Search for Dark Matter Gauge Bosons with the Mainz Microtron (MAMI)

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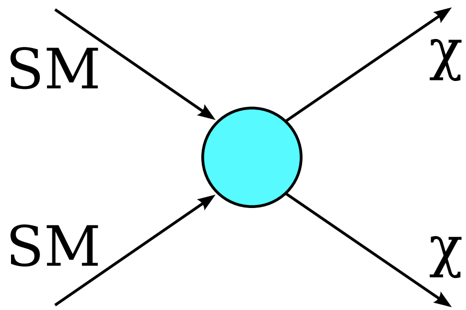
Erice 2010

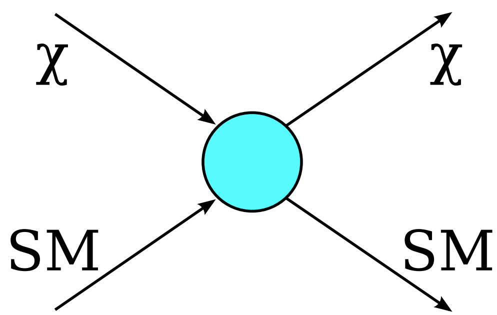
- Motivation: the A'-Boson
  - The photon of dark matter
- How can we detect it?
  - Di-Lepton-Production
- Pilot experiment at MAMI
- Possible experimental program at MAMI
- Summary

Conventional strategies for dark matter search



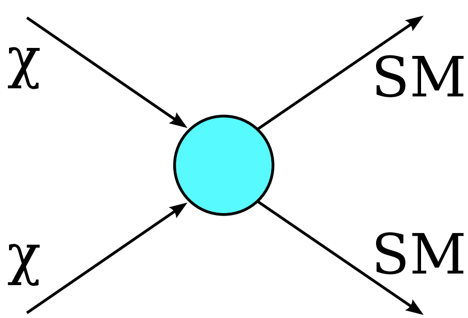
Direct Production:

Tevatron, LHC



Direct Search:

CDMS, DAMA/LIBRA,
XENON, CRESST, LUX,
COUPP, KIMS, ...



Indirect Search:

PAMELA, Fermi, HESS,
ATIC, WMAP, ...

A more general approach

Assumptions:

- There is dark matter (SUSY or something else)
- Dark matter interacts with Standard Model matter (besides gravity)
- Dark matter interacts via a “dark force”

Question:

- What is the character of this “dark force”?
- Scalar, pseudo-scalar, vector bosons?
- Massive or mass-less? Mass range?
- Size of the coupling constant?

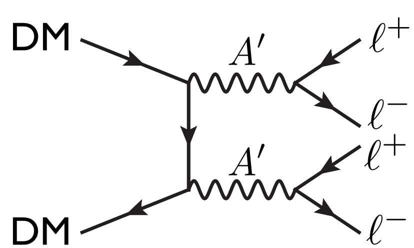
?

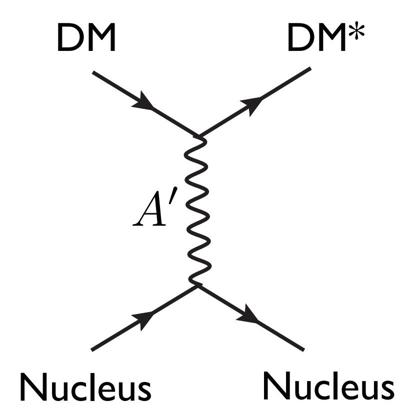
The A' Boson

- Positron excess, but no antiproton excess (PAMELA, INTEGRAL 511 keV line, etc.)
- Large annihilation cross section
- Relic Abundance of DM in cosmology requires low cross section
- Direct Scattering $\Rightarrow$ DAMA/LIBRA modulation
- g-2 anomaly of the myon

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

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

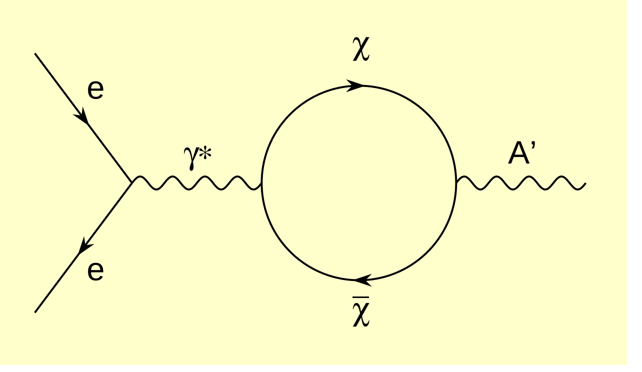




N. Arkani-Hamed, *et al.*, Phys. Rev. D 79 (2009) 015014

Kinetic mixing

Dark matter couples to $U(1)$ bosons γ and A':



- Renormalization of charge:

  $\Rightarrow$ Mixing standard-model charge — "dark" charge

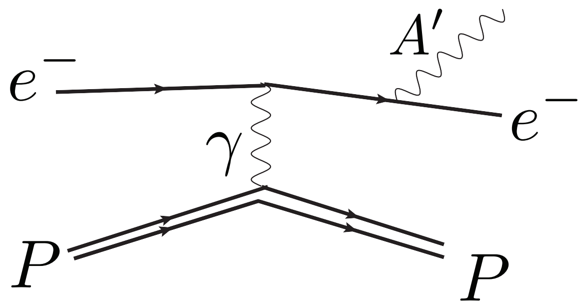
- Coupling constant ε of electric charge to A'
- ε has to be small, if m_χ large
- Boson mass $m_{A'} > 0$ $\Rightarrow$ decay suppressed, macroscopic lifetime

$\Rightarrow$ Look for χ at high energies OR for A' at low energies!

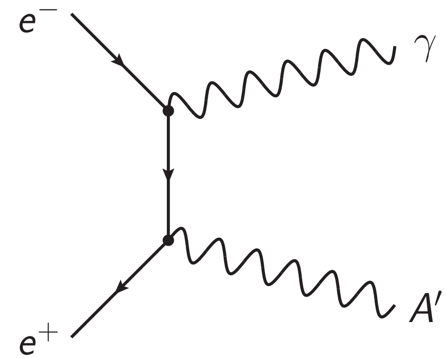
B. Holdom, Phys. Lett. B 166 (1986) 196

Fixed target or collider?

Cross Section

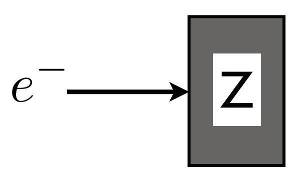


$$\sigma \propto \frac{\alpha^3 \varepsilon^2 Z^2}{m_{A'}^2} \sim 1\,\mathrm{pb}$$

