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Searching for the Dark Photon at MAMI

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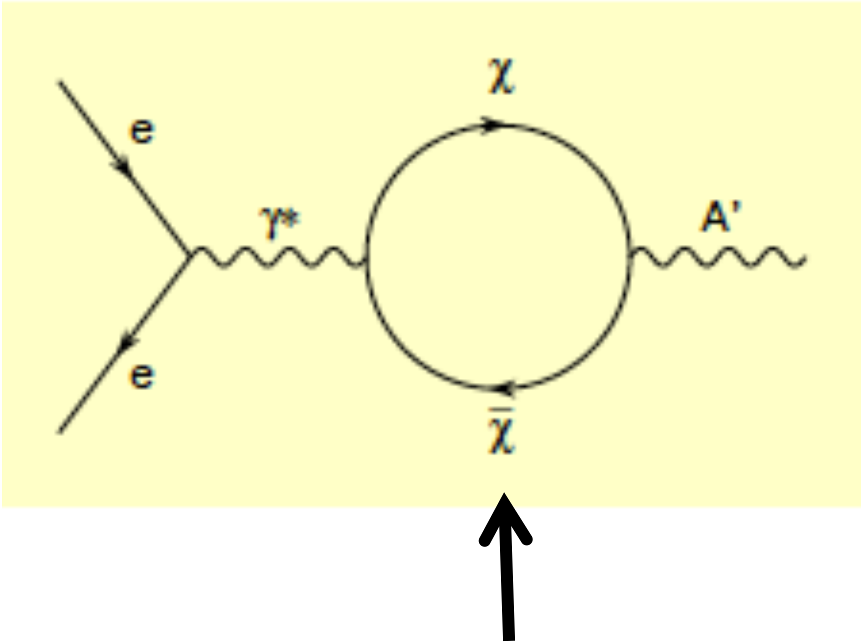
Outline

- **Brief Introduction**
- **MAMI accelerator, experiments**
- **Experiences from Pilot Run (A1 Spectrometers)**
- **Other opportunities (displaced vertex)**
- **Conclusions & Outlook**

New Sub-GeV Forces: Dark Photon

Holdom [1986]
Fayet [1977]

Standard
Model
Sector
U(1)



Hidden
Sector
U(1)'

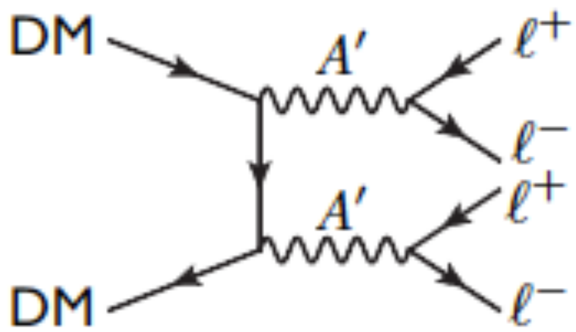
Kinetic mixing, coupling strength ε

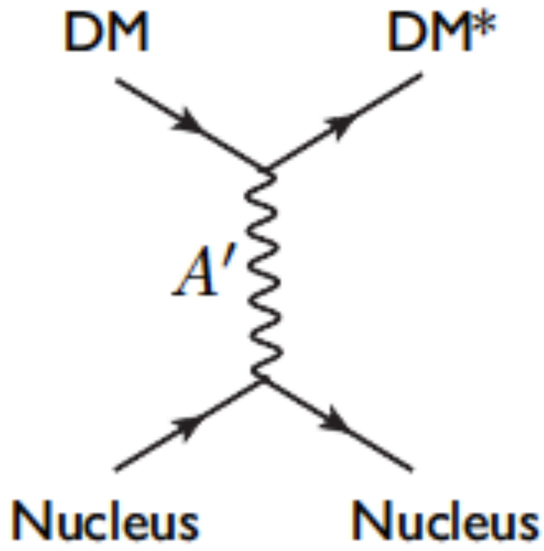
- Coupling strength ε of A' to normal matter
- ε small for large χ masses
- ε so far only constraint to be < 10^{-2} by $(g\text{-}2)_\mu$, $(g\text{-}2)_e$
- Mass of A' boson could be bound to be in GeV range

Dark Photon coupling to Dark Matter ?

Arkani-Hamad et al. [2009]
Pospelov, Ritz [2008]

Appealing to let dark matter couple to A' boson

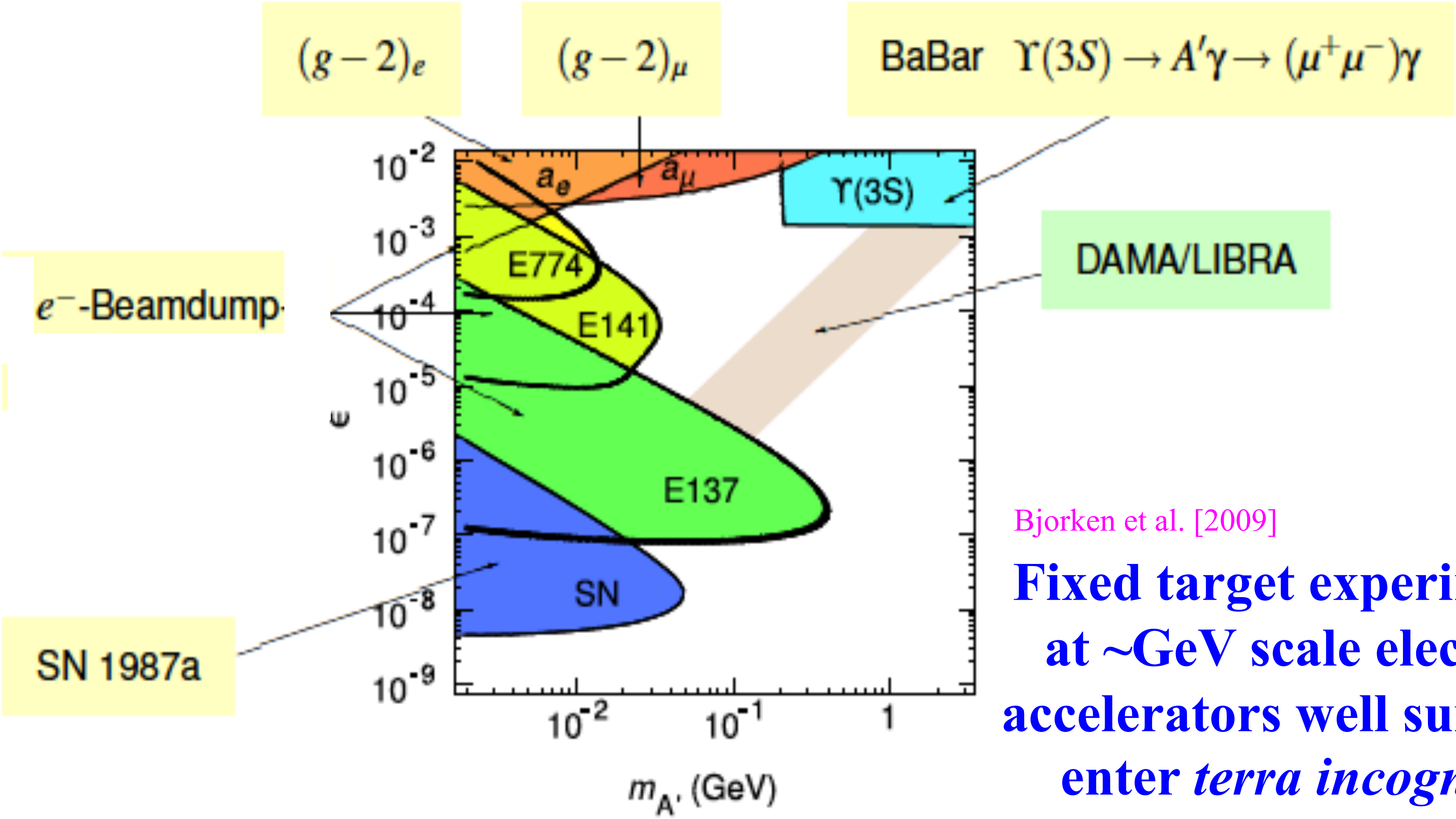




Positron excess seen by satellite experiments PAMELA, FERMI; INTEGRAL 511 keV photon line; no antiproton excess → light A' ?

