Search for Dark Photons at the Mainz Microtron and at MESA

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The Ultra-Light Frontier
MITP Mainz, Germany

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- Motivation
- Experiments at the Mainz Microtron (MAMI)
- Future Possibilities
  - Shielded Vertex
  - MESA Accelerator
  - Beam-dump Experiments
- Summary

Dark Photon: Motivation

- Assumption:
  There is an interaction between Dark Matter and Standard Model matter beyond gravitation

  - Structur formation in the early universe
  - Blue-print for “Matter”: Quantum field theory

  $\Rightarrow$ Particle models of DM predict a Dark Sector
  $\Rightarrow$ Interaction included!

- Simplest solution: “Dark photon”

  - $U(1)$ gauge boson of DM – SM Interaction
  - Massive but NOT HEAVY

IDEA: don’t look for DM Particles, look for the Interaction

Kinetic mixing

Dark matter couples to $U(1)$ boson
Mixing between γ and γ' via kinetic term

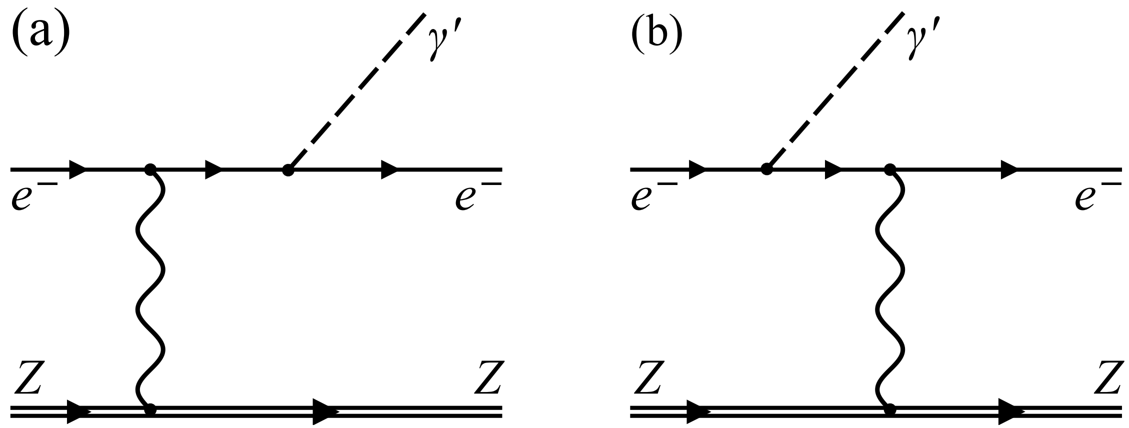
$$\mathcal{L} = \cdots + -\frac{1}{4}F_{\mu\nu}^{\text{SM}}F_{\text{SM}}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}^{\text{hidden}}F_{\text{hidden}}^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}^{\text{SM}}F_{\text{hidden}}^{\mu\nu} + m_{\gamma'}^{2}A_{\mu}^{\text{hidden}}A_{\text{hidden}}^{\mu}$$

- Renormalization of Charge:
  $\Rightarrow$ Mixing Standard Model Charge – “dark” charge
- Parametrized by mixing parameter ε of γ'/γ mixing
- Boson mass $m_{\gamma'} > 0$ $\Rightarrow$ decay suppressed, *macroscopic* lifetime

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

Experimental Method

Radiative Production from a heavy target



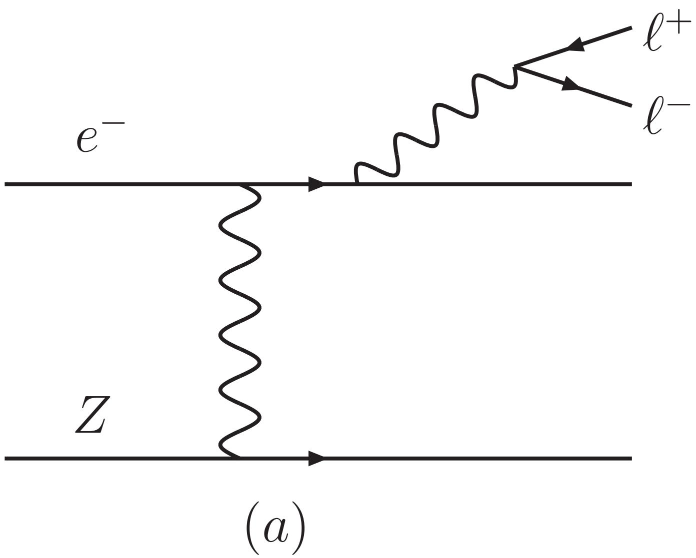
- Radiative production

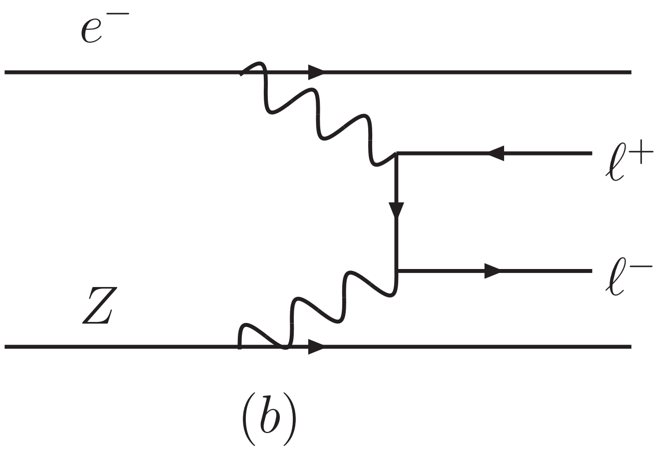
$$e + Z \;\rightarrow\; e + Z + \gamma'$$
$$\hookrightarrow e^+ + e^-$$

  - Heavy target nucleus (Tantalum, $Z = 73$)
  - Cross section is peaked in forward direction
  - Macroscopic decay length of a few μm

- Subsequent decay to lepton pair
  - Detection of lepton pair
  - Possible Signal: Peak at $m_{\gamma'}^2 = (e^+ + e^-)^2$
  - High resolution neccessary

Backgrounds





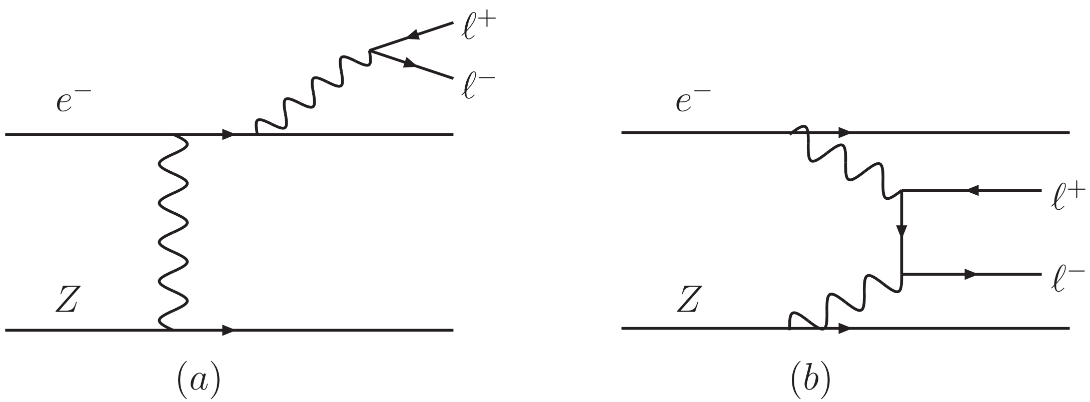
- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

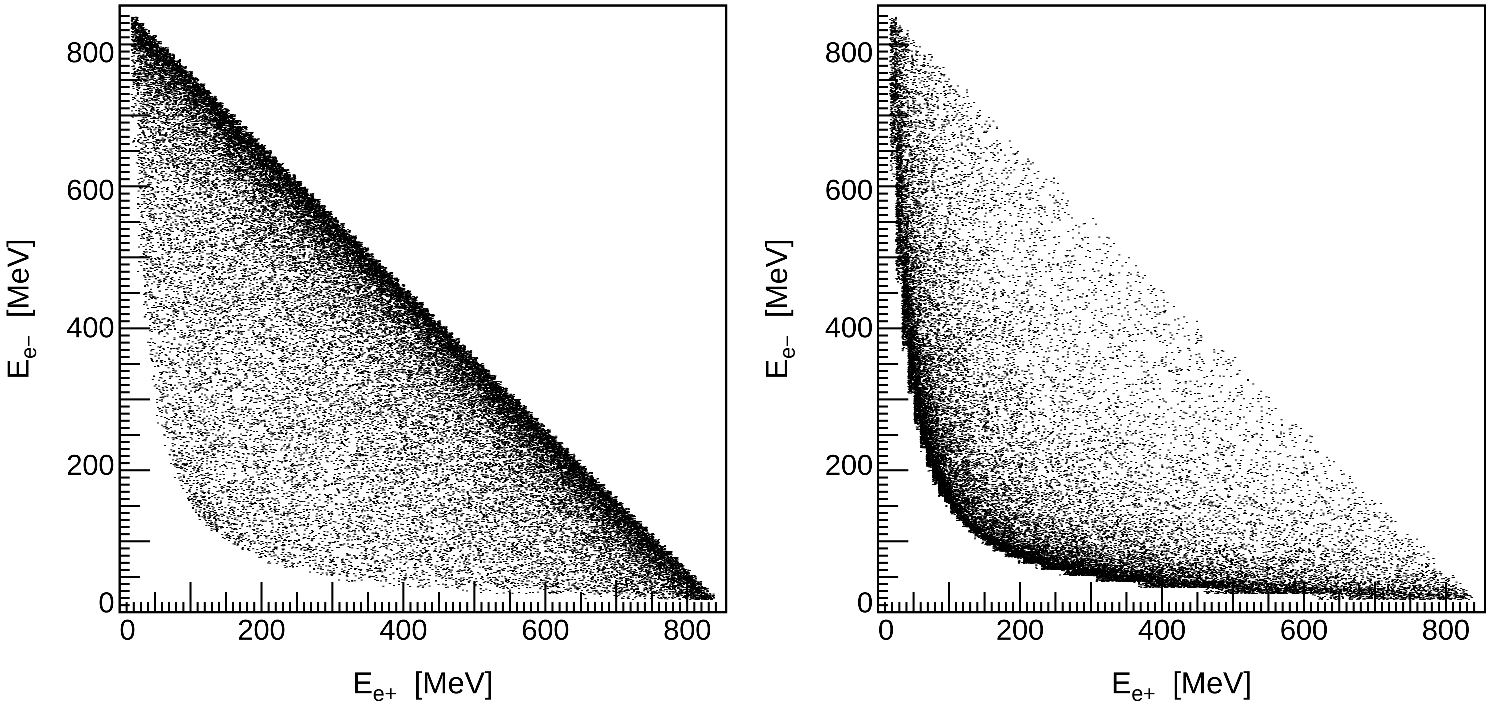
- Computable in QED
- Peak for l^* on mass shell
- Energy transfer to l^- or l^+
- $\Rightarrow$ Kinematically reducable

+ crossing and anti-symmetrization!

