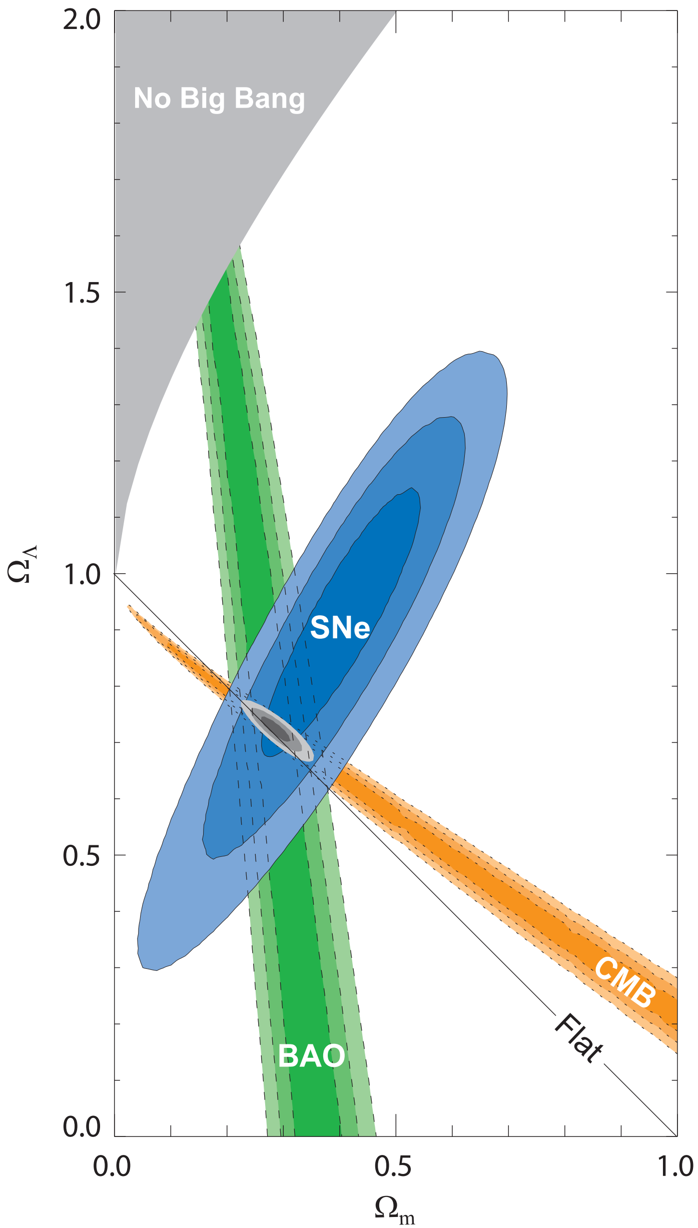
SEARCH FOR DARK PHOTONS WITH ACCELERATORS

Harald Merkel
Johannes Gutenberg-Universität Mainz

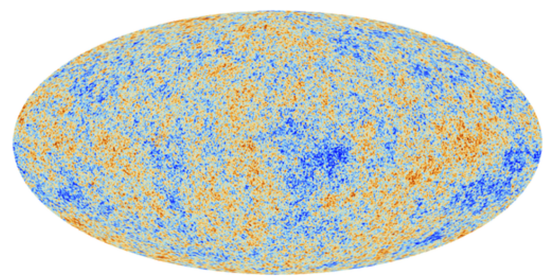
MESON 2014

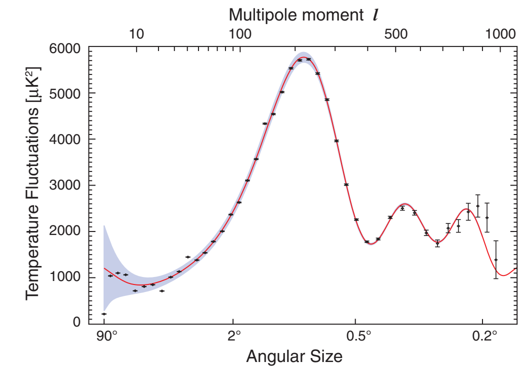
- Motivation
  - Evidence for Physics beyond the Standard Model
  - Candidates from Particle Physics
  - The γ' Boson
- How can we detect a “Dark Photon”?
  - Di-Lepton-Production
  - Cross sections
- Fixed Target Experiments
  - Mainz Microtron
  - JLab
- Meson Decays
- Summary

Dark Matter

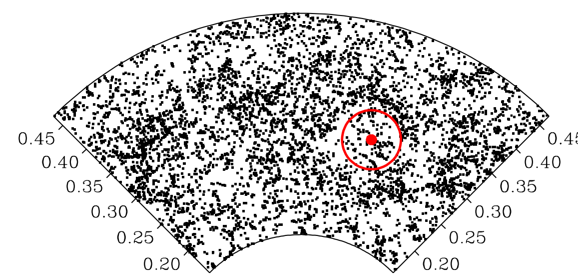


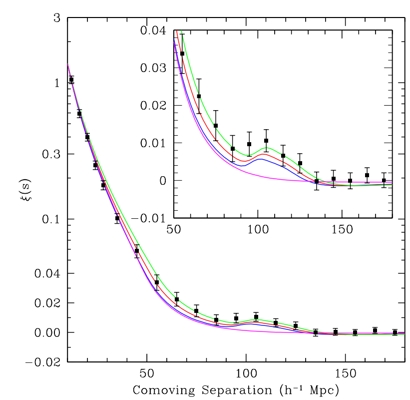
- Supernova Type Ia (SNe)
- Cosmic Microwave Background





- Baryon Acoustic Oscillations





$\Rightarrow$

Ω_Λ	=	69.2%	Dark Energy
Ω_{CDM}	=	25.9%	Cold Dark Matter
Ω_b	=	4.9%	Baryonic Matter

PDG 2013

Dark matter candidates in particle physics

Properties:

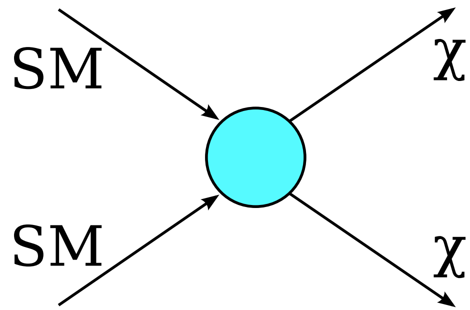
- Massive
- Slow (cold)
- Almost no interaction with standard model matter
- Produced during big bang

Candidates:

- Baryonic dark matter, gas clouds, black holes, MACHOs
  ↯ Contradicts primordial nucleosynthesis, no observations
- Hot dark matter, e.g. neutrinos
  ↯ Phase space contradicts structure formation
- Cold dark matter
  - WIMPs: Weakly Interacting Massive Particles?
  - Axion?
  - Lightest Supersymmetric Particle (LSP)?
  - Neutralino, Sneutralino, Gravitiono, Axino, ...?

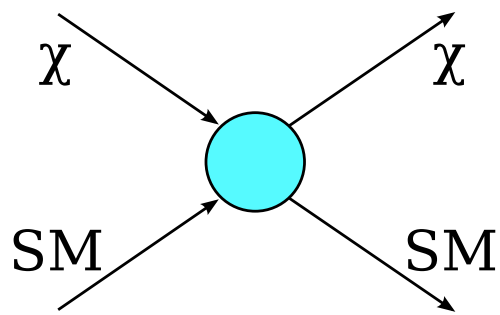
$\Rightarrow$ Hypothesis: dark matter is made of unknown particles

Conventional strategies for dark matter search in particle physics



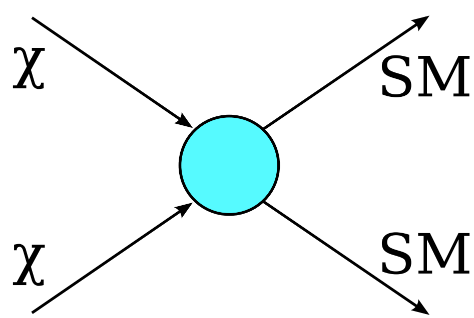
Direct Production:

LHC



Direct Search:

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



Indirect Search:

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

A bottom up approach: Looking for the Interaction

Assumptions:

- There are dark matter particles (SUSY or something else)
- More than ONE dark matter particle?
  $\Rightarrow$ dark sector
- 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?

?

Or top down Motivation...

How to “construct” an extension of the Standard Model:

1. Demand a new symmetry group
2. Symmetry breaking to recover Standard Model at low energies!

Consequences:

- Extra $U(1)$ gauge bosons ubiquitous in well motivated extensions
  - large gauge symmetries must be broken
  - $U(1)$s are the lowest-rank local symmetries
- $U(1)$ gauge bosons may be hidden (no interaction with SM)
- Example: $U(1)$ gauge factors in string compactifications:

$$E_8 \times E_8 \to E_6 \times E_8 \to \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{standard model}} \times U(1)_{\text{hidden}}$$

  from breaking of second E_8

- No reason for $U(1)$ boson to be heavy!

Kinetic mixing

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

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

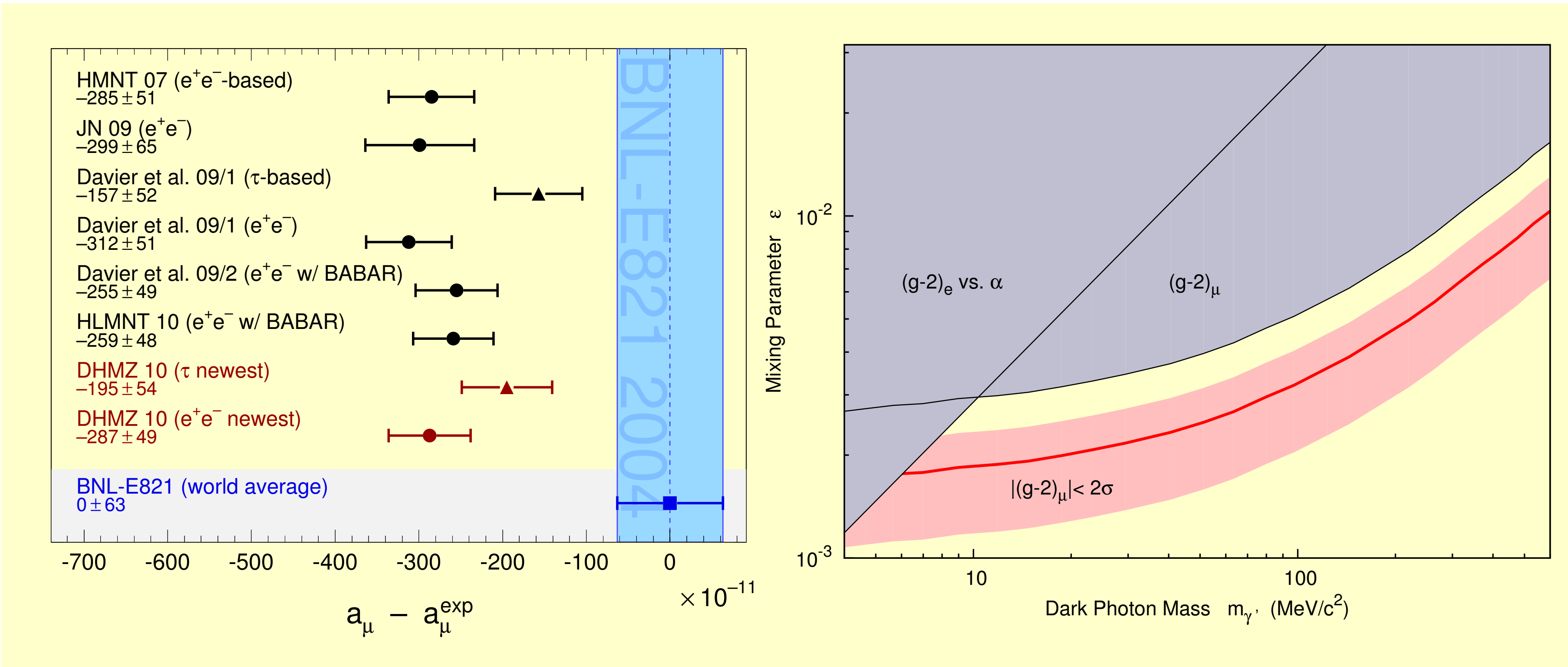
- Renormalization of Charge:
  $\Rightarrow$ Mixing Standard Model Charge – “dark” charge
- Parametrized by mixing parameter ε of γ'/γ mixing
- Boson mass $m_{\gamma'} > 0 \Rightarrow$ decay suppressed, *macroscopic* lifetime

$\Rightarrow$ Look for χ at high energies
OR
Look for γ' at low energies (but small coupling)!

