Searching a Dark Photon with HADES

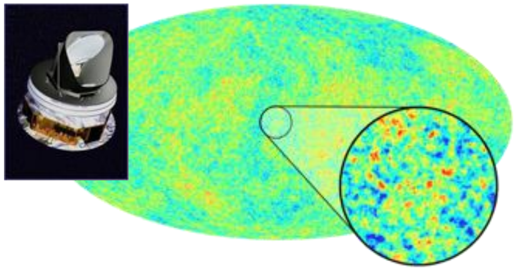
Romain Holzmann, GSI Darmstadt
for the HADES collaboration

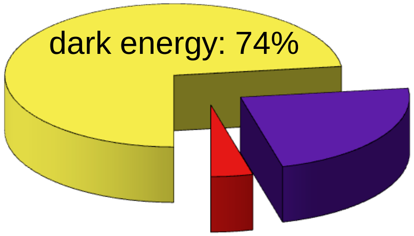
Dark Matter in the Universe

Many astronomical & astrophysical observations support the existence of a large amount of non-baryonic matter, so-called Dark Matter, in the universe:

- Cosmic microwave background (CMB) anisotropies:

PLANCK full sky survey





- Pattern and dynamics of large-scale structures in the universe (galaxies, clusters of galaxies)
  In particular: rotational-velocity profiles of galaxies

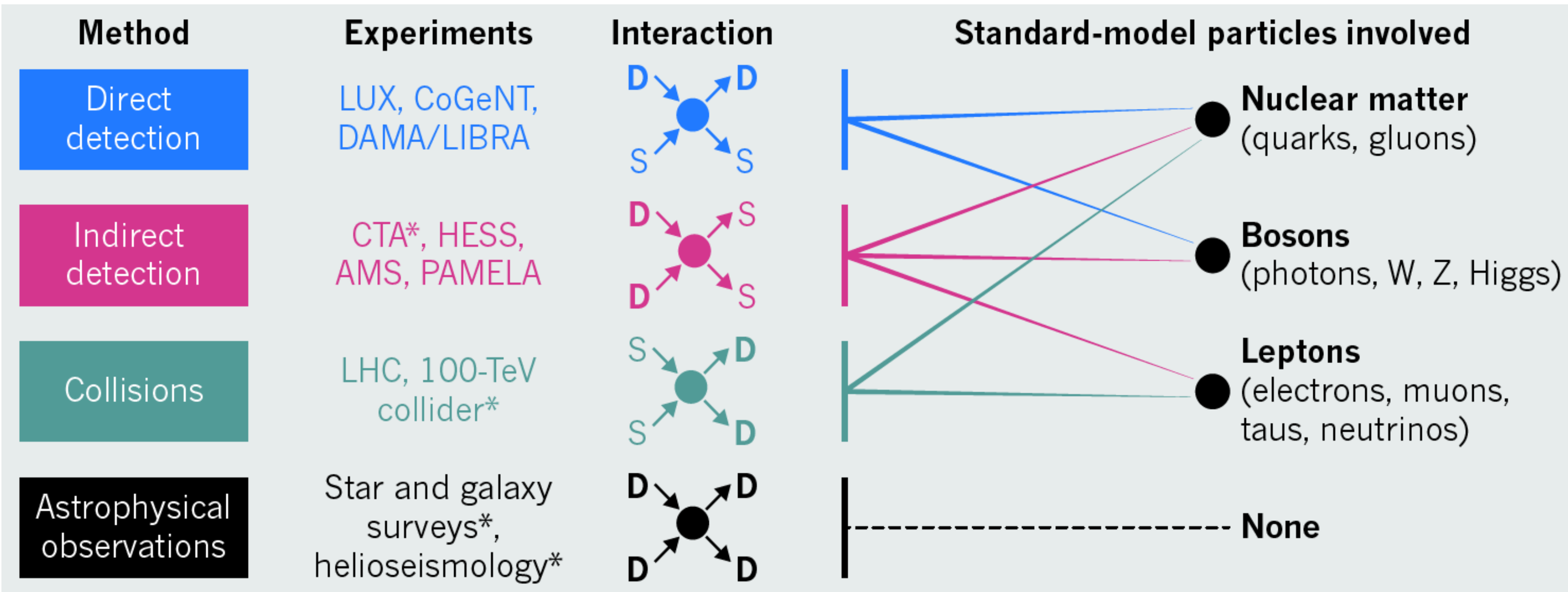
- Gravitational lensing of far-away objects

- Also, hints from cosmic ray spectrum:
  e^+/e^- excess (PAMELA, AMS-02), narrow γ line (Fermi)

Recent reviews:
Bertone, Hooper & Silk, Phys. Rept. 405 (2005)
(see also PDG review on dark matter
and Livio & Silk, Nature 507, March 2014)

Observation of Dark Matter particles

D = dark-matter particle, **S** = standard-model particle



taken from Livio & Silk, in *Nature 507 (March 2014)*

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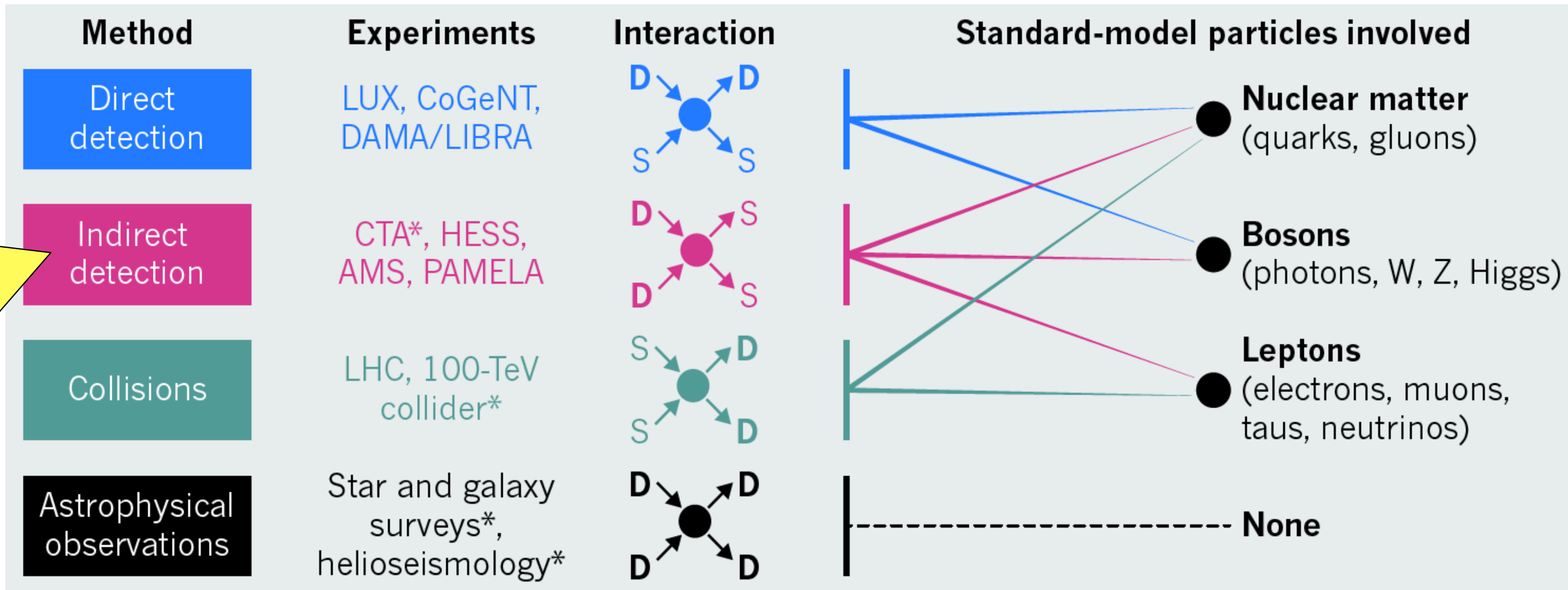


taken from Livio & Silk, in *Nature 507 (March 2014)*

Our search has focus on DM manifestations in **radiative meson decays**

Standard Model and Dark Matter

- Electromagnetic interaction
- Weak interaction
- Strong interaction
- + Gravity

Electroweak unification

GUT

Standard Model: $\mathbf{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}$

Standard Model and Dark Matter

- Electromagnetic interaction
- Weak interaction
- Strong interaction
- + Gravity

Electroweak unification (electromagnetic + weak interaction); GUT (electroweak + strong interaction)

Standard Model: $\mathbf{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_D \otimes \ldots}$ ← hidden sector(s)

Kinetic mixing of the $U(1)_Y$ and $U(1)_D$ gauge bosons provides a natural portal to this hidden sector via an effective interaction:

$$\mathcal{L}_{\text{mix}} = \epsilon\, e\, A^D_\mu\, J^\mu_{EM}$$

← L.B. Okun, Sov. Phys. 56 JETP (1982); B. Holdom, PLB 166 (1986)

Photon and Dark Photon (or U boson or A') mix at level ϵ, with $\epsilon^2 = \alpha'/\alpha$.

Where M_U = sub-MeV – multi-GeV and $\epsilon = 10^{-12} - 10^{-2}$ (model-dependent!)

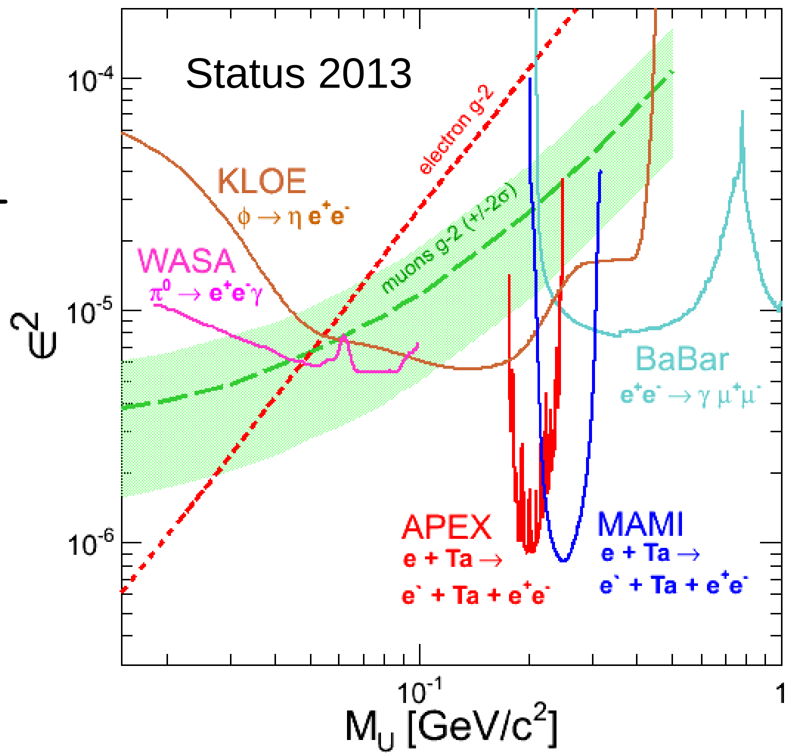
If $m_U > 2\, m_e$, the dark vector boson can decay into lepton (e^+e^- or $\mu^+\mu^-$) or hadrons.