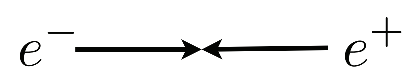


$$\sigma \propto \frac{\alpha^2 \varepsilon^2}{E_{cm}^2} \sim 1\,\mathrm{fb}$$

Luminosity

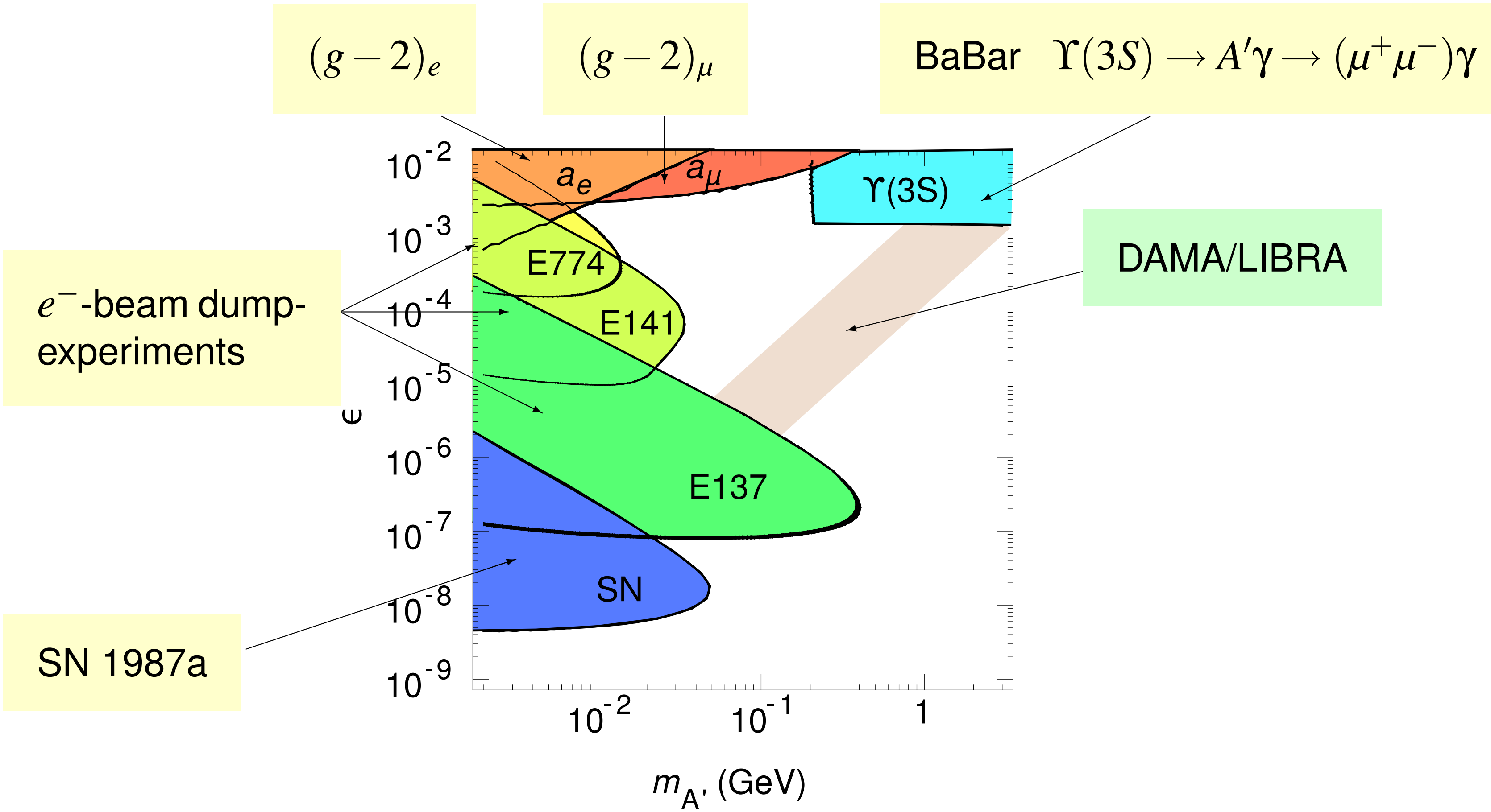


$$\sim \text{few}\ \ ab^{-1}/10\,\text{days}$$



$$\sim \text{few}\ \ ab^{-1}/100\,\text{years}$$

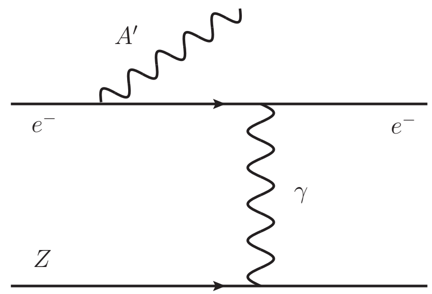
Parameter range for mass and coupling of A' boson



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

J. D. Bjorken *et al.*, Phys. Rev. D 80, 075018 (2009)

Quasi-photoproduction off heavy target



Weizsäcker-Williams approximation:

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

with

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

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

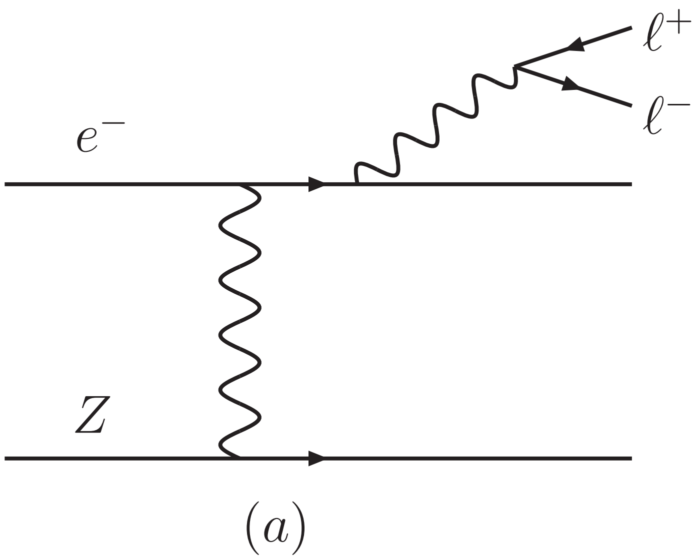
$$\tilde{\chi} \approx 5\sim 10 \quad \text{(photon flux)}$$

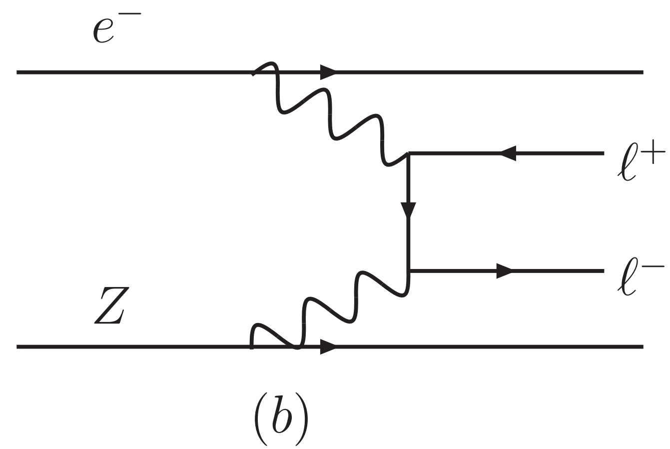
lifetime:

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

J. D. Bjorken *et al.*, Phys. Rev. D 80, 075018 (2009)

Backgrounds



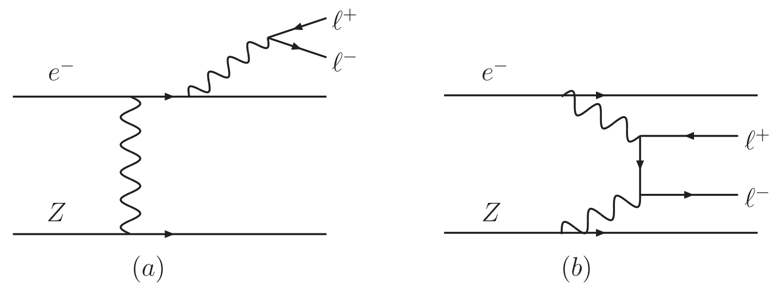


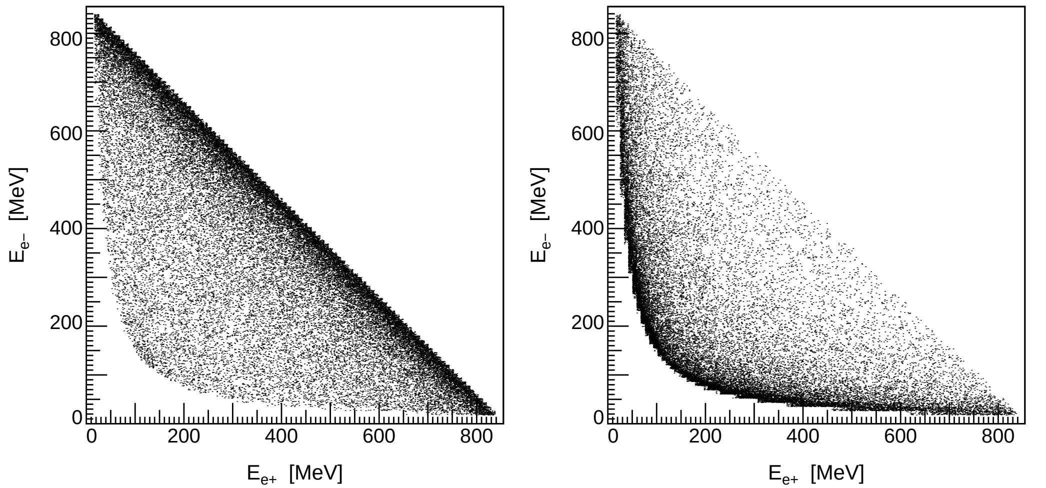
- Virtual photon instead of A'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

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

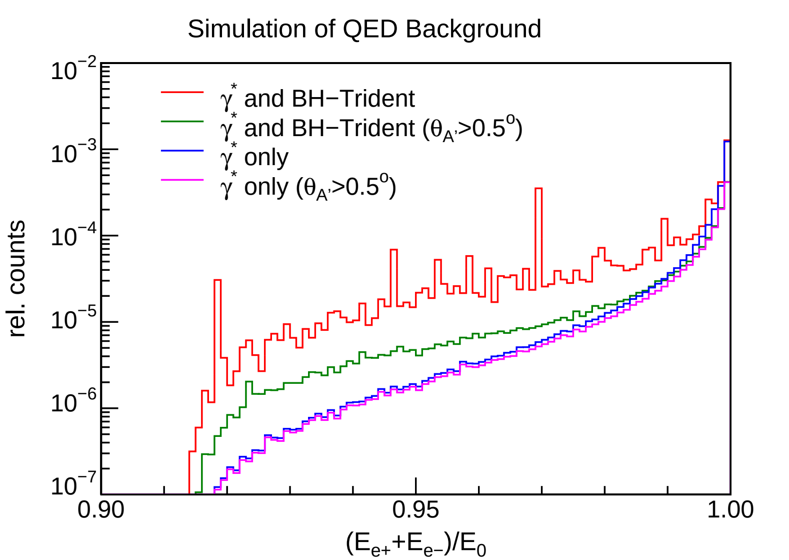
Other backgrounds: measurement!

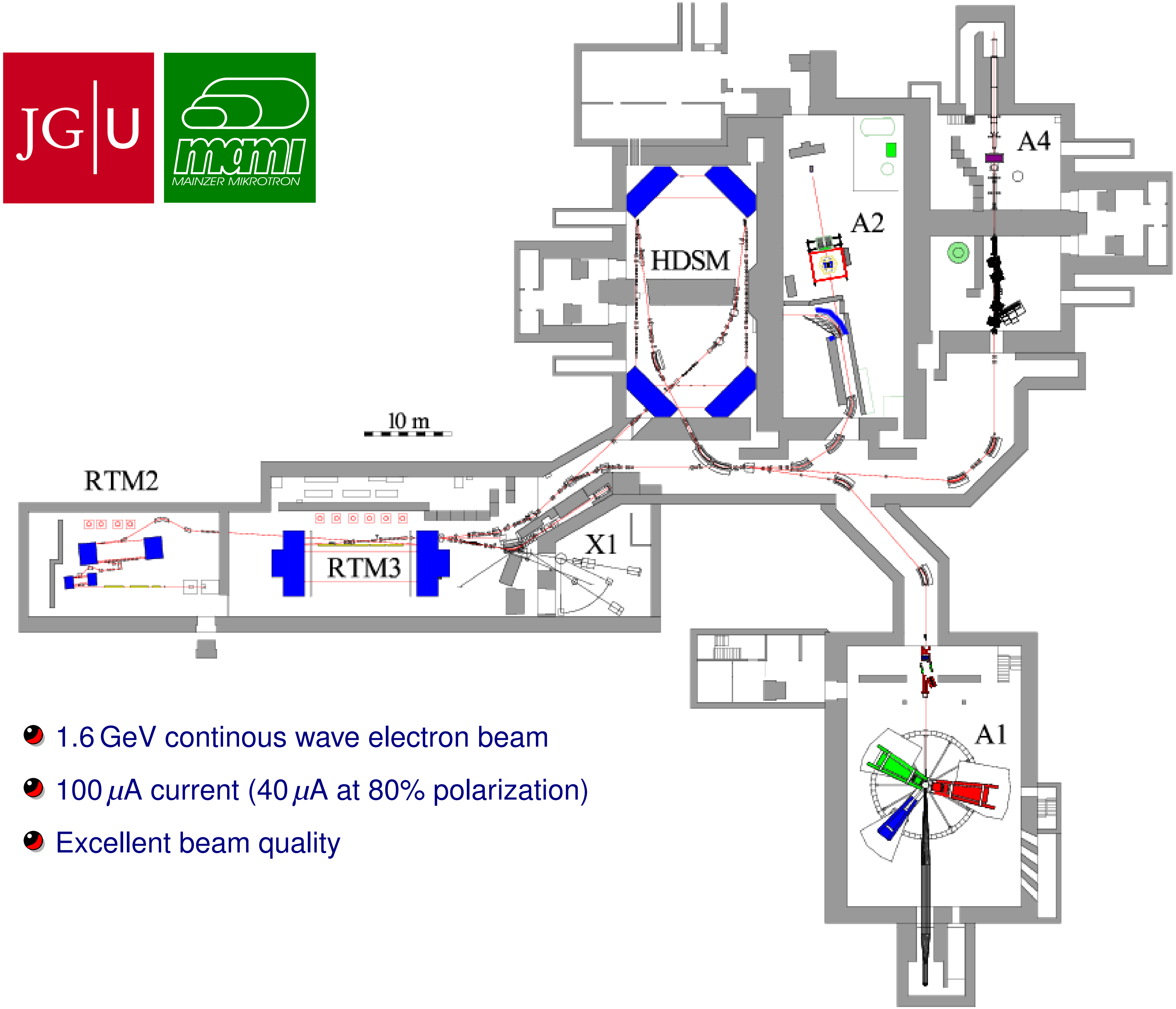
Bethe-Heitler background





- 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:

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

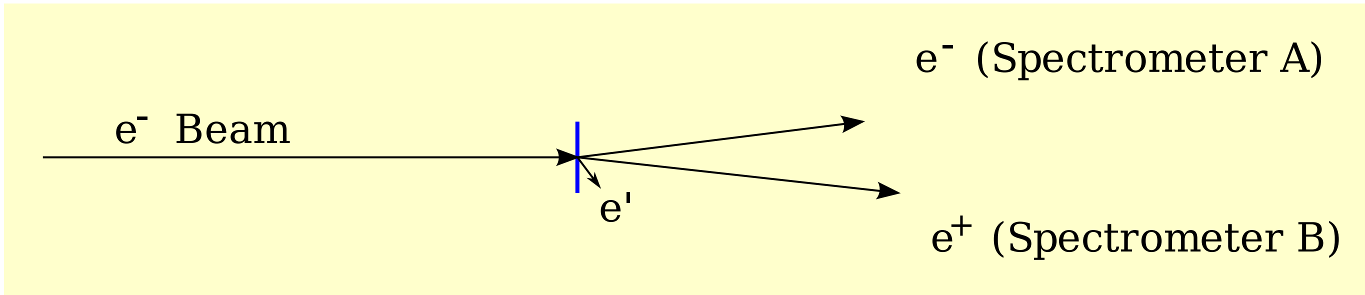
Spectrometer B:

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

Spectrometer C:

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

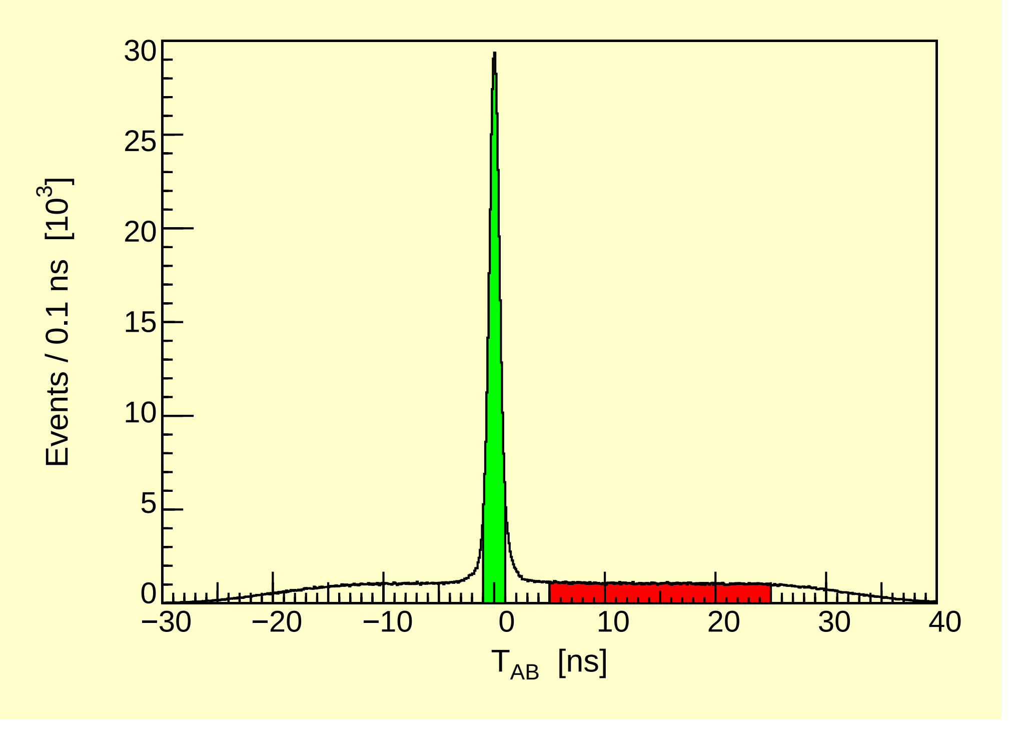
Pilot experiment



- 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 A' boson ($x = 1$)
- Minimal angles for spectrometers
- Spectrometer setup as symmetric as possible (background reduction)

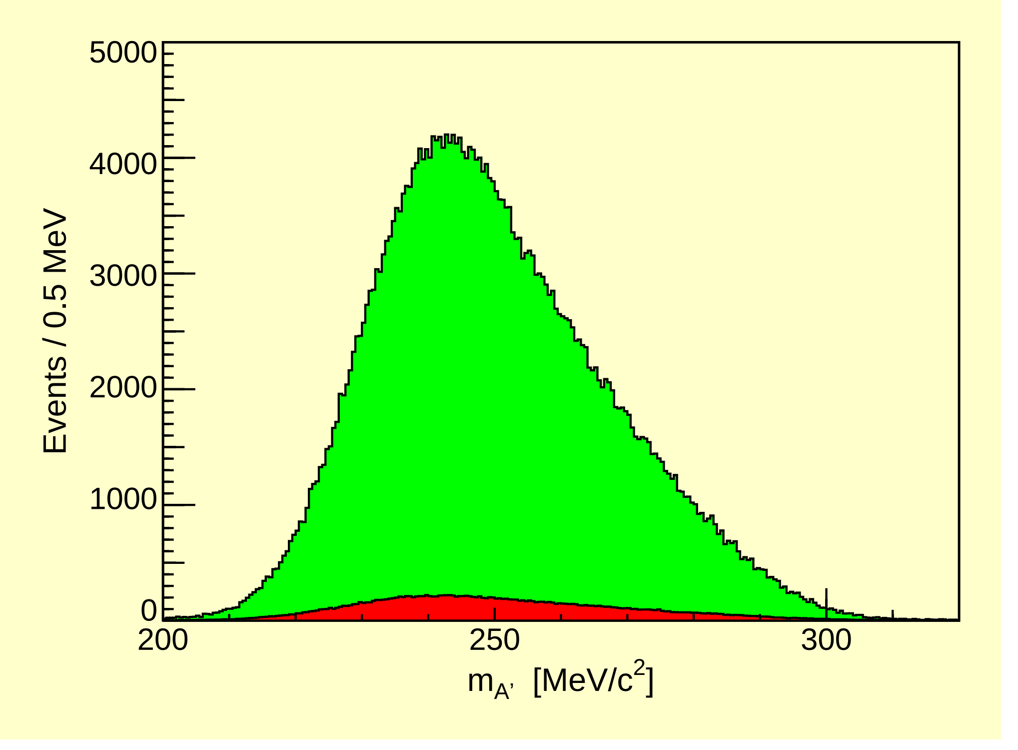
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV$/c$
	$\theta_{e^-} =$	22.8 $^\circ$
Spectrometer B	$p_{e^+} =$	470.0 MeV$/c$
	$\theta_{e^+} =$	15.2 $^\circ$