DAMA/LIBRA annual modulation could be explained by DM scattering on electrons via A' exchange

Allowed Parameter Range for A'

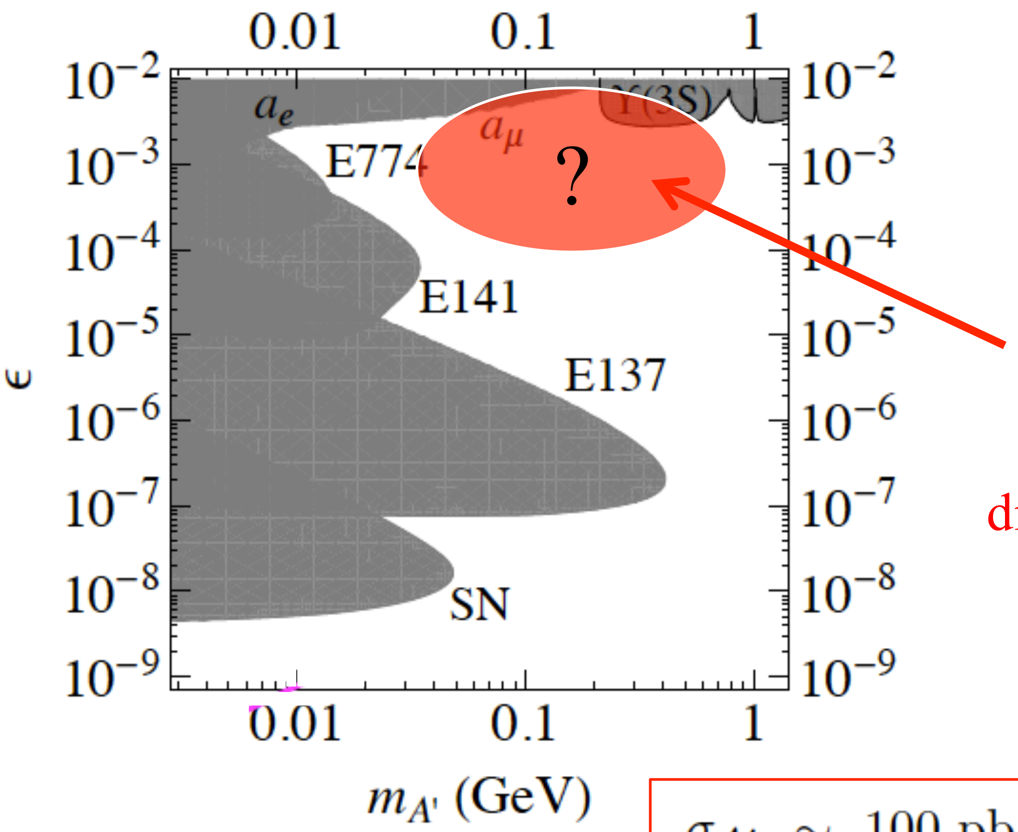


Bjorken et al. [2009]

Fixed target experiments at ~GeV scale electron accelerators well suited to enter *terra incognita*

High ε - Region

Bjorken et al. [2009]
Essig et al. [2010]



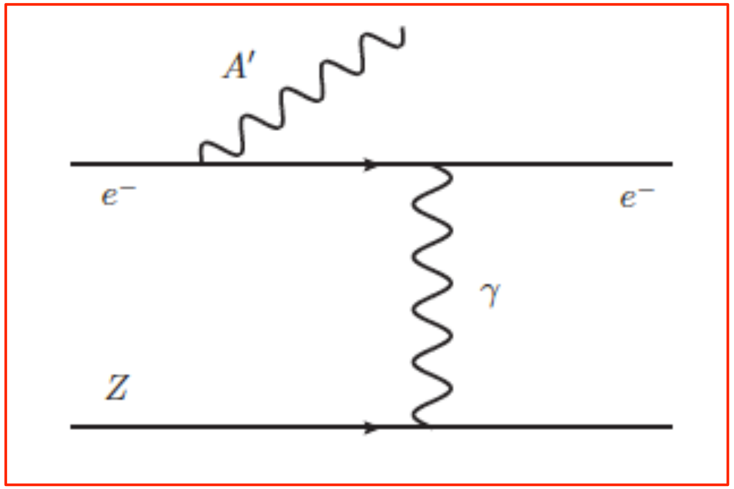
parameter range accessible
by MAMI, an 1.6 GeV e⁻ CW;

displaced vertex cannot be resolved.

$$\sigma_{A'} \sim 100\,\text{pb}\left(\epsilon/10^{-4}\right)^2 (100\,\text{MeV}/m_{A'})^2$$

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

Electron - Nucleus Scattering Experiments



Quasi-photo production off heavy high-Z target

High ε region:

1. measure decay of A' to e+e- pair
2. choose high $x=E_{A'}/E_0$ (→ $U(x,\Theta)$ minimized)
3. look for signal by 'bump hunting' over QED background and additional other background

Weizsäcker – Williams approximation

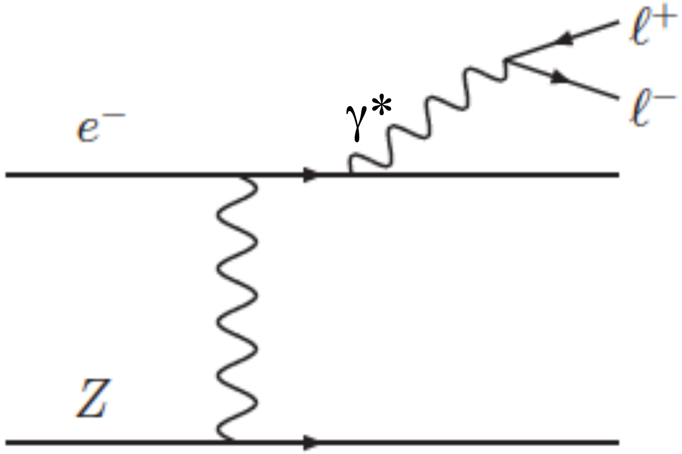
$$\frac{d\sigma}{dx\,d\cos\theta_{A'}} \approx \frac{8Z^2\alpha^3\varepsilon^2E_0^2x}{U^2}\tilde{\chi}\left[\left(1-x+\frac{x^2}{2}\right)-\frac{x(1-x)m_{A'}^2\left(E_0^2x\theta_{A'}^2\right)}{U^2}\right]$$

with
$$x = \frac{E_{A'}}{E_0}$$
$$U(x,\theta_{A'}) = E_0^2x\theta_{A'}^2+m_{A'}^2\frac{1-x}{x}+m_e^2x$$
$$\tilde{\chi} \approx 5\sim 10 \quad \text{(photon flux)}$$

Bjorken et al. [2009]
Essig et al. [2010]

QED Background

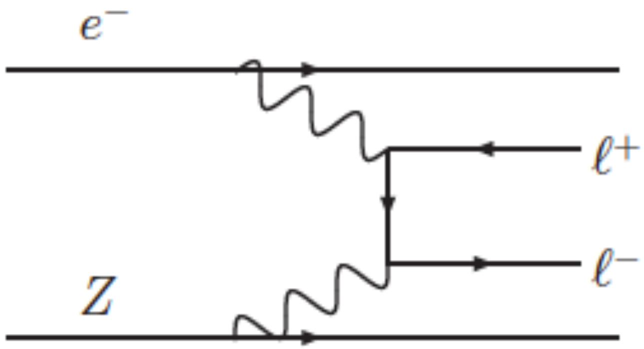
s-channel process



- same final state as signal
- similar differential cross section

➔ irreducible background
➔ calculable in QED

t-channel process

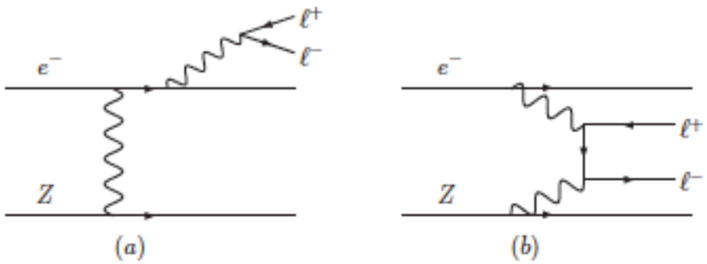


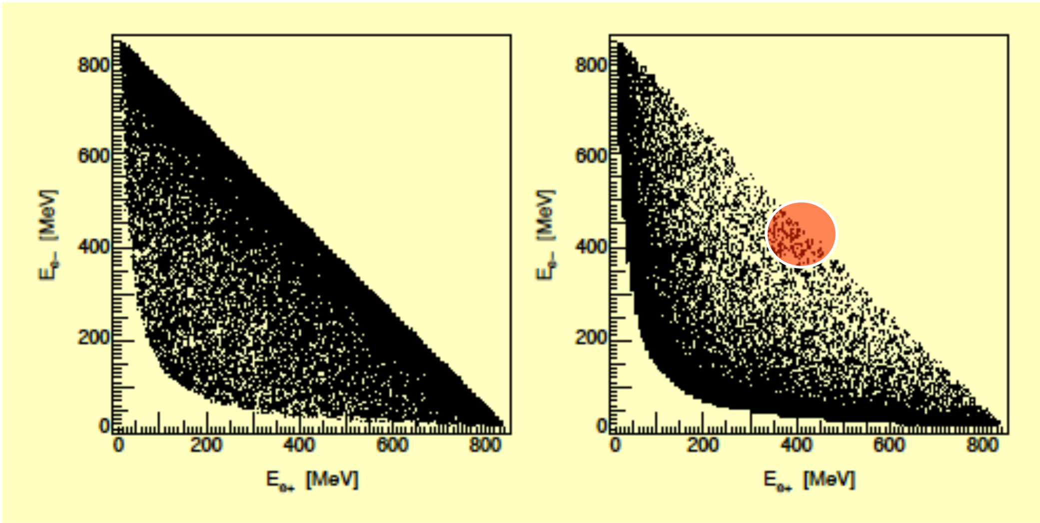
- same final state as signal
- differential cross section different
- increases with beam energy

➔ can be reduced by angular cuts
➔ calculable in QED (ongoing work)

Other background channels ?➔ pilot run !

