Experiments at MAMI/MESA

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

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Outline

- Accelerator facilities MAMI/MESA
- Beam Normal Single Spin asymmetries
  - BNSA with hydrogen target (A4 collaboration)
  - BNSA with heavier nuclei (A1 collaboration)
- P2 Experiment
  - Search for new physics: precision determination of $\sin^2\Theta_W$
  - Present status
- Spin asymmetries at MAGIX

MAinz **MI**crotron MAMI

mami
MAINZER MIKROTRON

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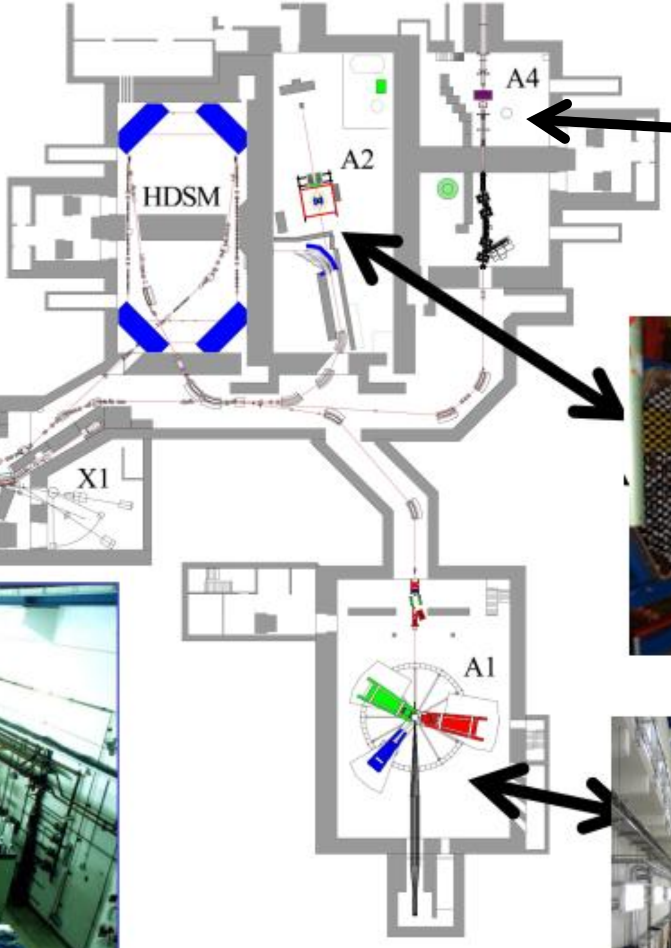
MAinz MIcrotron MAMI

Electron Accelerator for Fixed Target Experiments

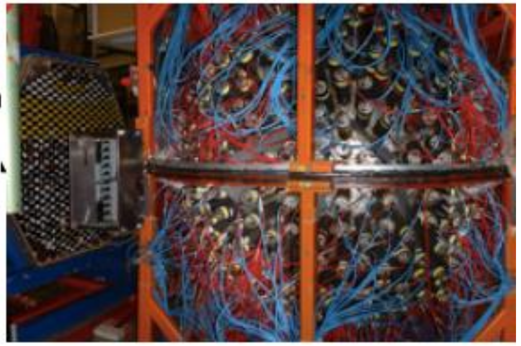
E_{max} (e-) = 1.6 GeV

I_{max} ~ 100 μA (CW)

- Resolution $\sigma_E < 0.100$ MeV
- Polarization 85%
- Reliability: 7000 hours / year



A4:
Parity violation

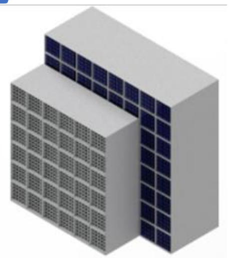


A2:
Tagged photons

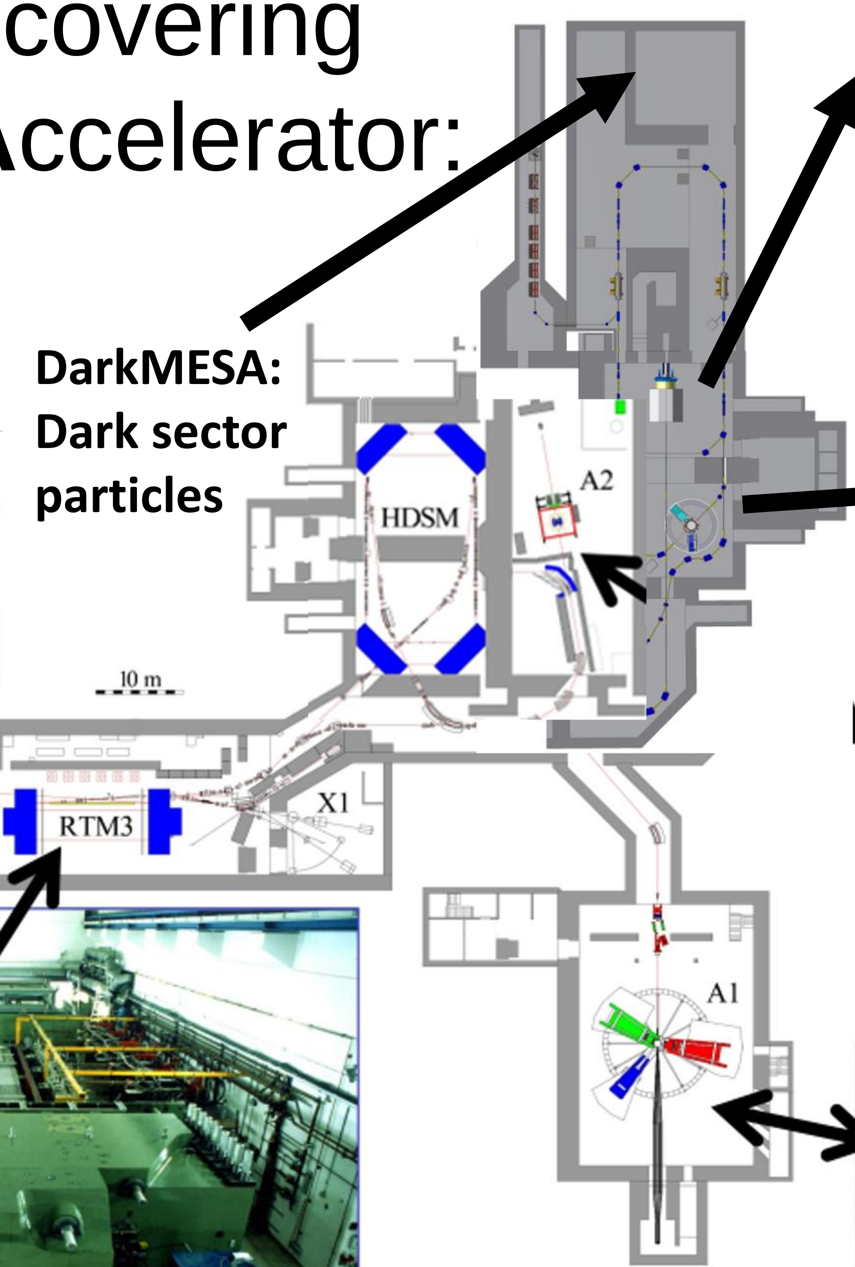
A1:
Electron scattering

Mainz Energy recovering Superconducting Accelerator: MESA

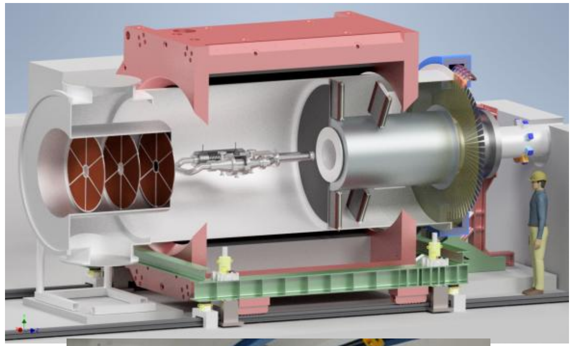
- E_{max} (e^-) 155 MeV
- I_{max}: 1 mA



- Polarization 85%
- CW beam

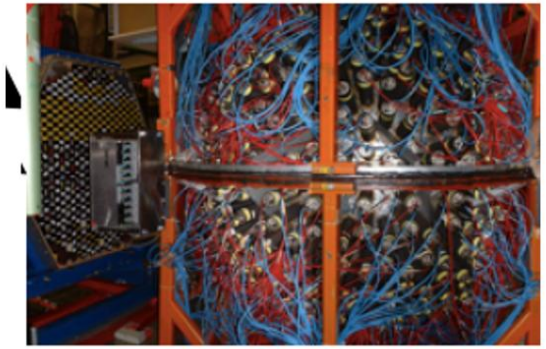


DarkMESA:
Dark sector particles



P2:
Weak mixing angle

MAGIX:
High precision electron scattering



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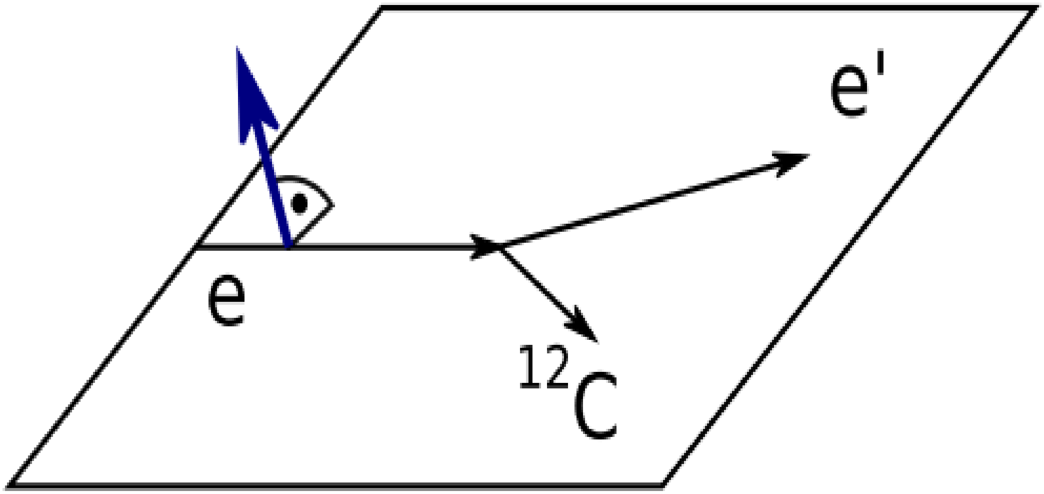
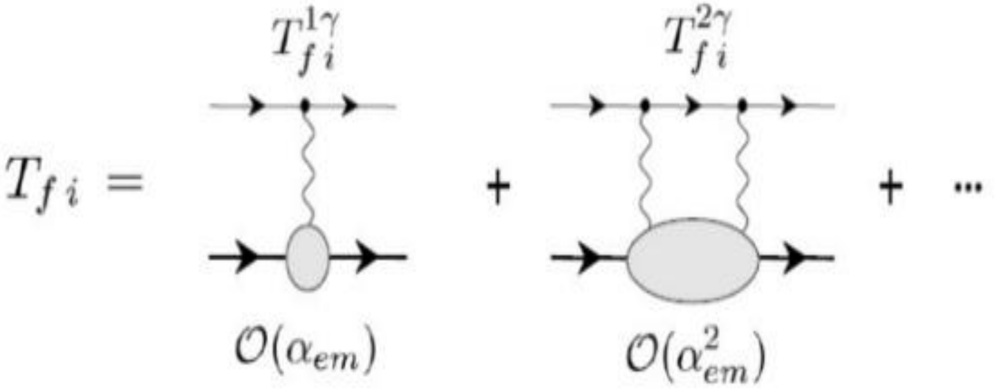
Beam normal spin asymmetries

- Transversely polarized electrons
- Unpolarized nuclei
- Cross section asymmetry: Two-photon exchange
- Theoretical treatment of A_n is non-trivial: All possible intermediate states need to be related to the absorptive part of $M_{\gamma\gamma}$





$$A_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{2\,\mathrm{Im}\left(\mathcal{M}_{\gamma}^{*} \cdot |\mathcal{M}_{\gamma\gamma}|\right)}{|\mathcal{M}_{\gamma}|^{2}}$$

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Beam normal spin asymmetries

Existing Calculations:

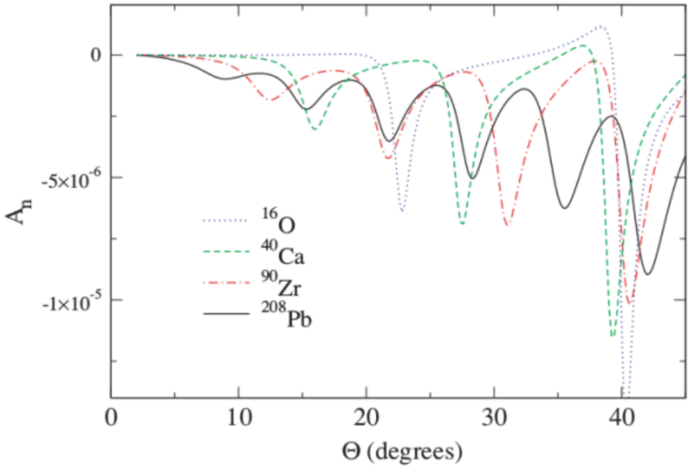
Cooper & Horowitz
[Phys. Rev. C72, 034602 (2005)]

- All orders of photon exchange
- Coulomb distortion effects
- Only elastic intermediate state

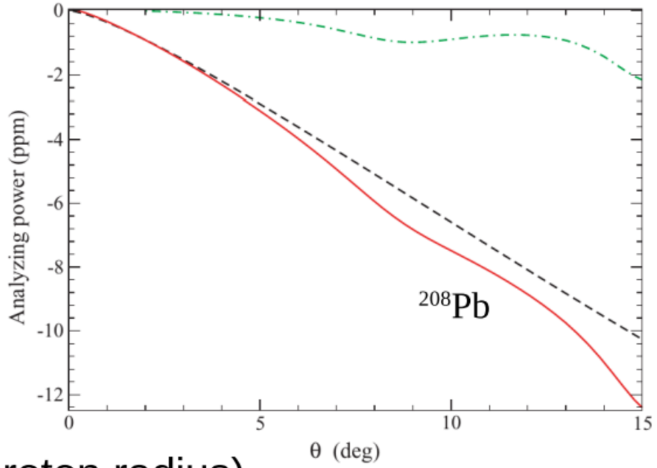
Gorchtein & Horowitz
[Phys. Rev. C77, 044606 (2008)]

- Full range of intermediate excitation states
- Only 2 photon exchange
- Limited to small forward angles

