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

Achim Denig
November 1st, 2023

Precision Experiments at the MESA Accelerator

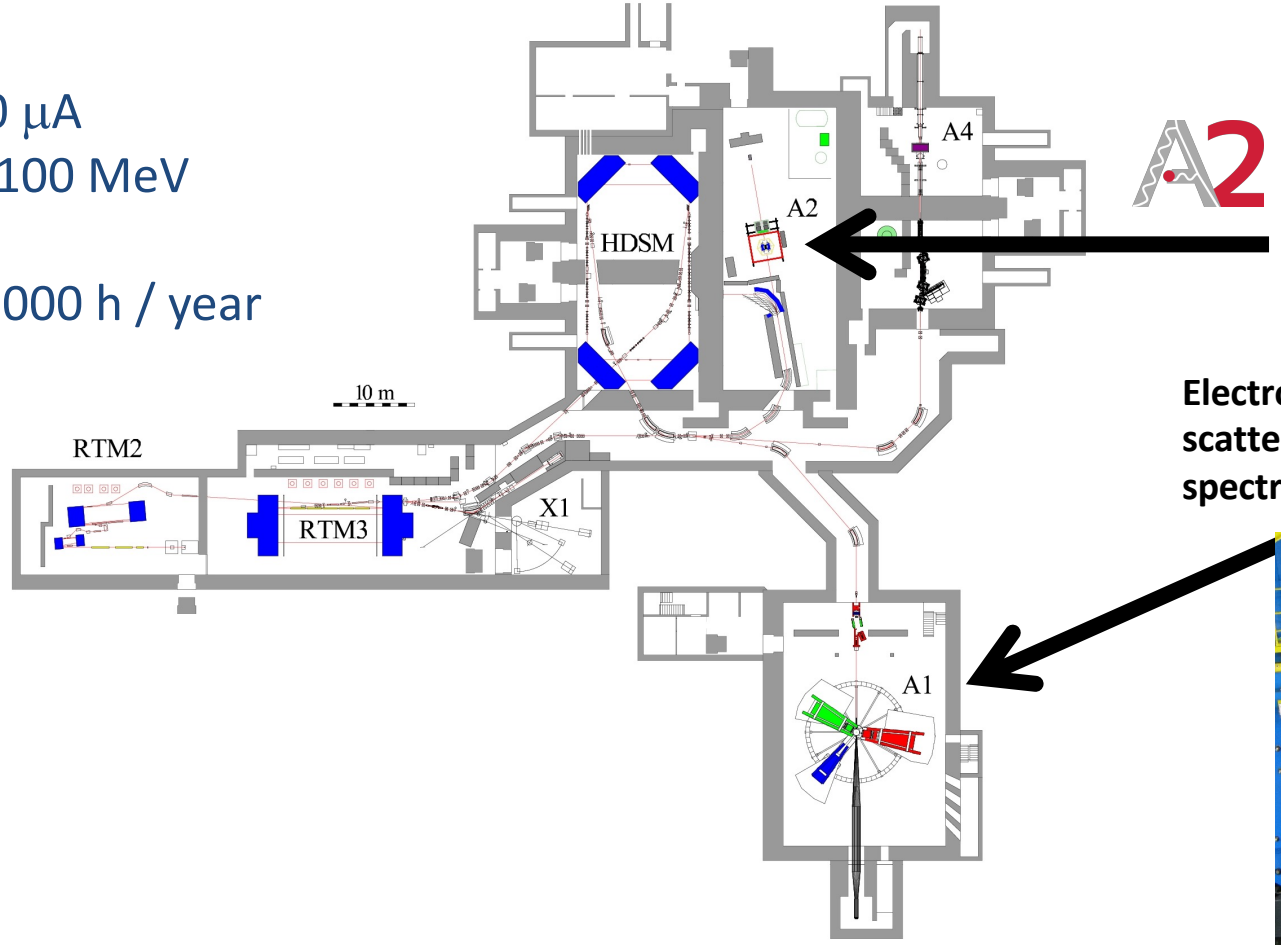
15th European Research Conference on
Electromagnetic Interactions with Nucleons and Nuclei
Paphos, Cyprus

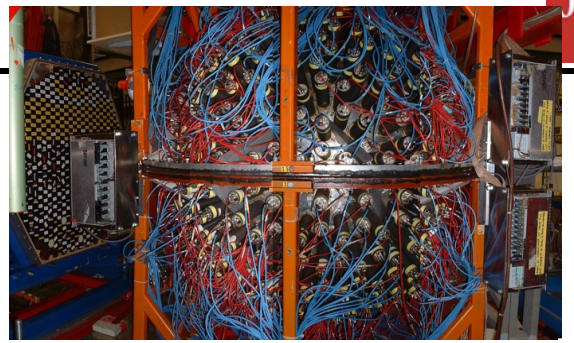
MAGIX
DARK MESA

The Mainz Microtron MAMI

Electron Accelerator E = 0.185 GeV - 1.6 GeV (CW)
operated at JGU Mainz
Hallmarks

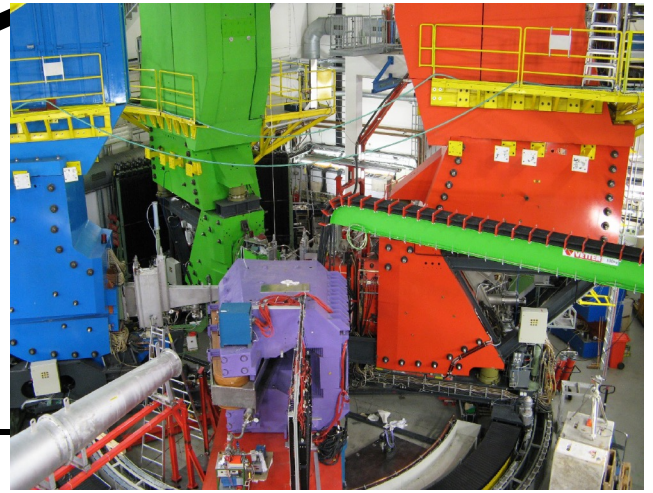
- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: up to 7000 h / year





Photon scattering (A2 hall) (Crystal Ball / TAPS calorimeters; Polarized frozen-spin target → currently at Univ. Bonn)

Electron scattering (high resolution spectrometer setup)



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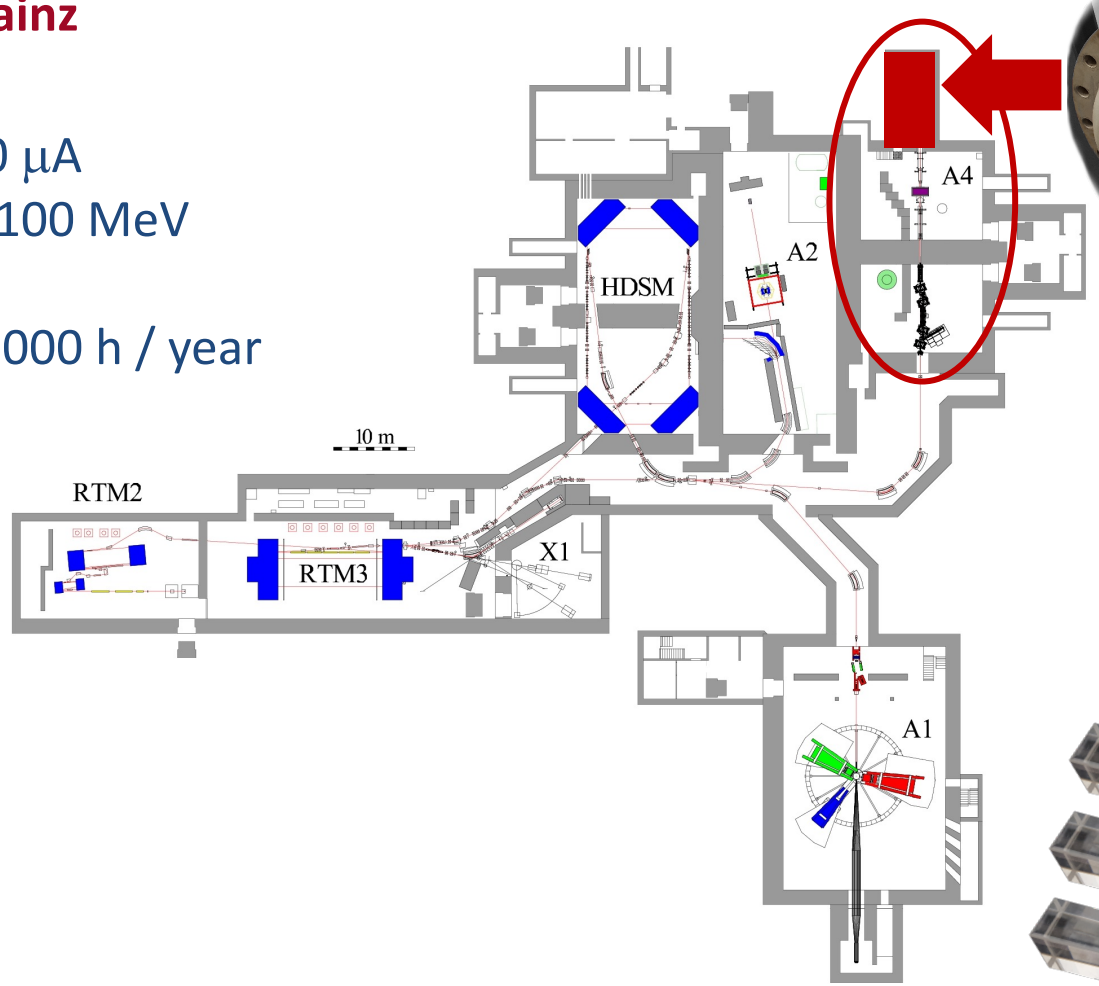
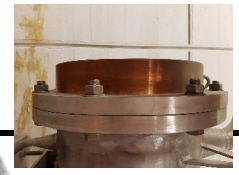
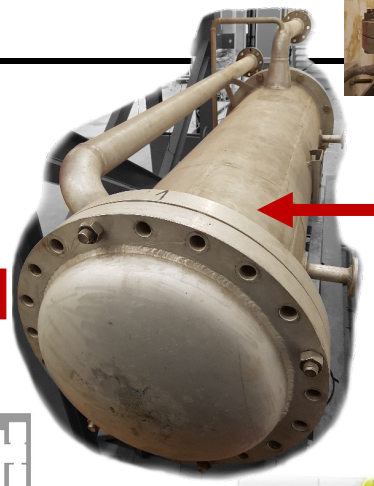
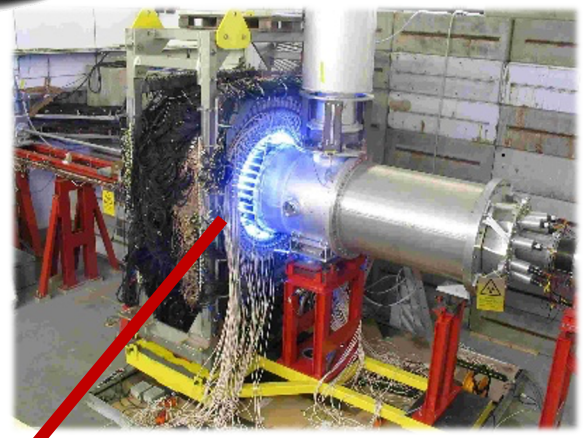
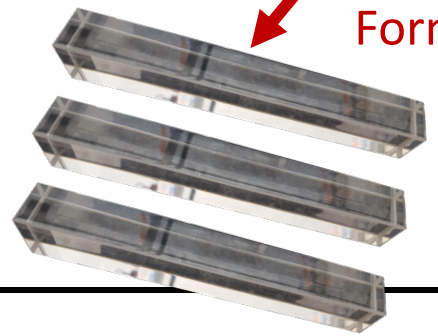






Former A4 beam dump:
Al, H_20, Cu → 20 X_0





Former A4 experiment:
1000 PbF_2 crystals
and PMTs

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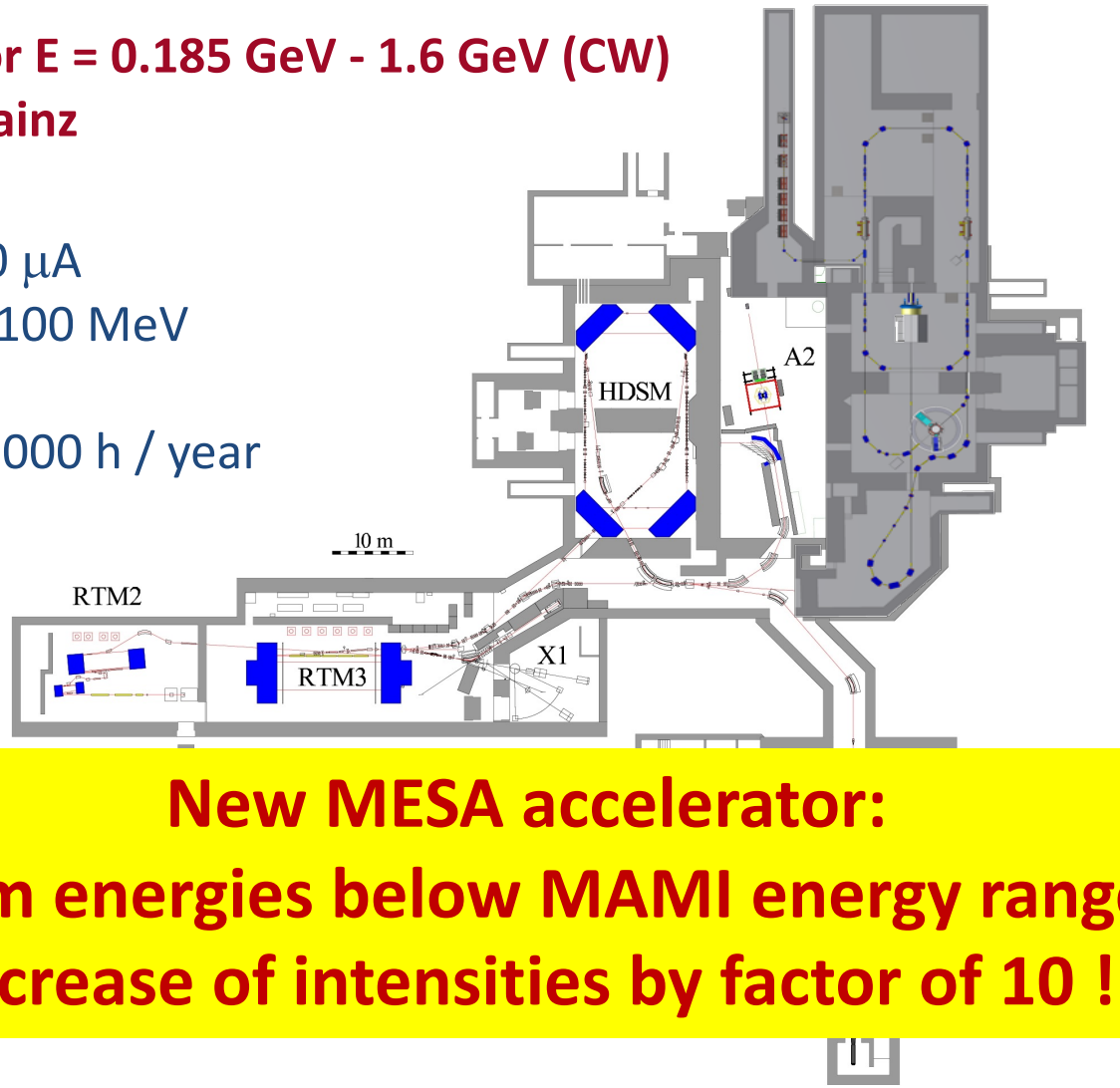

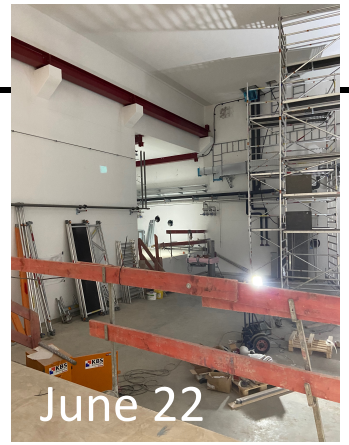

New experimental hall

New MESA accelerator:
Beam energies below MAMI energy range !
Increase of intensities by factor of 10 !

