KLOE results and perspectives for KLOE-2 on σ_{HAD}, a_μ^{HLO} and $\alpha(s)$ measurements

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KLOE-2 Workshop on e+e- collision physics at 1 GeV

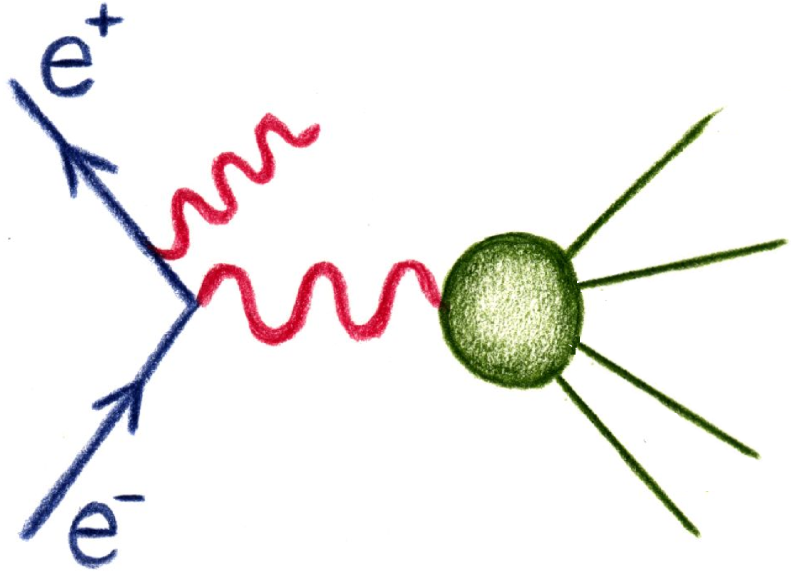
26-28 October 2016 *INFN - Laboratori Nazionali di Frascati, Italy*

Europe/Rome timezone

Outline

- ISR: a successful story
- Measurement of the 2π cross section and evaluation of $a_\mu^{\pi\pi}$:
  - Three different measurements (KLOE08, KLOE10, KLOE12) with different systematics confirm 3σ discrepancy on g-2
- Measurement of the running of the e.m. coupling constant $\alpha(s)$ below 1 GeV in the $e^+e^- \rightarrow \mu\mu\gamma$ process:
  - 6σ evidence of the hadronic contribution to $\Delta\alpha$
  - Extraction of Real and Im $\Delta\alpha$
  - Measurement of BR($\omega \rightarrow \mu\mu$)
- Measuring a_μ^{HLO} in the spacelike region
- Prospects for KLOE/KLOE2

ISR: a Successful Story



(see also W. Kluge, Nucl. Phys. Proc. Suppl. **181-182** (2008) 280)

Selected papers (apologizes for the ones missing)

Photon emission in muon pair production in electron-positron collisions V. N. Baier, V. A. Khoze, ZhETF 48 (1965) 946, Yad. Fiz. 2 (1965) 287

PHYSICAL REVIEW D VOLUME 12, NUMBER 1 1 J

Equivalent-particle approximations in electron and photon processes of higher-order QED*

Min-Shih Chen
Stanford Linear Accelerator Center, Stanford, California 94305 and Physics Department, University of Michigan, Ann Arbor, Michigan 48104†

Peter Zerwas‡
Stanford Linear Accelerator Center, Stanford, California 94305
(Received 6 March 1975)

Measuring $\sigma(e^+e^- \to \text{hadrons})$ using tagged photons

S. Binner, J.H. Kühn, K. Melnikov [1]
Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany

Received 15 April 1999
Editor: P.V. Landshoff

Radiative return at NLO and the measurement of the hadronic cross-section in electron–positron annihilatic

Germán Rodrigo[1a], Henryk Czyż[2,3b], Johann H. Kühn[1,4c], and Marcin Szopa[2]

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[2] Institute of Physics, University of Silesia, PL-40007 Katowice, Poland.
[3] Institute of Advanced Study, University of Bologna, I-40138 Bologna,Italy
[4] Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany.

Received: February 1, 2008

Eur. Phys. J. C 6, 637–645 (1999)
DOI 10.1007/s100529800953

THE EUROPEAN PHYSICAL JOURNAL C

The hadronic contribution to the muon $g-2$ from hadron production in initial state radiation events at the e^+e^- collider DAΦNE

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Dipartimento di Fisica dell'Università di Lecce and INFN, Sezione di Lecce, via Arnesano I-73100 Lecce, Italy

KLOE MEMO n^{o}195
August 13, 1999

Measurement of the hadronic cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ from initial state radiative events $\pi^+\pi^-\gamma$ with the KLOE detector

Gabriella Cataldi, Achim Denig, Wolfgang Kluge, Graziano Venanzoni
Institut für Experimentelle Kernphysik, Universität Karlsruhe

A. $e^+e^- \to \gamma f$ (hard-photon bremsstrahlung)

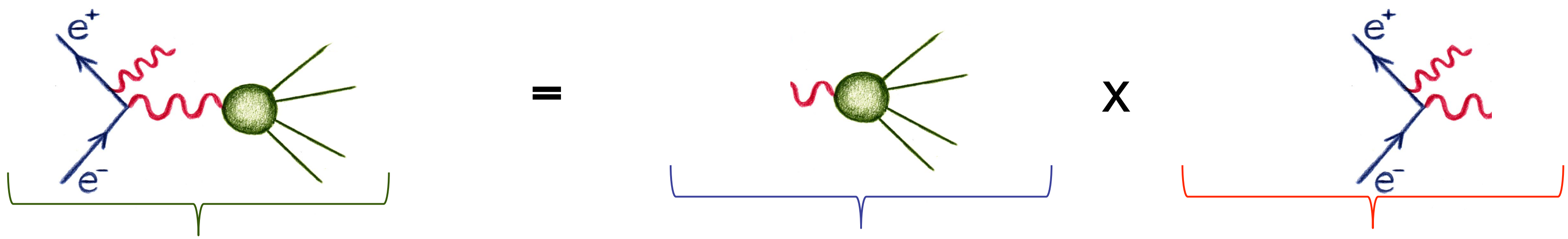
This bremsstrahlung process[3] is shown in Fig. 6(a). It can serve as an instrument to study the low-energy behavior of the e^+e^- annihilation because the hard photon can carry away a large portion of the initial energy. Denoting by $(1-x)$ the fraction of energy the photon snatches away from the incident lepton, the invariant mass M of the final state f reads

Chen Zerwas, 1974!

ISR: Initial State Radiation

Neglecting final state radiation (FSR):

$$\frac{d\sigma(e^+ e^- \rightarrow hadrons + \gamma)}{dM^2_{hadr}} = \frac{\sigma(e^+ e^- \rightarrow hadrons, M^2_{hadr})}{s} H(s, M^2_{hadr})$$



measured cross section | resulting cross section | radiator function

Theoretical input: precise calculation of the radiation function $H(s, M^2_{hadr})$

➔ **EVA + PHOKHARA MC Generator**

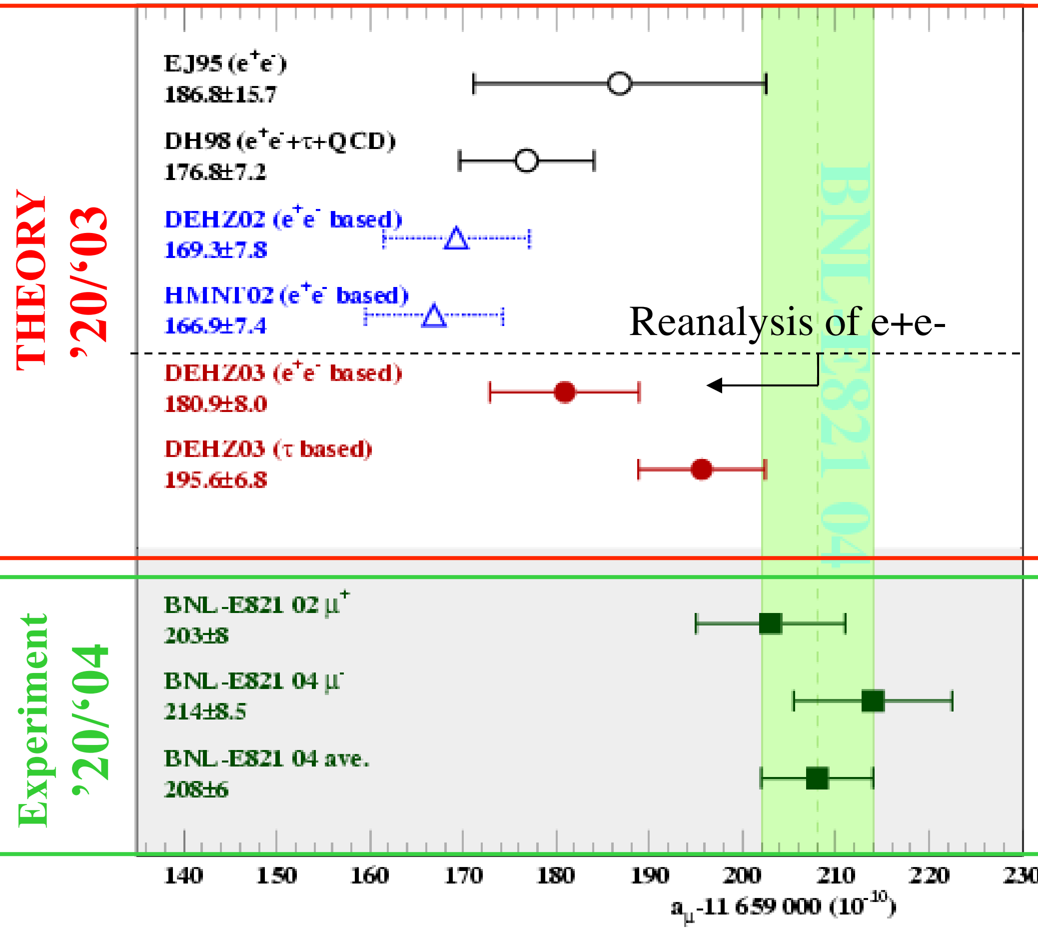
Binner, Kühn, Melnikov; Phys. Lett. B 459, 1999

H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003

(exact next-to-leading order QED calculation of the radiator function)

IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ with ISR using 2001 data ($140 pb^{-1}$) PLB606(2005)12 $\Rightarrow$ ~3σ discrepancy btw a_μ^{SM} and a_μ^{exp}

a_μ SM prediction vs experiment (around '04)



New cross section data have recently lowered theory error:

a) CMD-2 (Novosibirsk/VEPP-2M) $p^+ p^-$ channel with 0.6% precision < 1 GeV

b) t-Data from ALEPH /OPAL/CLEO

$e^+ e^-$ - Data: 2.7 σ - Deviation

τ – Data: 1.4 σ - Deviation

Experiment BNL-E821

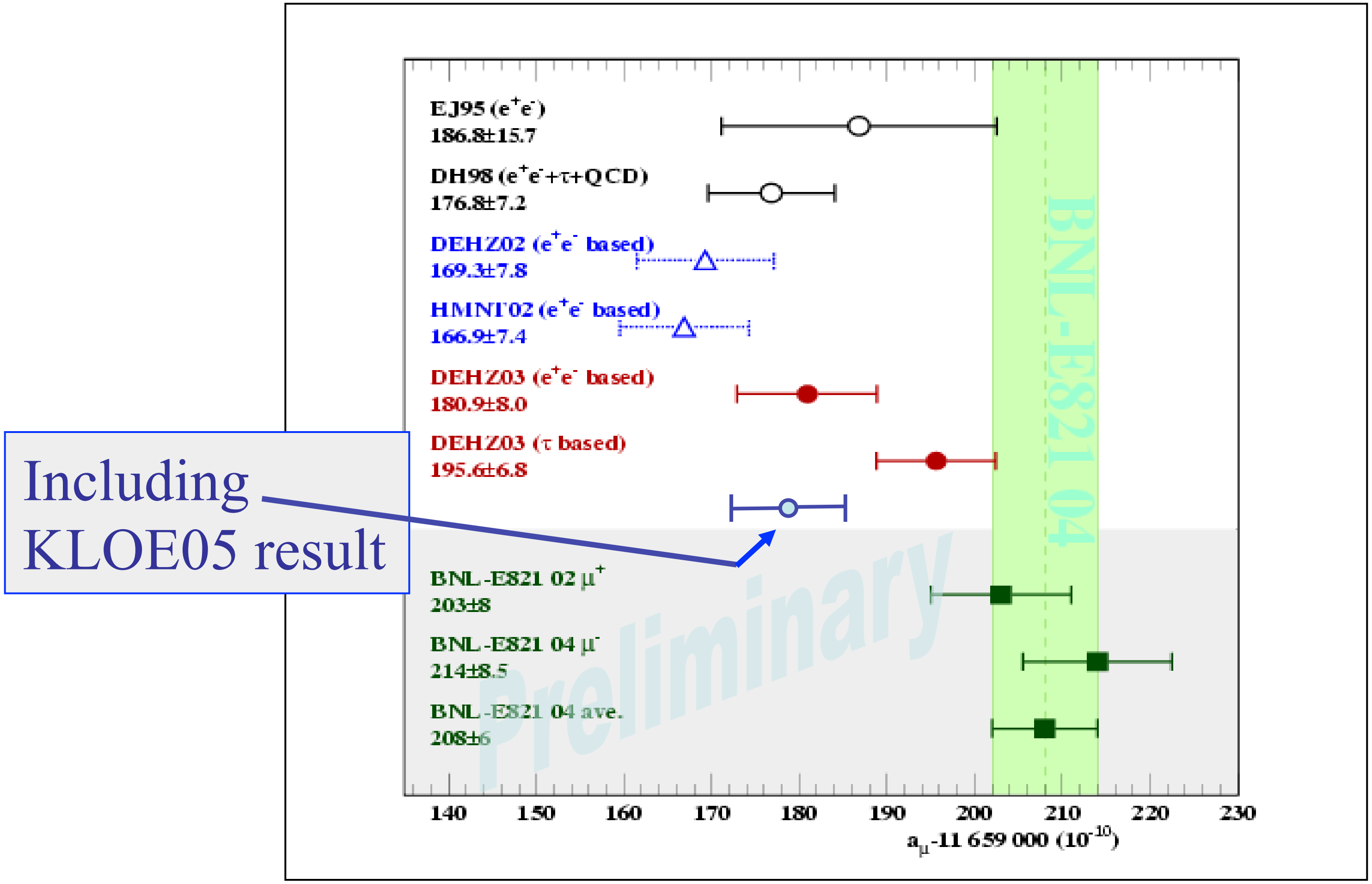
Values for μ^+(2002) and μ^-(2004) in agreement with each other.

Precision: 0.5ppm

Very confused situation!!

2005: KLOE: **PLB606(2005)12**

1) confirmed a ≈3σ deviation btw theory and experiment for $(g\text{-}2)_{\mu}$!
2) KLOE agrees with e^+e^- (Novosibirsk) data; disagrees with τ



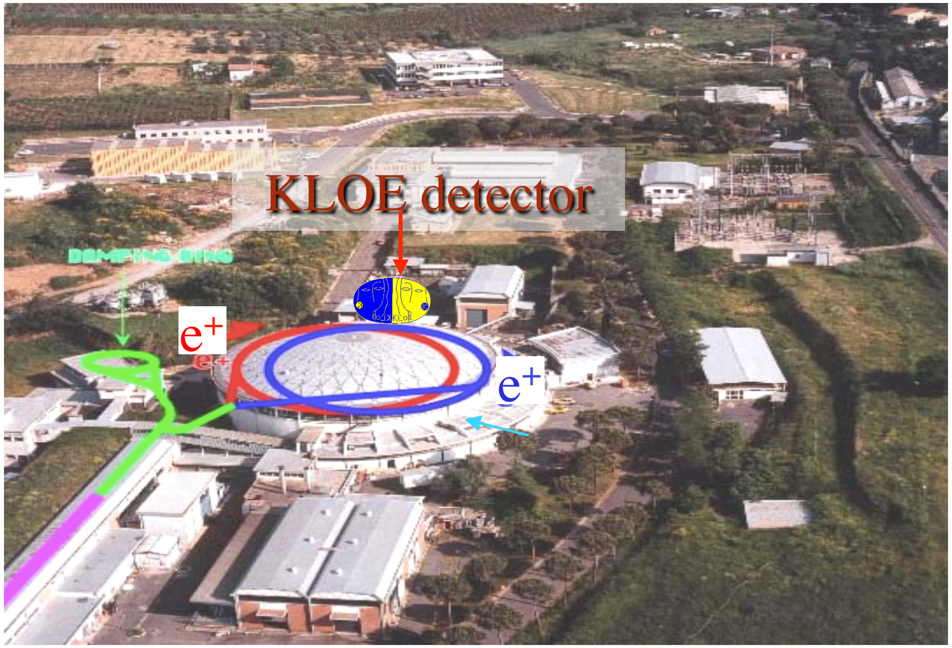
Due to an error on the trigger efficiency (which didn't affect the evaluation of $a_{\mu}^{\pi\pi}$) and superior data quality KLOE05 was superseded by KLOE08

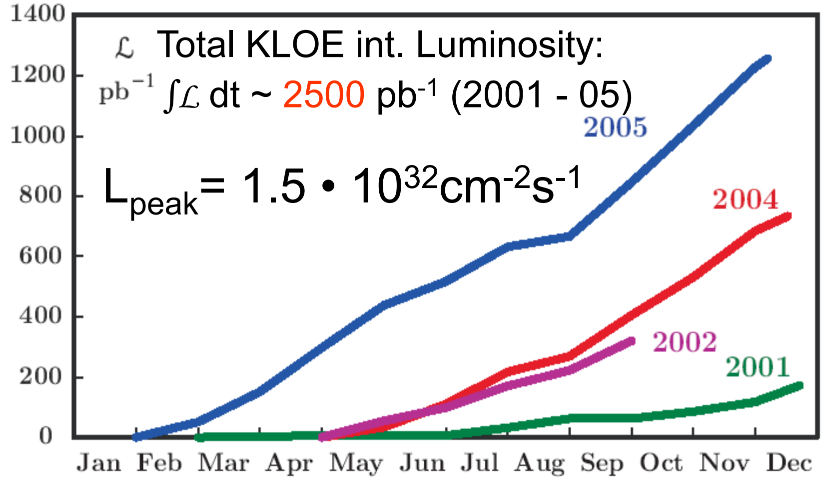
Measurements of the pion form factor & $a_\mu^{2\pi}$ at KLOE

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

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

Integrated Luminosity





2006

- Energy scan (4 points around m_Φ-peak)
- 240 pb^{-1} at $\sqrt{s}$ = 1000 MeV (off-peak data)

KLOE05 measurement (PLB606(2005)12) was based on 140pb^{-1} of 2001 data!

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

KLOE08 measurement (PLB670(2009)285) was based on 240pb^{-1} from 2002 data!

NEW: KLOE12 measurement (PLB720(2013)303) based on 240 pb^{-1} of 2002 data ***from $\pi\pi\gamma/\mu\mu\gamma$ ratio***

Event Selection: Small Angle (SA)

Pion tracks at large angles

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

a) Photons at small angles

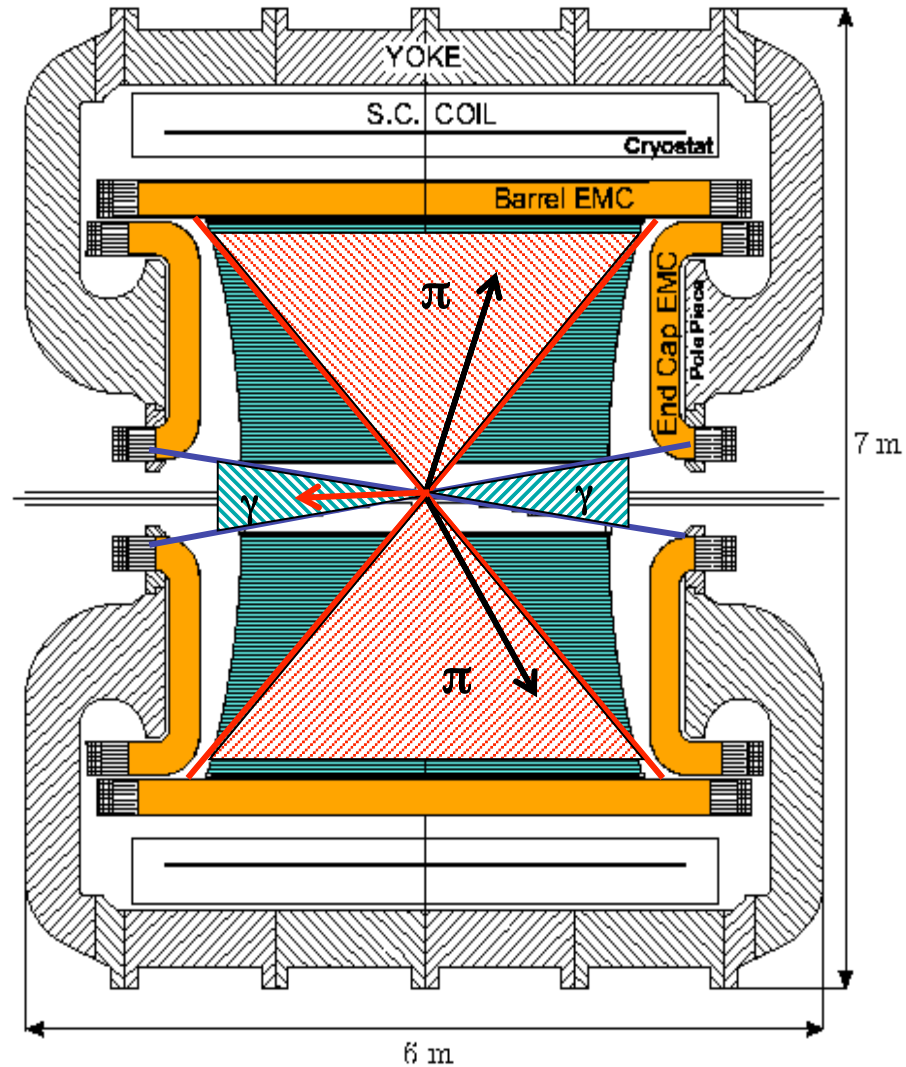
$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

➔ 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

KLOE



Event Selection: Large Angle (LA)

Pion tracks at large angles

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

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

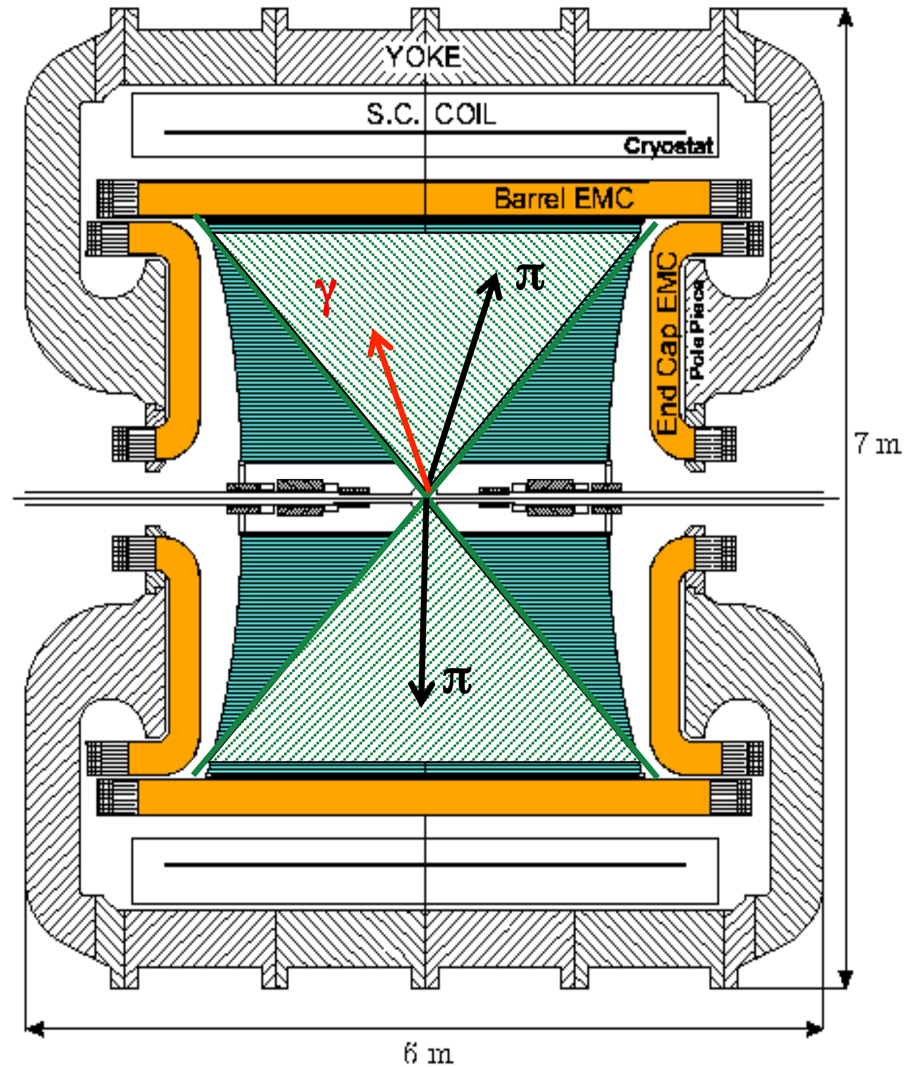
b) Photons at large angles

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

➔Photon is explicitly measured in the detector!

