Recent results on light pseudoscalar mesons

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Outline

- Introduction
- Masses of light quarks from $\eta \rightarrow 3\pi$ decays
- Transition Form Factors (space-like and time-like)
- Dark Photon searches involving pseudoscalar mesons
- Conclusions

Introduction

- **Light pseudoscalar mesons offer a unique possibility to test symmetries and symmetry breaking mechanisms in QCD at low energy**

- **Strong and e.m. interactions of the pseudoscalars are generally described by Chiral Perturbation Theory (χPT) and its extensions**
  ⇒ Octet of quasi-Goldstone bosons, π, η, K mesons, from spontaneous breaking of chiral symmetry + the singlet η′(958)

- **Large samples of pseudoscalar mesons are available from experiments at e^+e^- colliders (KLOE@DAΦNE, BESIII@BEPCII, SND and CMD-3 at VEPP2000, BaBar and Belle at the B-Factories), from fixed target (WASA@COSY) and also from photoproduction experiments (CLAS@JLAB, A2@MAMI) , …**

  ⇒ precision measurements can be done

$\eta \rightarrow 3\pi$ 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 ⇒ Large ππ final state interactions

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

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

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

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

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

(from PDG)

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

- **Taylor expansion around the center**

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

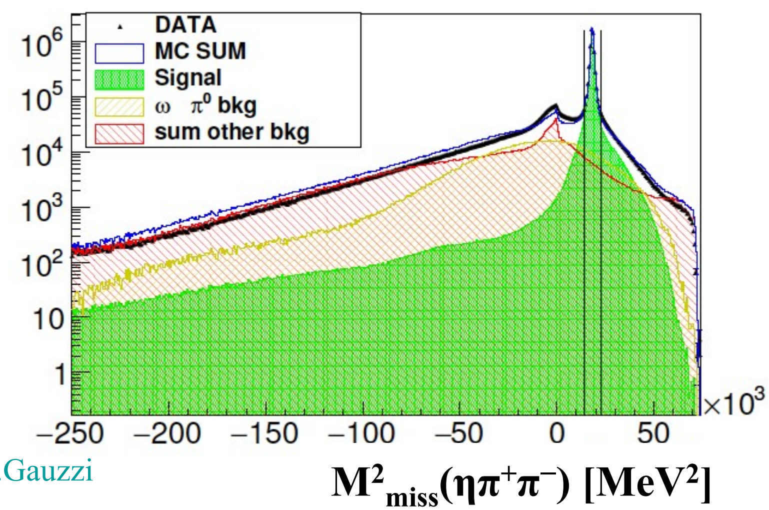
$$Q_\eta = M_\eta - 2M_{\pi^\pm} - M_{\pi^0}$$

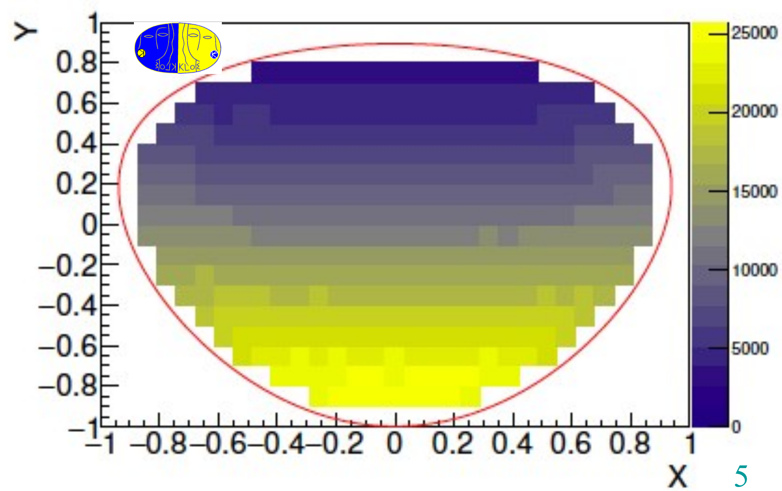
$$\Rightarrow \quad |A(X,Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots)$$

- **Odd powers of X are C-violating ⇒ *c* and *e* are expected to vanish**

- **KLOE@DAΦNE: $e^+e^- \rightarrow \phi(1020) \rightarrow \eta\gamma$ with $\eta \rightarrow \pi^+\pi^-\pi^0$ ⇒ $\pi^+\pi^- + 3\gamma$**
L = 1.6 fb^{-1} ⇒ 4.7 × 10^6 events

[JHEP1605(2016)019]

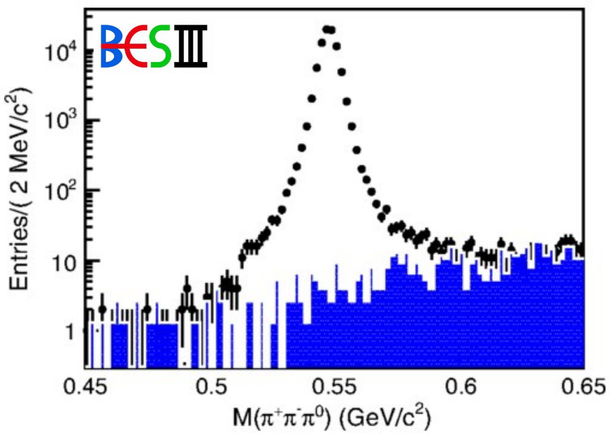


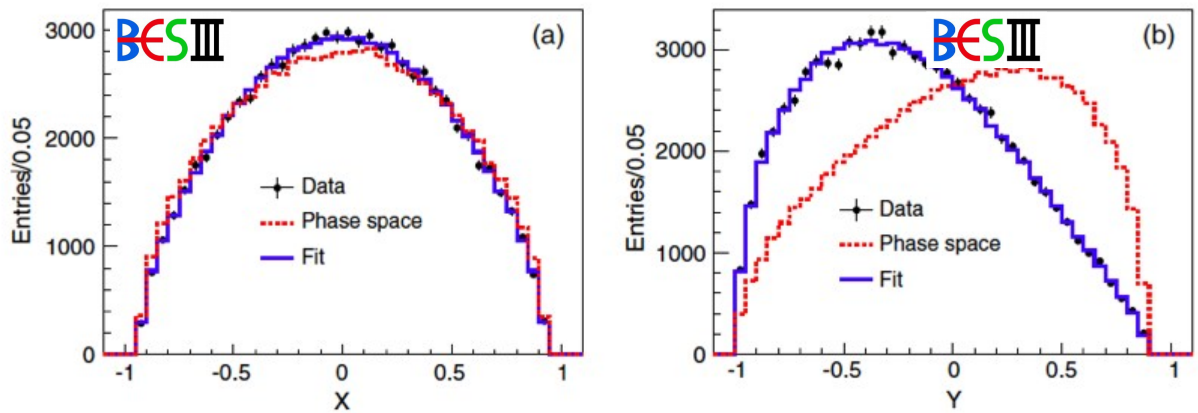


$\eta \to \pi^+\pi^-\pi^0$ Dalitz Plot

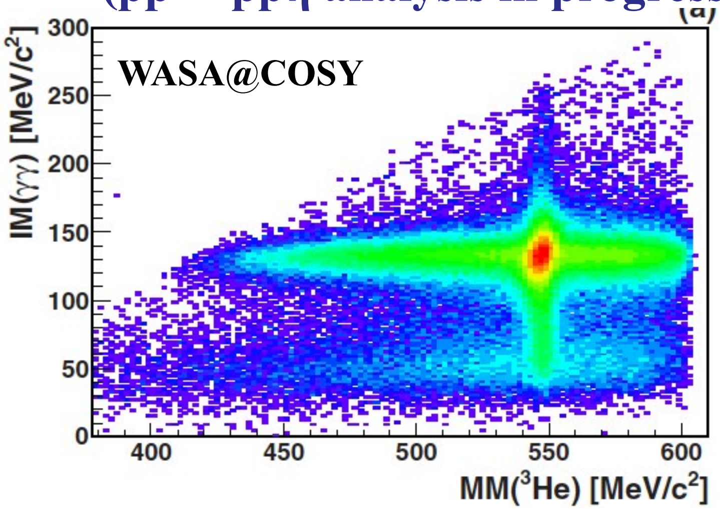
- **BESIII@BEPCII:** $e^+e^- \to J/\psi \to \eta\gamma$ **with** $\eta \to \pi^+\pi^-\pi^0$ $\Rightarrow \pi^+\pi^- + 3\gamma$ **final state**

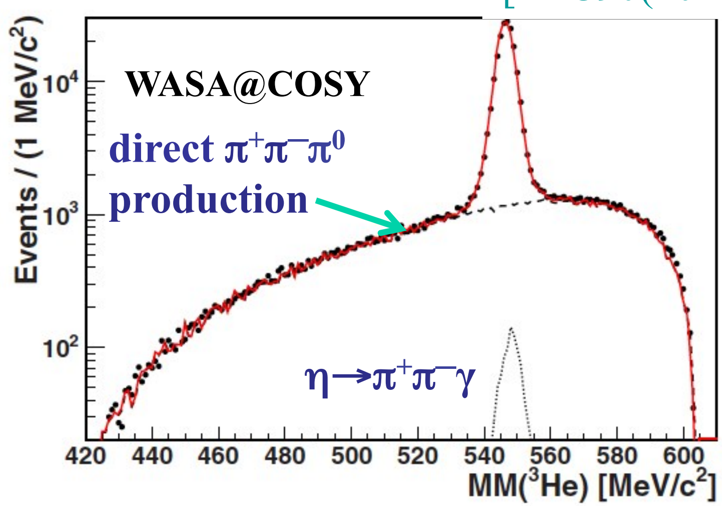
L = ~ 80000 events from a sample of 1.31 × 10⁹ J/ψ produced [PRD92(2015)012014]





- **WASA@COSY:** $pd \to {}^3He\,\eta$, **with** $\eta \to \pi^+\pi^-\pi^0$ **@ 1 GeV, 1.74×10⁵ η candidates (pp→ ppη analysis in progress)** [PRC90(2014)045207]





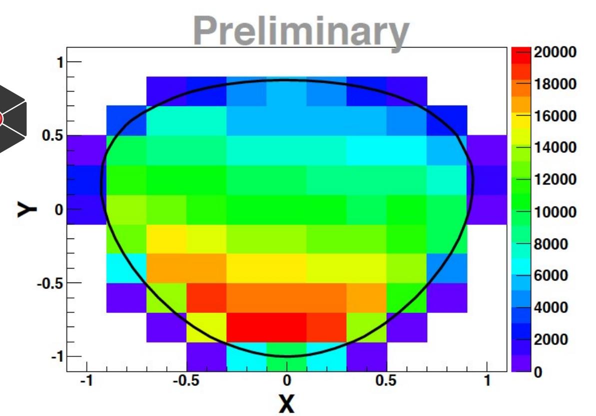
$\eta \rightarrow \pi^+\pi^-\pi^0$

	a	*b*	*d*	*f*	*g*
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	-1.095 ± 0.004	0.145 ± 0.006	0.081 ± 0.007	0.141 ± 0.011	-0.044 ± 0.016
NNLO χPT	-1.271 ± 0.075	0.394 ± 0.102	0.055 ± 0.057	0.025 ± 0.160	
NREFT	-1.213 ± 0.014	0.308 ± 0.023	0.050 ± 0.003	0.083 ± 0.019	-0.039 ± 0.002
JPAC	-1.117 ± 0.035	0.188 ± 0.014	0.079 ± 0.003	0.090 ± 0.003	-0.063 ± 0.012
χPT + K-T eq.	-1.147 − -1.154	0.181 − 0.202	0.107 − 0.116	0.088 − 0.90	

- ⇒ $c = 0.002 \pm 0.003 \pm 0.001$; $e = -0.006 \pm 0.007 \pm 0.005$ (KLOE ‘08)
- Experiments agree within the uncertainties
- KLOE ‘16 sensitive also to g parameter
- χPT is not able to reproduce all the DP parameters
- Better agreement with models that combine χPT and dispersion relations to treat ππ final state interactions

- New measurement in progress at CLAS@JLAB with g12 data set, ~ 10^6 events expected

[Kunkel, MESON2016]



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[Bijnens-Ghorbani, JHEP11(2007)030
Schneider et al., arXiv:1010.3946
Guo et al., arXiv:1608.01447
Albaladejo-Moussallam PoS(CD15)057

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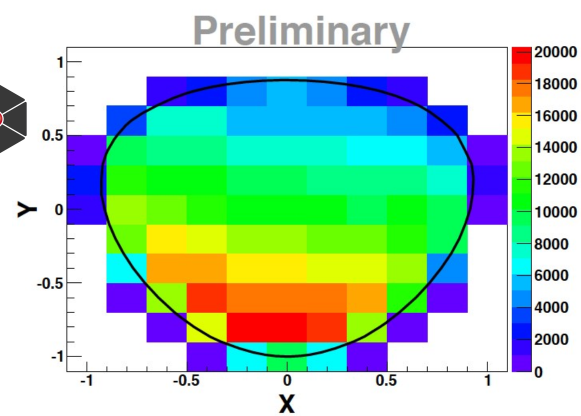


- New measurement in progress at CLAS@JLAB with g12 data set, ~ 10^6 events expected

[Kunkel, MESON2016]

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

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

$$Z = X^2 + Y^2 = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3T_i}{Q_\eta} - 1\right)^2 \qquad Q_\eta = M_\eta - 3M_{\pi^0}$$

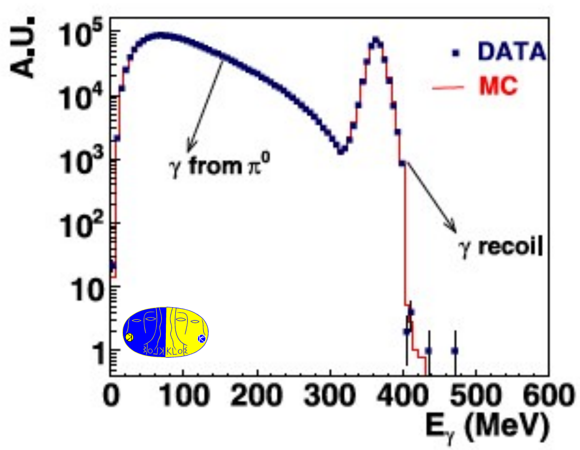
$\Rightarrow$ $|A(Z)|^2 = N(1 + 2\alpha Z + \ldots)$ **(α = 0 in χPT @ LO)**

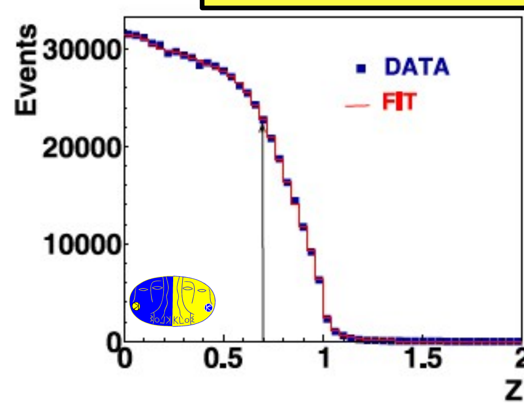
[PLB694(2010)16]

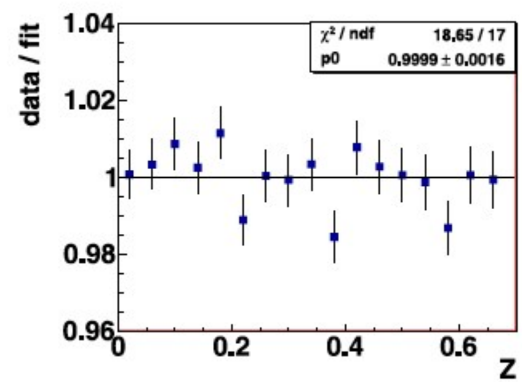
- **KLOE@DAΦNE ('10):** $e^+e^- \to \phi \to \eta\gamma$ **with** $\eta \to \pi^0\pi^0\pi^0$**, 7 prompt γ final state**

L = 420 pb^{-1} $\Rightarrow$ ~ 5 × 10^5 events

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

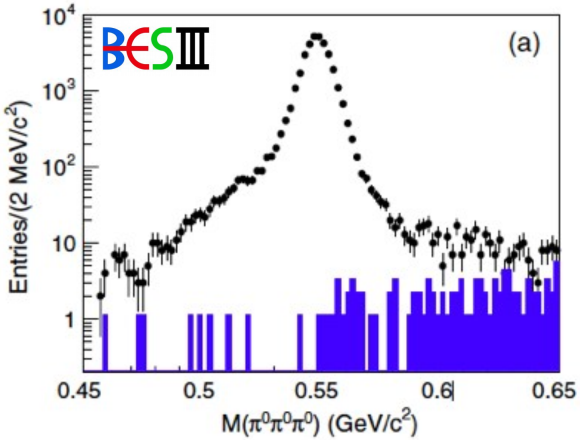


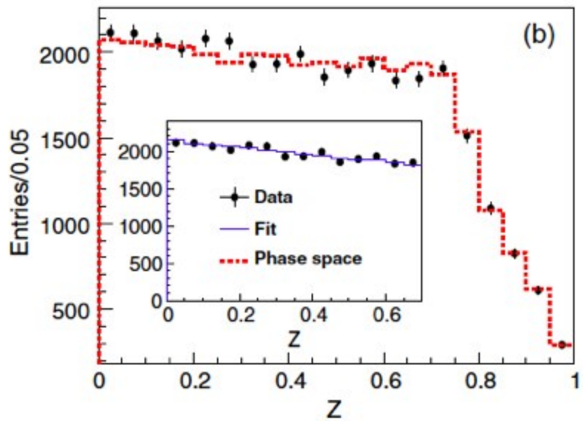




$\eta \to \pi^0\pi^0\pi^0$

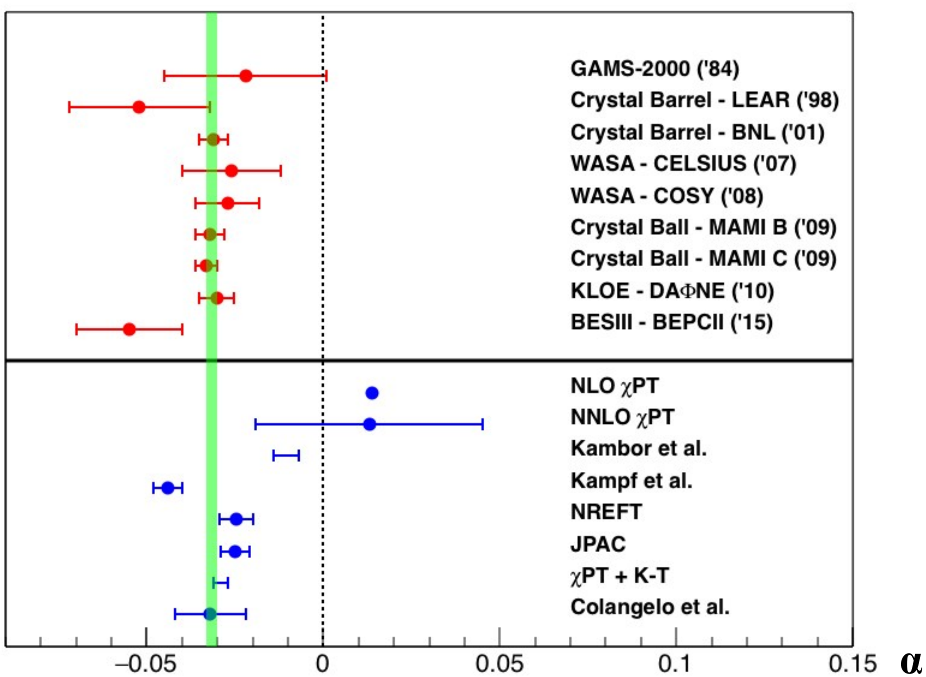
- **BESIII@BEPCII:** $e^+e^- \to J/\psi \to \eta\gamma$ **with** $\eta \to \pi^0\pi^0\pi^0$**, ~ 34000 events**





