Search for dark forces with KLOE / KLOE-2

E. Graziani

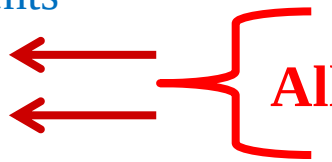
INFN – Roma 3

on behalf of the KLOE-2 Collaboration

From the 2009 SLAC Workshop on Dark Forces

There are several different experimental ways (on earth) to take a look at the dark world:

- fixed target experiments
- e^+e^- machines
- rare meson decays



All results with KLOE detector & data set

KLOE/KLOE-2 is an a very good position to probe a light dark sector at the GeV scale:

- It operates on DAϕNE **exactly** at that scale: E_{cm}~ 1 GeV
- Most of the interesting dark process cross sections at e^+e^- colliders scale with 1/s: a factor ~100 wrt to B factories, which almost compensates the integrated luminosity
- It's a unique place to study some rare meson decays (it's a ϕ factory, folks!)

Dark forces at KLOE: outline

✓ Decay of the ϕ meson into a U boson + pseudoscalar η:

$\phi \to \eta U$, $U \to e^+e^-$, $\eta \to \pi\pi\pi$ → **Phys.Lett. B706 (2012) 251**
Phys.Lett. B720 (2013) 111

✓Associated Uγ production: $e^+e^- \to U\gamma \to \mu^+\mu^-\gamma$ → **Phys.Lett. B736 (2014) 459**
$e^+e^- \to U\gamma \to e^+e^-\gamma$ → **Phys.Lett. B750 (2015) 633**
$e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$ → **Phys.Lett. B757 (2016) 356**

✓ Higgsstrahlung process, in the $m_{h'} < m_U$ scenario, with an invisible Higgs:
$e^+e^- \to Uh' \to \mu^+\mu^-$ + missing energy → **Phys.Lett. B747 (2015) 365**

U boson search in $\phi \to \eta e^+e^-$ decays

Mesons undergoing radiative decays to photons could also decay to a U boson with branching fraction BR $(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times$ BR $(X \to Y\gamma)$

form factor

$\sigma(\phi \to \eta U) \approx$ 40 fb for $FF_{\phi\eta} \approx 1$ and $\varepsilon \approx 10^{-3}$

$\sigma(\phi \to \eta e^+e^-) = 0.7$ nb

Selected decay chains:

$U \to e^+e^-$ and $\eta \to \pi^+ \pi^- \pi^0$ (BR = 22.7%) **Phys.Lett. B706 (2012) 251-255**

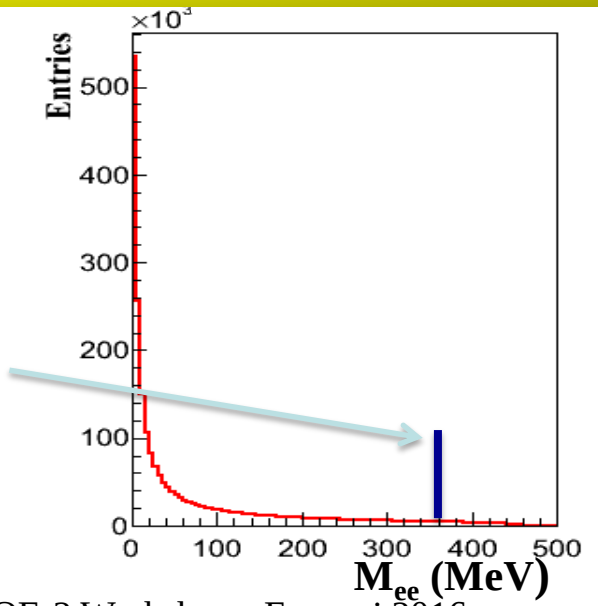
$\eta \to \pi^0 \pi^0 \pi^0$ (BR = 32.6%)

Combined result **Phys.Lett. B720 (2013) 111**

Irreducible background: $\phi \to \eta\, e^+e^-$, $\eta \to \pi\pi\pi$

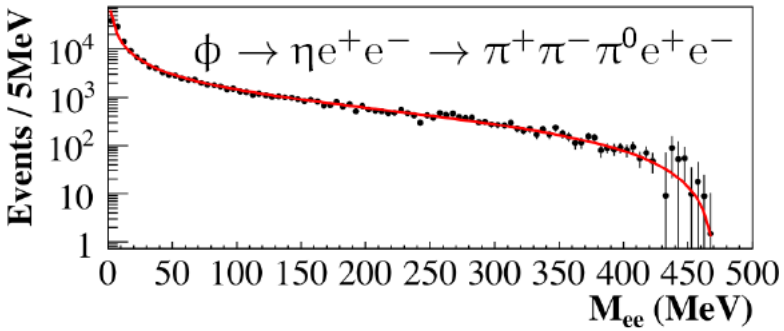
Simulated with a Vector Meson Dominance parameterization

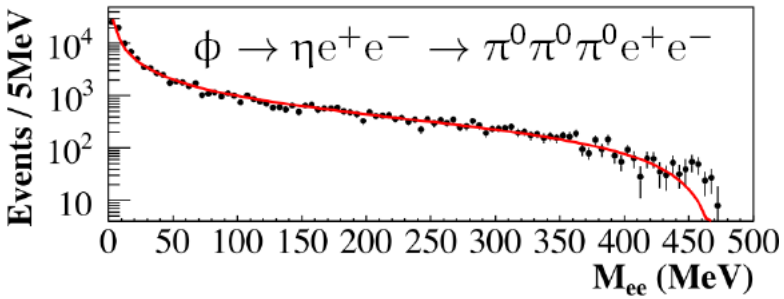
Signal → narrow peak above the continuum background



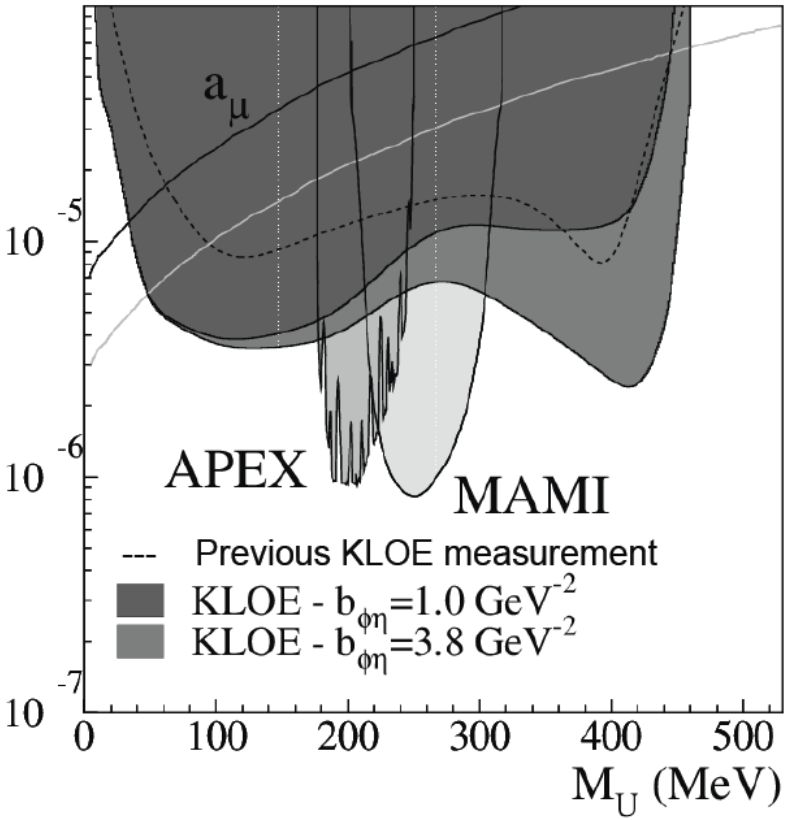
U boson search in $\phi \to \eta e^+e^-$ decays: 90% CL upper limits

Di-electron mass spectrum





- **No clear signal above background → UL evaluation**
- background → fit of the M_{ee} distribution excluding the region around M_U → CL_S method

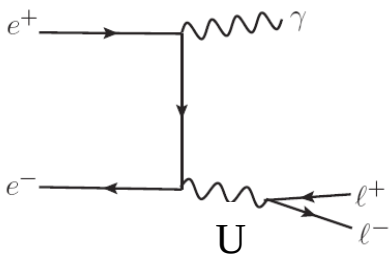


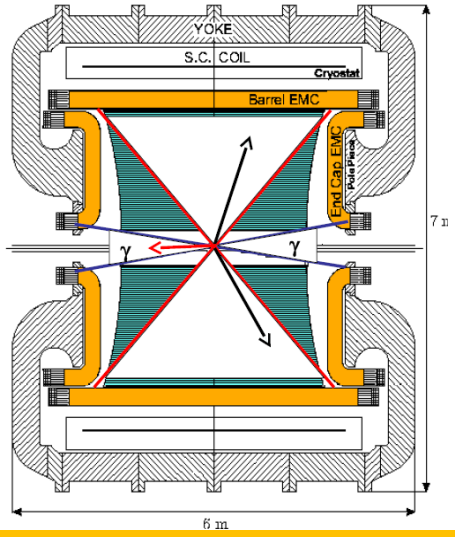
$\varepsilon^2 \leq 1.7 \times 10^{-5}$ @ 90% C.L. for $30 < M_U < 400$ MeV

$\varepsilon^2 \leq 8.0 \times 10^{-6}$ @ 90% C.L. for $50 < M_U < 210$ MeV

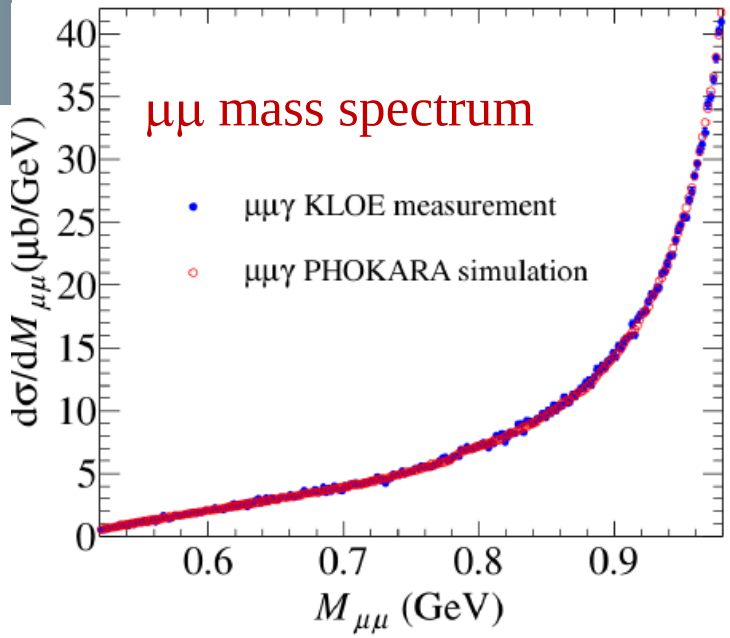
Phys.Lett. B720 (2013) 111

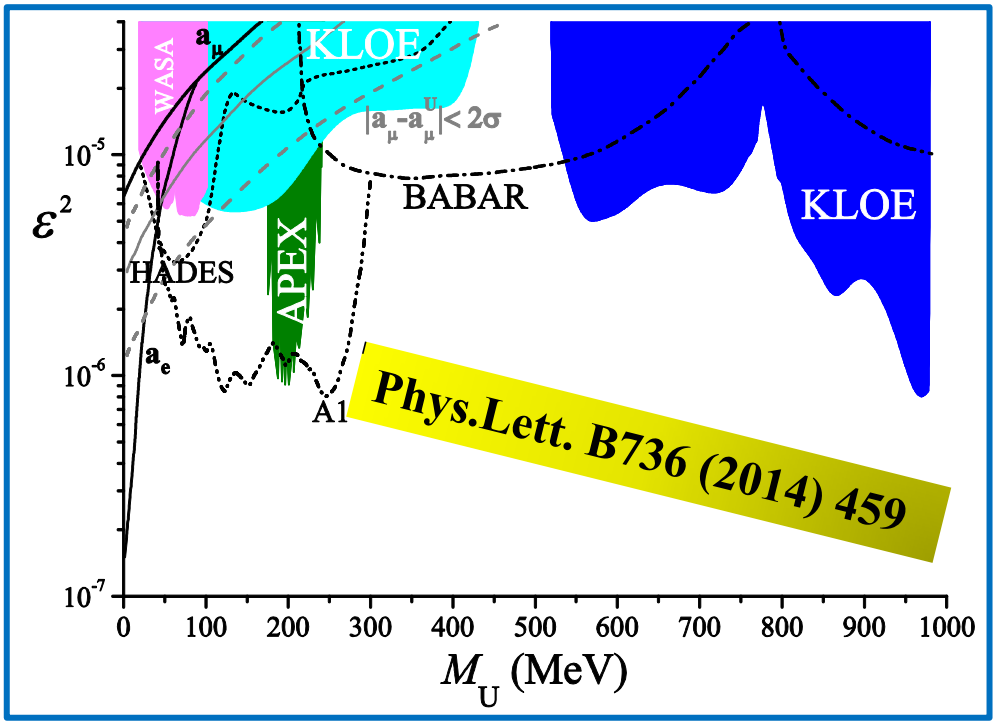
U boson search in $e^+e^-\to\mu^+\mu^-\gamma$





- undetected small angle photon $\theta_\gamma<15°$, $\theta_\gamma>165°$
- two opposite sign charged tracks $50°<\theta_\mu<130°$