- Threshold region accessible
- Lower signal statistics
- Increased contribution from FSR and $\phi \rightarrow \pi^+\pi^-\pi^0$ (use off peak data)

KLOE



KLOE08 result

Systematic errors on $a_\mu^{\pi\pi}$:

Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
p/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
$\sqrt{s}$ dep. Of H	0.2%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

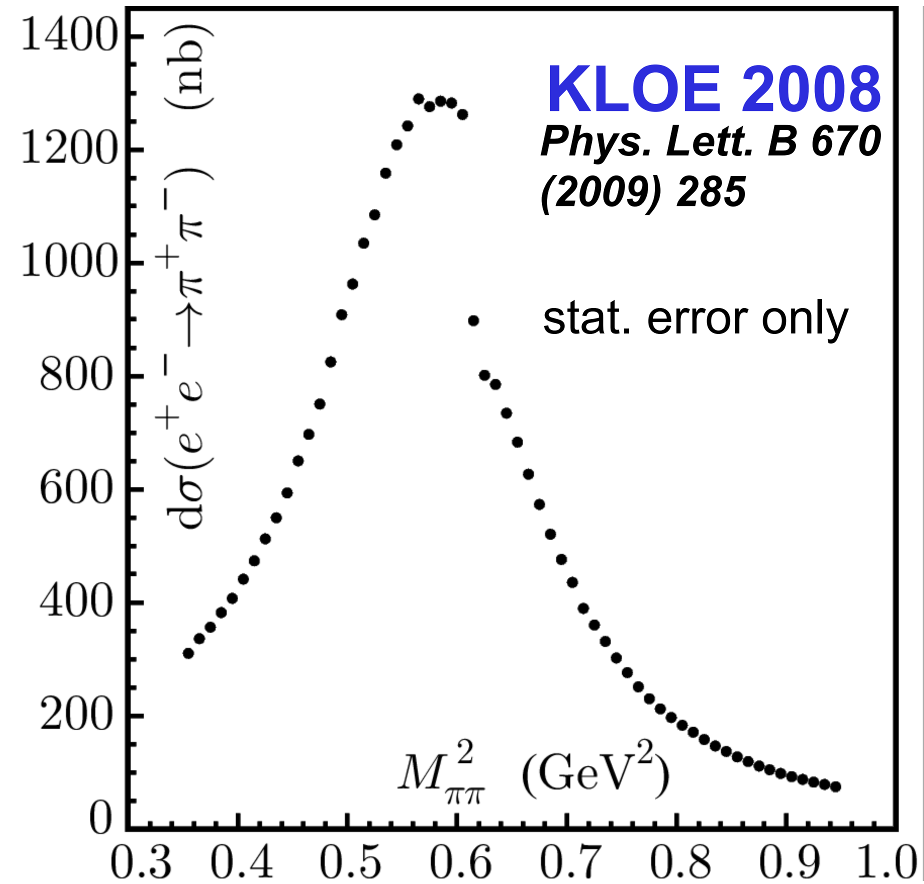
experimental fractional error on a_μ = 0.6 %

FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	0.1%

theoretical fractional error on a_μ = 0.6 %

$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s)K(s)ds$$

$\sigma_{\pi\pi}$, undressed from VP, inclusive for FSR as function of $(M^0_{\pi\pi})^2$



$a_\mu^{\pi\pi}(0.35\text{-}0.95\,\mathrm{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{sys} \pm 2.3_{theo}) \cdot 10^{-10}$

KLOE10 result: Pion Form Factor

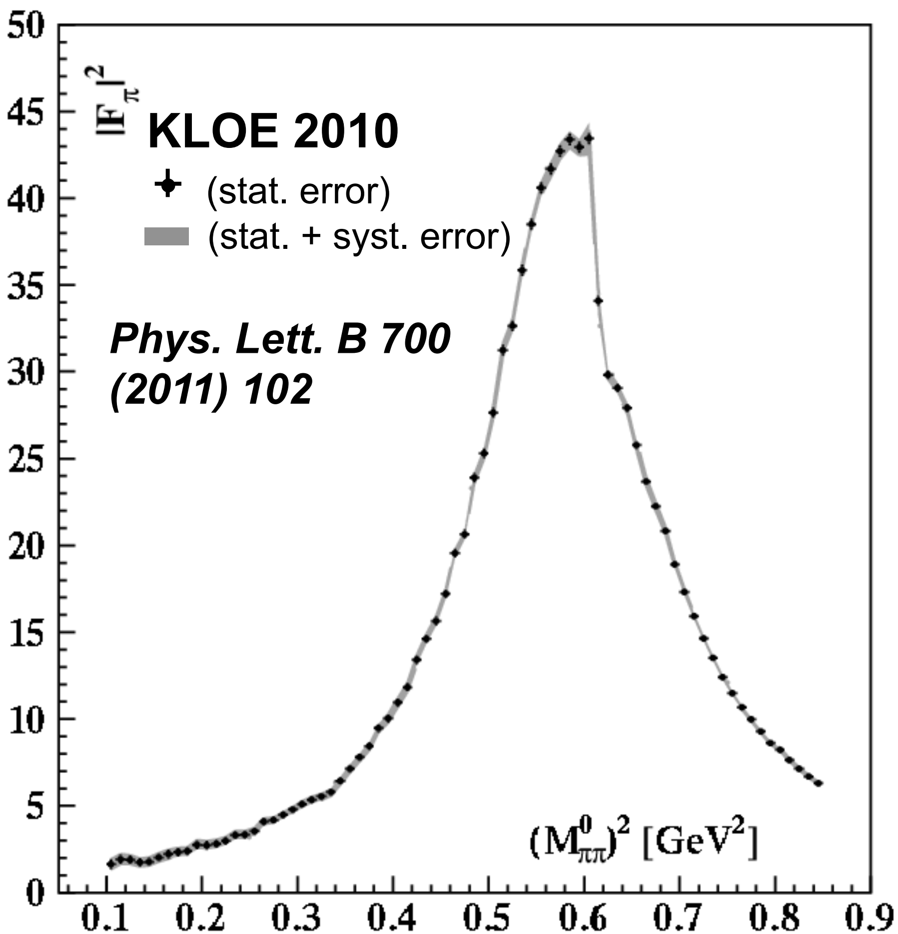


Table of systematic errors on a_m^{pp}(0.1-0.85 GeV^2):

Reconstruction Filter	< 0.1%
Background	0.5%
f_0+rp	0.4%
Omega	0.2%
Trackmass	0.5%
p/e-ID and TCA	< 0.1%
Tracking	0.3%
Trigger	0.2%
Acceptance	0.4%
Unfolding	negligible
Software Trigger	0.1%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

experimental fractional error on a_μ = 1.0 %

FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	< 0.1%

theoretical fractional error on a_μ = 0.6 %

Disp. Integral:

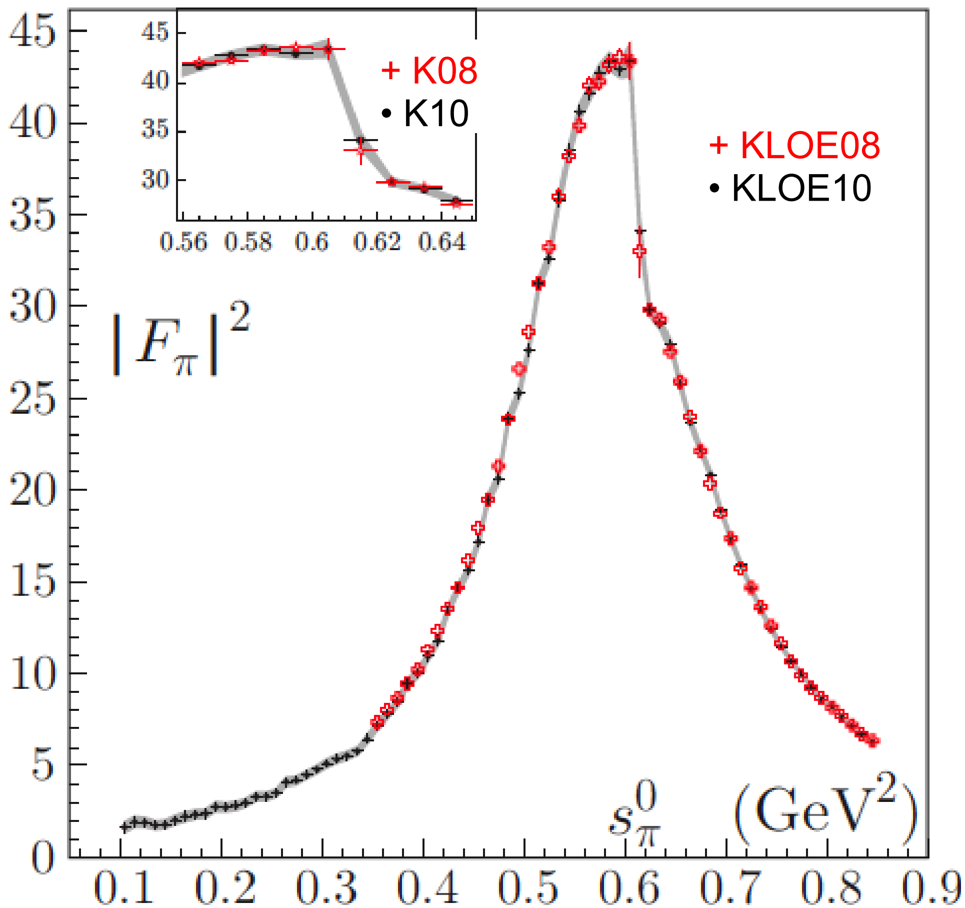
$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

$$a_\mu^{\pi\pi}(0.1\text{-}0.85\ \text{GeV}^2) = (478.5 \pm 2.0_{stat} \pm 4.8_{sys} \pm 2.9_{theo}) \cdot 10^{-10}$$

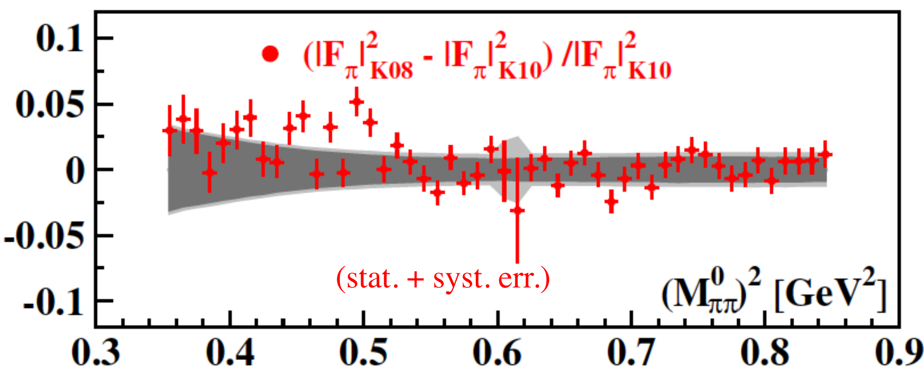
0.4% 1.0% 0.6%

Comparison of results: KLOE10 vs KLOE08

KLOE08 result compared to KLOE10:



Fractional difference:



band: KLOE10 error

Excellent agreement with KLOE08, expecially above 0.5 GeV^2

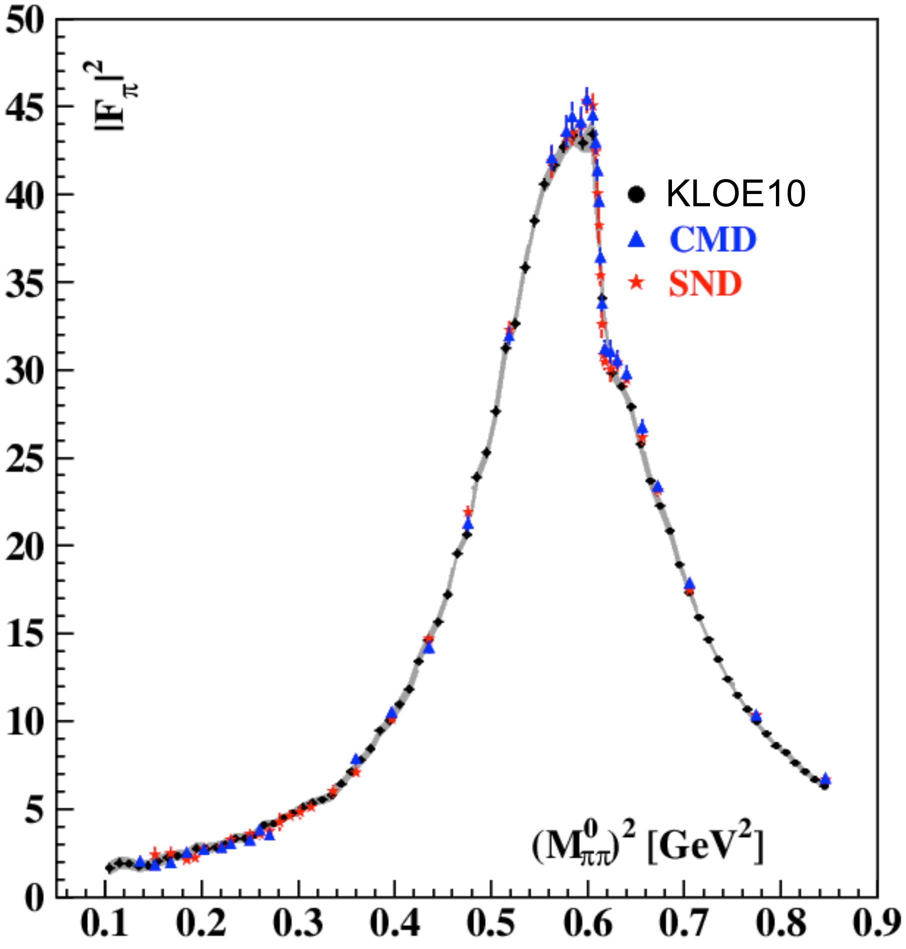
Combination of KLOE08 and KLOE10:

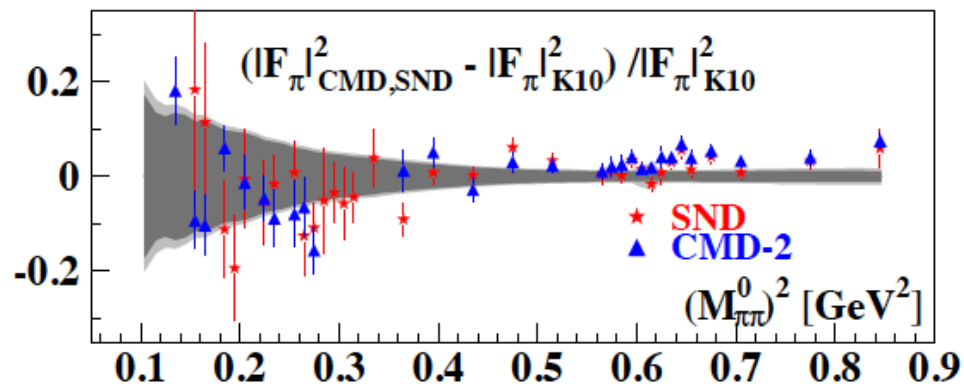
$a_\mu^{\pi\pi}(0.1\text{-}0.95\ \text{GeV}^2) = (488.6 \pm 5.0) \cdot 10^{-10}$

KLOE covers ~70% of total a_μ^{HLO} with a fractional error of 1.0%

Comparison of results: KLOE10 vs CMD-2/SND

CMD and SND results compared to KLOE10: Fractional difference





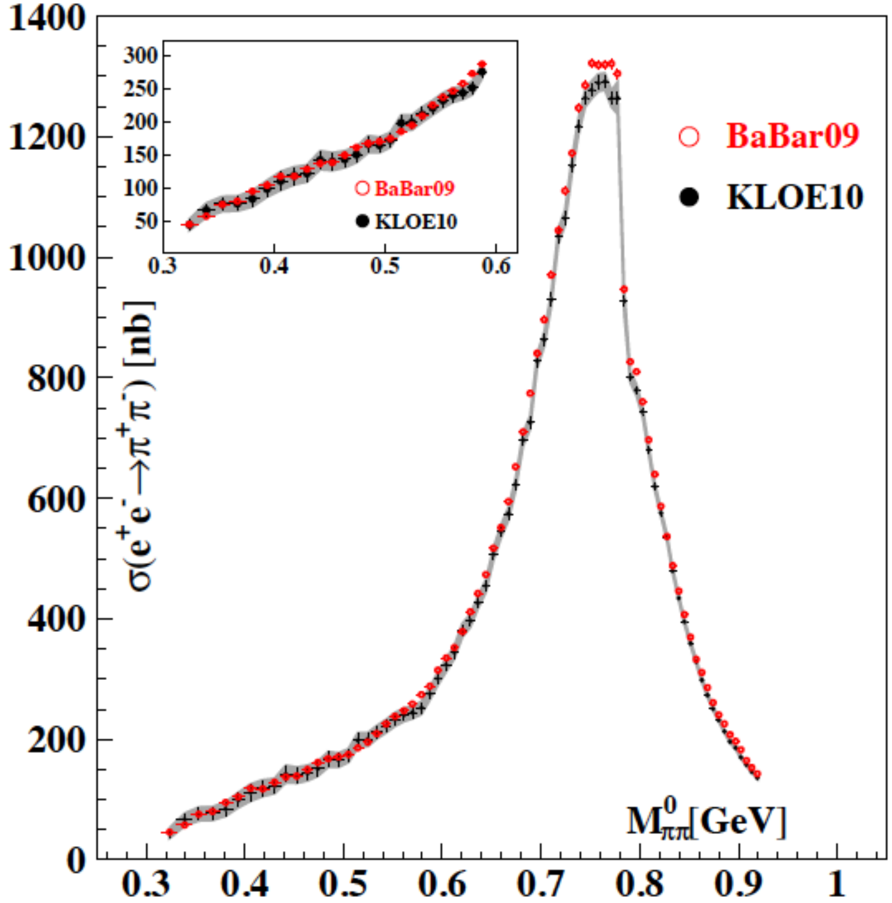
band: KLOE10 error

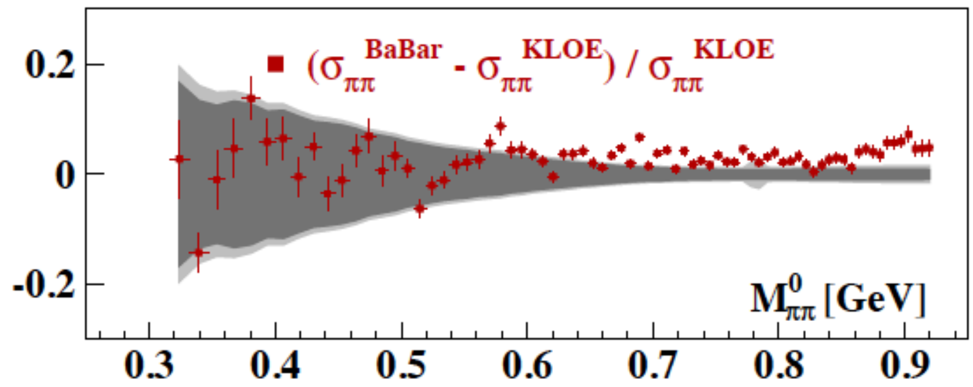
Below the ρ peak good agreement with CMD-2/SND.

