

The MESA facility

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8th International Symposium on Symmetries in Subatomic Physics



Outline

1 MESA accelerator

2 Experiments at MESA

- P2
- DarkMESA
- MAGIX

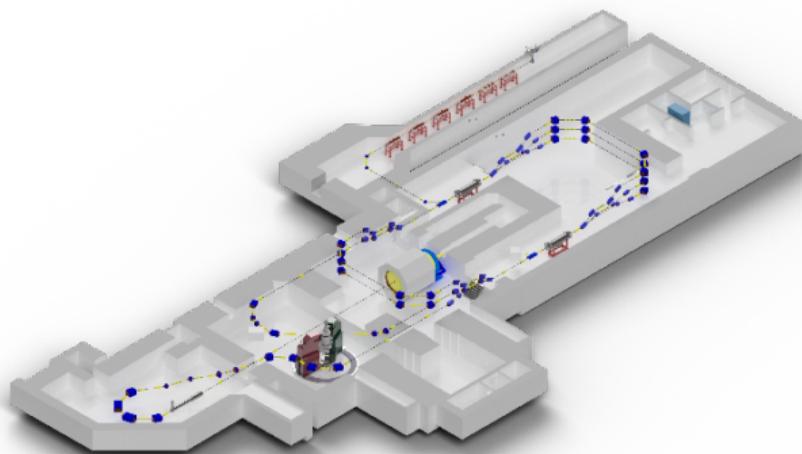
3 Summary

Motivation

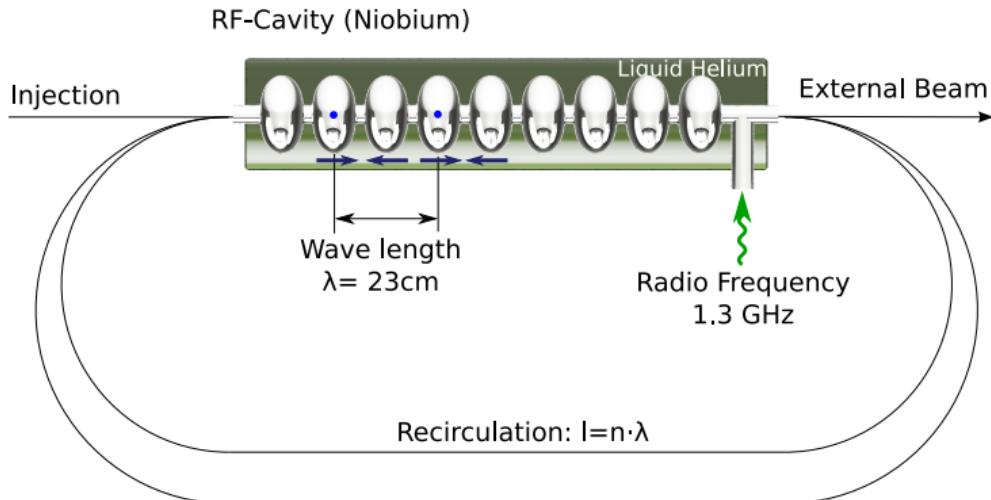
- Standard model very successful
 - Prediction of charm-, top-quark, higgs boson,...
- Known: Still something missing
 - Cosmic microwave background / galaxy rotation curve
 - Dark matter
 - Anomalous magnetic moment $(g - 2)_{\mu,e}$
 - Maybe something new
- Search for extension of the standard model
 - ⇒ High precision
 - ⇒ High intensity
 - ⇒ High energy
 - Deviations from SM prediction
 - Small cross sections
 - Direct production

MESA – Mainz Energy-recovering Superconducting Accelerator

- Future accelerator in Mainz
- Super-conducting, recirculating LINAC
- Two cryo modules with $\Delta E = 25 \text{ MeV}$
- External beam mode
 - Beam energy up to 155 MeV (3 circulations)
 - Beam current up to 1 mA
 - Polarised beam
- Energy recovering mode
 - Beam energy up to 105 MeV (2 circulations)
 - Beam current up to 10 mA