[PRD92(2015)012014]

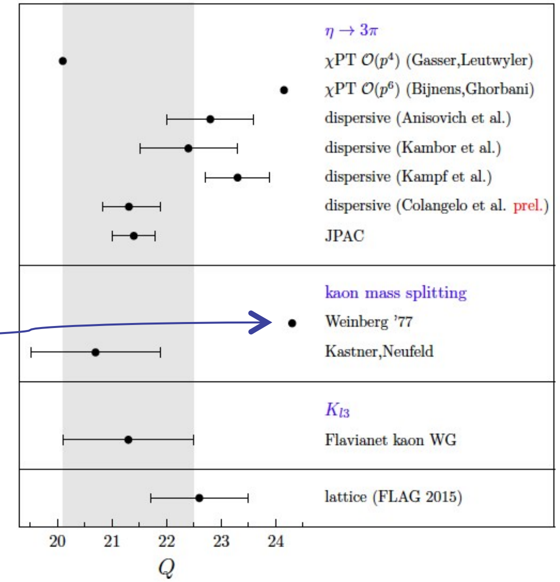
$$\alpha = -0.055 \pm 0.014 \pm 0.004$$



- **χPT is not able to obtain a negative slope**
- **Again better agreement with dispersive approaches**

Light quark masses

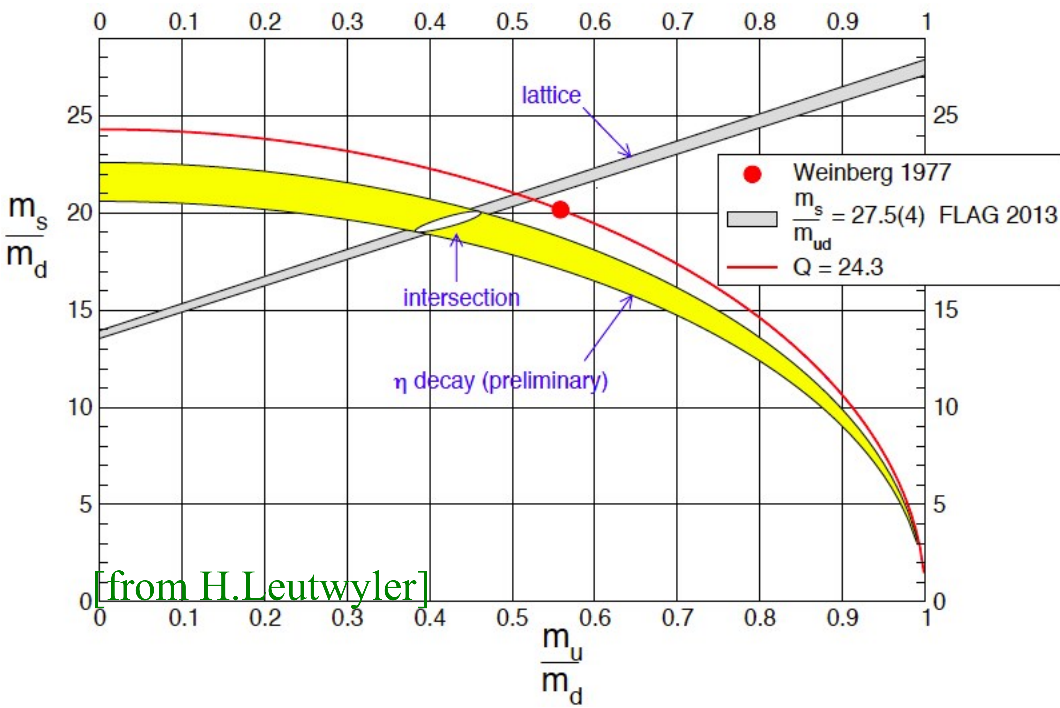
- Dispersive methods make use of fits to the experimental Dalitz Plots to derive the subtraction constants, and to obtain the Q ratio

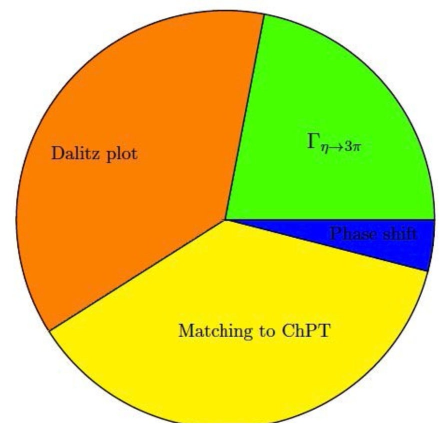


(violation of Dashen theorem Q_{Dash}=24.3)

[E.Passemar – Meson 2016]

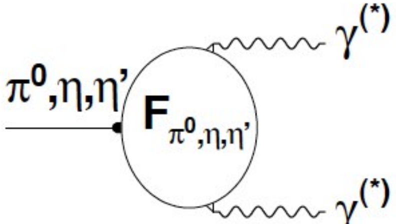
Combining with lattice QCD information one can obtain the quark mass ratios





Uncert. on Q based on fit to KLOE('08)
Future expts. can reduce the errors (JEF at JLAB)

Transition Form Factors and $(g\text{-}2)_\mu$



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

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

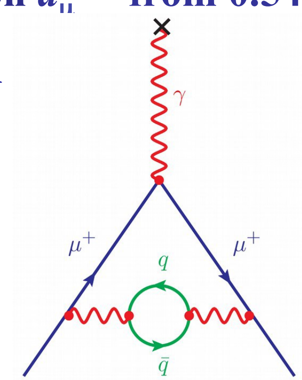
- **$a_\mu^{exp} - a_\mu^{SM} = (31.25 \pm 8.54)\times 10^{-10} \Rightarrow \sim 3.7\ \sigma$ discrepancy [$a_\mu = (g_\mu-2)/2$]**

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

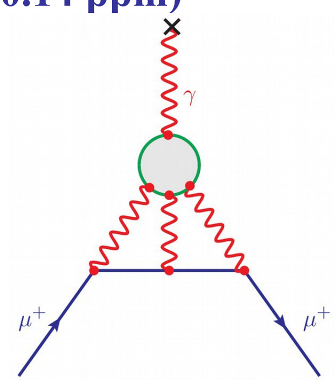
(future g-2 expts at FNAL and J-PARC goal: reduce the uncert. on a_μ^{exp} from 0.54 to 0.14 ppm)

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

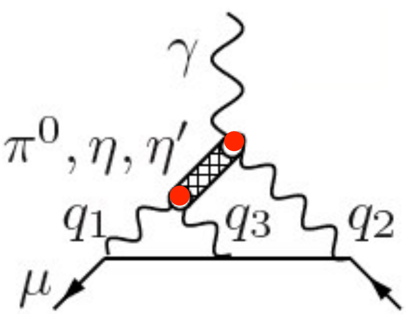
($a_\mu^{LbL} = (11.6 \pm 3.9)\times 10^{-10}$[Jegerlehner-Nyffeler P.Rep.477(2009)]**)**



Vac. pol.



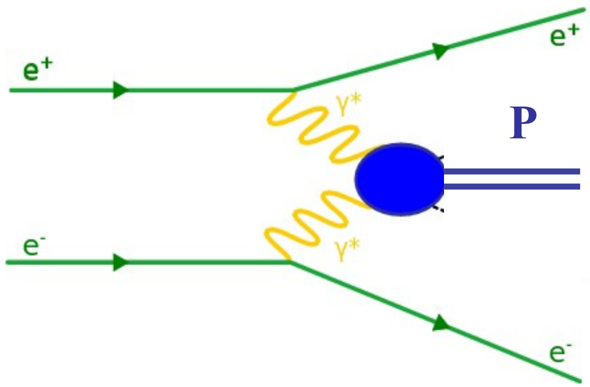
HLbL



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

Space-like FF in γγ physics

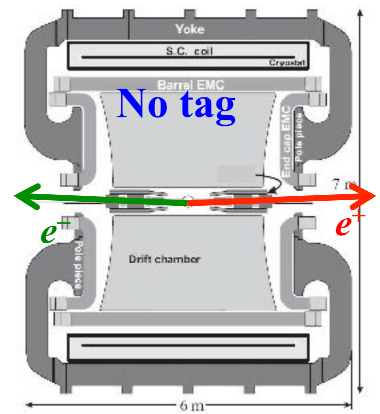
- At e^+e^- colliders can be measured by means of γγ processes



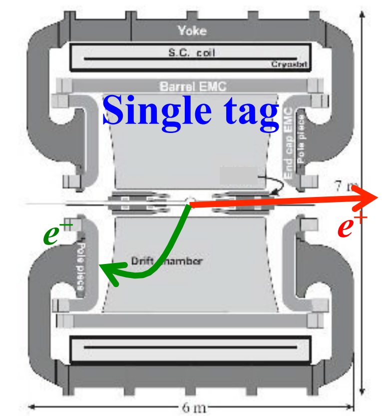
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-\mathbf{P} \quad [\mathbf{C(P) = +1}]$$

$$\mathcal{F}_{\mathbf{P}\gamma\gamma}(\mathbf{Q_1^2, Q_2^2}); \quad \mathbf{Q_i^2} = -\mathbf{q_i^2}$$

$$\sigma \propto \alpha^2 (\ln\sqrt{\mathbf{s}})^2$$



- **No tag:** quasi-real photons, $q^2_i \approx 0$
  ⇒ radiative width of the meson **Γ(P→γγ)**
- **Single tag:** one scattered lepton detected ⇒ $F(Q^2,0)$



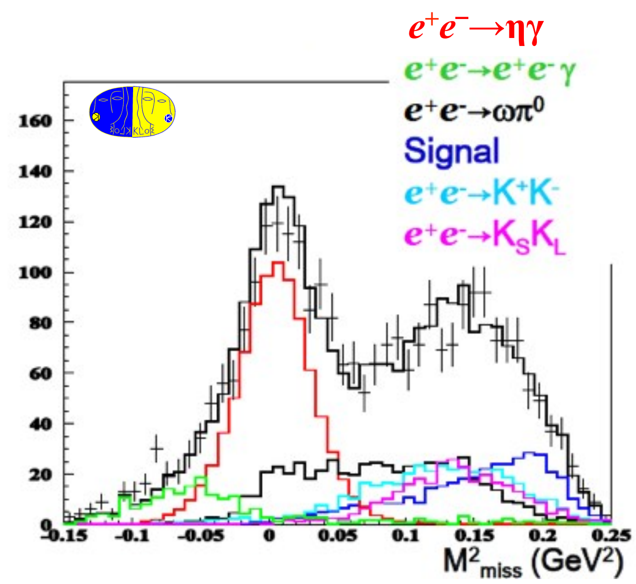
- **Double tag:** detect both leptons ⇒ $F(Q_1^2,Q_2^2)$
  but cross-sections very small

- **Special tagging devices:** very small angle detectors for scattered $e^\pm$ to tag events with photons with low virtuality

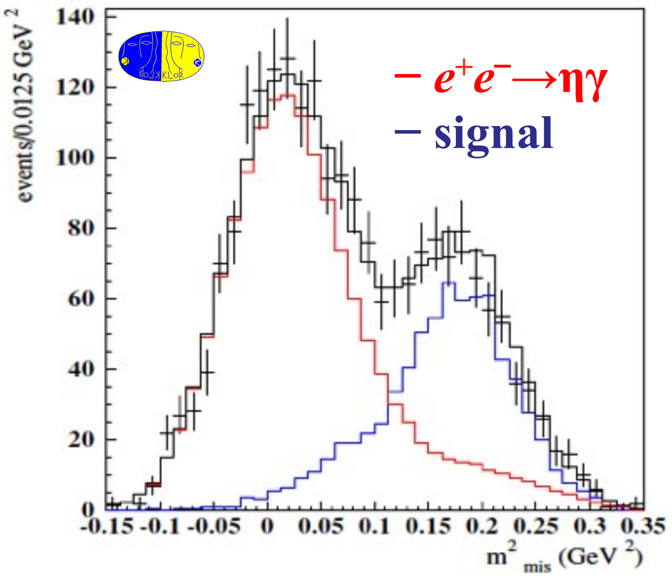
$\gamma^*\gamma^* \to \eta$

- **No tag:** KLOE, L = 240 pb^{-1} @ $\sqrt{s}$ = 1 GeV
- Off-peak data to reduce bckg from $\phi(1020)$ decays

- $\eta \to \pi^+\pi^-\pi^0$: events with two tracks and two prompt photons



- $\eta \to \pi^0\pi^0\pi^0$: events with no tracks and 6 prompt photons



combining the two channels:

$$\sigma(e^+e^- \to e^+e^-\eta) = (32.7 \pm 1.3 \pm 0.7)\ \text{pb}$$

$$\Rightarrow \Gamma(\eta \to \gamma\gamma) = (520 \pm 20 \pm 13)\ \text{eV}$$

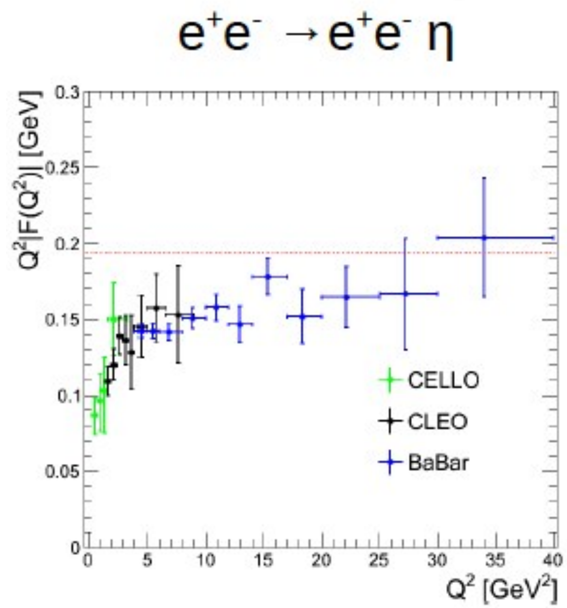
[JHEP01(2013)119]

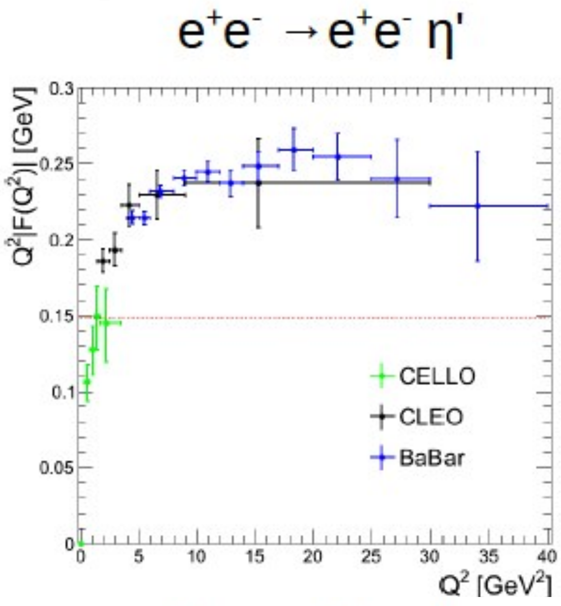
$F_{P\gamma\gamma^*}(Q^2)$ – single tag

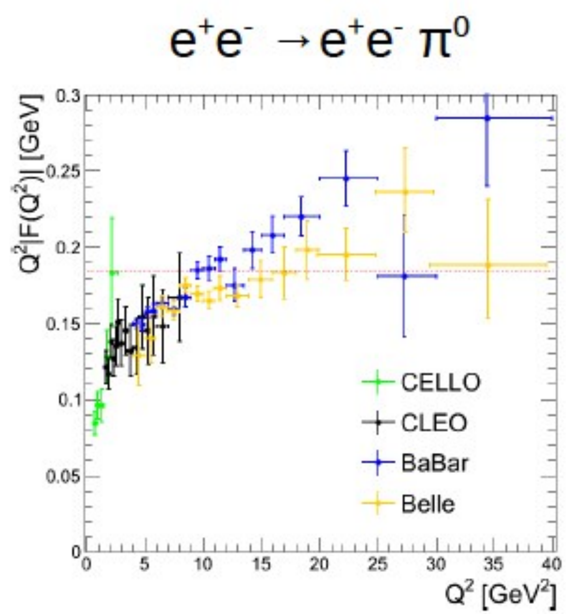
- Most recent measurements at B-factories. BaBar@PEPII and Belle@KEKB

Red line:QCD asympt. behaviour [Brodsky-Lepage PRD24(1981)1808]

$$F_{P\gamma\gamma}(Q^2) \sim \frac{2f_P}{Q^2}$$







- π^0 FF: discrepancy between BaBar [PRD80(2009)052002] and Belle [PRD86(2012)092007]

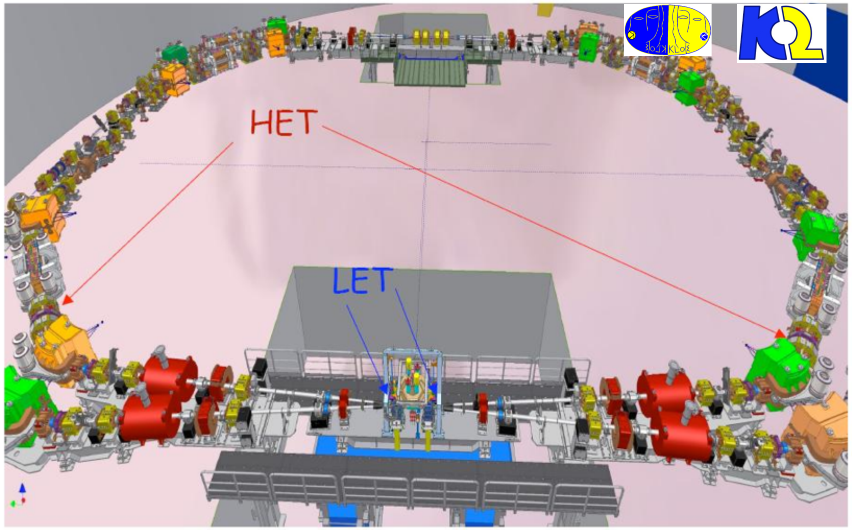
- Low Q^2 ($\lesssim$ 1 GeV^2) region almost unexplored ⇒important to constrain TFF parametrization

- BESIII is analyzing the 2.9 fb^{-1} collected at the ψ(3770) peak ⇒ $F(Q^2,0)$ at $0.3 < Q^2 < 3$ GeV^2 Study of systematics in progress

$F_{\pi^0\gamma\gamma^*}(Q^2)$ with taggers

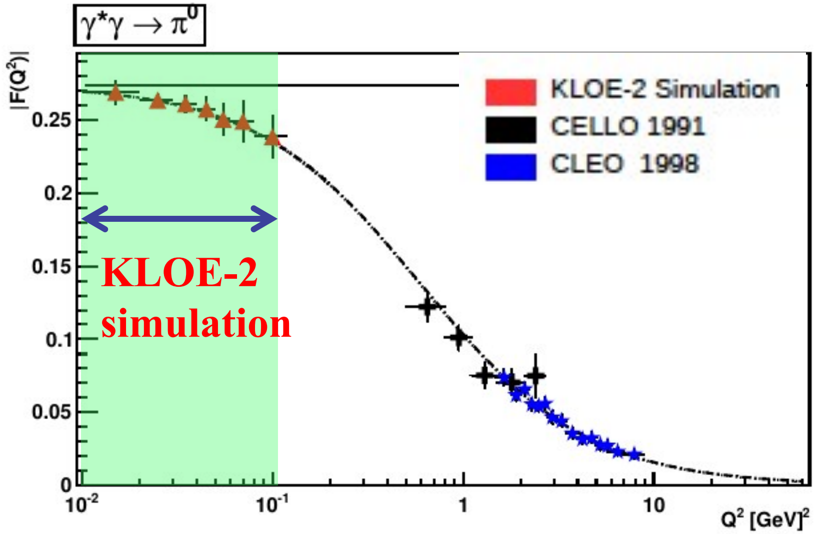
- **KLOE-2: 2 tagging devices:**
  Low Energy Tagger (LET): crystal calorimeters, to detect scattered e^+/e^- of $E \approx 150 - 350$ MeV

