Measurement of the running of the fine structure constant and $\gamma - \gamma$ physics at KLOE2

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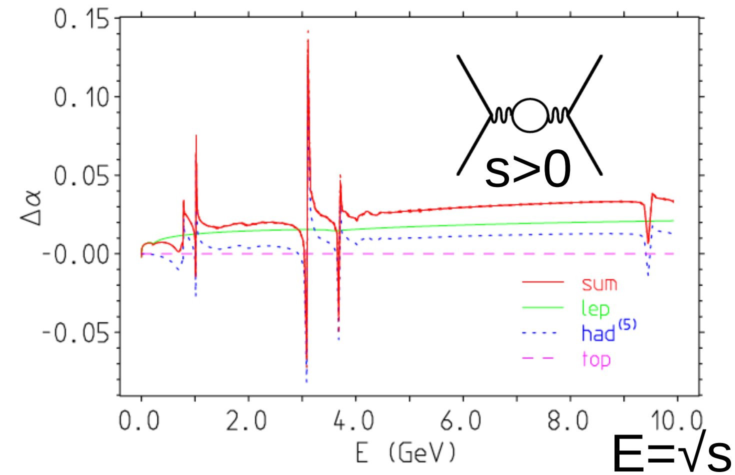
September 20, 2016

Outline

- New $e^+e^- \to \mu^+\mu^-\gamma$ cross section measurement
- Measurement of the $\alpha(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$ process
- Extraction of Real and Imaginary part of $\Delta\alpha(s)$
- Measurement of BR($\omega \to \mu^+\mu^-$)from $e^+e^- \to \mu^+\mu^-\gamma$ process
- $\gamma\gamma$ Physics at KLOE-2
- Conclusions

α running and the Vacuum Polarization

- Due to Vacuum Polarization effects $\alpha(q^2)$ is a running parameter from its value at vanishing momentum transfer to the effective q^2.



- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:

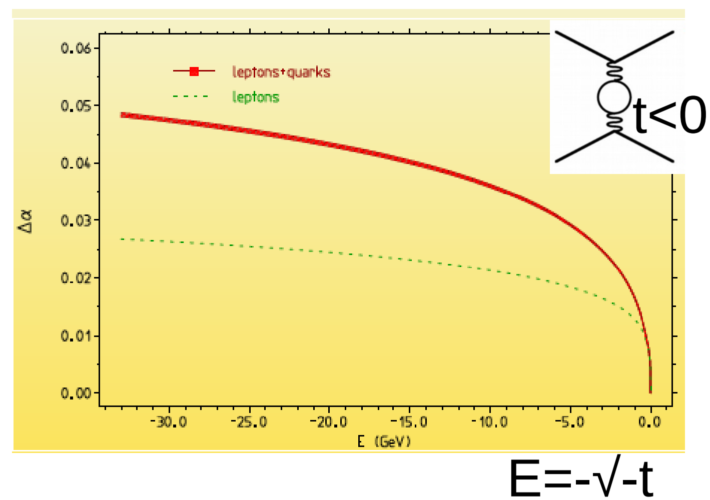
$$e^2 \rightarrow e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))};$$

$$\alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha} \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

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

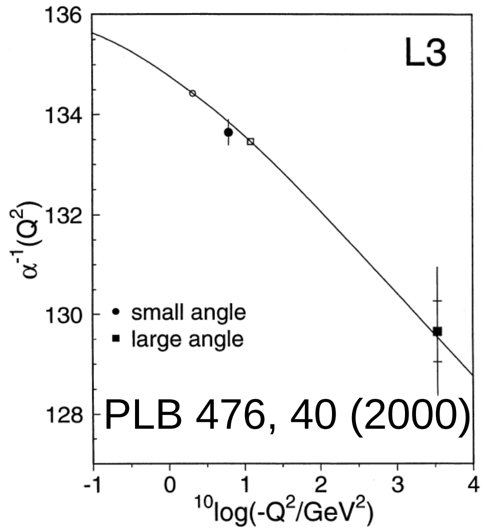
$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

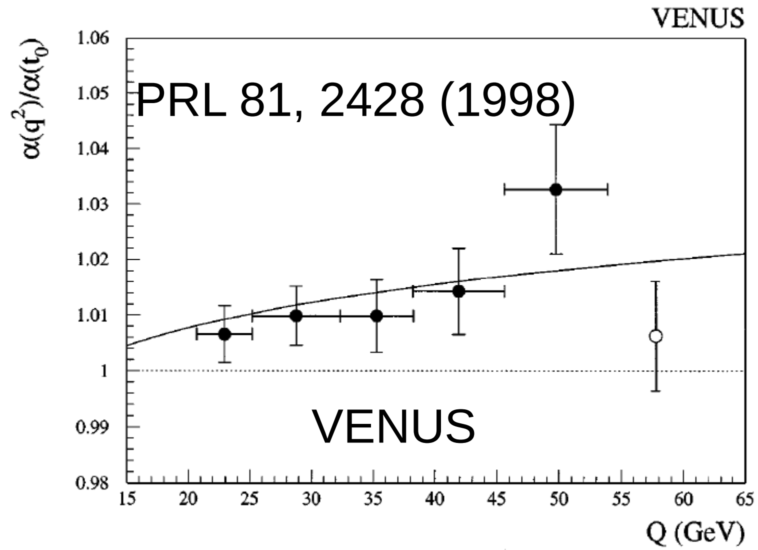
- $\Delta\alpha$ takes a contribution by non perturbative hadronic effects ($\Delta\alpha^{(5)}_{had}$) which exhibits a different behaviour in time-like and spacelike region

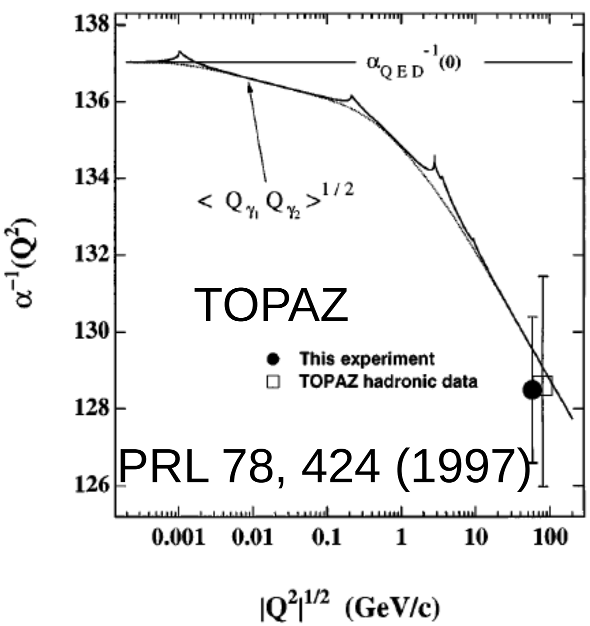


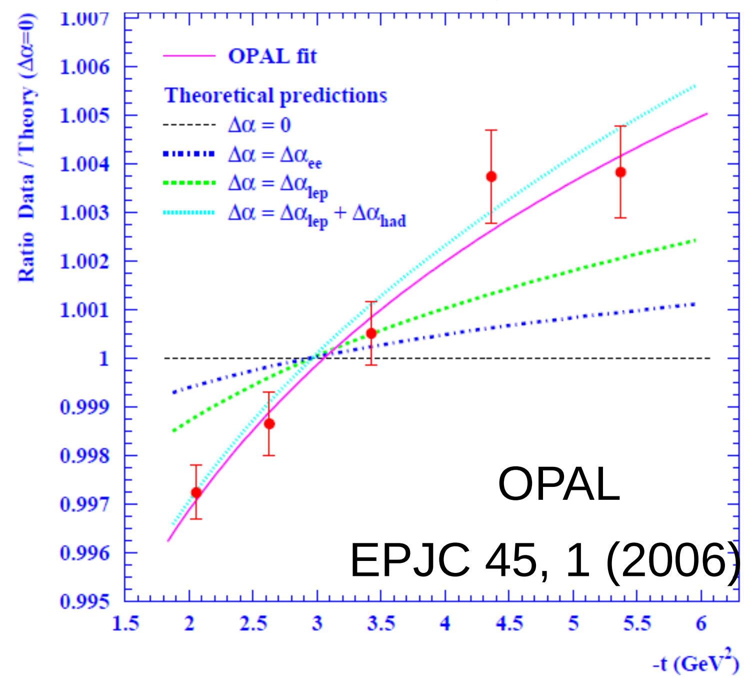
Existing measurements

Very few measurements of the running of the α coupling constant has been performed up to now, most of them in spacelike region and only one direct measument in timelike region (TOPAZ) at large momentum transfer.









KLOE measurement of α(s) below 1 GeV

- Measurement of the running of the fine structure constant α in the time-like region $0.6<\sqrt{s}<0.975$ GeV obtained via :

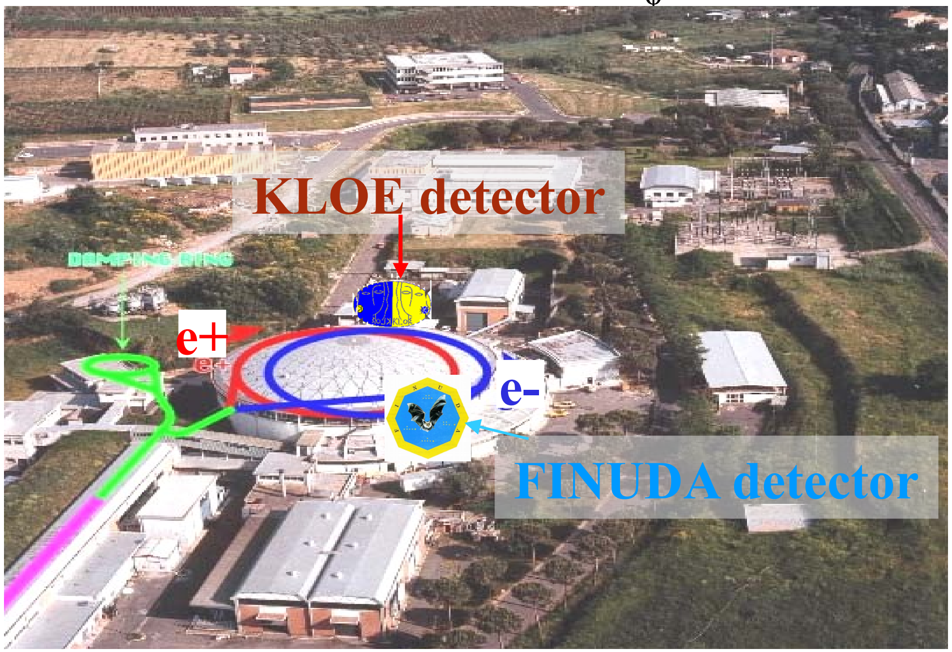
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{d\sigma_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}}{d\sigma^0_{MC}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}} \quad : \frac{\text{data}}{\text{MC with } \alpha(s) = \alpha(0)}$$

FSR correction done by by using PHOKHARA MC event generator

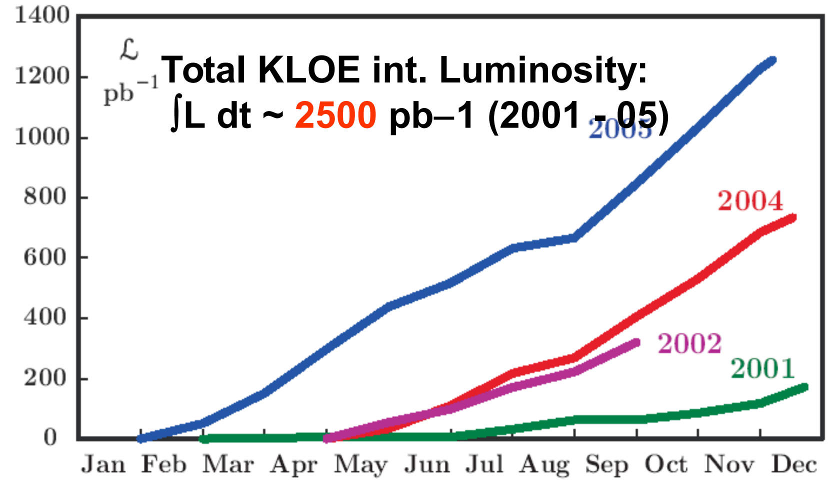
- Statistical significance of the hadron contribution to the running α(s) is evaluated
- for the first time in a single experiment the real and Imaginary part of Δα
- Measurement of BR($\omega \to \mu^+\mu^-$) .