T. Beranek, H.M., M. Vanderhaeghen, Phys. Rev. D88, 015032 (2013).

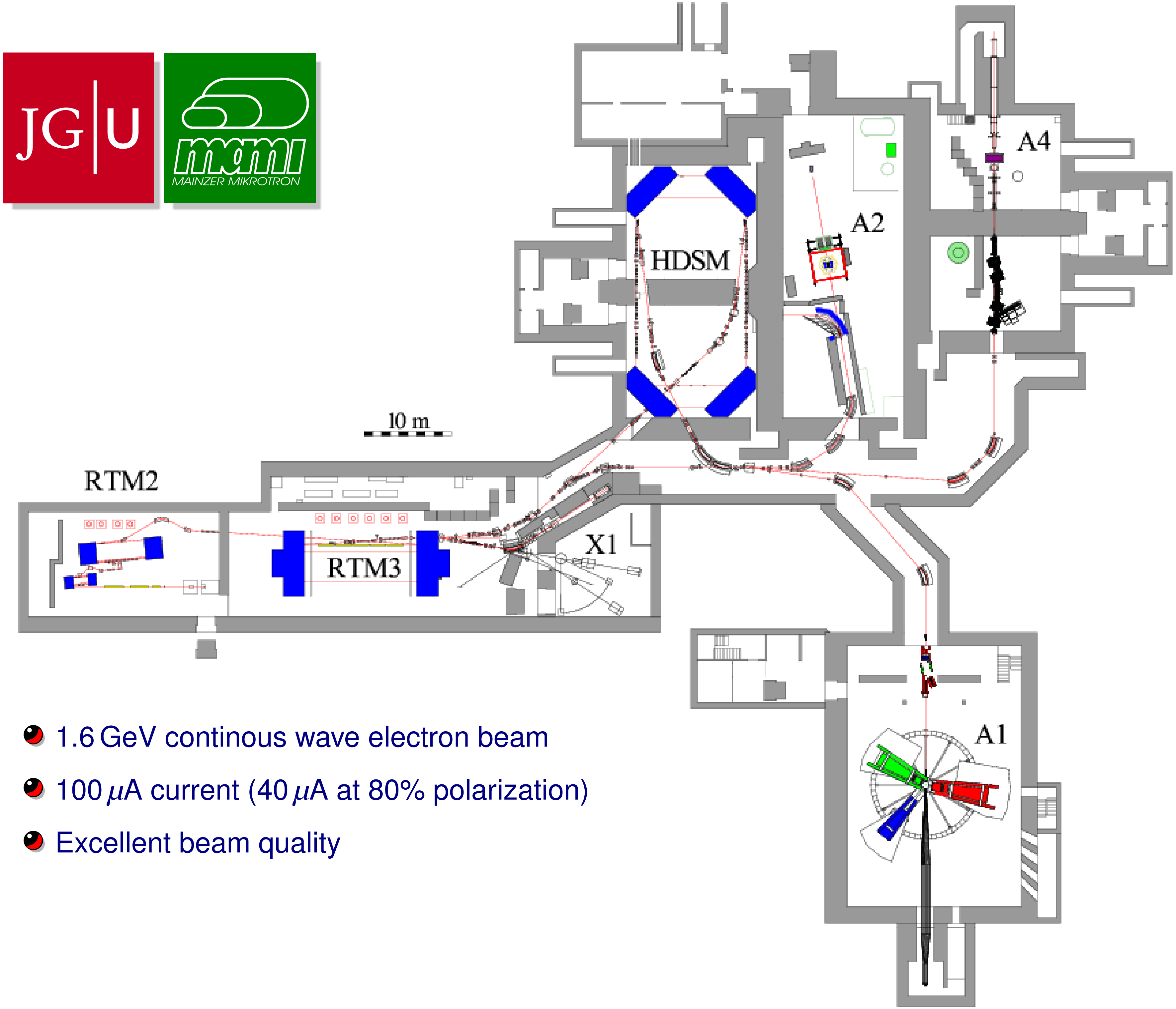
Bethe-Heitler Background





- Peak at $m_{e^+e^-} = 0$
- Peak for asymmetric production
- Minimum for symmetric production at maximum of energy transfer

The Experiment



- 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:

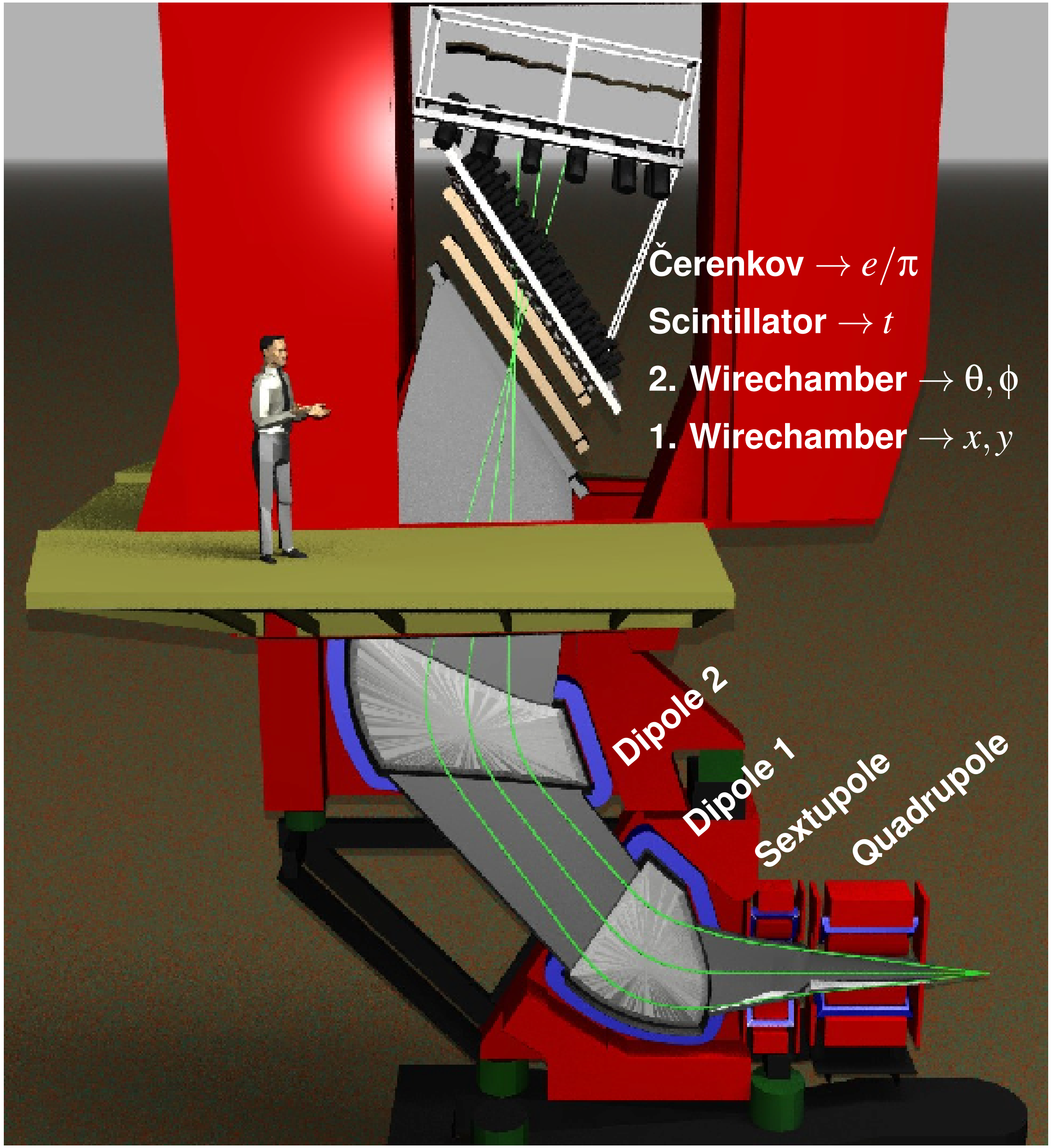
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

Spectrometer C:

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

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

A1: Spectrometer A



- Momentum resolution:

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

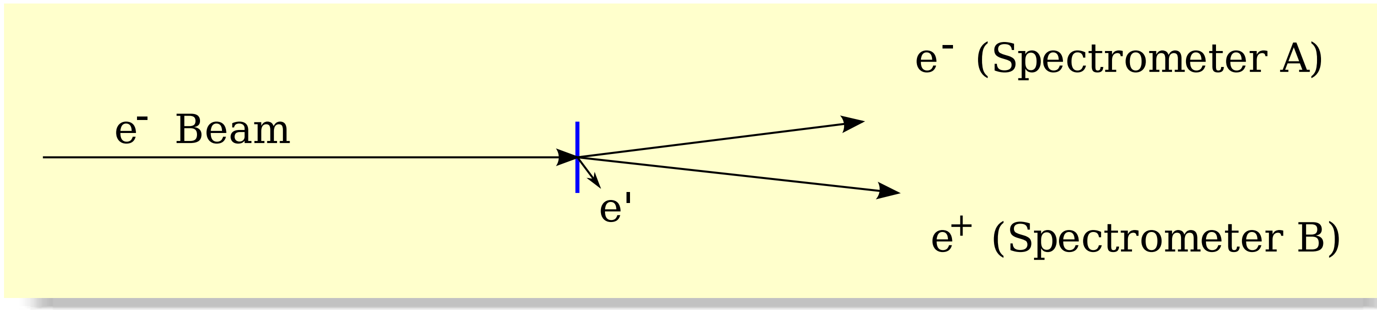
- Momentum acceptance:

$$\Delta p/p = 20\%$$

- Solid angle:

$$\begin{aligned}\Delta\Omega &= 11.5^\circ \times 8.0^\circ \\ &= 28\,\text{msr}\end{aligned}$$

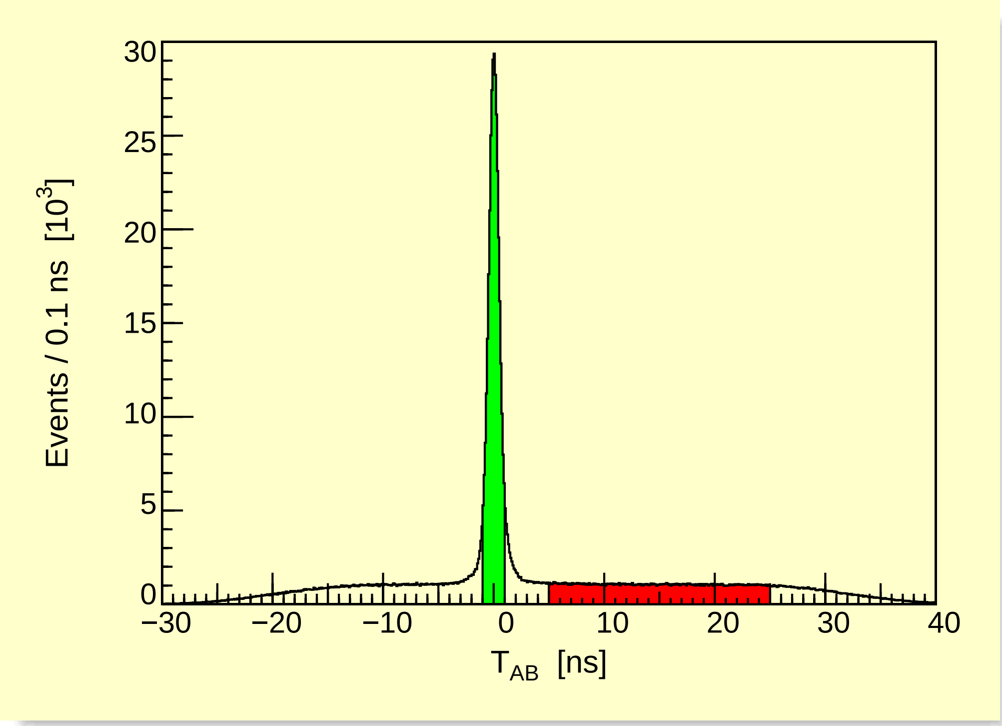
Experimental Details



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

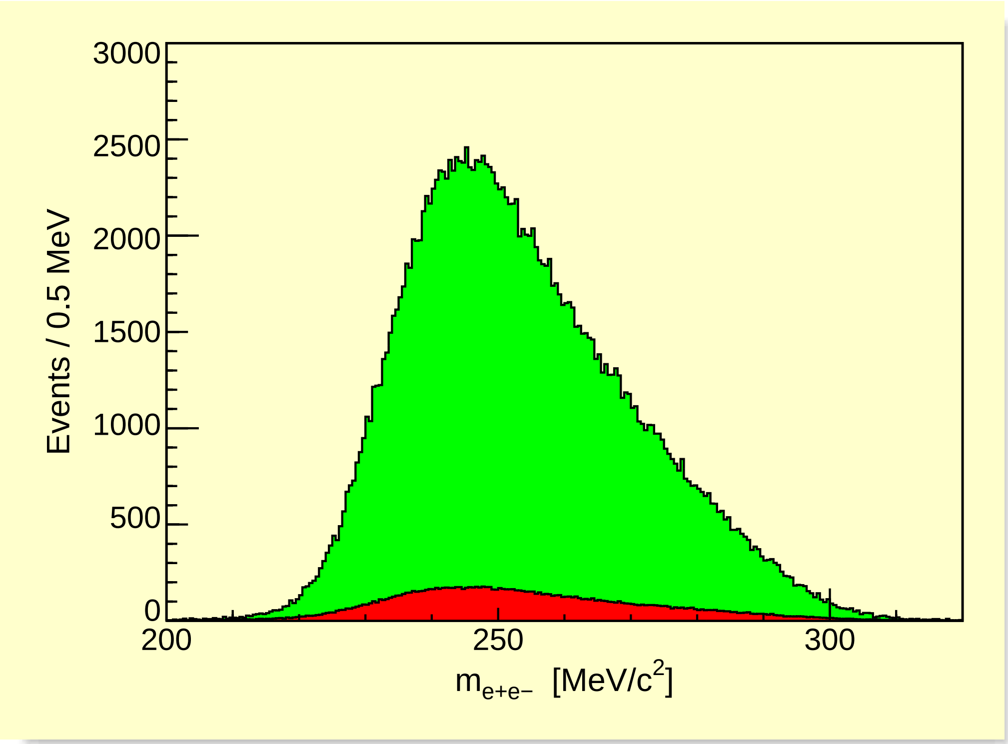
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV/c
	$\theta_{e^-} =$	22.8 °
Spectrometer B	$p_{e^+} =$	470.0 MeV/c
	$\theta_{e^+} =$	15.2 °