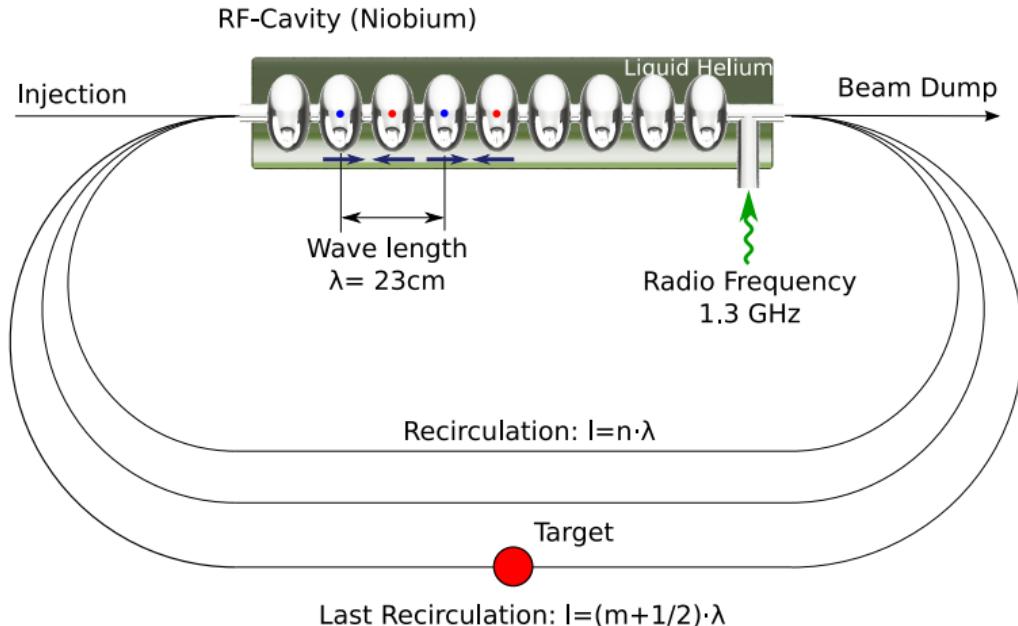


MESA – Principle of an energy recovery linac



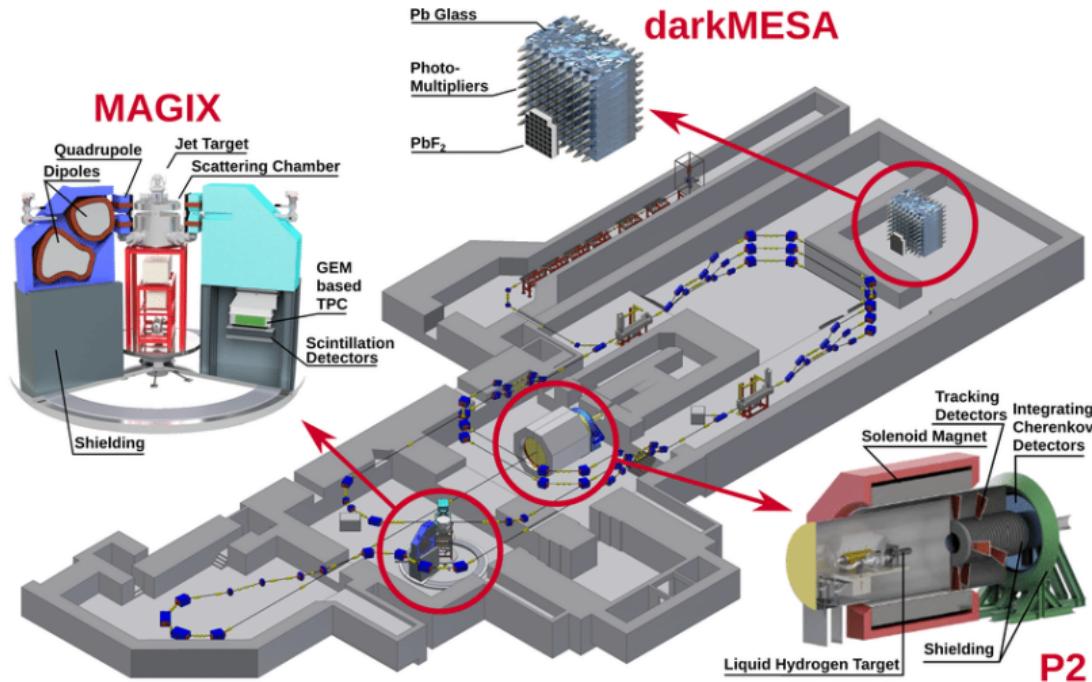
- Recirculating linear accelerator → increase beam energy
- Last return path: $(m + \frac{1}{2})\lambda \rightarrow$ Phase shift
- Energy feed back to cavities → increase beam current

MESA – Principle of an energy recovery linac



- Recirculating linear accelerator → increase beam energy
- Last return path: $(m + \frac{1}{2})\lambda$ → Phase shift
- Energy feed back to cavities → increase beam current

Experiments @ MESA



⇒ MAGIX

- High resolution Spectrometer
- Internal gas target

⇒ DarkMESA

- Search for dark sector particles

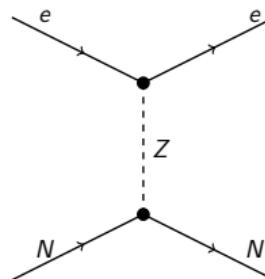
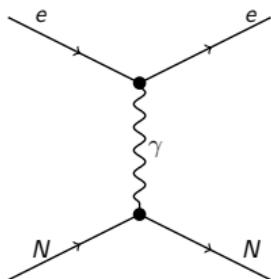
⇒ P2

- Parity-violating e-p-scattering
- External beam mode

P2 - The weak mixing angle

- Electro-weak unification

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$



- Electric charge

$$Q_{em}(p) = +e$$

$$Q_{em}(n) = 0$$

- Weak charge

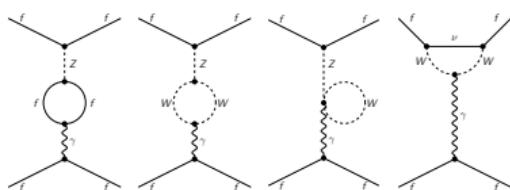
$$Q_W(p) = 1 - 4\sin^2 \theta_W$$

$$Q_W(n) = -1$$

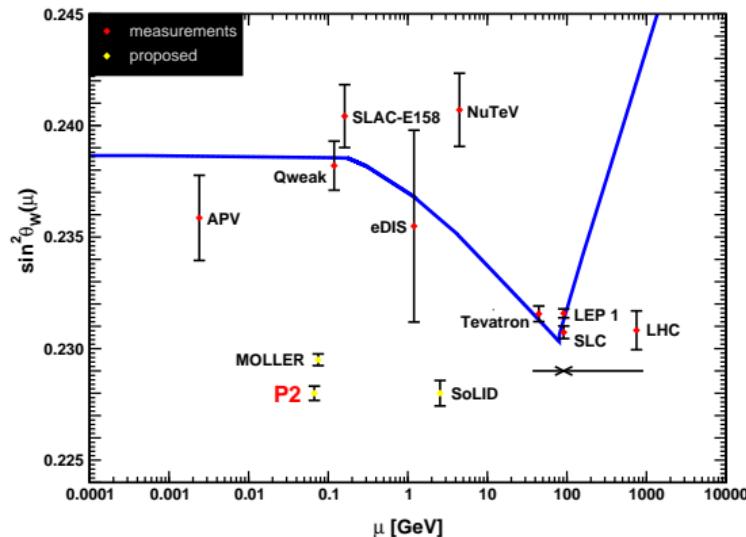
- $\sin^2 \theta_W$ central parameter of the standard model

P2 - Running of the weak mixing angle

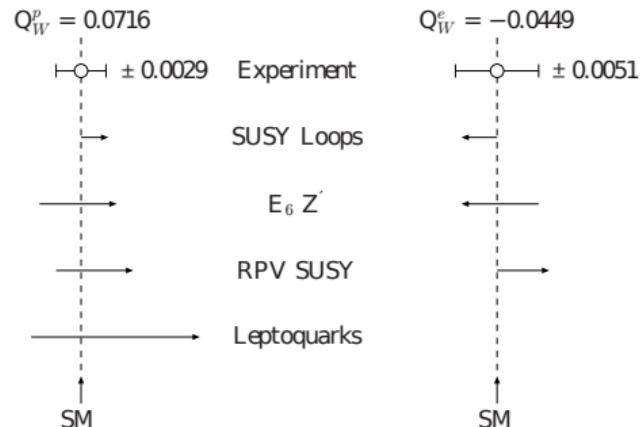
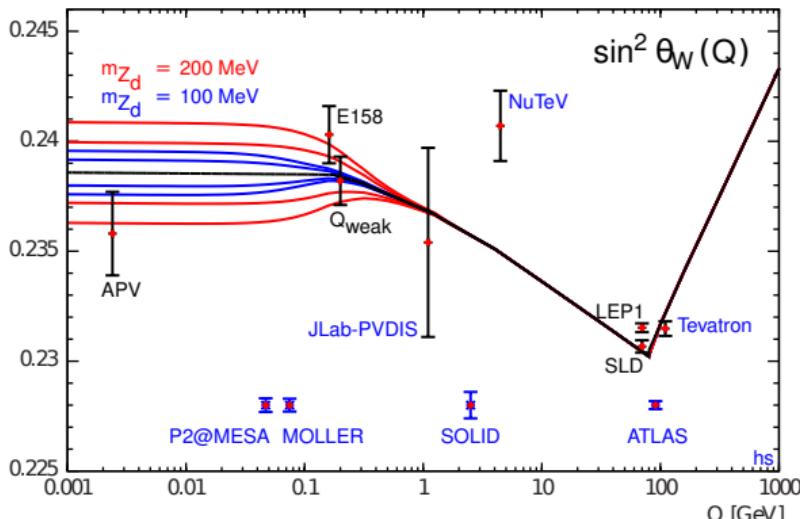
- $\sin^2 \theta_w$ central parameter of the standard model
- Scale dependence of $\sin^2 \theta_w$
Quantum corrections are absorbed into an effective running



