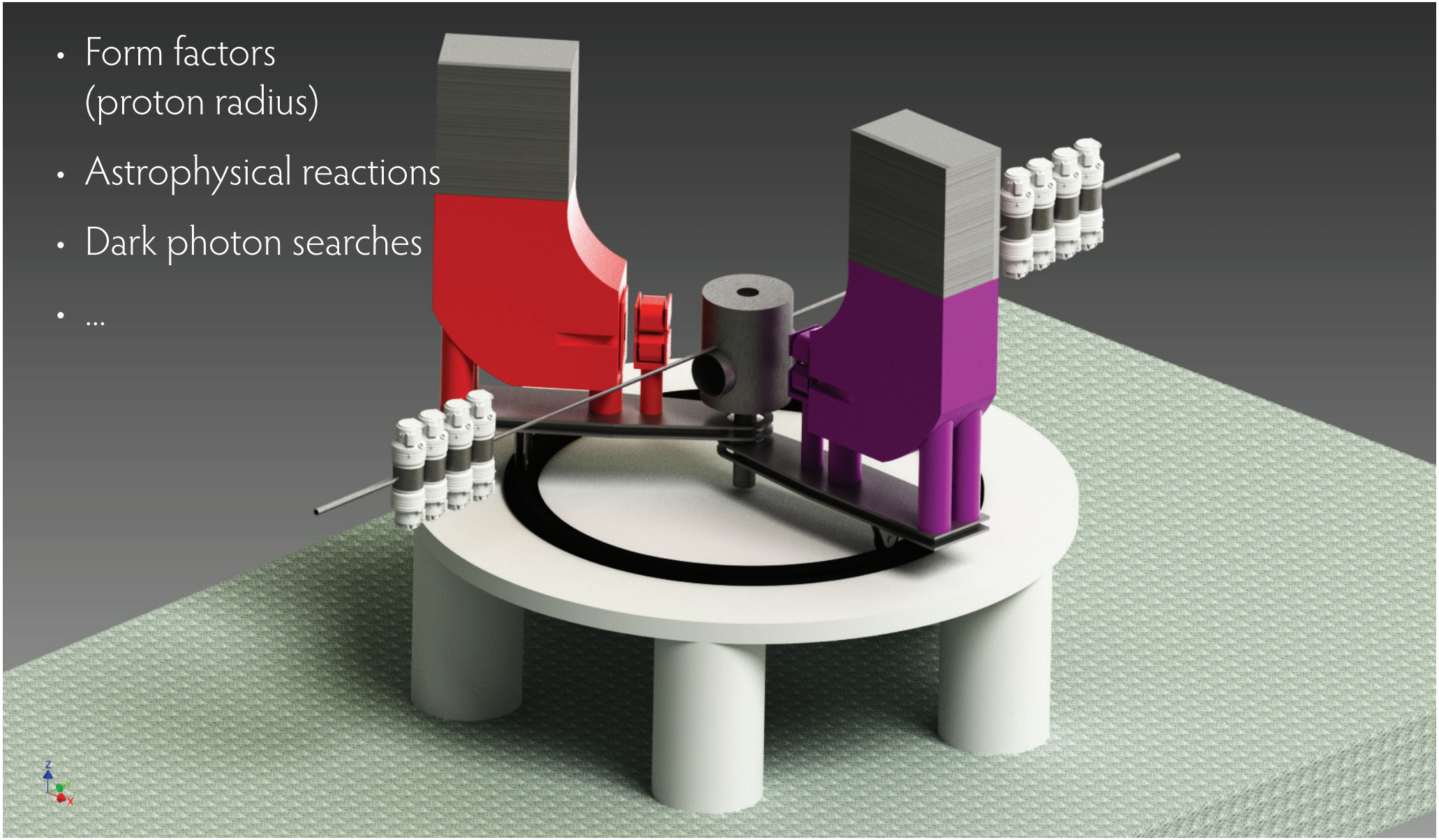
Energy recovery

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

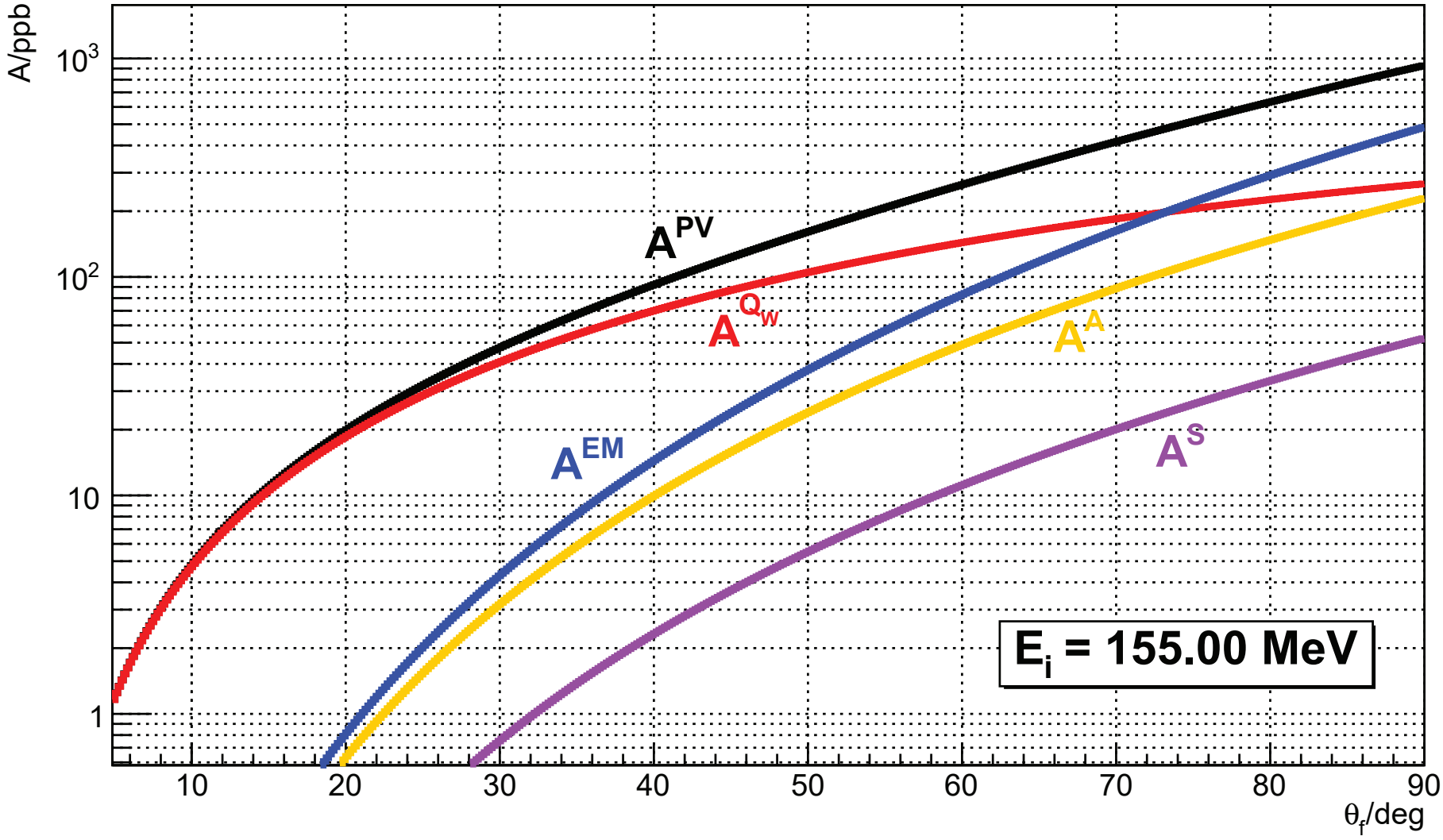