DAΦNE: A φ-Factory in Frascati (near Rome)

e^+e^- collider with $\sqrt{s} = m_\phi \approx 1.0195$ GeV



Integrated Luminosity



Peak Luminosity $L_{peak} = 1.5 \cdot 10^{32} cm^{-2}s^{-1}$

α-running and mmg cross section measurement (paper ready for submission) ***based on 1.7 fb^{-1} of 2004-2005 KLOE data***

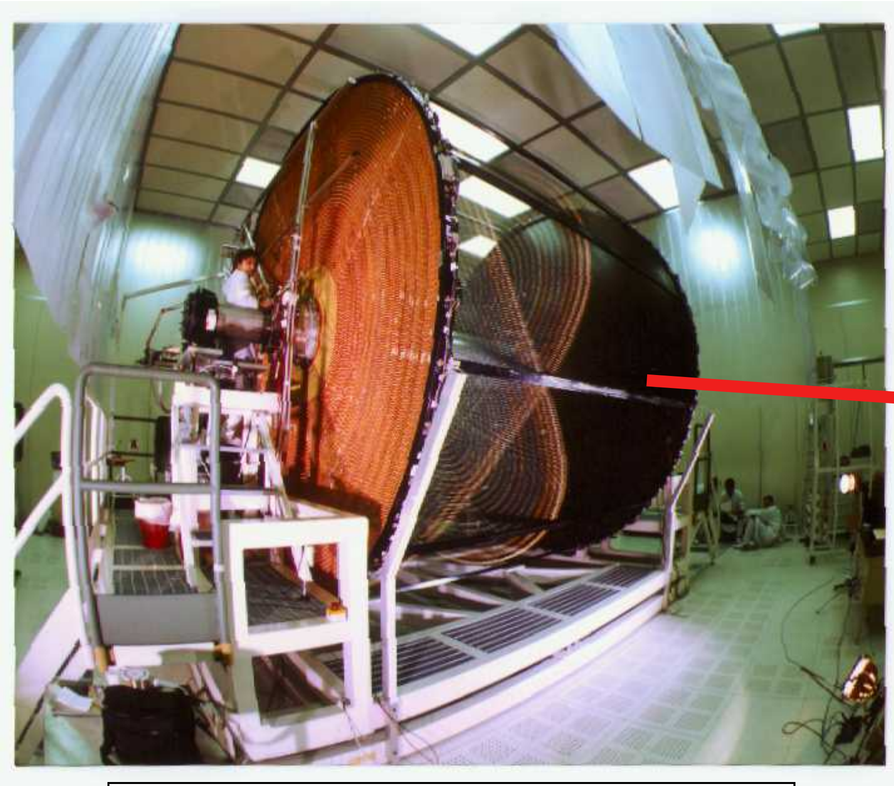
Two-pion KLOE10 mesurement (PLB700 (2011)102) ***based on 233 pb^{-1} of 2006 data (at 1 GeV, different event selection)***

Two-pion KLOE08 measurement (PLB670(2009)285) ***was based on 240pb^{-1} of 2002 data***

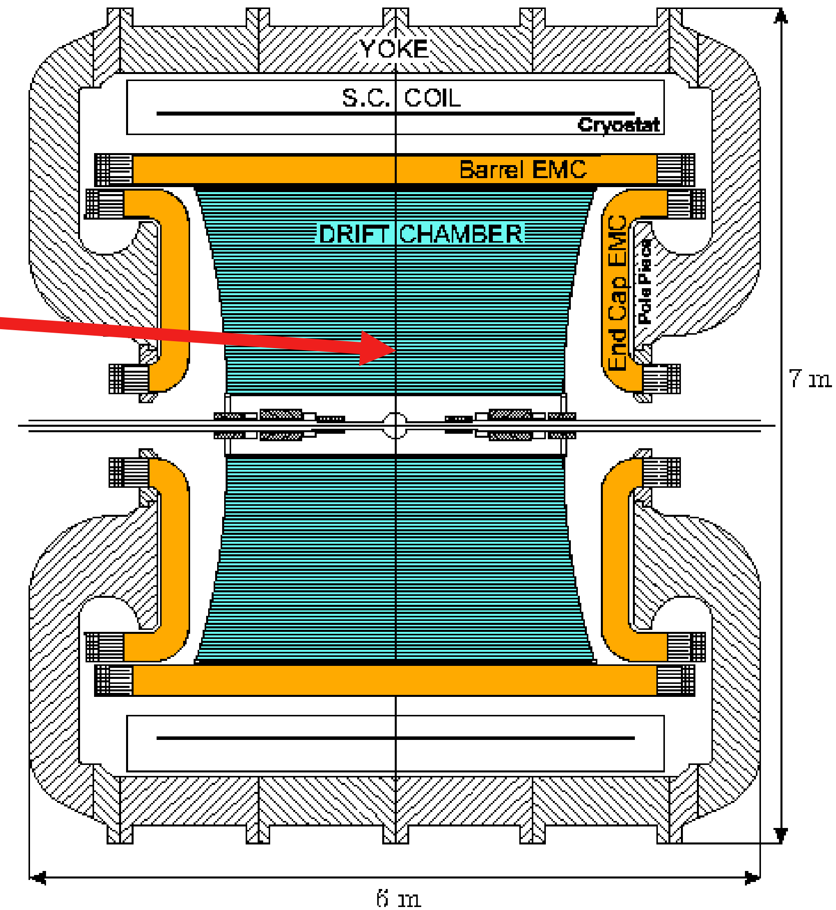
KLOE12 measurement (PLB720(2013)336) ***based on 240 pb^{-1} of 2002 data (from ππγ/μμγ ratio)***

KLOE Detector

Drift chamber



Full stereo geometry, 4m diameter,
52140 wires 90% Helium, 10% iC_4H_{10}



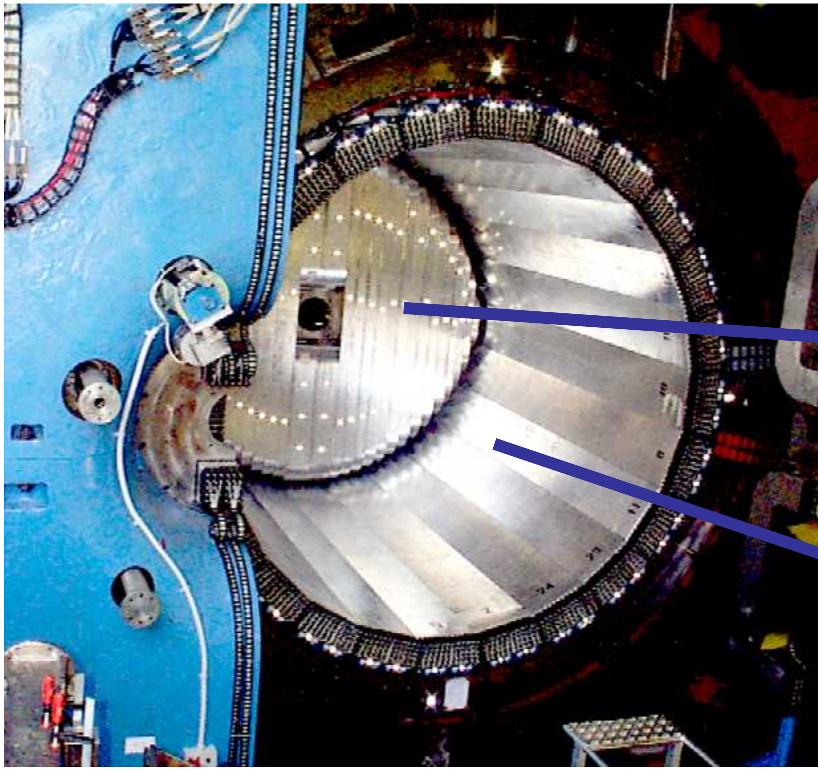
σ_p/p = 0.4% (for 90^0 tracks)

$\sigma_{xy} \approx 150\ \mu m$, $\sigma_z \approx 2$ mm

Excellent momentum resolution

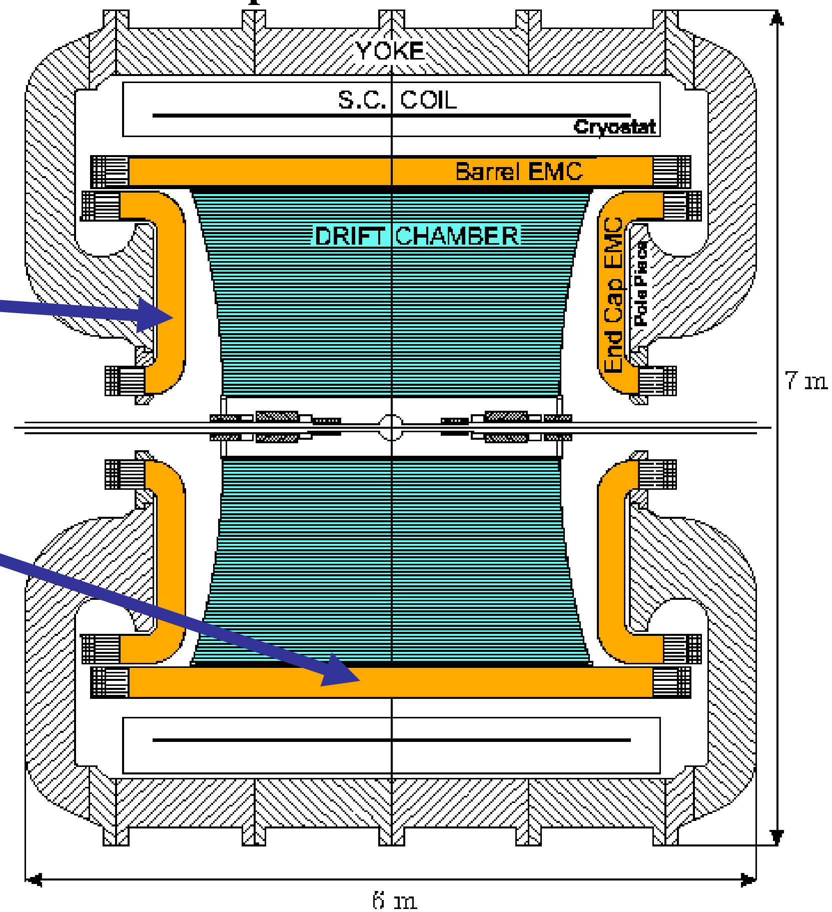
KLOE Detector

Electromagnetic Calorimeter



Pb / scintillating fibers (4880 PMTs)

Endcap - Barrel - Modules



$\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$

$\sigma_T = 54 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 100 \text{ ps}$

(Bunch length contribution subtracted from constant term)

