

Achim Denig

Institute for Nuclear Physics

Johannes Gutenberg University Mainz



Cluster of Excellence
PRISMA⁺

Precision Physics,
Fundamental Interactions
and Structure of Matter

Precision Hadron Physics at MESA



The 12th International Workshop on the Physics of Excited Nucleons

The Mainz Microtron MAMI

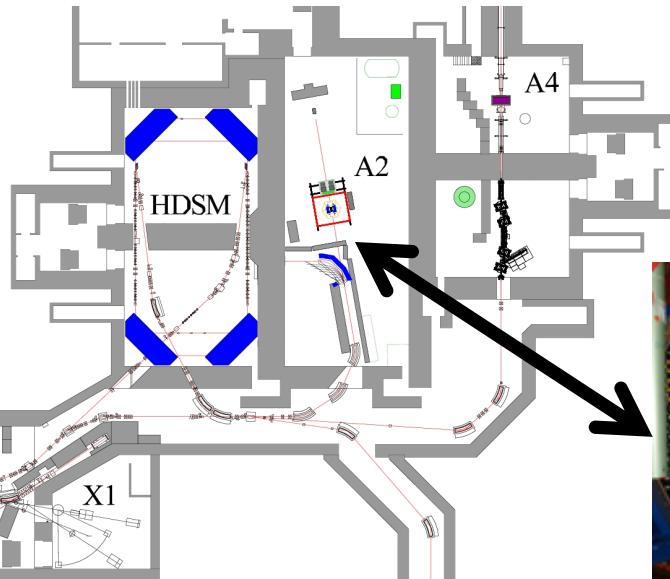


Electron Accelerator for Fixed Target Experiments

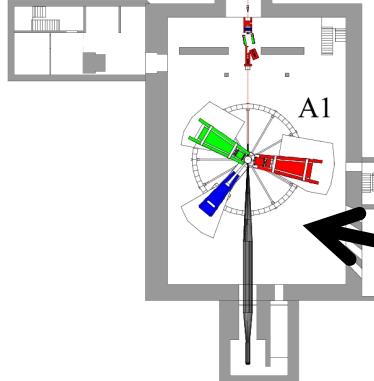
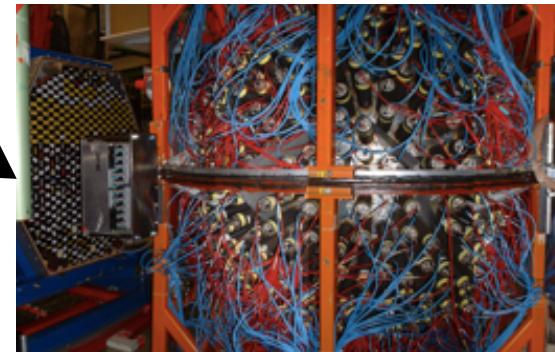
$E_{\max} (\text{e-}) = 1.6 \text{ GeV}$

$I_{\max} \sim 100 \mu\text{A} (\text{CW})$

- Resolution $\sigma_E < 0.100 \text{ MeV}$
- Polarization 85%
- Reliability: 7000 hours / year



A2 tagged photon beam facility



A1 electron scattering facility



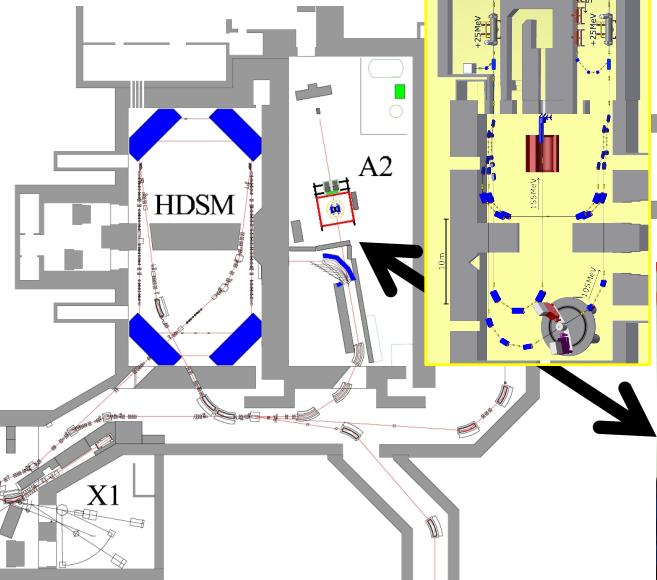
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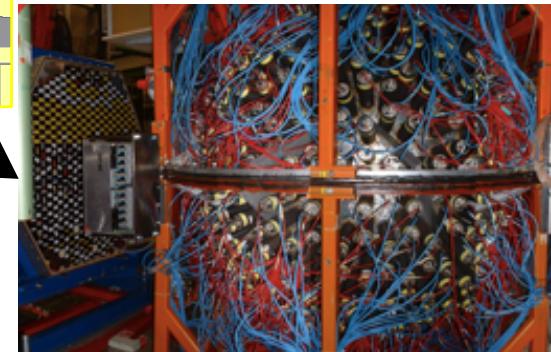
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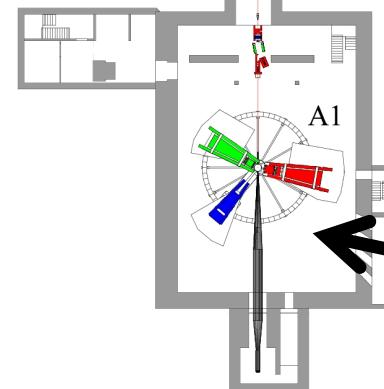
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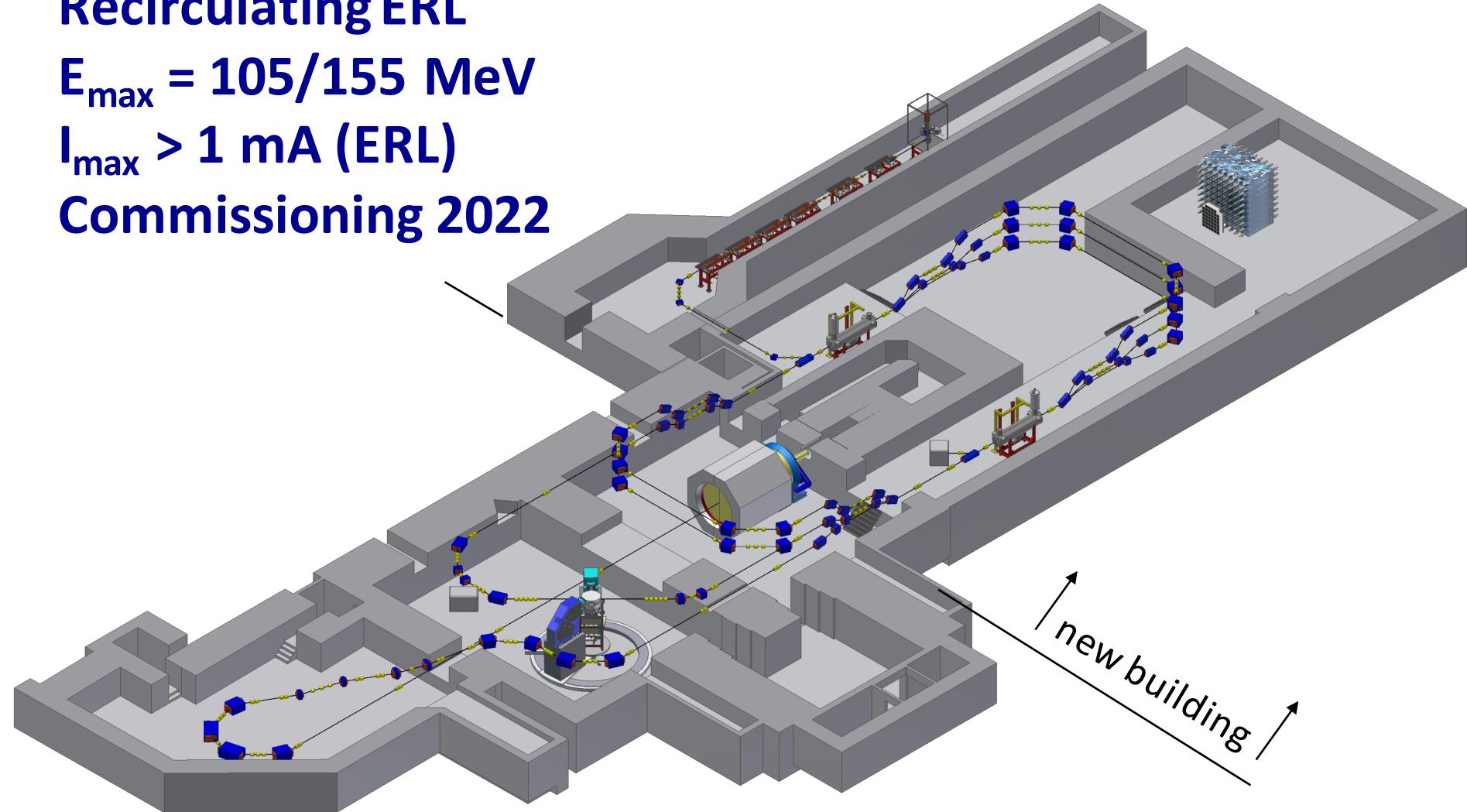
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

$E_{\max} = 105/155 \text{ MeV}$

$I_{\max} > 1 \text{ mA (ERL)}$

Commissioning 2022



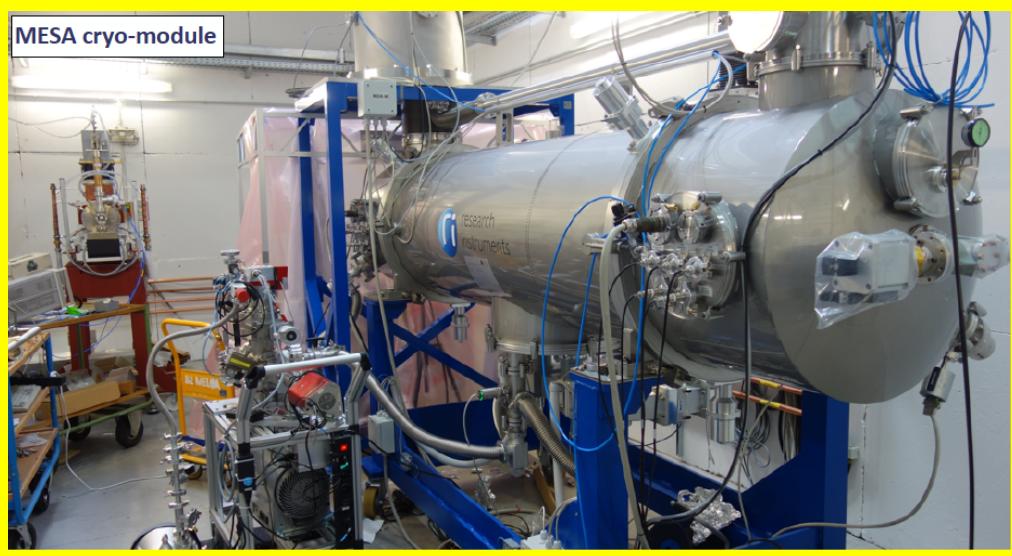
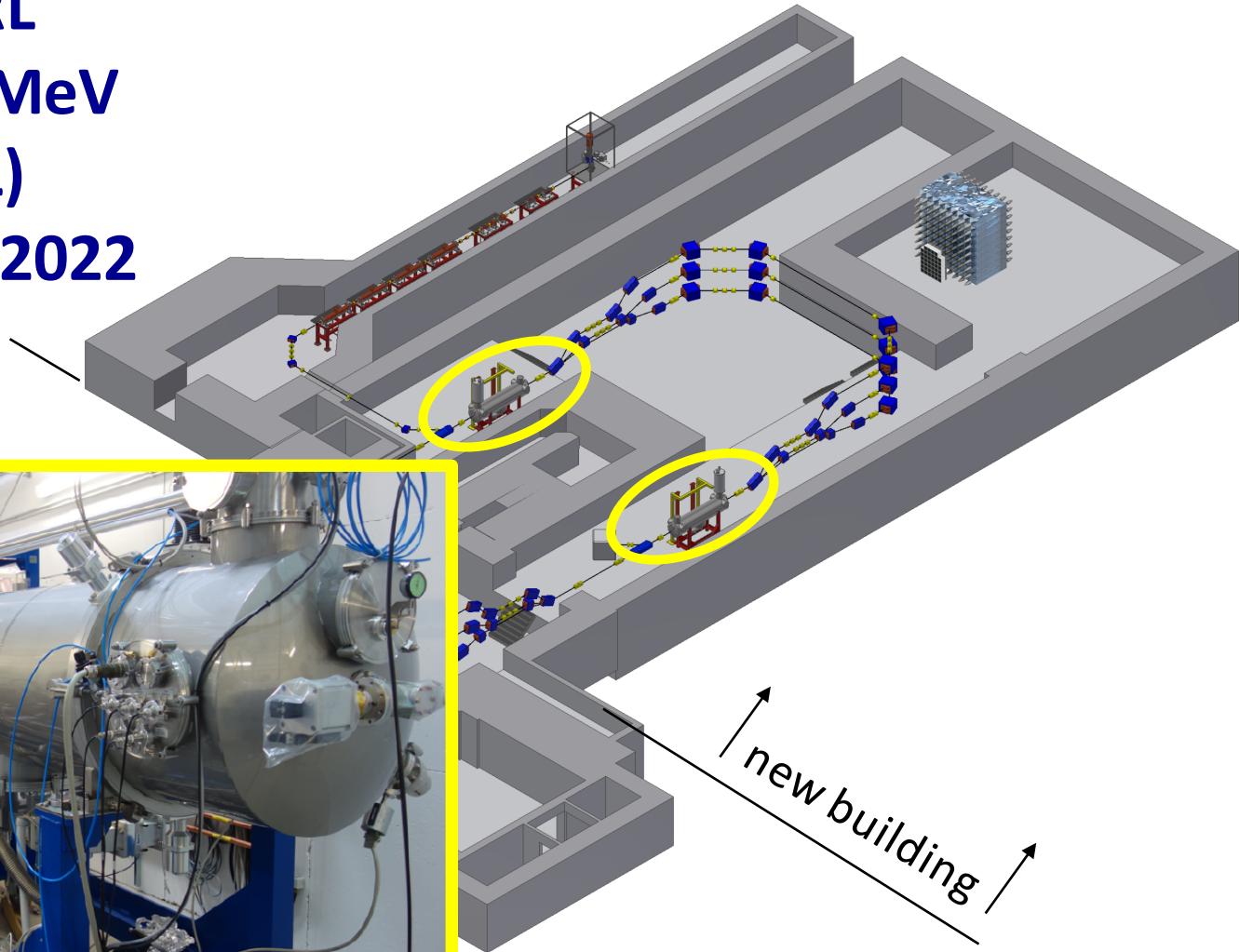
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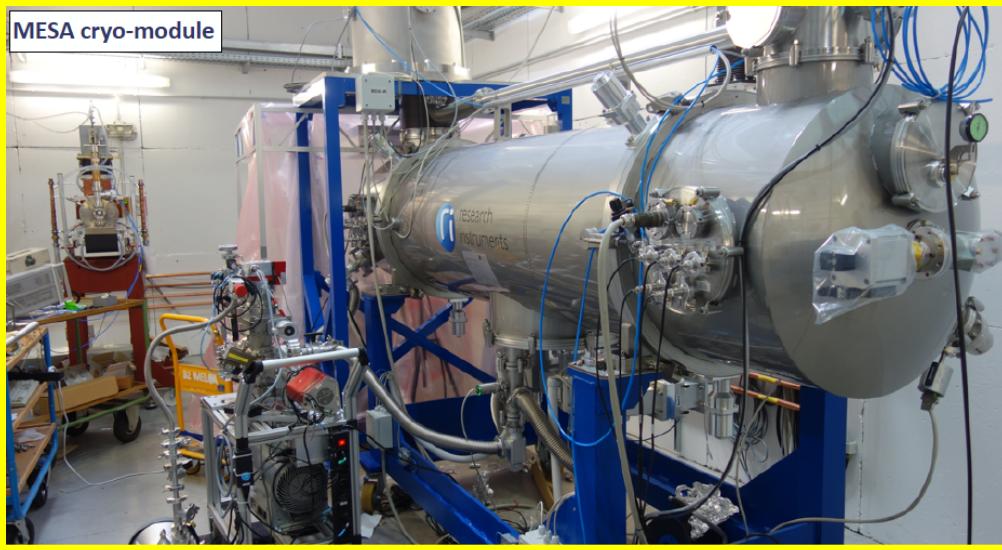
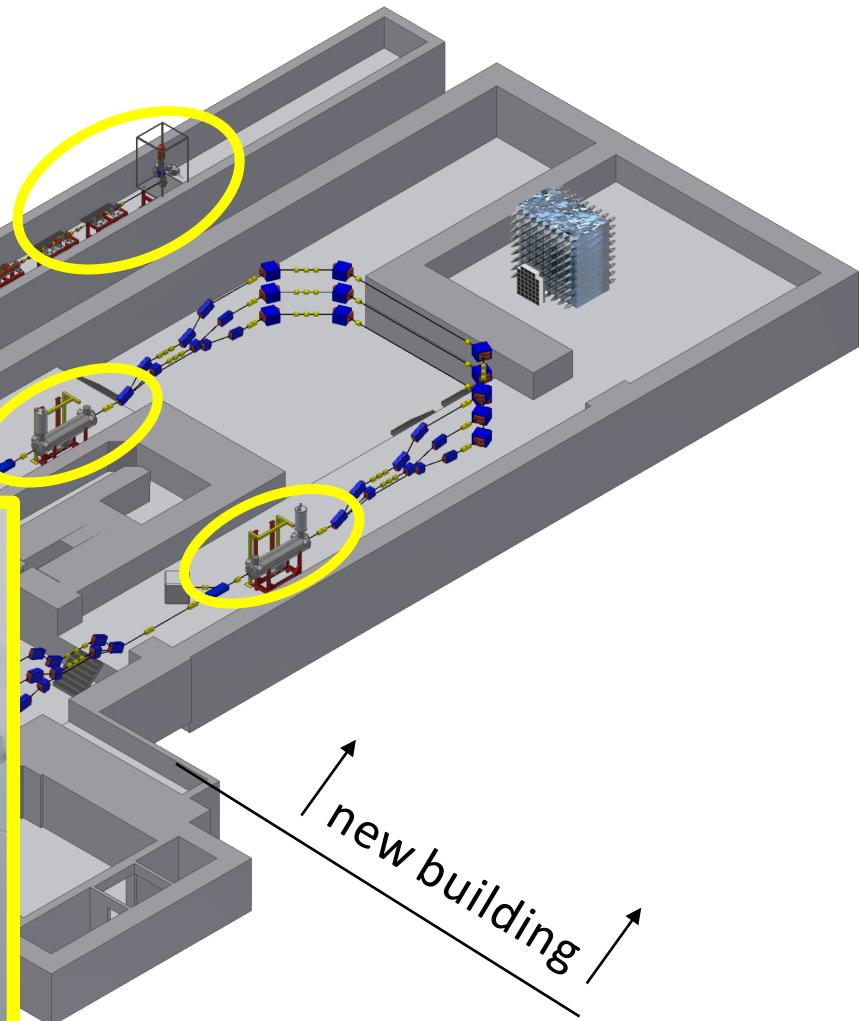
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Superconducting Accelerator



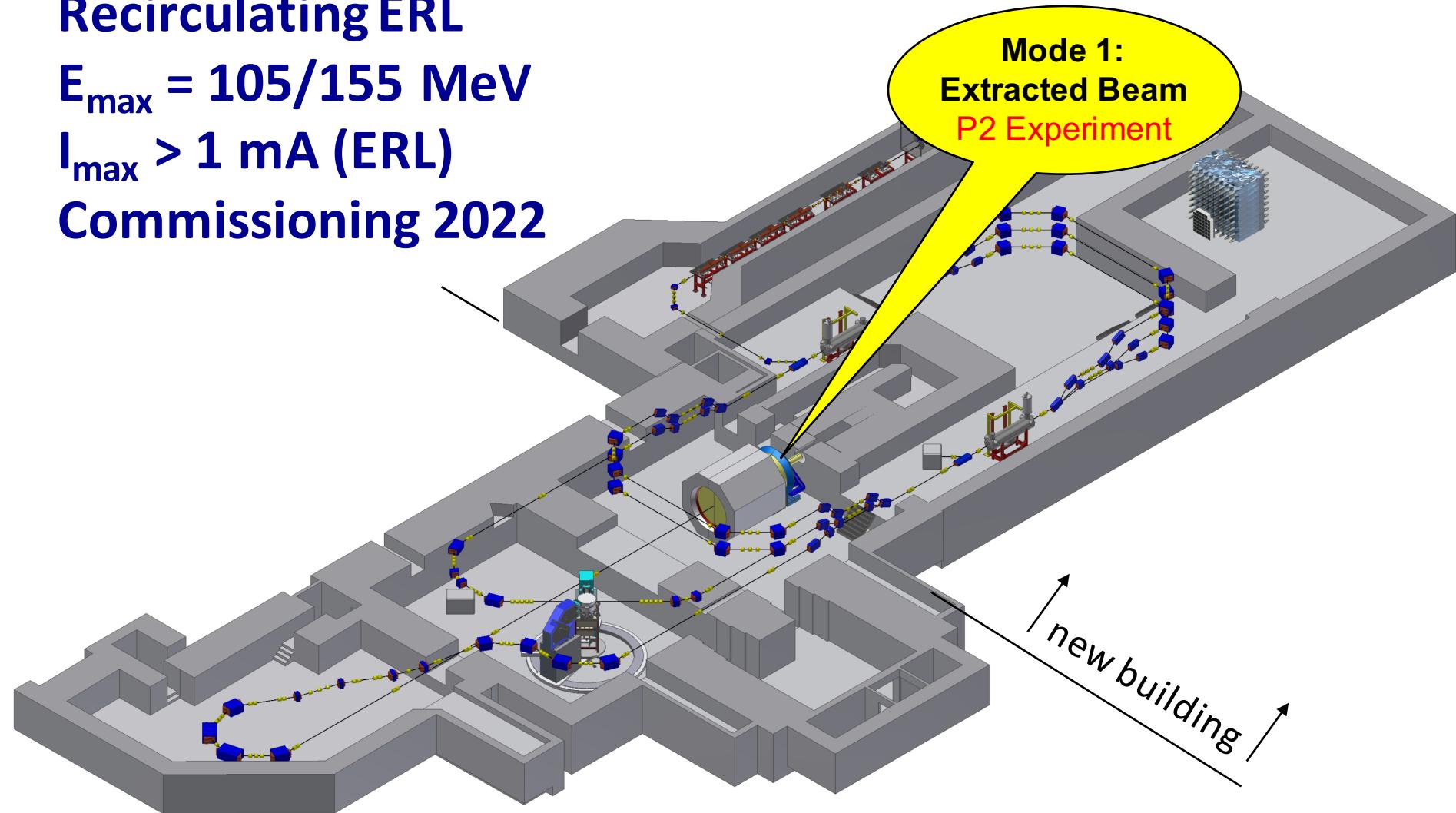
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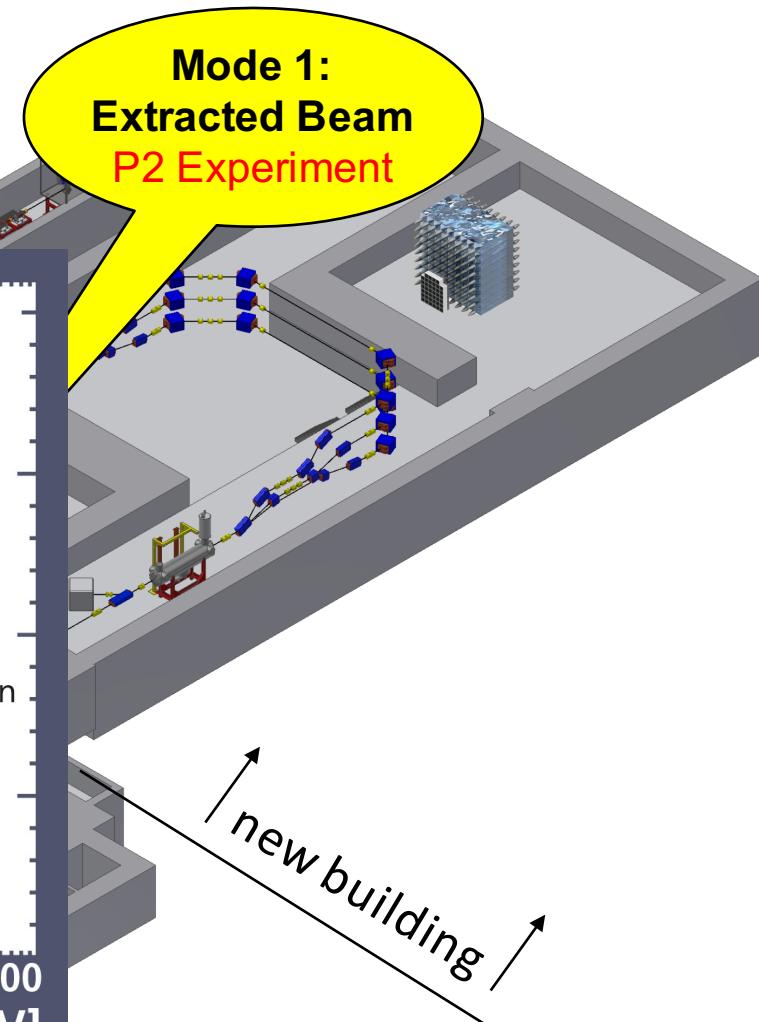
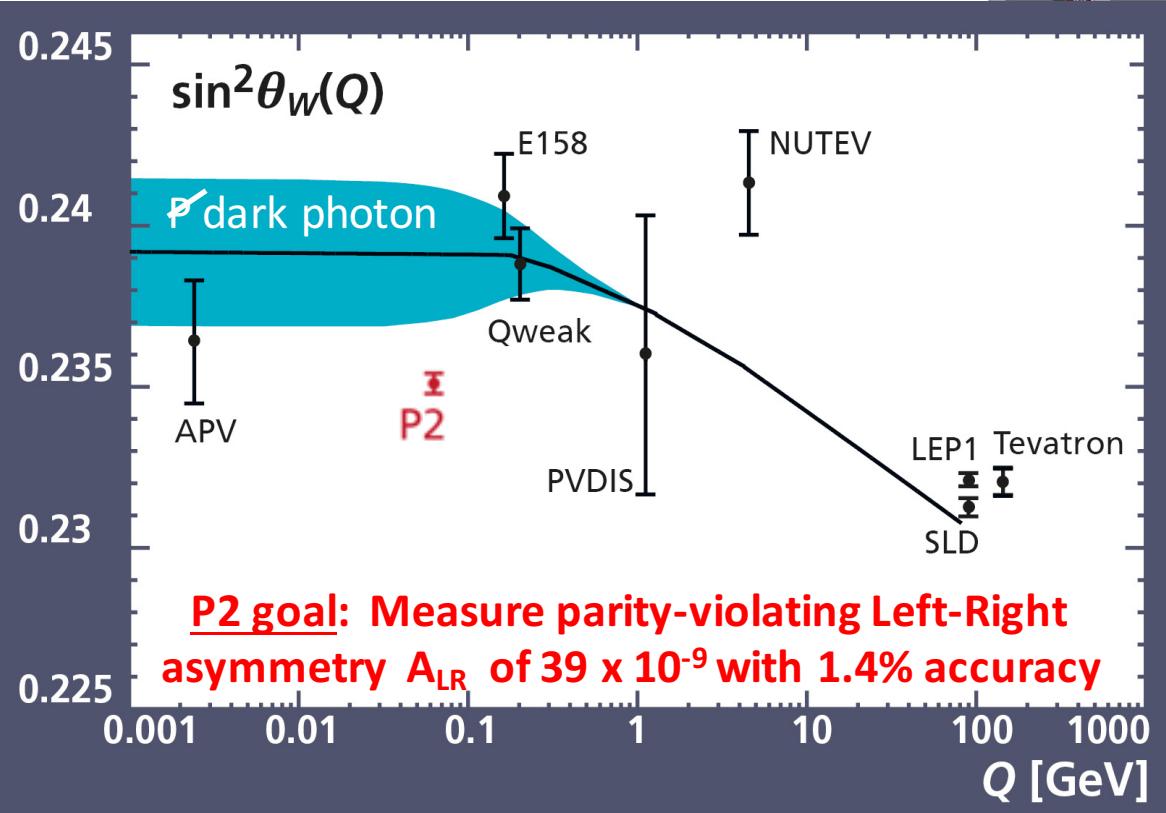


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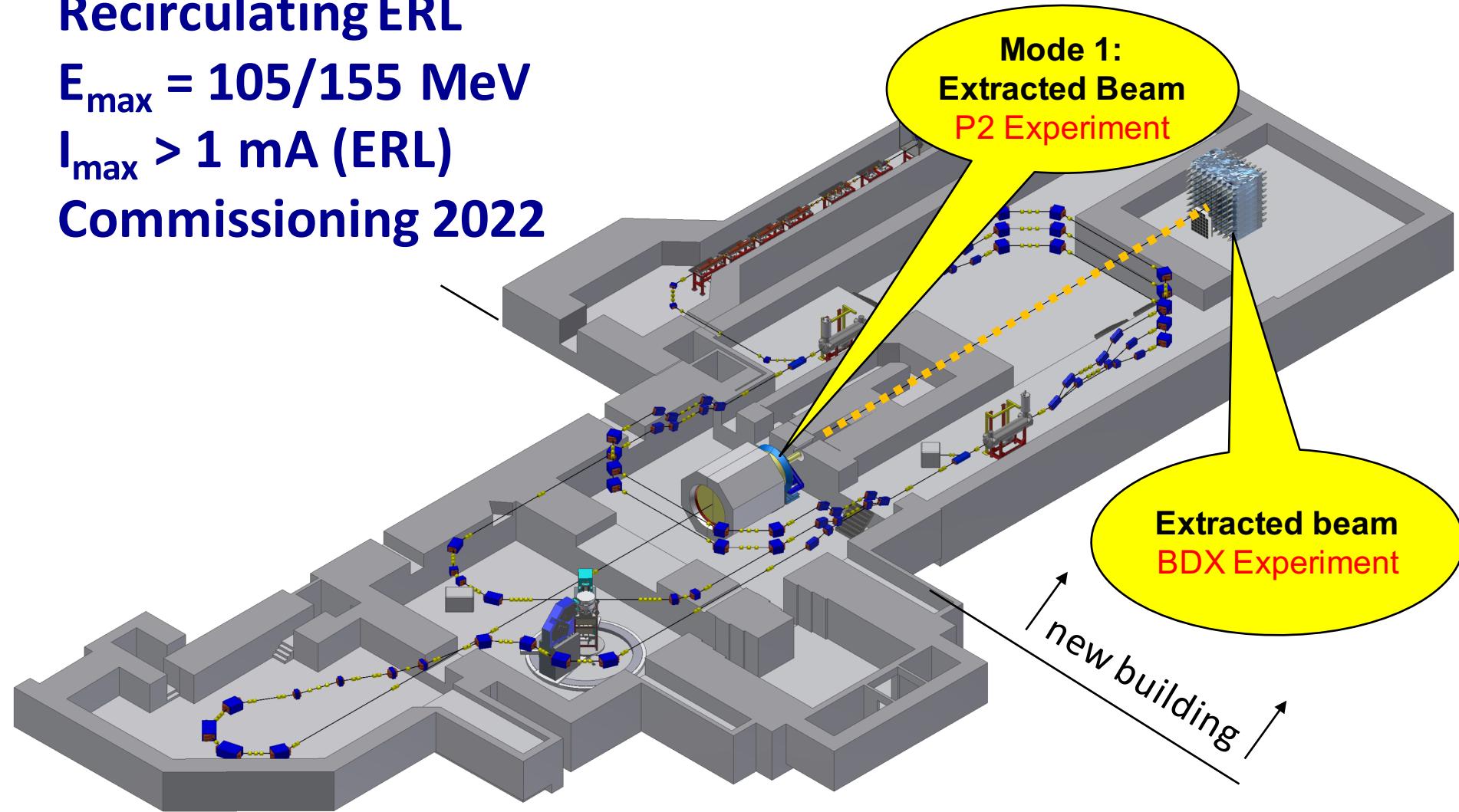
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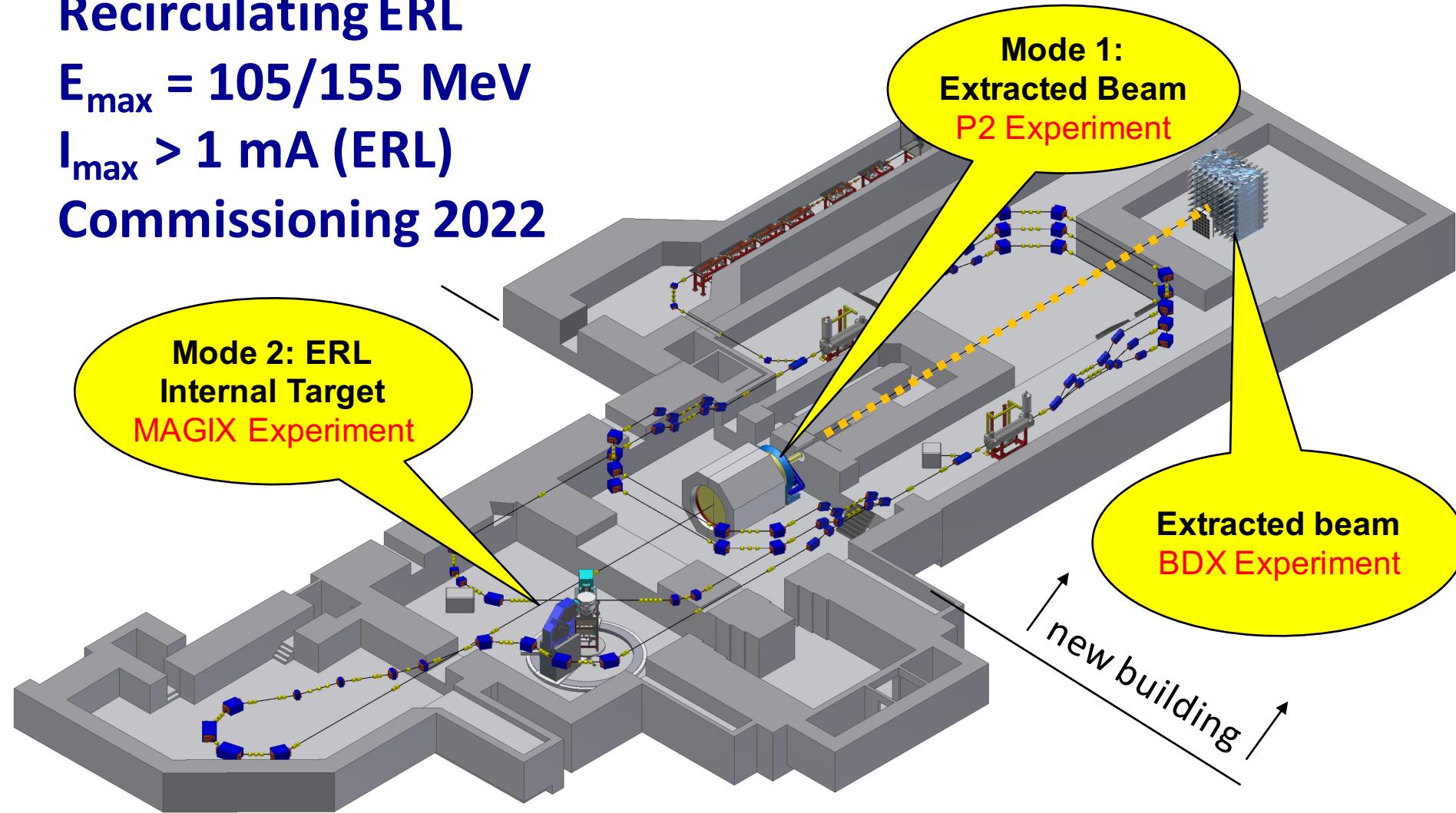
Commissioning 2022

