CRC1044

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PRISMA Cluster of Excellence
Collaborative Research Center CRC-1044
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MESA: Precision Physics at Low-Energy High-Intensity Accelerators

December 11, 2012
DESY Seminar Hamburg

The Success of the Year 2012

July 2012
Higgs discovery
→ Last particle of the Standard Model discovered

But what about New Physics ?

New Physics is highly motivated

Observations:

- Baryogenesis
- Dark matter
- Neutrino sector

Conceptual:

- Unification of forces
- Gravity not included
- No theory of flavour structure
- Fine tuning for Higgs mass

But what about New Physics ?

2012: No clear indications for New Physics at the LHC

- New Physics **mass exclusion limits up to ~ 1 TeV scale or beyond**
- Indications for **CP violation in the D-meson sector** (compatible with SM?)
- **Rare B-decays** (LHCb):

  → „smoking gun" signals for New Physics in flavour sector found to be in agreement with SM prediction;
  LHCb BR measurement of $B_s \rightarrow \mu^+\mu^-$

Two Long-Standing Puzzles ....

1) **Electroweak mixing angle $\sin^2\theta_W$ (legacy of LEP/SLD era):**
   → discrepancy btw. LEP/CERN and SLC/SLAC

   MESA Impact: PRiSMA

   → Precision measurement of $\sin^2Q_W$ at low energies

   Precision Frontier

2) **Anomalous magnetic moment of the muon $(g\text{-}2)_\mu$**
   → discrepancy btw. SM and direct measurement (3 … 4 σ)

   MAMI / MESA Impact: mami MAINZER MIKROTRON PRiSMA

   → Direct search for MeV … GeV scale New Physics to explain $(g\text{-}2)_\mu$ puzzle: Dark Photons

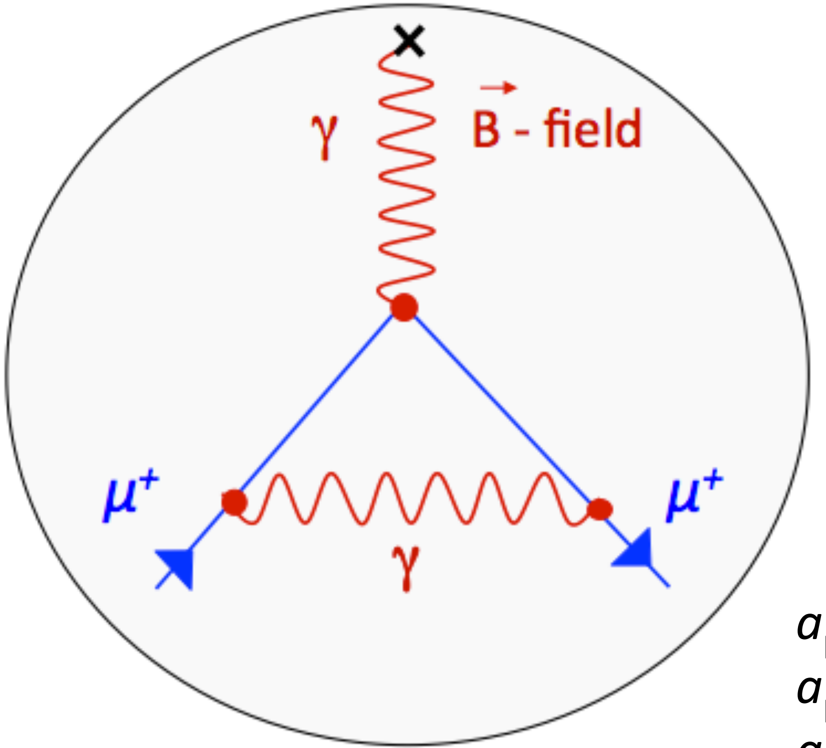
   Discovery Programme

Muon Anomalous Magnetic Moment: $(g\text{-}2)_\mu$

Magnetic Moment: $\vec{\mu} = \mu_B\ g\ \vec{S}$

$a_\mu = (g\text{-}2)_\mu / 2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\ 11\ 659\ 180.2 \pm 4.9\ ) \cdot 10^{-10}$

Davier et al. PRL 2011



$a_\mu^{QED} = (11\ 658\ 471.809 \pm 0.015) \cdot 10^{-10}$

$a_\mu^{weak} = (15.4 \pm 0.2) \cdot 10^{-10}$

$a_\mu^{strong} = (693.0 \pm 4.9) \cdot 10^{-10}$

Muon Anomalous Magnetic Moment: $(g\text{-}2)_\mu$

Magnetic Moment: $\vec{\mu} = \mu_B \; g \; \vec{S}$

$a_\mu = (g\text{-}2)_\mu / 2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,180.2 \pm 4.9\,) \cdot 10^{-10}$

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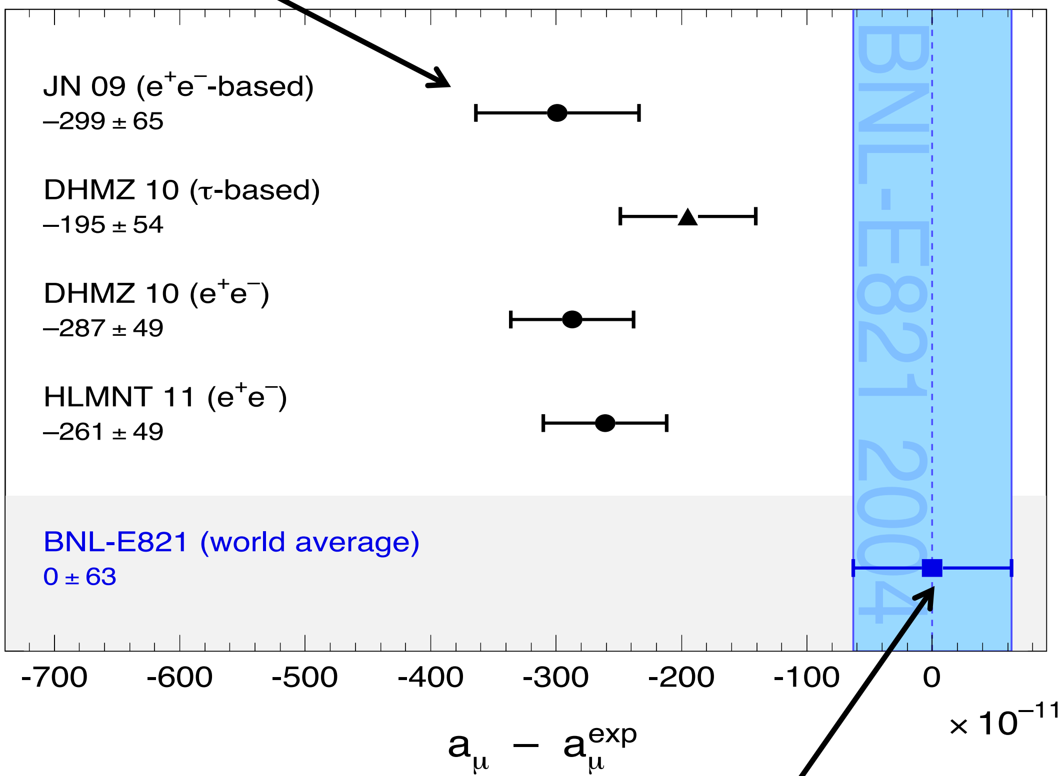


$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$

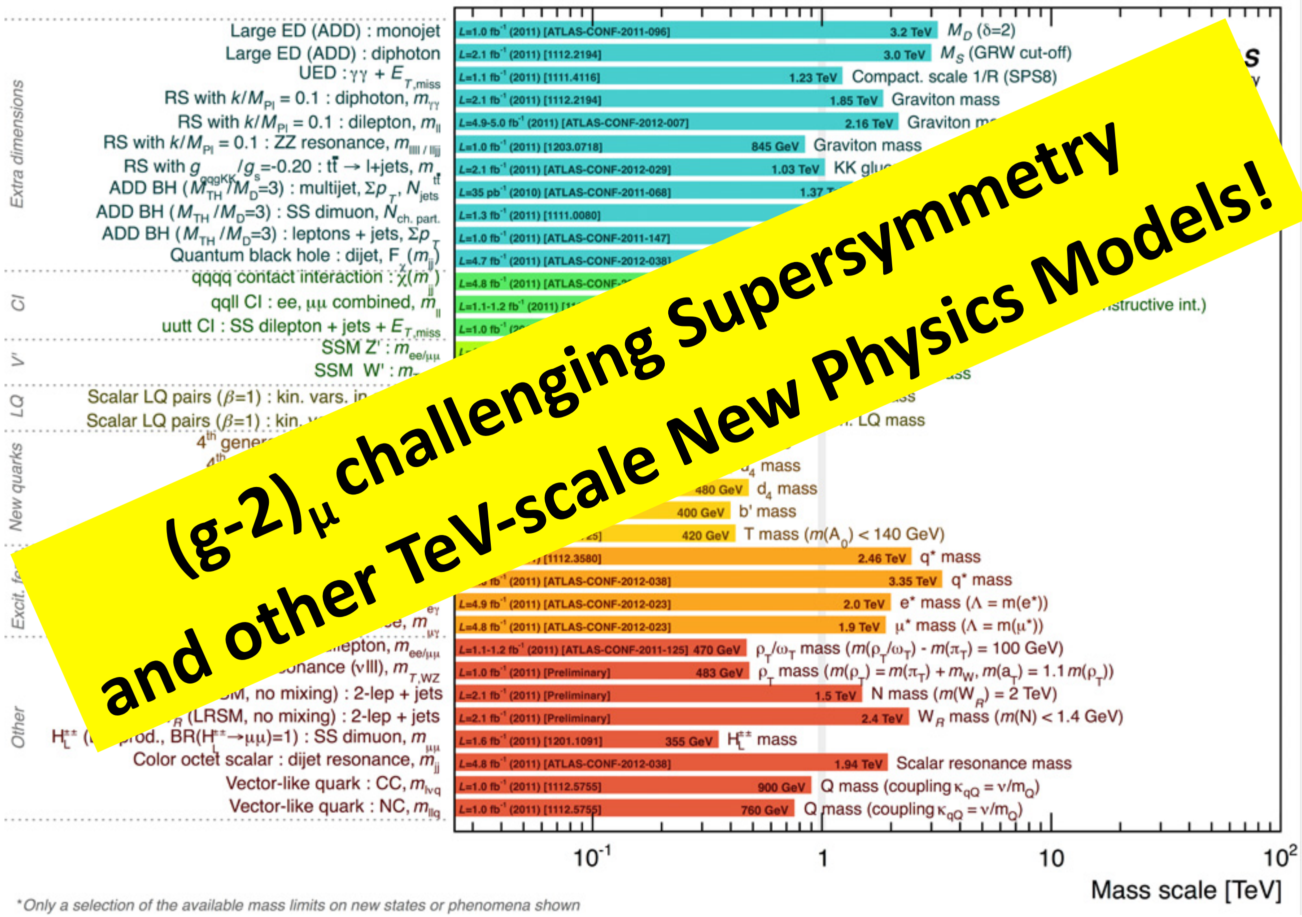
$(28.7 \pm 8.0) \cdot 10^{-10}$ $(3.6\ \sigma)$

Error(s) or New Physics ?

