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

Graziano Venanzoni
(for the KLOE collaboration)
Laboratori Nazionali di Frascati

CERN, 23 March 2010

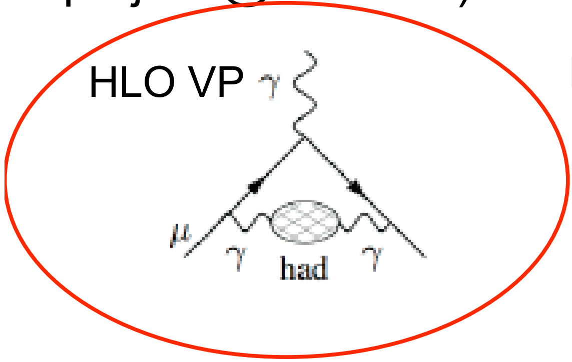
Outlook

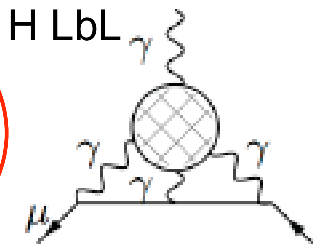
- Hadronic contribution to $(g-2)_\mu$ and ISR measurement ("Radiative Return")
- KLOE measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$:
  - Small (photon) angle measurements (KLOE05, KLOE08)
  - Large (photon) angle measurement (KLOE09) New!
- Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar
- New measurement well advanced:
  - Extraction of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$ by $\mu\mu\gamma$ normalization
- Test of Final State radiation (FSR) by Forward-Backward asymmetry in $e^+e^- \rightarrow \pi^+\pi^-\gamma$
- Conclusion & Outlook

Muon anomaly

$$a_\mu = \frac{(g_\mu - 2)}{2}$$

- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.
- Theoretical error δa_μ^{SM} (~$6\mathrm{x}10^{-10}$) dominated by HLO VP ($4\div5\mathrm{x}10^{-10}$) and HLbL ($[2.5\div4]\mathrm{x}10^{-10}$)
- Experimental error δa_μ^{EXP} ~$6\ \mathrm{x}10^{-10}$(E821). Plan to reduce it to $1.5\ 10^{-10}$ by the new g-2 experiment @FNAL (and also by new project @ J-PARC)

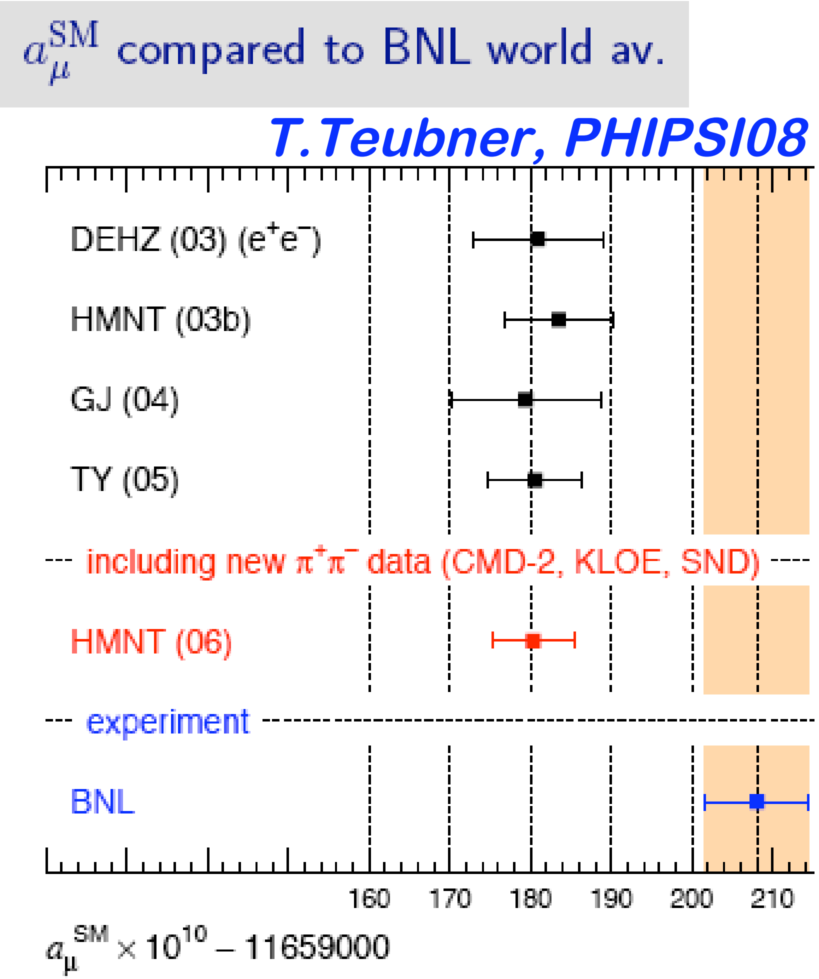




$a_\mu^{HLO} = (690.9\pm\mathbf{4.4})10^{-10}$
[Eidelman, TAU08]

δa_μ^{HLO} ~0.7%

$a_\mu^{HLbL} = (10.5\pm2.6)10^{-10}$
[Prades, de Rafael & A. Vainshtein 08]
$(11\ \pm4)10^{-10}$ (Jegerlehner, Nyffler)


T.Teubner, PHIPSI08

$$a_\mu^{EXP} - a_\mu^{TH} = (27.6 \pm 8.1) \cdot 10^{-10}, \ \sim 3.4\sigma$$

a_μ^{HLO}:

L.O. Hadronic contribution to a_μ can be estimated by means of a dispersion integral:

$$a_\mu^{had} = \left(\frac{\alpha\ m\mu}{3\pi}\right)^2 \int_{4\,m_\pi^2}^{\infty} ds\, \frac{R(s)\,\hat{K}(s)}{s^2}$$

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

1 / s^2 makes low energy contributions especially important:

$\boxed{e^+e^- \to \pi^+\pi^-}$

in the range < 1 GeV contributes to 70% !

- K(s) = analytic kernel-function
- above sufficiently high energy value, typically 2…5 GeV, use *pQCD*

Input:

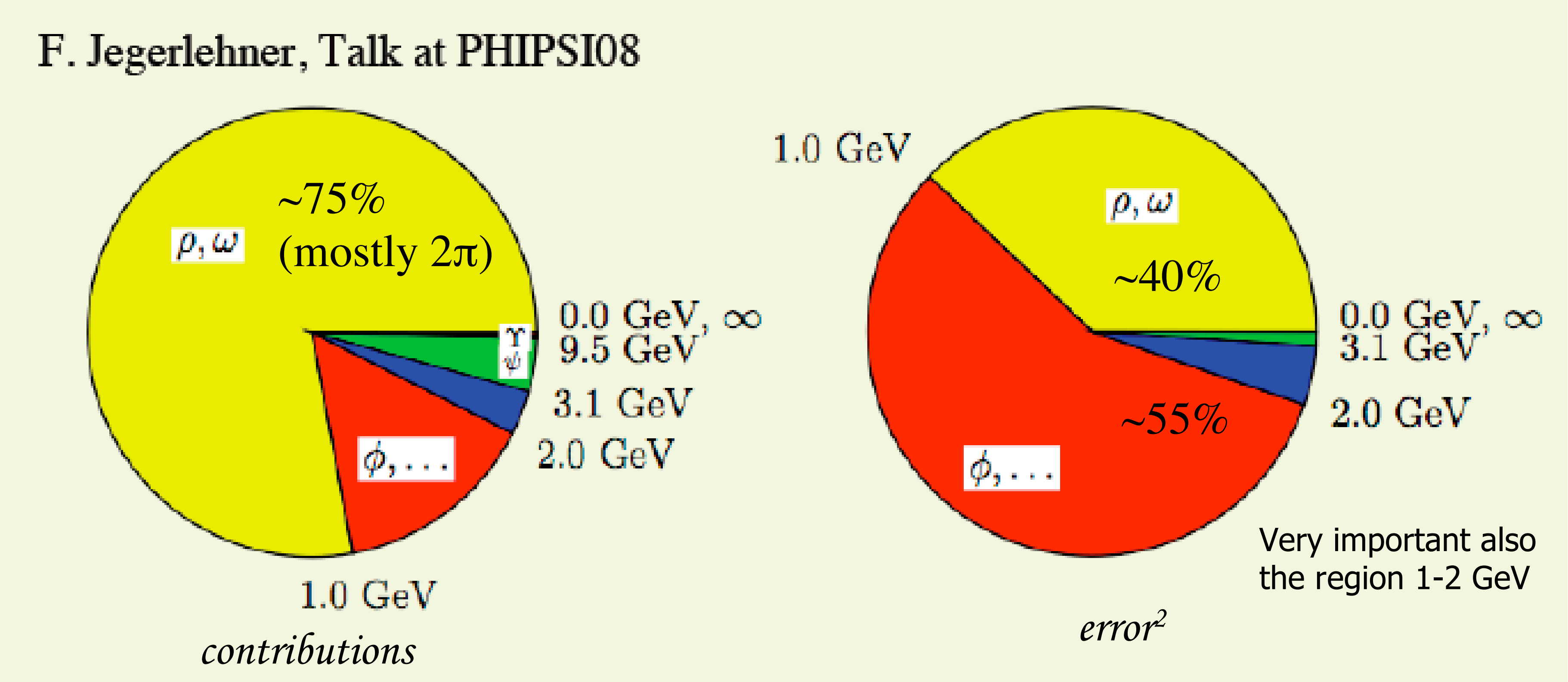
a) hadronic electron-positron cross section data (G.dR 69, E.J.95, A.D.H.’97,….))

b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

Alemany, Davier, Hoecker ‘97

Dispersion Integral:

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


F. Jegerlehner, Talk at PHIPSI08

Very important also the region 1-2 GeV

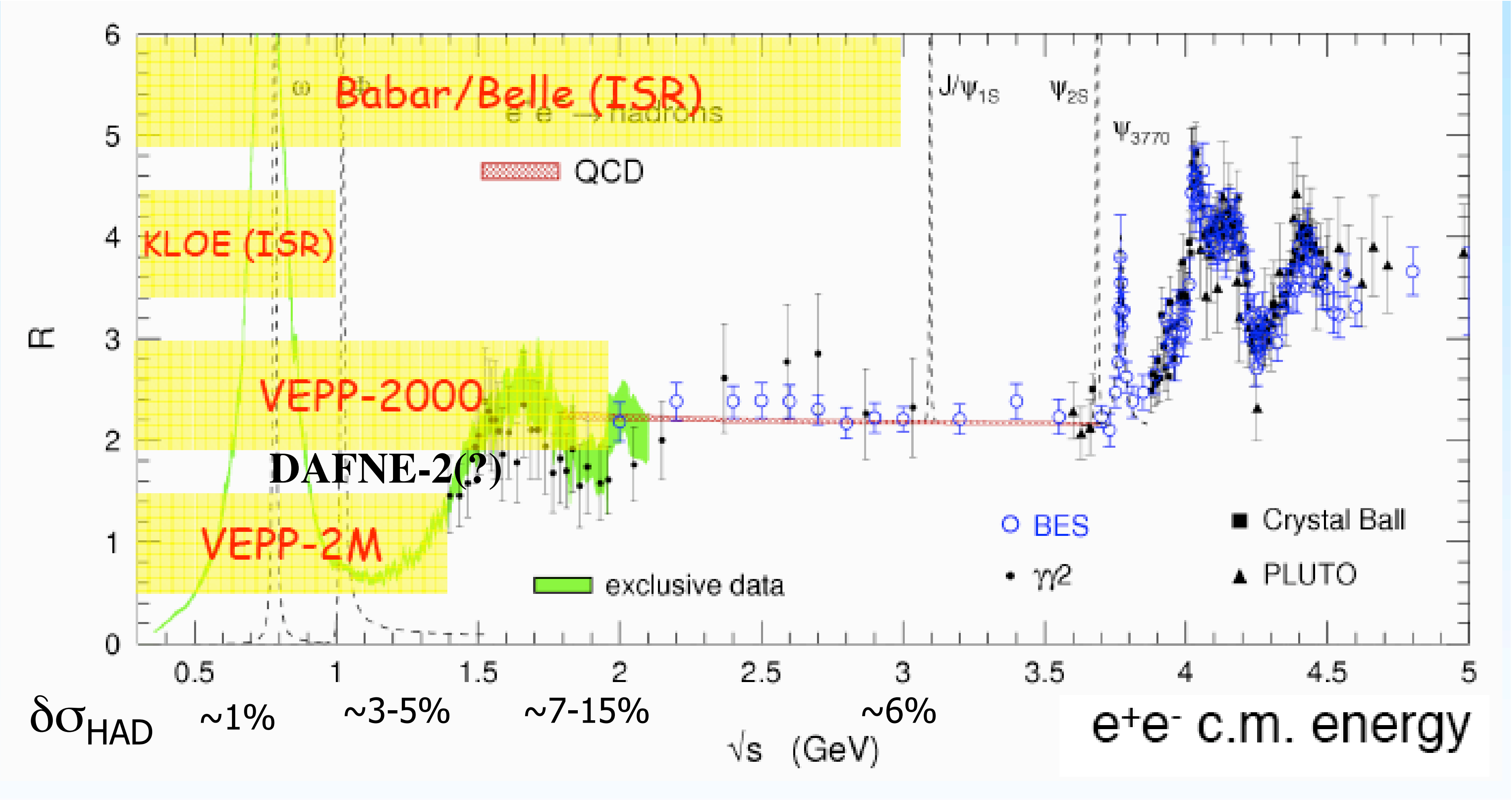
Experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{had}!

→ 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



Cross section data:

At low energies (< 2 GeV) only measurements of exclusive channels, two approaches:

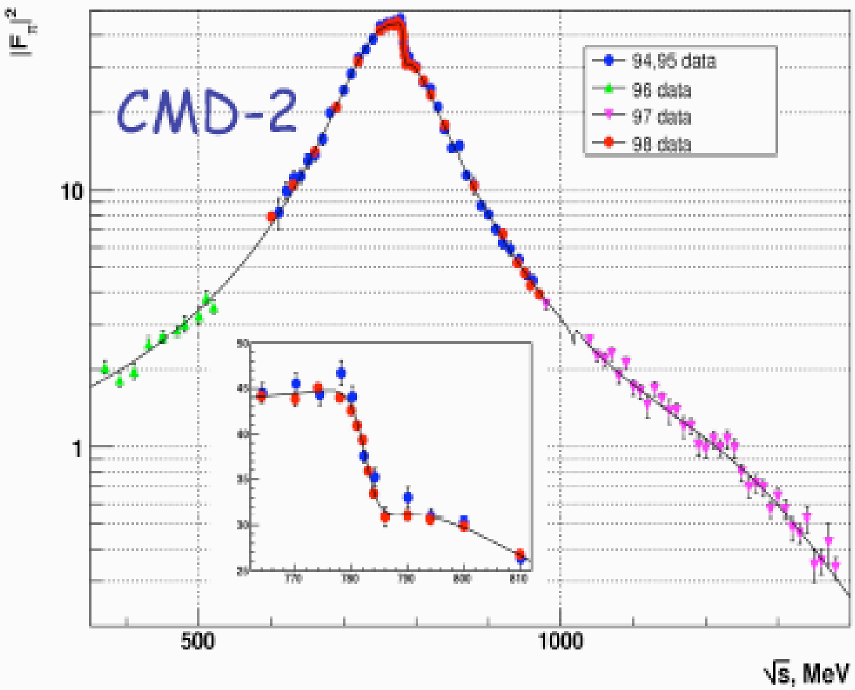
Energy scan (CMD2, SND):

- energy of colliding beams is changed to the desired value
- “direct” measurement of cross sections
- needs dedicated accelerator/physics program
- needs to measure luminosity and beam energy for every data point

Radiative return (KLOE, BABAR, BELLE):

- runs at fixed-energy machines (meson factories)
- use initial state radiation process to access lower lying energies or resonances
- data come as by-product of standard physics program
- requires precise theoretical calculation of the radiator function
- luminosity and beam energy enter only once for all energy points
- needs larger integrated luminosity

Pion form factor @ Novosibirsk (with energy scan)

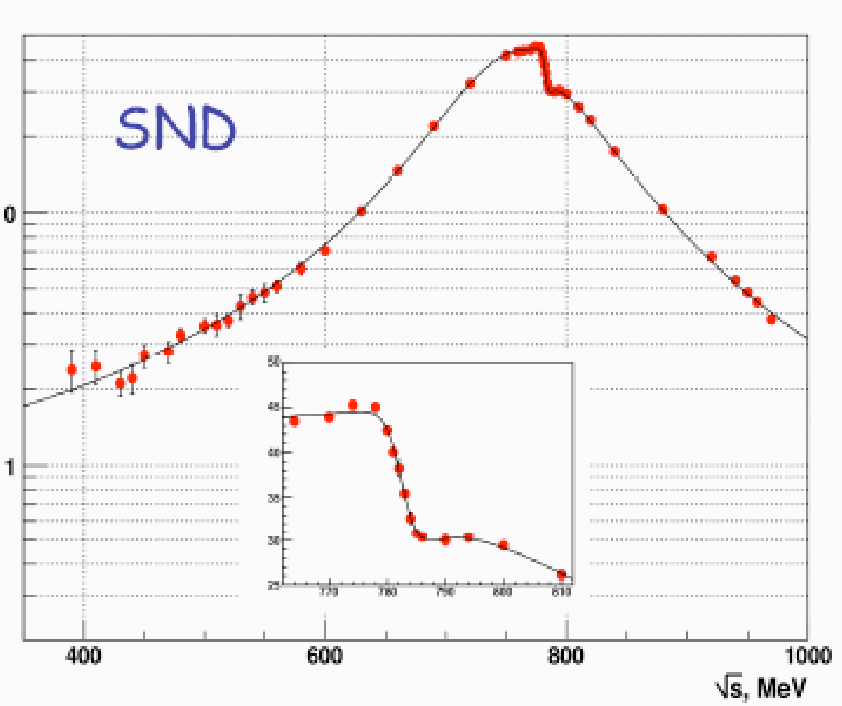


Systematic error

0.7% ⟷ 0.6% / 0.8% ⟷ 1.2-4.2% ⟷

CMD-2 ~ $9 \cdot 10^5$ ev.

SND ~ $8 \cdot 10^5$ ev.



