Search for Gauge Bosons of the Dark Sector with Accelerators

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"Hadrons from Quarks and Gluons"
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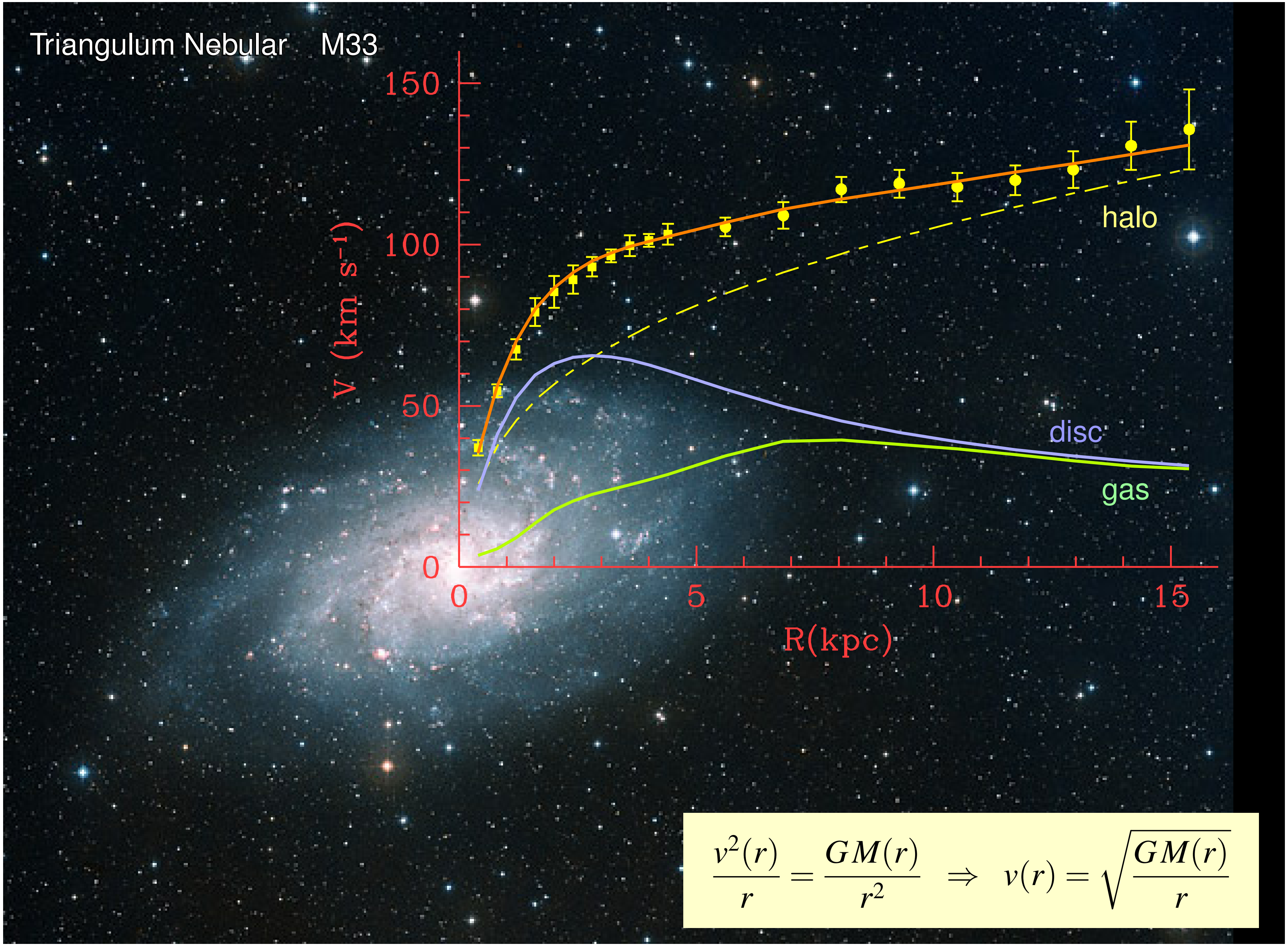
- Motivation
  - Evidence for Physics beyond the Standard Model
  - Candidates from Particle Physics
  - The γ' Boson
- How can we detect a "Dark Photon"?
  - Di-Lepton-Production
  - Cross sections
- Pilot Experiment at the Mainz Microtron (MAMI)
  - Experiment
  - Results
- Experimental program at MAMI and other electron facilities
- Summary

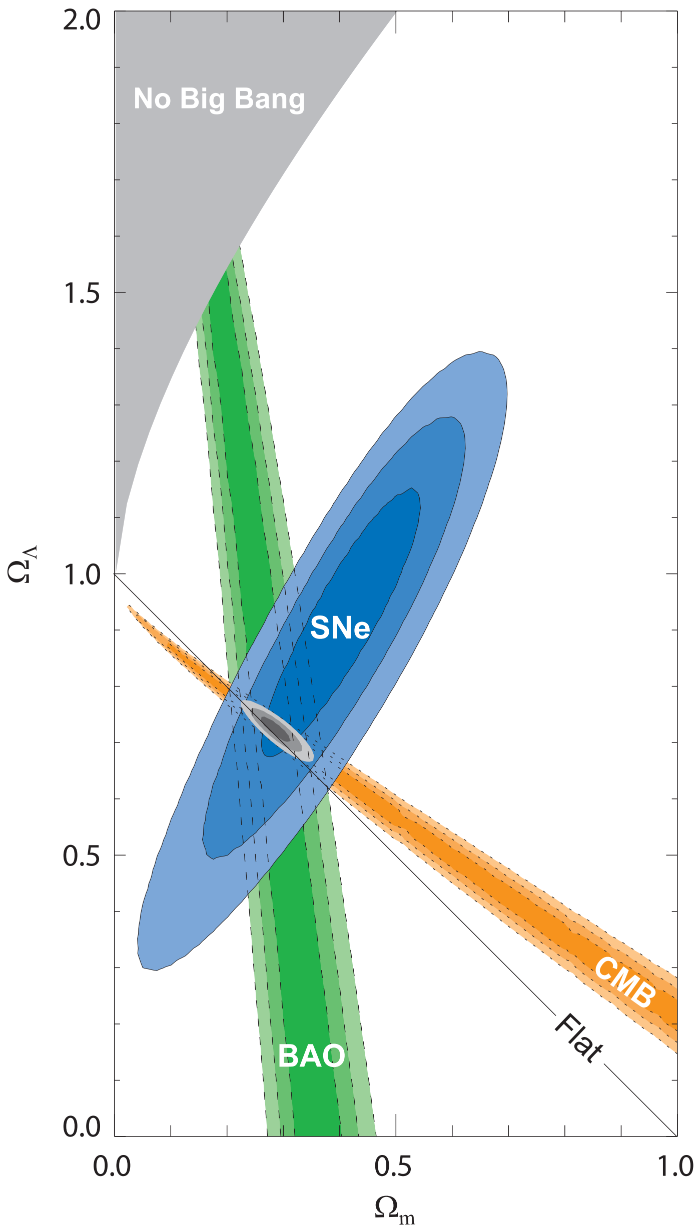
Rotation Curves of Galaxies



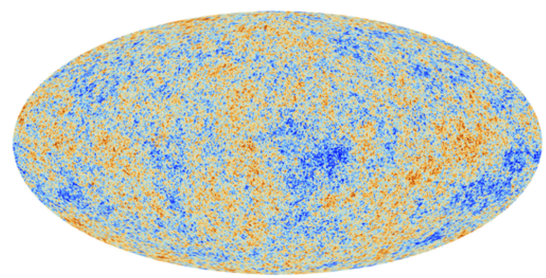
$$\frac{v^2(r)}{r} = \frac{GM(r)}{r^2} \Rightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

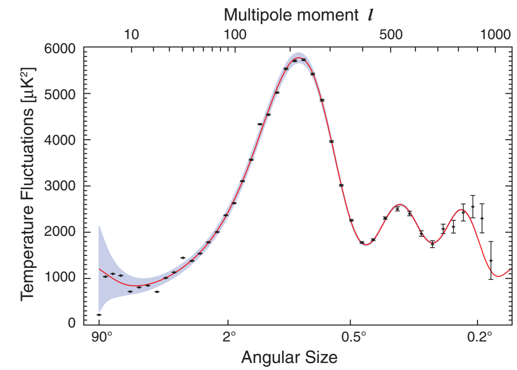
F. Zwicky, ApJ, 86 (1937) 217, E. Corbelli, P. Salucci, MNRAS 311 (2002), 441 – 447

Dark Matter in Cosmology

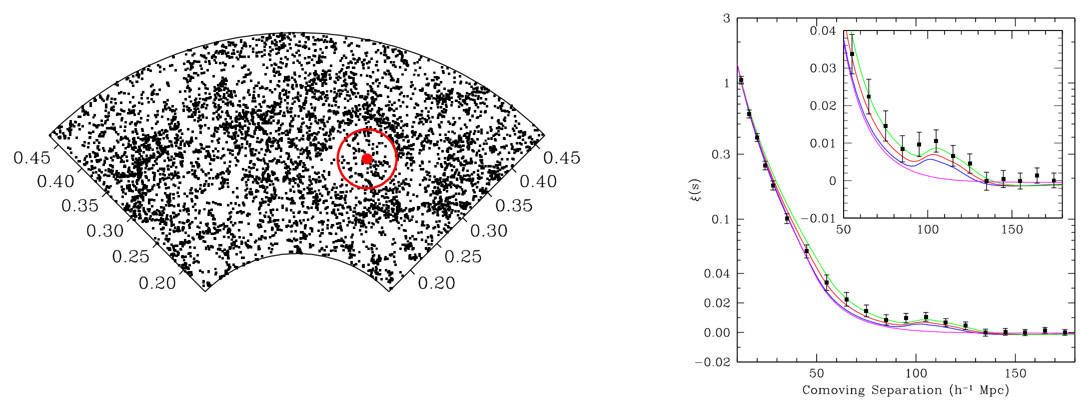


- Supernova Type Ia (SNe)
- Cosmic Microwave Background





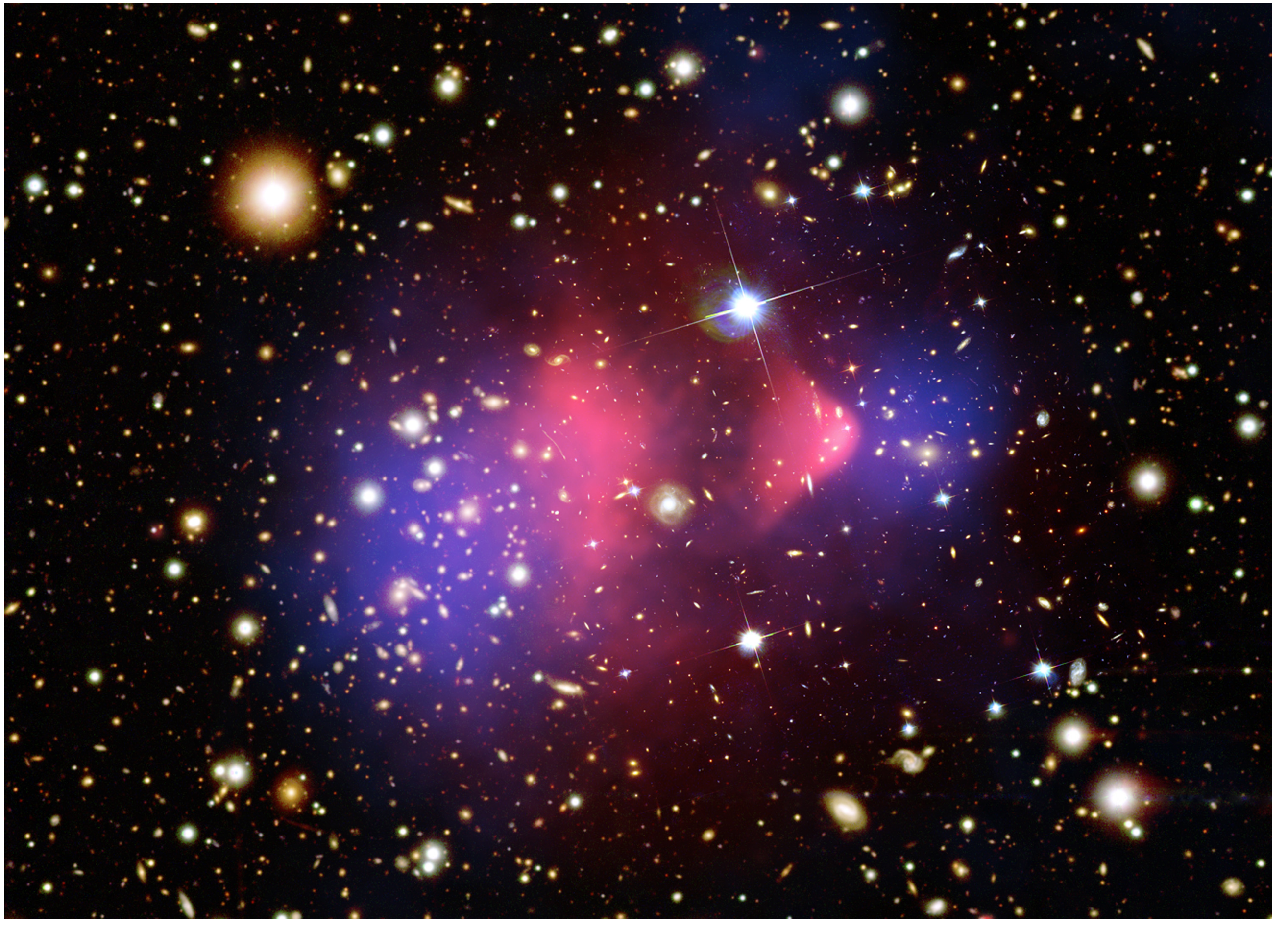
- Baryon Acoustic Oscillations

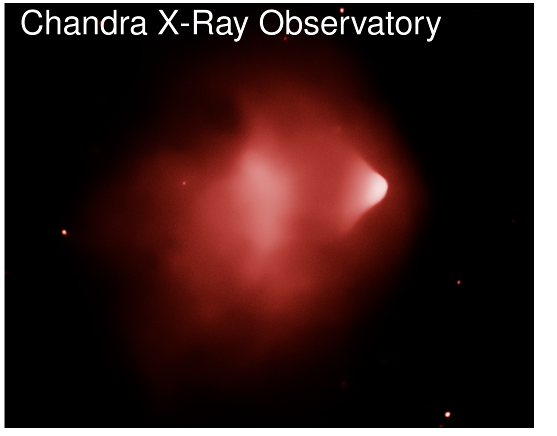


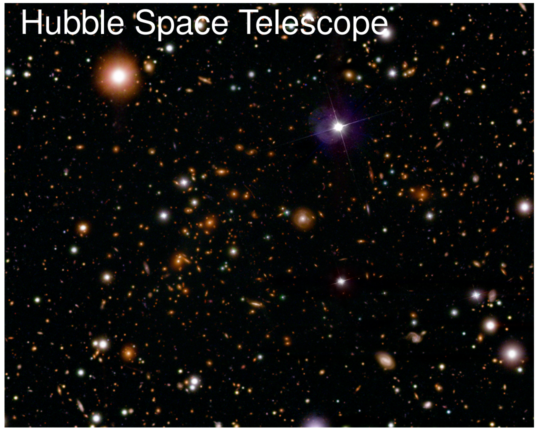
$$
\Rightarrow \quad \begin{array}{lll} \Omega_\Lambda & = 74\% & \text{Dark Energy} \\ \Omega_{CDM} & = 21\% & \text{Cold Dark Matter} \\ \Omega_b & = 4\% & \text{Baryonic Matter} \end{array}
$$