Reaction identification: coincidence time



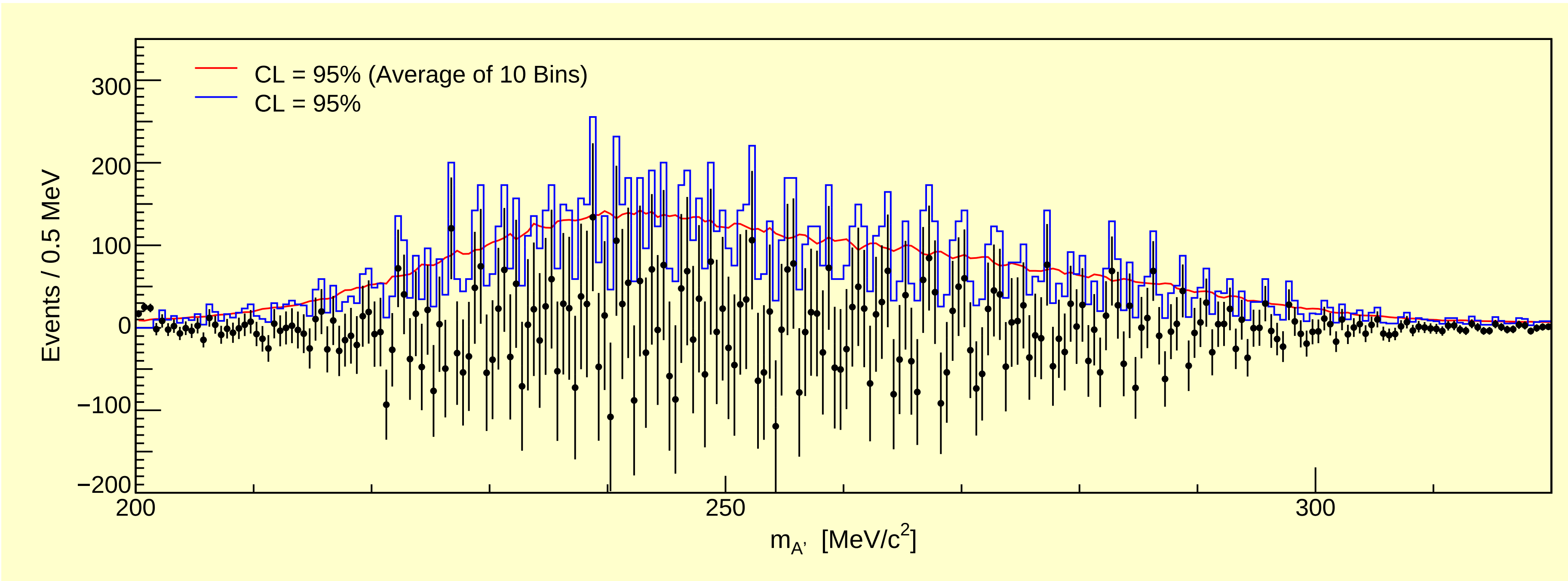
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,$m
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge B}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

Invariant mass of e^+e^- pair



- Mass of e^-e^+ pair $\quad m_{A'}^2 = (e^- + e^+)^2$
- Decay outside of target $\Rightarrow$ Spectrometer resolution defines mass resolution
- Measurement of spectrometer resolution via elastic scattering
- Simulation of mass resolution for this kinematics $\quad \Rightarrow \quad \delta m < 500 keV$

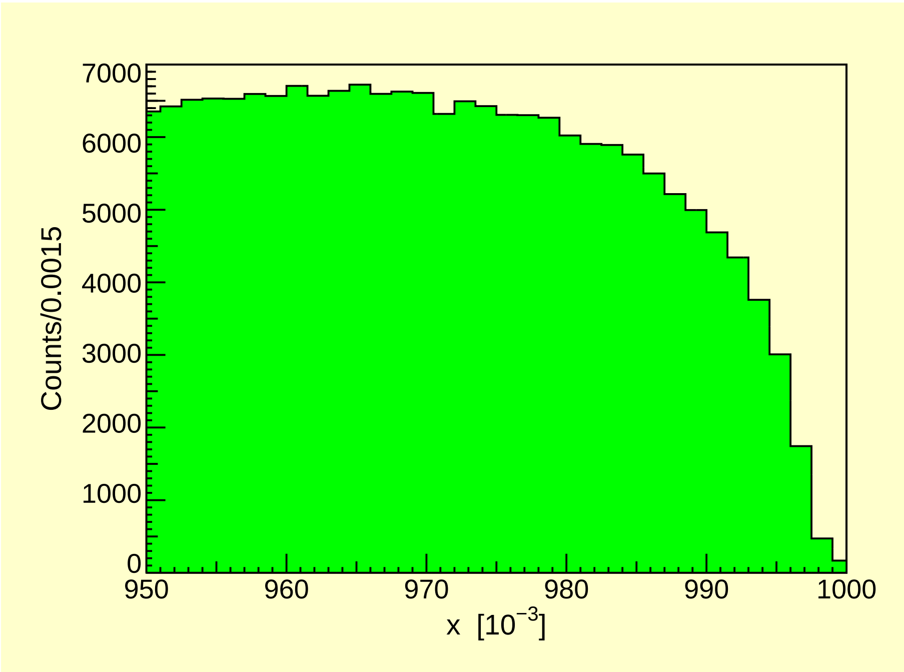
Exclusion limits



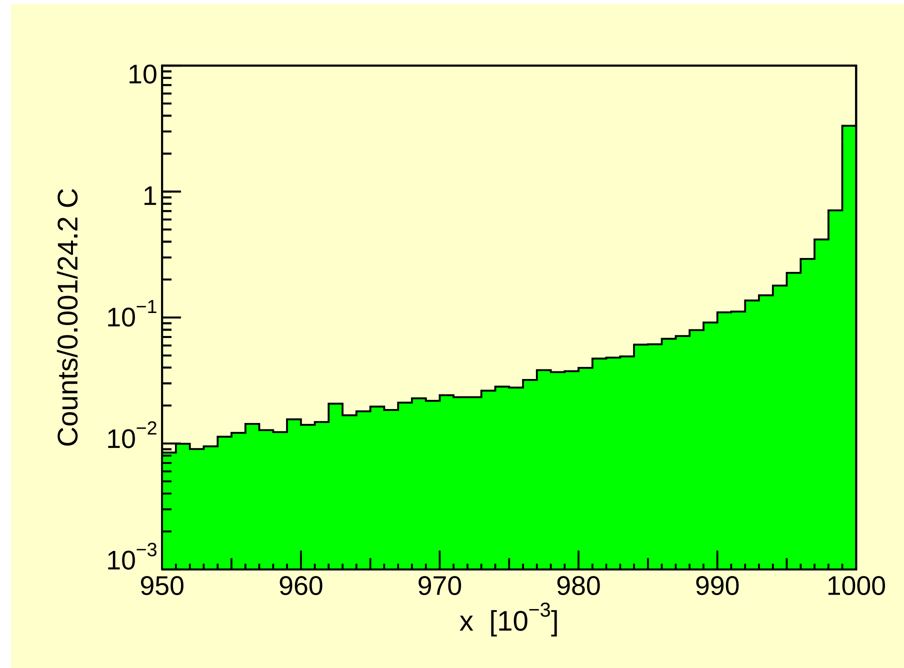
- Confidence interval by Feldman-Cousins algorithm
- "Model" for Background-subtraction:
  average of 3 Bins left and right of central bin
- Resolution $\delta m < 500\,\mathrm{keV}$ = bin width
- Averaging (mean of 10 bins) only for "subjective judgment"

Problem: model for cross section

Experiment:

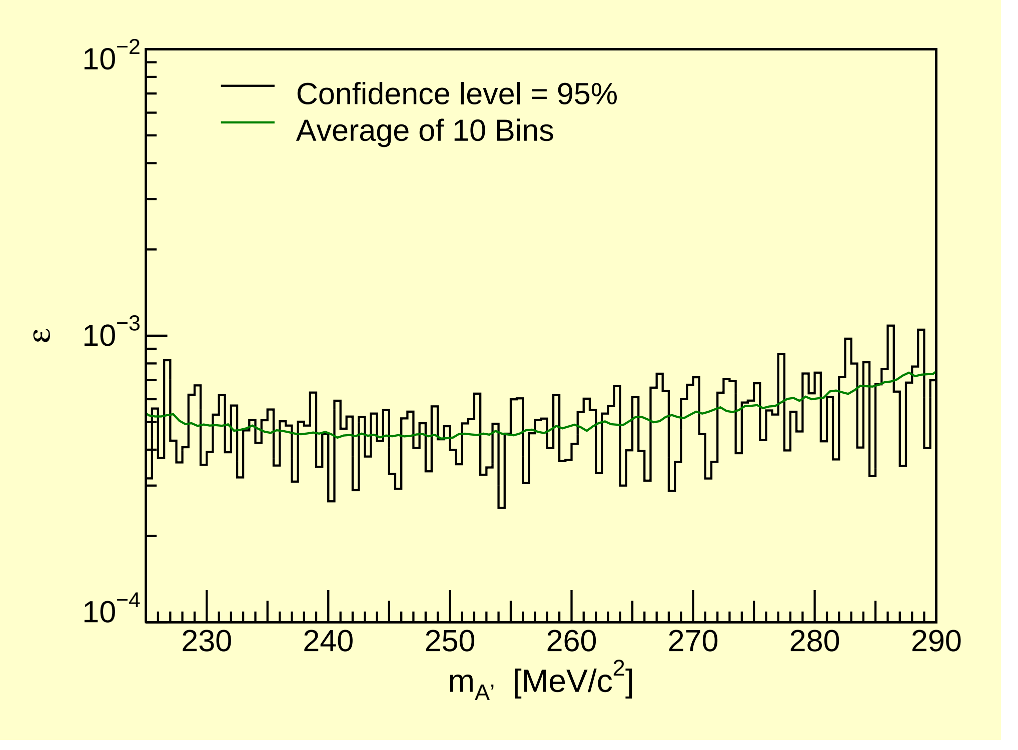


Simulation:



- Fraction of transferred energy $x = E_{A'}/E_0$
- Weizsäcker-Williams approximation does *not* correspond to experiment
- Reason: neglected phase space of recoiling nucleus at $x = 1$
- $\Rightarrow$ Reaction identification!
- $\Rightarrow$ Kinematics of experiment was not (yet) optimal!

Exclusion limit for coupling ε



Problem: Weizsäcker-Williams approximation fails in peak region

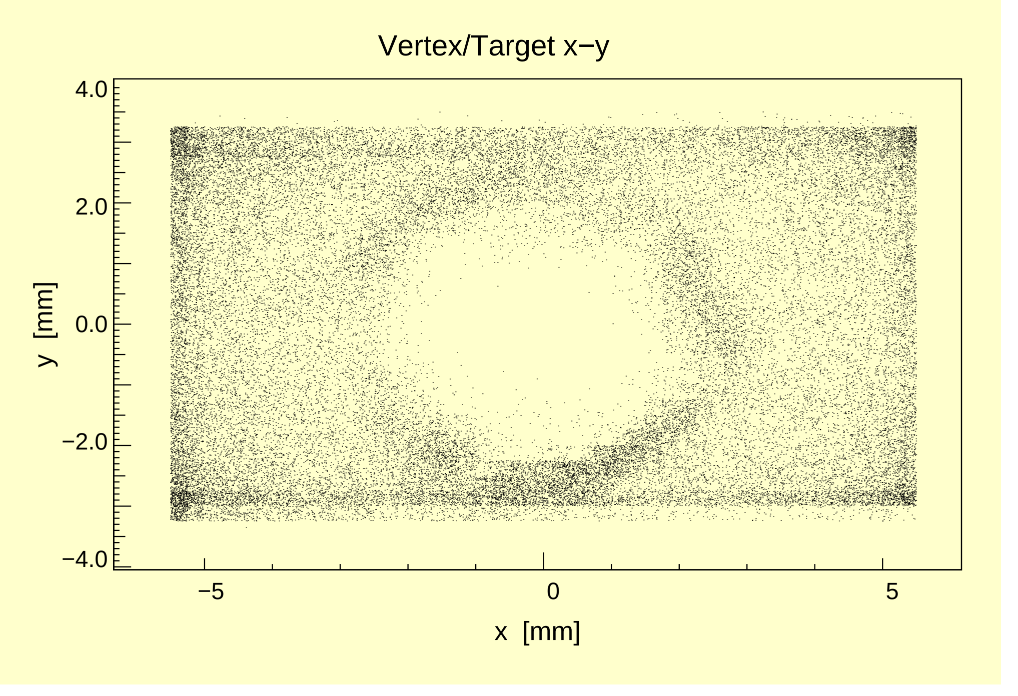
- Subtraction of accidental background
- Model: continuum dominated by $\gamma^* \longrightarrow e^+ + e^-$ (?)
- Conversion factor from ratio of cross sections:

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

$\Rightarrow$ Preliminary exclusion limit from 6 days of beam time $\varepsilon < 5 \cdot 10^{-4}$

Limitations of the experiment

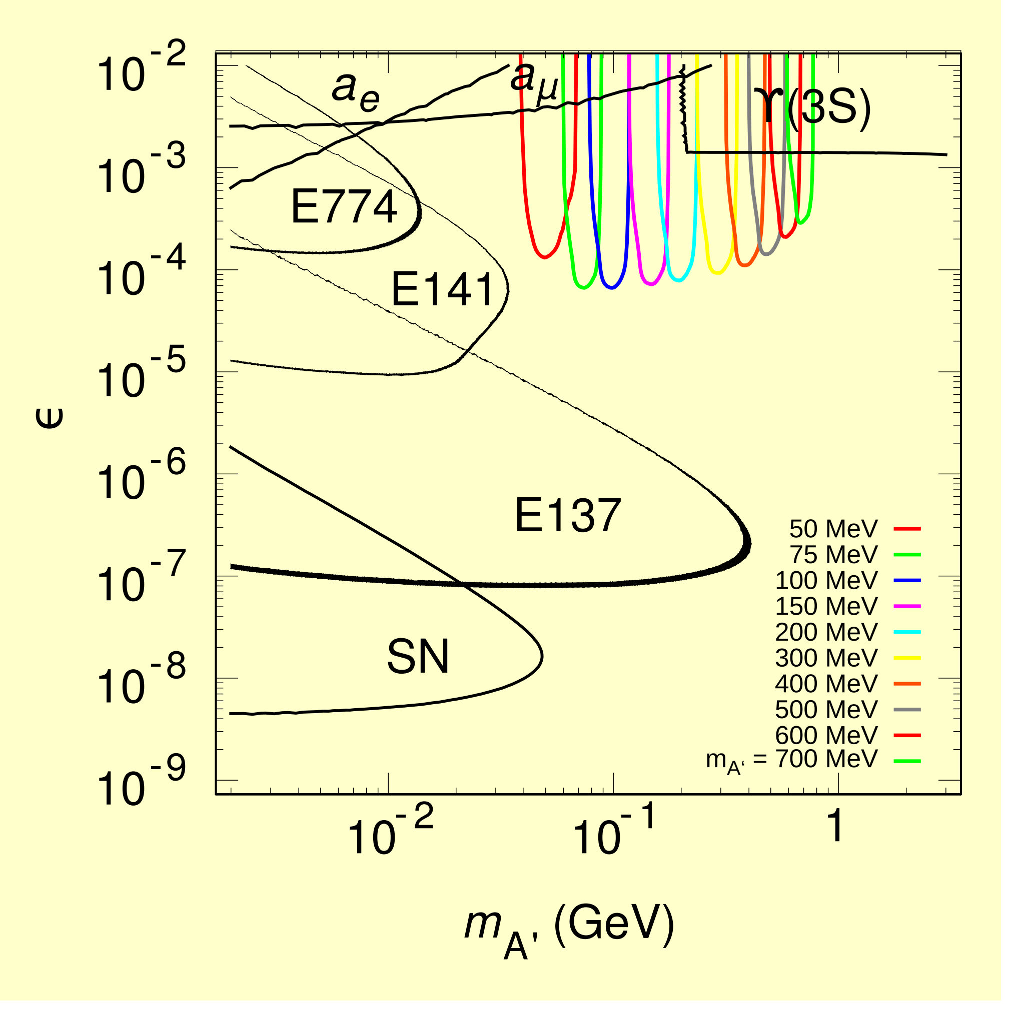
$100\,\mu\mathrm{A}$ beam current for 20 min on 0.05 mm ^{181}Ta target (melting point: 3017 $^\circ$C):



