PHYSICS PROGRAM OVERVIEW

Harald Merkel

Johannes Gutenberg-Universität Mainz

MAGIX Collaboration Meeting

Mainz, February 15^{th}, 2017

- General Considerations
- Physics program
  - Form-factor Measurements
  - Astropyhsical S-Factors
  - Few body physics
  - Search for exotic particles
- Summary

Design Considerations: Why is MESA special?

Electron scattering experiments are done since several decades:

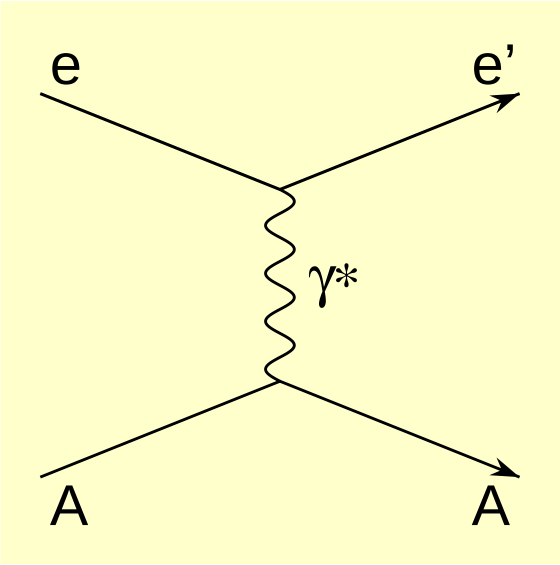
- Everything is already measured...
- Beam Energy of $E_0 = 105\,\text{MeV}$ is not difficult to achieve
- Luminosity of extracted beam experiments is larger
- Nuclear physics energy range, *e.g.* γ-Spectroscopy

BUT: Energy Recovering Linac:

- Moderate internal current ($I = 10\,\text{mA}$) ***which can be used for experiments!***
- Use of Gas-Targets and still enough luminosity $\Rightarrow$ ***vanishing target density!***
- Polarization degrees of freedom

$\Rightarrow$ Precision Experiments

Design Considerations: General form of cross section



- Coupling e and $Z\,e$ at vertices
- 4-momentum of the photon

$$q = e - e' = \begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix} - \begin{pmatrix} E' \\ 0 \\ E'\sin\theta \\ E'\cos\theta \end{pmatrix} \qquad \Rightarrow \qquad q^2 = -Q^2 = -4\,E\,E'\sin^2\frac{\theta}{2}$$

- Photon propagator $\quad \mathcal{M} \sim \frac{1}{q^2}$

$$\Rightarrow \qquad \sigma \sim |\mathcal{M}|^2 \sim \frac{1}{q^4} \sim \frac{1}{\sin^4\frac{\theta}{2}}$$

Design Considerations: General form of cross section

$$\frac{d\sigma}{dE'd\Omega} = \frac{4\,Z^2\,\alpha^2\,E'^2}{q^4}\left\{\quad\right\}$$

Pointlike spin $\frac{1}{2}$ particles:

$$\left\{\quad\right\}_{e\mu\to e\mu} = \left(\cos^2\frac{\theta}{2} - \frac{q^2}{2m^2}\sin^2\frac{\theta}{2}\right)\delta\left(\nu + \frac{q^2}{2m}\right)$$

Particles with structure:

$$\left\{\quad\right\}_{ep\to ep} = \left(\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} - 2\tau G_M^2\sin^2\frac{\theta}{2}\right)\delta\left(\nu + \frac{q^2}{2m}\right)$$

Breakup/Production cross section:

$$\left\{\quad\right\}_{e\mu\to eX} = W_2(\nu,q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,q^2)\sin^2\frac{\theta}{2}$$

Required Angular Resolution

Cross sections with better than 1% accuracy

$$\sigma \sim \frac{1}{q^4} \sim \frac{1}{\sin^4\frac{\theta}{2}}$$

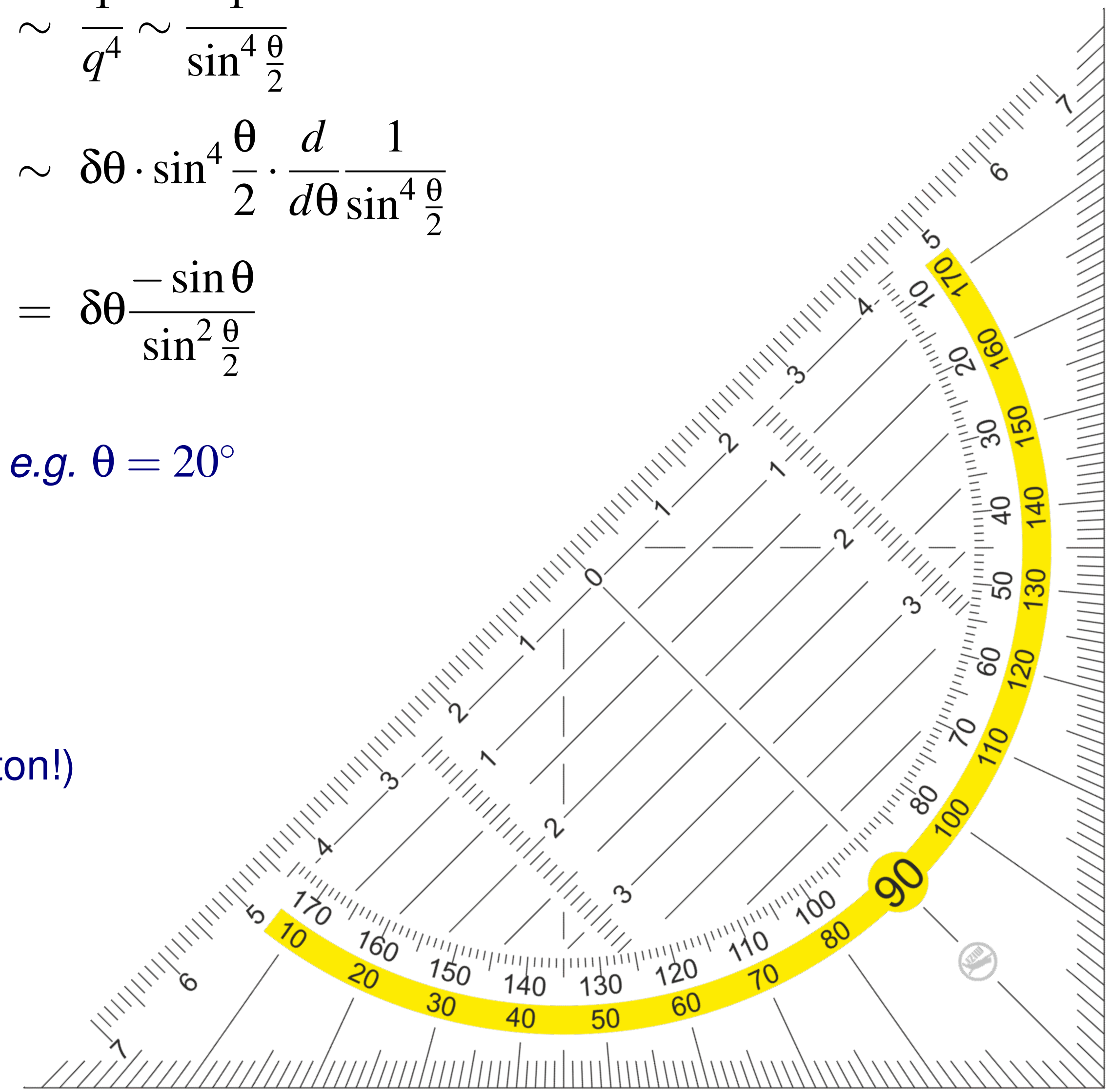
$$\frac{\delta\sigma}{\sigma} \sim \delta\theta \cdot \sin^4\frac{\theta}{2} \cdot \frac{d}{d\theta}\frac{1}{\sin^4\frac{\theta}{2}}$$

