Low-energy Direct Searches for Dark Photons

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for the A1 collaboration @ MAMI

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“Mainz MAMI”

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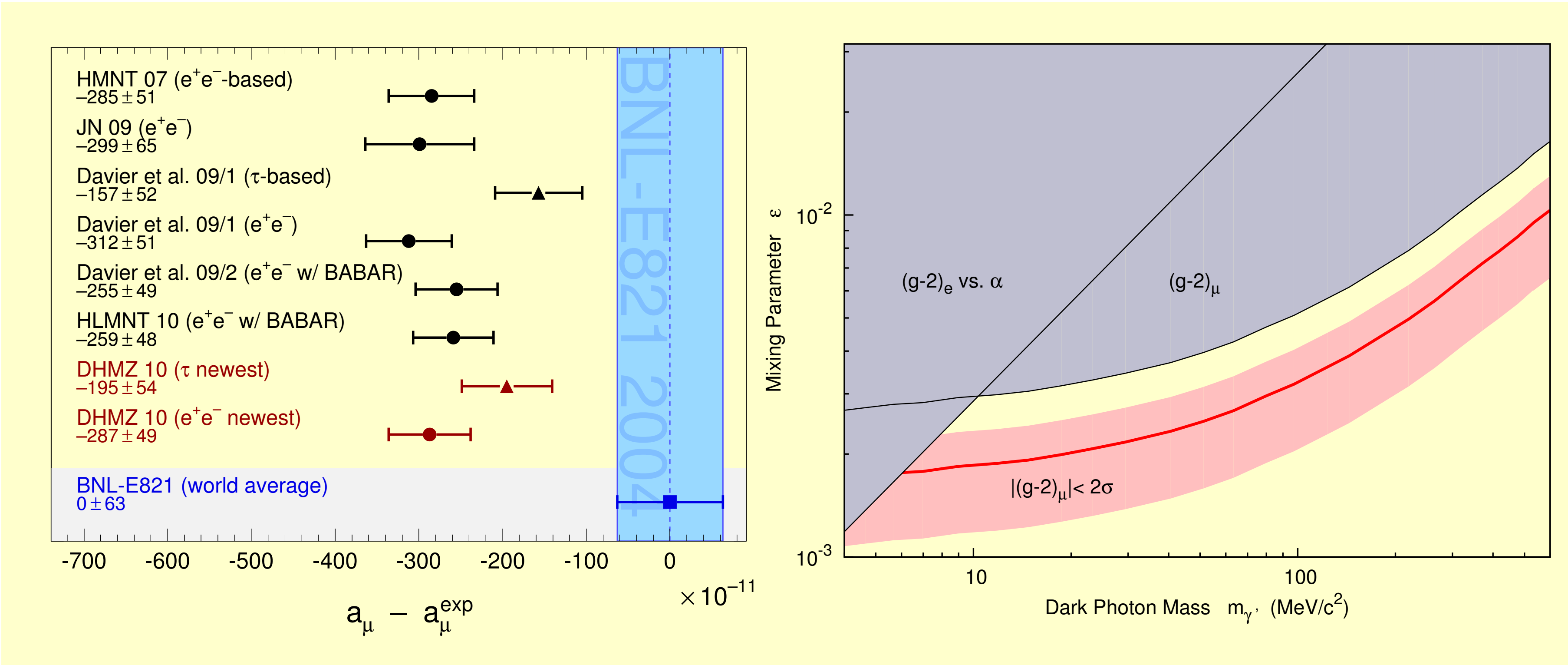
- A few reminders
- How can we detect a “Dark Photon”?
  - Di-Lepton-Production
  - Cross sections
- Pilot Experiment at the Mainz Microtron (MAMI)
  - Experiment
  - Results
- Summary and Outlook

most slides: courtesy of Harald Merkel

Location of Mainz, Germany

Location of Mainz, Germany

Anomalous magnetic moment of the muon



- Precision measurement of $(g-2)$ of the muon at BNL
- Significant discrepancy with Standard Model calculations
- Possible explanation: Additional $U(1)$ boson γ'

G. W. Bennet *et al.*, Phys. Rev. **D73** (2006) 072003
M. Pospelov, Phys. Rev. **D80** (2009) 095002
P. Fayet, Phys. Rev. **D75** (2007) 115017

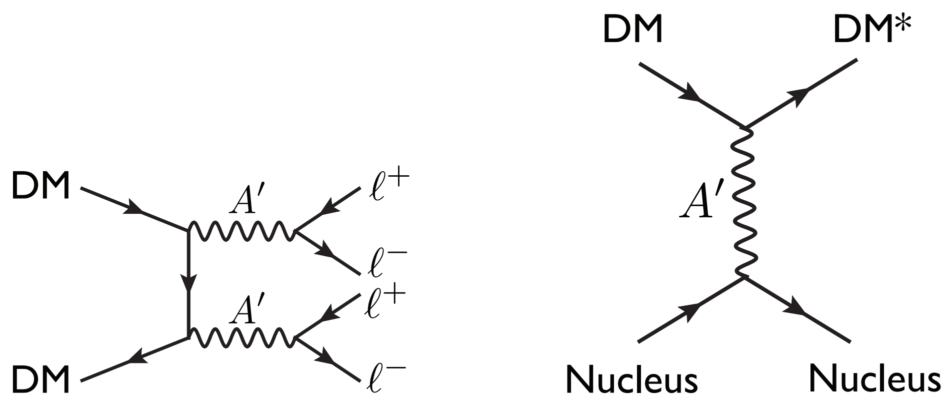
The γ' Boson (or A', ϕ, U-Boson, ...)

- $g-2$ anomaly of the muon
- Direct Scattering $\Rightarrow$ DAMA/LIBRA modulation
- Positron excess, but no anti-proton excess (PAMELA, INTEGRAL 511 keV line, etc.)

  $\Rightarrow$ Large annihilation cross section
- BUT: Relic Abundance of DM in cosmology requires low cross section

