The KLOE-2 Experiment at DAΦNE

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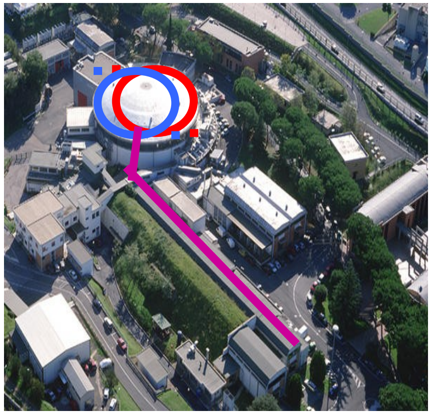
On behalf of KLOE-2 Collaboration

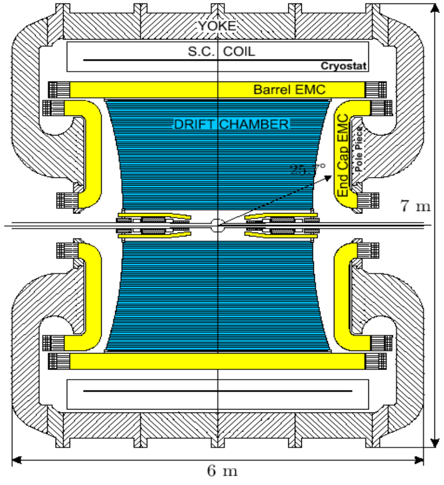
Heavy Quarks and Leptons 2016 Conference
Virginia Tech, 24th May 2016

KLOE-2 succeeds KLOE with **upgraded detectors** and **higher luminosity** (crab-waist collision scheme) of DAΦNE collider



INFN Collider $e^+ e^-$ at 1019 MeV or off

Large-size drift chamber 9:1 He:C_4H_{10} , $\sigma_{vtx} \approx 1$ mm, $\sigma_{p_T}/p_T < 0.4\%$
El-mag calorimeter scint. fibers/Pb, $\sigma_E/E = 5.7\%/\sqrt{E}$, $\sigma_t = 55/\sqrt{E}$*100 ps; Cover 98% of 4π



KLOE-2
Inner tracker: 4-layer cyllindrical GEM tracker surrounding interaction point better vertex resolution (4x improvement) and low-p_T acc.

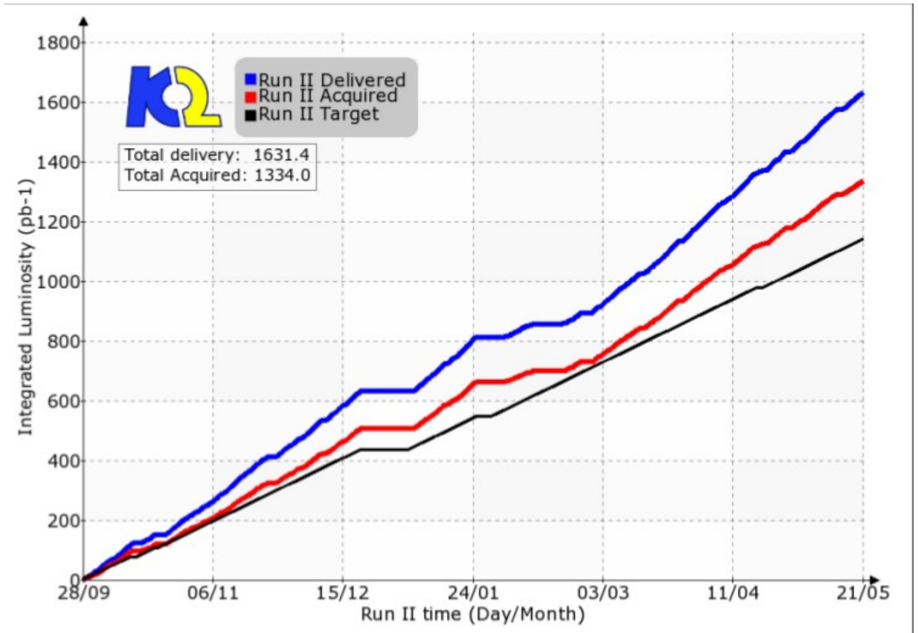
Electron taggers HET (E>400 MeV) and LET (160-230 MeV): Improved $e^+ e^-$ acceptance for γγ physics

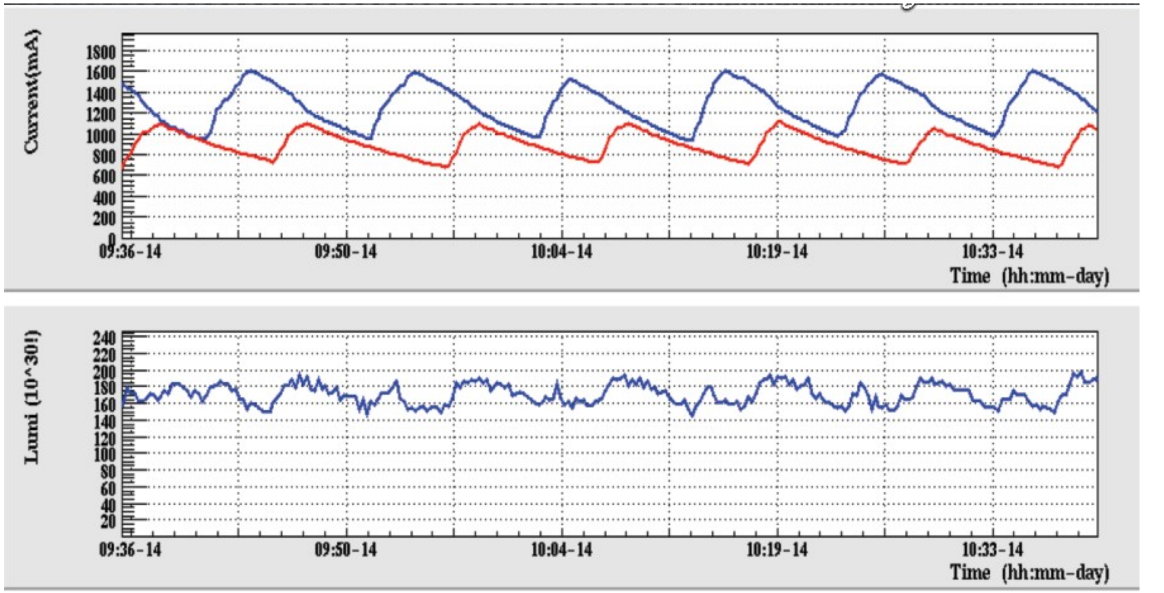
Near-beam calorimeters: CCALT - acceptance of γ down to 10°, QCALT - improved acceptance of K_L decay products

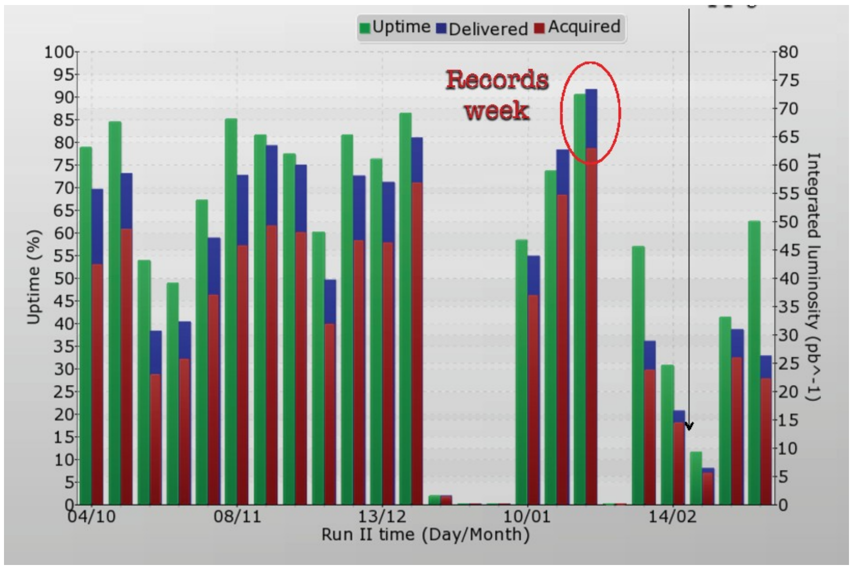
Upgrades of DAQ (Power7 brds + disks), tape library (upgradable to 175 PB), data servers (integrated Power8) and network

DAΦNE and KLOE-2 performance

Current data-taking campaigne: > 5 fb^{-1} to be taken in next couple of years with new equipments







Total luminosity delivered 21st May: 2.7 nb^{-1}

Maximum luminosity delivered weekly: 76.3 pb^{-1}

KLOE-2 **physics program**, defined E.Phys.J. C68(2010)619 + upcoming ideas

- Search for dark force at ~ 1 GeV scale

Theoretical model involving additional gauge group U(1), resulting with spin-1 gauge boson U (a.k.a. *dark photon, A', γ',* able to couple to dark-matter WIMP candidates); experimental bounds on U mass and couplings

- Kaon physics

Testing CPT and Lorentz invariance, search for quantum decoherence

- Precision measurements in hadronic physics at low energy

Transition form-factors of Φ to pseudoscalar mesons π^0, η

GeV-scale dark matter candidates search

Theoretical **proposal**: B.Holdom, PLB 166B(1986)196
Theoretical **predictions for rates** in resonance decays and e^+e^-:
P.Fayet, PRD 70(2007)115017

