Low Energy Physics with ERLs

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Center for Frontiers in Nuclear Science

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What this is about

Many low-energy physics still unresolved.
This is a selection of highlights where ERLs will improve the science. I had to make a selection, yours might be different!

- Elastic scattering / proton radius
- Weak interaction
- Nuclear physics with rare isotopes
- Photo-nuclear physics
- Dark "photon" searches

Elastic electron-hadron scattering

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

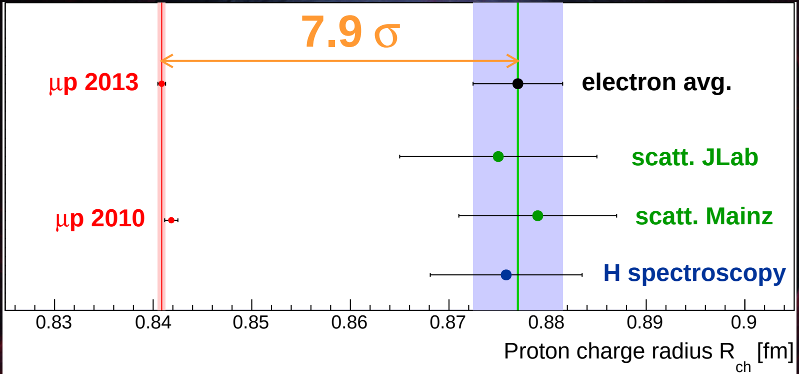
with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\,(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

- Rosenbluth formula
- Electric and magnetic form factor encode the shape of the proton/nucleus
- Fourier transform (almost) gives the spatial distribution, in the Breit frame

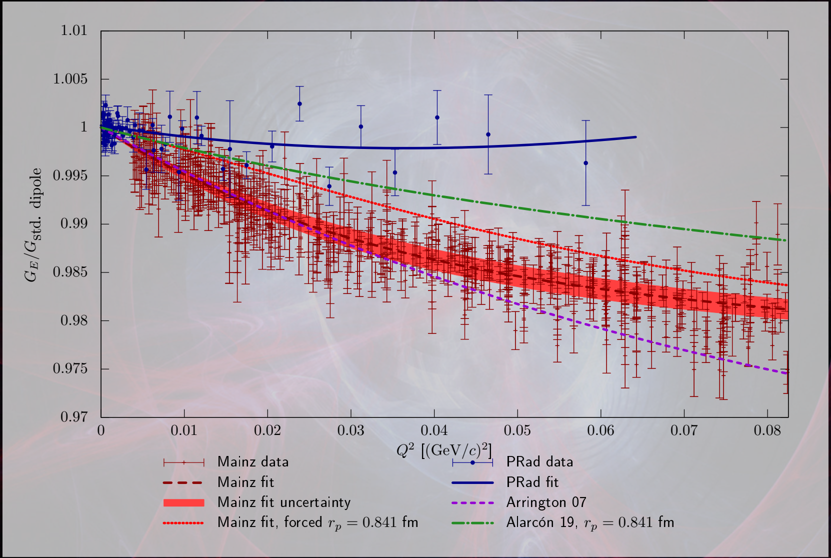
Charge radius

$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left. \frac{d\left(G_M/\mu_p\right)}{dQ^2} \right|_{Q^2=0}$$

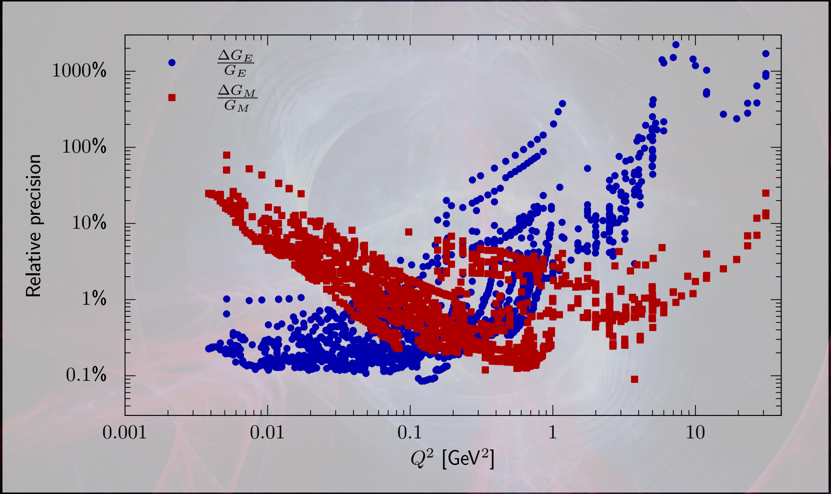


Motivated many spectroscopy (MPQ, Paris, York,...) and scattering experiments (PRAD-I/II@JLAB, ULQ2@TOHOKU, many@Mainz, AMBER@CERN, MUSE@PSI)

