A High Precision Determination of the Weak Mixing Angle at Low Momentum Transfer

The P2 Experiment

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Funded by the European Union

European Research Council
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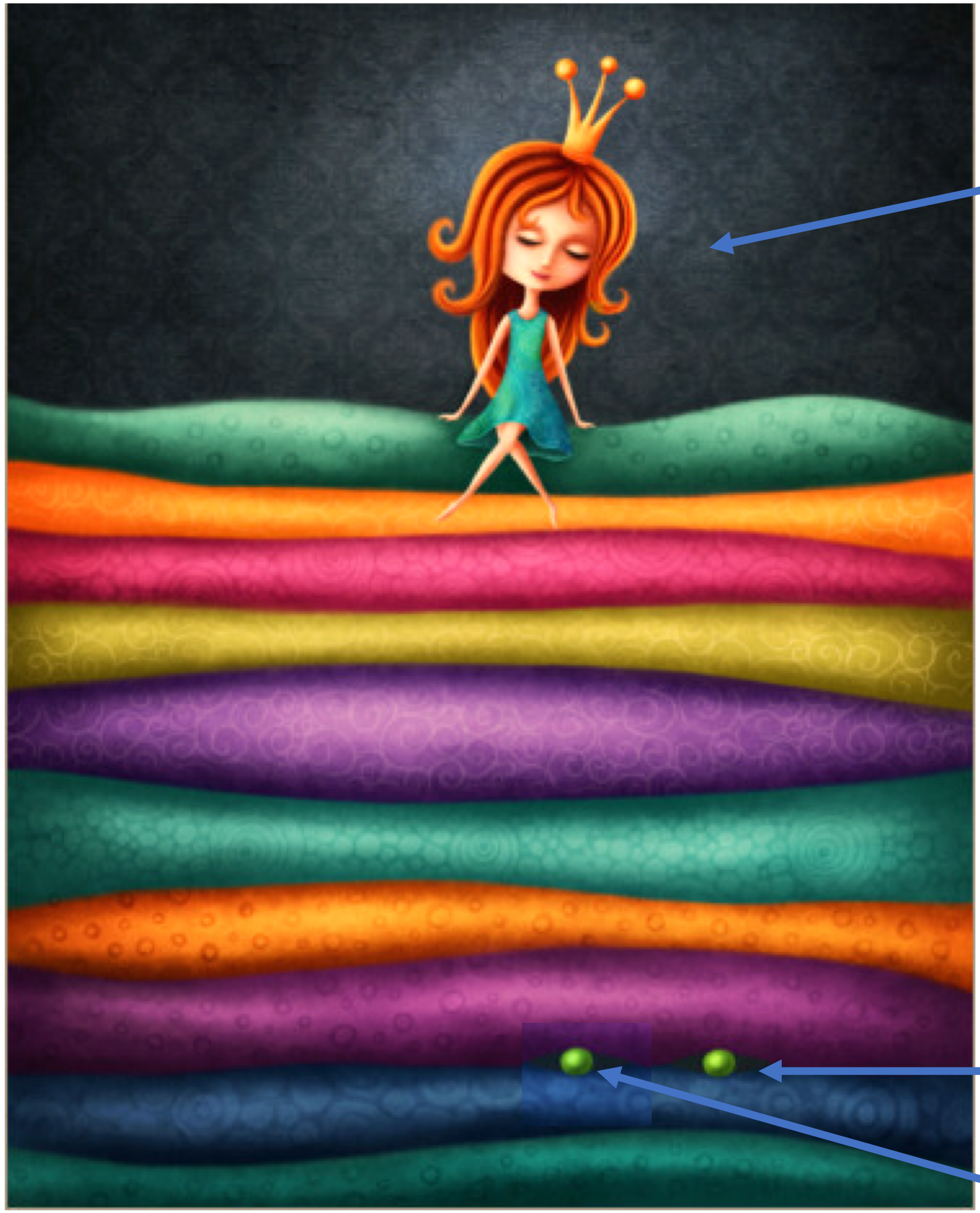
Hans Christian Andersen: “Physics Beyond the Standard Model"



Detector

Nature

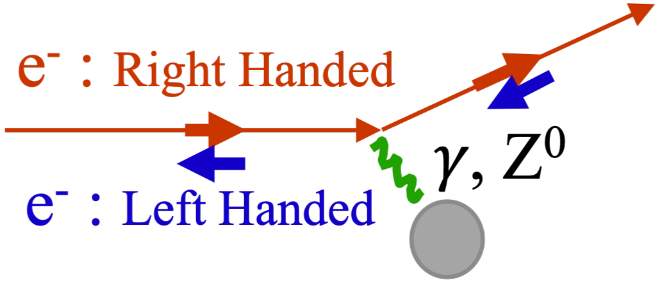
Weak Interaction

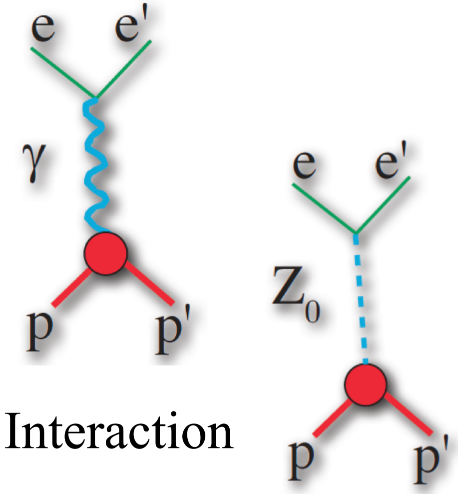
New Interaction or particles (BSM)

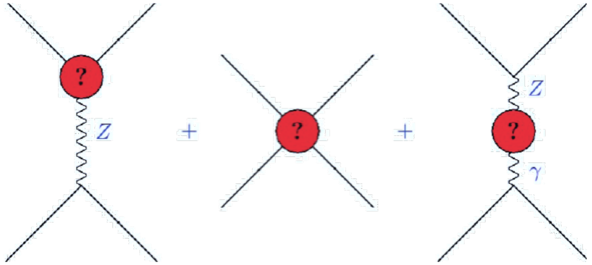
The Princess and the Pea

P2 Goal:

- Hit fixed protons with R&L electrons – measure difference in scattering rates
- Measure $\mathbf{Q_W^p}$ and the weak mixing angle $\mathbf{\sin^2(\theta_W)}$ and to extremely high precision

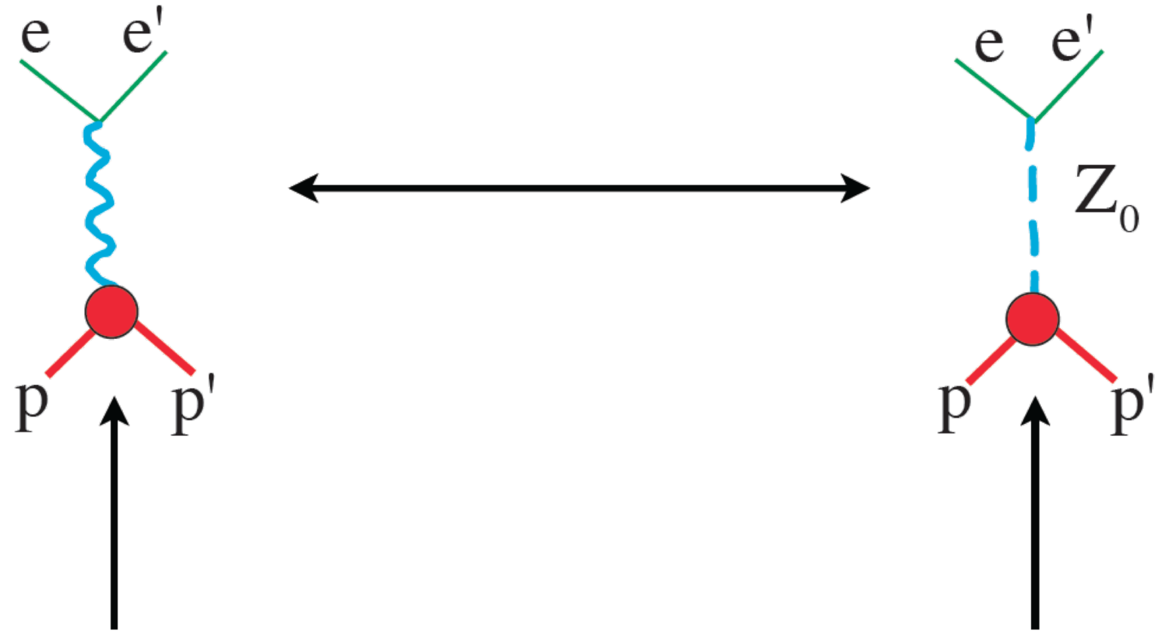






The role of the weak mixing angle

The relative strength between the weak and electromagnetic interaction is determined by the weak mixing angle: $\sin^2(\theta_W)$



$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 - 4\sin^2\theta_W$
weak charge of the proton

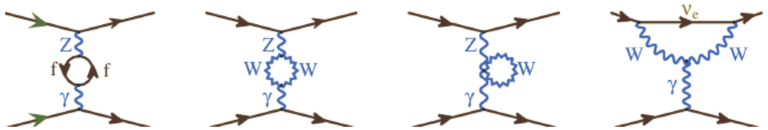
$$Q_W^p = -2(2C_{1u} + C_{1d})$$

$Q_W(n) = -1$

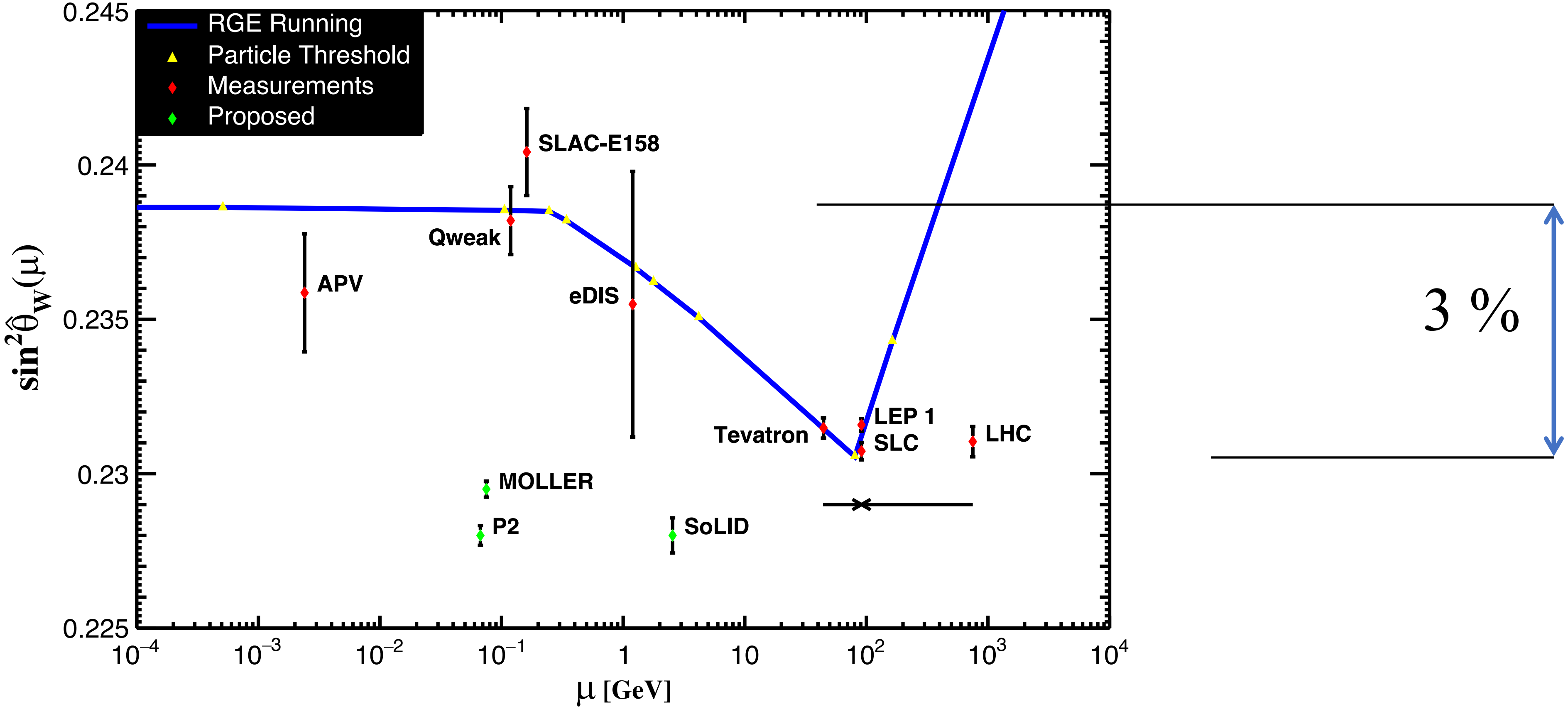
$\sin^2\theta_W$: a central parameter of the standard model accessible through the weak charge