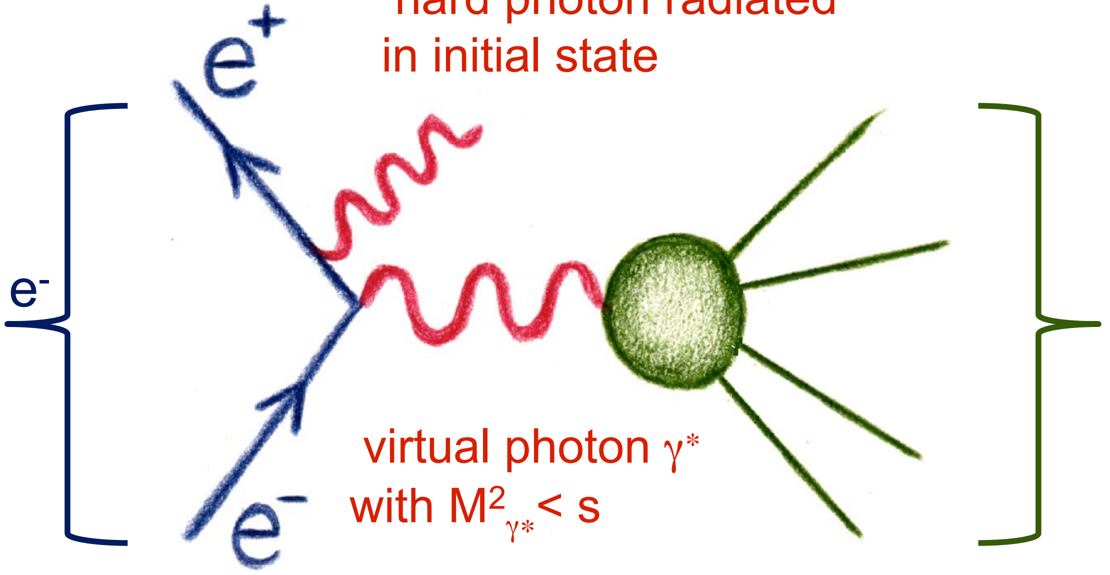
Systematic error

3.2% ⟷ 1.3% ⟷ 8

Good agreement between the two spectra

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 $\sqrt{s}$).



hard photon radiated in initial state

incoming e^+ and e^- with $M^2_{ee} = s$

hadrons

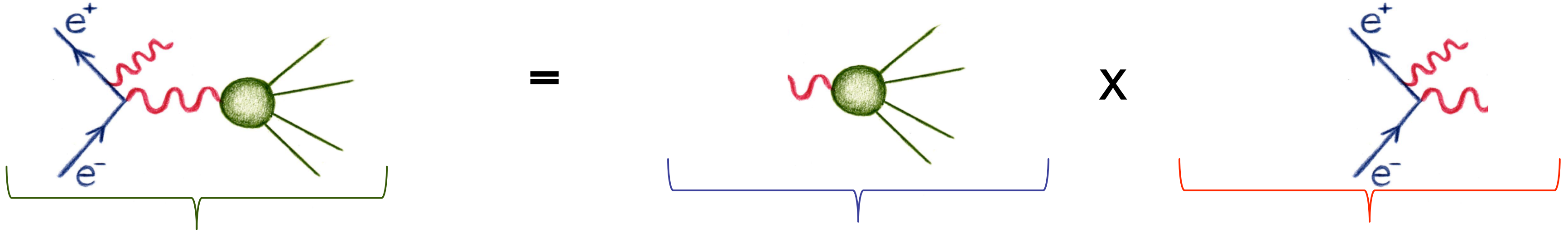
virtual photon γ^* with $M^2_{\gamma*} < s$

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):

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



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

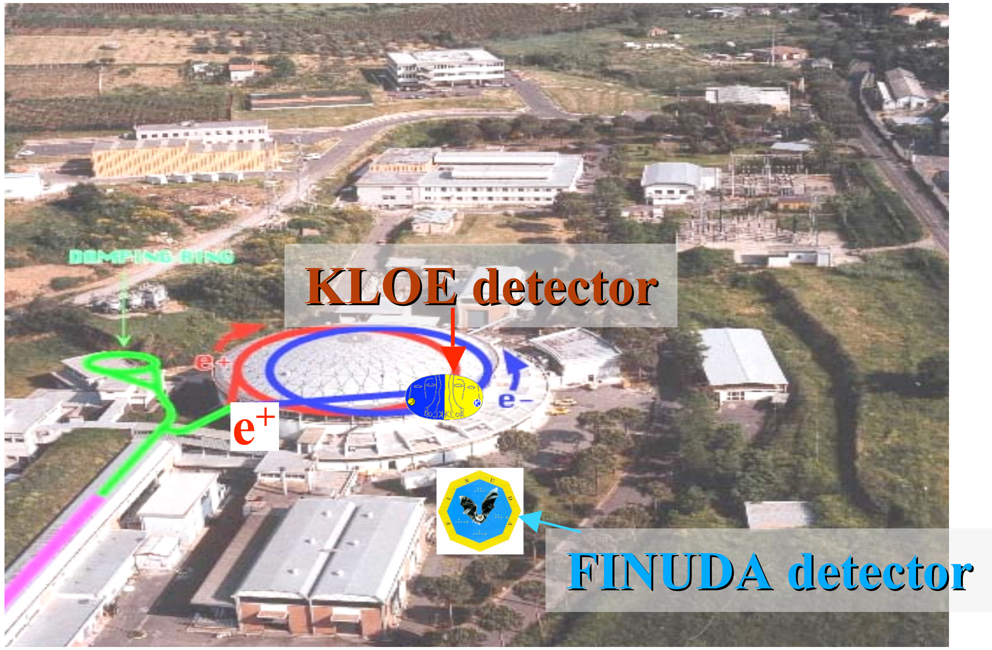
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003

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

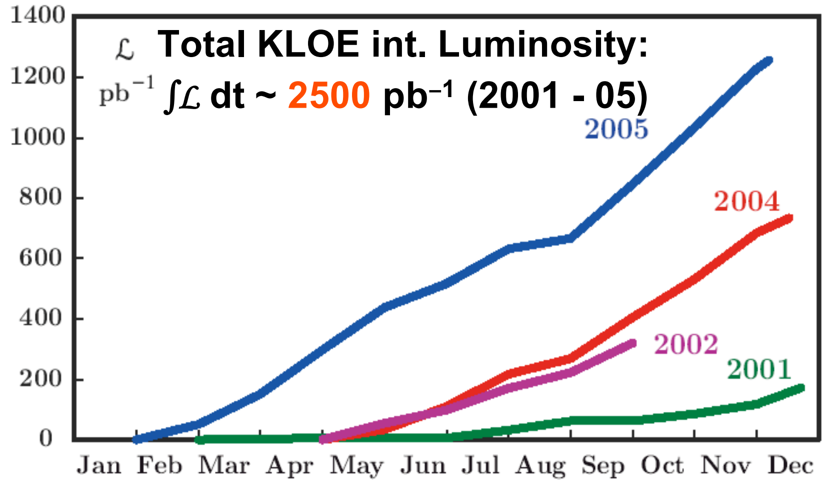
IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^-\to\pi^+\pi^-)$ with ISR using 2001 data (140pb^{-1}) **PLB606(2005)12** ⇒ ~3σ discrepancy btw a_μ^{SM} and a_μ^{exp}

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:

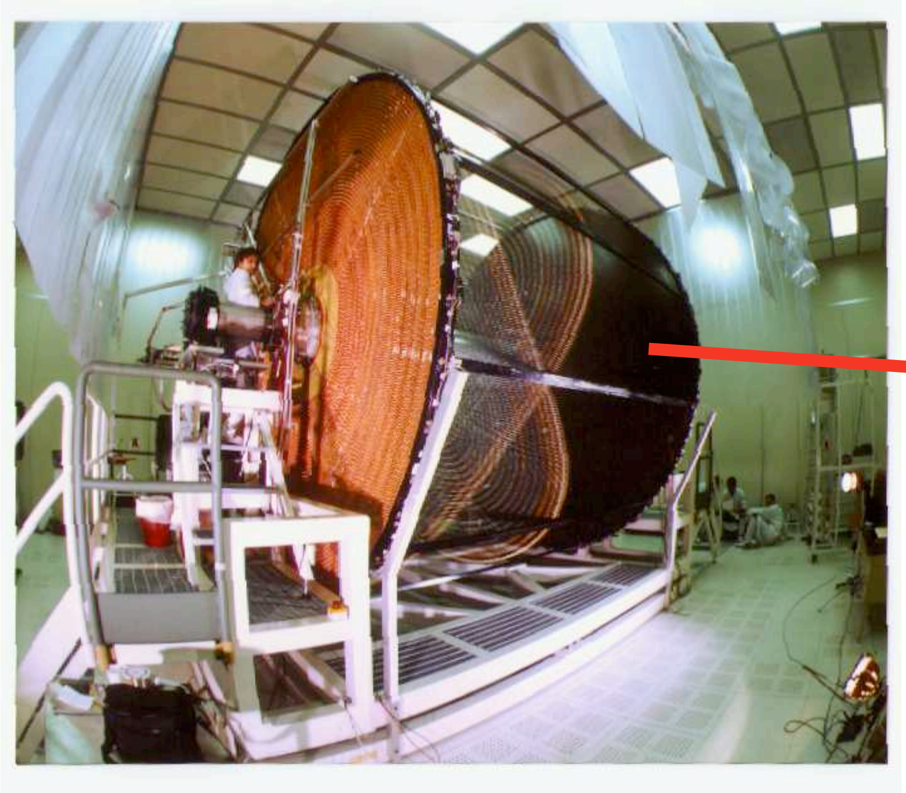
- **Energy scan (4 points around m_Φ-peak)**
- **$240\ pb^{-1}$ at $\sqrt{s} = 1000$ MeV (off-peak data)**

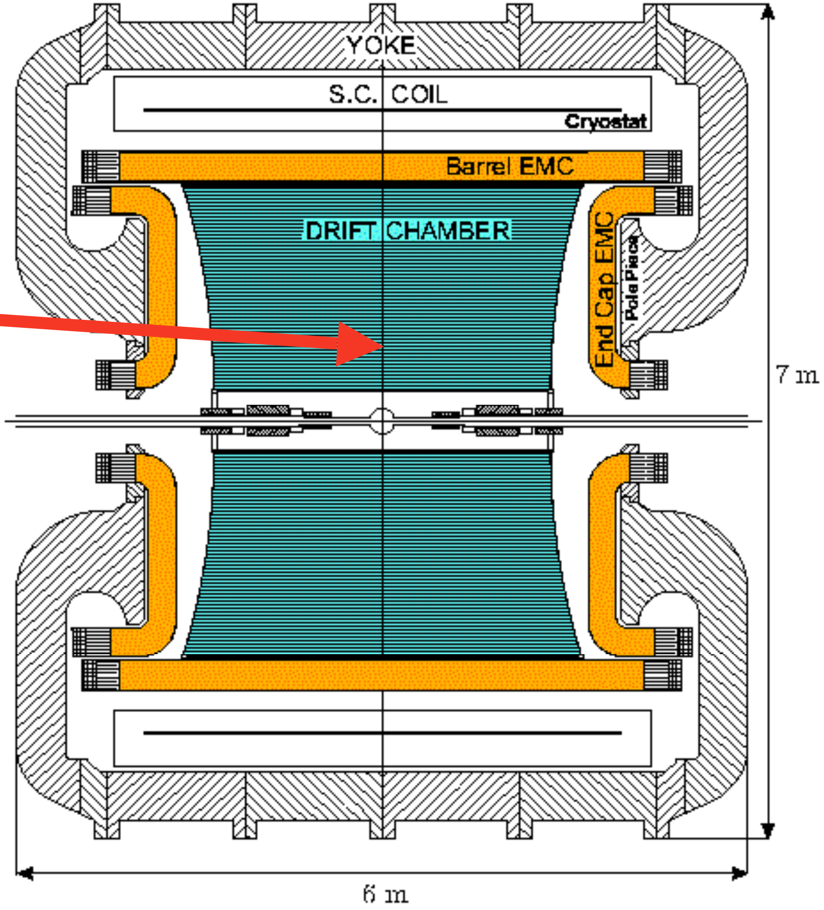
KLOE08 measurement (PLB670(2009)285) was based on $240 pb^{-1}$ from 2002 data!