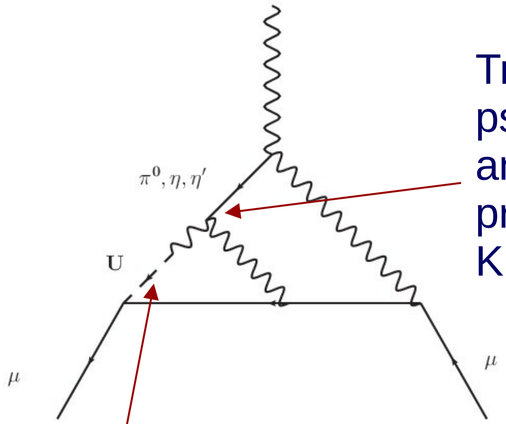
Can interact via mixing term with ordinary photon and subsequently decay into known particles

$$\mathcal{L}_{\mathrm{mix}} = \frac{\epsilon}{2} \mathsf{F}_{\mu\nu} \mathsf{G}^{\mu\nu}, \qquad \epsilon = \alpha_{\mathrm{em}}/\alpha_{\mathrm{dark}}$$

$$\epsilon \simeq 10^{-2} - 10^{-8}$$

Electromagnetic

Dark gauge field

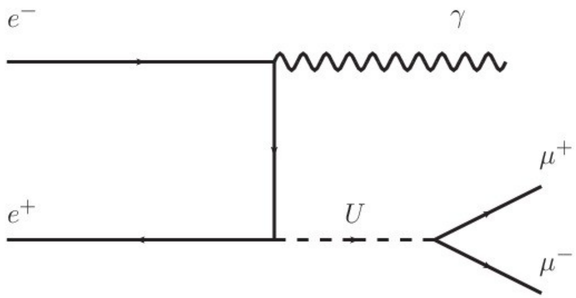


Transition FF of pseudoscalars - another research program in KLOE/KLOE-2

U could be light (with possible interesting consequences)
In addition, U→μμ suggested to cause **g-2 anomaly** of μ

Processes studied in search for U boson

- Associated production of U and γ



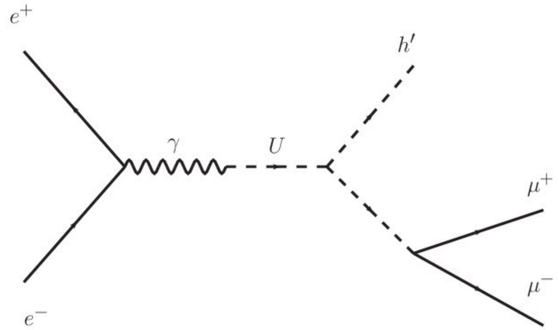
KLOE-2

$e^+ e^- \rightarrow U \gamma \rightarrow \mu^+ \mu^- \gamma$ PLB, 736(2014)459

$e^+ e^- \rightarrow U \gamma \rightarrow e^+ e^- \gamma$ PLB, 750(2015)633

$e^+ e^- \rightarrow U \gamma \rightarrow \pi^+ \pi^- \gamma$ PLB, 757(2016)356

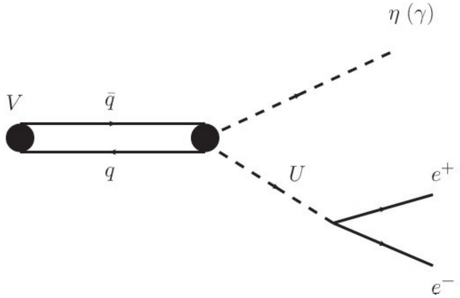
- Search for Higgsstrahlung



$e^+ e^- \rightarrow \mu^+ \mu^- +$ (missing energy)

KLOE-2, PLB 747(2015)365

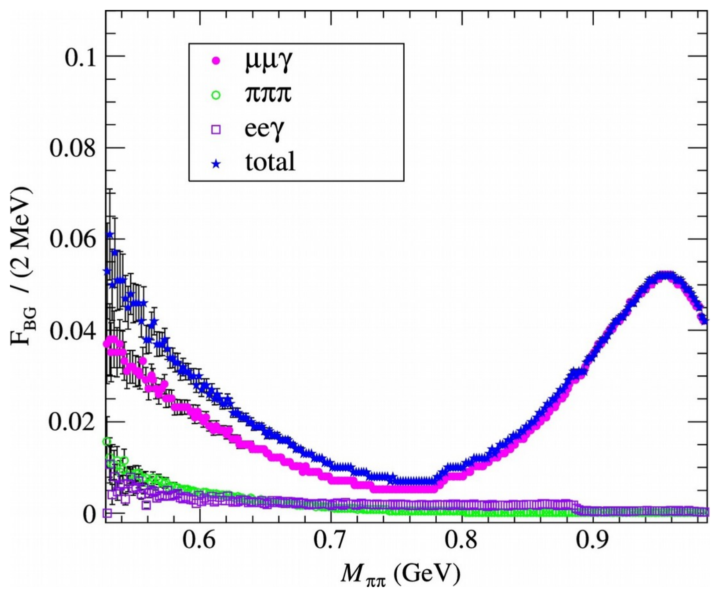
- Decay $\Phi \rightarrow \eta U$, $\eta \rightarrow 3\pi$



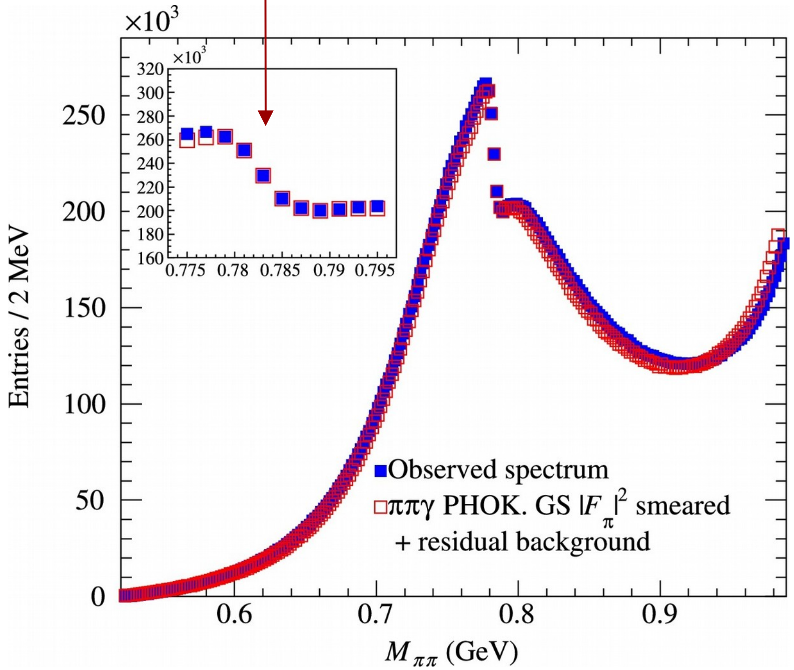
KLOE-2, PLB 720(2013)111

Results for U → $\pi^+ \pi^-$ on 1.93 fb^{-1}

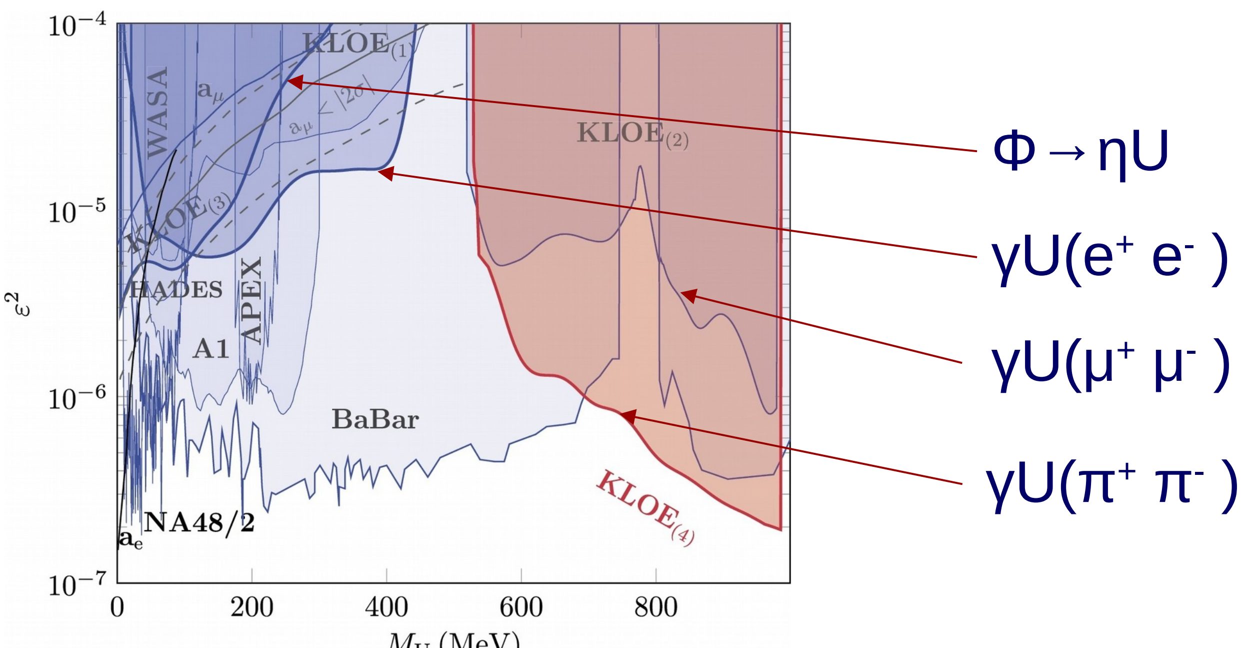
MC fractional backgrounds (norm. to ππγ) after cuts



Very good mass description:
PHOKARA+$|F_\pi|$ Gounaris-Sakurai
in ω-ρ interference region

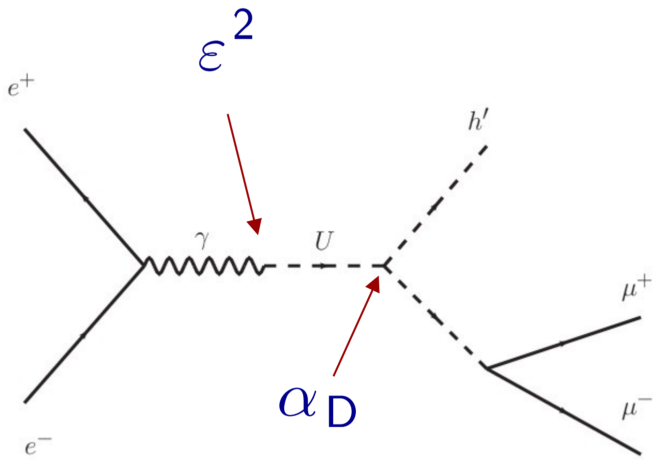


Summary for associated Uγ
and Dalitz Φ → ηU: 90% exclusion regions



KLOE-2, PLB 757(2016)356

Search for **Higgsstrahlung $e^+ e^- \rightarrow \mu^+ \mu^-$ + (missing energy)**