$$= \delta\theta \frac{-\sin\theta}{\sin^2\frac{\theta}{2}}$$

$\Rightarrow$ to measure cross sections to 1% at *e.g.* $\theta = 20^\circ$
we need an angular resolution of

$$\delta\theta < 0.05^\circ$$

(similar constrains for Direction of Photon!)



Experimental technique: Reaction identification by “Missing Mass”

Example: Elastic Scattering from Carbon $e + ^{12}\mathrm{C} \rightarrow e + ^{12}\mathrm{C}$, Electron detected

4-momenta of particles:

$$e = \begin{pmatrix} E_0 \\ 0 \\ 0 \\ E_0 \end{pmatrix} \qquad A = \begin{pmatrix} m_A \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad e' = \begin{pmatrix} E' \\ 0 \\ E' \sin\theta \\ E' \cos\theta \end{pmatrix}$$

4-momentum conservation:

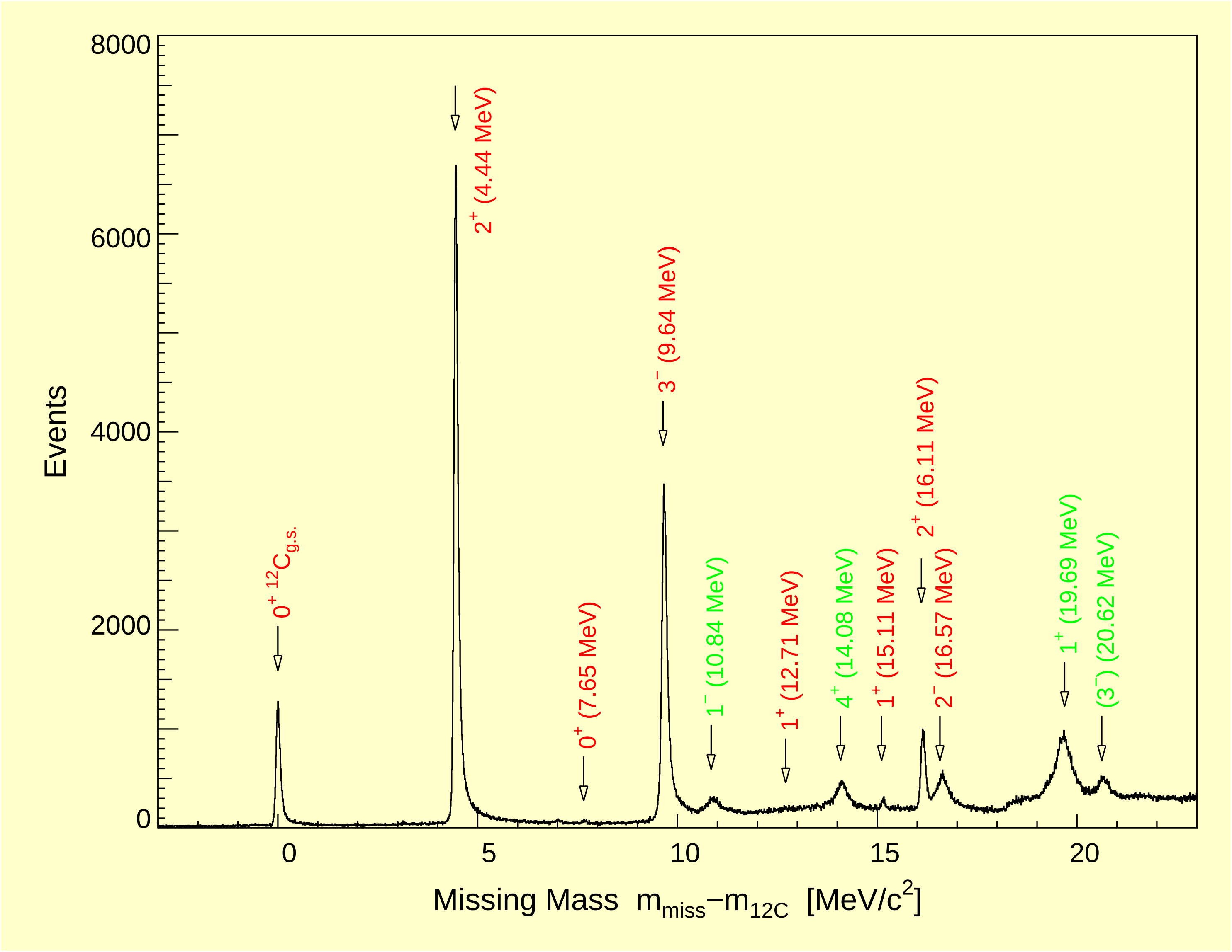
$$e + A = e' + A' \quad \Rightarrow \quad A' = e - e' + A = \begin{pmatrix} E_0 - E' + m_A \\ 0 \\ -E' \sin\theta \\ E_0 - E' \cos\theta \end{pmatrix}$$

Missing mass = mass of not detected particle:

$$m_{miss}^2 = A'^2 = (E_0 - E' + m_A)^2 - E'^2 \sin^2\theta - (E_0 - E' \cos\theta)^2$$