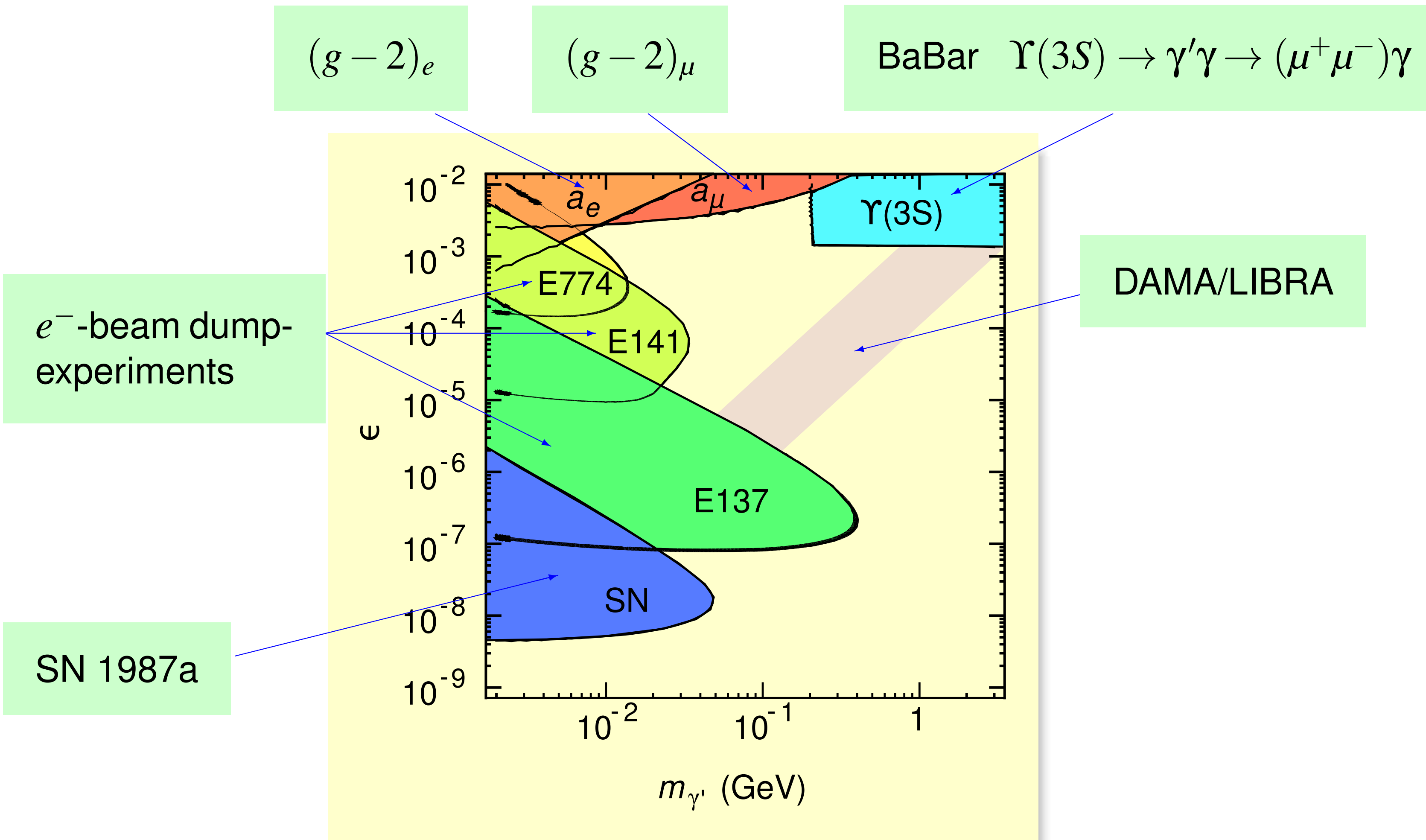
  $\Rightarrow$ Sommerfeld enhancement of cross section for low velocities
  - Large cross section in leptons
  - Small cross section in hadrons

$\Rightarrow U(1)$ Vector Boson γ' with Mass in GeV range



N. Arkani-Hamed, *et al.*, Phys. Rev. **D79** (2009) 015014

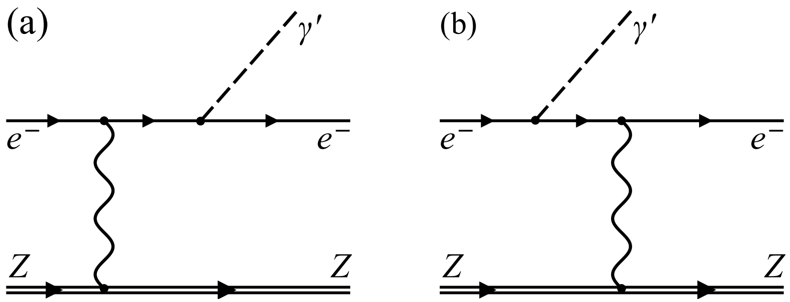
Parameter range for mass and coupling of γ' boson



- Interesting range: $10^{-8} < \varepsilon < 10^{-2}$ $\quad 10\,\text{MeV} < m_{\gamma'} < 1000\,\text{MeV}$
- Energy range of MAMI!

J.D. Bjorken *et al.*, Phys. Rev. **D80** (2009) 075018

Quasi-photoproduction off heavy target



Weizsäcker-Williams approximation:

$$\frac{d\sigma}{dx\,d\cos\theta_{\gamma'}} \approx \frac{8Z^2\alpha^3\varepsilon^2E_0^2x}{U^2}\tilde{\chi}\left[(1-x+\frac{x^2}{2})-\frac{x(1-x)m_{\gamma'}^2\left(E_0^2x\theta_{\gamma'}^2\right)}{U^2}\right]$$

with
$$x = \frac{E_{\gamma'}}{E_0}$$

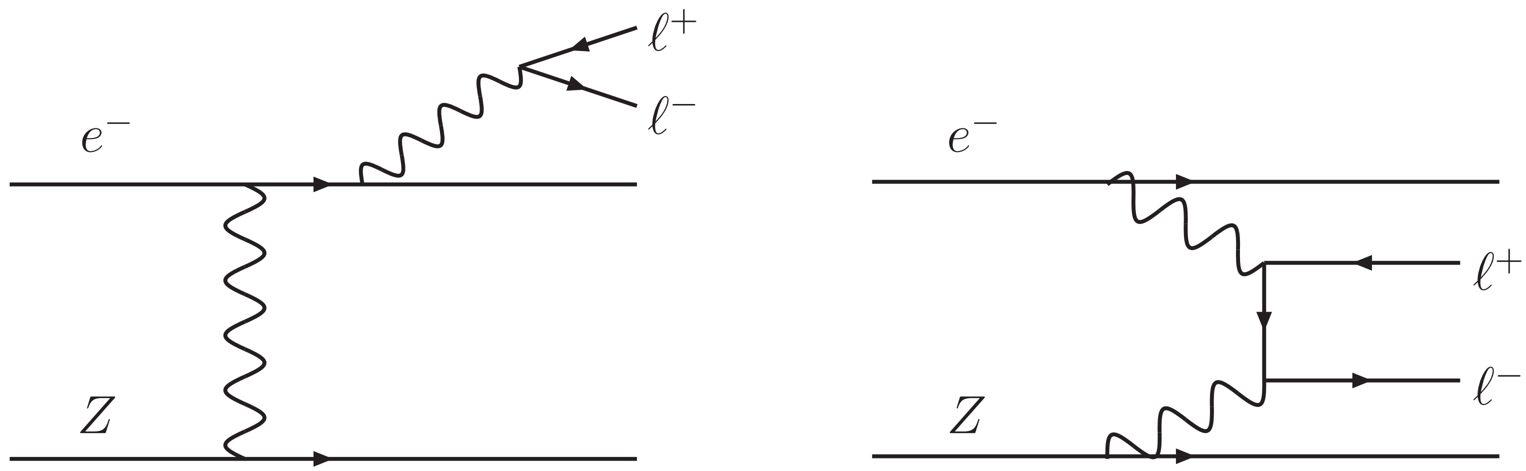
$$U(x,\theta_{\gamma'}) = E_0^2x\theta_{\gamma'}^2+m_{\gamma'}^2\frac{1-x}{x}+m_e^2x$$

Lifetime:

$$\gamma c\tau \sim 1\text{ mm}\left(\frac{\gamma}{10}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,\text{MeV}}{m_{\gamma'}}\right)$$

J.D. Bjorken *et al.*, Phys. Rev. **D80** (2009) 075018

Backgrounds



(a) (b)

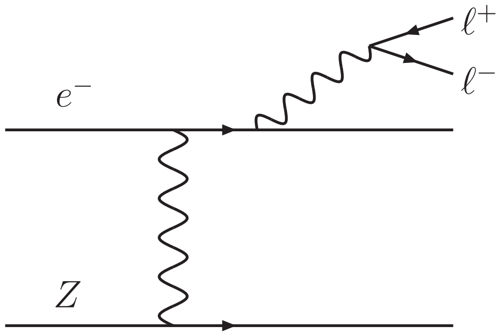
- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

- Computable in QED
- Peak for l^* on mass shell
- Energy transfer to l^- or l^+
- $\Rightarrow$ Kinematically separable

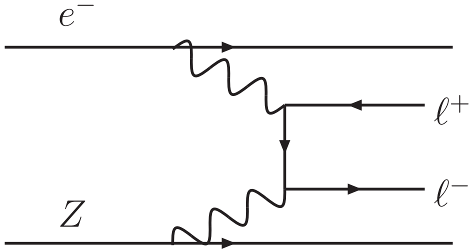
Other backgrounds: measurement!

