Spin Physics at MAMI and MESA

Frank Maas, Institut für Kernphysik and Helmholtz-Institut Mainz

25th International Spin Symposium (SPIN 2023)

Durham, NC, **September, 25 -29, 2023.**

HIM PRiSMA+

Outline

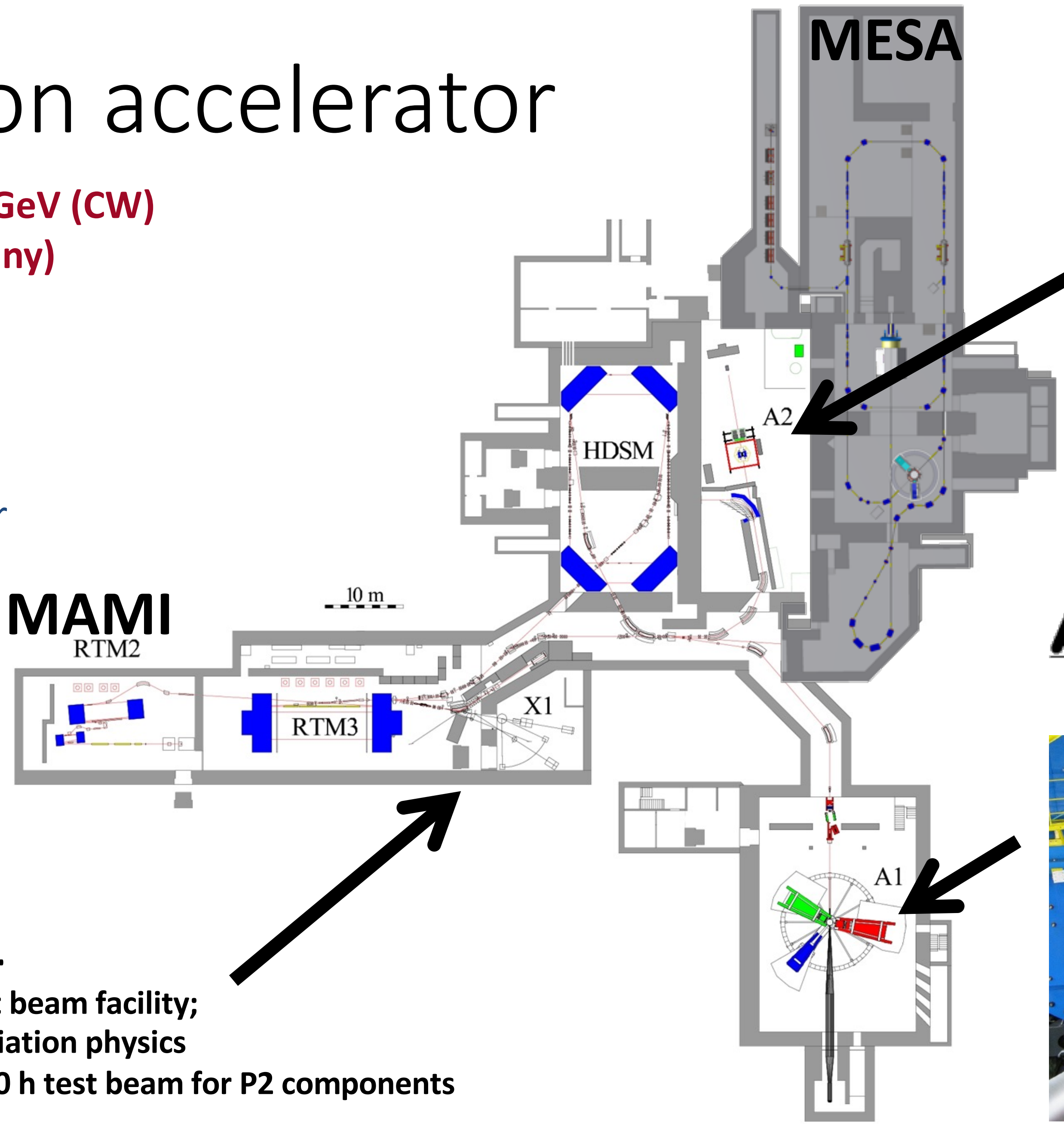
- Selected recent results and plans from MAMI
- Outlook on Spin Physics program at MESA

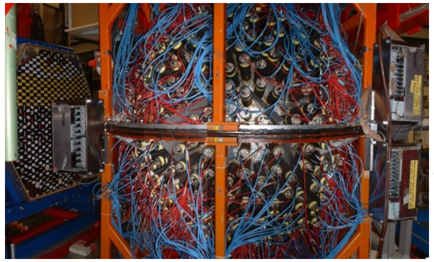
Selection of topics which are flashed
Thanks to T. Kolar, M. Thiel, A. Thomas, M. Ostrick, C. Sfienti, S. Schlimme
for the many transparencies

MAMI Electron accelerator

Electron Accelerator E_{max} =1.6 GeV (CW)
operated at JGU Mainz (Germany)
Hallmarks

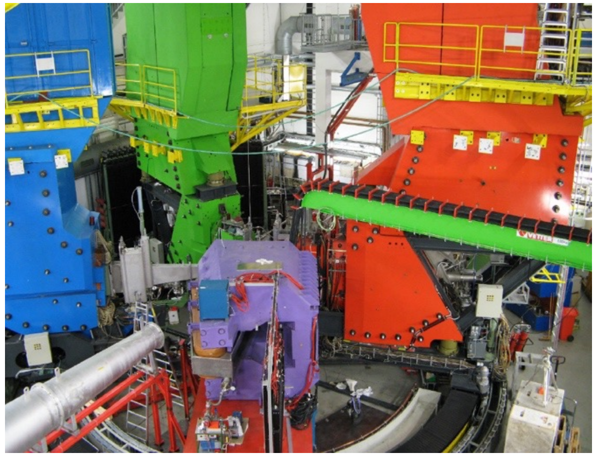
- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: up to 7000 h / year





Tagged Photon Scattering (A2 hall)
Crystal Ball / TAPS calorimeters;
Polarized frozen-spin target

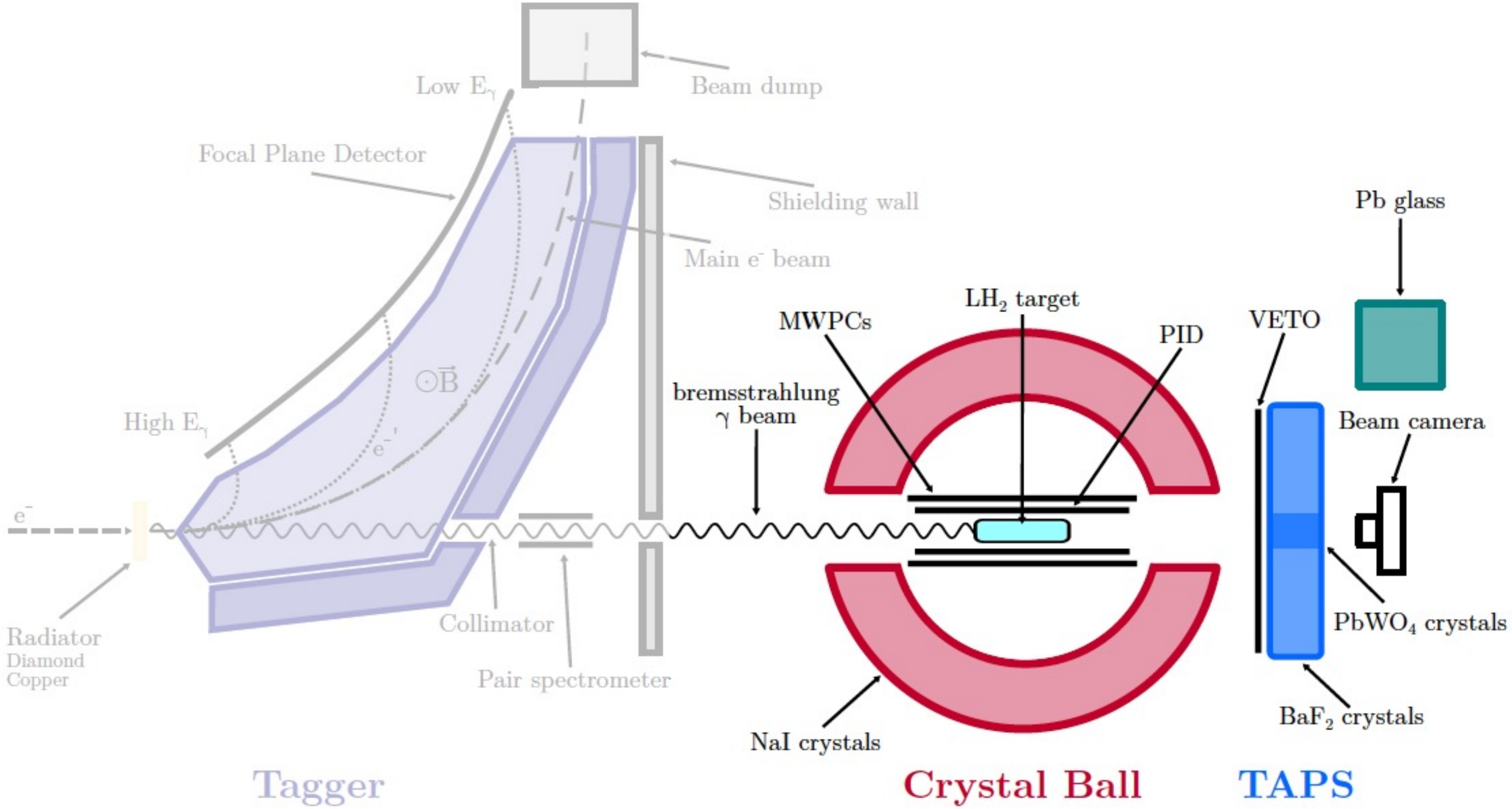
Electron scattering
(A1 hall)
High resolution
Magnetic spectrometers



X1

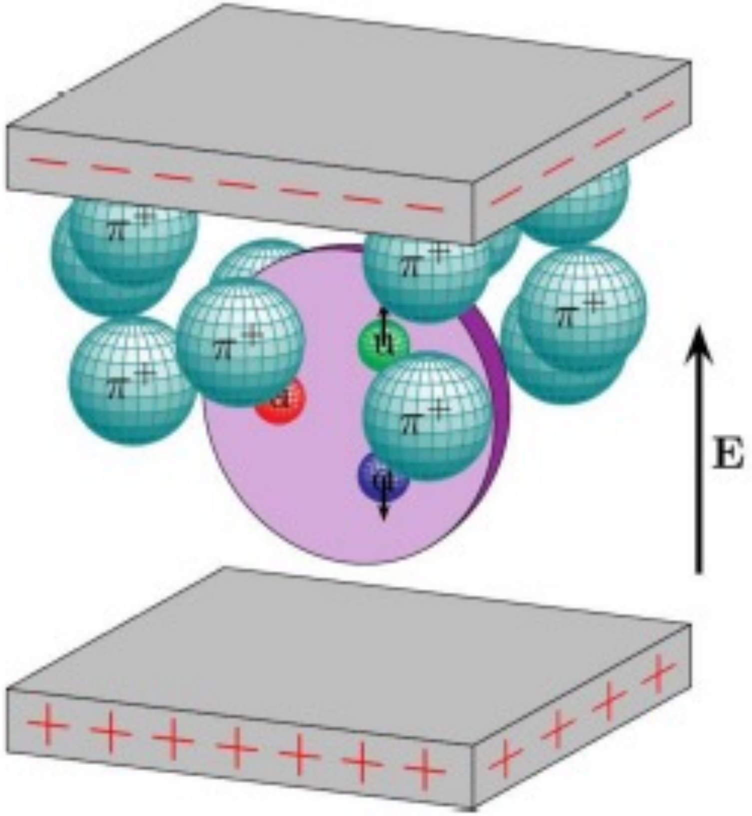
Test beam facility;
Radiation physics
2000 h test beam for P2 components

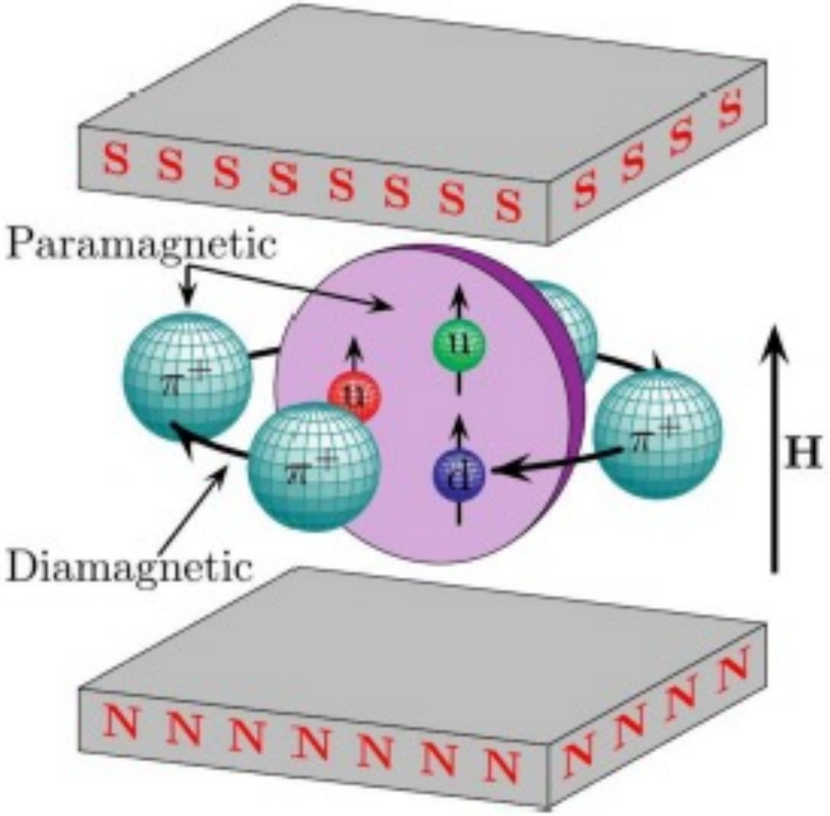
A2 Setup at MAMI



Polarized and unpolarized target available

Proton Polarizabilities





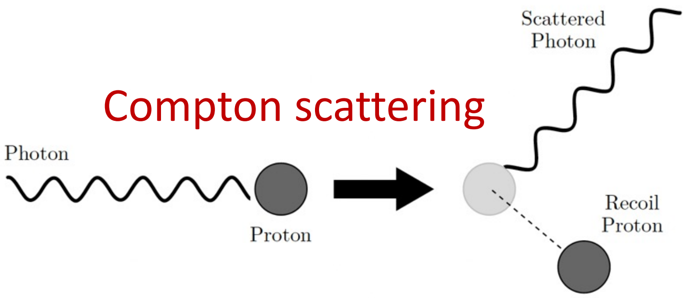
Proton Polarizabilities @ A2/MAMI

Reaction of nucleon under influence of an EM field provides fundamental information of the nucleon; very sensitive test of theories (H/BχPT, Disp. Rel.).

- Electric Polarizability: α_{E1}
- Magnetic Polarizability: β_{M1}

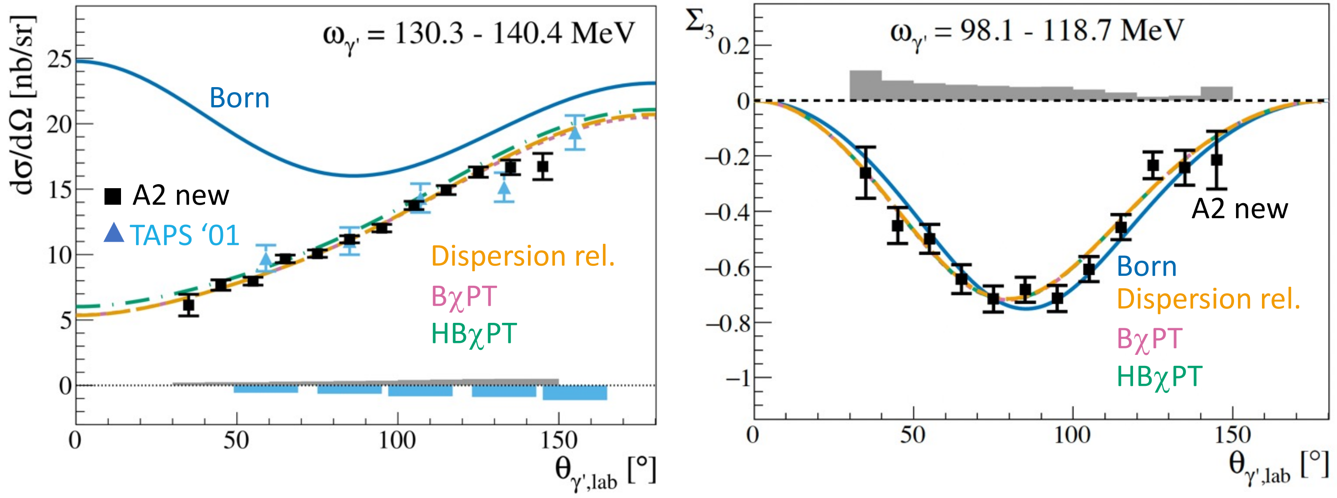
$$H_{\text{eff}}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