- Z-pole: high precision, deviations
- Low Q : large uncertainties



P2 - Physics beyond the standard model



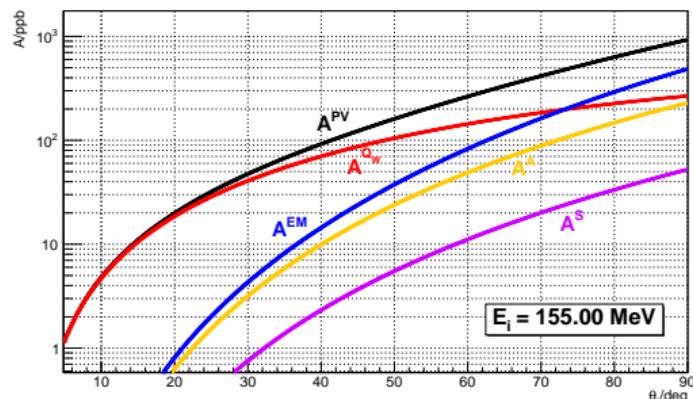
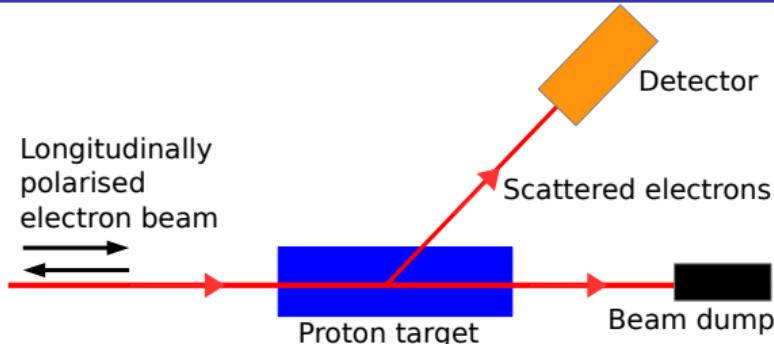
- Sensitivity towards hypothetical new particles/interactions
- Dark Z-boson
 - New light vector boson
 - Kinematic and mass mixing with γ/Z
- Combination of $Q_W(p)$ and $Q_W(e)$
- Complementary access to new physics

P2 - Parity-violating electron scattering

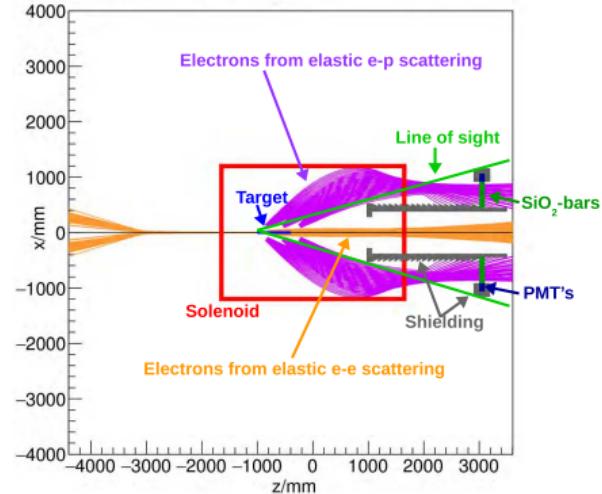
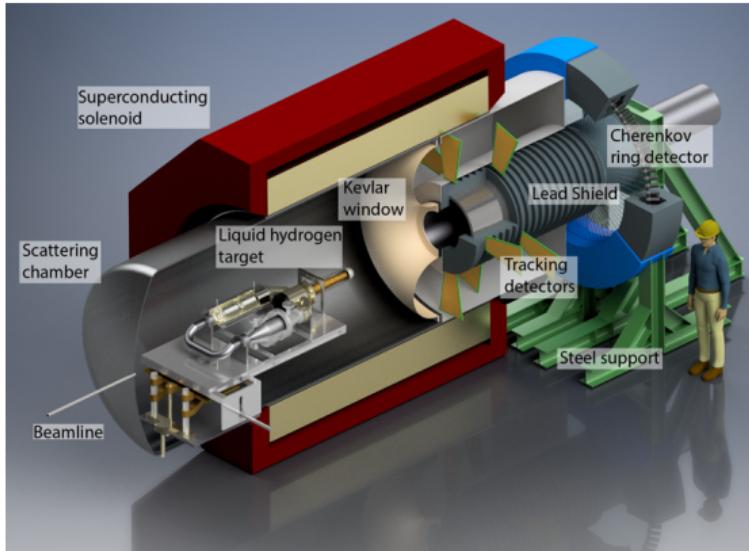
- Longitudinally polarised electron beam
- Detect scattered electrons
- Cross section: $\sigma_{ep}^{\pm} = |M_{\gamma} + M_Z^{\pm}|^2$
- Weak interaction: Parity violating
 $\Rightarrow \sigma_{ep}^{+} \neq \sigma_{ep}^{-}$

$$A_{ep}^{PV} = \frac{\sigma_{ep}^{+} - \sigma_{ep}^{-}}{\sigma_{ep}^{+} + \sigma_{ep}^{-}}$$
$$= \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} [Q_W(p) - F(E, Q^2) + \Delta_{\square}(E, Q^2)]$$

- $Q_W(p)$: Weak charge (dominant at low Q^2)
- $F(E, Q^2)$: Hadron structure
- $\Delta_{\square}(E, Q^2)$: Corrections from box diagrams