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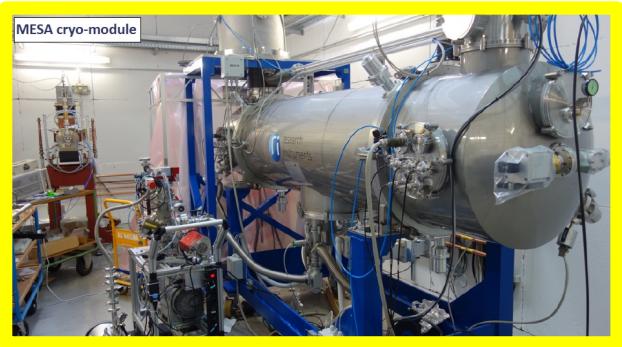
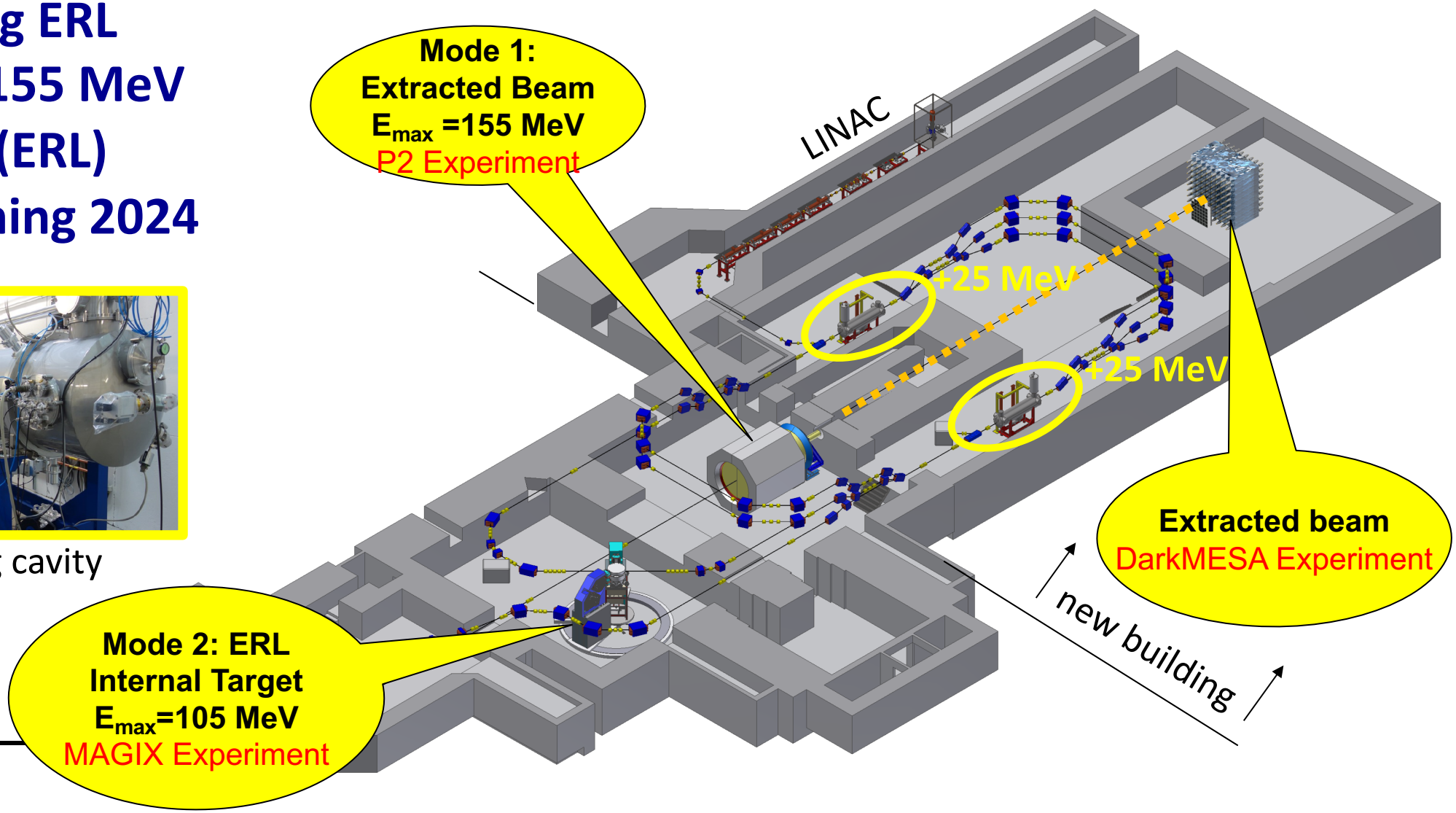
Mainz Energy-Recovering Superconducting Accelerator (MESA)

Superconducting technology
Recirculating ERL
E_{max} = 105/155 MeV
I_{max} > 1 mA (ERL)
Commissioning 2024



Superconducting cavity

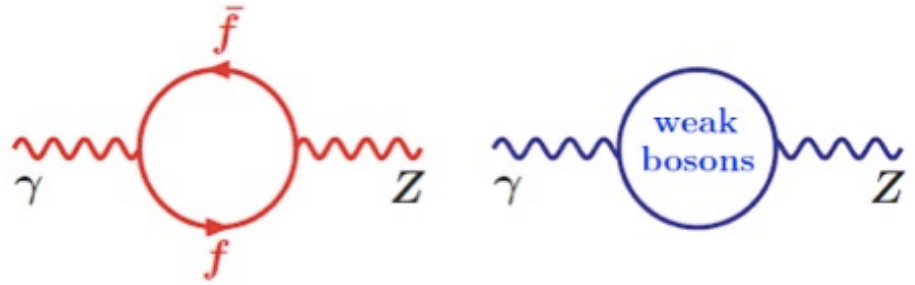


P2 Experiment

MESA Extracted Beam Mode

Measurement of: $\sin^2\Theta_W = (e/g)^2 = 1 - (M_W/M_Z)^2$

Rad. corrections strongly correlated with quarks, W-Bosons, Higgs, …



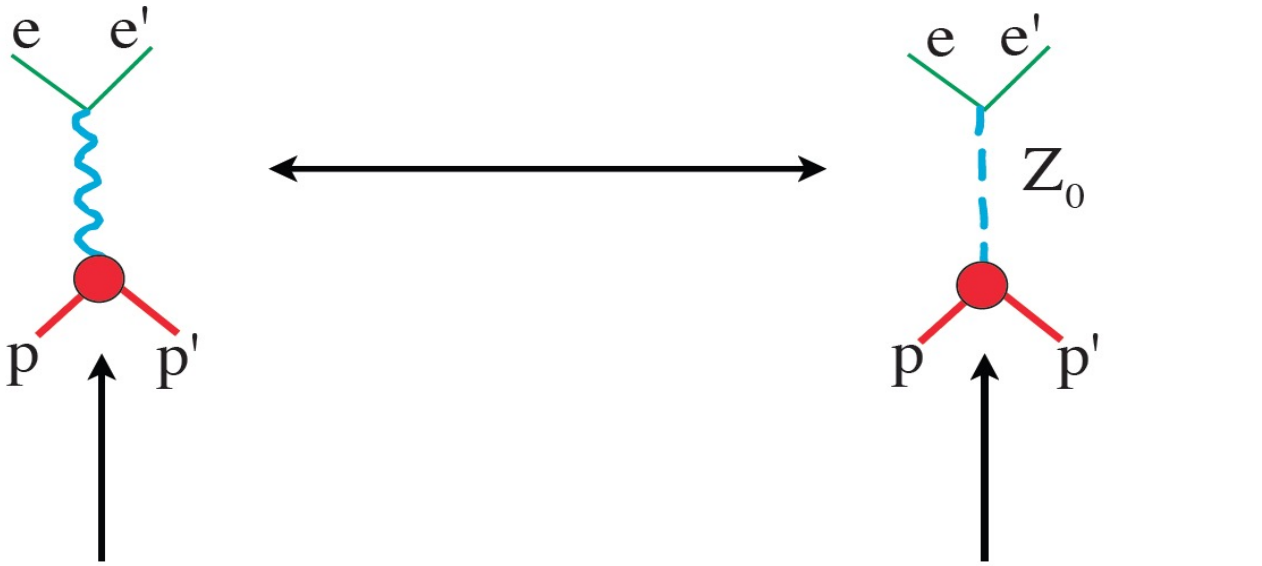
Leads to running (Q^2 dependence) of $\sin^2\Theta_W$ → Precision test of SM

Measurement of the Weak Charge of the Proton

Scattering of longitudinally polarized electrons on unpolarized protons

→ **Z boson exchange** in electron-proton scattering introduces **parity-violating effect**

→ Measure **parity-violating Left-Right cross section asymmetry A_{LR}**



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

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

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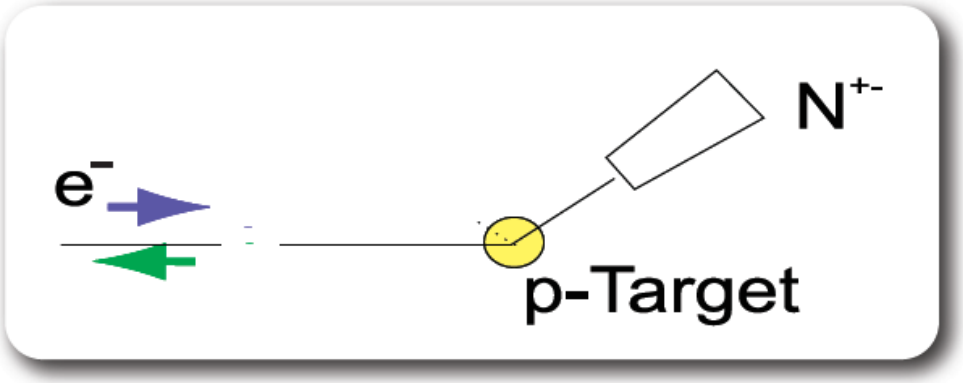

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weak charge of proton

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

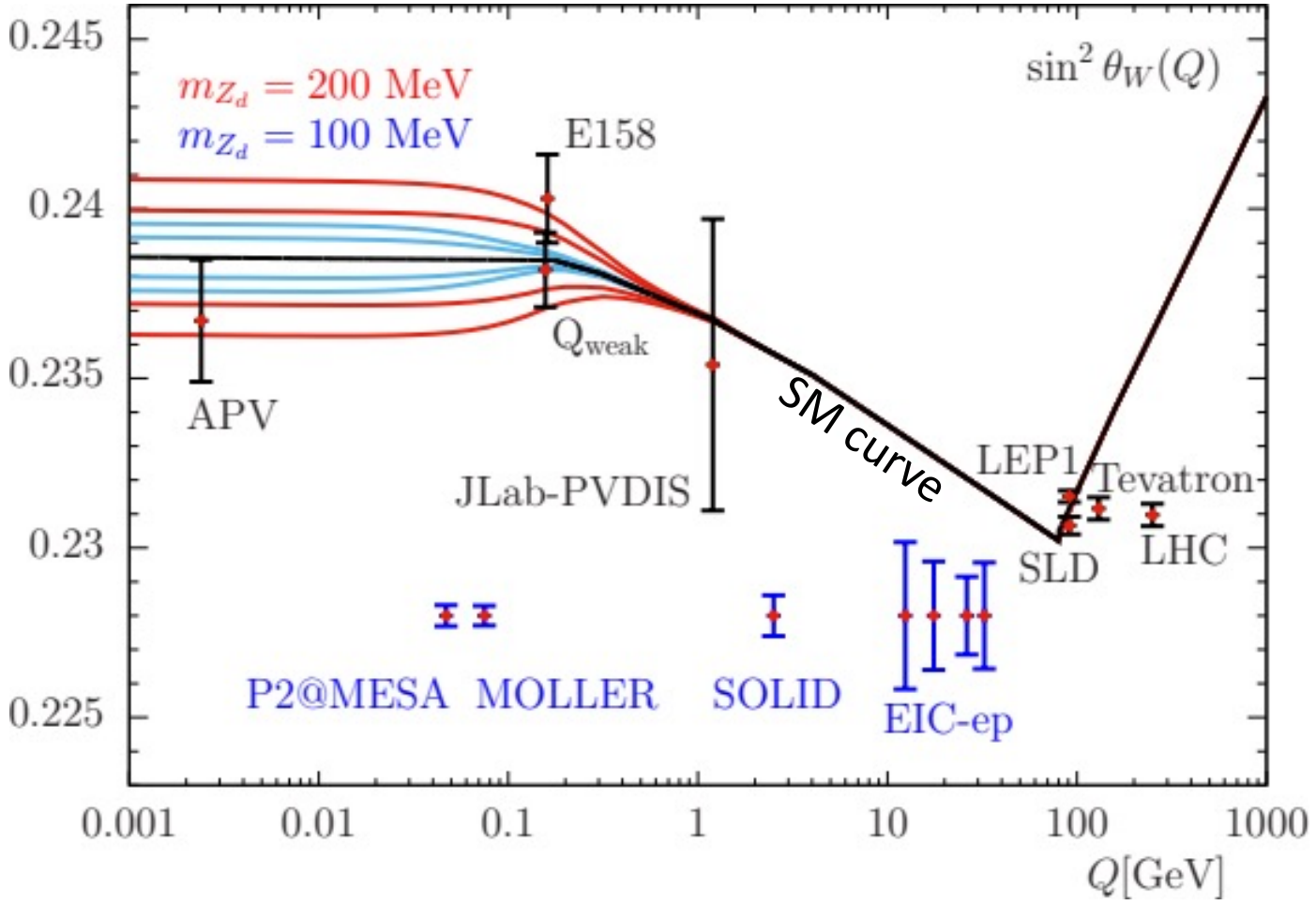
$$Q_W = 1 - 4\sin^2 Q_W(Q^2)$$

hadron structure

P2@MESA goal:

Measure parity-violating Left-Right asymmetry A_{LR} of 20 x 10^{-9} with 2.4% precision –> 0.16% error on $\sin^2\Theta_W$