Running of the weak mixing angle

Universal quantum corrections: can be absorbed into a scale dependent, "running" $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$



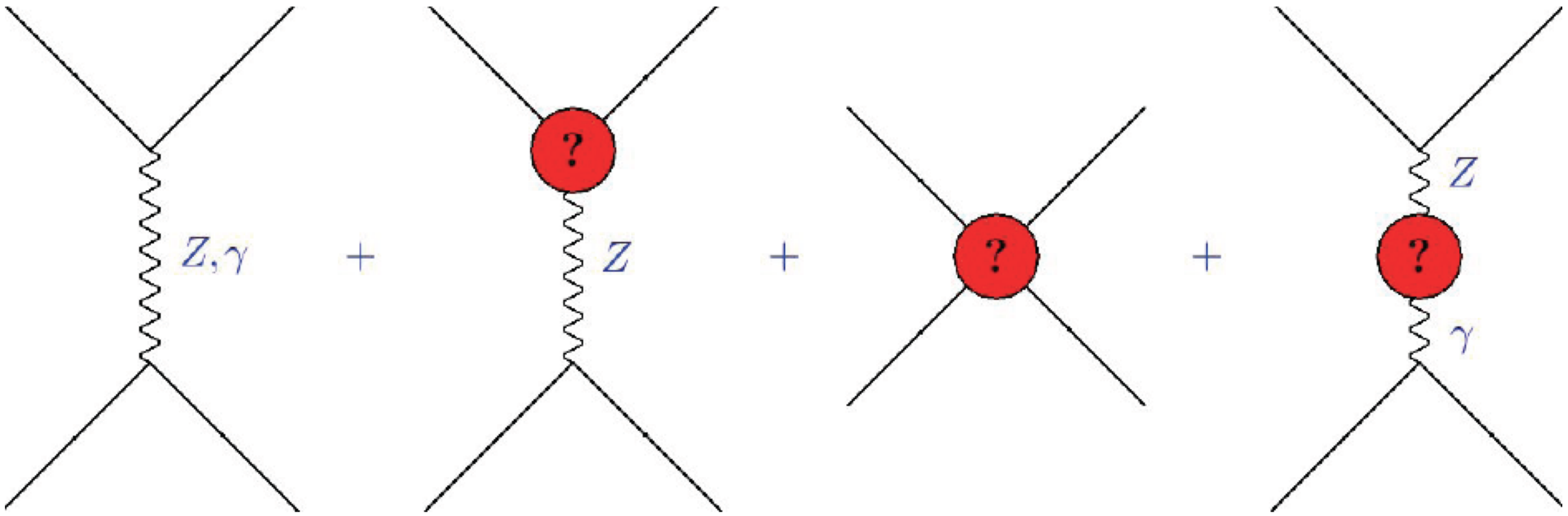
The relationship between Q^p_W and $\sin^2\theta_w$ is modified at the 1-loop level and is dependent on the energy scale at which the experiment is carried out



Ultra High Precision Measurement

Determination of the weak mixing angle with 0.15% accuracy, mass scale 45 TeV

High Precision:
Sensitivity to new physics Beyond the Standard Model



Extra Z

Mixing with Dark photon or Dark Z

Contact interaction EFTs

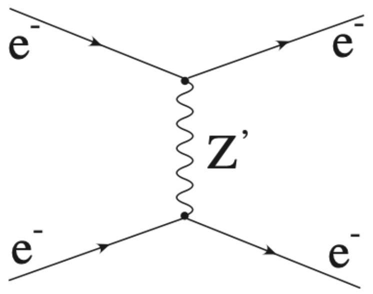
New Fermions

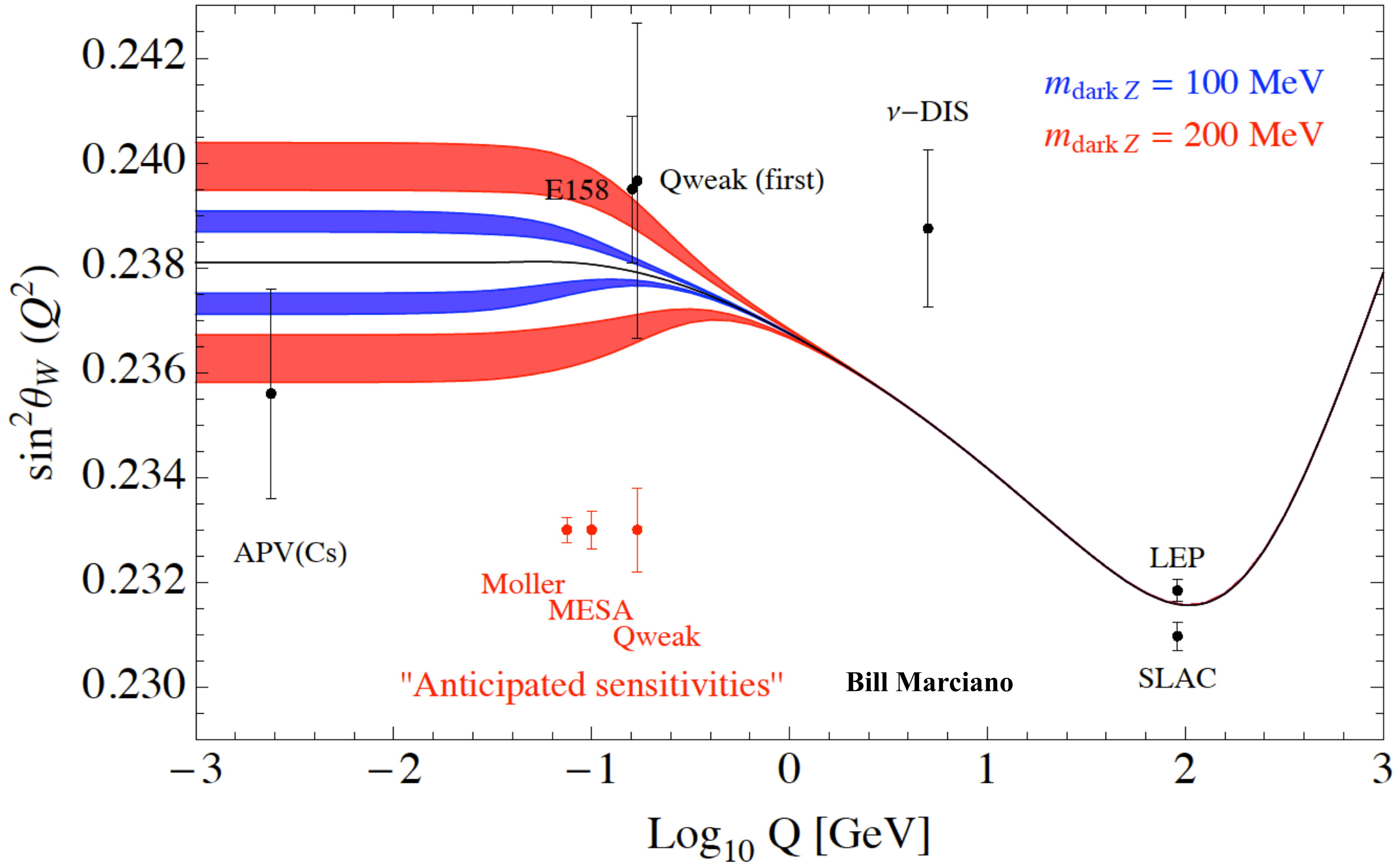
Sensitivity to new physics at a scale from 70 MeV up to 50 TeV

Running $\sin^2\theta_W$ and Dark Parity Violating Z

BSM: The Dark Z

Heavy Photons (A' mixed with Z_0): The Dark Z





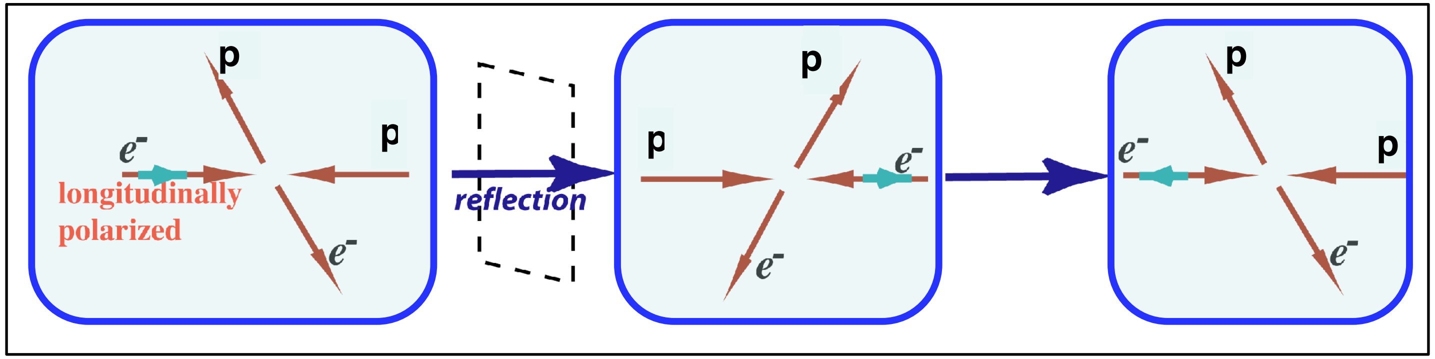
Formulation PVES Experiment

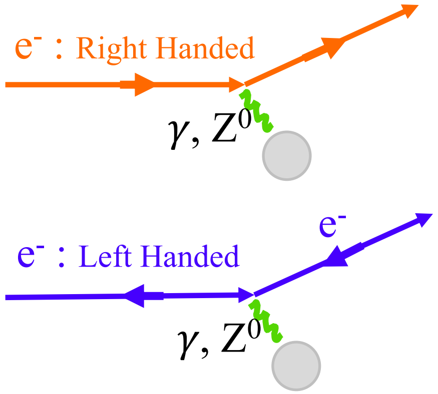
Problem: The weak interaction is weak: $M_{weak} << M_{\gamma}$

Solution: Harness the fact that the weak force is parity violating & spin doesn't reverse under **P**

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p} \rightarrow (-\boldsymbol{r})\times(-\boldsymbol{p}) = \boldsymbol{r} \times \boldsymbol{p} = \boldsymbol{L} \; ! : \boldsymbol{L} \rightarrow \boldsymbol{L}$$

Reverse space + Keep Spin Same = Reverse spin + Keep Space Same



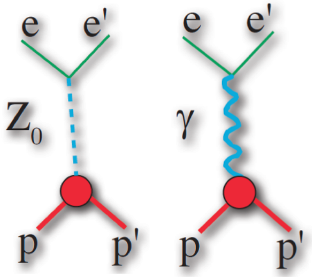


Reverse Spin and measure rate asymmetry

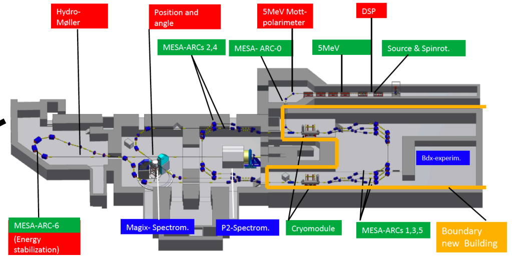
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\sigma \propto |M_{\gamma} + M_{weak}|^2 \sim |M_{\gamma}|^2 + 2M_{\gamma}(M_{weak})^* + \ldots$$

