Search for dark forces with KLOE

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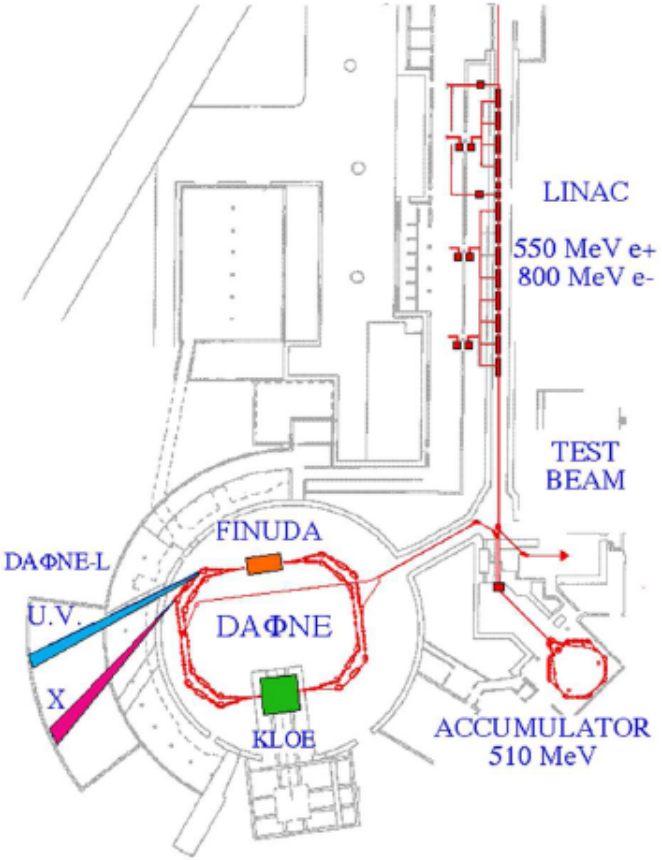
INFN – Roma 3

on behalf of the KLOE-2 Collaboration

DAϕNE: the Frascati ϕ factory



- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches, 2.7 ns bunch spacing
- $I^-_{peak} \sim 2.4$ A $I^+_{peak} \sim 1.5$ A
- Injection during data taking
- Crossing angle: 2×12.5 mrad

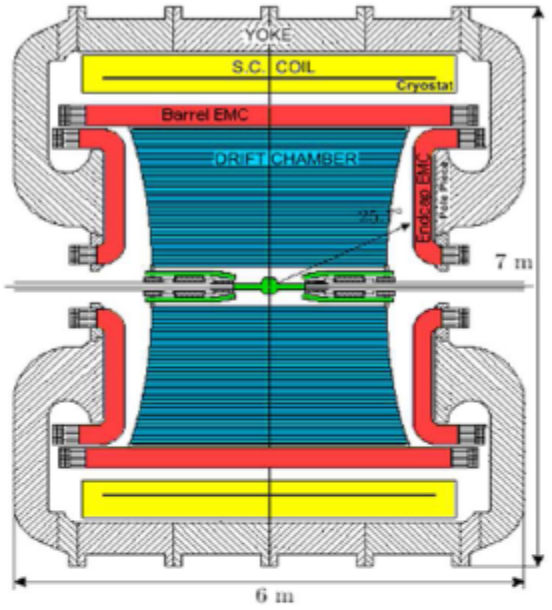
❖ Running period: 1999-2007

❖ Best performances:

➢ $L_{peak} = 1.4 \times 10^{32}\ cm^{-2}s^{-1}$

➢ $\int L dt = 8.5\ pb^{-1}/day$

The KLOE experiment at DAϕNE

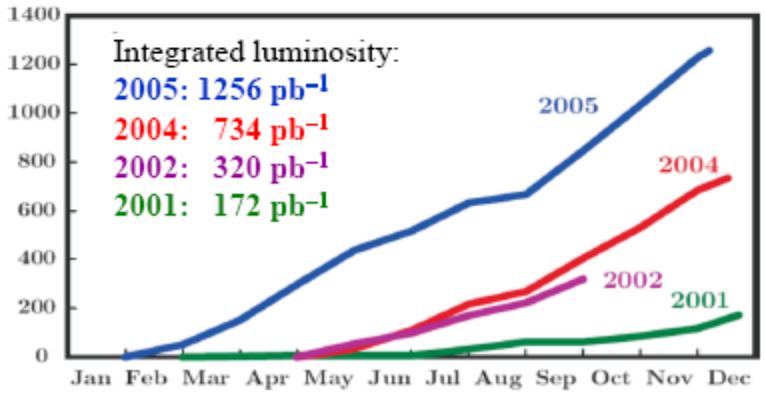


Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)**
- **$\sigma_{xy} \approx 150$ μm ; $\sigma_z \approx 2$ mm**

Electromagnetic calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- **$\sigma_E / E = 5.7\% / \sqrt{(E(GeV))}$**
- **$\sigma_t = 57$ ps $/ \sqrt{(E(GeV))} \oplus 100$ ps**
- **PID capabilities**



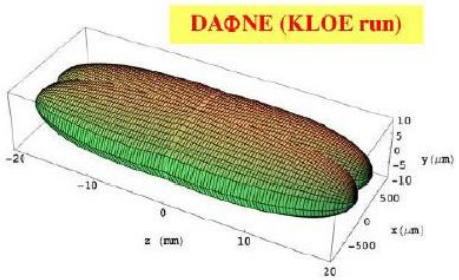
Data taking ended on March 2006

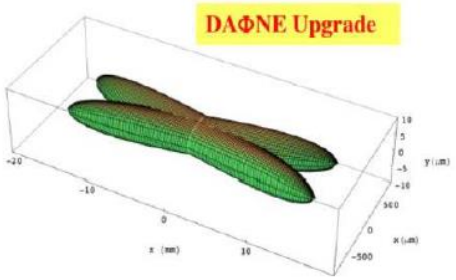
- **2.5 fb^{-1} on tape @ $\sqrt{s} = M_\phi$ (8×10^9 ϕ)**
- **~10 pb^{-1} @ 1010, 1018, 1023, 1030 MeV**
- **250 pb^{-1} @ 1000 MeV**

From DAϕNE to DAϕNE-2, from KLOE to KLOE-2

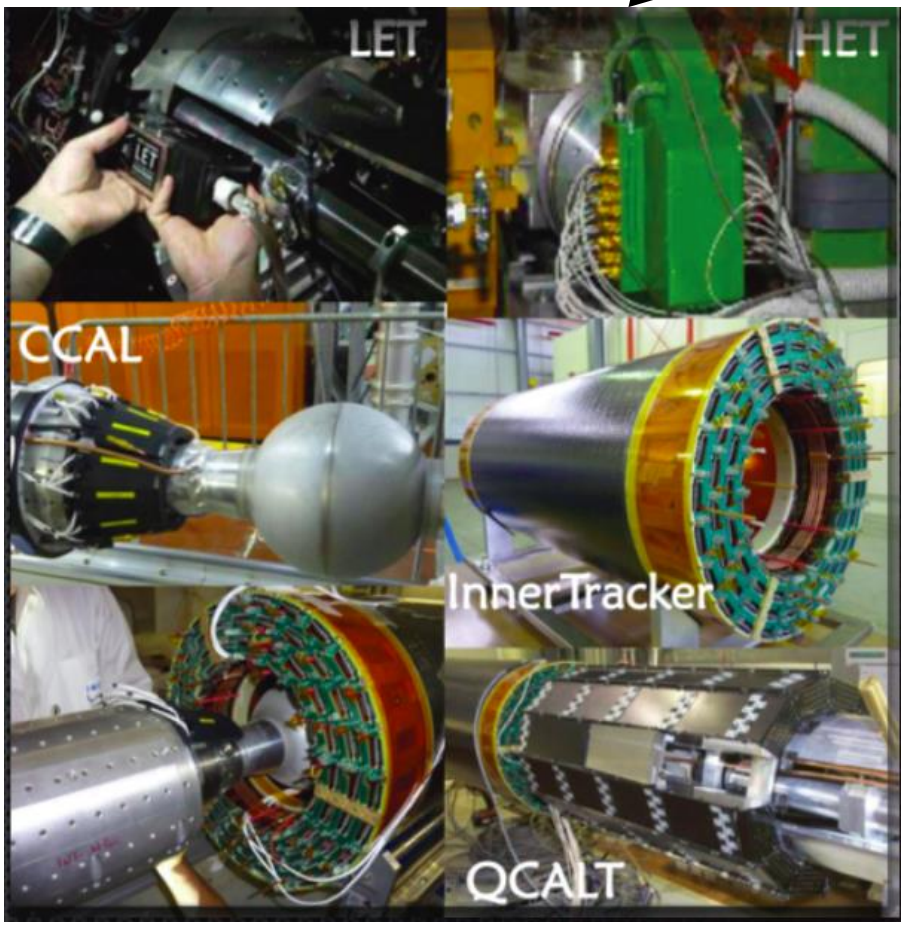
New interaction region: large beam crossing angle + sextupoles for crabbed waist optics.

Increase ₤ by a factor ~1.5÷2





Run started in November 2014

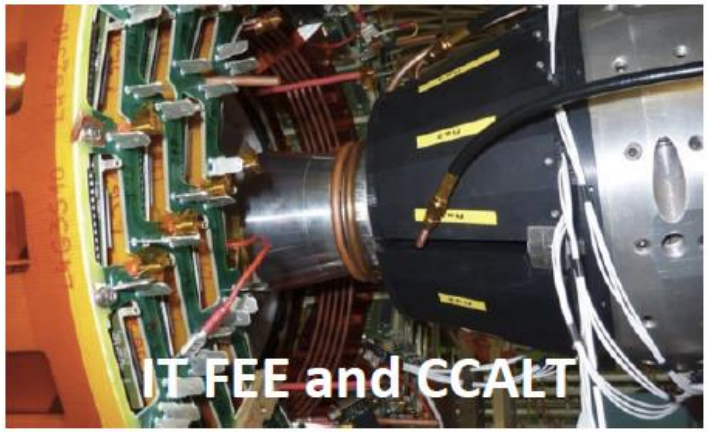


- ✓ milestone: 1 fb^{-1} of good data by mid 2015
- ✓ next milestone: 2.5 fb^{-1} by July 2016 (on track)

→ IT: four layers of cylindrical triple GEM near IP

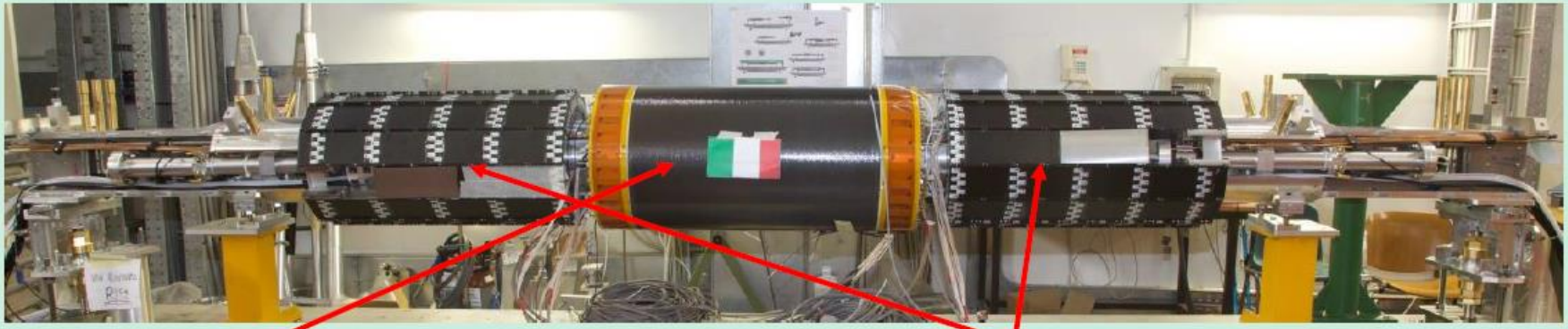
We aim at $L_{int} > 5\ fb^{-1}$ on the ϕ meson peak within the next 2 years