Proton electric form factor



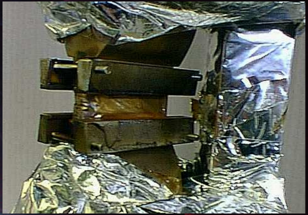
Situation for G_M is even worse



Improvements possible at an ERL

- Current gen: systematic errors dominate

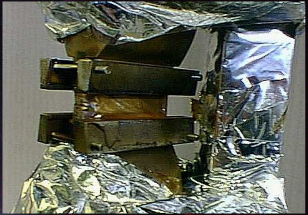
Improvements possible at an ERL



- Current gen: systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target

Improvements possible at an ERL

- Current gen: systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target
- Eliminated with cluster jet target (MAGIX@MESA)
  - point-like
  - no walls
  - but less density. ERLs to the rescue!
- Rinse, repeat with D, ^{3}He, ^{4}He, ...



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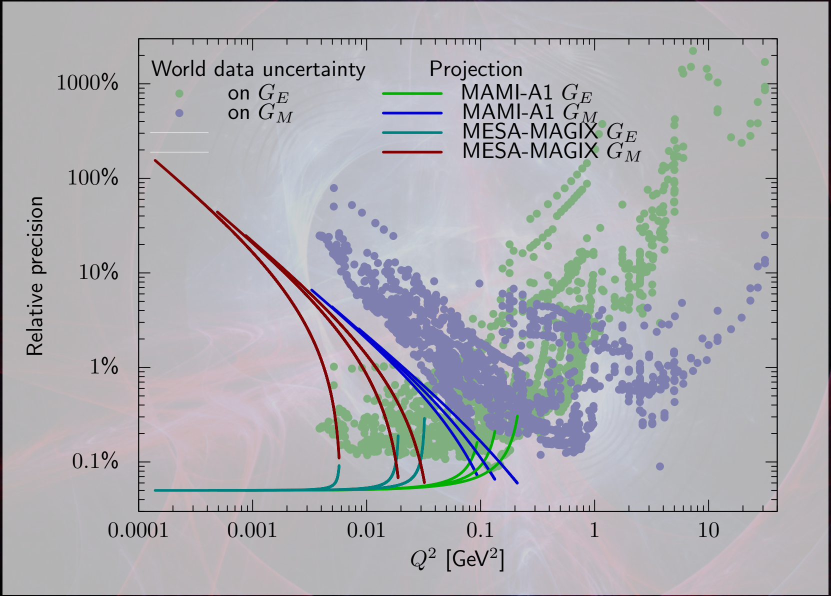
Proton FF at MAGIX@MESA



Weak interactions

Search for BSM physics via deviations from SM predictions!

$$\frac{G_F}{\sqrt{2}} g_{ij}^{ef} \to \frac{G_F}{\sqrt{2}} g_{ij}^{ef} + \eta_{ij}^{ef} \frac{4\pi}{(\Lambda_{ij}^{ef})^2}$$

P2 at MESA

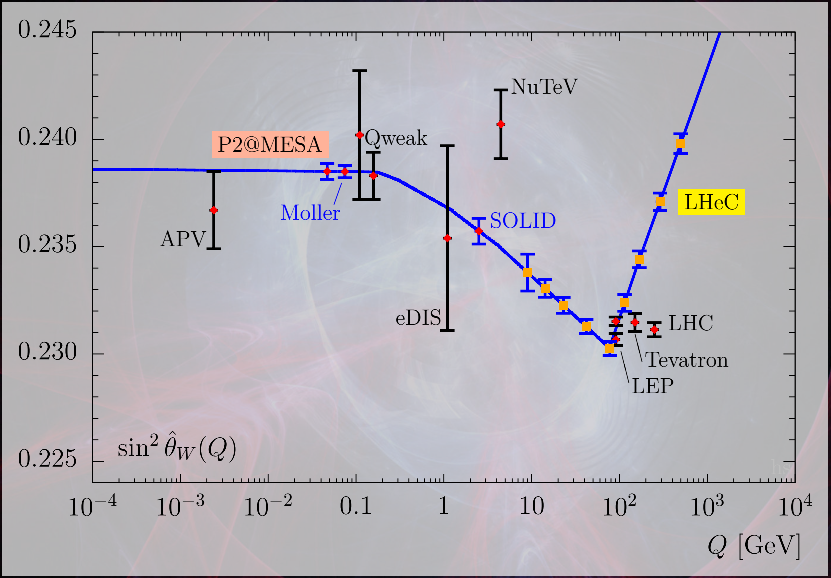
...will run in non-ERL mode! Maximum luminosity with thick target.

