KLOE-2 Results on Hadron Physics

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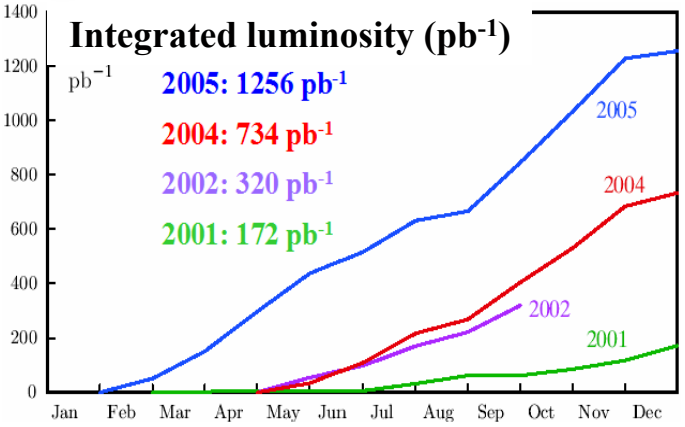
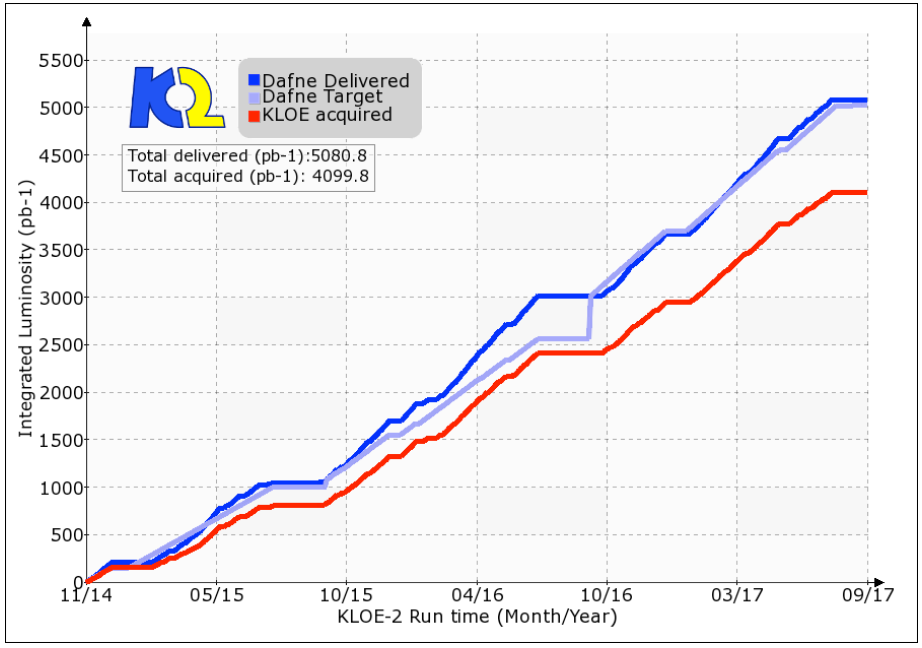
Outline

- **KLOE/KLOE-2 @ DAΦNE**
- **Measurement of the running of α_{em}**
- **Dalitz Plot of $\eta \to \pi^+\pi^-\pi^0$**
- **Transition Form Factors of $\phi \to \pi^0 e^+e^-$, $\phi \to \eta e^+e^-$**
- **Conclusions**

KLOE/KLOE-2 @ DAΦNE

- **DAΦNE** ϕ-factory: e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$
  $\sigma_{peak} \approx 3.1$ μb
- Best performance in KLOE run:
  $L_{peak} = 1.4 \times 10^{32}$ cm^{-1}s^{-1} $\int Ldt = 8.5$ pb^{-1}/day
- KLOE data sample: 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9$ ϕ's)
  + 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV
- DAΦNE upgrade: new interaction scheme;
  large beam crossing angle + crabbed waist sextupoles
- KLOE-2 data-taking started on November 2014
- DAΦNE lumin.: peak ~ 2×10^{32} cm^{-2} s^{-1}
  $\int Ldt \sim 10$ pb^{-1}/day
- Collected Luminosity ≈ 4 fb^{-1}



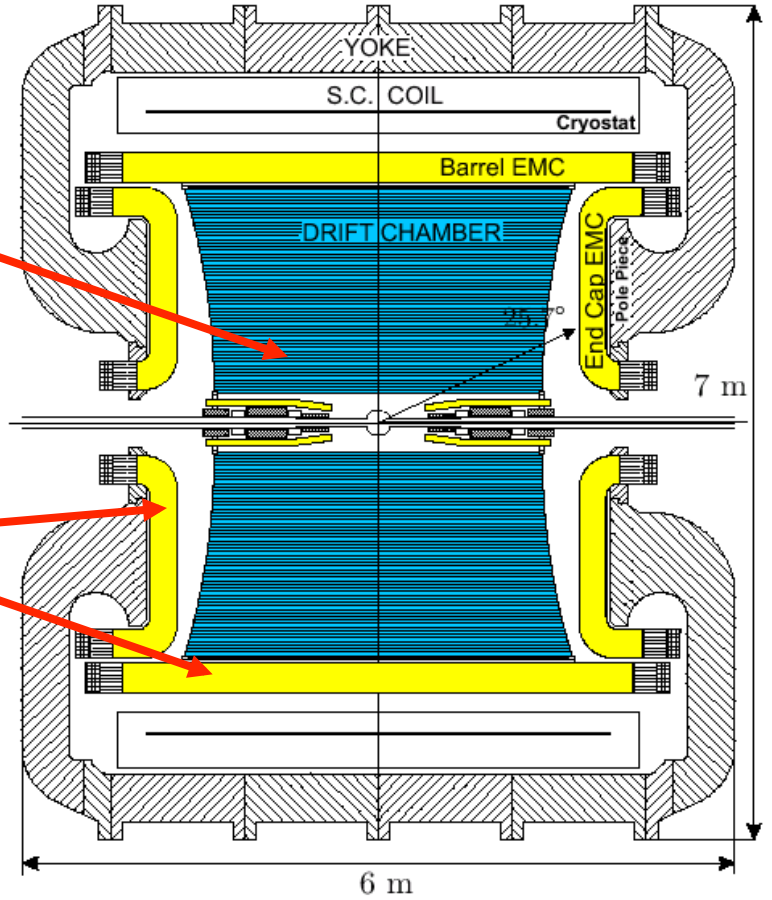


End of data-taking: 31 March 2018
Luminosity goal: 5 fb^{-1}

KLOE

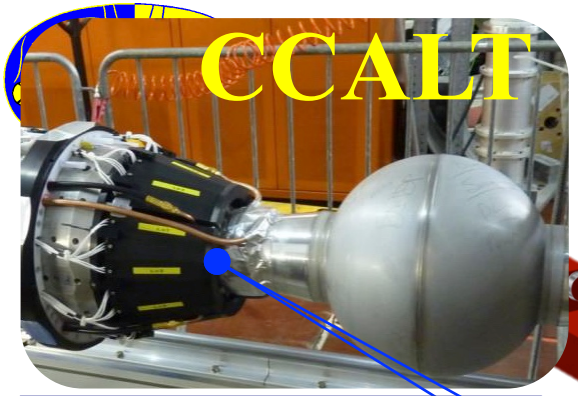
Drift chamber:
- gas: 90% He-10% iC_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 3$ mm

Calorimeter (Pb-Sci.Fi.):
- $\sigma_E/E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 55\ ps/\sqrt{(E(GeV))} \oplus 100\ ps$
- 98% of 4π