E821 measurement $a_\mu^{exp} = (\,11\,659\,208.9 \pm 6.3\,) \cdot 10^{-10}$

Supersymmetry and (g-2)$_\mu$?

$$\Delta a_\mu^{\text{SUSY}} \approx +13\cdot 10^{-10}\,\text{sgn}(\mu)\left(\frac{100\text{ GeV}}{m_{\text{SUSY}}}\right)^2 \tan\beta \quad = 28 \times 10^{-10}$$



(g-2)$_\mu$ challenging Supersymmetry and other TeV-scale New Physics Models!

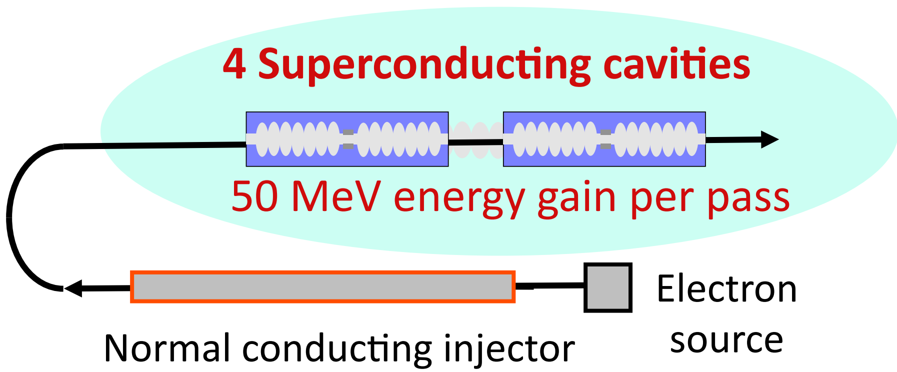
Mainz Energy-Recovering Superconduct. Accelerator

MESA: High-Intensity CW Electron Accelerator
200 MeV @ 10 mA current

PRISMA

- **Experiments in low-energy precision physics**
  - Precision measurement of electroweak mixing angle $\sin^2\Theta_W$
  - Search for the Dark Photon
  - Precision Particle, Hadron, and Nuclear Physics

- **Challenging accelerator project**
  - High-gradient superconducting cavities (1.3 GHz)
  - Energy-Recovering (ERL) technology



A Precision Measurement of $\sin^2\Theta_W$ at MESA

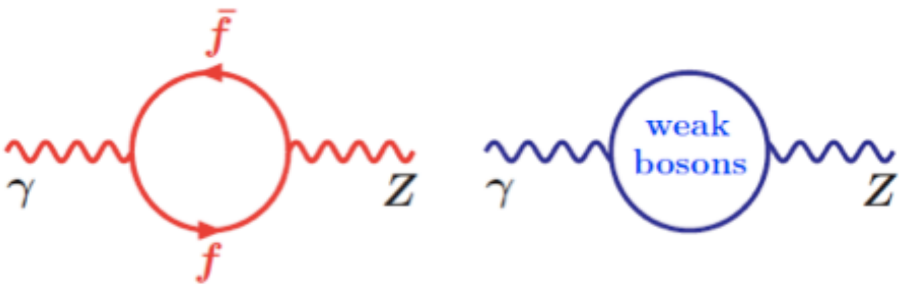
$sin^2\theta_W$ within the Standard Model and Beyond

Probably the key parameter of the SM:
The Electroweak mixing angle θ_W

$$\sin^2\Theta_W = (e/g)^2 = 1 - (M_W/M_Z)^2$$

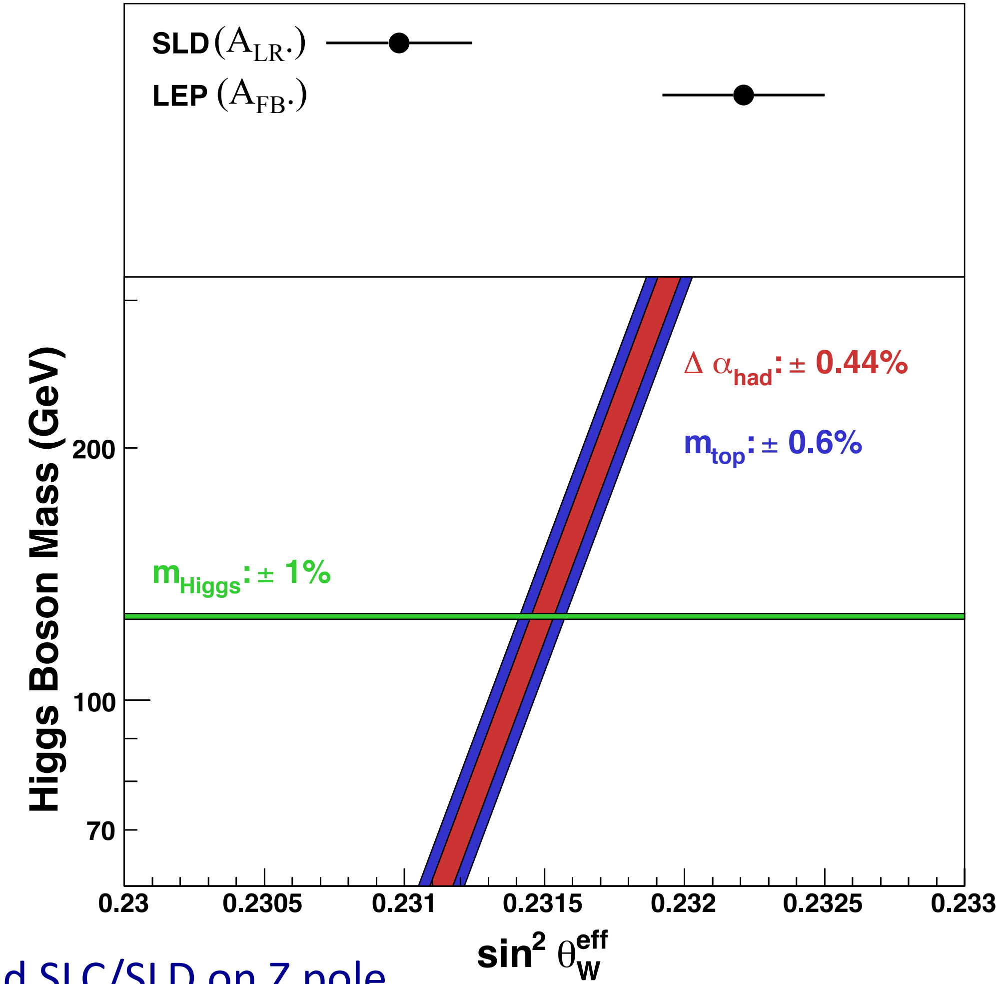
Incorporates:
$SU(2)_L x U(1)_Y$ + Higgs Mechanism+ Renormalizability

Rad. corrections strongly correlated with masses of top quark, Higgs, New Physics!



Low Q^2 → High sensitivity to New Physics

EW Precision Physics after Higgs Discovery



Experimental status:

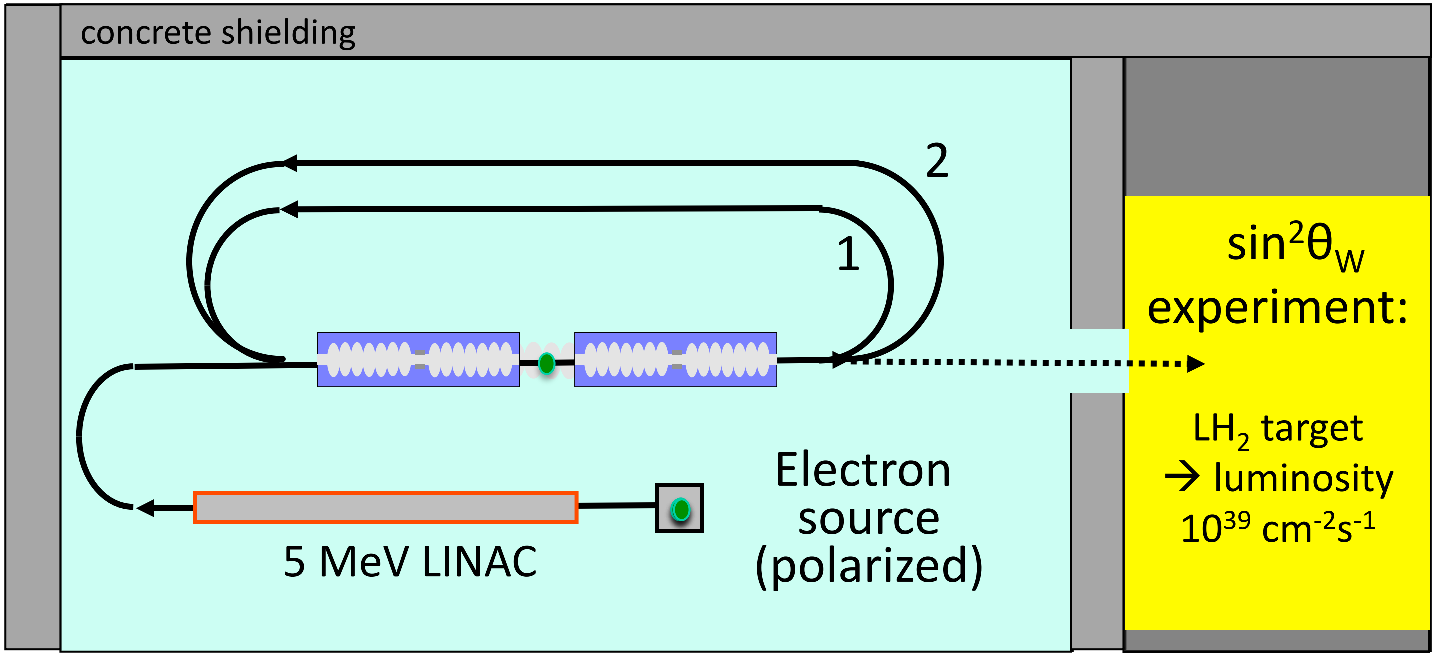
- 2 precision measurement at LEP and SLC/SLD on Z pole
- Low Energy experiments (e-e- , Neutrino scattering, APV)

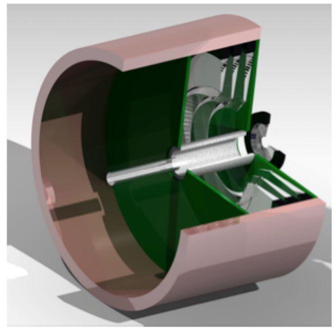
Accelerator MESA (Extracted Beam Mode)

Extracted beam mode:

→ 2 recirculating arcs

→ 155 MeV beam energy @ 150 µA





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

Scattering of longitudinally polarized electrons on unpolarized protons

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

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

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

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

hadron structure

MESA goal:

Measure parity-violating Left-Right asymmetry A_{LR} of 20×10^{-9} with 1.8% precision

Why low beam energies?