Compton scattering

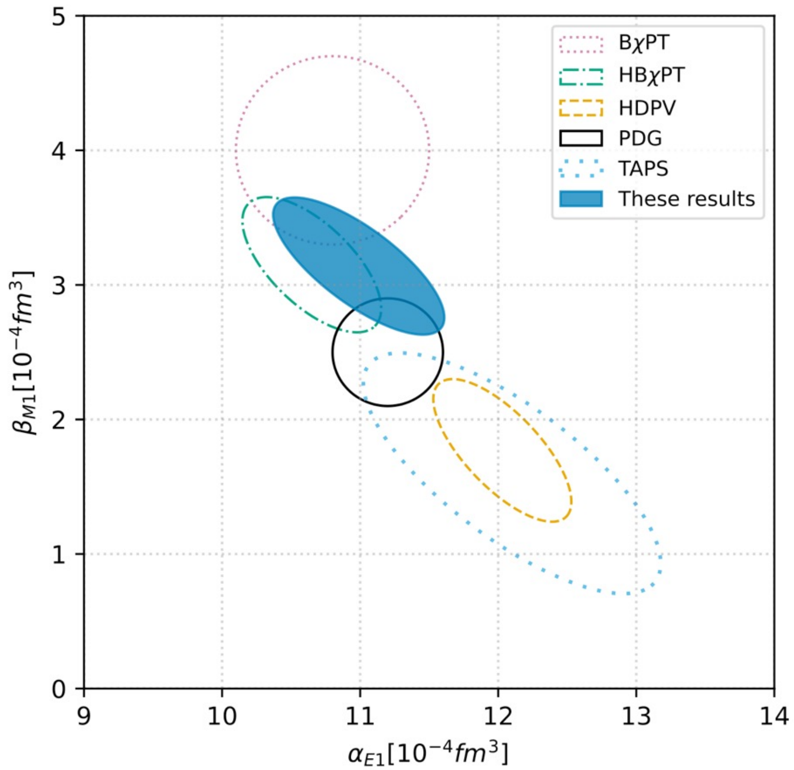


- in addition 4 Spin Polarizabilities

Exploit linear beam polarization to measure asymmetry $\Sigma_3 \equiv \frac{d\sigma^\perp - d\sigma^\parallel}{d\sigma^\perp + d\sigma^\parallel}$



PRL 128 (2022) 132503



	stat	syst.	spin polar.	model dep.

$$\alpha_{E1} = 10.99 \pm 0.16 \pm 0.47 \pm 0.17 \pm 0.34$$

$$\beta_{M1} = 3.14 \pm 0.21 \pm 0.24 \pm 0.20 \pm 0.35$$

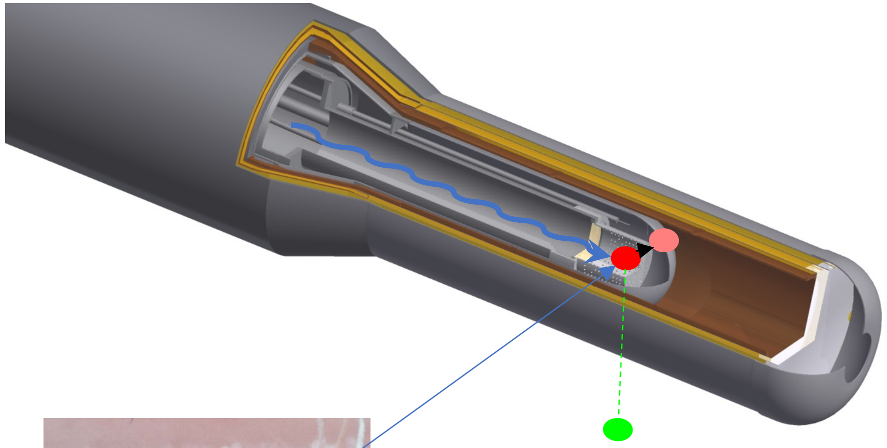
stat syst. spin polar. model dep.

PRL 129 (2022) 102501

Talk by D. Hornidge

Polarized target which acts as detector (active target)

Mike Biroth (UMainz):
The Mainz Active Polarized Proton Target - Review and Perspectives

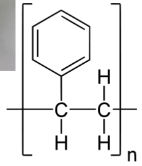


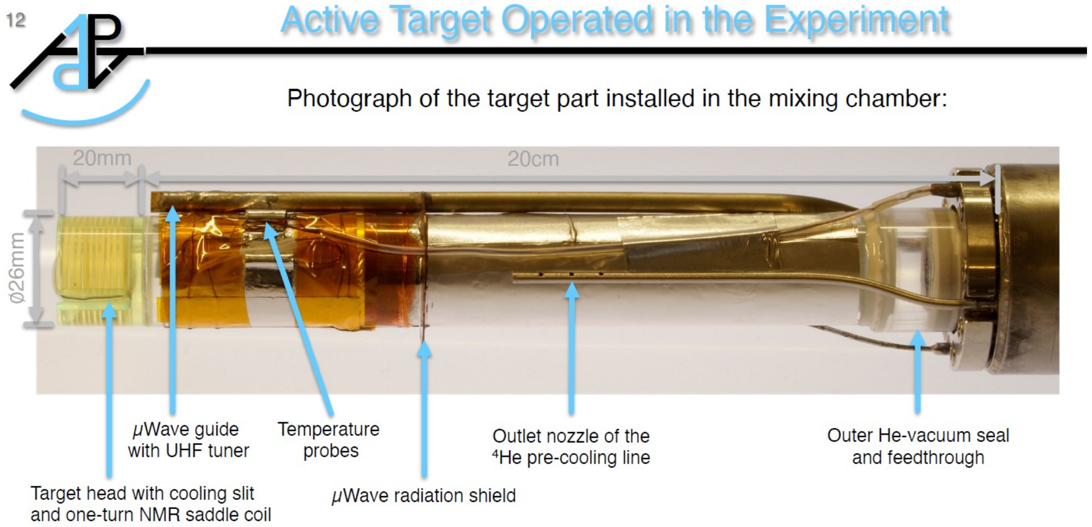
butanol ($C_4H_9[OH]$)

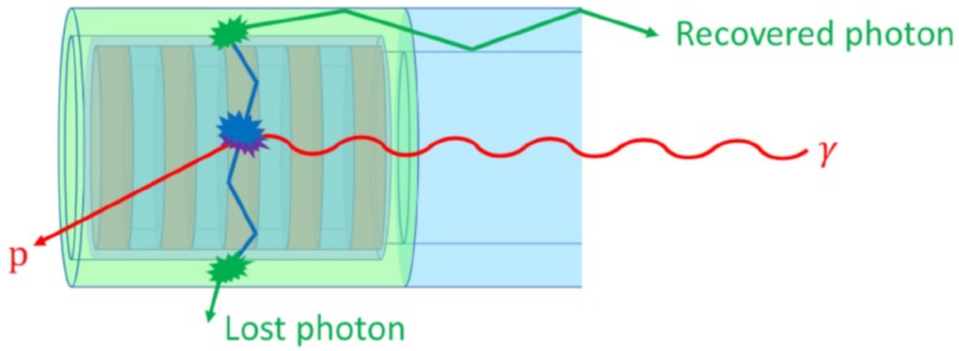
replace

- find a suitable radical for DNP
- polarize
- get the light out

polystyrene

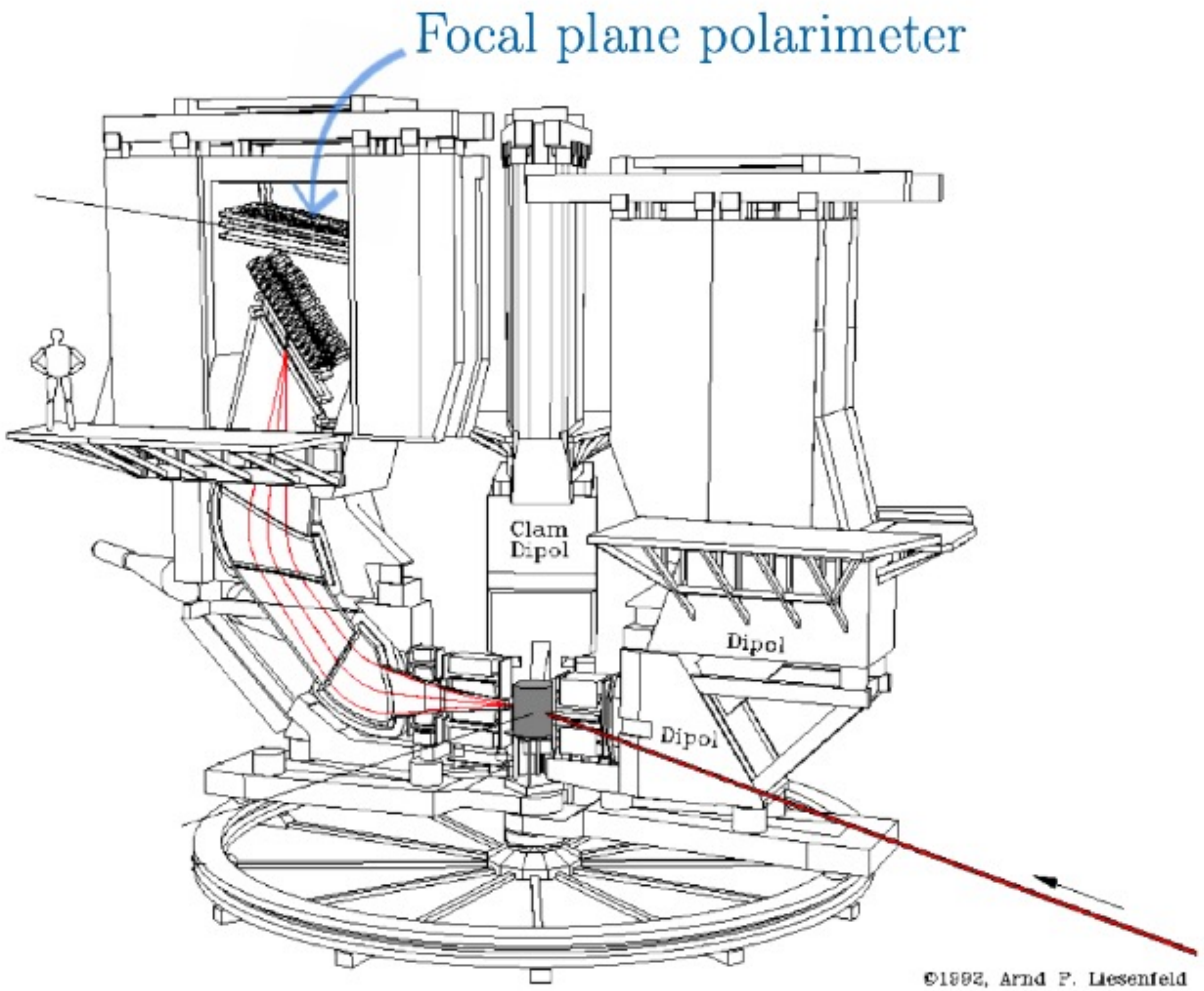






Talk by H. Dutz

○ Three-spectrometer setup (A1 hall, MAMI)



Proton generalized Polarizabilities @ A1/MAMI

Accessible via Virtual Compton Scattering:

Virtuality of photon gives access to Generalized Polaribilitiess :
$\alpha_E(Q^2)$; $\beta_M(Q^2)$ (+ 4 spin GPs)

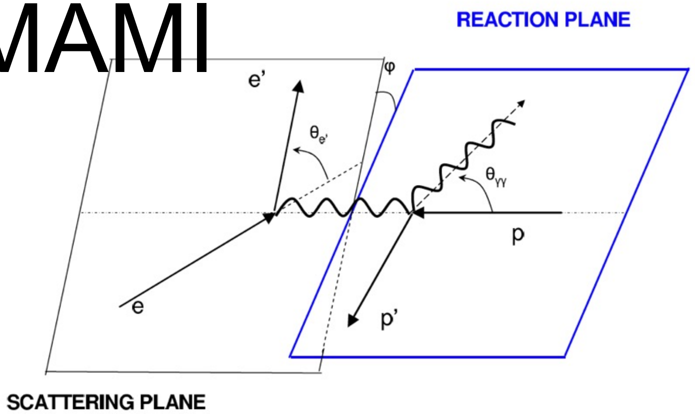
→ mapping out the spatial distribution of the polarization densities

→ Fourier transform of densities of electric charges and magnetization of a nucleon deformed by an applied EM field

in plane

oop (8.5°)

Proton generalized Polarizabilities @ A1/MAMI



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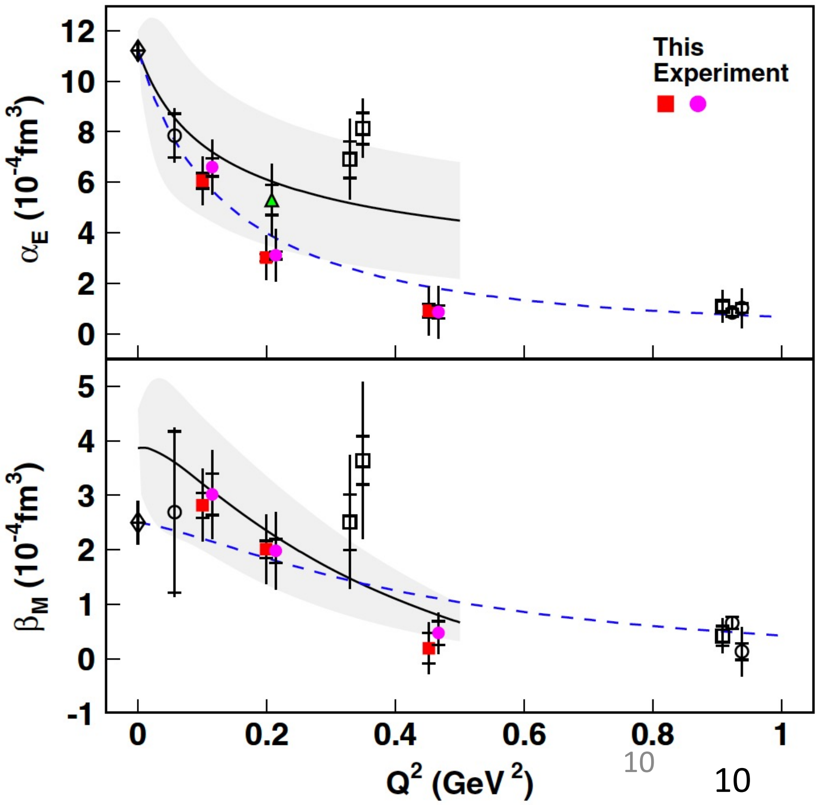
PRL123 (2019) 192302



New MAMI data in two measurement campaigns:

- Detailed understanding of systematics (4 PhD students)
- Out of plane (oop) measurement to access kinematic range, in which higher order terms small and extraction possible
- Final extraction according to LEX (low energy expansion) and DR
- First extration of N-Δ transition FF via gamma channel

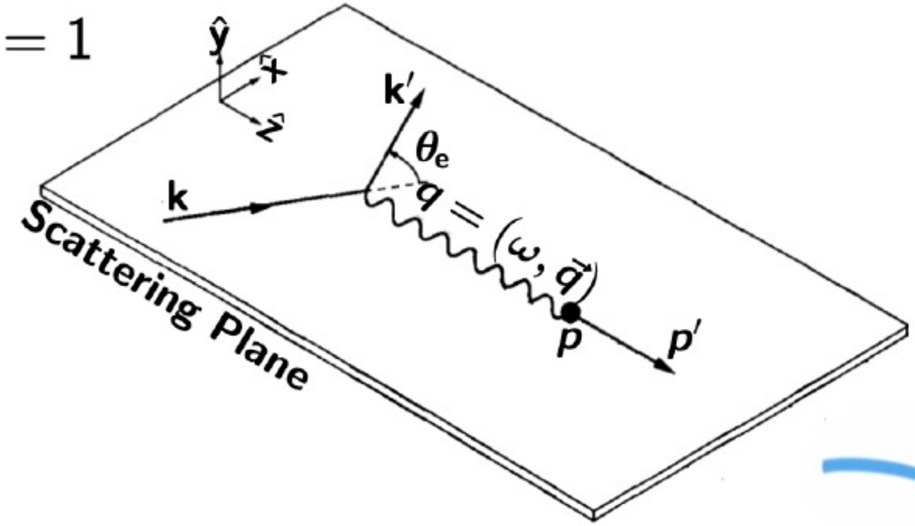
in plane

oop (8.5°)

Polarization transfer in $A(\vec{e}, e'\vec{p})$

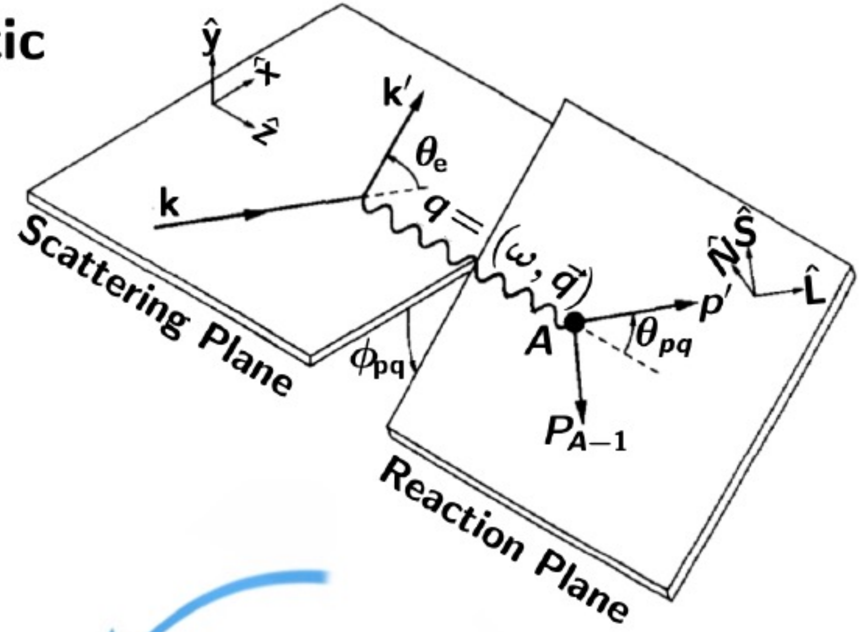
Elastic

$A = 1$



Quasi-elastic

$A > 1$



$$\frac{(P'_x/P'_z)_{\mathrm{A}}}{(P'_x/P'_z)_{\mathrm{H}}} \propto \frac{(G_E/G_M)_{\mathrm{A}}}{(G_E/G_M)_{\mathrm{H}}}$$