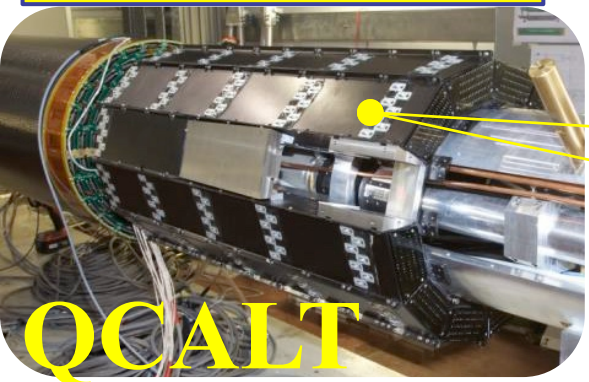


Magnetic field: 0.52 T

KLOE-2

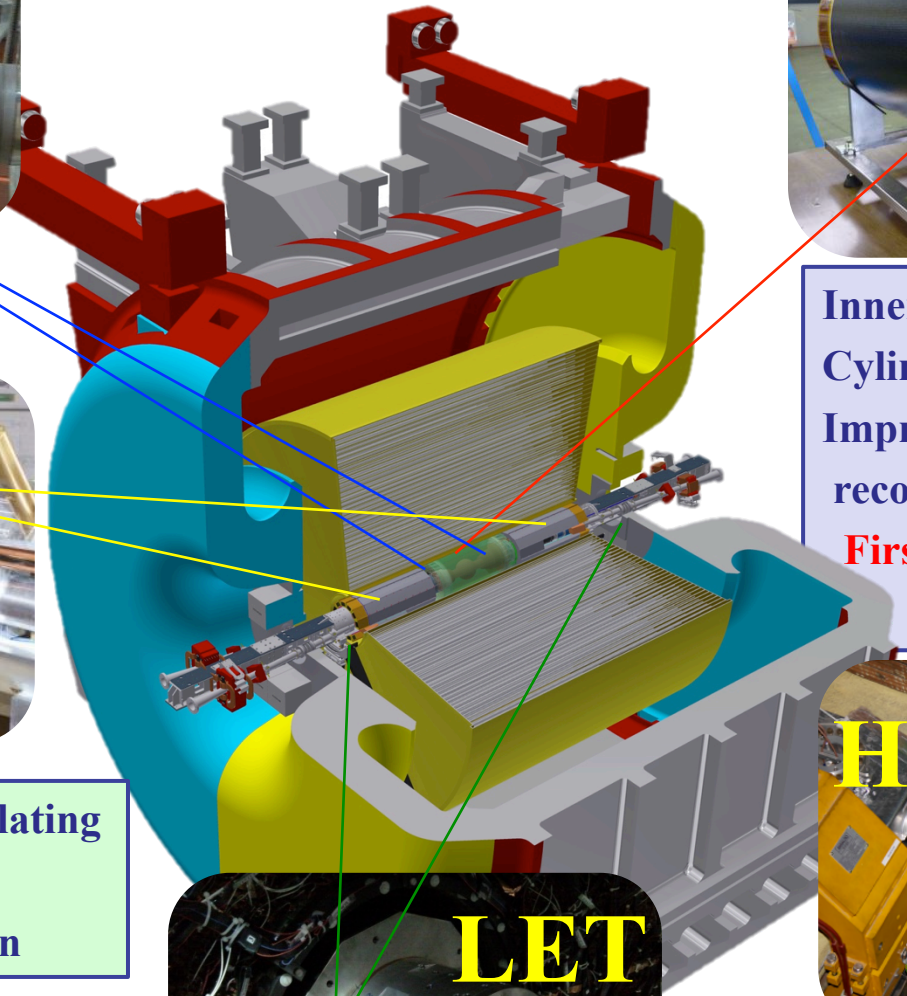


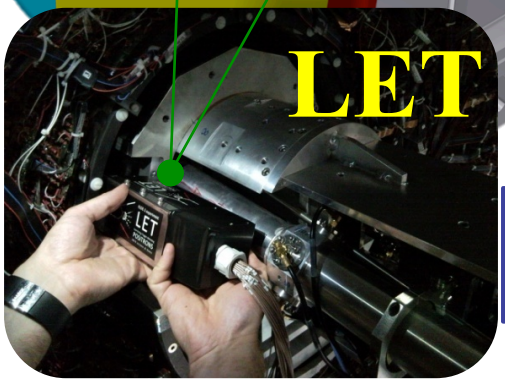
CCALT – LYSO Crystal
w SiPM - Low polar angle

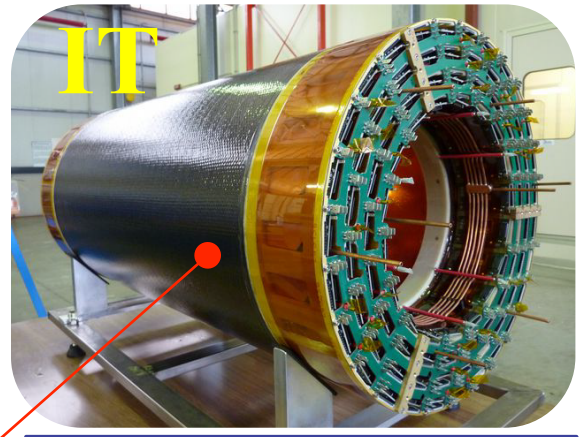


QCALT – Tungsten / Scintillating
Tiles w SiPM
Quadrupole Instrumentation

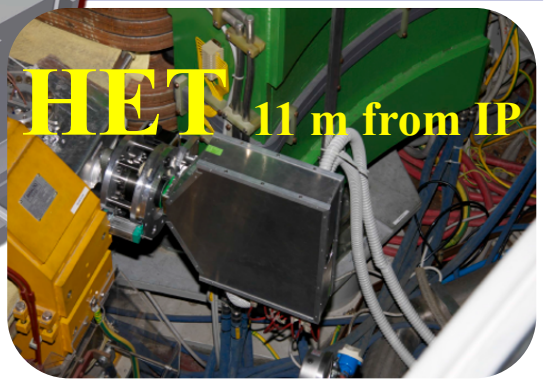
LET: 2 calorimeters LYSO + SiPMs
@ ~ 1 m from IP







Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vertex
reconstruction
First time CGEM in high
energy experiment



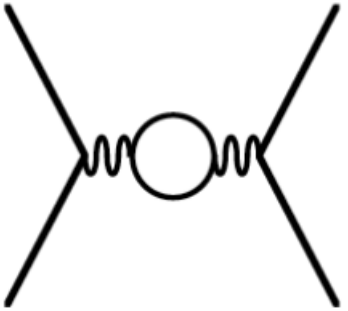
HET: Scintillator hodoscope +PMTs
pitch:5 mm; placed at 11 m from IP

Running of α(s)

- The Fine-structure constant α is a running parameter due to vacuum polarization effects

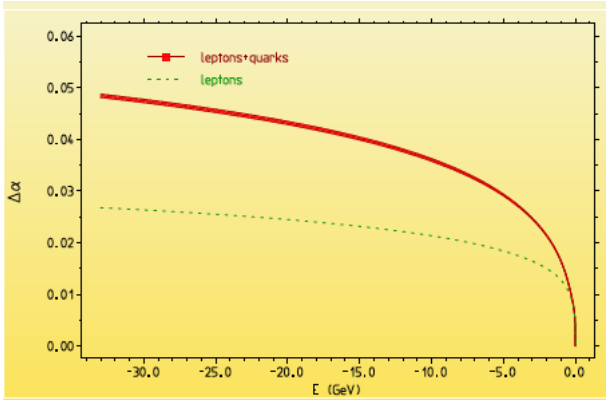
$$\alpha(q^2) = \frac{\alpha(0)}{1 - \Delta\alpha} \qquad \Delta\alpha(q^2) = -[\Pi(q^2) - \Pi(0)]$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$

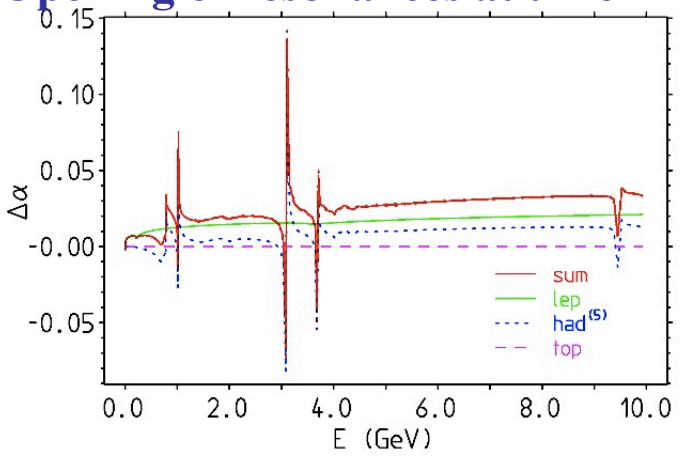


- Hadronic contribution not perturbative can be evaluated with dispersion relation ⇒ $\Delta\alpha^{(5)}_{had}(q^2) = -\frac{\alpha(0)q^2}{3\pi}\int_{s_0}^{\infty}\frac{R_{had}(s)}{s(s - q^2 - i\varepsilon)}ds$

Smooth behaviour at space-like q^2



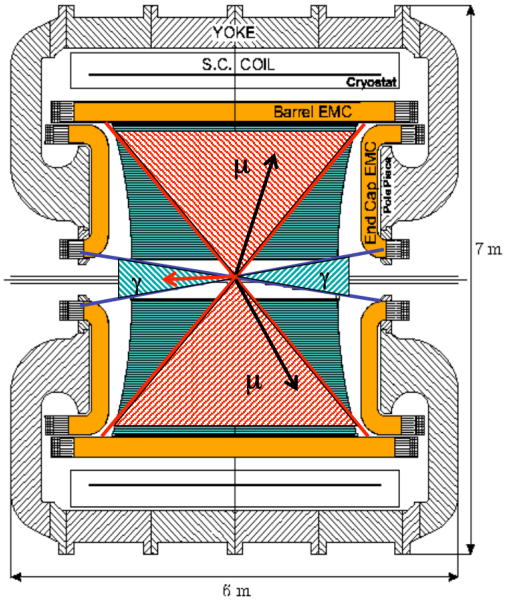
Opening of resonances at time-like q^2



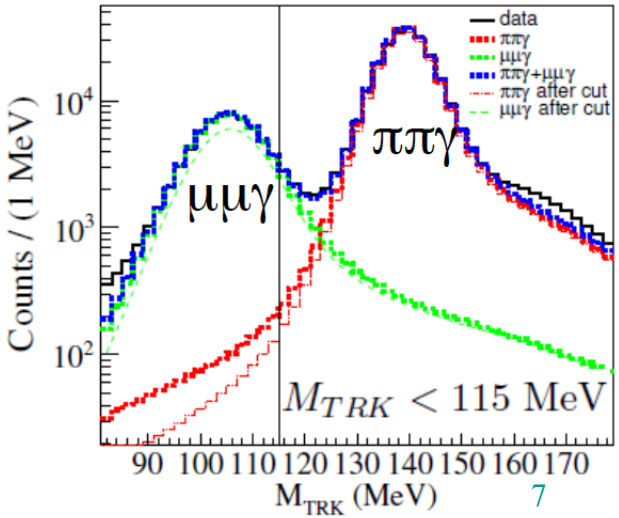
Measurement of α(s)

- $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ data from ISR; $s=q^2=M(\mu^+\mu^-)$
- Corrected for FSR (PHOKARA MC generator)
- Normalization to MC with $\alpha = \alpha(0)$

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{d\sigma^{ISR}_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))/d\sqrt{s}}{d\sigma^{0}_{MC}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))/d\sqrt{s}}$$



- 2 tracks at large angle ($50° < \vartheta < 130°$)
- Photon at small angle ($\vartheta < 15°$ or $\vartheta > 165°$) to reduce FSR
- Photon not detected; momentum reconstructed from kinematics $\vec{p}_\gamma = -(\vec{p}_+ + \vec{p}_-)$

