

SEARCH FOR A “DARK PHOTON” WITH THE MAINZ MICROTRON

Harald Merkel

Johannes Gutenberg-Universität Mainz, Germany

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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

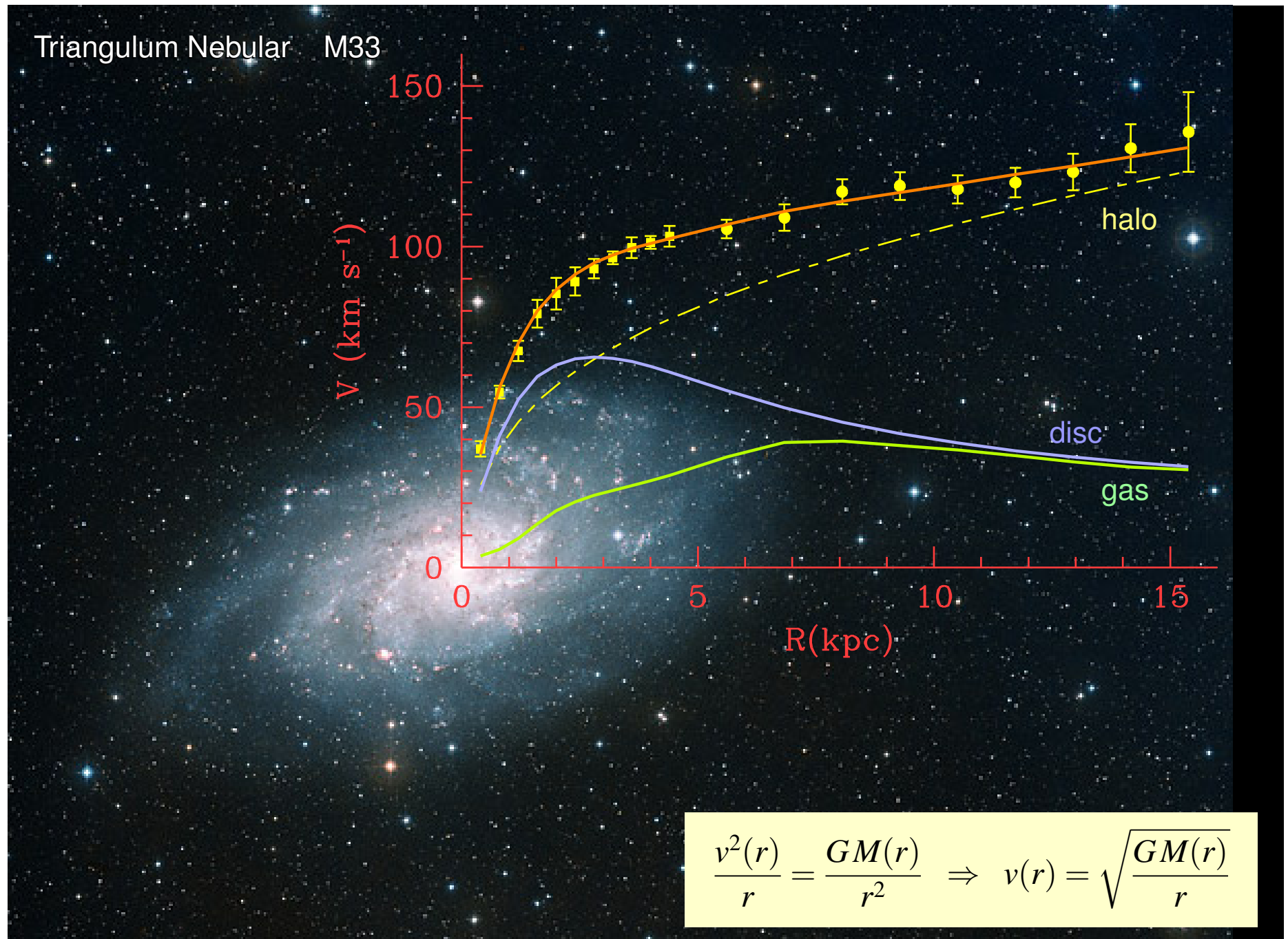
Experiment at the Mainz Microtron (MAMI)

- ▶ Experiment
- ▶ Results

Outline of an experimental program at MAMI

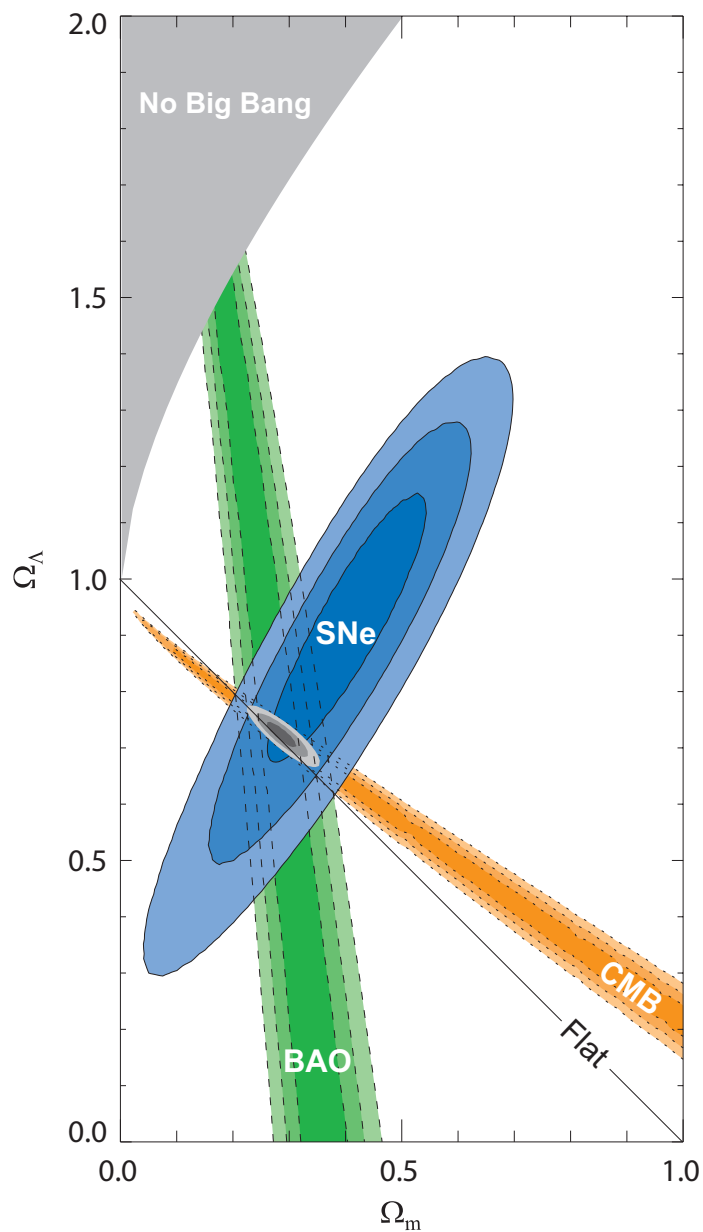
Summary

Rotation Curves of Galaxies



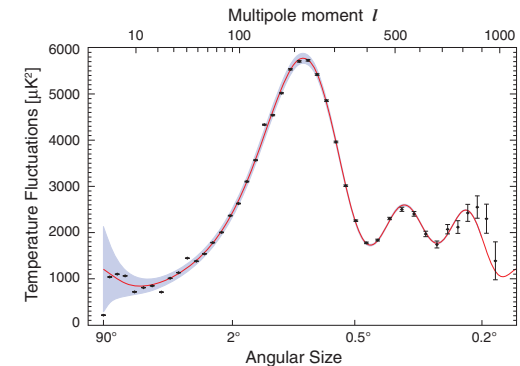
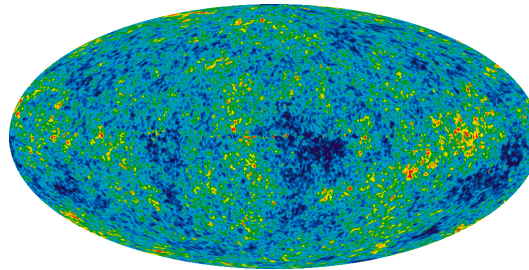
F. Zwicky, ApJ, 86 (1937) 217, E. Corbelli, P. Salucci, MNRAS 311 (2002), 441 – 447

Dark Matter in Cosmology

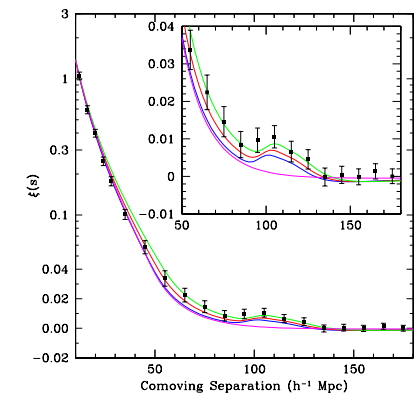
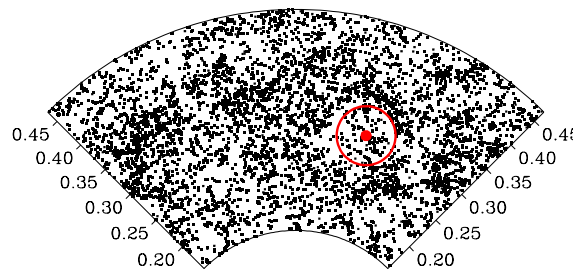


● Supernova Type Ia (SNe)

● Cosmic Microwave Background



● Baryon Acoustic Oscillations



$\Rightarrow$
 $\Omega_\Lambda = 74\%$ Dark Energy
 $\Omega_{\text{CDM}} = 21\%$ Cold Dark Matter
 $\Omega_b = 4\%$ Baryonic Matter

Dark matter candidates in particle physics

Properties:

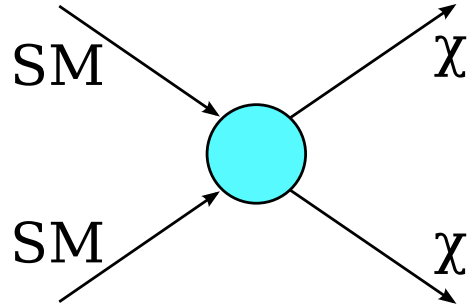
- Massive
- Almost no interaction with standard model matter

Candidates:

- Baryonic dark matter, gas clouds, MACHOs
 - ⚡ Contradicts primordial nucleosynthesis
- 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, Gravitino, Axino,...

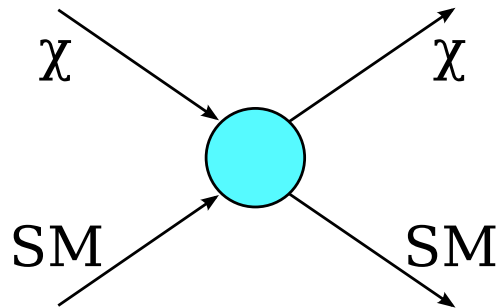
⇒ Cold dark matter

Conventional strategies for dark matter search



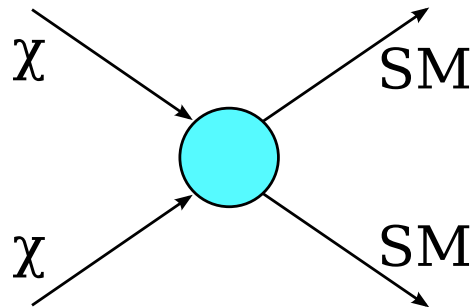
Direct Production:

Tevatron, 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 is dark matter (SUSY or something else)
- 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...

- Extra $U(1)$ gauge bosons ubiquitous in well motivated extensions of the SM with large rank local gauge group:
 - ▶ 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)
- $U(1)$ gauge factors in string compactifications:

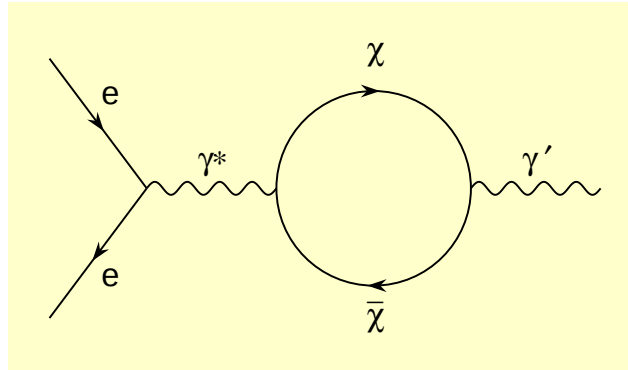
$$E_8 \times E_8 \rightarrow E_6 \times E_8 \rightarrow \underbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}_{\text{standard model}} \times U(1)_{\text{hidden}}$$

from breaking of second E_8

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

Kinetic mixing

Dark matter couples to $U(1)$ bosons γ and γ' :



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

• Renormalization of charge:

⇒ Mixing standard-model charge — “dark” charge

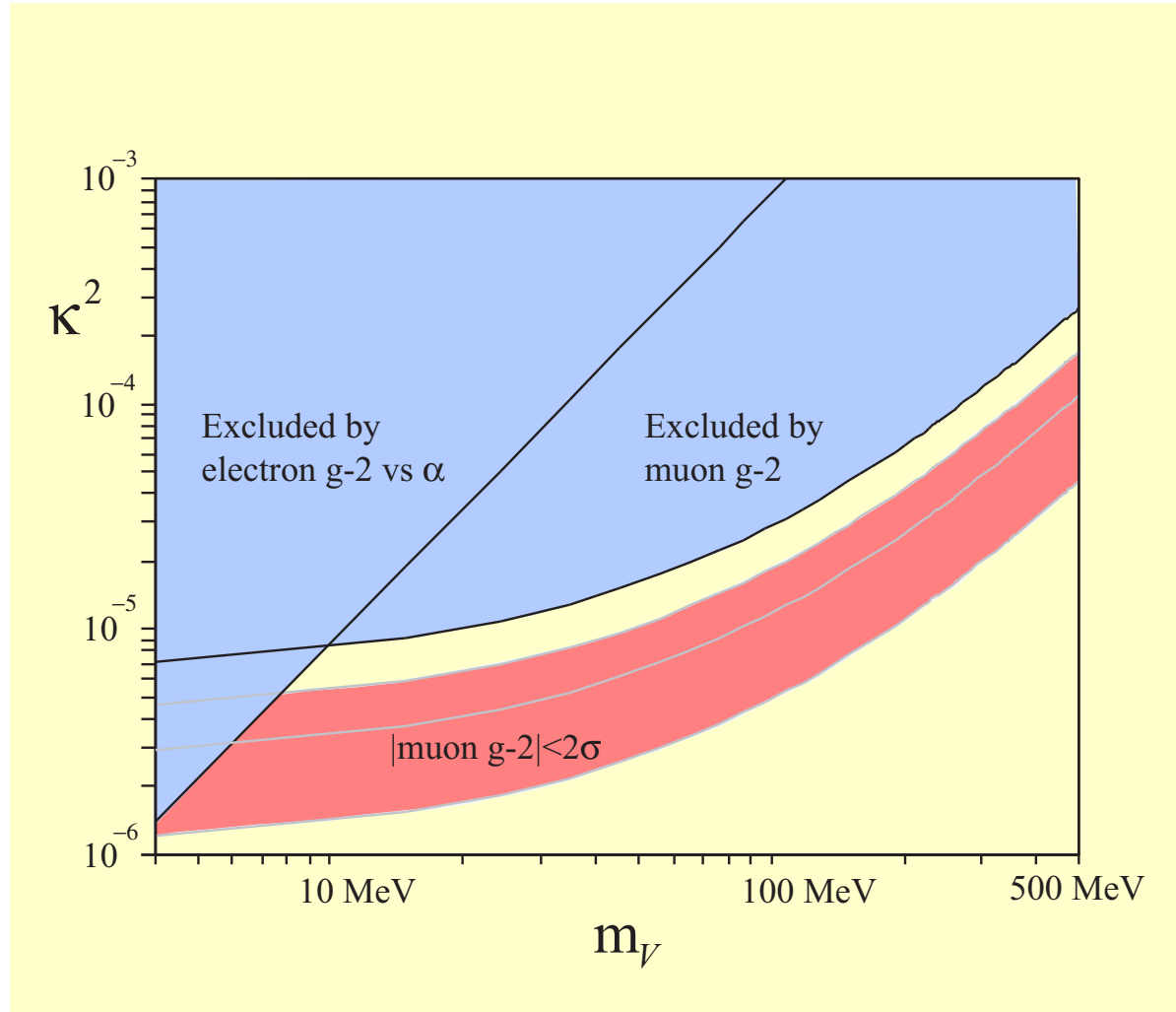
• Coupling constant ϵ of electric charge to γ'

• Boson mass $m_{\gamma'} > 0 \Rightarrow$ decay suppressed, macroscopic lifetime

⇒ Look for χ at high energies OR for γ' at low energies!