Sensitivity to nuclear density, medium modifications and short range correlations

Polarization d.f. in $A(e, e'p)$

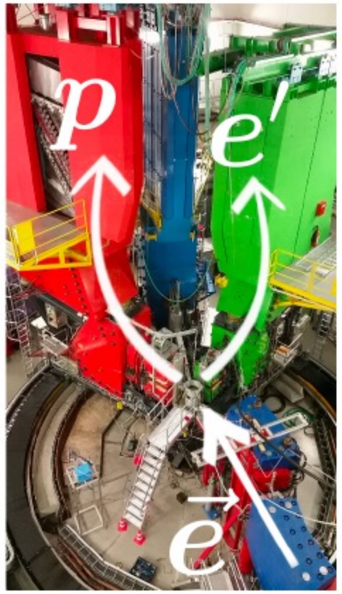
el. analyzing power $A(\vec{e}, e'p)$

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}E_{e'}\mathrm{d}\Omega_{e'}\mathrm{d}E_{p'}\mathrm{d}\Omega_{p'}} = \frac{|\vec{p}\,'|E_{p'}}{8\pi^2}\frac{E_{e'}}{E_e}\frac{\alpha^2}{Q^4}L_{\mu\nu}W^{\mu\nu} = \Sigma + h\Omega = \frac{\sigma_0}{2}\left[1 + \vec{P}\cdot\vec{\sigma} + h(A + \vec{P}\,'\cdot\vec{\sigma})\right]$$

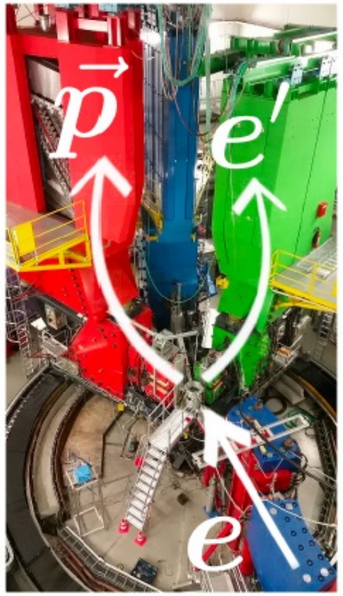
induced $A(e, e'\vec{p})$

transferred $A(\vec{e}, e'\vec{p})$

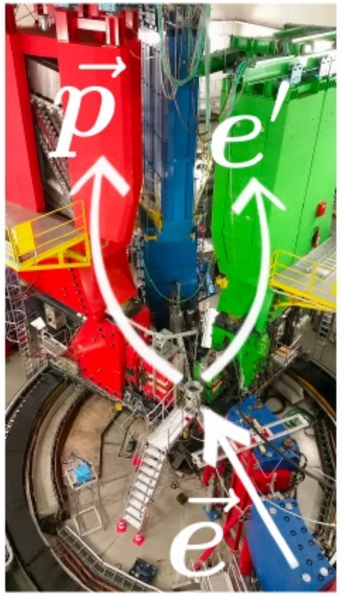
- Electron analyzing power



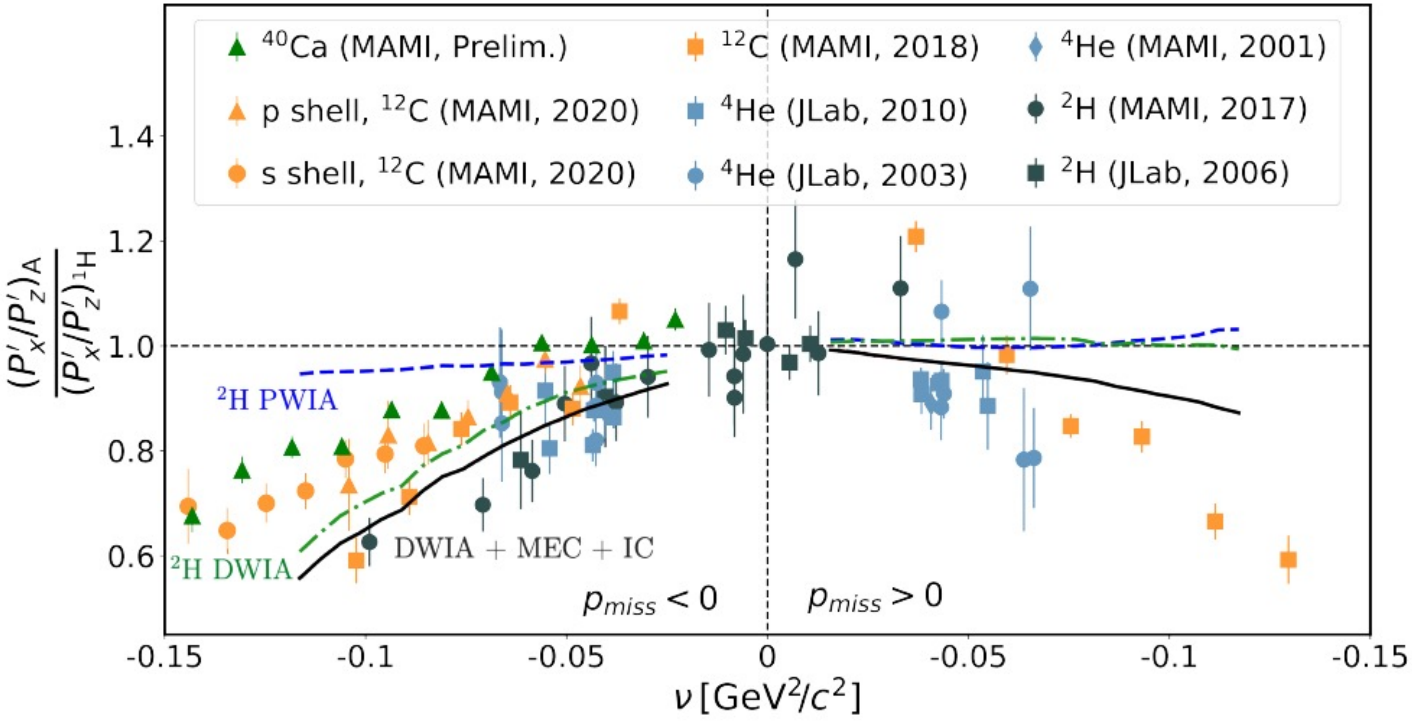
- Induced polarization



- Transferred polarization



Polarization transfer in $A(\vec{e}, e'\vec{p})$



→ We measured transfer for several target nuclei

^{2}H

PLB **769** 21 (2017)

PLB **781** 107 (2018)

PLB **795** 599 (2019)

^{12}C

PLB **781** 95 (2018)

PRC **101**, 064615 (2020)

PLB **811** 135903 (2020)

^{40}Ca

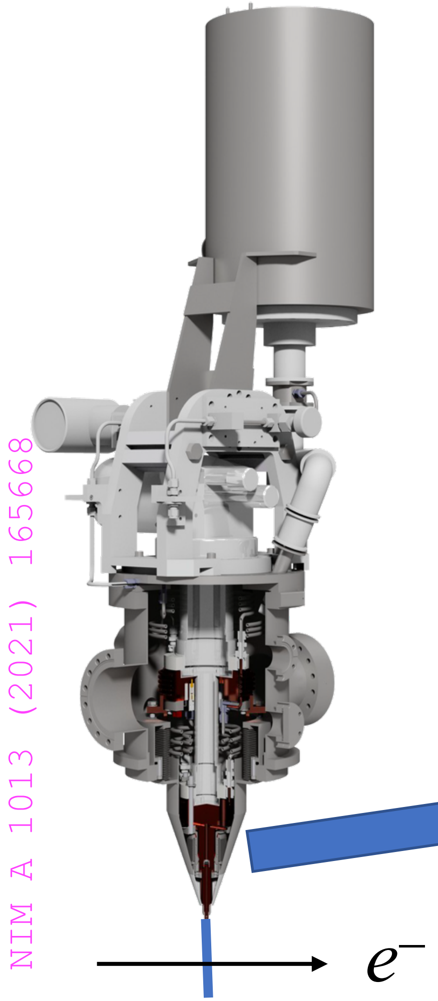
(arXiv:2306.05565, submitted to PLB)

→ Virtuality measures how far of its mass shell is proton

$$\nu = (m_p^2)_{\text{bound}} - m_p^2$$

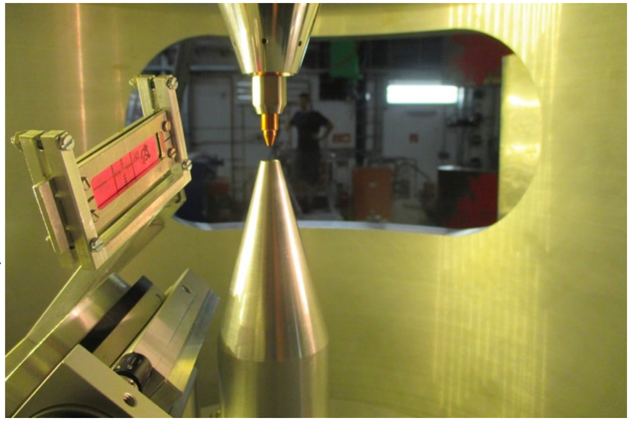
- The double ratio is sensitive to other many-body effects such as final state interaction

supersonic Gas-Jet Target (a1/MAMI, later Magix/MESA)

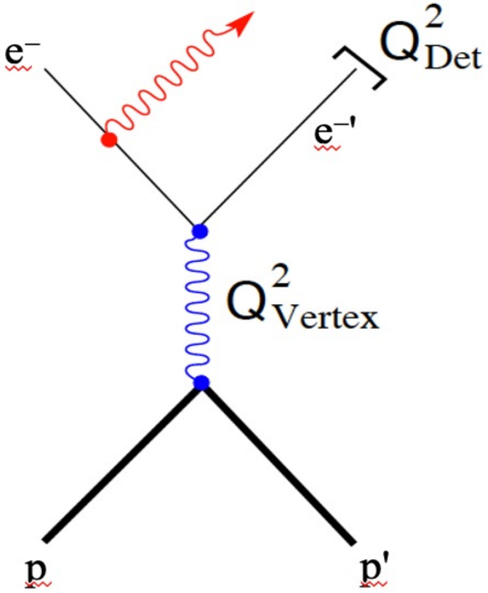


Construction of a high-density gas jet target in cooperation with University of Münster (A. Khoukaz)

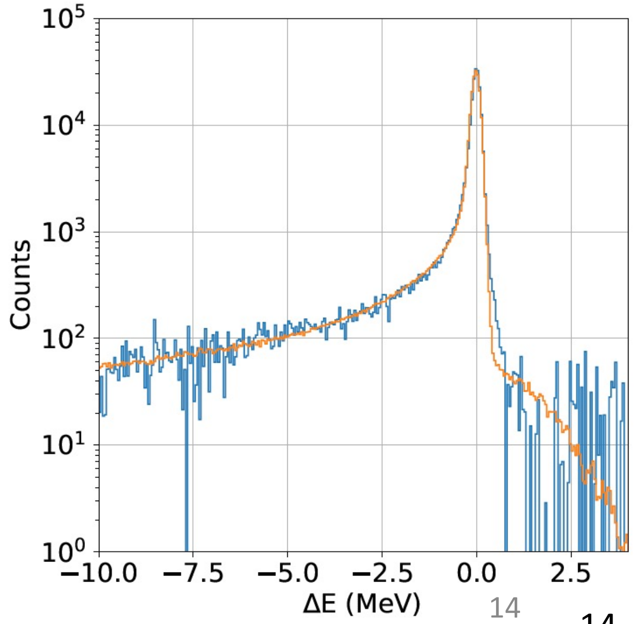
- Future MAGIX experiment at MESA: combination of light gas jet target with ERL electron beam
- Commissioning at A1/MAMI already now
  → Measurement of electron-proton scattering (proton EM factors = flagship project @ Mainz)
  → Most precise determination of proton radius in electron scattering (Bernauer et al. 2010); accuracy limited by scattering of electrons at walls of liquid hydrogen target
- New measurement of G_E with gas jet target via Initial state radiation
  → access low momentum transfer 0.01 GeV²/c²



window-less, thin, point-like target !



Phys.Rev.C 106 (2022) 4, 044610



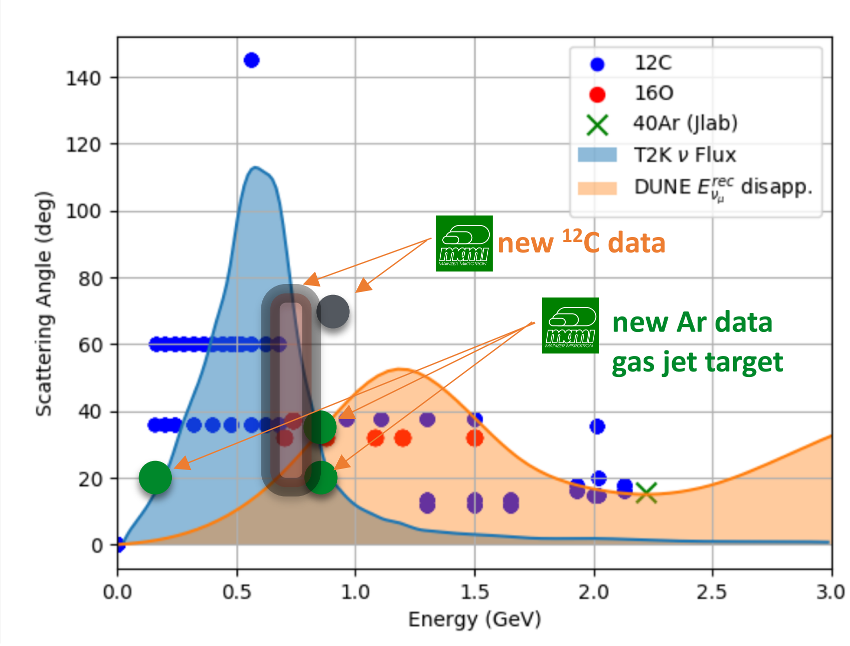
Electrons for neutrinos A1

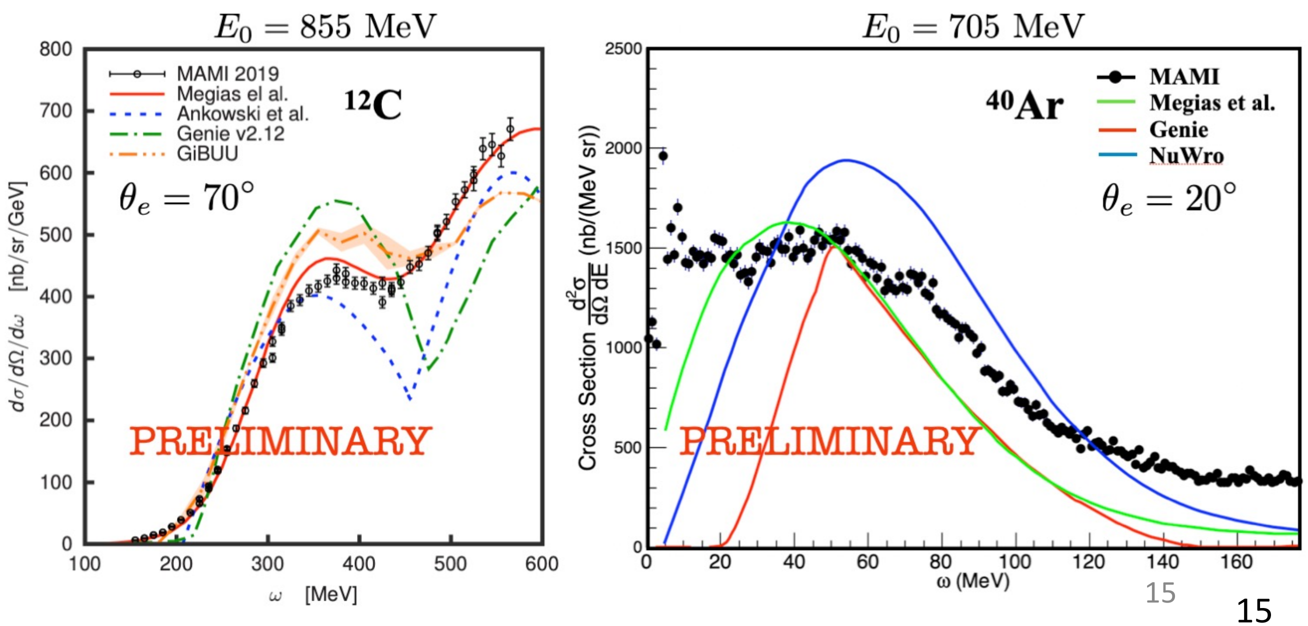
Interpretation of current and future generation of **neutrino experiments** (DUNE,T2K, Hyper-K, Mini-Boone, ...) requires knowledge of **neutrino-nucleus interaction:**
^{12}C, ^{16}O, ^{40}Ar

→ **Check and calibrate MC-generators** via dedicated program of **electron-nucleus measurements**

