KLOE measurement of $\sigma(e^+e^-\to\pi^+\pi^-(\gamma))$ with Initial State Radiation and the $\pi\pi$ contribution to the muon anomaly

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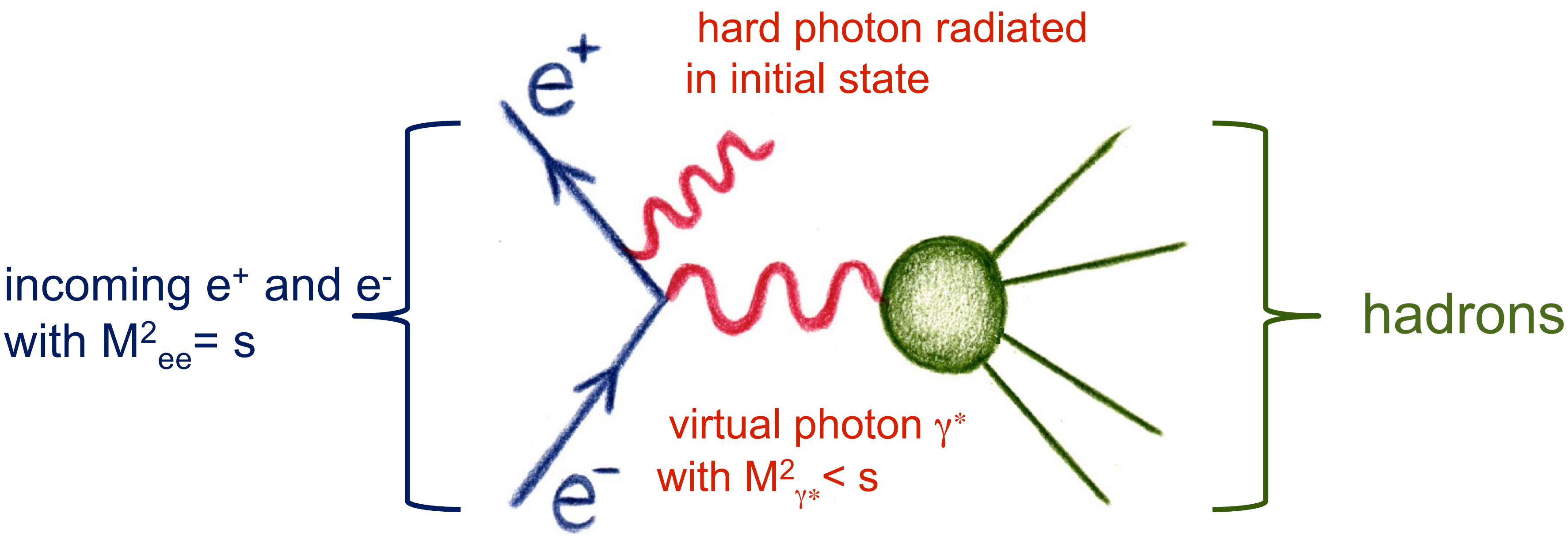
TAU2010, Manchester, 15 September 2010

Outlook

- KLOE measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$:
  - Small (photon) angle measurements (KLOE05, KLOE08)
  - Large (photon) angle measurement (KLOE10)
- Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar
- New measurement well advanced:
  - Extraction of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$ by $\mu\mu\gamma$ normalization
- Future prospects with KLOE-2
- Conclusions

ISR: Initial State Radiation

Particle factories (DAΦNE, 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 $\sqrt{s}$).

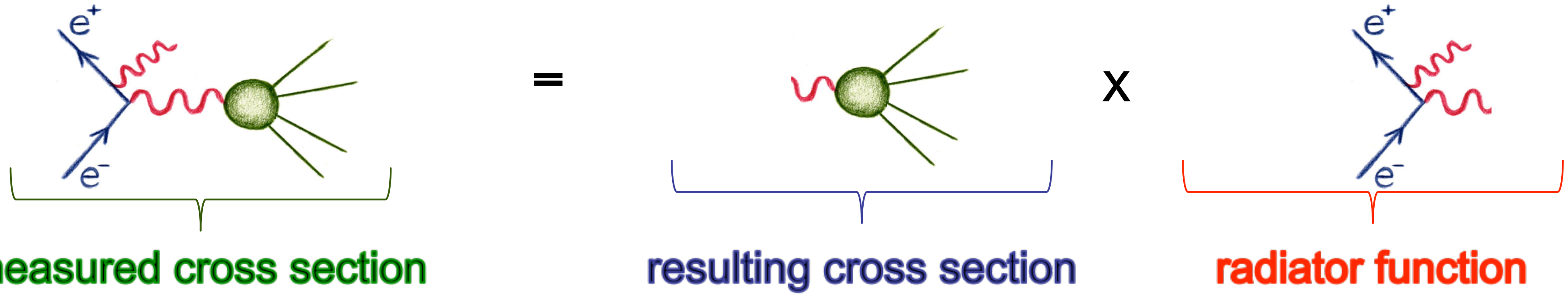


The emission of a hard γ in the bremsstrahlung process in the initial state reduces the energy available to produce the hadronic system in the e^+e^- collision.

ISR: Initial State Radiation

Neglecting final state radiation (FSR):

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



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

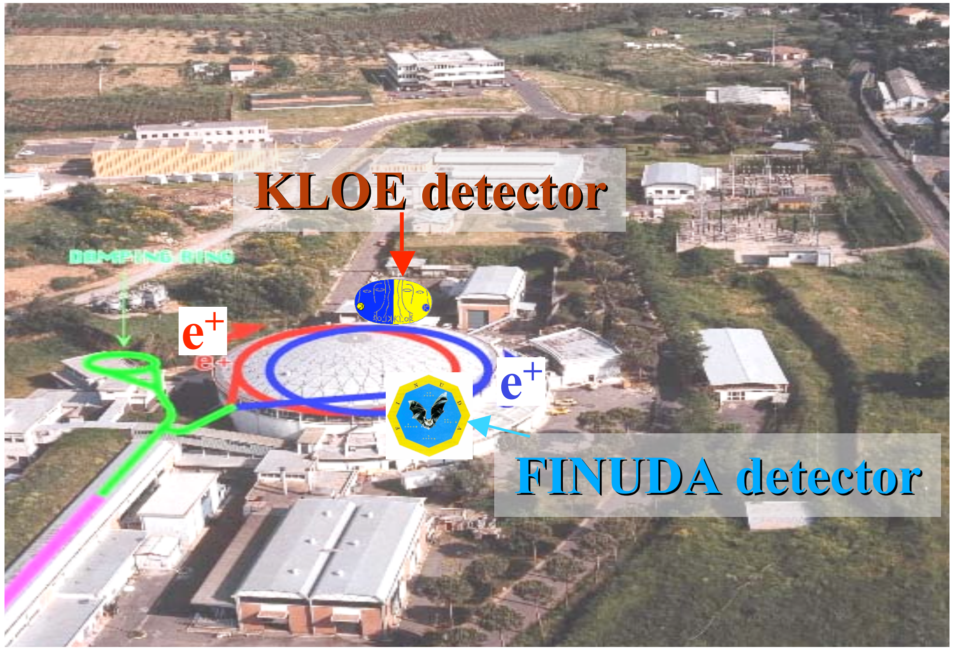
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003

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

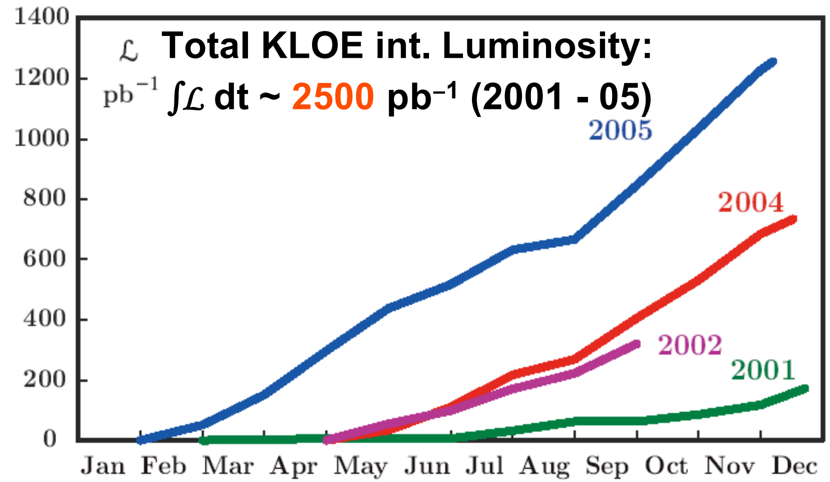
IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ with ISR using 2001 data (140pb^{-1}) PLB606(2005)12 $\Rightarrow$ ~3σ discrepancy btw a_μ^{SM} and a_μ^{exp}

DAΦNE: A Φ-Factory

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



Integrated Luminosity



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

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

2006:

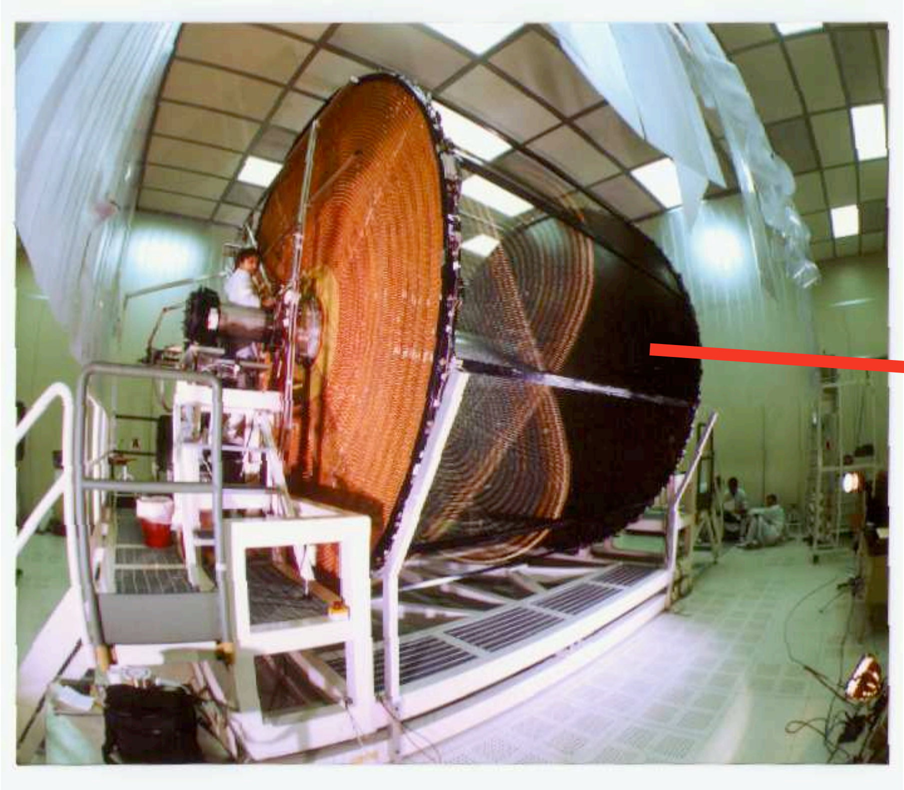
- **Energy scan (4 points around m_Φ-peak)**
- **$240 pb^{-1}$ at $\sqrt{s}$ = 1000 MeV (off-peak data)**

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

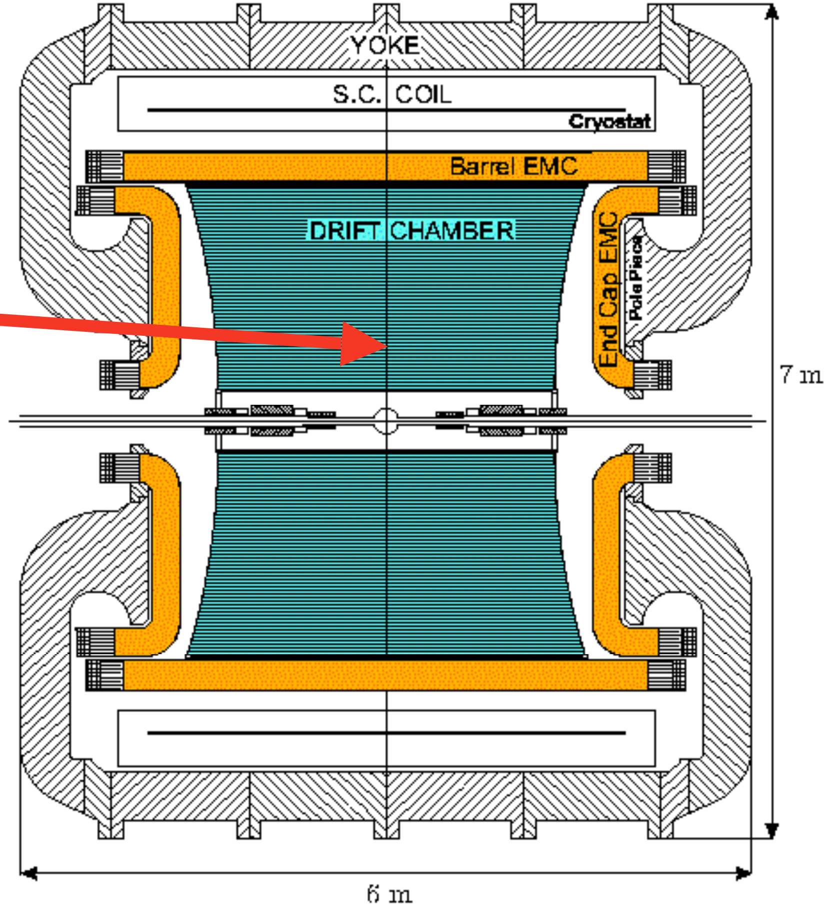
*The **new** measurement (KLOE10) is based on 233 pb^{-1} of 2006 data (different event selection). sub. to PLB*