Mode 2: ERL
Internal Target
MAGIX Experiment

Mode 1:
Extracted Beam
P2 Experiment

Extracted beam
BDX Experiment

new building



MESA Physics Programme

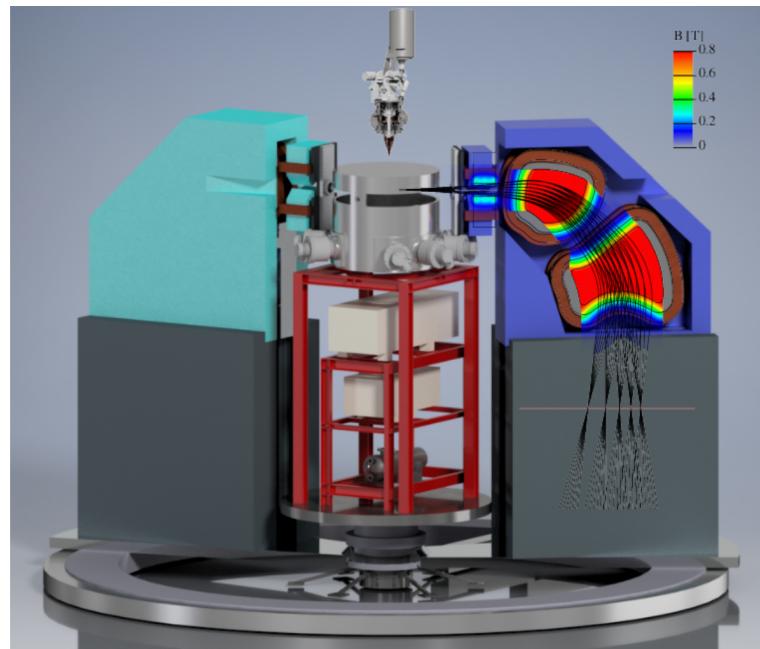
	ERL Mode MAGIX expt.	Extracted Beam Mode P2 expt.	Extracted Beam Mode BDX expt.
Nucleon Form Factors	✓		
EW Mixing Angle		✓	
Nuclear Astrophysics	✓ $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$	neutron skin of nuclei ✓	
Few Body Physics	✓		
Light Dark Matter Search	✓		✓

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Internal Gas Target

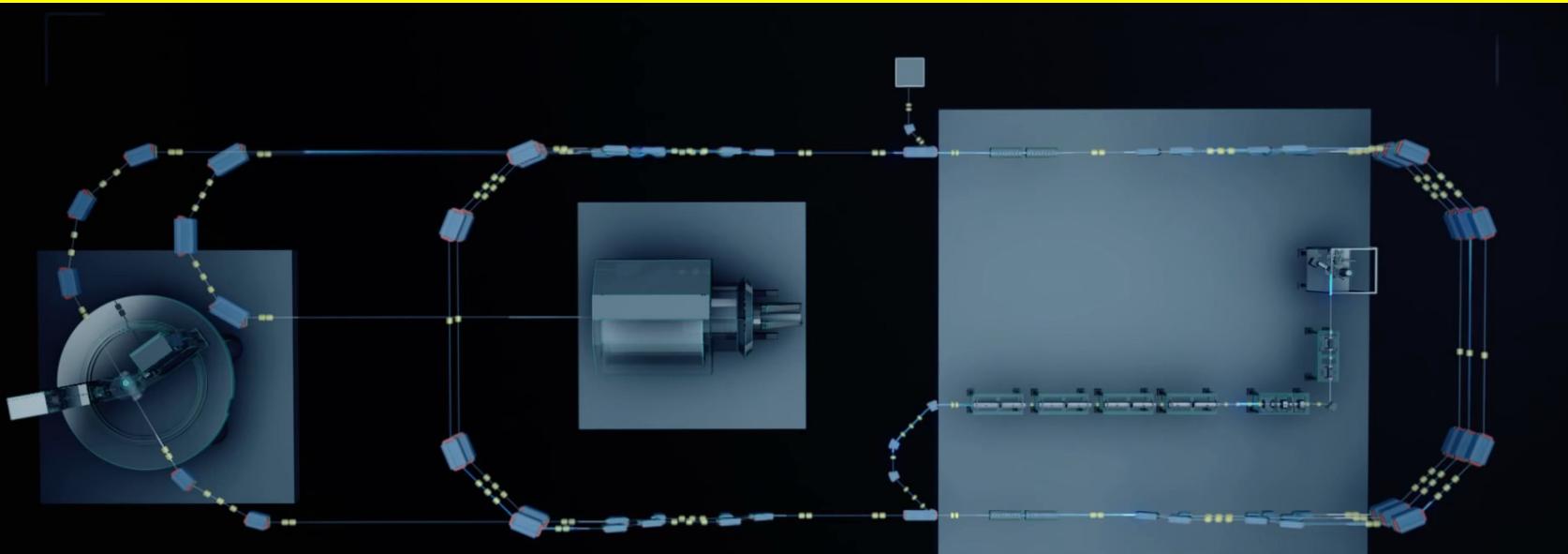
Experiment MAGIX



in MESA ERL Mode

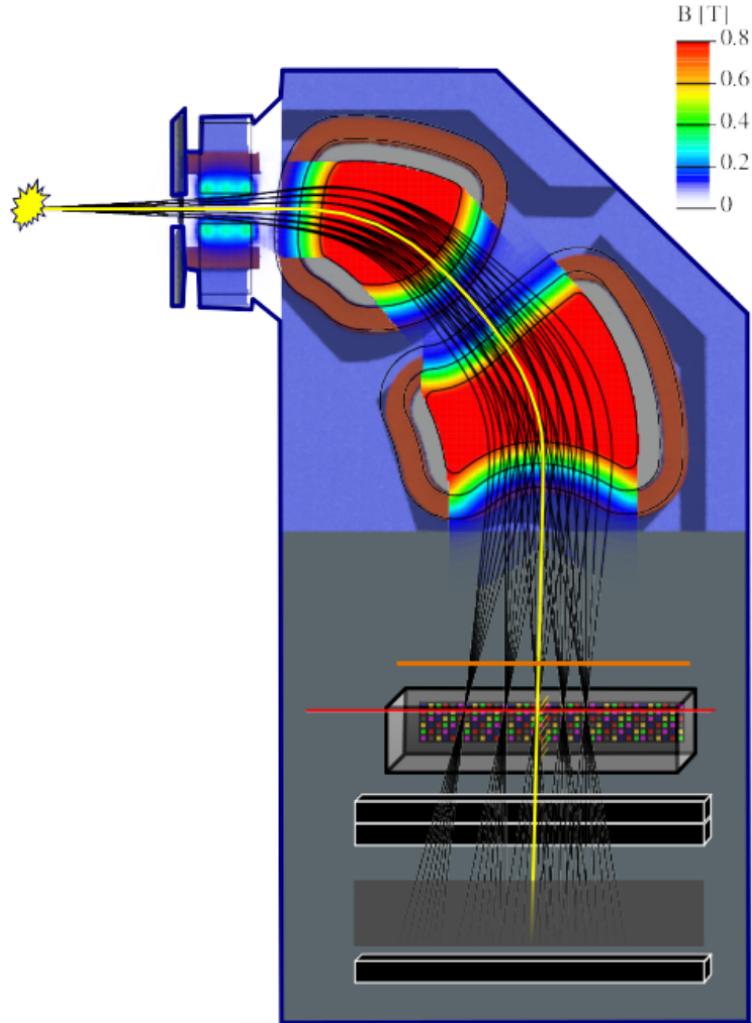
Internal Target Experiment @ ERL

**Operation of a high-intensity (polarized) ERL beam
in conjunction with light internal target**
→ a novel technique in nuclear and particle physics
→ measurement of low momenta tracks with high accuracy
→ competitive luminosities



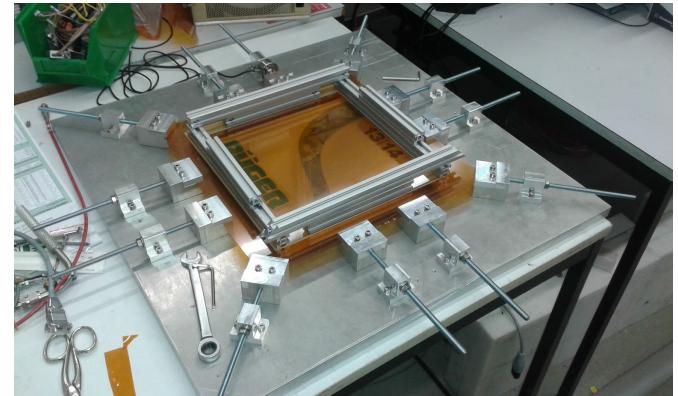
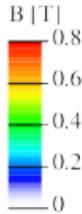
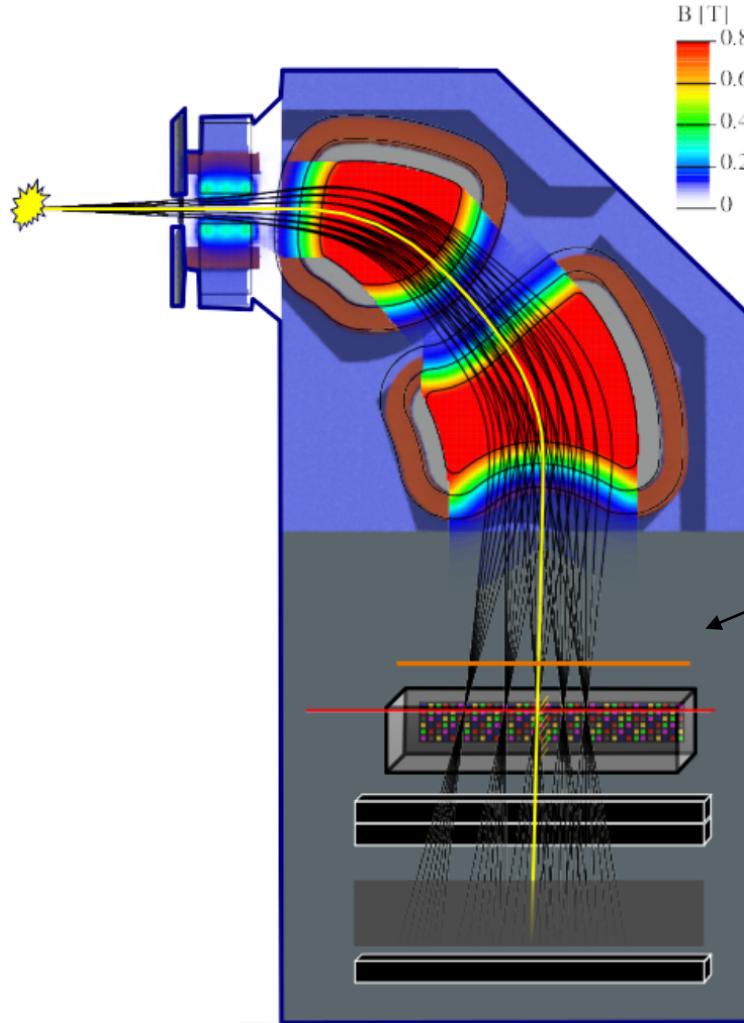


Magnetic spectrometer





Magnetic spectrometer



TPC-based focal plane detector

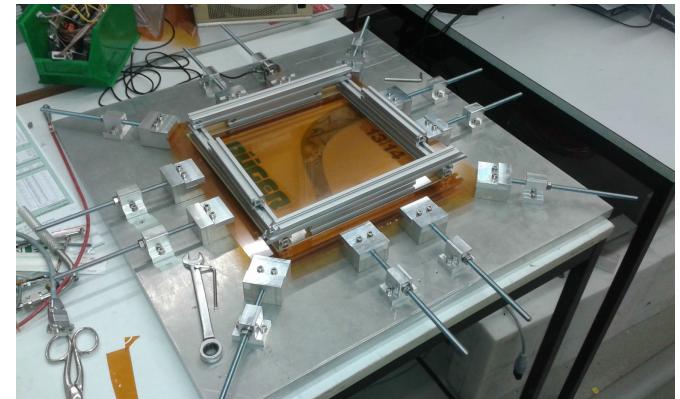
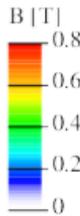
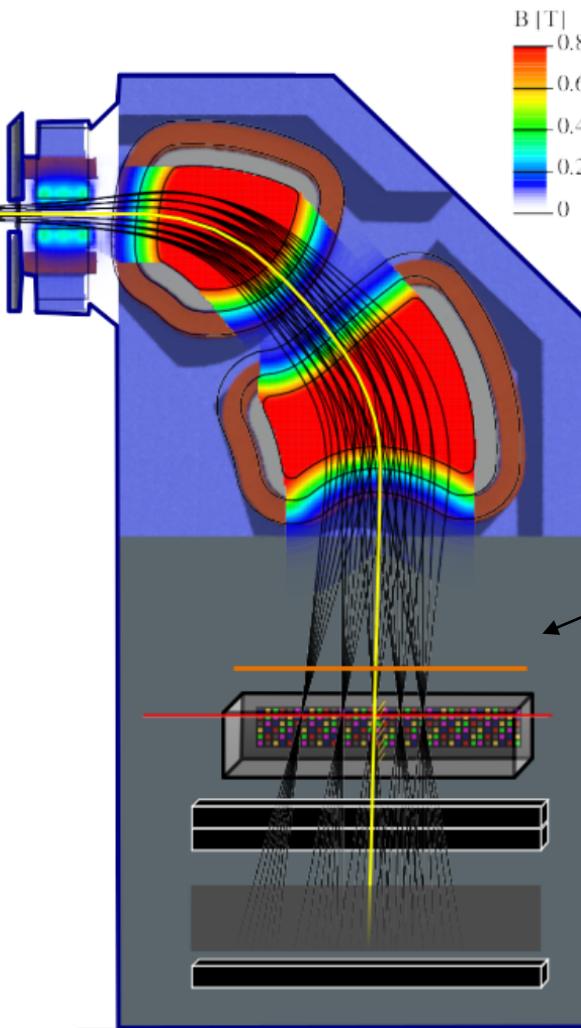
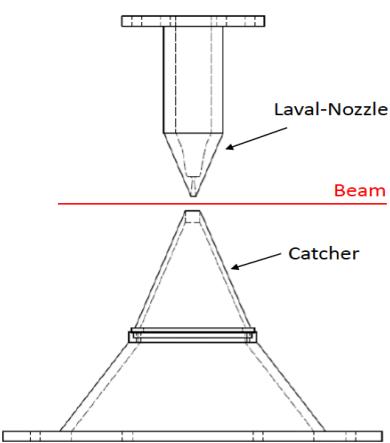
- 10^{-4} momentum resolution
- Requires spatial resolution of $50 \mu\text{m}$
- Open field cage
- GEM readout

MAinz Gas Internal EXperiment



Magnetic spectrometer

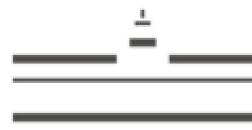
Cryogenic
gas jet target



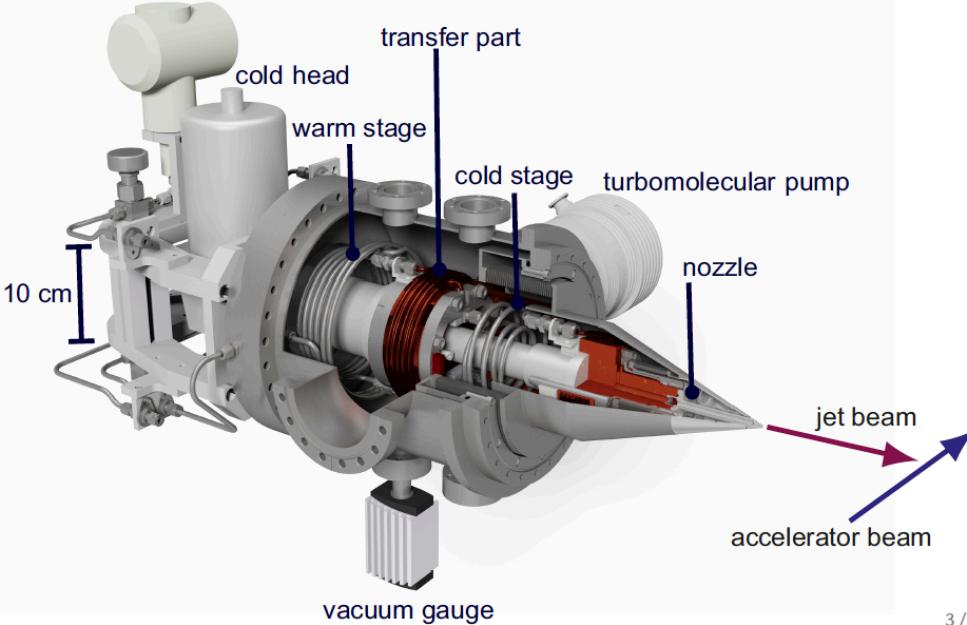
TPC-based focal plane detector

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Supersonic Gas-Jet-Target



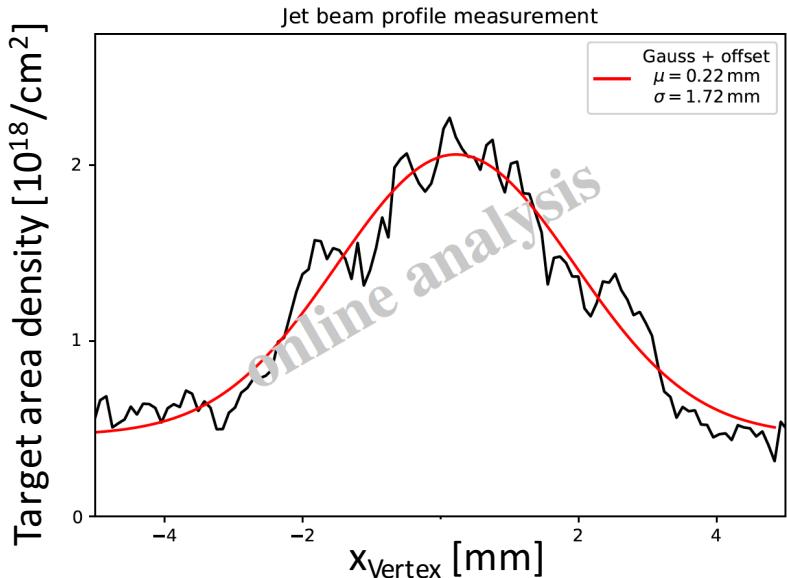
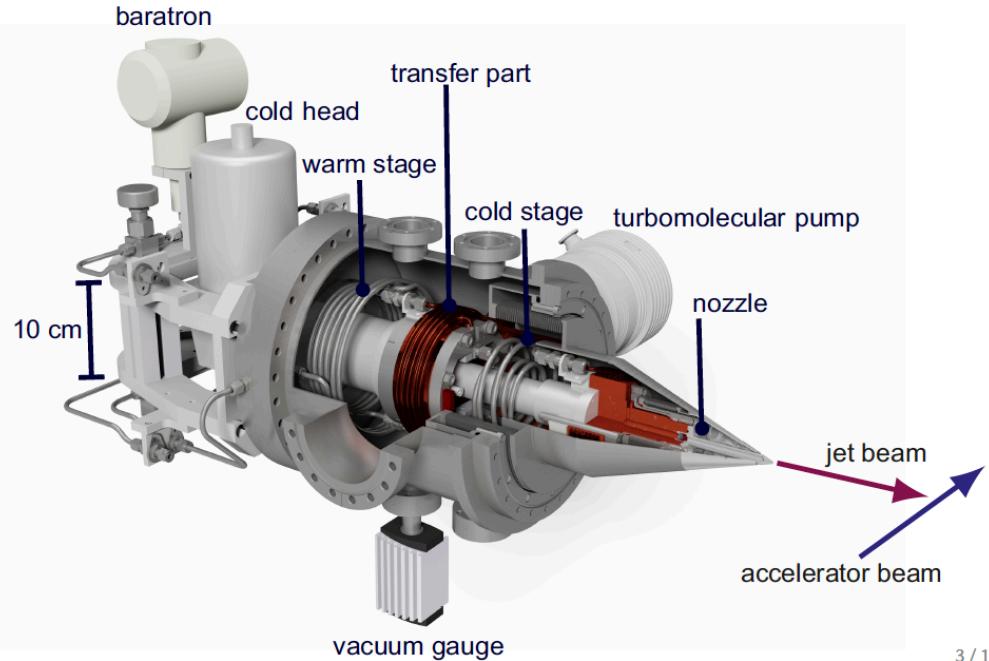
baratron



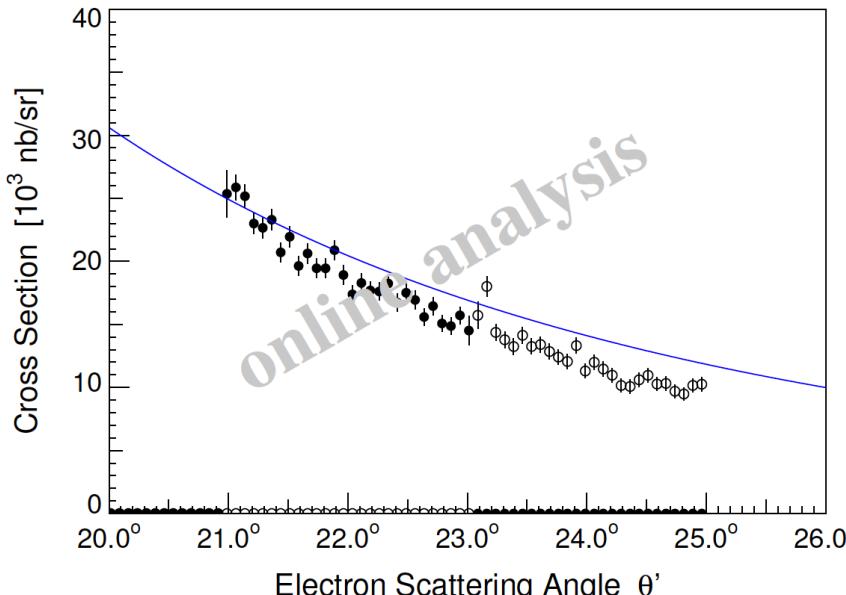
- Windowless !
- Supersonic gas jet
- Higher gas density ($10^{19}/\text{cm}^2$)
- Cryogenic
- $\text{H}_2, {}^3\text{He}, {}^4\text{He}, \text{O}_2, \dots, \text{Xe}$
- $O(10^{35} \text{ cm}^{-2} \text{ s}^{-1}) @ 10^{19}/\text{cm}^2$

3 / 15

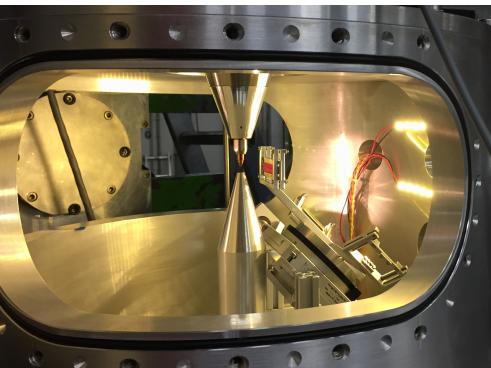
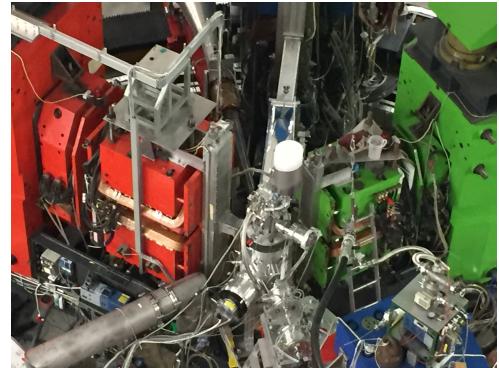
Supersonic Gas-Jet-Target



Elastic Scattering Hydrogen ($\rho = 2 \times 10^{18} \text{ cm}^{-2}$)



Commissioned in 2017/18 at A1/MAMI

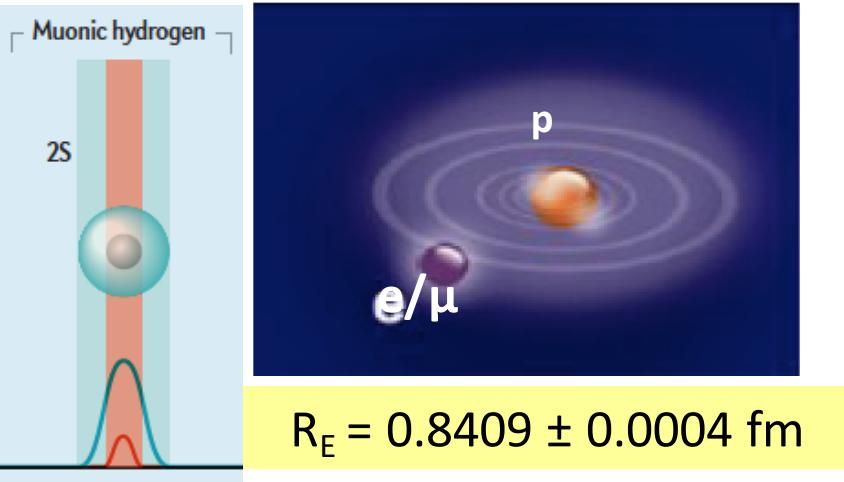


Electromagnetic Form Factors at MAGIX



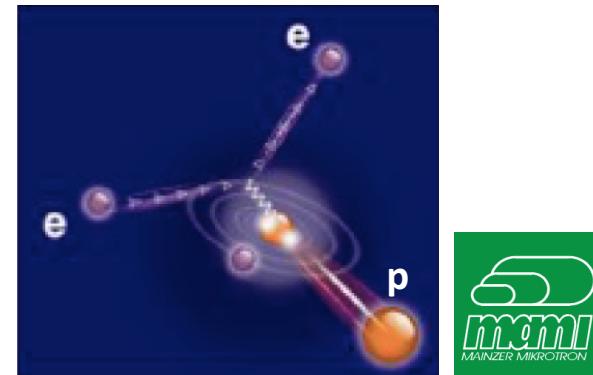
The Proton Radius Puzzle

Atomic Spectroscopy (PSI: Lamb Shift in muonic hydrogen)



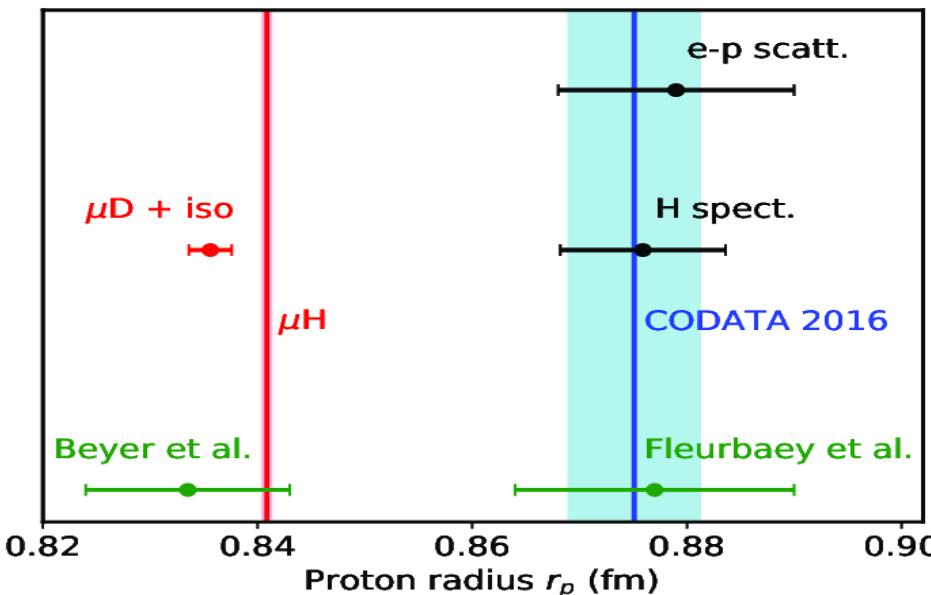
Nature (2012)
Science (2013)

Electron Scattering on proton (EM form factor measurements)



$$R_E = 0.879 \pm 0.008 \text{ fm}$$

PRL (2010)
PRD (2014)



The New York Times

EM Form Factors of the Proton

Elastic form factors in ep scattering:

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

$$\varepsilon = \left(1 + 2(1+\tau) \tan^2 \frac{\theta_e}{2} \right)^{-1}$$

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G_E: spatial
electric charge distribution

G_M: distribution of
magnetic moments

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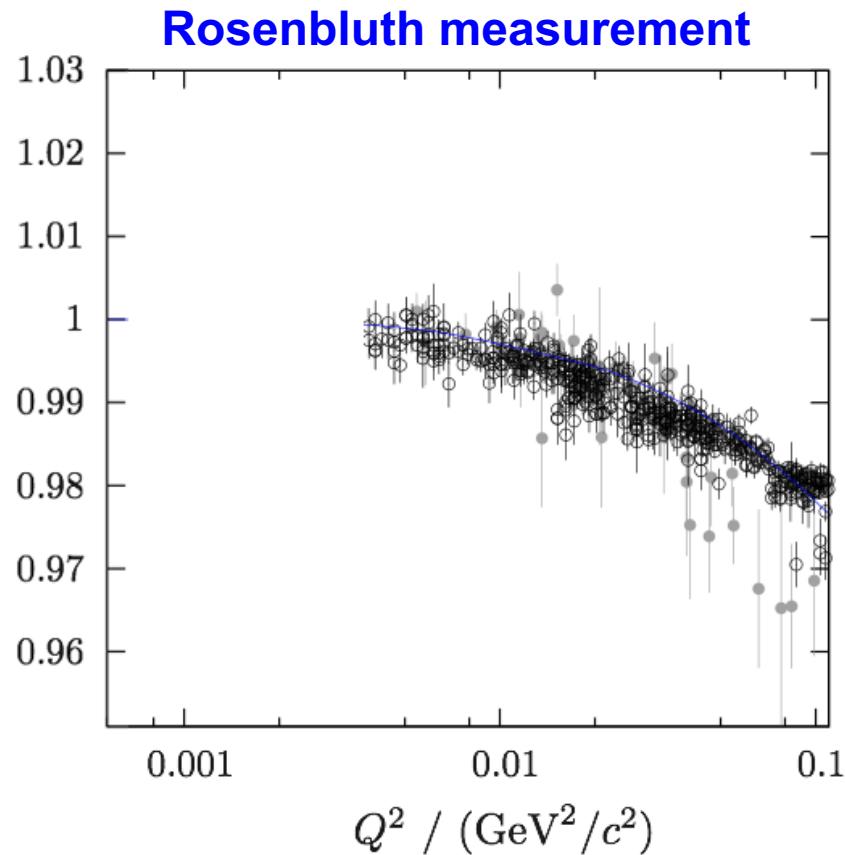
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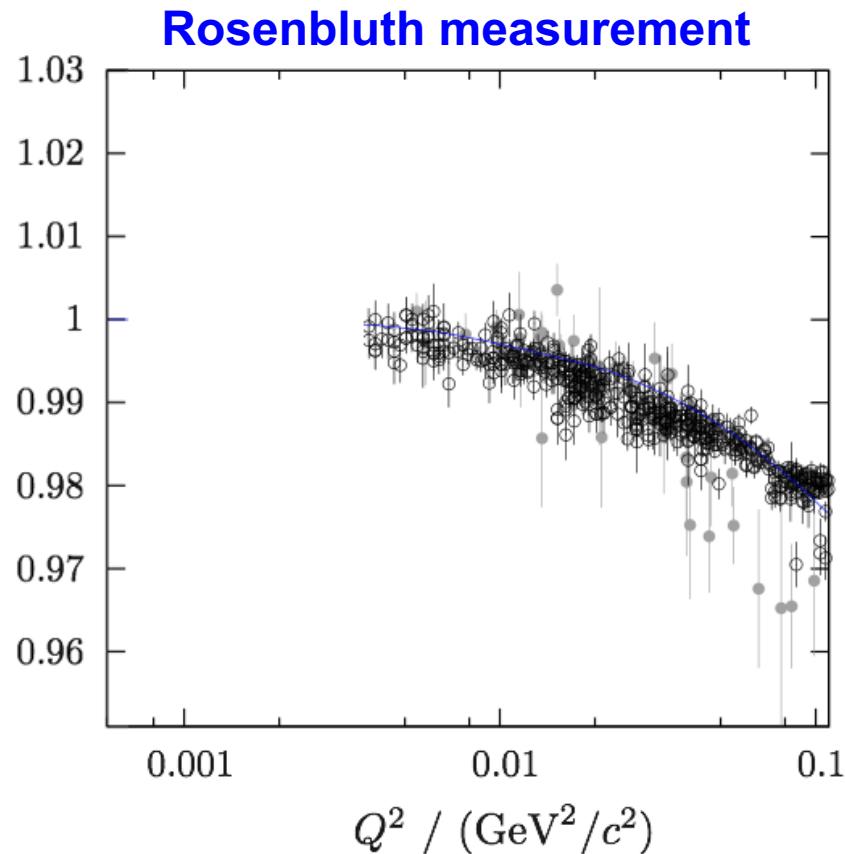
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$G_E^p / G_{\text{Dipole}}$



Proton charge radius:

$$\langle r_{E/M}^2 \rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \left. \frac{dG_{E/M}(Q^2)}{dQ^2} \right|_{Q^2=0}$$

PRL10 (A1): $\langle r_E \rangle = 0.879(8) \text{ fm}$

PRL '10, 242001: Bernauer et al.
PRC '14 015206: Bernauer et al.

Proton Radius Puzzle - What is going on?

