Searches for Dark Photons at the Mainz Microtron

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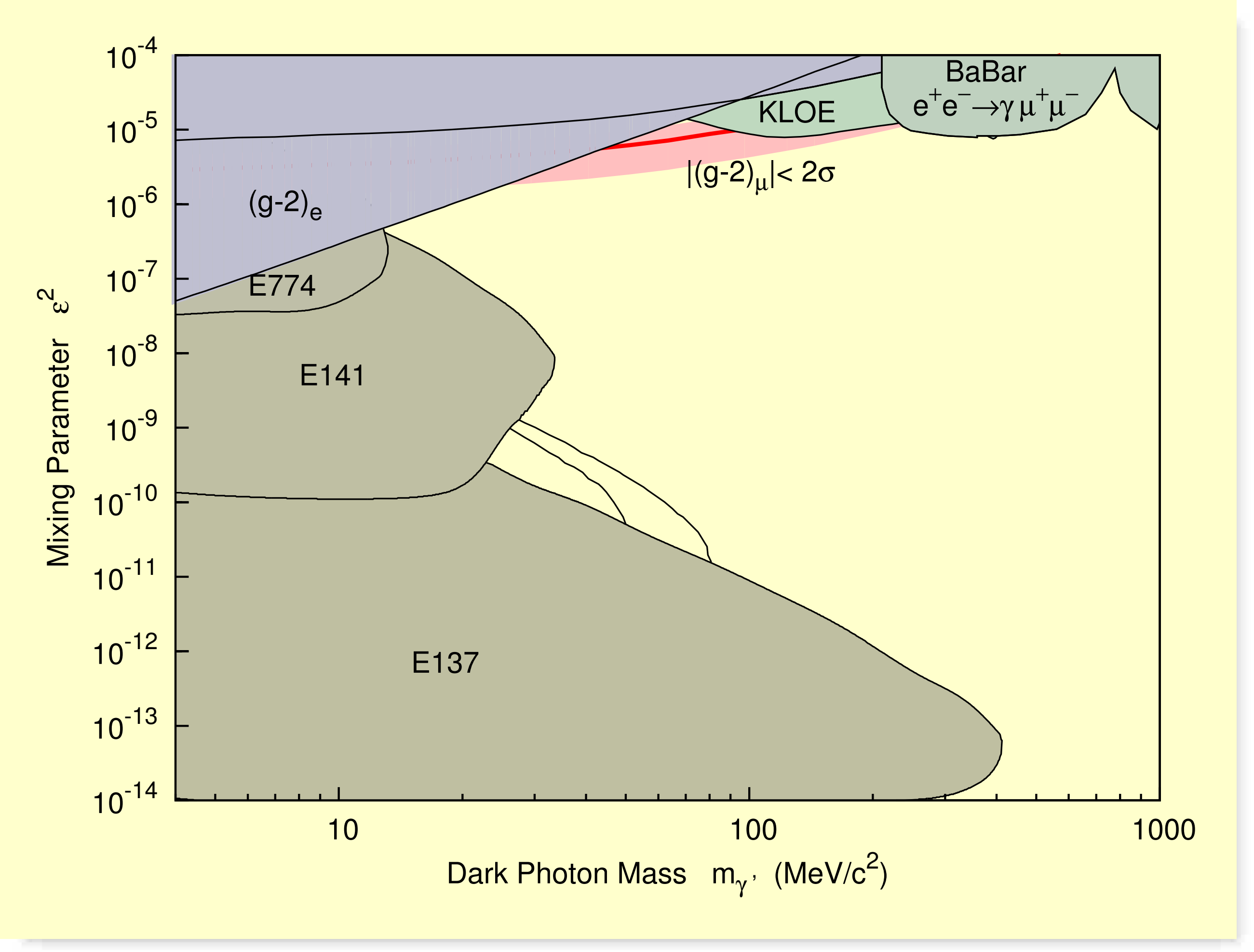
Dark Forces at Accelerators Workshop
Frascati, 16th – 19th October, 2012

- The Mainz Microtron (MAMI)
- Pilot experiment
- Extended mass range
  - New settings
  - Improved simulation
- Low mixing region: displaced vertex
- Low mass region
  - The MESA accelerator
  - Septum at A1
  - MAMI Energy reduction

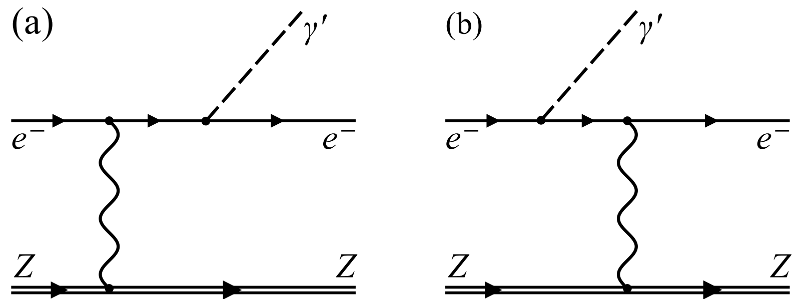
Exclusion limits from Beam-dump and Collider Experiments



- New limits from beam-dump experiments (S. Andreas)
- Improved exclusion limit for $(g-2)_e$
- $\Rightarrow$ Consequences for low mass experiments

S. Andreas, C. Niebuhr, and A. Ringwald, arXiv:1209.6083 [hep-ph]
H. Davoudiasl, H. -S. Lee, and W. J. Marciano arXiv:1208.2973 [hep-ph]
M. Endo, K. Hamaguchi, and G. Mishima, arXiv:1209.2558 [hep-ph]

Quasi-real Photo-Production off heavy target



Weizsäcker-Williams approximation:

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

with

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

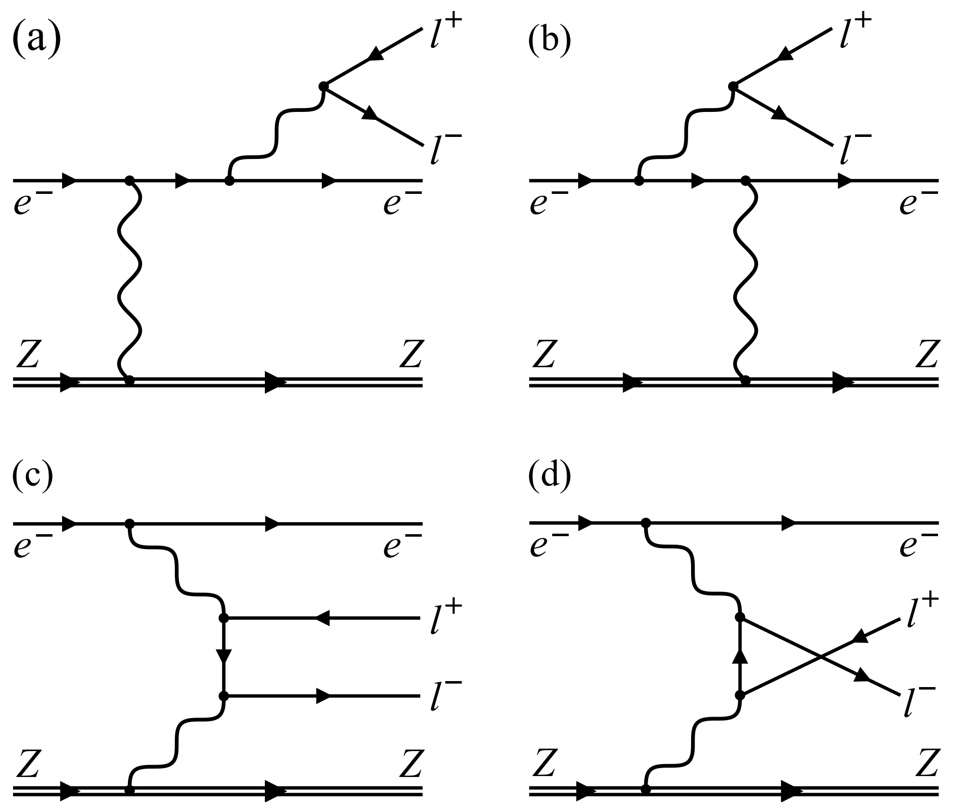
$$U(x,\theta_{\gamma'}) = E_0^2\,x\,\theta_{\gamma'}^2 + m_{\gamma'}^2\frac{1-x}{x} + m_e^2\,x$$

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. D 80, 075018 (2009)