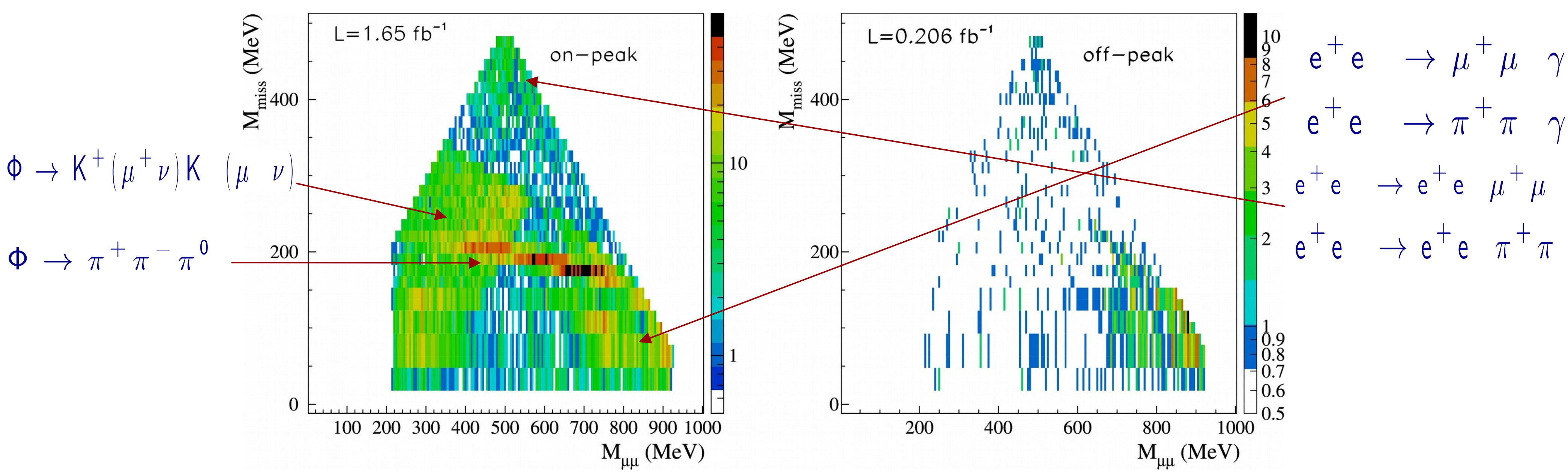


Depending on h' and U mass hypothesis, different detection strategies, e.g.

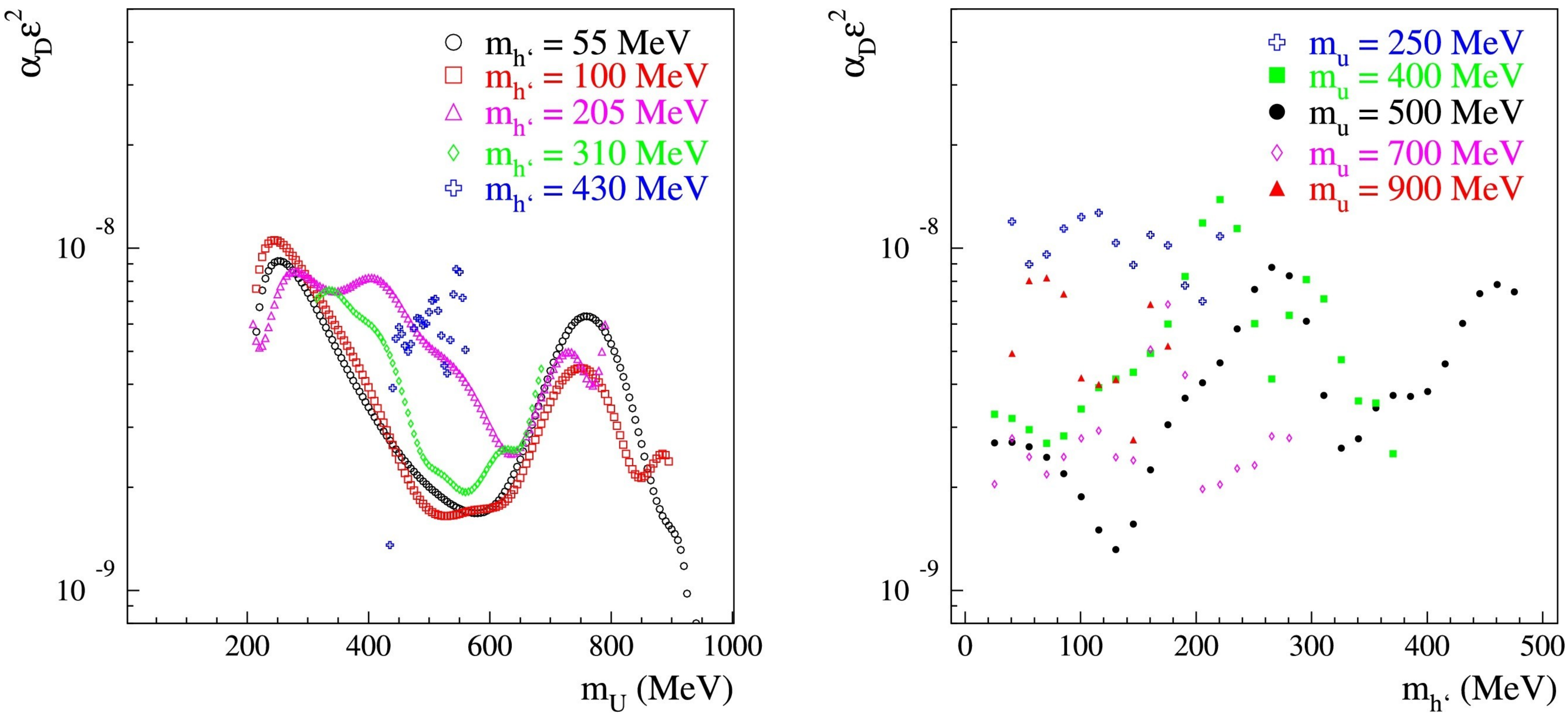
$m_{h'} > m_U$ h'→UU, explored by BaBar, Belle

$m_{h'} < m_U$ long lifetime, missing-mass only: KLOE-2 search

Two data samples analysed for different backgrounds:
1.65 fb^{-1} on-peak (√s=1019 MeV), 0.21 fb^{-1} off-peak (√s=1000 MeV)



KLOE-2, PLB 747(2015)365



90% CL upper limits on $\alpha_D \varepsilon^2(m_U)$ $\alpha_D \varepsilon^2(m_{h'})$ (smoothed)

KLOE-2, PLB 747(2015)365

CP, CPT and related issues

- Three-pion decays of K_S

  CP violation in $K_S \rightarrow 3\pi^0$ and tightening constraints on phase of ε using $K_S \rightarrow \pi^+ \pi^- \pi^0$; also slight improvement of unceretainty on Bell-Steinberger relation

- Sidereal-time and decay-time dependences of decays of entangled $K_L K_S$ pairs

  Fundamental tests of Standard Model extension violating CPT and Lorentz invariance; search for possible dissipative effects in vacuum (decoherence)

- Decay-time dependence of CPT-coupled final states from decays of entangled $K_L K_S$ pairs

  Test of CPT invariance using time evolution of $I(K_{e3}, K_{3\pi^0})/I(K_{\pi^+\pi^-}, K_{e3})(\Delta t)$

- Charge asymmetries of semi-leptonic decays of K_L and K_S

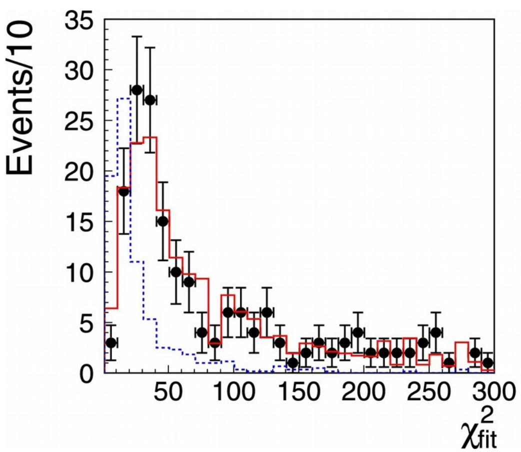
  Search for CPT violation using charge asymmetries

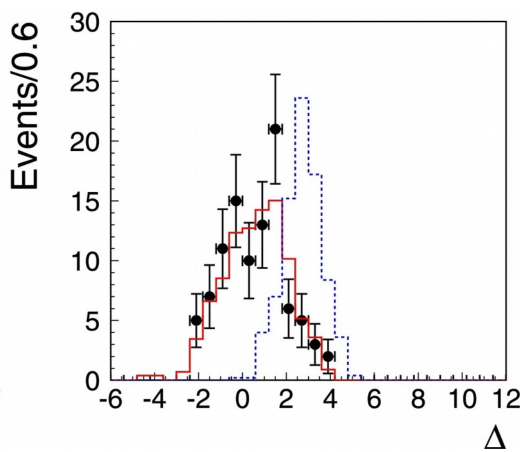
$K_S \to 3\pi^0$ unambiguously requires CP violation, as $J^{PC}_{\pi^0} = 0^{-+}$

K_S tagged by K_L interactions in calorimeter (K_L crash E deposit > 100 MeV) & timing; then look for events with 6 γ-clusters in calorimeter