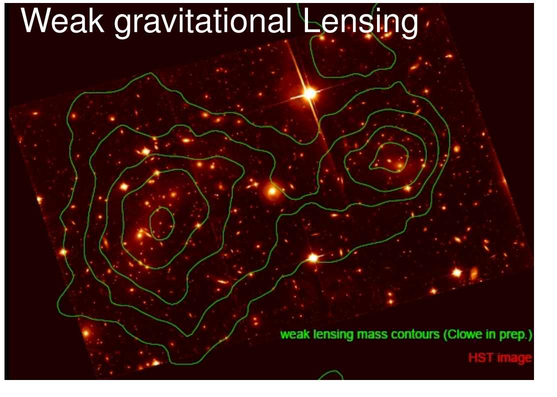
M. Kowalski *et al.* Ap.J. 686 (2008) 749
D. J. Eisenstein, *et al.*, ApJ 633 (2005), 560

Galaxy Cluster 1E 0657-56 “Bullet-Cluster”









- Visible Light: Stars (no collision)
- X-Rays: Intergalactic gas (Collision, e.m. shock waves)
- Gravitational Lens: Mass distribution (no collision)

$\Rightarrow$ Baryonic mass lags behind total mass

D. Clowe *et al.*, Ap. J. 648 (2006) L109

Dark matter candidates in particle physics

Properties:

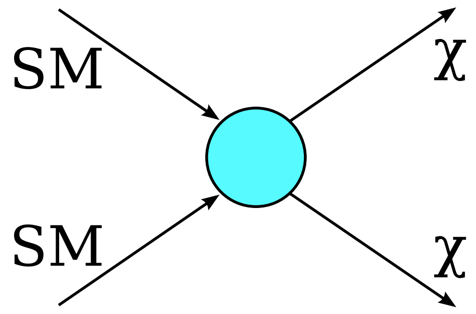
- Massive
- Slow (cold)
- Almost no interaction with standard model matter
- Produced during big bang

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, ...?

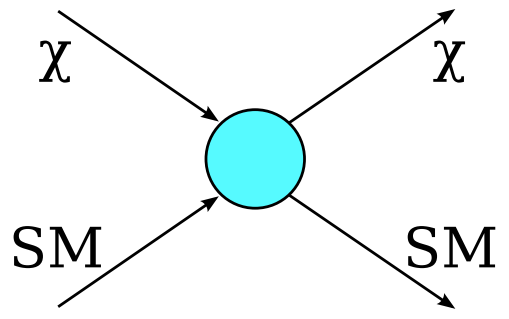
$\Rightarrow$ Hypothesis: dark matter is made of unknown particles

Conventional strategies for dark matter search in particle physics



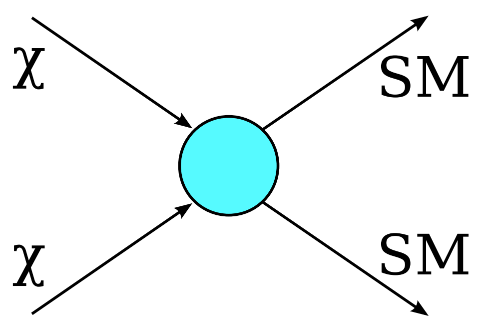
Direct Production:

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

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

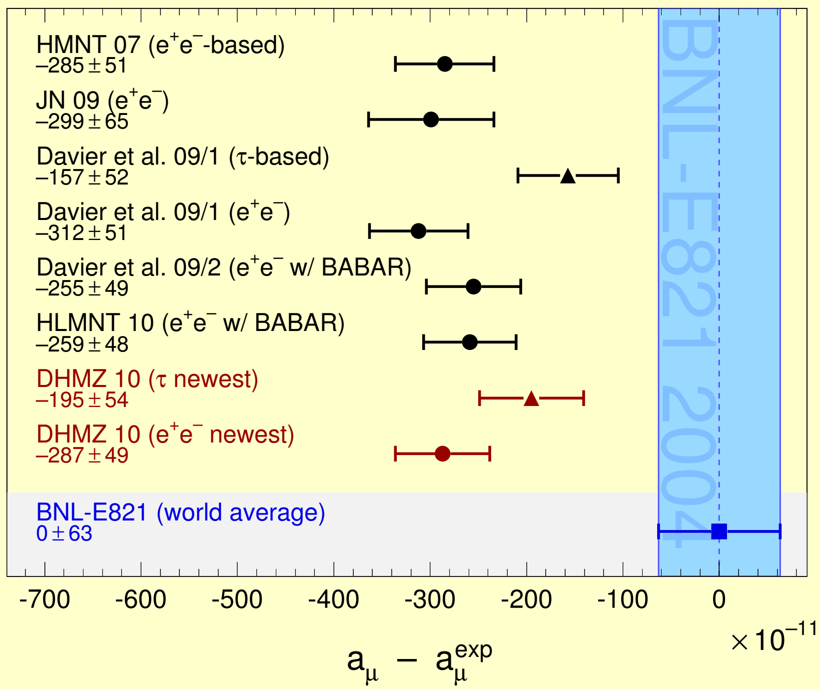
- Renormalization of Charge:
  $\Rightarrow$ Mixing Standard Model Charge – “dark” charge
- Parametrized by mixing parameter ε of γ'/γ mixing
- Boson mass $m_{\gamma'} > 0 \Rightarrow$ decay suppressed, *macroscopic* lifetime

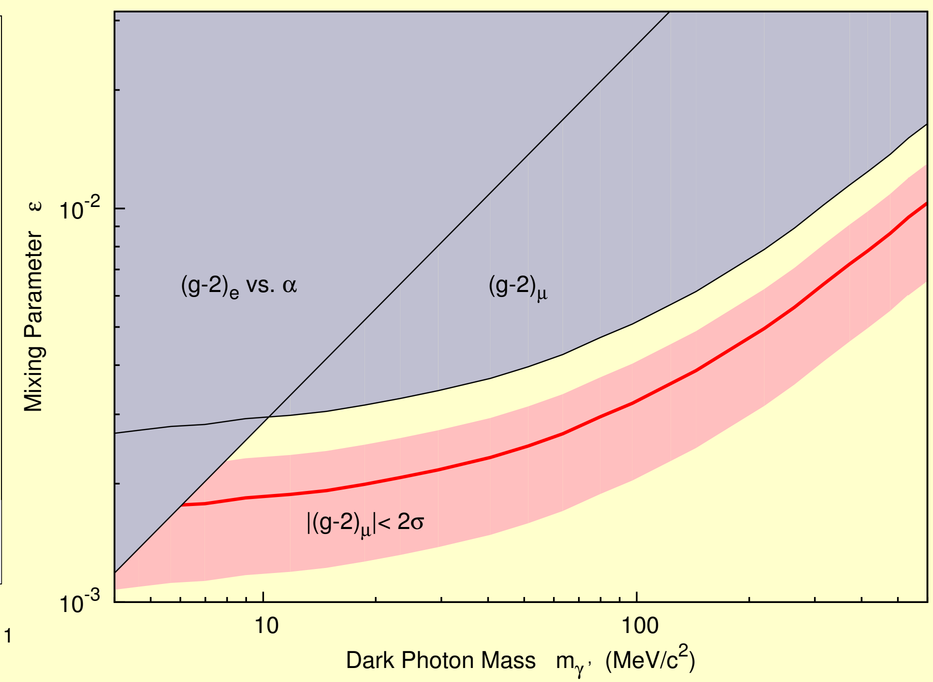
$\Rightarrow$ Look for χ at high energies
OR
Look for γ' at low energies (but small coupling)!

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'

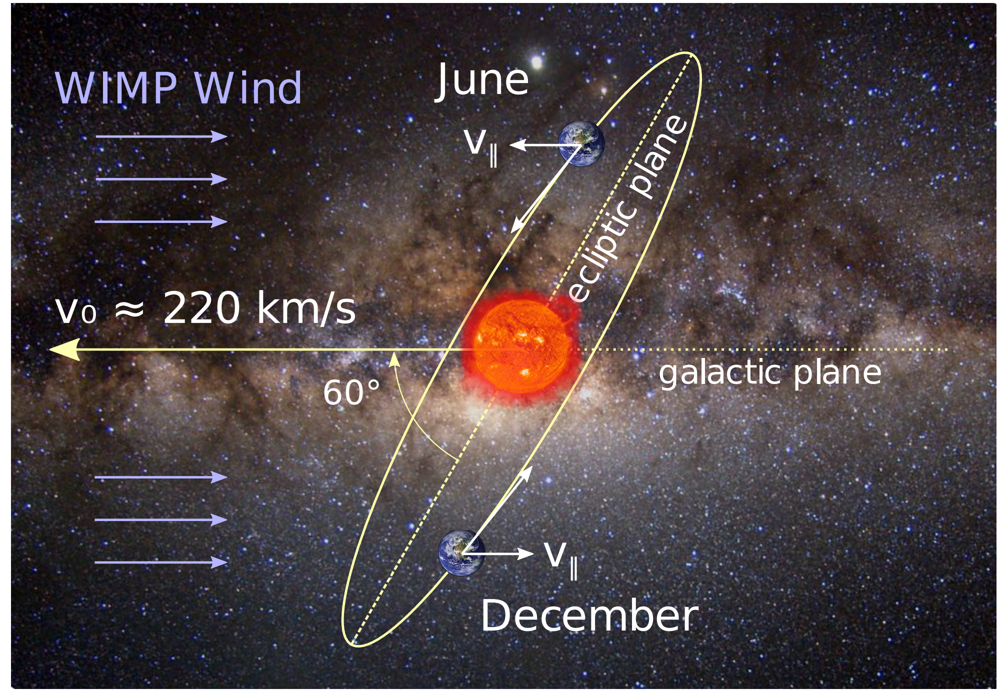
G. W. Bennet *et al.*, Phys. Rev. D 73, 072003 (2006)
M. Pospelov, Phys. Rev. D 80, 095002 (2009)