Is there experimental evidence?

Anomalous magnetic moment of the Muon



G. W. Bennet *et al.*, Phys. Rev. D 73, 072003 (2006)

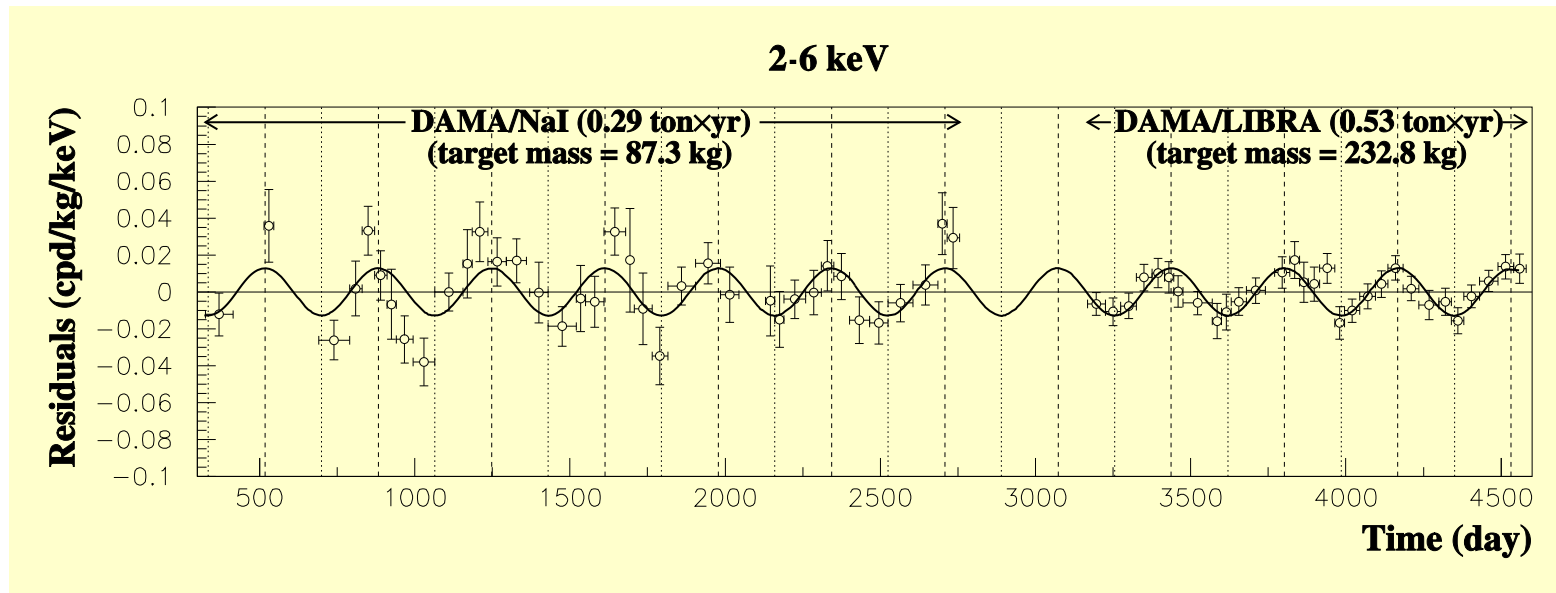
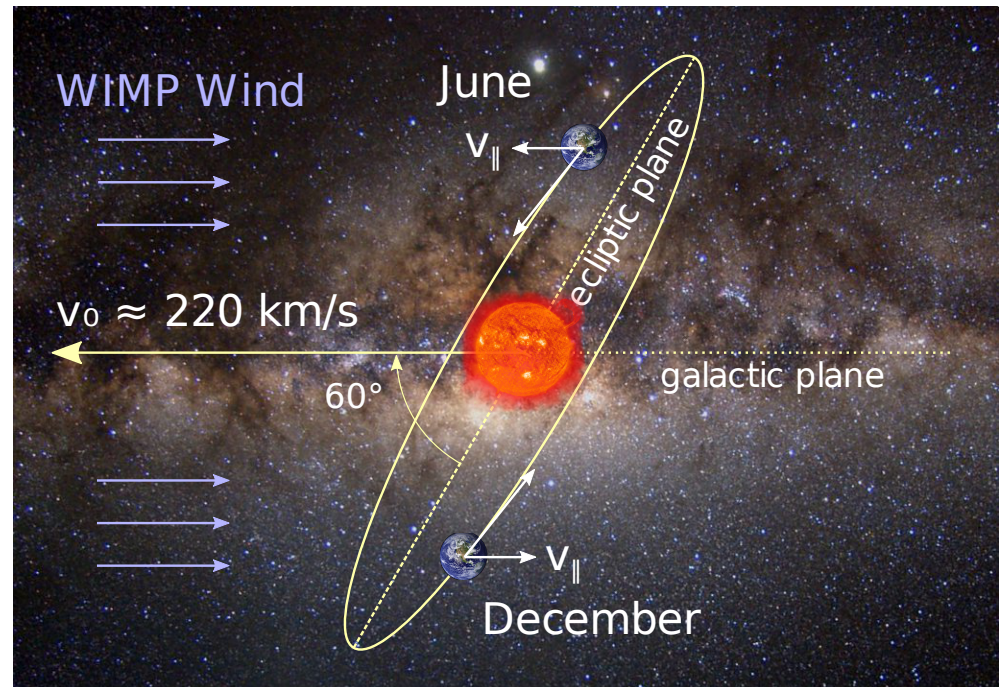
M. Pospelov, Phys. Rev. D 80, 095002 (2009)

DAMA/NaI and DAMA/LIBRA

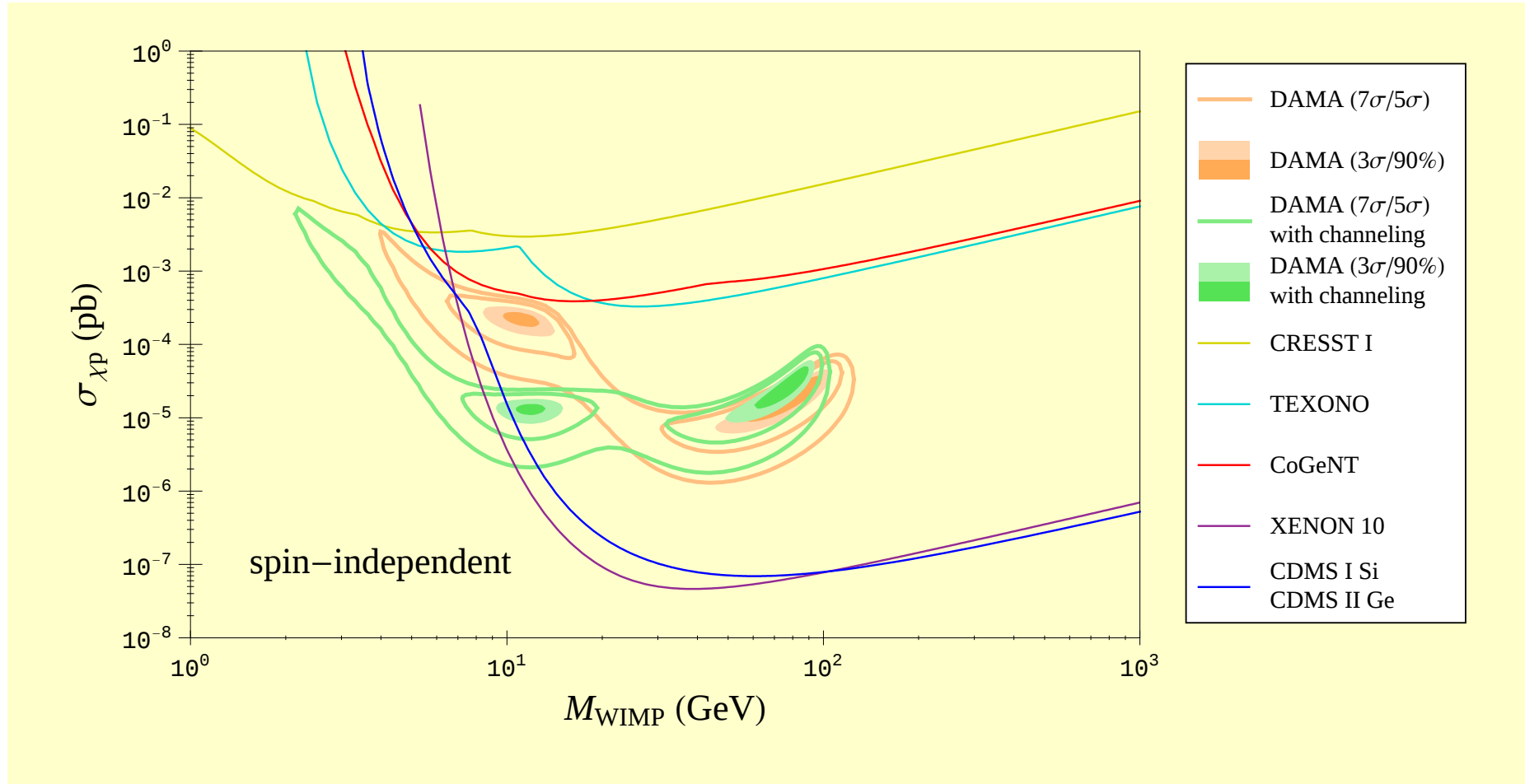
- NaI detectors in Gran Sasso
- Elastic scattering $\chi + N \rightarrow \chi + N$
- Seasonal modulation:

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

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

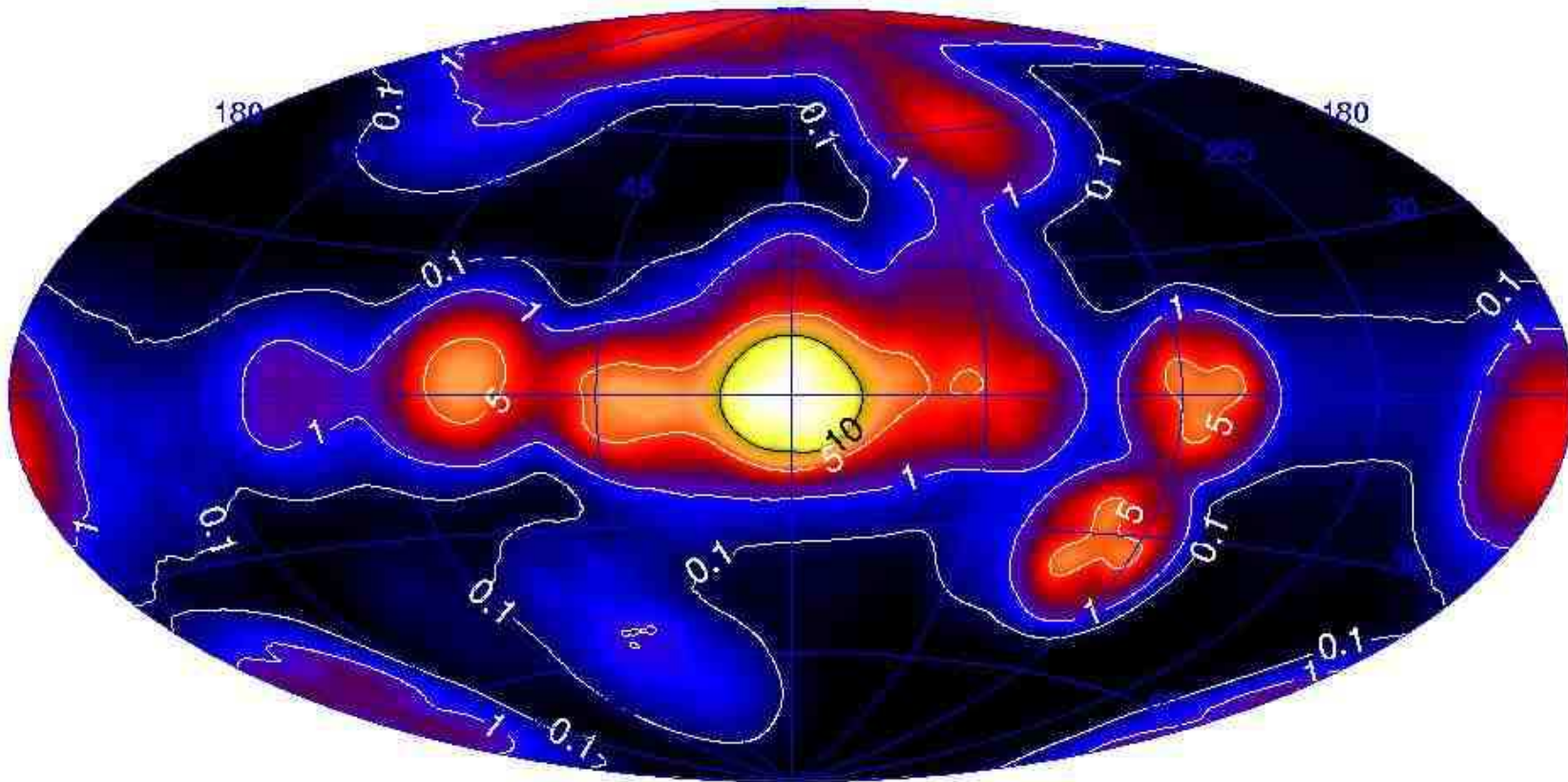
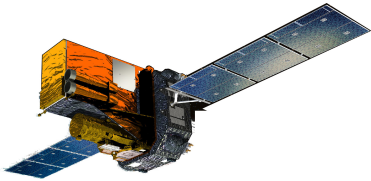


Problem: DAMA/LIBRA and the other experiments...