KLOE Detector

Drift chamber



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



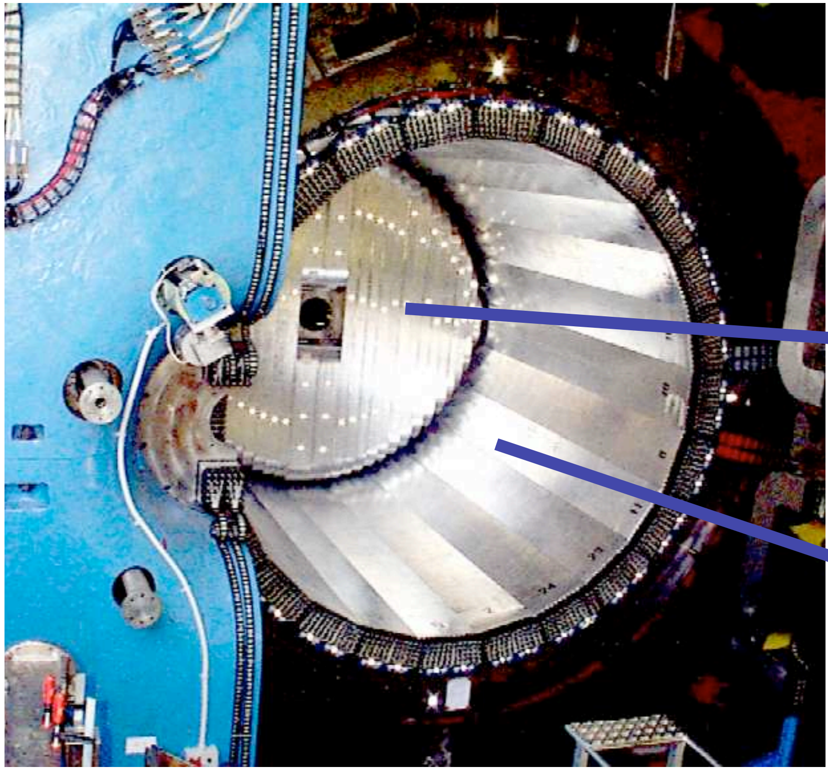
σ_p/p = 0.4% (for 90^0 tracks)

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

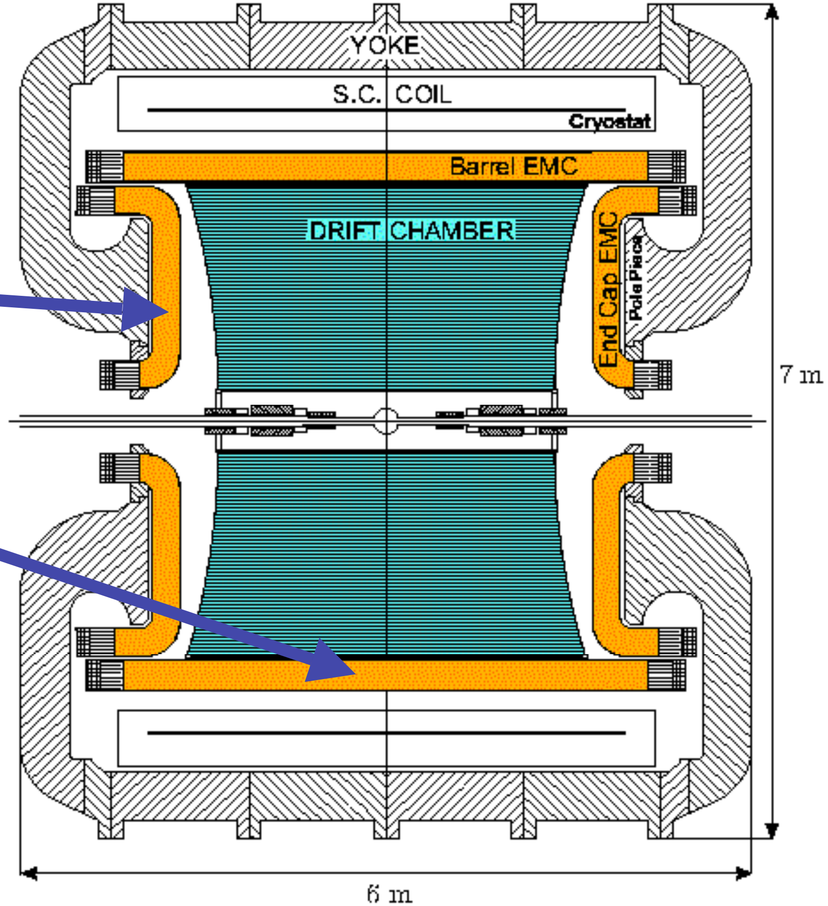
Excellent momentum resolution

KLOE Detector

Electromagnetic Calorimeter



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



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

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

(Bunch length contribution subtracted from constant term)

Excellent timing resolution

Extracting $\sigma_{\pi\pi}$ and $|F_\pi|^2$ from $\pi\pi\gamma$ events

a) Via absolute Normalisation to VLAB Luminosity (as in 2005 analysis):

1)

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

$d\sigma_{\pi\pi\gamma(\gamma)}/dM^2$ is obtained by subtracting background from observed event spectrum, divide by selection efficiencies, and ***int. luminosity***:

2)

$$\sigma_{\pi\pi}(\mathrm{s}) \approx s \frac{d\sigma^{obs}_{\pi\pi\gamma(\gamma)}}{dM^2_{\pi\pi}} \cdot \frac{1}{H(\mathrm{s})}$$

Obtain $\sigma_{\pi\pi}$ from (ISR) - radiative cross section $d\sigma_{\pi\pi\gamma(\gamma)}/dM^2$ via theoretical radiator function H(s):

3)

$$|\mathrm{F}_\pi|^2 = \frac{3s}{\pi\alpha^2\beta^3_\pi}\sigma_{\pi\pi}(\mathrm{s})$$

Relation between $|F_\pi|^2$ and the cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

b) Via bin-by-bin Normalisation to rad. Muon events *(analysis is in a well advanced phase, see later)*

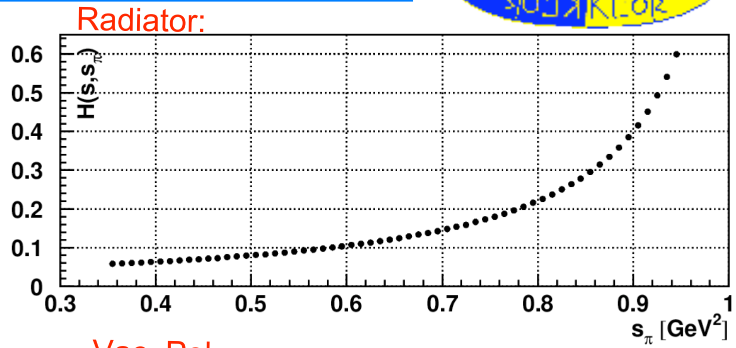
Radiative Corrections

Radiator-Function $H(s,s_\pi)$ (ISR):

- **ISR-Process calculated at NLO-level**
  PHOKHARA generator
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

Precision: 0.5%

$$s \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi)$$

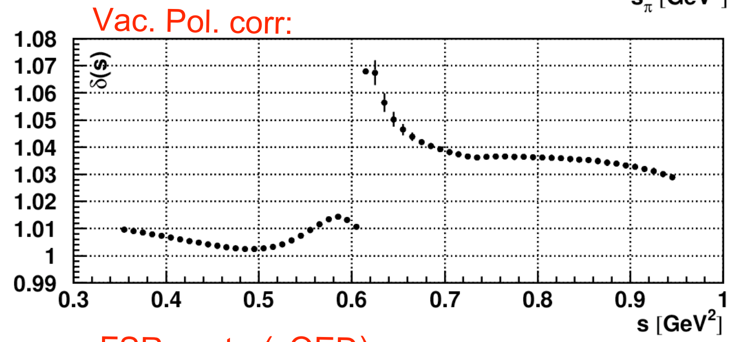


Radiative Corrections:

i) Bare Cross Section

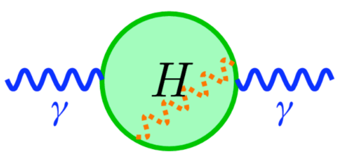
divide by Vacuum Polarisation $\delta(s)=(\alpha(s)/\alpha(0))^2$

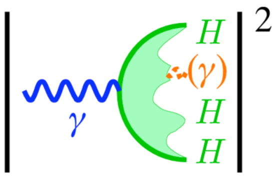
➔ from F. Jegerlehner

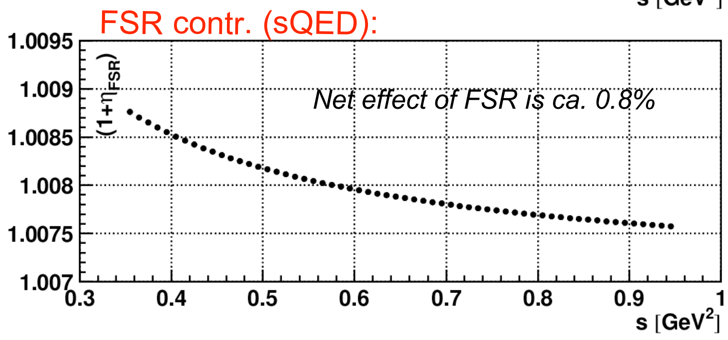


ii) FSR

Cross section $\sigma_{\pi\pi}$ must be incl. for FSR
for use in the dispersion integral of a_μ

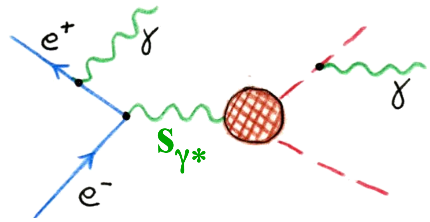






FSR corrections have to be taken into account in the efficiency eval. (Acceptance, M_{Trk}) and in the mapping $s_\pi \rightarrow s_{\gamma*}$

(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)



$s_{\gamma*} > s_\pi$

SA Event Selection (KLOE08)

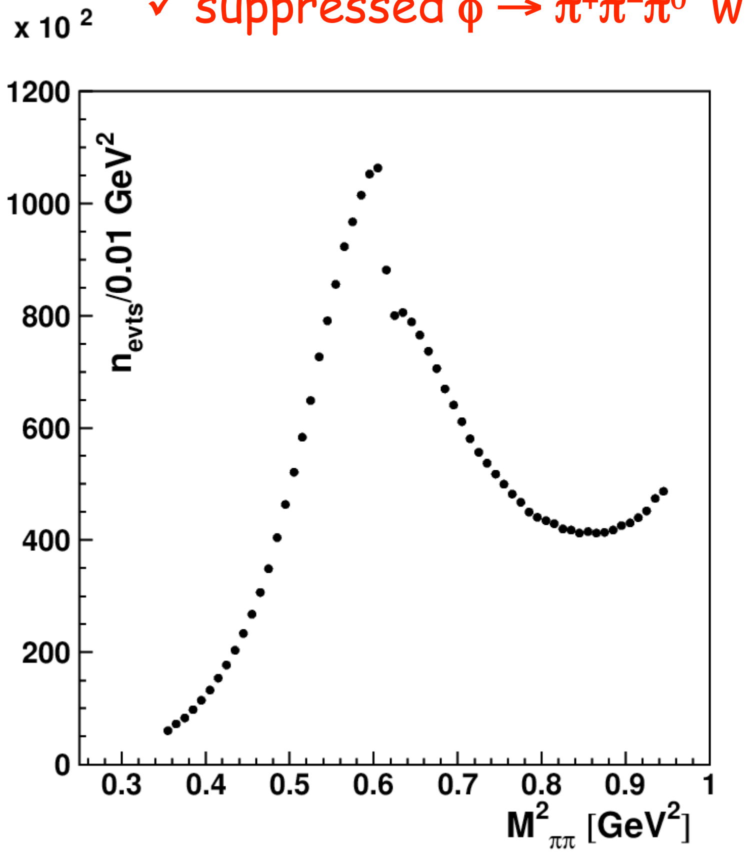
a) 2 tracks with $50^o < \theta_{track} < 130^o$

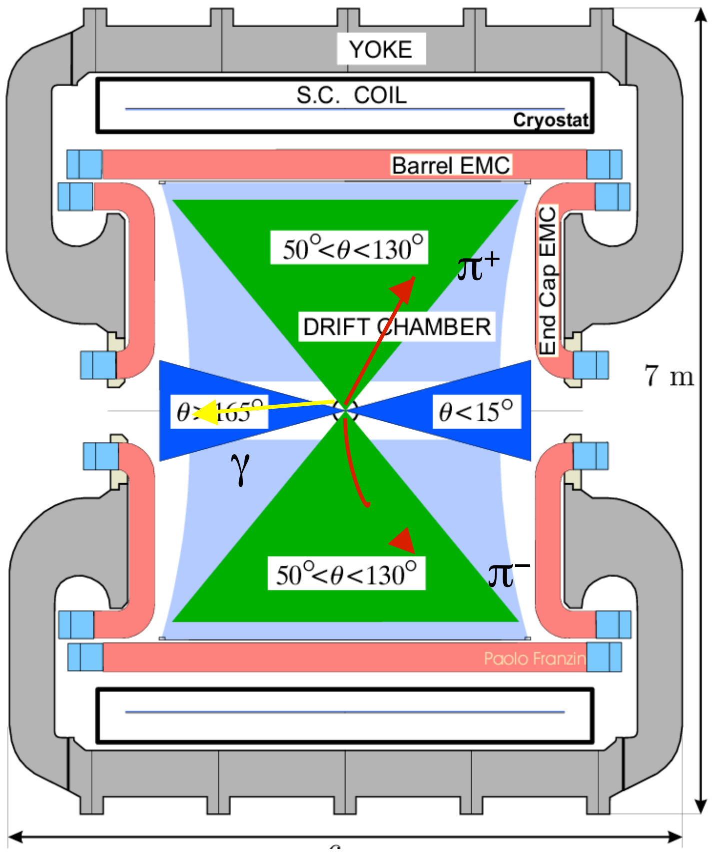
b) small angle (not detected) γ

($\theta_{\pi\pi} < 15^o$ or $> 165^o$)

- ✓ high statistics for ISR
- ✓ low relative FSR contribution
- ✓ suppressed $\phi \to \pi^+\pi^-\pi^0$ wrt the signal