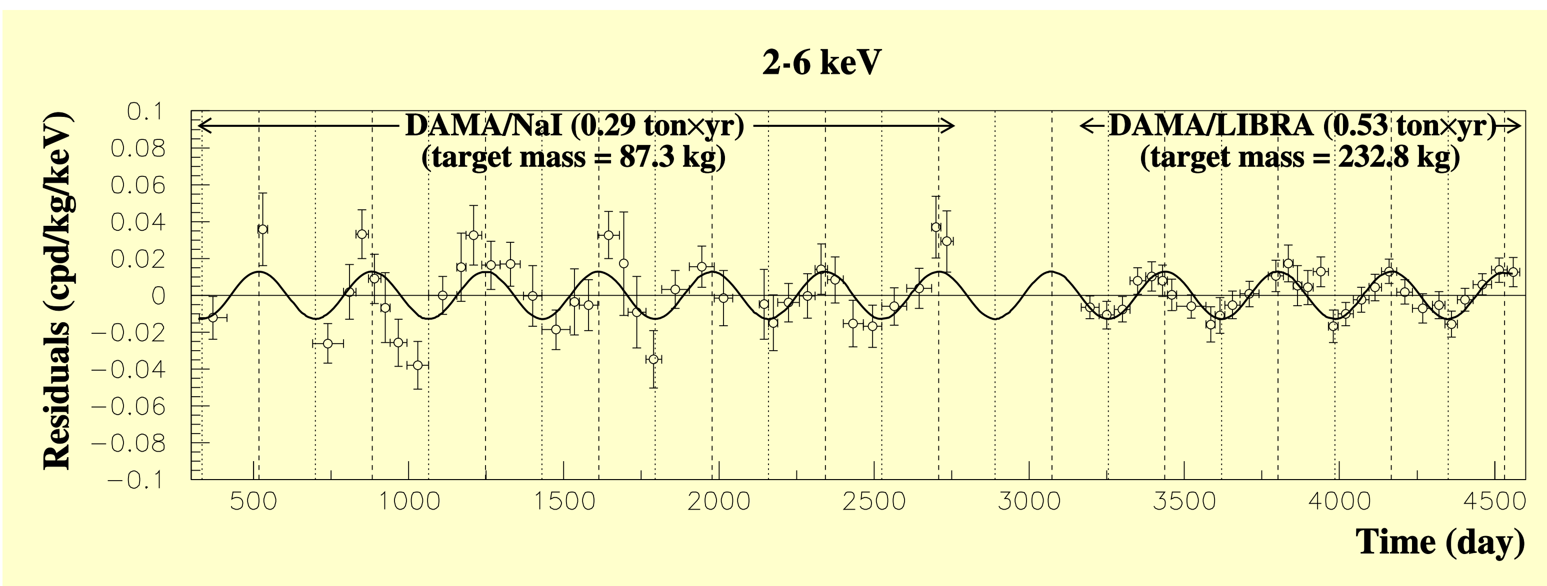
DAMA/NaI and DAMA/LIBRA

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

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

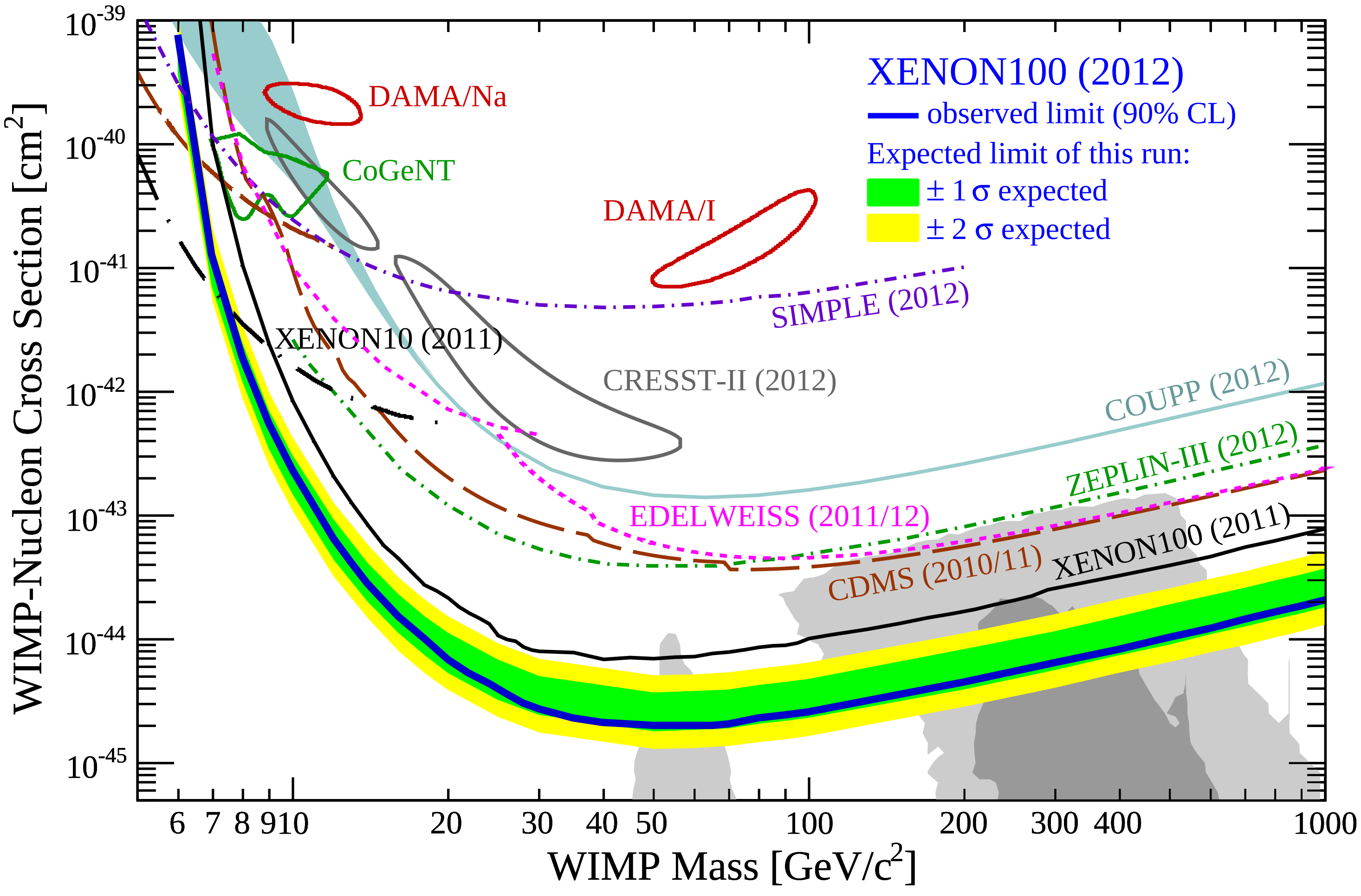
- Expected Phase: June 2nd ($t_0 = 152$)
- 8.2σ signal with $t_0 = 144 \pm 8$





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

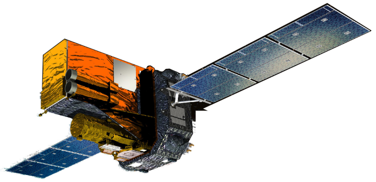
Problem: DAMA/LIBRA and the other experiments...

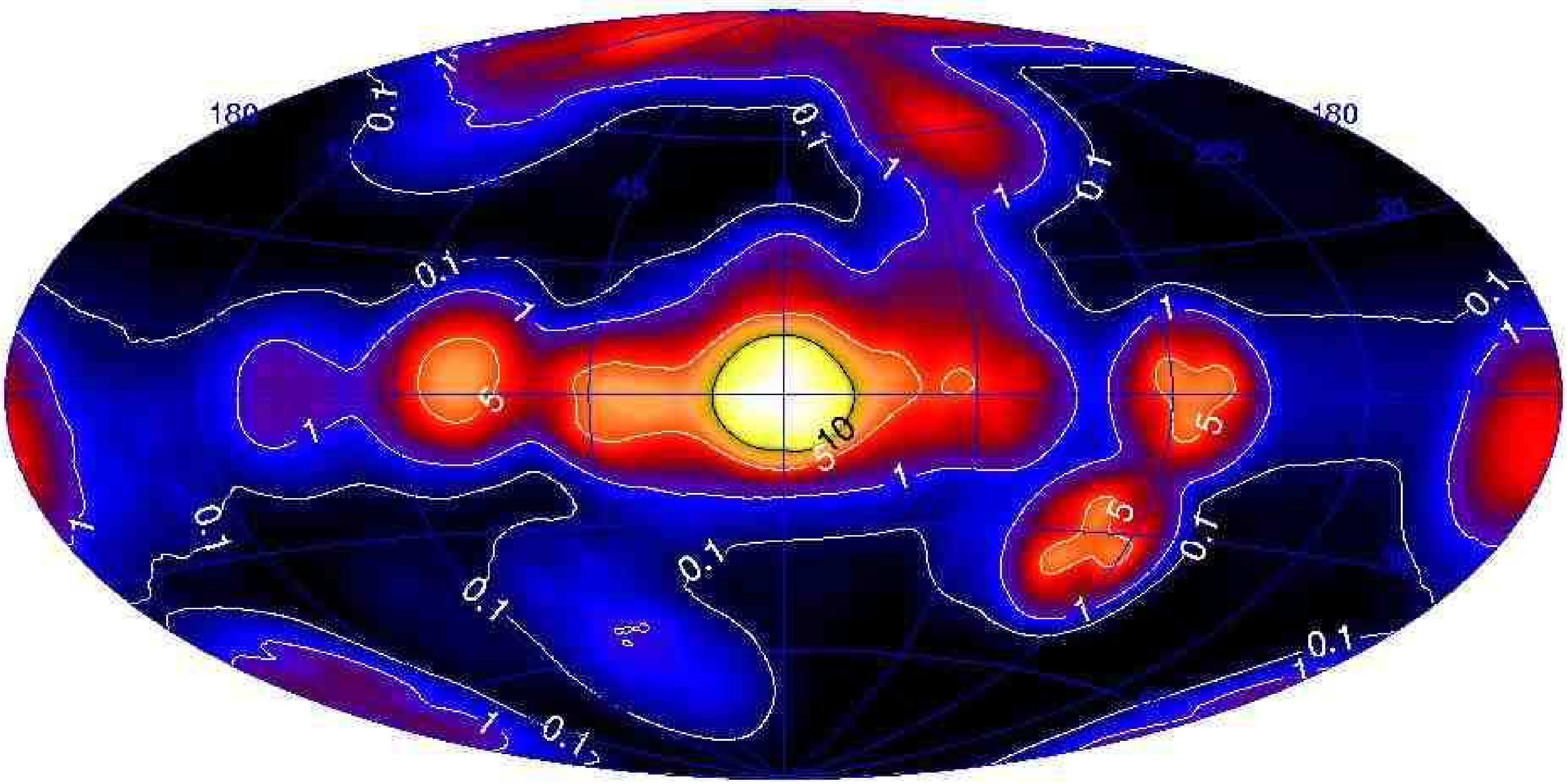


- Signals with annual modulation by DAMA and CoGeNT?
- XENON100, CDMS: coincidence experiments
- ⇒ Possible solution: reaction mechanism (electrons, excited DM)