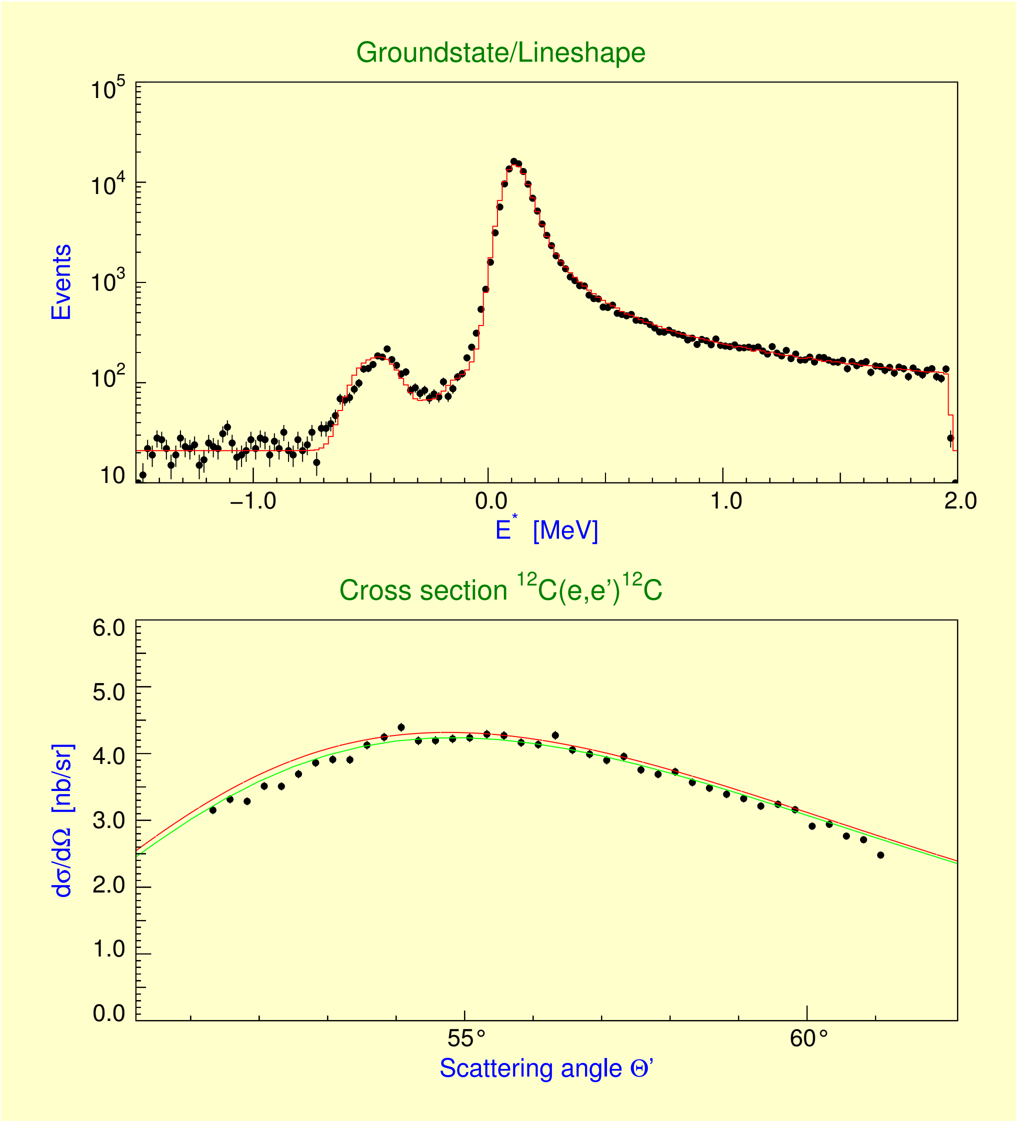
$\Rightarrow$ Elastic scattering, if $m_{miss} = m_{A'} = m_A$

Momentum Resolution



Elastic scattering on Carbon, $E = 450\,\text{MeV}$

Resolution



⇒ Resolution $\delta p/p < 10^{-4}$ required! ⇒ Focussing Magnetic Spectrometers

Physics Program at Magix

Physics Program to employ the strengthes of MESA and Magix

- High beam intensity $\leftrightarrow$ low target density
- Excellent beam quality $\Rightarrow$ Precision physics
- High degree of beam/target polarization

Selected Examples:

- Elastic Scattering (Form-Factor Measurements): Magnetic Radius
- Nuclear Physics: Tests of ab-initio Calulations in Few-Body Physics
- Astrophysics: S-Factor
- Search for exotic particles:
  - Search for Dark Photons
  - Invisible Decay of Dark Photons
  - Beam-Dump Experiments

Magnetic Radius of the Proton

Proton Radius Puzzle, electric Form-Factors, etc.: trivial...

Magnetic Radius from limit $Q^2 \to 0$

- Suppressed by $\tau = \frac{Q^2}{4m_p^2}$ in cross section

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

- Beam-Recoil polarization is limited by proton recoil momentum $|\vec{p}_p| > 300\,\frac{\text{MeV}}{c}$
- Beam-Target polarization:

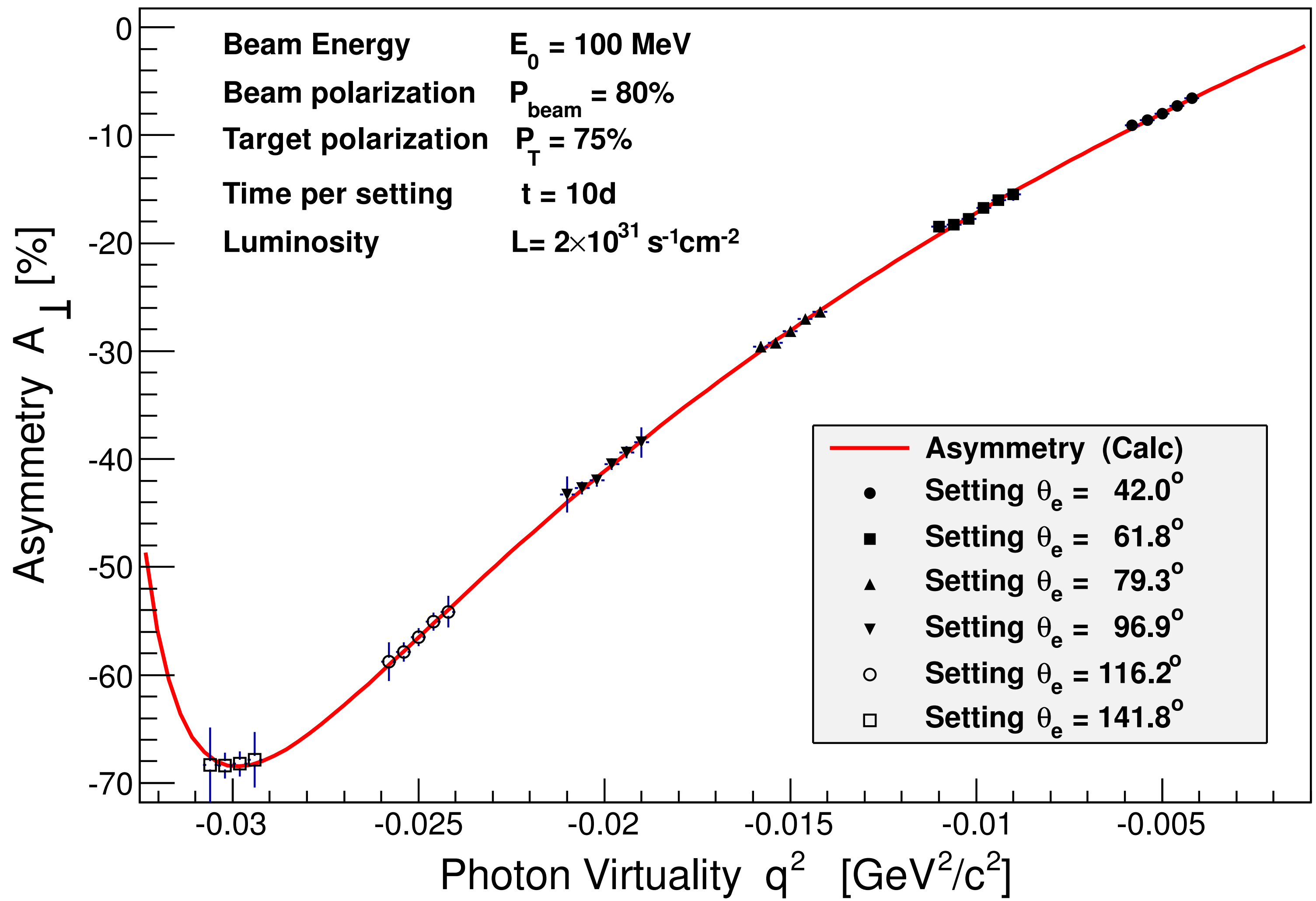
$$A(\theta^*,\phi^*) = A_I \sin\theta^* \cos\phi^* + A_S \cos\theta^*$$

$$A_I = -2\sqrt{\tau(1+\tau)}\tan\frac{\theta}{2} \frac{G_E\, G_M}{G_E^2 + \left(\tau + 2\tau(1+\tau)\tan^2\frac{\theta}{2}\right) G_M^2}$$

$$A_S = -2\,\tau\sqrt{1+\tau+(1+\tau)^2\tan^2\frac{\theta}{2}}\,\tan\frac{\theta}{2} \frac{G_M^2}{G_E^2 + \left(\tau + 2\tau(1+\tau)\tan^2\frac{\theta}{2}\right) G_M^2}$$

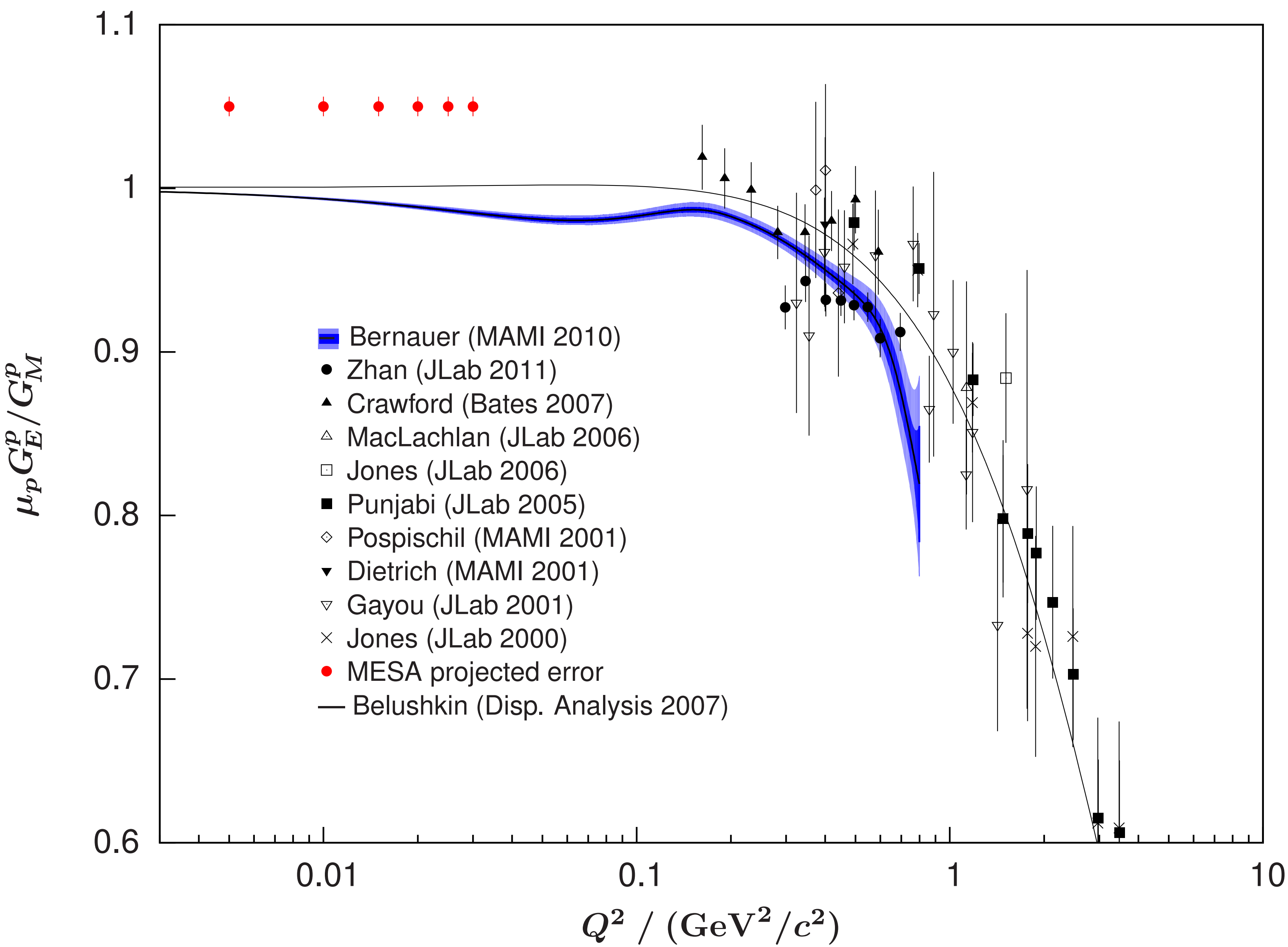
$$\left.\begin{array}{l}\phi^* = 0\\ \theta^* = 0, \frac{\pi}{2}\end{array}\right\} \Rightarrow A_\perp = \frac{A_l}{A_s} \sim \frac{G_E}{G_M}$$