Above the ρ peak KLOE10 slightly lower (as KLOE08)

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference





band: KLOE10 error

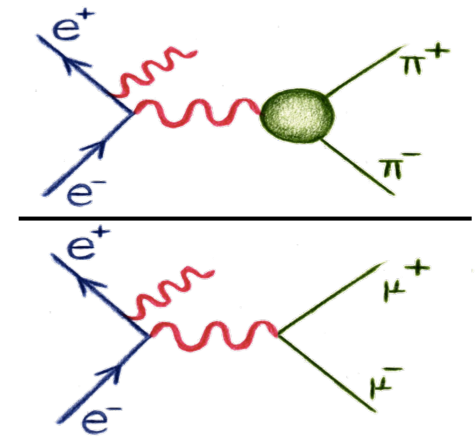
Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above

KLOE12 measurement from $\pi\pi\gamma/\mu\mu\gamma$

An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

$$|F_\pi(s')|^2 \approx \frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3} \quad \frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

kinematical factor ($s_{mm}^{Born} / s_{pp}^{Born}$) — meas. quantities



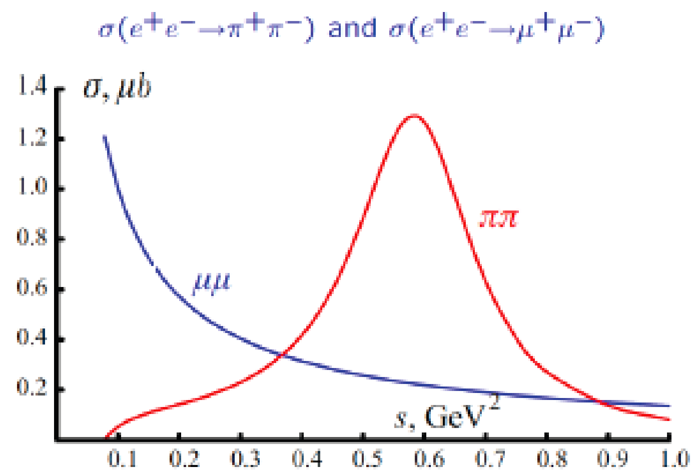
Many radiative corrections drop out:

- *radiator function*
- *int. luminosity from Bhabhas*
- *Vacuum polarization*

Separation btw $\pi\pi\gamma$ and $\mu\mu\gamma$ using M_{TRK}

- *muons:* $M_{Trk} < 115$ *MeV*
- *pions :* $M_{Trk} > 130$ *MeV*

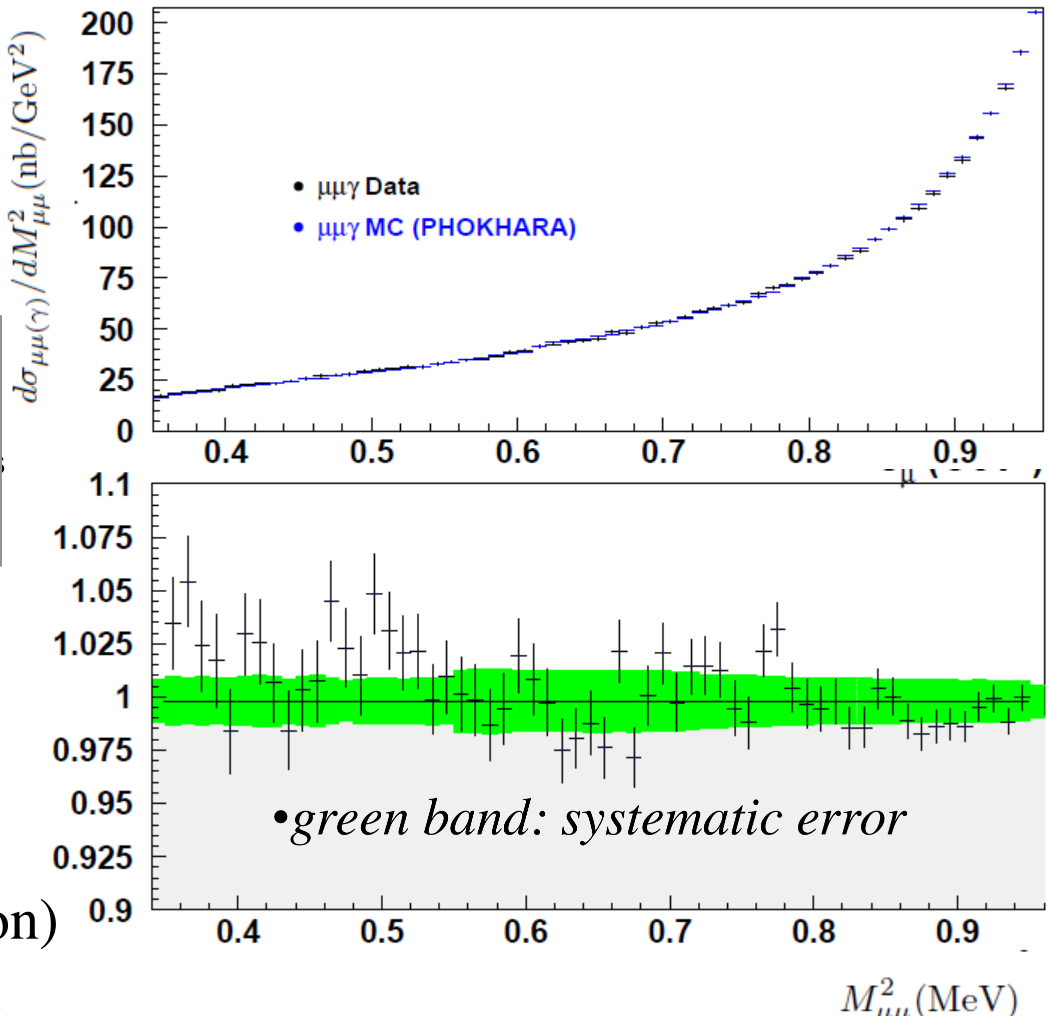
Very important control of π/μ *separation in the* ρ *region!* $(\sigma_{\pi\pi} >> \sigma_{\mu\mu})$



μμγ cross section: data/MC comparison

$$\frac{d\sigma^{obs}_{\mu\mu\gamma(\gamma)}}{dM^2_{\mu\mu}} = \frac{\Delta N_{Obs} - \Delta N_{Bkg}}{\Delta M^2_{\mu\mu}} \cdot \frac{1}{\varepsilon_{Sel}} \cdot \frac{1}{\int L dt}$$

$$\frac{d\sigma^{DATA}_{\mu\mu\gamma(\gamma)}}{d\sigma^{MC}_{\mu\mu\gamma(\gamma)}} = 0.998 \pm 0.001_{stat} \pm 0.011_{sys}$$

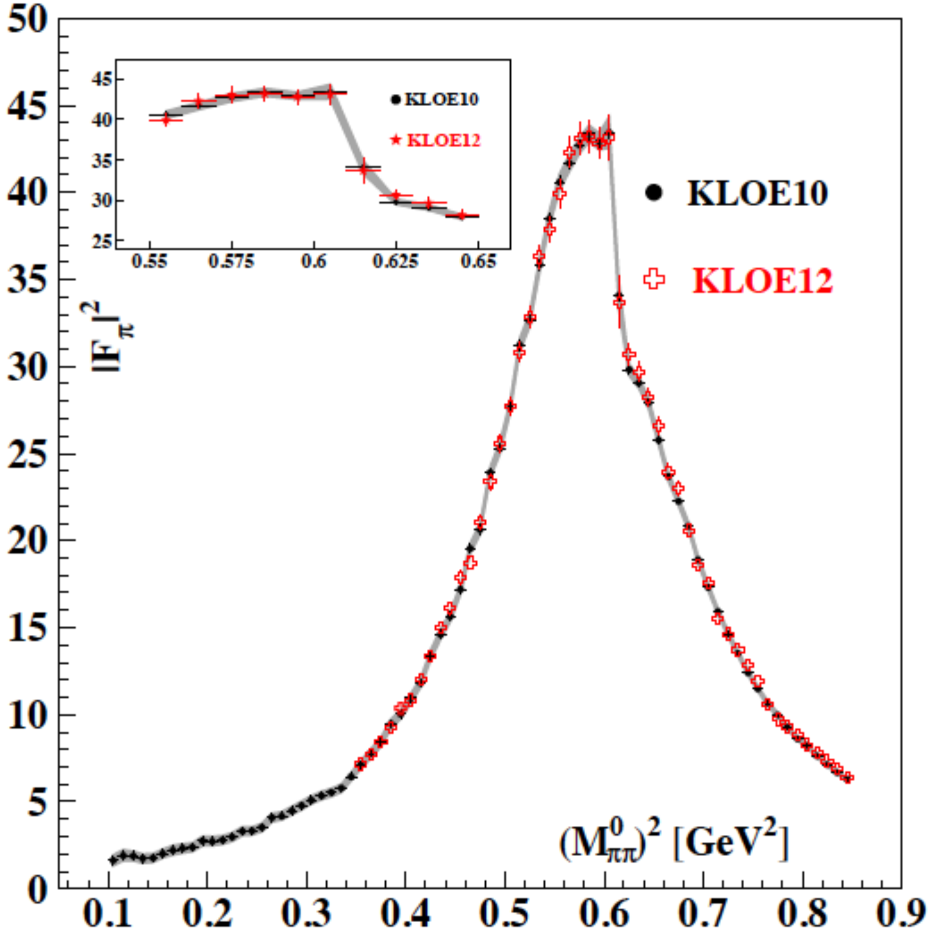


- •The systematic error has been averaged on $M^2_{\mu\mu}$
- •Good agreement with PHOKHARA MC (NLO Calculation)
- •Consistency check of Radiator function, Luminosity, etc…

Comparison of results: KLOE12 vs KLOE10

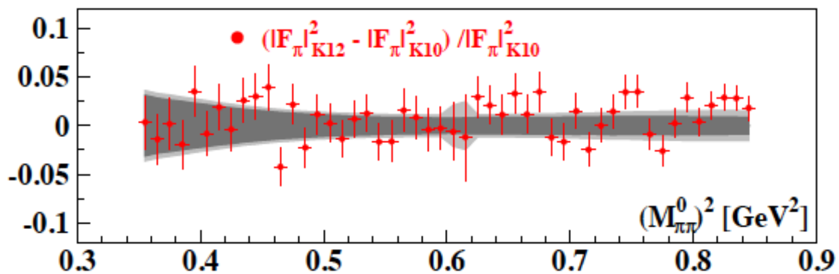
KLOE12 result compared to KLOE10:

Phys. Lett. B 720 (2013) 303



	$a_\mu^{\pi\pi}(0.35-0.95\ \mathrm{GeV}^2)\times 10^{10}$
KLOE12	$385.1 \pm 1.1_{stat} \pm 2.7_{sys+theo}$
KLOE08	$387.2 \pm 0.5_{stat} \pm 3.3_{sys+theo}$

Fractional difference:



band: KLOE10 error

Excellent agreement between the two independent measurements!

Analysis	$a_\mu^{\pi\pi}(0.35-0.85\ \mathrm{GeV}^2)\times 10^{10}$
KLOE12	$377.4 \pm 1.1_{stat} \pm 2.7_{sys+theo}$
KLOE10	$376.6 \pm 0.9_{stat} \pm 3.3_{sys+theo}$

$a_\mu=(g_\mu-2)/2$ at 2013

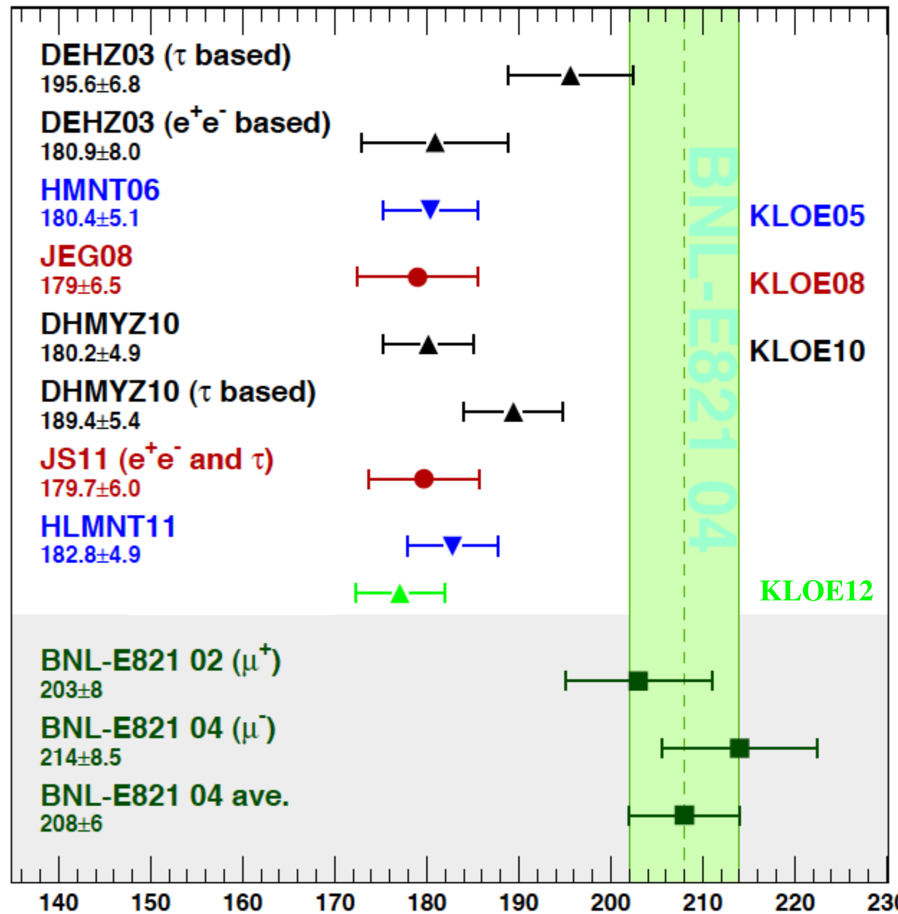
Theoretical predictions compared to the BNL result

- **The latest inclusion of all e^+e^- data gives a discrepancy btw a_μ^{SM} and a_μ^{EXP} of 3 to 4σ**

- **Remaining differences on $\sigma_{\pi\pi}$ btw different experiments (mainly KLOE/BaBar) to be clarified [Δa_μ^{EXP-SM} =2.4÷3.7σ]**

- **(Reduced) discrepancy with τ data (new I. corr.,ee,τ data). JS11 claims to have solved it**

KLOE12 in agreement with previous KLOE measurements and confirms the 3σ discrepancy!



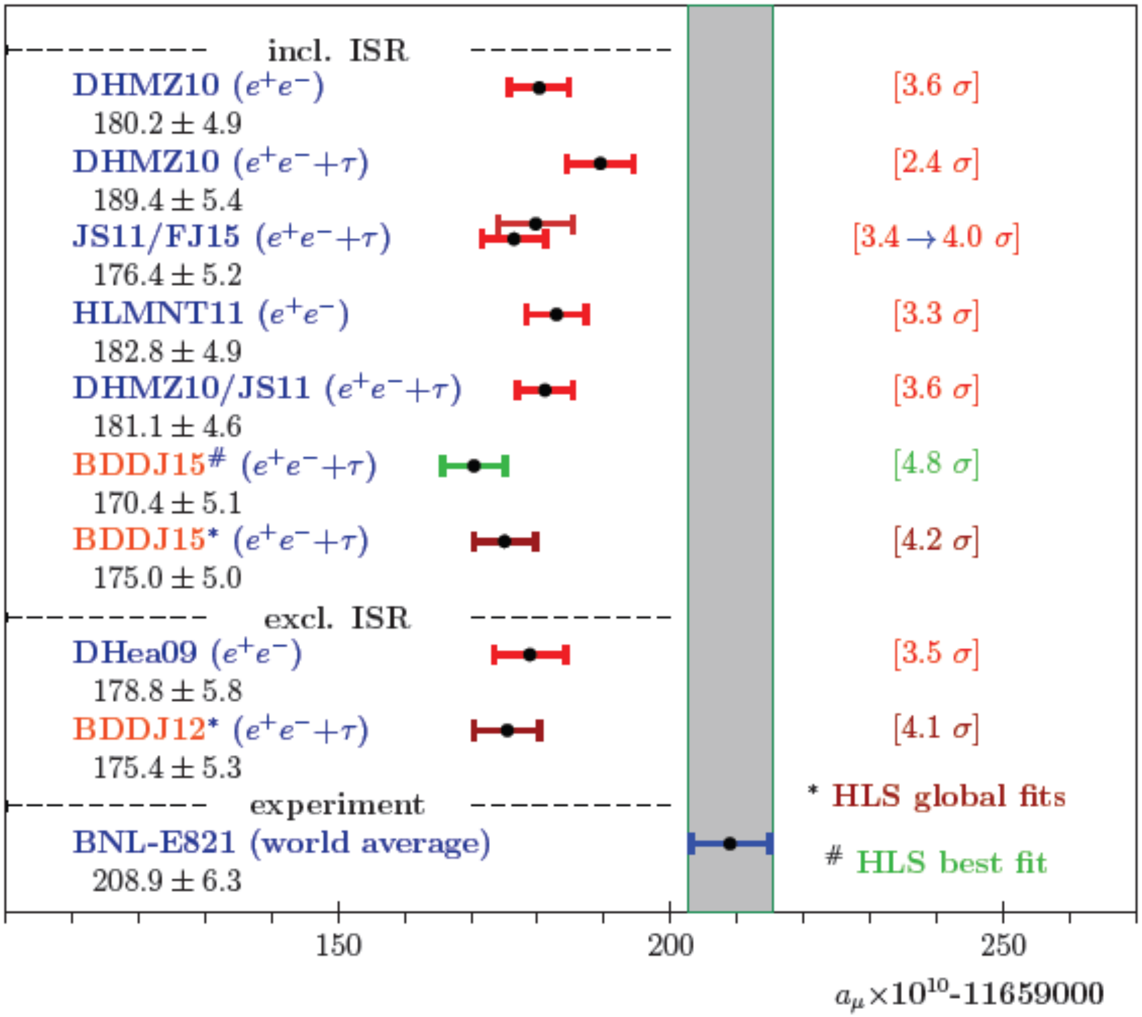
Very important the new g-2 experiments (at FNAL and JPARC)!

a_μ^{SM}: overview, recent analyses

T. Teubner TAU2016

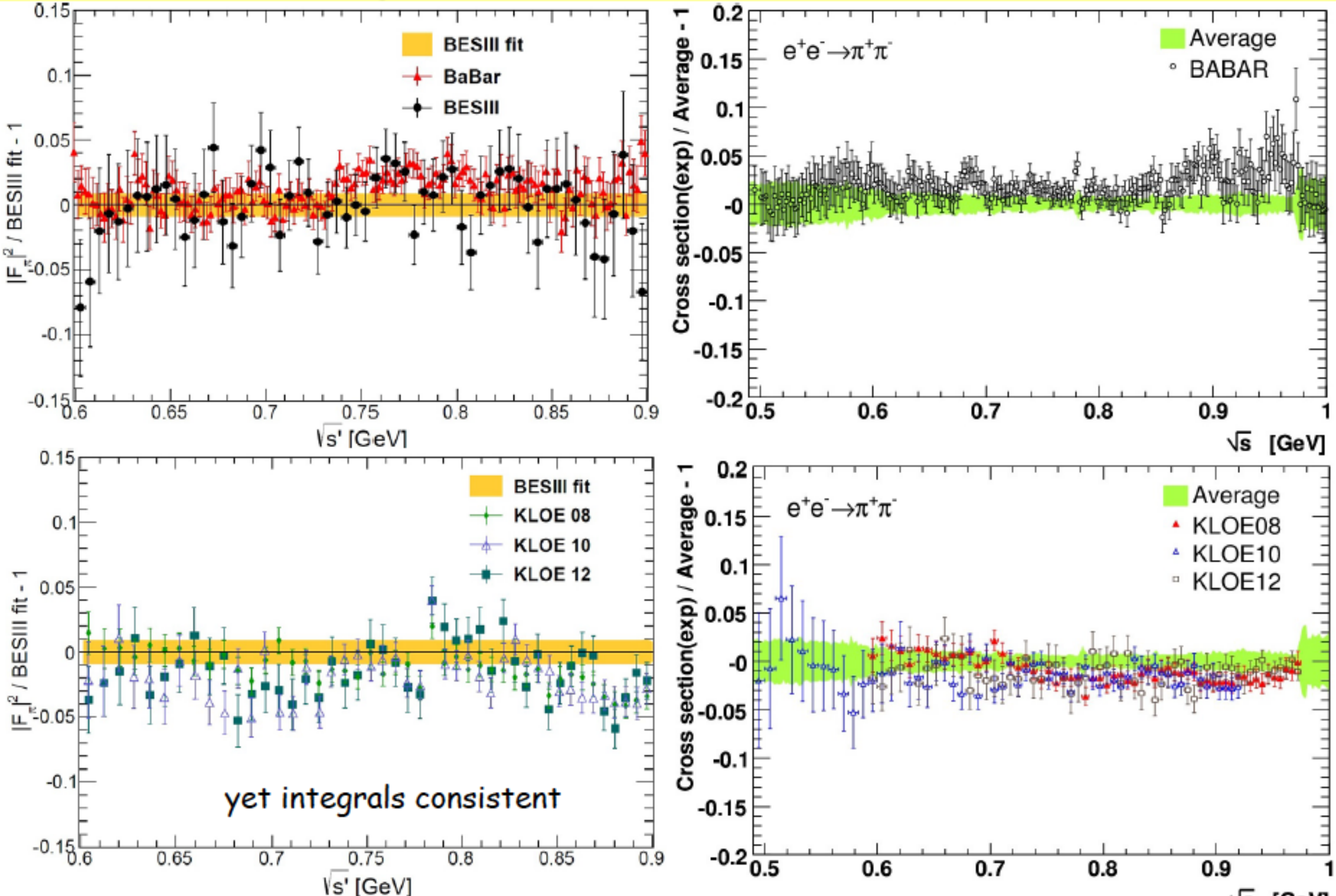
➔ for more details see M Davier's talk tomorrow

From Fred Jegerlehner's arXiv:1511.04473:

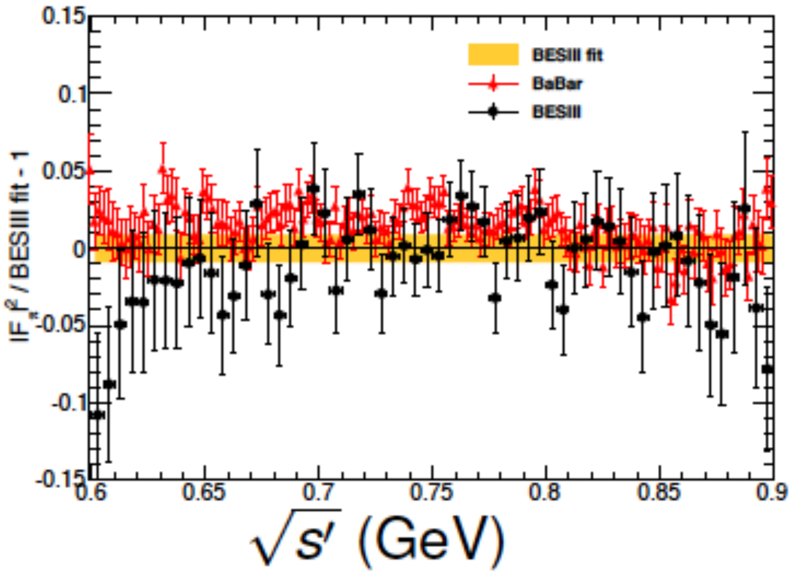


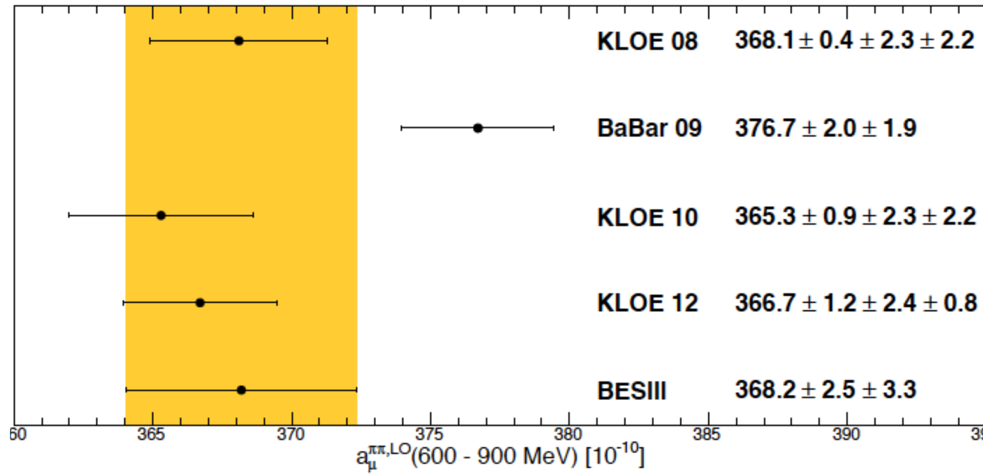
τ corrected for missing isospin cor. agree and can be averaged with e^+e^- (FJ11)