QED Background



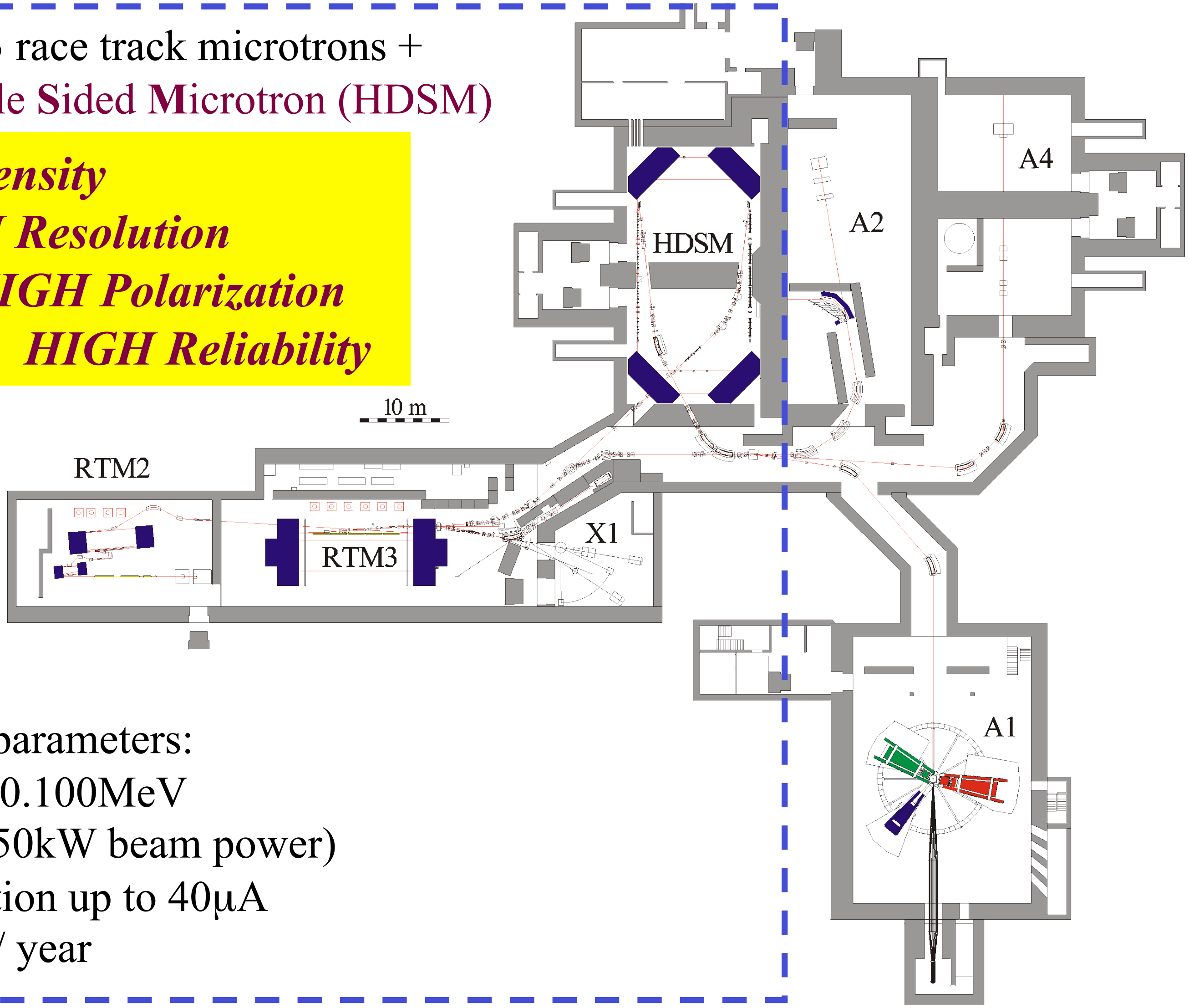


Background: - peaks at $m_{e+e-} \rightarrow 0$
- is minimized for symmetric production of E_{e+}, E_{e-}
- x-dependence under study → allows optimize S/B ratio

Mainz Microtron MAMI-C: E_{max}=1.6 GeV

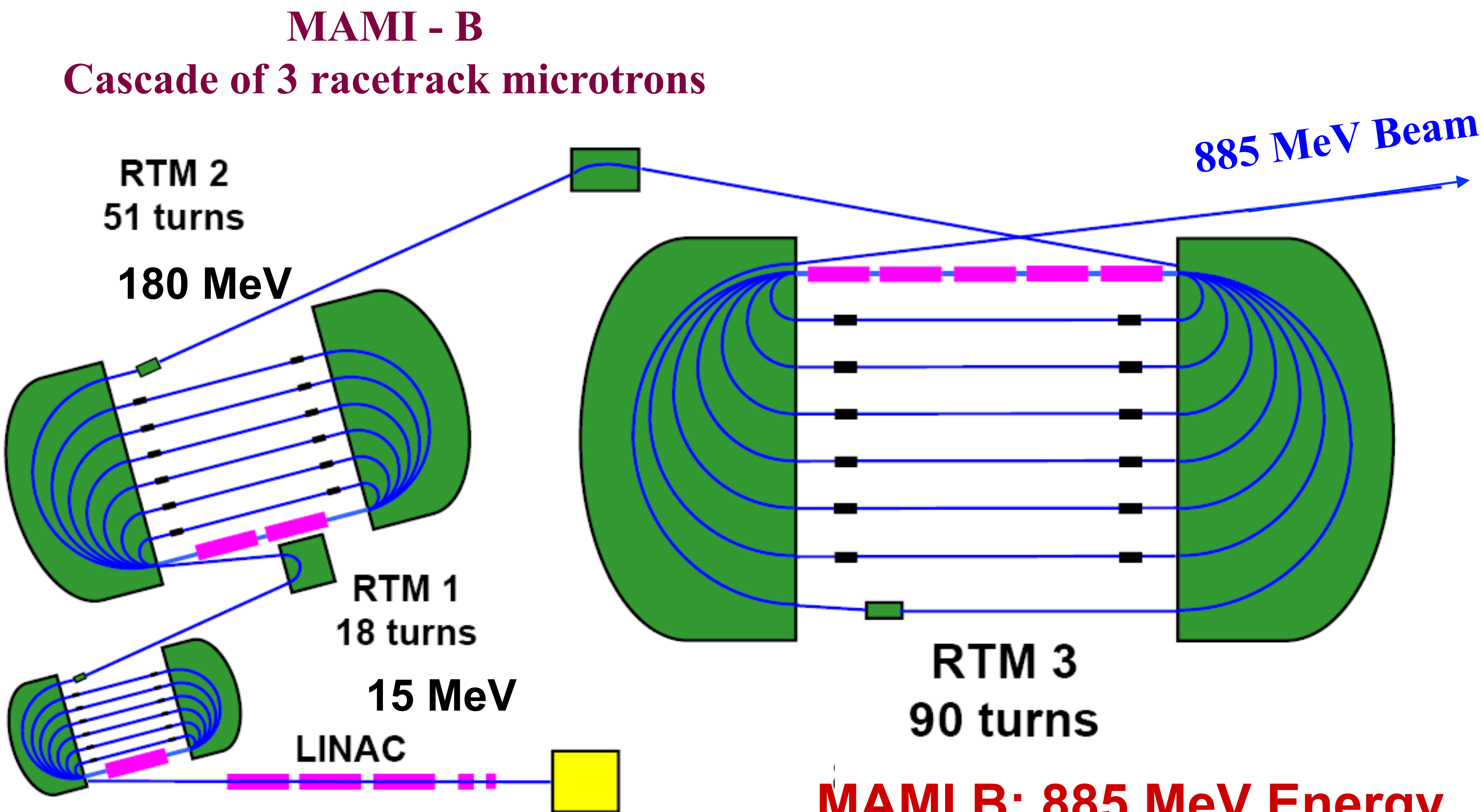
Cascade of 3 race track microtrons +
Harmonic **D**ouble **S**ided **M**icrotron (HDSM)

HIGH Intensity
HIGH Resolution
HIGH Polarization
HIGH Reliability



MAMI C beam parameters:
- 1604 MeV, σ_E<0.100MeV
- max. 100µA (150kW beam power)
- ca. 80% Polaration up to 40µA
- ca. 7000 hours / year