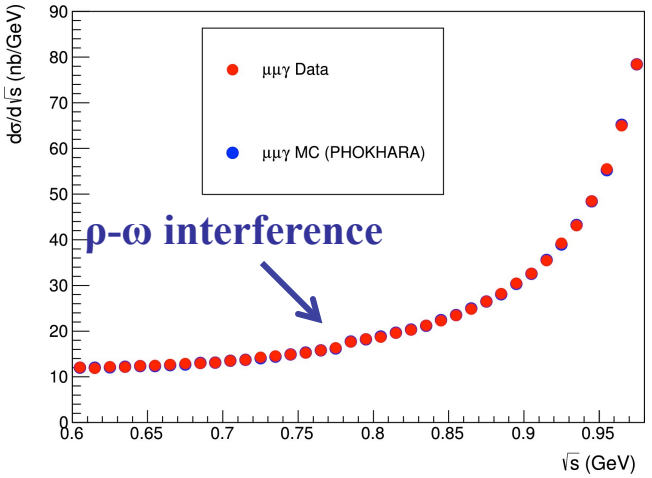


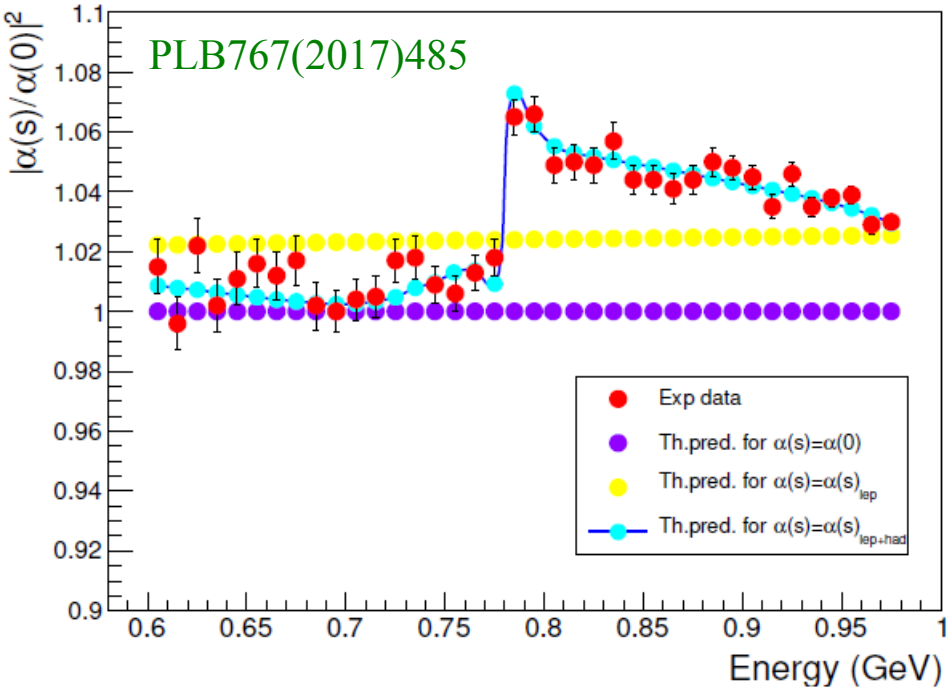
- $L = 1.7\ pb^{-1}$
- Main bckg: $e^+e^- \to \pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $e^+e^-\gamma$
- About 4.5×10^6 $\mu^+\mu^-\gamma$ events selected
- Residual bckg < 1%

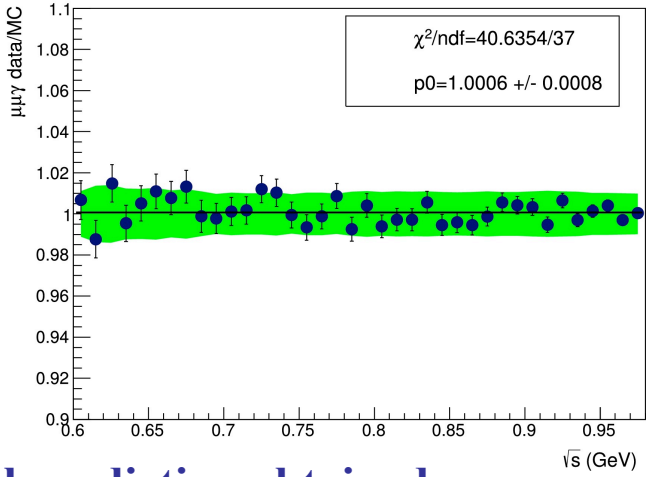
Measurement of α(s)

$$\frac{d\sigma(e^+e^- \to \mu^+\mu^-\gamma(\gamma))}{d\sqrt{s}} = \frac{N_{obs} - N_{bckg}}{\Delta\sqrt{s}} \times \frac{1-\delta_{FSR}}{\varepsilon(s)L}$$

- **Systematic uncert. ~ 1%**



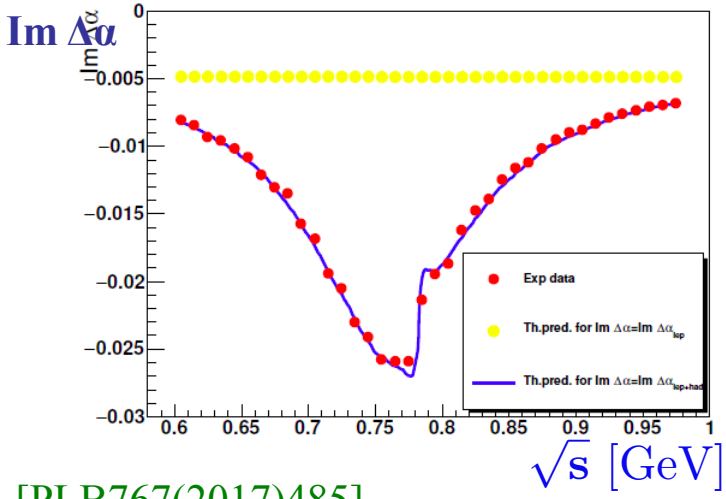




Theoretical prediction obtained from dispersion relations (F.Jegerlehner)

Re Δα and Im Δα

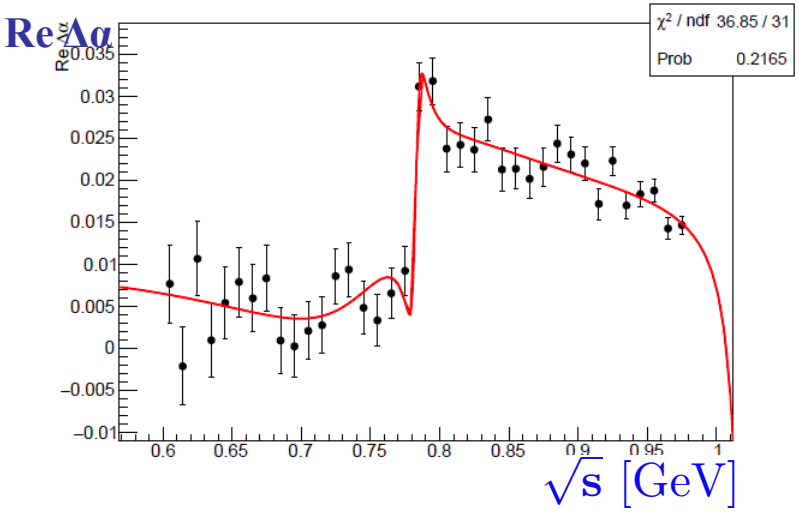
- Δα is complex in the time-like region
- Optical theorem: $\mathrm{Im}\ \Delta\alpha = -\frac{\alpha}{3}R(s)$
- Im Δα from $\sigma(e^+e^-\to\pi^+\pi^-)$ from KLOE data (theoretical curve from ππ compilation w\out KLOE)



[PLB767(2017)485]

$$\mathrm{Re}\ \Delta\alpha = \sqrt{|\alpha(0)/\alpha(s)|^2 - (\mathrm{Im}\ \Delta\alpha)^2}$$

- Fit: BW for ω(782) and ϕ(1020) + Gounaris-Sakurai param. for ρ(770) + non resonant term



	Fit	PDG
M_ρ [MeV]	775 ± 6	775.26 ± 0.25
Γ_ρ [MeV]	146 ± 9	147.0 ± 0.9
M_ω [MeV]	782.7 ± 1.1	782.65 ± 0.12
$Br(\omega\to\mu^+\mu^-)Br(\omega\to e^+e^-)$	$(4.3 \pm 1.8)\times 10^{-9}$	$(6.5 \pm 2.3)\times 10^{-9}$
χ^2/ndf	1.19	

$$Br(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4 \pm 1.7) \times 10^{-5}$$

(PDG: $(9.0 \pm 3.1) \times 10^{-5}$)

$\eta \to 3\pi$ and light quark masses

- **Strong decay, isospin violating, e.m. contribution negligible (Sutherland theorem)**

$$\mathcal{L} = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

- **The quark masses are free parameters of the theory, can be determined from experimental inputs**

$$\Gamma(\eta \to 3\pi) \propto |A(s,t,u)|^2 \propto Q^{-4}$$

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

$$[\hat{m} = \tfrac{1}{2}(m_u + m_d)]$$

(Dashen theorem: e.m. contribution to $K^0/K^\pm$ mass difference equal to the $\pi^0/\pi^\pm$ one ⇒ Q = 24.3 is expected)

- **Slow convergence of the χPT series**

$$\Gamma_{LO}(\eta \to 3\pi) = \quad 66 \text{ eV}$$

$$\Gamma_{NLO}(\eta \to 3\pi) = 160 - 210 \text{ eV}$$

$$\Gamma_{NNLO}(\eta \to 3\pi) = 230 - 270 \text{ eV}$$

⇒ Large ππ final state interactions

$$\Gamma(\eta \to \pi^+\pi^-\pi^0) = (300 \pm 12) \text{ eV}$$

$$\Gamma(\eta \to 3\pi^0) = (428 \pm 17) \text{ eV}$$

(from PDG)

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

- Taylor expansion around the center

$$X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta} \qquad Y = 3\frac{T_0}{Q_\eta} - 1$$

