Achim Denig

Institute for Nuclear Physics
Johannes Gutenberg University Mainz

Recent Results and future Perspectives for Hadron Physics at Mainz

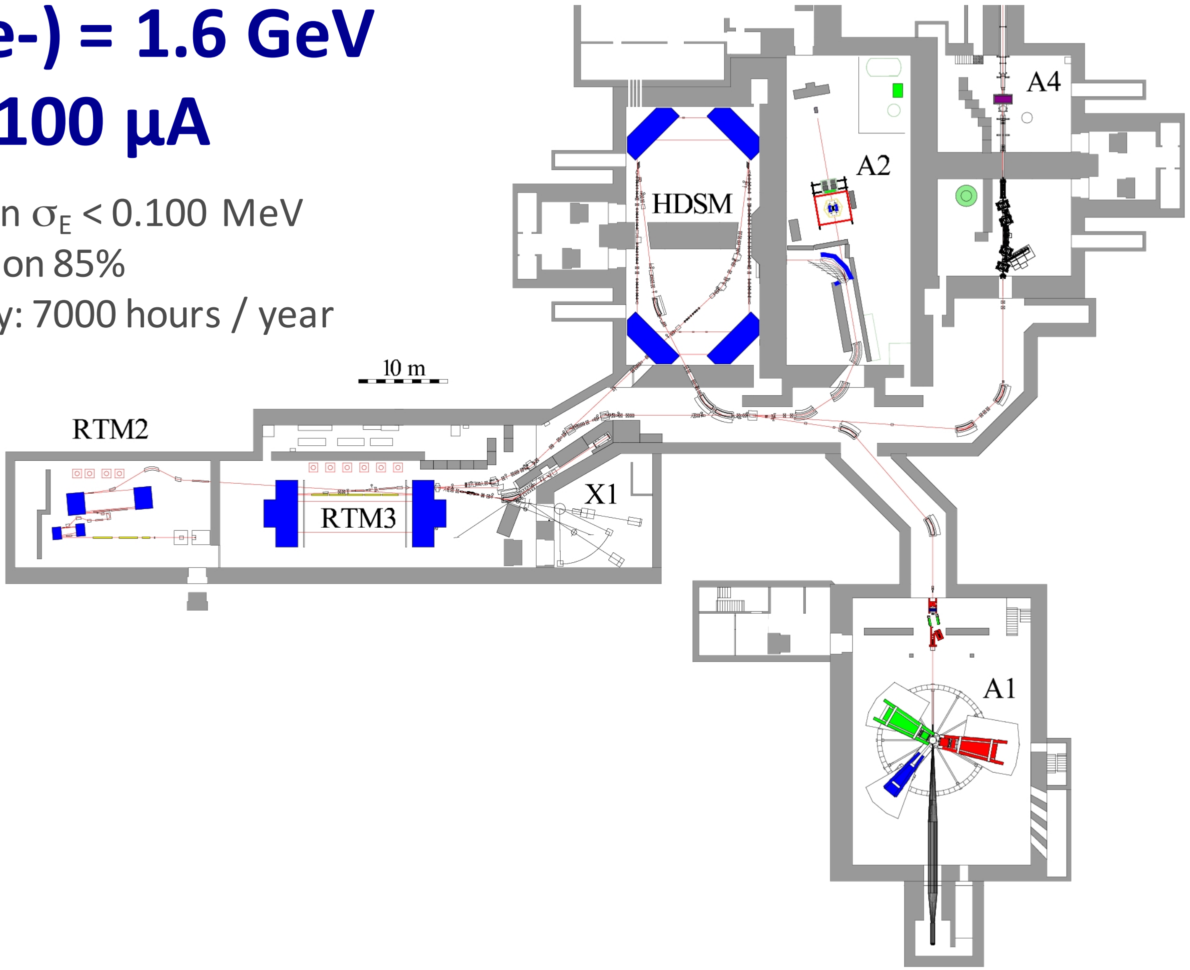
July 26, 2018
Weihai, Shandong Province, China
10th Intl. Workshop on Hadron Physics and Opportunities Worldwide

The Mainz Microtron MAMI

Electron Accelerator for Fixed Target Experiments

E_{max} (e-) = 1.6 GeV
I_{max} ~ 100 µA

- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: 7000 hours / year



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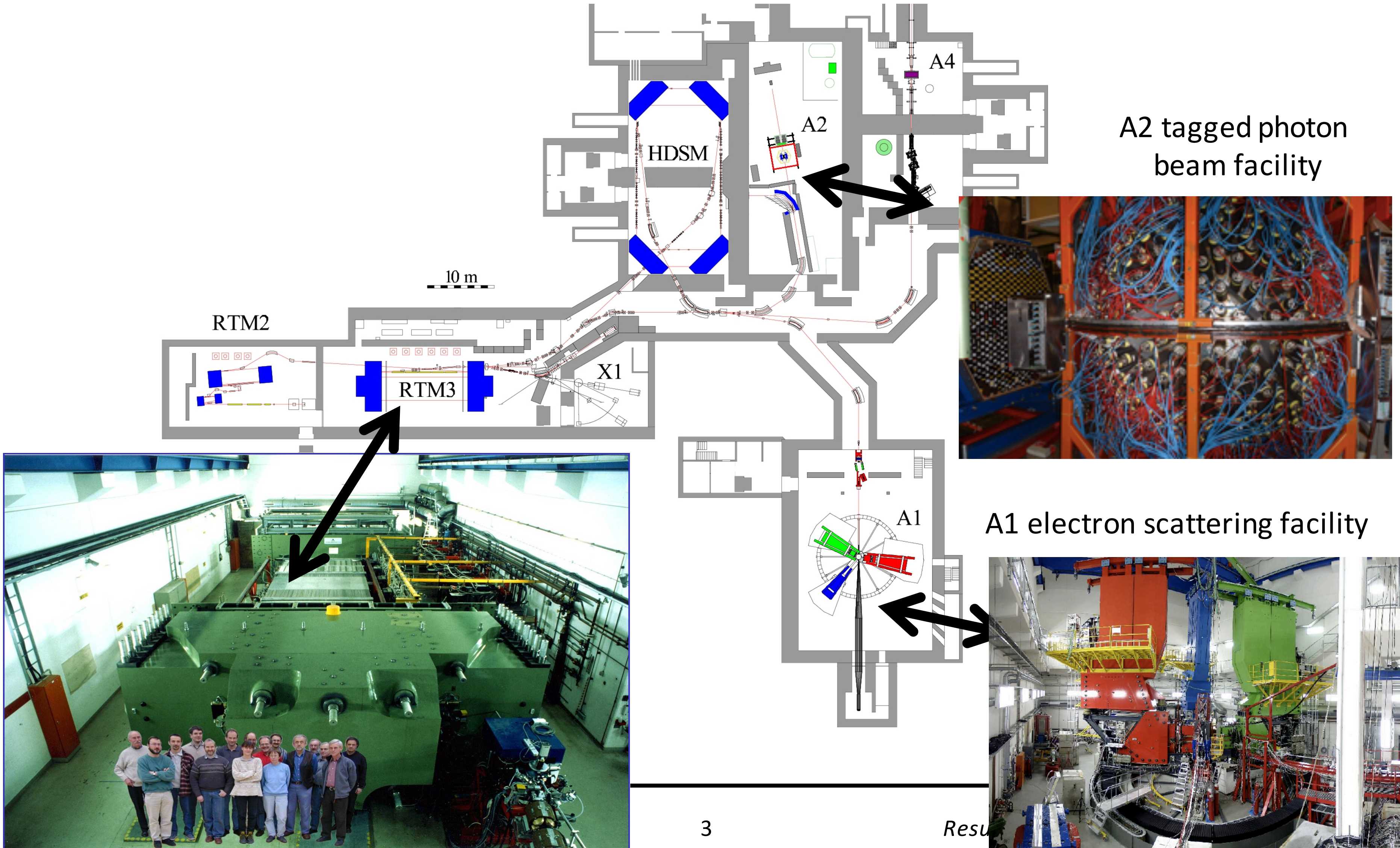

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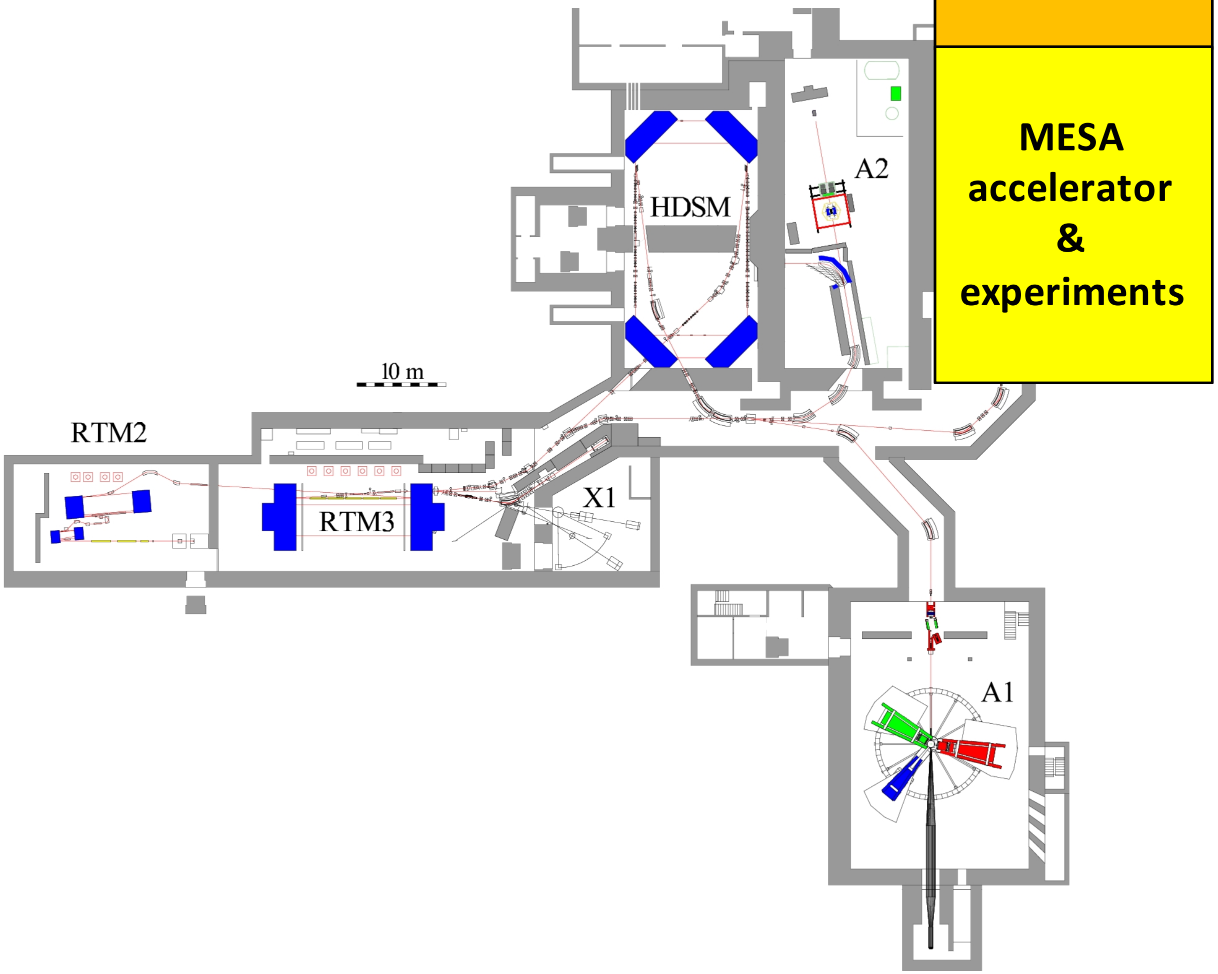
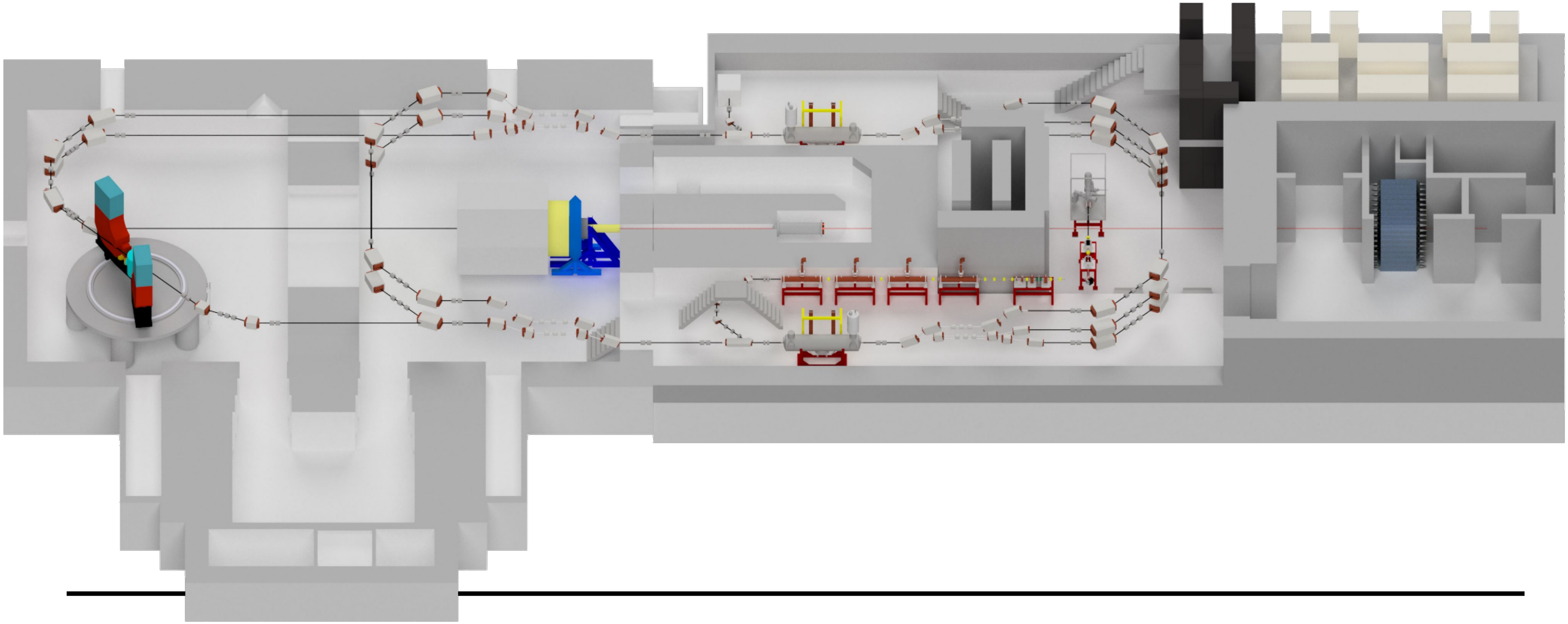


Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

E_{max} = 105/155 MeV

I_{max} > 1 mA (ERL)



MESA Accelerator

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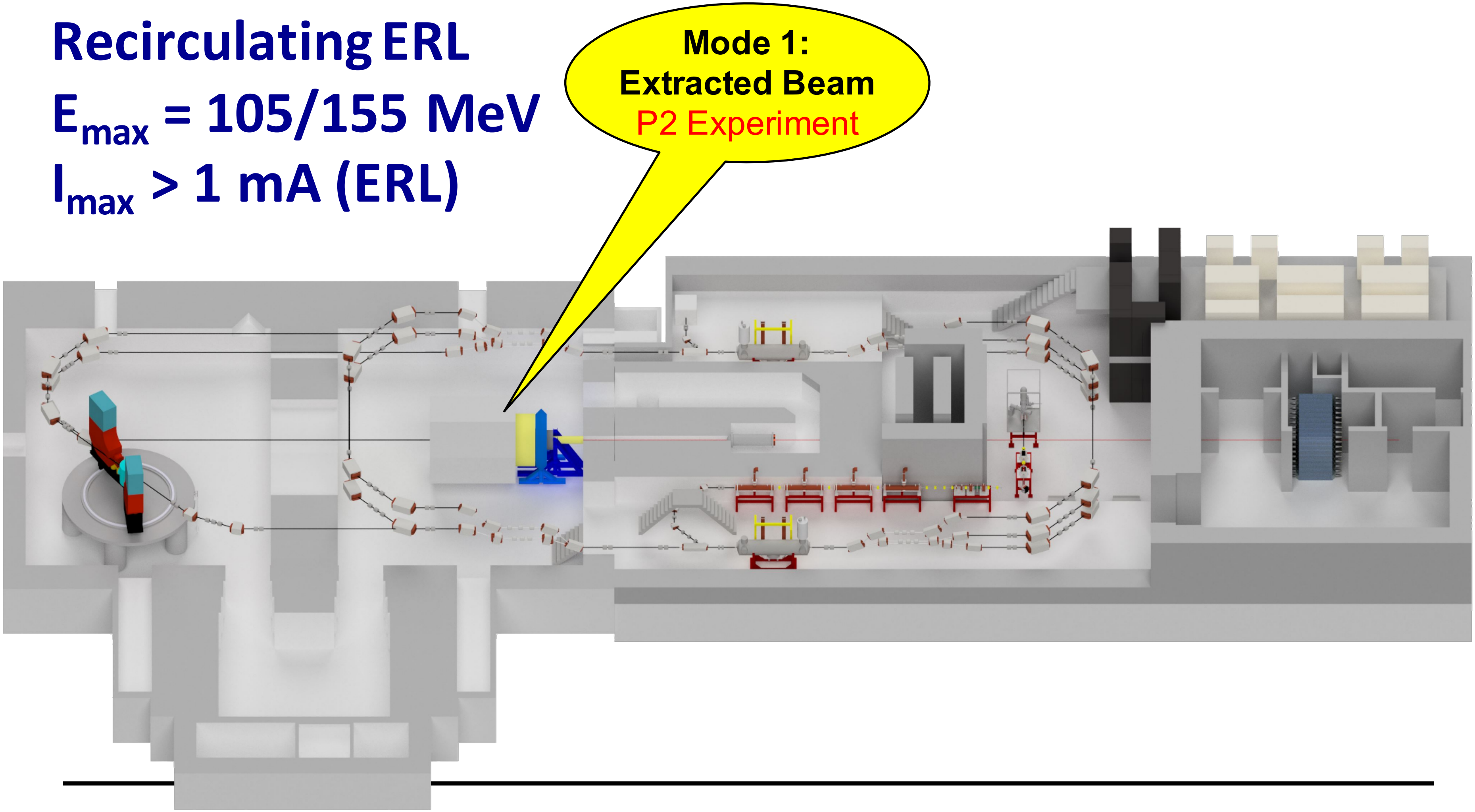

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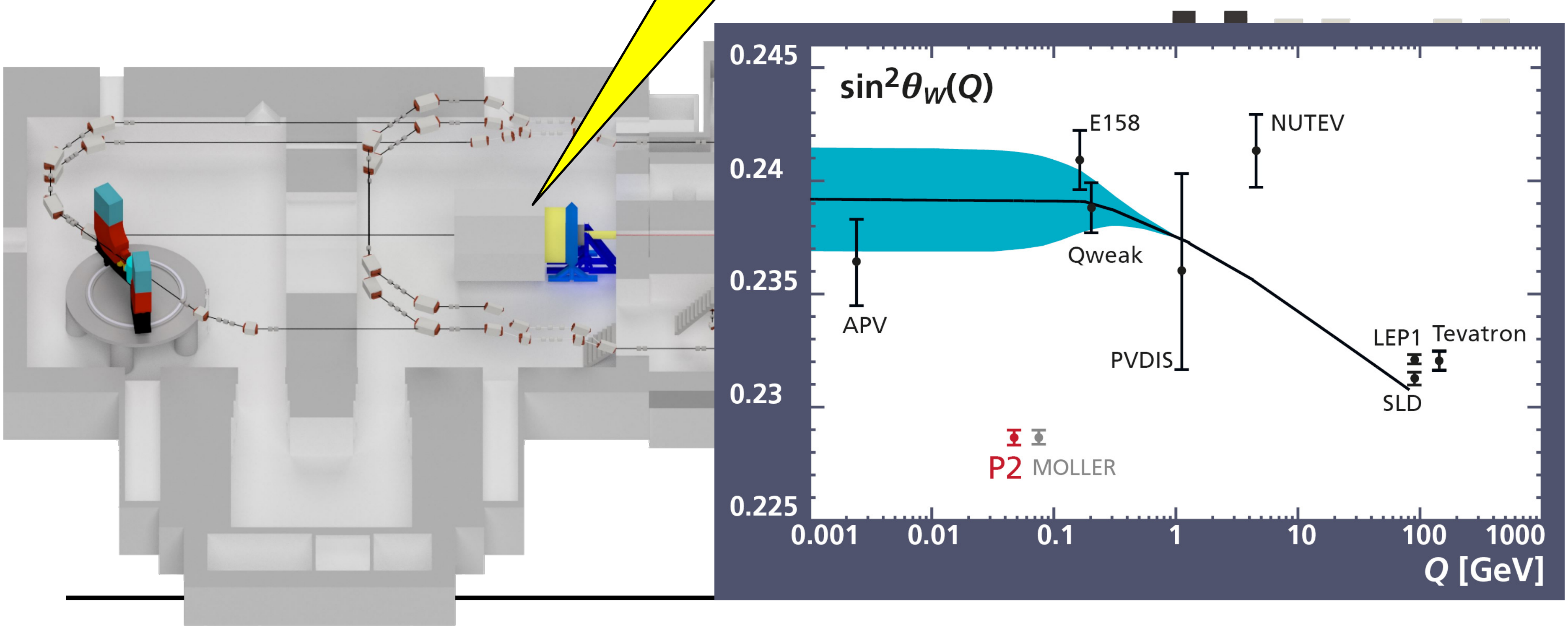
Mode 1:
Extracted Beam
P2 Experiment



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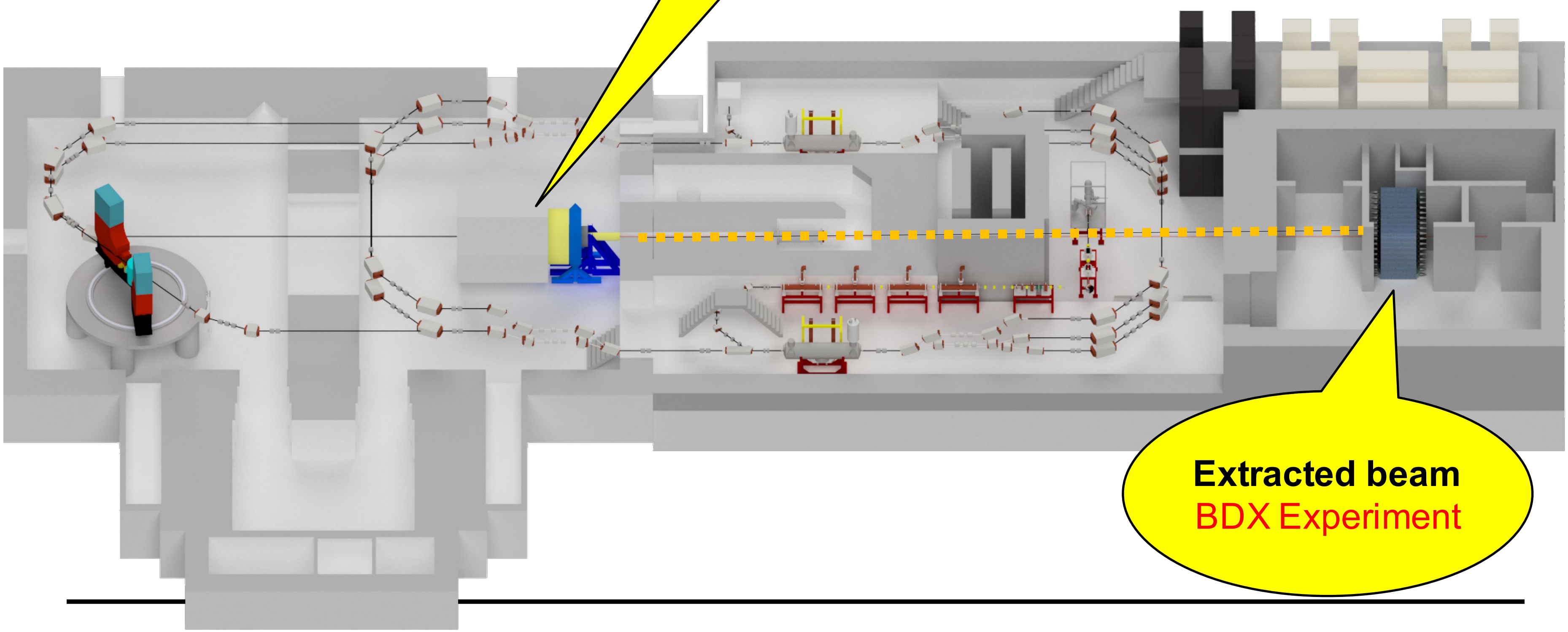

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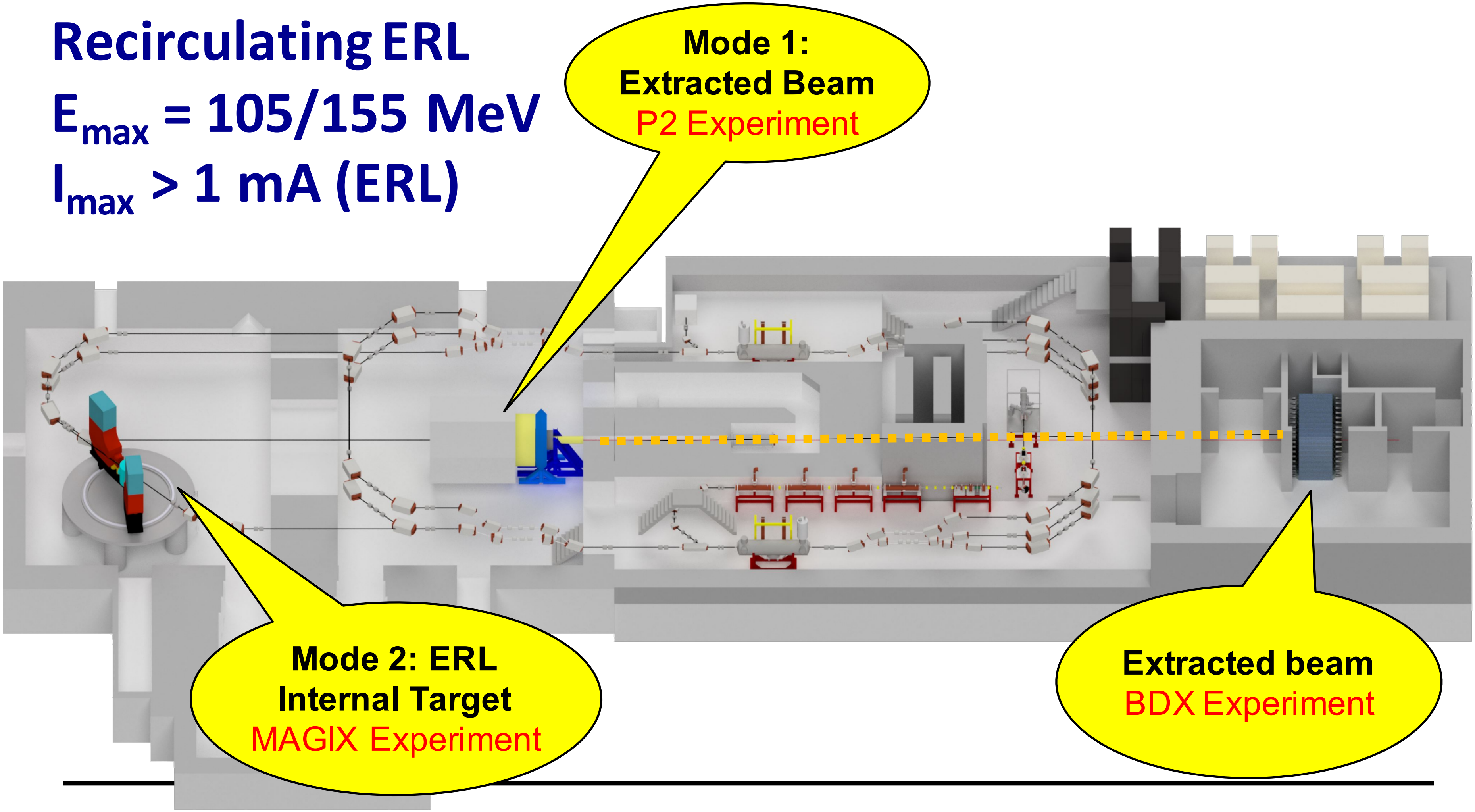

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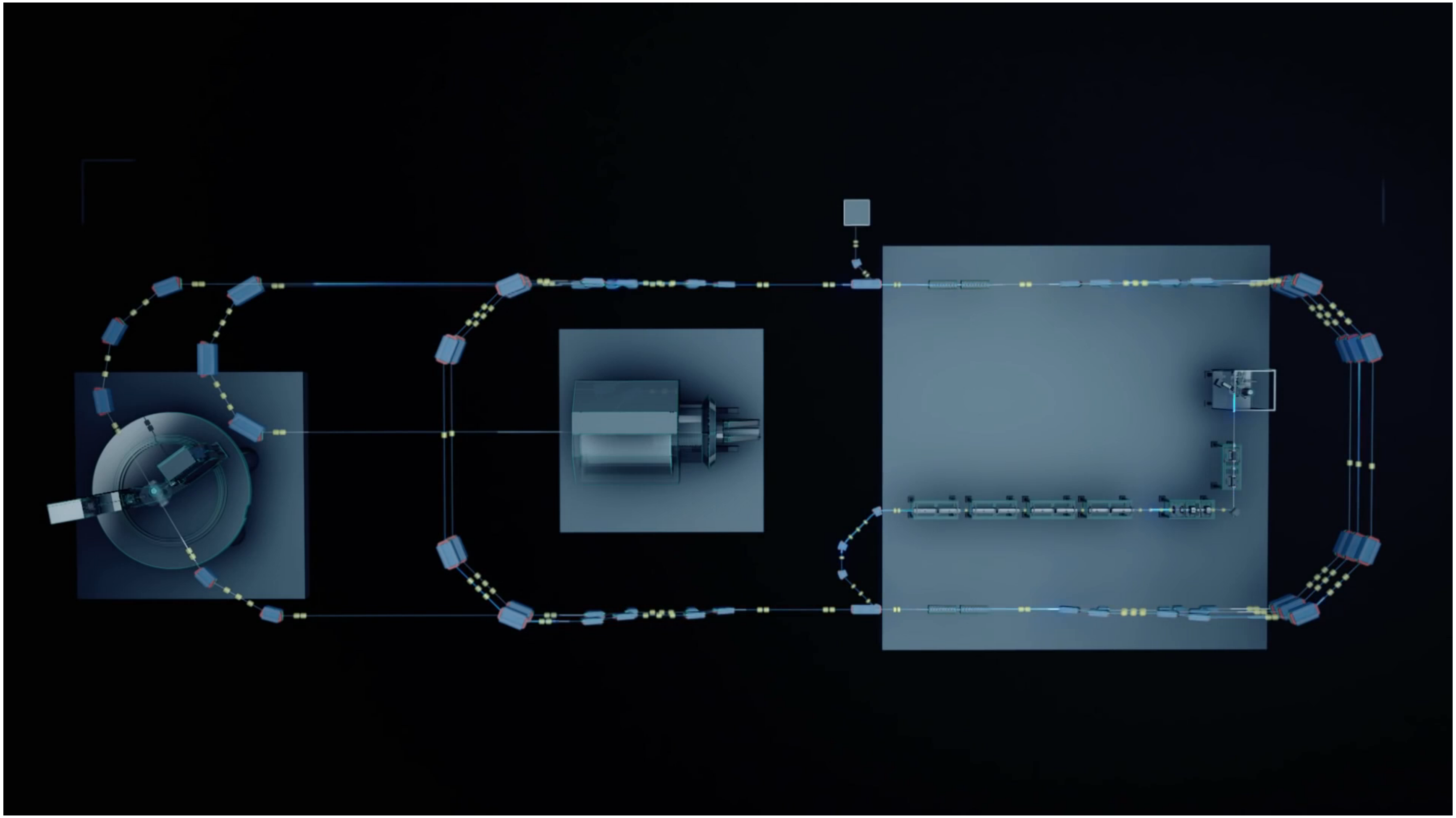

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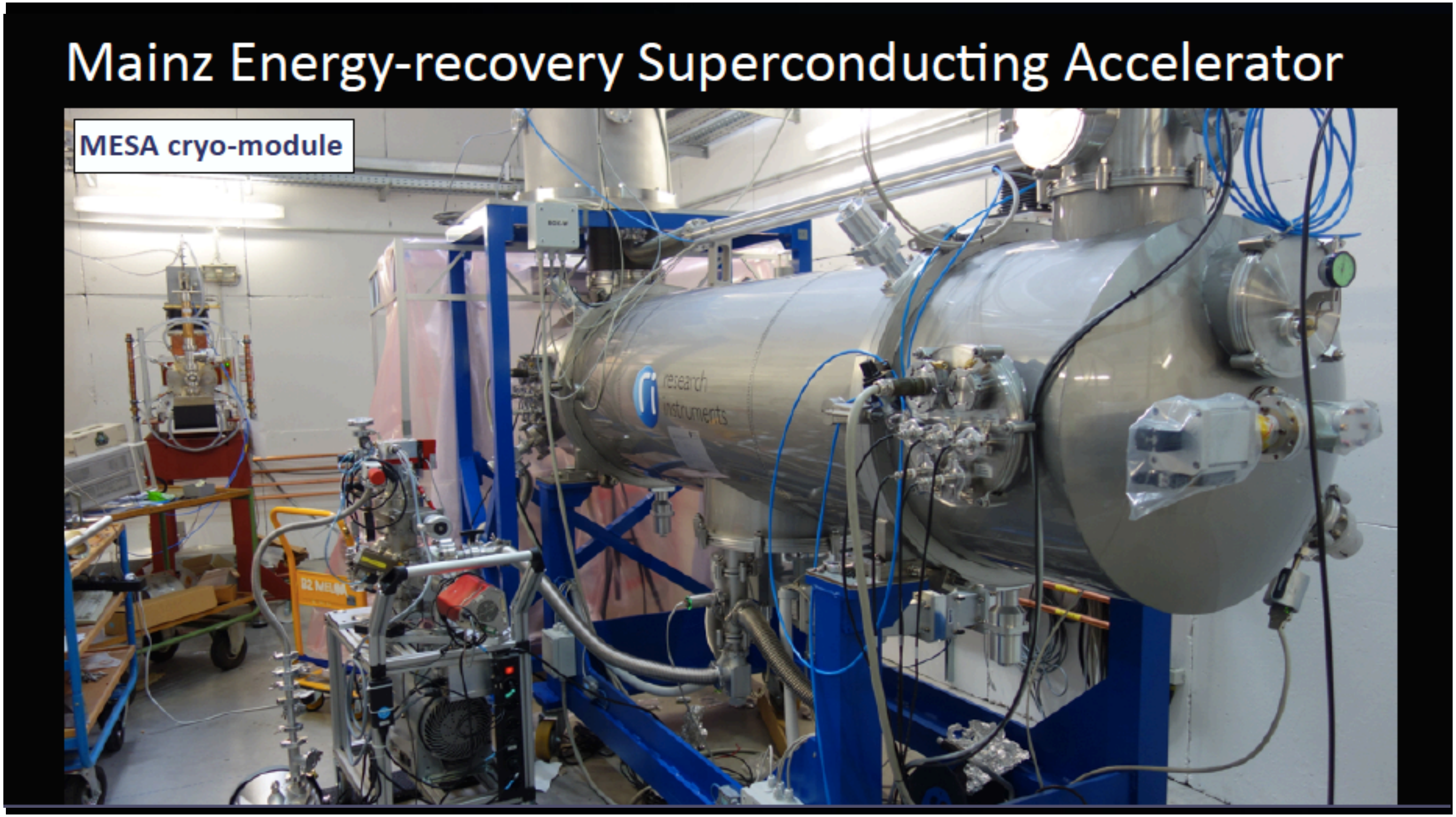


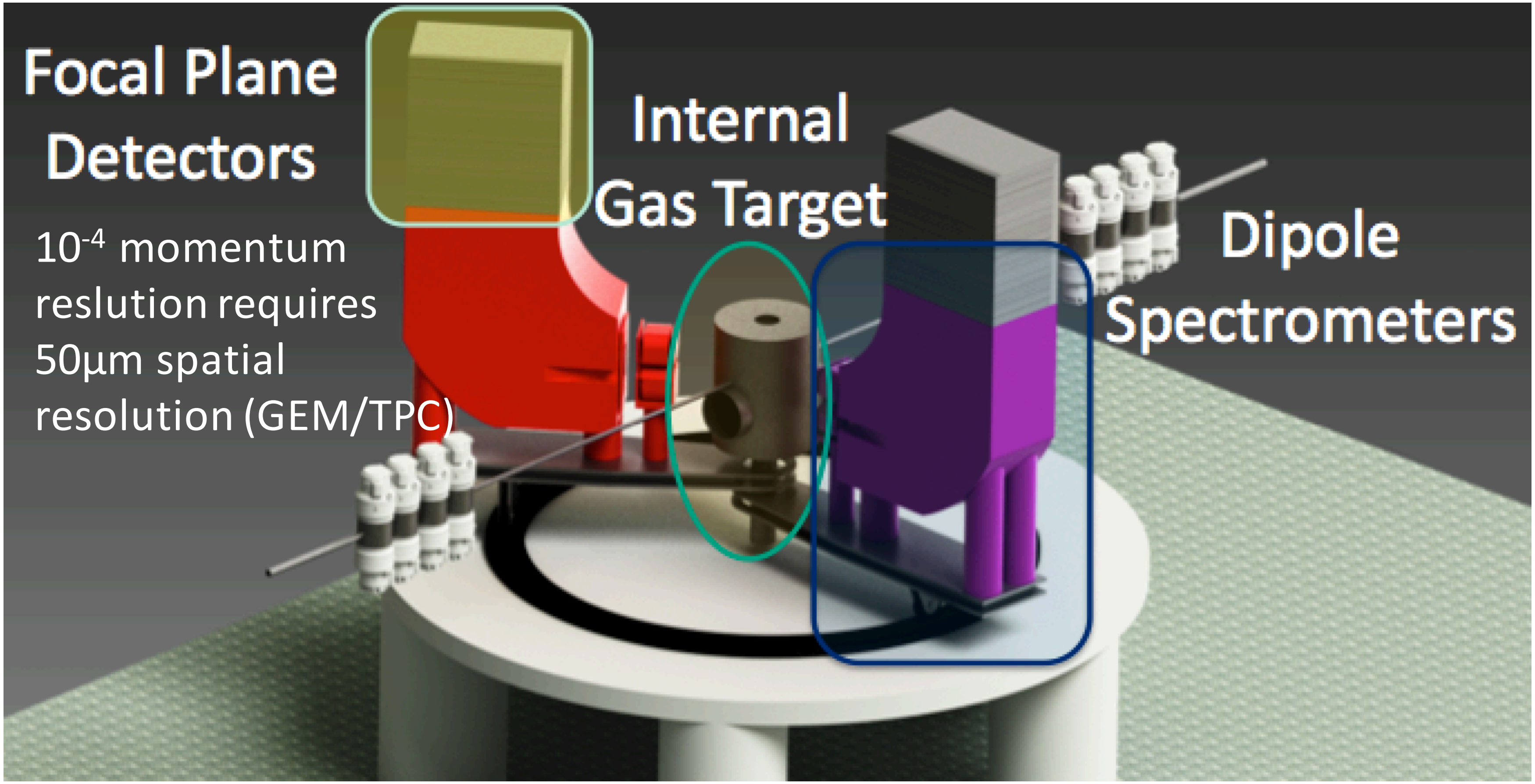
MAinz Gas Internal EXperiment

Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target

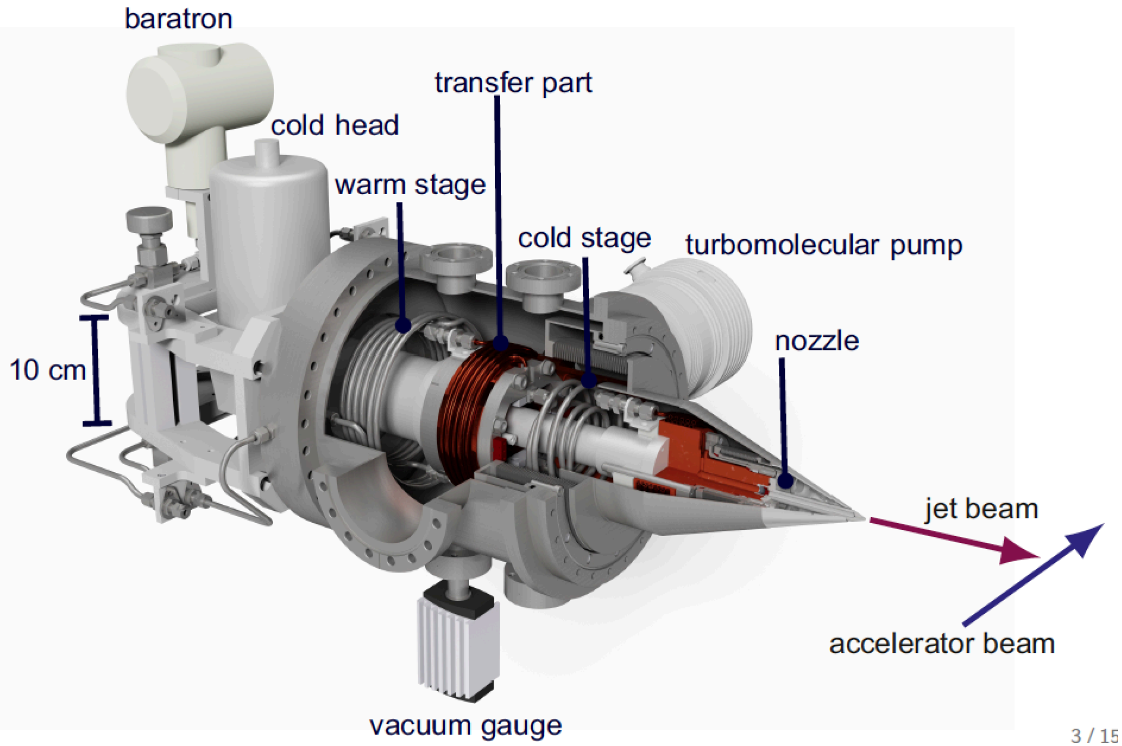
→ **a novel technique in nuclear and particle physics**