Magnetic Radius of the Proton - Asymmtry



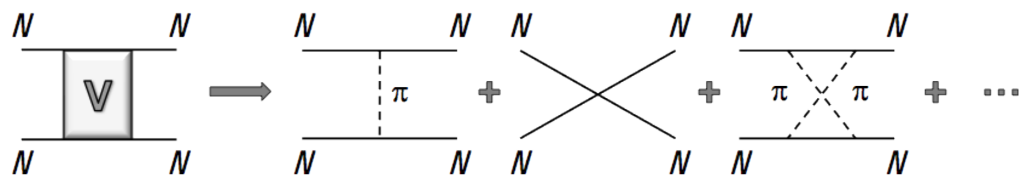
- (Conservative) assumptions for target ≈ Blast target
- Statistical error only (systematic error should be small!)

Magnetic Radius of the Proton - Errors



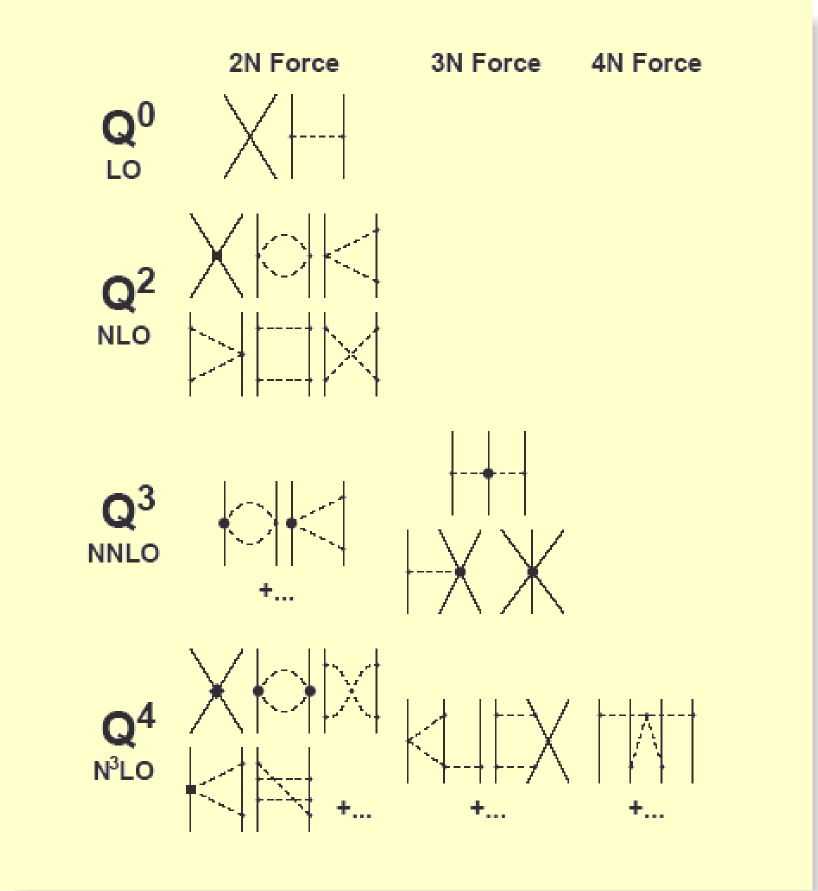
Tests of ab-initio Calulations in Few-Body Physics

- Ab initio calculations e.g. with Effective Field Theory
- Consistent chiral expansion of elementary NN-interaction



- Consistent expansion of Few-Body-Systems
- Very promising, but

How can we test this?



How can we test Ab-Initio-Calculations?

- Challenge for theory: Reaction dynamics

  Possible solution:

  - Use EFT input for potentials
  - Faddeev Calculations for dynamics (e.g. J. Golak, H. Witała, ...)
  - Prediction of dynamic observables
  - Promising: Polarization observables

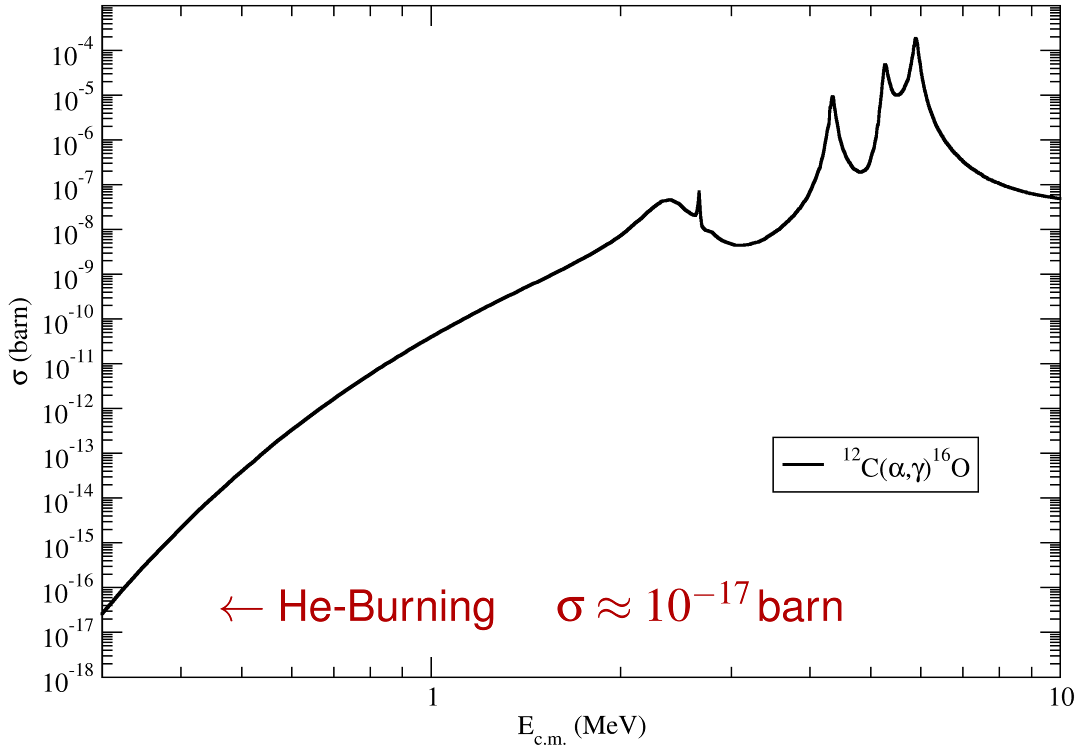
- Challenge for experiments: Low Momentum Region

  Needed:

  - High resolution (separate excited states!)
  - Low momentum (use gas targets!)
  - High luminosity (in spite of gas target!)
  - High degrees of beam and target polarization (in spite of high luminosity!)