Excellent timing resolution

Event Selection

KLOE

muon tracks at large angles

$50^o < \theta_\mu < 130^o$

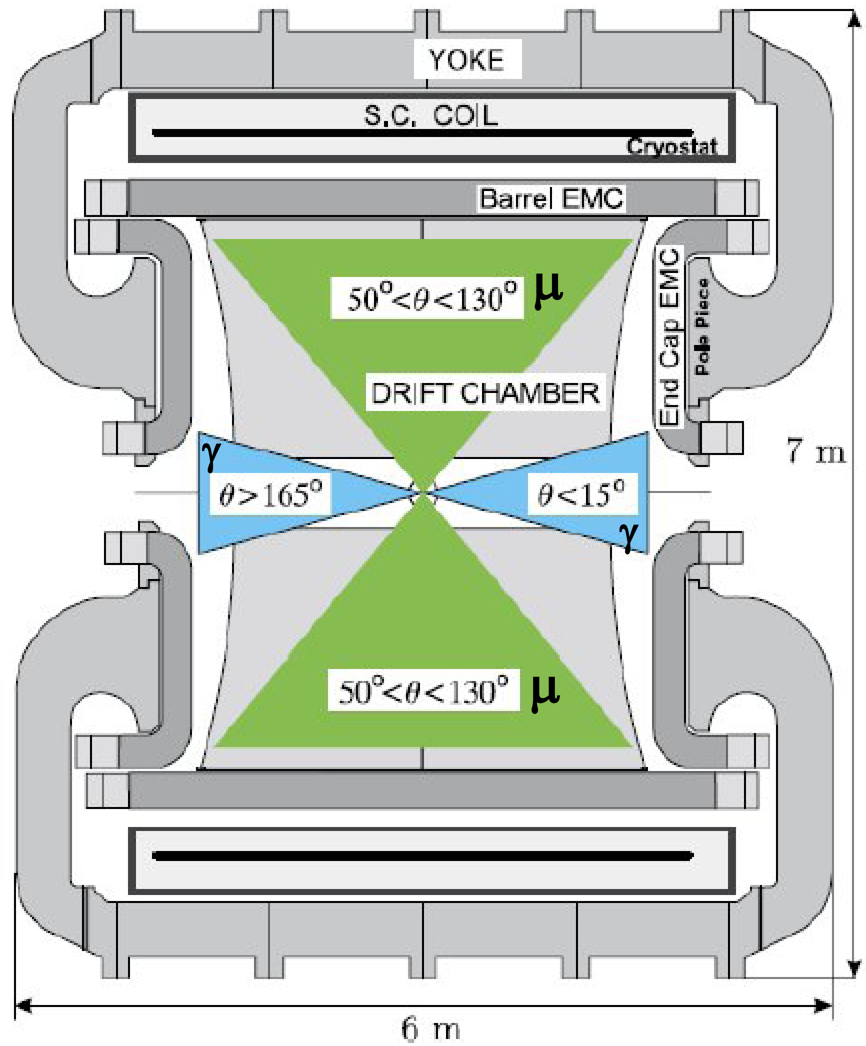
a) Photons at small angles

$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

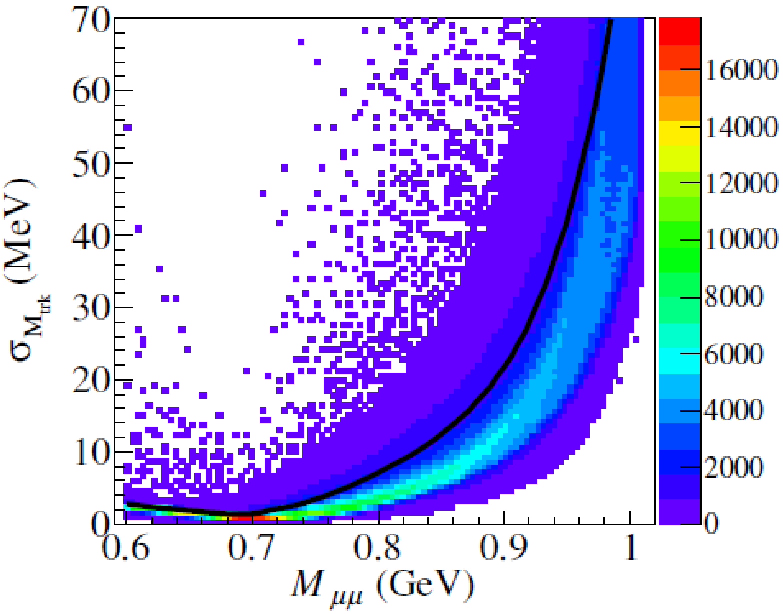
→ Photon momentum from kinematics:

$$\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$$

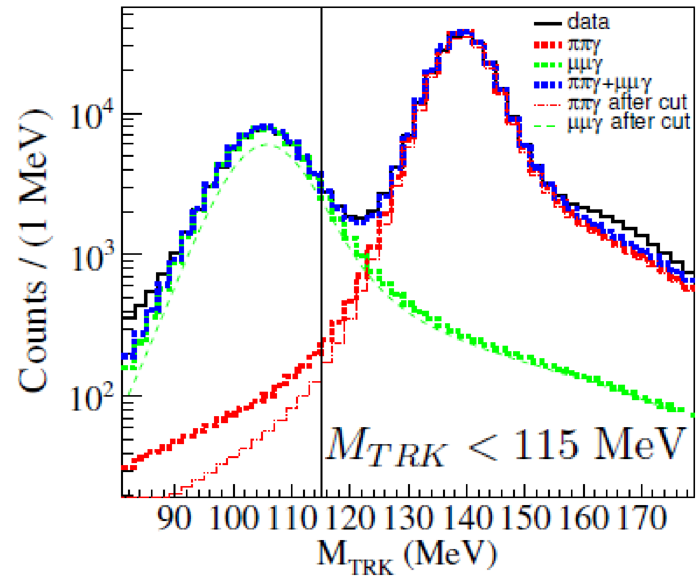
- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination



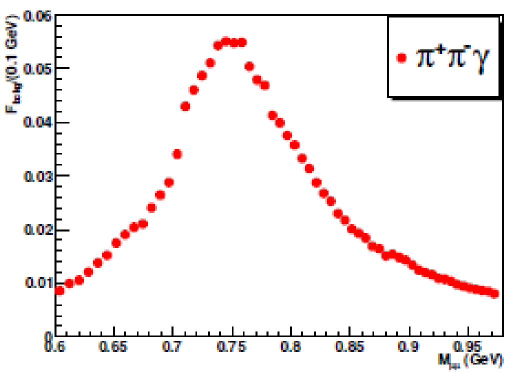
Main cuts

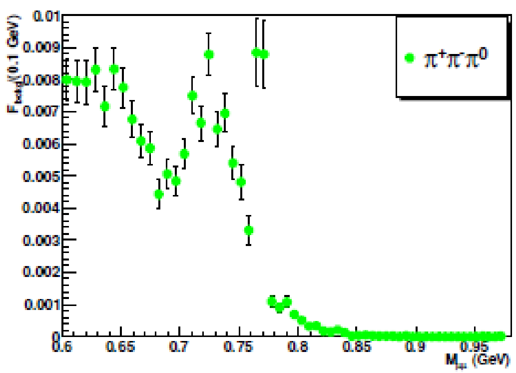


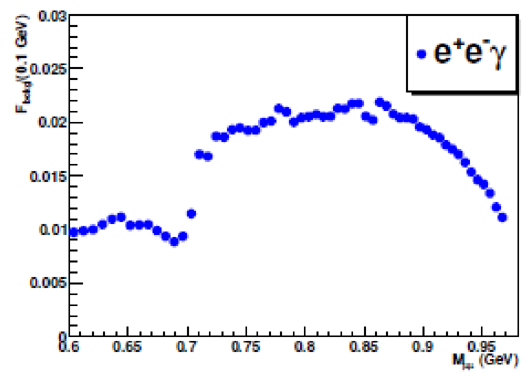
$$(\sqrt{s} - \sqrt{|p_+|^2 + M_{TRK}^2} - \sqrt{|p_-|^2 + M_{TRK}^2})^2 - (p_+ + p_-)^2 = 0$$



Main residual background:





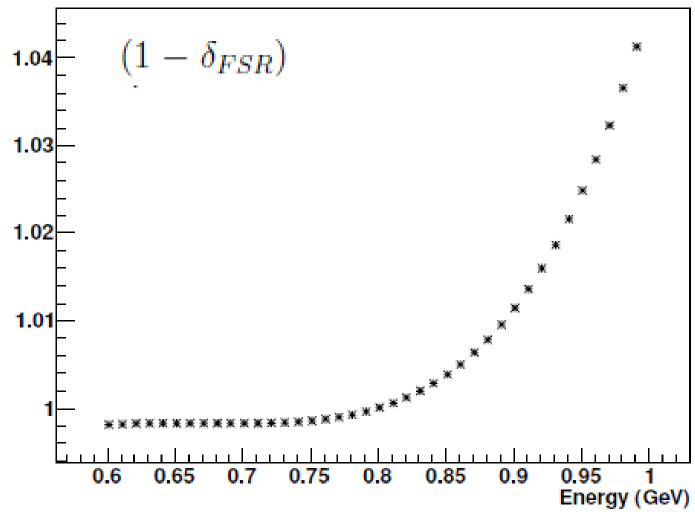


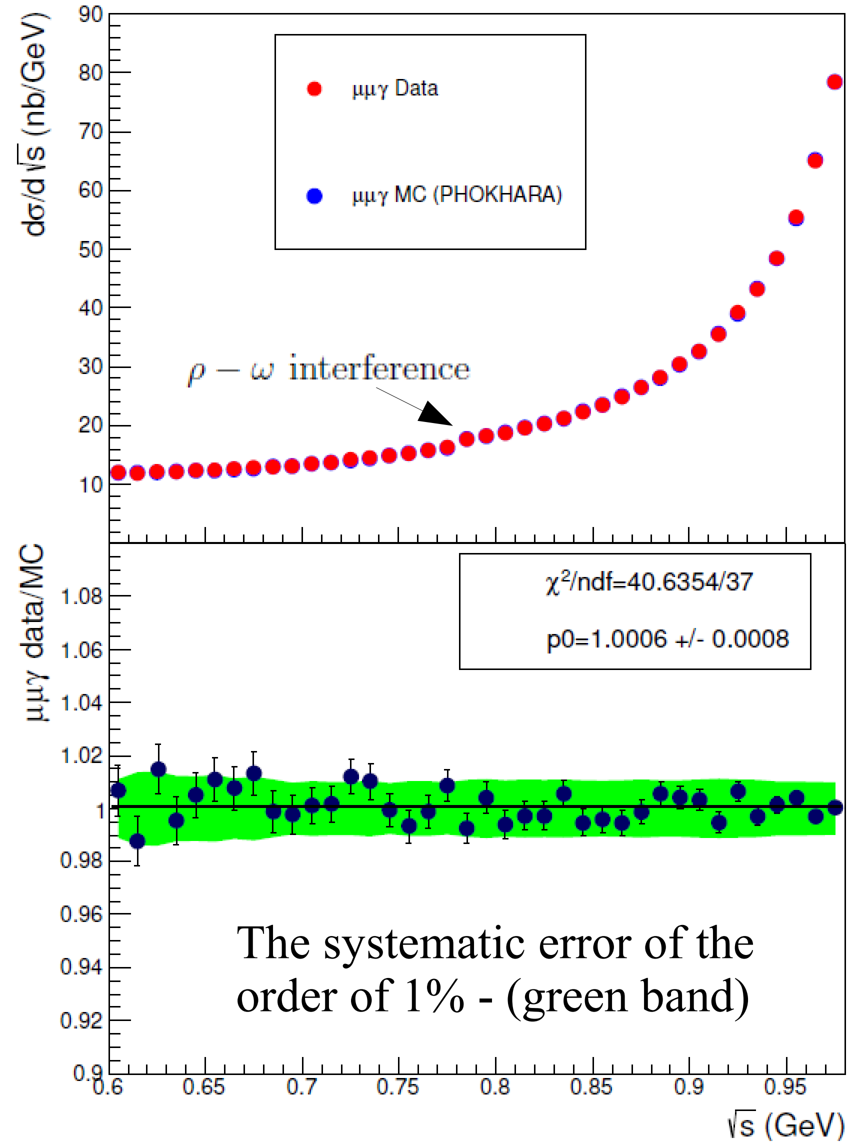
About 4.5 x 10^6 events pass these selection criteria.

μμγ cross section measurement

$$\left.\frac{d\sigma(e^+e^- \to \mu^+\mu^-\gamma(\gamma))}{d\sqrt{s}}\right|_{ISR} = \frac{N_{obs} - N_{bkg}}{\Delta\sqrt{s}} \cdot \frac{(1-\delta_{FSR})}{\epsilon(\sqrt{s}) \cdot L}$$

FSR Correction





Integrated Luminosity 1.7 fb^{-1}

Excellent agreement with NLO QED dressed cross section (with VP effects) H. Czy_z, A. Grzelinska, J.H. Khn, G. Rodrigo, Eur. Phys. J. C 39 (2005) 411.