Reaction identification: coincidence time



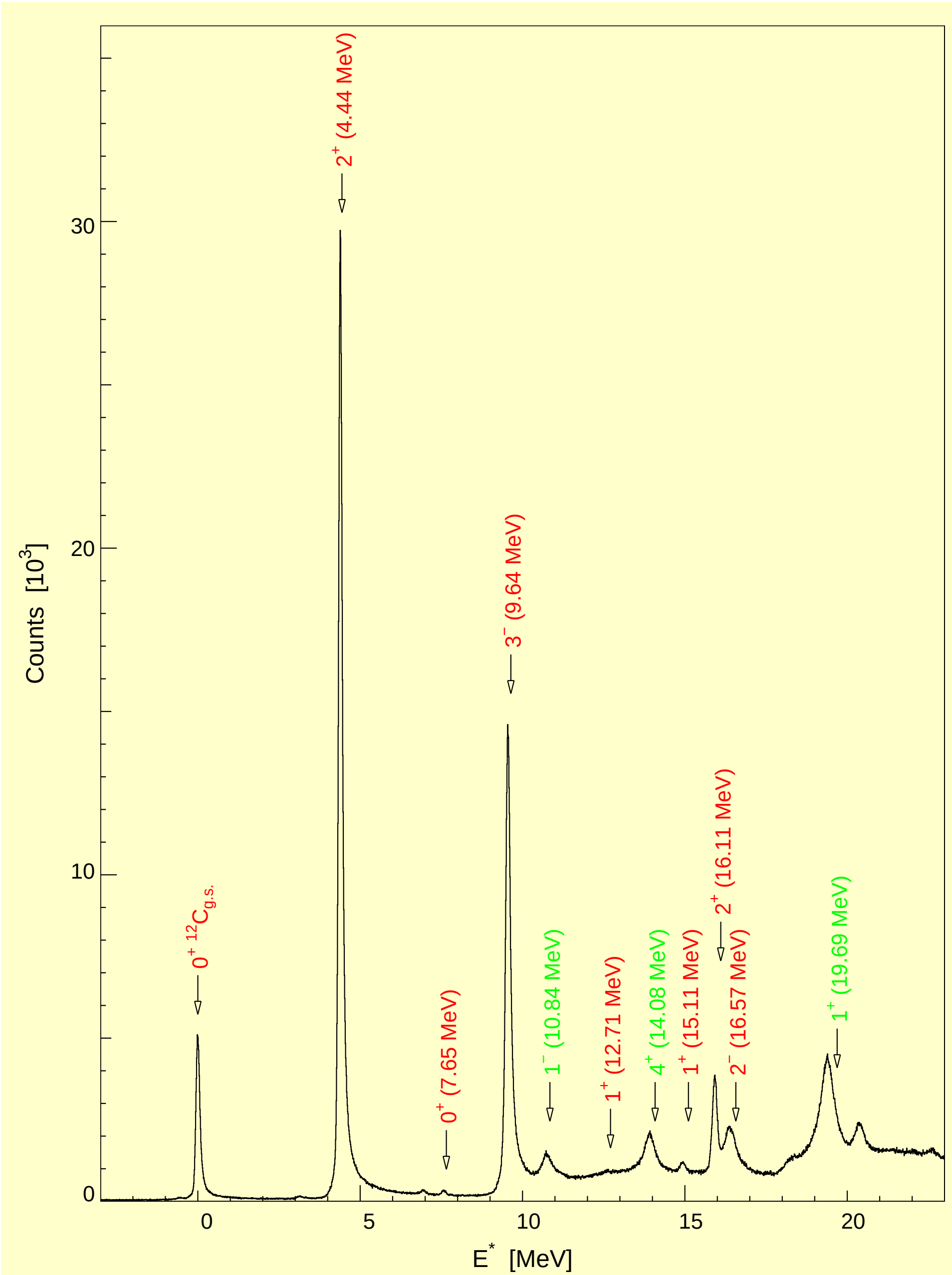
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\mathrm{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge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

Invariant mass of e^+e^- pair



- Mass of e^-e^+ pair $\quad m_{\gamma'}^2 = (e^- + e^+)^2$
- What is the expected peak width?

Determination of the Mass Resolution

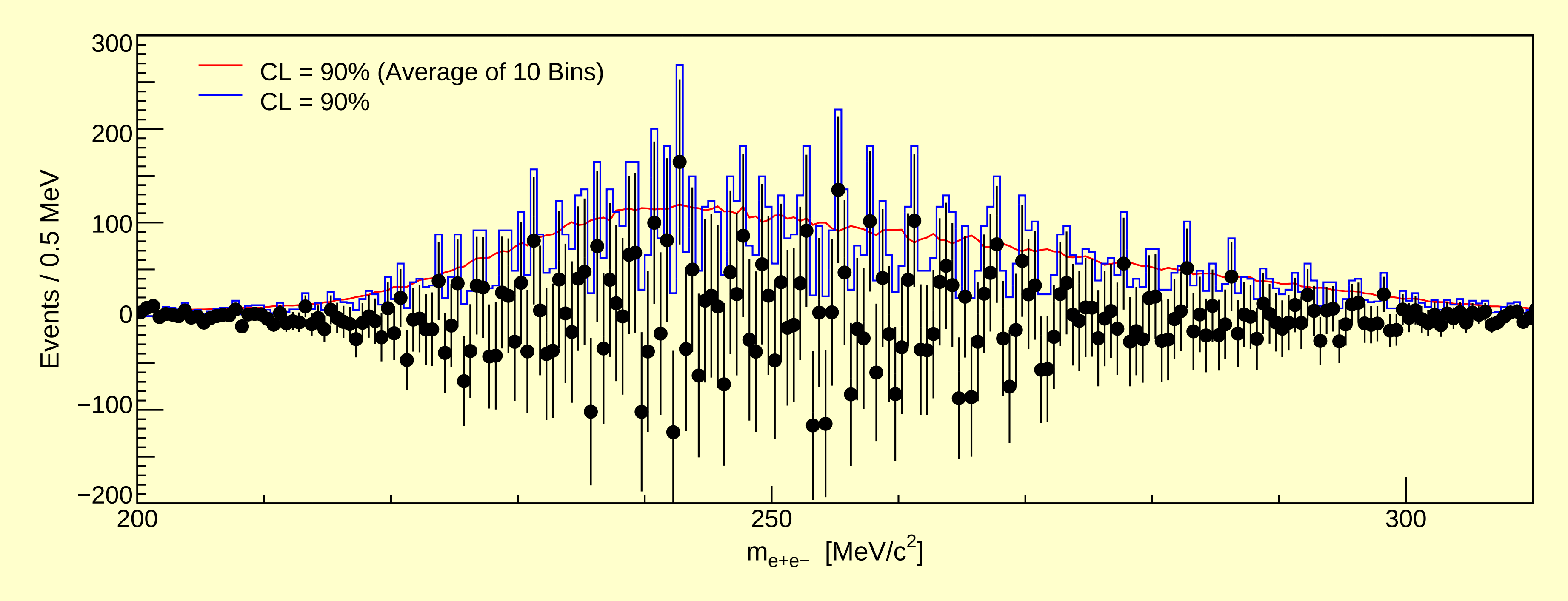


- Elastic Scattering
  - Natural width $\ll$ Resolution
  - Line width gives upper bound
  - $\delta p/p < 10^{-4}$ for Spectrometer
- Input to Full Simulation
  - Multiple Scattering
  - Radiative corrections
  - Decay length
  - Missing mass resolution

$0.21 < \delta m_{e^+e^-} < 0.92\,\mathrm{MeV}/c^2$ FWHM

N.B.: Systematic error of $\delta m_{e^+e^-} < 10^{-3}$!

Exclusion limits



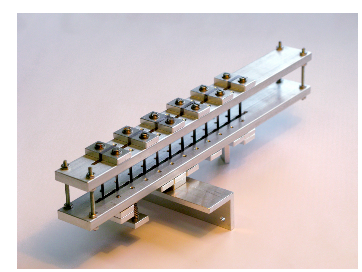
- Confidence interval by Feldman-Cousins algorithm
- “Model” for Background-subtraction: local fit with polynomial
- Resolution = bin width
- Averaging (mean of 10 bins) only for “subjective judgment”

Data 2014 - Settings

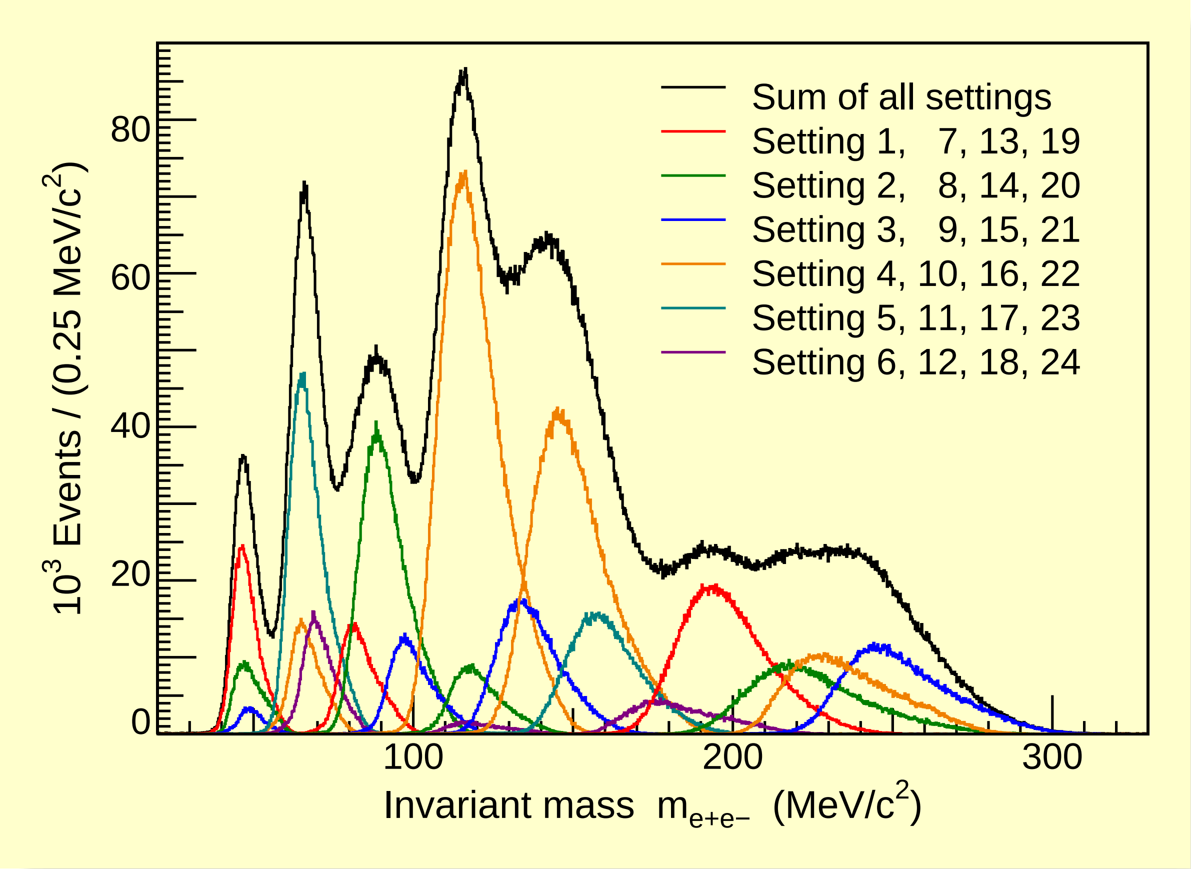
Settings	E_0 (MeV)	p_A (MeV/c)	p_B (MeV/c)	$\bar{I}_0$ (μA)	Target (mg/cm^2)		t t
1	180	78.7	98.0	2.2	Foil	9.4	12h 30' 56"
2	240	103.6	132.0	5.5	Foil	9.4	46h 53' 18"
3	255	110.1	140.4	7.0	Foil	9.4	43h 49' 11"
4	300	129.5	164.5	11.7	Foil	9.4	37h 56' 03"
5	360	155.4	197.6	16.6	Foil	9.4	5h 15' 29"
6	435	190.7	247.7	43.4	Foil	9.4	44h 3' 27"
7	495	213.7	271.6	7.0	Stack	113.1	36h 25' 16"
8	585	250.0	317.3	16.3	Stack	113.1	29h 37' 03"
9	720	309.2	392.7	19.4	Stack	113.1	76h 0' 20"