Searching the U in electromagnetic processes

All EM processes can be modified by mixed-in dark photon ➔ search e.g. in:

- $e^- + A \rightarrow e^- + X + U$ (APEX, MAMI/A1)
- $\Phi \rightarrow \eta + U$ (KLOE-2)
- $\pi^0 \rightarrow \gamma + U$ (WASA, HADES)
- $\eta \rightarrow \gamma + U$ (HADES)
- $e^+ e^- \rightarrow \mu^+ \mu^- + U$ (BaBar, Belle, BES3)
- various beam-dump expts.
- $g - 2$ (e and μ data)

World set of U boson searches: upper limit (CL=90%) on ε^2



Theory:

P. Fayet, PLB 95 (1980) 285, etc.
Pospelov et al., PLB 662 (2008) 53
Pospelov, PRD 80 (2009) 095002
Batell et al., PRD 79 (2009) 114008
Reece & Wang, JHEP 0907 (2009) 051

Constraints from the muon g–2 anomaly

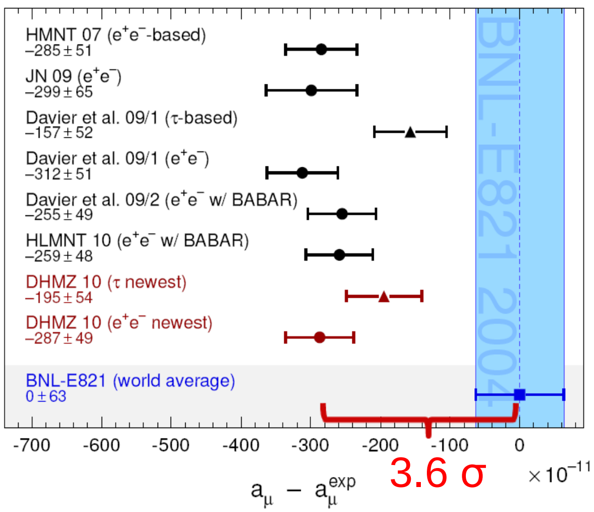
- Dirac: point-like spin-½ particle has a gyromagnetic factor g = 2
- QED high-order terms lead to g > 2 ➔ g-2 anomaly
- Very precisely measured and calculated for the electron:

$$\left.\begin{array}{l}(g_e\text{-}2)_{exp} = 0.00231930436146(56) \\ (g_e\text{-}2)_{theo} = 0.00231930436225(172)\end{array}\right\}$$ exp & theory agree within errors

- Remeasured recently at the Brookhaven AGS for the muon:

$$\left.\begin{array}{l}(g_\mu\text{-}2)_{exp} = 0.0023318418(13) \\ (g_\mu\text{-}2)_{theo} = 0.0023318360(10)\end{array}\right\}$$ 3.6 σ mismatch! ➔ maybe due to new physics e.g. a dark photon ???

with
$a_\mu = (g\text{-}2)/2$



Muon g-2 status:
Exp.: G. Bennet et al., PRD 73 (2006)
Theo: M. Davier et al., EPJC 71 (2011)

Constraints on the U boson from g-2:
M. Pospelov, PRD 80 (2009)
M. Endo et al., PRD 86 (2012)

Searching the U in electromagnetic processes

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- $e^+ e^- \rightarrow \mu^+ \mu^-$ (BaBar, Belle, BES3)
- various beam-dump expts.
- e and μ g -2 anomaly

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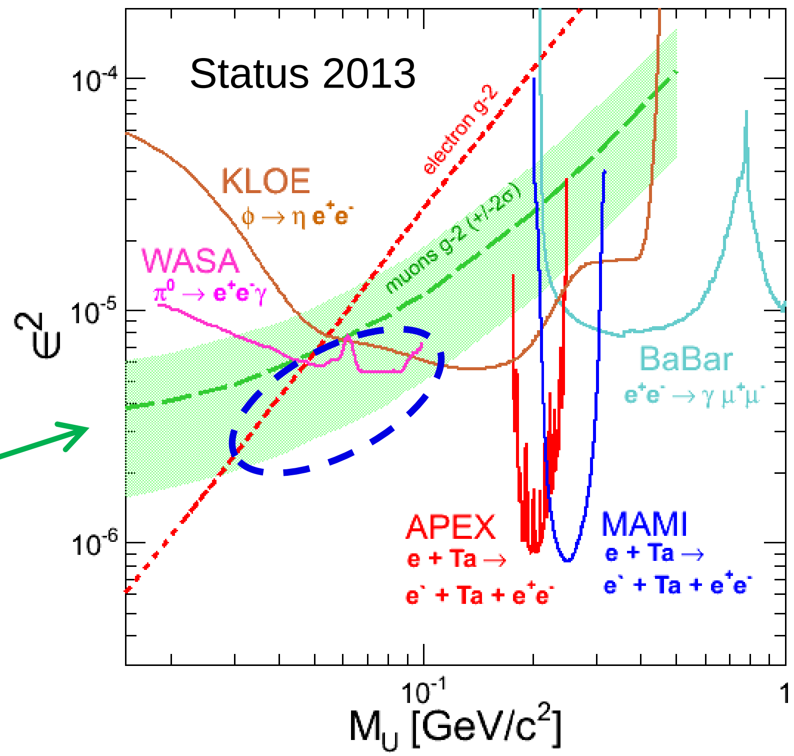

➔ Band favored by muon g - 2 anomaly is not fully excluded yet!

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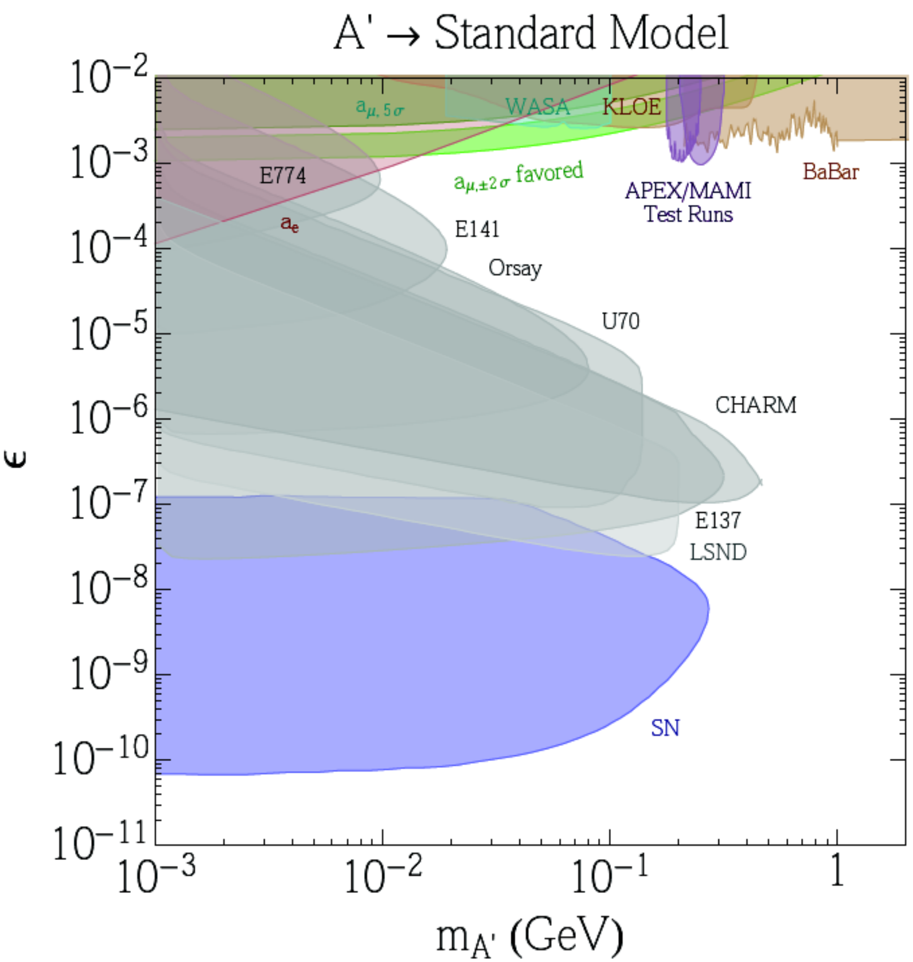
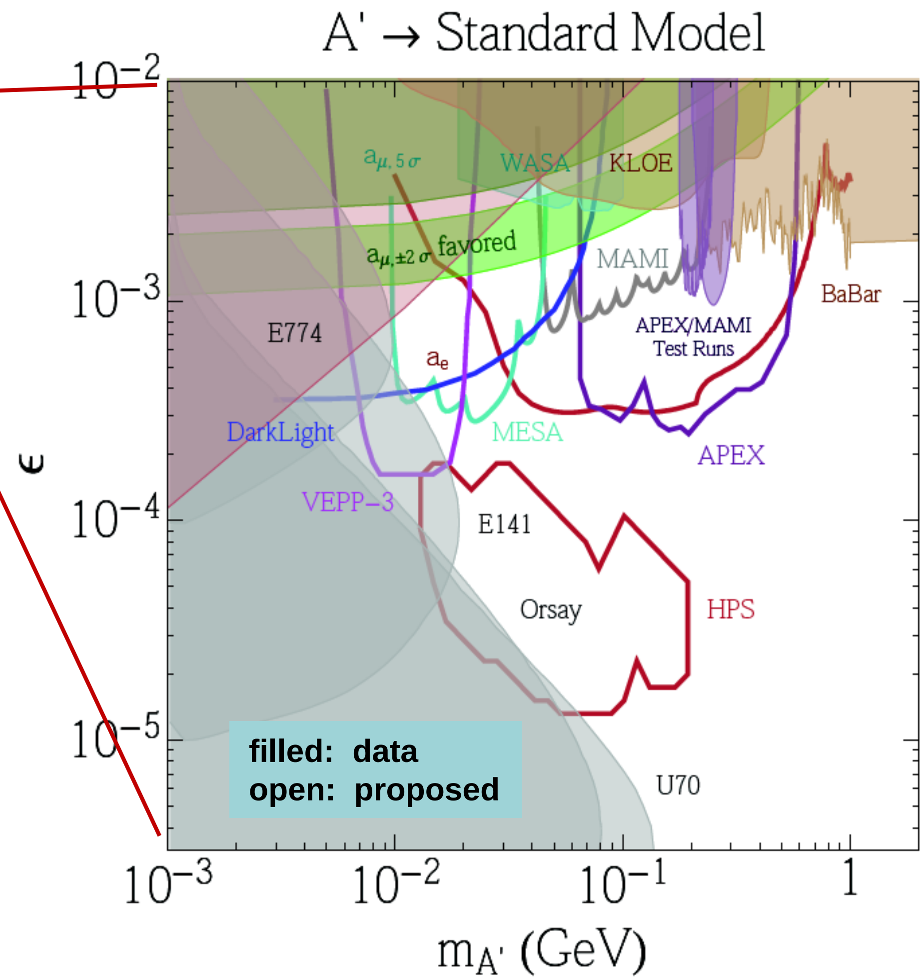
Constraints on Dark Photon (status 2013)



