Constraints on Dark Photon Production from Dilepton Sources at SIS Experiment

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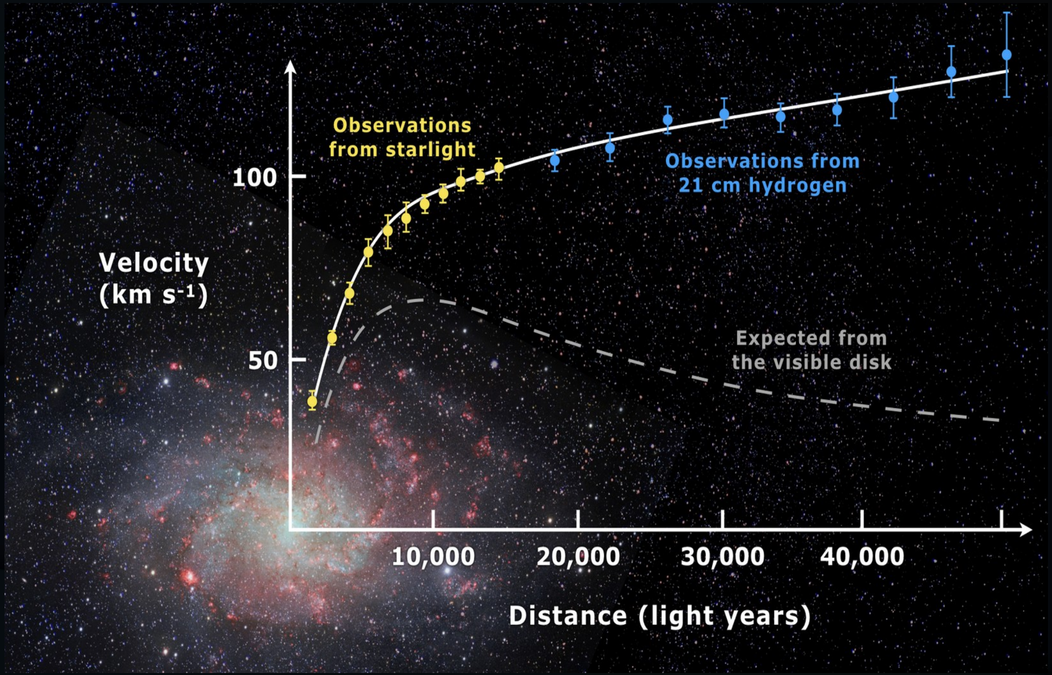
Introduction to Dark Matter

Dark Matter: First Observations

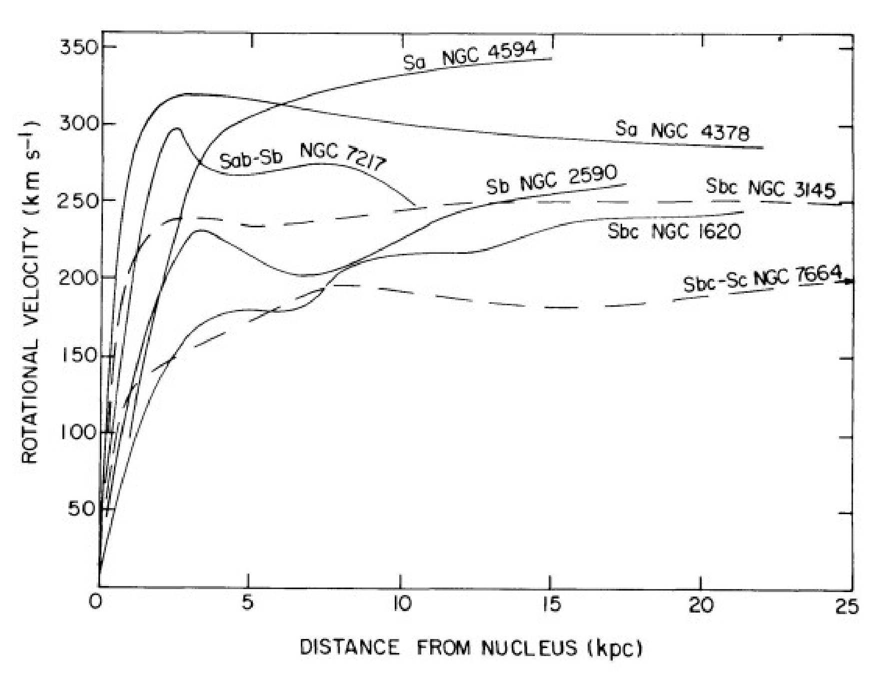
- Observations in 1930s and 1970s
- F. Zwicky: observation of galaxy clusters
- V. Rubin: rotation anomalities in galaxies
- Rotation velocity too large for stable galaxies
- Rotation curves!



[1] Rotation Velocity in dependence on radius

Rotation Curves

- Flat Curves for large distances
- Result: some extra matter had to be present in the galaxies
- Observed via its gravitational impact
- No visible matter (no e.m. interactions) → Dark Matter (DM)



[2] Rotation Curves of 7 galaxies

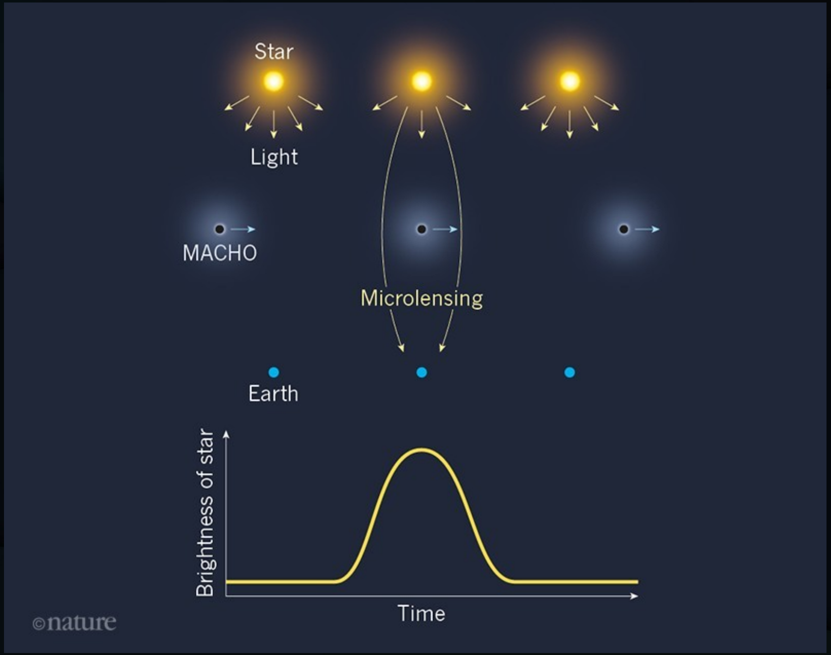
Possible explanations

- Invisible Standard Model (SM) matter (MACHOs)
- MOND hypothesis
- Invisible non-SM matter

Pinwheel Spiral Galaxy

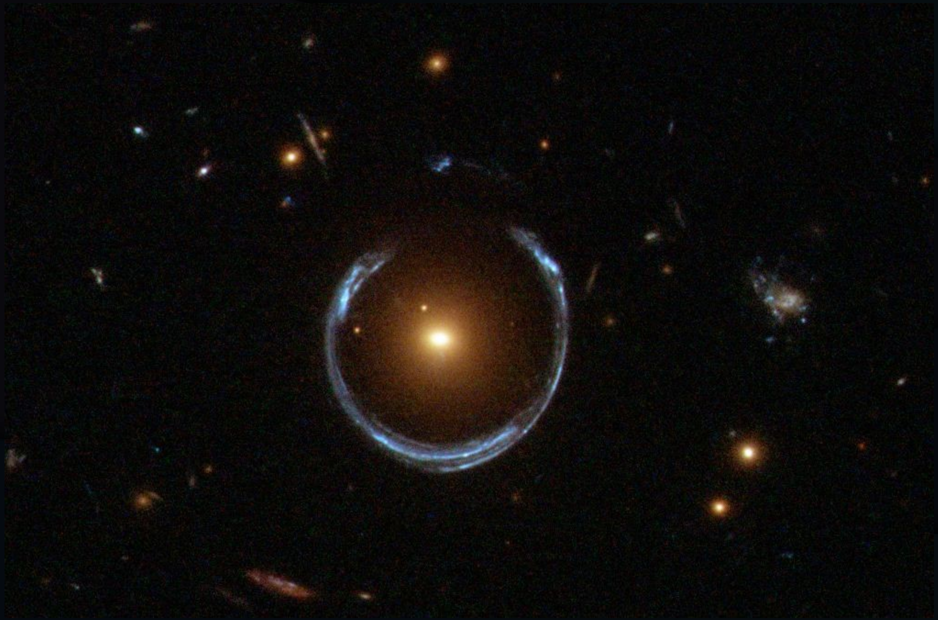
Gravitational Lensing and MACHOs

- Massive Astrophysical Compact Halo Object
- Massive objects act as lenses
- Due to General Relativity, light is distorted
- Observation of MACHOS possible
- MACHOS make <1%
- Ruled out as candidates!