  High Energy Tagger (HET): scintillator hodoscopes placed after the first bending dipoles of DAΦNE, $420 < E < 495$ MeV



  - **Both e^+ and e^- in the HET**
    $Q^2_1, Q^2_2 \sim 0 \Rightarrow \Gamma(\pi^0 \to \gamma\gamma)$
    (PrimEx@JLAB $\Gamma(\pi^0 \to \gamma\gamma) = (7.82 \pm 0.14 \pm 0.17)$ eV
    Theory: $\Gamma(\pi^0 \to \gamma\gamma) = (8.09 \pm 0.11)$ eV)

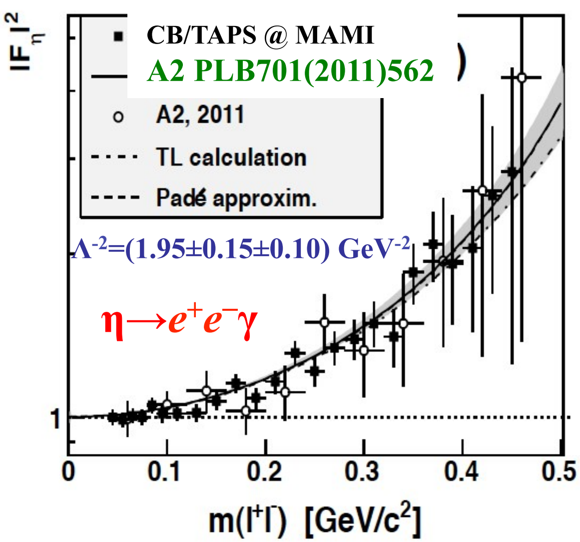
  - **One lepton in the HET and the other in the main detector $\Rightarrow F(Q^2,0)$ at $Q^2 < 0.1$ GeV^2**

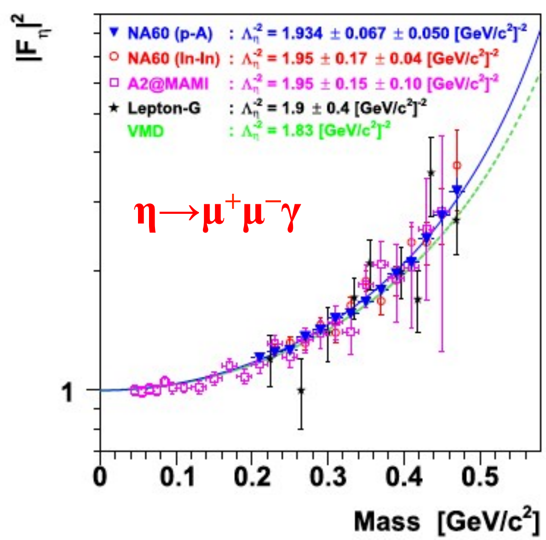


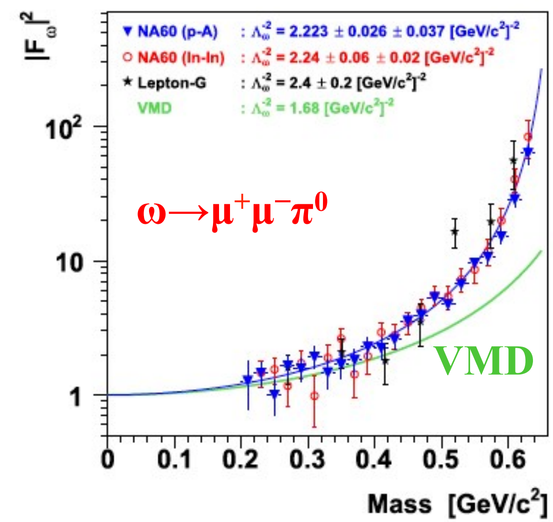
- **BESIII will install $PbWO_4$ calorimeters at very small angles**

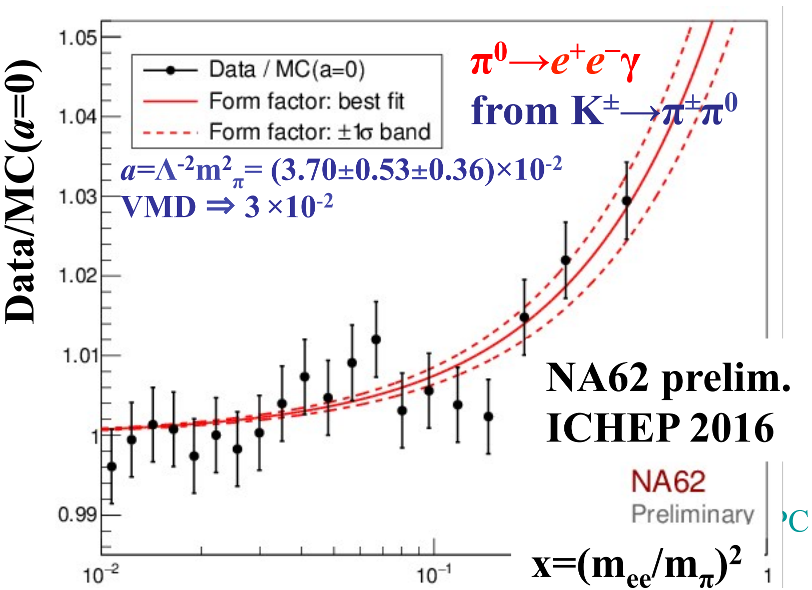
Time-like FFs from Dalitz decays

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









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

$\eta \rightarrow e+e-\gamma/\mu+\mu-\gamma$	Λ^{-2} [GeV^{-2}]	VMD
A2@MAMI	1.95 ± 0.15 ± 0.10	1.83
NA60 (In-In)	1.95 ± 0.17 ± 0.04	
NA60 (p-A)	1.934 ± 0.067 ± 0.050	
$\pi0 \rightarrow e+e-\gamma$		
NA62	2.03 ± 0.29 ± 0.20	1.7
$\omega \rightarrow \pi0\mu+\mu-$		
NA60 (In-In)	2.24 ± 0.06 ± 0.02	1.68
NA60 (p-A)	2.223 ± 0.026 ± 0.037	

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

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

$\Rightarrow$ 2 tracks + 6 prompt γ's

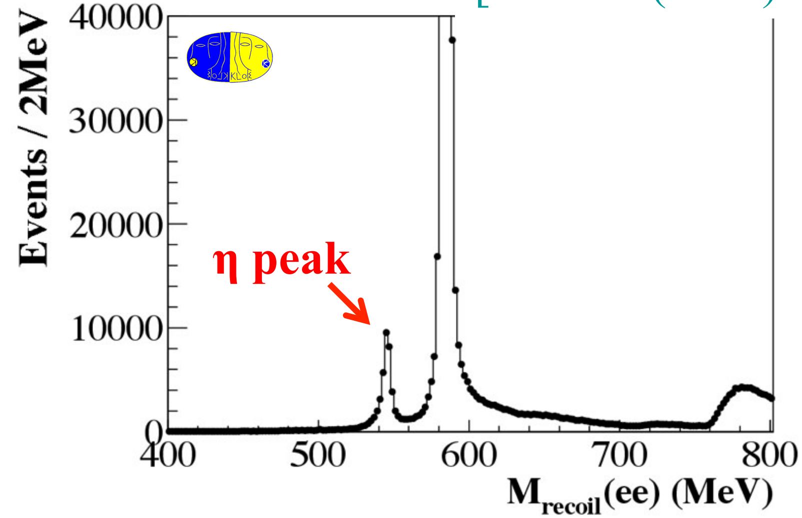
$$BR(\phi \to \eta e^+e^-) = (1.075 \pm 0.007 \pm 0.038) \times 10^{-4}$$

Previous measurement from Novosibirsk VEPP-2M

SND: $(1.19 \pm 0.19 \pm 0.12)\times10^{-4}$ [PLB504(2001)275]

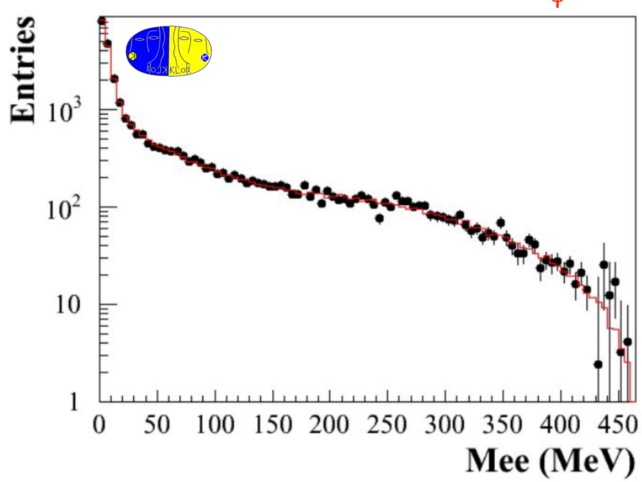
CMD2: $(1.14\pm0.10 \pm 0.06)\times10^{-4}$ [PLB501(2001)191]

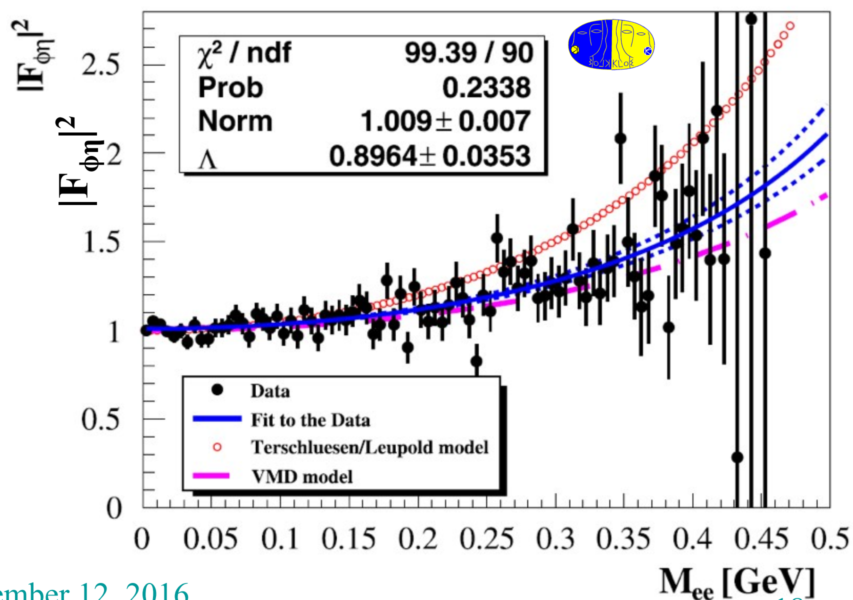
[PLB742(2015)1]



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

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



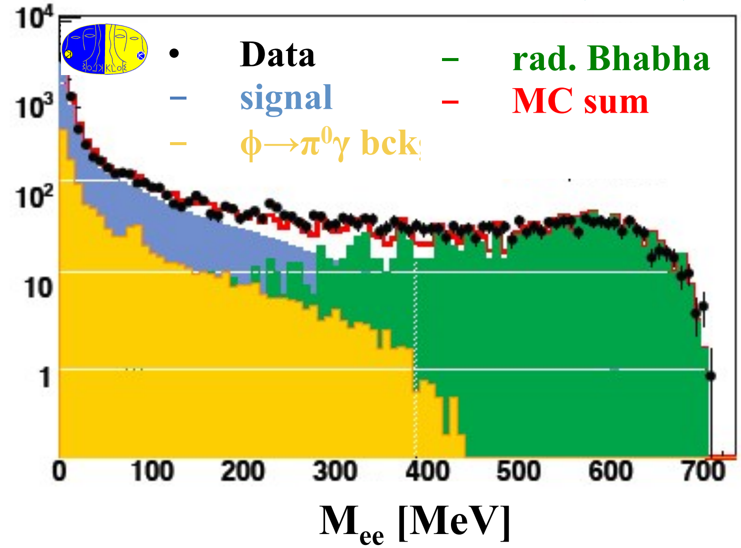


$\phi \to \pi^0 e^+ e^-$ TFF

[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

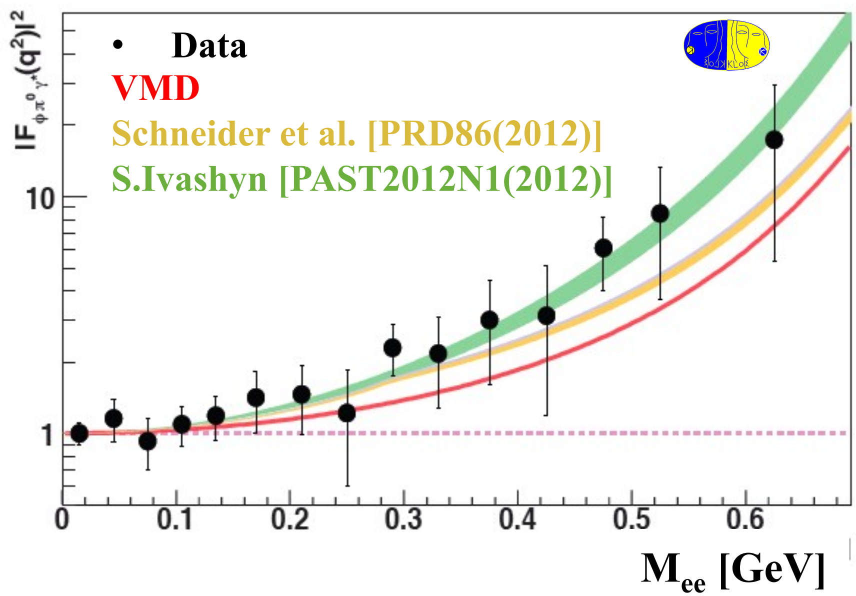


$$BR(\phi \to \pi^0 e^+ e^-) =$$
$$= (1.35 \pm 0.05^{+0.05}_{-0.10}) \times 10^{-5}$$

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

CMD-2: $BR = (1.22 \pm 0.34 \pm 0.22) \times 10^{-5}$

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

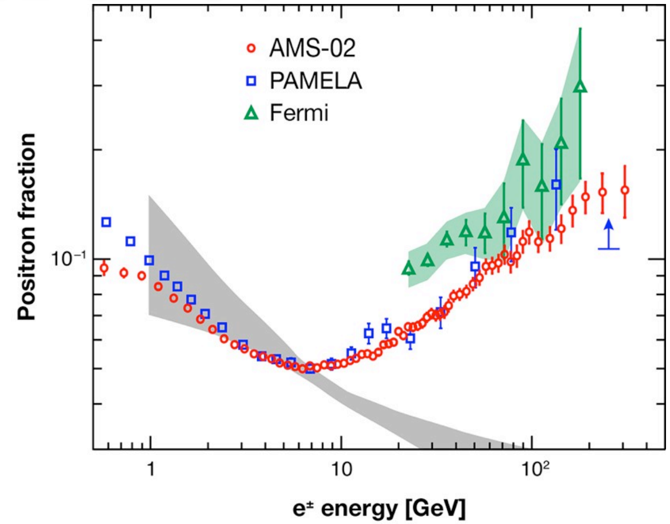


⇒ does not agree with VMD

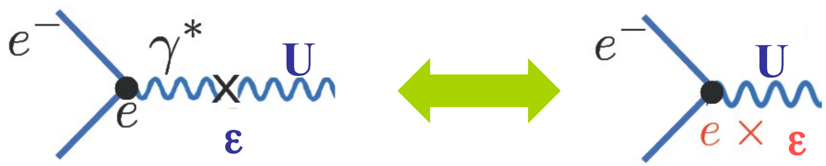
Dark Photon searches

- Several astrophysical anomalies (AMS02, PAMELA, FERMI, INTEGRAL,DAMA, …) can be explained by the presence of a new $U(1)_D$ gauge particle, the so-called Dark Photon (U, A′, γ′ , …)

[Arkani-Hamed at al.,PRD79(2009)015014]



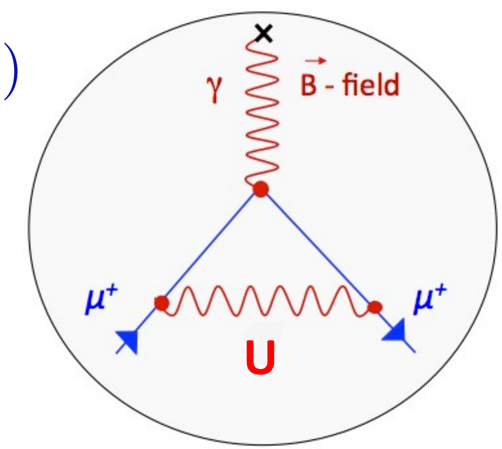
- This massive dark photon mixes with the ordinary photon



$$\mathcal{L}_{\mathbf{mix}} = -\frac{\varepsilon}{\mathbf{2}} \mathbf{F}^{\mathbf{QED}}_{\mu\nu} \mathbf{F}^{\mu\nu}_{\mathbf{Dark}} \quad \Rightarrow \alpha_{\mathbf{D}} = \varepsilon^{\mathbf{2}} \alpha_{\mathbf{em}}$$

$$(\varepsilon \sim \mathbf{10}^{-\mathbf{2}} - \mathbf{10}^{-\mathbf{4}})$$

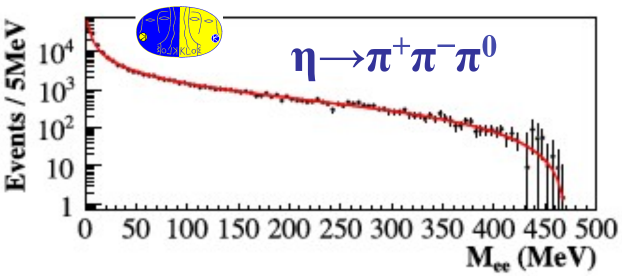
- This new force carrier could also explain the $(g\text{-}2)_\mu$ discrepancy

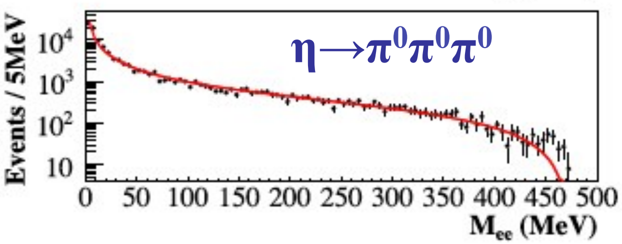


[Pospelov,PRD80(2009)095002]

Dark Photon searches

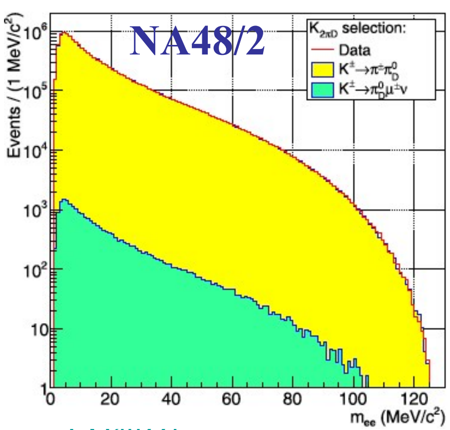
- Dalitz decays involving light pseudoscalar mesons can be used to search for Dark Photons, in the hypothesis that the U is the lightest particle of the dark sector, by looking for spikes in the dilepton invariant mass distribution ($U \to \ell^+\ell^-$)