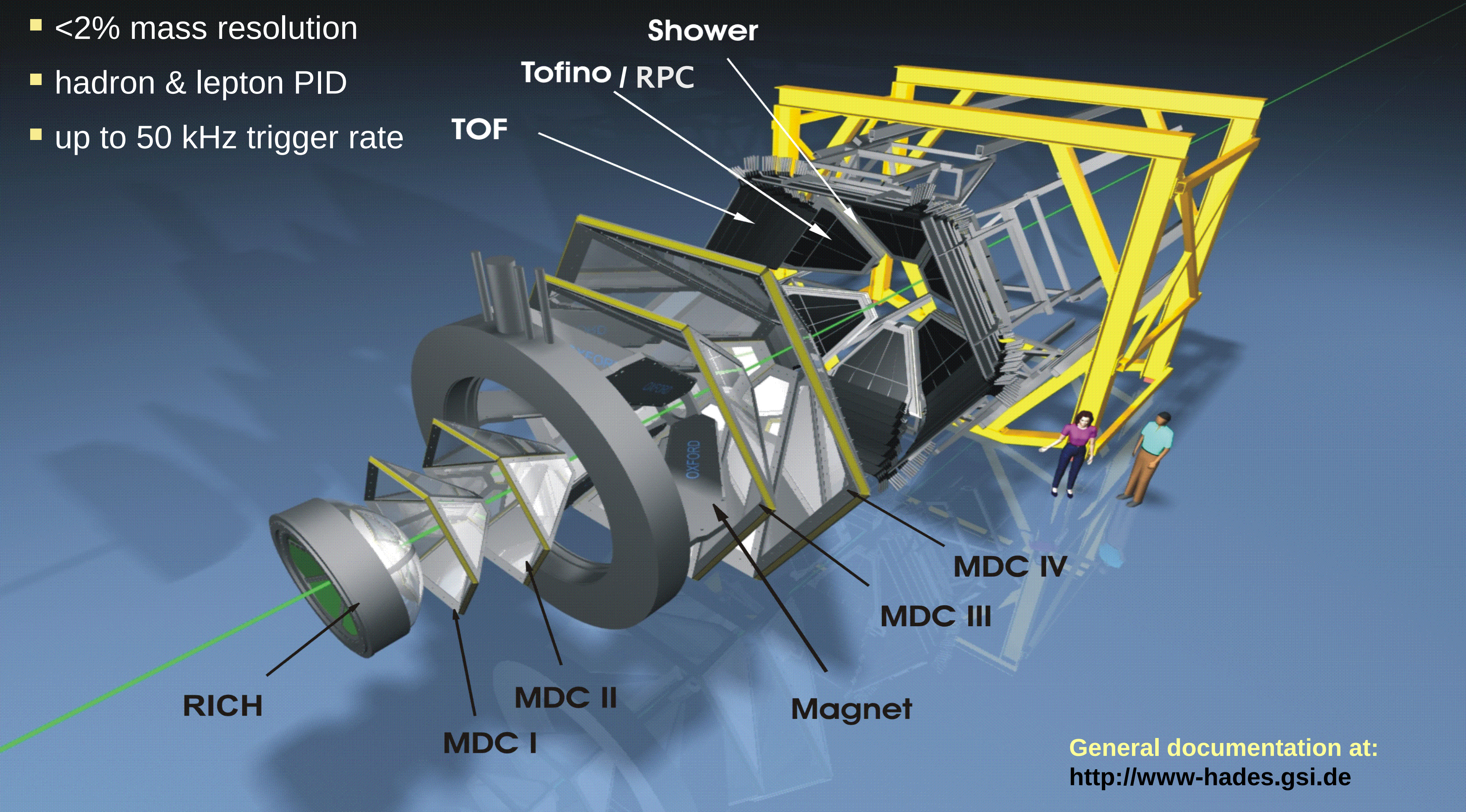


taken from 2013 Snowmass Working Group Report, Essig et al, arXiv:1311.0029 [hep-ph]

The HADES experiment at GSI

High Acceptance DiElectron Spectrometer

- large acceptance
- <2% mass resolution
- hadron & lepton PID
- up to 50 kHz trigger rate



General documentation at:
http://www-hades.gsi.de

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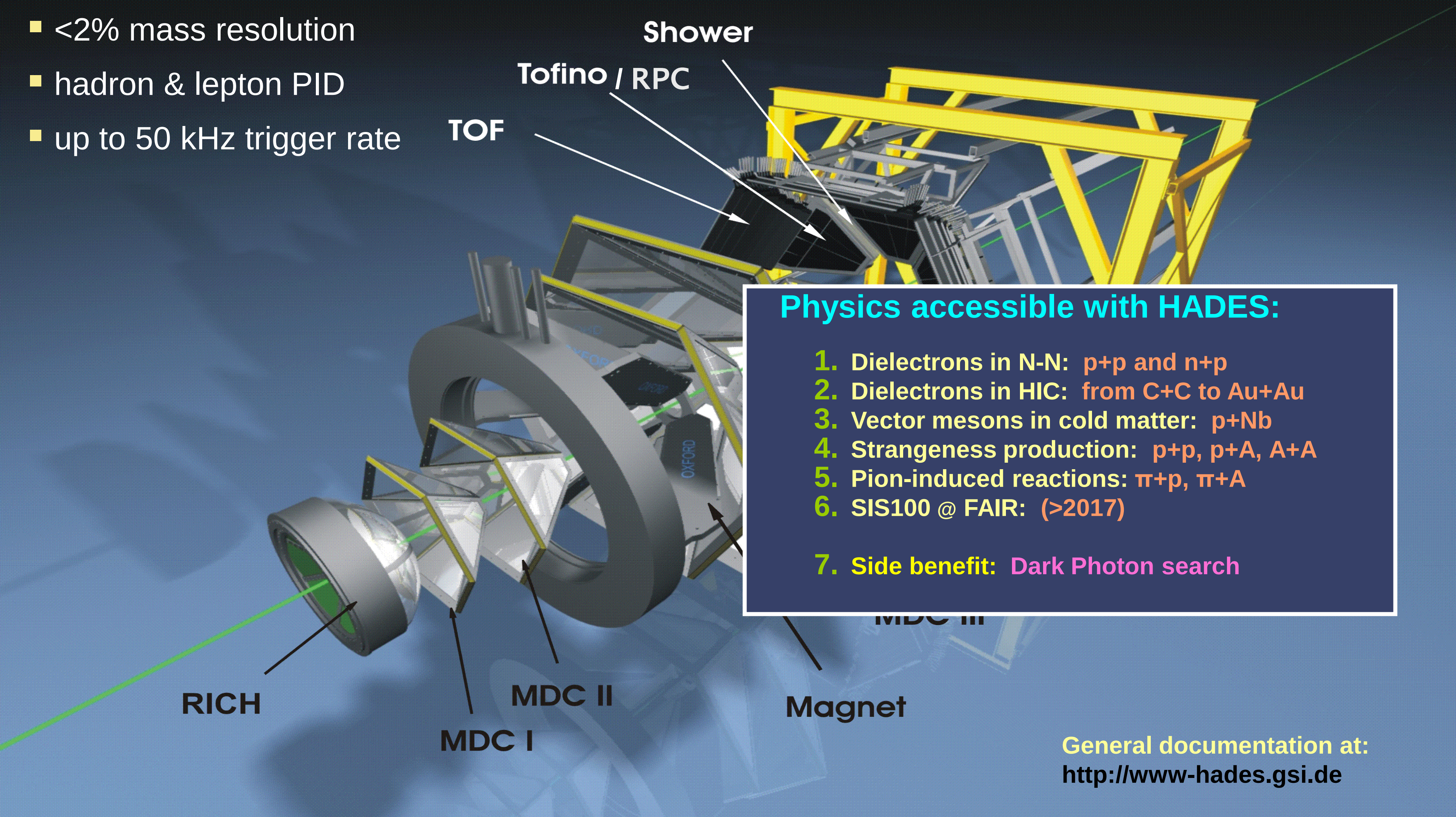


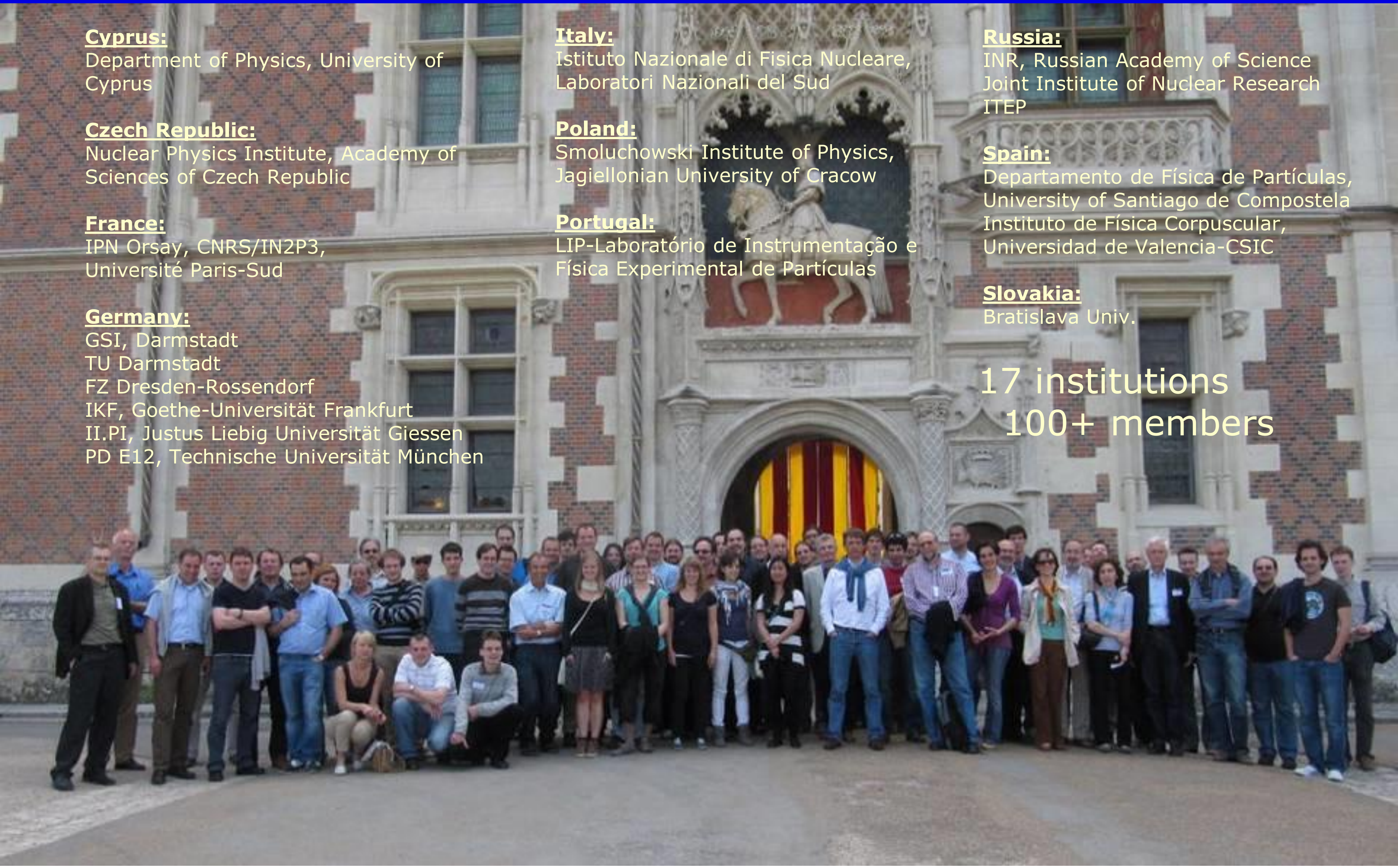
Physics accessible with HADES:

1. Dielectrons in N-N: p+p and n+p
2. Dielectrons in HIC: from C+C to Au+Au
3. Vector mesons in cold matter: p+Nb
4. Strangeness production: p+p, p+A, A+A
5. Pion-induced reactions: π+p, π+A
6. SIS100 @ FAIR: (>2017)

7. Side benefit: Dark Photon search

General documentation at:
http://www-hades.gsi.de

The HADES Collaboration



Cyprus:
Department of Physics, University of Cyprus

Czech Republic:
Nuclear Physics Institute, Academy of Sciences of Czech Republic

France:
IPN Orsay, CNRS/IN2P3,
Université Paris-Sud

Germany:
GSI, Darmstadt
TU Darmstadt
FZ Dresden-Rossendorf
IKF, Goethe-Universität Frankfurt
II.PI, Justus Liebig Universität Giessen
PD E12, Technische Universität München