→ **MAMI energy range complementary to program at JLAB**

courtesy Sören Schlimme

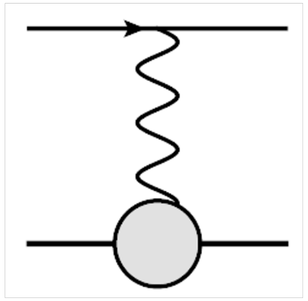




Two photon exchange in elastic electron scattering

high-precision experiments ➡ need to go beyond Born approximation

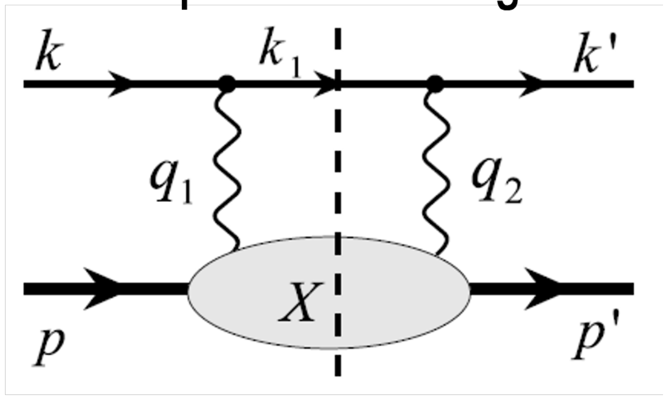
one-photon exchange



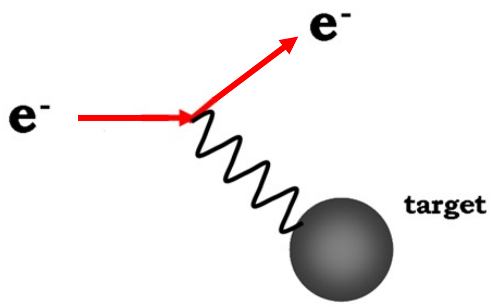
purely real

+

two-photon exchange



has imaginary part



interference of one- and two-photon exchange causes

beam-normal single spin asymmetry A_n

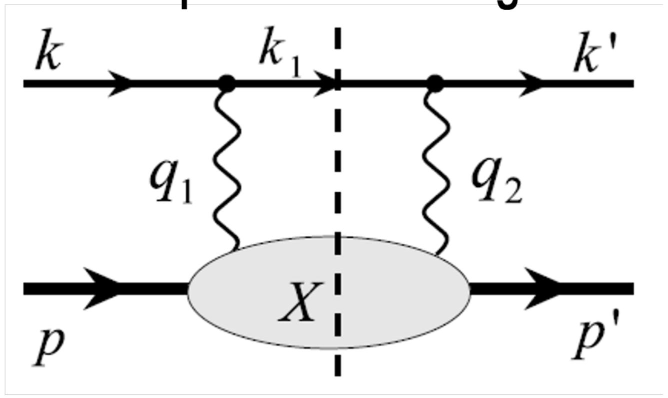
De Rújula et al., Nucl. Phys. B35, 365 (1971)

Talk by M. Thiel and P. Blunden

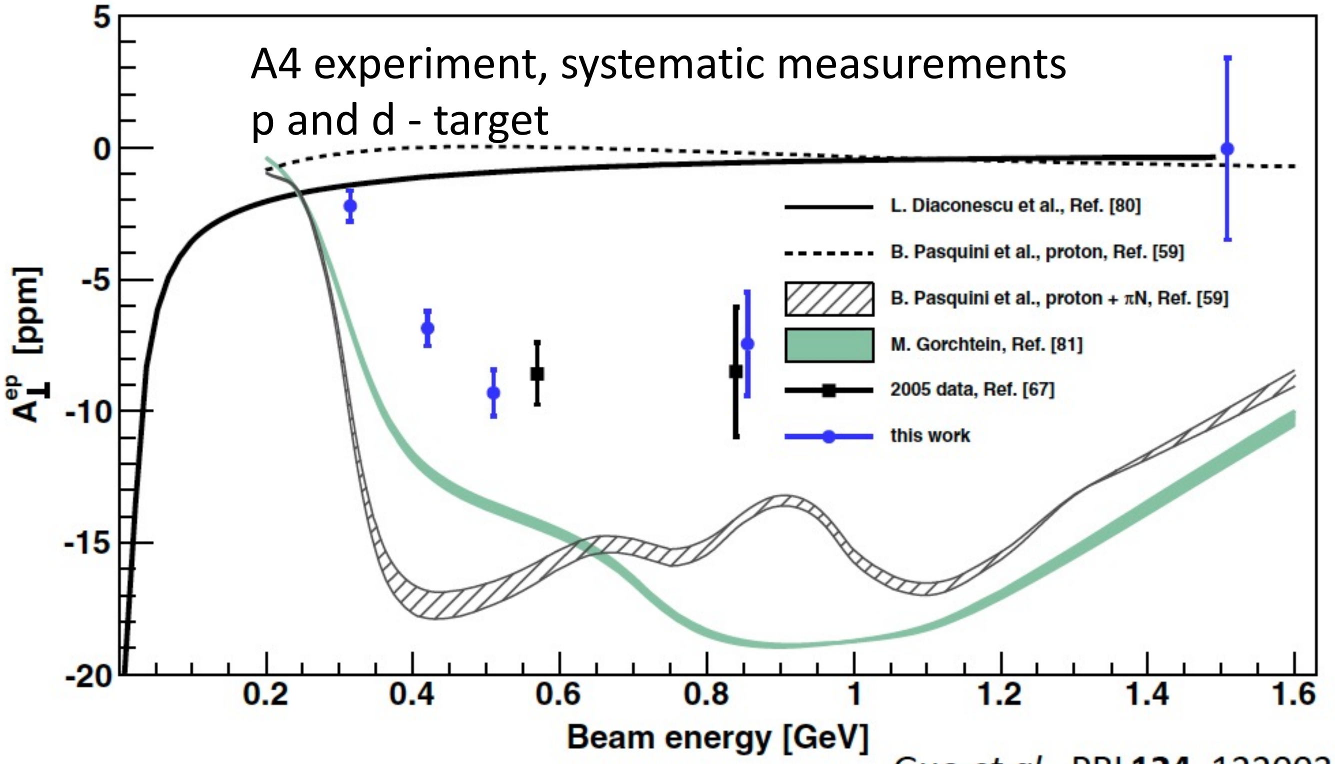
➡ **allows access of imaginary part of 2γ exchange amplitude**

Two photon exchange on elastic electron scattering

two-photon exchange

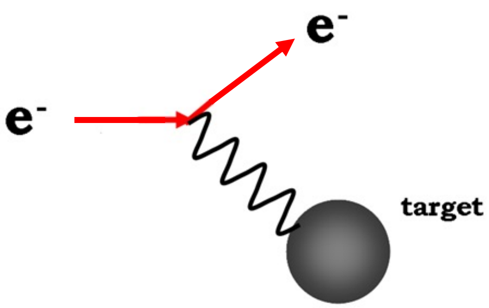


has imaginary part



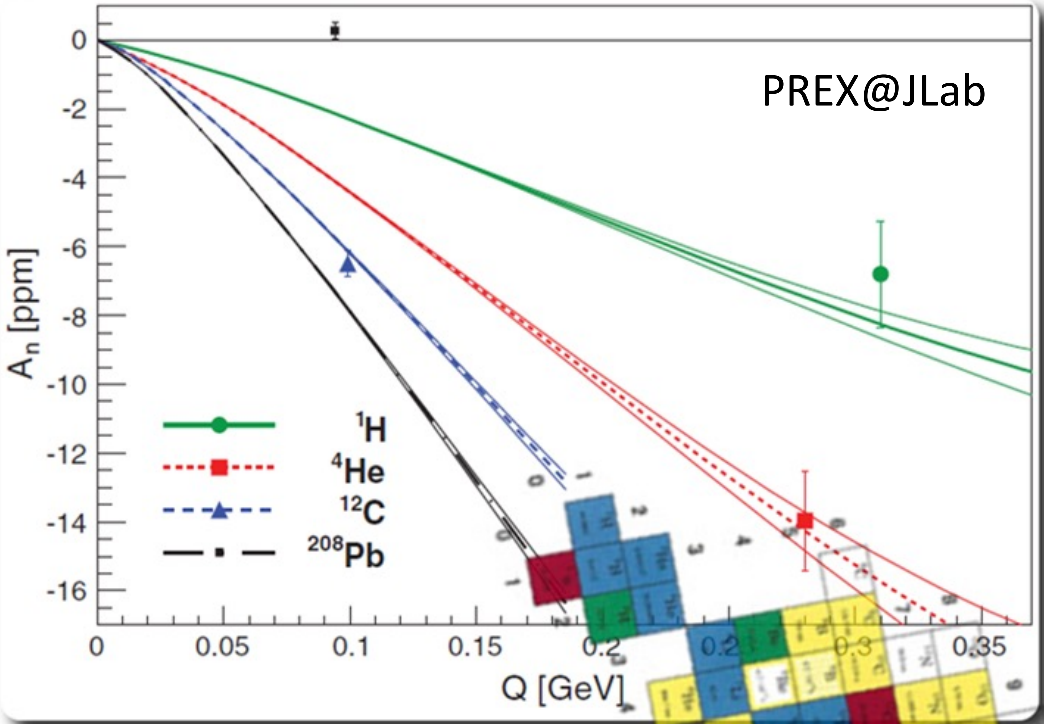
Guo *et al.*, PRL**124**, 122003 (2020)

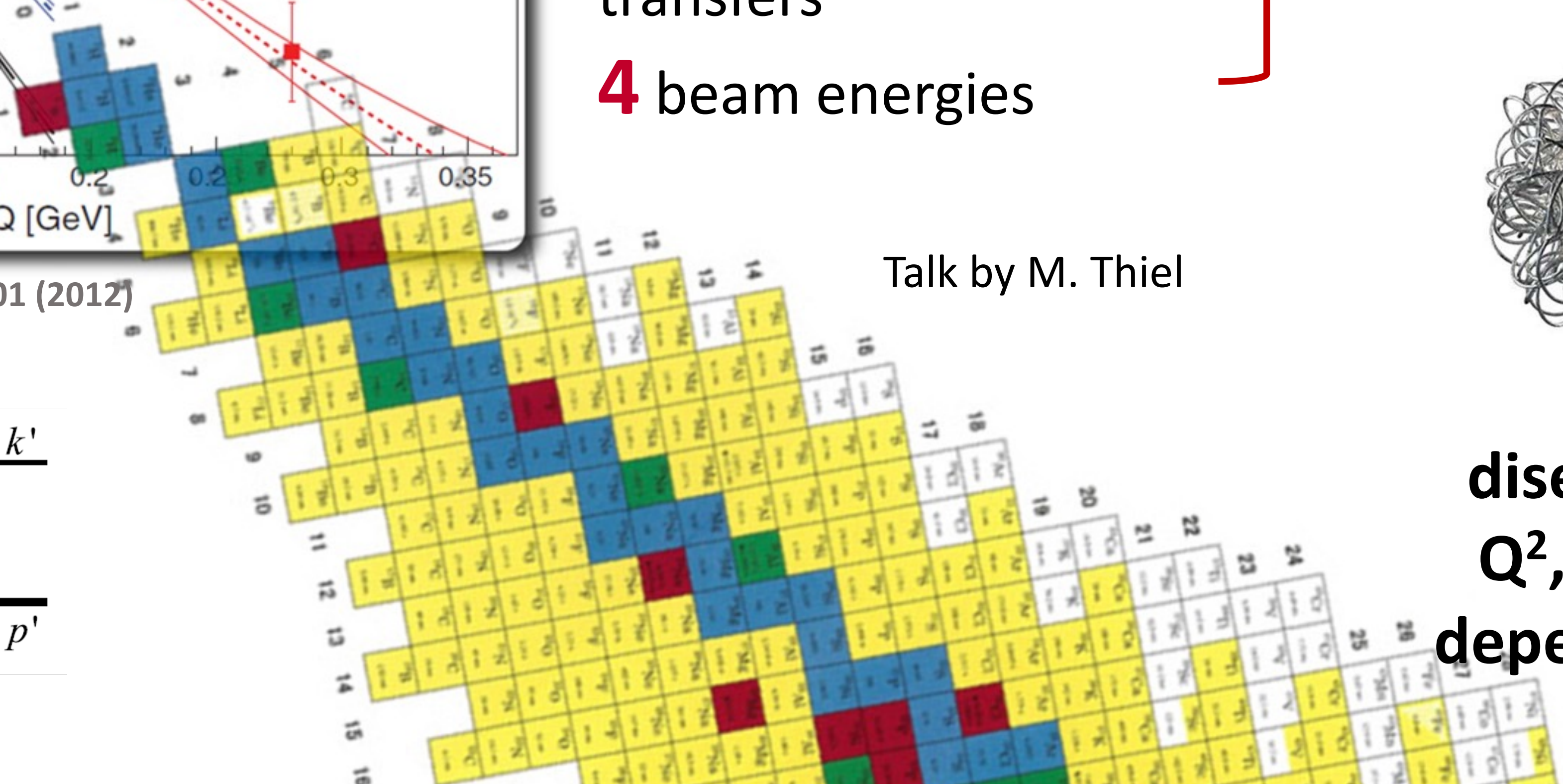
- Many observables: Target normal spin asymmetry, Beam normal spin asymme
- Different physics for proton target or nu target



Talk by P. Blunden

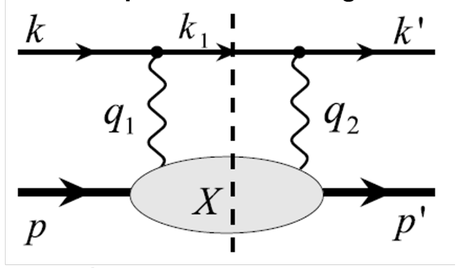
the whole nuclear chart in a small band





S. Abrahamyan et al., PRL 109, 192501 (2012)

two-photon exchange



has imaginary part

4 nuclei at:

2 scattering angles

3 four-momentum transfers

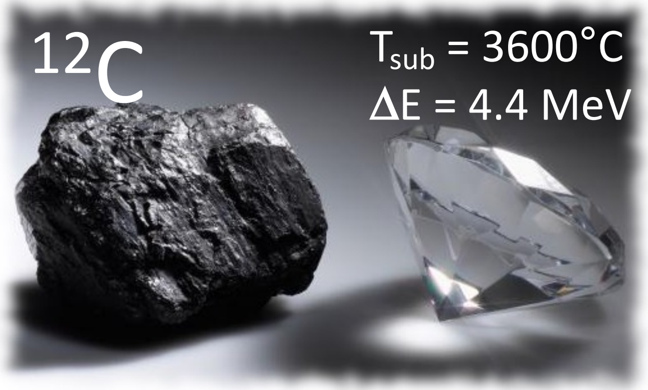
4 beam energies

systematic study needed

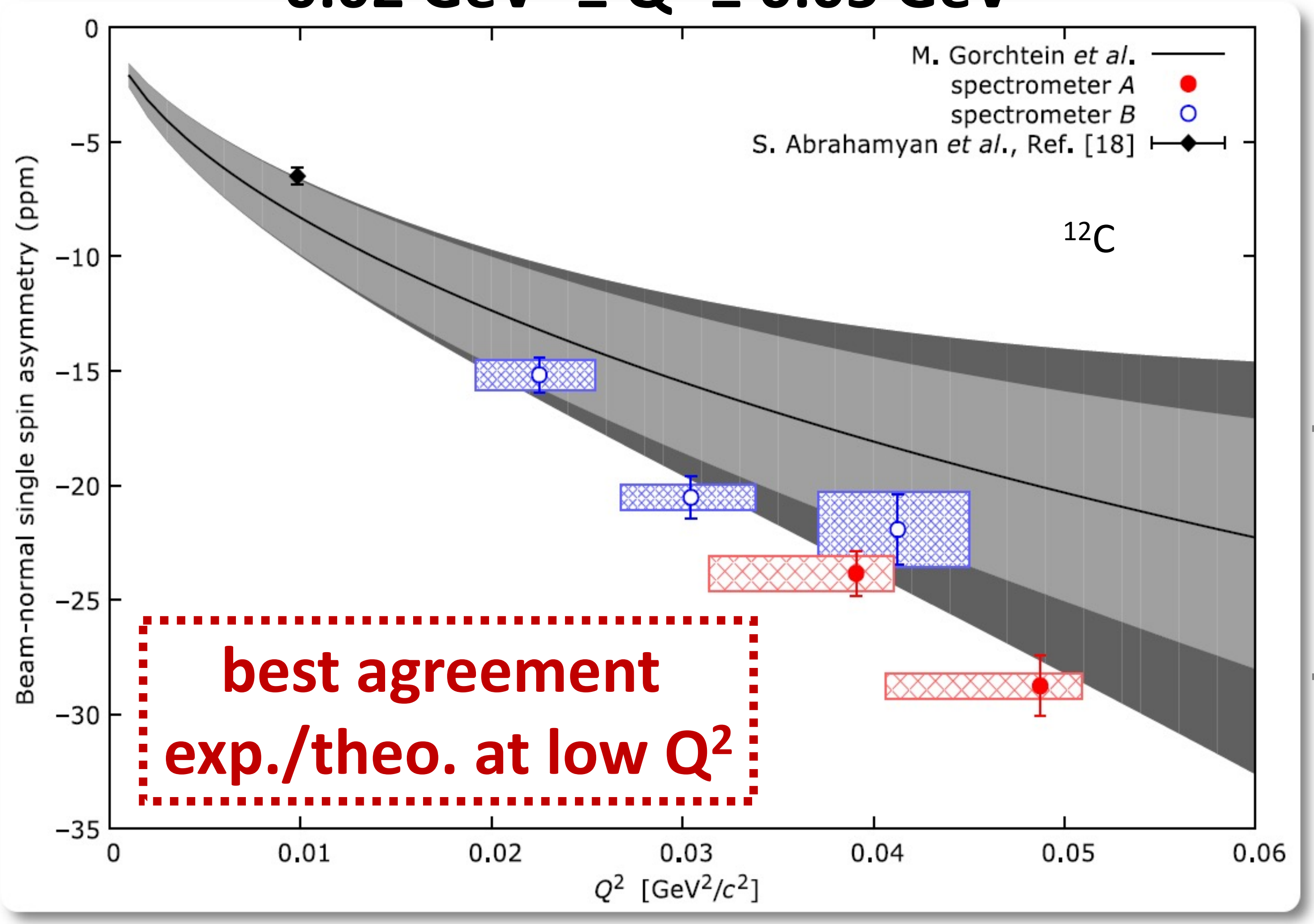
to disentangle Q^2, Z and E dependencies !