- Air activation
- Optimization of kinematics
- Target cooling
- Shielding

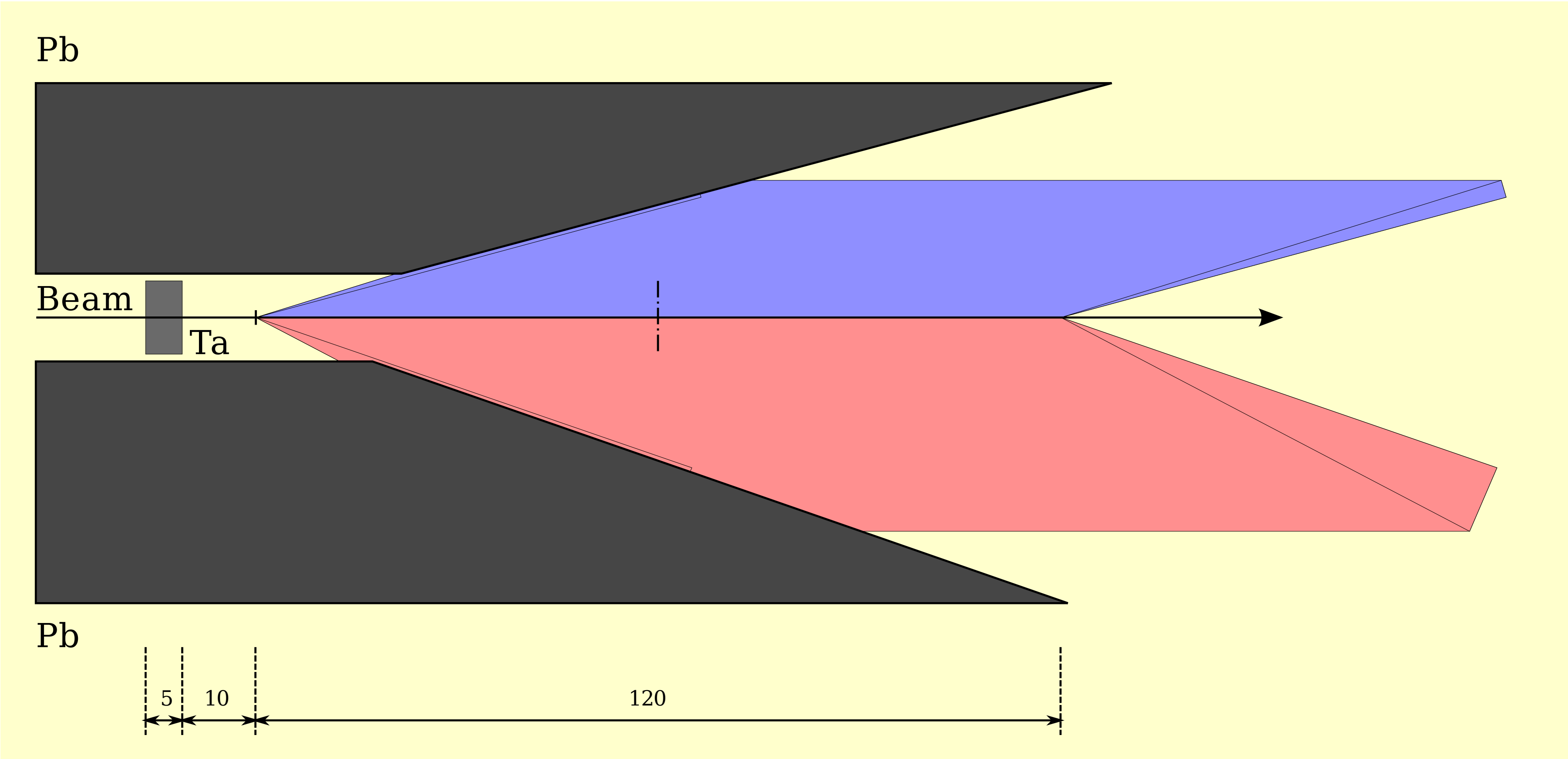
$\Rightarrow$ 1 order of magnitude higher count rates possible

Simulation: exclusion limits



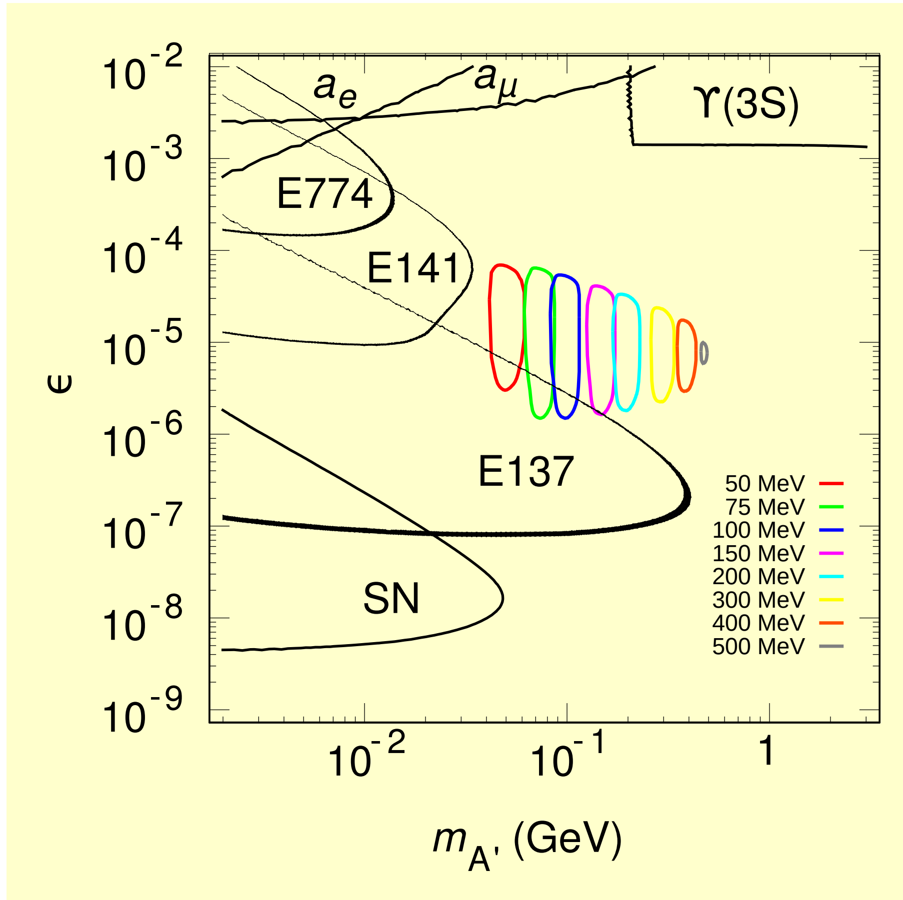
- Cross section of J. D. Bjorken *et al.*
- Improvement of theory desirable
- Marked regions: 2σ exclusion (preliminary)