Close Comparison of $\pi^+\pi^-$ Cross Sections

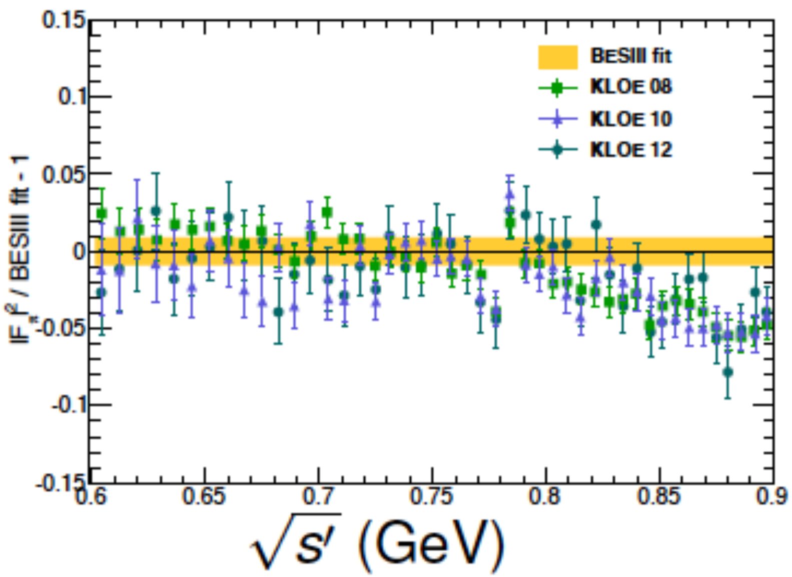


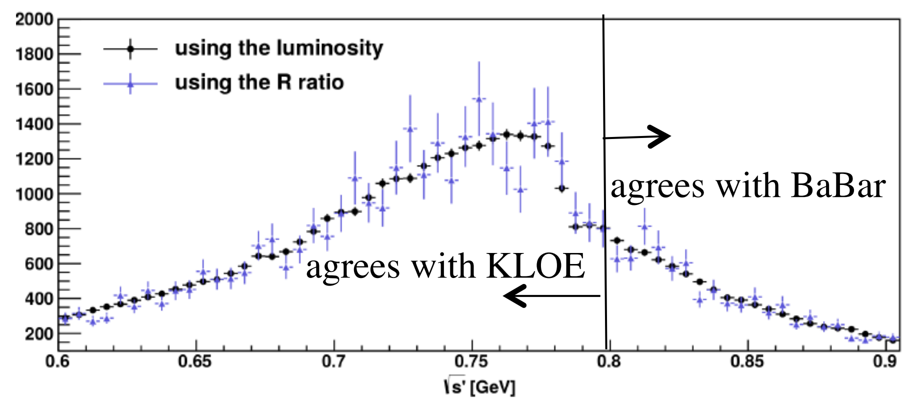
Comparison with BESIII





BESIII well agrees on $a_\mu^{\pi\pi}$ with KLOE and confirms 3σ on g-2

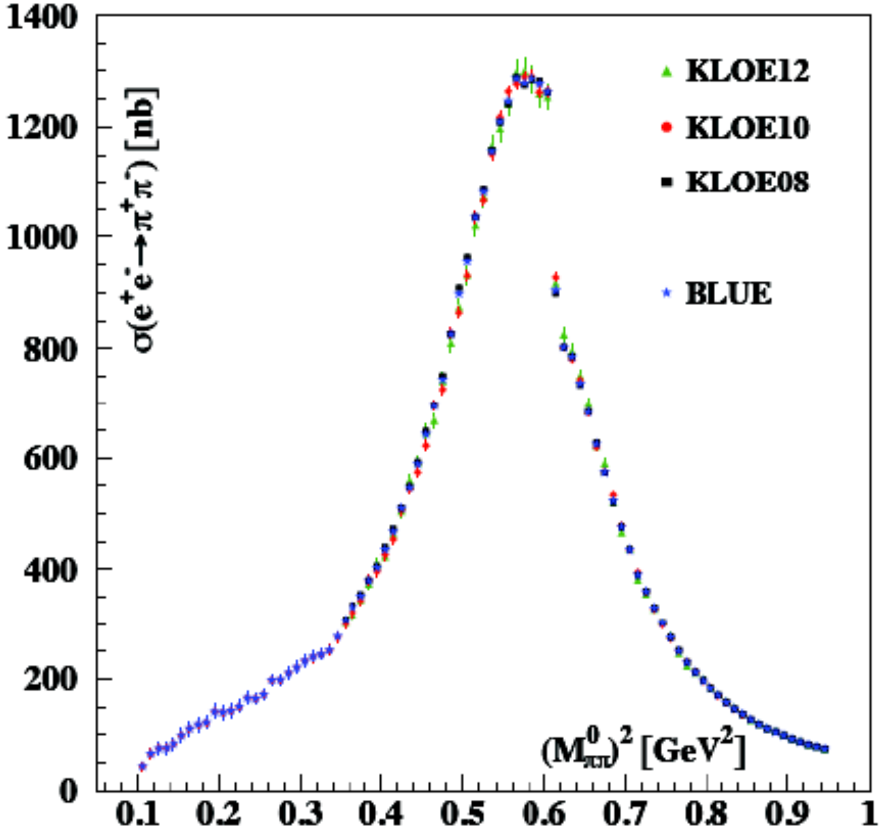




BESIII $\sigma_{\pi\pi}$ spectrum

Preliminary combination of KLOE08,10,12

by Stefan E. Müller



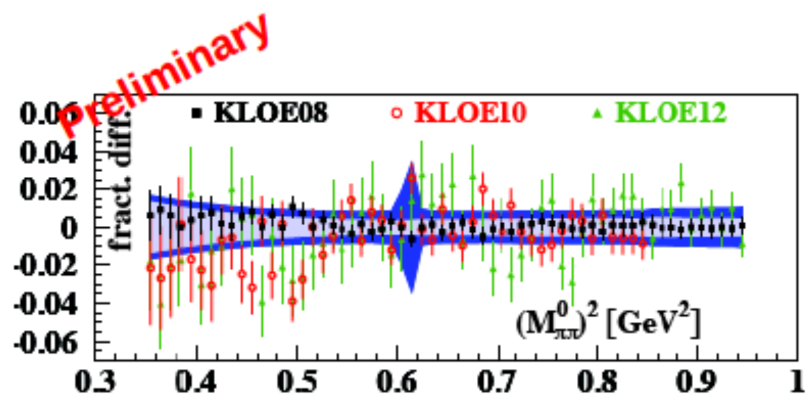
$a_\mu^{\pi\pi}(0.1\text{-}0.95\ GeV^2) = (487.8\pm5.7)\cdot 10^{-10}$

In progress

Combination of KLOE08,KLOE10, and KLOE12 using the Best Linear Unbiased Estimate (BLUE) based on:

A. Valassi, NIM A500 (2003) 391

G. D'Agostini, NIM A346 (1994) 306



$$\frac{|F_{KLOEXX}|^2-|F_{BLUE}|^2}{|F_{BLUE}|^2}$$

Grey band: Stat. errors

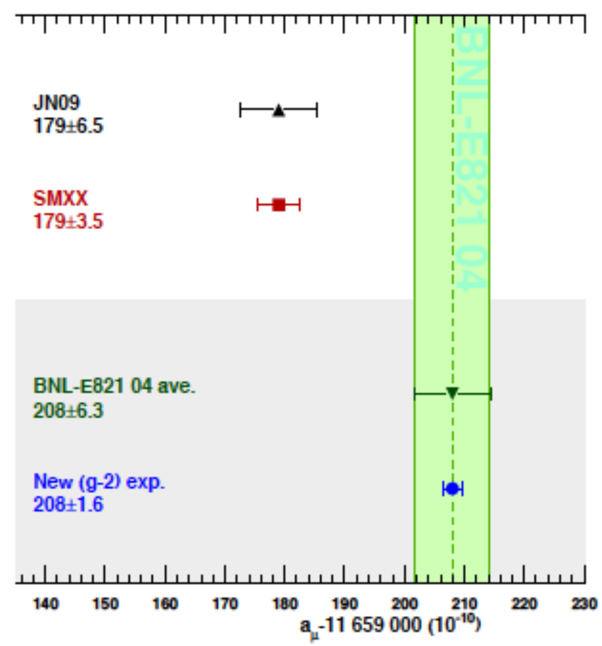
Blue band: Stat. + Syst. errors

Measurement of F_π with $2fb^{-1}$

- By using the full KLOE statistics (2 fb^{-1}) ~0.4% can be reached in the region 0.6-1 GeV (small angle region)
- To reach the same accuracy in the wider region 2π-1 GeV, a **dedicate** high-statistics ($2fb^{-1}$) **run @1 Ge**V is necessary.
- Such an accuracy together with expected improvements above 1 GeV would allow to **halve** the error on a_μ^{HLO}

	$\delta(\sigma)/\sigma$ present	δa_μ present	$\delta(\sigma)/\sigma$ prospect	δa_μ prospect
$\sqrt{s} < 1$ GeV	0.7%	33	0.4%	19
$1 < \sqrt{s} < 2$ GeV	6%	39	2%	13
$\sqrt{s} > 2$ GeV		12		12
total		53		26

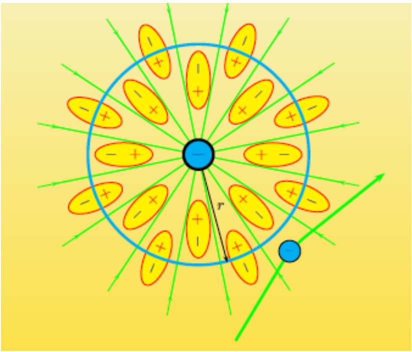
D. Babusci et al. arXiv:1007.5219



Measurements of the running of the e.m. coupling constant $\alpha(s)$ via $e^+e^- \rightarrow \mu^+\mu^-\gamma$

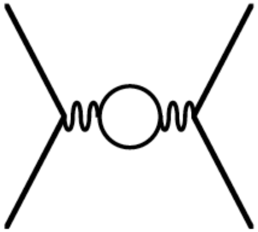
(submitted to PLB)

α_{em} running and the Vacuum Polarization



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

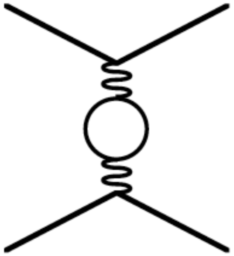
- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:



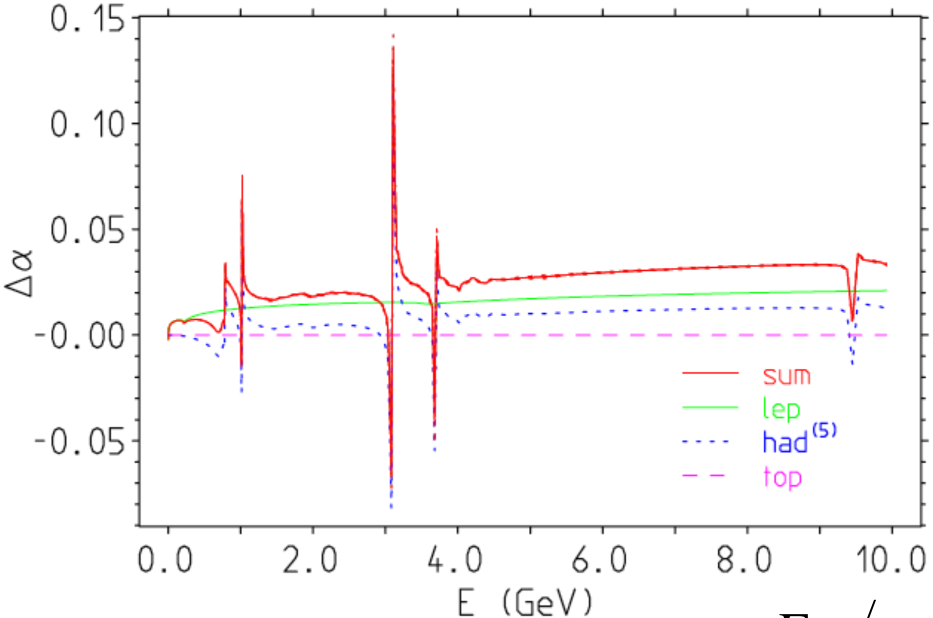
$$e^2 \rightarrow e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

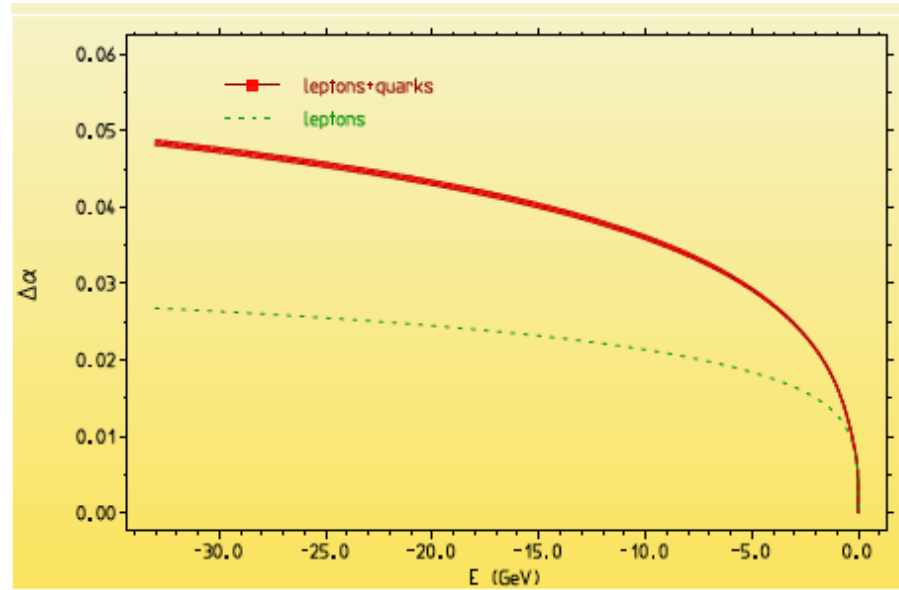
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$

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



Running of α_{em}

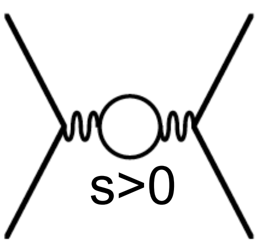




$E=\sqrt{s}$ $\quad$ $E=-\sqrt{-t}$

Time-like

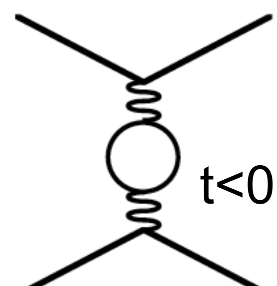
Behaviour characterized by the opening of resonances



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

Space-like

Very smooth behaviour

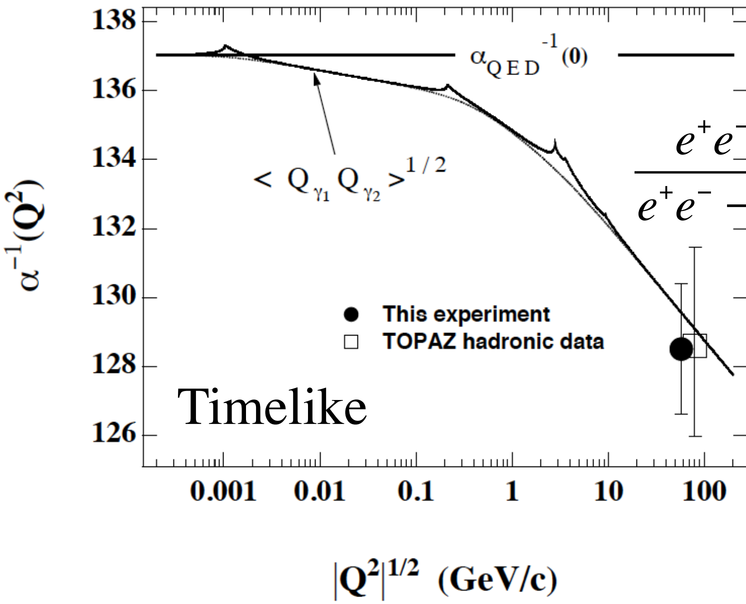


t<0

$$\Delta\alpha_{had}^{(5)}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s+q_0^2)}$$

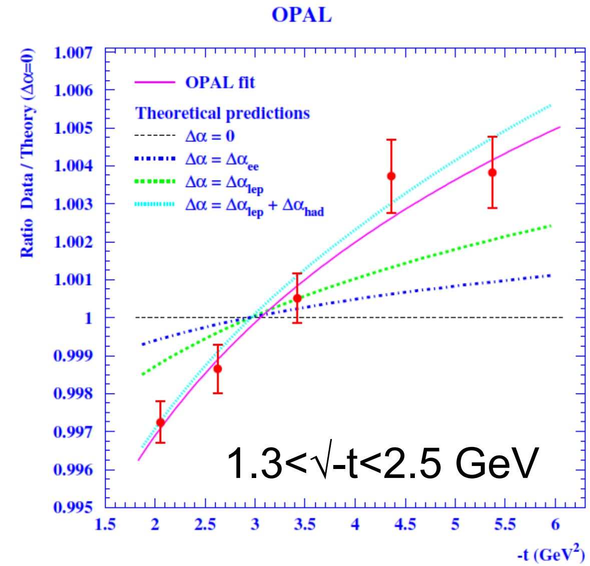
Direct measurement of α_{em} running

e+e- collider TRISTAN at √s=57.8 GeV,

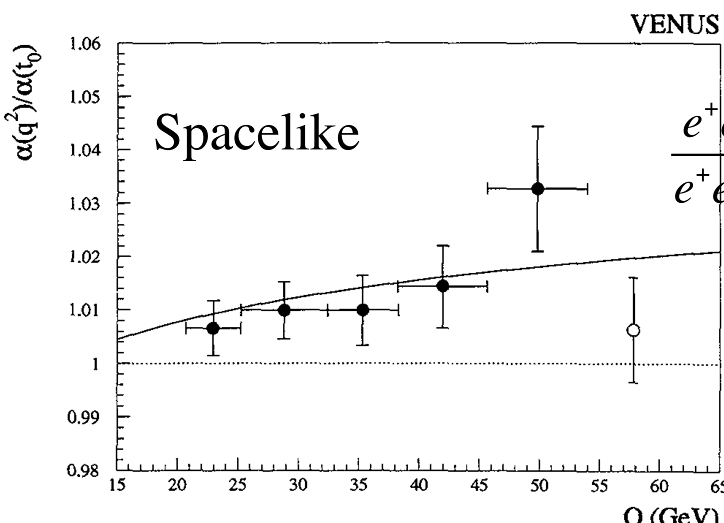


$$\frac{e^+e^- \to \mu^+\mu^-}{e^+e^- \to e^+e^-\mu^+\mu^-}$$

e+e- collider LEP at √s=189 GeV, using **Bhabha** events

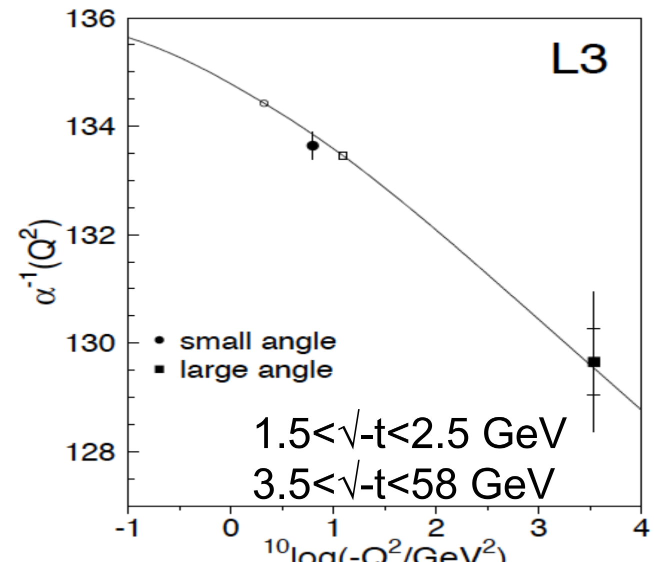


Spacelike



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

10<√-t<54 GeV



Previous tests of the hadronic contribution to VP

1) 70's: g-2 experiment at CERN: evidence for hadronic contribution to g-2 at 6σ

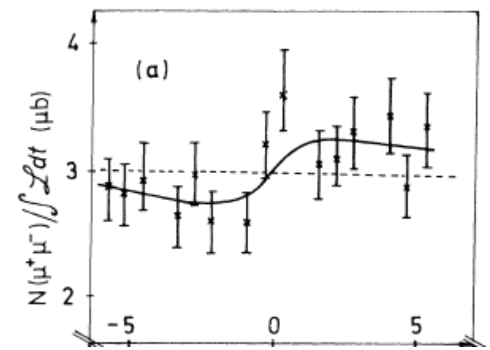
exp

$$a_\mu = 1\ 165\ 924\ (8.5) \times 10^{-9}\ (7\ \text{ppm}).$$

theo

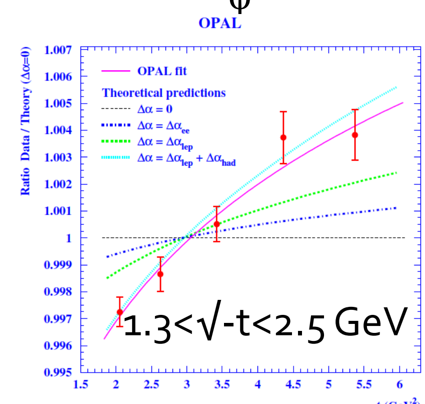
QED terms	Muon	Numerical values ($\times 10^9$)	
2nd order: A	0.5	Total QED:	1 165 852 (1.9)
4th order: B	0.765 782 23	Strong interactions:	66.7 (8.1)
6th order: C	24.452 (26)	Weak interactions:	2.1 (0.2)
8th order: D	135 (63)	Total theory:	1 165 921 (8.3)
10th order: E	420 (30)		