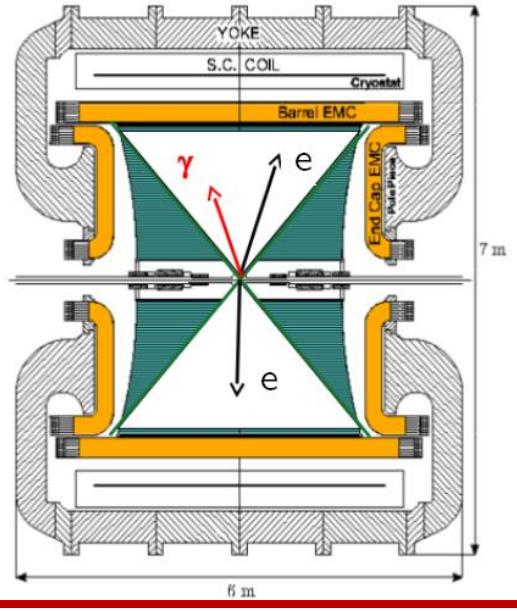
Results based on only 240 pb^{-1}

potential factor 3 improvement in sensitivity

U boson search in $e^+e^-\to e^+e^-\gamma$

- detected large angle photon $\theta_\gamma<50°$, $\theta_\gamma>130°$
- two opposite sign charged tracks $50°<\theta_e<130°$
- M_{TRK} to separate from $\mu\mu\gamma$, $\pi\pi\gamma$

✓ allows to explore the $2m_e$ threshold region
✓ great suppression of t-channel Bhabha
✓ background contamination ≈1.5%

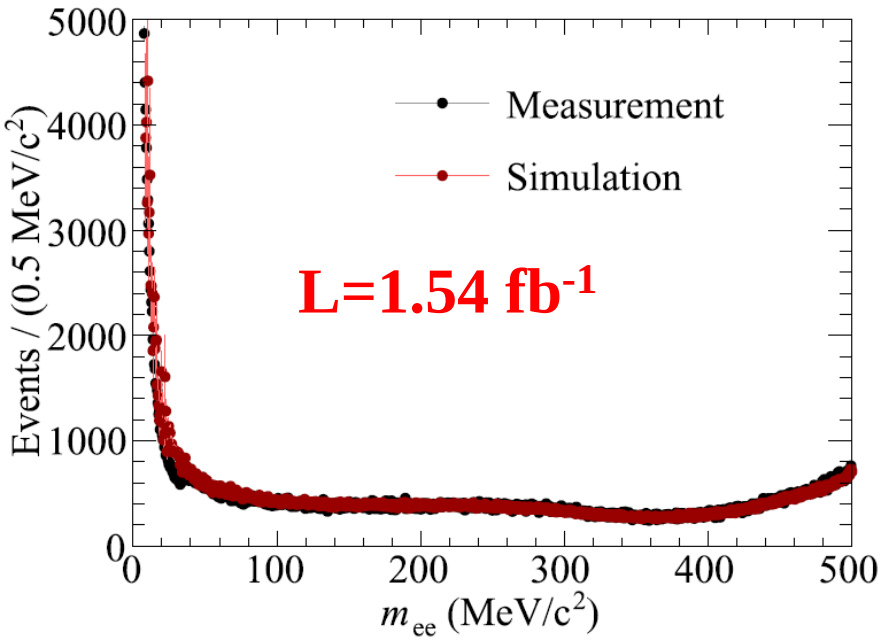


e^+e^- mass spectrum

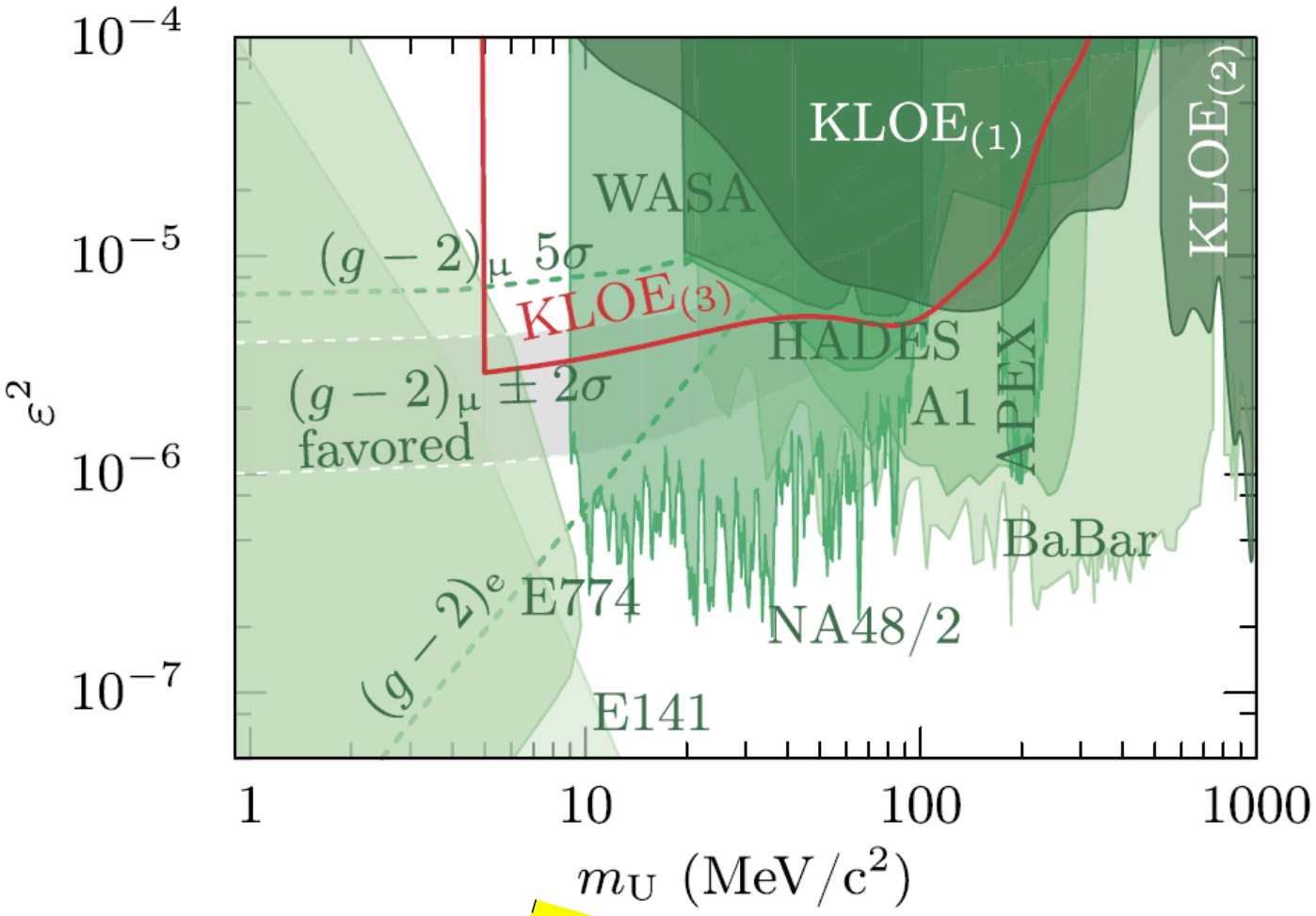
Babayaga-NLO simulation (with weighted events)

Background estimated from data

No peak observed → UL CL_S technique

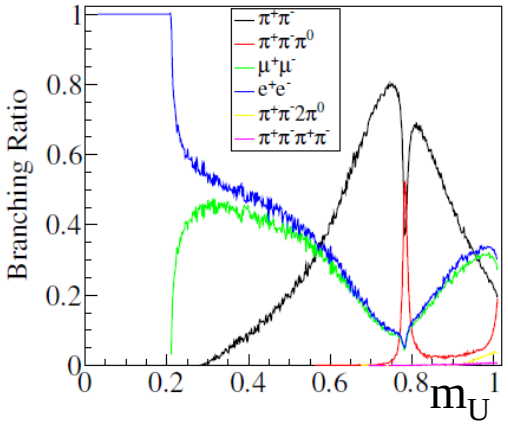


U boson search in $e^+e^- \to e^+e^-\gamma$: 90% CL upper limits

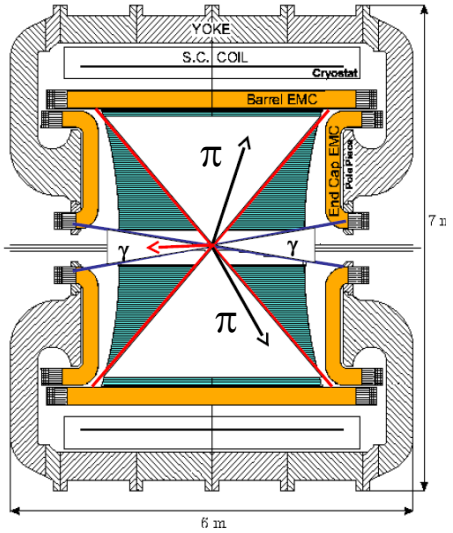


Phys.Lett. B750 (2015) 633

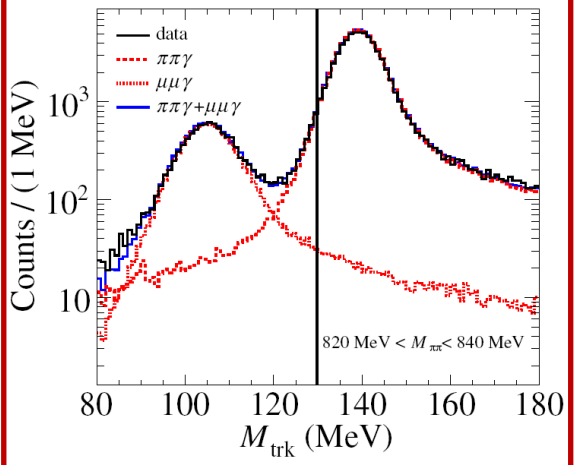
U boson search in $e^+e^- \to \pi^+\pi^-\gamma$



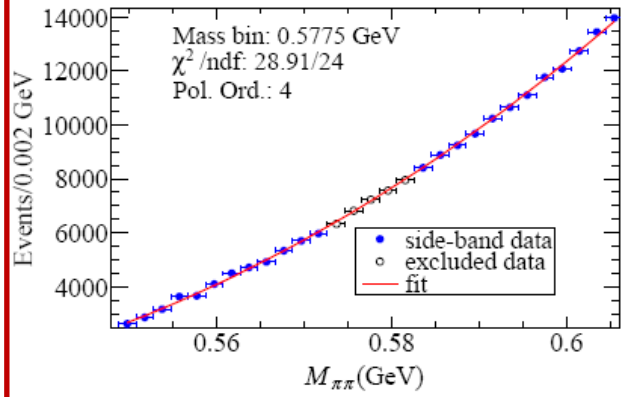
- undetected small angle photon θ_γ<15°, θ_γ>165°
- two opposite sign charged tracks 50°<θ_π<130°