→ **Dramatically reduced hadronic uncertainties** from γZ box diagrams (QWEAK 1.2 GeV)

→ At low energies there is a **significantly enhanced sensitivity to resolve New Physics**

Precision Measurement of $\sin^2\Theta_W$

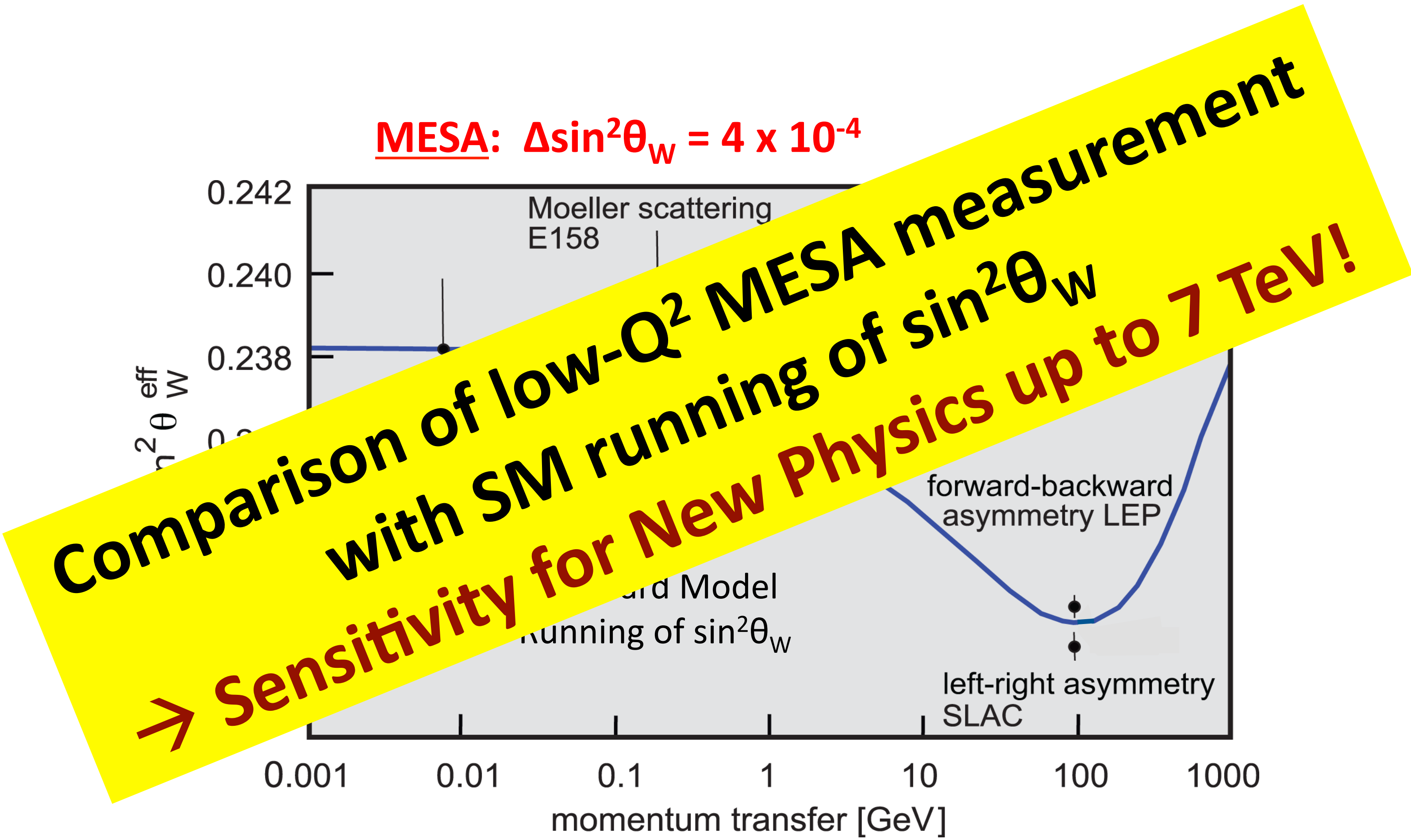
courtesy: Frank Maas

	A4 / MAMI	MESA	Challenge
Asymmetry	1-15 ppm	10-20 ppb	HC beam fluct.
Rates	100 MHz	0.2 - 1 THz	2kHz flipping
Polarimetry	1.5 % (4%)	0.5 %	hydro-Moller
Electronics	Counting	Integrating	18 bit, 500 kHz ADCs
Spectrometer	Calorimeter	Magnetic spectrometer	Solenoid/ Toroid
Liquid H_2 Target	120 W	3.9 kW	beam raster, new target cell

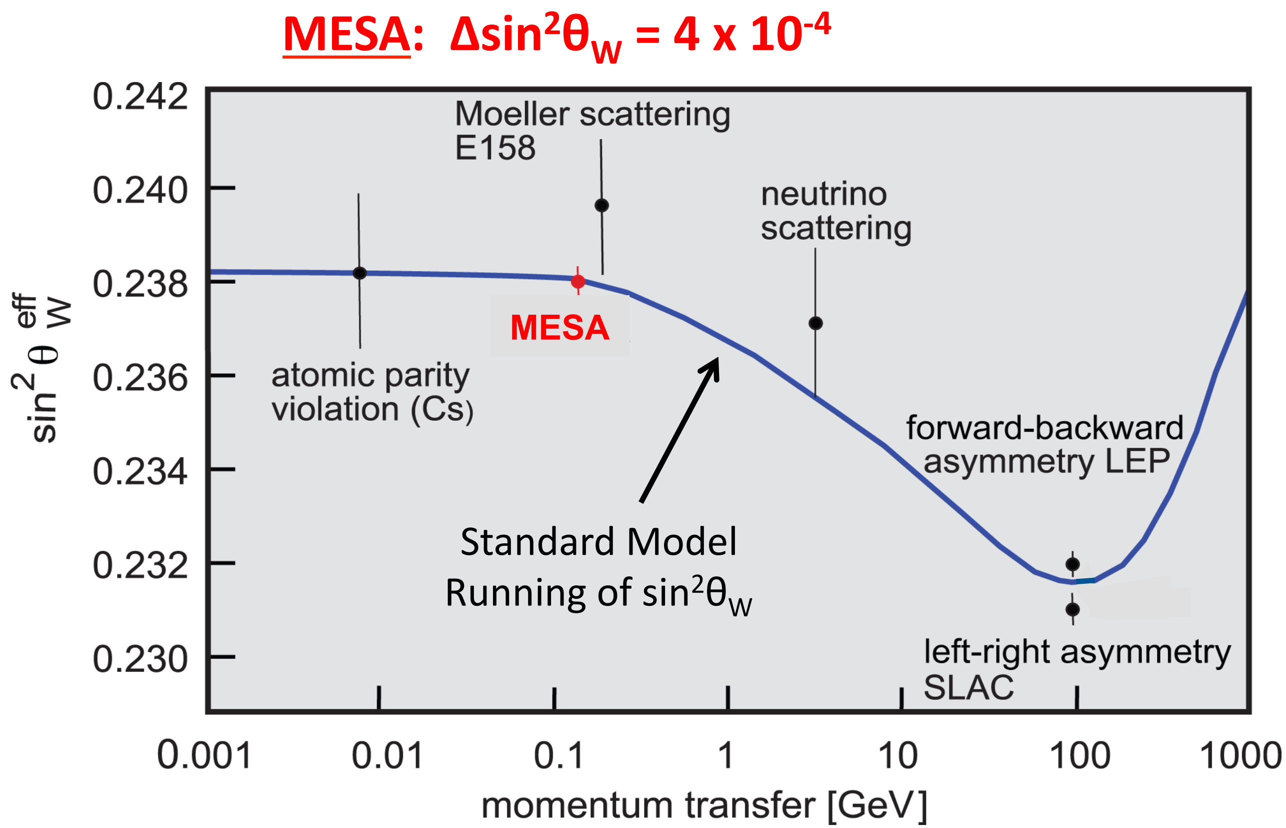
Main challenges

- 15 years of experience in parity-violating e-p measurements (A4@MAMI)
- Strong international collaboration (MØLLER expt.)