Initial $K_L K_S$ sample 6×10^8, E & 6γ 77×10^3

$$\Delta = (m_\phi/2 - \sum E_\gamma)/\sigma_E$$





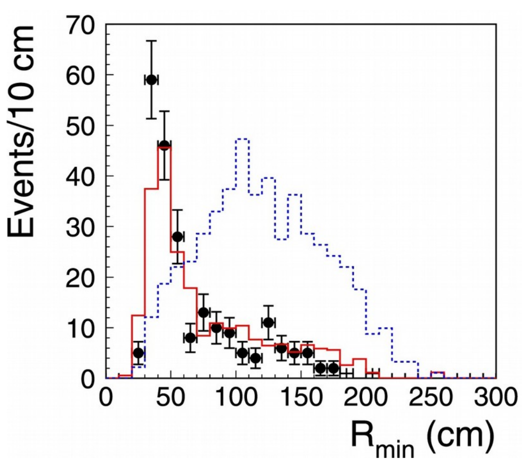
Normalization sample: $K_S \to 2\pi$

KLOE-2, PLB 723(2013)54

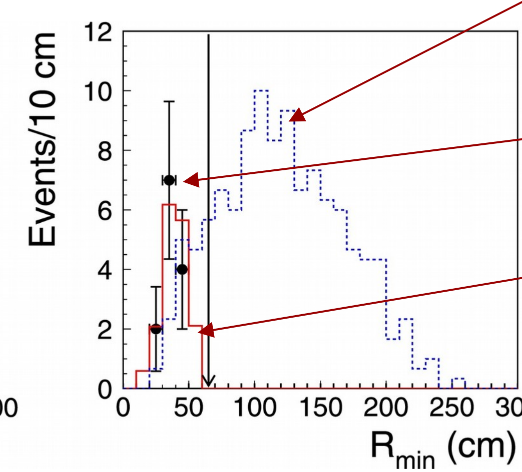
No events after cuts

$$\mathcal{B}(K_S \to 3\pi^0) < 2.6 \times 10^{-8} \quad (90\%\,CL)$$

$\chi^2_{fit} < 57.2$



$\Delta > 1.88$



Simulated $K_S \to 3\pi$

Data

Simulated background

$$\eta_{000} = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} = \sqrt{\frac{\tau_L \mathcal{B}(K_S \to 3\pi^0)}{\tau_S \mathcal{B}(K_L \to 3\pi^0)}} < 0.0088 \quad (90\%\,CL)$$

Minimal dist between reconstructed clusters

$K_S \to \pi^+ \pi^- \pi^0$;

its mere existence does not ensure CP violation (contains also CP- conserving component)

Still, the measurement is important

- Uncertainties of both η_{000} and η_{+-0} contribute to phase of ε via Im(Γ_{12})

$$\boldsymbol{\Gamma}_{12} = 2\pi \sum_{\mathrm{f}} \mathcal{B}(\mathrm{K_S} \to \mathrm{f})\left[1 - |\eta_\mathrm{f}|^2 - 2\Im(\eta_\mathrm{f})\right]$$

L. Lavoura, MPL A7(1992)1387

- Current experimental accuracy on BR is 30% (CPLEAR, NA48 and E621, 10-20 years ago)

- KLOE-2 pretends to measure BR with 20% accuracy on 1.7 fb^{-1} of old data and significantly improve on new data, measured directly (not from interference between CP-violating and CP-conserving parts).
 It is ongoing analysis in KLOE-2

Testing Standard Model Extension violating CPT and Lorentz invariance

Couplings of quarks to SME field

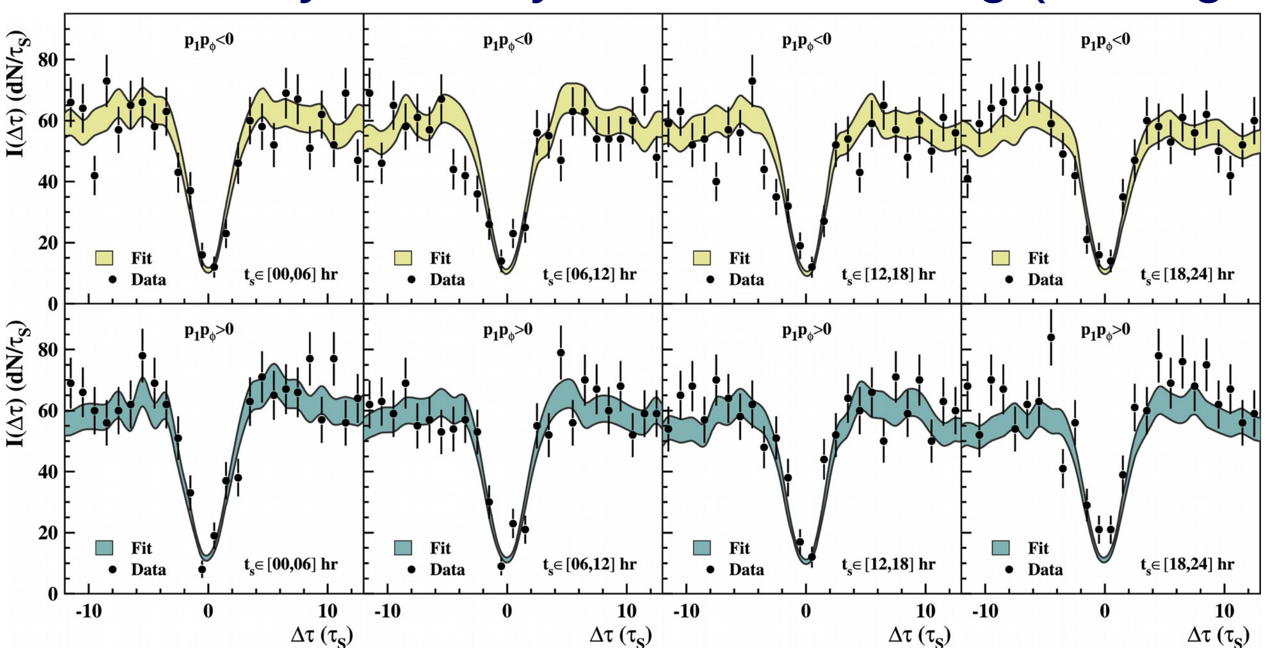
D.Calladay, V.A. Kostelecky, PR D55(1997)6760

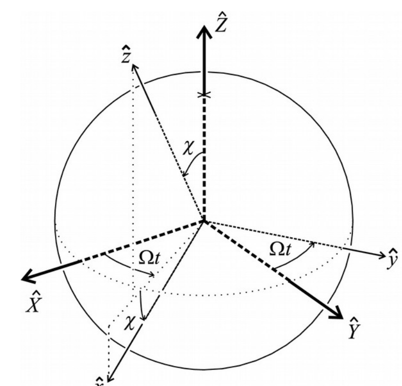
Assume additional CPT- violating term in weak Lagrangian $a_\mu \bar{\psi}\gamma^\mu\psi$

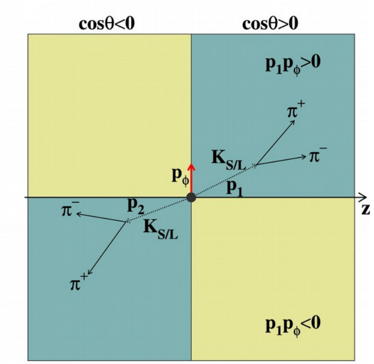
CPT (W.Pauli, P.Luders et al.) and anti-CPT theorems (O.Greenberg) suggest that CPT-violation entails Lorentz violation, hence directional dependence, e.g. w.r.t. distant stars, hence possible sidereal time (lab orientation and earth angular velocity) dependednce of

$$\delta = i\sin(\phi)\frac{e^{i\phi}}{\Delta m}\gamma(\Delta a_0 - \vec{\beta}\cdot\Delta\vec{a})$$

and decay intensity of two interfering (entangled) kaons







KLOE-2, PL B730(2014)89

KLOE-2, entangled pairs $\Phi \to K_L\ K_S \to \pi^+\ \pi^-\ \pi^+\ \pi^-$

$\Delta a_0=(-6.0\pm7.7\pm3.1)*10^{-18}$ GeV
$\Delta a_x=(0.9\pm1.5\pm0.6)*10^{-18}$ GeV
$\Delta a_y=(-2.0\pm1.5\pm0.5)*10^{-18}$ GeV
$\Delta a_z=(3.1\pm1.7\pm0.5)*10^{-18}$ GeV

KLOE exhibits the best sensitivity, closer to **$m_K^2/m_P=0.2*10^{-19}$ GeV**

LHCb, arXiv: 1603.04804, 2016 mixing

$B^0 \to J/\psi\ K_S$

$\Delta a_{x,y,\parallel} \approx 10^{-15}$ GeV
$\Delta a_{\perp} \approx 10^{-13}$ GeV

$B_s \to J/\psi\ K^+\ K^-$

$\Delta a_{x,y,\parallel} \approx 10^{-14}$ GeV
$\Delta a_{\perp} \approx 10^{-12}$ GeV

D0, PRL 115(2015)161601, mixing B_s

$\Delta a_{\parallel} \approx 10^{-13}$ GeV
$\Delta a_{\perp}<1.2*10^{-12}$ GeV

BaBar, PRL 100(2000)131802
entangled $\Psi(4S) \to BB \to (Xl\nu)(Xl\nu)$

$\Delta a_{\perp\parallel} \approx 10^{-13}$ GeV

FOCUS, PLB 556(2003)7, mixing D

$\Delta a_{\perp\parallel} \approx 10^{-13}$ GeV

CPT violation and decoherence

$\Phi \to K_L K_S \to (\pi^+ \pi^-)(\pi^+ \pi^-)$

Search for a possible loss of entanglement due to possible vacuum background effects (e.g. gravitational at microscale)
If exists, evolution of the pure into mixed state (decoherence) necessarily violates CPT (theorem by R.Ward, 1980)

- Decay of interference term $I(\Delta t) \sim \ldots + 2(1 - \underline{\zeta})e^{-\Gamma\Delta t}\cos(\Delta m \Delta t)$

$\zeta = (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \times 10^{-7}$ (basis-dependent quantity)

- Ill-defined CPT operator $|i\rangle \sim |K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle + \underline{\omega}(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle)$

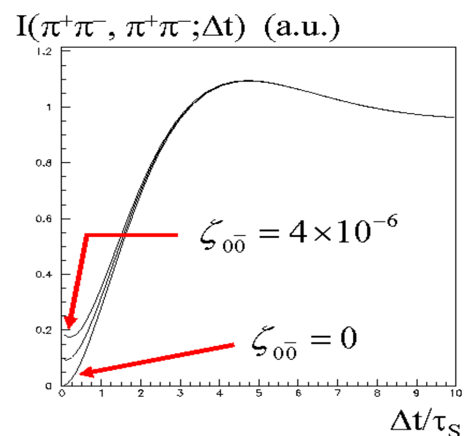
$\Re(\omega) = (-1.6^{+3.0}_{-2.1} \pm 0.4_{syst}) \times 10^{-4}$ $\Im(\omega) = (-1.7^{+3.3}_{-3.0} \pm 1.2_{syst}) \times 10^{-4}$

