PATRAS Conference Mainz
Schloss Waldthausen
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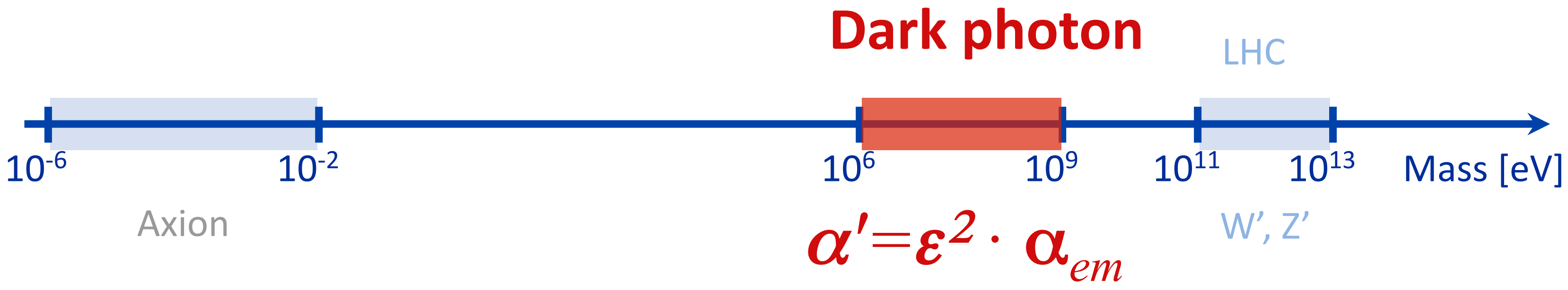
# Dark Photon Searches at MAMI and MESA

Achim Denig
University of Mainz

# *Dark Photon*

**New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications**




**Search for the O(GeV/$c^2$) mass scale in a world-wide effort**

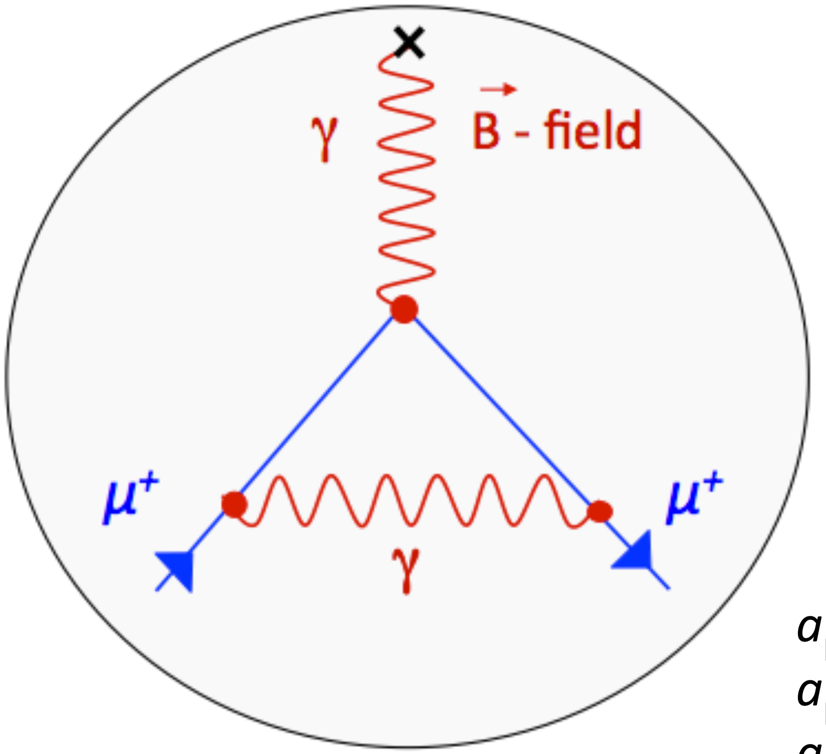
- Could explain large number of **astrophysical anomalies (INTEGRAL, PAMELA, AMS, DAMA/LIBRA, PLANCH…)** Arkani-Hamed et al. (2009)
- Could explain presently seen **deviation of 3.6σ between** Standard Model prediction and direct $(g-2)_\mu$ measurement Pospelov et al. (2008)
- **Proton radius puzzle, BR( Higgs → γγ), Relation to parity violation, ....**

# *Muon Anomalous Magnetic Moment: $(g\text{-}2)_\mu$*

## Magnetic Moment: $\vec{\mu} = \mu_B \; g \; \vec{S}$

$a_\mu = (g\text{-}2)_\mu / 2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,180.2 \pm 4.9\,) \cdot 10^{-10}$

Davier et al. PRL 2011




$a_\mu^{QED} = (11\,658\,471.809 \pm 0.015) \cdot 10^{-10}$

$a_\mu^{weak} = (15.4 \pm 0.2) \cdot 10^{-10}$

$a_\mu^{strong} = (693.0 \pm 4.9) \cdot 10^{-10}$

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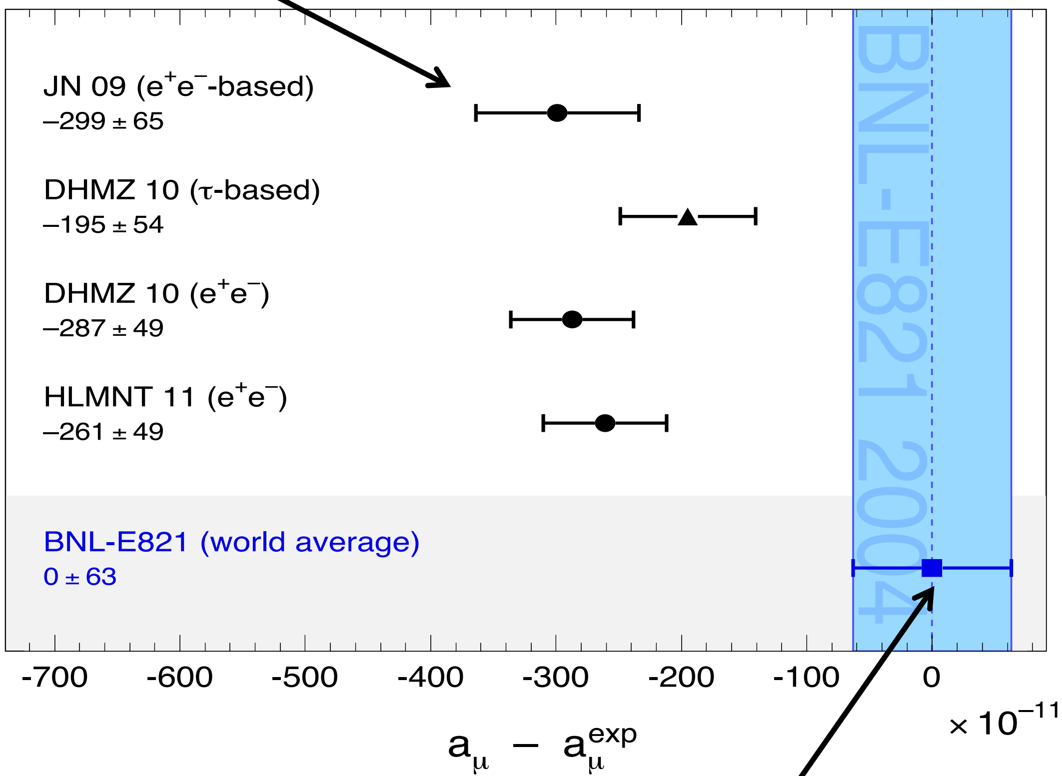



$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$

$(28.7 \pm 8.0) \cdot 10^{-10}$ $(3.6\ \sigma)$

**Error(s) or New Physics ?**

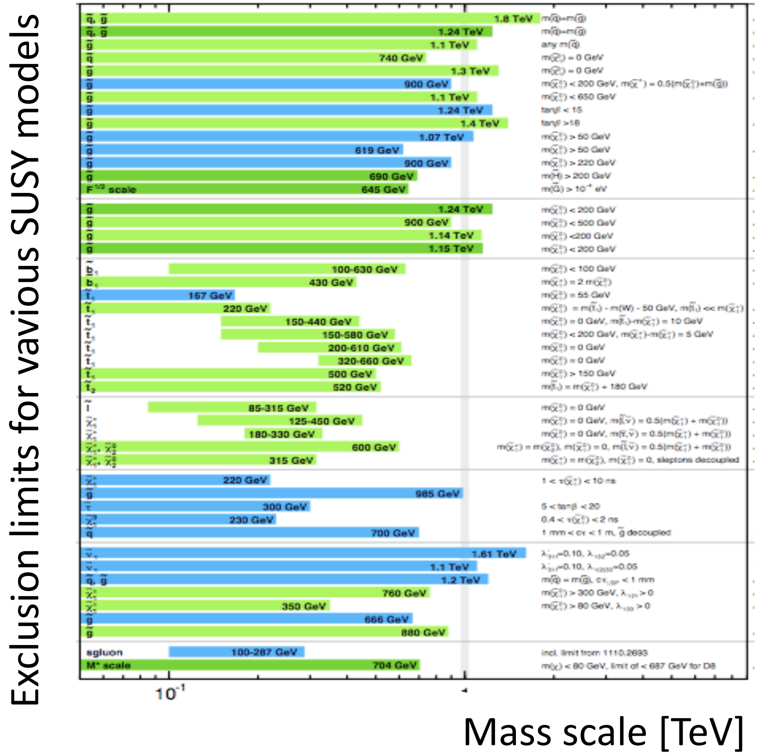
E821 measurement $a_\mu^{exp} = (\,11\,659\,208.9 \pm 6.3\,) \cdot 10^{-10}$

# *Explanations for $(g\text{-}2)_\mu$ puzzle*

## Supersymmetry ?

$$\Delta a_\mu^{\mathrm{SUSY}} \approx +13\cdot 10^{-10}\,\mathrm{sgn}(\mu)\left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2 \tan\beta$$

$$= 28 \times 10^{-10}$$



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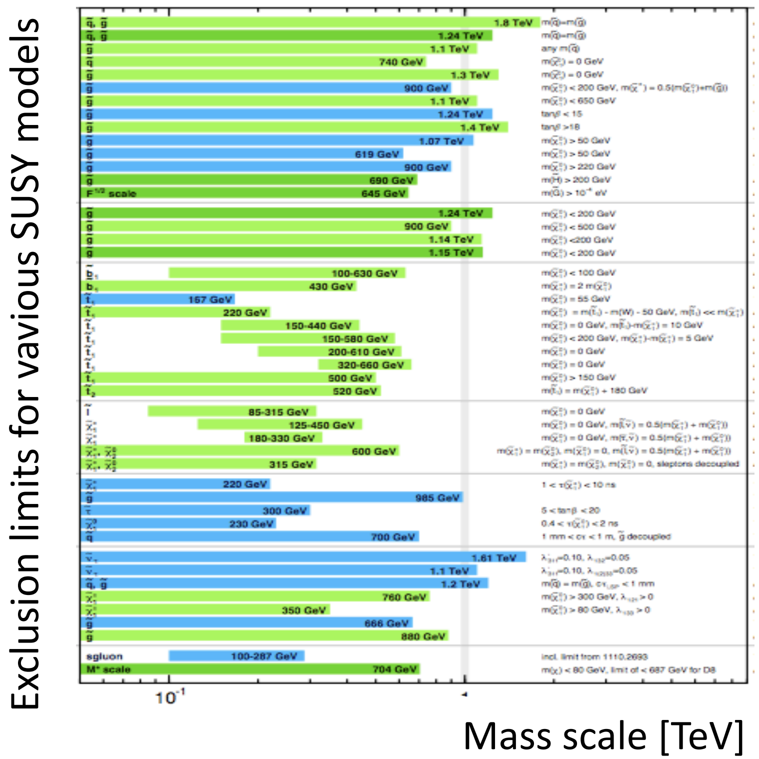
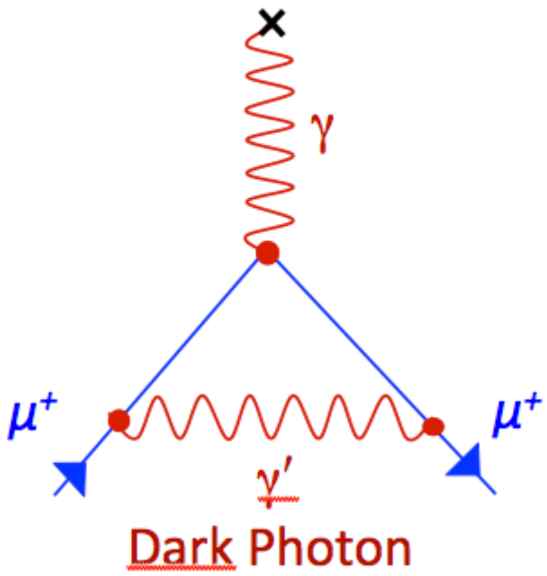