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

Is there experimental evidence?

Anomalous magnetic moment of the muon



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

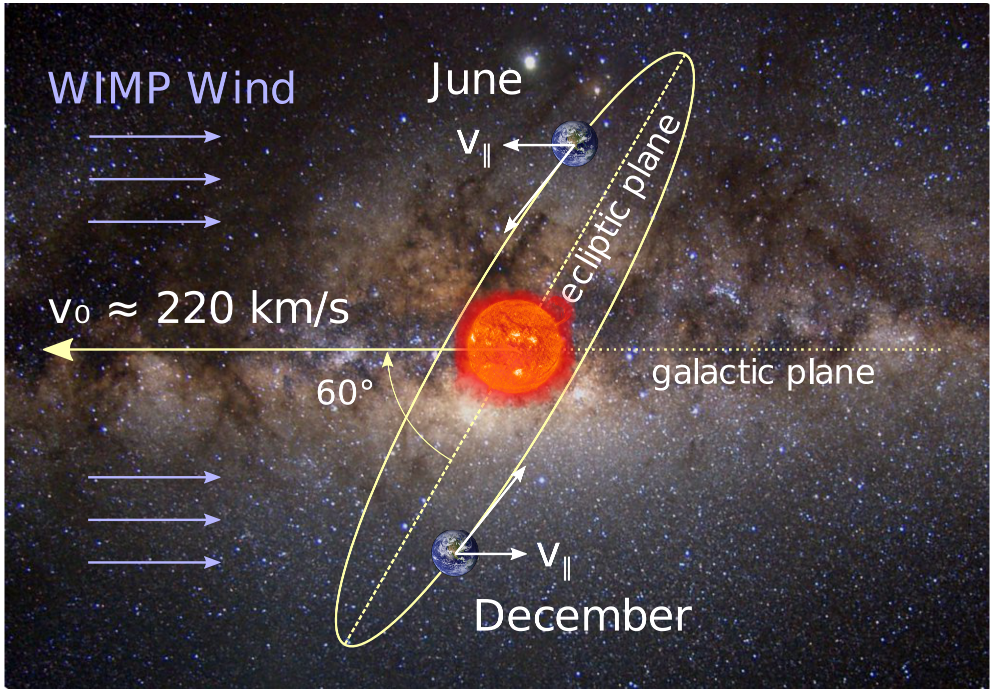
G. W. Bennet *et al.*, Phys. Rev. D 73, 072003 (2006)
M. Pospelov, Phys. Rev. D 80, 095002 (2009)
P. Fayet, Phys. Rev. D75, 115017 (2007)

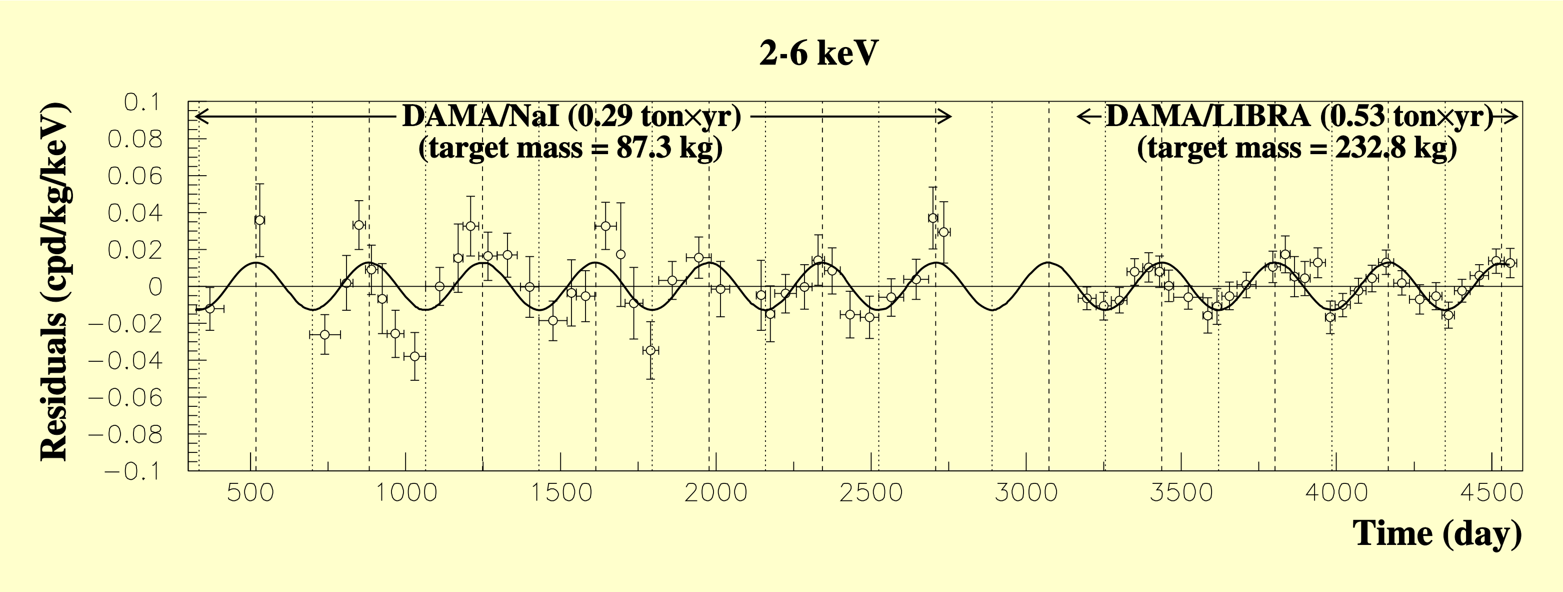
DAMA/NaI and DAMA/LIBRA

- NaI detectors in Gran Sasso
- Elastic scattering $\chi + N \rightarrow \chi + N$
- Seasonal modulation:

$$S_0 + A\cos\omega(t - t_0)$$

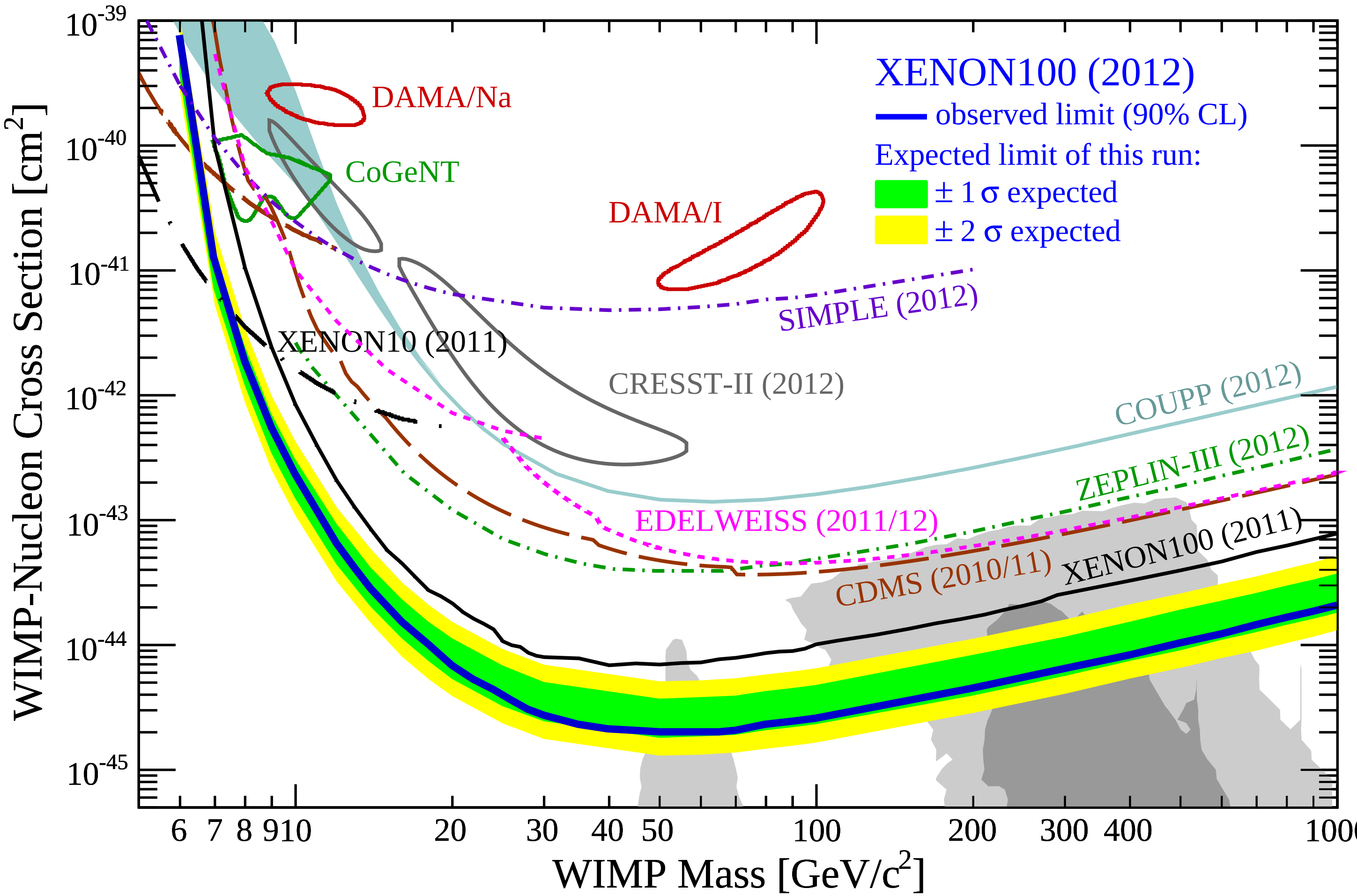
- Expected Phase: June 2nd ($t_0 = 152$)
- 8.2σ signal with $t_0 = 144 \pm 8$





R. Bernabei *et al.*, Eur. Phys. J. C (2008) 56: 333-355

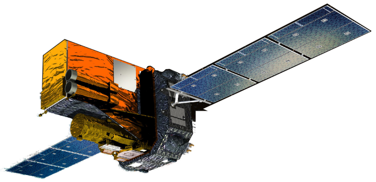
Problem: DAMA/LIBRA and the other experiments...