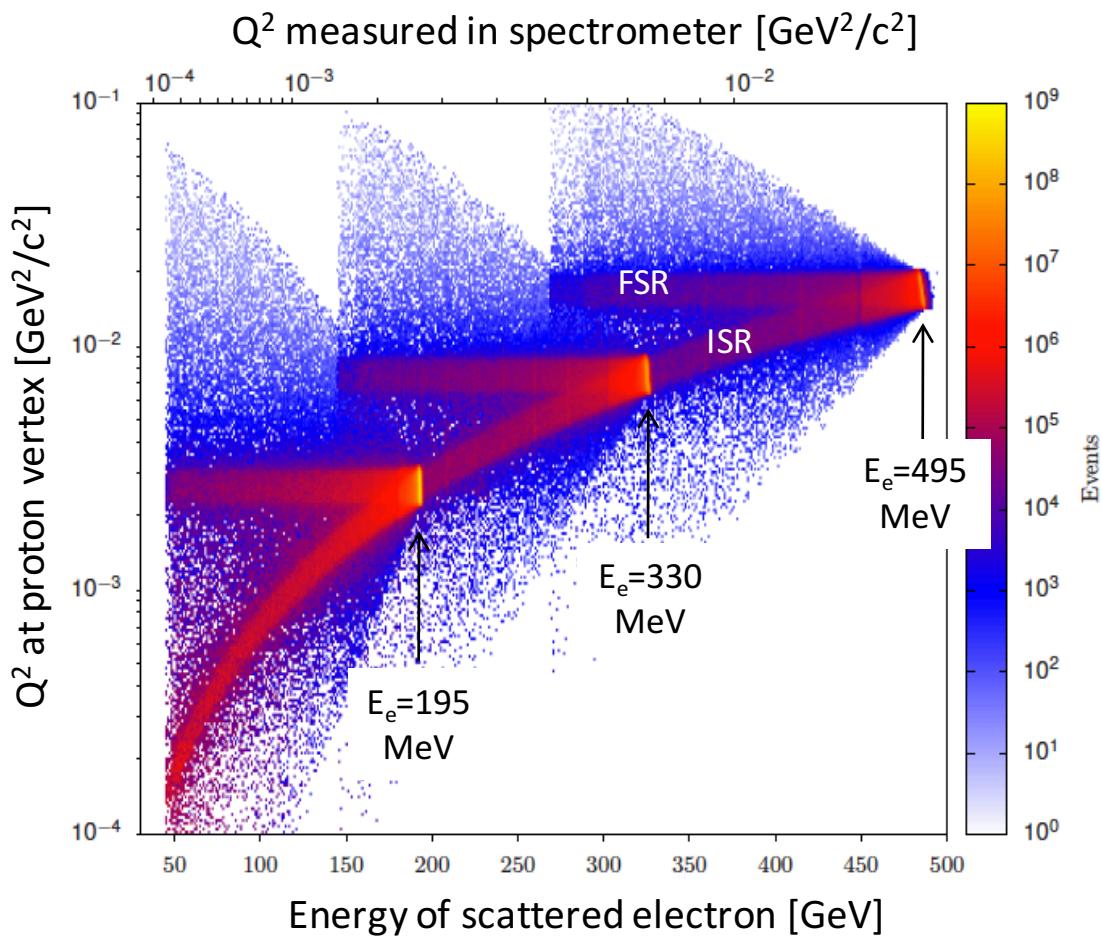
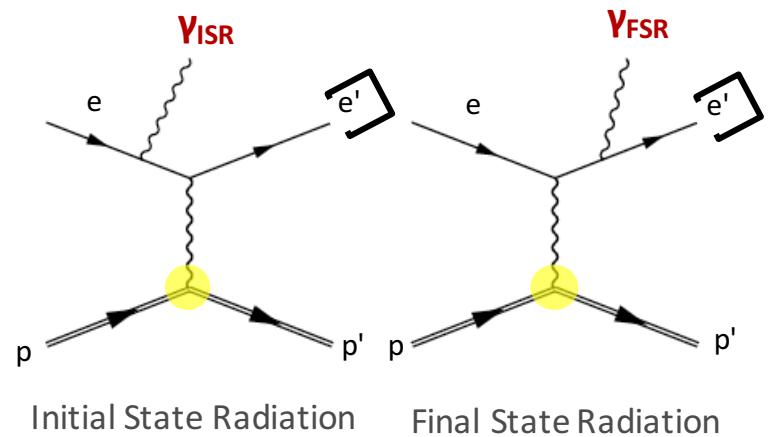
JG|U



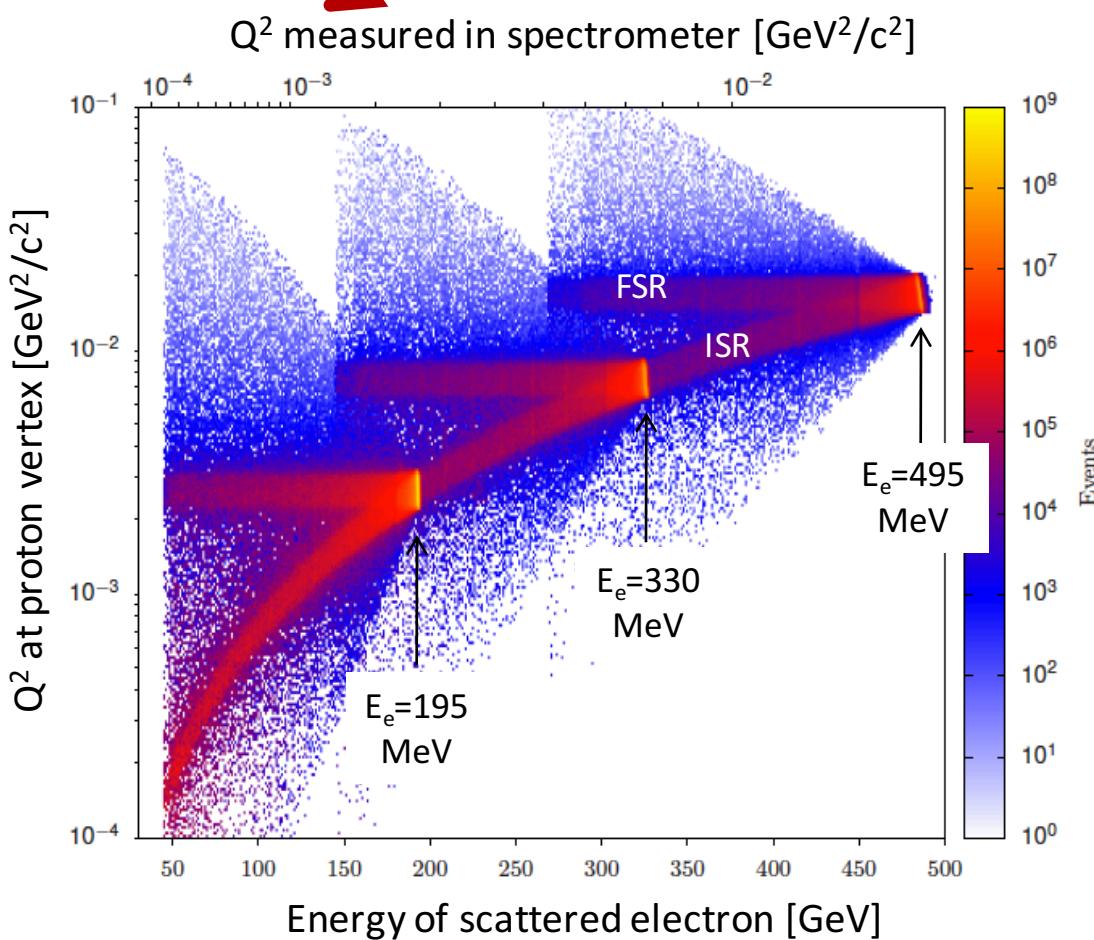
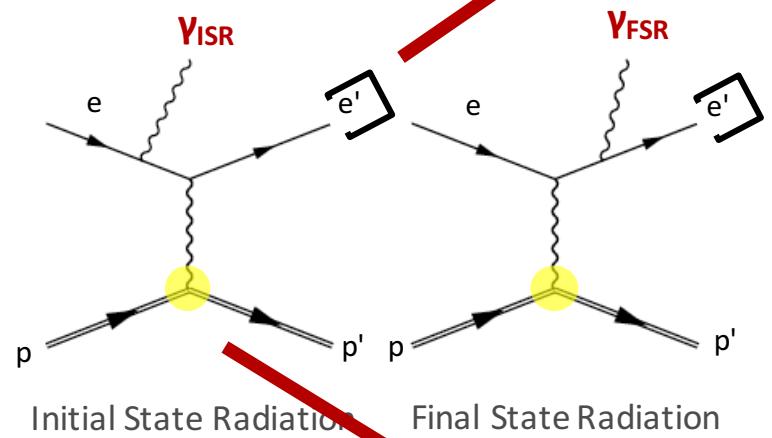
A worldwide effort in atomic physics,
hadron/particle physics and theory

- New Physics explanation ?
Lepton – Non-Universality !
Different coupling of electron-proton vs. muon-proton
→ light or heavy new particles (**Dark Photon**)?
- Electron scattering expts.
not at sufficiently low Q^2
or – radiative corrections not understood
or – normalization errors
or ?

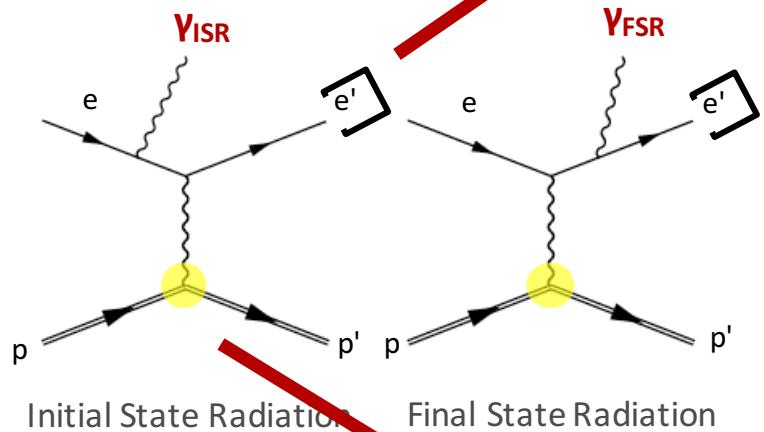
ISR Measurement of EM Form Factors



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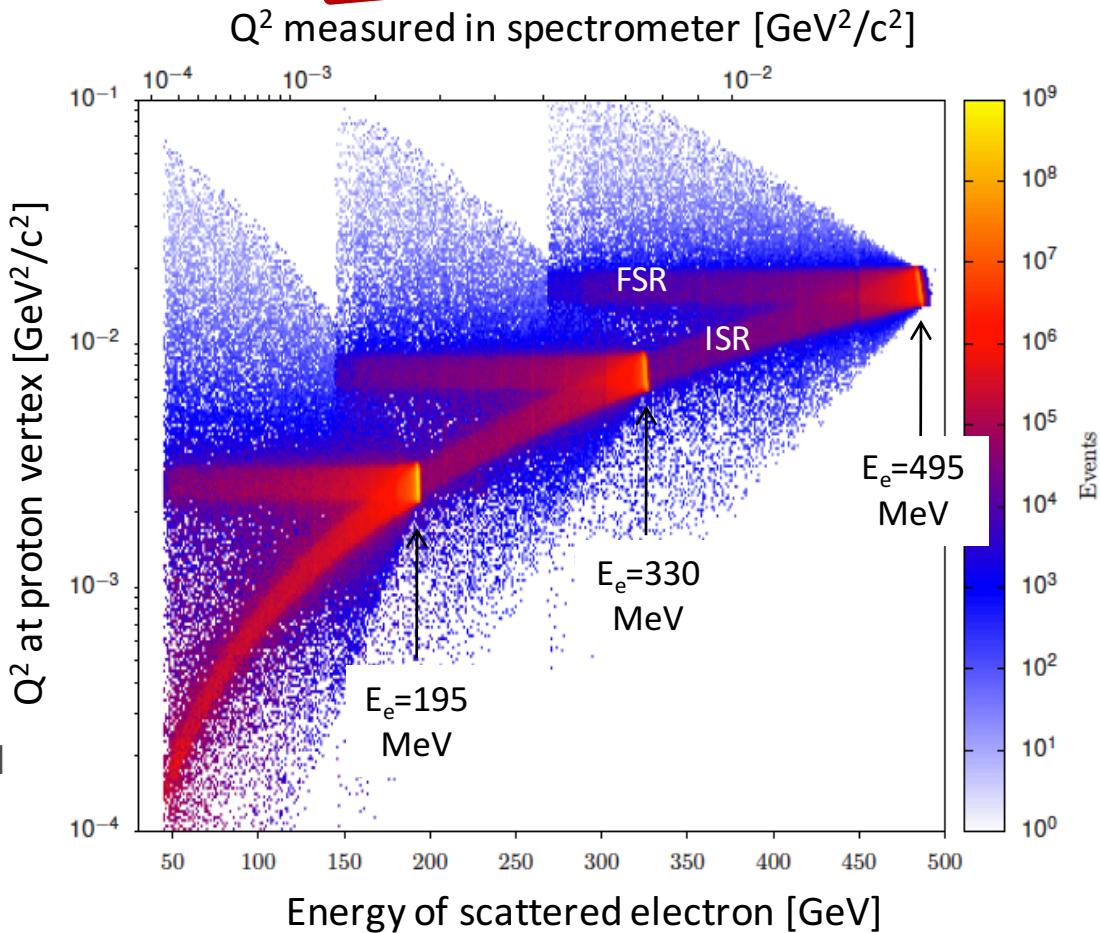


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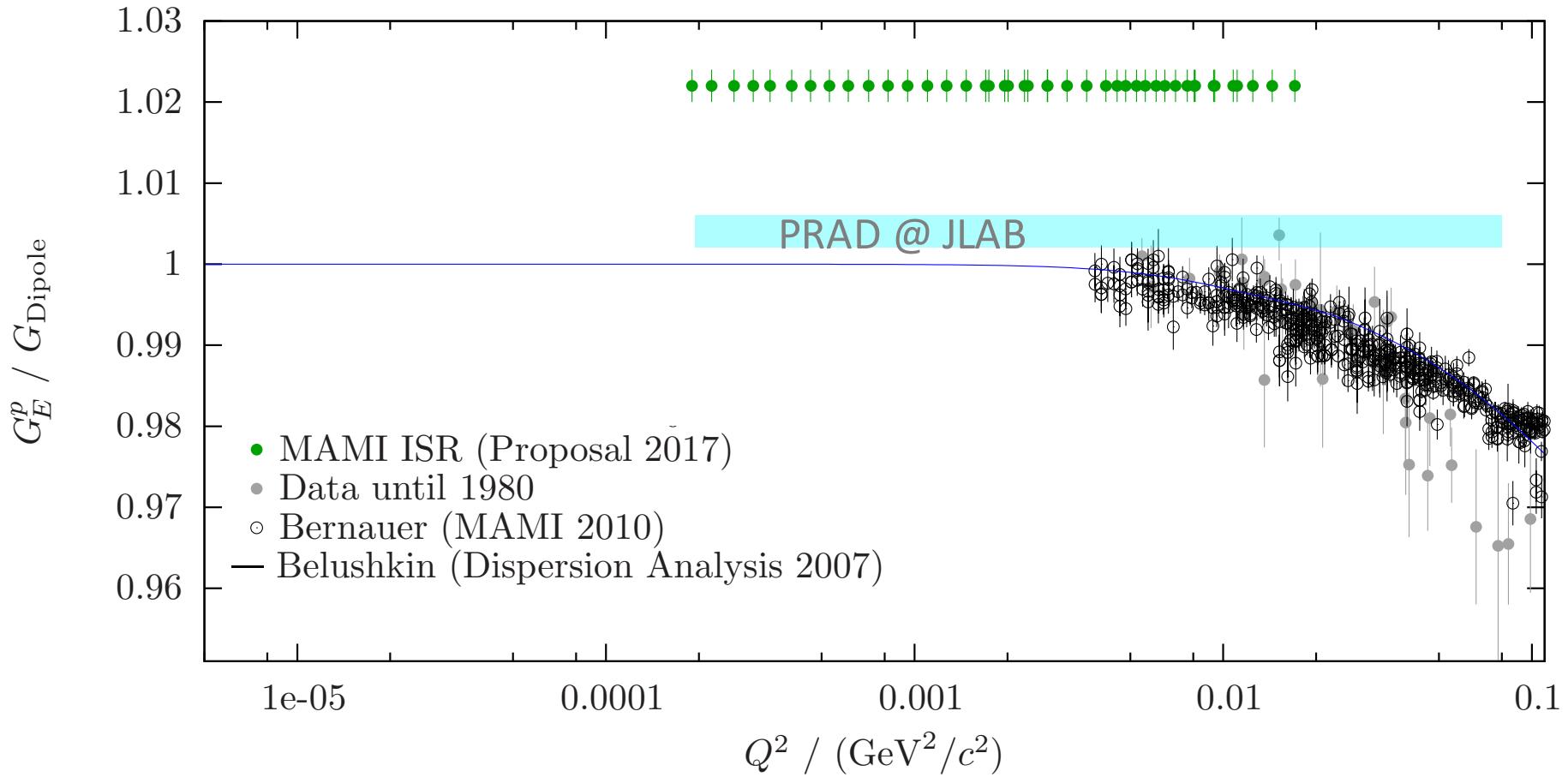
Strategy:

- Very low values of Q^2 by using ISR events
- Measure momentum spectrum of scattered electron
- Needs very good understanding of QED radiative corrections and FSR

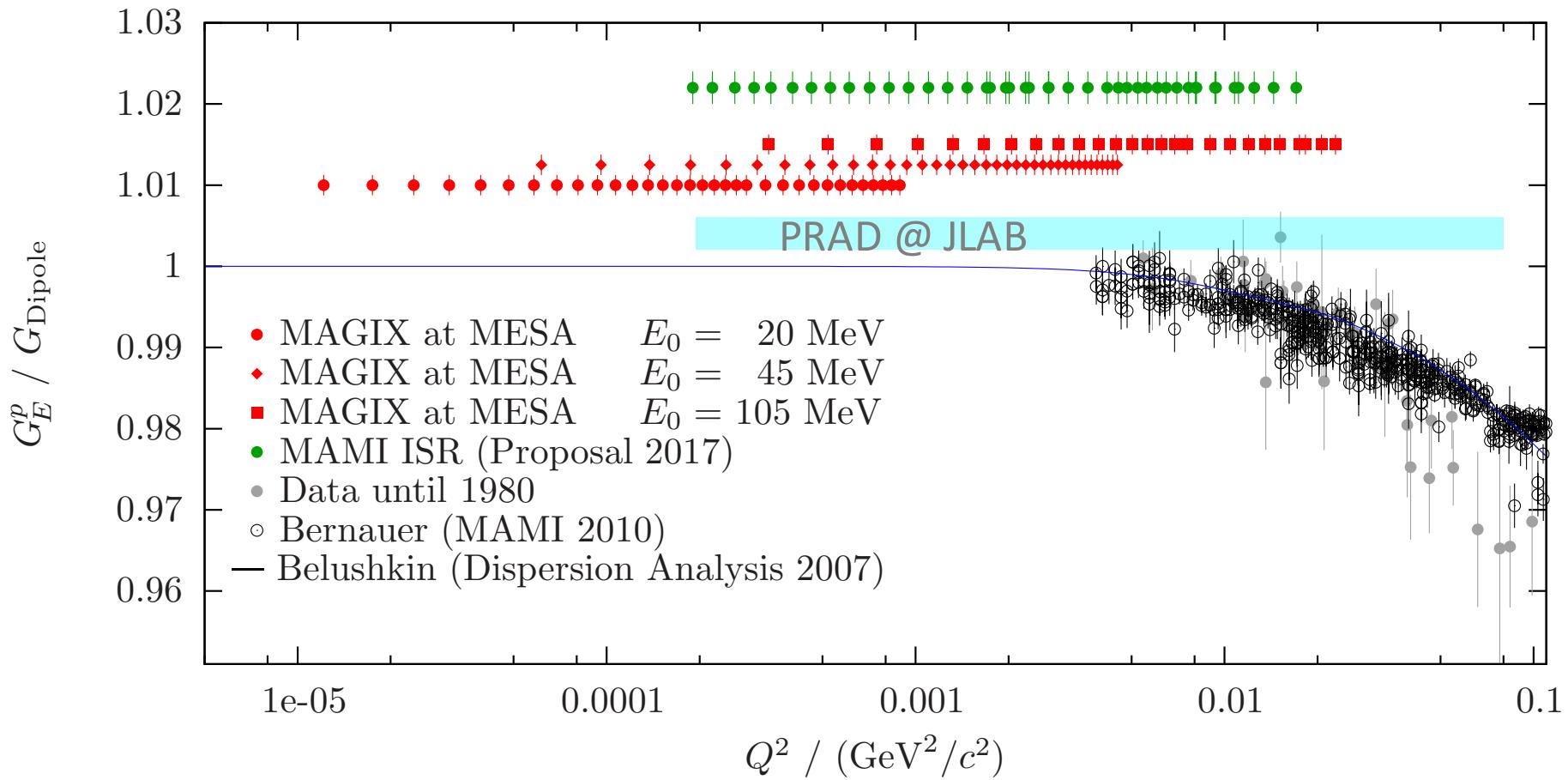


→ Access low Q^2 values down to 2×10^{-4} , limited by systematic effects @ target walls

The Quest for Low- Q^2 Scattering Data



The Quest for Low- Q^2 Scattering Data



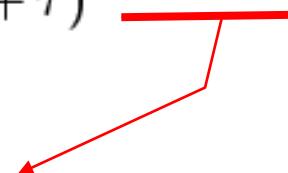
Magnetic Form Factor @ MAGIX



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long. polarization of virtual photon

Low Q^2 accessible with low E_{beam}



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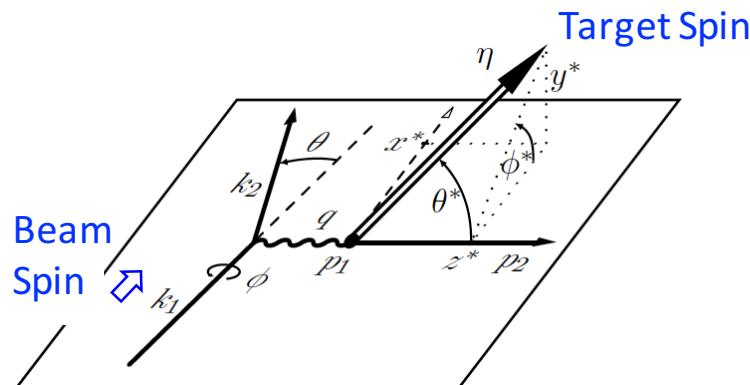
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Suppressed at low Q^2 due to τ

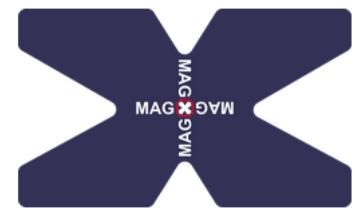
→ Double polarization measurement

Beam Target Asymmetry !



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

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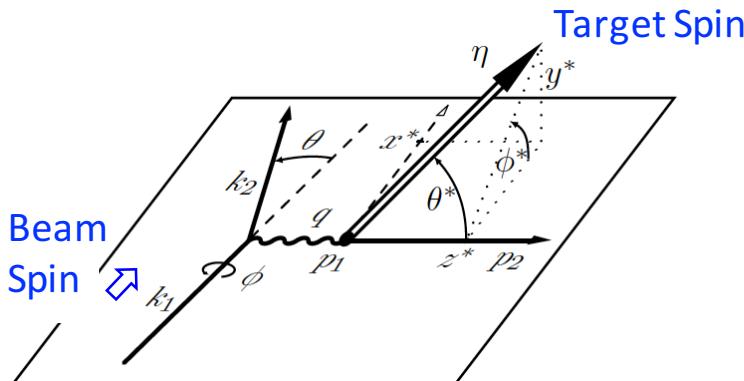
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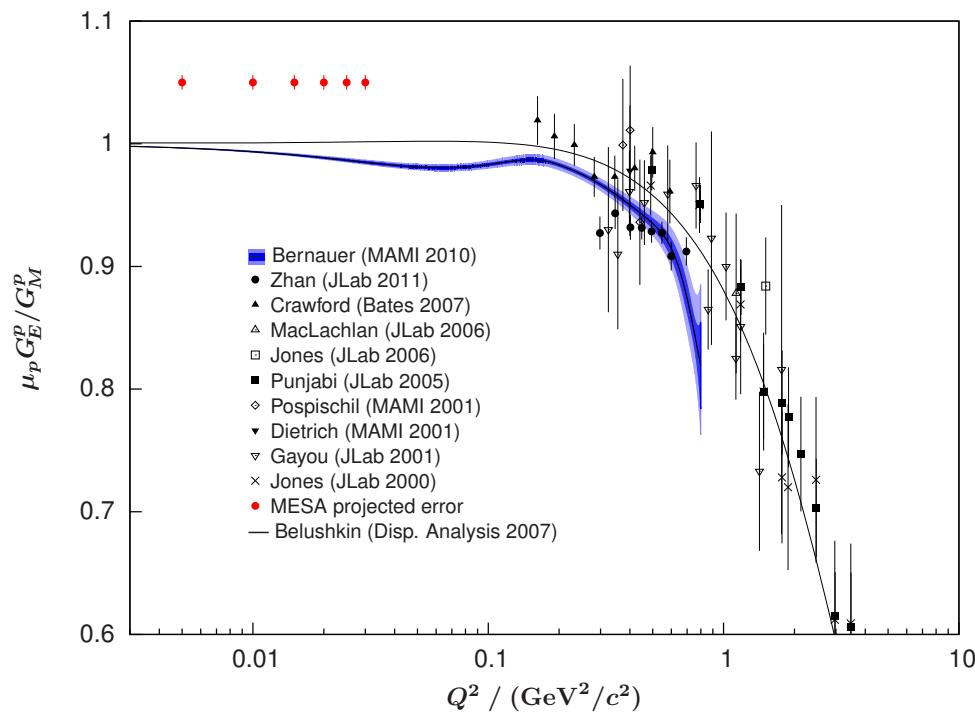
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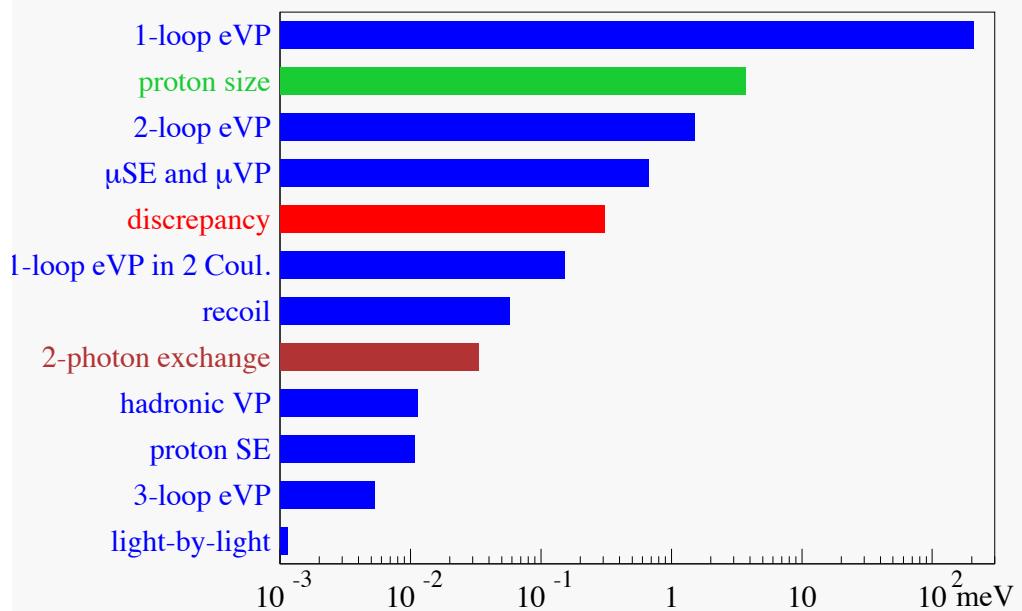
Proton Radius Puzzle - What is going on?

JG|U



A worldwide effort in atomic physics,
hadron/particle physics and theory

- Unknown QED / hadronic correction
in μH data ?



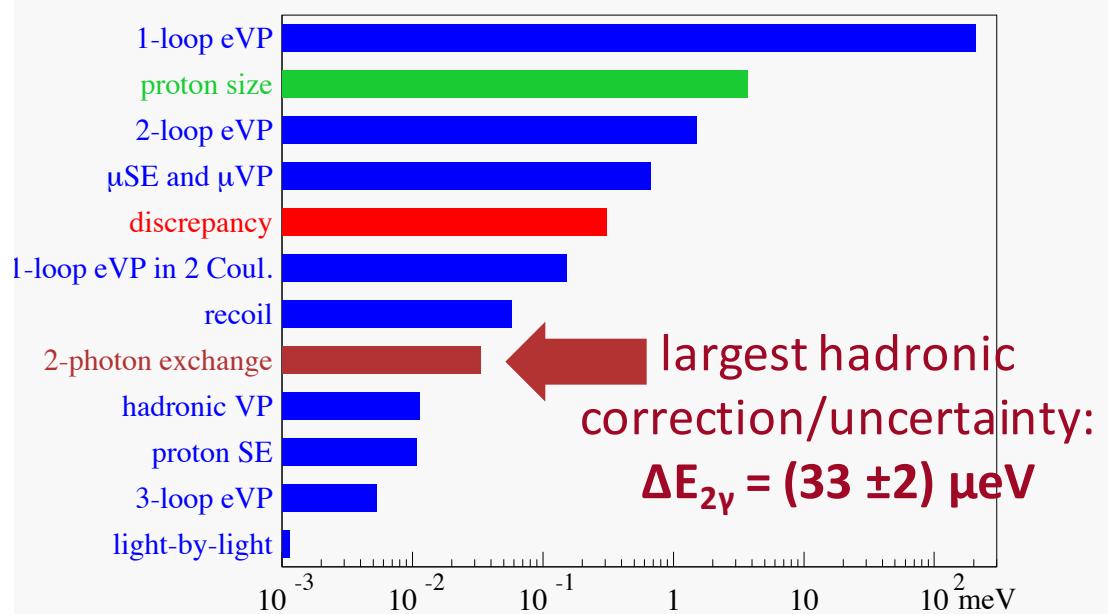
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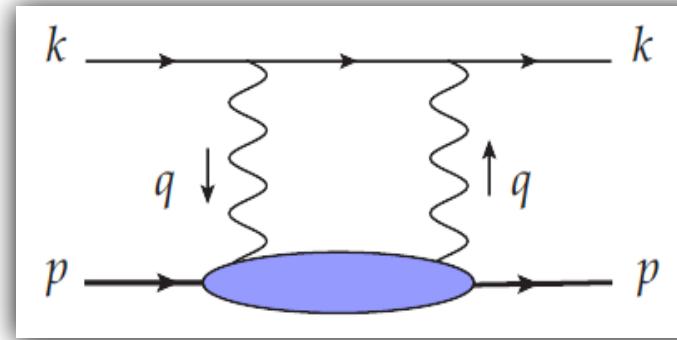


Polarisability Corrections in Light Nuclei Systems

μH : $\Delta E^{\text{TPE}}(2P - 2S) = (33 \pm 2) \mu\text{eV}$
dispersive analysis

Carlson, Vanderhaeghen (2011)

accuracy comparable with present
experimental precision
→ Related to proton polarizability

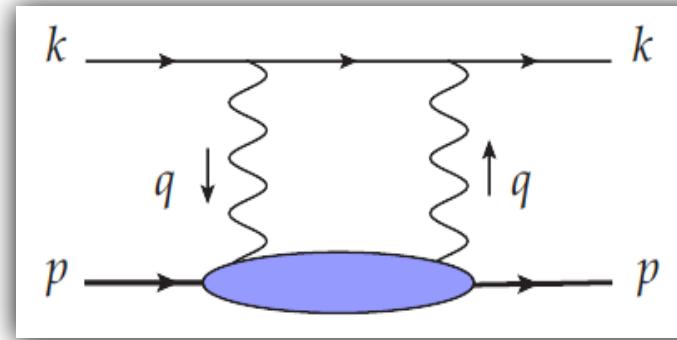


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accuracy comparable with present
experimental precision
→ Related to proton polarizability



μD : $\Delta E^{\text{TPE}} = (1727 \pm 20) \mu\text{eV}$ nucleon potentials from chiral EFT

Hernandez et al. (2014)

accuracy factor 5 worse than present experimental precision

$\mu^3\text{He}^+$: $\Delta E^{\text{TPE}} = (15.46 \pm 0.39) \text{ meV}$ nucleon potentials from chiral EFT

Nevo Dinur, Ji, Bacca, Barnea (2016)

$(15.14 \pm 0.49) \text{ meV}$ dispersive analysis

Carlson, Gorchtein, Vanderhaeghen (2016)

Polarisability Corrections in Light Nuclei Systems

μH : $\Delta E^{\text{TPE}} (2P - 2S) = (33 \pm 2) \mu\text{eV}$
dispersive analysis

Carlson, Vanderhaeghen (2011)

accuracy comparable with present
experimental precision
→ Related to proton polarizabilities

μD : $\Delta E^{\text{TPE}} = (172 \pm 10) \mu\text{eV}$

Hernan

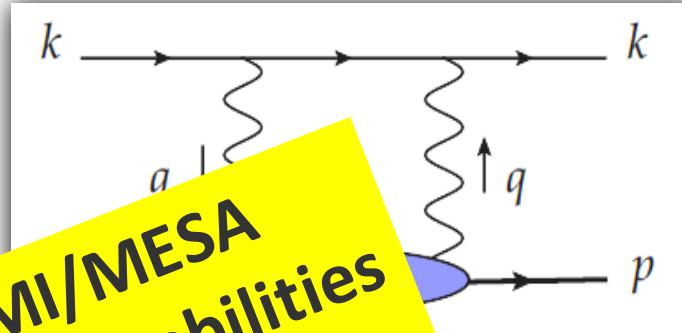
and in the field of few-body physics
for measurements of proton polarizabilities
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$\mu^3\text{He}^+$: $(15.46 \pm 0.39) \text{ meV}$ nucleon potentials form chiral EFT

