

SEARCH FOR THE DARK PHOTON AT MAINZ

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➊ Motivation

- ▶ The γ' Boson (“Dark Photon”)

➋ How can we detect a “Dark Photon”?

- ▶ Di-Lepton-Production
- ▶ Cross sections

➌ Experiments at the Mainz Microtron (MAMI)

- ▶ Pilot Experiment
- ▶ Results

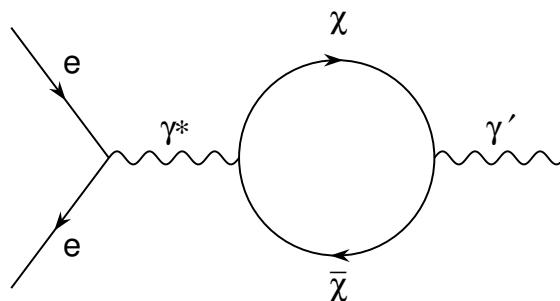
➍ Experimental program at MAMI and other electron facilities

➎ Summary

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

- Proposed massive $U(1)$ gauge boson of the dark matter sector
- Theoretical well motivated
- Kinetic mixing with the ordinary photon γ

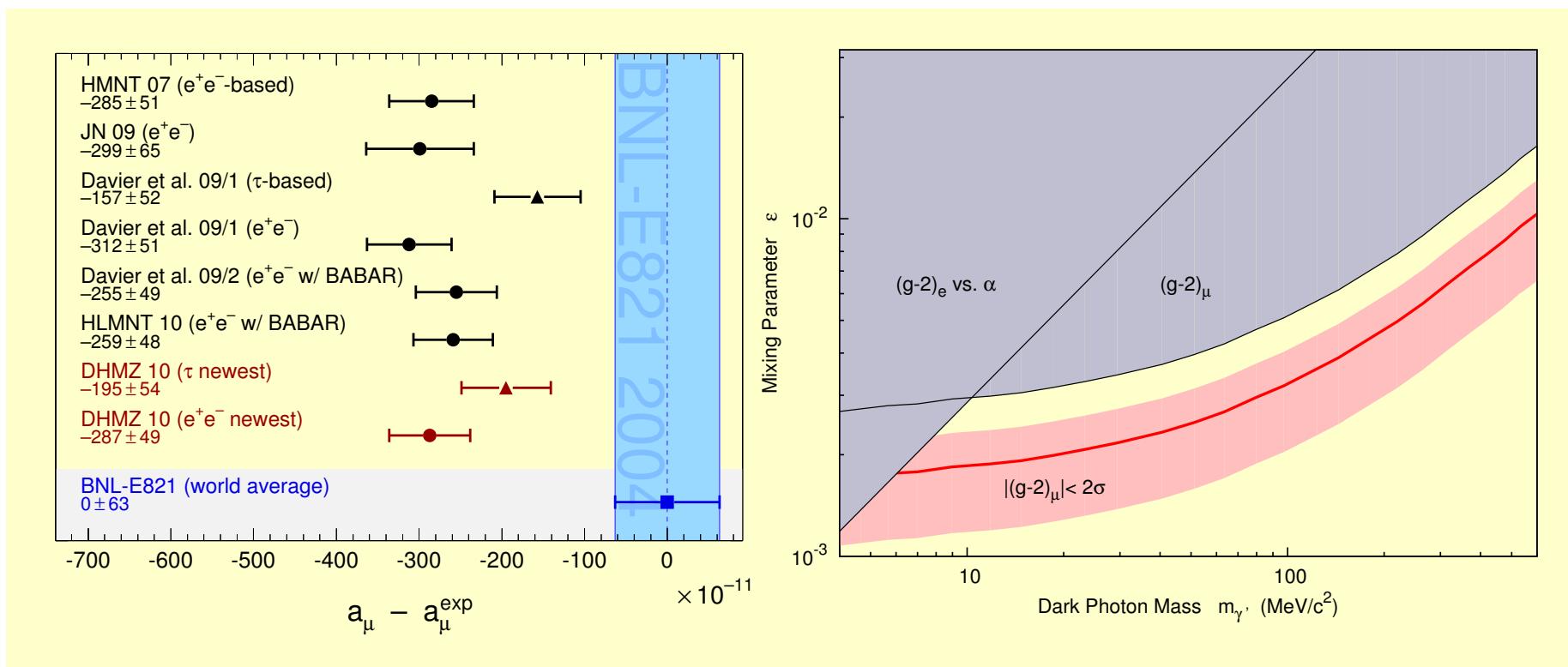
B. Holdom, Phys. Lett. B 166 (1986) 196



$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu}^{\text{SM}} F_{\text{SM}}^{\mu\nu} - \frac{1}{4} F_{\mu\nu}^{\text{hidden}} F_{\text{hidden}}^{\mu\nu} + \frac{\epsilon}{2} F_{\mu\nu}^{\text{SM}} F_{\text{hidden}}^{\mu\nu} + m_\gamma^2 A_\mu^{\text{hidden}} A_\mu^{\text{hidden}}$$

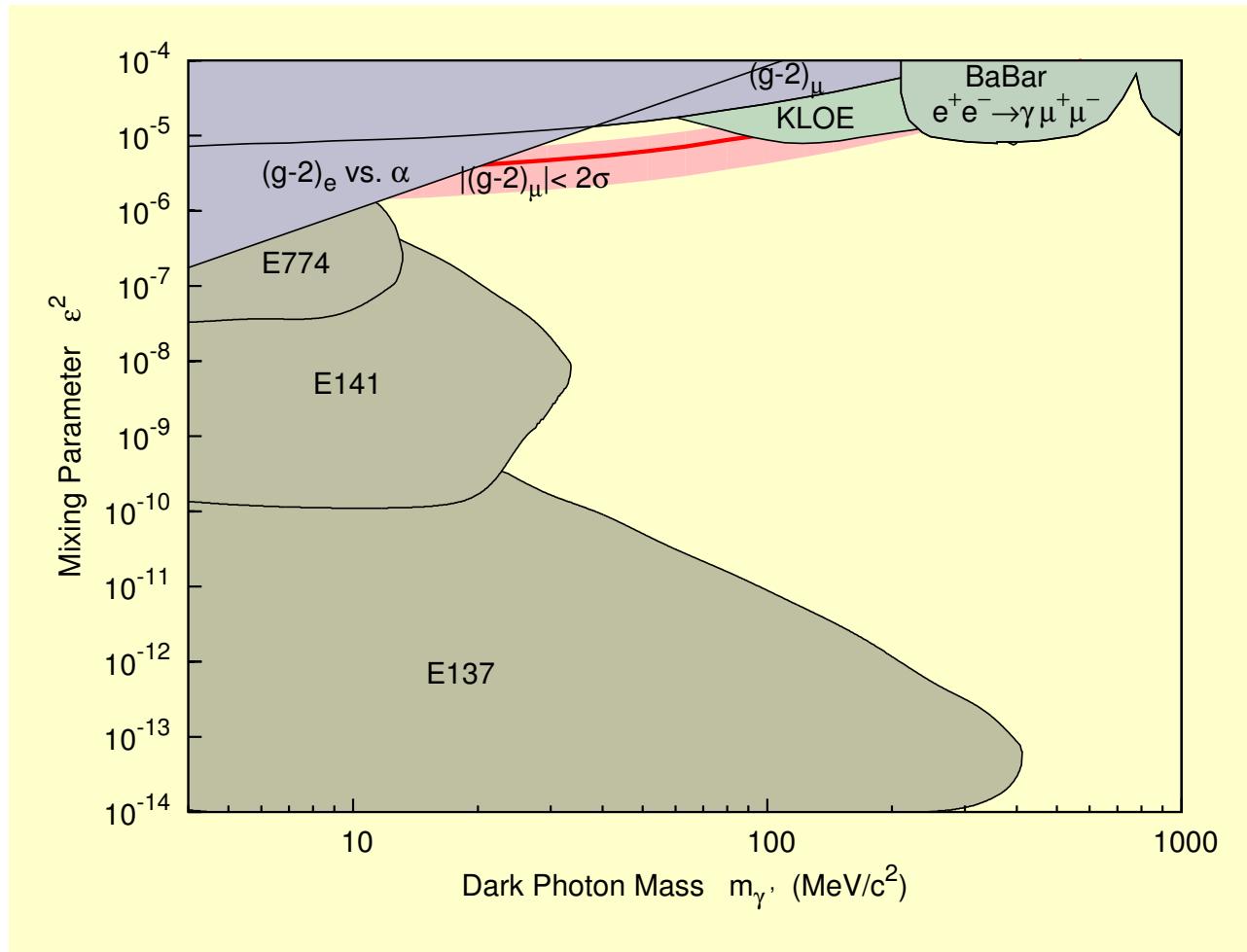
- Mixing parameter ϵ of γ'/γ mixing
- Experimental evidence?
 - ▶ Astro-physical phenomena, e.g. positron excess in cosmic rays
 - ▶ Precision experiments, e.g. $g - 2$ of the muon
 - ▶ Summary: N. Arkani-Hamed, *et al.*, Phys. Rev. D 79 (2009) 015014

Anomalous magnetic moment of the muon



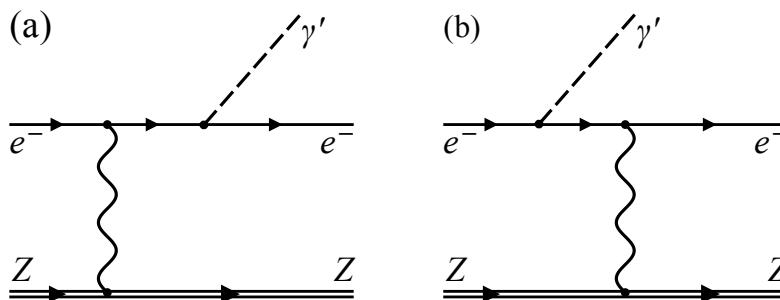
- ➊ Precision measurement of $(g - 2)$ of the muon at BNL
- ➋ Significant discrepancy with Standard Model calculations
- ➌ Possible explanation: Additional $U(1)$ boson γ' in loop graphs

Parameter range for mass and coupling of γ' boson



- Constraints from astro-physics and cosmology
- Interesting range: $10^{-8} < \varepsilon < 10^{-2}$ $10\text{MeV} < m_{\gamma'} < 1000\text{MeV}$
- Energy range of MAMI!