- Dissipative decoherence (GeV)

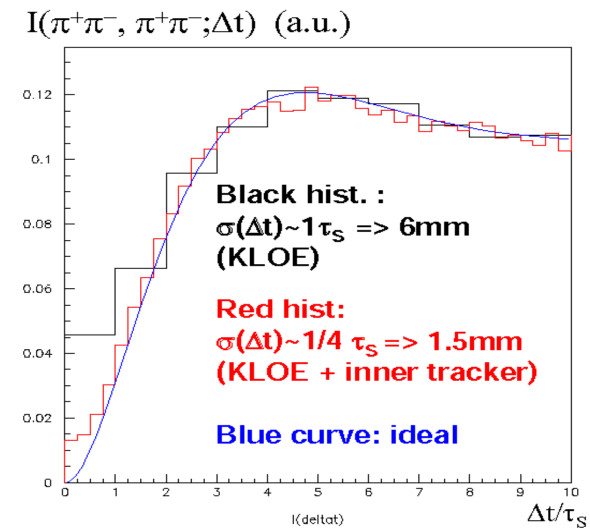
$$\dot{\rho} = i[\rho, H] + \tilde{H}(\underline{\alpha, \beta, \gamma})\rho$$

$\alpha = (-0.5 \pm 2.8) \times 10^{-17}$
$\beta = (0.25 \pm 0.23) \times 10^{-18}$
$\gamma = (0.11 \pm 0.25) \times 10^{-20}$

Possible signal of decoherence concentrated at very small Δt



Theoretical distribution



Reconstructed distribution (MC)

KLOE, PLB 642(2006)315, FoP 40(2010)852,
KLOE-2: more statistics, better low Δt resolution, other decay channels

Test CPT invariance in decay-time evolution of CPT-coupled channels

J. Bernabeu, A. di Domenico,
P. Villanueva-Perez, JHEP 1510(2015)139

Observables $$R_{2,4}(\Delta t) = \frac{I(K_{e\pm3}, 3\pi^0; \Delta t)}{I(2\pi, K_{e\pm3}; \Delta t)} \frac{\mathcal{B}(K_L \to 3\pi^0)}{\mathcal{B}(K_S \to 2\pi)} \frac{\Gamma_L}{\Gamma_S}$$

exhibit calculable dependence on Re(δ), in particular asymptotically

$$R_{2,4}(\Delta t) \sim 1 \mp 4\Re(\delta), \qquad \text{for } \Delta t \gg \tau_S$$

Statistical sensitivity of $R_{2,4}$ ranges from $3*10^{-3}$ to $1.5*10^{-3}$ for KLOE-2 luminosity between 5 fb^{-1} and 20 fb^{-1}.

Will be the second measurement after 18 y.o. CPLEAR, 1998, Re(δ)≈10^{-3}, comparable accuracy, another method;

Much desired: knowledge on Im(δ) more precise (10^{-5}) and better cross-checked: KLOE, NA48, combined analyses; Im(δ) contributes to Bell-Steinberger rule and Re(δ) does not.

Ongoing analysis in KLOE-2

Test of CPT invariance using asymmetries of semi-leptonic decays (or yet another way to chase δ ..)

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi \quad e^+\nu) \qquad \Gamma(K_{S,L} \to \pi^+ e \quad \bar{\nu})}{\Gamma(K_{S,L} \to \pi \quad e^+\nu) + \Gamma(K_{S,L} \to \pi^+ e \quad \bar{\nu})}$$

$$= 2[\Re(\epsilon) \pm \Re(\delta) \qquad \Re(y) \pm \Re(x \quad)]$$

CPT violation assuming ΔS=ΔQ

$$A_S - A_L = 4[\Re(\delta) + \Re(x_{-})]$$

Small term describing violation ΔQ=ΔS rule, assuming CPT; experimentally (PDG) -0.002 ± 0.006

Current experimental knowledge: $\sigma(A_L)=0.7*10^{-4}$ (KTeV), $\sigma(A_S)=10^{-2}$ (KLOE)

PLB636(2006)173

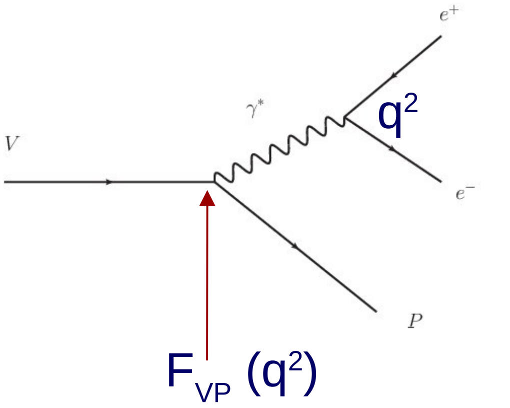
Ongoing analysis in KLOE-2

Disproportion; crucial to measure A_S

4 times statistics from KLOE & further improvement with new KLOE-2 data

New results on transition form factors of Φ to pseudoscalar mesons $\Phi \rightarrow P\, e^+ e^-$

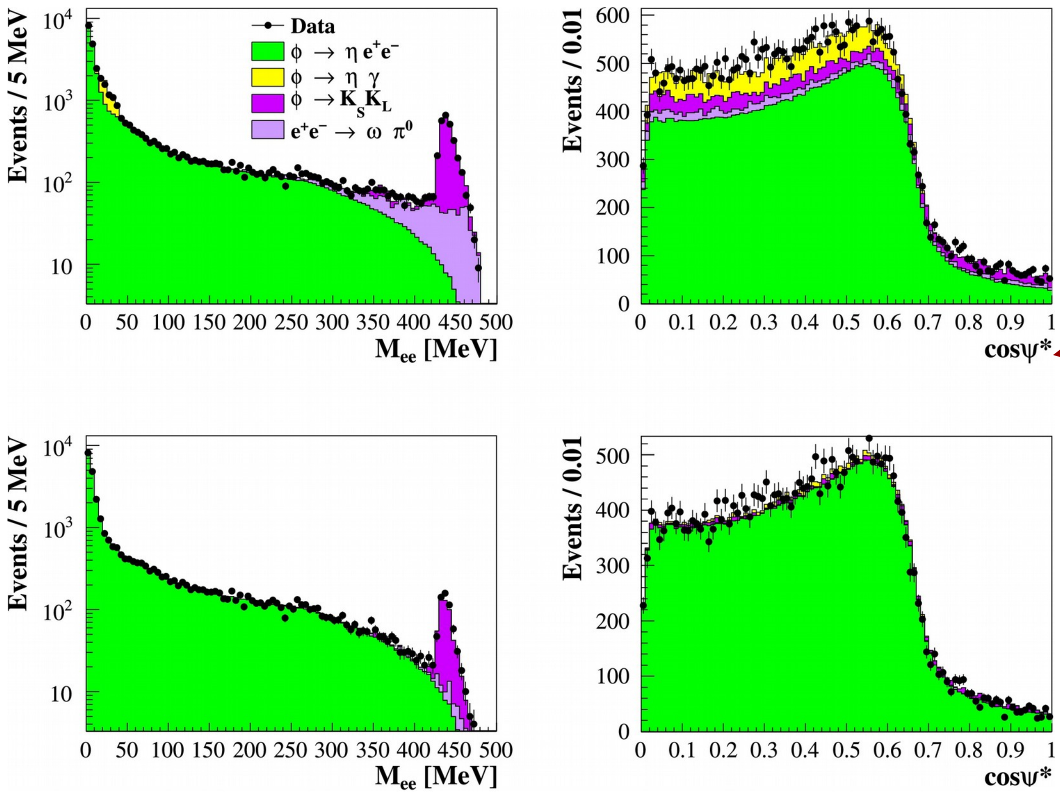
η, π^0



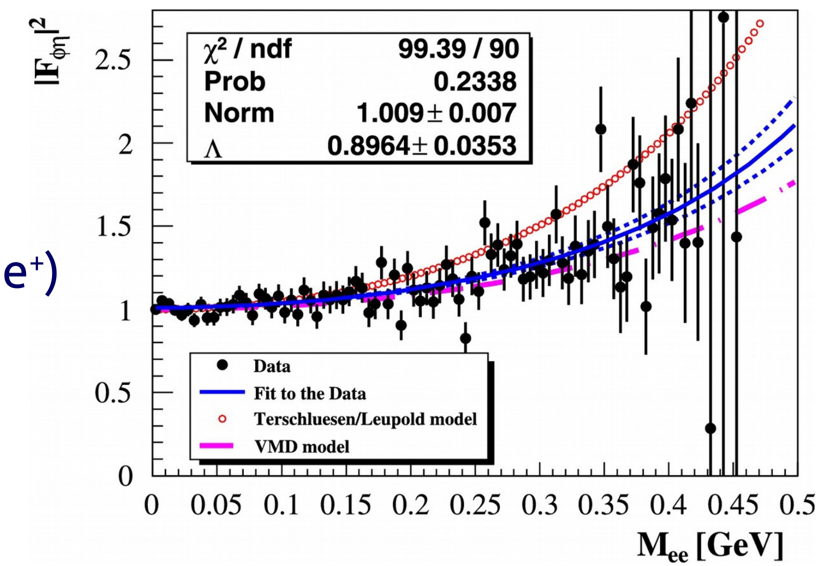
Needed to validate non-VMD models of form factors

VMD fails to describe some transitions, e.g. $\omega \rightarrow \pi^0 \mu^+ \mu^-$

$\Phi \rightarrow \eta(\pi^0\, \pi^0\, \pi^0)\, e^+ e^-$ 30 000 events, <3% bckrd, 1.7 fb^{-1}



Angle (ηe^+)