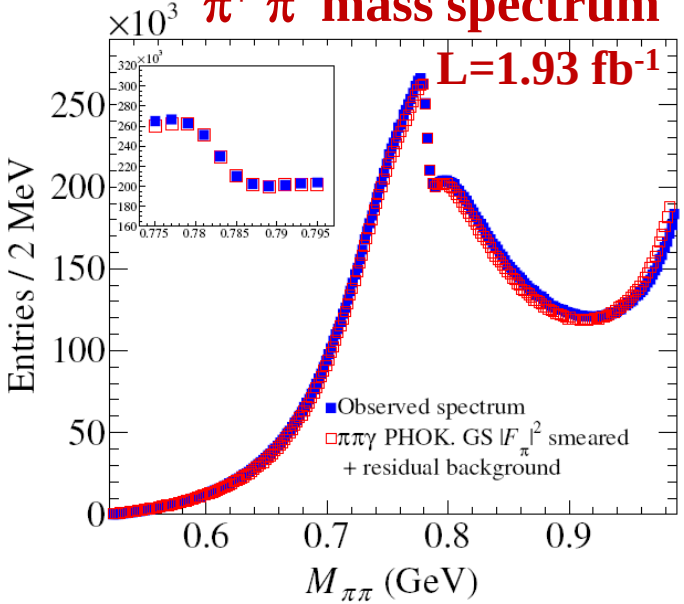
π/μ separation



background evaluation

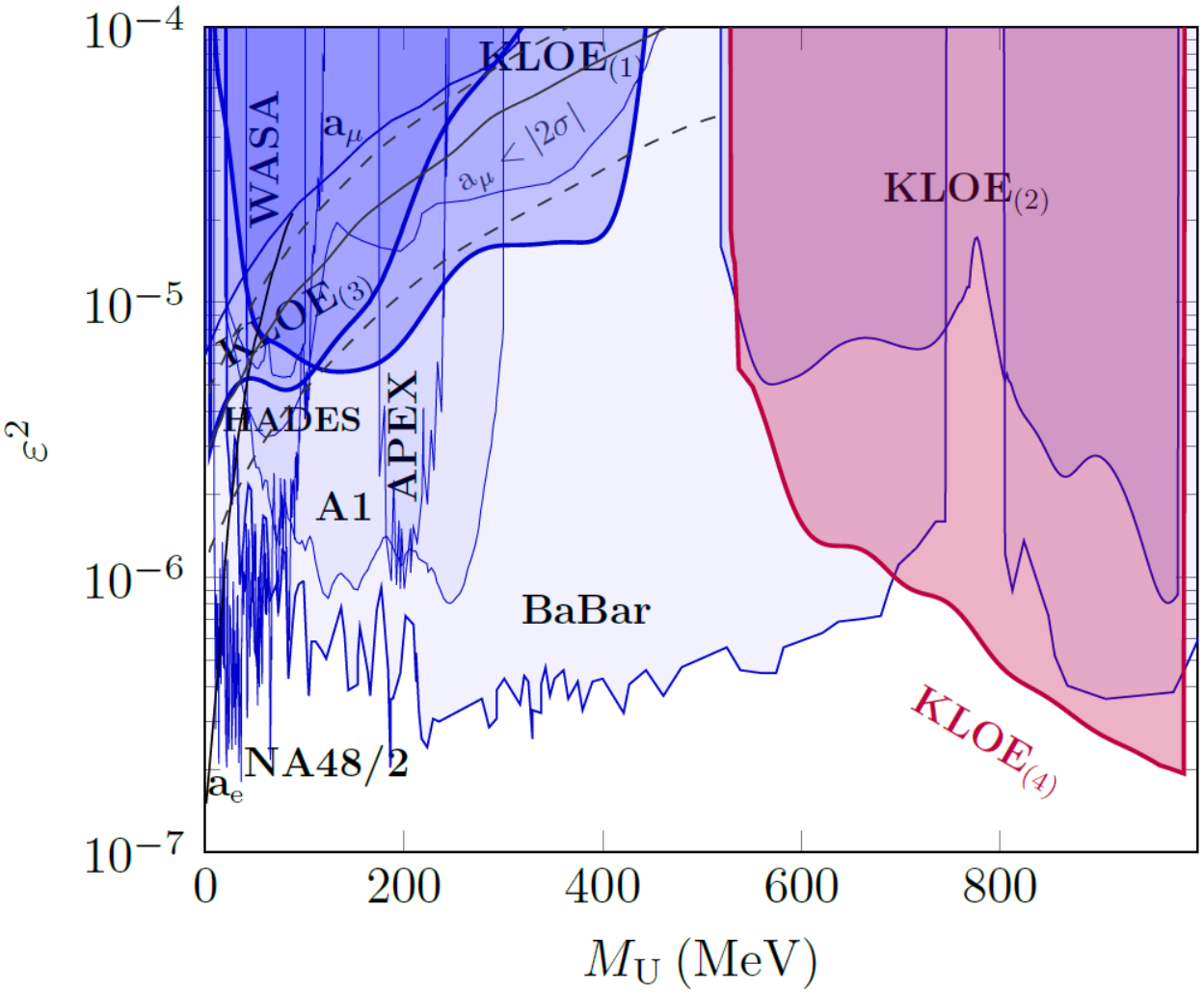


$\pi^+\ \pi^-$ mass spectrum



U boson search in $e^+e^- \to \pi^+\pi^-\gamma$: 90% CL upper limits

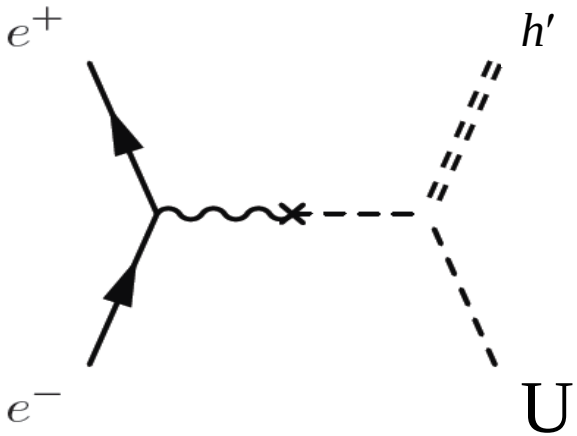
L=1.93 fb^{-1}



KLOE$_{(1)}$ → Dalitz $\phi \to \eta e^+e^-$
KLOE$_{(2)}$ → $e^+e^- \to \mu^+\mu^-\gamma$
KLOE$_{(3)}$ → $e^+e^- \to e^+e^-\gamma$
KLOE$_{(4)}$ → $e^+e^- \to \pi^+\pi^-\gamma$

Phys.Lett. B757 (2016) 356

The $e^+e^- \to h'U$ higgsstrahlung process



Very different scenarios depending on

$\varepsilon = 10^{-3}$

$\alpha_D = \alpha_{em}$

$m_{U,h'} \sim 100$ MeV

→ **$m_{h'} < m_U \Rightarrow$ "invisible"**

→ $m_{h'} > m_U \Rightarrow h \to uu \to 4l, \pi + 2l, \pi$

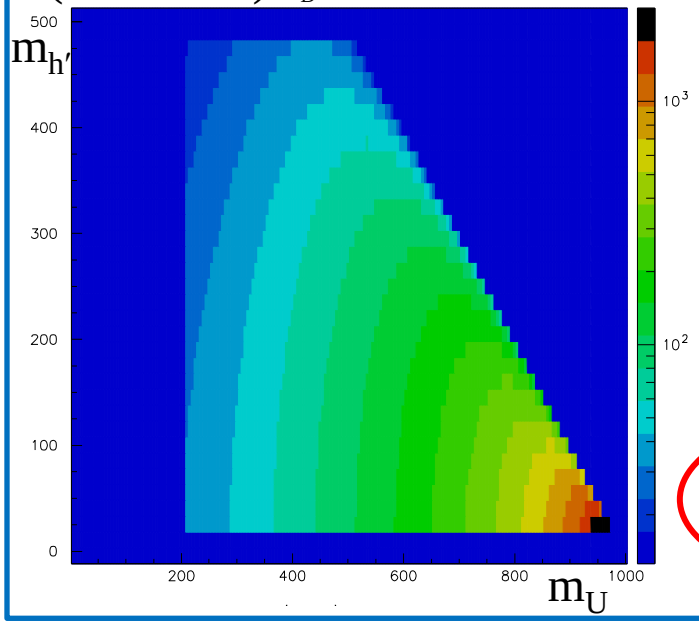
→ $\tau_{h'} > 5\ \mu s \to \beta\gamma c\tau > 100$ m

rapidly increasing with decreasing ε

invisible up to $\varepsilon \approx 10^{-2} \div 10^{-1}$ depending on $m_{h'}$

We studied only the muon case $m_{h'} < m_U$: $e^+e^- \to \mu^+\mu^-$ + missing energy

$\sigma(e^+e^- \to h'U)$ $\alpha_D = \alpha$, $\varepsilon = 10^{-3}$, $s = 1$ GeV^2 fb

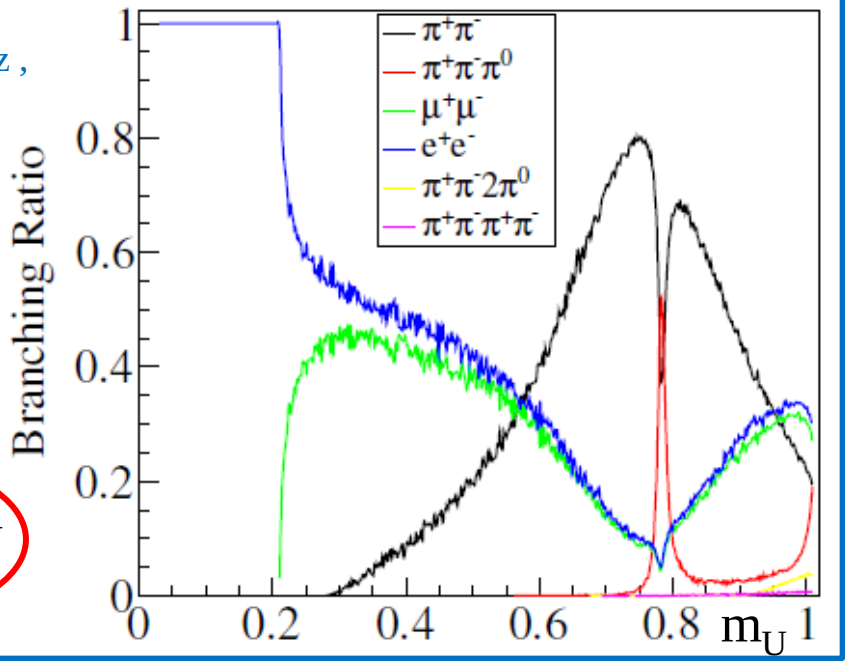


Batell, Pospelov, Ritz ,

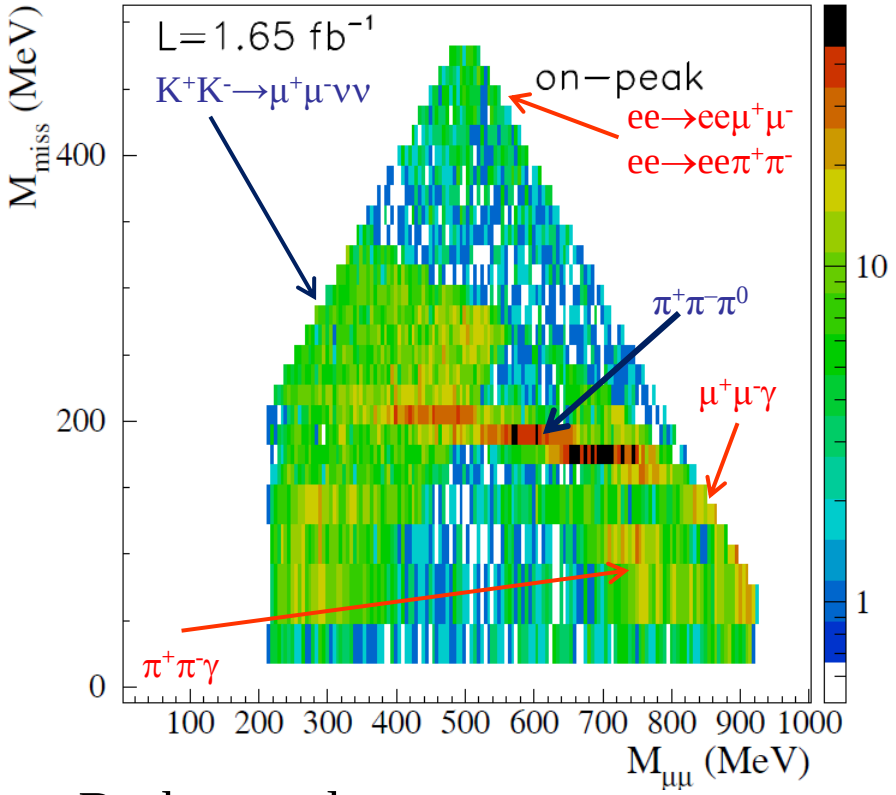
Phys. Rev. D **79**,

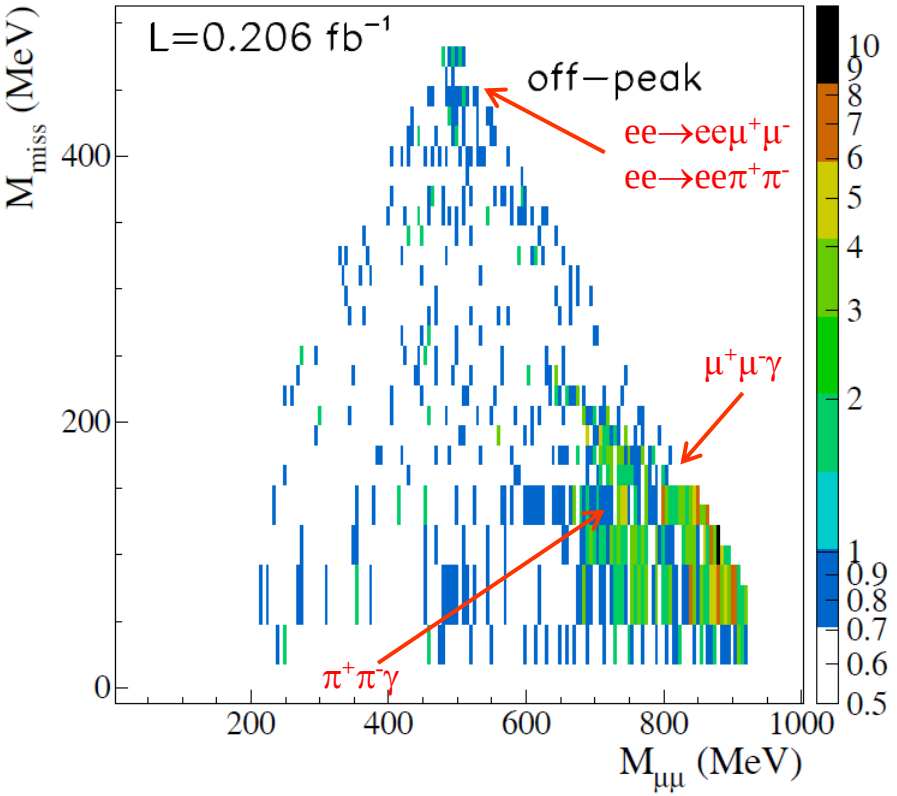
115008 (2009)