2) '73: $\phi(1020)$ contribution to VP at ACO (Orsay e+e-) in the $e^+e^- \to \mu+\mu-$ process: evidence at 3σ in the region ±5 MeV around the ϕ peak



-5 MeV m_ϕ 5 MeV

3) 2006: OPAL at LEP: evidence for hadronic contributon Δa_{had} (t) (t<0) at 3σ in Bhabha scattering at small angle



KLOE measurement of $\alpha(s)$ below 1 GeV with 1.7 fb^{-1}

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

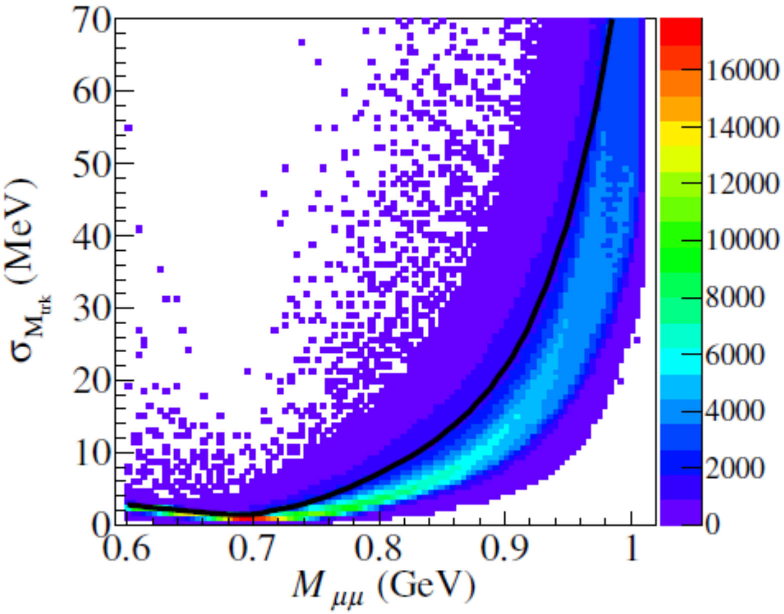
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{d\sigma_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}}{d\sigma^0_{MC}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}}$$

: $\dfrac{\text{data}}{\text{MC with } \alpha(s) = \alpha(0)}$

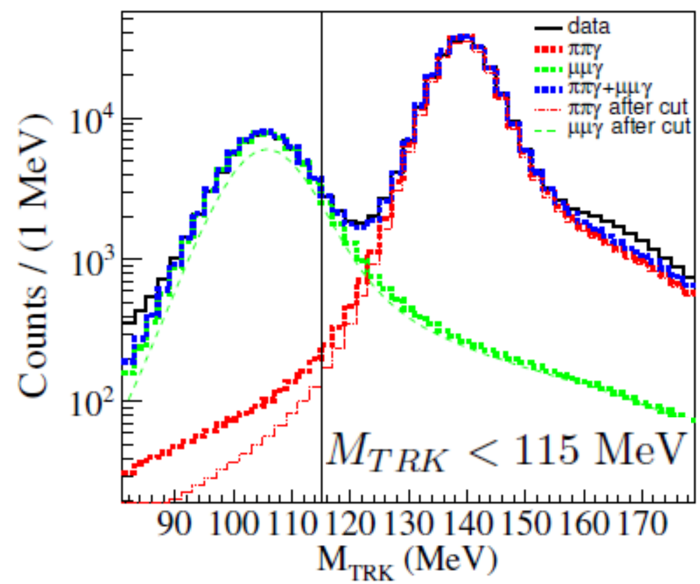
FSR correction done by by using PHOKHARA MC event generator

- Statistical significance of the hadron contribution to the effective $\alpha(s)$ is evaluated
- For the first time in a single experiment the real and Imaginary part of $\Delta\alpha$
- Measurement of BR($\omega \to \mu^+\mu^-$)

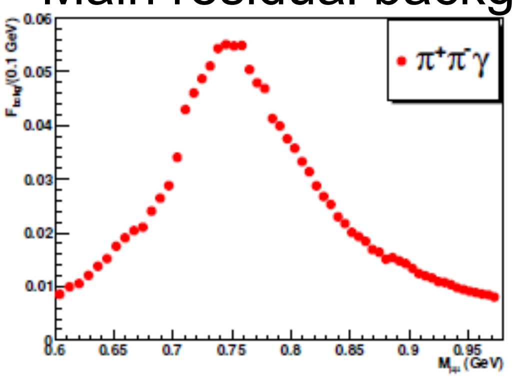
Main cuts

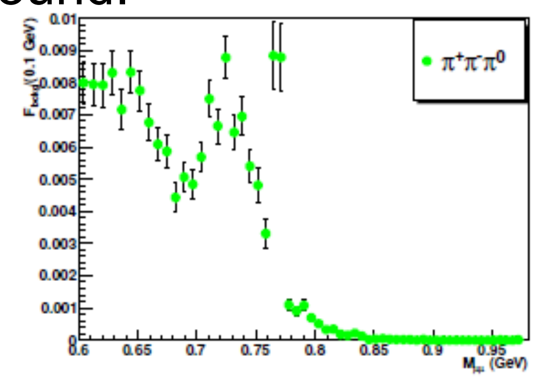


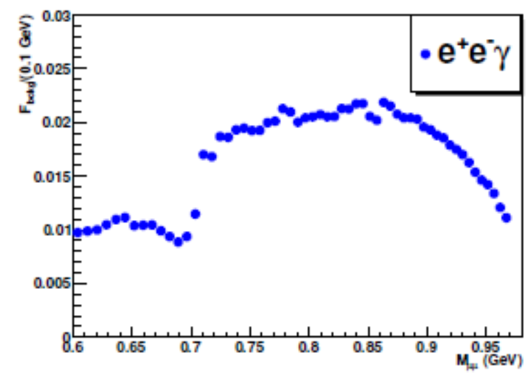
$$(\sqrt{s} - \sqrt{|p_+|^2 + M_{TRK}^2} - \sqrt{|p_-|^2 + M_{TRK}^2})^2 - (p_+ + p_-)^2 = 0$$



Main residual background:



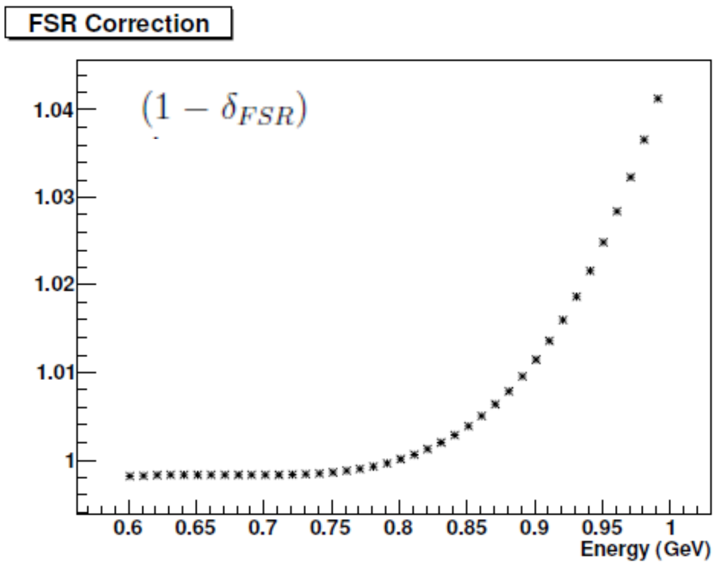


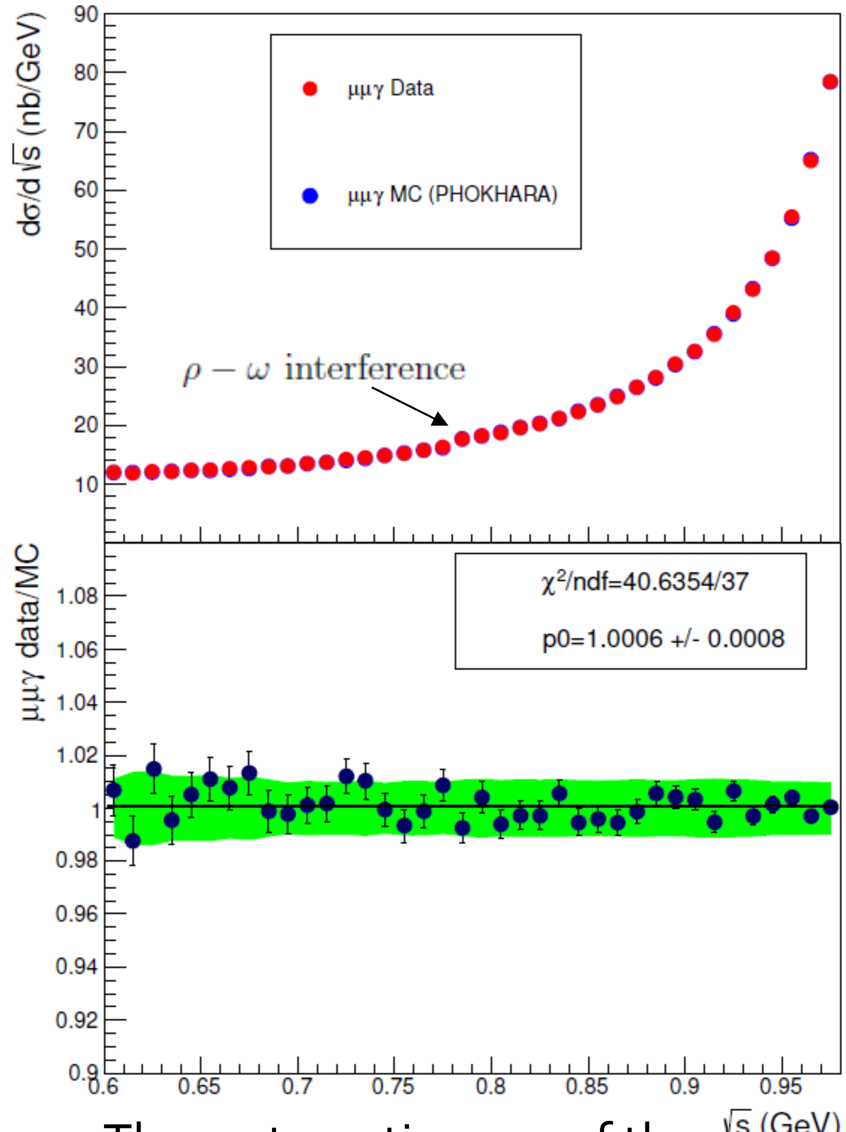


About 4.5×10^6 μμγ events pass these selection criteria

μμγ cross section measurement

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





Integrated Luminosity 1.7 fb^{-1}

Excellent agreement with NLO μμγ(γ) cross section (PHOKHARA NLO)

The systematic error of the order of 1% - (green band)

Measurement of the running of $\alpha(s)$

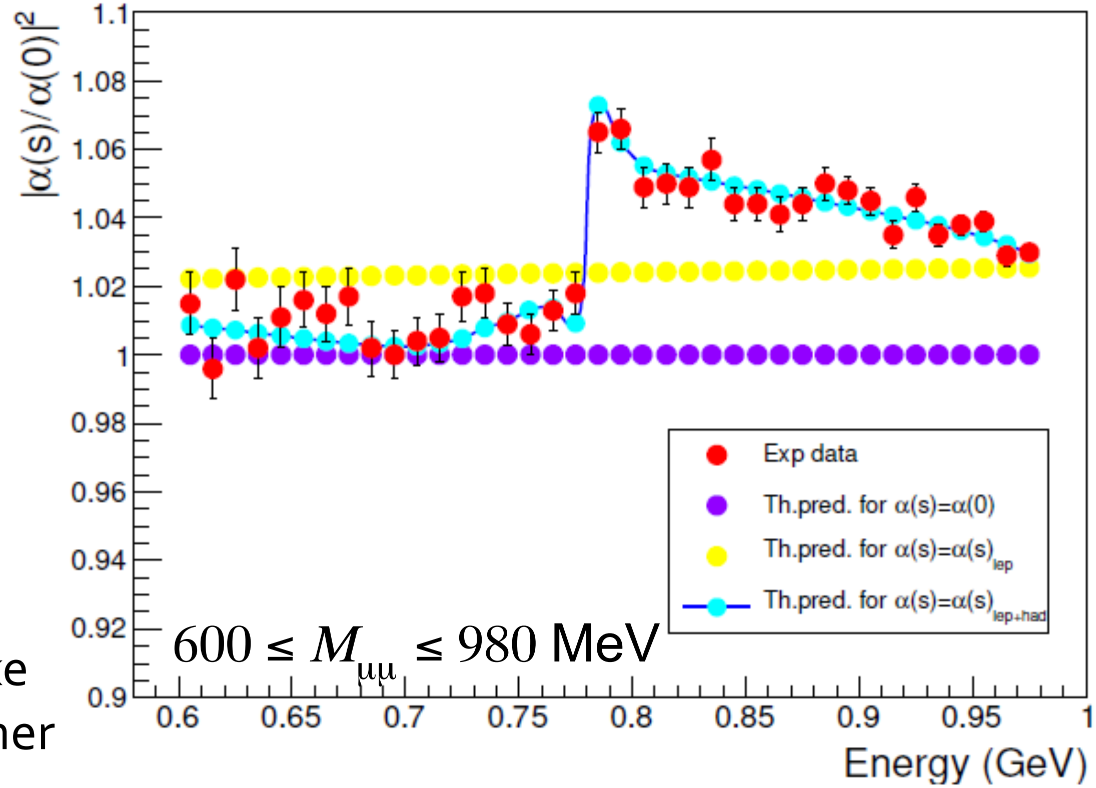
$$|\frac{\alpha(s)}{\alpha(0)}|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

MC with $\alpha=\alpha(0)$

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

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

(we neglect the top contribution)



– Δa_{had} obtained by dispersive approach using data in time-like region provided by F. Jegerlehner
- Excellent agreement with other R compilation (Teubner / Ignatov)

Systematic error at ~1% level

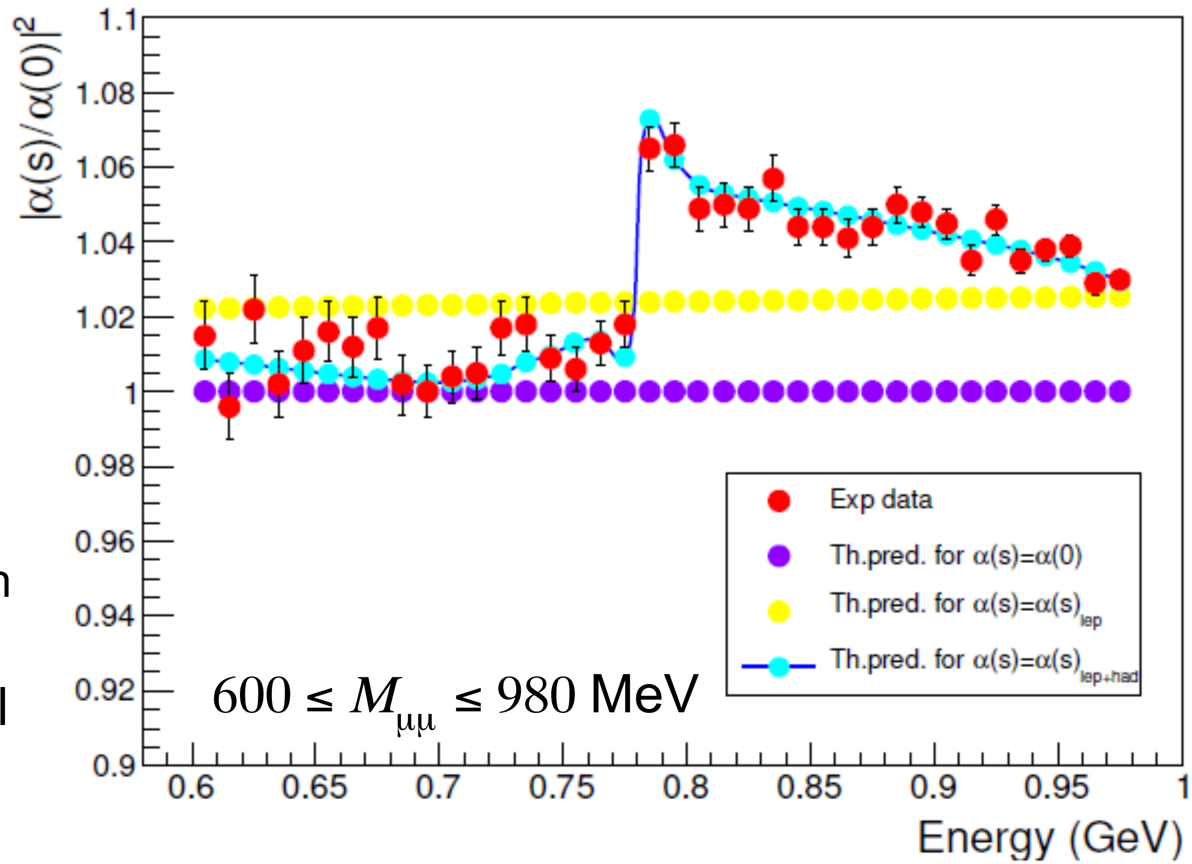
$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha(0)s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$$

$$R(s) = \frac{\sigma_{tot}(e^+e^-\to\gamma*\to hadrons)}{\sigma_{tot}(e^+e^-\to\gamma*\to\mu^+\mu^-)}$$

Test of leptonic and hadronic contribution to $\alpha(s)$

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

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



Hypothesis	$\chi^2/d.o.f$ stat.	$\chi^2/d.o.f.$ stat.+ syst.
$\Delta\alpha(s) = 0$	2189/37	382/37
$\Delta\alpha(s)_{lep}$	475/37	119/37

Real and Imaginary 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%.

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

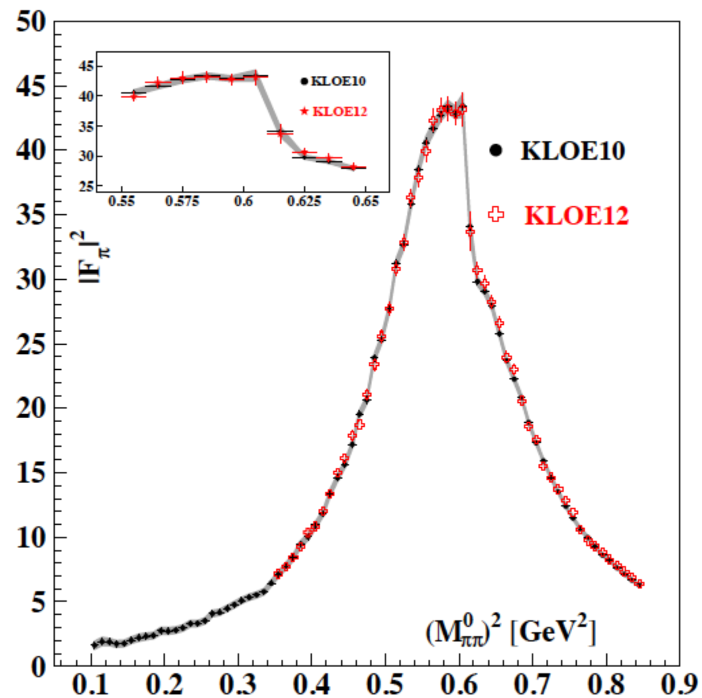
$$Im\Delta\alpha = -\frac{\alpha}{3} R(s) \qquad R(s) = \sigma_{tot} \Big/ \frac{4\pi\alpha(s)^2}{3s}$$

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

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

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

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



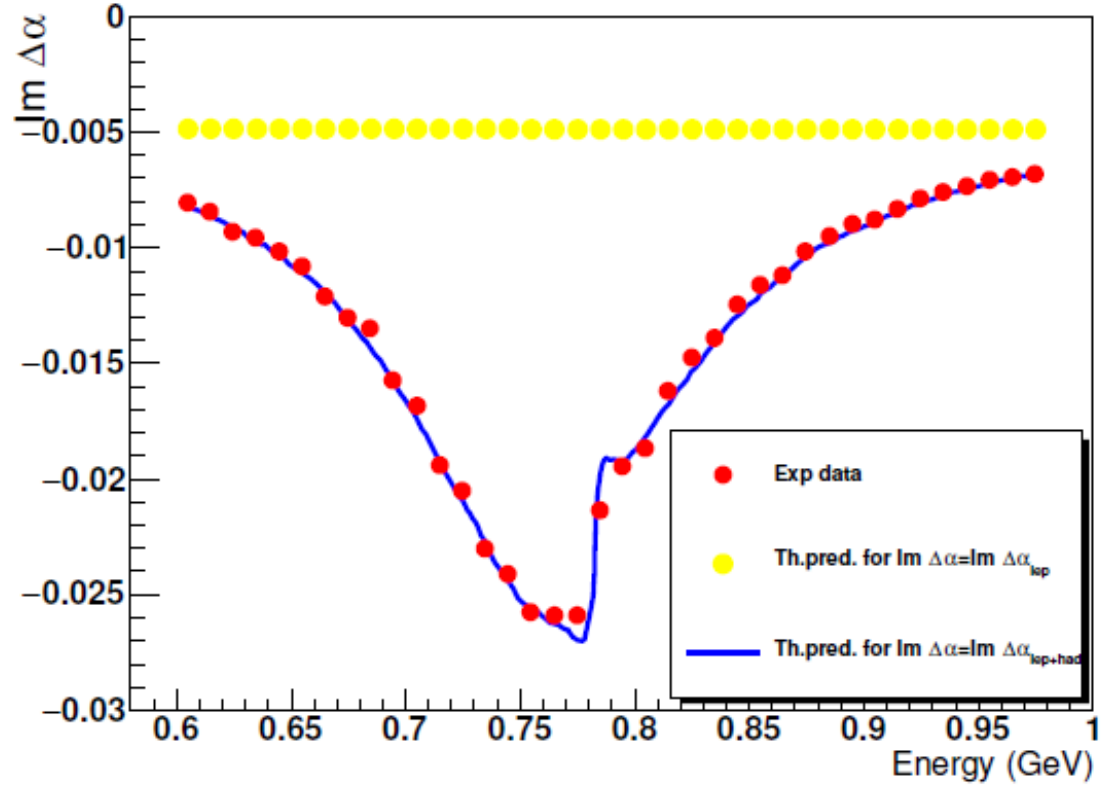
Physics Letters B 720 (2013) 336-343

In collaboration with F. Jegerlehner

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

Results obtained for the 2π contribution to Δα by using KLOE12 measurement of the pion form factor (red full circles) and the ones obtained by using the $R_{had}(s)$ compilation with the 2π channel only and removing KLOE data (blue solid line).