Interference between electromagnetic and weak neutral current amplitudes gives rise Parity violating asymmetry

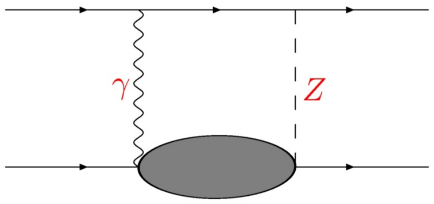


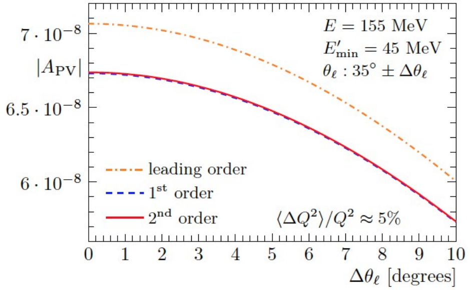
P2: Parity violating electron proton scattering at MESA/Mainz



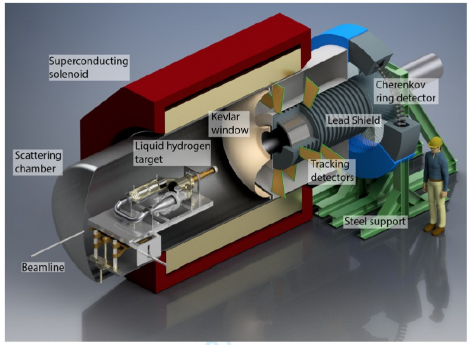
$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p)-\sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p)+\sigma(\overleftarrow{e}p)} = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right) + A_F$$

False asymmetries: control of target and accelerator



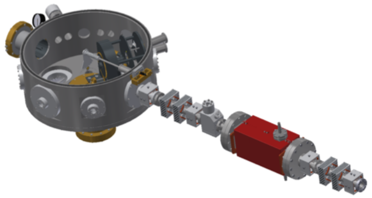


Cross section asymmetry A_{LR}^{exp}

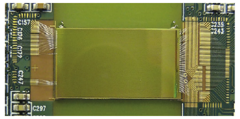


Magnetic spectrometer
Cherenkov detector
Read-out electronics
Data acquisition

Beam polarisation P
Polarimetry



Momentum transfer $< Q^2 >$
Tracking system



Low Beam Energy, Low Q^2 Theory:
QED corrections
EW corrections (two loop)
Hadron structure $F(Q^2)$ Form factor,
Strangeness form factors
Measure:
Axial form factor

A_{ep}=-28 ppb +- ΔA_{ep}= 0.5 (1.8 %) After 11,000 h
$\Delta \sin^2\theta_W/\sin^2\theta_W$= 0.15 %

Accessing Q_W^p with PVES

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A^p$$

Forward angle — Backward angle

$$Q_{weak}^p = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

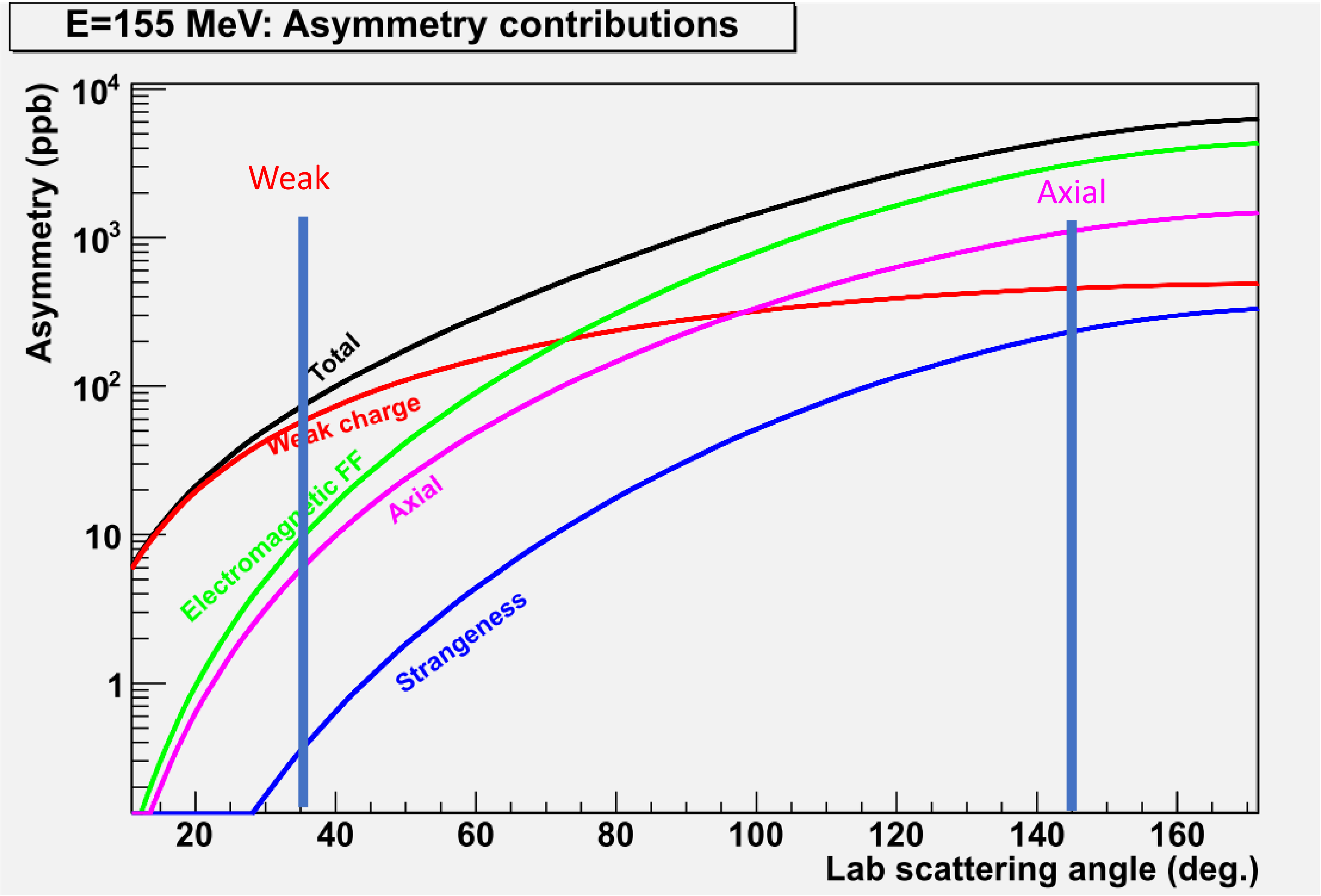
low Q^2, proton structure is small

$$A_{PV} = -\frac{Q^2 G_F}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 B(\theta, Q^2)\right]$$

- E_{beam} = 155 MeV, 25-45°
- Q^2 = 0.0045 GeV^2
- 60 cm target, 150 uA, 10^4 hours
- A_{ep}=-28 ppb +- ΔA_{ep}= 0.5 (1.8 %) After 11,000 h
- $\Delta\sin^2\theta_W/\sin^2\theta_W$= 0.15 %

EM FF data plus PVES
Strange quark studies
constrain B well at low Q^2

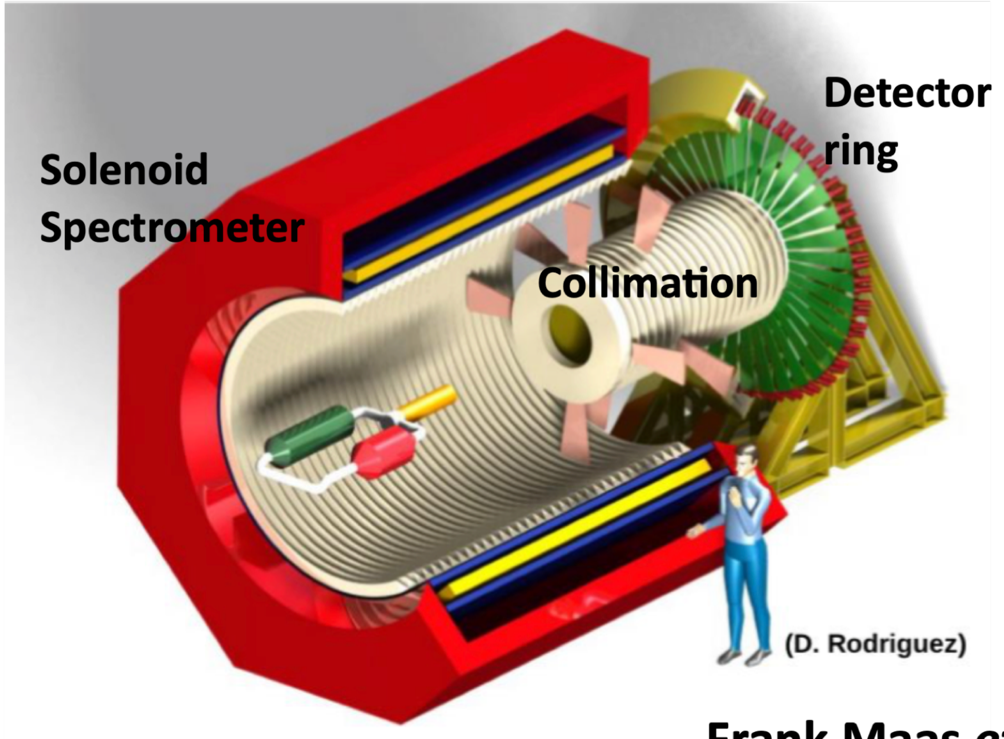
Optimization of PV Asymmetry measurement