[3] Microlensing Effect of MACHO

Observation of MACHOs



[4] Einstein Ring

- 1993: 1/1.8mio. Monitored stars was MACHO
- Even after improved measurements: very low percentage
- MACHOs very unlikely to be Dark Matter

MOND hypothesis

- ‘Modified Newtonian Dynamic‘
- Changing 2nd newtonian law
- Significant changes for $a<<a_0$ at large distances
- Causes constant speed at high distances

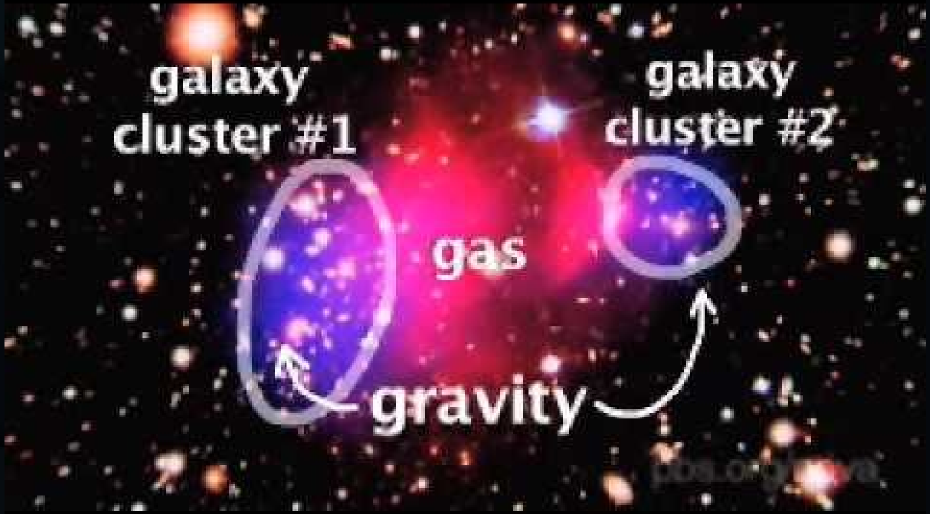
$$F = m\ \mu(|a|/a_0)\, a$$

Evidence for Dark Matter: Bullet Cluster

[5] Picture of Bullet Cluster

Dark Matter in Bullet Cluster

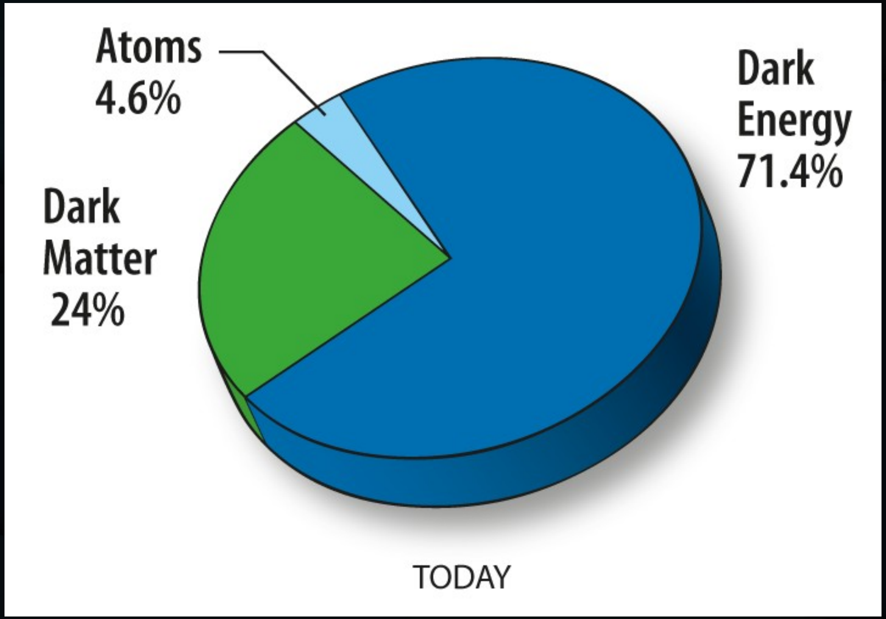
- Clusters collided
- Baryonic mass remained in collision zone
- Main part of mass remained in the clusters
- Indication for DM!



[6] Matter Distribution in Bullet Cluster

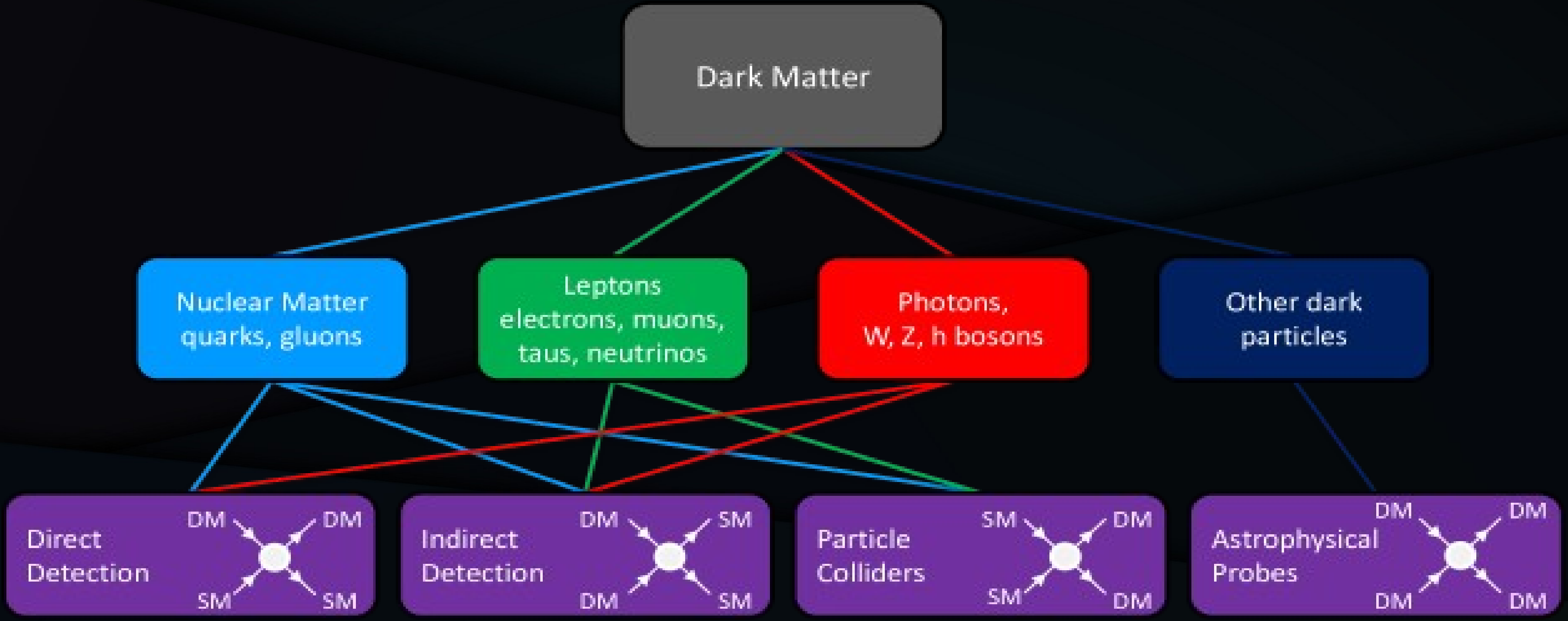
Results

- Dark Matter: most likely explanation
- No e.m. interactions
- No baryons (no self-interaction, no interactins with gas in BC)
- Gravitational effects!
- DM must make about 25% of universe‘s matter
- DM is assumed to consist of WIMPs (Weakly Interacting Massive Particles)