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

- Mass range 40 MeV $< m_{\gamma'} <$ 300 MeV
- 9 different beam energies
- finally 24 settings (e^+ in A or B?)



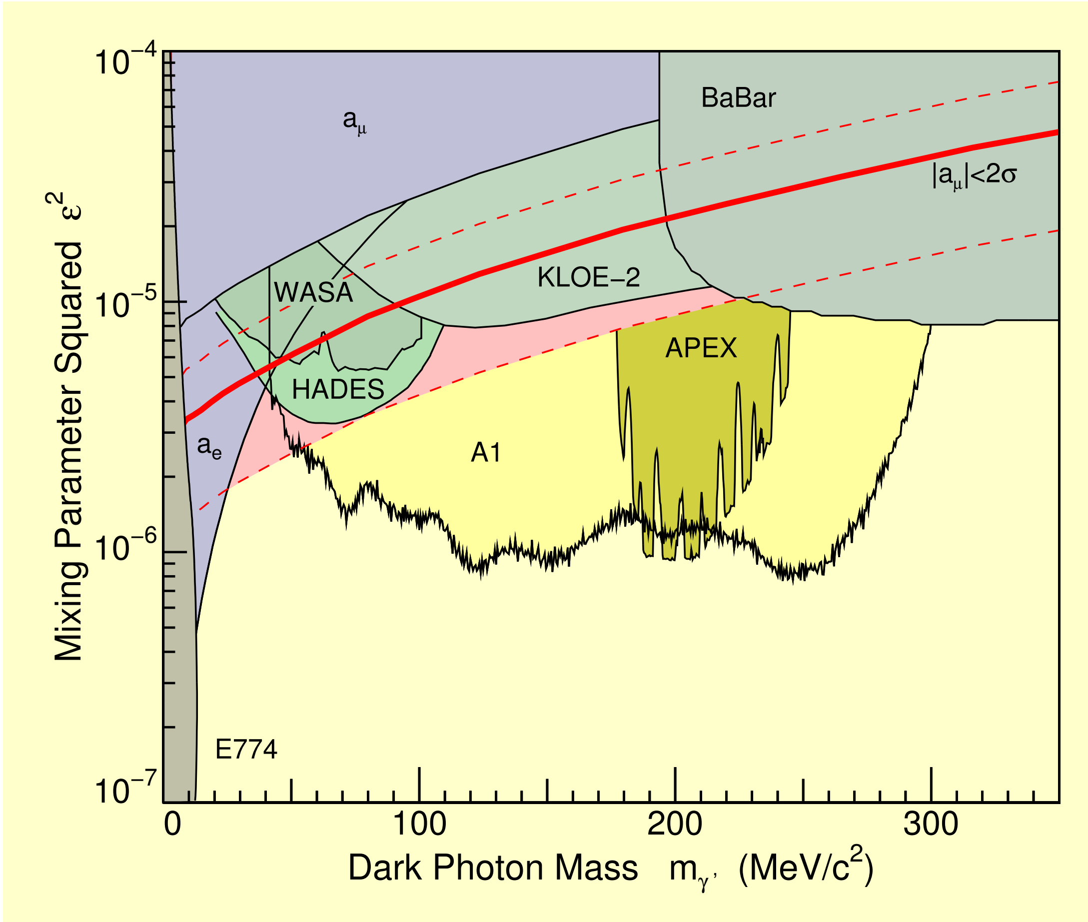
All Settings



Are we allowed to add up all settings?

- NMR Probe for magnetic field $\delta B/B < 10^{-4}$
- Hall Probe for magnetic field $\delta B/B < 10^{-3}$
- Extensive calibration with elastic lines (during ISR experiment)

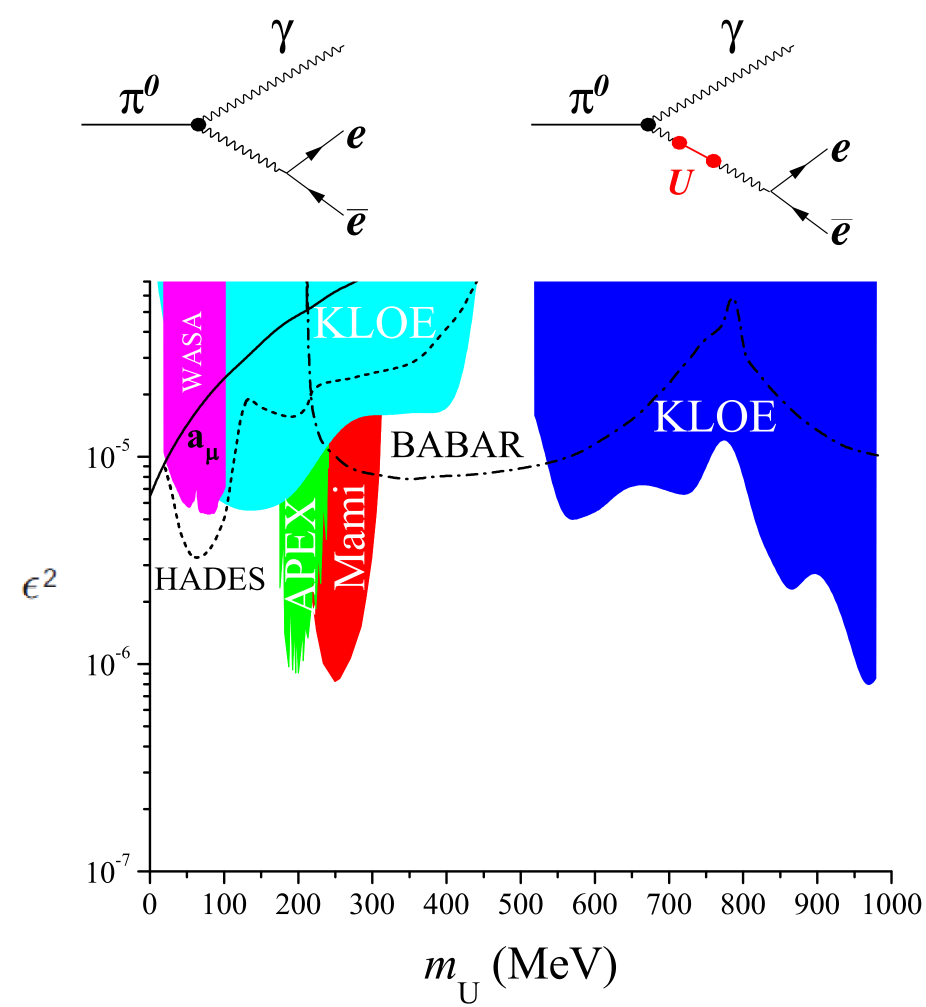
Exclusion limits MAMI 2014



- 24 kinematical settings
- Including data from pilot experiment H.M. *et al.* PRL **106** (2011) 251802
- Sensitivity $\varepsilon^2 > 8 \cdot 10^{-7}$

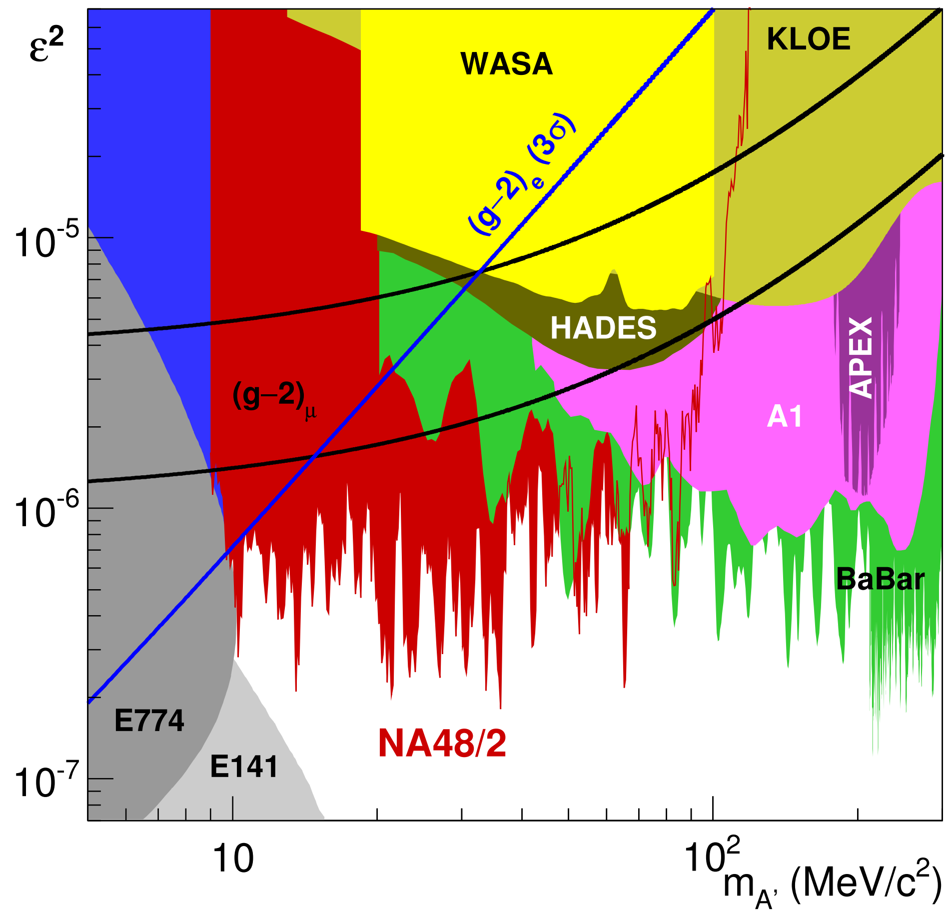
H.M. *et al.*, Phys. Rev. Lett. **112** (2014)