Meas. of the running of α(s)

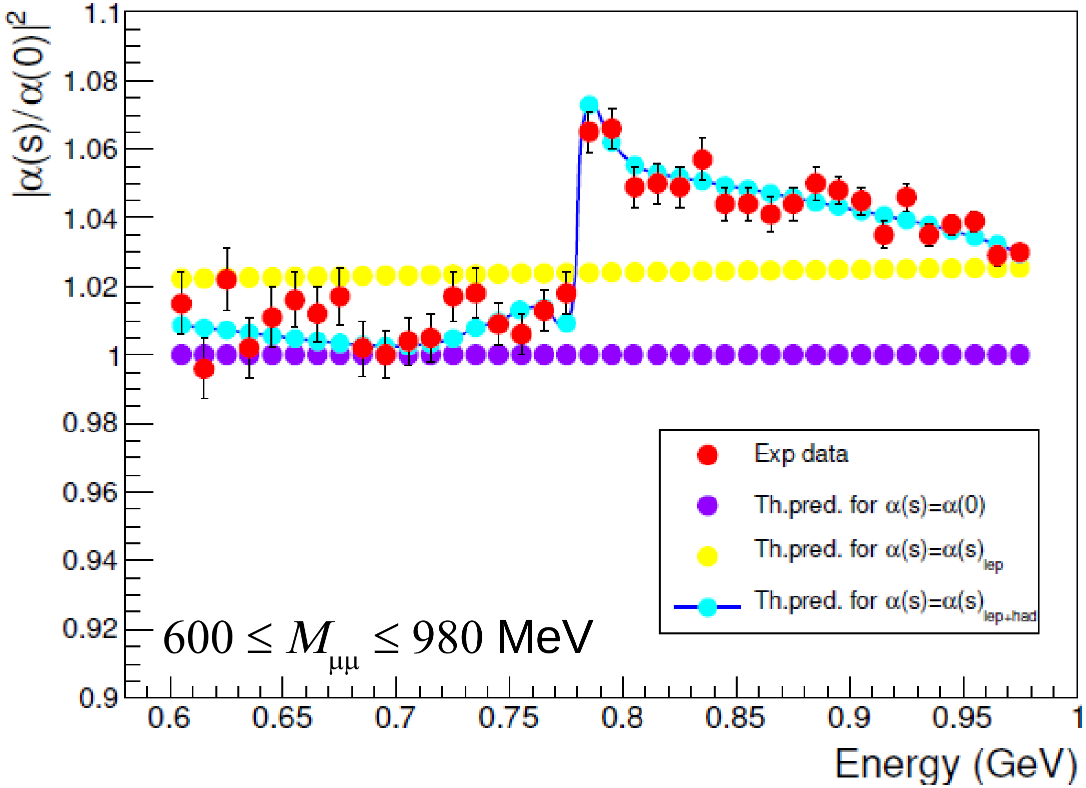
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

MC with VP removed

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = 1/(1-\Delta\alpha(s))$$

$$\Delta\alpha(s) = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

(we neglect the top contribution)



"Theoretical prediction" (provided by the alphaQED package [1])

$\Delta\alpha_{lep}$ computed in QED with negligible error;

$\Delta\alpha_{had}$obtained by a compilation of data in time-like region (with 0.1% accuracy).

Excellent agreement with other R compilation (Teubner / Ignatov)

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha(0)s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)} \qquad R(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma* \to hadrons)}{\sigma_{tot}(e^+e^- \to \gamma* \to \mu^+\mu^-)}$$

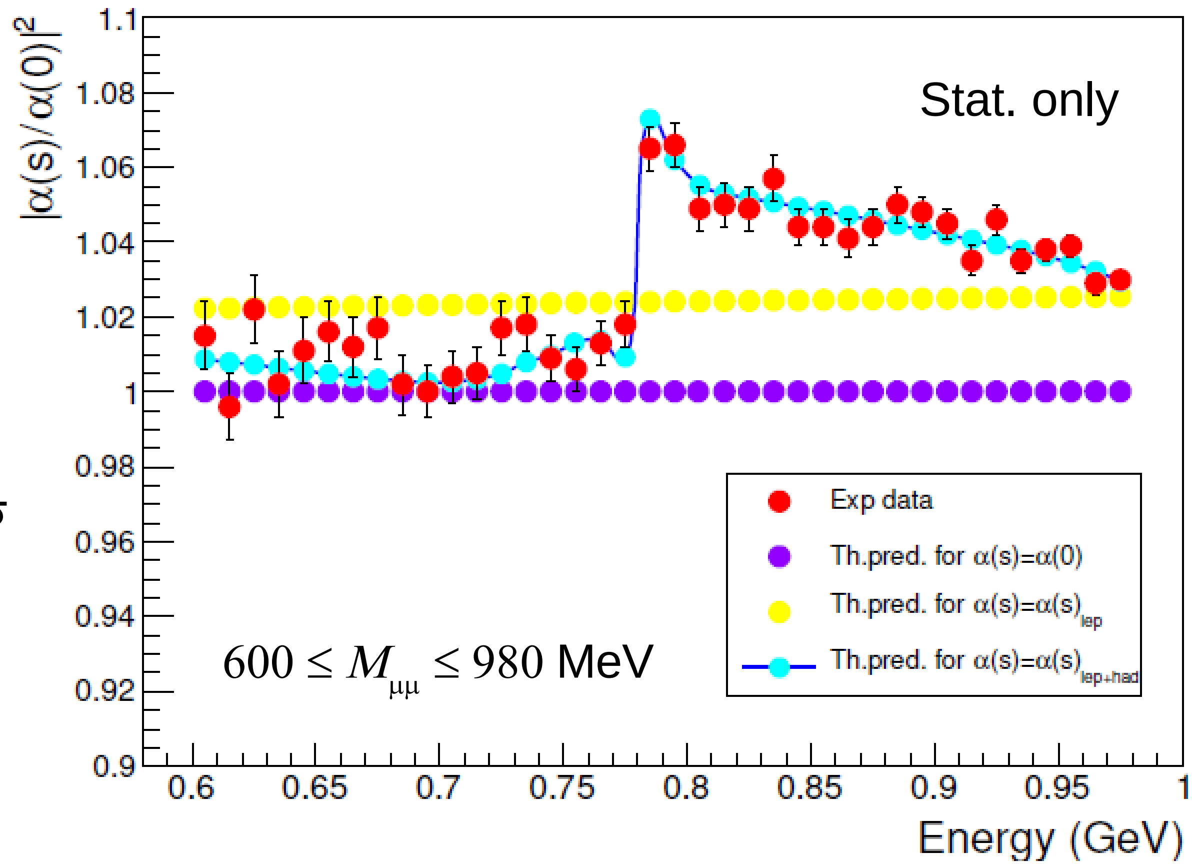
[1] F. Jegerlehner, alphaQED package [version April 2012] http://www-com.physik.hu-berlin.de/ fjeger/alphaQED.tar .gz; F. Jegerlehner, Nuovo Cim. C 034S1 (2011) 31; Nucl. Phys. Proc. Suppl. 162 (2006) 22.

Meas. of the running of α(s)

Systematic uncertainty is at the 1% level.

χ^2 based statistic test for two hypotheses: no running and running due to lepton pairs only is performed.

We exclude the only-leptonic hypothesis at 6 σ
Our result is also consistent with the lepton and hadron hypothesis with a statistical significance of 0.3 ($\chi 2/ndf$ = 41.2/37).



[1] F. Jegerlehner, alphaQED package [version April 2012] http://www-com.physik.hu-berlin.de/ fjeger/alphaQED.tar .gz; F. Jegerlehner, Nuovo Cim. C 034S1 (2011) 31; Nucl. Phys. Proc. Suppl. 162 (2006) 22.

Systematics

<table>
<tr><th>Syst. errors</th><th>$\sigma_{\mu\mu\gamma}$</th><th>$|\alpha(s)/\alpha(0)|^2$</th></tr>
<tr><td>Trigger</td><td colspan="2">$< 0.1\%$</td></tr>
<tr><td>Tracking</td><td colspan="2">s dep. (0.5% at ρ-peak)</td></tr>
<tr><td>Particle ID</td><td colspan="2">$< 0.1\%$</td></tr>
<tr><td>Background subtraction</td><td colspan="2">s dep. (0.1% at ρ-peak)</td></tr>
<tr><td>M_{TRK}</td><td colspan="2">0.4%</td></tr>
<tr><td>σ_{MTRK}</td><td colspan="2">s dep. (0.05% at ρ-peak)</td></tr>
<tr><td>Acceptance</td><td colspan="2">s dep. (0.3% at ρ-peak)</td></tr>
<tr><td>Software Trigger</td><td colspan="2">0.1%</td></tr>
<tr><td>Luminosity</td><td colspan="2">0.3%</td></tr>
<tr><td>$\Delta\alpha_{had}$ dep. (Normalization)</td><td>-</td><td>0.2%</td></tr>
<tr><td>FSR treatment</td><td colspan="2">0.2%</td></tr>
<tr><td>Rad. function H</td><td>-</td><td>0.5%</td></tr>
<tr><td>Total systematic error</td><td>s dep. (0.7% at $\rho-$peak)</td><td>(0.9% at $\rho-$peak)</td></tr>
</table>

Re and Im. part of $\Delta\alpha(s)$

In the contribution to the running of α, the imaginary part is usually neglected. This approximation is not sufficient in the presence of resonances like the ρ meson, where the accuracy of the cross section measurements reaches the order of (or even less than) 1%.

$$Re\,\Delta\alpha = 1 - \sqrt{|\alpha(0)/\alpha(s)|^2 - (Im\,\Delta\alpha)^2}.$$

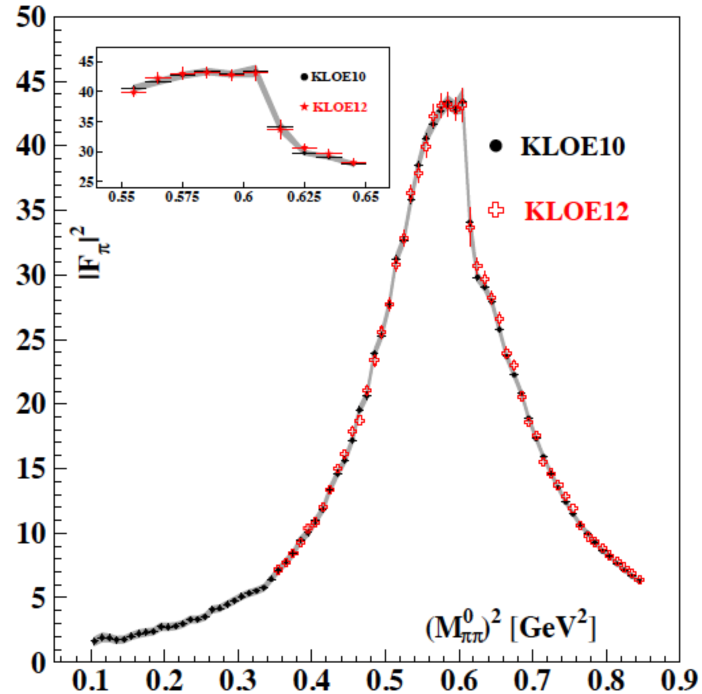
$$Im\Delta\alpha = -\frac{\alpha}{3}R(s) \quad \text{where} \quad R(s) = \sigma_{tot}\Big/\frac{4\pi\alpha(s)^2}{3s}$$

$$R(s) = R_{lep}(s) + R_{had};$$

$$R_{lep} = \sqrt{1 - \frac{4m_l^2}{s}}\left(1 + \frac{2m_l^2}{s}\right) \quad (l = e, \mu, \tau)$$

$$R_{had}(s) = \frac{1}{4}\left(1 - \frac{4m_\pi^2}{s}\right)^{\frac{3}{2}} |F_\pi^0(s)|^2$$