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





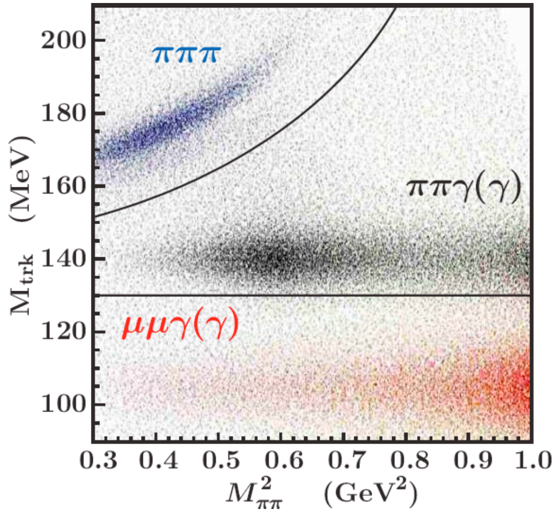
statistics: 240pb^{-1} of 2002 data

3.1 Mill. Events between 0.35 and 0.95 GeV^2

Event Selection

- Experimental challenge: control backgrounds from
  - $\phi \to \pi^+\pi^-\pi^0$
  - $e^+e^- \to e^+e^- \gamma$
  - $e^+e^- \to \mu^+\mu^- \gamma$,

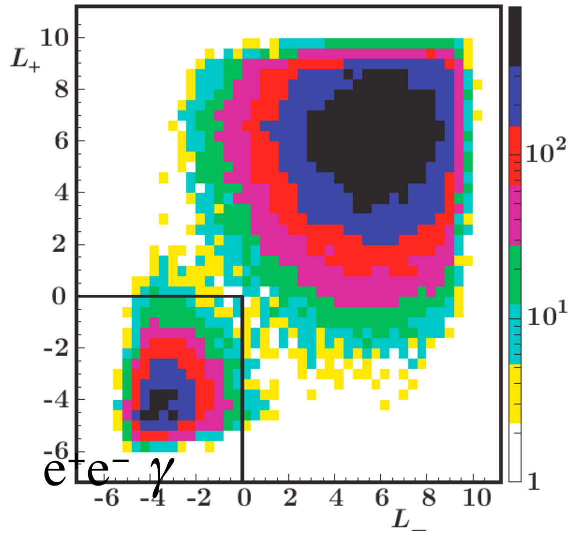
  removed using kinematical cuts in *trackmass* M_{Trk} - $M_{\pi\pi}^2$ plane



M_{Trk}: defined by 4-momentum conservation assuming 2 charged particle (of same mass) and one γ in the final state

$$\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2}\right)^2 - (p_1 + p_2)^2 = 0$$

$\pi^+\pi^- \gamma$,

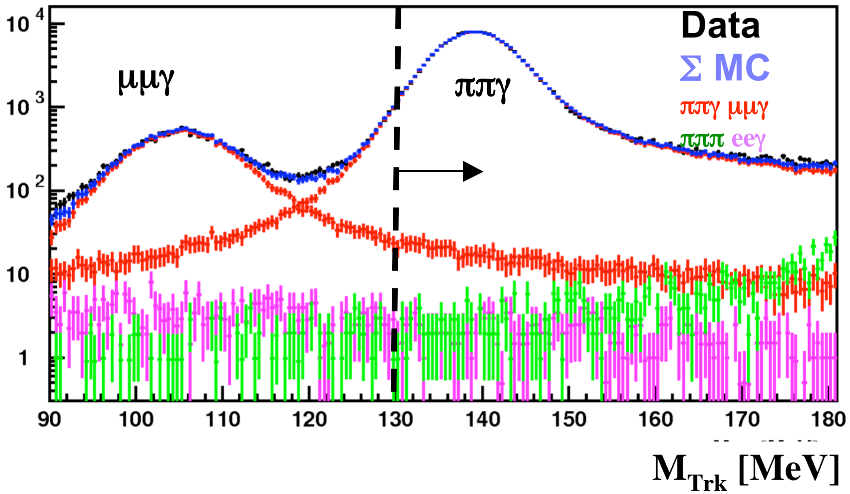


To further clean the samples from radiative Bhabha events, we use a particle ID estimator (PID) for each charged track based on Calorimeter Information and Time-of-Flight.

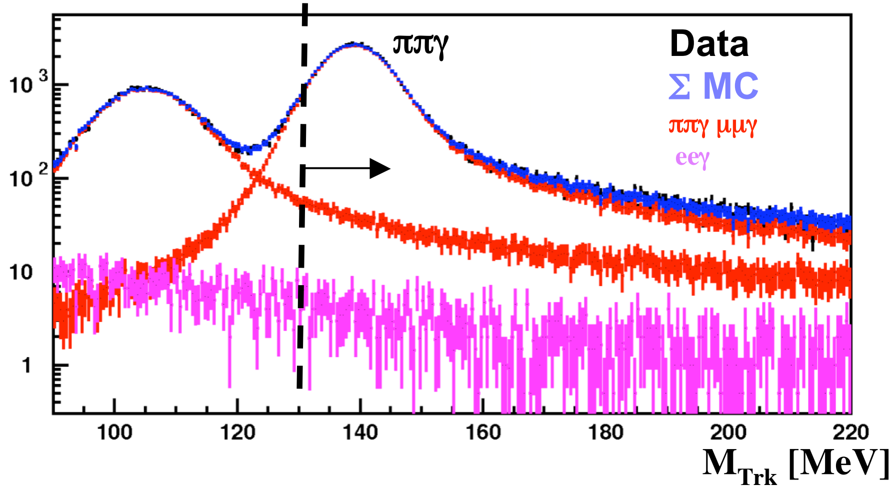
Background:

Main backgrounds estimated from MC shapes fitted to data distribution in M_{Trk} ($\pi\pi\gamma/\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)

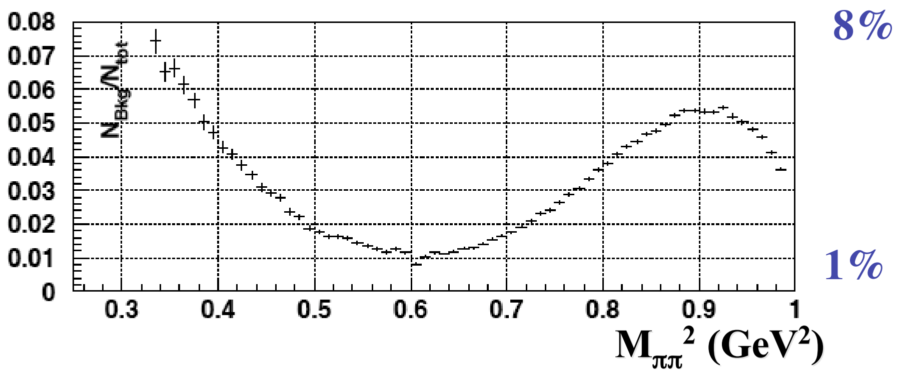
$0.60 < M_{\pi\pi}^2 < 0.62$ GeV^2, χ^2/ndof = 158/180



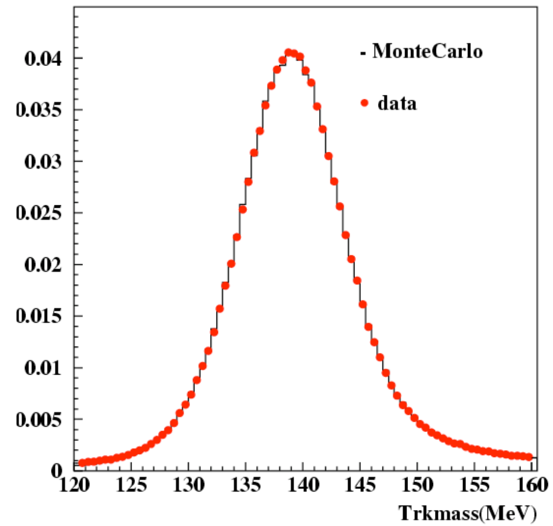
$0.84 < M_{\pi\pi}^2 < 0.86$ GeV^2 χ^2/ndof = 179/258



Tot bckg ($\mu\mu\gamma$, $\pi\pi\pi$ and $ee\gamma$) **contribution**



- Excellent agreement on M_{TRK} distribution between data and MC



Luminosity:

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

F. Ambrosino et al. (KLOE Coll.)
Eur.Phys.J.C47:589-596,2006

$55° < \theta < 125°$

acollinearity $< 9°$

$p \geq 400$ MeV

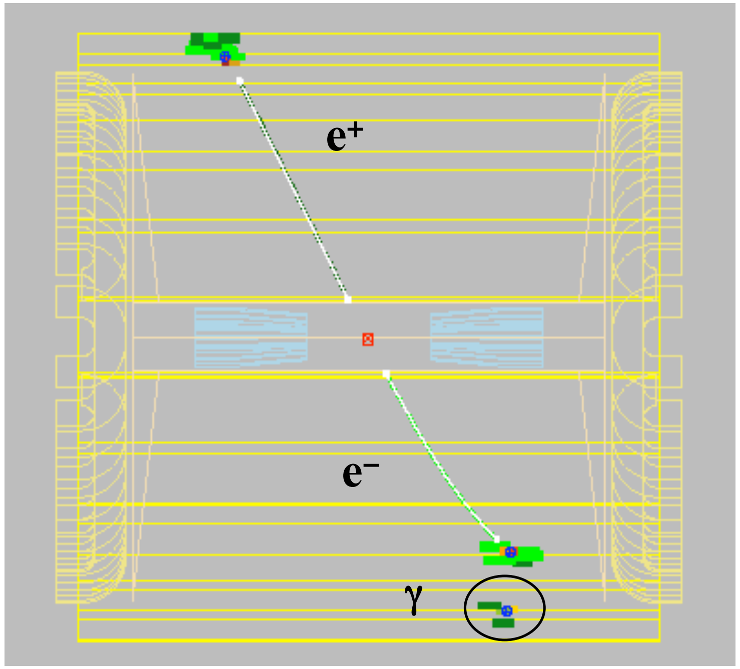
$$\int \mathcal{L}\,\mathrm{dt} = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

generator used for σ_{eff}

BABAYAGA (Pavia group):

C. M.C. Calame et al., NPB758 (2006) 22

new version (**BABAYAGA@NLO**) gives 0.7% decrease in cross section, and better accuracy: 0.1%



Systematics on Luminosity	
Theory	0.1 %
Experiment	0.3 %
TOTAL 0.1 % th ⊕ 0.3% exp = 0.3%	

Luminosity:

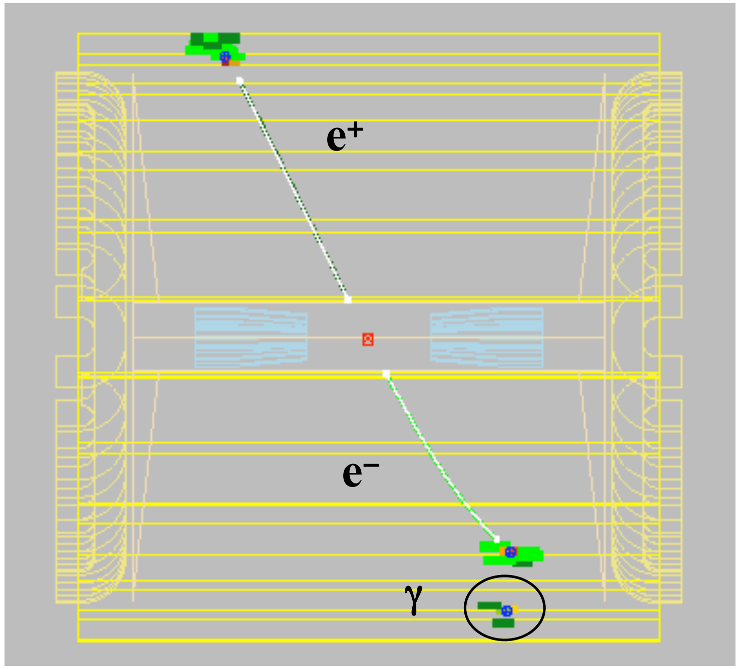
KLOE measures $\mathcal{L}$ with Bhabha scattering

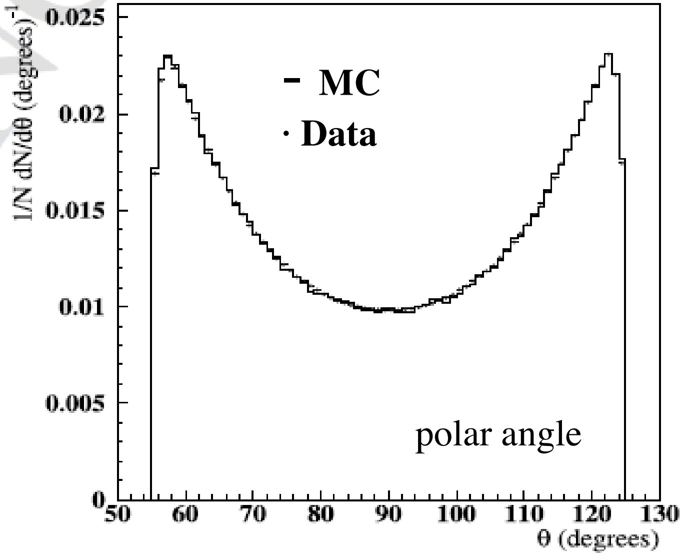
$55° < \theta < 125°$

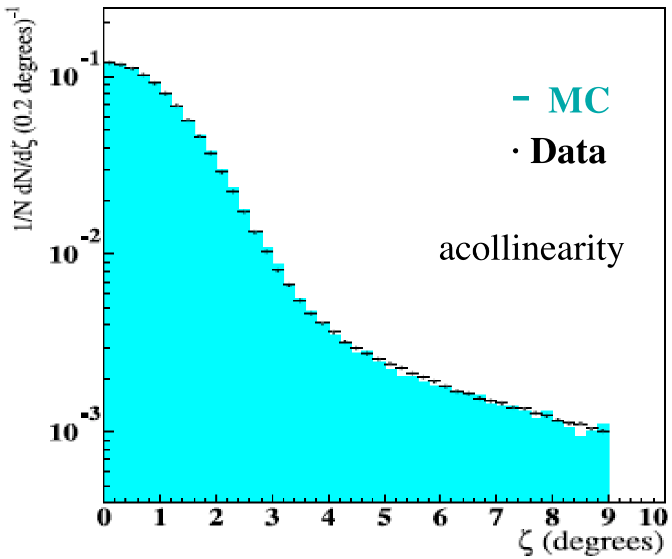
acollinearity < 9°

p ≥ 400 MeV

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







KLOE result (KLOE08)