A Low-Q^2 Measurement of $\sin^2\theta_W$ at MESA



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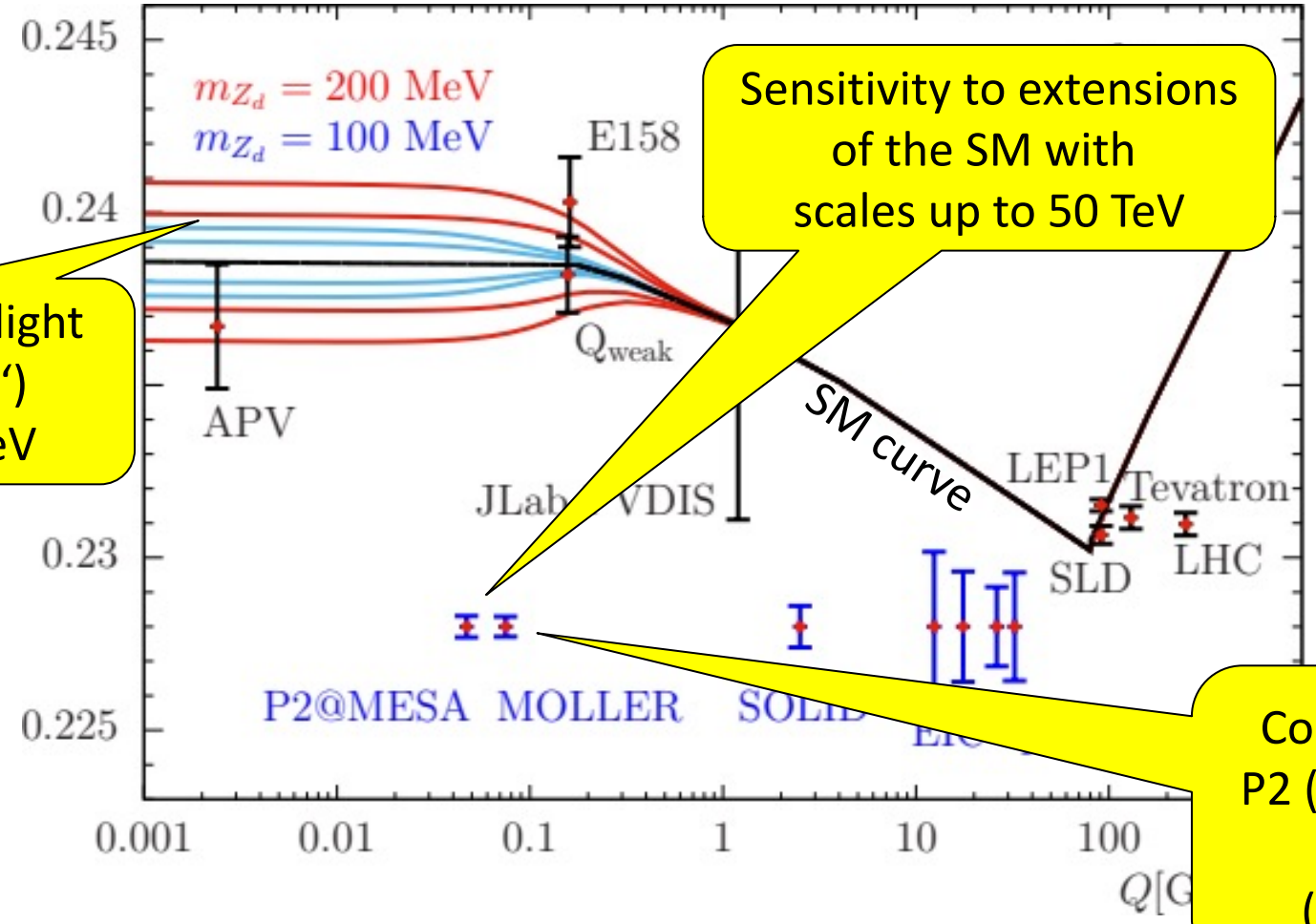


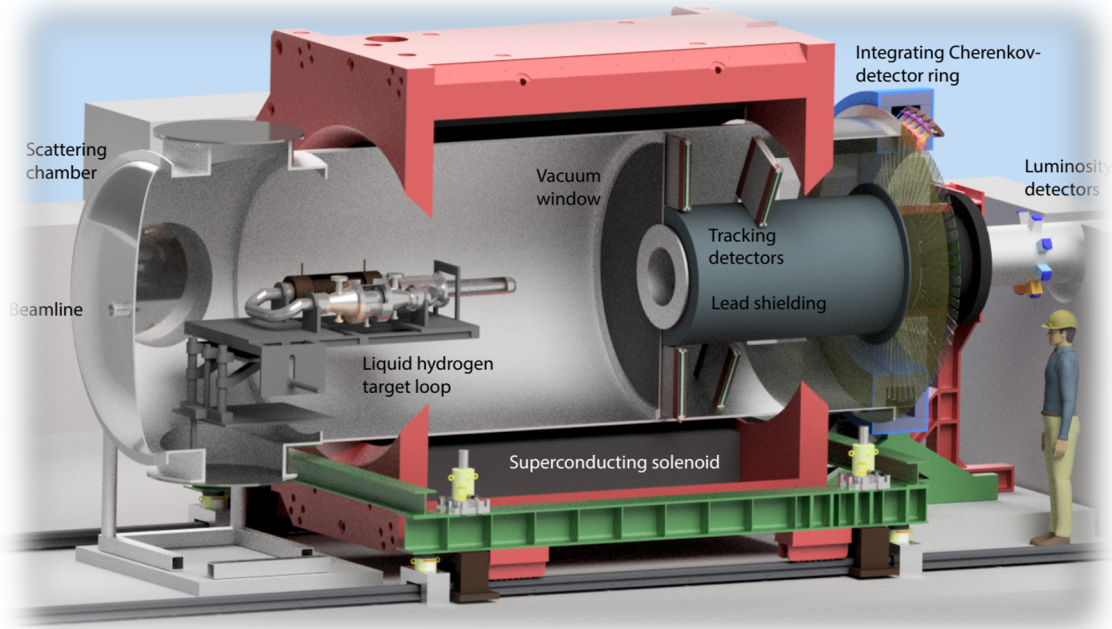
Sensitivity to light particles (Z‘) few 100 MeV

Sensitivity to extensions of the SM with scales up to 50 TeV

Complementarity between P2 (proton weak charge) and Moeller@JLAB (electron weak charge)

P2 Experiment

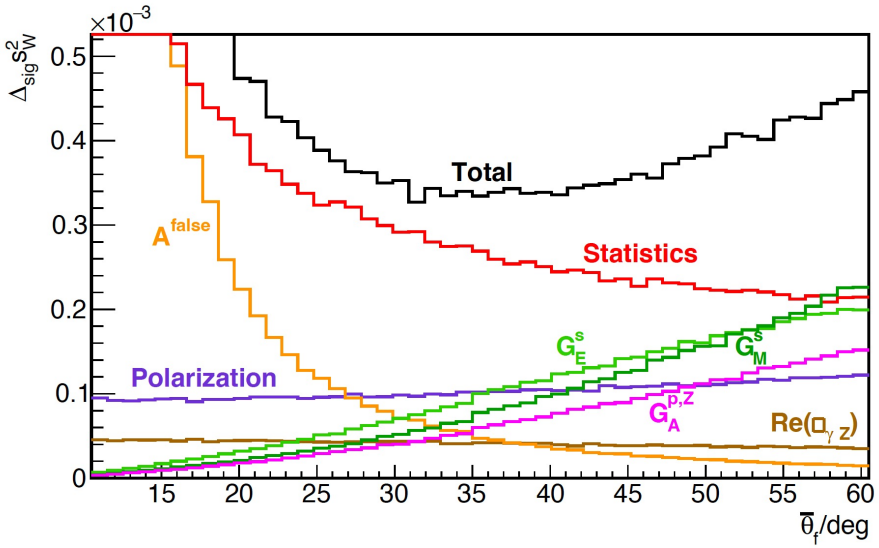
arXiv: 1802.04759



E_{beam}	155 MeV
$\overline{\theta_f}$	35°
$\delta\theta_f$	20°
s_W^2	0.23116
$\Delta_{exp} s_W^2$	$3.7 \cdot 10^{-4}$ (0.16%)
$\Delta_{exp,stat} s_W^2$	$3.1 \cdot 10^{-4}$ (0.13%)
$\Delta_{exp,P} s_W^2$	$0.7 \cdot 10^{-4}$ (0.03%)
$\Delta_{exp,false} s_W^2$	$0.6 \cdot 10^{-4}$ (0.03%)
$\Delta_{exp,t.w.} s_W^2$	$1.2 \cdot 10^{-4}$ (0.05%)
$\Delta_{exp,t.p.} s_W^2$	$0.1 \cdot 10^{-4}$ (0.00%)
$\Delta_{exp,\Box_{\gamma Z}} s_W^2$	$0.4 \cdot 10^{-4}$ (0.02%)
$\Delta_{exp,nucl.FF} s_W^2$	$1.2 \cdot 10^{-4}$ (0.05%)

P2 - Parity violation experiments → $3 \cdot 10^{22}$ EOT (!)

- Superconducting solenoid
- Integrating Cherenkov detector ring
- Tracking detectors (HV-MAPS)
- Chain of polarimeters (90% polarization)
- LH_2 target (60cm) and solid state targets (^{12}Ca, ^{208}Pb)



Physics Program of P2 Experiment

Hydrogen

Measurement of parity-violating A_{LR} and **extraction of proton weak charge** → Improvement QWEAK x 3

$$A_{LR} = \frac{\sigma(e\uparrow) - \sigma(e\downarrow)}{\sigma(e\uparrow) + \sigma(e\downarrow)} \propto (1 - 4\sin^2\theta_W)$$

^{12}C

Measurement of parity-violating A_{LR} and **extraction of ^{12}C weak charge** → First precision measurement

$$A_{LR} \propto -24 \cdot \sin^2\theta_W$$

complementary to hydrogen measurement in BSM reach

Pb

Measurement of parity-violating A_{LR} and **extraction of weak form factor**

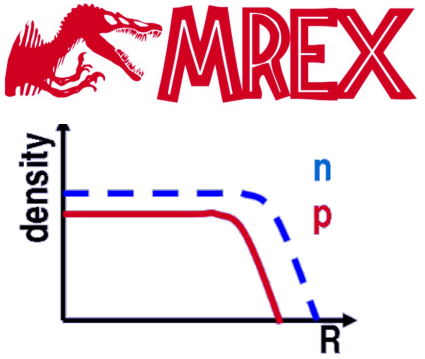
- sensitive to neutron skin thickness
- related to the Equation of State (EOS)
- relation to neutron star density

→ Improvement upon PREX x 2

$$A_{LR} \propto \frac{F_{\text{weak}}(Q^2)}{F_{\text{charge}}(Q^2)}$$

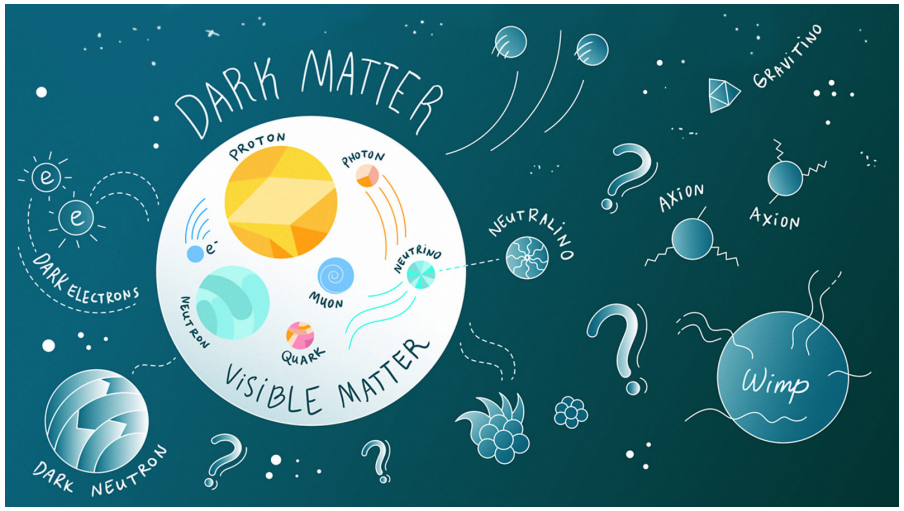
dominated by neutrons

dominated by protons



DarkMESA Experiment

Parasitically running to P2
MESA Extracted Beam Mode

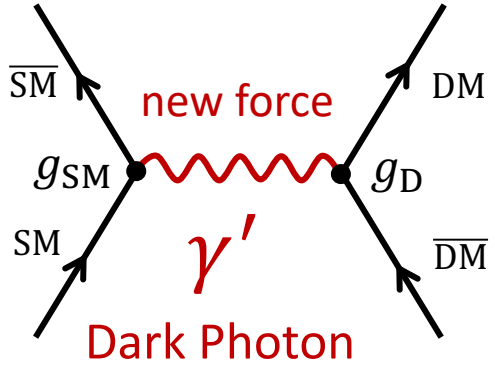


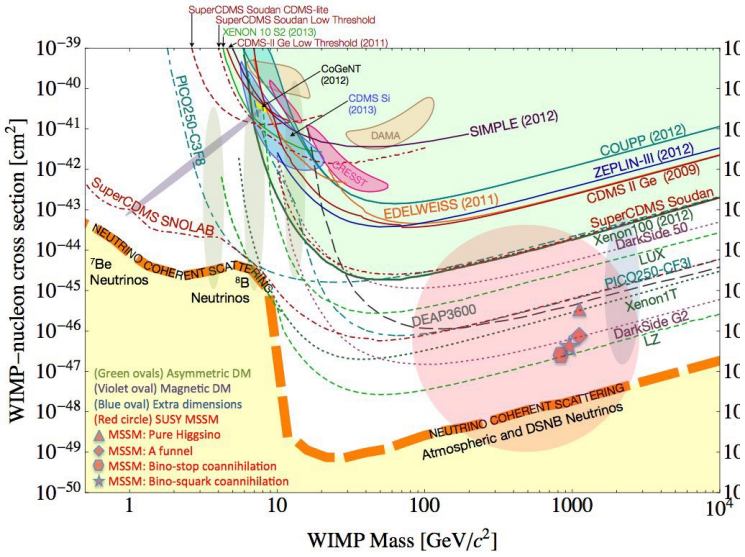
DARK MESA

Light Dark Matter (LDM)

Light Dark Matter

MeV < m_{DM} < ~ GeV

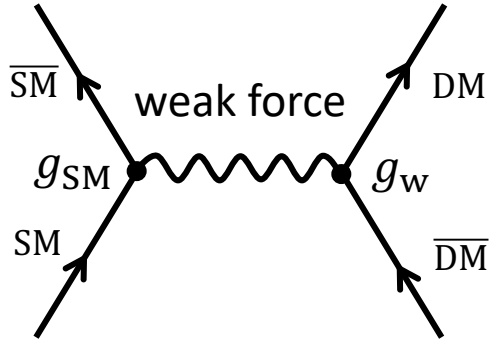




- Thermal relic targets exist for the MeV-GeV mass scale
- LDM requires a beyond SM force
- Rich phenomenology of portals: vector, higgs, neutrino, axion

WIMPs

GeV < m_{DM} < ~ TeV



- Matching relic abundance for the electroweak mass scale
- WIMPs require only SM interaction
- No positive evidence after LHC and galactic DM searches