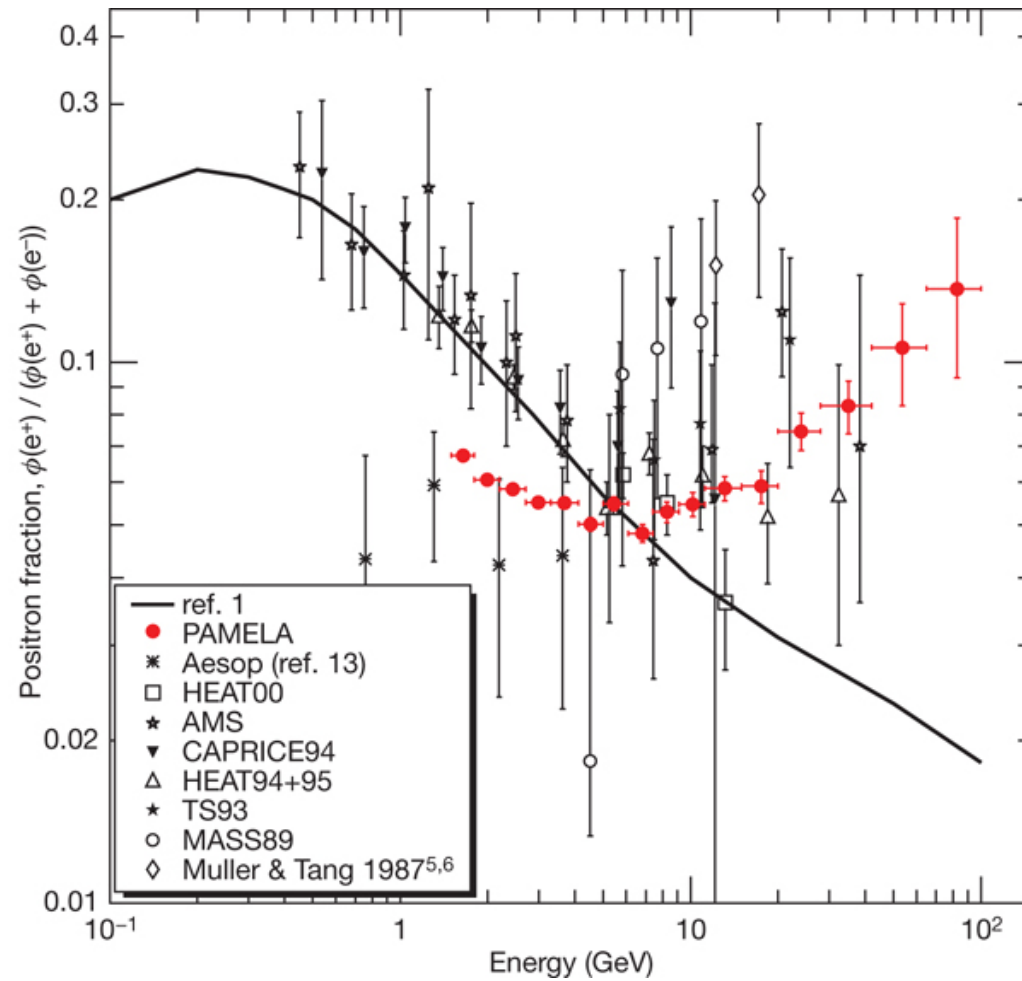
- Contradiction with 90% CL
- XENON/CDMS I/CDMS II: coincidence experiments
- $\Rightarrow$ Possible solution: interaction only with electrons

SPI Spectrometer/INTEGRAL: 511 keV Gamma radiation



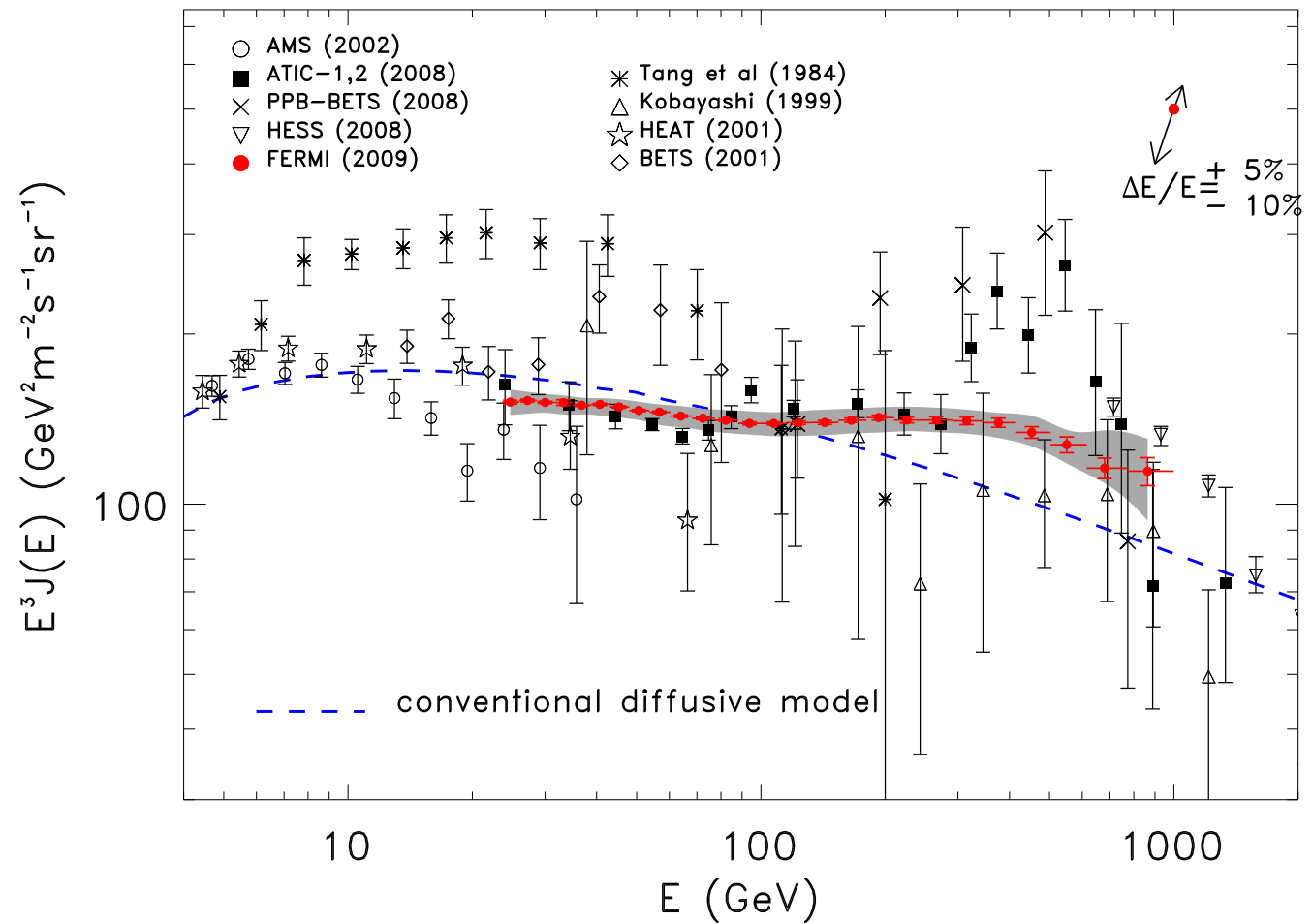
⇒ Positrons from annihilation $e^+ + e^-$

PAMELA: positron excess



⇒ Excess of positrons for $E > 10 \text{ GeV}$

Positron excess



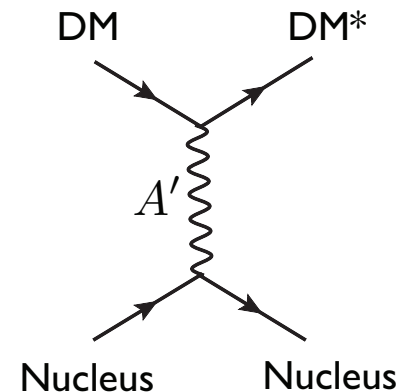
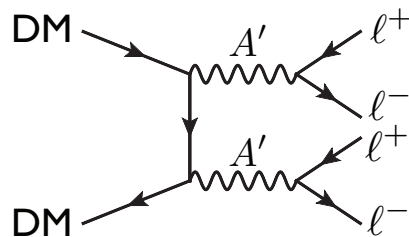
⇒ Candidat for dark matter $E \approx 600 \text{ GeV?}$

The γ' Boson (or A' , ϕ , ...)

- $g - 2$ anomaly of the myon
- Positron excess, but no antiproton excess (PAMELA, INTEGRAL 511 keV line, etc.)
- Large annihilation cross section
- Relic Abundance of DM in cosmology requires low cross section
- Direct Scattering $\Rightarrow$ DAMA/LIBRA modulation

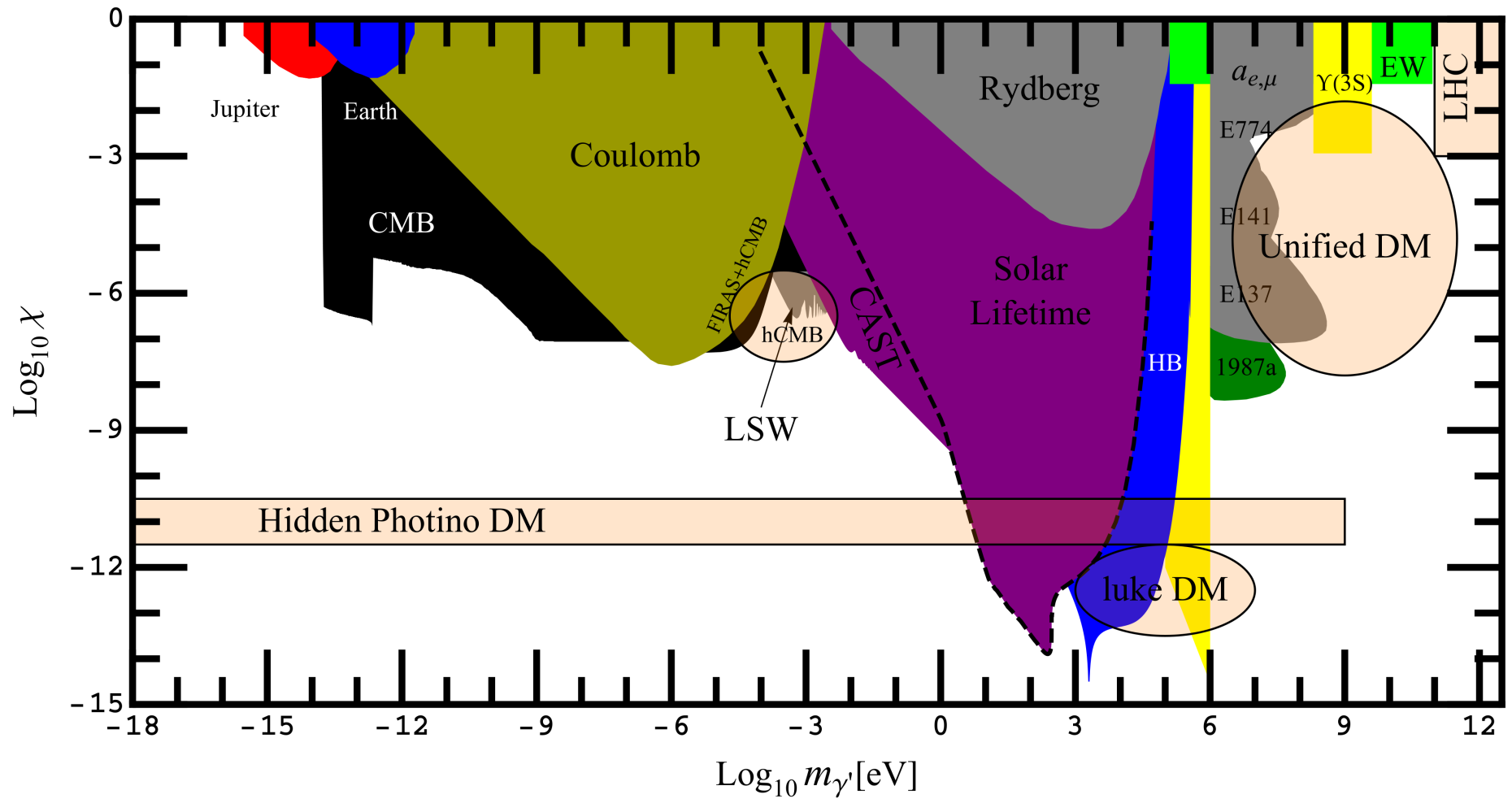
- $\Rightarrow$
- ▶ Sommerfeld enhancement of cross section for low velocities
 - ▶ Large cross section in leptons
 - ▶ Small cross section in hadrons

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

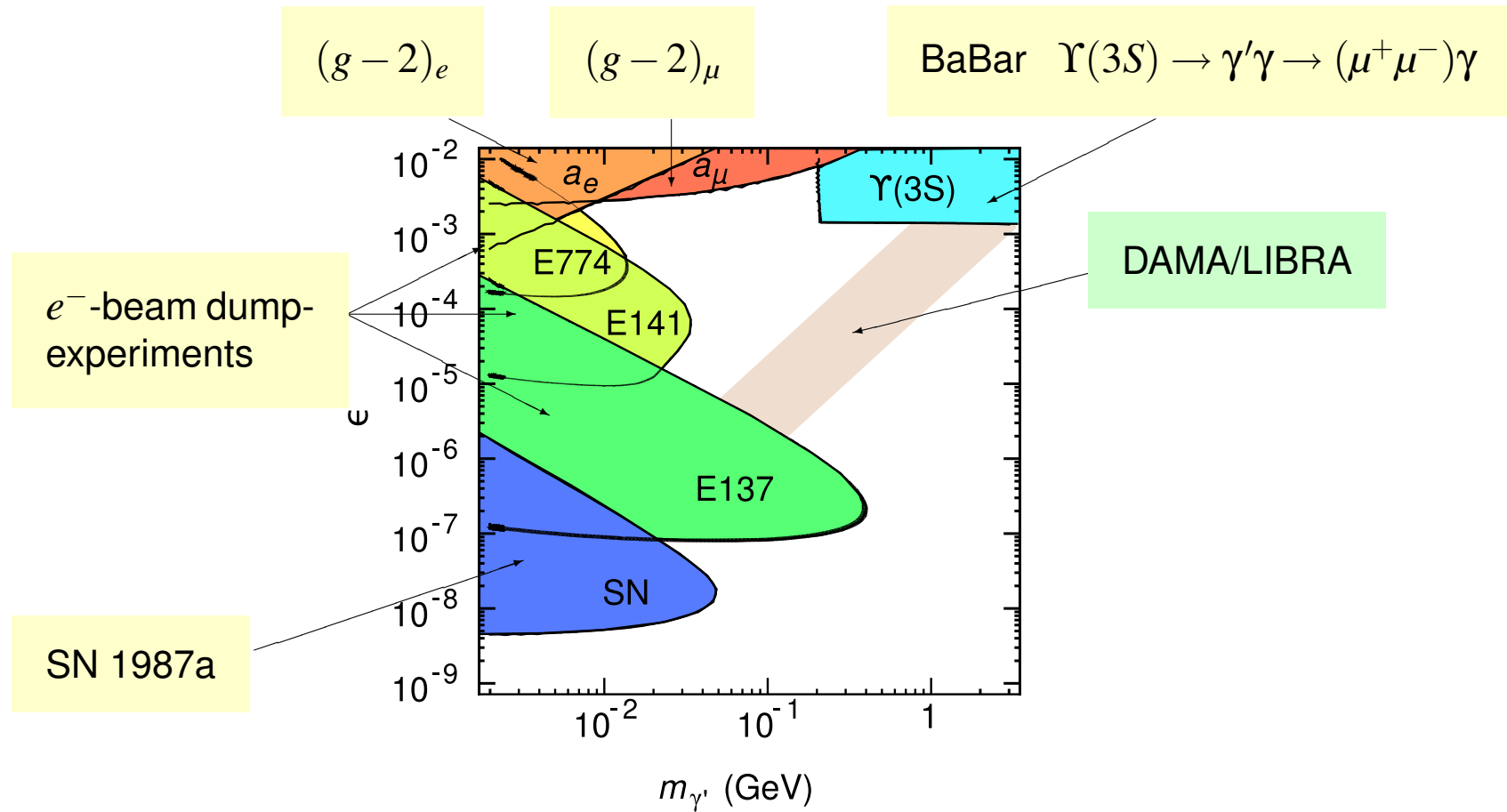


Exclusion limits for the “dark photon”

Existing bounds for dark photons



Parameter range for mass and coupling of γ' boson

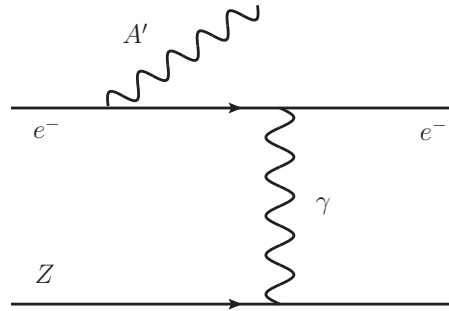


● Interesting range: $10^{-8} < \epsilon < 10^{-2}$ $10 \text{ MeV} < m_{\gamma'} < 1000 \text{ MeV}$

● Energy range of MAMI!