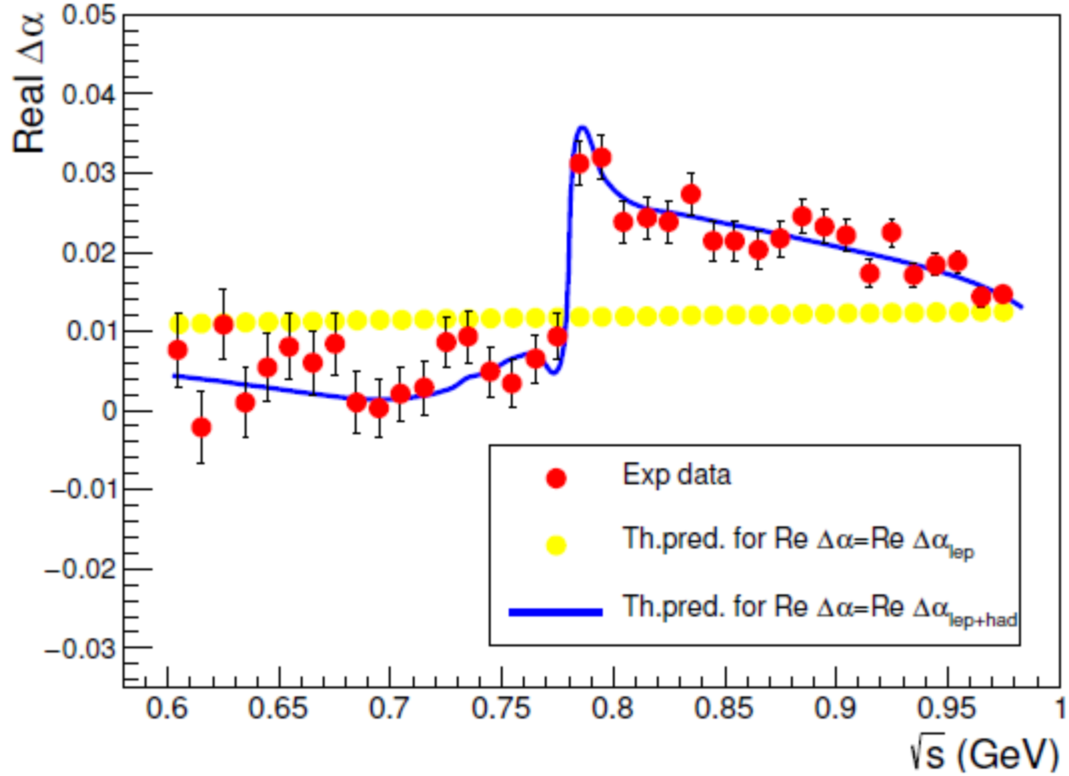
$$Im\Delta\alpha = -\frac{\alpha}{3} R(s)$$



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

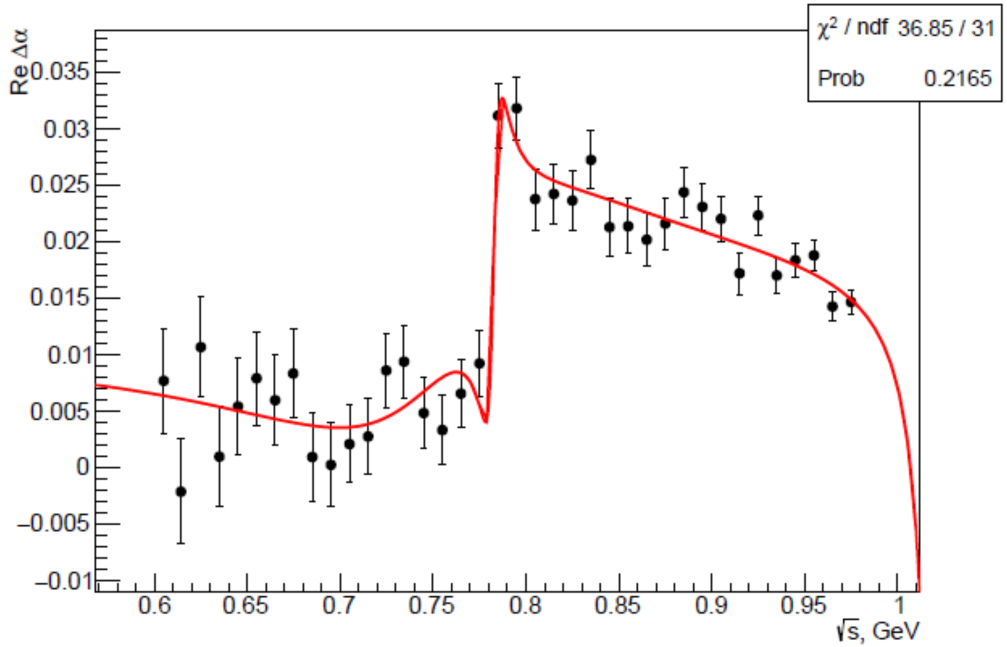
$$Re\,\Delta\alpha = 1 - \sqrt{|\alpha(0)/\alpha(s)|^2 - (Im\,\Delta\alpha)^2}.$$

ReΔα obtained by KLOE μμγ data compared with theoretical prediction with leptonic contribution only and with leptonic and hadronic contributions. Excellent agreement for Re Δα(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)

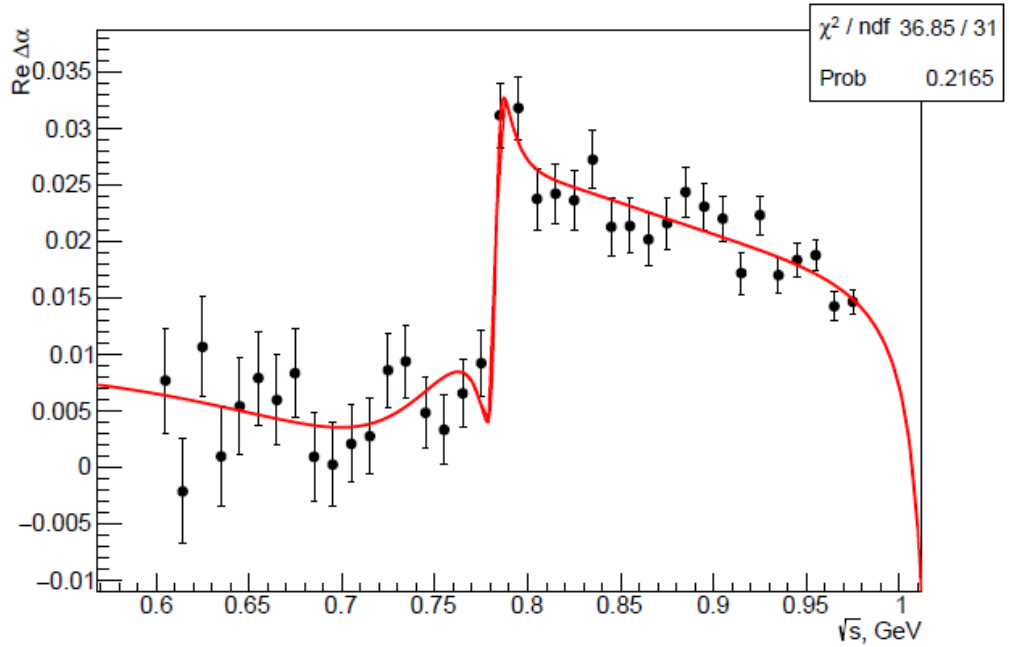
Assuming lepton universality and multiplying for the phase space correction

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

$$BR(\omega \to \mu^+\mu^-) =$$

$$= (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$$

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



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	-

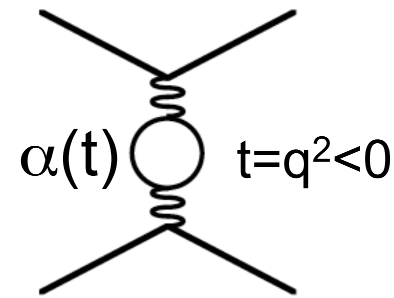
Inclusion of ω−ρ interference don't change the result (within the error)

Proposal: Measuring a_μ^{HLO} in the space-like region

[*C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni*
Phys.Lett. B746 (2015) 325-32]

a_μ^{HLO} from space-like region

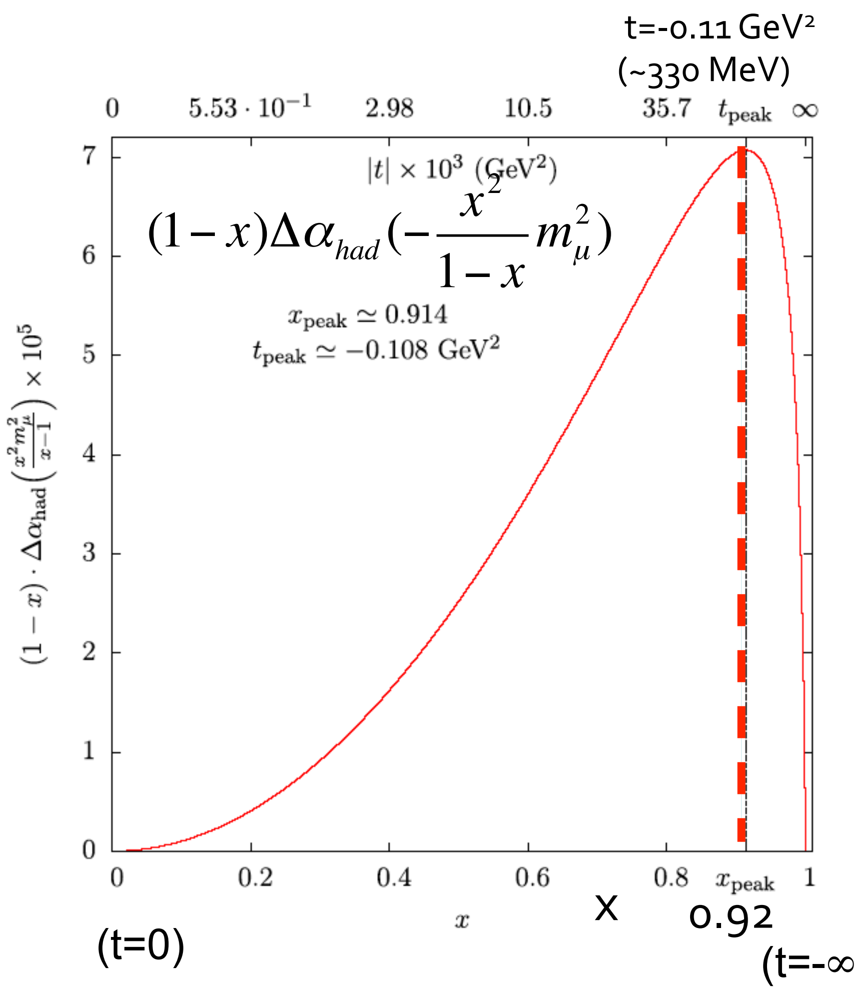
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

- **a_μ^{HLO} is given by the integral of the curve** (smooth behaviour)
- **It requires a measurement of** the hadronic contribution to the effective electromagnetic coupling in the space-like region **$\Delta\alpha_{had}$(t) (t=q²<0)**
- **It enhances** the contribution from **low** q² region (below 0.11 GeV²)
- **Its precision** is determined by the **uncertainty** on $\Delta\alpha_{had}$ (t) in this region



Experimental considerations

Using Bhabha at small angle (to emphasize t-channel contribution) to extract $\Delta\alpha$:

$$\left(\frac{\alpha(t)}{\alpha(0)}\right)^2 \sim \frac{d\sigma_{ee\to ee}(t)}{d\sigma^0_{MC}(t)}$$

Where $d\sigma^o_{MC}$ is the MC prediction for Bhabha process with α(t)=α(o), and there are corrections due to RC…

$$\Delta\alpha_{had}(t) = 1 - \left(\frac{\alpha(t)}{\alpha(0)}\right)^{-1} - \Delta\alpha_{lept}(t)$$

$\Delta\alpha_{lep}(t)$ theoretically well known!

Which experimental accuracy we are aiming at?
$\delta\Delta\alpha_{had}$~1/2 fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t)$.

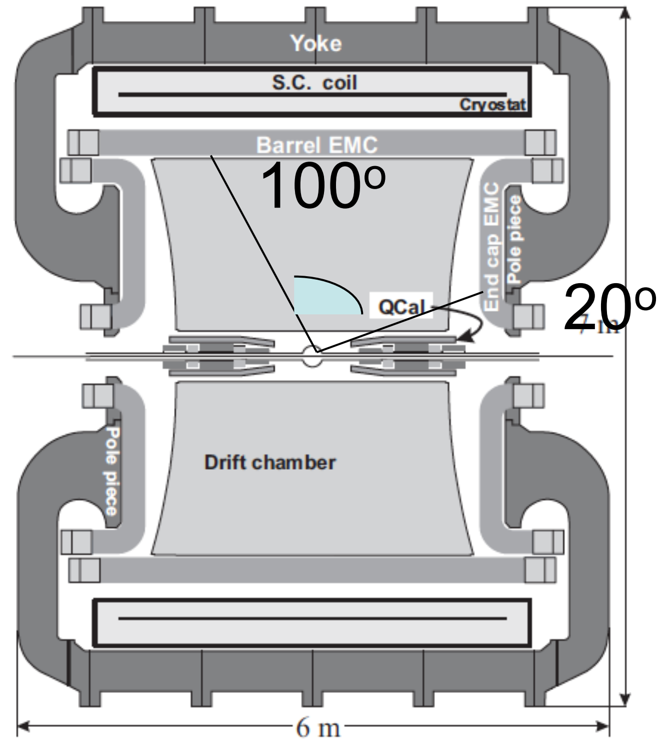
If we assume to measure $\delta\Delta\alpha_{had}$ at 5% at the peak of the integrand ($\Delta\alpha_{had}\sim10^{-3}$ at $x=0.92$) → fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t) \sim 10^{-4}$!

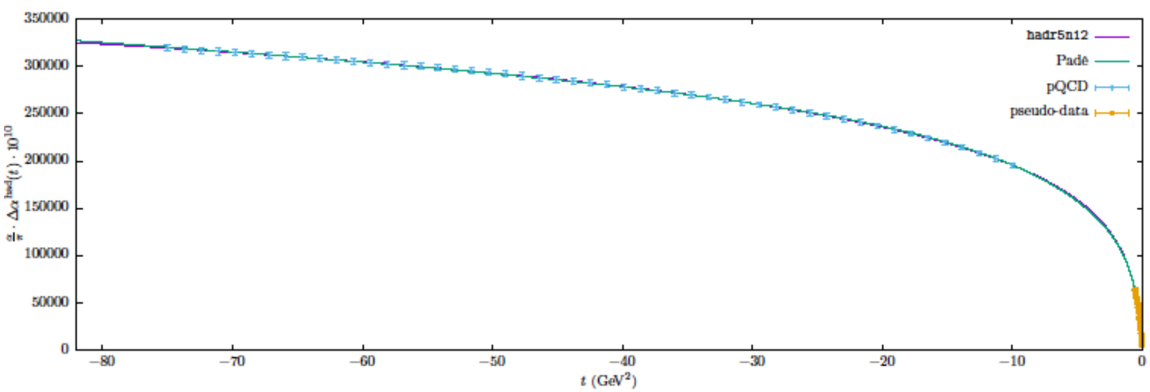
Very challenging measurement (one order of magnitude improvement respect to date) for systematic error

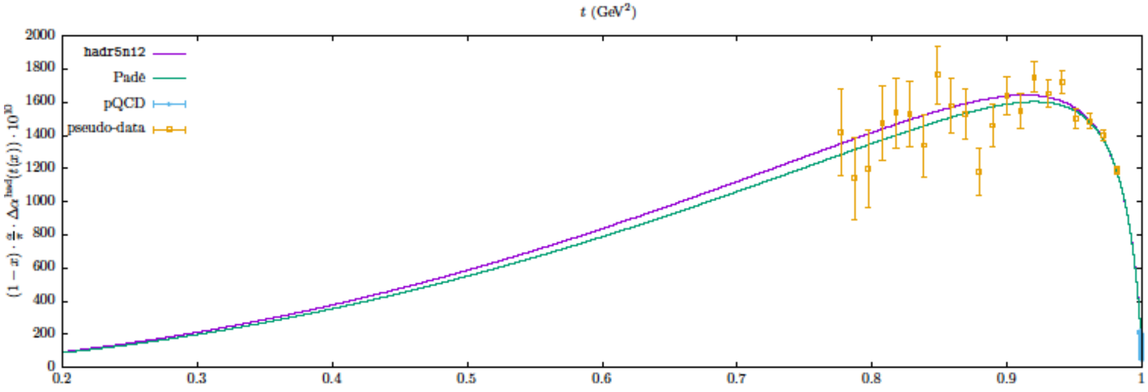
What can be done a KLOE/KLOE2?

We did the following simulation:

- 20 points between $20^o<\theta<100^o$ ($0.03<-t<0.59$ GeV^2; $0.78<x<0.98$) @ $\sqrt{s}=1$ GeV
- For each point $\delta\sigma_{e+e-}/\sigma_{e+e-}\sim10^{-4}$ (stat and syst)
- We fit $\Delta\alpha_{had}(t)$ using our points+ pQCD for $-t>10$ GeV^2 with a polinomial function (like lattice)







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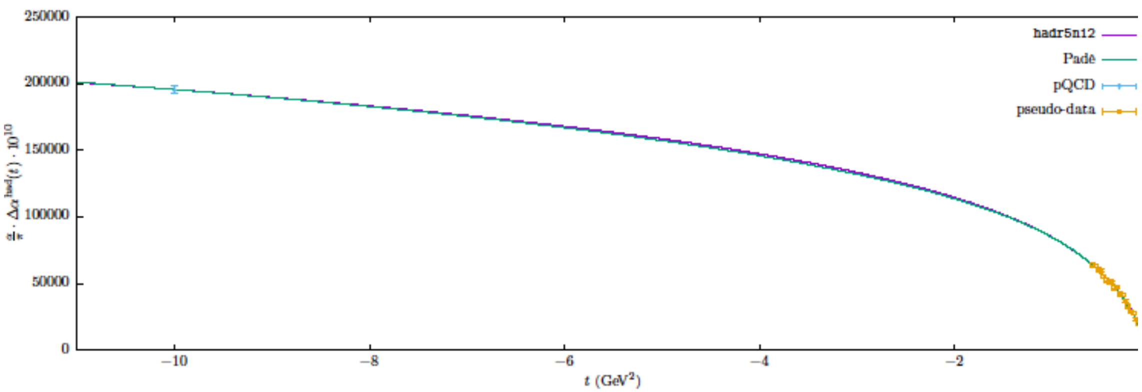
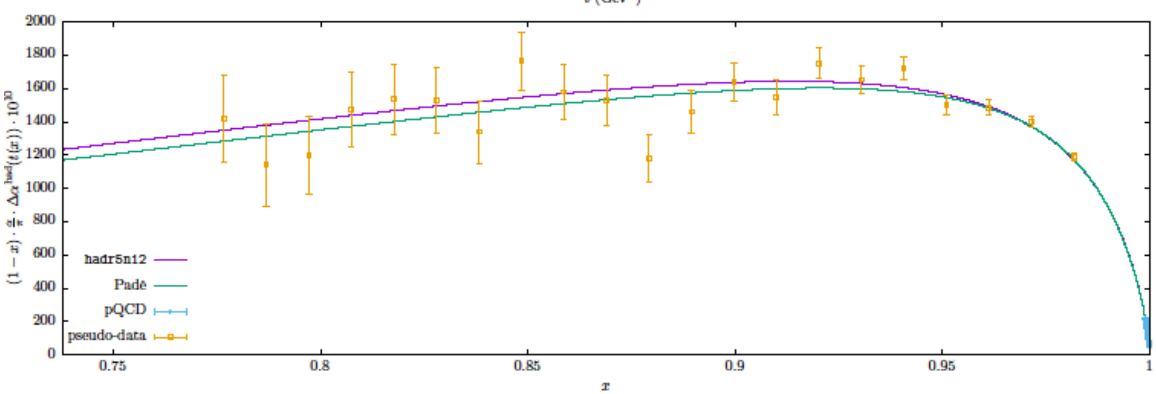
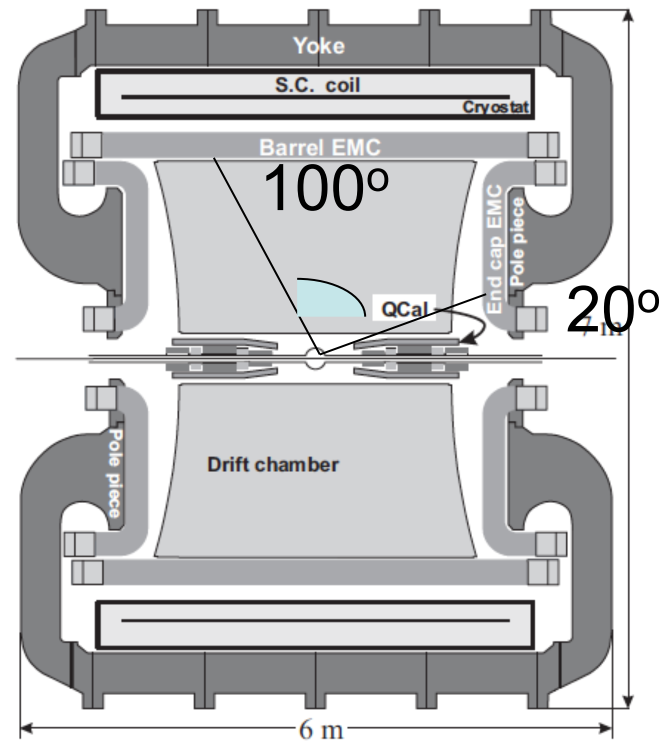






$\delta a_\mu^{HLO}\sim3\%_{stat}\oplus7\%_{syst}$

(preliminary)

Considerations

- Results for KLOE/KLOE2 are preliminary and most likely conservative. For example we don't include lattice data which populate the complementary region $1<t<5$ GeV^2 where we could expect a large improvement;

- A (strong) limitation with KLOE data is that we cannot use small angle Bhabha due to the QCAL occupancy, and therefore we should use $\gamma\gamma$ for the normalization (at 10^{-4}!)

- This may be overcome at KLOE-2 where small angle detector exist or by a **dedicated** detector with an ultimate goal of $\sim 10^{-5}$ uncertainty (10 ppm).

- In this case a goal of ~% on a_μ^{HLO} can be expected. Very challenging to keep under control systematic errors at $10^{-4\div5}$ level!