MAGIX Spectrometer

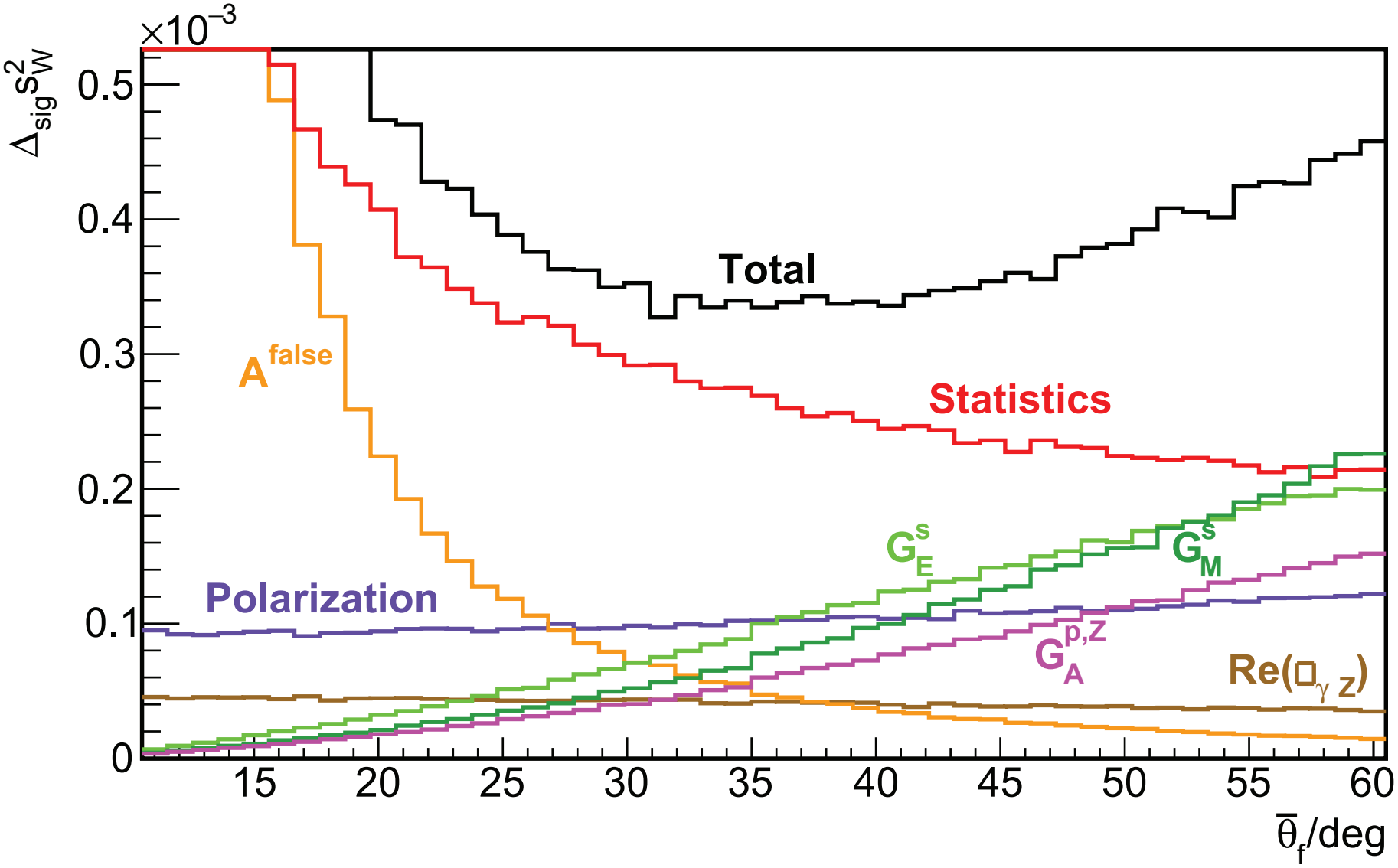
- Form factors (proton radius)
- Astrophysical reactions
- Dark photon searches
- ...