KLOE-2 detector upgrades

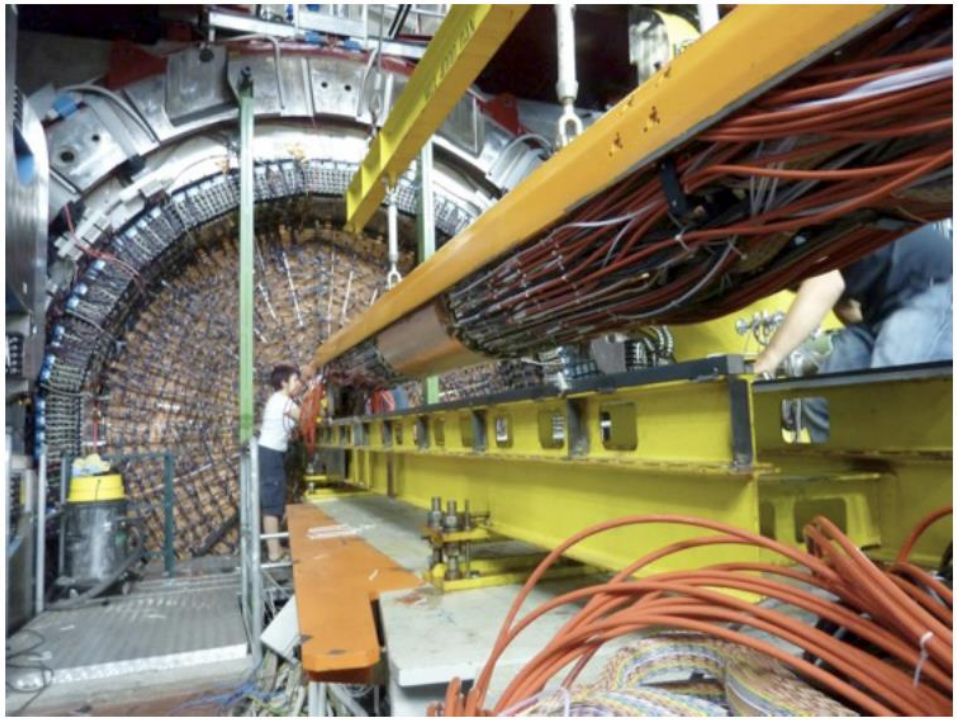


- 4 tagger stations with e^+/e^- detectors for $\gamma - \gamma$ physics
- The inner tracker, cylindrical 3-GEM, for improving vertex resolution near the IR
- The calorimeters, CCALT (lyso-crystals) and QCALT (scintillator tiles and fibers readout by SiPM), to improve the acceptance at low polar angle and to instrument the final focusing region

The KLOE-2 upgrade: IR region



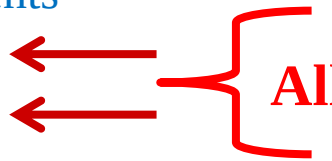
Integration and installation on the beam line successfully completed in 2013



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**
$e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$ → **arXiv:1603.06086, accepted by PLB**

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

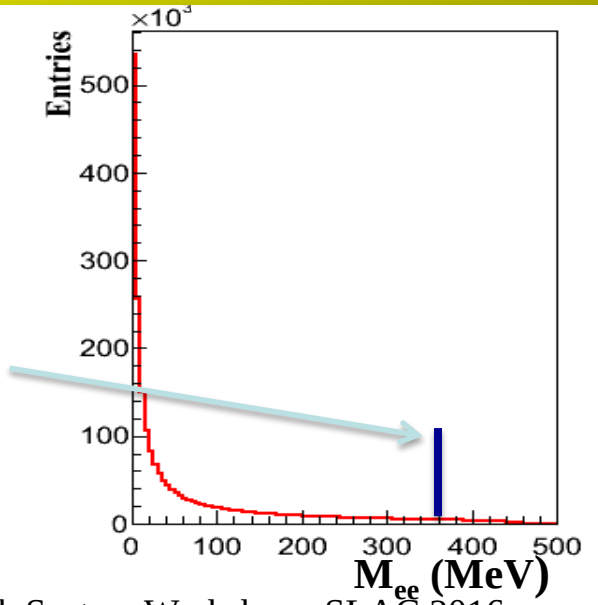
Phys.Lett. B706 (2012) 251-255

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

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

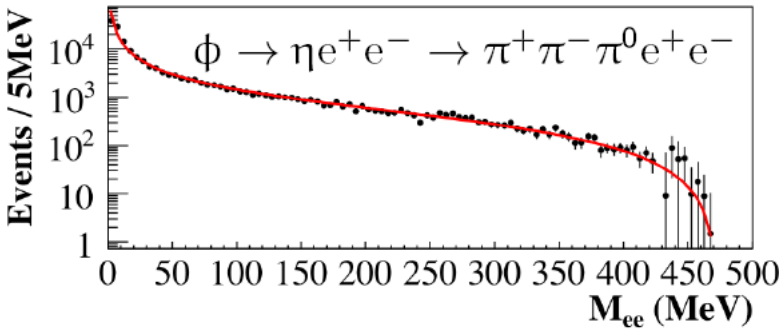
Simulated with a Vector Meson Dominance parameterization

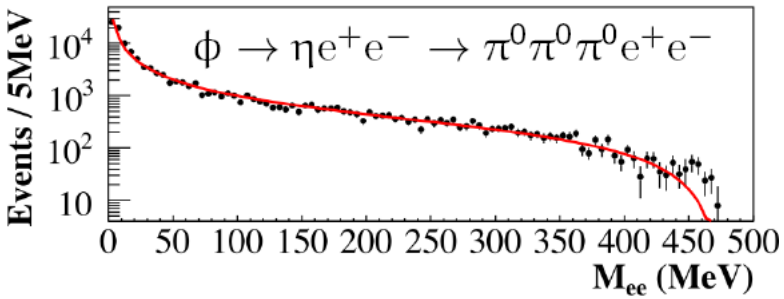
Signal → narrow peak above the continuum background



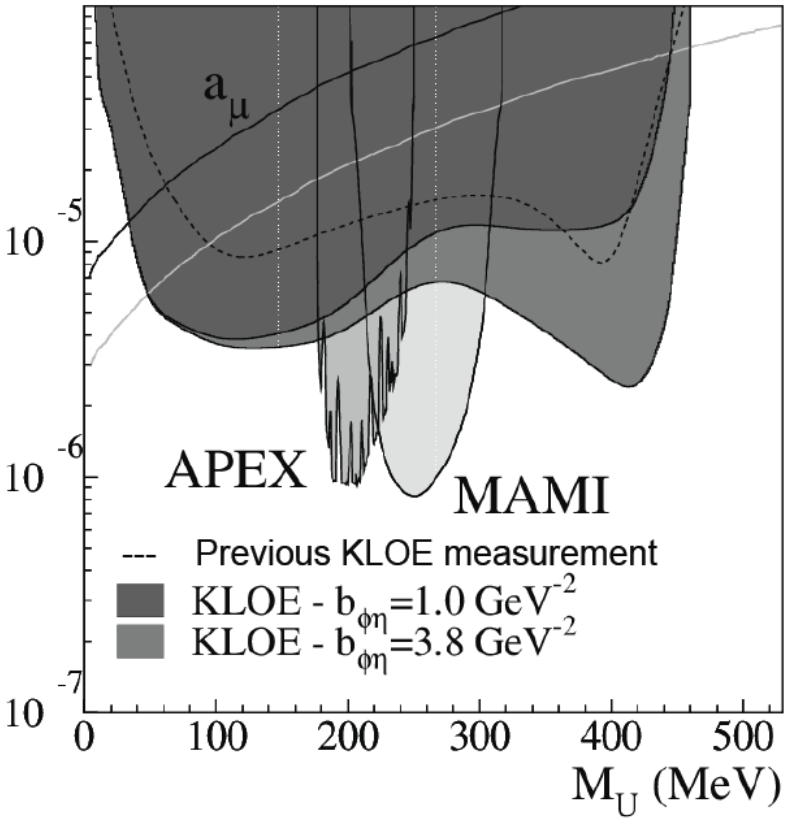
U boson search in $\phi \to \eta e^+e^-$ decays: 90% CL upper limits

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

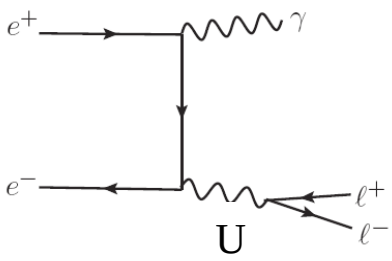


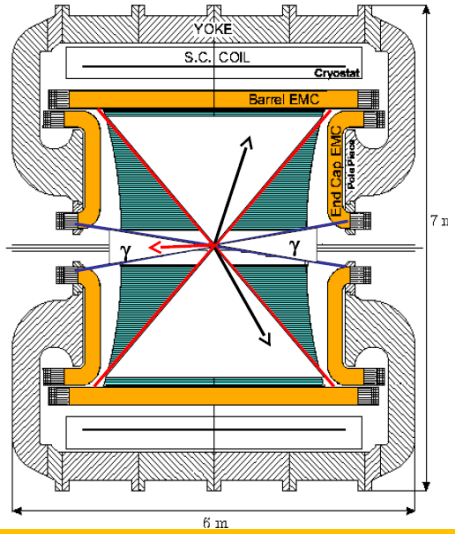
$\varepsilon^2 \leq 1.7 \times 10^{-5}$ @ 90% C.L. for $30 < M_U < 400$ MeV

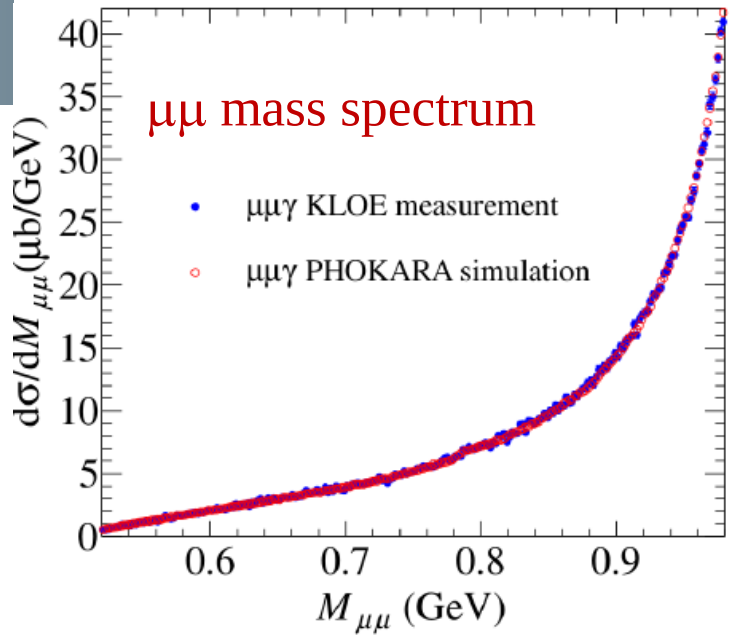
$\varepsilon^2 \leq 8.0 \times 10^{-6}$ @ 90% C.L. for $50 < M_U < 210$ MeV