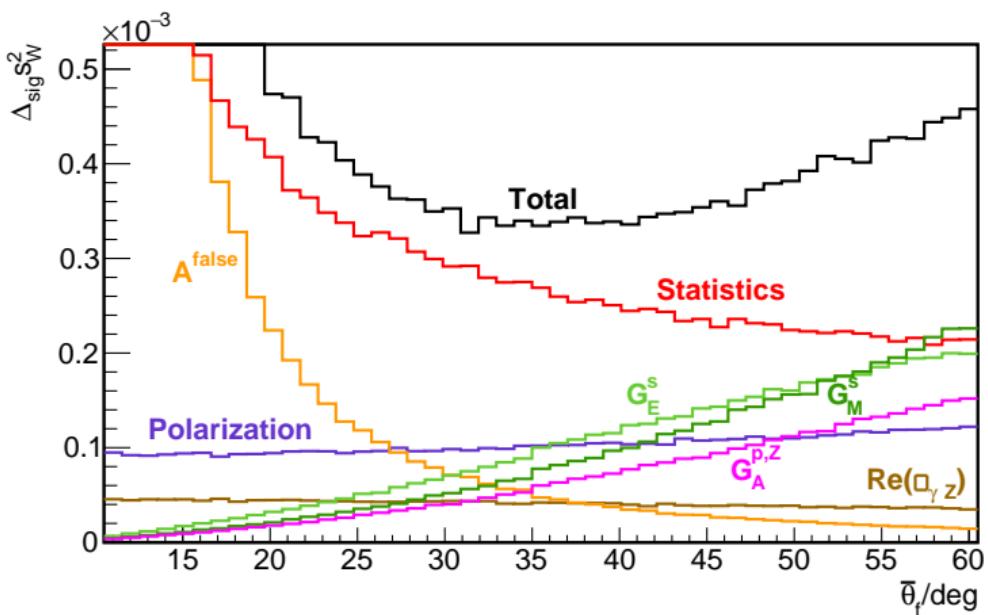
The P2 detector



- Detect elastic e-p-scattering
- Expected asymmetry: $\langle A^{\text{raw}} \rangle_{\text{exp}} = -24.03 \text{ ppb}$
 - ⇒ High statistics needed
 - ⇒ Large solid angle
 - ⇒ High luminosity $\mathcal{L} = 1.2 \cdot 10^{39} \text{ cm}^{-2}\text{s}^{-1}$

- Control of systematic uncertainties
 - ⇒ Fast helicity reversal
 - ⇒ Polarisation measurement
 - ⇒ Tracking detectors
 - ⇒ Beam parameter control
 - ⇒ ...

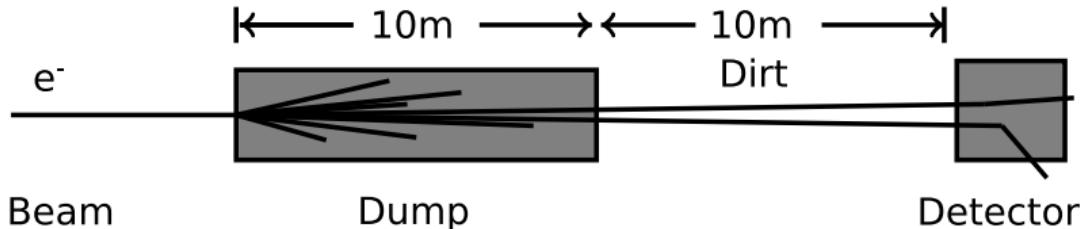
P2 - Achievable precision



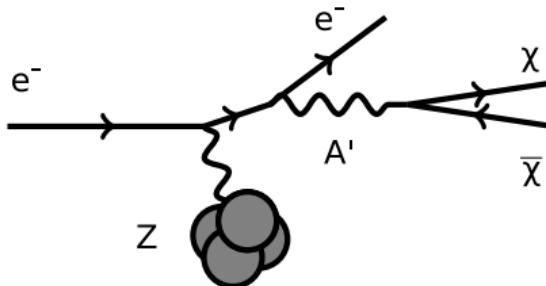
- Beam current: $150 \mu\text{A}$
- Measuring time: 10000 h
- Beam polarisation:
 $P = 0.85, \Delta P/P = 0.5\%$
- Raw asymmetry $\langle A^{\text{raw}} \rangle_{\text{exp}} = -24.03 \text{ ppb}$
- $\Delta_{\text{tot}} \langle A^{\text{raw}} \rangle_{\text{exp}} = 0.58 \text{ ppb (2.41\%)}$
⇒ Relative uncertainty on
 $\sin^2 \theta_W$: 0.16%

- Measure the Proton weak charge
 - Very high precision $\frac{\Delta \sin^2 \theta_w}{\sin^2 \theta_w} = 0.16\%$
 - Sensitivity towards new physics on mass scales up to 50 TeV
- Measurement of the ^{12}C weak charge
 - Additional complementary measurement
 - $Q_W(^{12}\text{C}) = -24 \sin^2 \theta_W$
- ^{208}Pb neutron skin, $\frac{\Delta R_n}{R_n} = 0.5\%$ possible
 - $A^{PV} \approx \frac{G_F Q^2}{4\pi\alpha_{em}\sqrt{2}} \frac{F_w(Q^2)}{F_{Ch}(Q^2)}$
 - Neutron skin of heavy nuclei \leftrightarrow neutron-rich matter
- Parity violating asymmetry under backward angle
 - Hadronic structure, e.g., strangeness content

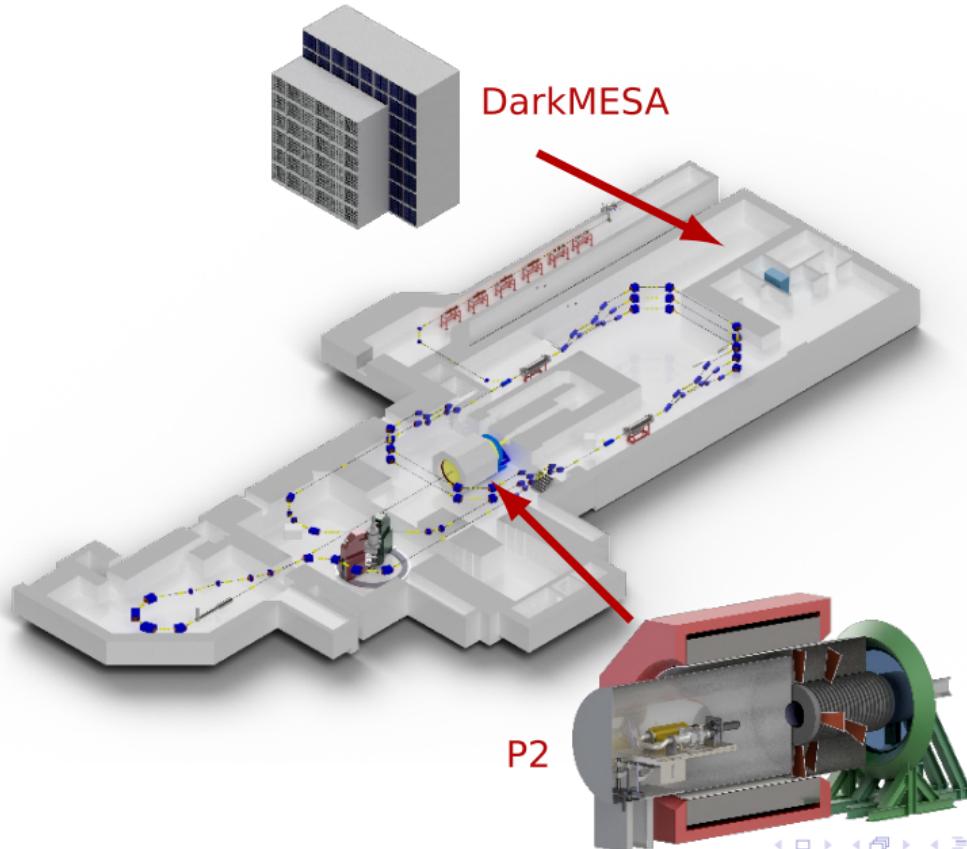
DarkMESA - Idea behind beam dump experiments