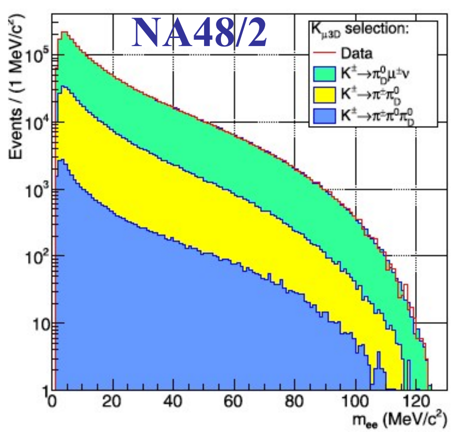


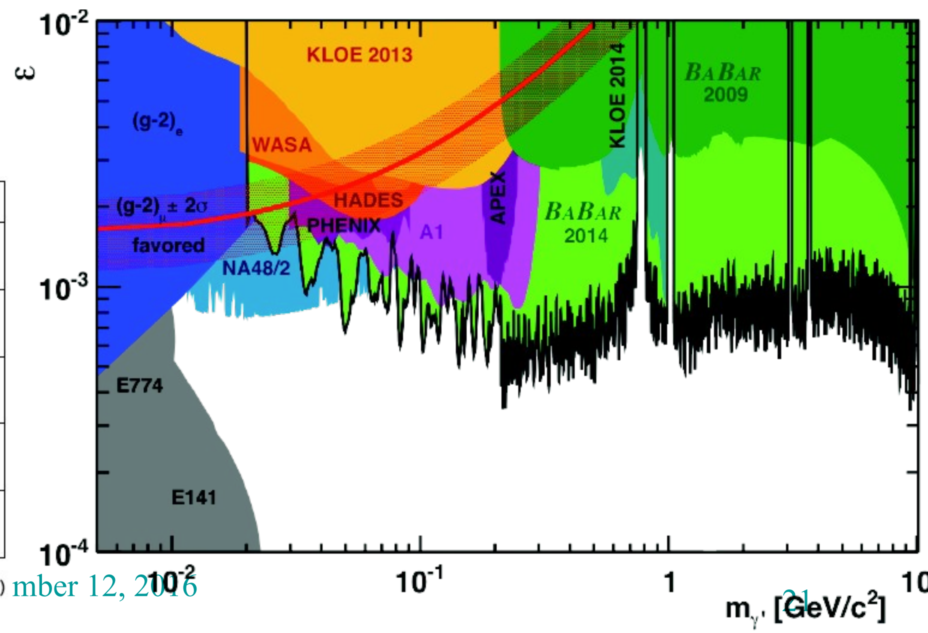


- $\phi \to \eta e^+e^-$: KLOE [PLB720(2013)111]
- $\pi^0 \to e^+e^-\gamma$: WASA, HADES, NA48/2

[WASA, PLB726(2013)187
HADES, PLB731(2014)265
NA48/2, PLB746(2015)178]







Conclusions

- **The study of the light pseudoscalar mesons is still alive as research field**
- **Large samples of pseudoscalar mesons are produced by e^+e^- colliders, fixed target experiments, photoproduction, …**
- **Precision tests of Effective Field Theories (like Chiral Perturbation Theory and its extensions) can be performed**
- **Essential for the construction of the models to understand new phenomena like exotics, hybrid mesons, …**
- **Precision measurements at low energy can also give indications about Physics beyond the Standard Model**
- **More data available in the future: experiments in data taking (KLOE-2, BESIII), new experiments (JEF)**

KLOE-2 Physics Workshop @ LNF

https://agenda.infn.it/conferenceDisplay.py?confId=11722

CP and T violation, CPT and QM tests
K_S decays, η decays and chiral lagrangians
ϕ decays, light hadron spectroscopy and TFFs
γγ physics

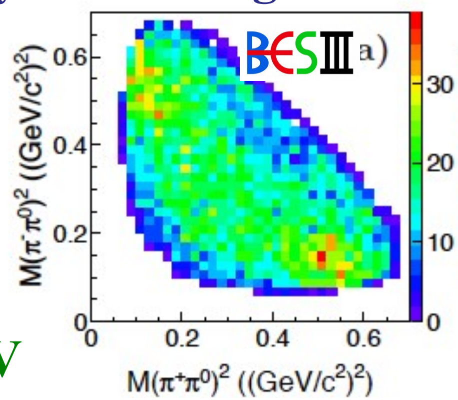
Dark force searches
Hadronic contribution to $(g\text{-}2)_\mu$
Low energy kaon interactions
Future machines and new detectors

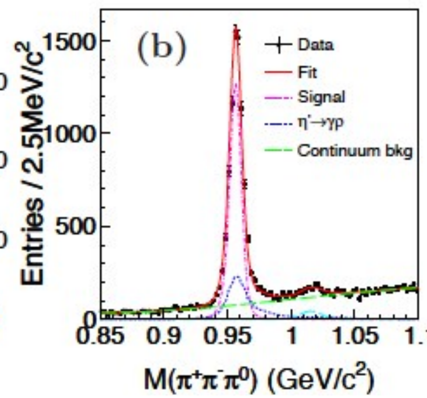
Spare slides

$\eta'(958) \to 3\pi$

[arXiv:1606.03847]

- **BESIII, $e^+e^- \to J/\psi \to \eta'\gamma$, combined analysis of charged and neutral channels from a sample of 1.31×10^9 J/ψ produced**
- **$\eta' \to \pi^+\pi^-\pi^0$: ~ 8000 events**
- **$\eta' \to \pi^0\pi^0\pi^0$: ~ 2000 events**



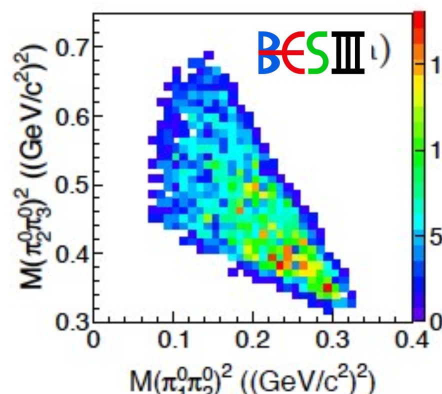


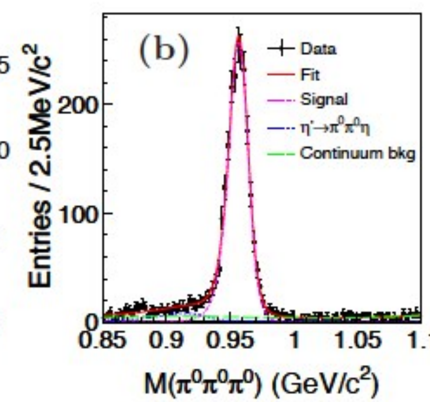
- **Sizeable contribution of P-wave**

$\eta' \to \rho^\pm\pi^\mp$, ρ pole 775.49 – i (68. 5± 0. 2) MeV

- **Evidence of S-wave resonant contribut.**

(512±15)−i(188 ±12) MeV ⇒ $f_0(500)$

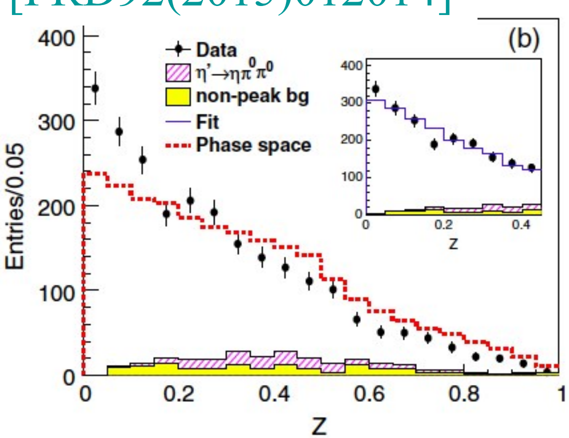




- **$\eta' \to \pi^0\pi^0\pi^0$ Dalitz plot slope**

$\alpha = -0.640 \pm 0.046 \pm 0.047$

[PRD92(2015)012014]



$$r_\pm = \frac{Br(\eta' \to \pi^+\pi^-\pi^0)}{Br(\eta' \to \eta\pi^+\pi^-)} = (8.87 \pm 0.98) \times 10^{-3}$$

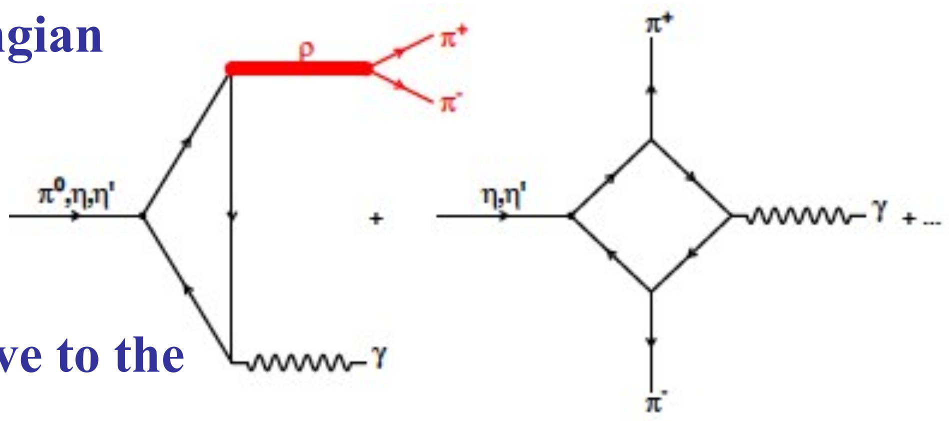
$$r_0 = \frac{Br(\eta' \to \pi^0\pi^0\pi^0)}{Br(\eta' \to \eta\pi^0\pi^0)} = (16.42 \pm 1.94) \times 10^{-3}$$

Final state interaction more relevant than for η

Dispersive methods under development also for η′

$\eta/\eta' \to \pi^+\pi^-\gamma$ and the Box Anomaly

- The coupling of the 3 pseudoscalars with the photon is described by the WZW lagrangian ⇒ resonant term (ρ dominated) and a contact term represented by the box diagram.
- The decay widths and the dipion mass spectra are expected to be sensitive to the relative contributions of the two terms



- Recently a parametrization of the decay amplitude to disentangle perturbative and non-perturbative effects has been proposed

$$\frac{d\Gamma}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\Gamma_0(s_{\pi\pi})$$ [Stollenwerk et al.PLB707(2012)184]

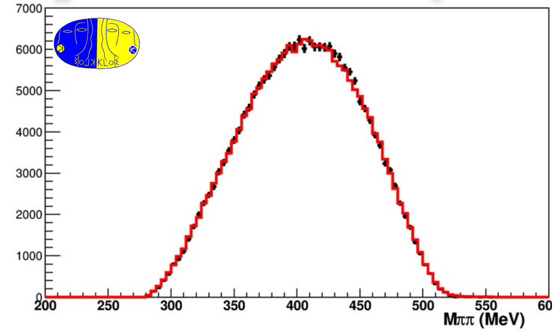
F_V = pion FF (well known from experiments and theory)

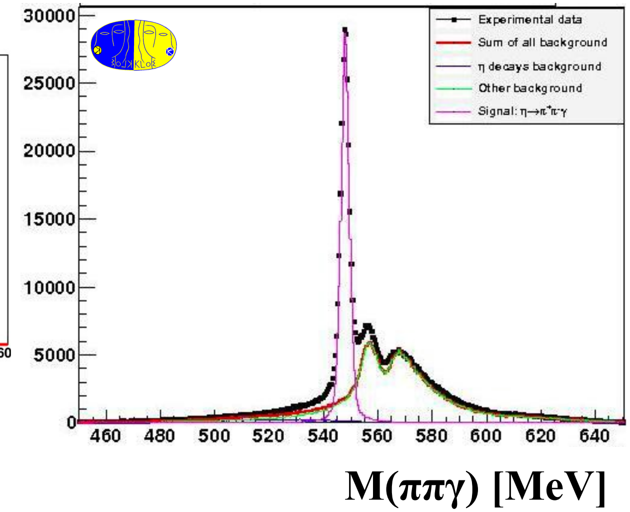
Γ_0 = phase space and kinematics

$$P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \beta s^2_{\pi\pi} + \dots$$ (perturbative part - process specific)

A, α, β, …, can be related to the parameters of the underlying effective theory

$\eta \rightarrow \pi^+\pi^-\gamma$





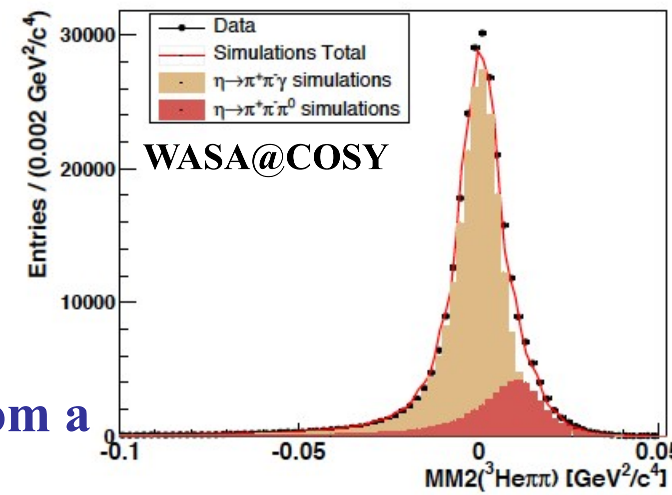
- **KLOE ('13): $e^+e^- \rightarrow \phi \rightarrow \eta\gamma$**
  L = 558 pb^{-1}; ~ 2×10^7 events

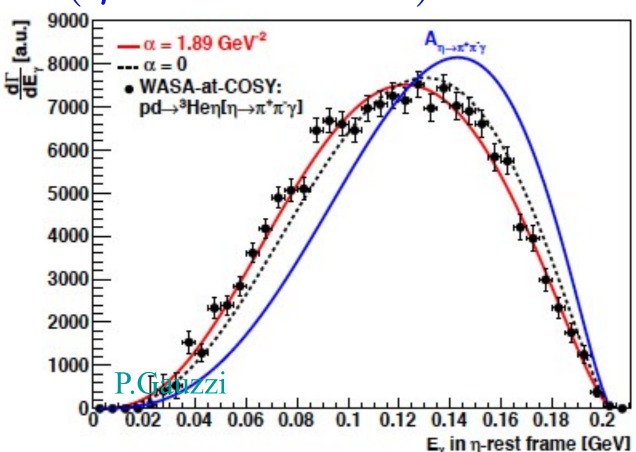
$$\frac{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005 \pm 0.0028$$

$$\alpha = (1.32 \pm 0.08 \pm 0.10)\ \mathrm{GeV}^{-2}$$

- **New result from WASA, pd→^{3}He η with $\eta \rightarrow \pi^+\pi^-\gamma$** [arXiv:1509.06588]

$$\frac{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.206 \pm 0.003 \pm 0.008$$





Fit to the spectrum from a previous analysis [PLB707(2012)243]

$$\alpha = (1.89 \pm 0.25 \pm 0.59)\ \mathrm{GeV}^{-2}$$

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

	$\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\eta\to\pi^+\pi^-\pi^0)$	α [GeV^{-2}]
Gormley et al. ('70)	0.201 ± 0.006	1.8 ± 0.4 (*)
Layter et al. ('73)	0.209 ± 0.004	-0.9 ± 0.1 (*)
CLEO ('07)	0.175 ± 0.007± 0.006	
WASA ('12)	0.206 ± 0.003 ± 0.008 ('15)	1.89± 0.25 ± 0.59
KLOE ('13)	0.1856 ± 0.0005 ± 0.0028	1.32 ± 0.08 ± 0.10
(*) Fit of the spectra from Stollenwerk et al., PLB707(2012)184		

- **KLOE in agreement with CLEO measurement**
- **WASA in agreement with the older measurements**
  - ⇒ **2 – 3 σ discrepancy**

$$\Gamma(\eta \to \pi^+\pi^-\gamma) = \mathbf{51.6 - 61.6}\ \mathrm{eV}$$

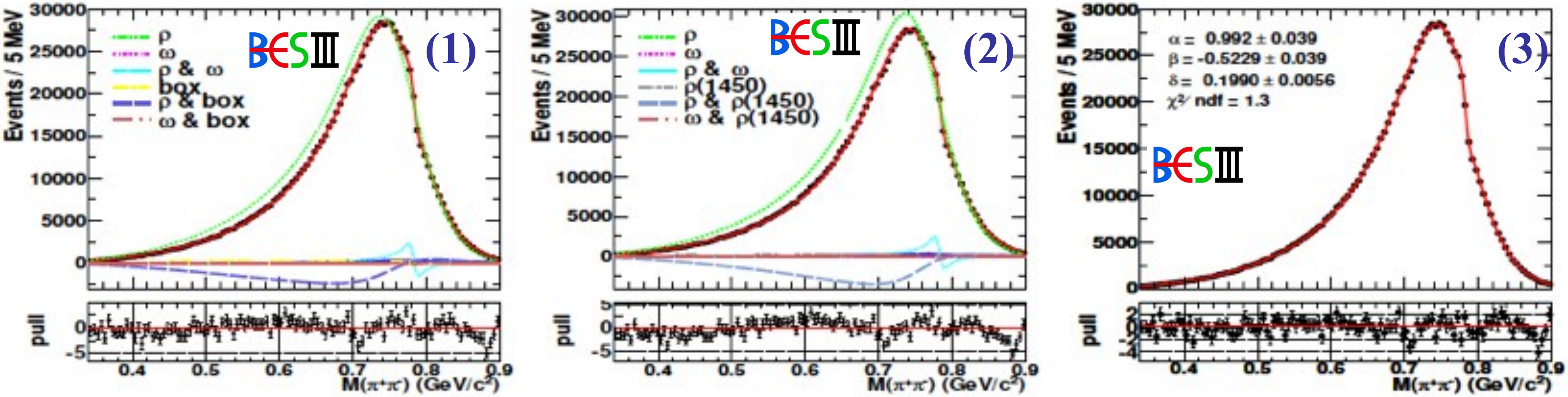
⇒ **sizeable effect of the contact term**

[Benayoun et al., EPJC31(2003)525]

- **Stollenwerk et al. parametrization**
  - ⇒ **sensitive only to α term**
  - **Spectra from older data are inconsistent**
  - **KLOE and WASA agree within the uncertainties**

$\eta' \to \pi^+\pi^-\gamma$

- BESIII: $e^+e^- \to J/\psi \to \eta'\gamma$ with $\eta' \to \pi^+\pi^-\gamma$; 9×10^6 events found



[BESIII, PoS(CD15)032]

Different fits:

1. ρ(770) + ω(782) + Contact Term
2. ρ(770) + ω(782) + ρ(1450)

➡ **Both fits are good, the situation is not clear**

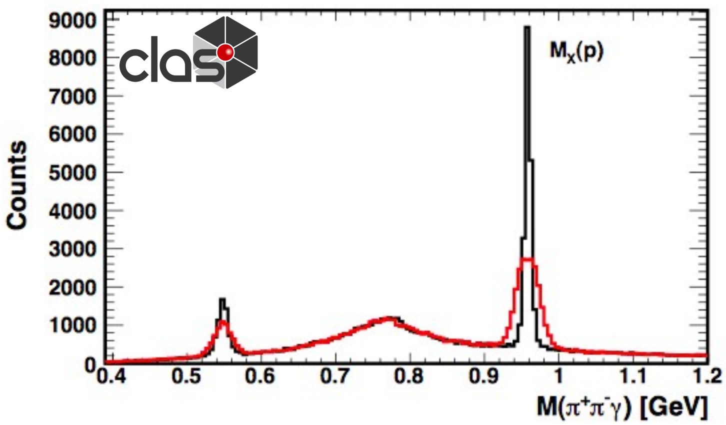
3. Parametrization from Stollenwerk et al. ⇒