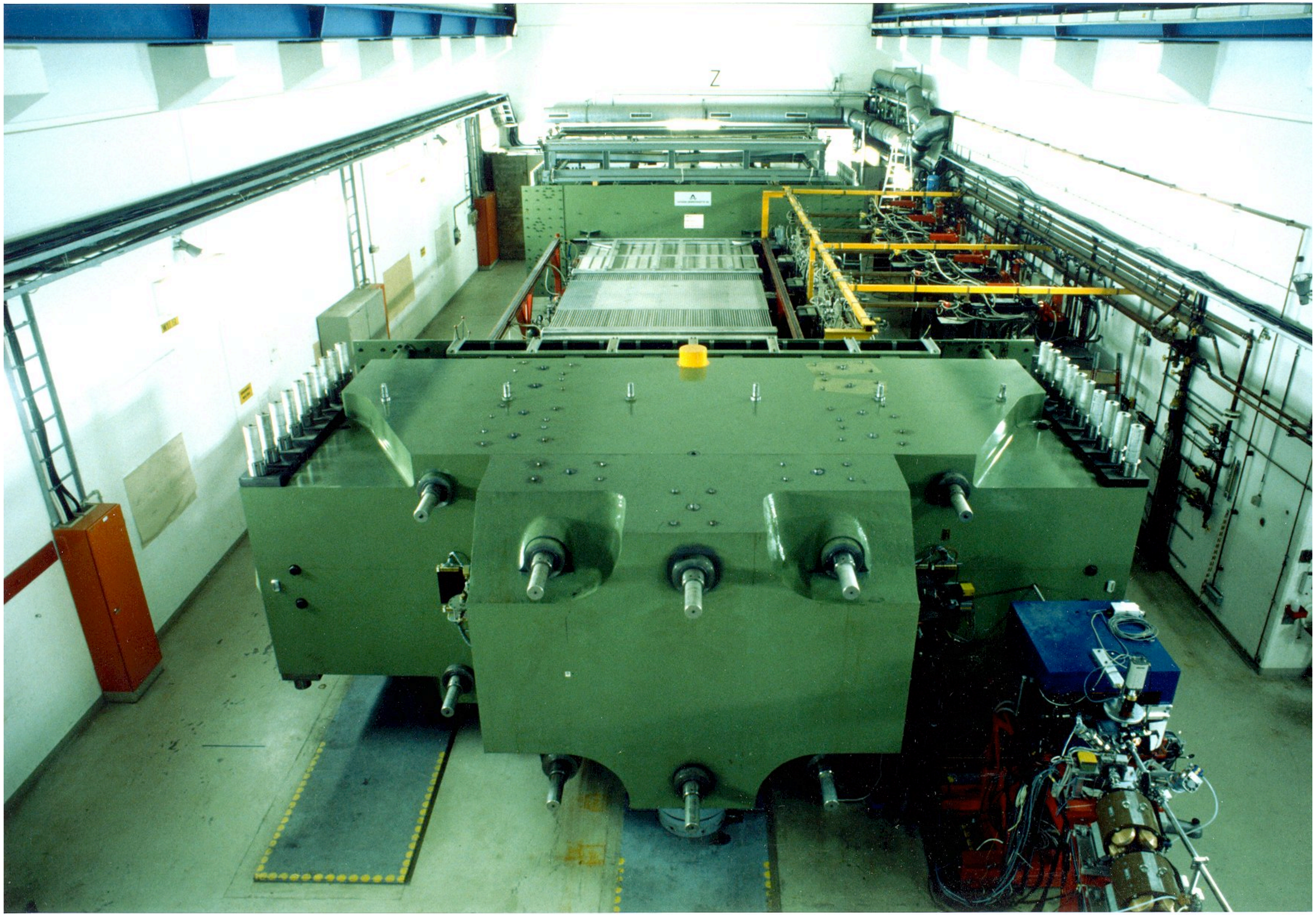
MAMI-B



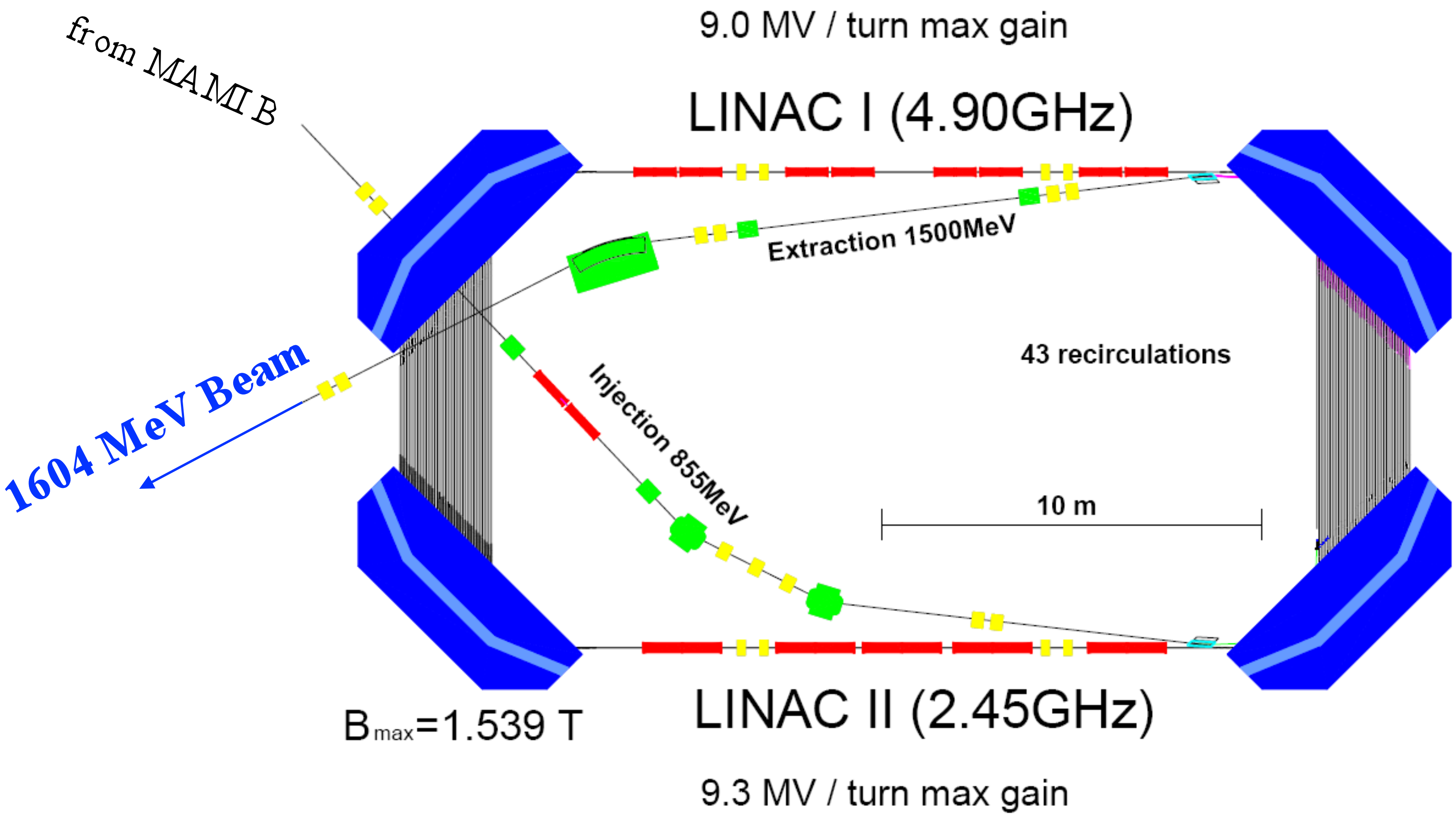
MAMI B: 885 MeV Energy

CW: bunch structure 0.4 nsec

MAMI-B

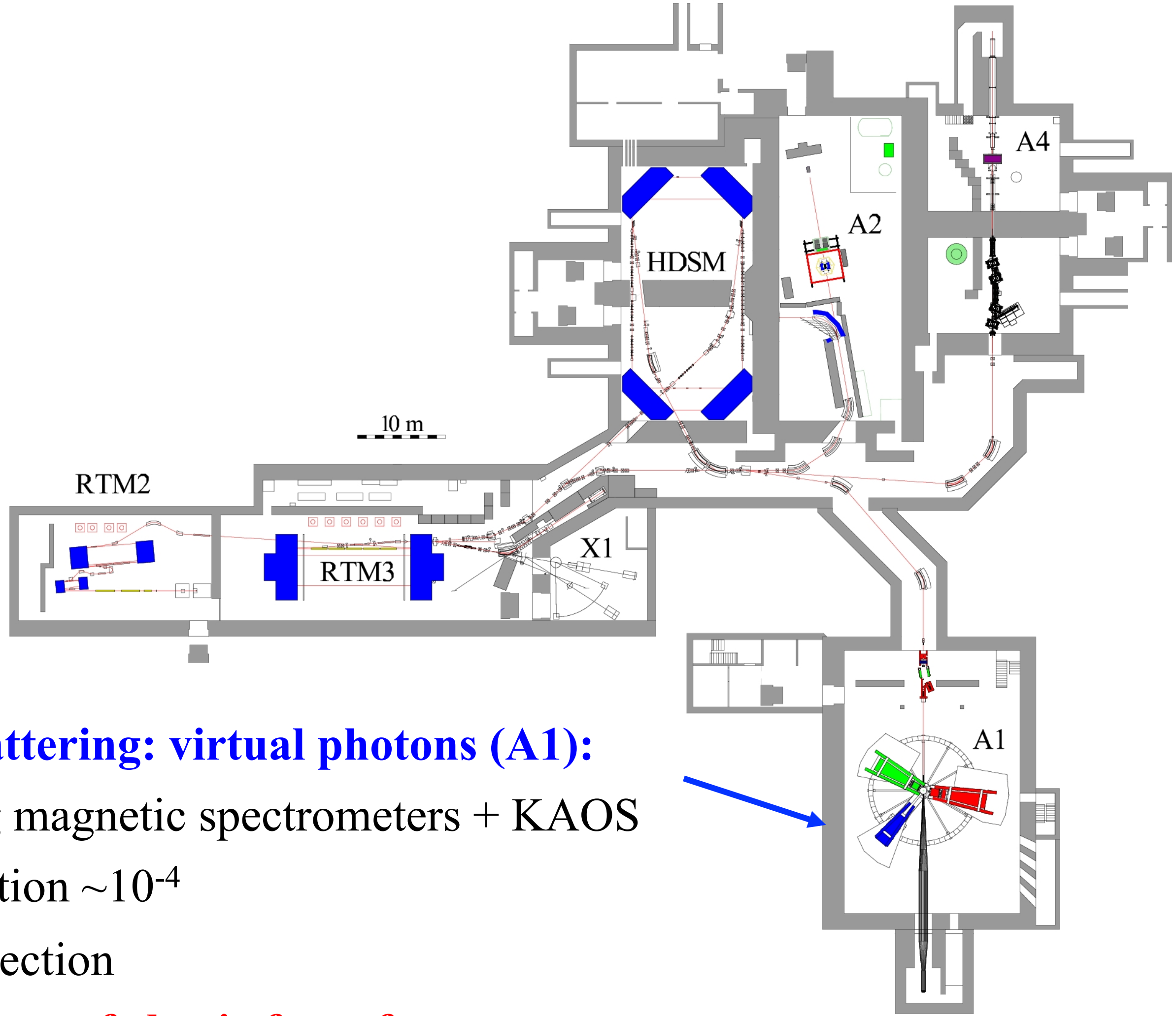


Mainz Microtron MAMI



Harmonic Double Sided Microtron (HDSM)