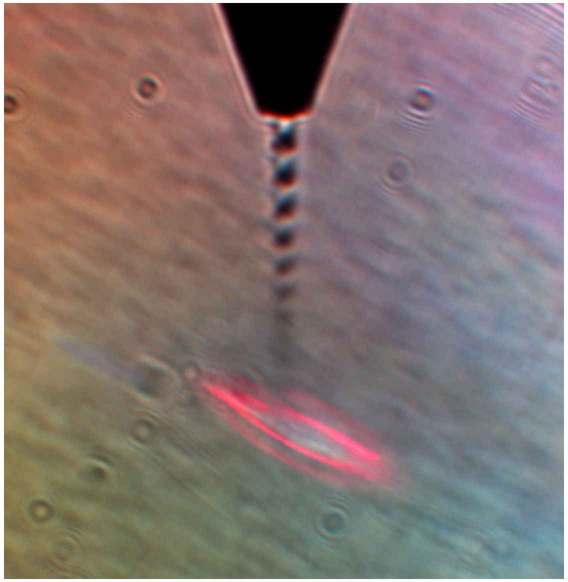
→ **measurement of low momenta tracks with high accuracy**

→ **competitive luminosities**



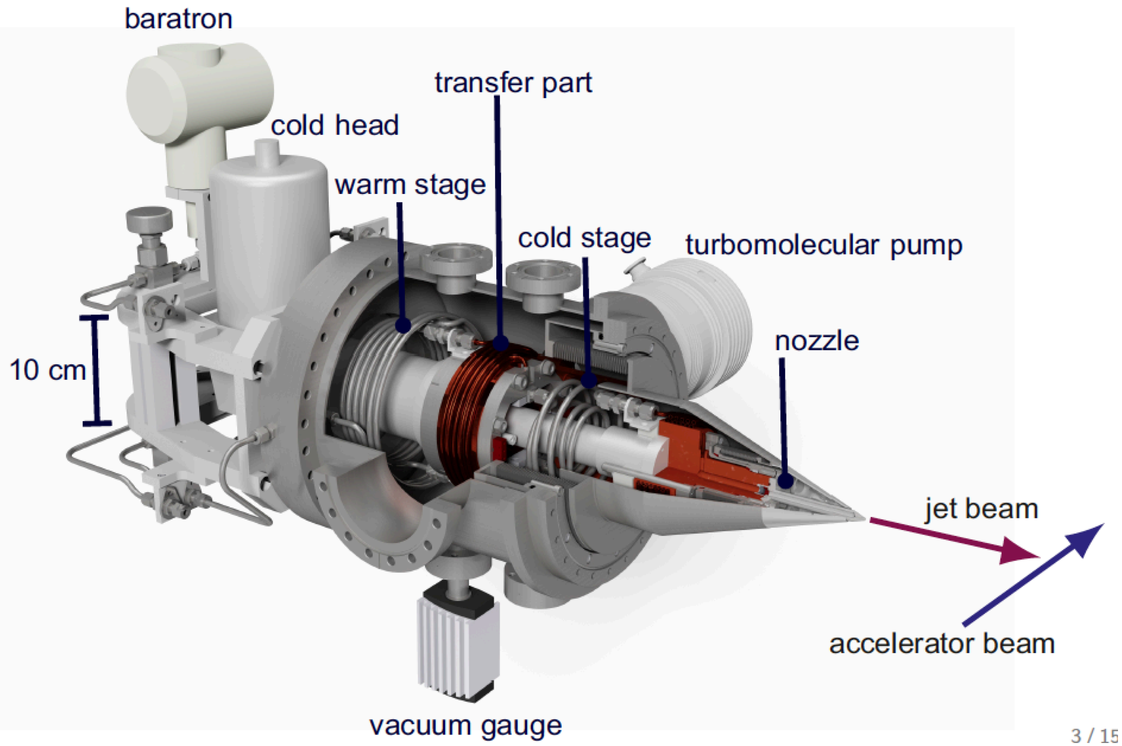
Supersonic Gas-Jet-Target

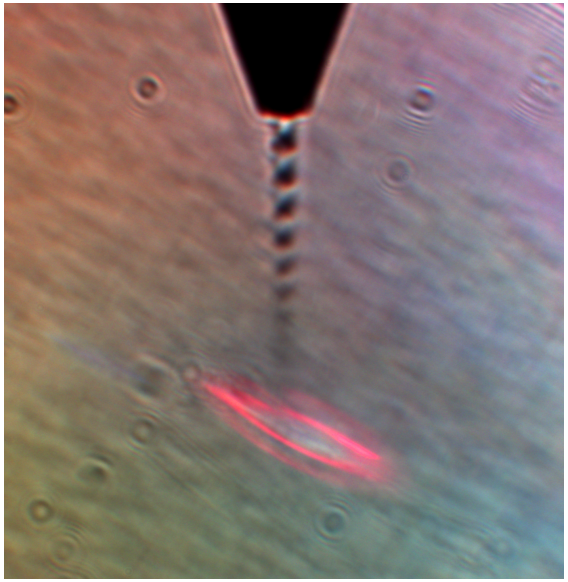




- Windowless !
- Supersonic gas jet
- Higher gas density ($10^{19}/cm^2$)
- O(mm) target length
- H_2, ^3He, ^4He, O_2, ….., Xe
- *O(10^{35} cm^{-2} s^{-1})* @ $10^{19}/cm^2$

Supersonic Gas-Jet-Target





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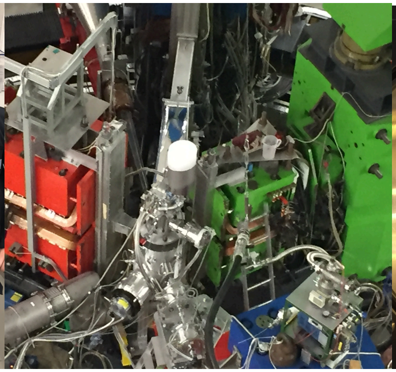
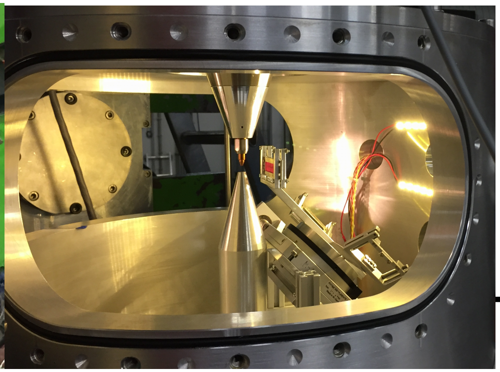
Commissioned in 2017/18





New Vistas in Low-Energy Precision Physics (LEPP)

4-7 April 2016
Kupferbergterrasse Mainz
Europe/Berlin timezone

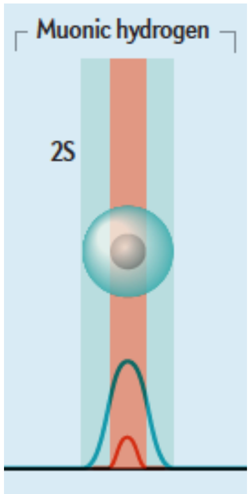
- Overview
- Scientific Programme
- Timetable
- Contribution List
- Participant List
- Accomodation
- Travel
- Venue & Social Events

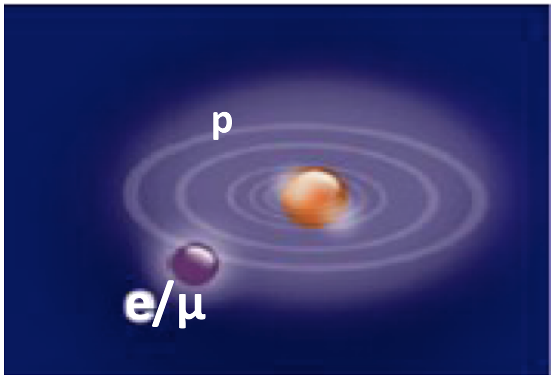
- **Electromagnetic Formfactors** and Polarisabilities of Nucleons
- Few Body Physics
- Nuclear Astrophysics,
- **Dark Photon Searches**,
- **Light Dark Matter Searches**
- ....

Proton Radius Puzzle

The Proton Radius Puzzle

Atomic Spectroscopy
(PSI: Lamb Shift in muonic hydrogen)

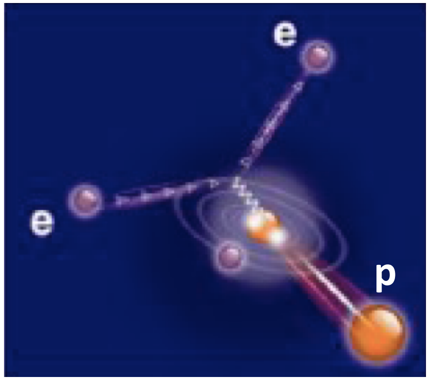




$R_E = 0.8409 \pm 0.0004$ fm

Nature (2012), Science (2013)

Electron Scattering on proton
(EM form factor measurements)



$R_E = 0.879 \pm 0.008$ fm

PRL (2010), PRD(2014)

Proton charge radius:

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

The Proton Radius Puzzle

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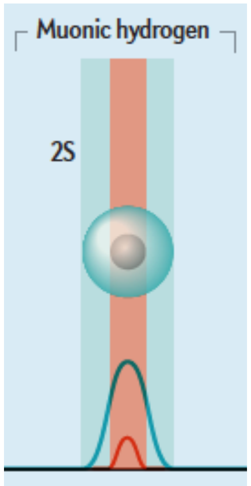

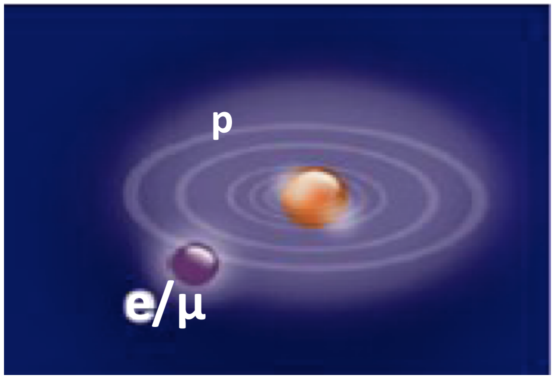

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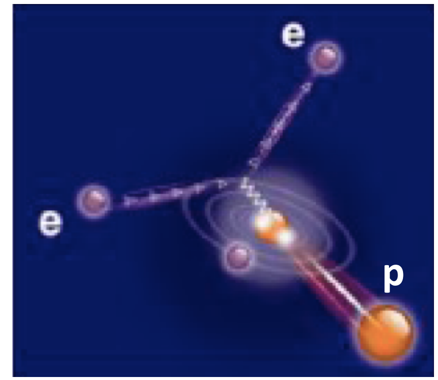

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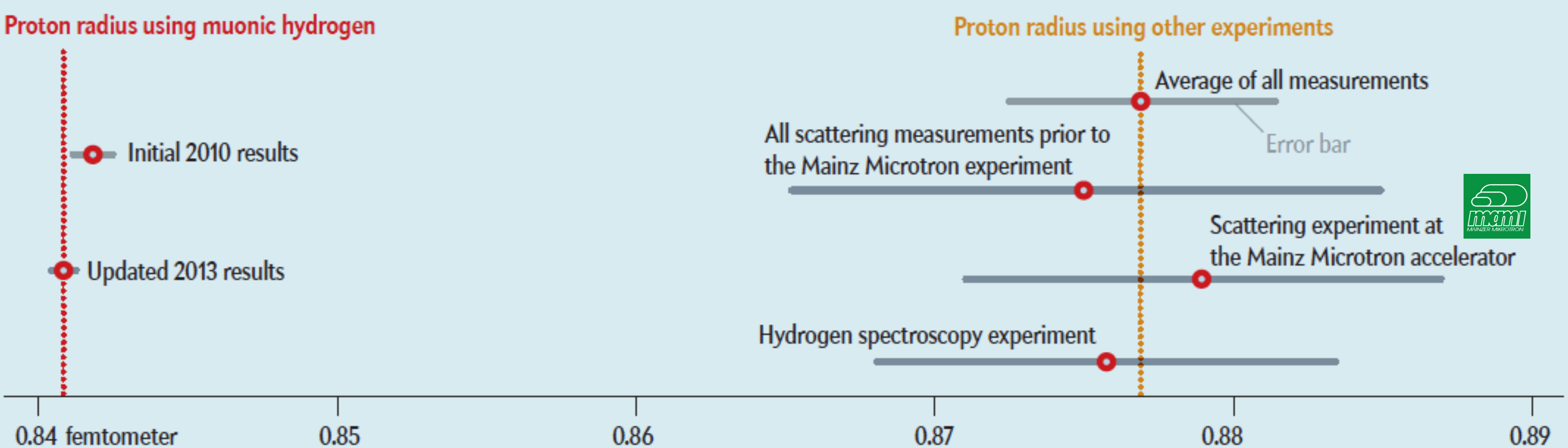


Proton Radius Puzzle - What is going on?

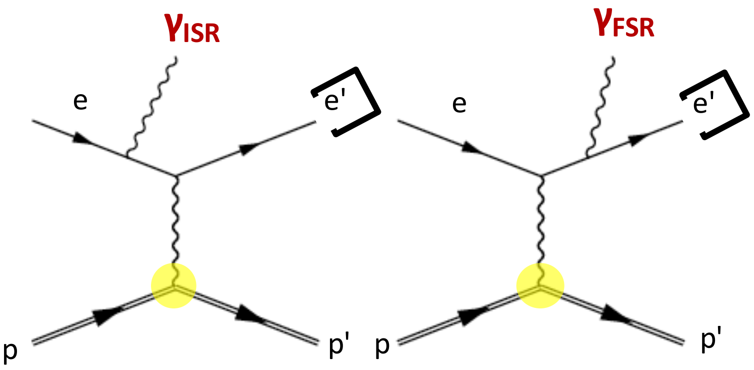
A worldwide effort in atomic physics, hadron/particle physics and theory

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

- **Unknown QED / hadronic correction in μH data ?** Main limitation from two-photon processes

- **Electron scattering expts. not at sufficiently low Q^2**
  or – radiative corrections not understood
  or – normalization errors
  or …. ?

ISR Measurement of EM Form Factors

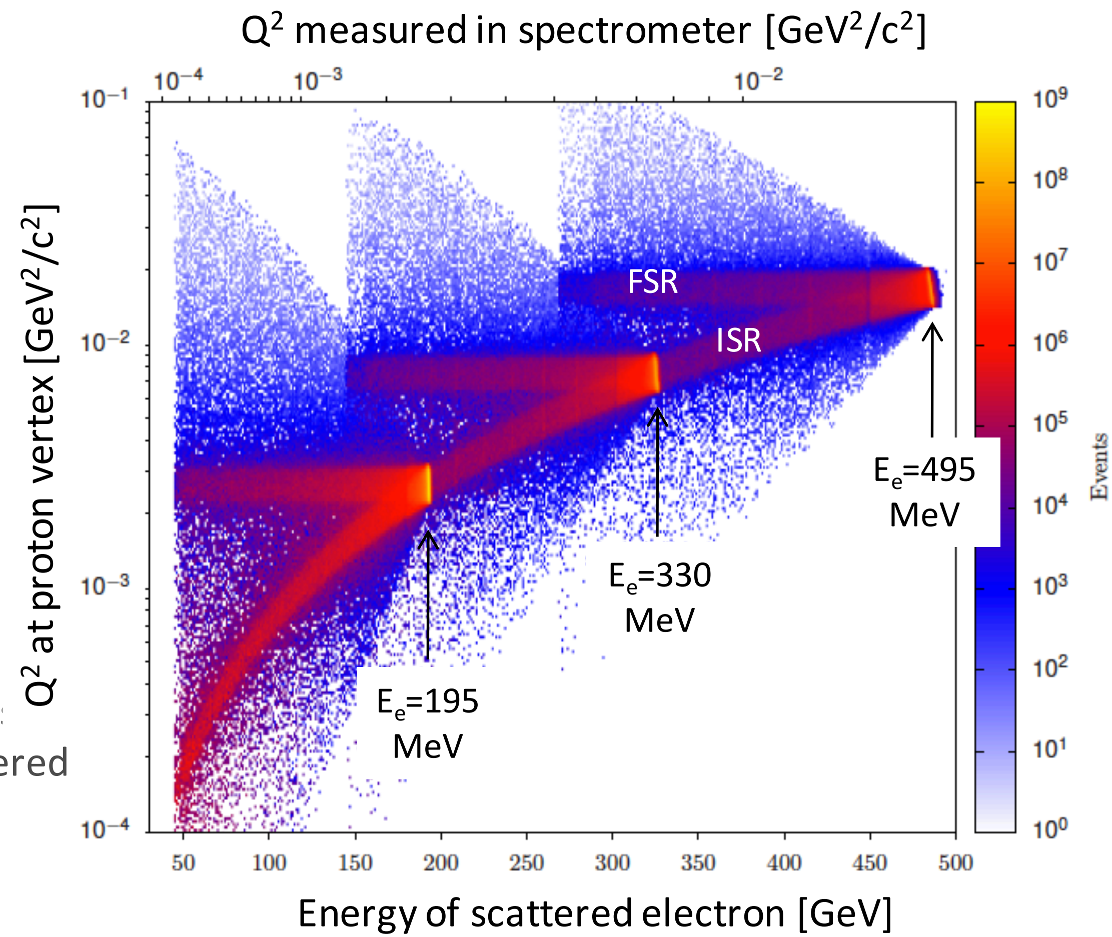


Initial State Radiation   Final State Radiation

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 $2x10^{-4}$**



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

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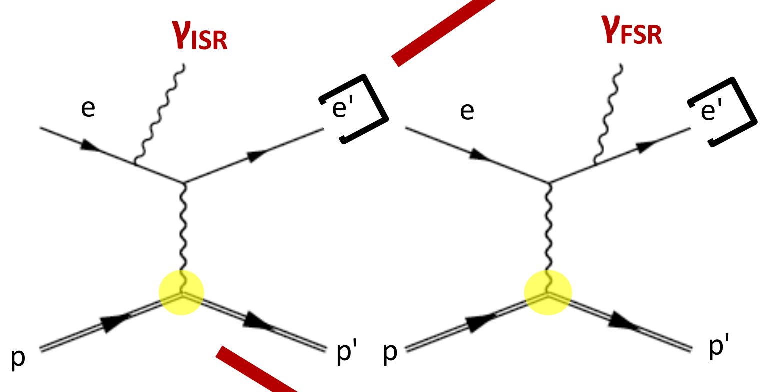
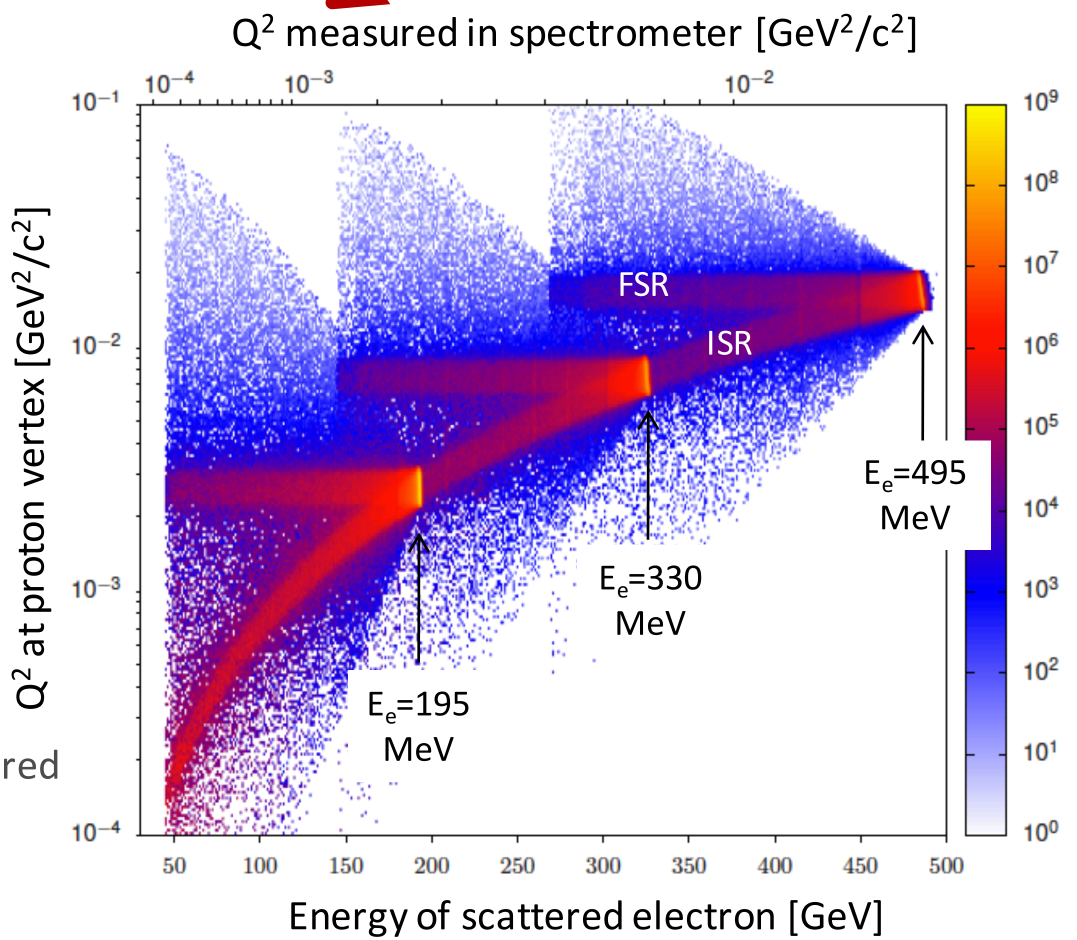


Initial State Radiation

Final State Radiation



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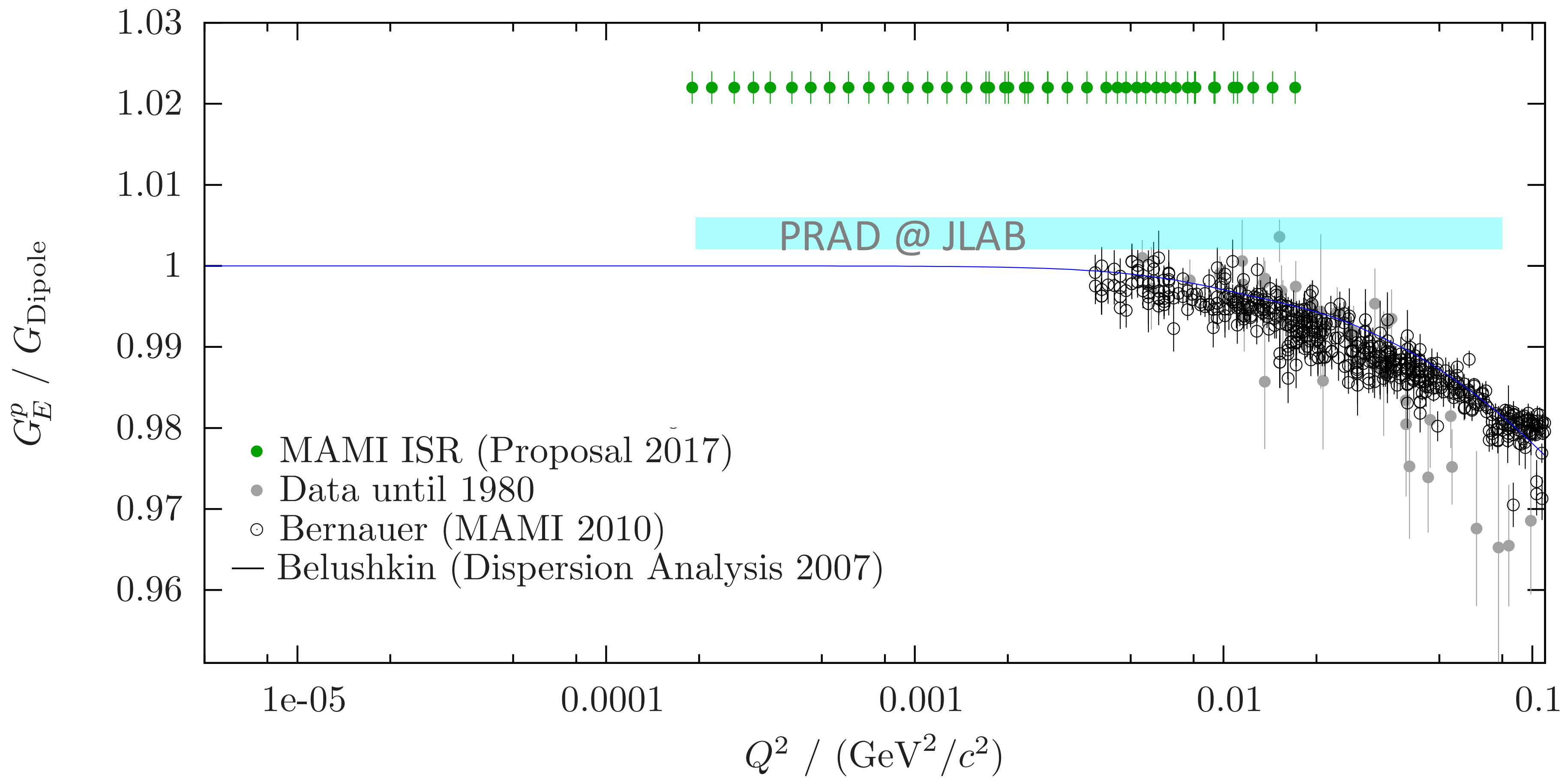
The Quest for Low-Q^2 Scattering Data



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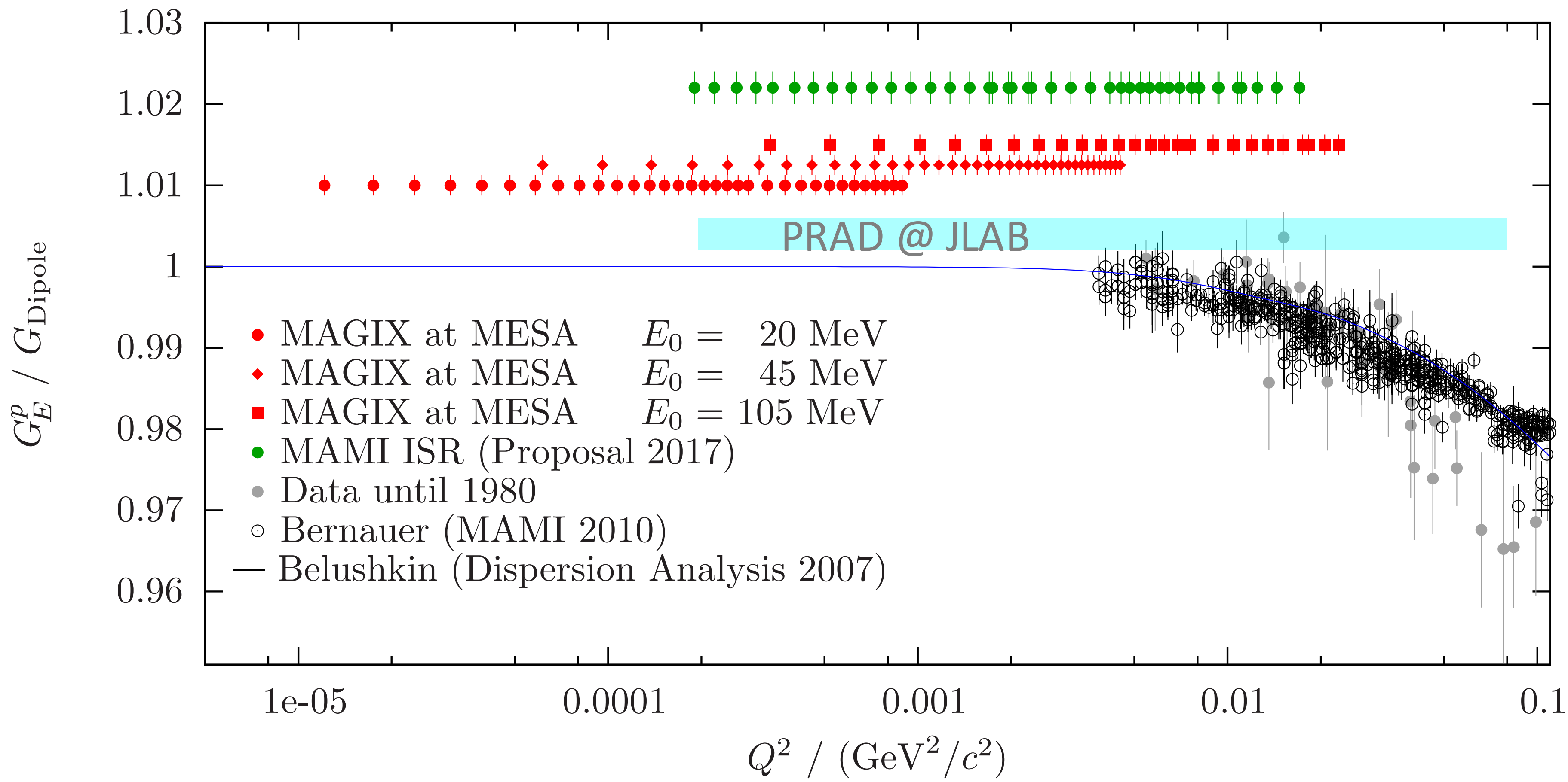

Magnetic Form Factor @ MAGIX

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

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

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 !

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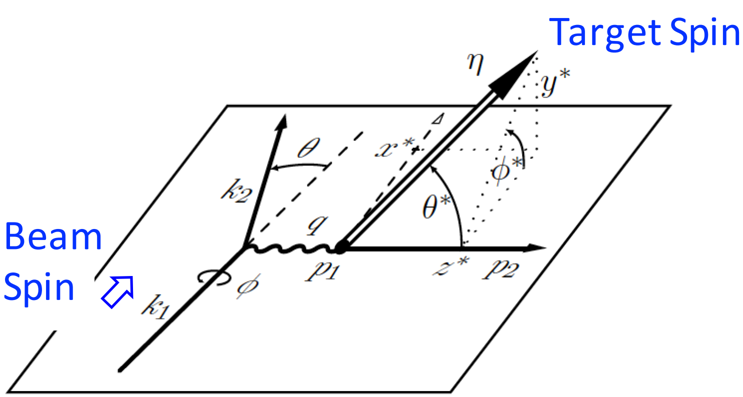

$$\left.\begin{array}{l}\phi^* = 0 \\ \theta^* = 0, \frac{\pi}{2}\end{array}\right\} \Rightarrow A_\perp \sim \frac{G_E}{G_M}$$

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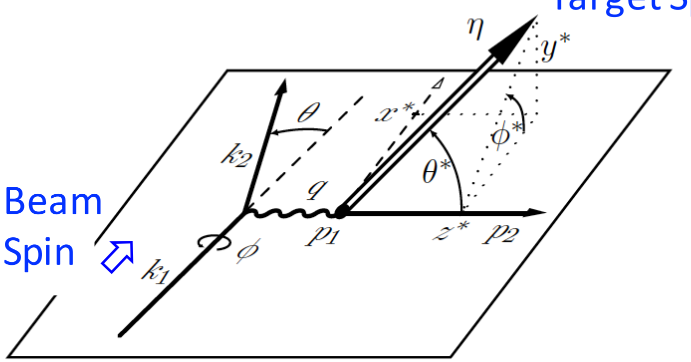
Target Spin

Beam Spin



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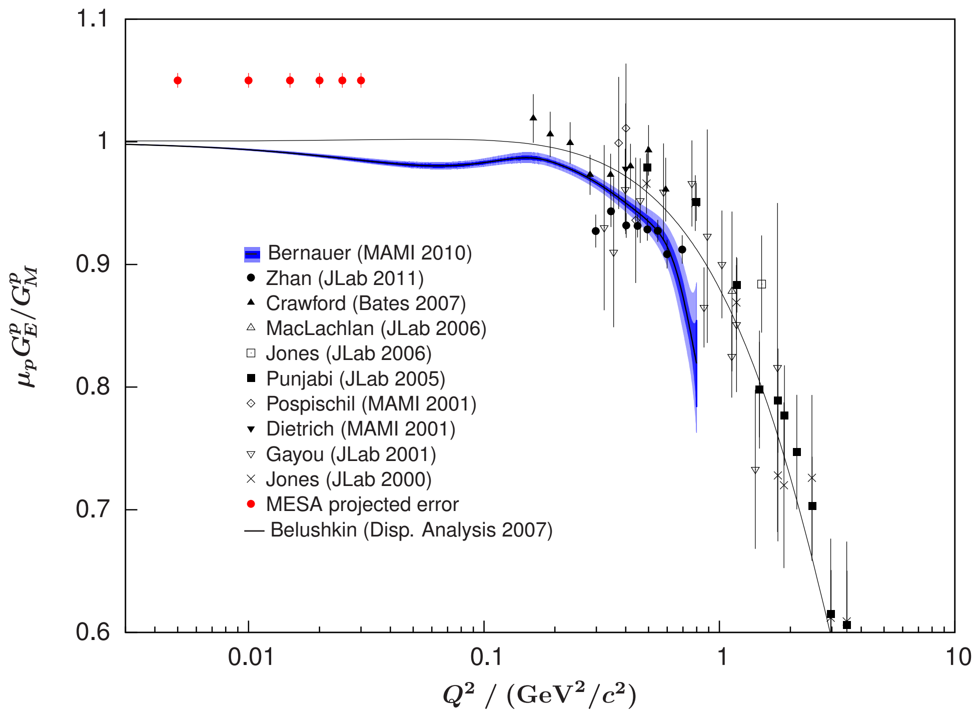
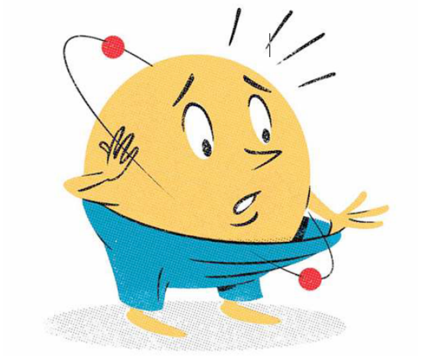


Mainz Proton Radius Programme



The New York Times

- 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 μH results / PSI

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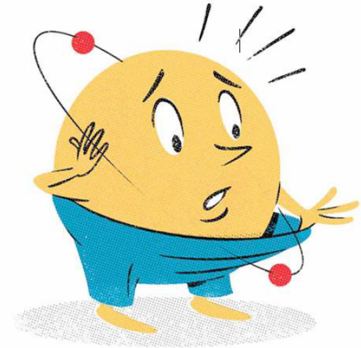

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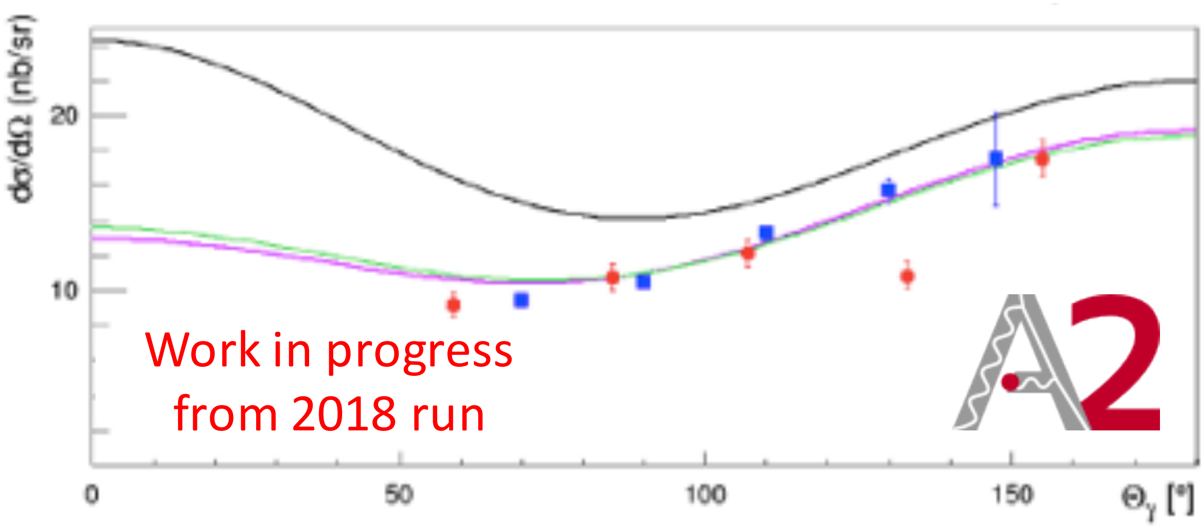

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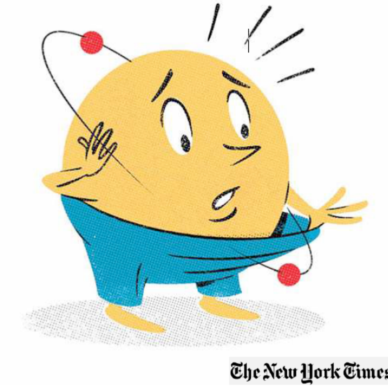

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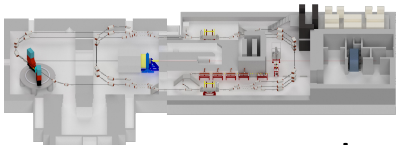
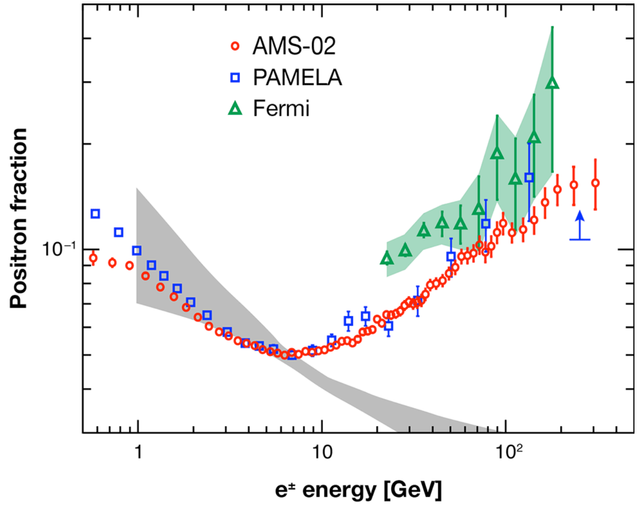


MESA

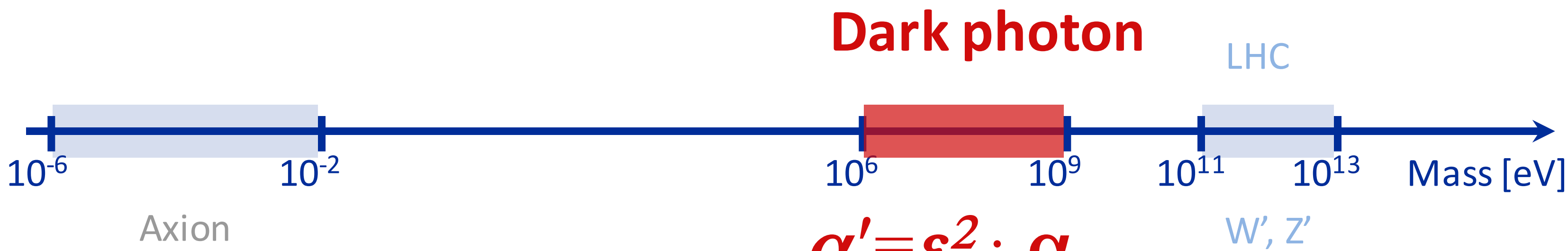
- Electric FF measurement at low Q^2
- Magnetic FF measurement at low Q^2 using double polarization
- Elastic FF measurements for Few-Body-Systems (d, ^{3}He, ^{4}He, ...) as well as break-up measurements
- Polarizability measurements of proton and of Few-Body-Systems

Search for the Dark Photon



Dark Photon

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



$$\alpha' = \varepsilon^2 \cdot \alpha_{em}$$

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)

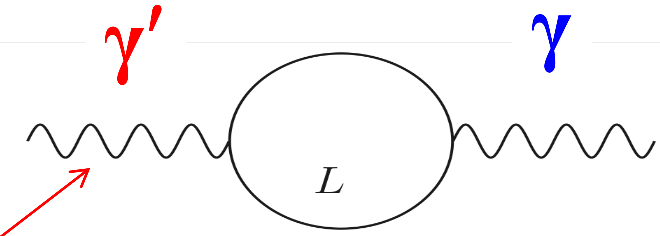
- Could explain presently seen **deviation of 3.6σ between $(g-2)_\mu$** Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov(2008)

Kinetic Mixing and Dark Matter

Holdom [1986]

A way to relate the dark sector to the SM (coupling ~ ε^2)

Dark Sector $U(1)_d$



Standard Model Sector U(1)

Dark Photon
(aka A′, U, Z_d, ...)

Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

Kinetic Mixing and Dark Matter

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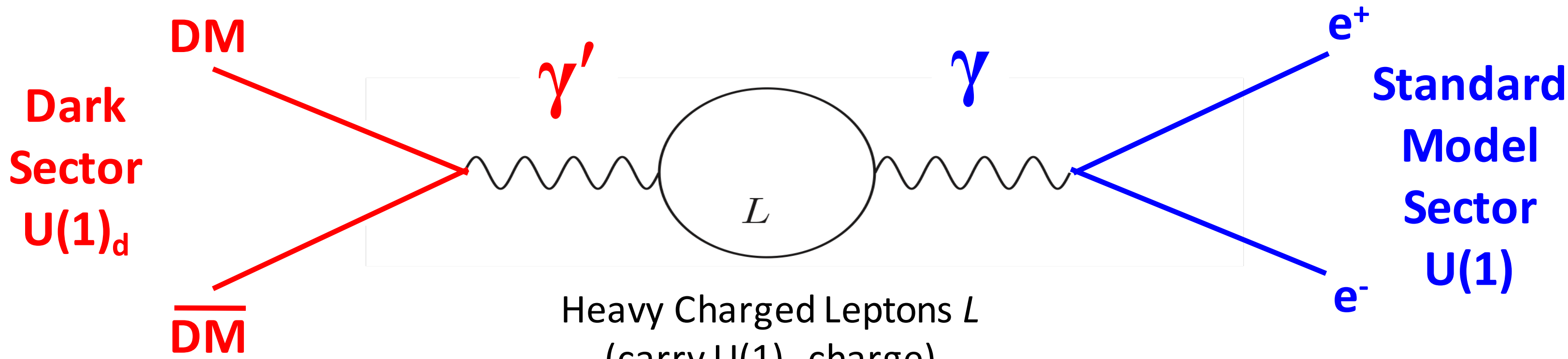
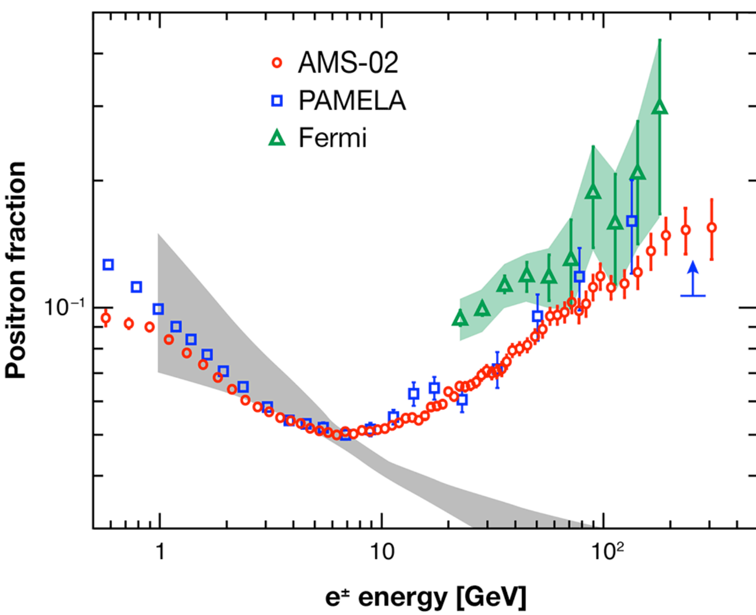
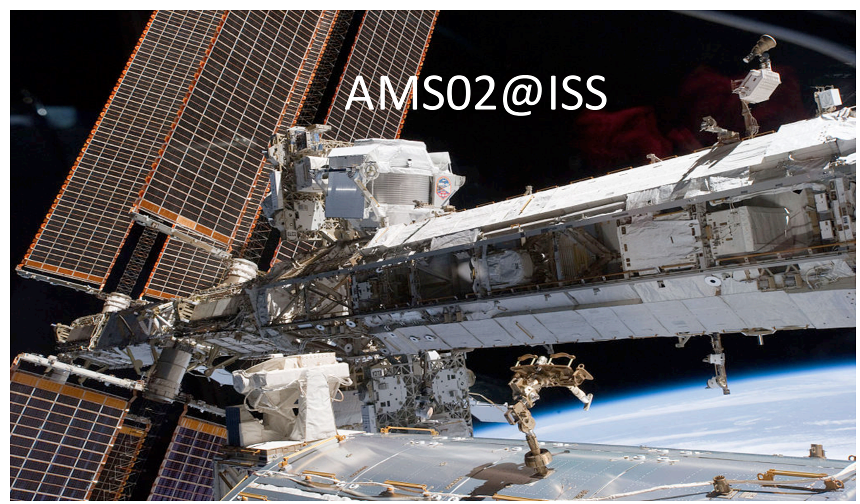


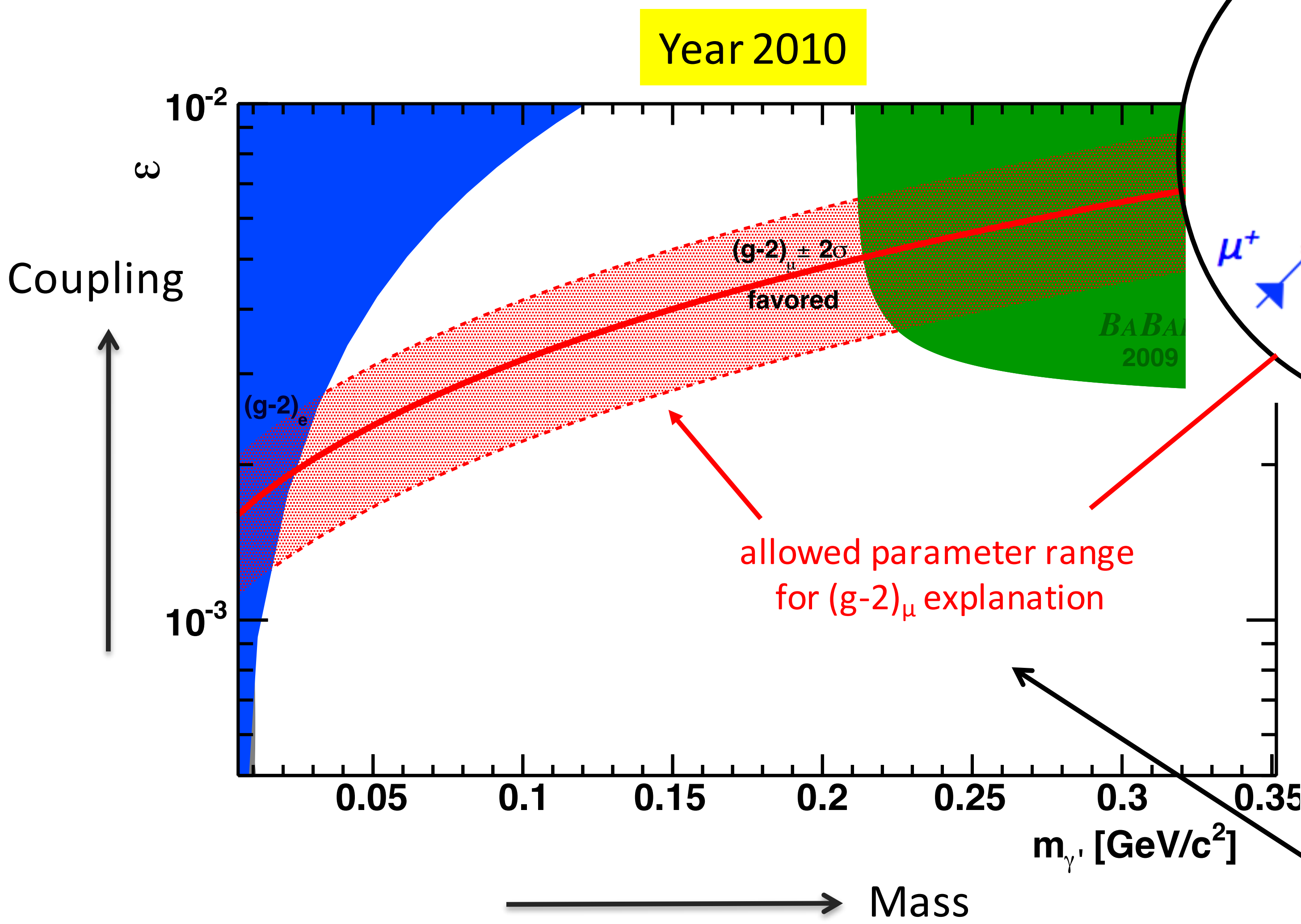
Heavy Charged Leptons L
(carry $U(1)_d$ charge)

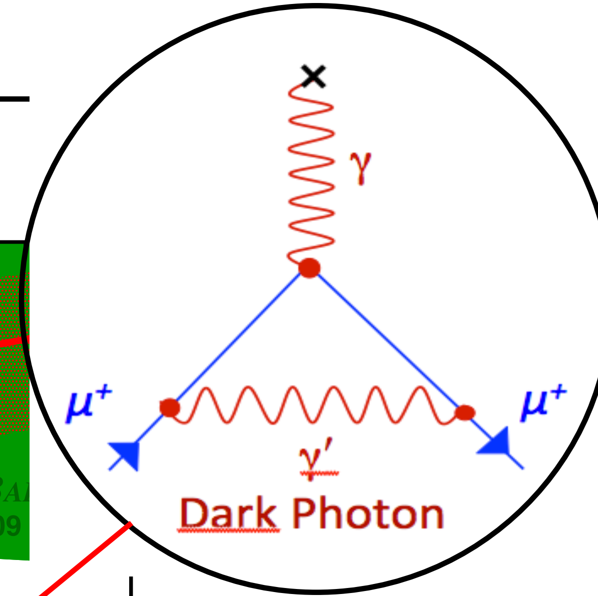
Excess of positrons in cosmic ray spectrum due to Dark Matter annihilation?





Dark Photon Status in 2010





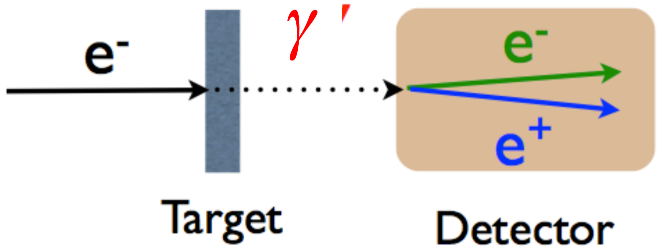
terra incognita
white region
motivated by
dark matter !

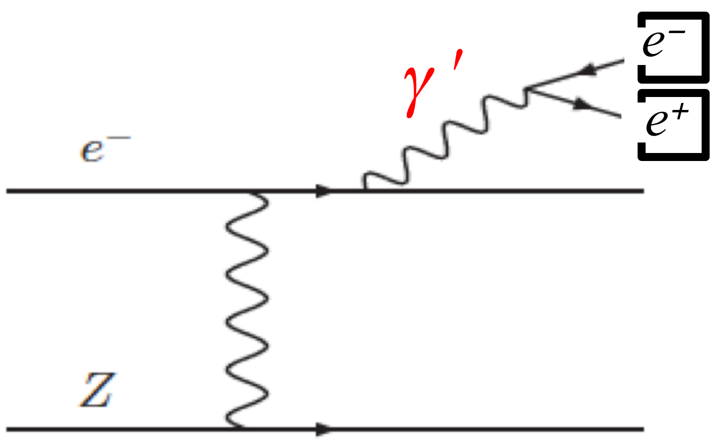
Results from A1

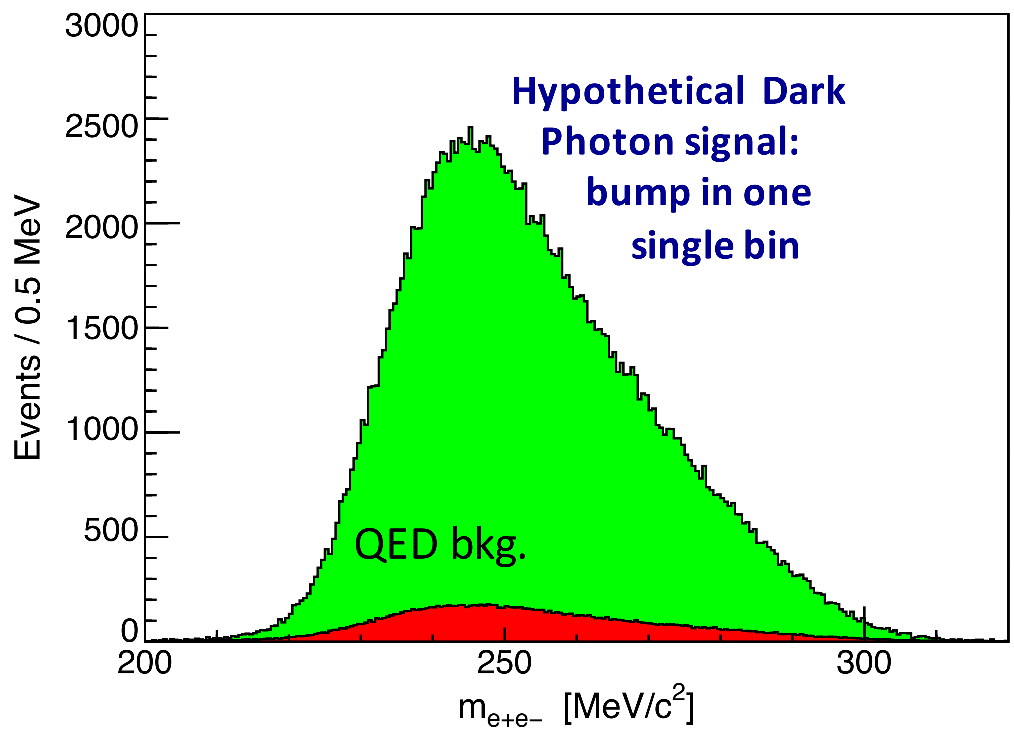
Low-Energy Electron Accelerators with high Intensity ideally suited for Dark Photon search

`Bjorken et al. (2009)`

Signal process

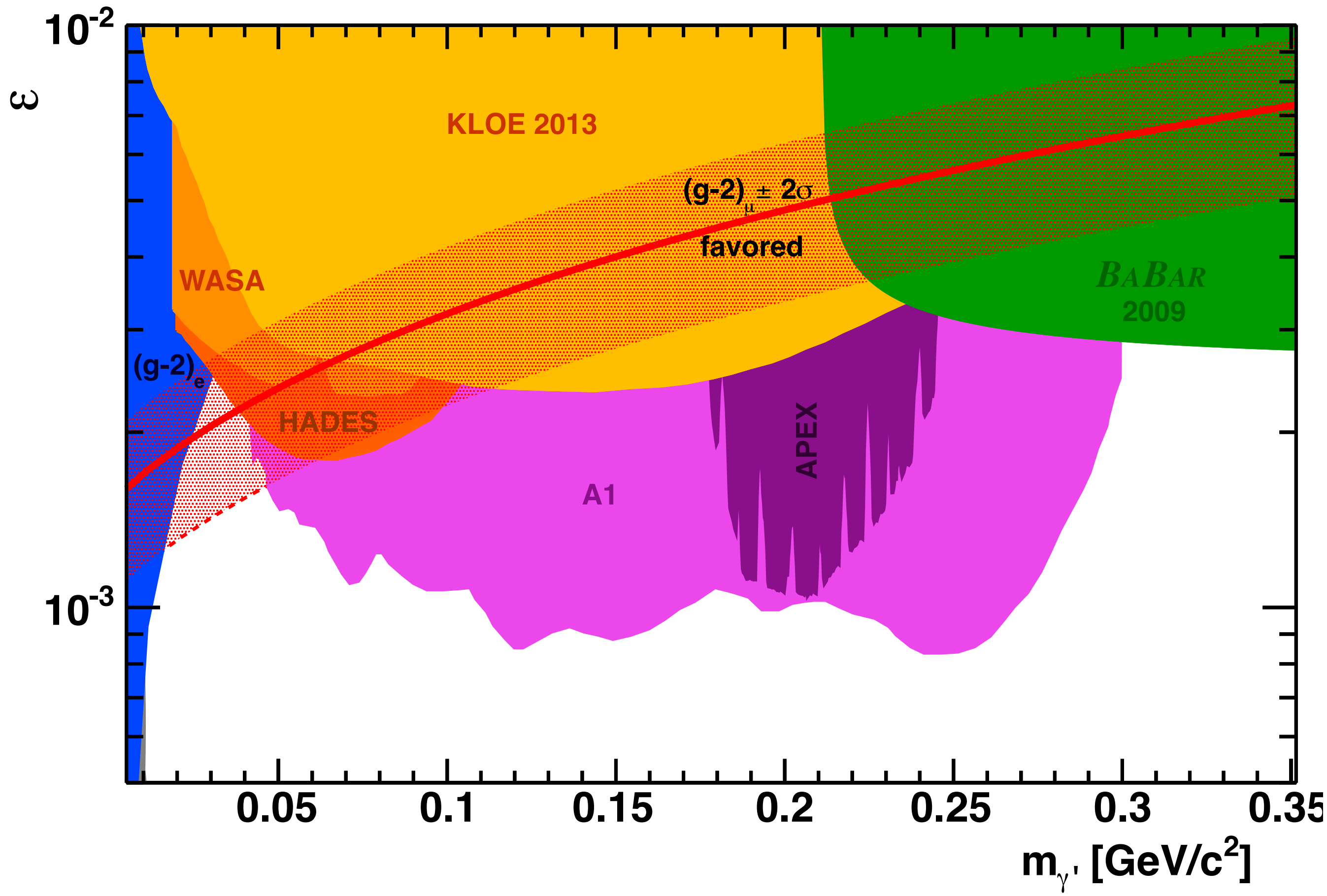






Results from A1

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

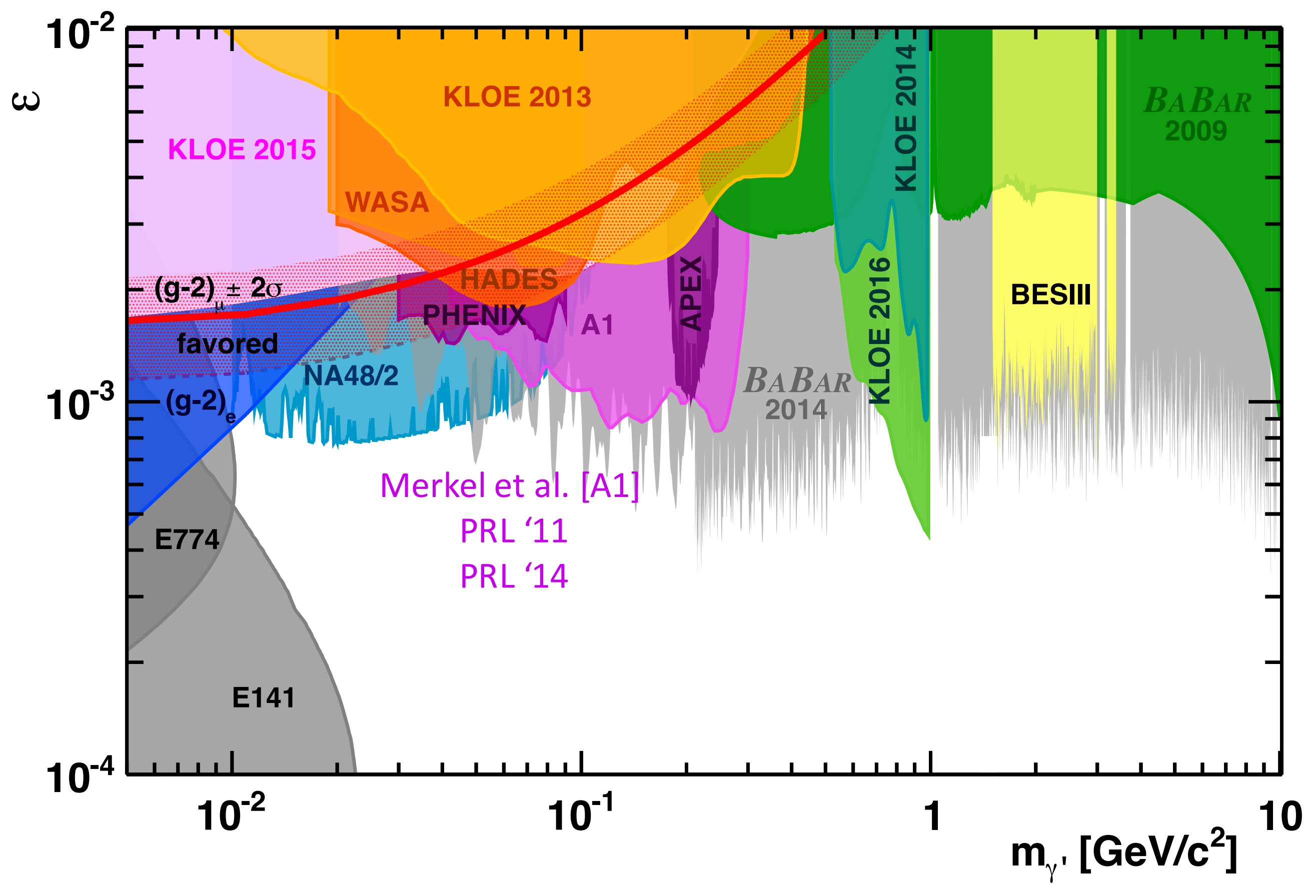


- E_{beam} 180 - 855 MeV
- 100 μA beam current
- Stack of Ta targets
- 22 kinematic settings
- O(1 month) of beam tim

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

Results from A1/MAMI

Year 2017

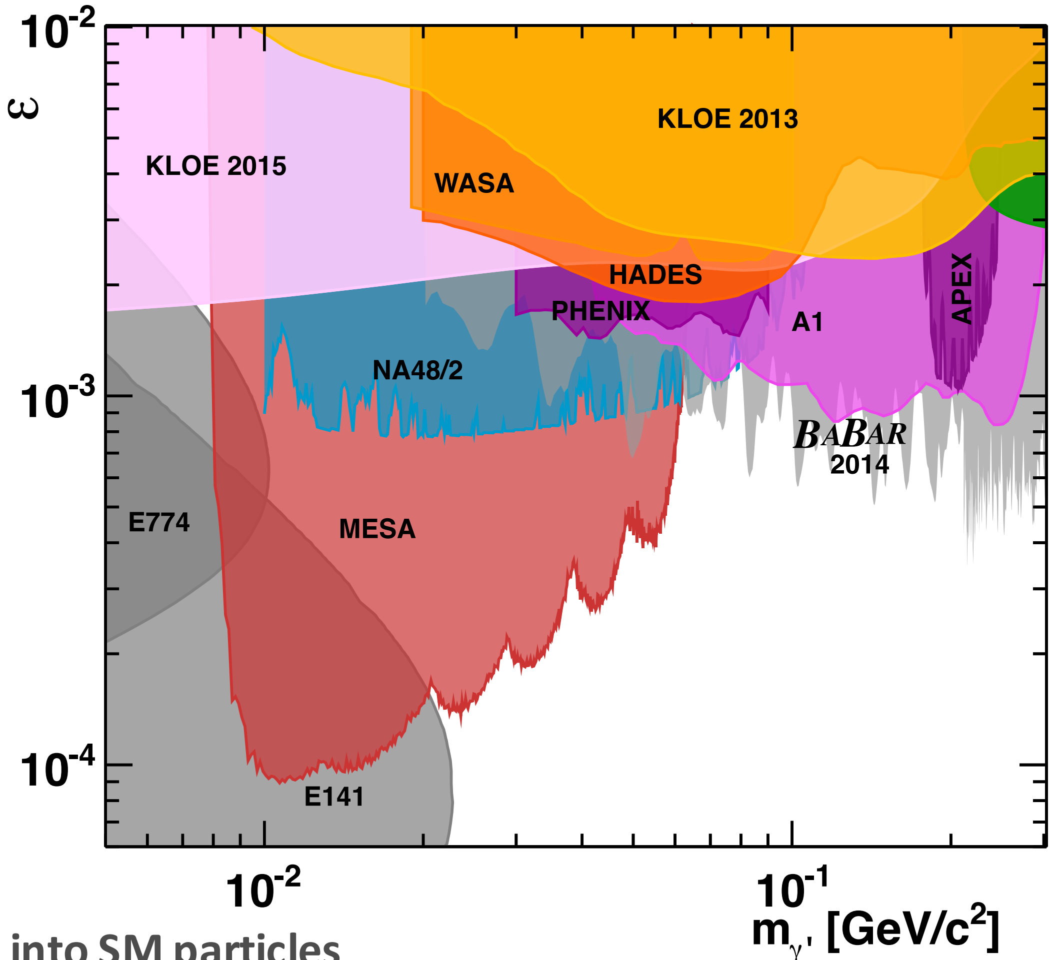


→ **at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g-2)_\mu$**

Dark Sector Searches at MAGIX

Features:

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



MAGIX / MESA

Model 1: Dark Photon decaying into SM particles

→ parameter range motivated by Dark Photon relation to Dark Matter

$$m_{\gamma'} \ll m_{\mathrm{DM}}$$

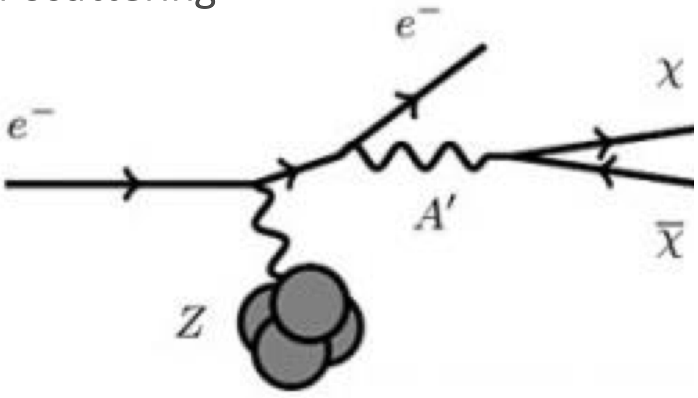
Dark Sector Searches at MAGIX

Model 2: Dark Photon decaying into light Dark Matter $m_{\gamma'} > 2m_{\mathrm{DM}}$

→ exploit excellent momentum resolution of MAGIX (proton recoil!)

→ Main background: Virtual Compton scattering

$$e + p \rightarrow e' + p + \mathrm{X}$$
$\hookrightarrow$ *invisible*

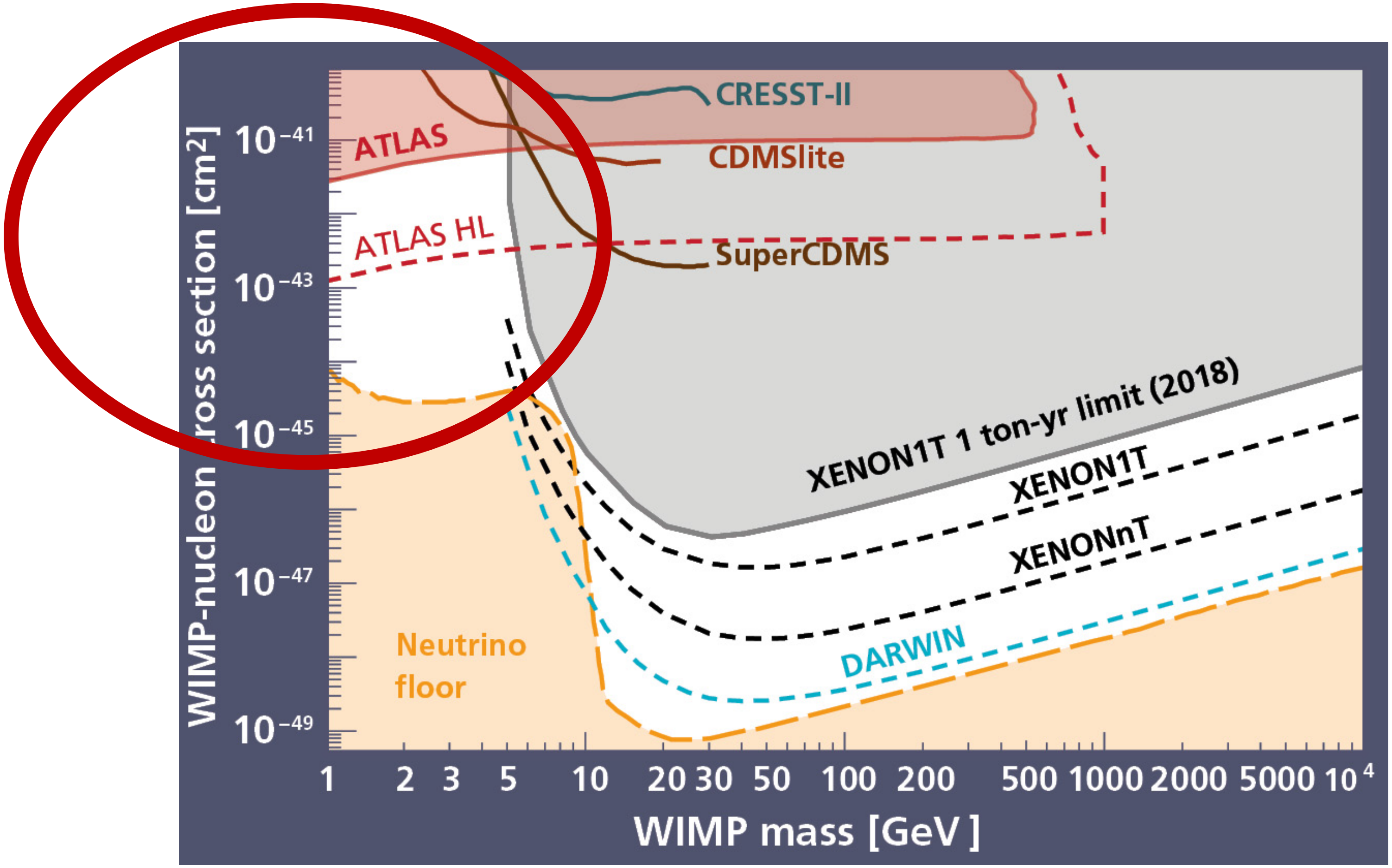


$$m^2_{\gamma'} = (e + p - e' - p')^2$$

Sensitivity at MAGIX currently calculated
(use of thin HVMAPS detectors for proton recoil under study)

Light Dark Matter Searches

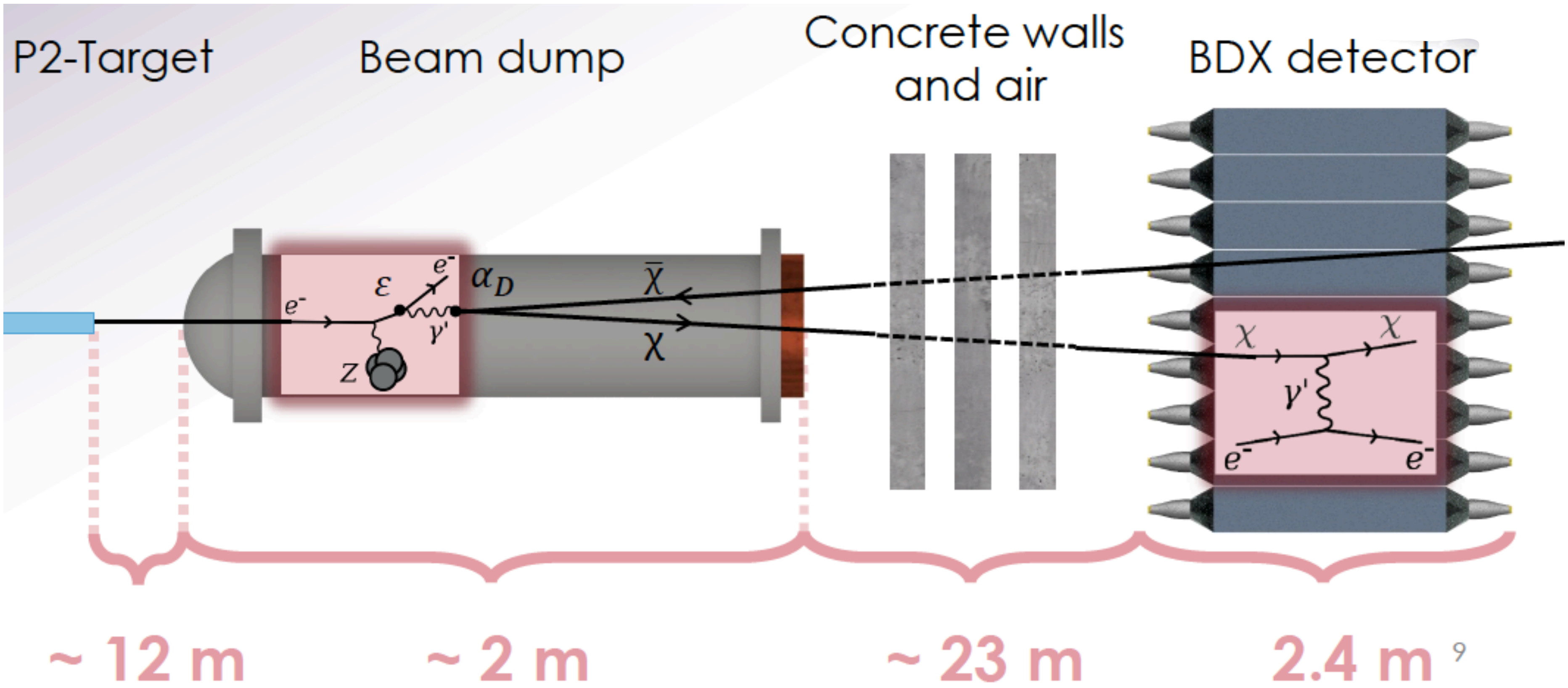
Parameter range accessible



Search for
Light Dark Matter
in a Beam Dump
Experiment

Beam Dump Experiment (BDX) @ MESA

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



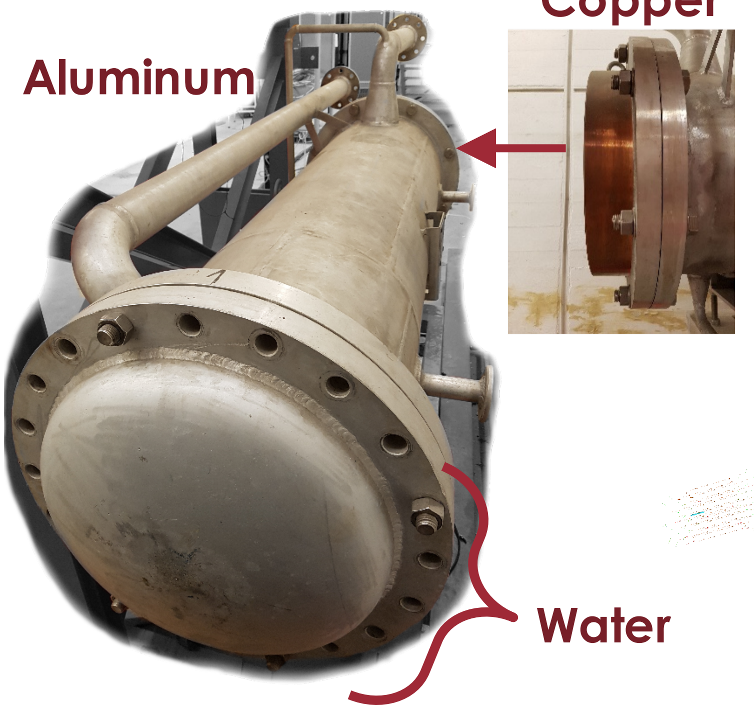
This beam dump is going to be the P2 beam dump

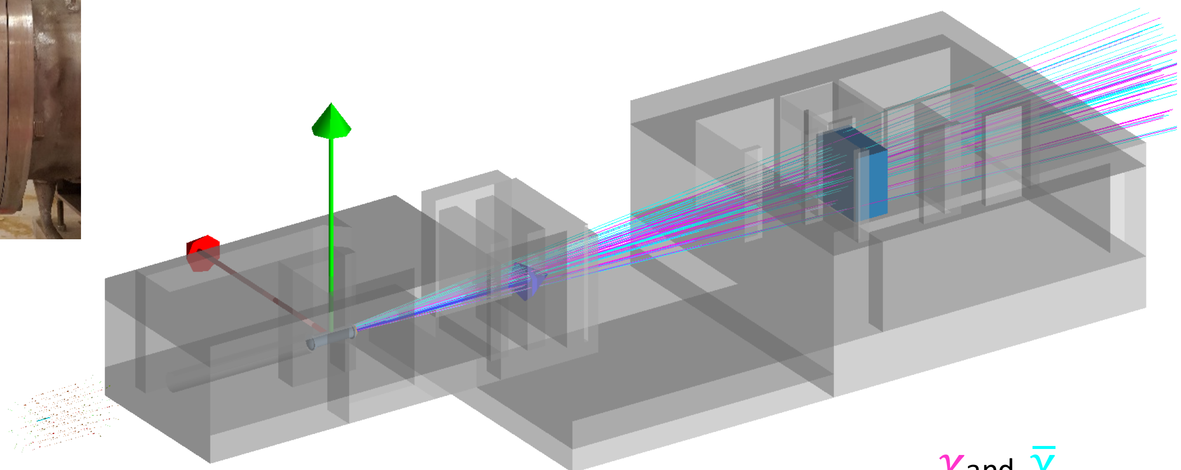
10,000 hours @ 150 µA

→ 10^{23} electrons on target (EOT)

Beam Dump Experiment (BDX) @ MESA

- Full GEANT4 simulation (P2 target, beam dump, BDX detector volume, walls etc.)
- Addition of 2.5 mm W plate before beam dump to increase (dark) photon rate?
- No neutrino background due to low beam energy, reduced neutron background
- First detector layout: lead glass blocks

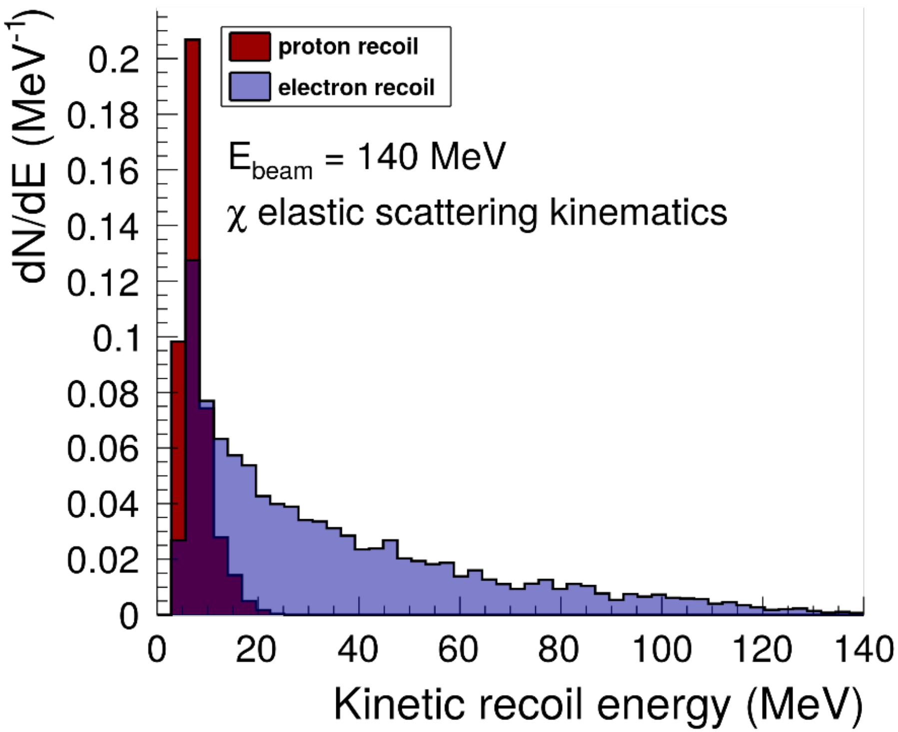




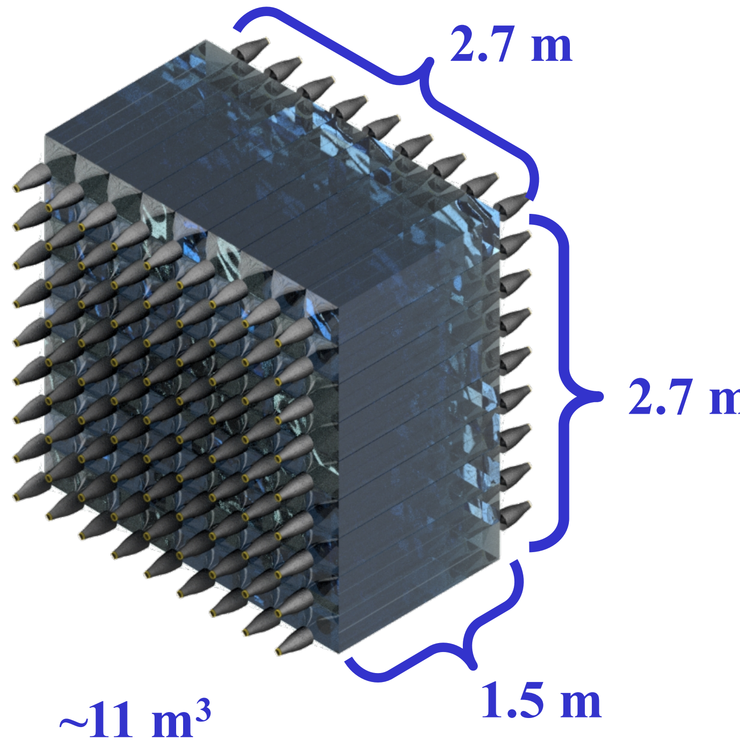
χ and $\bar{\chi}$
(example for
$m_{\gamma'} = 100$ MeV
and $m_{\chi} = 1$ MeV)