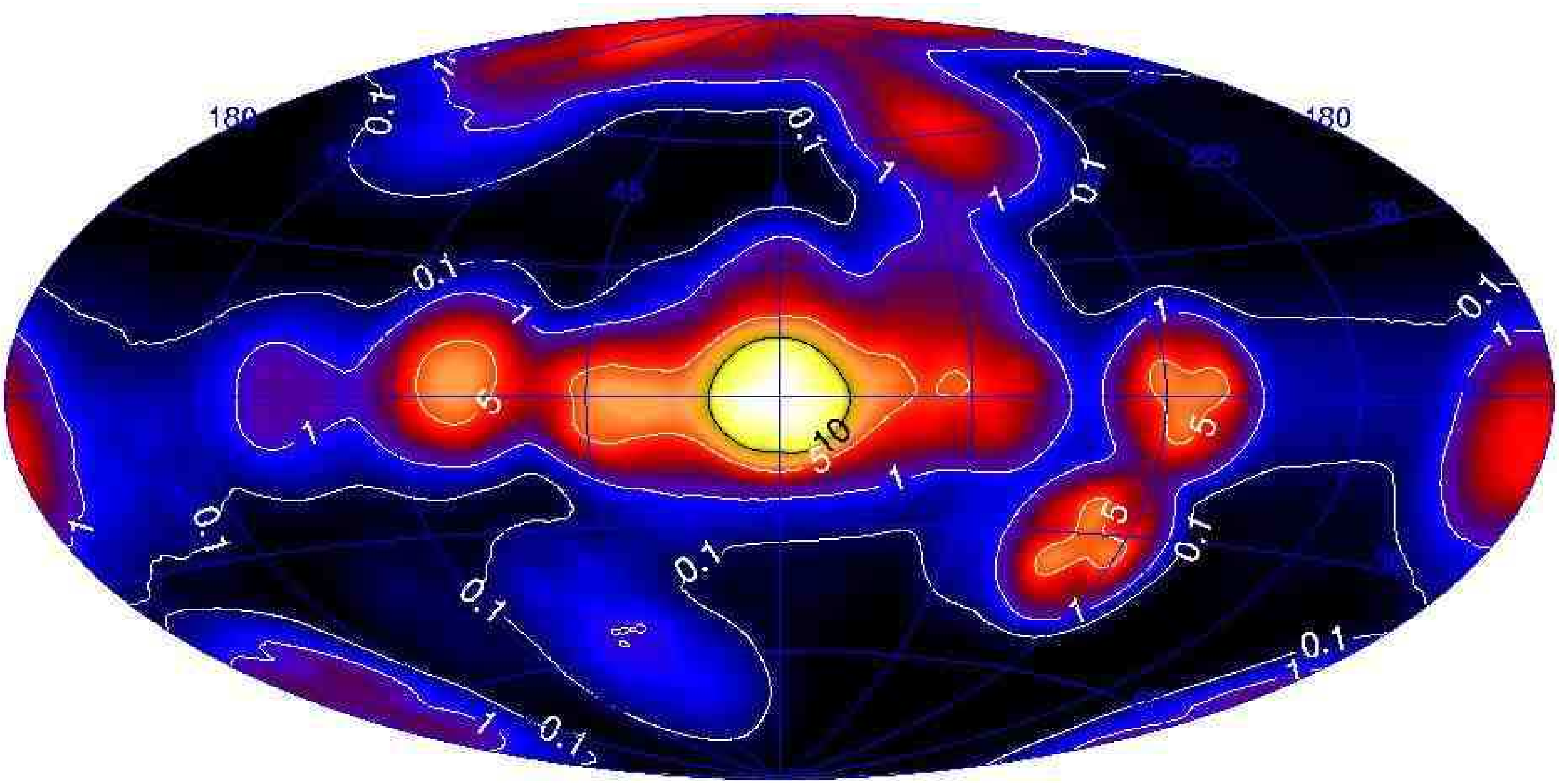


- Signals with annual modulation by DAMA and CoGeNT?
- XENON100, CDMS: coincidence experiments
- ⇒ Possible solution: reaction mechanism (electrons, excited DM)

E. Aprile *et al.*, Phys. Rev. Lett. 109, 181301 (2012)

SPI Spectrometer/INTEGRAL: 511 keV Gamma radiation

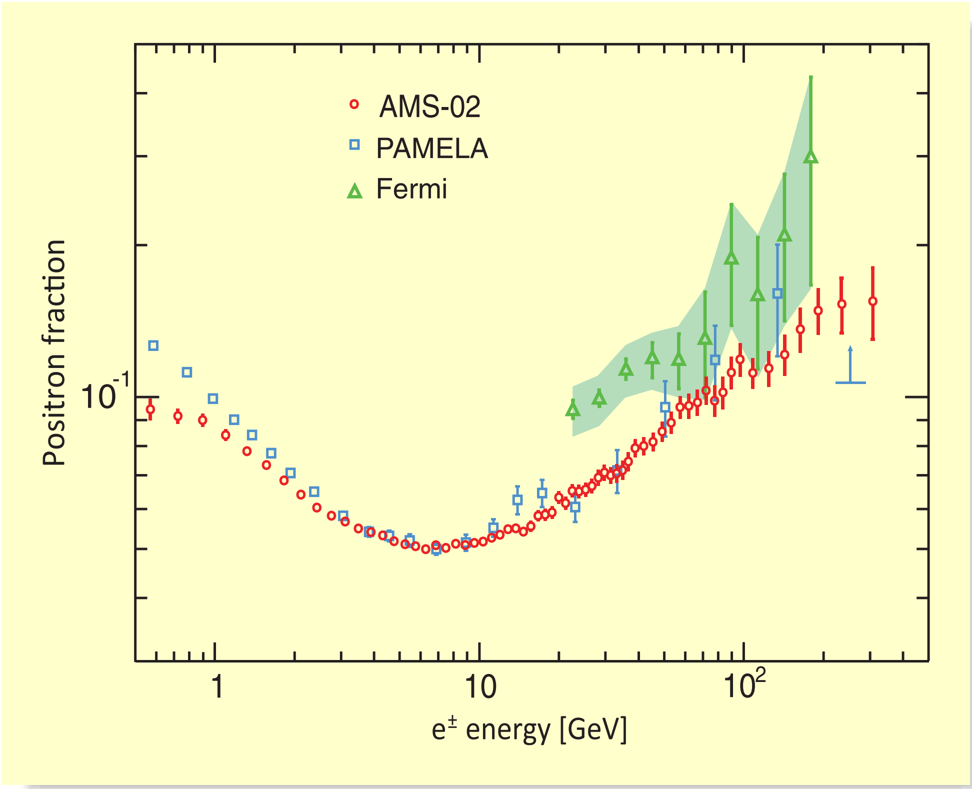




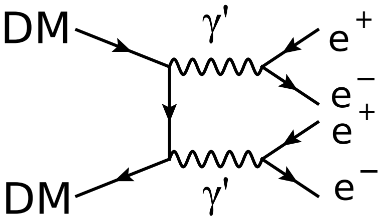
$\Rightarrow$ Positrons from annihilation $e^+ + e^-$

J. Knödlseder *et al.*, Astron. Astrophys. 441 (2005) 513

PAMELA, Fermi-LAT, AMS-02: Positron Excess



- Positron excess at large energies
- Consistent with a common source for e^+ and e^-
- Isotropic!!!!



M. Aguilar, Phys. Rev. Lett. 110, 141102 (2013)

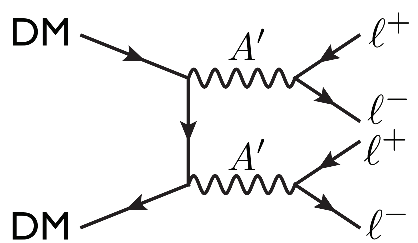
The γ' Boson (or A', ϕ, U-Boson, ...)

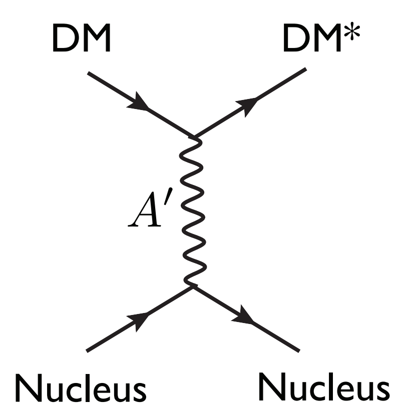
- $g-2$ anomaly of the muon
- Direct Scattering $\Rightarrow$ DAMA/LIBRA modulation
- Positron excess, but no anti-proton excess (PAMELA, INTEGRAL 511 keV line, etc.)

  $\Rightarrow$ Large annihilation cross section
- BUT: Relic Abundance of DM in cosmology requires low cross section

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

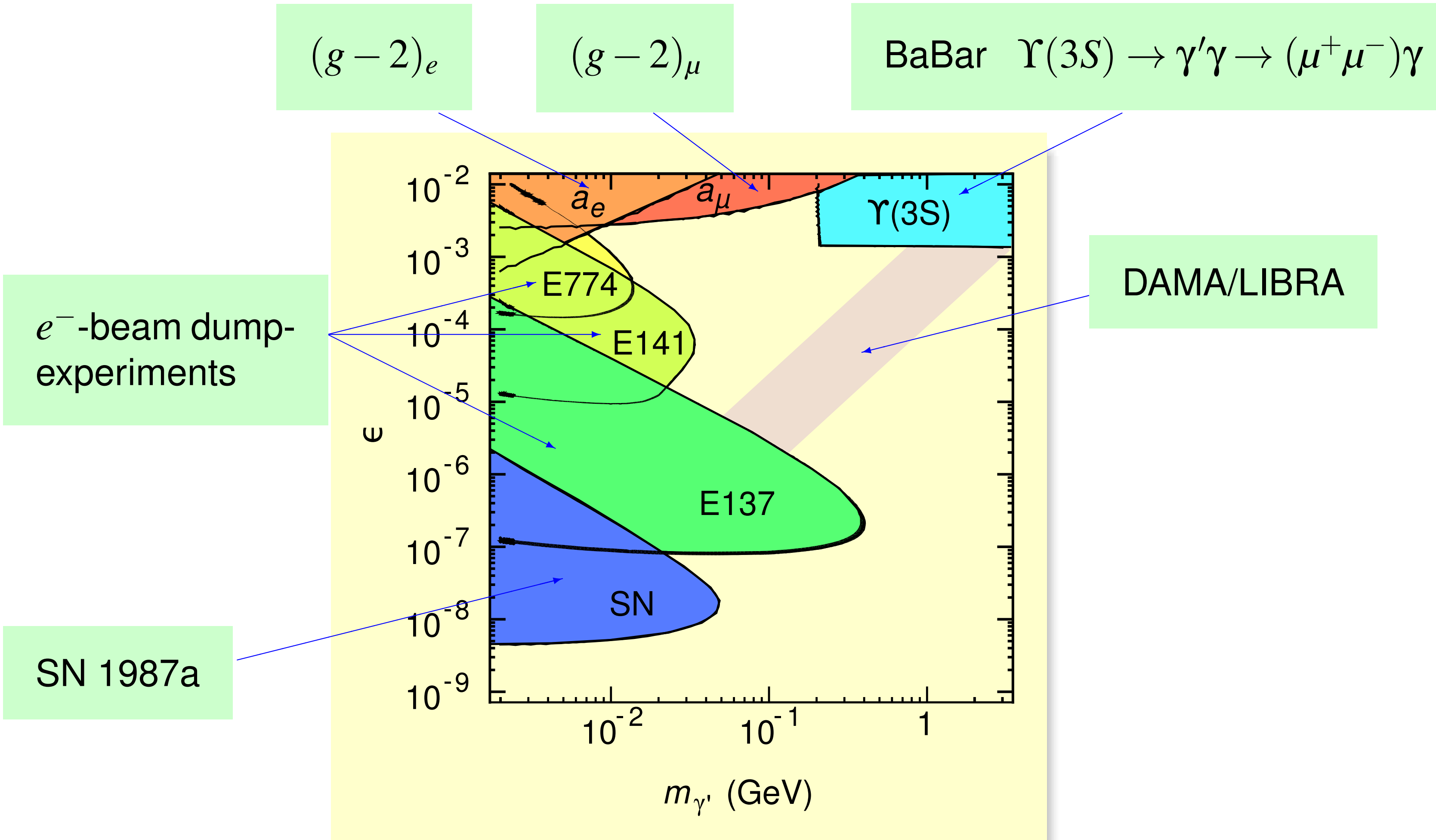
$\Rightarrow U(1)$ Vector Boson γ' with Mass in GeV range





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

Parameter range for mass and coupling of γ' boson

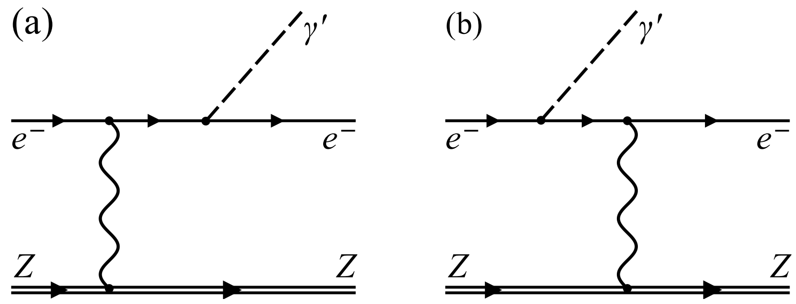


- Interesting range: $10^{-8} < \varepsilon < 10^{-2}$ $\quad 10\,\text{MeV} < m_{\gamma'} < 1000\,\text{MeV}$
- Energy range of MAMI!