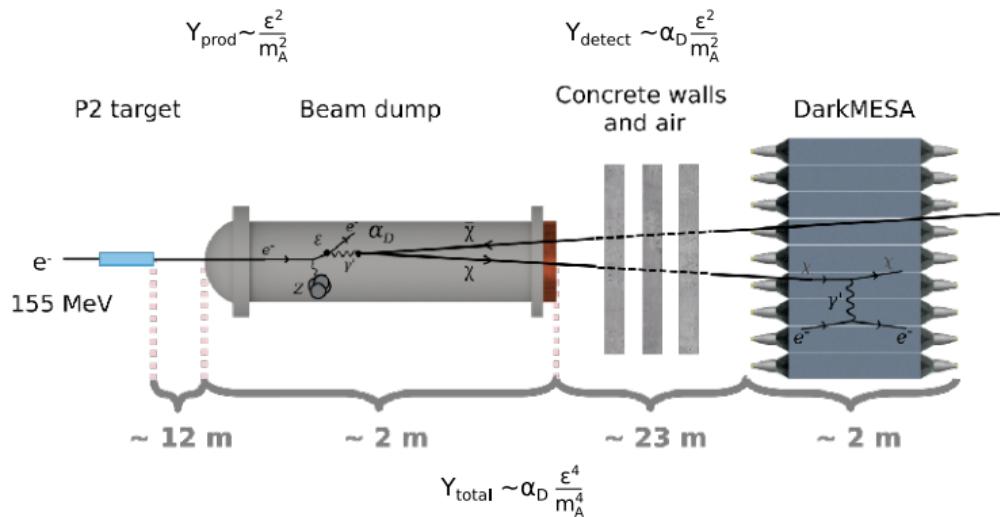
- Production in a beam dump, e.g. via pair production



- Knowledge of production mechanism is NOT crucial for experiment
- Produces a "beam of dark matter"
- Dark matter particles now with enough recoil energy
⇒ Simple detector



DarkMESA



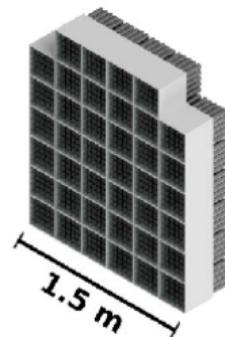
- P2: $\mathcal{O}(10^4 \text{ h})$ of high intensity beam on beam dump
- Below π production threshold \Rightarrow no μ, ν produced
- Beam with direction, time structure possible
- Neutrons can be shielded, still active veto needed

The DarkMESA detector

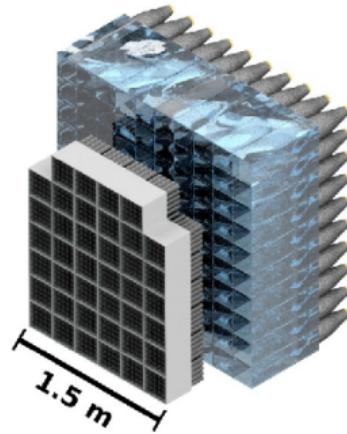
Prototype



Phase A



Phase B



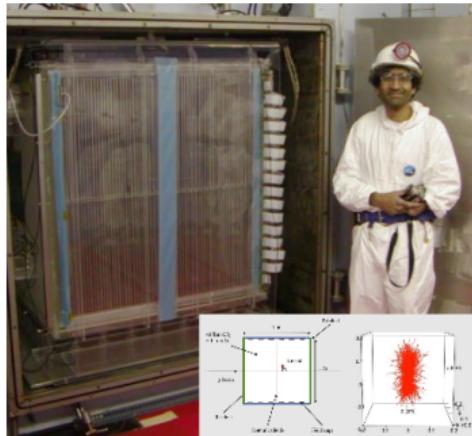
- 0.004 m^3 PbF-Crystals
- Mounted in 5×5 matrix

- 0.12 m^3 PbF-Crystals

- 0.12 m^3 PbF-Crystals
- 0.58 m^3 SF5 (Lead glass blocks)
- 2000 crystals from former A4/WA48 experiments

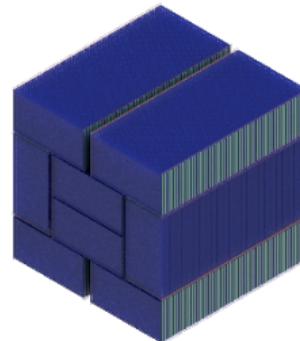
DarkMESA - Detector upgrades

DarkMESA - Drift



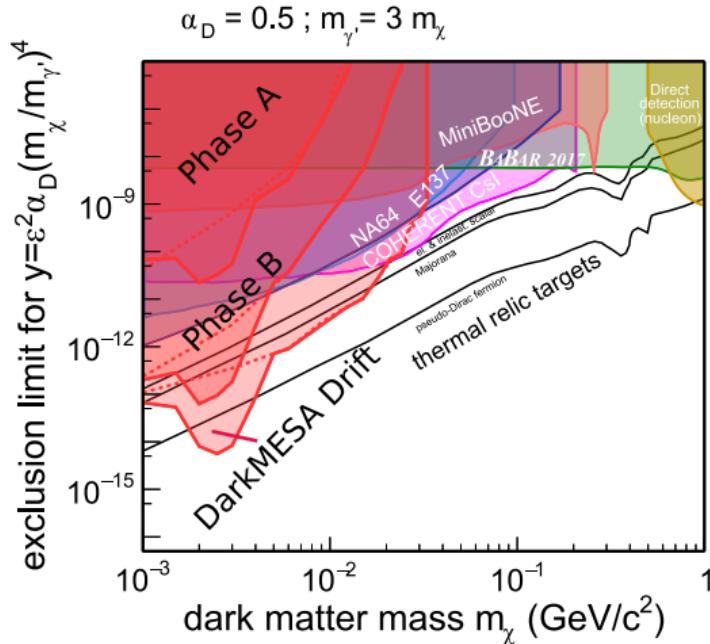
- Time projection chamber
- CS_2 at 90 mbar
- $\sim 1 \text{ m}^3$ active volume
- Nuclear recoil threshold: 20 keV
⇒ Extended parameter space

Phase C



- Material: Radiation protection glass, e.g., SCHOTT-RD30
- Moderate costs: $137 \text{ k€}/\text{m}^3$
- High density: $3.13 \text{ g}/\text{cm}^3$