Beam Dump Experiment (BDX) @ MESA

Depending on parameter range **large energy deposit**



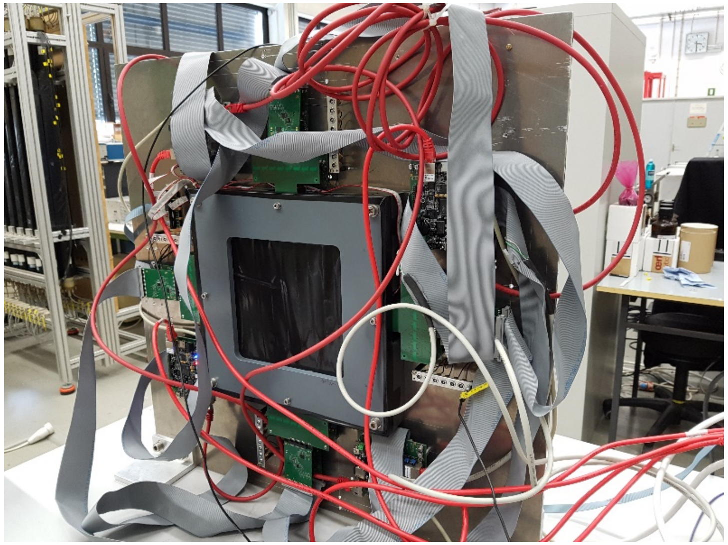
Lead glass detector setup



	Cherenkov	Scintilator
Detector volume	low-cost	expensive
Light yield	lower	higher

Beam Dump Experiment (BDX) @ MESA

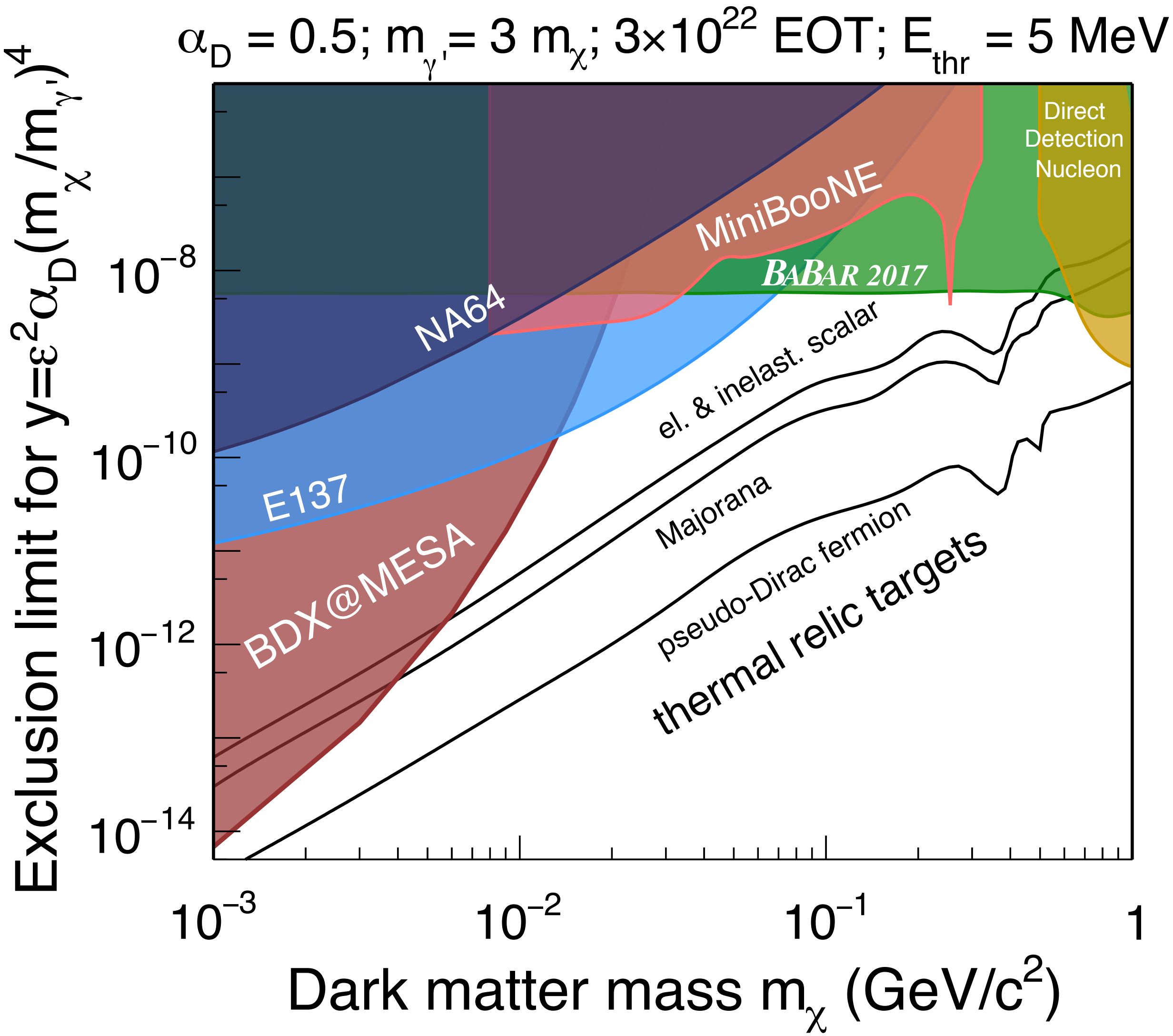
MAMI test beam this week



- 14 MeV electron beam
- Seven detector prototypes
  - Mainly scintillation light:
    - 2 x BGO
  - Cherenkov light:
    - 2 x PbF_2 (in two different lengths)
    - 3 x lead glass (SF5, SF6 & SF57HTultra)
- Fibre detector as trigger system

	X [mm]	Y [mm]	Z [mm]	Density [g/cm³]
SF 5	70	55	160	4.07
SF 6	30	55	160	5.18
SF 57 HTultra	40	55 (180)	160	5.51
BGO	21	21	230	7.13
PbF_2 (1)	Frustum of a pyramid		150	7.77
PbF_2 (7)	(30x30 / 26x26)		185.4	7.77

Beam Dump Experiment (BDX) @ MESA



Conclusions

- MAMI accelerator (1.6 GeV high intensity electron beam, polarized) producing highly competitive results for decades

- Exciting physics topics at the intensity / precision frontier (proton radius, EW mixing angle, dark photon physics, ...)

- New MESA accelerator (order of magnitude of increase of statsitics) under construction at Mainz, commissioning in 2021

- Competitive programme in nuclear, hadron, and particle physics

Conclusions

- MAMI accelerator (1.6 GeV high intensity electron beam, polarized) producing highly competitive results for decades

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- New MESA accelerator (order of magnitude of increase of statsitics) under construction at Mainz, commissioning in 2021

- Competitive programme in nuclear, hadron, and particle physics

THANK YOU !

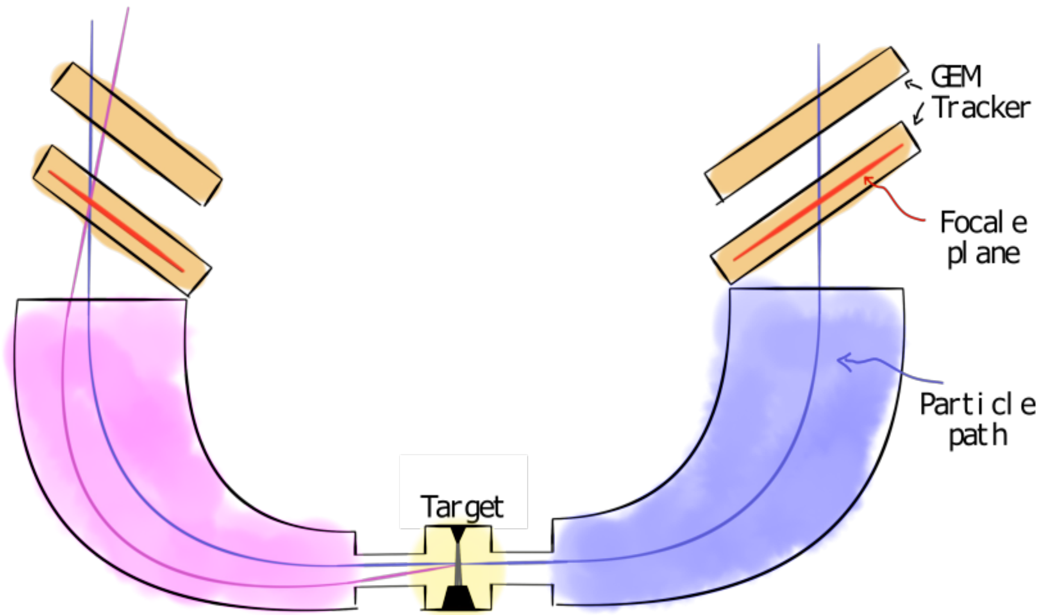
NEW COLLABORATORS WELCOME !

BACKUP

The MAGIX Spectrometers

High resolution spectrometers MAGIX:

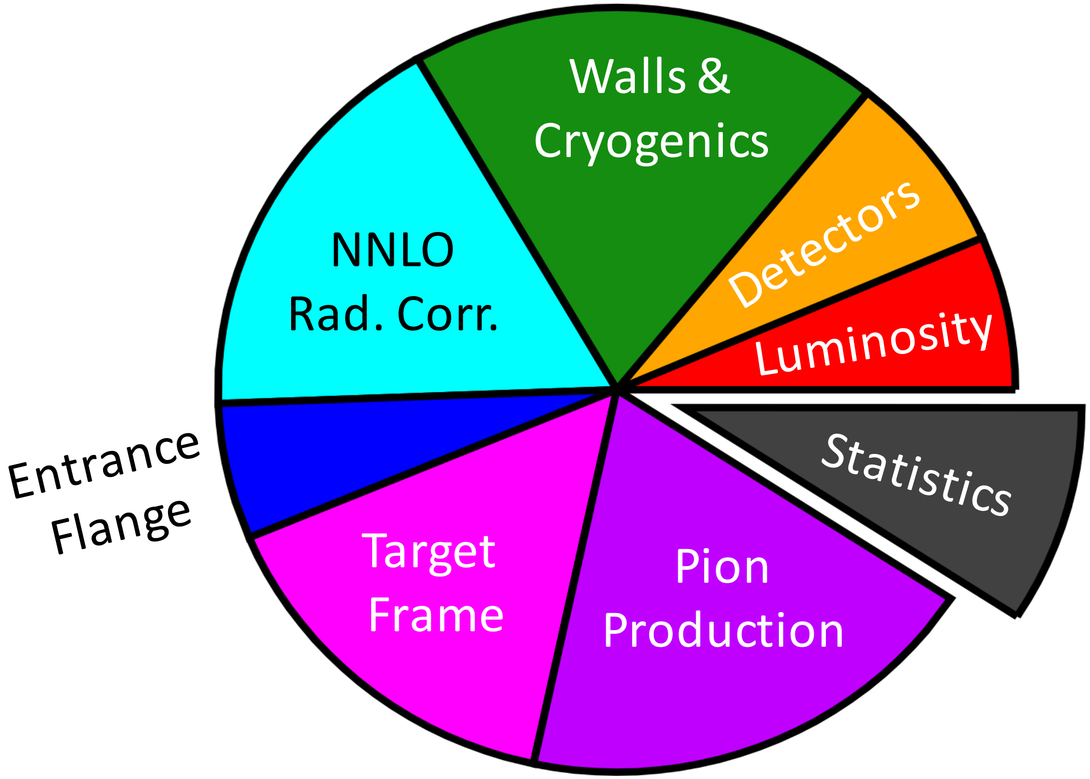
- double arm, compact design
- momentum resolution: $\Delta p/p < 10^{-4}$
- acceptance: ±50 mrad
- GEM- or TPC-based focal plane detectors

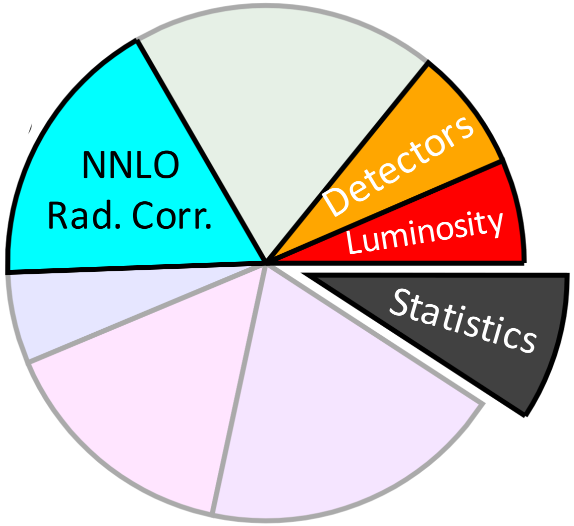


- Gas Jet or polarized T-shaped target for polarized target measurements

ISR Measurement with Gas-Jet-Target

Existing ISR measurement:
Systematic uncertainties ~1%

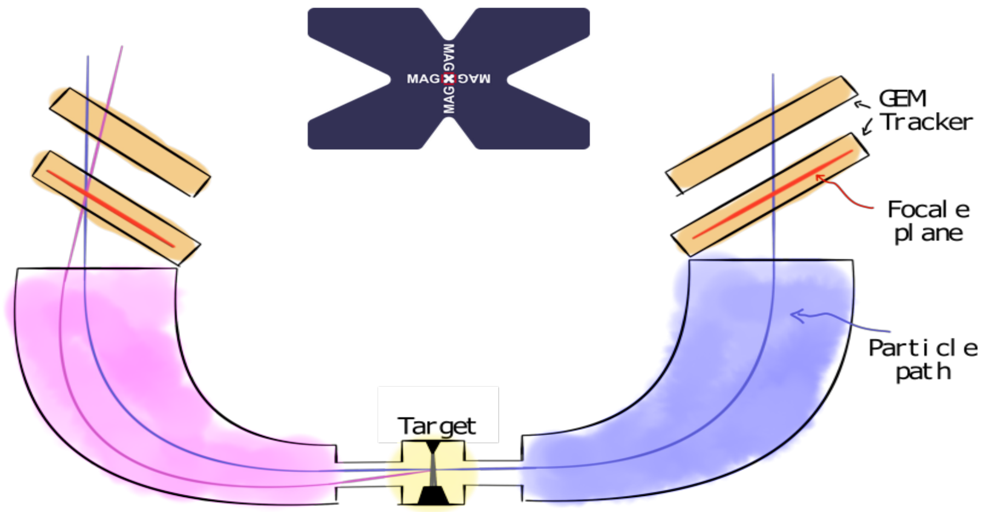




Remaining contributions after measurement with gas jet target and slight additional modifications:
Sytematic uncertainty < 0.5%

courtesy M. Mihovilovic

Detector Development



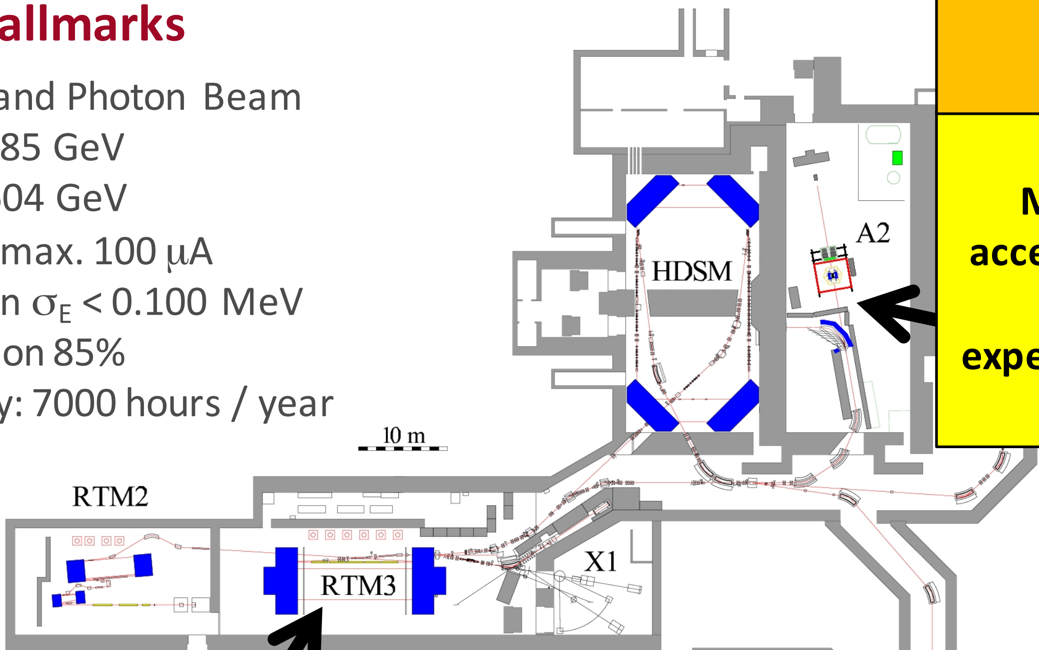
The Mainz Microtron MAMI

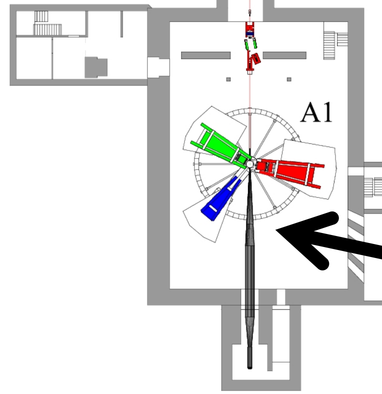
New exptl. hall

MESA accelerator & experiments

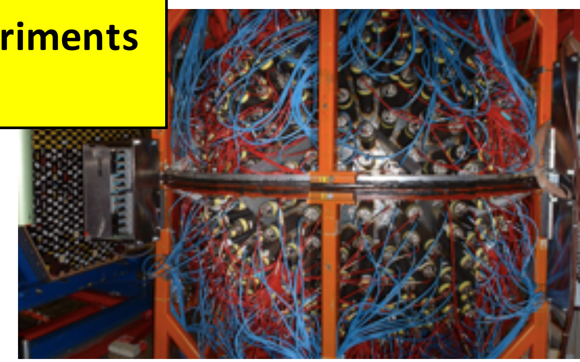
MAMI Hallmarks

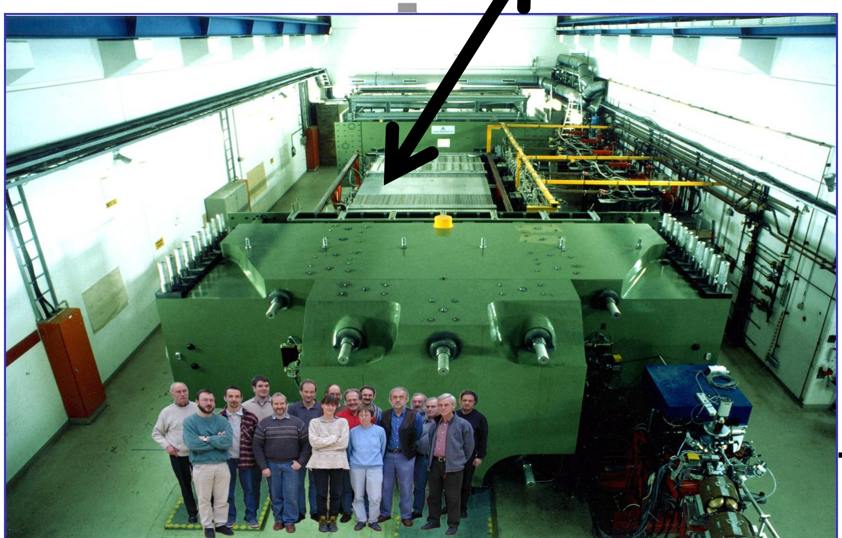
- Electron and Photon Beam
  $E_{min} = 0.185$ GeV
  $E_{max} = 1.604$ GeV
- Intensity max. 100 μA
- Resolution $\sigma_E < 0.100$ MeV
- Polarization 85%
- Reliability: 7000 hours / year





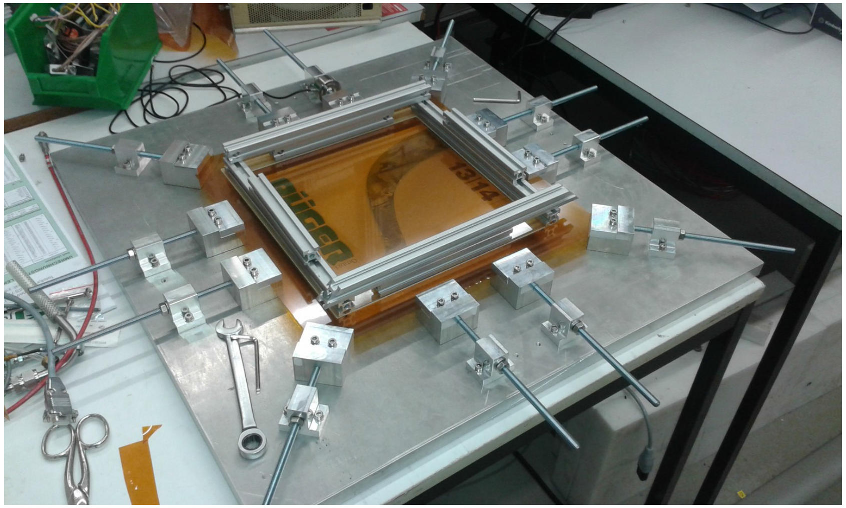
A2 tagged photon beam facility





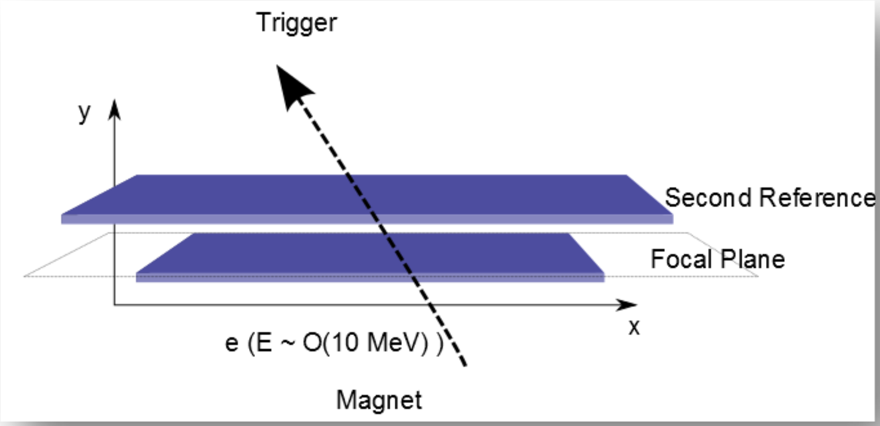
A1 electron scattering facility

GEM Focal Plane Detectors



2 Sensitive layers (30x120 cm^2)

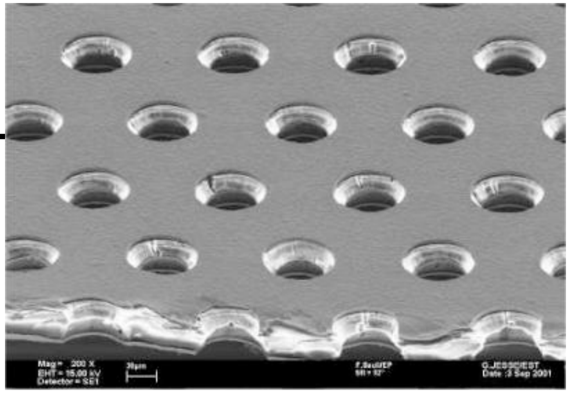
- The first centered on the focal plane
- The second with a sizable lever arm to measure the angle



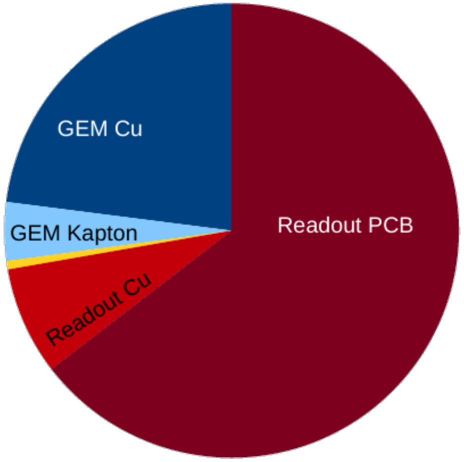
GEM Detectors (2 or 3 layers)

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

GEM Detectors



Material budget of standard GEM foils too high for low-energy environment at MAGIX

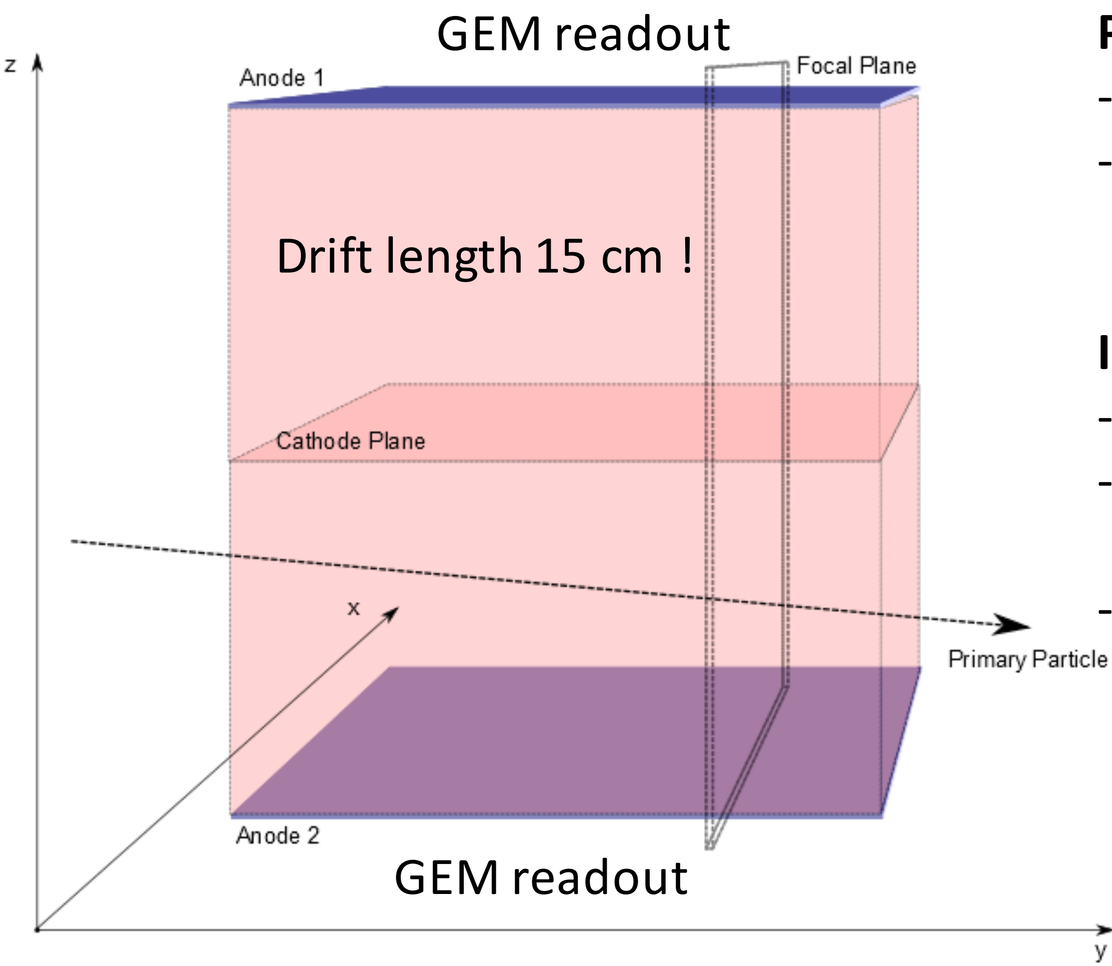


Default triple GEM detector
0.96% X_0

GEM readout on a Kapton foil

GEM copper reduction:
Replacing copper with an atomic layer of Chromium

Small Drift TPC as a Focal Plane Detector ?

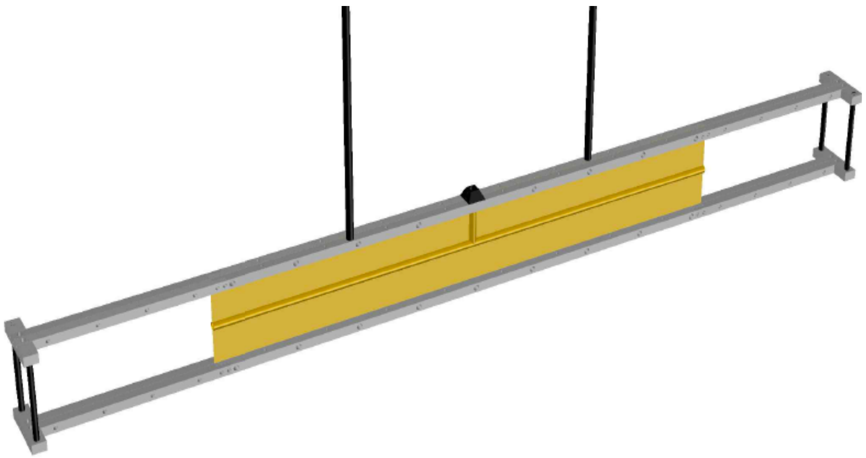


Pro's:
- minimize material budget
- improved spatial and angular resolution

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

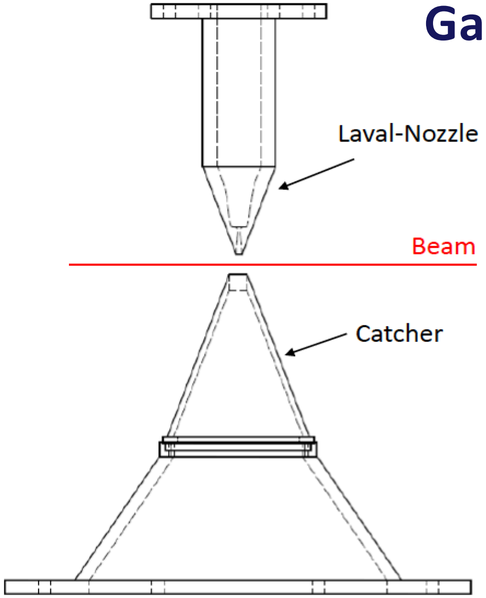
Internal Gas Targets for MAGIX

Thin T-shaped foil



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

Gas-Jet-Target

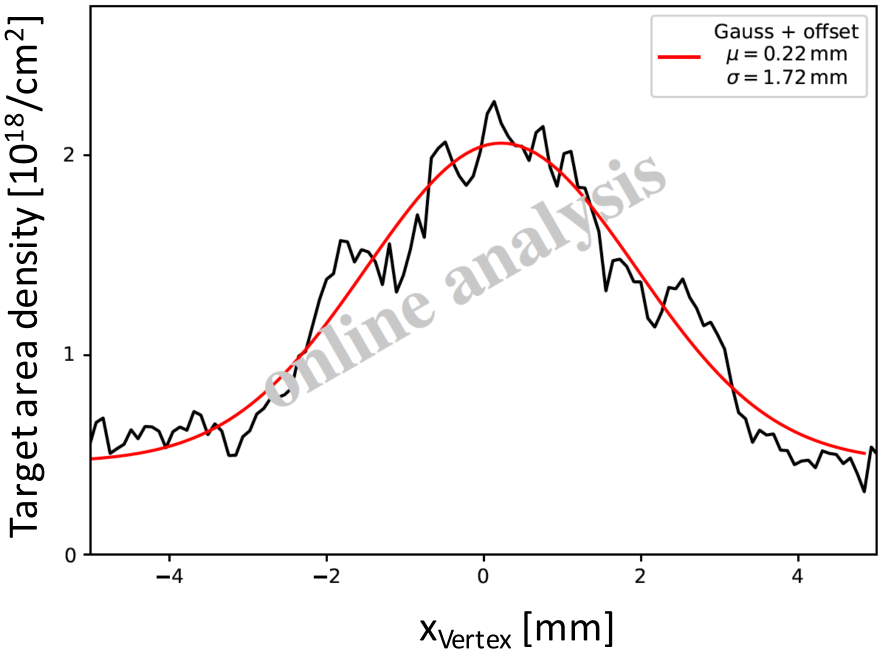


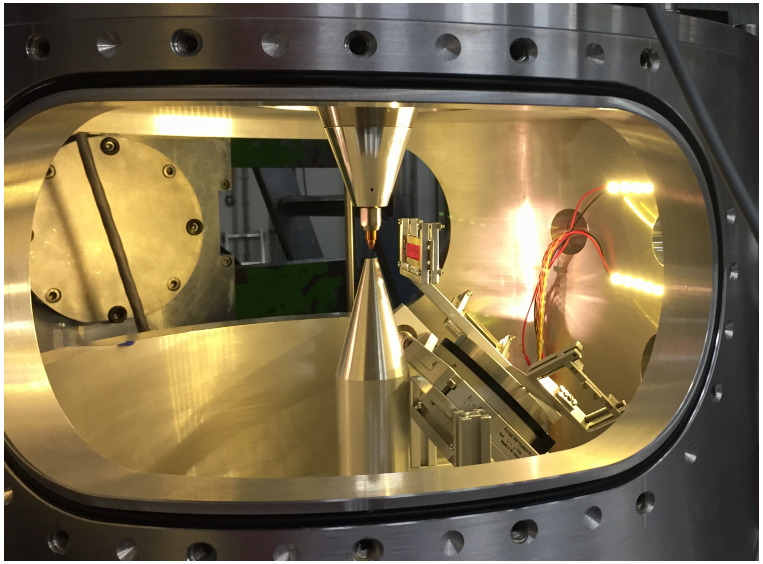
- Windowless !
- Supersonic gas jet
- Higher gas density (10^{19}/cm^2)
- O(mm) target length
- H_2, ^3He, ^4He, O_2, ….., Xe
- *O(10^{35} cm^{-2} s^{-1})* @ 10^{19}/cm^2

Supersonic Gas-Jet-Target

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 x 10^{18} /cm^2 achieved
- Cluster beam width 1.72 mm

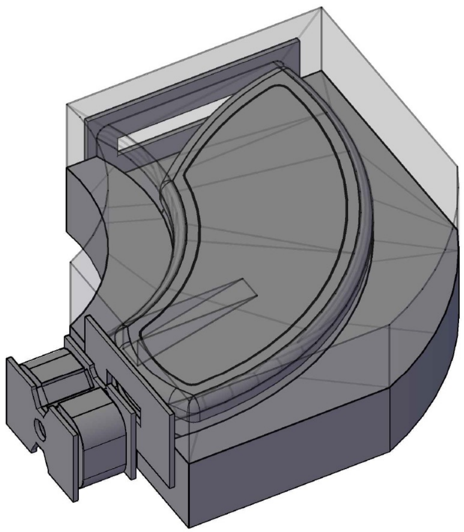


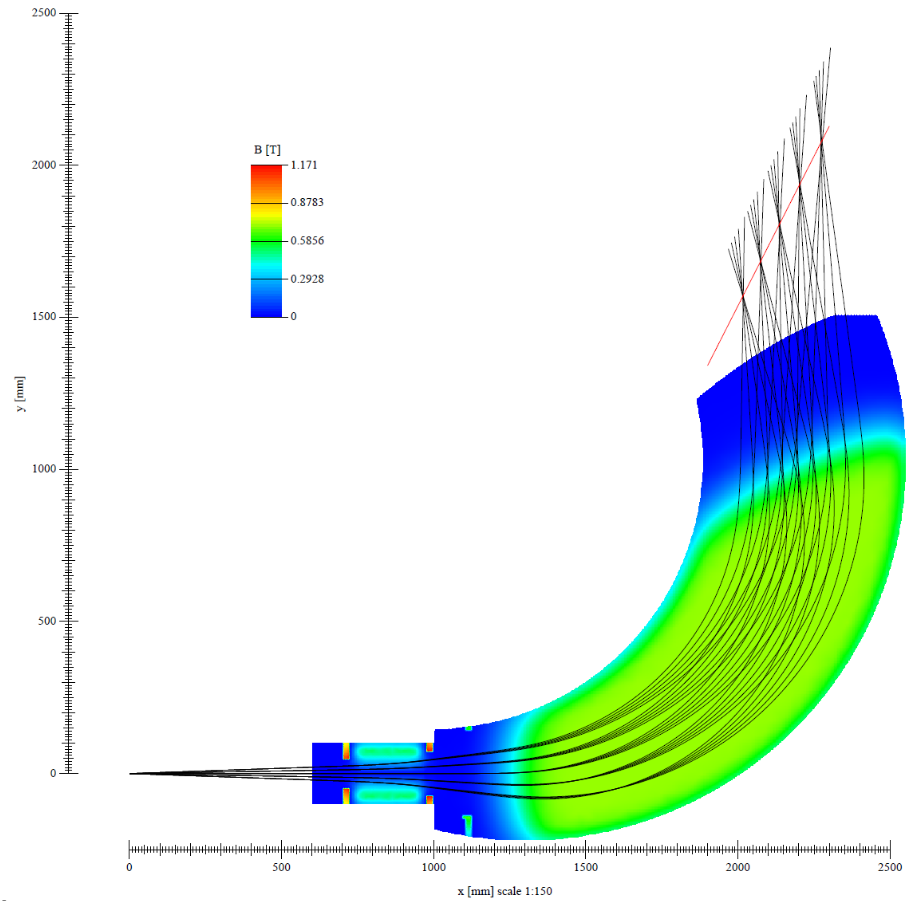


The MAGIX Spectrometers

Simple Design: Quadrupole + Dipole

- 200 MeV maximum momentum
- 90 MeV momentum acceptance @ 200 MeV



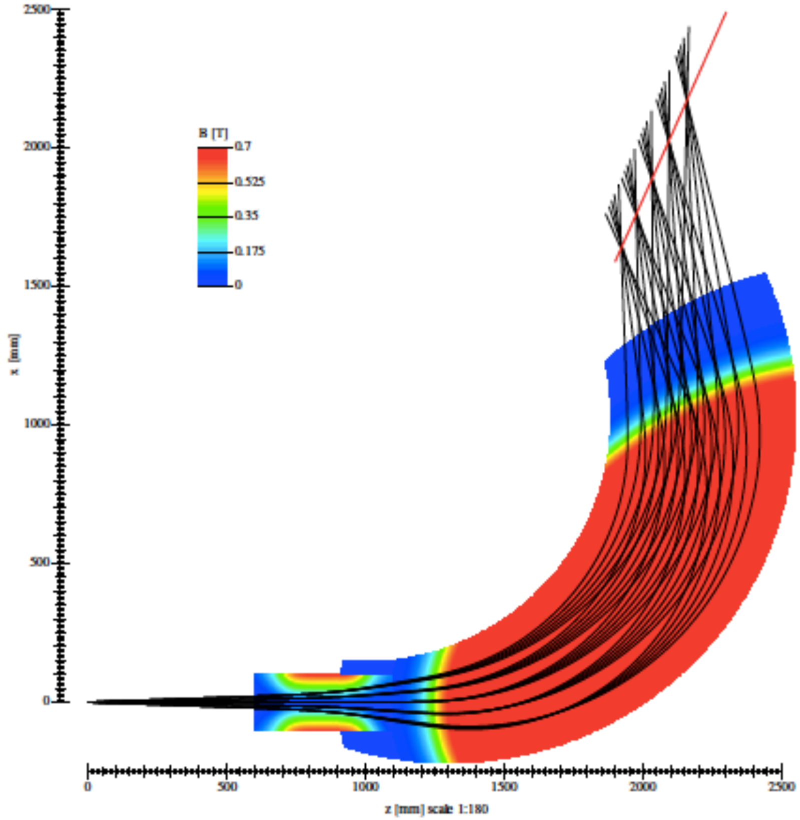


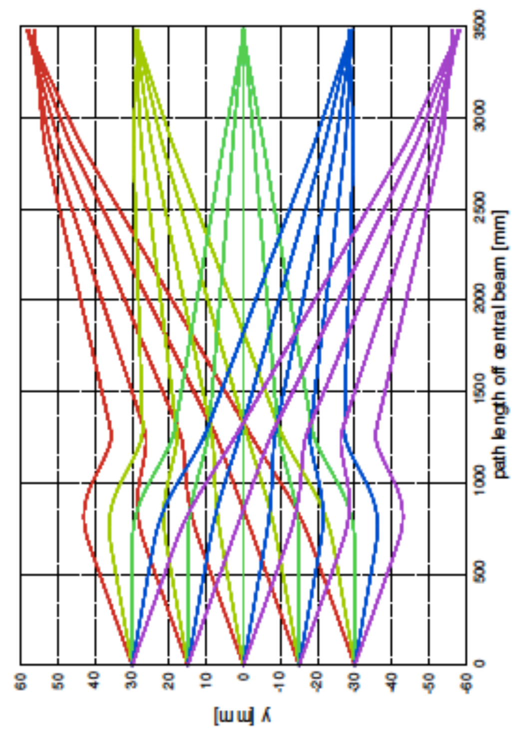
Finite-element simulations

- 10^{-4} relative momentum resolution
- Assuming 50 µm resolution in the focal plane