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

SPI Spectrometer/INTEGRAL: 511 keV Gamma radiation

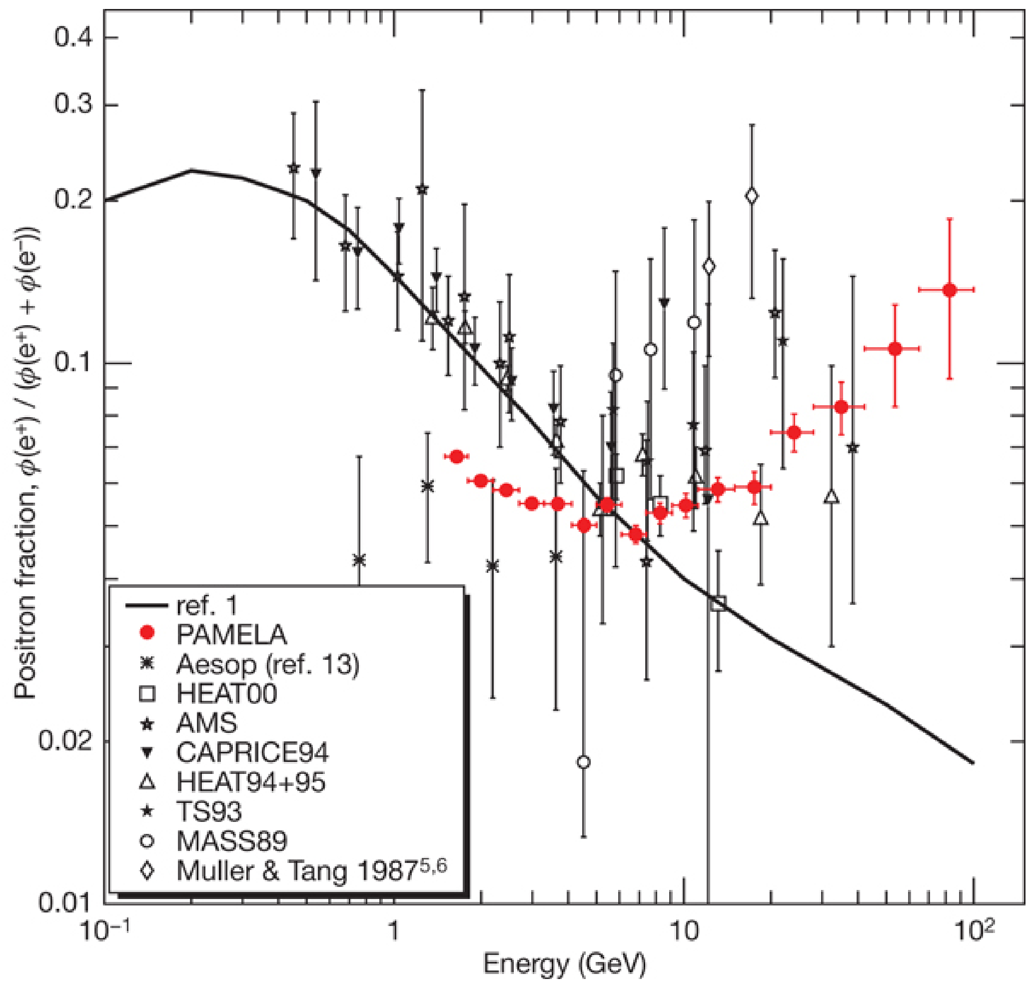




$\Rightarrow$ Positrons from annihilation $e^+ + e^-$

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

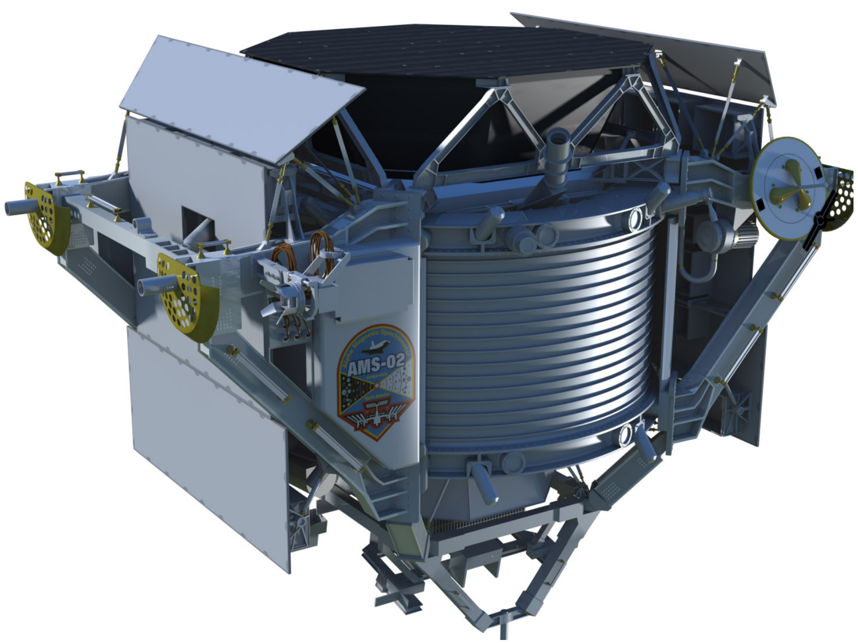
PAMELA: positron excess

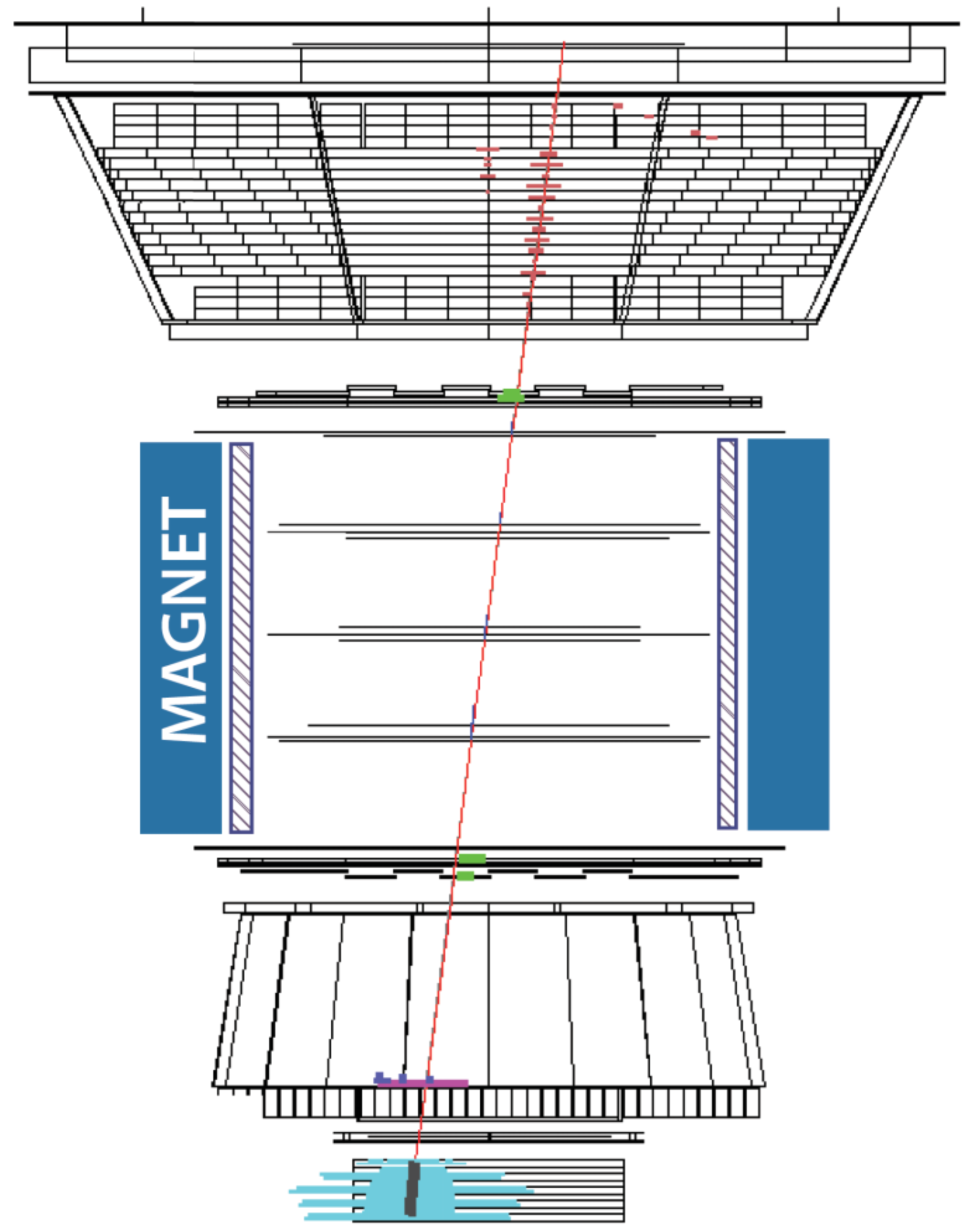


⇒ Excess of positrons for $E > 10\,GeV$

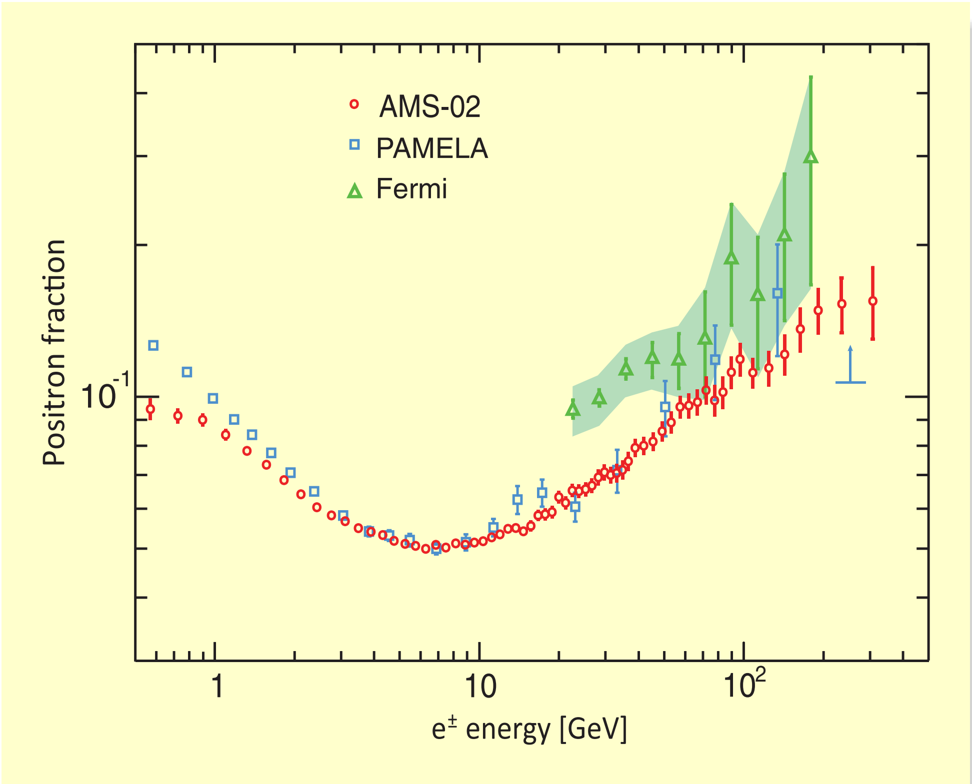
O. Adriani *et al.*, Nature 458, 607-609 (2009)

Alpha Magnetic Spectrometer (AMS-02) at the ISS

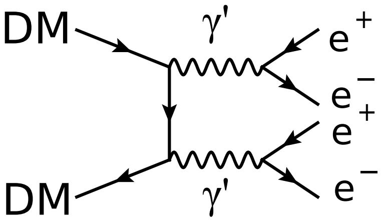




AMS-02: Positron Excess



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



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

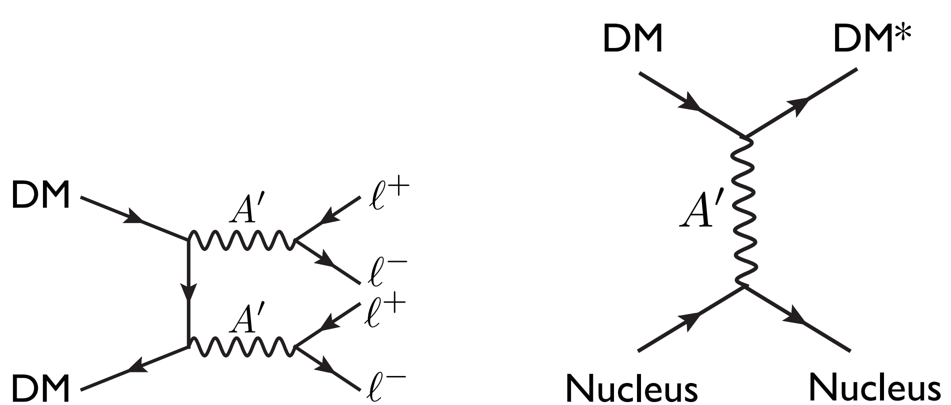
The γ' Boson (or A', ϕ, ...)

- $g-2$ 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

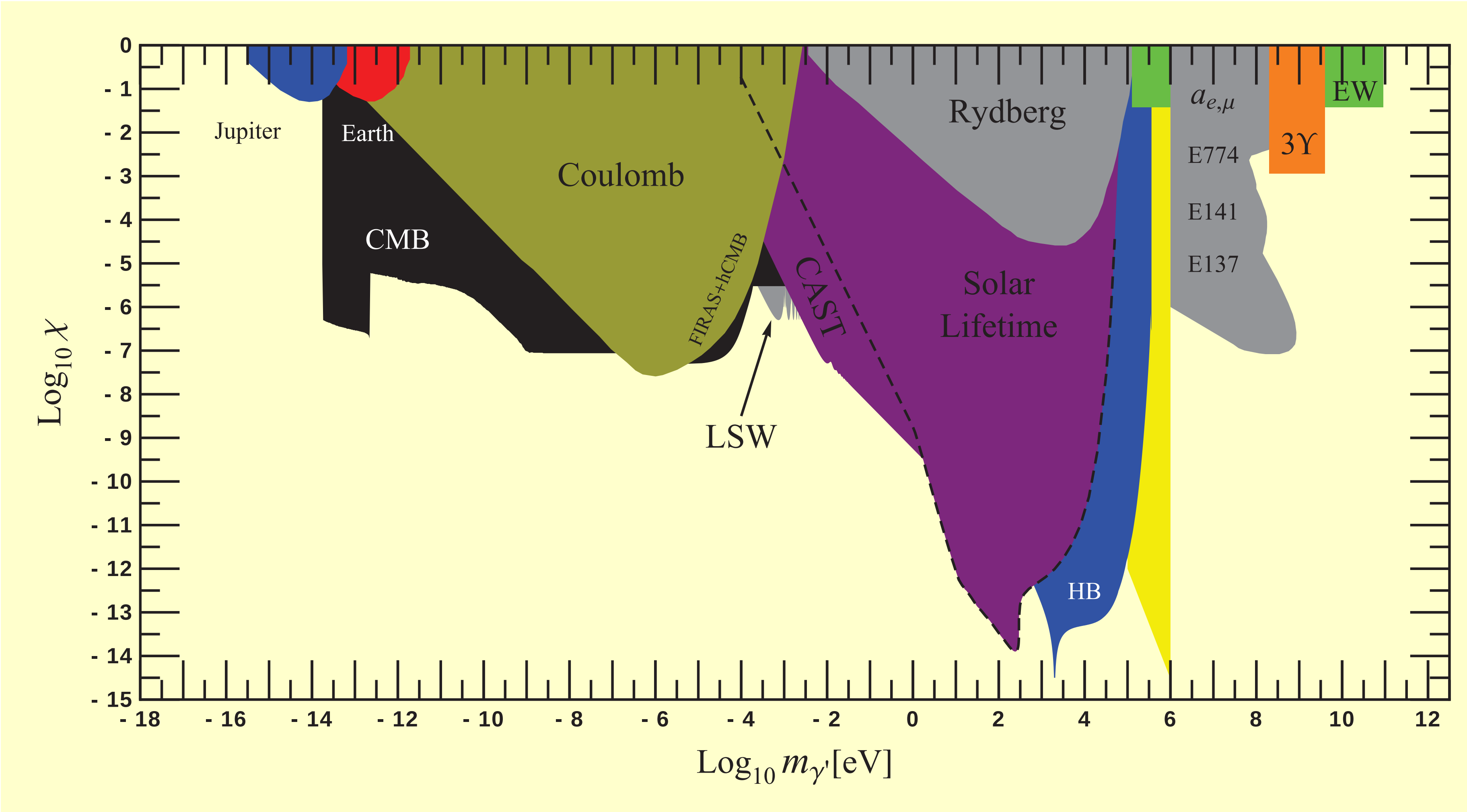
  $\Rightarrow$ Sommerfeld enhancement of cross section for low velocities
  - Large cross section in leptons
  - Small cross section in hadrons

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



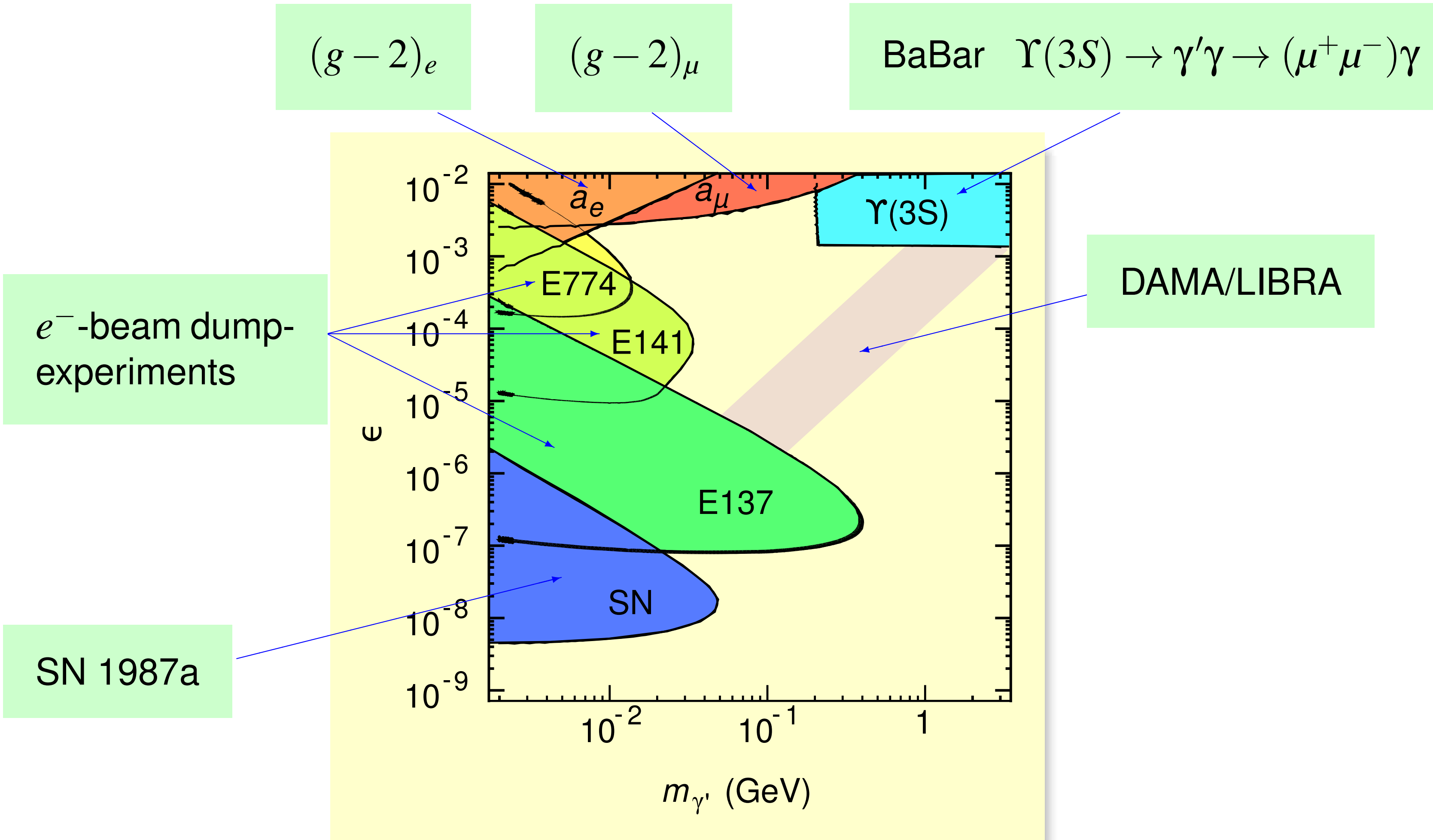
N. Arkani-Hamed, *et al.*, Phys. Rev. D 79 (2009) 015014

Existing bounds for dark photons



J. Jaeckel and A. Ringwald, Annu. Rev. Nucl. Part. Sci. (2010) 60:405-437

Parameter range for mass and coupling of γ' boson

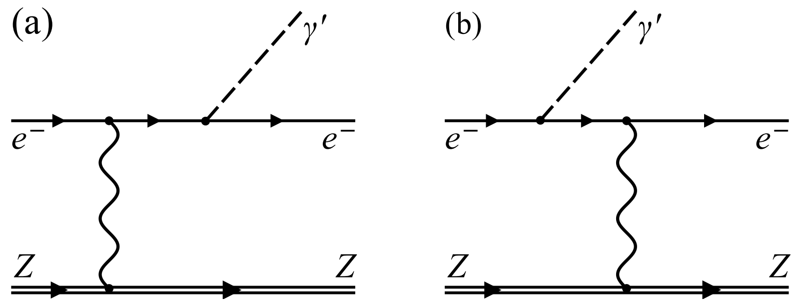


- Interesting range: $10^{-8} < \varepsilon < 10^{-2}$ $\quad 10\,\mathrm{MeV} < m_{\gamma'} < 1000\,\mathrm{MeV}$
- Energy range of MAMI!