$$A^{PV} = \frac{d\sigma^{+}_{ep} - d\sigma^{-}_{ep}}{d\sigma^{+}_{ep} + d\sigma^{-}_{ep}}$$

$$A^{PV} = \frac{-G_F Q^2}{4\pi\alpha_{em}\sqrt{2}} \left[Q_W(p) - F(E, Q^2) \right]$$

$E = 155$ MeV, $25^\circ < \theta < 45^\circ$, $Q^2 = 0.0045\,\mathrm{GeV}^2$

Measurements landscape: weak mixing angle



Nuclear physics with RIBs

Goal: Explore e/m structure of exotic nuclei

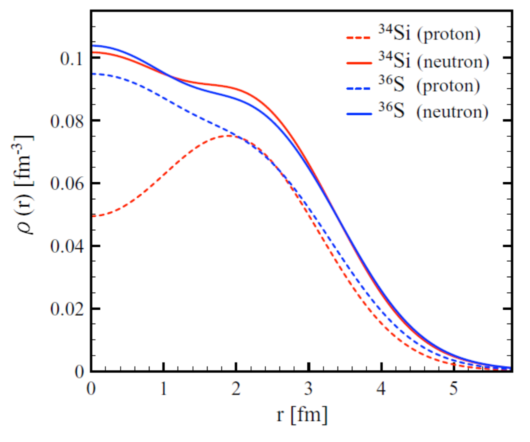
- Required Luminosity: 10^{28} to $10^{31} cm^{-2}s^{-1}$
- Classical exp's: Low current, thick target: $1 nA@10^{19} cm^{-2} \rightarrow 10^{28} cm^{-2}s^{-1}$
- Doesn't work for RIBs
  - Density down by factor of 10^{11}
- With ERL:
  - Beam current up by a factor of 10^{8}

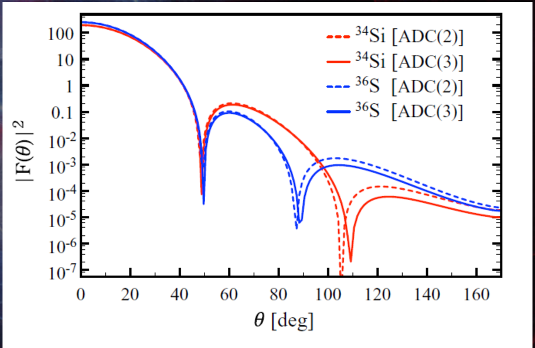
Not there yet. But feasible with moderate increase of ion capture capability.

DESTIN+Perle@ORSAY: Can do lower end of this scale (elastic scattering). Starting point for upgrade of ion capure rate.

Some examples

- Light systems: ^{6}He, ^{8}He, ^{12}Be, ^{17}C vs. ^{8}B, ^{14}O, ^{17,18}Ne (non-trivial p-n correlations)
- Bubble nuclei: ^{34}Si is supposed to have central depletion. Also: Sn, Xe
- Symmetry energy of nuclear EOS (neutron-rich vs proton-rich isotopes)





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Photonuclear: ERLs as light sources

Inverse Compton scattering to produce highly brilliant γ beams

- Key reactions for stellar evolution (cross section of NRF and (γ,particle))
- Technological and Commercial applications (nondestructive radionuclide assay, nuclear material control)
- Testing fundamental symmetries
- Constraining nuclear models
- New phenomena in nuclear collective modes

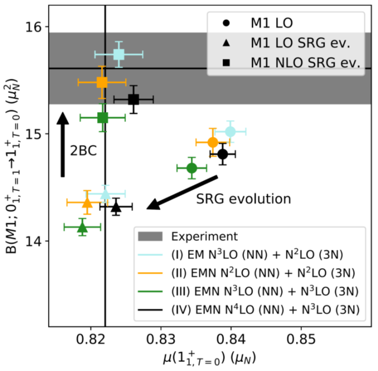
Fundamental Symmetries

Parity violation through weak nucleon-nucleon interaction. For example: parity doublets $J^{\pm}$

- (Beller et al.) Measurements at HIγs of $1^{\pm}$ ^{20}Ne: largest nuclear enhancement factor known today
  Can measure nuclear parity mixing with MeV photons with intensities achievable at an ERL.
- $0\nu\beta\beta$: Neutrino mass requires nuclear matrix elements with high precision. Photonuclear reactions test models for calculations.