A1 Experiment



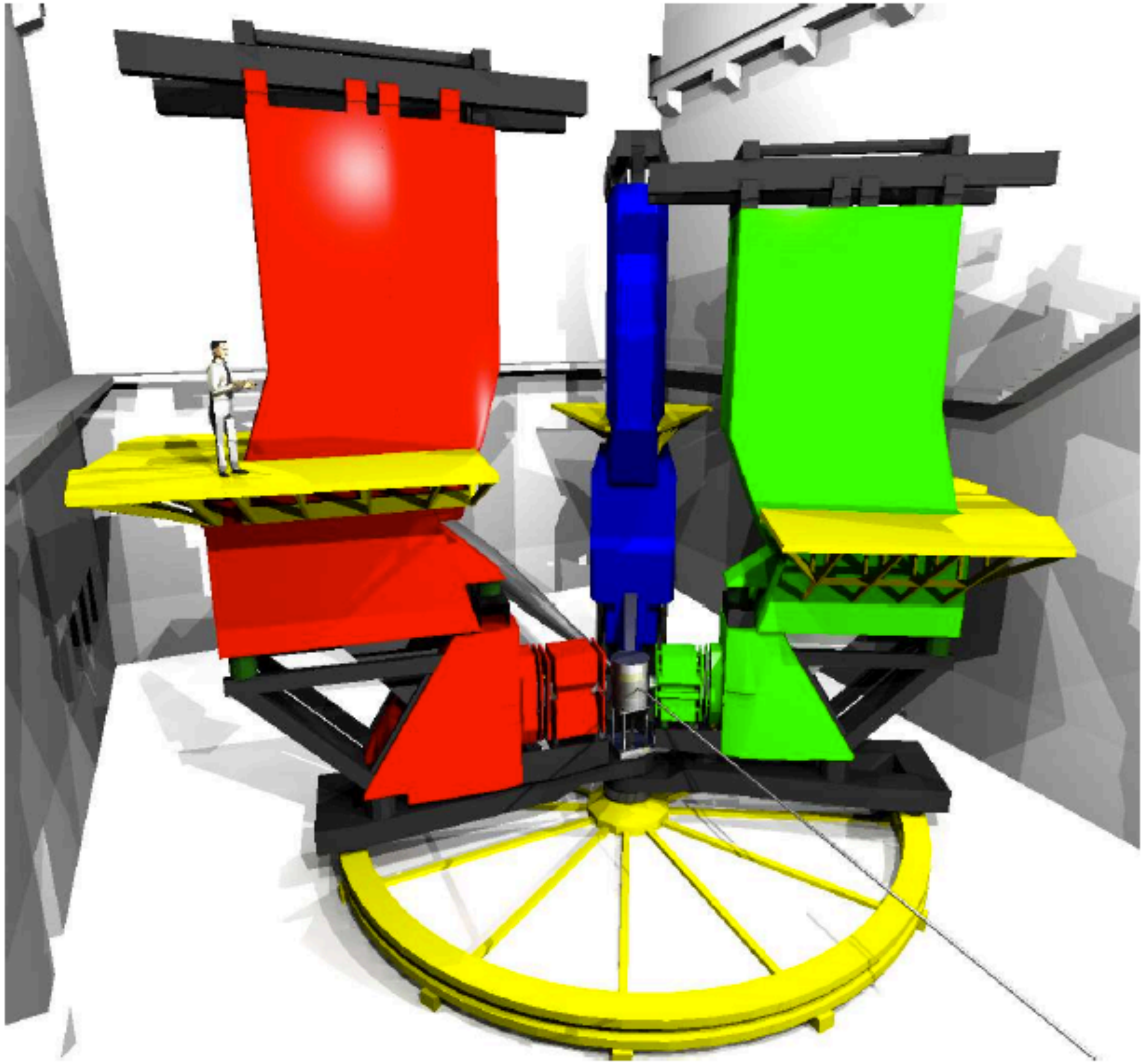
Electron scattering: virtual photons (A1):

- 3 focussing magnetic spectrometers + KAOS
- high resolution ~10^{-4}
- neutron detection
- **Measurement of elastic form factors**


A1

Dark Photon Search @ A1 Experiment

high momentum resolution ~10^{-4}



Spektrometer A:

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

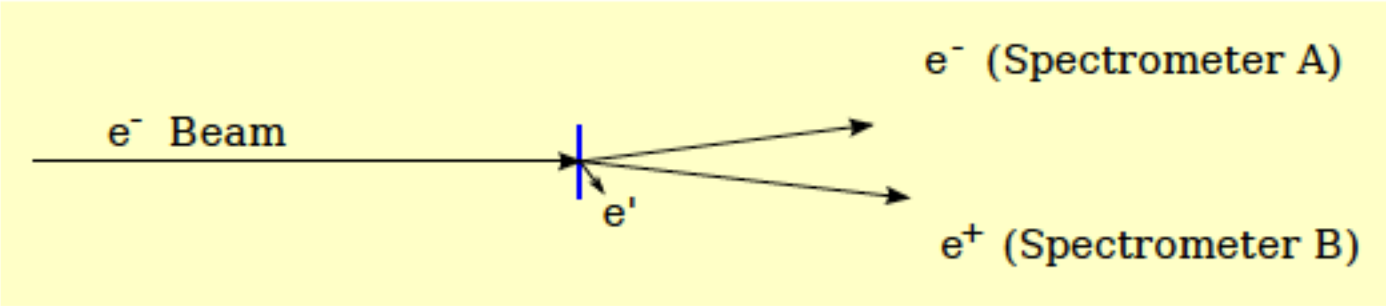
Spektrometer B:

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

Spektrometer C:

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

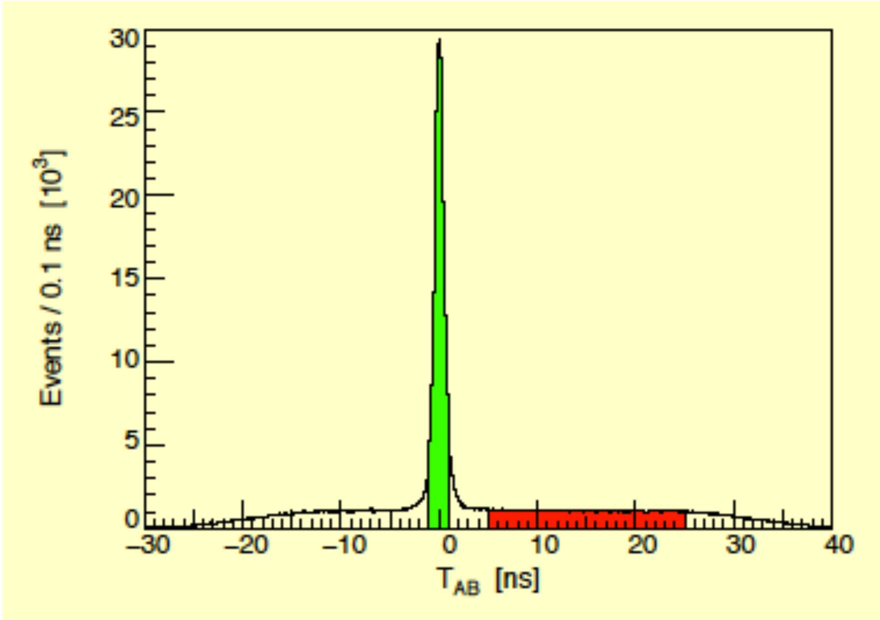
A Pilot Experiment at MAMI (6 Days)



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

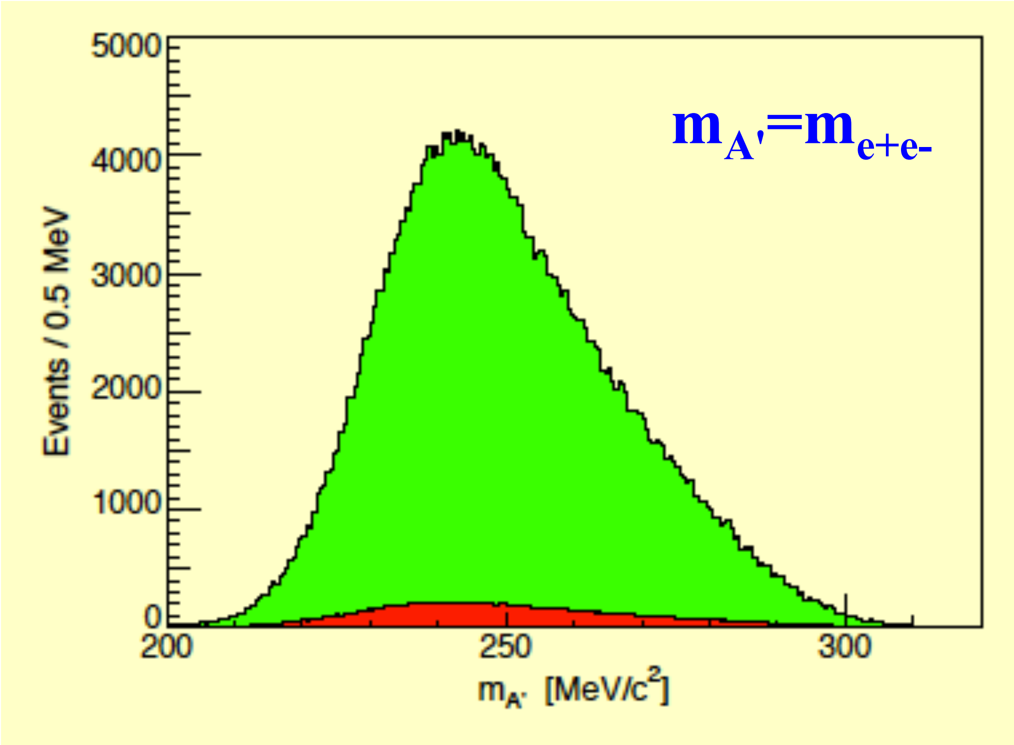
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV/c
	$\theta_{e^-} =$	22.8°
Spectrometer B	$p_{e^+} =$	470.0 MeV/c
	$\theta_{e^+} =$	15.2°