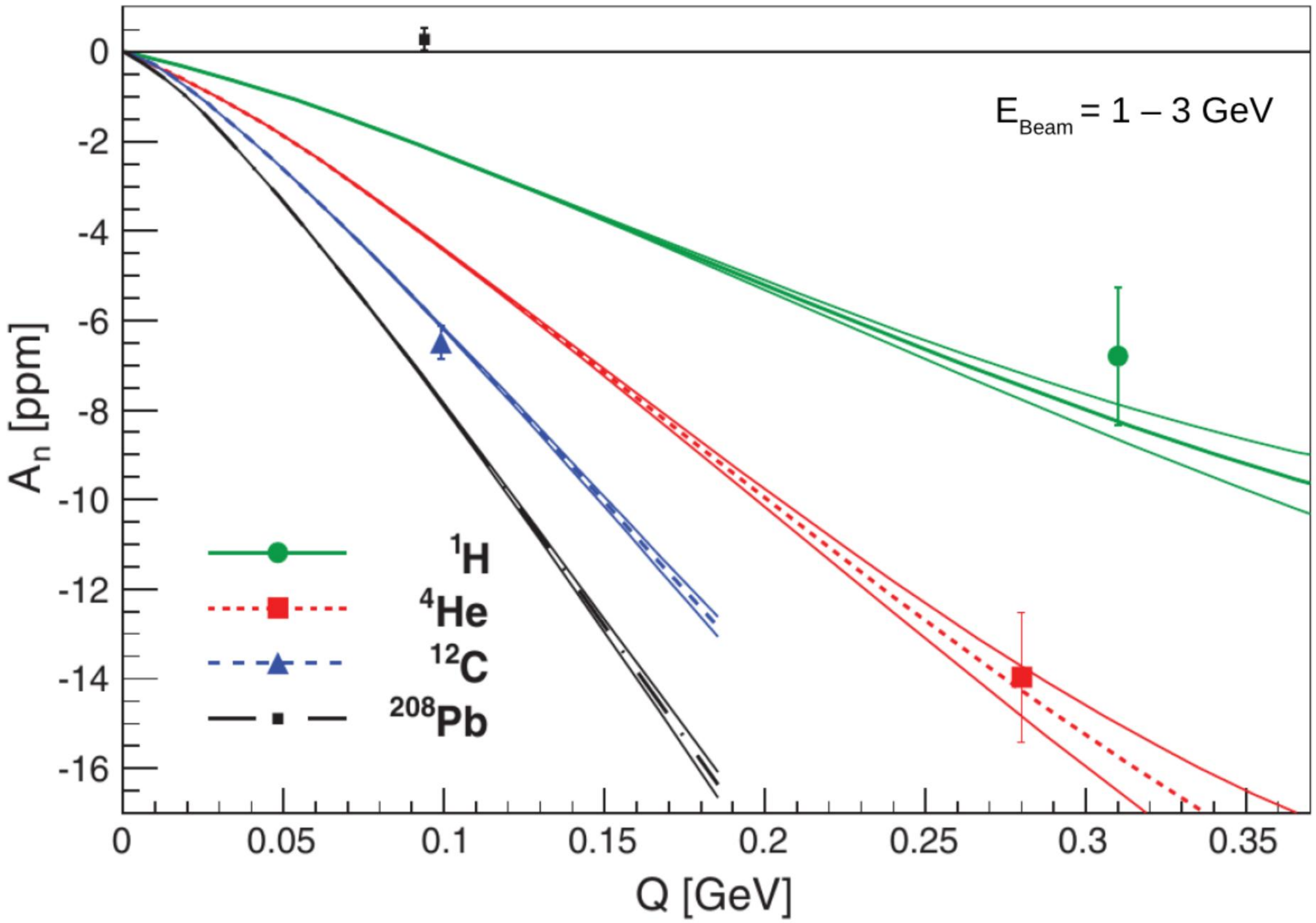
→ No consistent Theory, but
- Contribution to every PV experiment
- Contribution to other measurements (e.g. proton radius)



E_{Beam} = 850 MeV

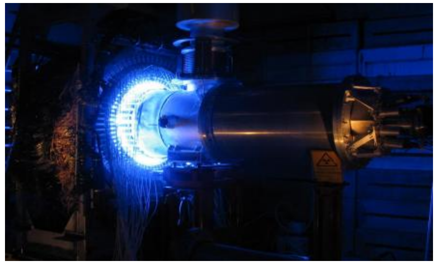


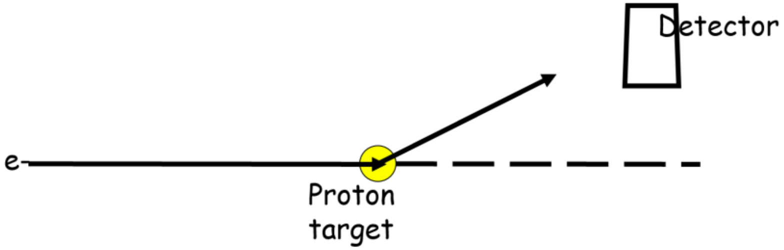
Beam normal spin asymmetries

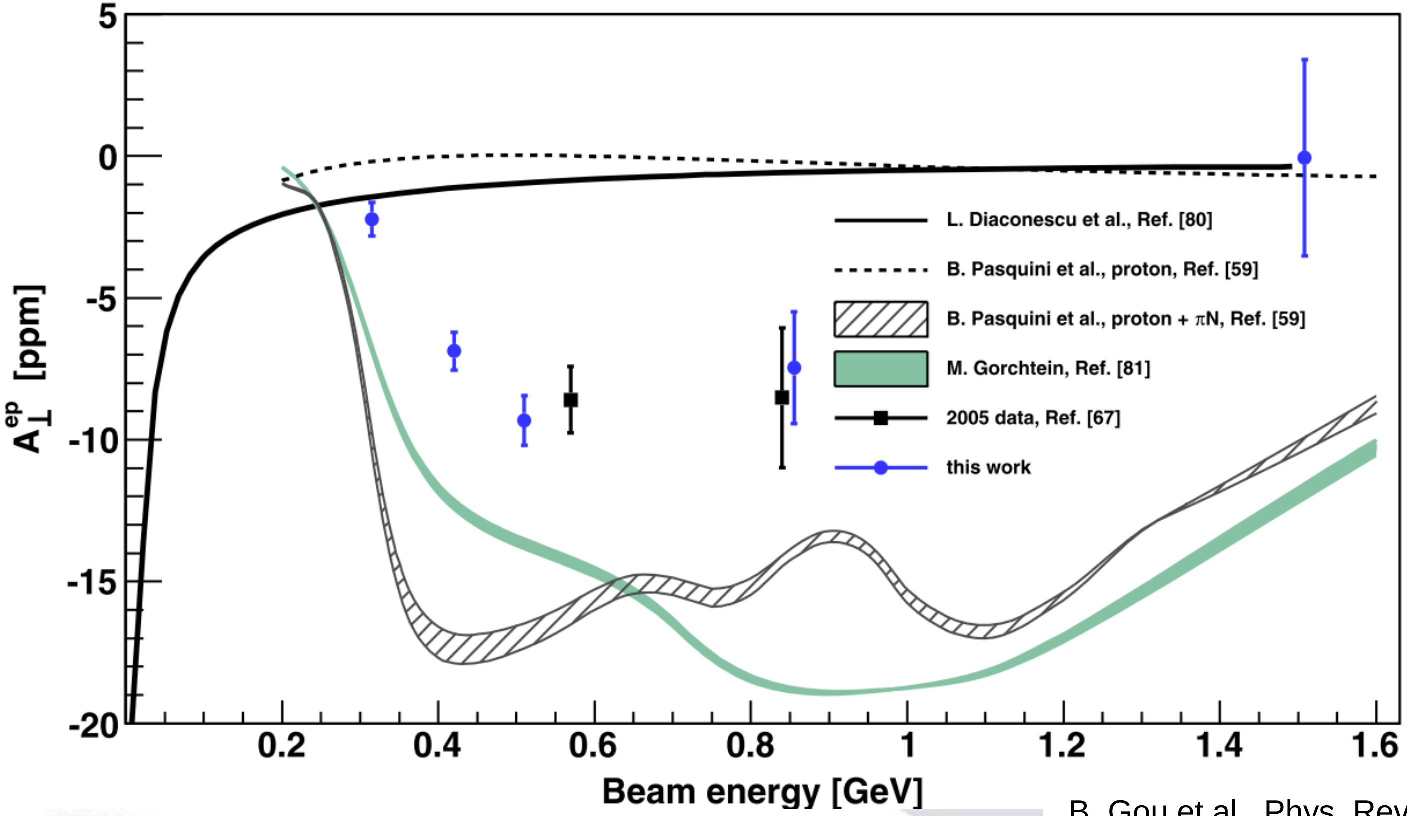


Measurement of A_n at PREX and HAPPEX

BNSA: Hydrogen results







Measurements by the A4 collaboration at MAMI

- Scattering angle 35°
- Various beam energies
- Excited intermediate nucleon states play an important role
- Significant discrepancies with the theoretical predictions

B. Gou et al., Phys. Rev. Lett. 124, 122003, 2020

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BNSA: Heavier nuclei

Measurements by the A1 collaboration at MAMI

- Electron beam:
  - E_{Beam} = 570 MeV
  - I_{Beam} = 20 µA
- Spectrometers:
  - Define scattering angles:
    $\Theta = 15° - 26°$
    $Q^2 = 0.02 – 0.05\ GeV^2/c^2$
  - Select elastic events
- Further requirements:
  - High quality vertically polarised beam
  - Precise knowledge of the polarisation
  - High rate capable detector system

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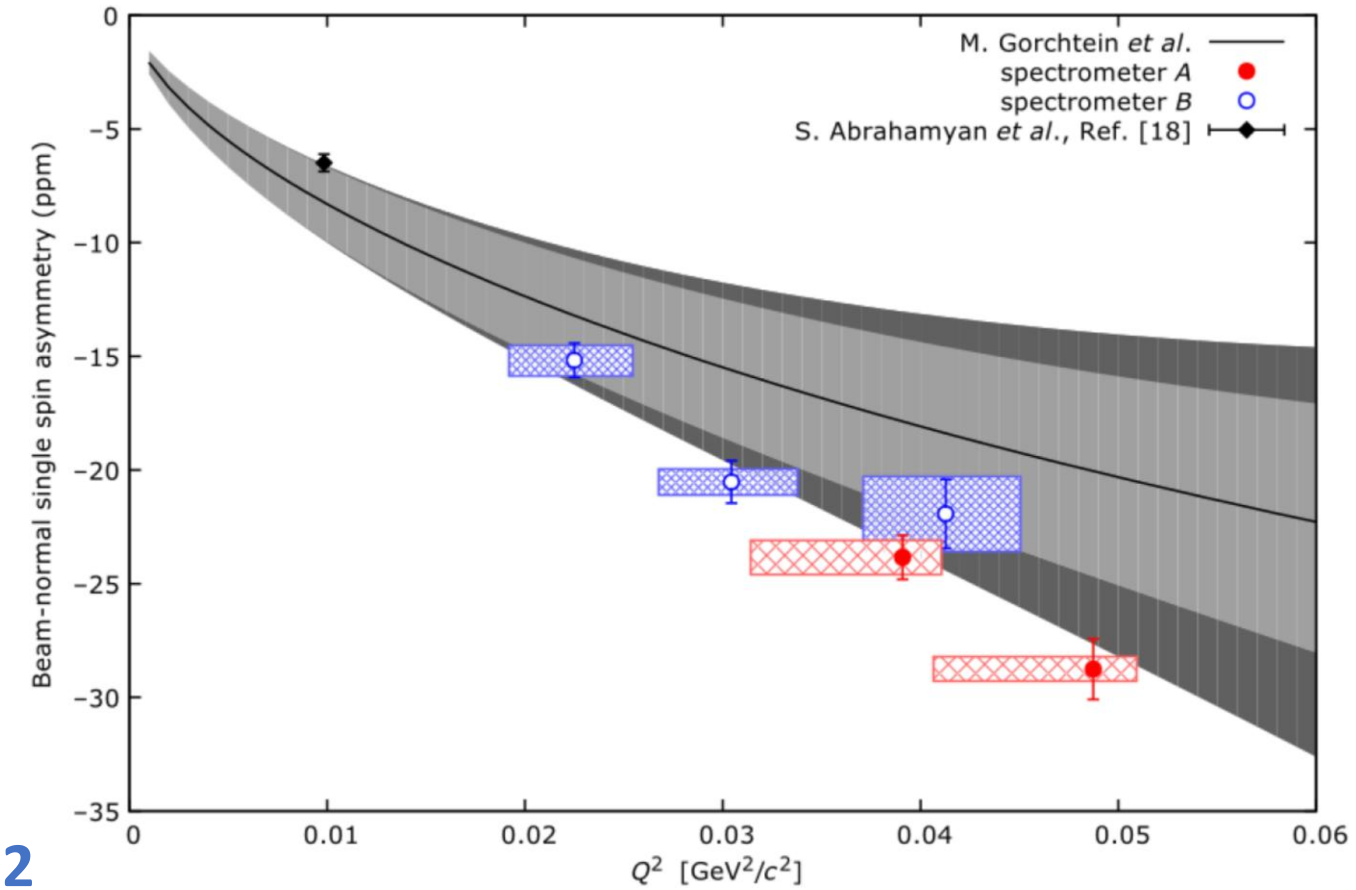

- **Measurements with C-12**

BNSA: Heavier nuclei

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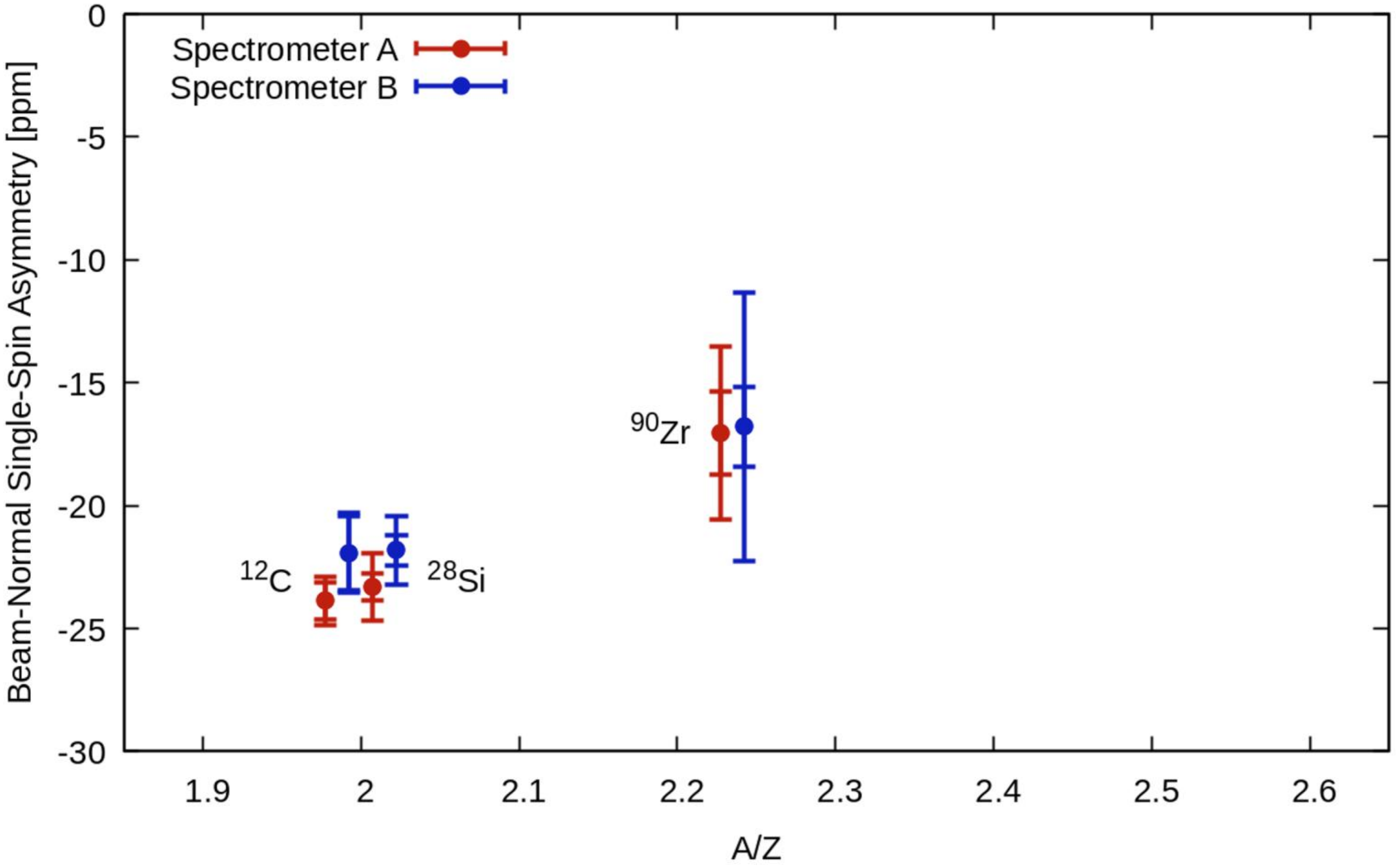