Principle of Measurement

Quasi-photonproduction off heavy target



Weizsäcker-Williams approximation:

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

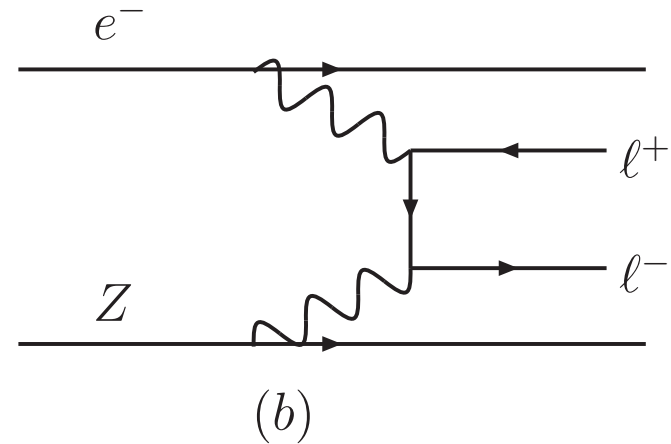
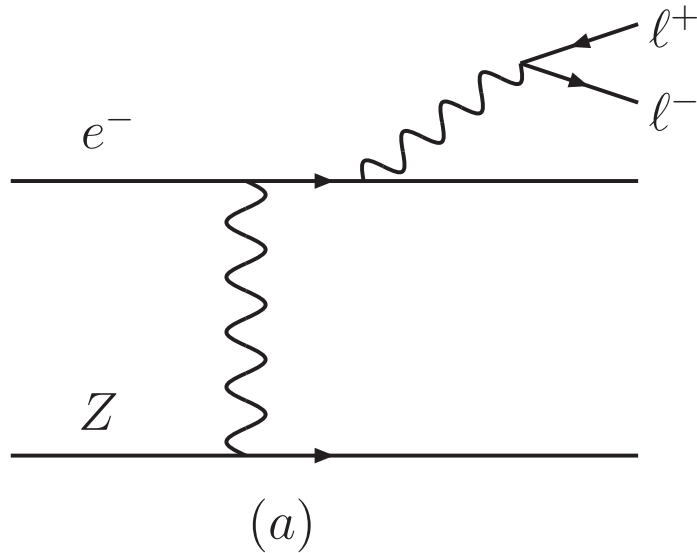
with $x = \frac{E_{\gamma'}}{E_0}$

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

Lifetime:

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

Backgrounds

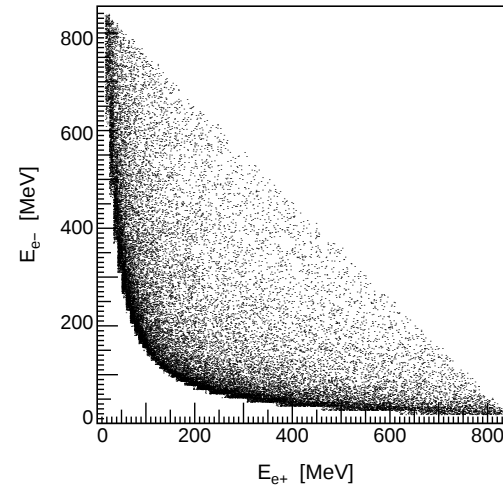
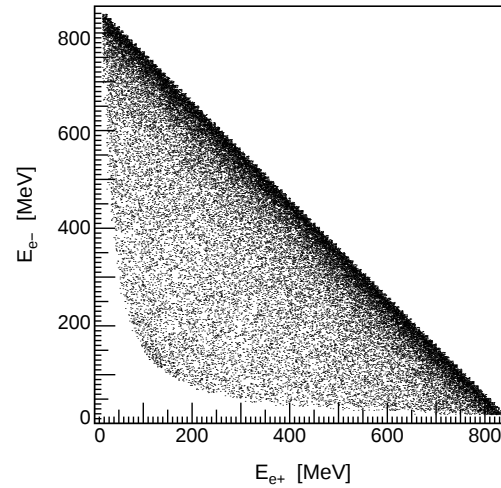
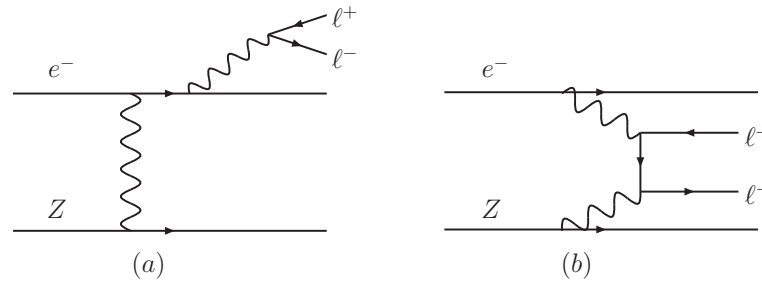


- Virtual photon instead of γ'
- Computable in QED
- Same shape of cross section
- $\Rightarrow$ Not separable

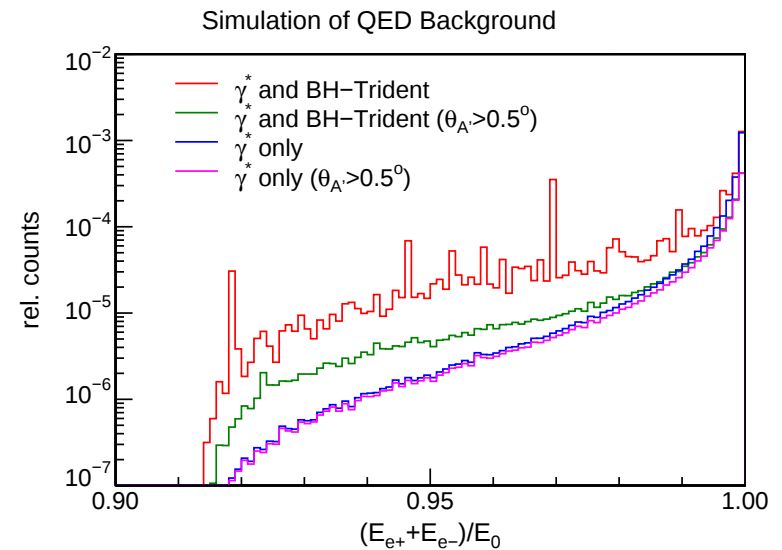
- Computable in QED
- Peak for l^* on mass shell
- Energy transfer to l^- or l^+
- $\Rightarrow$ Kinematically separable

Other backgrounds: measurement!

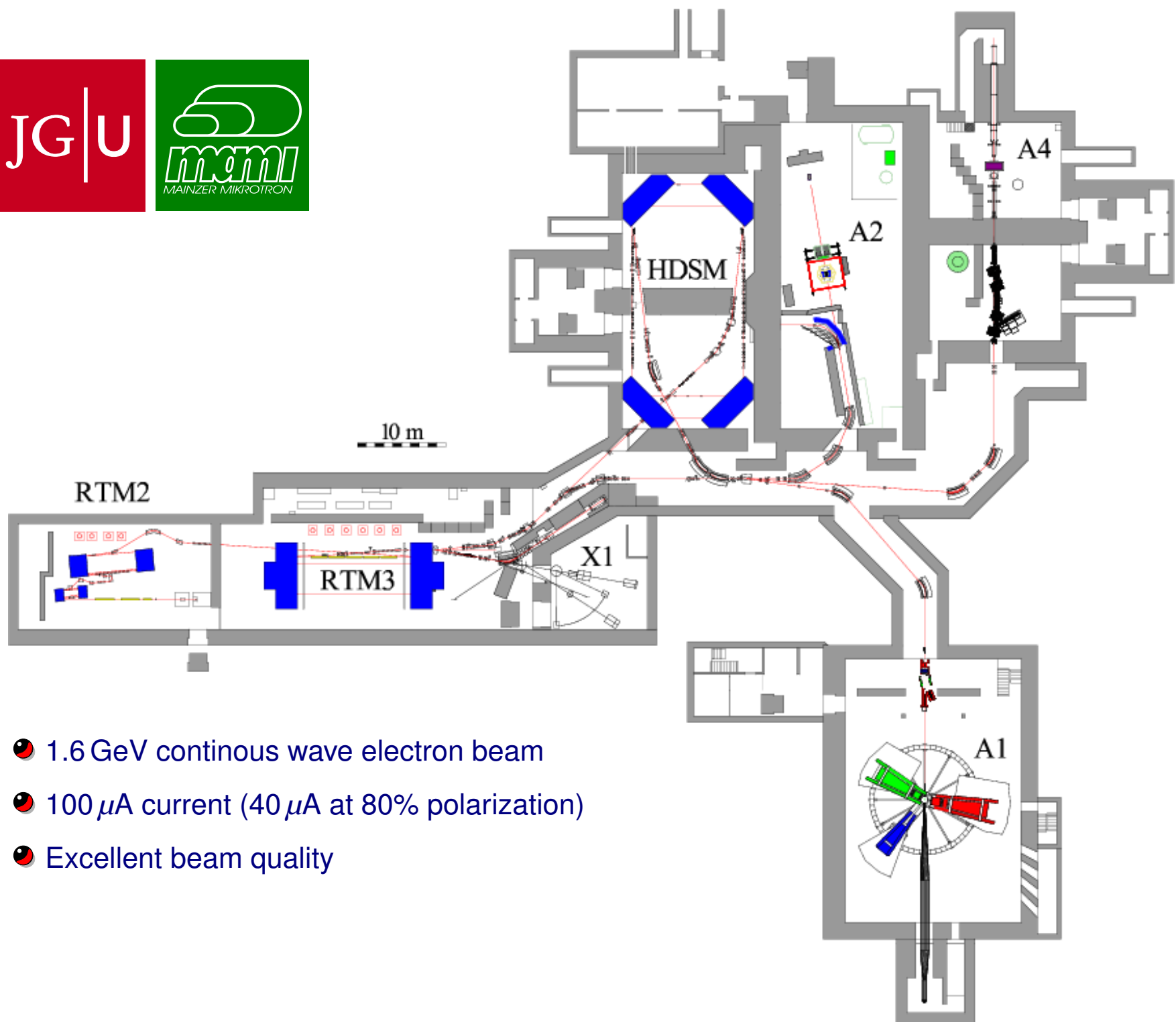
Bethe-Heitler background



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



The Experiment



- 1.6 GeV continuous wave electron beam
- 100 μA current (40 μA at 80% polarization)
- Excellent beam quality

A1: Spectrometer setup at MAMI



Spectrometer A:

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

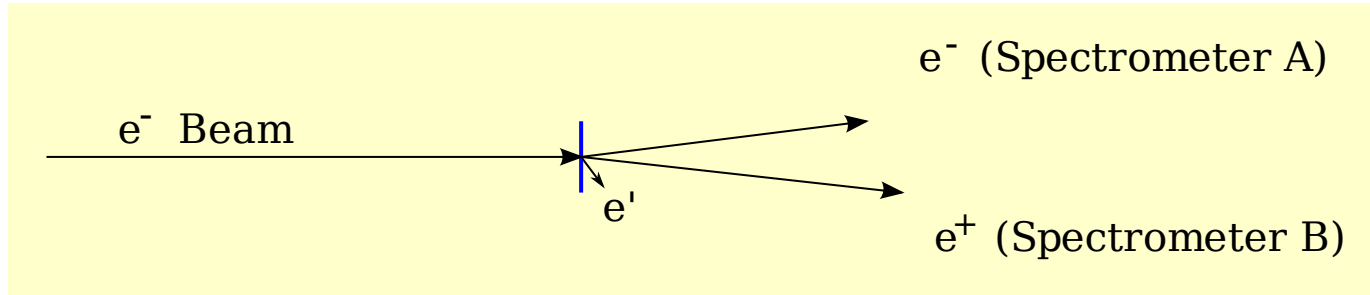
Spectrometer B:

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

Spectrometer C:

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

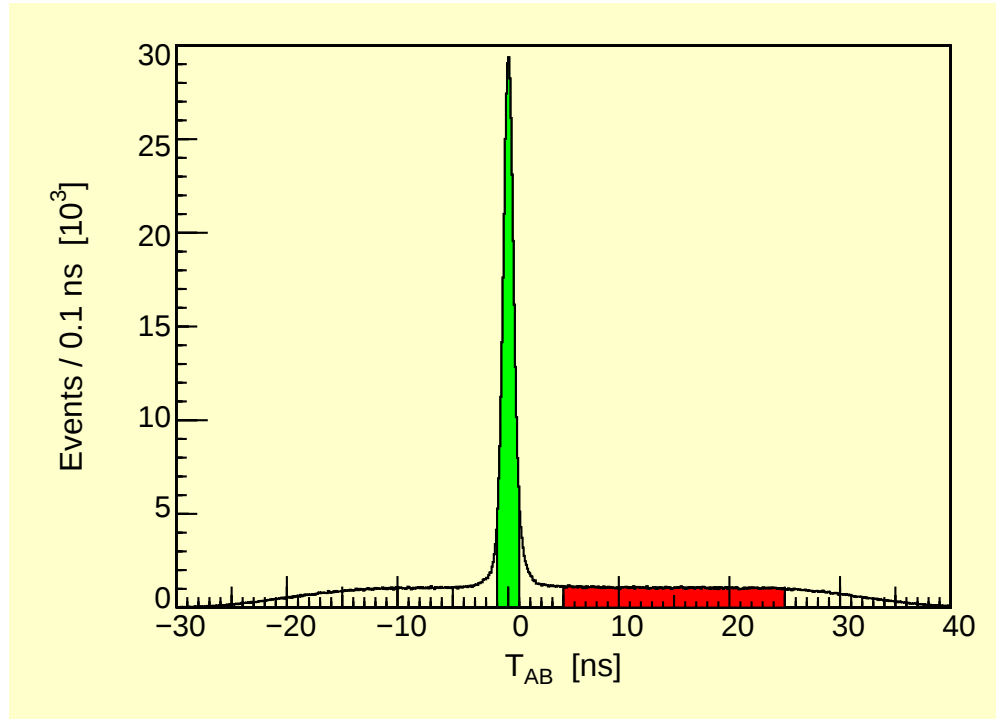
Pilot experiment



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

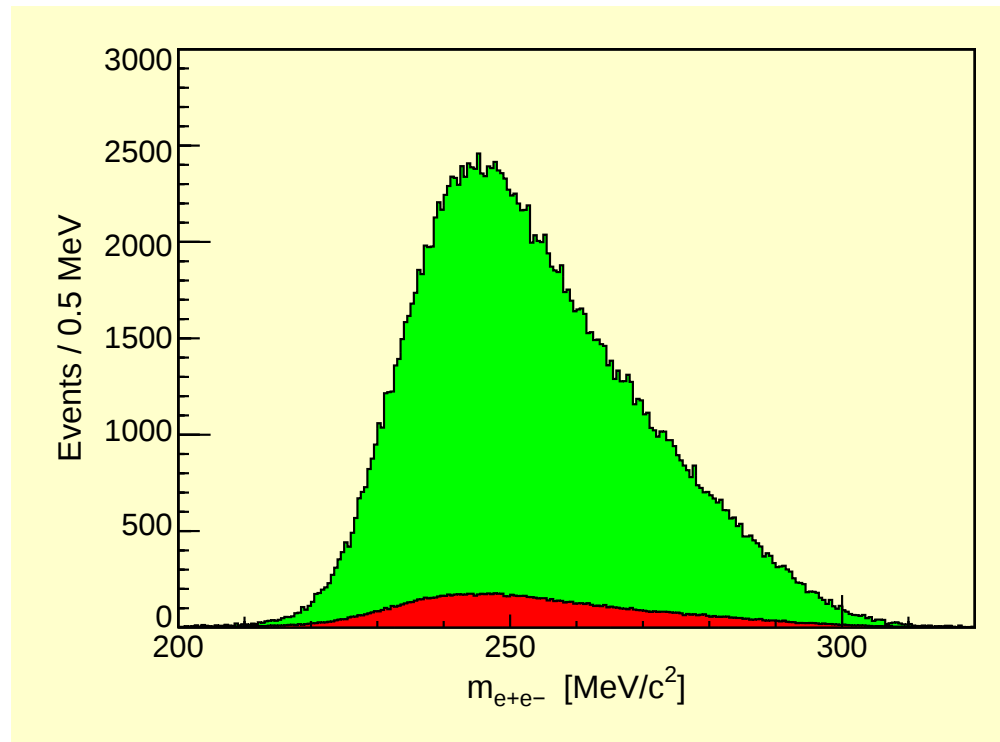
Beam energy	$E_0 = 855.0 \text{ MeV}$
Spectrometer A	$p_{e^-} = 338.0 \text{ MeV}/c$
	$\theta_{e^-} = 22.8^\circ$
Spectrometer B	$p_{e^+} = 470.0 \text{ MeV}/c$
	$\theta_{e^+} = 15.2^\circ$

Reaction identification: coincidence time



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

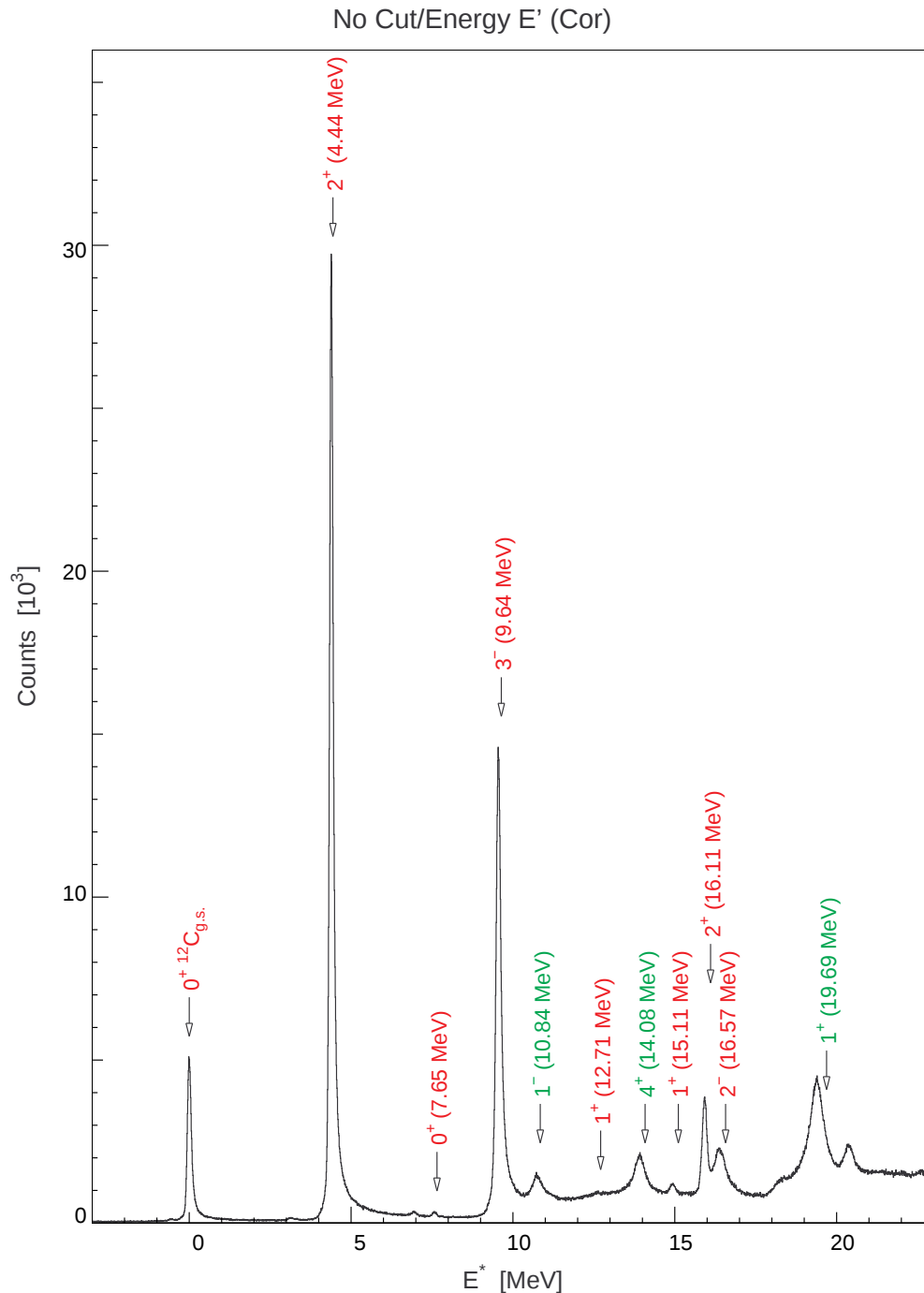
Invariant mass of e^+e^- pair



● Mass of e^-e^+ pair $m_{\gamma'}^2 = (e^- + e^+)^2$

● 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

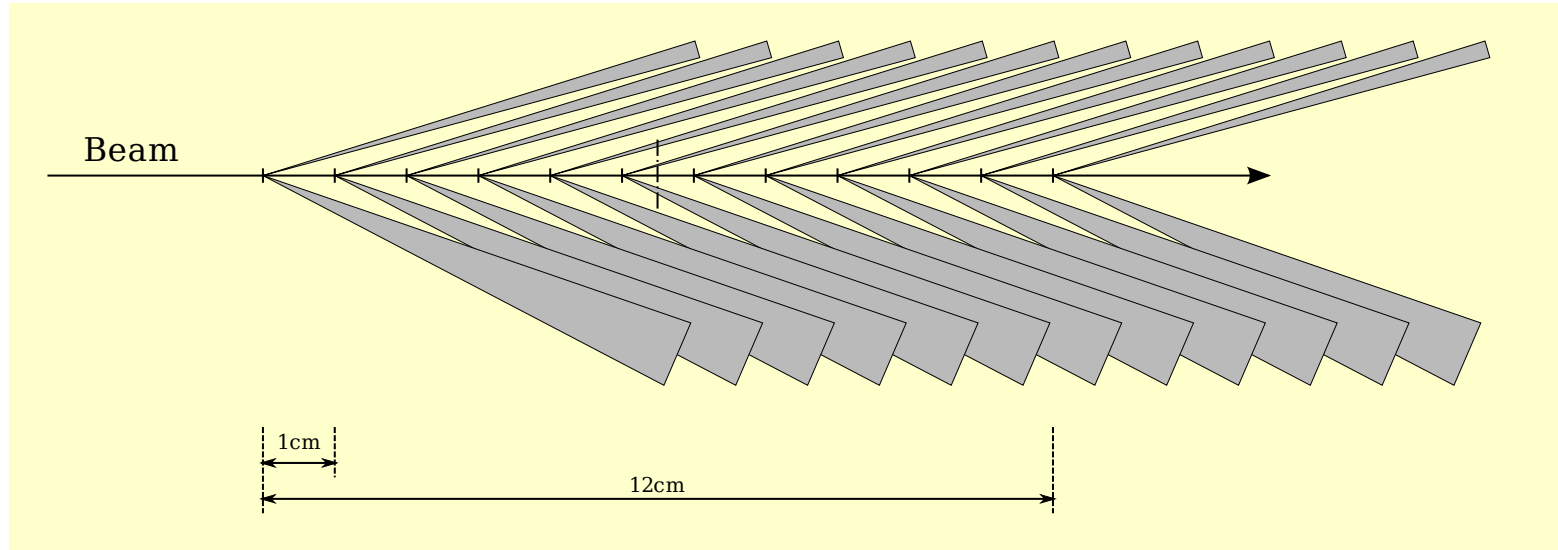
● Input to Full Simulation

- Multiple Scattering (—)
- Radiation correction (—)
- Decay length (+)
- Missing mass resolution (+)

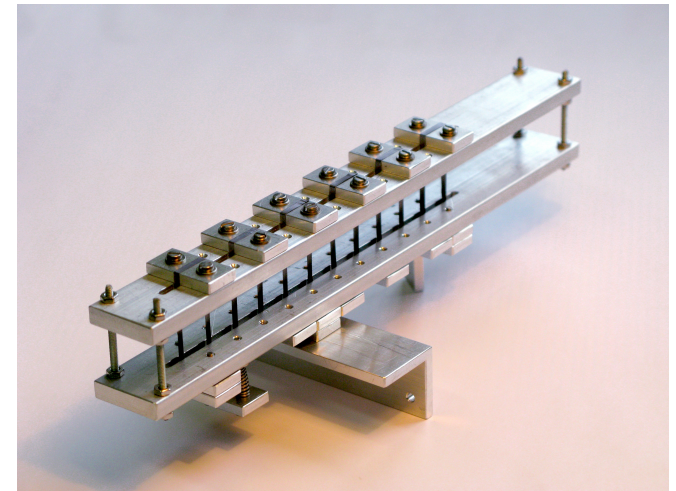
$$\Rightarrow \delta m_{e^+e^-} < 0.5 \text{ MeV}/c^2$$

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

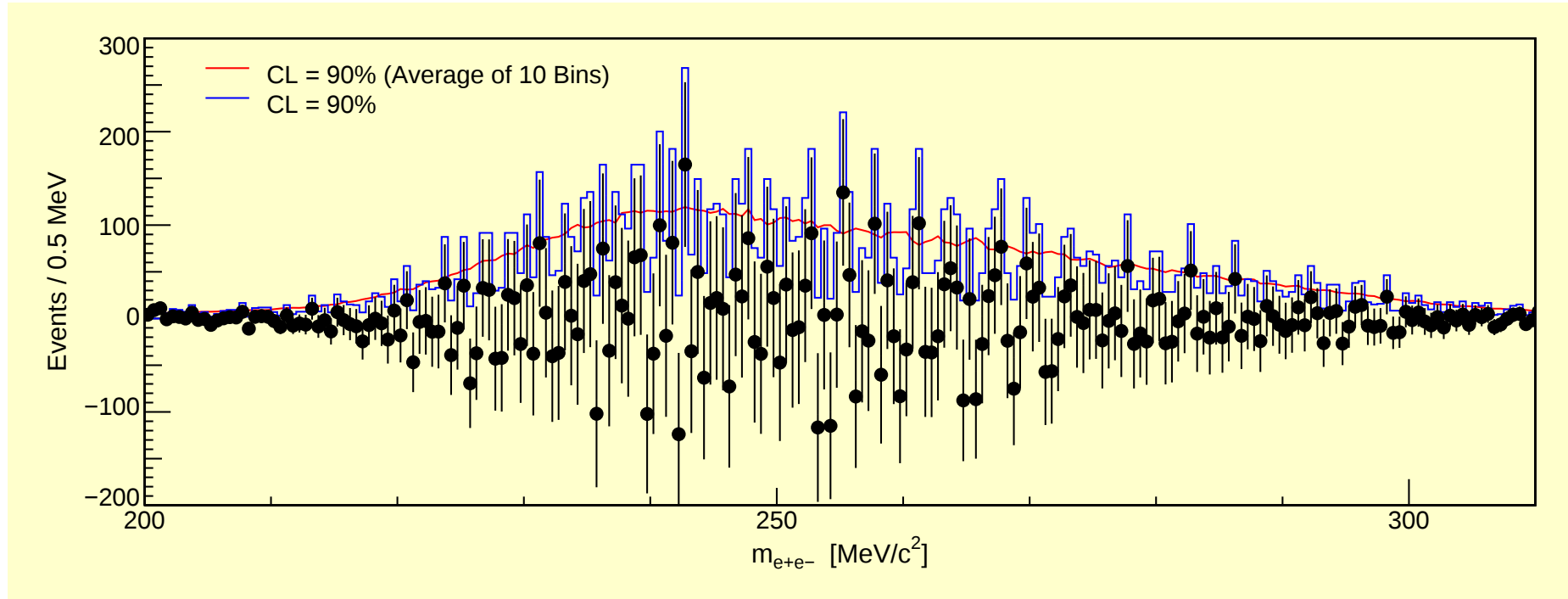
Target Design



- Mass distributed over 12 strips
- Single strip for multiple scattering
- Beam has to hit narrow target (2mm)



