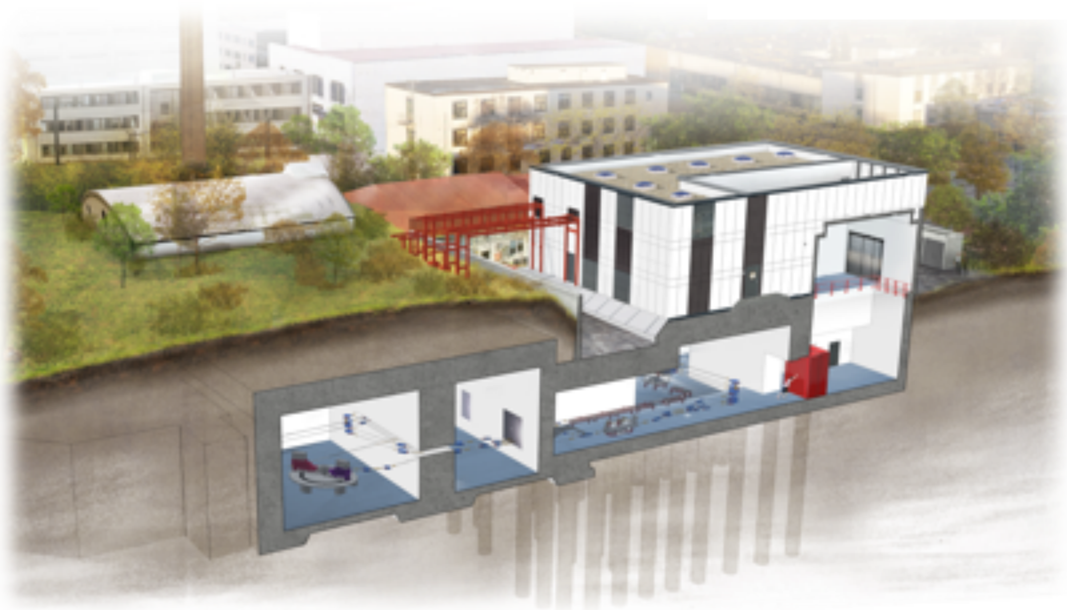


The MAMI and future MESA Facilities

Electromagnetic Observables for Low-Energy Nuclear Physics

Mainz, October 1st, 2018

Achim Denig

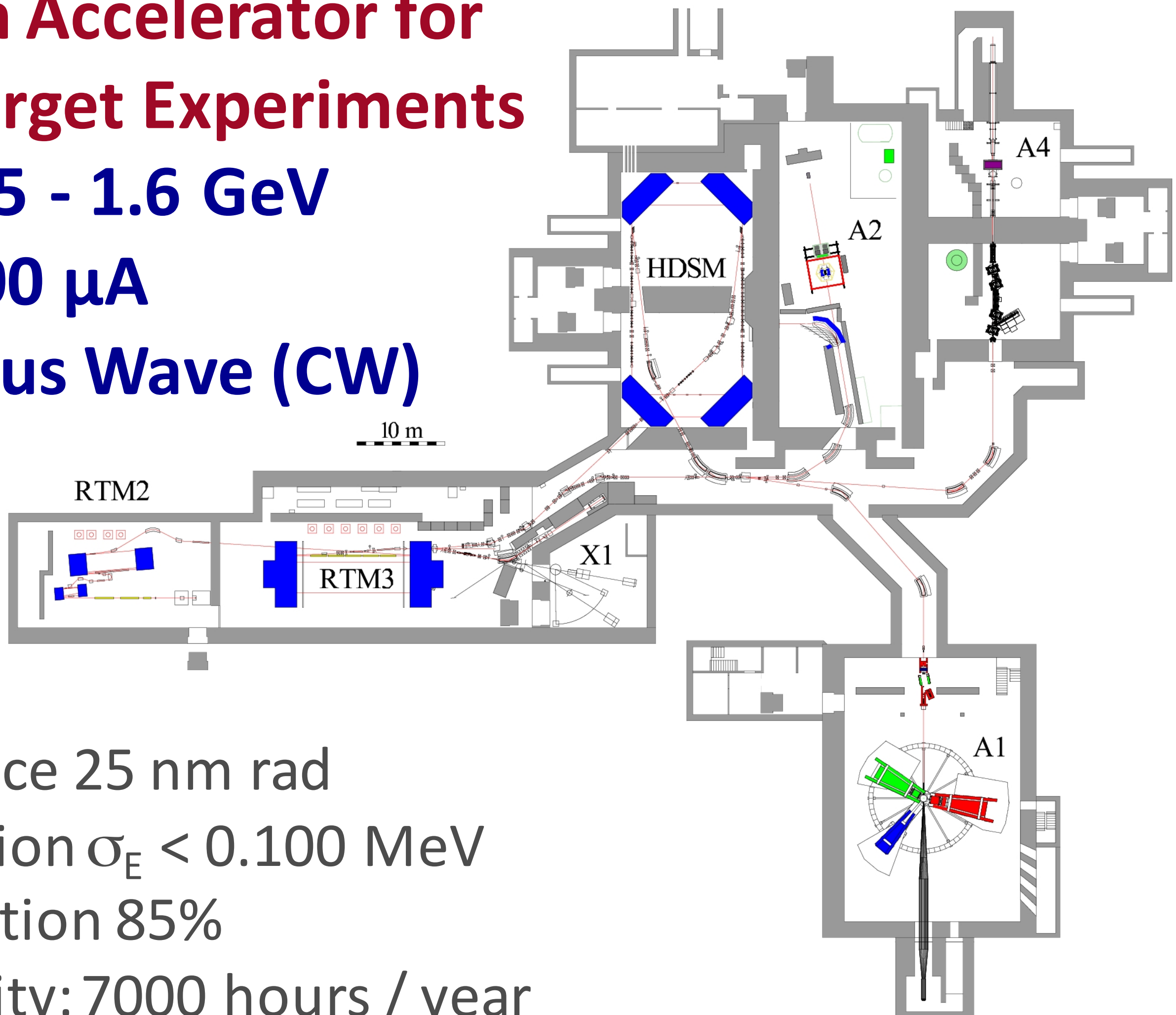
Mainz Microtron MAMI

Electron Accelerator for
Fixed Target Experiments

E = 0.185 - 1.6 GeV

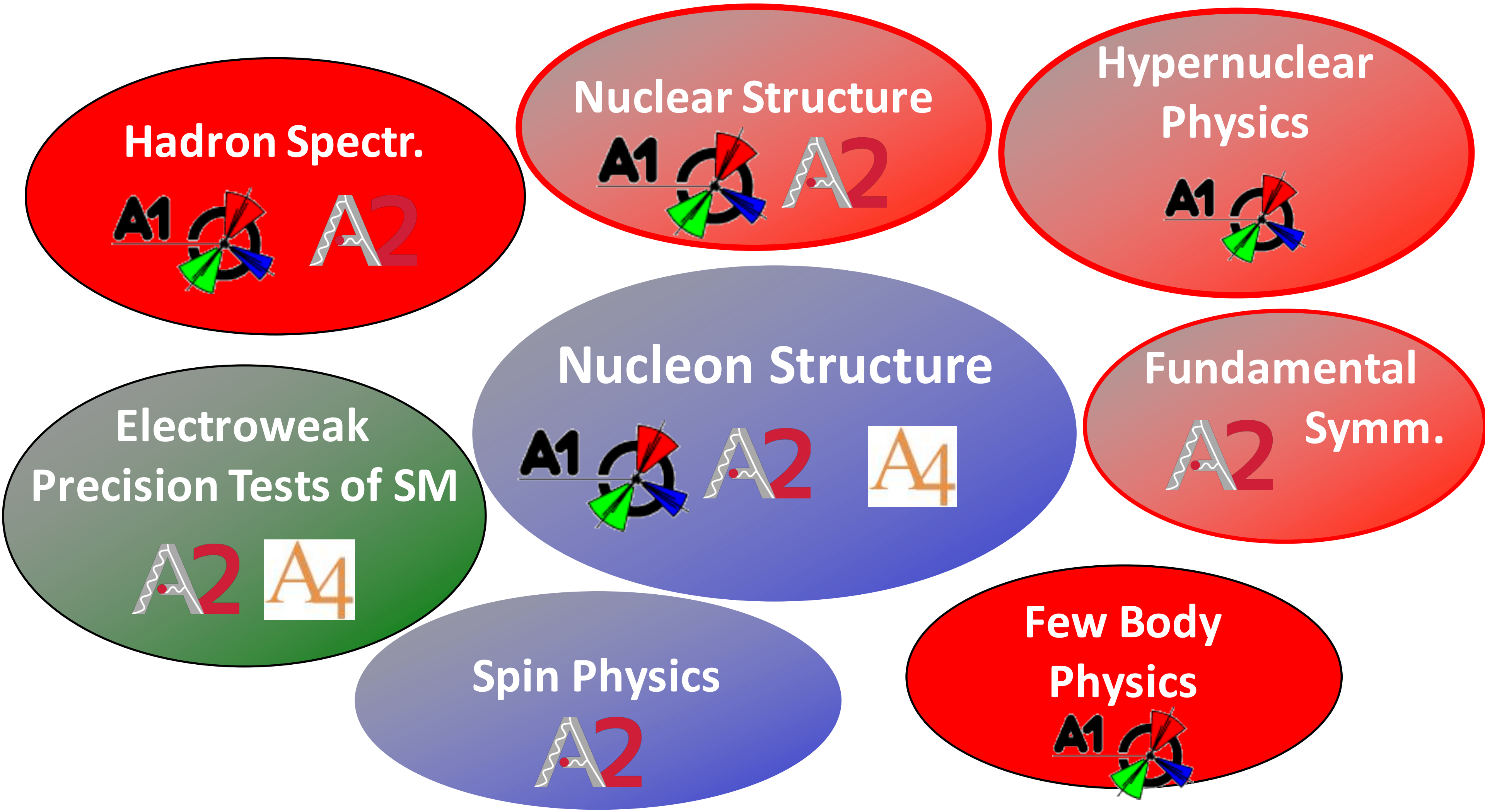
I_{max} ~ 100 µA

Continous Wave (CW)

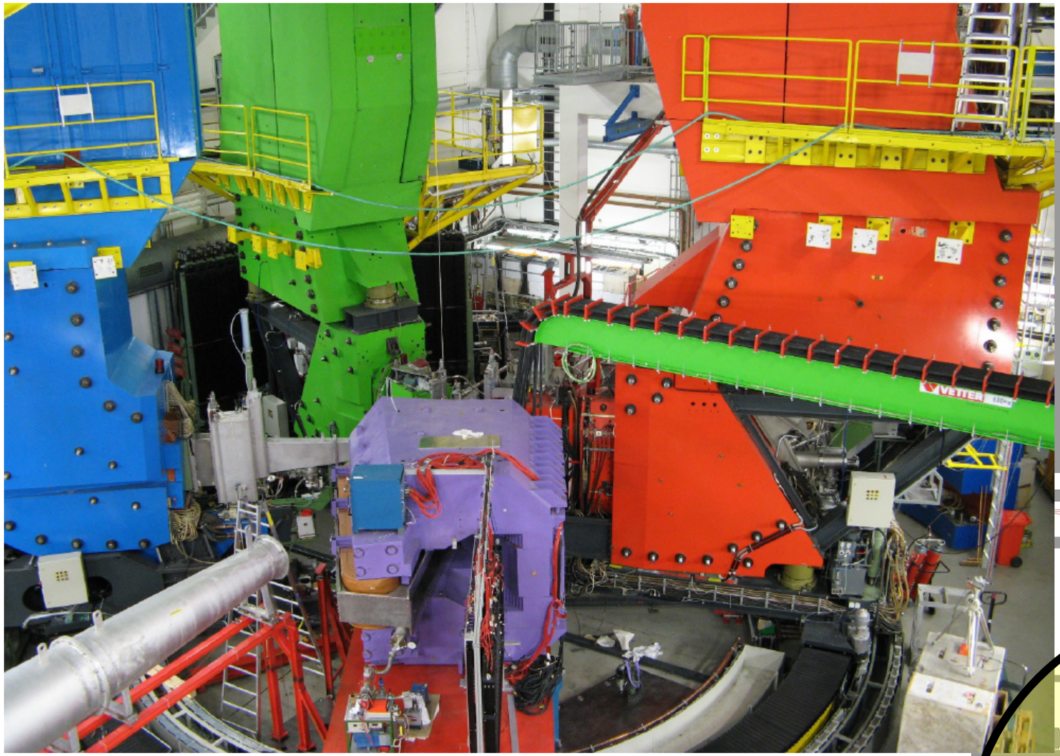


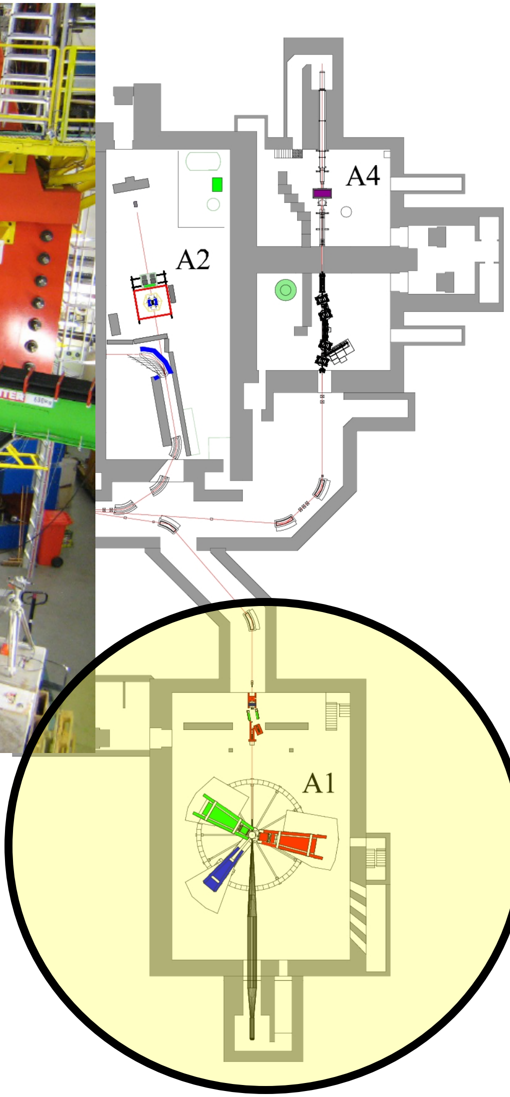
- Emittance 25 nm rad
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: 7000 hours / year

Hadron Physics at MAMI



Experiment A1: High-Resolution Spectrometers





Experiment A1: Electron Scattering

- 4 magnetic focussing spectrometers
- Resolution: $\delta p/p < 10^{-4}$
- Angular acceptance: <30 mrad