The MAGIX Spectrometers

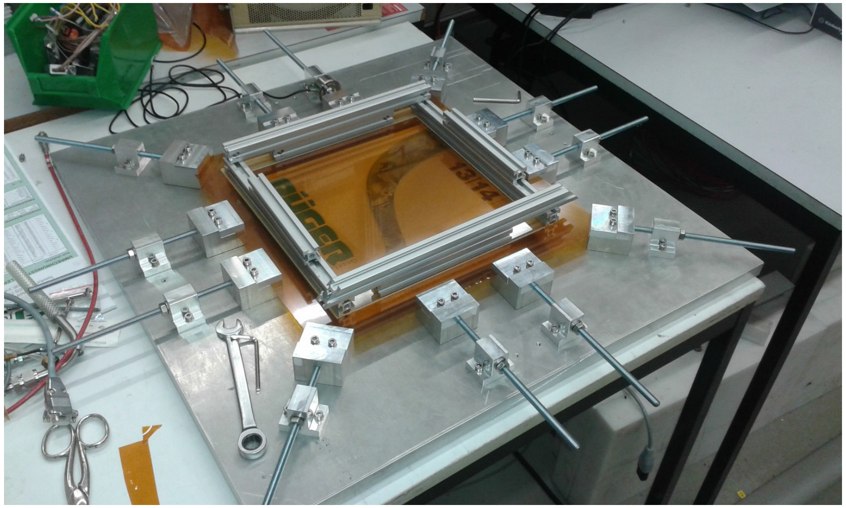
Magix - Optik





- Vertikal: Punkt-zu-Punkt
- ⇒ Impulsauflösung
- Horizontal: Parallel-zu-Punkt
- ⇒ Winkelauflösung

The Focal Plane Detectors



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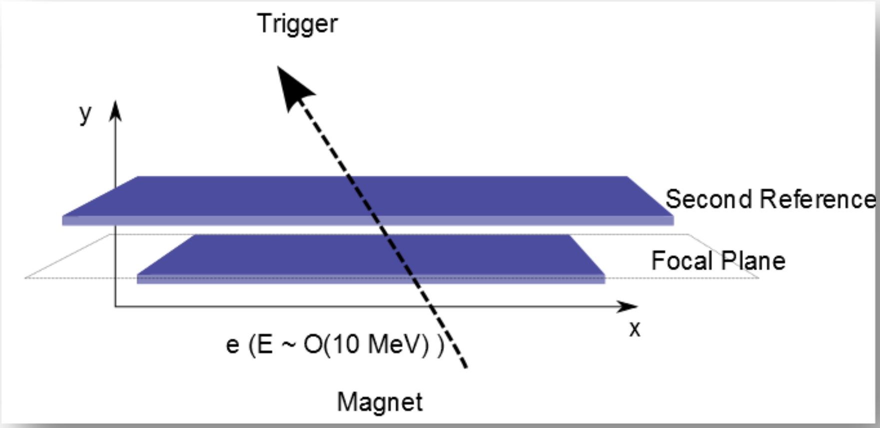
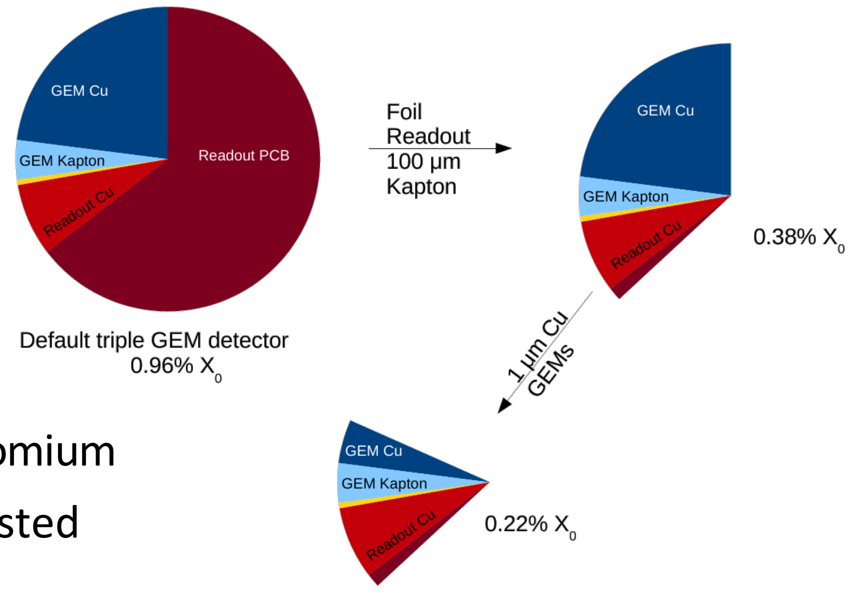


GEM Detectors (2 or 3 layers)

- 2D Strip readout
- 0.7% radiation length
- High rate capabilities
- Material reduction
- **Aim for 50 µm resolution**
- **1 MHz readout rate**

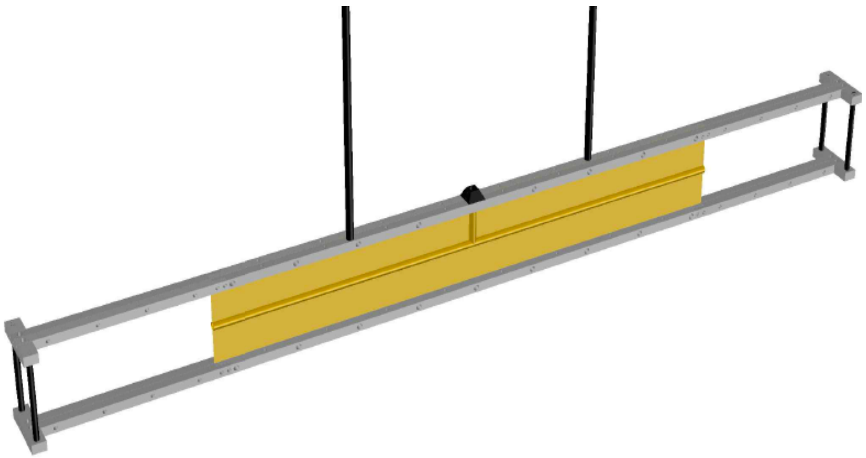
GEM Focal Plane Detectors



- 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(MHz/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(10-100 kHz) (in collaboration with the CERN RD51 group)

Internal Gas Targets for MAGIX

Thin T-shaped foil



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- Can use polarized gases
- Estimated luminosity with polarized beam *O(>> 10^{32} cm^{-2} s^{-1})*

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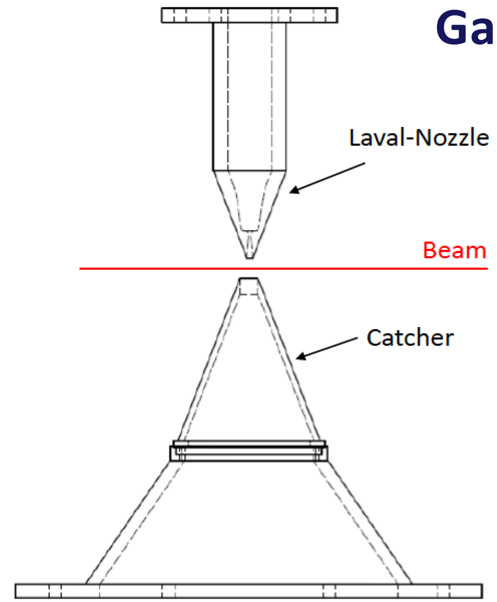
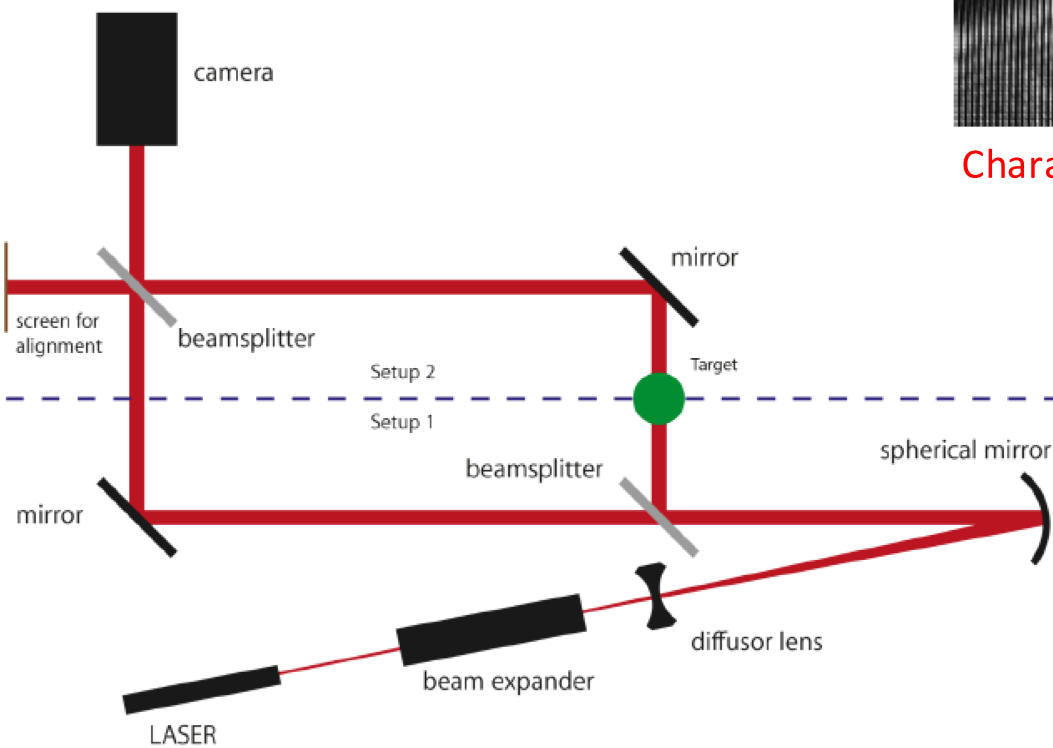
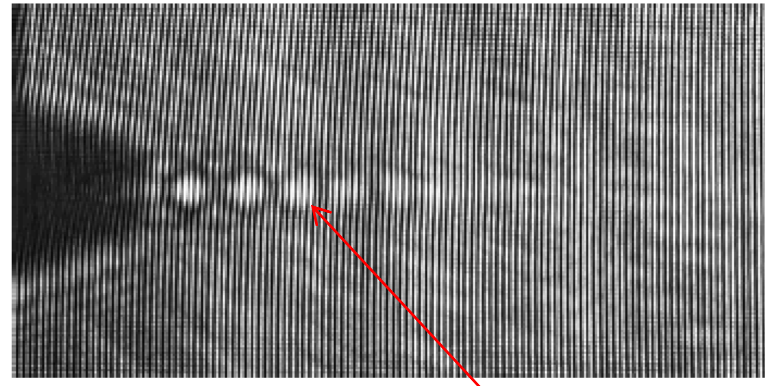


- Windowless !
- Supersonic gas jet
- Higher gas density ($10^{19}/cm^2$)
- O(mm) target length
- H_2, ^3He, ^4He, O_2, ….., Xe
- *O(10^{35} cm^{-2} s^{-1})* @ $10^{19}/cm^2$

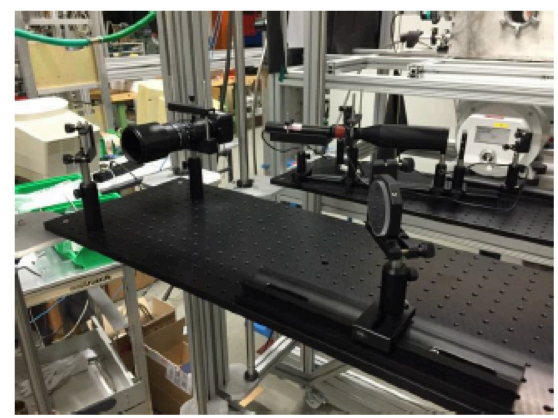
Measurement of Gas Density Profile

Mach-Zehnder Interferometry

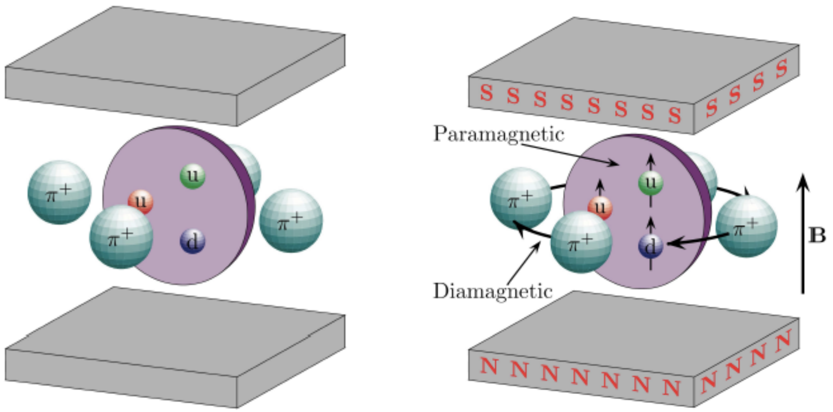




Characteristic profile of a supersonic gas jet



Nucleon Polarizabilities



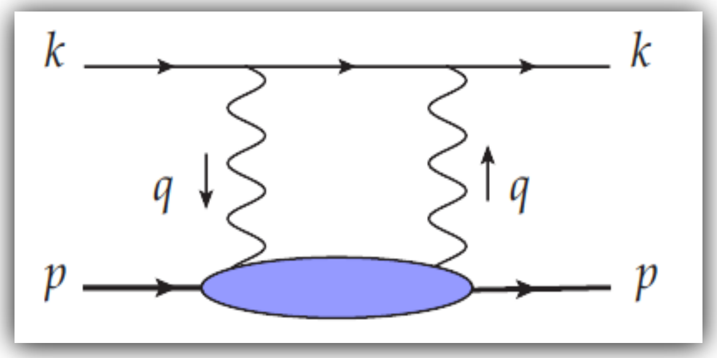
Polarisability Corrections in Light Nuclei Systems

μH: ΔE^{TPE} (2P - 2S) = (33 ± 2) μeV

dispersive analysis

Carlson, Vanderdhaeghen (2011)

accuracy comparable with present experimental precision



μD: ΔE^{TPE} = (1727 ± 20) μeV nucleon potentials form chiral EFT

Hernandez et al. (2014)

accuracy factor 5 worse than present experimental precision

μ^{3}He$^+$: ΔE^{TPE} = (15.46 ± 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)

Proton Polarizabilities

Reaction of nucleon under influence of an EM field
<--> Compton scattering

$$\gamma p \rightarrow \gamma' p'$$

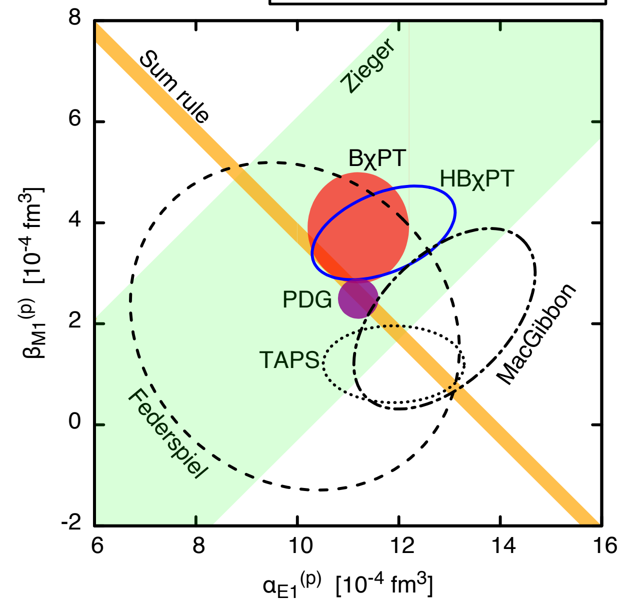
provides fundamental information of the nucleon;
very sensitive test of theories (H/BχPT, Disp. Rel.).

- **Electric Polarizability: α_{E1}**
- **Magnetic Polarizability: β_{M1}**

$$H_{\rm eff}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

- **Spin (Vector) Polarizabilities: γ_{E1E1}, γ_{M1M1}, γ_{M1E2}, γ_{E1M2}**

$$\alpha^p_{E1} = 11.2 \pm 0.4$$
$$\beta^p_{M1} = 2.5 \pm 0.4$$



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

Polarisierbarkeiten

Experiment	Status	
$\boldsymbol{\Sigma_{2x}}$	February 2011	$\surd$
$\boldsymbol{\Sigma_3}$	December 2012	$\surd$
α_{E1}, β_{M1}	June 2013	$\surd$
$\boldsymbol{\Sigma_{2z}}$	May 2014	$\surd$

1. Beam: circular
   Target: longitudinal

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

2. Beam: circular
   Target: transverse

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

3. Beam: linear, $\parallel$ and $\perp$ to scattering plane
   Target: unpolarized

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

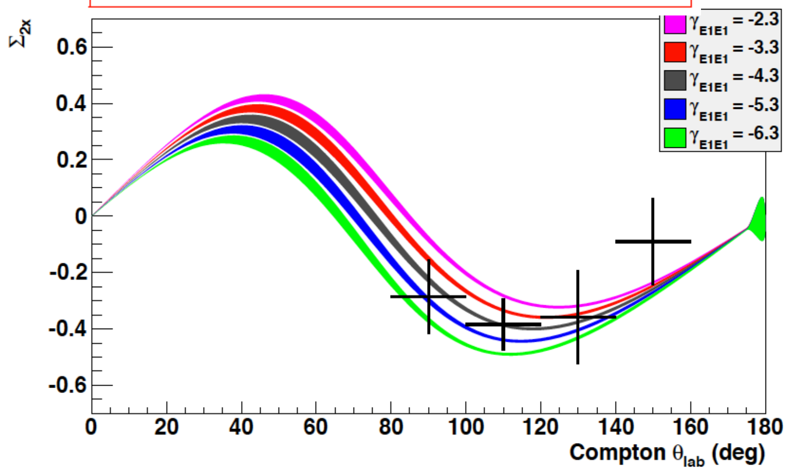
Proton Polarizabilities

Reaction of nucleon under influence of an EM field <--> Compton scattering provides fundamental information of the nucleon, very sensitive test of theories (H/BχPT, Disp. Rel.).

- **Electric Polarizability: α_{E1}**
- **Magnetic Polarizability: β_{M1}**
- **Spin (Vector) Polarizabilities: γ_{E1E1}, γ_{M1M1}, γ_{M1E2}, γ_{E1M2}**

$$H_{\text{eff}}^{(3)} = -4\pi\left[\tfrac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \tfrac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right]$$

$$\gamma_{E1E1} = (-4.6 \pm 1.6) \times 10^{-4}\ \text{fm}^4$$

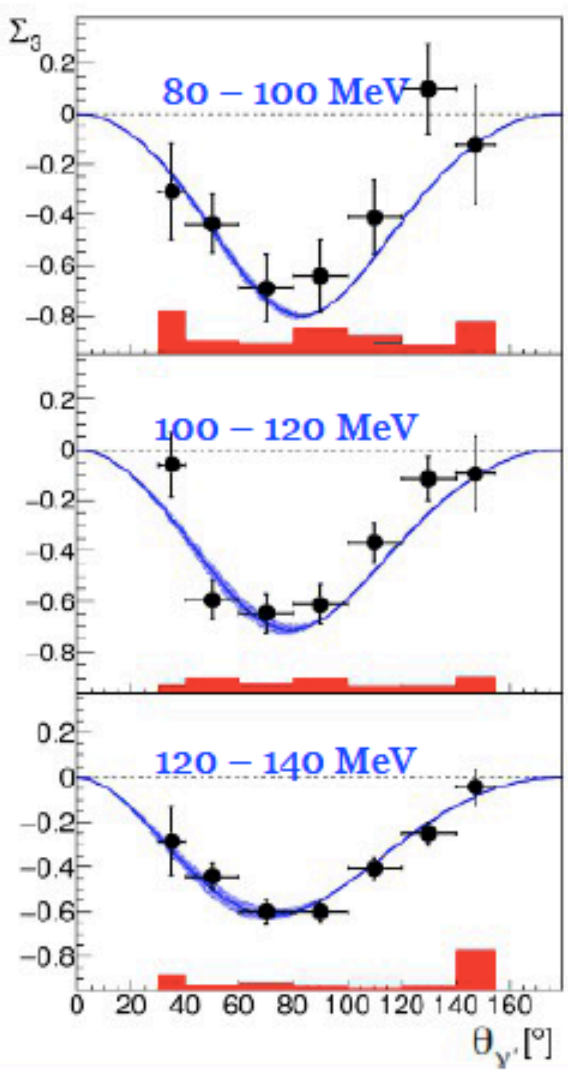


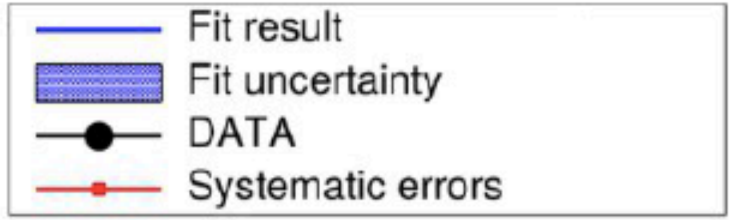
Martel et al. [A2] PRL'15

For the first time measured at MAMI via double polarization variables Σ_{2x}

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

First measurement of Σ_3 below pion threshold





Fit on our Σ_3 results using Baldin sum rule constraint gives:

BChPT framework:

$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 19.2/20$

HBChPT framework:

$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 17.1/20$

At low energy, the measurement of the beam asymmetry Σ_3 provides an alternative way to extract β_{M1}:

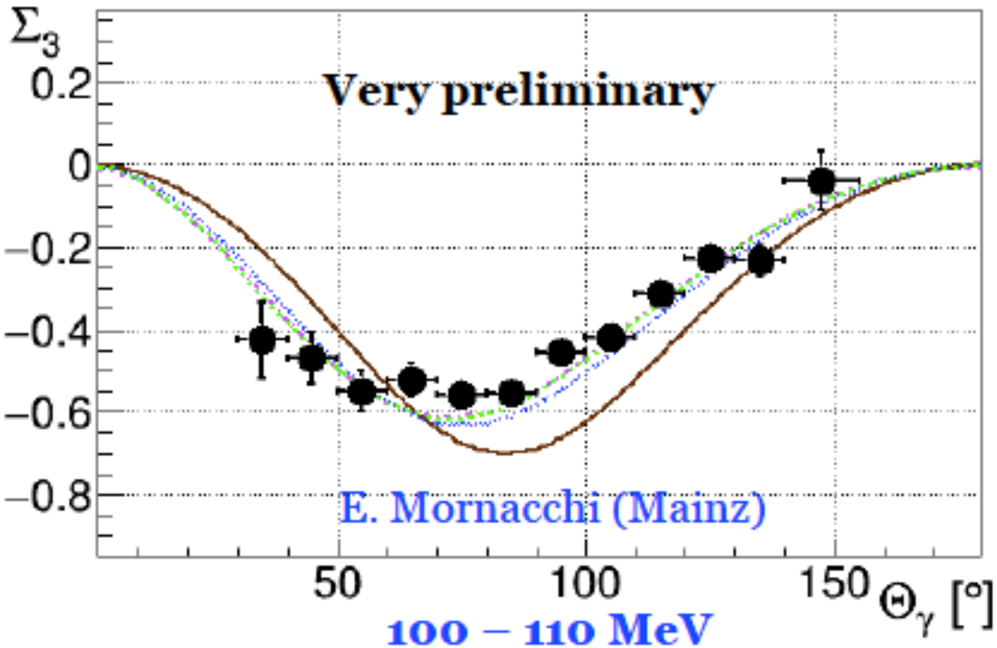
$$\frac{d\sigma}{d\Omega}(\theta,\phi)=\frac{d\sigma}{d\Omega}(\theta)\left[1+p_\gamma\Sigma_3\cos(2\phi)\right] \quad \text{where} \quad \Sigma_3=\frac{d\sigma_\perp-d\sigma_\parallel}{d\sigma_\perp+d\sigma_\parallel}$$

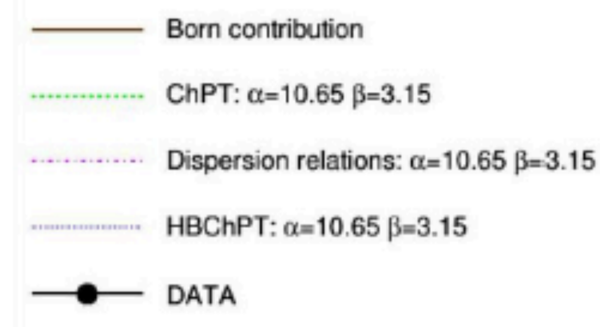
V. S., E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina, Eur.Phys.J. A53 (2017) no.1, 14

High-precision measurements of the beam asymmetry and unpolarized cross-section planned in the end of 2017!

New data set from the A2 Collaboration

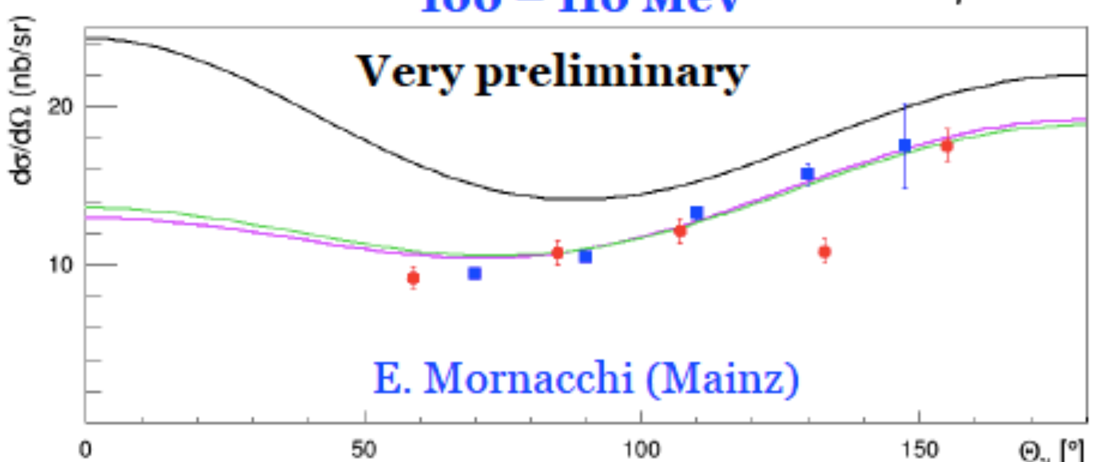
120 – 140 MeV

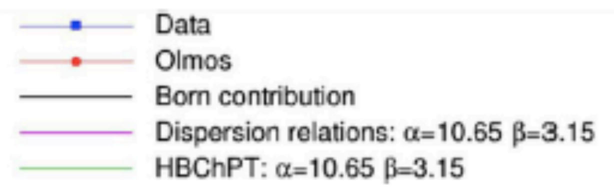




Data analysis ongoing:
Only ~60% of the available statistics

100 – 110 MeV



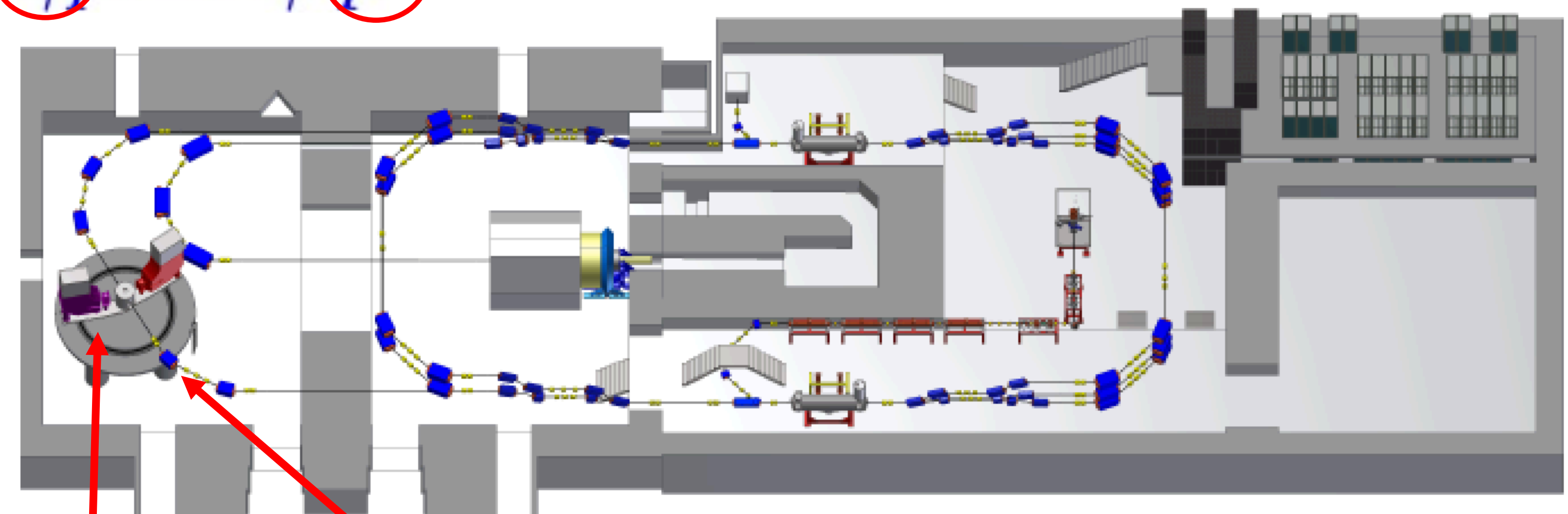


MAMI PAC (2016):
E.J. Downie, D. Hornidge,
P. Martel, V.S.

Highest statistics data set on Compton scattering below pion threshold!
<u>Proton scalar polarizabilities will be extracted with unprecedented precision</u>

Proton Polarizabilities @ MESA

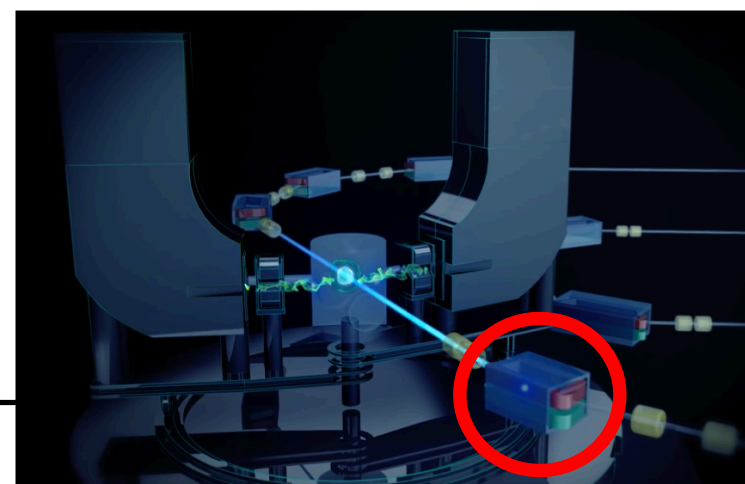
$\gamma p \rightarrow \gamma' p'$



Use dipole close to MAGIX as tagging spectrometer for scattered electron
→ quasi-real photon

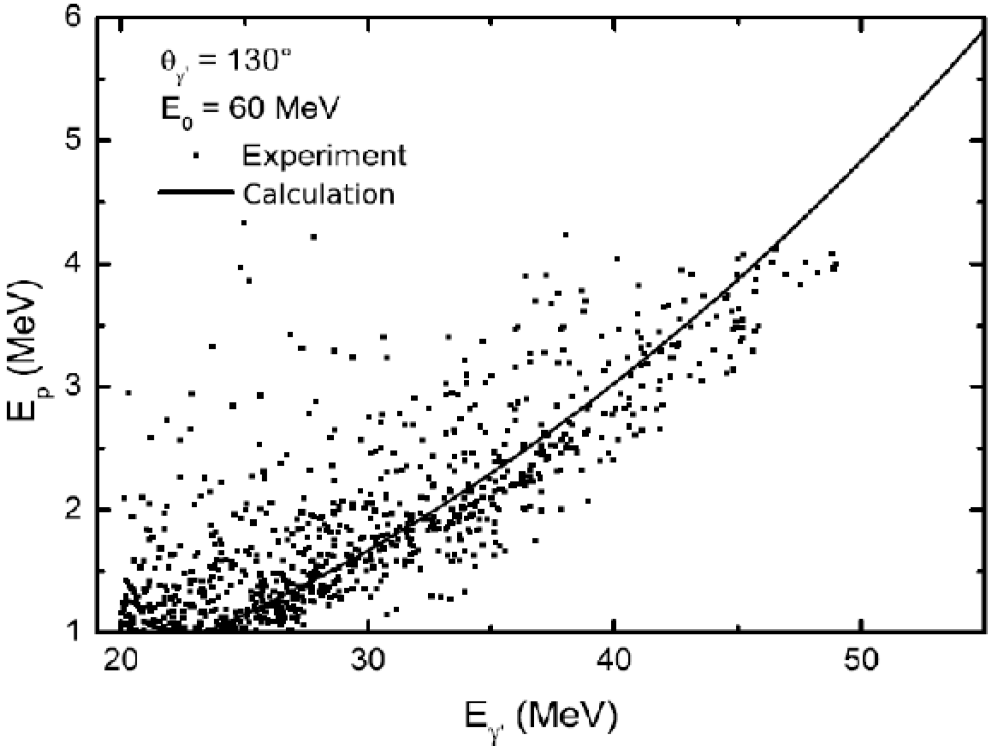
$E_{\gamma} = E_{MESA} - E'$

Low-energetic proton measured in one of the spectrometers



Proton Polarizabilities @ MESA

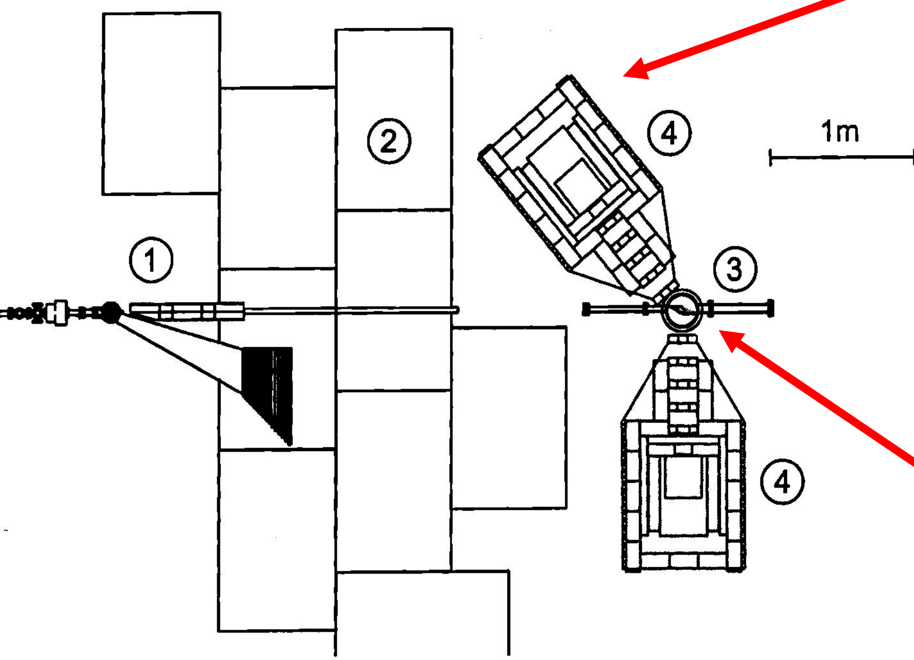
Measurement @ S-DALINAC / Darmstadt limited by beam intensity



Estimate for MESA: 110 MeV, 40 µA beam current:
8 000 000 detected γp pairs in 3 weeks of beam time
yielding Δα = 0.15, Δβ = 0.20 (stat. + syst. uncertainty)

Proton Polarizabilities @ MESA

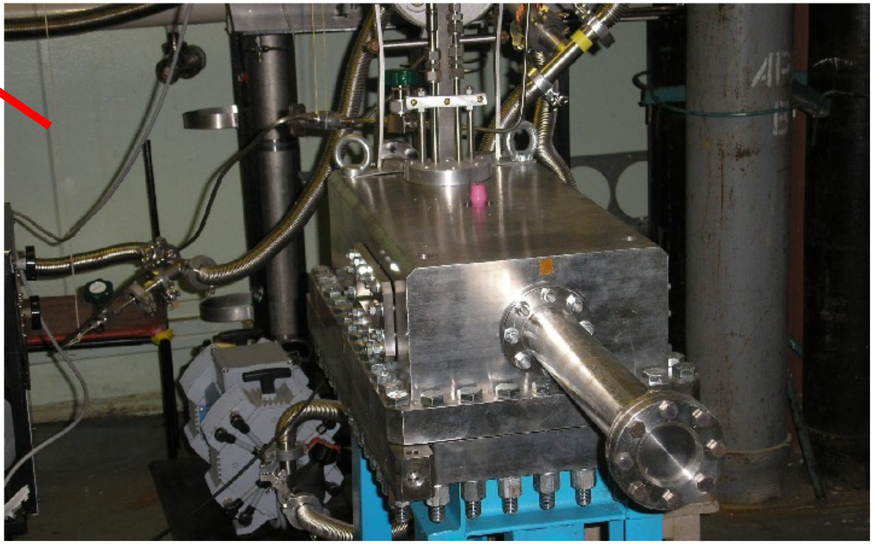
$\gamma p \rightarrow \gamma' p'$



Measurement of photon in final state via dedicated detectors

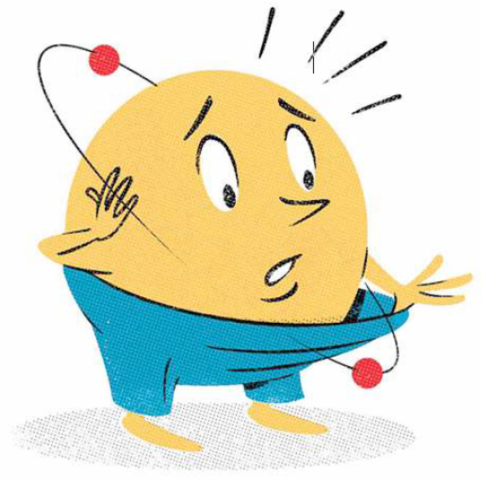
1 – bremsstrahlung facility,
2 – concrete shielding,
3 – high pressure ionization chamber (active target),
4 – γ-detectors (NaI) at θ_γ=130 and θ_γ =90 deg.

Evgeny Maev @ LEPP16



Highly-pressurized active target (TPC) developed by group from St. Petersburg (proton detection)

Nucleon
Form Factors



The New York Times

Proton Radius Puzzle - What is going on?

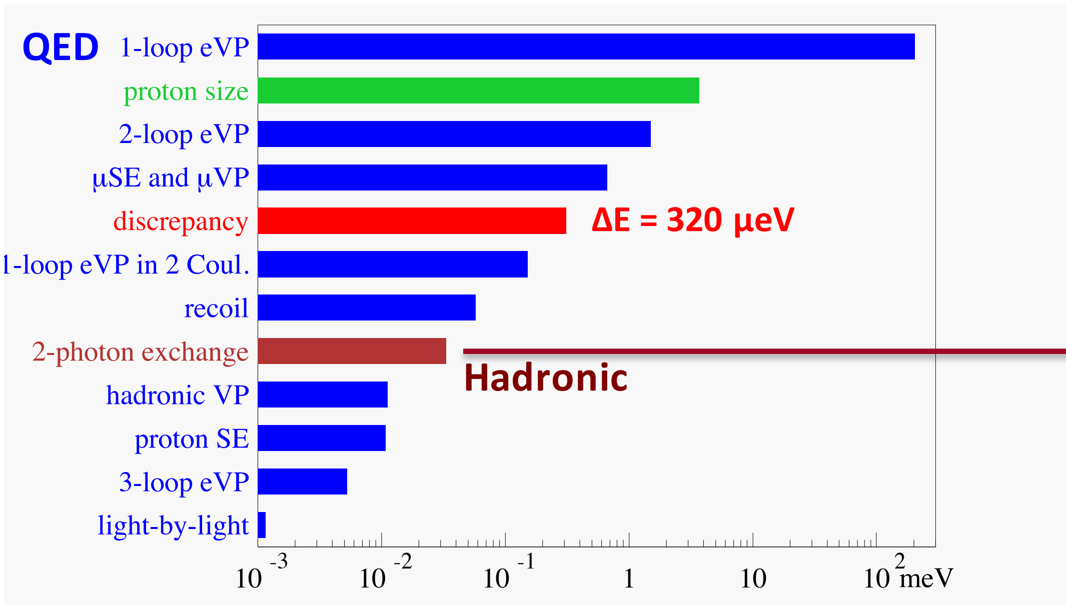
A worldwide effort in atomic physics, hadron/particle physics and theory

- **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**
  or – radiative corrections not understood
  or – normalization errors
  or …. ?