Conclusions

- KLOE has pioneered the ISR method, performing in the last 15 years factor a series of precision measurements with ISR which confirmed a 3σ discrepancy between a_μ^{SM} and the BNL measured value
- The running of the e.m. coupling constant α has been measured in the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in the 0.6 - 0.98 GeV $M_{\mu\mu}$ invariant mass range at 1.7 fb^{-1}.
- Clear contribution of the $\rho-\omega$ interference to the photon propagator with 6σ statistical significance.
- Imaginary and Real part of Δa extracted.
- By a fit of the real part of $\Delta a(s)$ and assuming lepton universality the branching ratio of $\omega \rightarrow \mu^+\mu^-$ has been extracted.

Prospects

- Finish the combination of KLOE08,10,12 (cov matrix still missing)
- F_{π} from ratio with full KLOE statistics (1.7 fb^{-1}); analysis of $\pi\pi\gamma$ missing
- With KLOE and KLOE2 possibility to perform ISR studies also with other hadronic final states (3π, 4π, ϕ->2π, etc..)
- Proposal to measure a_{μ}^{HLO} in the space-like region: accuracy at few % at KLOE/KLOE-2 using Bhabha process depending on the control of the systematic errors ($10^{-4} \div 10^{-5}$):

  →Even few points of $\Delta a^{had}(t)$ at $t=q^2<0$ (for example at $q^2=-0.1$ GeV^2→$x=0.9$) would be useful (never measured!)

SPARES

60'-70'(PRE)History of ISR (Apologize for missing articles)

- Photon emission in muon pair production in electron-positron collisions ($e^+ e^- \to \mu^+ \mu^- \gamma$, σtot, ISR, FSR, interference)V. N. Baier, V. A. Khoze, ZhETF 48 (1965) 946, Yad. Fiz. 2 (1965) 287
- Radiation accompanying two particle annihilation of an electron - positron pair (scalar final states $e^+ e^- \to \pi^+ \pi^- \gamma$, σtot, ISR, FSR, interference, formfactors) V. N. Baier, V. A. Khoze, Sov. Phys. JETP 21 (1965) 629, 1145 [Zh. Eksp. Theor. Fiz. 48 (1965) 946]
- Infra-red radiative corrections for resonant processes (ϱ, ω, ϕ intermediate states) G. Pancheri, Nuovo Cim. A 60 (1969) 321
- Radiative Corrections for Colliding Beam Resonances (application to ψ(3.1), ψ′ (3.7) intermediate states) M. Greco, G. Pancheri, Y. N. Srivastava, Nucl. Phys. B 101 (1975) 234
- **Secondary Reactions in electron - positron (electron) Collisions (pion form factor) M. S. Chen, P. M. Zerwas, Phys. Rev. D 11 (1975) 58**

End of the 1990s: ISR at DAFNE and KLOE

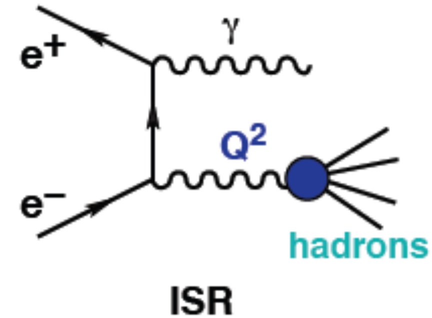
- Hadronic Cross Sections in Electron-Positron Annihilation with Tagged Photon A. B. Arbuzov, E. A. Kuraev, N. P. Merenkov, L. Trentadue, JHEP 9812:009, 1998
- The hadronic contribution to the muon g-2 from hadronic production in ISR events at e+e- collider DAFNE, S. Spagnolo, Eur. Phys. J. C6 (1999) 637
- Measuring σ (**e+ e– →** hadrons) using tagged photon S. Binner, H. Kühn, K. Melnikov, Phys. Lett. B 459 (1999) 279
- **Measurement of σ (e+ e– → $\pi^+\pi^-$) from ISR with KLOE (first realistic study) G. Cataldi, A. Denig, W. K., G. Venanzoni, KLOE memo #195, August 1999,**
- Bottomonium ϒ(ns) spectroscopy at **B**- Factories via hard photon emission M. Benayoun, S. I. Eidelman, V. N. Ivanchenko, Z. K. Silagadze Mod. Phys. Lett. A 14 (1999) 2605

Years 2000s : ISR at the per mill precision: PHOKHARA enters the game (selected entries)

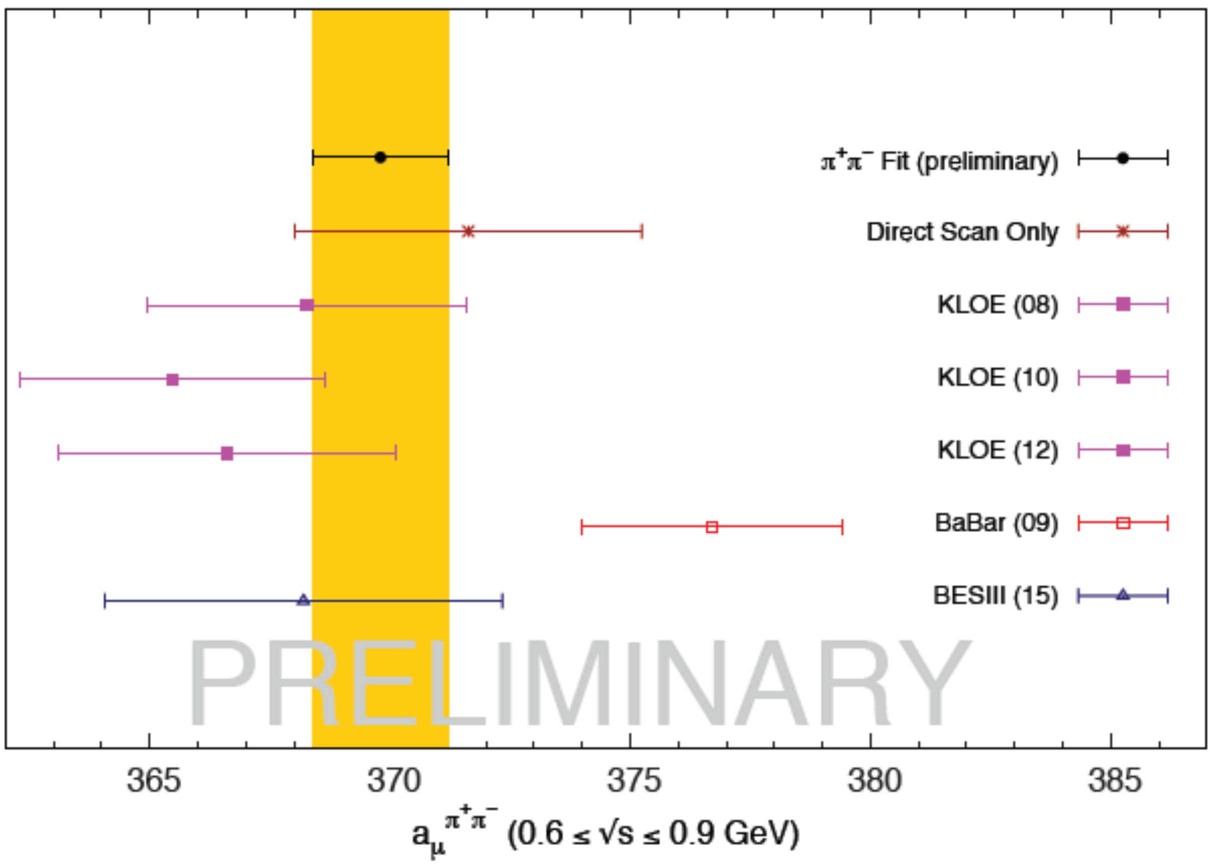
- NLO QED corrections to ISR in e+ e- annihilation and the measurement of sigma(e+ e- → hadrons) using tagged photons, G. Rodrigo, A. Gehrmann-De Ridder, M. Guilleaume and J. H. Kühn, Eur. Phys. J. C 22 (2001) 81
- The radiative return at small angles: Virtual corrections, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C 25 (2002) 215
- Radiative return at NLO and the measurement of the hadronic cross-section in electron positron annihilation, G. Rodrigo, H. Czyż, , J. H. Kühn and M. Szopa, Eur. Phys. J. C 24 (2002) 71
- The radiative return at Phi- and B-factories: Small-angle photon emission at next to leading order, H. Czyż , A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C 27 (2003) 563
- The radiative return at Phi and B-factories: FSR at next-to-leading order, H. Czyż , A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C 33 (2004) 333
- The radiative return at Phi- and B-factories: FSR for muon % pair production at next-to-leading order, H. Czyż , A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C 39 (2005) 411
- **Complete QED NLO contributions to the reaction e+e-→$\mu^+\mu^-\gamma$ and their implementation in the event generator PHOKHARA, F. Campanario, H. Czyż, J. Gluza, M. Gunia, T. Riemann, G. Rodrigo and V. Yundin, JHEP 1402 (2014) 114**

HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel: + KLOE12, + BES III from Rad. Ret.:



Prel. HKMNT combination w. full cov.-matrices:



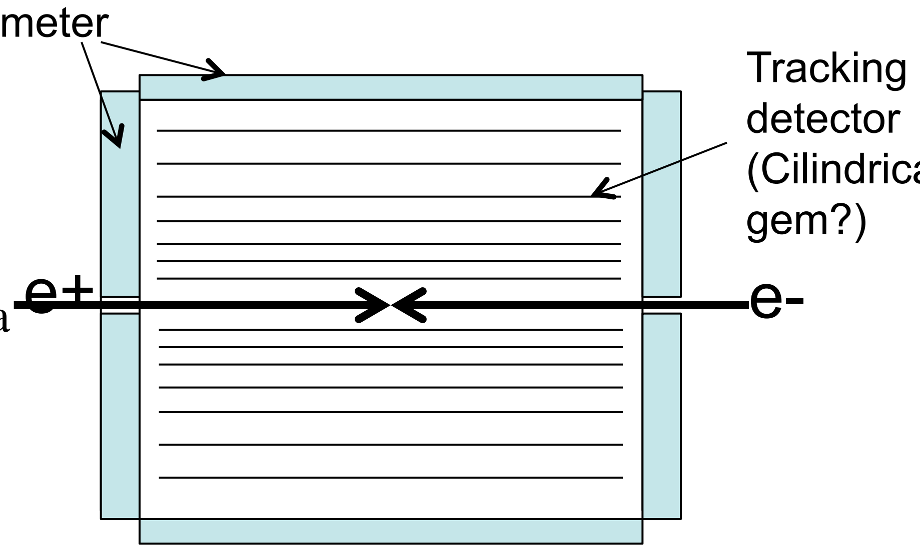
- χ^2_{min}/d.o.f. = 1.4
- further improvements expected from CMD-3, more also from BaBar?

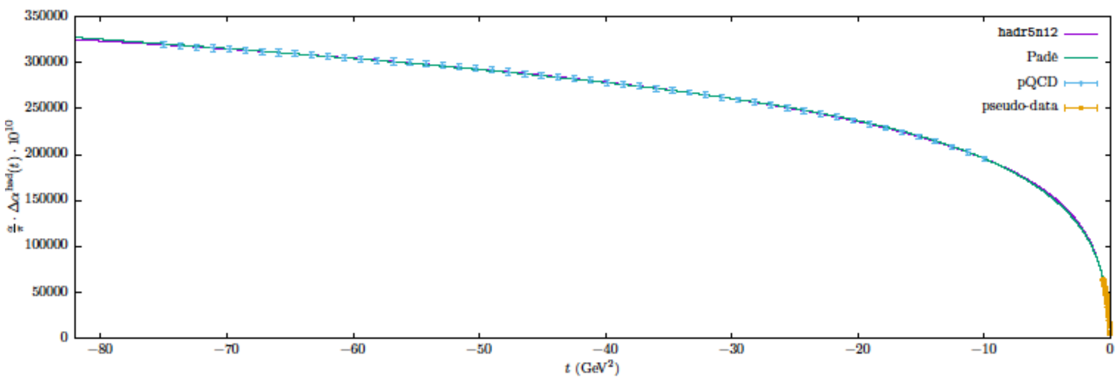
➔ see Simon Eidelman's talk on CMD-3

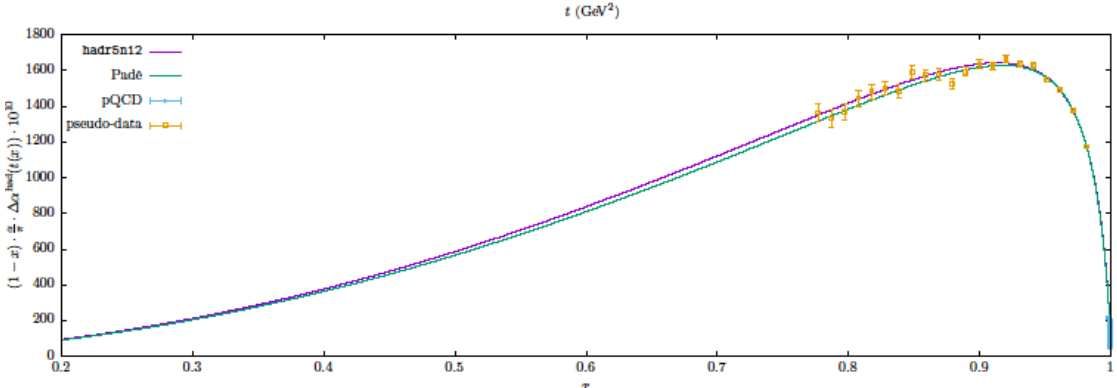
➔ Yaquian Wang's talk on BES III π FF & ISR

Measuring α(t) at 10ppm with a dedicated detector

- A dedicated detector with a coverage at small angle (< 5°) would allow to use small angle Bhabha for the normalization (N_0).
- The running of α can be obtained as "simple" ratio Ni/N_0 where Ni is the Bhabha events in the $\Delta\theta_\iota$ bin.
- One can achieve an error ~10^{-5} (stat+syst) on this ratio







Same simulation as in KLOE with 20 points and 10^{-5} (stat and syst) error for each point

Measuring $\alpha(t)$ at 10ppm with a dedicated detector

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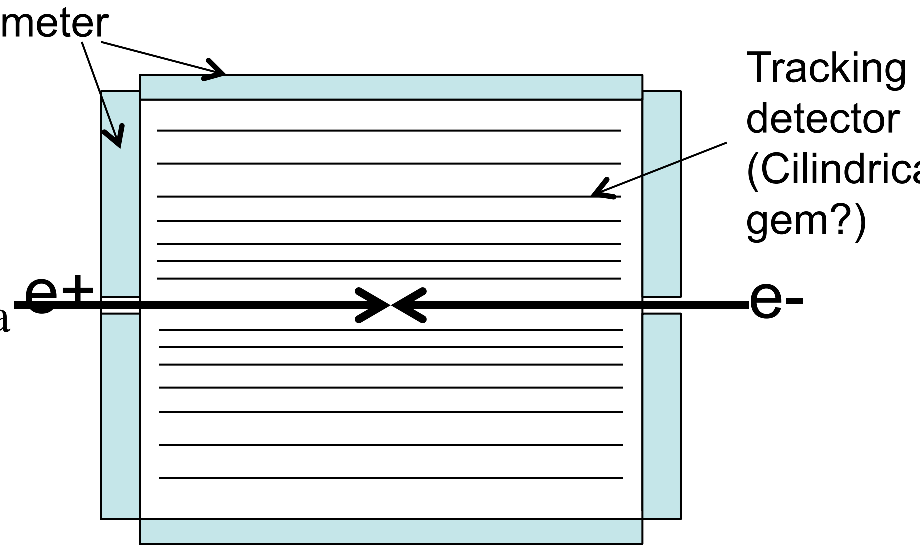
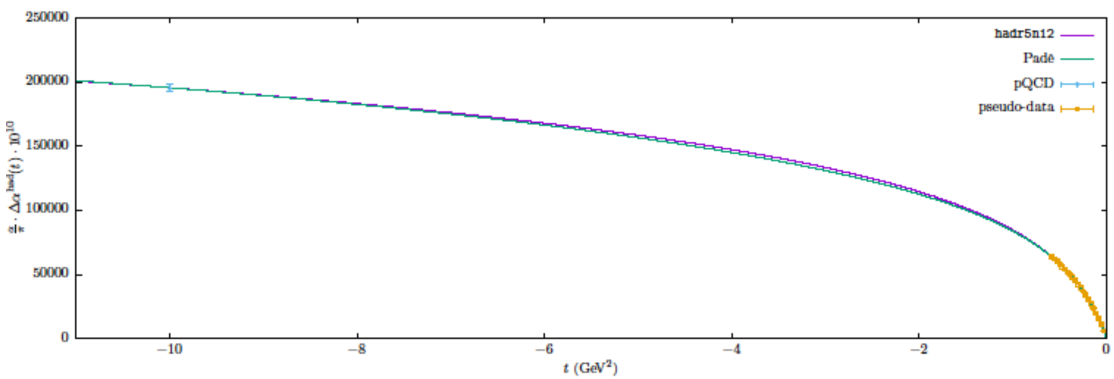
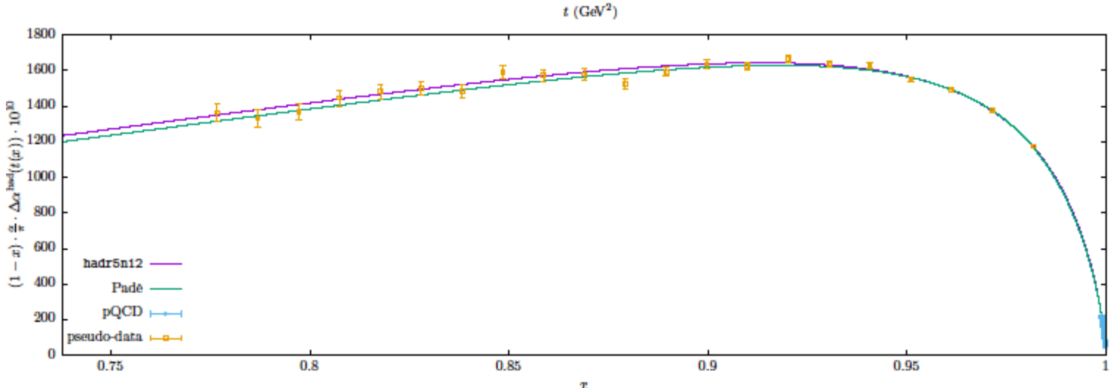
- One can achieve an error ~10^{-5} (stat+syst) on this ratio







δa_μ^{HLO}~$0.3\%_{stat} \oplus 1\%_{syst}$

(preliminary)

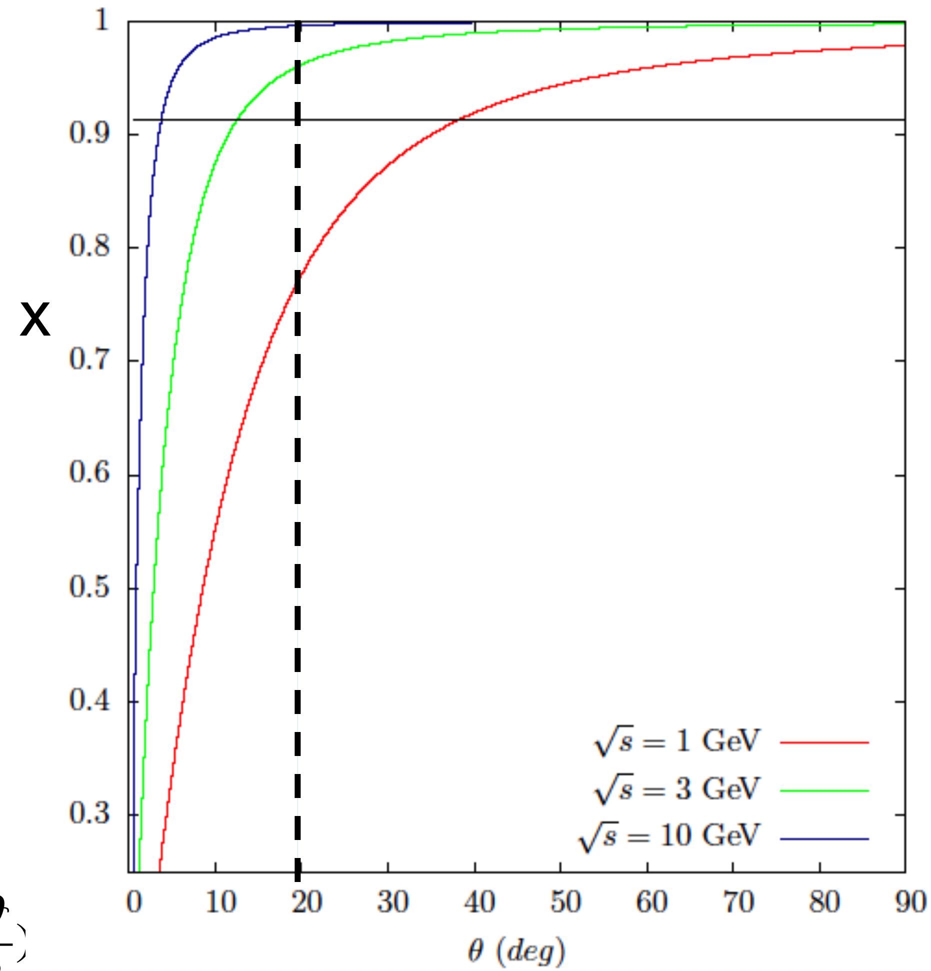
Experimental considerations - II

Most of the region (up to x~0.98) can be covered with a low energy machine (like Dafne/VEPP-2000 or tau/charm-B-factories)

Example:
Covering up to 60^0 at $\sqrt{s}$=1 GeV can arrive at x= 0.95(!)