- **More nuclei…**

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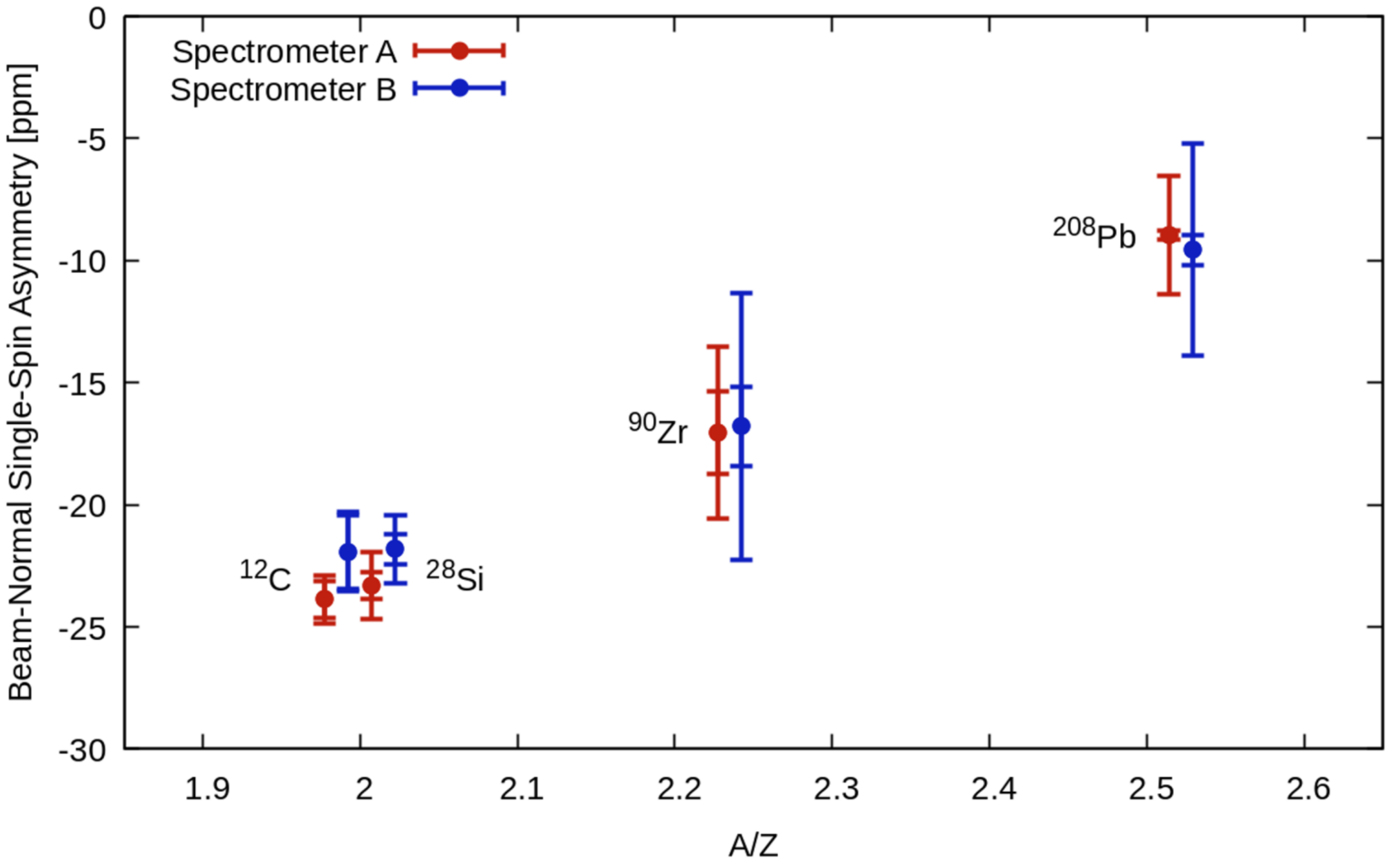
- Spectrometers:
  - Define scattering angles:
    Θ = 15° - 26°
    Q^2 = 0.02 – 0.05 GeV²/c²
  - Select elastic events

- **Most recent: ^{208}Pb**



A. Esser et al., submitted to PRL

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The Weak Mixing Angle

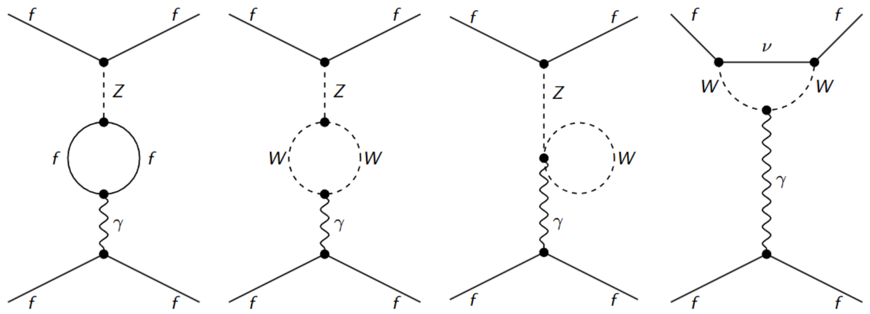
Tree level relations:

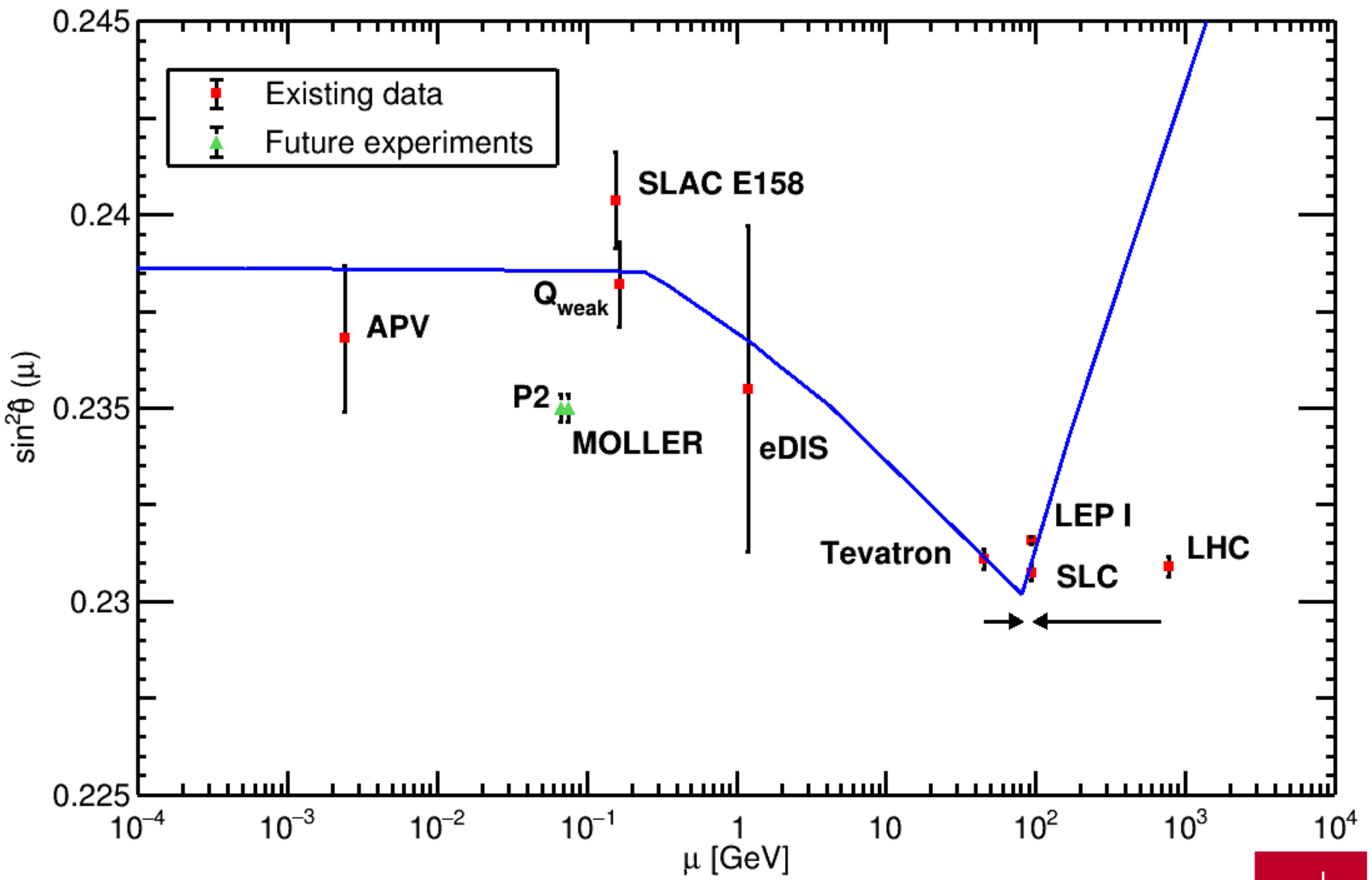
- Electric charge $e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$
- Masses of W and Z Boson $\cos\theta_W = M_W / M_Z$
- Myon decay constant $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}$

Important parameter of the Standard Model

The running of $\sin^2\Theta_W$

- Scale dependence of $\sin^2\Theta_w$

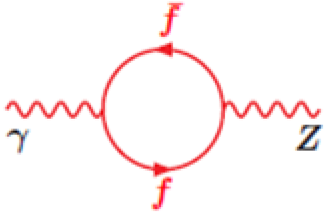




- Z-Pole: High precision, some tension between results
- Low Q: Large experimental uncertainties

Beyond the Standard Model

Including radiative corrections:



$$G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}(1+\Delta r)$$

with $\Delta r = \Delta r(\alpha, M_W, \sin\theta_W, m_{top}, M_{Higgs}, \ldots)$

New physics?

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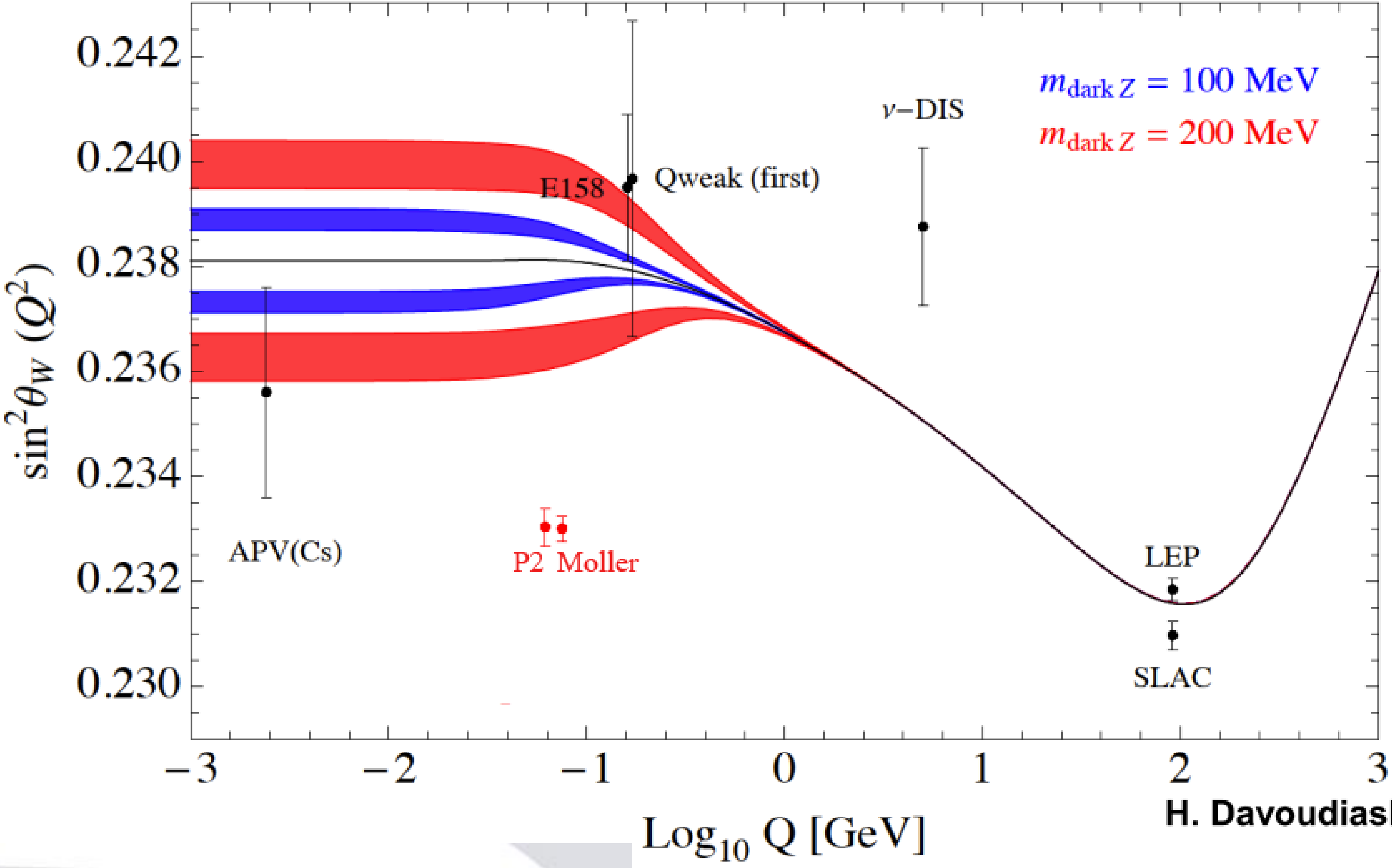
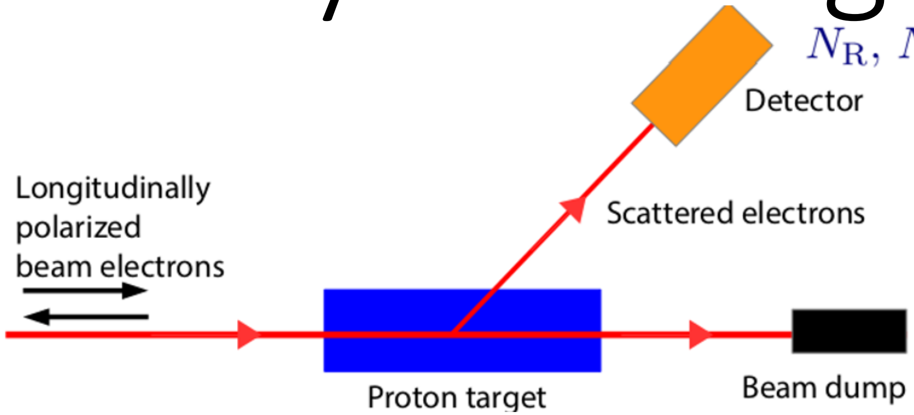
Example: Dark Parity Violation