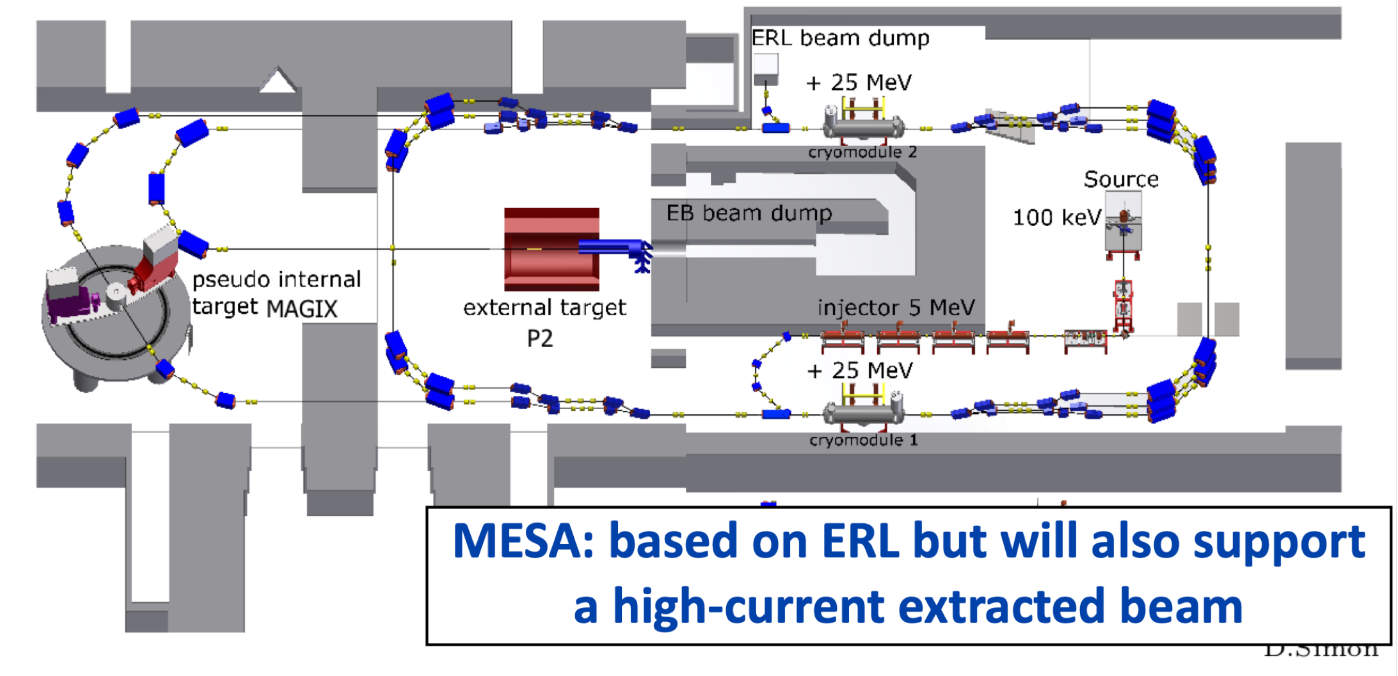


Kinematics: Low Q^2
FF, Axial, Strangeness Suppressed

Aux. measurem. backward angle

P2 at MESA / Mainz





MESA: based on ERL but will also support a high-current extracted beam

Frank Maas *et al.*, arXiv:1802.04759

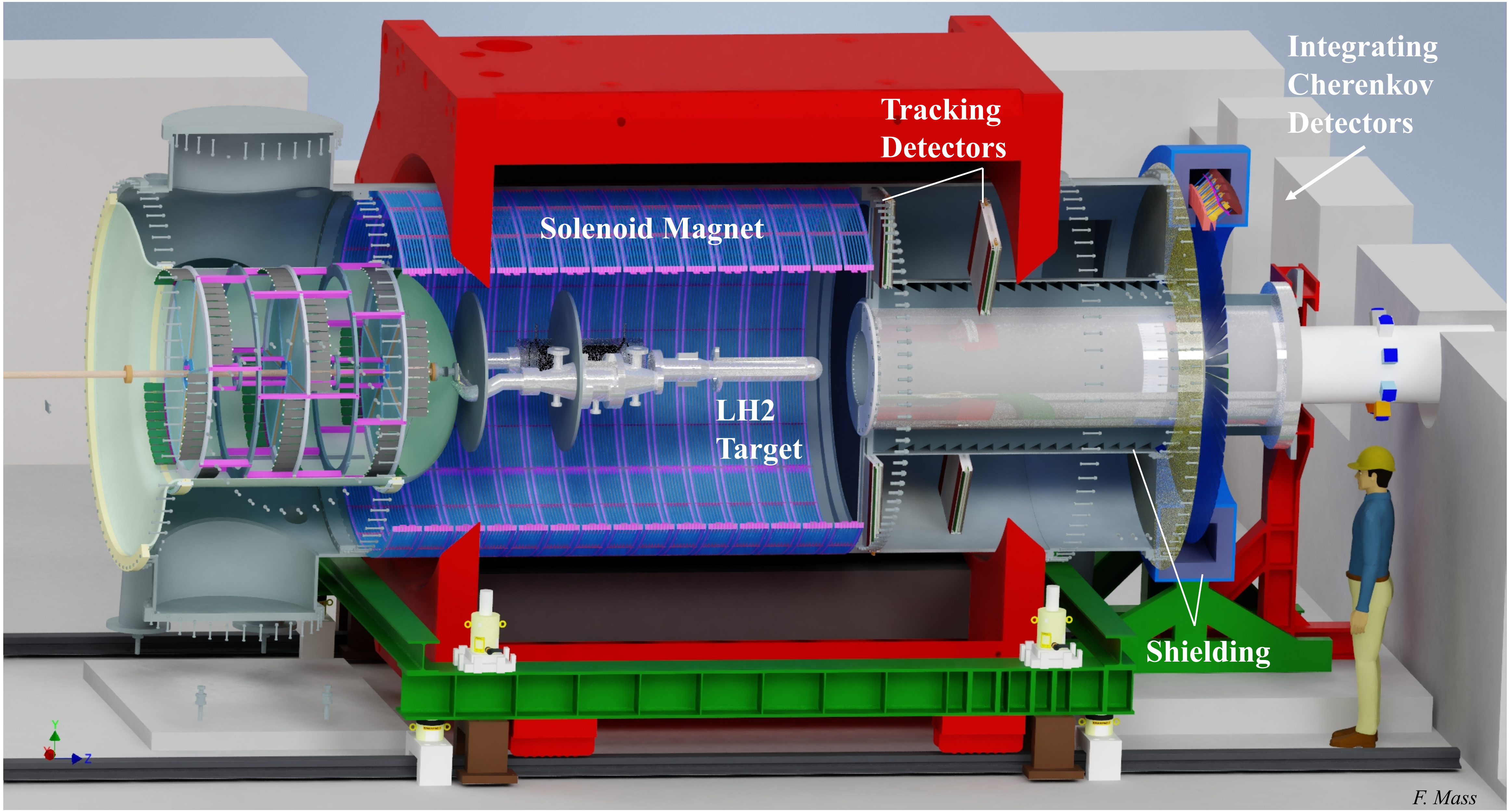
- E_{beam} = 155 MeV, 25-45°
- Q^2 = 0.0045 GeV^2
- 60 cm target, 150 uA, 10^4 hours

- A_{ep}=-28 ppb +- ΔA_{ep}= 0.5 (1.8 %) After 11,000 h
- $\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.15 %

3.3x more precise than Qweak, similar to best collider measurements
Mass scales up to 45 TeV

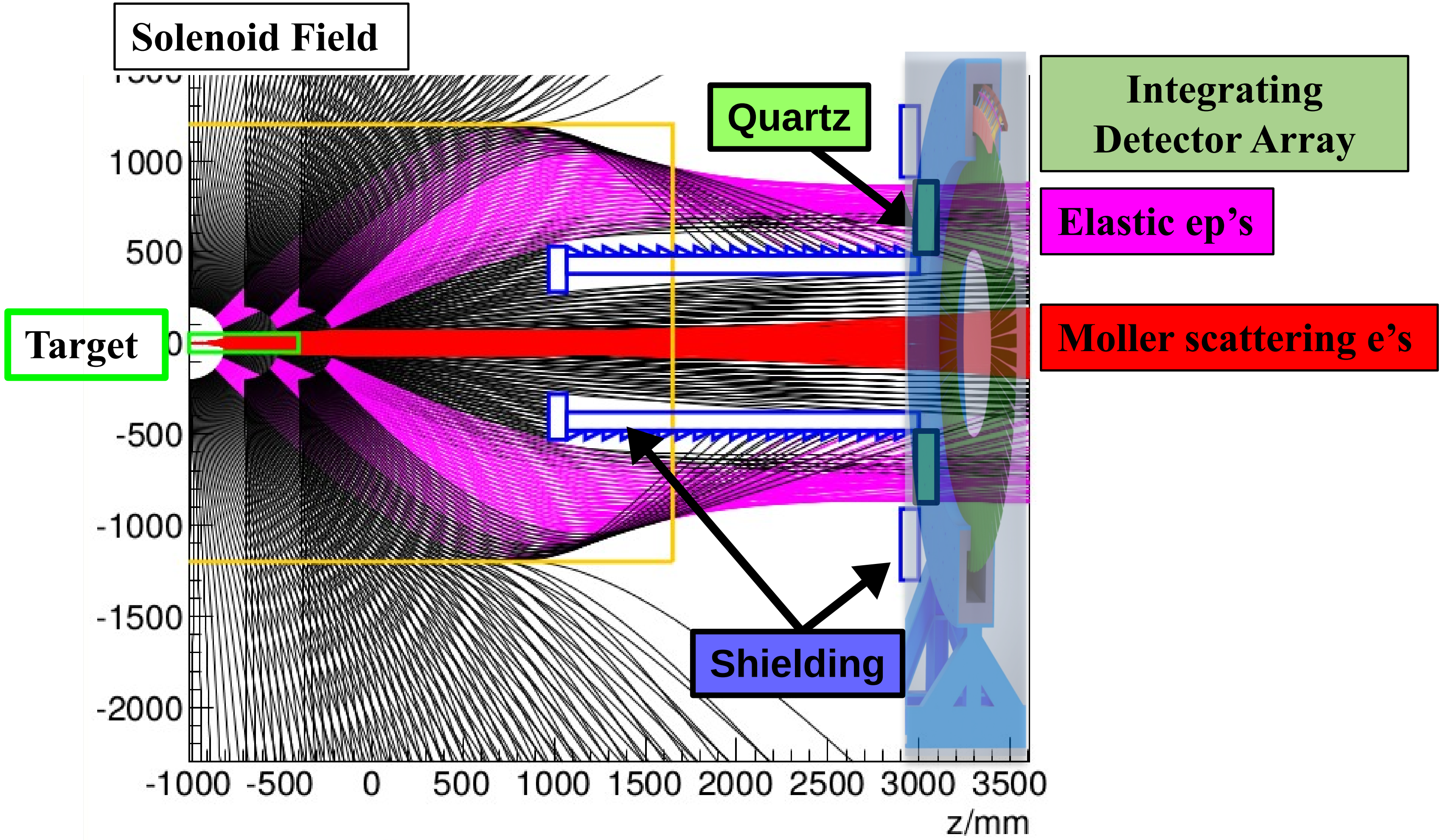
- MESA facility tailored to the experimental program