Vector Mediator: Dark Photon

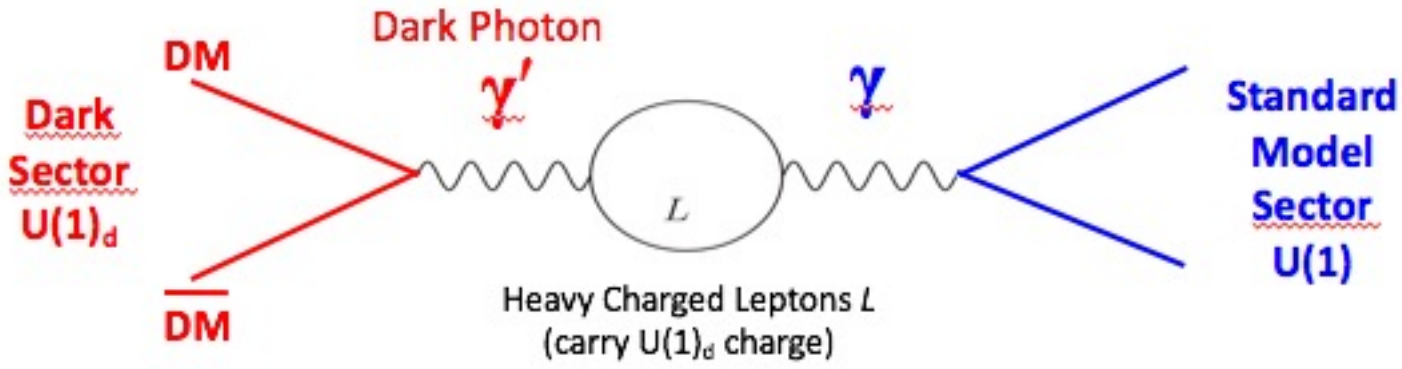
Model 1: $m_{\gamma'} \ll 2m_{DM}$

Dark Photon decaying into SM particles – coupling ϵ

→ MAGIX visible decay

$$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$$

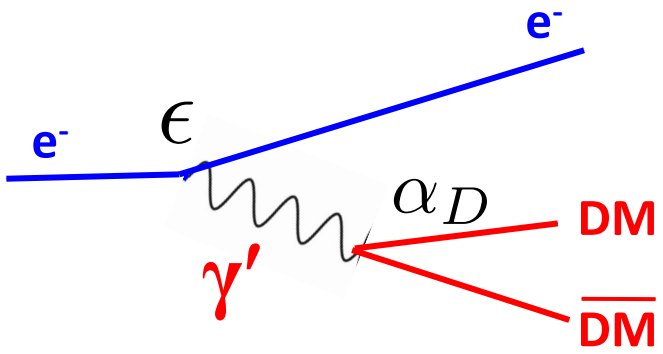
Holdom [1986]



Model 2: $m_{\gamma'} > 2m_{DM}$

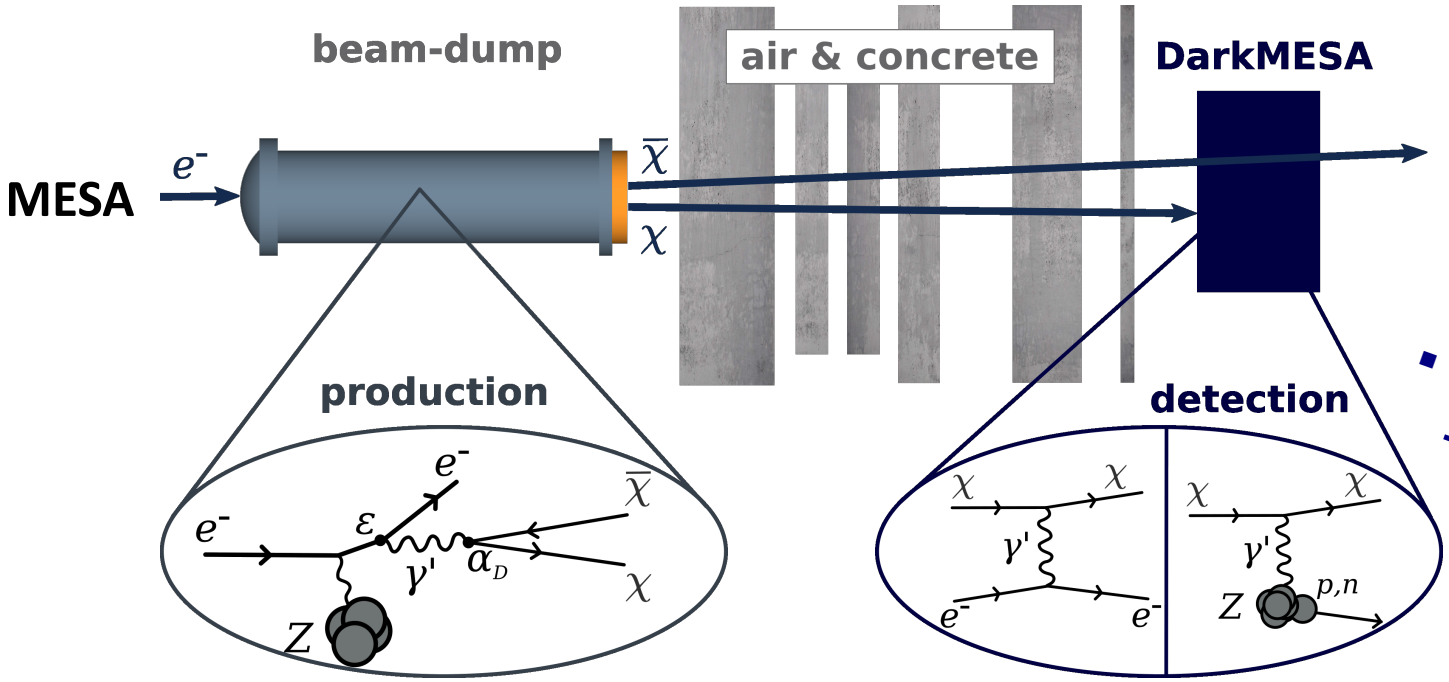
Dark Photon decaying into Dark Matter

→ MAGIX invisible decay and DarkMESA



Beam Dump Experiment DarkMESA

Model 2: $m_{\gamma'} > 2m_{DM}$



Background
- Detector shielded from beam-related SM
- MESA below π production threshold,
  → no neutrinos from π decay
- Cosmogenic background (μ, γ, p, n, e, ν, ….)
  → Active veto detector needed

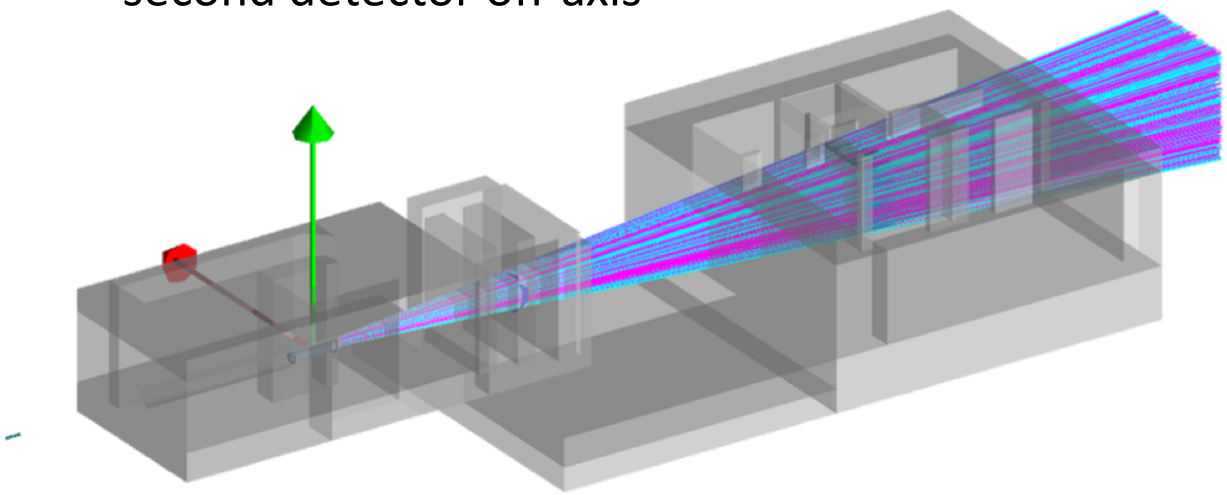
Electron Scattering of 3×10^{22} EOT (MESA) on Beam Dump

→ Collimated pair of Dark Matter particles !

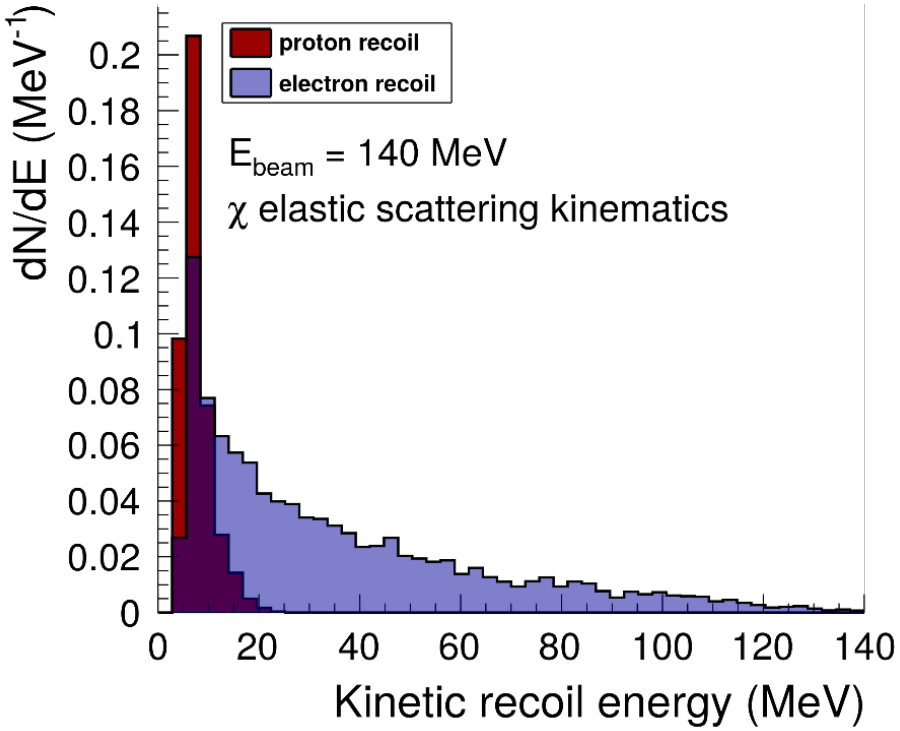
Beam Dump Experiment DarkMESA

Full GEANT4 simulation:
P2 target, beam dump, DarkMESA detector volume, walls etc.

Possibility to place a
second detector off-axis



→ **LDM interaction with DarkMESA material (electron recoil)**

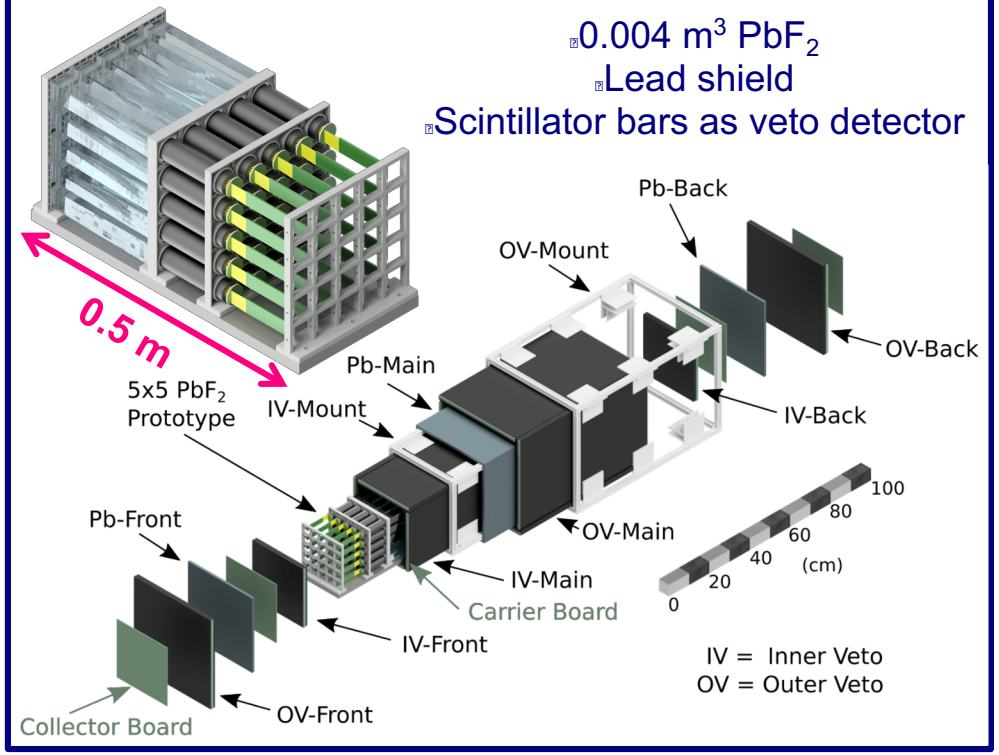


Baseline Concept: Inorganic crystal calorimeter
- Cherenkov (fast, no neutrons)
- Scintillator (higher light yield)

Detector Concept for DarkMESA

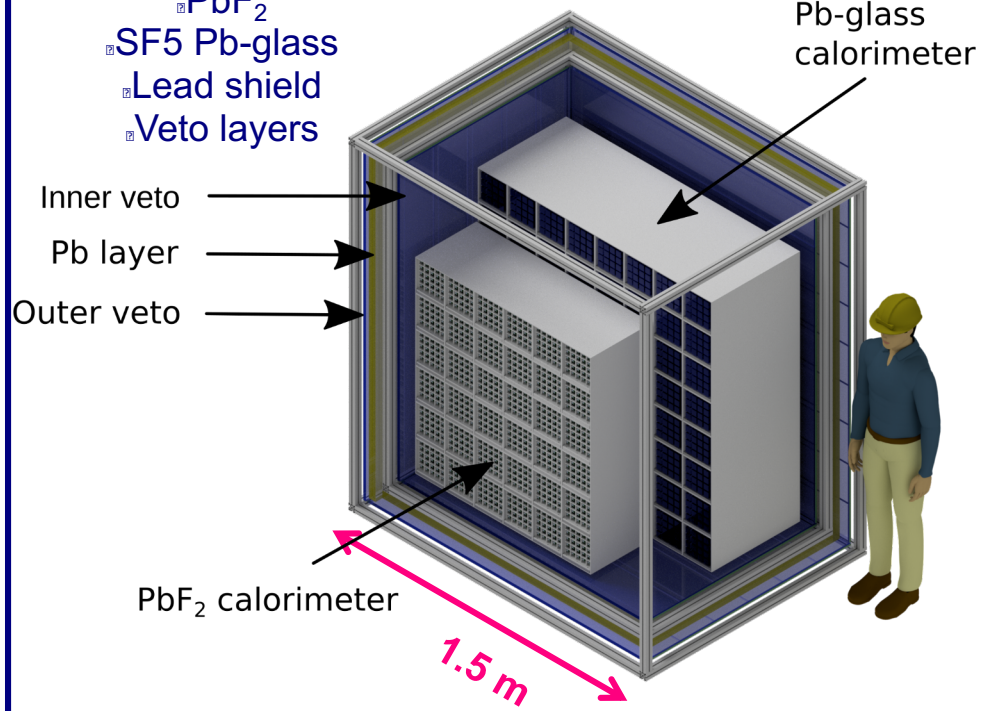
Phase A (prototype)