$$\sigma_{h'U} \propto \frac{1}{s}\frac{1}{(1-\frac{m_U^2}{s})^2}$$



$e^+e^- \to h'U$: results





Backgrounds

$\phi \to K^+ K^-$, $K^\pm \to \mu^\pm \nu$ ← ϕ decays

$\phi \to \pi^+\pi^-\pi^0$

$e^+e^- \to \mu^+\mu^-\gamma$

$e^+e^- \to \pi^+\pi^-\gamma$ ← continuum

$e^+e^- \to e^+e^-\mu^+\mu^-$

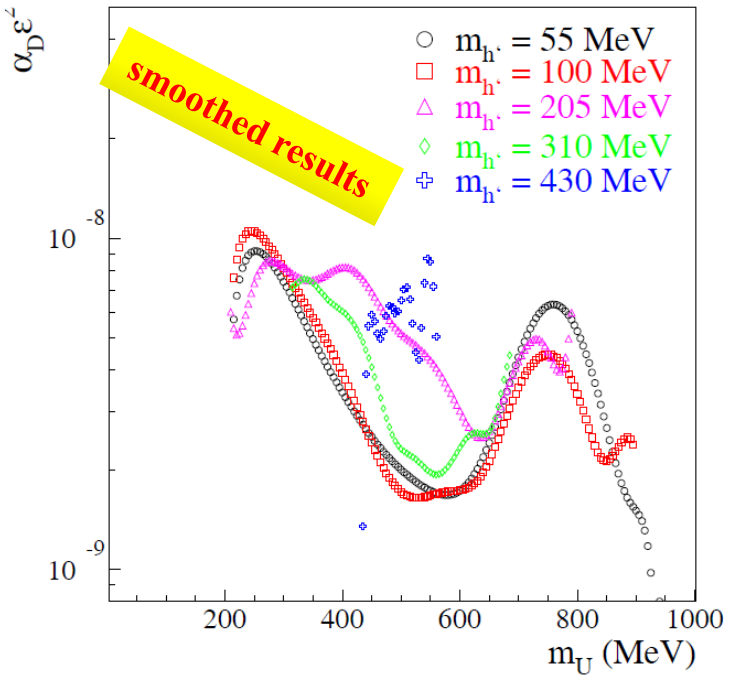
$e^+e^- \to e^+e^-\pi^+\pi^-$

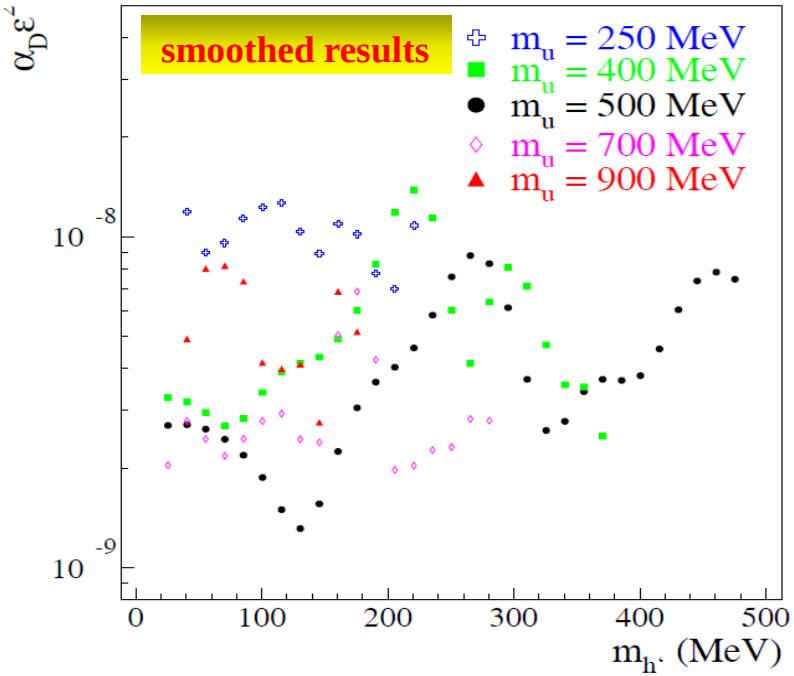
Binning such as to keep 90-95% of the signal in one bin

5 MeV bin in m_u ($M_{\mu\mu}$)

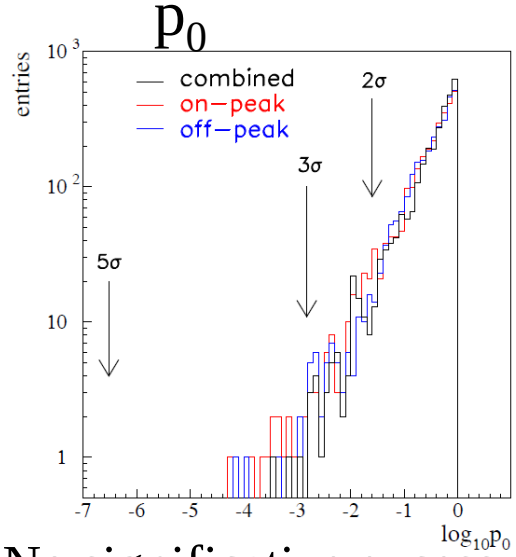
15÷50 MeV variable bin in m_h (M_{miss})

$e^+e^- \to h'U$: p_0 values and 90% CL upper limits





Phys.Lett. B747 (2015) 365



No significative excess

Limits ~ $10^{-8} \div 10^{-9}$ in $\alpha_D\varepsilon^2$ ($10^{-3} \div$ some 10^{-4} in ε if $\alpha_D = \alpha_{em}$)

Search complementary with BaBar/Belle

Dark forces at KLOE: summary and conclusions

❑ KLOE searched for a dark gauge U boson in six different processes:

• ϕ meson decay: $\Phi \to \eta U$ with $U \to e^+e^-$, $\eta \to \pi\pi\pi$	**Phys.Lett. B720 (2013) 111**
• $U\gamma$ associate production: $e^+e^- \to U\gamma \to \mu^+\mu^-\gamma$	**Phys.Lett. B736 (2014) 459**
• $U\gamma$ associate production: $e^+e^- \to U\gamma \to e^+e^-\gamma$	**Phys.Lett. B750 (2015) 633**
• $U\gamma$ associate production: $e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$	**Phys.Lett. B757 (2016) 356**
• Higgsstrahlung: $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy	**Phys.Lett. B747 (2015) 365**

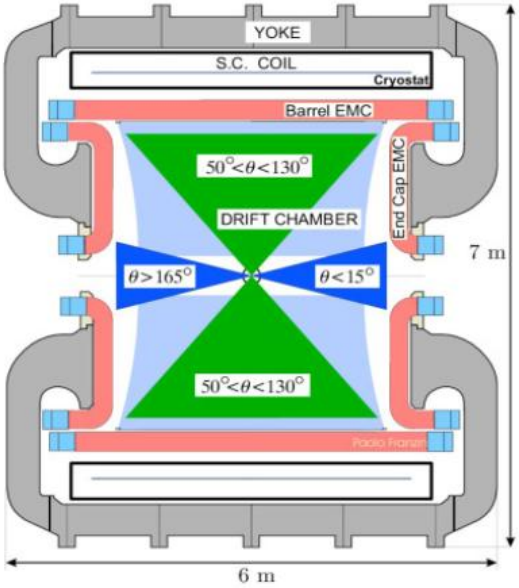
❑ We found no evidence and set upper limits on the mixing parameter ε^2 ($\alpha_D\varepsilon^2$), as a function of the U (and h′) mass, in the range $10^{-5} \div 10^{-7}$, depending on the process.

❑ All these measurements, performed with the KLOE data set, are statistically dominated, so…

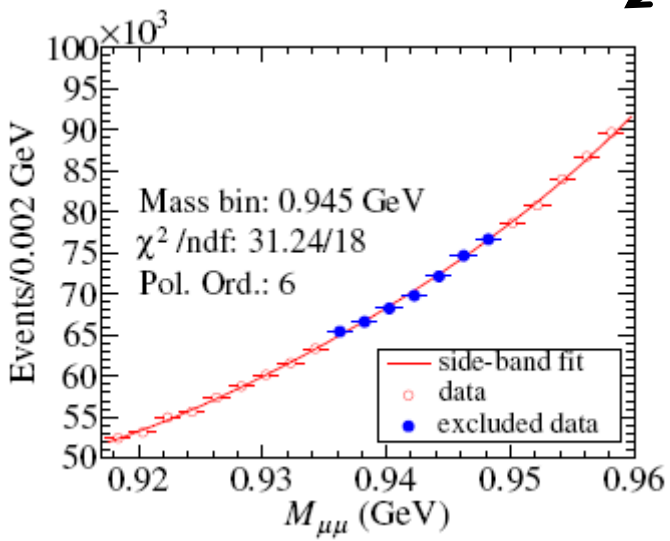
❑ … the increased DAϕNE delivered luminosity and the presence of the new detectors in KLOE-2 are expected to improve these limits by a factor … (see next slides).

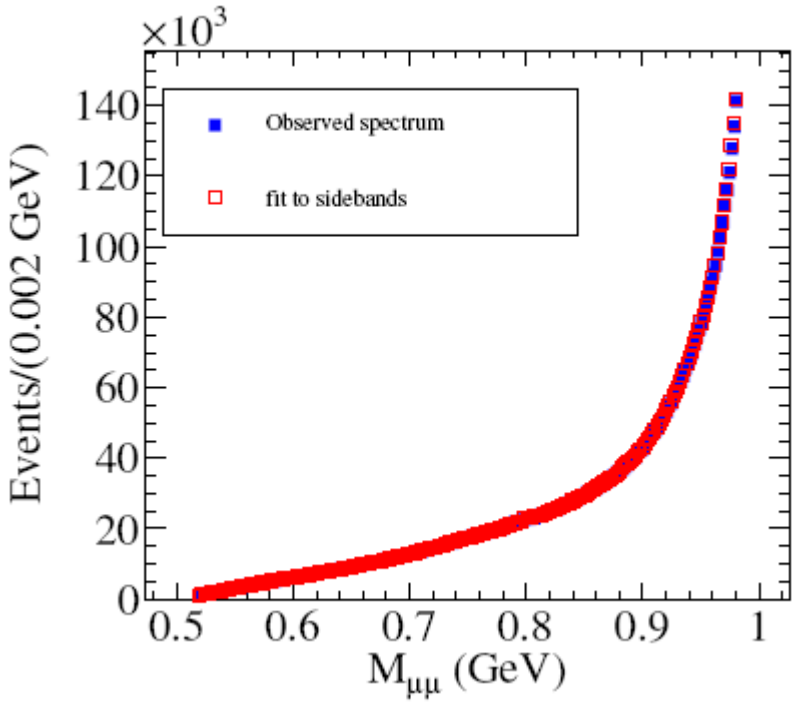
❑ New KLOE-2 run is well in progress. Stay tuned!

U boson search in $e^+e^- \to \mu^+\mu^-\gamma$: **new**

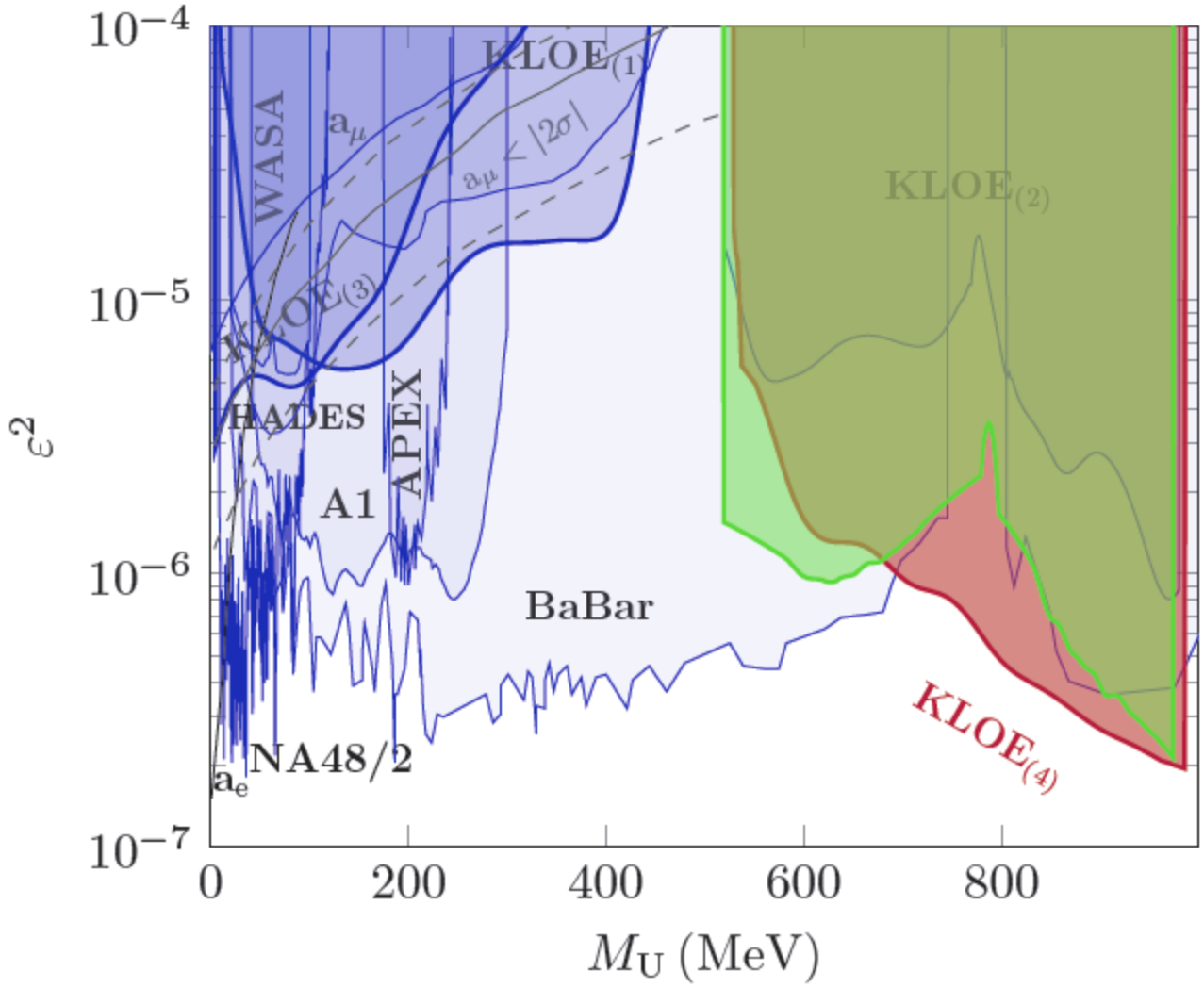


- Search extended to the full KLOE available statistics: 1.93 fb^{-1}
- More similar to the $\pi^+\pi^-\gamma$ analysis
- Background evaluated with the sideband fitting technique on the observed spectrum