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

Principle of Measurement

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

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

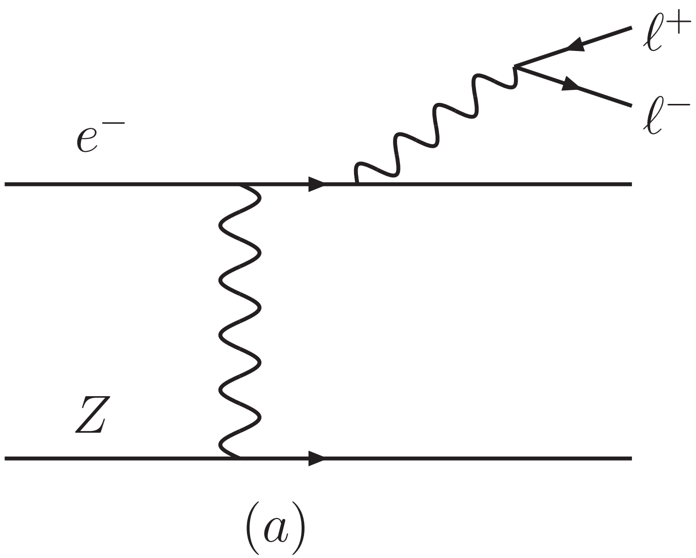
$$U(x,\theta_{\gamma'}) = E_0^2x\theta_{\gamma'}^2+m_{\gamma'}^2\frac{1-x}{x}+m_e^2x$$

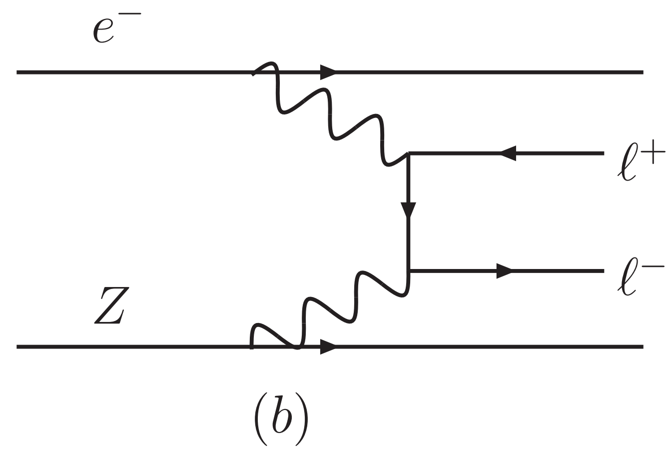
Lifetime:

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

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

Backgrounds



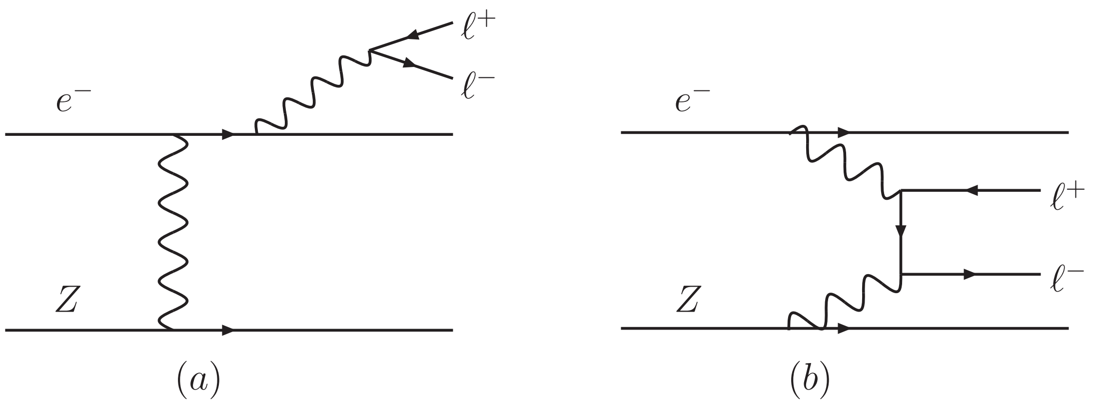


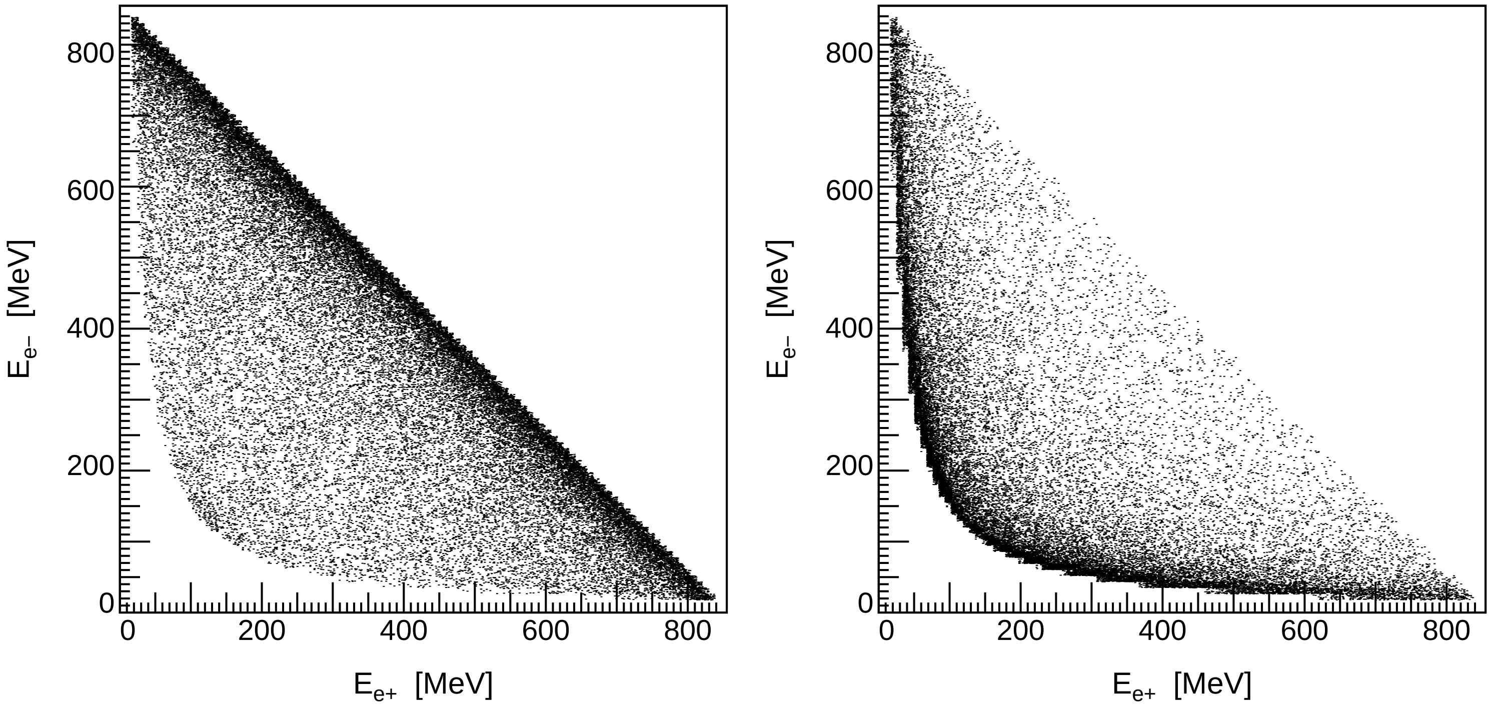
- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

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

Other backgrounds: measurement!

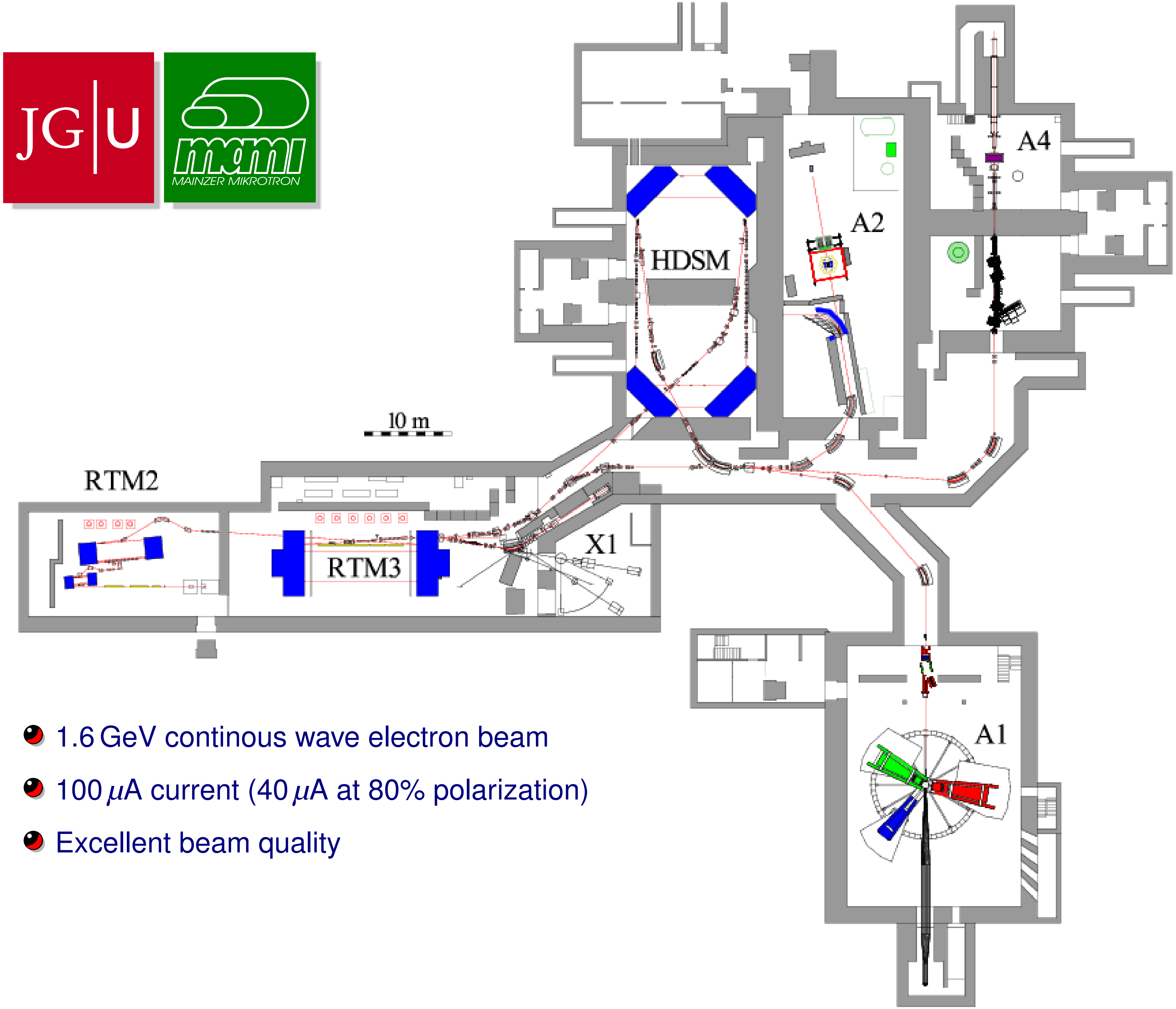
Bethe-Heitler Background





- 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:

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

Spectrometer B:

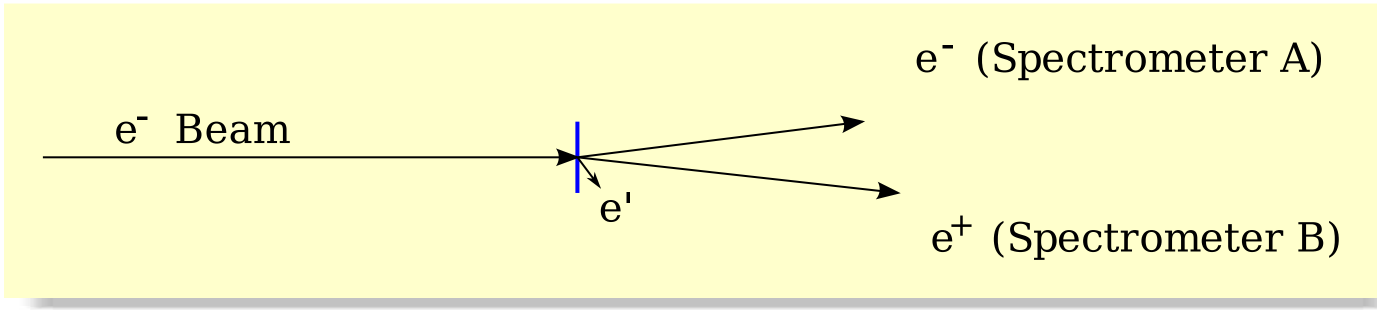
$$\begin{aligned} \alpha &> 8^\circ \\ p &< 870\,\frac{\mathrm{MeV}}{c} \\ \Delta\Omega &= 5.6\,\mathrm{msr} \\ \Delta p/p &= 15\% \end{aligned}$$

Spectrometer C:

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

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

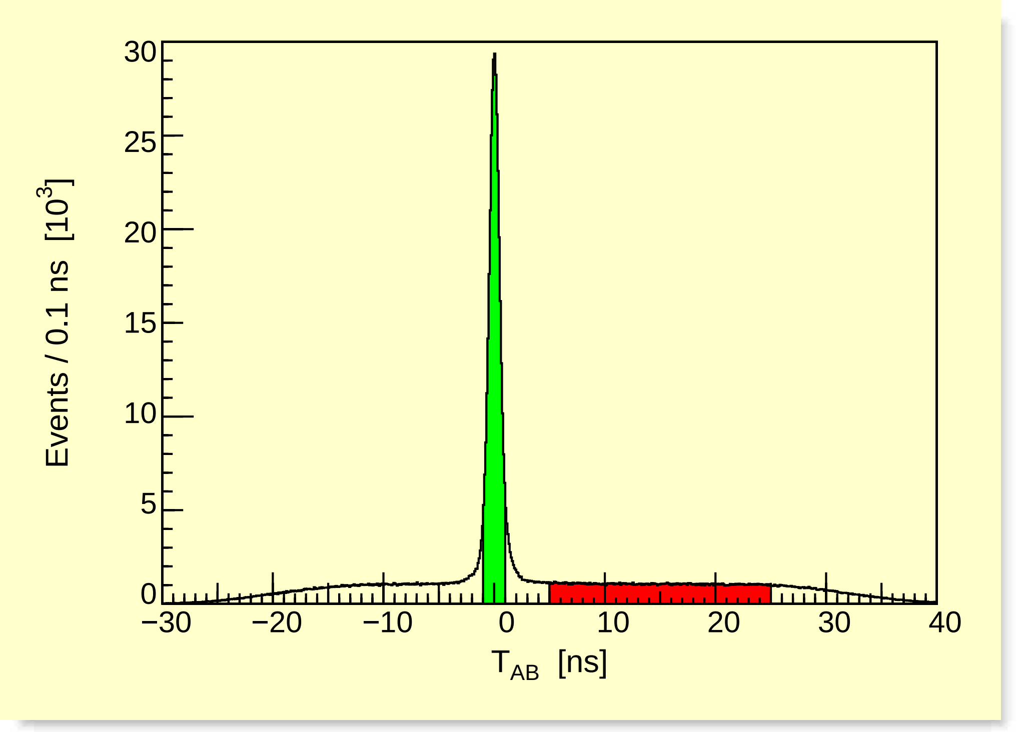
Pilot experiment



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

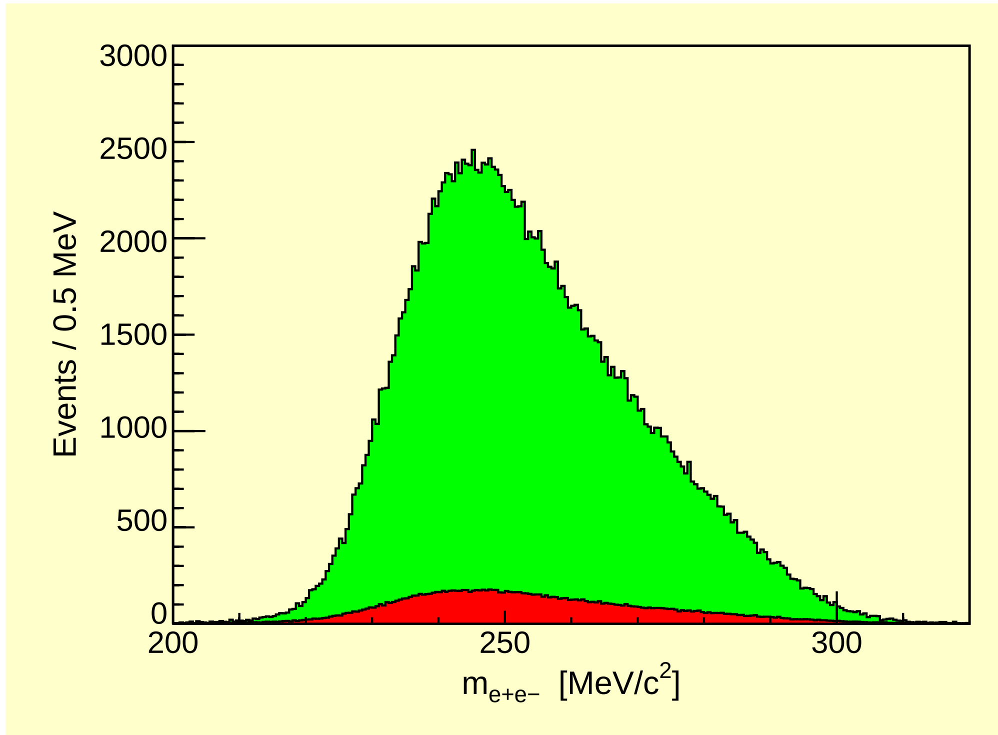
Beam energy	$E_0 =$	855.0 MeV
Spectrometer A	$p_{e^-} =$	338.0 MeV/c
	$\theta_{e^-} =$	22.8 $^\circ$
Spectrometer B	$p_{e^+} =$	470.0 MeV/c
	$\theta_{e^+} =$	15.2 $^\circ$

Reaction identification: coincidence time



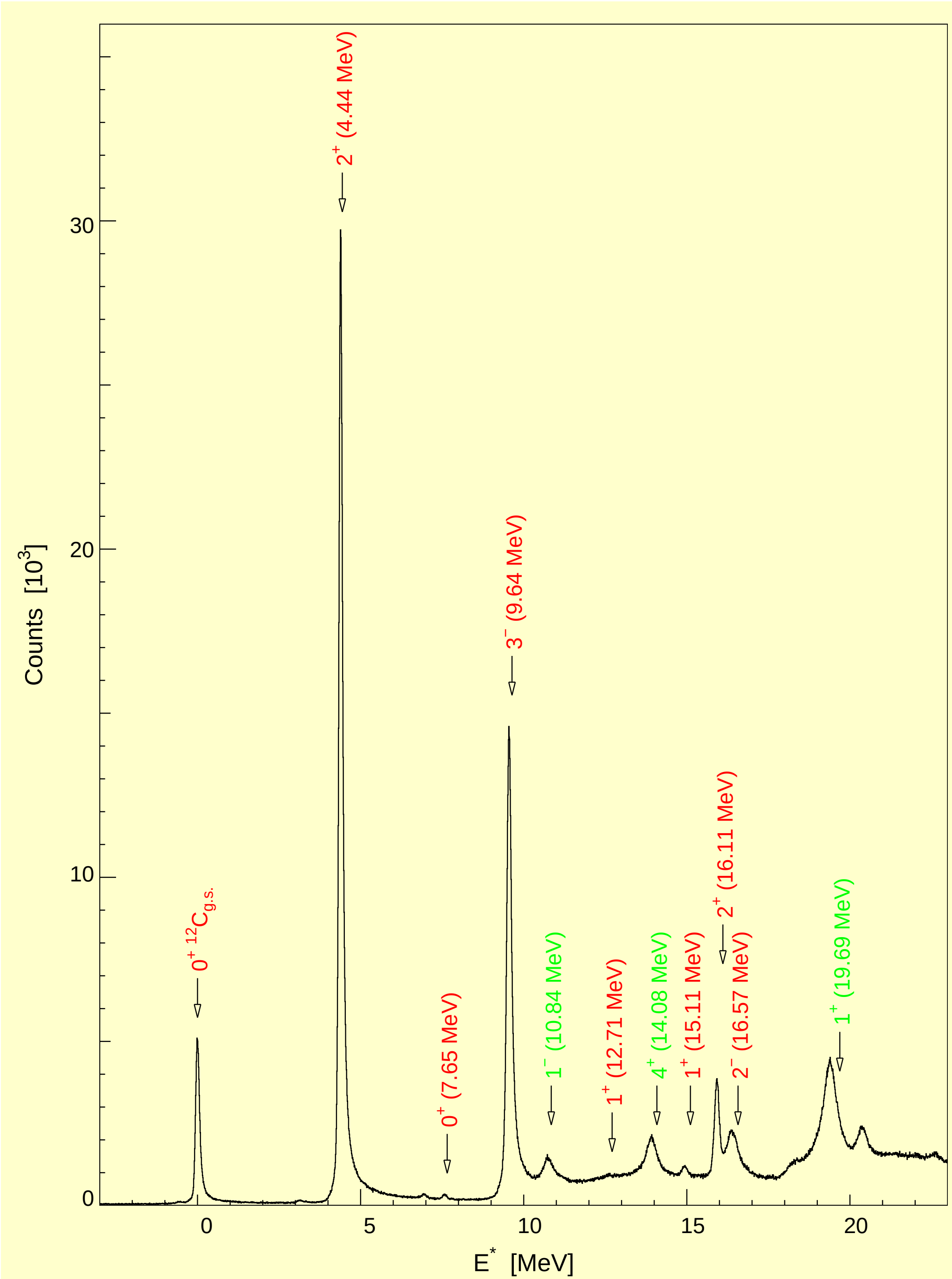
- Particle identification e^+, e^- by Cerenkov detectors
- Correction of path length in spectrometers $\approx 12\,\mathrm{m}$
  $\Rightarrow$ Time-of-Flight reaction identification
- Coincidence time resolution $\approx 1\,\mathrm{ns}$ FWHM
- Estimate of background: side band $5\,\mathrm{ns} < T_{A\wedge B} < 25\,\mathrm{ns}$
- 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

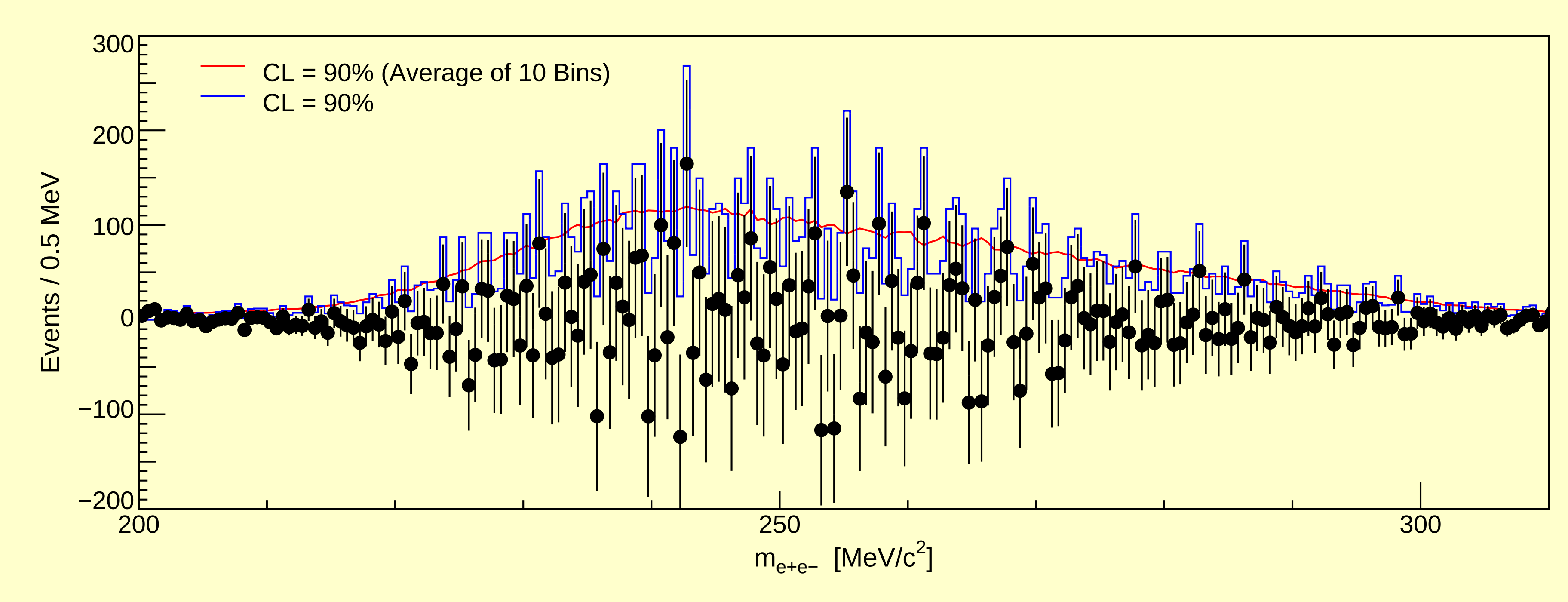


- Elastic Scattering
  - Natural width ≪ Resolution
  - Line width gives upper bound
  - $\delta p/p < 10^{-4}$ for Spectrometer
- Input to Full Simulation
  - Multiple Scattering $(-)$
  - Radiation correction $(-)$
  - Decay length $(+)$
  - Missing mass resolution $(+)$

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

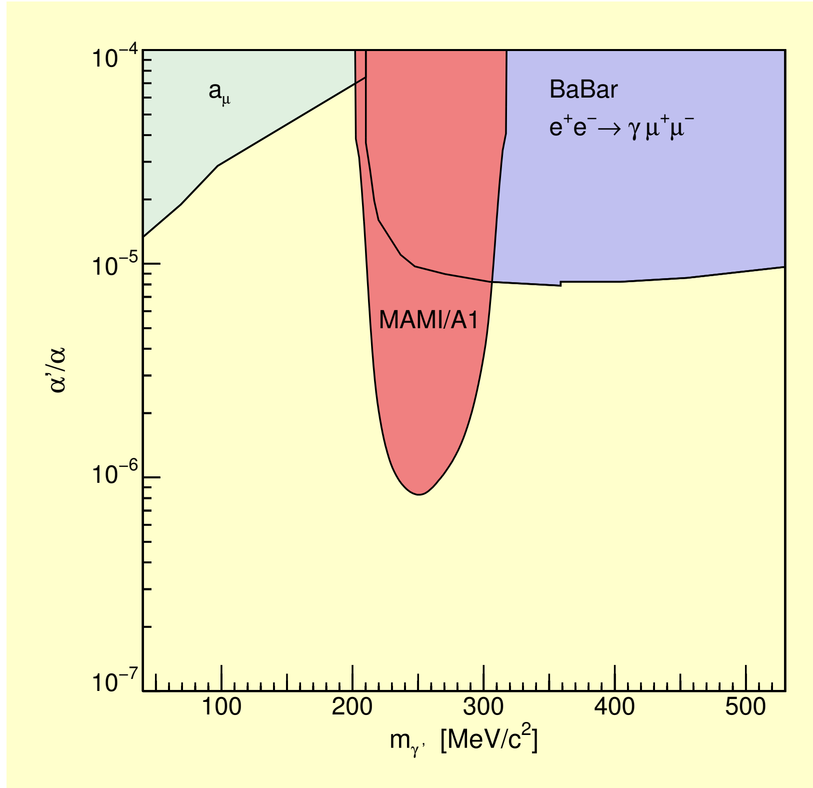
N.B.: Systematic error of $\delta m_{e^+e^-} < 10^{-3}$!

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 limit for mixing parameter ε



- Accidental background + Q.E.D. background
- Model deviates only on nuclear vertex, both for γ' and γ^*
- Conversion from ratio of cross sections:

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

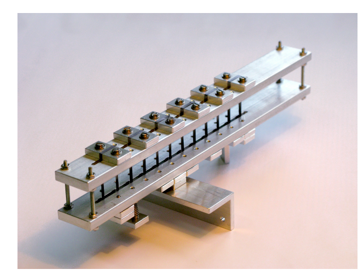
$\Rightarrow$ Exclusion limit from 4 days of beam time $\varepsilon < 10^{-3}$