- 0.004 m³ PbF_2
- Lead shield
- Scintillator bars as veto detector

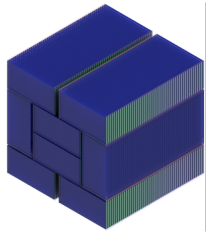


Phase B (increase volume / yield)

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



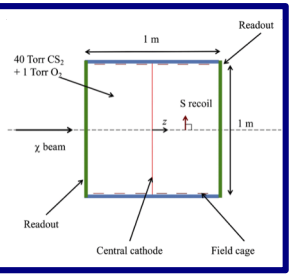
Phase C (range extension)



Radiation protection glas
e.g., SCHOTT-RD30

DRIFT -Time Projection Chamber
CS_2 at 50 mbar ~1 m³ active volume

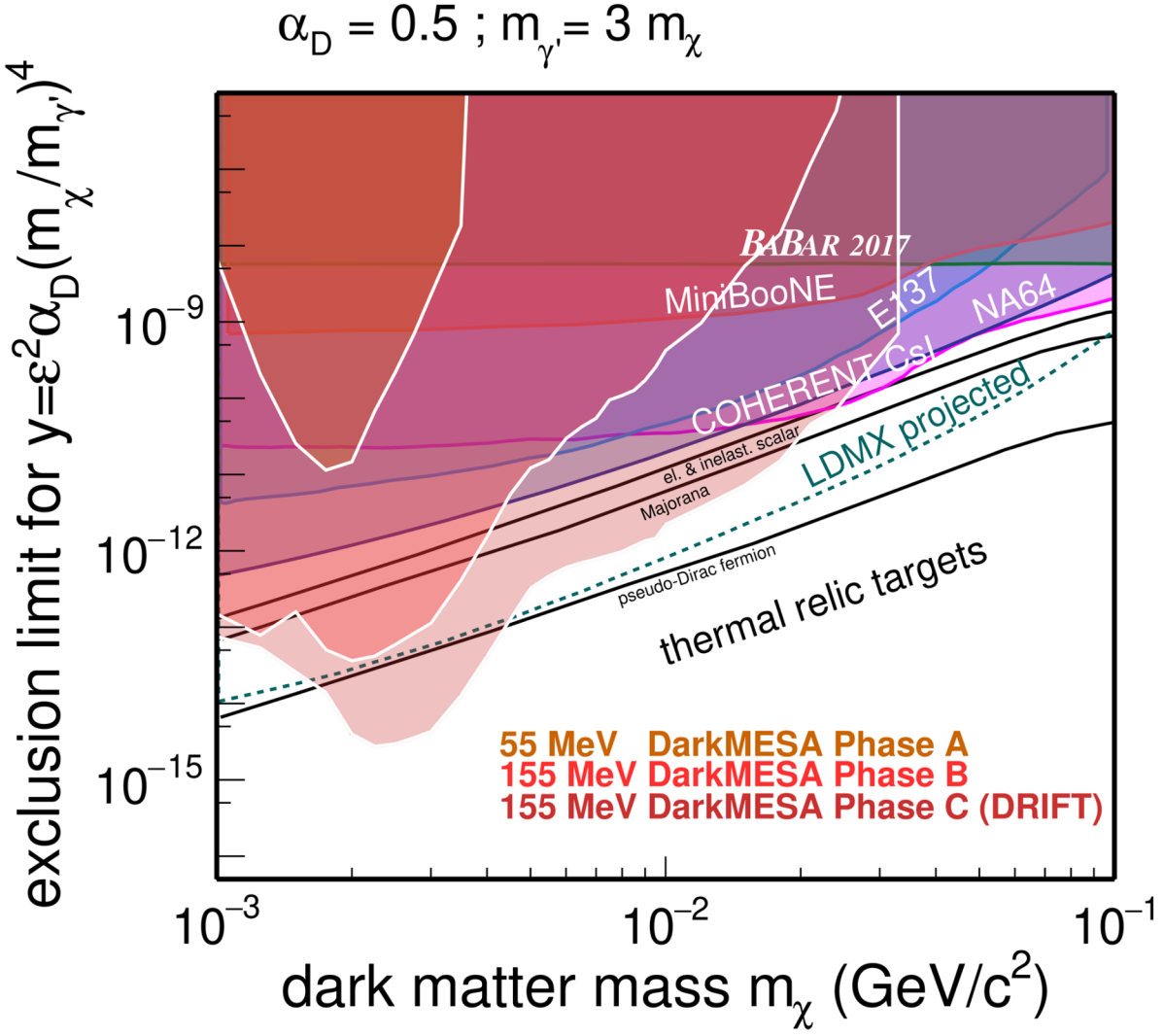
PRD 99 (2019) 061301(R)



DarkMESA Physics Reach

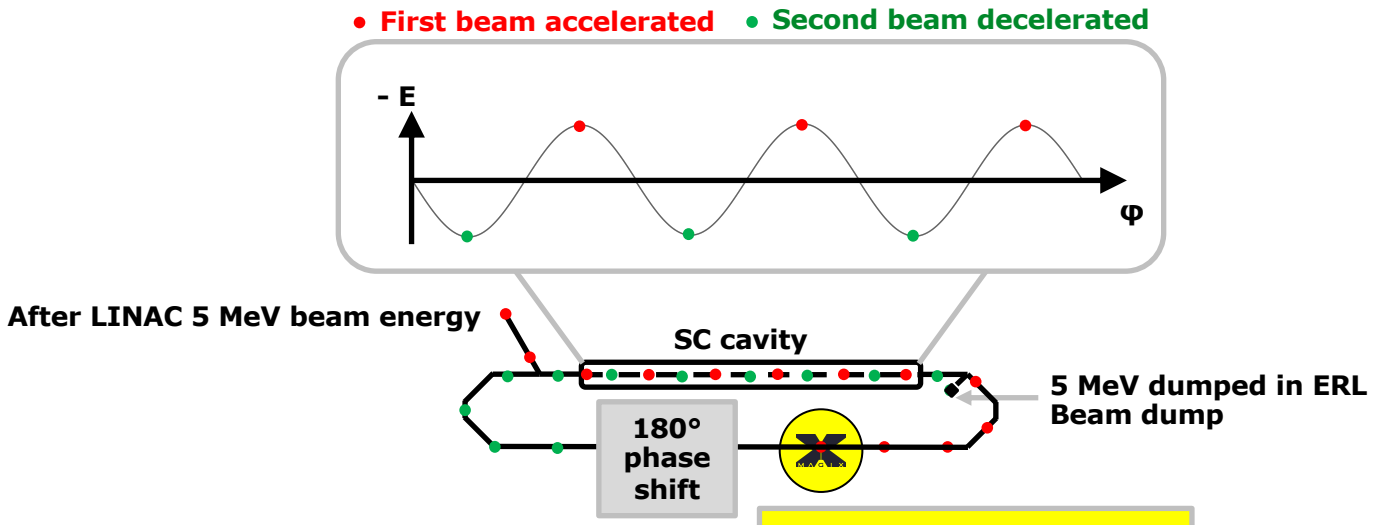
Run plan for DarkMESA

Phase	Detector	Period	Time	EOT
A	Prototype	1.-4. year	2,200 h	$7.42 \cdot 10^{21}$
B	PbF_2, SF5	4.-6. year	6,600 h	$2.22 \cdot 10^{22}$
C	+TPC	7.-12. year	13,200 h	$4.45 \cdot 10^{22}$



MAGIX Experiment

Energy-Recovering Mode (ERL) of MESA

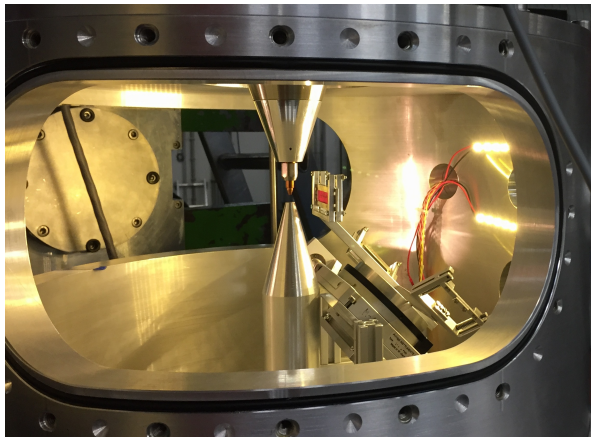


MAGIX intenal experiment

High-Resolution MAGIX Spectrometers

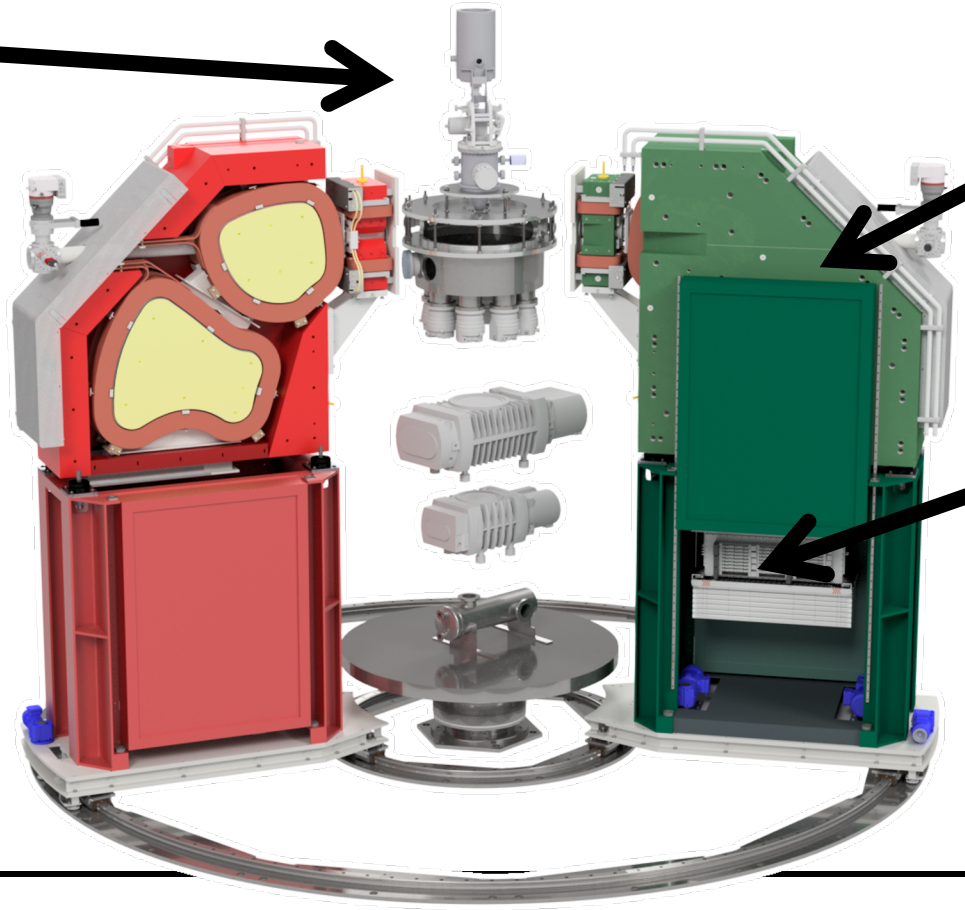
Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics

NIM A1013 (2021)



Supersonic crygenic gas jet target

- Windowless environment
- Commissioned at A1/MAMI
- Design density $10^{19}/cm^2$



Two identical spectrometers

- Two dipoles each
- One quadrupole each

TPC-based focal plane detector

- 10^{-4} momentum resolution
- Requires spatial resolution of O(100 µm)
- Open field cage
- GEM readout

High-Resolution MAGIX Spectrometers

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→ a novel technique in nuclear and particle physics

NIM A1013 (2021)

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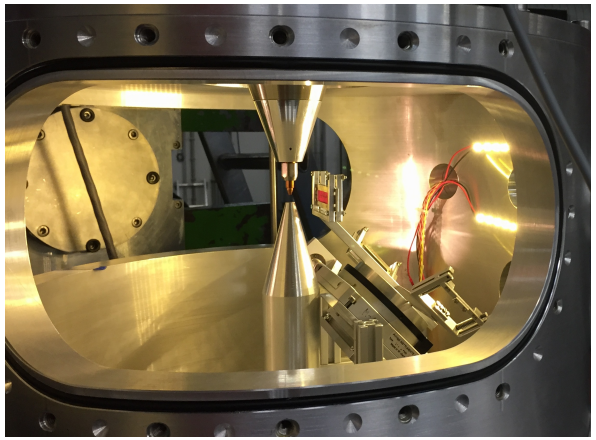