$\Rightarrow$ Magix @ MESA

Astrophysical S-Factor for $\alpha(^{12}C,^{16}O)\gamma$



How to overcome limits:

1. Timereversal (enhancement by factor 10 due to spin weight):

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

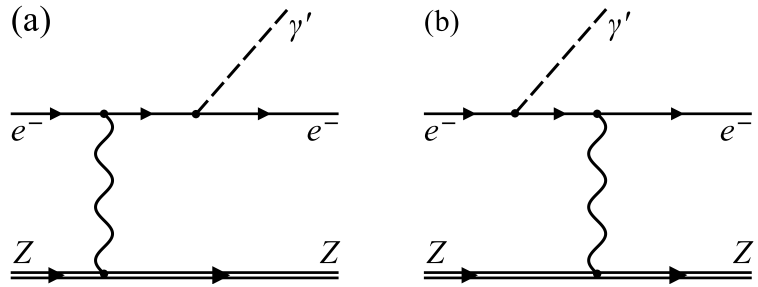
2. Covering the Threshold: Electroproduction in limit $Q^2 \rightarrow 0$

$$e + ^{16}O \rightarrow e' + ^{12}C + \alpha \quad \Leftrightarrow \quad \gamma^* + ^{16}O \rightarrow ^{12}C + \alpha$$

   Electron has large momentum, but virtual photon energy goes to zero!

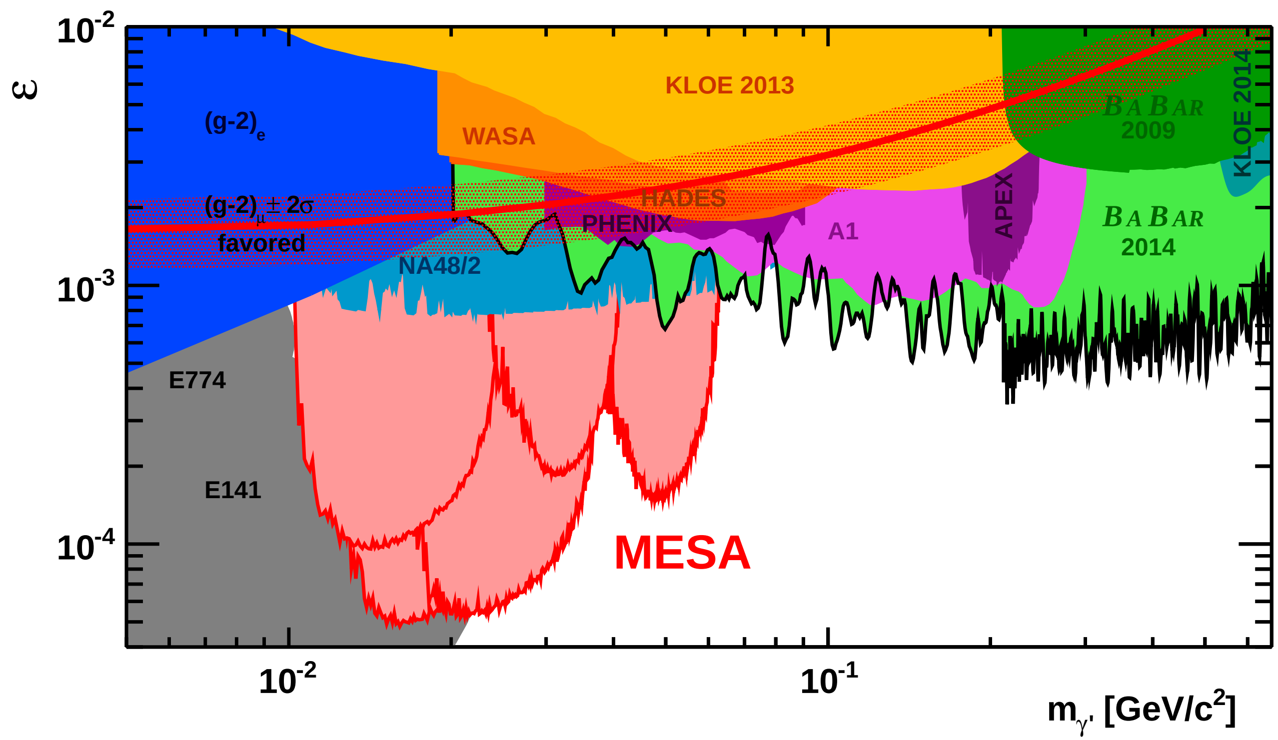
3. Detection of slow recoil $\alpha \Rightarrow$ gas target, recoil detector