Limits from Meson Decays



BaBar	$e^+e^- \to \Upsilon \to \mu^+\mu^-\gamma$	B. Aubert *et al.*, PRL 103, 081803 (2009)
KLOE-2	$\phi \to e^+e^-\gamma$	D. Babusci *et al.*, PLB 720 (2013)
WASA	$\pi^0 \to e^+e^-\gamma$	P. Adlarson *et al.*, PLB 726 (2013)
HADES	$p+p, p+Nb, Ar+KCl \to e^+ + e^-$	G. Agakishiev *et al.* PLB 731 (2014)
KLOE-2	$e^+e^- \to \mu^+\mu^-\gamma$	D. Babusci *et al.*, Phys. Lett. B736 (2014)

Results NA48

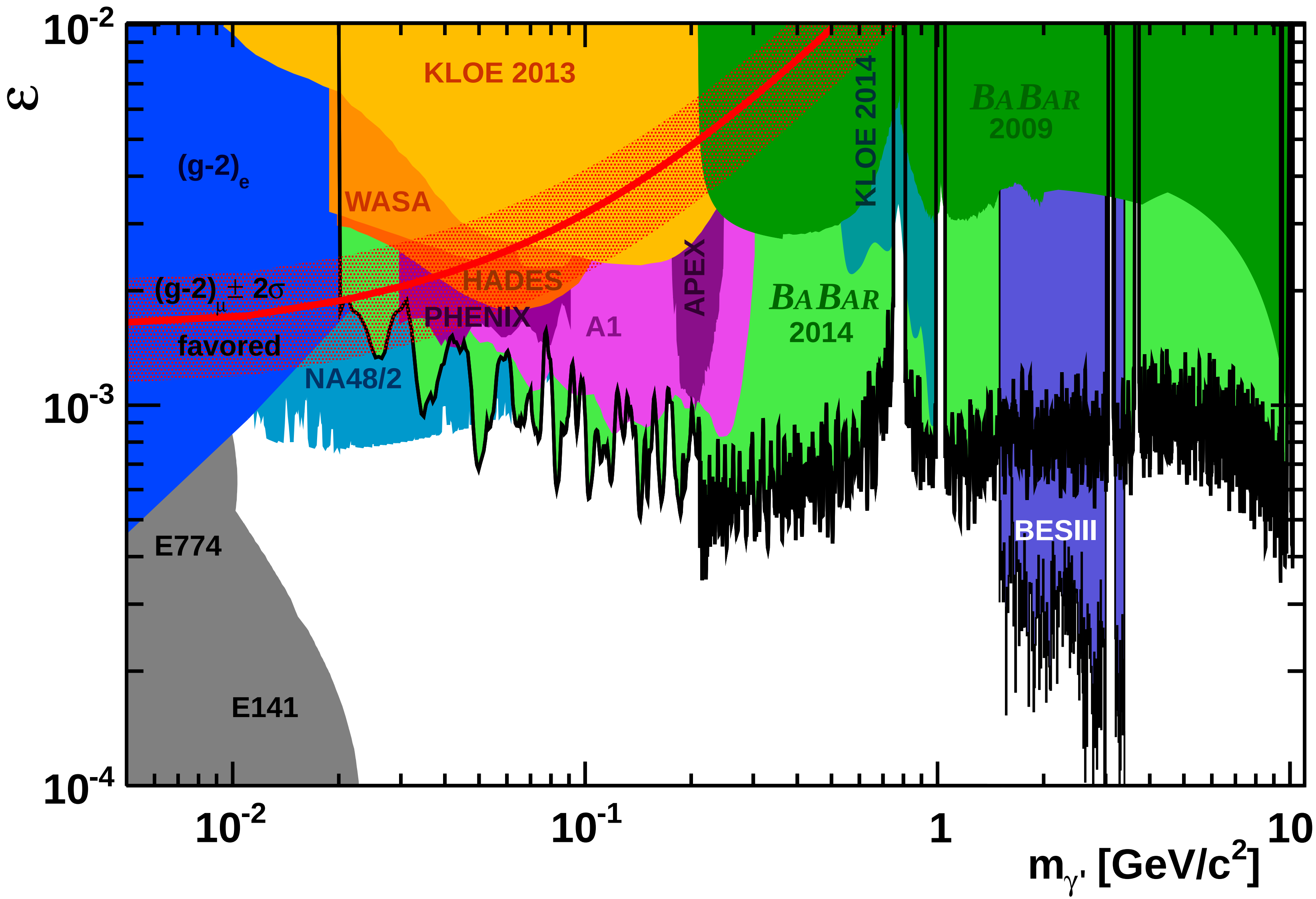


Decay Channel:

$$\pi^0 \to \gamma + e^+ + e^-$$

J.R. Batley et al. Phys.Lett. B746 (2015) 178-185

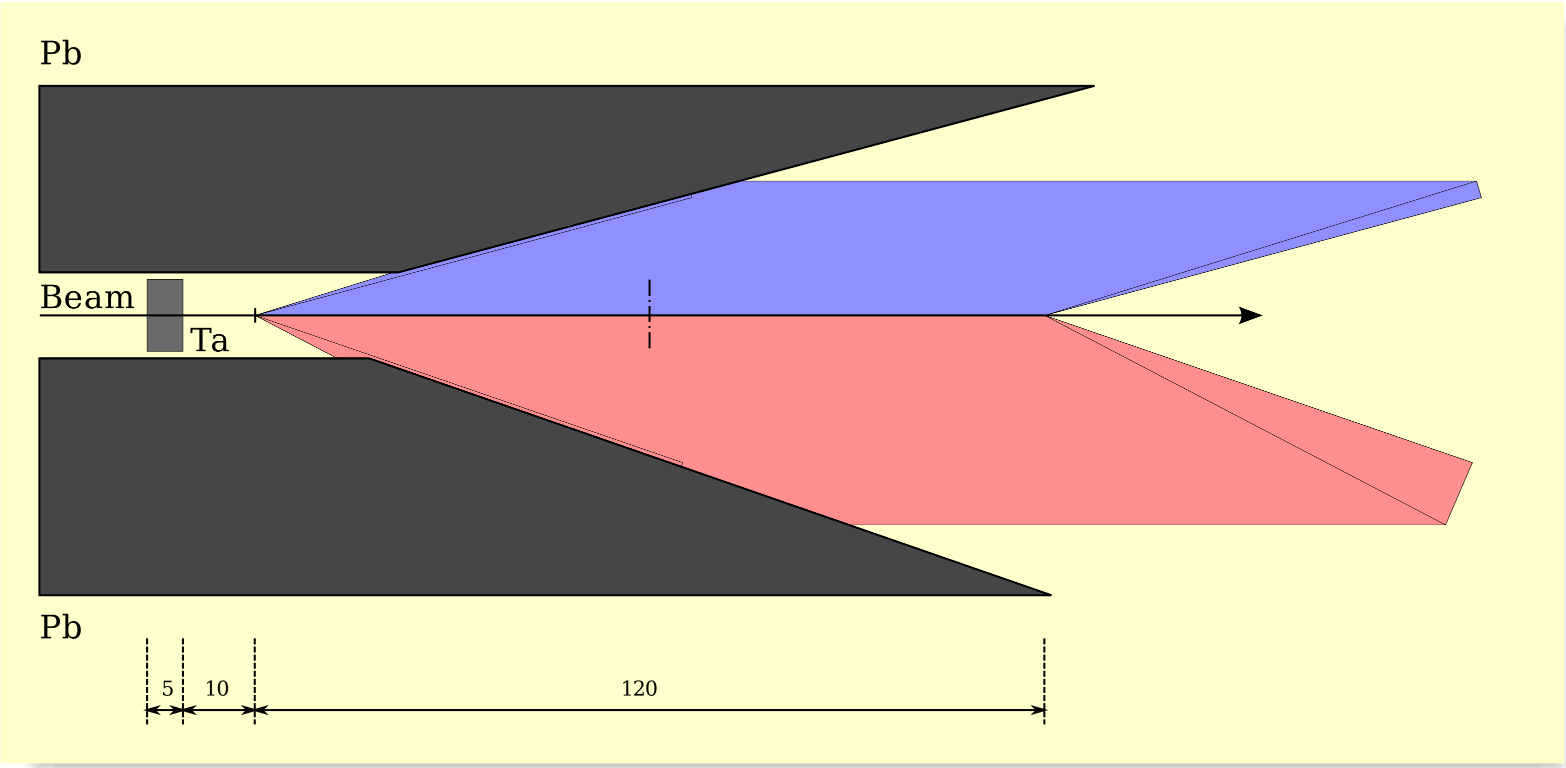
The next player: Bes III



B. Kloss (Mainz), to be published

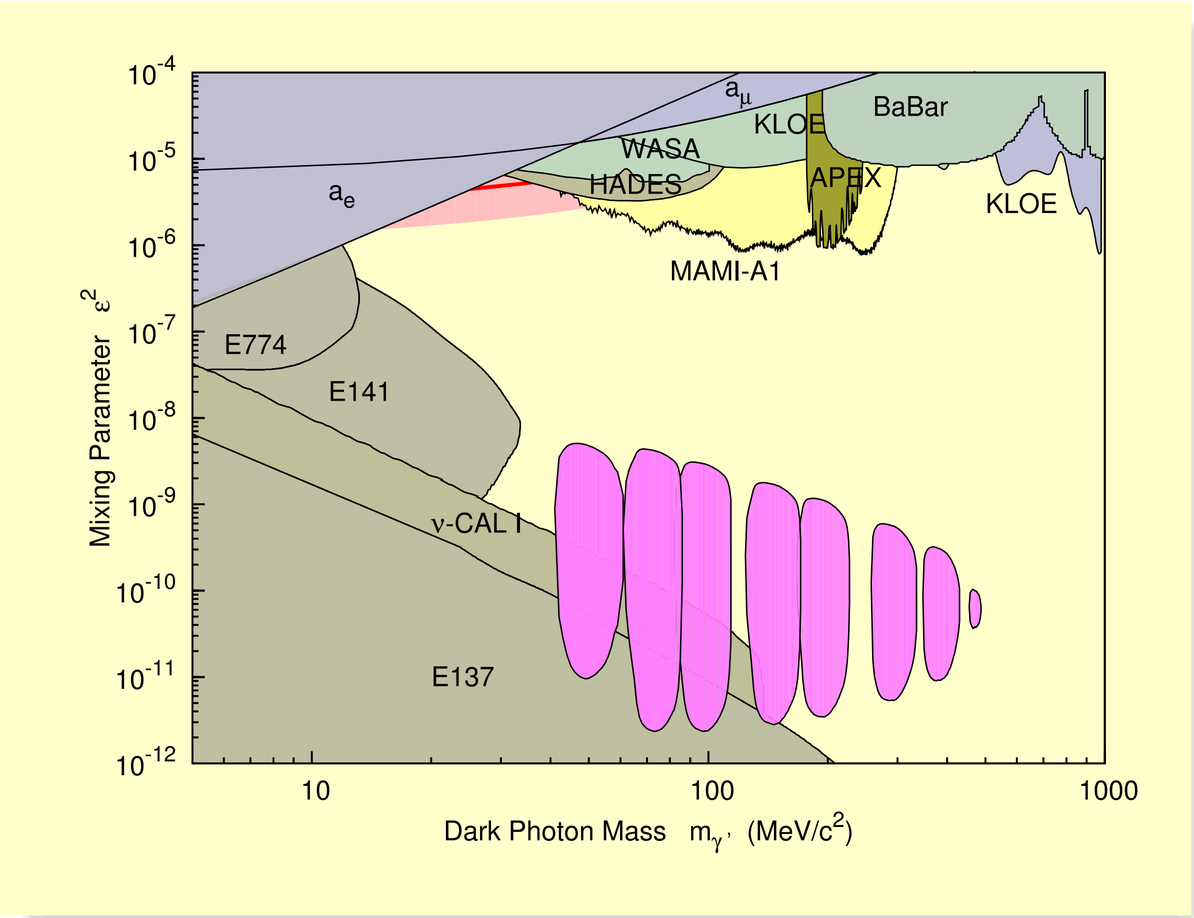
Possible improvements

Step 2: Secondary vertex $\rightarrow$ small coupling



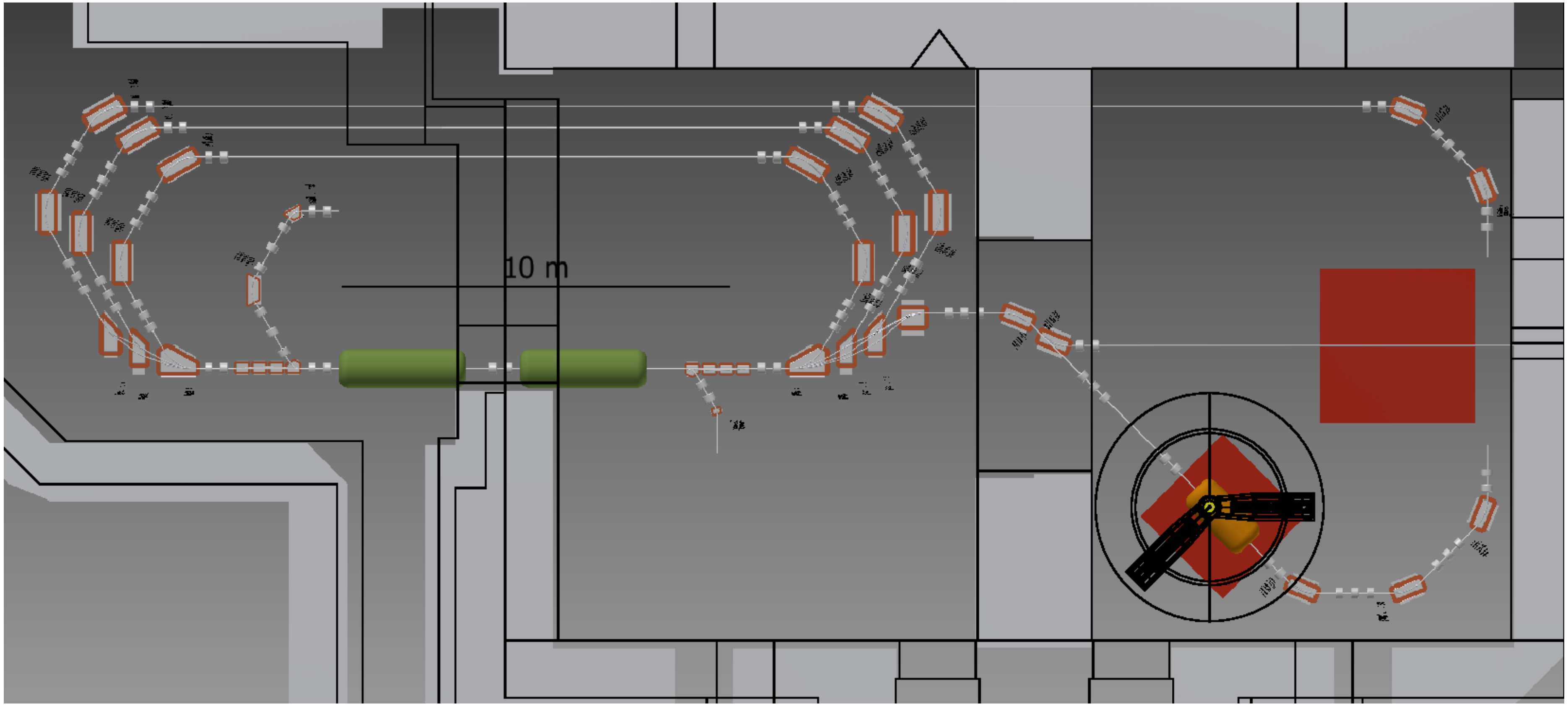
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm^2}}$ at 100 μA beam current
- First tests promising, more work to be done....
  - Backscattering > 0
  - Collimated shielding needed
  - Radiation, air activation

Step 2: Exclusion limits with shielded production vertex



- Macroscopic decay vertex distance $\varepsilon^2 < 10^{-8}$
- Luminosity $\varepsilon^2 > 10^{-11}$
- Coupling vs. lifetime $m_{\gamma'} < 500\,\mathrm{MeV}/c^2$
- Angular range $m_{\gamma'} > 30\,\mathrm{MeV}/c^2$

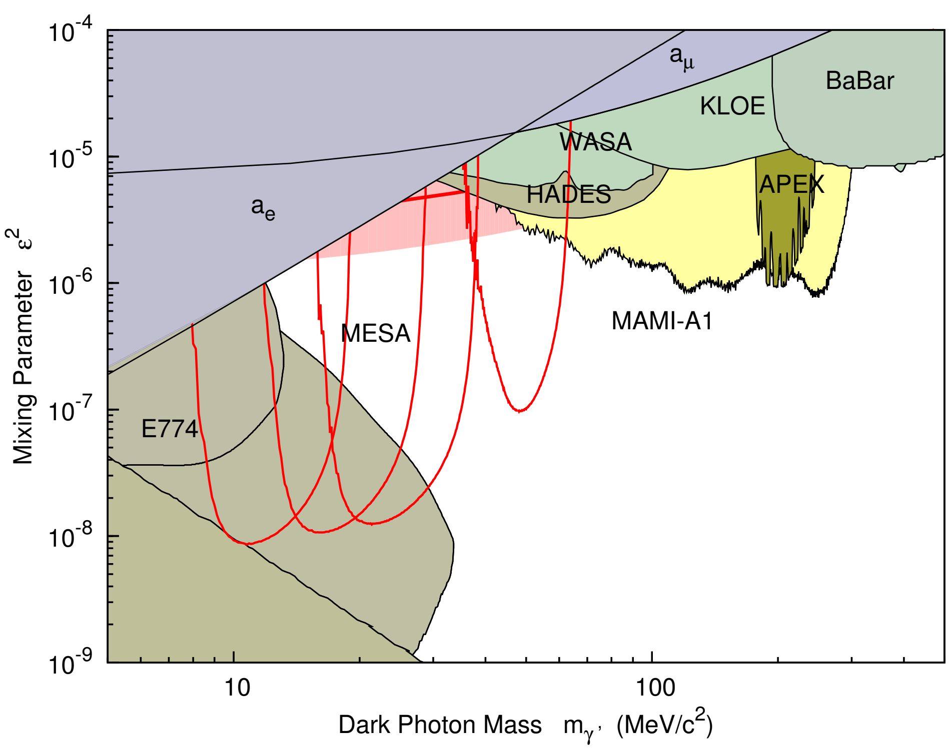
Step 3: Access to low mass region MESA Accelerator

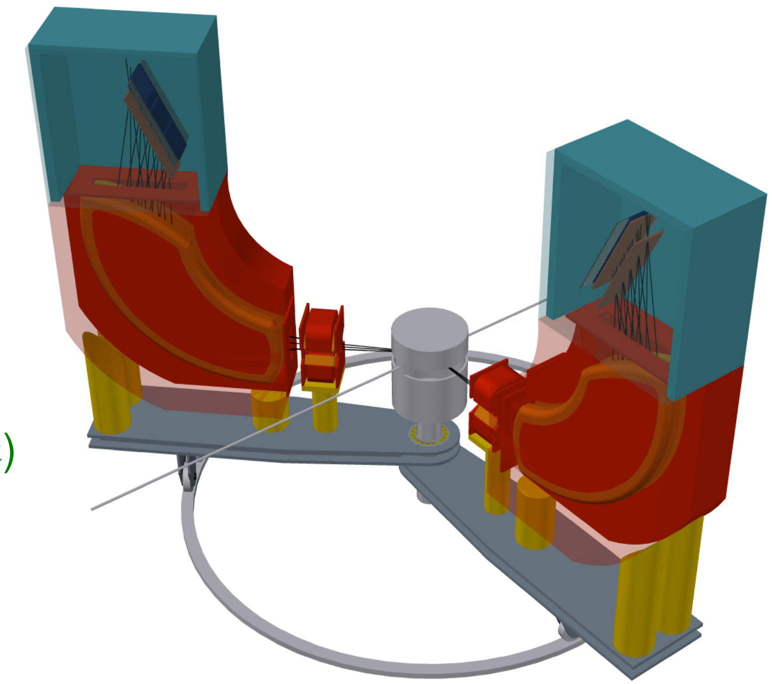


- Mainz Energy recovering Superconduction Accelerator
- up to 10 mA beam current
- Single pass accelerator ⇒ excellent beam quality
- $\Rightarrow L = 10^{35} \frac{1}{\mathrm{s\,cm}^2}$ with internal target

MESA Spectrometer Setup

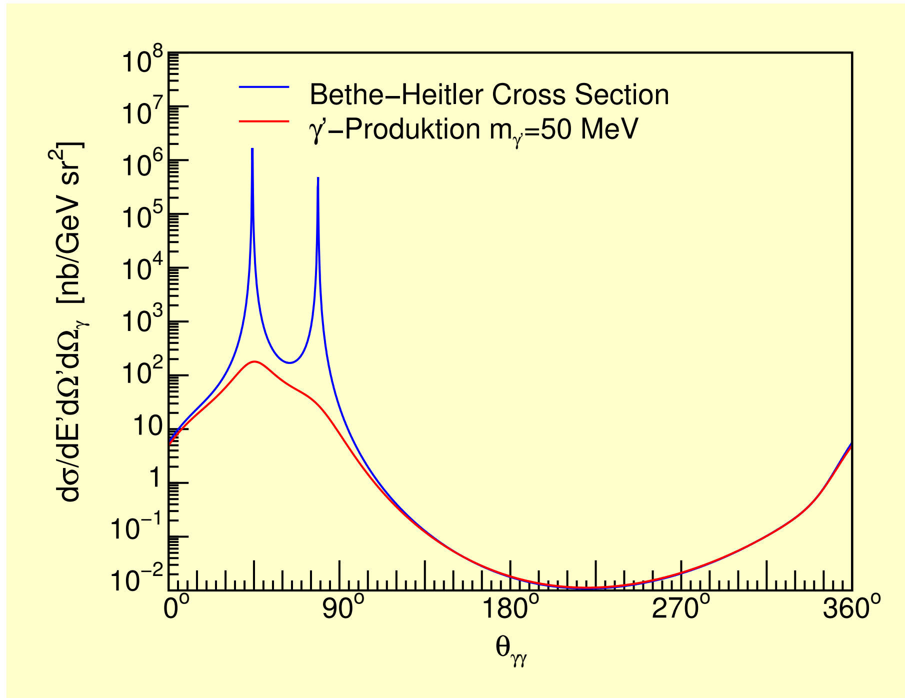
- Low energy precision physics: $\sigma \sim \sin^{-4}\frac{\theta}{2}$
- Multi-purpose spectrometer setup
- Dark Photon experiment:
  mass-resolution beats solid angle!
- Status:
  - Finite-elements design of magnets
  - (polarized) internal target design
  - Focal plane detectors (> 1 MHz count rate at $50\mu m$)





$\Rightarrow$ ideal for dark photon search!