ΔTOF_{AB}



- 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 $\approx 5\%$

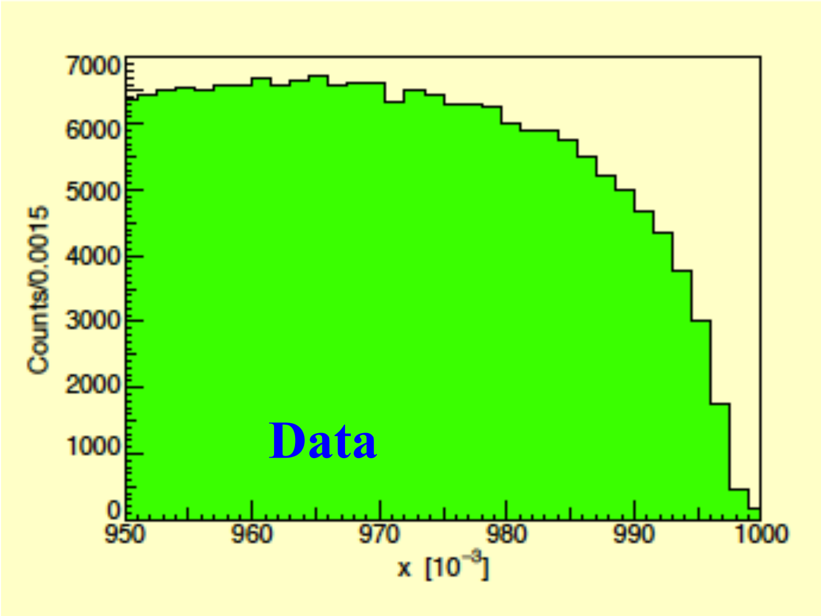
Invariant Mass Spectrum from 6 Days Pilot Run

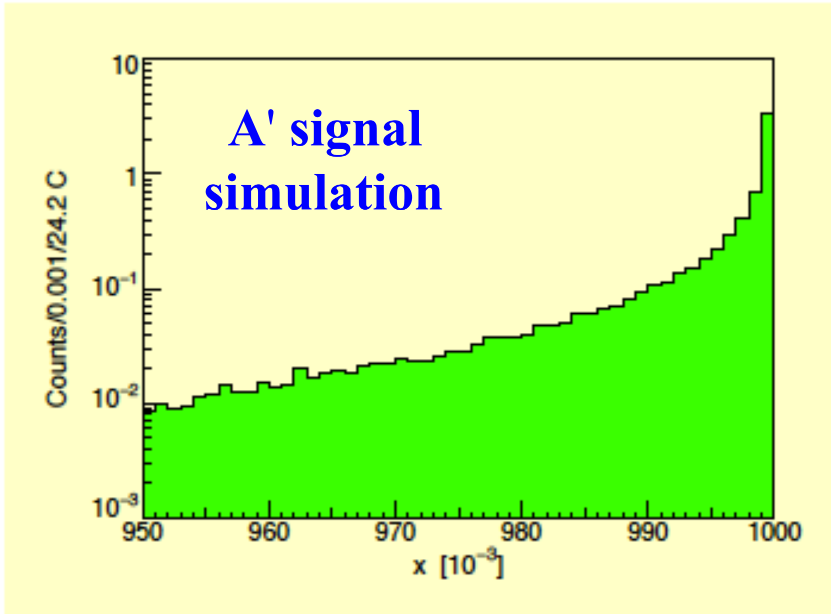


Background is low allowing to reach high sensitivities in ε !

- Decay outside of target ⇒ Spectrometer resolution defines mass resolution
- Measurement of spectrometer resolution via elastic scattering
- Simulation of mass resolution for this kinematics ⇒ $\delta m < 500 keV$

Dependence on x

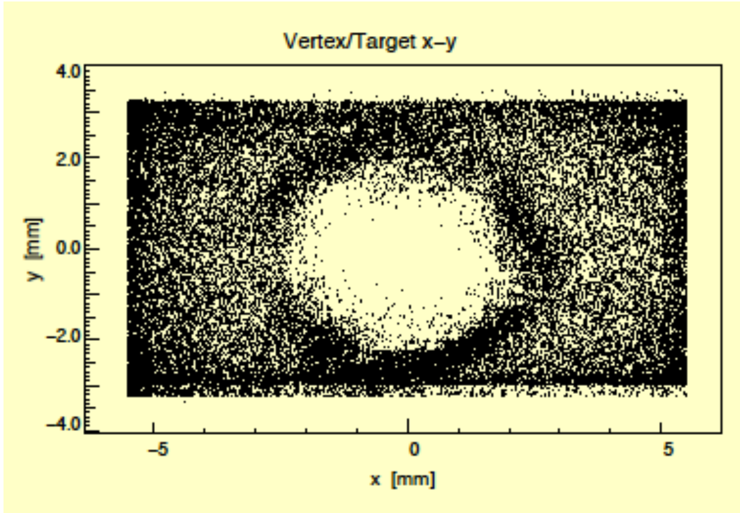




- Weizsäcker-Williams approximation not appropriate at high x values
- Reason: neglected phase space of recoil nucleus

→ x=1 seems not to be optimal working point for A' search
→ proof that for high x values no other unaccounted background available!

Lessons learnt from Pilot Experiment



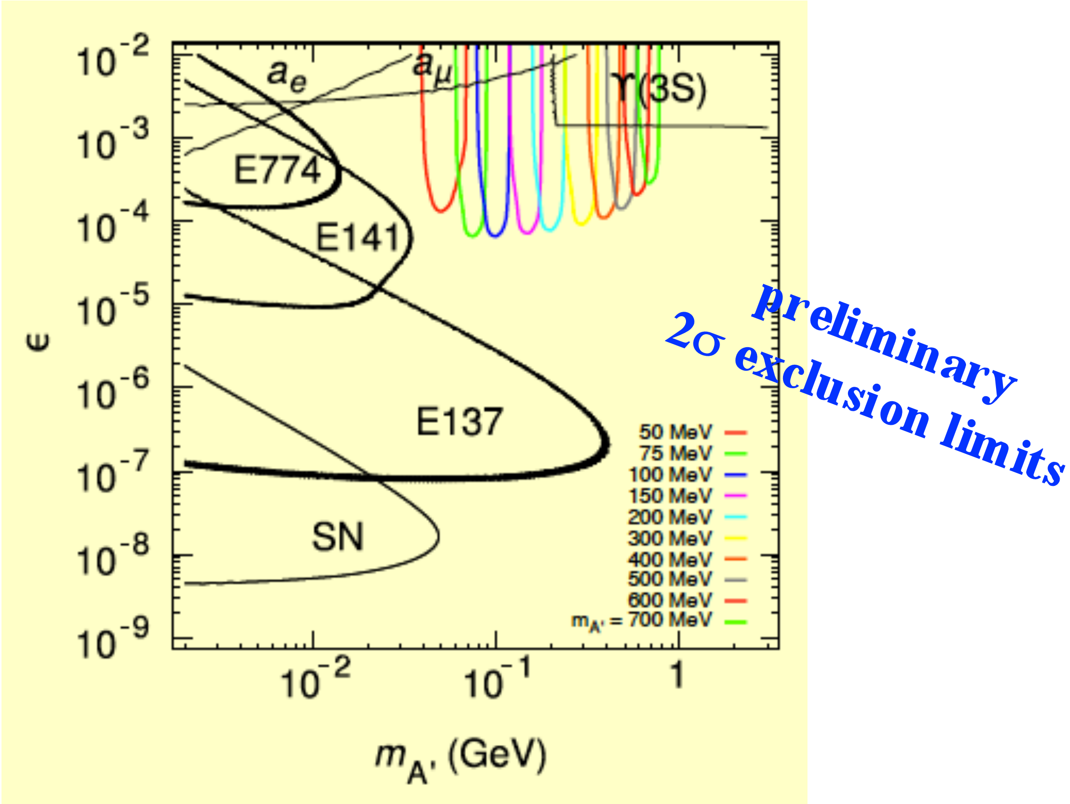
1. Beam current of 100μA straight on 0.05 mm Ta leads to melting of target → beam manipulation