Search for exotic particles: Dark Photons

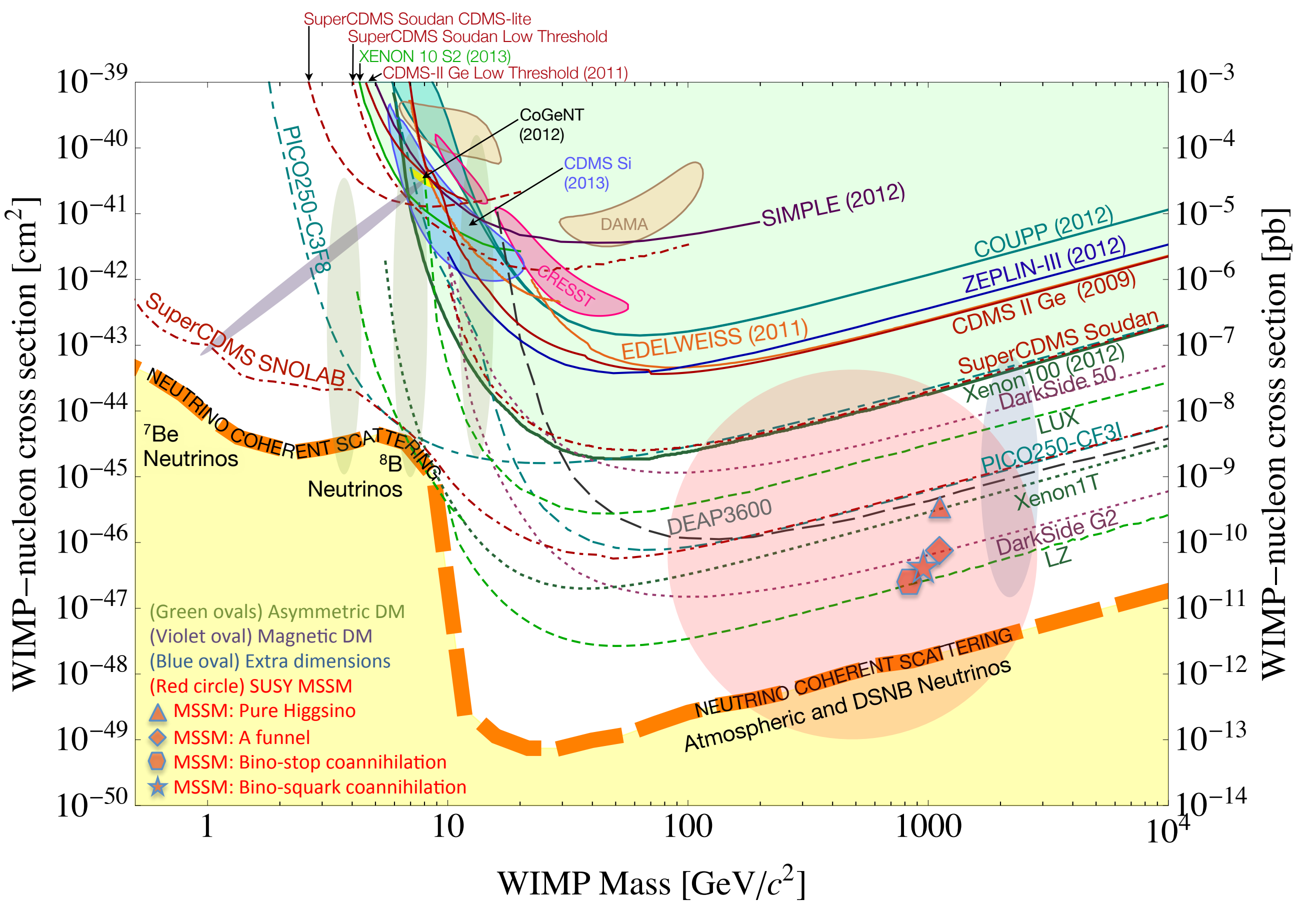


- Dark photon: Force carrier of the Dark Sector
- Radiative production

$$e + Z \rightarrow e + Z + \gamma'$$
$$\hookrightarrow e^+ + e^- \quad \text{(detected in Magix)}$$



Beam-Dump Experiments: Motivation

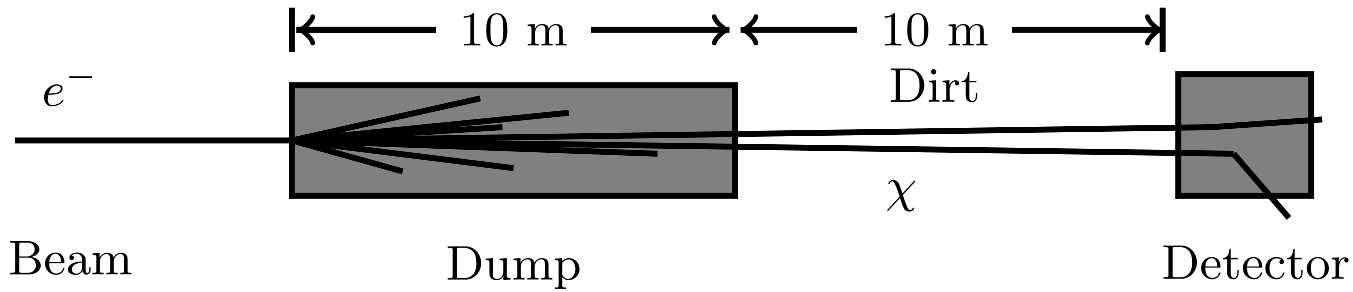


Direct detection experiments:

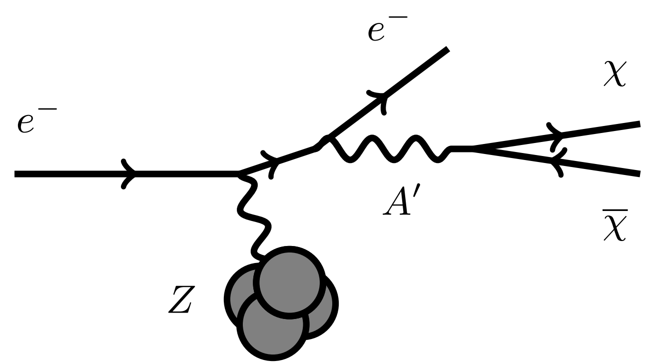
- No clear signal yet
- Limit of sensitivity (solar ν background) will be reached at some point
- Lower masses (*i.e.* low recoil energy) not accessible