[7] Dark Matter in our Universe

Measuring Approaches



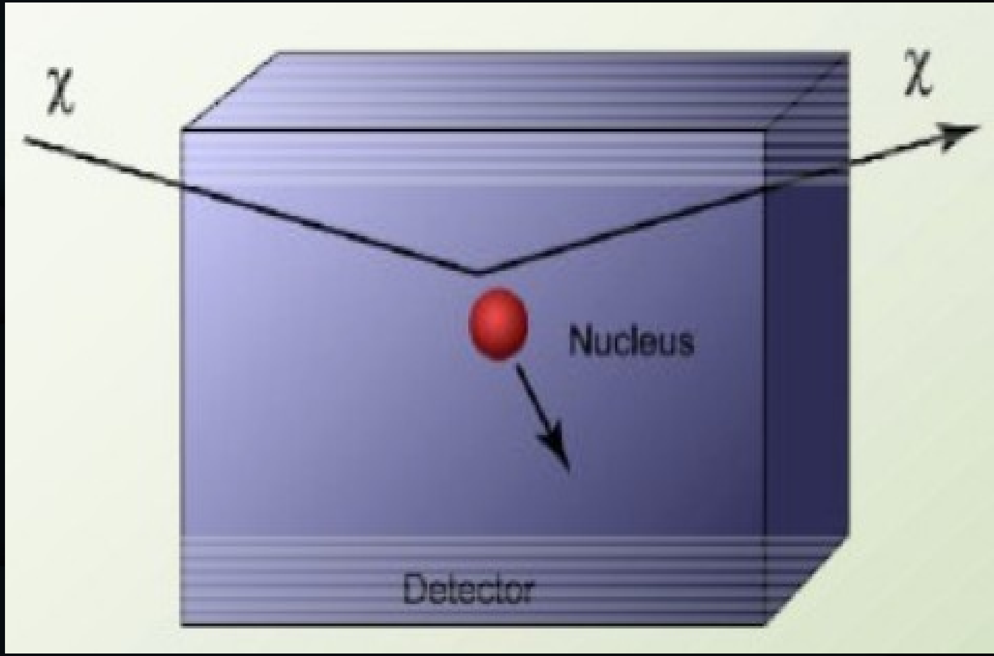
[8]

Astrophysical Probes

- Measurement of effects on structure formation of universe
- Hope to give insights about temperature of Dark Matter
- Research on self-interaction of DM
- Main research approach: Gravitational Lensing
- Testing for presence of dark sub-halos in halos of galaxies
- Observations could be consistent with hidden-sector models

Direct Detection

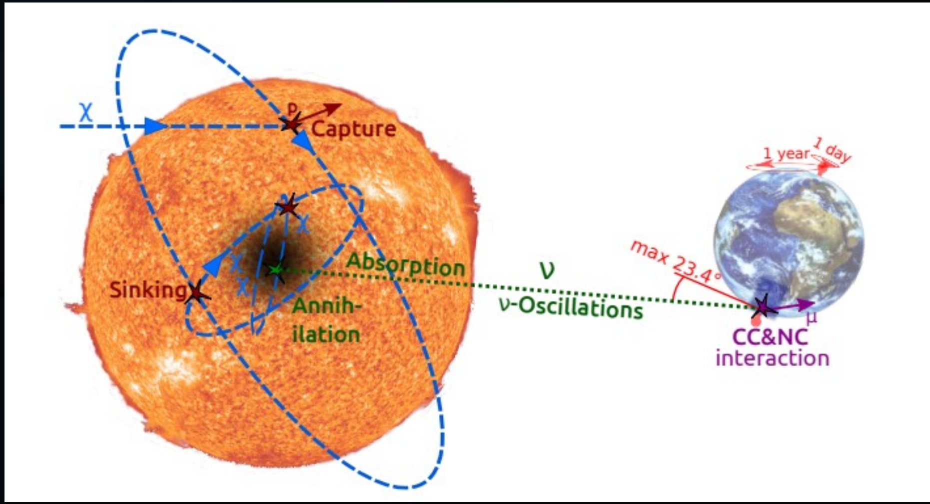
- DM particles pass earth
- Try to detect them in detectors
- Use weak interaction with baryonic matter
- WIMPs scatter from nucleus
- electrons/photons scatter from atomic electrons
- Assumption: homogeneous local DM density
- Mass energy range of detected DM: keV-MeV
- Problem: low scattering rate



[9] Direct Detection Method

Indirect Detection

- Annihilation products or decay
- Particles originated in outer space
- Stable messenger particles in SM: neutrinos, γ-rays, positrons
- Signals of several hundred GeV, according to DM mass
- WIMPS from outer space captured in sun
- Annihilation in sun
- Decay Products are measured on earth



[10] Indirect Detection from particles captured by sun

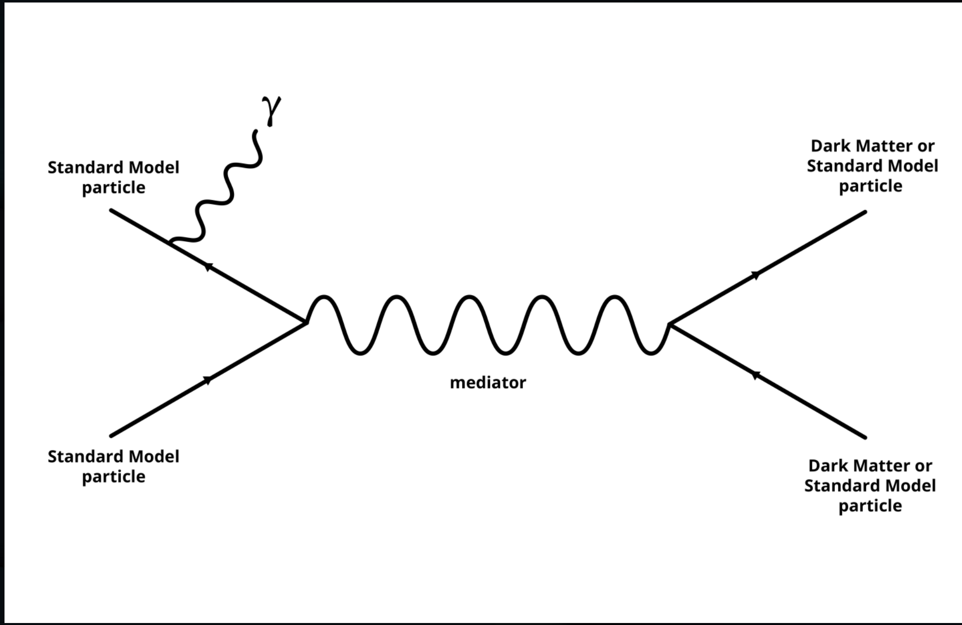
Particle Colliders

- Independent of astrophysical measures
- Focus again on weak interaction (WIMPs)
- Mediator Particles: Interaction via new, unknown particle
- Portal: interaction via SM particles

Extension of the Standard Model:
WIMPs, Dark Sector, and A‘ gauge bosons

WIMPs

- Weakly Interacting Massive Particles
- Interactions between DM and SM particles trought mediator particle
- Can range in mass and other properties
- Must be stable on scale of the universe
- Hard to detect



[11] Interaction of DM with SM through WIMP

Dark Sector

- Add new Sector to Standard Model
- Contains DM particles & interactions
- No single DM particle/interaction!
- Interaction via portals
- SM particles could decay into DM particles
- Additional decay modes

Portals

- Choice of portal depends on mediator‘s spin and parity
- Gauge symmetries restrict coupling of mediator to SM
- Focus: vector portal
- Coupling constant ε

Portal	Particles	Operator(s)
“Vector”	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
“Axion”	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
“Higgs”	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
“Neutrino”	Sterile neutrinos	$y_N L H N$

[12] Possible Portals

J. Alexander et al., 1608.08632 [hep-ph] (2016)

Dark Photons

- Coupling through vector portal
- Described by Dark Photon Lagrangian
- $F'_{\mu\nu}$: Dark Photon Field Strength

  $F'_{\mu\nu}=\partial_\mu A'_\nu - \partial_\nu A'_\mu$
- $B_{\mu\nu}$: SM hypercharge field strength

  $B_{\mu\nu}=\partial_\mu B_\nu - \partial_\nu B_\mu$
- ε: coupling constant (mixing parameter)
- A‘: Dark Photon Field
- $m_{A'}$: Dark Photon mass

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

$$\mathcal{L}_{\text{kin.mix.}} = \frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}.$$