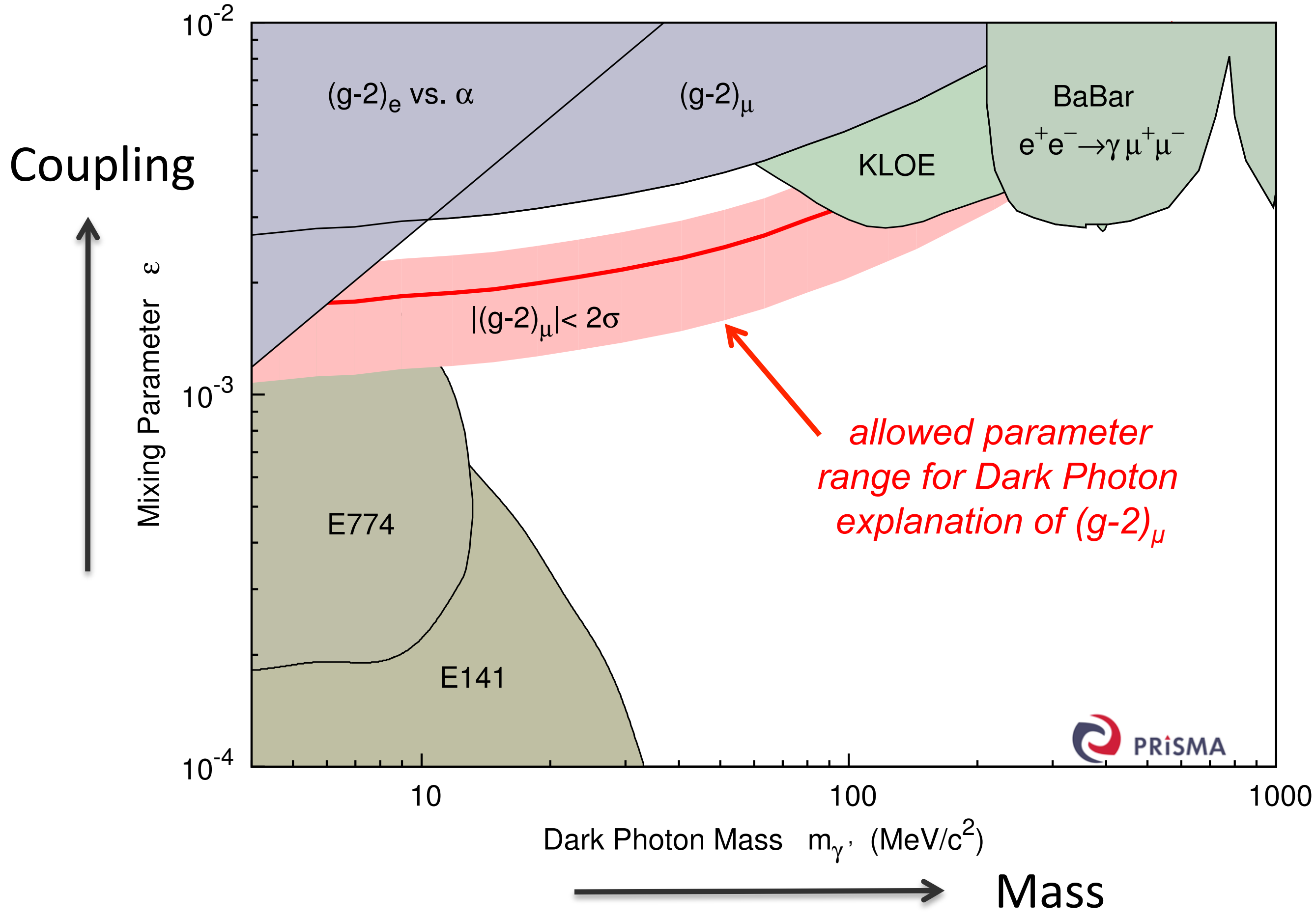

## Dark Photon ?

additional contribution to $(g\text{-}2)_\mu$




Free parameters:
- mass dark photon m(γ‘)
- coupling to SM matter ε

# The $(g\text{-}2)_\mu$ Parameter Range

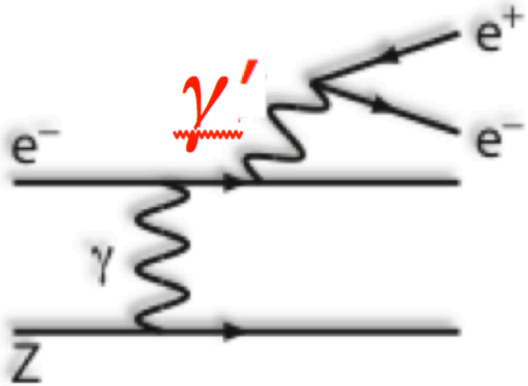


# *Searches using Fixed-Target Experiments*

Bjorken, Essig, Schuster, Toro (2009)

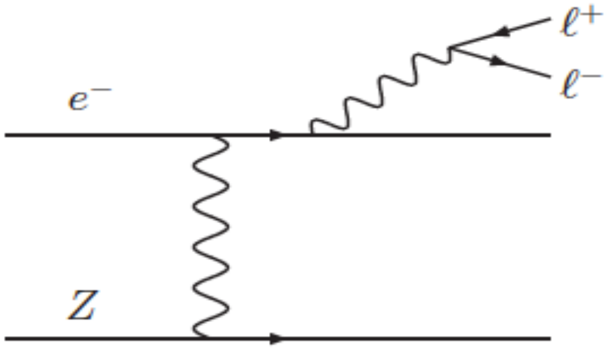
**Low-energy, high-intensity accelerators are ideally suited for Dark Photon searches**

**→ MAMI: $E_\gamma$ < 1.6 GeV**
**→ A1 spectrometer setup**

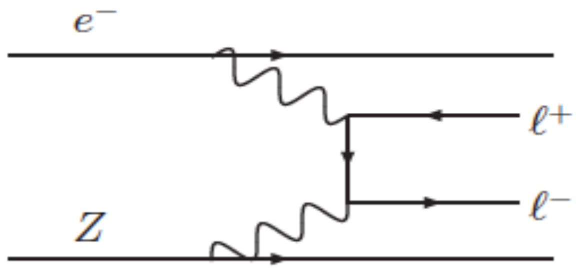



$m_{e+e-}$

**QED background processes:**




(a)



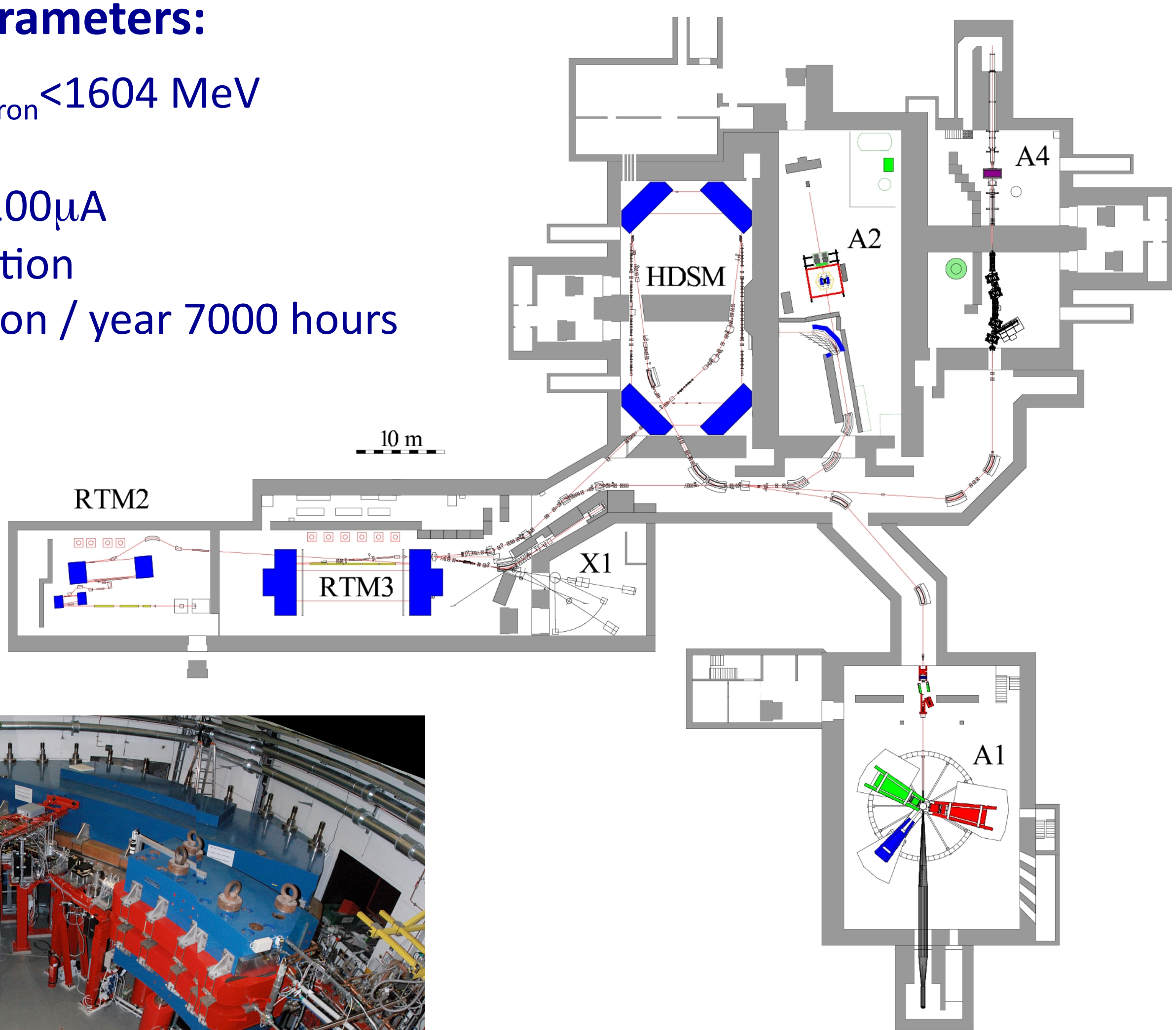

(b)

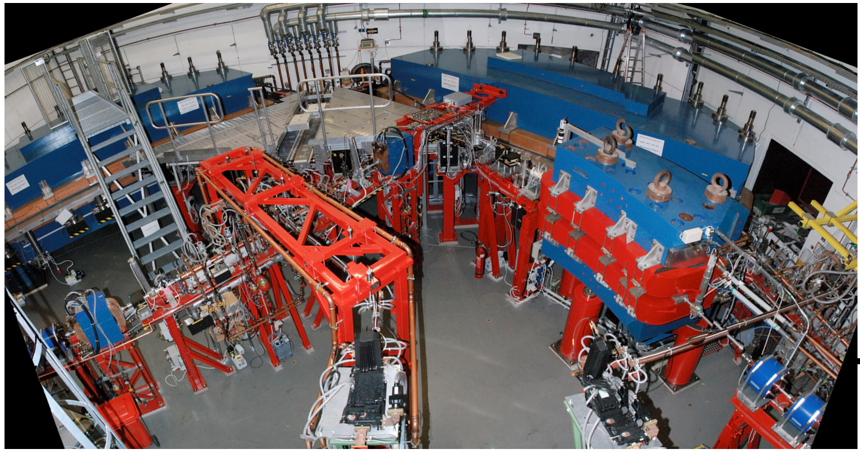
**→ T. Beranek**

# *1.6 GeV Electron Accelerator MAMI C*

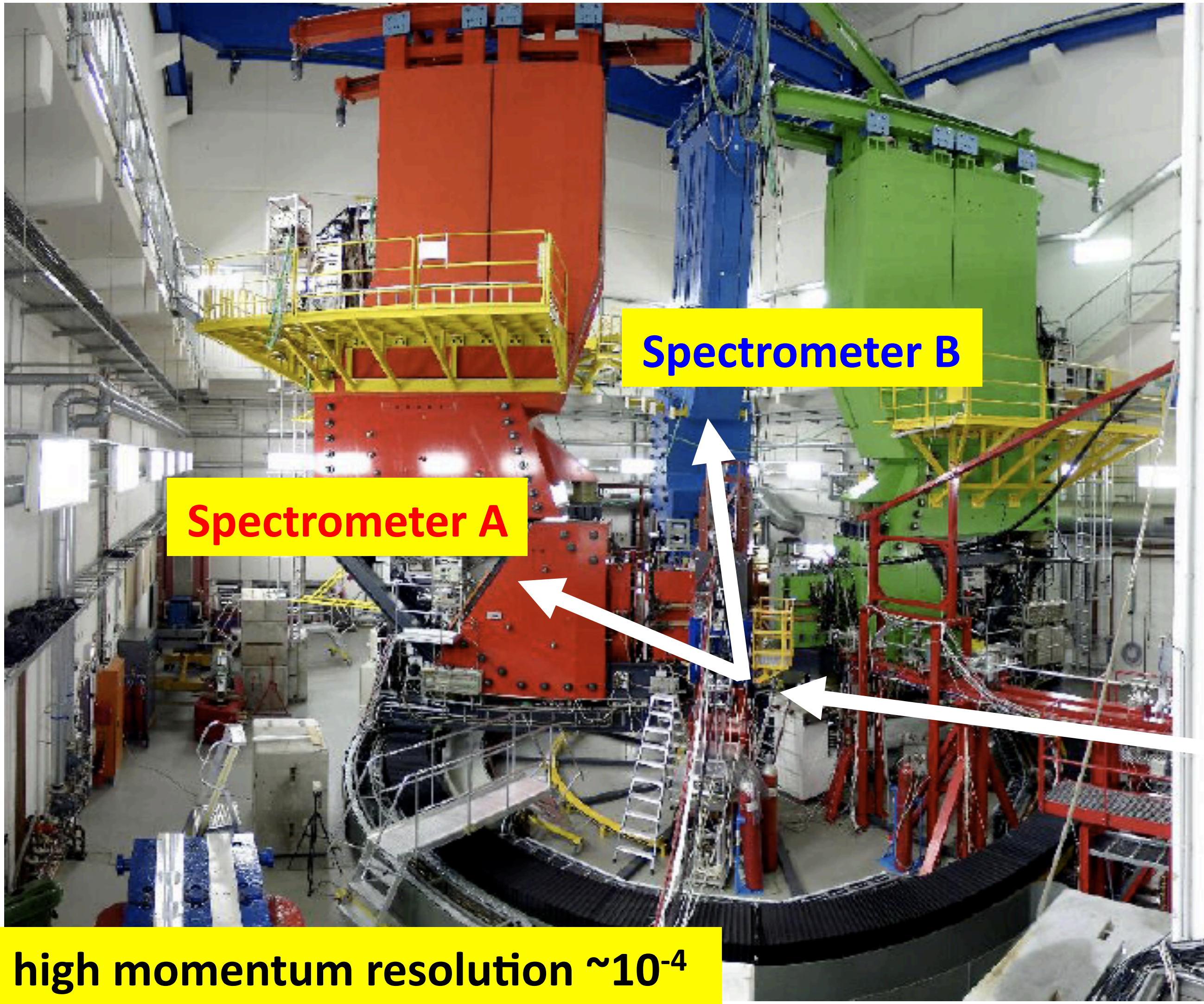
**MAMI beam parameters:**

- 180 MeV < $E_{electron}$<1604 MeV
- $\sigma_E$<0.100MeV
- Intensity up to 100$\mu$A
- ca. 80% Polarization
- hours of operation / year 7000 hours



# *A1 High Resolution Spectrometers*




Spektrometer A:

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

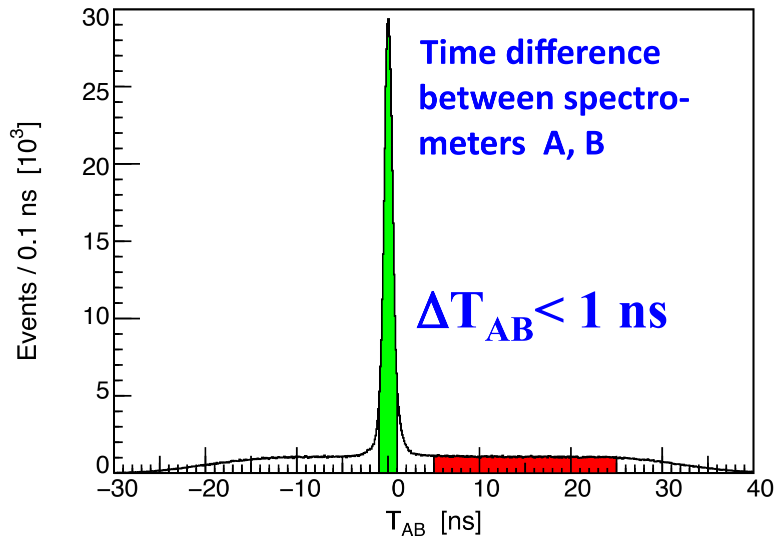
Spektrometer B:

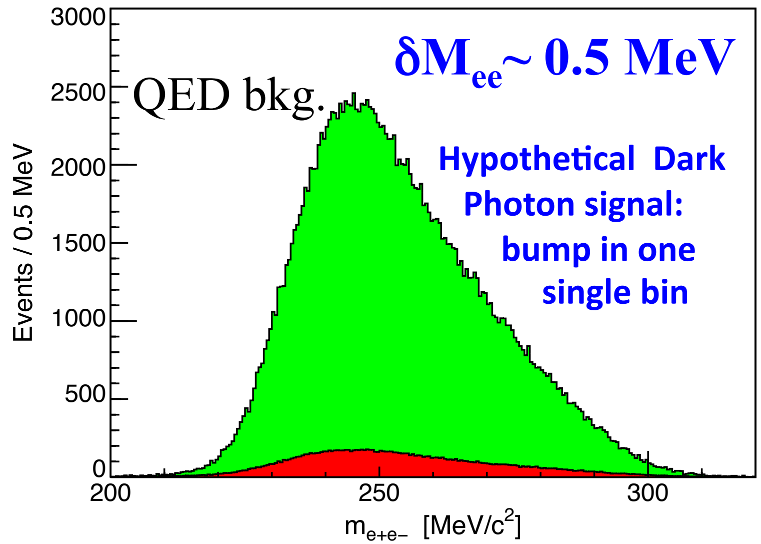
$$\begin{aligned} \alpha &> 8^\circ \\ p &< 870\,\frac{\mathrm{MeV}}{c} \\ \Delta\Omega &= 5.6\,\mathrm{msr} \\ \Delta p/p &= 15\% \end{aligned}$$

# *Dark Photon Search @ A1*

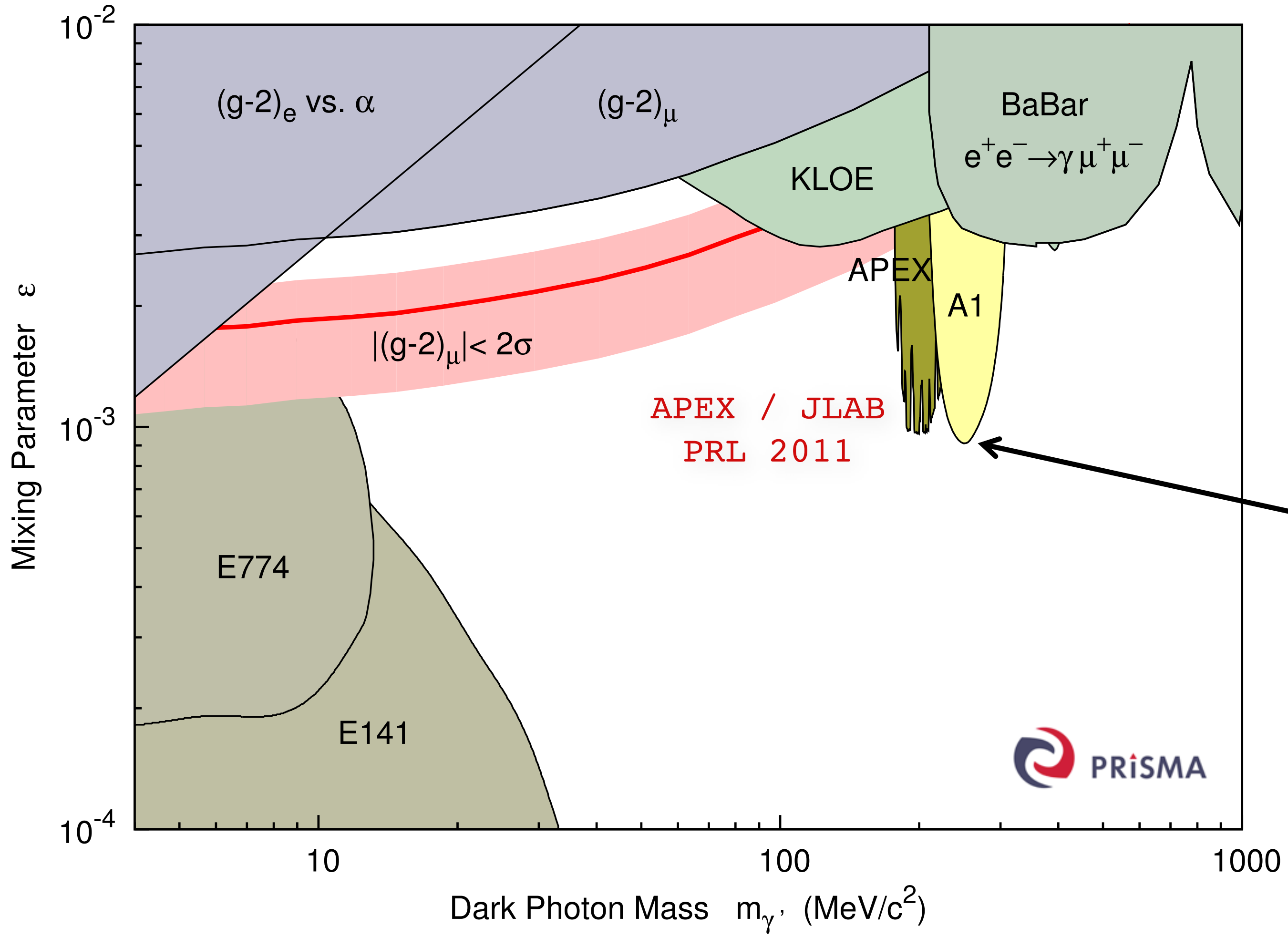
## Features 2010 pilot run (4 days)

- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current ~100µA → Luminosity ~$10^{39}$ $cm^{-2}s^{-1}$
- Kinematic configuration: - complete energy transfer to γ' boson
  - symmetric $e^-$ and $e^+$ momenta
- Cerenkov detector for electron/positron identification



# *Results from A1 Pilot Run (2010)*



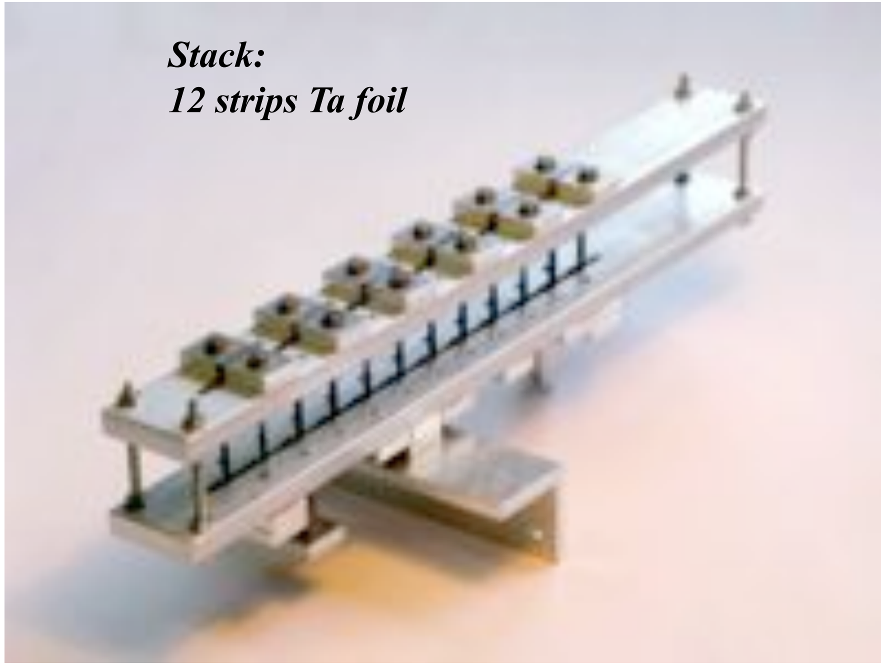

Exclusion range from
**MAMI / A1 spectrometers**
during **4-day pilot run**

A1/MAMI
PRL 2011

# A1 Production Run 2012

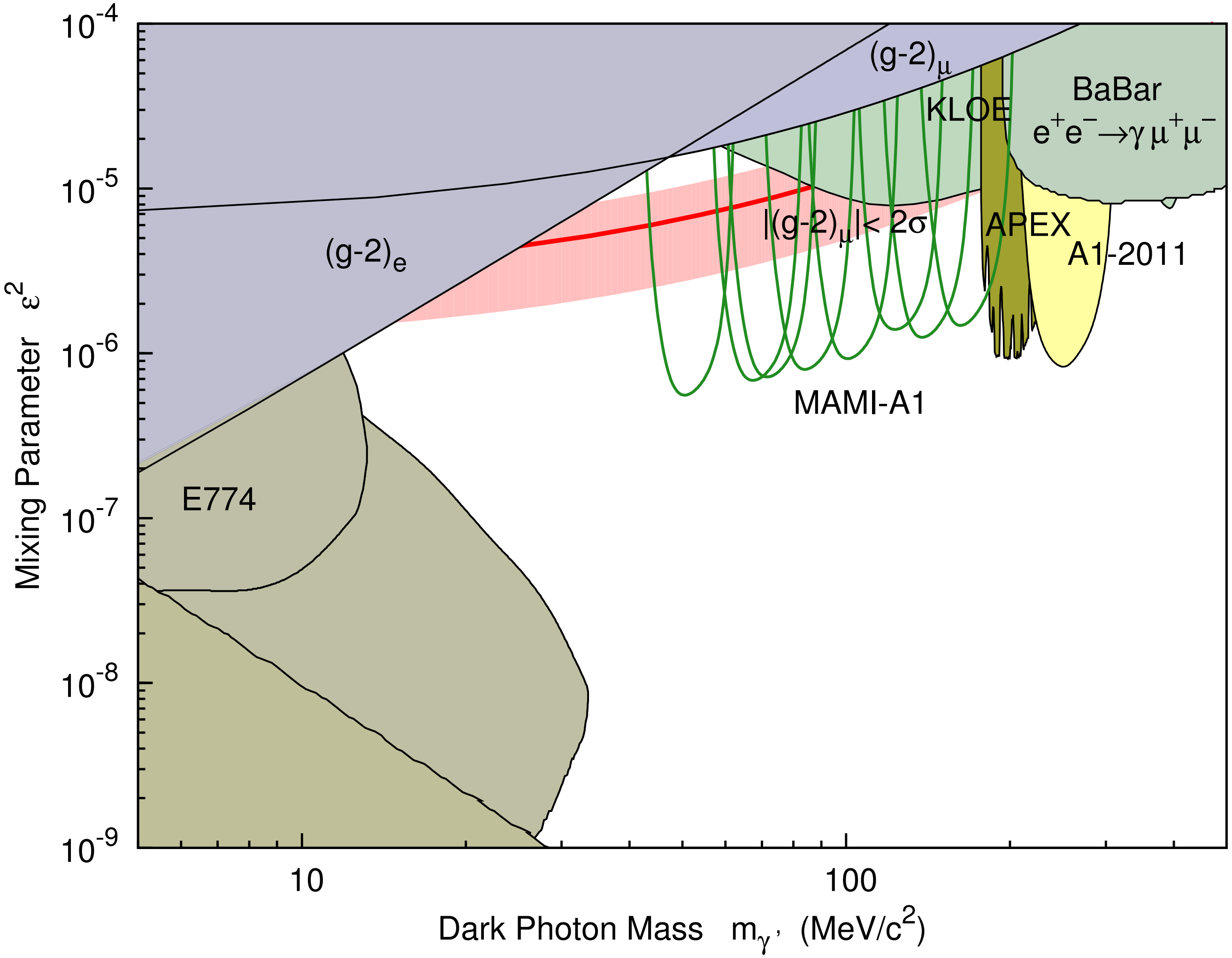
**Features 2012 run**

- Approx. 2 weeks of beam time
- 9 new kinematics settings
- Stack of 12-strip Ta foils
- Beam energies btw. 180 …. 720 MeV
- Beam intensities btw. 2.2 …. 43.4 µA