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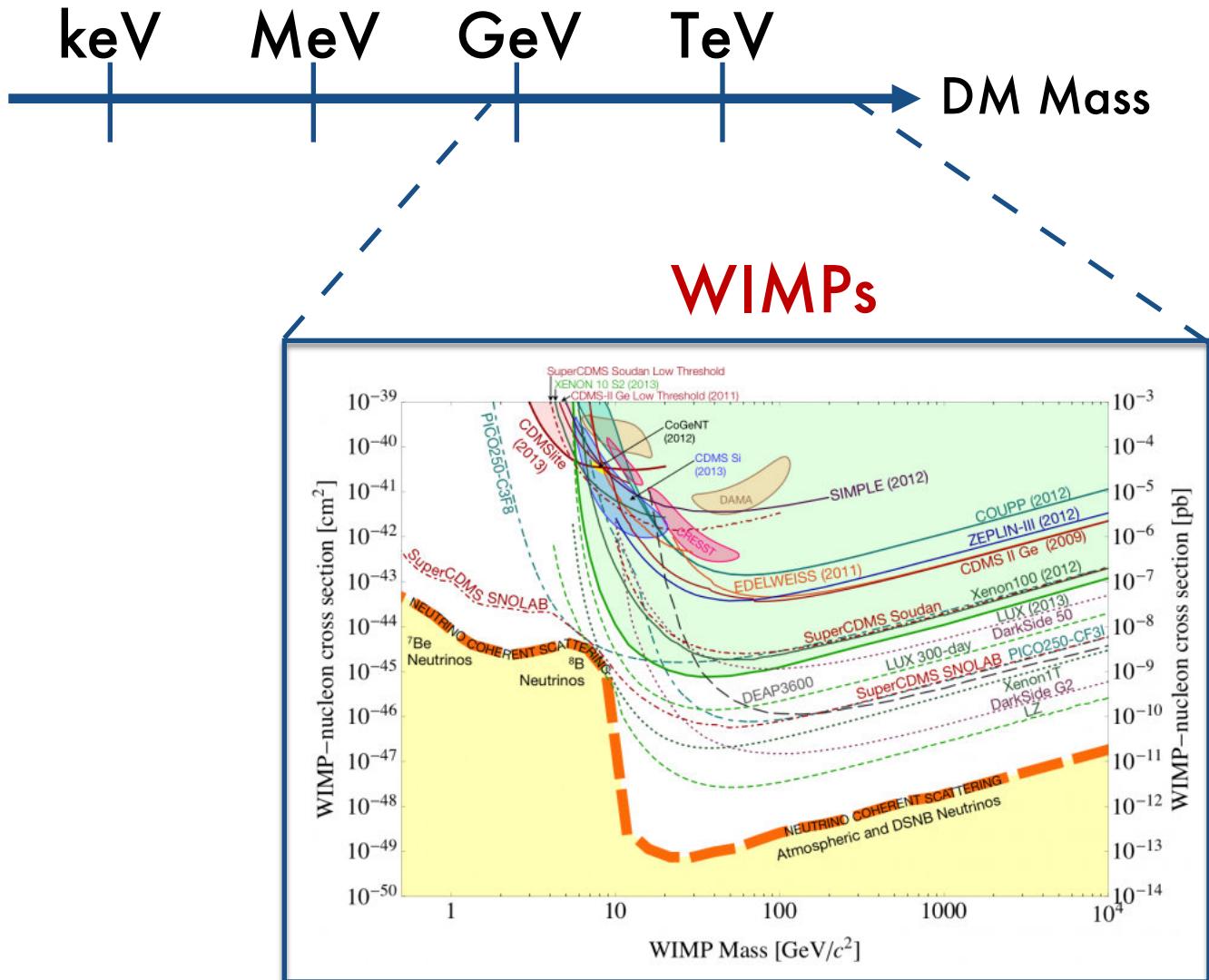
Carlson, Gorchtein, Vanderhaeghen (2016)

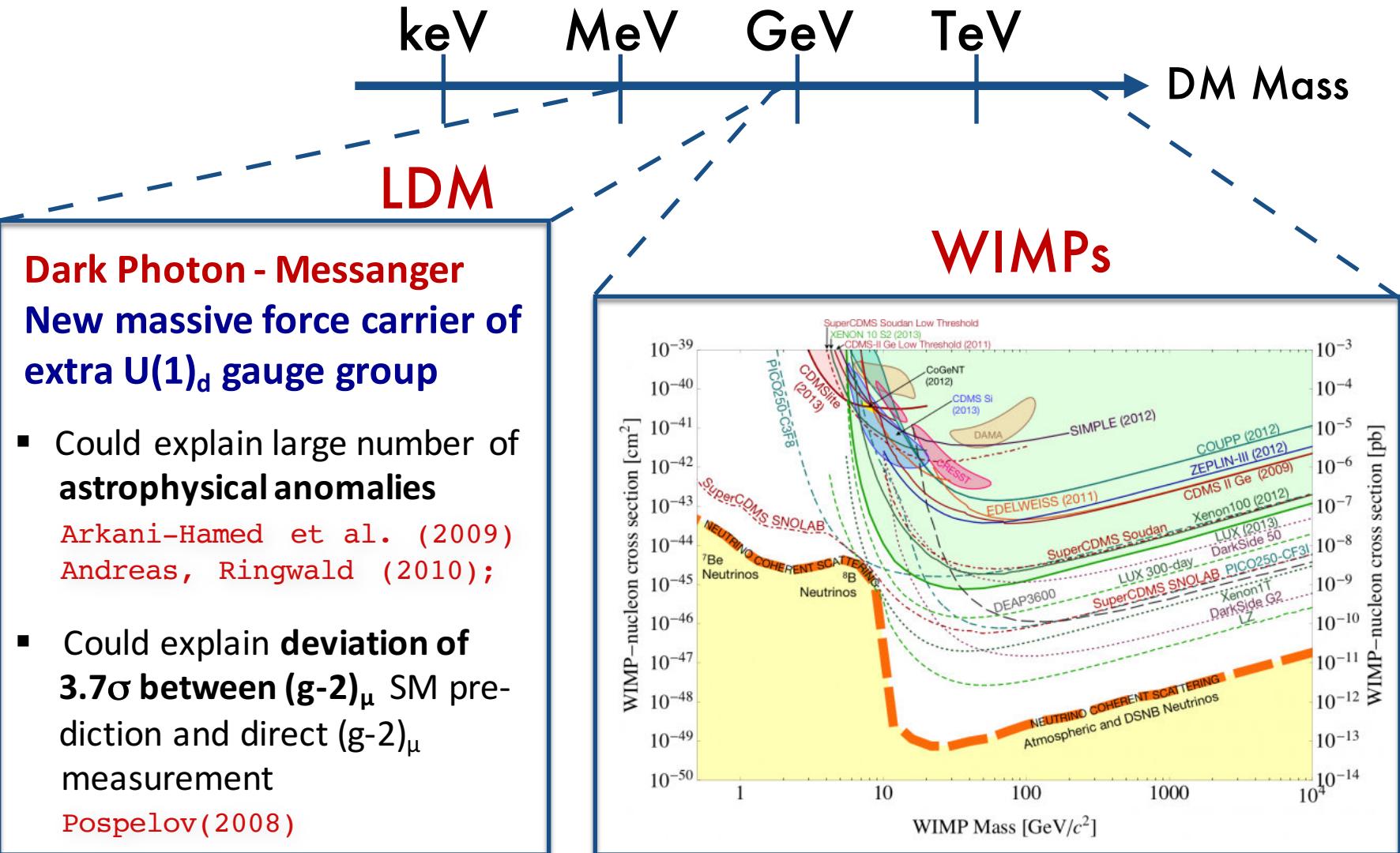


Light Dark Sector Searches



Dark Sector Searches



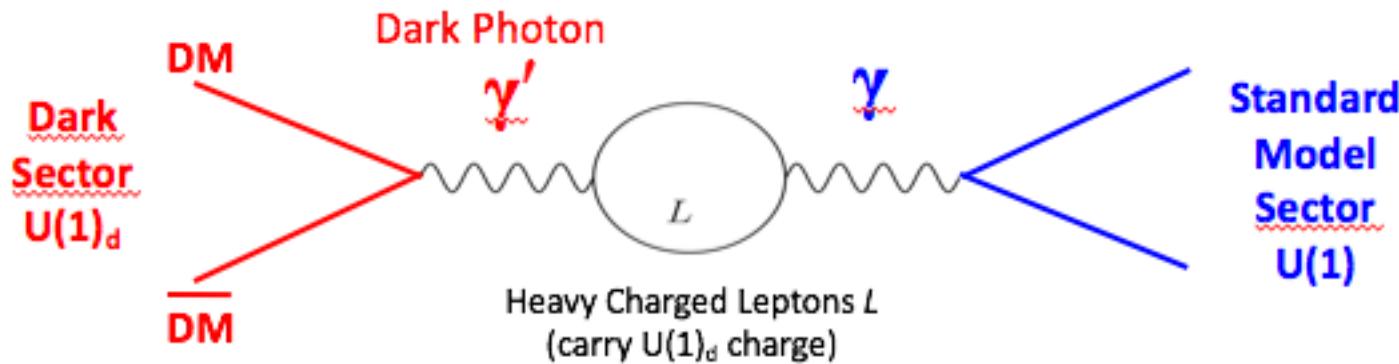


Dark Photon

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

Holdom [1986]

Dark Photon decaying into SM particles – coupling ϵ

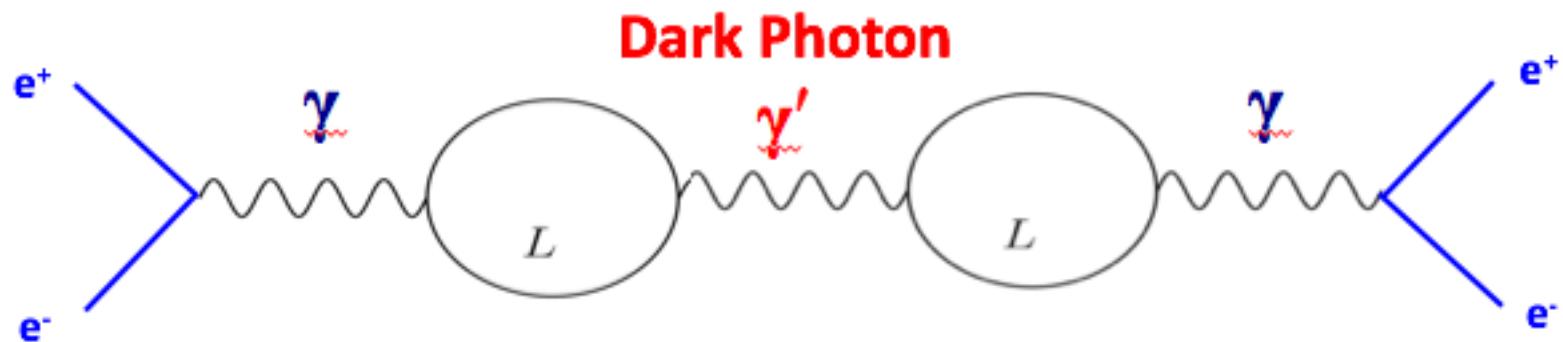


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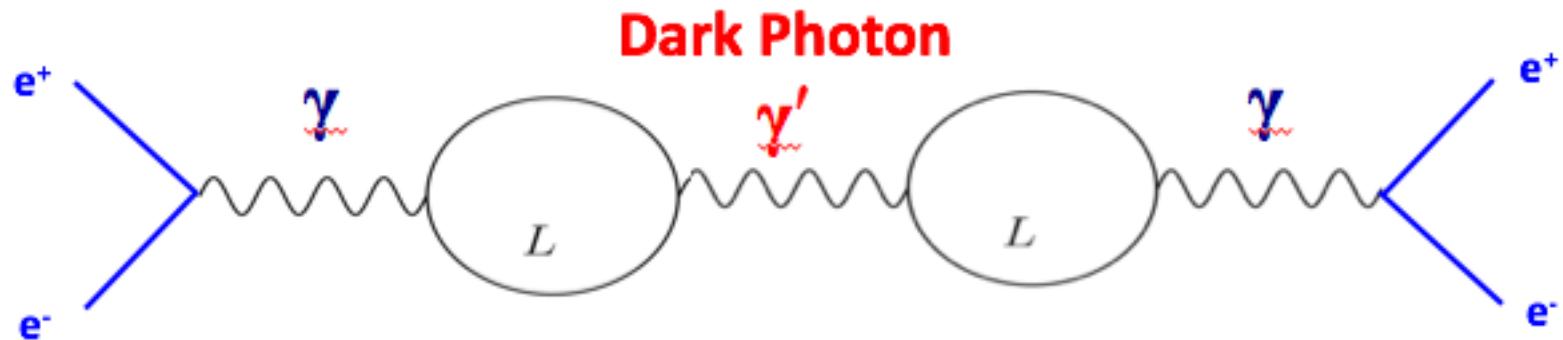


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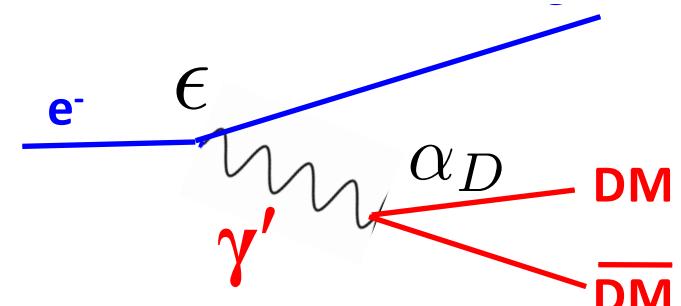


Model 2: $m_{\gamma'} > 2m_{\text{DM}}$

Dark Photon decaying into Dark Matter

→ invisible decay experiments

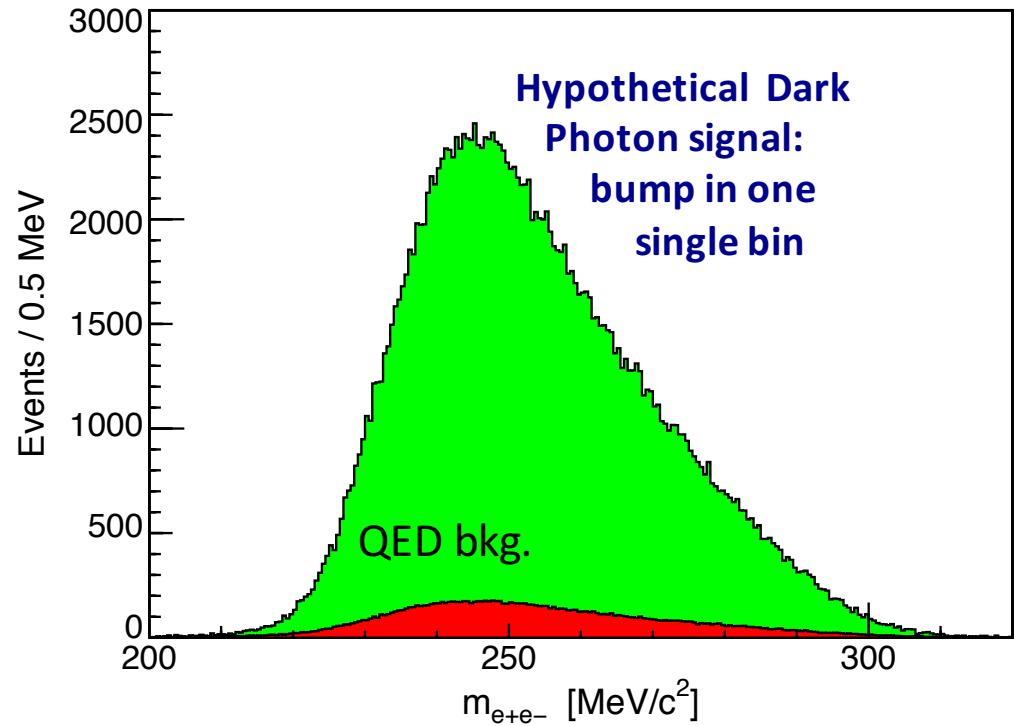
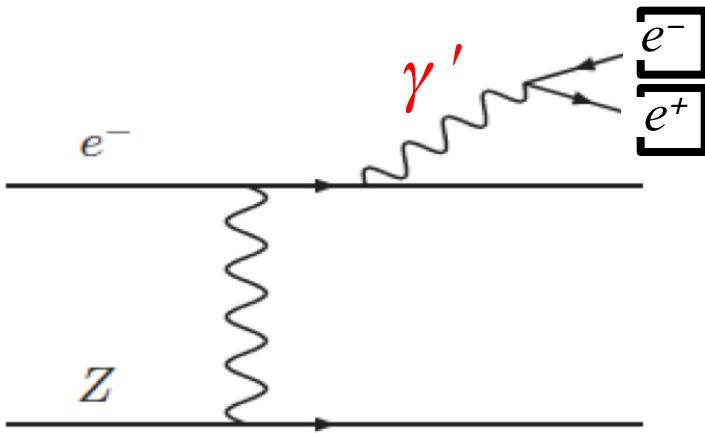
→ LDM detection



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

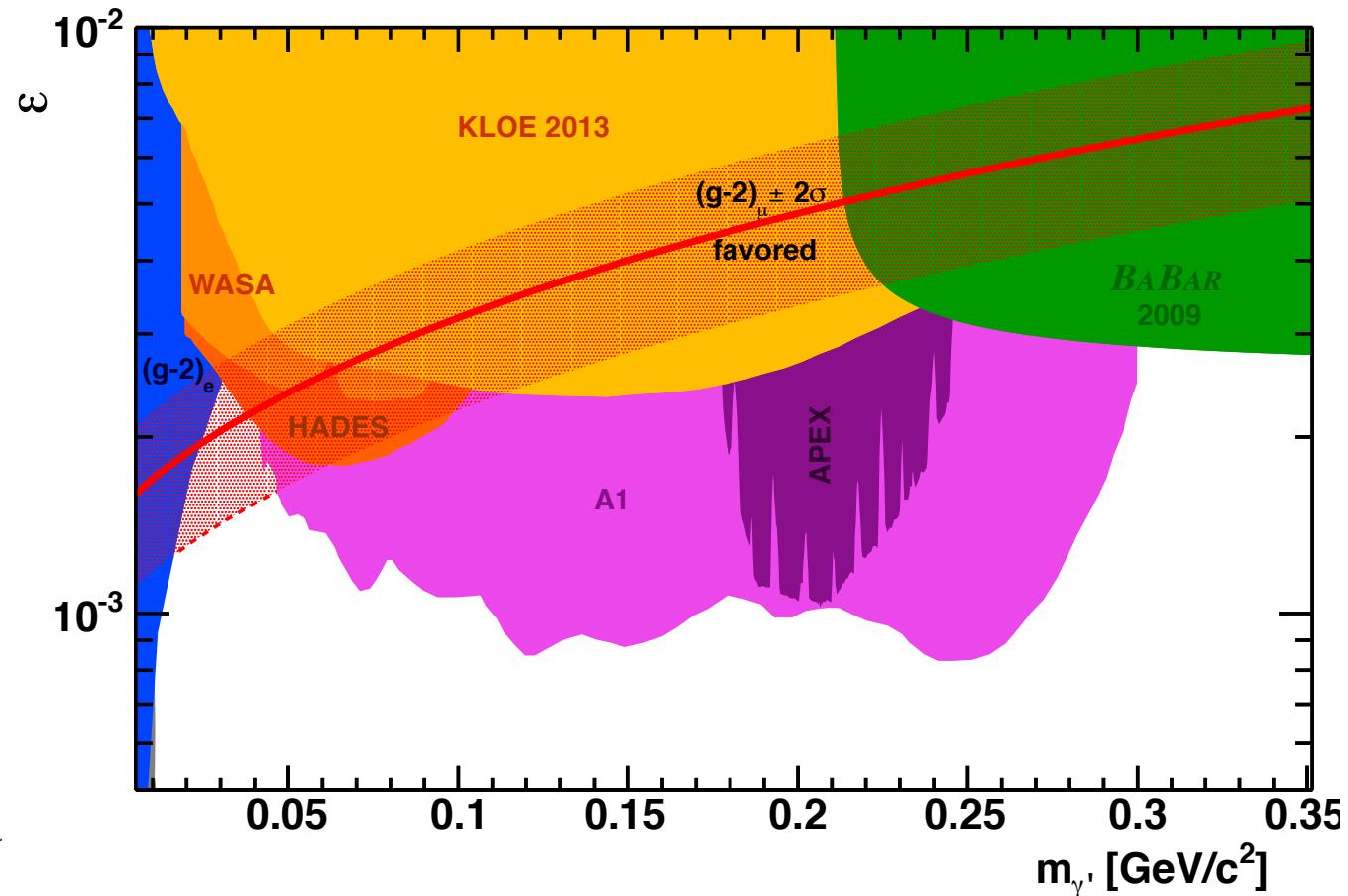
Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search (Bjorken et al.)

Signal process



Results from A1

Merkel et al. [A1]
PRL '11
PRL '14



- E_{beam} 180 - 855 MeV
- 100 μA beam current
- Stack of Ta targets
- 22 kinematic settings
- O(1 month) of beam time

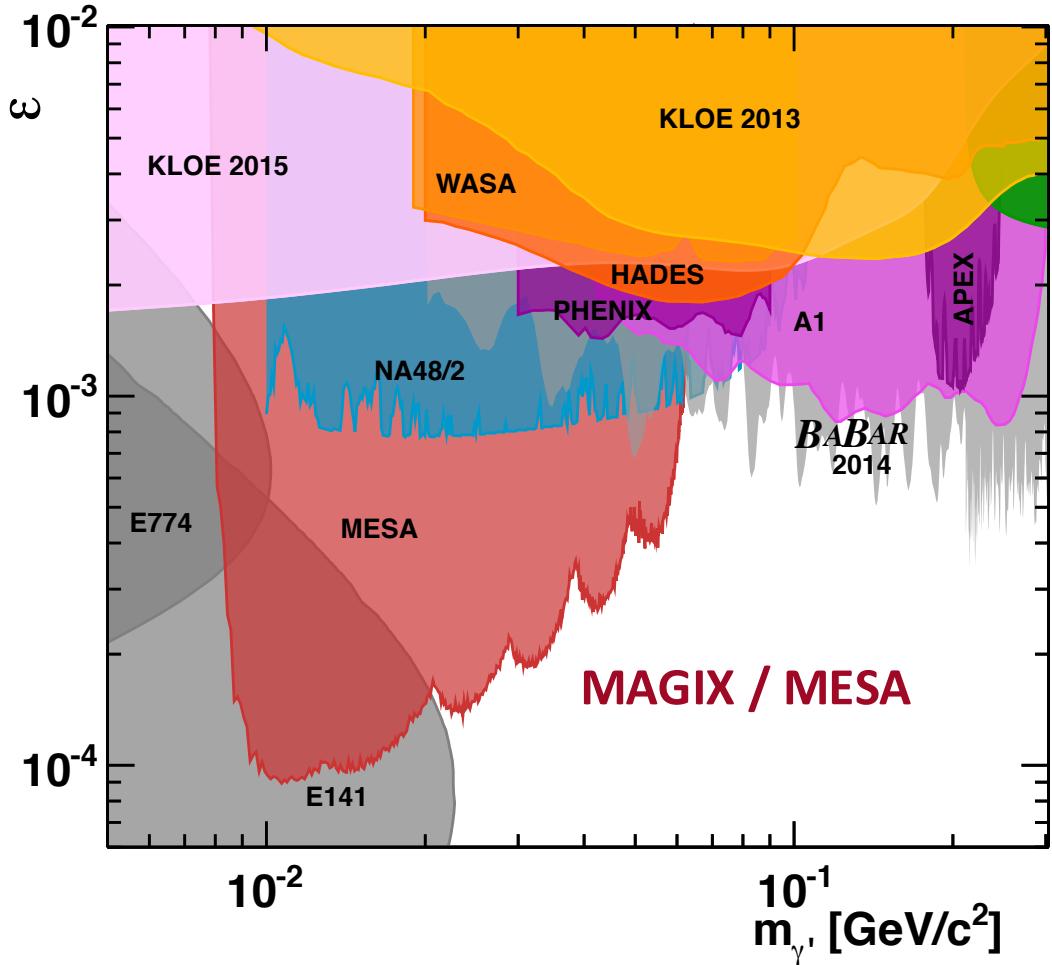
→ at time of publication most stringent
limit ruling out major part of the parameter range motivated by $(g-2)_\mu$

Dark Sector Searches at MAGIX

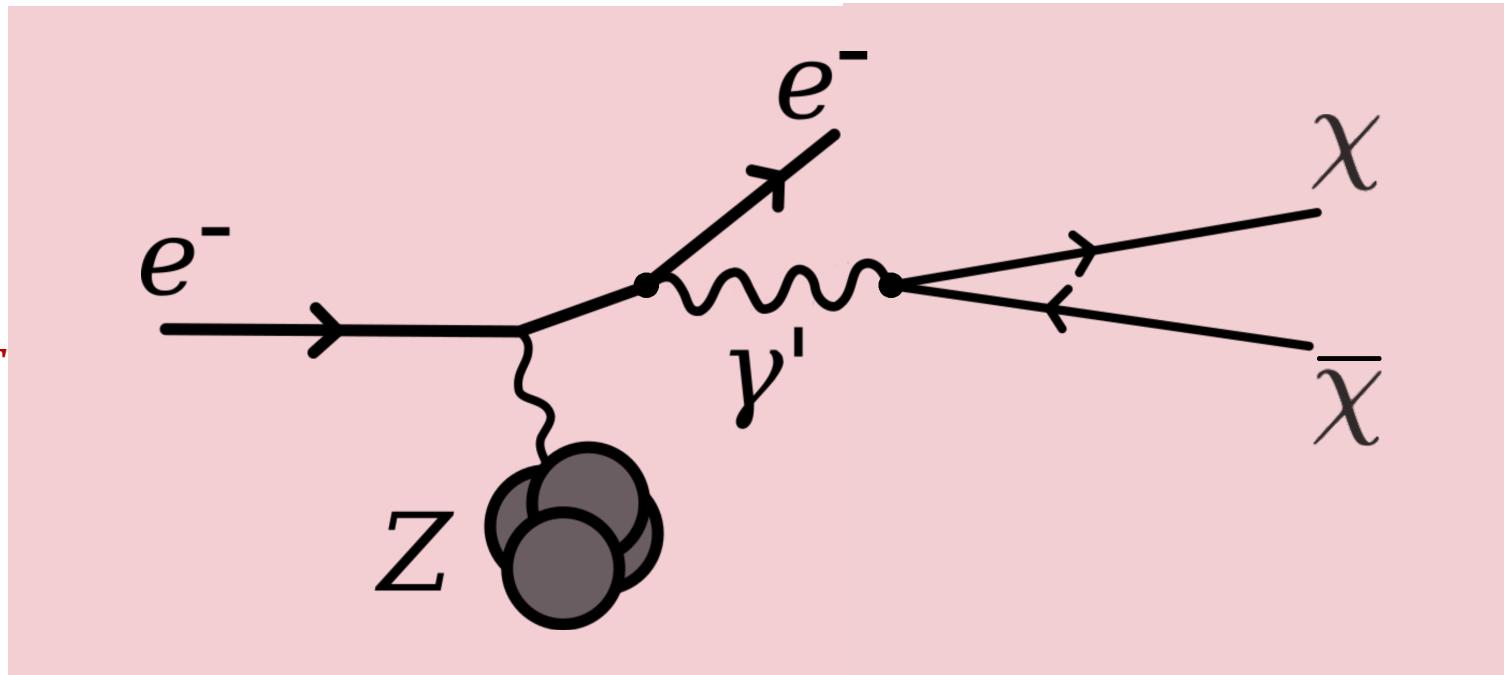


Features:

- Xe gas target
- Luminosity $10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- 6 month of data taking

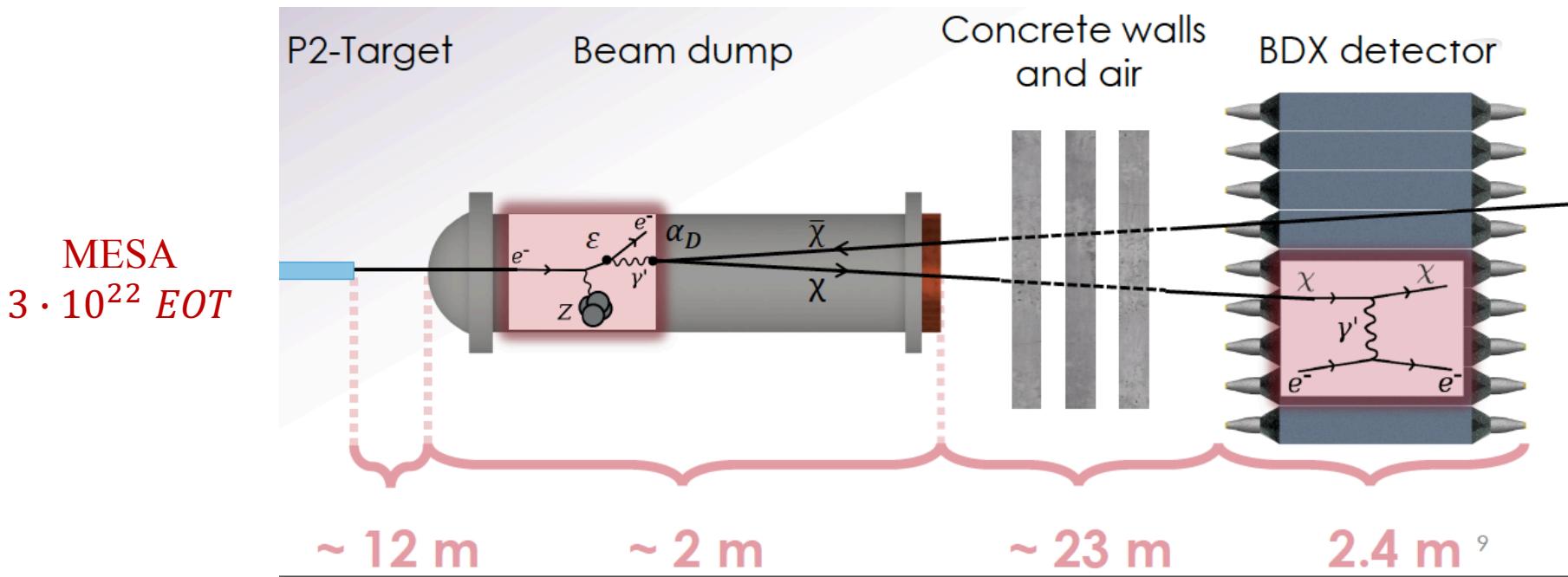


Model 2: $m_{\gamma'} > 2m_{\text{DM}}$



**Electron Scattering (MESA) on Beam Dump
→ Collimated pair of Dark Matter particles !**

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

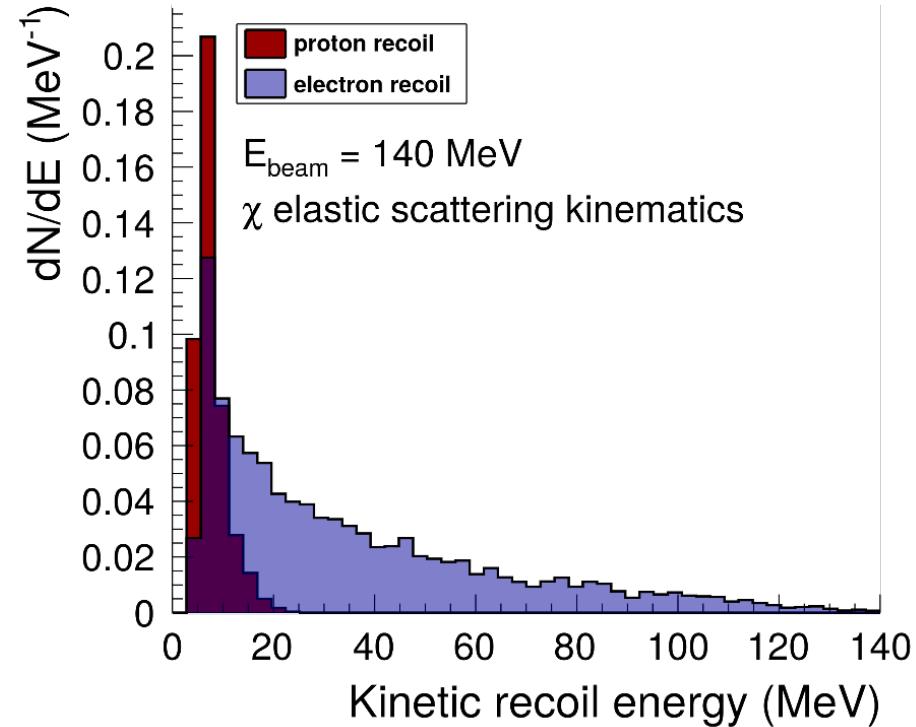
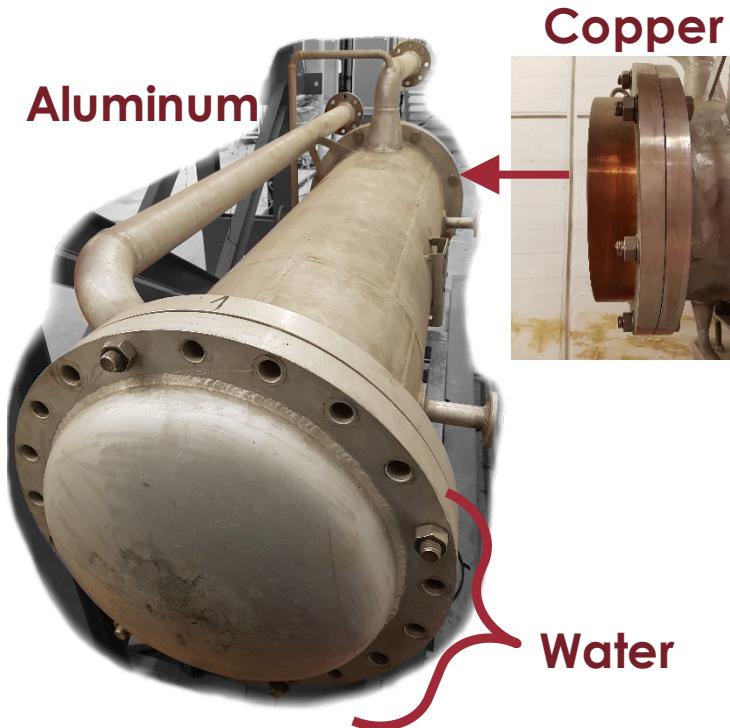


**Electron Scattering (MESA) on Beam Dump
→ Collimated pair of Dark Matter particles !**

Full GEANT4 simulation:

P2 target, beam dump, BDX detector volume, walls etc.

