PHI PSI 13

La Sapienza, Rome
September 9-13, 2013

MAinz MIcrotron MAMI:

Low-Energy Precision Physics with Electron Fixed-Target Experiments

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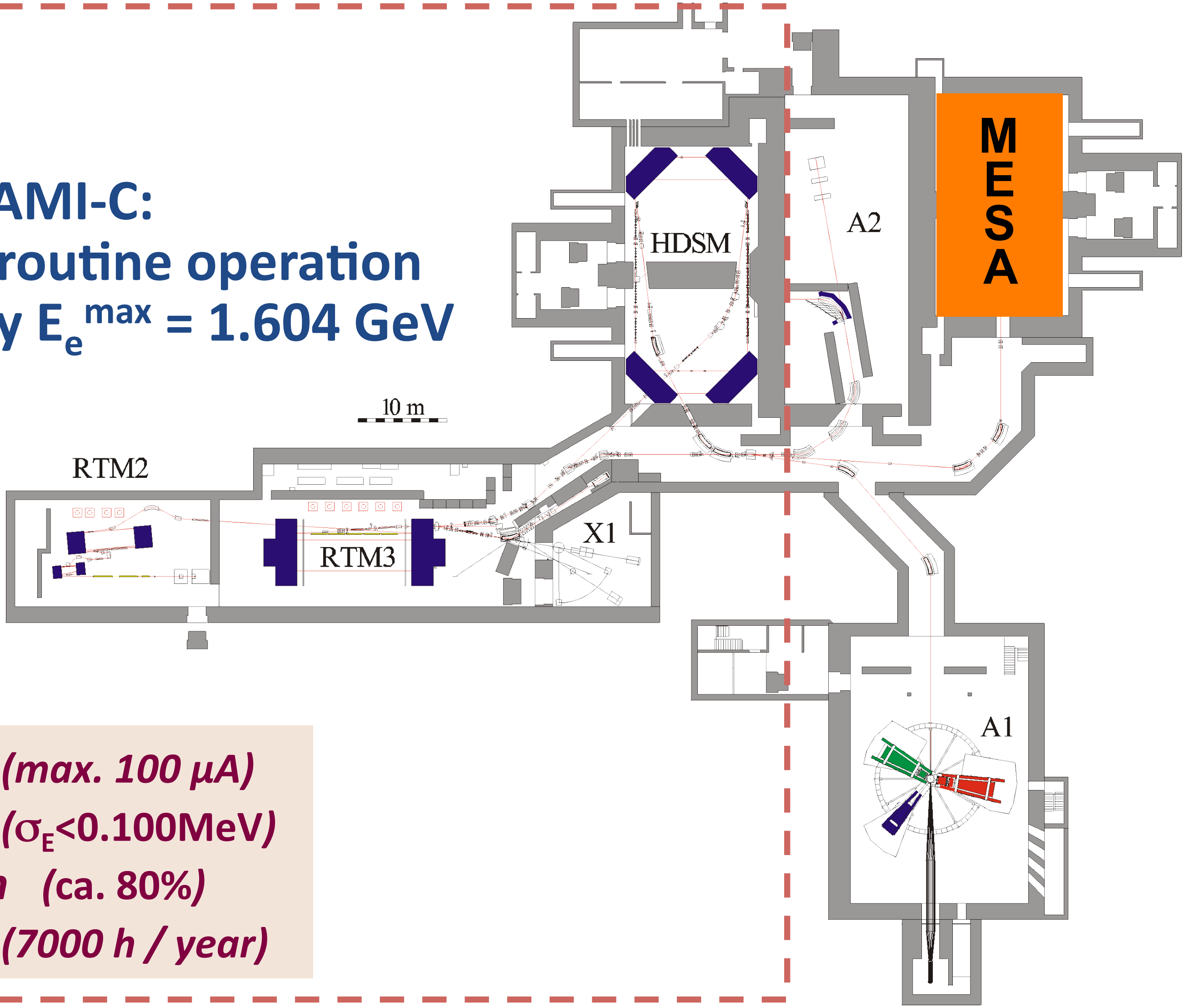
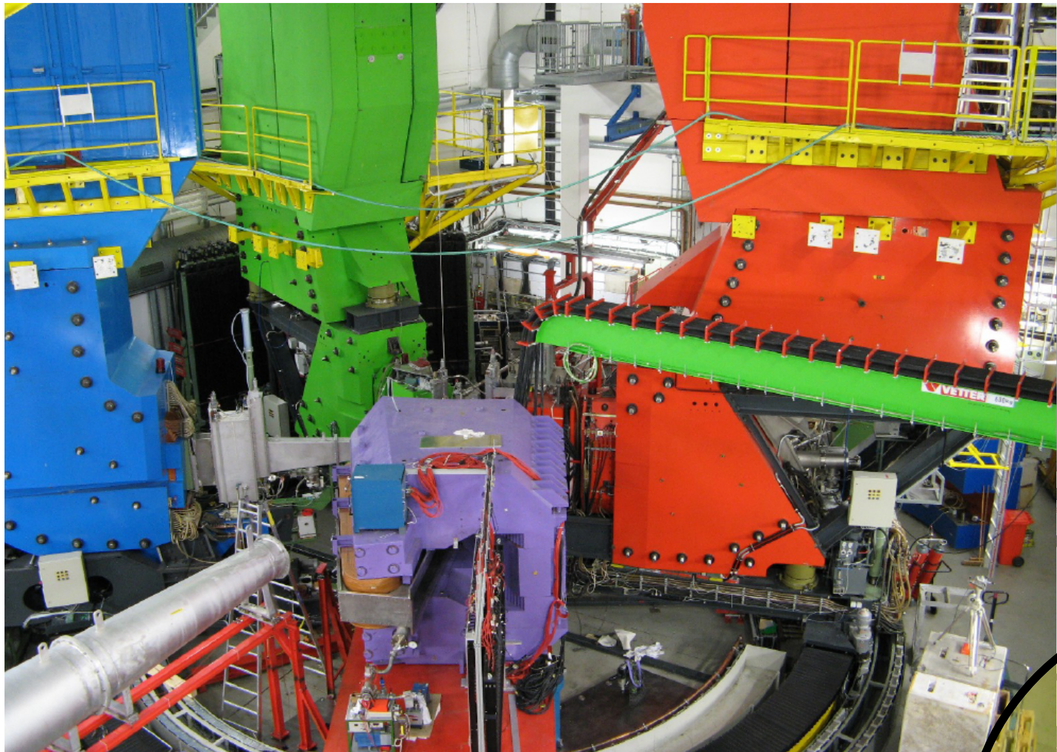
The MAMI Accelerator

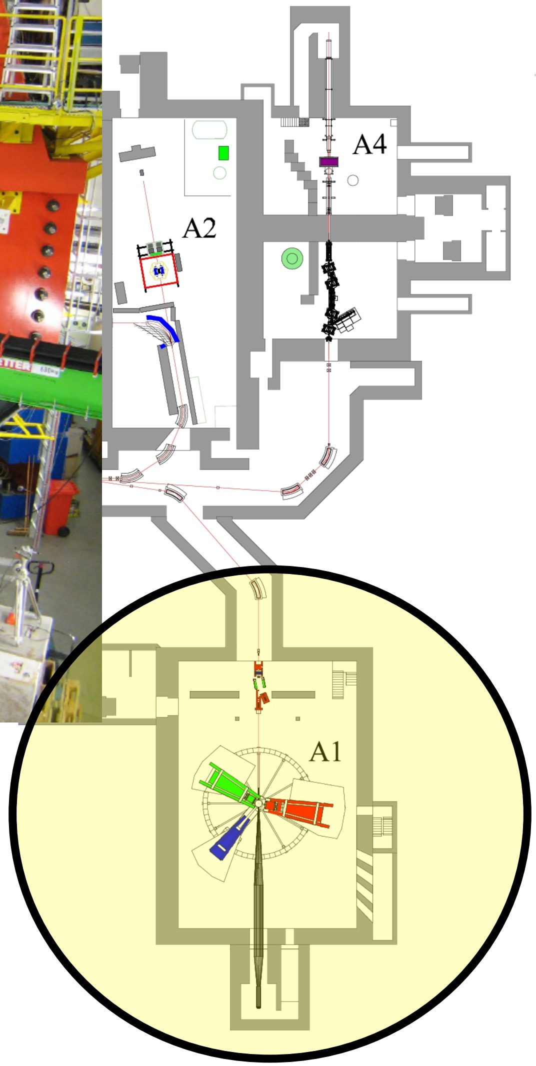
MAMI-C:
since 2007 in routine operation
→ Beam energy E_e^{max} = 1.604 GeV



HIGH Intensity *(max. 100 µA)*
HIGH Resolution *(σ_E<0.100MeV)*
HIGH Polarization *(ca. 80%)*
HIGH Reliability *(7000 h / year)*

Experiment A1: High-Resolution Spectrometers





Experiment A1: Electron Scattering

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

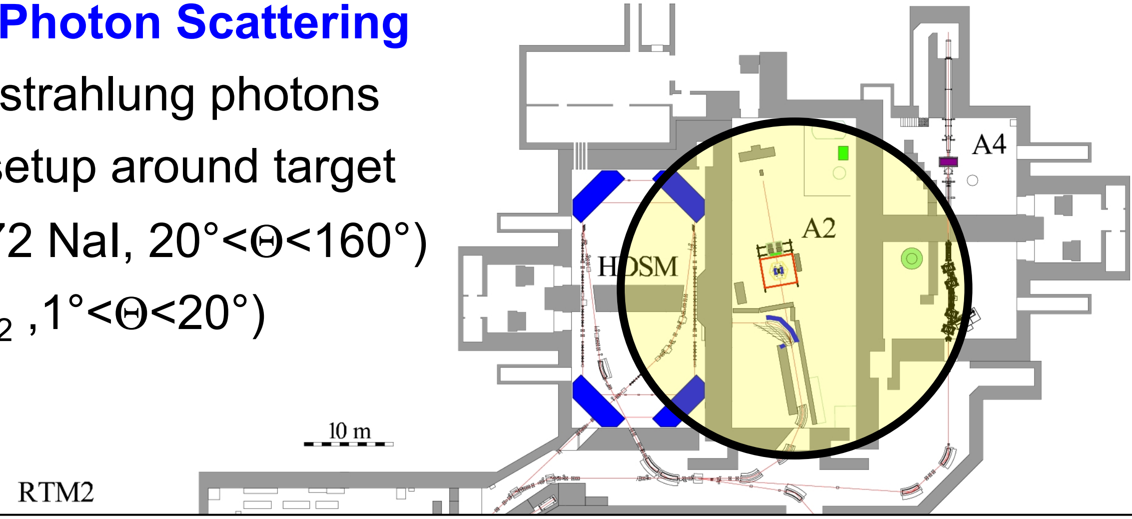
Experiment A2: Tagged Photon Beam

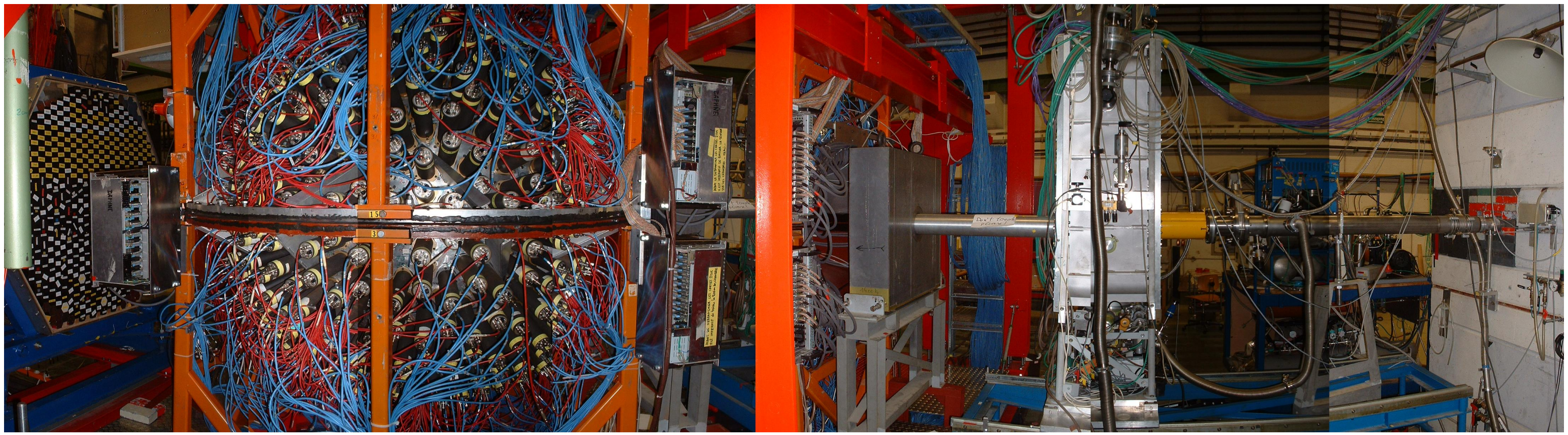
Experiment A2: Photon Scattering

- “Tagged” bremsstrahlung photons
- 4π calorimeter setup around target

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

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





Recent Results

Nucleon Structure

➔ **Nucleon EM FFs** to determine the **proton radius**

Rare meson decays

➔ **Input** to **HLbL contribution to (g-2)$_\mu$:** $\eta \to e^+e^-\gamma$

➔ **Test of ChPT** through rare decay $\eta \to \pi^0\gamma\gamma$

Search for New Physics

➔ **Dark photon** searches

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Search for New Physics

➔ **Dark photon** searches

➔ Measurement of the **electroweak mixing angle $\sin^2\Theta_W$**

Outlook: MESA accelerator

Nucleon EM Form Factors to determine the Proton Radius

EM Form Factors of the Proton

Elastic form factors in ep scattering:

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

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

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

G_E: spatial electric charge distribution

G_M: distribution of magnetic moments

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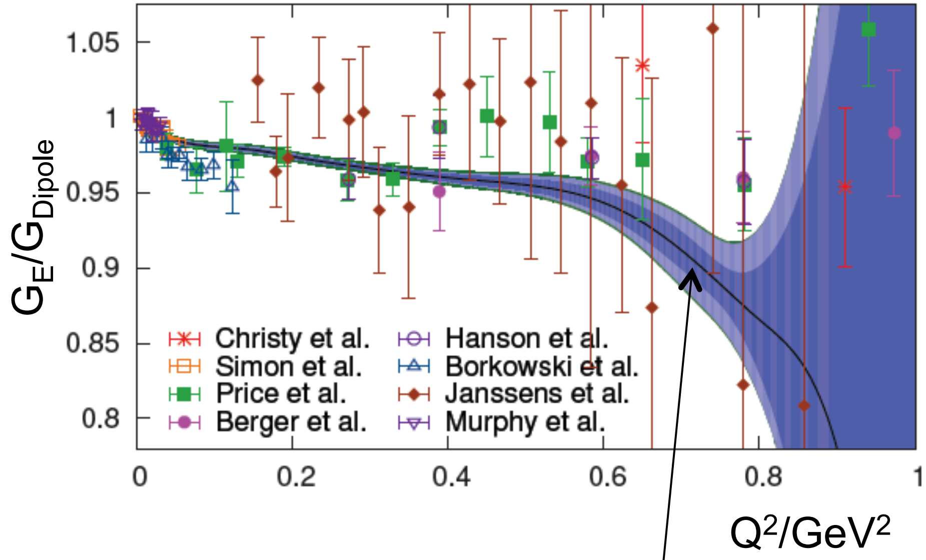
Super-Rosenbluth measurement



average of all fit models with uncertainties

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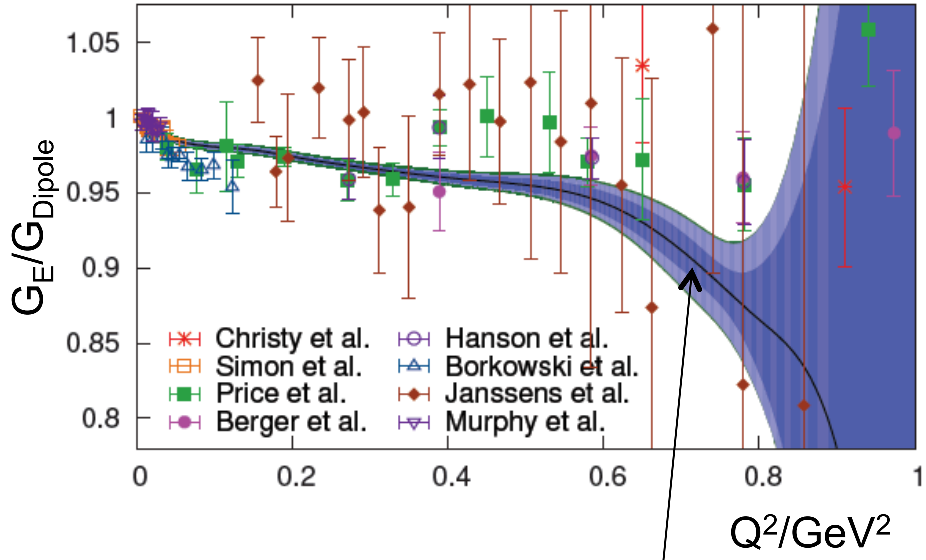


average of all fit models with uncertainties

Proton charge radius:

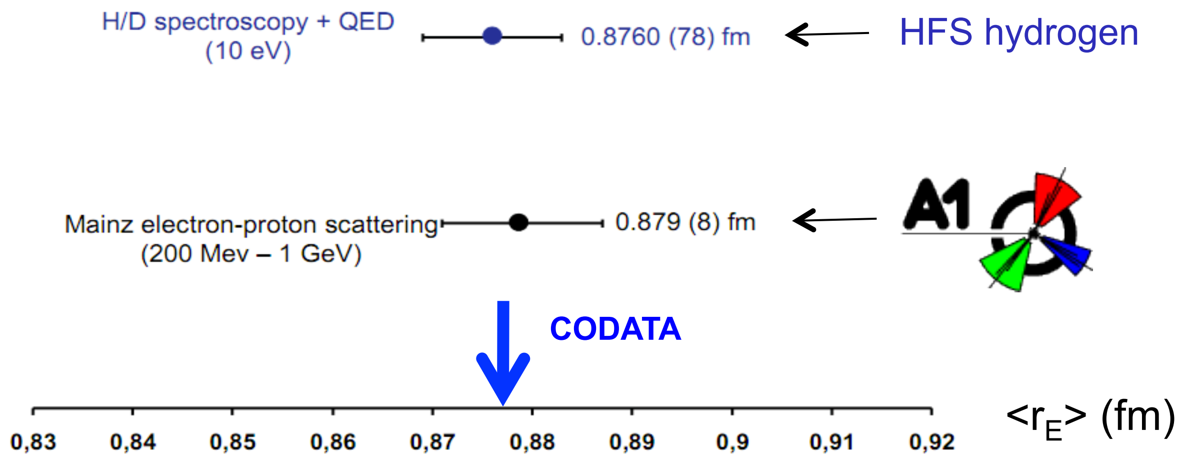
$$\left\langle r_{E/M}^2 \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \frac{dG_{E/M}(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

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

PRL '10, 242001: Bernauer et al.
arXiv 1307:6227: new technical paper

Proton Radius Puzzle

Comparison btw. electron scattering and atomic physics evaluations



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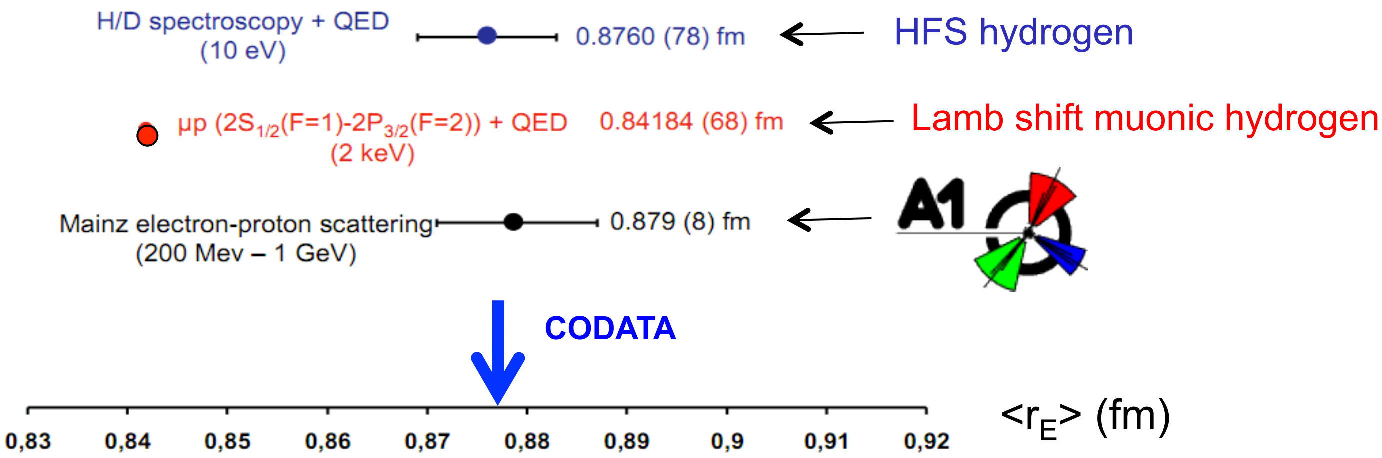

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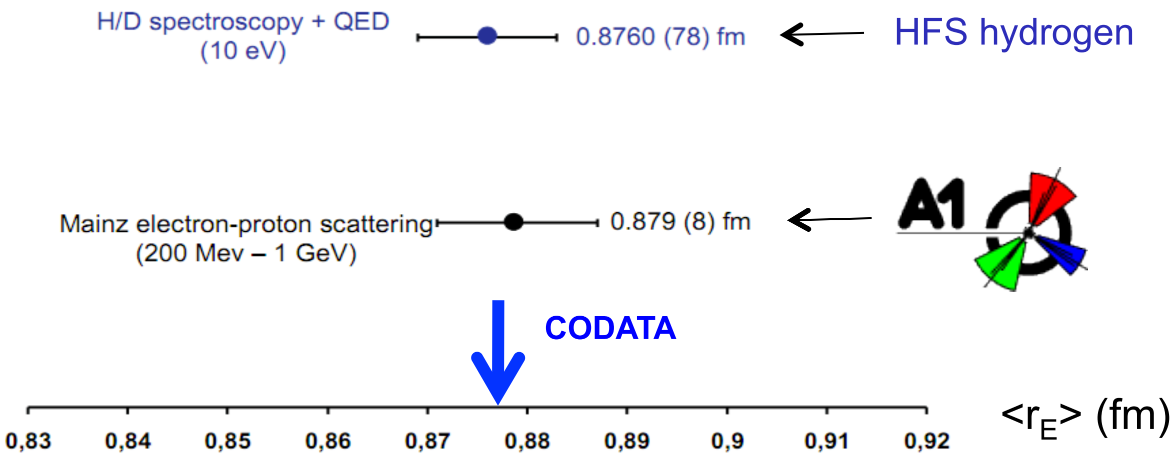


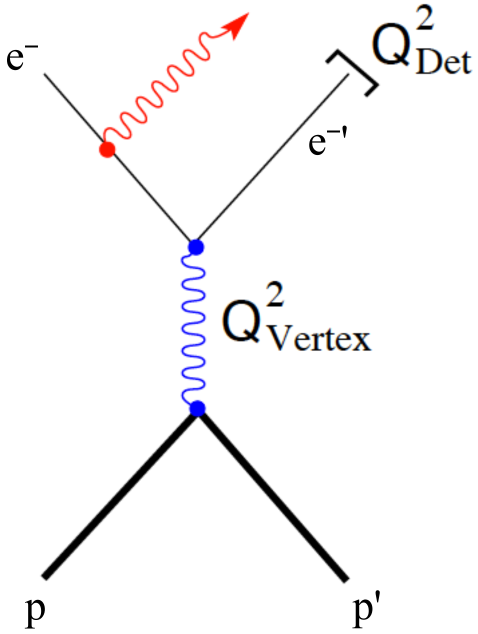
Error(s) or New Physics?