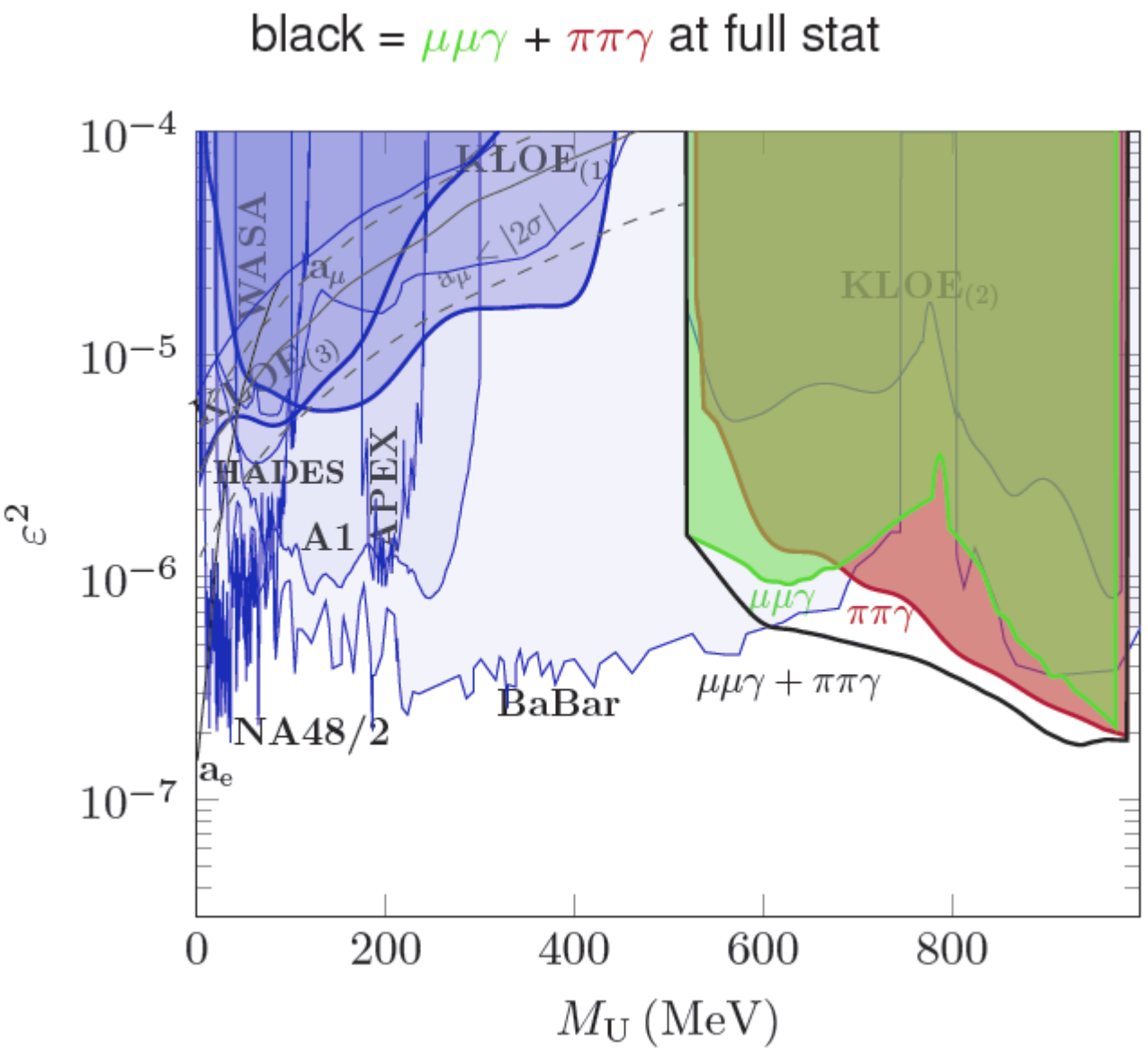
U boson search in $e^+e^- \to \mu^+\mu^-\gamma$: 90% CL upper limits



preliminary

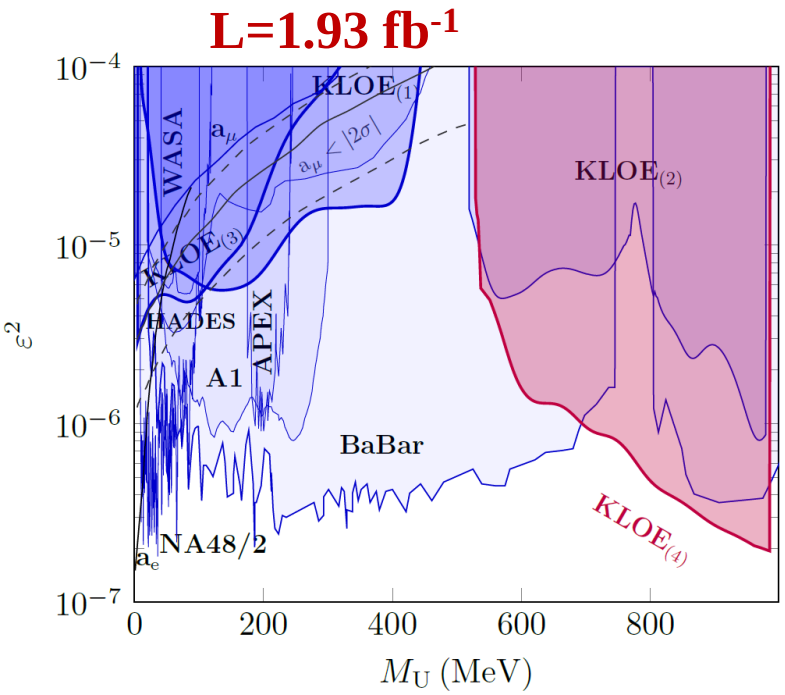
$\varepsilon^2 < 1.5 \times 10^{-6} - 2 \times 10^{-7}$ in the 519–973 MeV energy range

U search in $e^+e^- \to \mu^+\mu^-\gamma + \pi^+\pi^-\gamma$: 90% CL upper limits



preliminary

Dark forces at KLOE-2

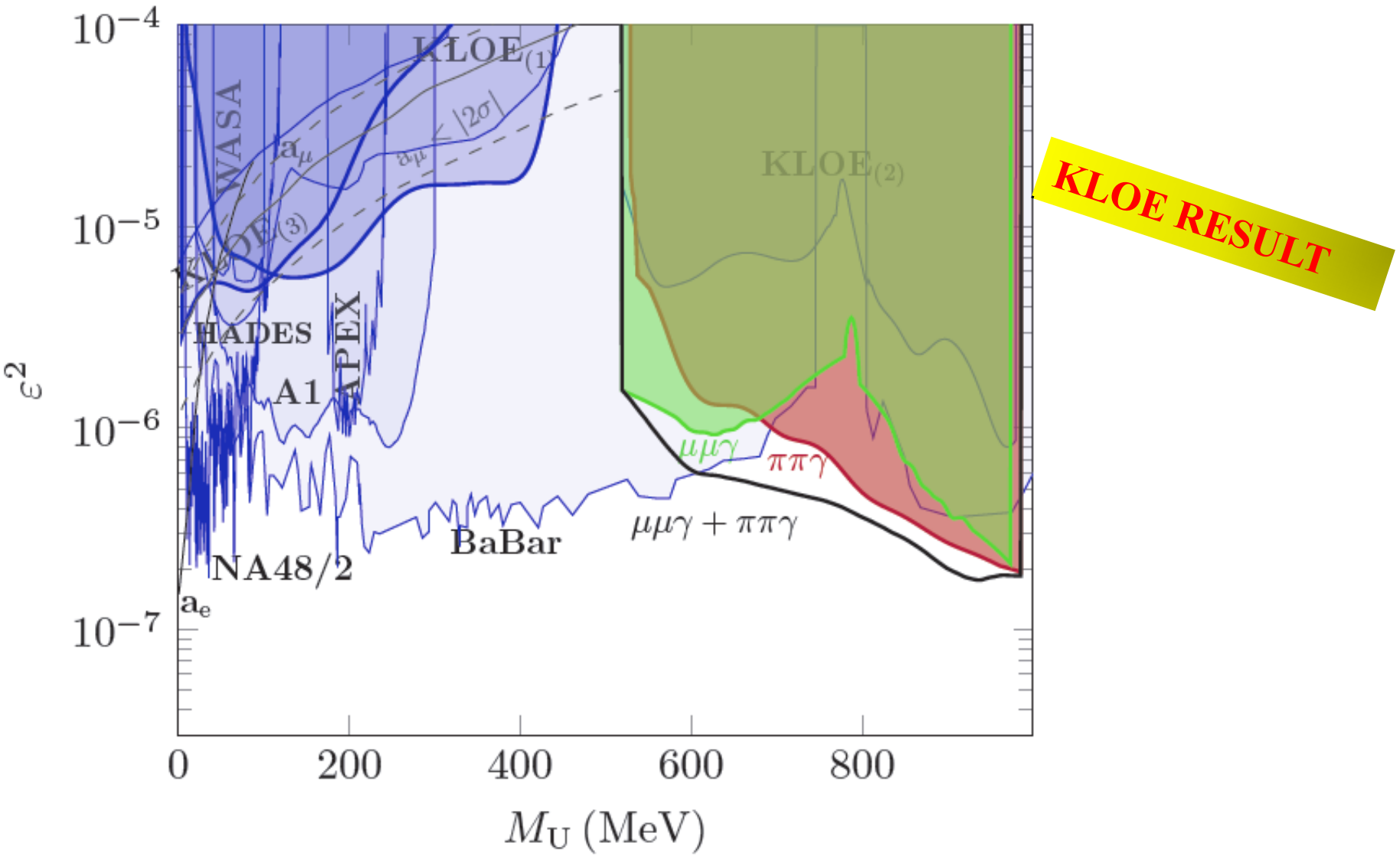


- The $\phi \to \eta e^+ e^-$ search is no more competitive with other results in the low mass region and will probably be dropped
- The most important new detector for the dark forces search is the Inner Tracker
- Improvements in both mass resolution measurement and vertex position reconstruction (still to be precisely quantified)

Our projections for KLOE-2 assume:

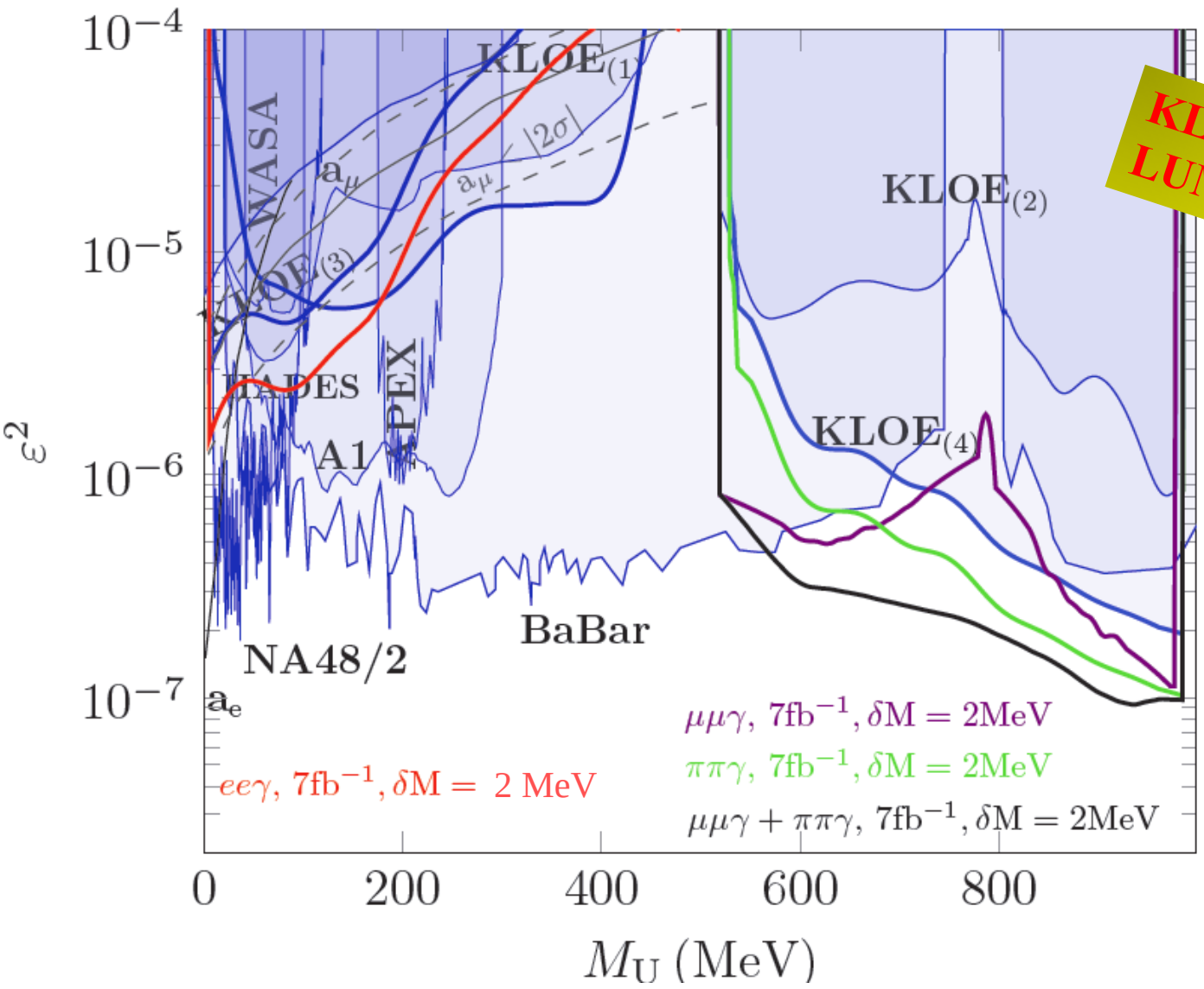
- L=5 fb^{-1} fully available for analyses
- 30% improvement in mass resolution (S/N ratio)
- 2÷3 improvement in vertex position ($K^{\pm}$ rejection).