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

Experimental Method

Quasi-photoproduction off heavy target



Weizsäcker-Williams approximation:

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

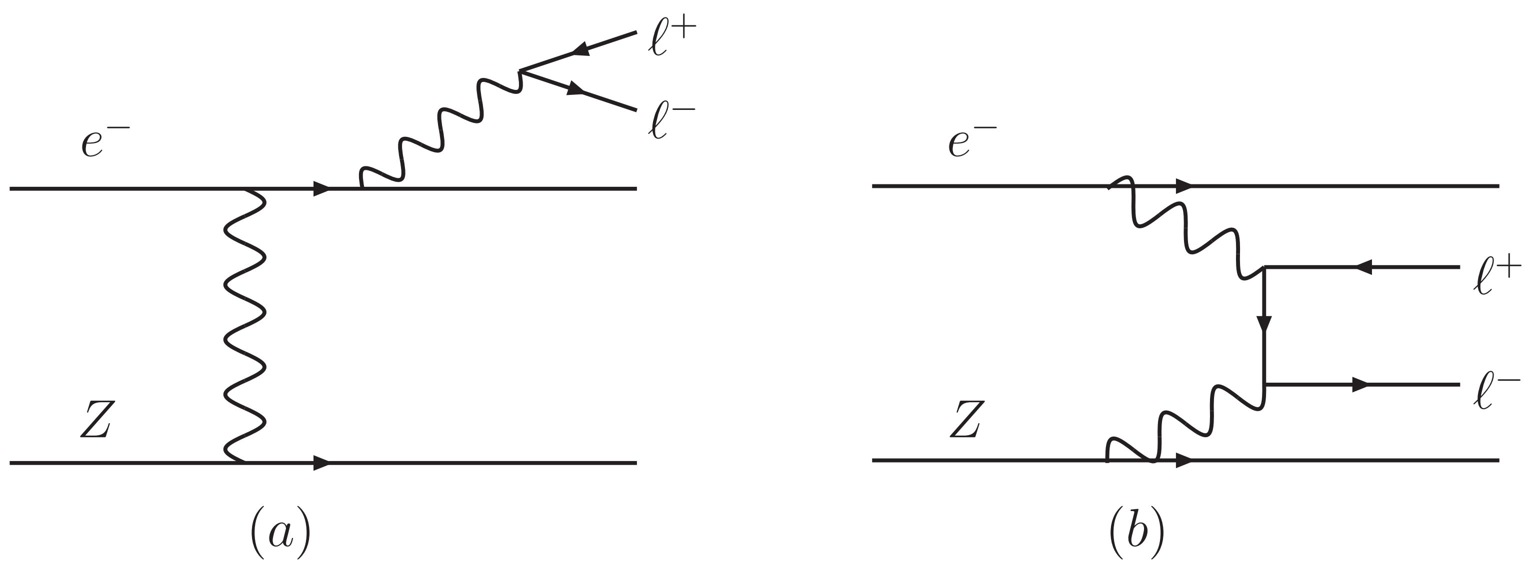
with
$$x = \frac{E_{\gamma'}}{E_0}$$
$$U(x,\theta_{\gamma'}) = E_0^2x\theta_{\gamma'}^2 + m_{\gamma'}^2\frac{1-x}{x} + m_e^2x$$

Lifetime:

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

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

Backgrounds



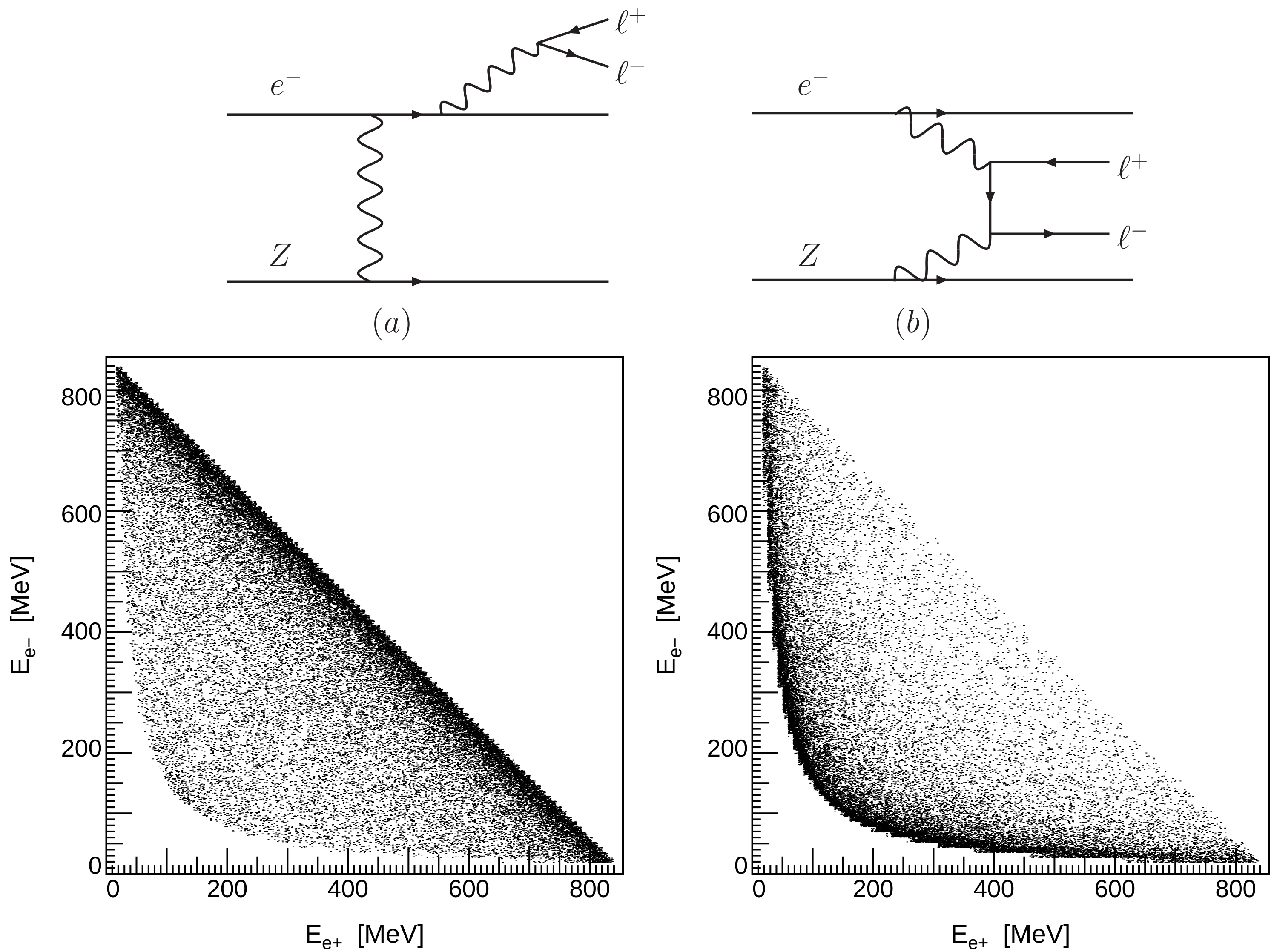
- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

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

Other backgrounds: measurement!

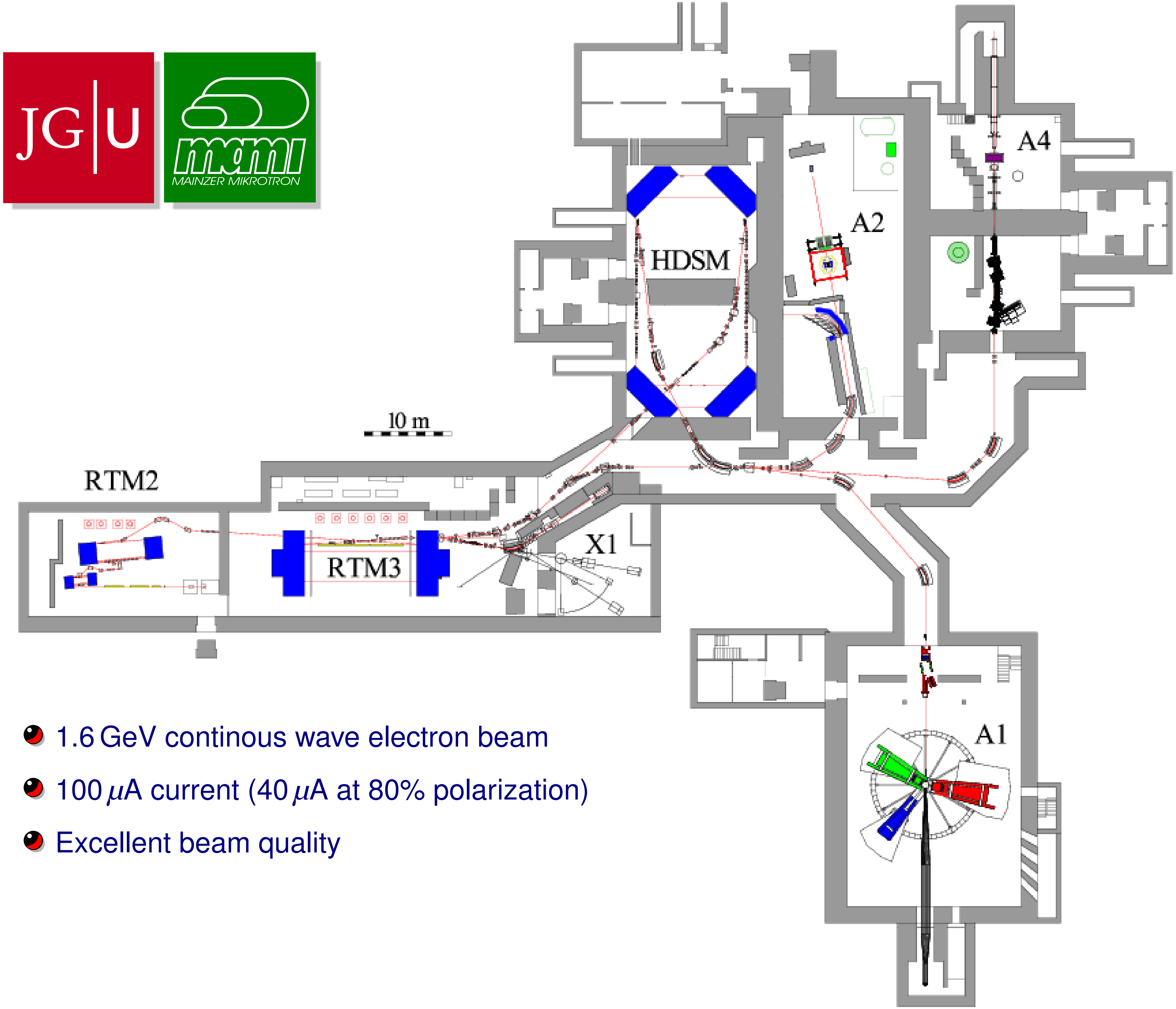
T. Beranek, H.M., M. Vanderhaeghen, Phys. Rev. D88, 015032 (2013).