→ LDM interaction with
BDX material (electron recoil)



Detector Concept for BDX @ MESA

Ideal Requirements:

1. Electron Detection > few MeV
2. Large Surface (Acceptance)
3. Large thickness (Int. Prob.)
4. Reliability (long running time)
5. Background rejection
 - Cosmics
 - Natural Backgrounds
 - Beam Backgrounds (Neutrons)



Baseline Concept

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

Detector Concept for BDX @ MESA

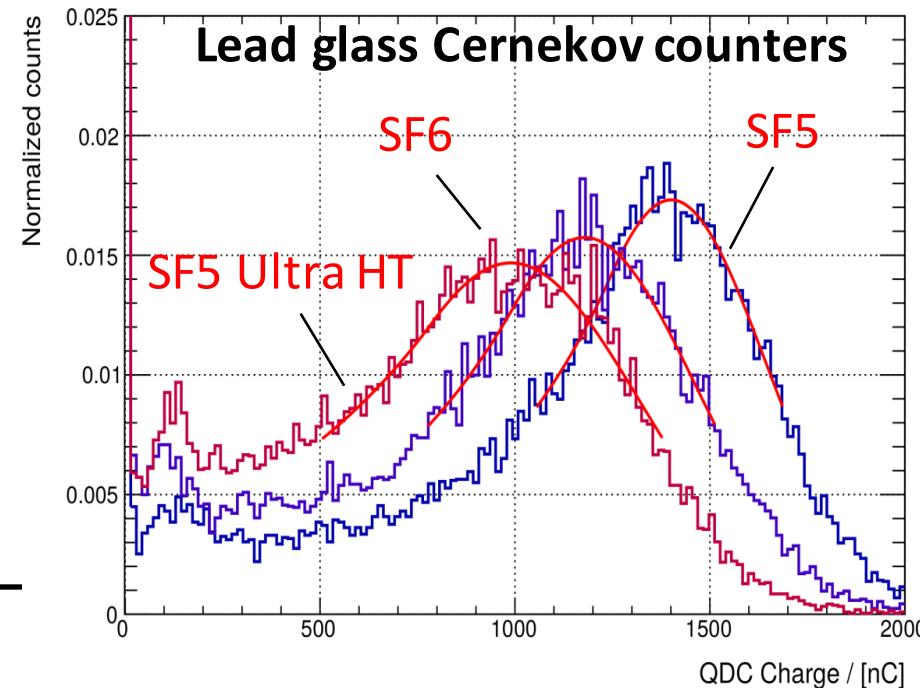
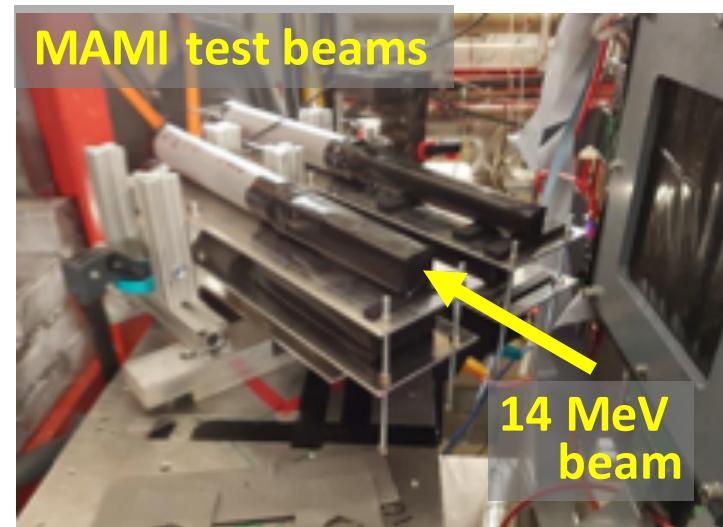
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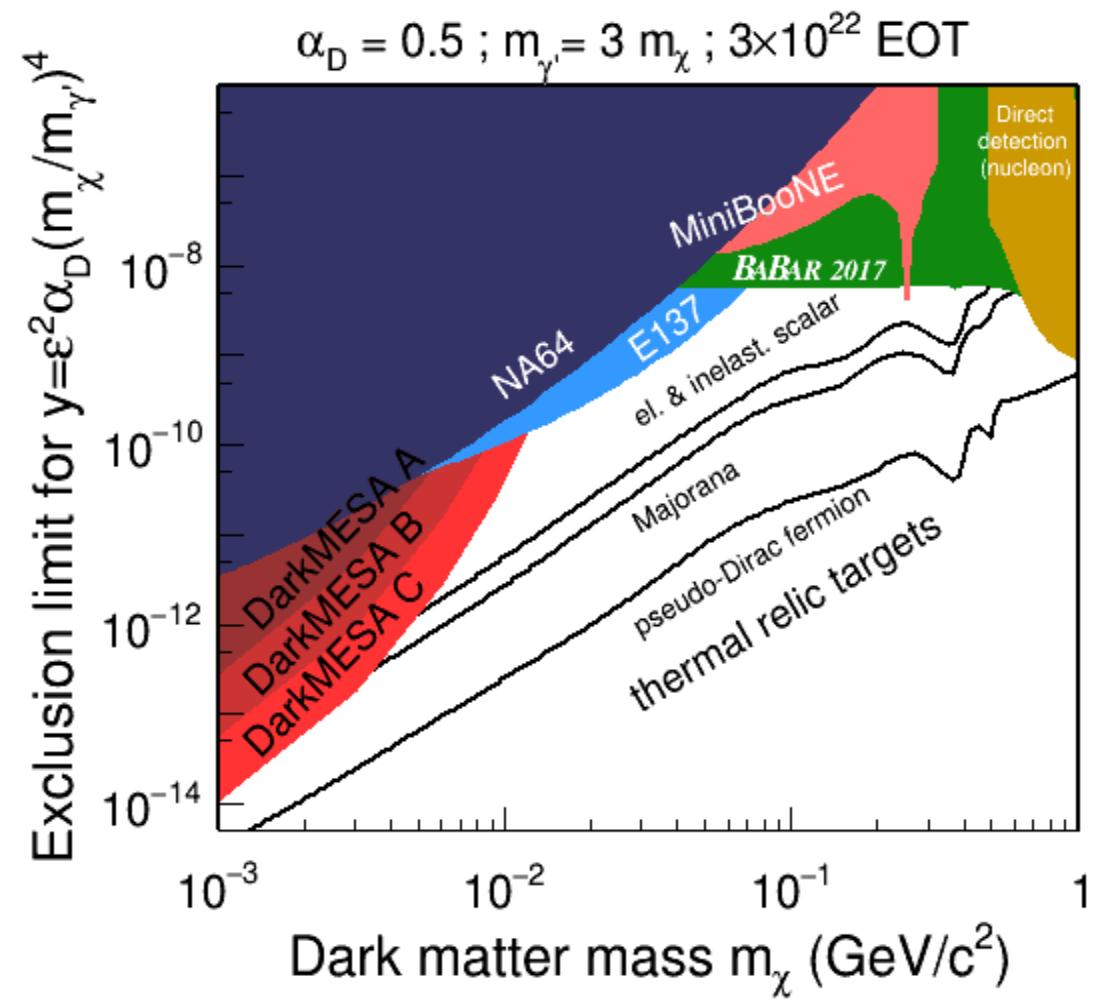
Baseline Concept

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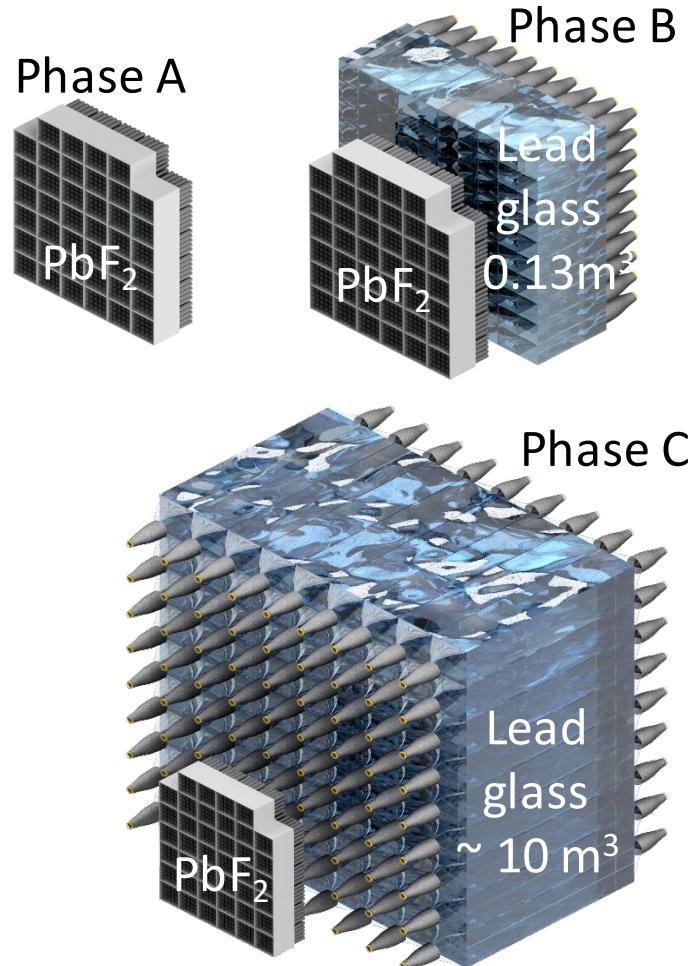


Beam Dump Experiment (BDX) @ MESA

JG|U

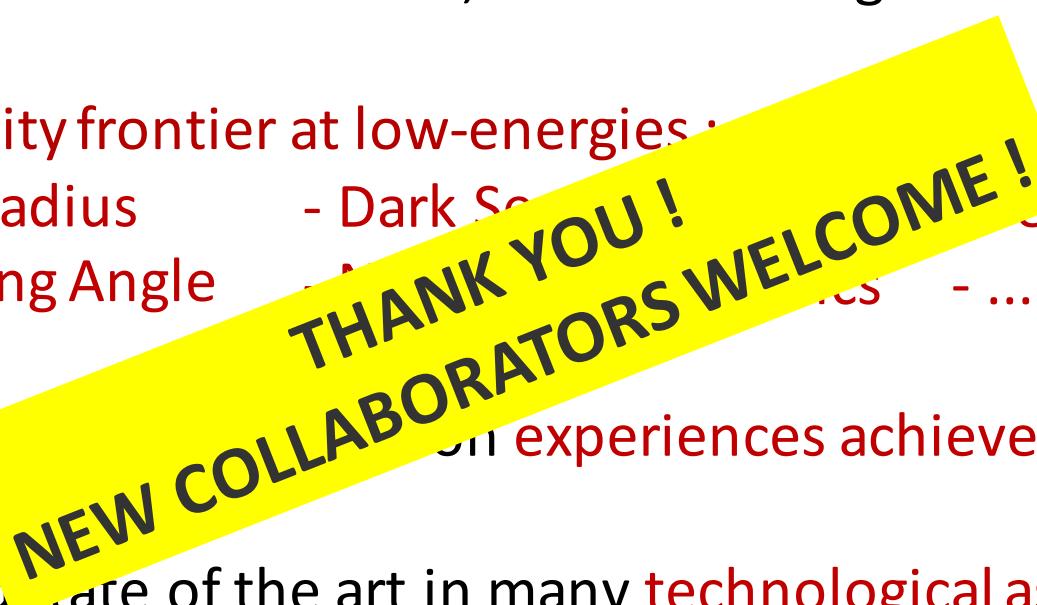


Detector layouts:



- New MESA electron accelerator (increase in intensity $\times 10$)
under construction at Mainz, commissioning in 2022
 - The intensity frontier at low-energies :
 - Proton Radius - Dark Sector - Few Body Physics
 - EW Mixing Angle - Nuclear Astrophysics -
 - Projection for MESA based on experiences achieved at MAMI
 - Go beyond state of the art in many technological aspects:
ultralight detectors, beam polarization, low energy detection, ...
 - Competitive programme in nuclear, hadron, and particle physics
-

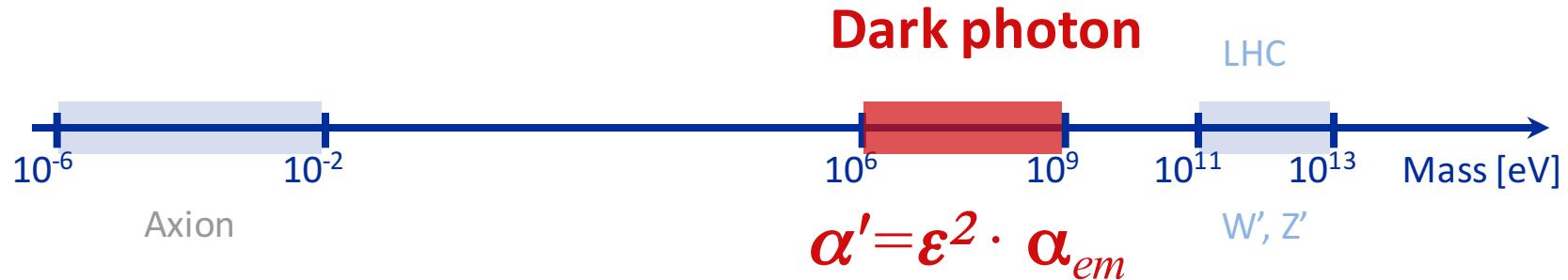
Conclusions

- New MESA electron accelerator (increase in intensity $\times 10$) under construction at Mainz, commissioning in 2022
 - The intensity frontier at low-energies :
 - Proton Radius
 - EW Mixing Angle
 - Dark ...
 - ...
 - Projected on experiences achieved at MAMI
 - Go beyond state of the art in many technological aspects: ultralight detectors, beam polarization, low energy detection, ...
 - Competitive programme in nuclear, hadron, and particle physics
- 

BACKUP

Dark Photon

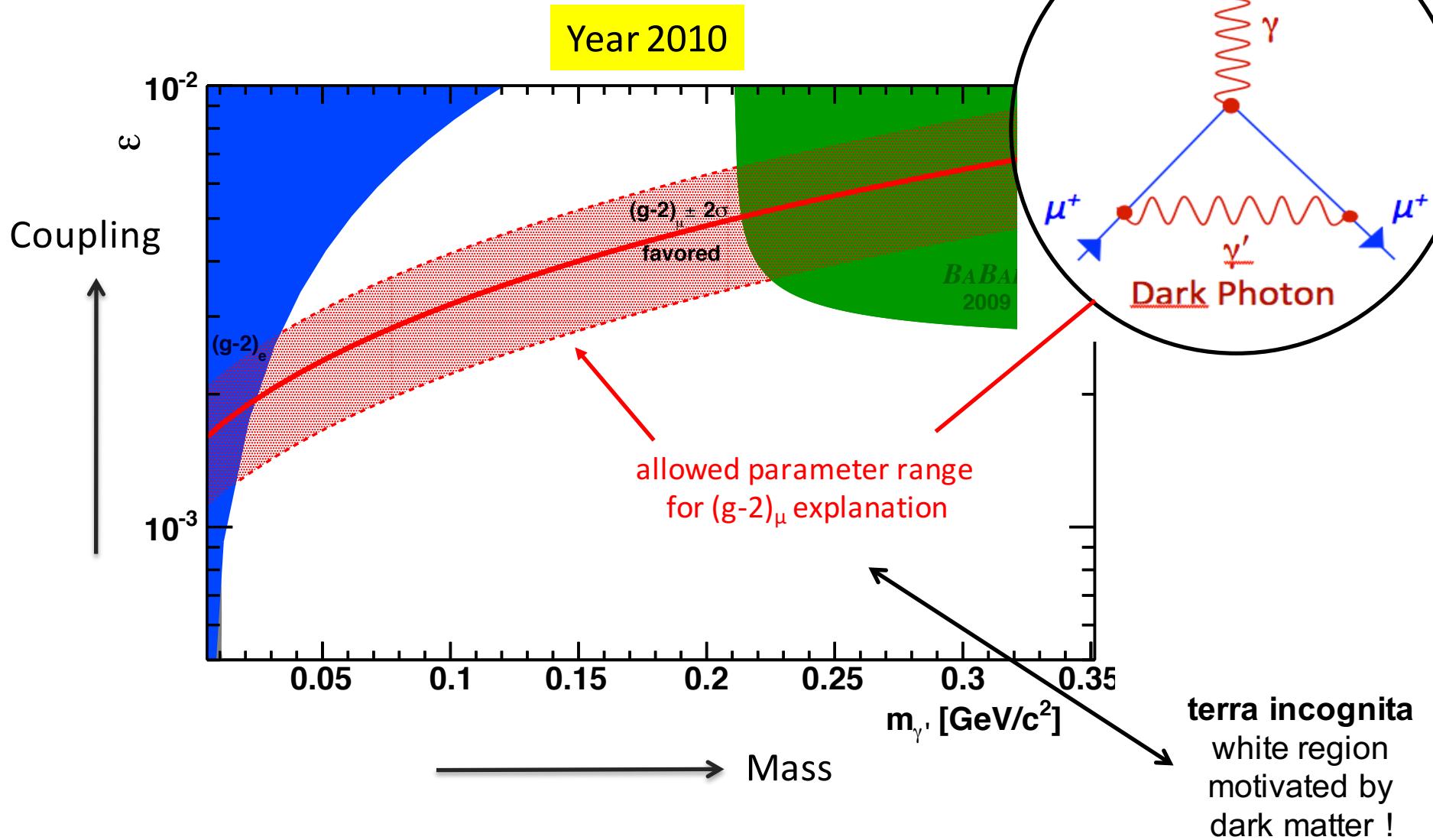
New massive force carrier of extra $U(1)_d$ gauge group;
predicted in almost all string compactifications



Search for the $O(\text{GeV}/c^2)$ mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
 $\text{Arkani-Hamed et al. (2009)}$
 $\text{Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)}$
- Could explain presently seen **deviation of 3.6σ between $(g-2)_\mu$**
 Standard Model prediction and direct $(g-2)_\mu$ measurement
 Pospelov (2008)

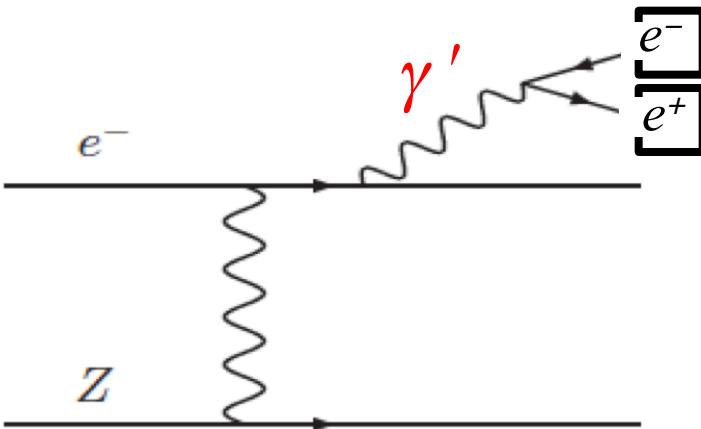
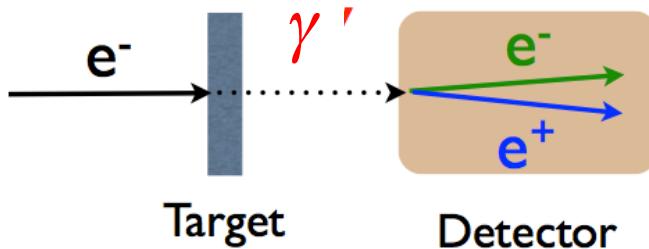
Dark Photon Status in 2010



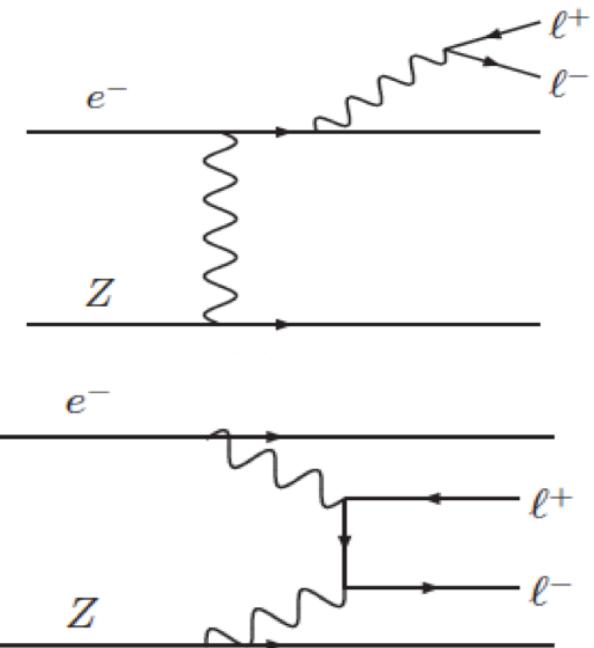
Results from A1

Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search
Bjorken et al. (2009)

Signal process



Background QED processes

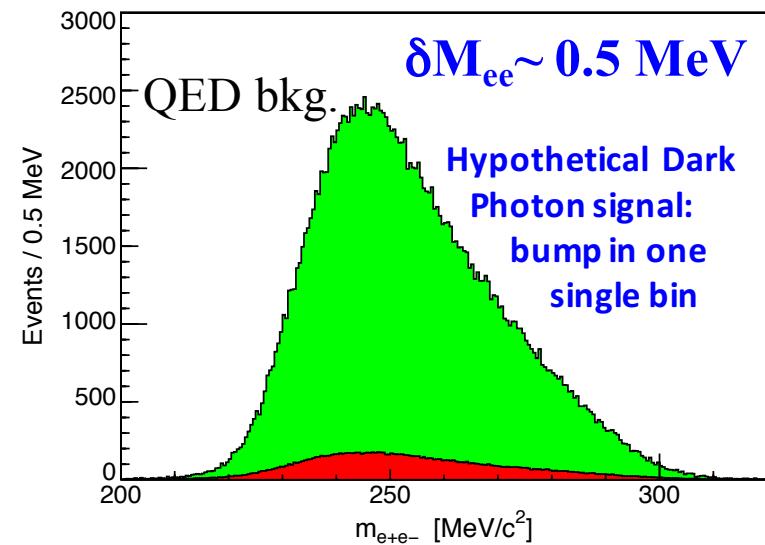
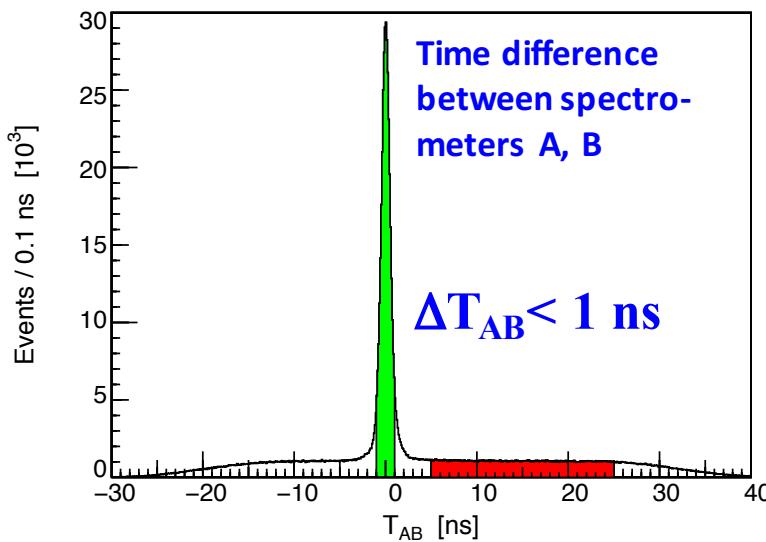


Dark Photon Search @ A1



Features 2010 pilot run (4 days)

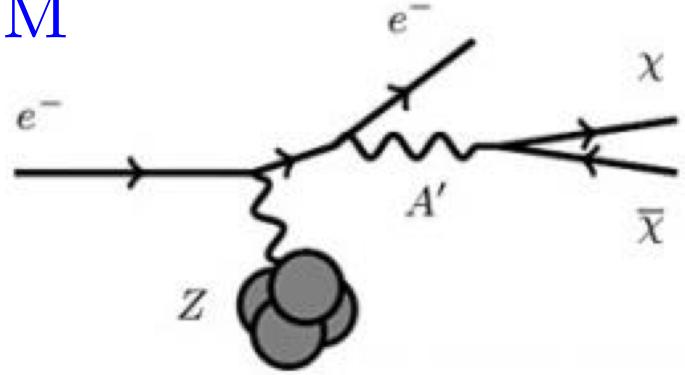
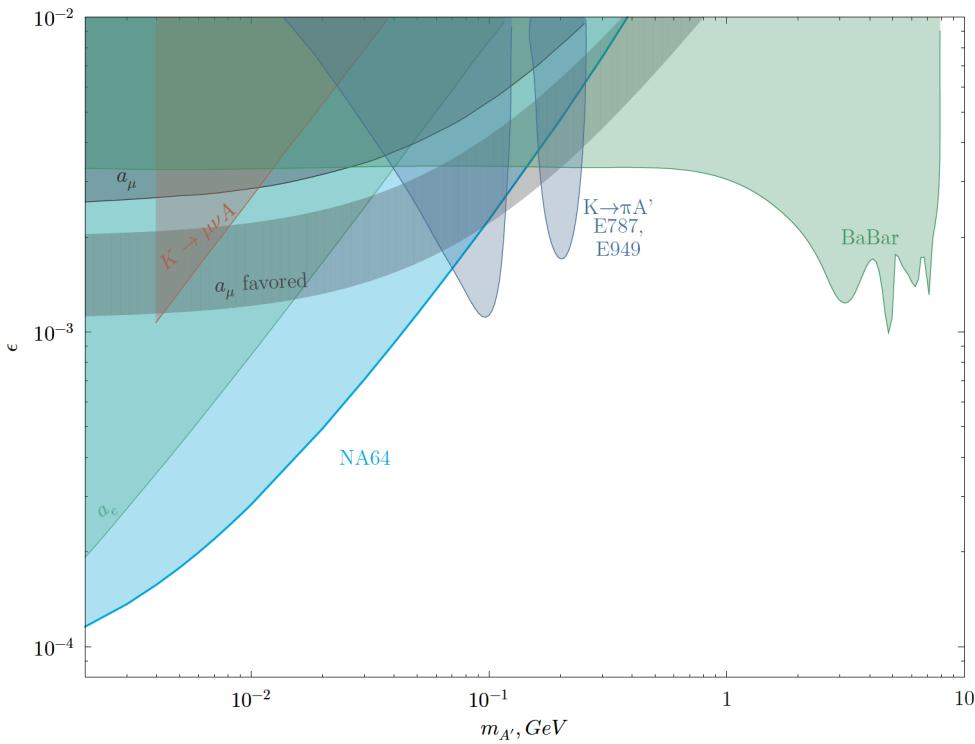
- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current $\sim 100 \mu\text{A}$ \rightarrow Luminosity $\sim 10^{39} \text{ cm}^{-2}\text{s}^{-1}$
- Kinematic configuration:
 - complete energy transfer to γ' boson
 - symmetric e^- and e^+ momenta
- Cerenkov detector for electron/positron identification



Invisible Decay of the Dark Photon

Model 2: Dark Photon coupling to light Dark Matter
(invisible decay!)

$$m_{\gamma'} > 2m_{\text{DM}}$$



- Dark Matter particle not seen
- Few constraints
- Could again explain $(g-2)_\mu$

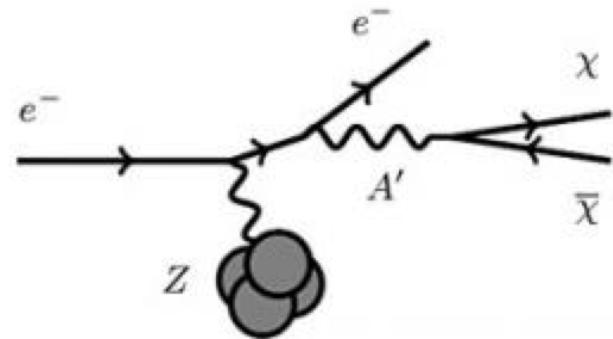
→ Missing energy / mass
→ Search for Dark Matter particle directly using dedicated low-background detectors

Invisible Dark Photon Decays

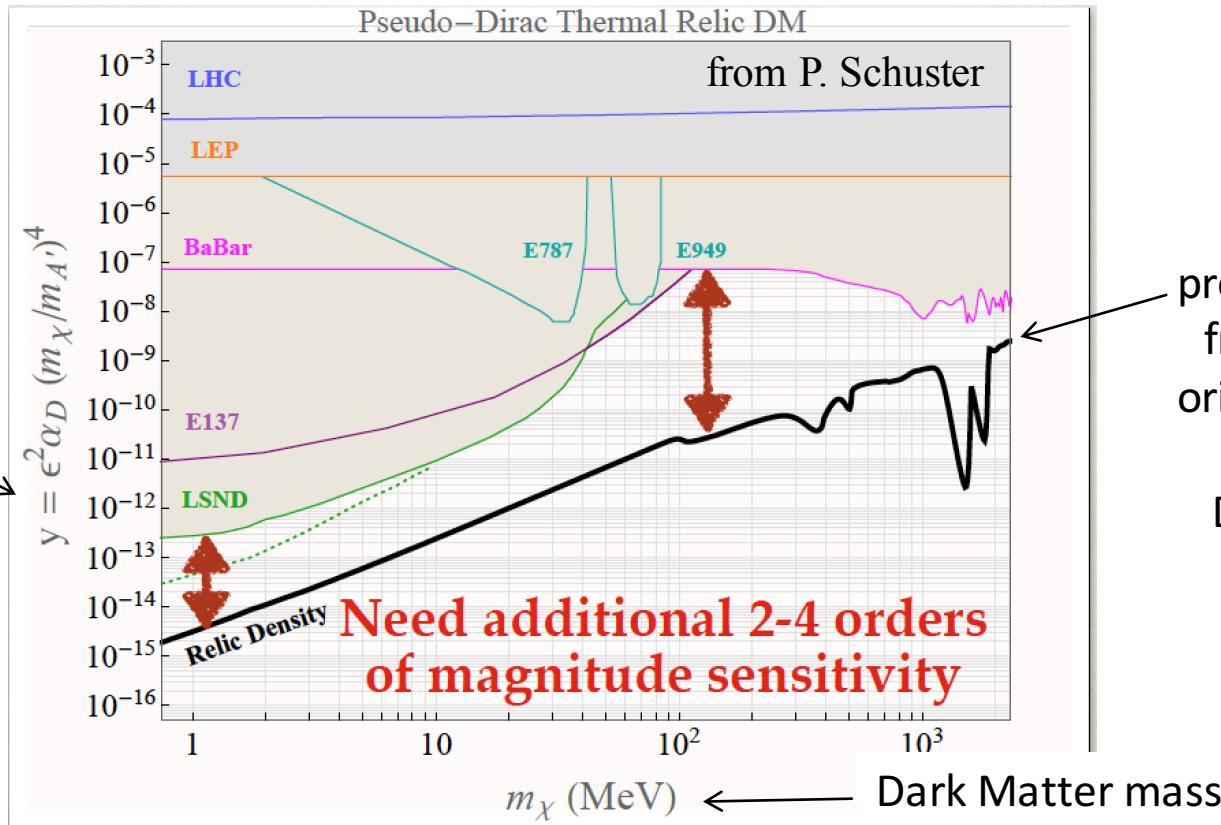
Model 2:

Dark Photon coupling to light Dark Matter (invisible!)