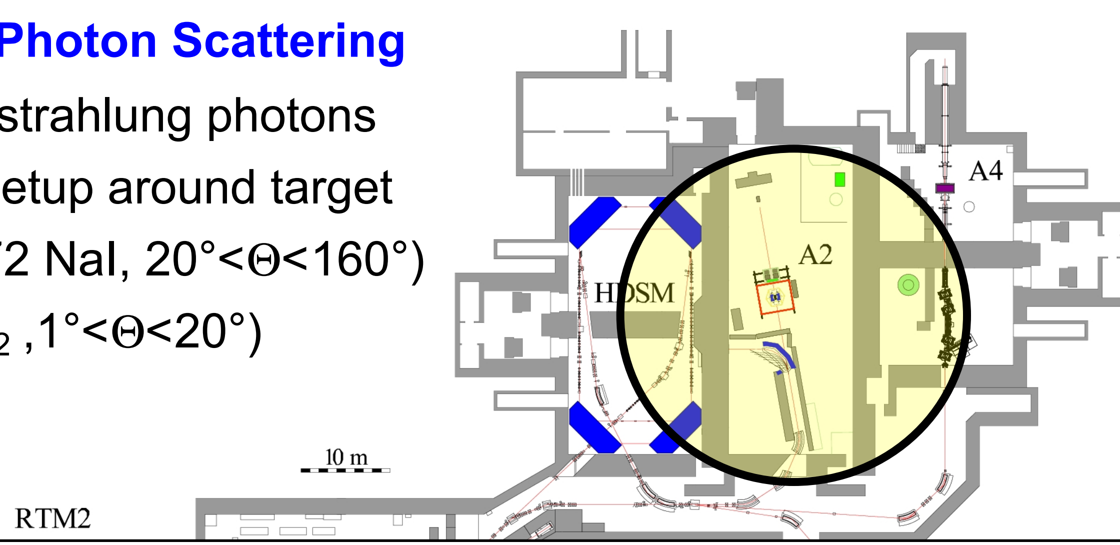
Experiment A2: Photon Beam Line

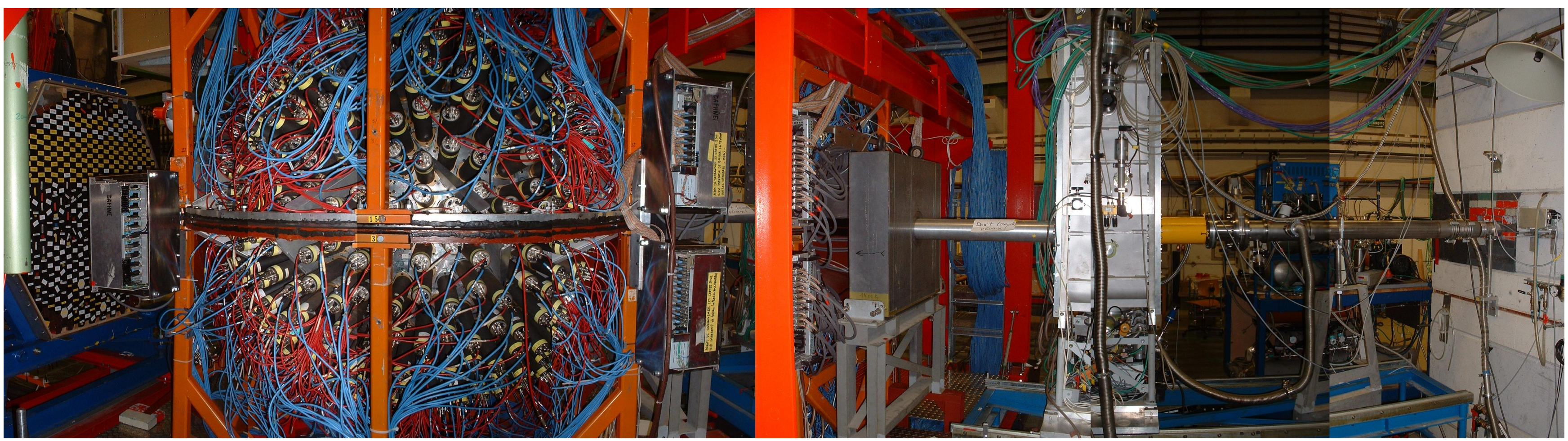
Experiment A2: Photon Scattering

- "Tagged" bremsstrahlung photons
- 4π calorimeter setup around target

  Crystal Ball (672 NaI, $20° < \Theta < 160°$)

  TAPS (384 BaF_2, $1° < \Theta < 20°$)





Mainz Microtron MAMI

Electron Accelerator for Fixed Target Experiments

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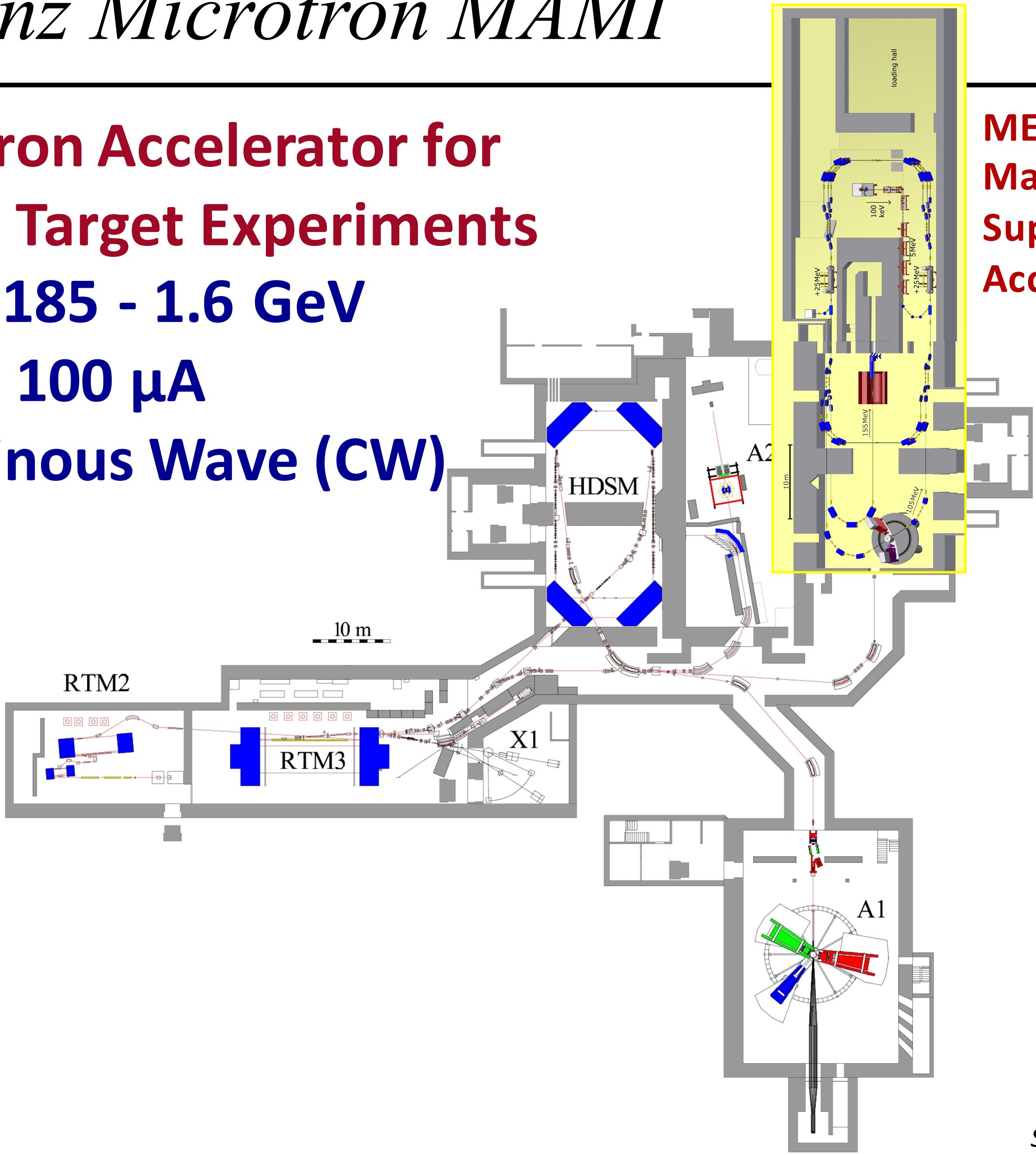


MESA
Mainz Energy-Recovering Superconducting Accelerator

MESA Accelerator

Mainz Energy-Recovering Superconducting Accelerator

Extracted Beam Mode

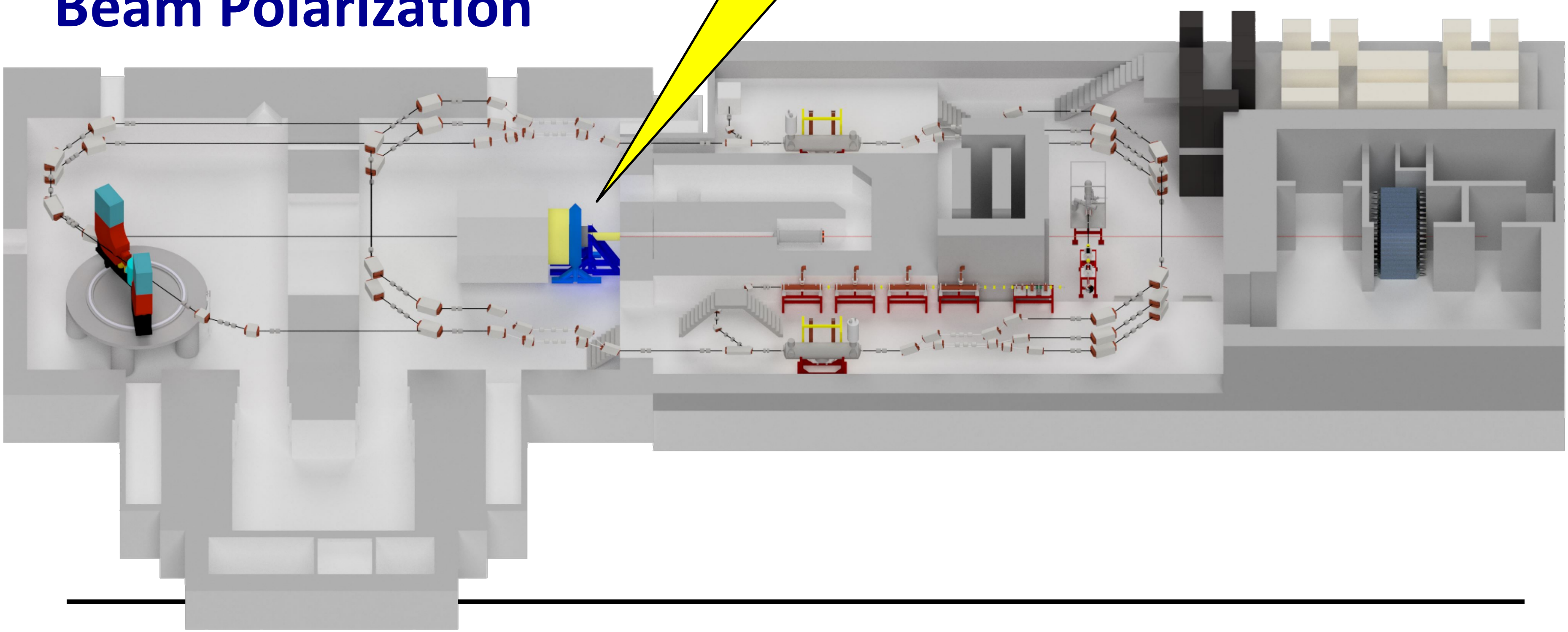
E_{max} = 155 MeV

I_{max} = 150 µA

Beam Polarization

Mode 1:
Extracted Beam
P2 Experiment

3 recirculations → 6 passes through SRF cavities



MESA Accelerator

Mainz Energy-Recovering Superconducting Accelerator

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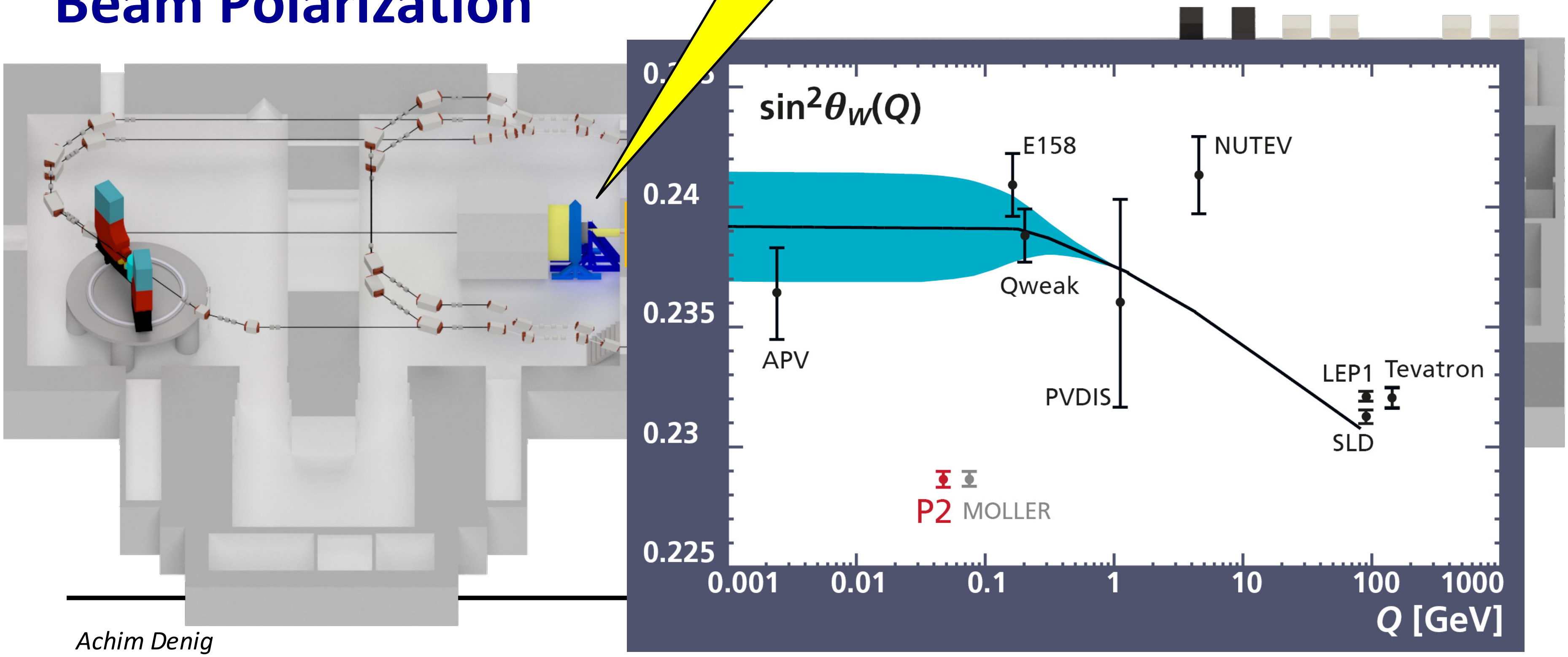

Achim Denig

MESA Accelerator

Mainz Energy-Recovering Superconducting Accelerator

Extracted Beam Mode

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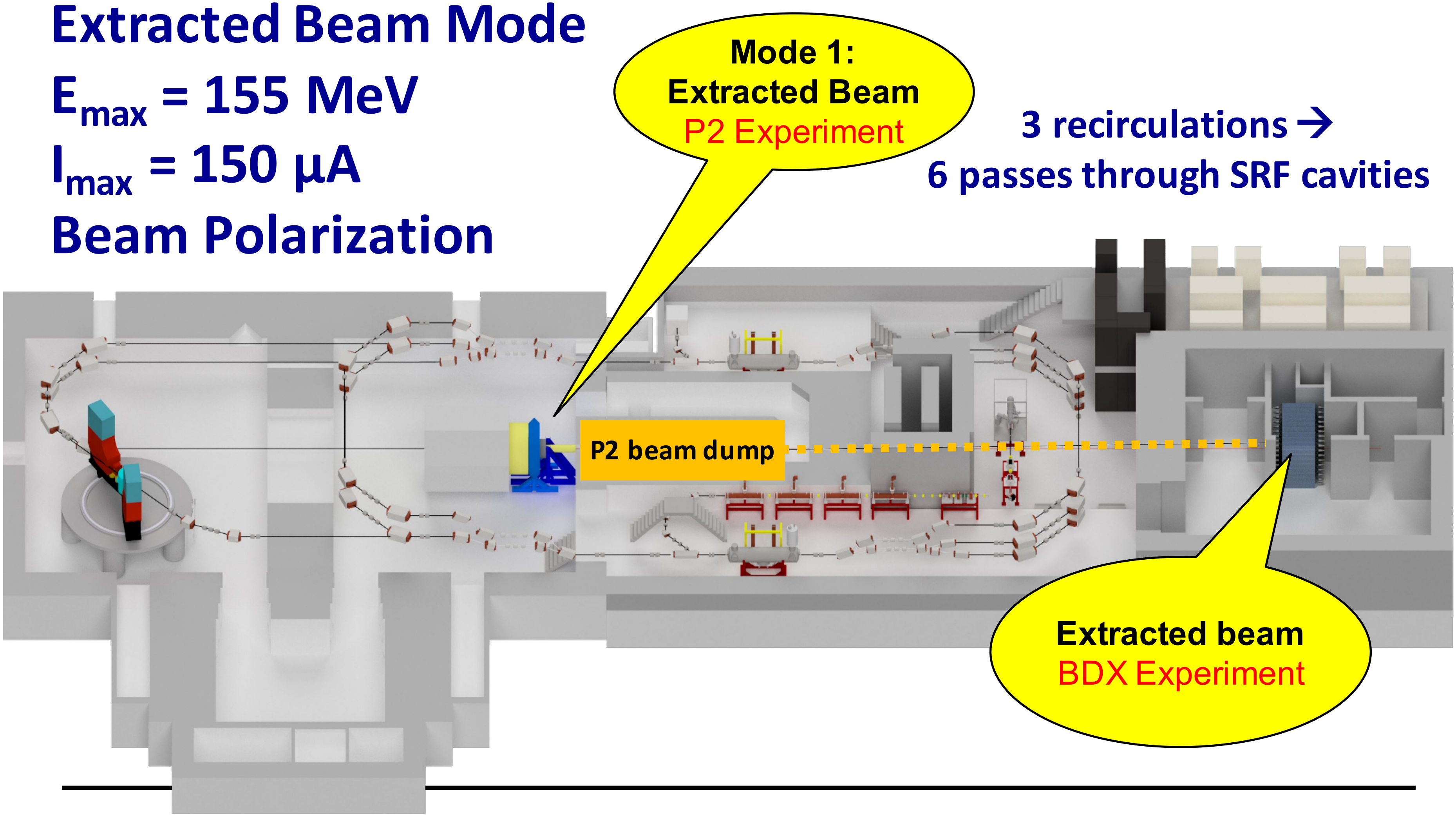