Talk by M. Thiel

results – Q^2 dependence



$0.02\ GeV^2 \leq Q^2 \leq 0.05\ GeV^2$



uncertainty of Compton slope parameter:

± 10%

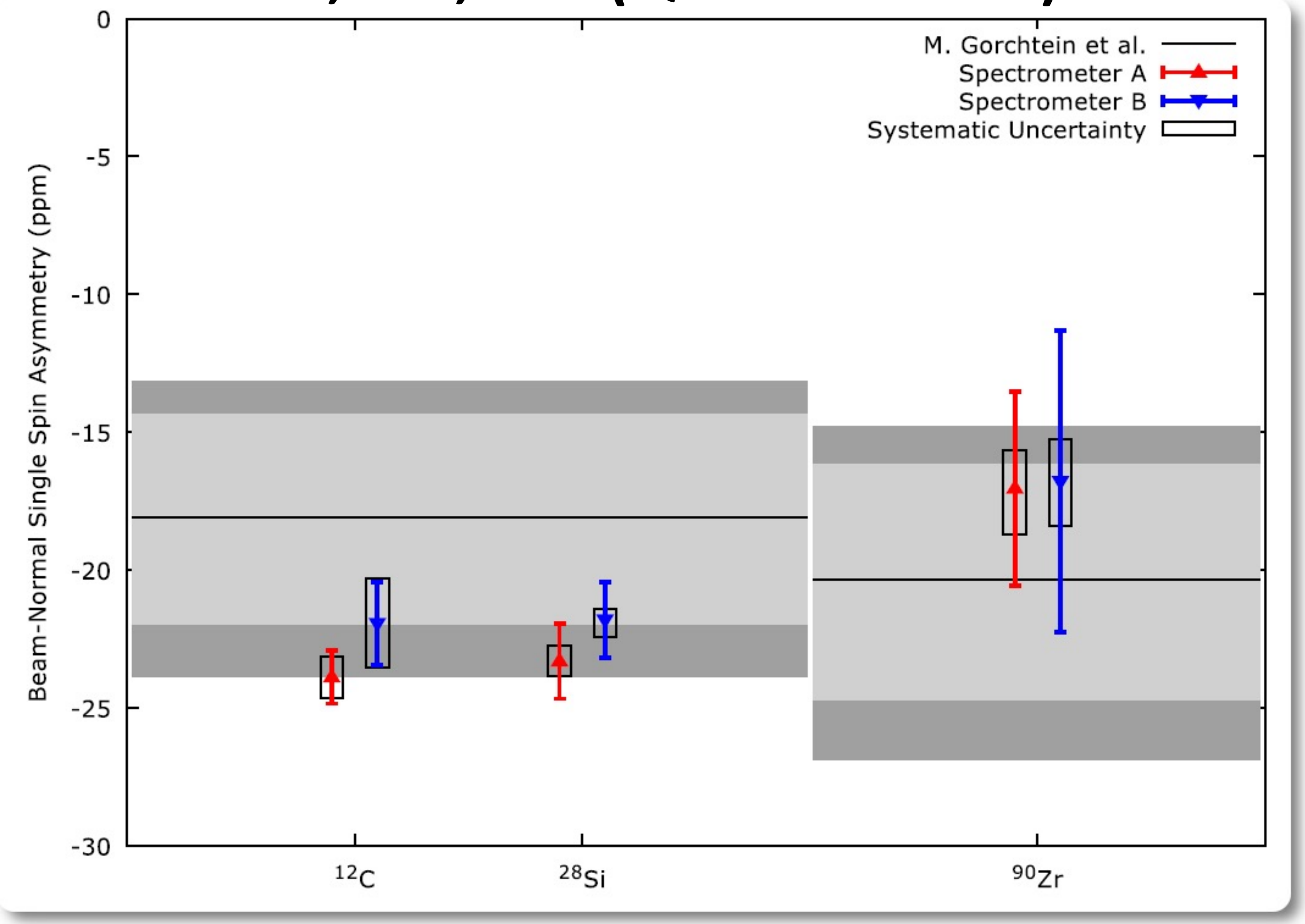
± 20%

A. Esser et al., PRL 121, 022503 (2018)

Talk by M. Thiel

results – A dependence

^{12}C, ^{28}Si, ^{90}Zr (Q^2 = 0.04 GeV^2)



A. Esser et al., PLB 808, 135664 (2020)

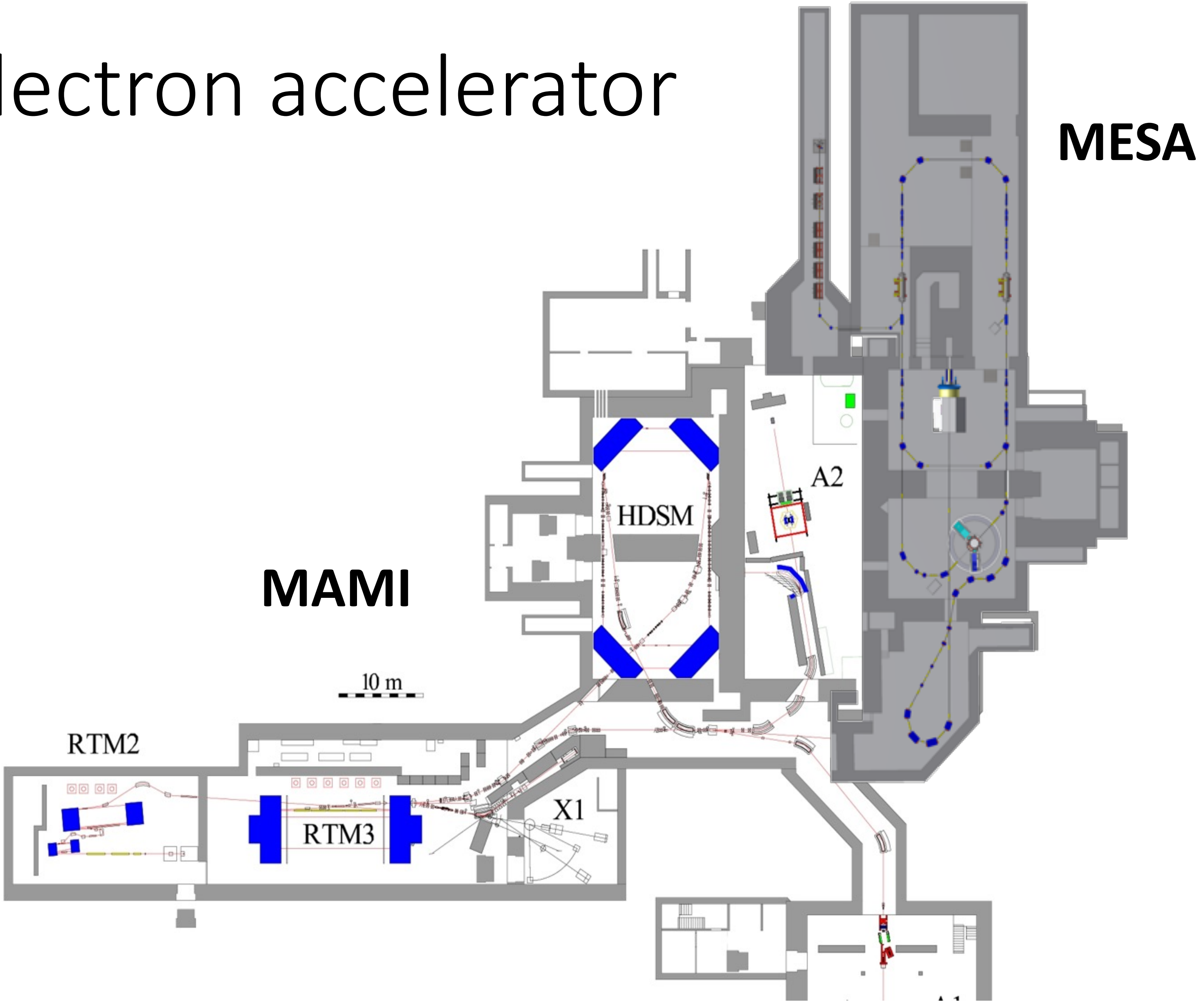
uncertainty of Compton slope parameter:

± 10%   ± 20%

Next steps: new DAQ electronics and lead target in A1-Spectrometers at MAMI

Talk by M. Thiel

MESA Electron accelerator

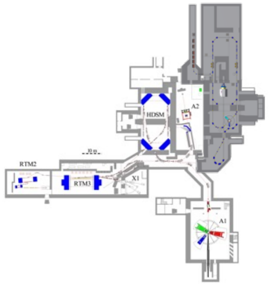


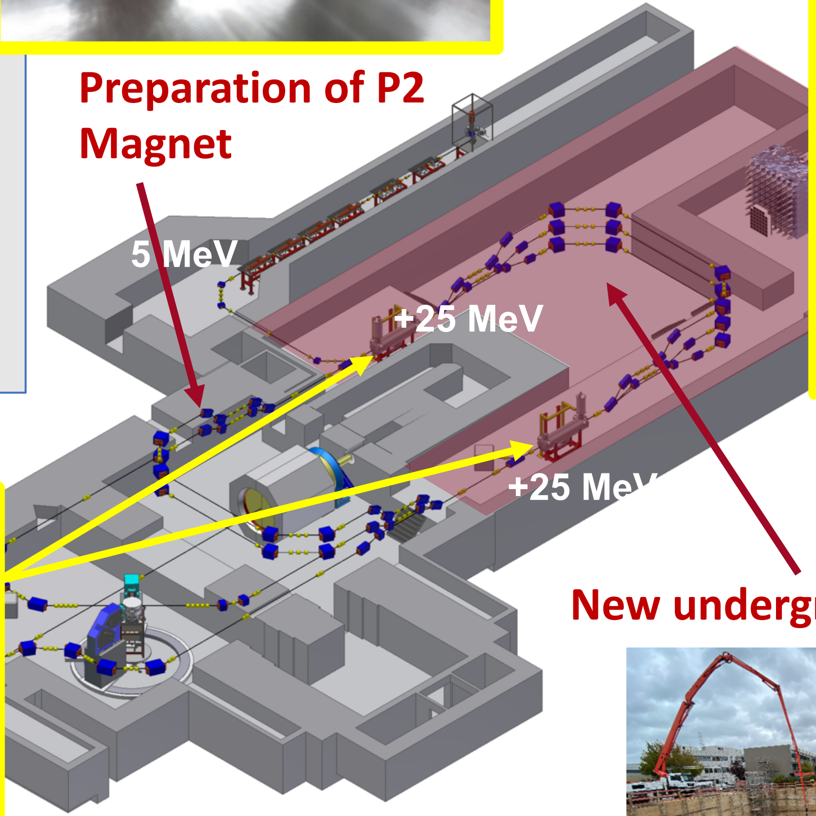
Mesa accelerator

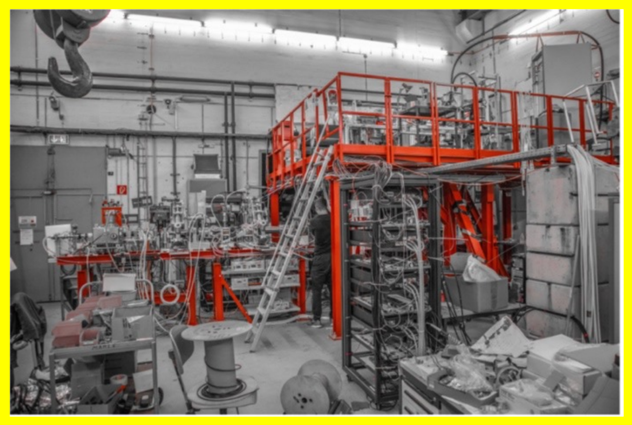
Key parameters MESA:

- Two operation modes: extracted beam (EB) or energy recovering (ERL)
- Max. beam energy 155 MeV (EB), 105 MeV (ERL)
- Beam current 150 µA (EB), 1 mA (ERL)
- Superconducting cavities
- Start commissioning 2024
- New research building (par. 91b GG)
- Can run in parallel to MAMI

Preparation of P2 Magnet

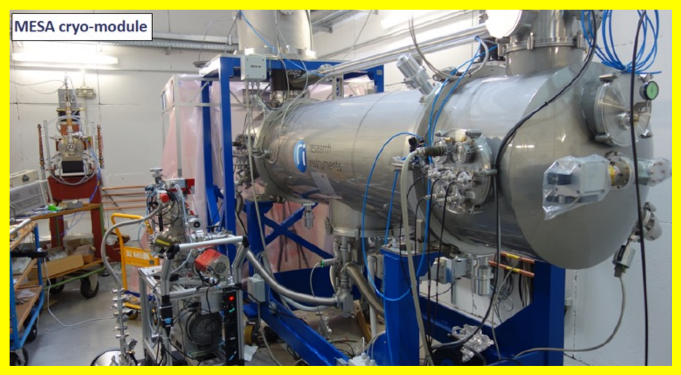






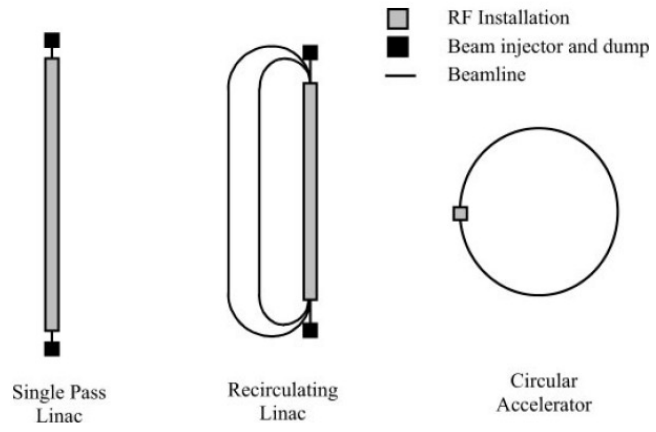
Polarized Source Test Setup

New underground experimental hall (par. 91b GG)

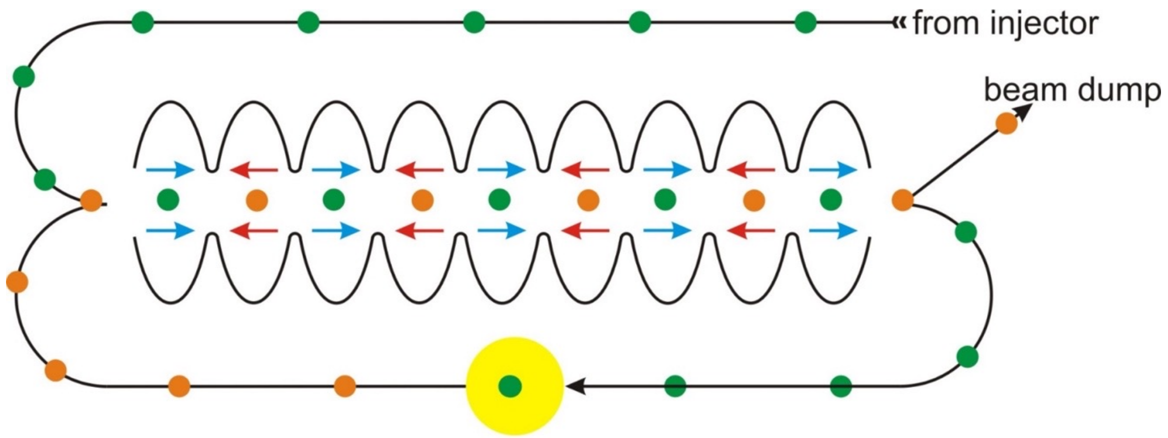


Cryomodules successfully tested

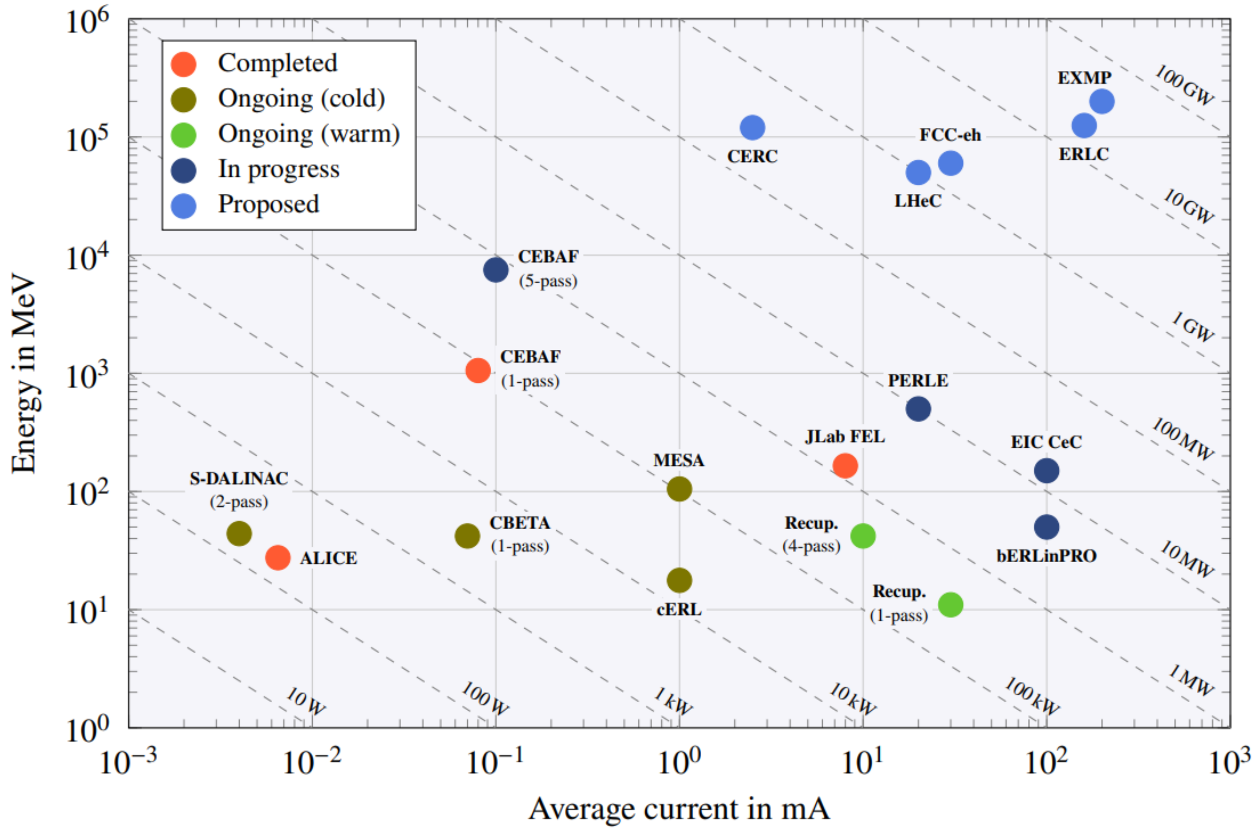
MESA Accelerator



Energy Recovering LINAC

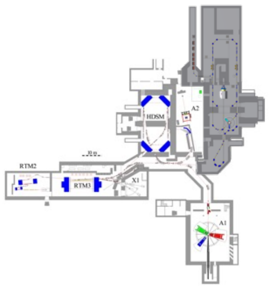


ERLs world-wide (status fall 2022)