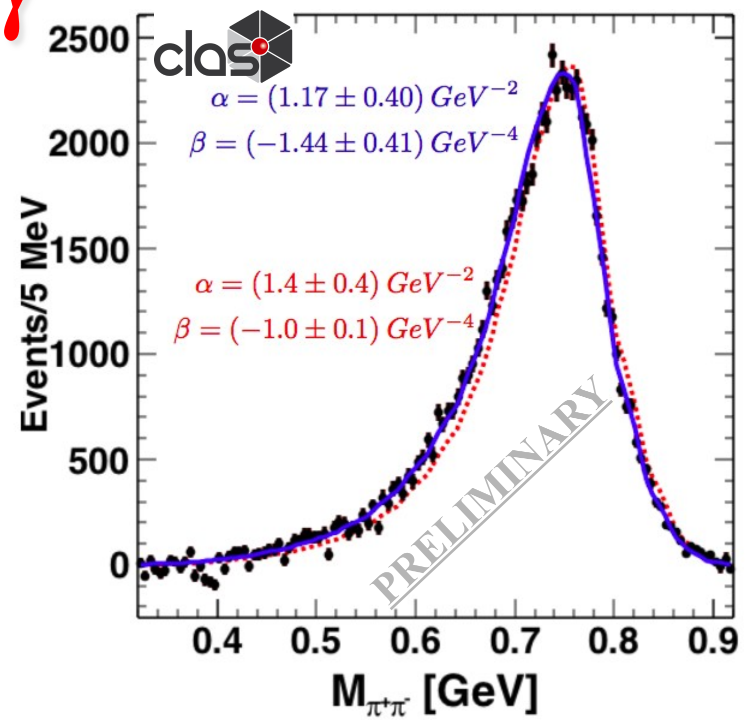
$$\alpha = (\mathbf{0.992 \pm 0.039 \pm 0.067})\ \mathrm{GeV}^{-2}$$
$$\beta = (\mathbf{-0.523 \pm 0.039 \pm 0.066})\ \mathrm{GeV}^{-4}$$

$\eta' \rightarrow \pi^+\pi^-\gamma$

- **CLAS, g11 data**
  $\gamma p \rightarrow pX$, $X \rightarrow \pi^+\pi^-\gamma$

(M.C.Kunkel Meson 2016)



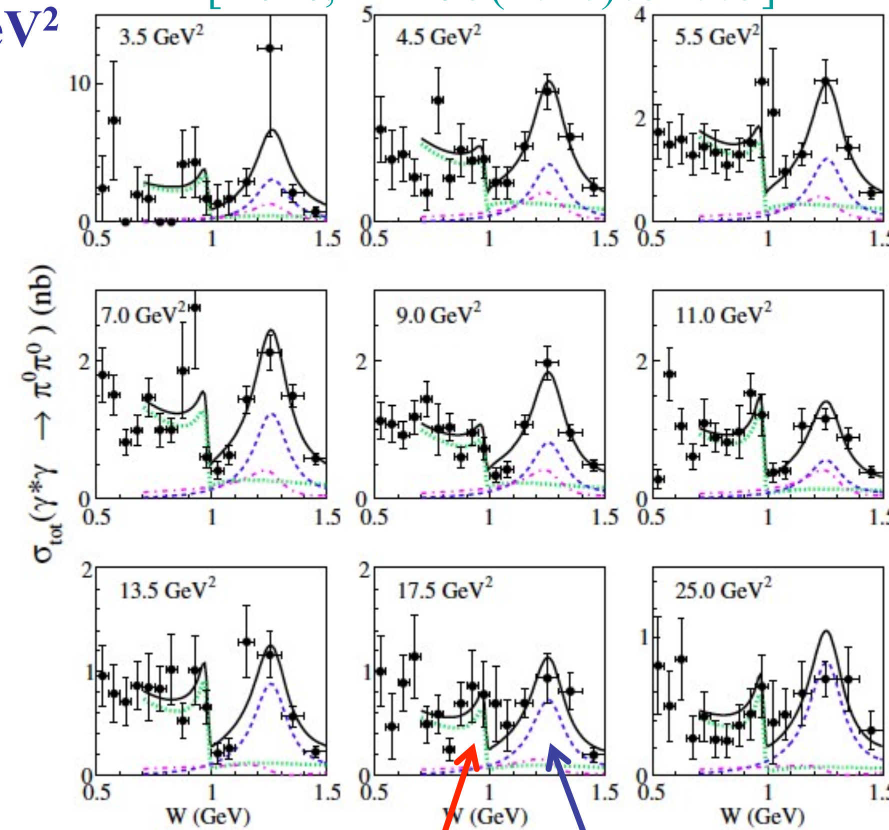


	α [GeV^{-2}]	β [GeV^{-4}]
GAMS-200 ('91)	2.7 ± 0.1 (*)	
Crystal Barrel ('93)	1.8 ± 0.5 (*)	
BESIII ('15)	0.992 ± 0.039 ± 0.067	-0.523 ± 0.039 ± 0.066
CLAS ('16)	1.17 ± 0.04	-1.44 ± 0.41
(*) Fit of the spectra from Stollenwerk et al., PLB707(2012)184		

$\gamma^*\gamma^* \rightarrow \pi\pi$

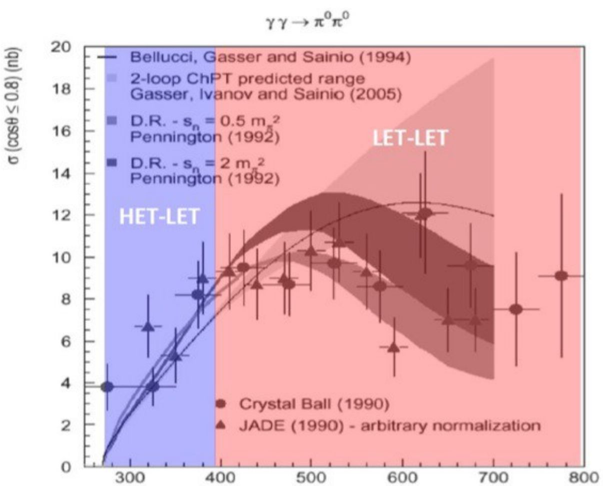
- **A recent dispersive approach to the calculation of the HLbL to $(g-2)_\mu$, pointed out the relevance also of the two-pion intermediate states and related its contribution to the $\gamma\gamma\rightarrow\pi\pi$ partial waves** [Colangelo et al., JHEP1409(2014)091]
- **Single tag measurement by Belle of $e^+e^-\rightarrow e^+e^-\pi^0\pi^0$ for Q^2 from 3 to 30 GeV^2 and for $0.5 < W_{\gamma\gamma} < 2.1$ GeV**
  Fit with S, D_0 and D_2 partial waves

[Belle, PRD93(2016)032003]



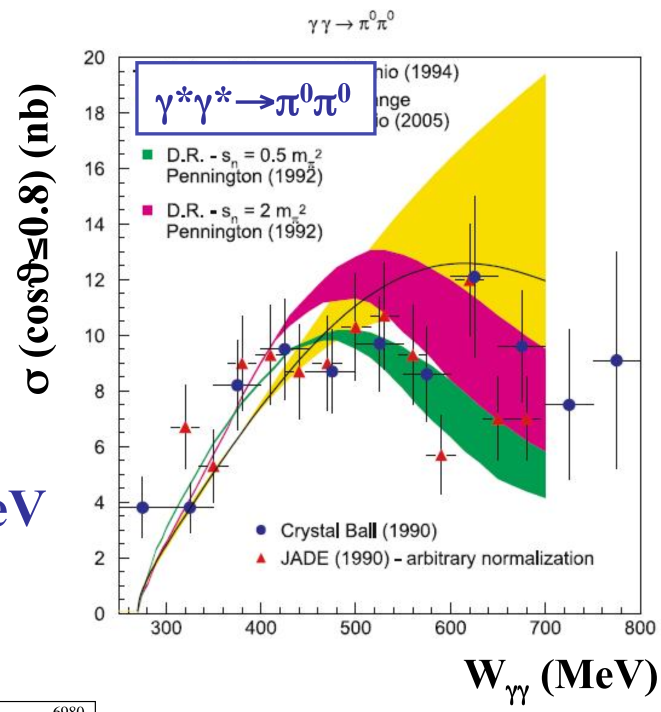
$f_0(980)$ $f_2(1270)$

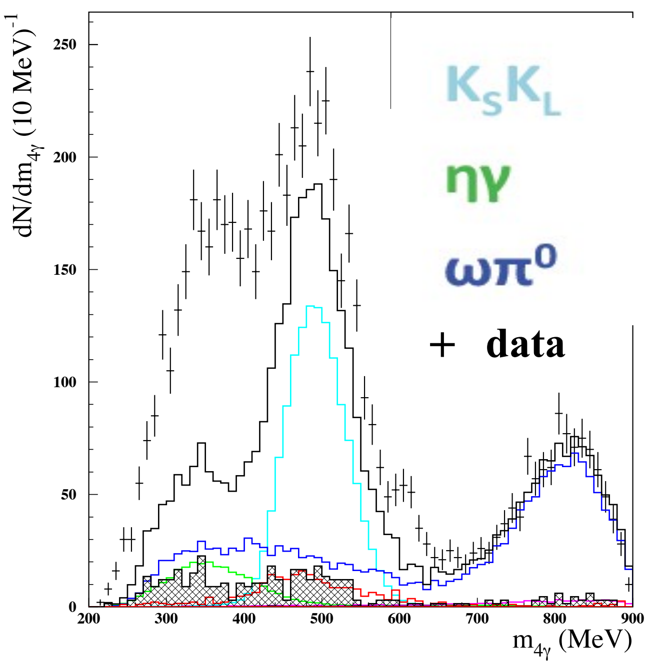
- **KLOE-2 with the taggers could investigate this process at lower $W_{\gamma\gamma}$ values (also study of $f_0(500)\rightarrow\pi^0\pi^0$)**

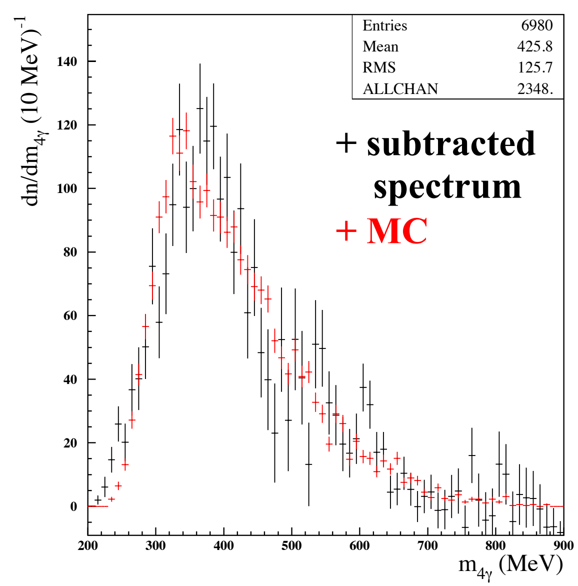


$\gamma^*\gamma^* \rightarrow \pi^0\pi^0$

- $e^+e^- \rightarrow e^+e^- \pi^0\pi^0$
- $\sigma(500) \rightarrow \pi^0\pi^0$?
- **Previous measurements by Crystal Ball and JADE**
- **KLOE data (no taggers) $L = 240\ pb^{-1}$ @ $\sqrt{s} = 1$ GeV**



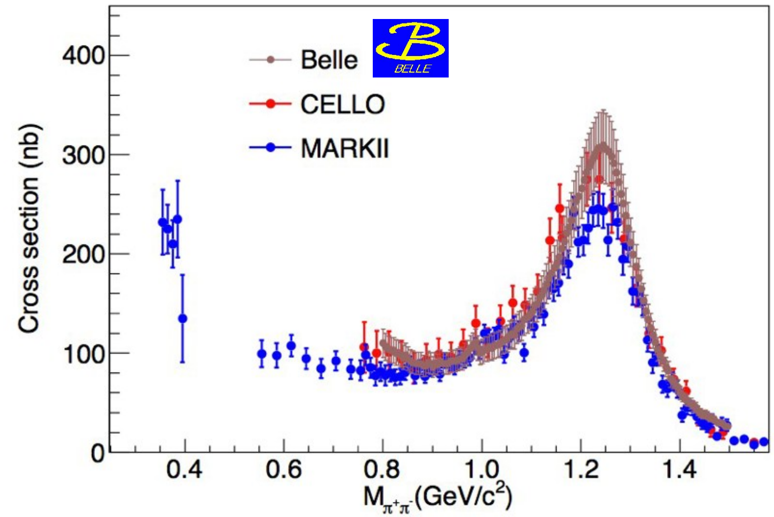




Clear excess of events with respect to the known background processes

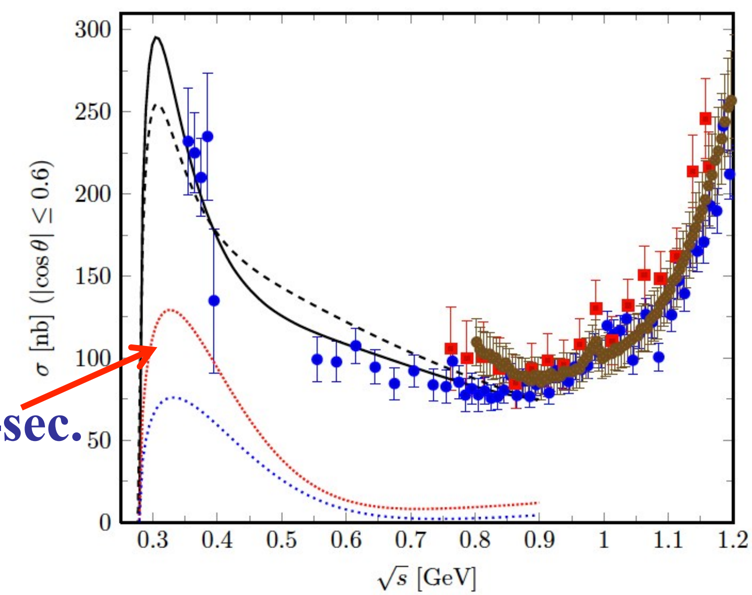
$\gamma^*\gamma^* \to \pi^+\pi^-$

- Most recent measurement by Belle (no tag) for $M_{\pi\pi}$ > 0.8 GeV [PRD75(2007)051101]
  ⇒ measurement of the f_0(980) partial widths
  No partial wave analysis

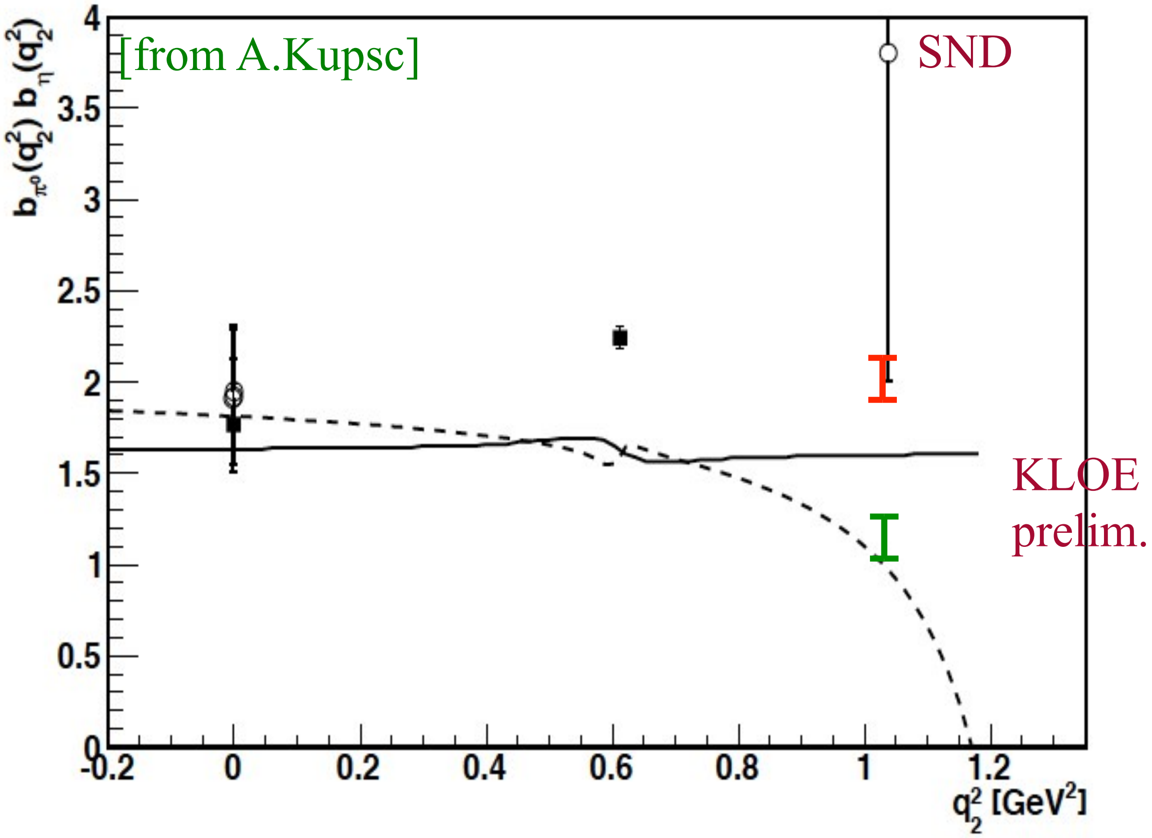


- Single tag measurement planned by BESIII using 1 fb^{-1} @ $\sqrt{s}$ = 4360 MeV
  ⇒ 0.2 < Q^2 < 2.0 GeV^2
  ⇒ ~ 5000 evts expected
  will cover the range $2m_\pi < M_{\pi\pi} < 2$ GeV

Single tag expected cross-sec.