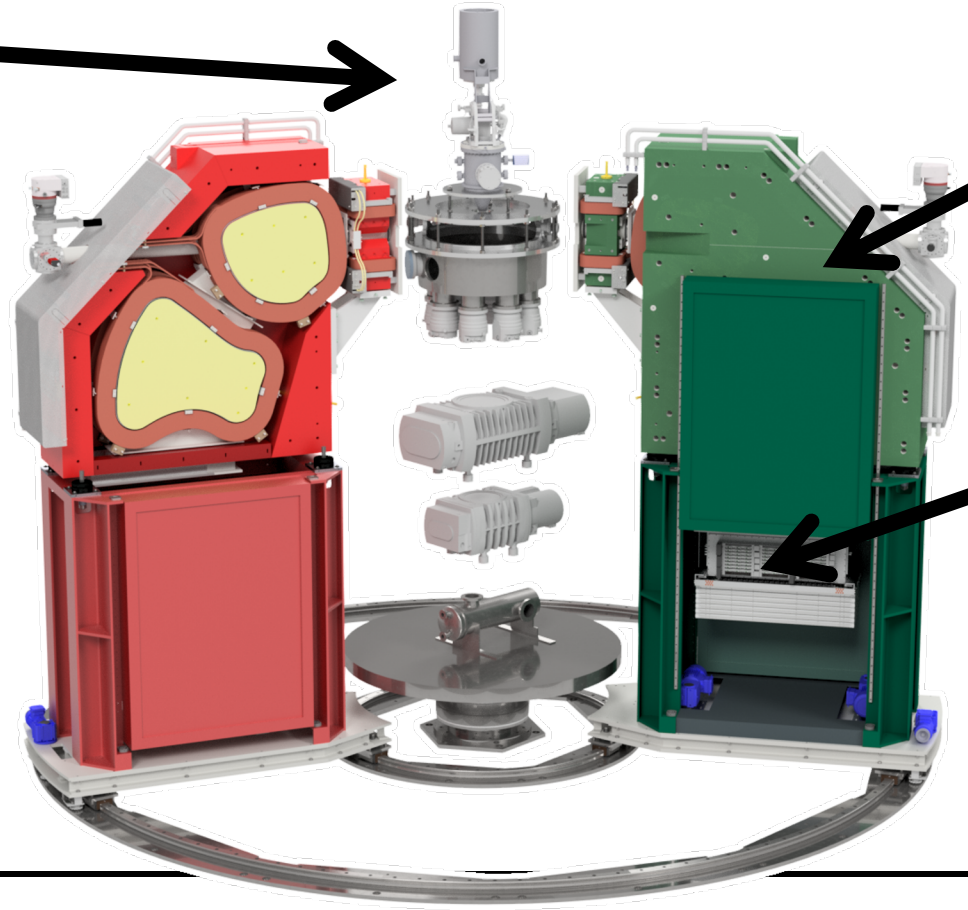

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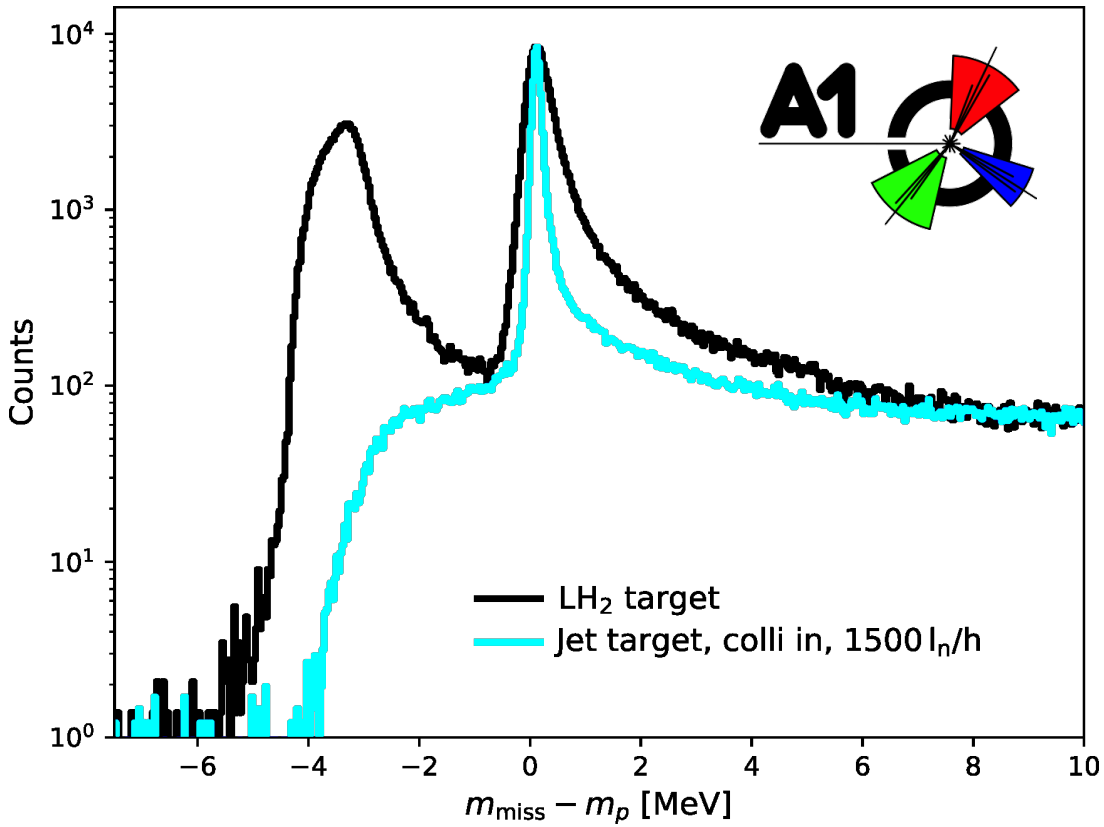
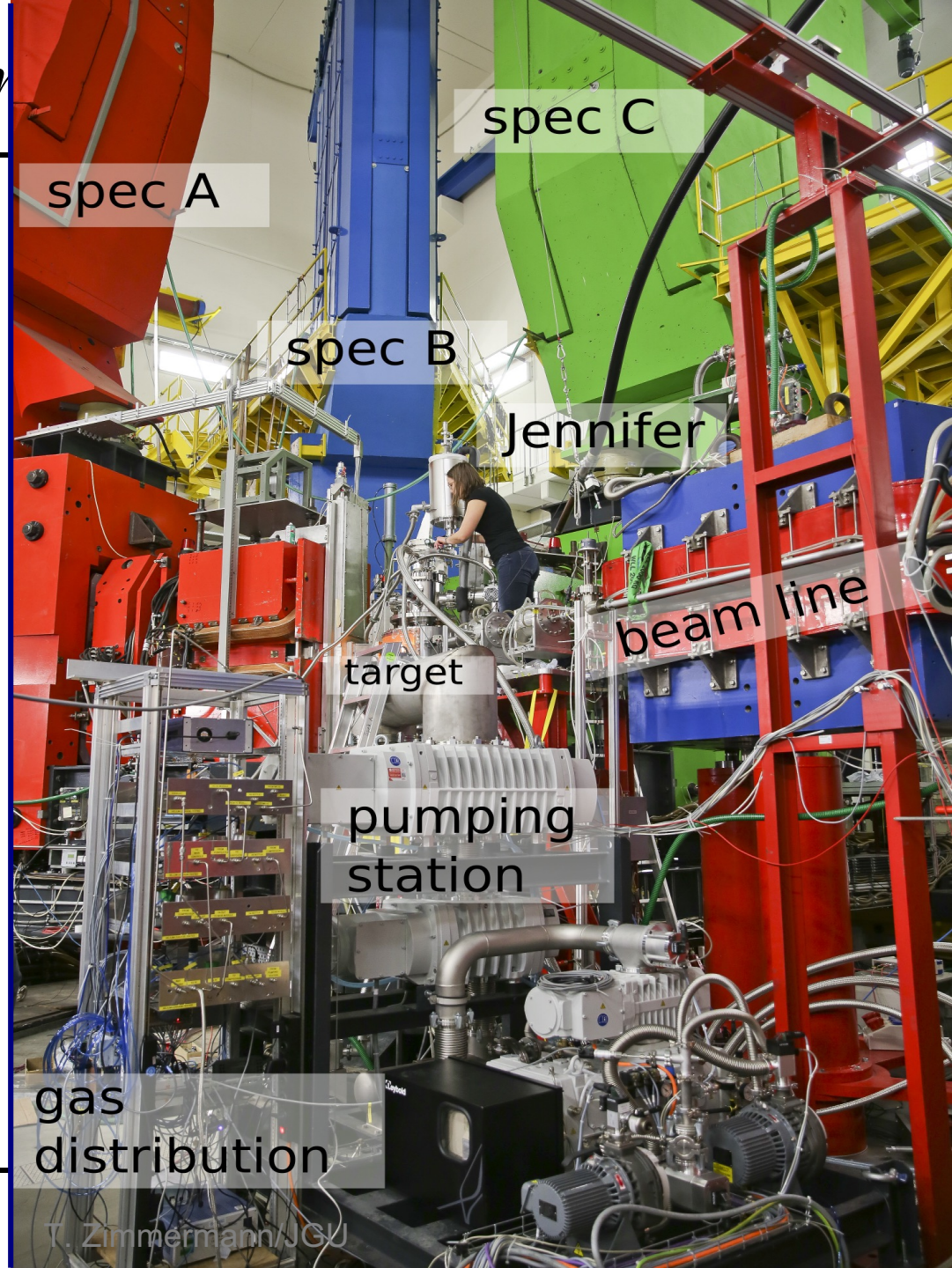


Gas Jet Target commissioned at A1/MAMI

→ Windowless design

→ Much less background from scattering (target walls!) compared to liquid hydrogen LH_2 target

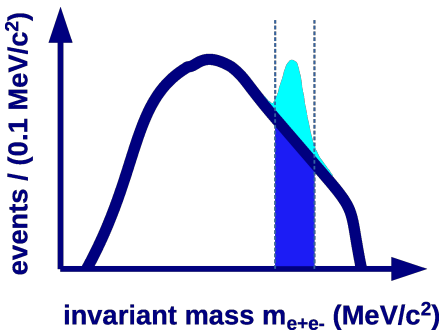


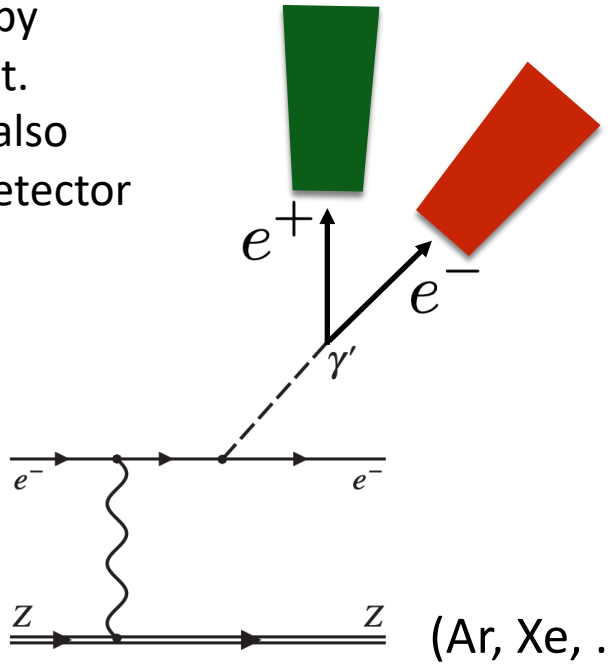
Dark Photon Search at MAGIX

Model 1: $m_{\gamma'} \ll 2m_{DM}$

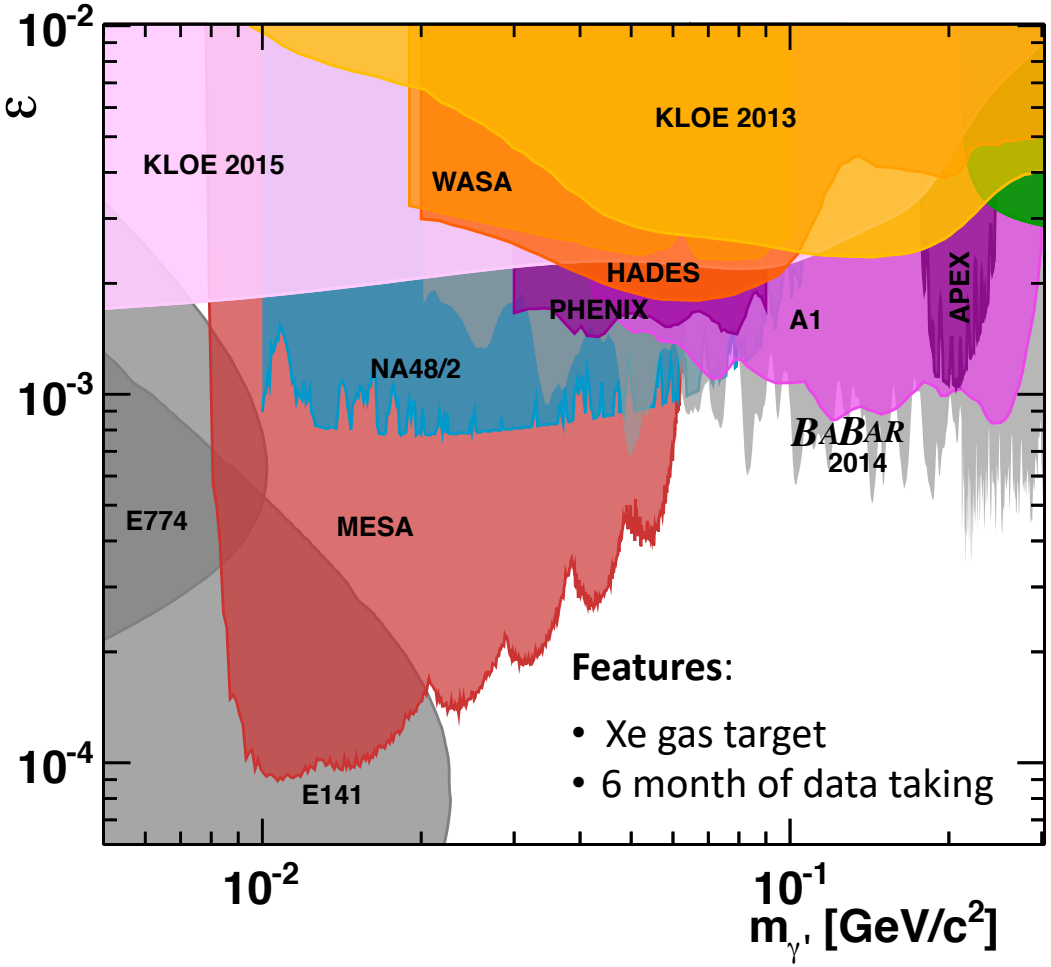
Dark Photon decaying into SM particles – coupling ε

- Method pioneered by A1/MAMI and APEX/JLAB
- Parameter range motivated by X17 anomaly of ATOMKI expt.
- Invisible dark photon decay also possible thanks to Si recoil detector



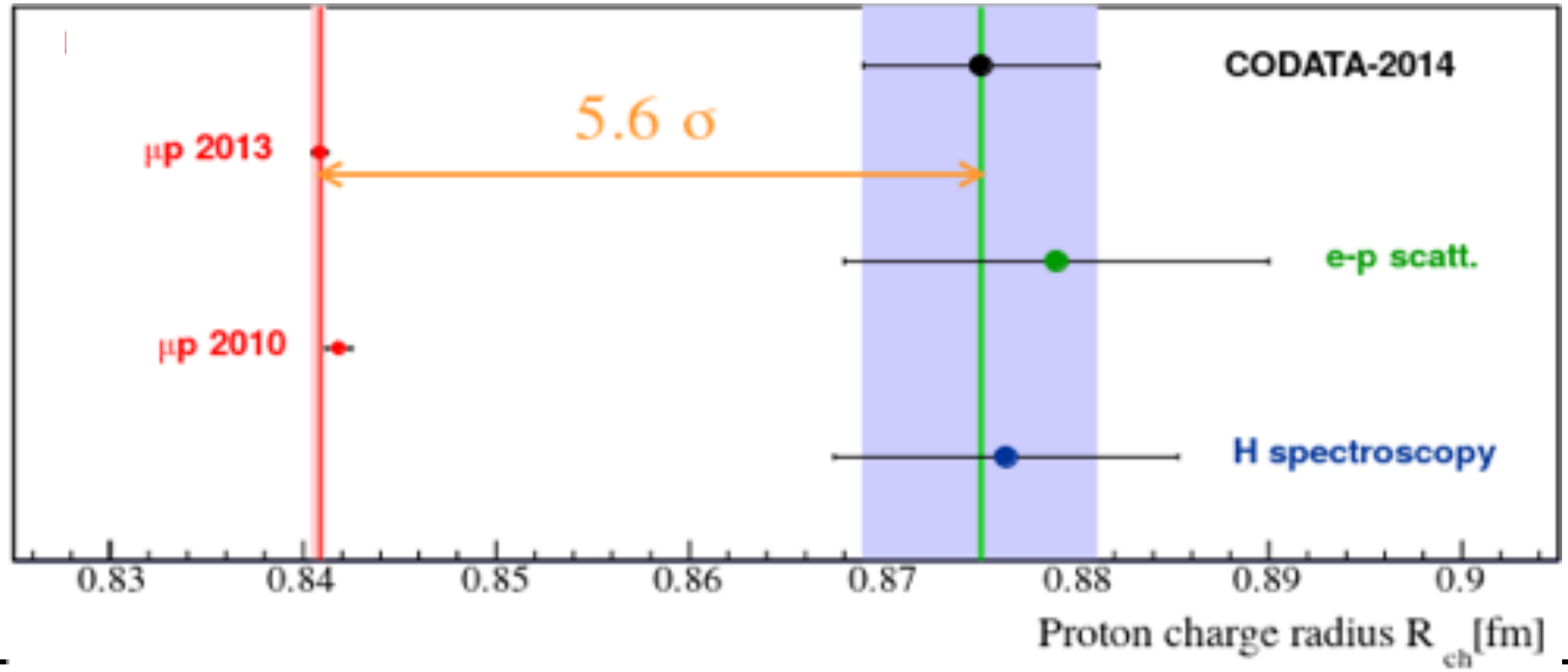


(Ar, Xe, ...)