2. Optimize kinematics
→ x parameter

3. German laws for air activation limited data taking (max. beam current, target)
→ target cooling
→ target shielding

An order of magnitude improvement seems plausible

Preliminary Exclusions Limits



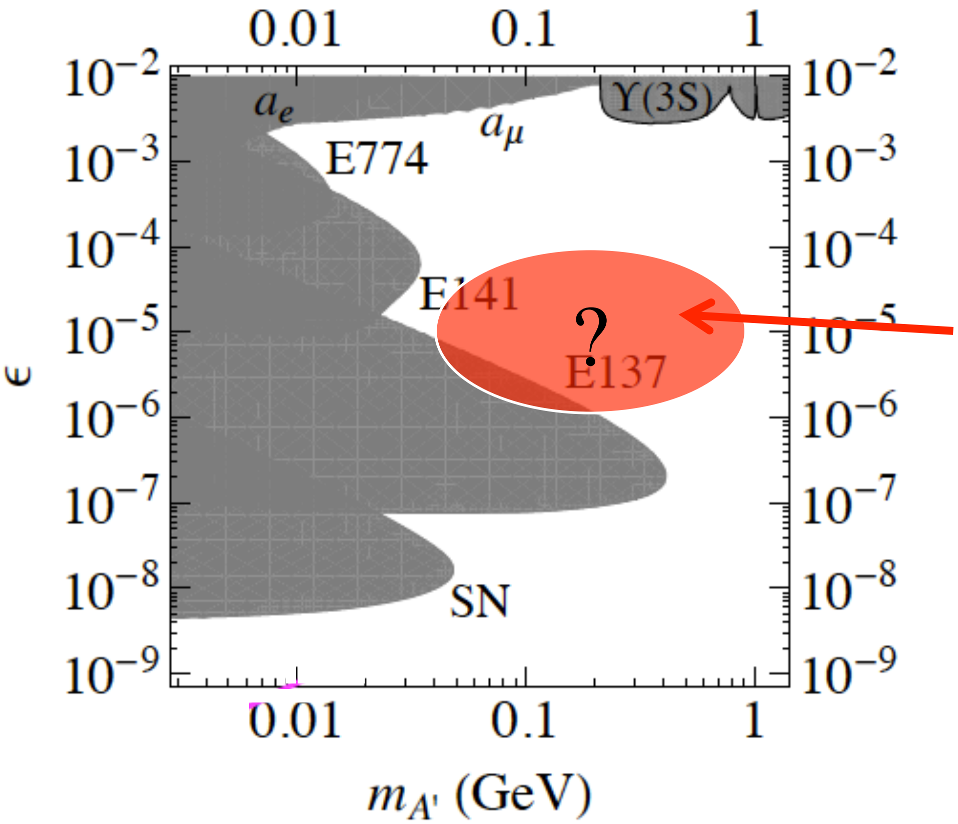
Limits based on [Bjorken et al. 2009]

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

→ t-channel exchange background further under study

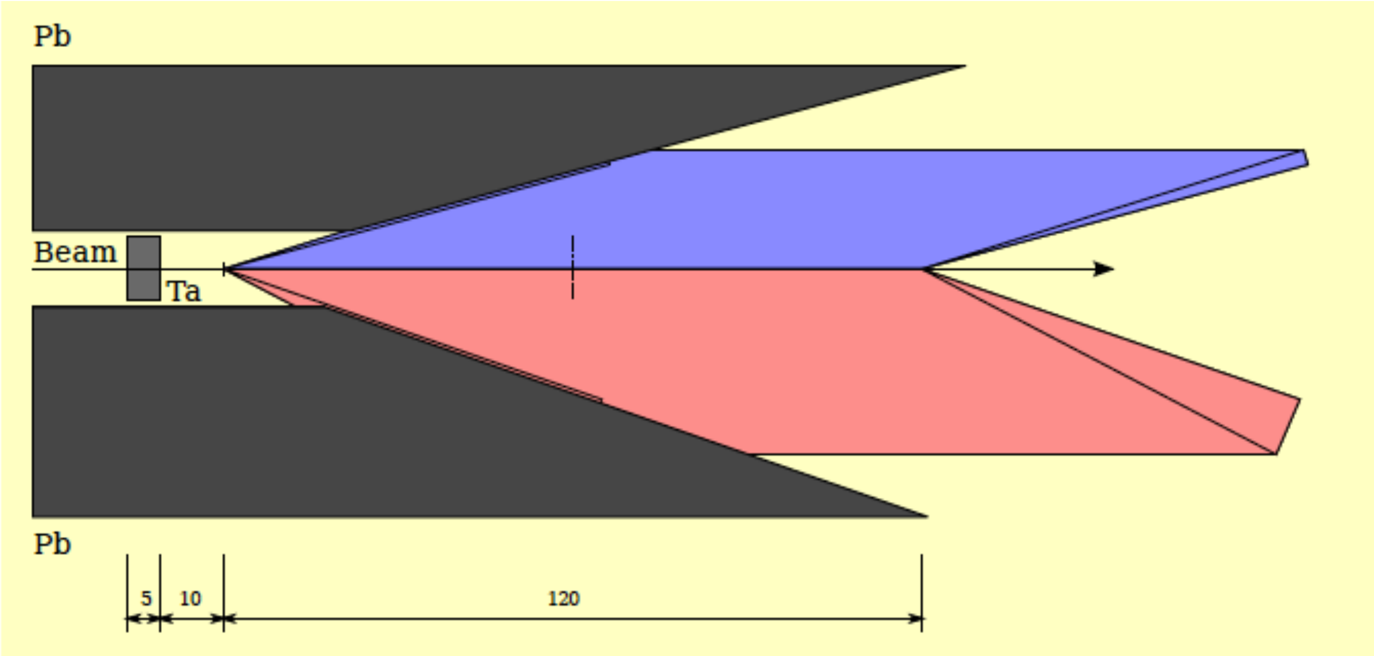
Further Ideas: Medium ε - Region

Bjorken et al. [2009]



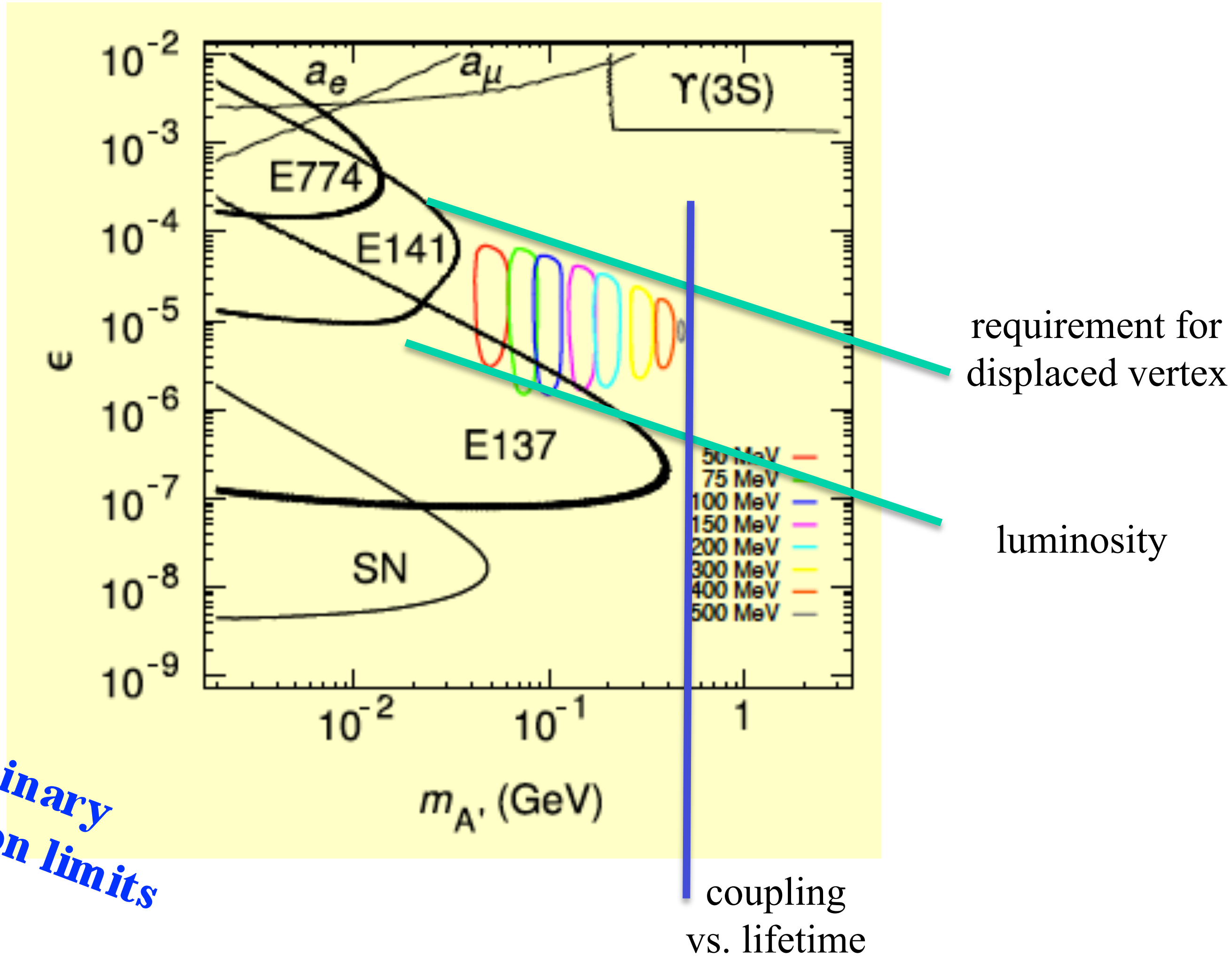
displaced vertex measurements

Displaced Vertex Measurement



- 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 $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{s\,cm^2}$ at 100 μA beam current
- Beam stabilisation, shielding, target cooling