Quasi-real Photo-Production off heavy target



Weizsäcker-Williams approximation:

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

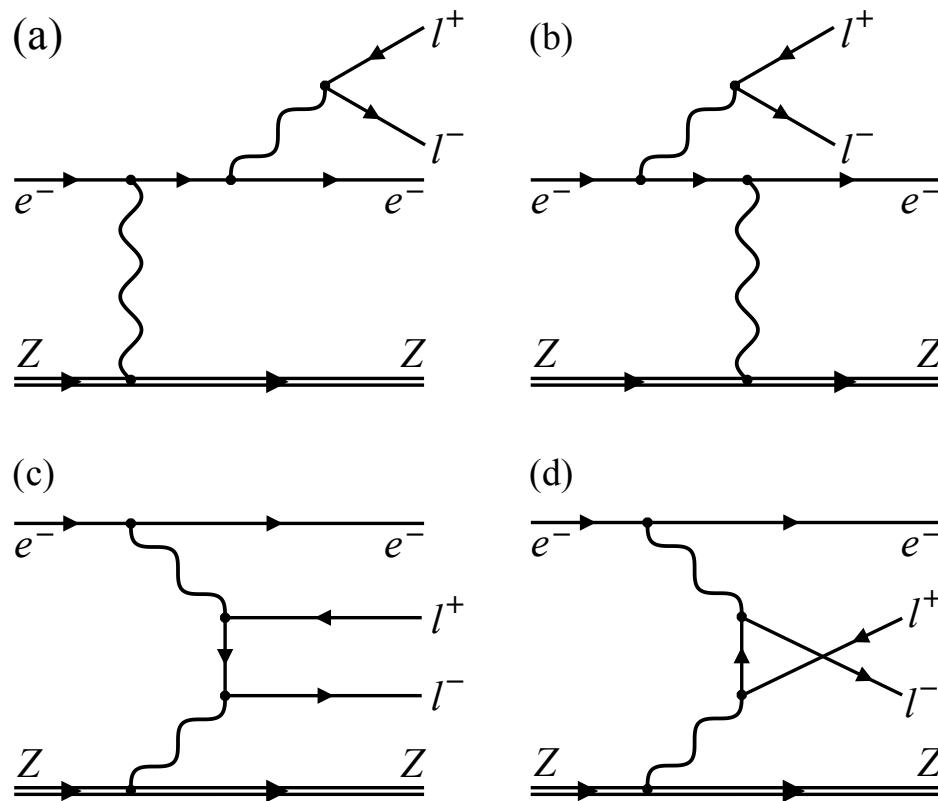
with $x = \frac{E_{\gamma'}}{E_0}$

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

Lifetime:

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

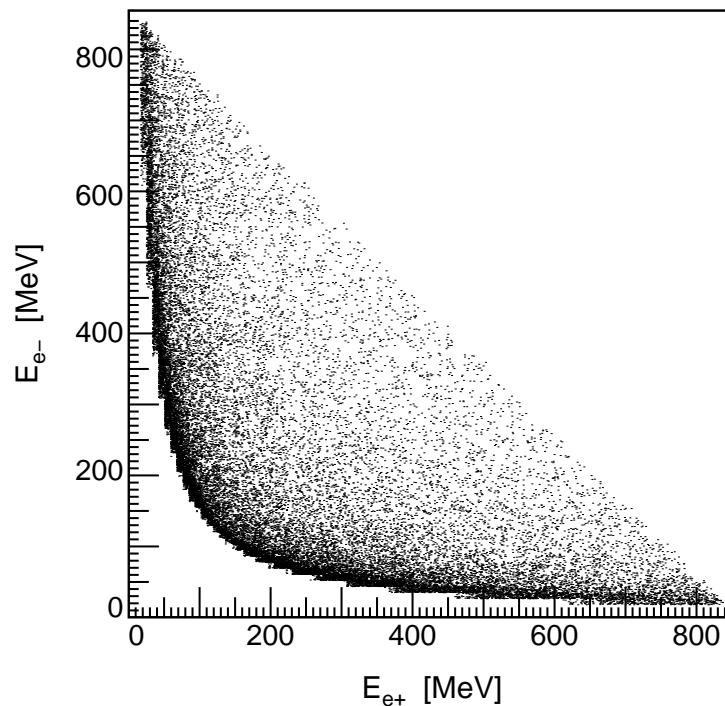
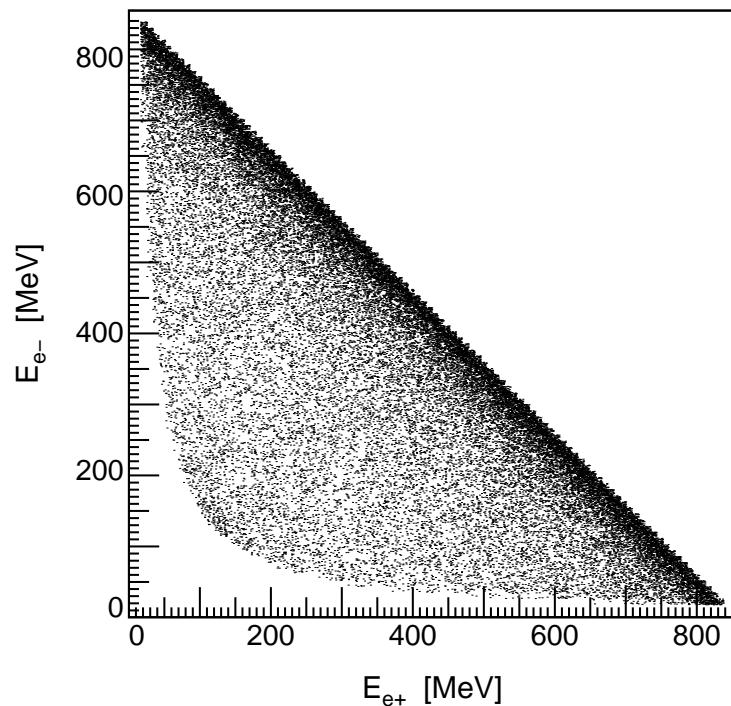
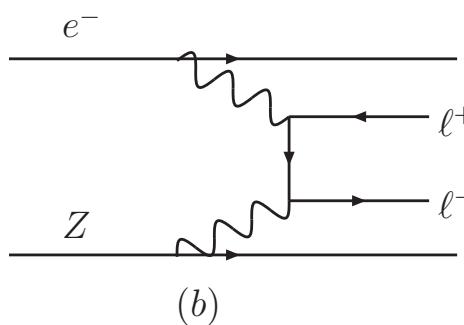
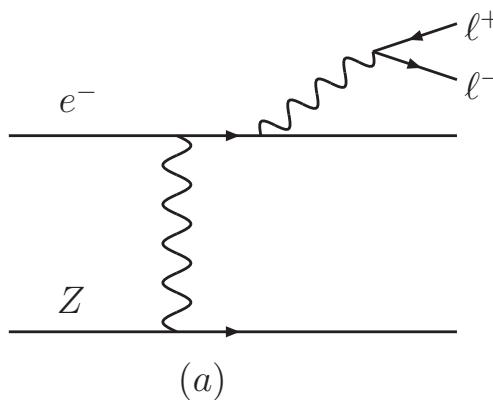
Backgrounds