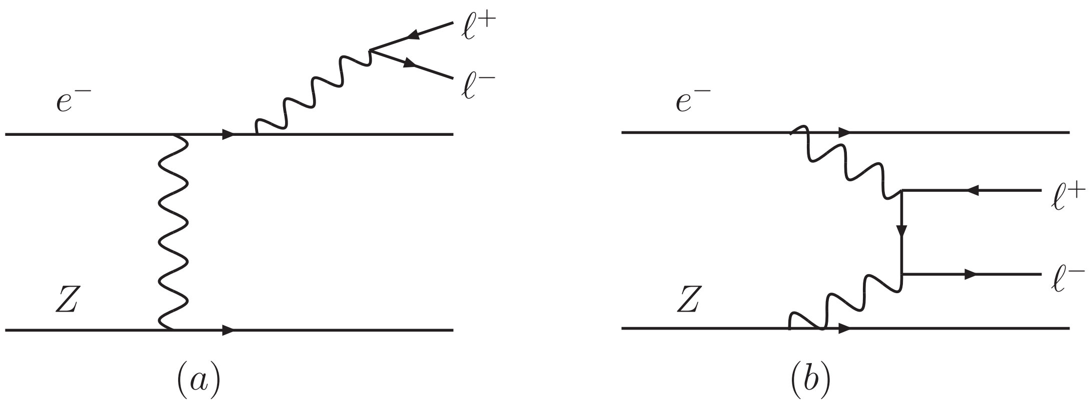
Backgrounds

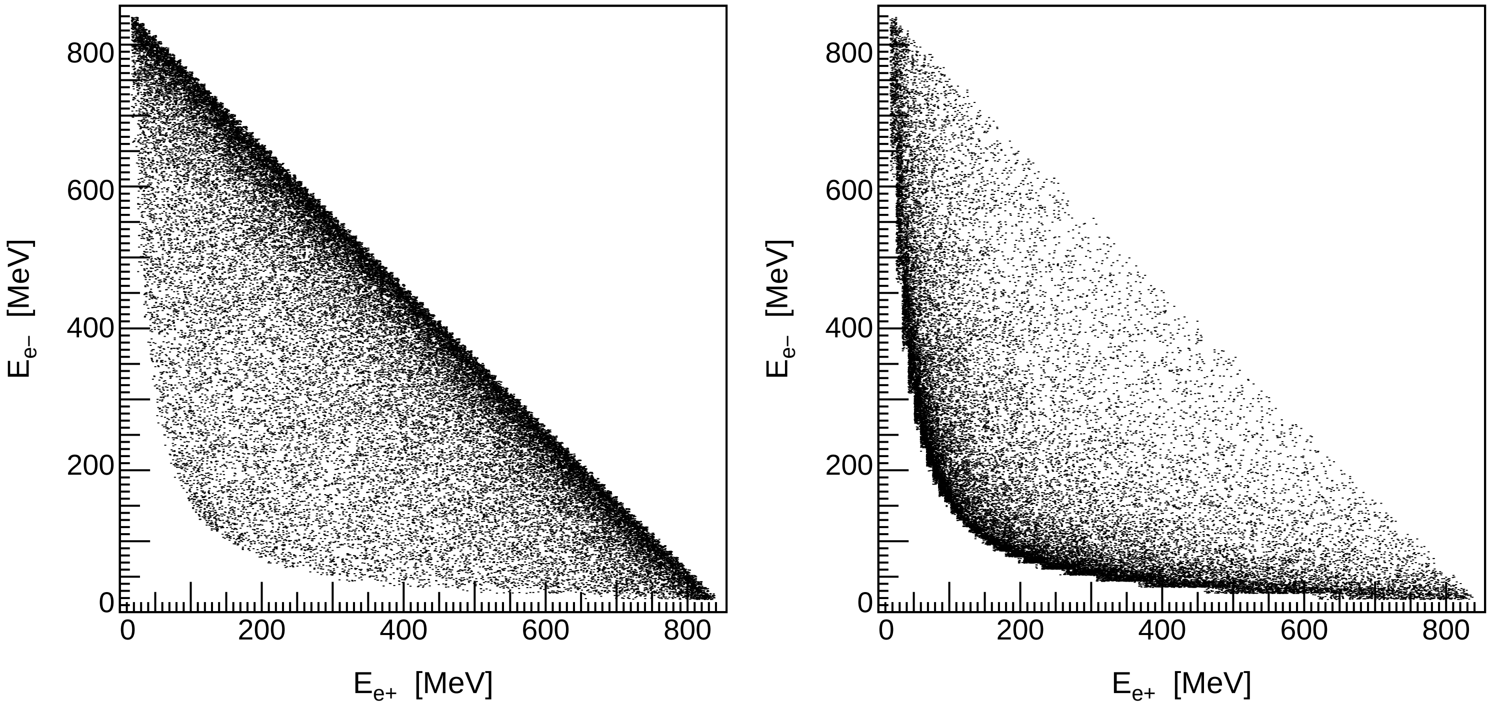


- Virtual photon instead of γ'
- Calculable in QED
- (a), (b): Same shape of cross section $\Rightarrow$ Not separable
- (c), (d): Peak for l^* on mass shell $\Rightarrow$ Suppression by kinematics

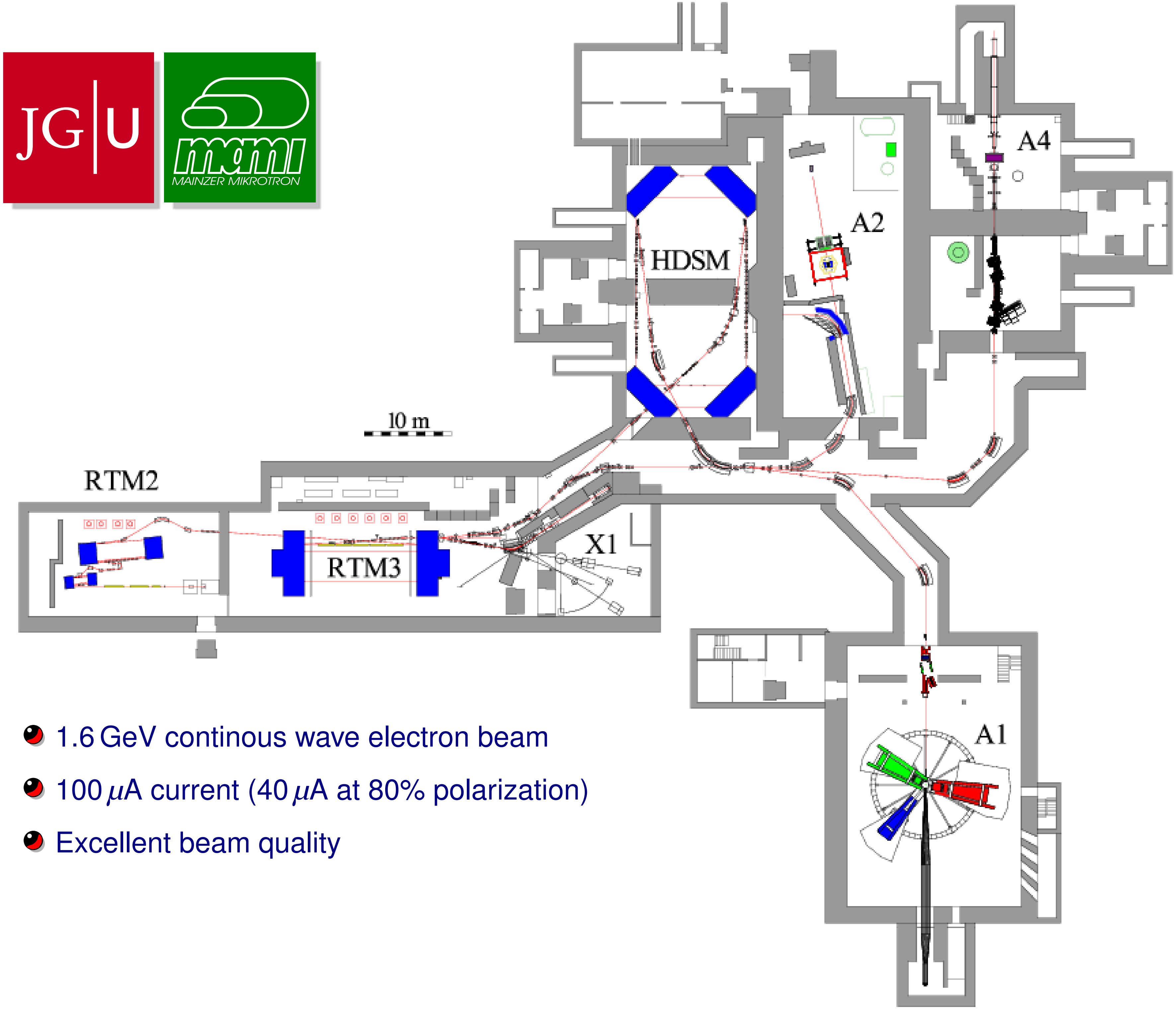
Other backgrounds: Measurement!

Bethe-Heitler Background





- 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:

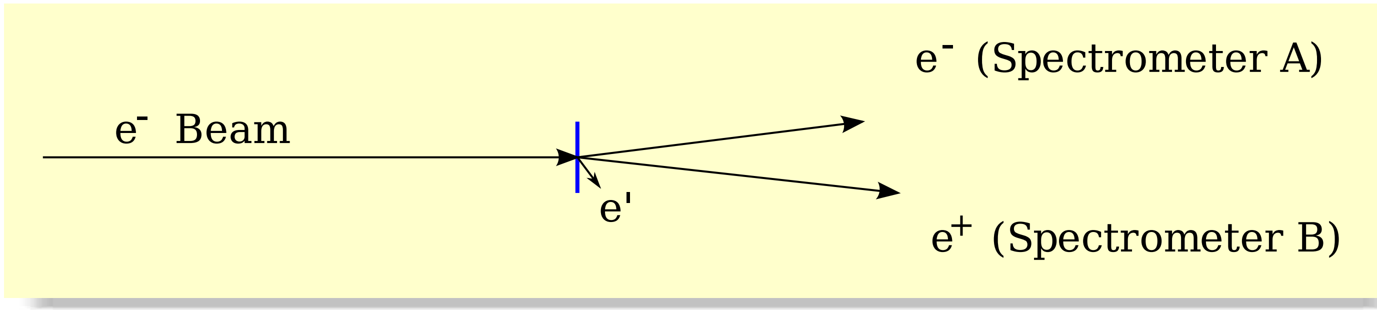
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

Spectrometer C:

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

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

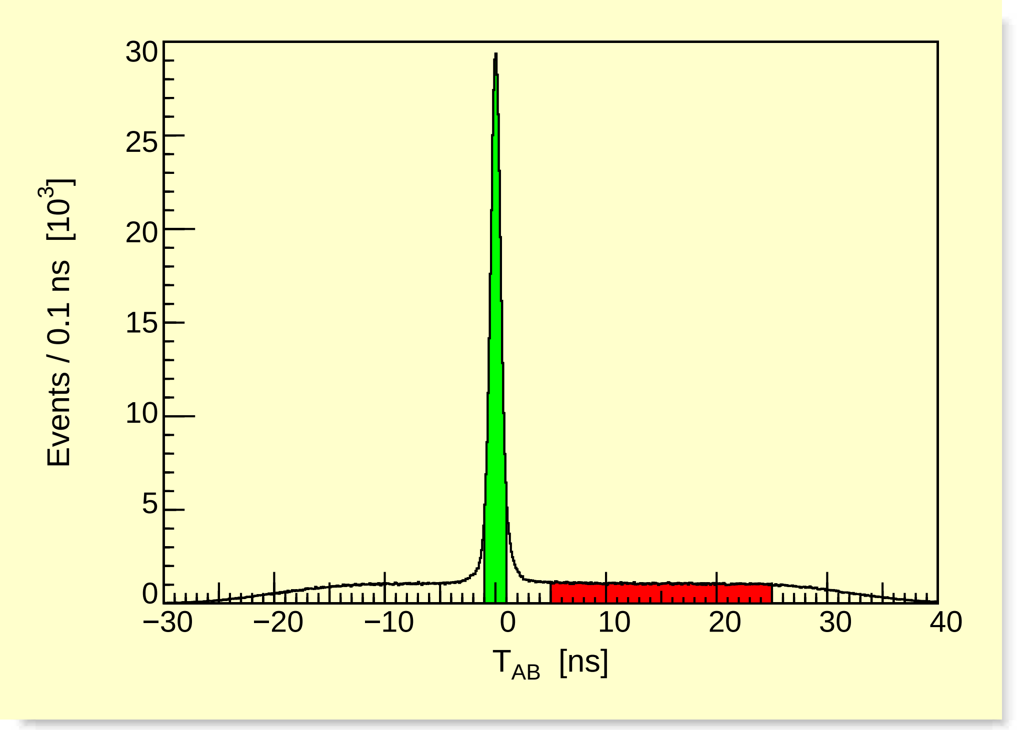
Pilot experiment



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

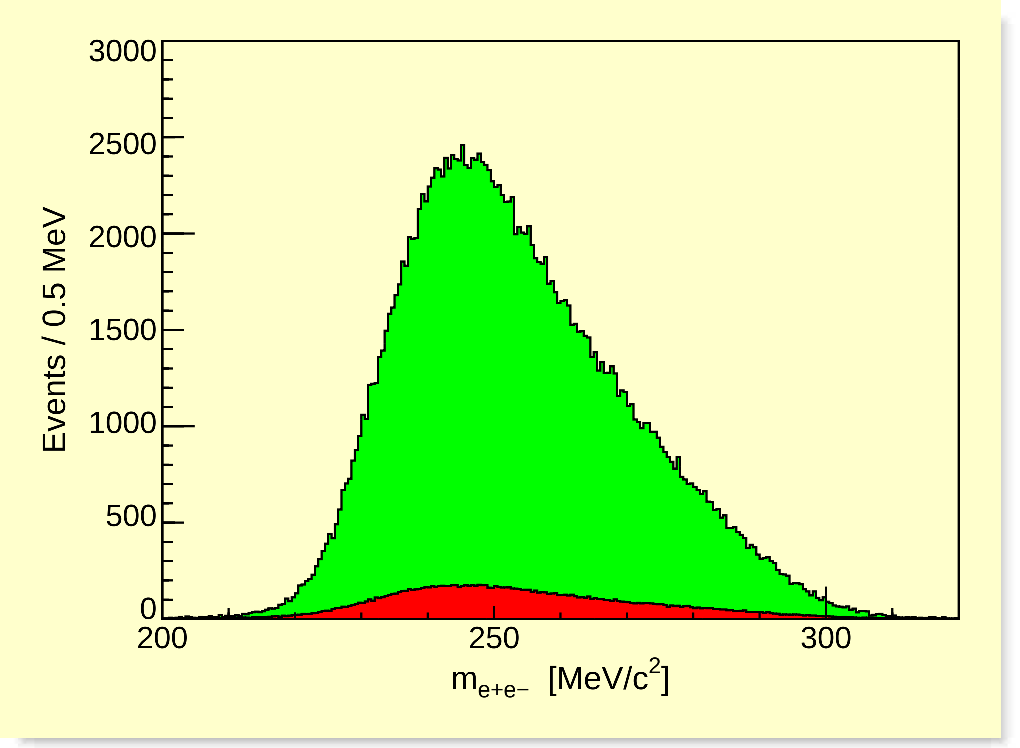
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV$/c$
	$\theta_{e^-} =$	22.8°
Spectrometer B	$p_{e^+} =$	470.0 MeV$/c$
	$\theta_{e^+} =$	15.2°

Reaction identification: coincidence time



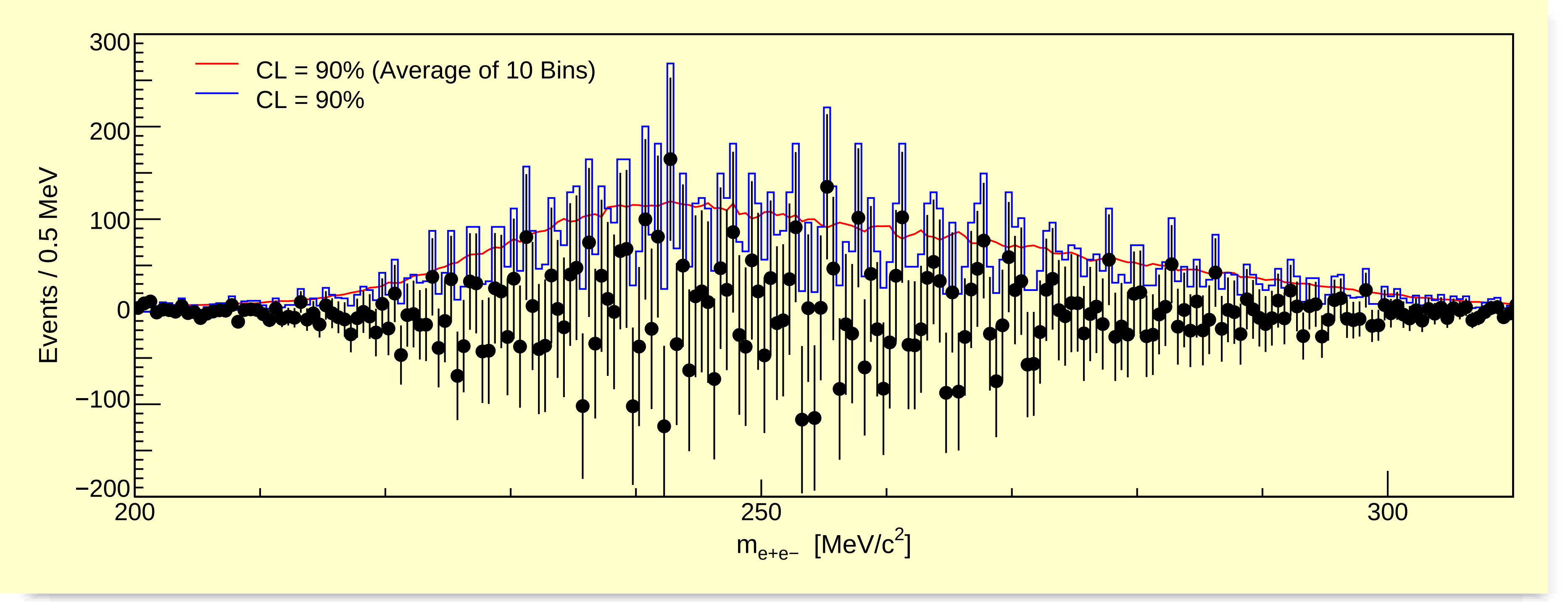
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\mathrm{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge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

Invariant mass of e^+e^- pair



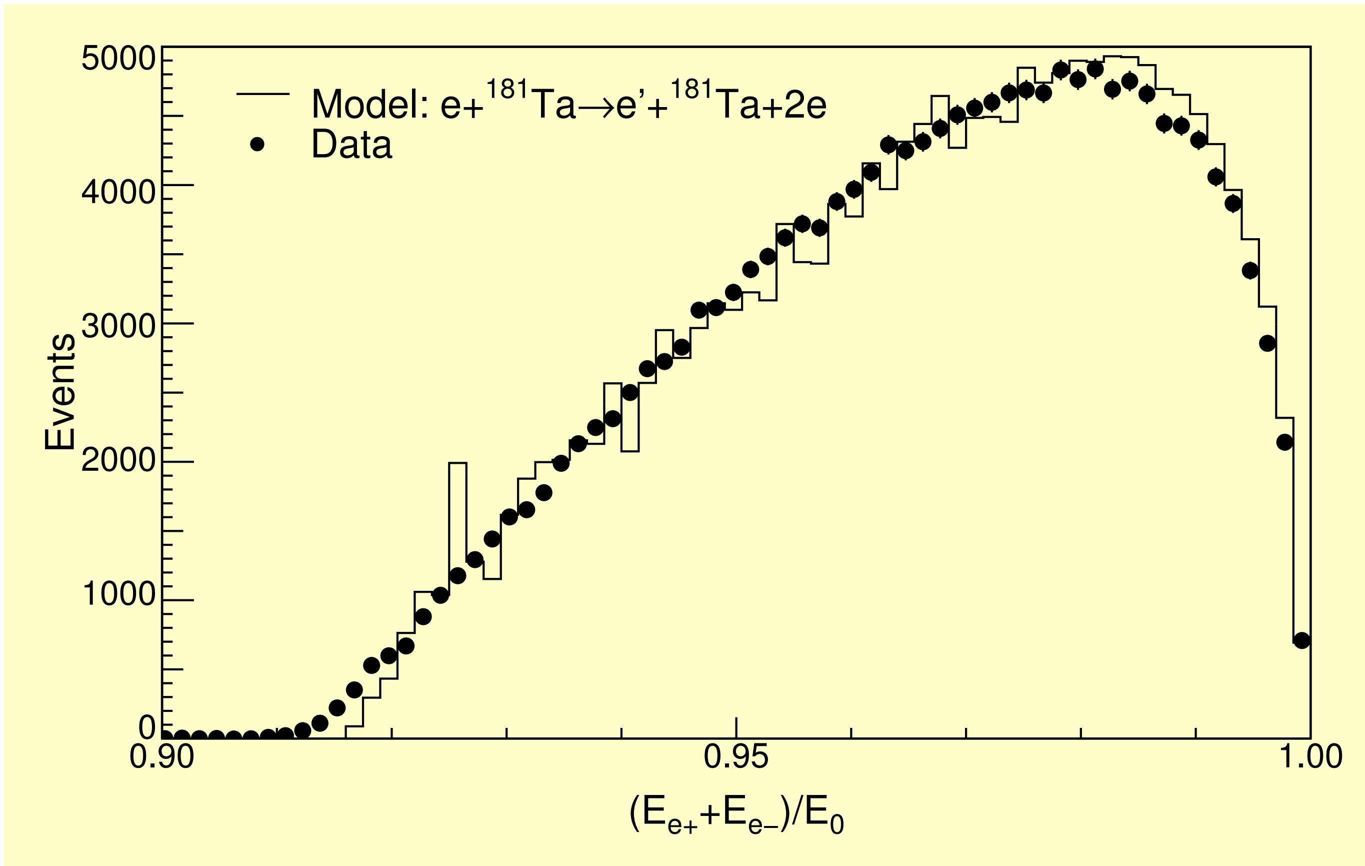
- Mass of e^-e^+ pair $\quad m^2_{\gamma'} = (e^- + e^+)^2$