Italy:
Istituto Nazionale di Fisica Nucleare,
Laboratori Nazionali del Sud

Poland:
Smoluchowski Institute of Physics,
Jagiellonian University of Cracow

Portugal:
LIP-Laboratório de Instrumentação e Física Experimental de Partículas

Russia:
INR, Russian Academy of Science
Joint Institute of Nuclear Research
ITEP

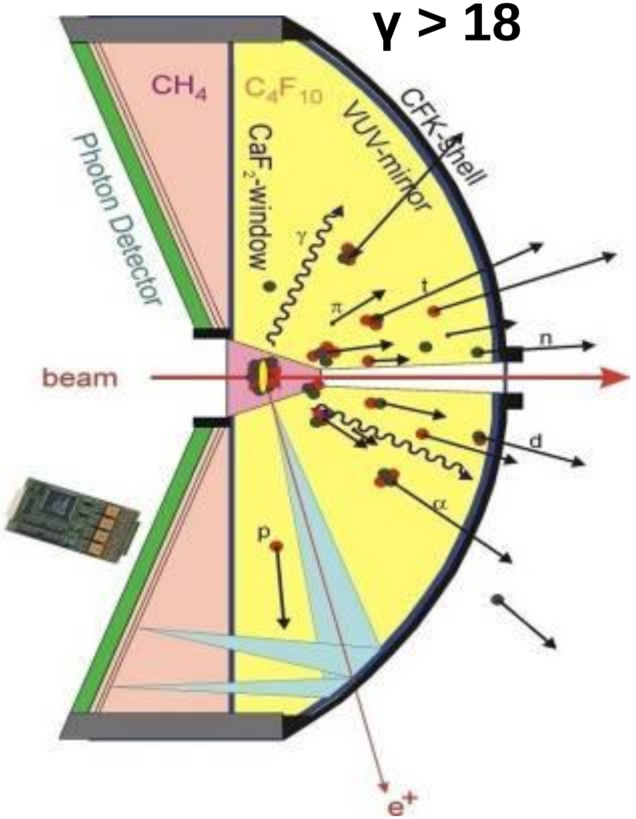
Spain:
Departamento de Física de Partículas,
University of Santiago de Compostela
Instituto de Física Corpuscular,
Universidad de Valencia-CSIC

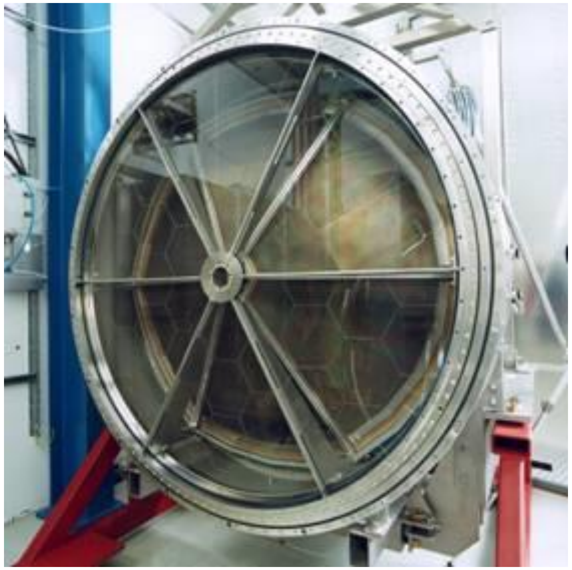
Slovakia:
Bratislava Univ.

17 institutions
100+ members

The RICH: excellent lepton ID

γ > 18





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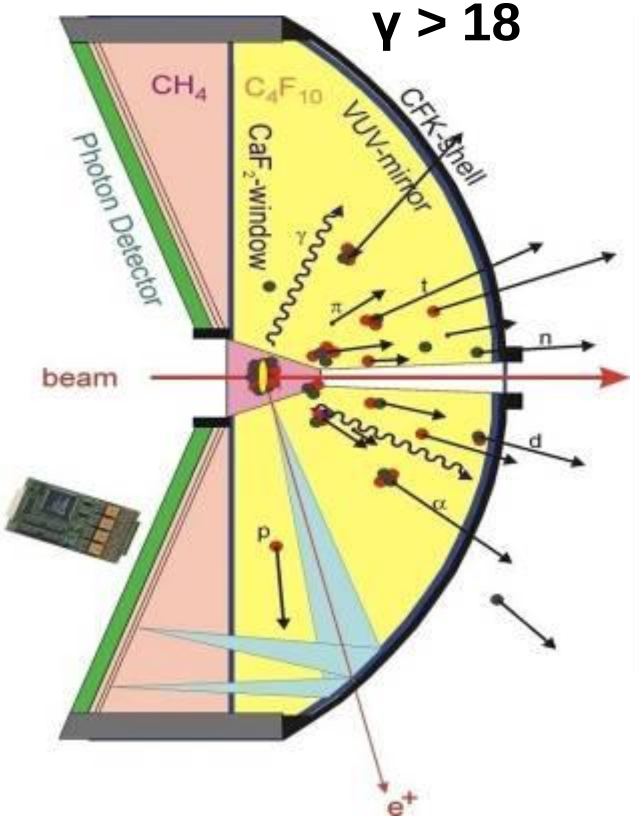
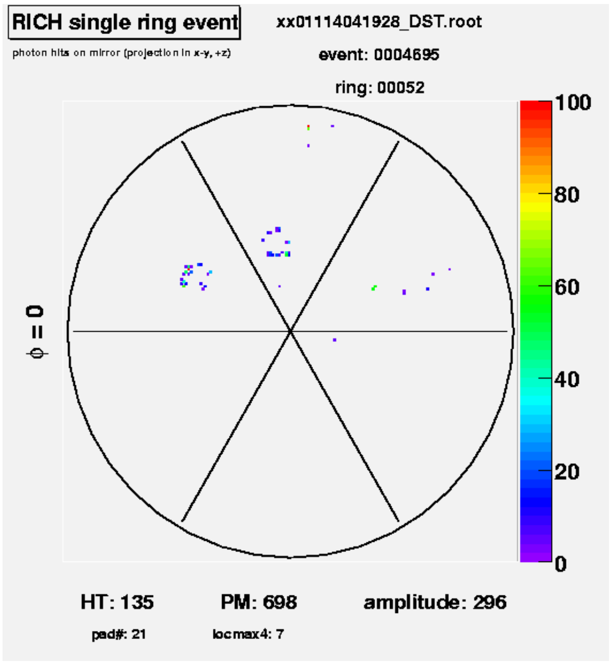
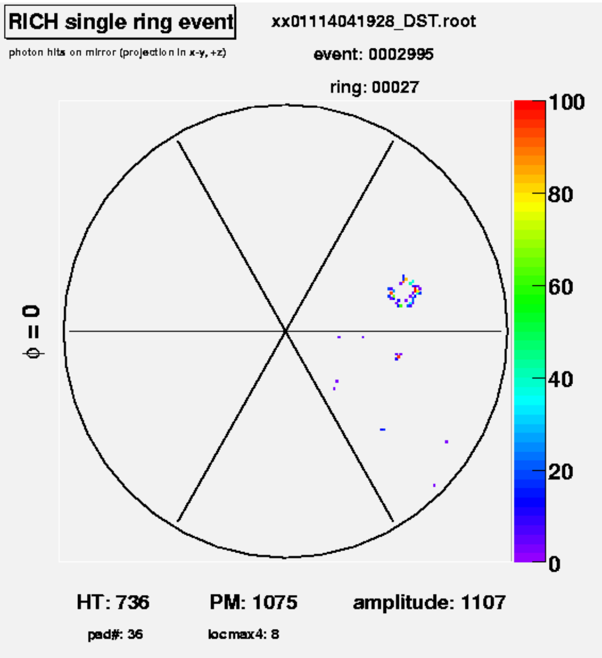
$\gamma > 18$

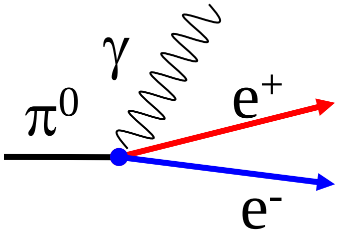




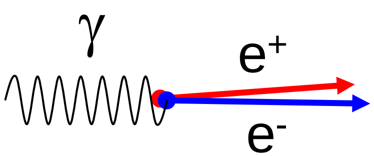


π^0 Dalitz pair

γ conversion pair



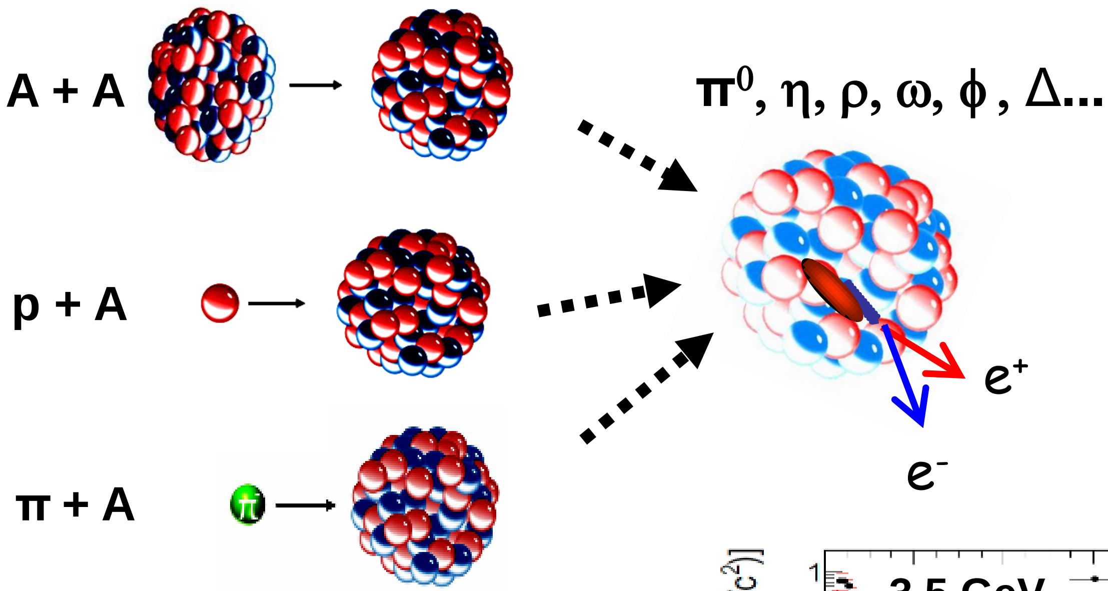
$\Theta \sim 15.2^0$



$\Theta \sim 2.2^0$

e^+e^- spectroscopy in few-GeV reactions

HADES

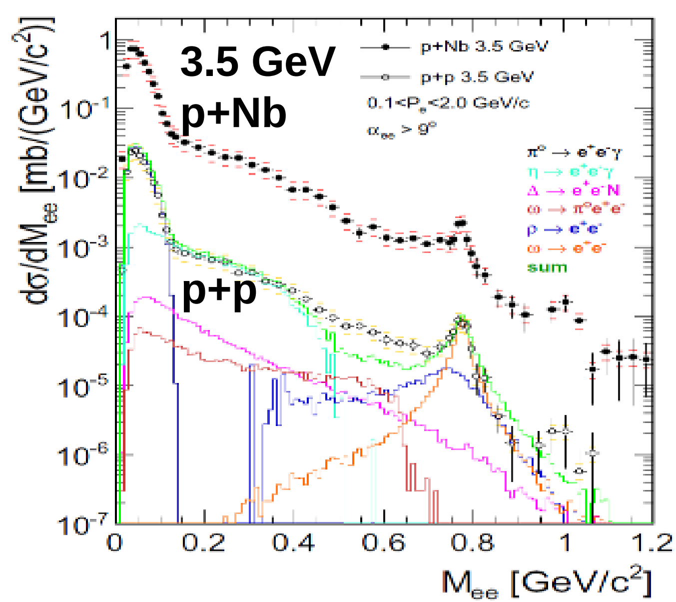


Modus operandi:

1. produce hadron
2. let decay into leptons
3. detect products
4. reconstruct inv mass