EM Form Factors and the Proton Radius (Puzzle ?)

Discrepancy between proton radius extractions from
muonic hydrogen spectroscopy and electron scattering/electronic hydrogen spectroscopy
(Situation 2016)

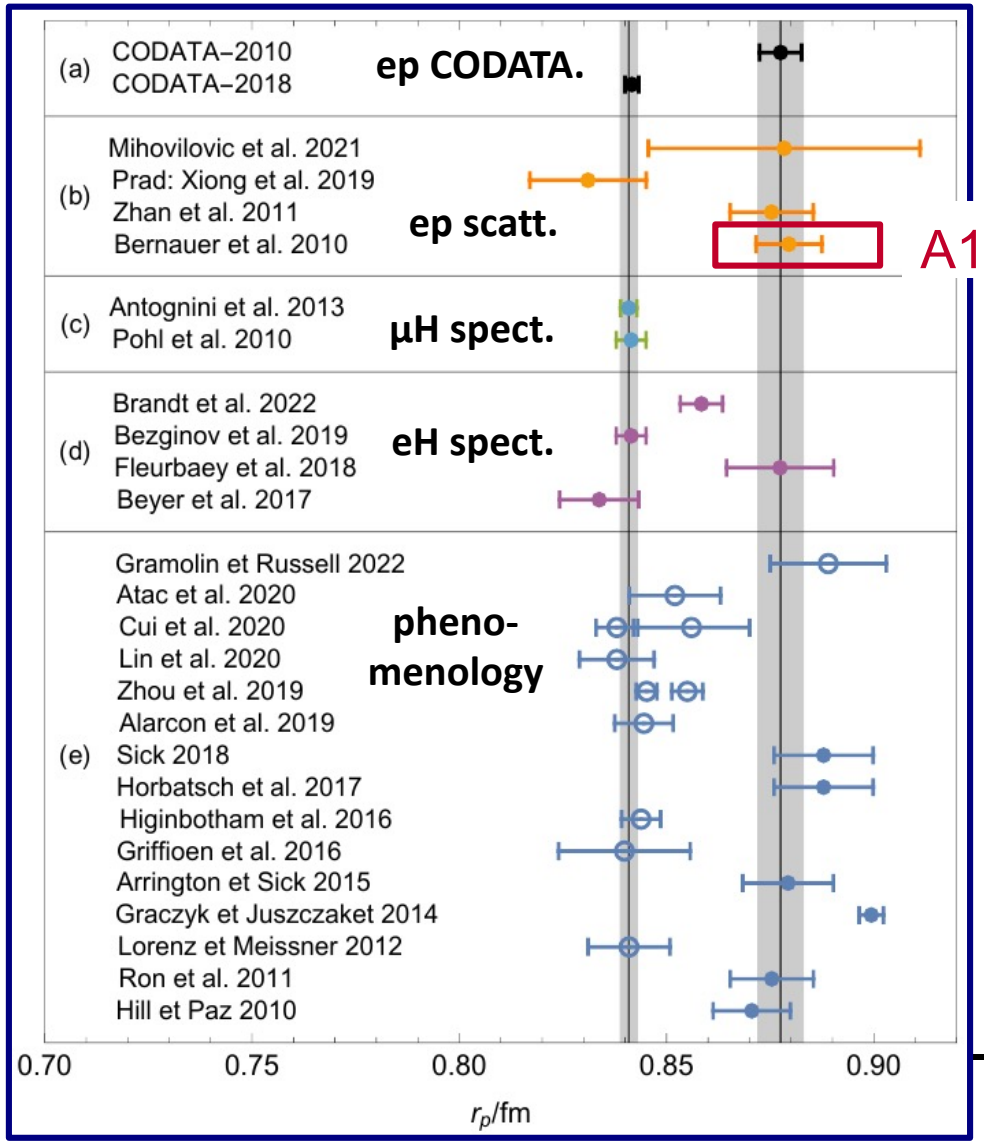


The Proton Radius (Puzzle ?)

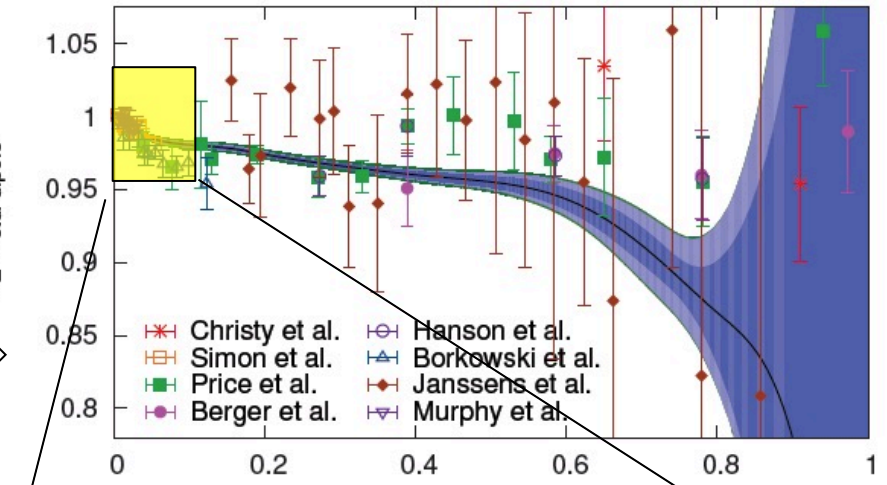
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{\varepsilon(1+\tau)} \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$

arXiv:2304.07035

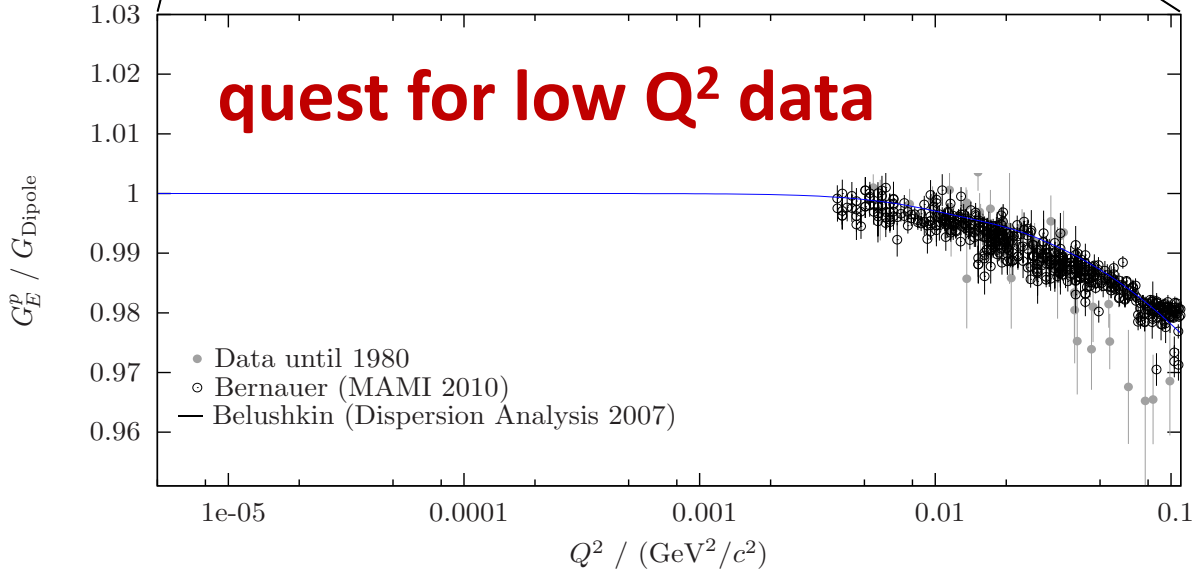
Situation 2023



A1/MAMI



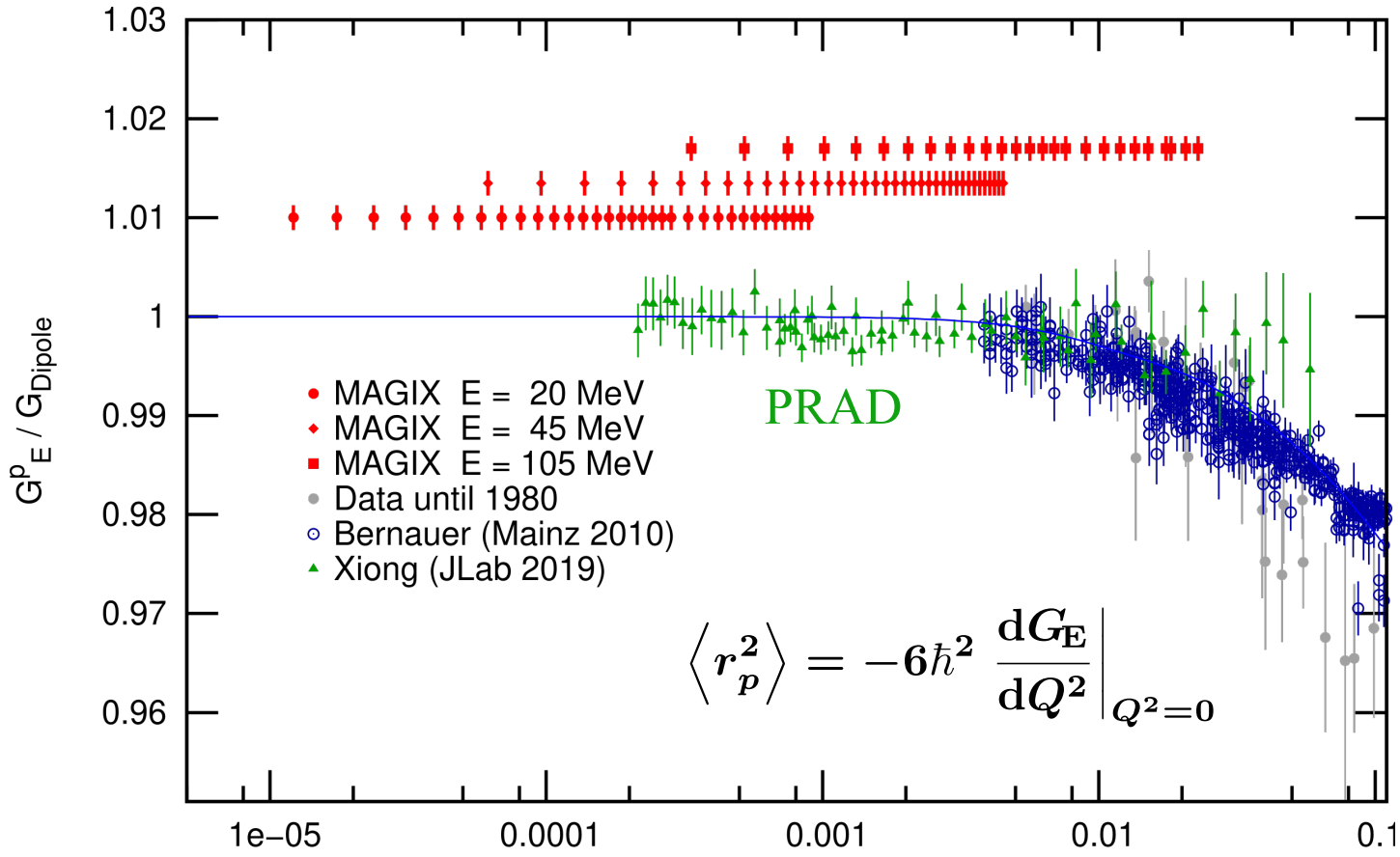
$$\left\langle r_p^2 \right\rangle = -6\hbar^2 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0}$$



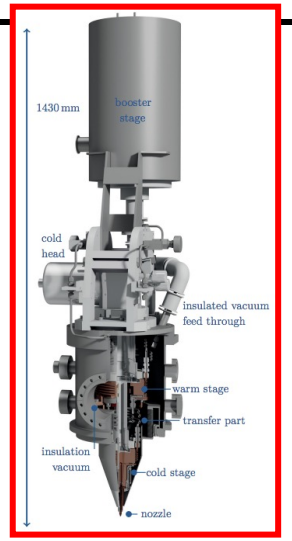
Electromagnetic Form Factors at MAGIX

MAGIX: Coverage from $Q^2 = 1 \cdot 10^{-5}$ to 0.03 GeV^2

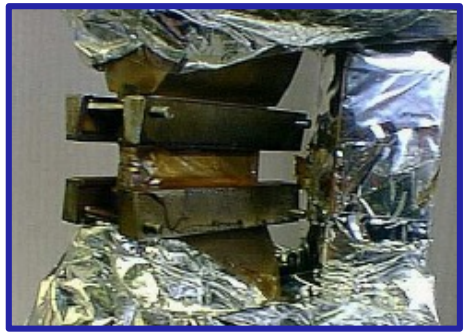
→ **proton charge and magnetic radius!**



MAGIX: truly windowless gas target



A1 data: scattering on LH_2 target target walls



Few Body Physics at MAGIX

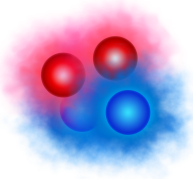
MAGIX provides ideal environment for precision Few Body Physics

→ Elastic scattering: improved determination of charge radii (d, ^{3}He, ^{4}He) from e$^-$ scattering

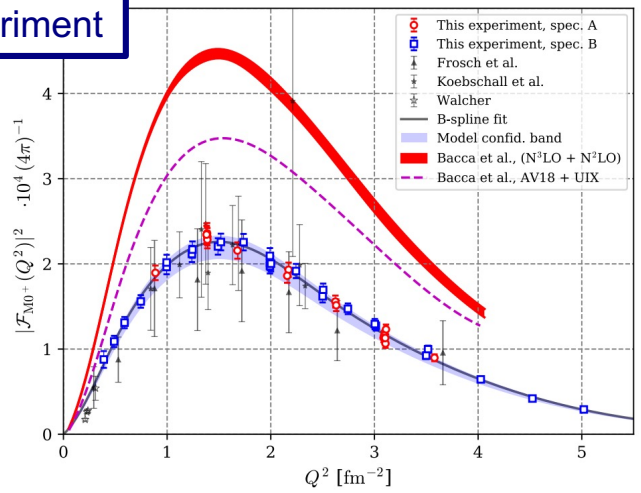
→ Inelastic processes as input for reduced model uncertainties of two-photon corrections and test of χEFT theory

Example:

^{4}He monopole TFF recently measured at A1/MAMI: Q^2 dependence of $e^- \, {}^4He \, (0^+) \rightarrow e^- \, {}^4He^* \, (0^+)$