U boson search in $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$



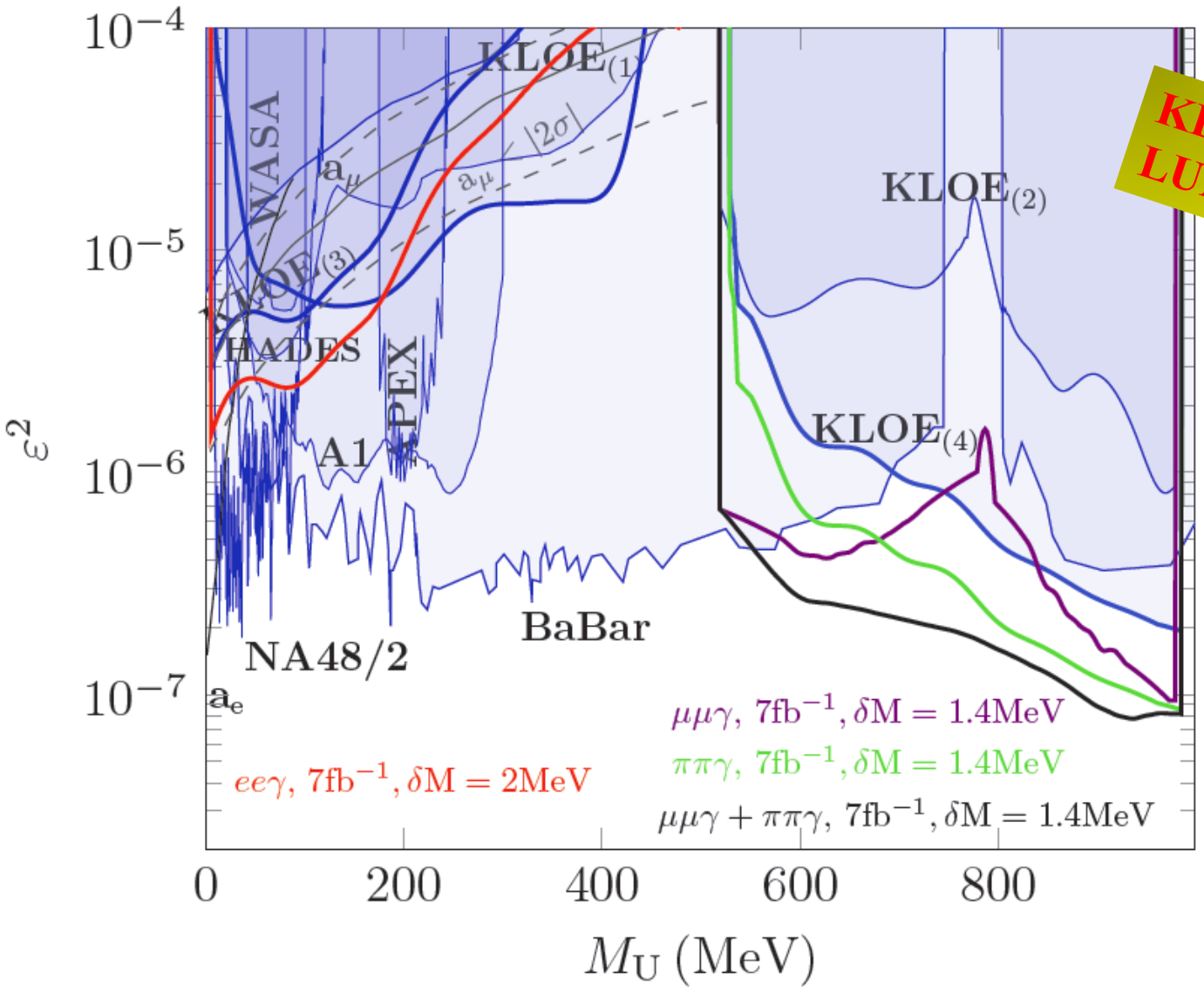
KLOE RESULT

U search in $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$: KLOE-2 projections



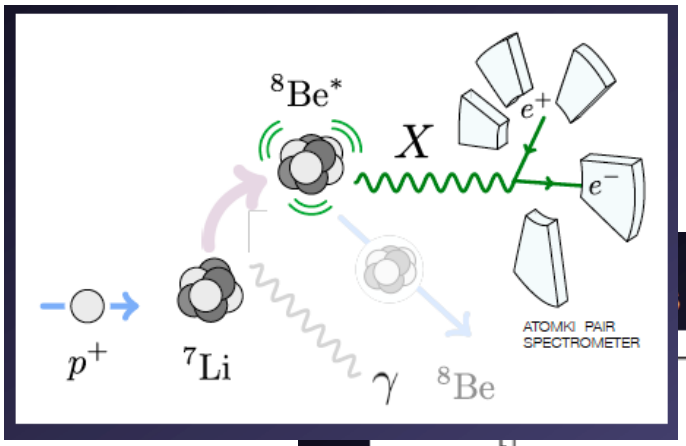
KLOE-2 PROJECTION: LUMINOSITY ONLY

U search in $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$: KLOE-2 projections

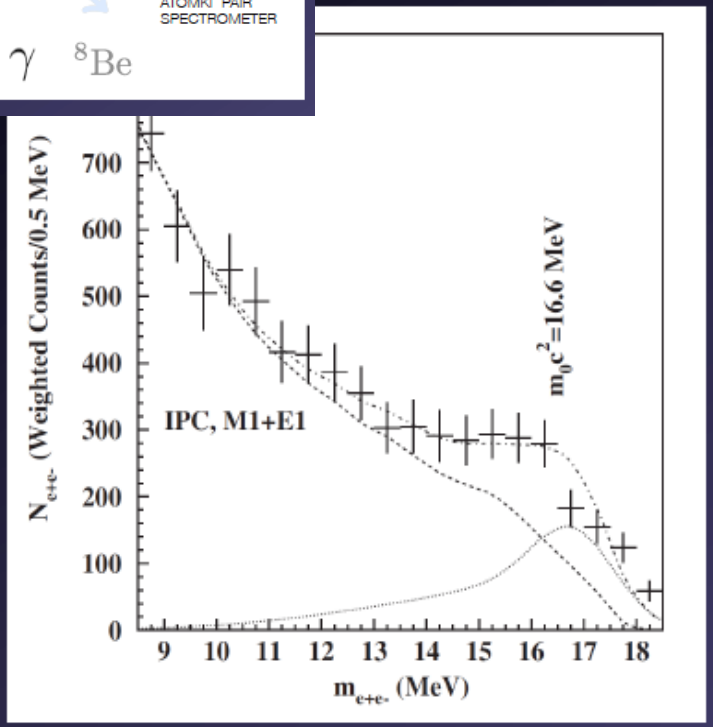


KLOE-2 PROJECTION: LUMINOSITY + IT

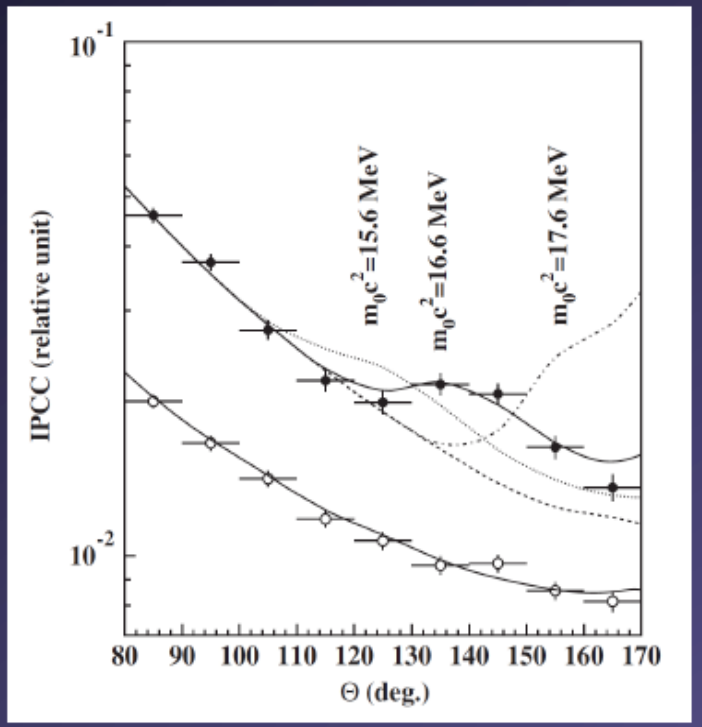
X boson at 17 Mev?



distribution of e^+e^-



Angular correlation of e^+e^- pairs

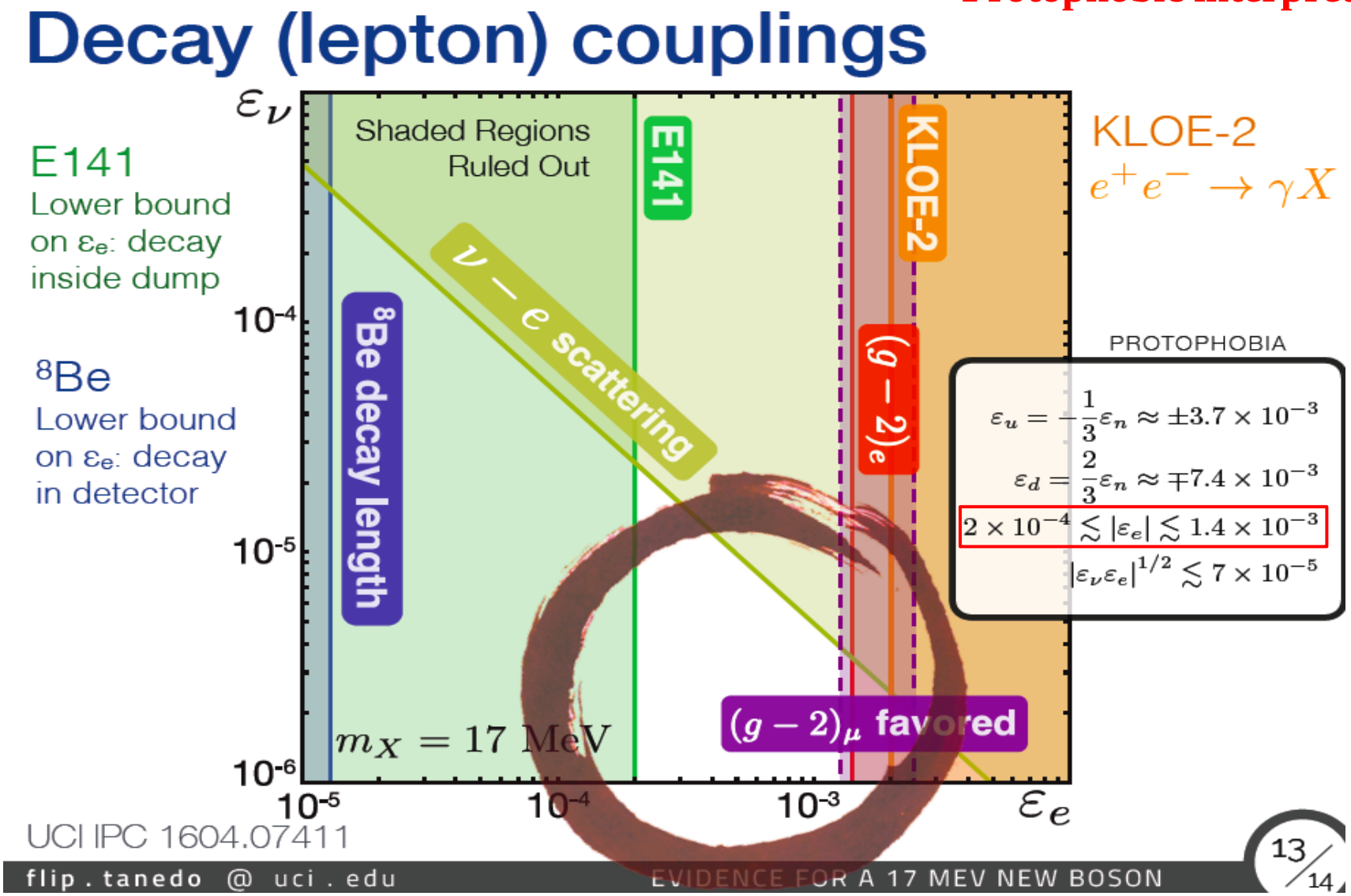


Krasznahorkay et al., PRL 116 (2016) 042501

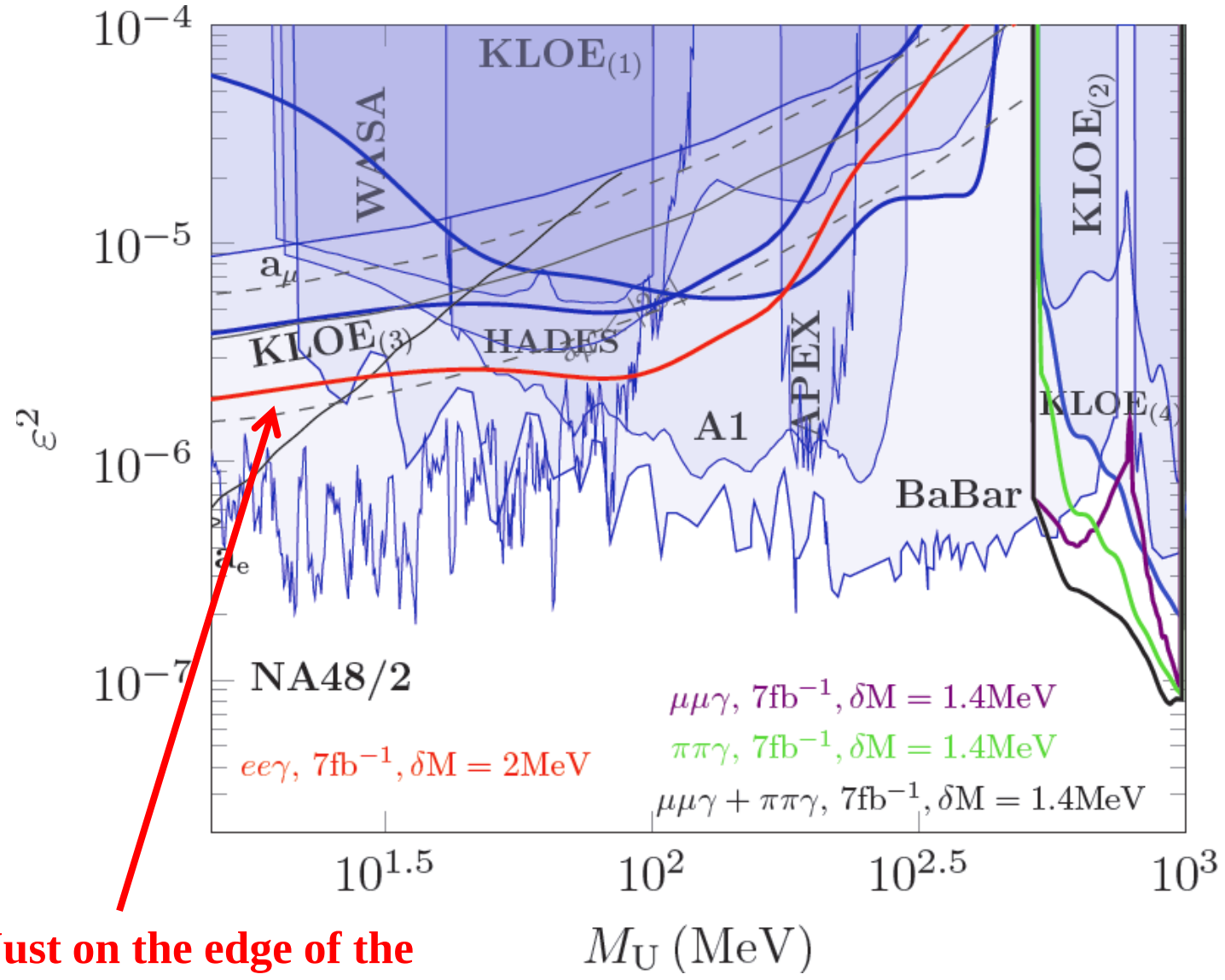
→ $m_X \approx 17$ MeV

X boson at 17 Mev?