J. Alexander et al., 1608.08632 [hep-ph] (2016)

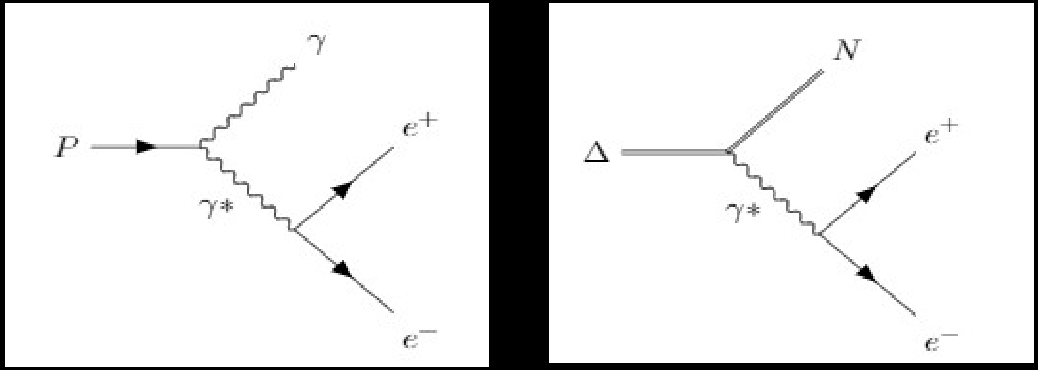
Search for Dark Matter at Particle Colliders

Search for Dark Photons at HADES

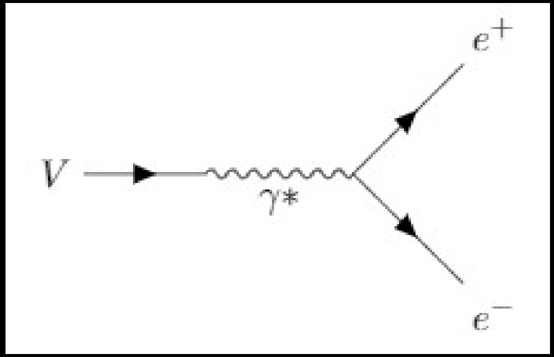
- Measurement of Dilepton Spectra
- At HADES: inclusive measurement
- p+p and p+Nb collisions at 3.5 GeV
- Ar+KCl collisions at 1.76 A GeV
- Research on Dilepton decays of π^0, η, and Δ resonances
- Search for Dark Photons using SIS18
- $U \rightarrow e^+e^-$
- Not possible without measuring SM background

Dilepton Sources

- Dilepton emission from different stages of reaction
- Not effected by final-state interactions
- Clear information about production channels
- Dilepton spectra dominated by π^0, η, and Δ dilepton decays at $m < 0.6$ GeV/c^2
- Direct decay: $h \rightarrow \gamma^* \rightarrow e^+e^-$
- Dalitz decays: $h \rightarrow \gamma\gamma^* \rightarrow \gamma e^+e^-$

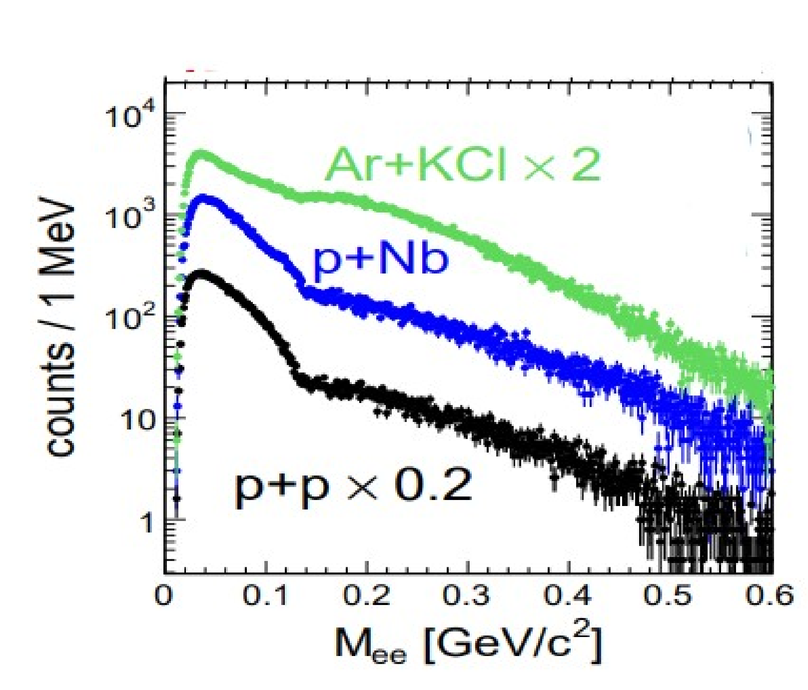


Dalitz decays of Pseudoscalar mesons and Δ-Resonances



Direct decay of vector meson

HADES measurements

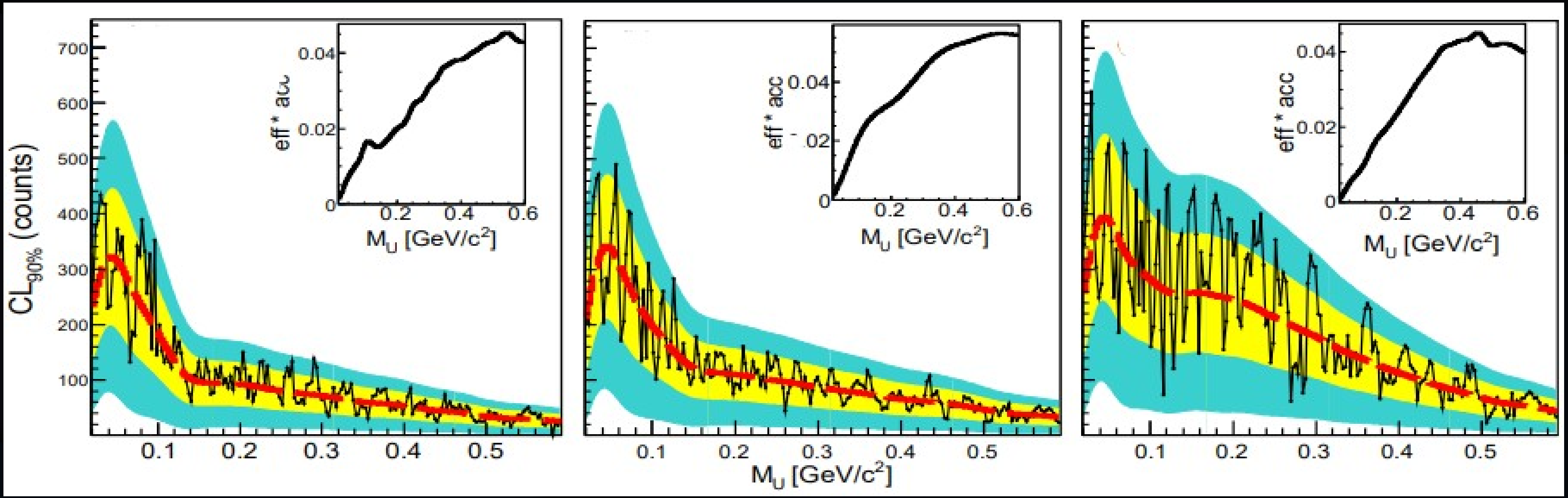


HADES inclusive dilepton spectra for p+p and p+Nb at 3.5GeV and Ar+KCl at 1.76 A GeV

- Not efficiency corrected
- Narrow gaussian added at every invariant mass point
- Gaussians do not exceed data by more than 90% confidence level
- Fluctuations are added by simulations
- If no signal is observed: upper limit can be found!
- ε^2 gives upper limit