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”

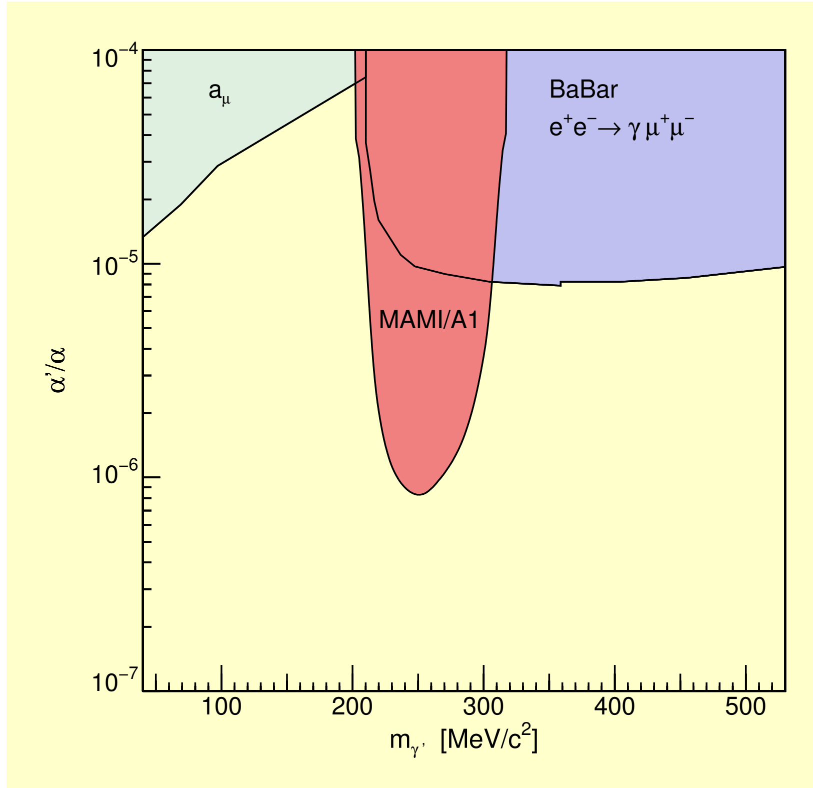
Simulation



- Full simulation with exact cross section per event
- Model: Coherent electro production off heavy nucleus
- Q.E.D., nuclear form factor, coherent sum of all contributions, radiative corrections, . . .
- Exact 1st order in four diagrams for background, 2 diagrams for signal

⇒ Describes data within a few percent

Exclusion limit for mixing parameter ε



- Accidental background + Q.E.D. background
- Model deviates only on nuclear vertex, both for γ' and γ^*
- Conversion from ratio of cross sections:

$$\frac{d\sigma(X \to \gamma' Y \to l^+l^-Y)}{d\sigma(X \to \gamma^* Y \to l^+l^-Y)} = \left(\frac{3\pi\varepsilon^2}{2N_f\alpha}\right)\left(\frac{m_{\gamma'}}{\delta_m}\right)$$

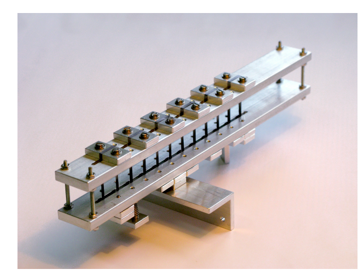
$\Rightarrow$ Exclusion limit from 4 days of beam time $\varepsilon < 10^{-3}$

H.M. *et al.*, Phys. Rev. Lett. 106 (2011) 251802

Data 2012 - Kinematical Settings

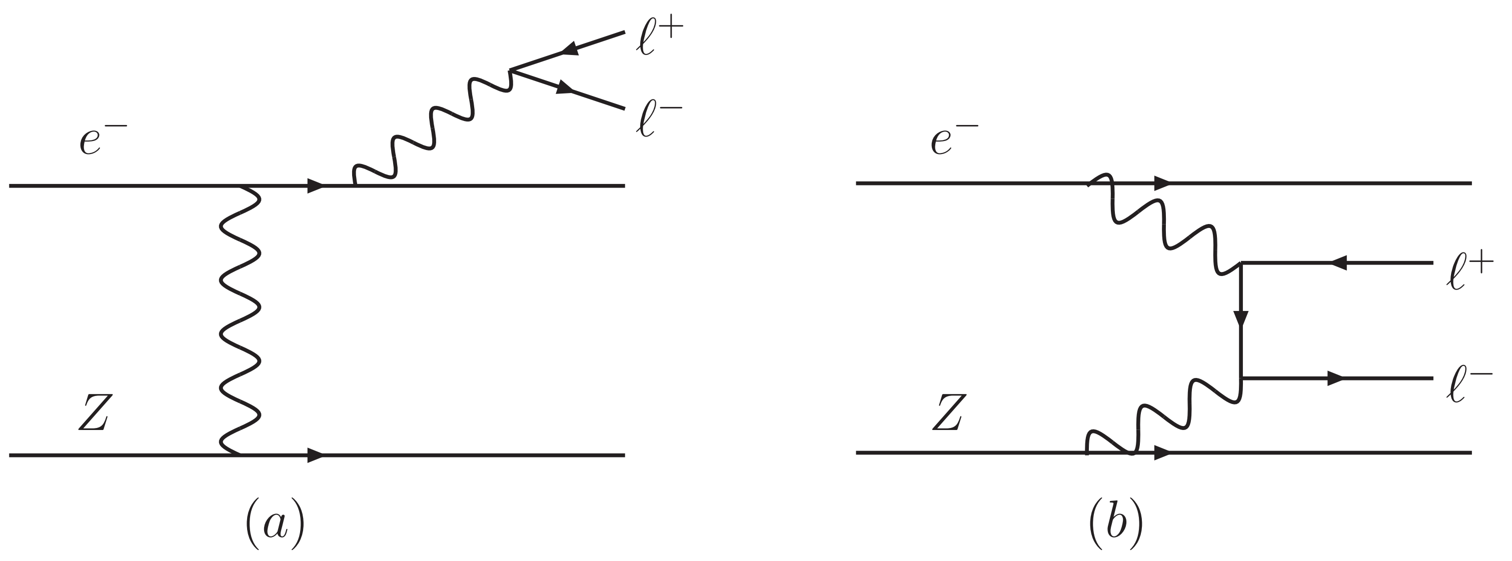
Setting	E_0 (MeV)	p_A (MeV/c)	p_B (MeV/c)	$\bar{I}_0$ (μA)	Target (mg/cm^2)		t t
DM2012_57	180	78.7	98.0	2.2	Foil	9.4	12h 30' 56"
DM2012_72	240	103.6	132.0	5.5	Foil	9.4	46h 53' 18"
DM2012_77	255	110.1	140.4	7.0	Foil	9.4	43h 49' 11"
DM2012_91	300	129.5	164.5	11.7	Foil	9.4	37h 56' 03"
DM2012_109	360	155.4	197.6	16.6	Foil	9.4	5h 15' 29"
DM2012_138	435	190.7	247.7	43.4	Foil	9.4	44h 3' 27"
DM2012_150	495	213.7	271.6	7.0	Stack	113.1	36h 25' 16"
DM2012_177	585	250.0	317.3	16.3	Stack	113.1	29h 37' 03"
DM2012_218	720	309.2	392.7	19.4	Stack	113.1	76h 0' 20"

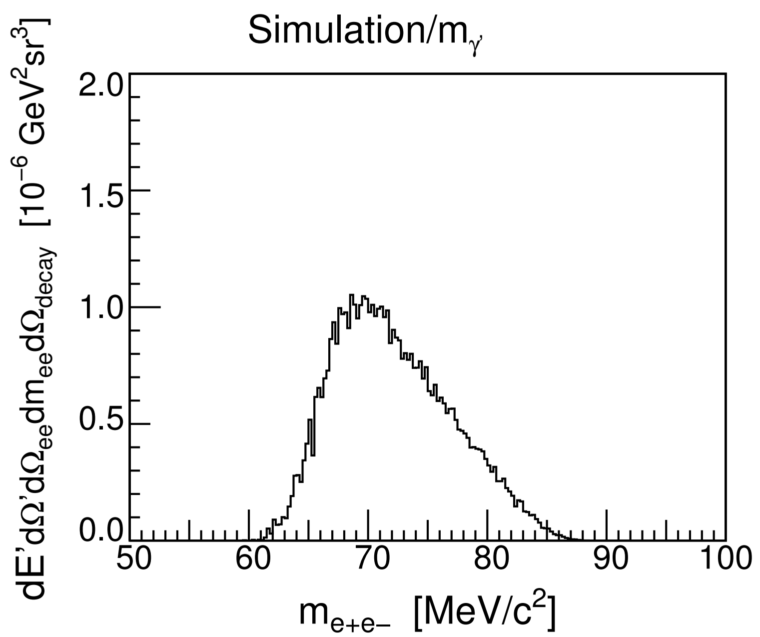
Spectrometer	Angle	Solid angle (msr)	$\Delta p/p$
A (electron)	20.01°	21.0	20%
B (positron)	15.63°	5.6	15%

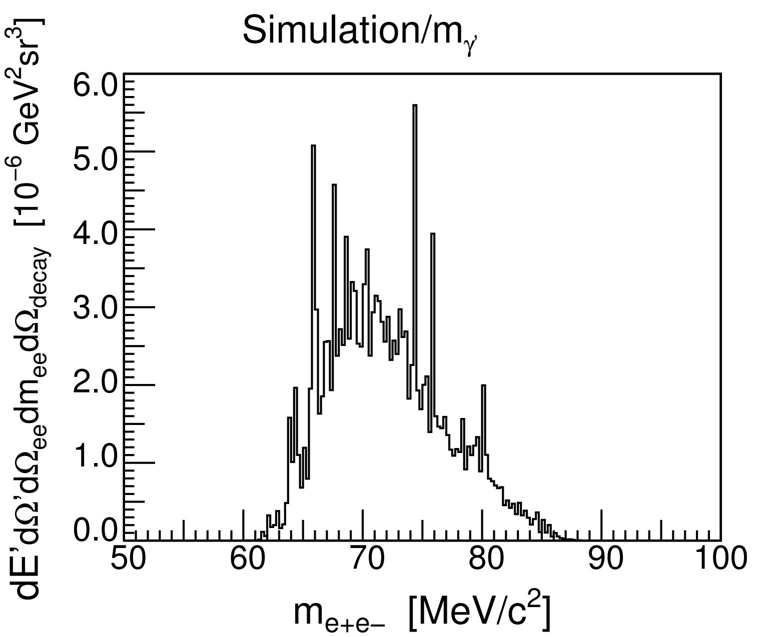


- Mass range $50\,\text{MeV} < m_{\gamma'} < 200\,\text{MeV}$
- 9 settings with different beam energy
- Need to improve simulation