TFF slope



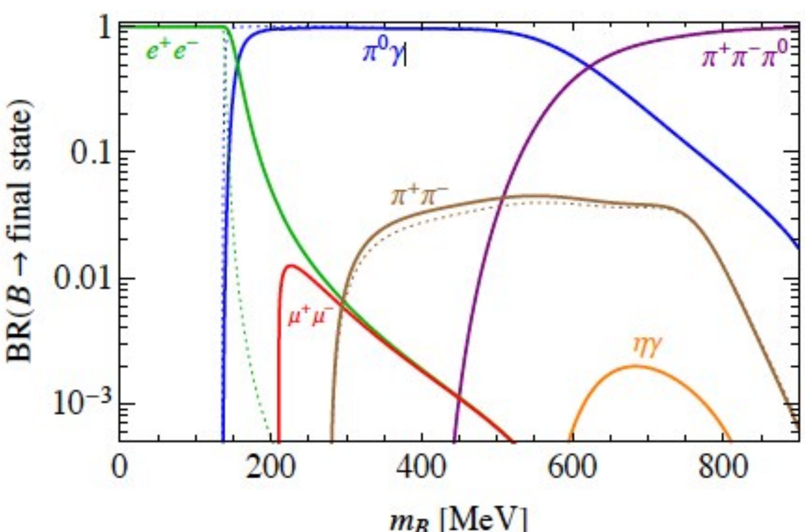
Dark B-boson searches

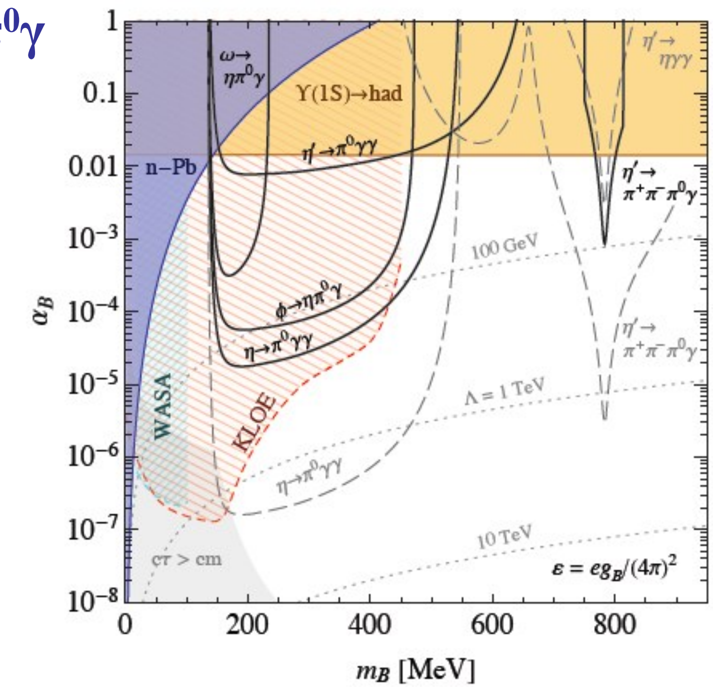
- **Leptophobic Dark Force mediator predominantly coupling to quarks (B-boson)**

[Tulin, PRD89(2014)114008]

$$\mathcal{L} = \frac{1}{3} g_B \bar{q}\gamma^\mu q B_\mu \qquad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\text{MeV})$$

- **Dominant decay channel (m_B < 600 MeV): $B \rightarrow \pi^0\gamma$**
- **Can be studied in processes like:**
  $\phi \rightarrow \eta B \Rightarrow \eta\pi^0\gamma$ final state (KLOE-2)
  $\eta \rightarrow B\gamma \Rightarrow \pi^0\gamma\gamma$ (KLOE-2, JEF+GlueX)





Mixing η – η′ @KLOE

- $\phi \to \eta'\gamma;\ \eta' \to \eta\,\pi^+\pi^-;\ \eta \to \pi^0\pi^0\pi^0$
  $\eta' \to \eta\pi^0\pi^0;\ \eta \to \pi^+\pi^-\pi^0$ } Final state: $\pi^+\pi^- + 7\,\gamma$
- $\phi \to \eta\gamma;\ \ \eta \to \pi^0\pi^0\pi^0$

$L = 427\ pb^{-1}$

$N_{\eta'\gamma} = 3407 \pm 61 \pm 43$ ev.

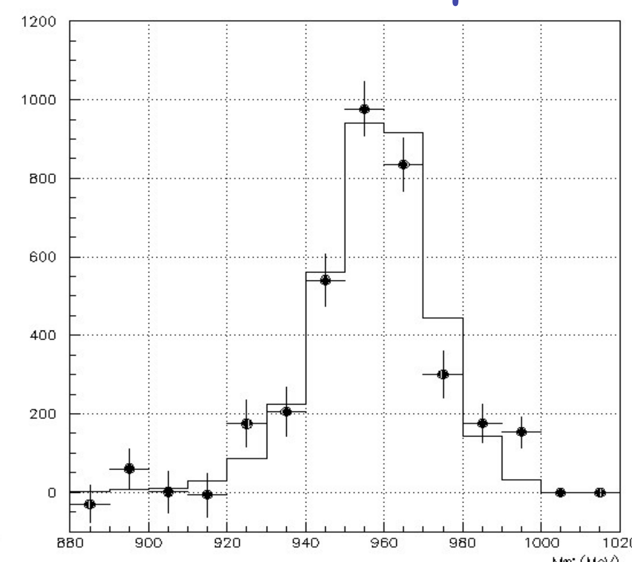
$N_{\eta\gamma} = 16.7 \times 10^6$ ev.

$$R = \frac{Br(\phi \to \eta'\gamma)}{Br(\phi \to \eta\gamma)} = (4.77 \pm 0.09 \pm 0.19) \times 10^{-3}$$

[systematics dominated by $\delta Br(\eta' \to \eta\pi\pi) = 3\%$]

$\Rightarrow Br(\phi \to \eta'\gamma) = (6.20 \pm 0.11 \pm 0.15) \times 10^{-5}$

Inv.mass of $\pi^+\pi^- + 6\gamma$ out of 7



$M_{\pi\pi6\gamma}$ (MeV)

[PLB648(2007)267]

- Pseudoscalar mixing angle: $\left(|q\bar{q}\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)\right)$

$$\eta = \cos\varphi_P |q\bar{q}\rangle - \sin\varphi_P |s\bar{s}\rangle$$

$$\eta' = \sin\varphi_P |q\bar{q}\rangle + \cos\varphi_P |s\bar{s}\rangle$$

$$R = \cot^2\varphi_P \left(1 - \frac{m_s}{\bar{m}} \cdot \frac{C_{NS}}{C_S} \cdot \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$\varphi_P = (41.4 \pm 0.3 \pm 0.9)°\ \Rightarrow \vartheta_P = (-13.3 \pm 0.3 \pm 0.9)°$

η′ gluonium content

$\eta' = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|G\rangle$

$X_{\eta'} = \cos\varphi_G \sin\varphi_P$

$Y_{\eta'} = \cos\varphi_G \cos\varphi_P$

$Z_{\eta'} = \sin\varphi_G$

[Rosner PRD27(1983) 1101, Kou PRD63(2001)54027]

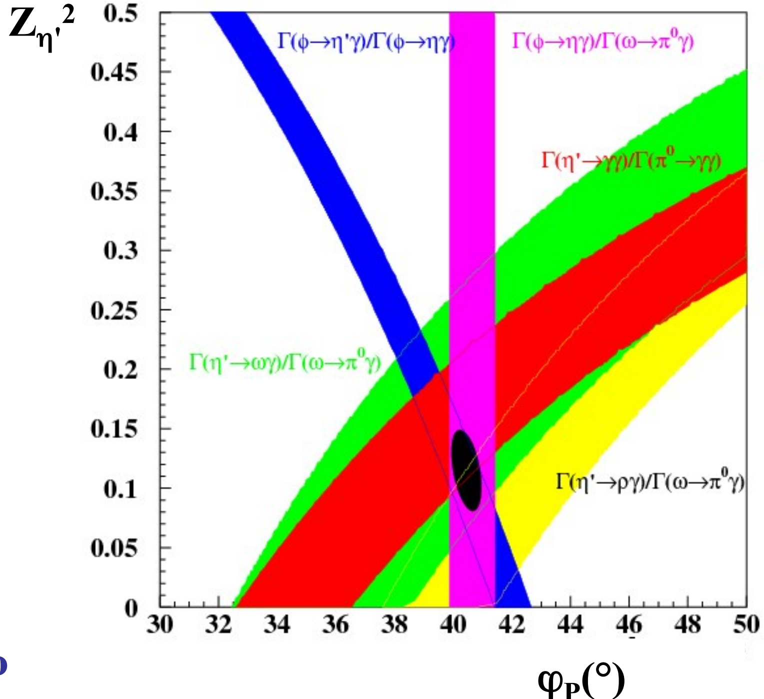
New fit: $R = \cot^2\varphi_P \cos^2\varphi_G \left(1 - \frac{m_s}{\bar{m}} \cdot \frac{C_{NS}}{C_S} \cdot \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)}, \frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\omega \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)},$$

$$\frac{\Gamma(\rho \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\phi \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\phi \to \pi^0\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(K^{*+} \to K^+\gamma)}{\Gamma(K^{*0} \to K^0\gamma)}$$

PDG08+ KLOE $\omega \to \pi^0\gamma$

	New fit	PLB648
$Z_{\eta'}^2$	0.12 ± 0.04	0.14 ± 0.04
φ_P (deg.)	40.4 ± 0.6	39.7 ± 0.7
C_{NS}	0.94 ±0.03	0.91 ±0.05
C_S	0.83 ±0.05	0.89 ±0.07
φ_V (deg.)	3.32 ± 0.10	3.2
m_s/m	1.24 ± 0.07	1.24 ± 0.07
χ^2/ndf	4.6/3	1.42 / 2
$P(\chi^2)$	20%	49%



[JHEP07(2009)105]

KLOE-2: by measuring the main η' Br's @ 1%
⇒ statistical significance of $Z_{\eta'}^2$ will increase to 4 – 5 σ

Mixing η – η′ @LHCb

[JHEP1501(2015)024]

- **Study of the η – η′ mixing from $B^0_{(s)} \to J/\psi\, \eta(')$ decays**

$$R_{\eta'} = \frac{\mathcal{B}(B^0 \to J/\psi\eta')}{\mathcal{B}(B^0_s \to J/\psi\eta')} = (2.28 \pm 0.65\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.13\,(f_s/f_d)) \times 10^{-2},$$

$$R_{\eta} = \frac{\mathcal{B}(B^0 \to J/\psi\eta)}{\mathcal{B}(B^0_s \to J/\psi\eta)} = (1.85 \pm 0.61\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.11\,(f_s/f_d)) \times 10^{-2},$$

$$R_s = \frac{\mathcal{B}(B^0_s \to J/\psi\eta')}{\mathcal{B}(B^0_s \to J/\psi\eta)} = 0.902 \pm 0.072\,(\text{stat}) \pm 0.041\,(\text{syst}) \pm 0.019\,(\mathcal{B}),$$

$$R = \frac{\mathcal{B}(B^0 \to J/\psi\eta')}{\mathcal{B}(B^0 \to J/\psi\eta)} = 1.111 \pm 0.475\,(\text{stat}) \pm 0.058\,(\text{syst}) \pm 0.023\,(\mathcal{B}),$$

$$\mathbf{R}_{\eta'} = \left(\frac{\mathbf{\Phi}^{\eta'}}{\mathbf{\Phi}_s^{\eta'}}\right)^3 \frac{\tan^2\theta_C}{2} \tan^2\phi_P$$

$$\mathbf{R}_{\eta} = \left(\frac{\mathbf{\Phi}^{\eta}}{\mathbf{\Phi}_s^{\eta}}\right)^3 \frac{\tan^2\theta_C}{2} \cot^2\phi_P$$

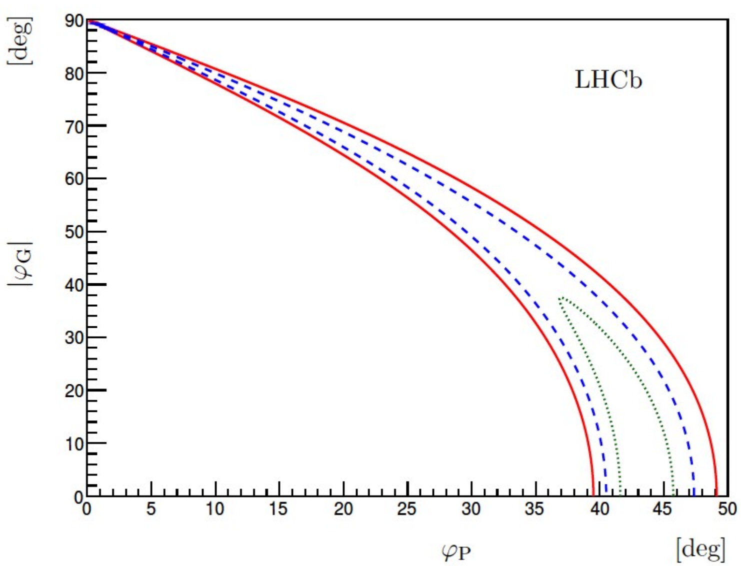
$$\phi_P = (46.3 \pm 2.3)^o$$

- **With gluonium content**

$$\frac{\mathbf{R}'}{\mathbf{R}'_s} = \tan^4\phi_P \qquad \mathbf{R}'\mathbf{R}'_s = \cos^4\phi_G$$

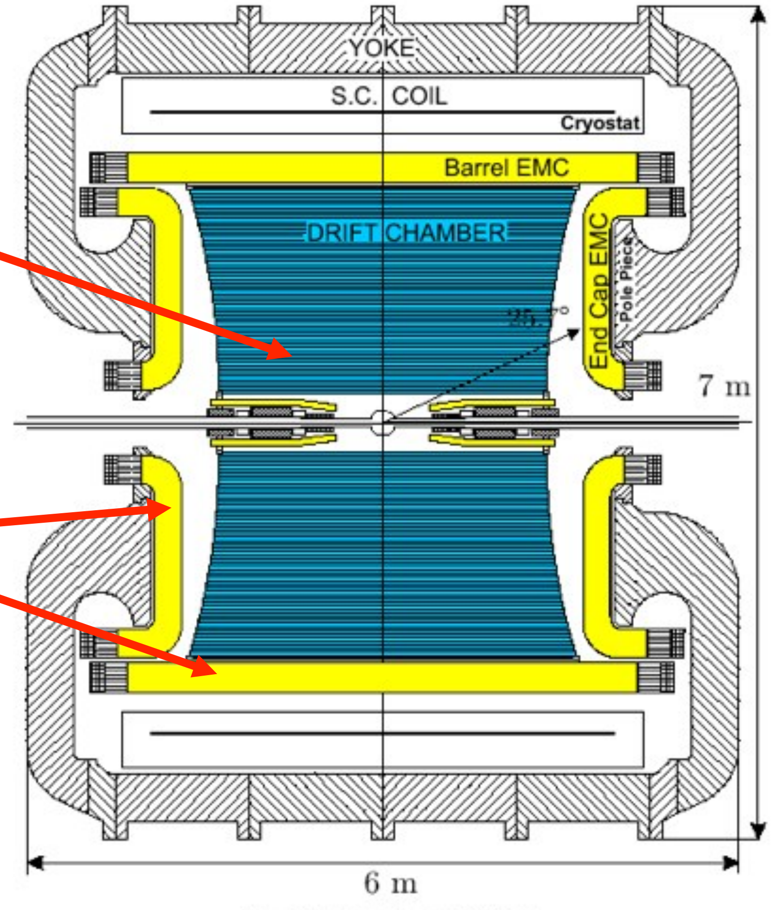
$$\mathbf{R}'_{(s)} = \mathbf{R}_{(s)} \left(\frac{\mathbf{\Phi}^{\eta}_{(s)}}{\mathbf{\Phi}^{\eta'}_{(s)}}\right)^3$$

$$\phi_P = (43.5^{+1.4}_{-2.8})^o \qquad \phi_G = (0.0 \pm 24.6)^o$$



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
- $\sigma_{vertex} \approx 1$ mm

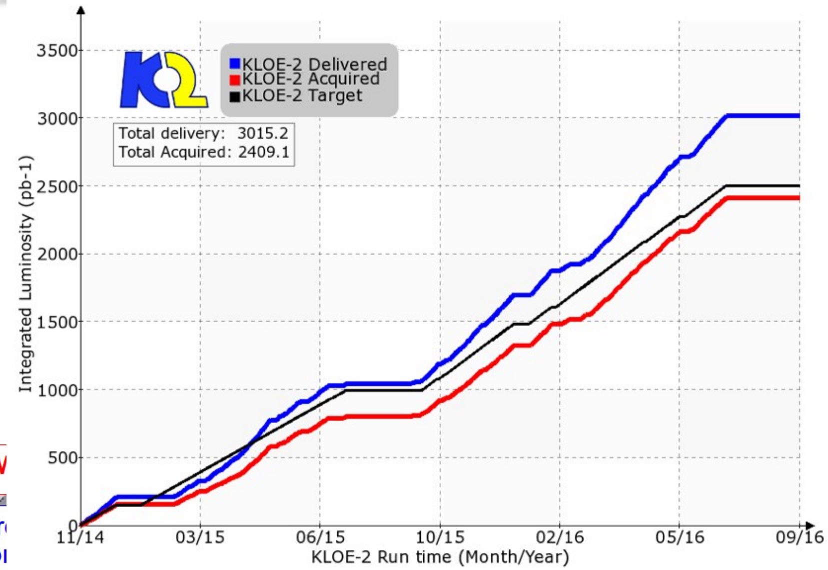


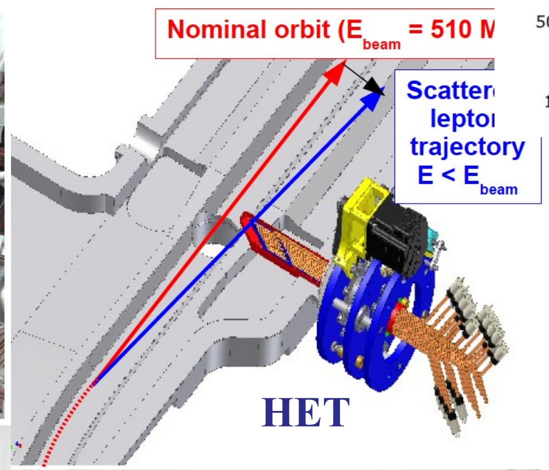
Calorimeter (Pb-Sci.Fi.):
- $\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_t = 55\ ps/\sqrt{E(GeV)} \oplus 100\ ps$
- 98% of 4π

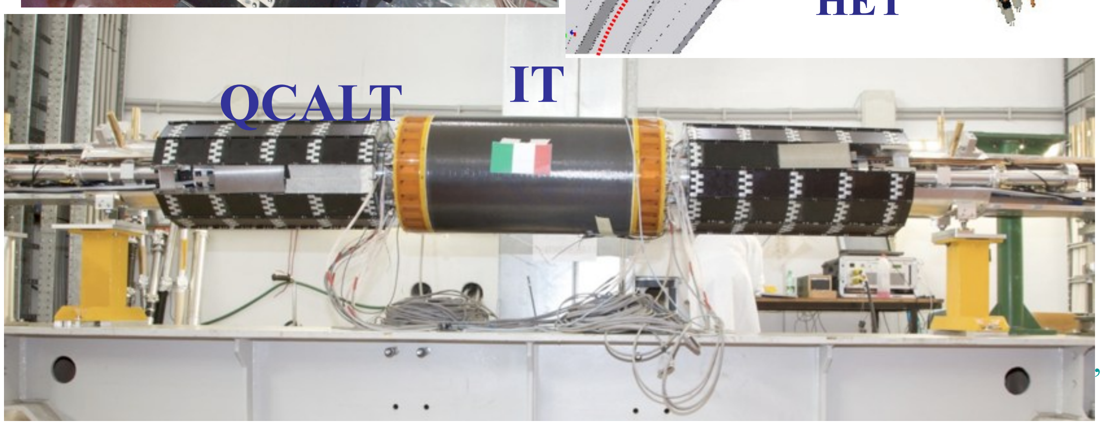
Magnetic field: 0.52 T

KLOE-2

- KLOE-2 data taking with the upgraded detector started on November 2014
- DAΦNE peak luminosity: 2.2×10^{32} cm^{-2} s^{-1}
- Integrated luminosity ~ 3 fb^{-1} (July 2016)
- KLOE-2 target ≥ 5 fb^{-1} by the end of 2017