Corrections in μH

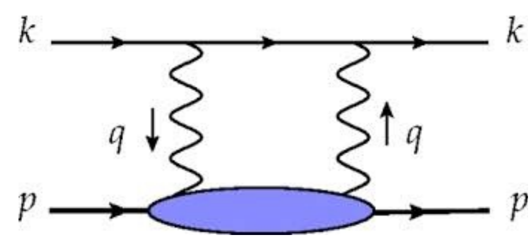
Corrections in muonic hydrogen Lamb Shift



Carlson, Vanderhaeghen 2011
Birse, Mc Govern 2012

largest hadronic correction / uncertainty:

$\Delta E_{2\gamma}$ = (33 ±2) μeV

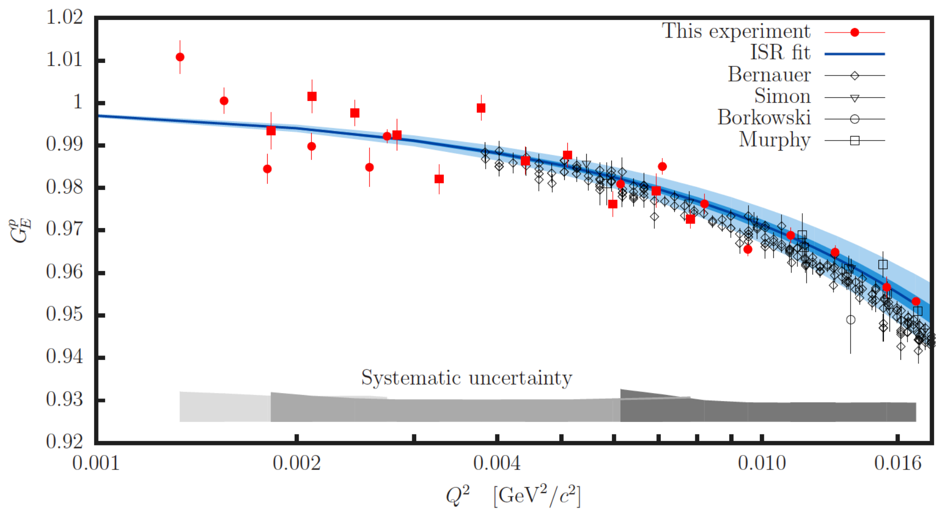


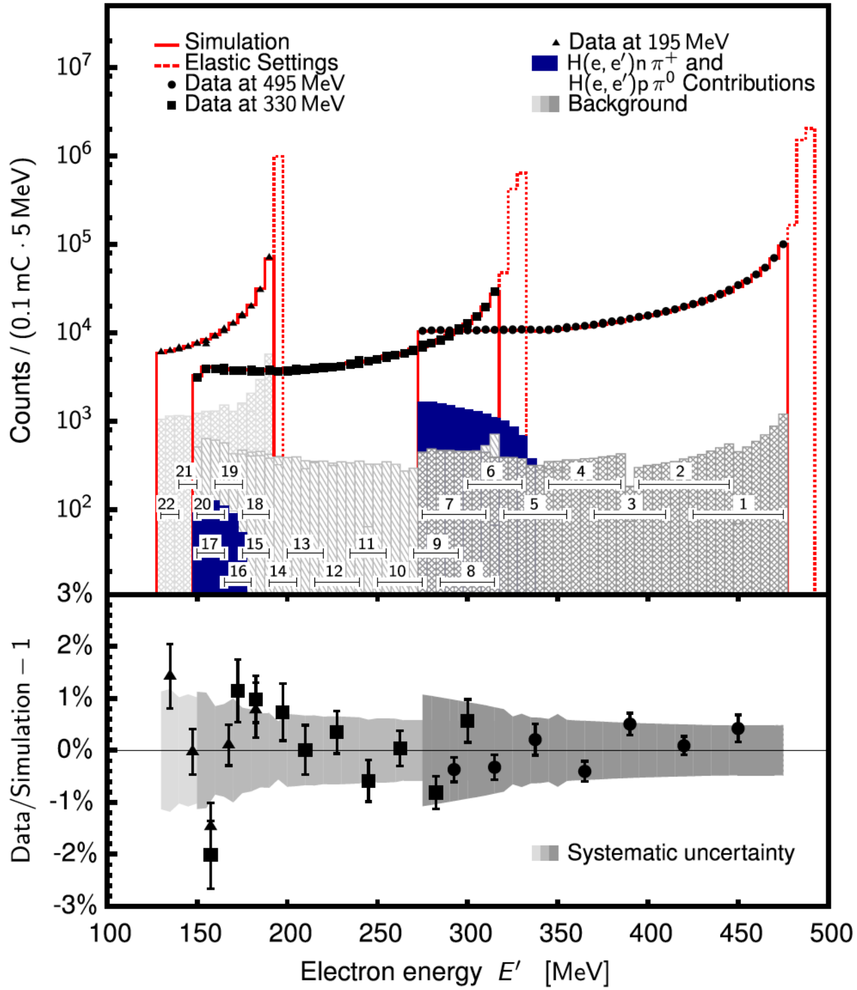
2-Photon exchange
→ Forward Compton scattering
→ **Uncertainty dominated by the magnetic polarizability β**
→ **New MAMI measurement @ A2**

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





Electron Scattering: Mainz Microtron MAMI

Elastic form factors in ep scattering:

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

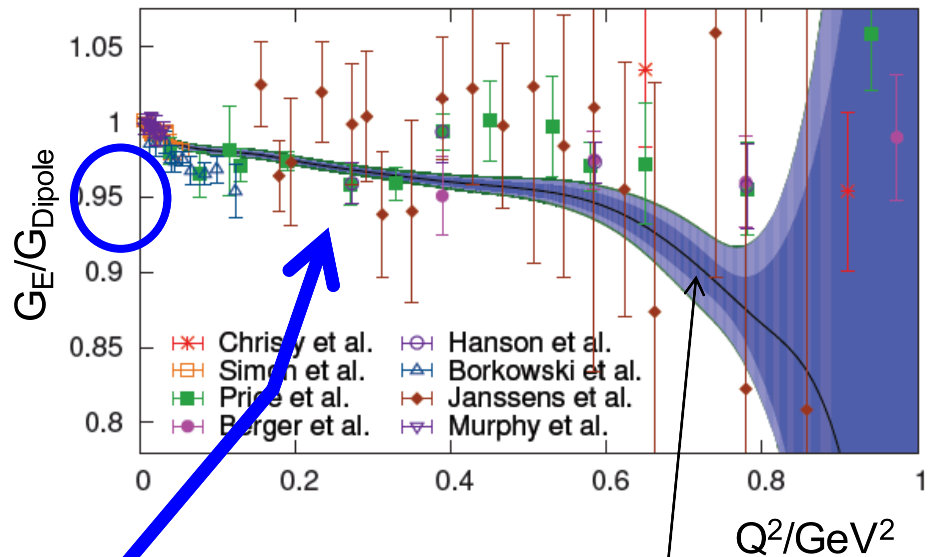
$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

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

G_E: spatial electric charge distribution

G_M: distribution of magnetic moments

Super-Rosenbluth measurement

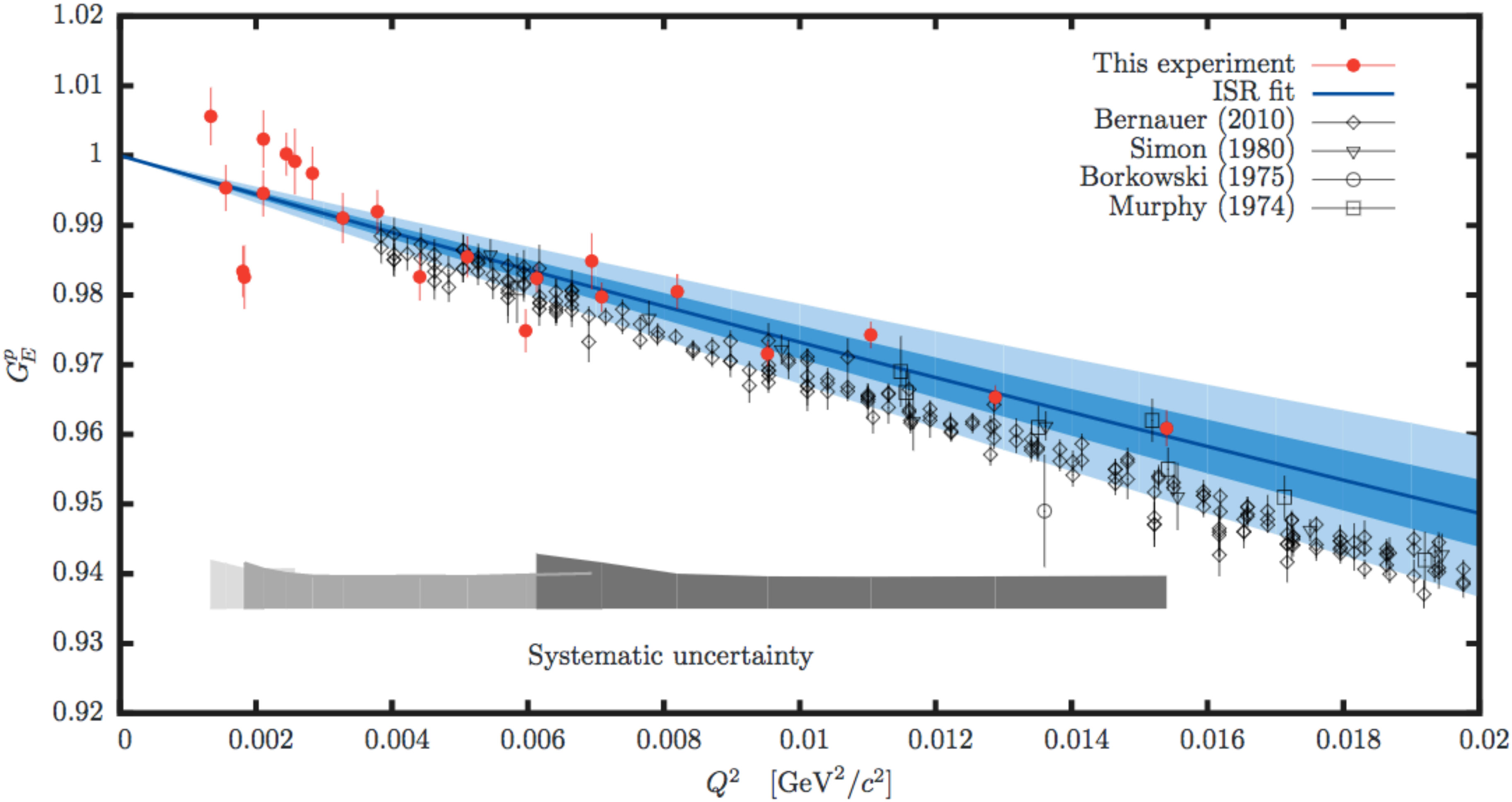


average of all fit models with uncertainties

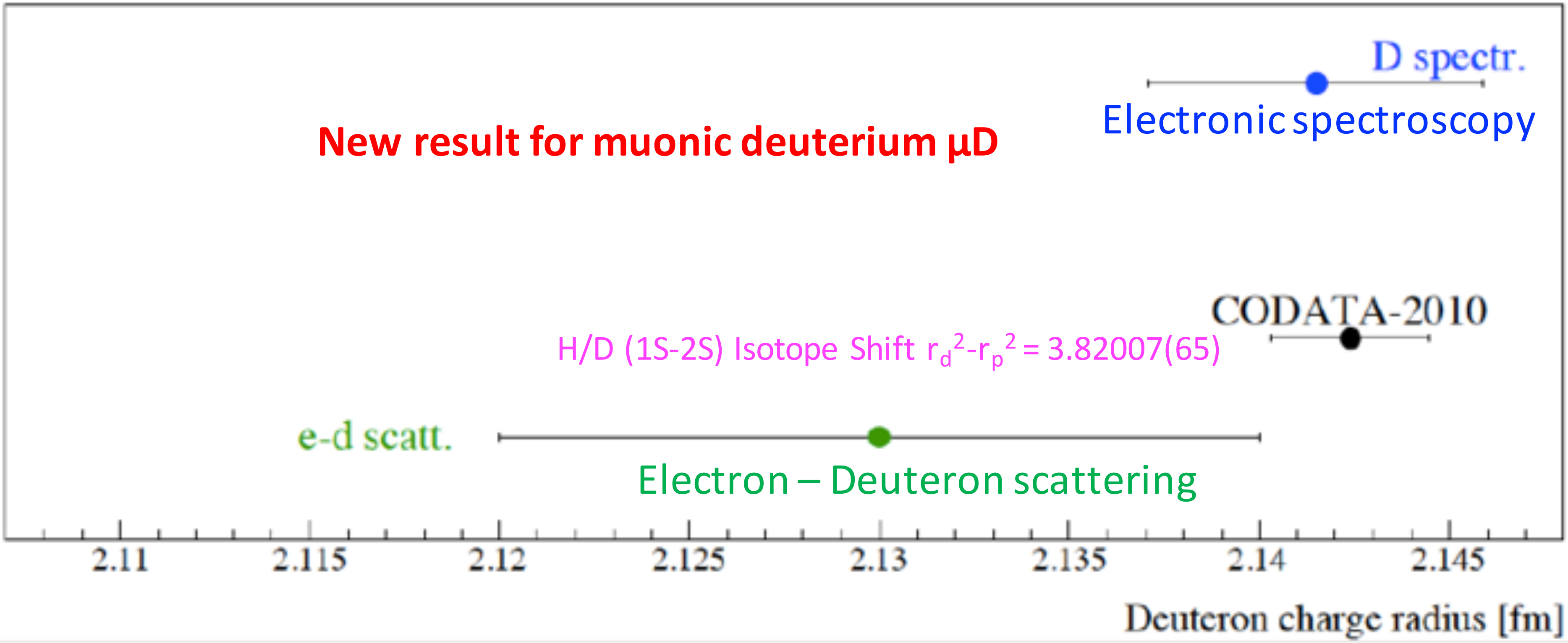
$R_E = 0.879 \pm 0.008$ fm

PRL '10: Bernauer et al.
PRD '13: new technical paper

ISR Measurement of EM Form Factors



Deuteron Radius from Muonic Deuterium



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**

EM Form Factors @ MESA

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

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

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

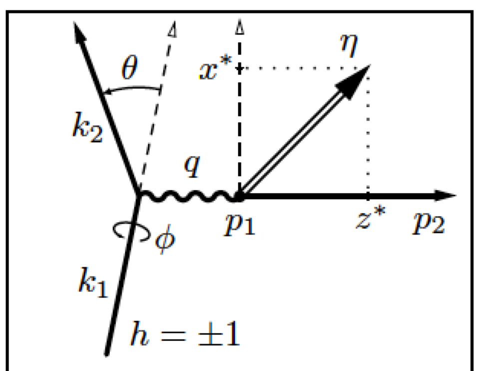
- Beam-Recoil polarization is limited by proton recoil momentum $|\vec{p}_p| > 300\,\frac{\text{MeV}}{c}$
- Beam-Target polarization:

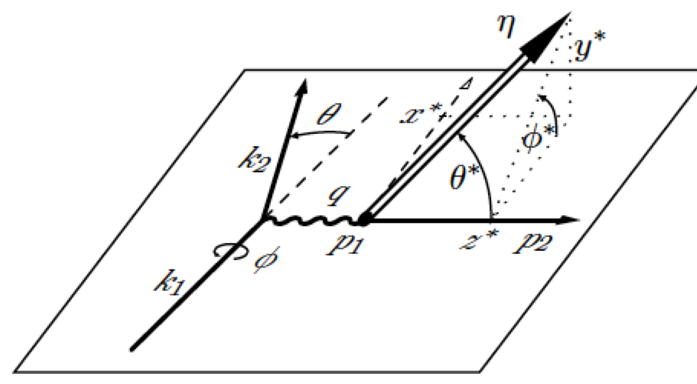
$$A(\theta^*,\phi^*) = A_I \sin\theta^* \cos\phi^* + A_S \cos\theta^*$$

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

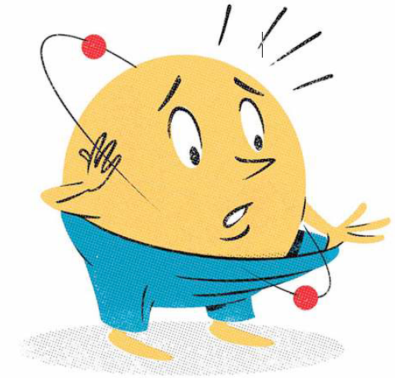
$$A_S = -2\,\tau\,\sqrt{1+\tau+(1+\tau)^2\tan^2\frac{\theta}{2}}\,\tan\frac{\theta}{2}\,\frac{G_M^2}{G_E^2 + \left(\tau + 2\tau(1+\tau)\tan^2\frac{\theta}{2}\right) G_M^2}$$

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



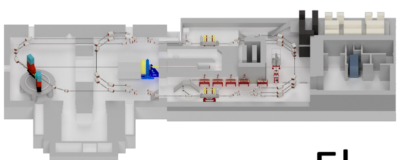


Mainz Proton Radius Programme



The New York Times

- 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



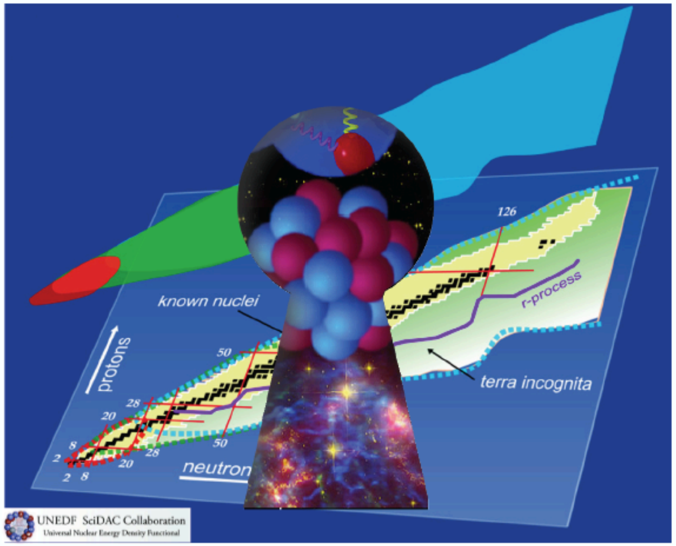
MESA

- 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}He, ^{4}He, ...) as well as break-up measurements
- Polarizability measurements of proton and of Few-Body-Systems

Few Body

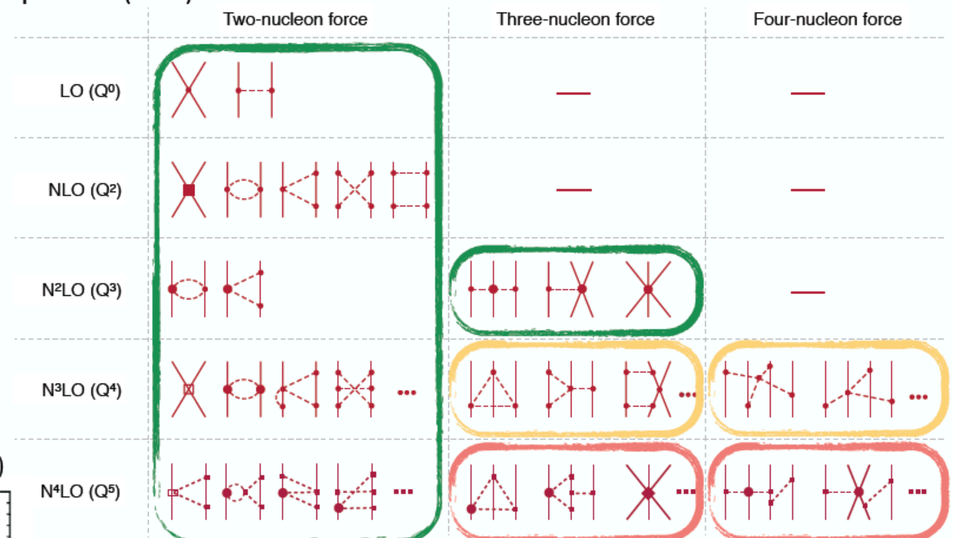
Physics

Few-Body Physics at MAGIX



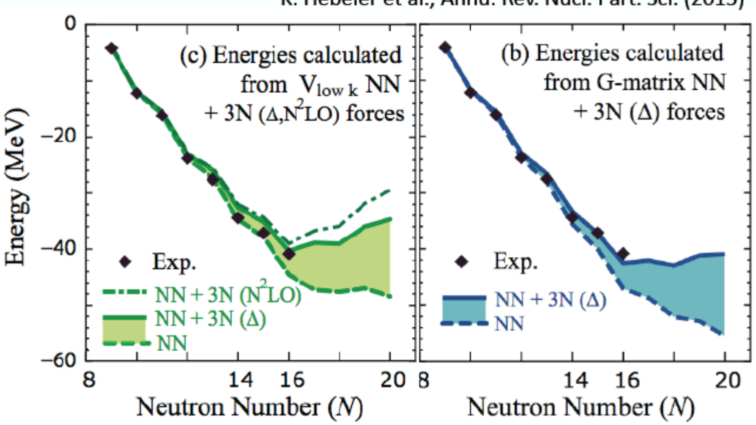
Linking low energy QCD to many-body systems.

E. Epelbaum (2015)



worked out and applied — worked out and to be applied — calculations in progress

K. Hebeler et al., Annu. Rev. Nucl. Part. Sci. (2015)



Jacek Golak / LEPP16

Work out framework based on ChPT to deal with EW processes

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

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) from E. Epelbaum *et al*. are available
  - 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.*)

BUT BEFORE MESA starts

- Energy ranges and phase-space regions best suited to study the nuclear current operator and three-nucleon force effects should be identified for considered reaction channels
- Achievable accuracy of theoretical predictions for various observables should be estimated
- Consistent chiral potentials and EM current operators are necessary as input to these calculations

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)
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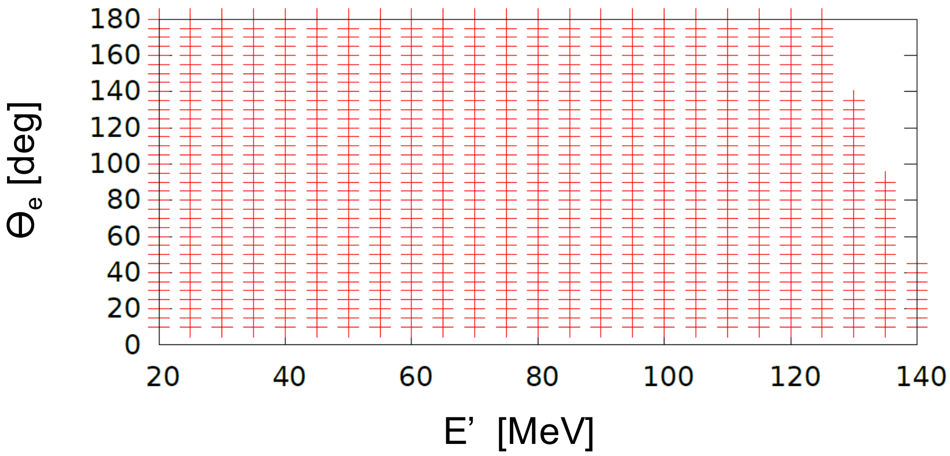
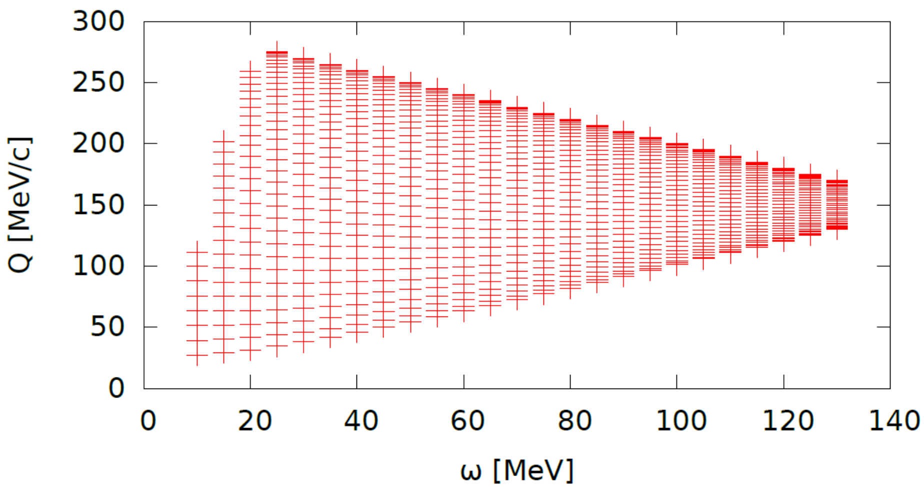
LEPP, Mainz, 7 April 2016

Introduction *(cont.)*





Expected MESA parameters

E= 150 MeV
E' > 20 MeV
Θ_e > 10 deg

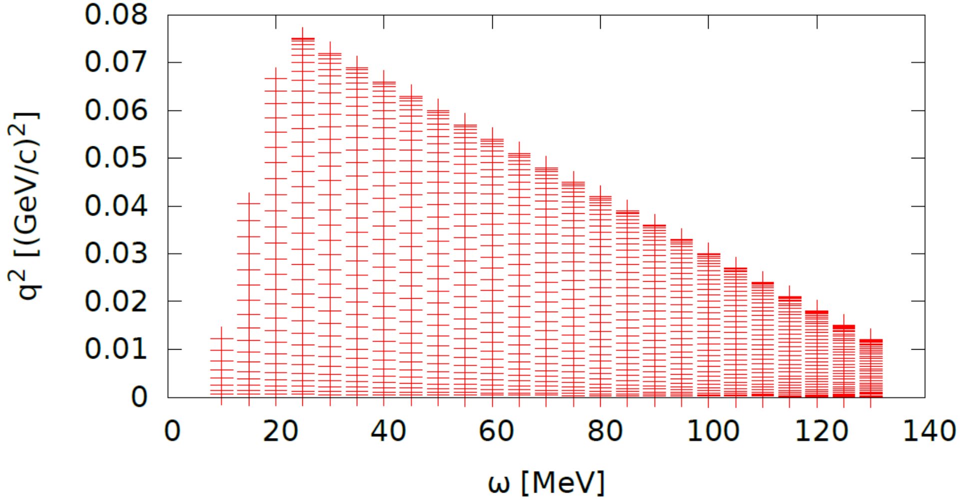
ideal to study few-nucleon dynamics within the nonrelativistic framework with the input from ChEFT !

magnitude of three-momentum transfer vs. energy transfer

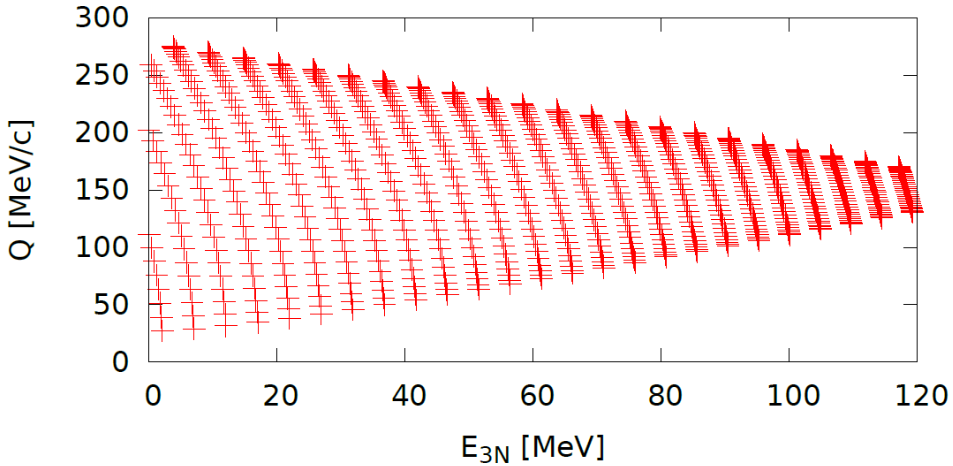
Introduction *(cont.)*

JAGIELLONIAN UNIVERSITY IN KRAKOW

S. Golek@LEPP 2017



four-momentum transfer squared vs. energy transfer

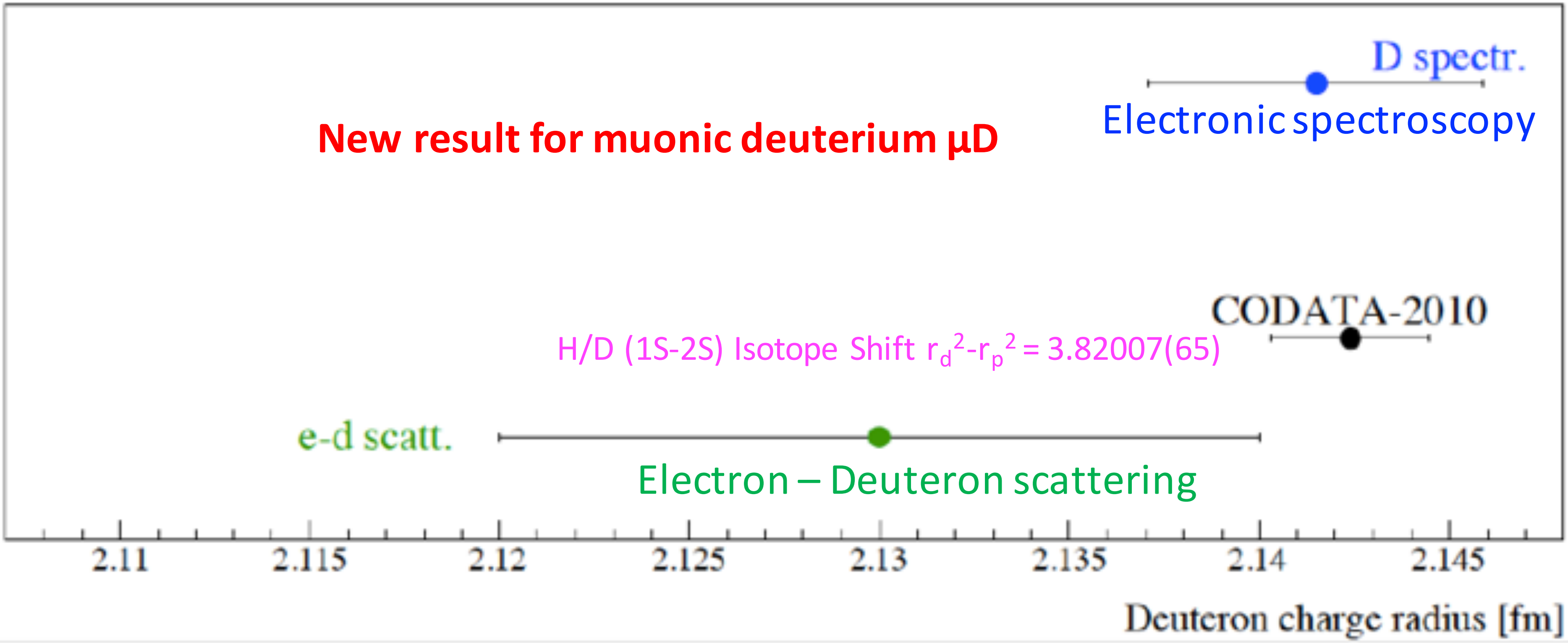


magnitude of three-momentum transfer vs. internal energy of 3N system

Few Body Systems

Also Puzzles ?

Deuteron Radius from Muonic Deuterium



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**

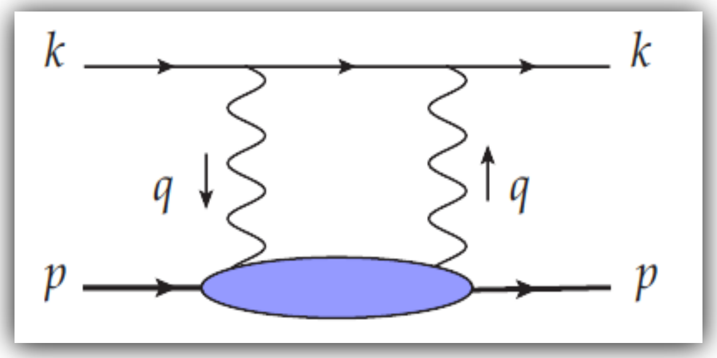
Polarisability Corrections in Light Nuclei Systems

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

dispersive analysis

Carlson, Vanderdhaeghen (2011)

accuracy comparable with present experimental precision



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

Hernandez et al. (2014)

accuracy factor 5 worse than present experimental precision

μ³He⁺: $\Delta E^{TPE} = (15.46 \pm 0.39)\ meV$ nucleon potentials form chiral EFT

Nevo Dinur, Ji, Bacca, Barnea (2016)

$(15.14 \pm 0.49)\ meV$ dispersive analysis

Carlson, Gorchtein, Vanderhaeghen (2016)

Magnetic Form Factor @ MAGIX

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

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

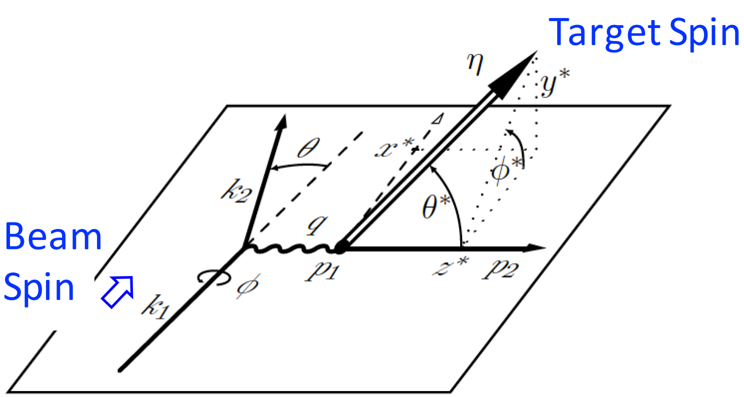
long. polarization of virtual photon

Low Q^2 accessible with low E_{beam}

Suppressed at low Q^2 due to τ

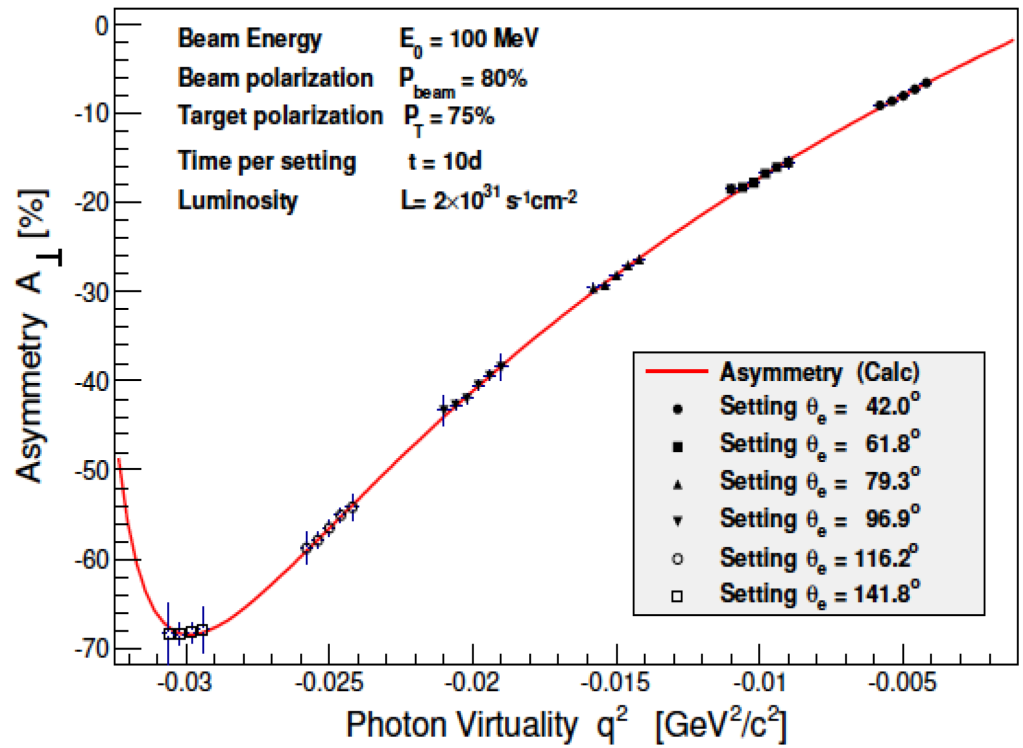
→ Double polarization measurement

Beam Target Asymmetry !