Phys.Lett. B720 (2013) 111

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







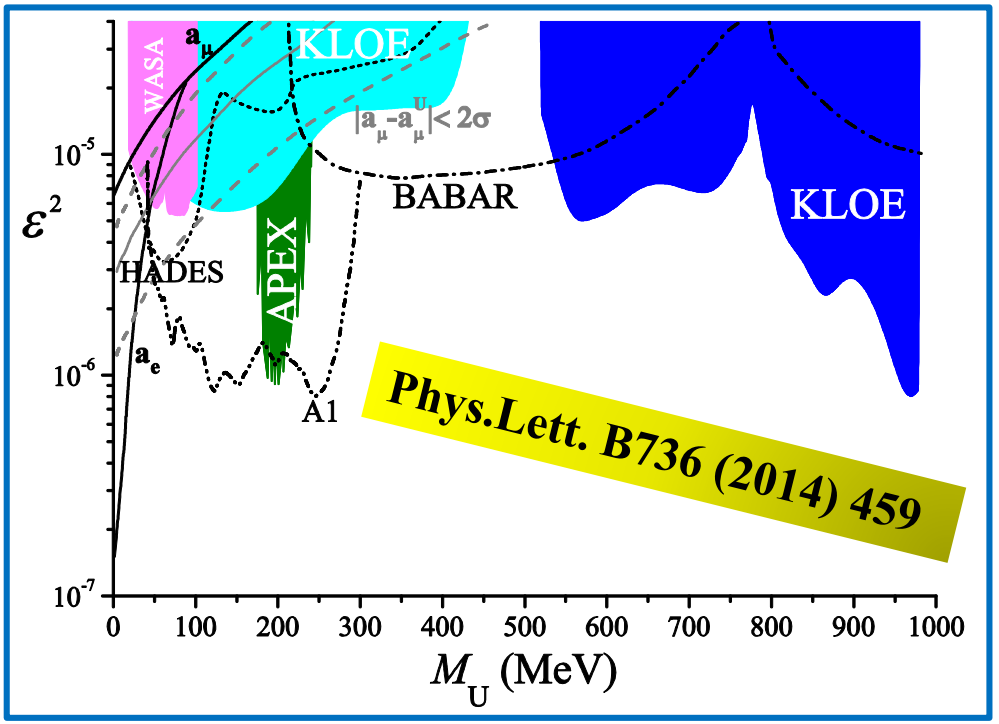
- undetected small angle photon $\theta_\gamma<15°$, $\theta_\gamma>165°$
- two opposite sign charged tracks $50°<\theta_\mu<130°$

CL_S technique

Results based on only 240 pb^{-1}

Using the 2.5 fb^{-1} full KLOE data set improves the sensitivity by a factor ~ 3

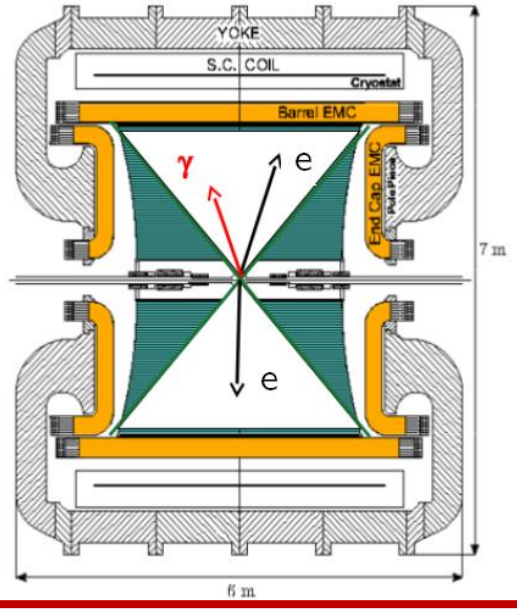
A further factor 2 in sensitivity expected from KLOE-2 experiment



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%

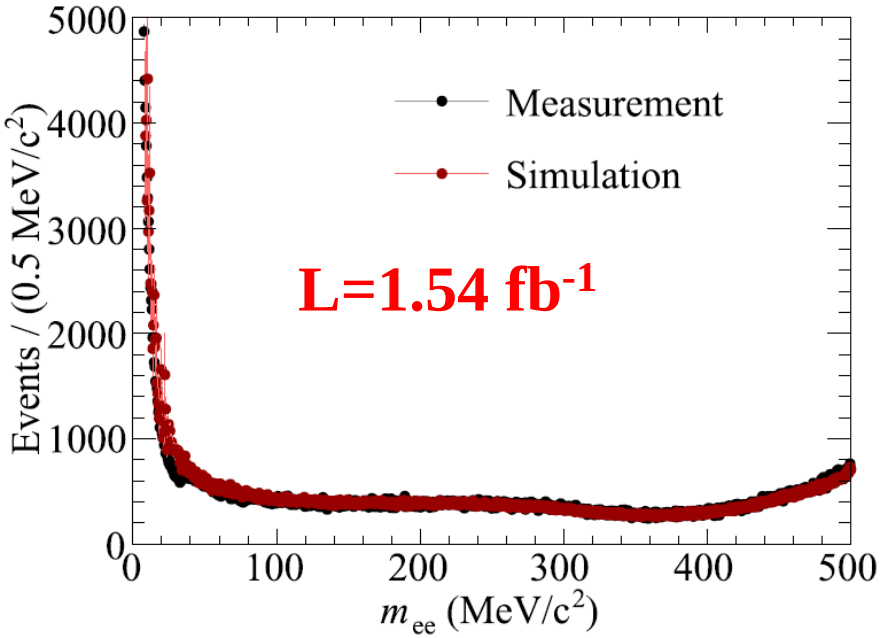


e^+e^- mass spectrum

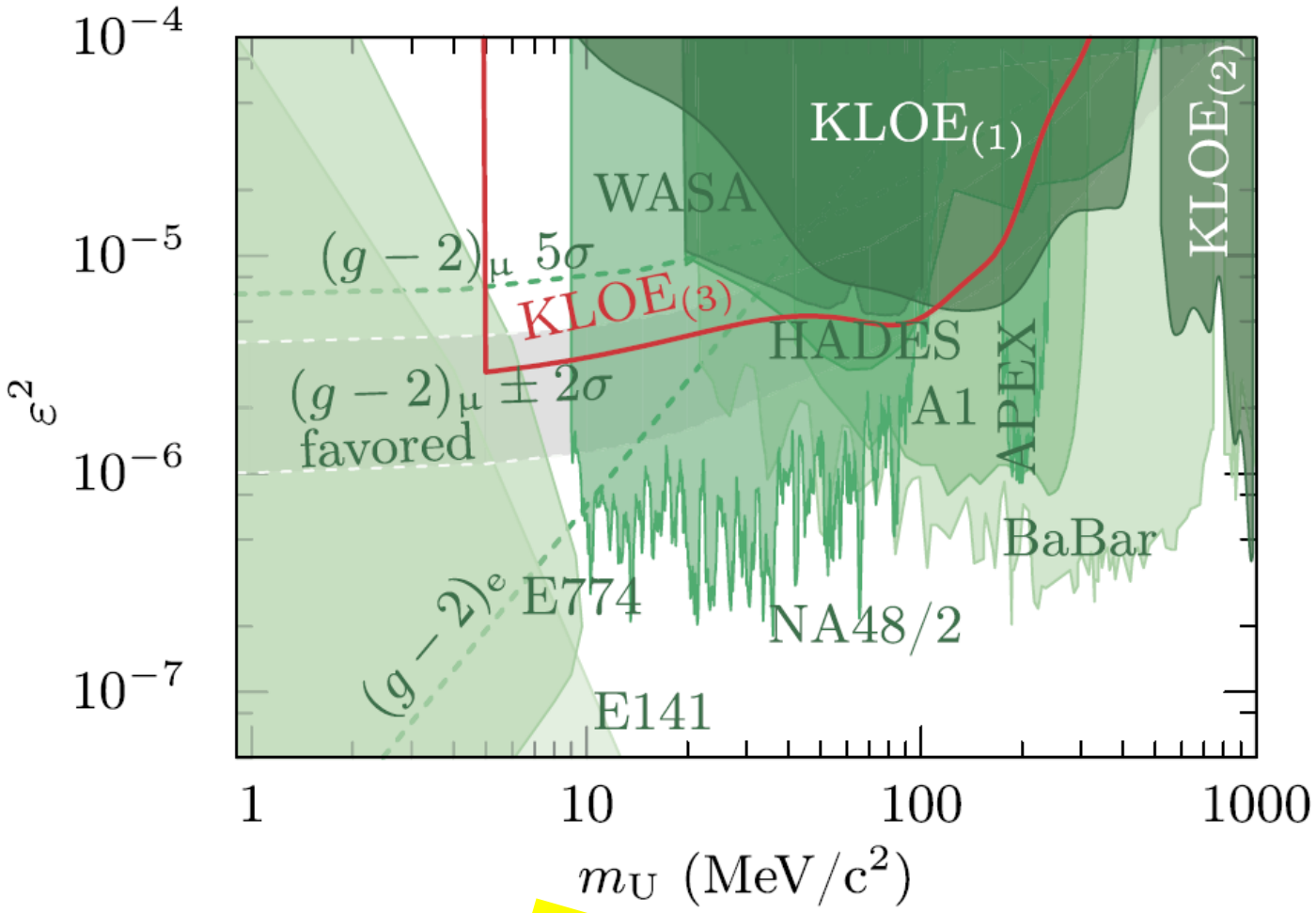
Babayaga-NLO simulation (with weighted events)

Background estimated from data

No peak observed → UL CL_S technique

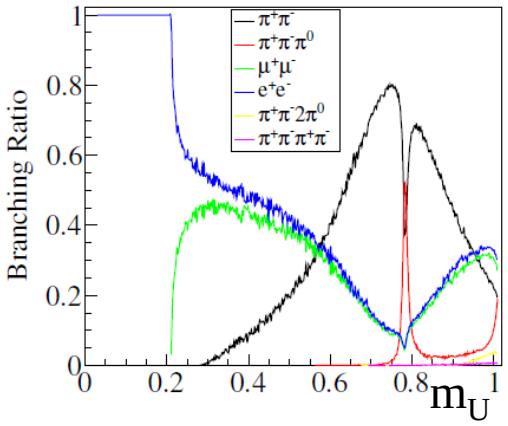


U boson search in $e^+e^- \to e^+e^-\gamma$: 90% CL upper limits

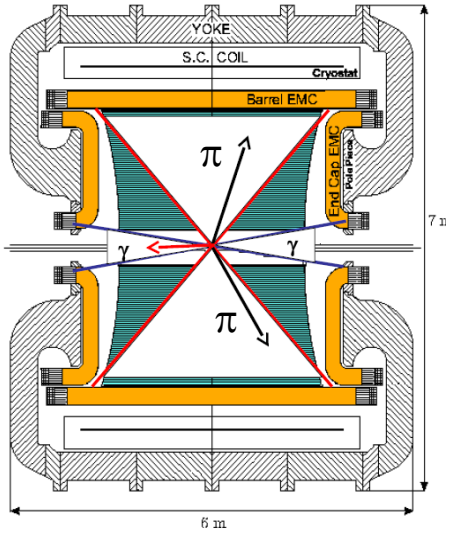


Phys.Lett. B750 (2015) 633

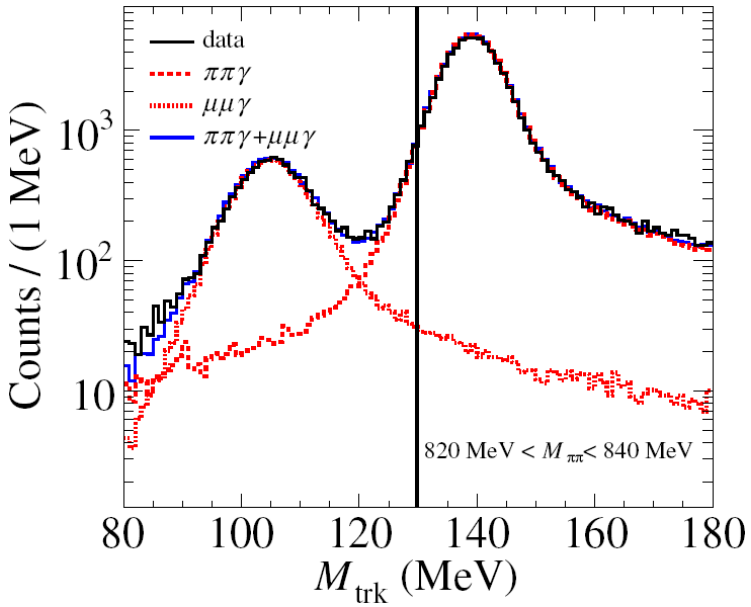
U boson search in $e^+e^- \to \pi^+\pi^-\gamma$