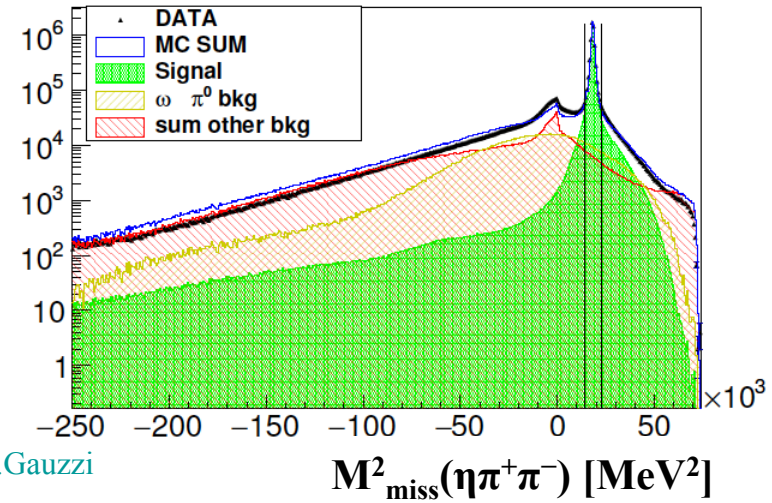
$$Q_\eta = M_\eta - 2M_{\pi\pm} - M_{\pi 0}$$

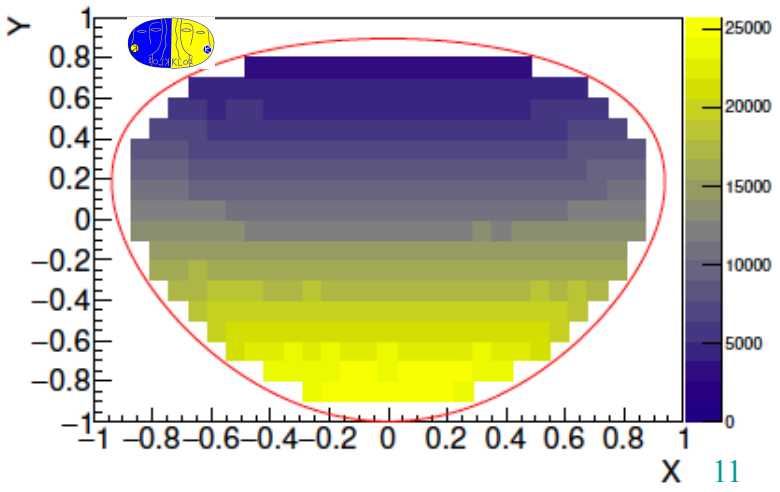
$$\Rightarrow \quad |A(X,Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots)$$

- Odd powers of X are C-violating ⇒ *c* and *e* are expected to vanish
- KLOE@DAΦNE: $e^+e^- \to \phi(1020) \to \eta\gamma$ with $\eta \to \pi^+\pi^-\pi^0$ ⇒ $\pi^+\pi^- + 3\gamma$

$L = 1.6\ fb^{-1}$ ⇒ 4.7×10^6 events

[JHEP1605(2016)019]

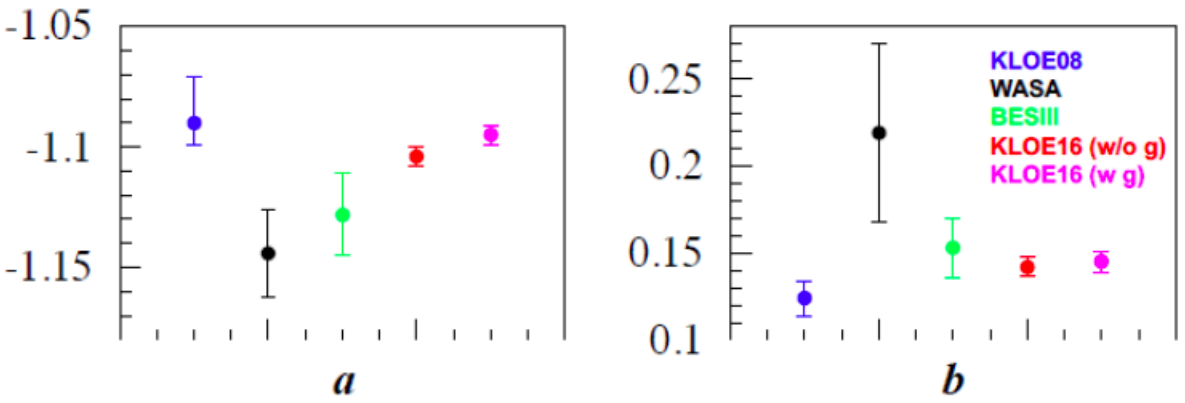




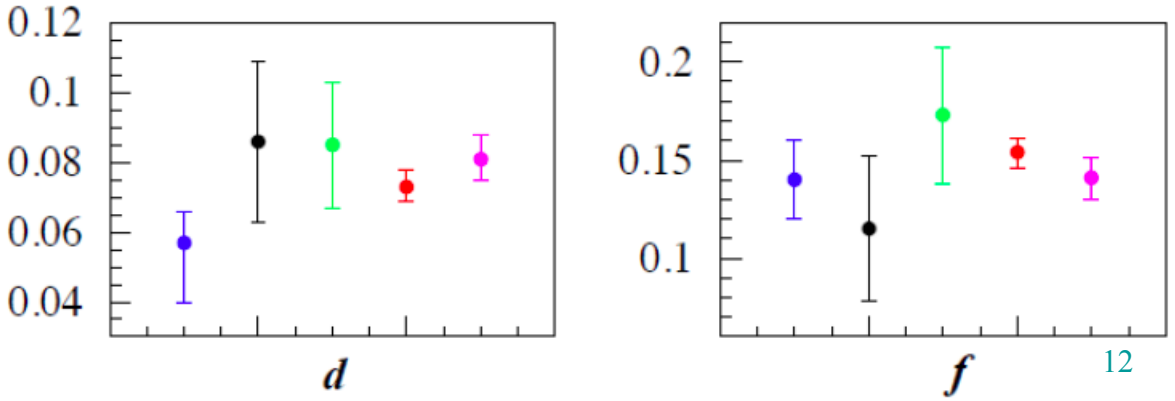
$\eta \to \pi^+\pi^-\pi^0$

	a	*b*	*d*	*f*	*g*
KLOE '16	−1.095 ± 0.004	0.145 ± 0.006	0.081 ± 0.007	0.141 ± 0.011	-0.044 ± 0.016
KLOE '16	−1.104 ± 0.004	0.142 ± 0.006	0.073 ± 0.005	0.154 ± 0.008	–
KLOE '08	-1.090 ± 0.020	0.124 ± 0.012	0.057 ± 0.017	0.14 ± 0.02	
WASA '14	-1.144 ± 0.018	0.219 ± 0.051	0.086 ± 0.023	0.115 ± 0.037	
BESIII '15	-1.128 ± 0.017	0.153 ± 0.017	0.085 ± 0.018	0.173 ± 0.035	

- KLOE '16 sensitive also to *g* parameter
- ⇒ *c* and *e* parameters compatible with zero



Next: Fit to the amplitude, instead of amplitude squared ⇒ in progress

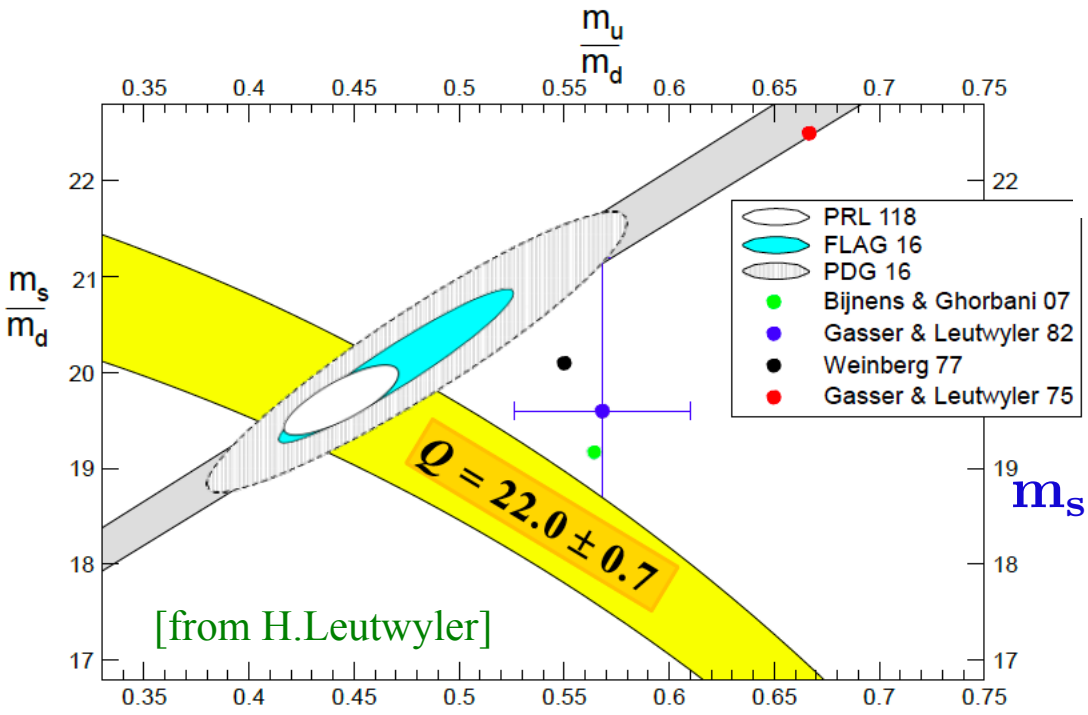


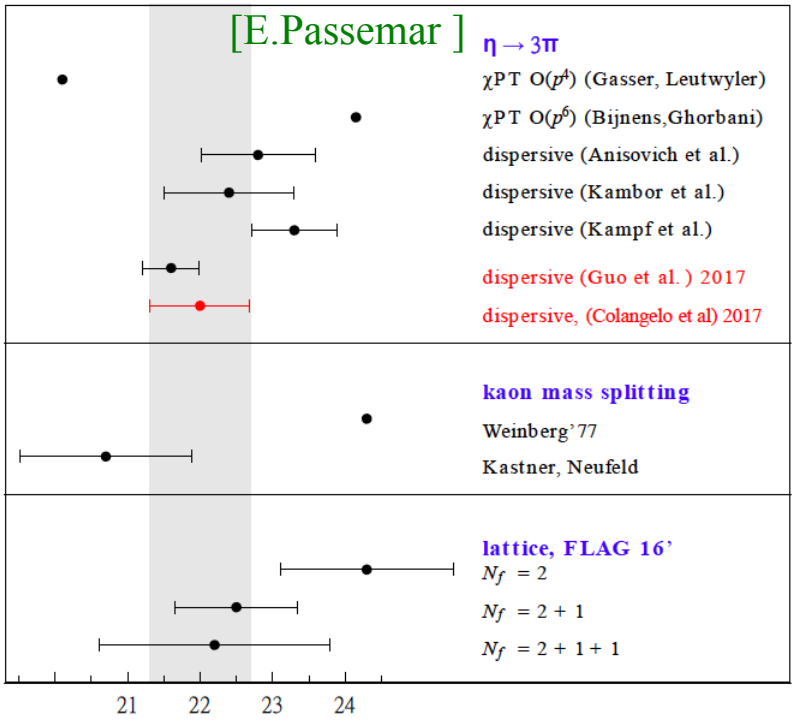
Light quark masses

- **Dispersive methods make use of fits to the experimental Dalitz Plots to derive the subtraction constants, and to obtain the Q ratio**