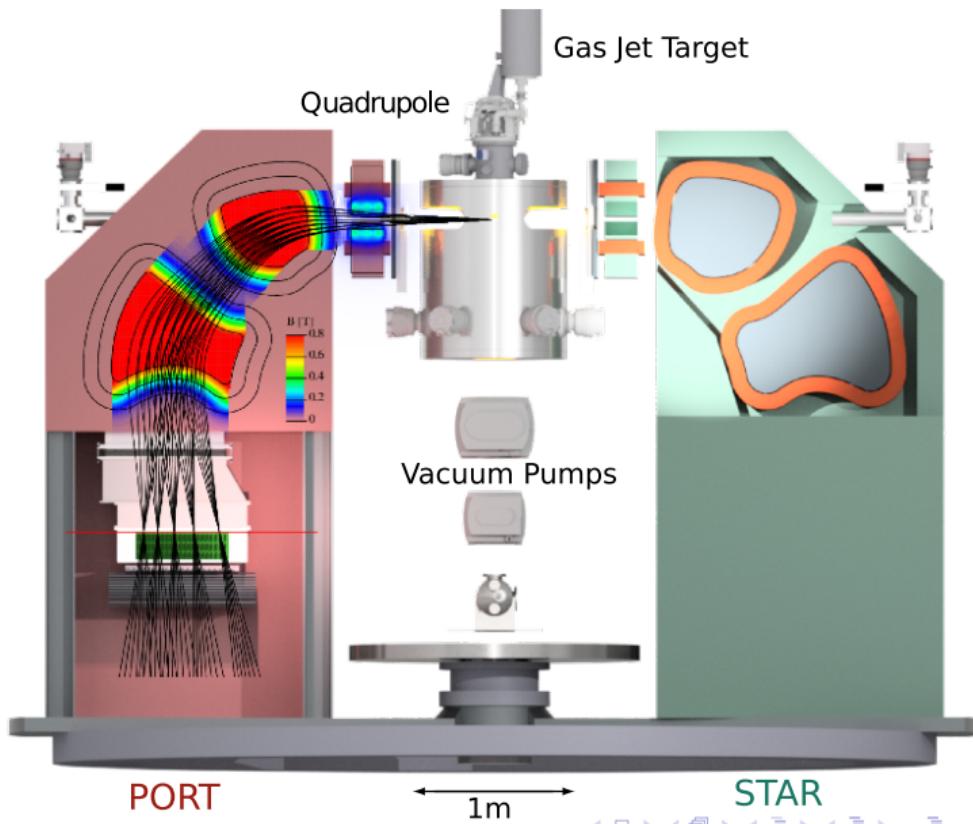
DarkMesa - Expected sensitivity



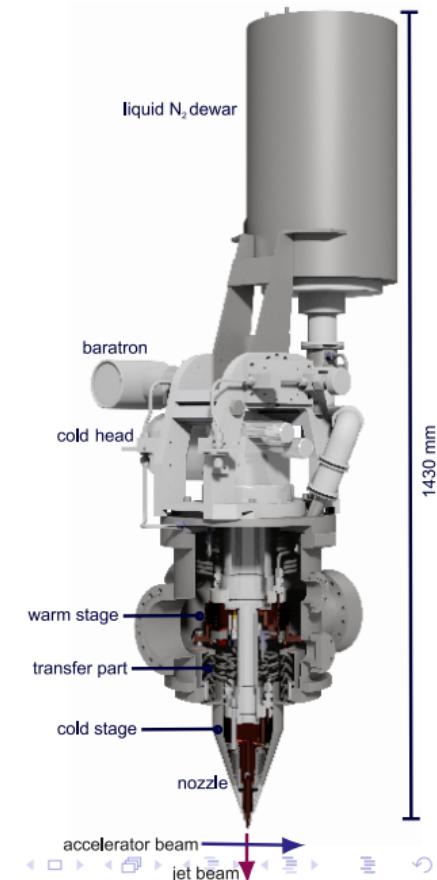
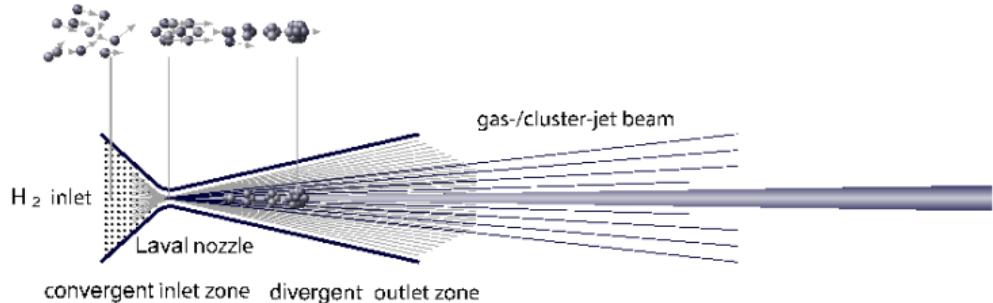
- Phase A: 2200 h
- Phase B: 6600 h

MAGIX - MAinz Gas Injection target eXperiment

- 2× Dipol
90° Bending
- $\frac{\delta p}{p} < 10^{-4}$
- GEM based TPC
- Scintillator Detector
- Muon Veto



MAGIX - The supersonic gas-jet target



MAGIX - Form factor of the nucleon

- Elastic Cross Section (Rosenbluth-Formula):

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e} \right)_{\text{Mott}} \frac{1}{1 + \tau} \left(G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2) \right)$$

with $\tau = \frac{Q^2}{2m_p^2}$, $\epsilon = (1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2})^{-1}$

- $G_E(Q^2)$: Electric Form Factor → related to charge distribution
- $G_M(Q^2)$: Magnetic Form Factor → related to distribution of magnetic moments
- Normalization:

$$G_E^p(Q^2 = 0) = 1$$

$$G_E^n(Q^2 = 0) = 0$$

$$G_M^p(Q^2 = 0) = 2.79$$

$$G_M^n(Q^2 = 0) = -1.91$$

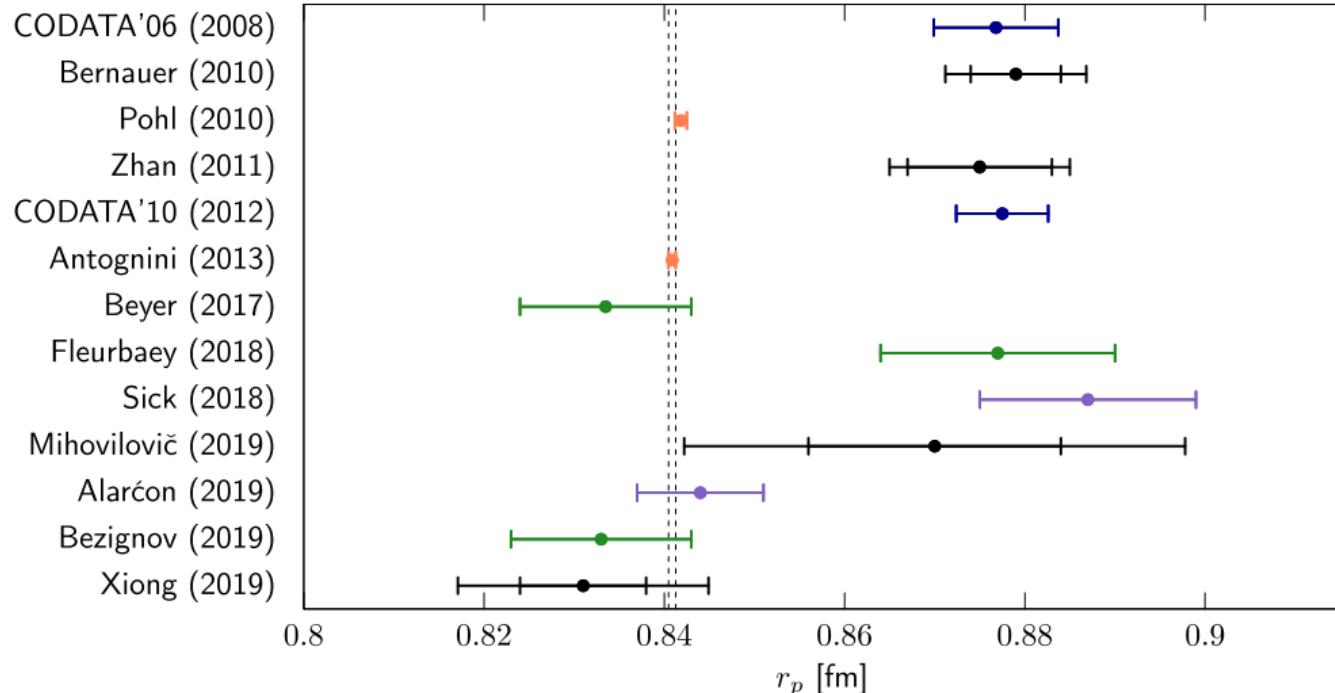
- Root-Mean-Square Radius:

$$\langle r_E^2 \rangle = -6 \frac{d}{dQ^2} G_E(Q^2) |_{Q^2=0}$$

$$\langle r_M^2 \rangle = -\frac{6}{\mu_p} \frac{d}{dQ^2} G_M(Q^2) |_{Q^2=0}$$

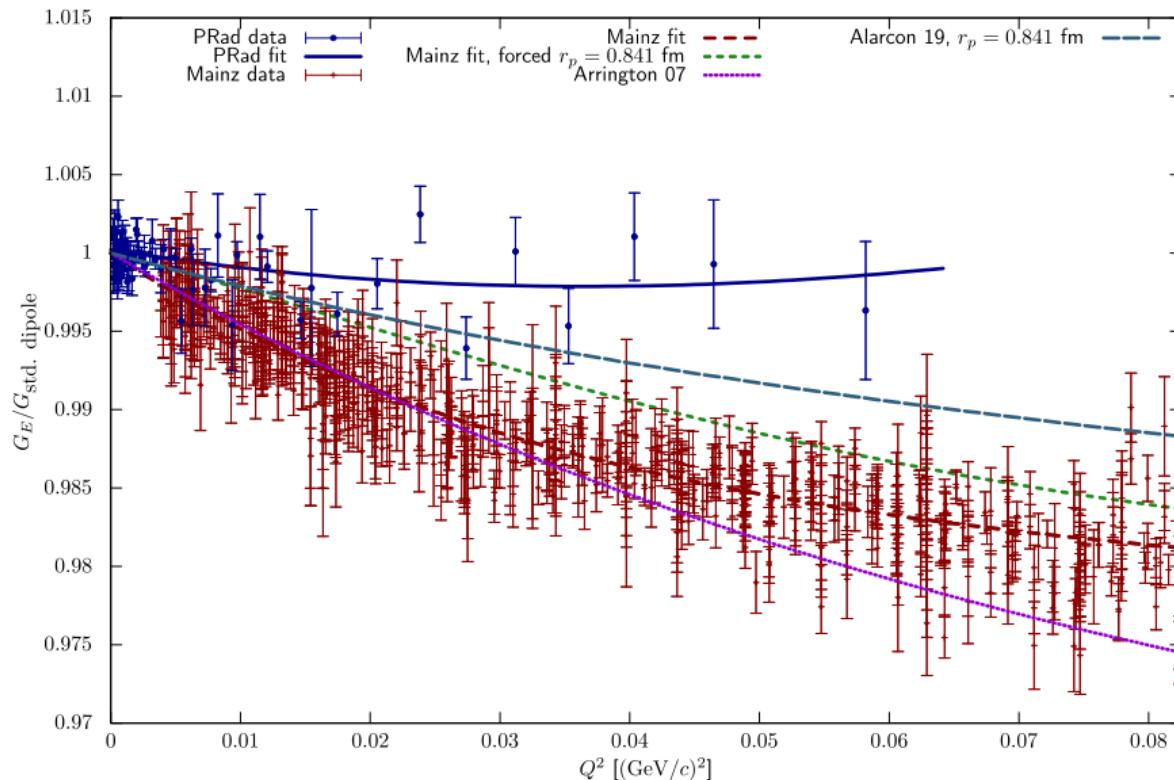
MAGIX - Proton radius puzzle

- Starting 2010: Electron scattering (Bernauer) inconsistent with spectroscopic results from muonic hydrogen (Pohl)



- New data now consistent?

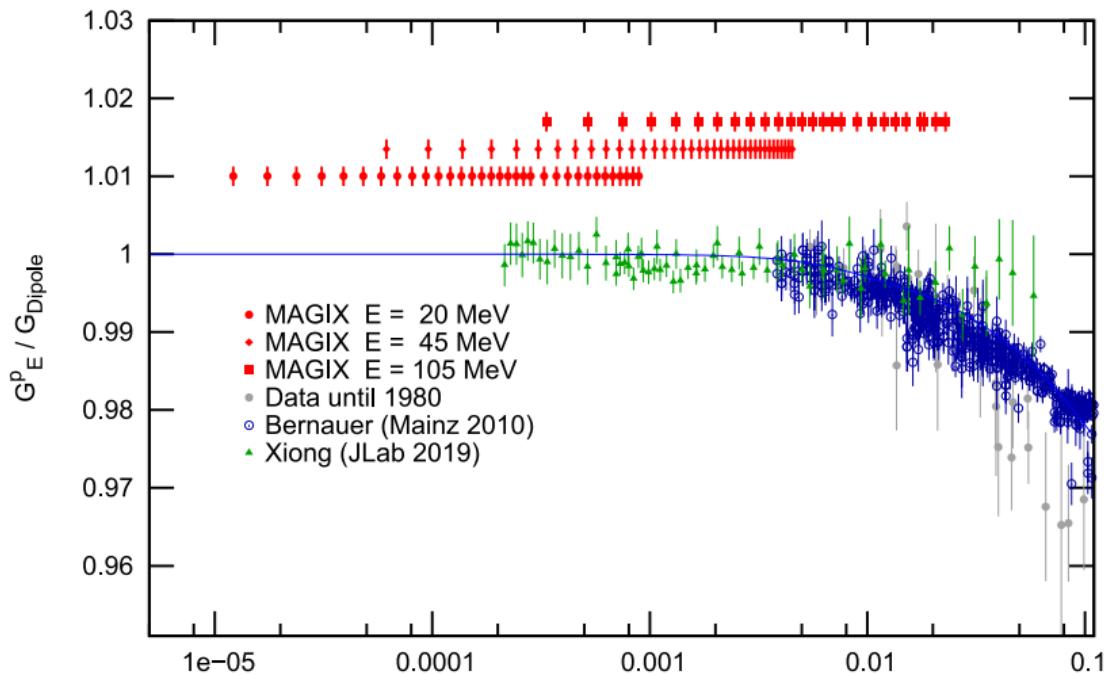
MAGIX - Proton radius puzzle



- Data still not consistent!