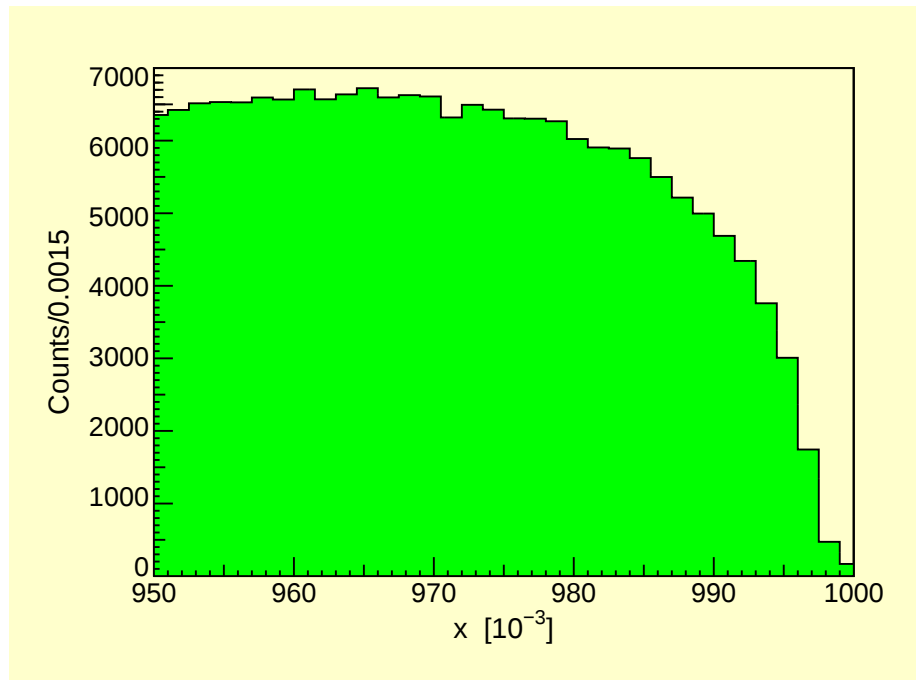
Exclusion limits



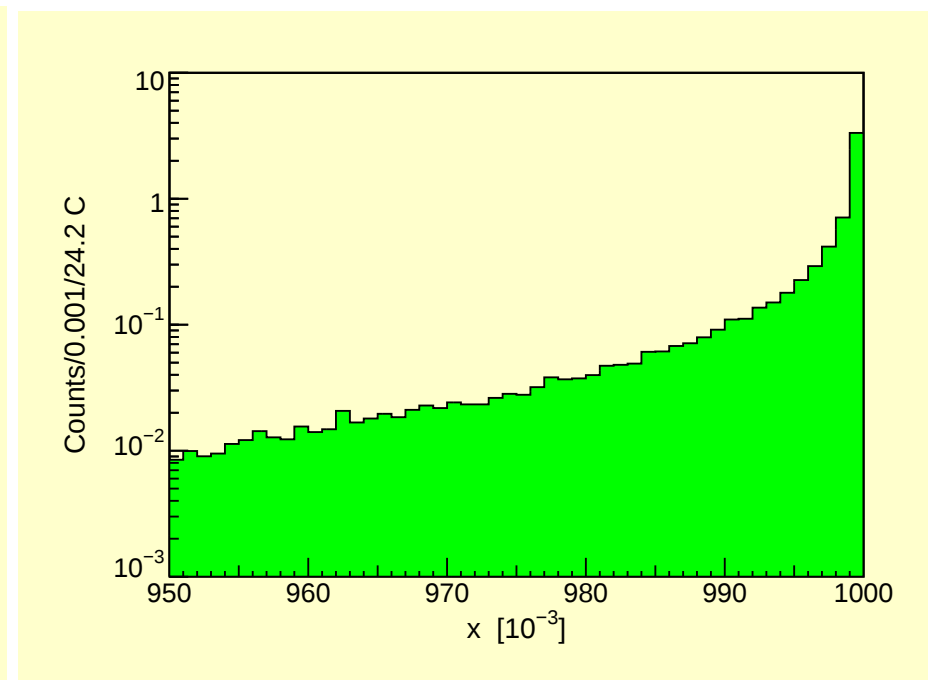
- Confidence interval by Feldman-Cousins algorithm
- “Model” for Background-subtraction:
average of 3 Bins left and right of central bin
- Resolution $\delta m < 500 \text{ keV} = \text{bin width}$
- Averaging (mean of 10 bins) only for “subjective judgment”

Problem: model for cross section

Experiment:

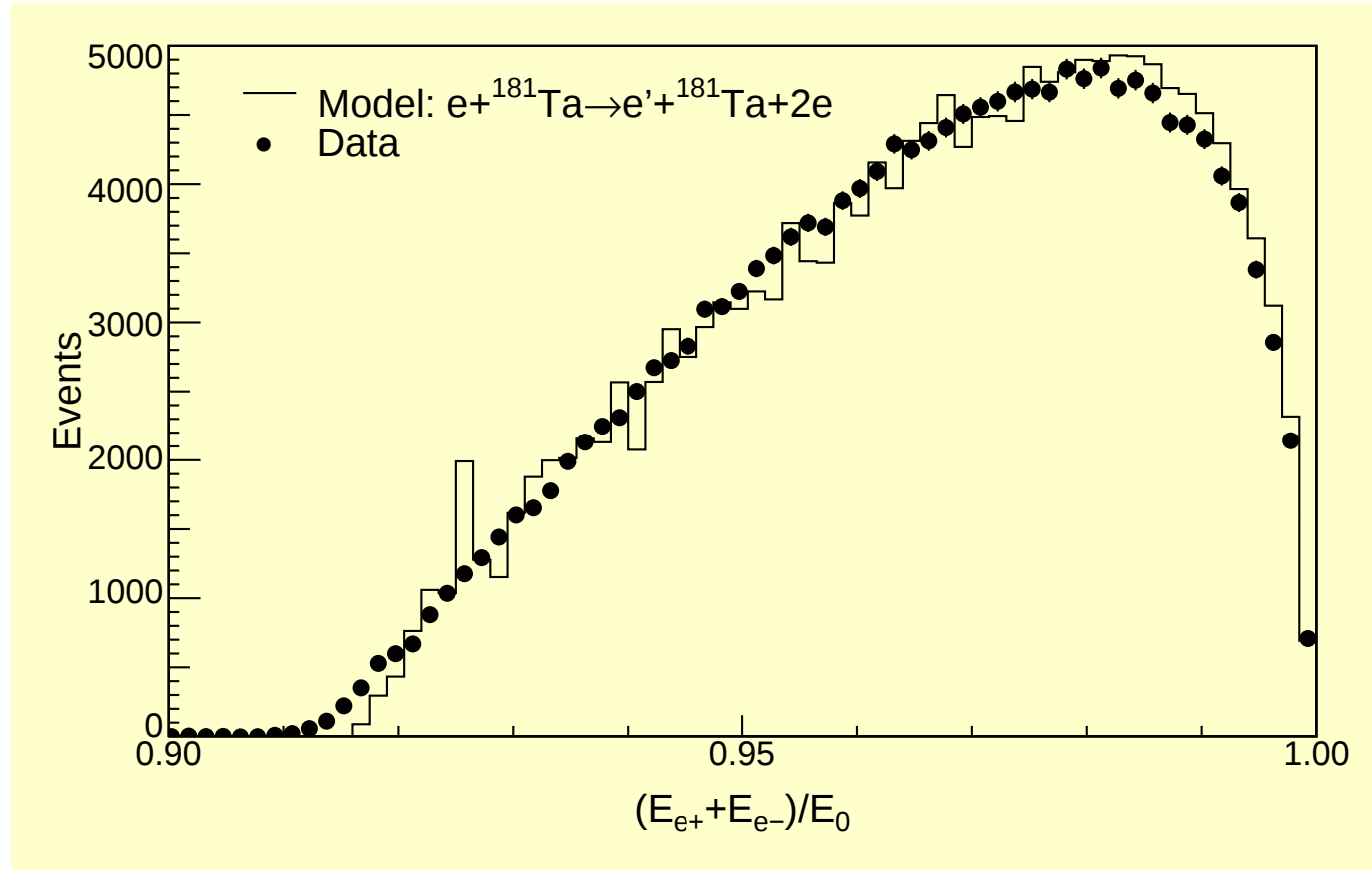


Simulation:



- Fraction of transferred energy $x = E_{\gamma'}/E_0$
- Weizsäcker-Williams approximation does *not* correspond to experiment
- Reason: neglected phase space of recoiling nucleus at $x = 1$
- $\Rightarrow$ Reaction identification!
- $\Rightarrow$ Kinematics of experiment was not (yet) optimal!

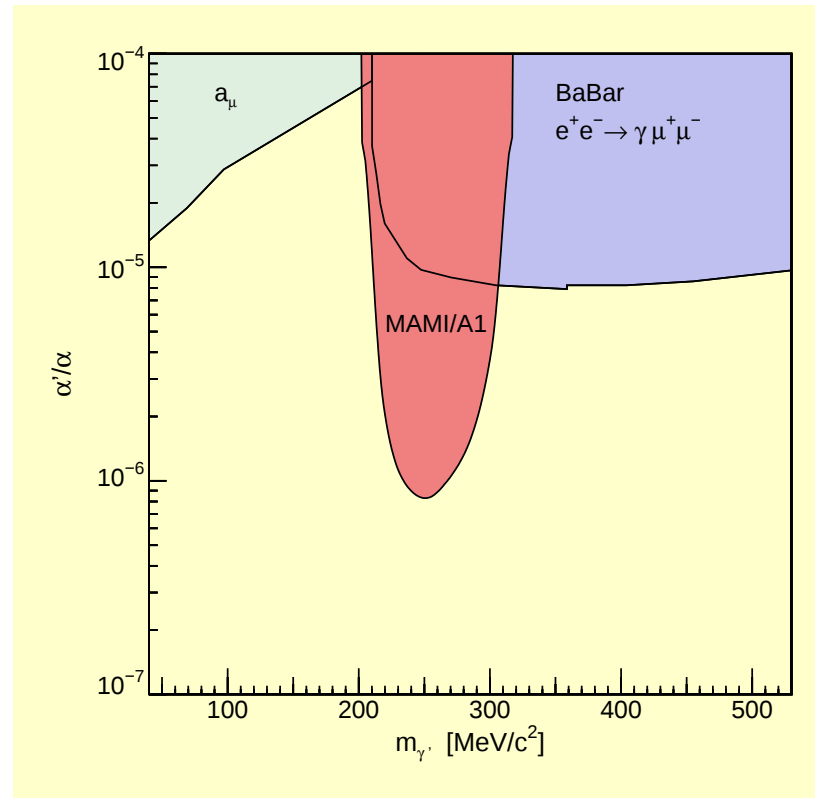
Improved Model



- Electroproduction instead of Photoproduction
- Coherent production off heavy nucleus
- Q.E.D., nuclear form factor, coherent sum of all contributions, radiation corrections, ...

⇒ Describes data within a few percent

Exclusion limit for coupling ε



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

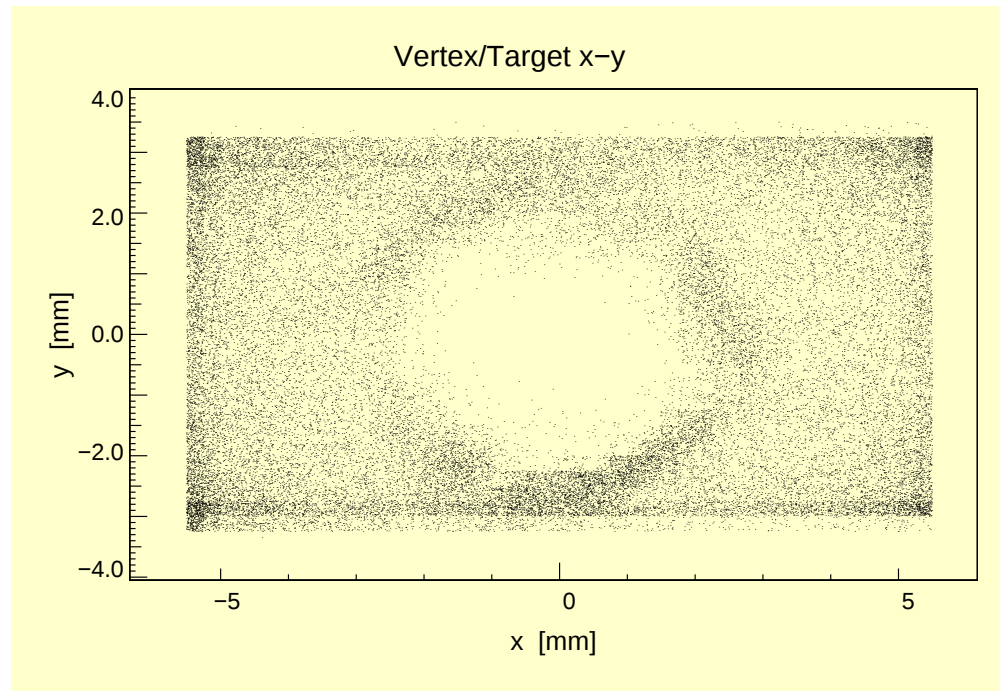
$$\frac{d\sigma(X \rightarrow \gamma' Y \rightarrow l^+ l^- Y)}{d\sigma(X \rightarrow \gamma^* Y \rightarrow l^+ l^- Y)} = \left(\frac{3\pi\varepsilon^2}{2N_f\alpha} \right) \left(\frac{m_{\gamma'}}{\delta_m} \right)$$

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

Future Plans

Limitations of the experiment

$100\mu\text{A}$ beam current for 20 min on 0.05 mm ^{181}Ta target (melting point: 3017°C):