T. Beranek, H. Merkel, M. Vanderhaeghen, Phys. Rev. **D88** (2013) 015032.

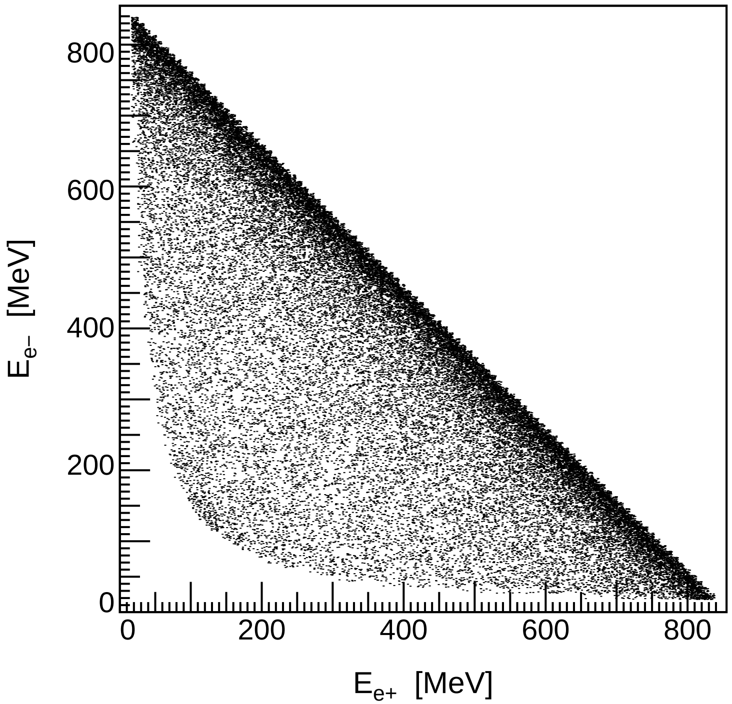
Bethe-Heitler Background

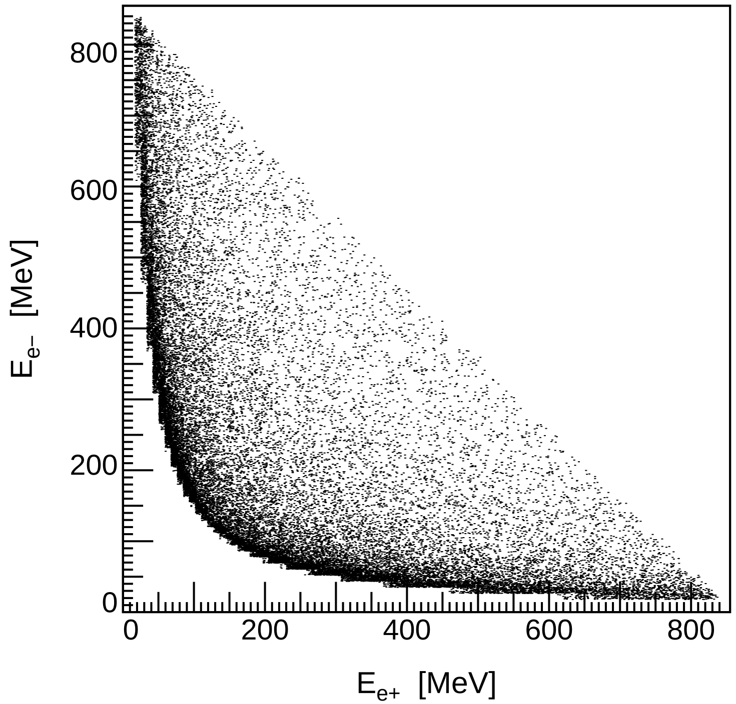


(a)

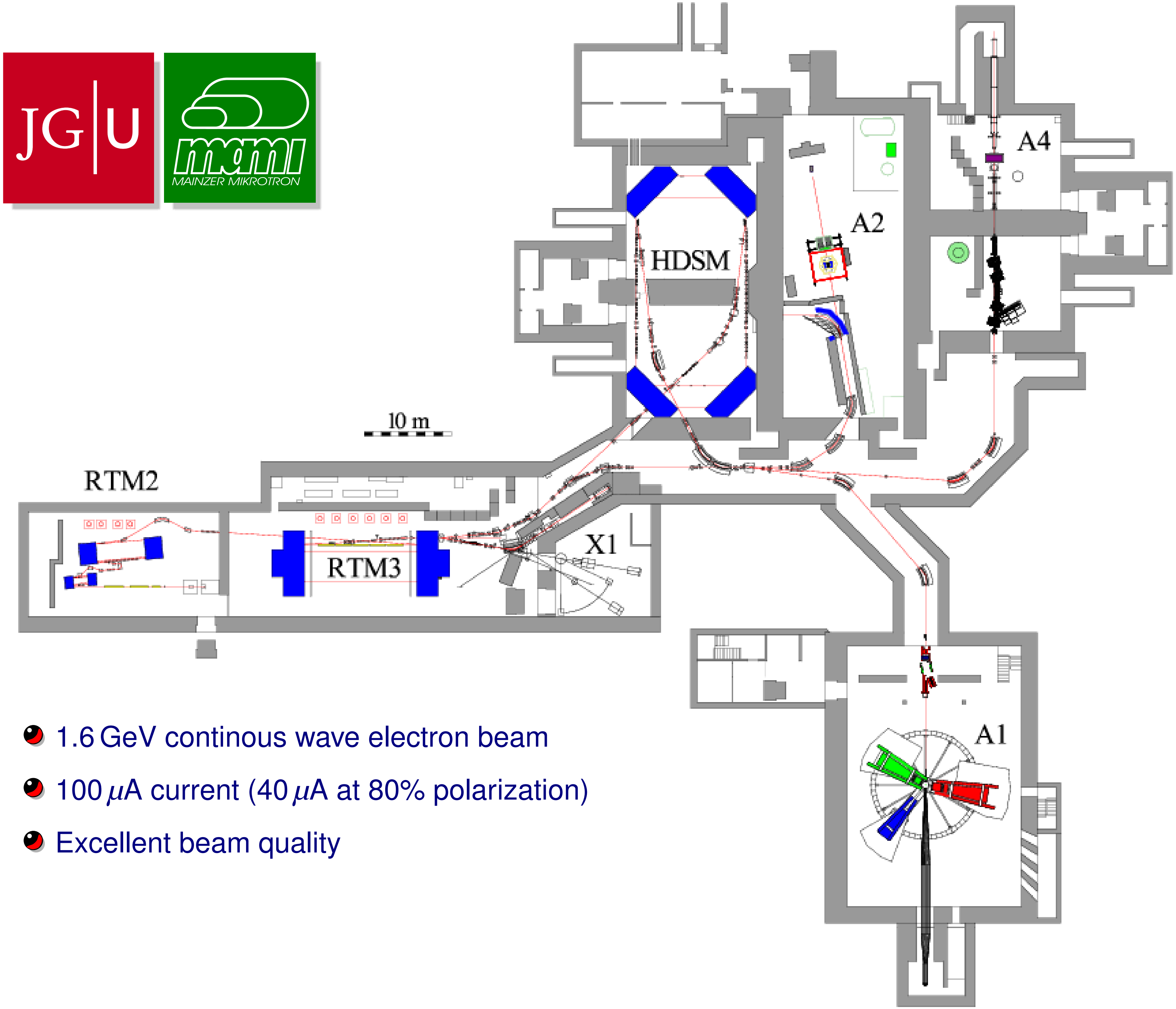


(b)