H. Davoudiasl

Parity violating ep scattering



$$\Rightarrow A_\mathrm{RL} = \frac{N_\mathrm{R} - N_\mathrm{L}}{N_\mathrm{R} + N_\mathrm{L}}$$

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

The weak charge of the proton (tree level):

$$Q_W(p) = 1 - 4\sin^2\theta_W$$

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

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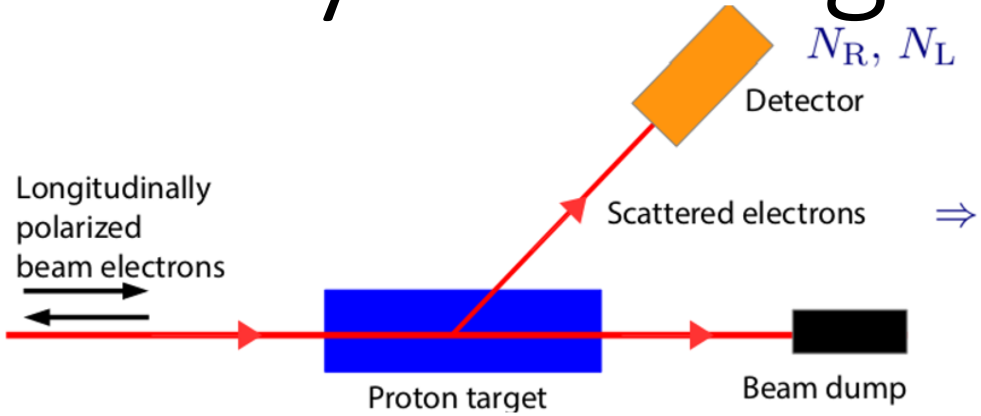
Parity violating ep scattering



$$\Rightarrow A_{RL} = \frac{N_R - N_L}{N_R + N_L}$$

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

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$$Q_W(p) = 1 - 4\sin^2\theta_W$$

$$\frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W} = \frac{1}{11}$$

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

1.5% precision in $Q_W(p)$ results in a precision of 0.13% in $\sin^2\Theta_W$

Parity violating ep scattering

Asymmetry in the cross section of elastic electron-proton scattering for left- and right-handed polarized electrons

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

The weak charge of the proton (tree level):

$$Q_W(p) = 1 - 4\sin^2\theta_W = \frac{1}{11}$$

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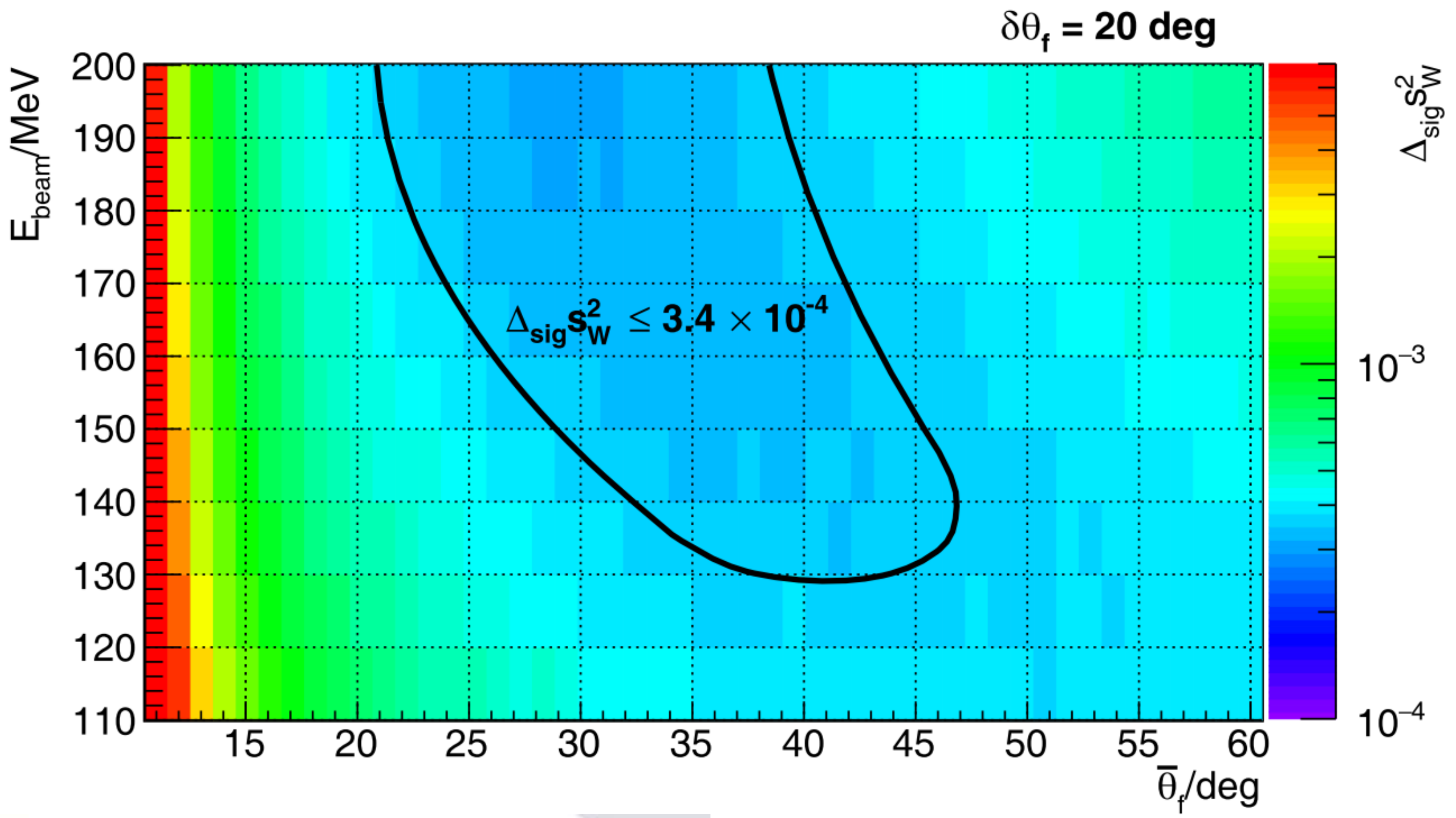
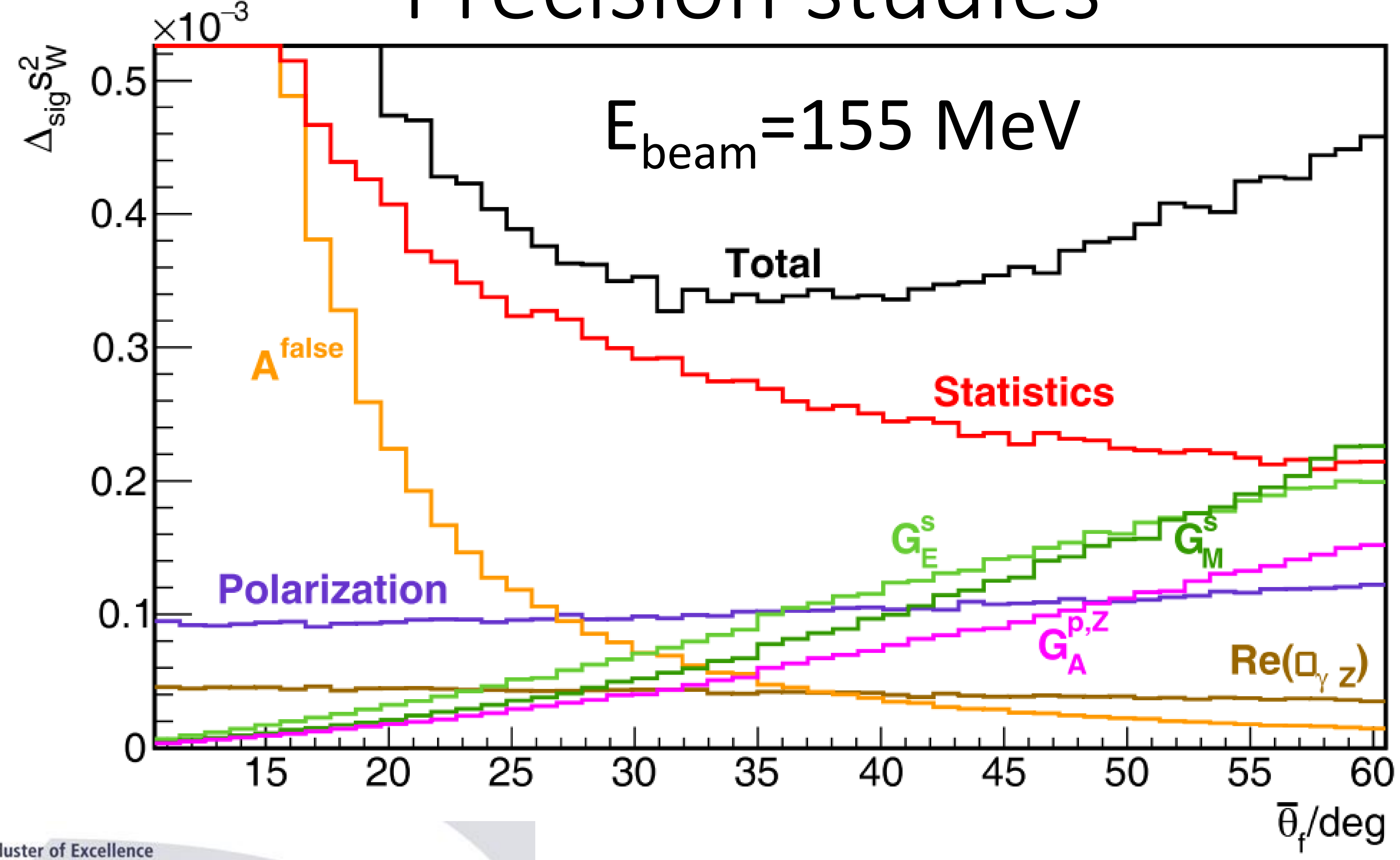
Precision studies

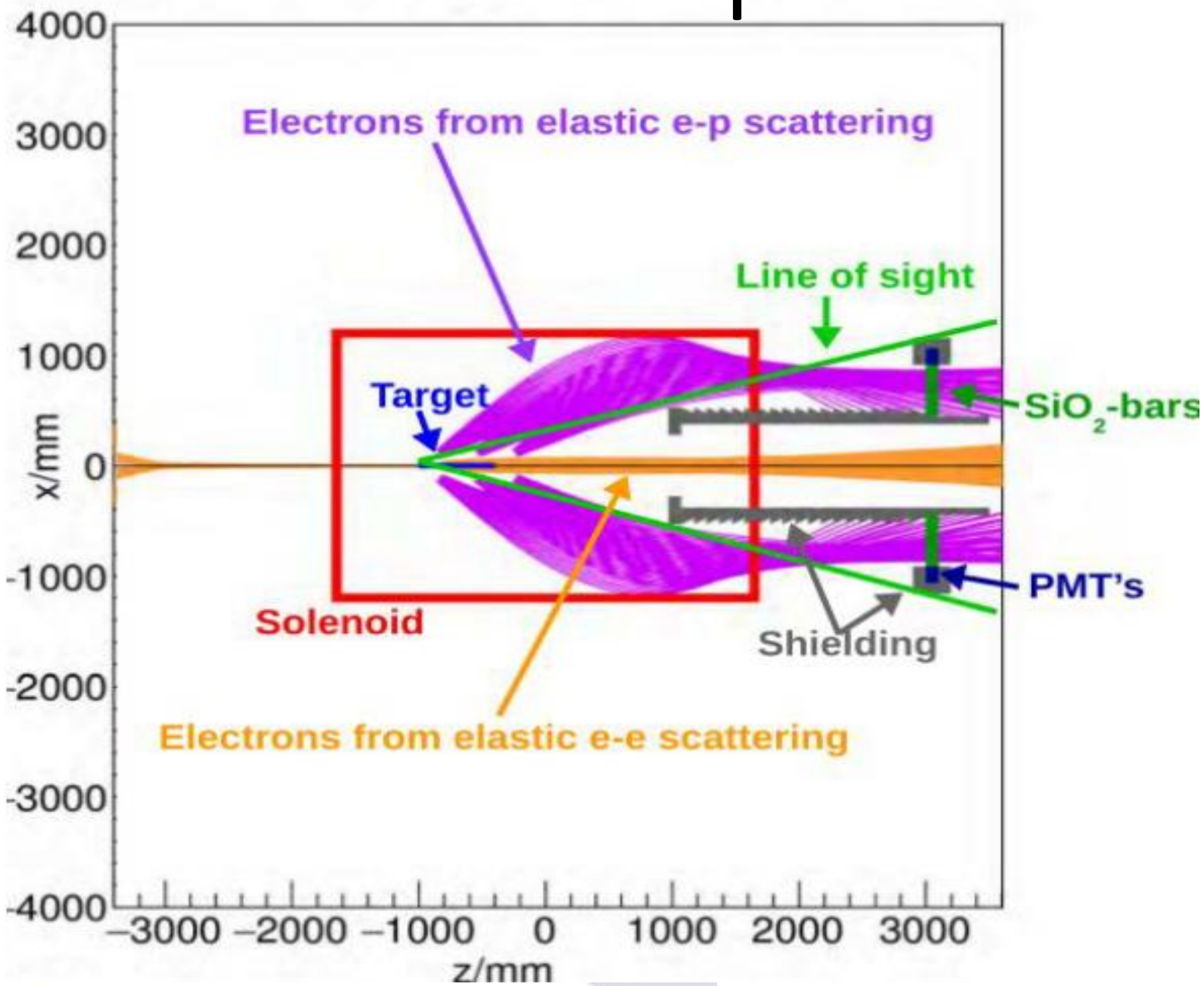
Find the best kinematics in the energy/scattering angle plain:



Precision studies

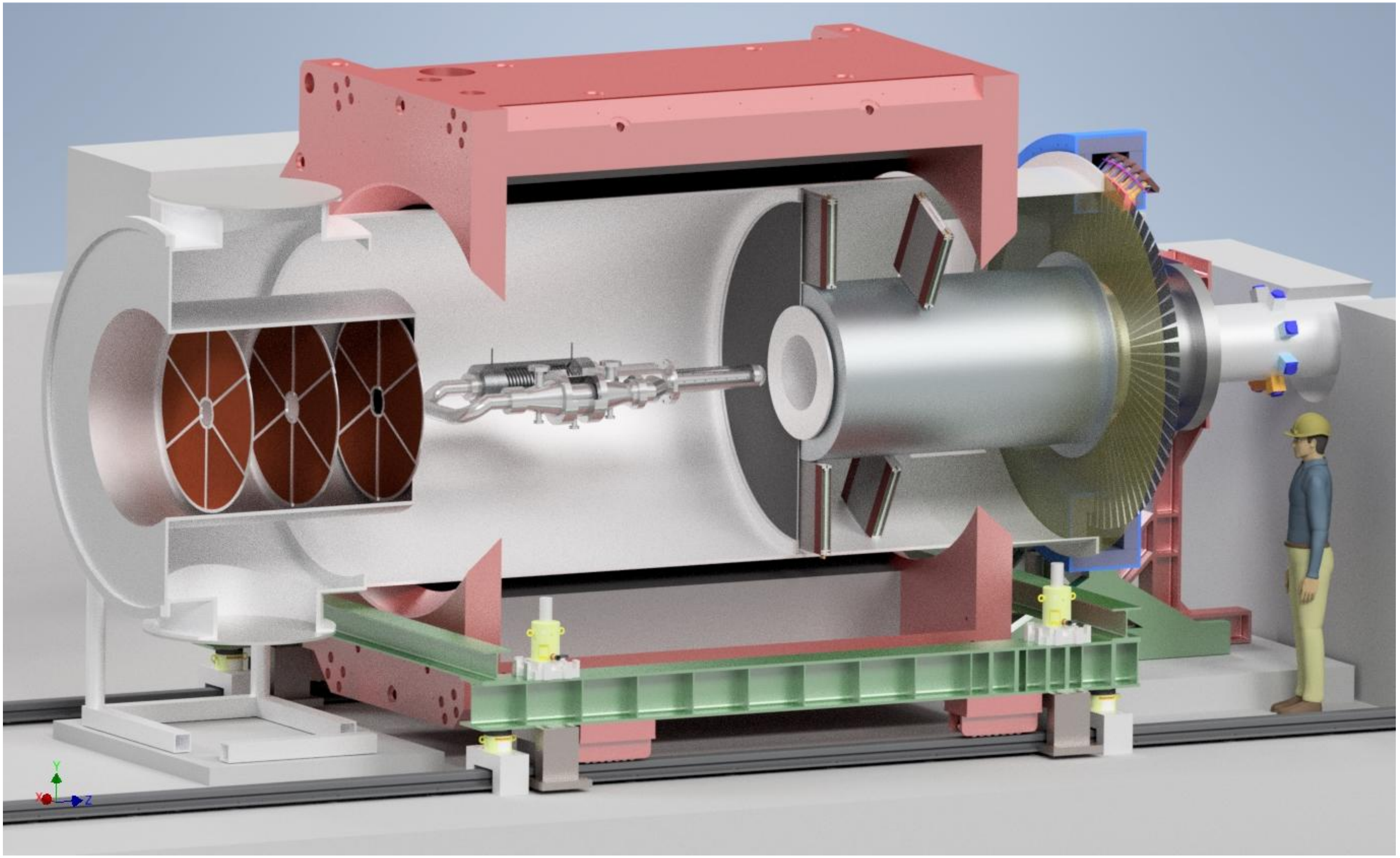


P2 Experiment



- Electron beam, E=155 MeV, I=150 μA
- Target: 60 cm liquid hydrogen
- Superconducting solenoid, B_{max}= 0.7 T
- Electron detection: 72 fused silica bars
- Q^2 determination: Tracking detector (HV-MAPS)
- Backward angle detector (Micromegas)

P2 Experiment



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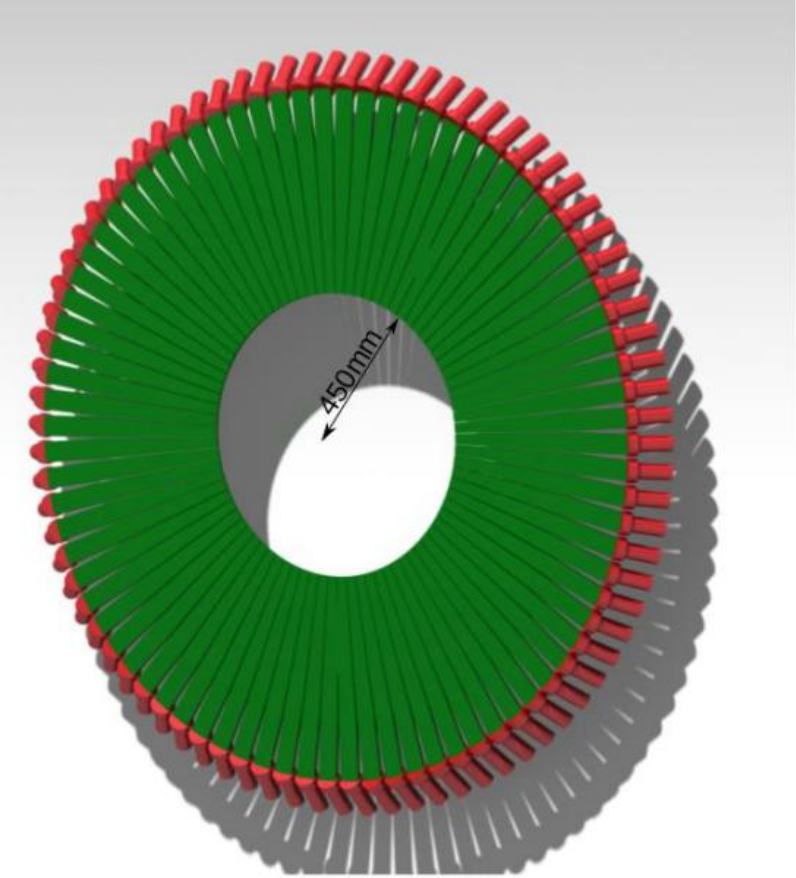
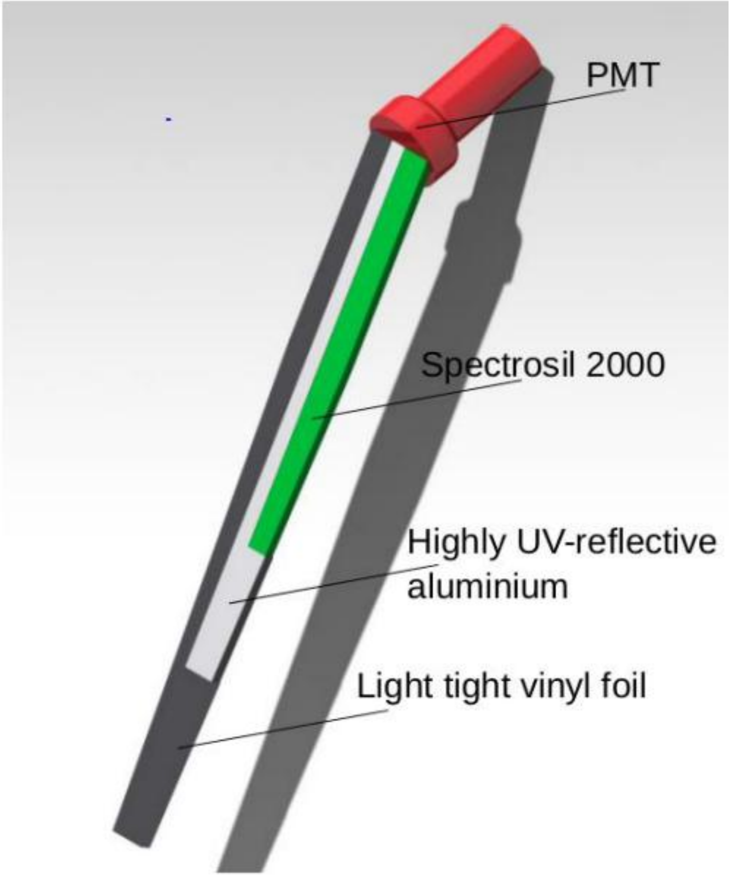
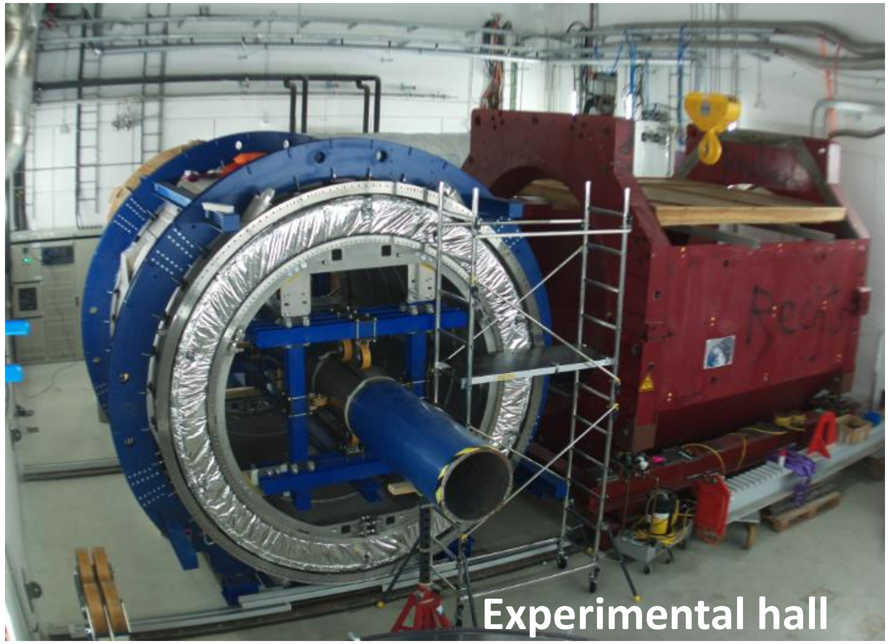
P2: Cherenkov detectors

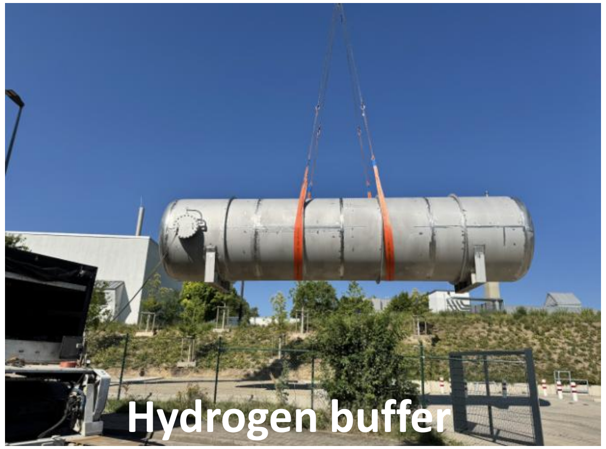


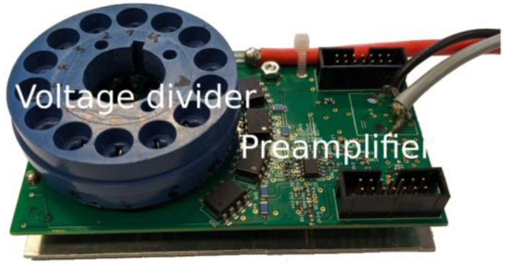


- 72 detector modules
- Material: Fused silica
  (Spectrosil 2000, Heraeus)
- Fast, radiation hard
- Light readout by PMT
  (9305 QKB from ET)

P2: Installation in progress







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P2: Cryogenics

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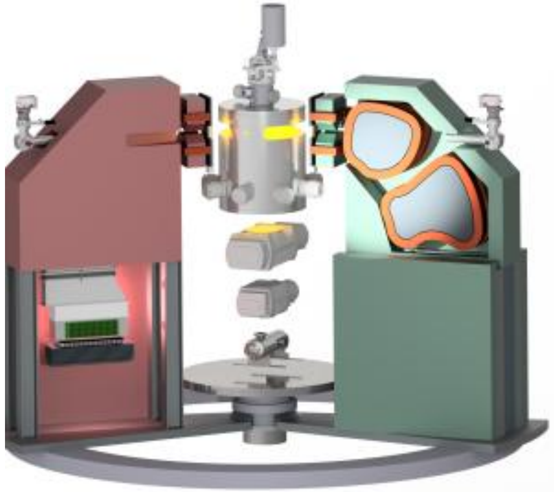
Installation at MESA

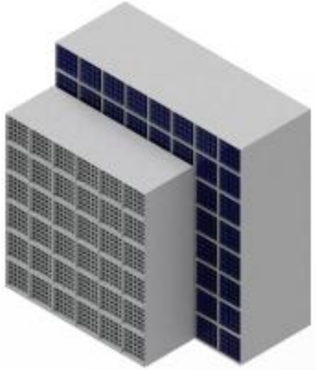
MAGIX

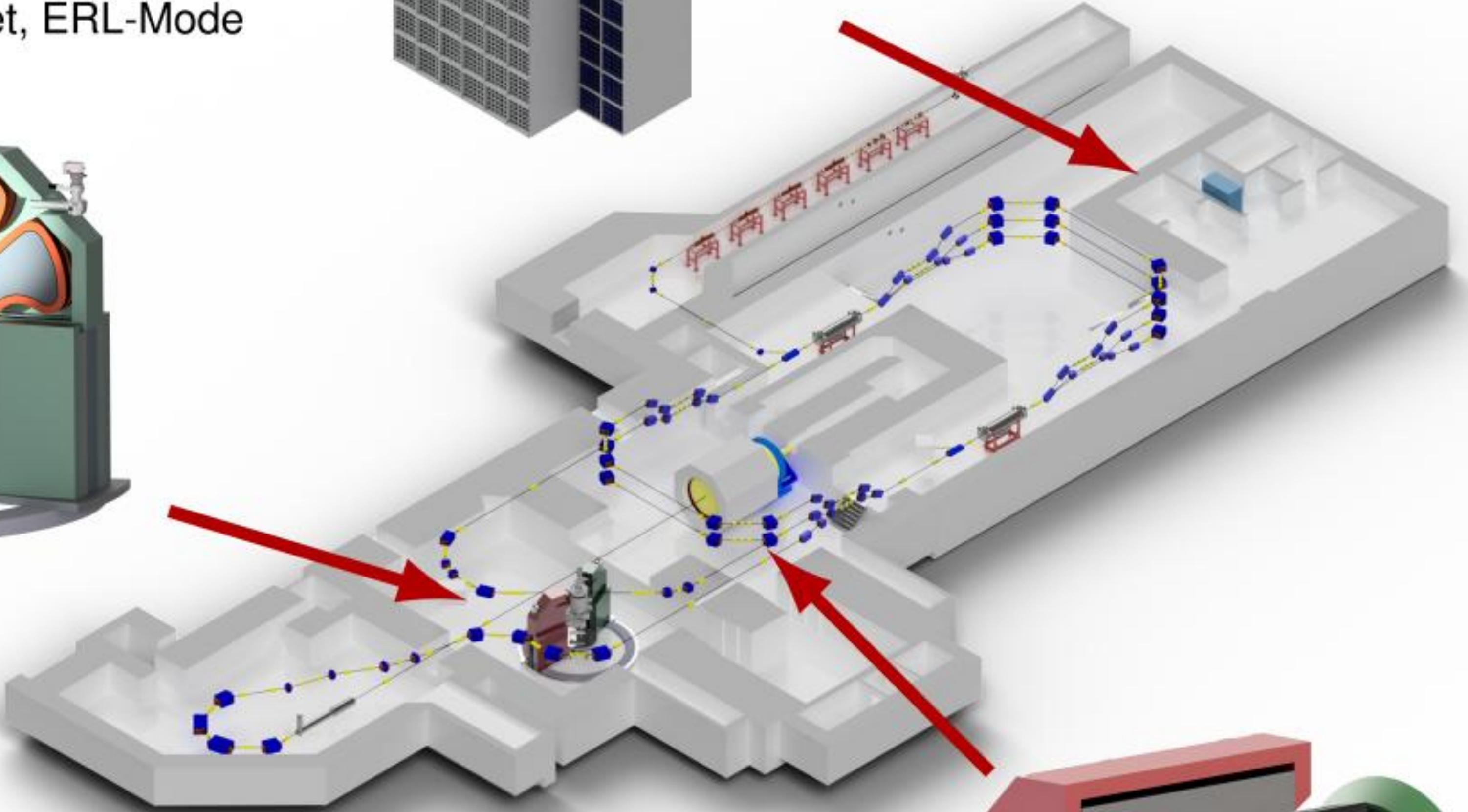
- High Resolution Spectrometers
- Internal Gas Target, ERL-Mode