P. Cushman, *et al.*, arXiv:1310.8327

Beam-Dump Experiments: Idea

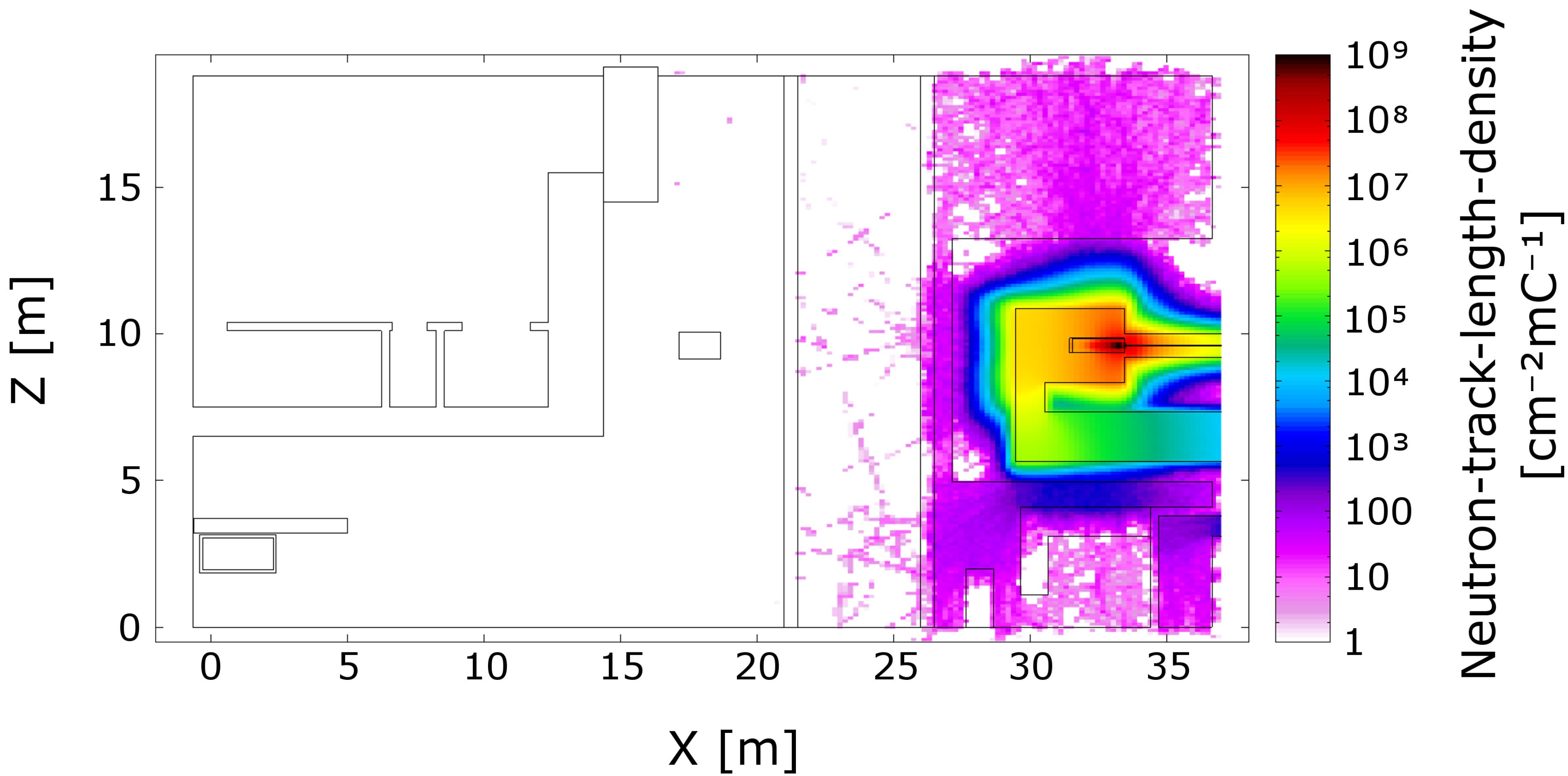


- Production in beam dump, *e.g.* via pair production



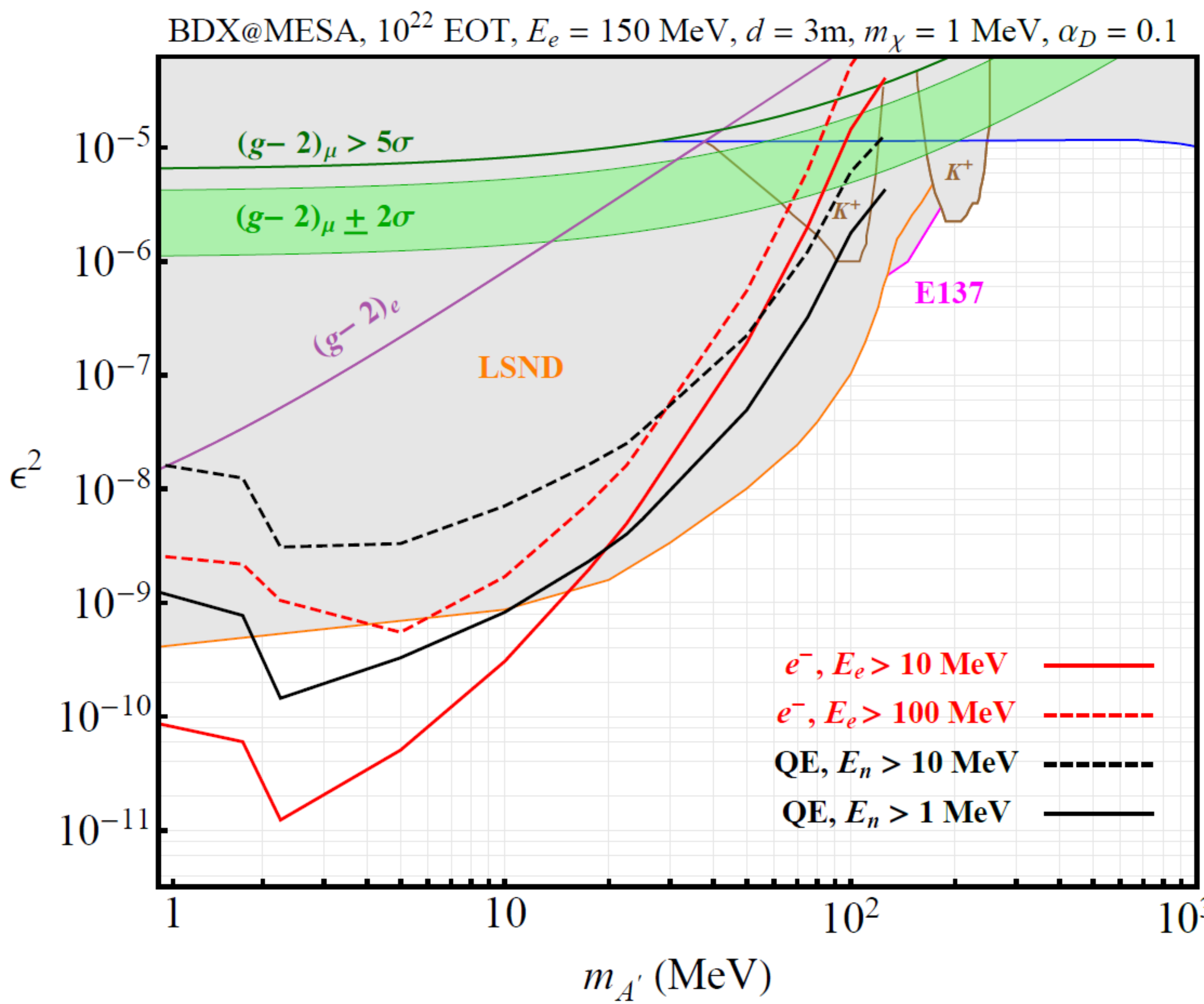
- “Dark Matter Beam”?
- Dark Matter particles have enough recoil energy!
- Detection with simple detector, *e.g.* scintillator cube
- ... or with sophisticated DM Detector ...

FLUKA Simulation



- Neutrons can be shielded
- Below pion threshold: negligible ν background
- Clean conditions, detailed layout of hall needed for further design

Magix Sensitivity



- Reasonable sensitivity for low mass region
- Multidimensional plot: Assumptions for dark photon mass, m_χ

Calculations: G. Krnjaic

Summary

MAGIX:

- High Resolution Spectrometers
- High density or high polarization internal target
- Multi-purpose setup for precision physics

Physics Program

- Precision form factors: Magnetic Radius of the Proton
- Nuclear Astrophysics: S-Factor measurements
- Few-Body physics
- Search for exotic particles