*Our **new** measurement (KLOE09) is based on $233\ pb^{-1}$ of 2006 data (different event selection)*

KLOE Detector

Drift chamber





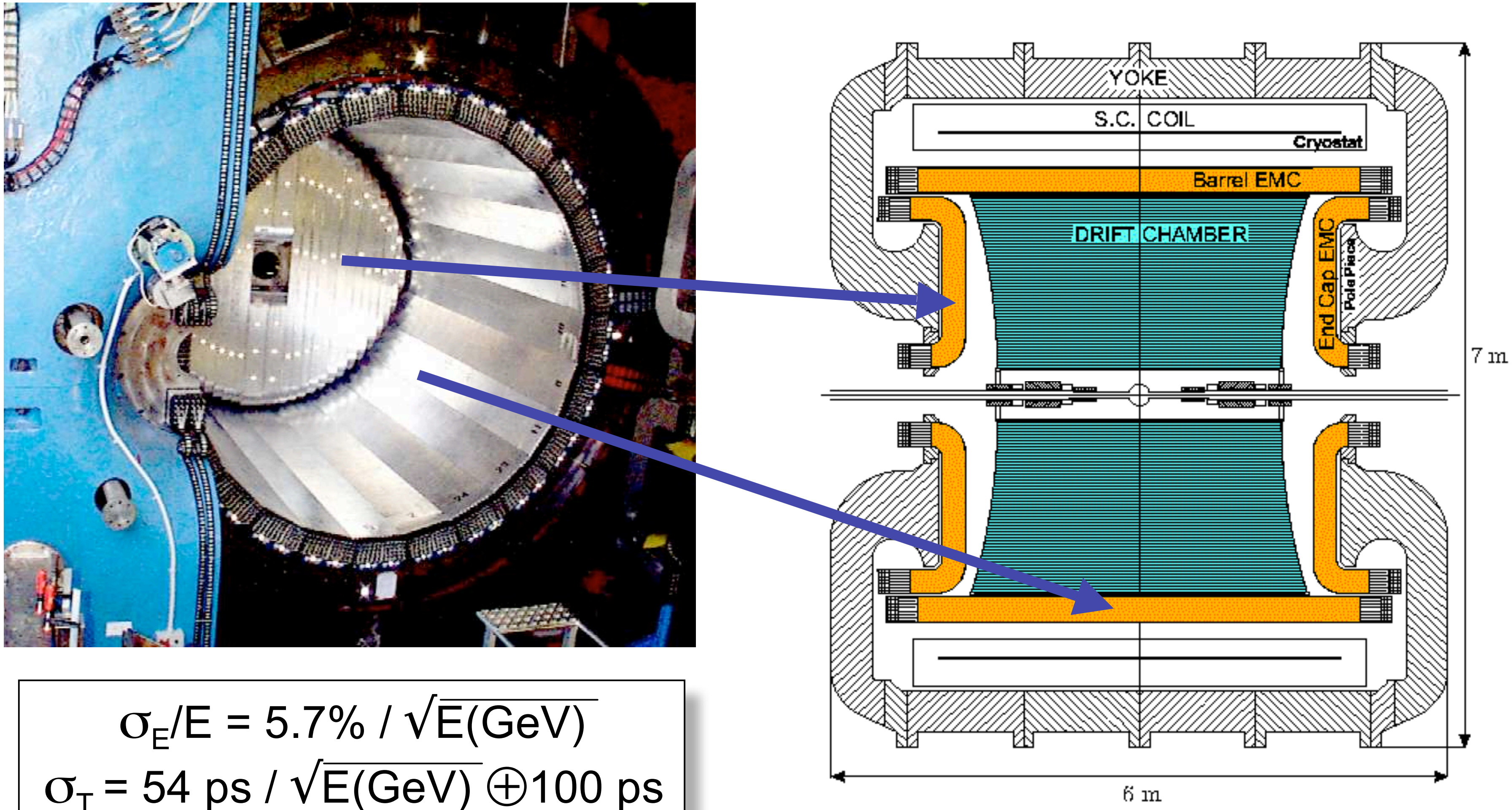
σ_p/p = 0.4% (for 90^0 tracks)

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

Excellent momentum resolution

KLOE Detector

Electromagnetic Calorimeter



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

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

(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)

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

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

2)

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

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

3)

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

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

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

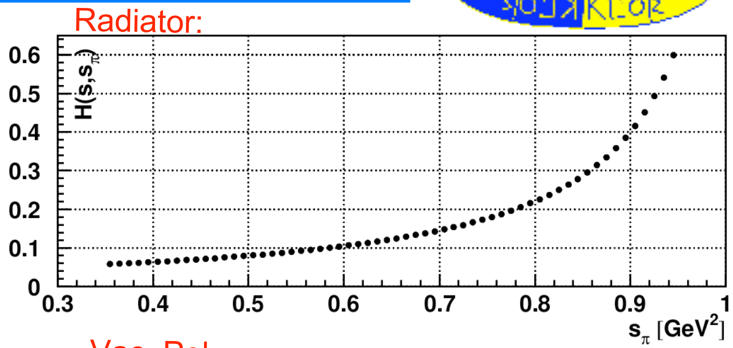
Radiative Corrections

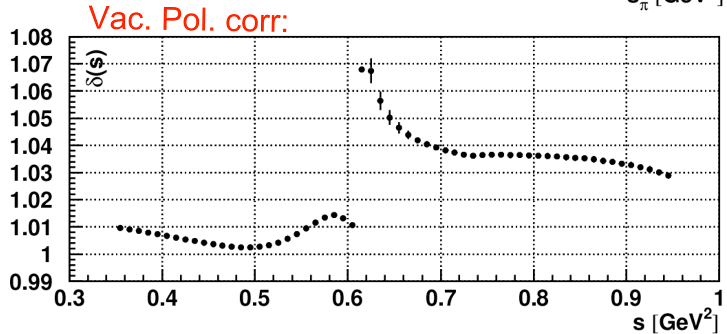
Radiator-Function $H(s,s_\pi)$ (ISR):

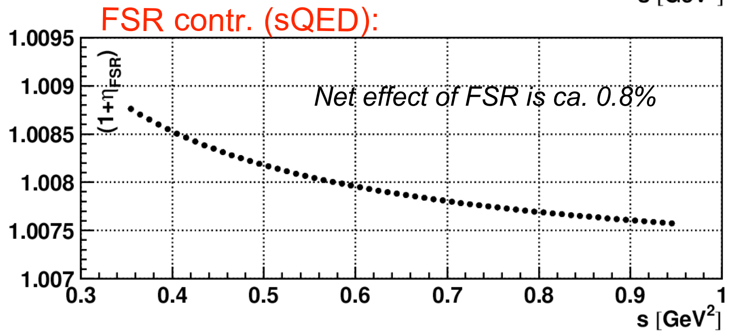
- **ISR-Process calculated at NLO-level**
  PHOKHARA generator
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

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 $\delta(s)=(\alpha(s)/\alpha(0))^2$

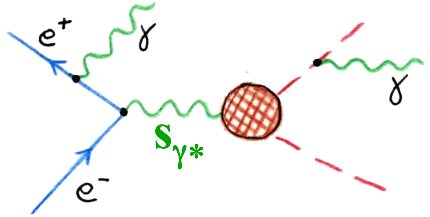
➔ from F. Jegerlehner

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)



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

Measurement of $\sigma(e^+e^-\rightarrow\pi^+\pi^-(\gamma))$ with photon emitted at Small Angle (“*SA Analysis*„)

Event Selection (KLOE08)

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

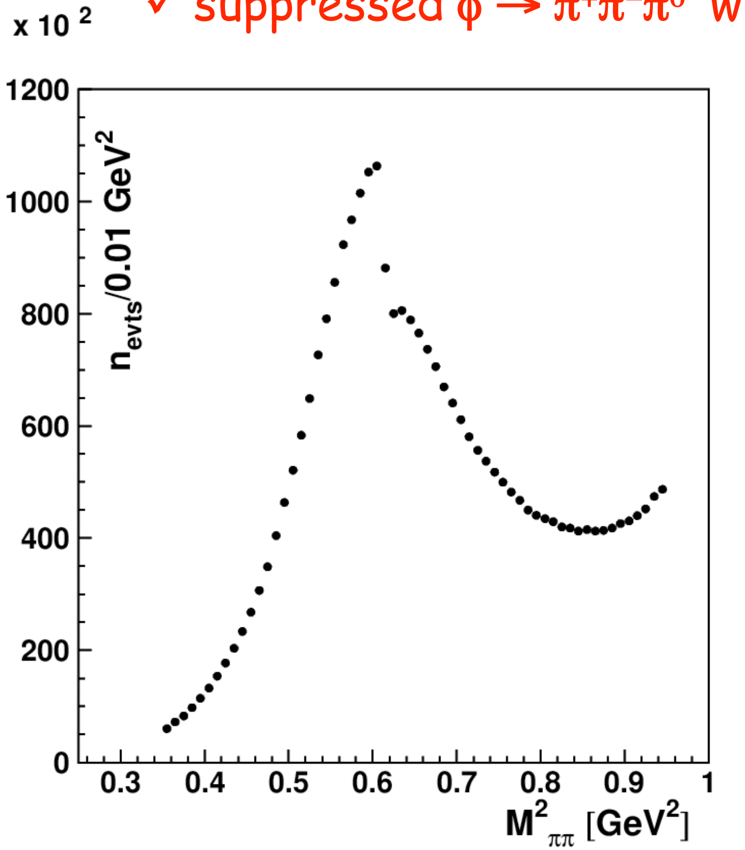
b) small angle (not detected) γ
($\theta_{\pi\pi} < 15^\circ$ or $> 165^\circ$)