DarkMESA

- Search for Dark Sector Particles





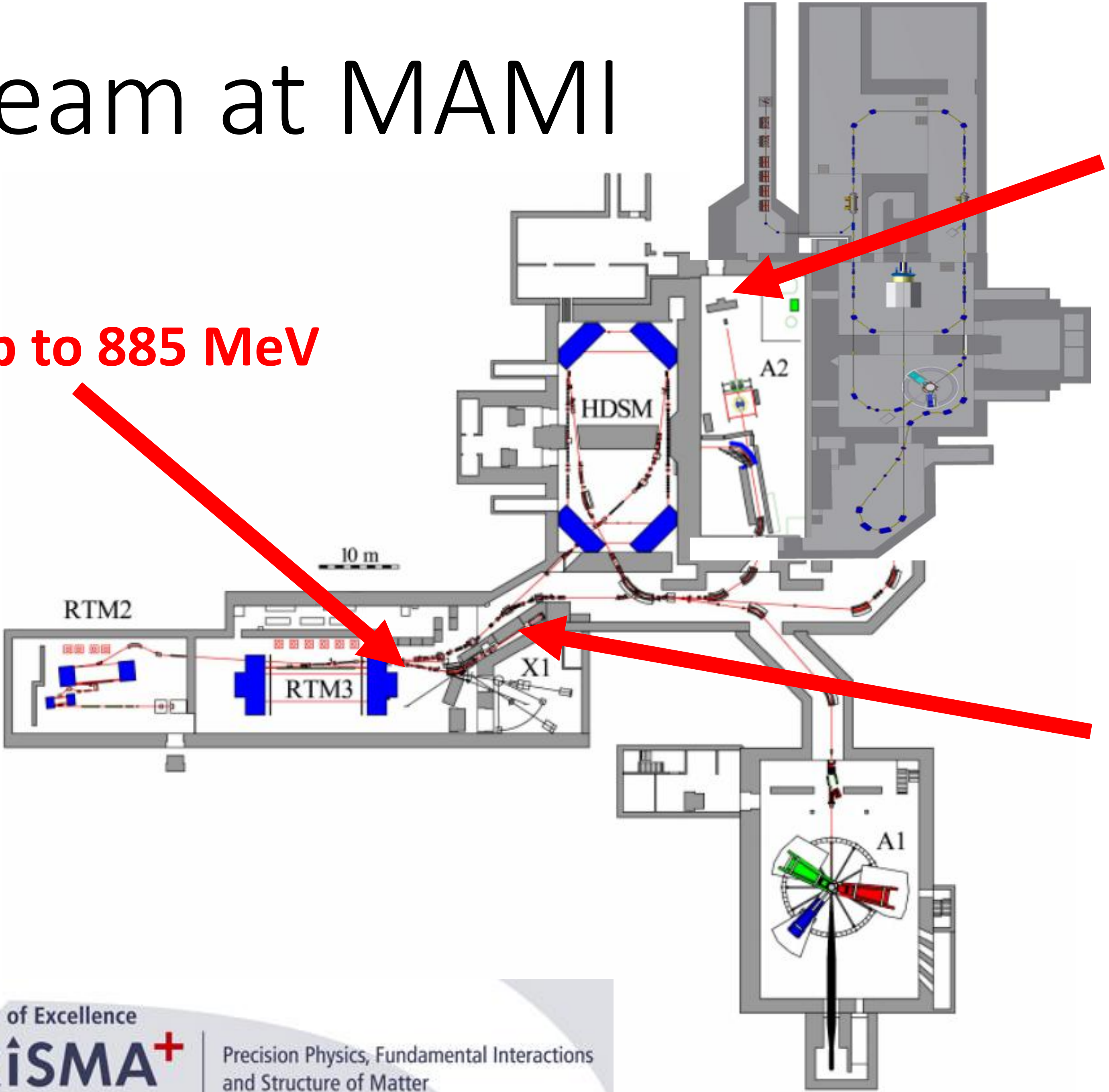
P2

- Parity-Violating $\vec{e}$-scattering
- Extracted Beam (155 MeV, $150\,\mu$A)

Test beam at MAMI

Electrons
180 MeV up to 885 MeV

Photons
10 MeV up to 1.6 GeV



Radiation hardness

mami
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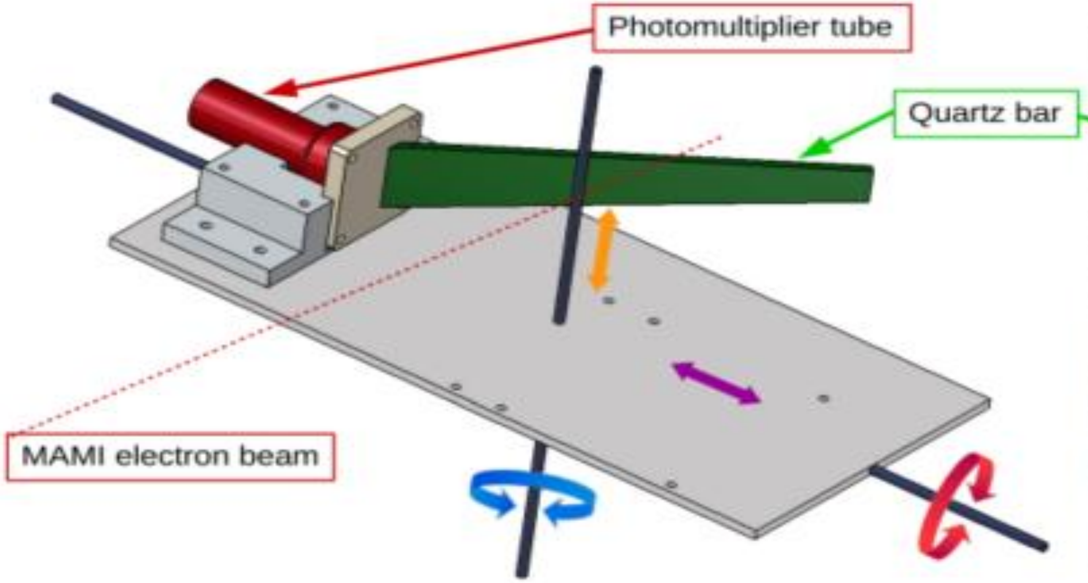
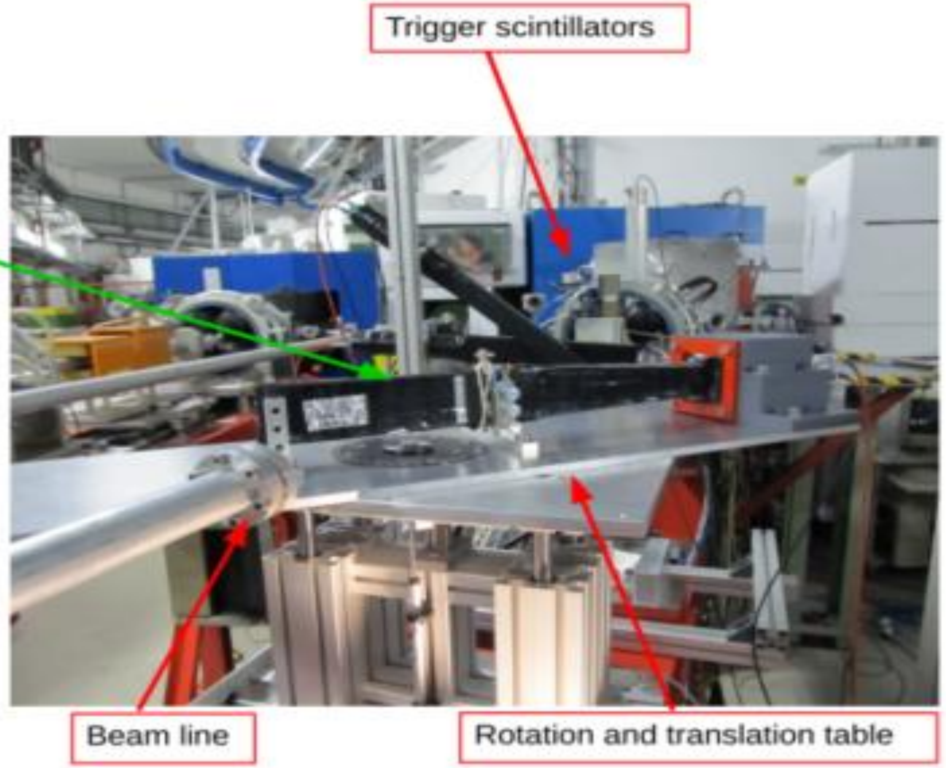
Test with electrons

- Beam rate 1 kHz … 10 MHz
  0.1 fA … 1 pA
- Beam rate 0.5 GHz … 3 GHz
  100 pA … 0.5 nA
- Prototype testing

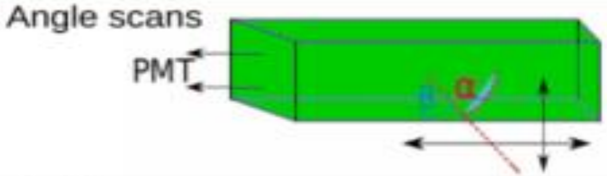
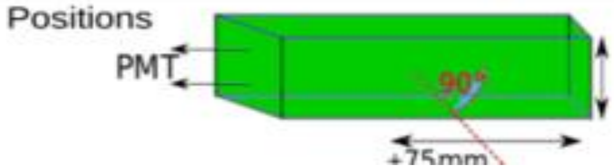
Test with electrons

Measure detector response to electrons
depending on location and angle of impact

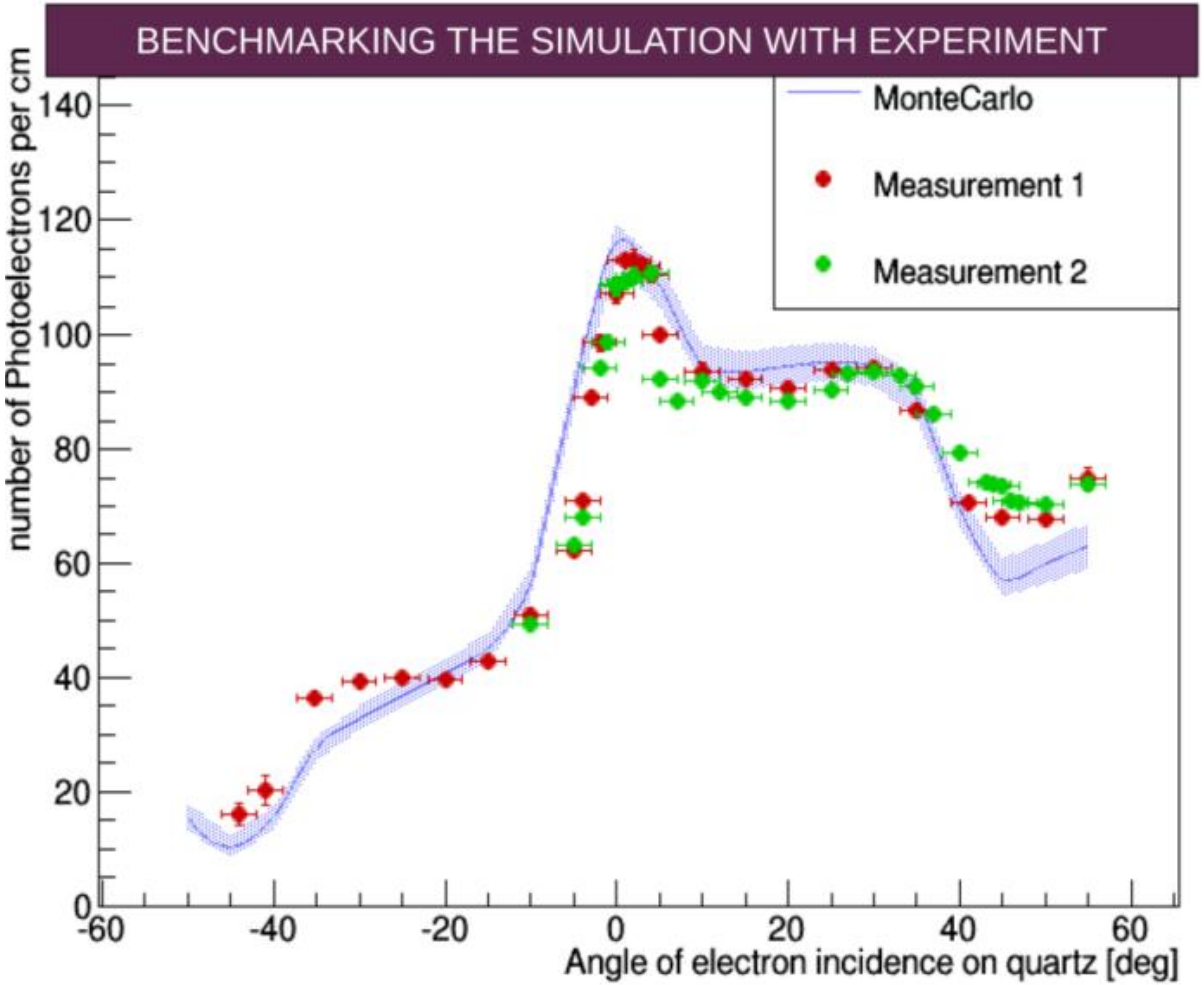




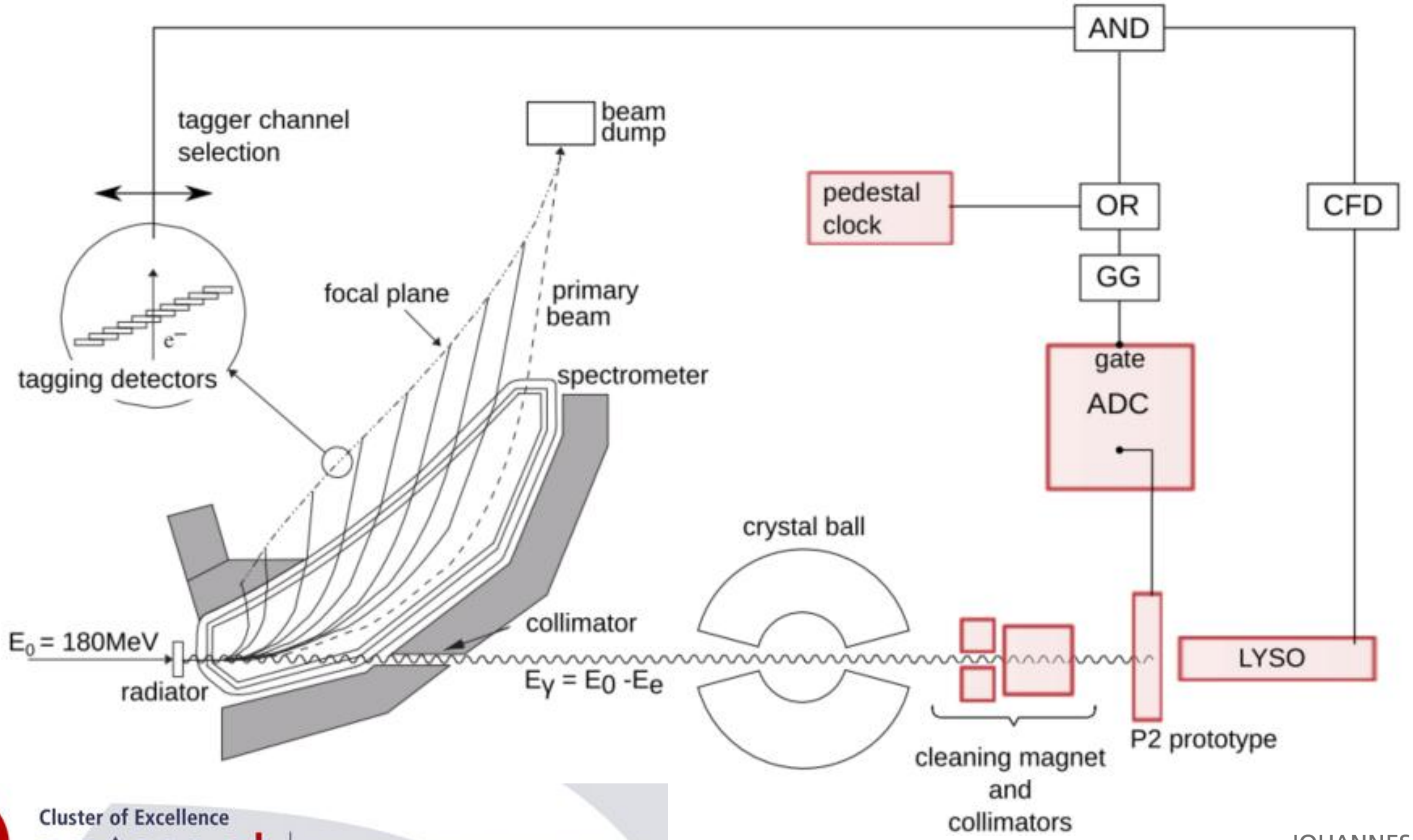
>4000 MEASUREMENT RUNS DONE AT MAMI with different conditions:

	**Geometries** • Quartz bars 10 mm / 15 mm • "outlet optic": cuboid and wedged • Measurements with and without light guide	**Quartz materials** • Heraeus Suprasil 2A • Heraeus Spectrosil 2000
	**Polishes** • Flamepolished • Mechanical • Optical polish 	**Reflective materials** • Mylar • Alanod 4300UP • Millipore ImmobilonP

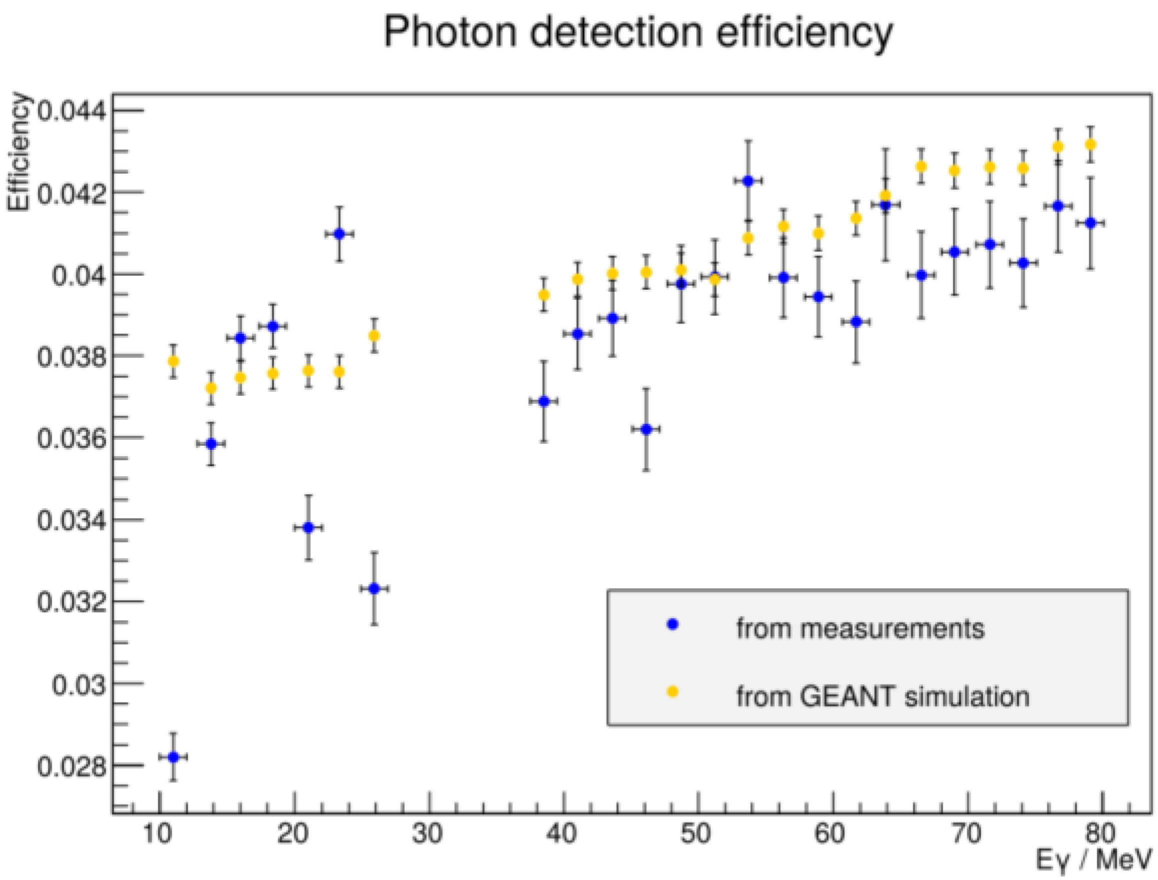
Benchmarking the simulation

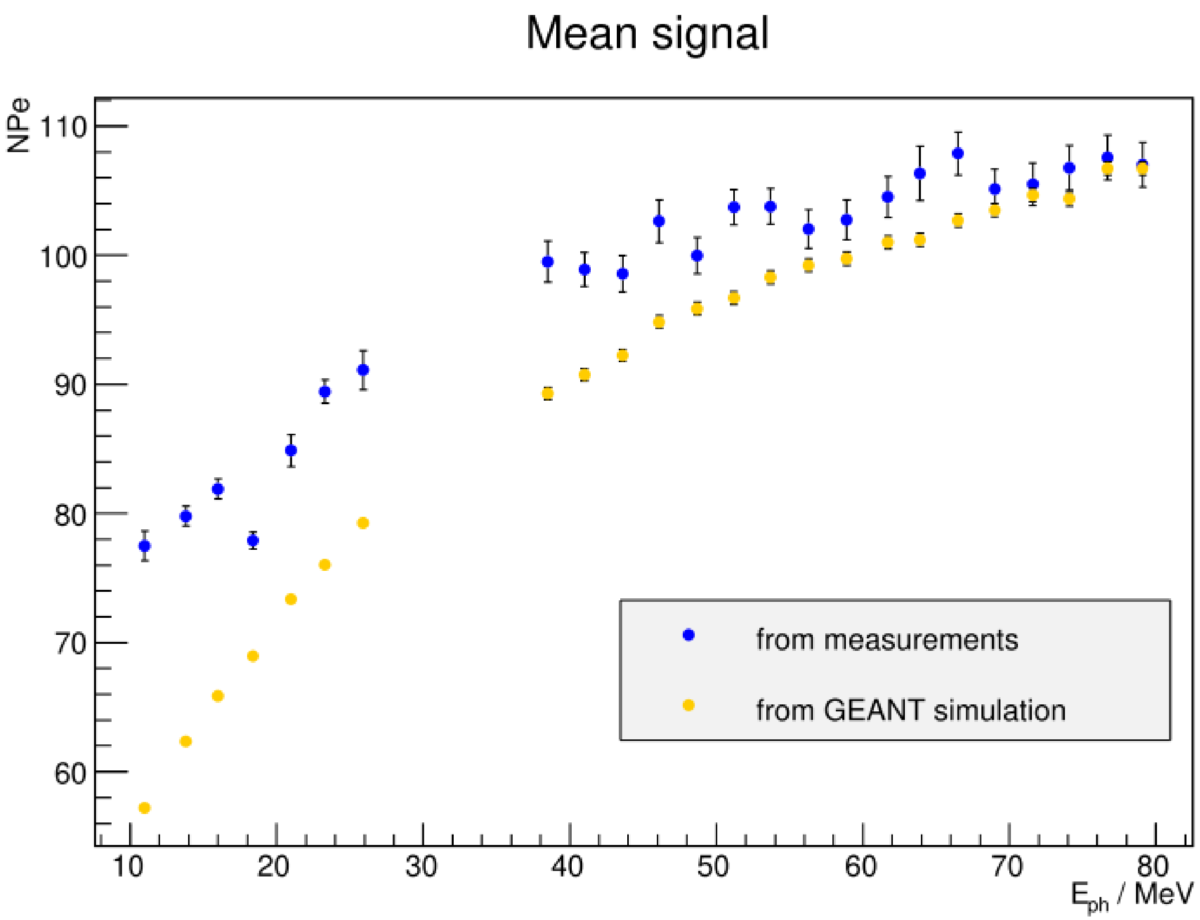


Tests with tagged photons



Tests with photons





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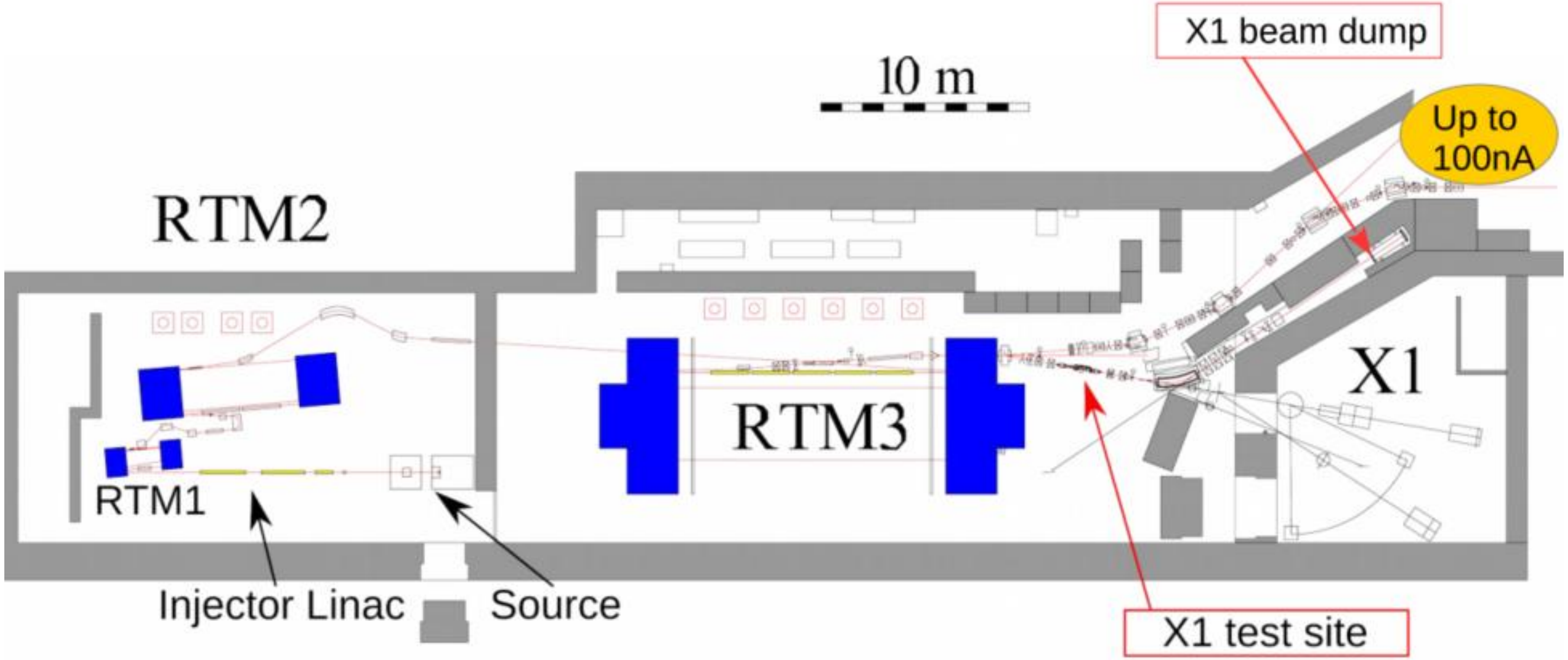
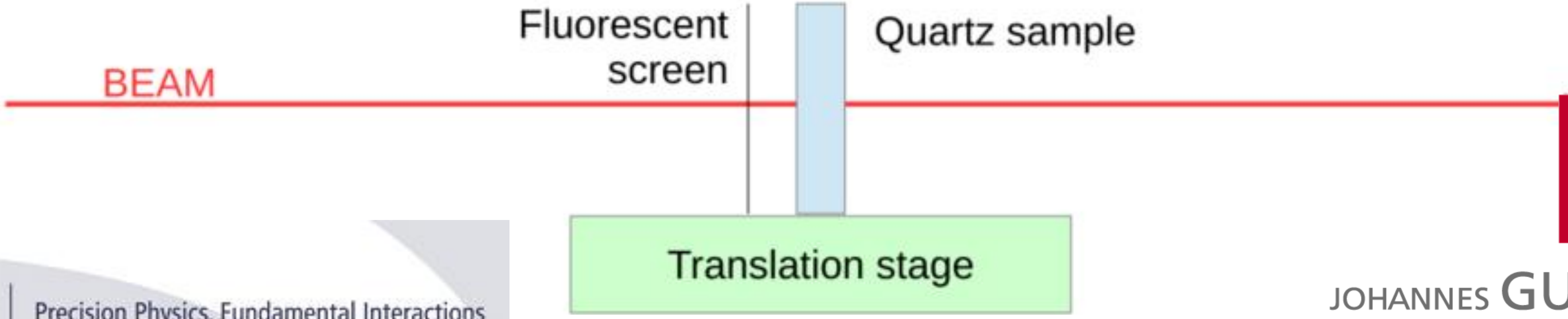
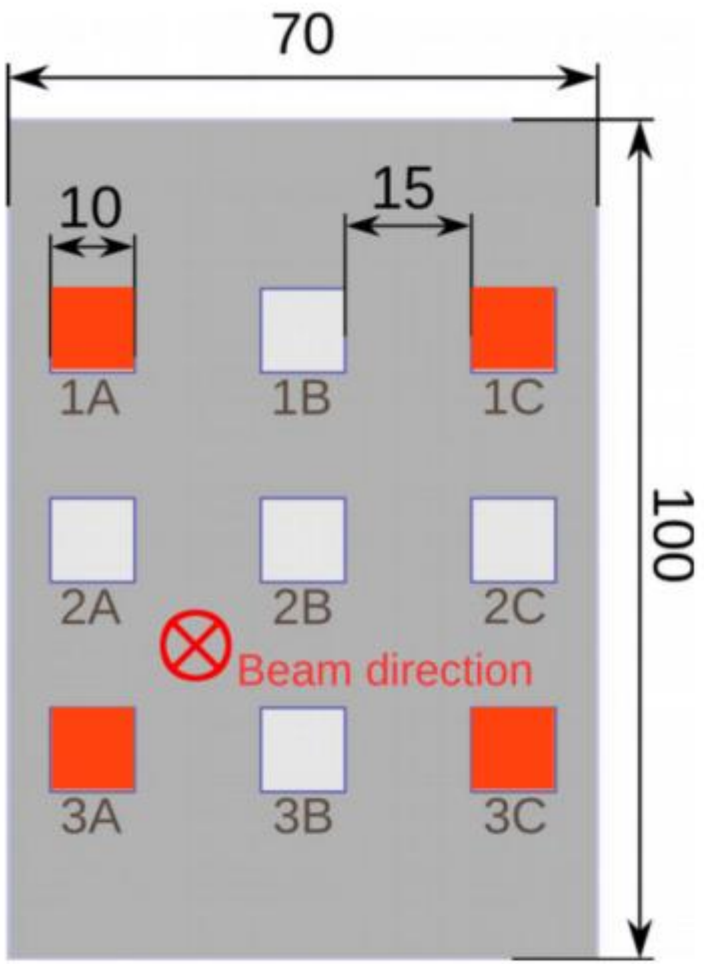
Radiation hardness tests