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

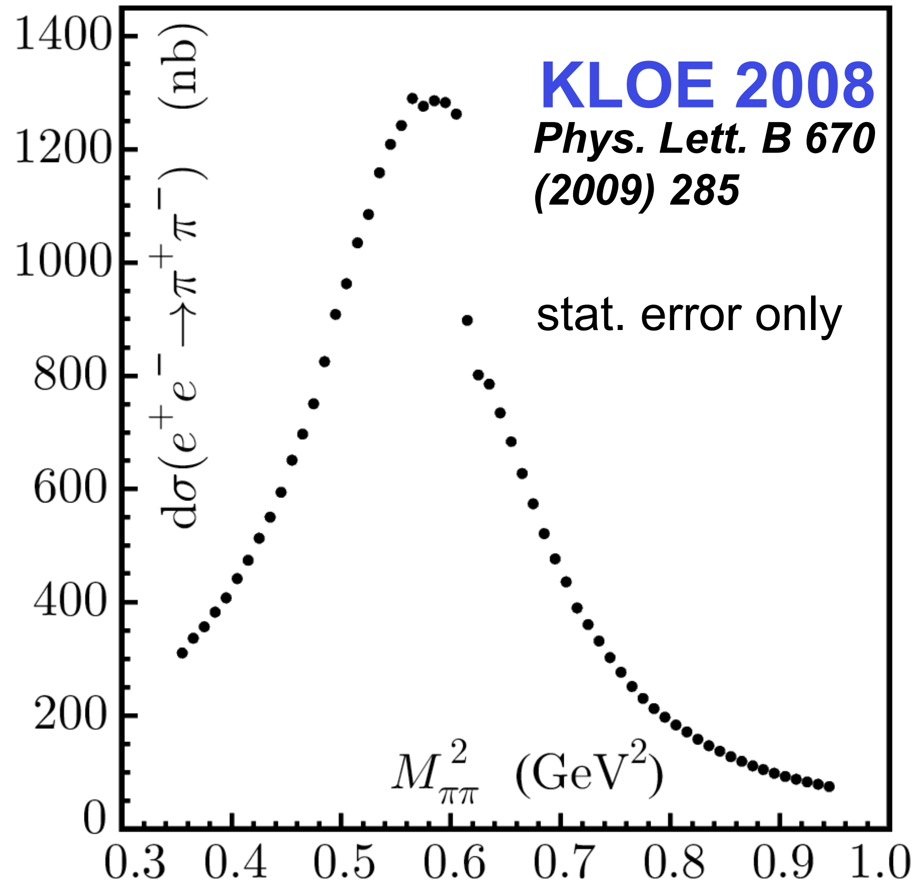
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
π/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_{π})	negligible
Unfolding	negligible
Software Trigger	0.1%
$\sqrt{s}$ dep. Of H	0.2%
Luminosity$(0.1_{th} \oplus 0.3_{exp})$%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

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



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

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

LA Event Selection (KLOE10)

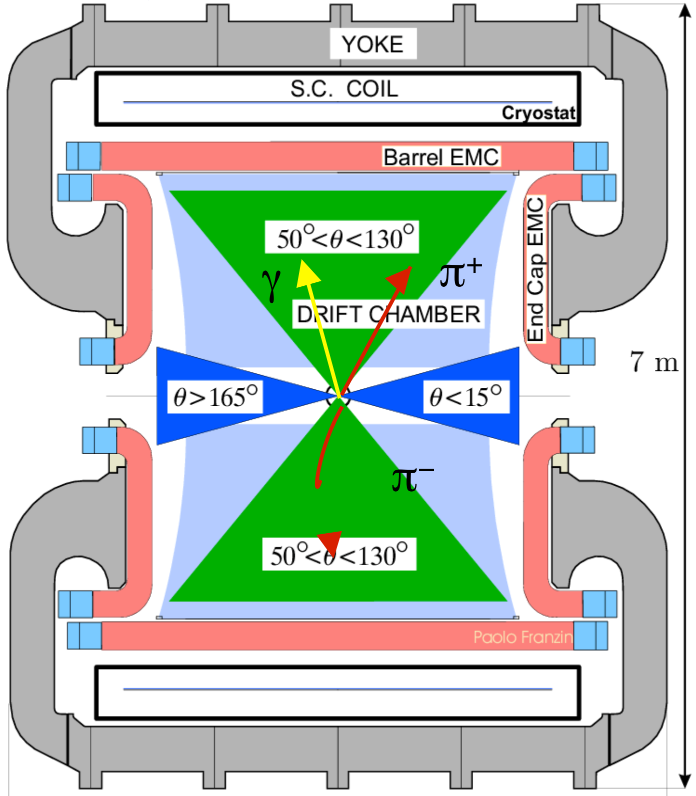
2 pion tracks at large angles
$50^o < \theta_\pi < 130^o$

Photons at large angles
$50^o < \theta_\gamma < 130^o$

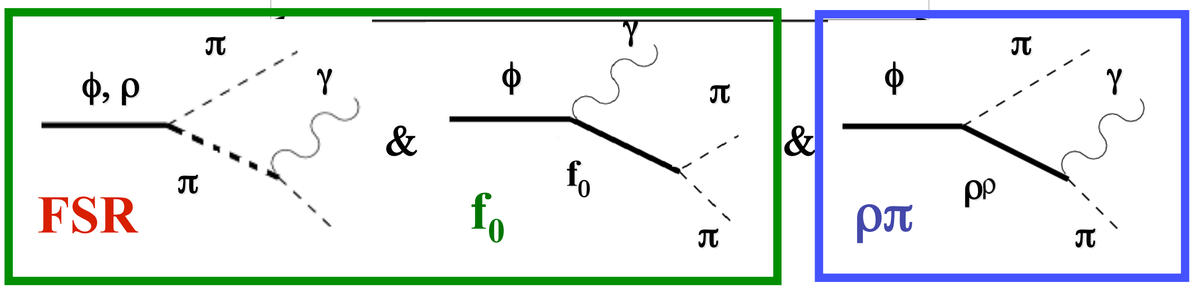
- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **γ_{ISR} photon detected (4-momentum constraints)**

- ✓ **lower signal statistics**
- ✓ **larger contribution from FSR events**
- ✓ **larger $\phi \to \pi^+\pi^-\pi^0$ background contamination**
- ✓ **irreducible background from ϕ decays ($\phi \to f_0\,\gamma \to \pi\pi\,\gamma$)**

At least 1 photon with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 20$ MeV ➔ photon detected



Threshold region non-trivial
due to irreducible FSR-effects, which have to be estimated from MC using phenomenological models (interference effects unknown)



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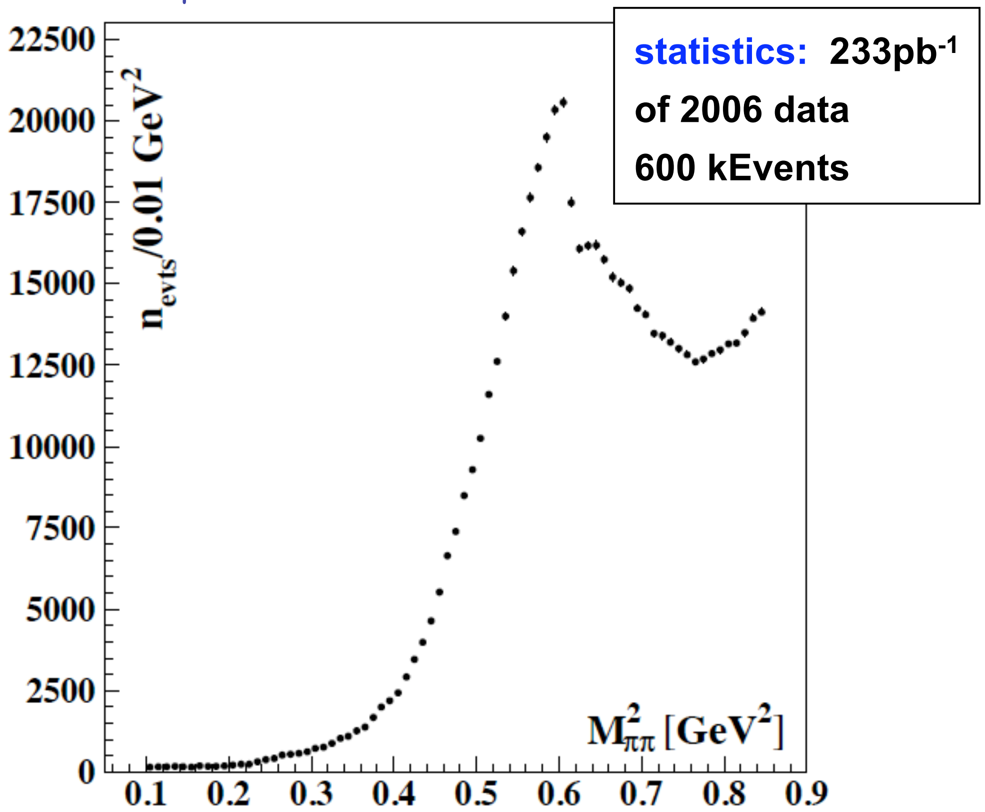
At least 1 photon with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 20$ MeV ➔ photon detected



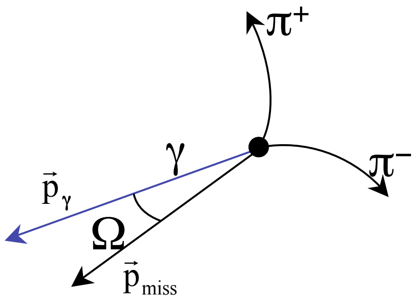
Use data sample taken at $\sqrt{s} \cong$ **1000 MeV**, 20 MeV below the ϕ-peak

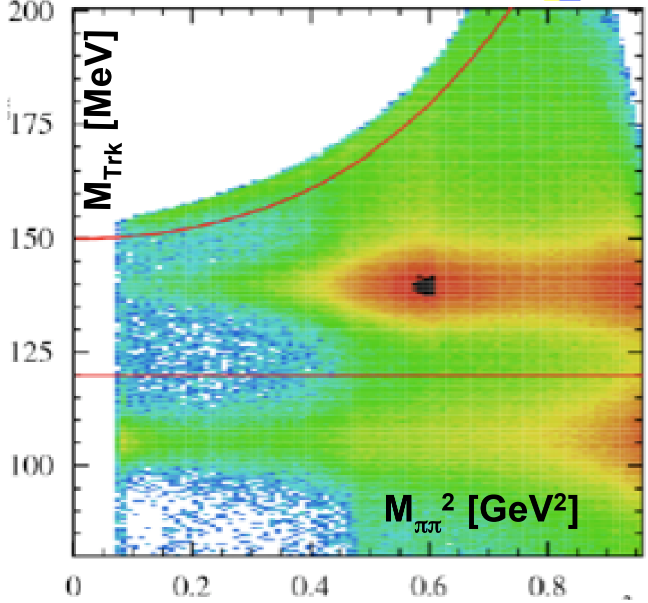
Event selection

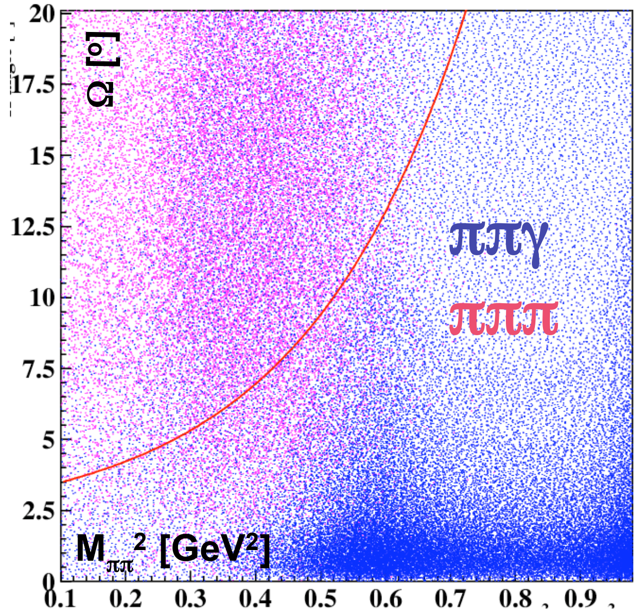
- Experimental challenge: Fight background from
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma$,
  - $e^+e^- \rightarrow e^+e^-\gamma$
  - $\phi \rightarrow \pi^+\pi^-\pi^0$

  separated by means of kinematical cuts in *trackmass* M_{Trk} and the angle Ω between the photon and the missing momentum

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







To further clean the samples from radiative Bhabha events, a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight is used.