Problems of simulation at low masses







Variance reduction with inverse transform sampling

Needed: generator with probability distribution

$$dy = \frac{1}{q^4} \sin\theta d\theta$$

Inverse transform sampling (Important: $m_e \neq 0$, i.e. $q^2 \neq -4\,E\,E' \sin^2\frac{\theta}{2}$):

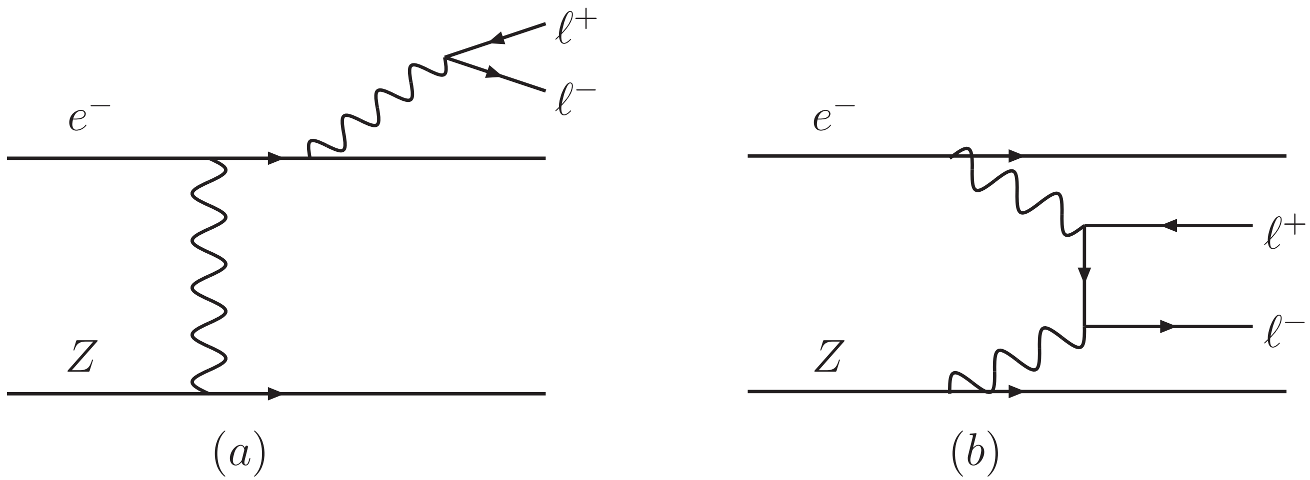
$$f(\theta') = \int_0^{\theta'} \frac{1}{q^4} \sin\theta \, d\theta = -\frac{1}{2\,p_0\,p'(p_0^2 + p'^2 - (E_0 - E')^2 - 2\,p_0\,p' \cos\theta')}$$

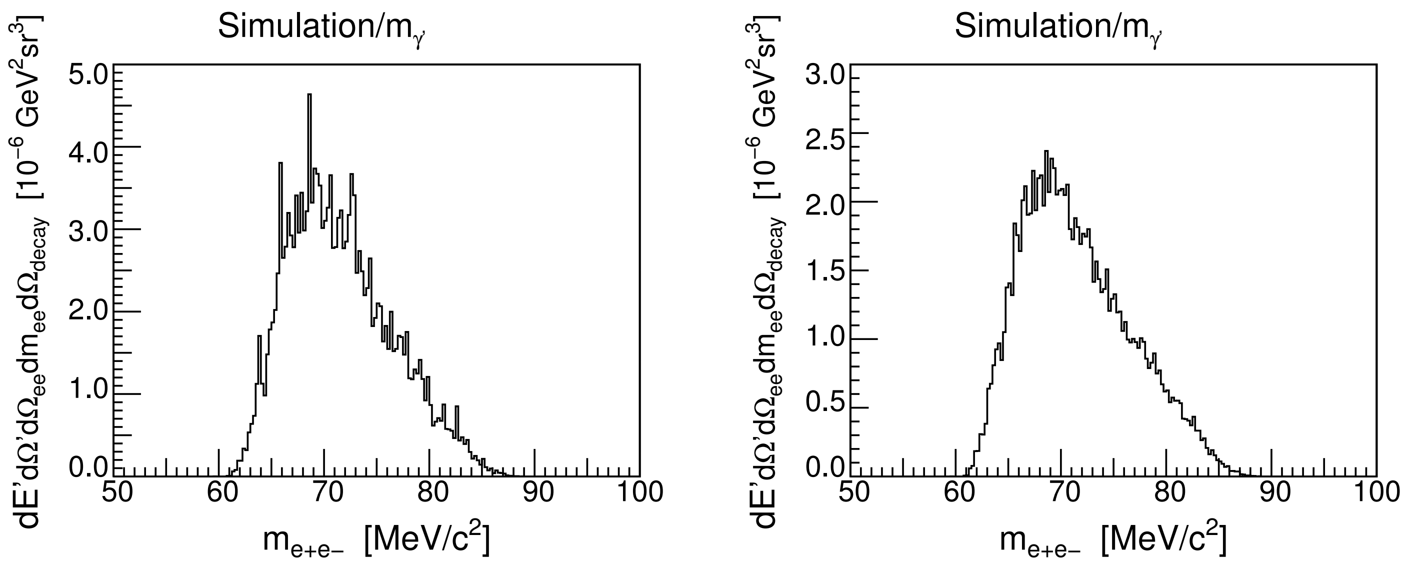
$\Rightarrow$ Inverse:

$$\theta = f^{-1}(y) = \text{arccos}\left(\frac{\frac{1}{y} + 2\,p_0\,p'(-(E_0 - E')^2 + p_0^2 + p'^2)}{4\,p_0^2\,p'^2}\right)$$

with random number $y \in [f(0), f(\pi)]$

Variance reduction with inverse transform sampling

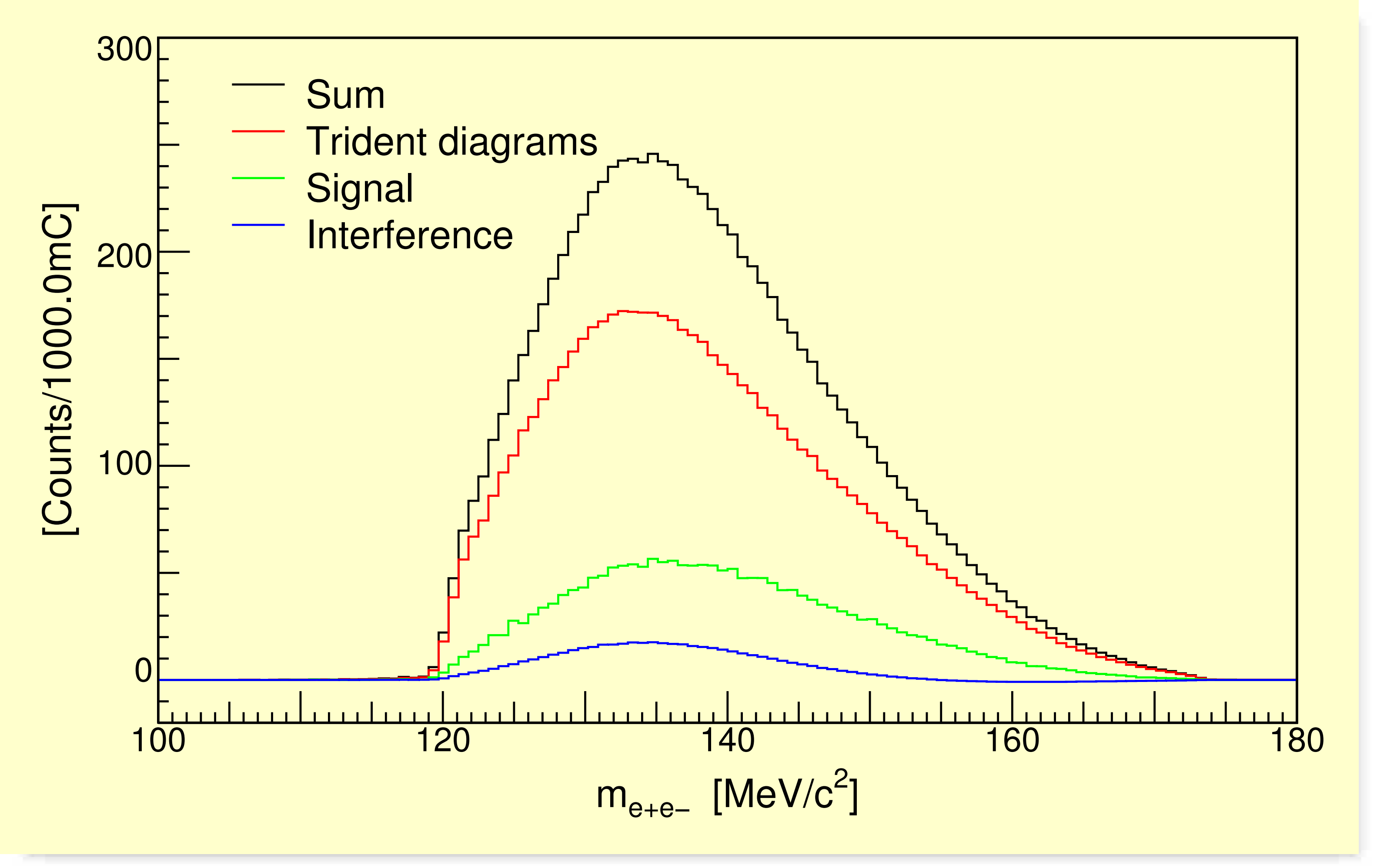




Solution: $|(a)+(b)|^2 = |(a)|^2 + 2\,(\mathrm{Re}(a)\mathrm{Re}(b)+\mathrm{Im}(a)\mathrm{Im}(b)) + |(b)|^2$