⇒ Q= 22.0 ± 0.7

[G.Colangelo et al,PRL118(2017)022001]





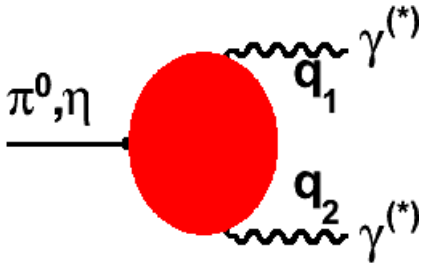
Combining with lattice QCD, one can obtain the quark mass ratios

$$m_s/\hat{m} = 27.30 \pm 0.34 \text{ (latt. QCD)}$$

$$\Rightarrow m_u/m_d = 0.44 \pm 0.03$$

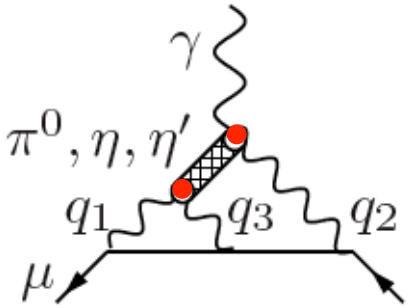
[G.Colangelo et al.]

Transition Form Factors



$\mathcal{F}_{P\gamma\gamma}(q_1^2, q_2^2)$

- **Transition Form Factors describe the coupling to photons and provide information about the nature of mesons**

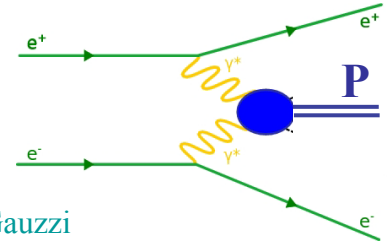


- **TFFs are related to the $a_\mu = (g_\mu - 2)/2$ discrepancy (> 3 σ) Hadronic LbL scattering is dominated by the exchange of single pseudoscalar mesons**

- **TFFs are accessible at KLOE/KLOE-2 both for time-like and space-like q^2**

  - Time-like ⇒ Dalitz decays: $\phi \to \eta e^+e^-$; $\phi \to \pi^0 e^+e^-$

  - Space-like ⇒ γγ processes (KLOE-2: $\gamma^*\gamma^* \to \pi^0$ with taggers to reduce bckg)



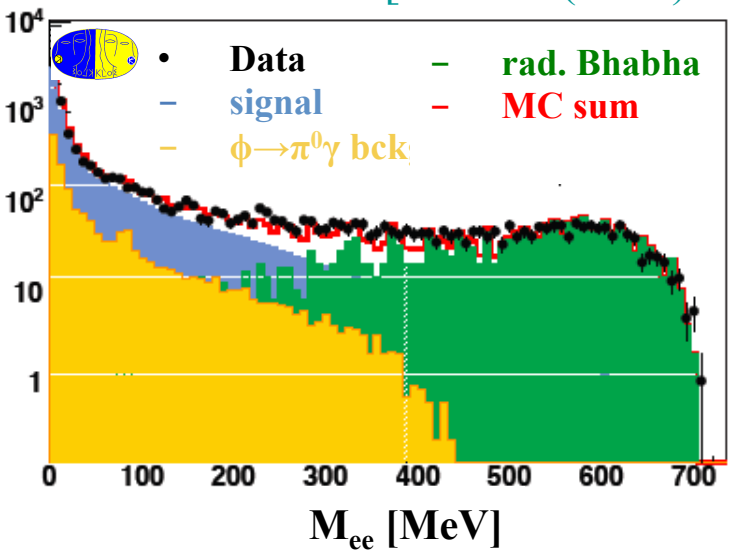
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-\mathrm{P} \quad [\mathrm{C(P)} = +1]$$

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

[PLB757(2016)362]

- KLOE: Events with 2 tracks + 2 prompt γ
- ~ 8.8 × 10^3 events selected
- Background: radiative Bhabha scattering

  $\phi \to \pi^0\gamma$ with photon conversion



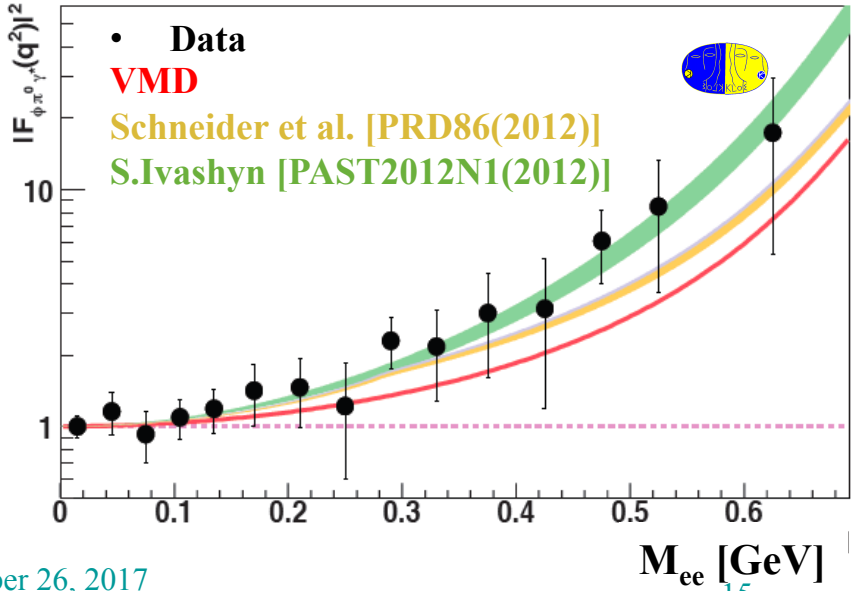
$$BR(\phi \to \pi^0 e^+ e^-) = (1.35 \pm 0.05^{+0.05}_{-0.10}) \times 10^{-5}$$

SND:BR($\phi \to \pi^0 e^+ e^-$) = (1.01±0.28±0.29)×10^{-5}

CMD-2: BR = (1.22 ± 0.34 ± 0.22)×10^{-5}

$$\Lambda^{-2} = (2.02 \pm 0.11)\ \text{GeV}^{-2}$$

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$



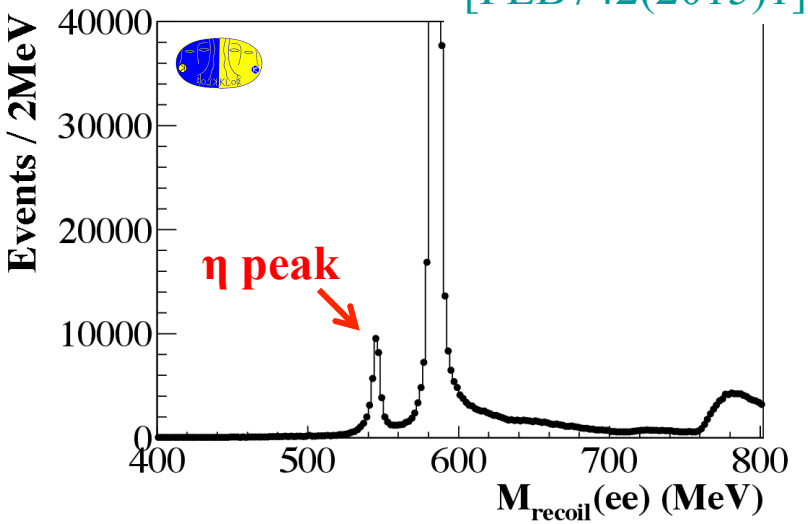
$\phi \to \eta e^+e^-$ TFF

[PLB742(2015)1]

- **KLOE:** ~ 30000 $\phi \to \eta e^+e^-$, $\eta \to \pi^0\pi^0\pi^0$

⇒ 2 tracks + 6 prompt γ's

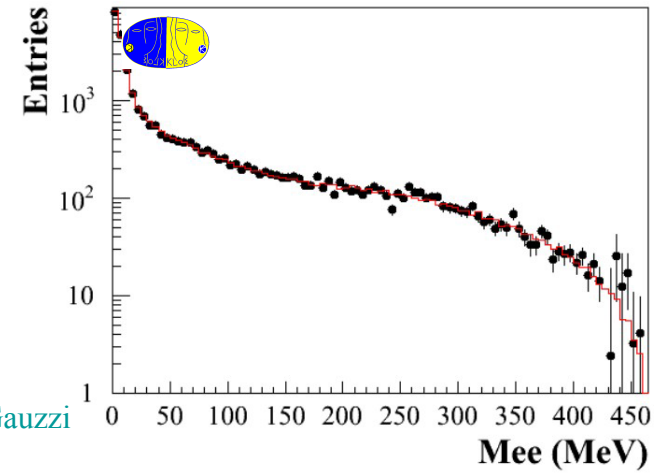
$$BR(\phi \to \eta e^+e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$$