Bethe-Heitler Background



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

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:

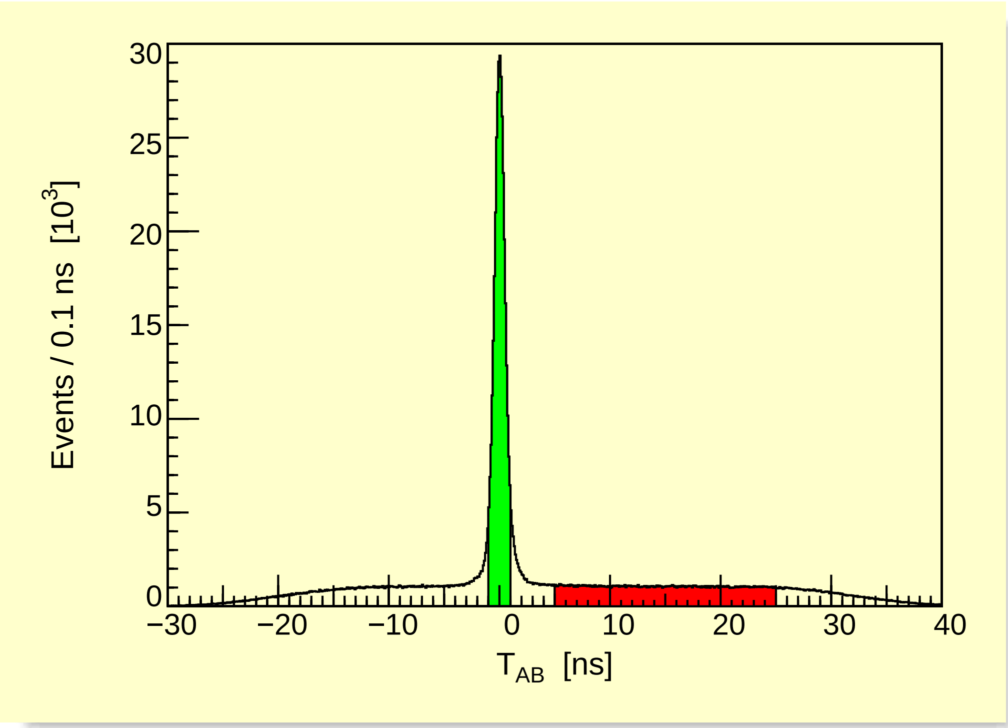
$$\alpha > 8^\circ$$
$$p < 870\,\frac{\text{MeV}}{c}$$
$$\Delta\Omega = 5.6\,\text{msr}$$
$$\Delta p/p = 15\%$$

Spectrometer C:

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

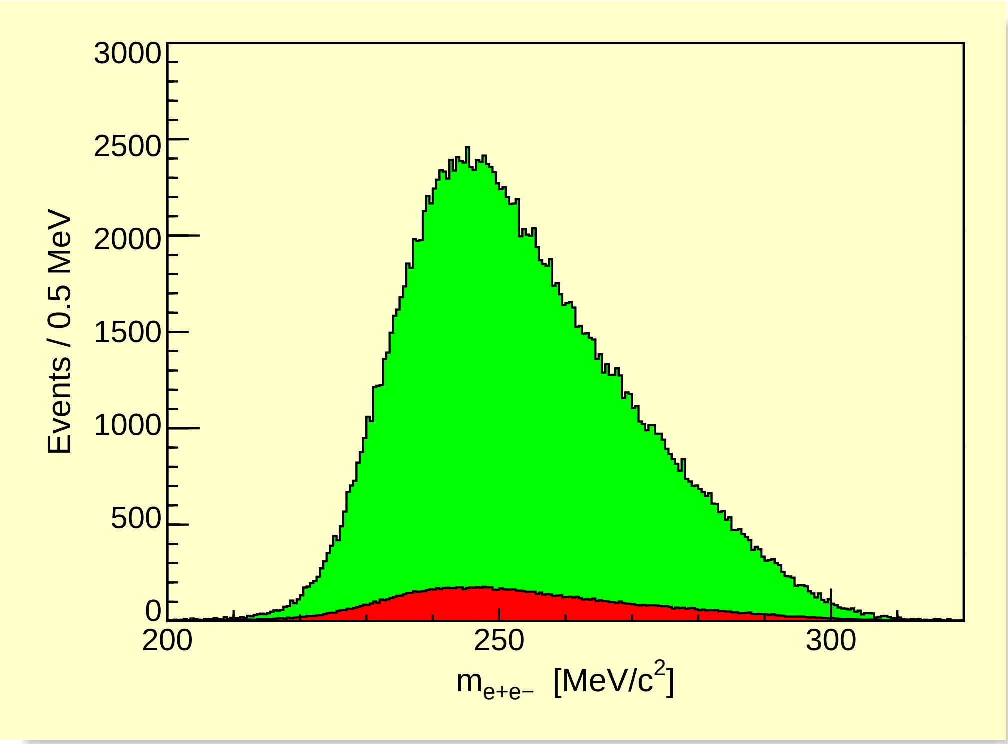
$$\delta p/p < 10^{-4}$$

Reaction identification: coincidence time



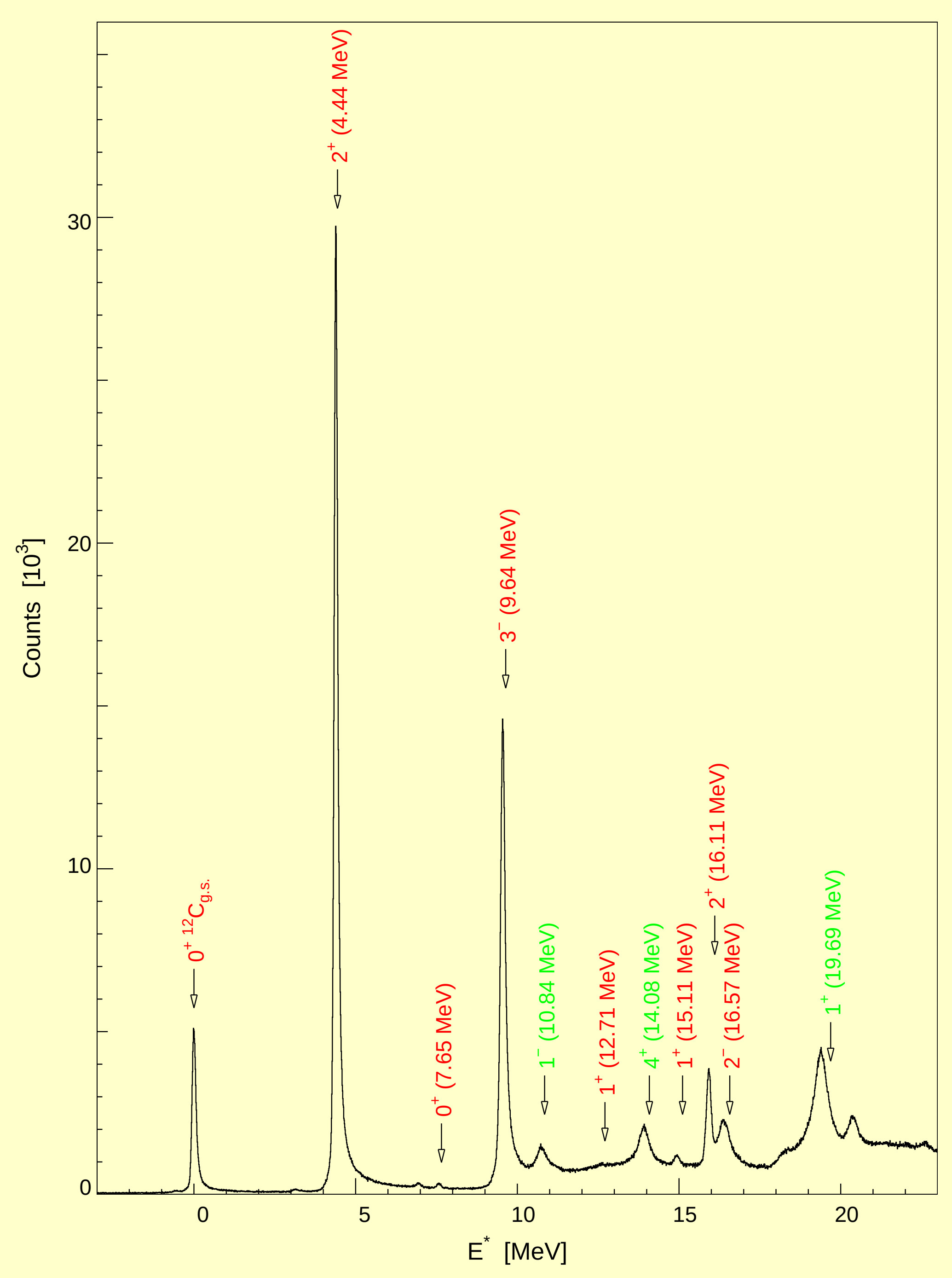
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\mathrm{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge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

Invariant mass of e^+e^- pair



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

Determination of the Mass Resolution

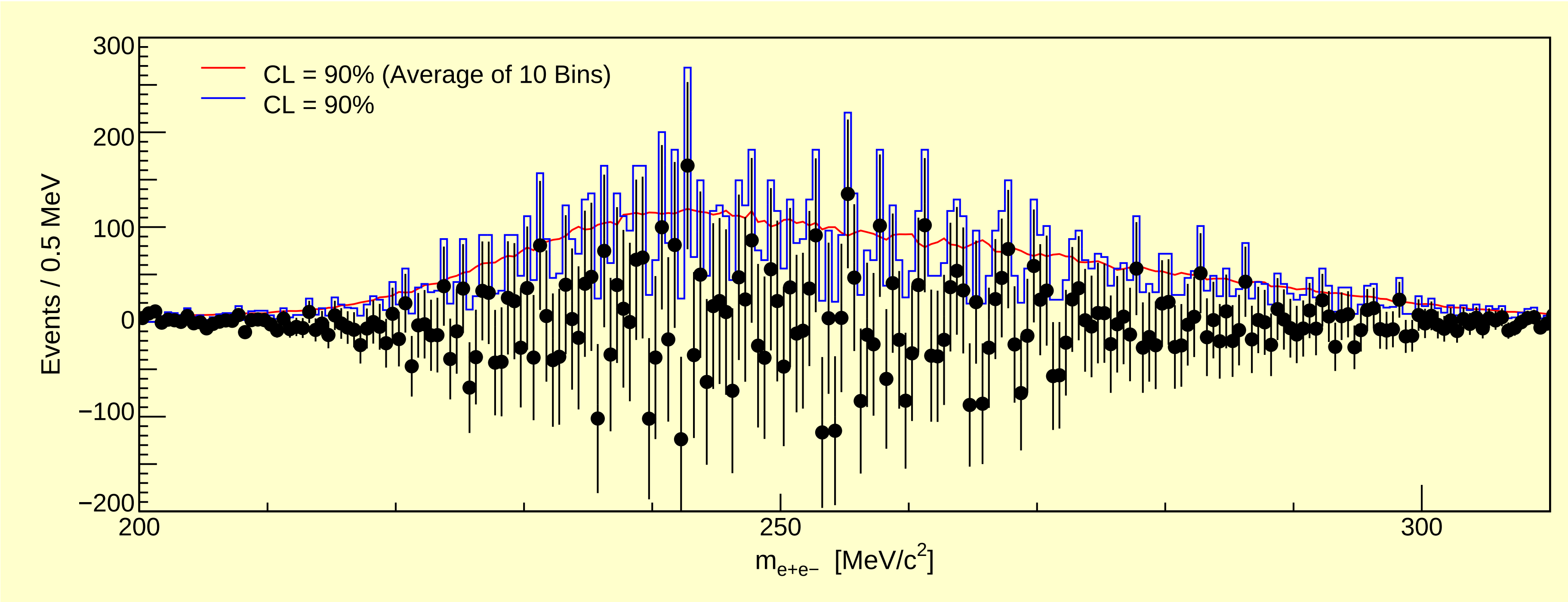


- Elastic Scattering
  - Natural width $\ll$ Resolution
  - Line width gives upper bound
  - $\delta p/p < 10^{-4}$ for Spectrometer
- Input to Full Simulation
  - Multiple Scattering $(-)$
  - Radiation correction $(-)$
  - Decay length $(+)$
  - Missing mass resolution $(+)$