Constraining nuclear models

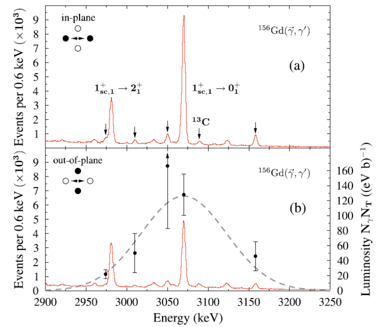
- Ab initio calculations of light nuclei very advanced.
- Photonuclear Relative Self-Absorption (RSA) is strong method to measure isovector M1 exitation strength, gives two-body currents.
- Needs very high luminosities of $10^4 \gamma/(s\Gamma_0)$



New phenomena in nuclear collective modes

Fundamental building blocks of nuclear structure: Giant Dipole Resonance (GDR), Scissors Mode (ScM) and proton-neutron quadrupole-photon excitations.

- GDR: Known for 100 years, very little known about γ-decay to ground/excited states.
- ScM: Quadrupole deformation of proton/neutron subsystems. M1 dominant, E2 hardly known. E2/M1 accessible via brilliant MeV-range photons.



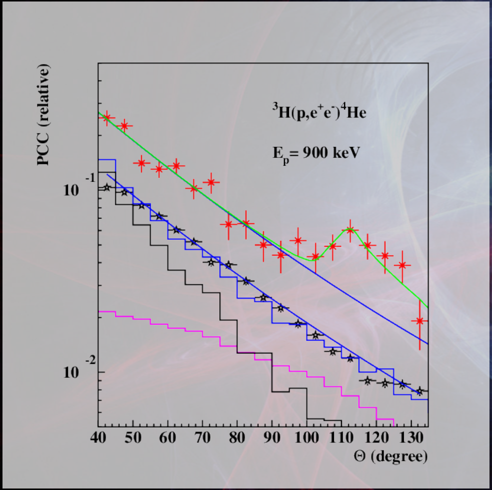
PRL 118 212502

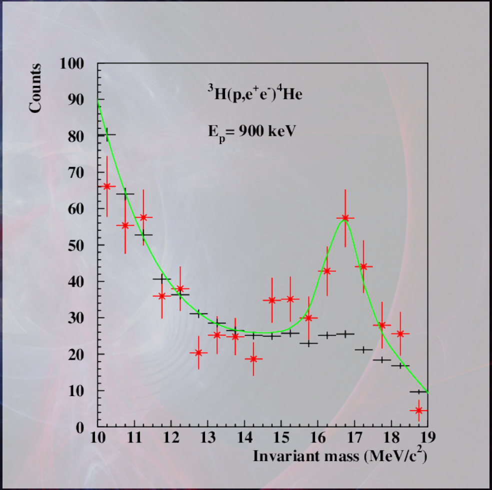
Dark “photon“ searches

- Proposed dark photon-like force carrier (or not so photon like)
- At low masses O(10-100) MeV, hard to search with classical machines
  - Thin target, or too much systematics
  - Opportunity to measure full final state
  - O(100)uA to O(10-100) mA for optimal luminosity
- Several experiments planned with different kinematics, targets etc.

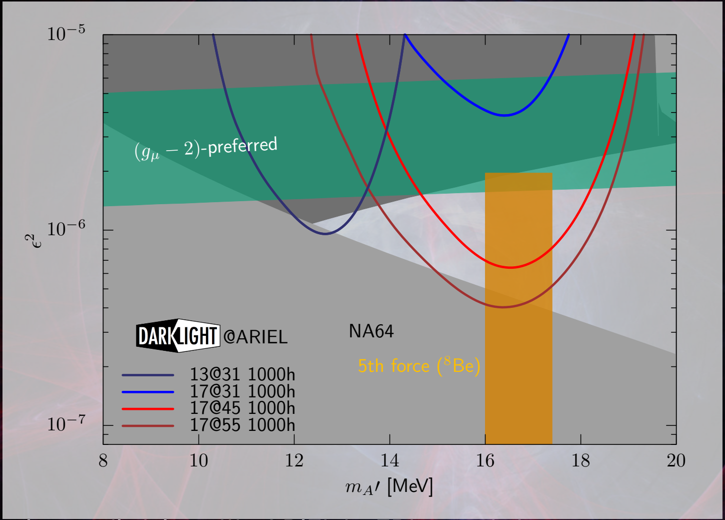
Example: DarkLight@ARIEL

- DarkLight original planned for LERF, as a 4π experiment
- But: protophobic fifth force to explain ^{8}Be, ^{4}He anomalies (ATOMKI)





DL@ARIEL reach



Full reach only available with ARIEL in ERL mode!

Summary

- This is just a selection!
- Rich program in many fields
- Main ERL benefits for low-energy physics
  - Large luminosity with thin targets
  - Excellent beam quality at small energies