Protophobic interpretation

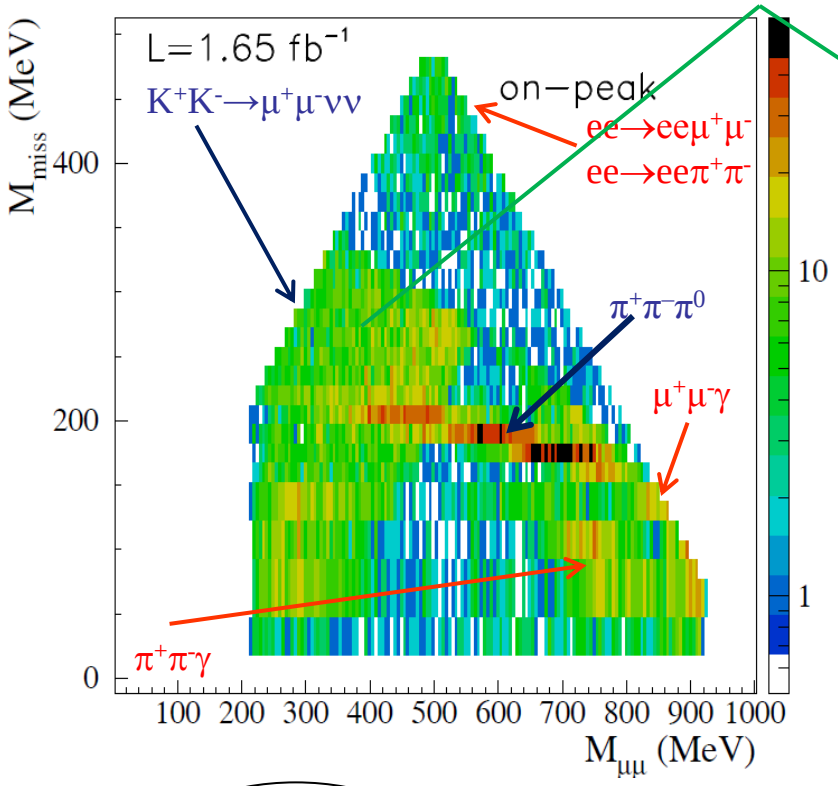


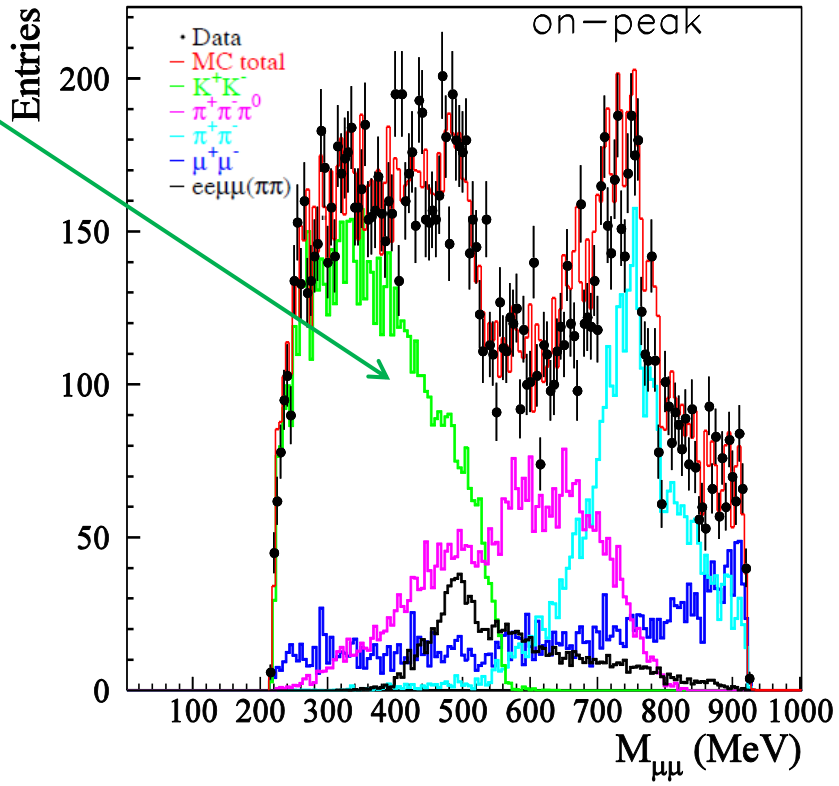
X boson at 17 Mev?

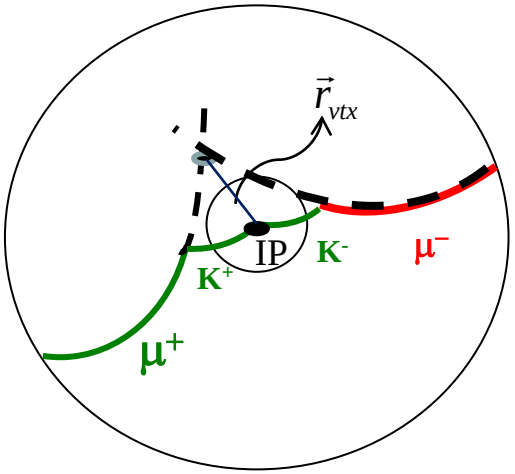


Just on the edge of the allowed region in ε_e

The $e^+e^- \to h'U$ process at KLOE-2



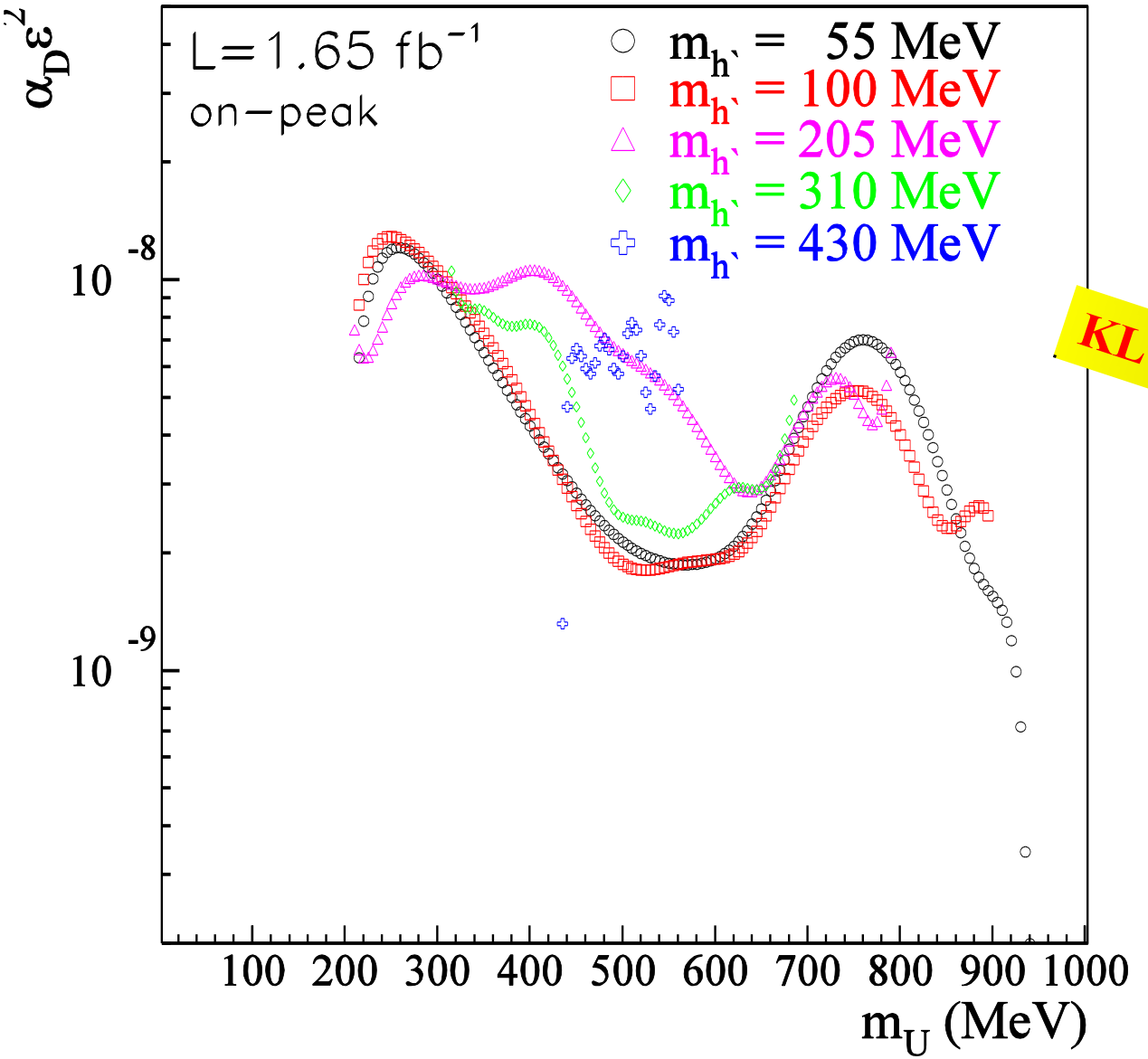




With a better vertex resolution up to a farther factor 3 reduction of $K^{\pm}$ background

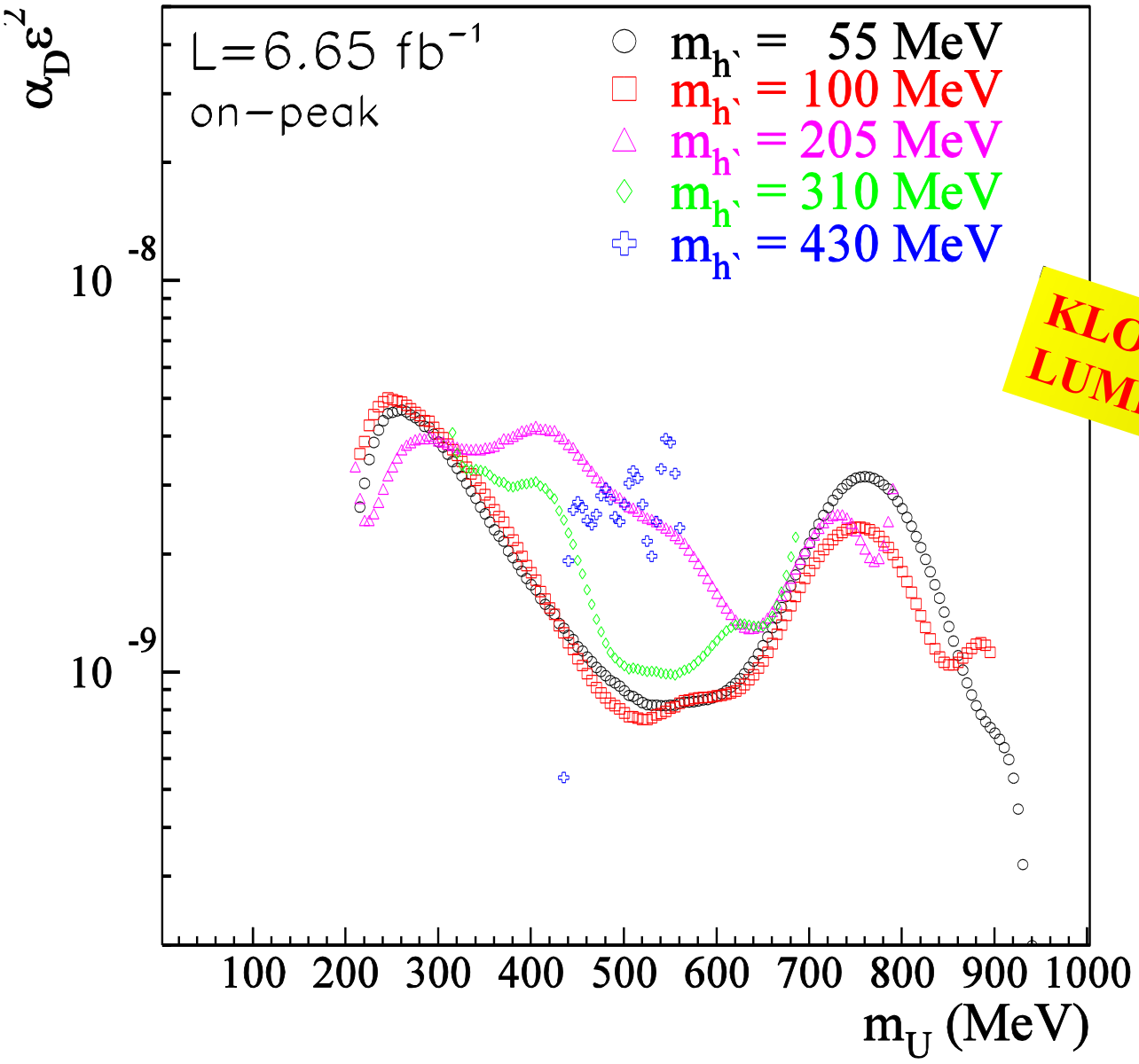
Mass resolution improvement in principle affect both $\mu^+\mu^-$ mass and missing mass (only invariant mass taken into account)