G. Agakishiev et al., Phys.Lett.B 731 (2014) 265-271

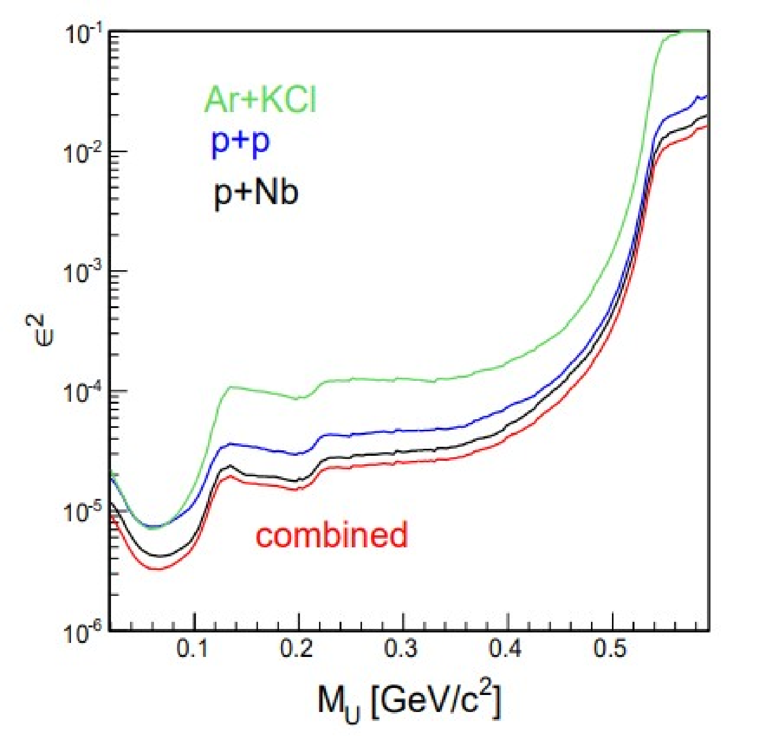
HADES results

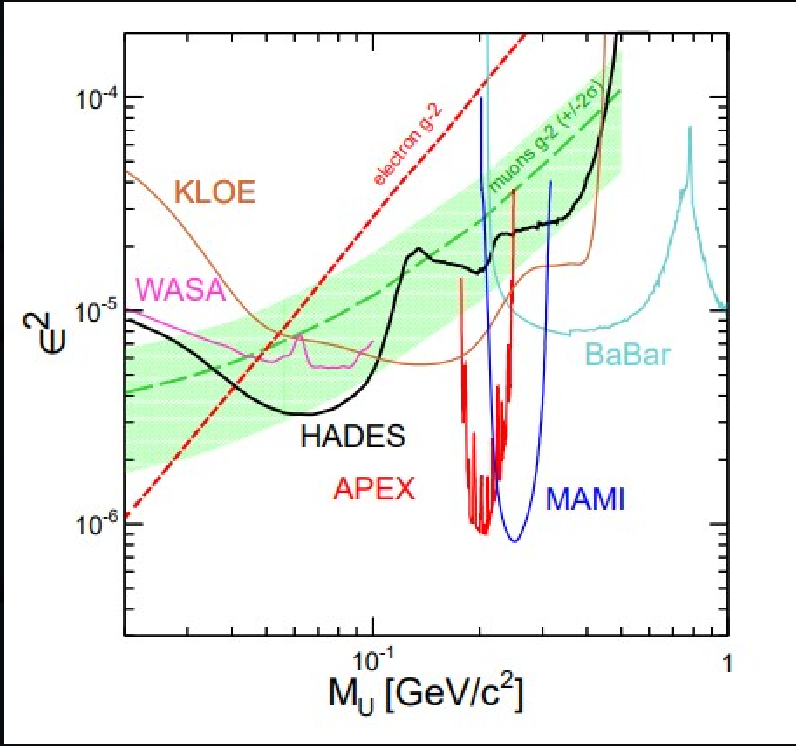


Extracted 90% confidence level (Confidence Level) upper limits for a narrow $U \rightarrow e^+e^-$ signal found by HADES for p+p (left), p+Nb (middle) and Ar+KCl (right).

G. Agakishiev et al., Phys.Lett.B 731 (2014) 265-271

HADES upper limit





G. Agakishiev et al., Phys.Lett.B 731 (2014) 265-271

Finding an Upper Limit

Extract ε^2 from theoretical calculations

- Calculate dilepton spectra and U-Boson decay using PHSD
- Total U-Boson cannot overshoot sum of SM decays by more than given acceptance (20%)
- Extract ε^2 from PHSD results
- Using sum of SM contribution

  and U-Boson contribution

$$\frac{dN}{dM}^{total} = \frac{dN}{dM}^{sumSM} + \epsilon^2 \frac{dN}{dM}^{sumU}$$

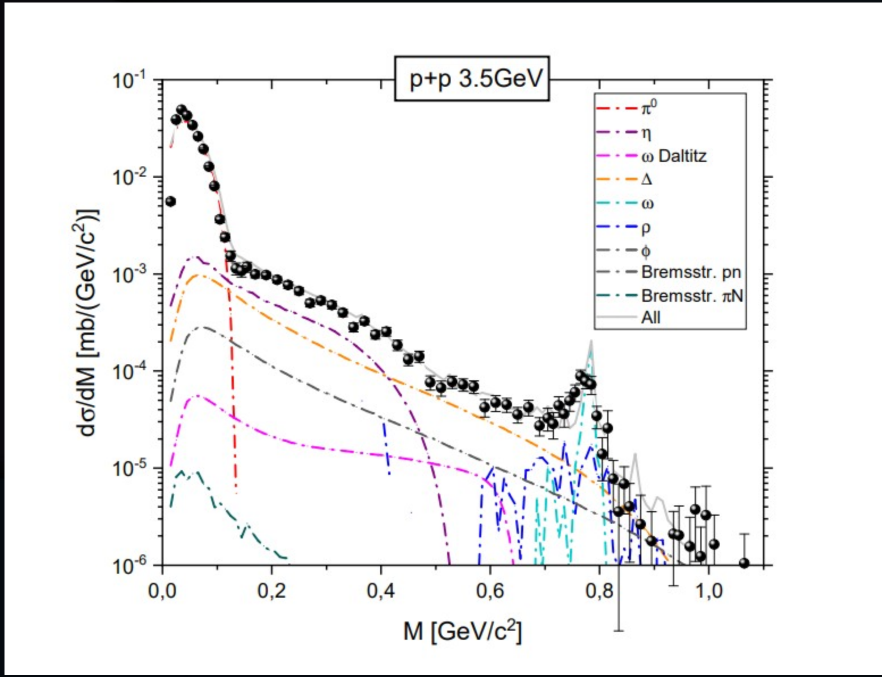
$$\epsilon^2 = 0.2 \cdot \left(\frac{dN}{dM}^{sumSM}\right) / \left(\frac{dN}{dM}^{sumU}\right)$$

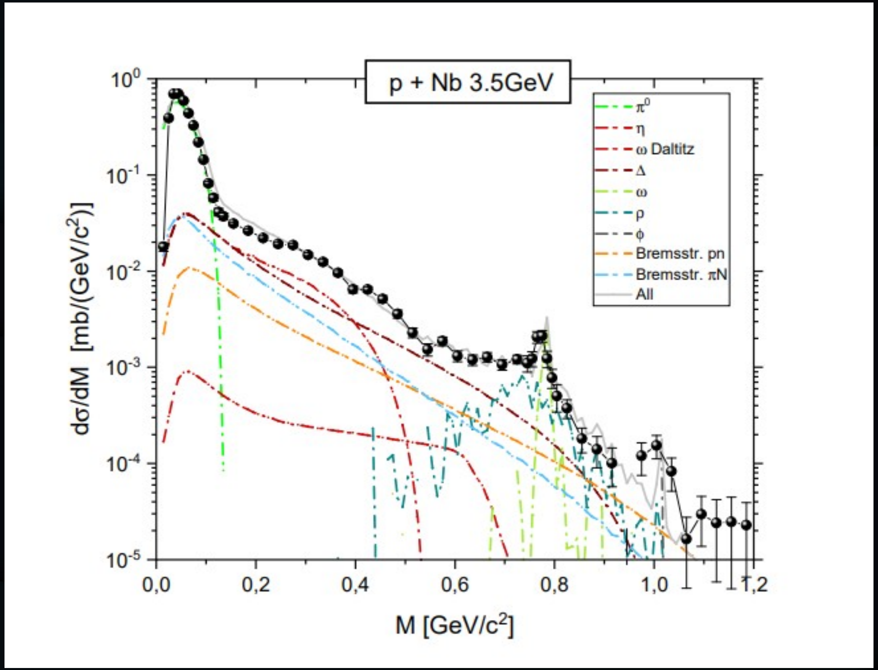
Calculations: PHSD

- Parton Hadron String Dynamics
- Transport theory for strongly interacting systems
- Full description of evolution of relativistic heavy-ion collision, including interactions in the hadronic phase
- **Initial** A+A collision
- Formation of **QGP**: dissolution of pre-hadrons → **partonic stage**
- Hadronization → **Hadronic stage** (Hadron-Hadron interaction)
- Low energies: only hadronic degrees of freedom relevant
- QGP phase not importatnt for HADES energies!
- Used to calculate background
- Extended for U-Boson contributions