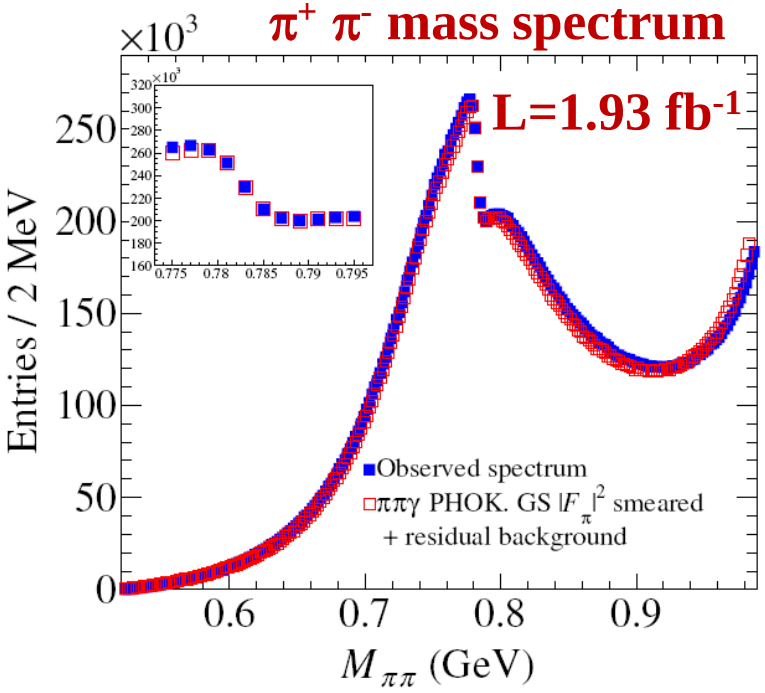
- undetected small angle photon θ_γ<15°, θ_γ>165°
- two opposite sign charged tracks 50°<θ_π<130°



π/μ separation

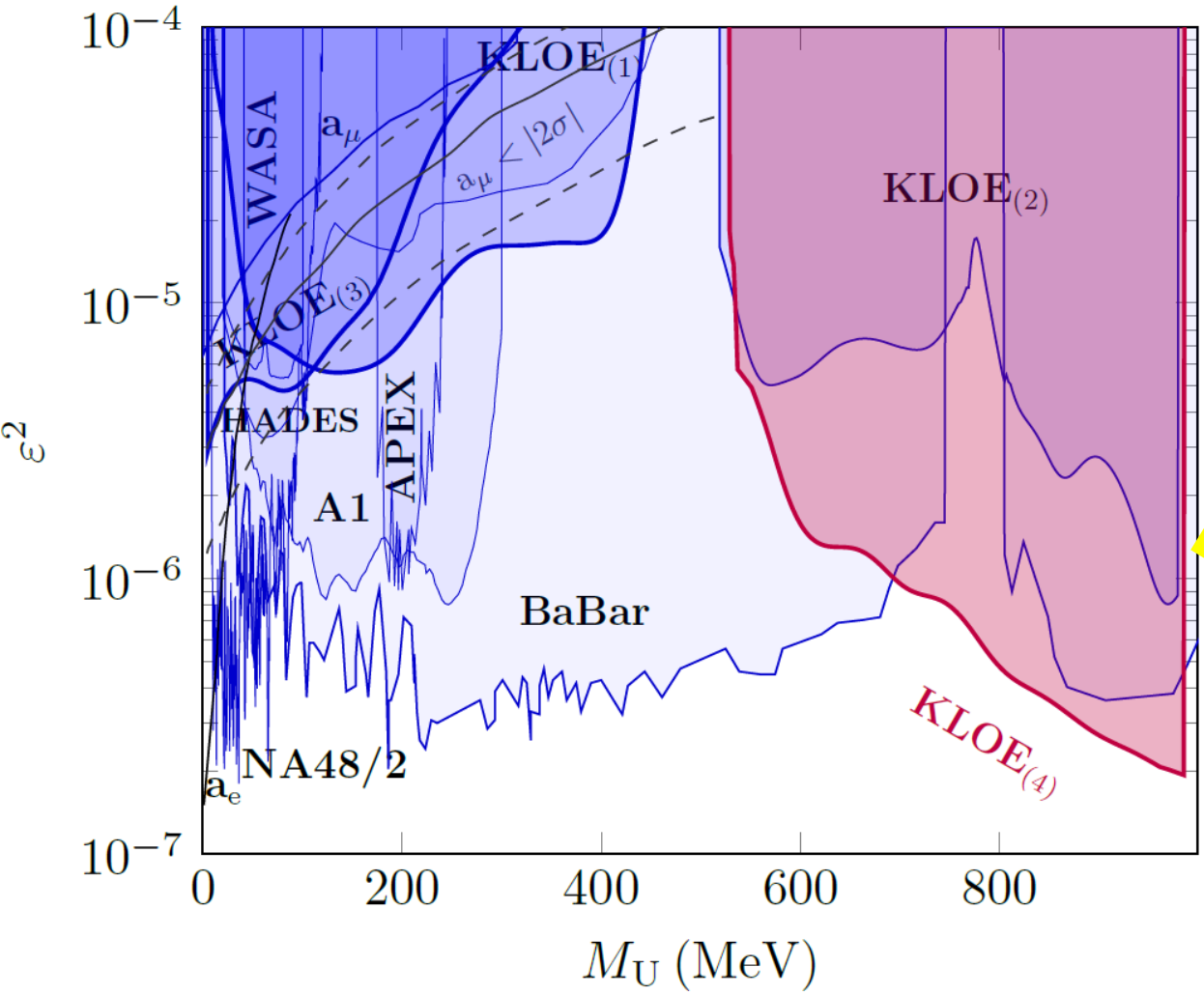


$\pi^+\pi^-$ mass spectrum



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

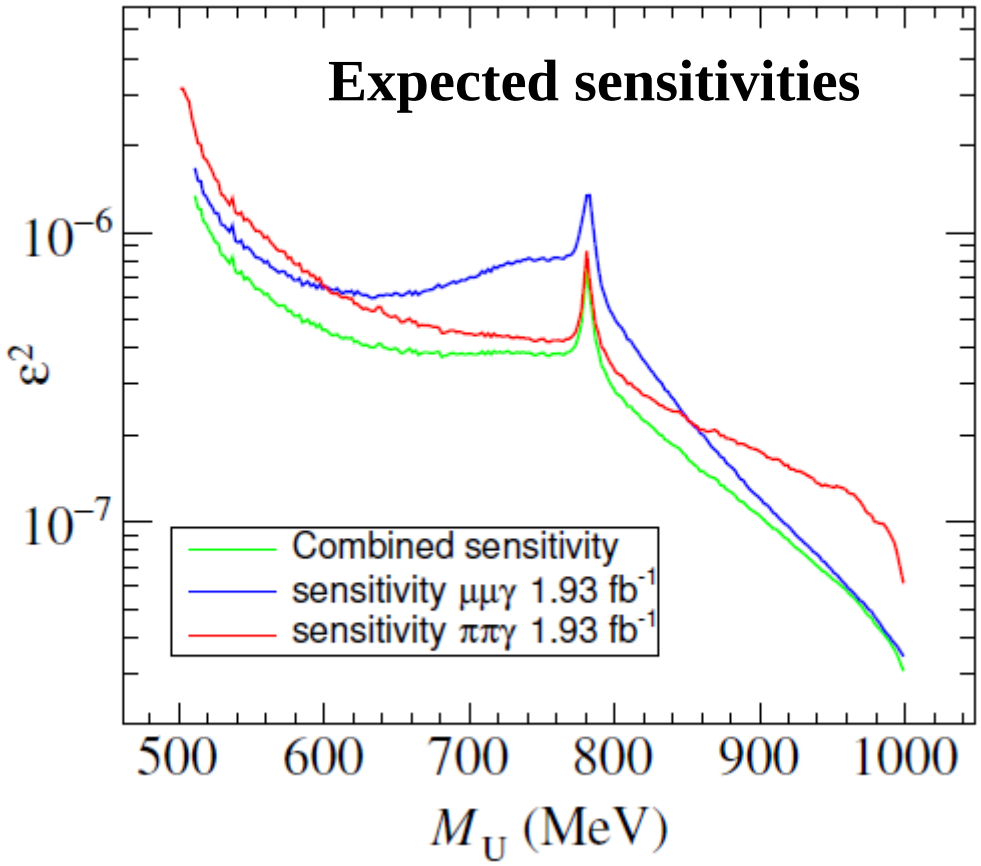
L=1.93 fb^{-1}



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$_{(4)}$ → $e^+e^- \to \pi^+\pi^-\gamma$

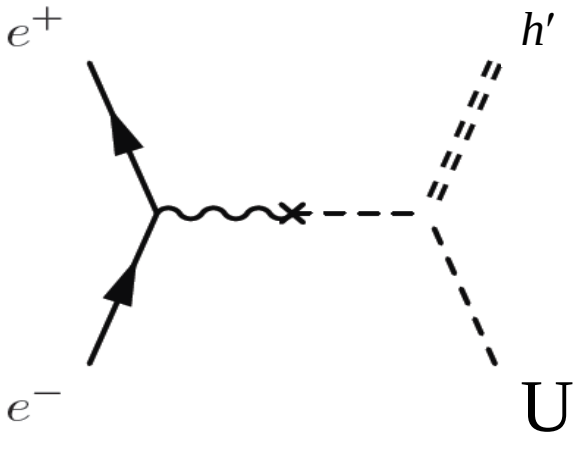
arXiv:1603.06086, accepted by PLB

Combining $\pi^+\pi^-\gamma$ with $\mu^+\mu^-\gamma$ full statistics



Yet to be performed in real analysis situation

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



Very different scenarios depending on

See C. Hearty's talk →

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

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

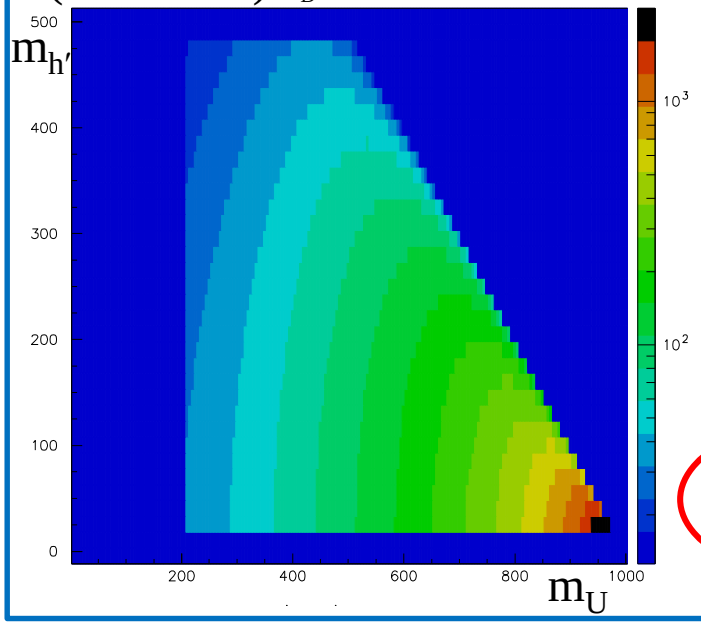
- $\varepsilon = 10^{-3}$
- $\alpha_D = \alpha_{em}$
- $m_{U,h'} \sim 100$ MeV

→ $\tau_{h'} > 5\ \mu s \to \beta\gamma c\tau > 100$ m (rapidly increasing with decreasing ε)