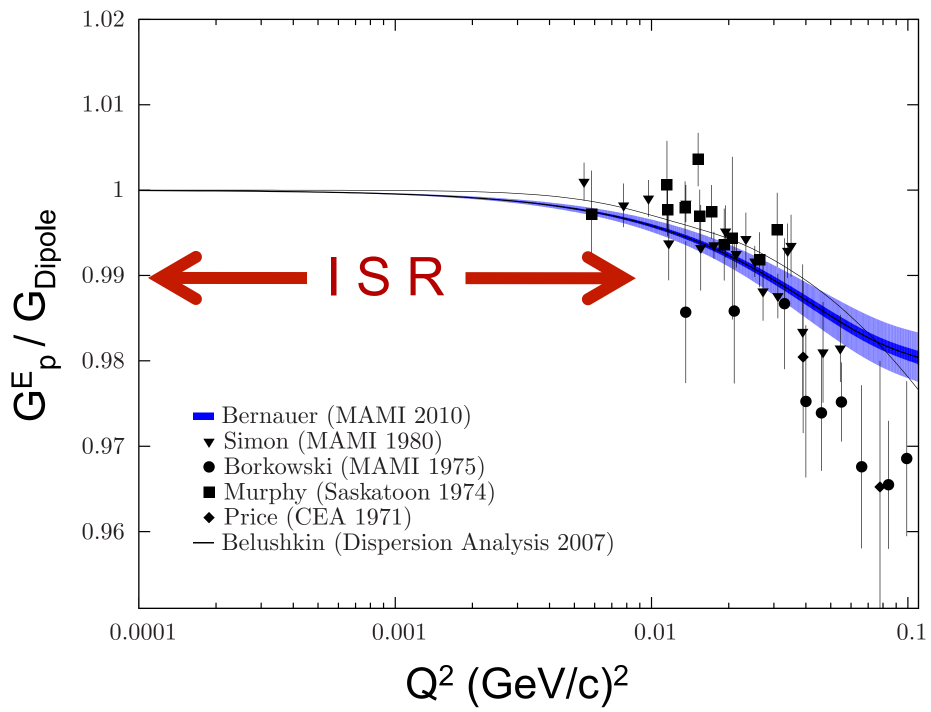
Hadronic or QED uncertainties?
→No obvious mistake found!

Dark photon or other new physics?
→Only dedicated models viable!

Several new experiments planned to shed new light on puzzle
→ Mainz: Initial State Radiation

New: ISR Measurement of EM Form Factors





Strategy:

- Reach very low values of Q^2 by using events with Initial State Radiation
- Measure momentum spectrum of scattered electron after ISR
- Needs very good understanding of QED radiative corrections

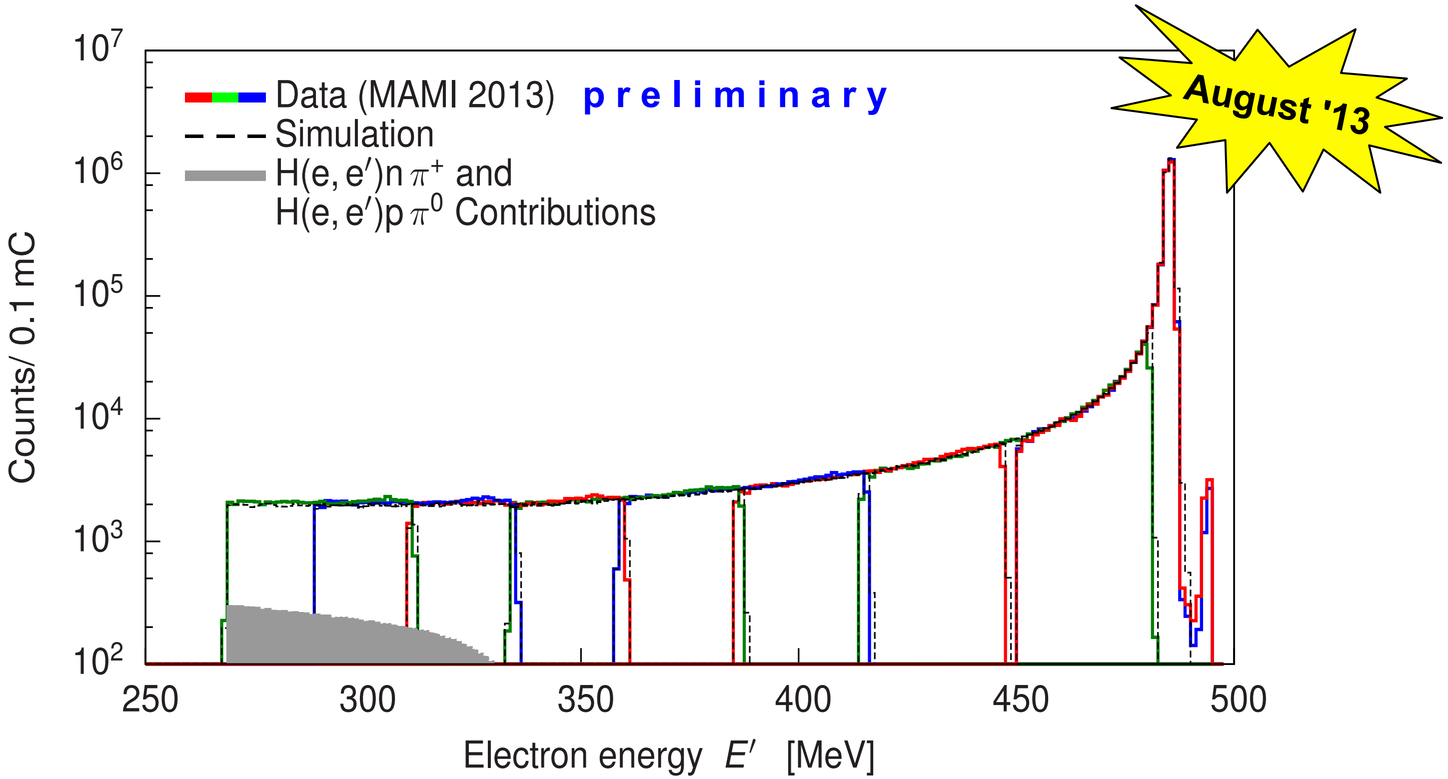
→ determine proton radius with competitive precision

New: ISR Measurement of EM Form Factors

Recent beam time (08/13):

- 3 MAMI energy settings: 495, 330, 195 MeV
- luminosity measurement with second spectrometer

→ **after few online calibrations agreement with QED prediction on few % level**



Rare eta decays* at the Crystal Ball /TAPS:

$$\eta \to e^+ e^- \gamma$$

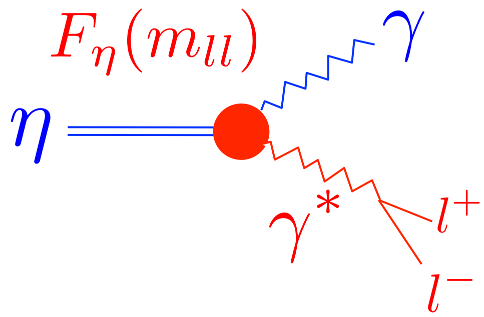
$$\eta \to \pi^0 \gamma\gamma$$

* Results based on $6x10^7$ eta mesons produced in 6 weeks of beam time in 2007/2009

Timelike EM Form Factor: $\eta \to e^+e^-\gamma$

$$\frac{d\Gamma(\eta \to l^+l^-\gamma)}{dm_{ll}\Gamma(\eta \to \gamma\gamma)} = [QED] \cdot |F_\eta(m_{ll})|^2$$

↑ pointlike eta



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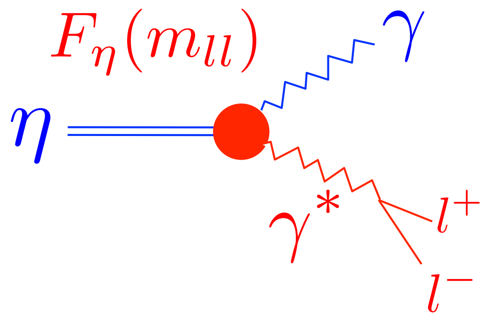


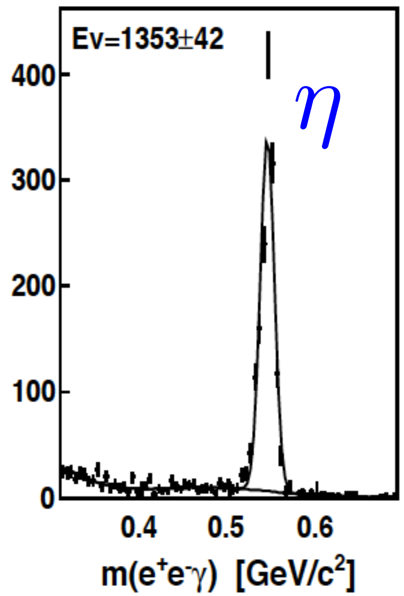
$\mathbf{m(e^+e^-) = 45MeV/c^2}$ $\mathbf{370MeV/c^2}$

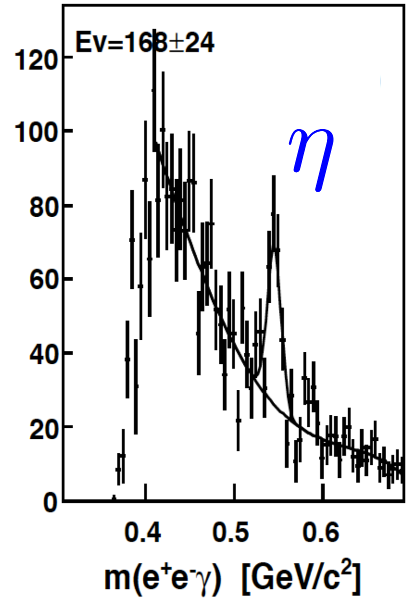
Features:

- Upgrade of existing result (PLB 701, 562)
  → factor 10 more statistics: **18,000 events**

- Normalization to η → γγ

- Accuracy:
  $m_{ee} < 2m_\mu$: most accurate measurement
  $m_{ee} > 2m_\mu$ similar to recent NA60/CERN measurement of η → μμγ (Acta Phys. Pol. B5, 465)





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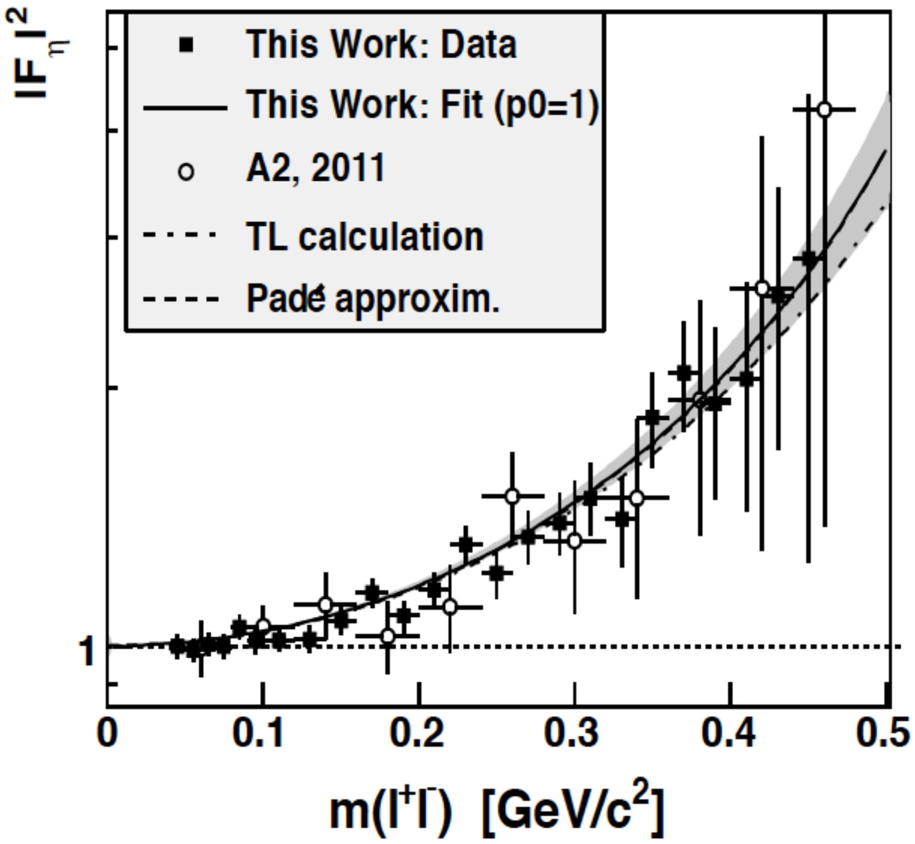
Measurement to be submitted to Phys. Rev. C:
S. Prakhov, M. Unverzagt et al. (A2 collab.)