→ MESA is one of few ongoing ERL activities

→ The **first** facility which will have a thin target and be used for physics experiments



MESA experiments

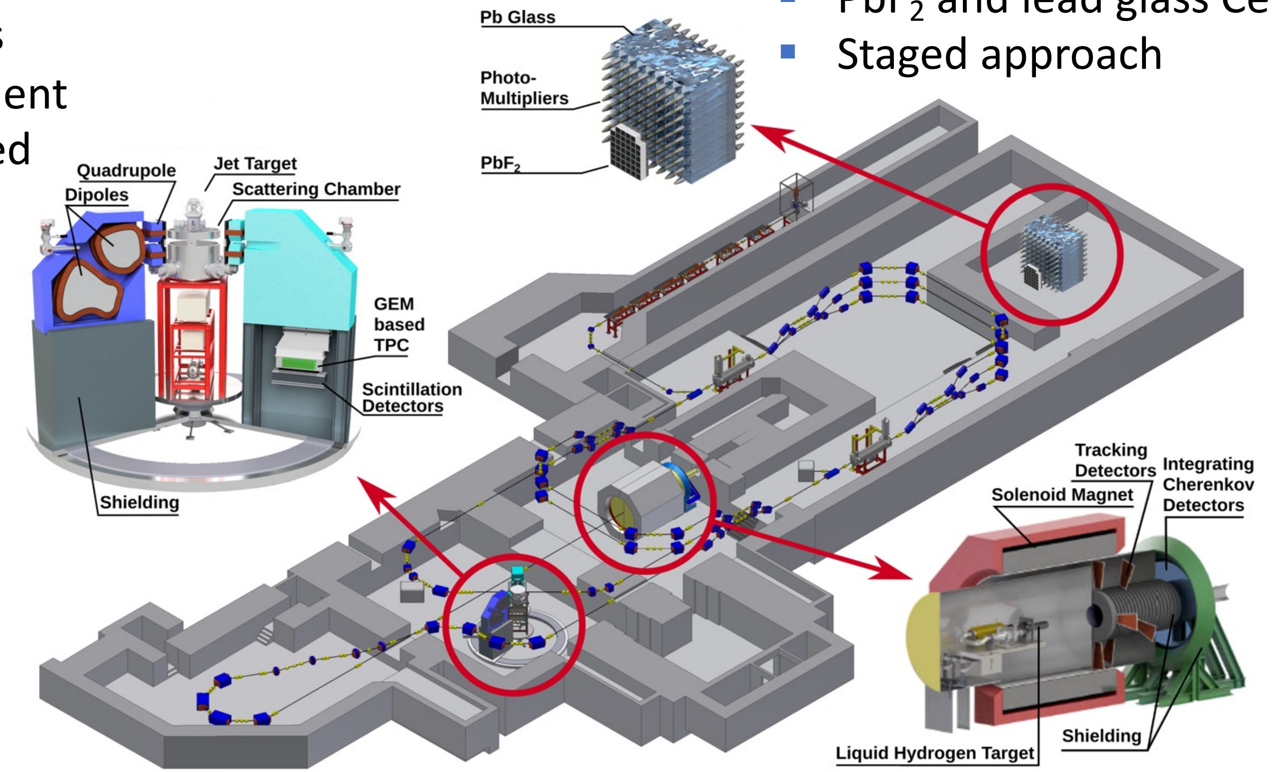
DarkMESA

- Beam dump experiment
- Direct detection of light dark matter
- PbF_2 and lead glass Cerenkov calorimeter
- Staged approach

MAGIX experiment

- Operated in ERL mode of MESA
- Double-arm spectrometers
- Internal gas target experiment
- Gas jet target commissioned at A1/MAMI already

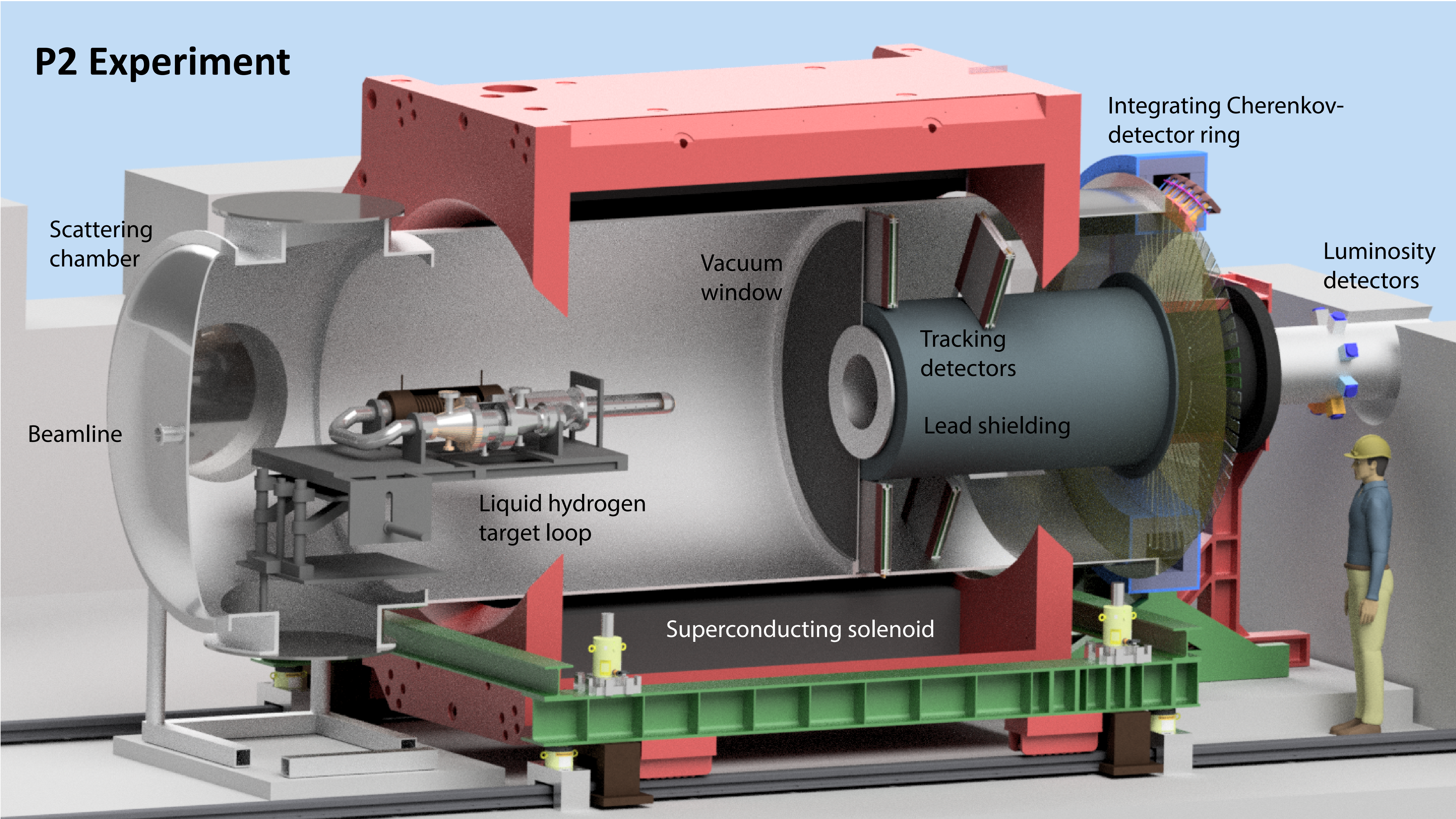
Main components of MAGIX and P2 presently constructed in industry and assembled in house (funding via major research instrumentation program of federal government)
Phase 1 deteccctor for DarkMESA almost ready.



P2

- Extracted beam mode
- Parity violation experiment
- 10^{22} Electrons / a
- $\sin^2\theta_W$ and neutron skin

Talk by E. Downie, R. Thapa, M. Gericke



P2 Experiment
Scattering chamber
Beamline
Vacuum window
Tracking detectors
Lead shielding
Liquid hydrogen target loop
Superconducting solenoid
Integrating Cherenkov-detector ring
Luminosity detectors

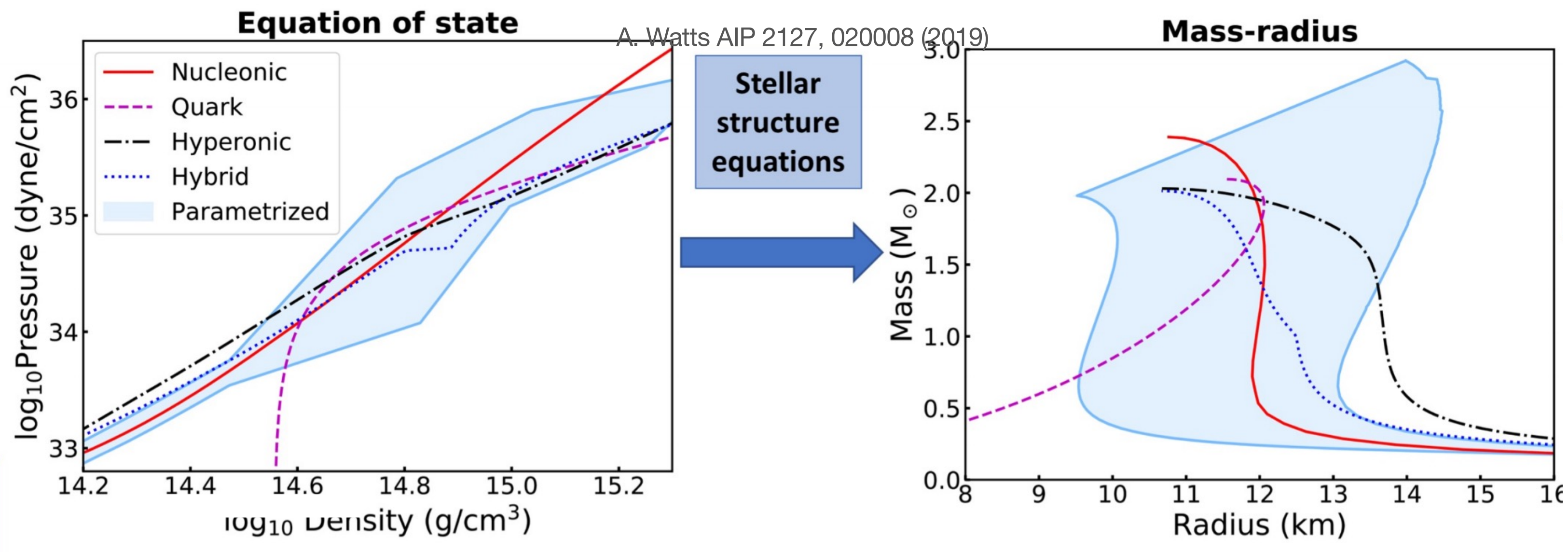
Nuclear physics in P2: Equation of state?

- Neutron Stars are bound by gravity **NOT** by the strong force
- Neutron Stars satisfy the **Tolman-Oppenheimer-Volkoff** equation ($v_{esc}/c \approx 1/2$)

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2, \quad P = P(\varepsilon) \quad \text{(EOS)}$$

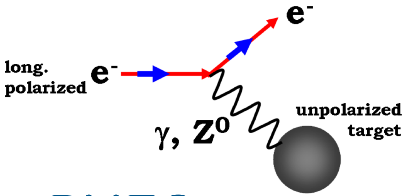
- Only Physics that the TOV equation is sensitive to: **Nuclear equation of State**



A. Watts AIP 2127, 020008 (2019)

P2-Detector …we call it:

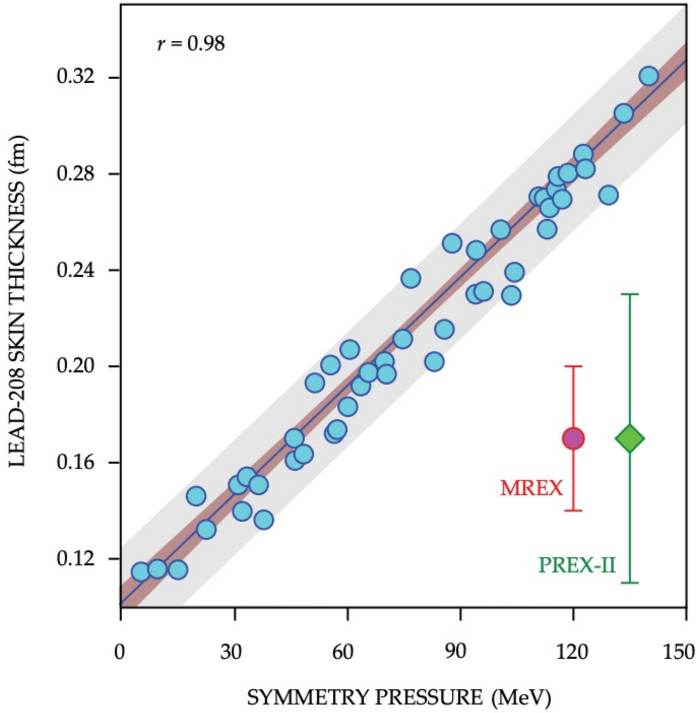
PV-Asymmetry

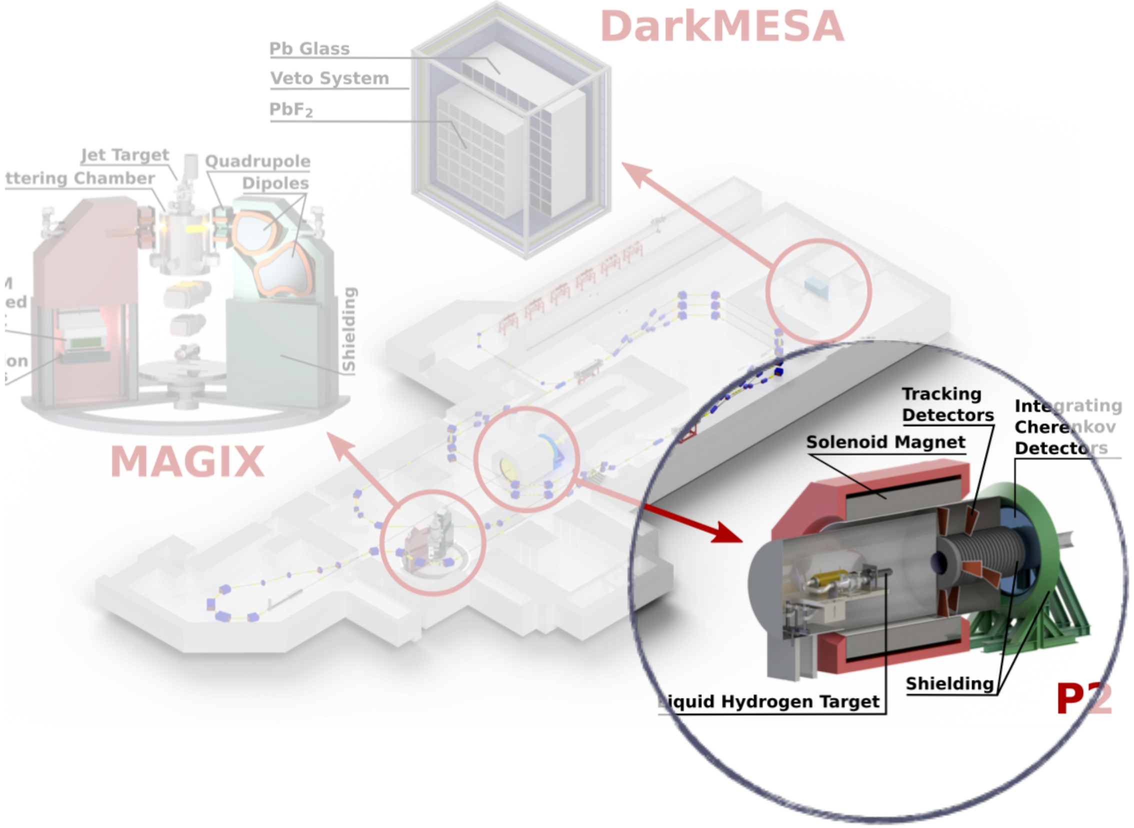


PVES

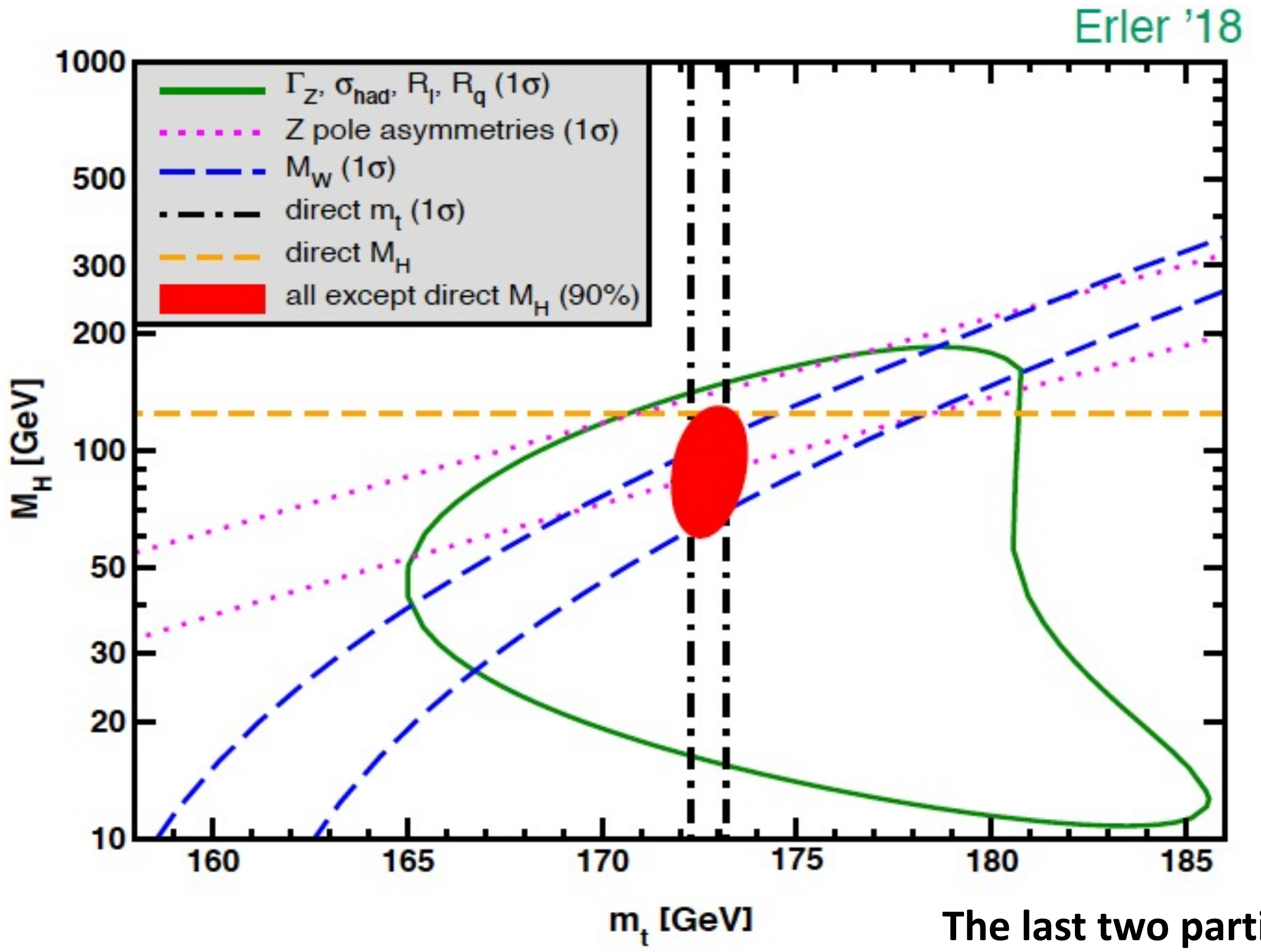
Measurement of the neutron disctribution in lead

J. Piekarewicz et al. Physics Today 72, 7, 30 (2019)





Direct observation versus precision measurements



Direct measurements:

$M_H = 125.14 \pm 0.15$ GeV

$m_t = 172.74 \pm 0.46$ GeV

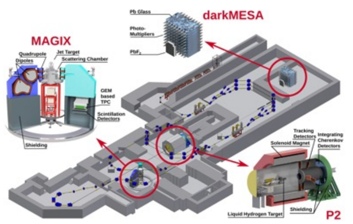
Indirect prediction:

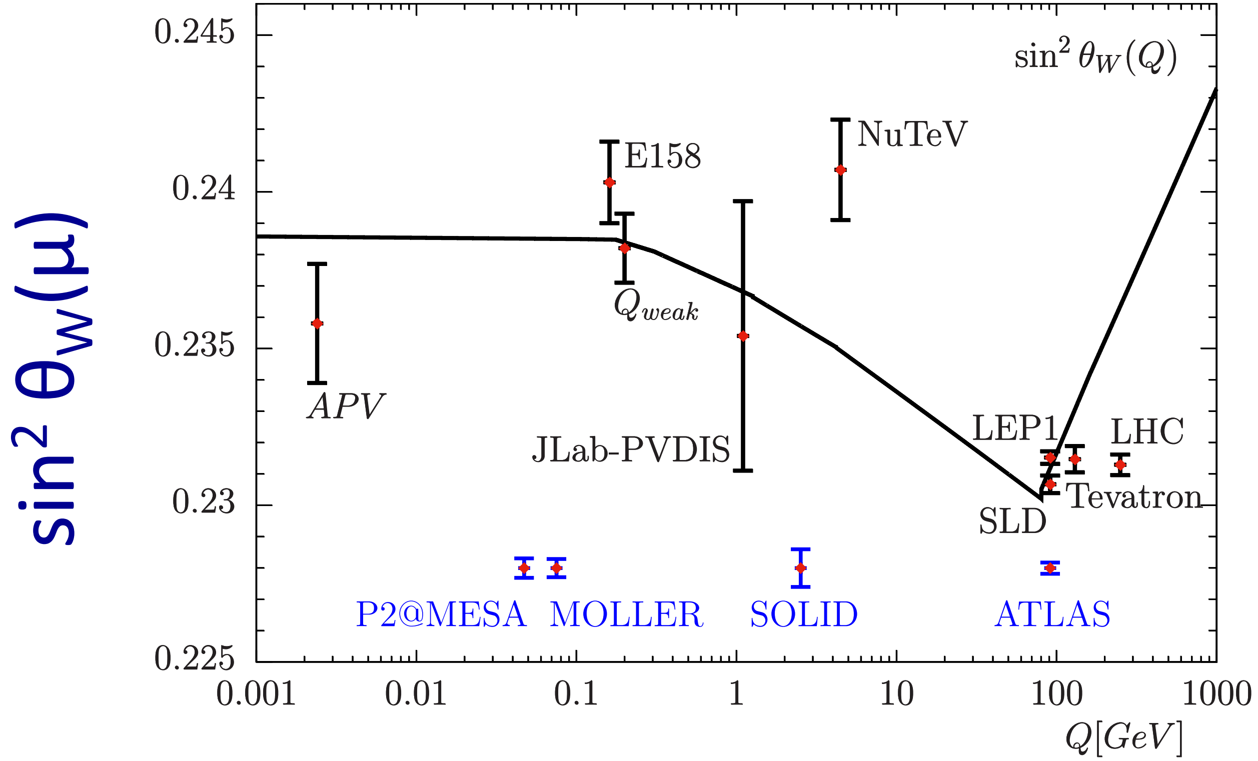
$M_H = 90^{+17}_{-16}$ GeV

$m_t = 176.4 \pm 1.8$ GeV

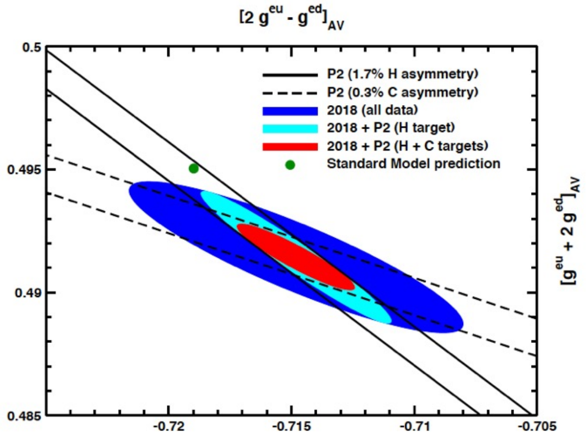
The last two particles of the standard model have been seen in indirect searches before their direct production

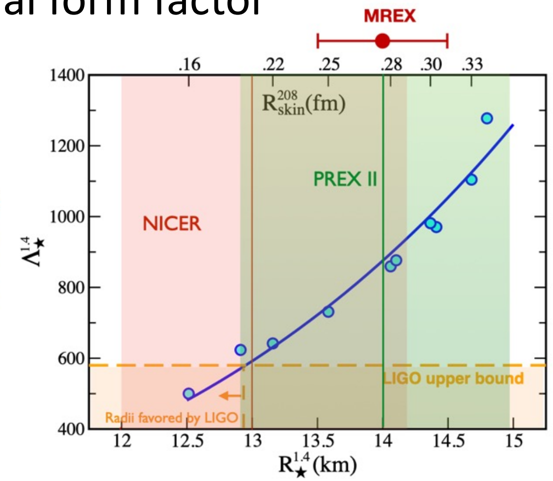
P2: High precision determination of the weak mixing angle at low energy





- Parity violating asymmetry in elastic electron scattering
- 25 times smaller asymmetry, 5 times smaller relative error
- Low energy test of the standard model
- PV brother of the dark photon: down to 70 MeV
- Proton: weak mixing angle, test of new physics up to 49 TeV
- Carbon: weak mixing angle, test of new physics up to 49 TeV
- Lead: neutron skin of nuclei: infer the radius of neutron stars
- Transverse asymmetries: nuclear phjysics
- Precise measurement of axial form factor





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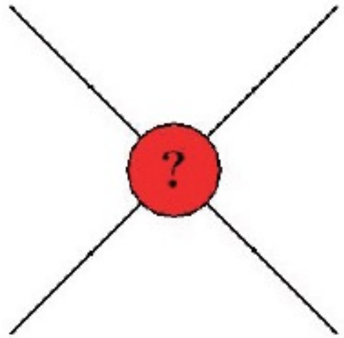
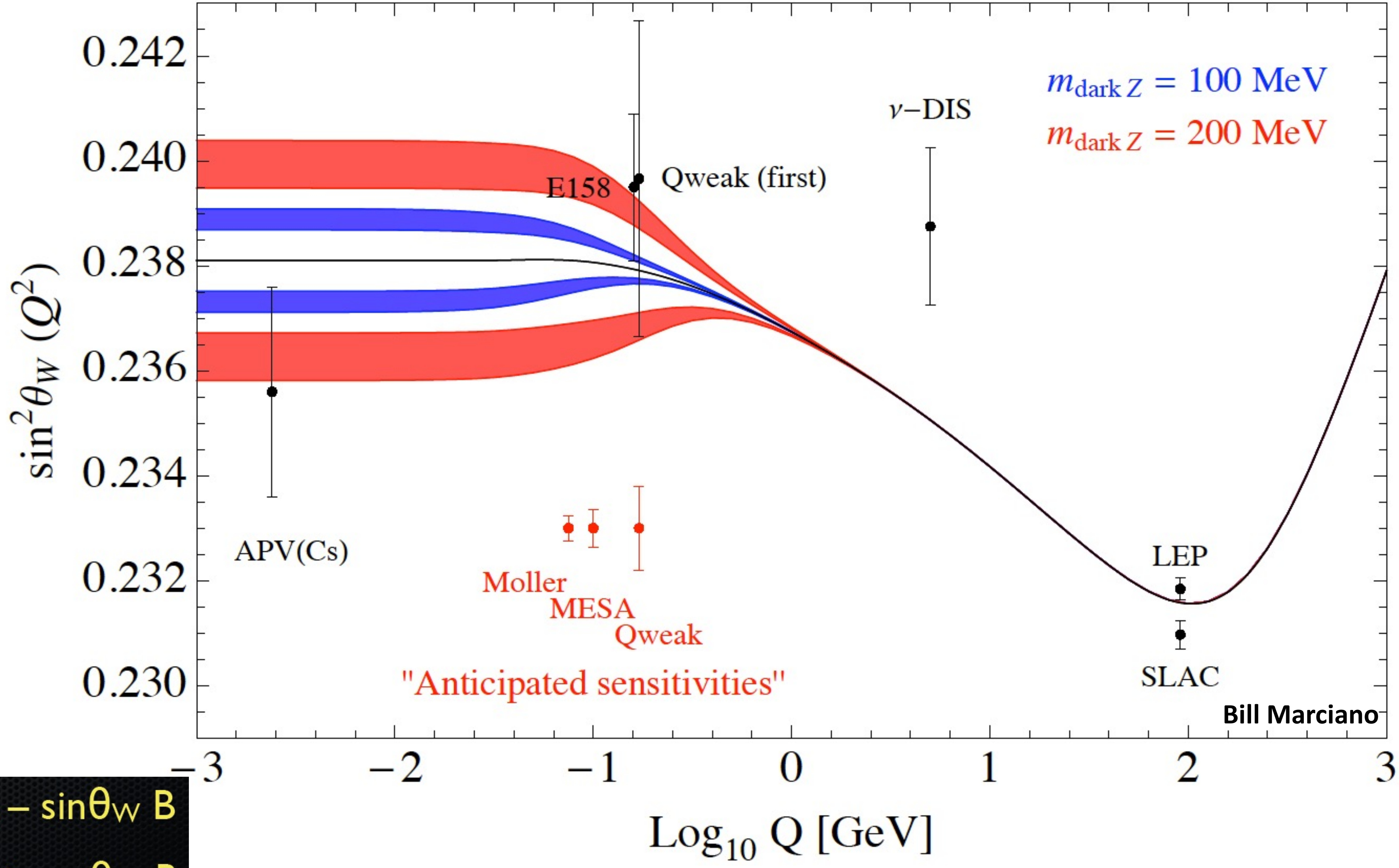
Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4\pi$)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Effective field theory approach (EFT)



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



$Z = \cos\theta_W W_3 - \sin\theta_W B$

$A = \sin\theta_W W_3 + \cos\theta_W B$

Future wEFT constraints from APV and PVES

Adam Falkowski at Mainz MITP workshop: Impact on low energy measurements

Current QWEAK, PVDIS, and APV cesium experiments:

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0.74 \pm 2.2 \\ -2.1 \pm 2.5 \\ -39 \pm 54 \end{pmatrix} \times 10^{-3}$$

Projections from combined P2, SoLID, and APV radium experiments:

$$\begin{pmatrix} \delta g_{AV}^{eu} \\ \delta g_{AV}^{ed} \\ 2\delta g_{VA}^{eu} - \delta g_{VA}^{ed} \end{pmatrix} = \begin{pmatrix} 0 \pm 0.70 \\ 0 \pm 0.97 \\ 0 \pm 7.4 \end{pmatrix} \times 10^{-3}$$

$$\mathcal{L}_{\mathrm{wEFT}} \supset -\frac{1}{2v^2} \sum_{q=u,d} g_{AV}^{eq} (\bar{e}\,\bar{\sigma}_\rho e - e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c \sigma^\rho \bar{q}^c)$$
$$- \frac{1}{2v^2} \sum_{q=u,d} g_{VA}^{eq} (\bar{e}\,\bar{\sigma}_\rho e + e^c \sigma_\rho \bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c \sigma^\rho \bar{q}^c)$$

AA, Grilli Di Cortona, Tabrizi 1802.08296

AA, Gonzalez-Alonso in progress

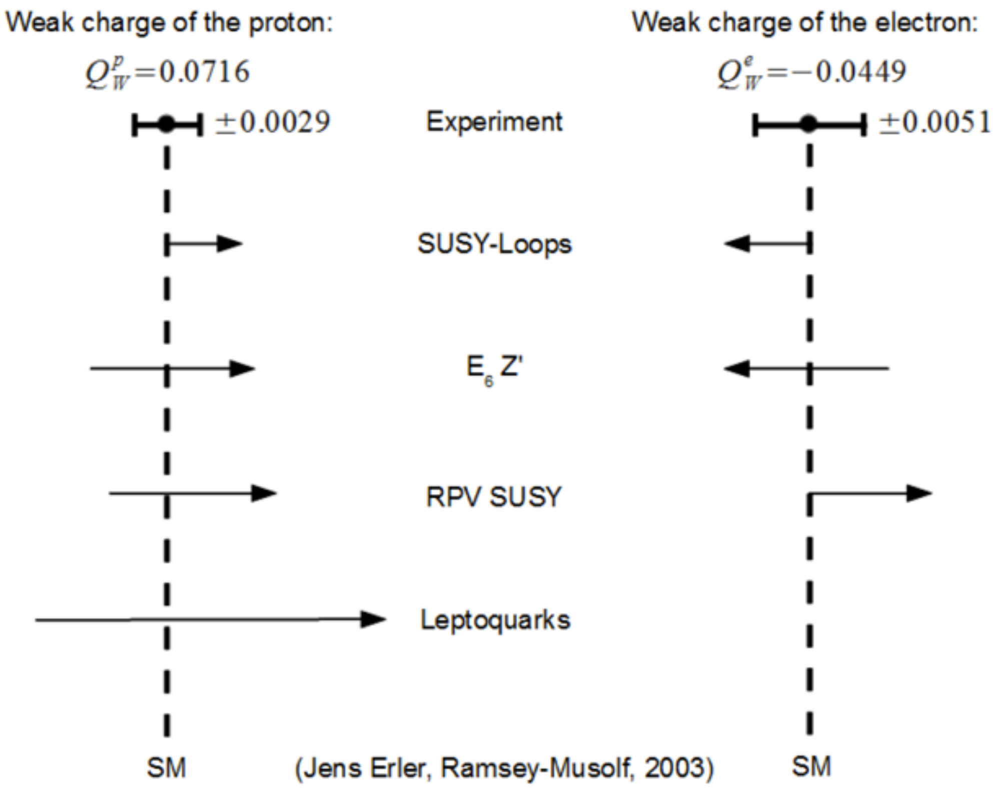
Three PV experiments with three different probes for new physics