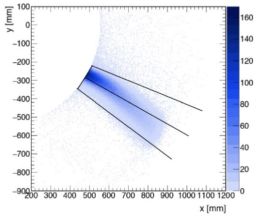
- P2 Start Commissioning in 2026

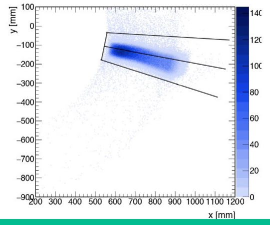


Main components of P2 presently constructed in industry and assembled at MESA

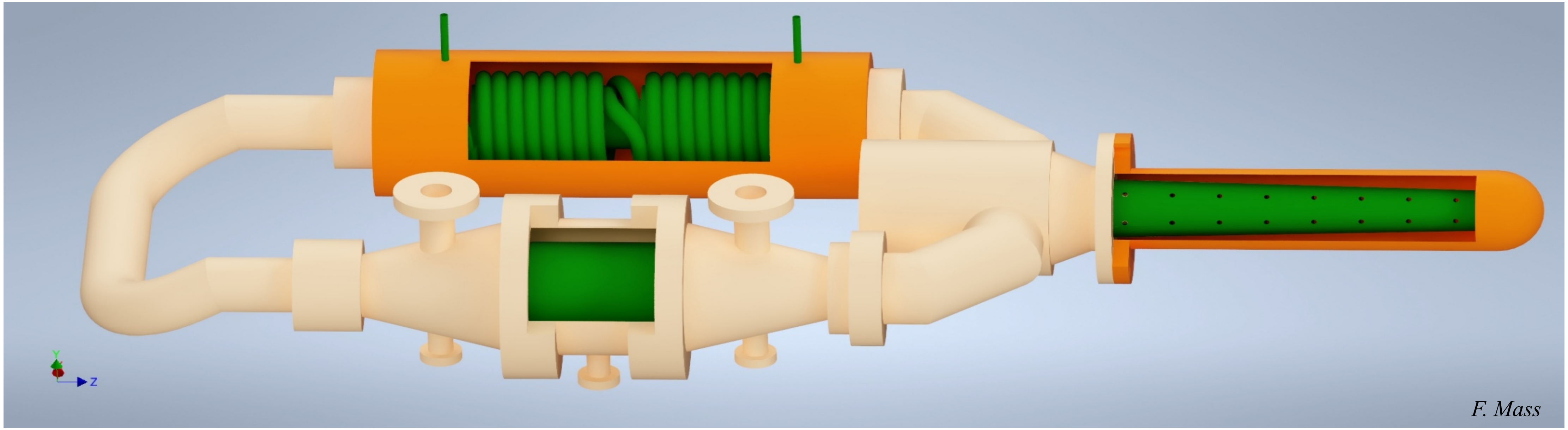
P2-experimental principle





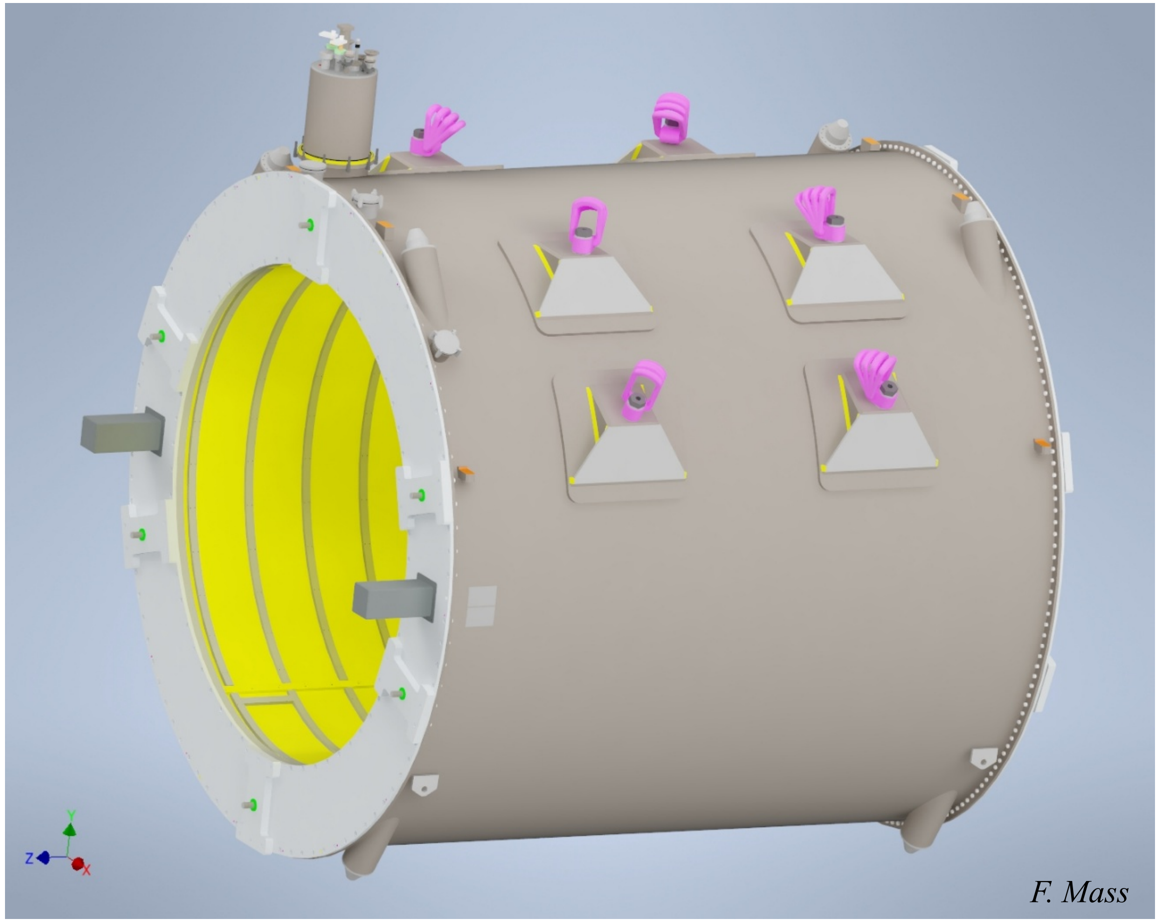


High Power Liquid H_2 Target



- 60 cm beam interacting zone
- Operating temperature < 20 K
- Coolant gasous He at ~ 10 K
- Required cooling power up to 4000W
- High, turbulant flow

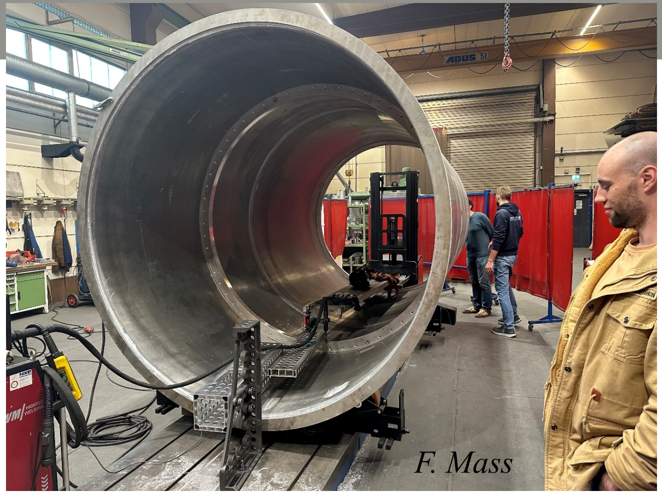
Super Conducting Magnet



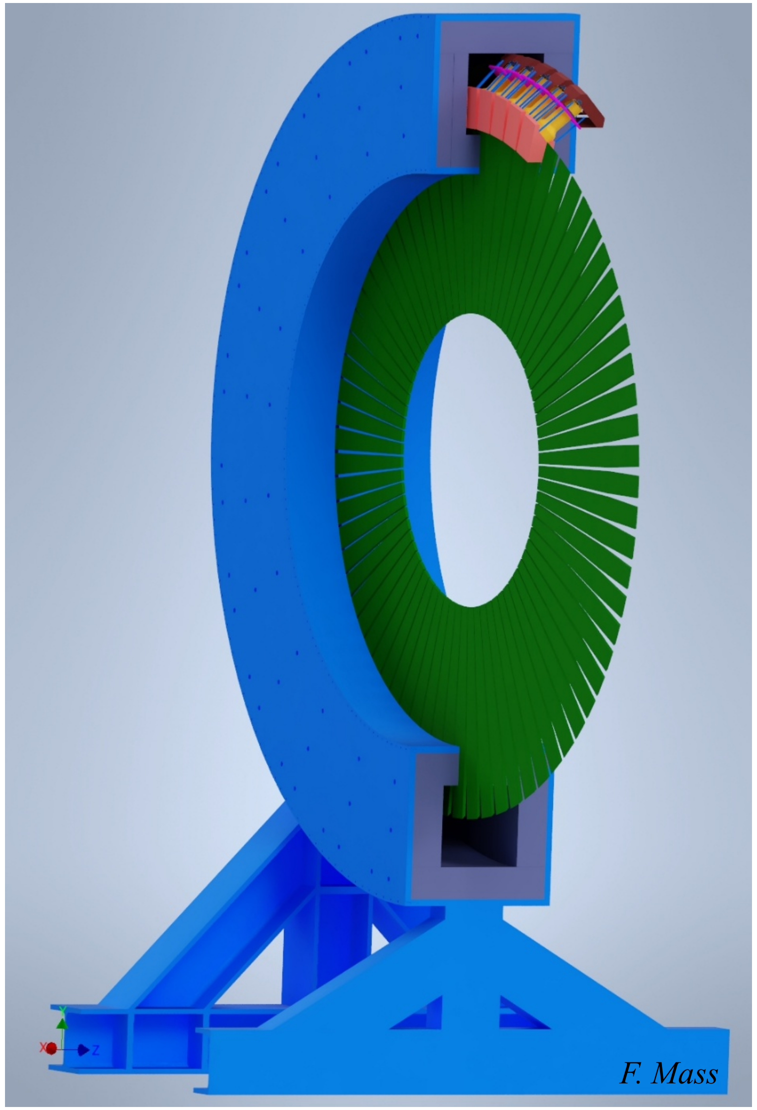
- Superconducting Magnet (NbTi)
- FOPI yoke
- Operating Temperature < 6K
- B-field of 0.6T at 640 A
- Maximum field of 0.7 T
- Power consumption of 2800 W (4V and 700 A)
- Quench protection