MESA contribution to $sin^2\theta_W$

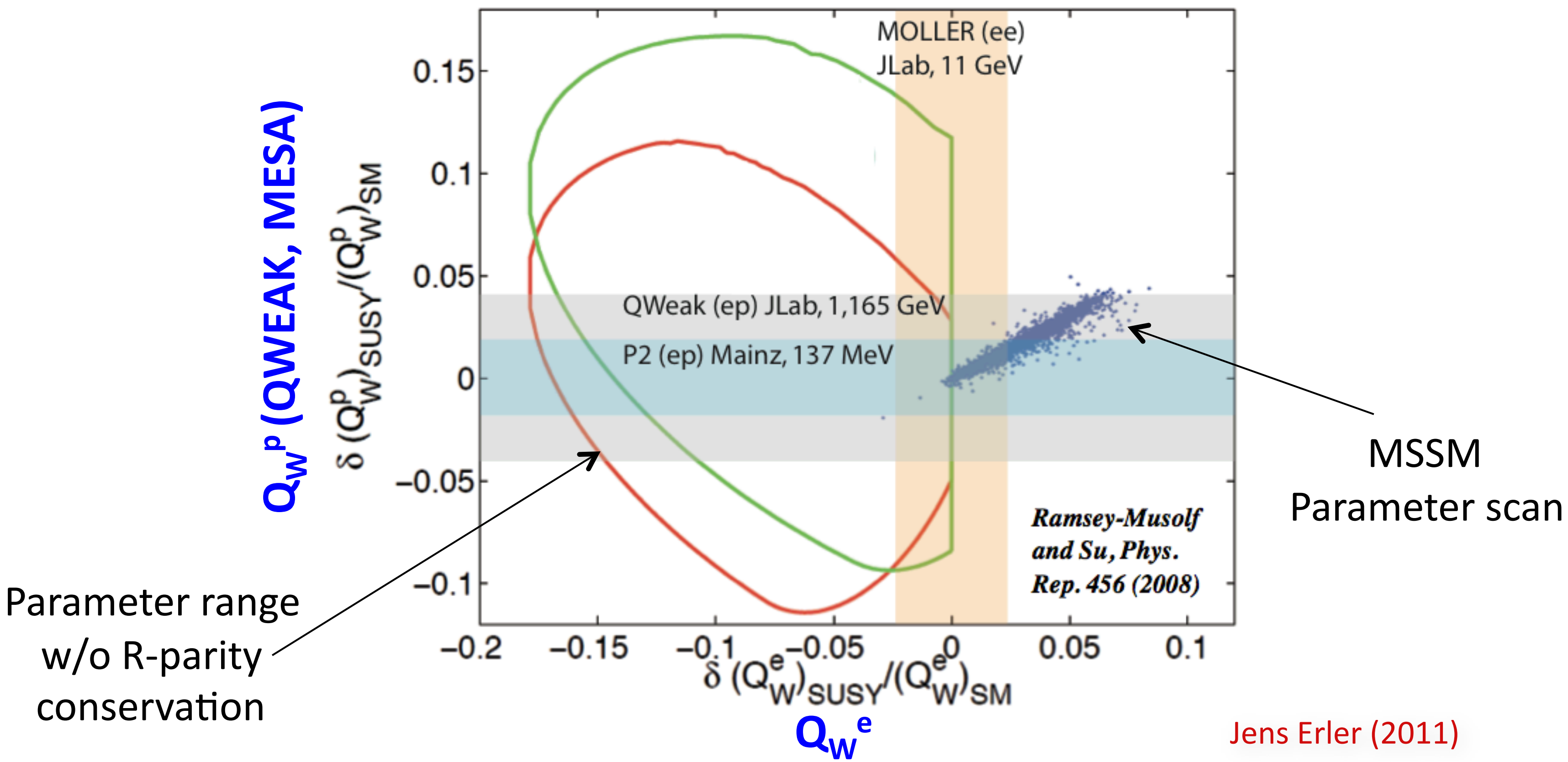


MESA contribution to $sin^2\theta_W$



Complementarity btw. e⁻p and e⁻e⁻ Scattering

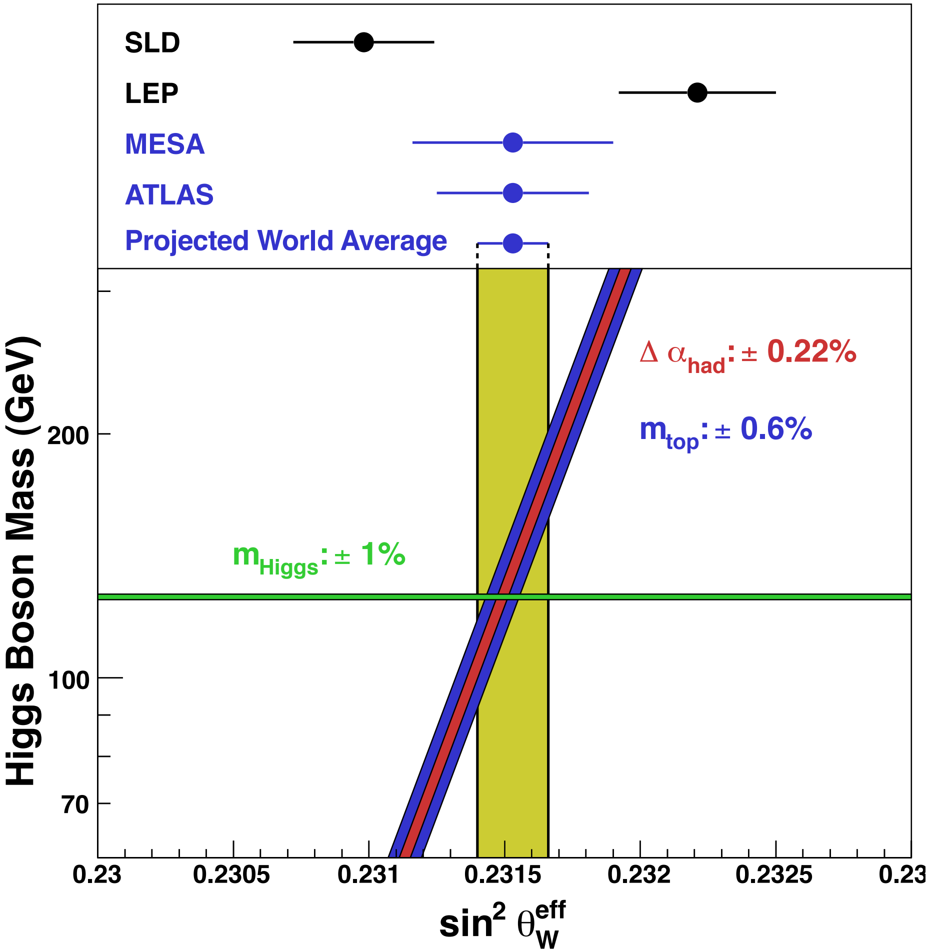
Complementarity btw. Q_W^p (MESA) and future Q_W^e (Moller@JLAB)



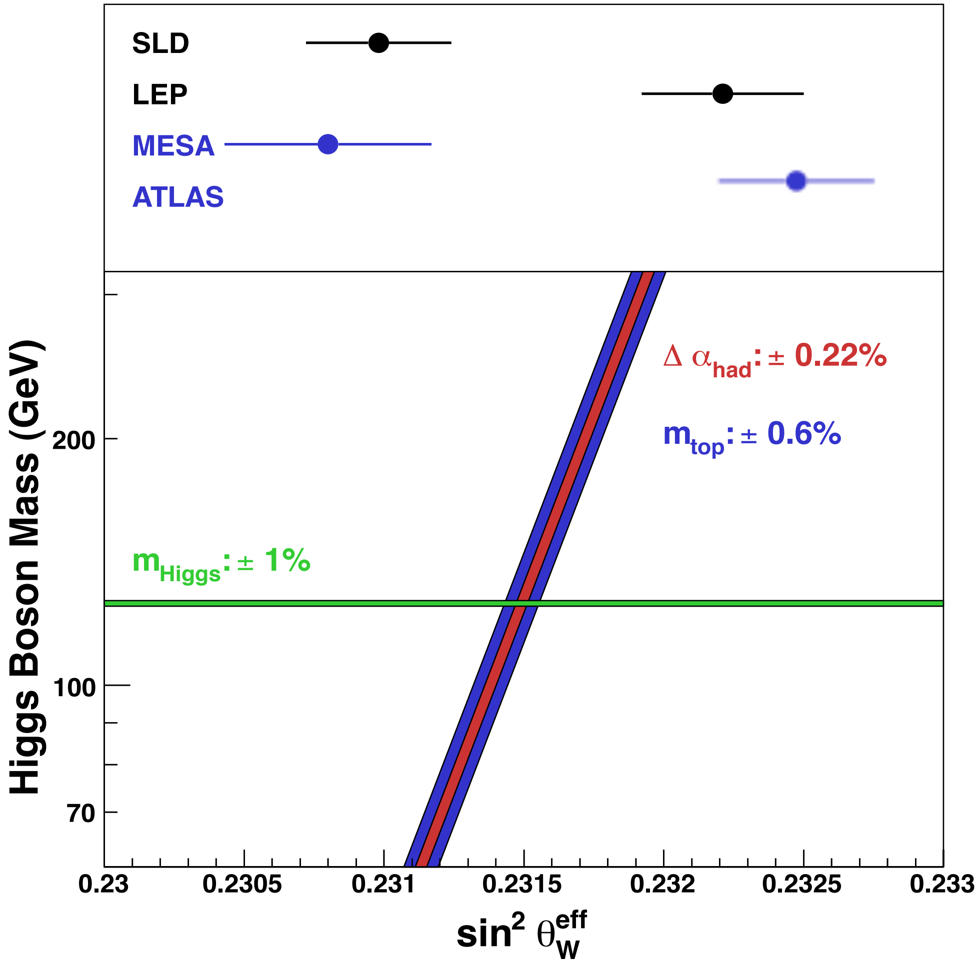
Jens Erler (2011)

Possible Scenarios 2016+

Scenario:
No physics beyond the SM



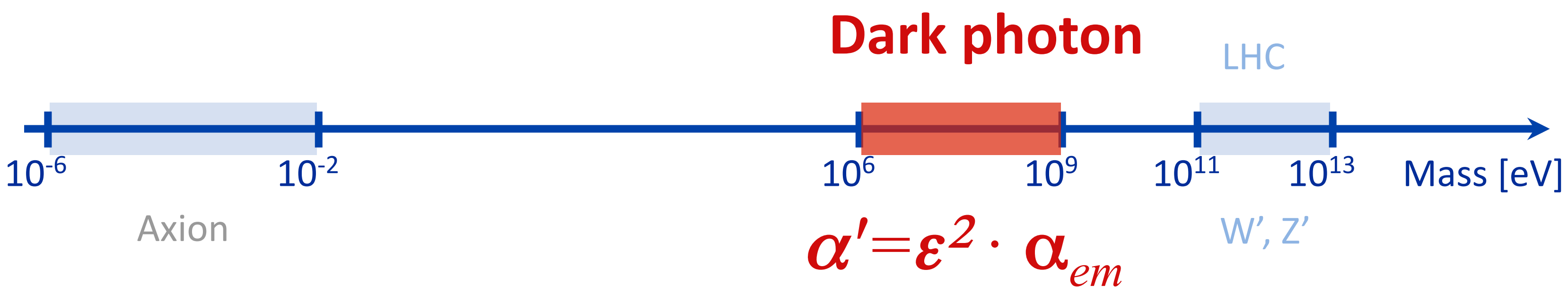
Scenario:
Physics beyond the SM



A Search for the Dark Photon at MAMI and MESA

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)

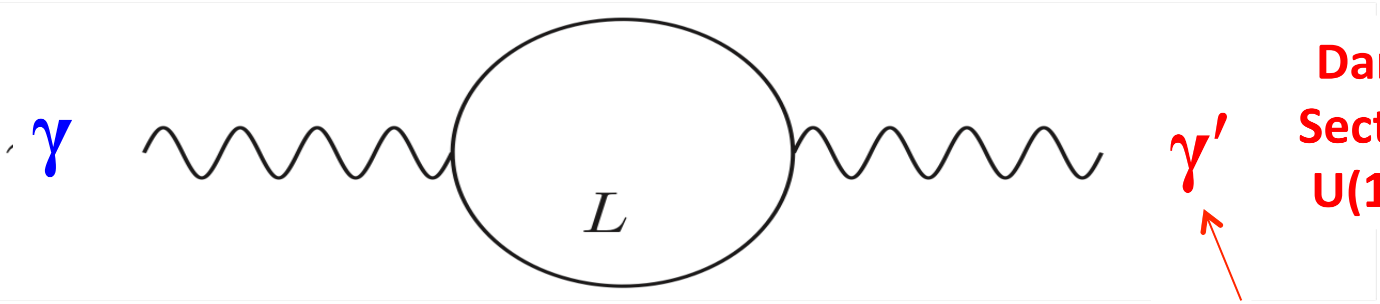
- Could explain presently seen **deviation of 3.6σ between $(g-2)_\mu$** Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov(2008)

Kinetic Mixing and Dark Matter

Holdom [1986]

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

Standard Model Sector U(1)