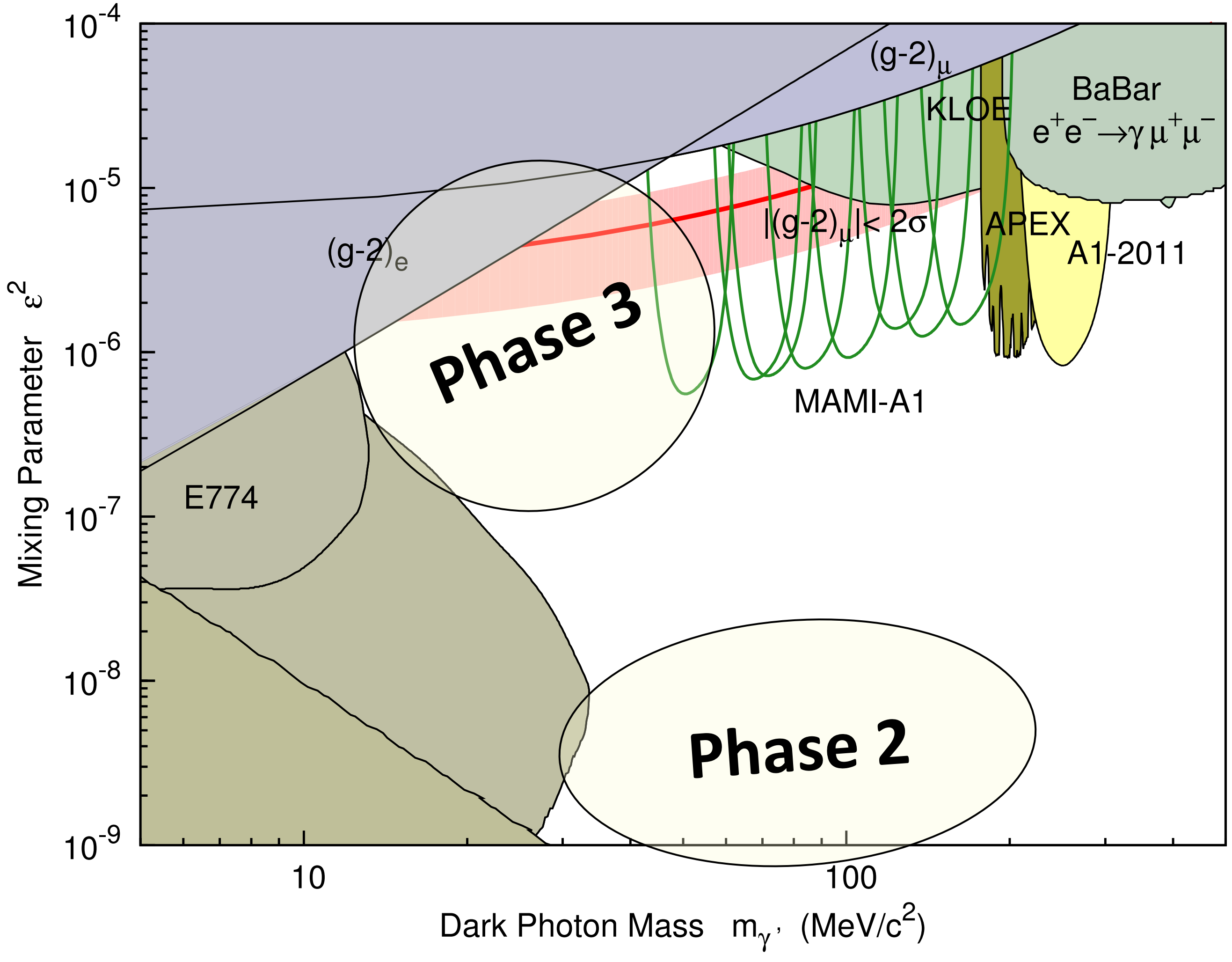



**QED corrections, see T. Beranek (exchange diagram)**
**→ additional run with similar settings in 02/2013**

# *Expected Range from 2012/13 A1-Runs*



# Expected Range from 2012/13 A1-Runs



# Phase 2: Accessing the Low Epsilon Region

**Exploiting a displaced vertex technique → low epsilon values**

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

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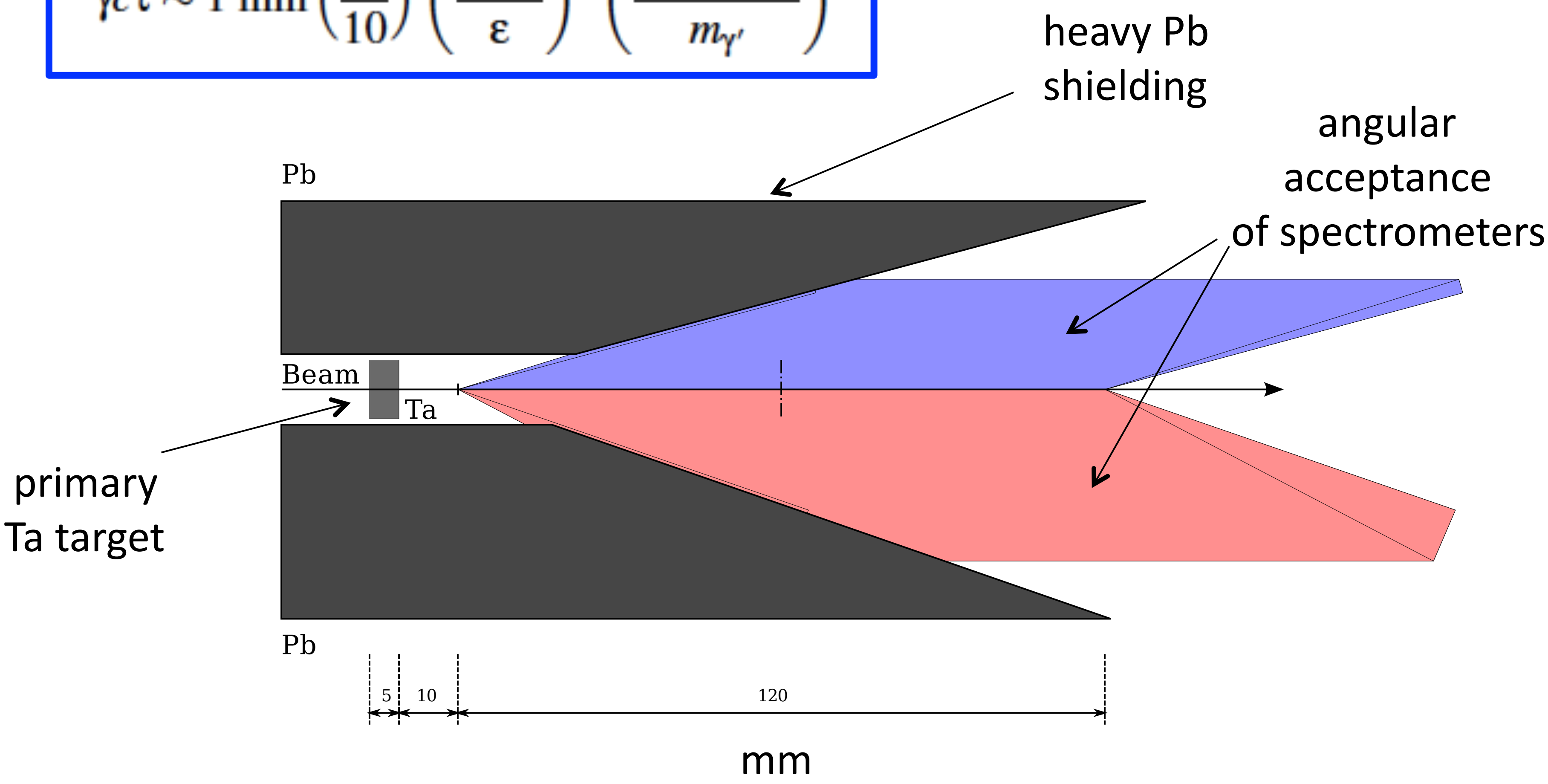

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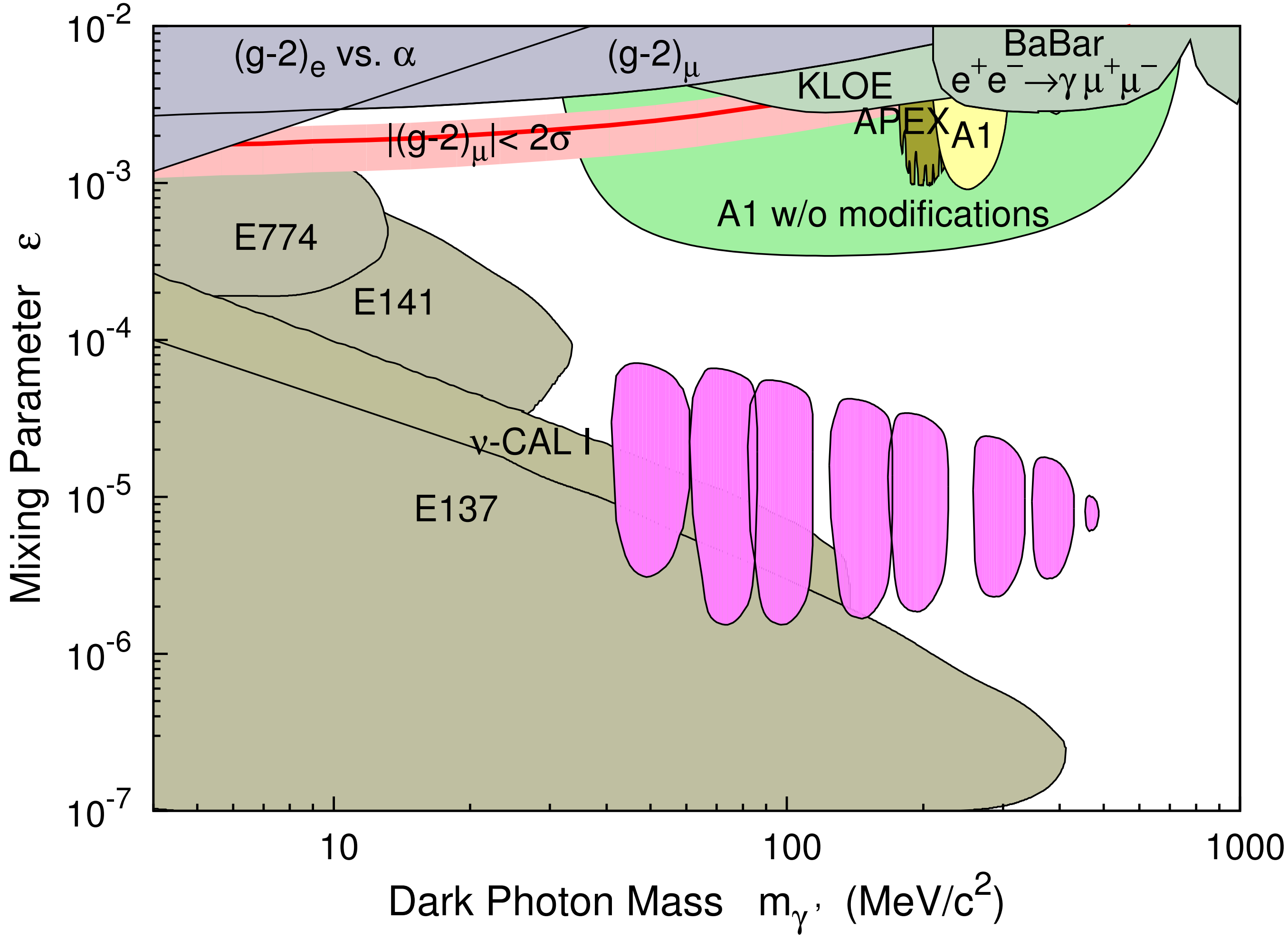


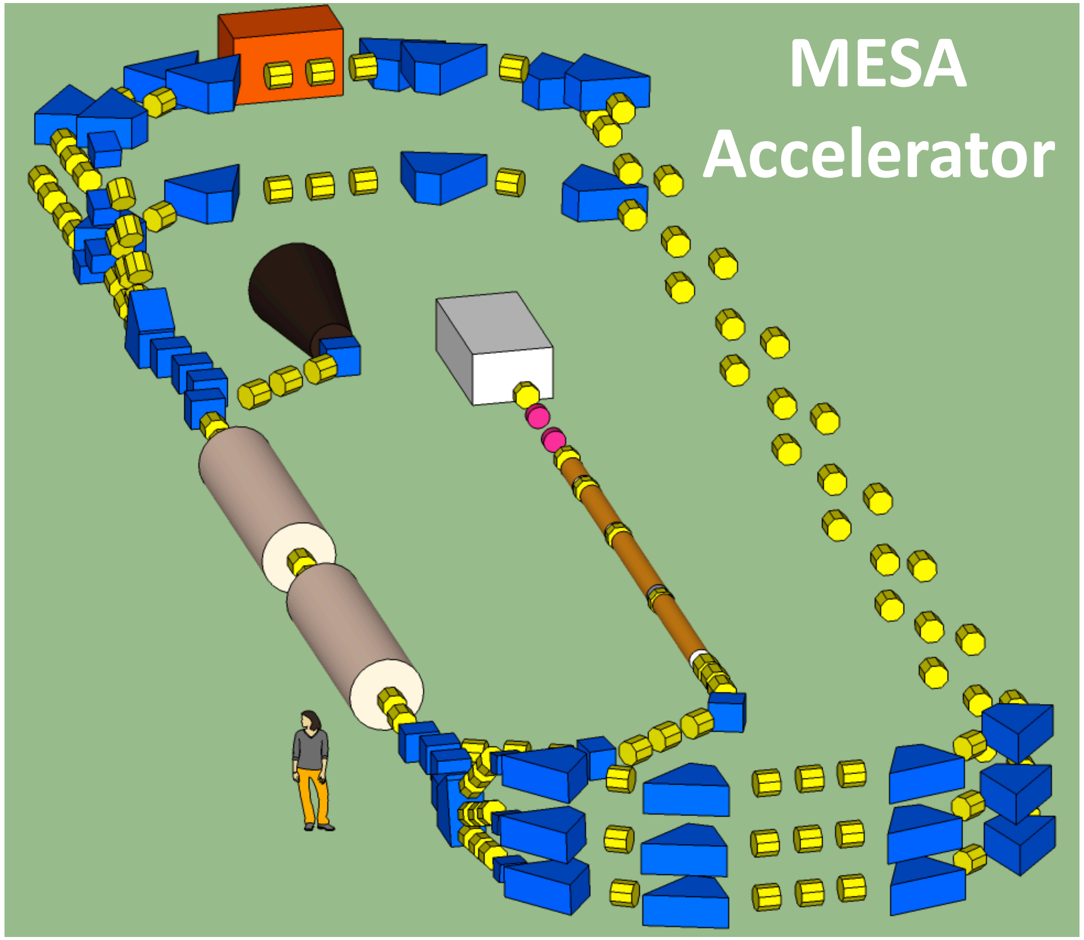
# *Phase 3: Accessing the Low Mass Region*

## Mainz Energy-Recovering Superconducting Accelerator

$E_{max}$ = 200 MeV
$I_{max}$ = 10 mA

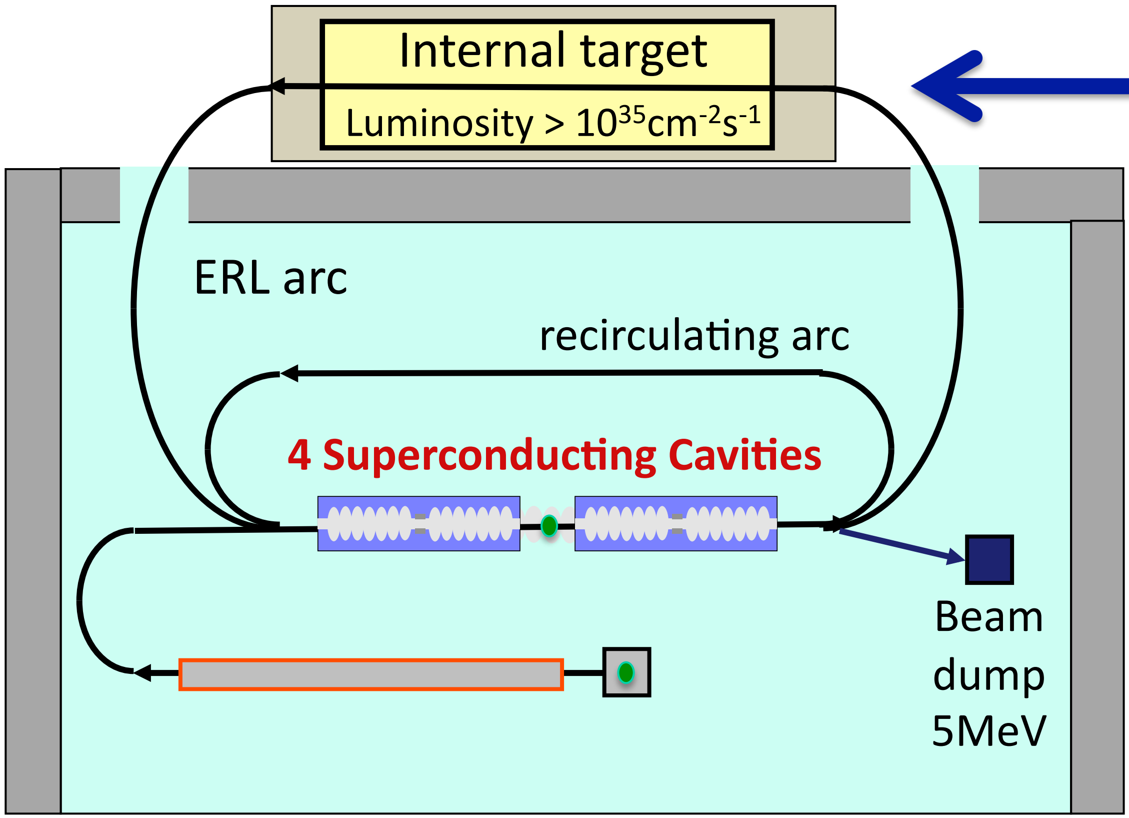
**2 Modes:**
- Internal Gas Target
  (ERL mode)
- Extracted Beam
  (Non-ERL mode)