- Outer Diameter 3.3m
- Inner Diameter 2.4 m

Central Scattering Chamber



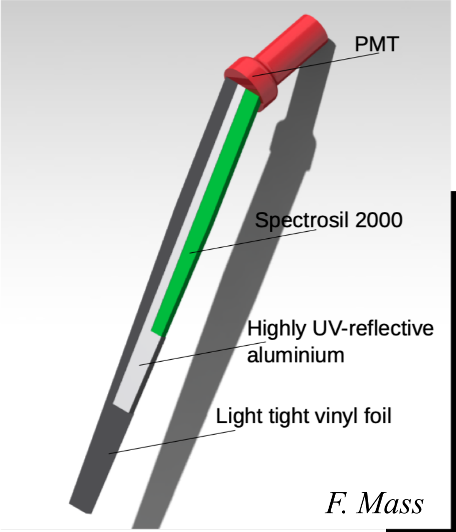
Fused Silica Cherenkov Detector

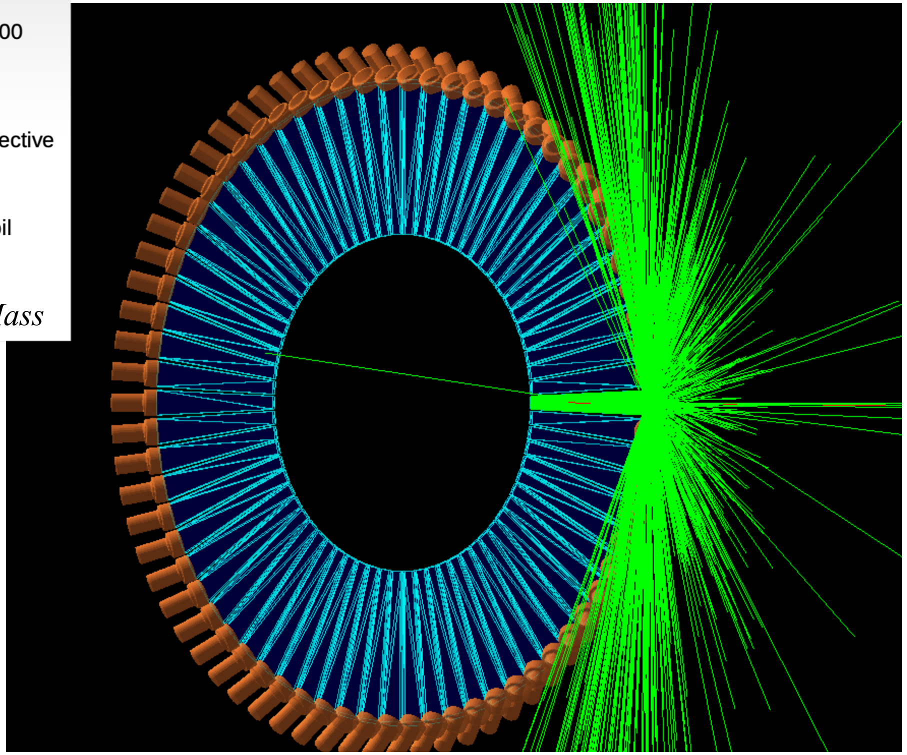


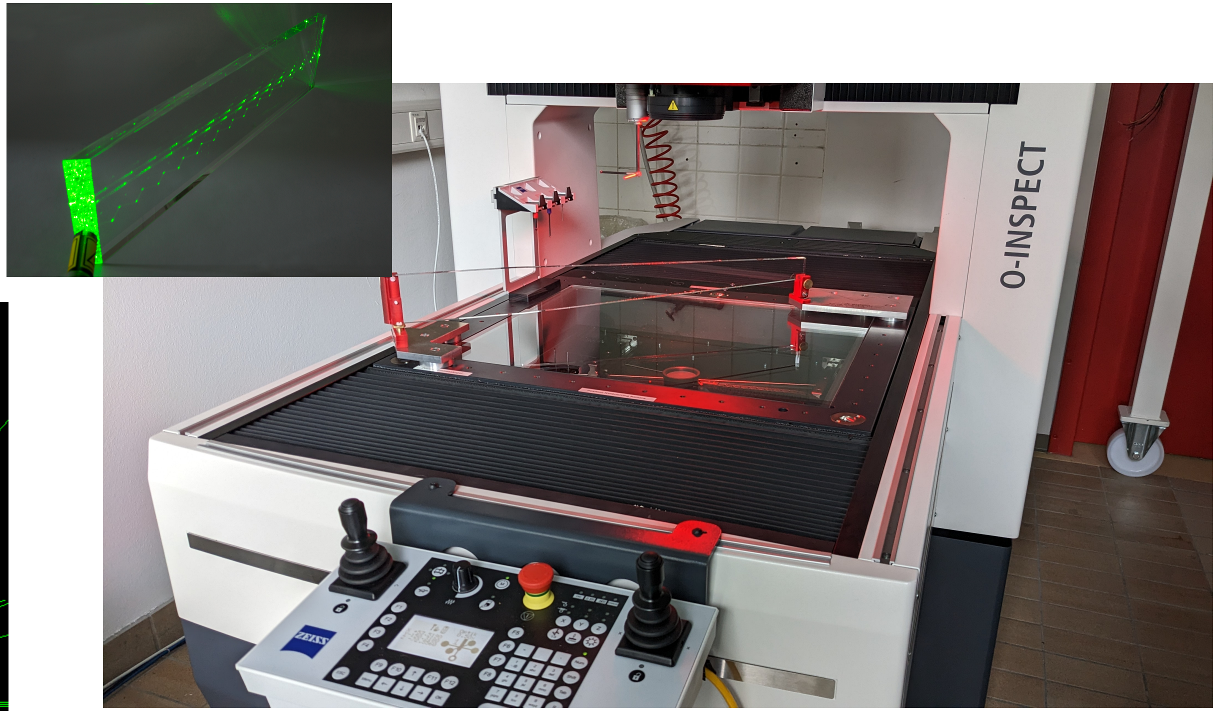
- Detector ring consists of 72 wedged fused silica bars
- Cover angle range of 25° to 45°
- Hit rate 10^{11} Hz
    - Integrating measurement
- Single event detection
    - Q^2 measurement
    - Special PMT base developed
- Collaboration with Manitoba
- All PMTs are delivered and characterisation ongoing
- All fused silica bars delivered and measured

Quartz glass detector concept

- Cherenkov detector ring consisting of **72 fused silica bars**
- Covering **full azimuth 25° - 45° polar angle**
- **Integrating detector**



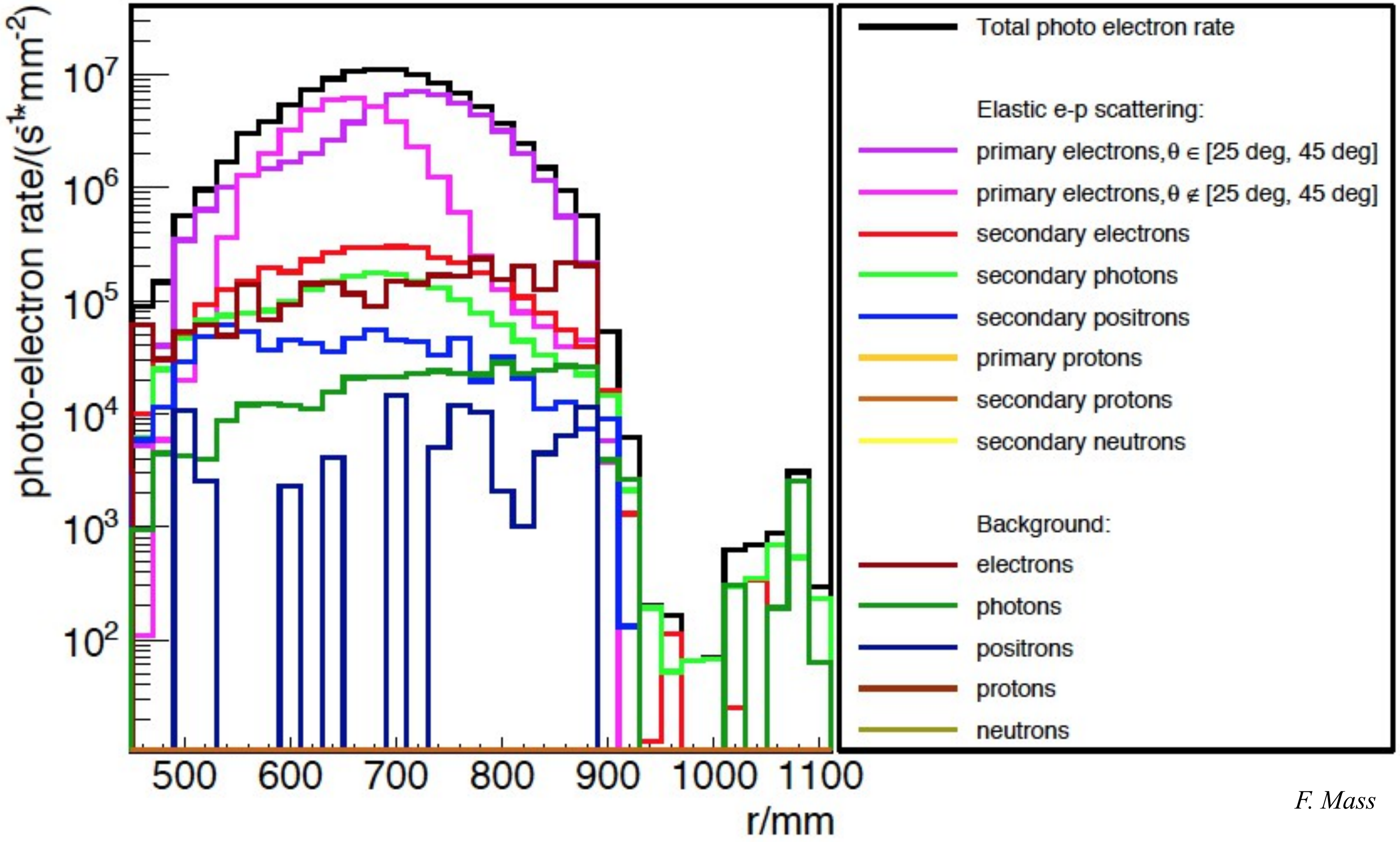


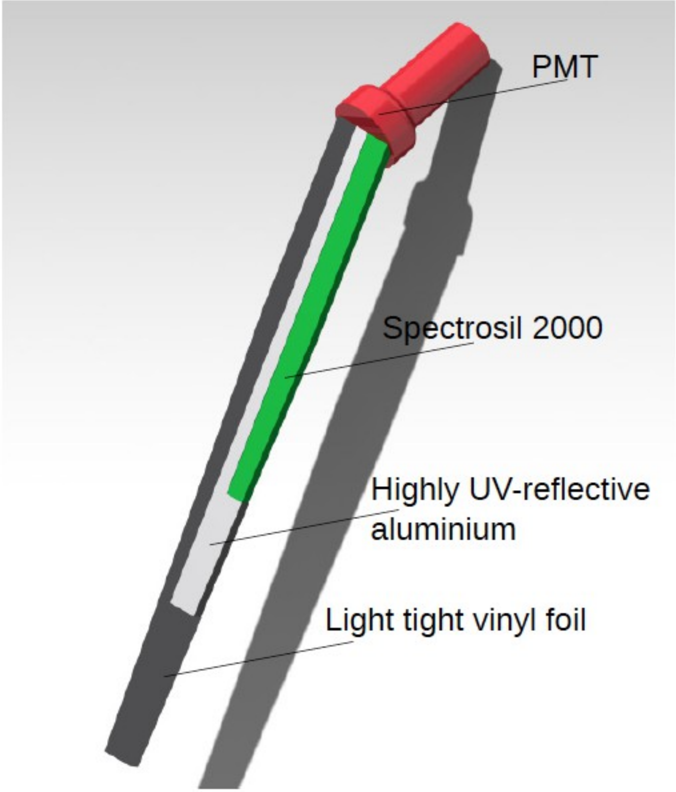


- Extended experimental study
- Quartz glass, PMTs, reflector
- Radiation hardness