● Air activation

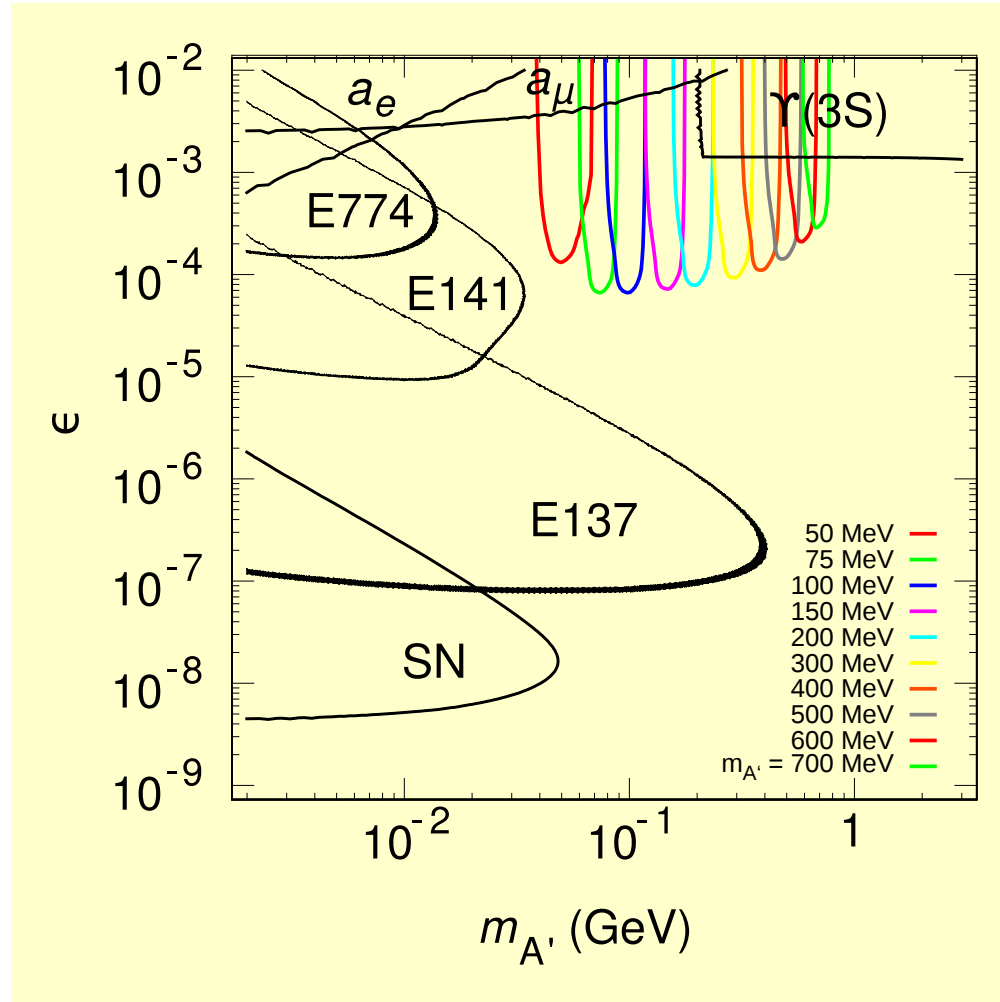
● Optimization of kinematics

● Target cooling

● Shielding

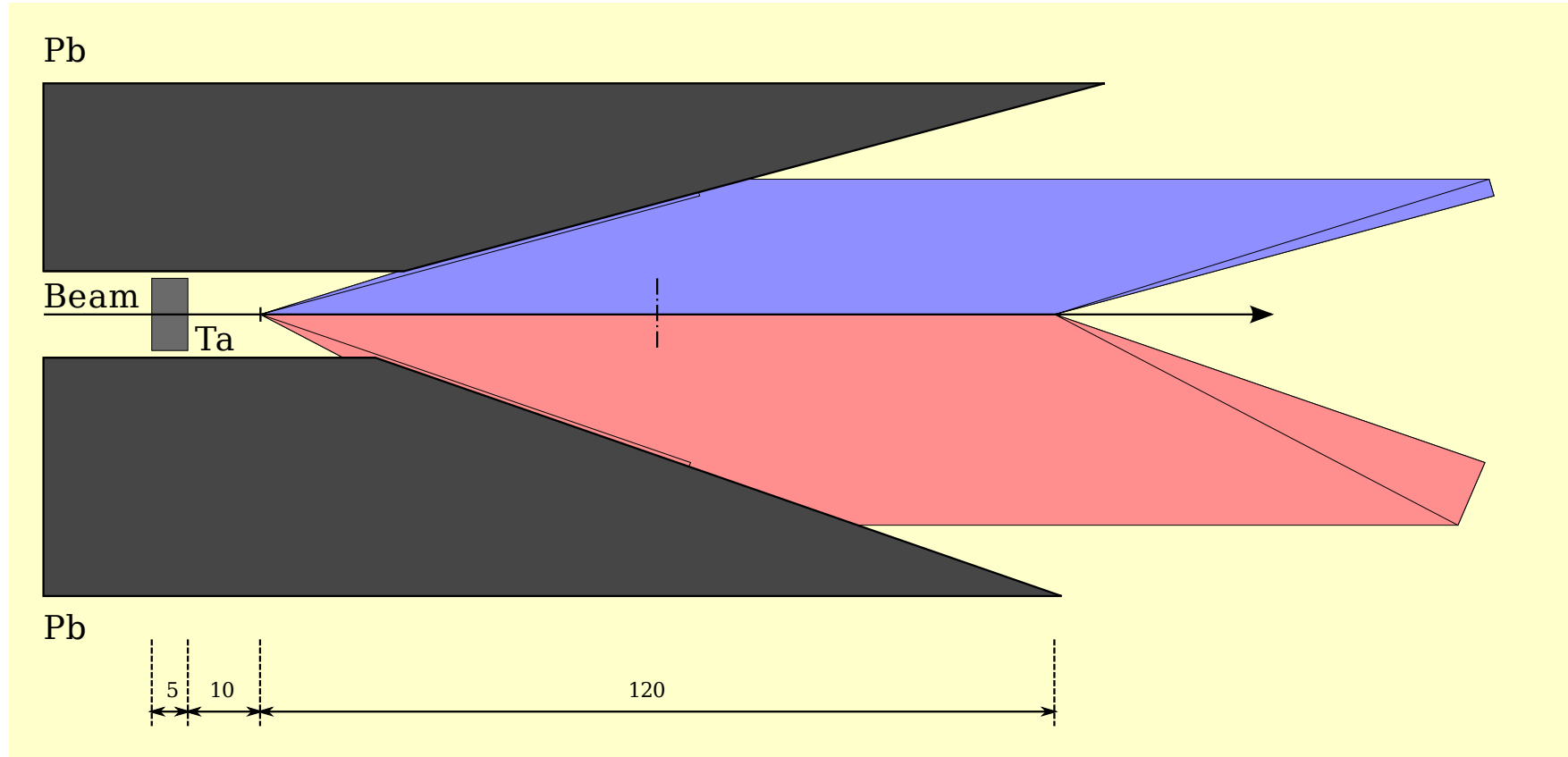
} $\Rightarrow$ 1 order of magnitude higher count rates possible

Simulation: exclusion limits



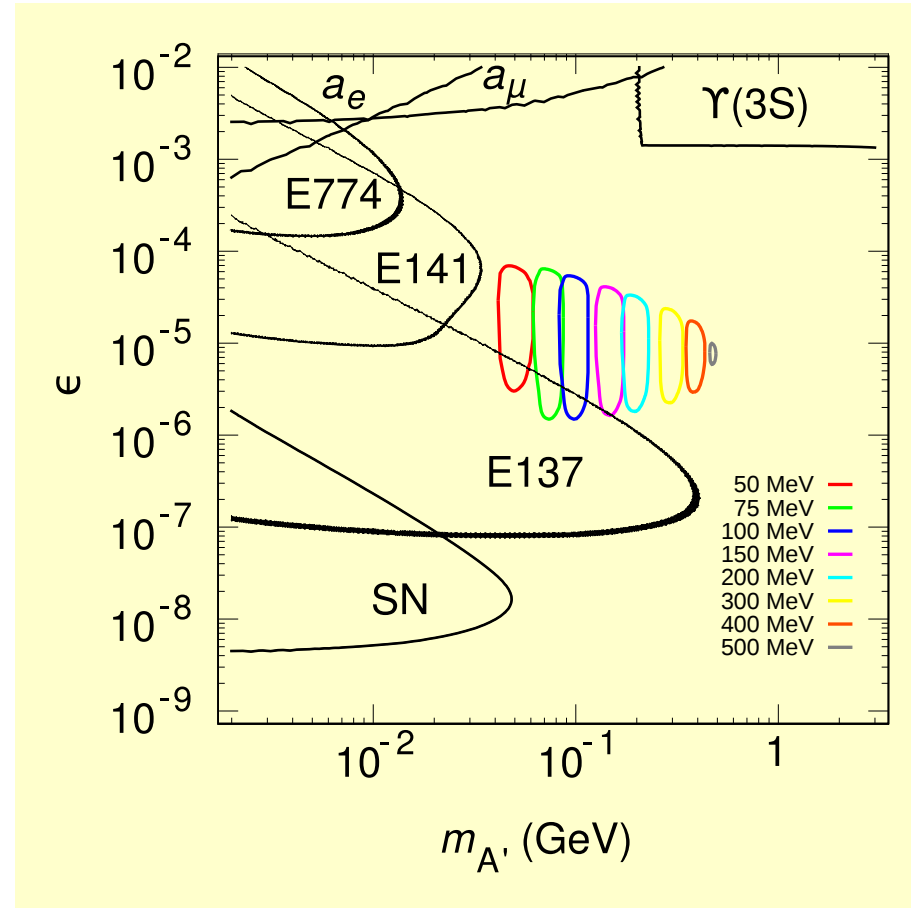
- Background now well understood
- Several settings, change of incident beam energy
- Marked regions: 2σ exclusion

Step 2: Secondary vertex $\rightarrow$ small coupling



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

Step 2: Exclusion limits with shielded production vertex



● Macroscopic decay vertex distance

$$\epsilon < 10^{-4}$$

● Luminosity

$$\epsilon > 10^{-6}$$

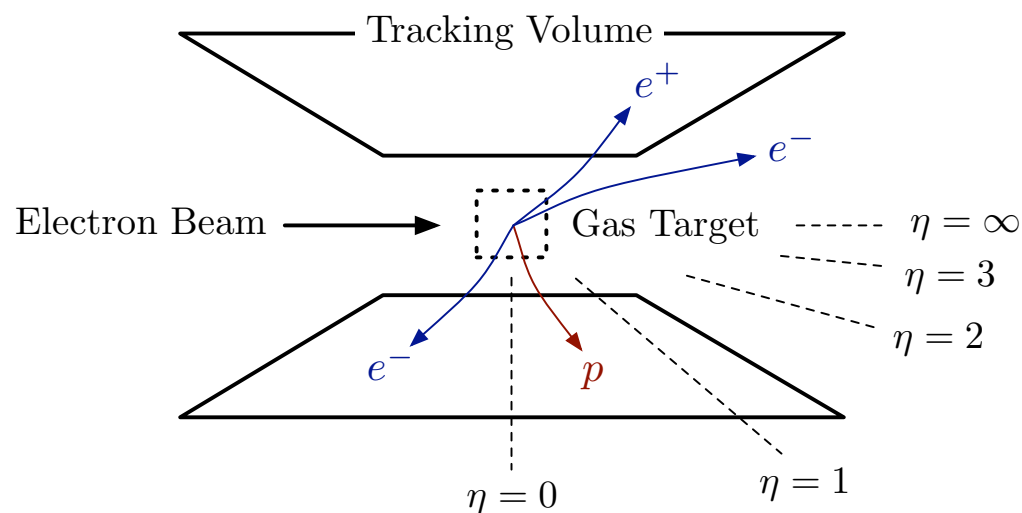
● Coupling vs lifetime

$$m_{\gamma'} < 500 \text{ MeV}/c^2$$

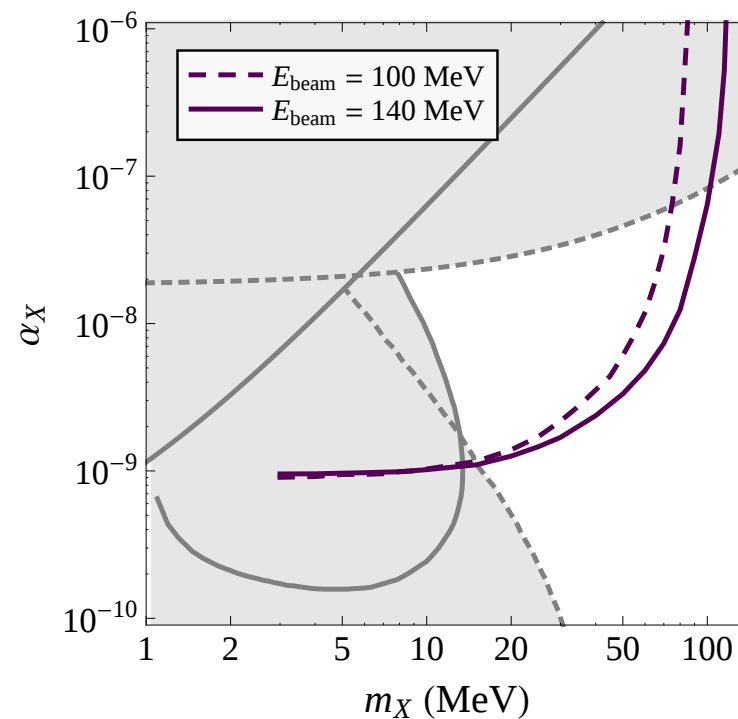
● Angular range

$$m_{\gamma'} > 30 \text{ MeV}/c^2$$

Step 3: Access to low mass region

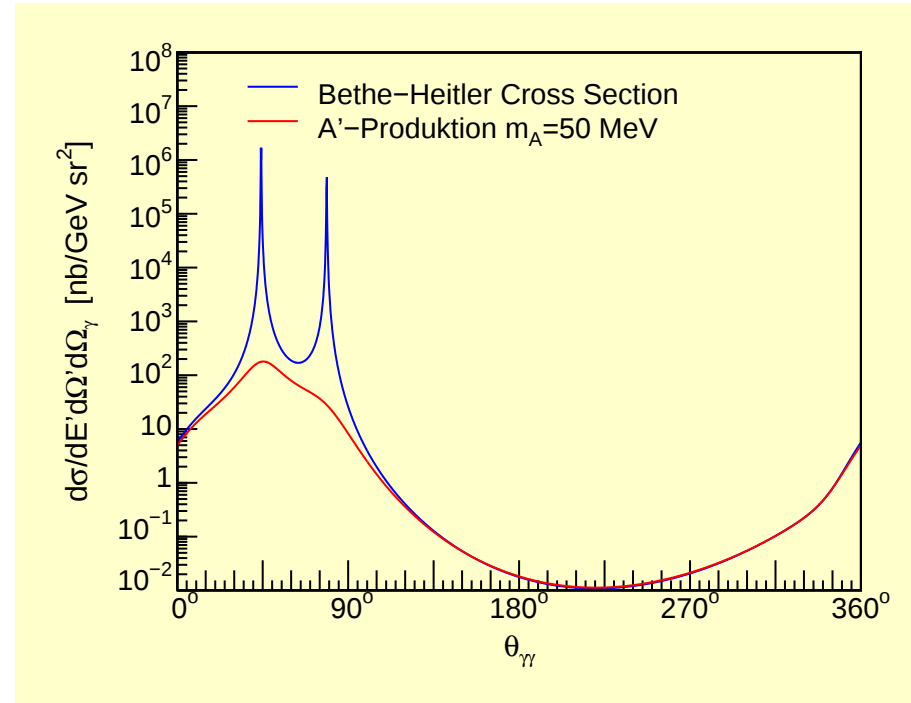


Reach for 1 ab^{-1} (Vector)



- 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), MESA at Mainz

Alternative: Production off the proton → Missing mass



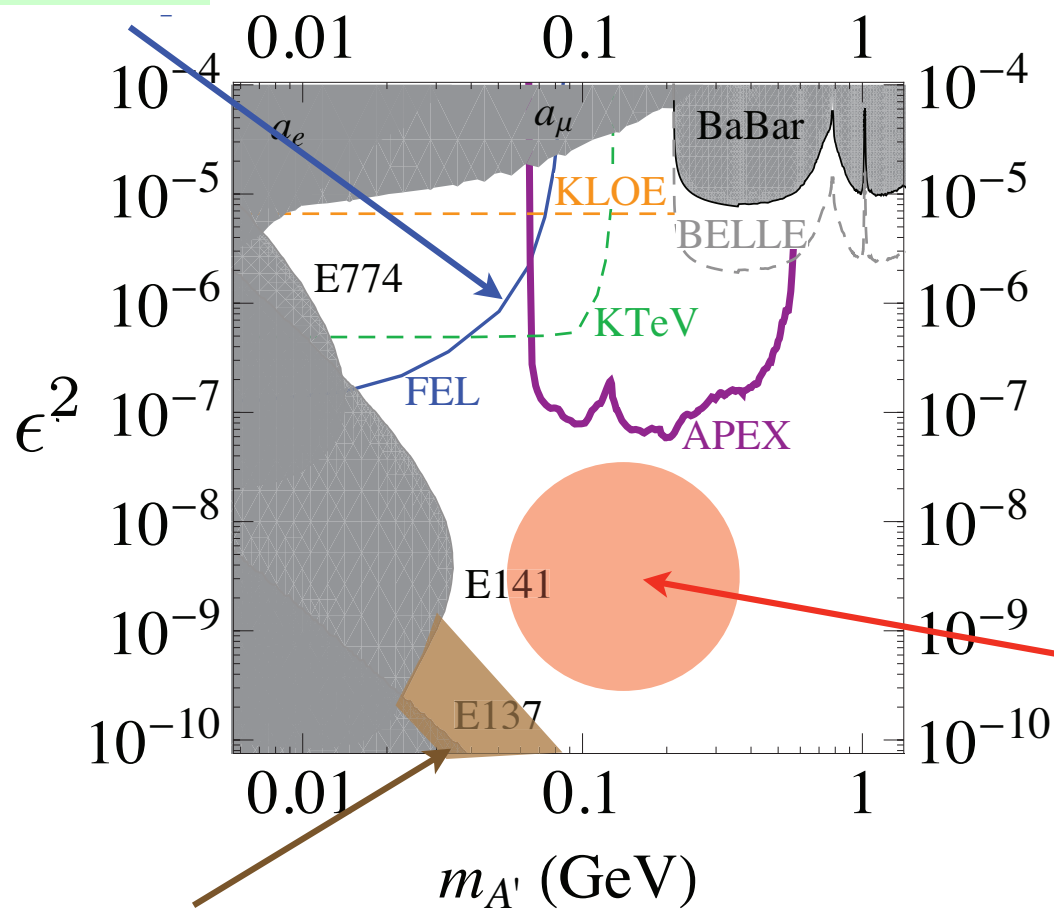
$$e + p \rightarrow e' + p + \gamma' \\ \quad \quad \quad \hookrightarrow e^+ + e^-$$