Step 2: Secondary vertex → small coupling



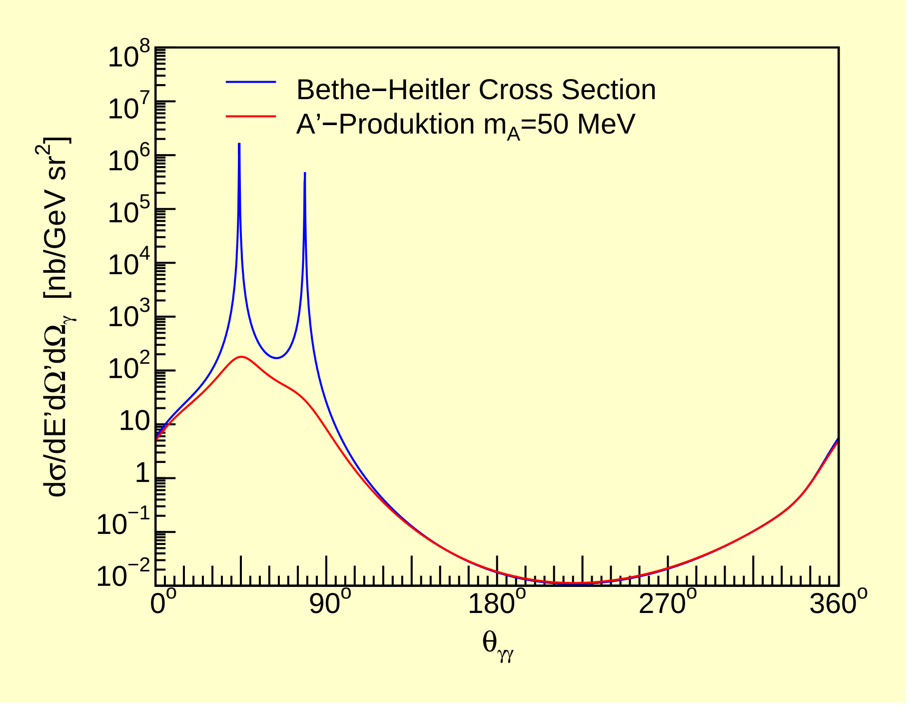
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm}^2}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

Step 2: Exclusion limits with shielded production vertex



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

Step 3: Production off the proton → small masses



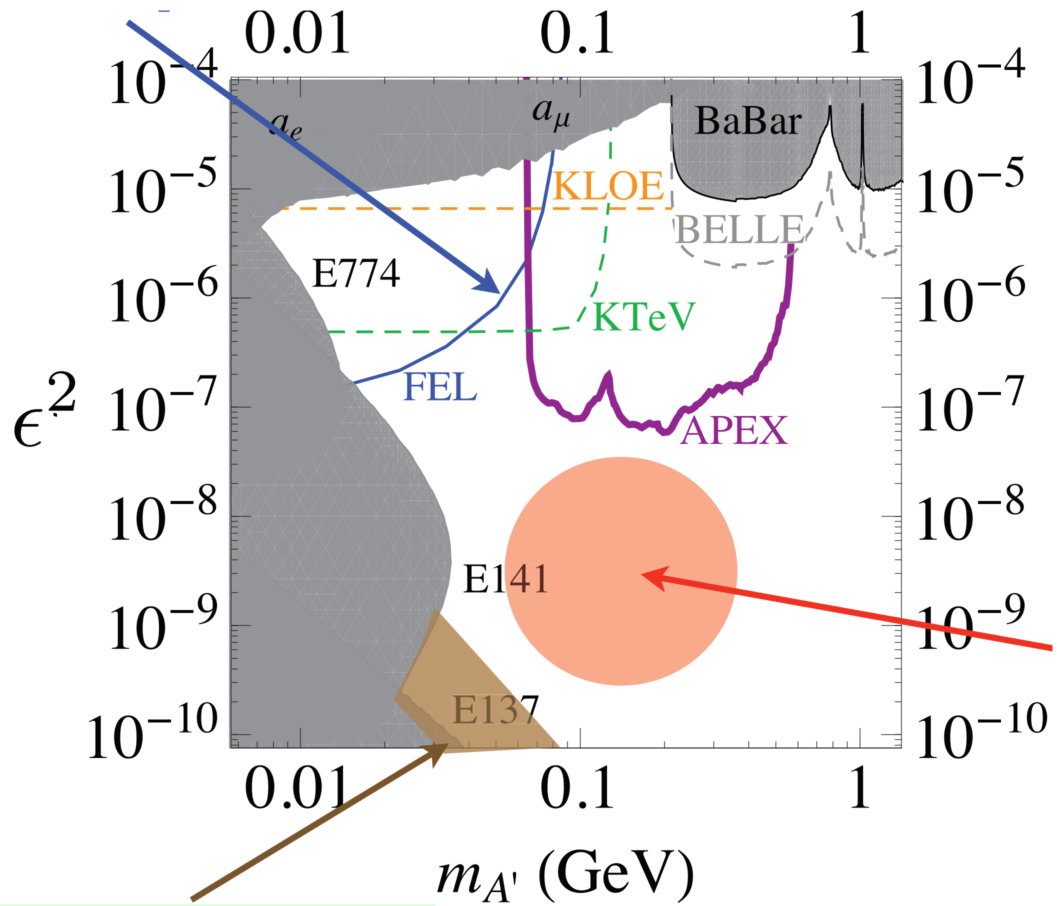
$$e + p \;\rightarrow\; e' + p + A'$$
$$\hookrightarrow e^+ + e^-$$

- A' detection via missing mass $\quad m_{A'}^2 = (e + p - e' - p')^2$
- No restriction by decay
- Background: virtual Compton scattering: $e + p \rightarrow e' + p + \gamma$ + radiative tail
- Vertex identification with high suppression factor $(10^8 \ldots 10^{10})$ necessary
- Detector development

Other projects

JLab Free Electron Laser
Freytsis et al. arXiv:0909.2862

KLOE, BELLE: Rare Meson Decays

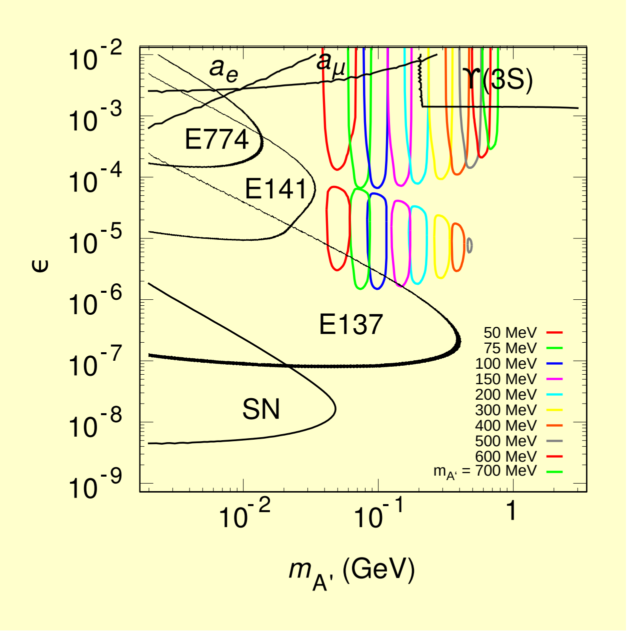


JLab Hall B

HIPS Proposal (Desy)
Beamdump

APEX: JLab Hall A

Summary



- Experimental Program:
  - Step 1: Pair production on heavy target $\varepsilon > 10^{-4}$
  - Step 2: Shielded production vertex $10^{-6} < \varepsilon < 10^{-4}$
  - Step 3: Production on LH_2, Micro-vertex detector $m_{A'} < 40\,\mathrm{MeV}/c^2$
- Pilot experiment
  - Experiment is feasible, background is under control
  - Some work on theory required
  - First exclusion limit $5 \cdot 10^{-4} \rightarrow 10^{-4}$ reachable

$\Rightarrow$ Determination of significant exclusion limits for the A' boson is possible at MAMI/A1