H.M. *et al.*, Phys. Rev. Lett. 106 (2011) 251802

Data 2012/2013 - Settings

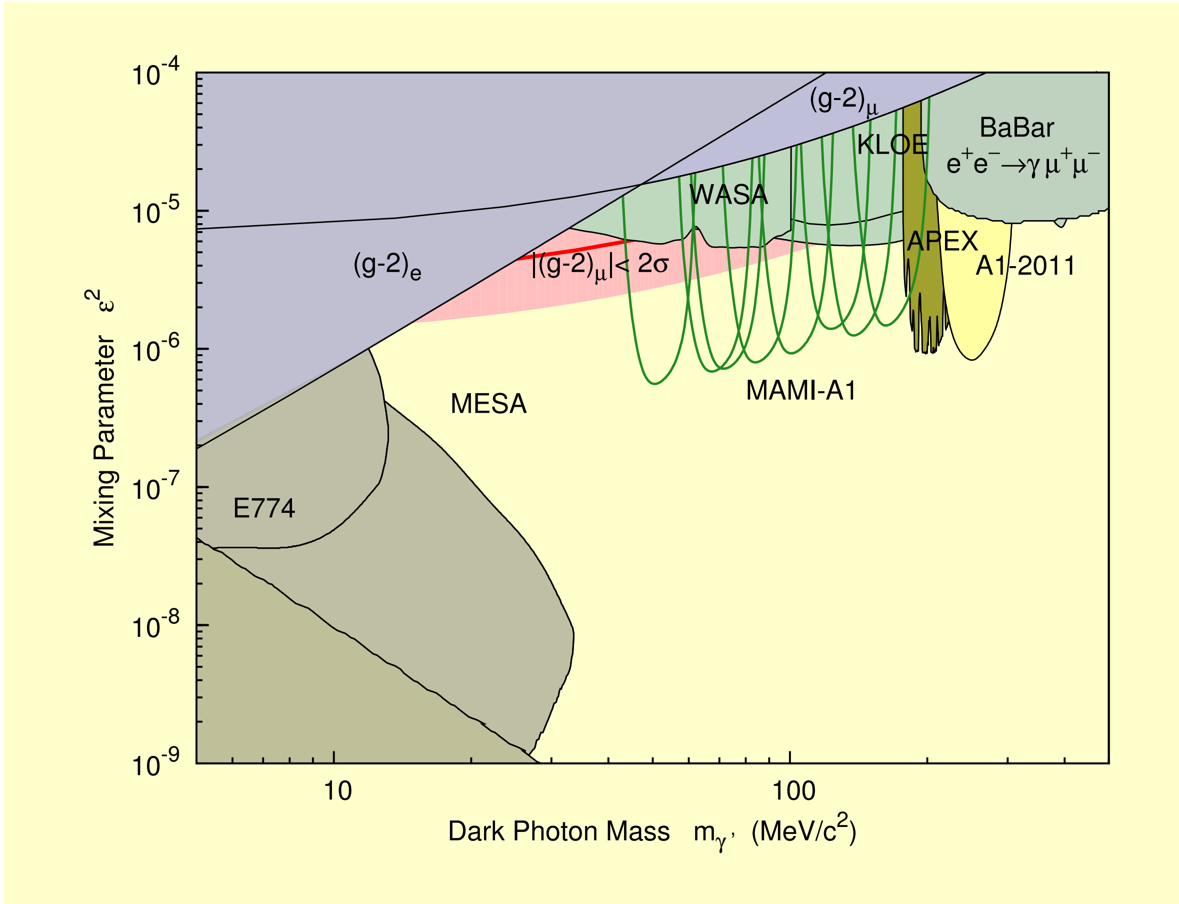
Settings	E_0 (MeV)	p_A (MeV$/c$)	p_B (MeV$/c$)	$\bar{I}_0$ (μA)	Target (mg$/$cm^2)	t t
DM2012_57	180	78.7	98.0	2.2	Foil 9.4	12h 30’ 56”
DM2012_72	240	103.6	132.0	5.5	Foil 9.4	46h 53’ 18”
DM2012_77	255	110.1	140.4	7.0	Foil 9.4	43h 49’ 11”
DM2012_91	300	129.5	164.5	11.7	Foil 9.4	37h 56’ 03”
DM2012_109	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”

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



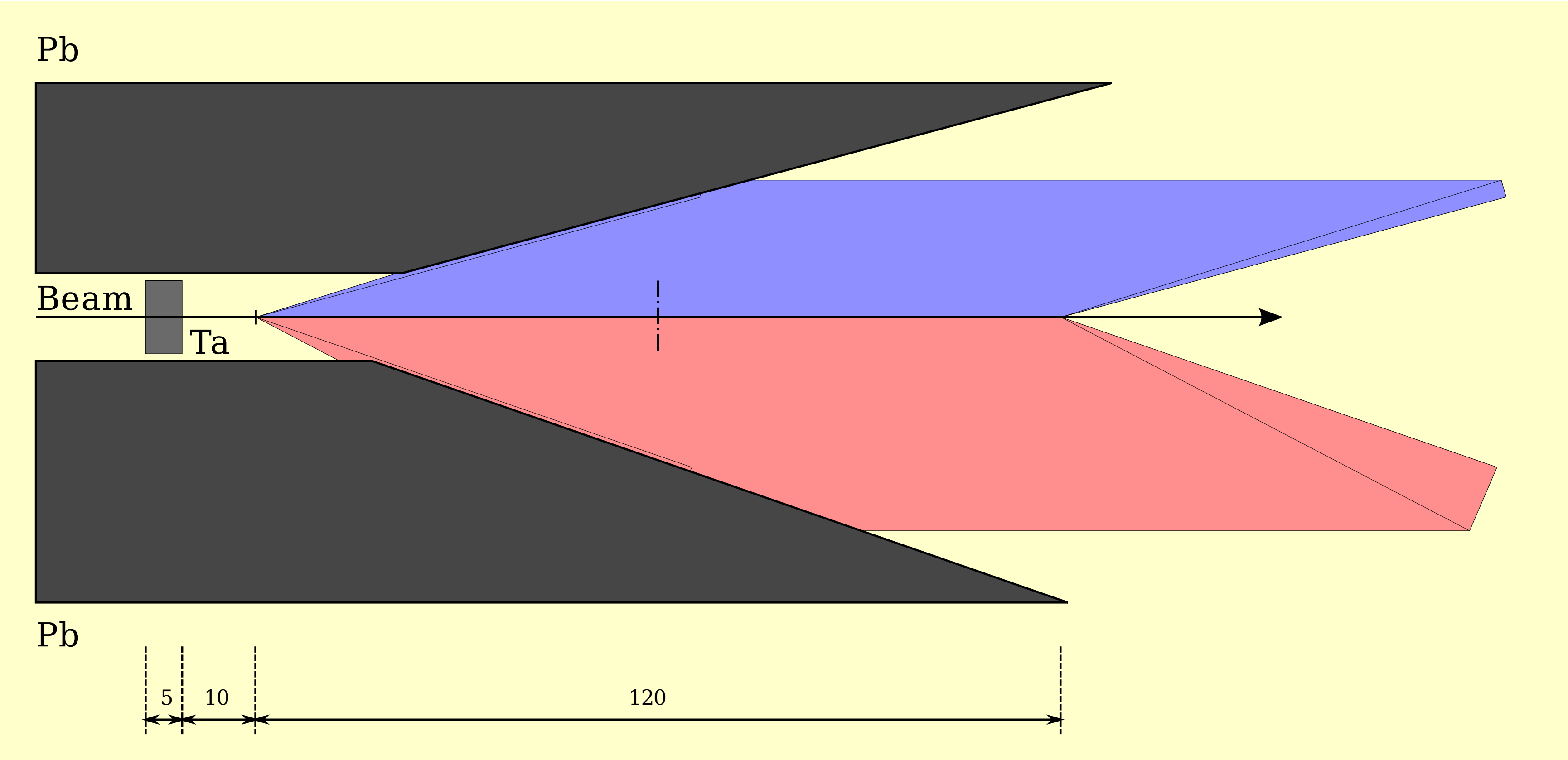
- Mass range   50 MeV $< m_{\gamma'} <$ 200 MeV
- 9 different beam energies

Data 2012/2013



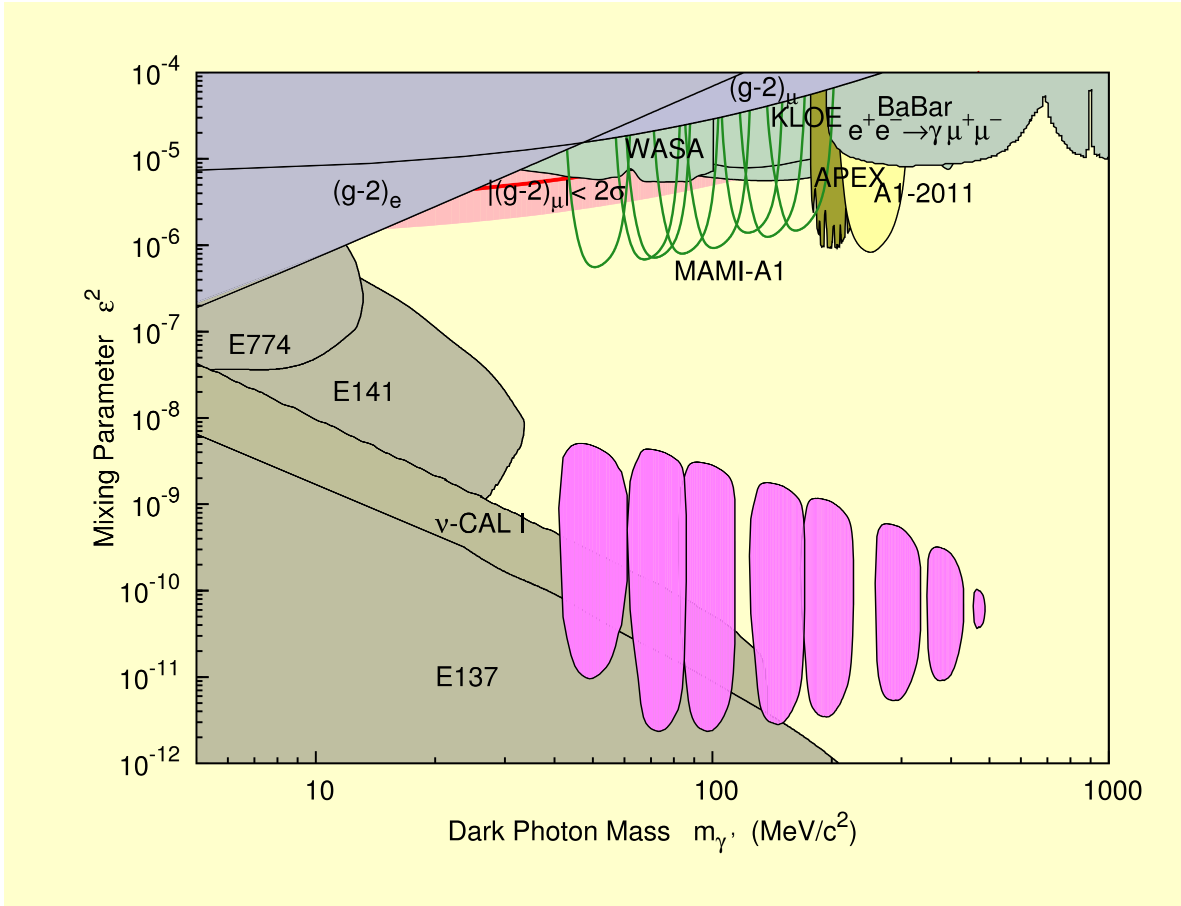
- Data taking finished
- Analysis nearly finished

Step 2: Secondary vertex → small coupling



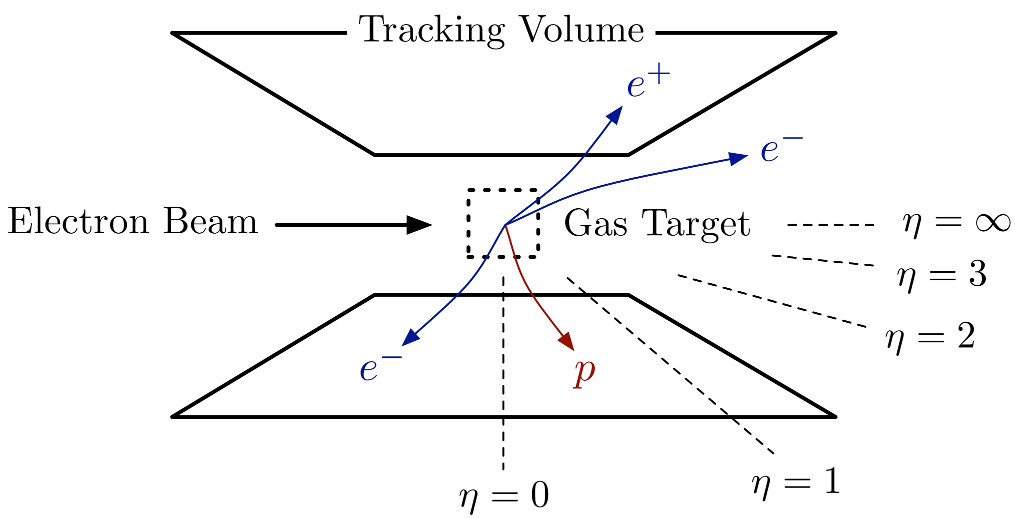
- Sensitive to decay length 10 mm – 130 mm
- $\Rightarrow \gamma c\tau =$4.35 mm – 1120 mm (10%-limit)
- $\Rightarrow \varepsilon = 10^{-6} - 10^{-5}$
- Target: 5 mm Ta $\Rightarrow L = 1.72 \cdot 10^{37} \frac{1}{\mathrm{s\,cm}^2}$ at 100 μA beam current
- Beam stabilization, shielding, target cooling

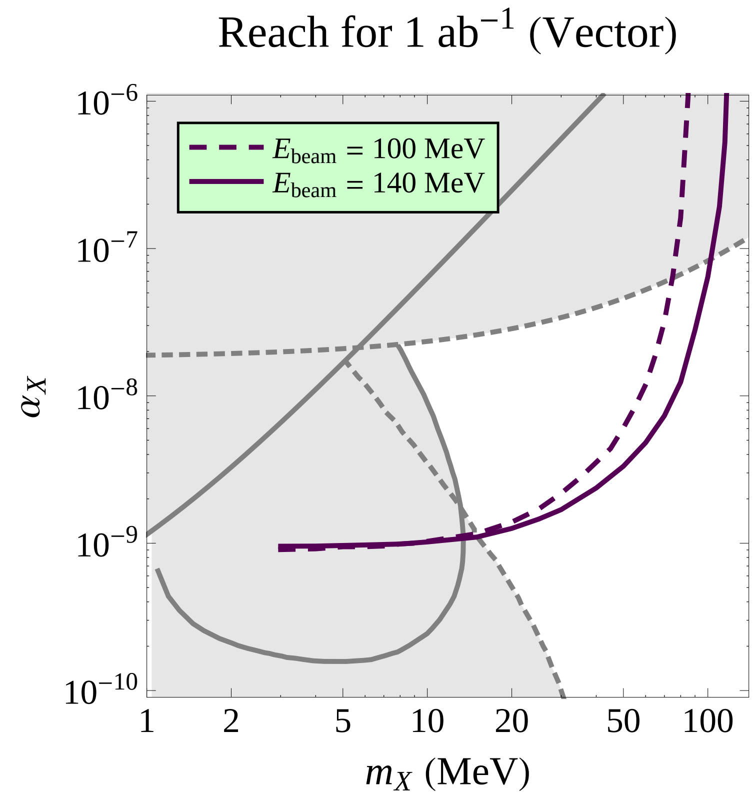
Step 2: Exclusion limits with shielded production vertex