- γ' detection via missing mass $m_{\gamma'}^2 = (e + p - e' - p')^2$
- No restriction by decay
- Background: virtual Compton scattering: $e + p \rightarrow e' + p + \gamma$ + radiative tail
- Vertex identification with high suppression factor ($10^8 \dots 10^{10}$) necessary
- Detector development

Other projects

JLab Free Electron Laser
Freytsis et al. arXiv:0909.2862

KLOE, BELLE: Rare Meson Decays

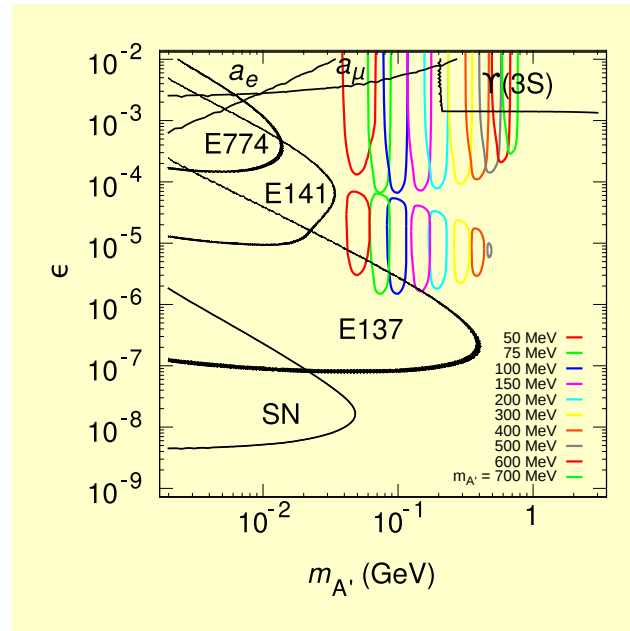


JLab Hall B

HIPS Proposal (Desy)
Beamdump

APEX: JLab Hall A

Summary



Experimental Program:

- ▶ Step 1: Pair production on heavy target
- ▶ Step 2: Shielded production vertex
- ▶ Step 3: Production on LH₂, Micro-vertex detector

$$\begin{aligned}\epsilon &> 10^{-4} \\ 10^{-6} &< \epsilon < 10^{-4} \\ m_{\gamma'} &< 40 \text{ MeV}/c^2\end{aligned}$$

Pilot experiment

- ▶ Experiment is feasible, background is under control
- ▶ Q.E.D. process well understood
- ▶ First exclusion limit $10^{-3} \rightarrow 10^{-4}$ reachable

⇒ Determination of significant exclusion limits for the γ' boson is possible at MAMI/A1

Backup Slides ...

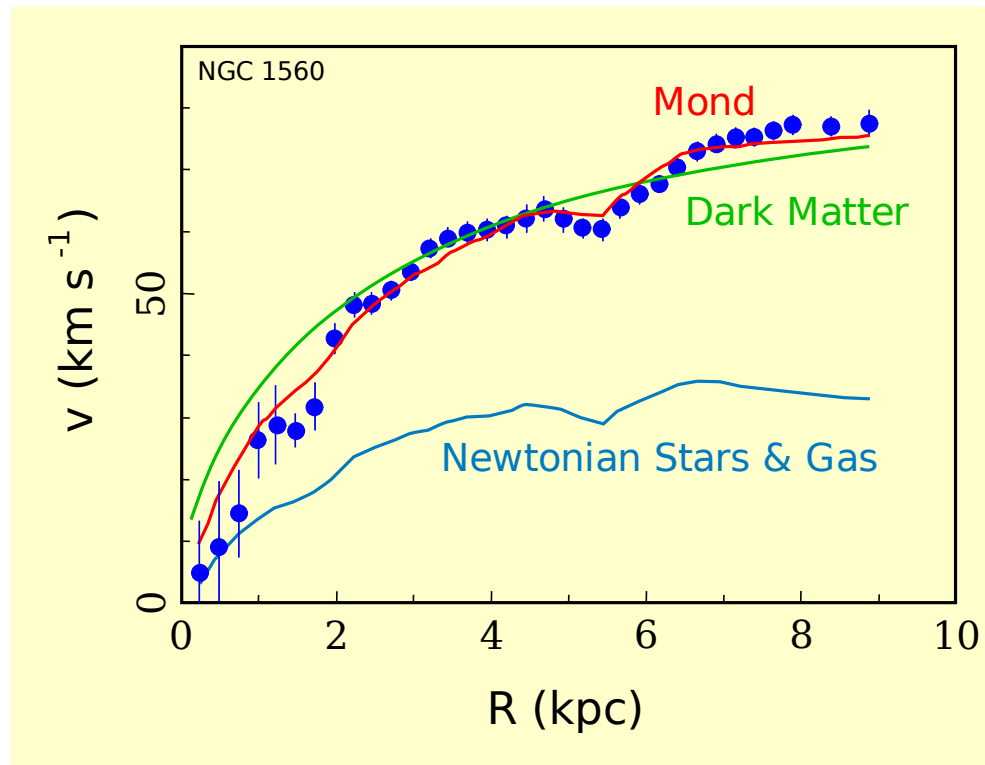
MOND-Hypothesis

MOND modification of Newtonian acceleration g_n (M. Milgrom, 1983):

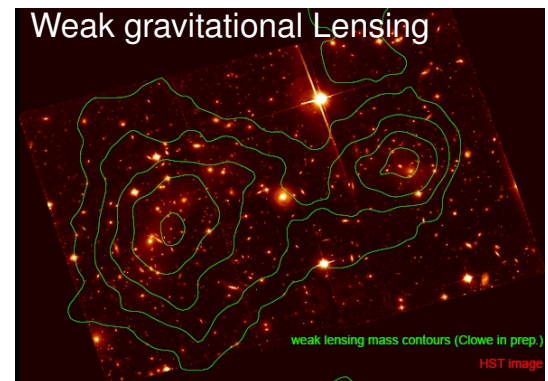
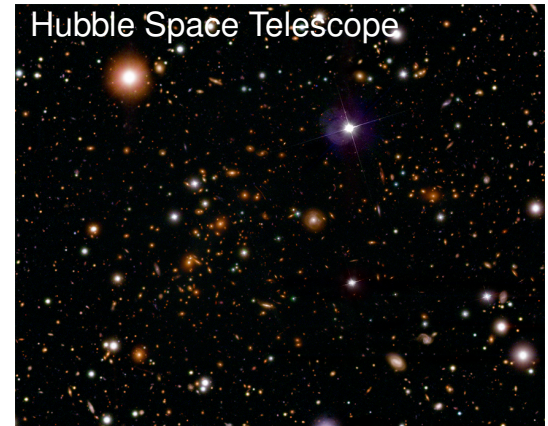
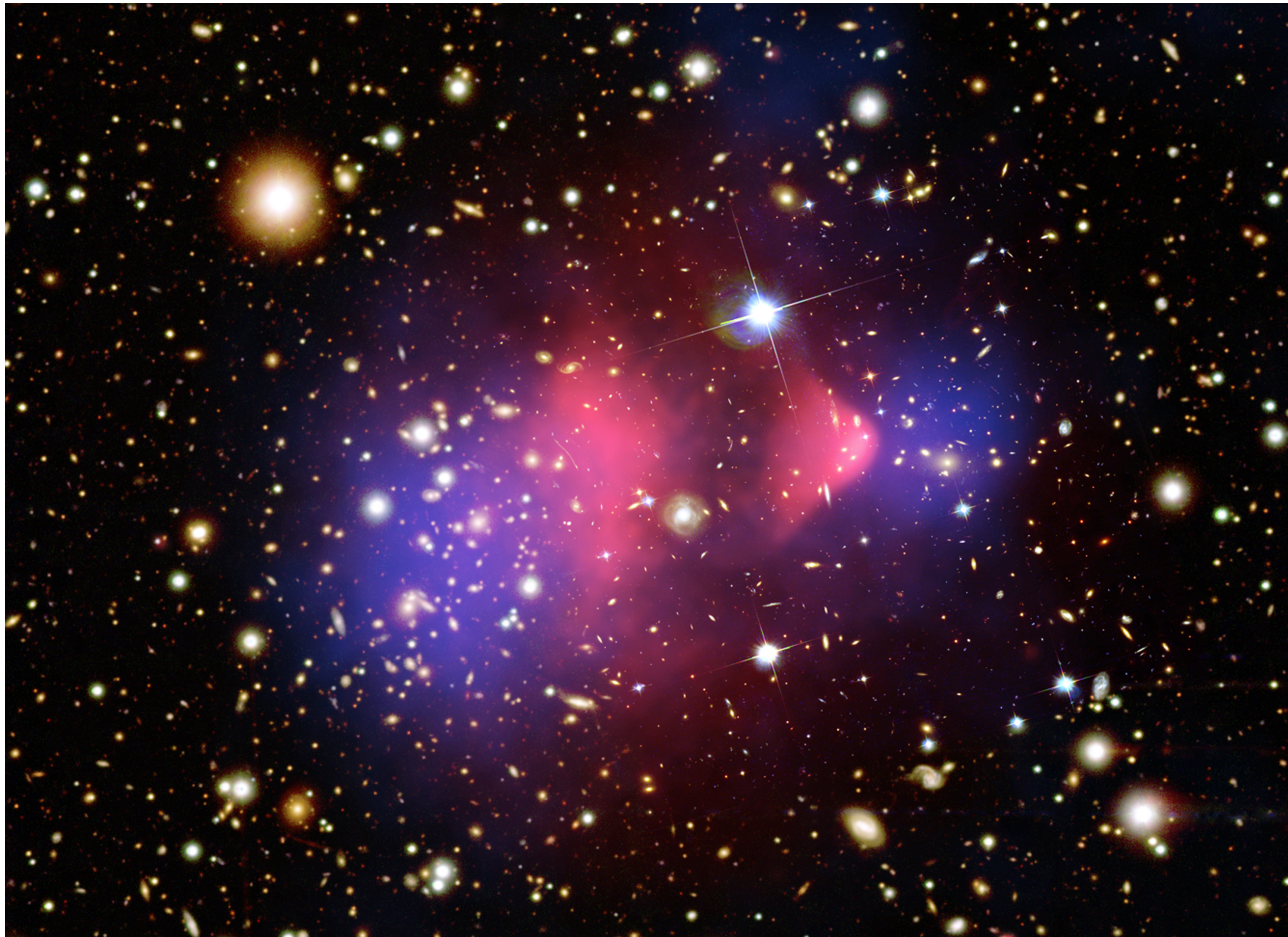
$$g \mu\left(\frac{|g|}{a_0}\right) = g_n$$

Function $\mu(x)$ with limits

$$\begin{aligned} \mu(x) &= x & \text{for } x \ll 1 \\ \mu(x) &= 1 & \text{for } x \gg 1 \end{aligned}$$



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)

⇒ Baryonic mass lags behind total mass

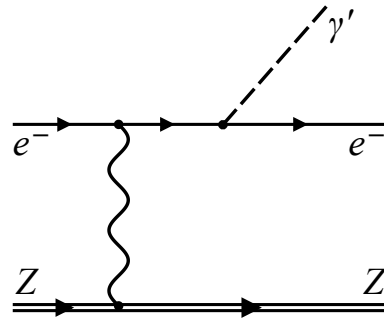
Abell 520 – Counter example to bullet cluster (?)



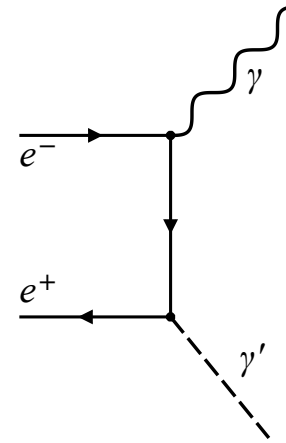
A. Mahdavi et al., *Astrophys. J.* 668, 806Y814 (2007)

Fixed target or collider?

Cross Section

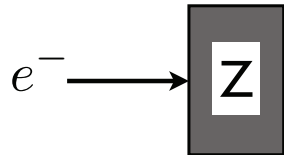


$$\sigma \propto \frac{\alpha^3 \epsilon^2 Z^2}{m_{\gamma'}^2} \sim 1 \text{ pb}$$



$$\sigma \propto \frac{\alpha^2 \epsilon^2}{E_{cm}^2} \sim 1 \text{ fb}$$

Luminosity



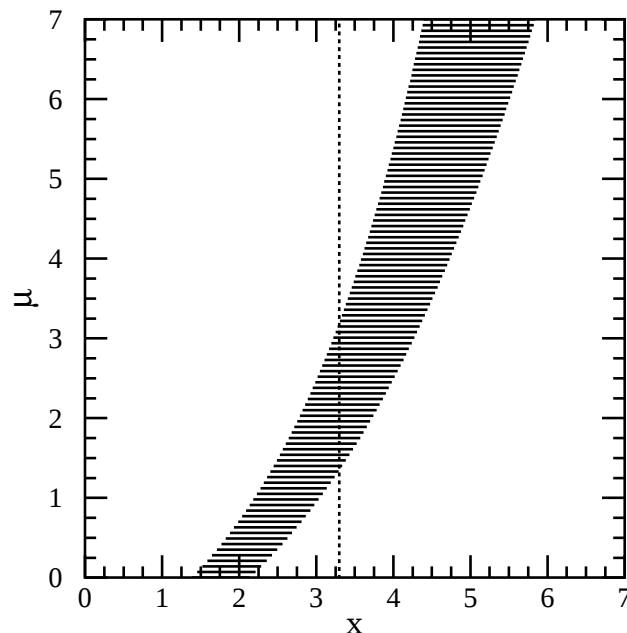
$\sim \text{few } ab^{-1} / 10 \text{ days}$



$\sim \text{few } ab^{-1} / 100 \text{ years}$

Feldman-Cousins-Algorithm

Example: $\mu = 0.5, b = 3$



n	$P(n \mu)$	μ_{best}	$P(n \mu_{\text{best}})$	R	rank	U.L.	central
0	0.030	0.	0.050	0.607	6		
1	0.106	0.	0.149	0.708	5	✓	✓
2	0.185	0.	0.224	0.826	3	✓	✓
3	0.216	0.	0.224	0.963	2	✓	✓
4	0.189	1.	0.195	0.966	1	✓	✓
5	0.132	2.	0.175	0.753	4	✓	✓
6	0.077	3.	0.161	0.480	7	✓	✓
7	0.039	4.	0.149	0.259		✓	✓
8	0.017	5.	0.140	0.121		✓	
9	0.007	6.	0.132	0.050		✓	
10	0.002	7.	0.125	0.018		✓	
11	0.001	8.	0.119	0.006		✓	

- n -Values sorted by $R = P(n|\mu)/P(n|\mu_{\text{best}})$ with $\mu_{\text{best}} = \max(0, n - b)$.
- Add to interval by order until confidence limit (e.g. $\alpha = 95\%$) is reached.
- Determine vertical interval for measured $x = n$.