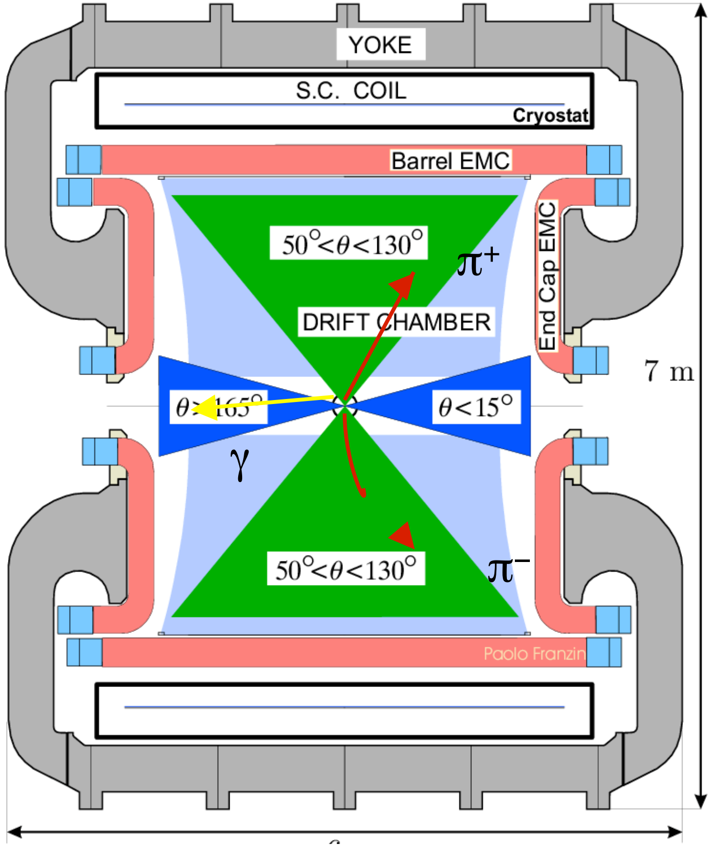
✓ high statistics for ISR

✓ low relative FSR contribution

✓ suppressed $\phi \to \pi^+\pi^-\pi^0$ wrt the signal

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





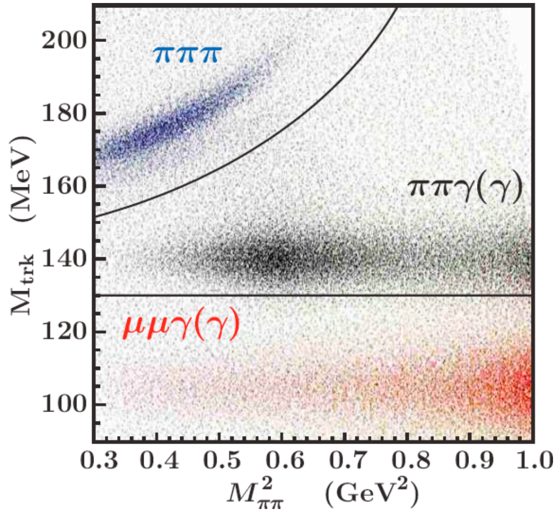
statistics: 240pb^{-1} of 2002 data

3.1 Mill. Events between 0.35 and 0.95 GeV^2

Event Selection

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

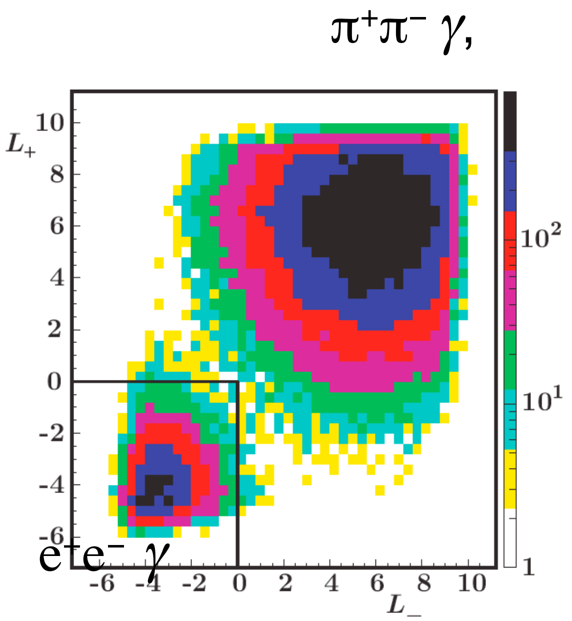
  removed using kinematical cuts in *trackmass* M_{Trk} - $M_{\pi\pi}^2$ plane



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

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

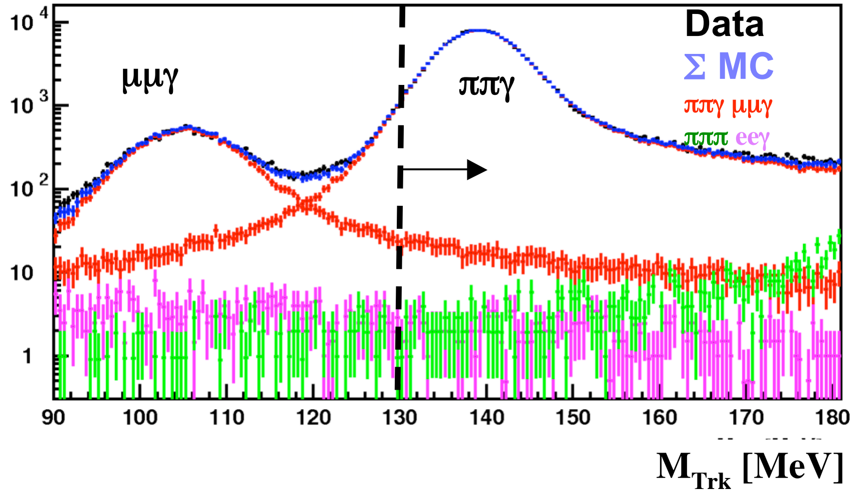
To further clean the samples from radiative Bhabha events, we use a particle ID estimator (PID) for each charged track based on Calorimeter Information and Time-of-Flight.



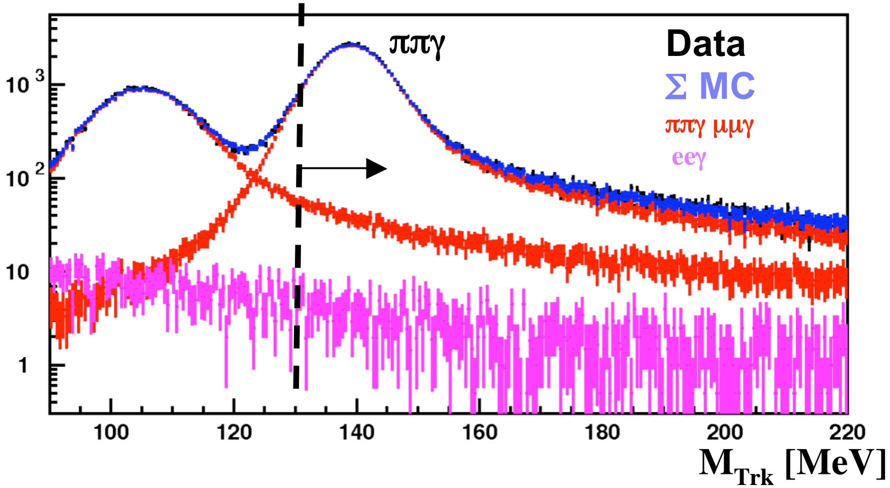
Background:

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

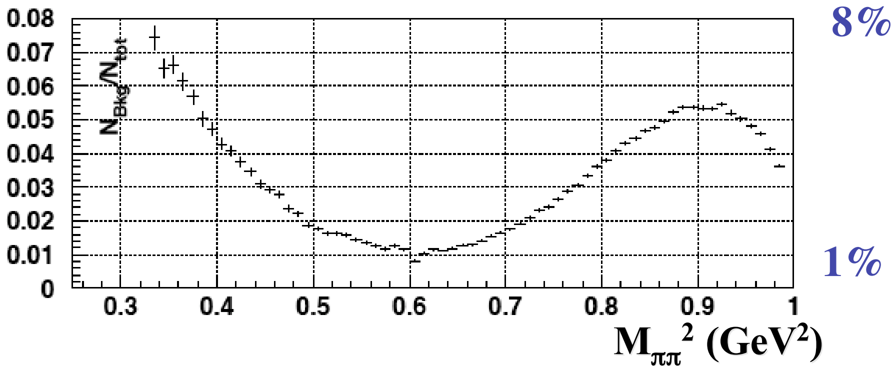
$0.60 < M_{\pi\pi}^2 < 0.62$ GeV^2, $\chi^2/ndof = 158/180$