A different situation can be obtained at tau/charm/B-factories (and at future ILC/FCCee machines) where smaller angles (below 20^o) are needed

$$t = -s\sin^2(\frac{\vartheta}{2})$$

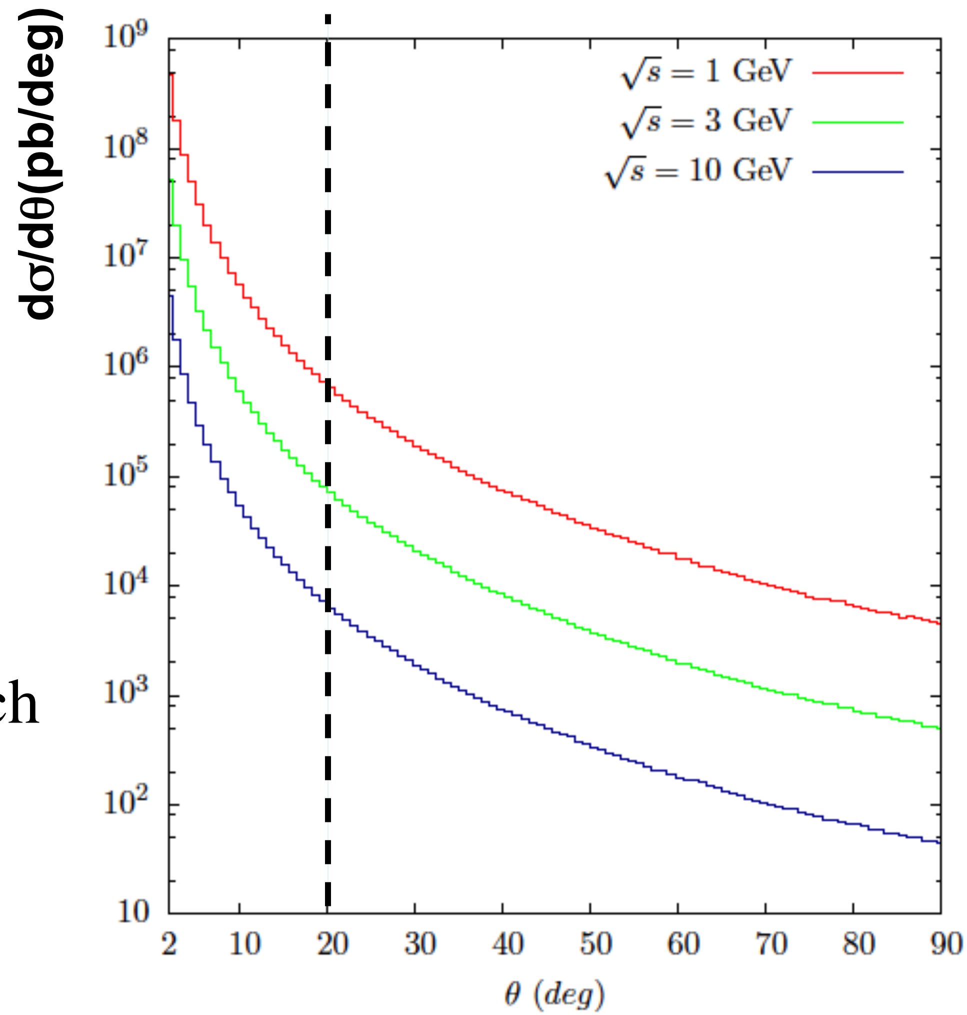


Statistical consideration

10^{-4} accuracy on Bhabha cross section requires at least 10^8 events which at 20^o mean at least:

- O(1) fb^{-1} @ 1 GeV
- O(10) fb^{-1} @ 3 GeV
- O(100) fb^{-1} @ 10 GeV

These luminosities are within reach at flavour factories!



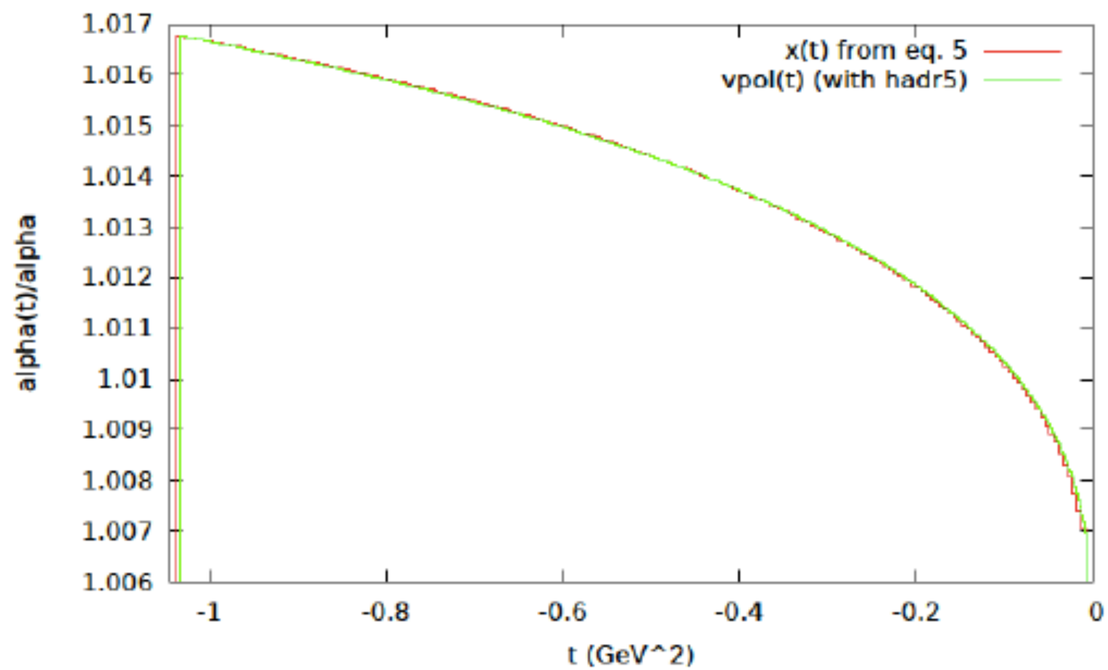
Additional considerations: s-channel

At low energy (<10 GeV) above 10^0 there is still a sizeable contribution from s-channel.
At LO no difficulty to deconvolute the cross section for the s-channel

Test with Babayaga:

s=1 GeV
$10^o<\theta<170^o$

$d\sigma_{born}/dt=1.52$ mb/GeV^2



However this picture changes with Rad. Corr.

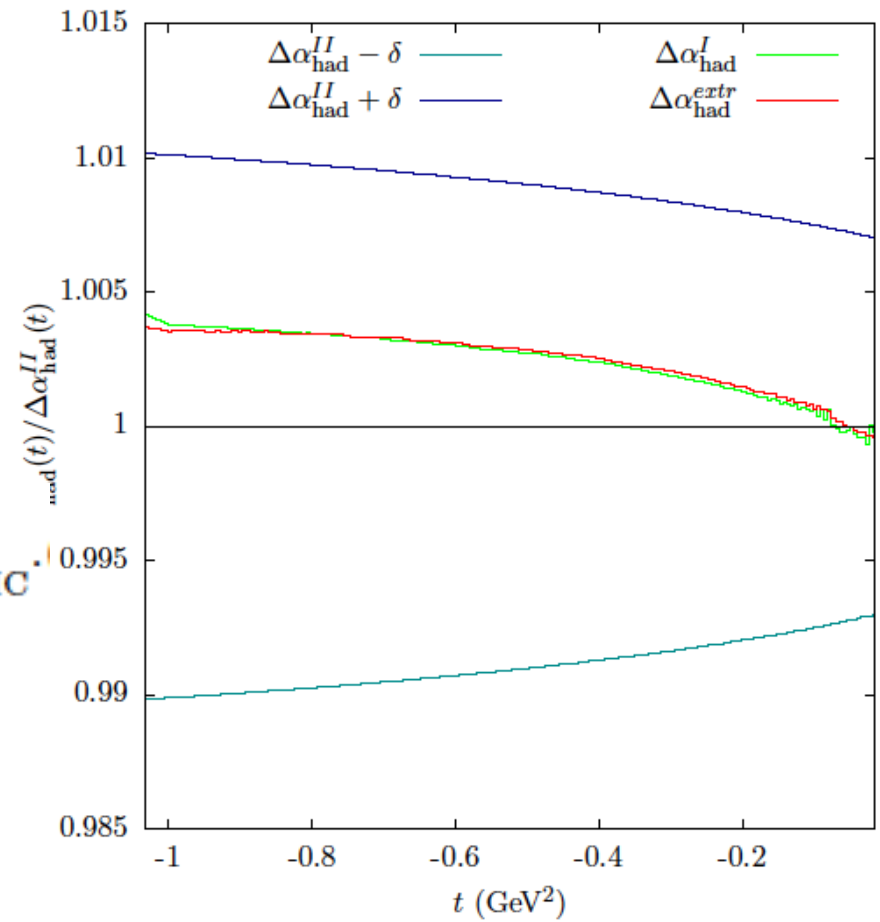
Additional considerations: Rad. Corr.

A Monte Carlo procedure has been developed to check if $\Delta\alpha_{had}(t)$ can be obtained by a minimization procedure with a different $\Delta\alpha_{had}(t)'$ inside

$$\frac{d\sigma}{dt}\bigg|_{\text{data}} = \frac{d\sigma}{dt}\Big(\alpha(t), \alpha(s)\Big)\bigg|_{\text{MC}},$$

→

$$\frac{d\sigma}{dt}\bigg|_{j,\text{data}} = \frac{d\sigma}{dt}\Big(\bar{\alpha}(t) + \frac{i_j}{N}\delta(t), \alpha(s)\Big)\bigg|_{j,\text{MC}}.$$



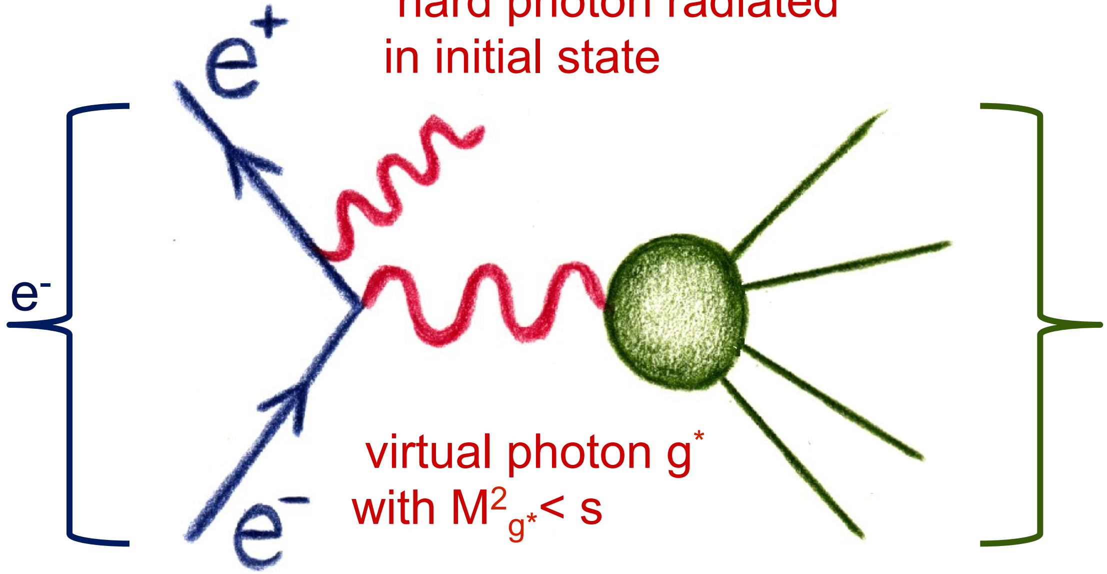
$\Delta\alpha_{had}(t)$ is obtained with $<10^{-4}$ error !

Systematics

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

ISR: Initial State Radiation

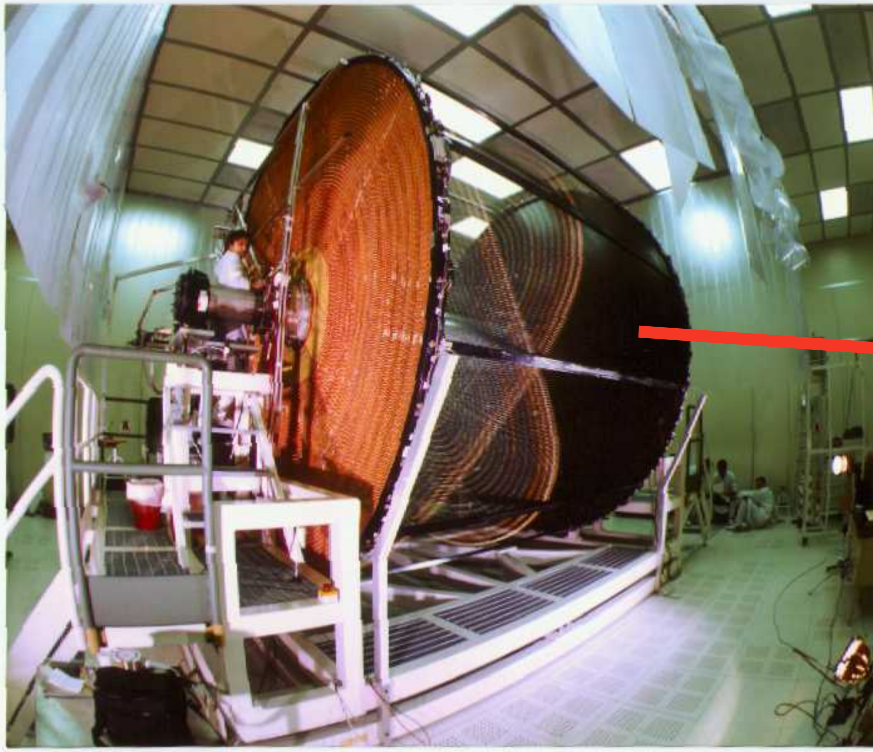
Particle factories (DAFNE, PEP-II, KEK-B) can measure hadronic cross sections as a function of the hadronic c.m. energy using initial state radiation (**radiative return** to energies below the collider energy $\sqrt{s}$).



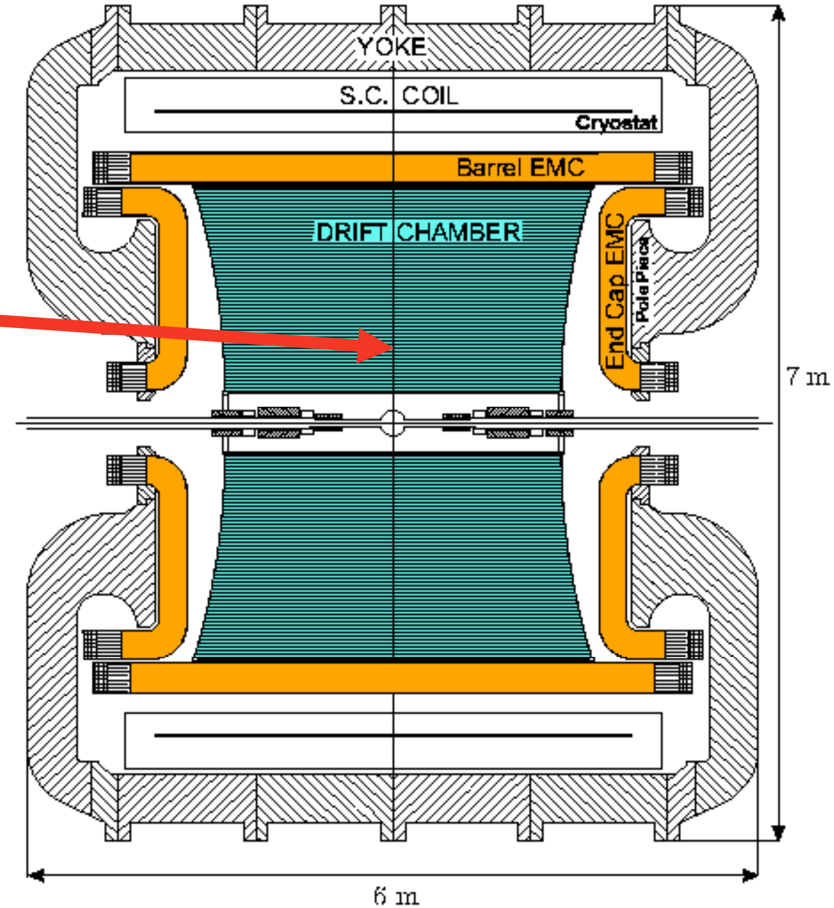
The emission of a hard γ in the bremsstrahlung process in the initial state reduces the energy available to produce the hadronic system in the e^+e^- collision.

KLOE Detector

Drift chamber



Full stereo geometry, 4m diameter, 52.140 wires **90% Helium, 10% iC_4H_{10}**



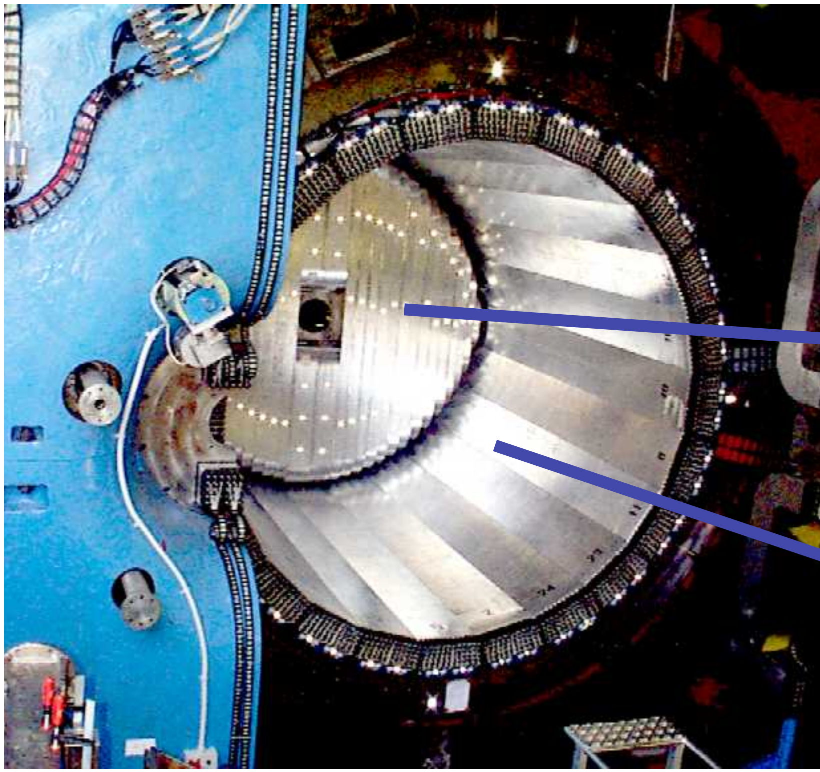
σ_p/p = 0.4% (for 90^0 tracks)

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

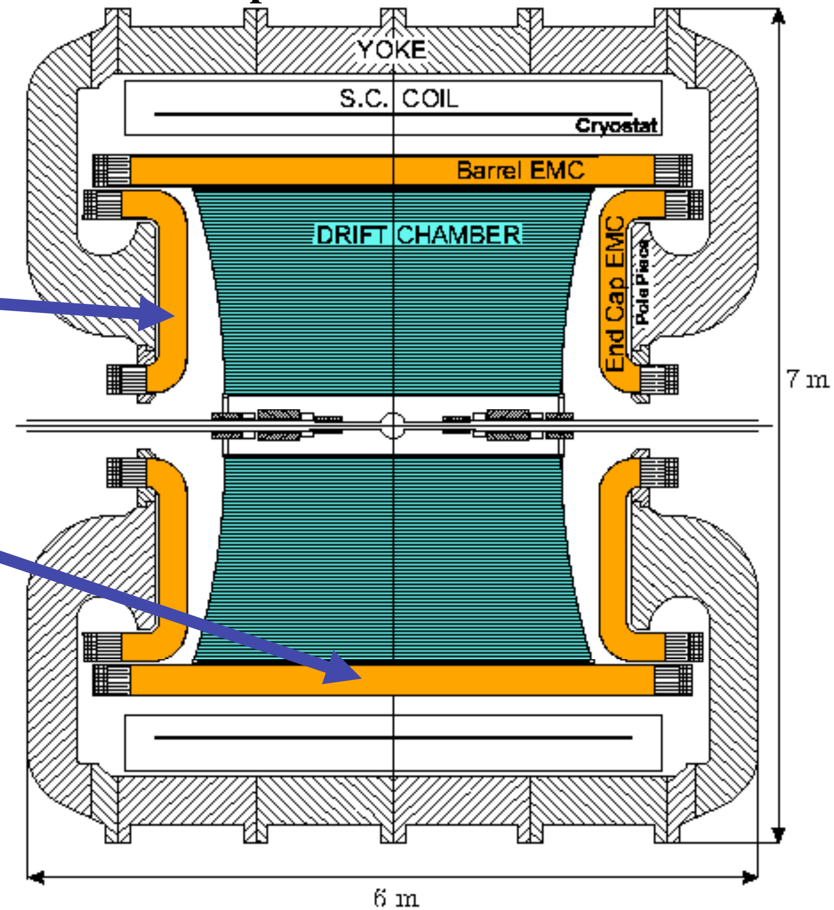
Excellent momentum resolution

KLOE Detector

Electromagnetic Calorimeter



Pb / scintillating fibres (4880 PMT)
Endcap - Barrel - Modules



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

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

(Bunch length contribution subtracted from constant term)

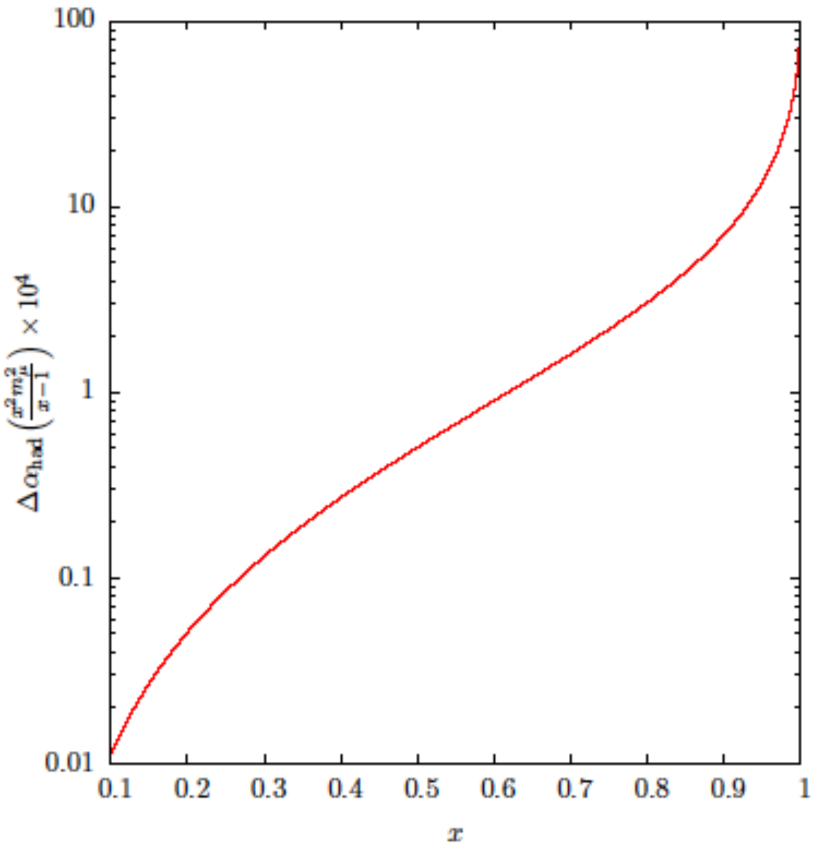
Excellent timing resolution

Additional consideration: Normalization

To compare Bhabha absolute cross section from data with MC we need Luminosity of the machine.

Two possibilities:

1) Use Bhabha at very small angle where the uncertainty on $\Delta\alpha_{had}$ can be neglected (for example at E_{beam}=1 GeV and θ=5°, $\Delta\alpha_{had}$ ~10^{-5}).
2) Use a process with $\Delta\alpha_{had}$=0, like $e^+e^- \rightarrow \gamma\gamma$. However very difficult to determine it at 10^{-4} accuracy.



Option 1) looks better to us as some of the common systematics cancel in the measurement !