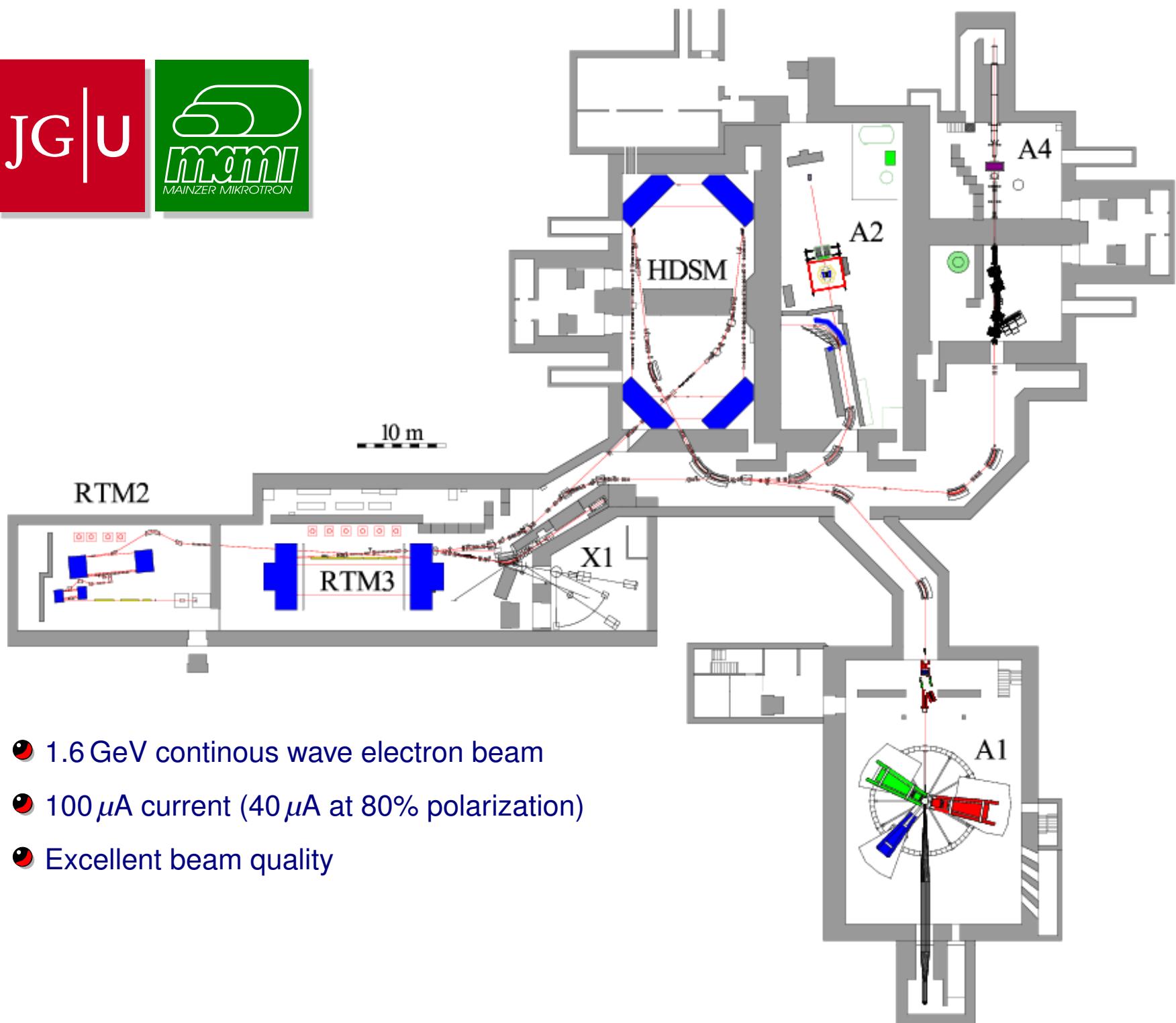
- ➊ Virtual photon instead of γ'
- ➋ Calculable in QED
- ➌ (a), (b): Same shape of cross section \Rightarrow Not separable
- ➍ (c), (d): Peak for l^* on mass shell \Rightarrow Suppression by kinematics

Other backgrounds: Measurement!

Bethe-Heitler Background



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



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:

$$\alpha > 55^\circ$$

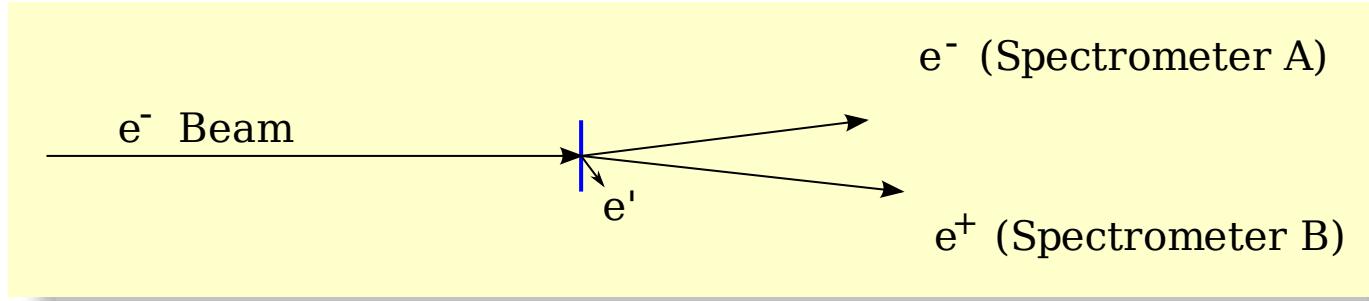
$$p < 655 \frac{\text{MeV}}{c}$$

$$\Delta\Omega = 28 \text{ msr}$$

$$\Delta p/p = 25\%$$

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

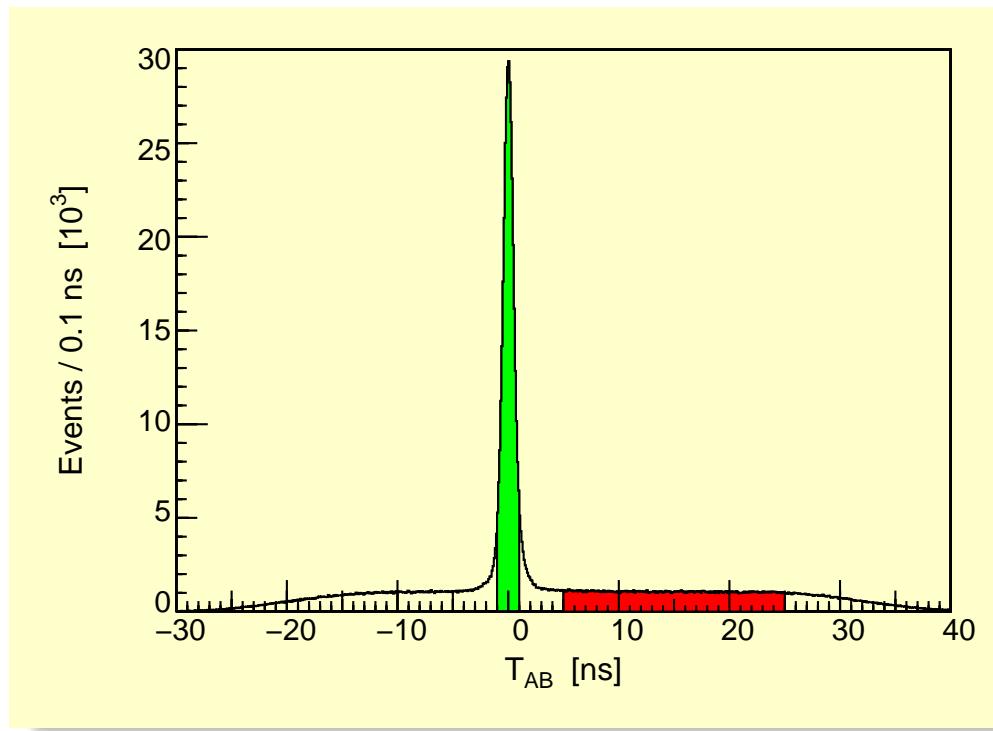
Pilot experiment



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

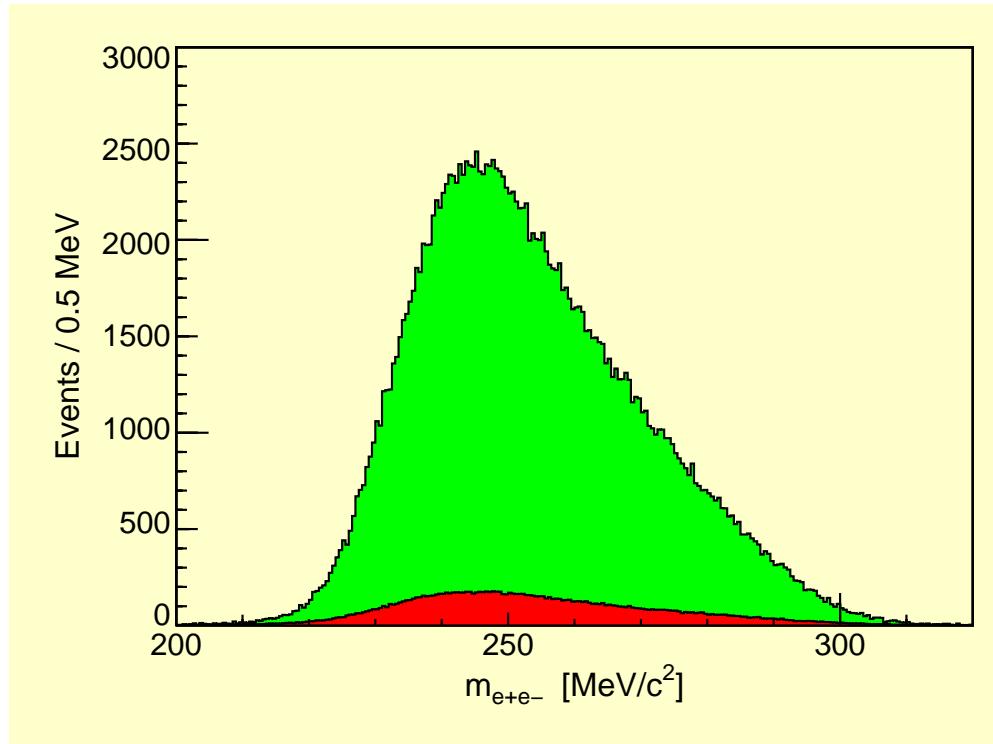
Beam energy	$E_0 = 855.0 \text{ MeV}$
Spectrometer A	$p_{e^-} = 338.0 \text{ MeV}/c$
	$\theta_{e^-} = 22.8^\circ$
Spectrometer B	$p_{e^+} = 470.0 \text{ MeV}/c$
	$\theta_{e^+} = 15.2^\circ$