PRiSMA



# *Phase 3: Accelerator MESA (ERL mode)*

**Energy-Recovering (ERL) mode:**
**105 MeV beam energy @ 10 mA**




**Projects:**

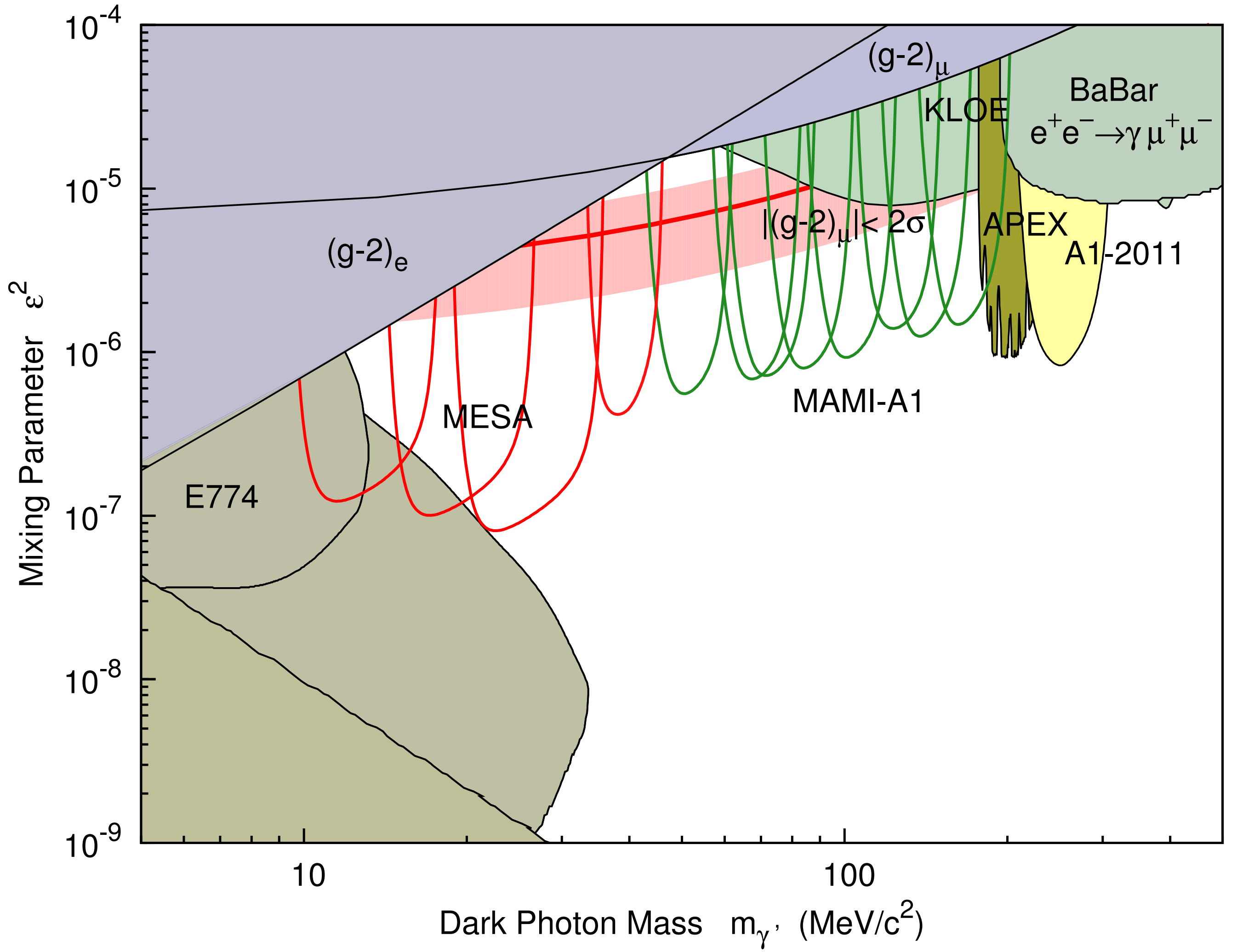
- Dark Photon
- Proton Radius
- Nuclear physics
- .....

# *Phase 3: Accessing the Low Mass Region*

**Two complementary approaches:**

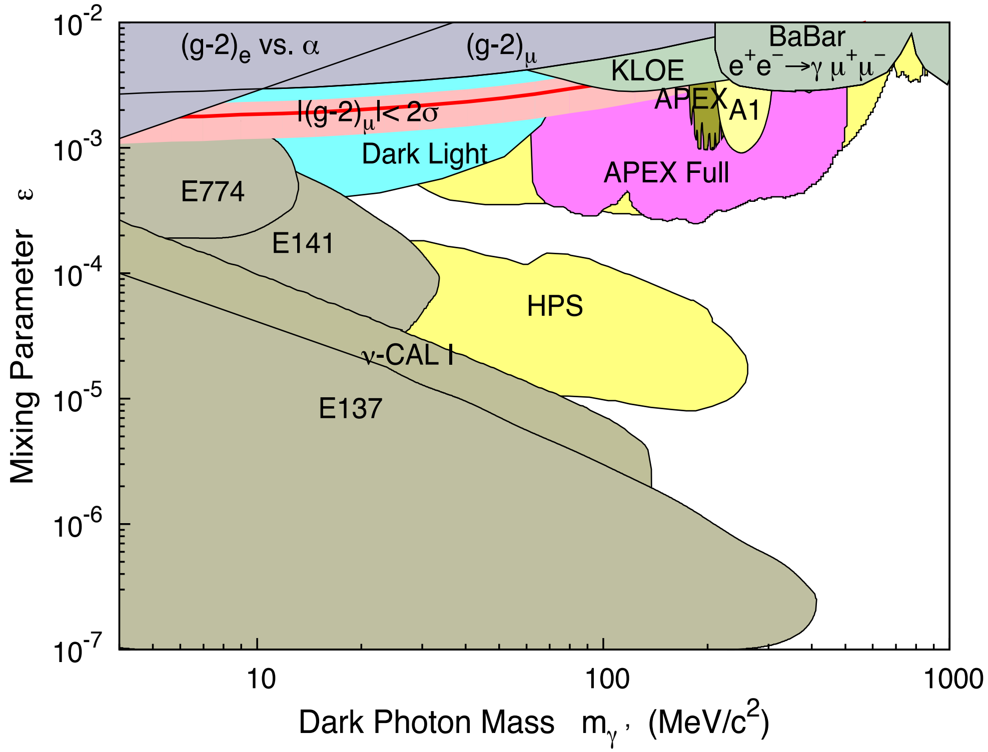
1. Large acceptance TPC
   → DarkLight @ JLAB-FEL
2. High resolution spectrometer setup
   → MESA

# Phase 3: Accessing the Low Mass Region



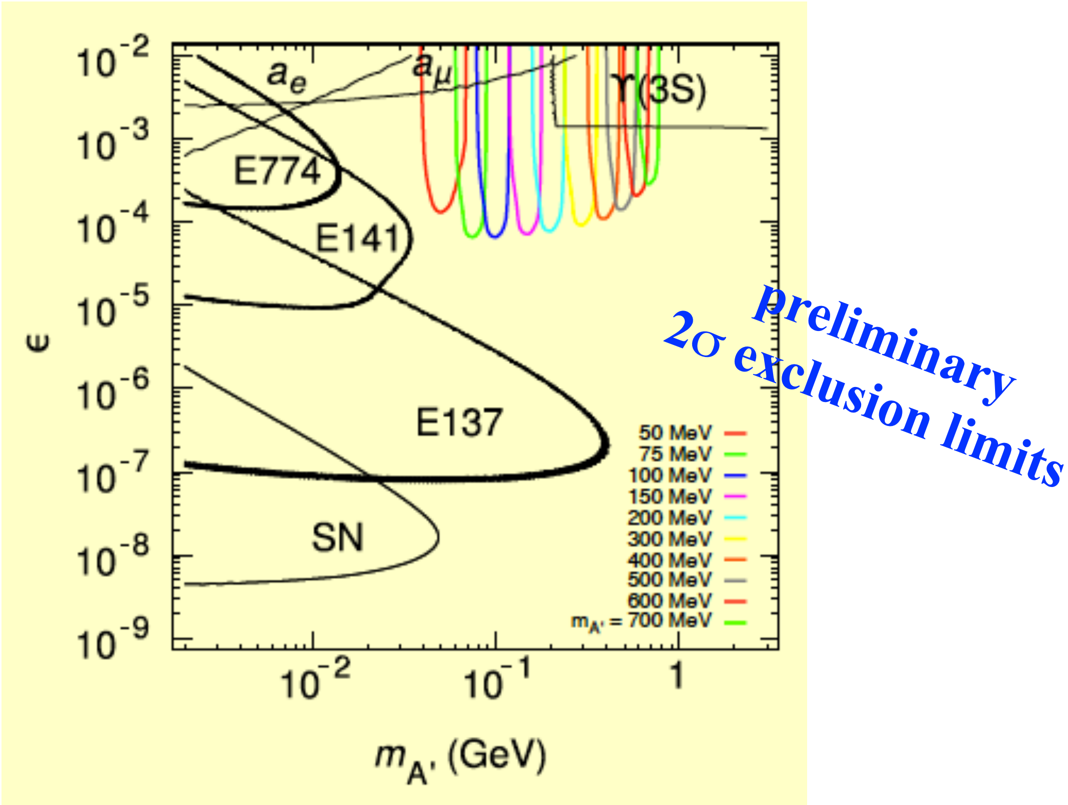
# *Conclusions*

- **Dark photon (~GeV mass)** phenomenologically well motivated
- **Electron fixed-target experiments** & high-resolution spectrometers competitive (Bjoerken et al.)
- **Mainz** dark photon search in **3 phases**:
  - A1 standard setup
  - A1 with displaced vertex
  - MESA accelerator
- Strong competition from JLAB, B-factories, WASA, ....



# BACKUP

# *Exclusions Limits*

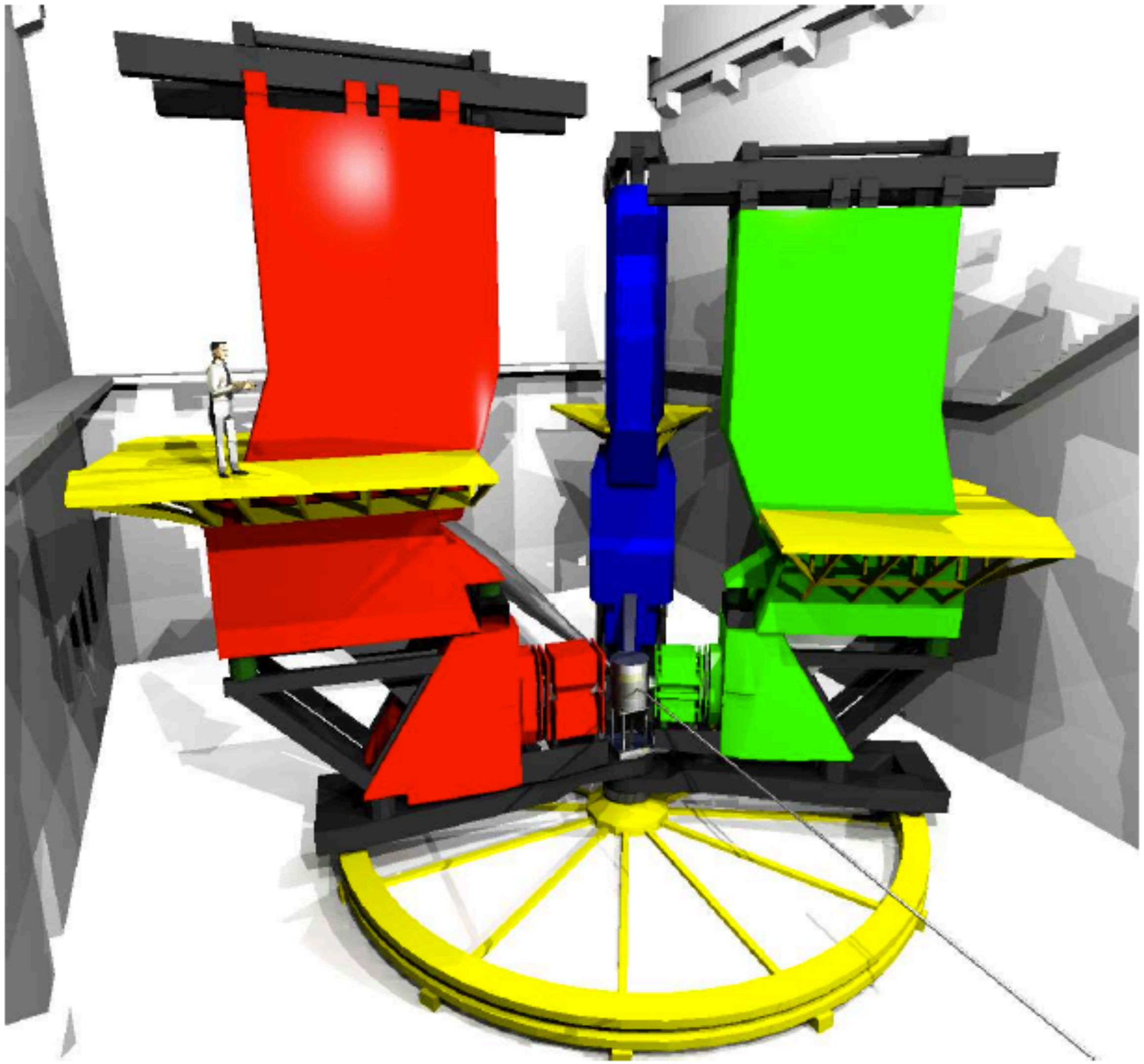



Limits based on [Bjorken et al. 2009]

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

# *Dark Photon Search @ A1 - HRS*

**highest momentum resolution ~$10^{-4}$**



Spektrometer A:

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Spektrometer B:

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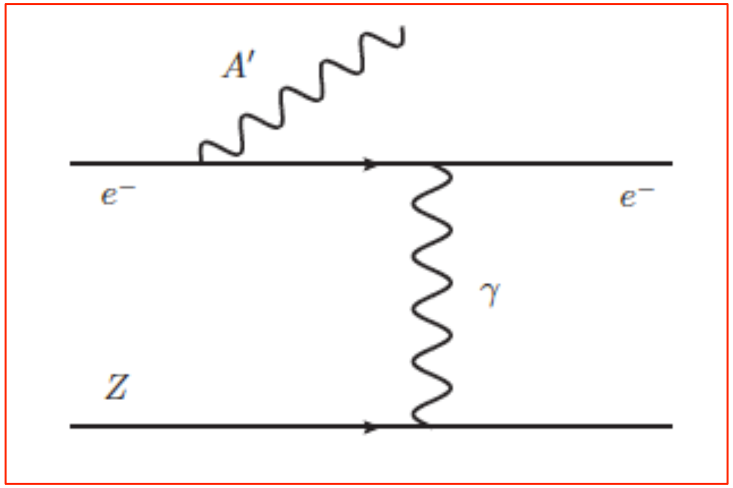
Spektrometer C:

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

# *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,Θ) minimized)
3. look for signal by 'bump hunting' over QED background and additional other background

**Weizsäcker – Williams approximation**

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

with

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

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

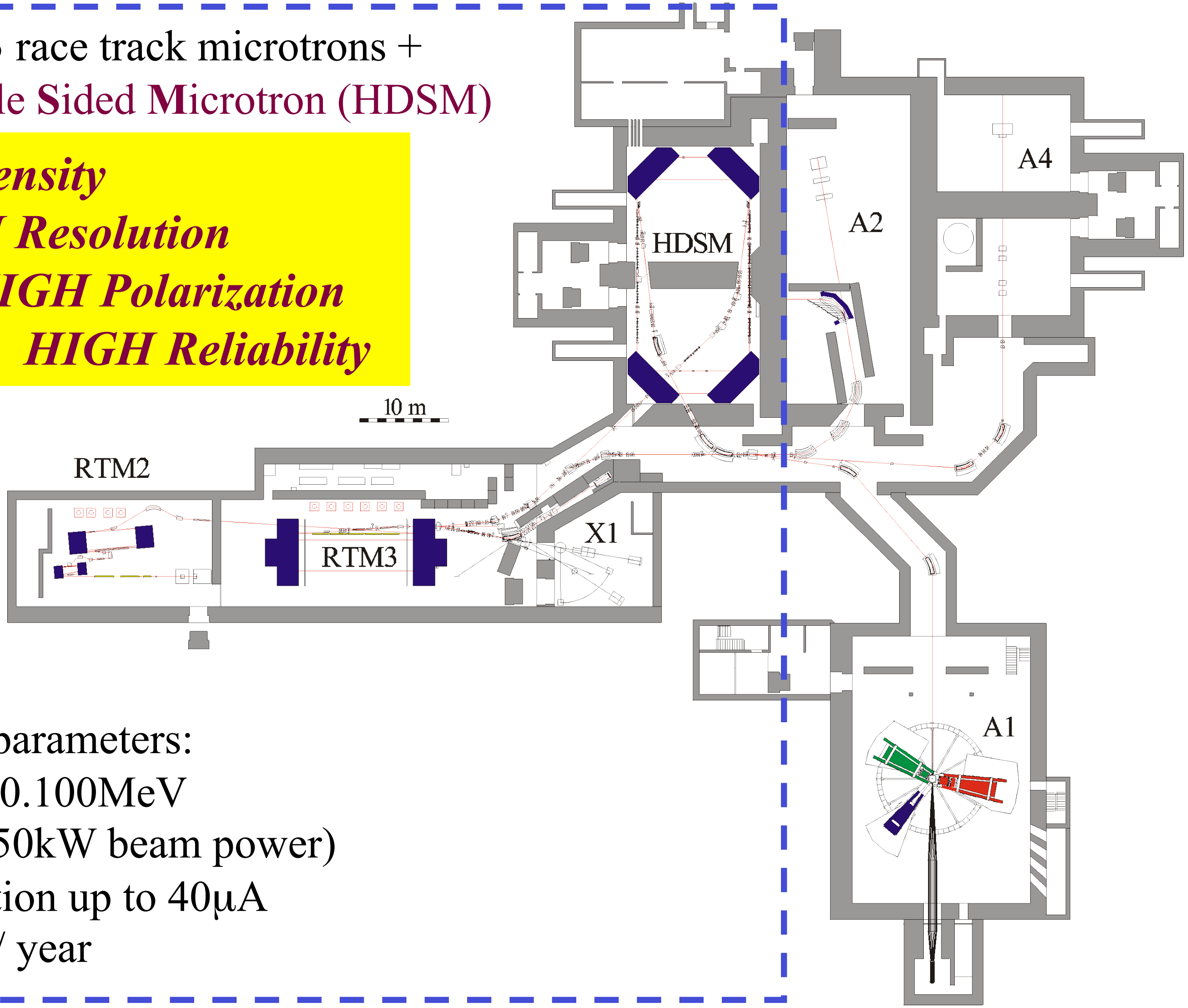
$$\tilde{\chi} \approx 5\sim 10 \quad \text{(photon flux)}$$

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

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

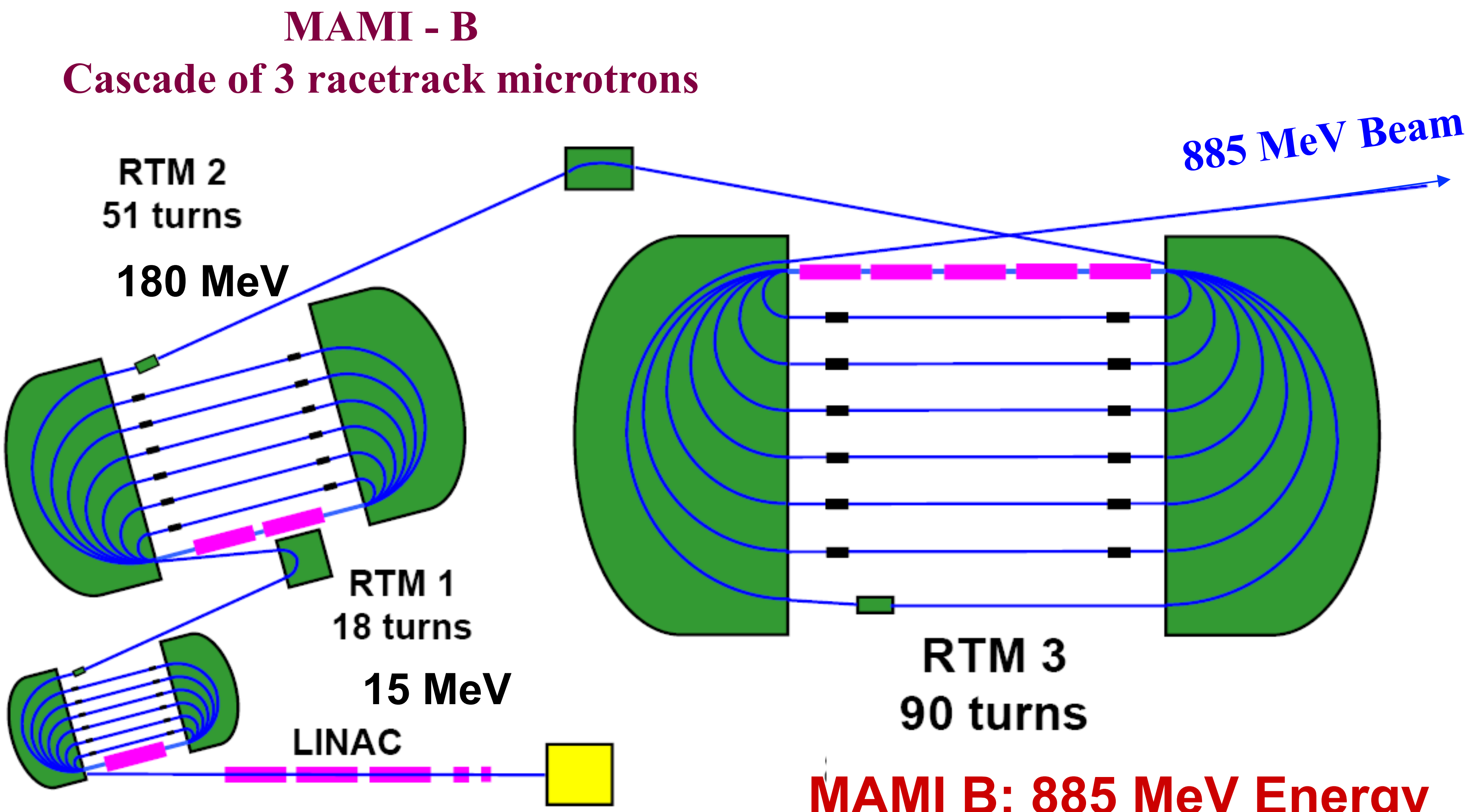
Cascade of 3 race track microtrons +
**H**armonic **D**ouble **S**ided **M**icrotron (HDSM)

***HIGH Intensity***
***HIGH Resolution***
***HIGH Polarization***
***HIGH Reliability***




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

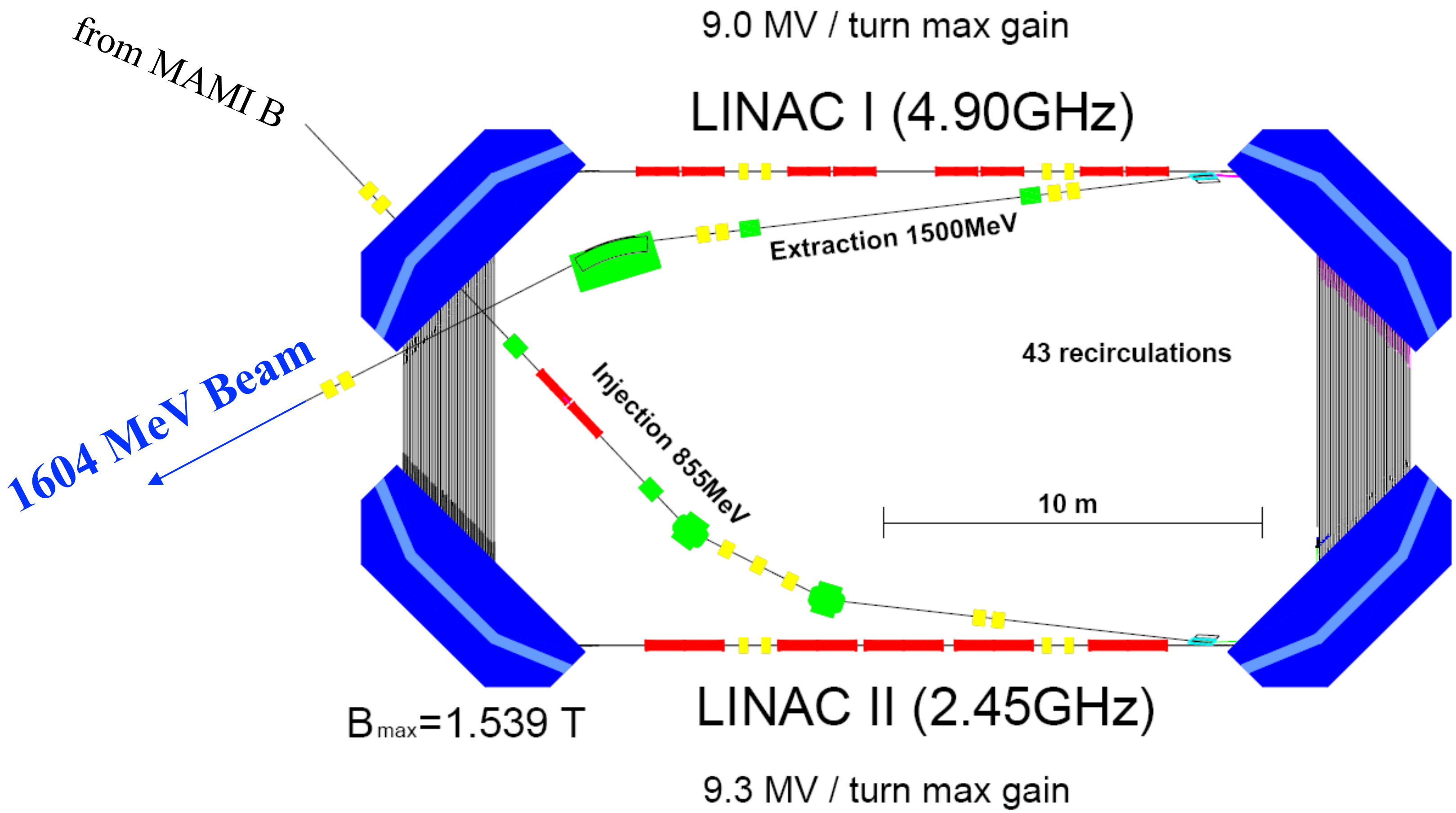
# MAMI-B




**MAMI B: 885 MeV Energy**

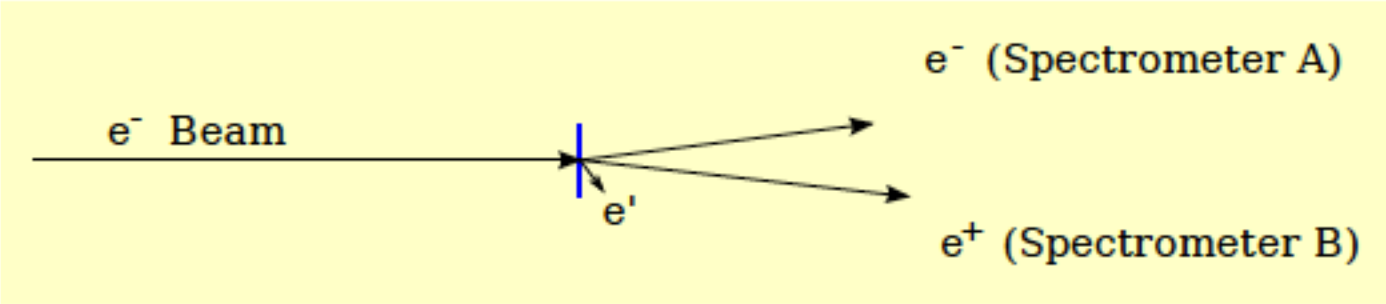
**CW: bunch structure 0.4 nsec**

# *Mainz Microtron MAMI*




**Harmonic Double Sided Microtron (HDSM)**

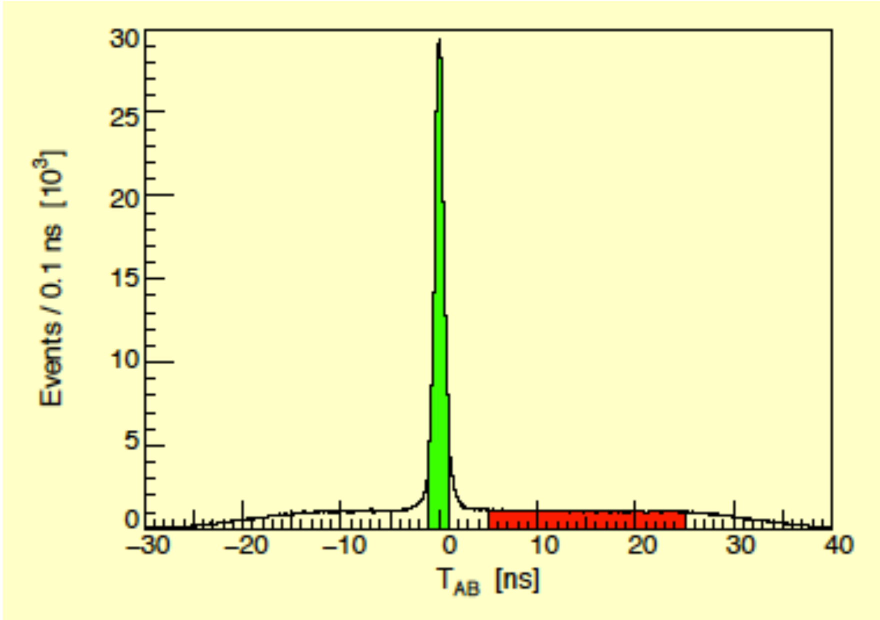
# *A Pilot Experiment at MAMI (6 Days)*




- 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)