P2-Detector response

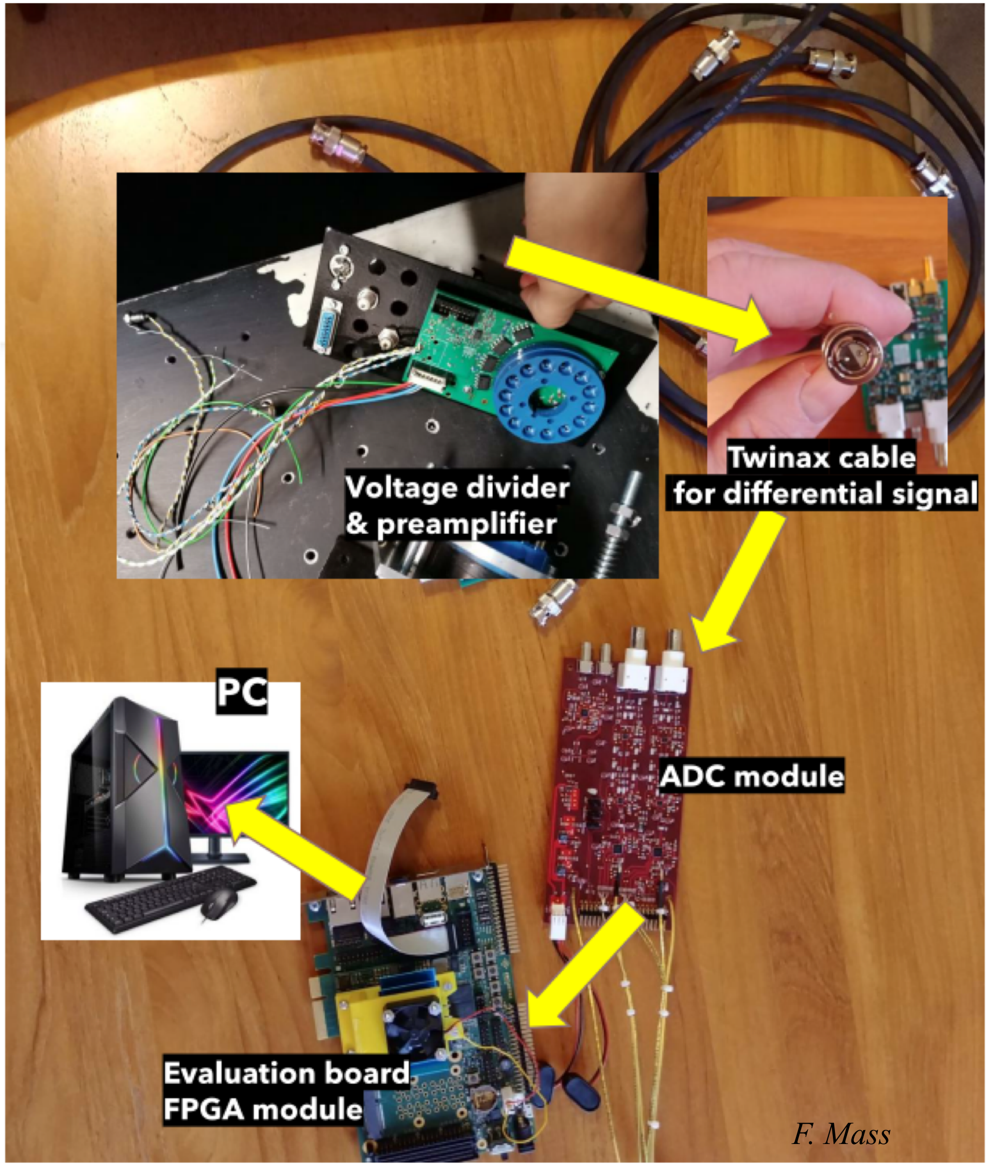
Full GEANT4 simulation





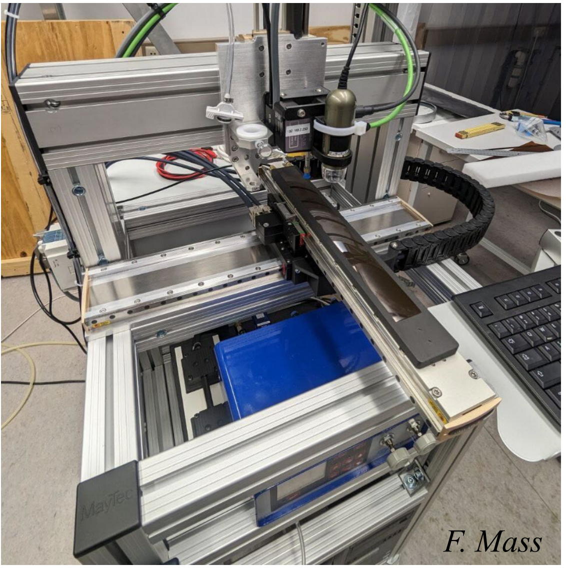
F. Mass

Integrating Mode Readout System

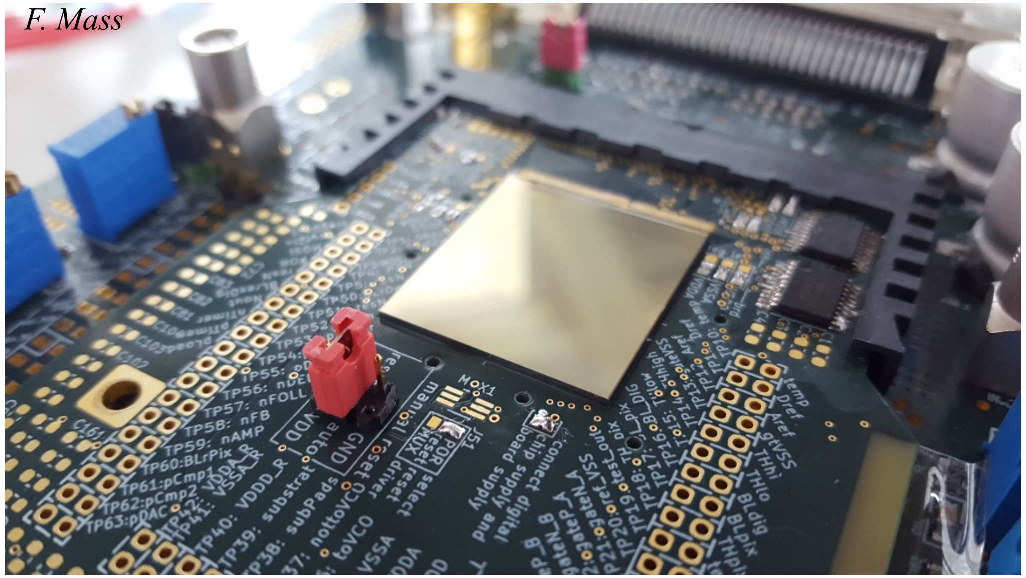


- Voltage divider & preamp
- Twinax cable for differential signal
- ADC module
- Evaluation board – FPGA module
- Sampling ADC developed by U. Manitoba and TRIUMF (Michael Gericke)
- 16 channel prototype for tests in Mainz

μPIX Tracking Detector



Assembling robot



MuPix10 sensor

Tracking Calibration

$\langle A(Q^2) \rangle$ is measured

$A(\langle Q^2 \rangle)$ is reported

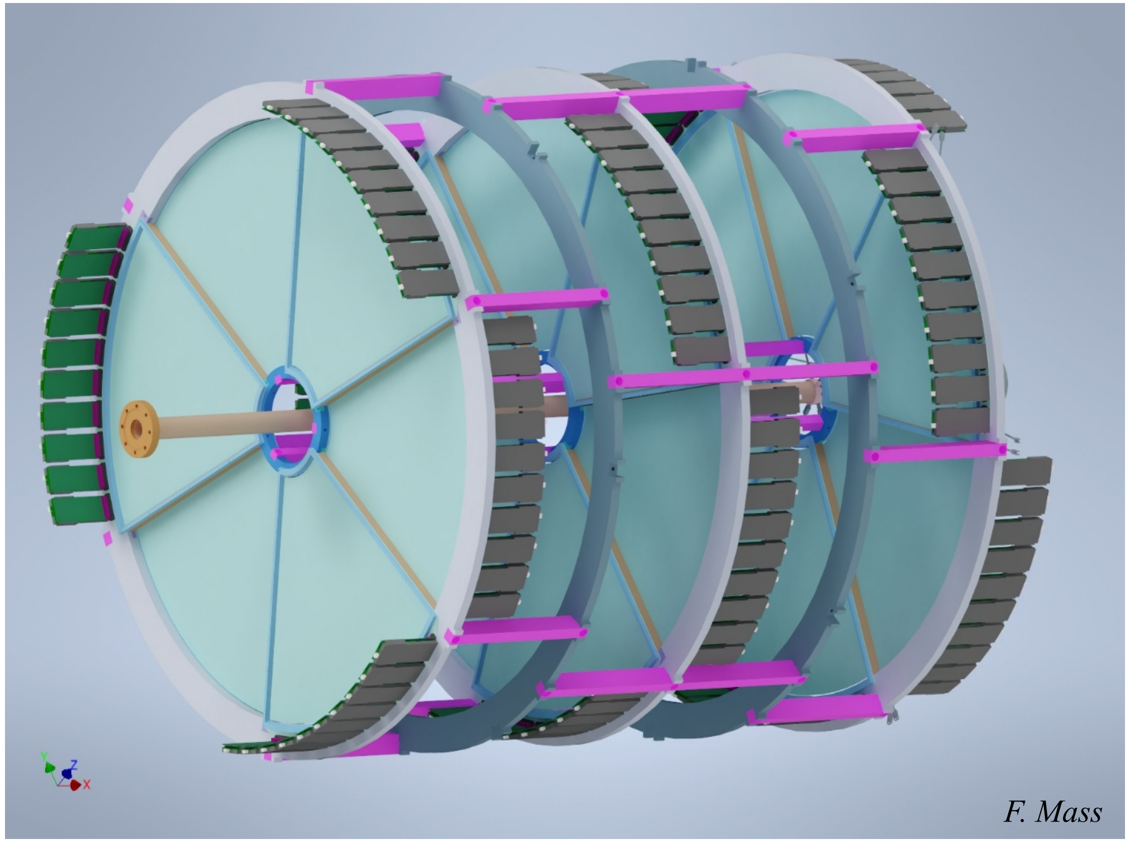
Simulation (using survey, field map) estimates the Q^2 distribution.

Spatial distributions are verified against tracking distributions

μPIX Tracking Forward Detector

- High resolution tracking for Q^2 measurement
- Covers at least one fused silica detector
- 4 segments with 2 double layer detectors
- 50 μm HV-MAPS sensors
- Resolution for track momentum ~ 2 MeV/c

Backward Tracking Detector



- Use 3 planes of Micromegas detectors
- Position measurement with detector
  - Determine momentum and vertex

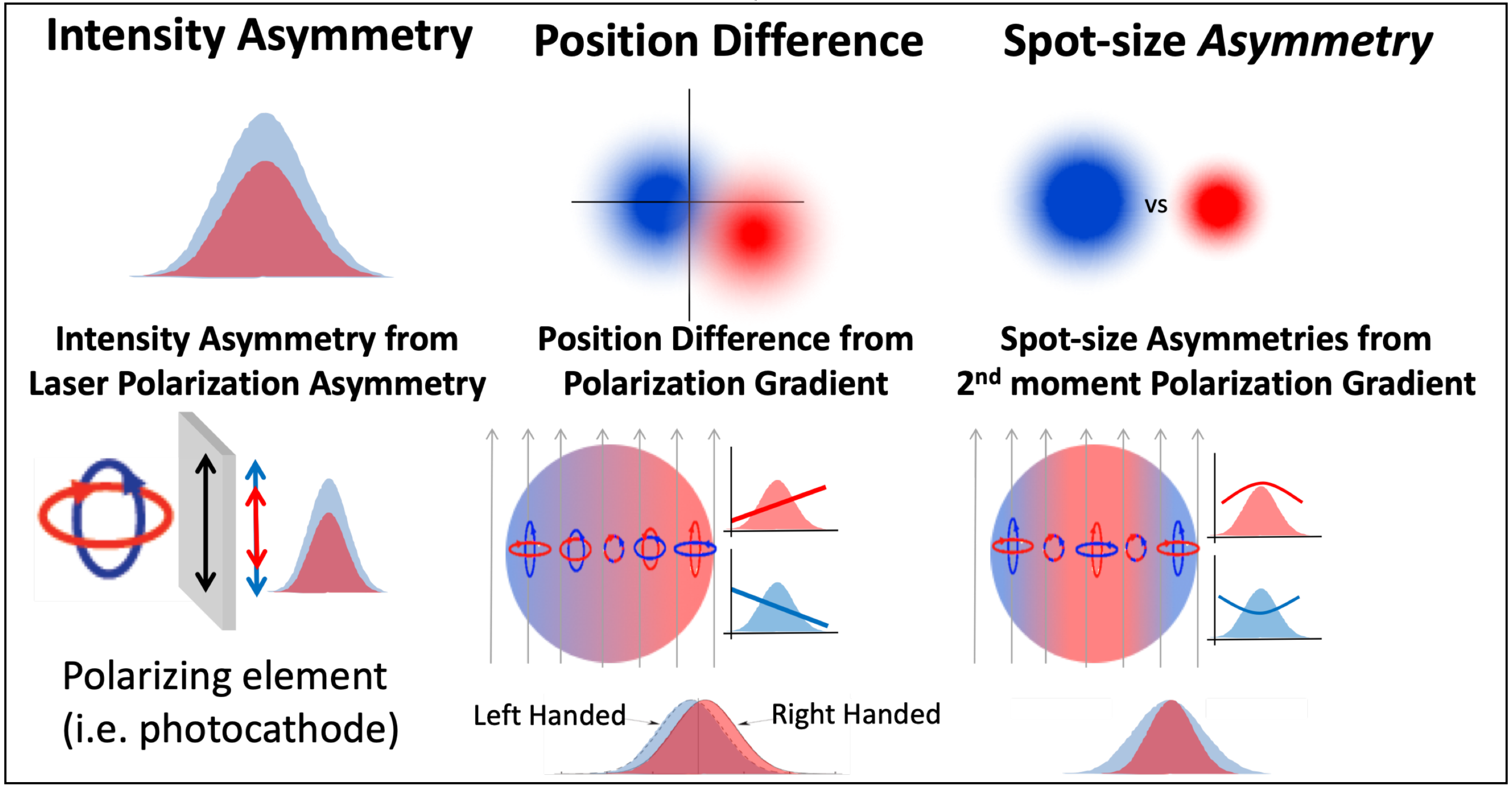
- 18 detector modules with 1280 channels each
- Cooperation with CEA Saclay

Physical Experiment: Systematics

"Never change more than one thing at a time"

Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

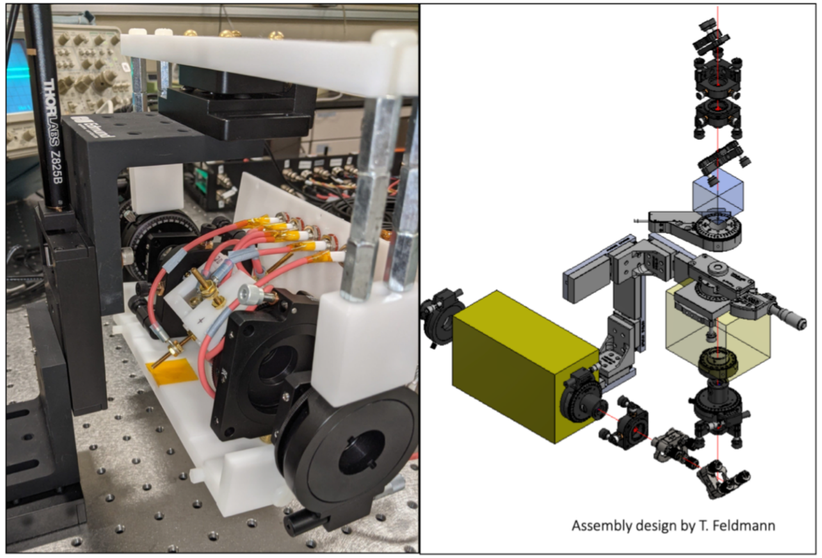


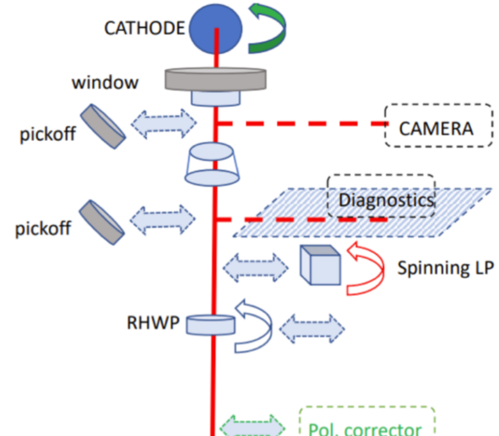
Beam Asymmetries Goals

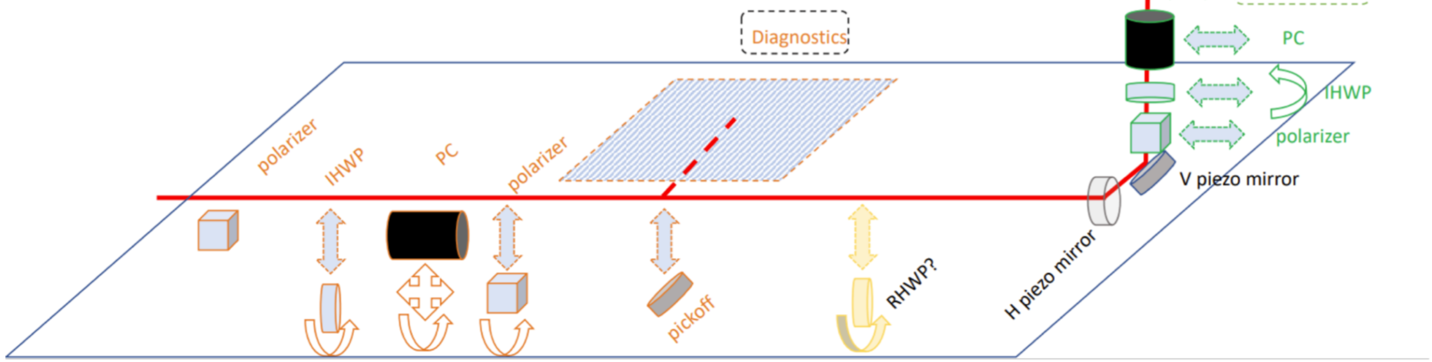
$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p)-\sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p)+\sigma(\overleftarrow{e}p)} = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right) + A_F$$

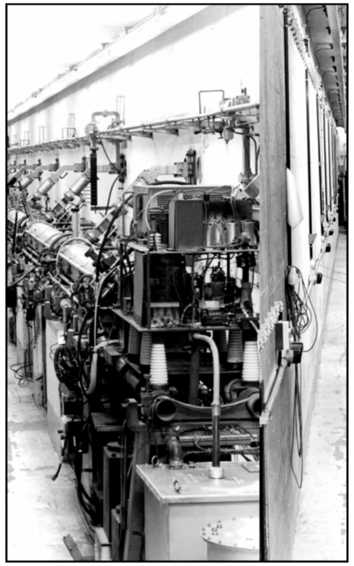
False asymmetries: control of target and accelerator

Indiana U. Pockels cell for MESA:



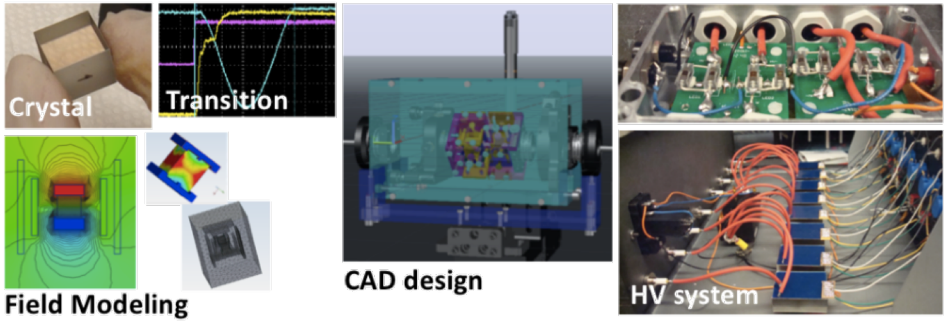






HCBA	A_F =10% A_{phys} =2.4 ppb
ΔE	0.2 eV
Δx	1.35 nm
Δy	1.35 nm
$\Delta\theta x$	0.76 nrad
$\Delta\theta y$	0.76 nrad

- RTP cell, 8HV system, position difference control via E-field gradients



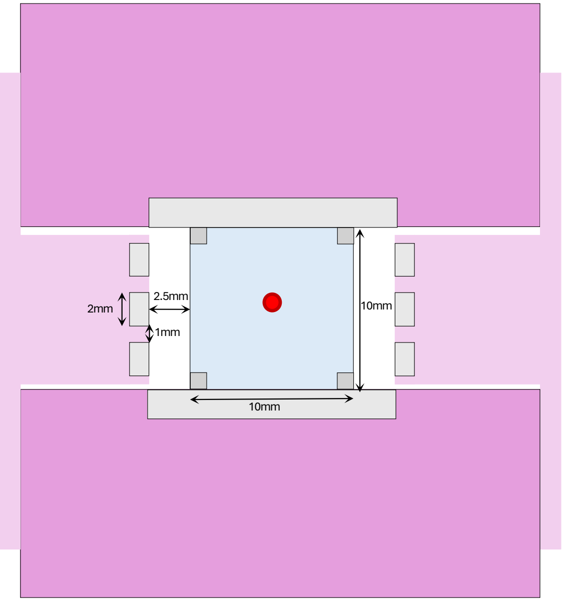
MESA Source for P2

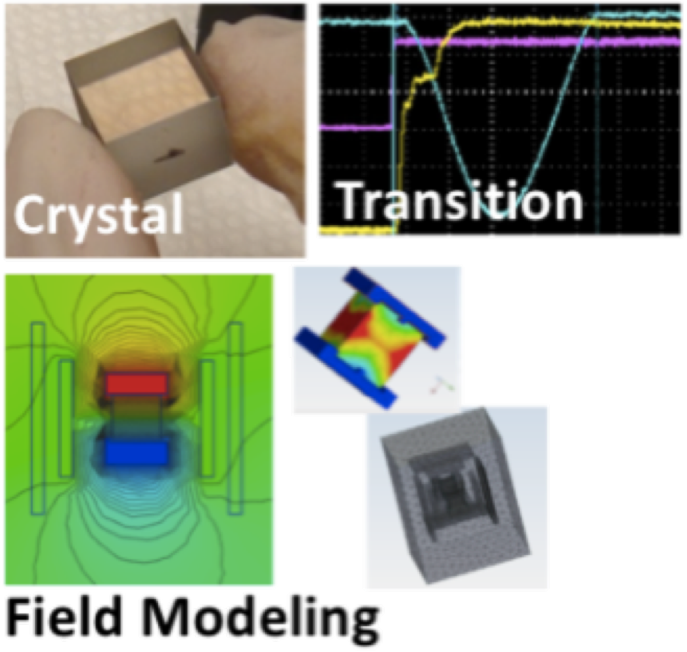
$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p)-\sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p)+\sigma(\overleftarrow{e}p)} = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right) + A_F \longleftarrow$$

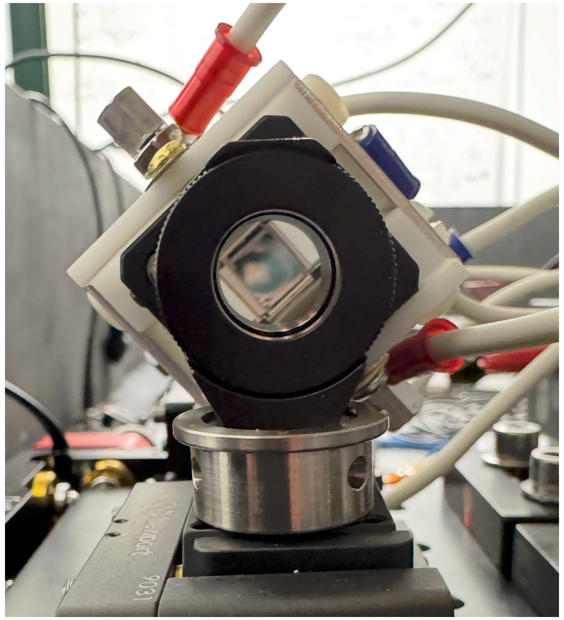
False asymmetries: control of target and accelerator

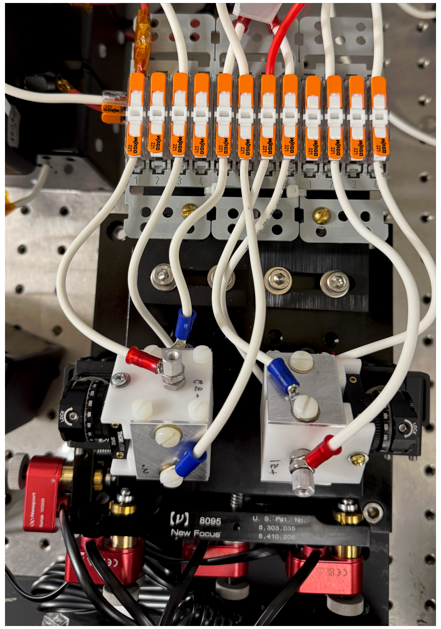
In development:

- 16HV system – vertically mounted
- +Spot size asymmetry control
- With 3-side panels control E-field 1st and 2nd moments









P2 parity violation experiments at Mainz: program

Strategic series of measurements from large asymmetries to ultimate precision

Much more physics from P2 program: Neutron Skin in heavy nuclei, weak charge in light nuclei

Electron spin longitudinal (PVES)
- Weak vector charge of the proton
- Weak axial form factor of the proton
- Weak vector charge of the neutron (Carbon)
- Neutron Skin of Ca and Lead (MREX)

P2@MESA Hydrogen	**P2@MESA Carbon**	**P2@MESA Calcium,Lead [MREX]**
$\Delta\sin^2\theta_W/\sin^2\theta_W = 0.15\ \%$	$\Delta\sin^2\theta_W/\sin^2\theta_W = 0.6\ \%\ (0.3\%)$	will improve the neutron skin thickness by a factor of two
Aux. measurem. backward angle	Aux. measurem. backward angle	In addition measurements of transverse asymmetries

Electron Spin transverse
- Two photon exchange amplitude in elastic electron proton scattering
- Two photon exchange amplitude in electron nucleus scattering

Summary

- Parity violating electron scattering:
  "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC with a sensitivity to new physics up to 50 TeV
- Determination of $\sin^2(\theta_W)$ with highest precision 0.15% (similar to Z-pole), test of running of $\sin^2(\theta_W)$, mass scale 45 TeV
- P2-Experiment (proton weak charge) at MESA
- Solenoid delivery in November 2024, all critical components delivered, installation of magnet yoke started, start commissioning in 2026
- New MESA energy recovering accelerator at 155 MeV, target precision is 2 % in weak proton charge i.e. 0.15% in $\sin^2(\theta_W)$,
- Sensitivity to new physics at a scale from 70 MeV up to 50 TeV
- Strategic series of measurements from large asymmetries to ultimate precision
- Final accuracy corresponds to a factor 3 improvement over Qweak-experiment
- Much more physics from P2 program: Neutron Skin in heavy nuclei, weak charge in light nuclei