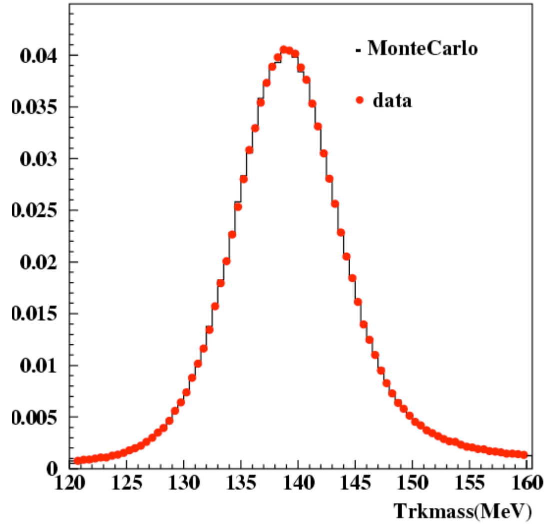
$0.84 < M_{\pi\pi}^2 < 0.86$ GeV^2 $\chi^2/ndof = 179/258$



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



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



Tracking efficiencies:

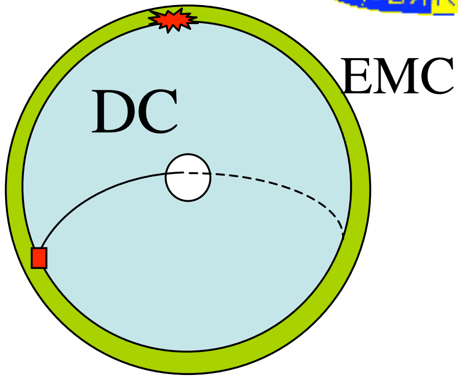
Two control samples

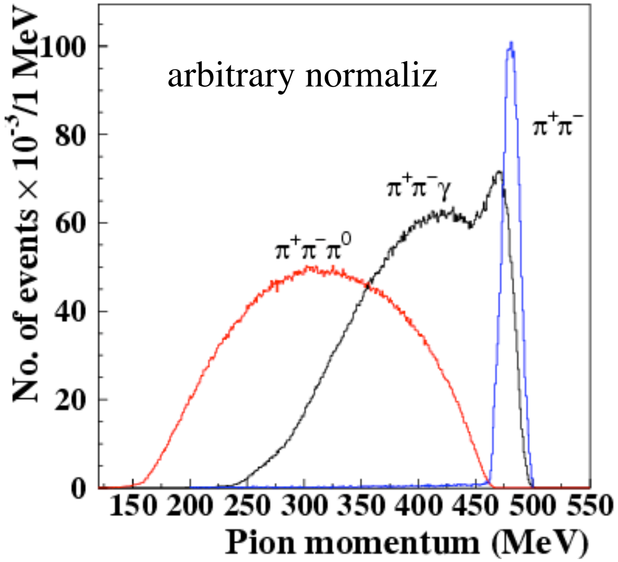
$\pi^+\pi^-\pi^0$

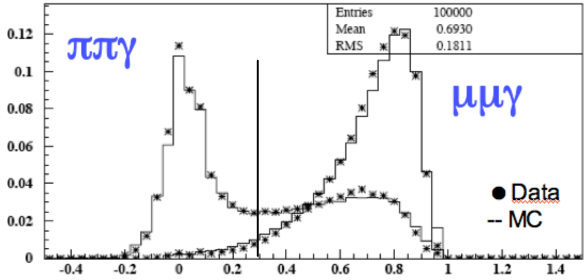
1) a tagging track recognized as a pion by PID, extrapolating back to the IP, which satisfies the trigger
2) 2 prompt clusters not associated to the tagging track with E>50 MeV and distant each other 60 cm
3) A constraint on the photon energy and time to further clean the sample, and improve missing momentum and energy

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

1) As for $\pi^+\pi^-\pi^0$ sample
2) 1 prompt clusters not associated to the tagging track with E>50 MeV
3) The tagging track must have p > 460 MeV (to reject $\pi^+\pi^-\pi^0$ events), the *candidate* track must have mass (built from 4 momentum conservation) M_{miss} > 120 MeV and NN < 0.3, to suppress $\mu^+\mu^-\gamma$ events





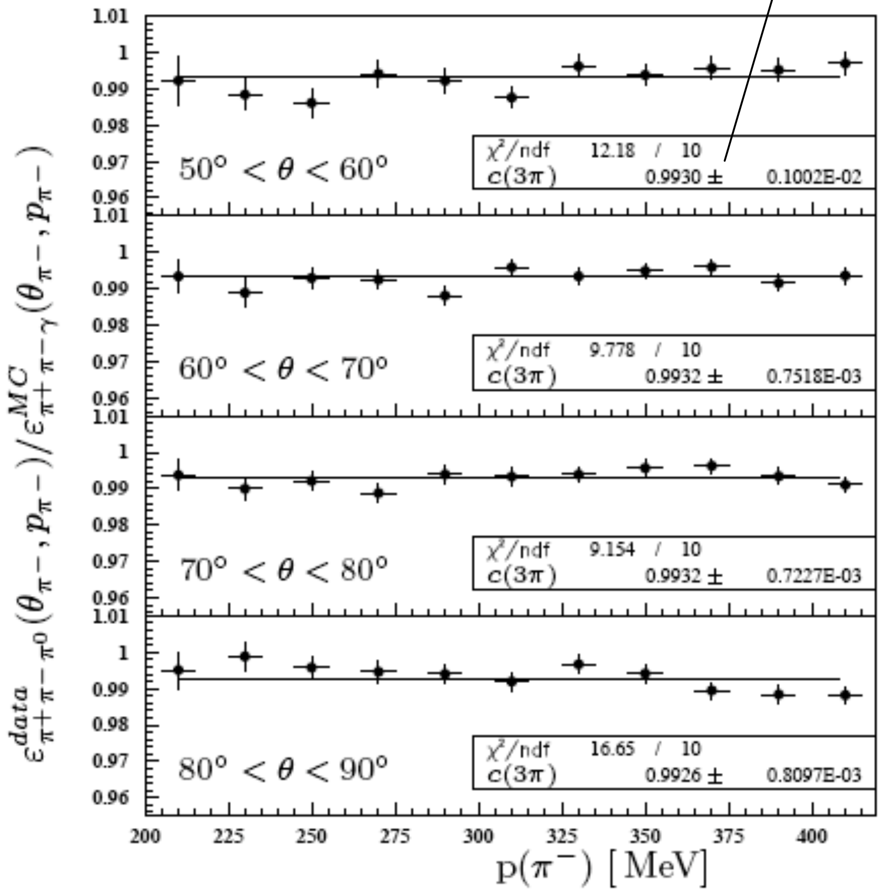


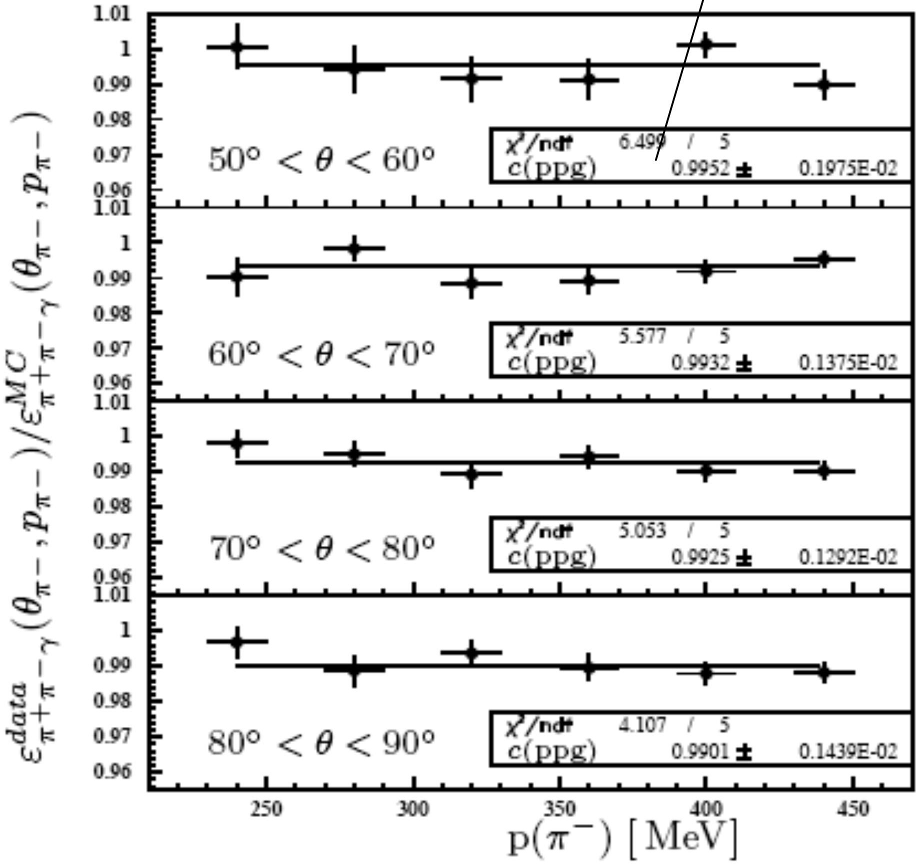
NN output

Data/MC corrections from $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$

$C_{3\pi} = 0.993 \pm 0.001$

$C_{\pi\pi\gamma} = 0.995 \pm 0.002$





When “weighted” for the $\pi\pi\gamma$ event distribution the two methods gives 0.3% fractional difference in $M^2_{\pi\pi}$ which is the systematic error