Choice of scattering angle

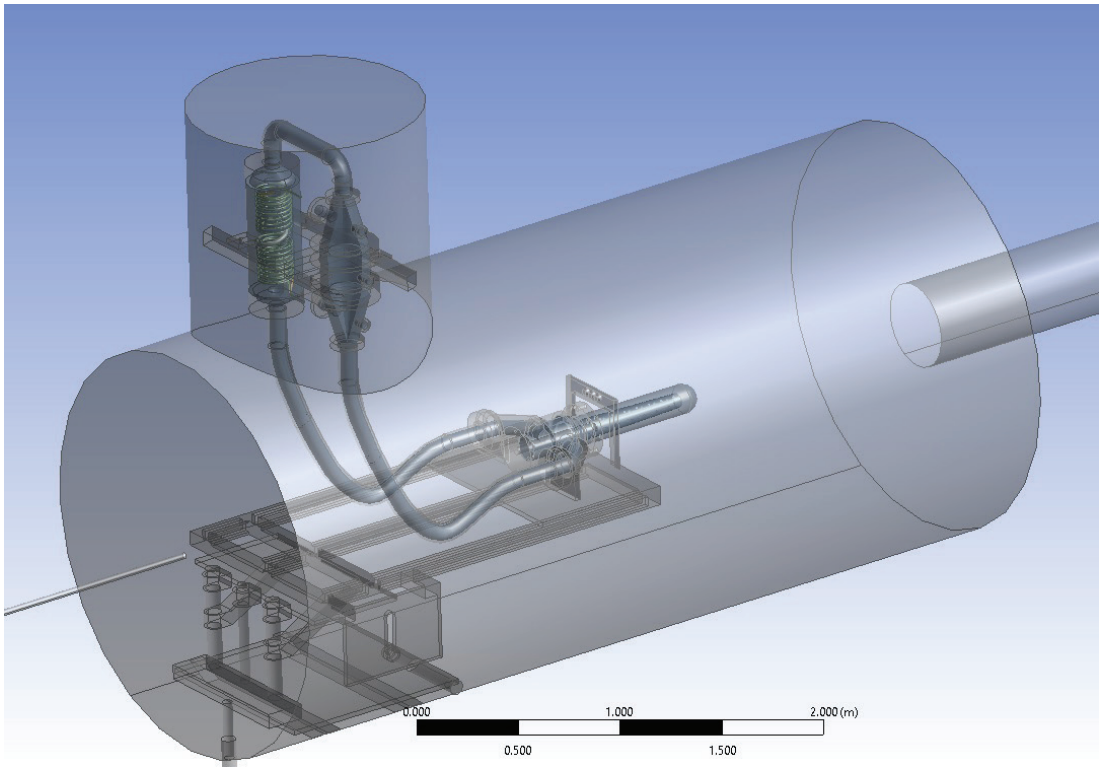


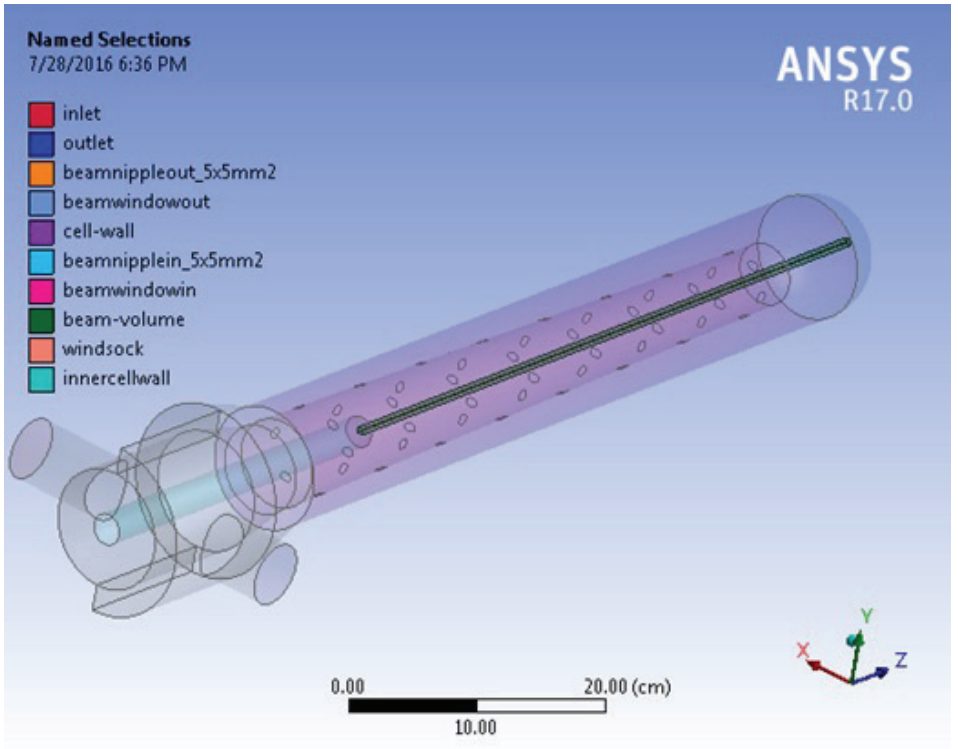
Choice of scattering angle



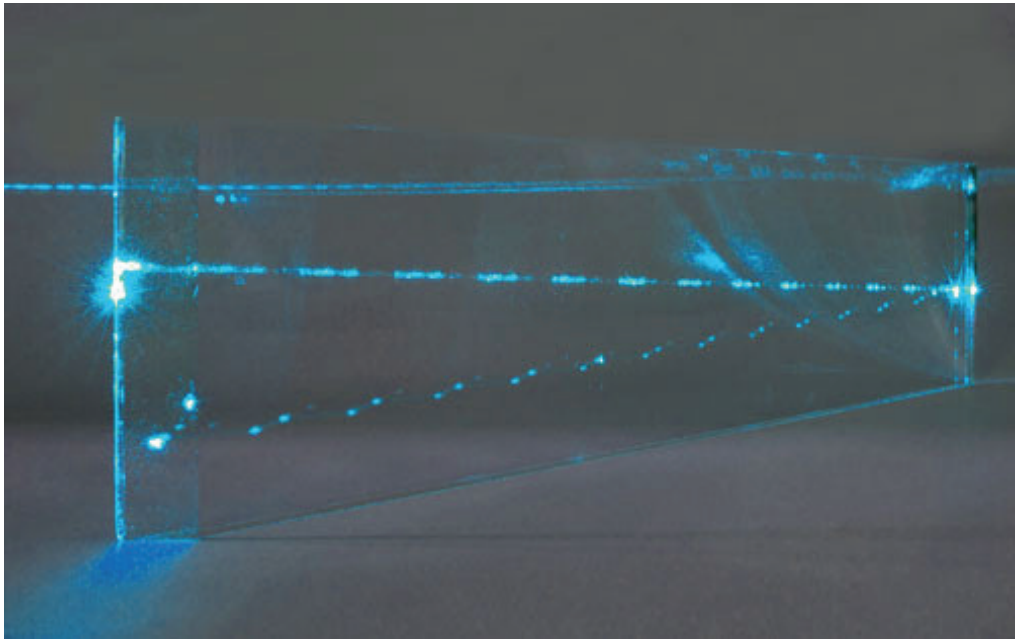
Target

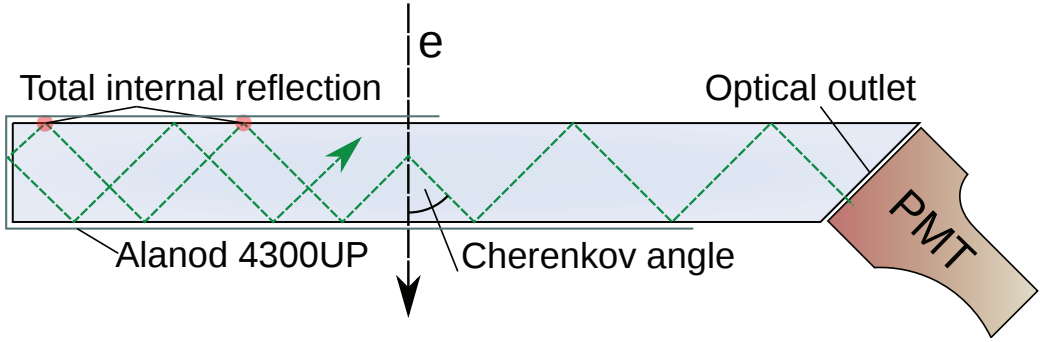
- 60 cm of liquid hydrogen
- 3.1 KW beam power deposited
- Should not boil...
- Challenging design using CFD tools (Silviu Covrig, JLab)