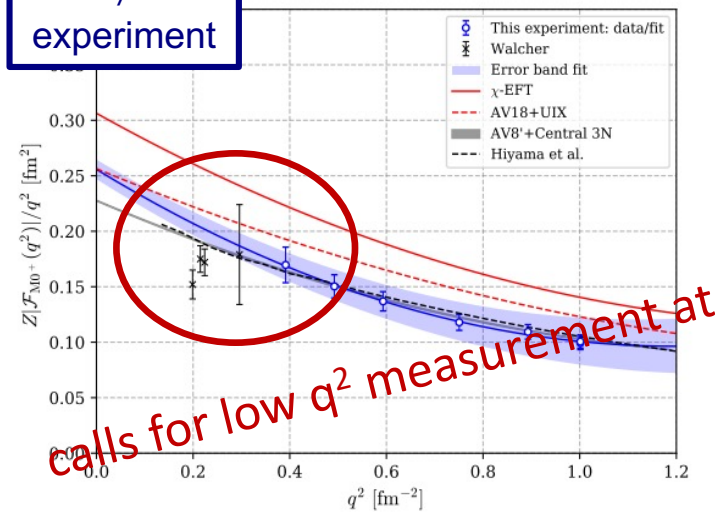


χEFT theory ≠ experiment

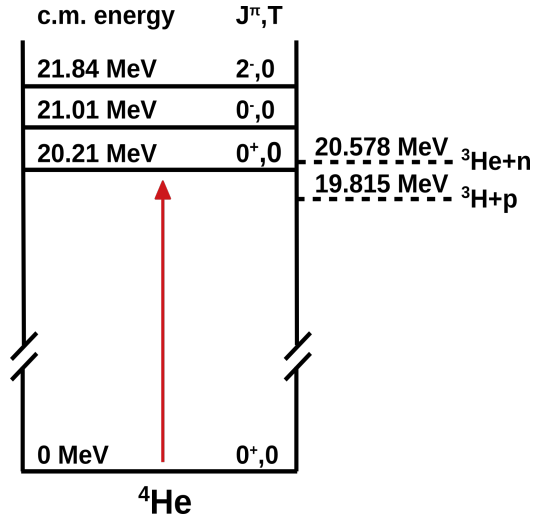


Kegel et al. [A1] PRL2023

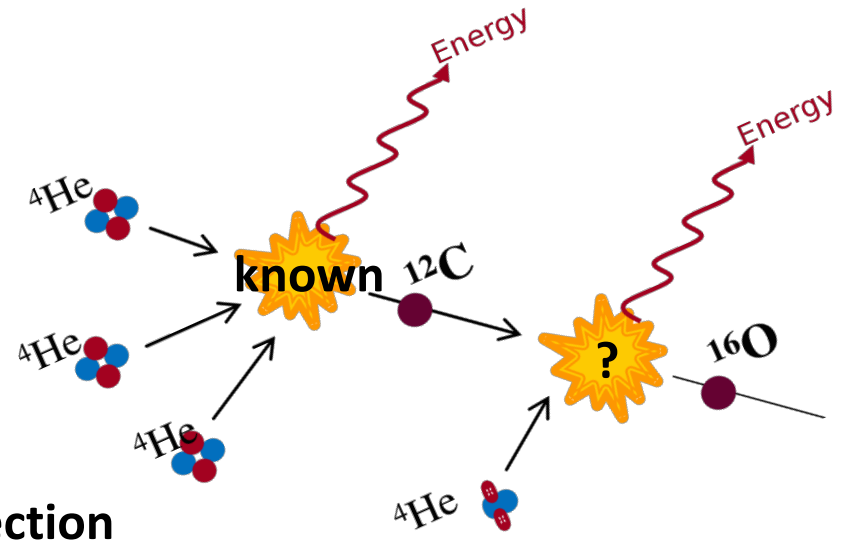
experiment ≠ experiment



calls for low q^2 measurement at MAGIX



Nuclear Astrophysics Reactions at MAGIX



Cross section as function of $E_{c.m.}$

$$\sigma(E) = \frac{1}{E} e^{-\frac{2\pi Z_1 Z_2 \alpha c}{v}} \cdot S(E)$$

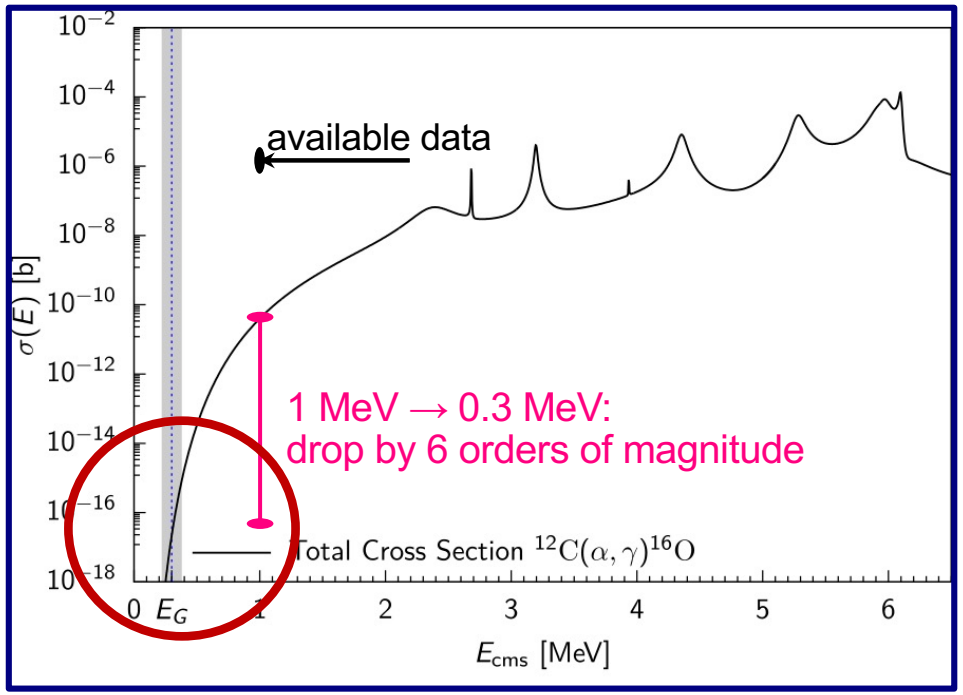
Compton wave length

Tunneling probability in fusion process

„S factor“

^{12}C (α,γ) ^{16}O reaction

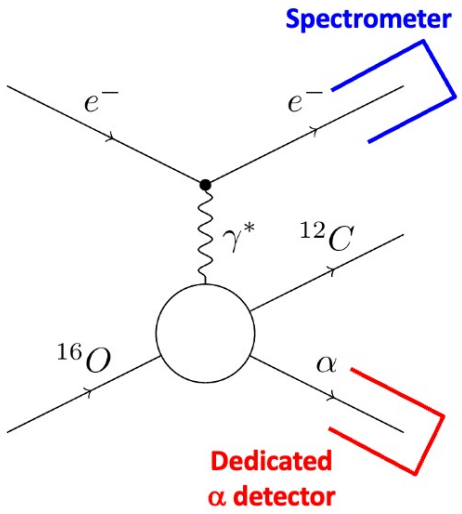
- Of fundamental importance for star burning
- Determines ^{12}C / ^{16}O abundance
- Influences the nucleosynthesis of heavy elements

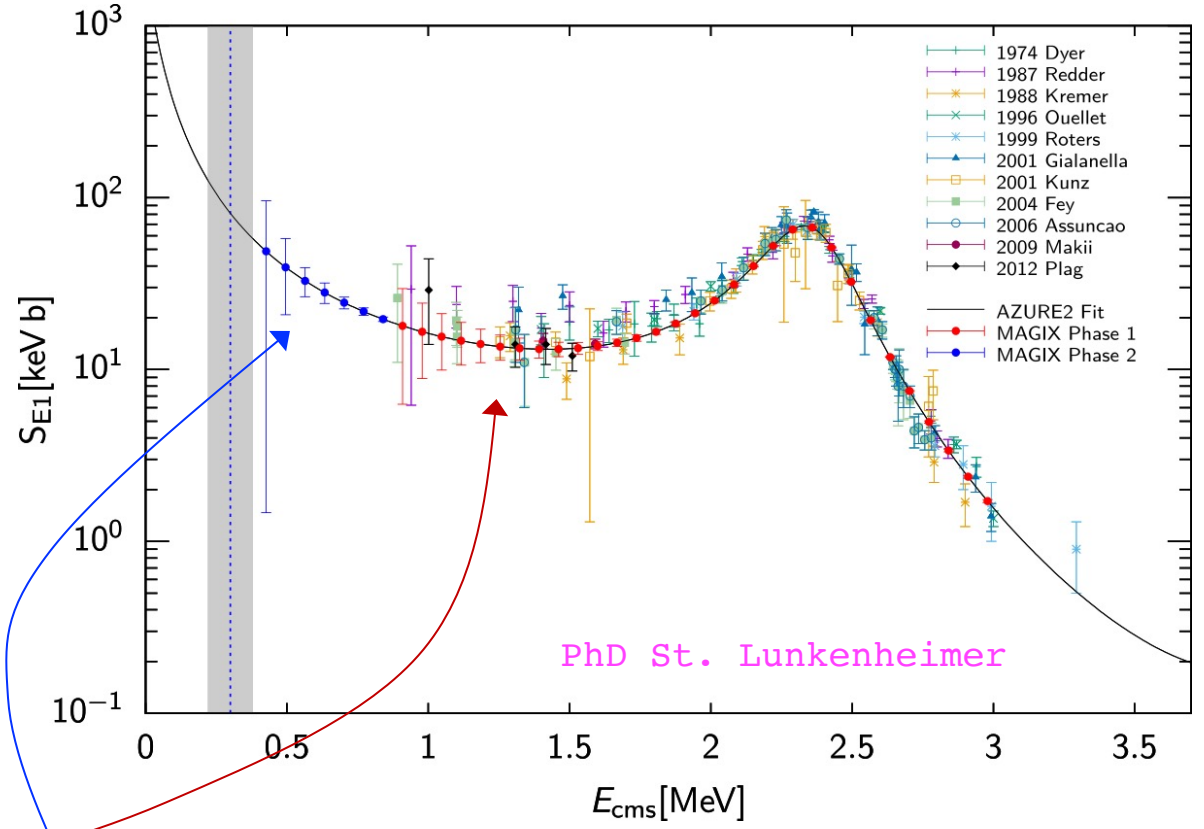


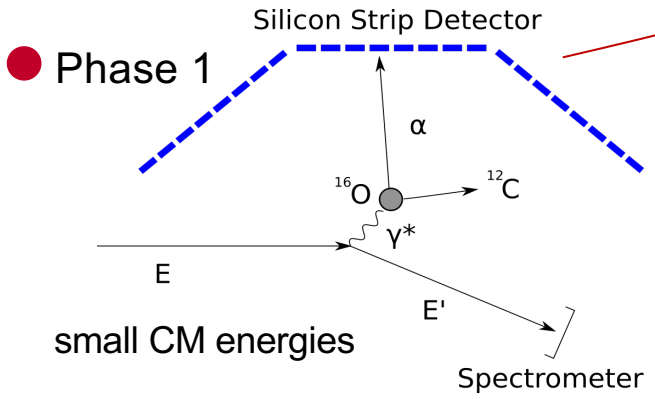
unknown nuclear physics → needs to be known at Gamow Peak ~0.3 MeV

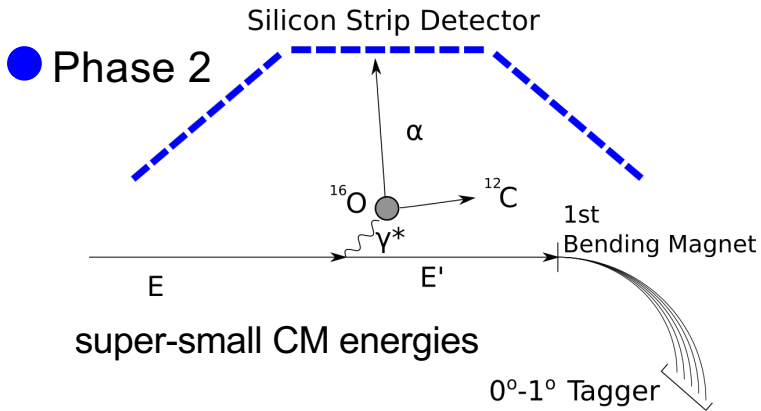
$^{16}O(\gamma,\alpha)^{12}C$ Reaction at MAGIX

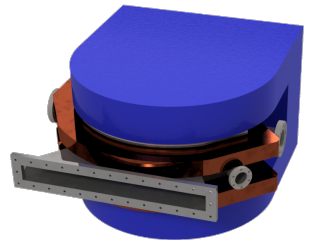
- Inverse reaction: $^{16}O(\gamma,\alpha)^{12}C$
- Chose kinematics with quasi-real photon
- Factor of 100 improvement in cross section wrt. original reaction
- Simulation of process
- Development of Si-detector for α particle detection









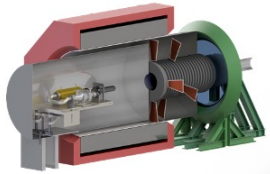


Conclusions

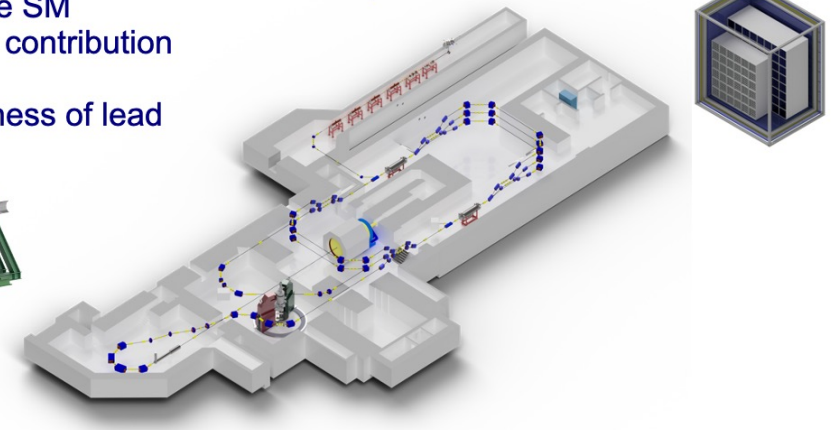
- New MESA electron accelerator (increase in intensity x 10 wrt. MAMI) currently being constructed at Mainz
- Energy-Recovery Linac mode: innovative and „green“ technique!
- 3 experiments under construction:

  → Parity-violation experiment P2
  → Versatile MAGIX spectrometer
  → Beam dump experiment DarkMESA

P2 – Parity Violation Experiments
- prec. meas. of $\sin^2\theta_W$ / search for physics beyond the SM
- axial FF + strange contribution to magnetic FF
- neutron skin thickness of lead



DarkMESA – Beam Dump Experiment
- quest for dark matter and other exotic particles



S. Schlimme

MAGIX – Versatile Electron Scattering Experiment
- Structure of Nucleons and Nuclei
- Few-Body Systems
- Nuclear Astrophysics
- Dark Sector Searches

→ **High intensity and low energy enabling exciting precision experiments in the areas of nuclear, hadron and particle physics**