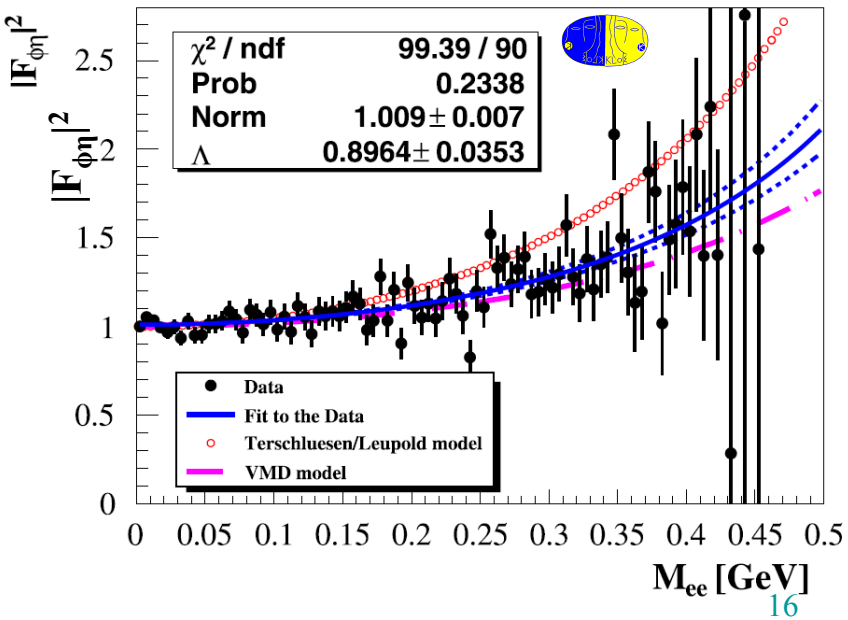


Previous measurement from Novosibirsk VEPP-2M
SND: $(1.19 \pm 0.19 \pm 0.12)\times10^{-4}$ [PLB504(2001)275]
CMD2: $(1.14\pm0.10 \pm 0.06)\times10^{-4}$ [PLB501(2001)191]

$$\Lambda^{-2} = (1.28 \pm 0.10^{+0.09}_{-0.08})\text{GeV}^{-2}$$

SND: (3.8 ± 1.8) GeV^{-2}; VMD: $\Lambda^{-2} \approx M_\phi^{\,2} \sim 1$ GeV^{-2}





Prospects for KLOE-2

Large sample of ϕ mesons ($N_\phi \approx 15\times10^9$):

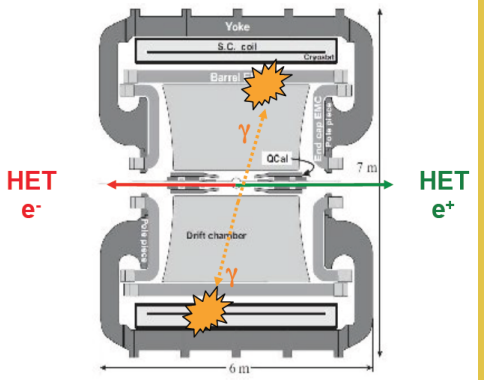
- Improve $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$
- Measurement of $\phi \to \eta\mu^+\mu^-$, $\phi \to \eta\pi^+\pi^-$

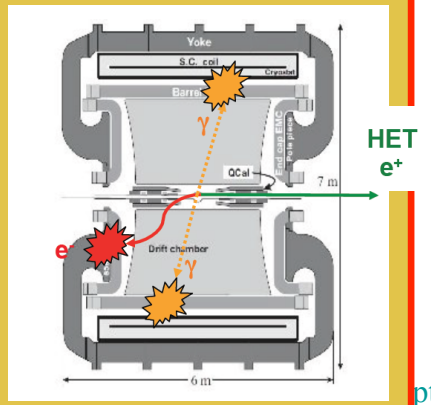
Rare η decays ($N_\eta \approx 2.5\times10^8$):

- $\eta \to \pi^0\gamma\gamma$ ($O(p^6)$ in ChPT)
- $\eta \to 4$ tracks ($\pi^+\pi^-e^+e^-$, $e^+e^-e^+e^-$, $\mu^+\mu^-e^+e^-$, $\pi^+\pi^-\mu^+\mu^-$)
- improve limits on $\eta \to \gamma\gamma\gamma$, $\pi^+\pi^-$

$\gamma^*\gamma^* \to \pi^0$: 2γ in EMC + e^+/e^- in the taggers

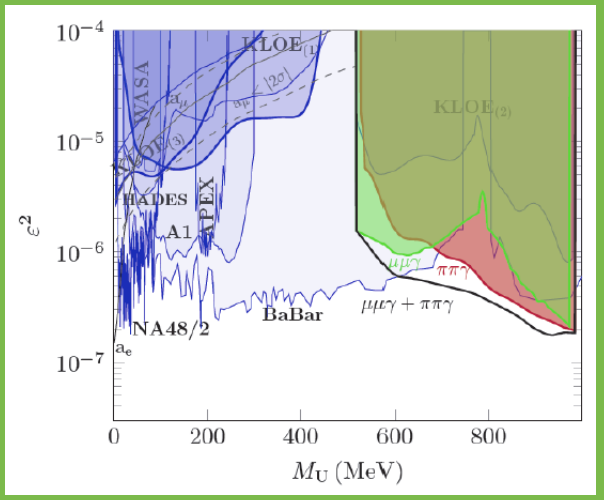
$\Rightarrow \Gamma(\pi^0\to\gamma\gamma)$; $\mathcal{F}_{\pi\gamma\gamma^*}(q^2,0)$ ($|q^2|< 0.1$ GeV^2)





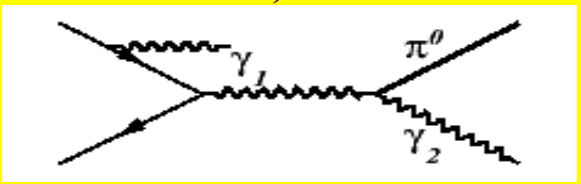
Dark Forces searches

- **Improve limits on Dark Photons:**
  $\phi\to\eta U$, $e^+e^- \to U\gamma$; $U\to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$



- **Search for a leptophobic B-boson, coupling to quarks**
  $\phi\to\eta B$, or $\eta\to B\gamma$, with $B\to\pi^0\gamma$

$e^+e^- \to \pi^0\gamma+\gamma_{ISR}$
(π^0 Transition Form Factor)



Conclusions

- **KLOE is continuing to exploit the high statistics data samples collected at DAΦNE to perform precision measurements in hadron physics:**
  - **running of α, real and imaginary part of Δα**
  - **precise measurement of the DP parameters of $\eta \to \pi^+\pi^-\pi^0$**
    ⇒constraints on the light quark masses
  - **Transition Form Factors in Dalitz decays, $\phi \to \pi^0 e^+e^-$, $\phi \to \eta e^+e^-$**
- **KLOE-2 will collect data until March 2018, L ~ 5 fb^{-1}**

⇒ we will continue the precision study of the light meson properties with increased statistics

Spare slides

KLOE-2 Physics

Kaon Physics:
- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of Im(ε′/ε)
- CKM V_{us}:
  K_S semileptonic decays and A_S
  (CP and CPT test)
  $K_{\mu 3}$ form factors, K_{l3} radiative corrections
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section:
- ISR studies with 3π, 4π final states
- F_π with increased statistics
- Measurement of a_μ^{HLO} in the space-like region using Bhabha process

Dark force searches:
- Improve limits on
  - Uγ associate production
    $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
  - Higgsstrahlung:
    $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- Leptophobic B boson search:
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Light meson Physics:
- η decays, ω decays
- Transition Form Factors
- C,P,CP violation: improve limits on
  $\eta \to \gamma\gamma\gamma, \pi^+\pi^-, \pi^0\pi^0, \pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \to K_S K_S \gamma$
- γγ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
- $e^+e^- \to \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)
- search for axion-like particles

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

- **Amplitude symmetric for the exchange of the pions**

$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q_\eta} - 1\right)^2 \quad \Rightarrow \quad |A(Z)|^2 = N(1 + 2\alpha Z + \ldots)$$

($\alpha = 0$ in χPT @ LO)

- **KLOE@DAΦNE ('10):**

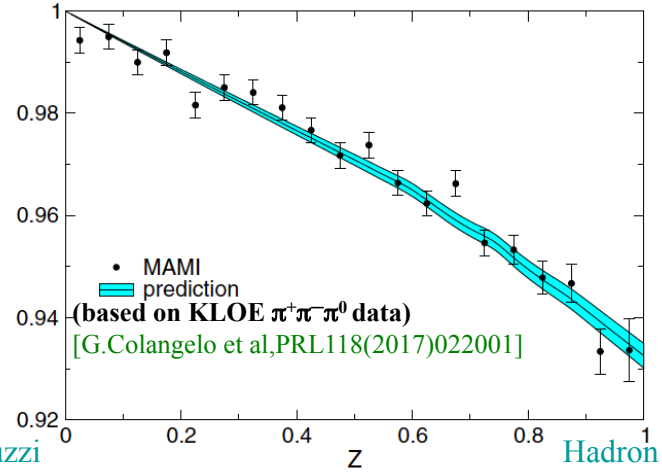
  $e^+e^- \to \phi \to \eta\gamma$ **with** $\eta \to \pi^0\pi^0\pi^0$