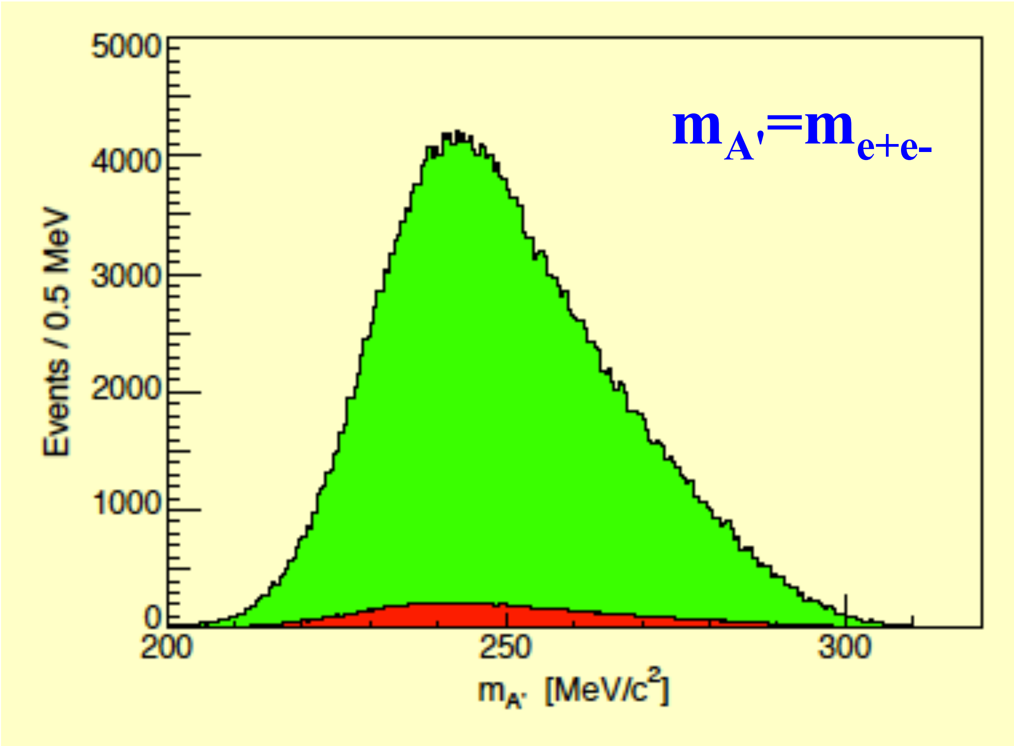
| | | |
|---|---|---|
| Beam energy | $E_0 =$ | 855.0 MeV |
| Spectrometer A | $p_{e^-} =$ | 338.0 MeV/$c$ |
| | $\theta_{e^-} =$ | 22.8° |
| Spectrometer B | $p_{e^+} =$ | 470.0 MeV/$c$ |
| | $\theta_{e^+} =$ | 15.2° |

# $\Delta TOF_{AB}$




- 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 $\approx 5\%$

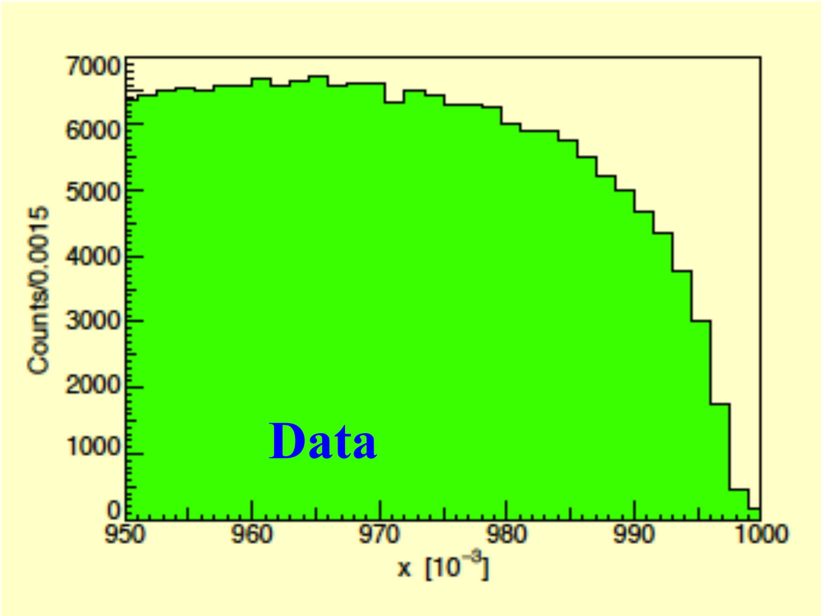
# *Invariant Mass Spectrum from 6 Days Pilot Run*

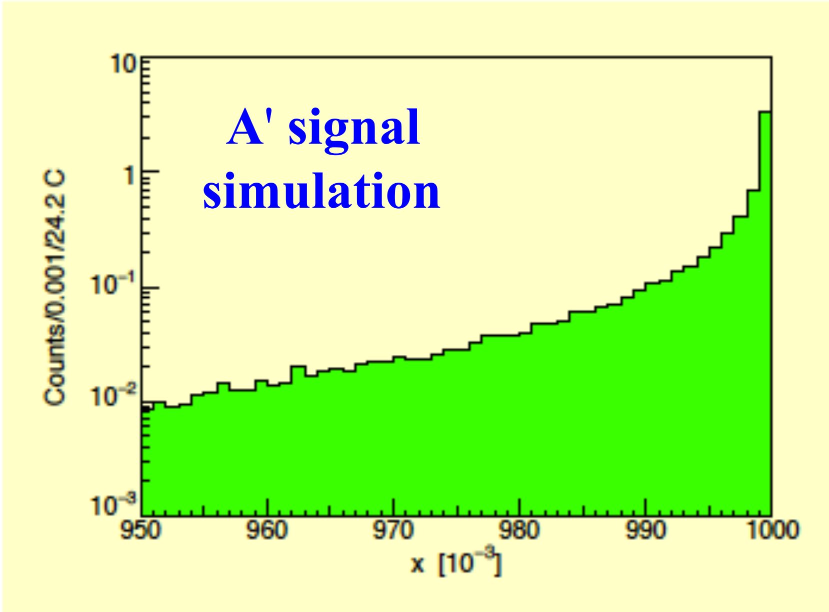



**Background is low allowing to reach high sensitivities in ε !**

- 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*



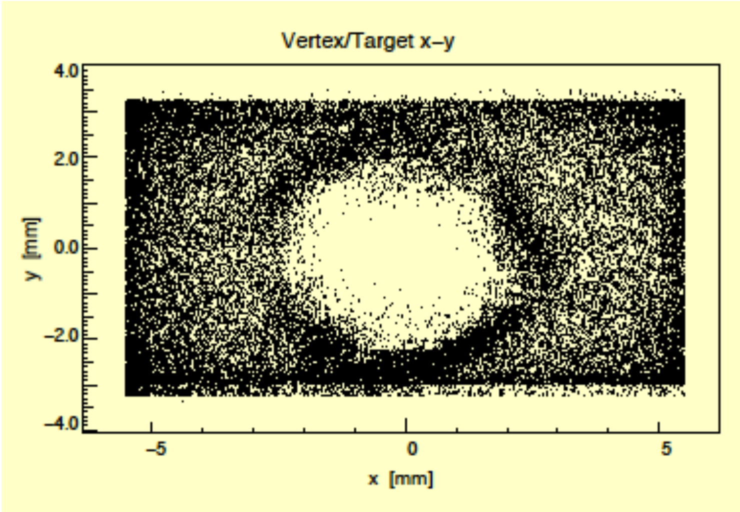




- Weizsäcker-Williams approximation not appropriate at high x values
- Reason: neglected phase space of recoil nucleus

→ 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

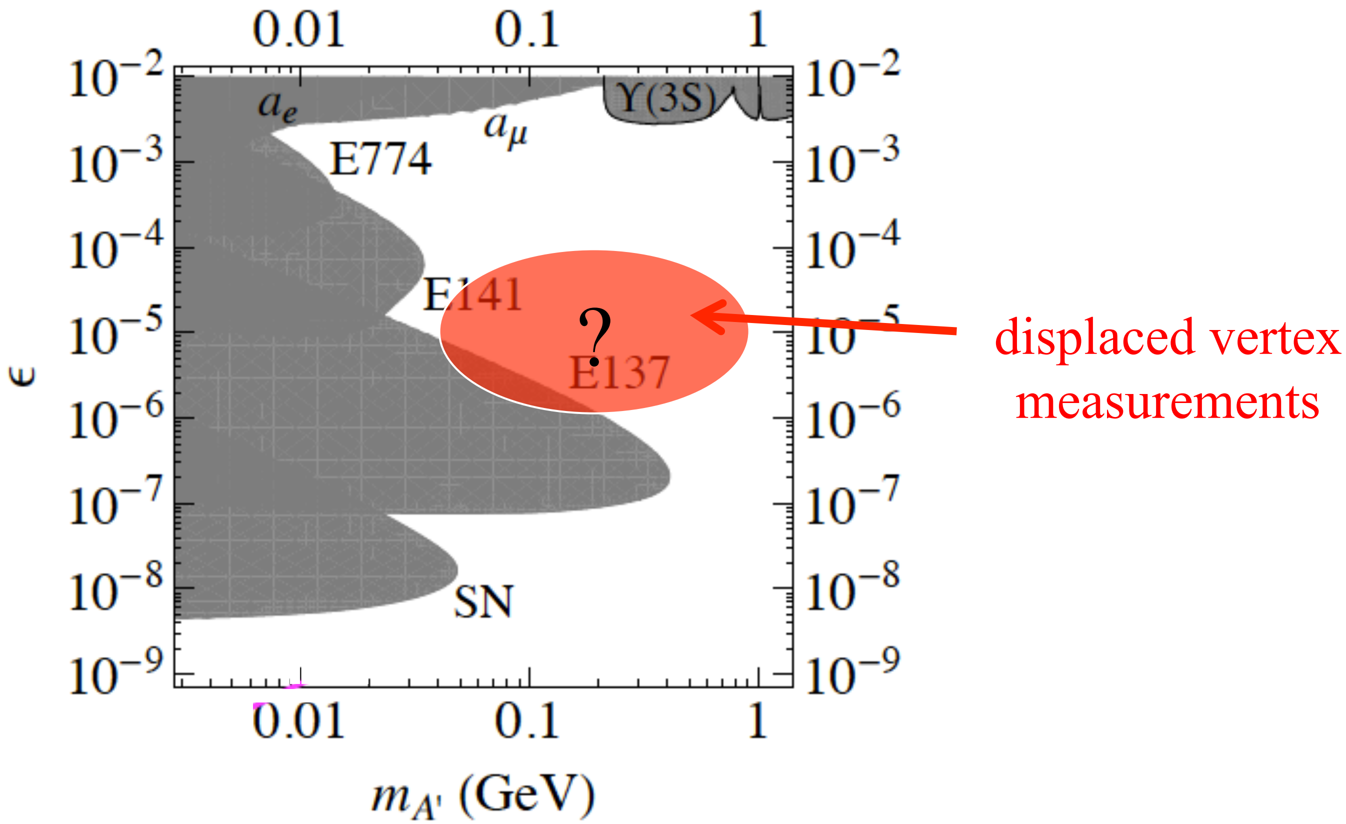
2. Optimize kinematics
   → x parameter

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

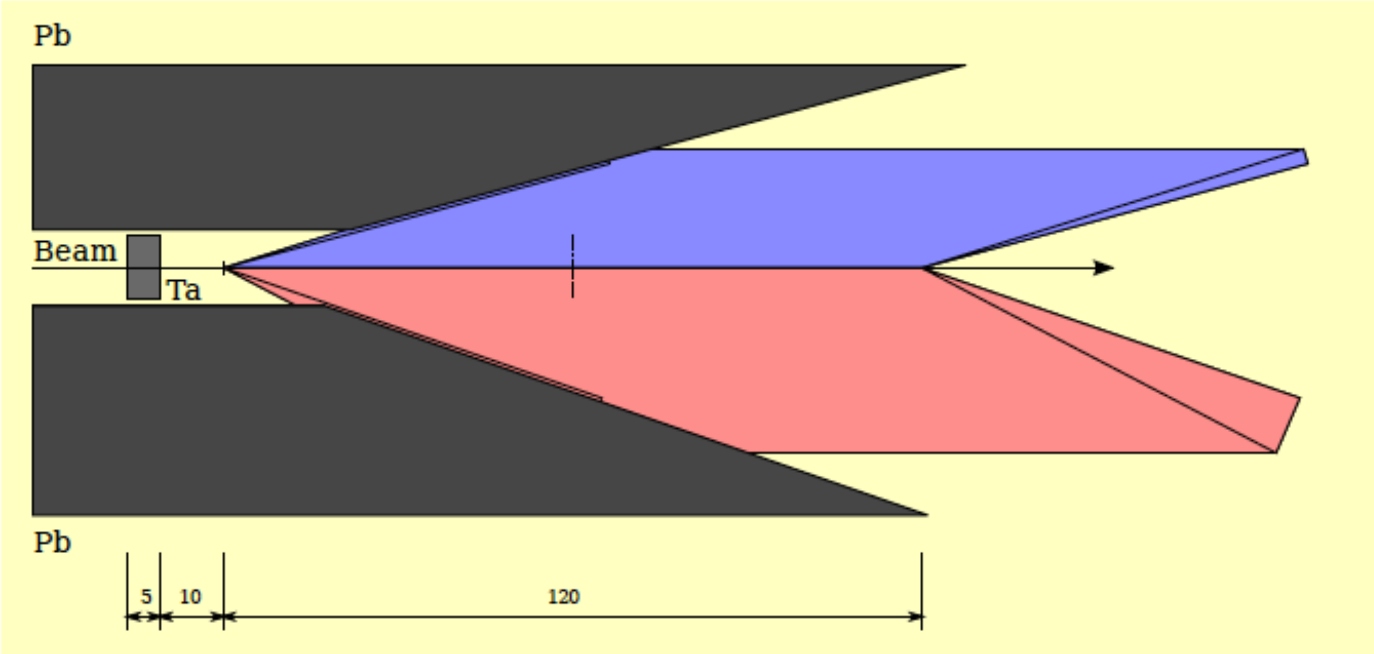
An order of magnitude improvement seems plausible