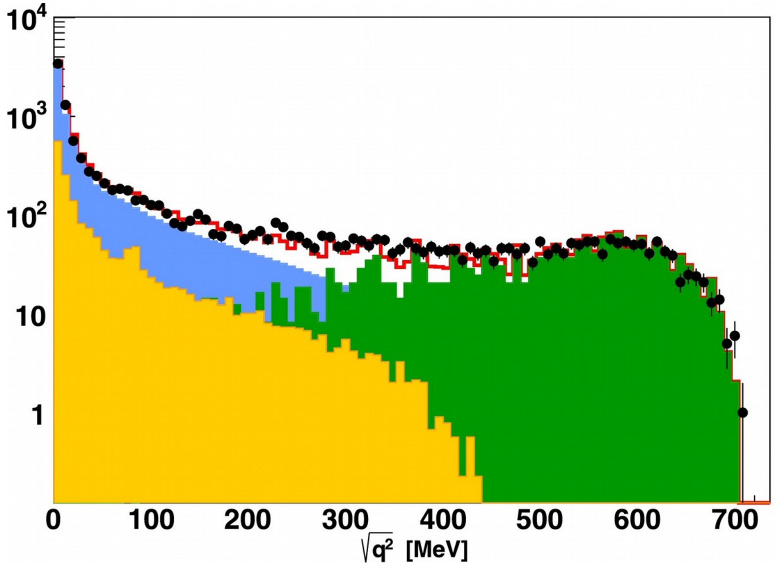
$$b_{\eta\Phi}(q^2 = 0) = 1.28 \pm 0.10^{+0.09}_{-0.08}\ \mathrm{GeV}^{-2}$$

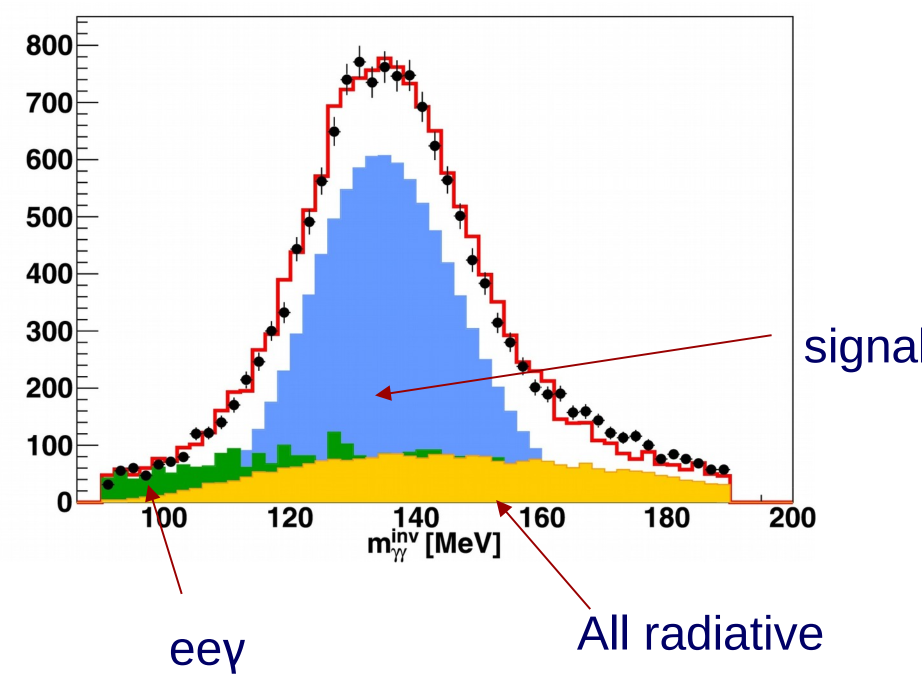
$$\mathcal{B}(\Phi \rightarrow \eta e^+ e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$$

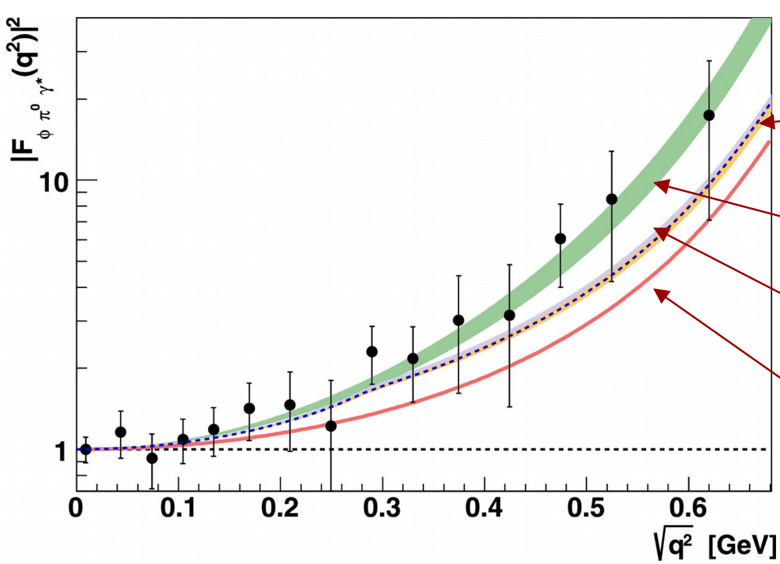
KLOE-2, PLB 742(2015)1

$\Phi \rightarrow \pi^0 e^+ e^-$

14670 event sample, 1.7 fb^{-1}







S. P. Schneider, B. Kubis, F. Niecknig, Phys. Rev. D 86 (2012) 054013. 219

S. Ivashyn, Prob. Atomic. Sci. Technol. 2012, N1 (2012) 179

I. Danilkin, et al., Phys. Rev. D 91 (2015) 094029

L. G. Landsberg, Phys. Rept. 128 (1985) 301

$$b_{\Phi\pi^0} = 2.02 \pm 0.11 \ \mathrm{GeV}^{-2}$$

KLOE-2, PLB 757(2016)362

$$\mathcal{B}(\Phi \rightarrow \pi^0 e^+ e^-) = (1.35 \pm 0.05^{+0.05}_{-010}) \times 10^{-5}$$

Summary & concluding remarks

KLOE-2 profits from enhanced DAΦNE luminosity and new detectors: GEM inner tracker, electron taggers and near-beam calorimeters; aiming to > 5 fb^{-1} in coming years

Search for BSM physics (dark matter below 1 GeV, testing CPT and Lorentz invariance) and low-energy hadronic physics

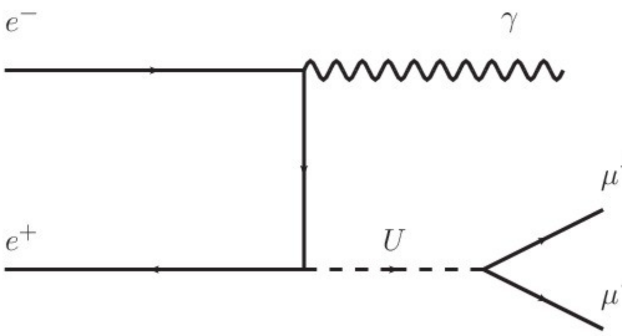
KLOE-2 will significantly improve all results on CPT and QM tests

- New results $e^+ e^- \to U\gamma$, $e^+ e^- \to \gamma \to Uh'$, $\Phi \to U\eta$, 90% CLs on α_{dark} vs M_U
- CP-violating $K_S \to 3\pi$,
- sidereal-time dependence of K_S K_L entanglement: limits on $\Delta a_\mu \approx 10^{-18}$ GeV, more stringent than c and b decays
- New, ongoing analyses of CPT-violating semi-leptonic asymmetries and entangled states decaying to CPT-coupled channels
- Extension of search for decoherence with new detectors (mainly inner tracker)
- Low-q^2 transition form factors $\Phi \to \eta\, \gamma^*$, $\Phi \to \pi^0\, \gamma^*$, able to discriminate models

Backup slides

Search for dark photon U: <u>associated Uγ production</u>
Signature: narrow peak on M_{+-} spectrum

KLOE-2



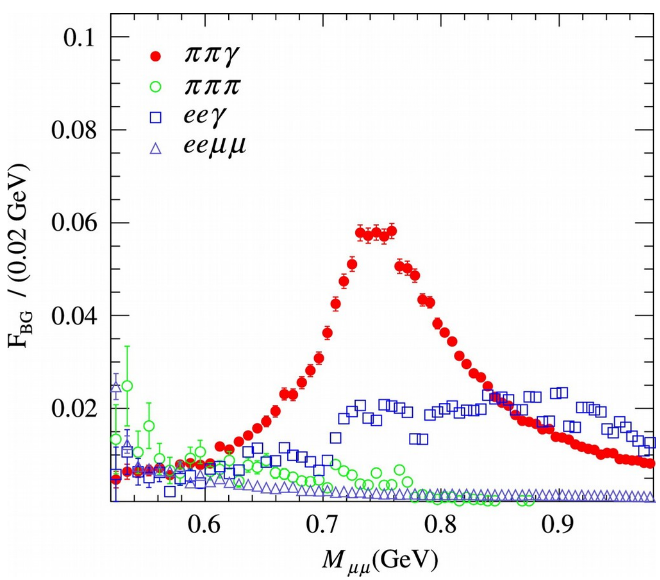
$e^+ e^- \rightarrow U\gamma \rightarrow \mu^+ \mu^- \gamma$ — PLB, 736(2014)459

$e^+ e^- \rightarrow U\gamma \rightarrow e^+ e^- \gamma$ — PLB, 750(2015)633

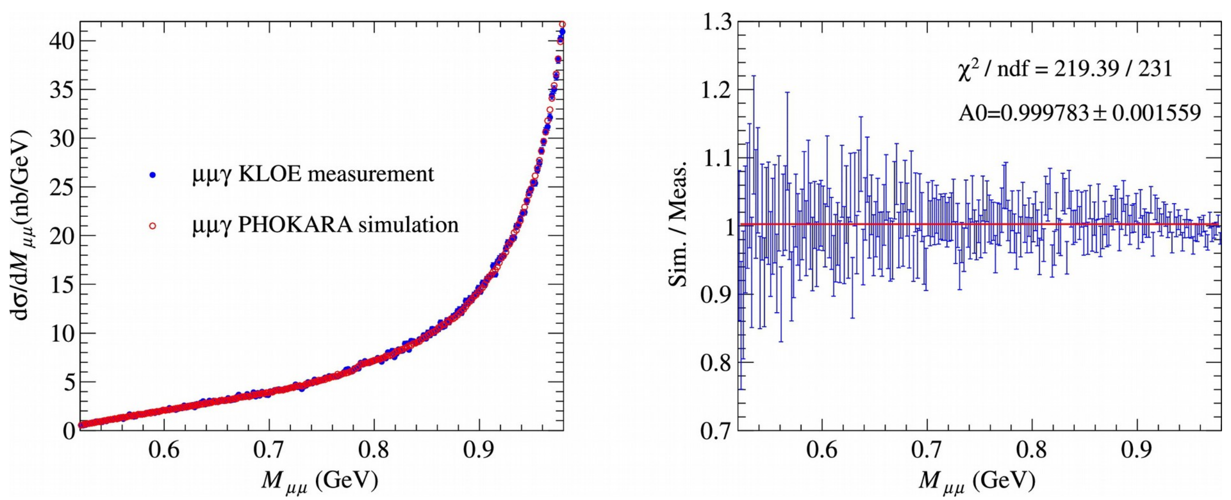
$e^+ e^- \rightarrow U\gamma \rightarrow \pi^+ \pi^- \gamma$ — PLB, 757(2016)356