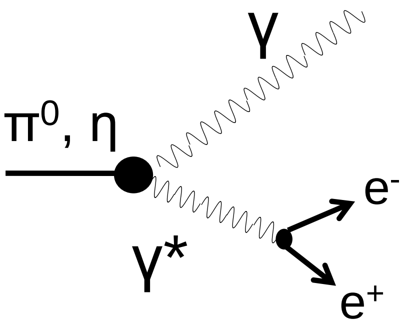
Pair invariant mass:

$$M_{ee} = \sqrt{(p_1 + p_2)^2}$$

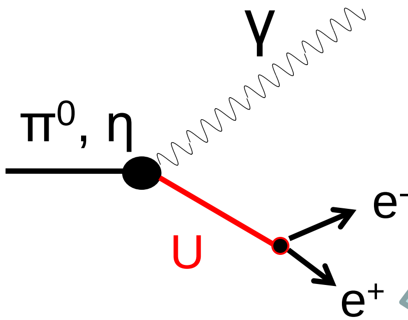


typical pair spectrum

U boson search in meson decays



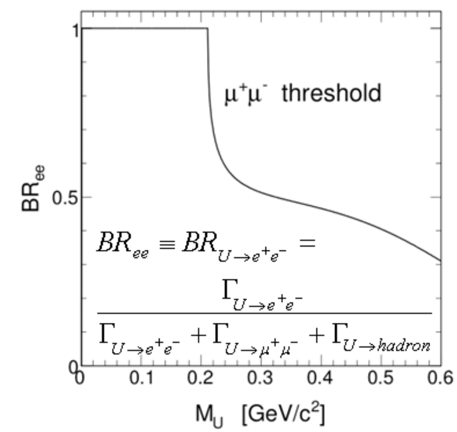
U(1) – U(1)$_D$
→ kinetic mixing →



Measurement of $\pi^0/\eta \to \gamma U \to \gamma e^+e^-$ in radiative decays:

- Search for a sharp structure in the e^+e^- pair spectrum
- U natural width is small (<<1 keV)
  → expected peak width = mass resolution of spectrometer

e+e- branch



Important requirements for the dark photon search:

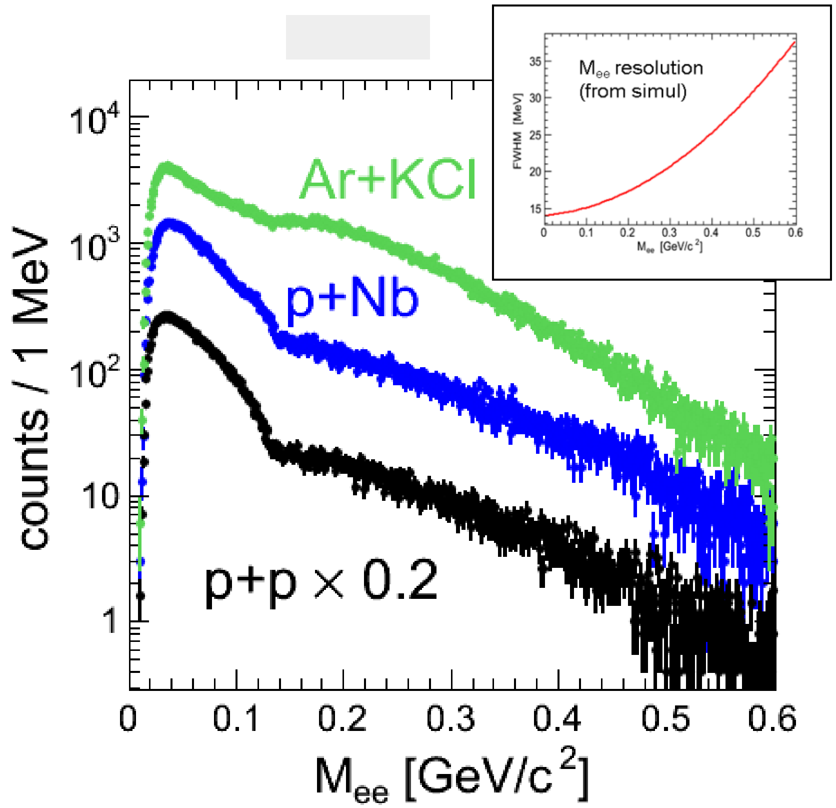
1. Large e^+e^- data samples
2. Very good mass resolution

Searching Dark Matter in HADES

A How-to-do

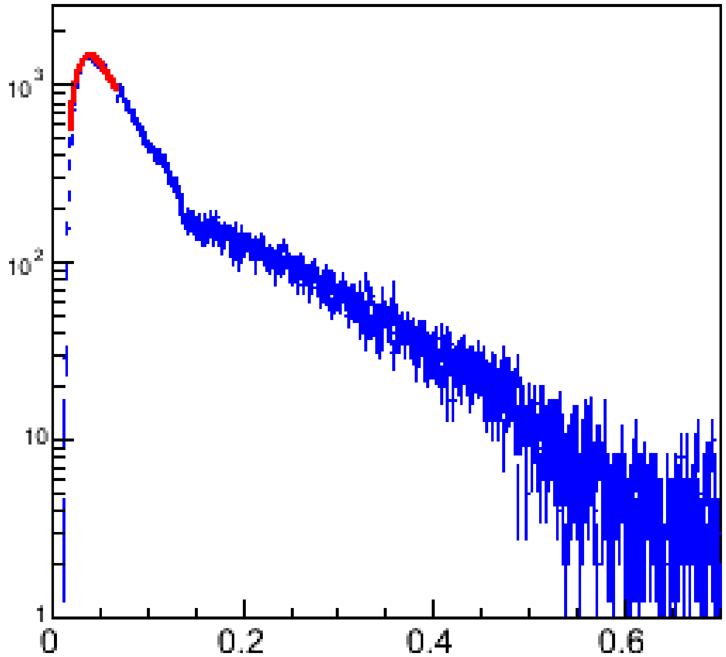
1. Search for a peak structure in the raw dN/dM_{ee} spectrum taking into account mass resolution
2. If no peak found, get an UL on peak
3. Transform this UL into an UL on the mixing parameter ε (or on ε^2)
4. Compare with other experiments
5. If better, publish result

Reaction	N_{LVL1}	N_{π^0}	N_η
p+p	3.0×10^9	2.5×10^9	1.5×10^8
p+Nb	7.7×10^9	5.9×10^9	3.0×10^8
Ar+KCl	2.2×10^9	7.7×10^9	1.9×10^8



Peak search procedure and UL

RAW invariant mass spectra



Analysis steps :

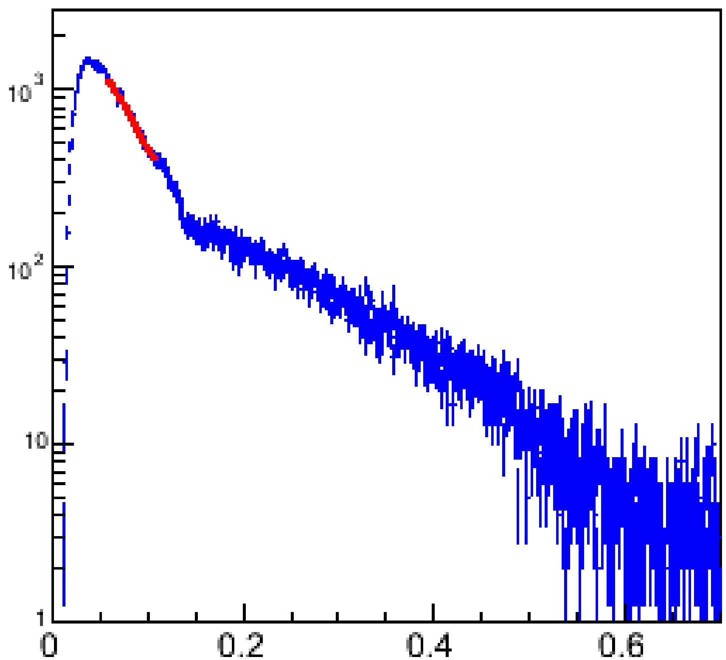
- Slide search region over data in 3-MeV steps
- Fit inspected region using sum of a 5^{th}-order polynomial and a Gauss
- Keep position and width σ of Gauss fixed
- Fit window has width $M_U \pm 4\sigma$
- Use counts & fitted bkg to get UL at $CL_{90\%}$

Input to the UL method (TRolke):

- total pair yield in peak region
- fitted background yield
- error on bkg from fit
- error on eff & acc correction = 15%

Peak search procedure and UL

RAW invariant mass spectra



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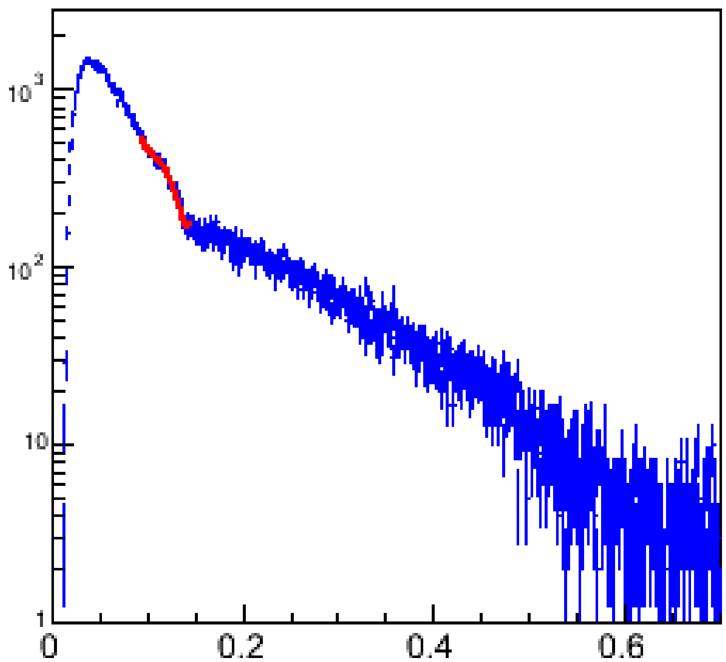

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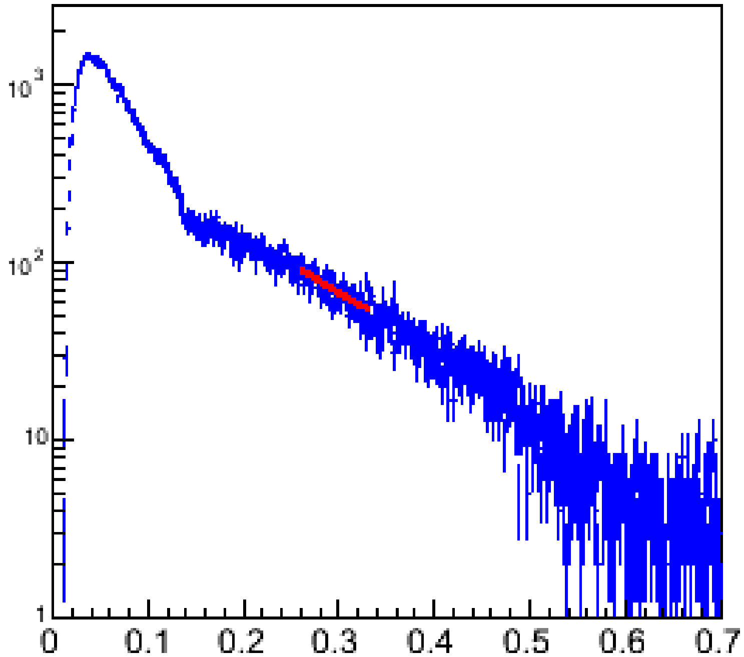

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Peak search procedure and UL