Weak Charge Of Proton: Qweak (Jlab), P2 (MESA)

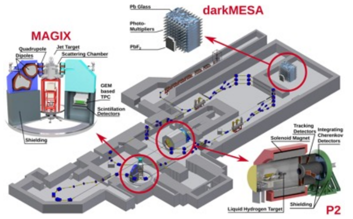
Weak Charge Of Electron: MOLLER (JLAB)

Weak Charge Of Quarks: SOLID (PVDIS) (JLAB)

- Complementary access by weak charges of proton and electron

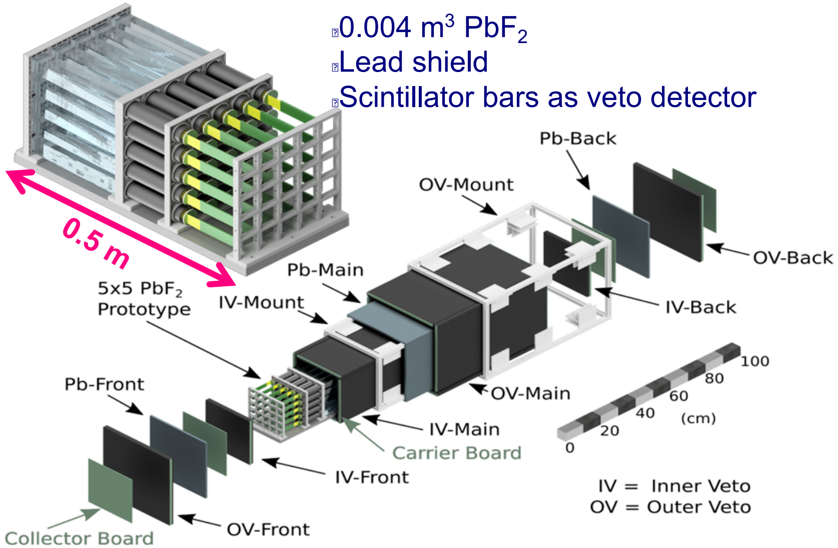


DarkMesa: beam dump experiment, search for dark photon



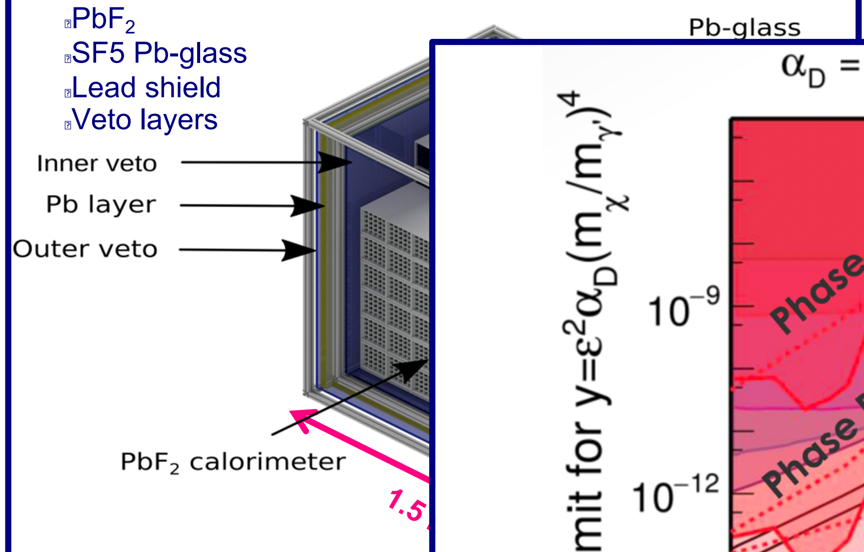
Phase A (prototype)

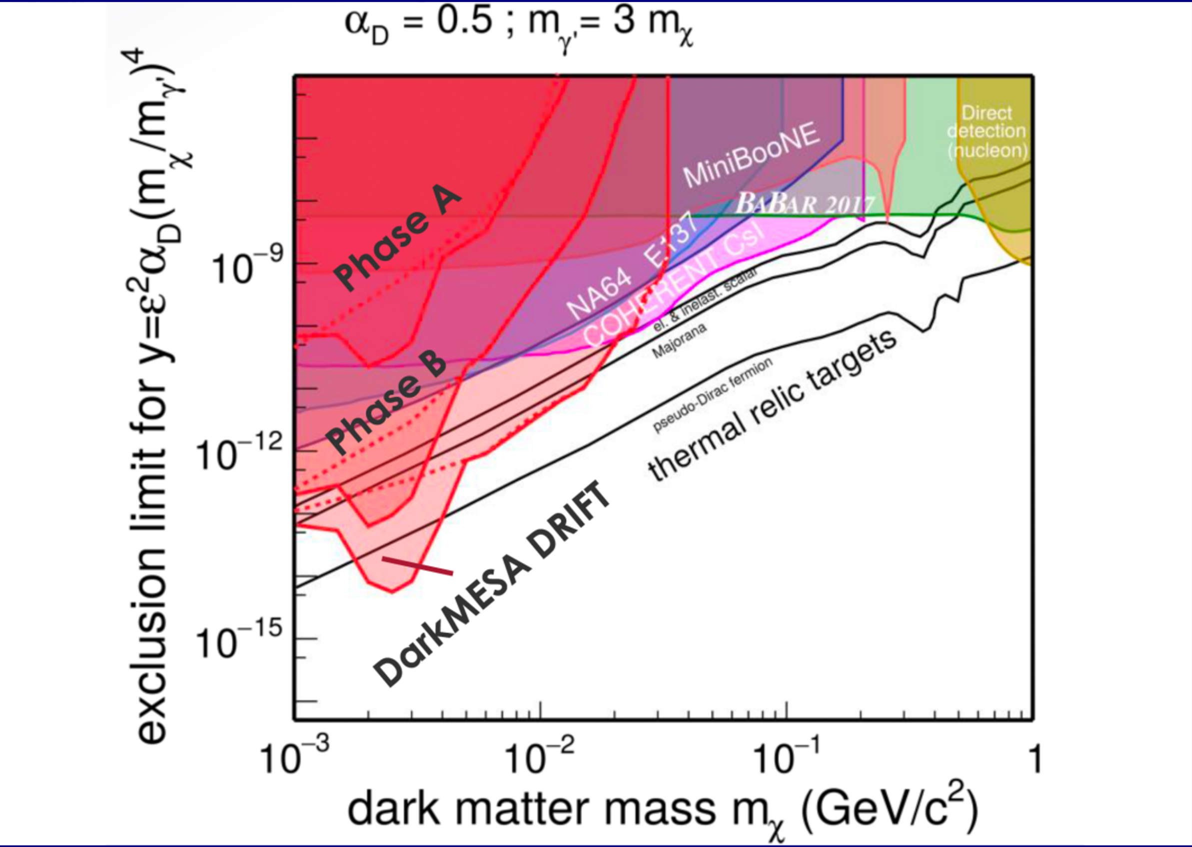
- $0.004\ m^3\ PbF_2$
- Lead shield
- Scintillator bars as veto detector



Phase B

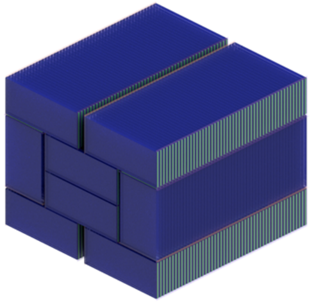
- PbF_2
- SF5 Pb-glass
- Lead shield
- Veto layers





Phase C (range extension)

D. P. S



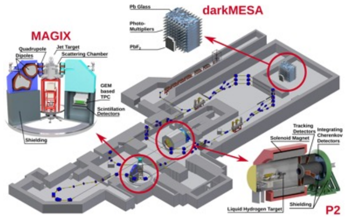
options

Radiation protection glas
e.g., SCHOTT-RD30
Moderate cost: 137 k€ / m³
High density: 3.13 g / cm³

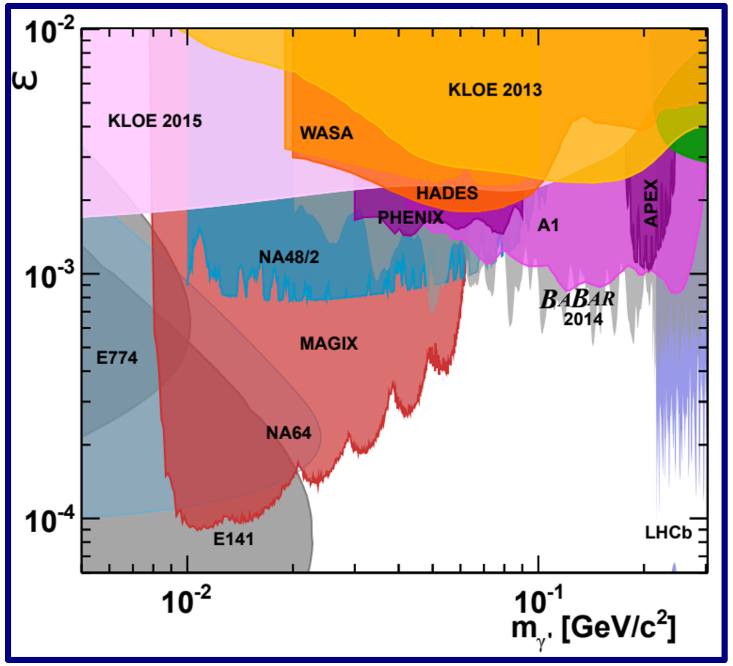
DRIFT -Time Projection Chamber
CS_2 at 50 mbar
~1 m³ active volume
Nuclear recoil threshold: 20 keV

⇒ Extended parameter space

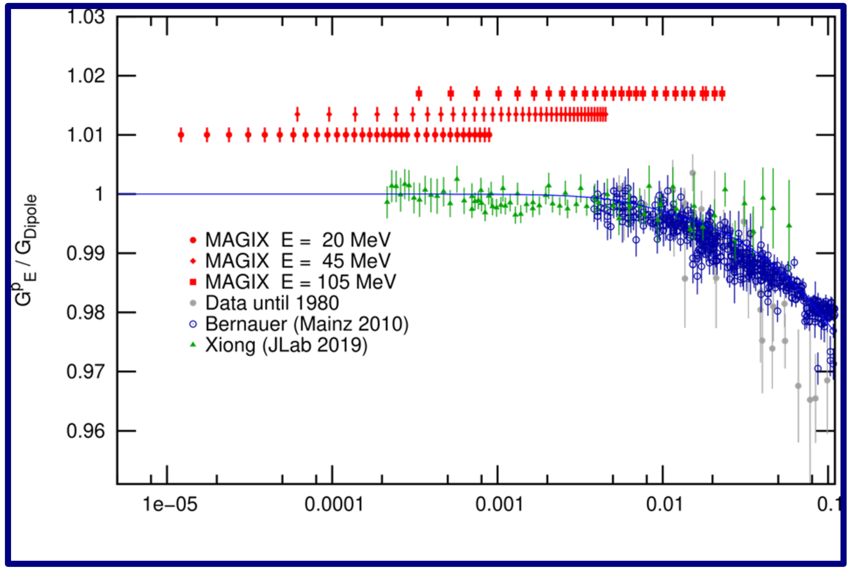
Magix: Magnetic spectrometer and Cluster Jet target (selection of topics)



Dark Matter search with MAGIX

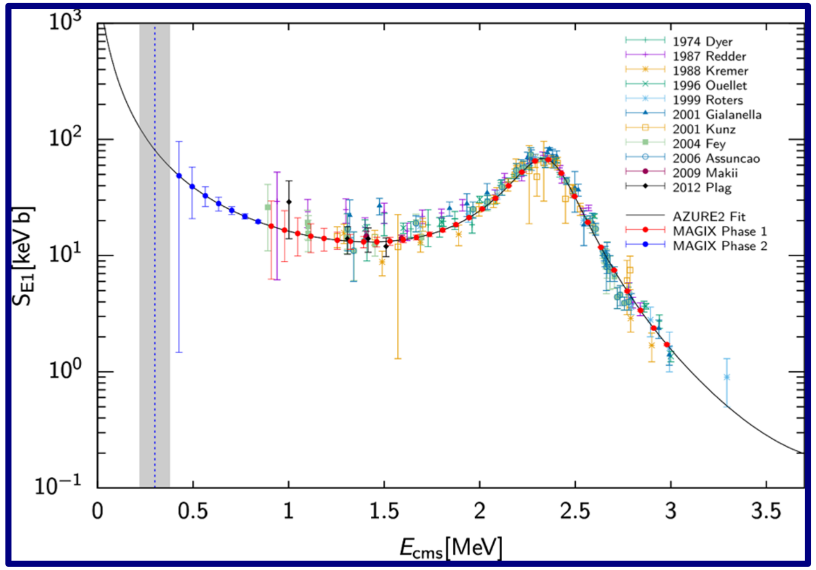


G_E and Proton Radius, projected stat. errors



- Coverage from Q2 = 1·10-5 to 0.03 GeV^2 ⇒ proton radius!
- Dominated by systematic error
- Windowless target, negligible background, high resolution, high efficiency, ...

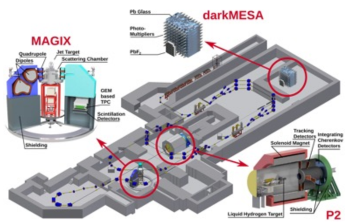
Nuclear Astrophysics, S-Factor measurement



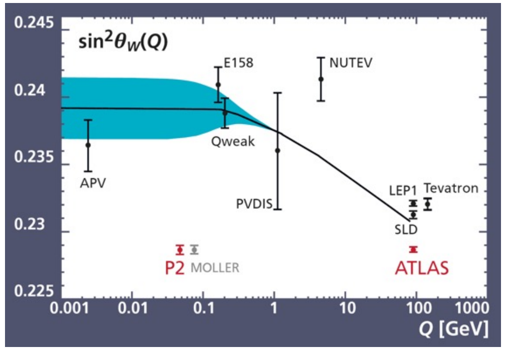
$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$:

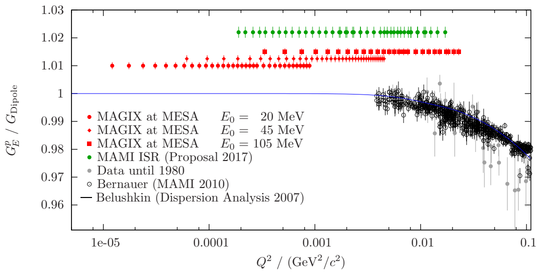
one of most important reactions to describe nucleosynthesis in burning of a star:

MESA Physics program



From Nuclear Physics to Hadron and Particle Physics



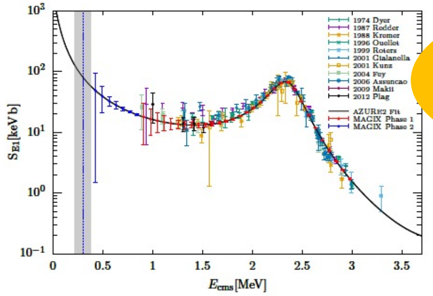


Low Q^2
EM Form Factor p,n
(MAGIX)

Precision Measurement of $\sin^2\theta_W$ via p,^{12}C
(P2)

Neutron Skin Pb
(P2-MREX)

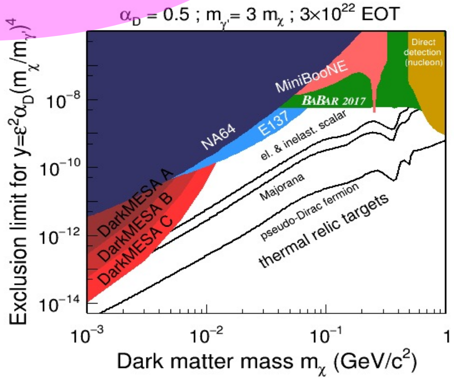
Search for Dark Photon and Axions
(MAGIX)



$^{12}C\ (\alpha,\gamma)\ ^{16}O$
(MAGIX)

Few Body Physics (MAGIX)

Light Dark Matter direct detection
(DarkMESA)



Summary and outlooK

- MAMI beam and experiment resultrs

- Diverse past and future program at MAMI with results at A1 and A2
(only small fraction in this talk, Hypernuclei, Pion transition FF in virtual Primakoff kinematics, FF …)

- Test beam at MAMI for MESA detectors and accelerator components instrumental

- Construction of MESA accelerator and MESA experiments MAGIX, P2, DarkMESA continuing successfully

- Exciting experimental program at MESA in nuclear, hadron and particle physics

- Staged approach for construction, commissioning and first measurements with MESA experiments
- Very rich results expected from all MESA experiments
- First experiments Q1/2025