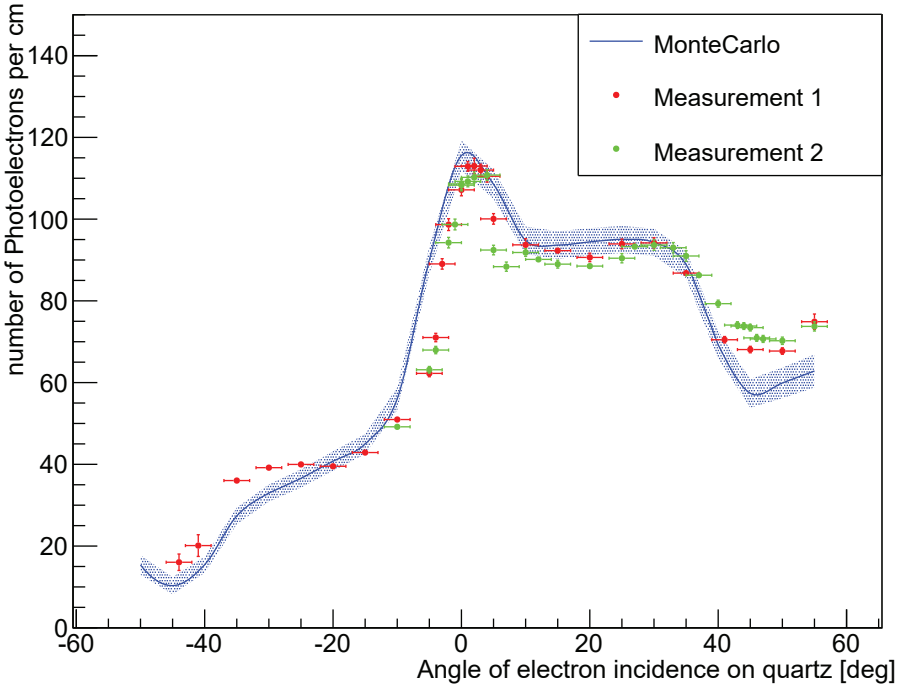




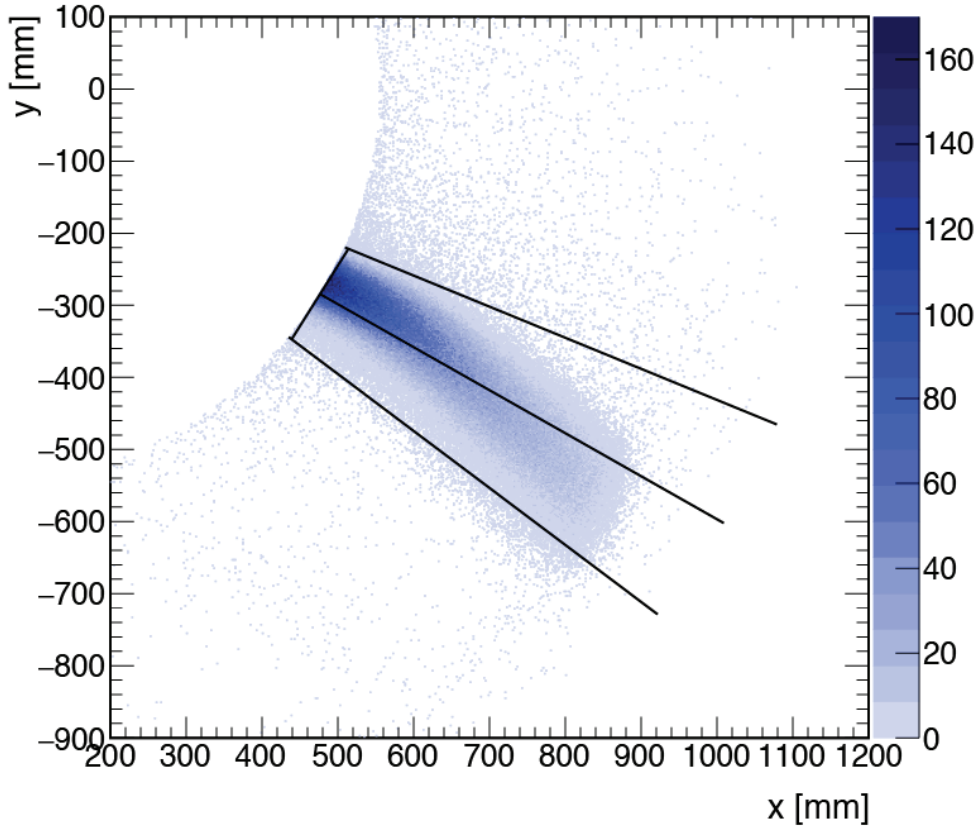
Quartz-Bars & Photomultipliers

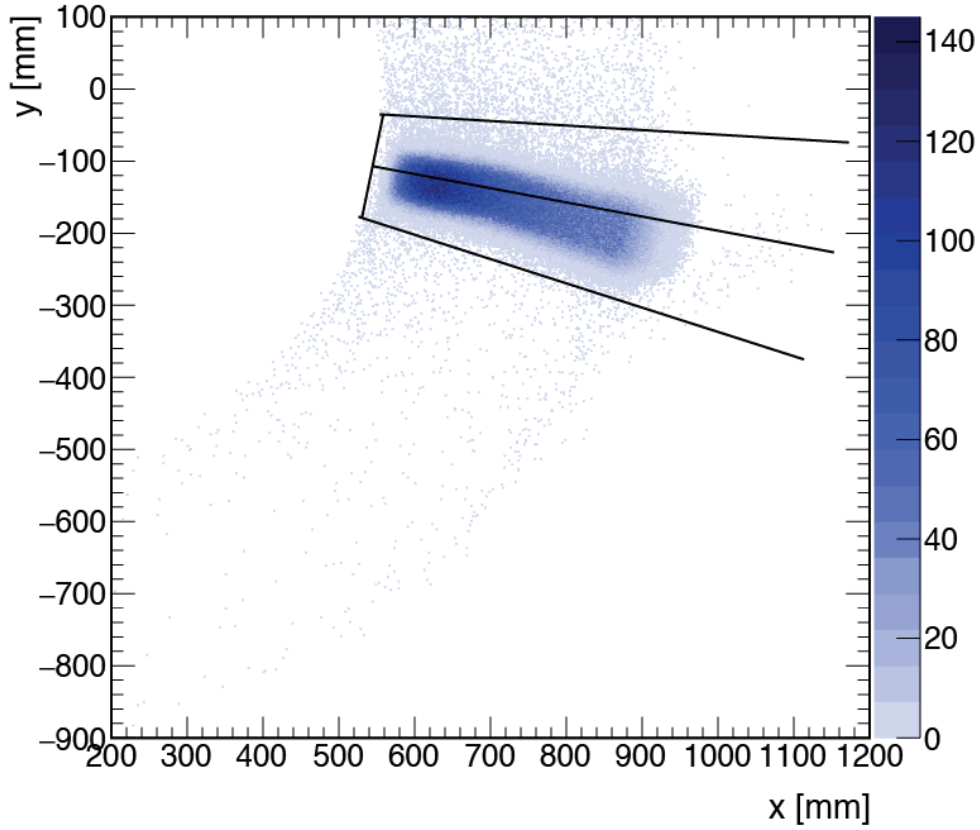






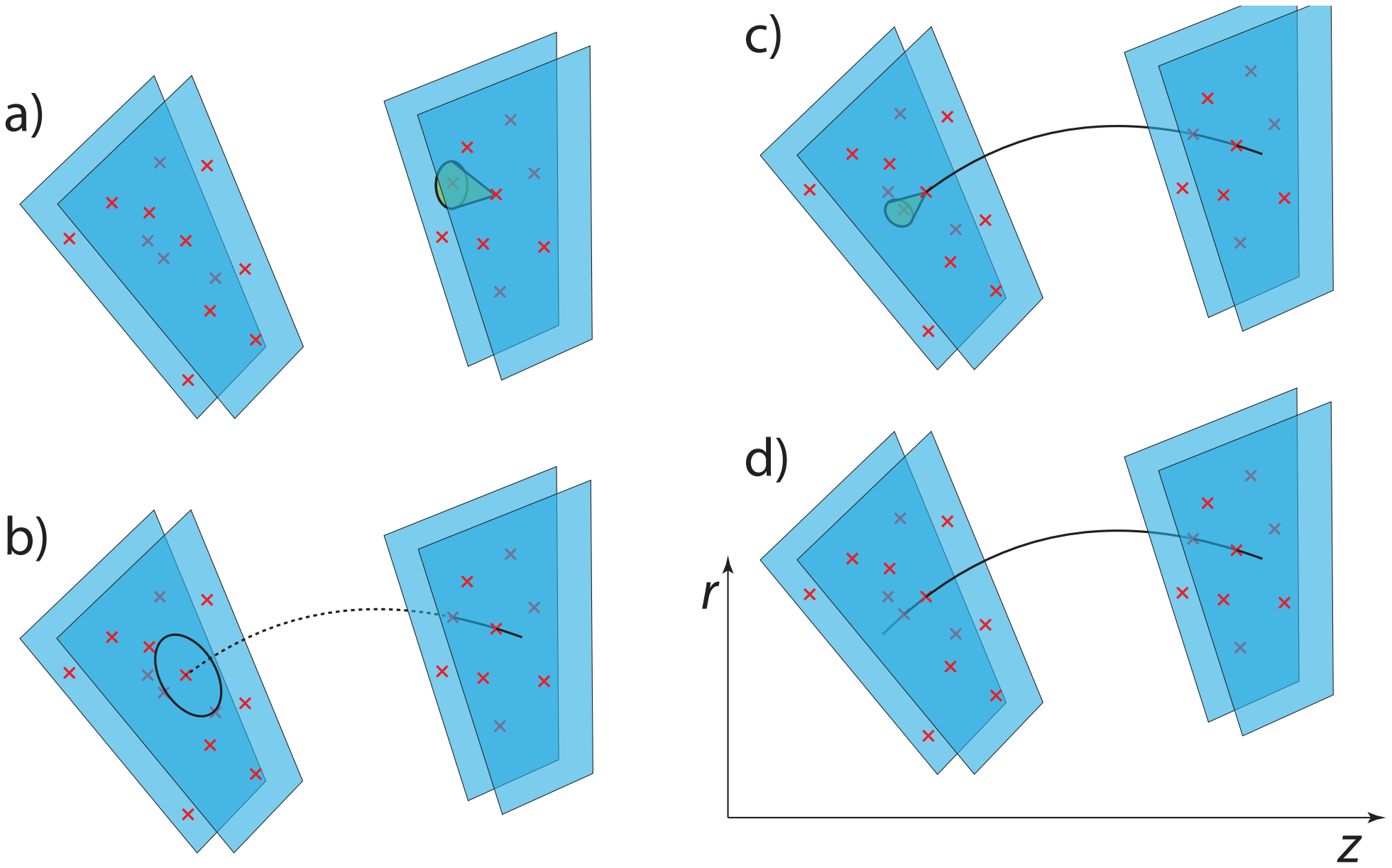
No need for full coverage