E. Bratkovskaya et al., Nucl.Phys.A 856 (2011) 162-182

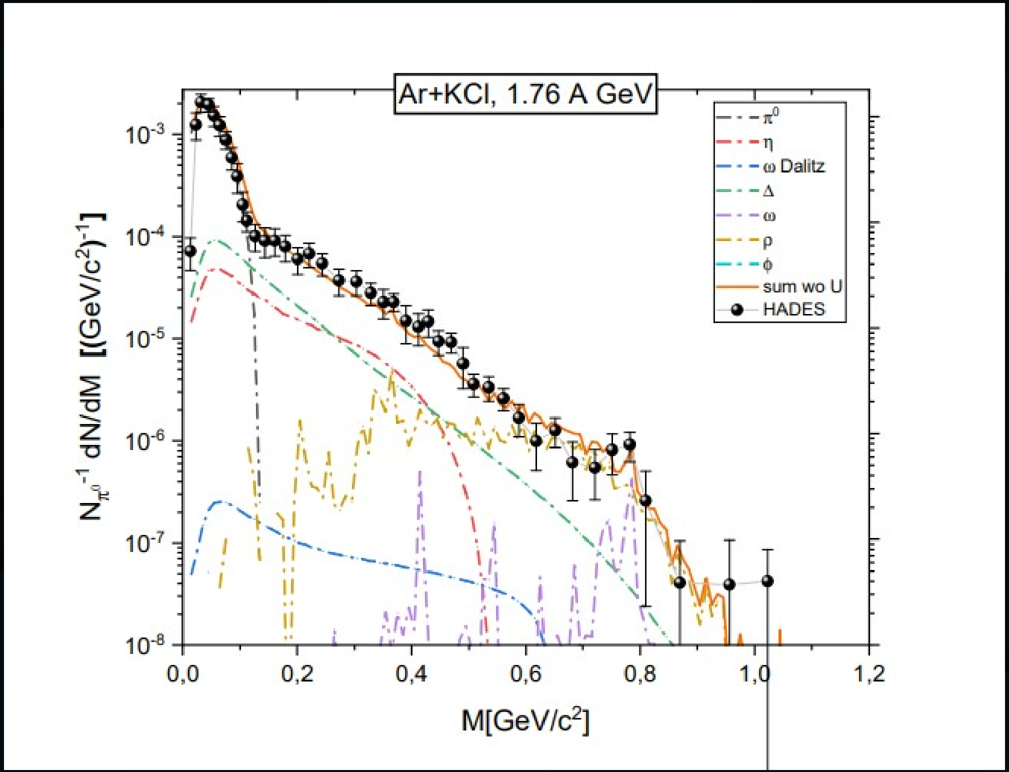
Calculation of Dilepton Sources





E. Bratkovskaya et al., Phys.Rev.C 87 (2013) 064907

Calculation of Dilepton Sources



E. Bratkovskaya et al., Phys.Rev.C 87 (2013) 064907

Calculation of U-Boson Production in PHSD

- Numerical calculation for π^0, η, and Δ Resonance production
- Relation of number of U-Bosons N_U to number of produced particles N_i:

$$\frac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}} = \frac{N_U^{\Delta}}{N_\Delta \, BR_{\Delta\to N\gamma}} \qquad \frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}} = \frac{N_U^{(i)}}{N_i \, BR_{i\to\gamma\gamma}}$$

- Decay widths:

$$\frac{\Gamma_{i\to\gamma U}}{\Gamma_{i\to\gamma\gamma}} = 2\epsilon^2 |F_i(q^2 = M_U^2)| \frac{\lambda^{3/2}(m_i^2, m_\gamma^2, M_U^2)}{\lambda^{3/2}(m_i^2, m_\gamma^2, m_\gamma^2)}$$

$$\frac{\lambda^{3/2}(m_i^2, 0, M_U^2)}{\lambda^{3/2}(m_i^2, 0, 0)} = \left(1 - \frac{M_U^2}{m_i^2}\right)^3$$

Width of π^0 and η

$$\frac{\Gamma_{\Delta\to NU}}{\Gamma_{\Delta\to N\gamma}} = \epsilon^2 \int A(m_\Delta) |F_\Delta(M_U^2)| \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)} dm_\Delta$$

Decay width averaged over Δ mass distribution ($A(m_\Delta)$) for broad state

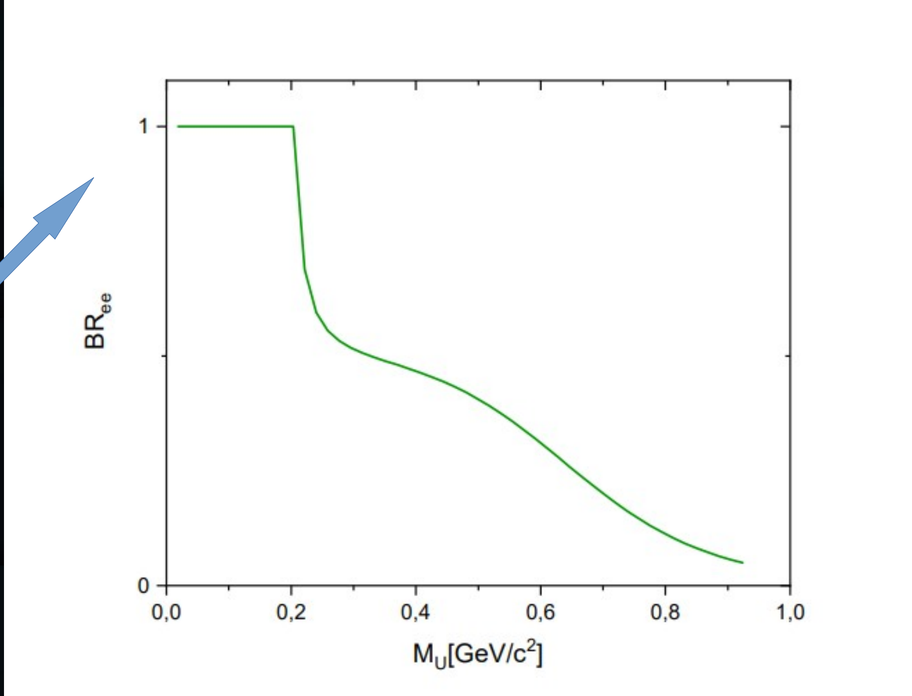
G. Agakishiev et al., Phys.Lett.B 731 (2014) 265-271

Branching Fraction

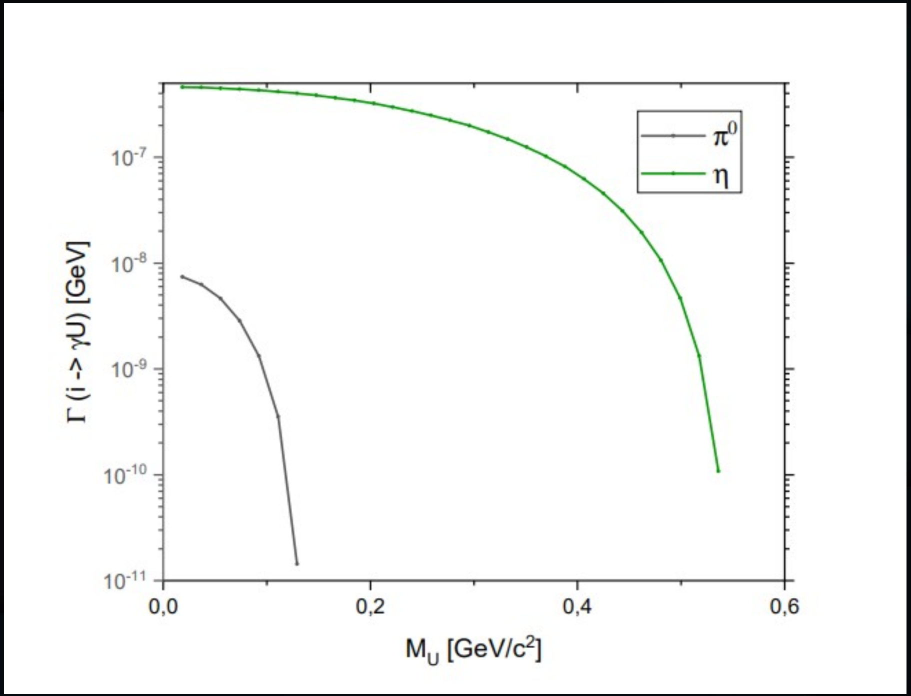
- Note: η and Δ access masses higher than $\mu^+\mu^-$ threshold
- Correction using branching fraction

$$BR_{ee} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{M_U^2}}\left(1 + \frac{2m_\mu^2}{M_U}\right)(1 + R(M_U))}$$