Reaction identification: coincidence time



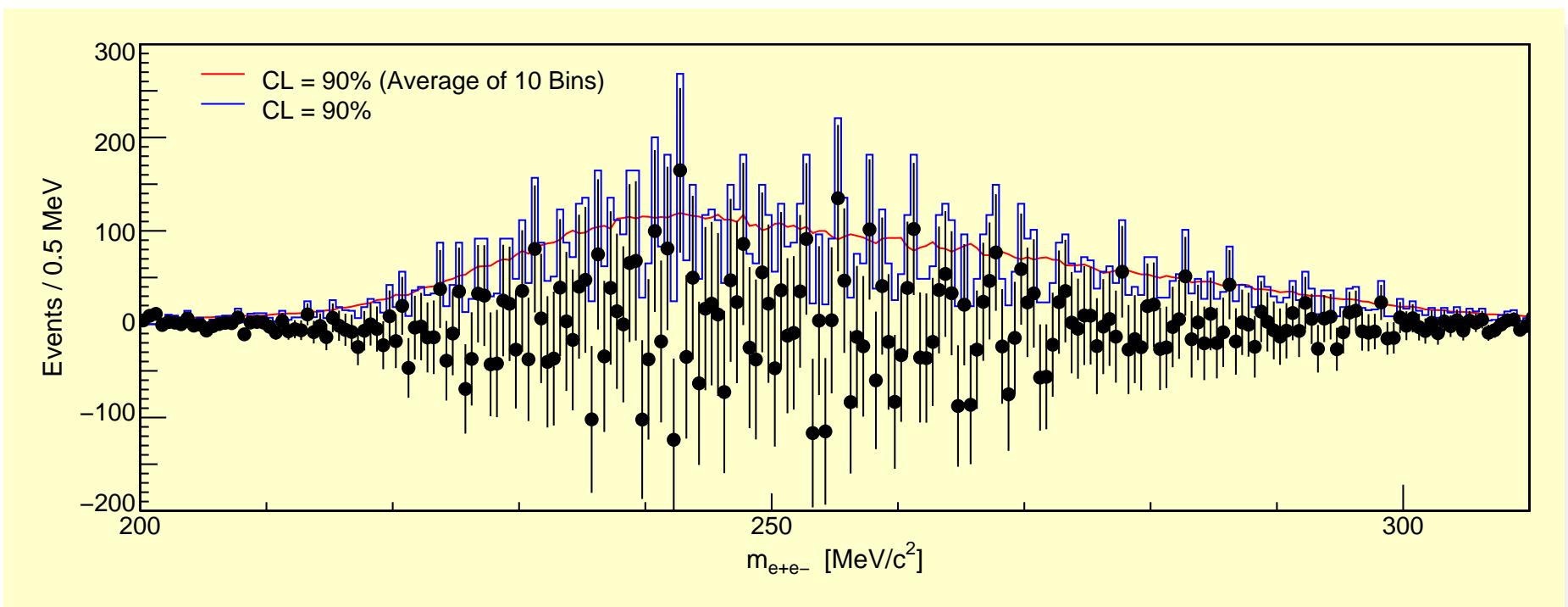
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\text{ m}$
⇒ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\text{ ns FWHM}$
- Estimate of background: side band $5\text{ ns} < T_{A \wedge B} < 25\text{ ns}$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

Invariant mass of e^+e^- pair



● Mass of e^-e^+ pair $m_{\gamma'}^2 = (e^- + e^+)^2$

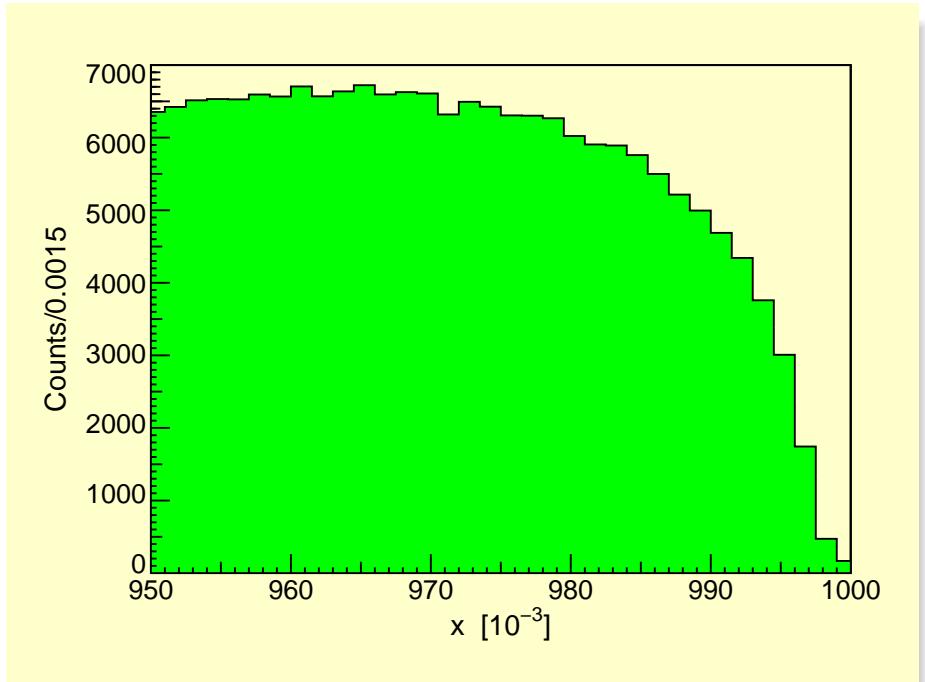
Exclusion limits



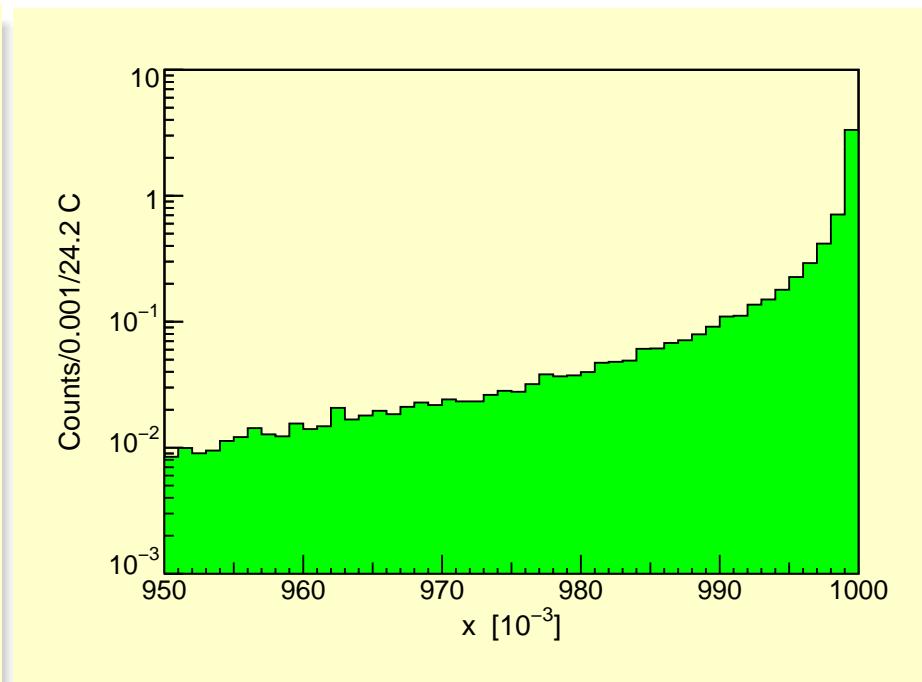
- Confidence interval by Feldman-Cousins algorithm
- “Model” for Background-subtraction:
average of 3 Bins left and right of central bin
- Resolution $\delta m < 500 \text{ keV} = \text{bin width}$
- Averaging (mean of 10 bins) only for “subjective judgment”

Problem: model for cross section

Experiment:

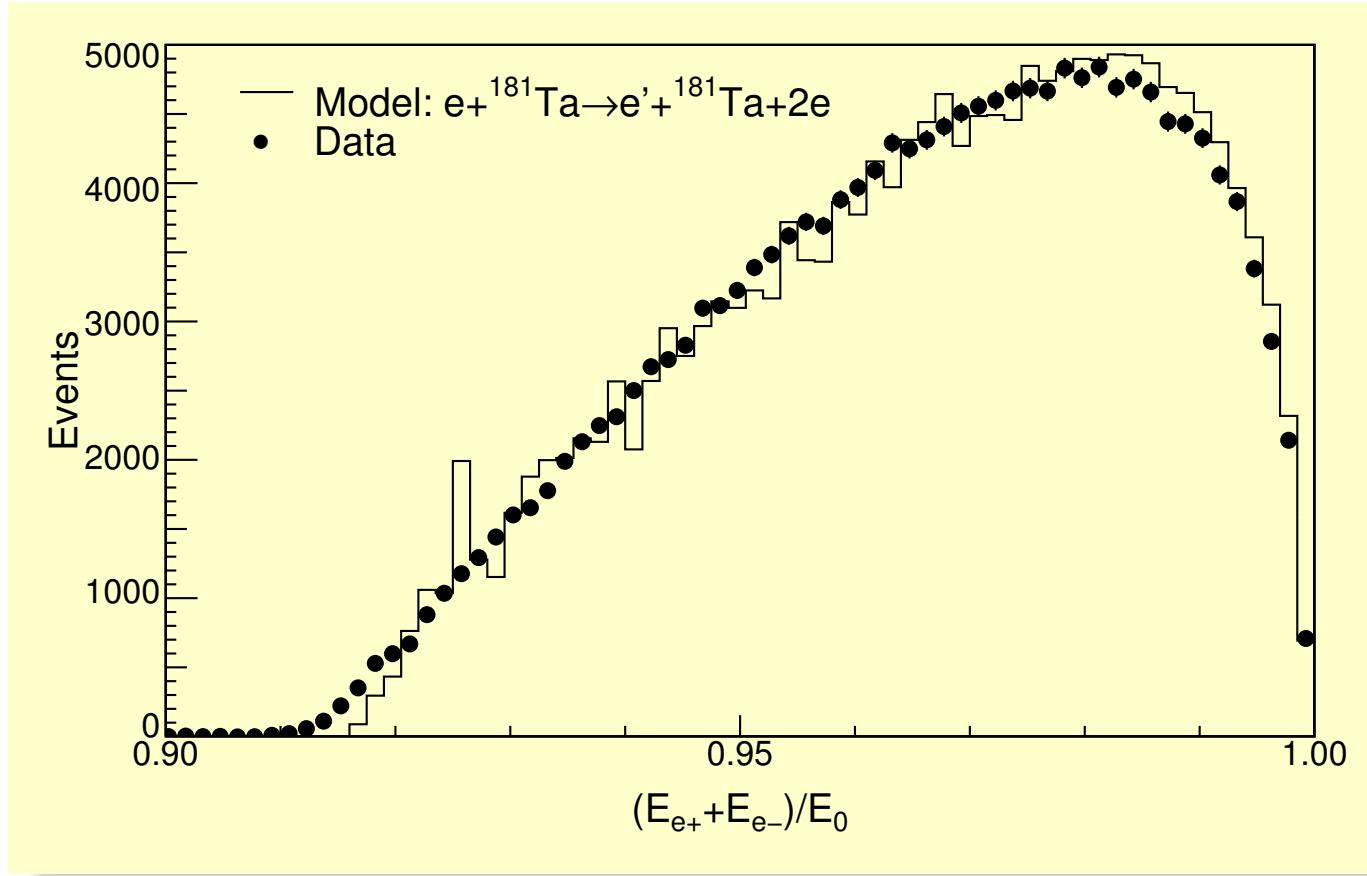


Simulation with Weizsäcker-Williams:



- Fraction of transferred energy $x = E_{\gamma'}/E_0$
- Weizsäcker-Williams approximation does *not* correspond to experiment
- Reason: neglected phase space of recoiling nucleus at $x = 1$, electron mass neglected

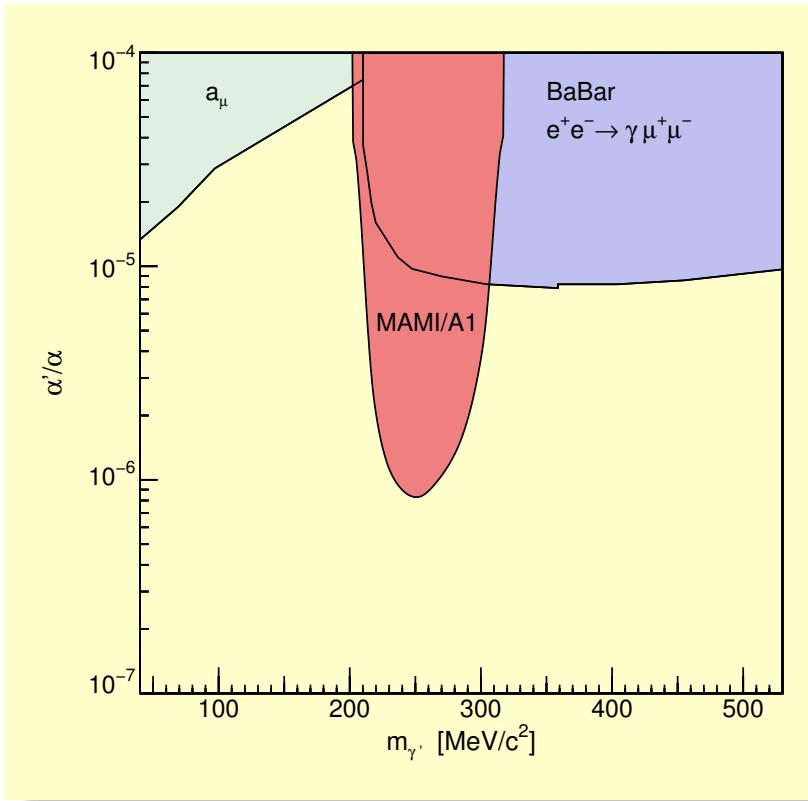
Improved Model



- ➊ Full Simulation
- ➋ Model: Coherent electro production off heavy nucleus
- ➌ Q.E.D., nuclear form factor, coherent sum of all contributions, radiative corrections, ...
- ➍ Exact 1st order in four diagrams for background, 2 diagrams for signal

⇒ Describes data within a few percent

Exclusion limit for mixing parameter ε

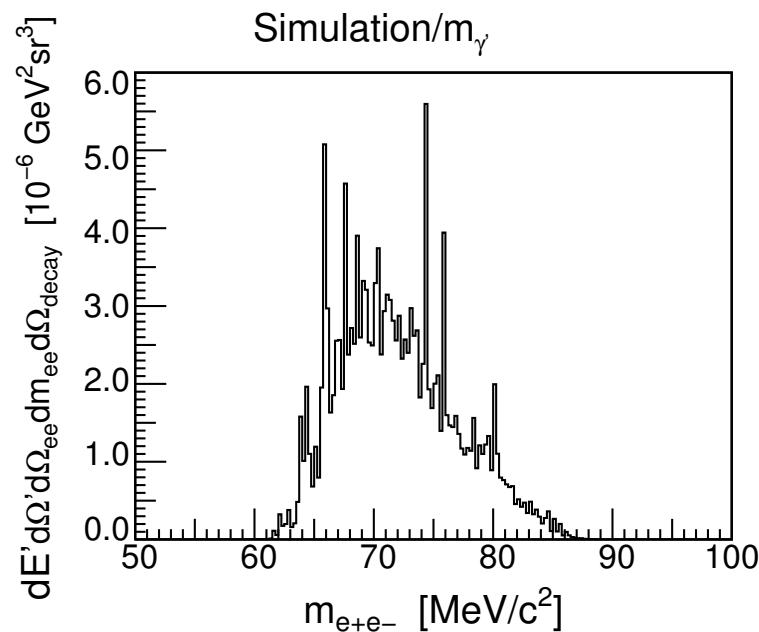
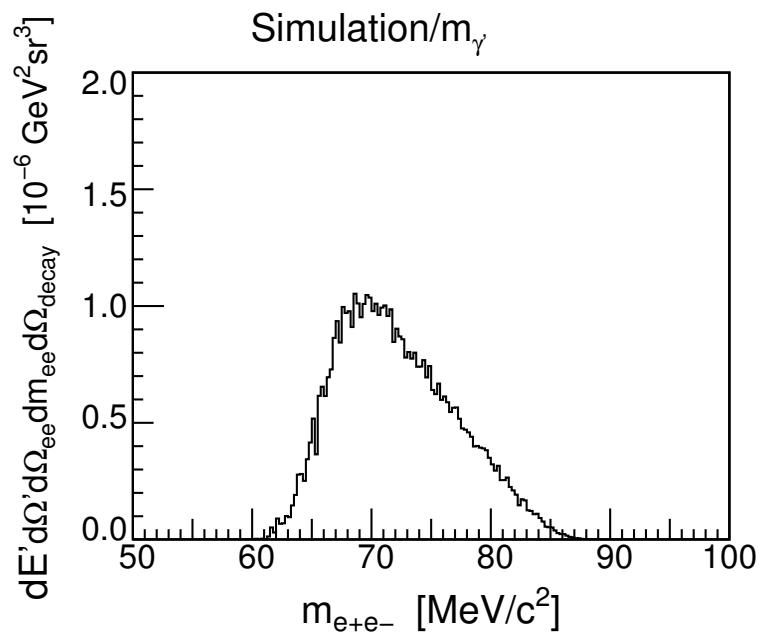
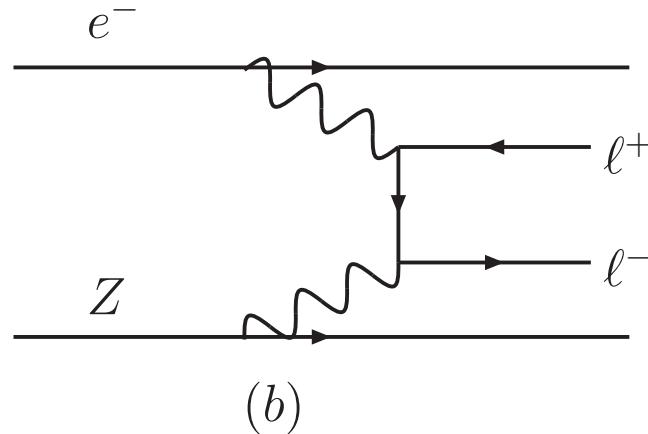
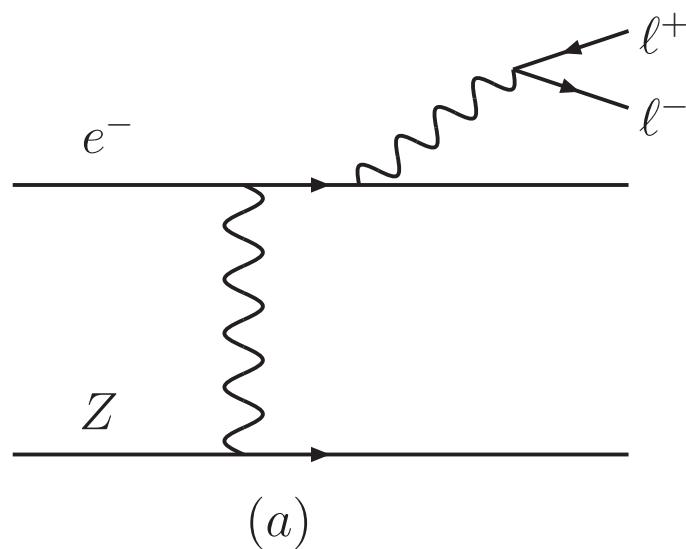