$$|F_\pi^0(s)|^2 = |F_\pi(s)|^2 \left|\frac{\alpha(0)}{\alpha(s)}\right|^2$$



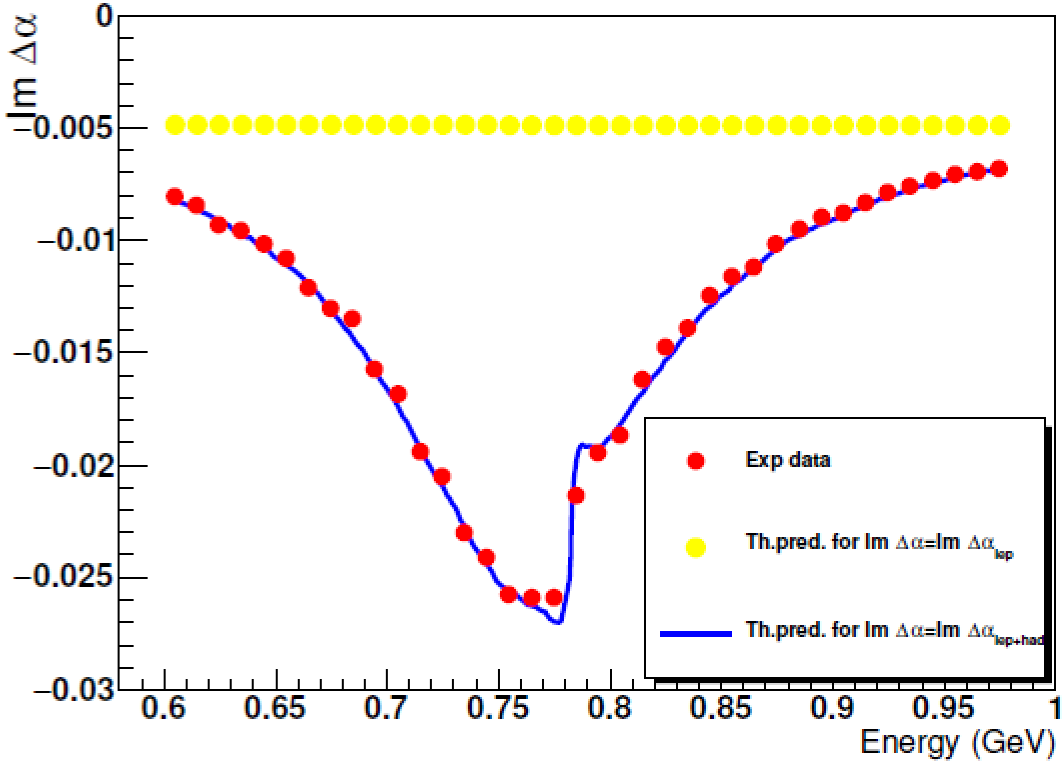
Physics Letters B 720 (2013) 336-343

work in collaboration with Fred Jegerlehner

Imaginary part of $\Delta\alpha(s)$

$$Im\Delta\alpha = -\frac{\alpha}{3} R(s)$$

Results obtained for the 2π contribution to $\Delta\alpha$ by using KLOE pion form factor [1] (red full circles) and the ones obtained by using the $R_{had}(s)$ compilation [2] with the 2π channel only and removing KLOE data (blue solid line).



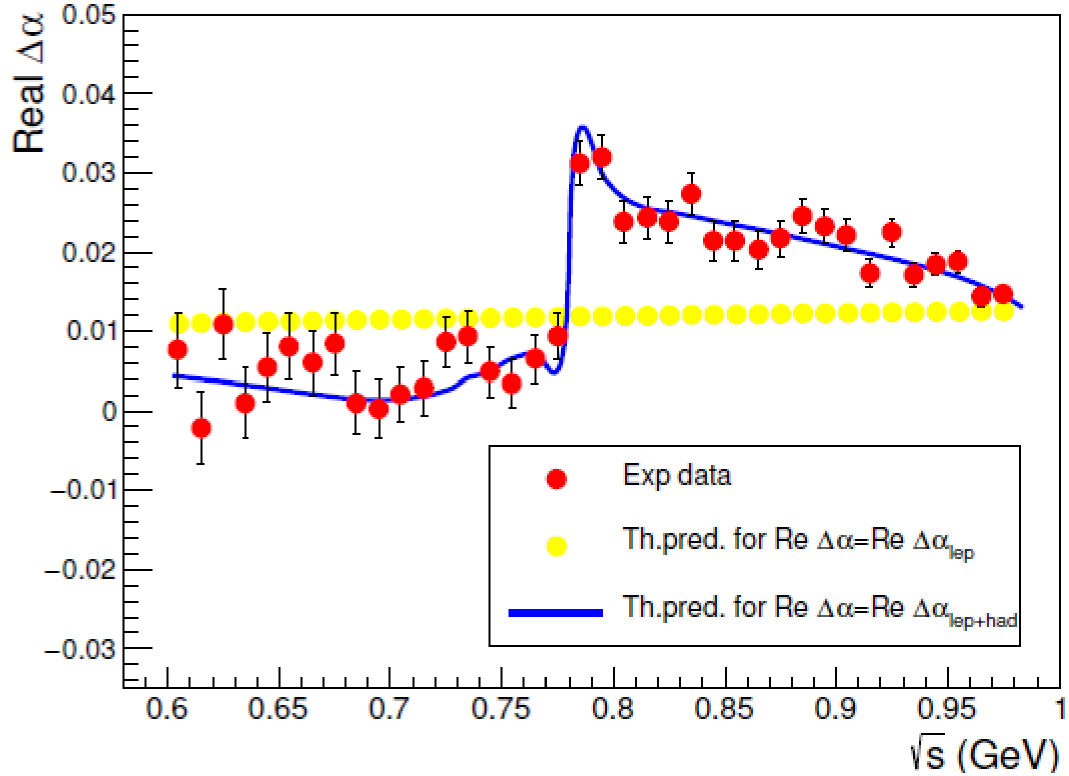
[1] Phys. Lett. B 720, 336 (2013)
[2] F. Jegerlehner, http://www-com.physik.hu-berlin.de/ fjeger/alphaQED.tar.gz;
F. Jegerlehner, Nuovo Cim. C 034S1 (2011) 31; Nucl. Phys. Proc. Suppl. 162 (2006) 22.

Real part of $\Delta\alpha(s)$

$$Re\,\Delta\alpha = 1 - \sqrt{|\alpha(0)/\alpha(s)|^2 - (Im\,\Delta\alpha)^2}.$$

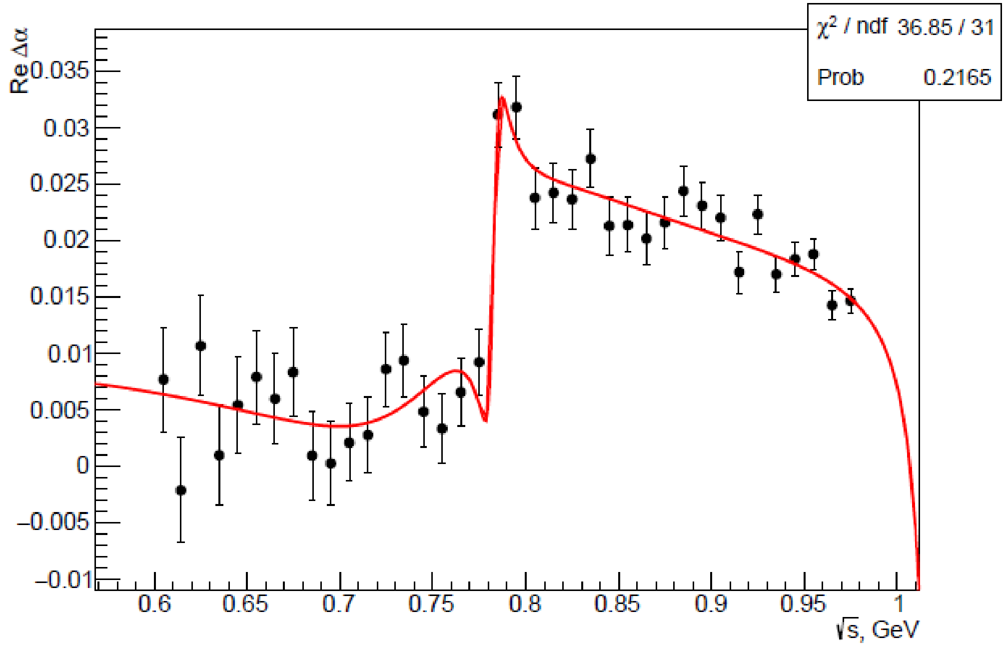
Experimental Re$\Delta\alpha$ in comparison with theoretical prediction with leptonic contribution only and with leptonic and hadronic contributions.

Excellent agreement for Re $\Delta\alpha(s)$ has been obtained with the data-based compilation.



Fit of Re Δα(s)

We fit ReΔα by a sum of the leptonic and hadronic contributions, where the hadronic contribution is parametrized as a sum of ρ(770), ω(782) and ϕ(1020) resonances components and a non resonant term (param. with a pol1).



$$Re\,\Delta\alpha_{V=\omega,\phi} = \frac{3\sqrt{BR(V\to e^+e^-)\cdot BR(V\to\mu^+\mu^-)}}{\alpha M_V}\frac{s(s-M_V^2)}{(s-M_V^2)^2+M^2\Gamma_V^2}$$ For ω, ϕ

$$F_\pi(s) = BW^{GS}_{\rho(s)} = \frac{M_\rho^2(1+d\Gamma_\rho/M_\rho)}{M_\rho^2 - s + f(s) - iM_\rho\Gamma_\rho(s)}$$ For ρ, neglecting interference with ω and high exc. stat. of ρ

Γ_ω , M_ϕ, Γ_ϕ, and BR($\phi\to e^+e^-$)BR($\phi\to\mu^+\mu^-$) fixed to PDG values [pdg]

[pdg] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update.

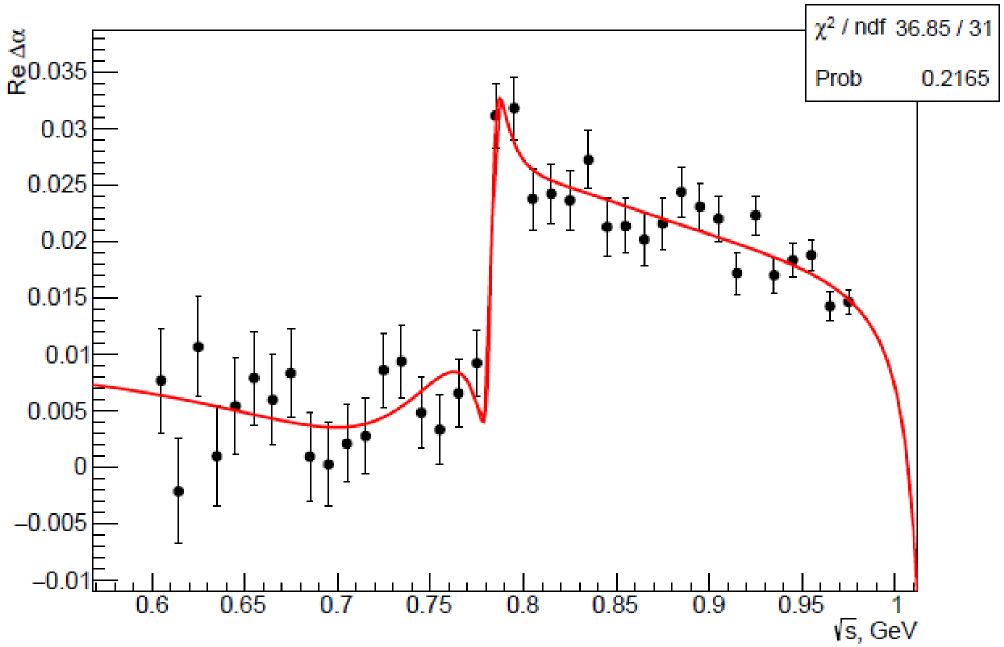
Fit of Re Δα(s)