Dark Sector $U(1)_d$

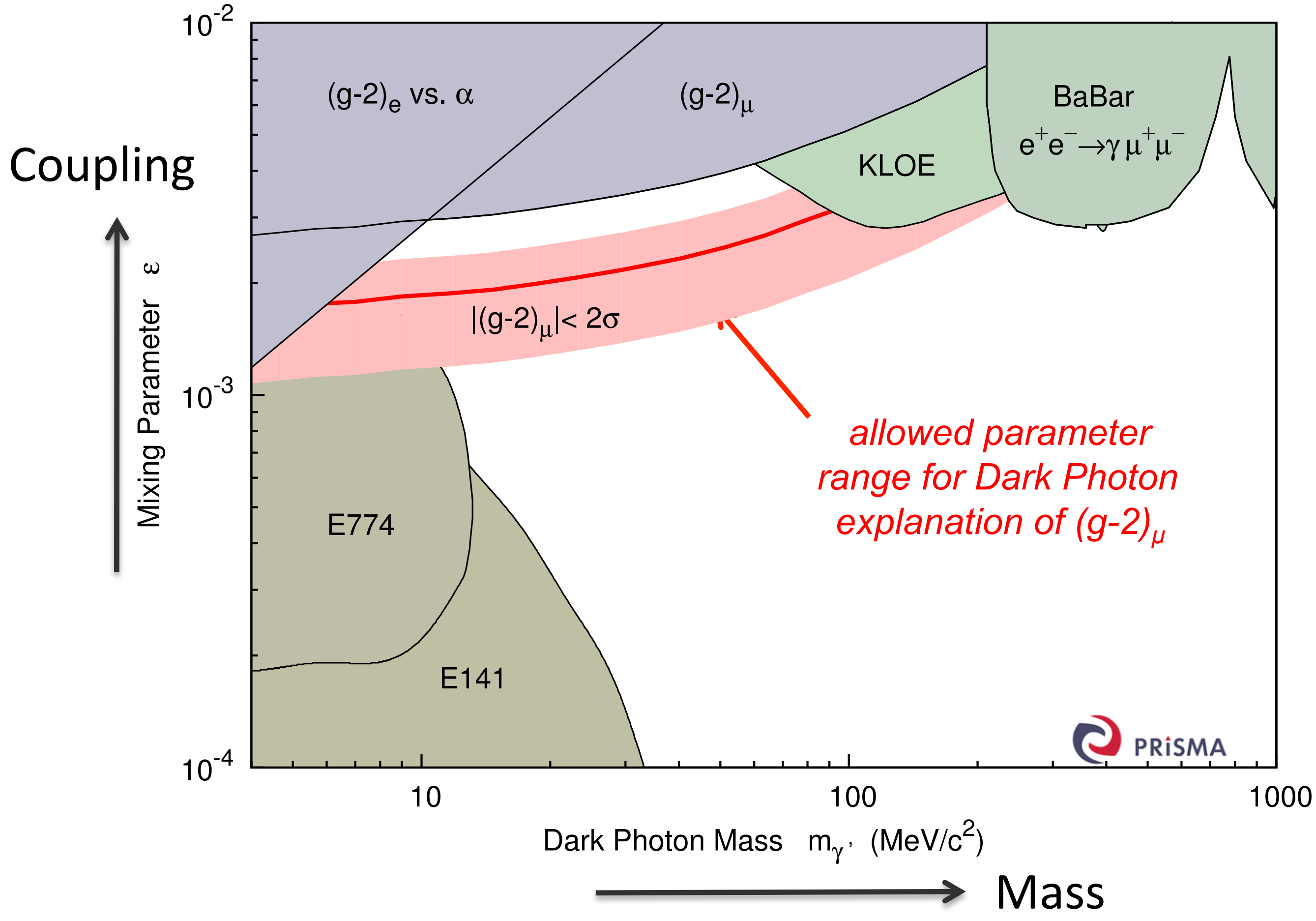
Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

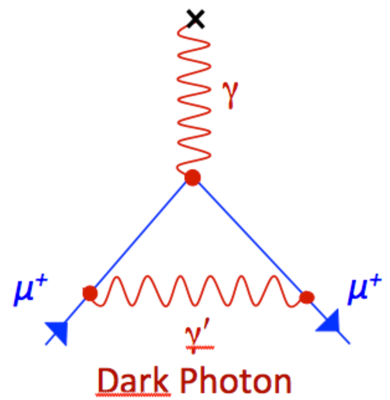
Dark Photon
(aka A′, U, Z_d, ...)

Features à la Arkani-Hamed: A theory of Dark Matter

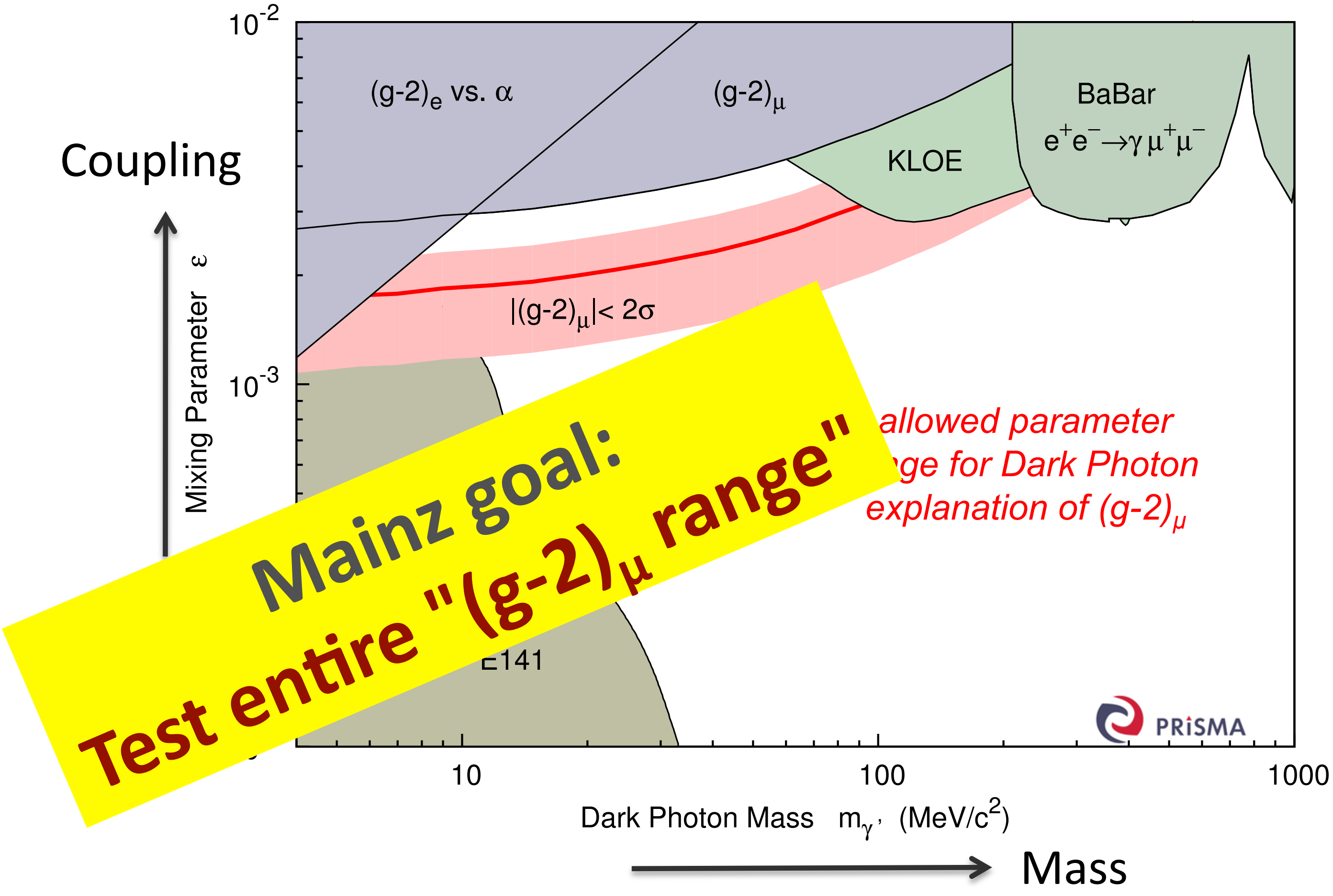
- More than one Dark Matter particle → Dark Sector
- dm + dm → e+e- explains positron excess
- Astrophysical anomalies (PAMELA, FERMI, DAMA/LIBRA, INTEGRAL, ...) suggest dark photon mass on GeV mass scala (and lighter than $2M_p$)
- Dark Matter annihilation enhanced by γ′ exchange

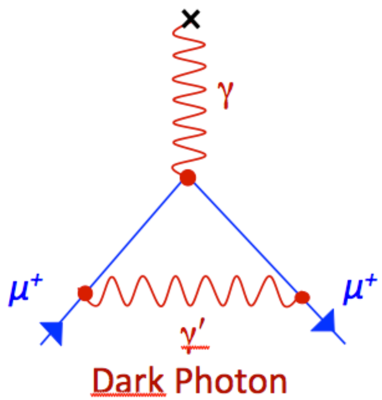
The $(g\text{-}2)_\mu$ Parameter Range





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





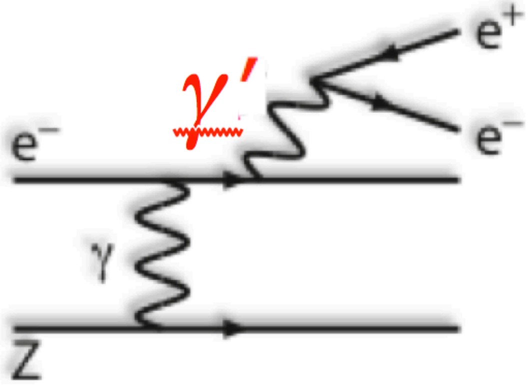
Searches using Fixed-Target Experiments

Bjorken, Essig, Schuster, Toro (2009)