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

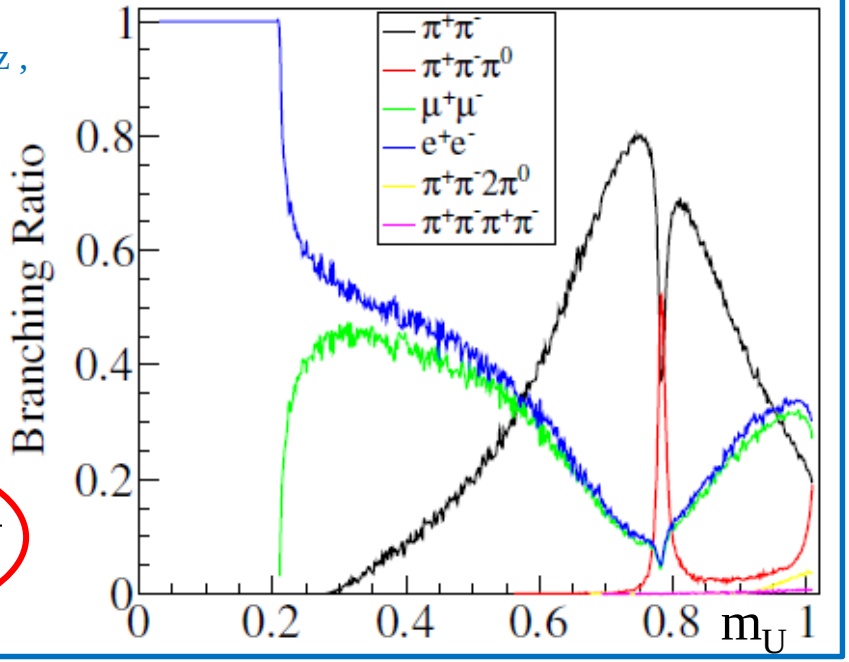
We studied only the muon case $m_{h'} < m_U$: $e^+e^- \to \mu^+\mu^- +$ missing energy

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

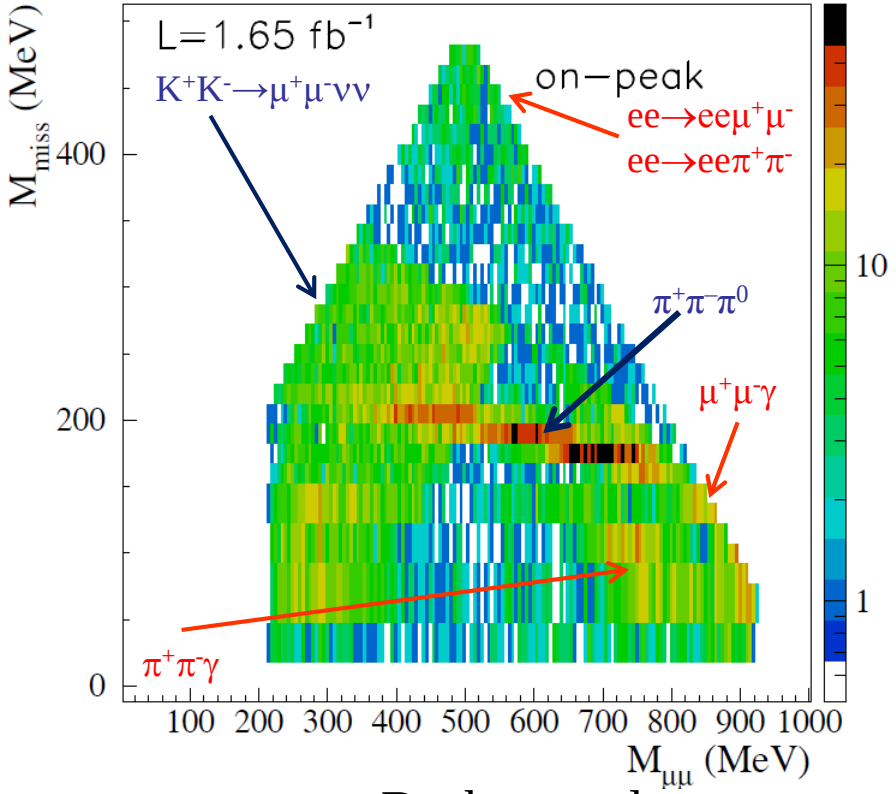


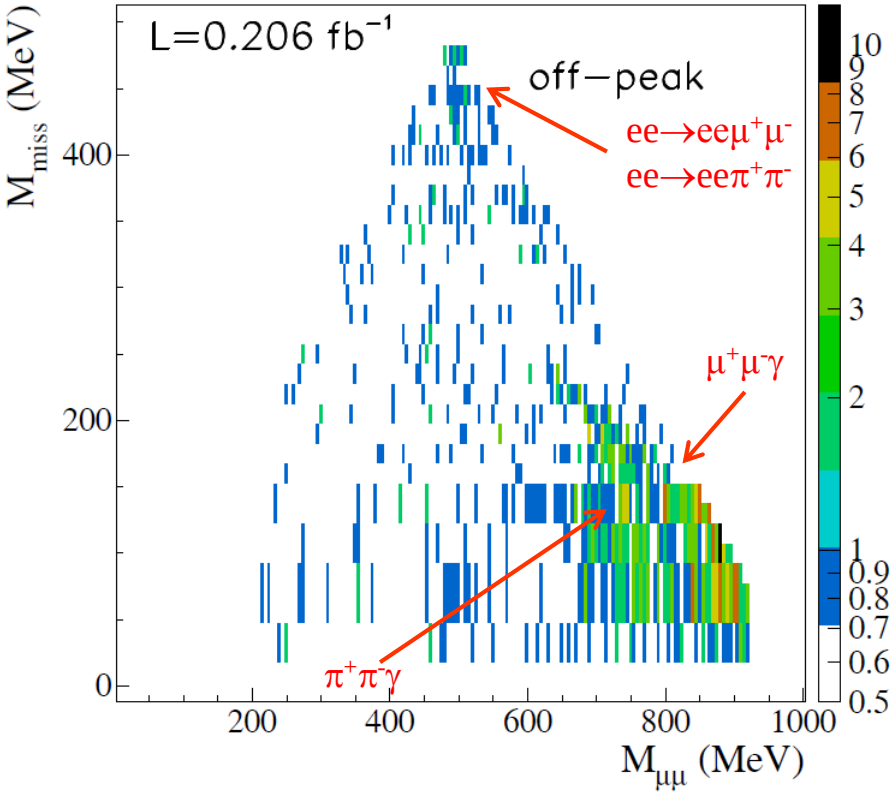
Batell, Pospelov, Ritz , Phys. Rev. D **79**, 115008 (2009)

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



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





Backgrounds

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

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

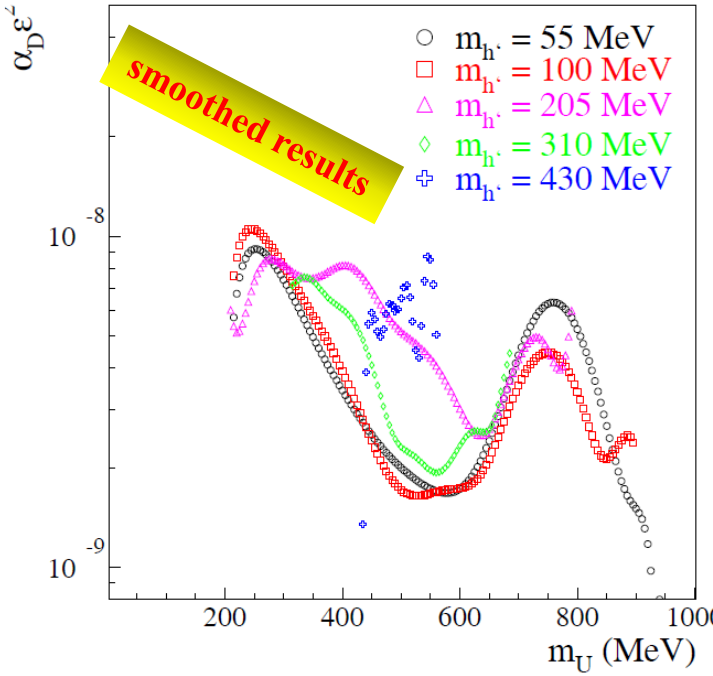
$e^+e^- \to \mu^+\mu^-\gamma$ ← continuum

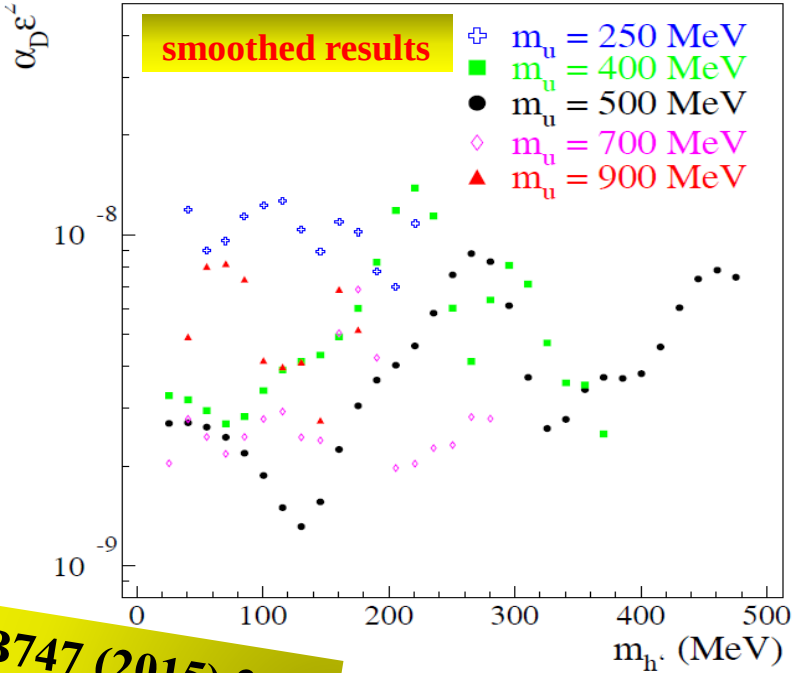
$e^+e^- \to \pi^+\pi^-\gamma$

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

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

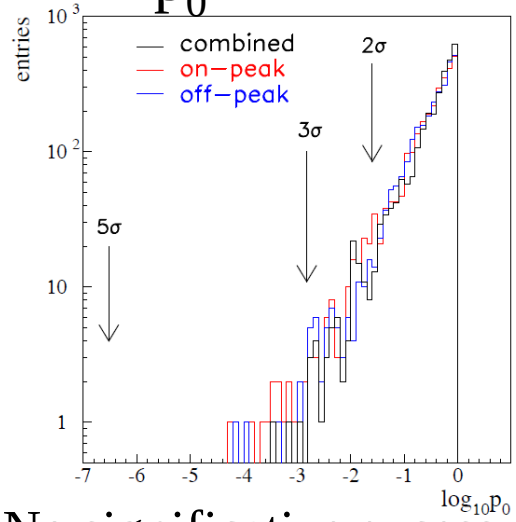
$e^+e^- \to h'U$: p_0 values and 90% CL upper limits





Phys.Lett. B747 (2015) 365

p_0



No significative excess

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

Search complementary with BaBar/Belle

Expect a ≈ 2.5 improvement in KLOE2 (luminosity + suppression of K^+K^- background due to IT) $\to$ full study of the $\varepsilon \approx 10^{-4}$ region

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: $e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$	**arXiv:1603.06086, accepted by PLB**
• Higgsstrahlung: $e^+e^- \to Uh' \to \mu^+\mu^-$ + missing 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-2 delivered luminosity and the presence of the new detectors in KLOE-2 are expected to improve these limits by a factor ~2 or better .