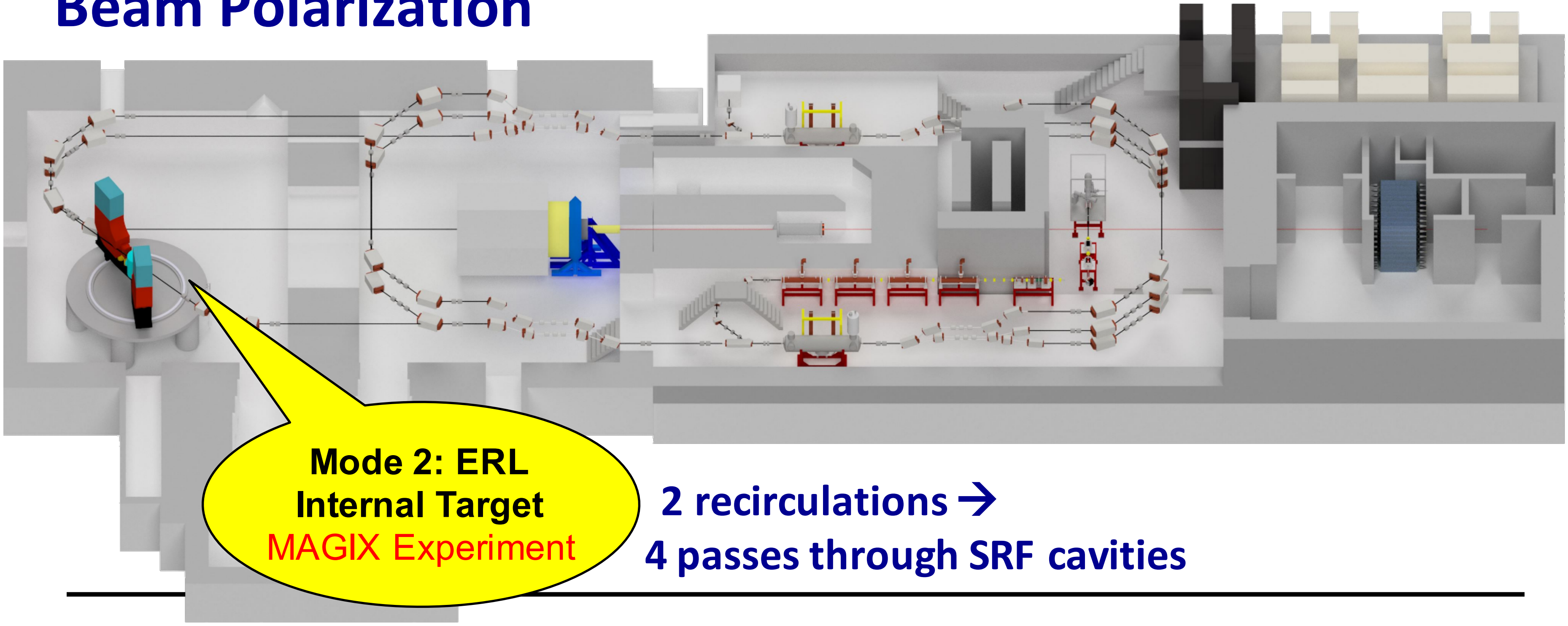
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL Mode

E_{max} = 105 MeV

I_{max} > 1 mA

Beam Polarization



Mode 2: ERL
Internal Target
MAGIX Experiment

2 recirculations →
4 passes through SRF cavities

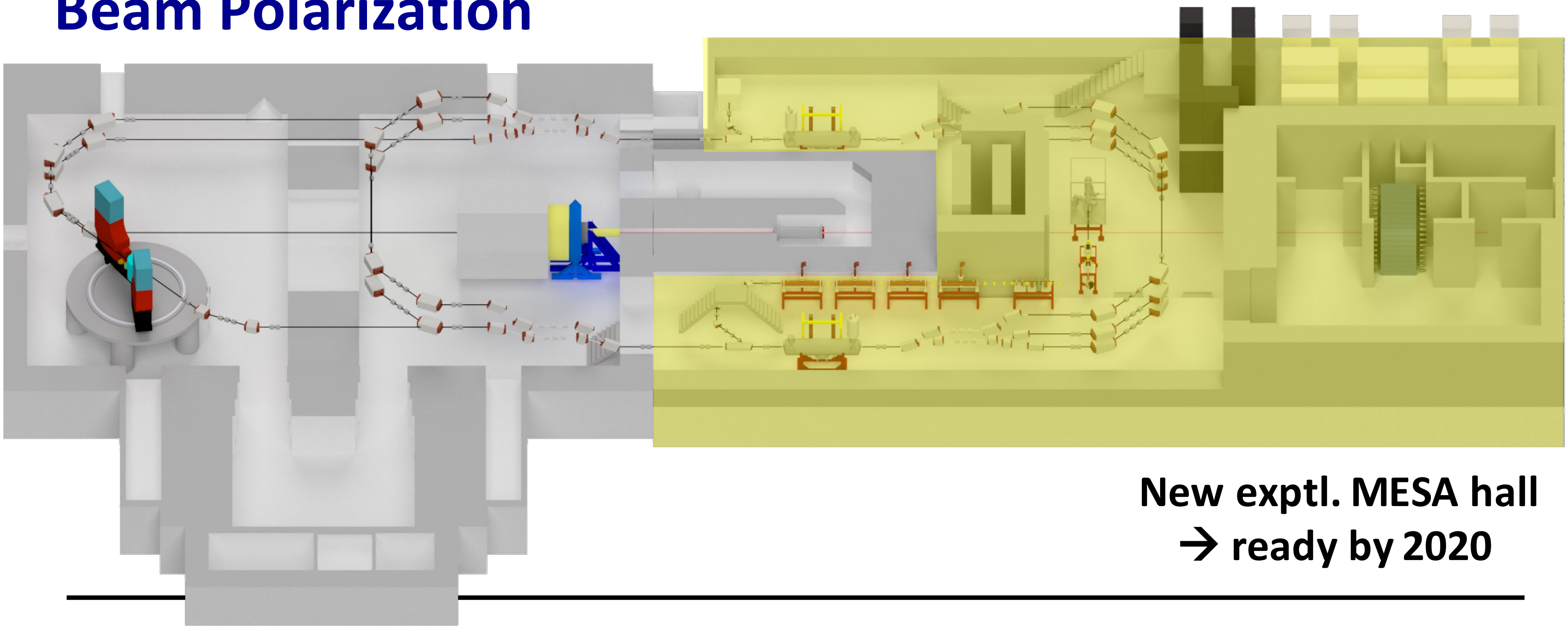
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL Mode

E_{max} = 105 MeV

I_{max} > 1 mA

Beam Polarization

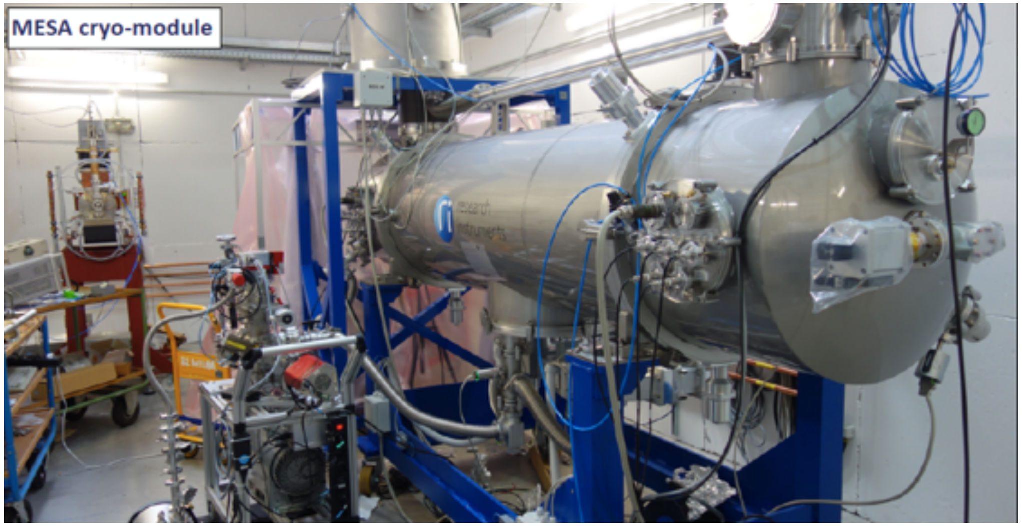


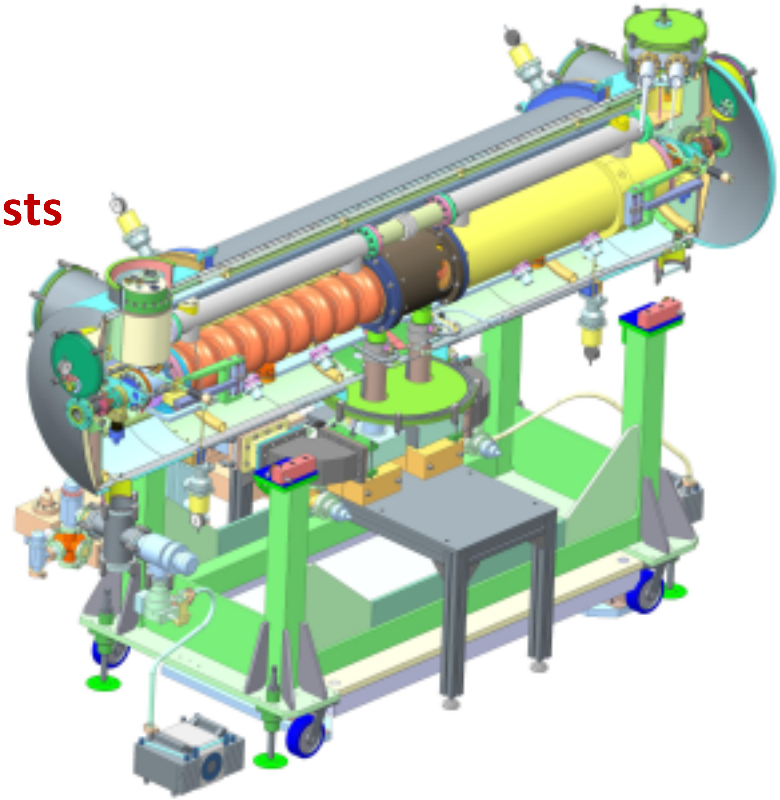
New exptl. MESA hall
→ ready by 2020

Status MESA Cryomodules

Cryomodules of the 'Rossendorf'-type
(2 x 9-cell TESLA/XFEL cavities)

→ Specifications achieved in successful DESY tests
→ 1 mA beam current
→ 2 modules being tested now in Mainz





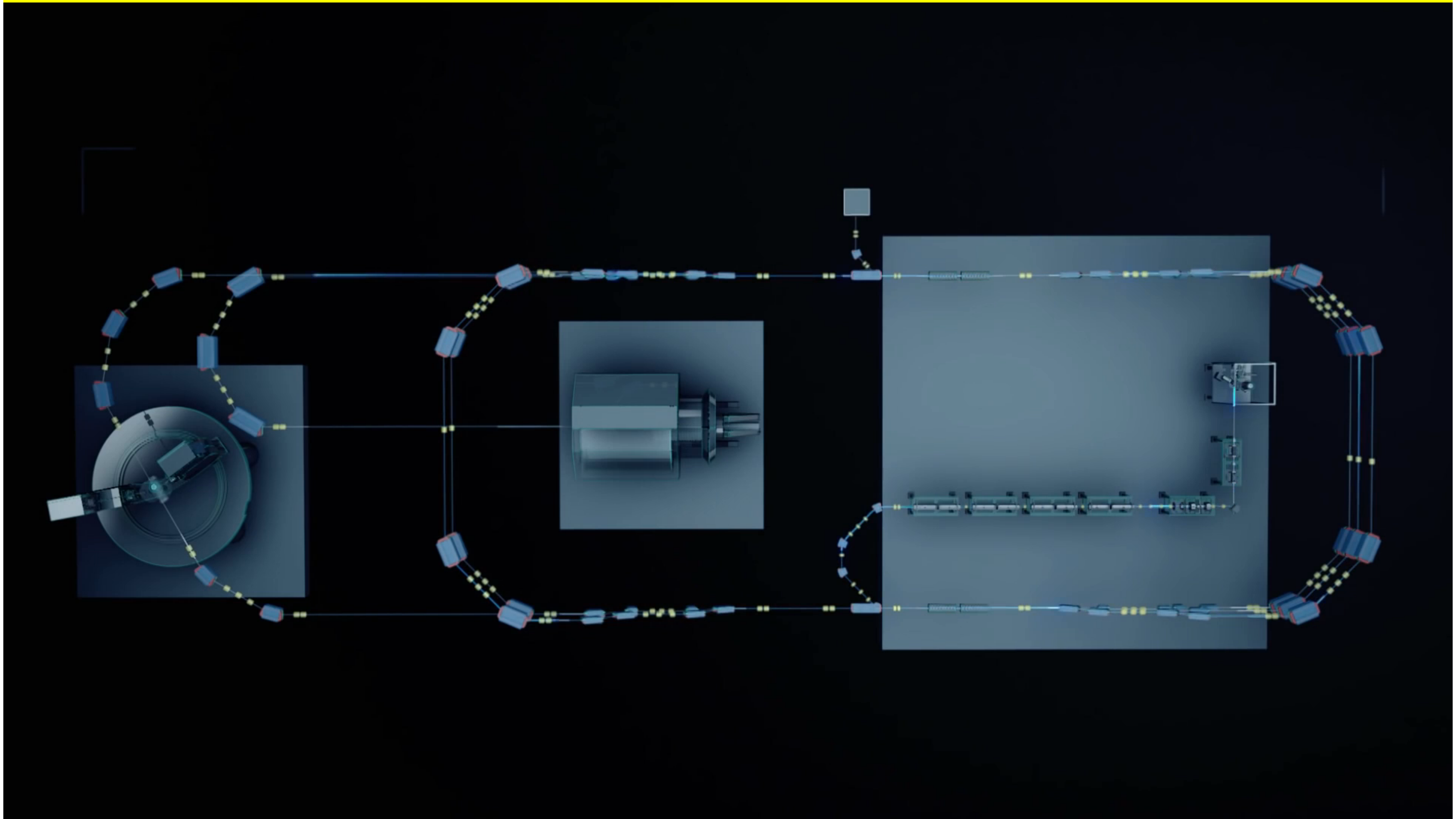
MESA commissioning 2021

Outline of this Talk

- The MAGIX experiment at MESA
- Nucleon Form Factor Measurements
- Few Body Programme at MAGIX
- Search for the Dark Photon and Light Dark Matter
- Conclusions