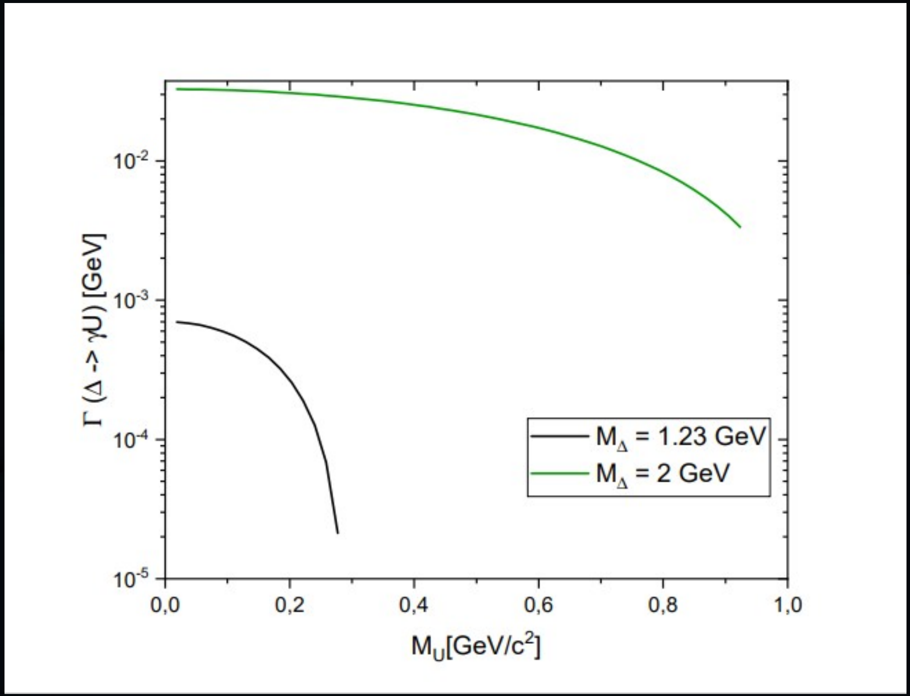
$$N_{U \to ee} = \epsilon^2 BR_{ee} L(M_U)$$



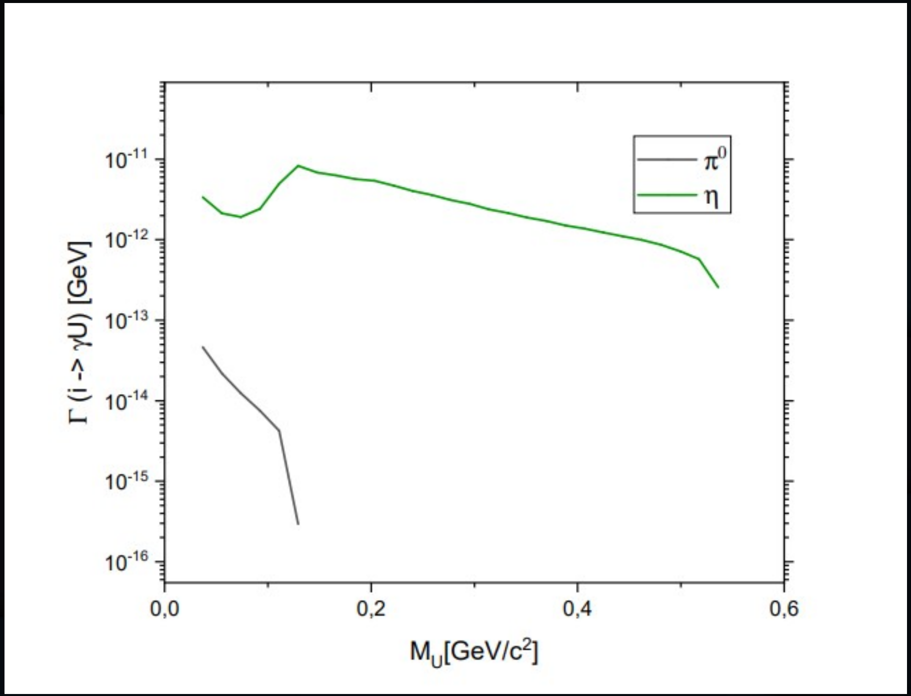
G. Agakishiev et al., Phys.Lett.B 731 (2014) 265-271



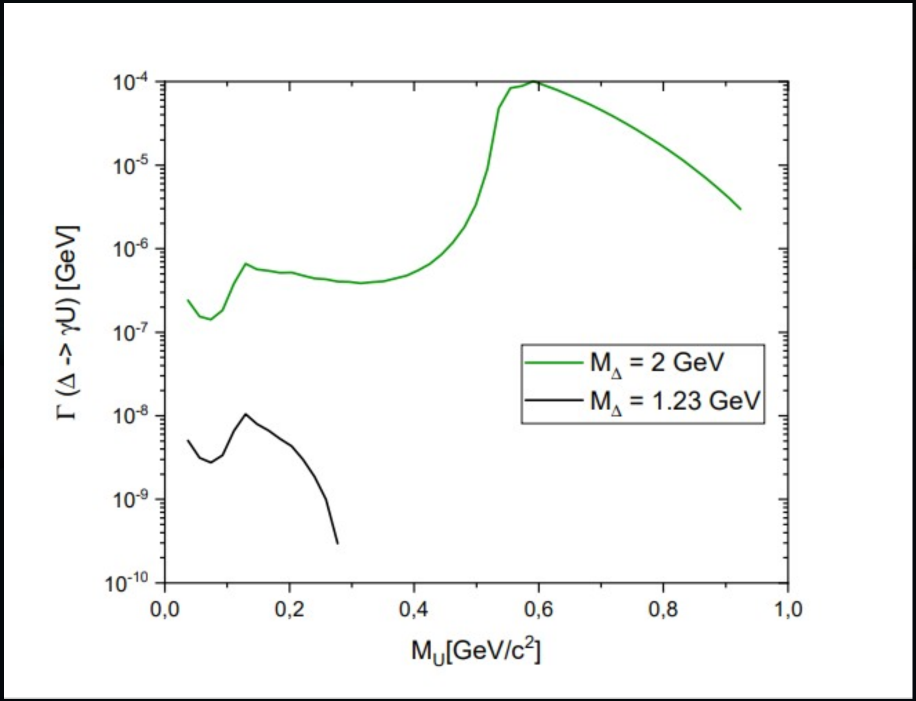
Width for π^0 and η, when $\varepsilon^2 = 1$