HADES

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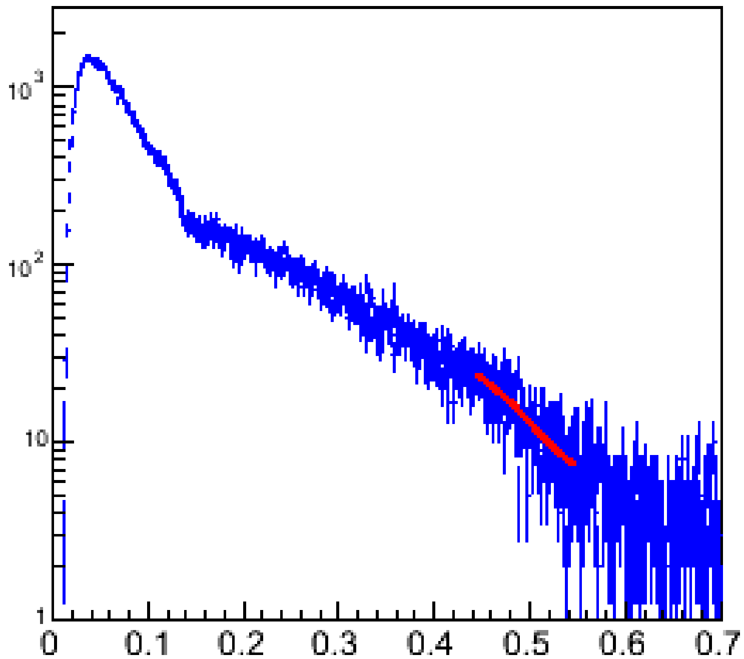

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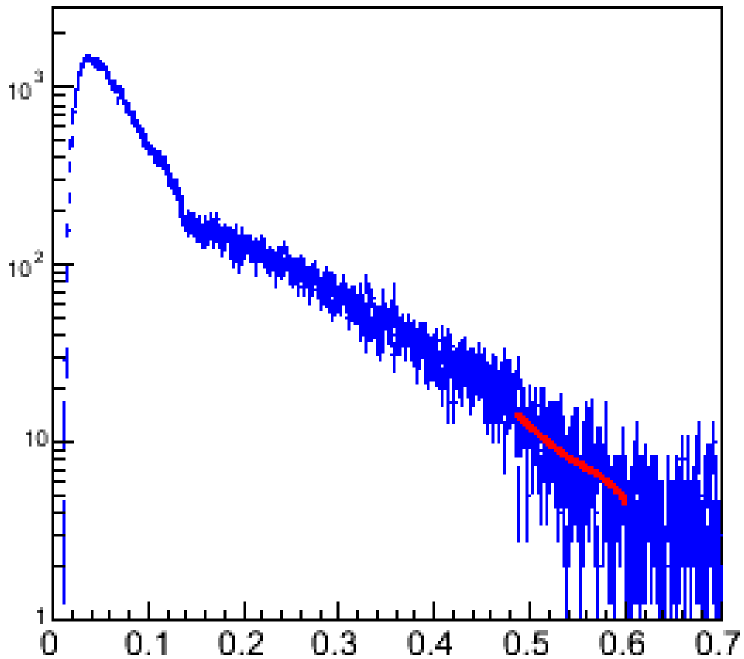

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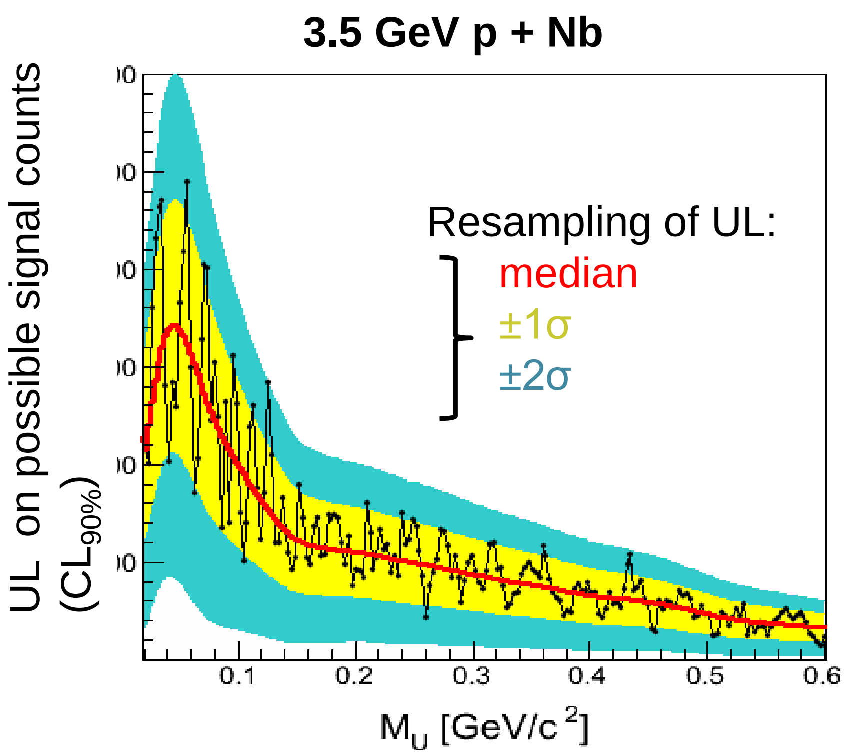
Smoothing the UL by resampling

HADES



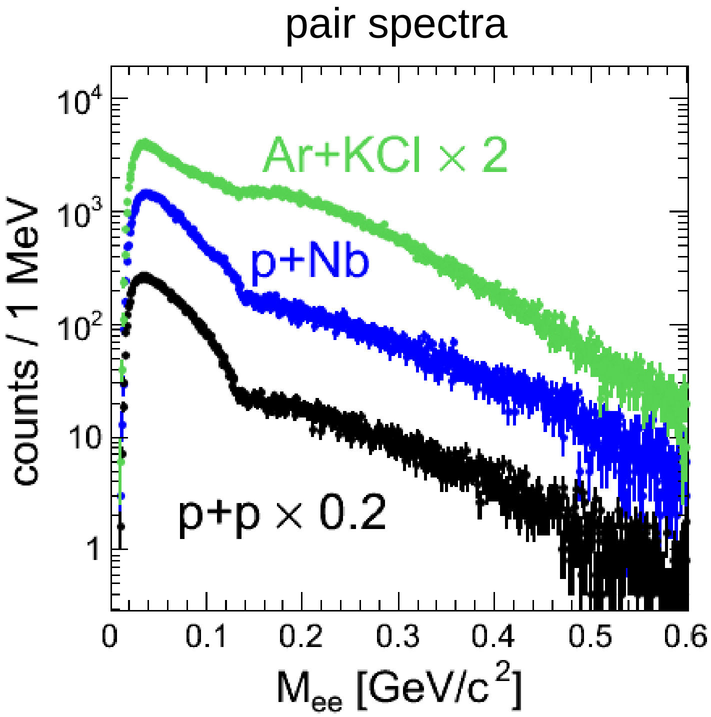
To reduce the statistical fluctuations on UL a resampling method was used based on the Asimov data set (Cowan et al.).

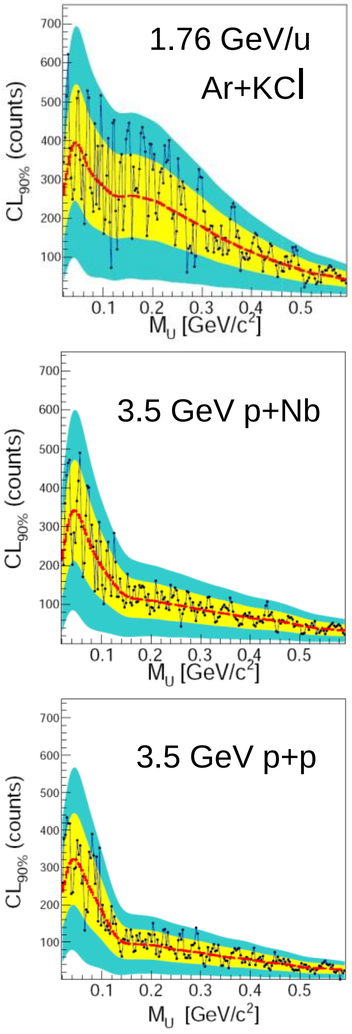
Statistical Methods:

W.A. Rolke et al. NIM. A 551 (2005) 493.

G. Cowan et al., Eur. Phys. J. C 71 (2011) 1554.

Smoothing the UL by resampling





U.L. on counts
\+ median & s.d.
(Asimov data set)

Transforming UL on counts to UL on ε²

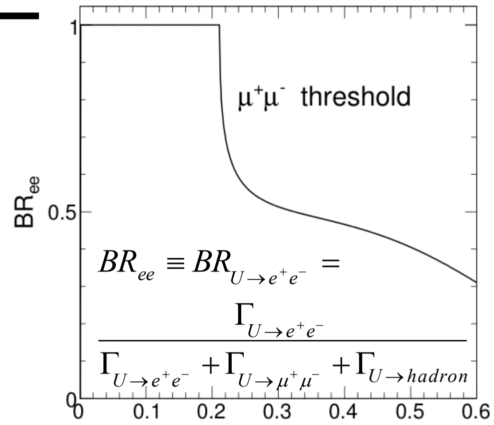
HADES

U boson „production rate“:

$$N_{U\to e+e-} = \varepsilon^2 BR_{U\to ee} L(M_u)$$

mixing parameter

kinematic factors
& form factors
& source parameters

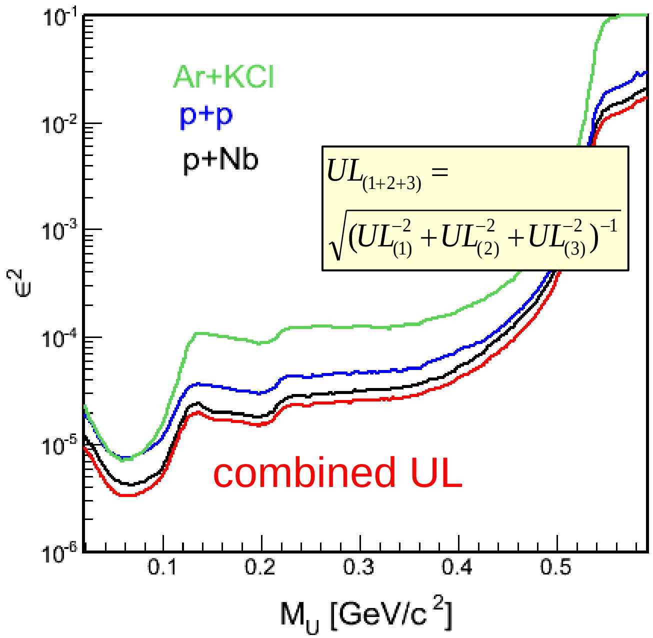


Cumulated luminosity:

$$L(M_U) = 2N_\eta BR_{\eta\to\gamma\gamma} |F_\eta|^2 (1 - \frac{M_U^2}{m_\eta^2})^3$$