Assuming lepton universality and multiplying for the phase space correction

$$\xi = \left(1 + 2\frac{m_\mu^2}{m_\omega^2}\right)\left(1 - 4\frac{m_\mu^2}{m_\omega^2}\right)^{1/2}$$

$$BR(\omega \to \mu^+\mu^-) =$$
$$= (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$$

$$(9.0 \pm 3.1) \cdot 10^{-5} \text{ from PDG}$$

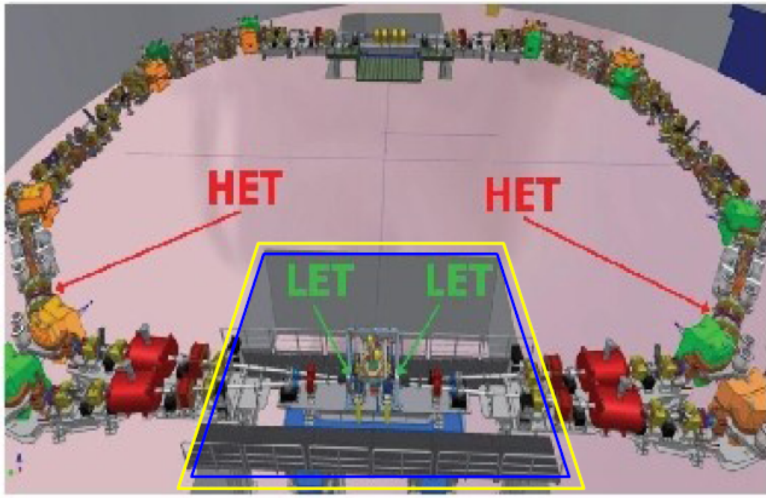


Parameter	Result from the fit	PDG
M_ρ, MeV	775 ± 6	775.26 ± 0.25
Γ_ρ, MeV	146 ± 9	147 ± 0.9
M_ω, MeV	782.7 ± 1.0	782.65 ± 0.12
$BR(\omega \to \mu^+\mu^-)BR(\omega \to e^+e^-)$	$(4.3 \pm 1.8) \cdot 10^{-9}$	$(6.5 \pm 2.3) \cdot 10^{-9}$
χ^2/ndf	1.19	-

Inclusion of omega/rho interference don’t change the result (within the error).

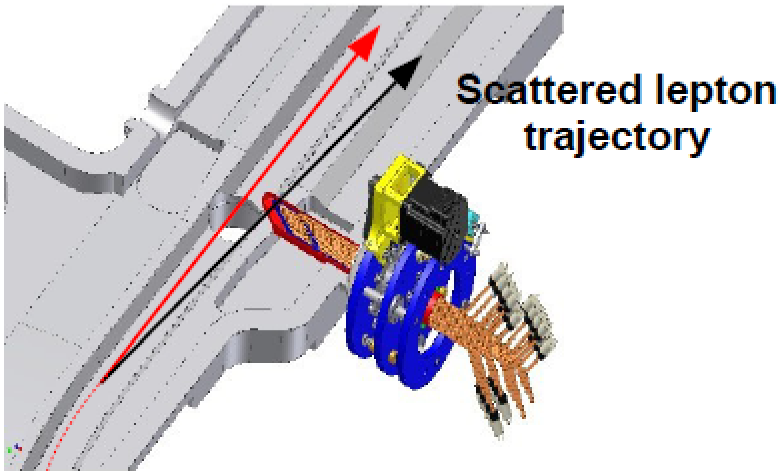
Thanks to F. Ignatov for useful discussions.

$\gamma\gamma$ physics at KLOE2



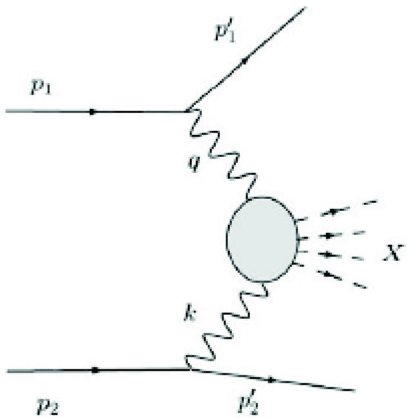
LET station (LYSO crystals) @ 2 m from the IP, in one of the QCALT wedges
It should detect final-state particles of about 200 MeV

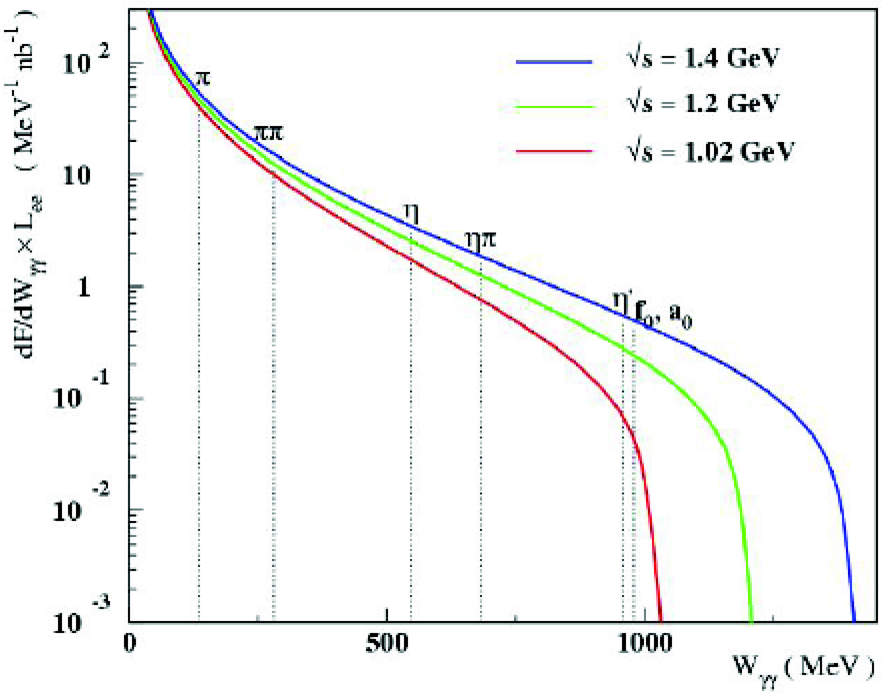
$$e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- X$$



HET station (scintillator strips) @ 11 m from the IP
DAFNE bending dipoles used as spectrometer
Energy acceptance for final-state particles expected in the range 410-490 MeV

γγ physics





- **X = ππ ⇒ search for σ(600)**
- **X = π^0, η, (η')**
  - **Γ(X→γγ)**
  - **Transition form factors $F_{X\gamma^*\gamma^*}(q_1^2,q_2^2)$**

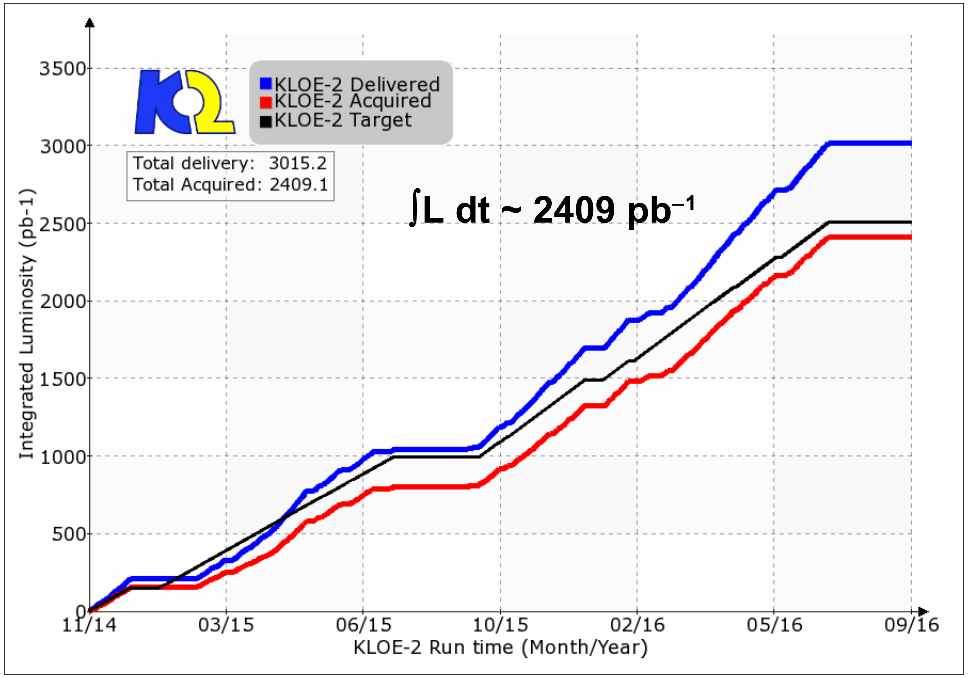
Main goal at present is the precision measurement of the π^0 width [Rev.Mod.Phys. 85 (2013) 49] using meson production γγ from scattering O(10^4) π^0 expected with 5 fb^{-1} with HET

DAΦNE and KLOE2 operation

Peak Luminosity L_{peak} = 2.21 • 10^{32}cm^{-2}s^{-1}
Max daily delivery: 13.4 pb^{-1}
Max daily acquired: 11.0 pb^{-1}

From November 2014 KLOE2 acquired an integrated luminosity of ~ 2.4 fb^{-1} (DAΦNE delivered 3 fb^{-1})

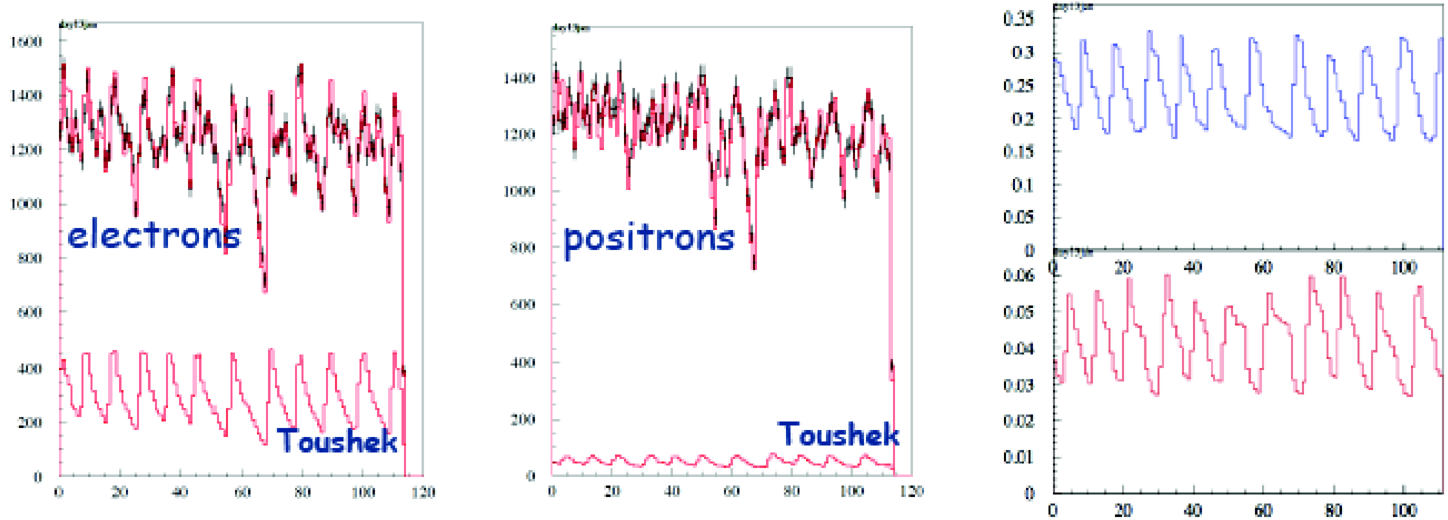
Performance and operation stability still improving and the goal to acquire 5 fb^{-1} by the end of 2017 appears feasible.