Vector Meson Dominance model:

$$F(m_{ll}) = \frac{1}{1 - \frac{m_{ll}^2}{\Lambda^2}}$$

$\Lambda^{-2}=(1.95 \pm 0.15_{stat} \pm 0.10_{syst})$ GeV^{-2}

in good agreement with all previous results

TL calculation: S. Leupold, C. Terschlüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas

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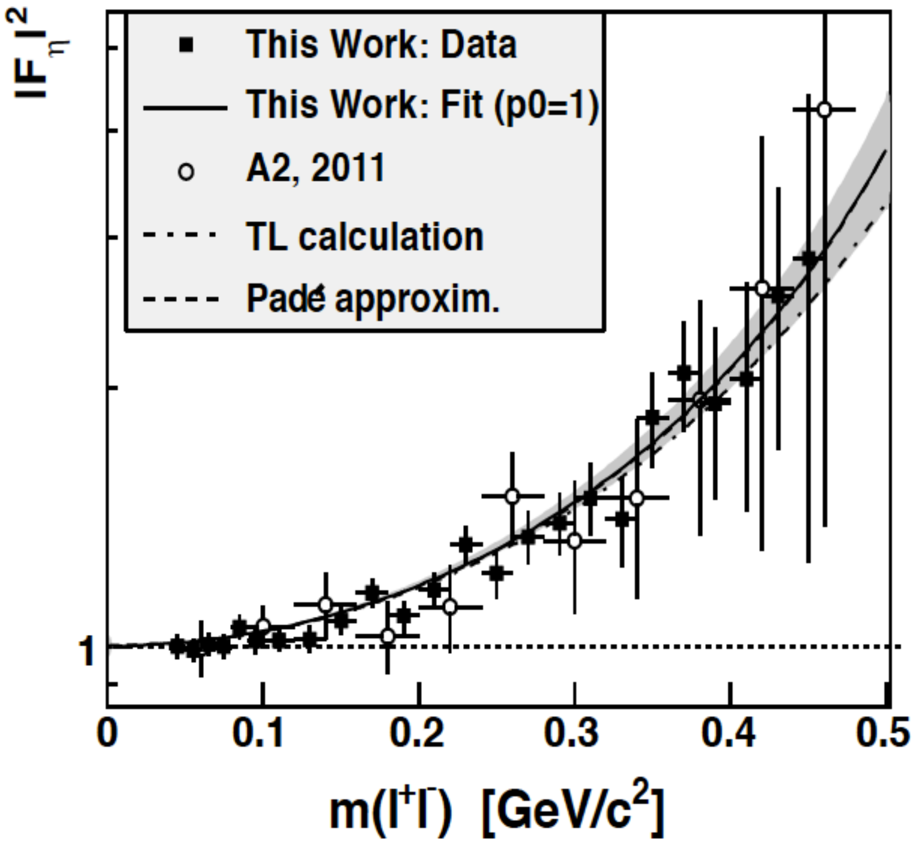

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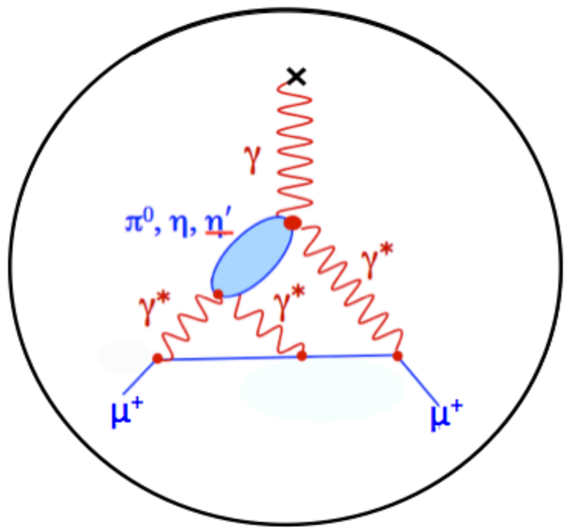
Important test of phenomeno-logical models in view of HLbL contribution to $(g-2)_\mu$



Test of ChPT: Rare eta decay $\eta \to \pi^0\gamma\gamma$

Features:

- No $O(p^2)$, $O(p^4)$ contrib. → **starts with $O(p^6)$ contribution**

→ **Interesting test of chiral dynamics**

- Previous **measurements** from CB@AGS, GAMS, WASA, KLOE, CB@MAMI **inconclusive**

→ **Experimentally very difficult channel**

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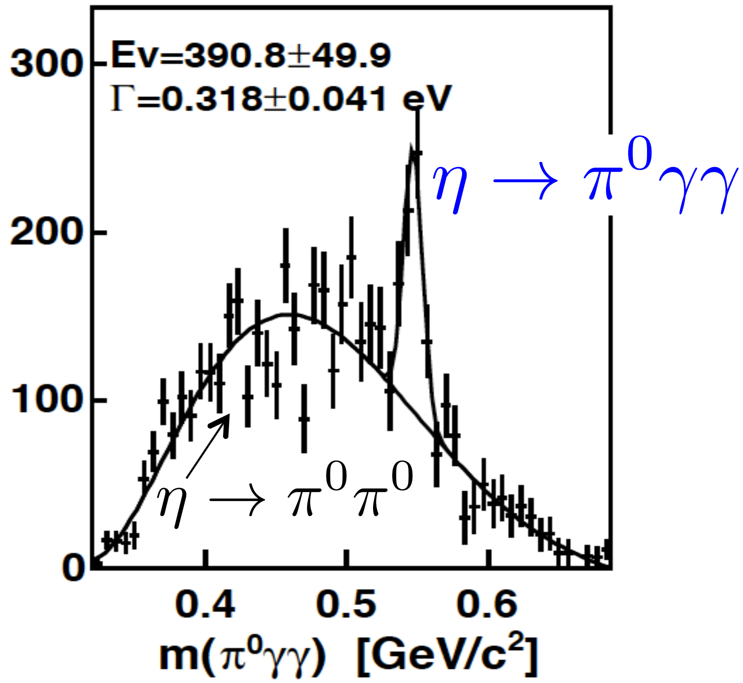
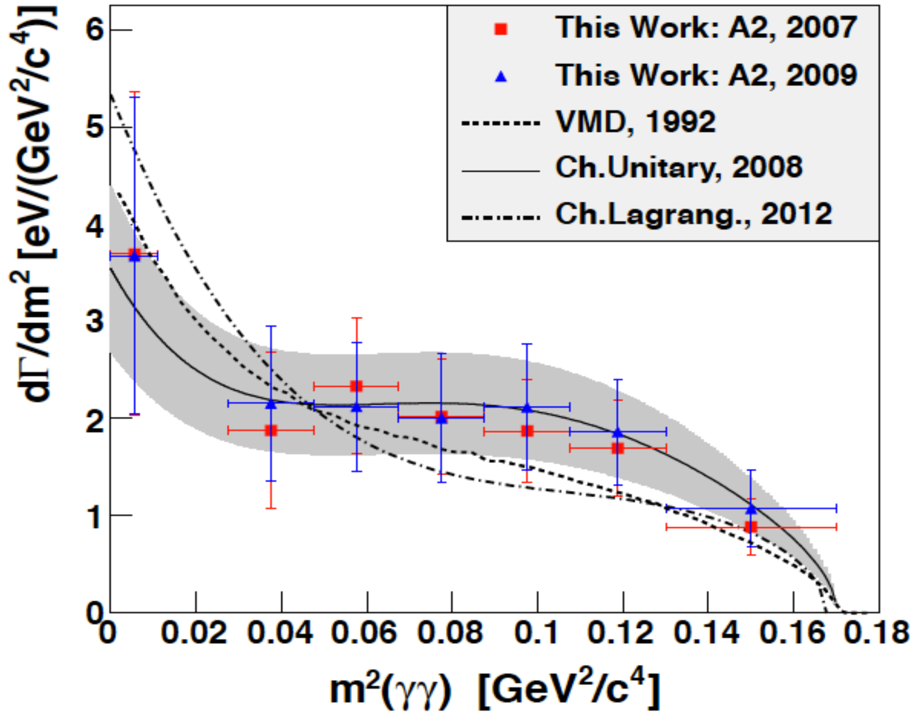


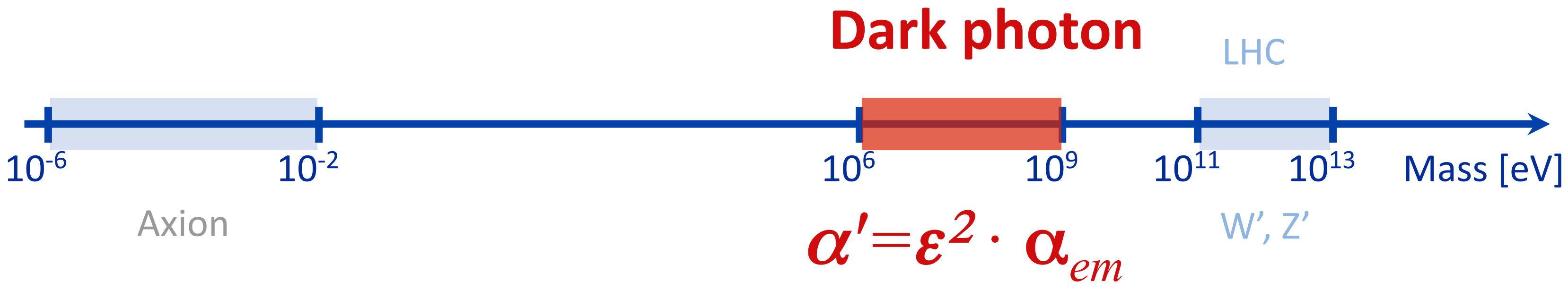
VMD: J.N.Ng et al.
Ch. Unitarity: E. Oset et al.
Ch. Lagrangian: M. Lutz et al.