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

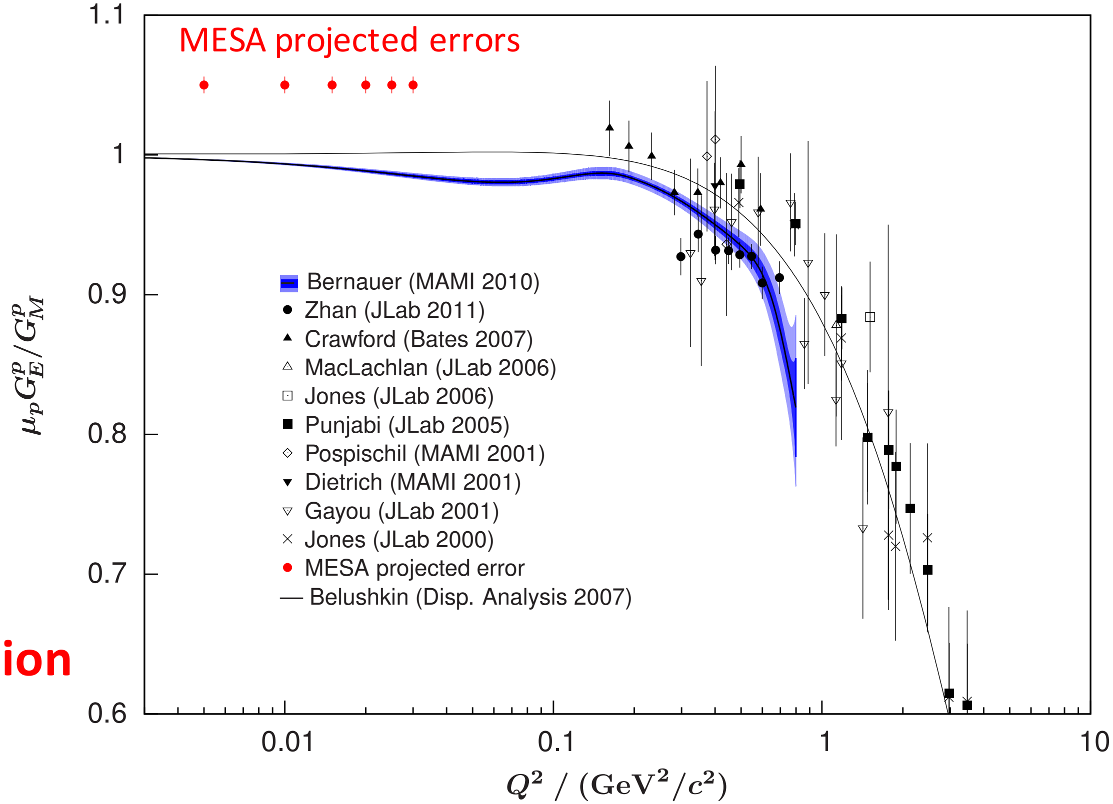
Method pioneered by BLAST / Bates



EM Form Factors @ MESA

Simulation:

- Polarized target, 3 x 10^{15} / cm^2 (very conservative)
- 80% polarisation
- 1mA beam current, 105 MeV

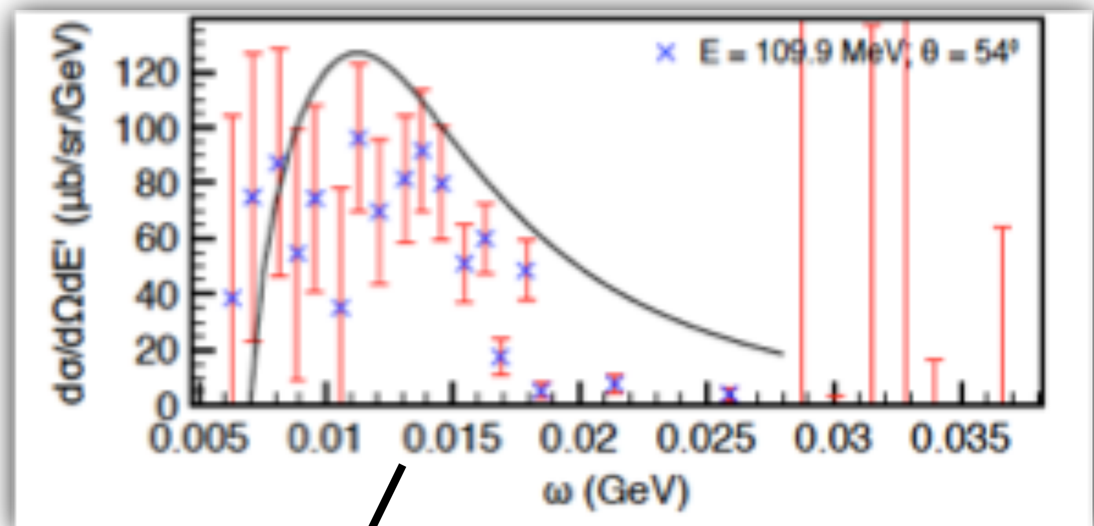


Electric/Magnetic Form Factor Ratio from Beam-Target Polarization

Hadronic Corrections in Light Nuclei Systems

Carlson, Gorchtein, Vanderhaeghen (2016)

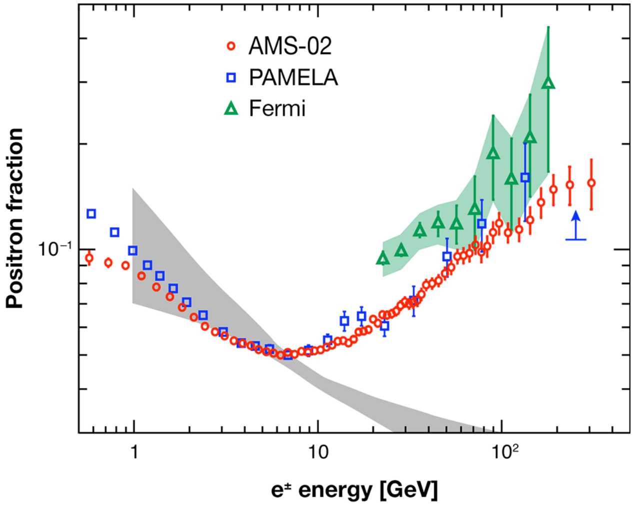
sample of present ^{3}He(e,e') data



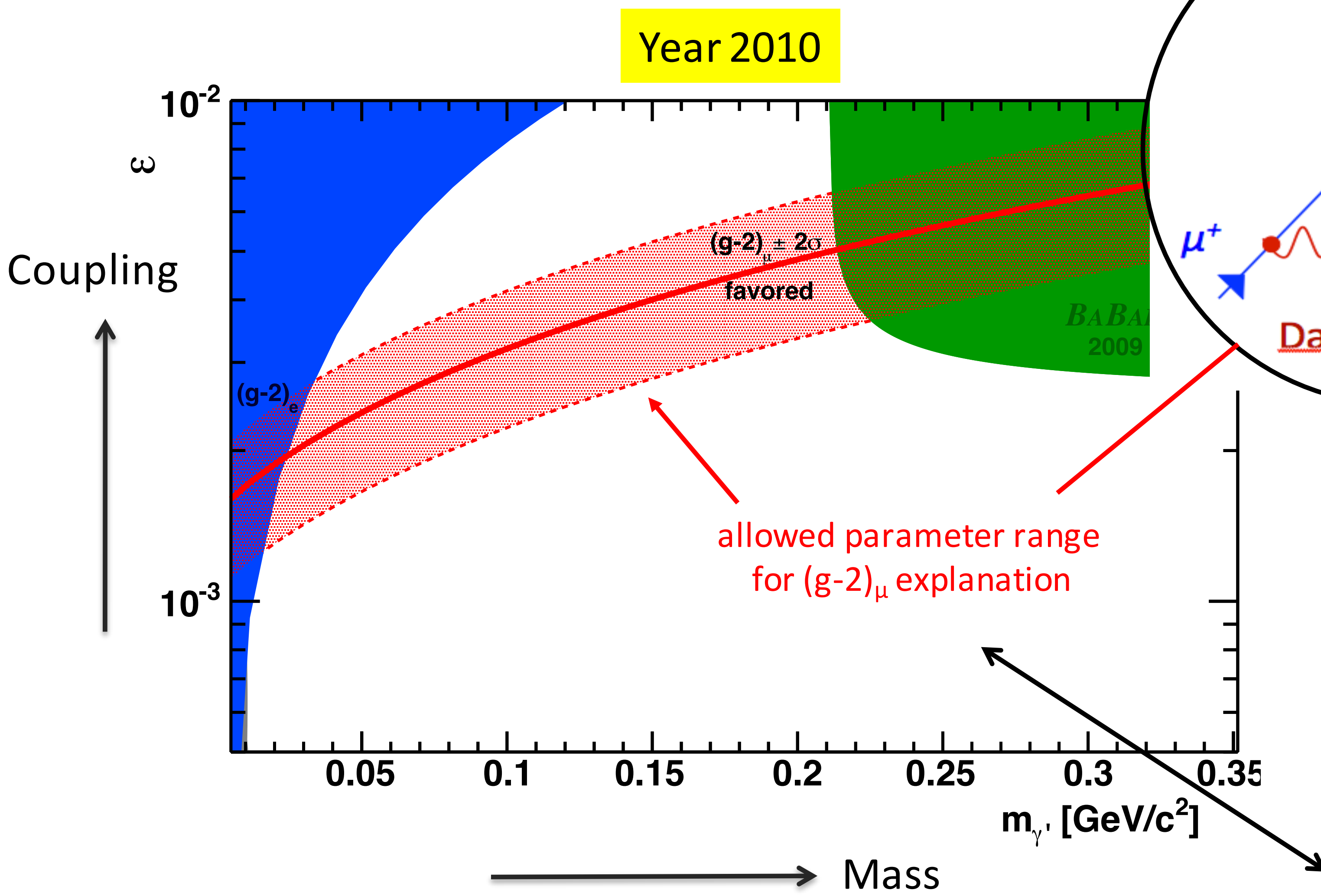
Kinematics	δa_2	$\delta(\Delta E_{2S}^{\rm nuclear})$	$\delta(\Delta E_{2S}^{\rm TPE})$
$E = 110$ MeV, $\theta = 54°$	± 0.014	0.40 meV	0.49 meV

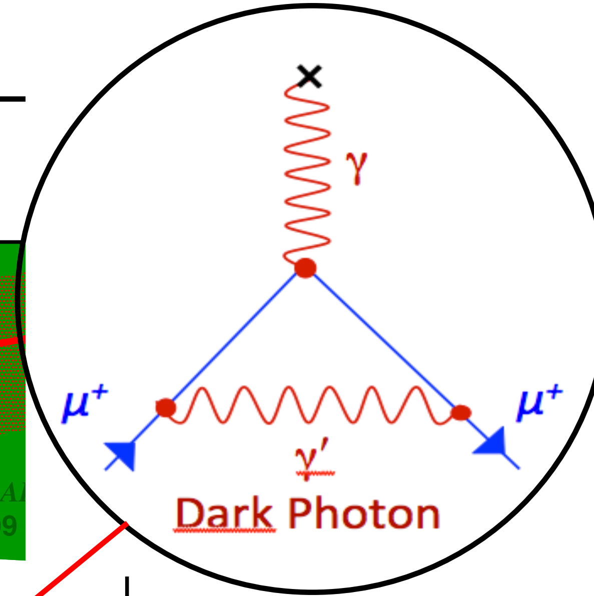
5% measurement of ^{3}He electrodisintegration cross section at MAGIX

Search for the Dark Photon



Dark Photon Status in 2010





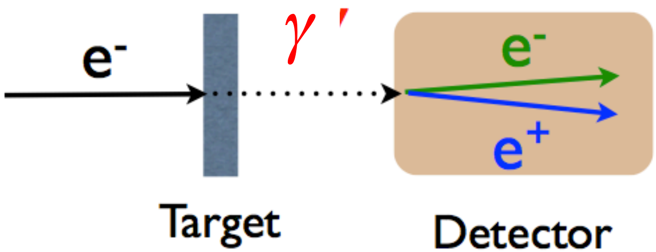
terra incognita
white region
motivated by
dark matter !

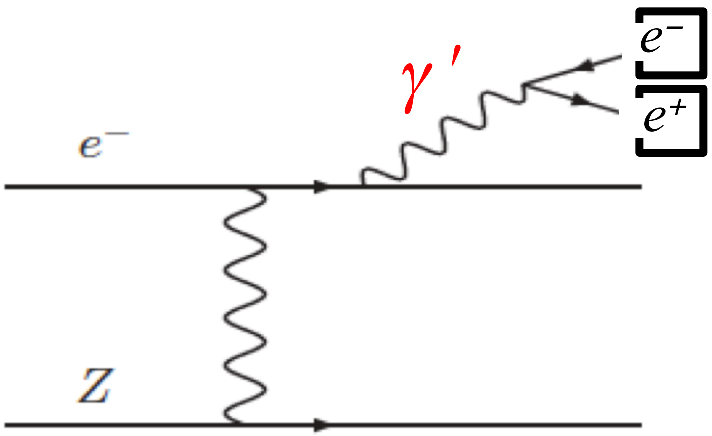
Results from A1

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

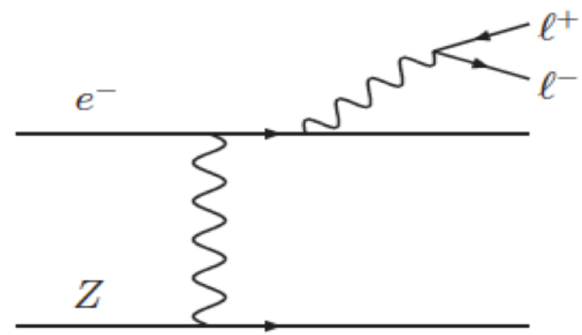
Bjorken et al. (2009)

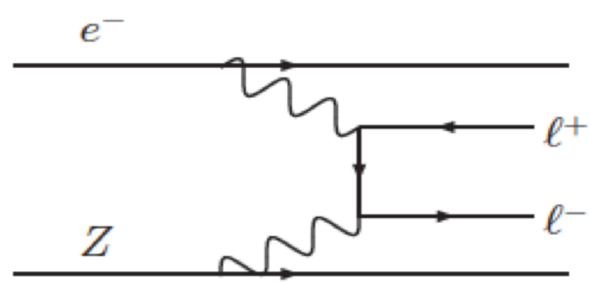
Signal process





Background QED processes

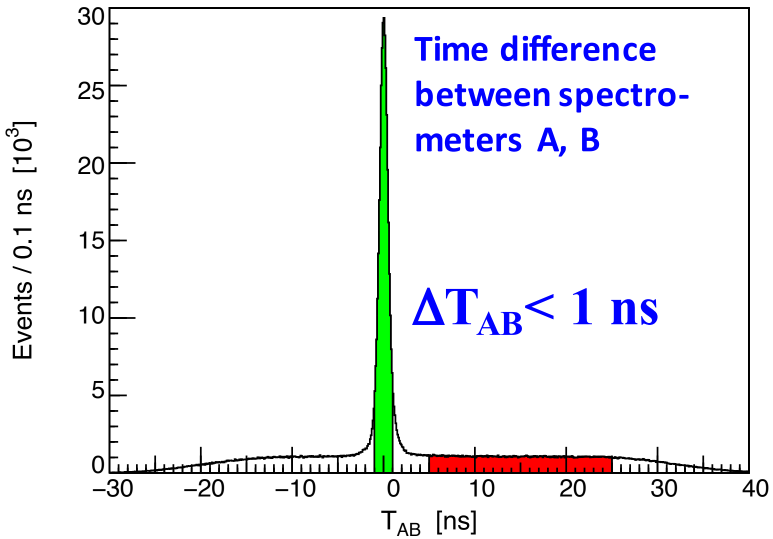


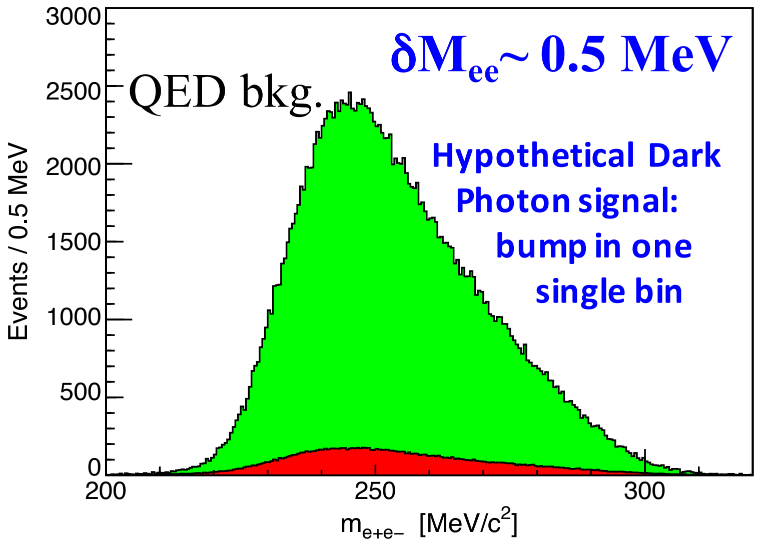


Dark Photon Search @ A1

Features 2010 pilot run (4 days)

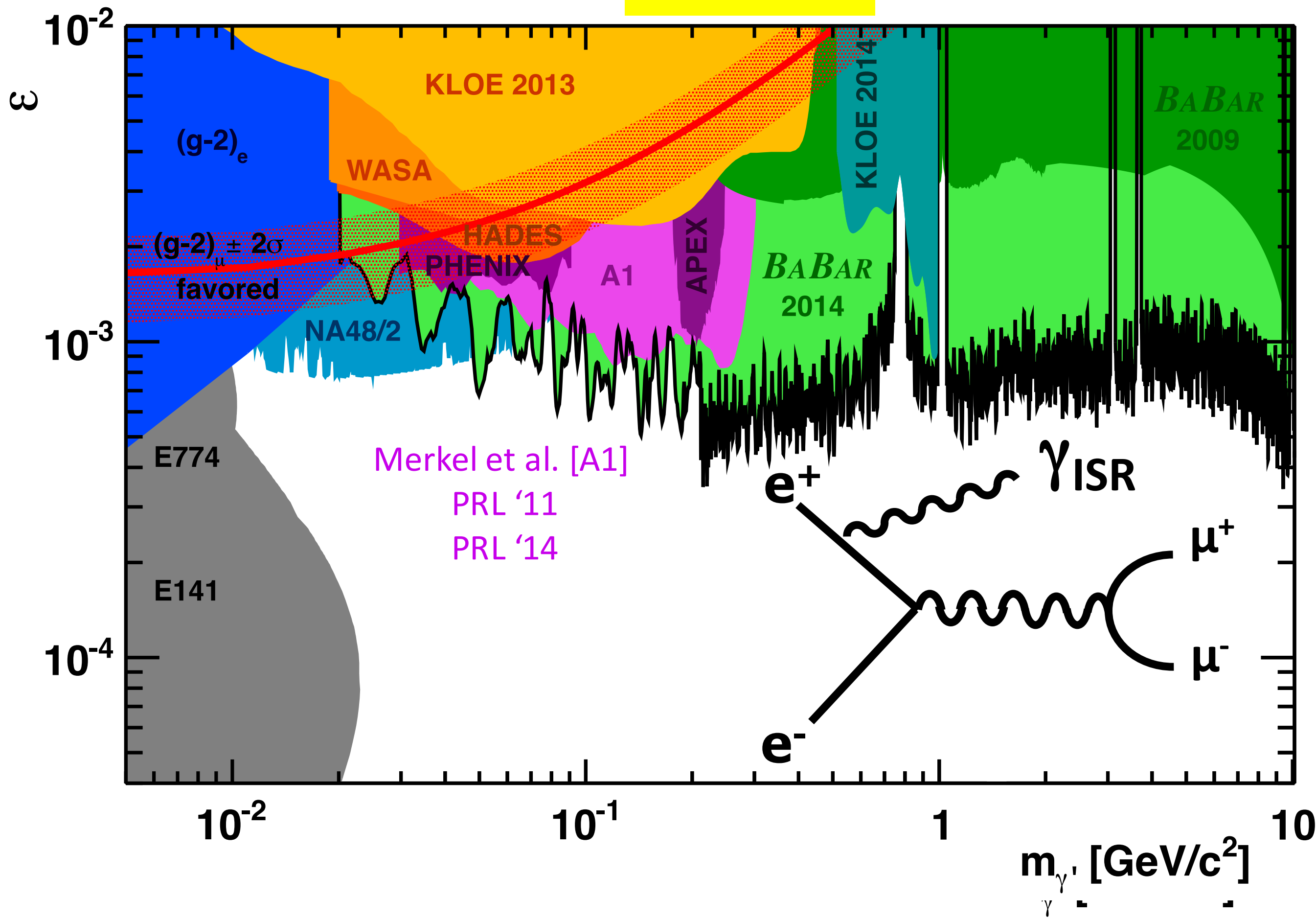
- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current ~100μA → Luminosity ~10^{39} $cm^{-2}s^{-1}$
- Kinematic configuration: - complete energy transfer to γ' boson
  - symmetric e^- and e^+ momenta
- Cerenkov detector for electron/positron identification





Results from A1/MAMI

Year 2017

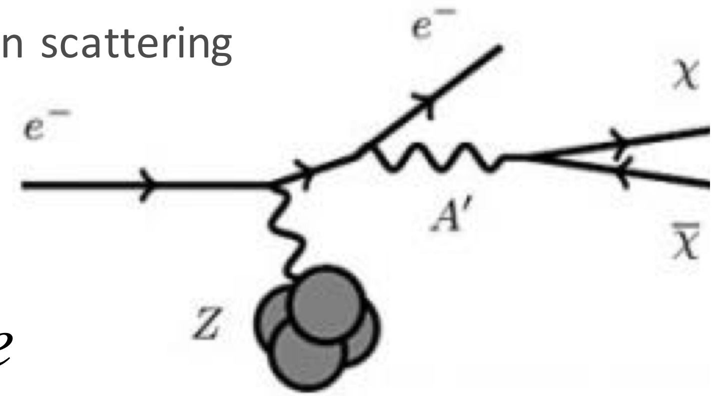


→ **at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g\text{-}2)_\mu$**

Dark Sector Searches at MAGIX

<u>Model 2</u>: Dark Photon coupling to light Dark Matter

→ could still explain $(g-2)_\mu$ discrepancy
→ exploit excellent momentum resolution of MAGIX (proton recoil!)
→ Main background: Virtual Compton scattering



$$e + p \rightarrow e' + p + \mathrm{X}$$
$$\hookrightarrow \textit{invisible}$$

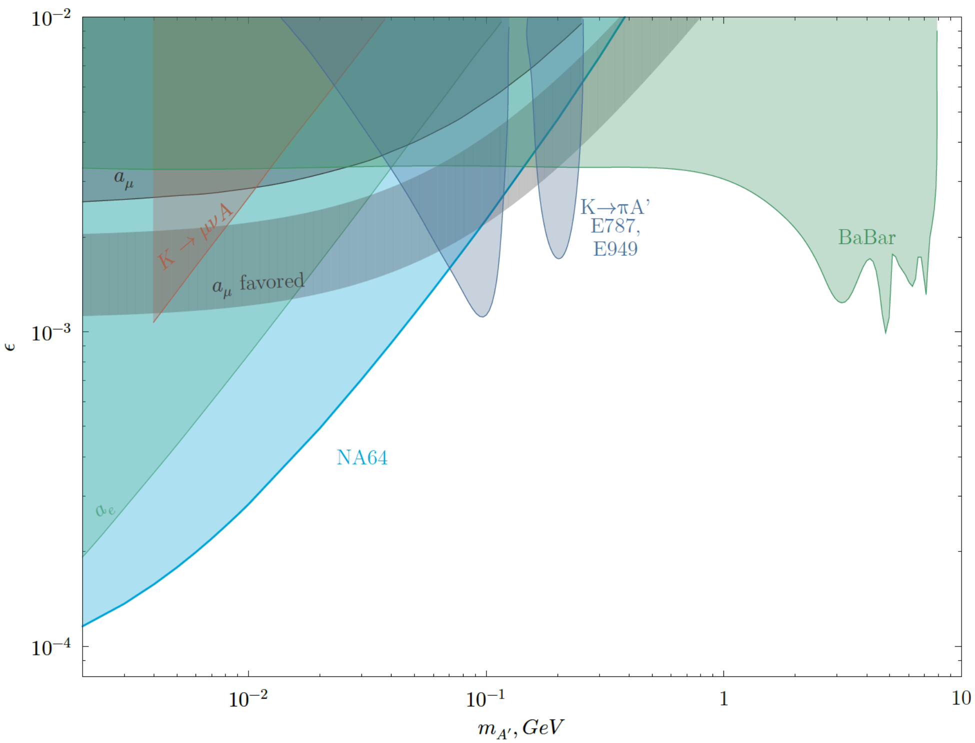
$$m_{\gamma'}^2 = (e + p - e' - p')^2$$

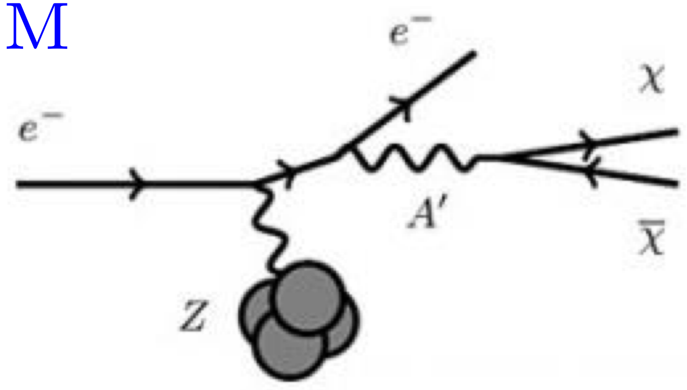
Sensitivity at MAGIX currently calculated within a bachelor thesis (use of thin HVMAPS detectors for proton recoil under study)

Invisible Decay of the Dark Photon

<u>Model 2</u>: Dark Photon coupling to light Dark Matter (invisible decay!)

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



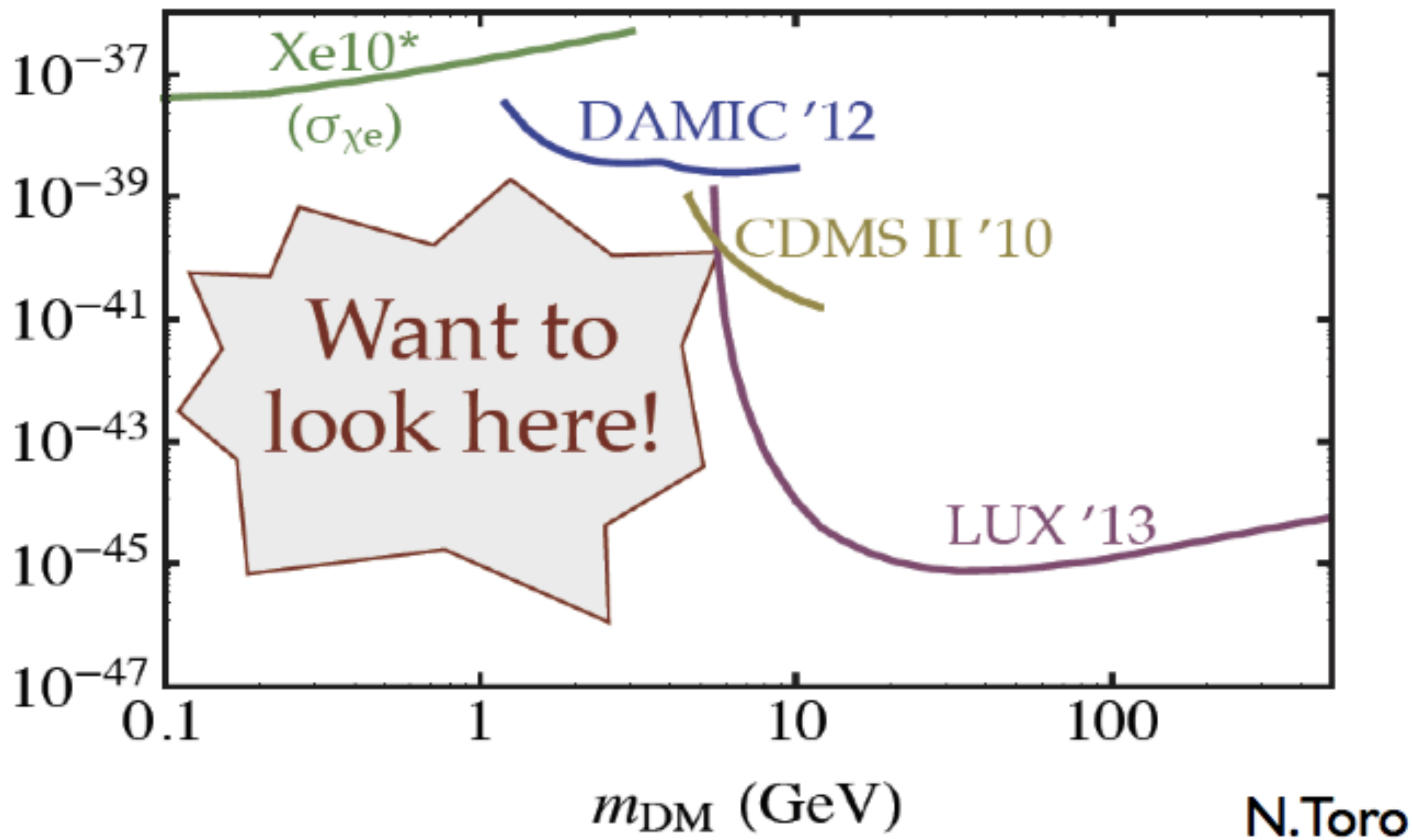


- Dark Matter particle not seen
- Few constraints
- Could again explain $(g\text{-}2)_\mu$

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

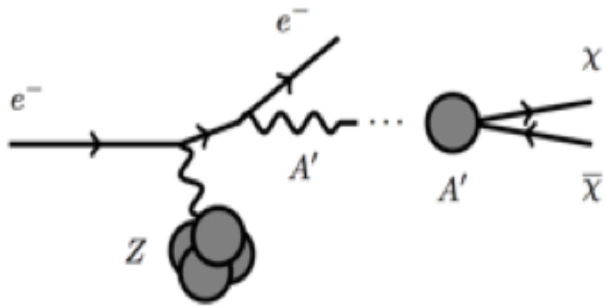
Beam Dump Experiment (BDX) @ MESA

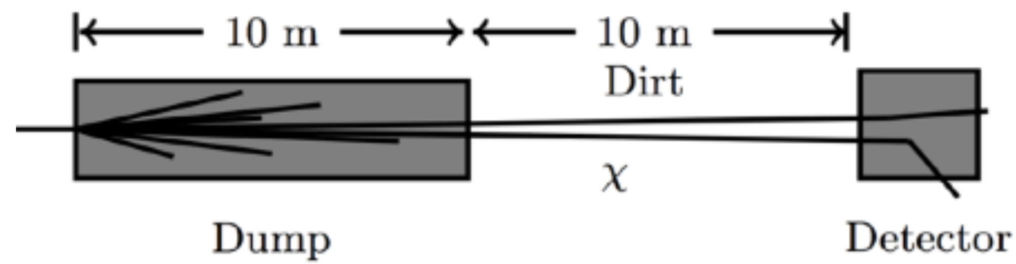
Dark Matter Exclusion Plots

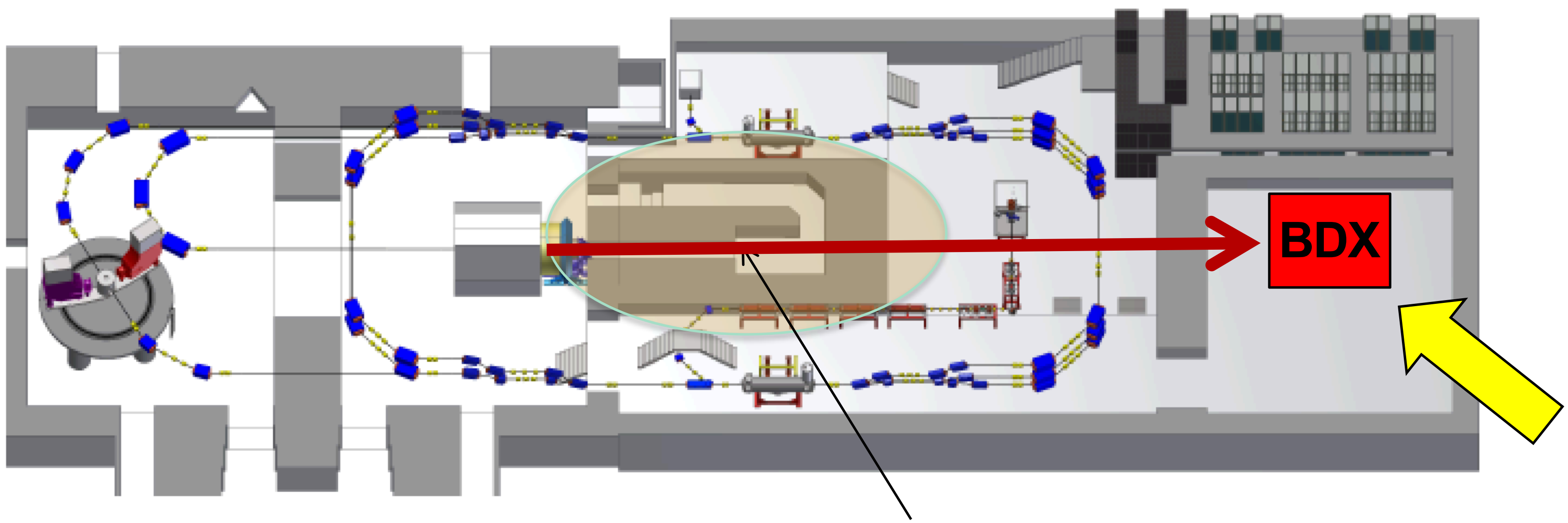


Beam Dump Experiment (BDX) @ MESA

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





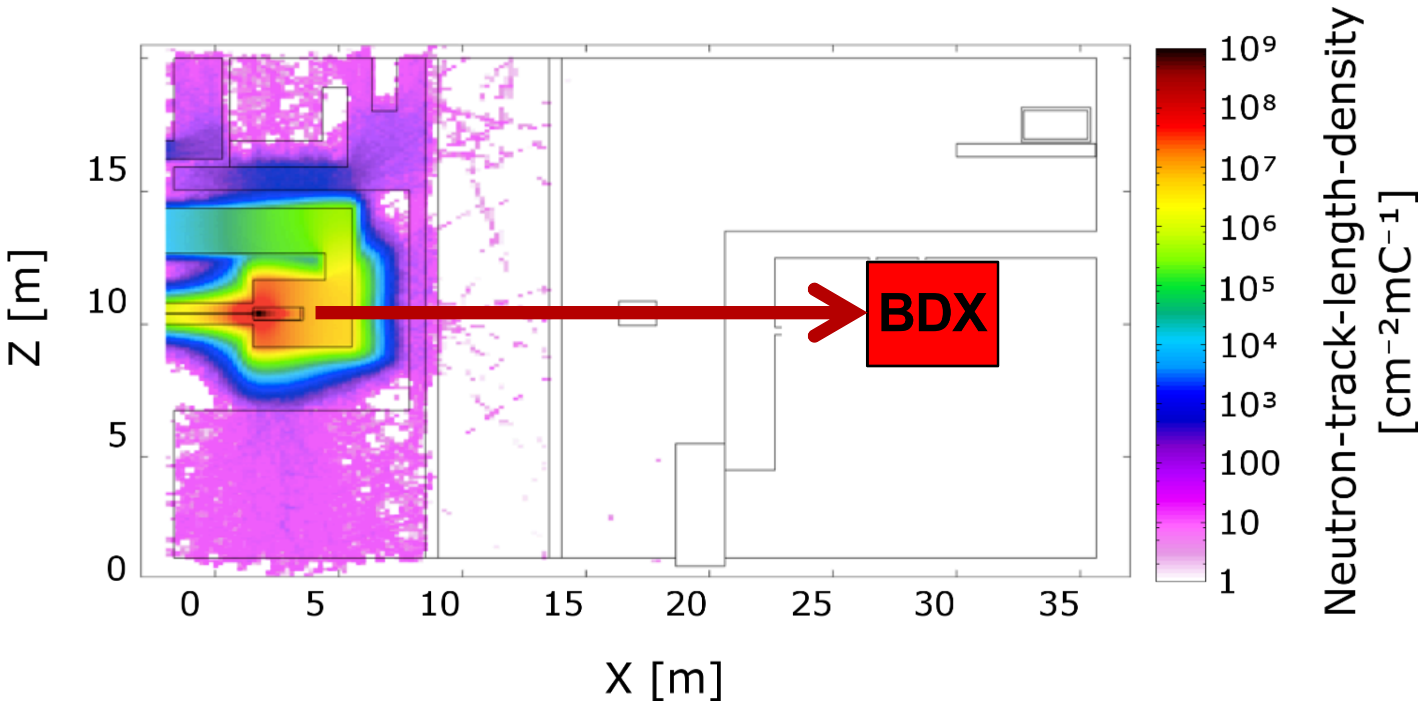


This existing beam dump is going to be the P2 beam dump

10,000 hours @ 150 μA

→ 10^{23} electrons on target (EOT)

BDX @ MESA

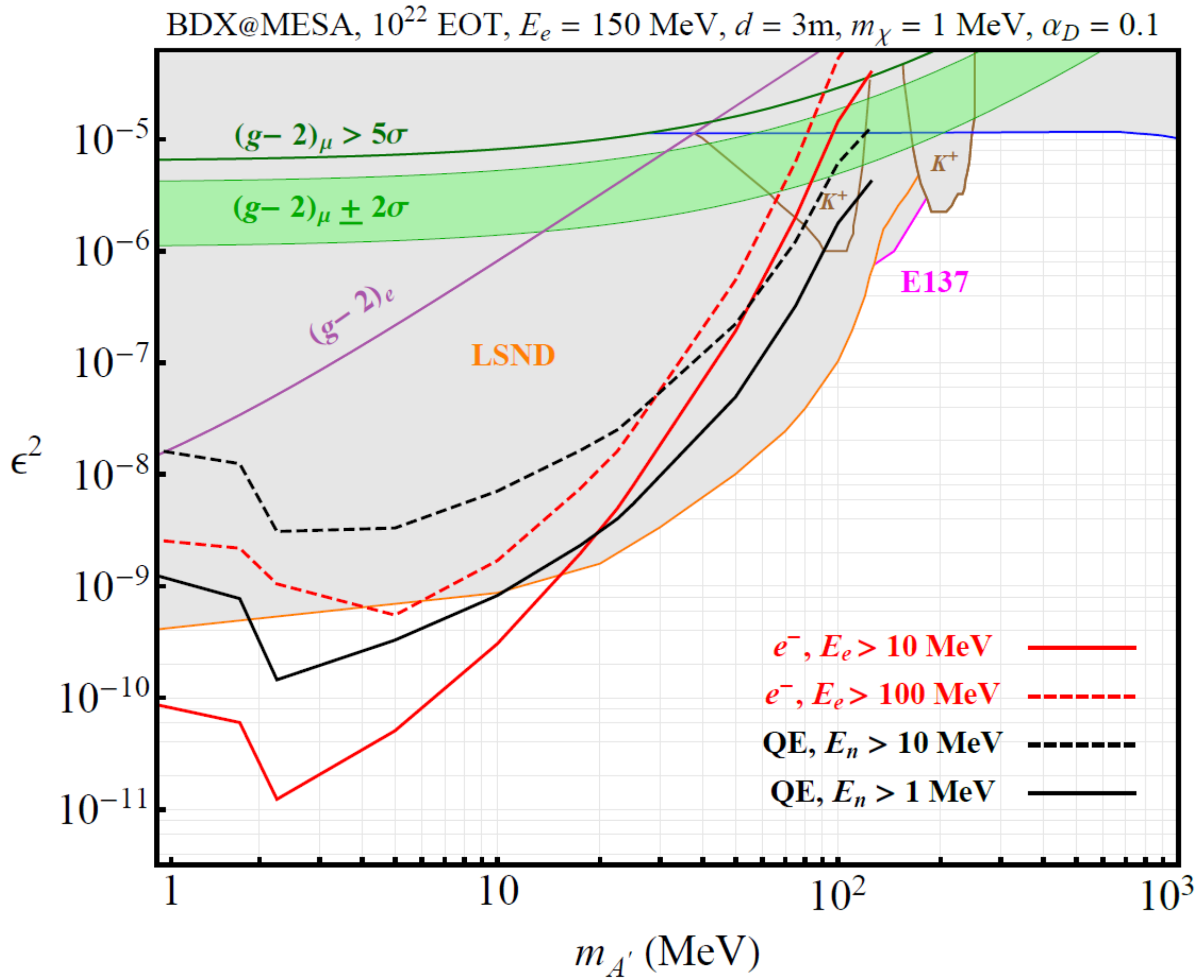


Background situation

- FLUKA simulation of neutron background promising (~10^{11} EOT)
- MESA running below pion production threshold → no neutrinos!

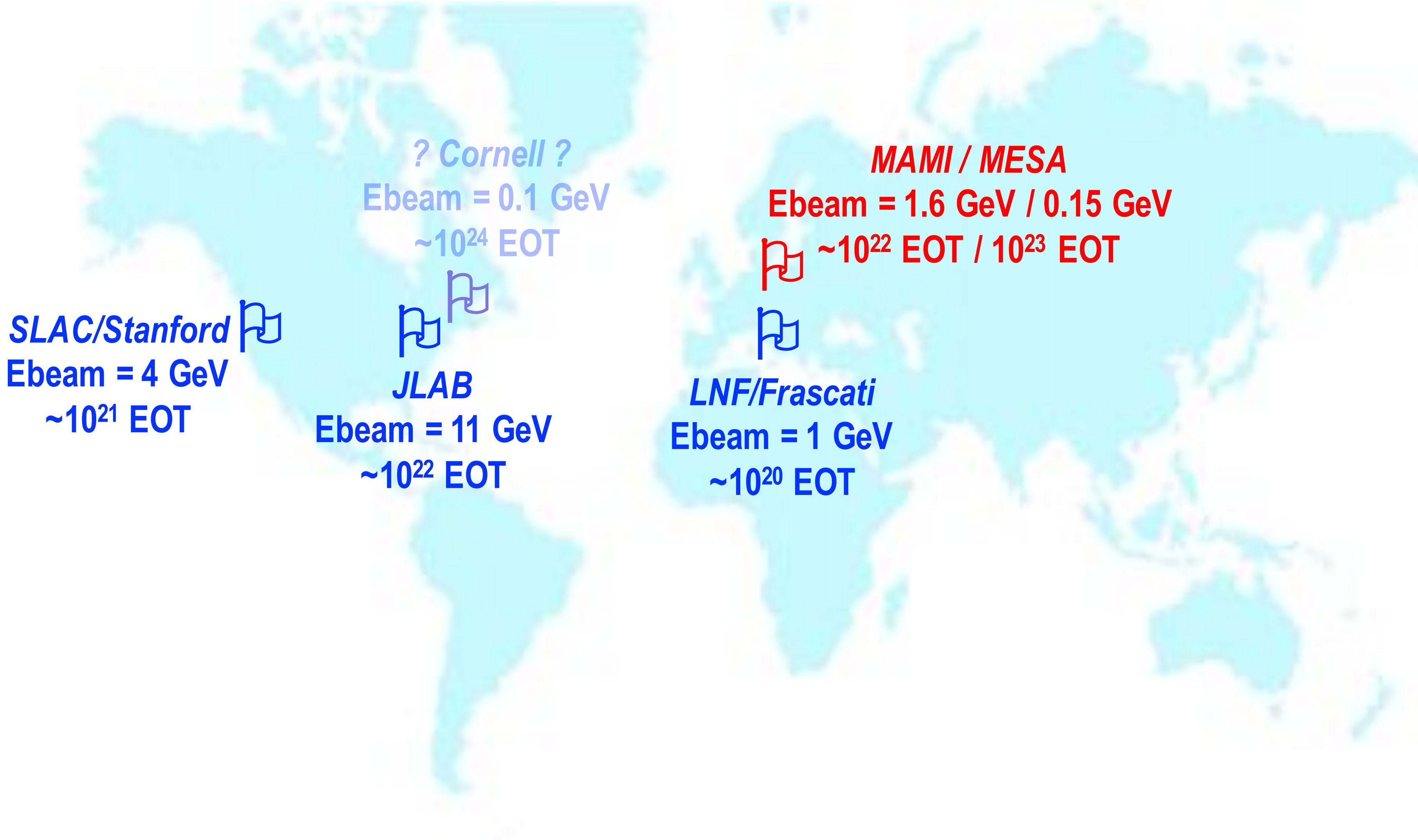
BDX @ MESA

Testing competititve parameter range



G. Krnjaic +
E. Izaguirre
Perimeter Inst.

BDX – Proposals Worldwide



BDX @ MAMI, Bunch-Structure

- Standard operation of MAMI with 2,45 GHz microwave frequency
  → bad for TOF purpose for BDX
- Recently single bunch tests carried out at MAMI
- Findings:

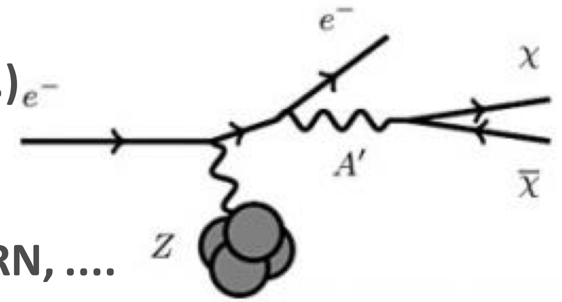
  - Bunch spacing can be varied almost arbitrarily
  - Drop of intensity
  - 12 ns bunch spacing @ 20 μA immediately achieved
  - 100 ns bunch spacing @ 3μA possible

- These numbers are conservativ estimates
  (A PhD student is working on this)

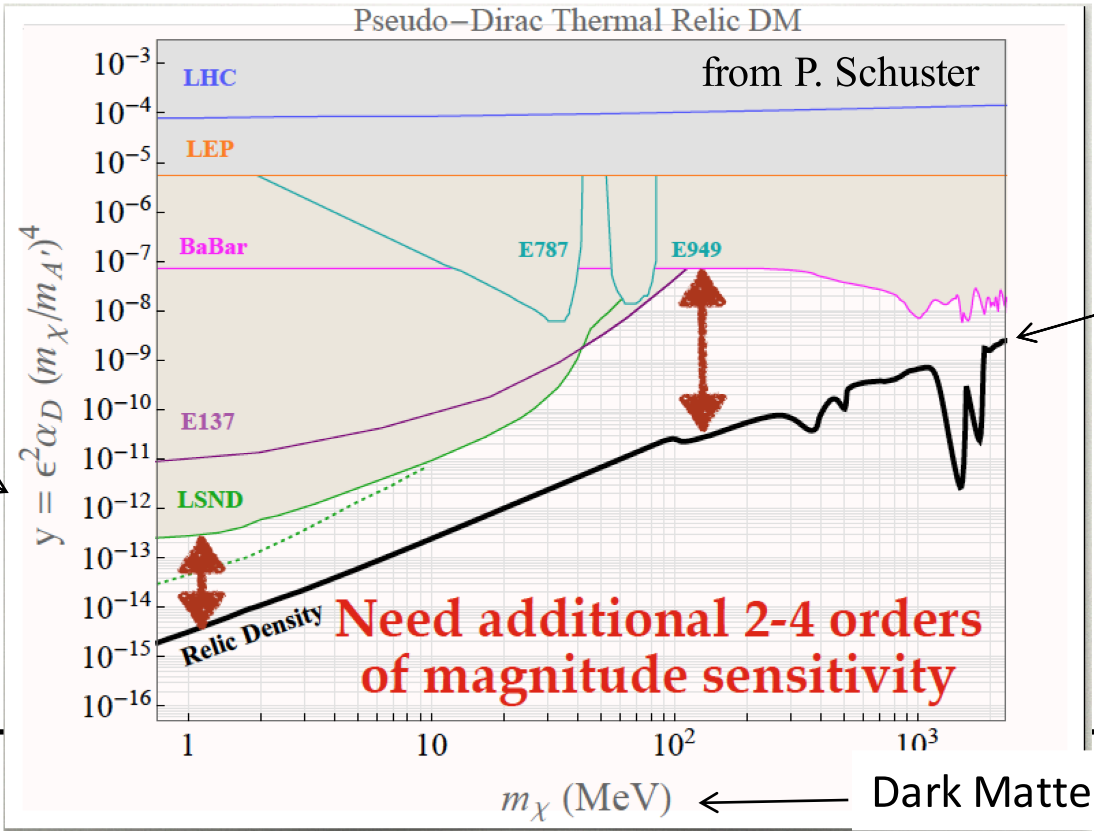
Dark Sector Workshop 2016 @ SLAC

<u>Model 1</u>: Dark Photon coupling to SM particles
Competition from many expts. (LHC-b, BELLE-II, JLAB, ...)