- Peak at $m_{e^+e^-} = 0$
- Peak for asymmetric production
- Minimum for symmetric production at $x = 1$



- 1.6 GeV continous wave electron beam
- 100 μA current (40 μA at 80% polarization)
- Excellent beam quality

A1: Spectrometer setup at MAMI

Spectrometer A:

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

Spectrometer B:

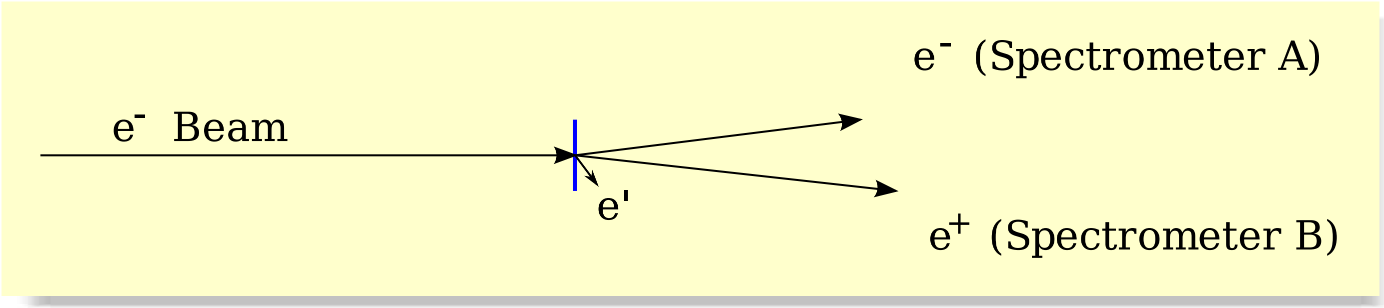
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

Spectrometer C:

$$\alpha > 55^\circ$$
$$p < 655\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 28\,\text{msr}$$
$$\Delta p/p = 25\%$$

$$\delta p/p < 10^{-4}$$

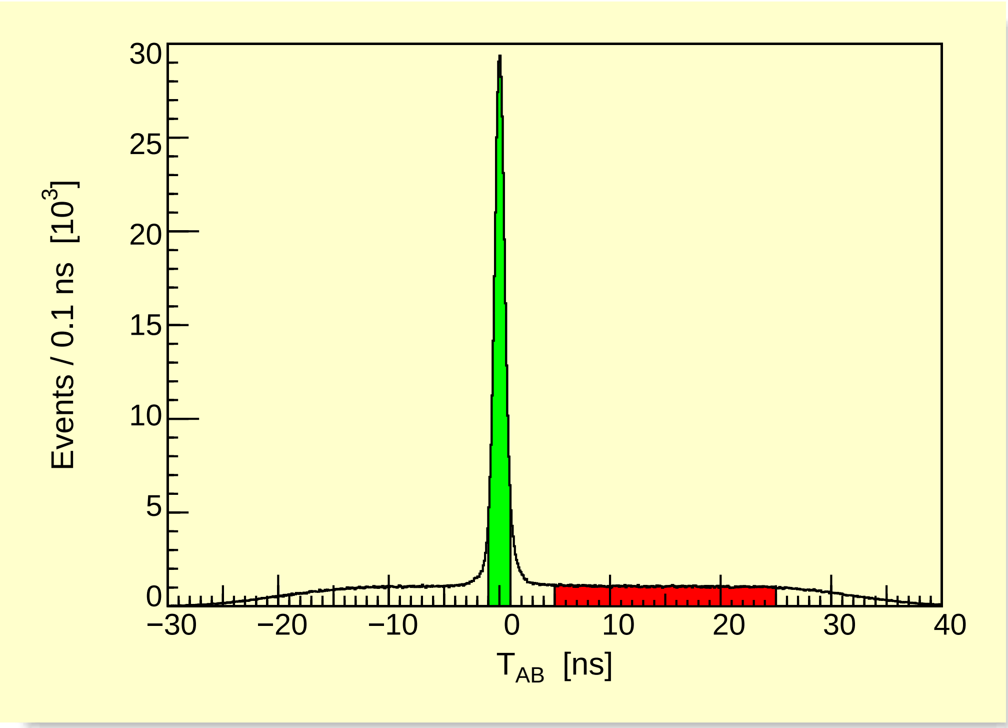
Pilot experiment



- Target: 0.05 mm Tantalum (mono-isotopic ^{181}Ta)
- Beam current: $100\mu\text{A}$
- Luminosity: $L = 1.7 \cdot 10^{35} \frac{1}{\text{s cm}^2}$ $\quad (L \cdot Z^2 \approx 10^{39} \frac{1}{\text{s cm}^2})$
- Complete energy transfer to γ' boson $(x = 1)$
- Minimal angles for spectrometers
- Spectrometer setup as symmetric as possible (background reduction)

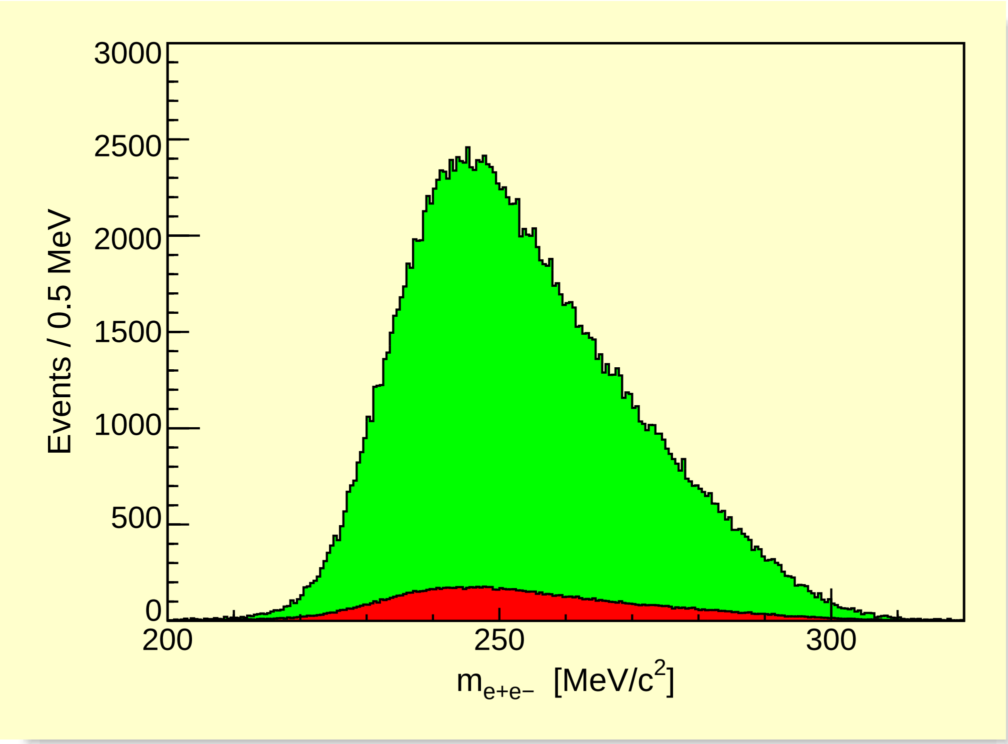
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV$/c$
	$\theta_{e^-} =$	22.8°
Spectrometer B	$p_{e^+} =$	470.0 MeV$/c$
	$\theta_{e^+} =$	15.2°