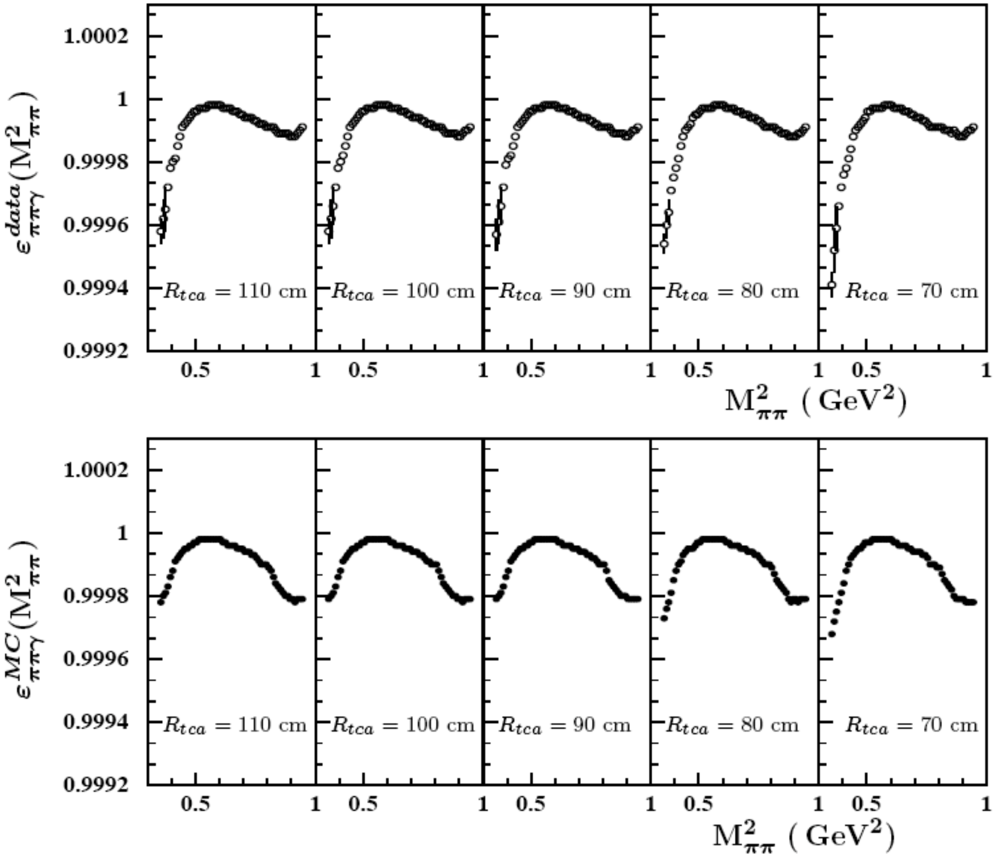
π/e PID and TCA efficiencies

$\pi^+\pi^-\gamma$ sample

1) Two tracks satisting ππγ “tracking” acceptance selection
2) a tagging track recognized as a pion by PID, extrapolating back to the IP, which satisfies the trigger
3) Look for a cluster with PID>0 associated to the *candidate* track in slices of θ,p

Efficiency ~1

data/MC correction =1 at R=90 cm



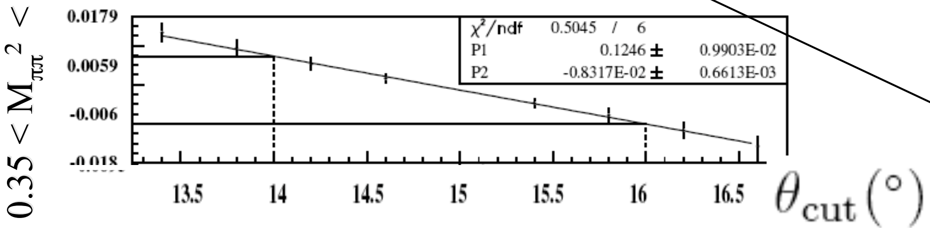
the systematic error is given varying the association radius, the effect on the correction data/MC is negligible

Acceptance

$\theta_{\pi\pi}$ is angle of the missing photon

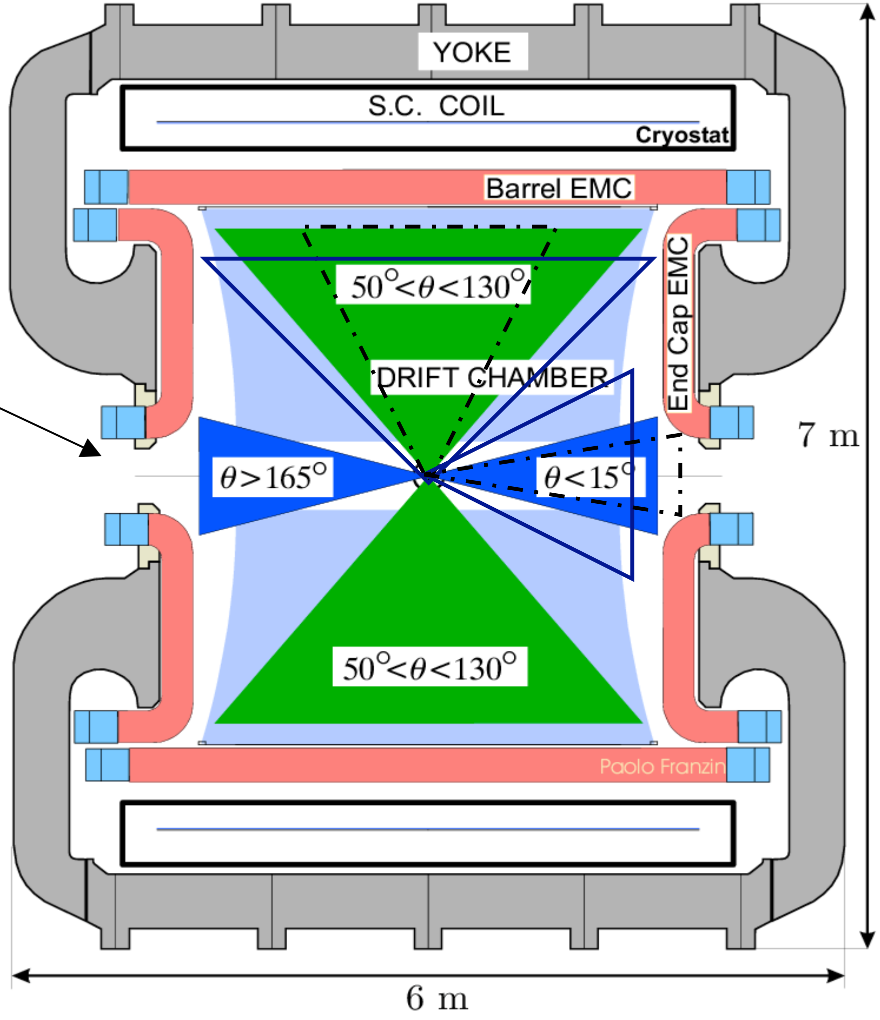
We study the impact of enlarging/reducing the fiducial volume on the geometrical acceptance in slices of $M^2_{\pi\pi}$

$$\frac{N_{\rm MC}(\theta_{\pi\pi} < \theta_{\rm cut})}{N_{\rm MC}(\theta_{\pi\pi} < 15^\circ)} - \frac{N_{\rm data}(\theta_{\pi\pi} < \theta_{\rm cut})}{N_{\rm data}(\theta_{\pi\pi} < 15^\circ)}$$



the spectrum variation is linear as a function of the cut, so the excursion at ± 1 degree is taken as systematic error

$M^2_{\pi\pi}$ range (GeV^2)	Systematic error (%)
$0.35 \le M^2_{\pi\pi} < 0.39$	0.6
$0.39 \le M^2_{\pi\pi} < 0.43$	0.5
$0.43 \le M^2_{\pi\pi} < 0.45$	0.4
$0.45 \le M^2_{\pi\pi} < 0.49$	0.3
$0.49 \le M^2_{\pi\pi} < 0.51$	0.2
$0.51 \le M^2_{\pi\pi} < 0.64$	0.1
$0.64 \le M^2_{\pi\pi} < 0.95$	-



Unfolding

Our bin width (0.01 GeV^2 is ~ 5 $\delta M_{\pi\pi}^2$)⇒Resolution Matrix almost diagonal!

- We use Bayesan approach

G. D'Agostini, Nucl. Instrum. Meth. A **362** (1995) 487

- method based on Bayes' theorem
  - no matrix inversion needed
  - can be applied to multidimensional problems
  - iterative algorithm; can start with a uniform distribution
- Bayes formula:

$$P(C_i|E_j)=\frac{P(E_j|C_i)\overbrace{P(C_i)}^{}}{\sum_{l=1}^{n_c}P(E_j|C_l)P(C_l)}$$

"true", normalized distribution

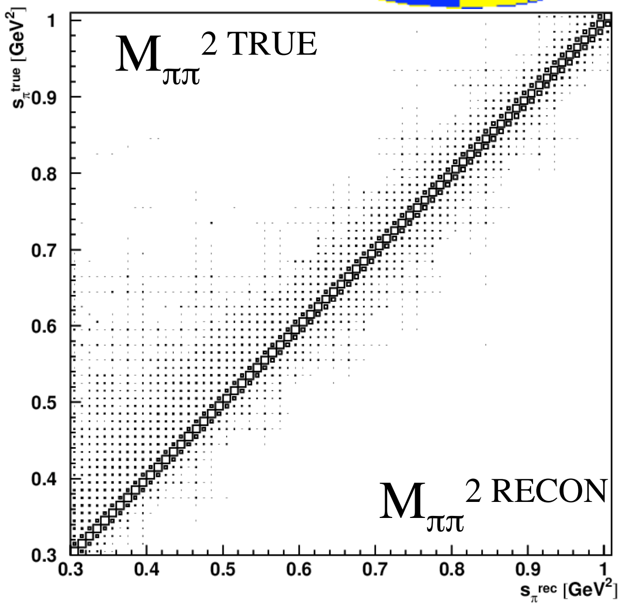
  - "if we observe a single event "(effect E_j)", the probability that it has been due to the i-th cause "(C_i)," is proportional to the probability of the cause times probability of the cause to produce the effect"

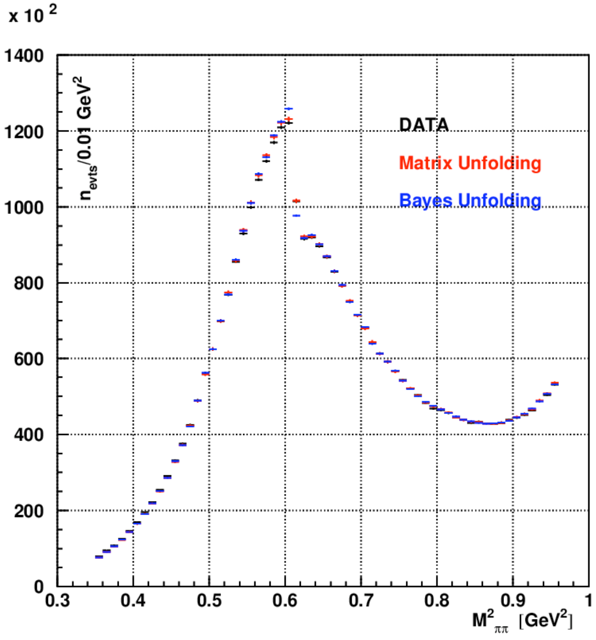
D'Agostini

- We compare the result with the simple matrix procedure.There is a difference only around ρ–ω region

$M^2_{\pi\pi}$ (GeV^2)	0.58	0.59	0.6	0.61	0.62
$\delta_{unf}(\%)$	0.4	0.3	2.1	4.0	0.4

- Very small effect for KLOE; systematic error negligible on a_μ !