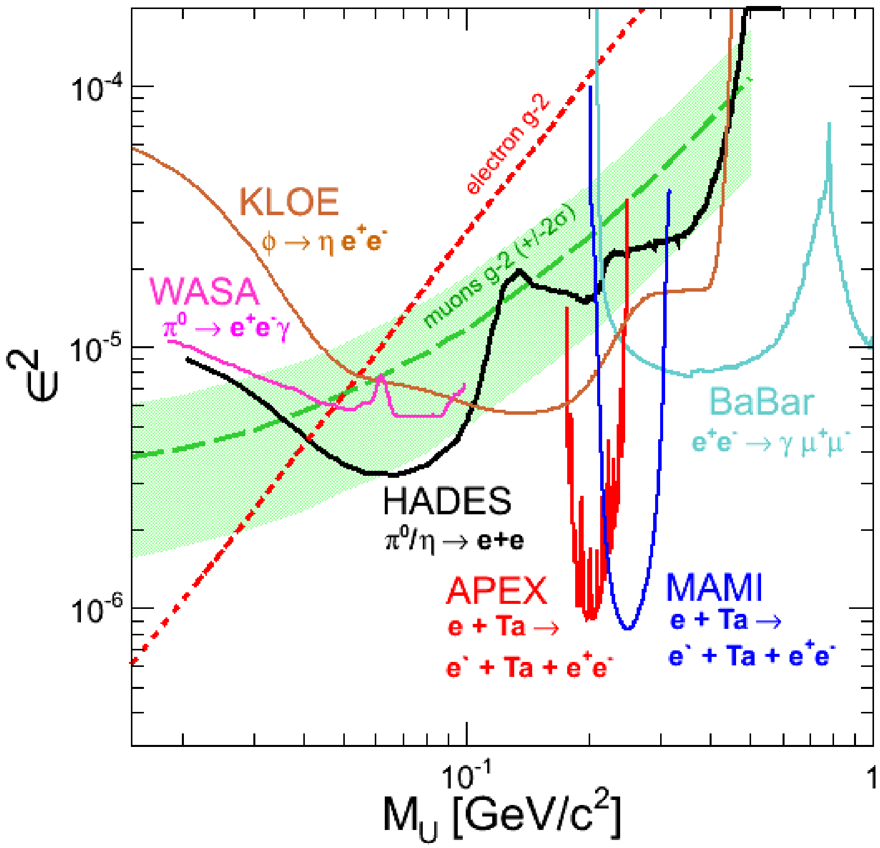
$$+2N_{\pi^0} BR_{\pi^0\to\gamma\gamma} |F_{\pi^0}|^2 (1 - \frac{M_U^2}{m_{\pi^0}^2})^3$$

$$+N_\Delta BR_{\Delta\to N\gamma} |F_\Delta|^2 \int A(m_\Delta) |F_\Delta|^2 \frac{\lambda^{3/2}(m_\Delta^2, m_N^2, M_U^2)}{\lambda^{3/2}(m_\Delta^2, m_N^2, 0)}$$



Comparison of HADES with World data

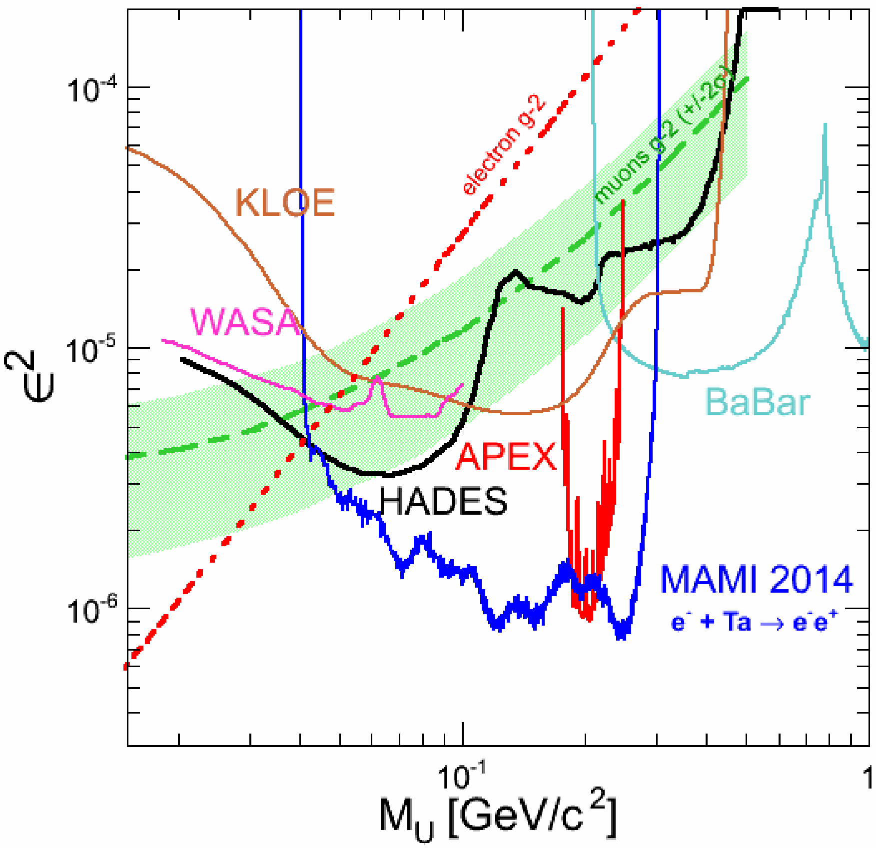
HADES: Phys. Lett. B 731 (2014) 265



- HADES coverage : $0.02 < M_U < 0.6$ GeV
- Clear improvement at low masses ($M_U < 0.1$ GeV/c^2)
- Parameter range favored by the muon g-2 anomaly excluded to large extent
- Added complementary information to the KLOE-2 results at $M_U > 0.13$ GeV

Comparison of HADES with World data

MAMI update: PRL 112 (2014) 221802



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- Clear improvement at low masses ($M_U < 0.1$ GeV/c^2)
- Parameter range favored by the muon g-2 anomaly excluded to large extent
- Added complementary information to the KLOE-2 results at $M_U > 0.13$ GeV

➔ **Updated MAMI A1** result further lowers UL in 40 – 200 MeV range, but does not yet fully exclude g-2 band!

What‘s coming up next ?

HADES

- Adding data from a recent Au+Au run, **HADES** can lower its UL by a factor ≈2
- Dedicated expts.are coming up
  APEX, HPS, VEPP-3, Dark Light

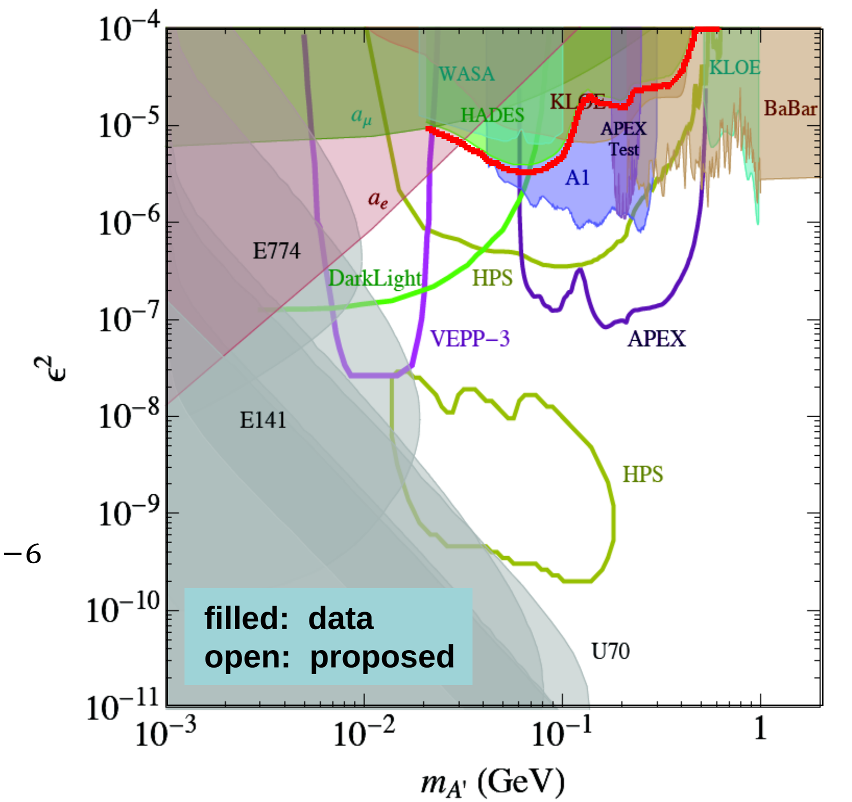
  ➔ expected to reach $10^{-9} - 10^{-8}$ level
- RHIC & LHC expts. entered game too:
  PHENIX, ALICE

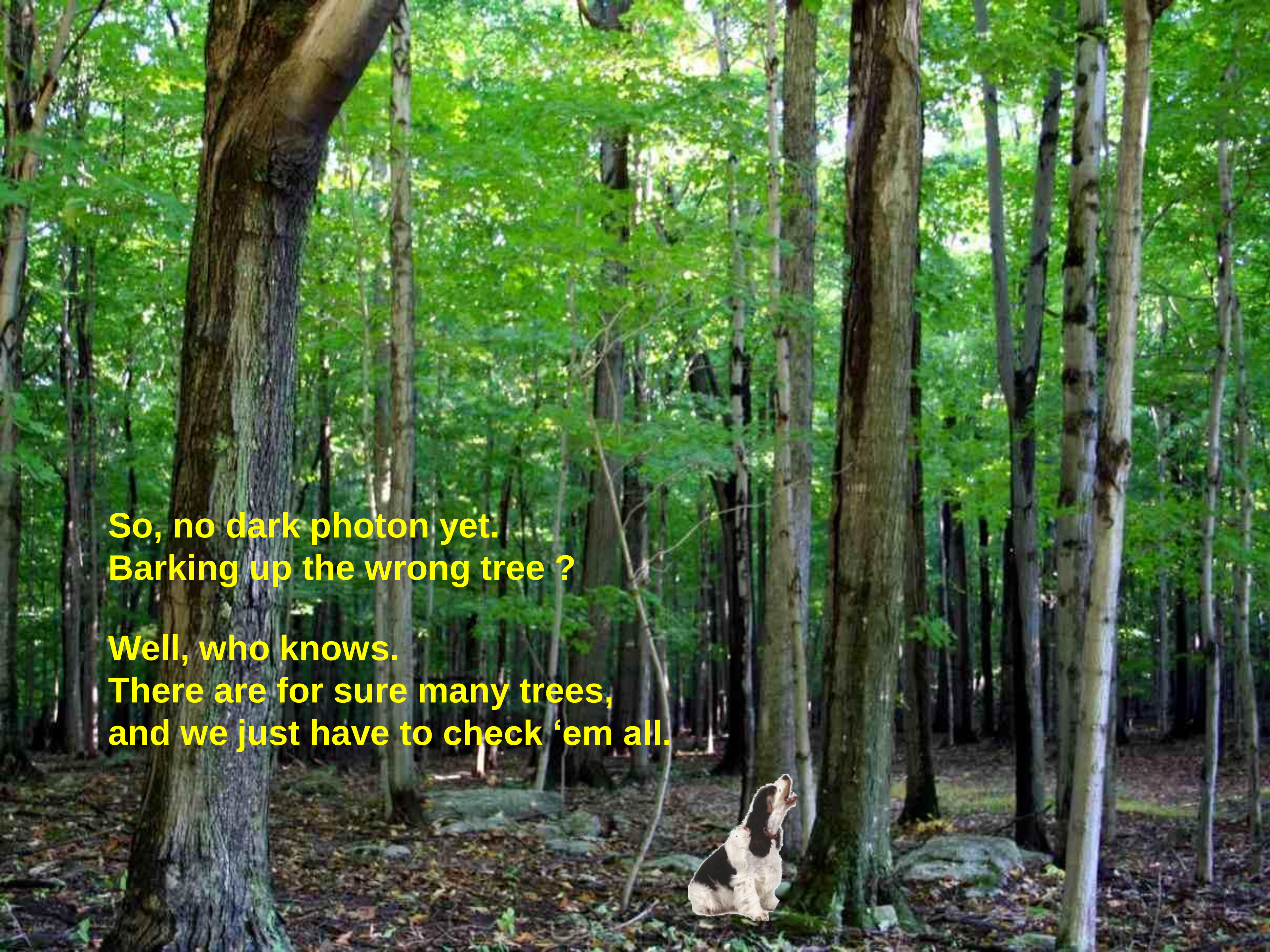
  ➔ present sensitivity approaching $\epsilon^2 \simeq 10^{-6}$