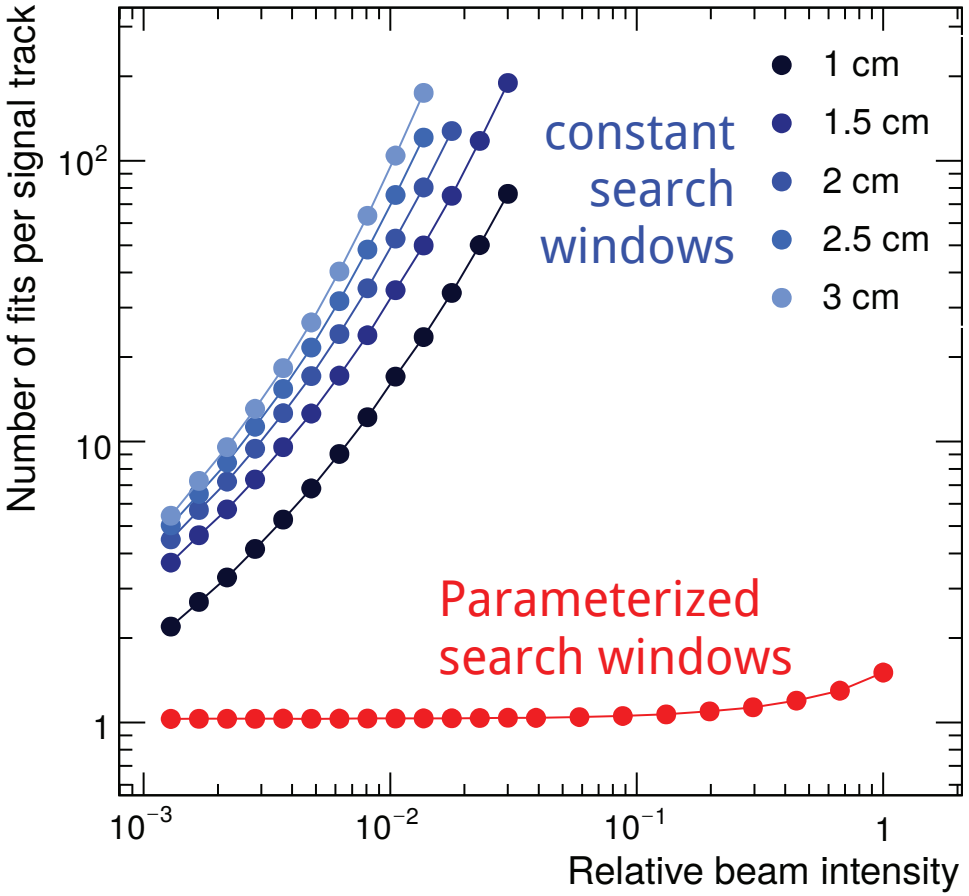


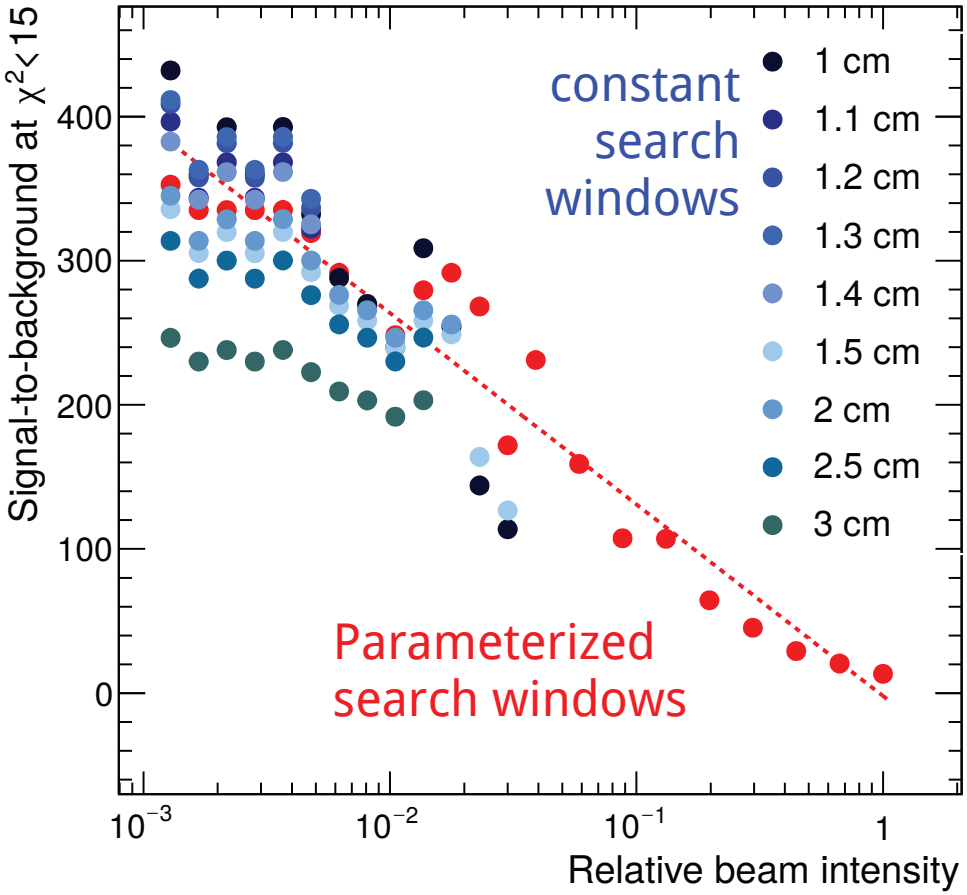
Parametrization based tracking

I. Sorokin

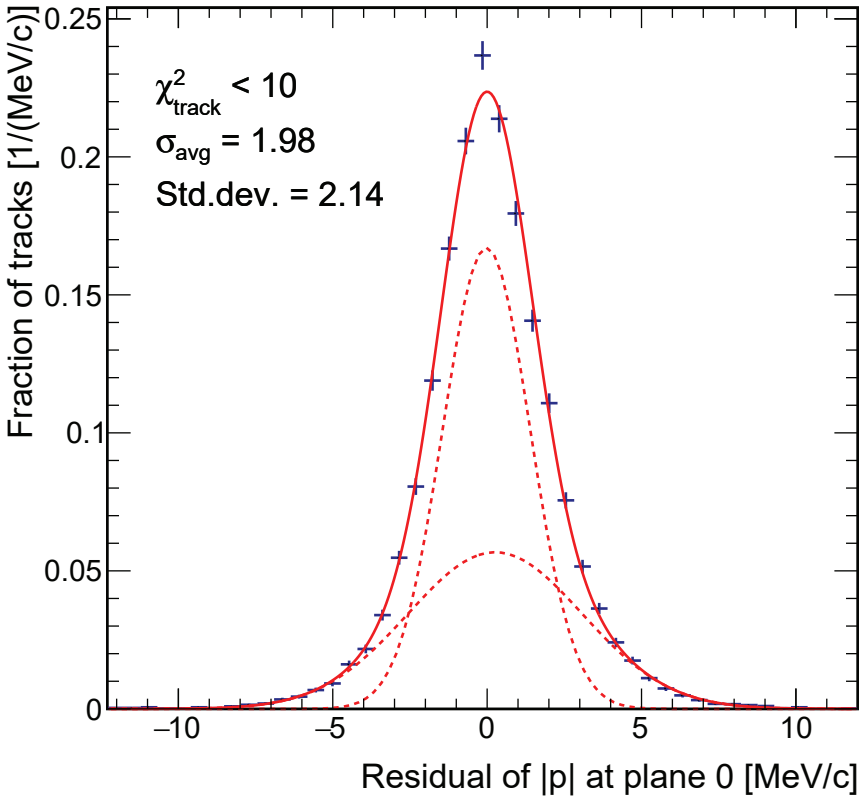


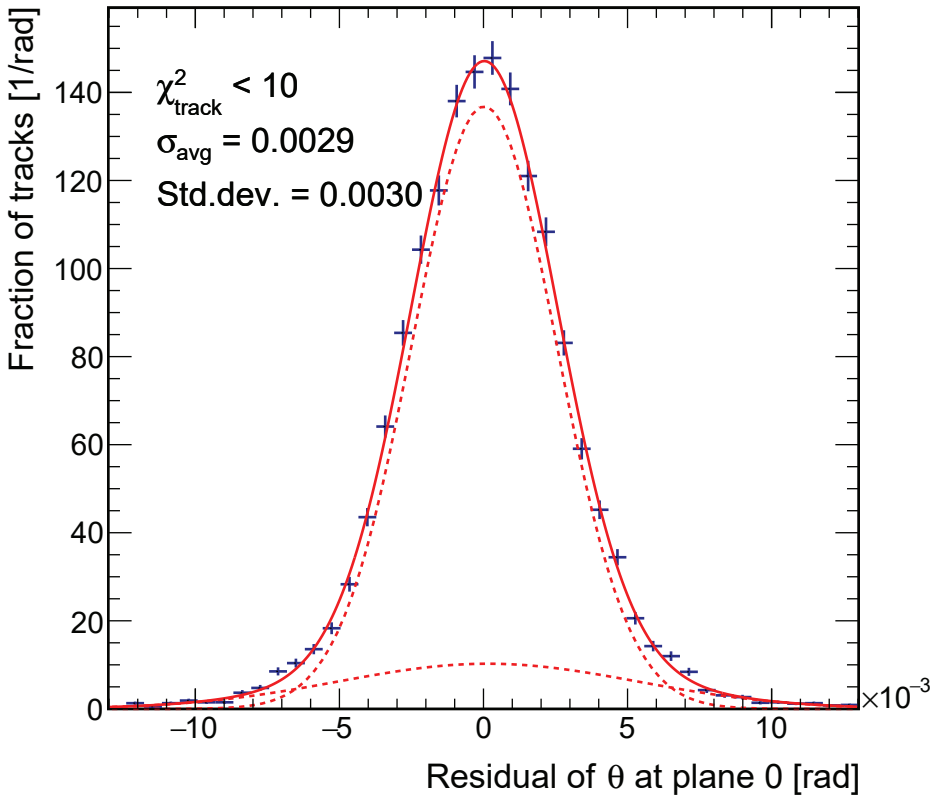
Tracking performance