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

TUNING

KLOE 2005 Run conditions

Operation at DAFNE was very stable

injections every 15 min

DC operation smooth

Triggers from intra-bunch scattering < 0.5 kHz

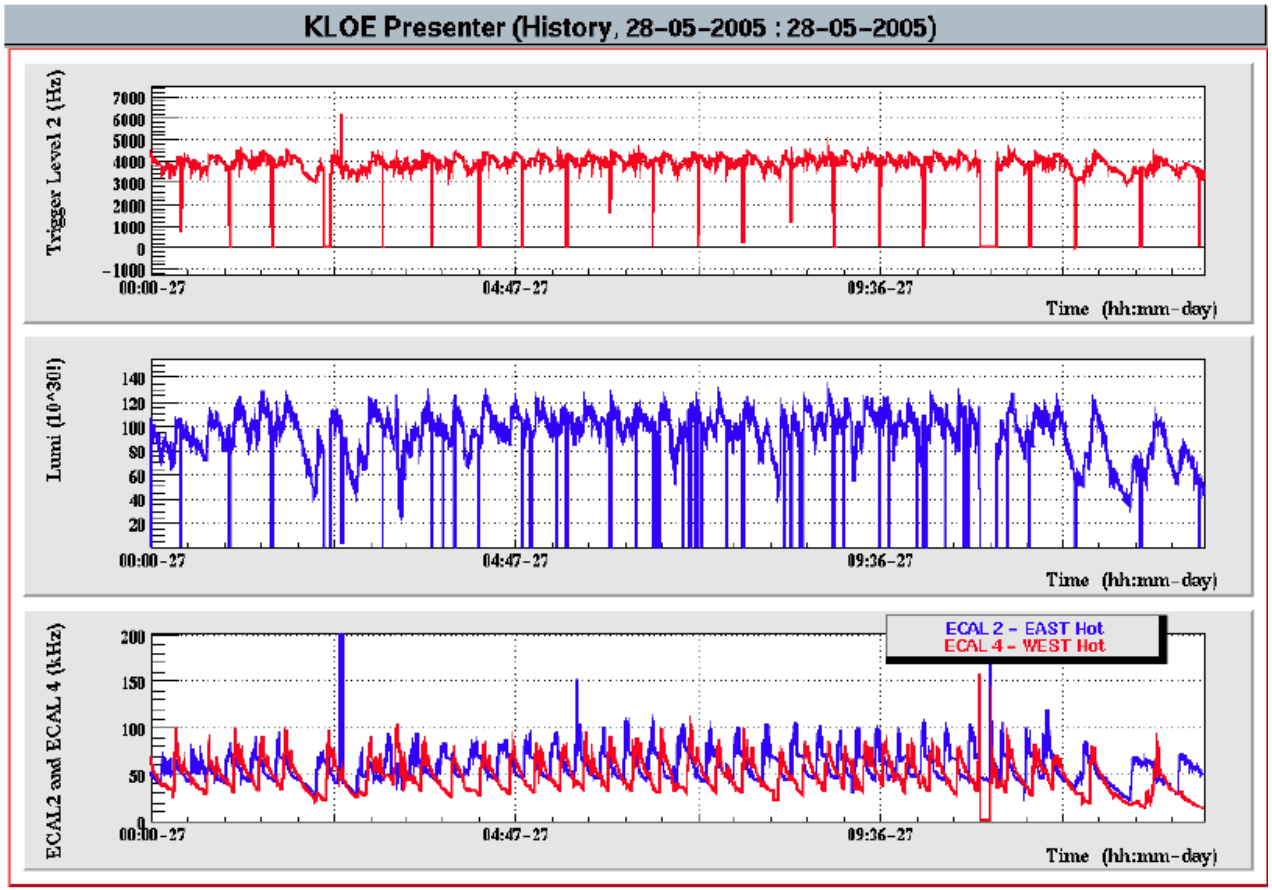
Typical Conditions:

T2 rate ~ 4 kHz,

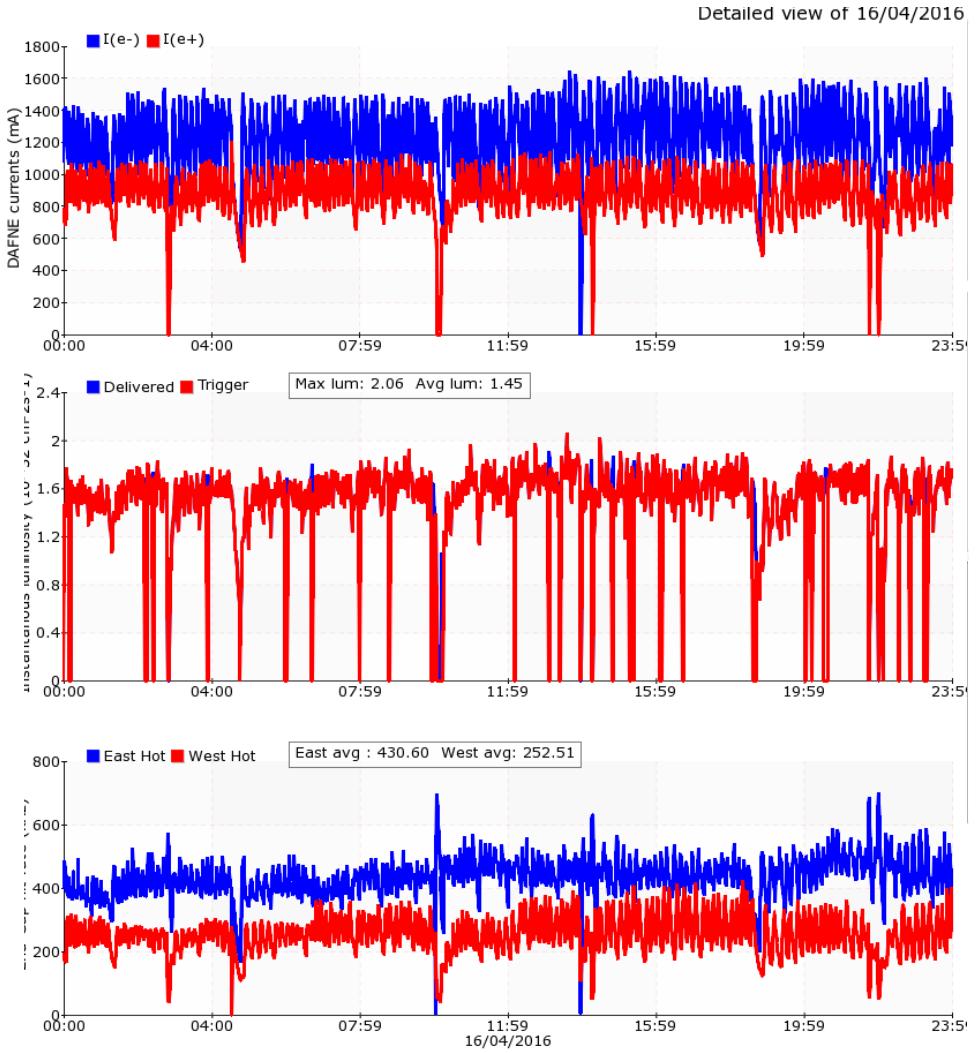
Lumi ~ 10^{32},

EndCap rates < 100 kHz

Overall, high quality data set



KLOE-2 Run conditions 2014-2016



Data taking began in November 2014.
Since then:

Continuous efforts from DAϕNE

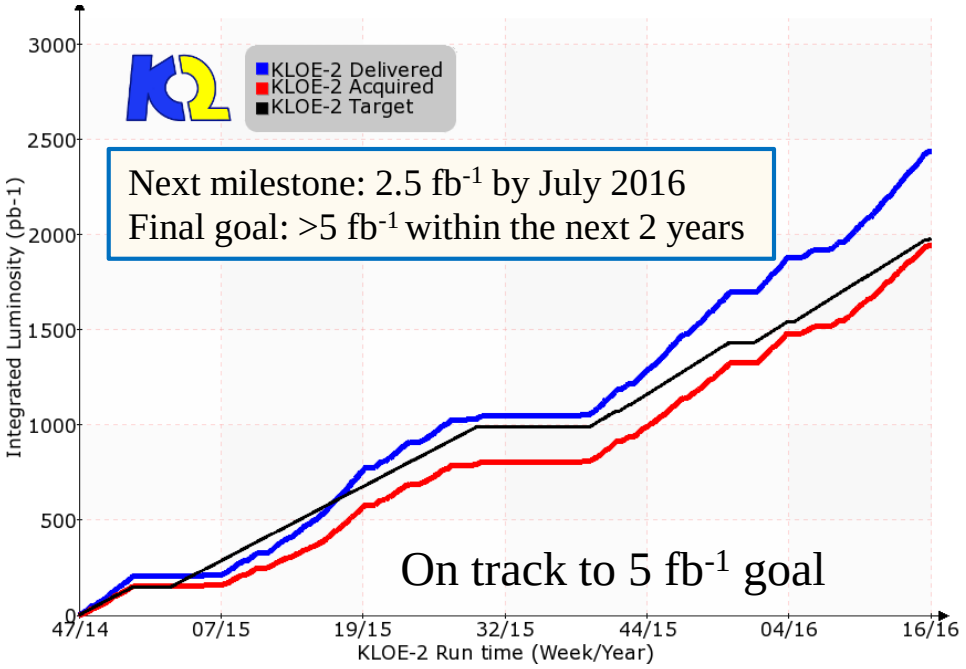
- to reach and keep more than 10 pb^{-1} of daily integrated luminosity
- to keep the background level at the operative threshold for KLOE-2 (IT and DC)

and KLOE-2

- to keep high data taking efficiency
- to lower recovering time after beam loss

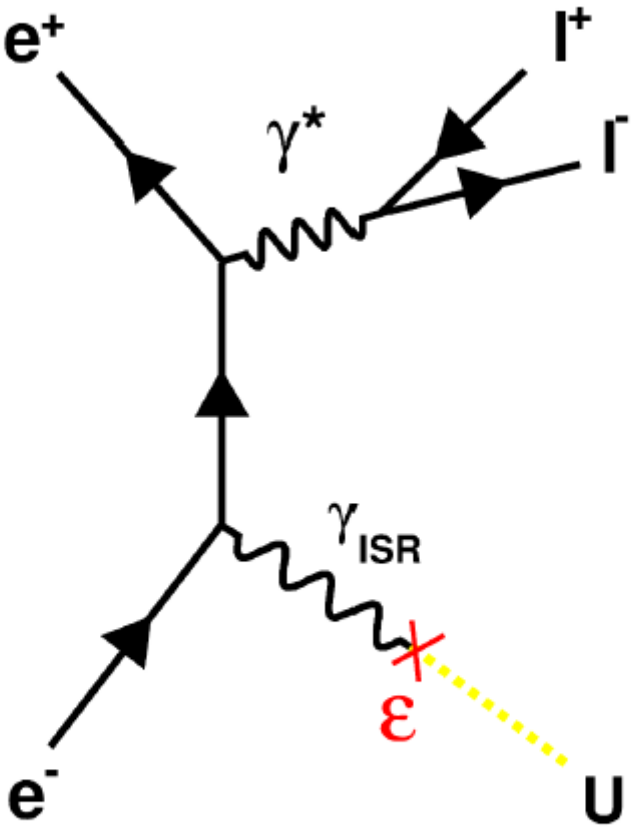
Dark forces at KLOE-2: present and future

- Increased luminosity
- Increase of machine background
- Detailed studies show the good quality of the collected data
- Background largely reduced by exploiting the excellent timing performance of the calorimeter
- No dark force analysis yet
- Expected improvement on mass resolution (better S/N ratio) and vertex reconstruction (better $K^{\pm}$ rejection)



New ideas

B boson search (leptophobic): $\phi \to \eta B$, $\eta \to \gamma\gamma$, $B \to \pi^0\gamma$ (5 γ final state, in progress)
Invisible U decays to light dark matter (smart ideas or single γ trigger)