  ➔ expect to reach $\epsilon^2 = 10^{-7}$ level
  after planned upgrades

  ➔ could access m_U>1 GeV region
  via QGP thermal radiation

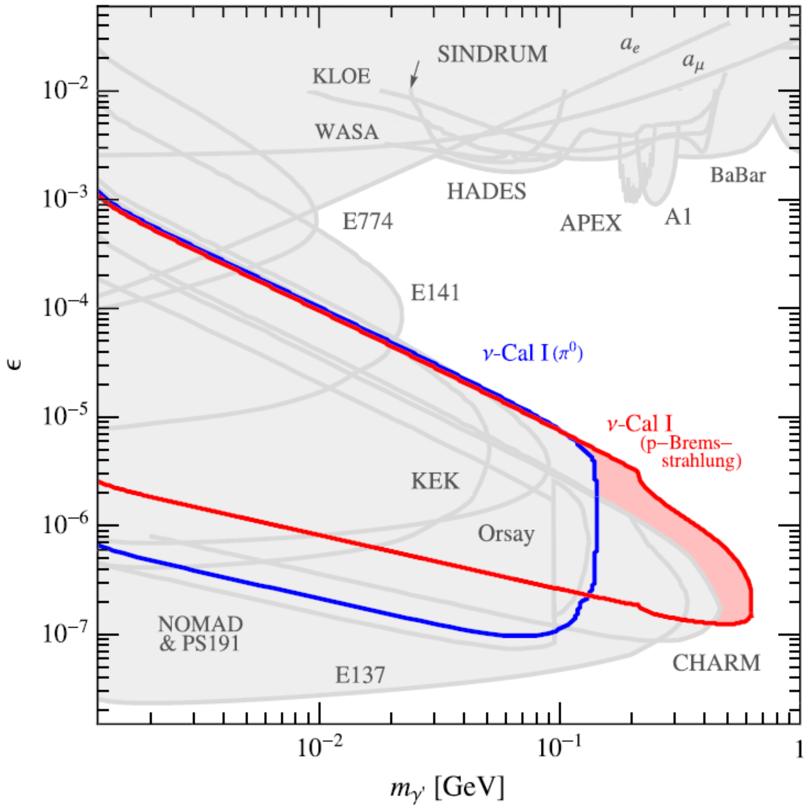
HADES 2014




So, no dark photon yet.
Barking up the wrong tree ?
Well, who knows.
There are for sure many trees,
and we just have to check ‘em all.

Update from U70 beam dump data

Blümlein & Brunner, Phys. Lett. B 731 (2014) 320



Analyzing:

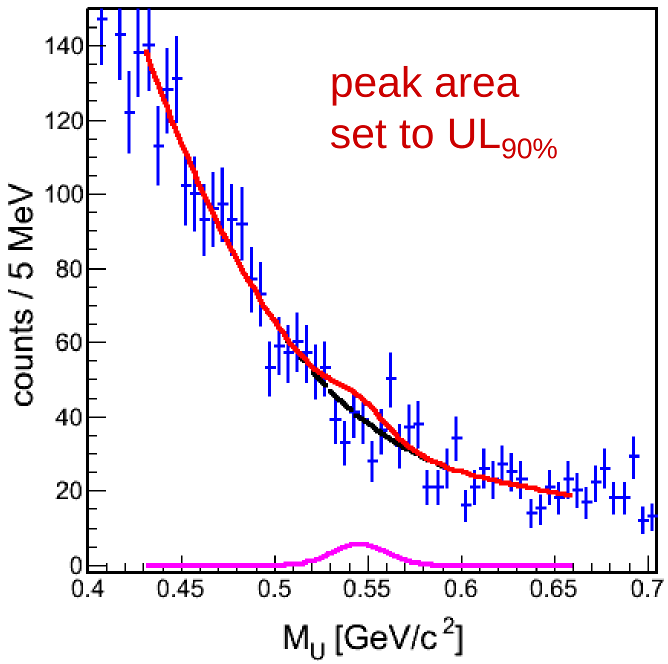
π^0 decays

p bremsstrahlung

More from HADES

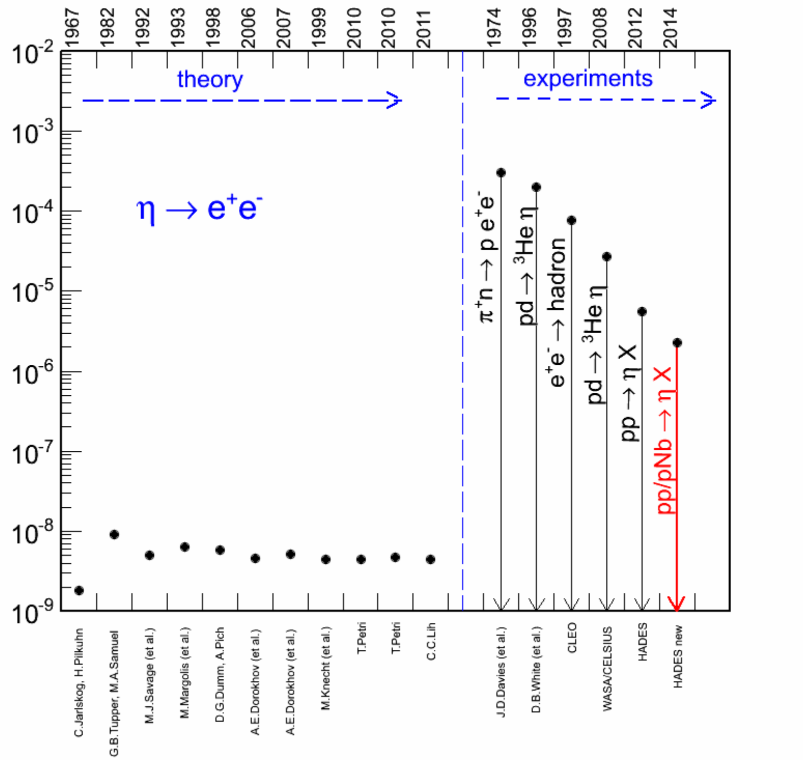
Bonus track: UL on $\eta \to e^+e^-$ decay

HADES



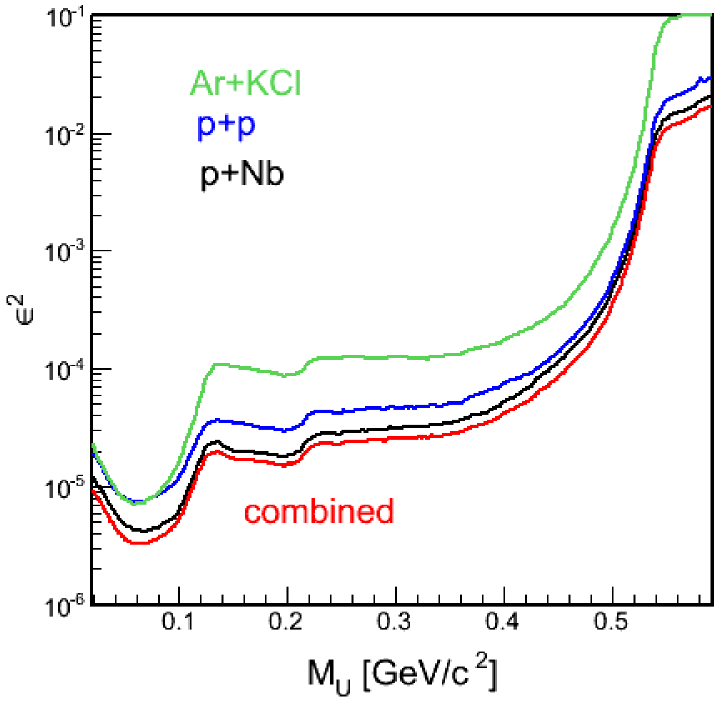
$BR_{\eta \to e+e-} < \mathbf{2.5\times10^{-6}}$ **at 90% CL**

HADES: Phys. Lett. B 731 (2014) 265



➔ Still far above QCD inspired theoretical expectations: $BR \simeq 5\times10^{-9}$

Combined UL on ε^2

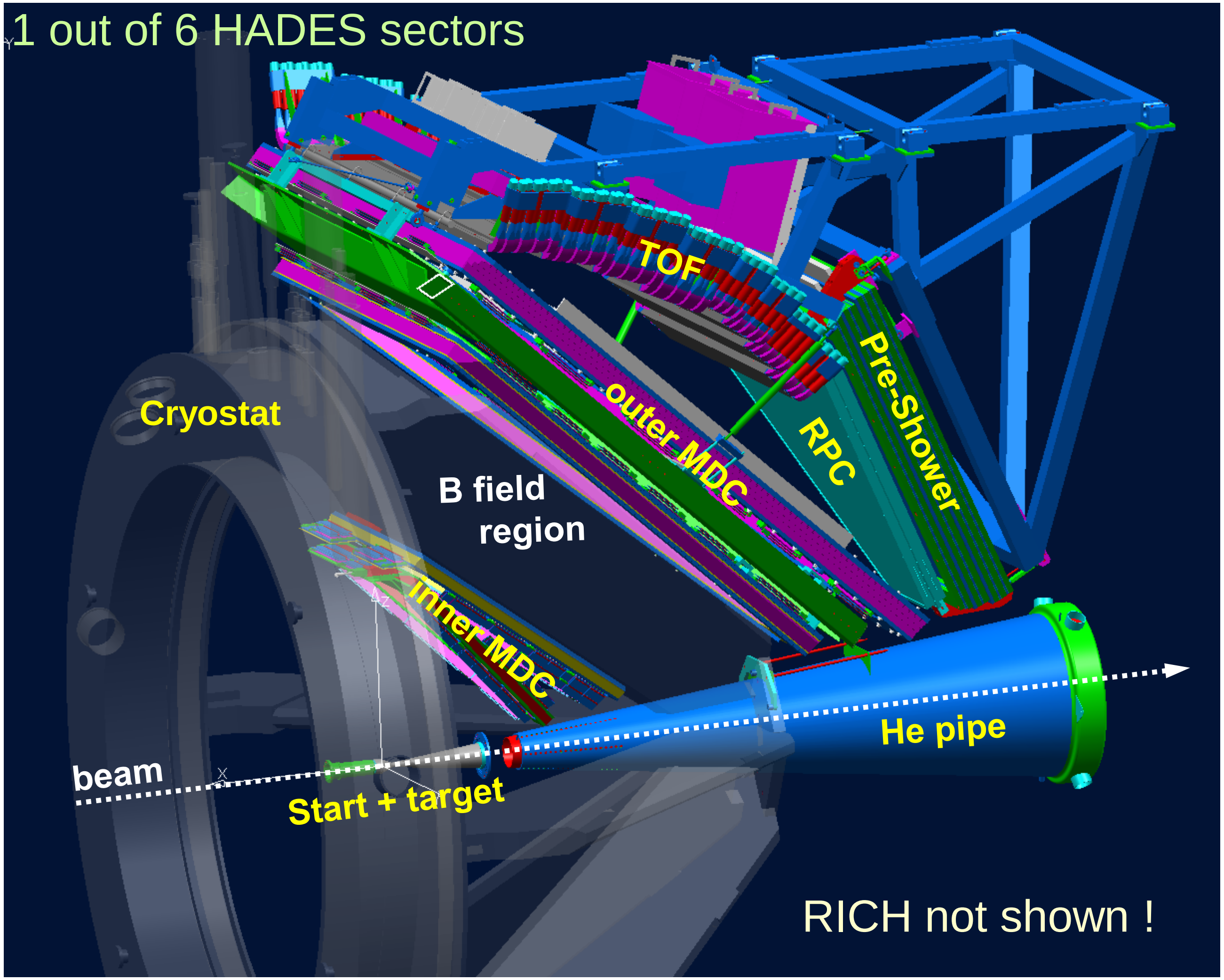


All 3 data sets are of comparable statistical quality and ULs can be joined into one combined UL following a statistics-driven ansatz:

$$UL_{(1+2+3)} = \sqrt{(UL_{(1)}^{-2} + UL_{(2)}^{-2} + UL_{(3)}^{-2})^{-1}}$$

The combined upper limit **$UL_{(1+2+3)}$** is overall about 10-20% lower than the p+Nb value taken alone.

Technical layout of HADES



HADES + FW

inner MDC

RICH readout