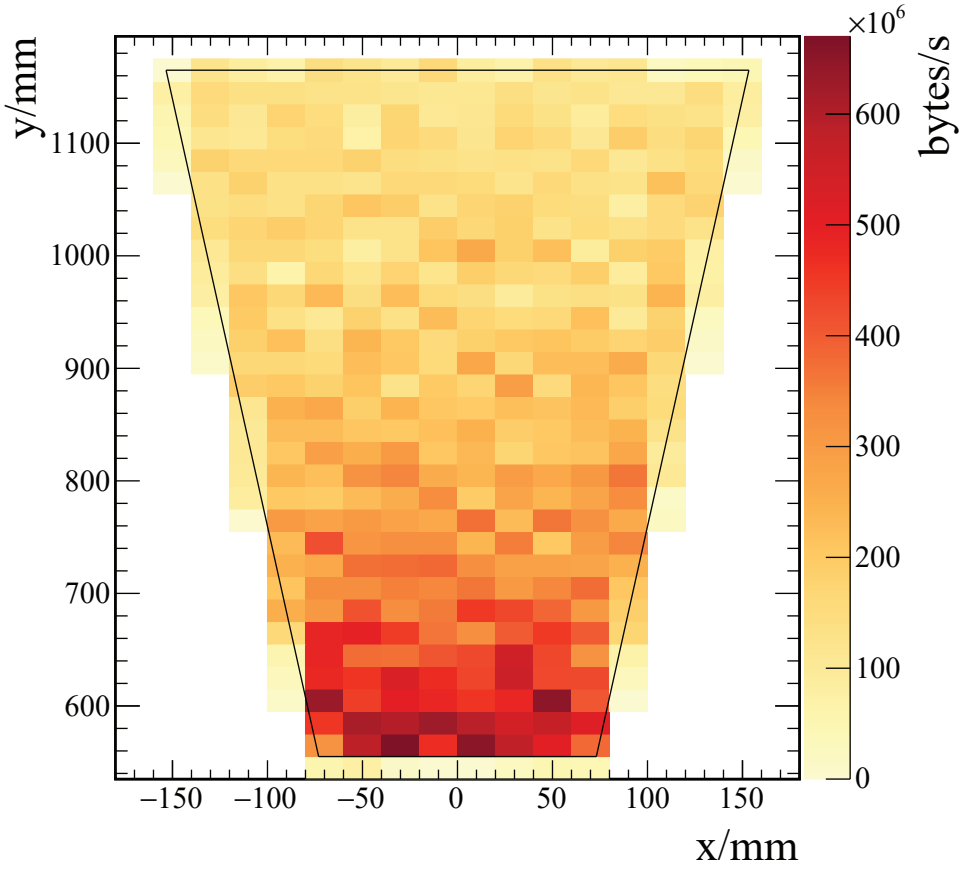
Tracking performance

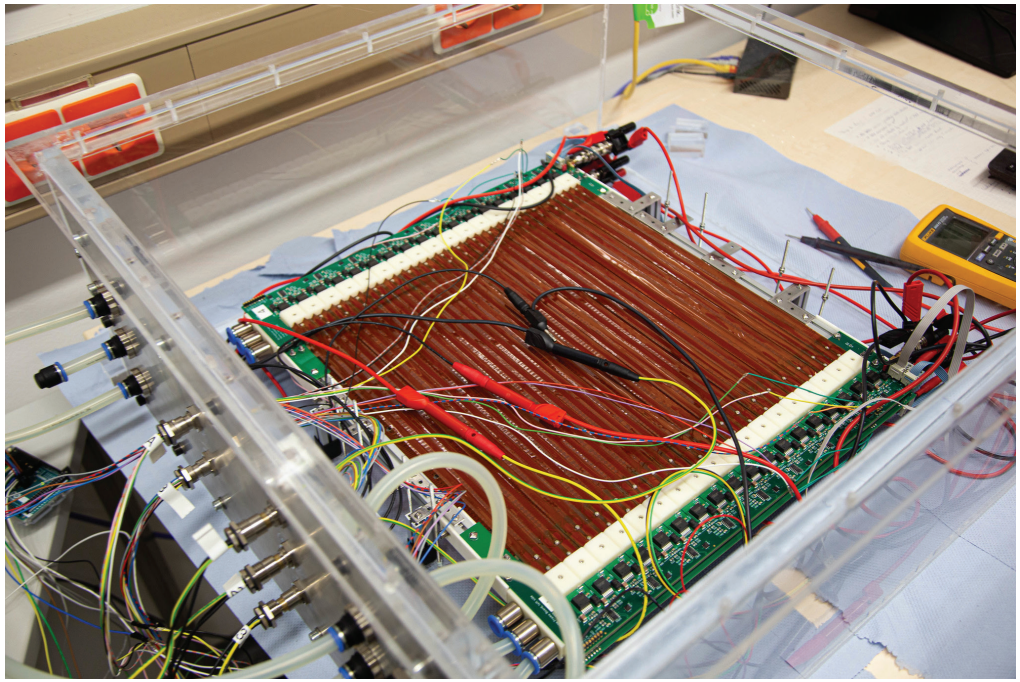
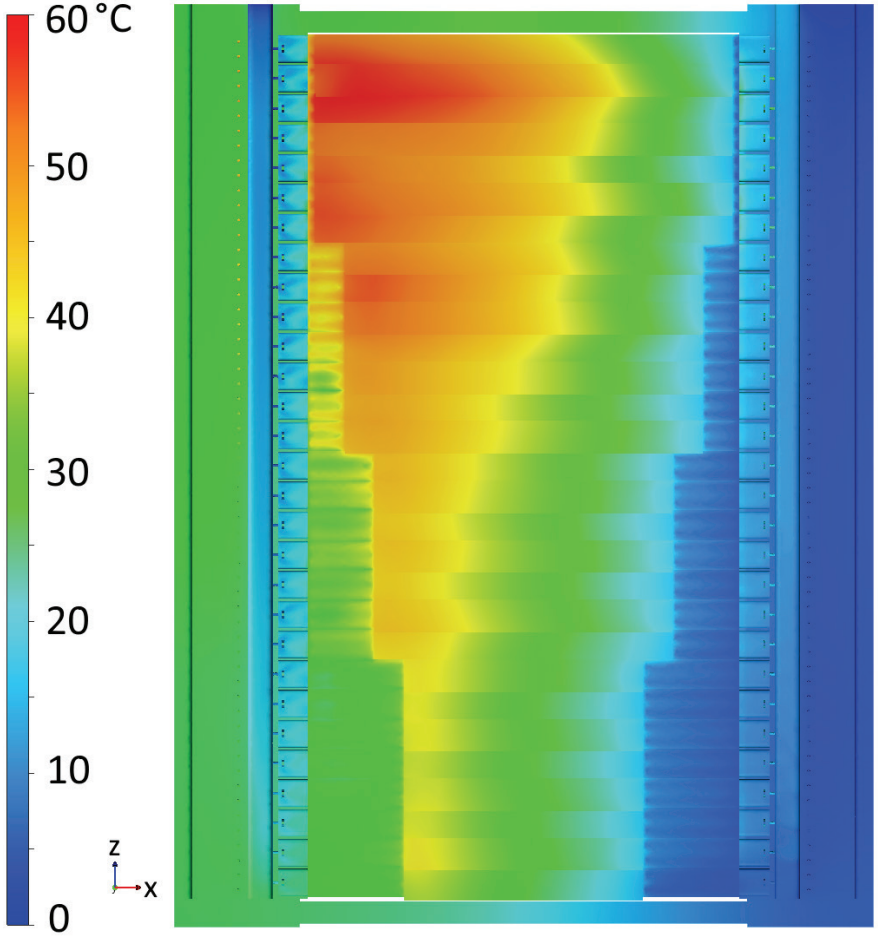




High rates

- We would like the tracker at or close to the nominal rate to study systematics
- We will probably remove the tracker for most of the 11'000 hours of running
- Need to deal with the very high instantaneous rate, but: all electrons are equal
- Gated operation to get a manageable DAQ system



Helium Gas Cooling

- Planning for a helium based gas cooling similar to Mu3e
- Works well in CFD simulation and in thermo-mechanical prototype
- However: Off-detector infrastructure daunting, even with the large helium plant in Mainz - other ideas are very welcome...