Focus of now-days interest, proposals for SLAC, LNF, CERN,

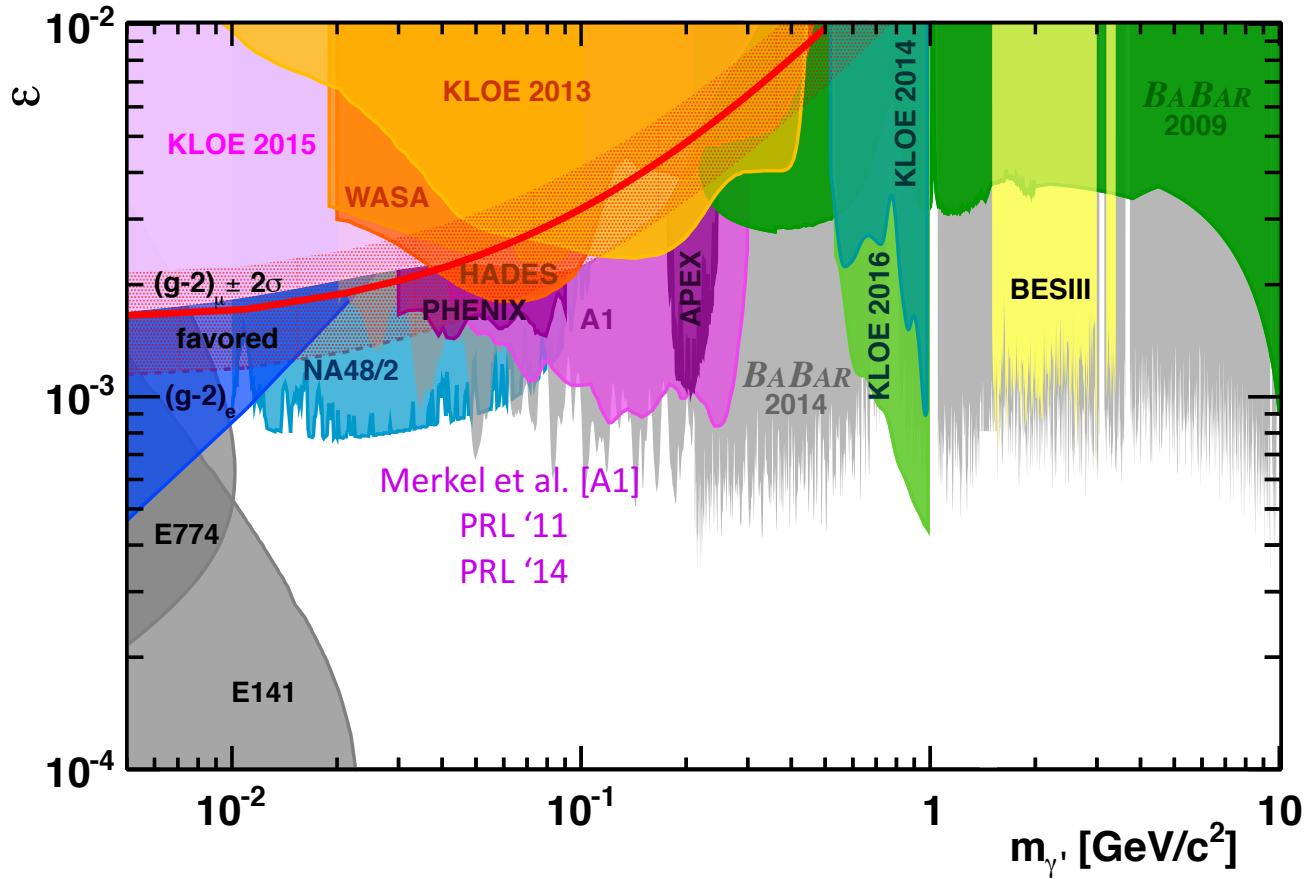


dimensionless
quantity
 $\sim (m_\chi/m_{A'})^2$



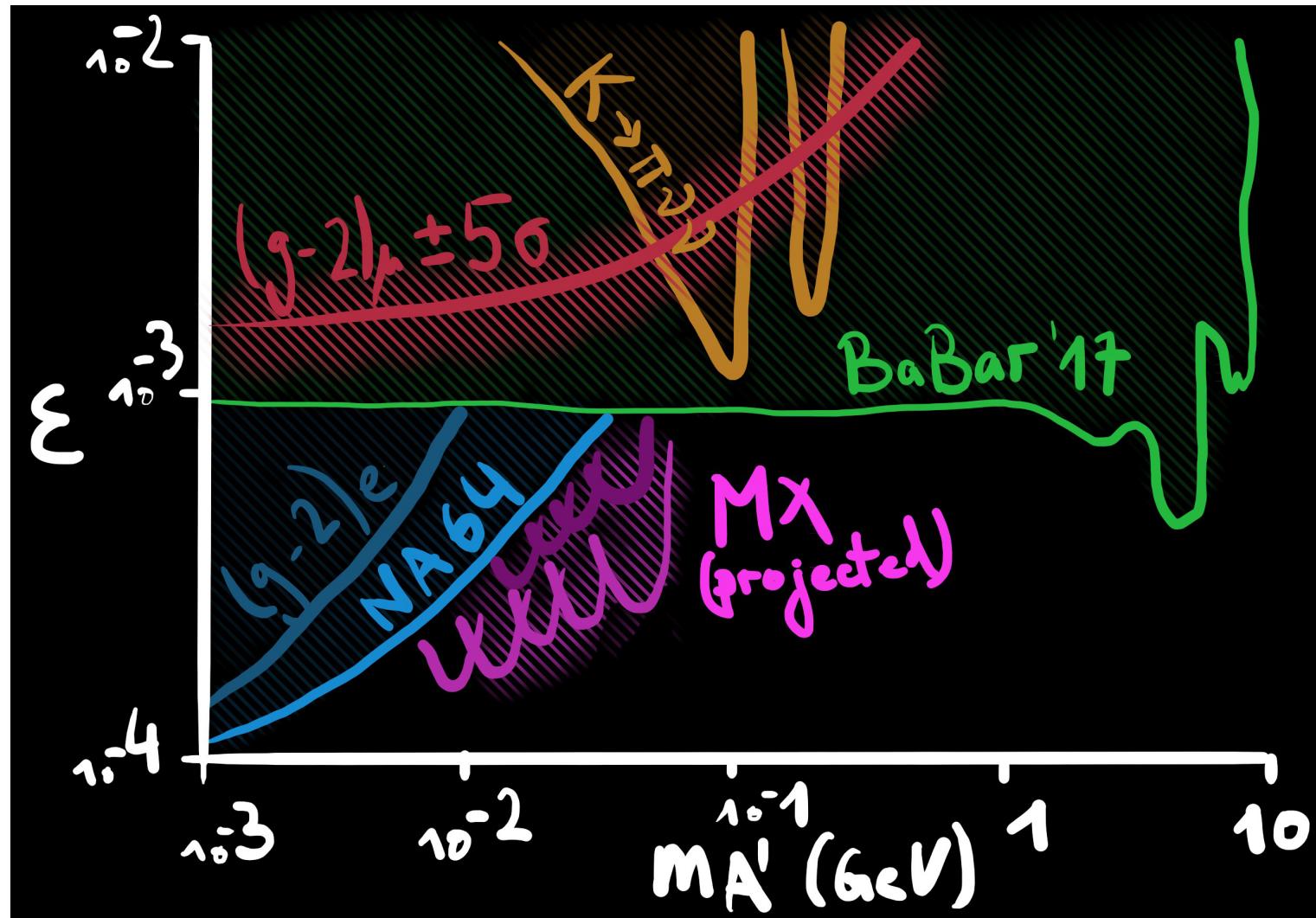
Results from A1/MAMI

Year 2017

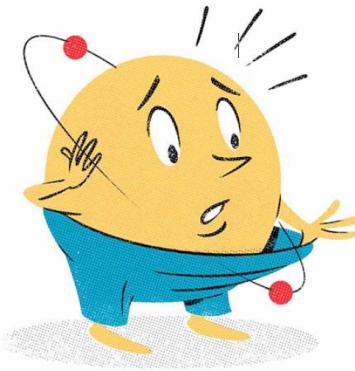
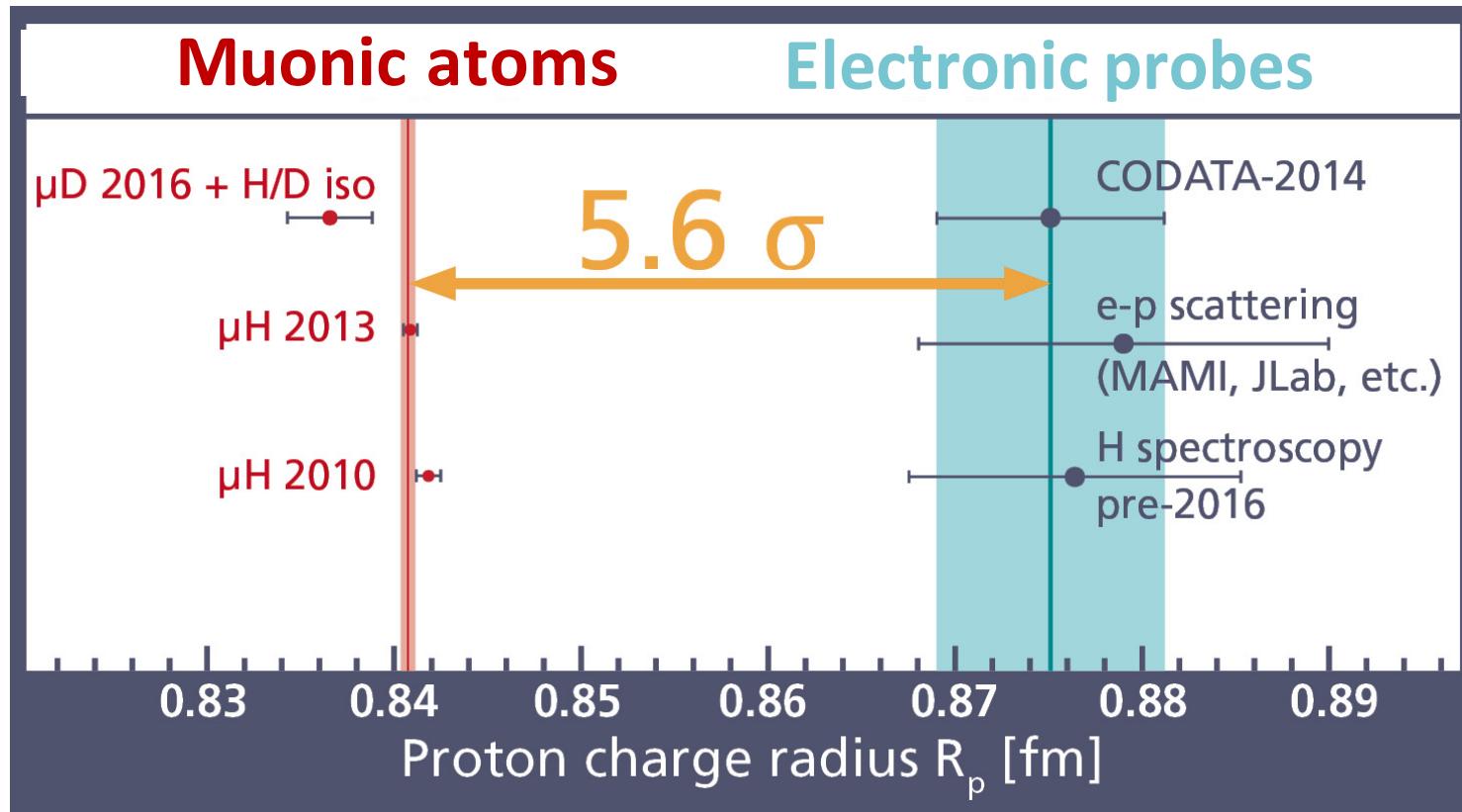


→ at time of publication most stringent
limit ruling out major part of the parameter range motivated by $(g-2)_{\mu}$

MAGIX Invisible Dark Photon Decay



The Proton Radius Puzzle



EM Form Factors of the Proton

Elastic form factors in ep scattering:

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

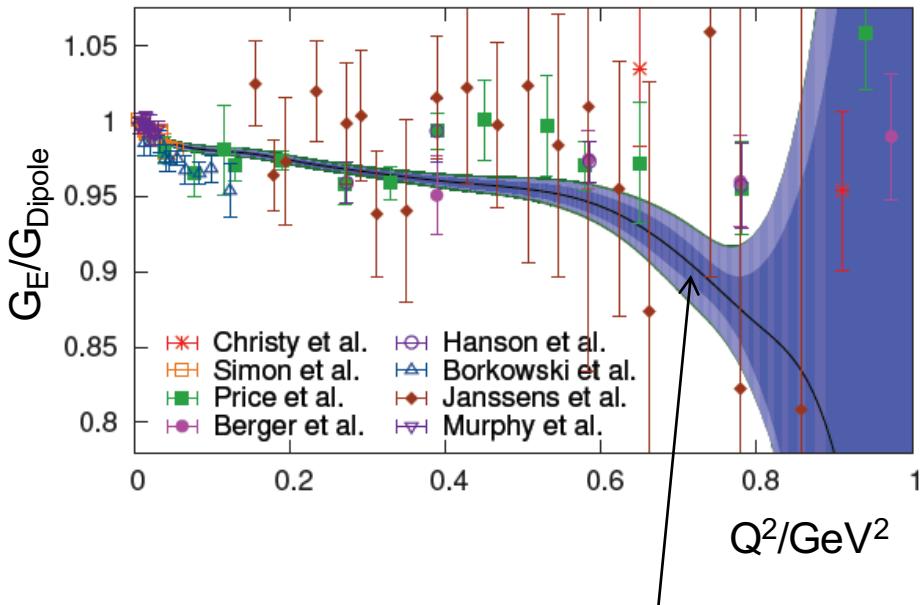
$$\varepsilon = \left(1 + 2(1+\tau) \tan^2 \frac{\theta_e}{2} \right)^{-1}$$

$$\tau = \frac{Q^2}{4m_p^2}$$

G_E : spatial electric charge distribution

G_M : distribution of magnetic moments

Super-Rosenbluth measurement



Mainz measurement
average of all fit models
with uncertainties

Proton charge radius:

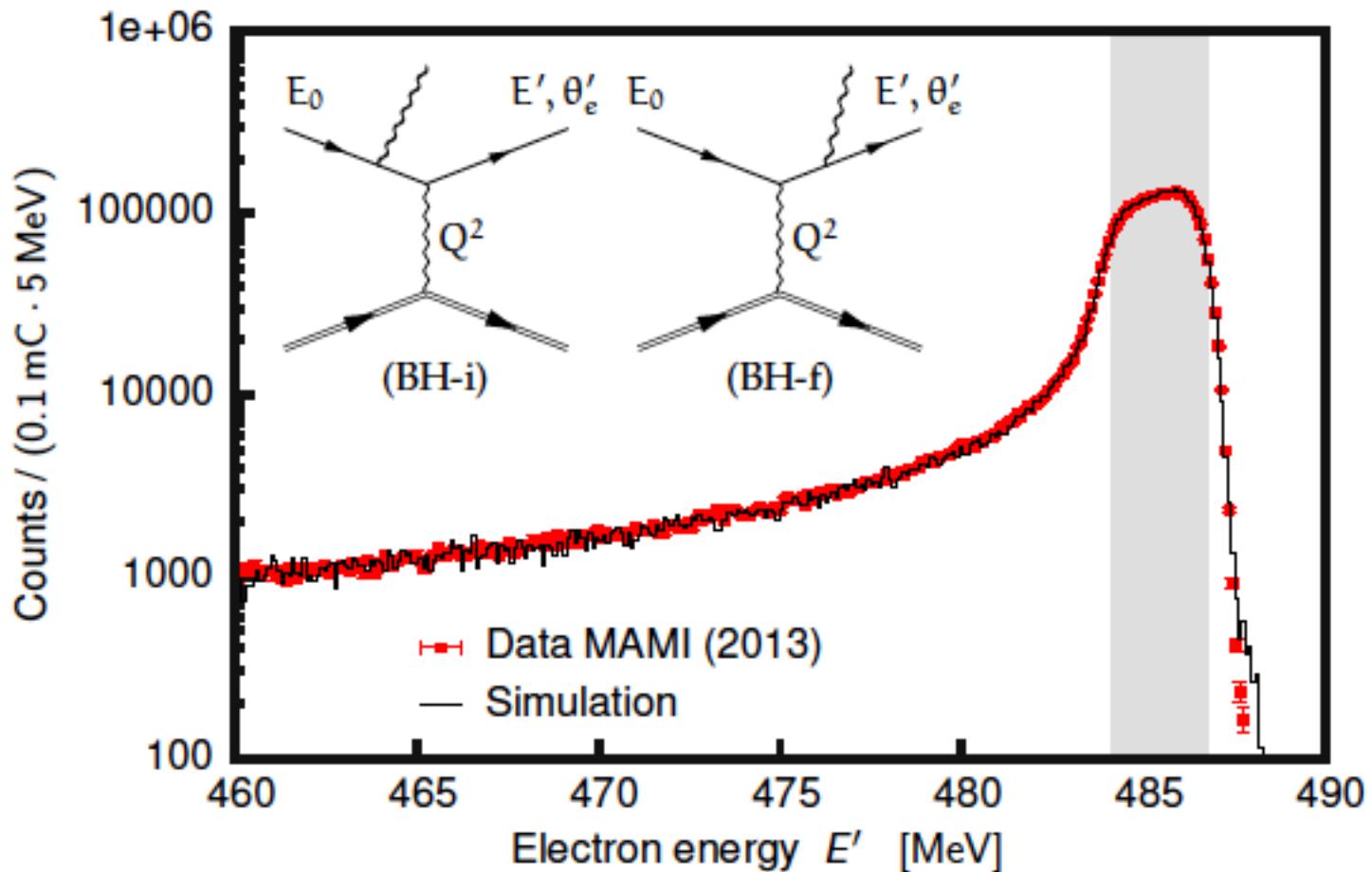
$$\langle r_{E/M}^2 \rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \left. \frac{dG_{E/M}(Q^2)}{dQ^2} \right|_{Q^2=0}$$

PRL10 (A1): $\langle r_E \rangle = 0.879(8) \text{ fm}$

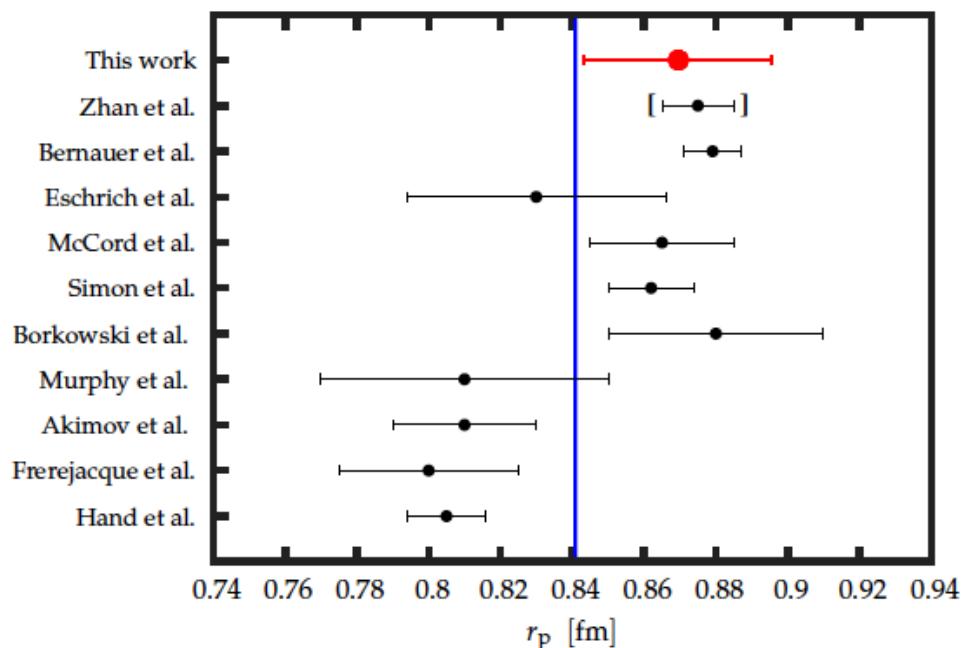
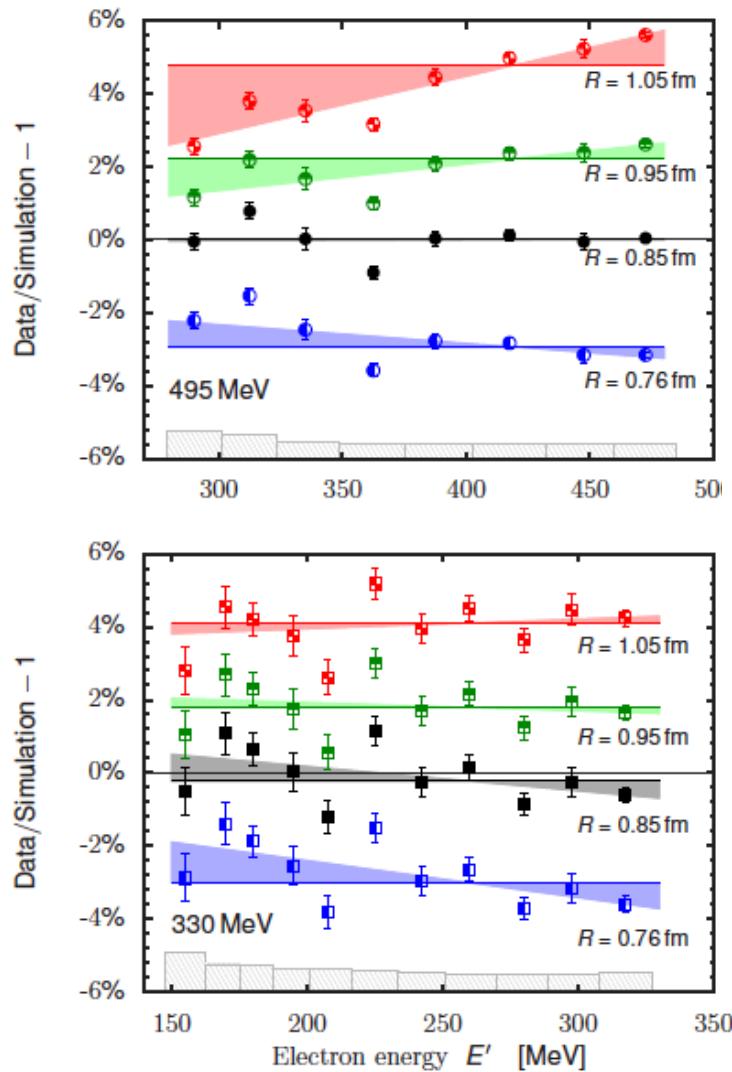
PRL '10, 242001: Bernauer et al.
PRC '14 015206: Bernauer et al.



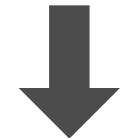
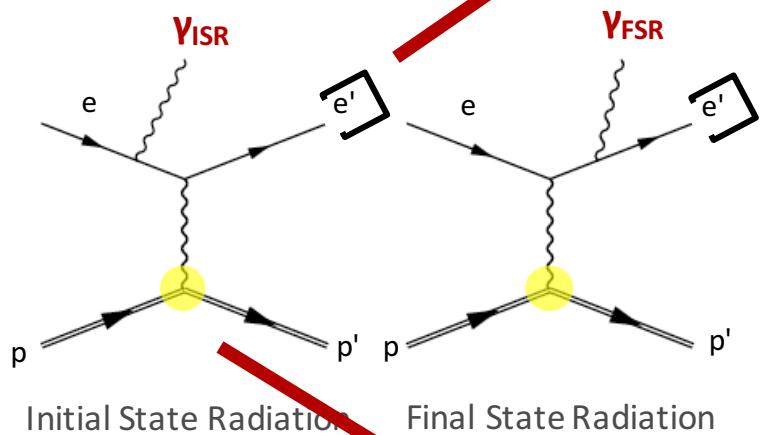
EM Form Factors of the Proton (ISR)



EM Form Factors of the Proton (ISR)



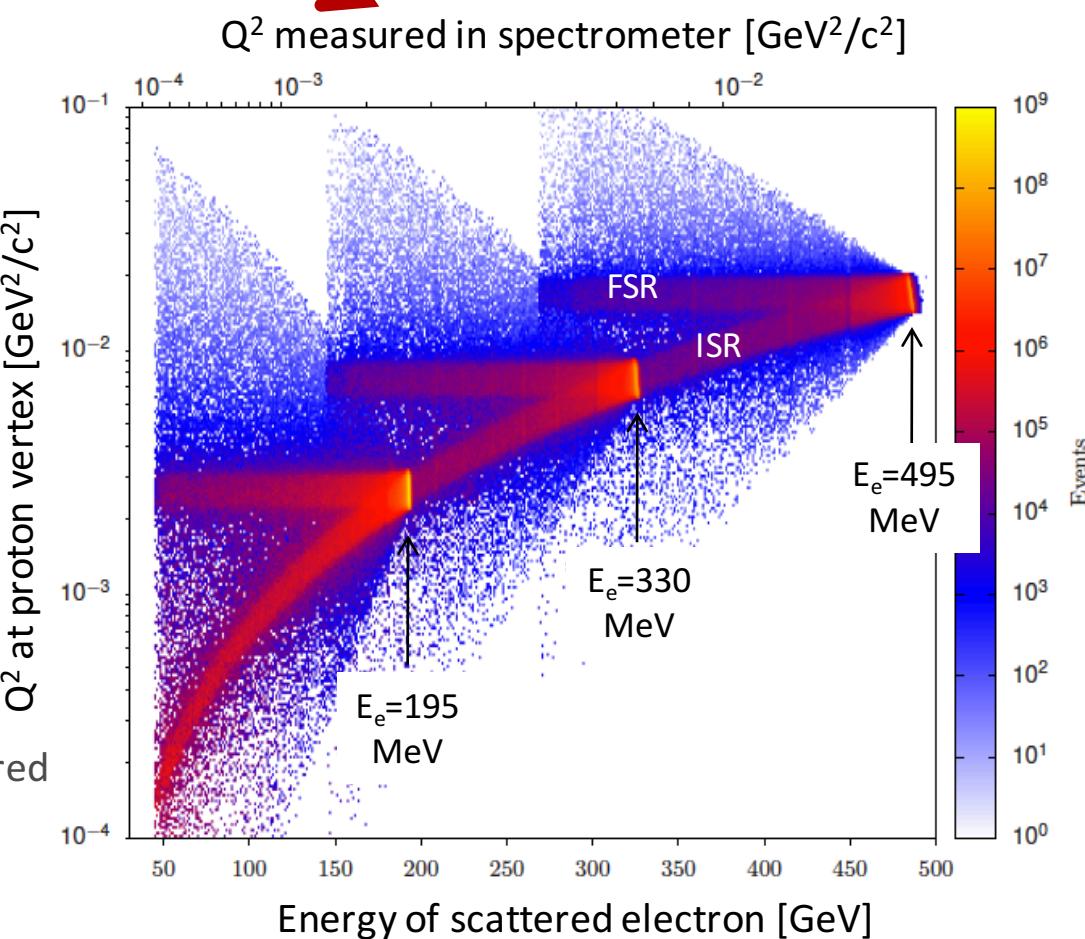
ISR Measurement of EM Form Factors



Strategy:

- Very low values of Q^2 by using ISR event
- Measure momentum spectrum of scattered electron
- Needs very good understanding of QED radiative corrections and FSR

→ Access low Q^2 values down to 2×10^{-4}



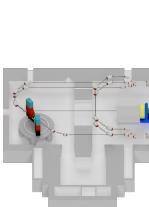
Mainz Proton Radius Programme



- Proton FF (repeat Bernauer) measurement with gas jet target (2019), ISR measurement as well
- TPC detector (PNPI St. Petersburg) measuring proton recoil (2020)
- Deuteron FF measurement (result expected 2018)
- A2 programme on proton polarizabilities (result expected 2019) to reduce two-photon correction / uncertainty of μ H results / PSI



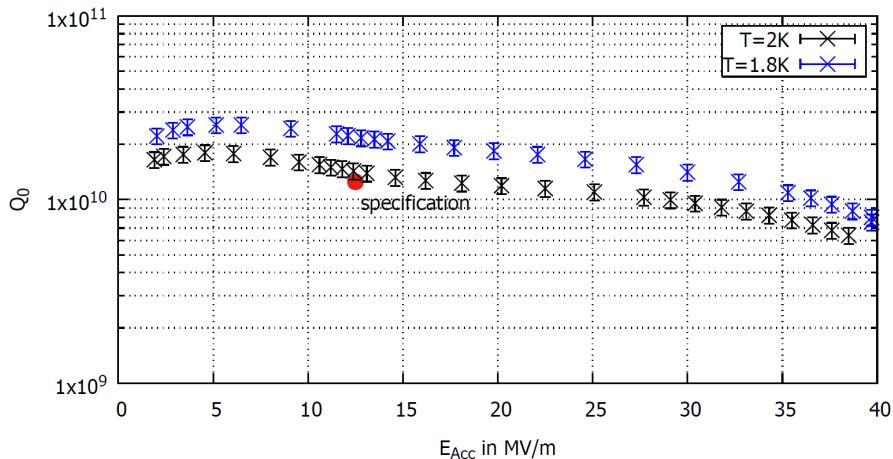
The New York Times



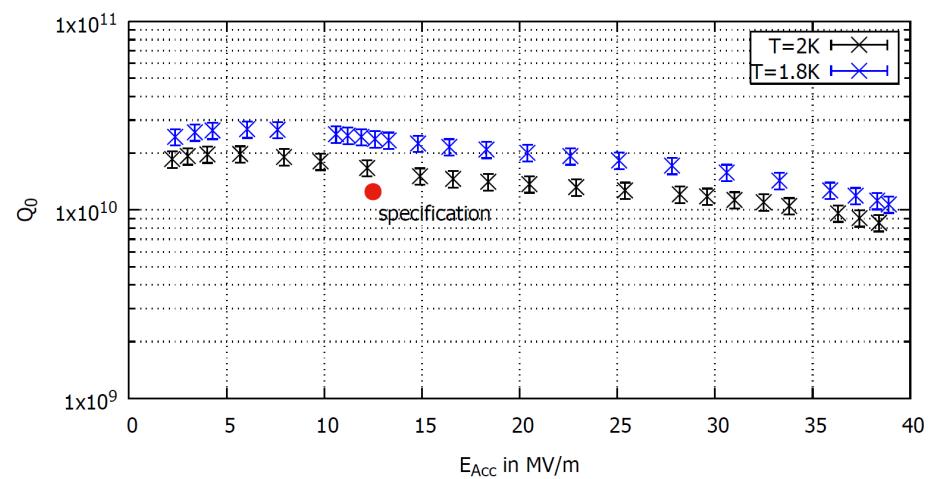
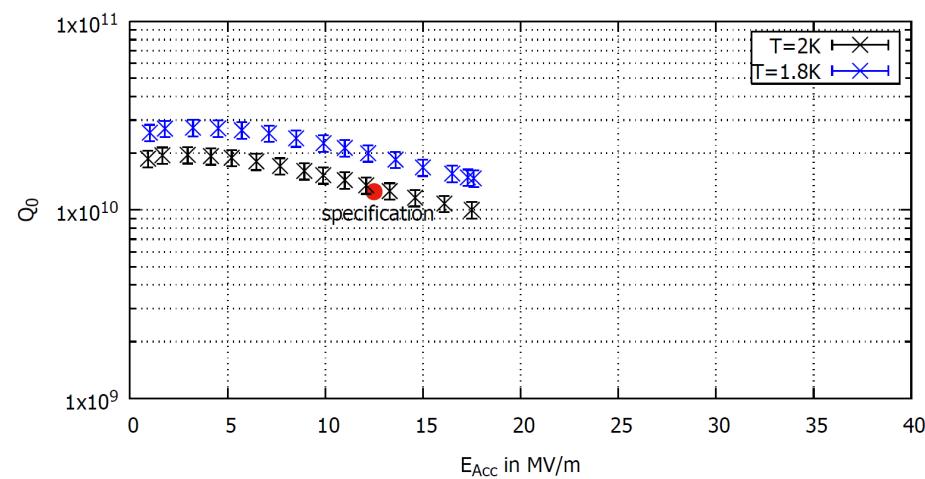
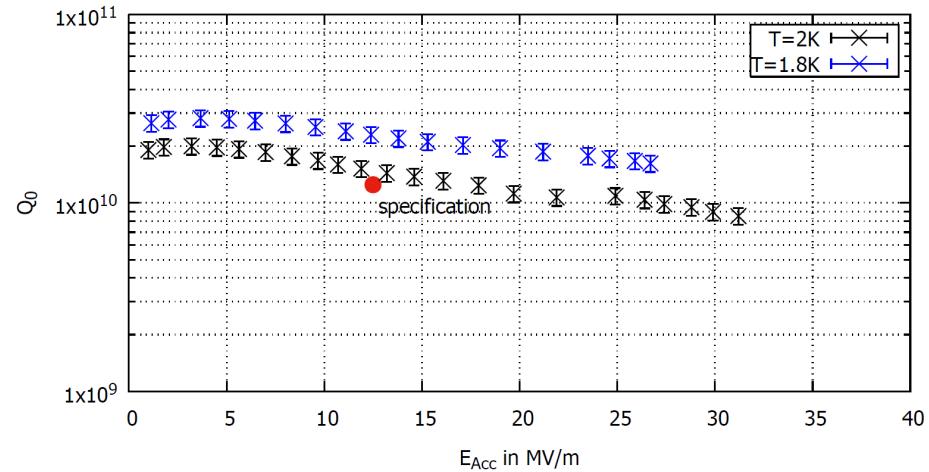
MESA

- Electric FF measurement at low Q^2
- Magnetic FF measurement at low Q^2 using double polarization
Work in progress
- Elastic FF measurements for Few-Body-Systems (d , ${}^3\text{He}$, ${}^4\text{He}$, ...) from 2018 run as well as break-up measurements
- Polarizability measurements of proton and of Few-Body-Systems

Vertical Test CAV007



Vertical Test CAV008

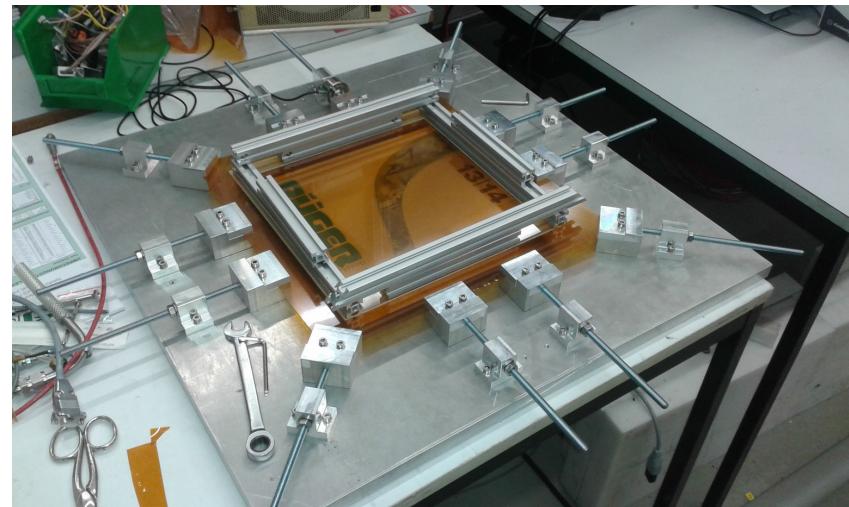
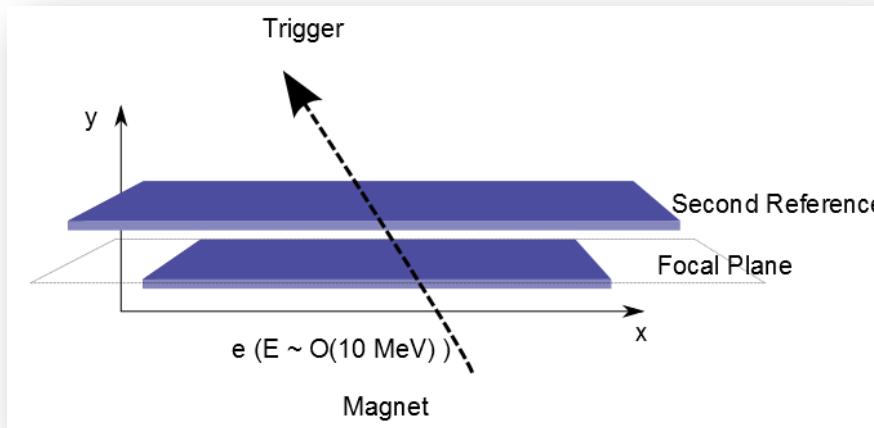


→ all resonators meet specs

GEM Focal Plane Detectors

2 Sensitive layers (30x120 cm²)

- The first centered on the focal plane
- The second with a sizable lever arm to measure the angle

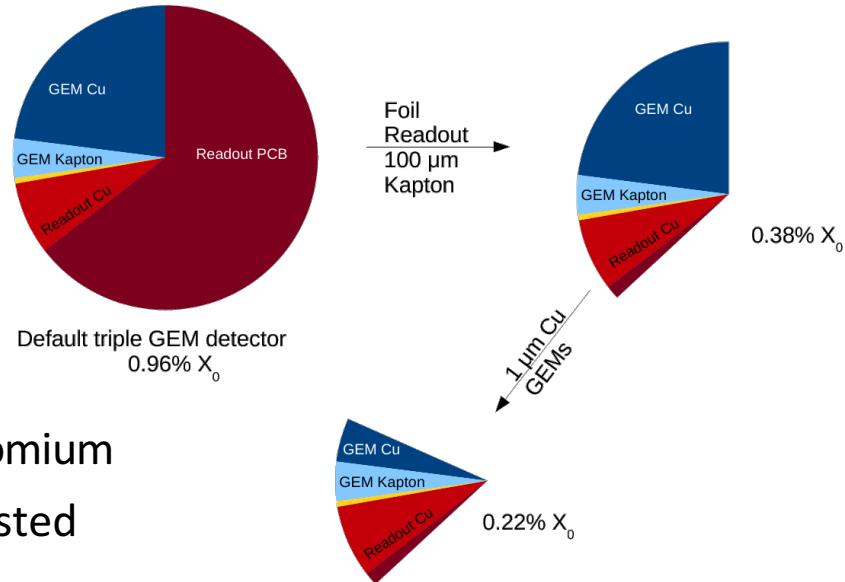


GEM Detectors (2 or 3 layers)

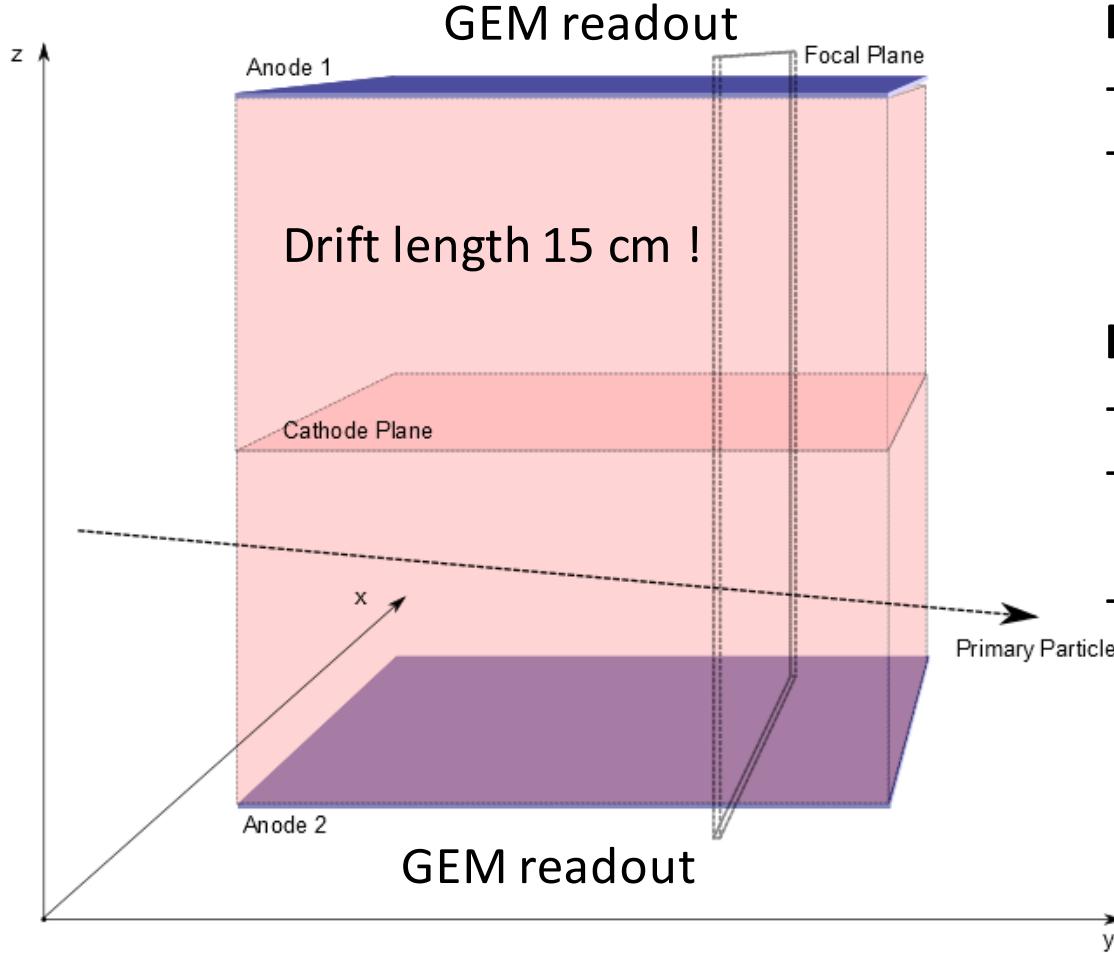
- 2D Strip readout
- High rate capabilities
- Aim for 50 μm resolution
- 1 MHz readout rate

GEM Focal Plane Detectors

- GEM readout on a Kapton foil
 - New pads and strips readout
 - First design to be tested in October
- GEM copper reduction
 - Replacing copper with an atomic layer of Chromium
 - First batch of Chromium GEMs successfully tested
 - Data analysis ongoing
- High-rate capability
 - Expected single count rate in the MAGIX spectrometers $O(\text{MHz}/\text{cm}^2)$
 - Successfully tested at MAMI with similar rates (standard and chromium GEMS alike)
 - New electronic system under development to achieve readout rates of $O(10\text{-}100 \text{ kHz})$ (in collaboration with the CERN RD51 group)



Small Drift TPC as a Focal Plane Detector ?