HET rates

Timeline of the e^-/e^+ rates: Run 80427

Background/Total



$$\text{HET-Rate} = \text{KLOE-Trigger-Rate} \times (c\,L + a_{e/p}\, I^2_{a/p})$$

HET rate dominated by single-arm Bhabha scattering.
Particles from intra-bunch scattering give in average 24% contribution for e^- and 4% for e^+ (average, Jan 2016)
It is the ideal device to provide fast, reliable feedbacks on the machine operation

Tagger data analysis

HET stations are completely noiseless

The timeline of the counting rate for electron AND positron stations shows only 2 visible contributions : from luminosity and from Touschek particles

Machine background reaches a maximal relative contribution of 30% for electron and 6% for positron beams

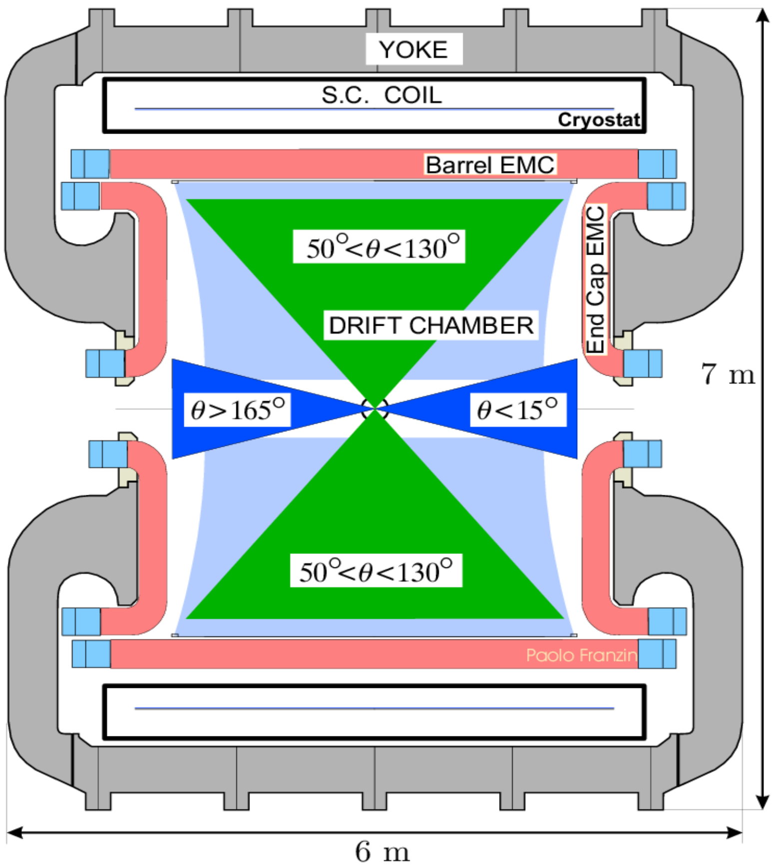
The total rate dominated by Bhabha scattering is at the level of 500-600 kHz

The rate of uncorrelated time-coincidences between KLOE and HET requires full reconstruction of a large fraction of the KLOE triggers

We have pre-filtered candidates of single-π^0 production from $\gamma\gamma$ scattering and a total of 450 pb^{-1} are being analysed

Conclusion

- Measurement of the hadronic contribution to the running of α with ISR differential cross section $d\sigma(e^+e^- \rightarrow \mu^+\mu^-\gamma)/d\sqrt{s}$ in the 0.6 - 0.98 GeV $M_{\mu\mu}$ invariant mass range at 1.7 fb^{-1} has been presented.
- Clear contribution of the $\rho-\omega$ interference to the photon propagator with more than 5σ statistical significance.
- Imaginary and Real part of $\Delta\alpha$ extracted with KLOE data.
- By a fit of the real part of $\Delta\alpha(s)$ and assuming lepton universality the branching ratio of $\omega\rightarrow\mu^+\mu^-$ has been extracted.
- The upgraded detector, KLOE-2, has already collected 2.4 fb^{-1} demonstrating the feasibility of the goal to record 5 fb^{-1} by the end of 2017.
- The analysis of meson production from $\gamma\gamma$ exploiting the KLOE-2 tagging system has been started. The goal is to improve to the percent level the precision of the π^0 radiative width and obtain the first measurement of the TFF at low momentum transfer.



SPARE SLIDES

Luminosity:

KLOE measures L with Bhabha scattering

Eur.Phys.J.C47:589-596,2006

$55° < \theta < 125°$; acollinearity $< 9°$; $p \geq 400$ MeV

$$\int \mathcal{L}\,dt = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

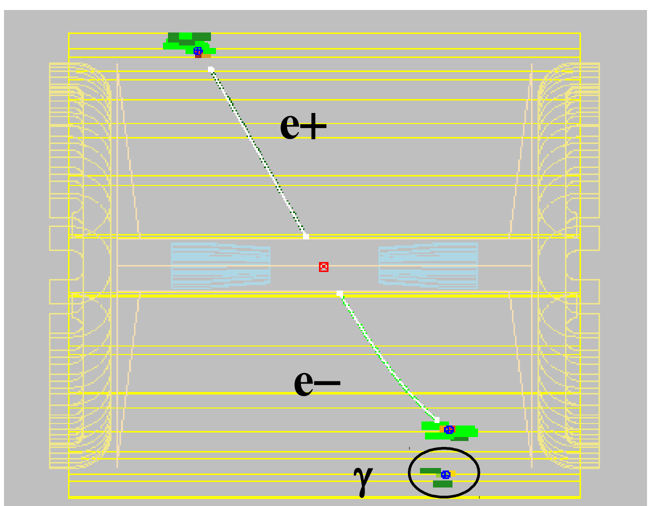
Generator used for σ_{eff}: **BABAYAGA** (Pavia)

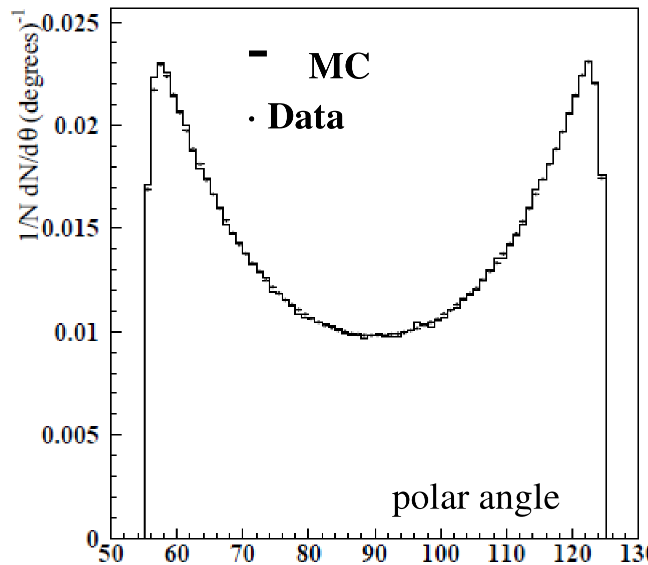
NPB758 (2006) 22

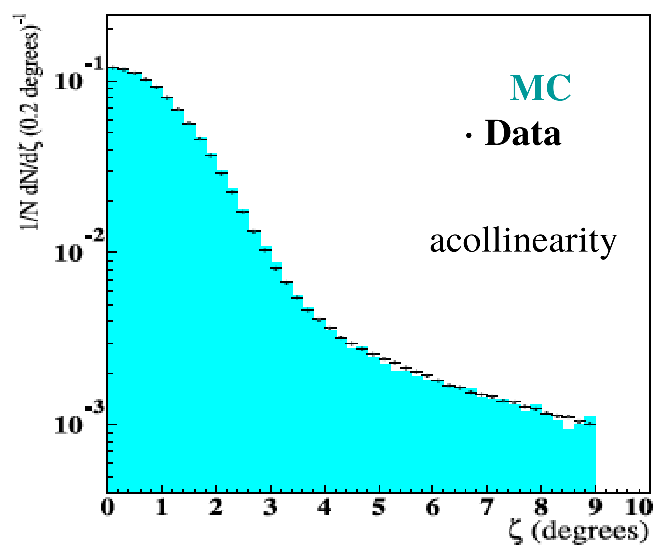
New version (**BABAYAGA@NLO**) gives 0.7% decrease in cros. sect., and better accuracy:0.1%

Systematics on Luminosity:

TOTAL 0.1 % th ⊕ 0.3% exp = 0.3%







Luminosity:

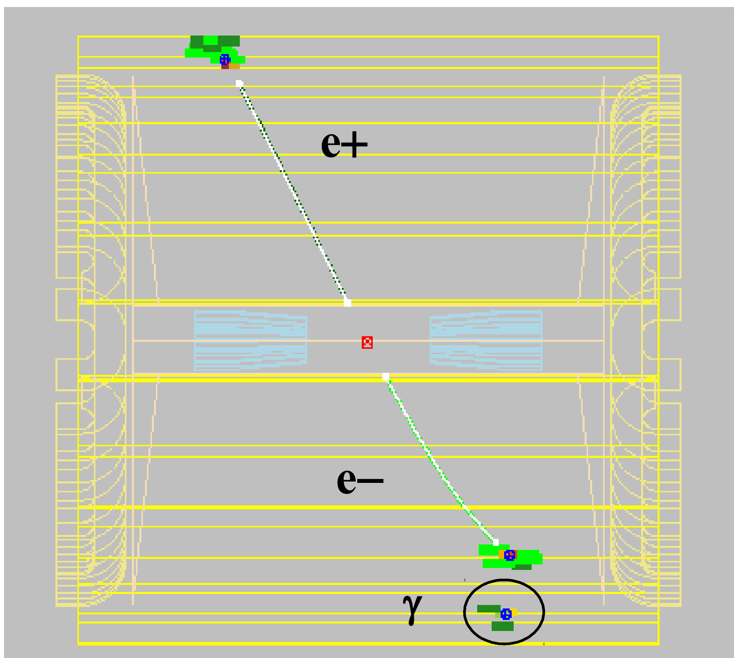
KLOE measures $\mathcal{L}$ with Bhabha scattering