A Search for the Dark Photon at MAMI

Dark Photon Search

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

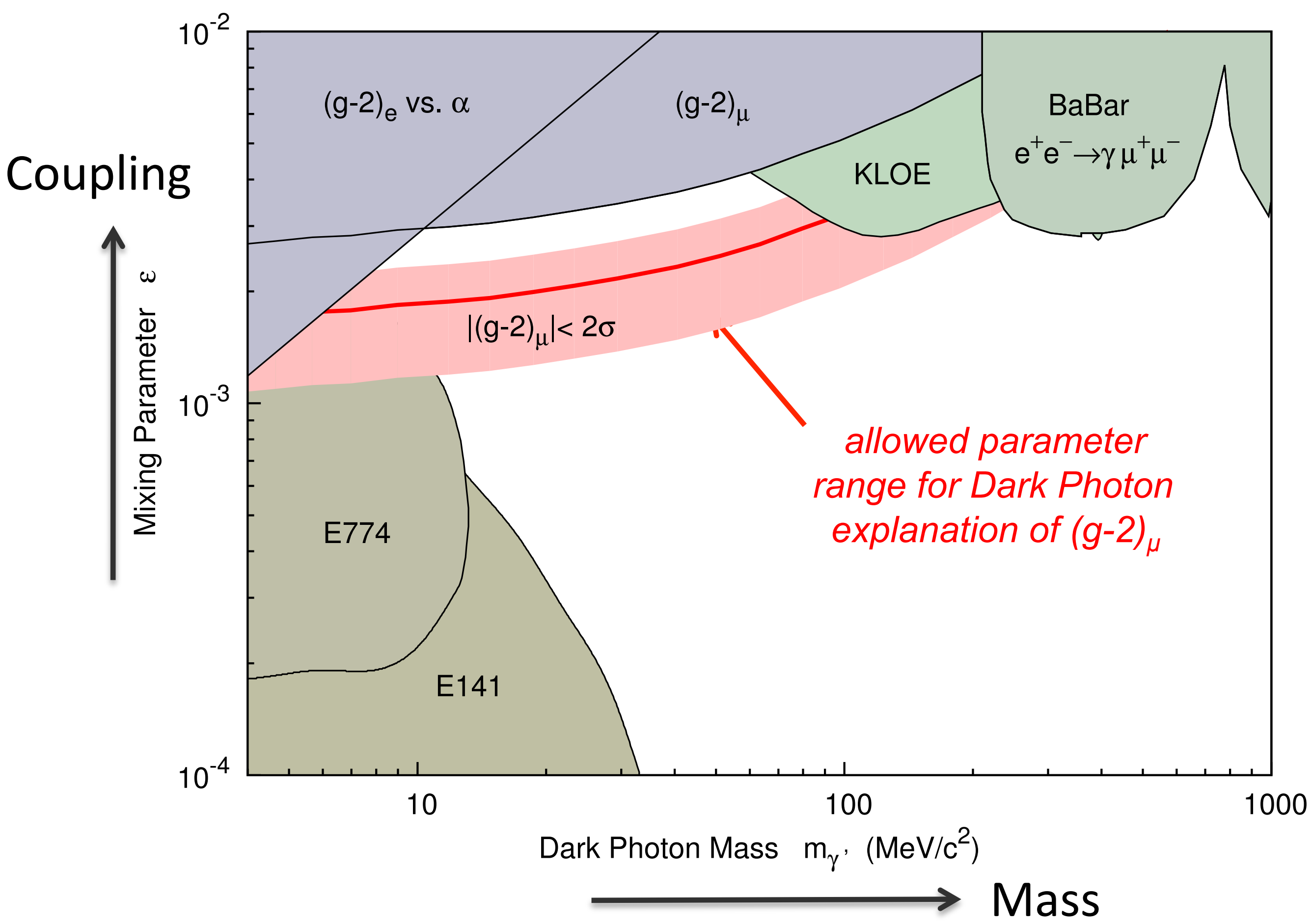


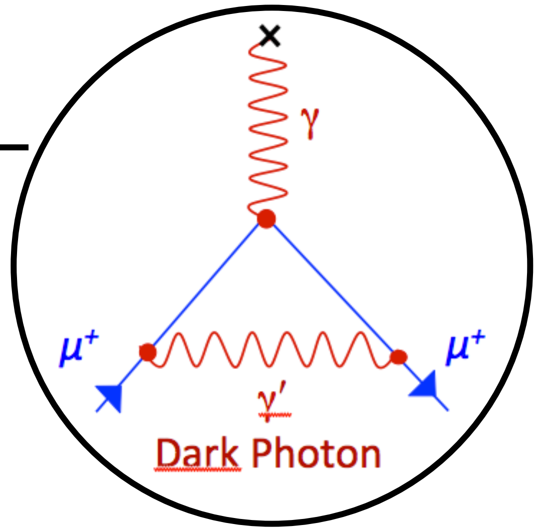
Search for the O(GeV/c^2) mass scale in a world-wide effort

- 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)

The $(g\text{-}2)_\mu$ Parameter Range





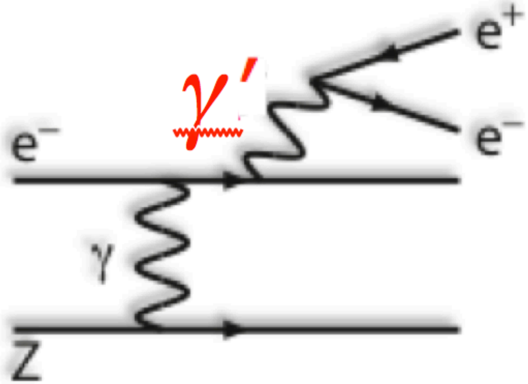
Searches using Fixed-Target Experiments

Bjorken, Essig, Schuster, Toro (2009)

Low-energy, high-intensity accelerators are ideally suited for Dark Photon searches

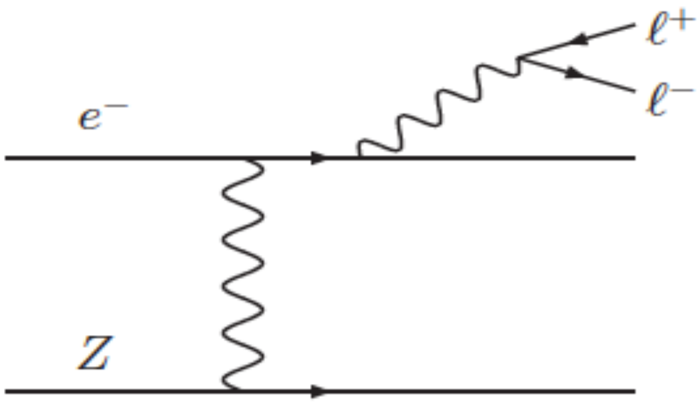
→ MAMI: $E_\gamma < 1.6$ GeV

→ A1 spectrometer setup

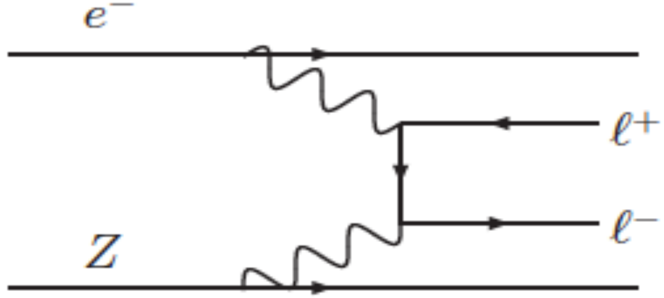


m_{e+e-}

QED background processes:

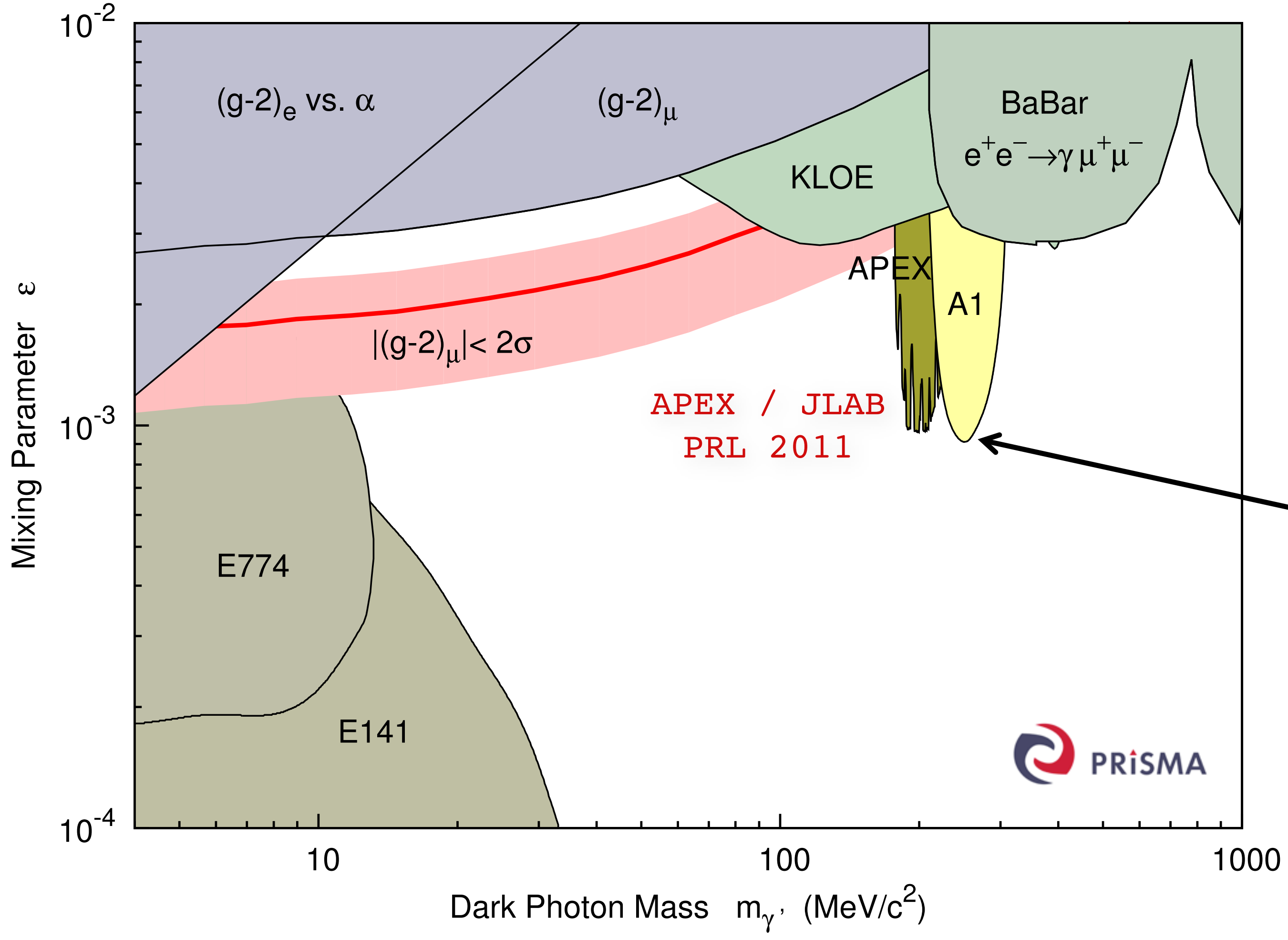


(a)



(b)

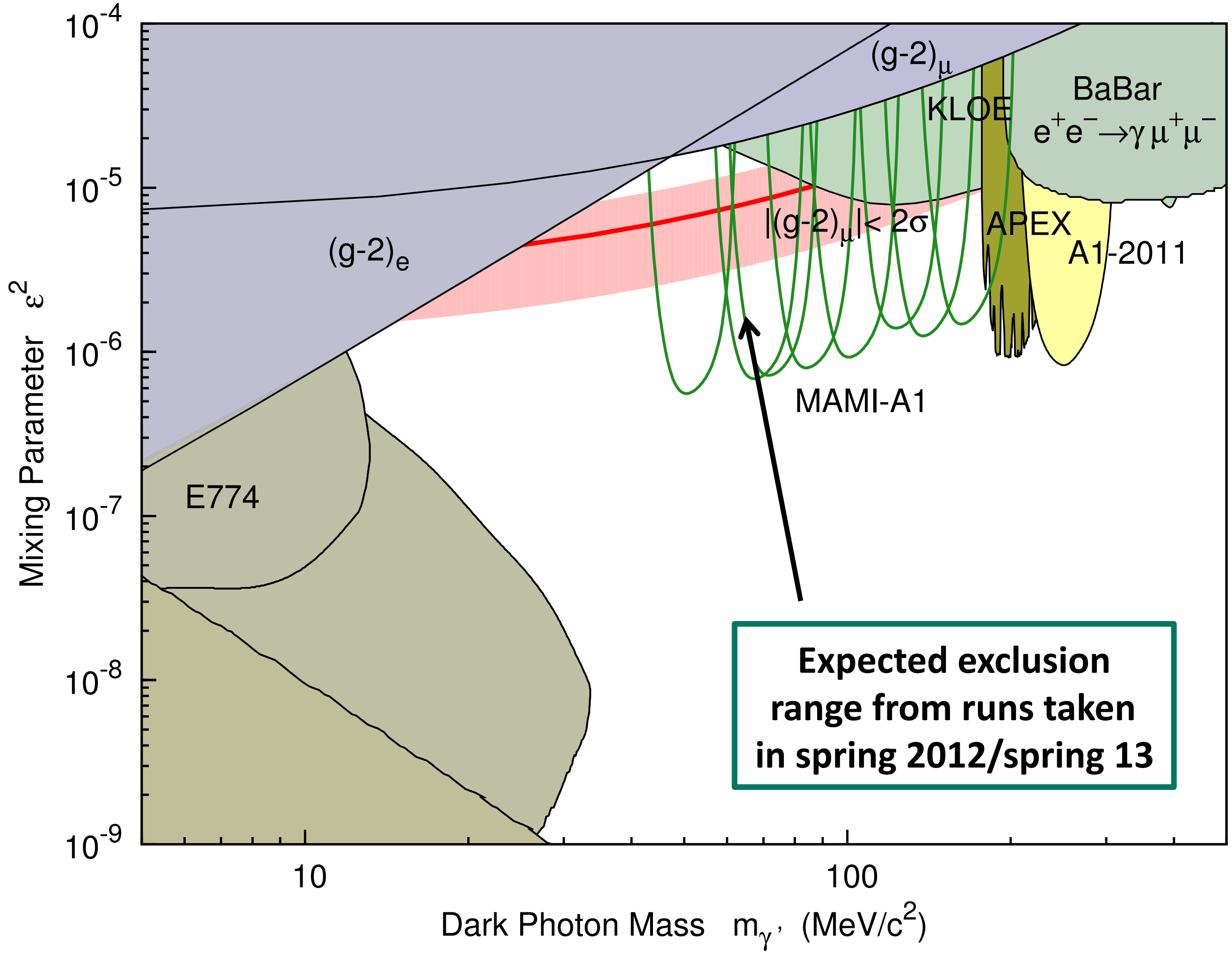
Results from A1 Pilot Run (2010)