# *Further Ideas: Medium ε - Region*

Bjorken et al. [2009]

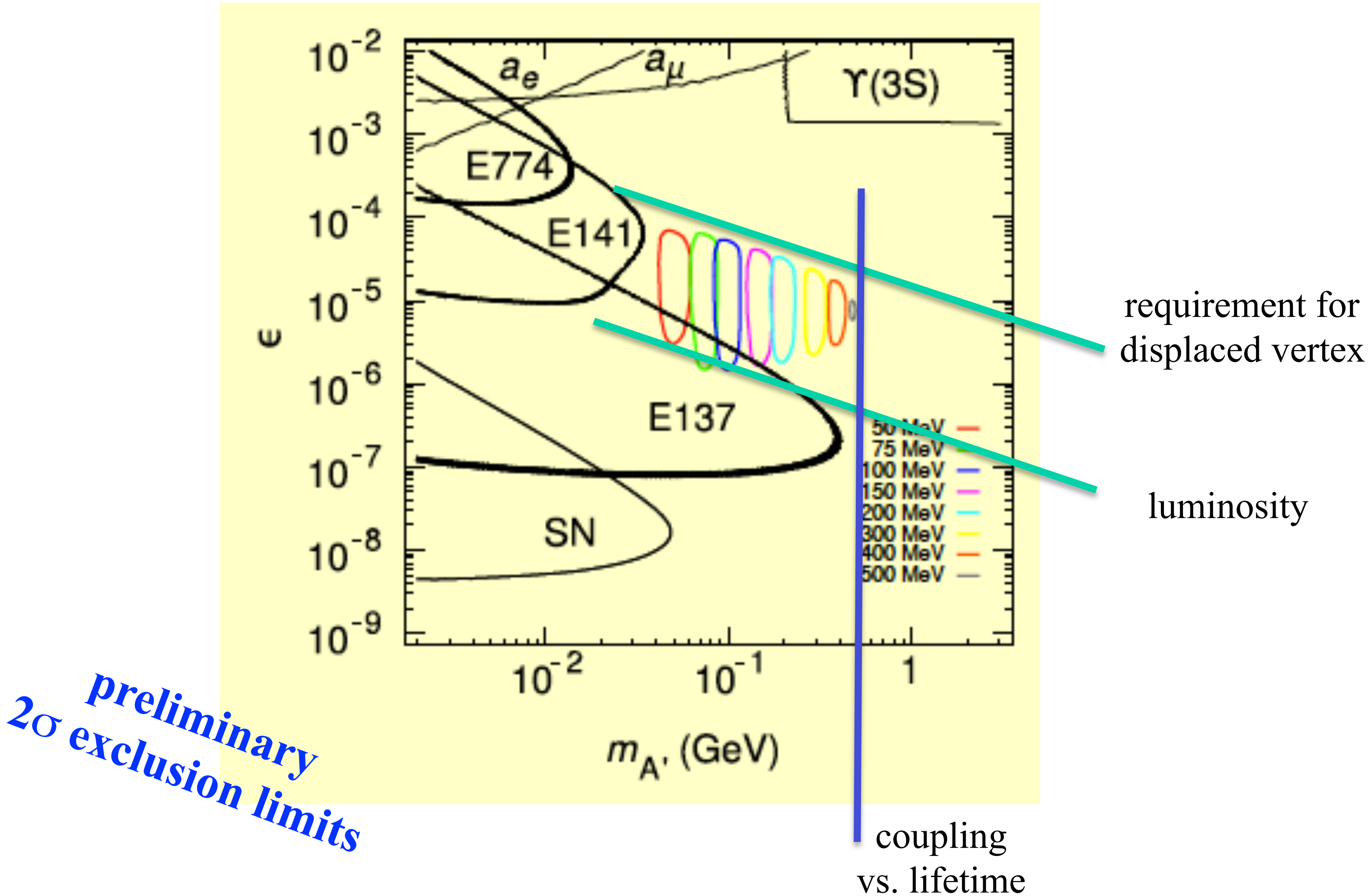


# *Displaced Vertex Measurement*



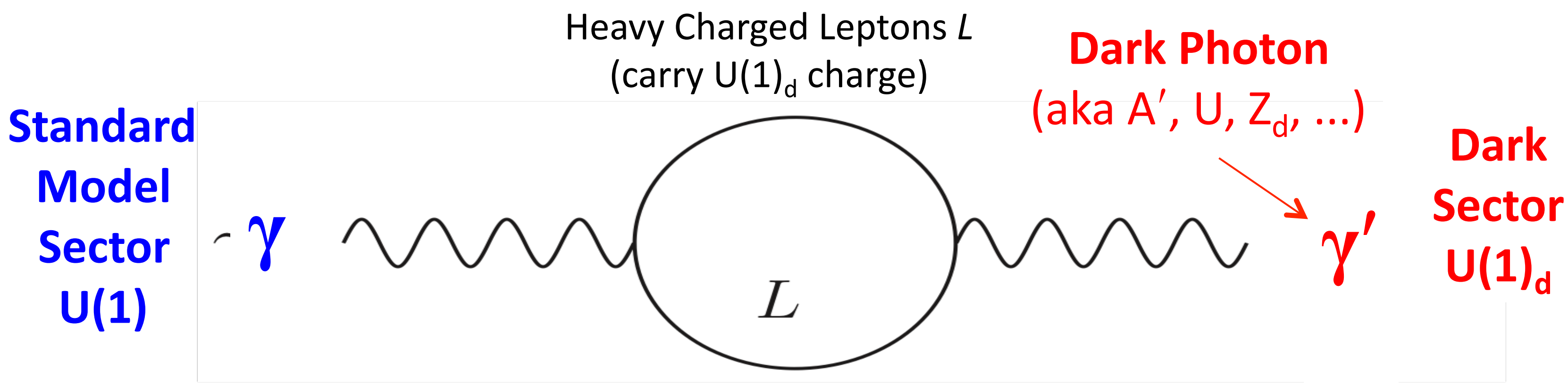

- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{s\,cm^2}$ at 100 $\mu$A beam current
- Beam stabilisation, shielding, target cooling

# *Displaced Vertex Measurement*



# *Kinetic Mixing*

Holdom [1986]

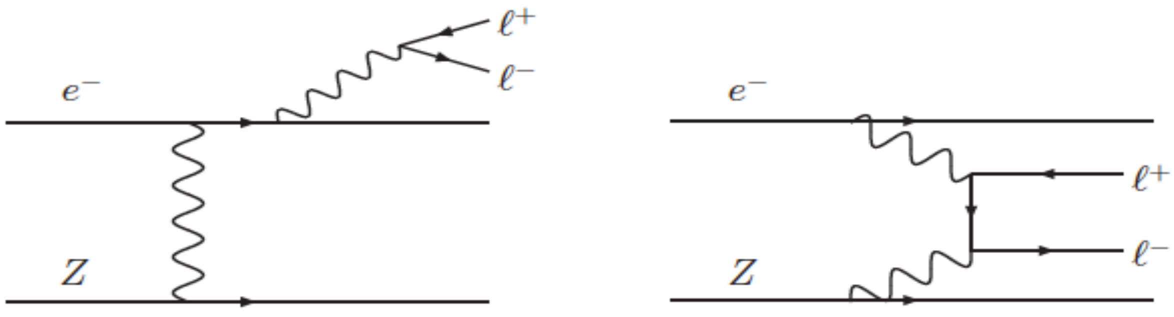


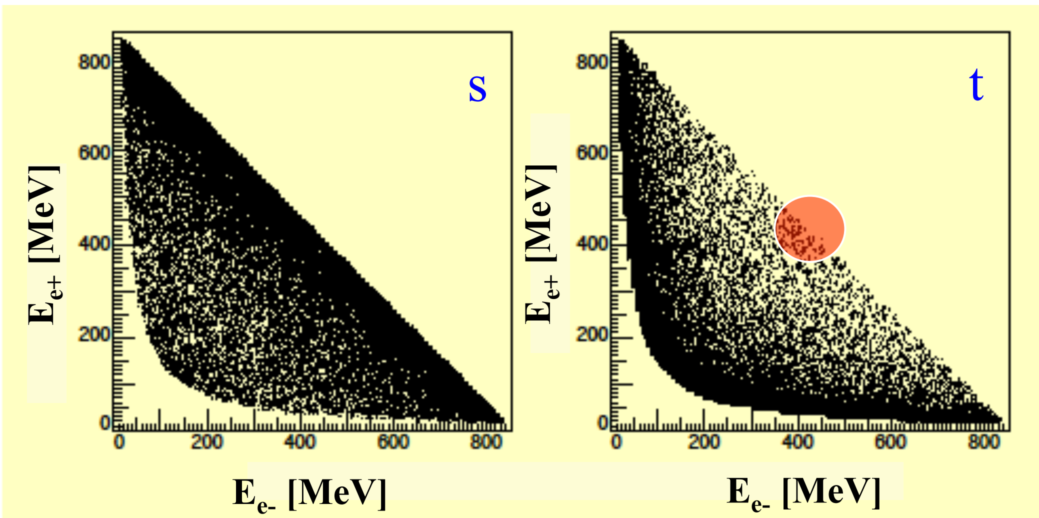

$$\mathcal{L} = \ldots + -\frac{1}{4} F_{\mu\nu}^{\mathrm{SM}} F_{\mathrm{SM}}^{\mu\nu} - \frac{1}{4} F_{\mu\nu}^{\mathrm{hidden}} F_{\mathrm{hidden}}^{\mu\nu} + \frac{\varepsilon}{2} F_{\mu\nu}^{\mathrm{SM}} F_{\mathrm{hidden}}^{\mu\nu} + m_{\gamma'}^2 A_\mu^{\mathrm{hidden}} A_{\mathrm{hidden}}^\mu$$

**A theory of Dark Matter**

- More than one Dark Matter particle → Dark Sector
- Astrophysical anomalies (PAMELA, FERMI, DAMA/LIBRA, AMS, INTEGRAL, ...) suggest dark photon mass on GeV mass scala (and lighter than $2M_p$)
- Dark Matter annihilation enhanced by γ′ exchange

# *QED Background*



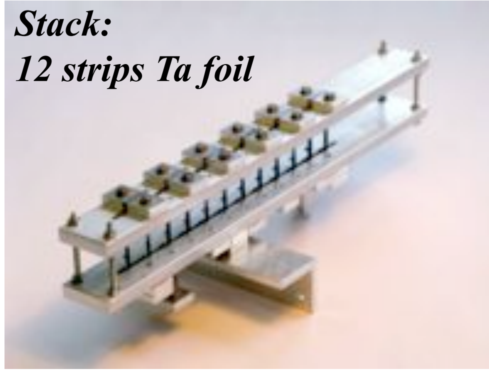




Background: - peaks at $m_{e+e-} \rightarrow 0$
- is minimized for symmetric production of $E_{e+}$, $E_{e-}$

# *A1 Production Run 2012*

## Features 2012 run

- Approx. 2 weeks of beam time
- 9 new kinematics settings
- Stack of 12-strip Ta foils
- Beam energies btw. 180 …. 720 MeV
- Beam intensities btw. 2.2 …. 43.4 µA




| Kinematik | $E_0$ (MeV) | $p_A$ (MeV/$c$) | $p_B$ (MeV/$c$) | $\bar{I}_0$ ($\mu$A) | Target | (mg/cm$^2$) | $t$ |
|---|---|---|---|---|---|---|---|
| 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" |

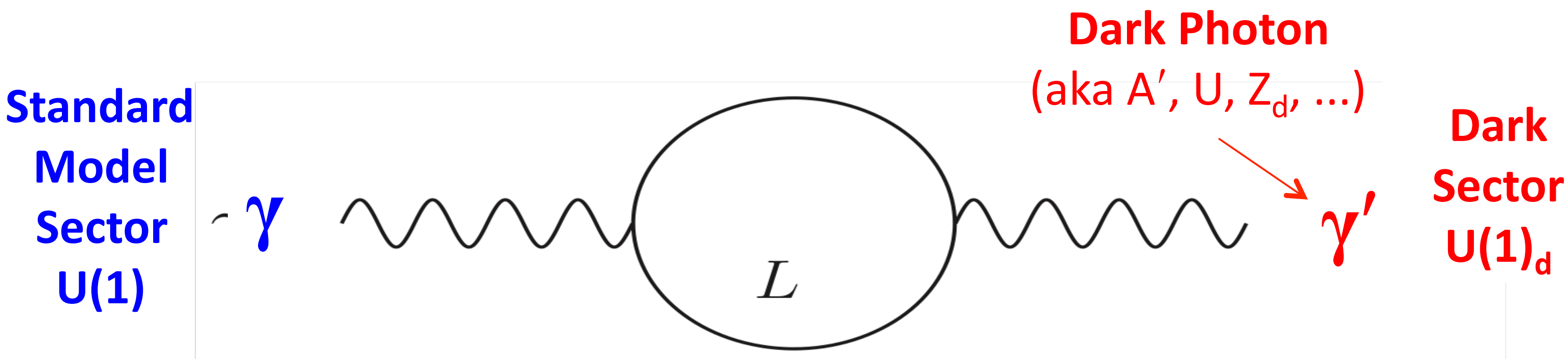
**QED corrections, see T. Beranek (exchange diagram)**
**→ additional run with similar settings in 02/2013**

# *Kinetic Mixing*

Holdom [1986]

**Lagrangian with kinetic mixing term:**

$$\mathcal{L} = \ldots + -\frac{1}{4}F^{\mathrm{SM}}_{\mu\nu}F^{\mu\nu}_{\mathrm{SM}} - \frac{1}{4}F^{\mathrm{hidden}}_{\mu\nu}F^{\mu\nu}_{\mathrm{hidden}} + \frac{\varepsilon}{2}F^{\mathrm{SM}}_{\mu\nu}F^{\mu\nu}_{\mathrm{hidden}} + m^2_{\gamma'}A^{\mathrm{hidden}}_{\mu}A^{\mu}_{\mathrm{hidden}}$$




Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

More models, e.g.