Reaction identification: coincidence time



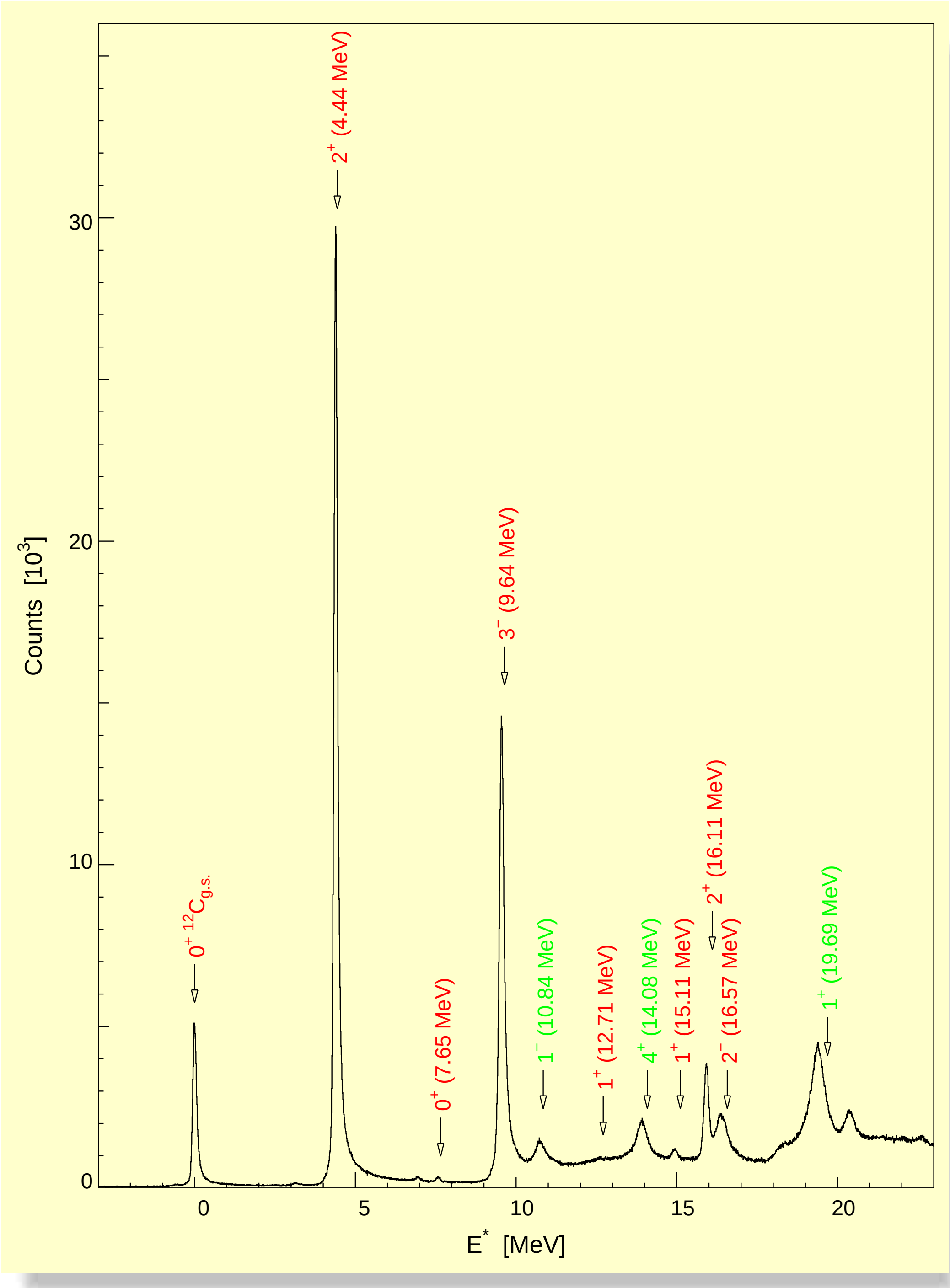
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\text{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\text{ns}$ FWHM
- Estimate of background: side band $5\,\text{ns} < T_{A\wedge B} < 25\,\text{ns}$
- Almost no accidental background $\approx 5\%$
- Above background: only coincident e^+e^- pairs!

Invariant mass of e^+e^- pair



- Mass of e^-e^+ pair $\quad m^2_{\gamma'} = (e^- + e^+)^2$
- What is the expected peak width?