Exclusion range from
MAMI / A1 spectrometers
during **4-day pilot run**

A1/MAMI
PRL 2011

Expected Range from 2012/13 A1-Runs



Outlook:

Perspectives for precision physics at MESA

MESA Accelerator

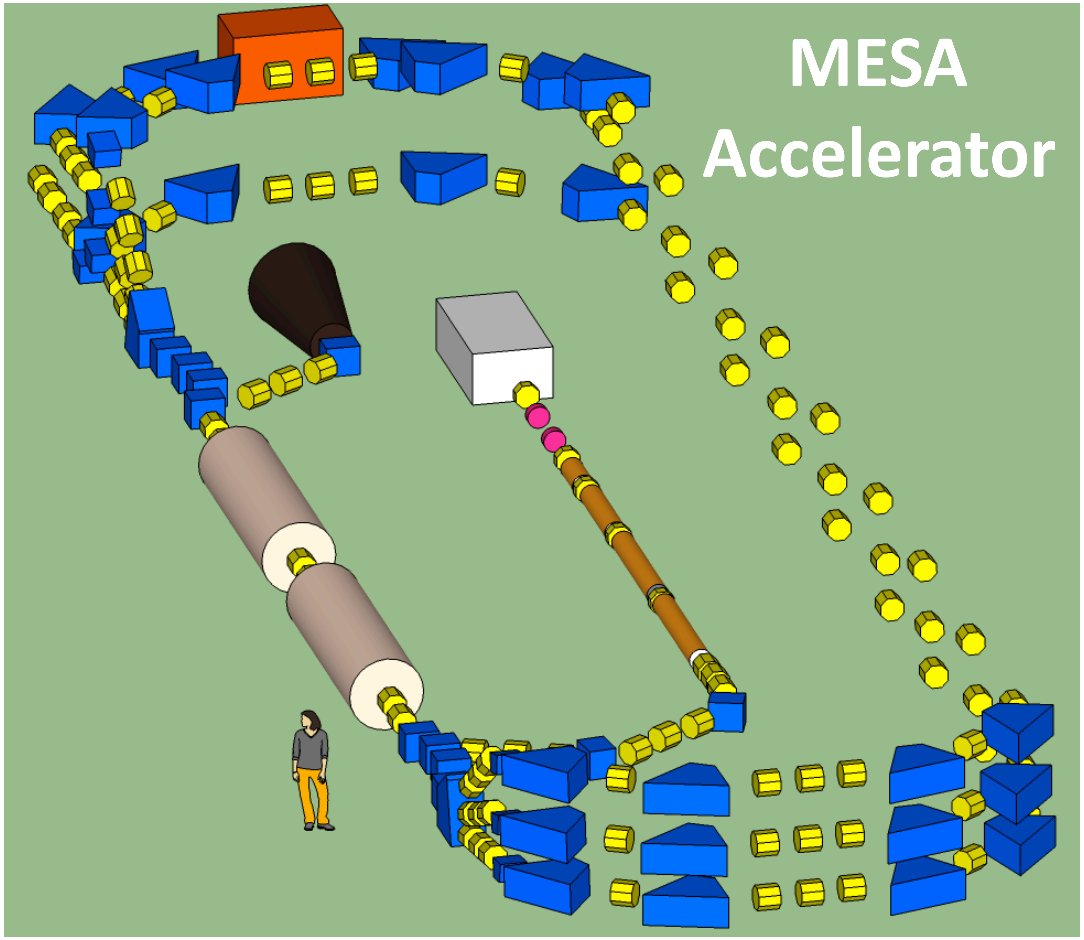
Mainz Energy-Recovering Superconducting Accelerator

E_{max} = 200 MeV
I_{max} = 10 mA

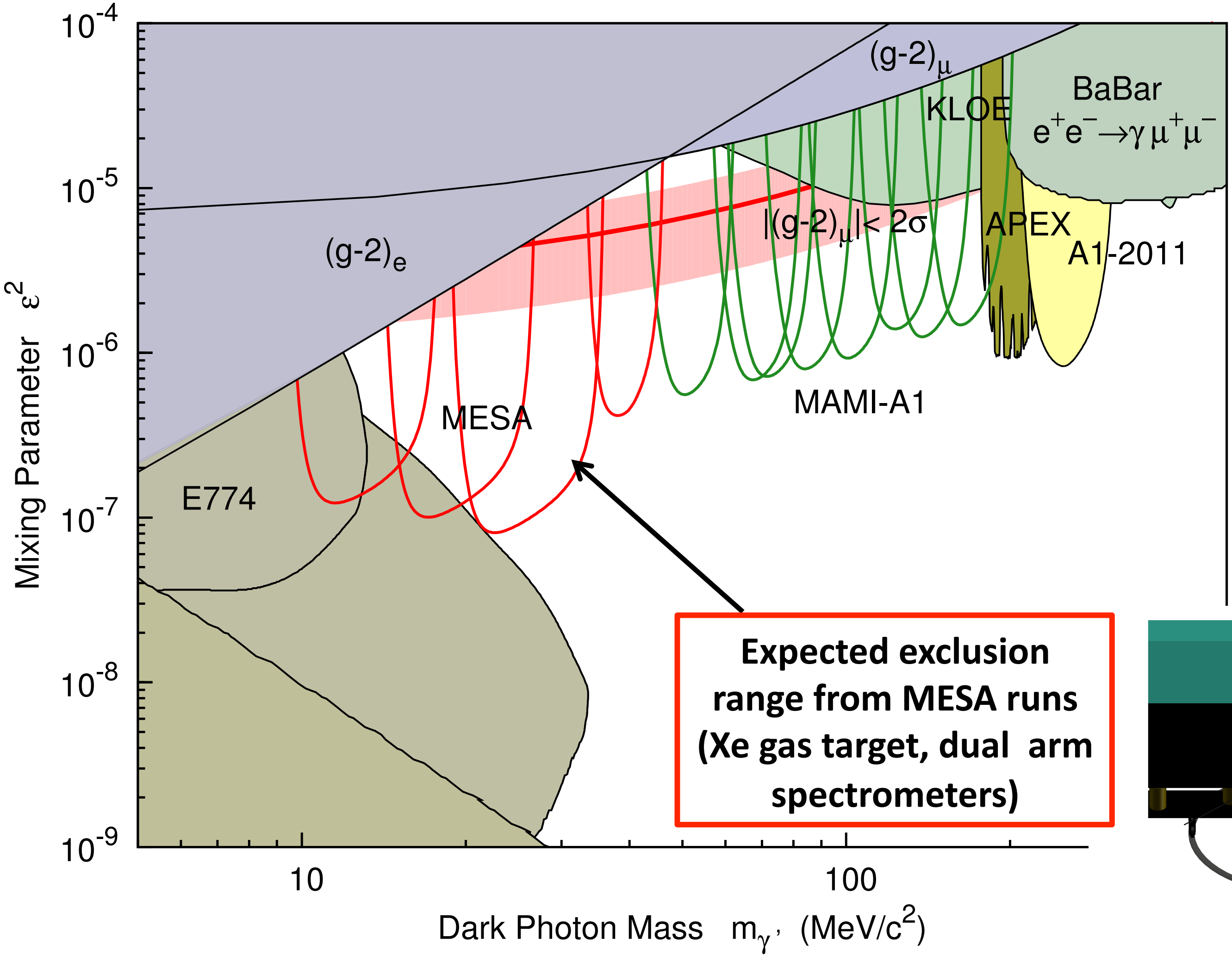
2 Modes:

- Internal Gas Target (ERL mode)
- Extracted Beam (Non-ERL mode)

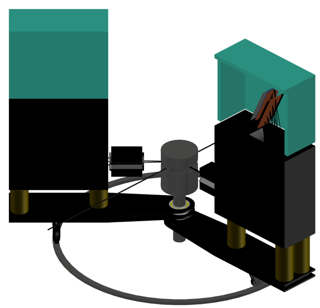
PRiSMA



Phase 3: Accessing the Low Mass Region



Expected exclusion range from MESA runs (Xe gas target, dual arm spectrometers)



MESA contribution to $sin^2\theta_W$

Scattering of long. polarized electrons (150 MeV) on protons

→ **Z boson exchange** introduces **parity-violating effect**

→ Measure **Parity-violating Left-Right cross section asymmetry A_{LR} of 20 x 10^{-9}**

$$A_{LR} = \frac{\sigma(e\uparrow) - \sigma(e\downarrow)}{\sigma(e\uparrow) + \sigma(e\downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(Q_W - F(Q^2))$$

$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

hadron structure ($F(Q^2)$)