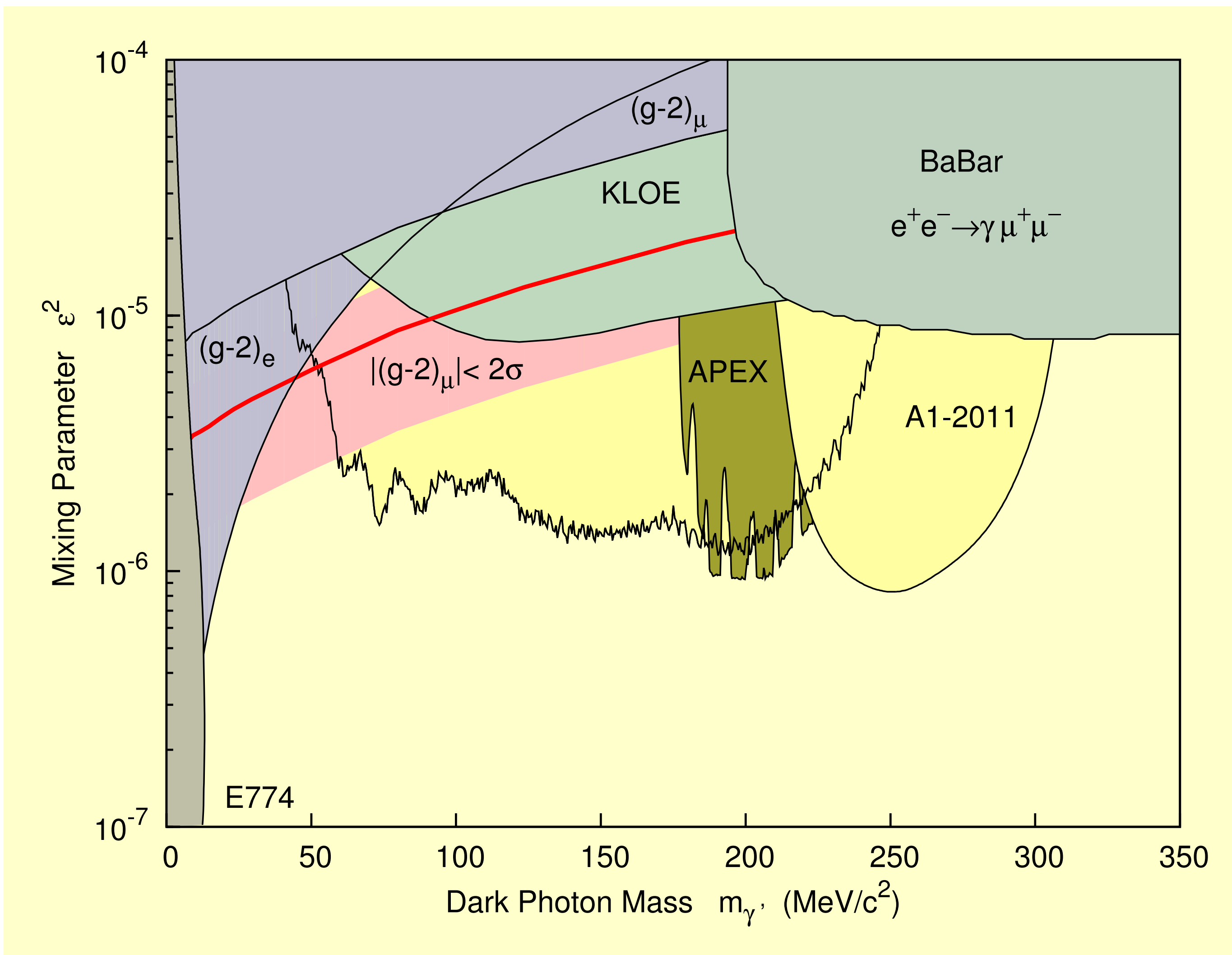
With weights divided by 1, $1/q^2$, $1/q^4$ (⇒negative weights!)

Separated Graphs

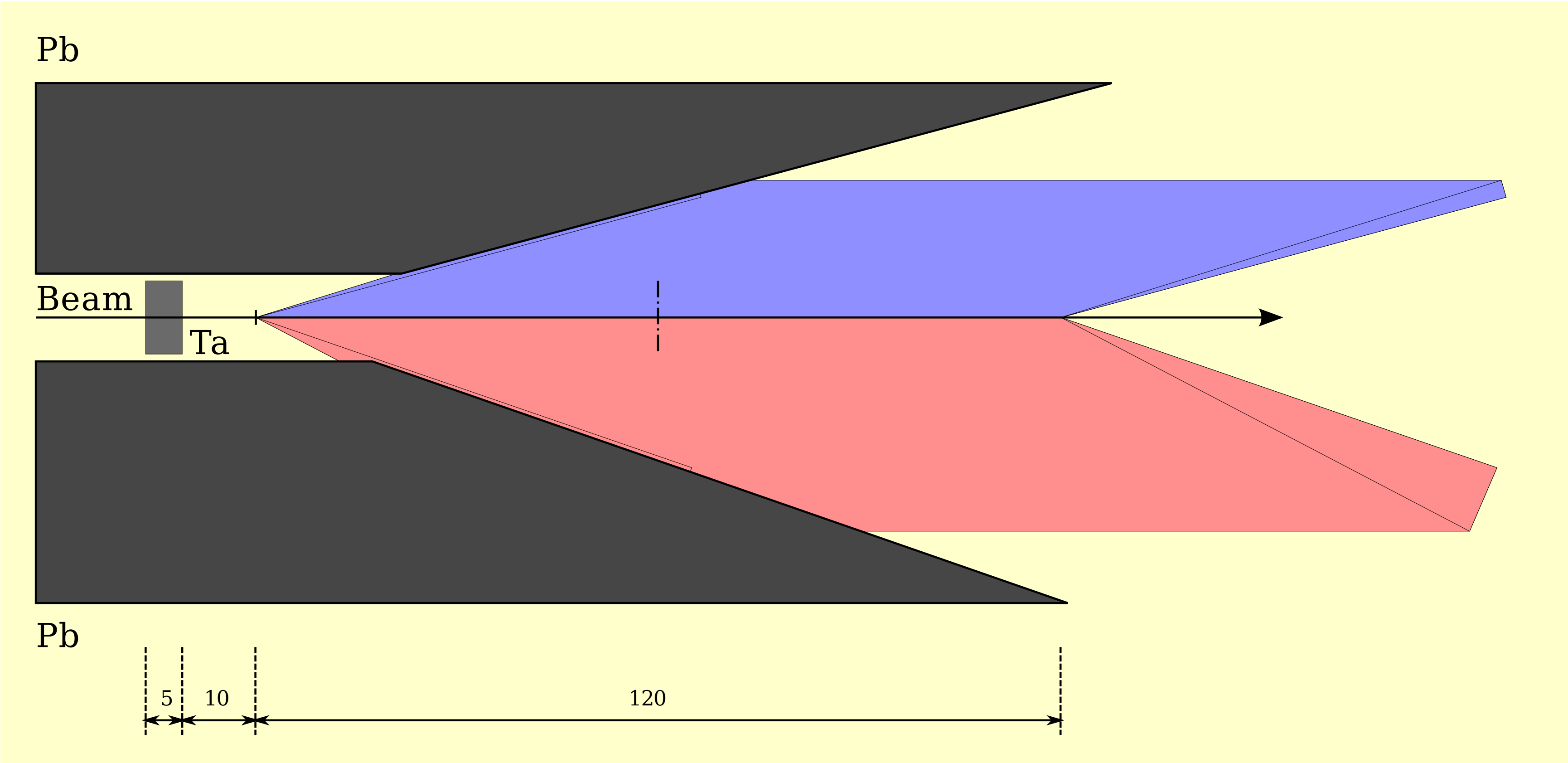


Extended mass range (data taking 2012, preliminary)

- Extension to lower mass region
- Several beam energy settings
- Lower mass limit: minimum angle between spectrometers