<u>Case $\mu^+ \mu^-$</u>

Backgrounds: PHOKARA, no narrow peaking



Data vs PHOKARA MC agreement



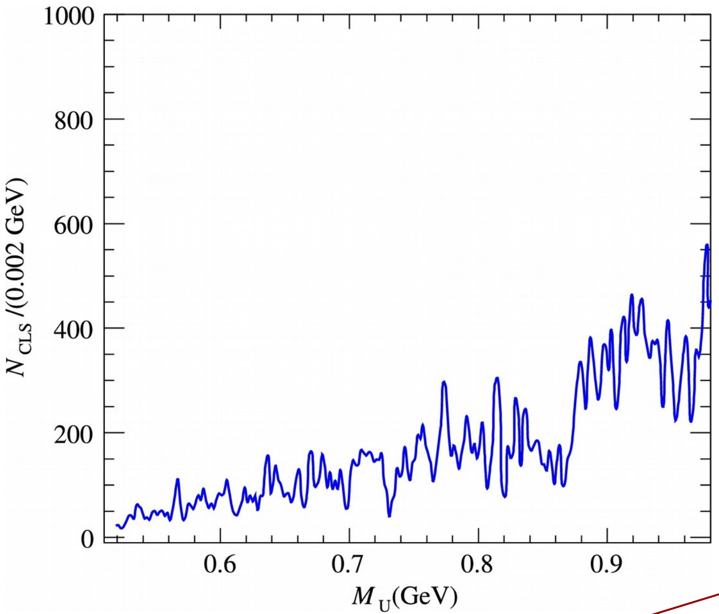
Results for U → μ⁺ μ⁻, based on 240 pb⁻¹

Expected sensitivity improvements:
Factor 3 from full KLOE data set &
factor 2 from new KLOE-2 data

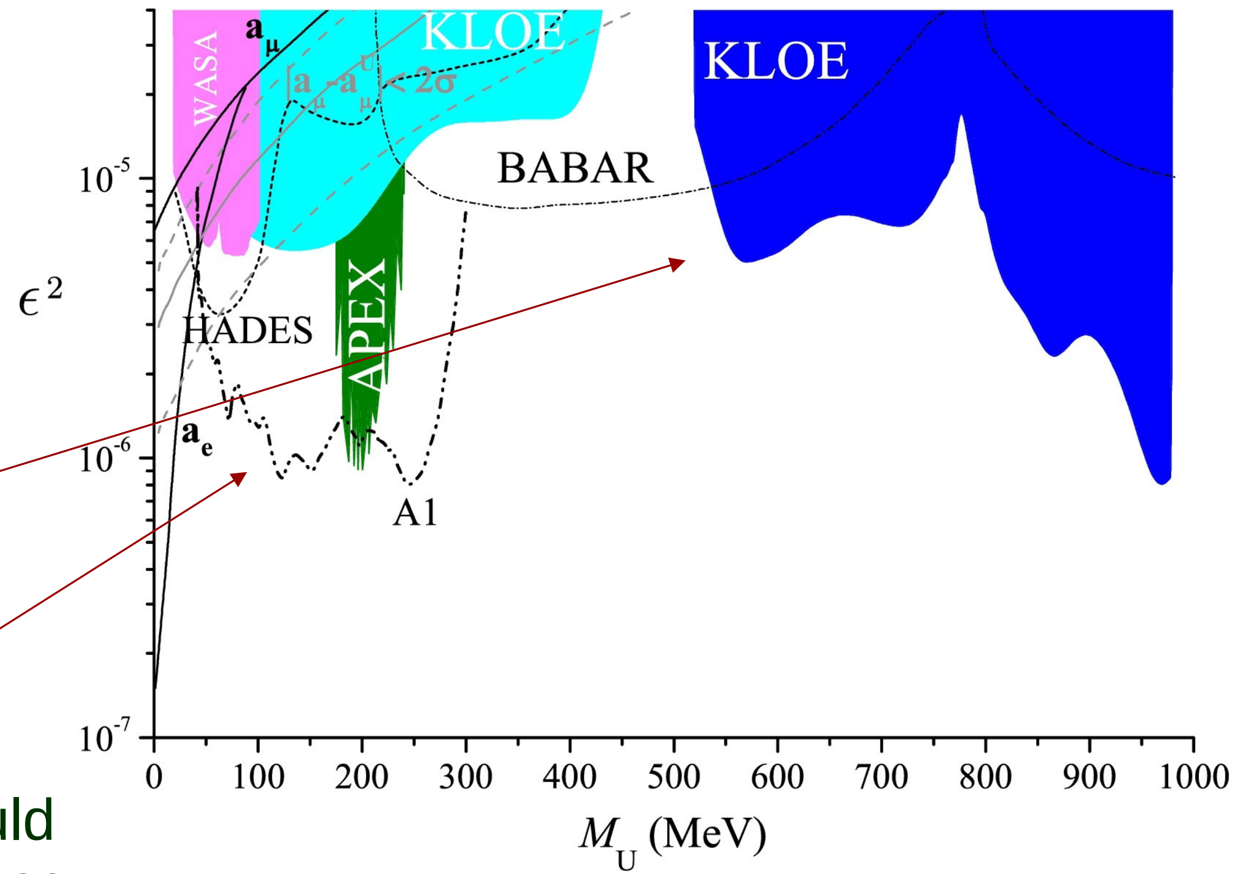
$$\epsilon^2 = \frac{N_{CLs}/(\varepsilon_{eff} L)}{HI}$$

γ radiation cross section, computed in NLO QED

Effective cross section ee → U→μμ



90% CL exclusion region

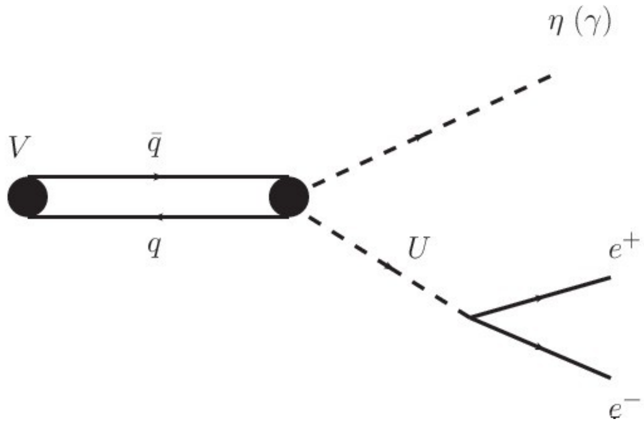


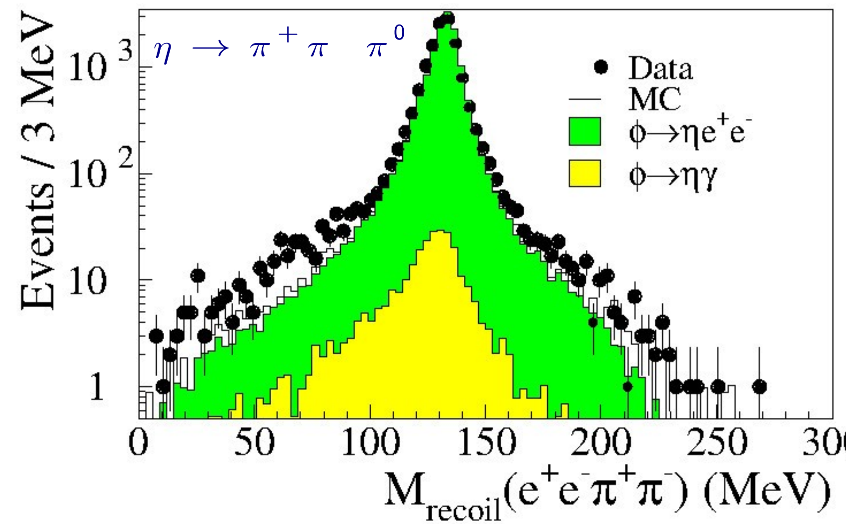
U boson parameters that could explain observed a_μ discrepancy with 2σ error band