… and look at the missing mass

Feasibility and sensitivity under evaluation

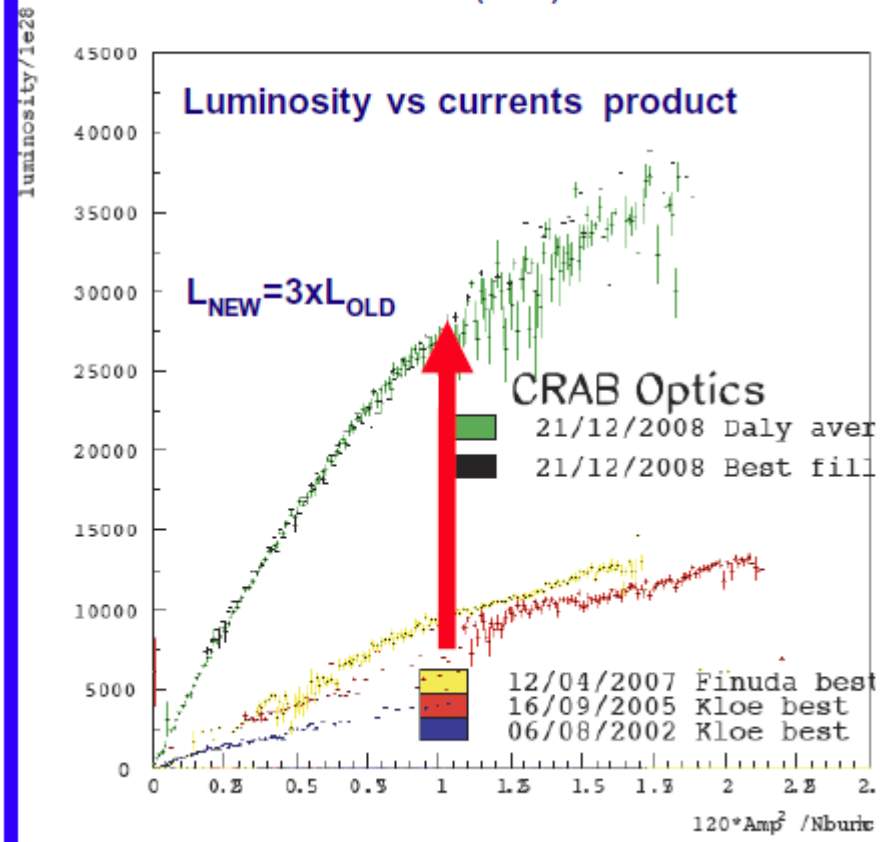
J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev., D80, 075018 (2009)

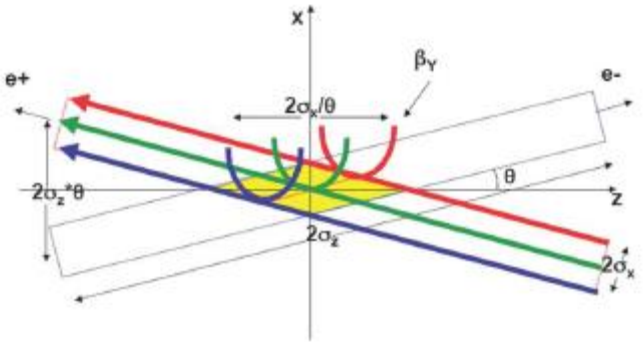
$$\frac{\mathrm{d}\sigma(\mathrm{e^+e^-} \to \mathrm{U}\gamma^\star \to \mathrm{U l^+ l^-})}{\mathrm{d}\sigma(\mathrm{e^+e^-} \to \gamma_{\mathrm{ISR}}\gamma^\star \to \gamma_{\mathrm{ISR}} \mathrm{l^+ l^-})} = \frac{3\pi}{2N_{\mathrm{f}}} \frac{\varepsilon^2}{\alpha} \frac{m_{\mathrm{U}}}{\delta m} \qquad N_{\mathrm{f}} = \frac{\Gamma_{\mathrm{i}}^{\mathrm{U}}}{\Gamma_{\mathrm{tot}}^{\mathrm{U}}}$$

SPARE SLIDES

Novel interaction scheme:
large angle beam crossing
+ crabbed waist sextupoles => SuperKEK

PRL104 (2010) 174801

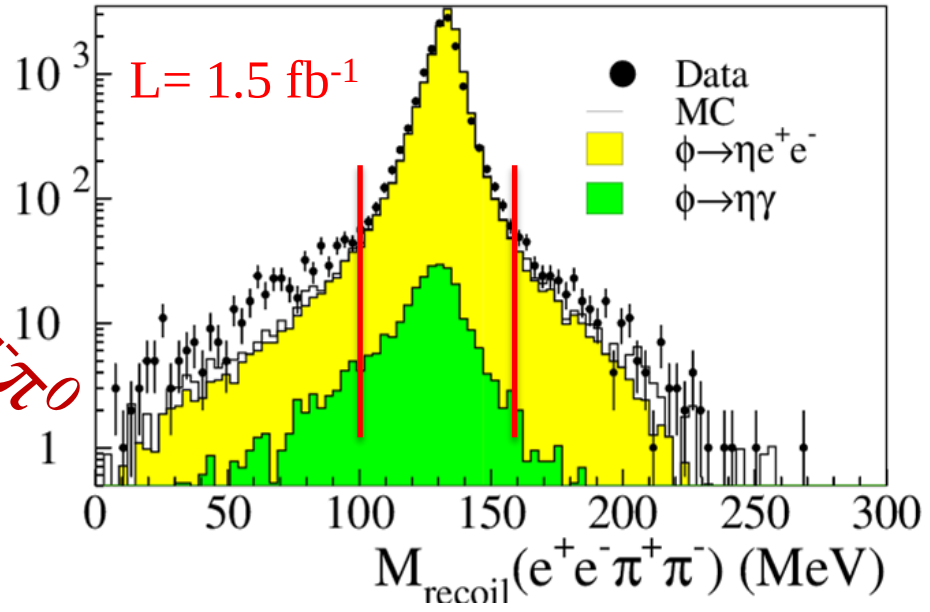




U boson search in $\phi \to \eta e^+ e^-$ decays: selections

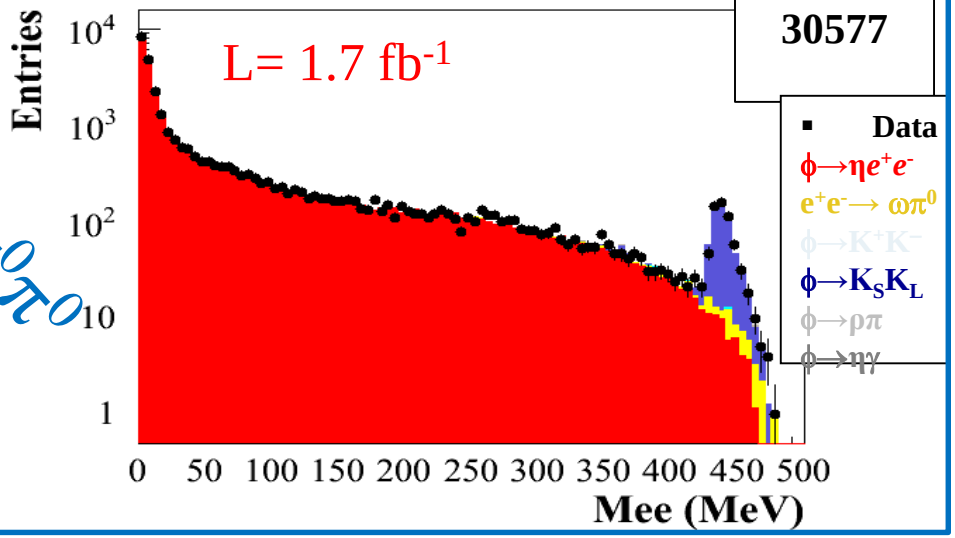
- 4 tracks + 2 photon candidates
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
  $70 < M_{\gamma\gamma} < 200$ MeV
  $535 < M_{recoil}(ee) < 560$ MeV
- γ conversion + $K_L K_S$ rejection (ToF)
- $100 < M_{recoil}(ee\pi\pi) < 160$ MeV

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

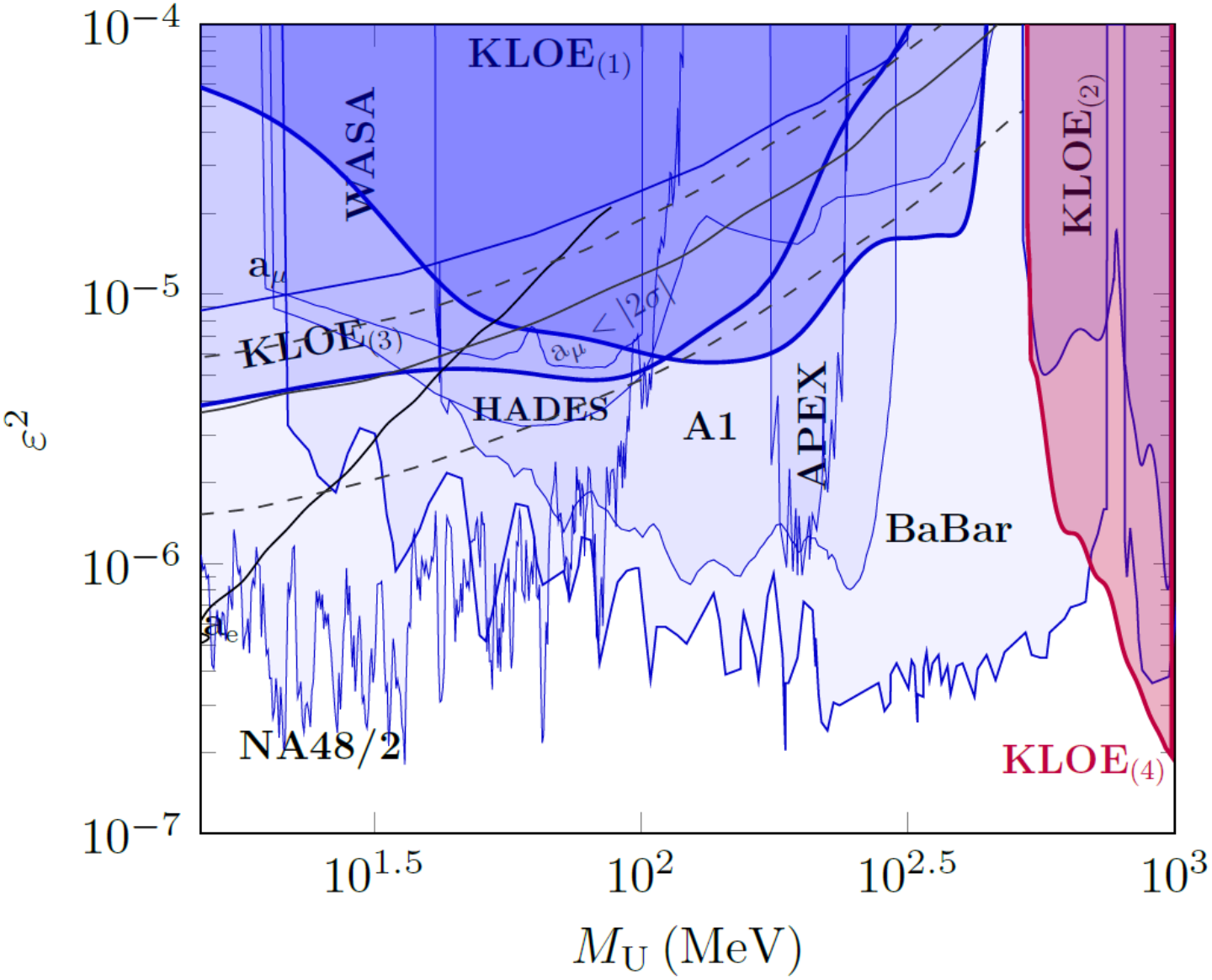


- 2 tracks + 6 photon candidates
- Six prompt photon candidates:
  $|T_\gamma - R_\gamma/c| < \min(3\sigma_T,\ 2\ ns)$
- $400 < M_{6\gamma} < 700$ MeV
- γ conversion + $K_L K_S$ rejection (ToF)
- $536.5 < M_{recoil}(ee) < 554.5$ (3σ cut)