MAGIX - Intended form factor measurements

- Wide coverage of low Q^2
- Dominated by systematic error
- Windowless target:
 - High resolution
 - High efficiency
 - Negligible background

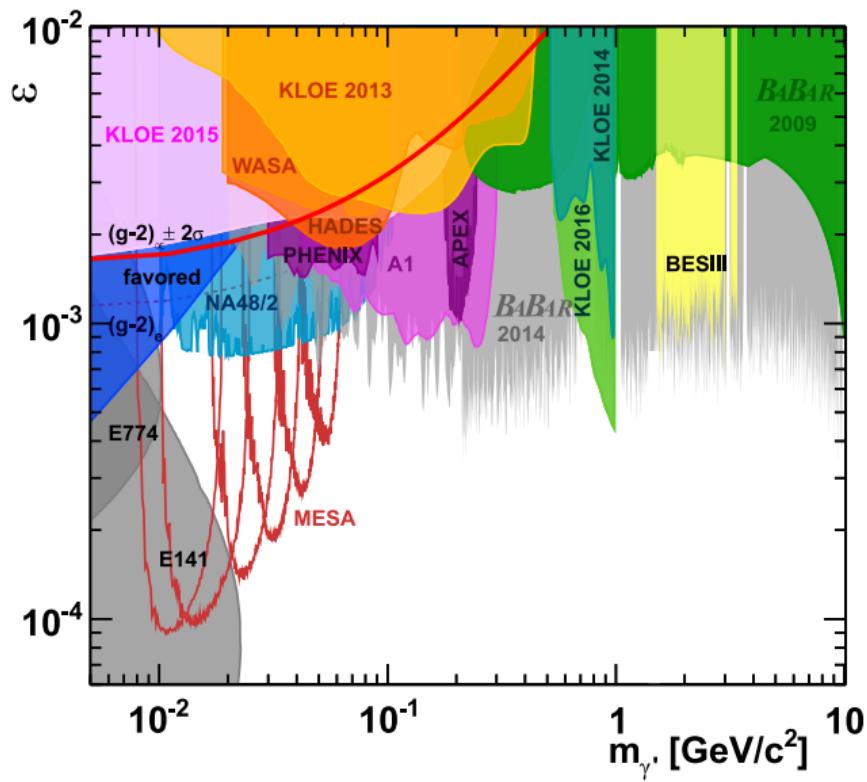


- Idea: not looking for the dark matter particle itself, but for the force carrier
- DM produced in Big Bang \Rightarrow there must be an interaction
- DM particles \rightarrow probably a dark sector?
- Force carrier: scalar/vector bosons?
- No reason for force carrier to be heavy!
- Simplest model: Dark photon as $U(1)$ boson
- Kinetic mixing with SM photon: mixing parameter ϵ

MAGIX - Dark Photon Search

- Coupling to electron → production with mixing $\sim \epsilon$
- Radiative decay into e^+ / e^- pairs :
$$e + Z \longrightarrow e + Z + \gamma'$$
$$\gamma' \longrightarrow e^+ + e^- \quad \text{detected}$$
- Total rate $\sim \epsilon^2$
- Experimental challenge:
 - Background by radiative pair production
 - Resolution always beats statistics!

⇒ MAGIX spectrometer



MAGIX - What else...

Topic	Reaction	Jet	Observables
Hadron Structure			
p Formfactor	$H(e, e')p$	H	$G_E(Q^2), G_M(Q^2), r_E, r_M$
d Formfactor	$D(e, e')d$	D	$A(Q^2), B(Q^2), r_d$
${}^3\text{He}$ Formfactor	${}^3\text{He}(e, e'){}^3\text{He}$	${}^3\text{He}$	r_E
${}^4\text{He}$ Formfactor	${}^4\text{He}(e, e'){}^4\text{He}$	${}^4\text{He}$	r_E
Few-Body Systems			
d Breakup	$D(e, e'p)$	D	$d\sigma/d\Omega$, polarizabilities
${}^3\text{He}$ inclusive	${}^3\text{He}(e, e')$	${}^3\text{He}$	Structure functions, R_L
${}^4\text{He}$ inclusive	${}^4\text{He}(e, e')$	${}^4\text{He}$	Structure functions, R_L
${}^4\text{He}$ monopole	${}^4\text{He}(e, e'){}^4\text{He}^*$	${}^4\text{He}$	Transition Formfactors $E({}^4\text{He}^*), \Gamma({}^4\text{He}^*)$
${}^{16}\text{O}$ inclusive	${}^{16}\text{O}(e, e')$	${}^{16}\text{O}$	Structure functions, R_L
${}^{40}\text{Ar}$ inclusive	${}^{40}\text{Ar}(e, e')$	${}^{40}\text{Ar}$	Structure functions, R_L
${}^3\text{He}$ exclusive	${}^3\text{He}(e, e'p/d)d/p$	${}^3\text{He}$	$d\sigma/d\Omega$
${}^4\text{He}$ exclusive	${}^4\text{He}(e, e'p/d)$	${}^4\text{He}$	$d\sigma/d\Omega$
Dark Sector			
Leptonic Decay	$\text{Ar}(e, A' \rightarrow e^+ e^-)$	${}^{40}\text{Ar}, \text{Xe}$	Lepton pair mass $m_{A'}$, peak search
Invisible Decay	$p(e, e'p)A'$	H	Missing mass $m_{A'}$, peak search
Astrophysical Reactions			
S-Factor Phase 1	${}^{16}\text{O}(e, e'\alpha){}^{12}\text{C}$	${}^{16}\text{O}$	$S_{E1}(E), S_{E2}(E)$
S-Factor Phase 2	${}^{16}\text{O}(e, e'\alpha){}^{12}\text{C}$	${}^{16}\text{O}$	$S_{E1}(E), S_{E2}(E)$

- MESA a new accelerator for precision physics
 - Extracted beam: tuned for dedicated parity violating experiments
 - Energy recovery linac: High current for internal targets
- P2 – Parity violating electron scattering
 - Precision measurement of the weak mixing angle
 - Running of $\sin^2 \theta_W$ sensitive to physics beyond the SM
- DarkMESA – Beam dump experiment
 - Using the run time demands and intensity of a PV experiment
 - Search for dark matter particles
- MAGIX – High resolution spectrometers
 - Energy recovery for high intensity/low multiple scattering
 - ⇒ precision experiments