- ⌚ Accidental background + Q.E.D. background
- ⌚ Model deviates only on nuclear vertex, both for γ' and γ^*
- ⌚ Conversion from ratio of cross sections:

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

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

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. $q^2 \neq -4 E E' \sin^2 \frac{\theta}{2}$):

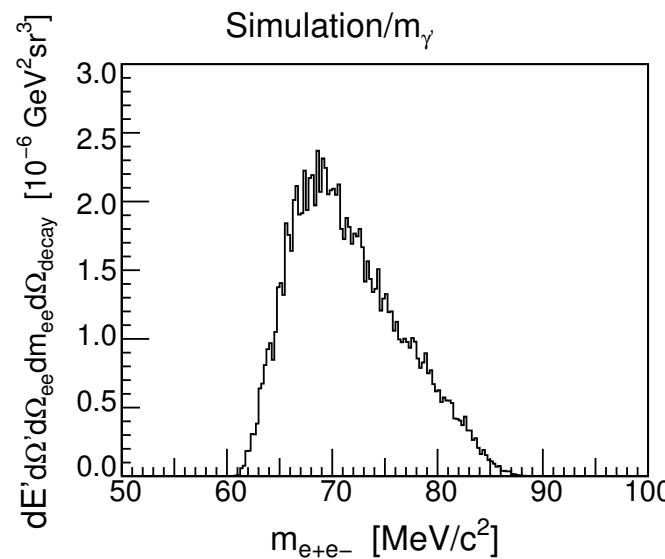
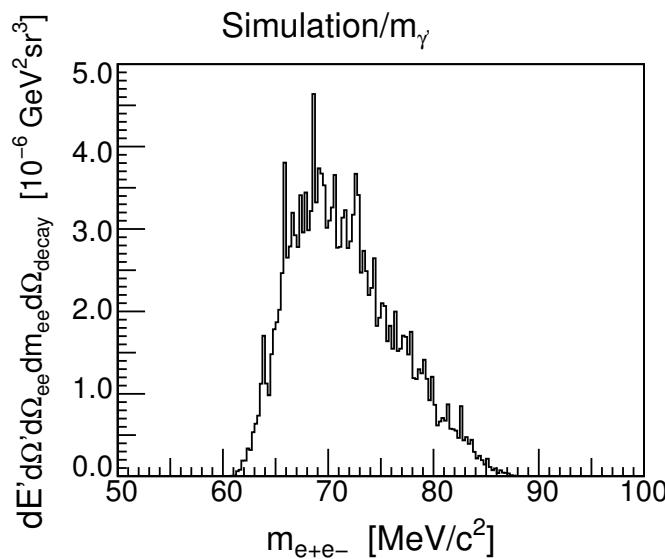
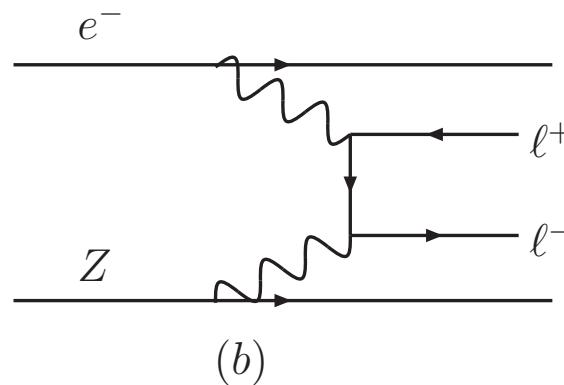
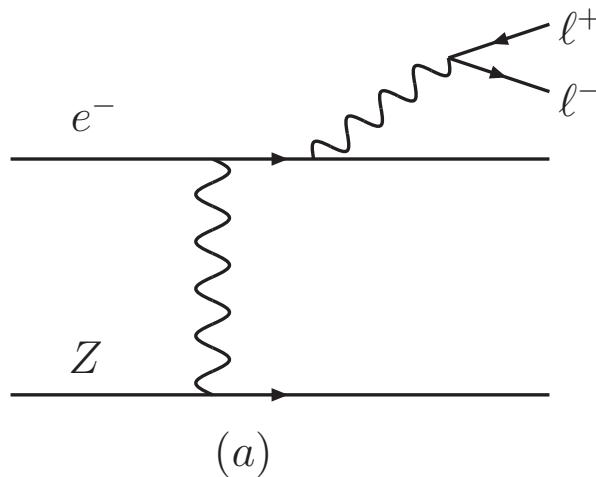
$$f(\theta') = \int_0^{\theta'} \frac{1}{q^4} \sin \theta d\theta = -\frac{1}{2 p_0 p' (p_0^2 + p'^2 - (E_0 - E')^2 - 2 p_0 p' \cos \theta')}$$

⇒ Inverse:

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

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

Variance reduction with inverse transform sampling

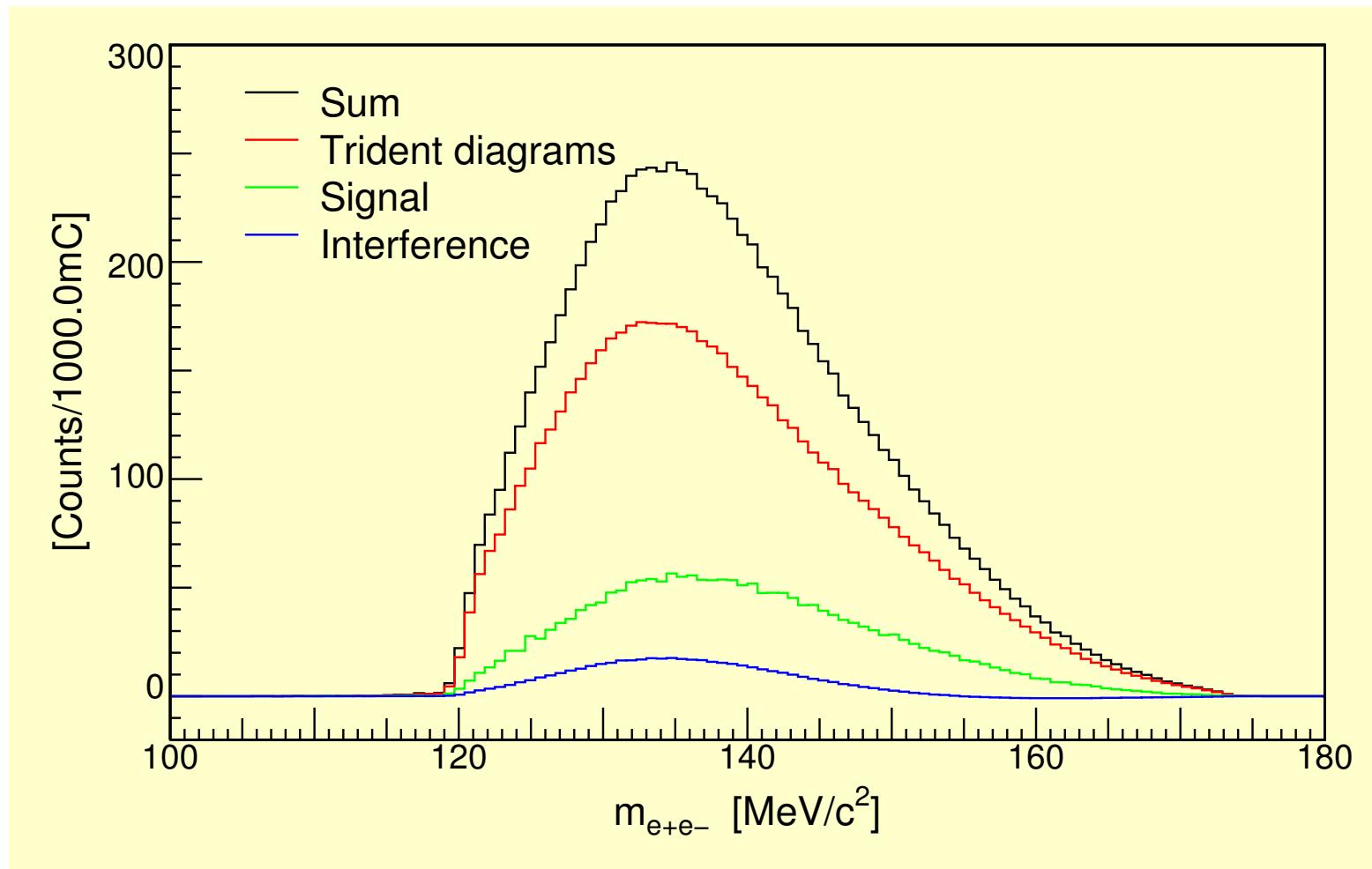


Solution: $| (a) + (b) |^2 = | (a) |^2 + 2(\text{Re}(a)\text{Re}(b) + \text{Im}(a)\text{Im}(b)) + | (b) |^2$

With weights divided by $1, 1/q^2, 1/q^4$

(\Rightarrow negative weights!)