$\Rightarrow$ $\delta m_{e^+e^-} < 0.5\,\mathrm{MeV}/c^2$ FWHM

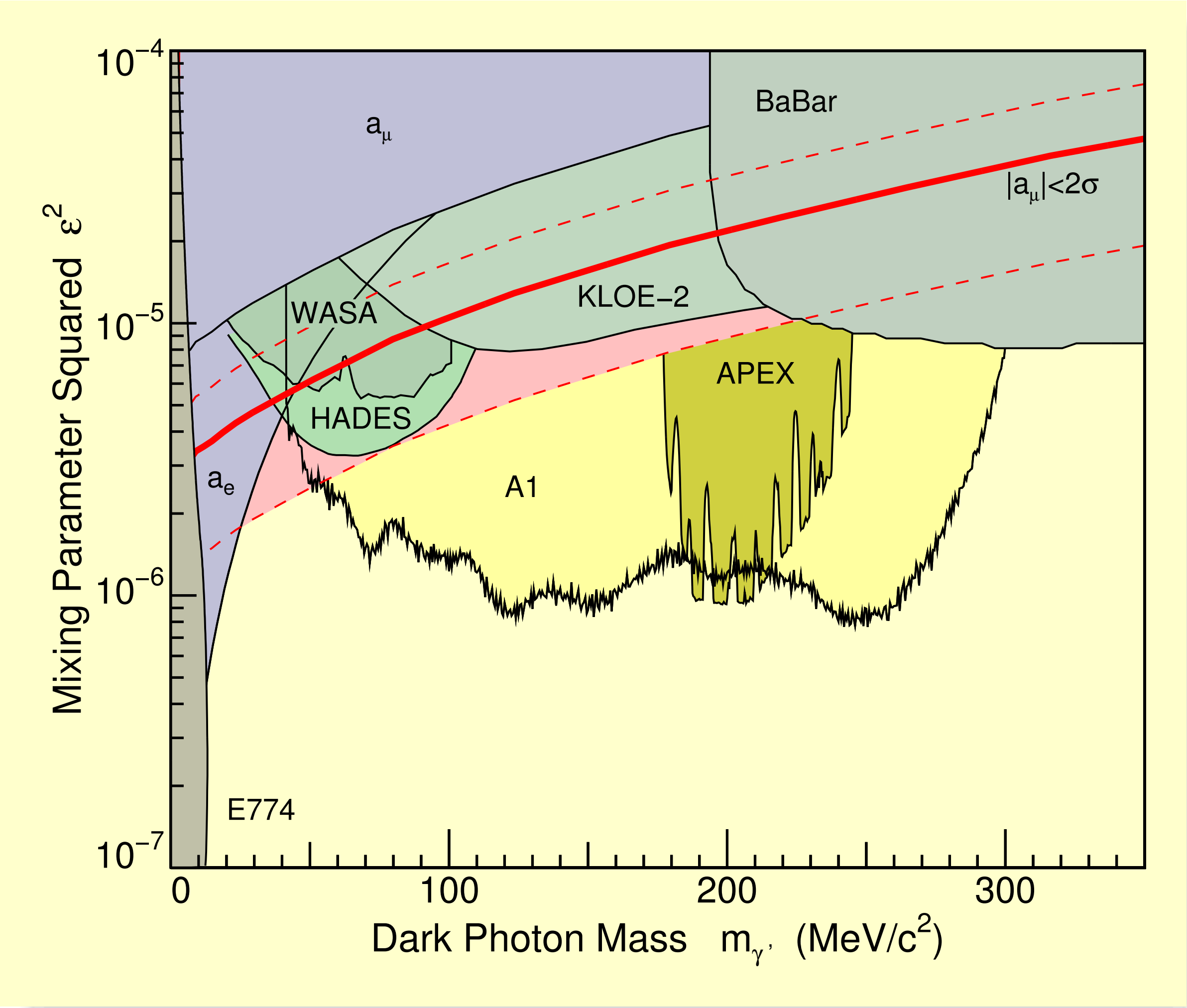
N.B.: Systematic error of $\delta m_{e^+e^-} < 10^{-3}$!

Exclusion limits



- Confidence interval by Feldman-Cousins algorithm
- “Model” for Background-subtraction:
  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”

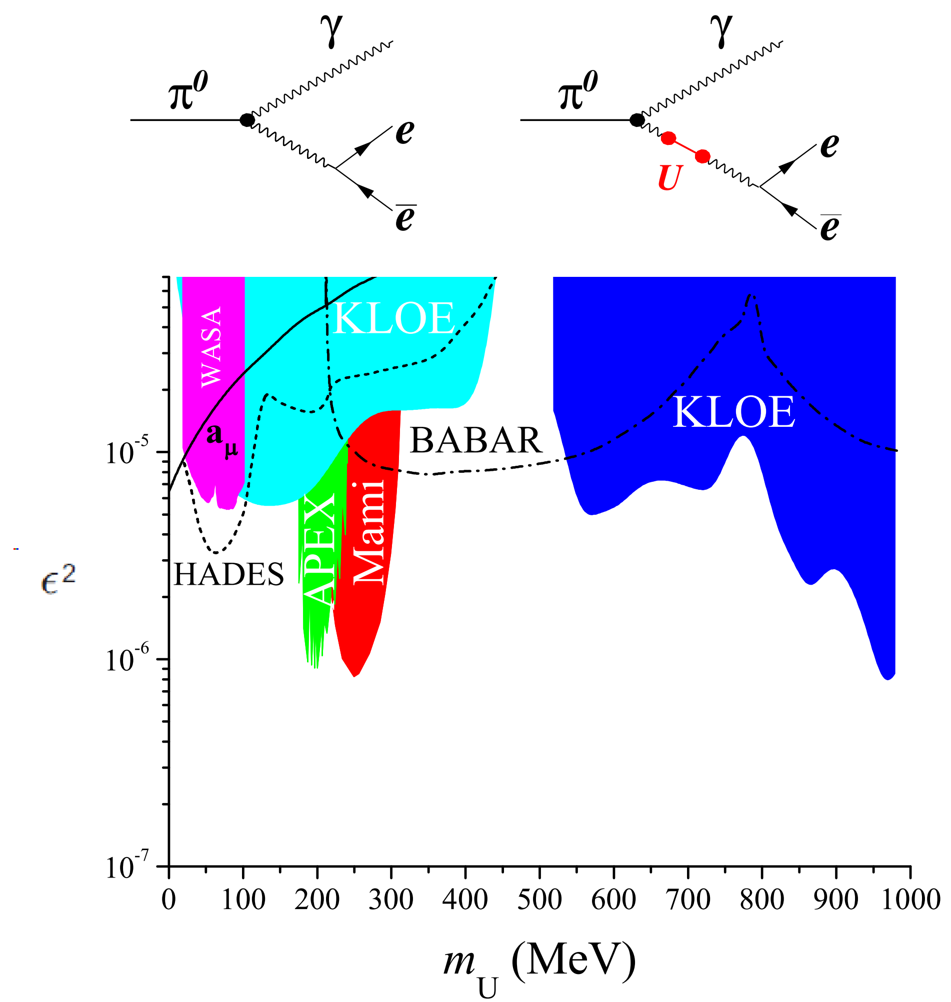
Exclusion limits MAMI 2014



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

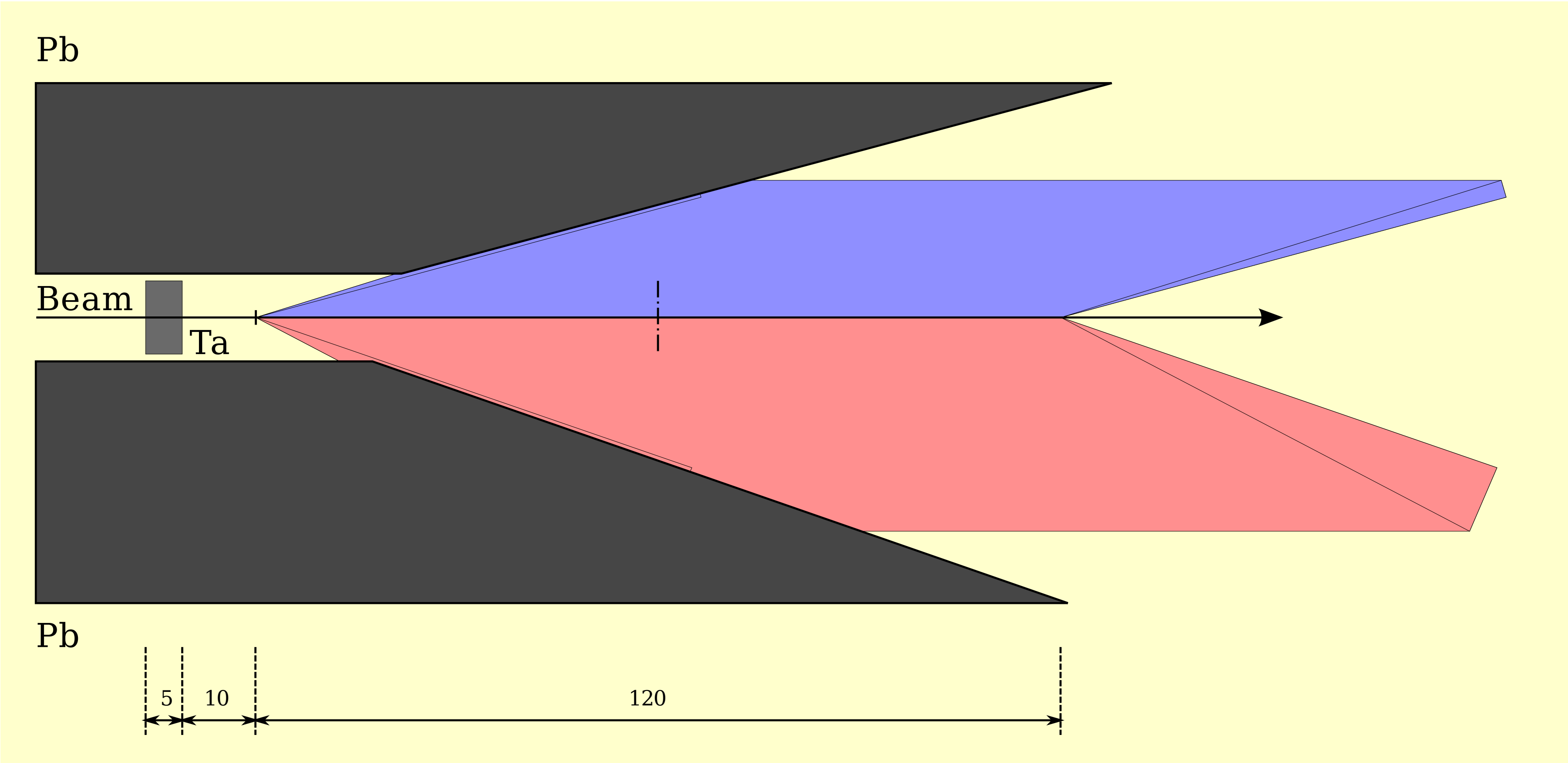
H.M. *et al.*, Phys. Rev. Lett. **112** (2014) (accepted for publication)