Internal Exper. MAGIX @ MESA ERL Mode

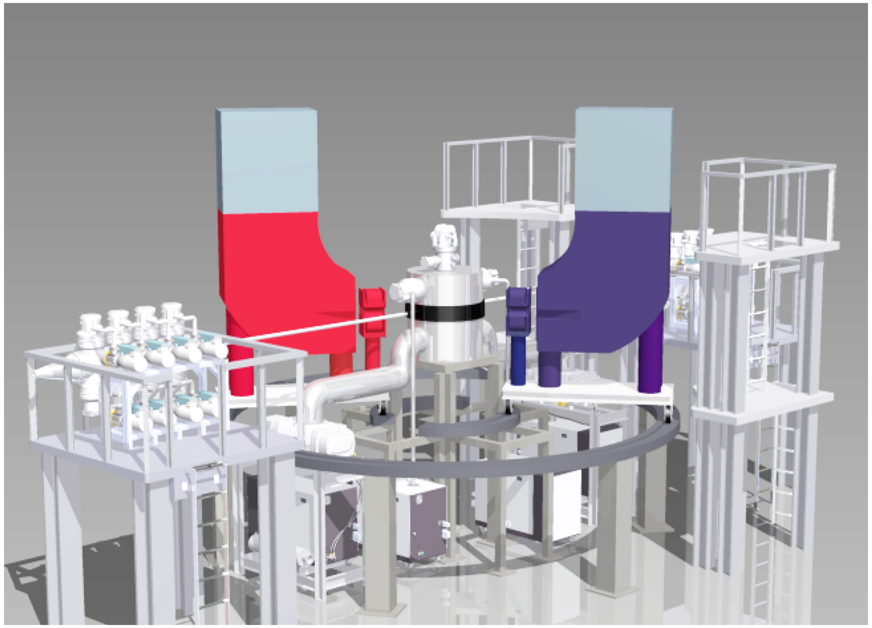
Operation of a high-intensity (polarized) ERL beam
in conjunction with light internal target
→ a novel technique in nuclear and particle physics
→ precise measurement of low momenta tracks at competitive luminosities

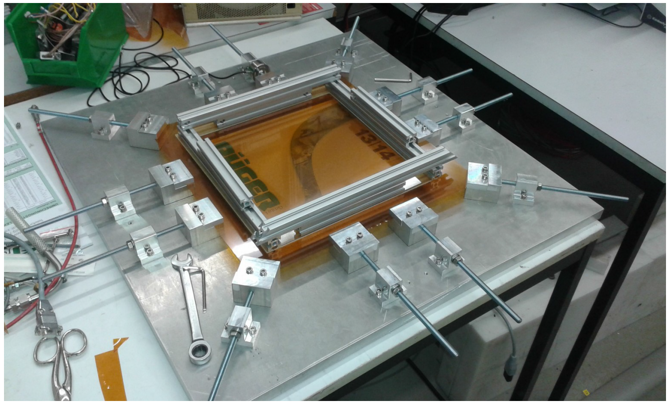


The MAGIX Spectrometers

High resolution spectrometers MAGIX:

- double arm, compact design
- momentum resolution: $\Delta p/p < 10^{-4}$
- acceptance: ±50 msr
- GEM- or TPC-based focal plane detectors

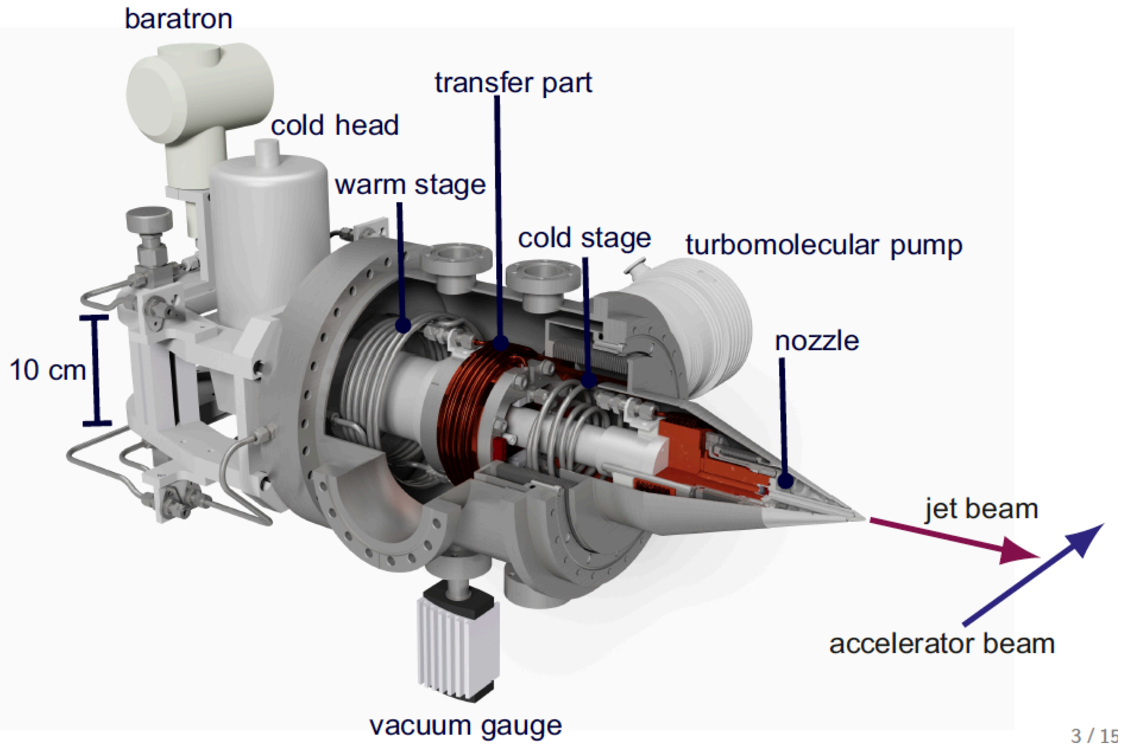


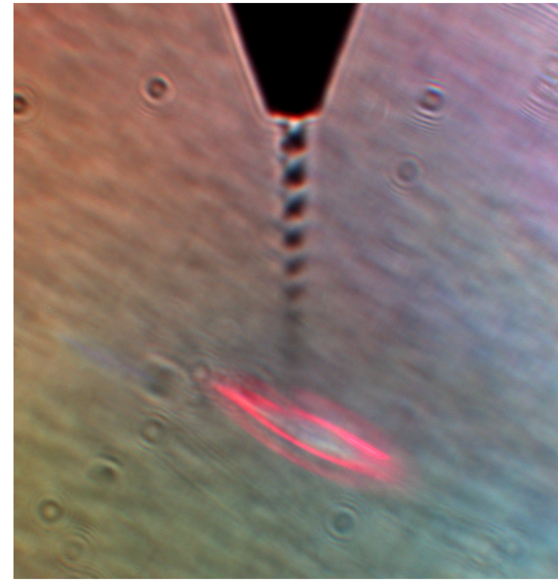


GEM technology for focal plane
Latest design: GEM-TPC

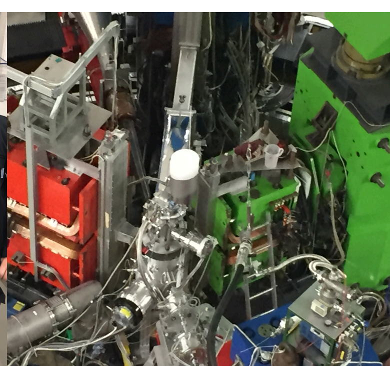
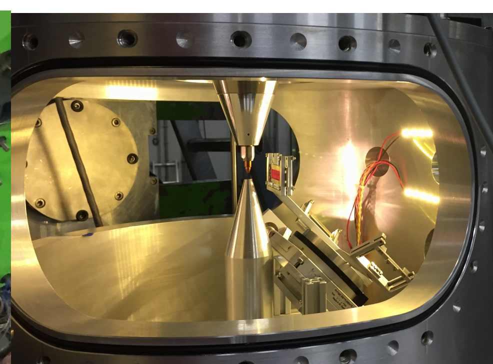
- Gas Jet or polarized T-shaped target for polarized target measurements

Supersonic Gas-Jet-Target





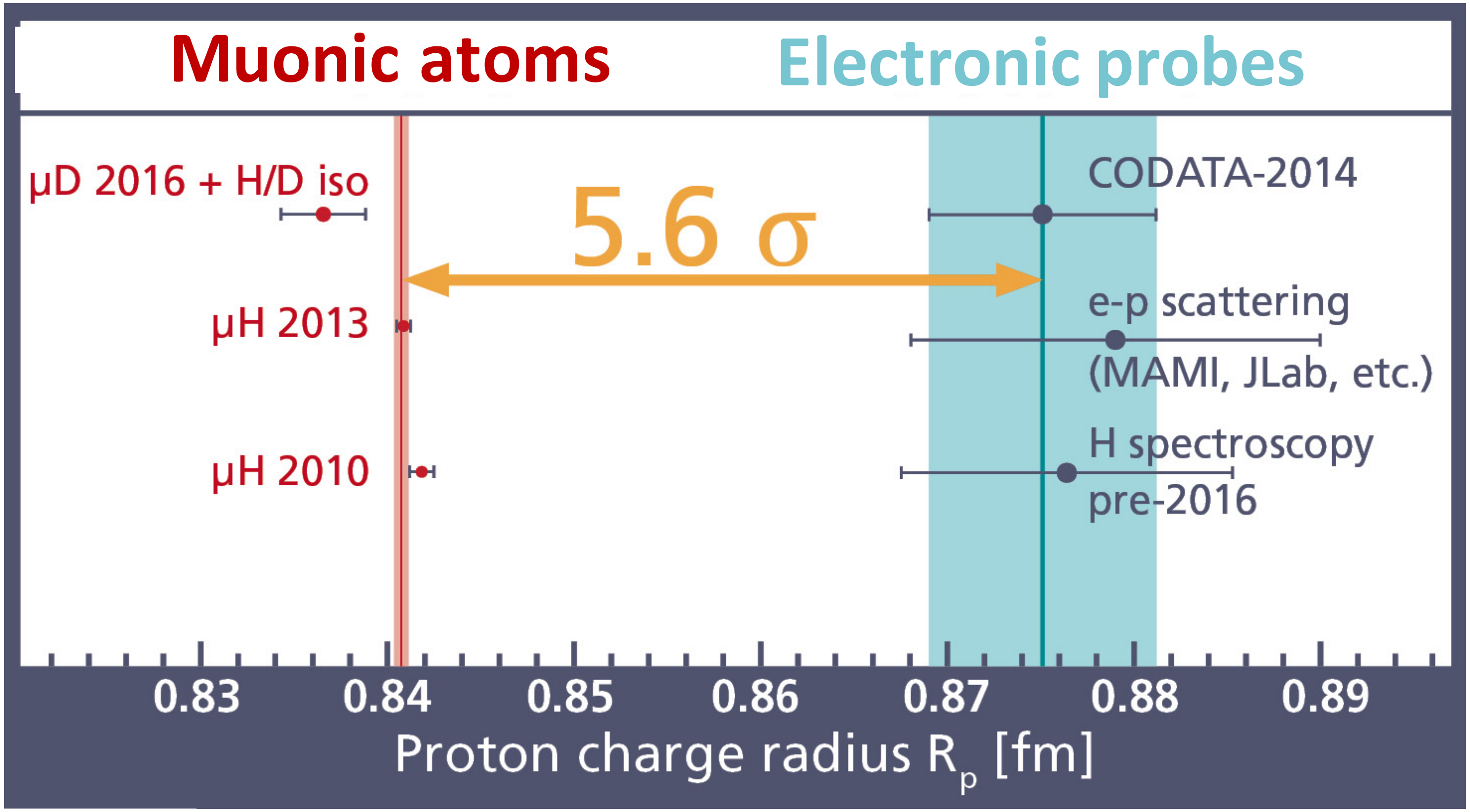
Commissioned in 2017/18

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

Nucleon
Form Factors

The Proton Radius Puzzle



EM Form Factors of the Proton

Elastic form factors in ep scattering:

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

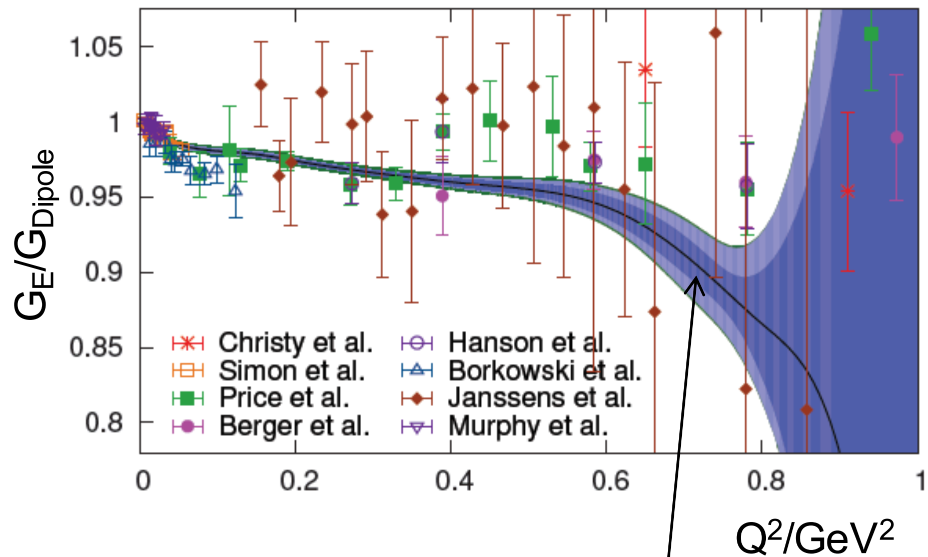
$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

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

G_E: spatial electric charge distribution

G_M: distribution of magnetic moments

Super-Rosenbluth measurement



average of all fit models with uncertainties

Proton charge radius:

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

PRL10 (A1): $\langle r_E \rangle$ = 0,879(8) fm

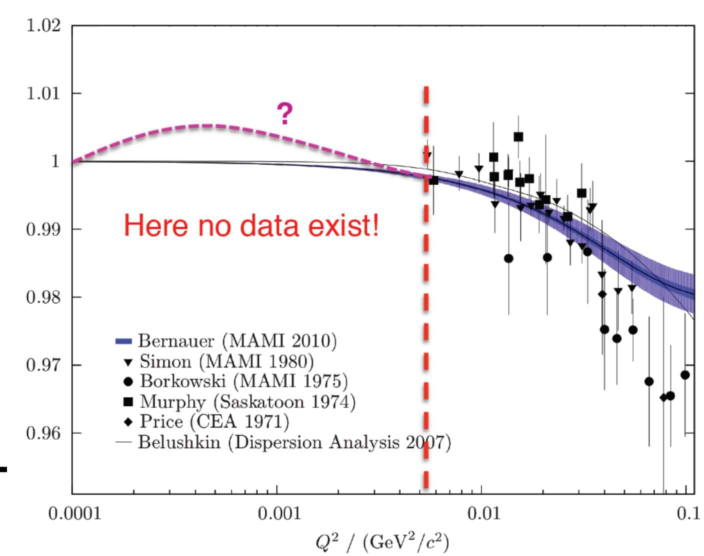
PRL '10, 242001: Bernauer et al.
PRC '14 015206: Bernauer et al.

Proton Radius Puzzle - What is going on?

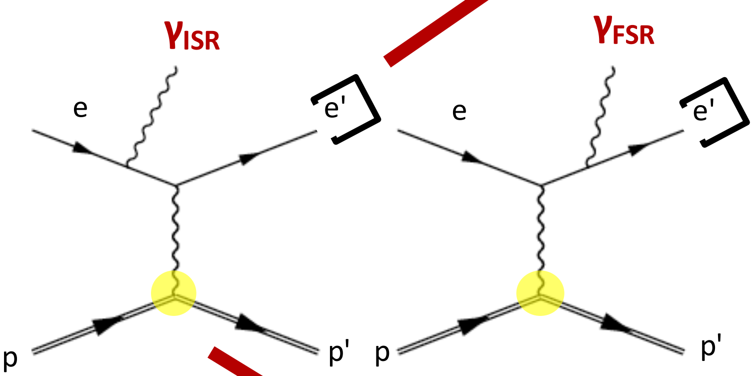
A worldwide effort in atomic physics, hadron/particle physics and theory

- **New Physics explanation ?**
  Lepton – Non-Universality !
  Different coupling of electron-proton vs. muon-proton
  → light or heavy new particles (Dark Photon)?