KLOE10 result: Pion Form Factor

arXiv:1006.5313

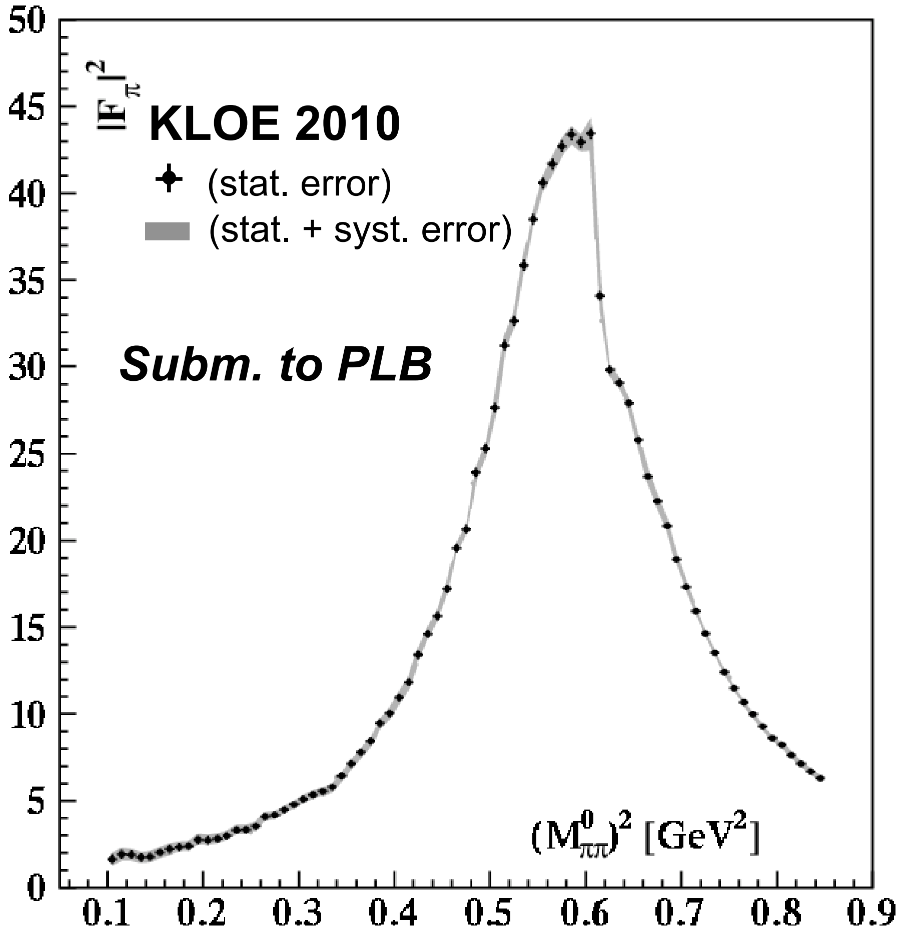


Table of systematic errors on $a_\mu^{\pi\pi}(0.1\text{-}0.85\ \mathrm{GeV}^2)$:

Reconstruction Filter	< 0.1%
Background	0.5%
$f_0+\rho\pi$	0.4%
Omega	0.2%
Trackmass	0.5%
π/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:

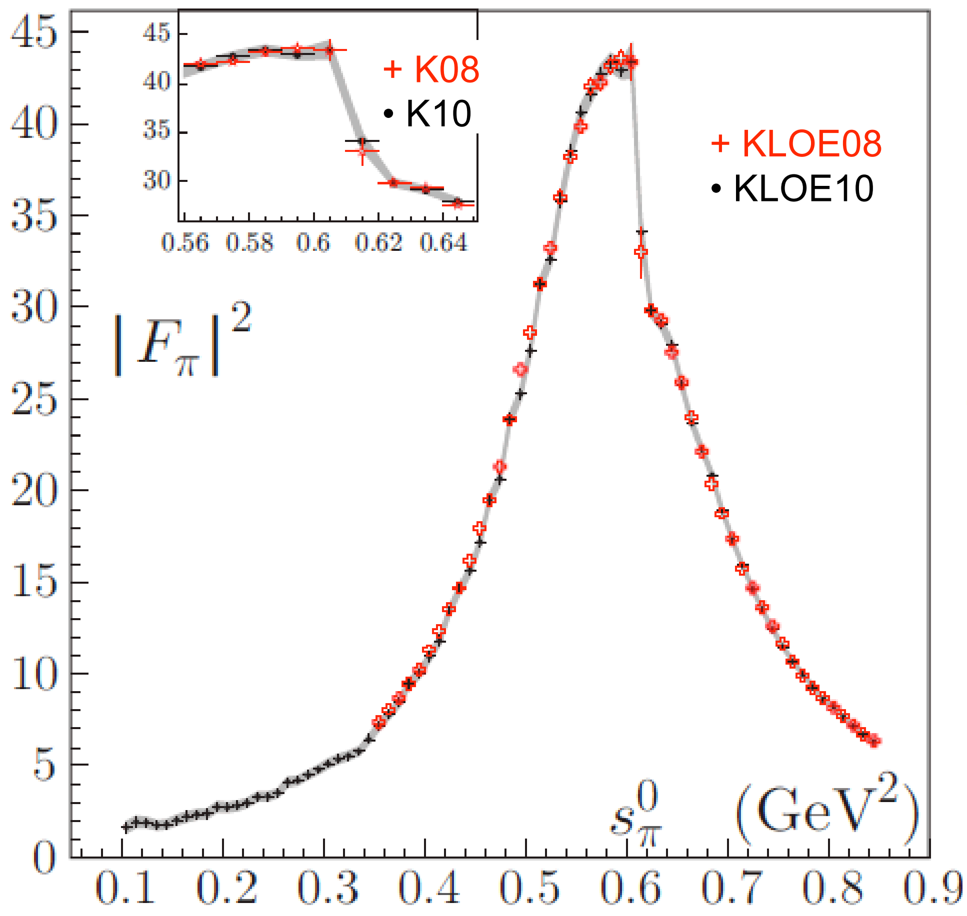
$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

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

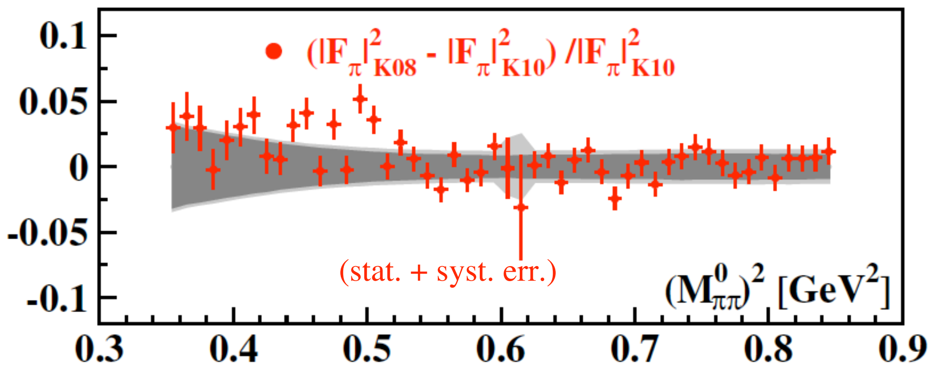
0.4% 1.0% 0.6%

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

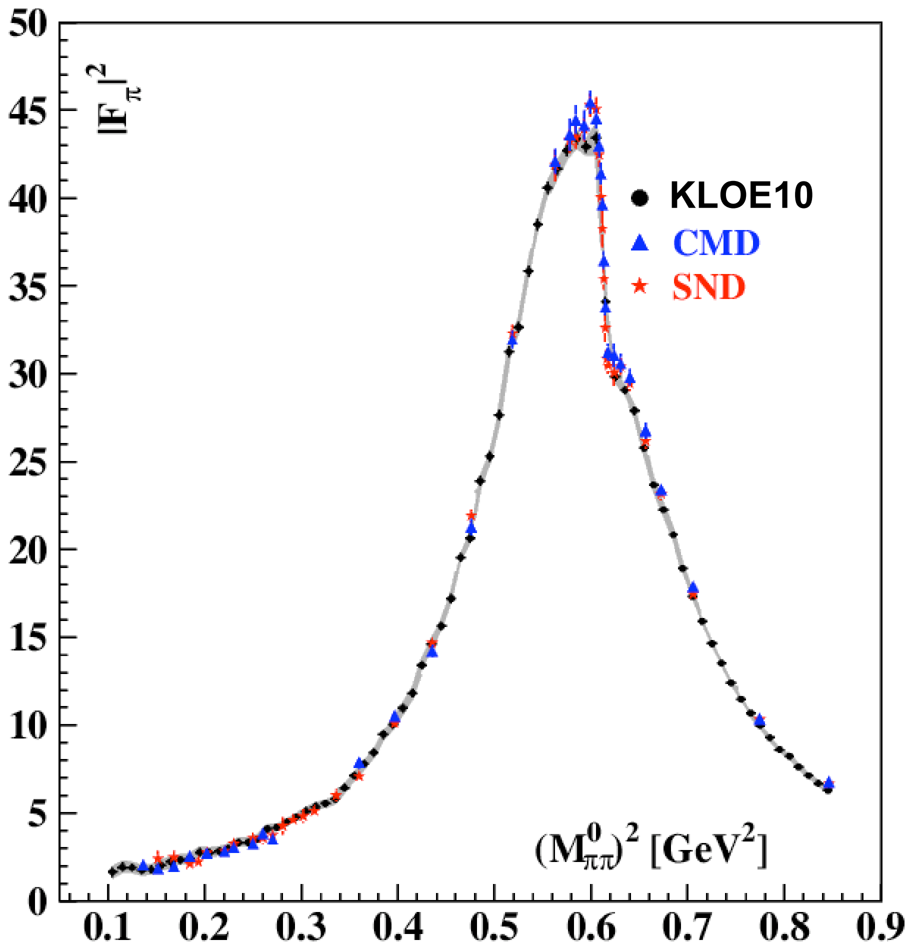
Combination of KLOE08 and KLOE10:

$a_\mu^{\pi\pi}$(0.1-0.95 GeV^2) = (488.6±5.0) · 10^{-10}

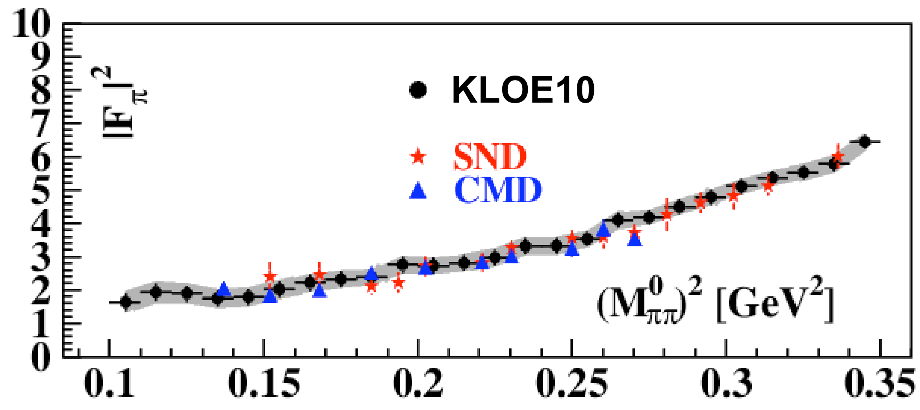
KLOE covers ~70% of total a_μ^{HLO} with a fractional error of 1.0%

Comparison of results: KLOE10 vs CMD-2/SND

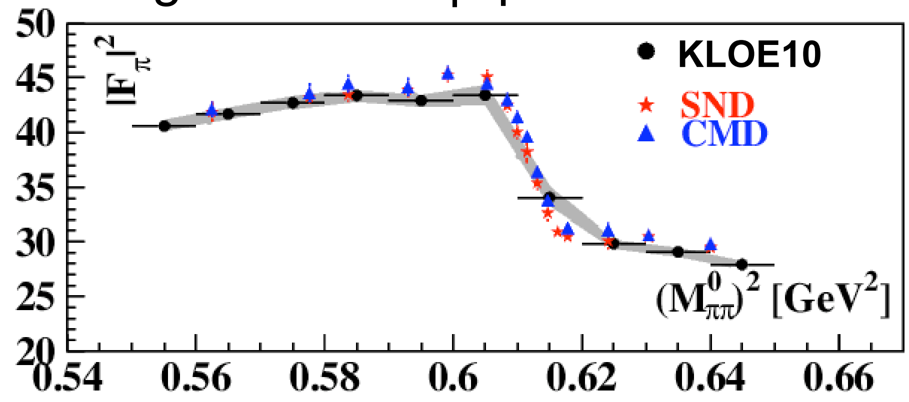
CMD and SND results compared to KLOE10:



Low $(\mathbf{M^0}_{\pi\pi})^2$: :



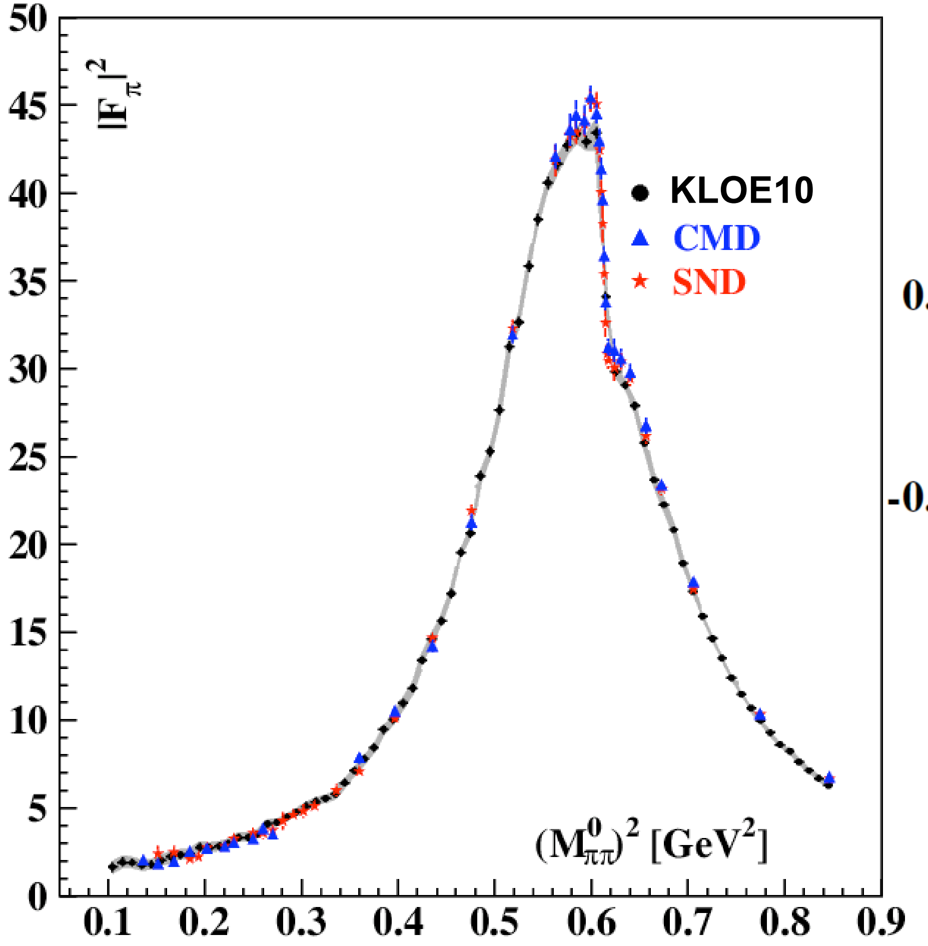
Region around ρ-peak:

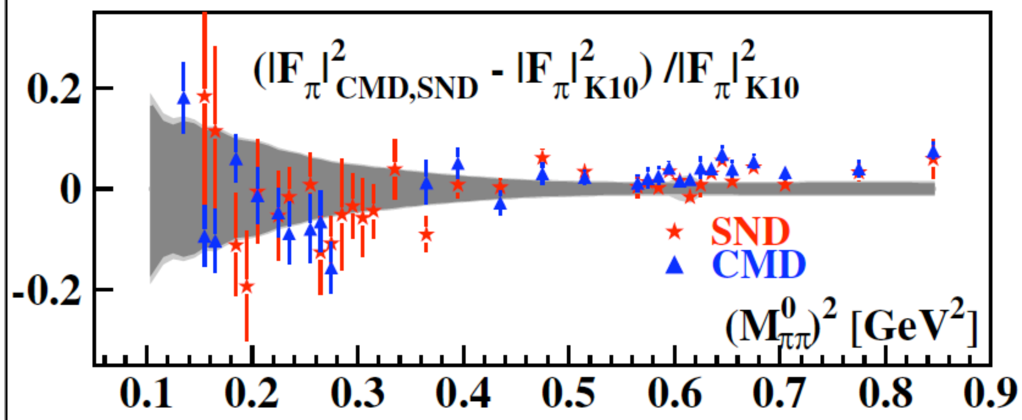


band: KLOE10 error

Comparison of results: KLOE10 vs CMD-2/SND

CMD and SND results compared to KLOE10: Fractional difference



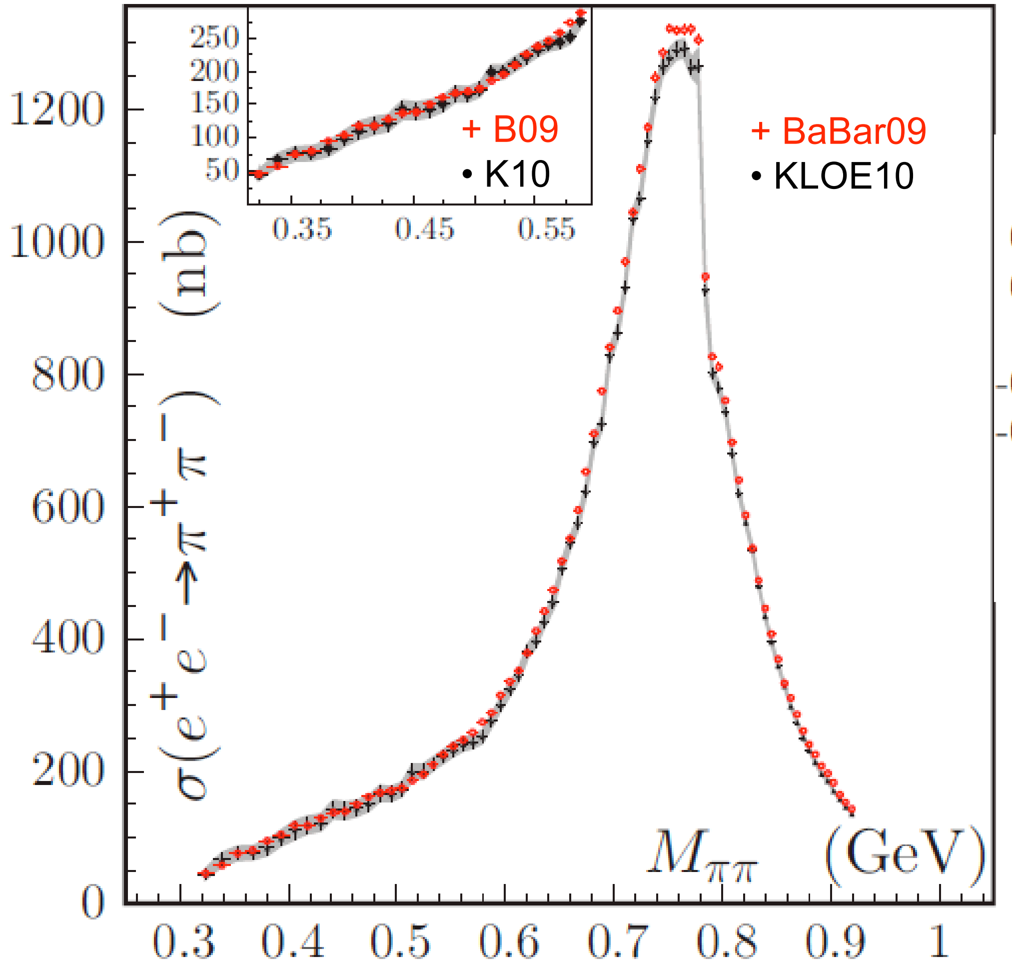


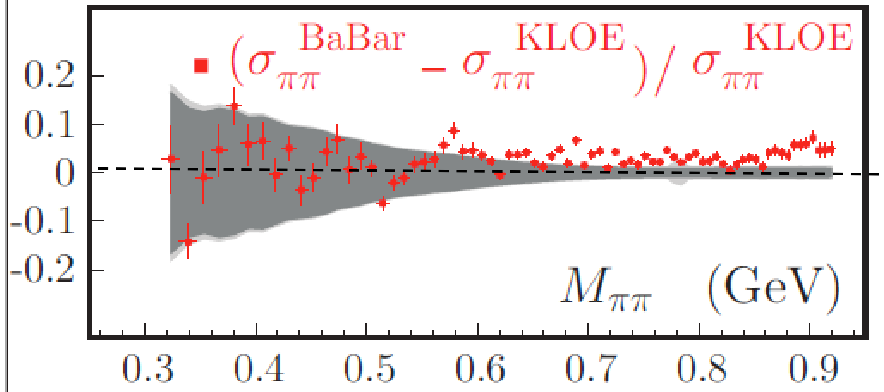
band: KLOE10 error

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

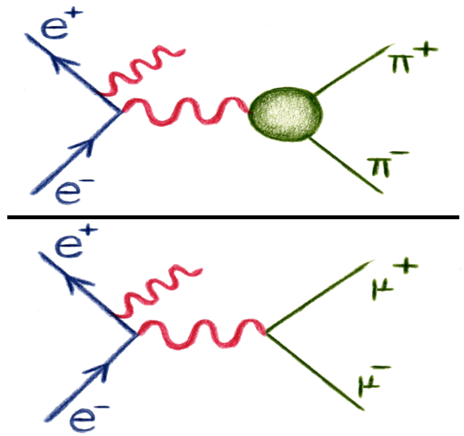
KLOE Measurement of $\sigma(e^+e^-\rightarrow\pi^+\pi^-(\gamma))$ by $\pi\pi\gamma/\mu\mu\gamma$ ratio

Analysis in a well advanced phase

$\sigma_{\pi\pi}$ measurement from π/μ

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).

$$|F_\pi(s')|^2 \approx \underbrace{\frac{4(1+2m_\mu^2/s')\beta_\mu}{\beta_\pi^3}}_{\text{kinematical factor } (\sigma_{\mu\mu}^{Born}/\sigma_{\pi\pi}^{Born})} \underbrace{\frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}}_{\text{meas. quantities}}$$



Many radiative corrections drop out:

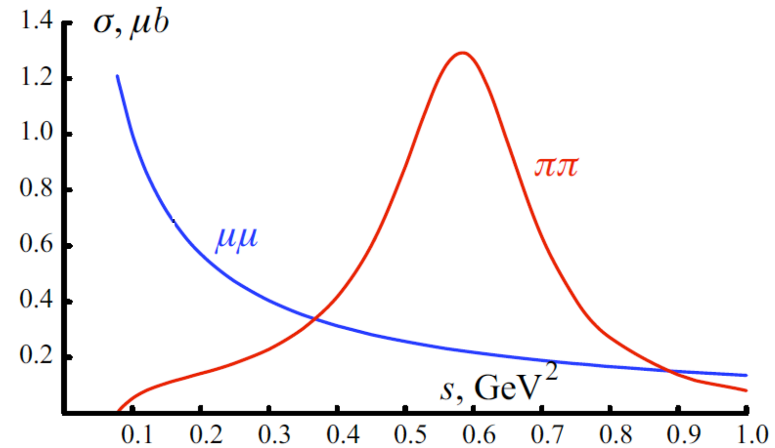
- *radiator function*
- *int. luminosity from Bhabhas*
- *Vacuum polarization*

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

- *muons:* $M_{Trk} < 120$ *MeV*
- *pions :* $M_{Trk} > 130$ *MeV*

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

$\sigma(e^+e^-\to\pi^+\pi^-)$ and $\sigma(e^+e^-\to\mu^+\mu^-)$



π/μ: Status of the Analysis

- 240 pb^{-1} of 2002 data sample (the same used in KLOE08 analysis): 0.87 Million $\mu\mu\gamma$ events expected (compared to 3.1 Million for $\pi\pi\gamma$)

- A lot of work has been done to achieve a control of ~1% in the muon selection, especially in the ρ region where π/μ ~10 (see later)

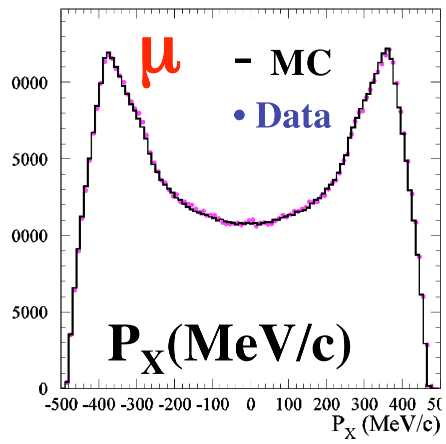
- We have achieved an excellent Data/MC agreement for muons in many kinematic variables (as we did for pions)

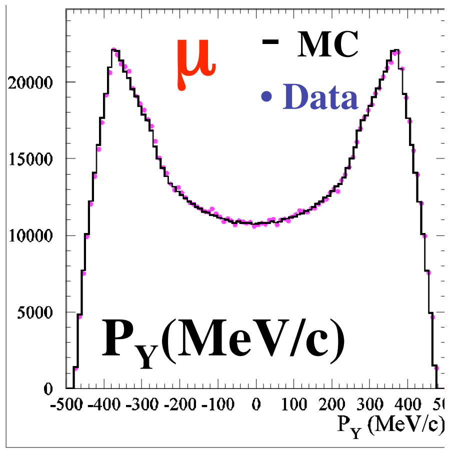
- Most of efficiencies for muons have been done and are ~100%

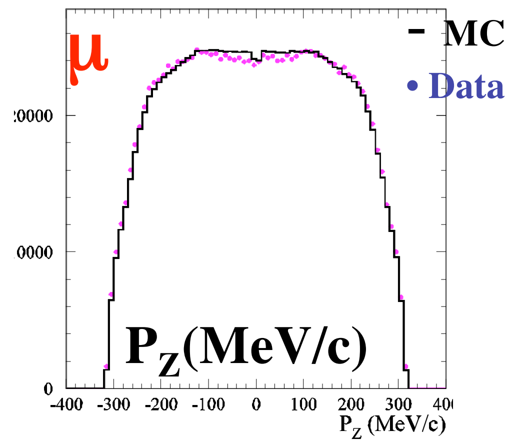
- We have not yet performed the absolute ratio $\mu\mu\gamma_{DATA}/\mu\mu\gamma_{MC}$ (test of QED) to check Radiator, Luminosity, FSR, etc…

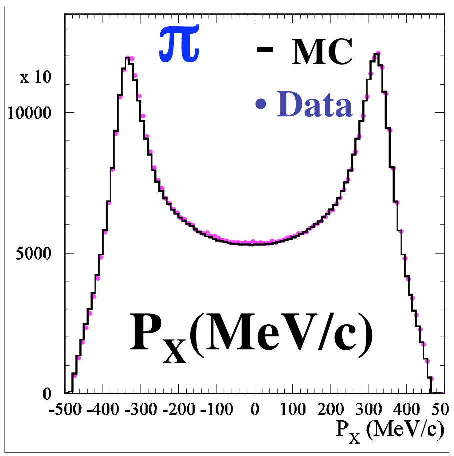
Results are expected soon…

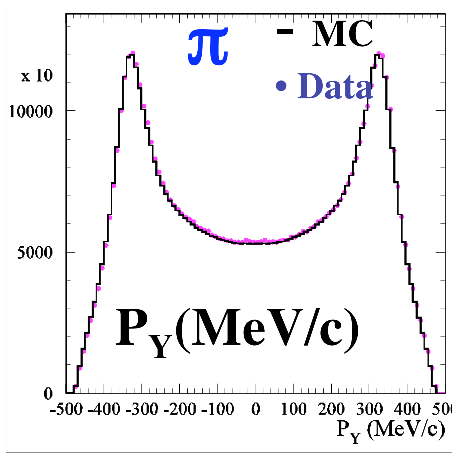
Example of data/MC comparison for μμγ and ππγ: momentum components of μ and π

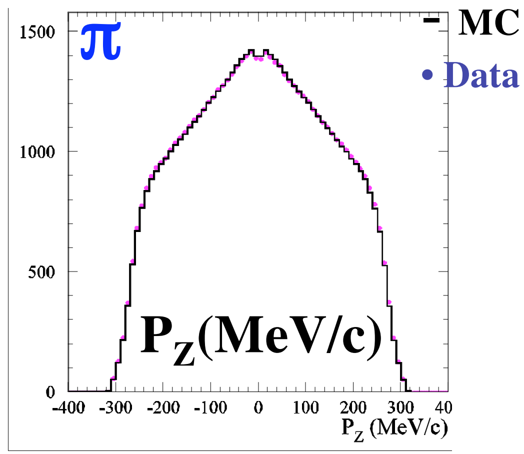












Test of Final State Radiation model by measurement of the Forward-Backward asymmetry in $e^+e^- \rightarrow \pi^+\pi^-\gamma$ process