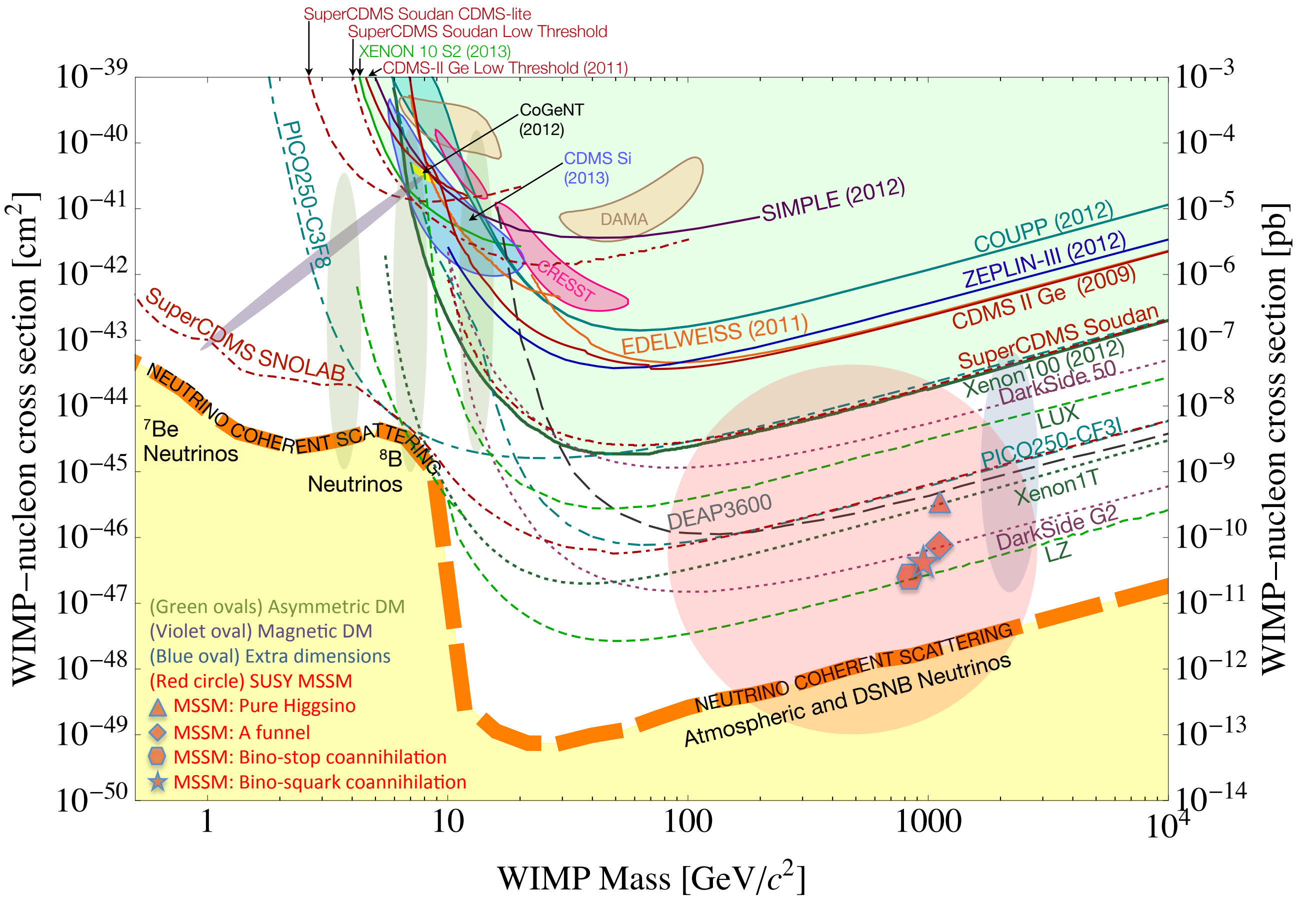
Invisible Decay



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

- γ' detection via missing mass $\quad m^2_{\gamma'} = (e + p - e' - p')^2$
- 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

Beam-Dump Experiments: Motivation

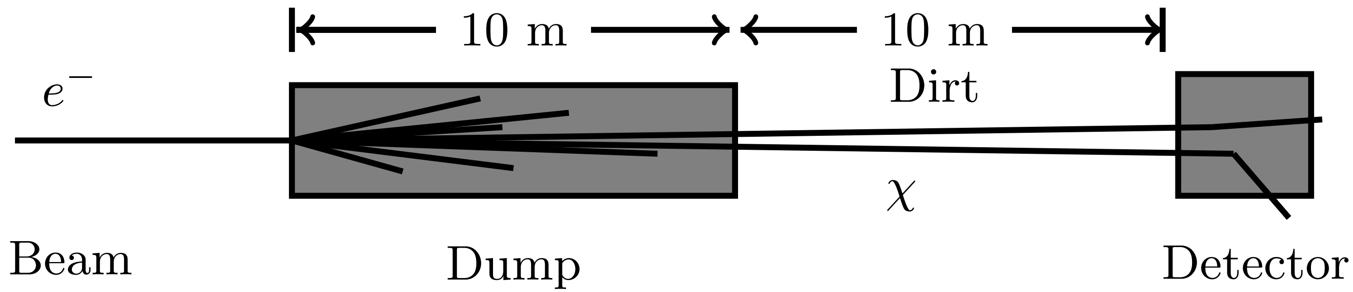


Direct detection experiments:

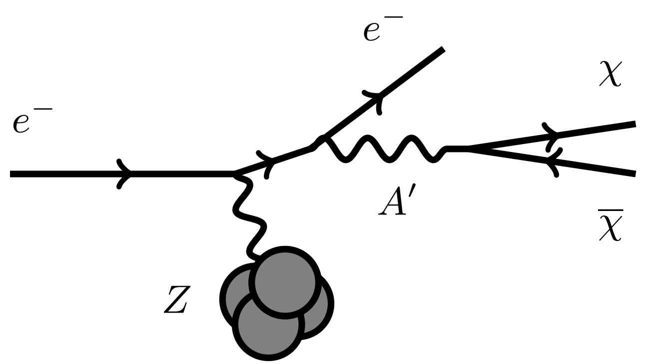
- No clear signal yet
- Limit of sensitivity (solar ν background) will be reached soon
- Lower masses (*i.e.* low recoil energy) not accessible

P. Cushman, *et al.*, arXiv:1310.8327

Beam-Dump Experiments: Idea

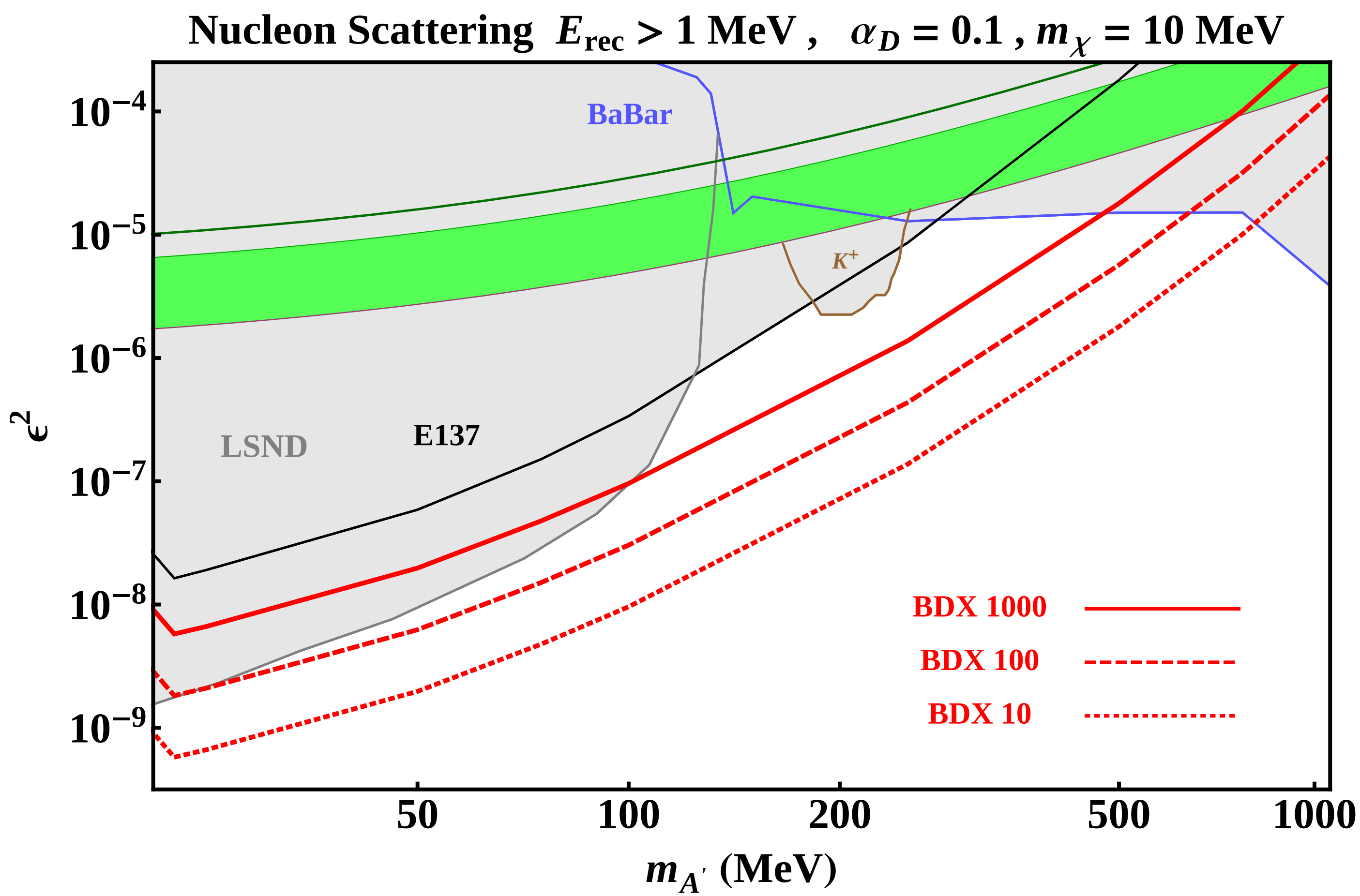


- Production in beam dump, *e.g.* via pair production



- We now have a Dark Matter Beam!
- Dark Matter particles have enough recoil energy!
- Detection with simple detector, *e.g.* scintillator cube
- ... or with sophisticated DM Detector ...