Separated Graphs

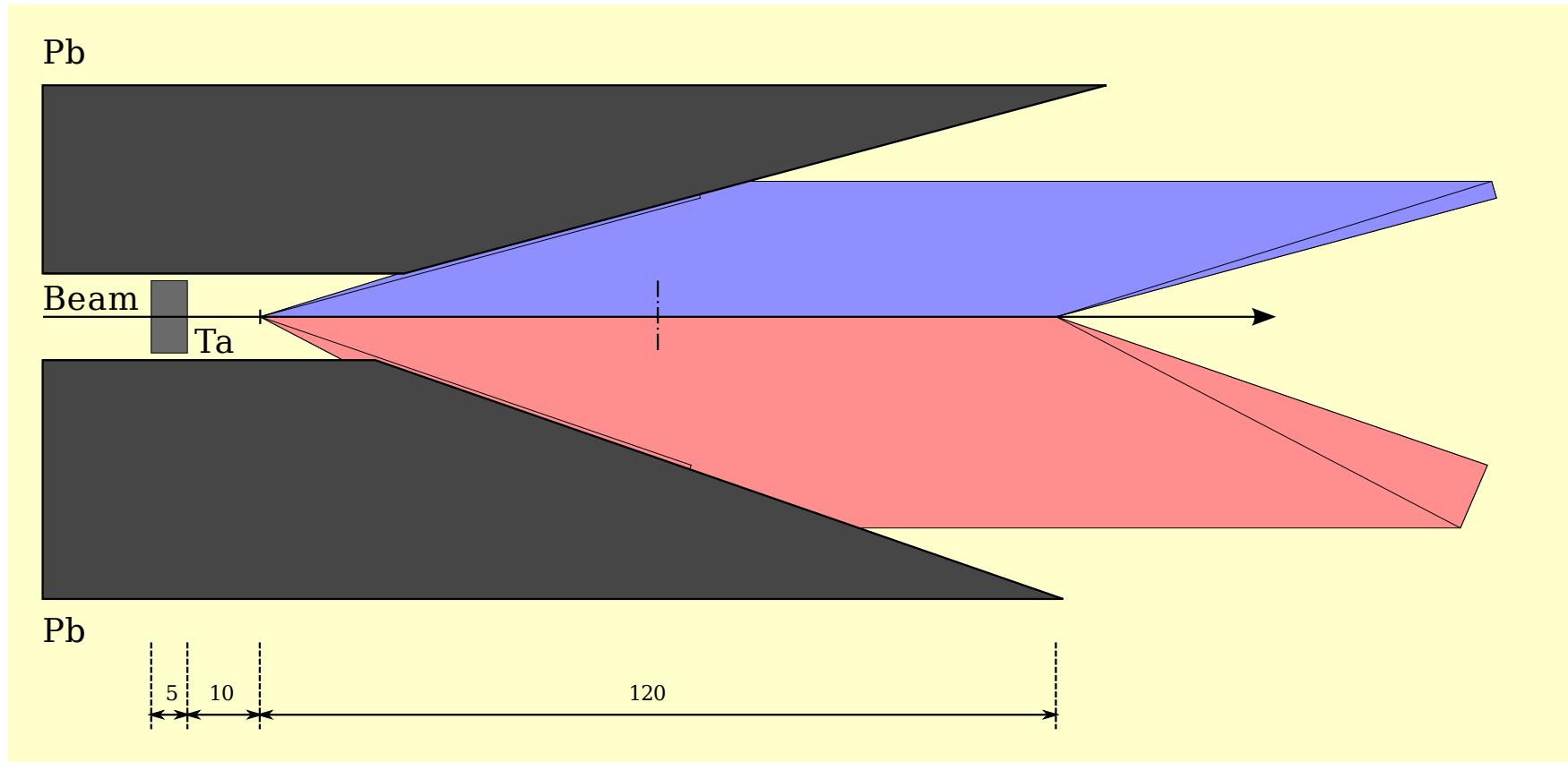


Extended mass range (data taking this year, preliminary)

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

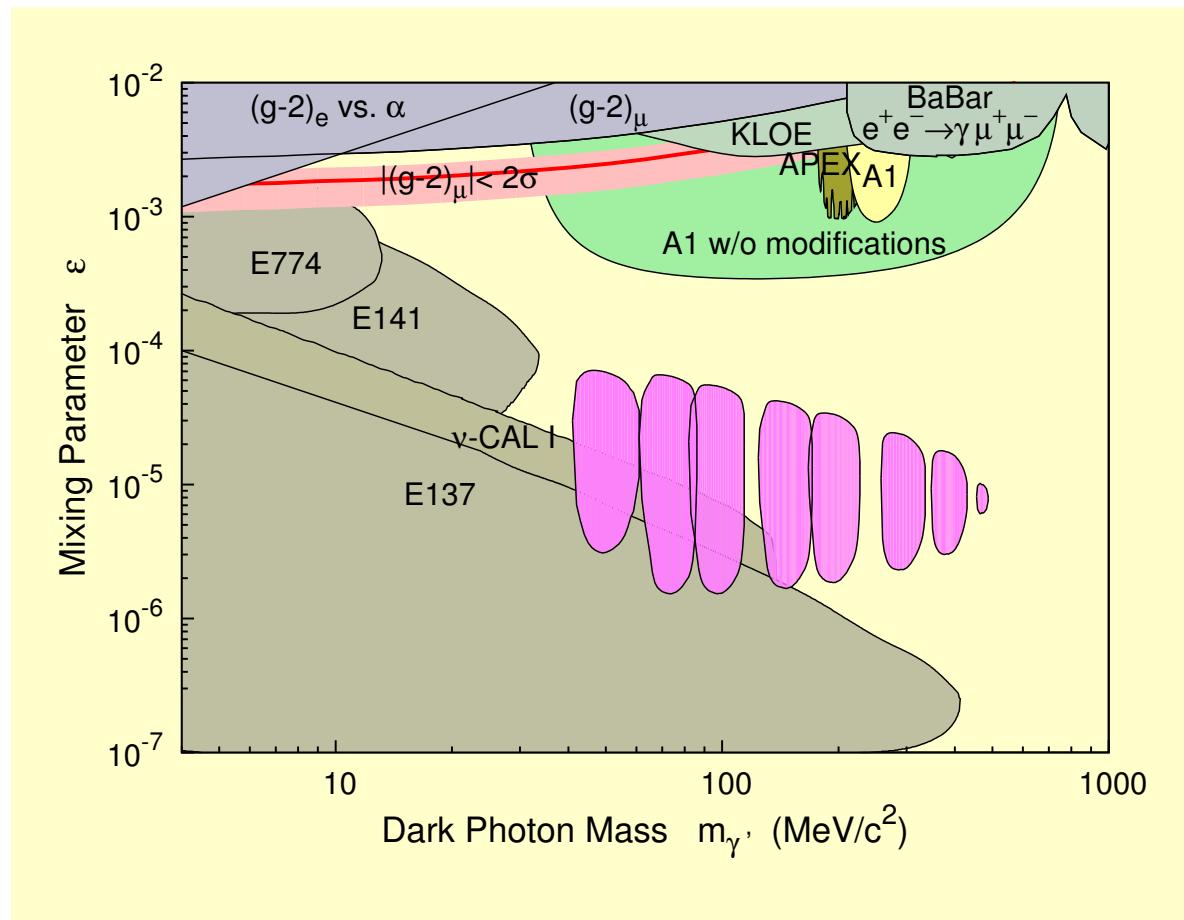
Preliminary data removed from web-version
Contact Harald Merkel <merkel@kph.uni-mainz.de> for private copy

Step 2: Secondary vertex \rightarrow small coupling



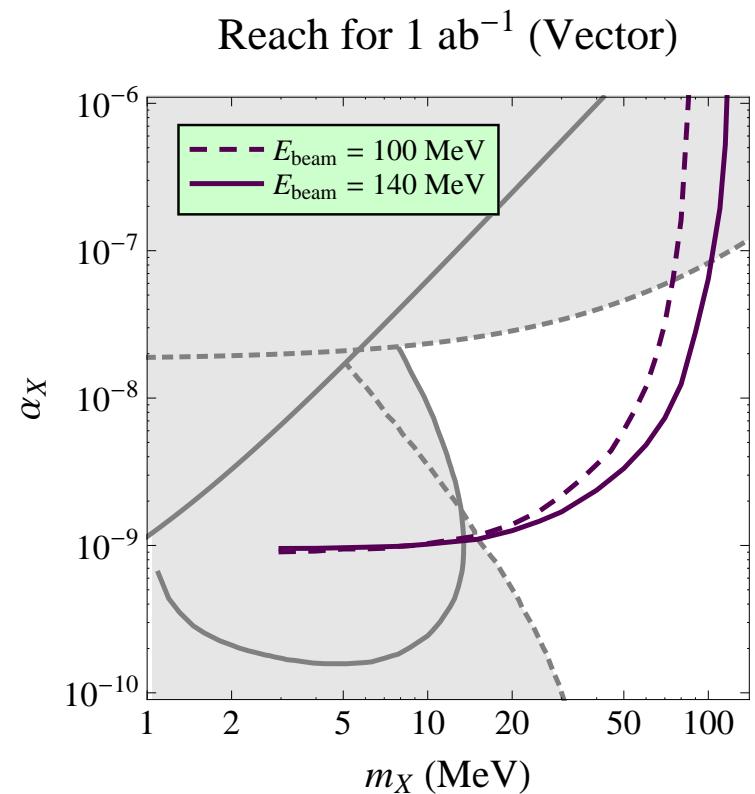
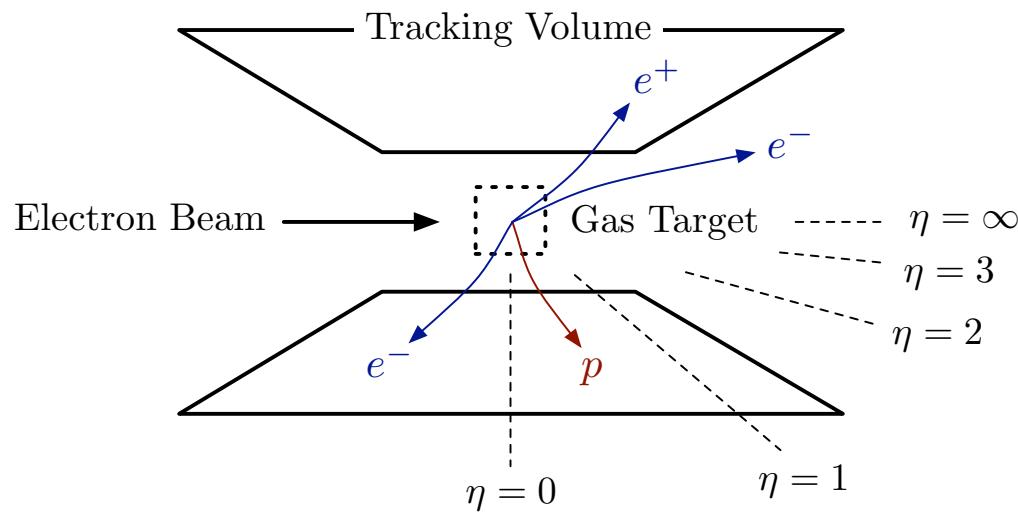
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau = 4.35 \text{ mm} - 1120 \text{ mm}$ (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\text{s cm}^2}$ at 100 μA beam current
- Beam stabilization, shielding,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