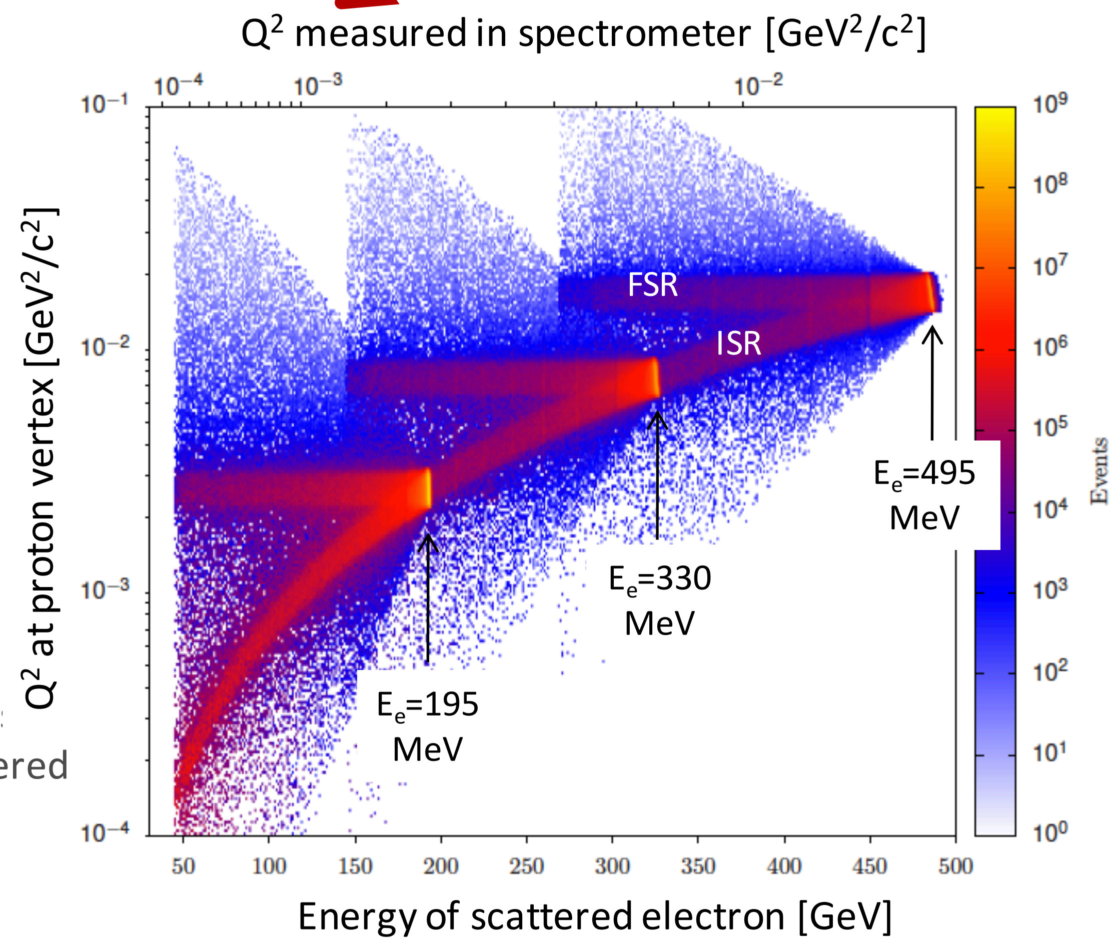
- **Electron scattering expts. not at sufficiently low Q^2 ?**
  → Provide data at lower Q^2!



ISR Measurement of EM Form Factors



Initial State Radiation   Final State Radiation



Strategy:

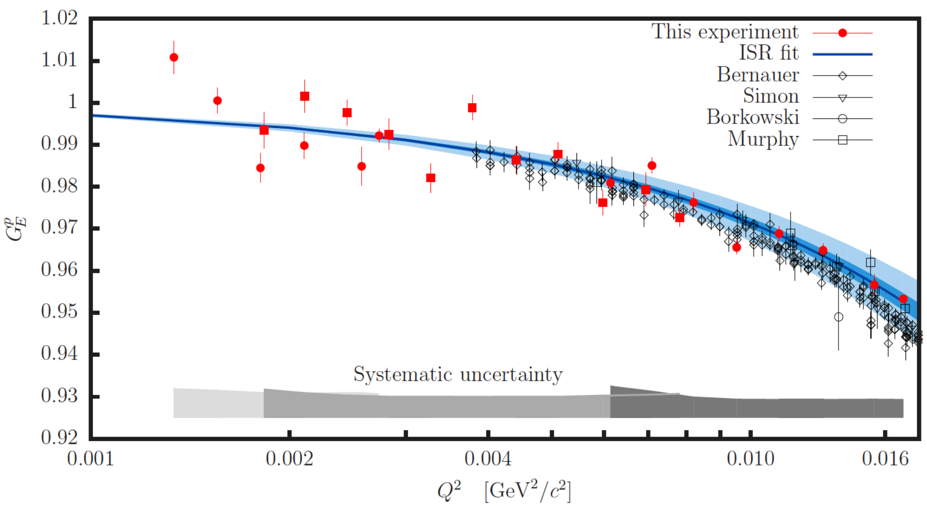
- Very low values of Q^2 by using ISR events
- Measure momentum spectrum of scattered electron
- Needs very good understanding of QED radiative corrections and FSR

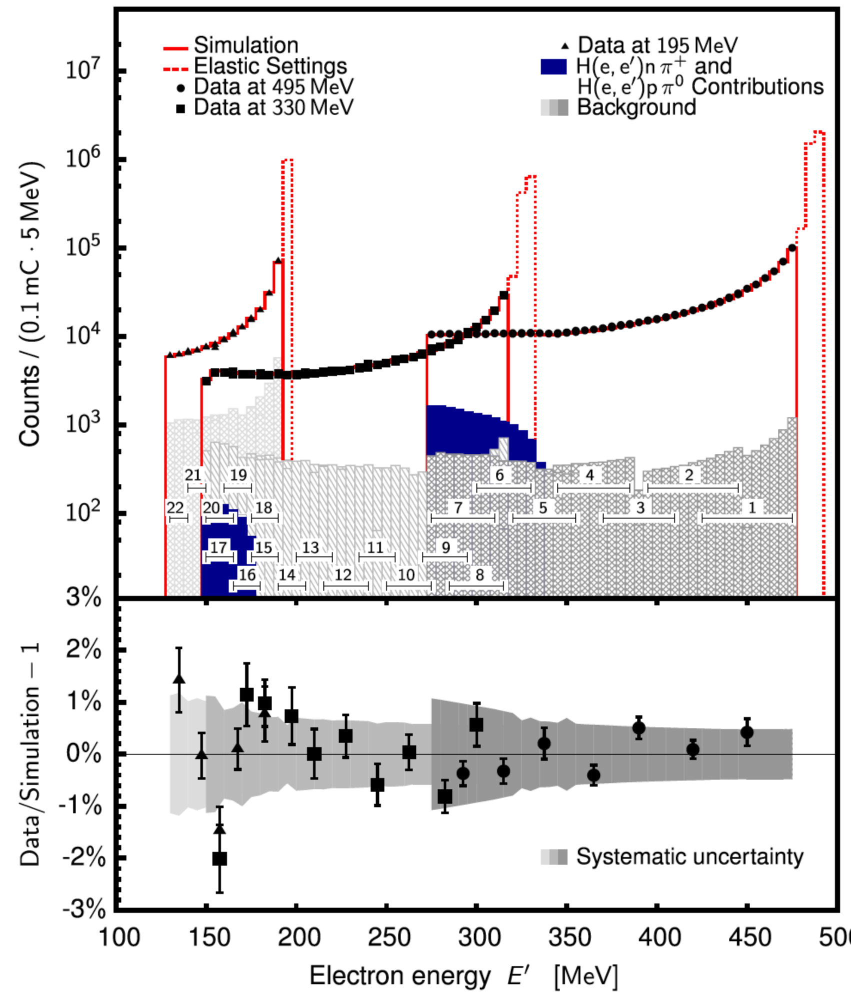
→ Access low Q^2 values down to 2×10^{-4}

ISR Measurement of EM Form Factors

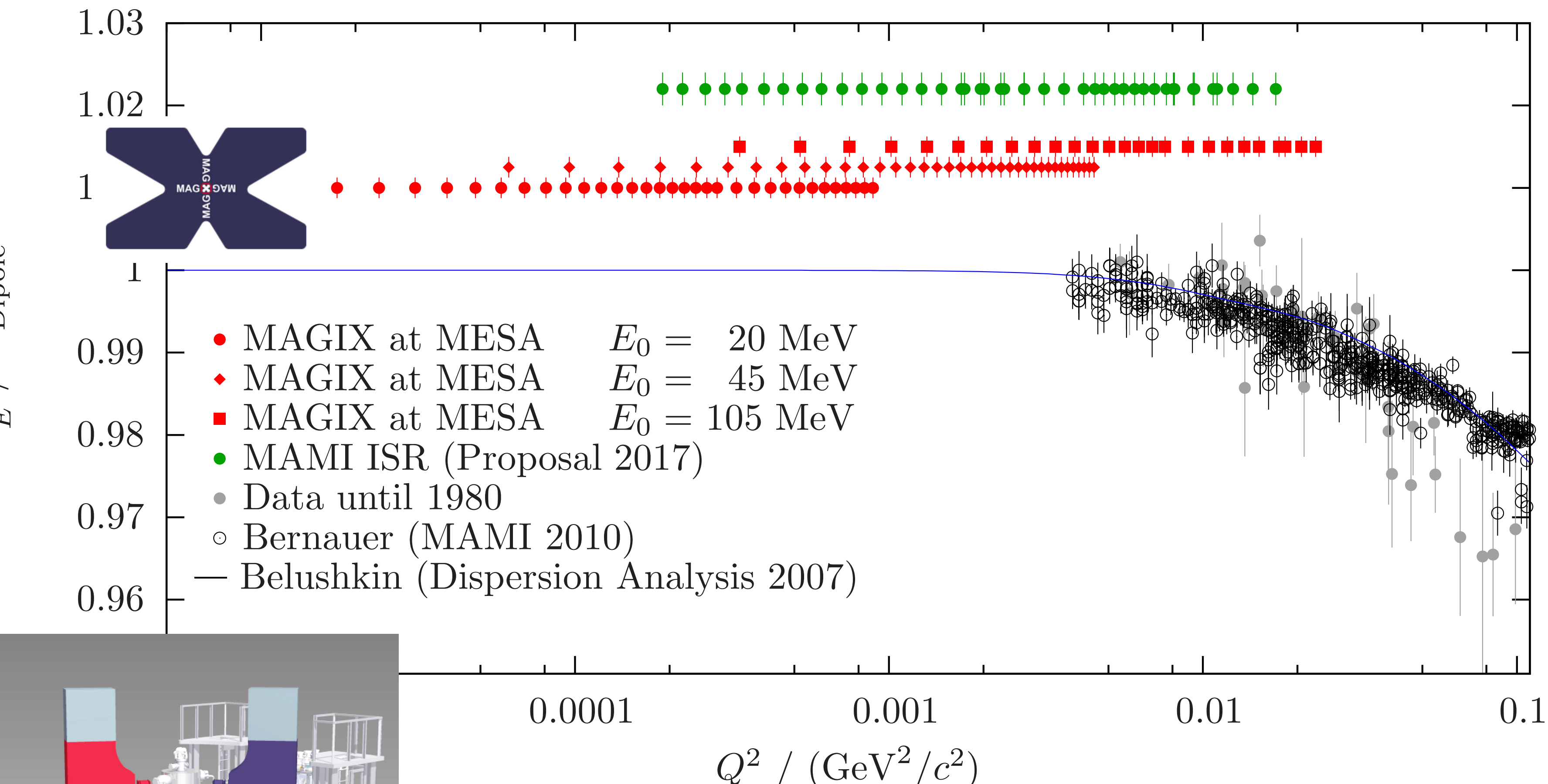
M. Mihovilovic, A.B. Weber et al. [A1 collaboration] Phys. Lett. B771 (2017) 194

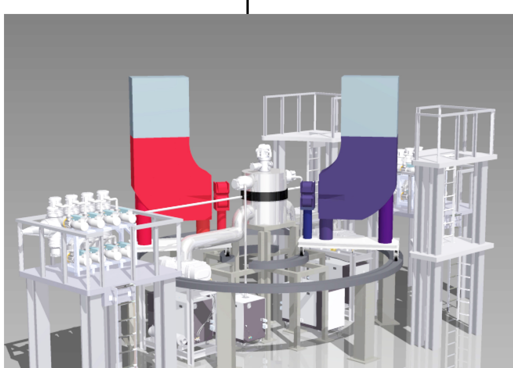
- Feasibility of method proven
- Access to unexplored Q^2 ranges below 4 x 10^{-3} GeV^2
- Significant systematic uncertainties





Low-Q^2 Scattering Data with MAGIX





Magnetic Form Factor @ MAGIX

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{\varepsilon(1+\tau)} \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right] \quad \tau = \frac{Q^2}{4m_p^2}$$

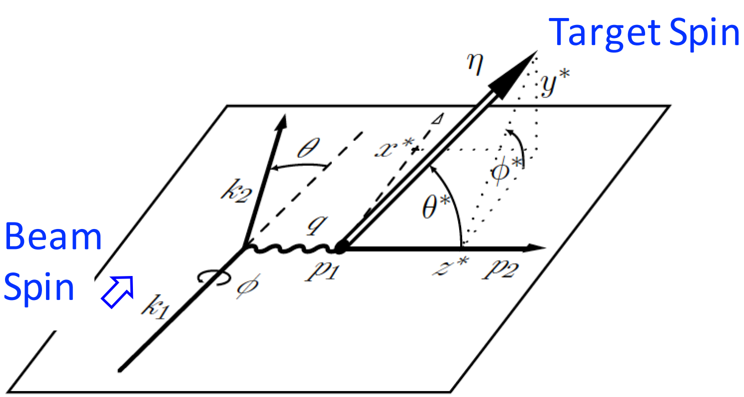
$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

long. polarization of virtual photon

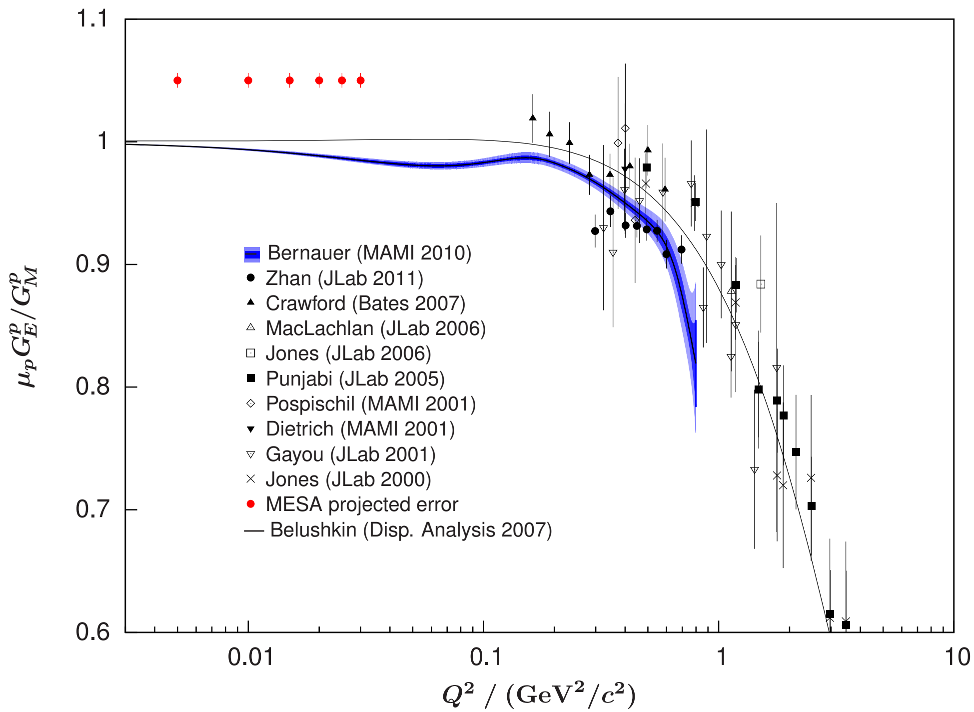
Low Q^2 accessible with low E_{beam}

Suppressed at low Q^2 due to τ

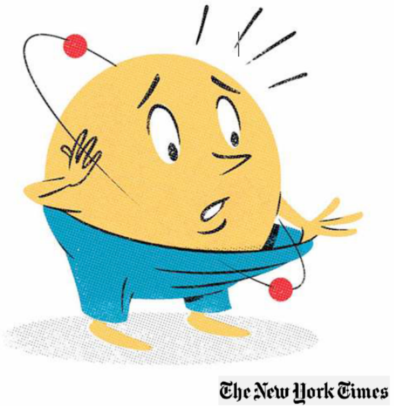
→ Double polarization measurement
Beam Target Asymmetry !