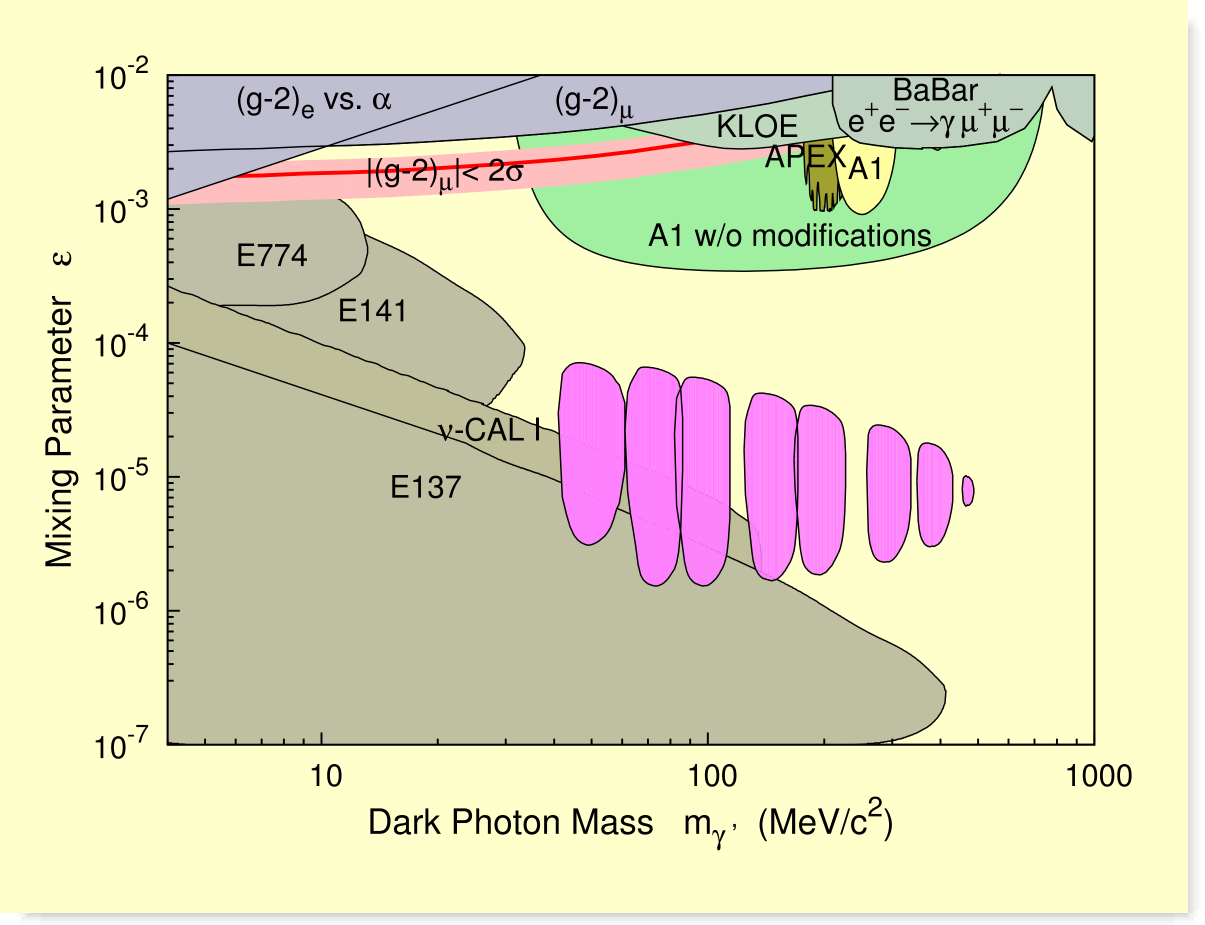


Step 2: Secondary vertex → small coupling



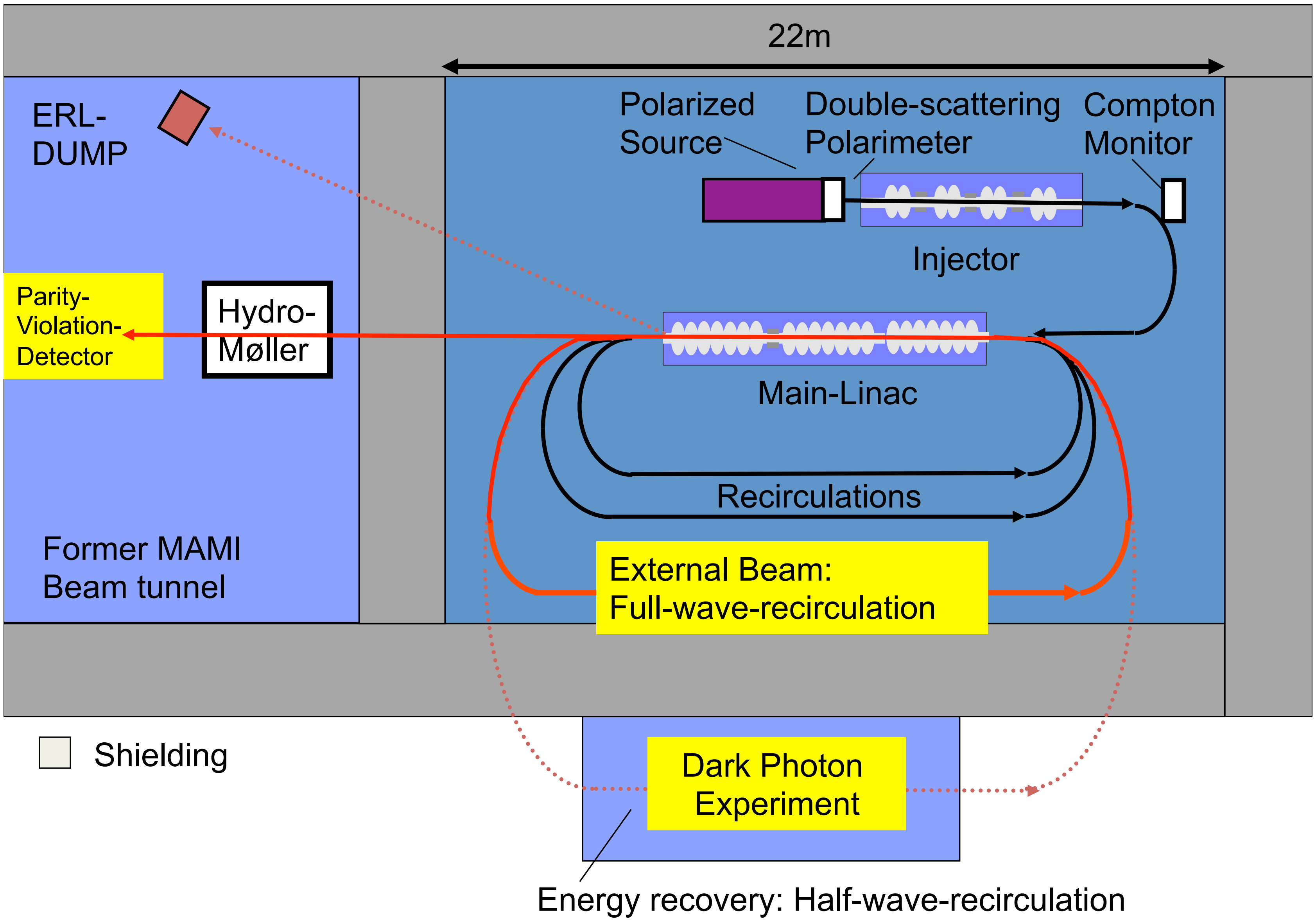
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c \tau =$4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm}^2}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

Step 2: Exclusion limits with shielded production vertex



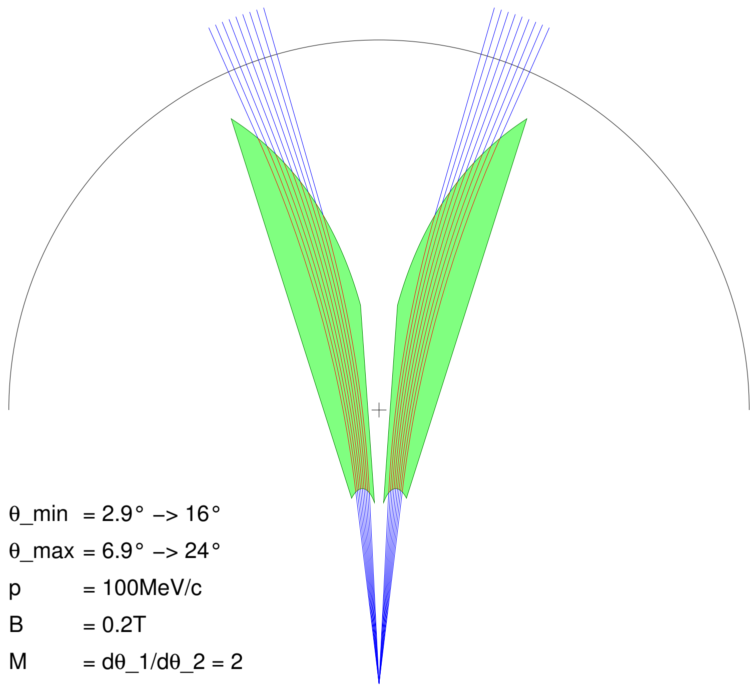
- Macroscopic decay vertex distance $\varepsilon < 10^{-4}$
- Luminosity $\varepsilon > 10^{-6}$
- Coupling vs lifetime $m_{\gamma'} < 500\,\mathrm{MeV}/c^2$
- Angular range $m_{\gamma'} > 30\,\mathrm{MeV}/c^2$

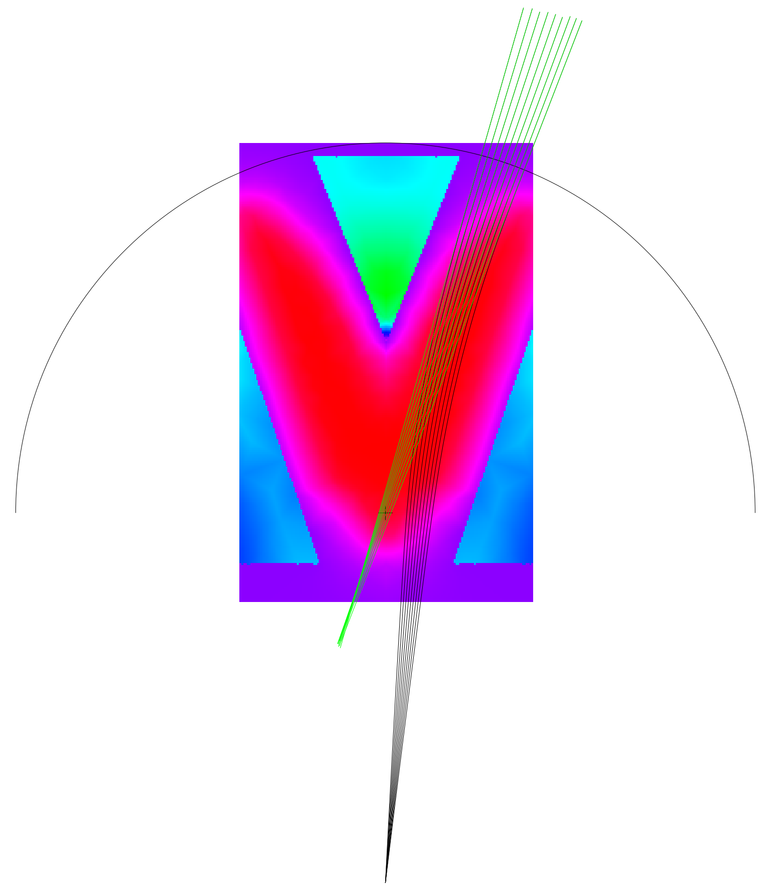
Step 3: Access to low mass region: MESA Accelerator



Energy recovering super-conducting linac $\Rightarrow L = 10^{35} \frac{1}{\mathrm{s\,cm^2}}$ with internal gas target