Step 2: Exclusion limits with shielded production vertex



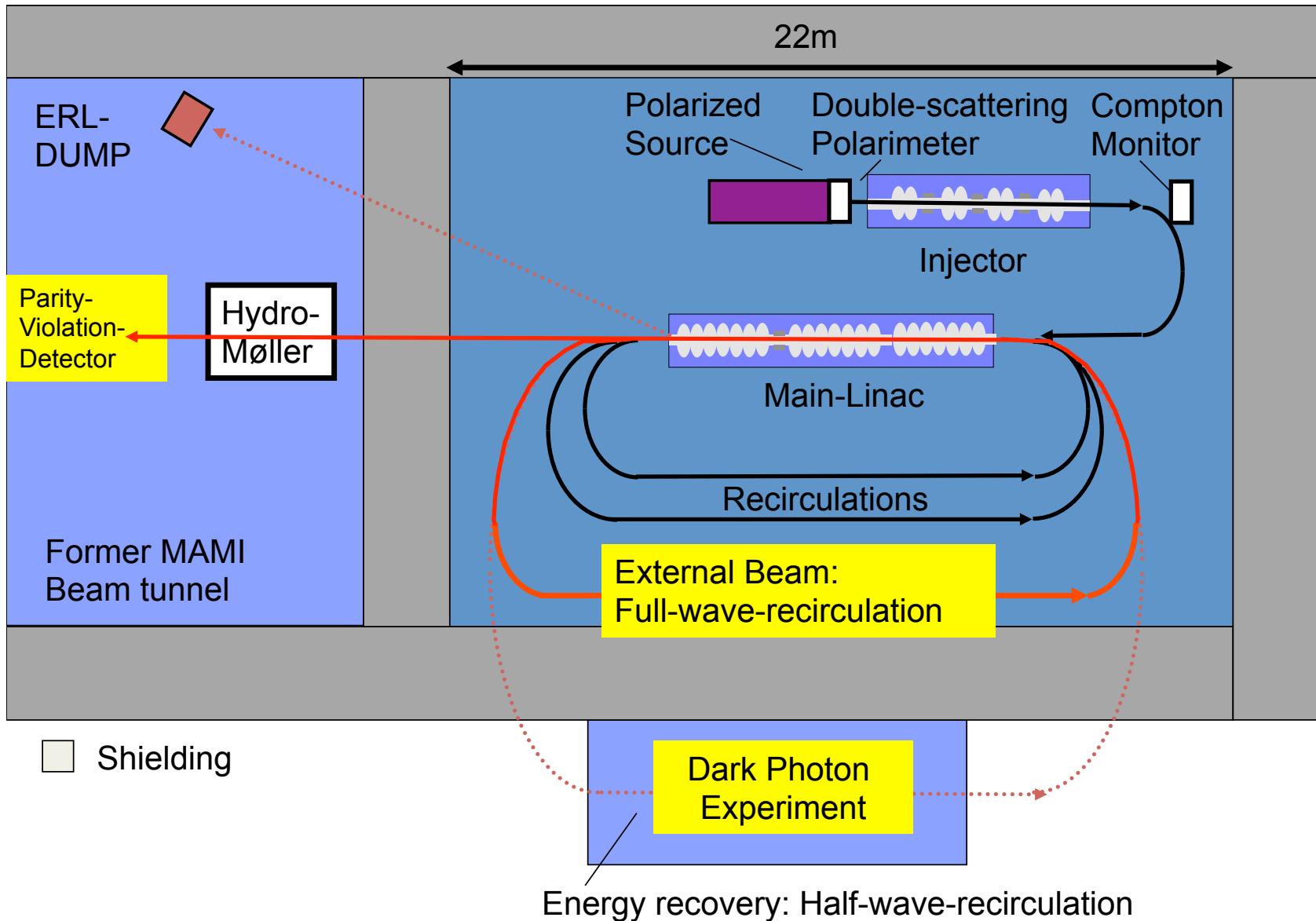
- Macroscopic decay vertex distance $\epsilon < 10^{-4}$
- Luminosity $\epsilon > 10^{-6}$
- Coupling vs lifetime $m_{\gamma'} < 500 \text{ MeV}/c^2$
- Angular range $m_{\gamma'} > 30 \text{ MeV}/c^2$

Step 3: Access to low mass region



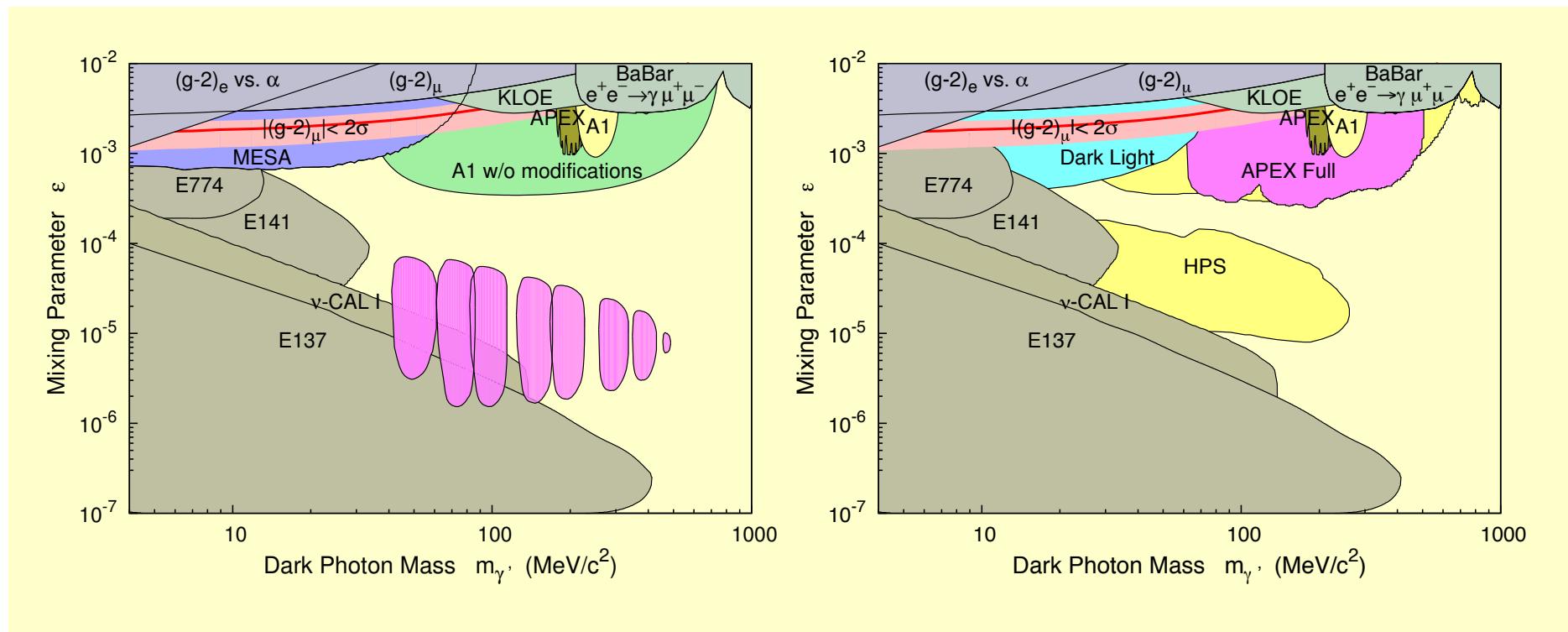
- ➊ Minimize multiple scattering by gas target
- ➋ Low energy – high current accelerator
- ➌ Needs 4π detector at 200 MHz count rate with high resolution
- ➍ DarkLight (JLab FEL), MESA at Mainz

Step 3: Access to low mass region: MESA Accelerator



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

Summary



● Experimental Program:

- ▶ Pair production on heavy target
- ▶ Low energy – high current
- ▶ Finite production vertex

$$\begin{aligned}\epsilon &> 4 \cdot 10^{-4} \\ m_{\gamma'} &< 50 \text{ MeV}/c^2 \\ 10^{-6} &< \epsilon < 10^{-4}\end{aligned}$$

● Pilot experiments at MAMI and APEX

- ▶ Experiment is feasible, background is well under control
- ▶ Q.E.D. process is understood and calculable within 1%
- ▶ First exclusion limits 10^{-3} , measurements will be continued

⇒ Determination of significant exclusion limits for the γ' boson is possible with existing facilities