Radiation hardness tests

Suprasil 3A, Spectrosil 2000

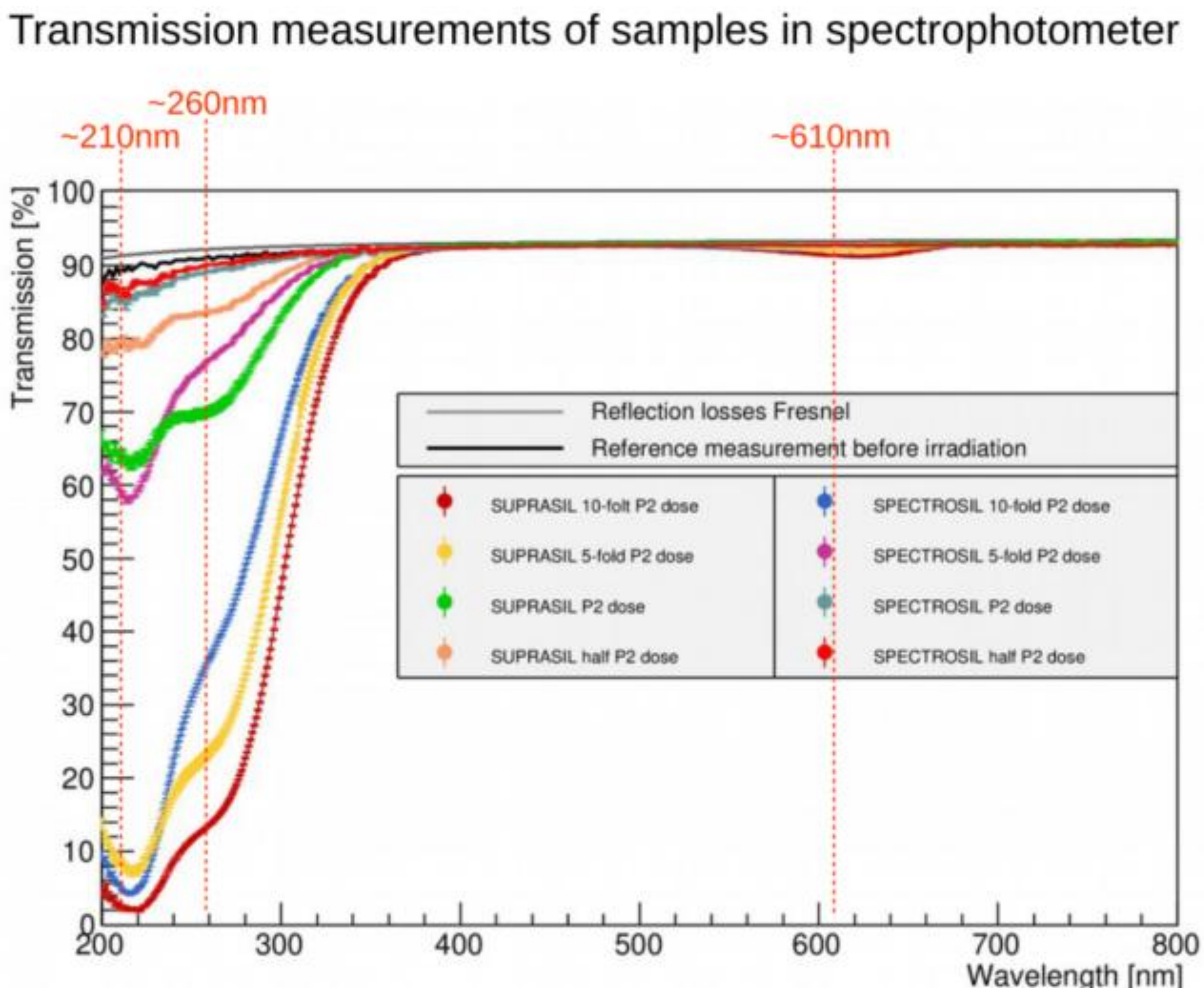


Sample dimensions

Beam spot:
- rastered over 1 cm x 1 cm areas
- visible on fluorescent screen

Monitor picture in MaMi control room: Beam spot on fluorescent screen in front of quartz samples

Radiation hardness tests



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Measurement with carbon-12

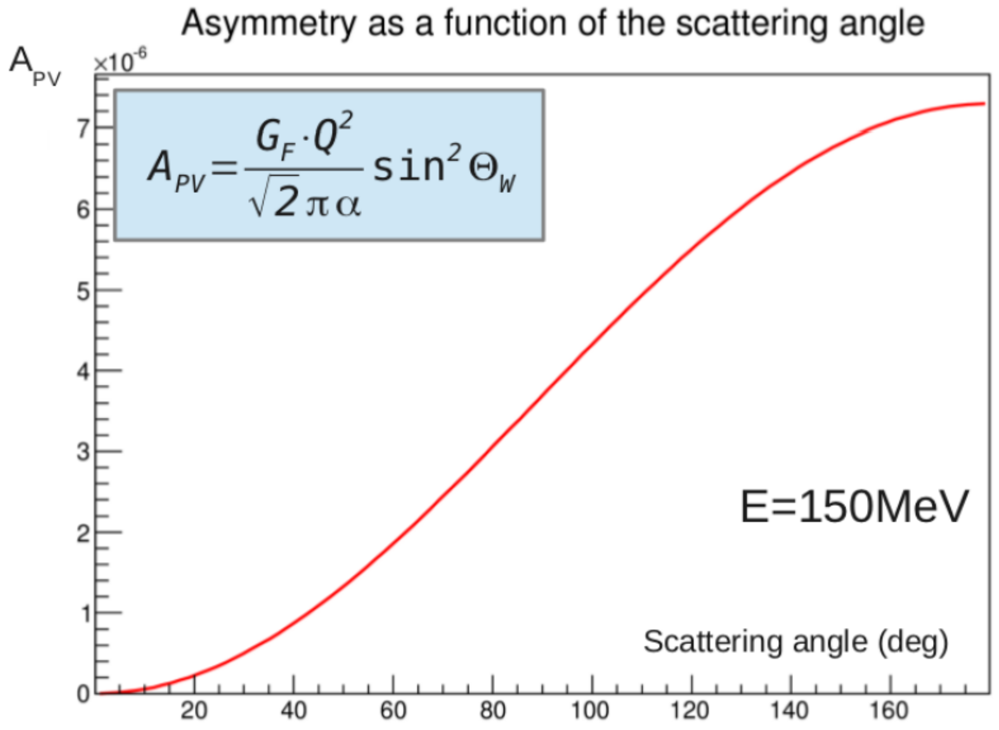
Weak charge $Q_W = 2T_3 - 4Q\sin^2\Theta_W$

Proton: $Q_W = 1 - 4\sin^2\Theta_W \approx 0.07$

^{12}C: $Q_W = -24\sin^2\Theta_W \approx -5.51$

=> Large asymmetry: 400 ppb

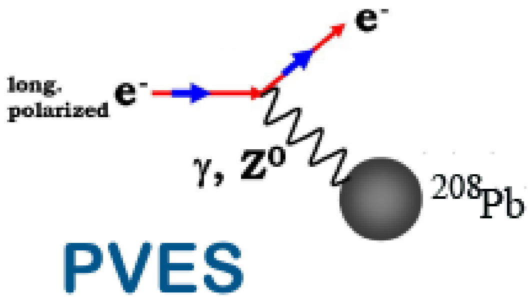
Carbon-12: Spin 0, Isospin 0: => No magnetic form factors, electric form factors cancel out in asymmetry formula

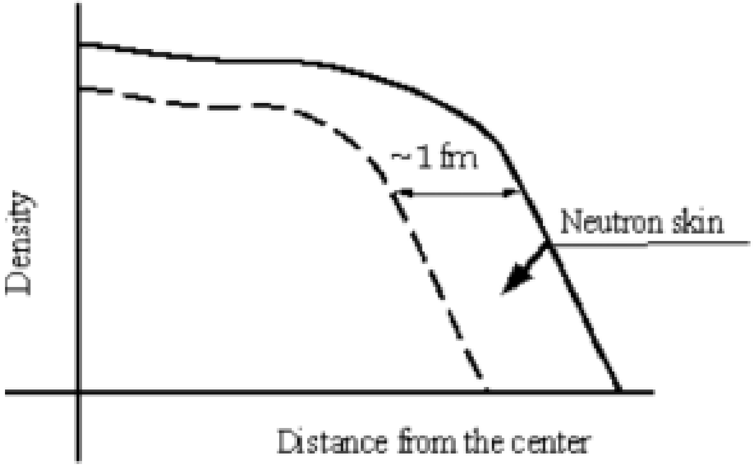


- Complimentary sensitivity to certain classes of new physics models
- Improved beam polarization measurement required

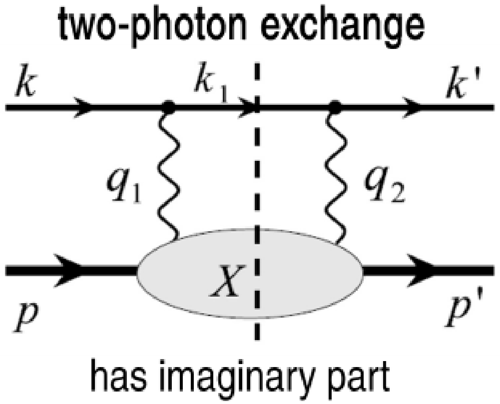
P2: further program

- ^{208}Pb: Neutron skin





- Two photo exchange amplitude



- ^{12}C: Complementary sensitivity to new physics

Weak charge $Q_W = 2T_3 - 4Q\sin^2\Theta_W$

Proton: $Q_W = 1 - 4\sin^2\Theta_W \approx 0.07$

^{12}C: $Q_W = -24\sin^2\Theta_W \approx -5.51$

P2: program

P2@MESA Hydrogen	P2@MESA Carbon	P2@MESA Calcium,Lead
A_{ep}=-28 ppb	A_{eC}= 416.3 ppb	A_{ePb}~ 700 ppb
ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h	ΔA_{ep}^{stat}= 2.7 ppb after 300 h ΔA_{ep}^{stat}= 0.9 ppb after 2500 h	MREX will improve the neutron skin thickness by a factor of two.
$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!	In addition measurements of transverse asymmetries
$\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.15 %	$\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.6 % (0.3%)	Two-Photon exchange amplitude
Aux. measurem. backward angle	Aux. measurem. backward angle	

Outline

- Accelerator facilities MAMI/MESA
- Beam Normal Single Spin asymmetries
  - BNSA with hydrogen target (A4 collaboration)
  - BNSA with heavier nuclei (A1 collaboration)
- P2 Experiment
  - Search for new physics: precision determination of $\sin^2\Theta_W$
  - Present status
- **Spin asymmetries at MAGIX**

Sherman function of nuclear resonances

- MESA beam energies and MAGIX spectrometers ideal for measuring low-energy nuclear resonances
- Resonances can constrain bulk nuclear properties
  - Possible correlation between dipole response (e.g., giant, pygmy dipole resonances) and neutron skin thickness R_{np}?
- Low-lying inelastic states background to R_{np} measurements with elastic parity-violating electron scattering (e.g. CREX, MREX)

- Polarized electron scattering observables contain additional sensitivity to structure of inelastic states
  - Sherman function (or analyzing power): transverse (vertical) spin asymmetry

$$S = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

  - Accessible at MAGIX with polarized MESA beam

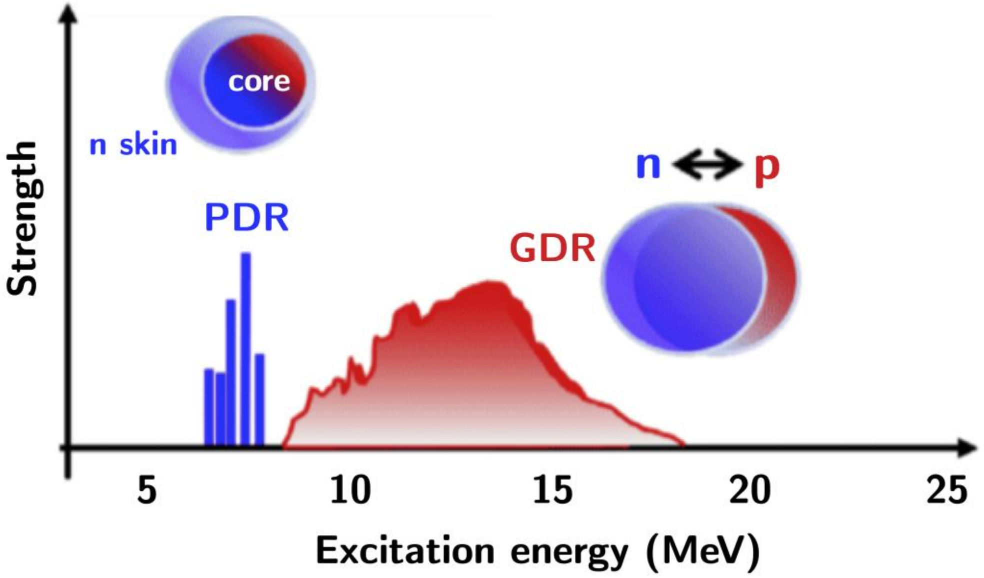


Figure adapted from *Prog. Part. Nuc. Phys. 106, 360 (2019)*

Summary and outlook

- MAMI: Measurement of BNSA for various nuclei
- MESA-P2: High precision determination of $\sin^2\Theta_W$ at low Q^2
    - Search for BSM physics
    - Extensive detector R&D
    - Start of measurements: Q4/2026
- MESA-MAGIX: Spin asymmetries for giant dipol resonances

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Precision studies

The parity violating asymmetry can be written as

$$A^{\mathrm{PV}} = \frac{-G_{\mathrm{F}}Q^2}{4\pi\alpha_{\mathrm{em}}\sqrt{2}}\left[Q_{\mathrm{W}}(\mathrm{p}) - F(E_{\mathrm{i}}, Q^2)\right]$$

with the form factor contribution

$$F(E_{\mathrm{i}}, Q^2) \equiv F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{A}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{S}}(E_{\mathrm{i}}, Q^2)$$

with

$$F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) \equiv \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{n},\gamma} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{n},\gamma}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

Electromagnetic FF

$$F^{\mathrm{A}}(Q^2) \equiv \frac{(1 - 4\sin^2\theta_{\mathrm{W}})\sqrt{1-\epsilon^2}\sqrt{\tau(1-\tau)}\,G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{A}}^{\mathrm{p},\mathrm{Z}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

Effective axial FF

$$F^{\mathrm{S}}(E_{\mathrm{i}}, Q^2) \equiv \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{s}} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{s}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2} + \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{u,d}} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{u,d}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

Strangeness FF

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