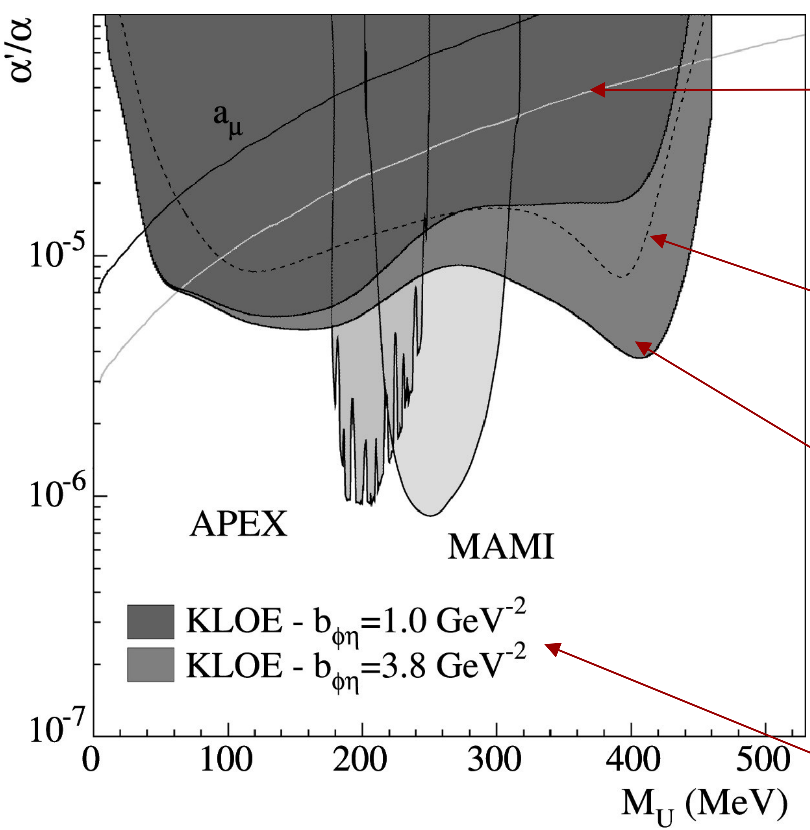
KLOE-2, PLB 736(2014)459

Decay $\Phi \to \eta U$, $\eta \to 3\pi$

KLOE-2, PLB 720(2013)111

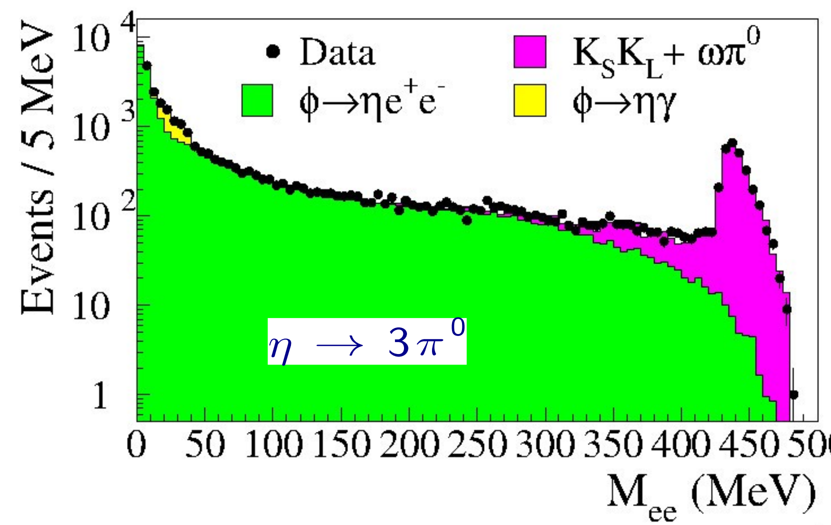






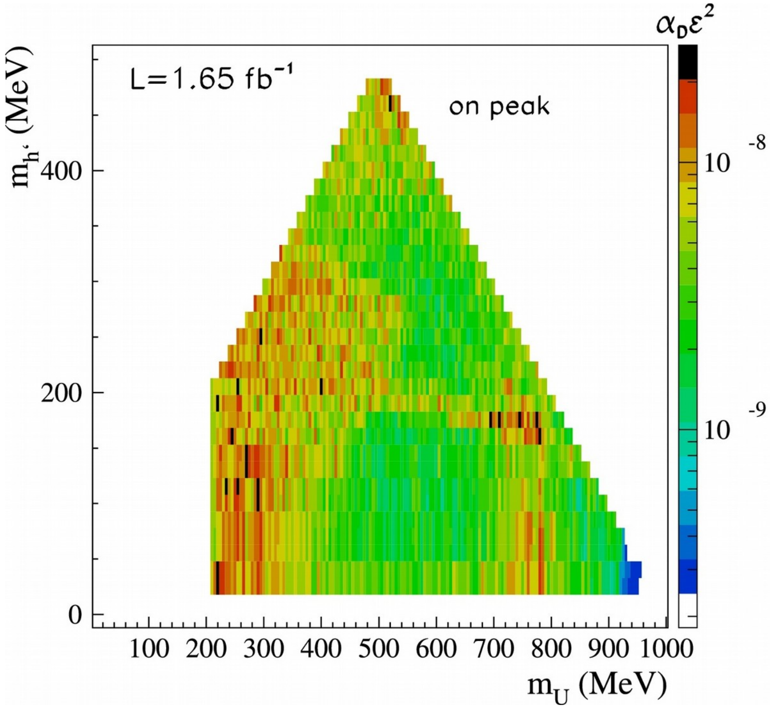
Needed to explain a_μ discrepancy

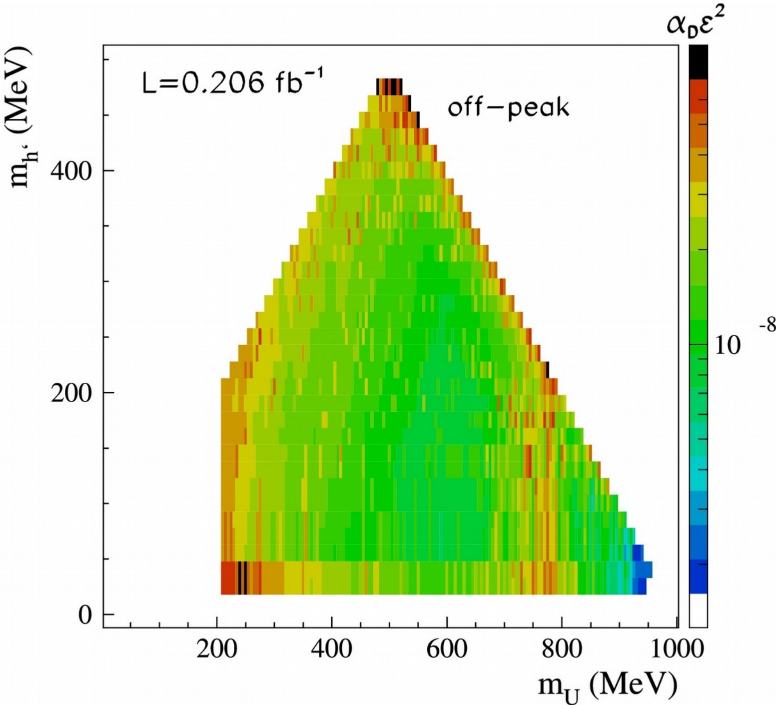
$\eta \to \pi^+\pi^-\pi^0$



$\eta \to \pi^+\pi^-\pi^0$ & $\eta \to 3\pi^0$

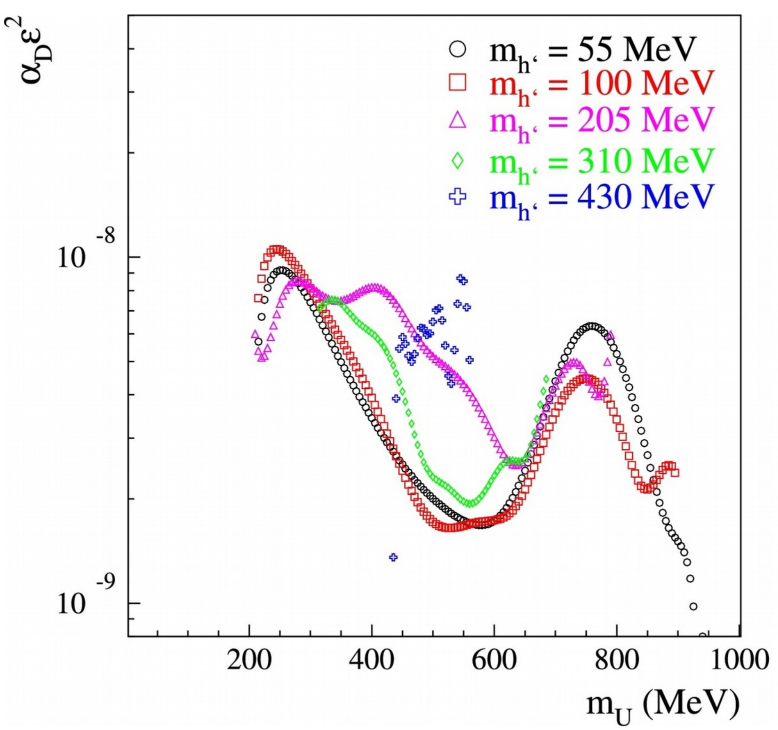
FF slopes $dF/dq^2|_{q=0}$ VMD theory & SND experiment

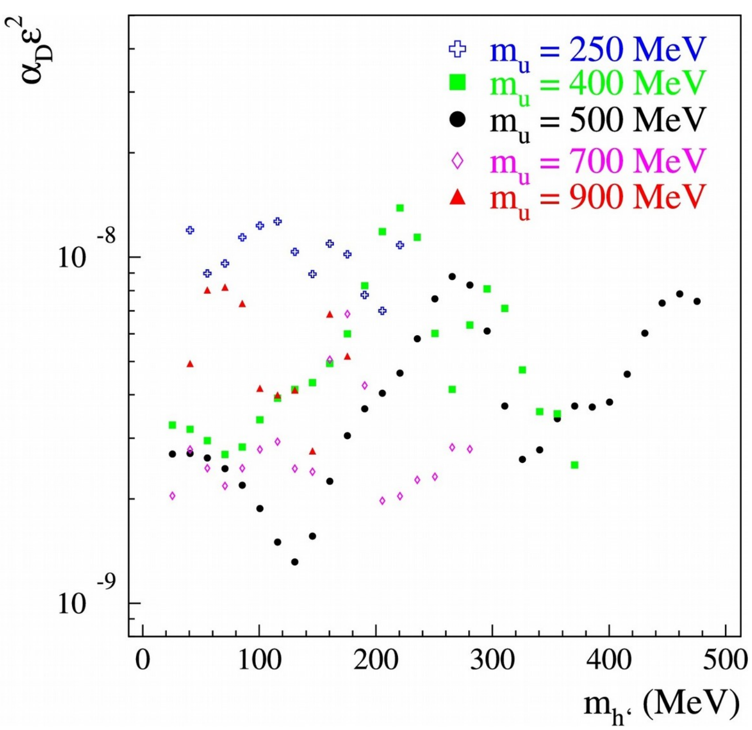




90% CL upper limits on $\alpha_D\varepsilon^2(m_{h'}, m_U)$

KLOE-2, PLB 747(2015)365





90% CL upper limits on

$\alpha_D\varepsilon^2(m_U)$

$\alpha_D\varepsilon^2(m_{h'})$

(smoothed)