$\eta \to \pi^0\pi^0\pi^0$

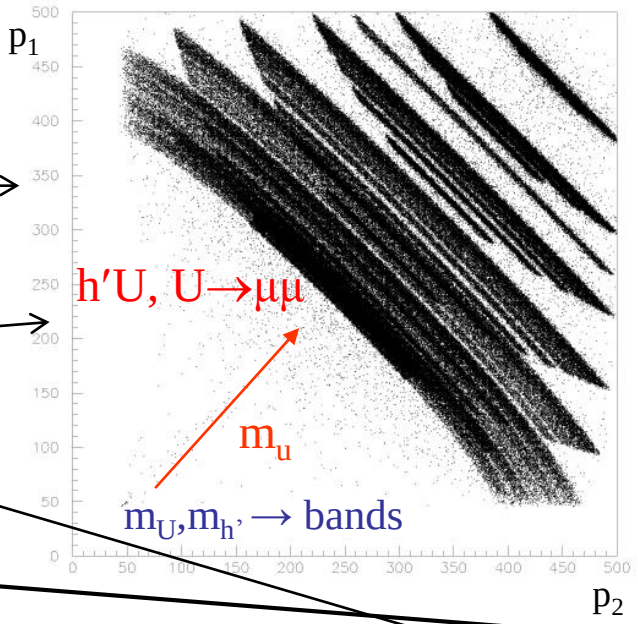


$e^+e^- \to \pi^+\pi^-\gamma$: 90% CL upper limits

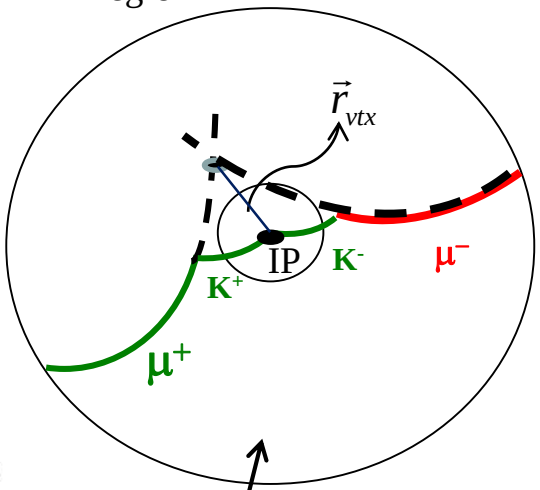


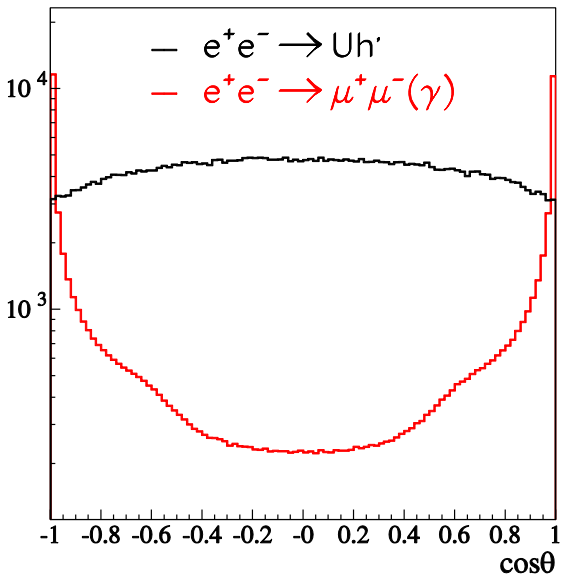
$e^+e^- \to h'U$: selections

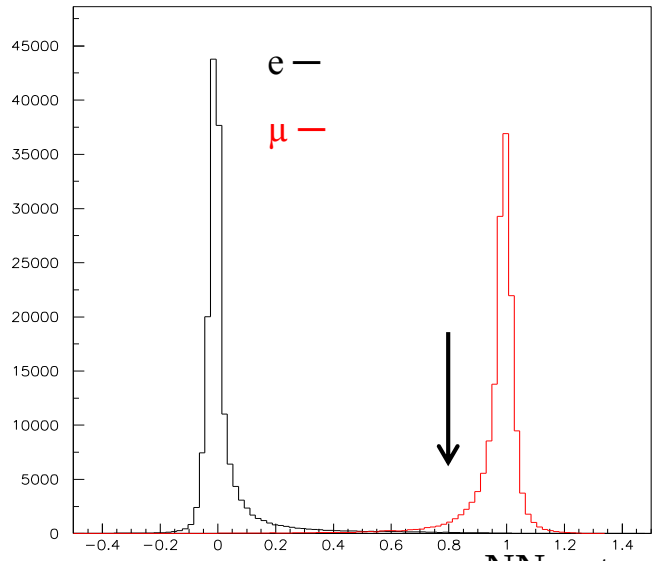
- two charged tracks, $q_1+q_2=0$
- vertex in a cylinder around IP
- $p_{1,2} < 460$ MeV
- $\cos\theta < 0.75$, $\cos\theta_{1,2} < 0.8$
- $p_1 + p_2 > 450$ MeV
- E_{miss}: calorimeter veto
- PID: two muons
- vtx-IP cut (anti K^+K^-)

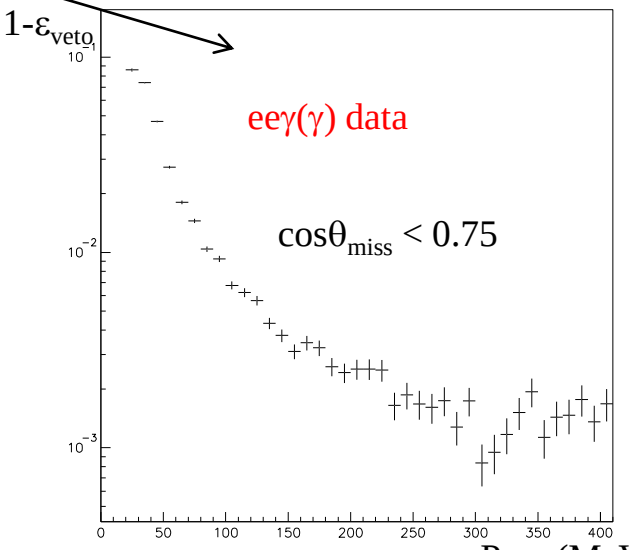


$K^+K^- \to \mu^+\mu^-\nu\nu$ decaying in the IP region

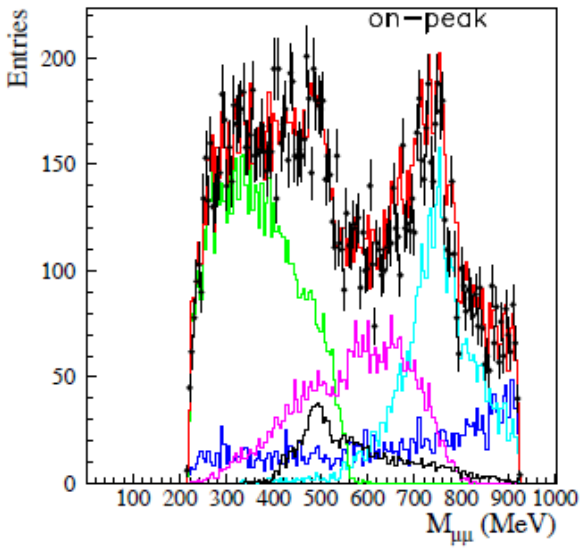


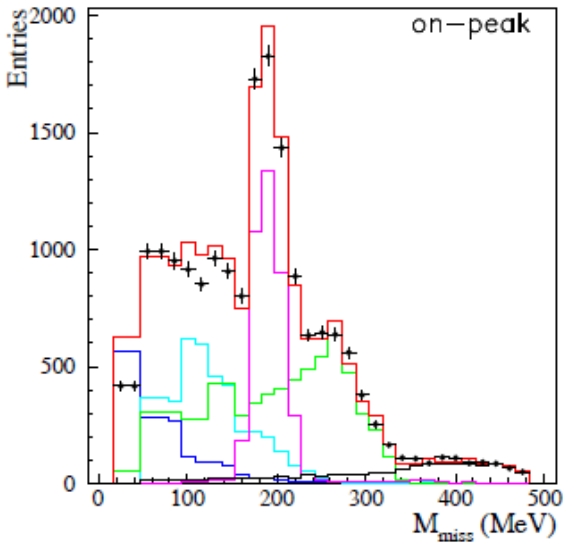


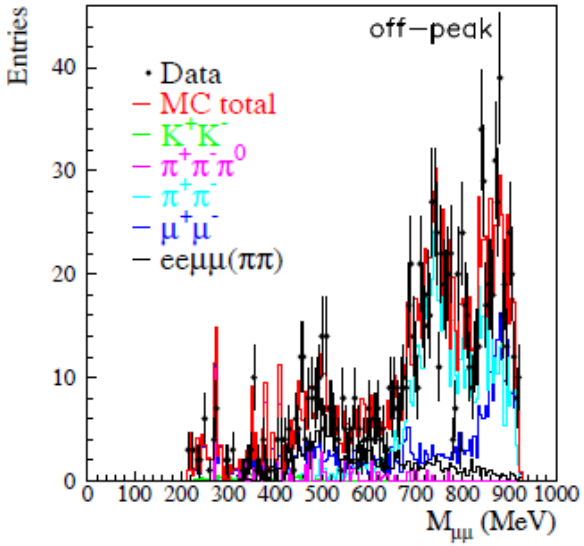


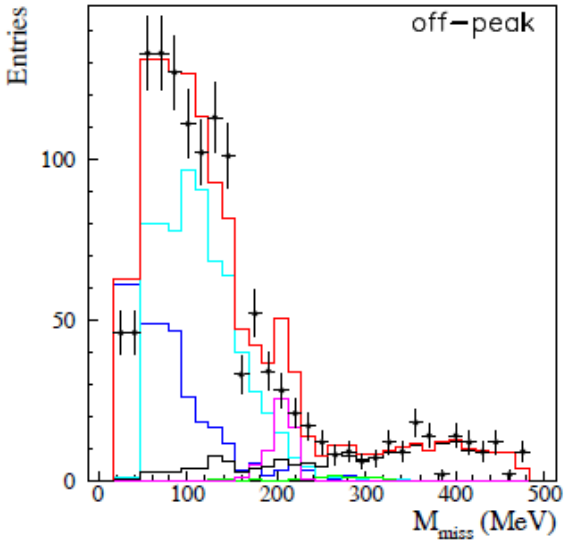


$e^+e^- \to h'U$: $M_{\mu\mu}$ and M_{miss} spectra

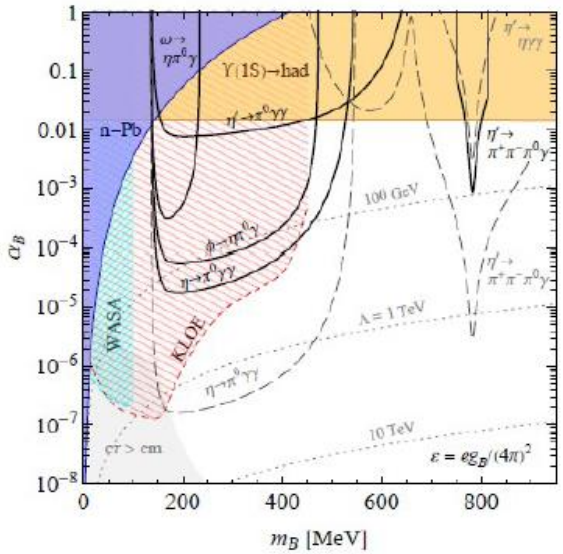








Leptophobic Dark Matter mediator search with KLOE-2



S. Tulin (Phys. Rev. D 89, 114008 (2014))

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

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

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

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

- $\Phi \to \eta B$ with $B \to \pi^0\gamma$
  - Channel used for a0(980) scalar meson
- Look for resonance in $\pi^0\gamma$ invariant mass

KLOE searches

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	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	