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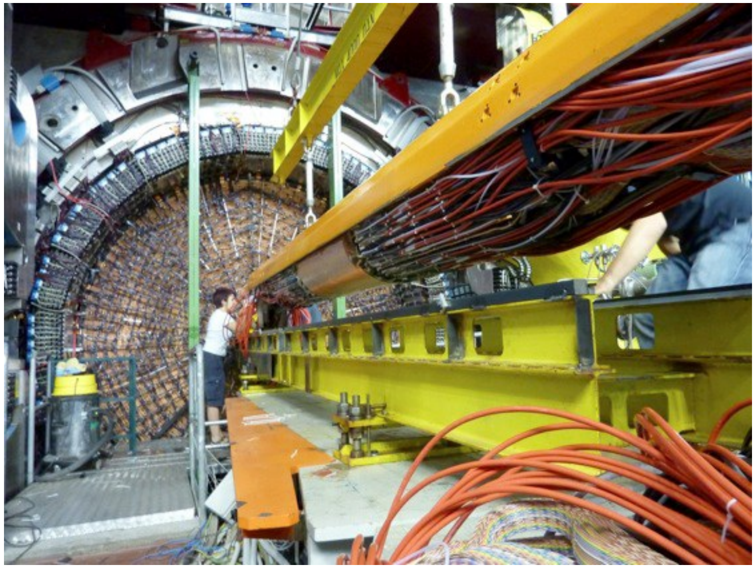
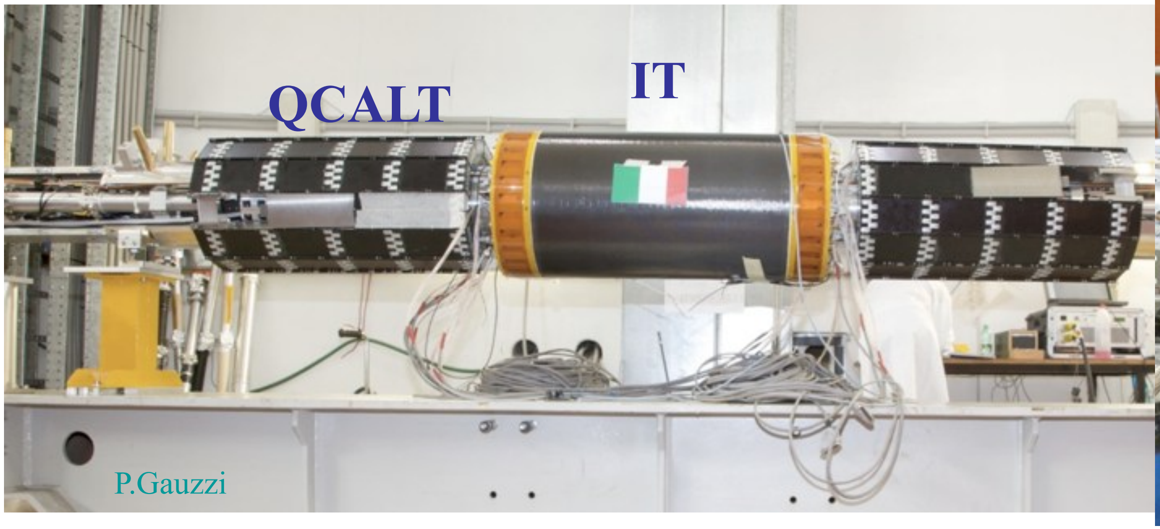
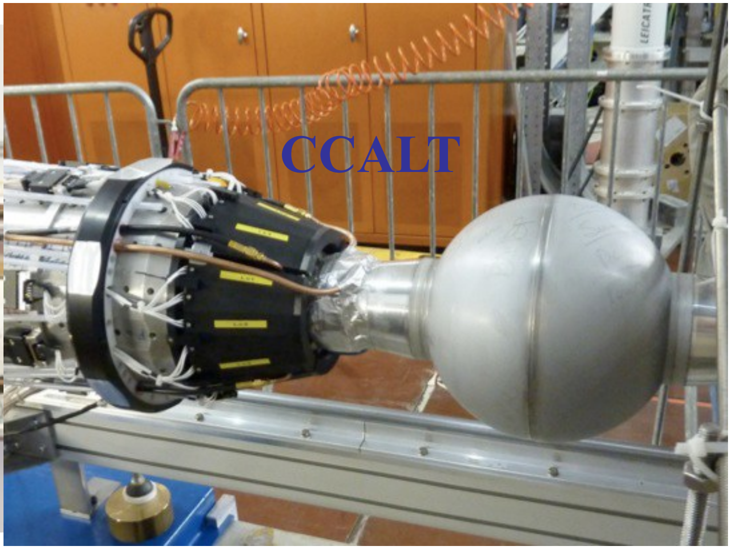
KLOE-2 upgrade

- Tagging system: LET + HET (see later)
- Inner Tracker : 4 layers of cylindrical triple GEM
  - improve acceptance for low momemtum tracks
  - better vertex recontruction
- QCALT: W + scint. tiles + SiPM
  - quadrupole coverage for K_L decays
- CCALT : LYSO + APD
  - increase acceptance for γ's from the IP (21° to 10°)







$\gamma\gamma$ physics @ KLOE-2

- KLOE-2 is running at the ϕ peak
- Large background from ϕ decays

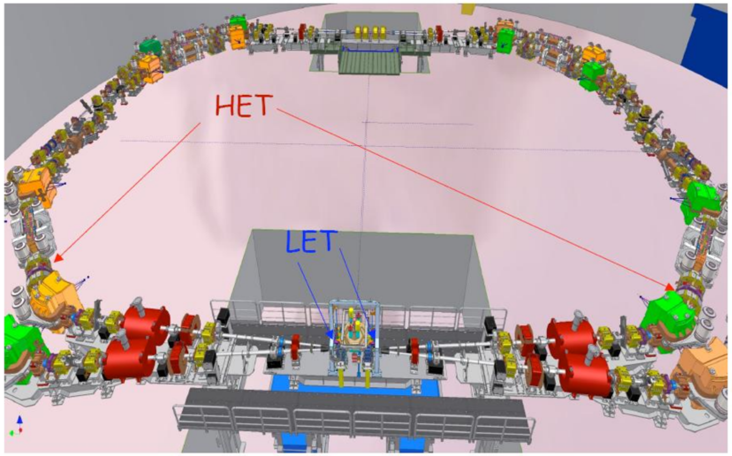
$\gamma\gamma$ process

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	$\sim 10^9$	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)K_L$	K_L	$\sim 2 \times 10^9$	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	$\sim 10^9$	
$\eta(\gamma\gamma)\gamma$	γ	$\sim 10^8$	η
$\pi^0(\gamma\gamma)\gamma$	γ	$\sim 5 \times 10^8$	π^0

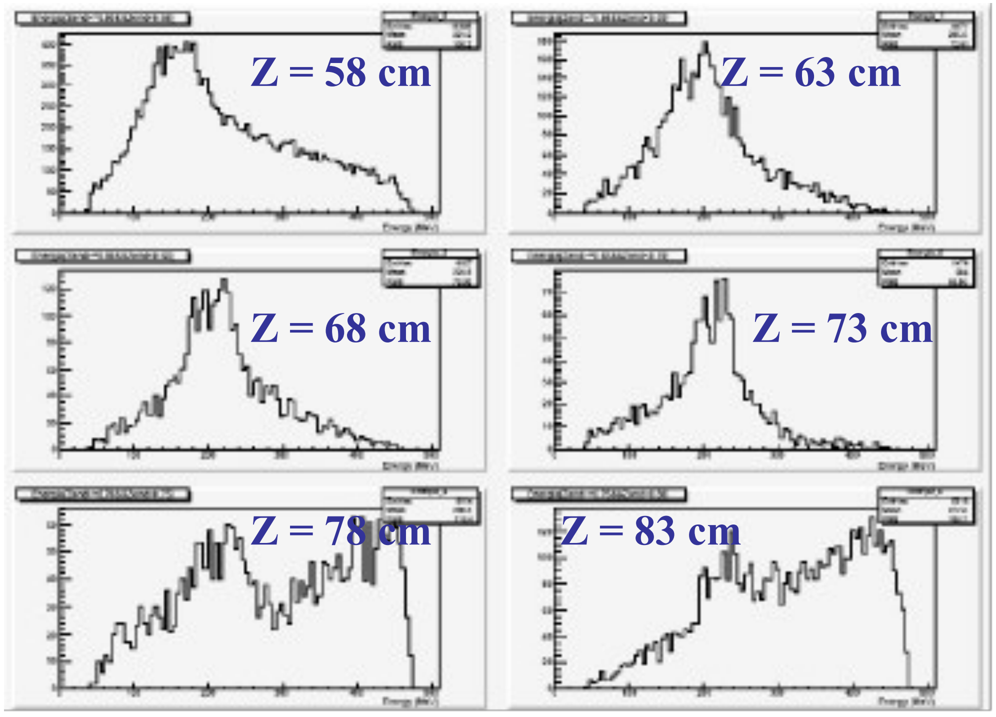
- Additional background from continuum processes

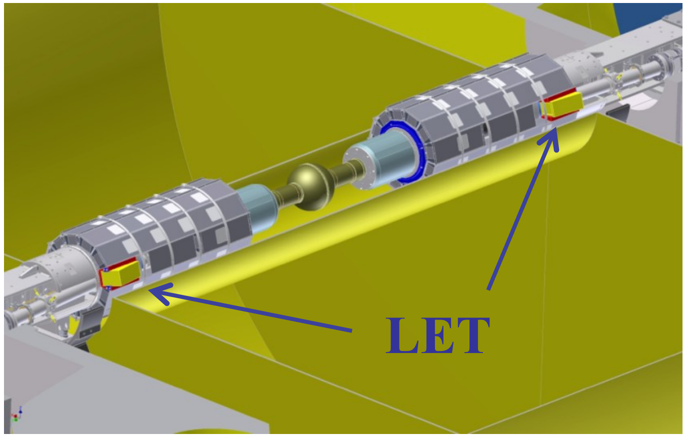


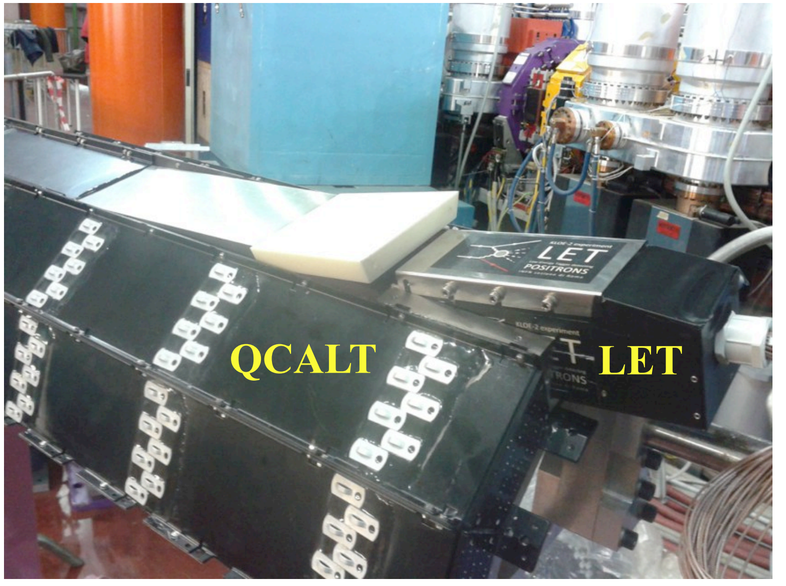
A tagging system is needed to reduce background

Low Energy Tagger

- **To detect e^+/e^- of E ≈ 150 – 350 MeV escaping from the beam-pipe**







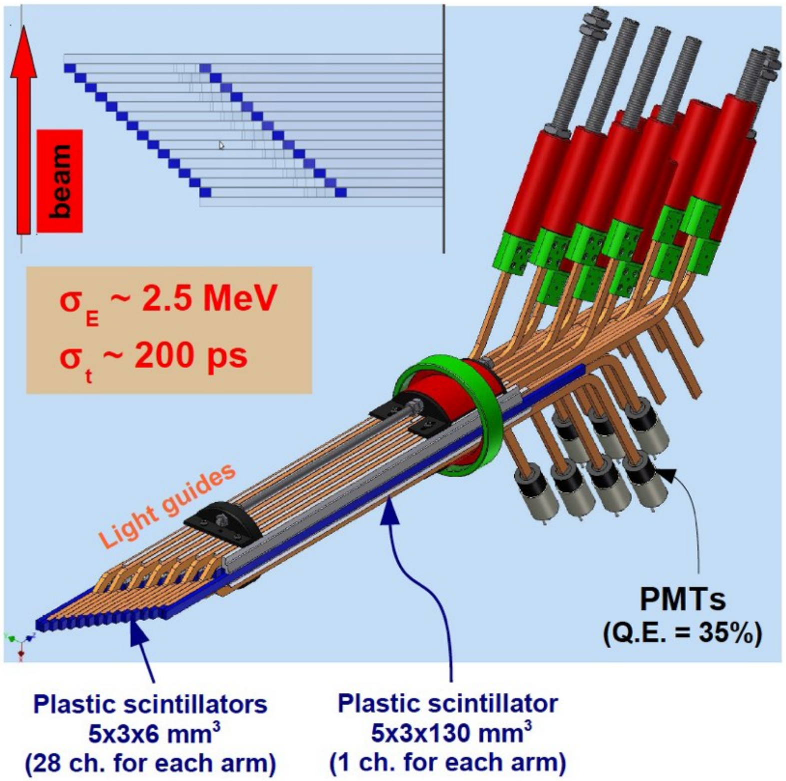
- **Weak correlation between E and scattering angle**

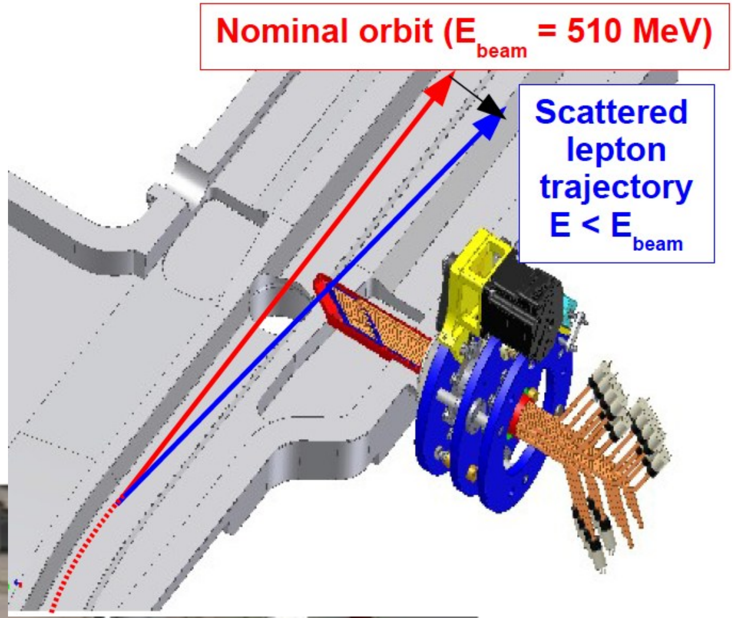
⇒ calorimeters: 20 × 2 LYSO crystals read-out by SiPM, placed at ~ 1 m from the IP

$\sigma_E/E < 10\%$ for E > 150 MeV

High Energy Tagger

- First bending dipole of DAΦNE acts as a spectrometer for the scattered e^+/e^-
  (420 < E < 495 MeV)
- Strong correlation between E and trajectory
- Scintillator hodoscope + PMTs; pitch: 5 mm placed at ~ 11 m from IP





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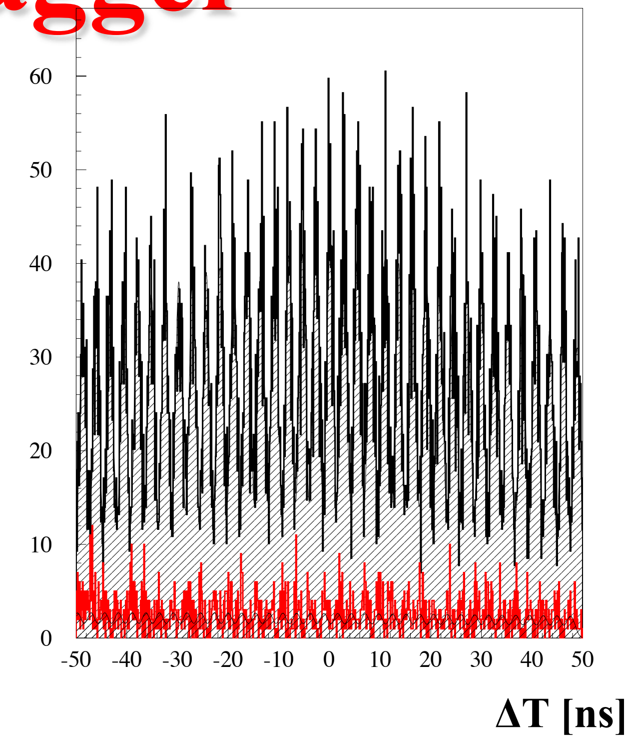
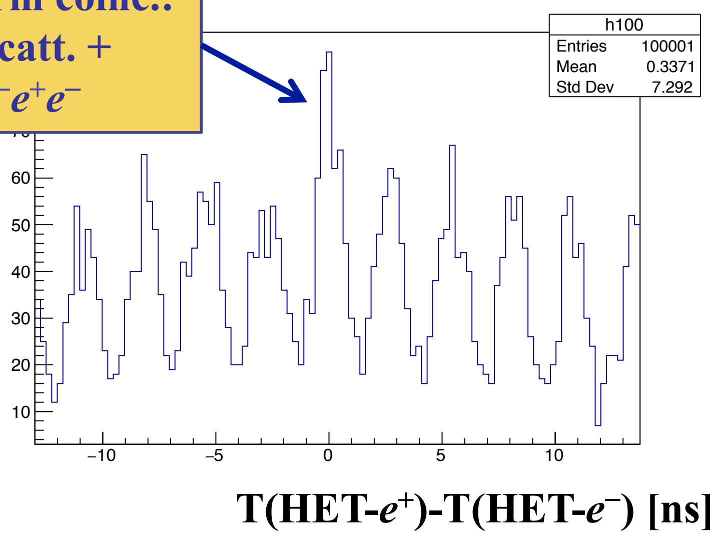
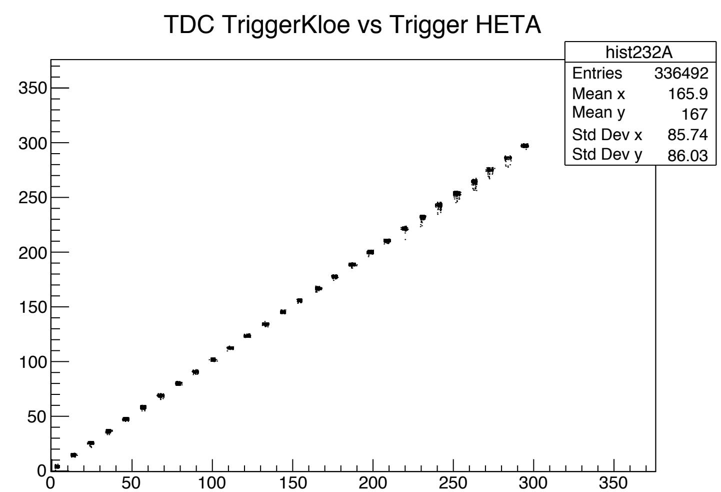
High Energy Tagger

- Low background (< 10%) evaluated with non colliding beams
- HET is acquired asynchronously w.r.t. the main KLOE detector
- HET signals corresponding to three DAΦNE revolutions are recorded for each KLOE trigger
- Synchronization is performed by using the “Fiducial” signal from DAΦNE