Determination of the Mass Resolution

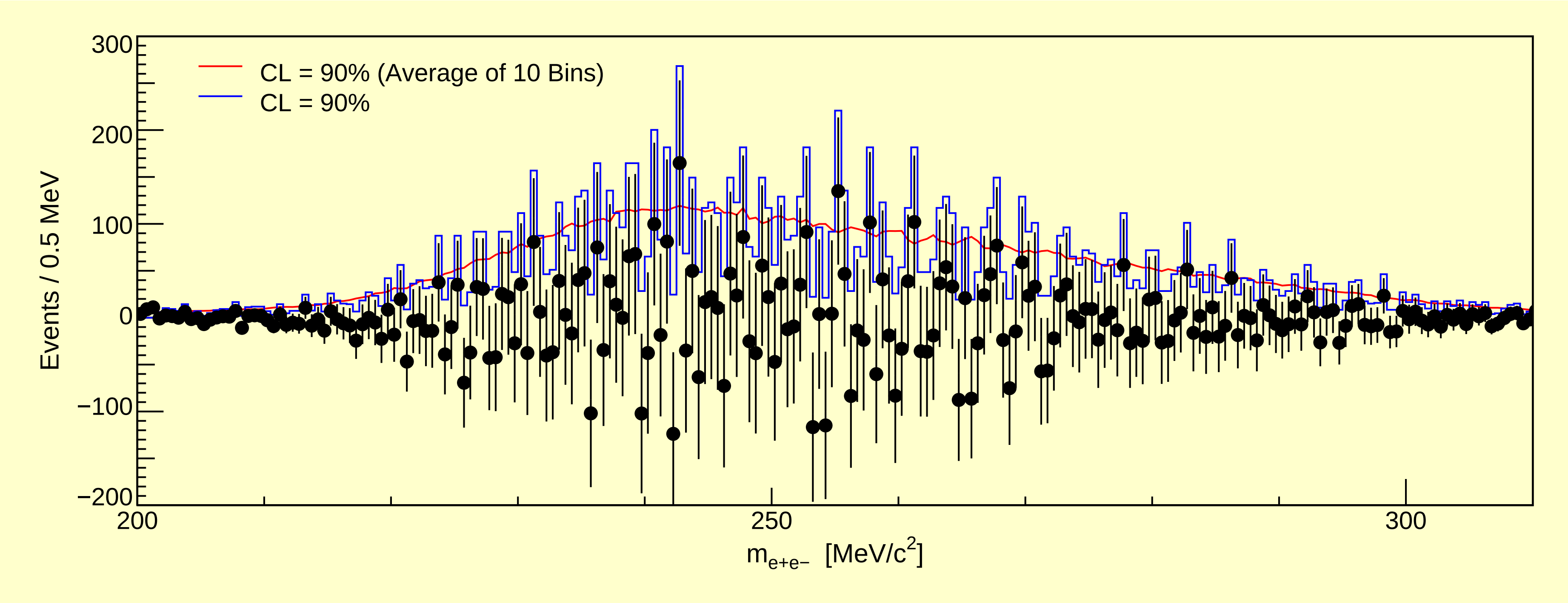


- Elastic Scattering
  - Natural width $\ll$ Resolution
  - Line width gives upper bound
  - $\delta p/p < 10^{-4}$ for Spectrometer
- Input to Full Simulation
  - Multiple Scattering $(-)$
  - Radiation correction $(-)$
  - Decay length $(+)$
  - Missing mass resolution $(+)$

$\Rightarrow$ $\delta m_{e^+e^-} < 0.5\,\mathrm{MeV}/c^2$ FWHM

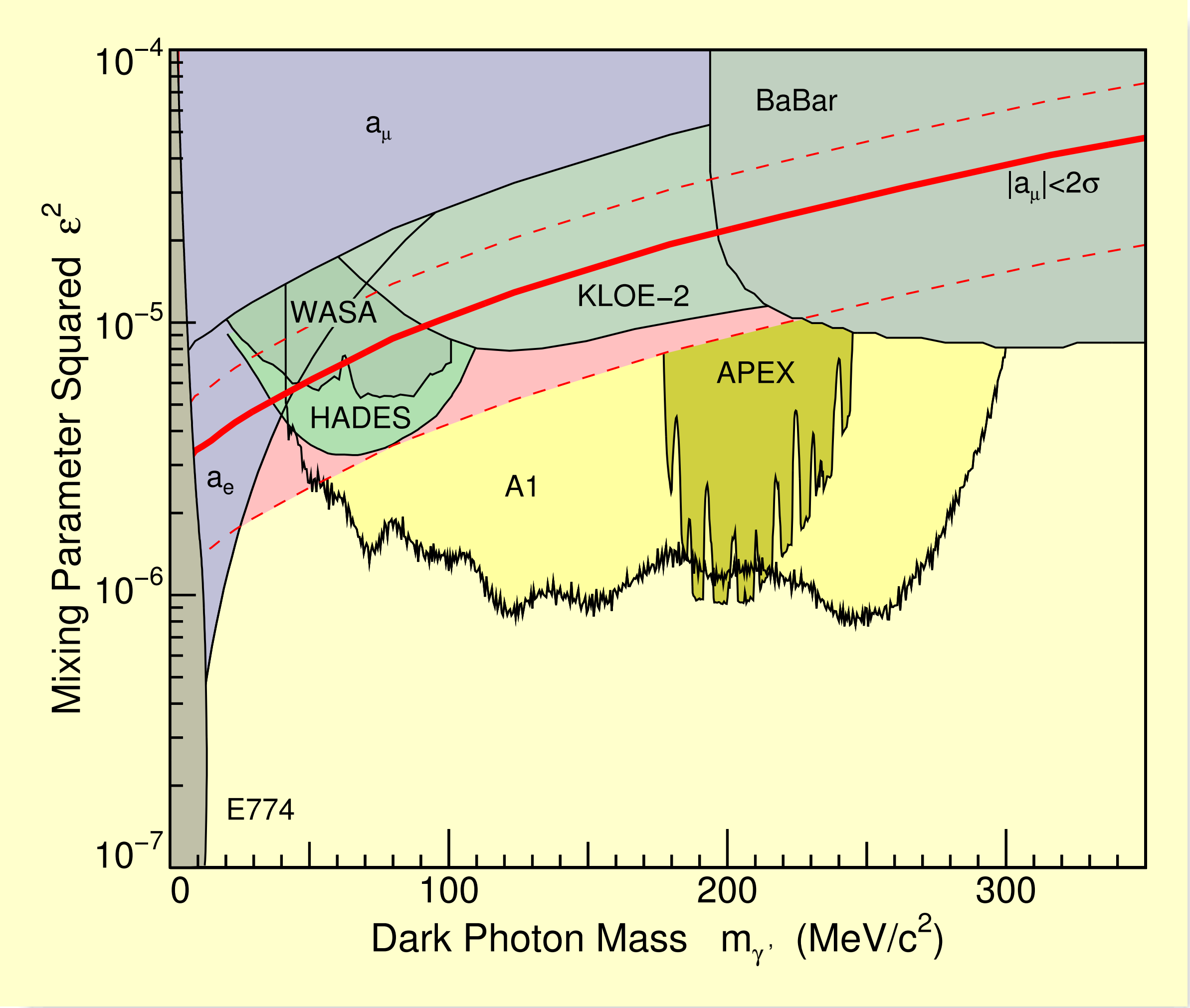
N.B.: Systematic error of $\delta m_{e^+e^-} < 10^{-3}$!

Exclusion limits



- Confidence interval by Feldman-Cousins algorithm
- “Model” for Background-subtraction:
  average of 3 Bins left and right of central bin
- Resolution $\delta m < 500\,\mathrm{keV}$ = bin width
- Averaging (mean of 10 bins) only for “subjective judgment”