<u>Model 2</u>: Dark Photon coupling to light Dark Matter (invisible!)
Focus of now-days interest, proposals for SLAC, LNF, CERN, ...



dimensionless quantity ~ $(m_\chi/m_{\gamma'})^2$



predicted range from thermal origin (i.e. from observed Dark Matter density)

Dark Matter mass

Invisible Dark Photon Decays

<u>Model 2</u>: Dark Photon coupling to light Dark Matter

→ could still explain $(g-2)_\mu$ discrepancy
→ exploit excellent momentum resolution of MAGIX (proton recoil!)
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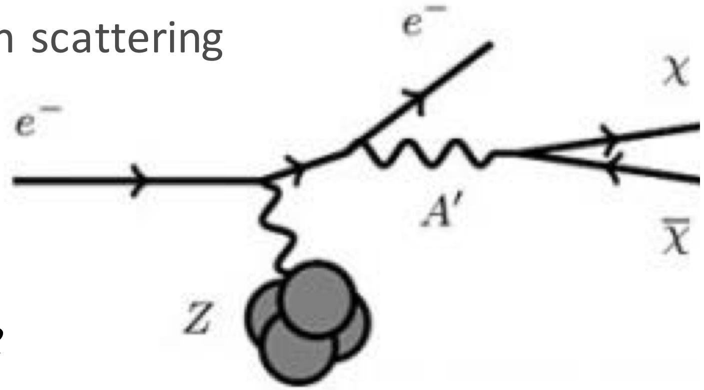
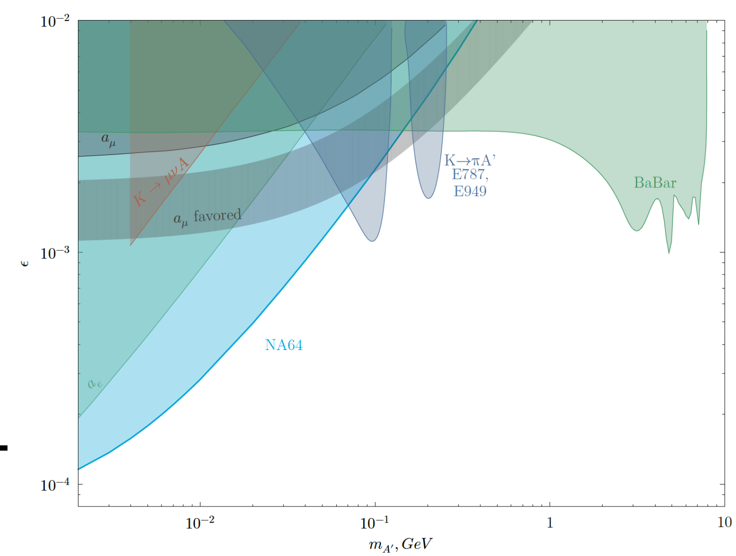


$$e + p \rightarrow e' + p + \mathrm{X}$$

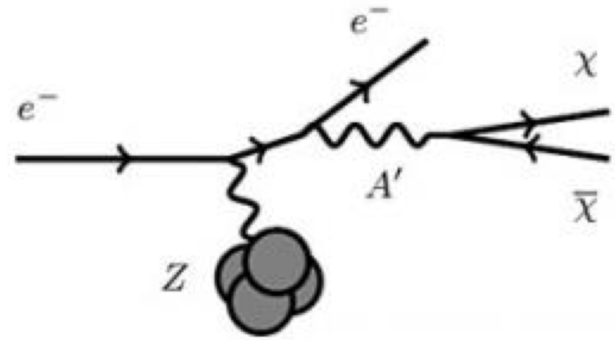
$\hookrightarrow$ *invisible*

$$m^2_{\gamma'} = (e + p - e' - p')^2$$

Dedicated detectors (Si?) for proton detection at very low momenta



Invisible Dark Photon Decays



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Dark Photon coupling to light Dark Matter (invisible!)
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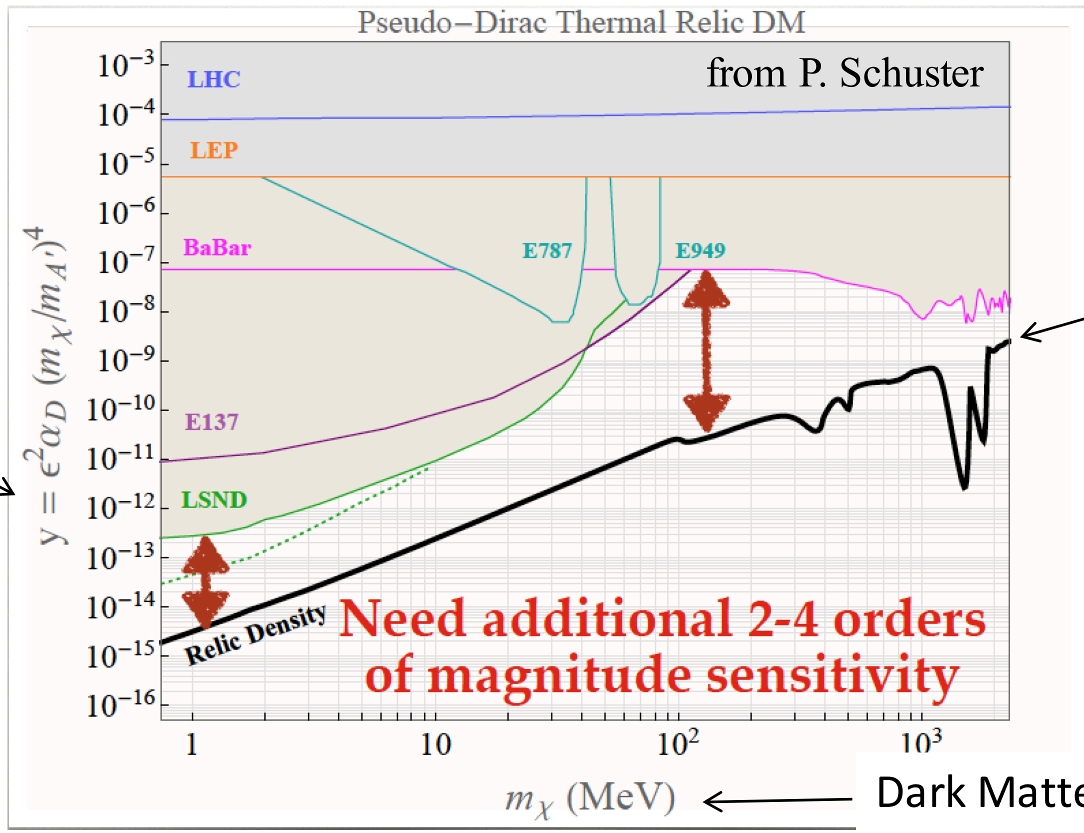
dimensionless quantity ~ ($m_\chi/m_{\gamma'}$)^2



predicted range from thermal origin (i.e. from observed Dark Matter density)

Dark Matter mass

MESA

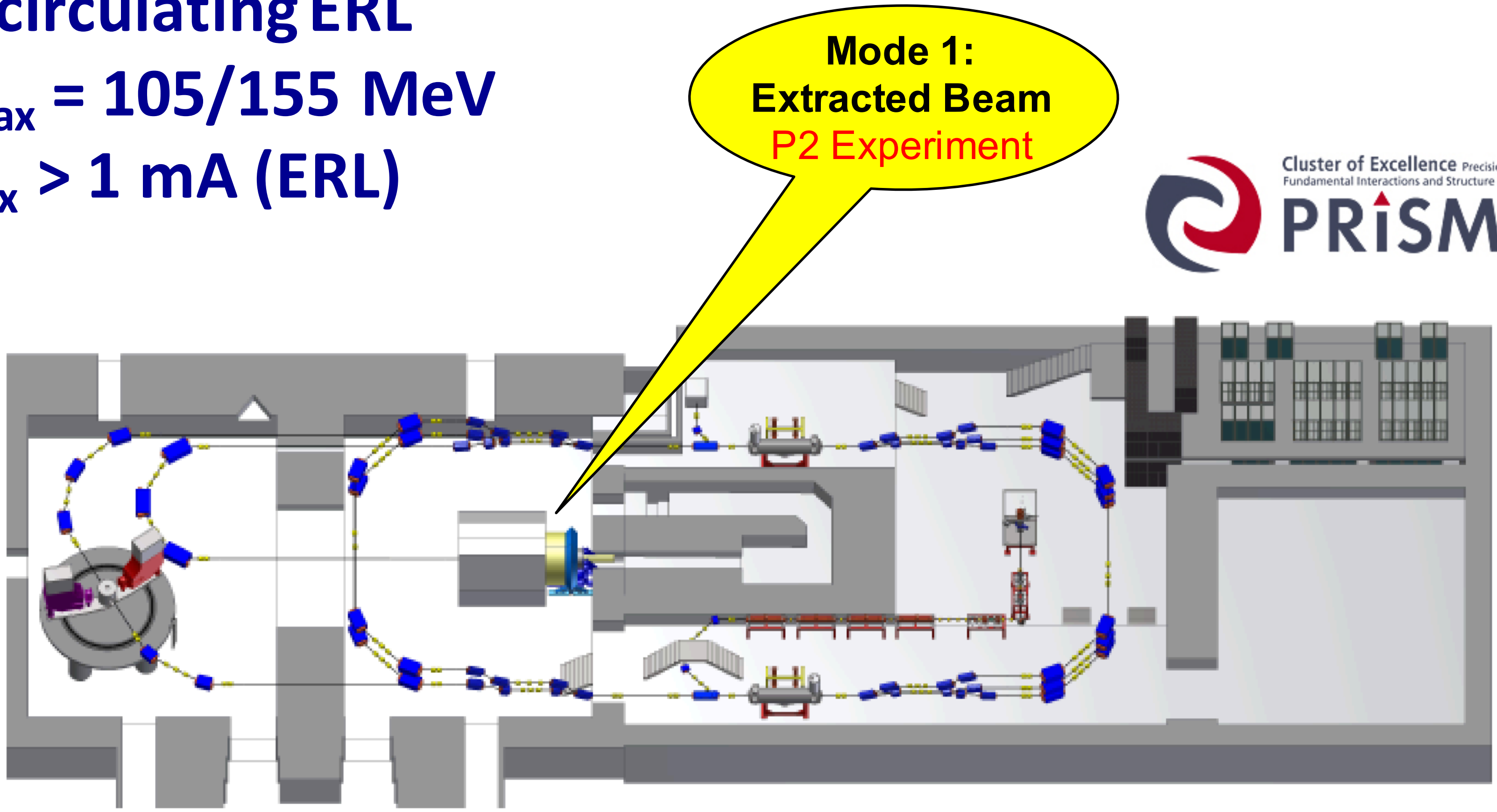
MESA Accelerator

Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

E_{max} = 105/155 MeV

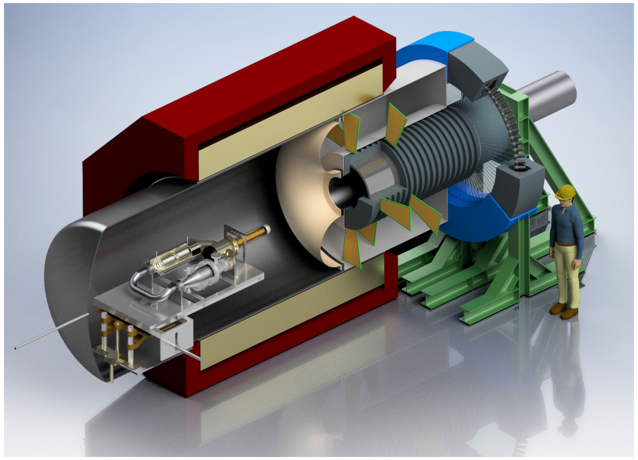
I_{max} > 1 mA (ERL)



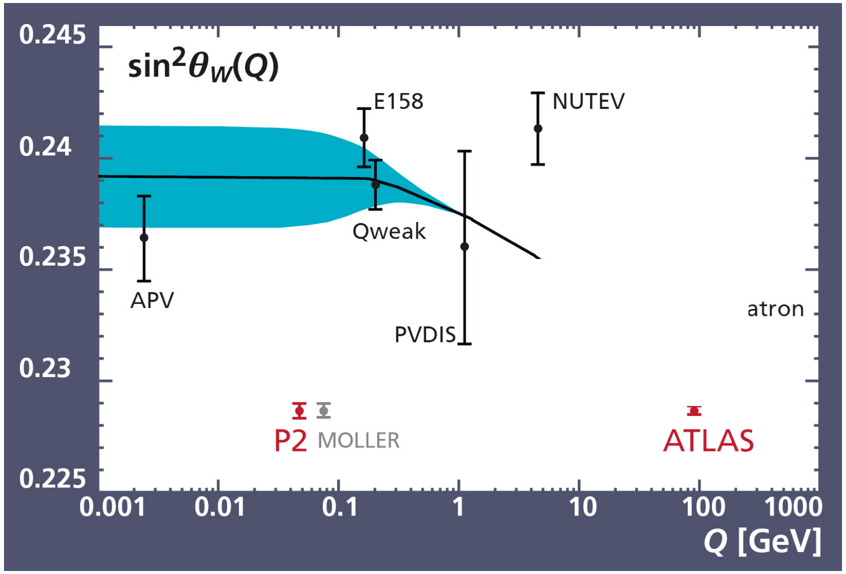
Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter PRISMA

P2: Precision Test of the Standard Model

P2 goal: $\delta \sin^2\theta_W = 0.00031$ (1.3‰)



EW mixing angle

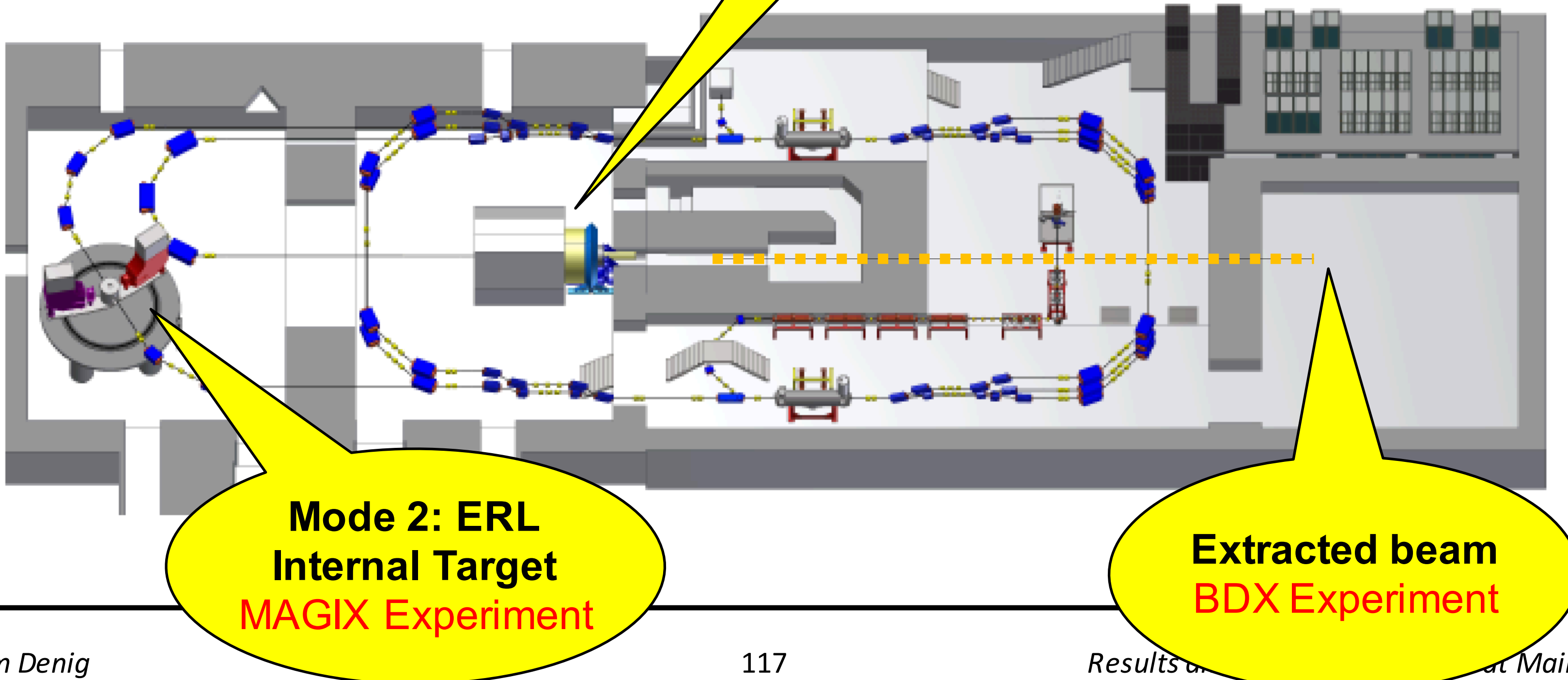


Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

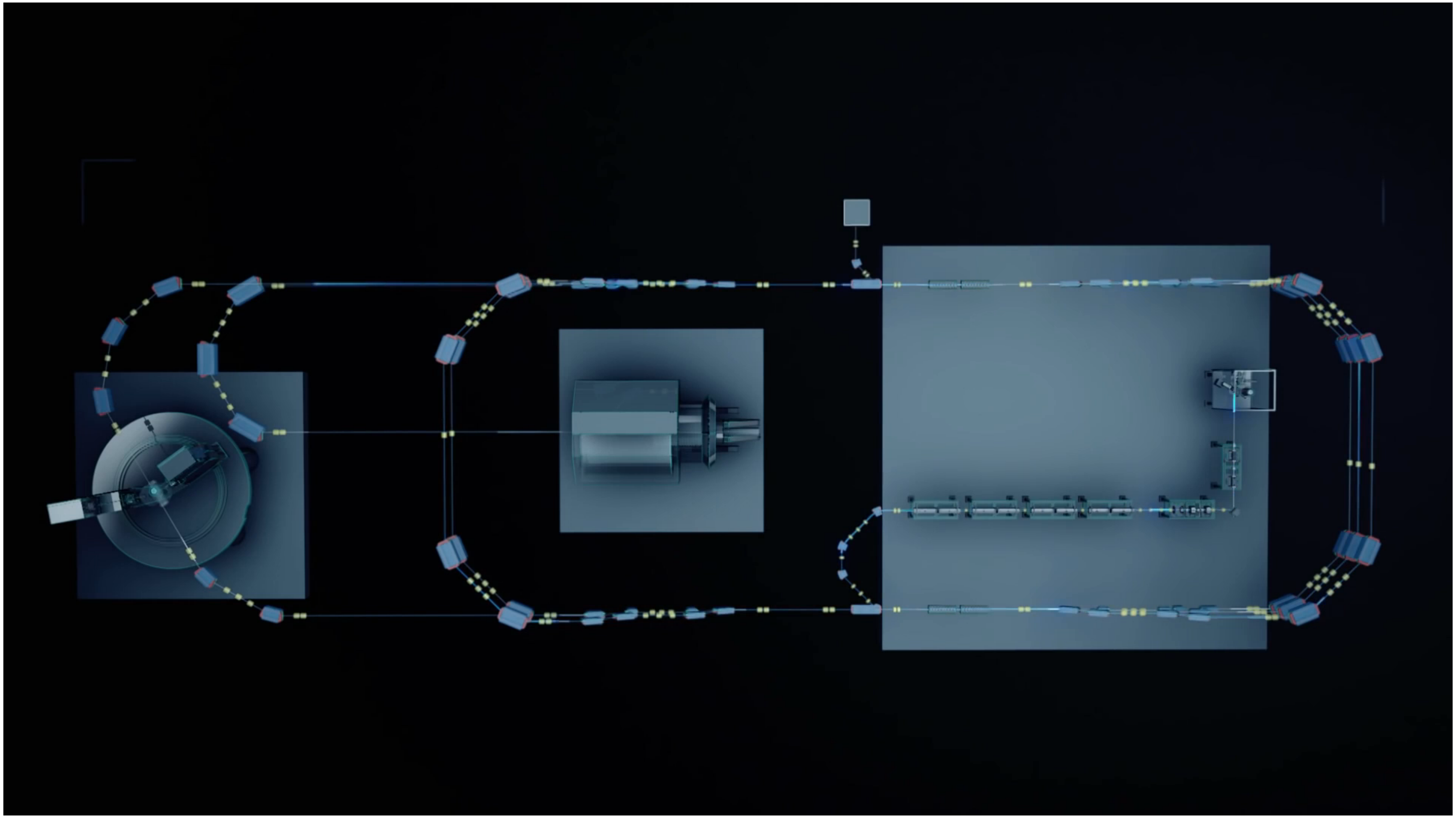
E_{max} **= 105/155 MeV**

I_{max} **> 1 mA (ERL)**



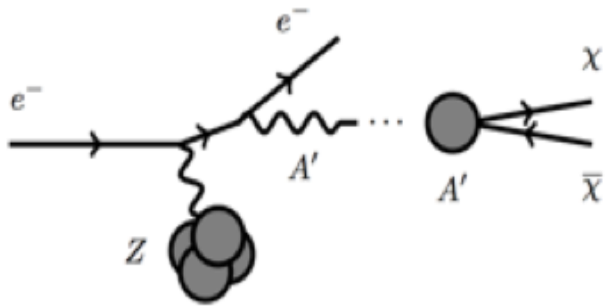
MAGIX at the Internal Target Setup of MESA

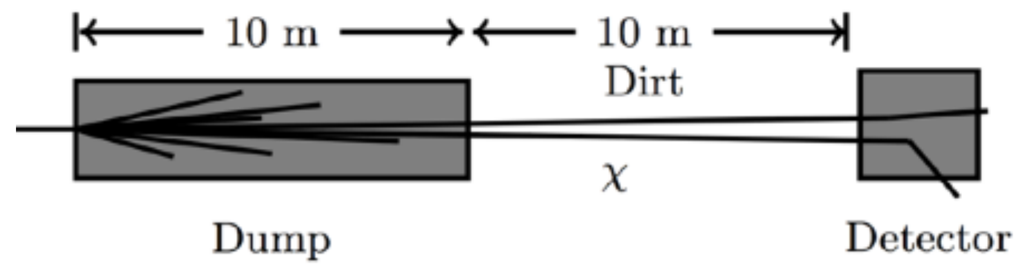
ERL mode: E_{max} = 105 MeV, I_{max} > 1 mA

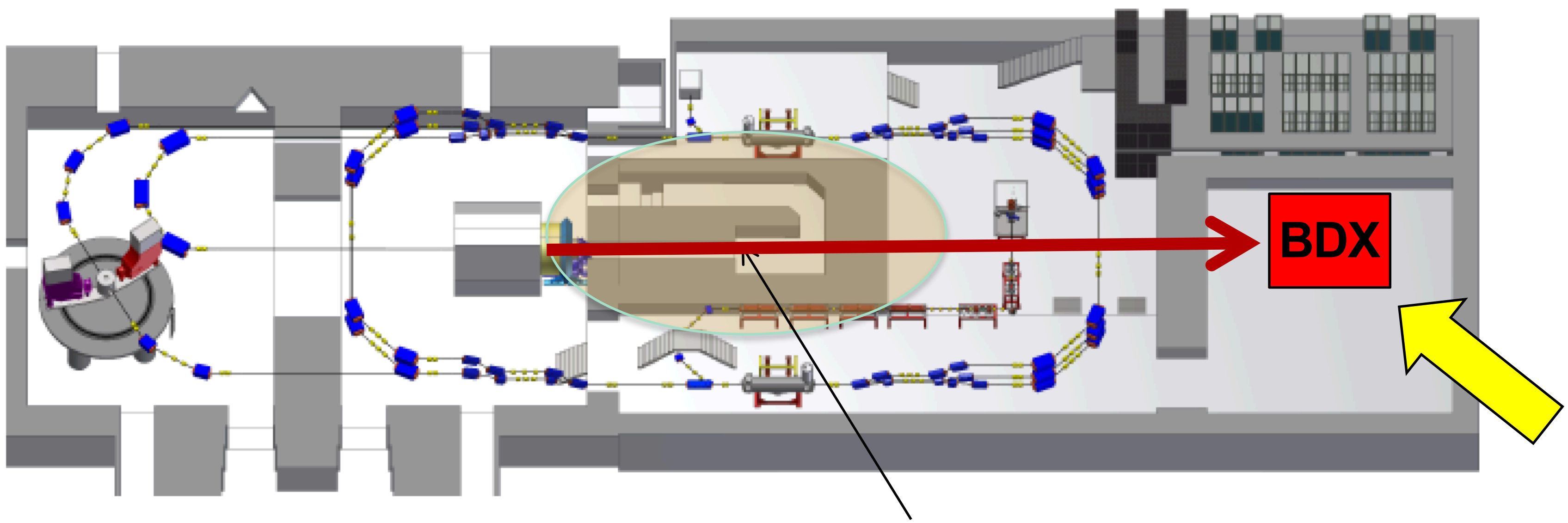


Beam Dump Experiment (BDX) @ MESA

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







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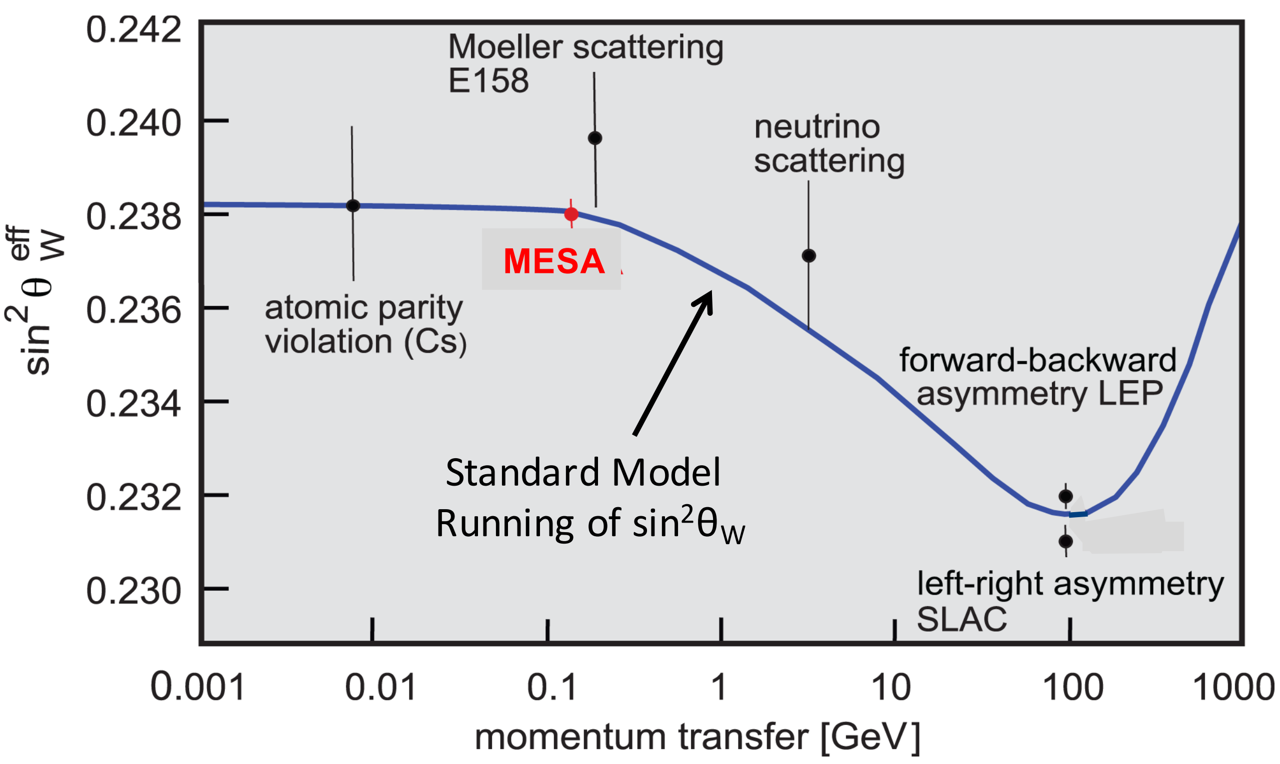
10,000 hours @ 150 μA

→ 10^{23} electrons on target (EOT)

P2 contribution to $\sin^2\theta_W$

MESA: $\Delta\sin^2\theta_W = 4 \times 10^{-4}$



Nuclear Astrophysics at MAGIX ?

JG|U

$^{12}C\ (\alpha,\gamma)\ ^{16}O$ reaction

- Of fundamental importance for star burning
- Determines ^{12}C / ^{16}O abundance
- Influences the nucleosynthesis of heavy elements

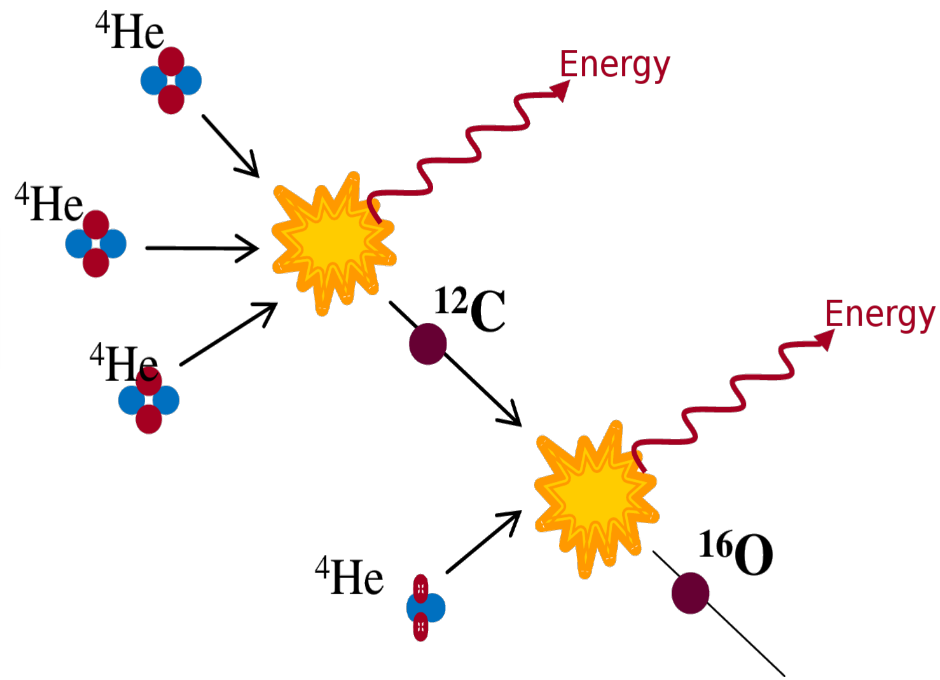
Cross section as function of $E_{c.m.}$

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

Compton wave length

Tunneling probability in fusion process

„S factor“ unknown nuclear physics

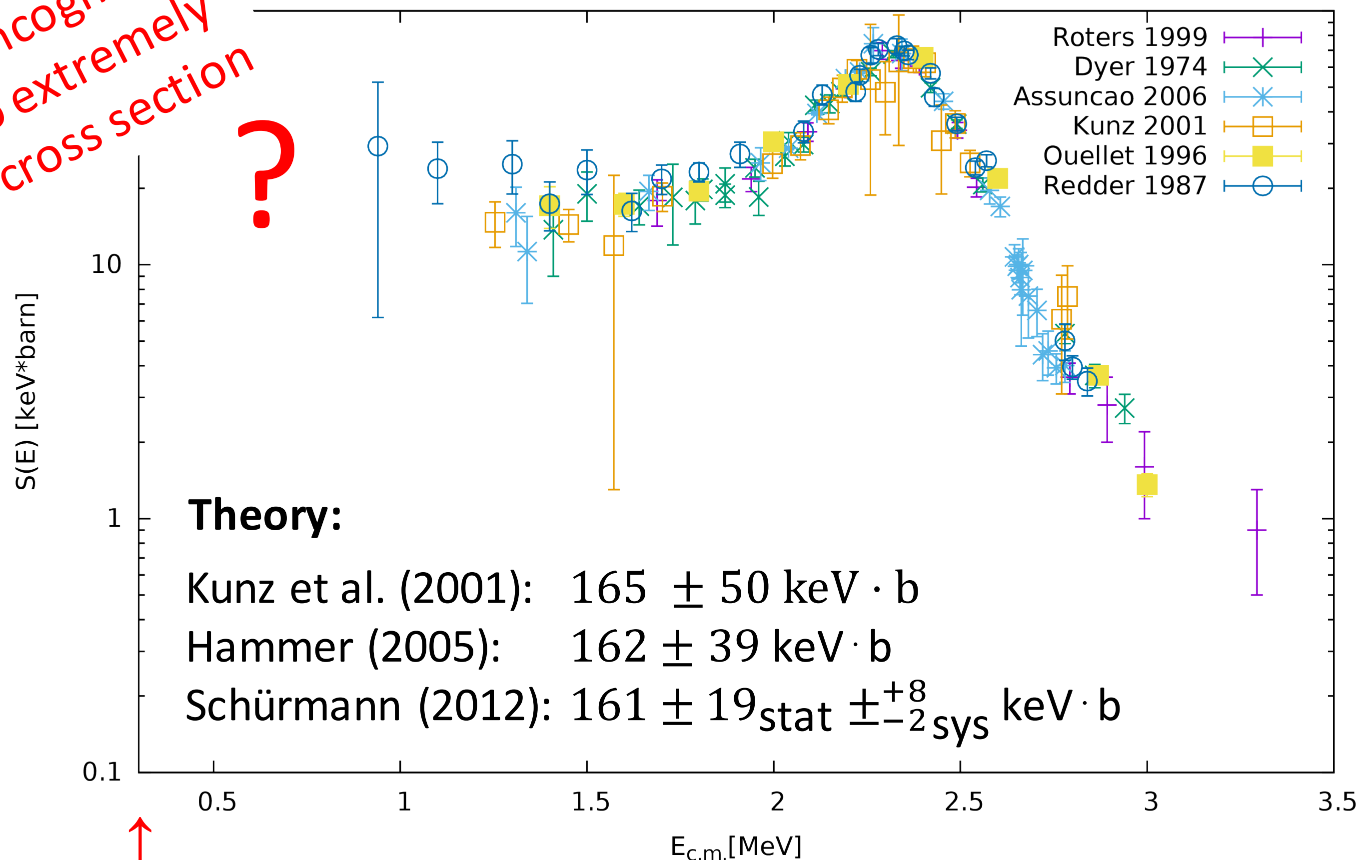


Nuclear Astrophysics at MAGIX ?

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

terra incognita
due to extremely
small cross section

?



Theory:

Kunz et al. (2001): 165 ± 50 keV · b

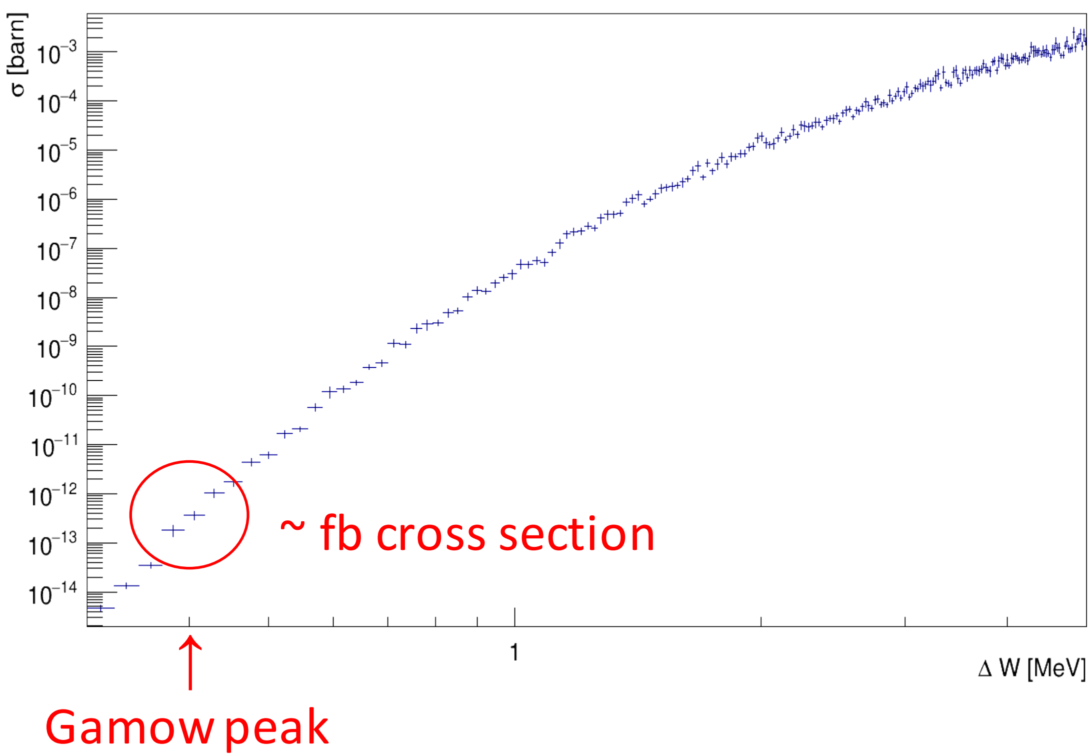
Hammer (2005): 162 ± 39 keV · b

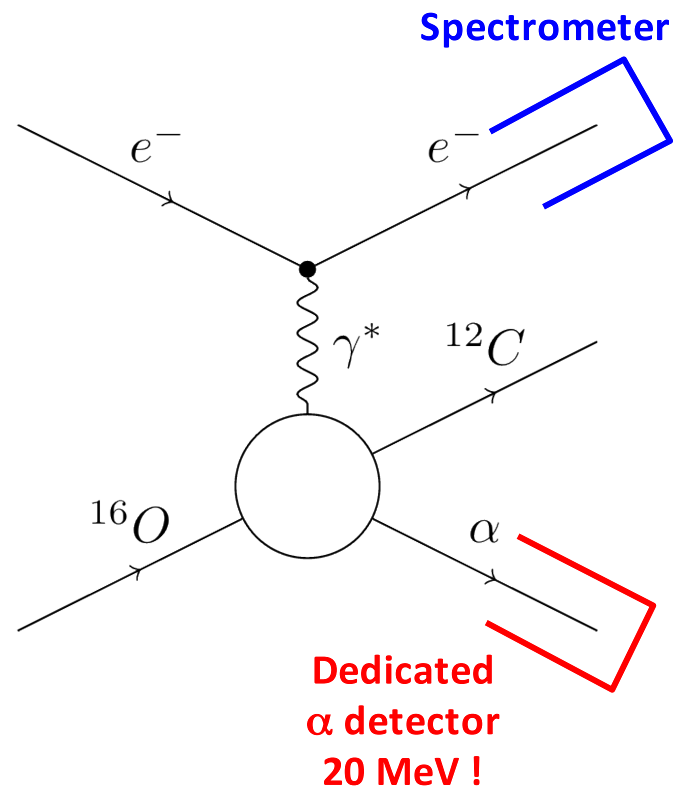
Schürmann (2012): $161 \pm 19_{stat} \pm^{+8}_{-2}{}_{sys}$ keV · b

↑
Gamow peak

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

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





To-Do:

- Simulate acceptences
- Study background
- Concept for α detection

Nuclear Astrophysics