MESA contribution to $sin^2\theta_W$

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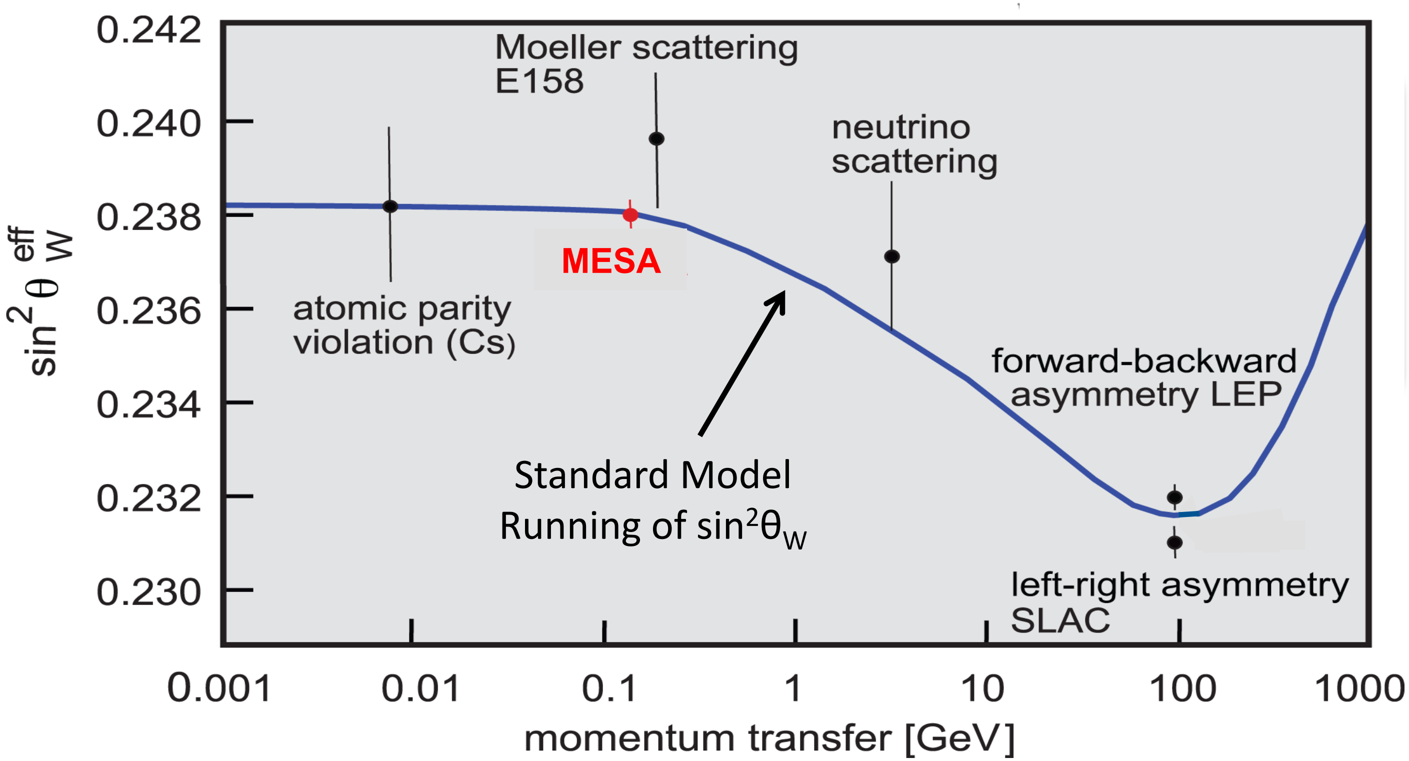
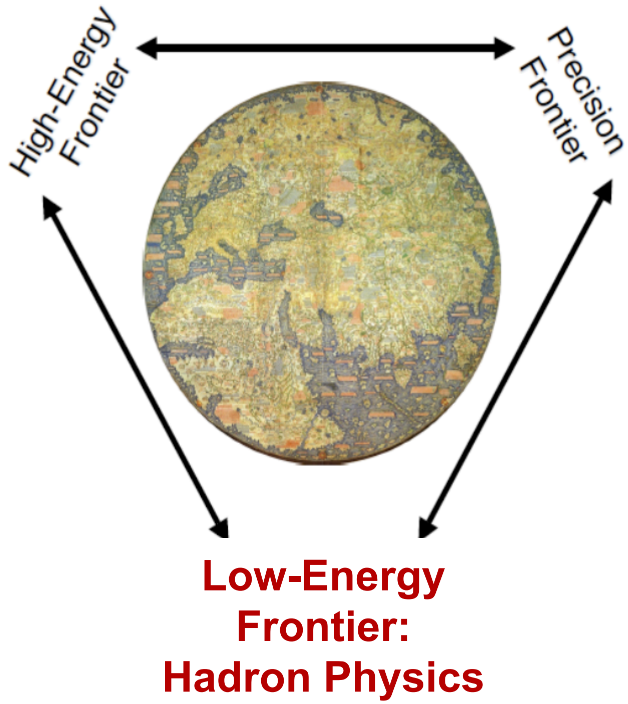
MESA: $\Delta sin^2\theta_W = 4 \times 10^{-4}$



Conclusions

SFB1044:
The low-energy frontier of the Standard Model

- Hadron physics: Improve our under-standing of low-energy QCD
- Mainz programme related to puzzles in low-energy particle physics
  → $(g\text{-}2)_\mu$
  → Proton radius
  → $\sin^2\Theta_W$



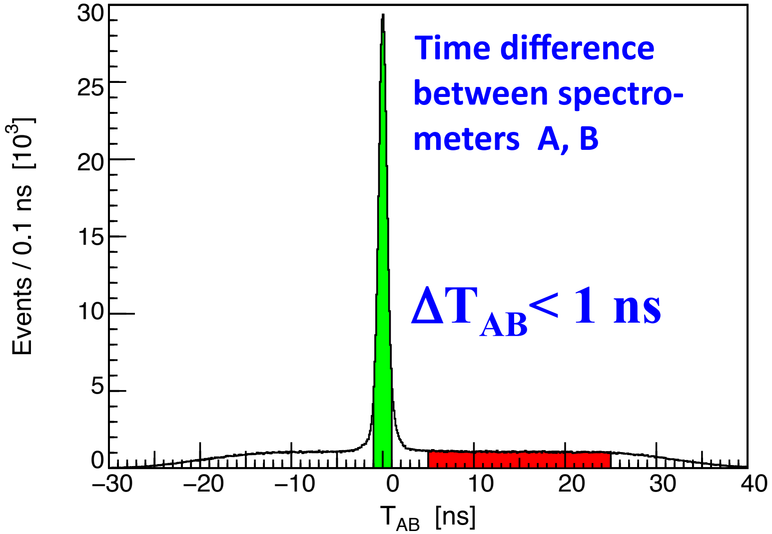
- Complementing MAMI expts. with e+e- expts. at BESIII

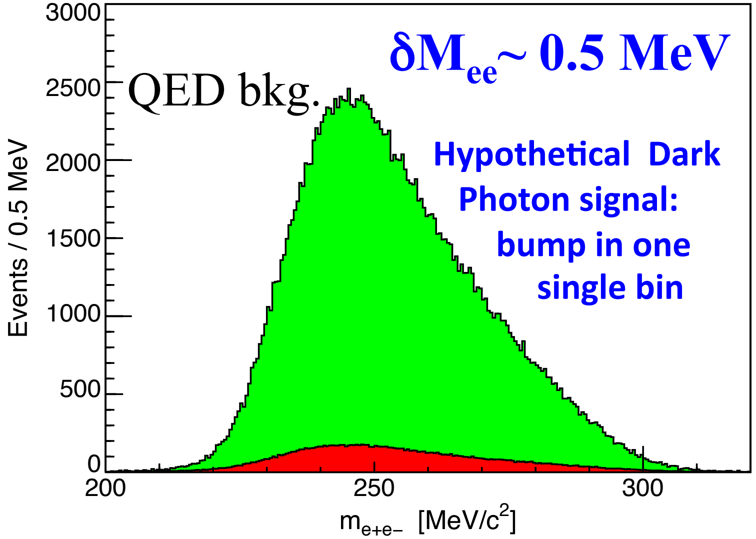
BACKUP

Dark Photon Search @ A1

Features 2010 pilot run (4 days)

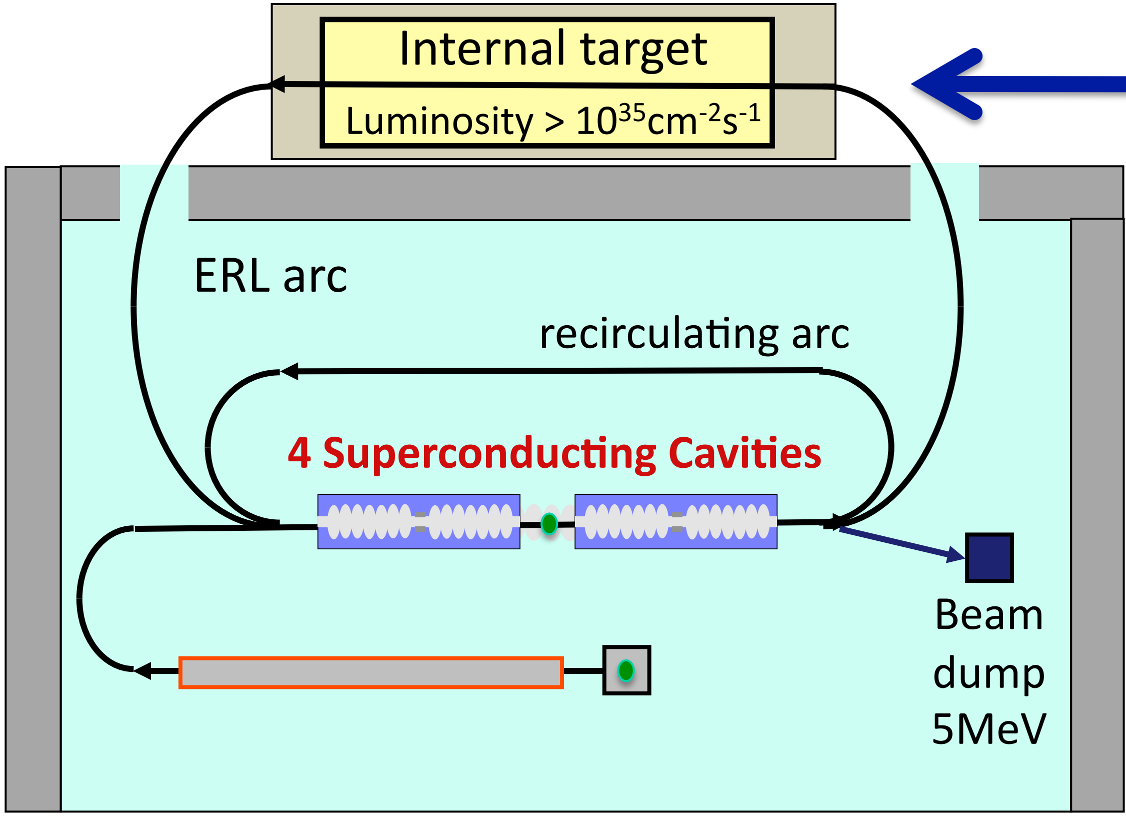
- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current ~100μA → Luminosity ~10^{39} $cm^{-2}s^{-1}$
- Kinematic configuration: - complete energy transfer to γ' boson
  - symmetric e^- and e^+ momenta
- Cerenkov detector for electron/positron identification





Internal Target Experiments at MESA

Energy-Recovering (ERL) mode:
105 MeV beam energy @ 10 mA



Projects:

- **Dark Photon**
- **Proton Radius**
- **Nuclear physics**
- **.....**

A Low-Q^2 Measurement of $\sin^2\theta_W$ at MESA

Scattering of longitudinally polarized electrons on protons

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

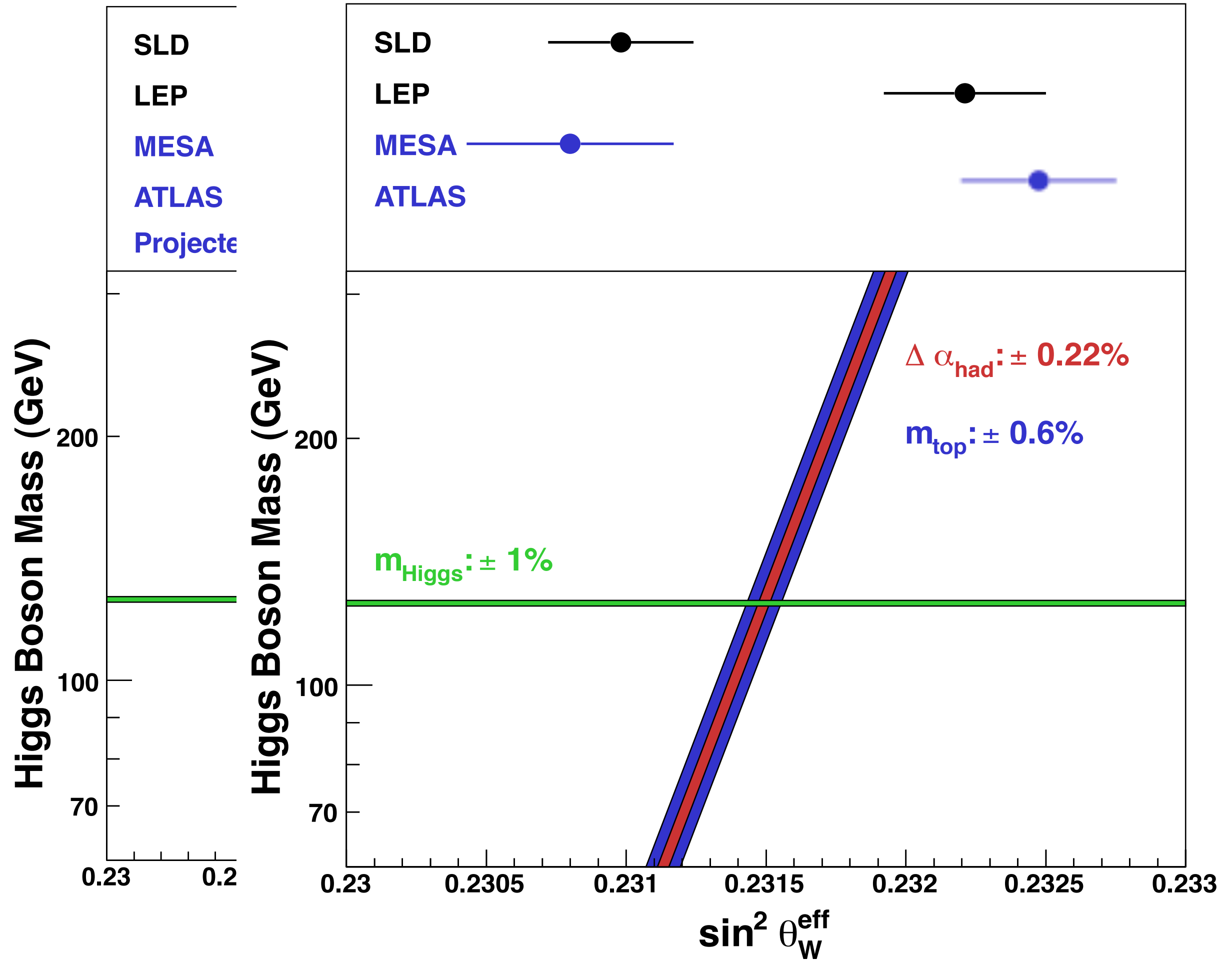
→ Measure **parity-violating Left-Right cross section asymmetry A_{LR}**