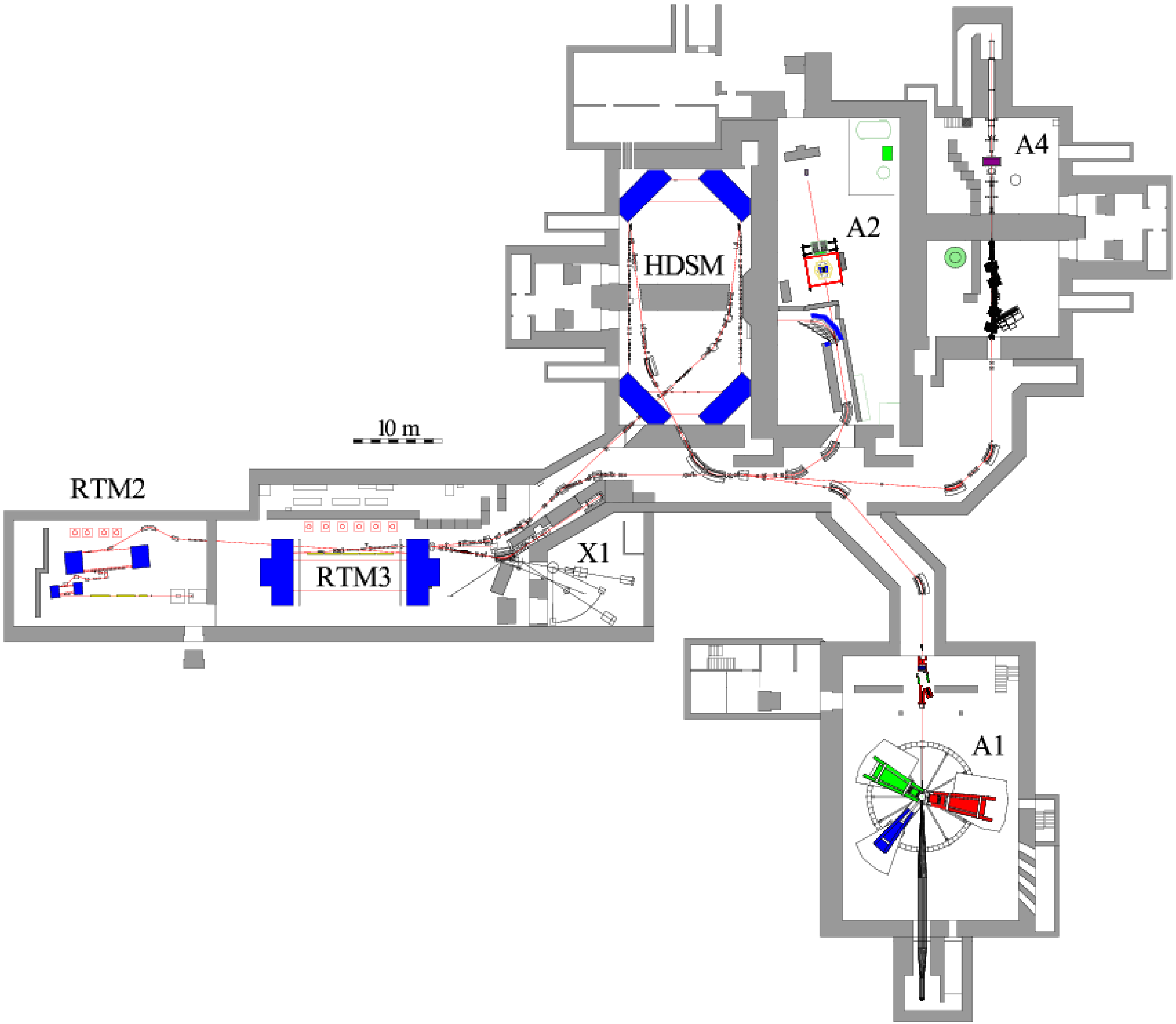
Letter of Intent at JLab: BDX



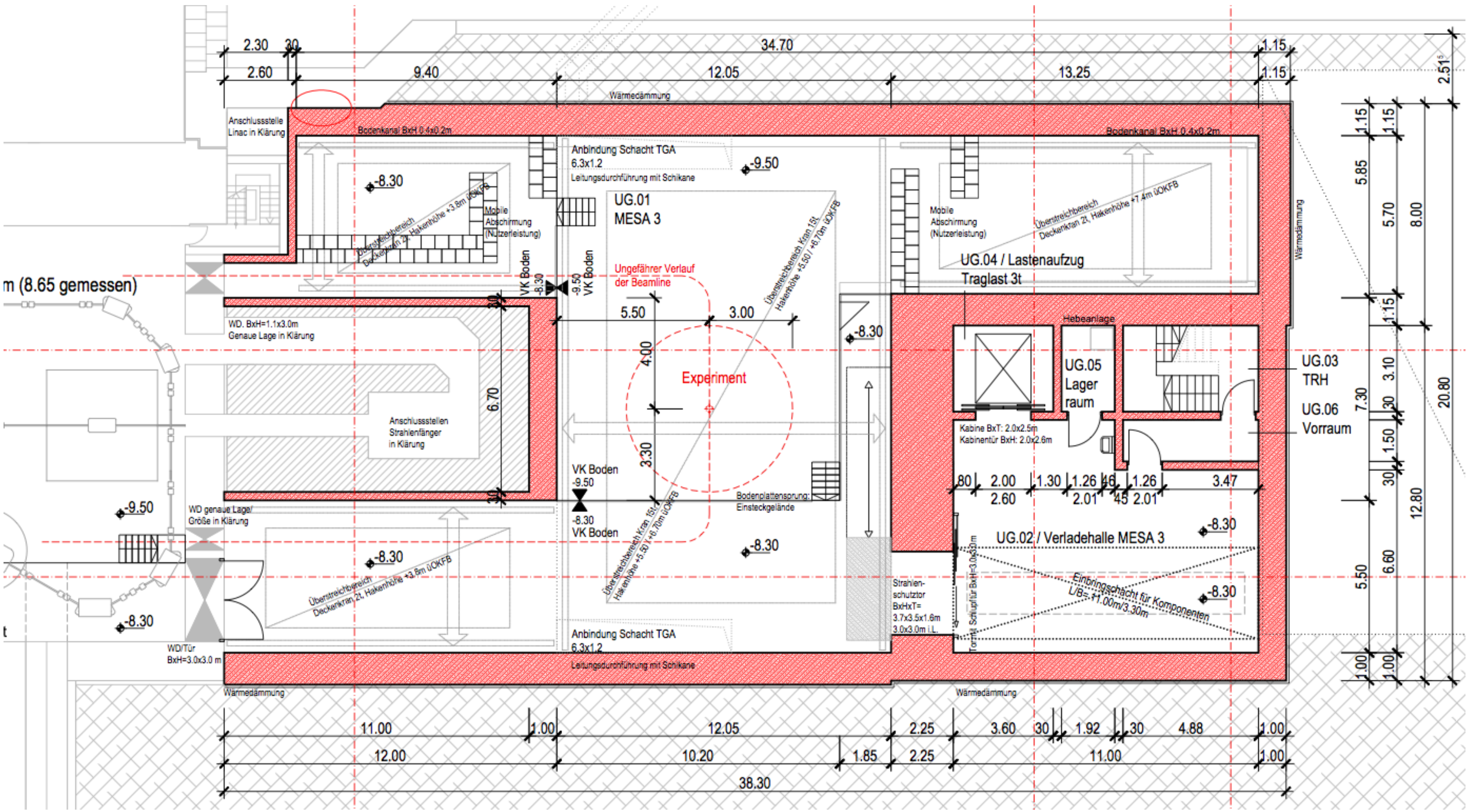
- 1 MeV energy deposition $\longrightarrow$ simple detector
- Background is crucial

M. Battaglieri *et al.*, arXiv:1406.3028

Mainz opportunities

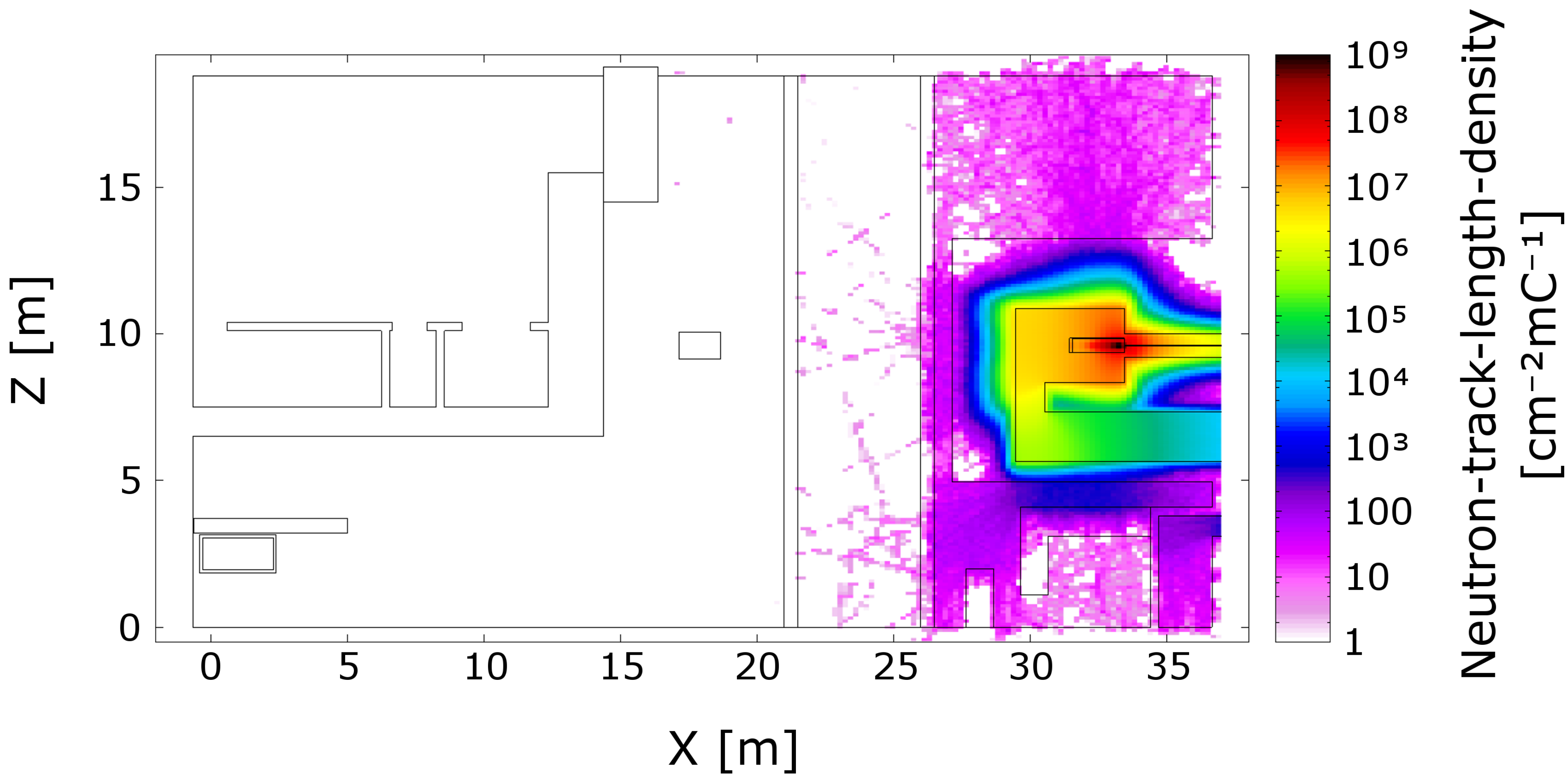


New Hall (just funded)



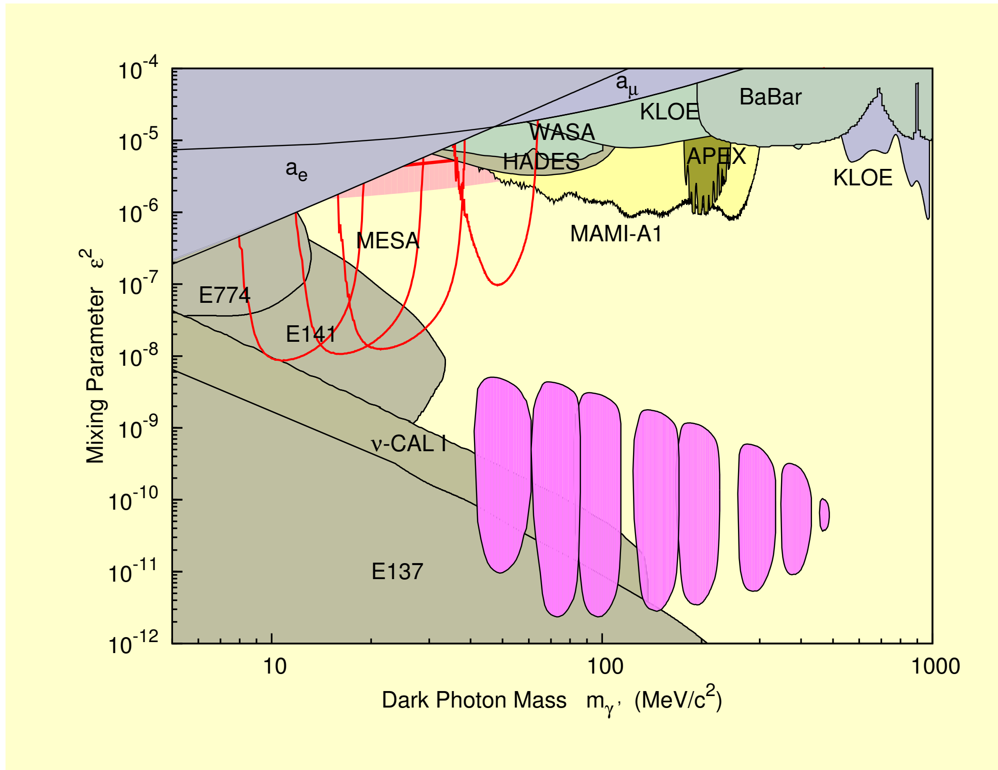
- Dedicated new hall for experiment
- Space for high resolution experiment
- Additional space for beam dump experiment: 1 mA beam on target for $50\%/a$

FLUKA Simulation



- Neutrons can be shielded
- Below pion threshold: negligible ν background
- Clean conditions, detailed layout of hall needed for further design

Summary



- Pair production on heavy target $\varepsilon^2 > 10^{-6}$
  $\Rightarrow (g-2)_\mu$ Region is nearly covered
- Finite production vertex $10^{-10} < \varepsilon^2 < 10^{-8}$
  $\Rightarrow$ Difficult, but first tests are promising
- Low energy – high current $m_{\gamma'} < 50\,\mathrm{MeV}/c^2$

$\Rightarrow$ New Accelerator dedicated to “Precision Frontier”
$\Rightarrow$ Beam Dump Experiments