Limits from Meson Decays



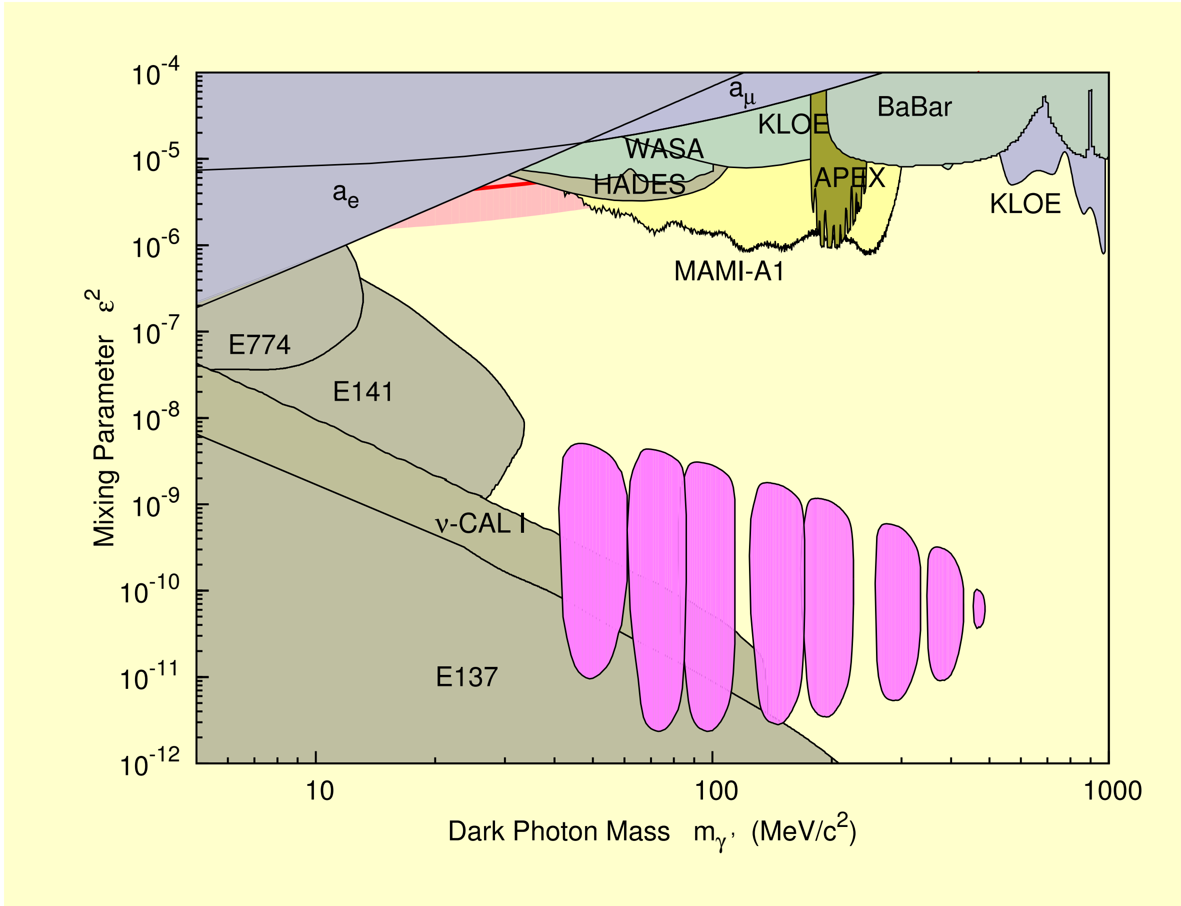
BaBar	$e^+e^- \to \Upsilon \to \mu^+\mu^-\gamma$	B. Aubert *et al.*, PRL 103, 081803 (2009)
KLOE-2	$\phi \to e^+e^-\gamma$	D. Babusci *et al.*, PLB 720 (2013)
WASA	$\pi^0 \to e^+e^-\gamma$	P. Adlarson *et al.*, PLB 726 (2013)
HADES	$p+p, p+Nb, Ar+KCl \to e^+ + e^-$	G. Agakishiev *et al.* PLB 731 (2014) M. Gumberidze, ‖ C
KLOE-2	$e^+e^- \to \mu^+\mu^-\gamma$	D. Babusci *et al.*, arXiv:1404.7772

Step 2: Secondary vertex → small coupling



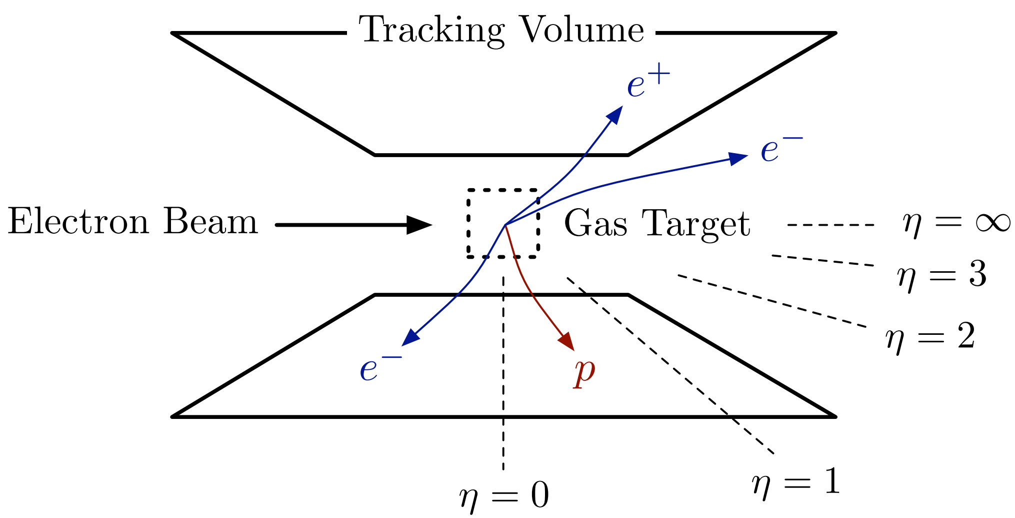
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm^2}}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

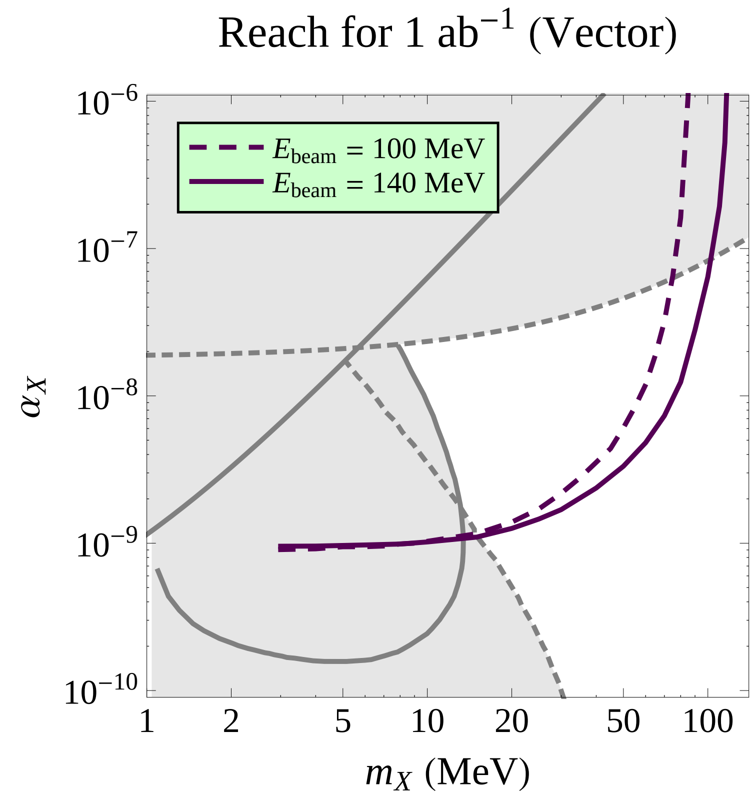
Step 2: Exclusion limits with shielded production vertex



- Macroscopic decay vertex distance $\varepsilon^2 < 10^{-8}$
- 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

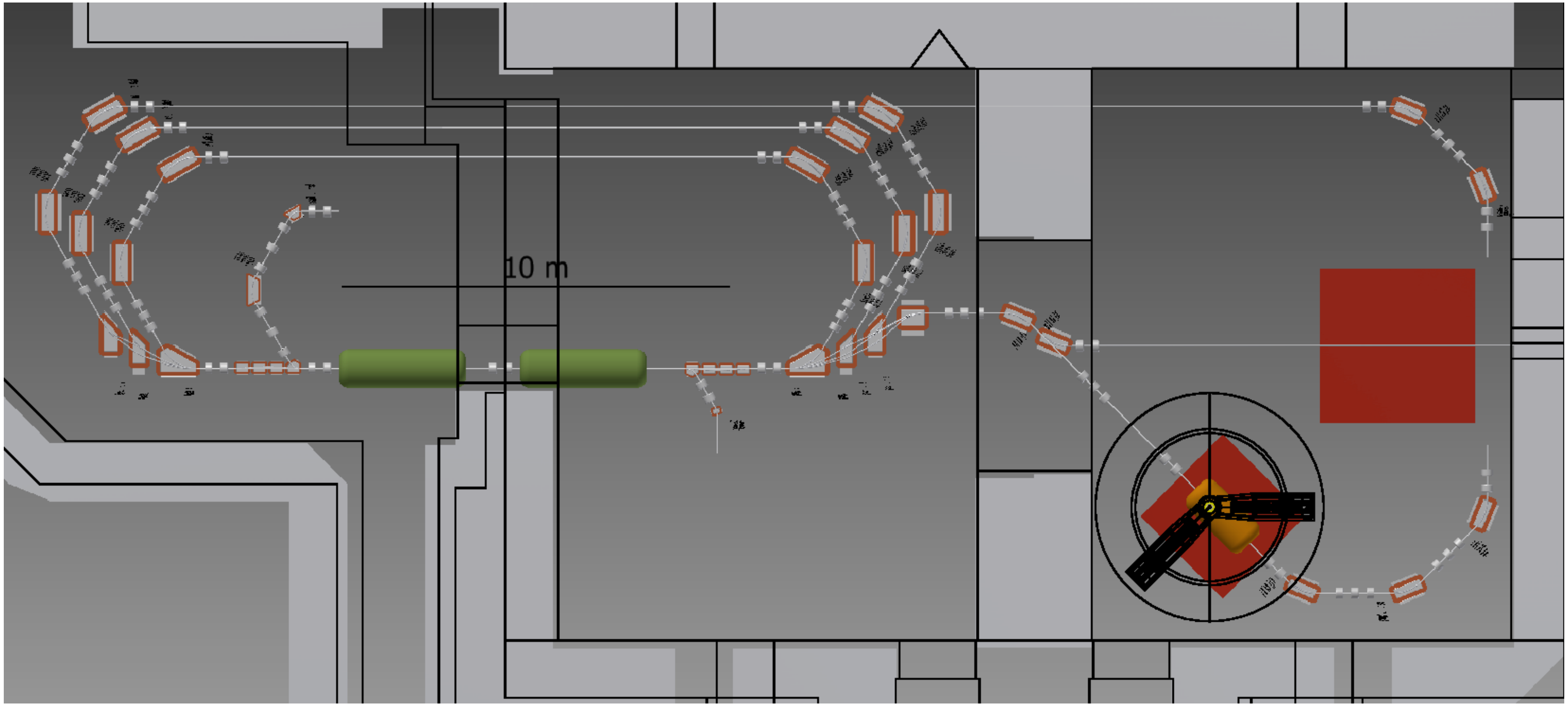




- Minimize multiple scattering by gas target
- Low energy – high current accelerator
- Needs 4π detector at 200 MHz count rate with high resolution
- DarkLight (JLab FEL)