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

Step 3: Access to low mass region

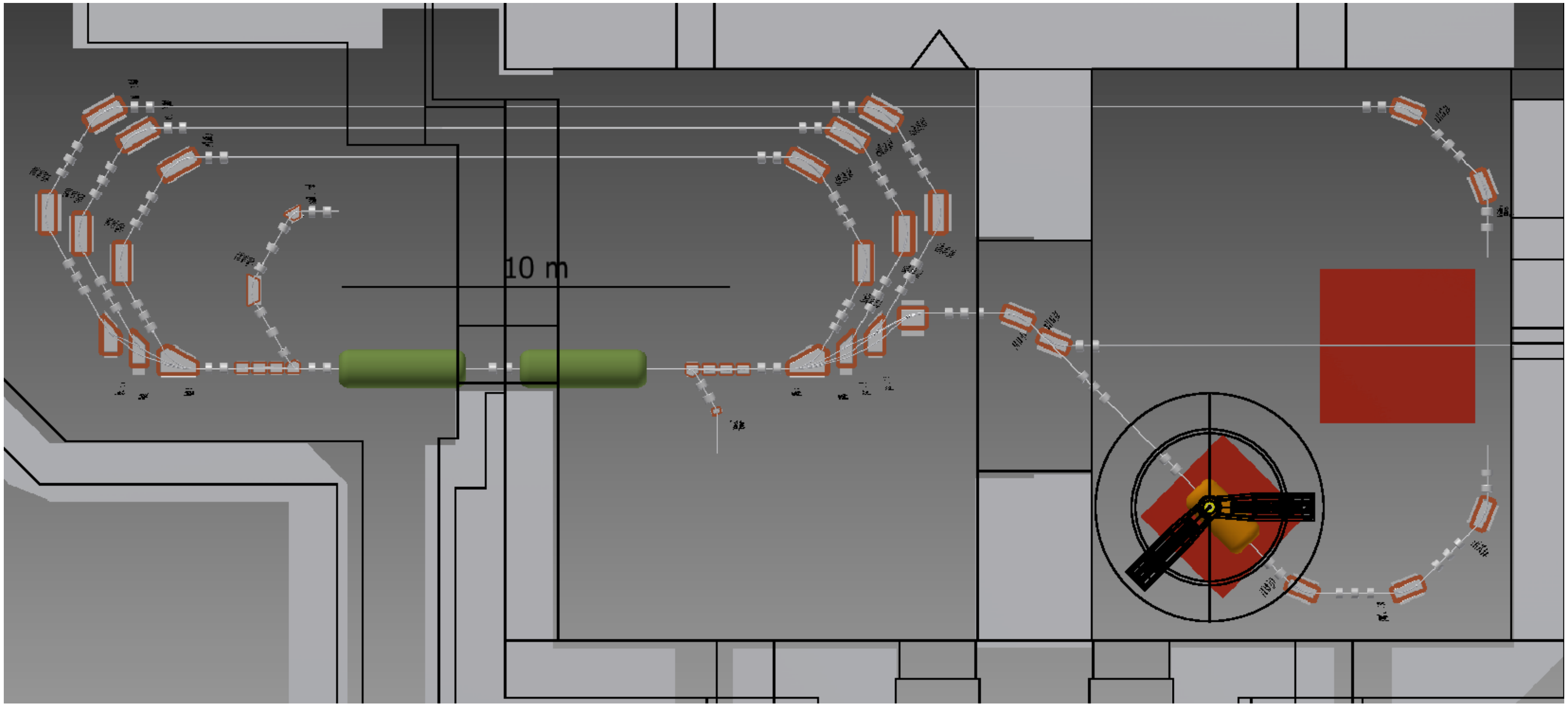




- Minimize multiple scattering by gas target
- Low energy – high current accelerator
- Needs 4π detector at 200 MHz count rate with high resolution
- DarkLight (JLab FEL)

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

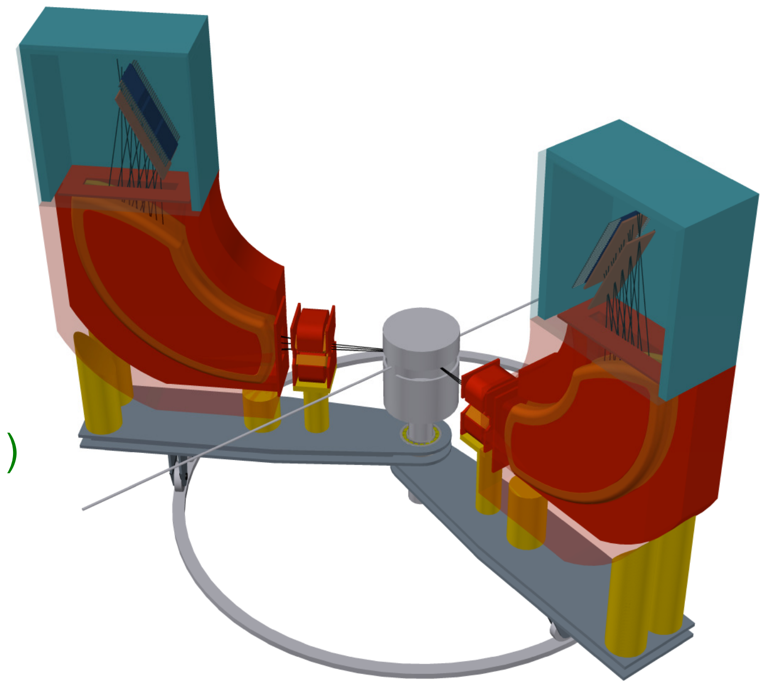
Step 3: Access to low mass region MESA Accelerator

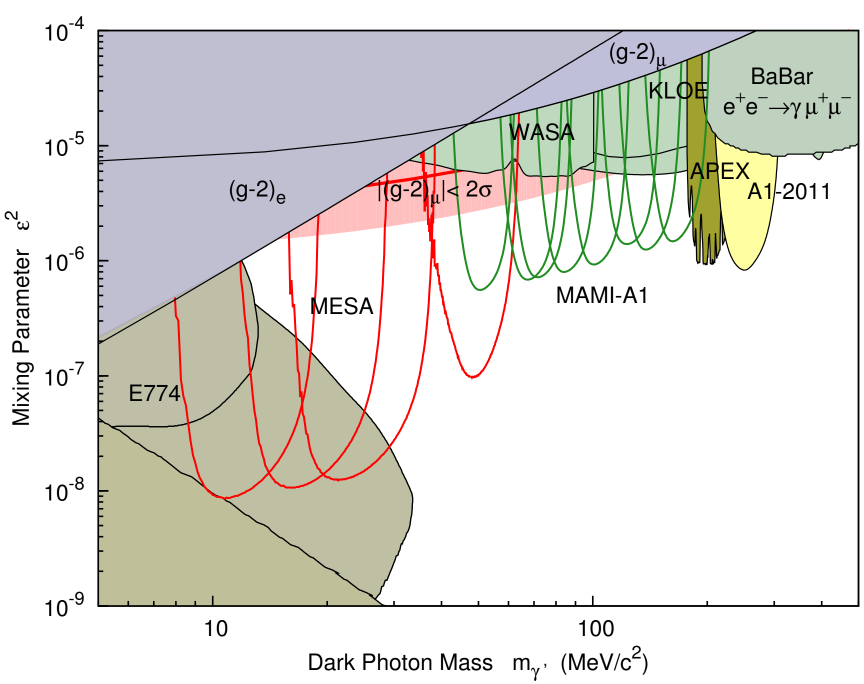


- Mainz Energy recovering Superconduction Accelerator
- up to 10 mA beam current
- Single pass accelerator ⇒ excellent beam quality
- $\Rightarrow L = 10^{35}\,\frac{1}{\mathrm{s\,cm^2}}$ with internal target

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 $50\mu m$)



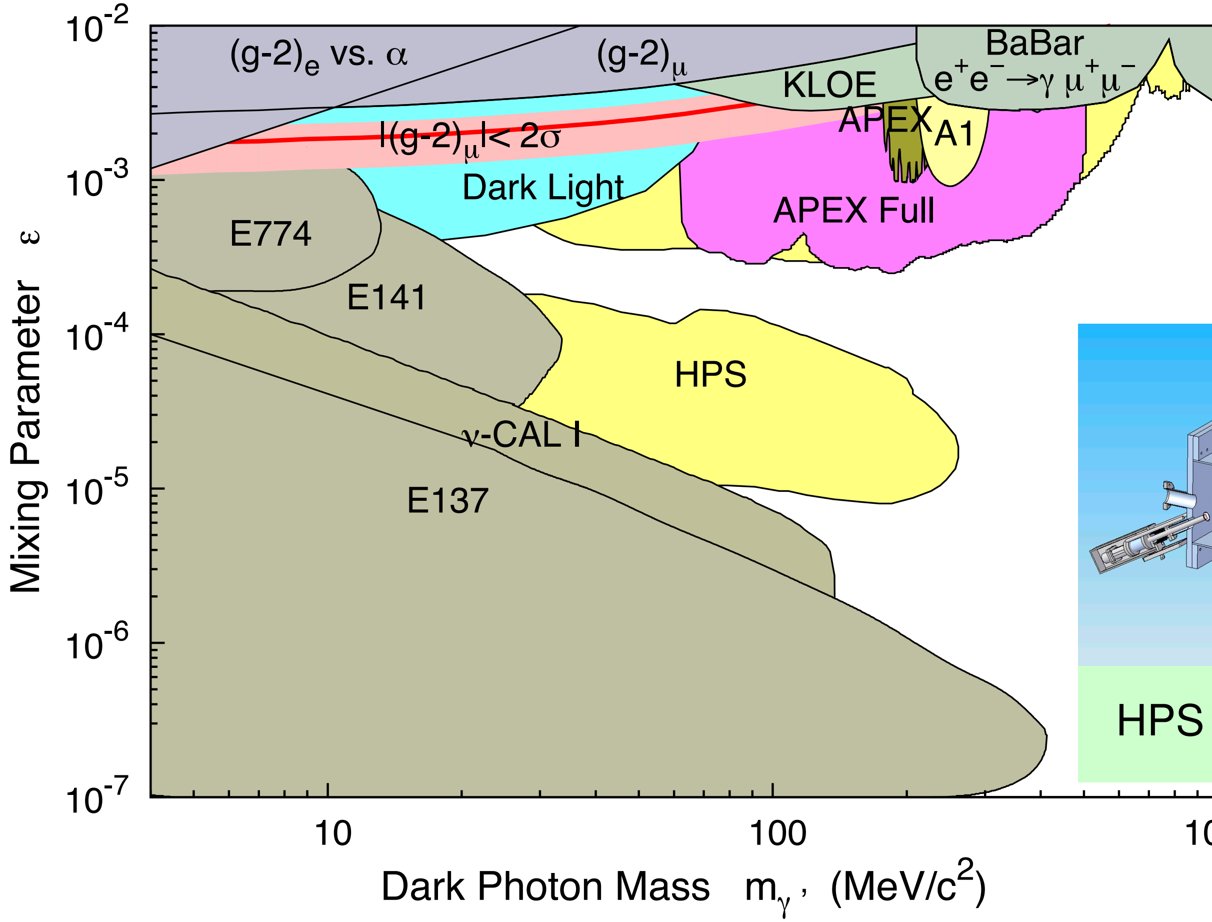


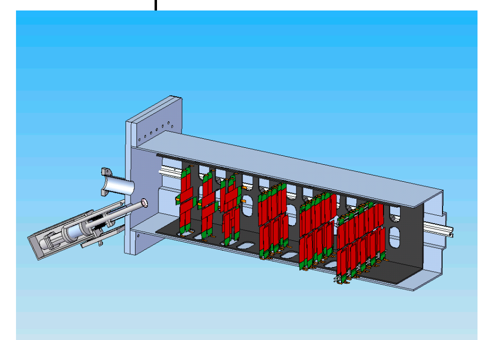
$\Rightarrow$ ideal for dark photon search!

JLab program

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

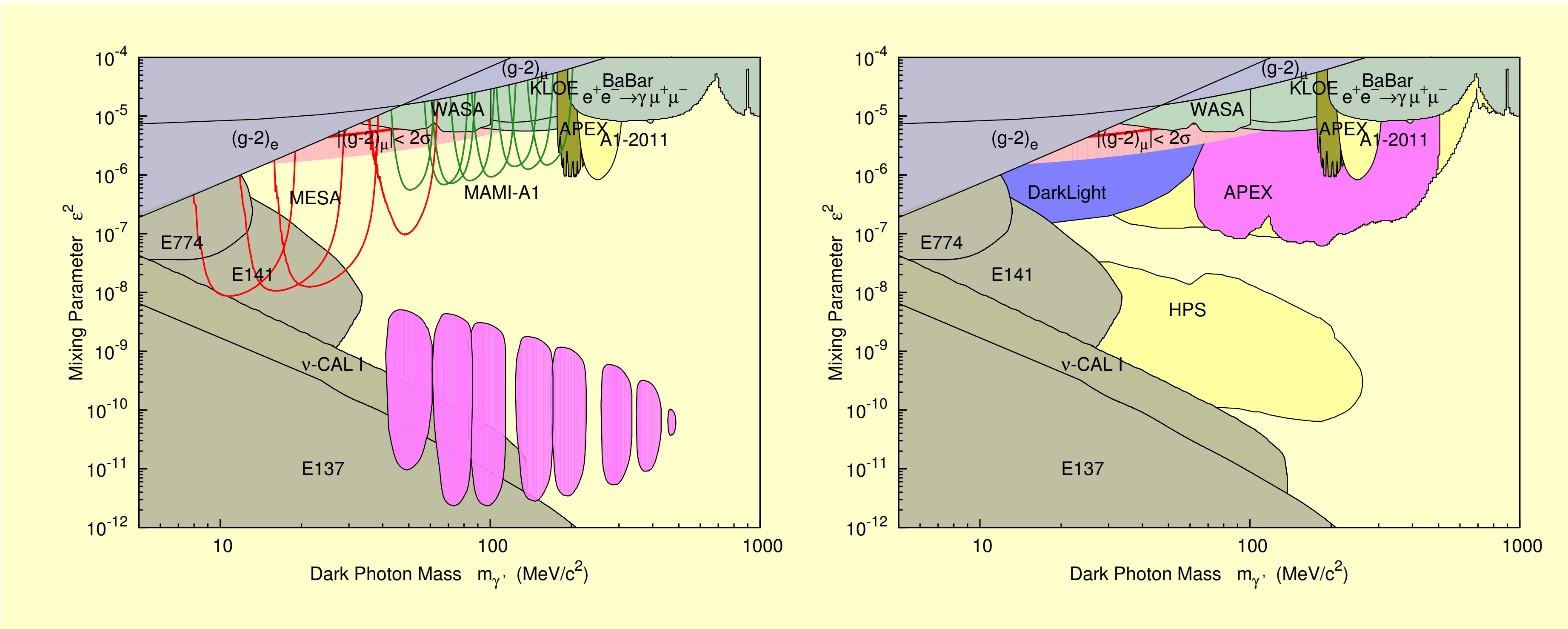
APEX (JLab Hall A)





HPS (JLab Hall B)

Summary



- Experimental Program:
  - Pair production on heavy target $\varepsilon > 4 \cdot 10^{-4}$
  - Low energy – high current $m_{\gamma'} < 50\,\mathrm{MeV}/c^2$
  - Finite production vertex $10^{-6} < \varepsilon < 10^{-4}$
- Pilot experiments at MAMI and APEX
  - Experiment is feasible, background is well under control
  - Q.E.D. process is understood and calculable within 1%
  - First exclusion limits 10^{-3}, measurements will be continued

$\Rightarrow$ Determination of significant exclusion limits for the γ' boson is possible with existing facilities