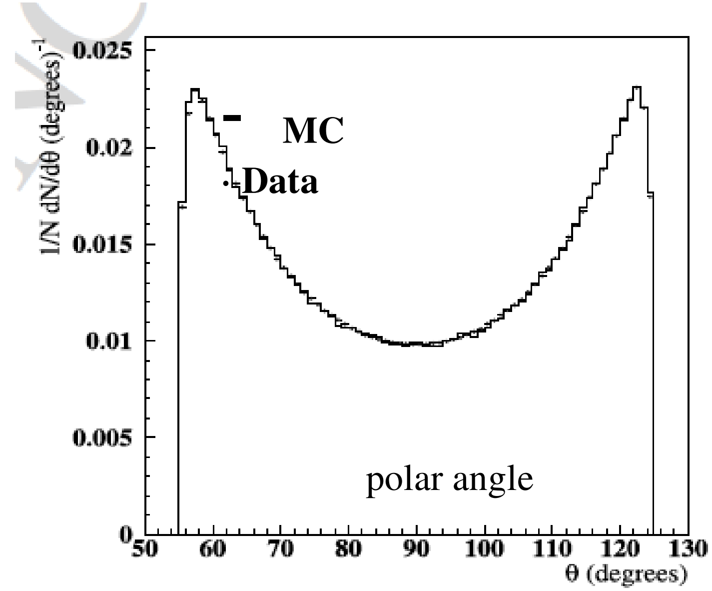
55° < θ < 125°

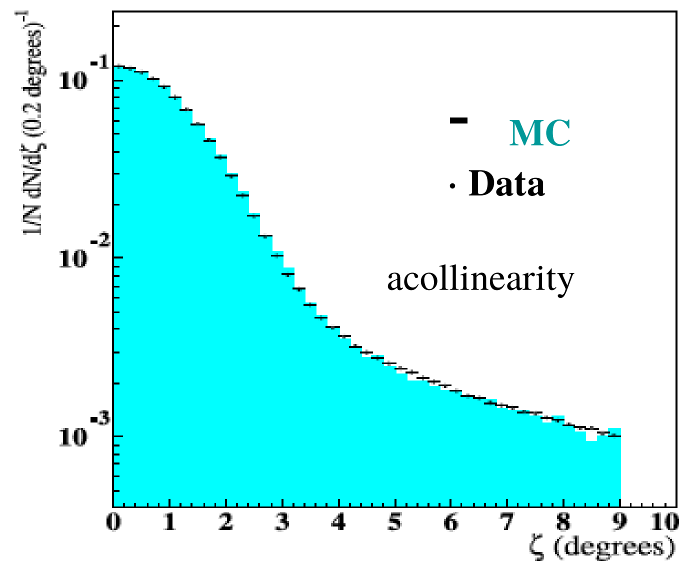
acollinearity < 9°

p ≥ 400 MeV

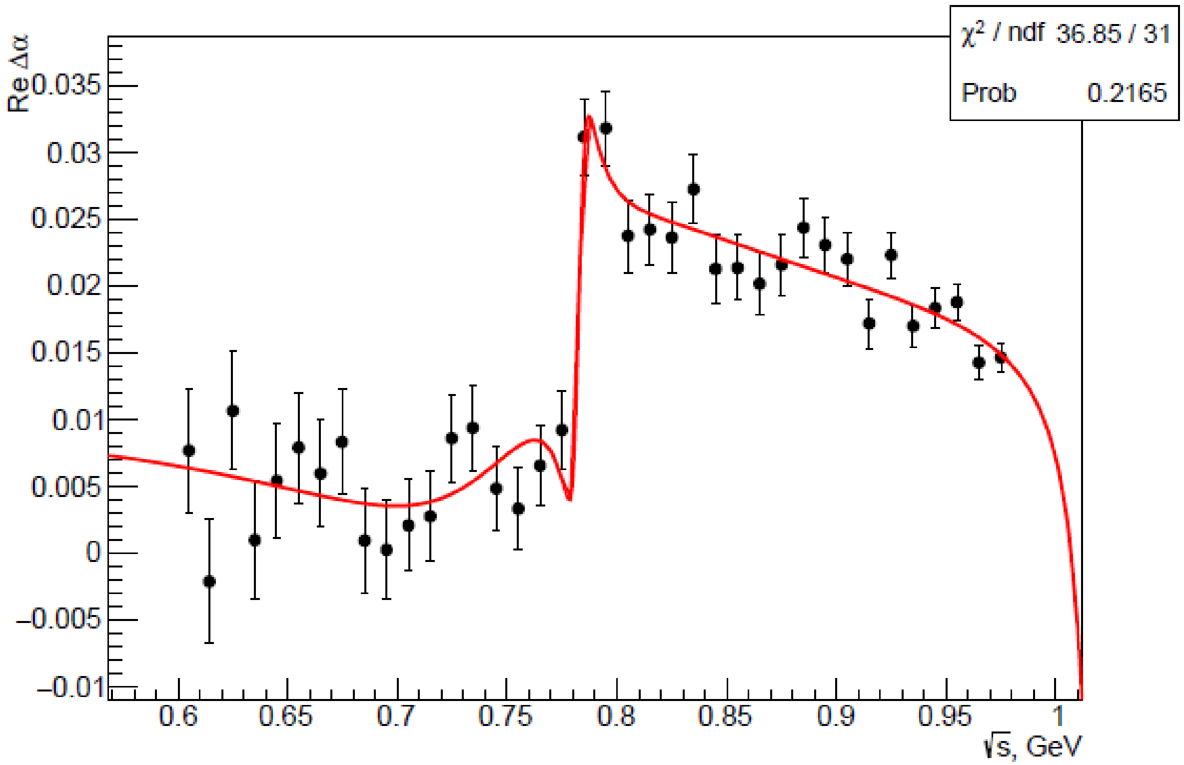
$$\int \mathcal{L}\,\mathrm{dt} = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$







Fit of Re Δα(s)

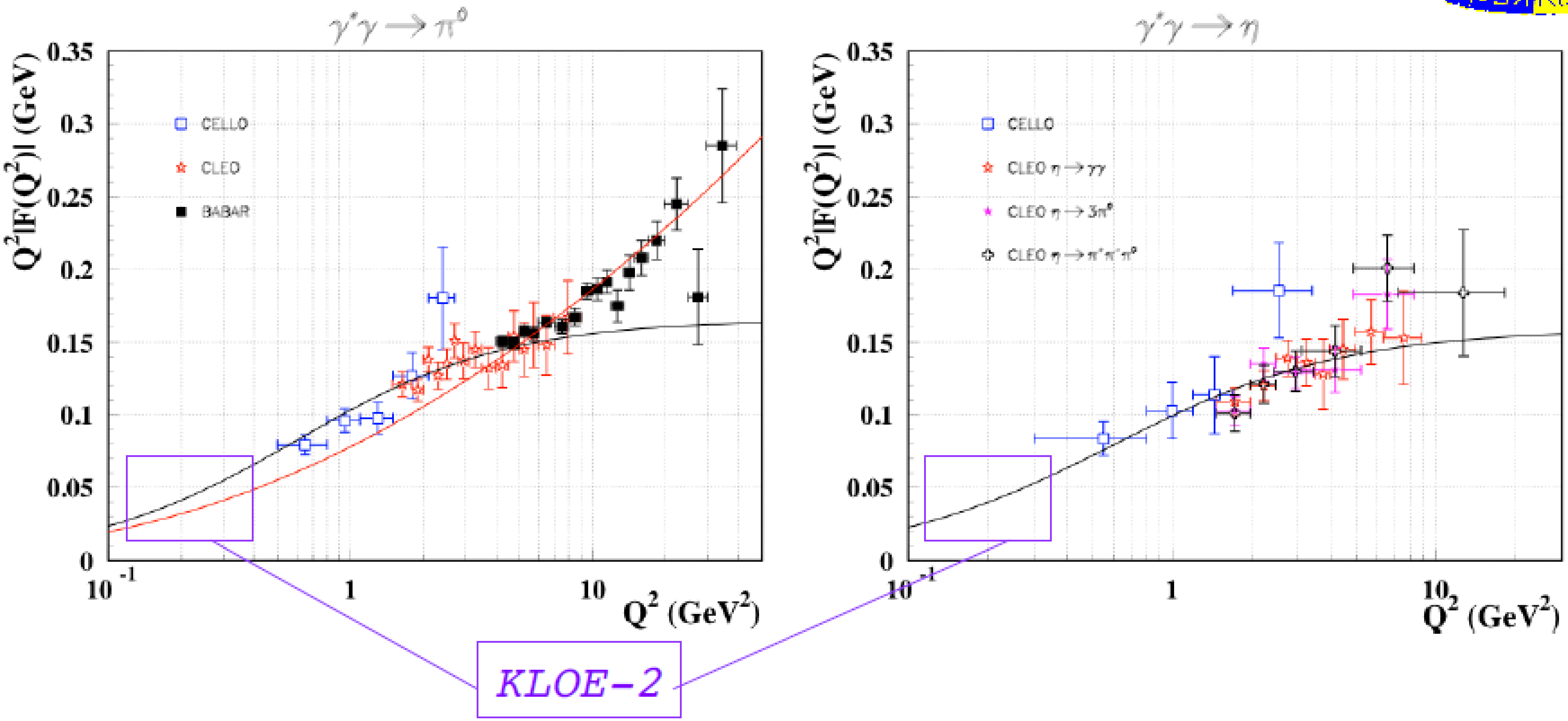


Parameter	Result from the fit	Result from the fit with $\rho-\omega$ interf.	PDG
M_ρ, MeV	775 ± 6	778 ± 7	775.26 ± 0.25
Γ_ρ, MeV	146 ± 9	147 ± 10	147 ± 0.9
M_ω, MeV	782.7 ± 1.0	783.4 ± 0.8	782.65 ± 0.12
$BR(\omega \to \mu^+\mu^-)BR(\omega \to e^+e^-)$	$(4.3 \pm 1.8) \cdot 10^{-9}$	$(4.4 \pm 1.8) \cdot 10^{-9}$	$(6.5 \pm 2.3) \cdot 10^{-9}$
χ^2/ndf	1.19	1.15	-

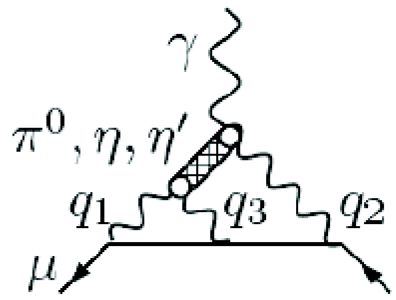
To study interf. effect we add:

$$\delta \frac{s}{M_\omega^2} BW_\omega(s) BW_\rho^{GS}$$

KLOE-2 contribution to a_μ^{LbL}

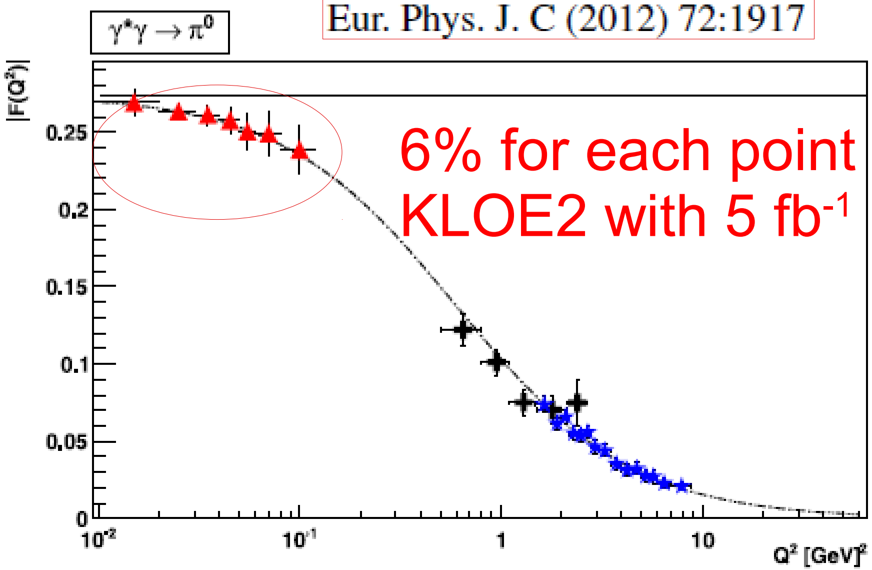


- **Measurement of $\Gamma(P\to\gamma\gamma)$**
- **Transition form factors $F_{P\gamma^*\gamma^*}(q_1^2,q_2^2)$:**
  - **input for the calculation of the Light-by-Light contribution to g-2 of the muon**



KLOE-2 contribution to a_μ^{LbL}

Eur. Phys. J. C (2012) 72:1917



By including KLOE-2→a reduction of a factor 2 in the error of $a_\mu^{\pi 0}$!

In addition the measurement of $\Gamma(\pi_0 \to \gamma\gamma)$ will constrain $F_{\pi 0}(q^2=0)$ (which is now obtained by WZW model $1/4\pi f_\pi$ w/o error). ~1% st. accuracy with 1 year of data taking.

A0 : CELLO, CLEO, PDG;

A1 : CELLO, CLEO, PrimEx;

A2 : CELLO, CLEO, PrimEx, KLOE-2;

B1 : CELLO, CLEO, BaBar, PrimEx;

B2 : CELLO, CLEO, BaBar, PrimEx, KLOE-2;

Model	Data	χ^2/d.o.f.	Parameters			$a_\mu^{LbyL;\pi^0} \times 10^{11}$
VMD	A0	6.6/19	$M_V = 0.778(18)$ GeV	$F_\pi = 0.0924(28)$ GeV		$(57.2 \pm 4.0)_{JN}$
VMD	A1	6.6/19	$M_V = 0.776(13)$ GeV	$F_\pi = 0.0919(13)$ GeV		$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$M_V = 0.778(11)$ GeV	$F_\pi = 0.0923(4)$ GeV		$(57.3 \pm 1.1)_{JN}$
LMD+V, $h_1 \neq 0$	B1	18/35	$\bar{h}_5 = 6.44(22)$ GeV^4	$\bar{h}_7 = -14.92(21)$ GeV^6	$h_1 = -0.17(2)$ GeV^2	$(72.4 \pm 1.6)^*_{JN}$
LMD+V, $h_1 \neq 0$	B2	19/43	$\bar{h}_5 = 6.47(21)$ GeV^4	$\bar{h}_7 = -14.84(7)$ GeV^6	$h_1 = -0.17(2)$ GeV^2	$(71.8 \pm 0.7)^*_{JN}$