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



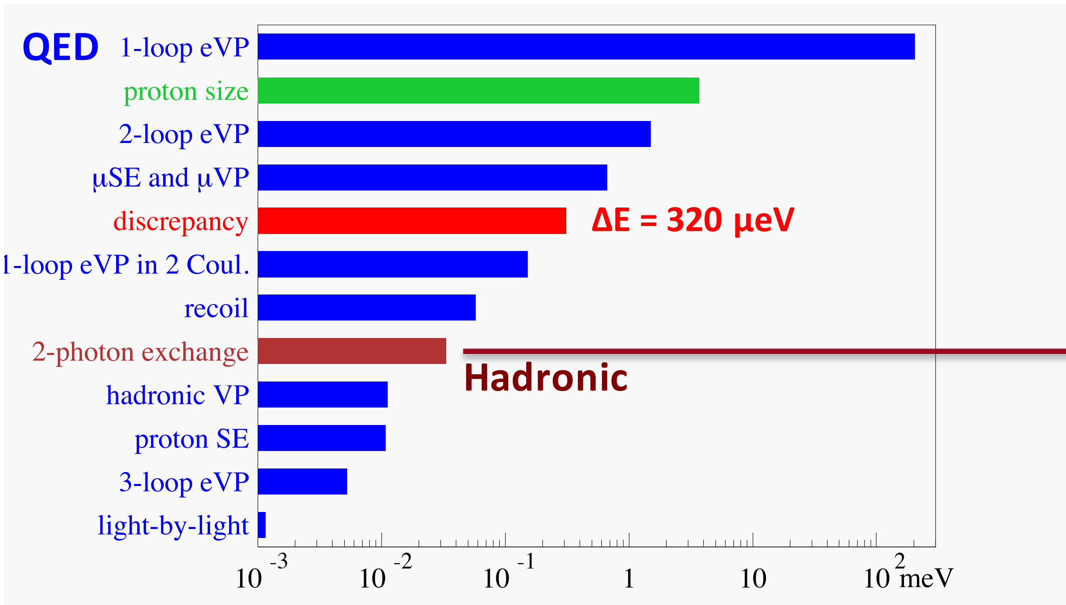
Proton Radius Puzzle - What is going on?

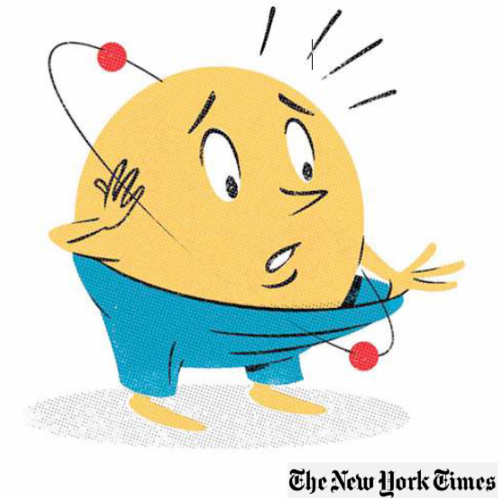


- **New Physics explanation ?**
  Lepton – Non-Universality !
- **Electron scattering expts. not at sufficiently low Q^2**
- **Unknown QED / hadronic correction in μH data ?**

Corrections in μH

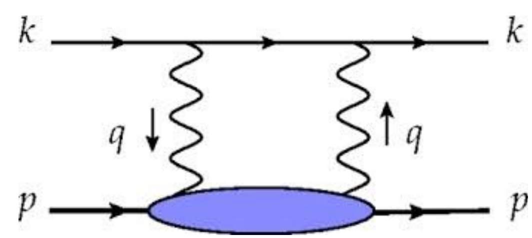
Corrections in muonic hydrogen Lamb Shift





largest hadronic correction / uncertainty:

$\Delta E_{2\gamma}$ = (33 ±2) μeV



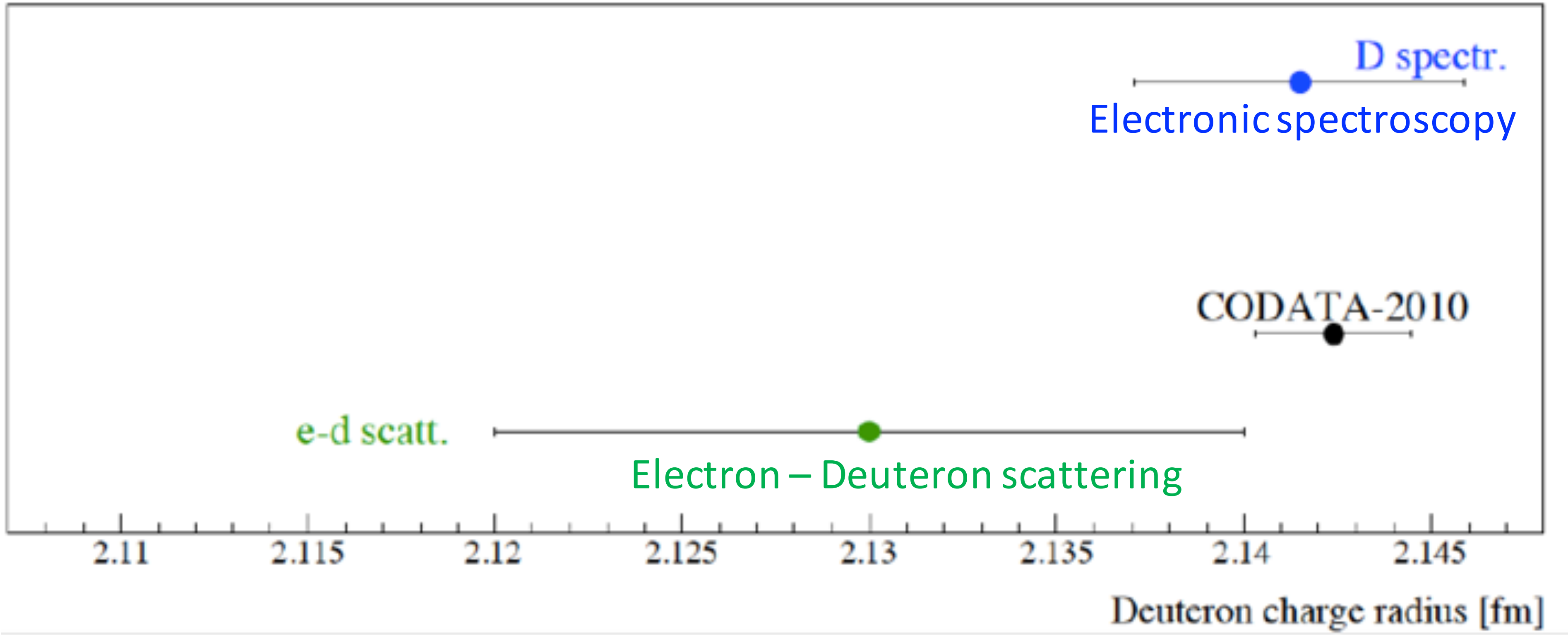
Carlson, Vanderhaeghen 2011
Birse, Mc Govern 2012

2-Photon exchange
→ Forward Compton scattering
→ **Uncertainty dominated by the magnetic polarizability β**

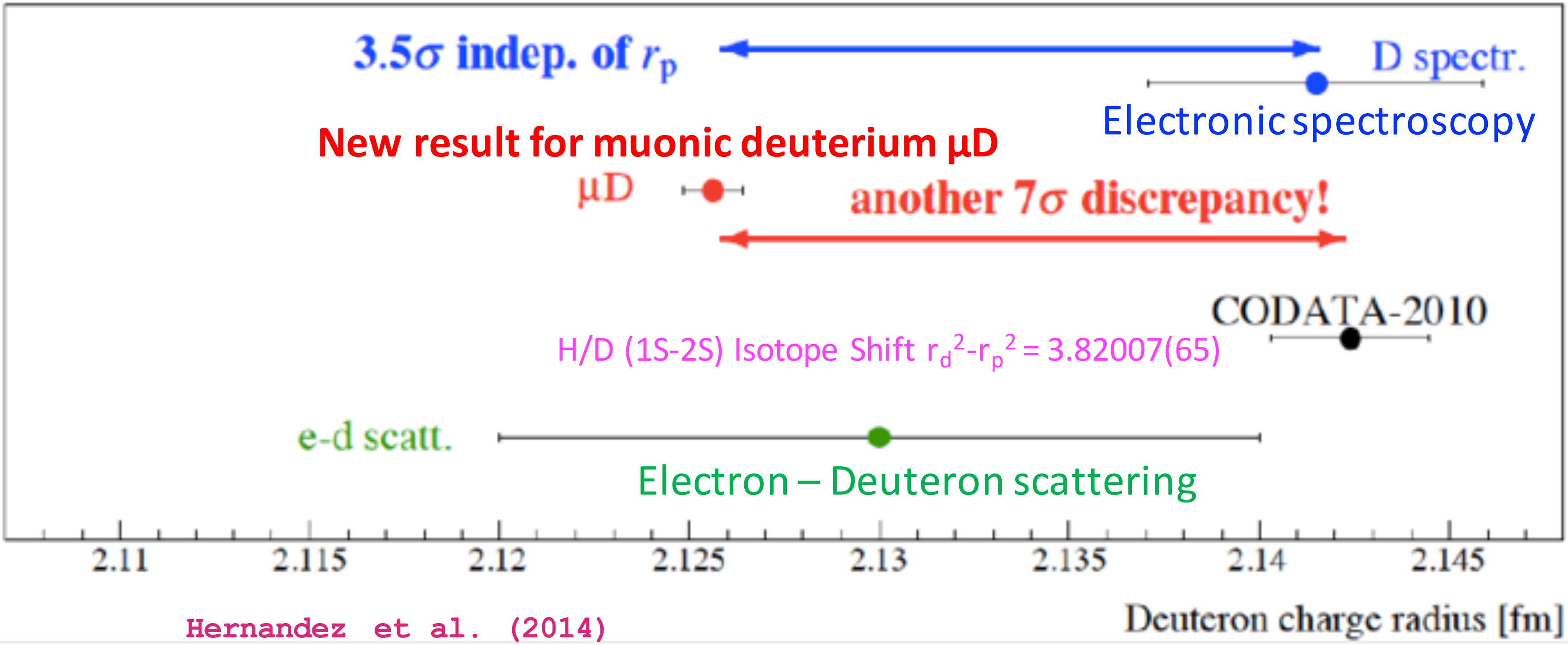
Few Body Systems

More Puzzles ?

Few Body Programme at MAGIX



Few Body Programme at MAGIX

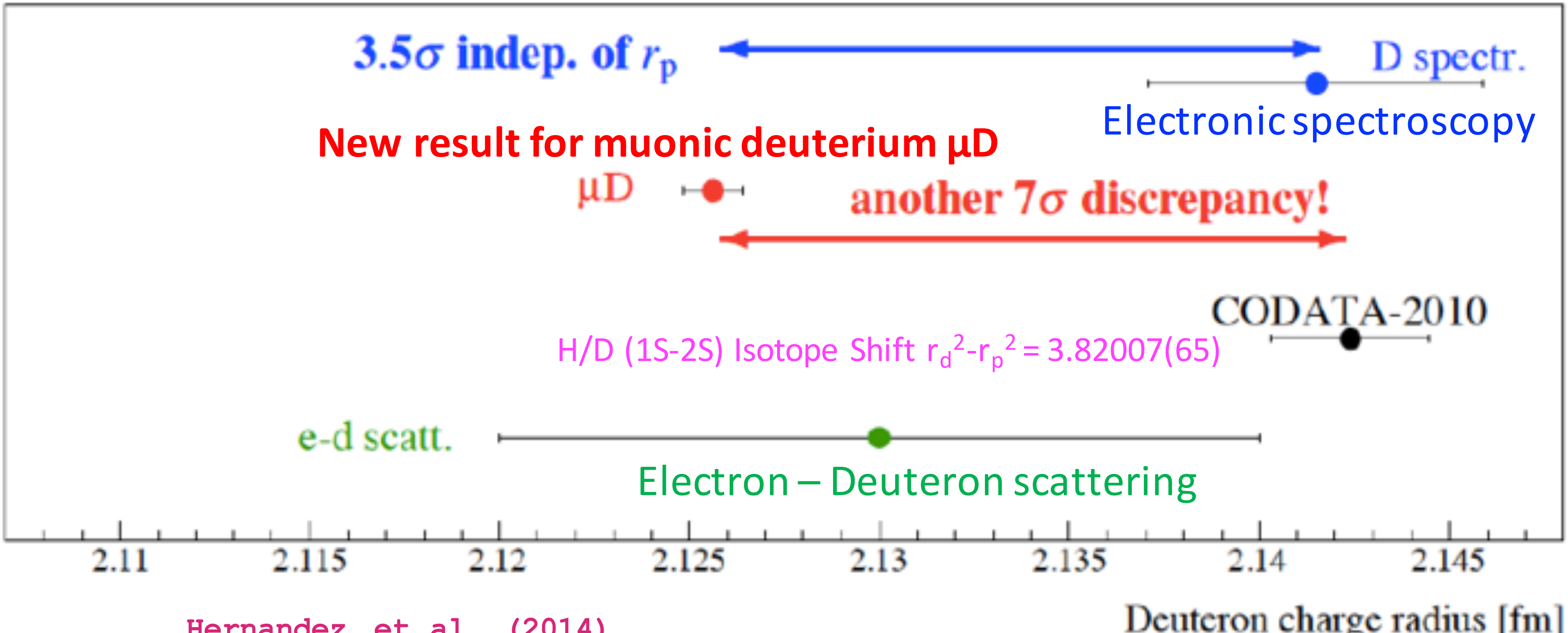


Hernandez et al. (2014)

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

accuracy factor 5 worse than present experimental intrinsic precision

Few Body Programme at MAGIX



Hernandez et al. (2014)

μD: $\Delta E^{TPE} = (1727 \pm 20)$ μeV nucleon potentials form chiral EFT

accuracy factor 5 worse than present experimental intrinsic precision

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

Nevo Dinur, Ji, Bacca, Barnea (2016)

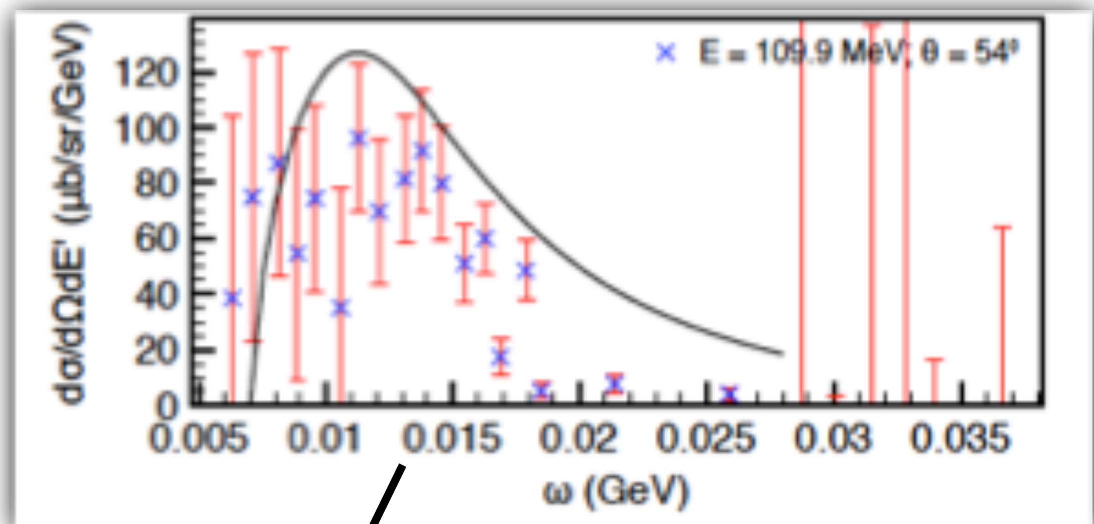
(15.14 ± 0.49) meV dispersive analysis

Carlson, Gorchtein, Vanderhaeghen (2016)

Hadronic Corrections in Light Nuclei Systems

Carlson, Gorchtein, Vanderhaeghen (2016)

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



Kinematics	δa_2	$\delta(\Delta E_{2S}^{\text{nuclear}})$	$\delta(\Delta E_{2S}^{\text{TPE}})$
$E = 110$ MeV			
$\theta = 54°$	±0.014	0.40 meV	0.49 meV
$\theta = 30°$	±0.0075	0.21 meV	0.35 meV
$\theta = 25°$	±0.0055	0.16 meV	0.33 meV
$\theta = 20°$	±0.0040	0.11 meV	0.30 meV

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

Conclusions and outlook (cont.)