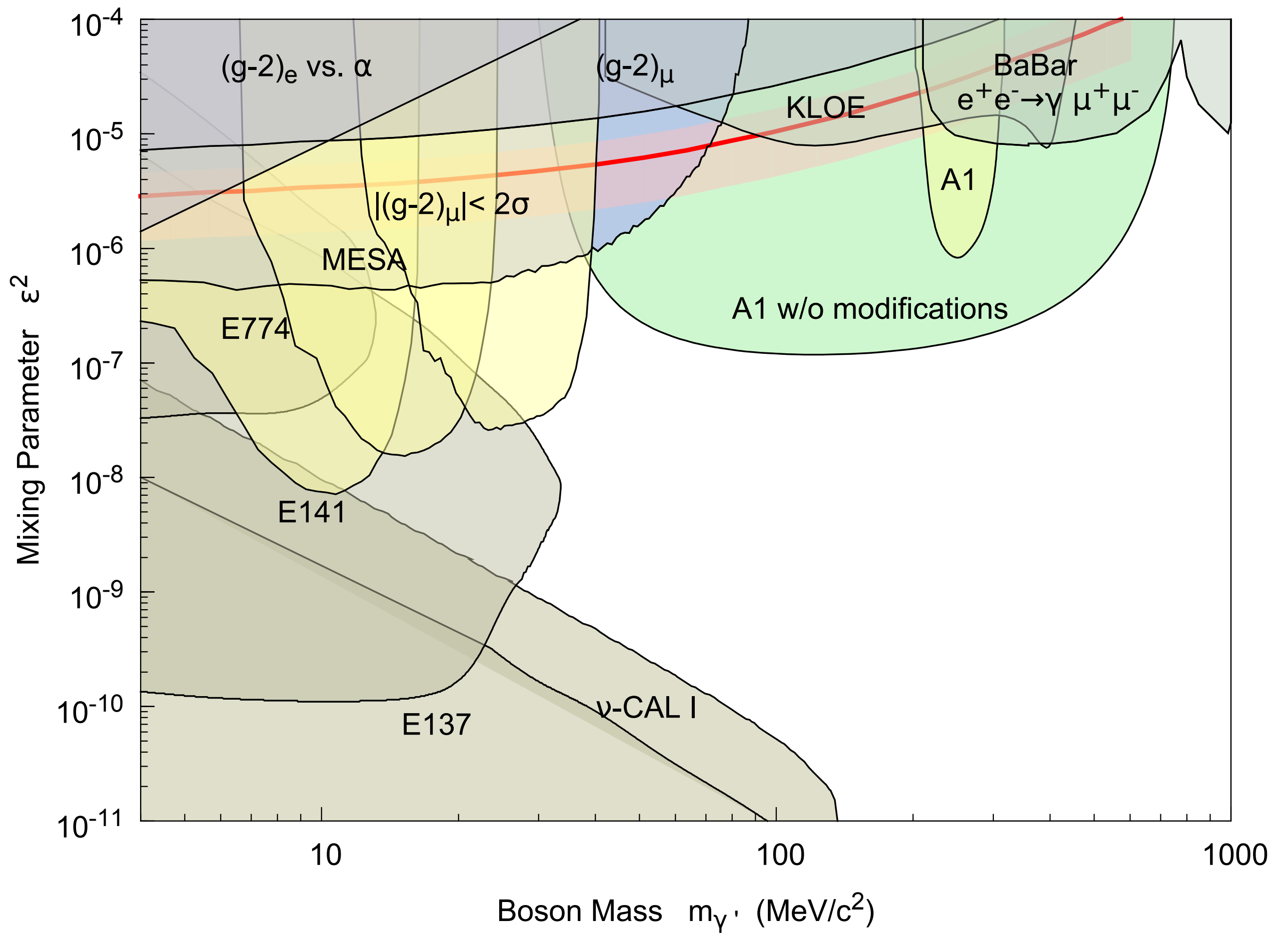
Magnifying Septum for the A1-Hall





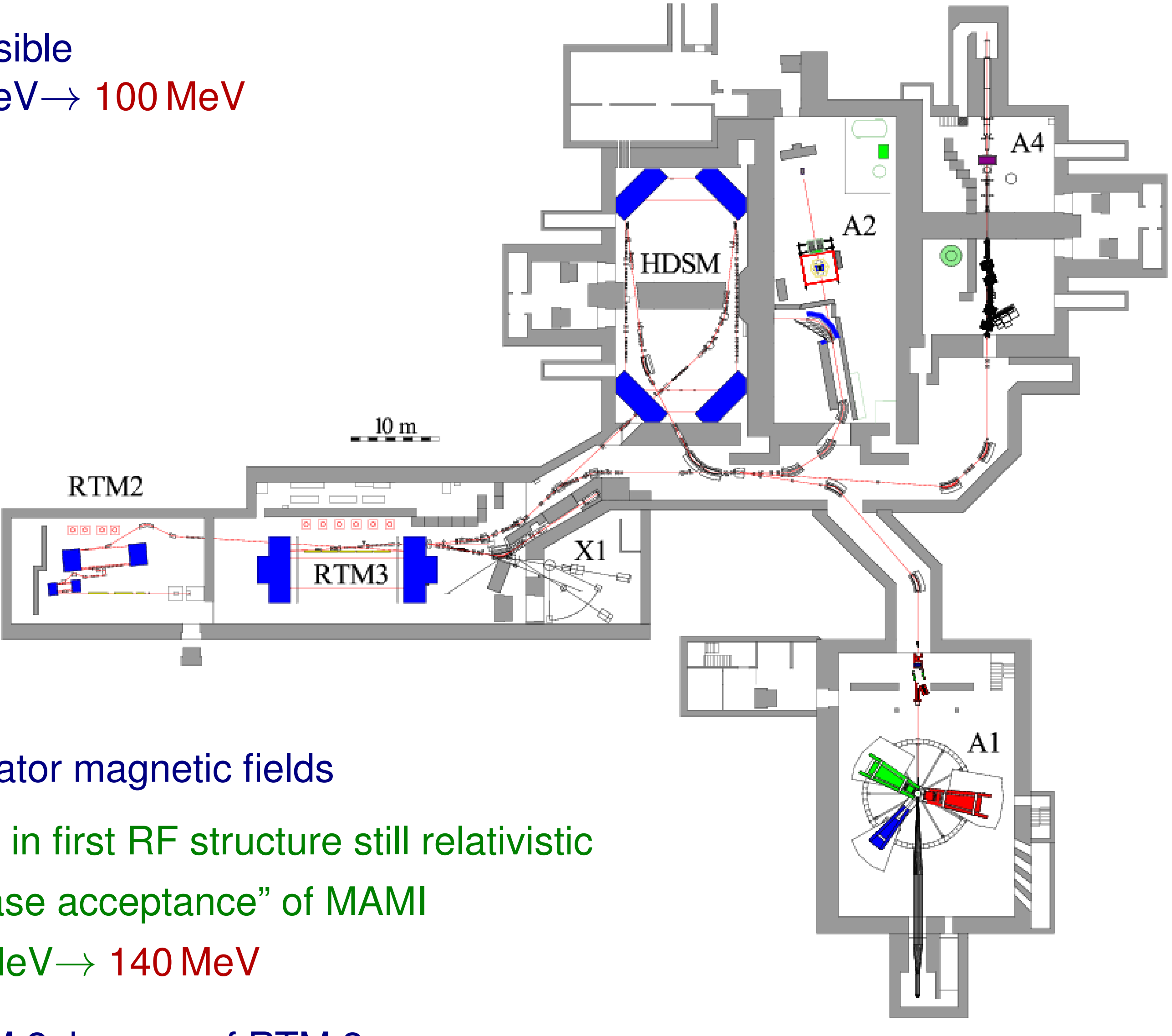
- Magnifying ($\approx \times 2$) septum to restore missing mass resolution
- Modest field values for low mass region $\rightarrow$ small (≈50 cm) normal conducting magnet
- Design studies with finite element calculations promising
- No extension to high mass region (KAOS 0°-Spectrometer instead, better at JLab?)

Exclusion limits for magnifying Septum in A1 Hall



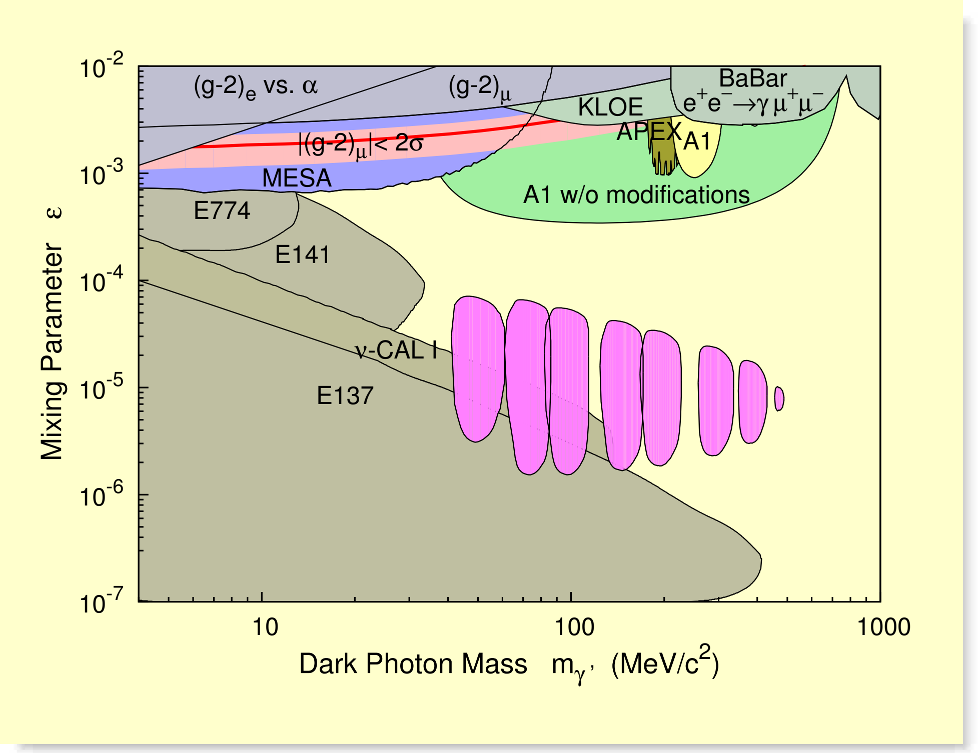
Minimal beam energy of the MAMI accelerator

- Low mass region is accessible with E_{Beam} reduced 180 MeV$\rightarrow$ 100 MeV



- Over-all scaling of accelerator magnetic fields
  - Scaling limit: electrons in first RF structure still relativistic
  - Exploring limits of "phase acceptance" of MAMI
  - So far achieved: 180 MeV$\rightarrow$ 140 MeV
- 100 MeV extraction of RTM 2, bypass of RTM 3
  - Historic 100 MeV extraction chamber is still available
  - Short part of a new beamline neccessary $\approx$ 4 dipole magnets

Summary



- 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 $10^{-6} < \varepsilon < 10^{-4}$
- Discrepancy on $(g-2)_\mu$
  - Region will be covered in the near future