Forward-backward asymmetry:

The FB asymmetry is an ideal tool to study the validity of FSR model in MC:

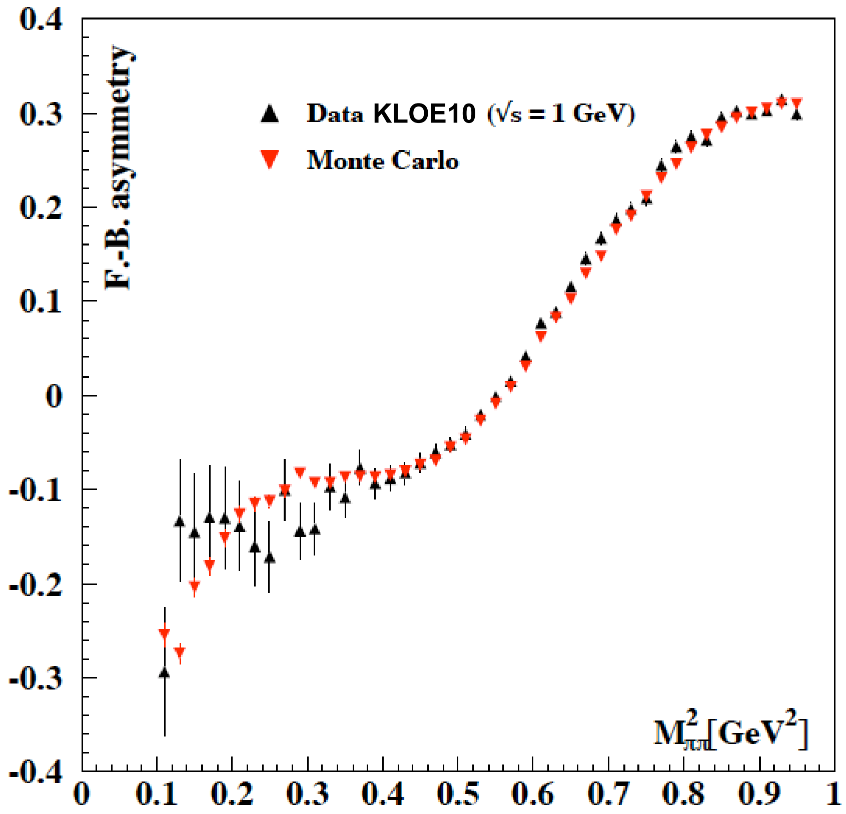
Binner, Kühn, Melnikov, Phys. Lett. B 459, 1999

$$A = \frac{N(\theta^{+} > 90^{o}) - N(\theta^{+} < 90^{o})}{N(\theta^{+} > 90^{o}) + N(\theta^{+} < 90^{o})}$$

In a similar way like FSR, radiative decays of the ϕ into scalar mesons decaying to $\pi^{+}\pi^{-}$ also contribute to the asymmetry.

Czyz, Grzelinska, Kühn, hep-ph/0412239

Good agreement between data and MC



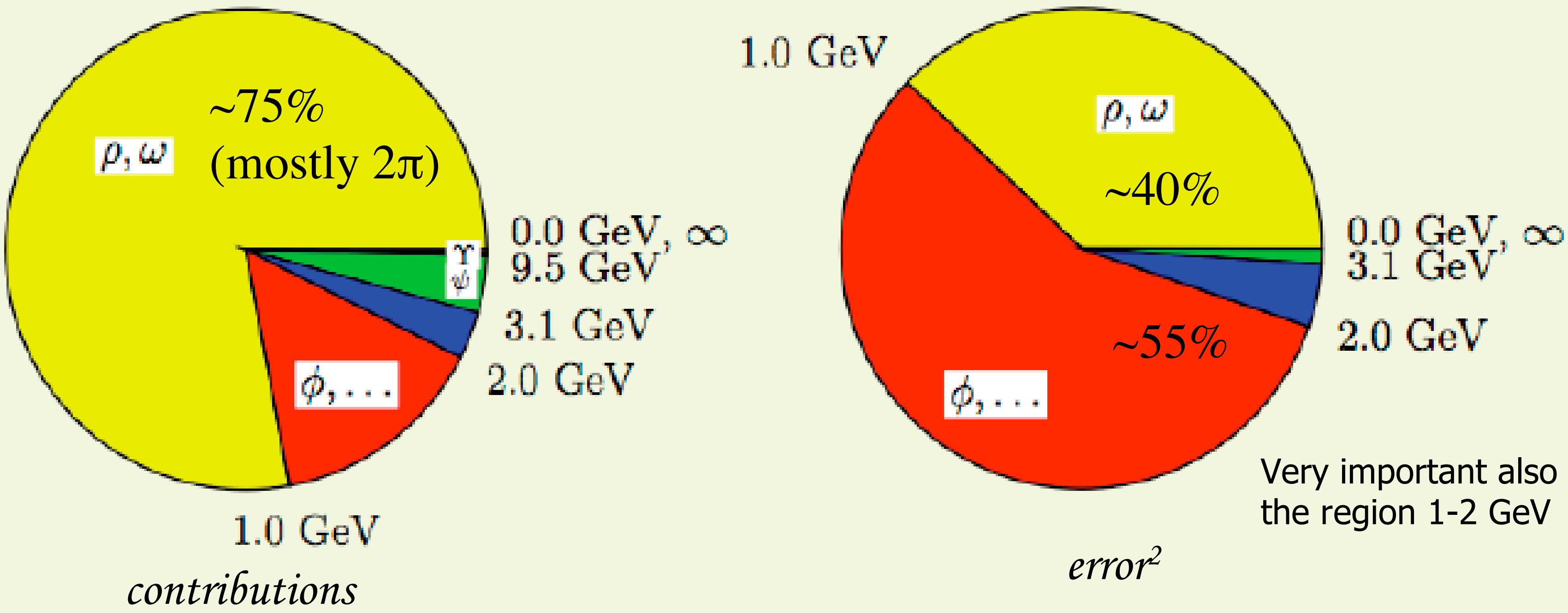
PHOKHARA-MC modified by O. Shekhovtsova using Kaon-Loop-Model used in KLOE analysis of $\pi^0\pi^0\gamma$ final state (Phokhara 6.1)

Prospects on σ_{HAD} with KLOE-2

Dispersion Integral:

Contribution of different energy regions to the dispersion integral and the error to a_μ^{had}

F. Jegerlehner, Talk at PHIPSI08



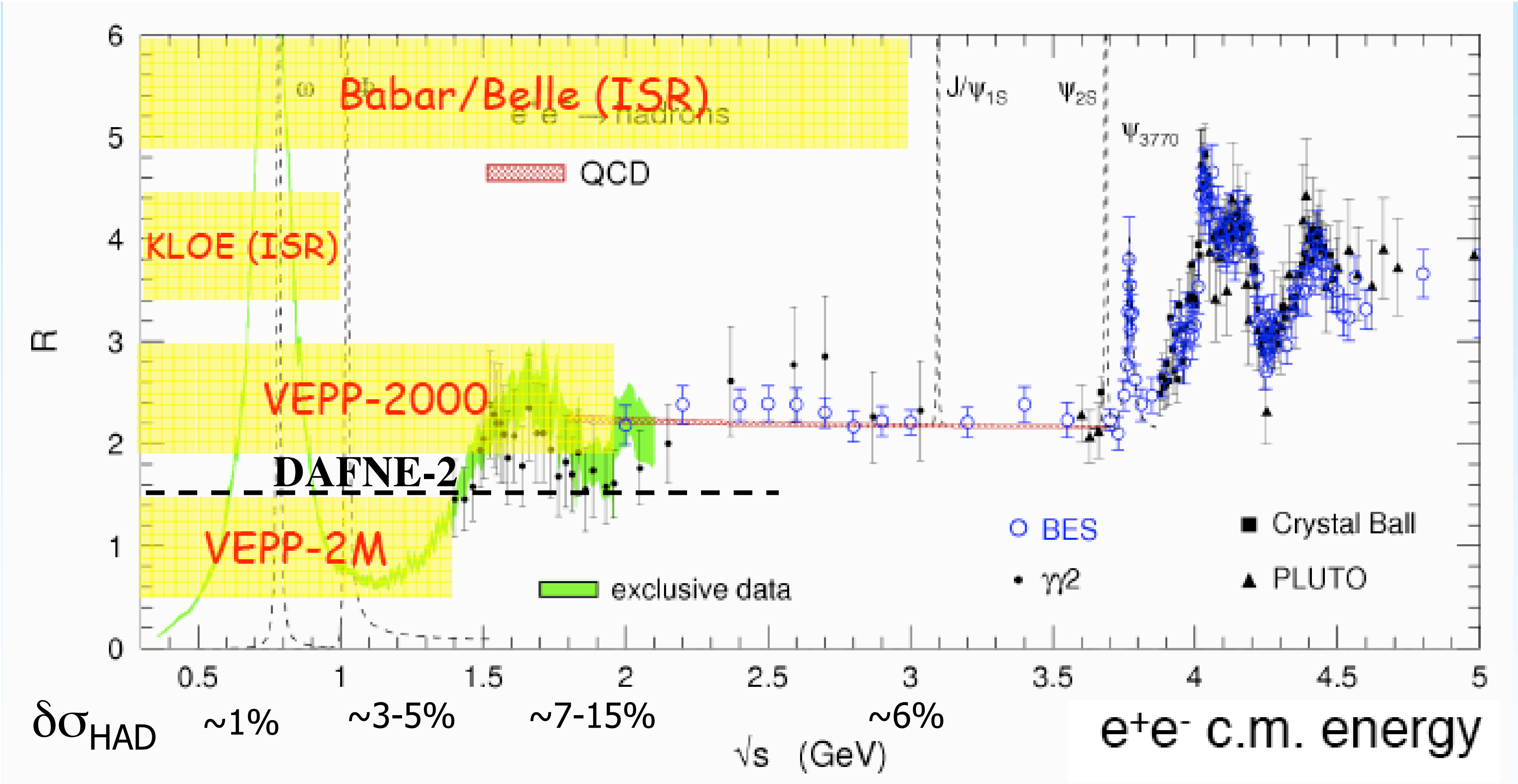
Experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{had}!

→ Needs precision measurements!

$\delta a_\mu^{exp} \rightarrow 1.5\ 10^{-10} = 0.2\%$ on a_μ^{HLO}

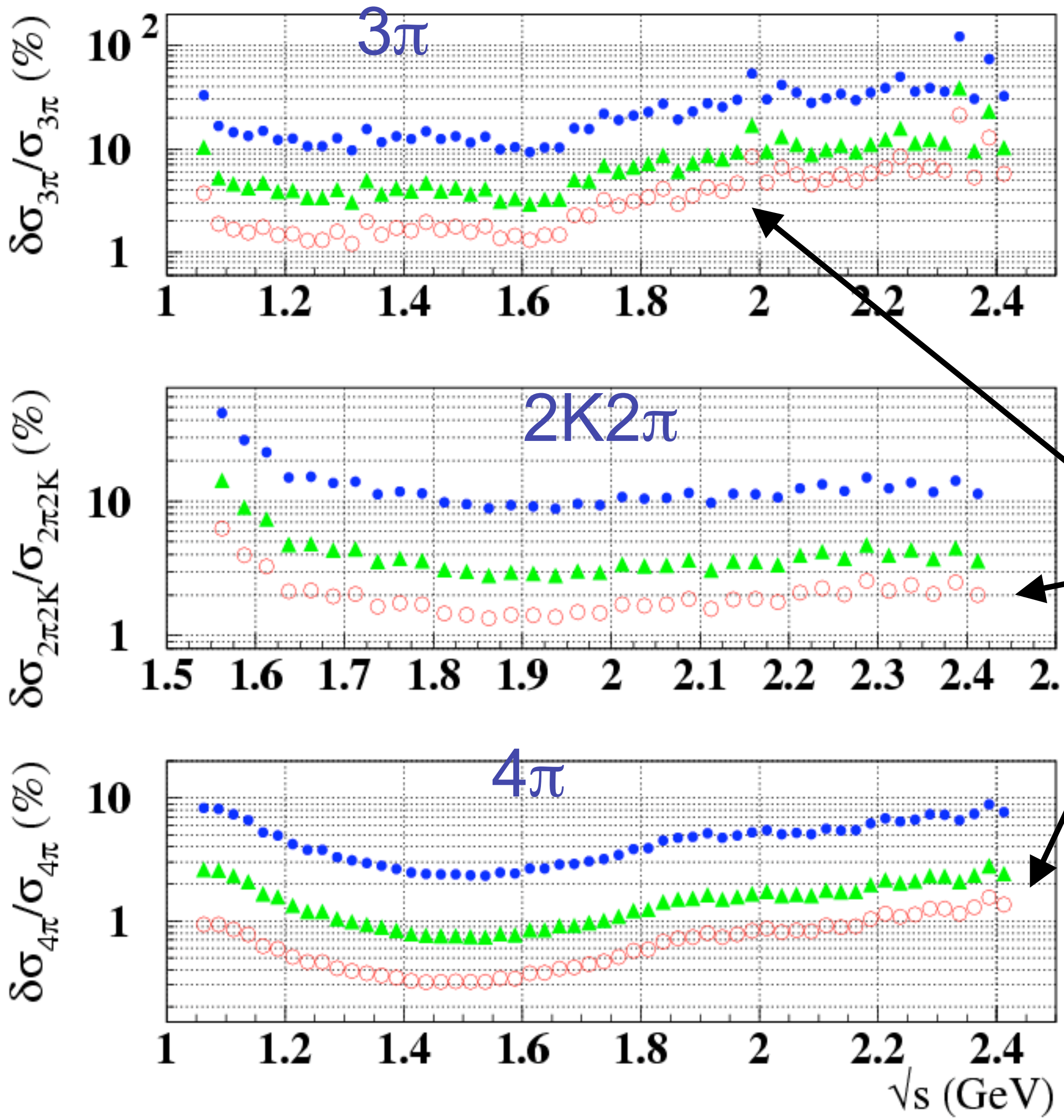
New g-2 exp.

e^+e^- data: current and future/activities



DAFNE-2: DAFNE upgraded in energy with a luminosity ~10^{32} $cm^{-2}s^{-1}$ (~5 pb^{-1} per day ⇔~1 fb^{-1}/year). Plan to measure σ_{HAD} at ~2% in the region up to 2-2.5 GeV (D. Babusci et al. **arXiv:1007.5219**)

Impact of DAFNE-2 on exclusive channels in the range [1-2] GeV with a scan (Statistical only)



BaBar, with the published L_{int} per point (90 fb^{-1})

BaBar, with 10 × (the present L_{int})

DAFNE-2, with 20 pb^{-1} per point (<1 week @10^{32} cm^{-2}s^{-1}),

- DAFNE-2 is **statistically** better than O(1ab^{-1}) B-factories
- Improvement on systematics come as well!