The $e^+e^- \to h'U$ process at KLOE-2



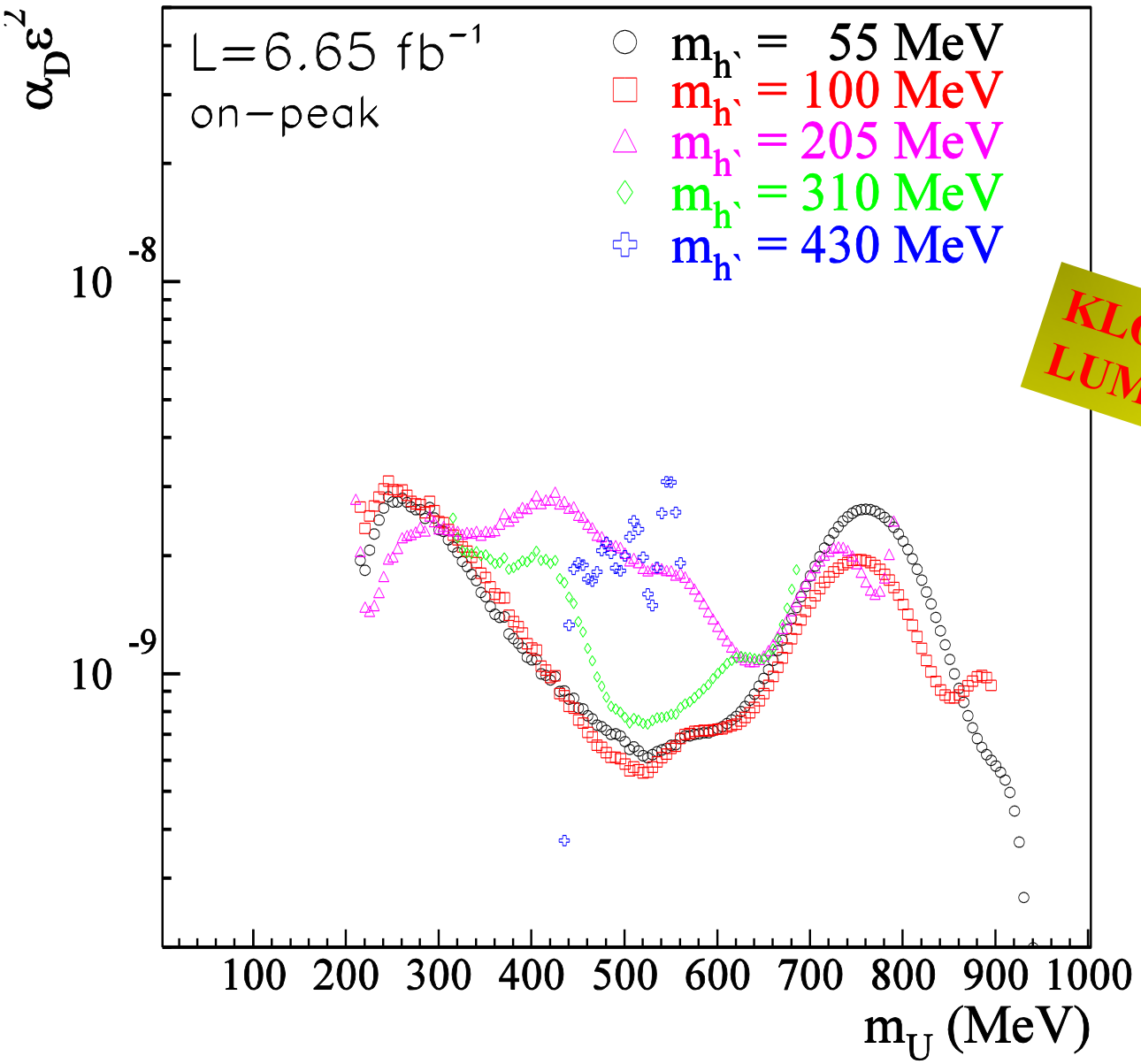
KLOE RESULT

The $e^+e^- \to h'U$ process at KLOE-2



KLOE-2 PROJECTION: LUMINOSITY ONLY

The $e^+e^- \to h'U$ process at KLOE-2



KLOE-2 PROJECTION: LUMINOSITY + IT

The $e^+e^- \to h'U$ process at KLOE-2

Only on-peak projections (no DAϕNE/KLOE-2 official schedule for an off-peak run)

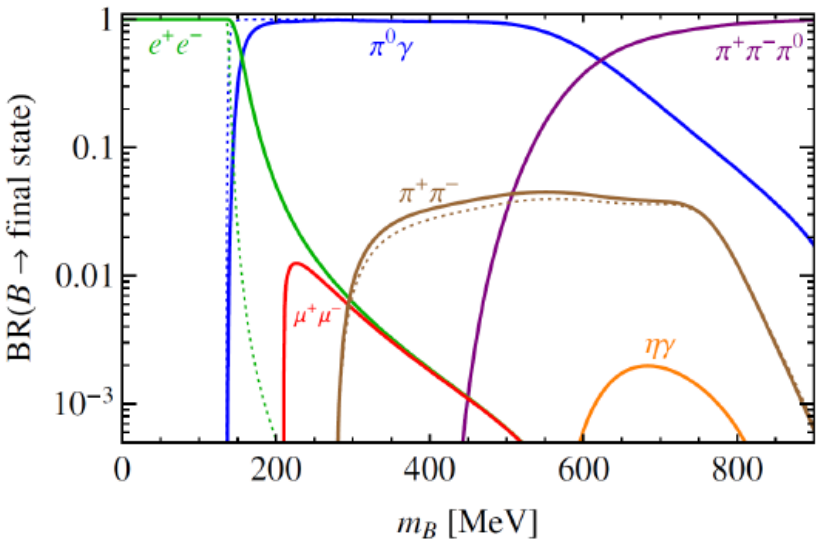
Possibility to add the **e^+e^- + missing energy** channel

- increase statistics (combine)
- gain access to the m_U<210 MeV region

Possibility to study the **$m_{h'} > m_U$** scenario

- 6 electrons final state, 3 x e^+e^- pairs at the same invariant mass, 2 x e^+e^- pairs at h' mass
- might give access to the m_U=17 MeV region
- feasibility to be demonstrated

Leptophobic B boson search at KLOE / KLOE-2



- B boson couples mainly to quarks
- Most basic model → coupling to baryon number

$$\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^\mu q B_\mu$$

$$g_B \lesssim 10^{-2} \times (m_B/100\ \text{MeV})$$

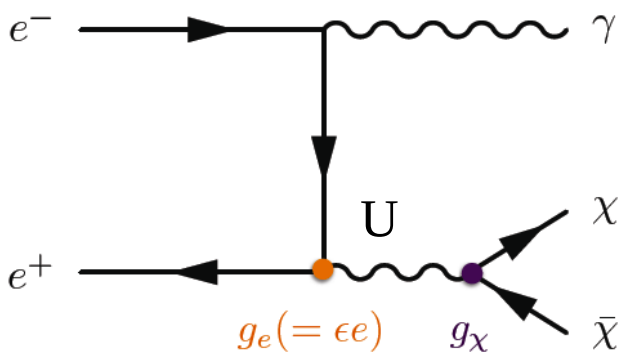
$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\text{MeV})^2$$

- $\phi \to \eta B$, $B \to \pi^0\gamma$ same as $a_0(980)$
- $\eta \to B\gamma$, $\eta \to \pi^0\gamma\gamma$

Decay → / Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

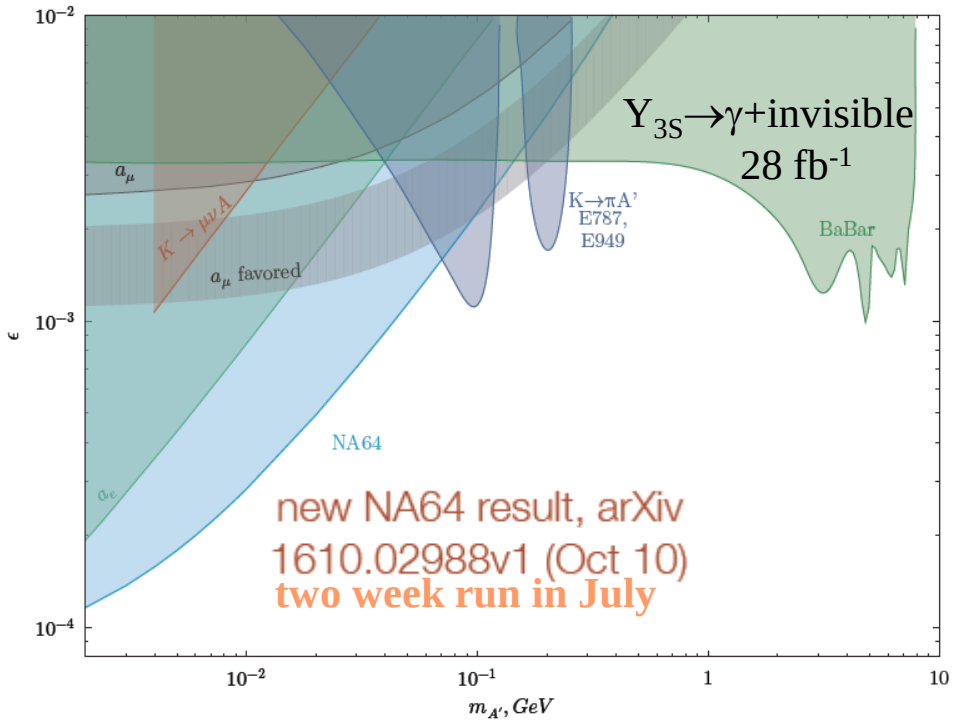
5 γ final states. Both processes currently investigated

Dark forces at KLOE-2: invisible U?



χ ≡ very light dark matter
NOT excluded by present limits

could explain $(g-2)_\mu$



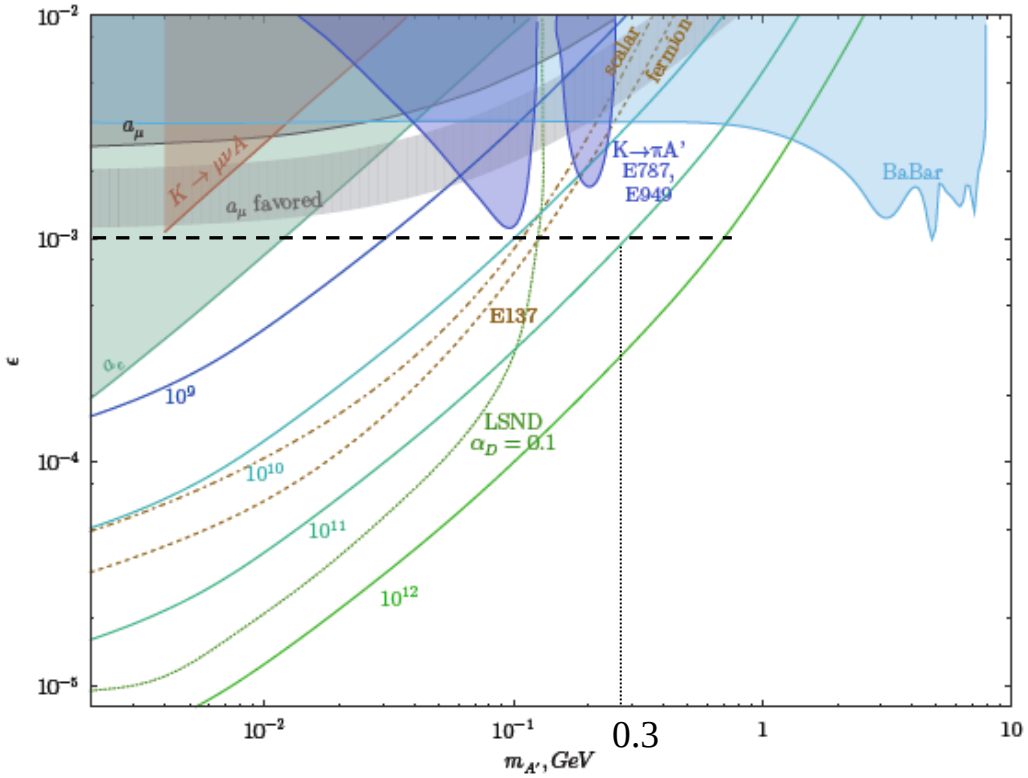
monochromatic photon

$E_\gamma = (s-m_U^2)/2\sqrt{s}$

A single photon trigger has been setup and is currently in test phase, with a threshold at ~ 350 MeV.

Dark forces at KLOE-2: invisible U? Prospects

preliminary evaluation: sensitivity at the $\varepsilon \sim 10^{-3}$ level with L=2 fb^{-1}



Belle II expectations seems to be MUCH better than simple projections from BaBar limits, even with phase 2 expected luminosity

Time for KLOE-2 is NOW

Dark forces at KLOE-2: summary and conclusions

- KLOE-2 sensitivities for $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$ will benefit of the increased luminosity and of the presence of the IT detector
- Expected exclusion limits should remain competitive. In the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ + $\pi^+\pi^-\gamma$ the should stay well below the BaBar ones above 500 MeV
- KLOE-2 sensitivities for the dark Higgsstrahlung search will benefit of the increased luminosity and wll greatly benefit of the presence of the IT
- The search for the invisible decays of the dark photon is just started and look promising
- New ideas are coming (leptophobic dark photons, axions, …). More new ideas are welcome!

THANK YOU!