Pro's:

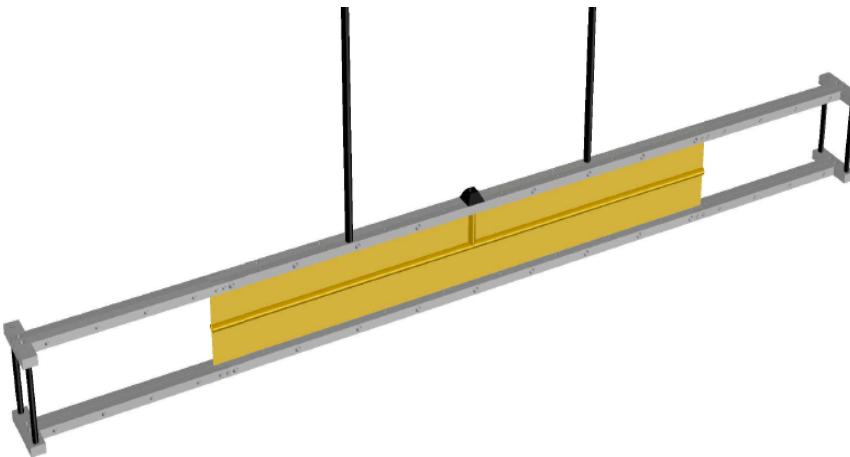
- minimize material budget
- improved spatial and angular resolution

Issues:

- rate capabilities
- space charge effects w/o B field (dipole field ?)
- readout electronics

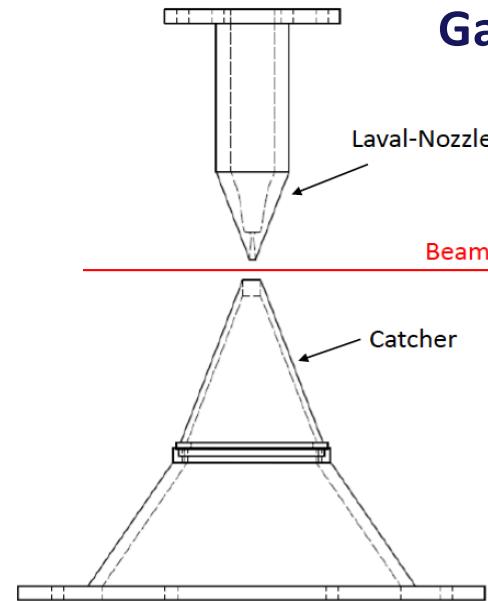
Internal Gas Targets for MAGIX

Thin T-shaped foil



- Length (~ 30 cm)
- First prototype with mylar foil
- Can use polarized gases
- Estimated luminosity with polarized beam $O(>> 10^{32} \text{ cm}^{-2} \text{ s}^{-1})$

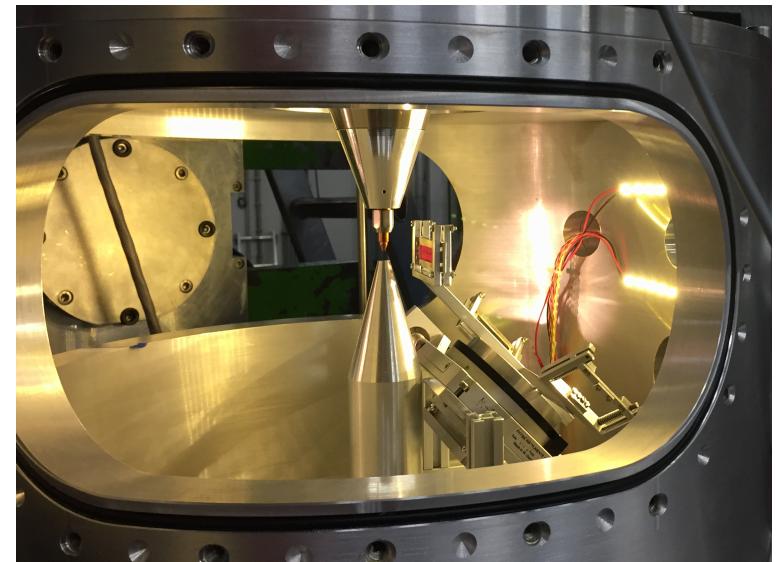
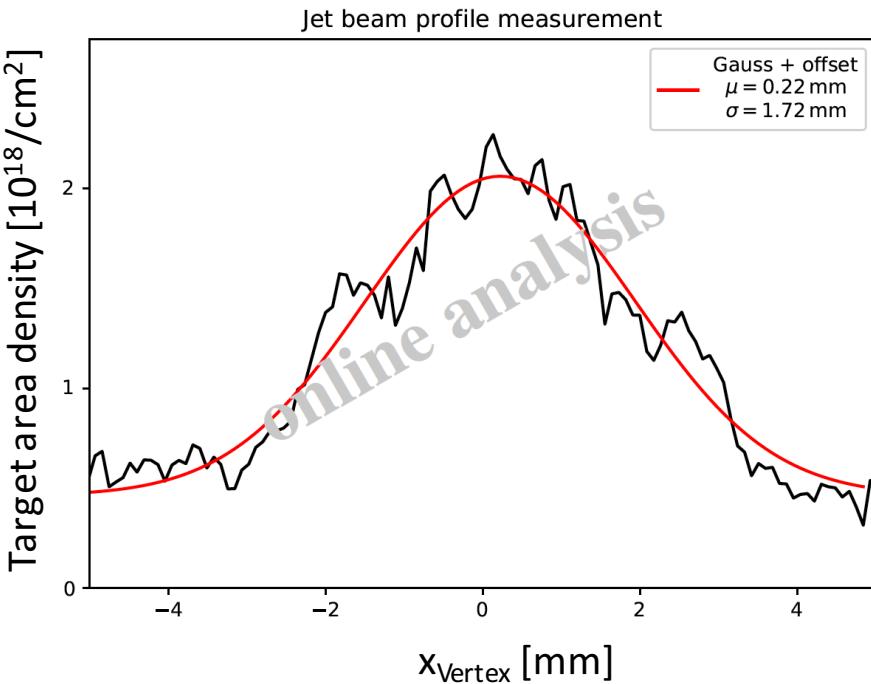
Gas-Jet-Target



- Windowless !
- Supersonic gas jet
- Higher gas density ($10^{19}/\text{cm}^2$)
- O(mm) target length
- H_2 , ^3He , ^4He , O_2 ,, Xe
- $O(10^{35} \text{ cm}^{-2} \text{ s}^{-1}) @ 10^{19}/\text{cm}^2$

Commissioning of jet target at A1/MAMI in 2017/18

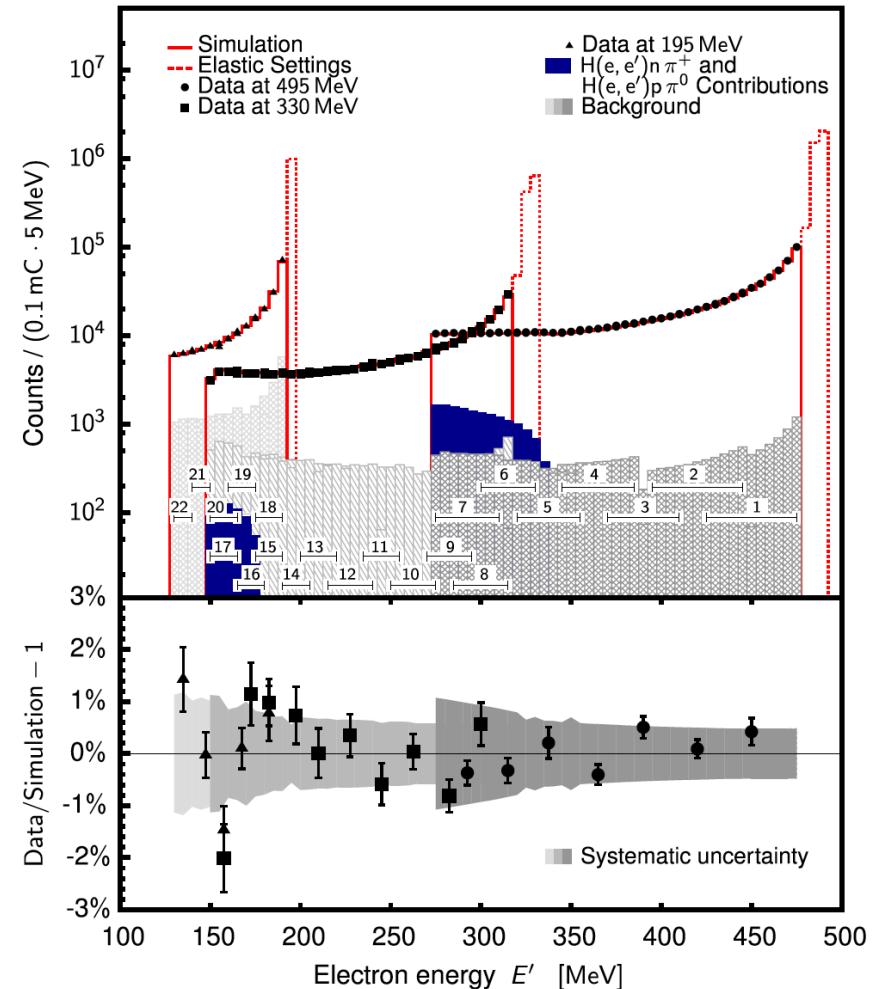
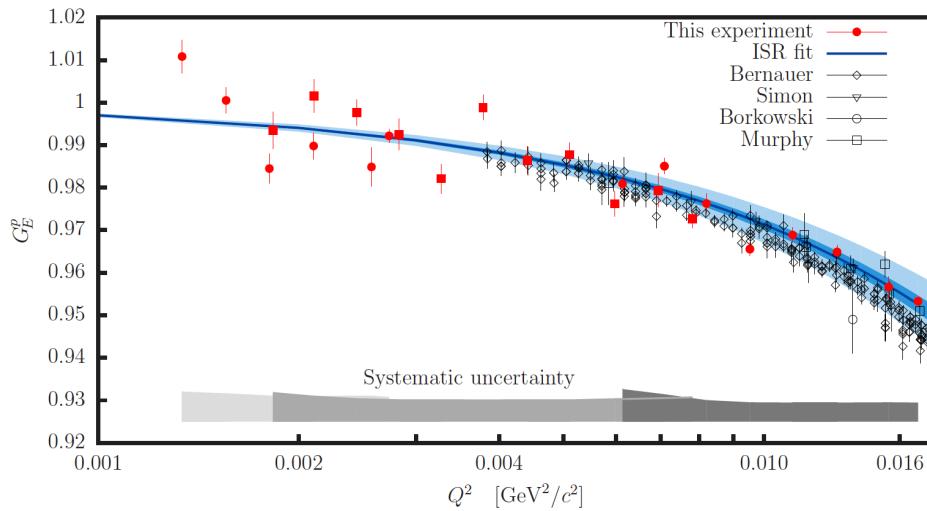
- Installation of jet target and of pumping system
- Measurem. of jet properties via elastic scattering
- Target density $> 2 \times 10^{18} / \text{cm}^2$ achieved
- Cluster beam width 1.72 mm



ISR Measurement of EM Form Factors

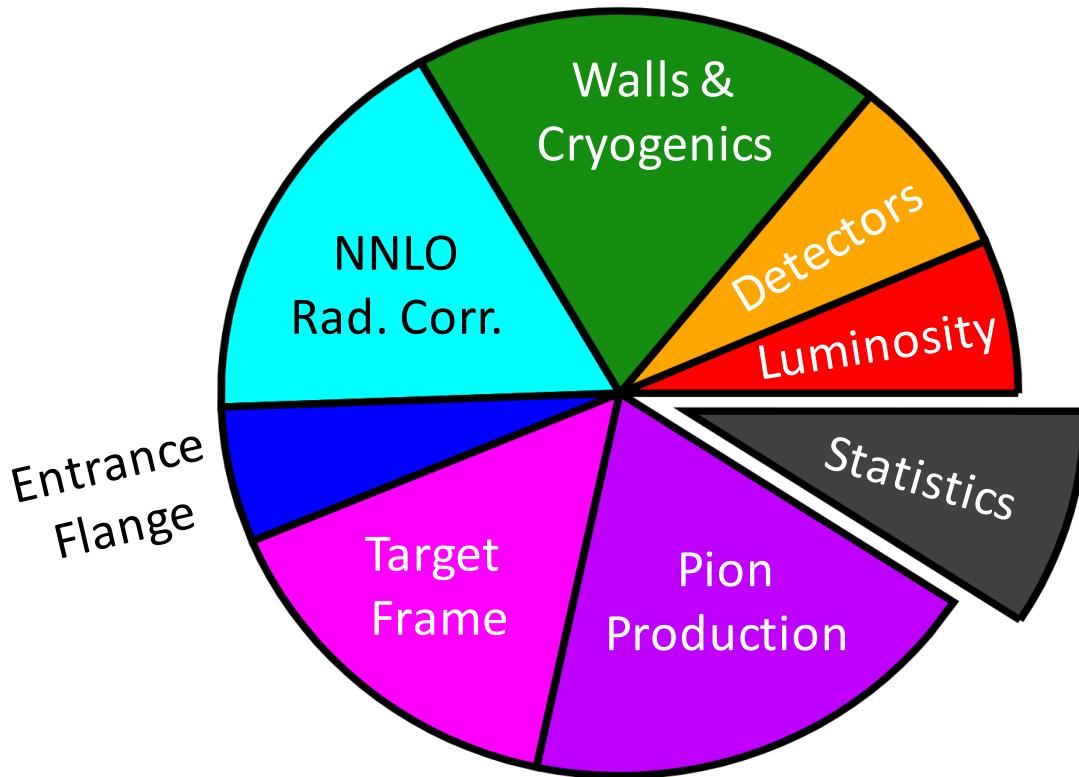
M. Mihovilovic, A.B. Weber et al. [A1 collaboration] Phys. Lett. B771 (2017) 194

- Feasibility of method proven
- Access to unexplored Q^2 ranges below $4 \times 10^{-3} \text{ GeV}^2$
- Significant systematic uncertainties

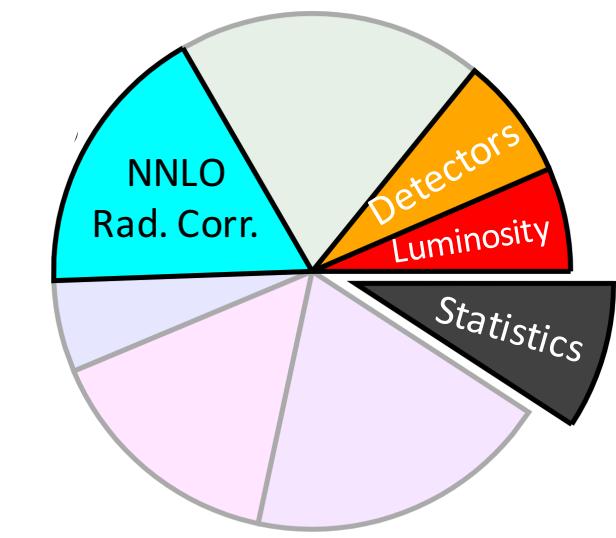


ISR Measurement with Gas-Jet-Target

Existing ISR measurement:
Systematic uncertainties $\sim 1\%$



courtesy M. Mihovilovic

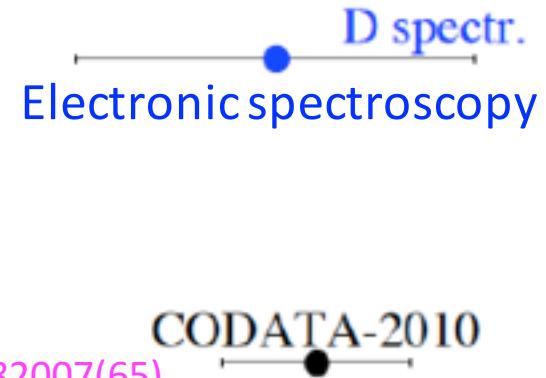


Remaining contributions
after measurement with
gas jet target and slight
additional modifications:
Systematic uncertainty $< 0.5\%$

Deuteron Radius from Muonic Deuterium

JG|U

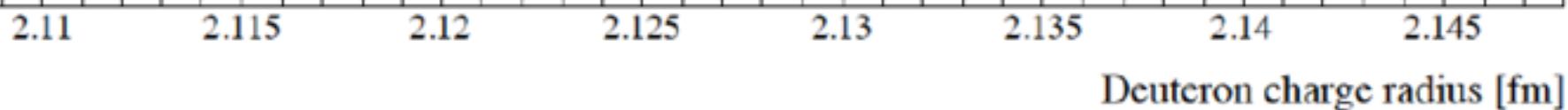
New result for muonic deuterium μD



$$H/D \text{ (1S-2S) Isotope Shift } r_d^2 - r_p^2 = 3.82007(65)$$

e-d scatt.

Electron – Deuteron scattering

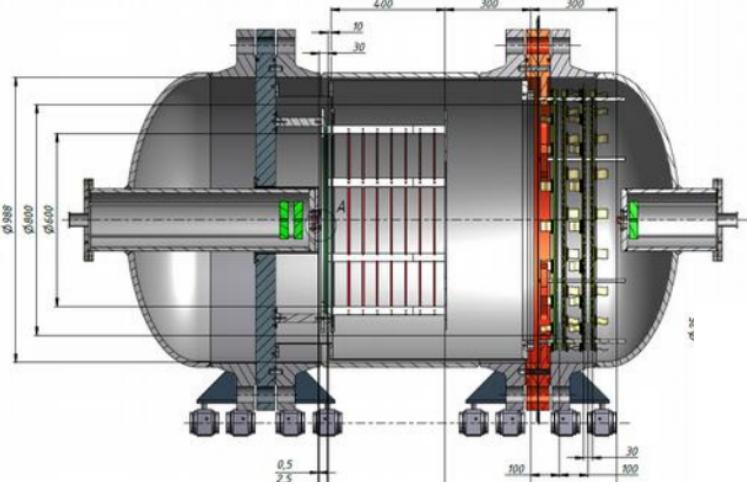


- Consequences:**
- Puzzle also seen in deuteron systems
 - In case of new physics explanation: no coupling to neutron
 - Isotope Shift in electronic and muonic systems identical
- Problem:**
- Uncertainty in μD dominated by hadronic corrections

Proton Radius Programme at MAMI

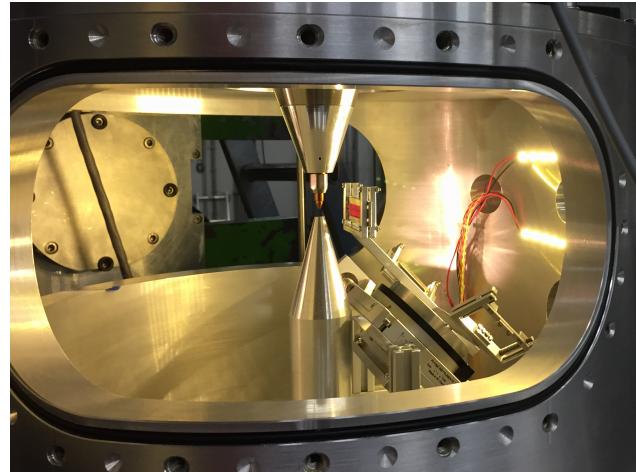


High-pressure TPC



Determine Q^2
from proton recoil

MESA gas jet target @ A1/MAMI



Repeat Bernauer measurement
(Rosenbluth separation)
→ Reduce main systematic effects
(windowless target)

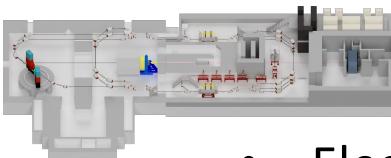


Repeat ISR measurement
→ Access to low Q^2

Mainz Proton Radius Programme



- Proton FF (repeat Bernauer) measurement with gas jet target (2019), ISR measurement as well
- TPC detector (PNPI St. Petersburg) measuring proton recoil (2020)
- Deuteron FF measurement (result expected 2018)
- A2 programme on proton polarizabilities (result expected 2019) to reduce two-photon correction / uncertainty of μ H results / PSI



MESA

- Electric FF measurement at low Q^2
- Magnetic FF measurement at low Q^2 using double polarization
- Elastic FF measurements for Few-Body-Systems (d , ${}^3\text{He}$, ${}^4\text{He}$, ...) as well as break-up measurements
- Polarizability measurements of proton and of Few-Body-Systems

EM Form Factors @ MESA



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

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

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

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

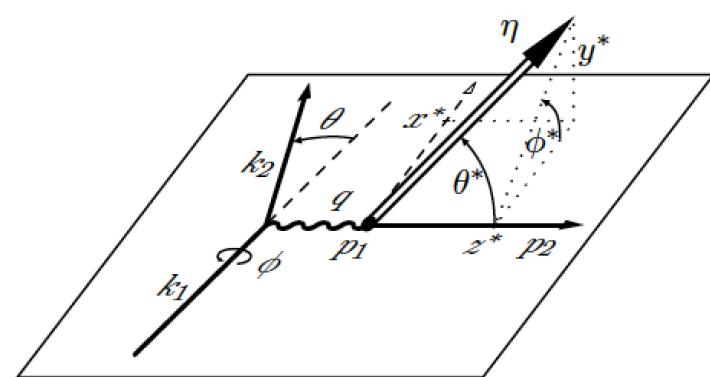
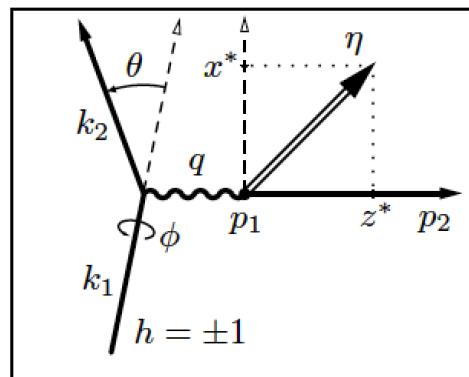
- Beam-Target polarization:

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

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

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

$$\begin{cases} \phi^* = 0 \\ \theta^* = 0, \frac{\pi}{2} \end{cases} \Rightarrow A_{\perp} = \frac{A_I}{A_S} \sim \frac{G_E}{G_M}$$



Mainz Proton Radius Programme



- Proton FF (repeat Bernauer) measurement with new gas jet target (2019), ISR measurement as well (2019+)
- TPC detector (PNPI St. Petersburg) measuring proton recoil (2020)
- Deuteron FF measurement (result expected 2018)
- A2 programme on proton polarizabilities (result expected 2019) to reduce uncertainty of muonic hydrogen result



MESA

- Electric FF measurement at low Q^2
- Magnetic FF measurement at low Q^2 using double polarization
- Elastic FF measurements for Few-Body-Systems (d , ${}^3\text{He}$, ${}^4\text{He}$, ...) as well as break-up measurements
- Polarizability measurements of proton and of Few-Body-Systems

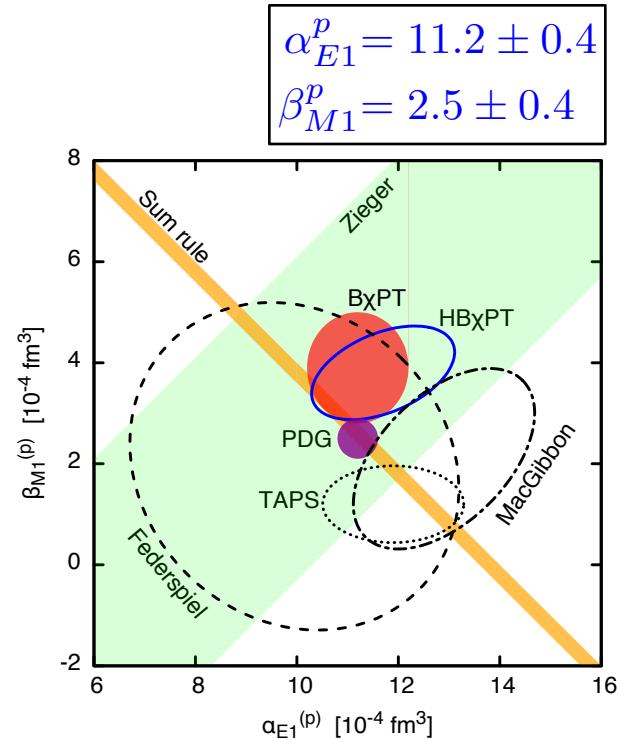
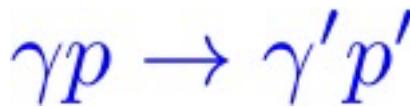


Proton Polarizabilities

Reaction of nucleon under influence of an EM field
 \leftrightarrow Compton scattering

provides fundamental information of the nucleon;
very sensitive test of theories (H/BxPT, Disp. Rel.).

- Electric Polarizability: α_{E1}
- Magnetic Polarizability: β_{M1} $H_{\text{eff}}^{(2)} = -4\pi \left[\frac{1}{2}\alpha_{E1} \vec{E}^2 + \frac{1}{2}\beta_{M1} \vec{H}^2 \right]$
- Spin (Vector) Polarizabilities: $\gamma_{E1E1}, \gamma_{M1M1}, \gamma_{M1E2}, \gamma_{E1M2}$



Attempts at MAMI to reduce magnetic
polarizability β by a factor of 2
using spin observables (difficult)

Polarisierbarkeiten

Experiment	Status	
Σ_{2x}	February 2011	✓
Σ_3	December 2012	✓
α_{E1}, β_{M1}	June 2013	✓
Σ_{2z}	May 2014	✓

① Beam: circular

Target: longitudinal

$$\Sigma_{2z} = \frac{\sigma_{+z}^R - \sigma_{+z}^L}{\sigma_{+z}^R + \sigma_{+z}^L} = \frac{\sigma_{+z}^R - \sigma_{-z}^R}{\sigma_{+z}^R + \sigma_{-z}^R}$$

② Beam: circular

Target: transverse

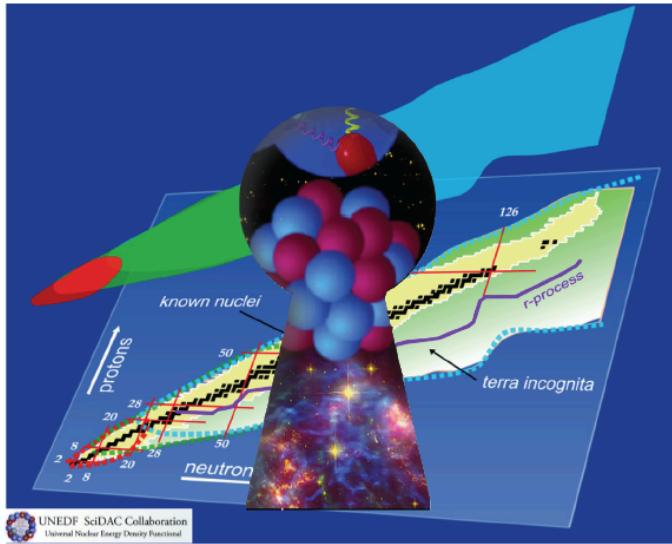
$$\Sigma_{2x} = \frac{\sigma_{+x}^R - \sigma_{+x}^L}{\sigma_{+x}^R + \sigma_{+x}^L} = \frac{\sigma_{+x}^R - \sigma_{-x}^R}{\sigma_{+x}^R + \sigma_{-x}^R}$$

③ Beam: linear, \parallel and \perp to scattering plane

Target: unpolarized

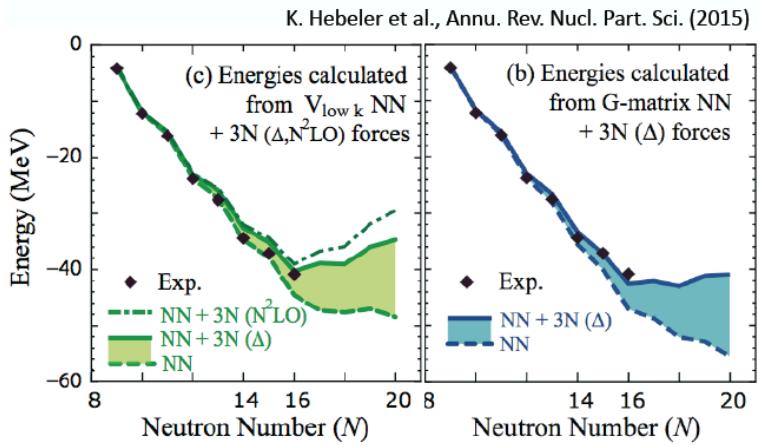
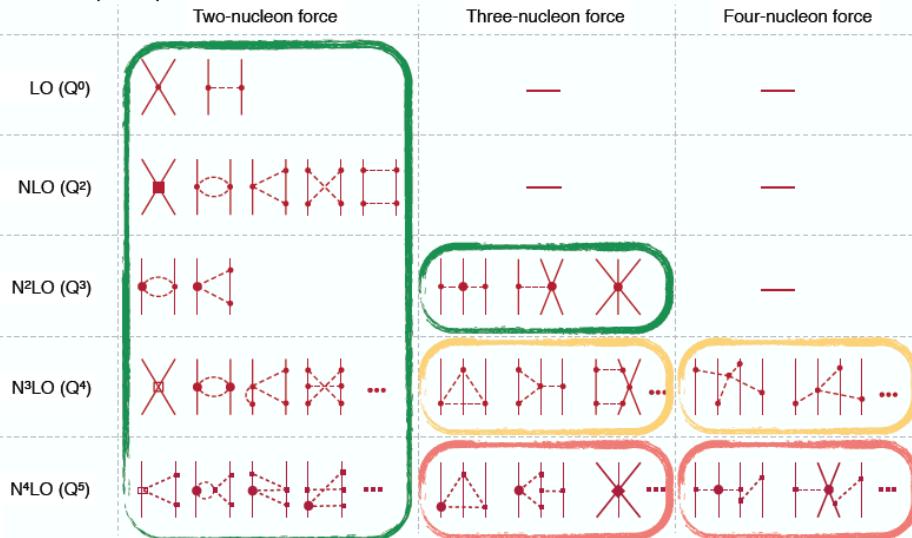
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

Few-Body Physics at MAGIX



Linking low energy QCD to many-body systems.

E. Epelbaum (2015)



Jacek Golak / LEPP16
Work out framework based on ChPT
to deal with EW processes

Conclusions and outlook

- Very robust momentum space framework to deal many electroweak processes has been constructed and tested (limitations)
- New input: improved chiral 2N and 3N potentials (even 4N potentials)
 - Substantial improvement in description of many observables
- LENPIC (Low Energy Nuclear Physics International Collaboration) to coordinate few-nucleon and many-nucleon Calculations
 - See Kai Hebeler's talk today !
- Consistent electroweak current operators are needed and are being prepared
 - MESA results will be of great importance !

Conclusions and outlook (cont.)

What should be measured?

Various observables in deuteron electrodisintegration (polarization might be crucial !)