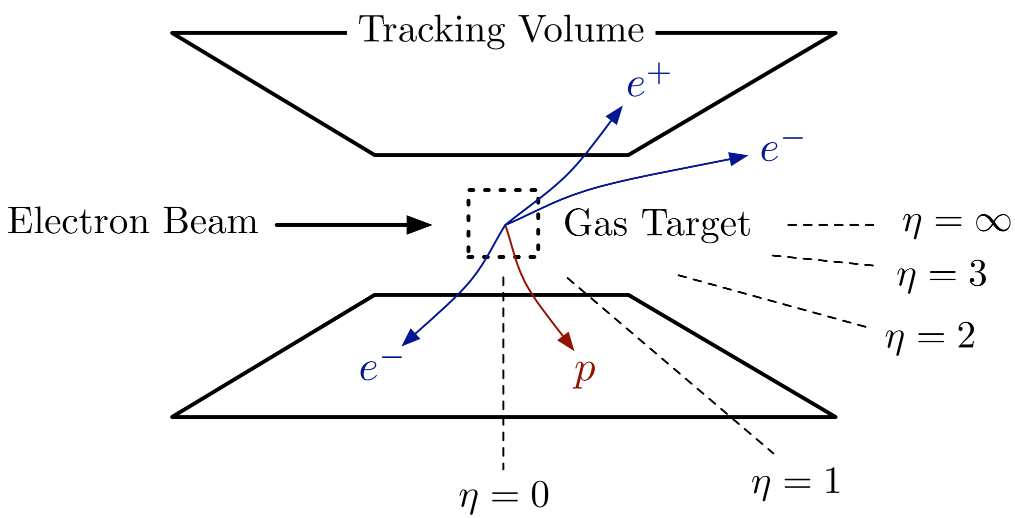
Exclusion limits MAMI 2014

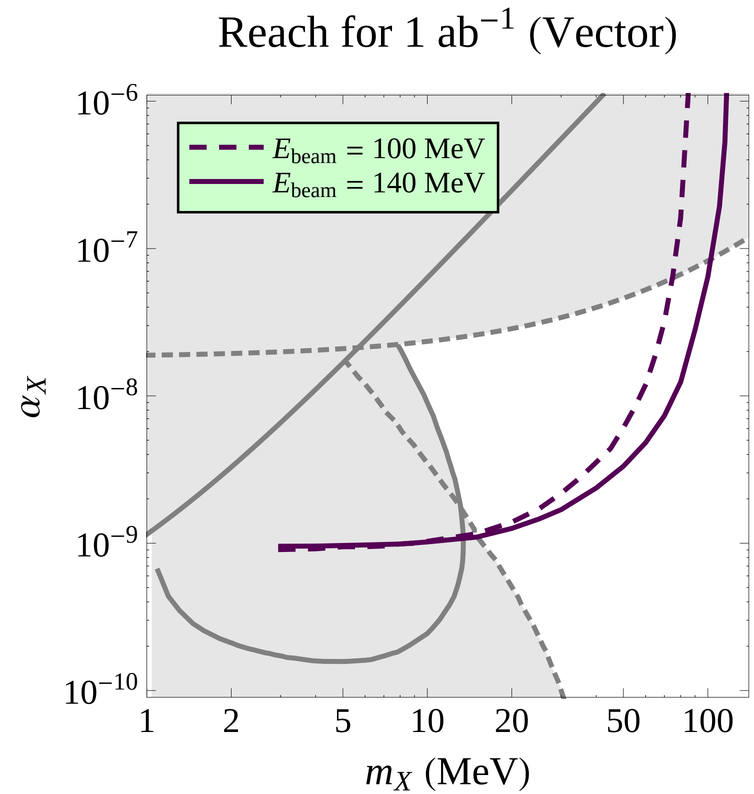


- 22 kinematical settings
- Including data from pilot experiment H. Merkel *et al.* PRL **106** (2011) 251802
- Sensitivity $\varepsilon^2 > 8 \cdot 10^{-7}$

H. Merkel *et al.*, Phys. Rev. Lett. **112** (2014) 015032

Next Step: Access to low mass region

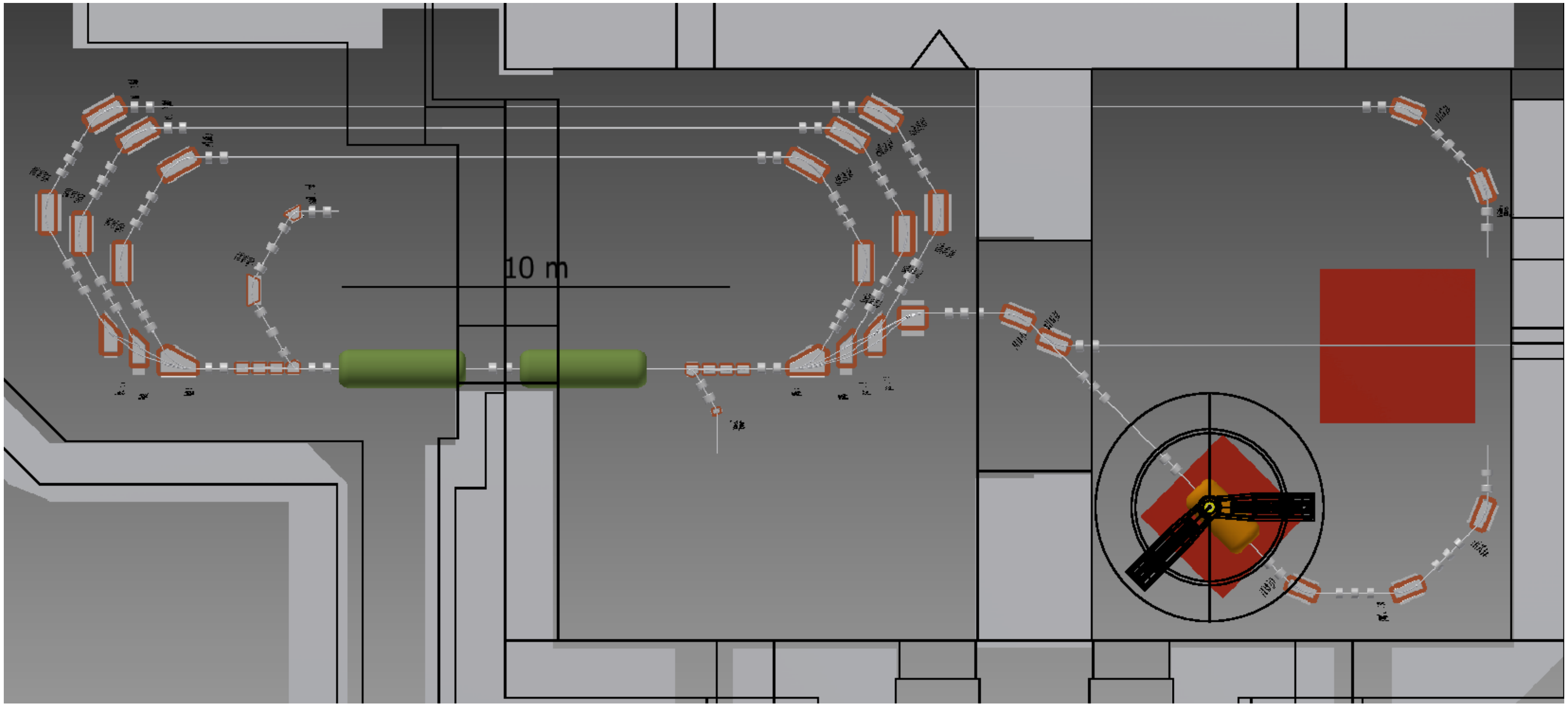




- Minimize multiple scattering by gas target
- Low energy – high current accelerator
- Needs 4π detector at 200 MHz count rate with high resolution
- DarkLight (JLab FEL)

M. Freytsis, G. Ovanesyan, J. Thaler, JHEP 01 (2010) 111, arXiv:0909.2862

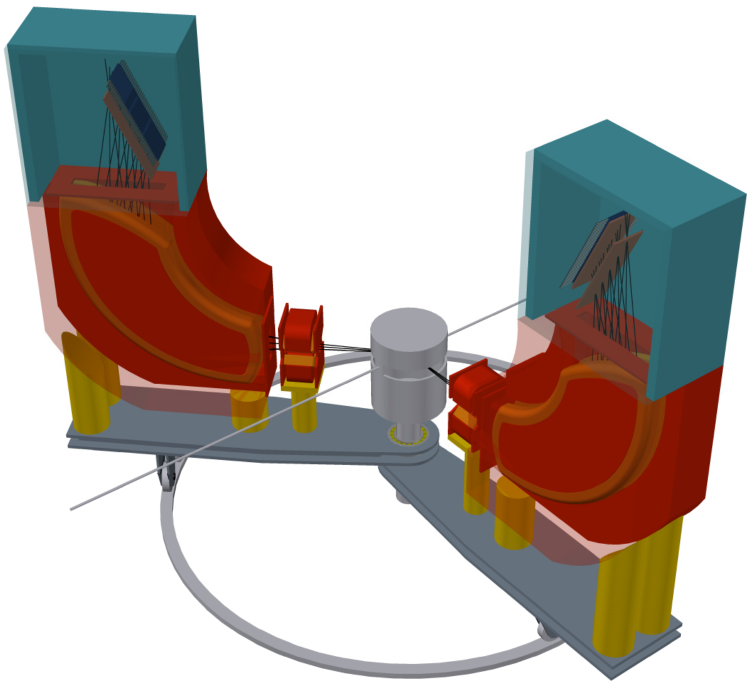
Next Step: Access to low mass region MESA Accelerator