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

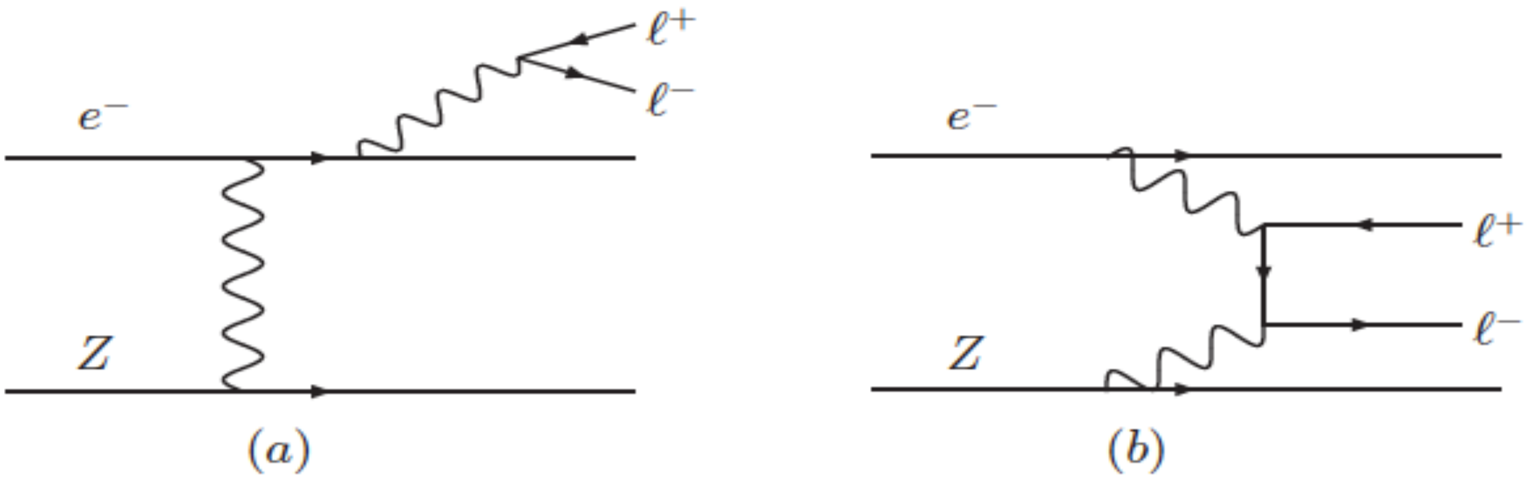
→ MAMI: E_γ < 1.6 GeV

→ A1 spectrometer setup



m_{e+e-}

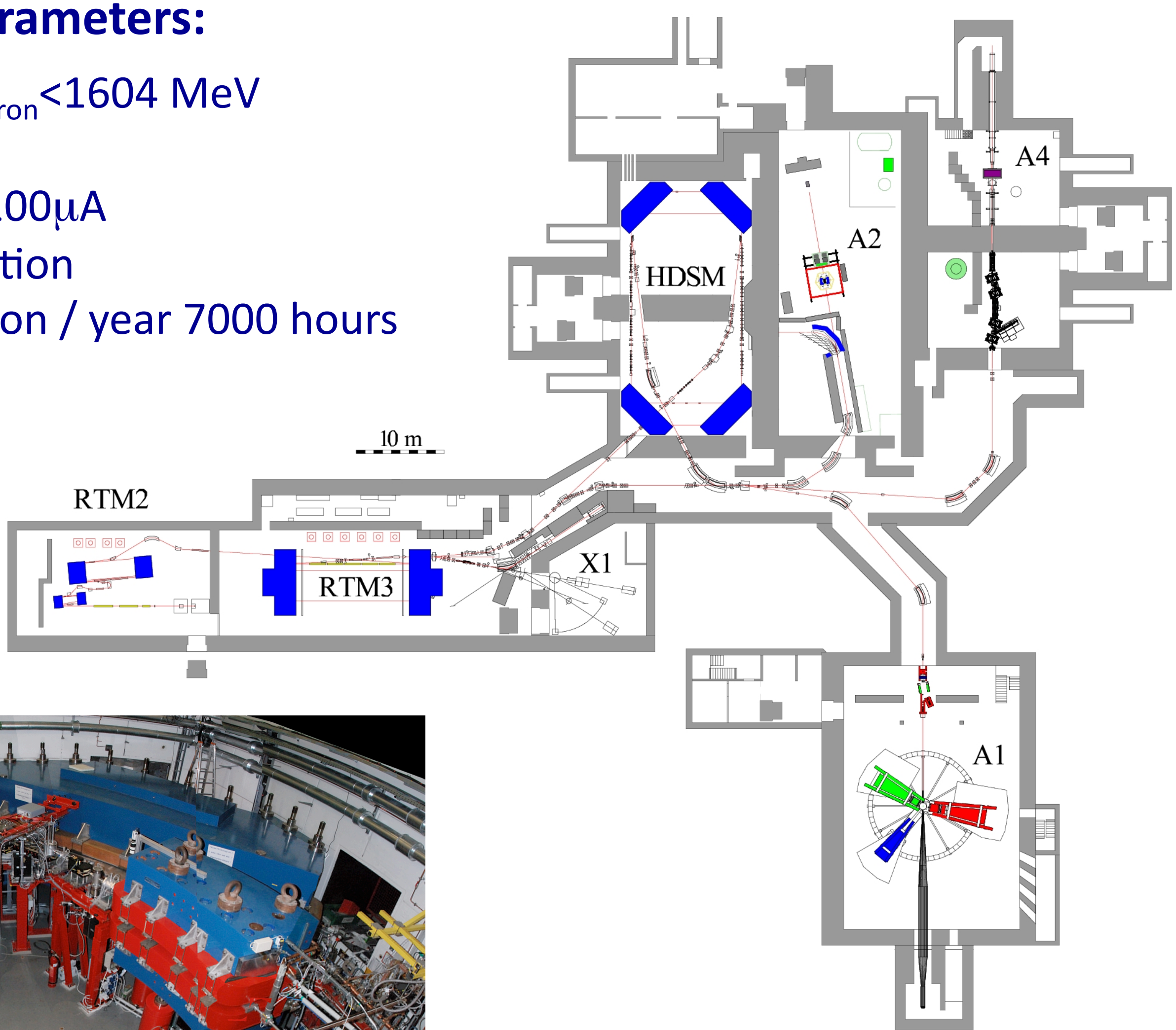
QED background processes:

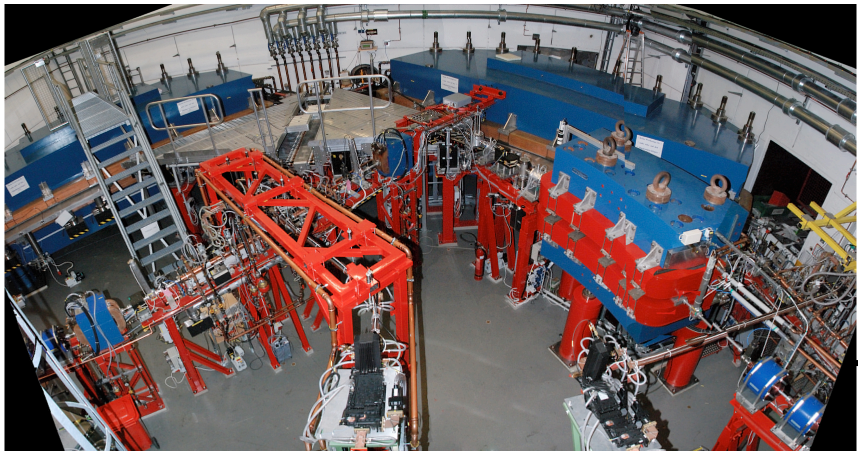


1.6 GeV Electron Accelerator MAMI

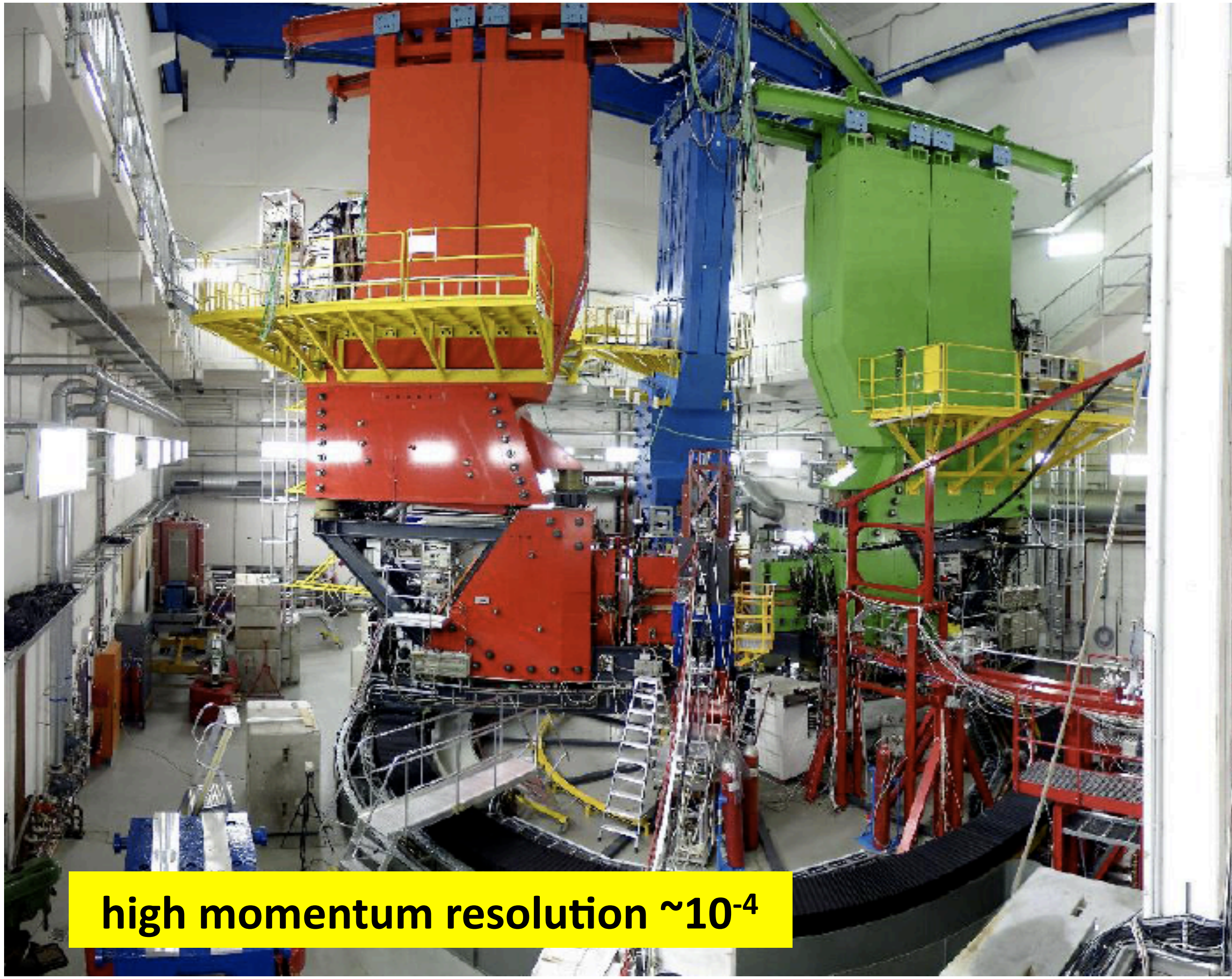
MAMI beam parameters:

- 180 MeV < $E_{electron}$<1604 MeV
- σ_E<0.100MeV
- Intensity up to 100μA
- ca. 80% Polarization
- hours of operation / year 7000 hours





A1 High Resolution Spectrometers



Spektrometer A:

$$\alpha > 20^\circ$$
$$p < 735\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 28\,\text{msr}$$
$$\Delta p/p = 20\%$$

Spektrometer B:

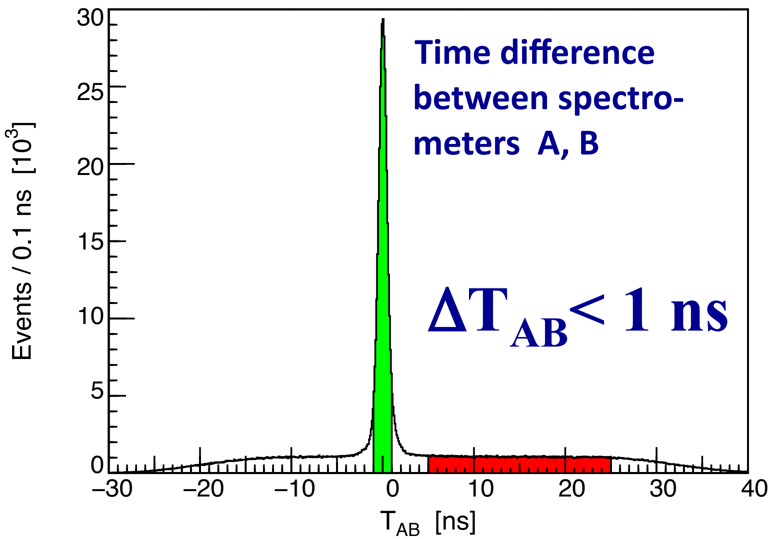
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