Width for Δ Resonance when $\varepsilon^2 = 1$



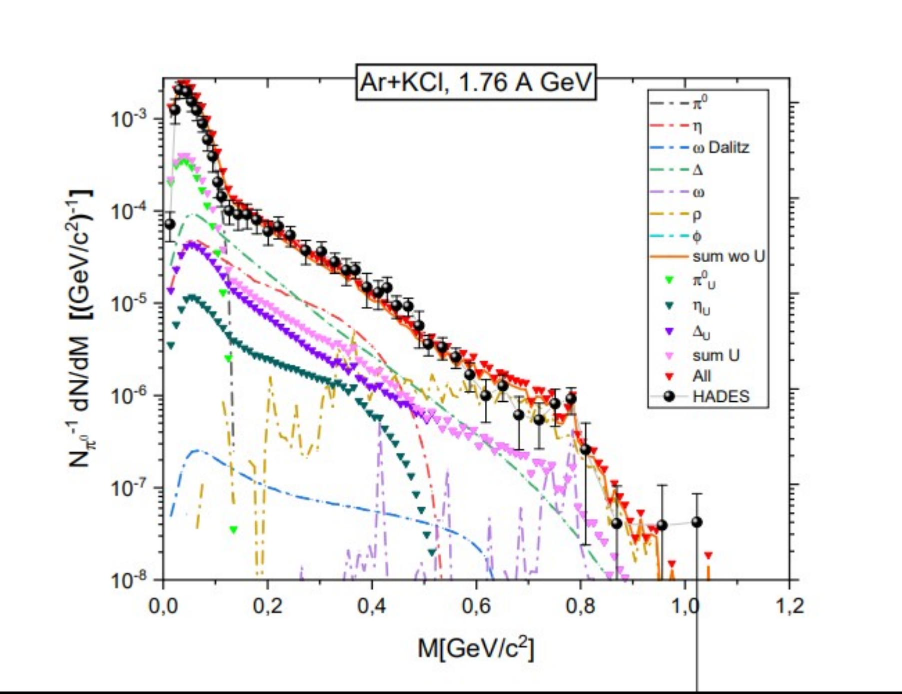
Width for π^0 and η for HADES ε^2

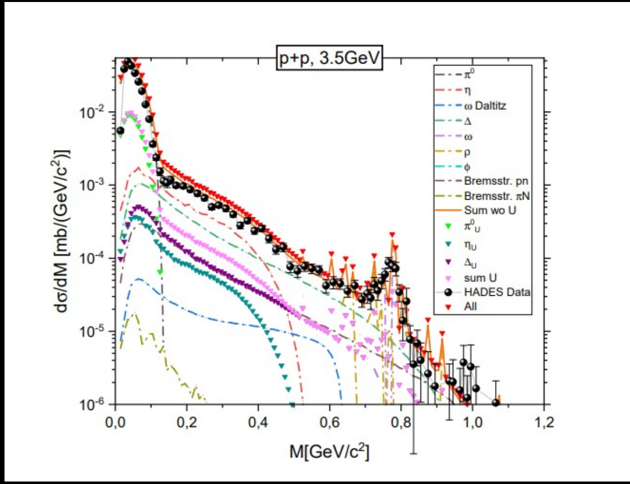


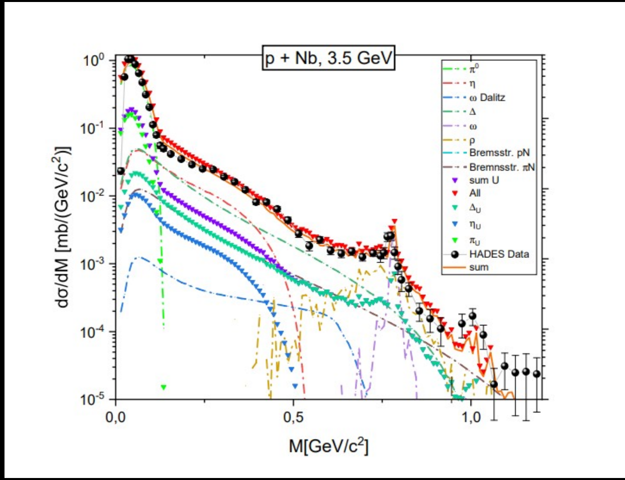
Width for Δ Resonance for HADES ε^2

U-Boson contribution from PHSD is then:

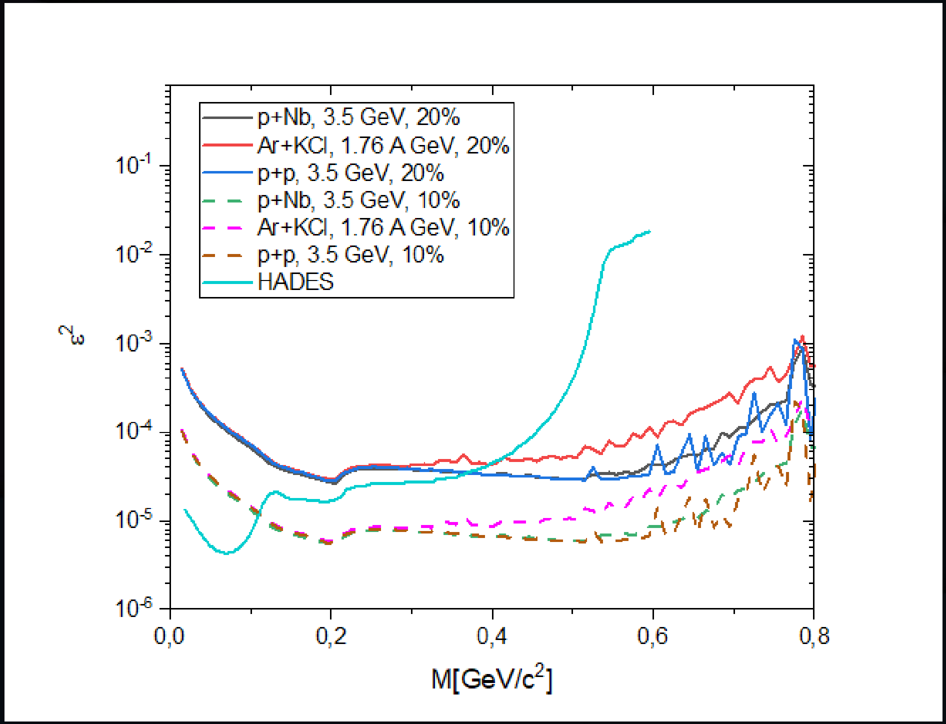
Estimation of a U-Boson signal using ε²







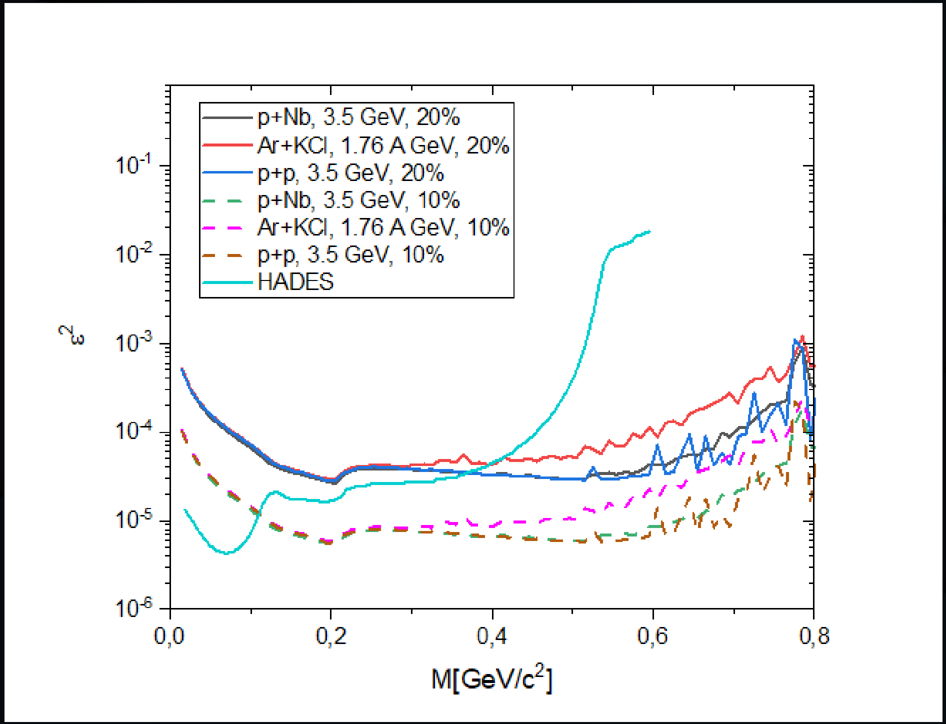
...with estimated ε² from PHSD

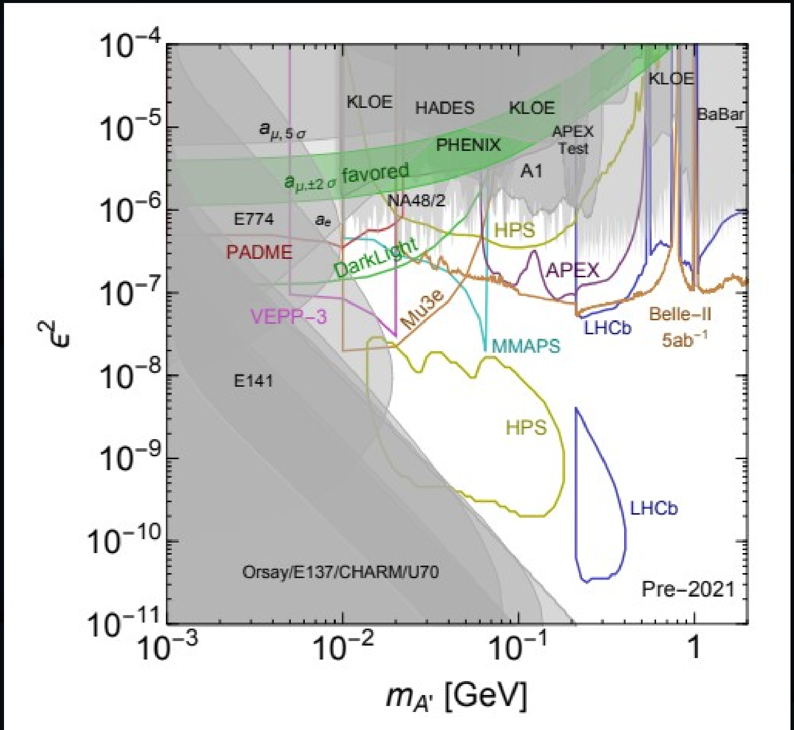


$$\frac{dN^{total}}{dM} = \frac{dN^{sumSM}}{dM} + \epsilon^2 \frac{dN^{sumU}}{dM}$$

$$\epsilon^2 = 0.2 \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}}{dM}\right)$$

Estimated ε² from PHSD





J. Alexander et al., 1608.08632 [hep-ph] (2016)

Summary

- Due to numerous observations, Dark Matter exists!
- Search for Dark Matter at particle colliders via WIMPs and Dark Sector interactions
- HADES searches for Dark Photons in dilepton spectra
- An upper limit ε can be obtained for U-Boson production
- Goal: find the upper limit using PHSD and HADES data!
- Result: theoretical upper limit for ε (20% divination from theoretical spectra)
- Good agreement with HADES spectra for p+p, p+Nb, and Ar+KCl!
- Good agreement compared to other experiments

Thank you for your attention!

Sources

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