Displaced Vertex Measurement



preliminary
2σ exclusion limits

MAINZER MIKROTRON

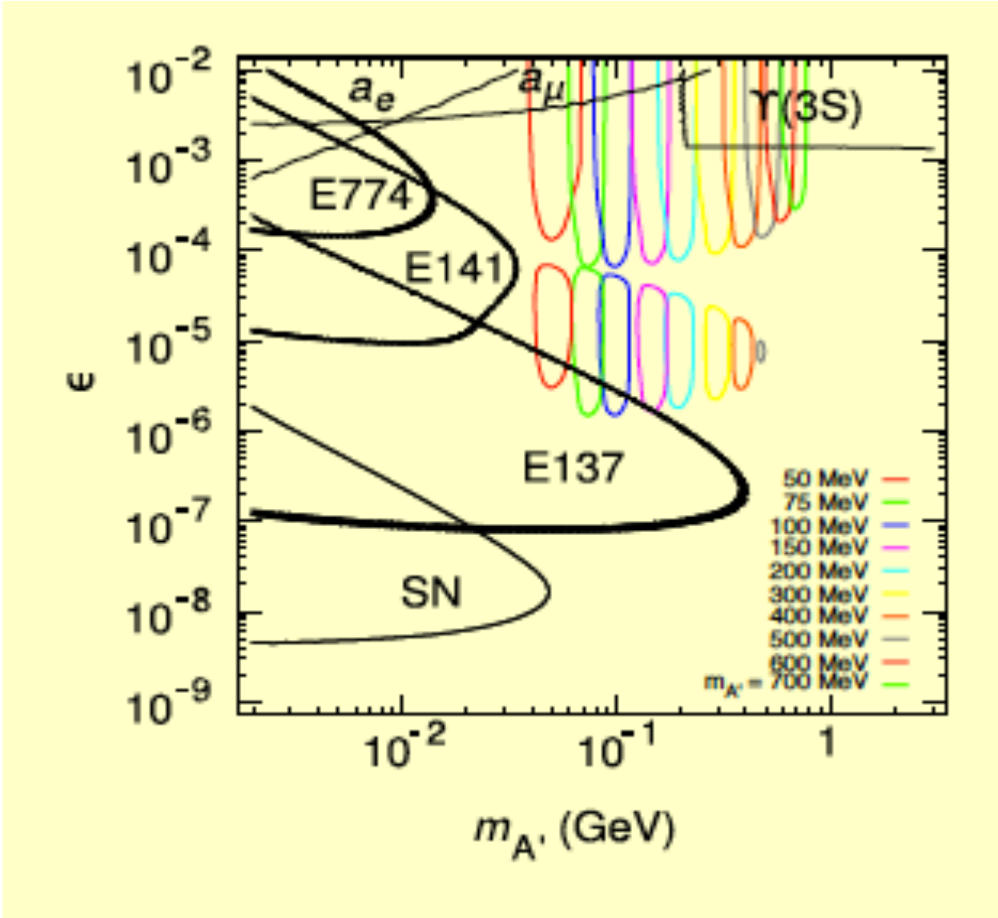
Conclusions

✓ **Certainly interesting subject**
should not concentrate too much on astrophysical anomalies

✓ **Mainz 1.6 GeV MAMI accelerator available**
lower beam energies compared to JLAB
successful pilot run @ A1; enter uncovered region
no show stopper identified
detailed MC simulation studies → address PAC

✓ **Some more work on theory side needed**
calculation beyond Weizsäcker-Williams approximation
define optimal S/B ratio

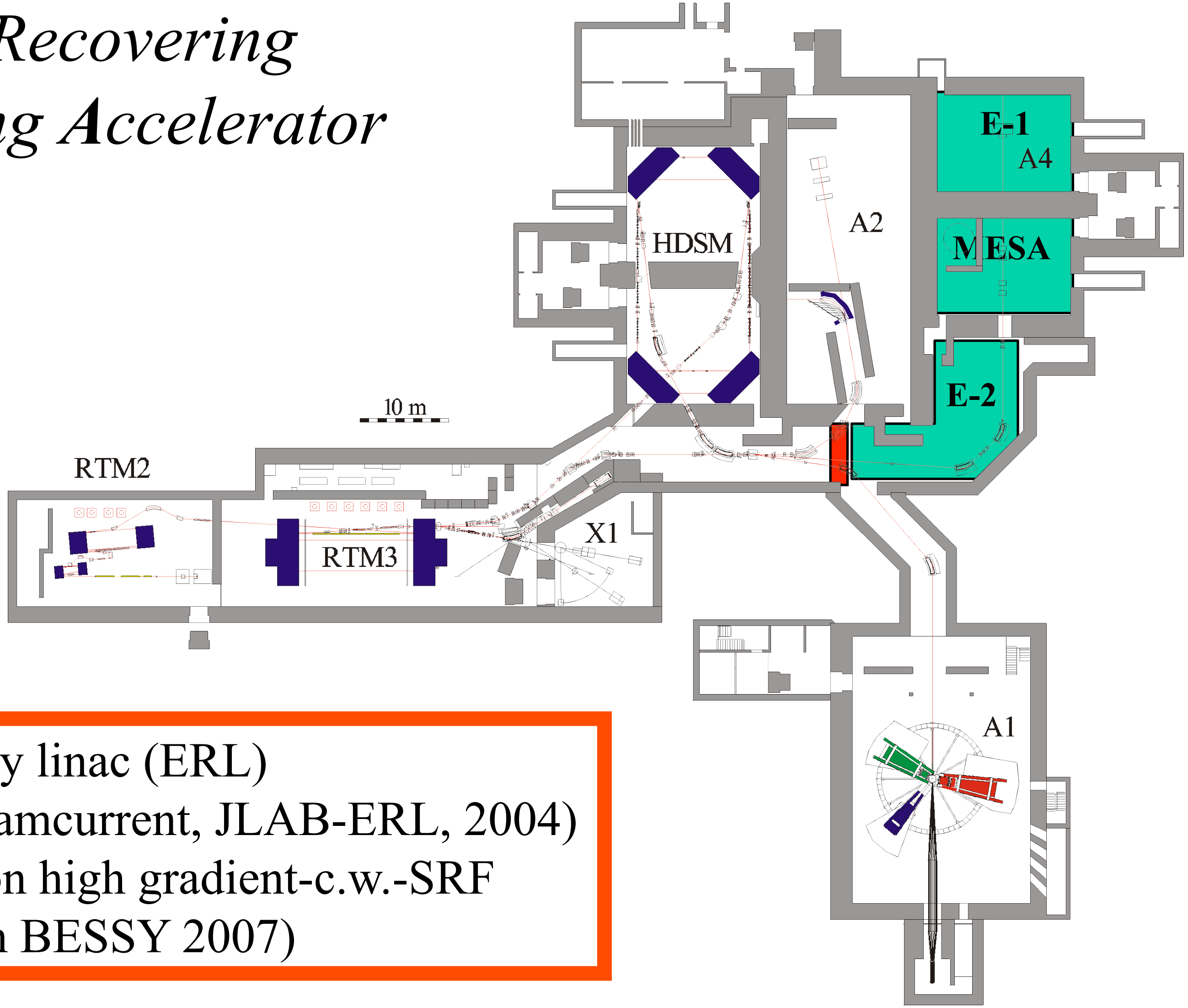
Conclusions



✓ **Future: project MESA ?**

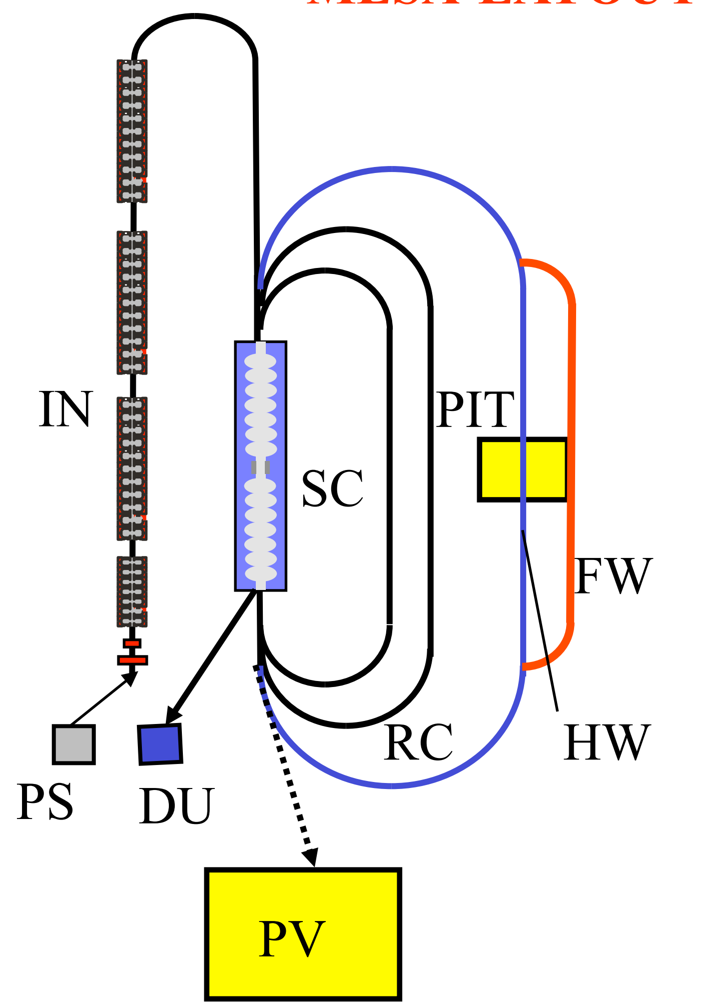
Outlook: MESA

***M**ainz **E**nergy Recovering **S**uperconducting **A**ccelerator*



1. Energy recovery linac (ERL)
   (10 mA c.w. beamcurrent, JLAB-ERL, 2004)
2. Improvements on high gradient-c.w.-SRF
   (e.g. 20 MeV/m BESSY 2007)

MESA



EXPERIMENTAL BEAM PARAMETERS:

Superconducting cavity: 33 MeV/turn

EB-mode:
150 μA, 137 MeV polarized beam
(liquid Hydrogen target L~10^{39})
→ New generation parity violation experiment
'working horse' of MESA

ERL-mode:
10mA, 104 MeV unpolarized beam
(Pseudo-Internal Hydrogen Gas target)

→ **possibilities for an A'**
experiment !?
high ε – low $m_{A'}$ region