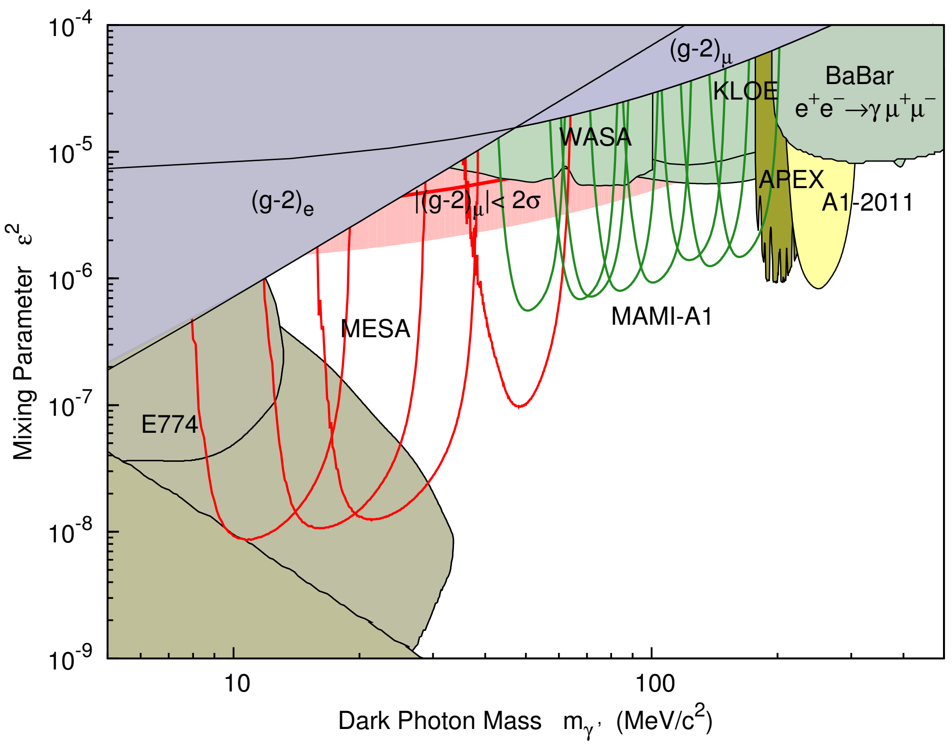


- Mainz Energy recovering Superconduction Accelerator
- up to 10 mA beam current
- Single pass accelerator ⇒ excellent beam quality
- $\Rightarrow L = 10^{35}\,\frac{1}{\mathrm{s\,cm^2}}$ with internal target

Next Step: Access to low mass region: MESA Accelerator

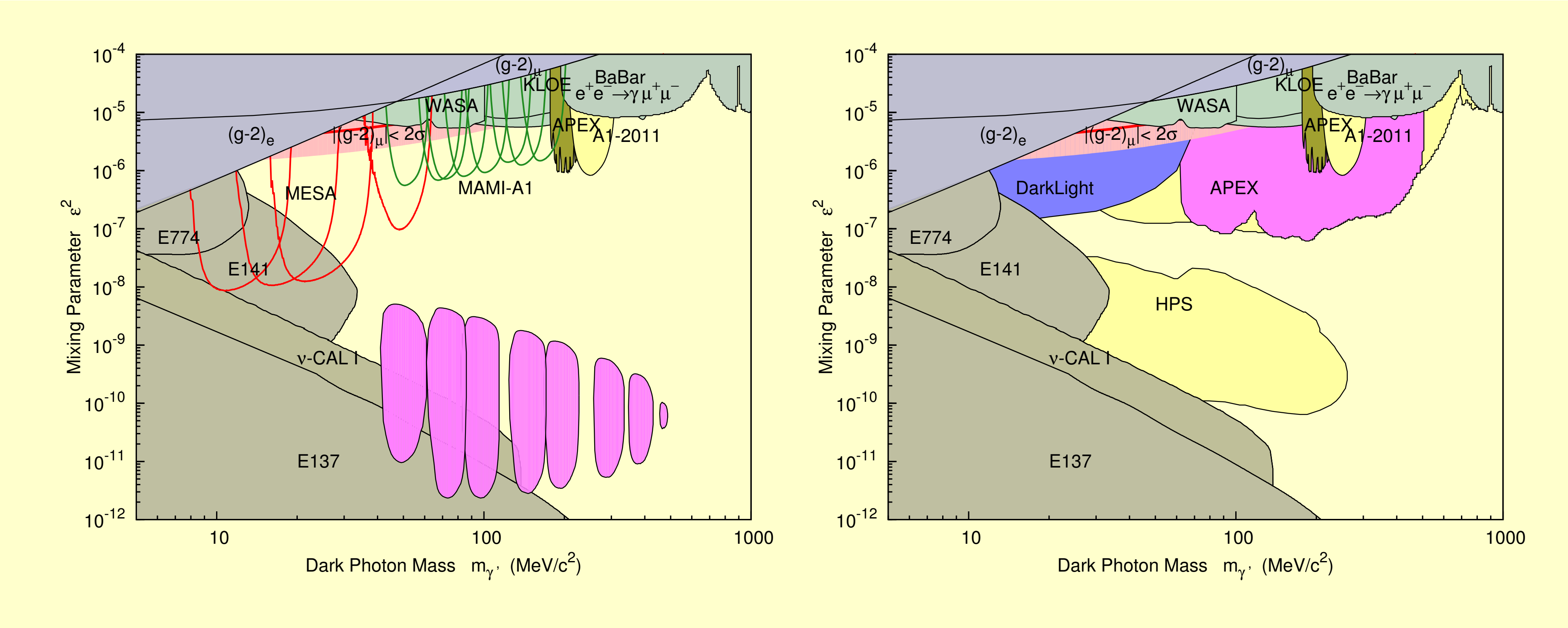
- Low energy precision physics: $\sigma \sim \sin^{-4}\frac{\theta}{2}$
- Multi-purpose spectrometer setup
- Dark Photon experiment:
  mass-resolution beats solid angle!
- Status:
  - Finite-elements design of magnets just finished
  - (polarized) internal target design
  - Focal plane detectors (> 1 MHz count rate at $50\mu m$)





⇒ ideal for dark photon search!

Summary and Outlook



- Experimental Program:
  - Pair production on heavy target $\varepsilon > 4 \cdot 10^{-4}$
  - Low energy – high current $m_{\gamma'} < 50\,\mathrm{MeV}/c^2$
  - Finite production vertex $10^{-6} < \varepsilon < 10^{-4}$
- Pilot experiments at MAMI
  - Experiment is feasible, background is well under control
  - Q.E.D. process is understood and calculable within 1%
  - First exclusion limits 10^{-3}

$\Rightarrow$ measurements will be continued with the MESA accelerator