Of course ISR can be done as well!

Conclusions

❑ KLOE has measured $\sigma_{\pi\pi}$ in the region 0.35 - 0.95 GeV^2 with ISR with ~1% systematic error (KLOE05, ***PLB 606, 12 (2005),*** superseeded by KLOE08, ***PLB 670, 285 (2009)***)

- *KLOE08 confirms the **discrepancy** of ~3σ between a_μ^{SM} and a_μ^{EXP}*

- *KLOE08 **$a_\mu^{\pi\pi}$** agrees with recent results from CMD2 and SND experiments. Reasonable agreement on $\sigma_{\pi\pi}$ shapes*

❑ KLOE has performed a new measurement of $\sigma_{\pi\pi}$ (KLOE10, submitted to PLB) in the range 0.1- 0.85 GeV^2 using data taken at 1.0 GeV (20 MeV below the ϕ–peak), with a different selection of KLOE08 → 1.0% systematic error

- *Very good agreement with KLOE08 in the overlapping region (0.35-0.85 GeV^2). Combination of the two measurements done*

$a_\mu^{\pi\pi}$(0.1-0.95 GeV^2) = (488.6±5.0) · 10^{-10}

- *Agreement within errors with BaBar below 0.6 GeV; BaBar lies higher (2-3%) above*

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

Outlook

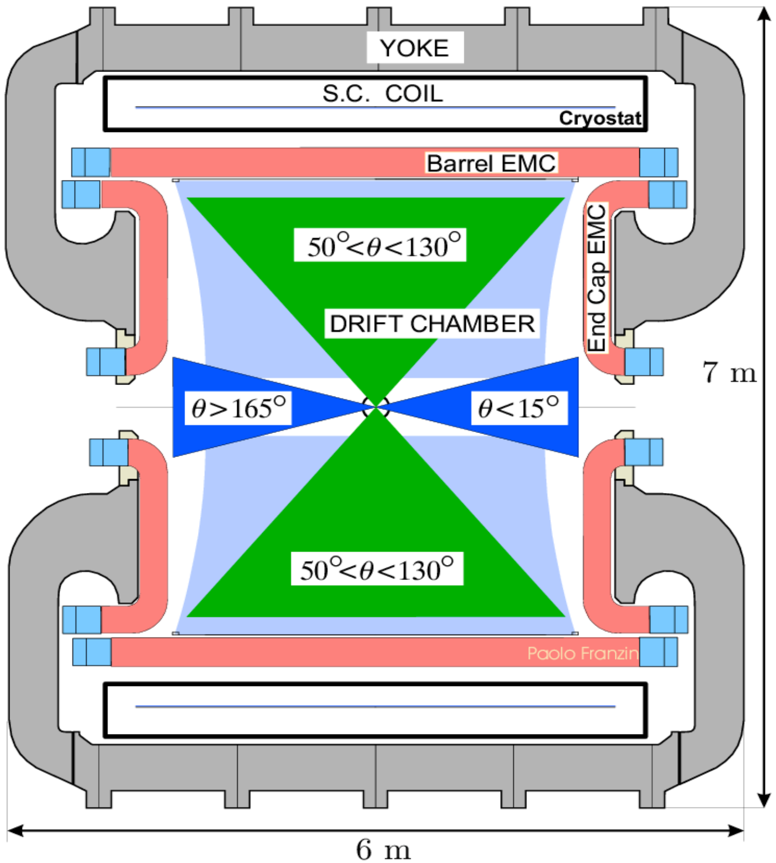
- Measurement of $\sigma_{\pi\pi}$ from $\pi\pi\gamma/\mu\mu\gamma$ ratio well advanced. Results are expected soon

- Test of FSR model by forward-backward asymmetry

- Still about 1.5 fb^{-1} of KLOE from 2004/2005 data to be analyzed (3 times the statistics used up to now)

- Very important for a_μ also the region between 1 and 2 GeV. Proposal to measure σ_{HAD} in this region with 1-2% with KLOE-2 at DAFNE upgraded in energy

  "Proposal for taking data with the KLOE-2 detector at the DAFNE collider upgraded in energy". D. Babusci et al. LNF-10-17(P), e-Print: arXiv:1007.521



SPARE SLIDES

$a_\mu=(g_\mu-2)/2$:

Theoretical predictions compared to the BNL result (2009)

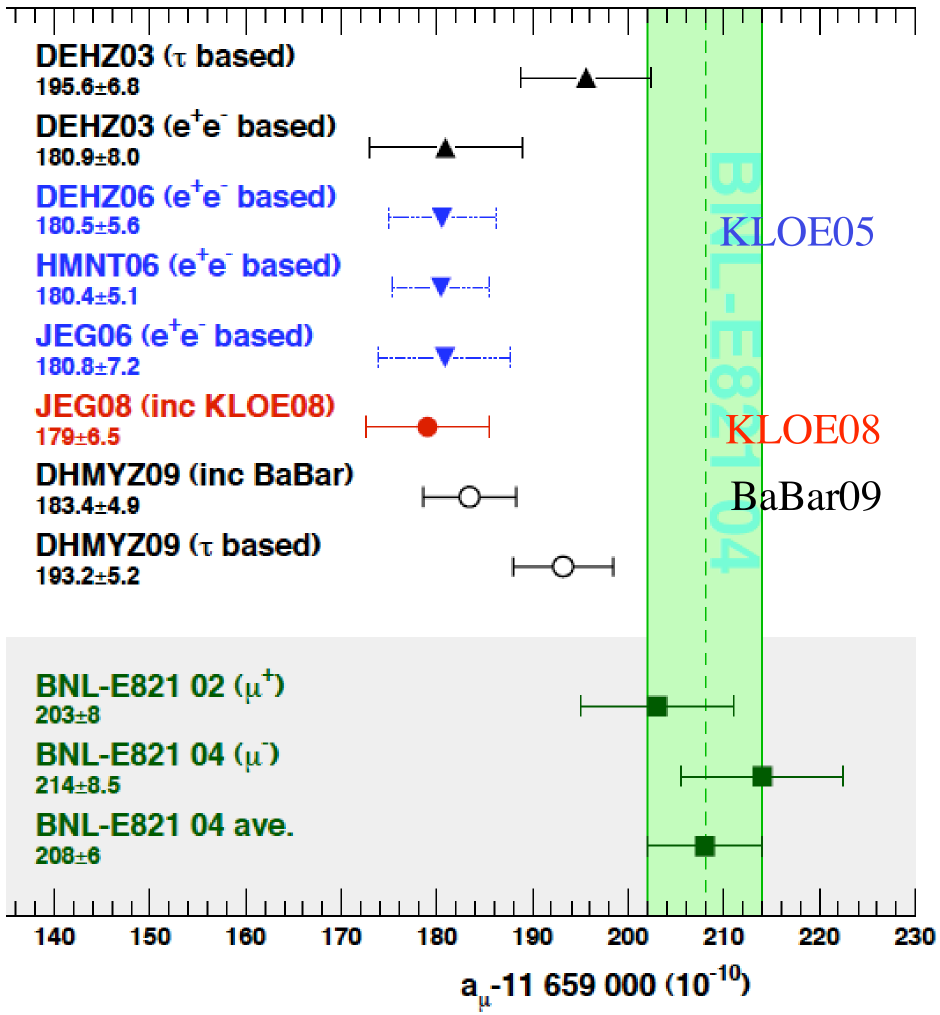
- The latest inclusion of all e^+e^- data (DHMYZ09) gives a discrepancy btw a_μ^{SM} and a_μ^{EXP} of 3.2σ

- Remaining differences on $\sigma_{\pi\pi}$ btw different experiments (mainly KLOE/BaBar) to be clarified [$\Delta a_\mu^{EXP-SM}=2.4\div3.7\sigma$]

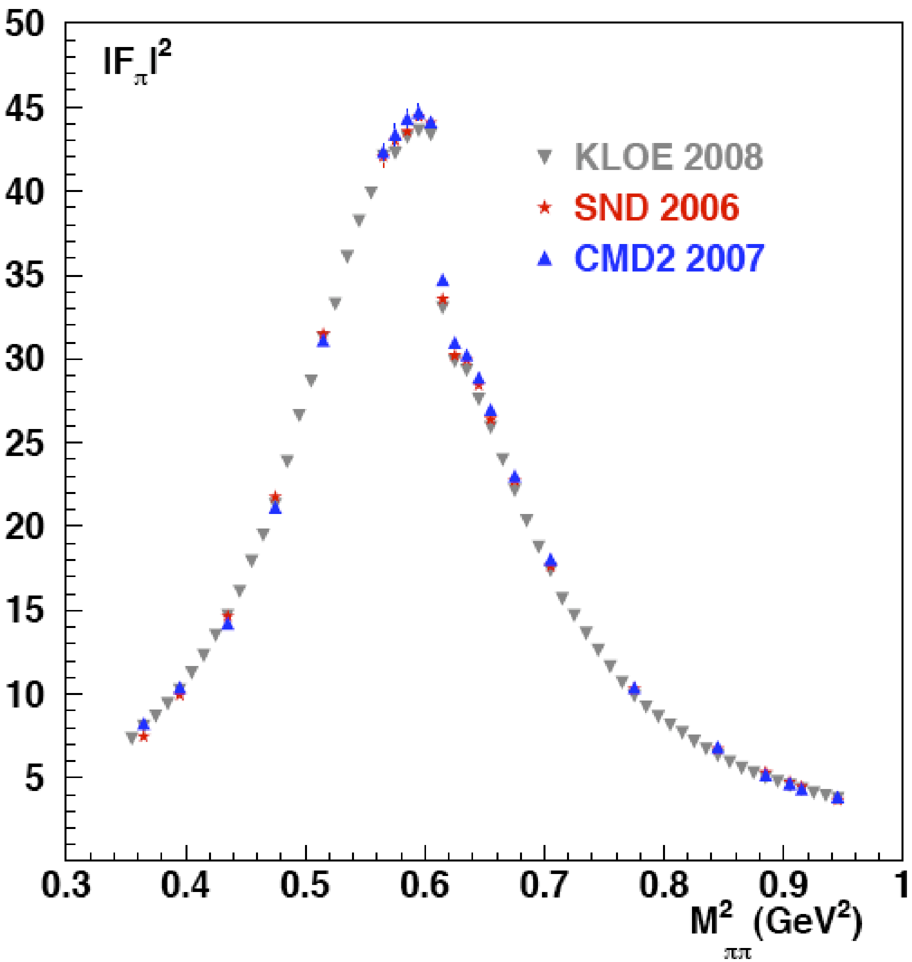
Davier

- (Reduced) discrepancy with τ data (new l. corr.,ee,τ data) [a_μ^{ee} - Δa_μ^{τ} =1.4σ]

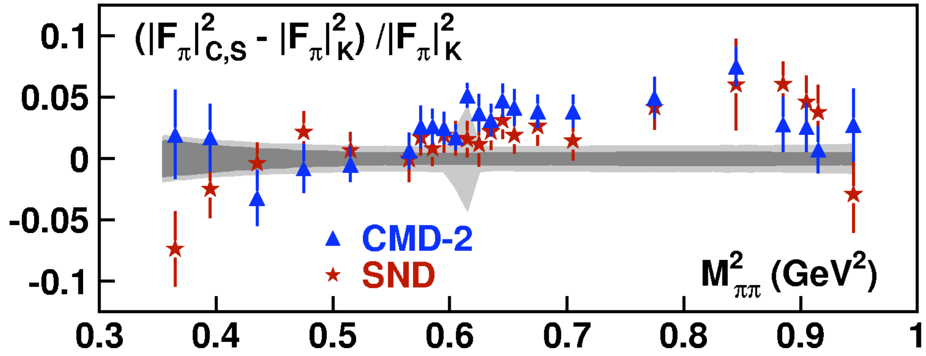
KLOE10 is not yet in.

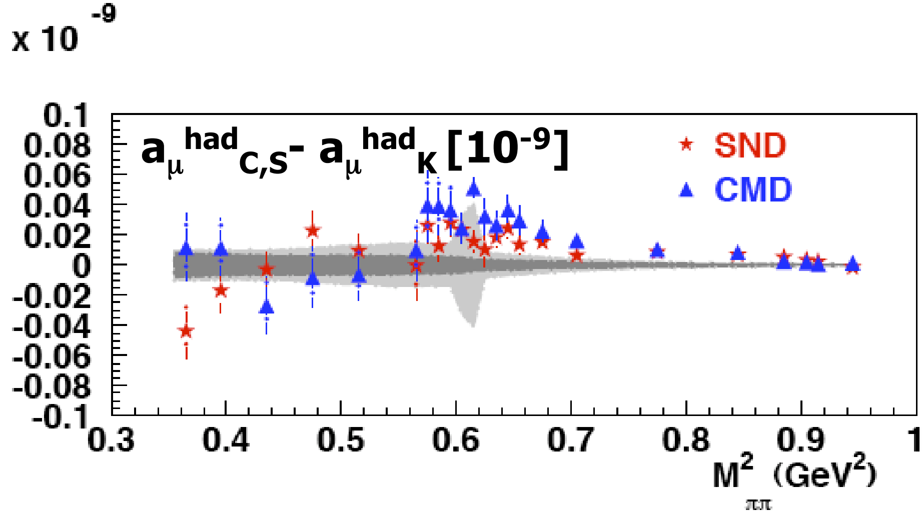


Comparison with CMD2/SND



only statistical errors are shown





band: KLOE error
data points: CMD2/SND experiments

CMD-2 and SND data have been averaged over width of KLOE bin (0.01 GeV^2)