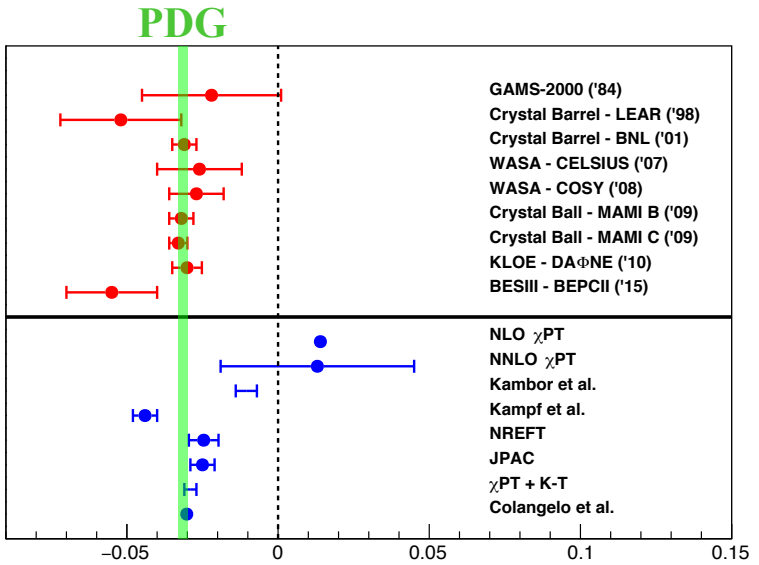
  L = 420 pb^{-1} $\Rightarrow \sim 5 \times 10^5$ events

$$\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0035}$$

[PLB694(2011)16]

- **Dispersive approaches predict a negative slope**





Dalitz Plot asymmetries

- Asymmetries ⇔ C violation ⇒ all consistent with zero

Left-Right asymmetry
(*c* and *e* parameters)

$$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11.0}) \times 10^{-4}$$

Quadrant asymmetry
$\not{C}$ in $\Delta I = 2$

$$A_Q = (1.8 \pm 4.5^{+4.8}_{-2.3}) \times 10^{-4}$$

Sextant asymmetry
$\not{C}$ in $\Delta I = 1$

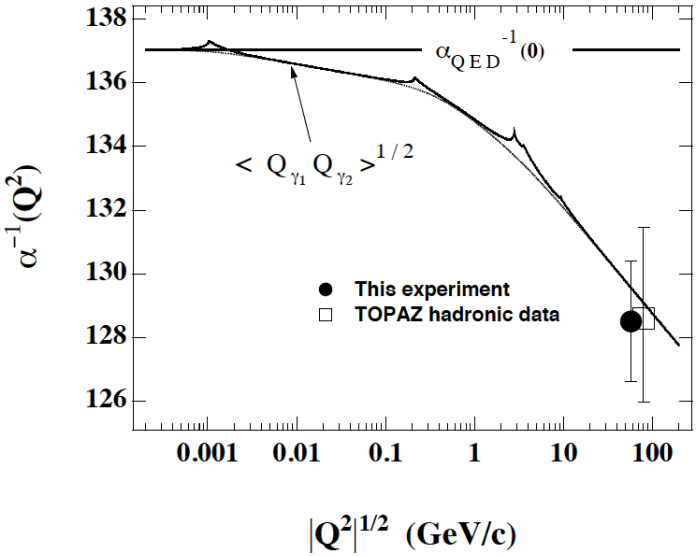
$$A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \times 10^{-4}$$

[JHEP1605(2016)019]

Running of α(s)

- **Previuos measurements**

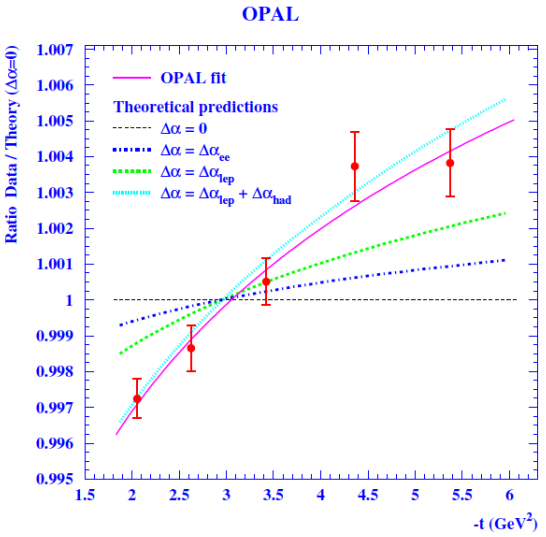
@ TRISTAN, √s = 57.8 GeV



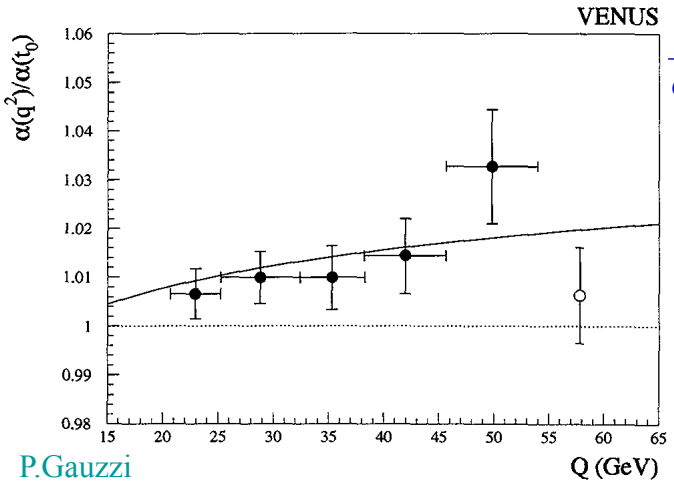
$$\frac{e^+e^- \to \mu^+\mu^-}{e^+e^- \to e^+e^-\mu^+\mu^-}$$

time-like

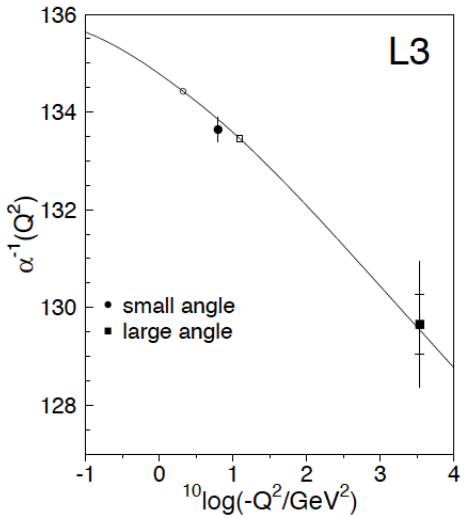
@ LEP, √s =189 GeV



space-like

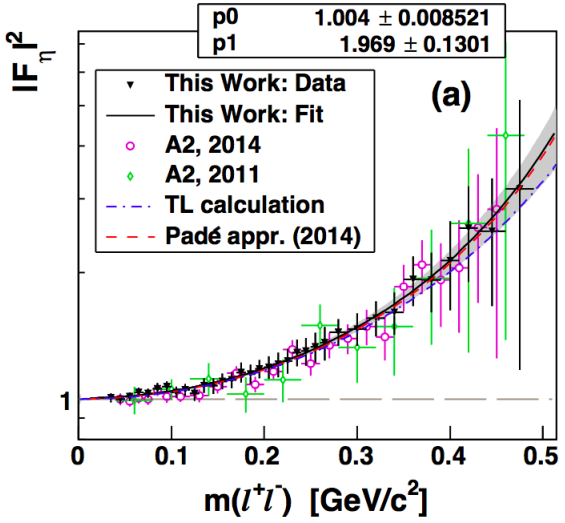


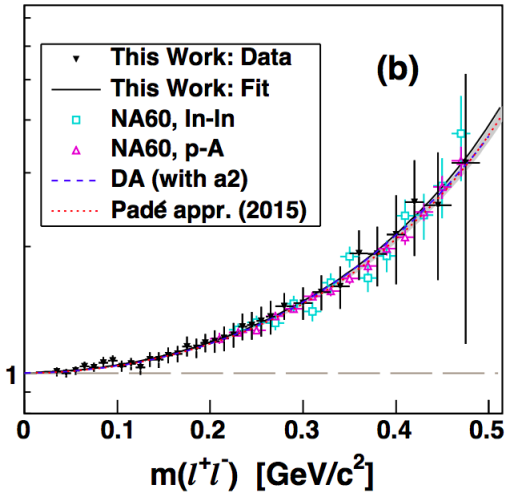
$$\frac{e^+e^- \to e^+e^-}{e^+e^- \to \mu^+\mu^-}$$

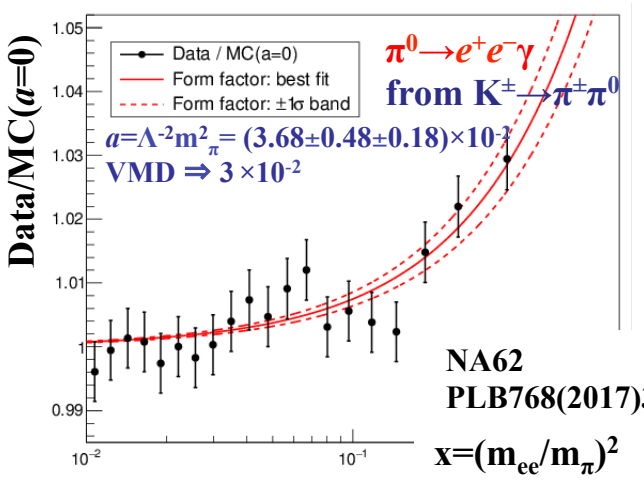


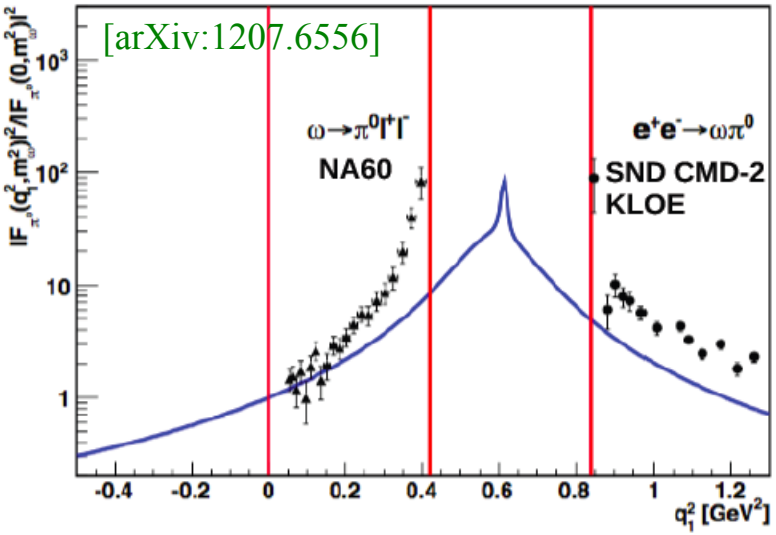
Time-like TFFs from Dalitz decays

- $P \to V\ell^+\ell^-$ or $V \to P\ell^+\ell^-$; q^2 = invariant mass of the lepton pair