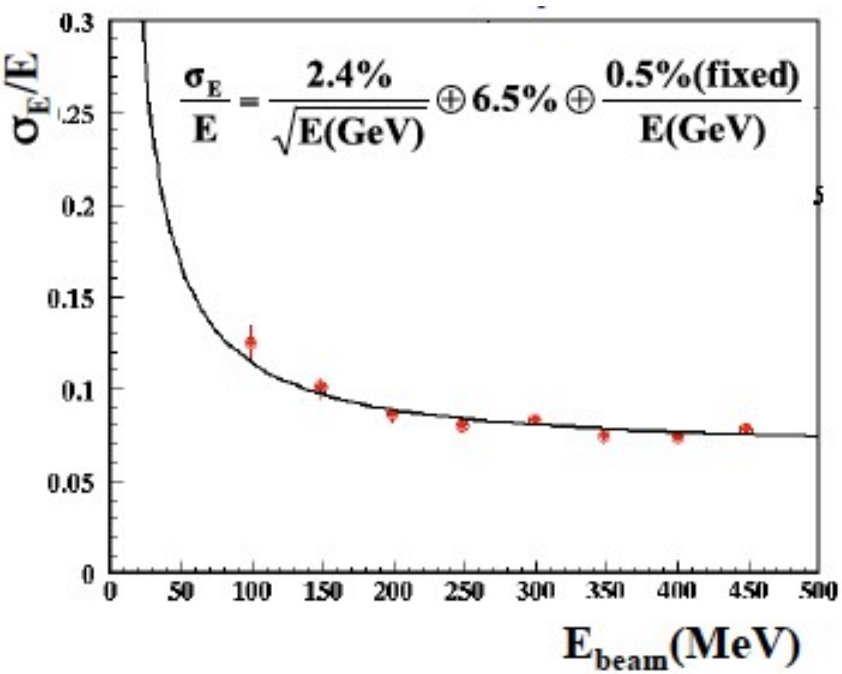


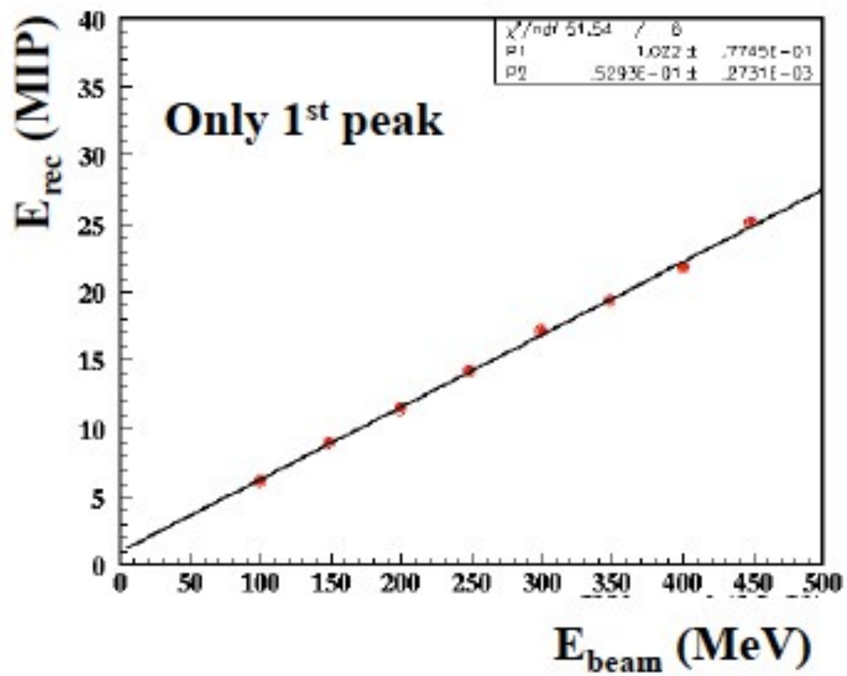
Double arm coinc.: Bhabha scatt. + $e^+e^-\rightarrow e^+e^-e^+e^-$





LET system and performance



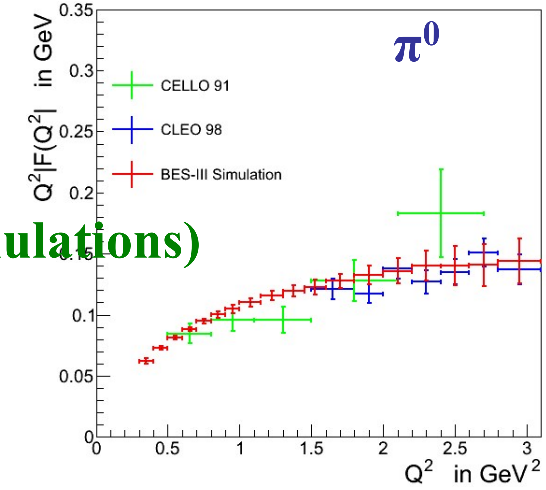


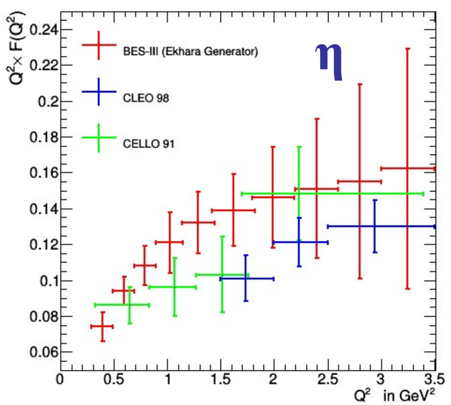
- 3rd term is fixed, since we have about 5 MeV noise
- Statistical term higher than expected (20 p.e./MeV → less than 1%/ $E^{1/2}$(GeV))
- Contribution to constant term due to lateral leakage (matrix not fully readout)
- There is an unknown contribution from the beam
- Resolution is better than 10% for E > 150 MeV

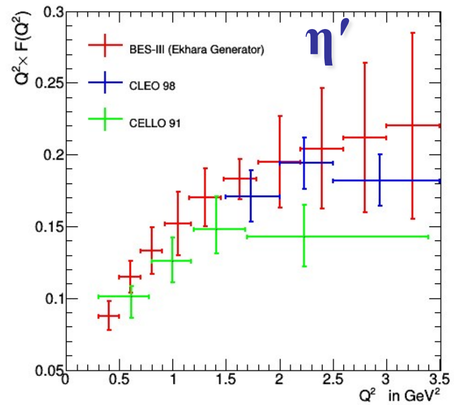
$F_{P\gamma\gamma^*}(Q^2)$

- BESIII, **single tag** L = 2.9 fb^{-1} collected at the ψ(3770) peak ⇒ $F(Q^2,0)$ at $0.3 < Q^2 < 3$ GeV^2 analyzed
  Study of systematics in progress

(BESIII simulations)

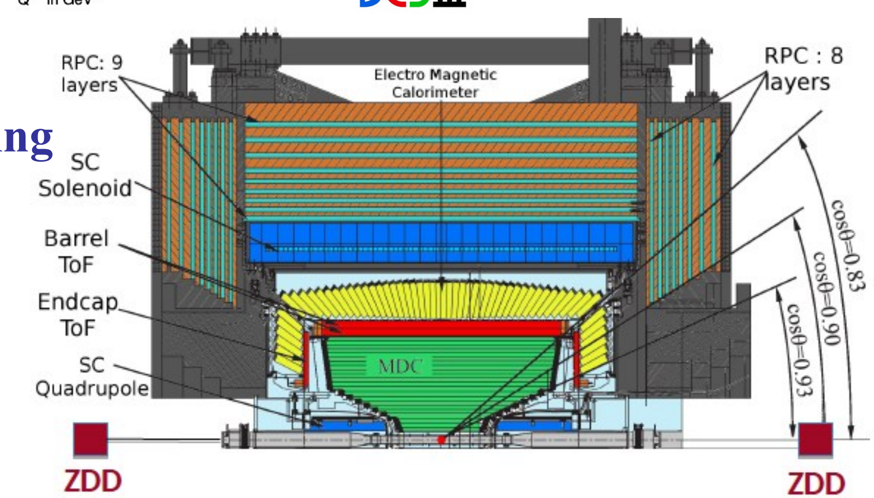






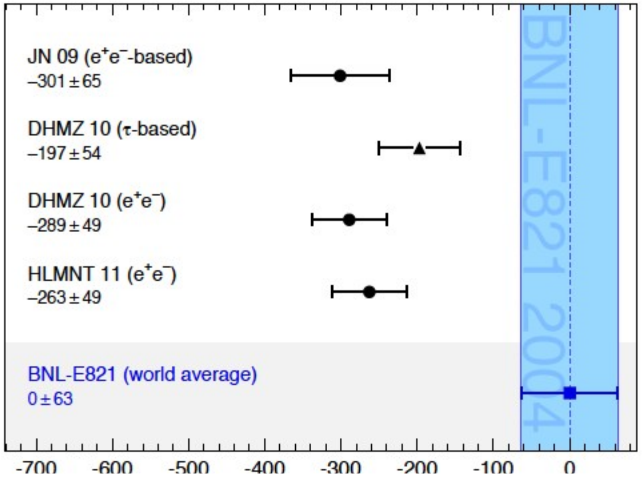
- **Tagger:** Zero Degree Detector (Pb + scintillating fibers) ⇒ Polar angle range : 1 – 10 mrad
- Upgrade foreseen with $PbWO_4$ calorimeters

BESIII



Muon g-2

- **Well knowk discrepancy between the expt. and the theoretical value of the muon anomaly [$a_\mu = (g_\mu - 2)/2$]**



- **$a_\mu^{exp} = 11659\ 208.9 \pm 6.3 \times 10^{-10}$ BNL-E821 (2006) (future g-2 expts at FNAL and J-PARC goal: reduce the uncert. on a_μ^{exp} from 0.54 to 0.14 ppm)**

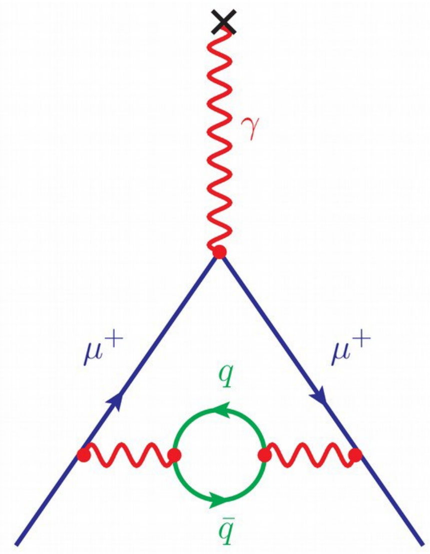
- $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$

Contribution	in units of 10^{-10}
QED	11658471.895 ± 0.008
Weak	15.4 ± 0.2
HVP(leading order)	692.3 ± 4.2
HVP(higher order)	-9.79 ± 0.07
HLBL	11.6 ± 4.0
Total	11659181.4 ± 5.8

Kinoshita et al., PRL 109 (2012) 111808
Czarnecki et al., PRD 67 (2003) 073006 + Erratum
Davier et al., EPJC 17 (2011) 1515 + Erratum
Hagiwara et al., CPC 34 (2010) 728
Jegerlehner, Nyffler, Phys.Rept. 477 (2009) 1

$$a_\mu^{exp} - a_\mu^{SM} = (31.25 \pm 8.54) \times 10^{-10} \Rightarrow \sim 3.7\ \sigma$$

Muon g-2

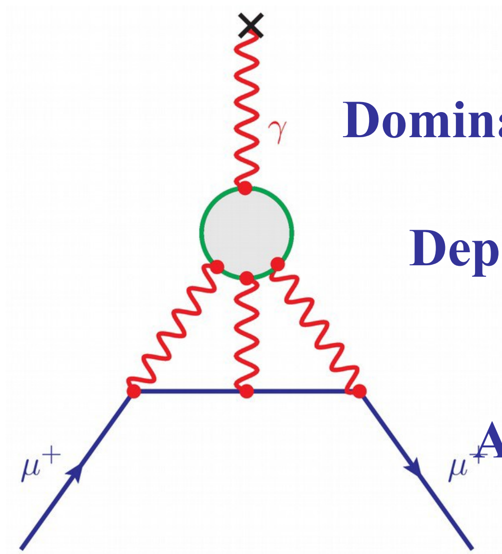


- Main contribution to the uncertainty ⇒ Hadronic Vacuum Polarization

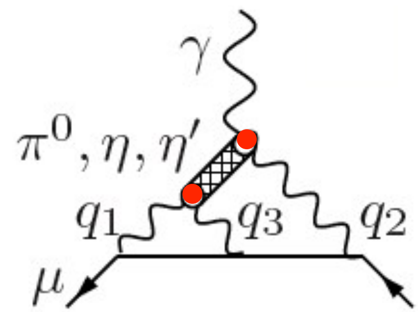
  Evaluated from the total $\sigma(e^+e^- \to \text{hadrons})$ via Dispersion Relation ⇒ accuracy increasing

- Second contribution ⇒ Hadronic Light-by-Light Scattering

  Will become dominant in the future



Dominated by single pseudoscalar exchange

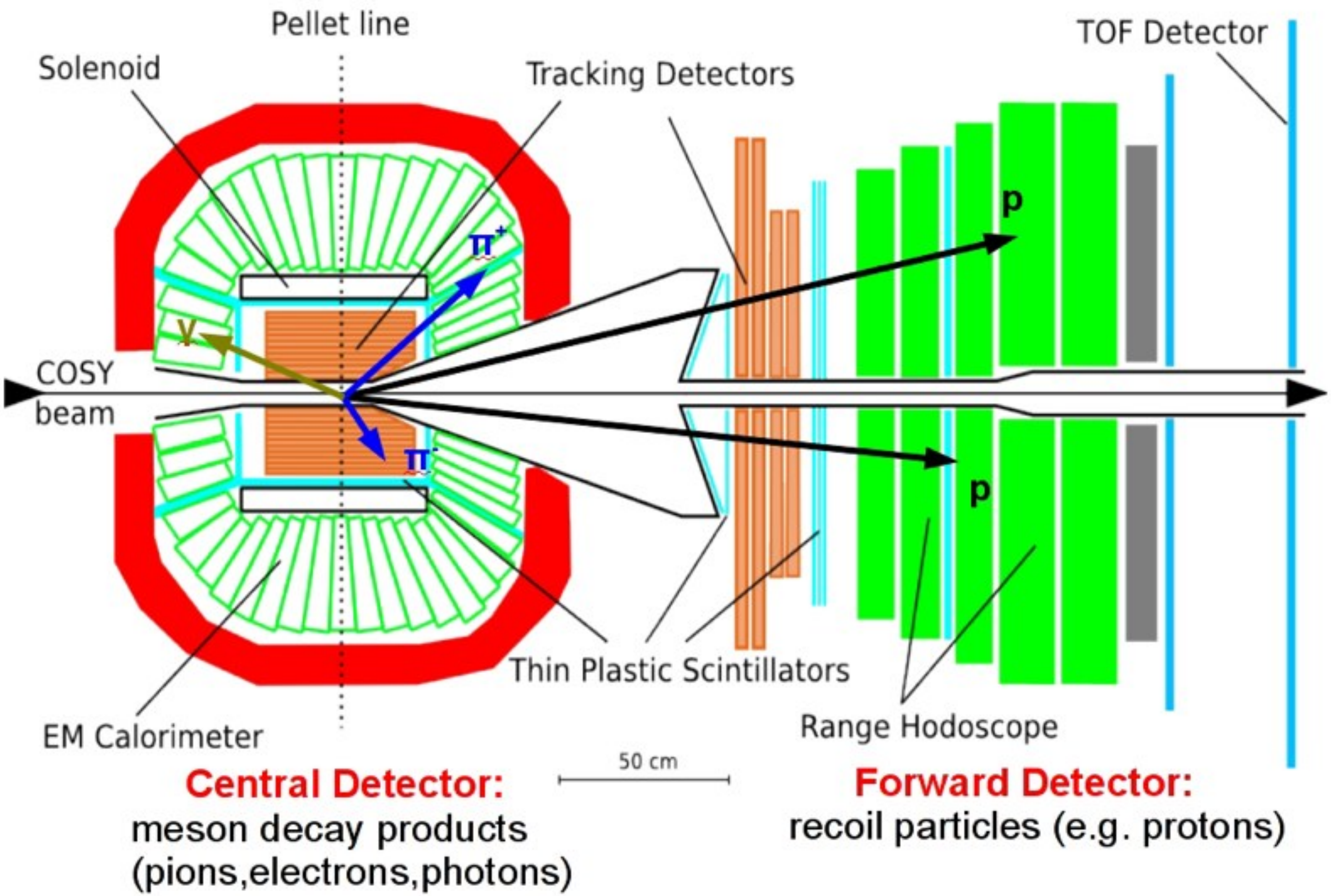


Depends on TFF parametrization

Also pion loop important

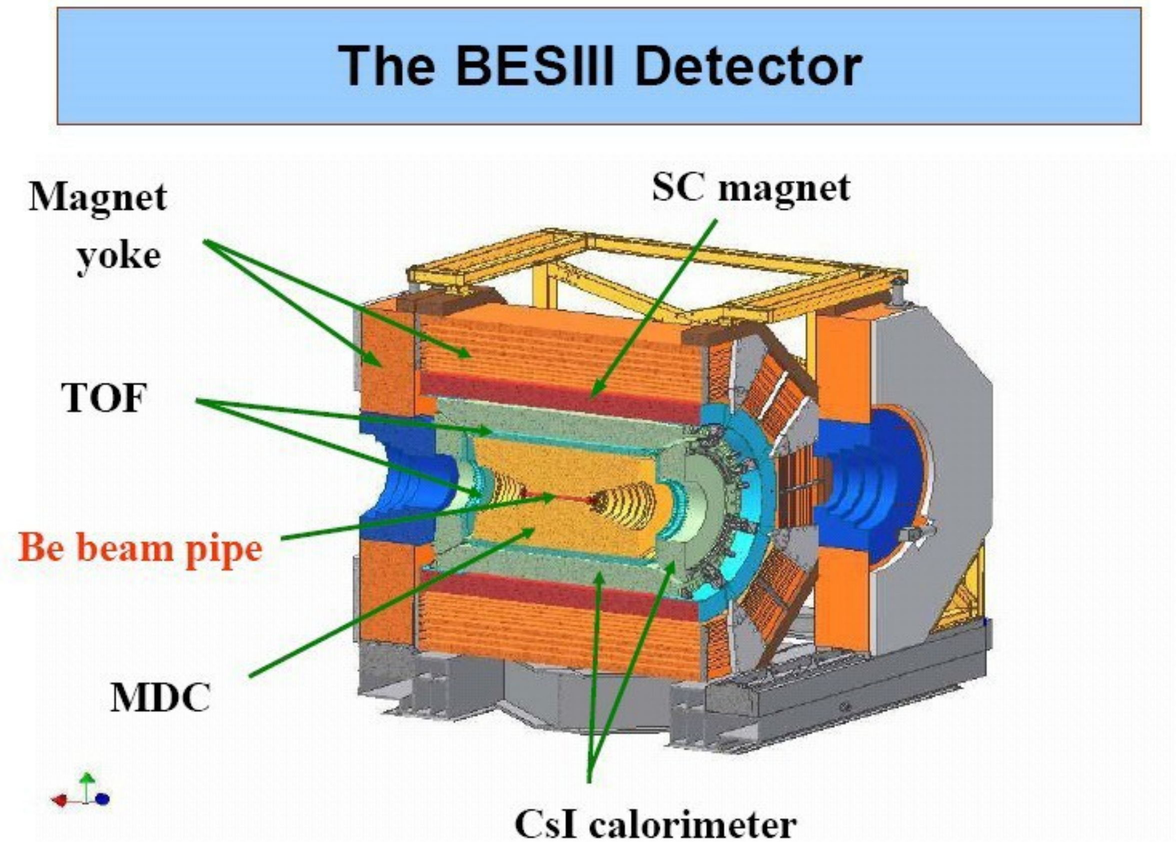
Dispersion Relations ⇒ related to $\gamma\gamma \to \pi\pi$ partial waves

WASA



Pellet line
Solenoid
Tracking Detectors
TOF Detector
COSY
beam
γ
π+
π-
p
p
Thin Plastic Scintillators
Range Hodoscope
EM Calorimeter
50 cm
Central Detector:
meson decay products
(pions,electrons,photons)
Forward Detector:
recoil particles (e.g. protons)

BESIII



- Main Drift Chamber (MDC)
  $\sigma(p)/p = 0.5\%$
  $\sigma_{dE/dx} = 6.0\%$
- Time-of-flight system (TOF)
  $\sigma(t) = 90ps$ (barrel)
  $\sigma(t) = 110ps$ (endcap)
- EMC
  6240 CsI(Tl) crystals
  $\sigma(E)/E = 2.5\%$
  $\sigma_{Z,\Phi}(E) = 0.5 – 0.7$ cm
- Muon Chambers
  8 – 9 layers of RPC
  p>400 MeV/c
  $\delta R\Phi = 1.4 \sim 1.7$ cm
- Superconducting Magnet
  1 T magnetic field