Possible Scenarios 2017+

Scenario: **Scenario:**

Metastable universe → No Physics beyond the SM

Physics beyond the SM



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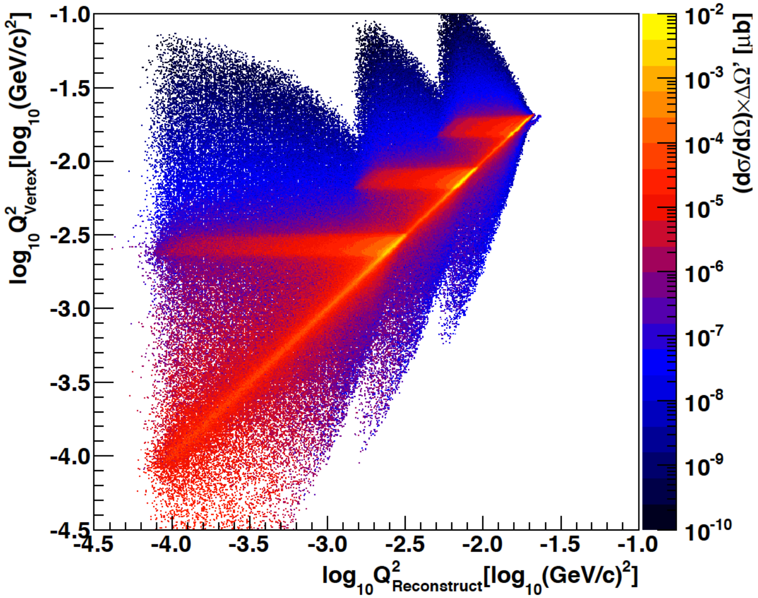

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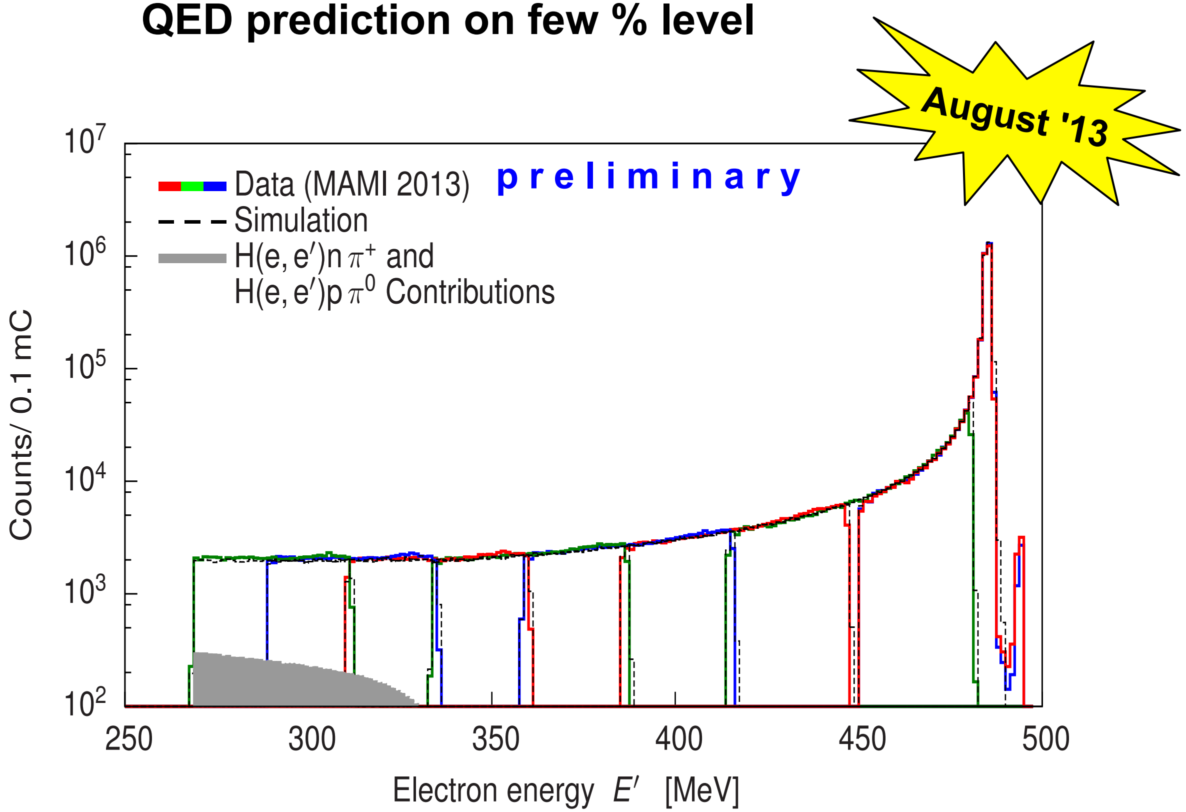

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$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

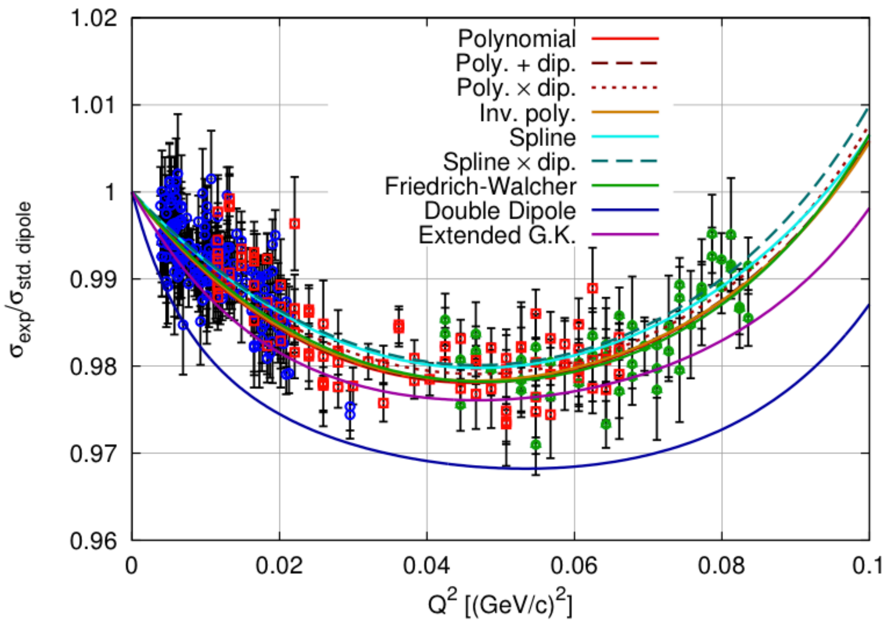
$$\tau = \frac{Q^2}{4m_p^2}$$

G_E: spatial electric charge distribution

G_M: distribution of magnetic moments

Super-Rosenbluth measurement (MAMI B):

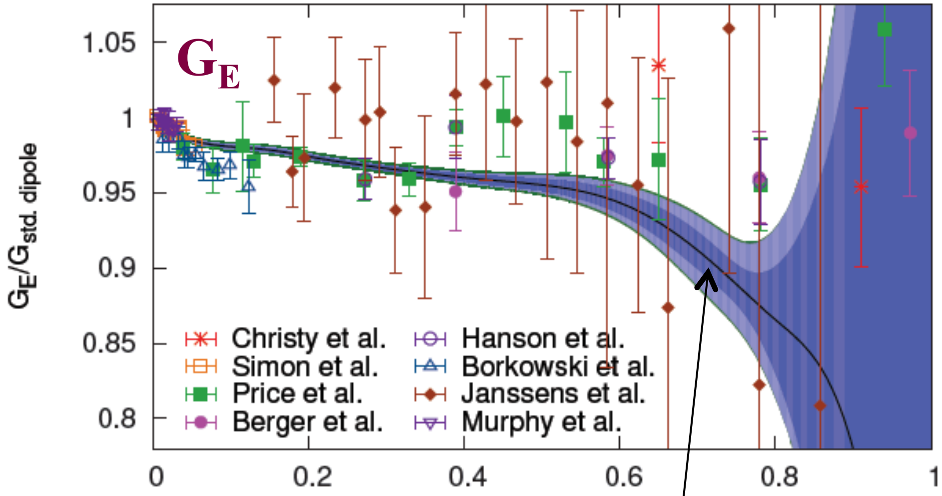
- Fit of form factor **directly** to cross section
- Extreme **redundance** in kinematics
  → all Q^2 and ε values in one fit
- **Systematic issues** (e.g. luminosity) independantly cross checked
- Various **fit functions** for form factors

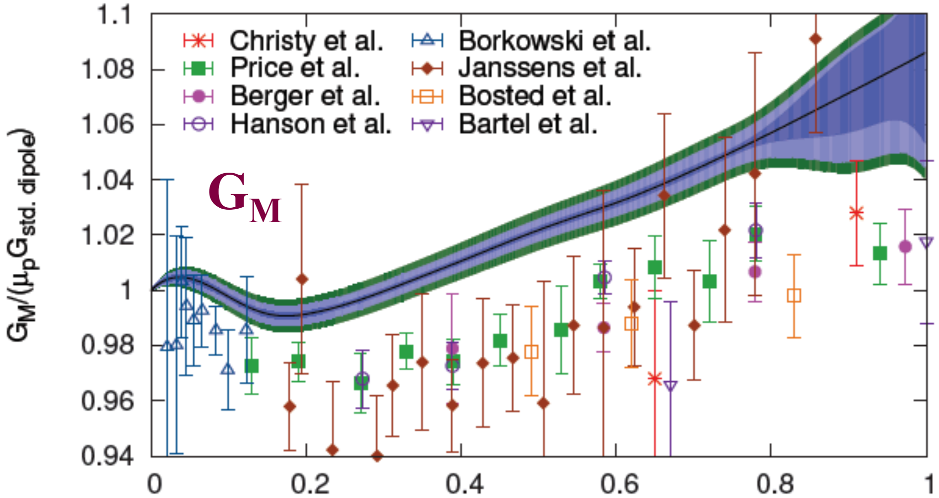


PRL '10, 242001: Bernauer et al.
arXiv 1307:6227: new technical paper

EM Form Factors of the Proton

Full Q^2 range





average of all fit models
with uncertainties

Proton radius:

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

PRL10 (A1): <r_E> = 0,879(8) fm

1307:6227 (incl. world data set e- scatt.)

<r_E> = 0,879(8) fm

EM Form Factors of the Proton

Basics

- The cross section in terms of G's has no interference terms:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta_{e'}}{2}\right)} \frac{E'}{E_0} \left\{ \frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta_{e'}}{2}\right) \right\}$$

Dividing kinematic factors out yields the reduced cross section convenient for 'Rosenbluth separations' for X(e,e'):

$$\sigma_R \equiv \tau G_M^2 + \varepsilon G_E^2$$

$$\tau \equiv \frac{Q^2}{4M^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_{e'}}{2}\right)\right]^{-1} \qquad Q^2 = 4EE'\sin^2\left(\frac{\theta_{e'}}{2}\right) + m_e^2 \quad (= -q^2)$$