$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

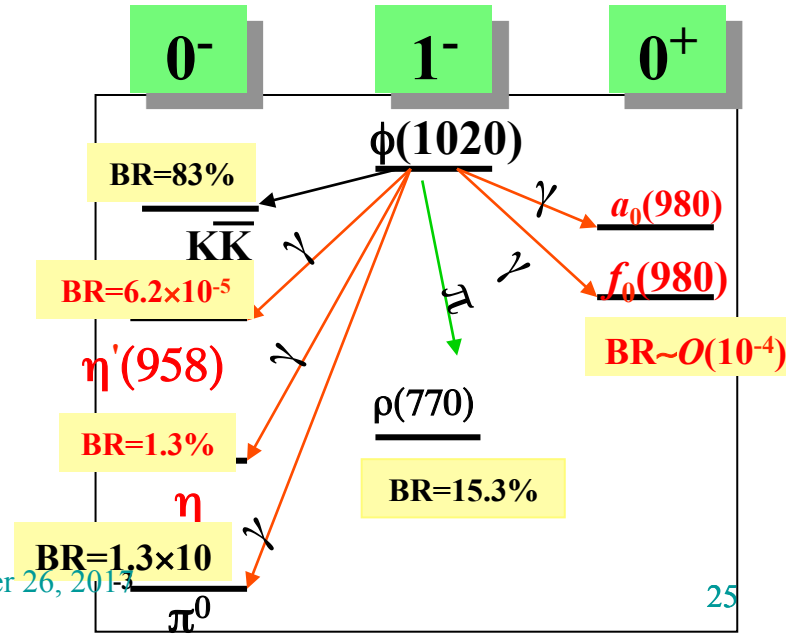
$\eta \to e+e-\gamma/\mu+\mu-\gamma$	Λ^{-2} [GeV^{-2}]	VMD
A2@MAMI	1.97 ± 0.13	1.83
NA60 (p-A)	1.934 ± 0.067 ± 0.050	
$\pi0 \to e+e-\gamma$		
NA62	2.03 ± 0.29 ± 0.20	1.7
$\omega \to \pi0\mu+\mu-/\pi0e+e-$		
NA60 (p-A)	2.223 ± 0.026 ± 0.037	1.68
A2@MAMI	1.99 ± 0.22	

Physics at a ϕ-factory

- **Kaon physics: $|V_{us}|$ and CKM unitarity, CP and CPT violation, rare decays, ChPT tests, quantum mechanics tests**
- **Scalar and pseudoscalar mesons in ϕ radiative decays and in $\gamma\gamma$ collisions**
  - $\eta \to 3\pi$ $\Rightarrow$ Constraints on light quark masses
  - $\eta\,(\eta') \to \pi^+\pi^-\gamma$ $\Rightarrow$ Study of the box anomaly
  - $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$ $\Rightarrow$ Transition Form Factors
    $\Rightarrow$ Search for light dark photons (U-Bosons)
  - $e^+e^- \to e^+e^-\eta\,(\pi^0)$ $\Rightarrow$ $\gamma\gamma \to \eta\,(\pi^0)$; Two-photon partial width
    $\Rightarrow$ Transition Form Factors

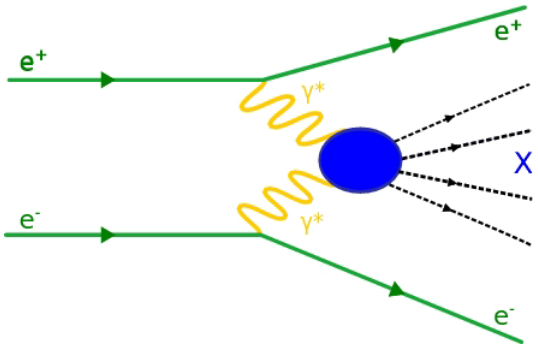
- **Hadronic cross-section via ISR $[e^+e^- \to \gamma\,(\pi^+\pi^-)]$: hadronic corrections to $(g\text{-}2)_\mu$**

Decay channel	Events (2.5 fb^{-1})
K^+K^-	3.7×10^9
K_LK_S	2.5×10^9
$\rho\pi + \pi^+\pi^-\pi^0$	1.1×10^9
$\eta\gamma$	9.7×10^7
$\pi^0\gamma$	9.4×10^6
$\eta'\gamma$	4.6×10^5
$\pi\pi\gamma$	2.2×10^6
$\eta\pi^0\gamma$	5.2×10^5

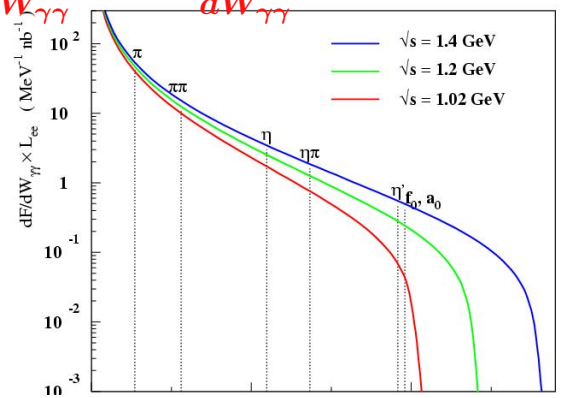


γγ physics @ KLOE

$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^- X \qquad [C(X) = +1]$$



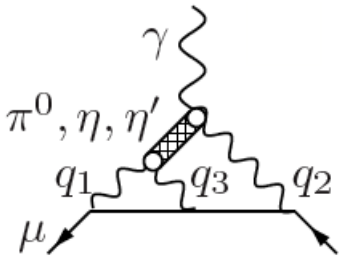
$$\frac{dN}{dW_{\gamma\gamma}} = L_{int}\frac{dF}{dW_{\gamma\gamma}}\sigma(\gamma\gamma \to X)$$



- **X = ππ ⇒ study of $f_0(500)$**
- **X = π^0 ⇒ Two-photon width Γ($\pi^0 \to \gamma\gamma$)**
  Transition form factor $\mathcal{F}_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2
  (constraints to the HLbL contribution to $(g-2)_\mu$)

X = η ⇒ Γ(η→γγ)=(520±20±13) eV, measured off-peak w/out taggers [JHEP01(2013)119]

- **KLOE-2 run at M_ϕ ⇒Large bckg from φ decays + bckg from continuum**



γγ process

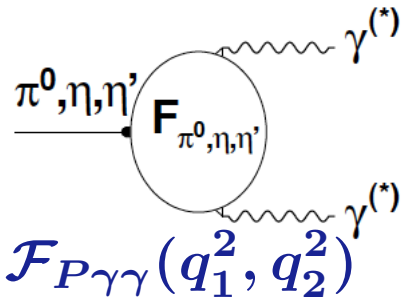
channel	Total Production (L = 10 fb^{-1})
$e^+e^- \to e^+e^-\pi^0$	4×10^6
$e^+e^- \to e^+e^-\eta$	10^6
$e^+e^- \to e^+e^-\pi^+\pi^-$	2×10^6
$e^+e^- \to e^+e^-\pi^0\pi^0$	2×10^4

φ decays

decay mode	esc.particle	events	bckg to:
$K_S(\pi^0\pi^0)\,K_L$	K_L	~ 10^9	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)\,K_L$	K_L	~ 2×10^9	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	~ 10^9	
$\eta(\gamma\gamma)\,\gamma$	γ	~ 10^8	η
$\pi^0(\gamma\gamma)\,\gamma$	γ	~ 5×10^8	π^0

Tagging needed to reduce background

Transition Form Factors



- **Transition Form Factors describe the coupling to photons and are important for the understanding of the nature of mesons**

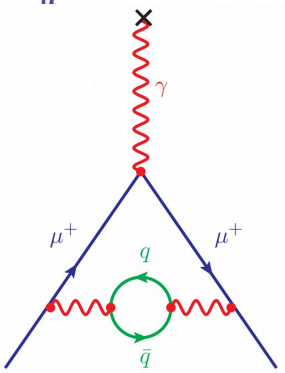
- $a_\mu^{exp} - a_\mu^{SM} = (31.25 \pm 8.54) \times 10^{-10} \Rightarrow \sim 3.7\,\sigma$ discrepancy $[a_\mu = (g_\mu - 2)/2]$

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$ → main contribution to the uncert. on a_μ^{SM}

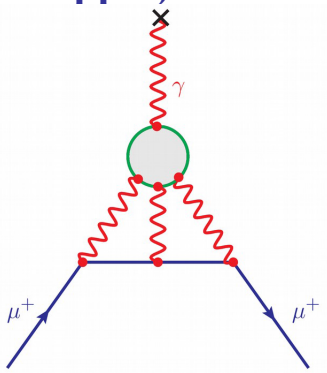
(future g-2 expts at FNAL and J-PARC goal: reduce the uncert. on a_μ^{exp} from 0.54 to 0.14 ppm)

- **The main contribution to a_μ^{had} is the Hadronic Vacuum Polarization, but the second one is the Hadronic Light-by-Light scattering**

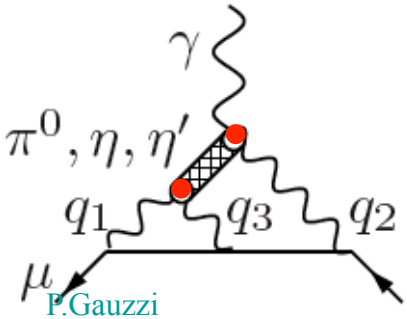
($a_\mu^{LbL} = (11.6 \pm 3.9) \times 10^{-10}$ [Jegerlehner-Nyffeler P.Rep.477(2009)])



Vac. pol.



HLbL



The HLbL scattering is dominated by the exchange of single pseudoscalar mesons (in particular single π^0) ⇒TFFs, but off-shell mesons