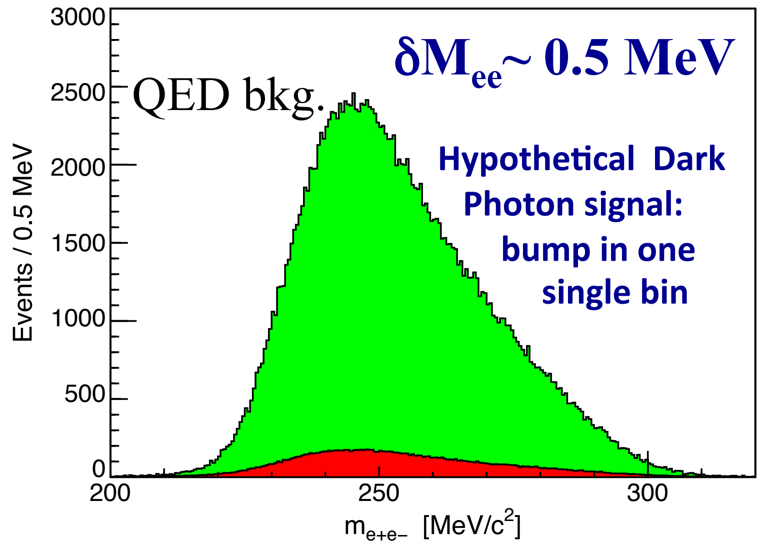
Dark Photon Search @ A1

2010 pilot run with A1/MAMI

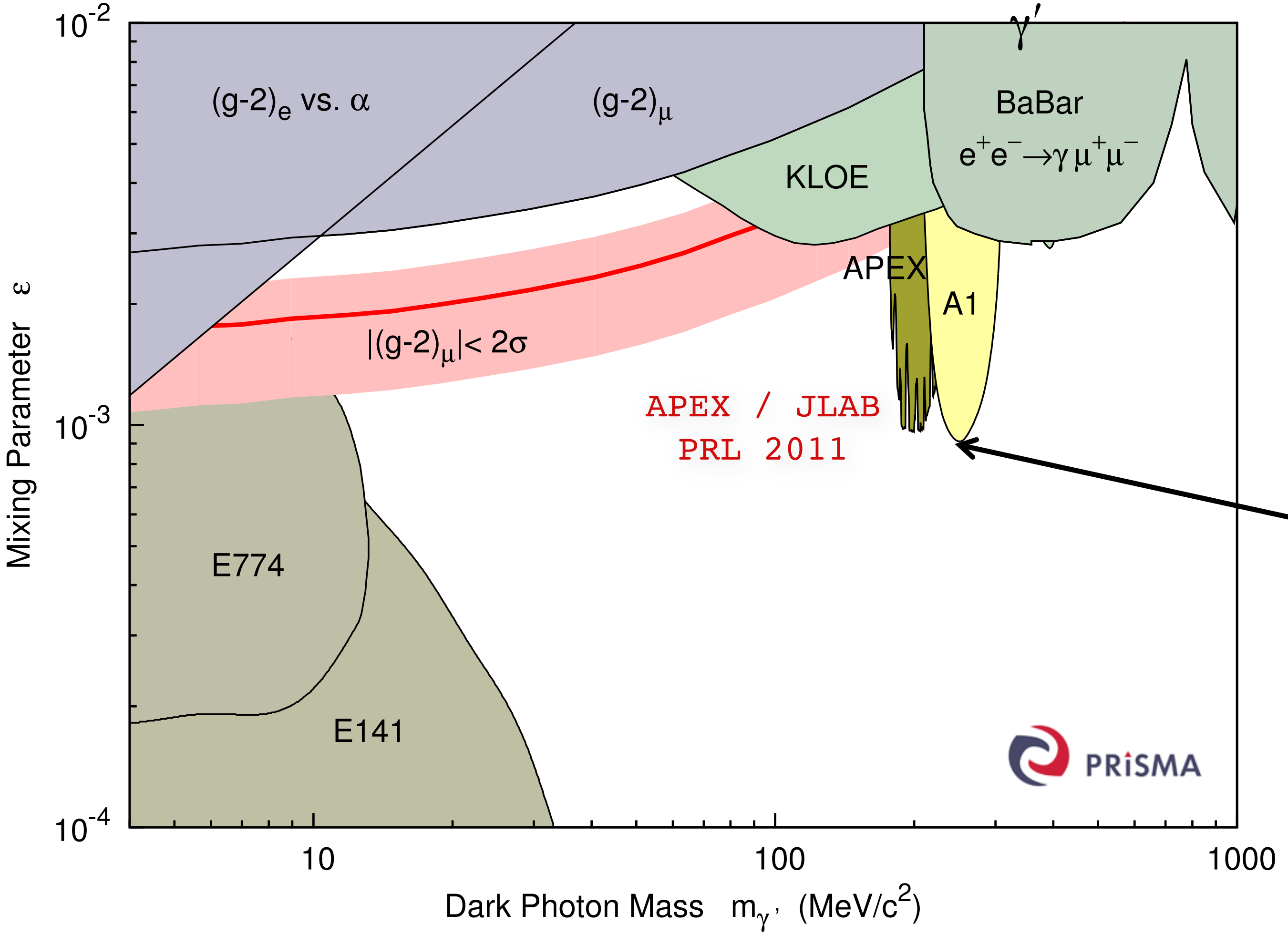
- 4 days of data taking
- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current ~100µA

  → **Luminosity ~10^{39} $cm^{-2}s^{-1}$**





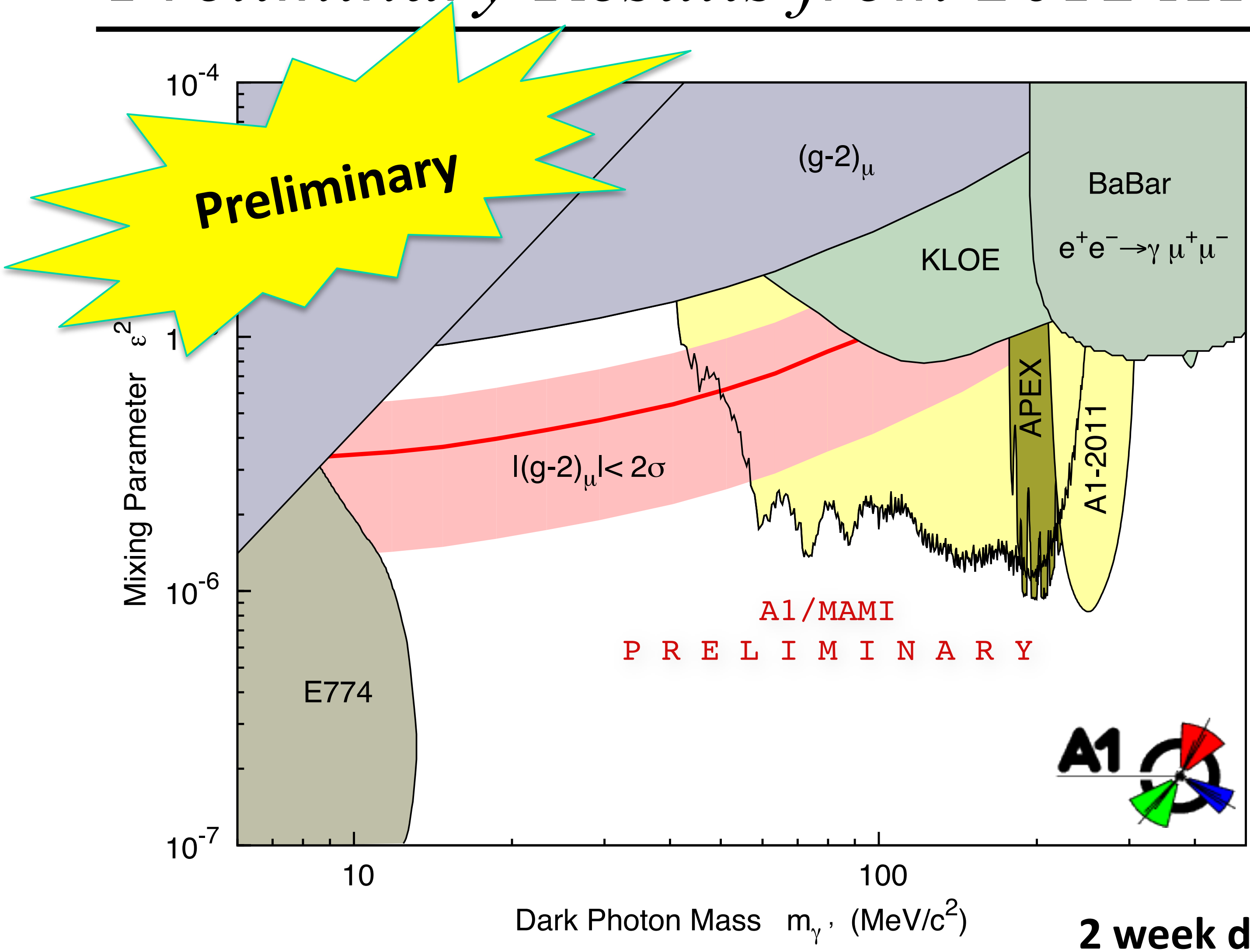
Results from A1 Pilot Run (2010)