What should be measured ?

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

Two-body break-up of ^{3}He

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

Three-body break-up of ^{3}He

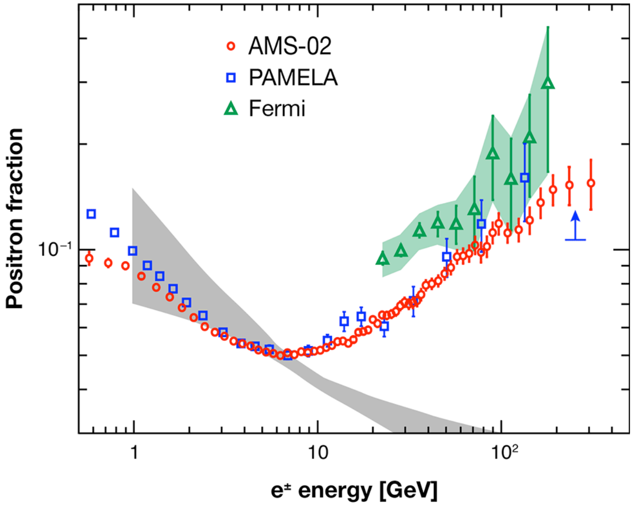
1. Semi-exclusive cross sections (proton and neutron) at various emission angles with respect to the momentum transfer
2. ^{3}He analyzing power
3. Spin-dependent helicity asymmetries

Jacek Golak / LEPP16

JAGIELLONIAN UNIVERSITY IN KRAKOW

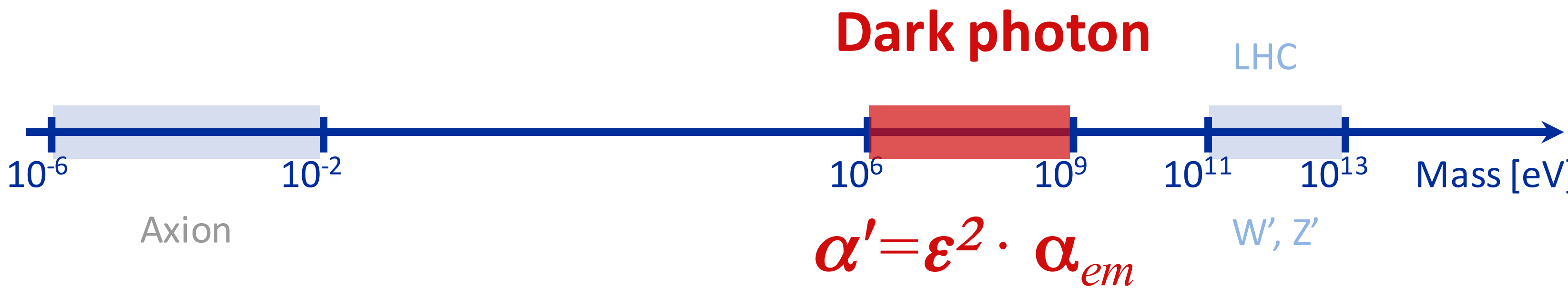
LEPP, Mainz, 7 April 2016

Search for the Dark Photon & Light Dark Matter



Dark Photon

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

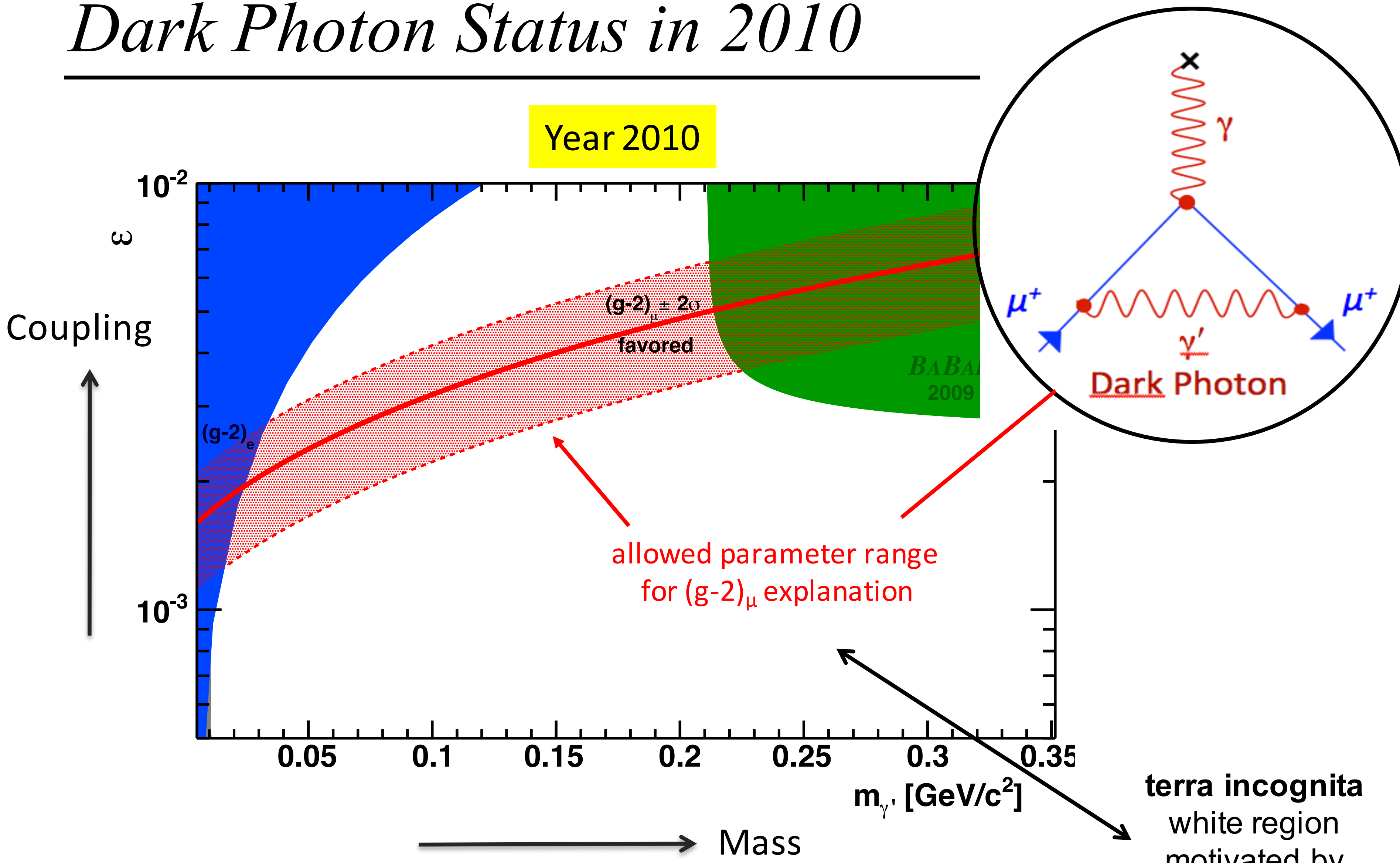


Search for the O(GeV/c²) mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
  Arkani-Hamed et al. (2009)
  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



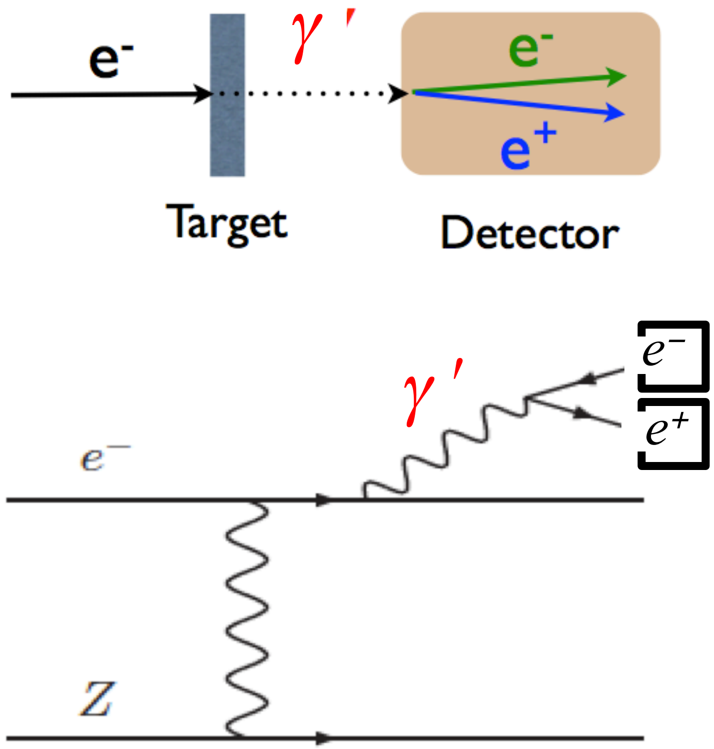
terra incognita
white region
motivated by
dark matter !

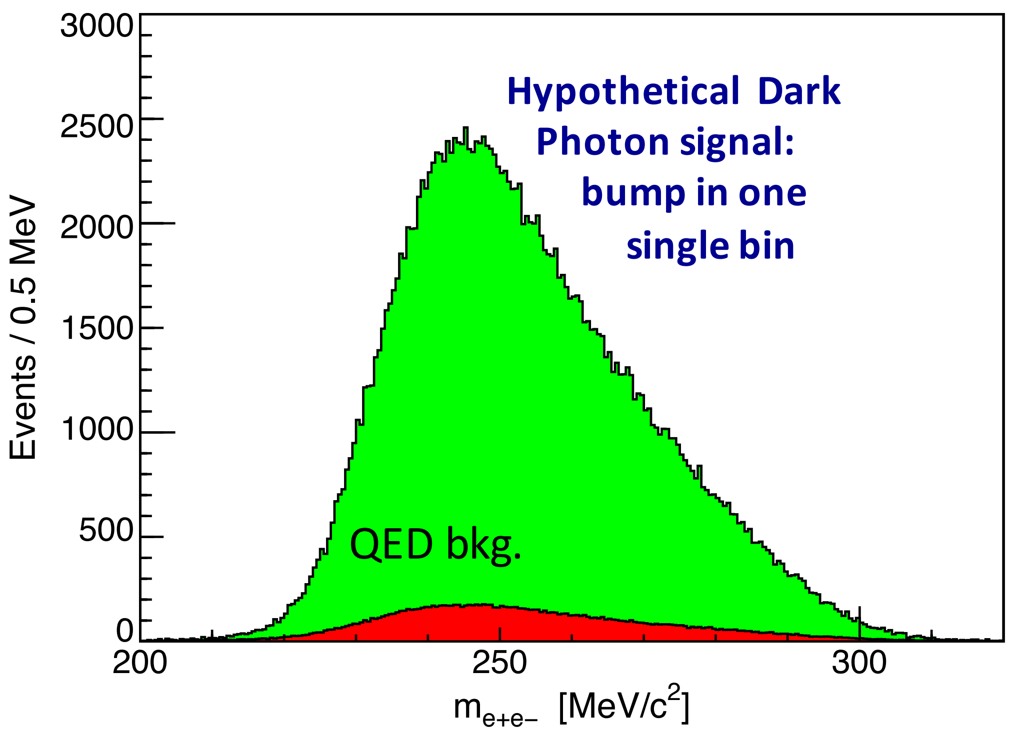
Results from A1

Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search

Bjorken et al. (2009)