M. Freytsis, G. Ovanesyan, J. Thaler, JHEP 01 (2010) 111

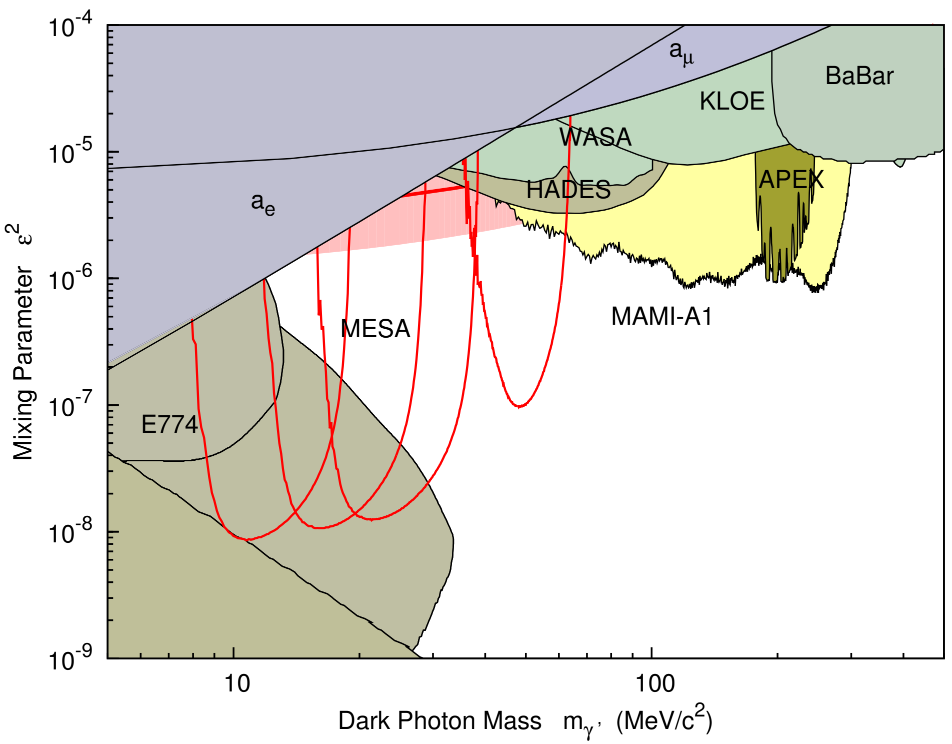
Step 3: Access to low mass region MESA Accelerator

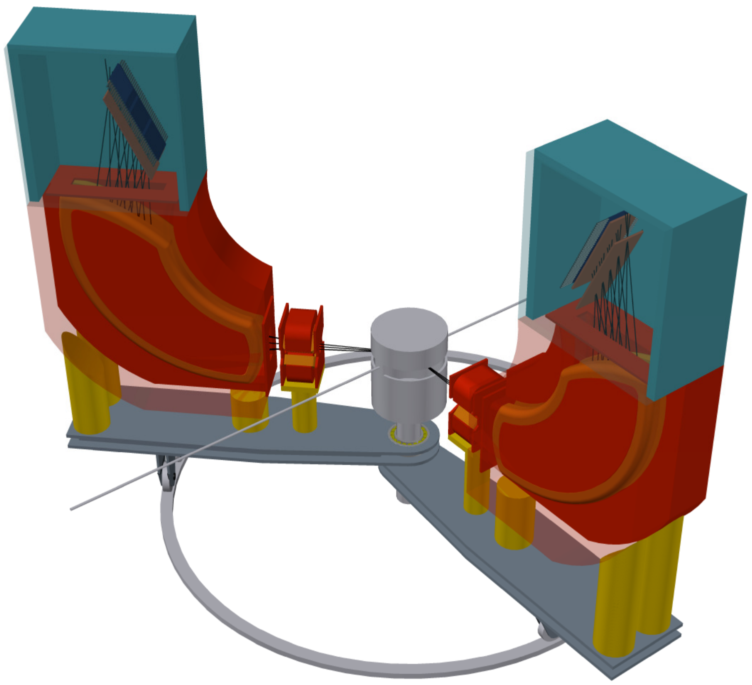


- Mainz Energy recovering Superconduction Accelerator
- up to 10 mA beam current
- Single pass accelerator ⇒ excellent beam quality
- $\Rightarrow L = 10^{35} \frac{1}{\mathrm{s\,cm}^2}$ with internal target

Step 3: Access to low mass region: MESA Accelerator

- 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 just finished
  - (polarized) internal target design
  - Focal plane detectors (> 1 MHz count rate at $50\mu m$)



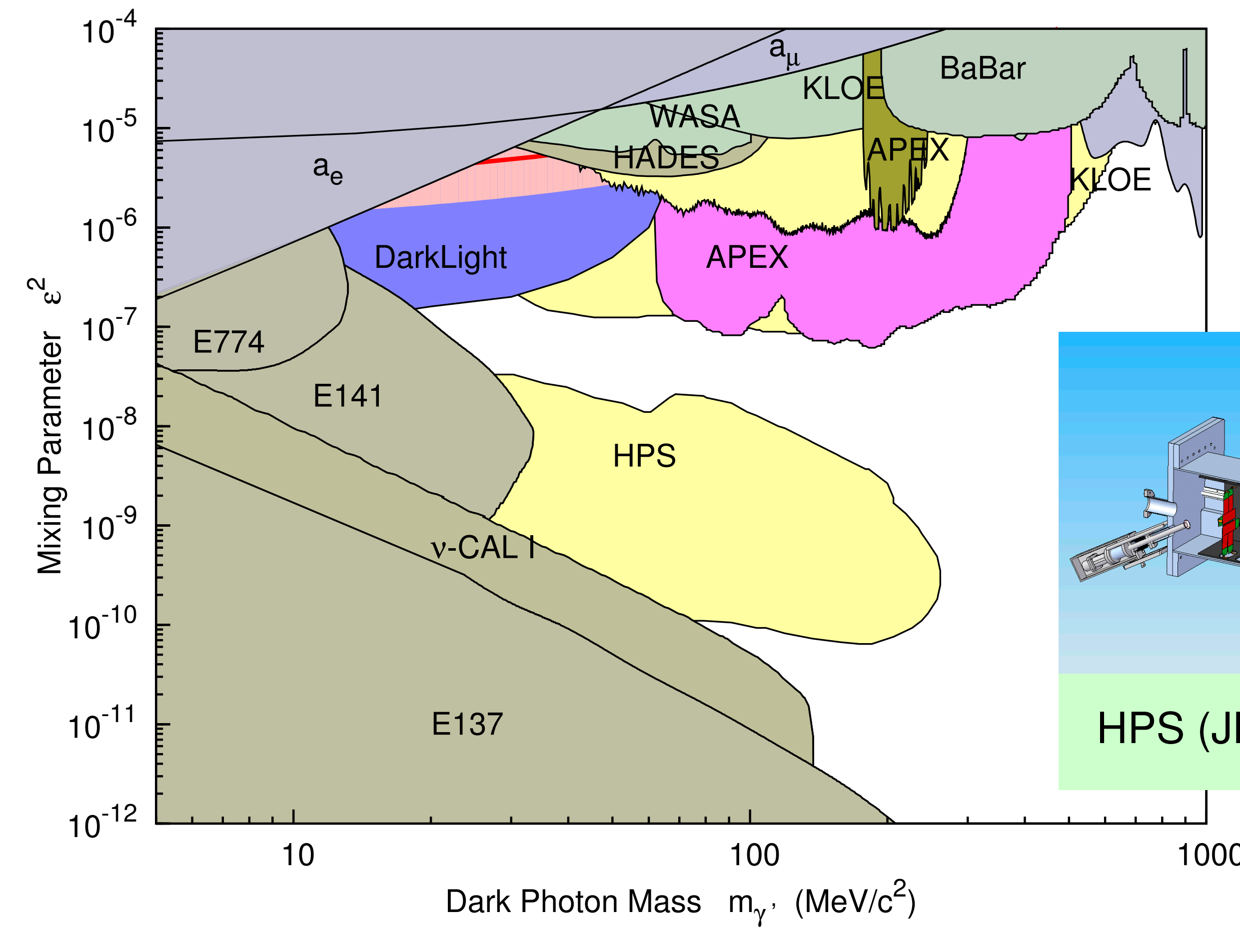


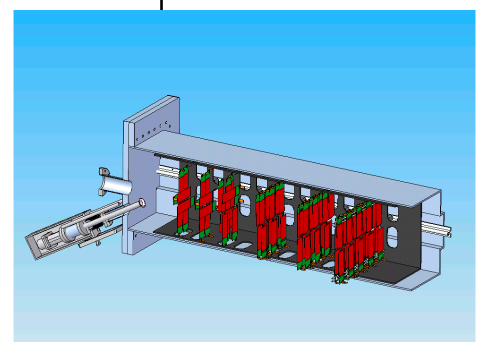
⇒ ideal for dark photon search!

JLab program

Dark Light (JLab FEL)
Freytsis *et al.* arXiv:0909.2862

APEX (JLab Hall A)

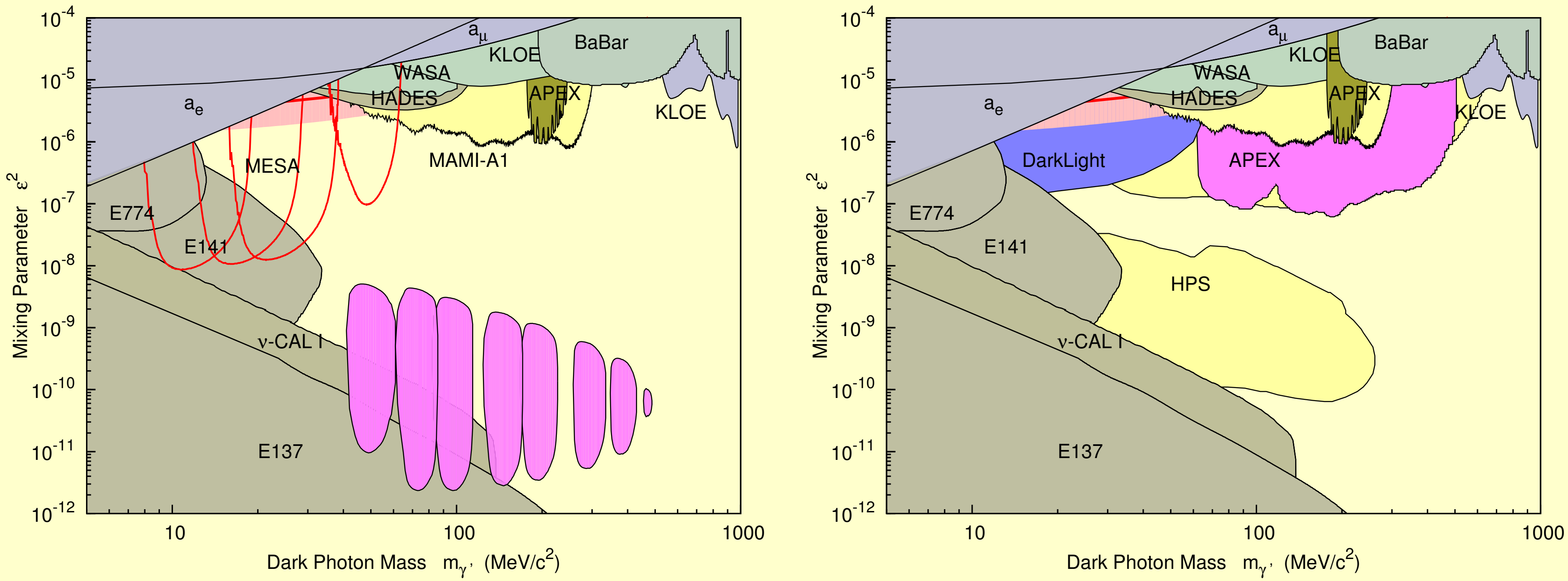




HPS (JLab Hall B)

APEX/HPS on high priority list!

Summary



- Well Motivated Extension of Standard Model
- Dedicated Fixed Target Experiments (MAMI, JLAB)
  - Pair production on heavy target $\varepsilon^2 > 10^{-6}$
  - Low energy – high current $m_{\gamma'} < 50\,\mathrm{MeV}/c^2$
  - Finite production vertex $10^{-10} < \varepsilon^2 < 10^{-8}$
- Limits from Meson Decays (BaBar, WASA, KLOE, HADES)

$\Rightarrow (g-2)_\mu$ will be decided soon, more limits are coming