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

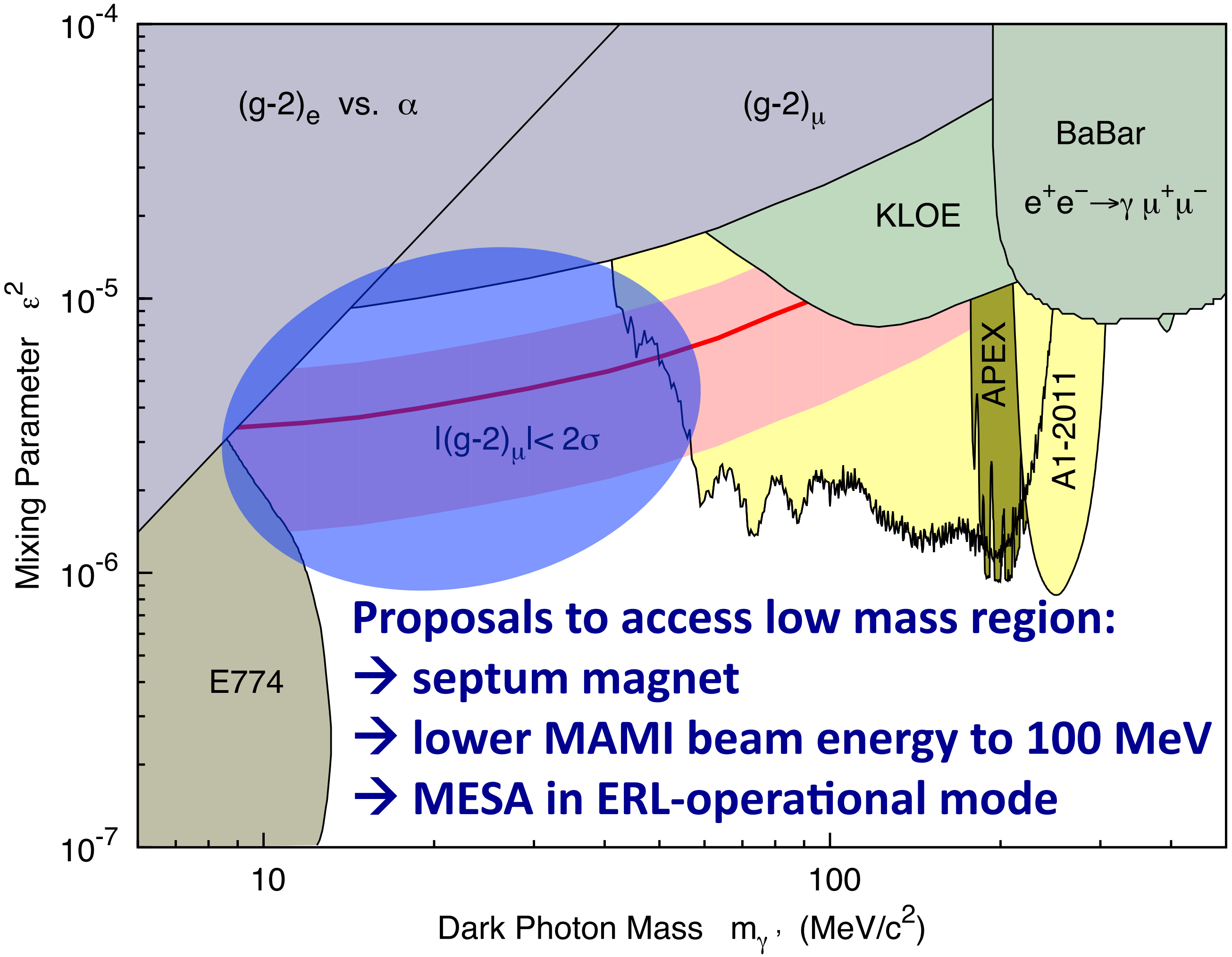
A1/MAMI
Merkel et al. PRL 2011

Preliminary Results from 2012 A1-Run



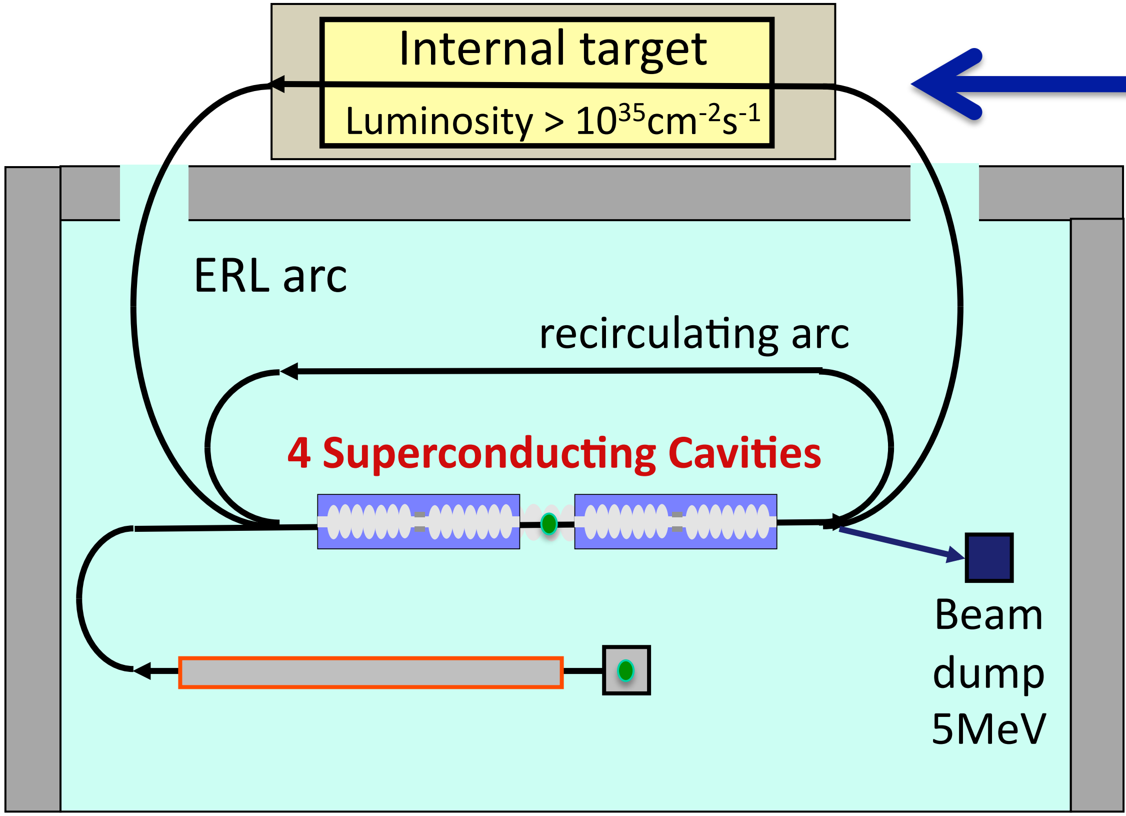
2 week data taking limited by rate of DCH readout!

Phase 2: Accessing the Low Mass Region



Accelerator MESA (ERL mode)

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



ERL mode: A novel exptl. technique

Projects:

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

Workshop to Explore Physics Opportunities with Intense, Polarized Electron beams with Energy up to 300 MeV

MIT, Cambridge, MA
March 14-16, 2013

With the availability of intense, polarized linac beams in the energy range up to 300 MeV, new types of experiments can be considered. The workshop is open to all good ideas but we solicit abstracts in the following categories:

- Parity violating electron scattering at low Q^2
- Search for dark photons
- Precision nucleon structure
- Nuclear physics, inc. astrophysical reactions
- Technology: facilities, high power targets, high intensity polarized electron sources, precision electron polarimetry, optimized detectors and high brightness beam diagnostics

Organizing Committee:

Kurt Aulenbacher (U. Mainz)
Roger Carlini (JLab) (Co-chair)
Achim Denig (U. Mainz)
Roy Holt (ANL)
Peter Fisher (MIT)
Krishna Kumar (UMass, Amherst)
Frank Maas (U. Mainz) (Co-chair)
Bill Marciano (BNL)
Richard Milner (MIT) (Co-chair)
George Neil (JLab)
Marc Vanderhaeghen (U. Mainz)

For information contact:

http://web.mit.edu/lns/PEB_Workshop/
Email: *pebworkshop@mit.edu*

Supported by: MIT PRiSMA Jefferson Lab Thomas Jefferson National Accelerator Facility

Conclusions

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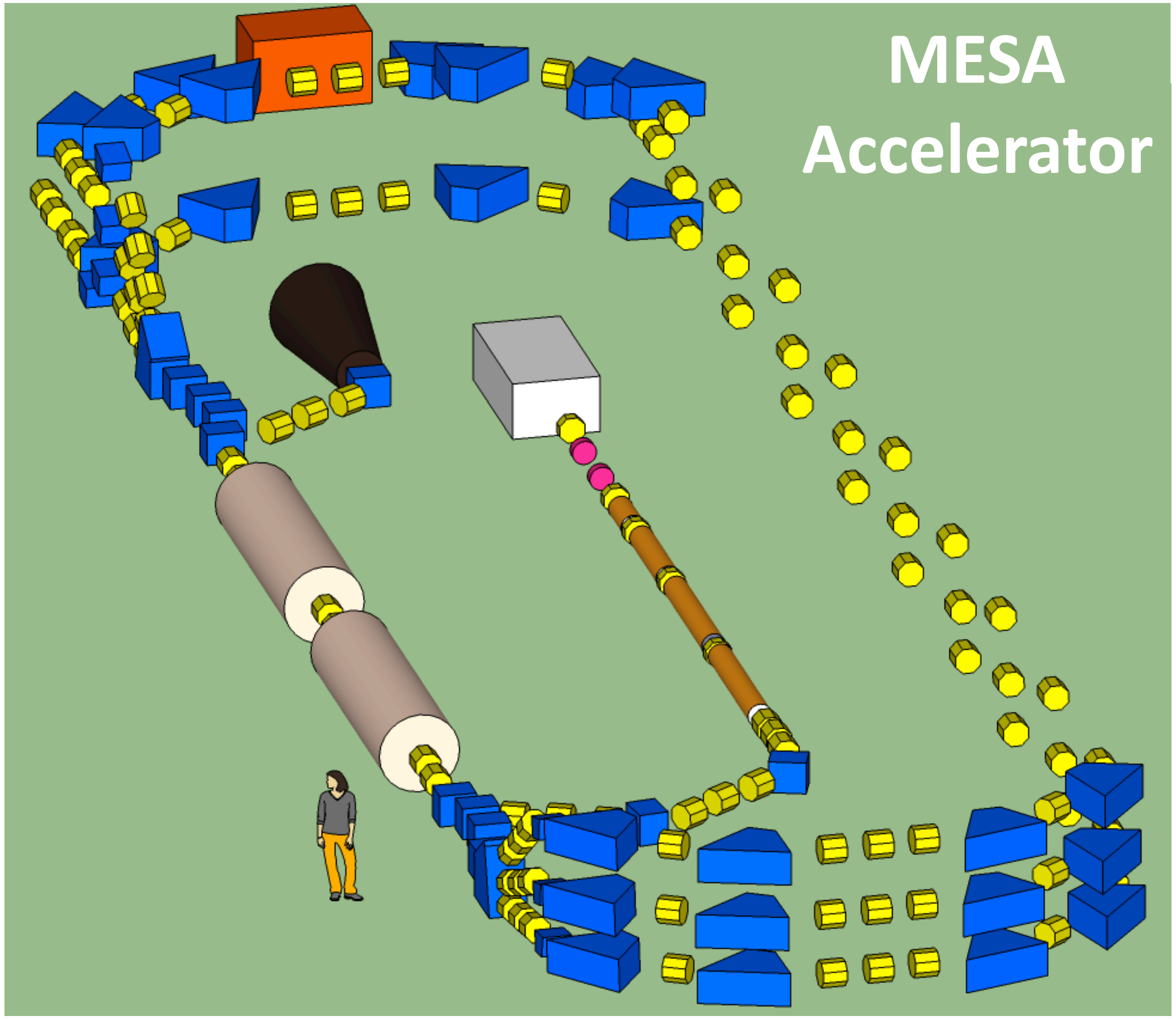
INTENSITY FRONTIER :
Complementary program in the LHC era

- **$\sin^2\theta_W$: Frontier program in electroweak precision physics**
  - Sensitivity to New Physics up to 7 TeV
- **Dark Photon: Fundamental discovery potential**
  - High-risk - high-gain experiment
- **Hadron and nuclear physics program at MESA**
  - Proton radius
  - Strangeness content of the nucleon
  - Neutron skin of nuclei

Can be done with MESA: 200 MeV Electron Accelerator



JG|U

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PRiSMA

W3 professorship
Experimental Hadron and
Particle Physics

" MESA: A must-do facility … for the price of an experiment "

(B. Marciano, 2011 MESA workshop)