Two-body break-up of ${}^3\text{He}$

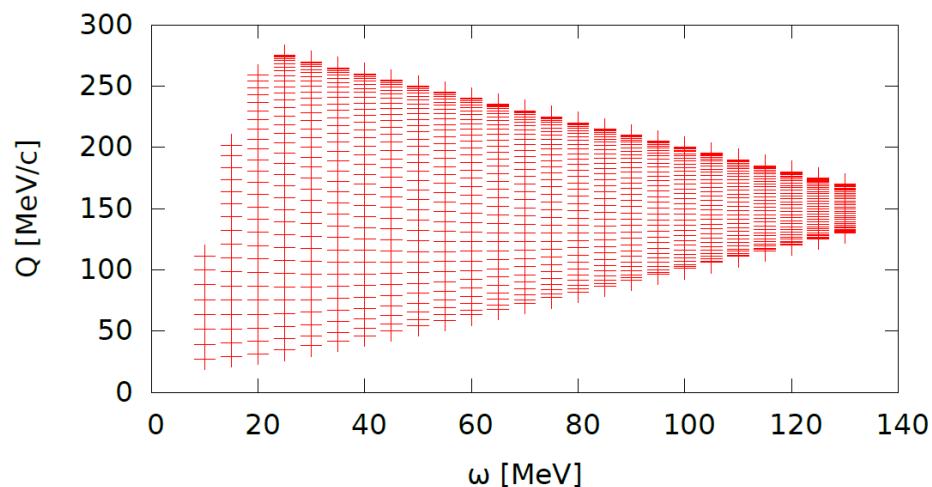
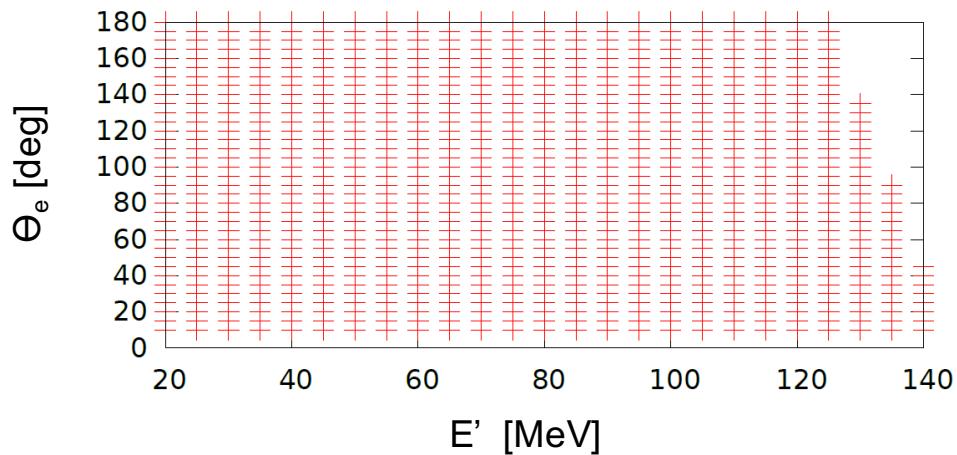
1. unpolarized proton angular distributions (for a wide range of angles)
2. ${}^3\text{He}$ analyzing power
3. Spin-dependent helicity asymmetries

Three-body break-up of ${}^3\text{He}$

1. Semi-exclusive cross sections (proton and neutron) at various emission angles with respect to the momentum transfer
2. ${}^3\text{He}$ analyzing power
3. Spin-dependent helicity asymmetries

Introduction (*cont.*)

Expected MESA parameters



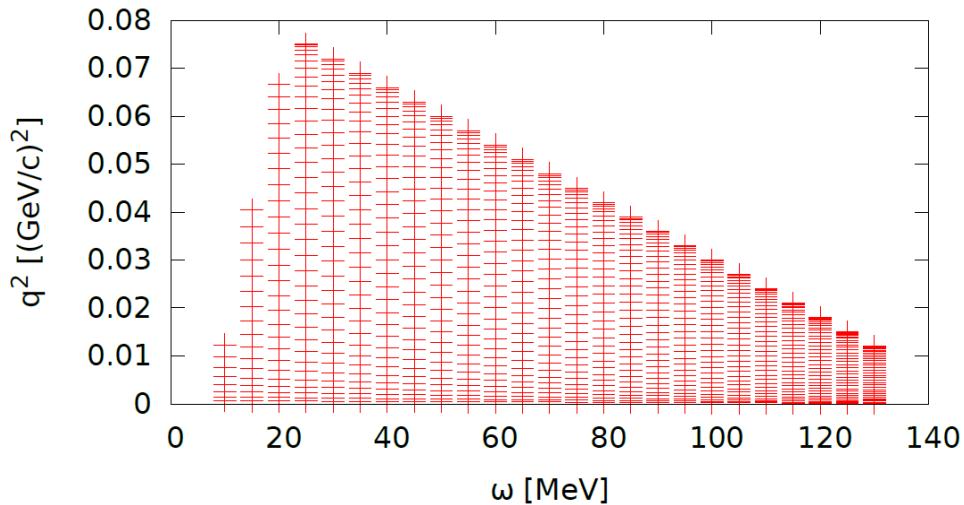
ideal to study few-nucleon dynamics within the nonrelativistic framework with the input from ChEFT !

magnitude of three-momentum transfer vs. energy transfer

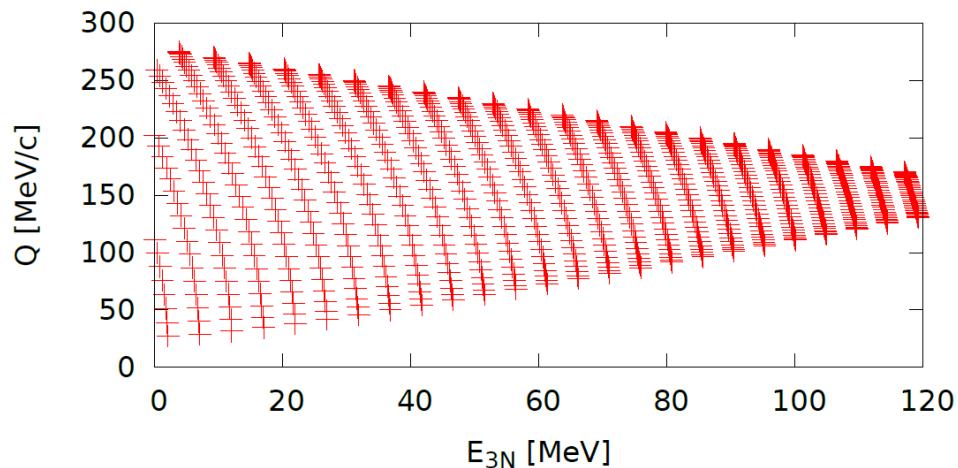
Introduction (*cont.*)



S. Golek@LEPP 2017



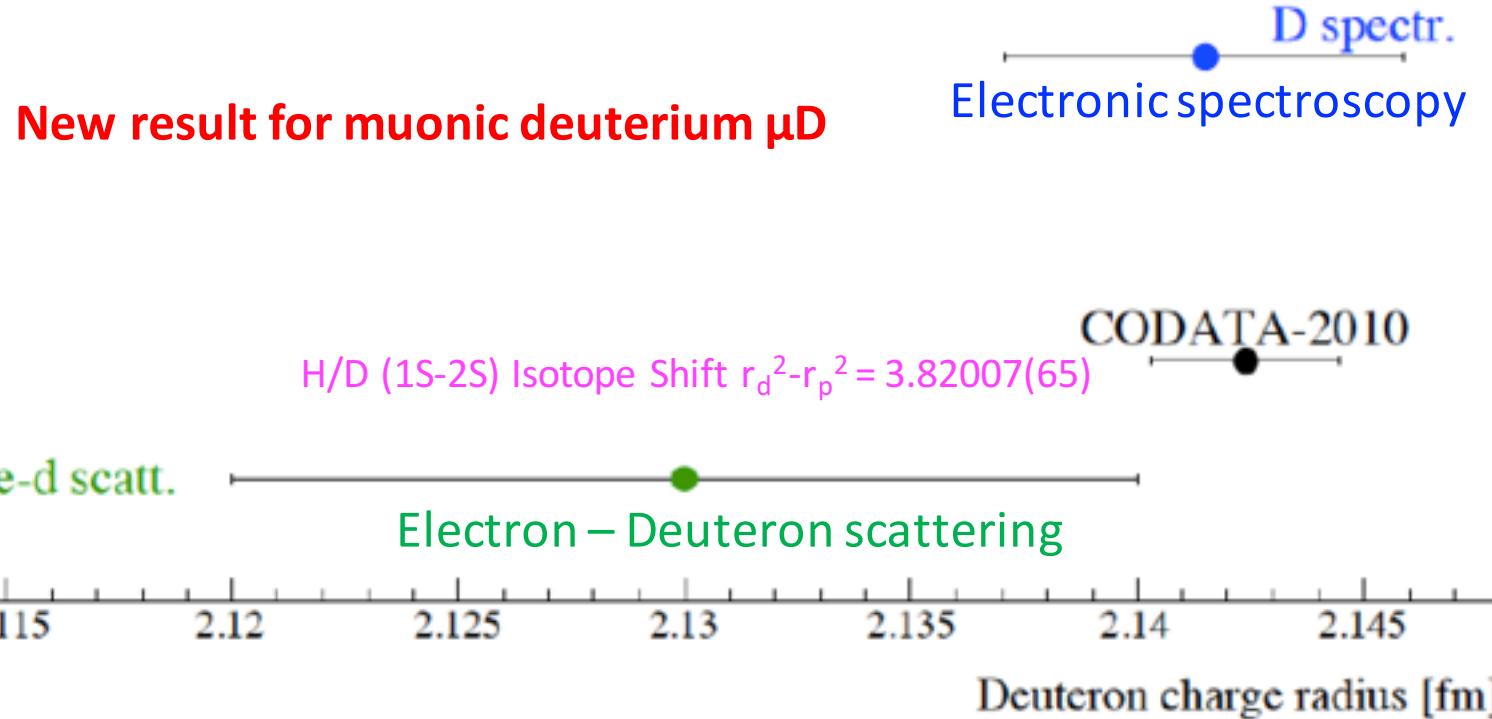
four-momentum transfer
squared vs. energy transfer



magnitude of three-
momentum transfer vs.
internal energy of $3N$ system

Deuteron Radius from Muonic Deuterium

JG|U

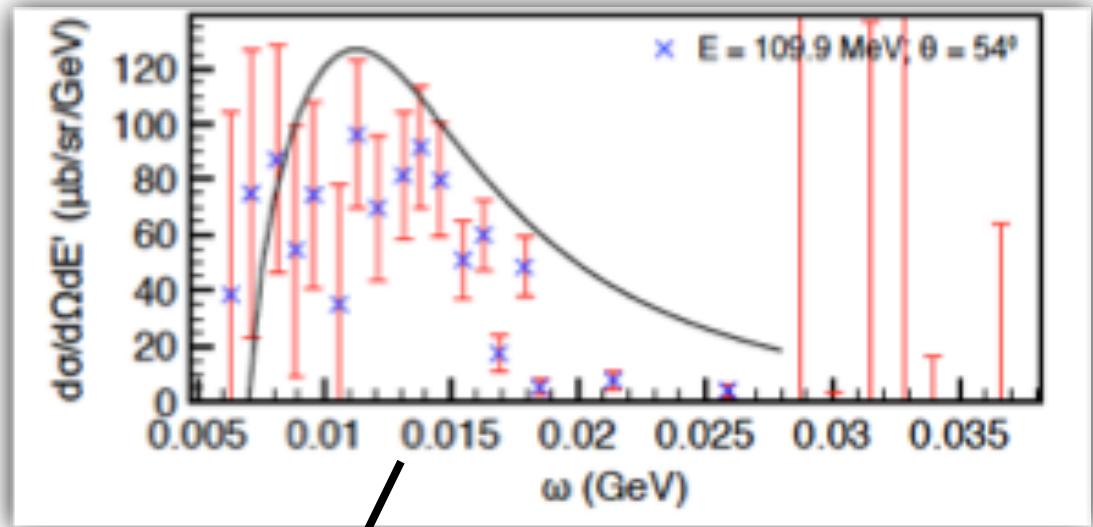


- Consequences:**
- Puzzle also seen in deuteron systems
 - In case of new physics explanation: no coupling to neutron
 - Isotope Shift in electronic and muonic systems identical
- Problem:**
- Uncertainty in μD dominated by hadronic corrections

Hadronic Corrections in Light Nuclei Systems

Carlson, Gorchtein, Vanderhaeghen (2016)

sample of present ${}^3\text{He}(e,e')$ data



Kinematics	δa_2	$\delta(\Delta E_{2S}^{\text{nuclear}})$	$\delta(\Delta E_{2S}^{\text{TPE}})$
$E = 110 \text{ MeV}$ $\theta = 54^\circ$	± 0.014	0.40 meV	0.49 meV

5% measurement of ${}^3\text{He}$
electrodisintegration
cross section at MAGIX

^{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

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

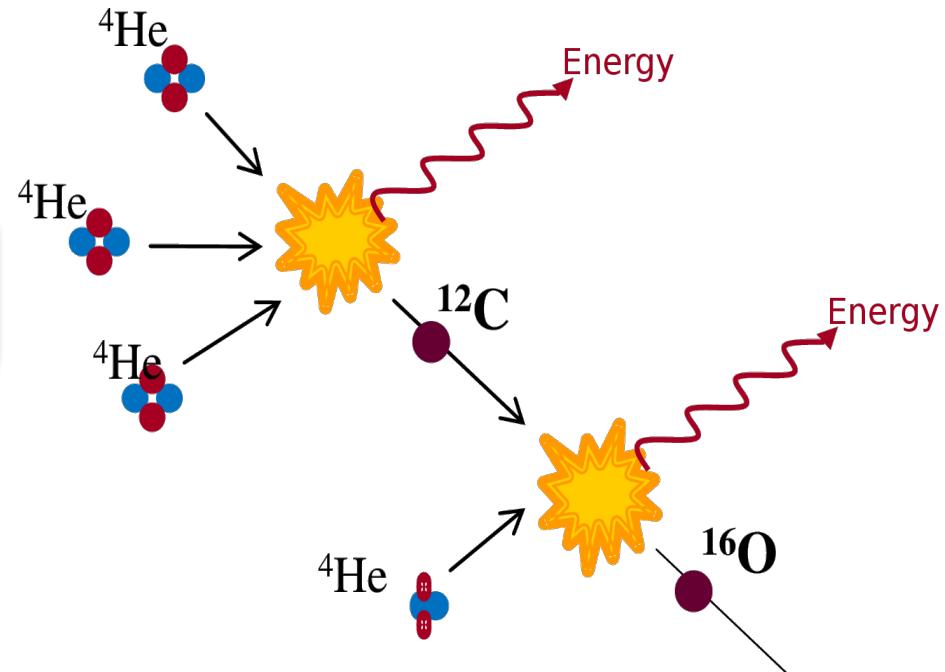
$$\sigma(E) = \frac{1}{E} e^{-\frac{2\pi Z_1 Z_2 \alpha c}{v}} \cdot S(E)$$

Compton
wave length

Tunneling
probability
in fusion process

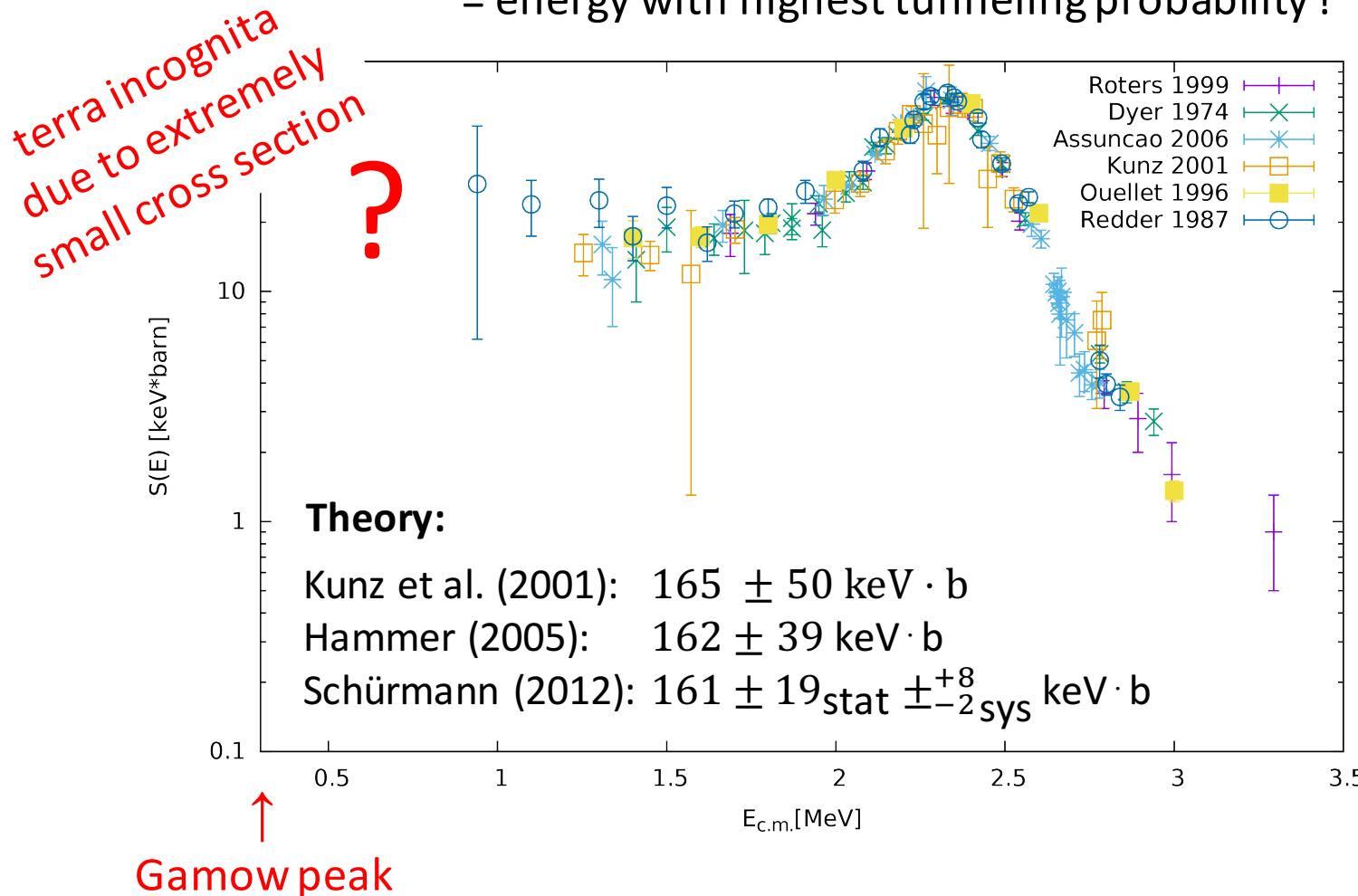
„S factor“

unknown nuclear physics



Nuclear Astrophysics at MAGIX ?

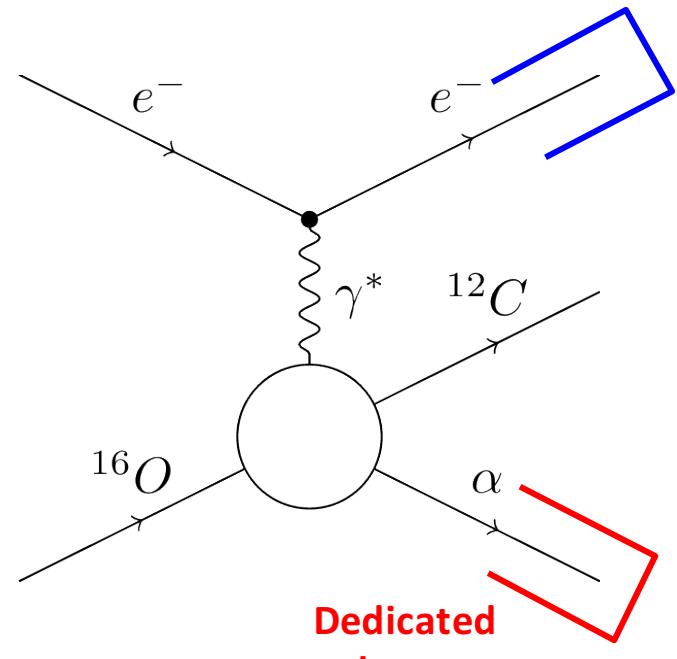
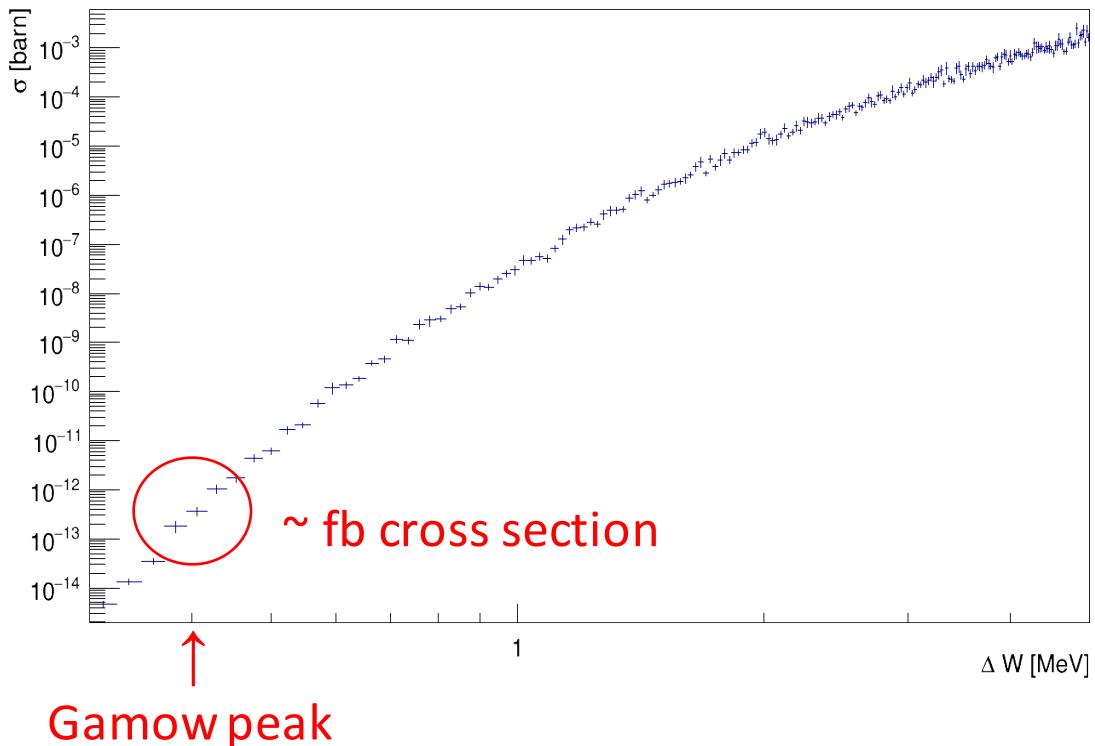
Needed: S-factor at $E_{c.m.} = 300$ MeV („Gamow peak“)
= energy with highest tunneling probability !



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



- Inverse reaction: $^{16}\text{O} (\alpha, \gamma) ^{12}\text{C}$
- Chose kinematics with quasi-real photon
- Factor of 100 improvement in cross section wrt. original reaction
- Simulation of process carried out



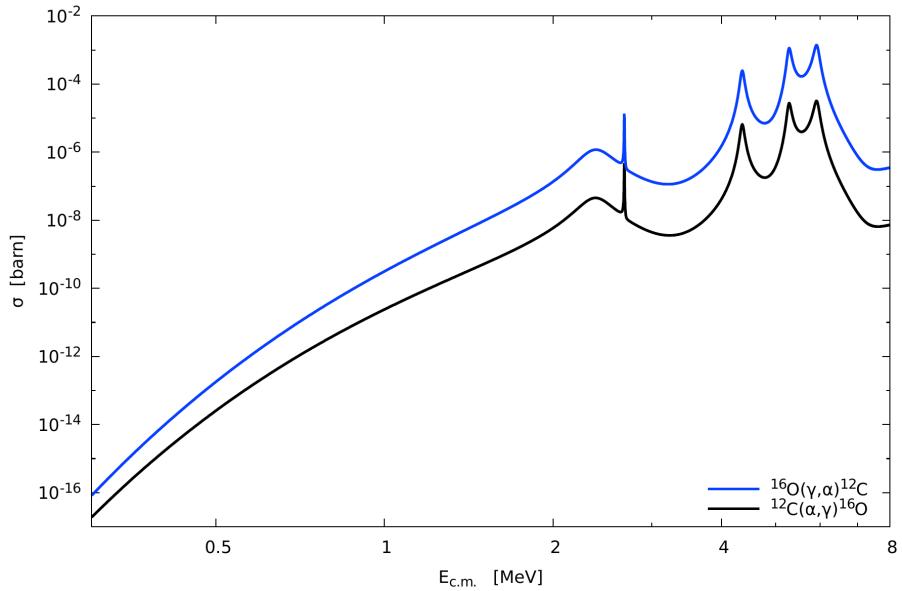
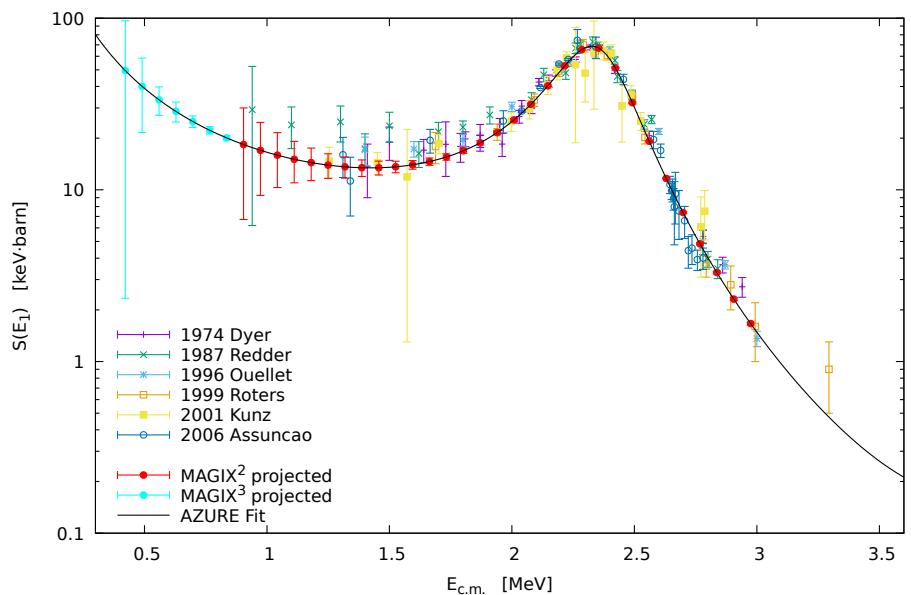
To-Do:

- Simulate acceptances
- Study background
- Concept for α detection

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



- Inverse reaction: $^{16}\text{O} (\alpha, \gamma) ^{12}\text{C}$
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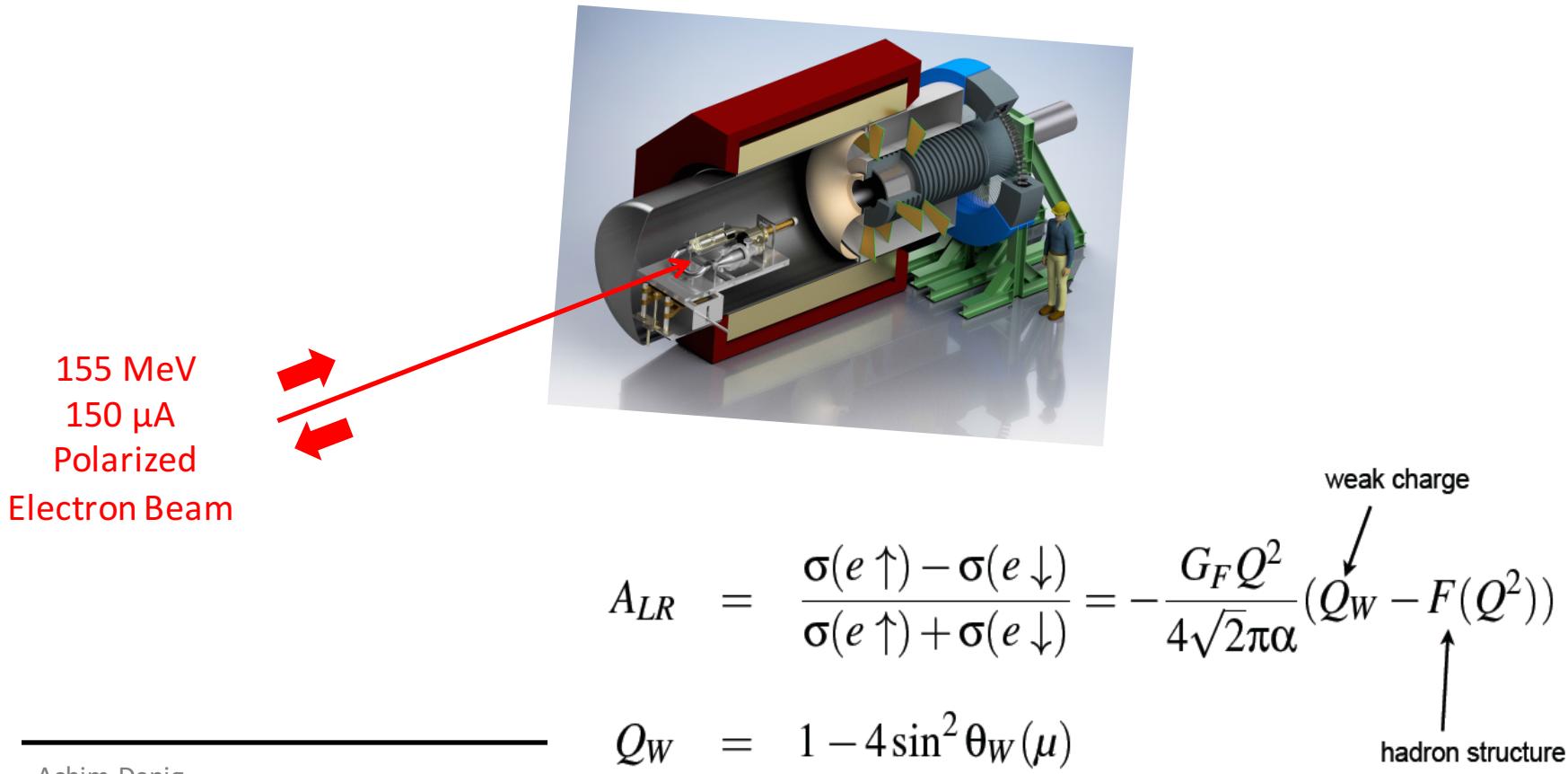


A Low- Q^2 Measurement of $\sin^2\theta_W$ @ P2

Scattering of longitudinally polarized electrons on unpolarized protons

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

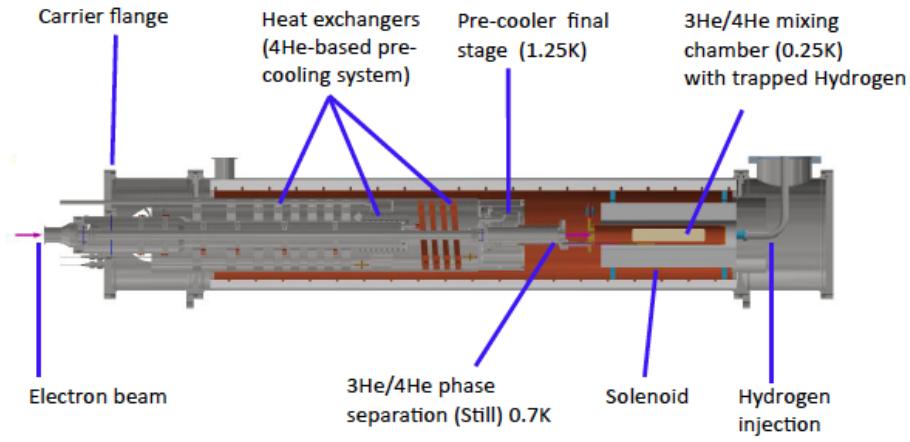
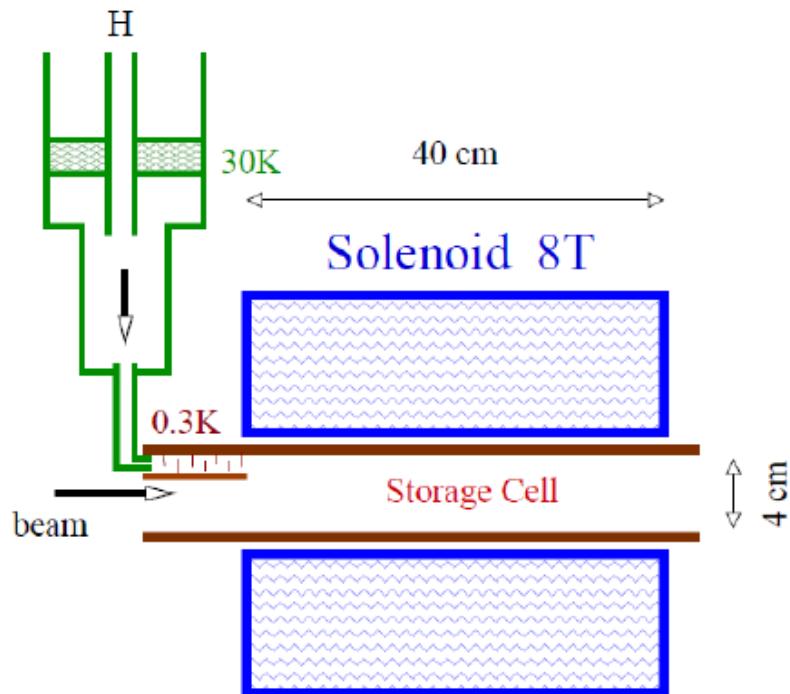
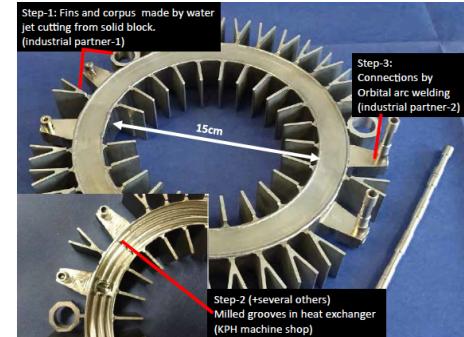
→ Measure parity-violating Left-Right cross section asymmetry A_{LR} (= 40×10^{-9})



Beam Polarimetry @ MESA

Strategy: Redundant measurement of beam polarization with < 1% accuracy each

- Double scatter Mott polarimeter @ 100 keV
- Single scatter Mott polarimeter @ 5 MeV
- Hydro Moeller Polarimeter @ 155 MeV (in situ)
exchange ferromagnetic probe by trapped polarized
hydrogen atoms (engineering challenge)
→ expected accuracy <0.5%



$$A_m = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} = P_T P_B \frac{\sin^2 \theta (7 + \cos^2 \theta)}{(3 + \cos^2(\theta))^2}$$