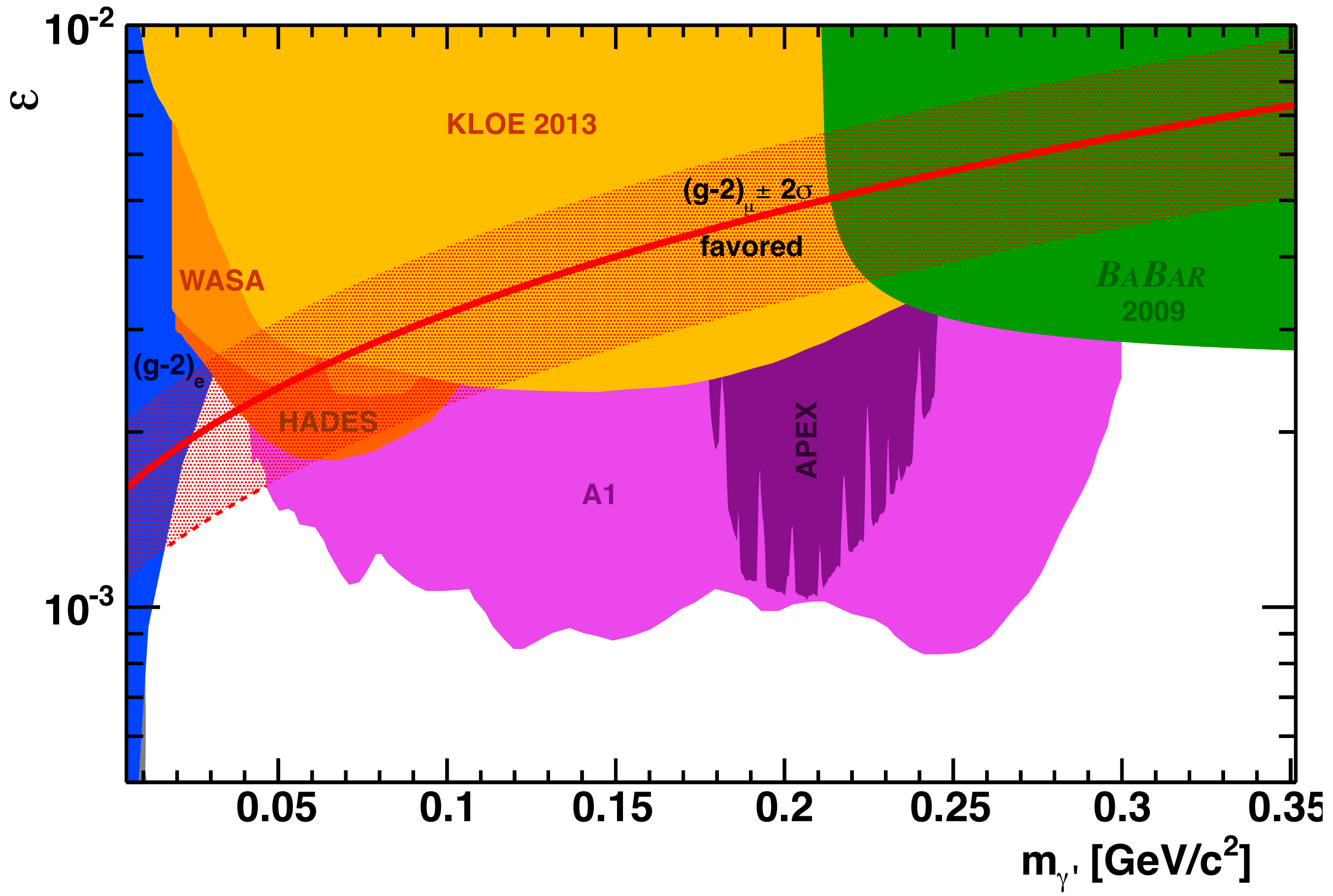
Signal process





Results from A1

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



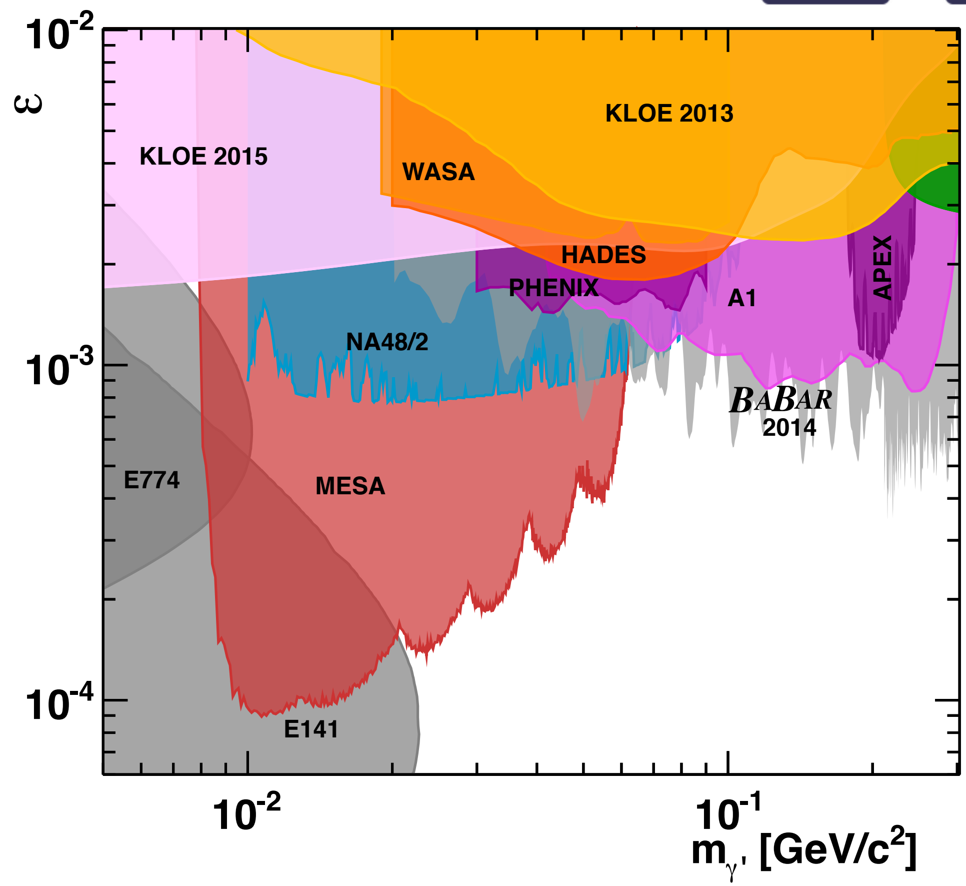
- E_{beam} 180 - 855 MeV
- 100 μA beam current
- Stack of Ta targets
- 22 kinematic settings
- O(1 month) of beam tir

→ 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:

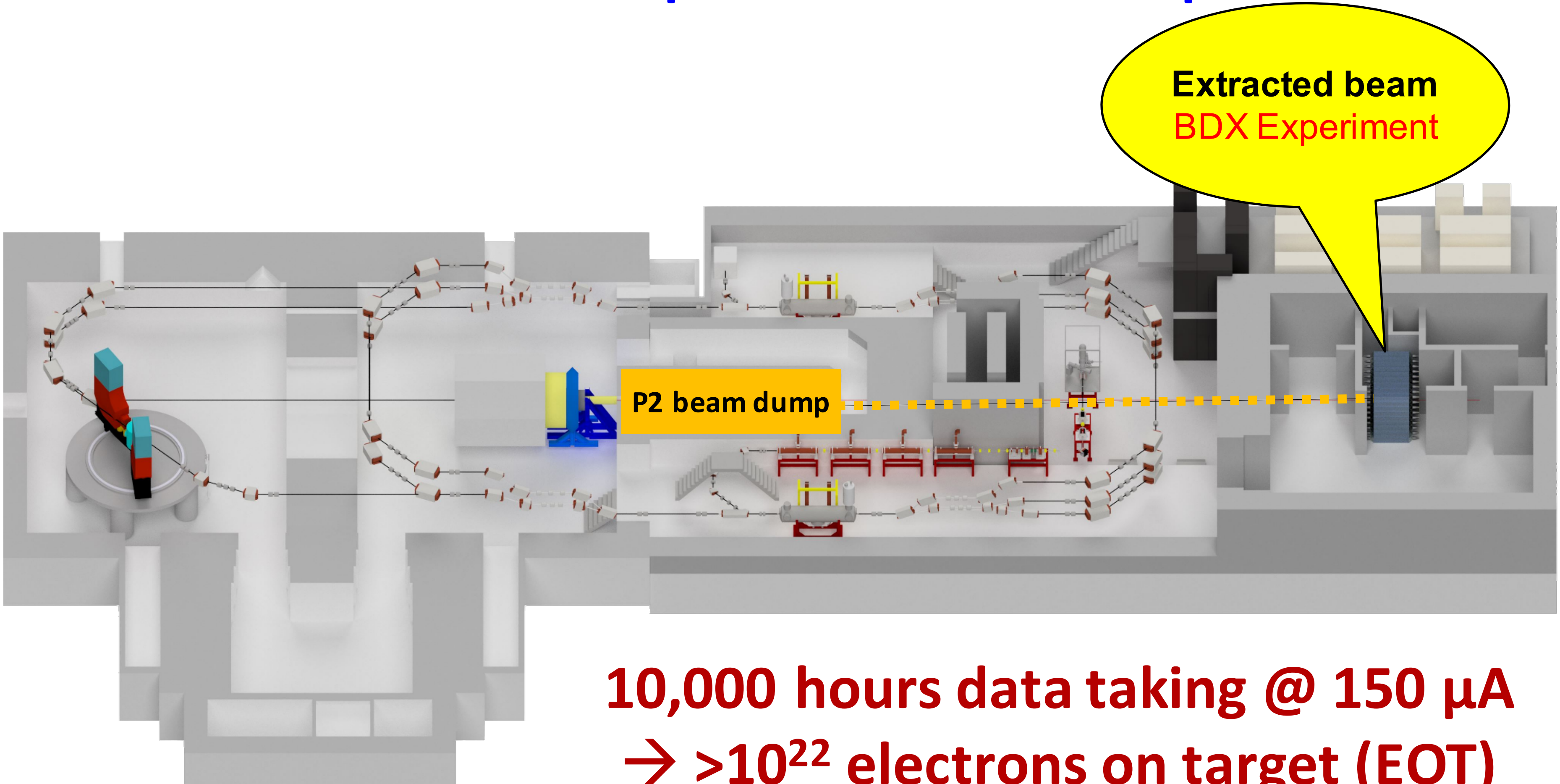
- Xe gas target
- Luminosity 10^{35} cm^{-2}s^{-1}
- 6 month of data taking



Model 1: $m_{\gamma'} \ll m_{\rm DM}$ **Dark Photon decaying into SM particles**

Beam Dump Experiment (BDX) @ MESA

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



10,000 hours data taking @ 150 µA
→ >10^{22} electrons on target (EOT)

Beam Dump Experiment (BDX) @ MESA

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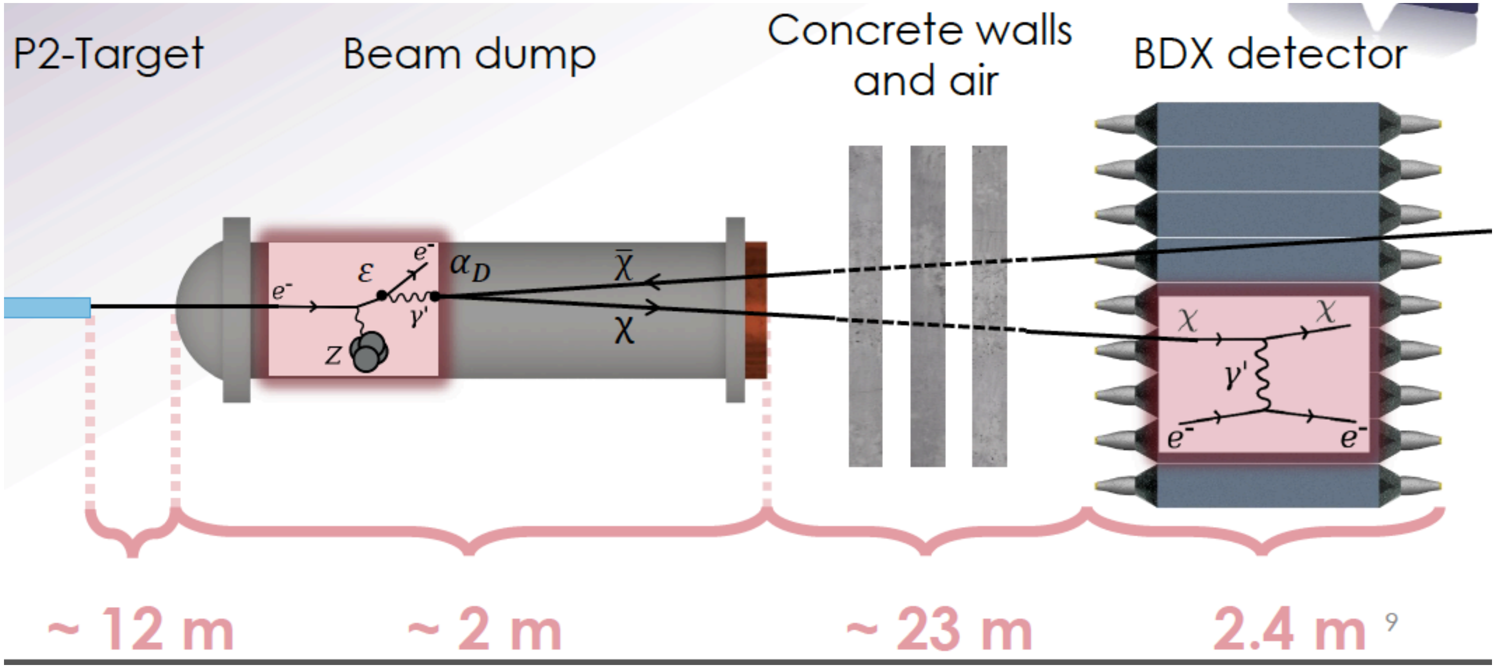

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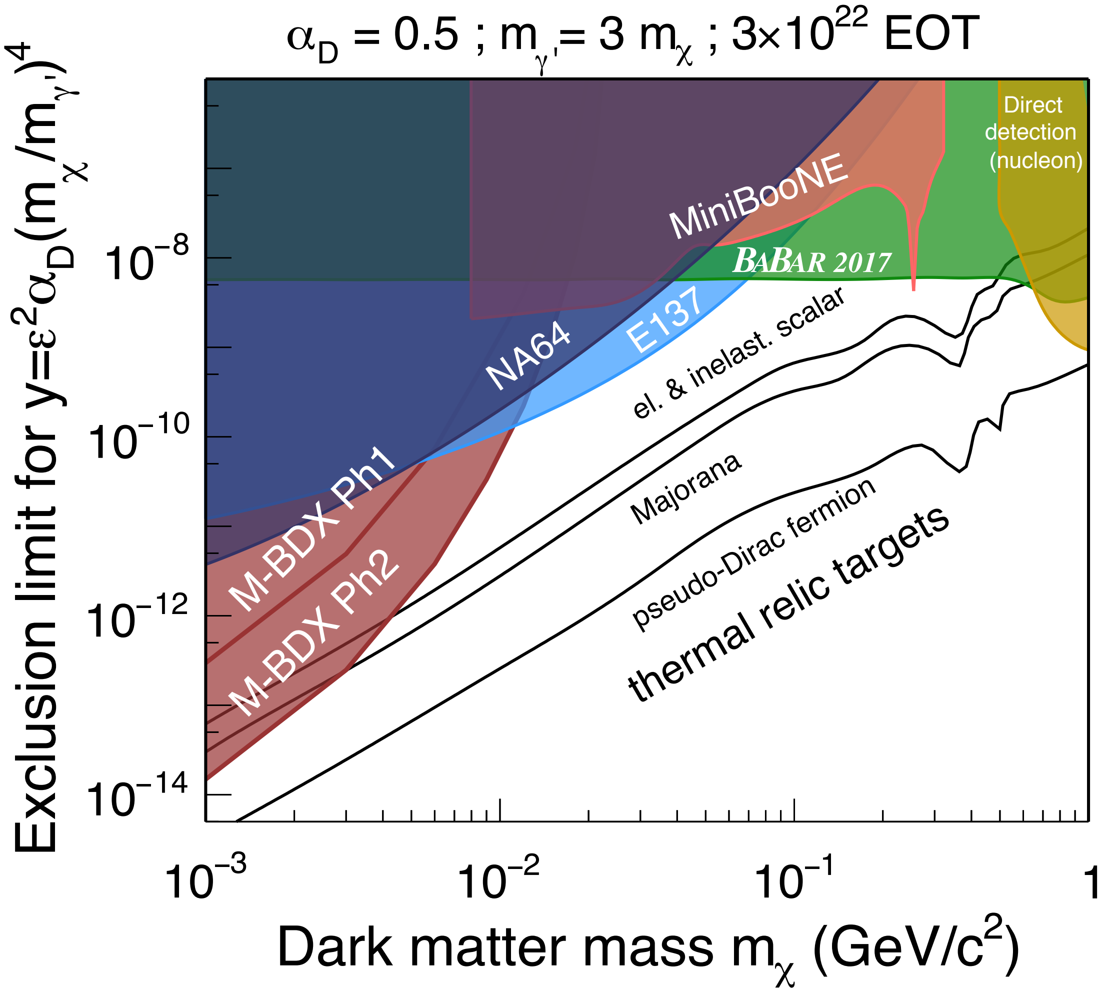
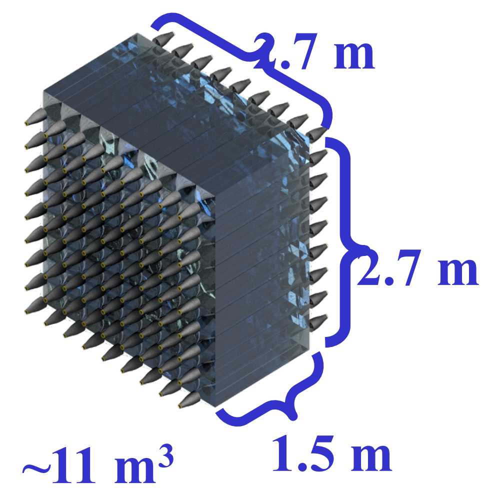


Detector layouts:

- Phase 1: existing PbF2 crystals of A4 experiment (0.13 m^3 volume)
- Phase 2: 11m^3 Leadglass calorimeter



Conclusions MAMI and MESA

- **MAMI electr. accelerator 185 - 1600 MeV**
  Legacy of low-energy hadron physics results

- **New MESA - accelerator < 155 MeV**
  up to 1 mA beam current
  extracted beam mode OR energy recovering mode (ERL)

- **MAGIX experiment at MESA** allows to combine high beam intensities with **internal windowless target** – precision experiments!

- Internal gas target can be operated with **gases from H_2 to Xe**

- **Timely programme in nuclear, hadron and particle physics**

- This workshop: discuss possibilities for **few-body physics**