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°

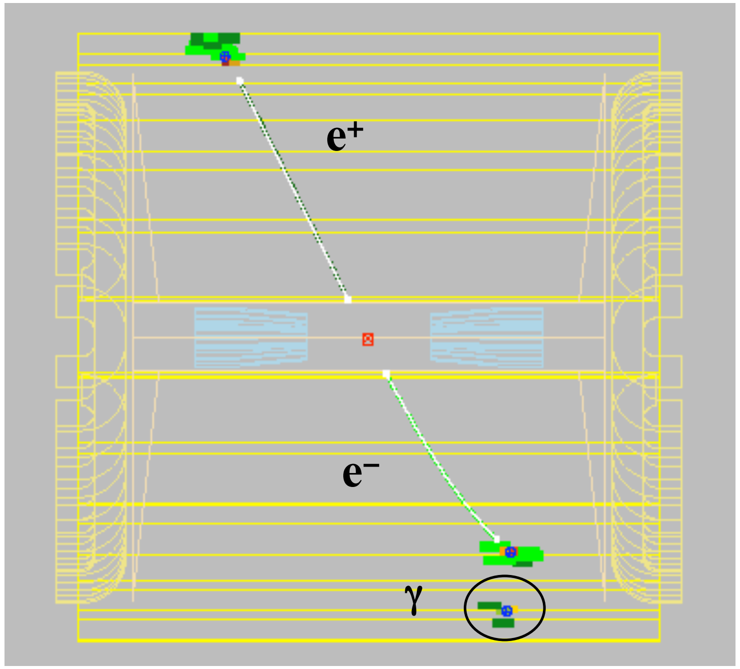
$p \geq 400$ MeV

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

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 $\oplus$ 0.3% exp = 0.3%	

Luminosity:

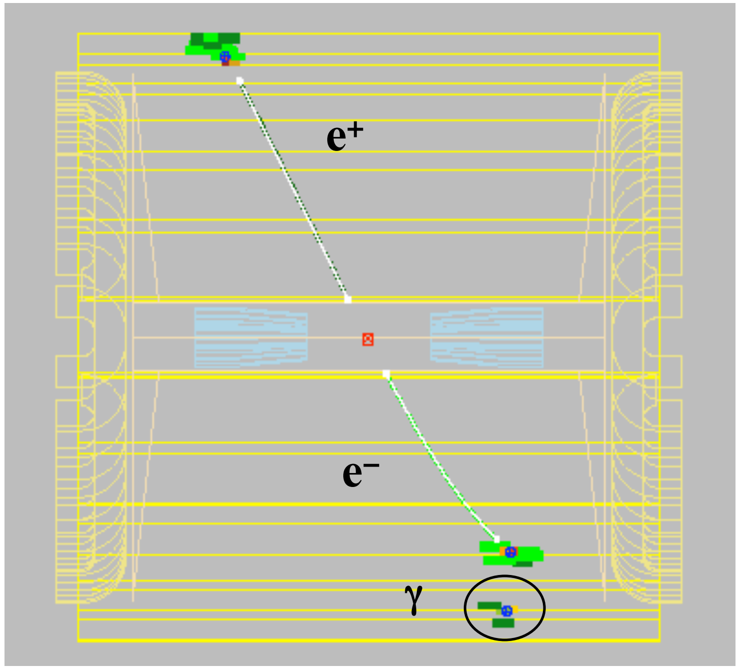
KLOE measures L with Bhabha scattering

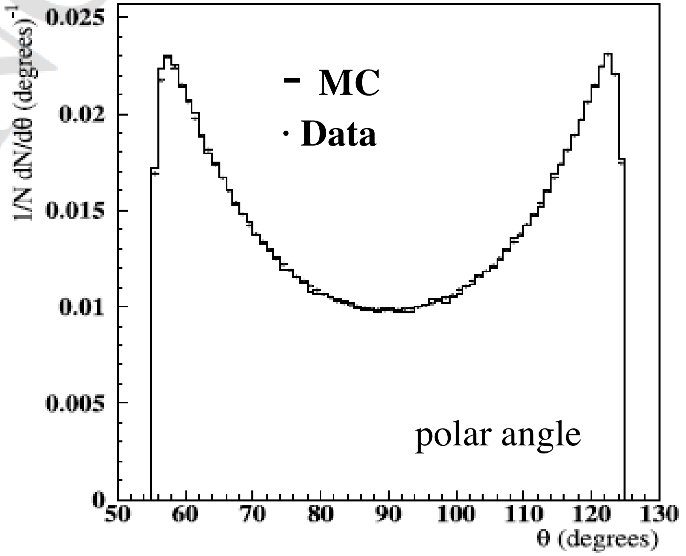
$55° < \theta < 125°$

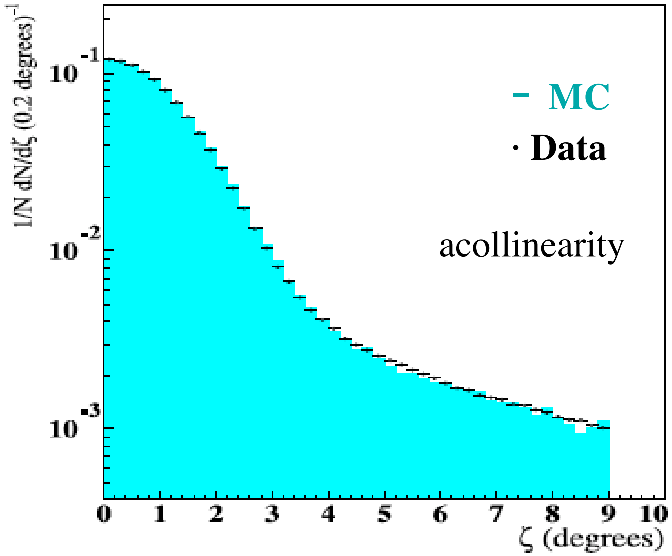
acollinearity < 9°

$p \geq 400$ MeV

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







KLOE result (KLOE08)

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

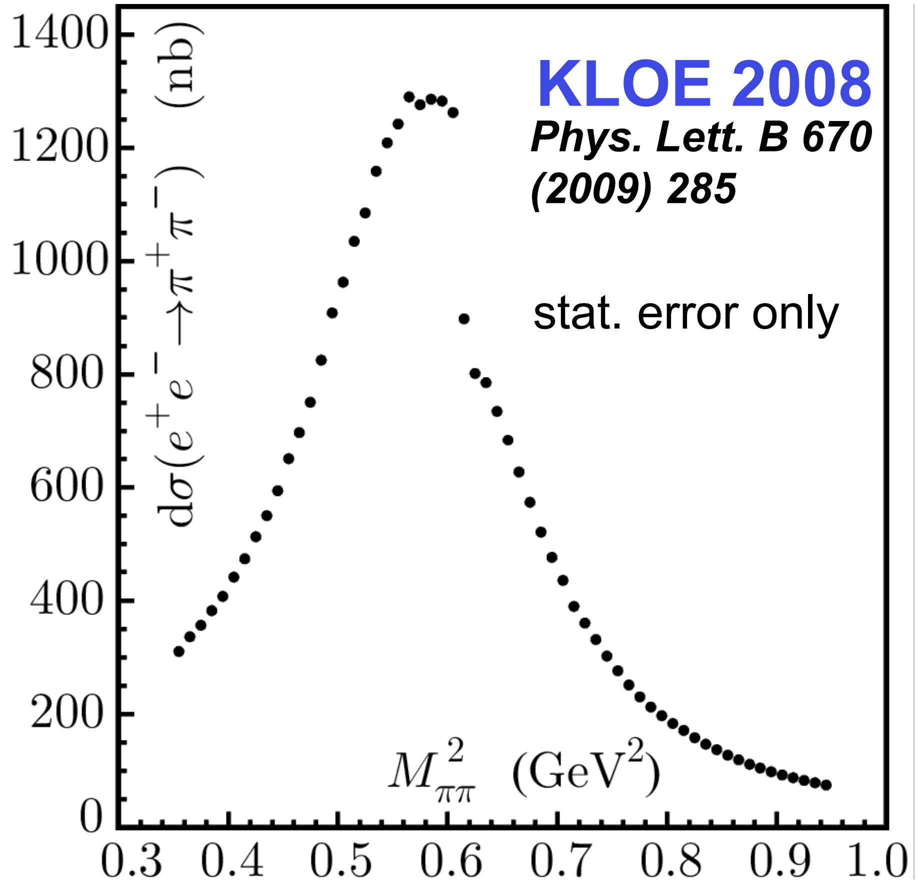
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
π/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
√ s dep. Of H	0.2%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

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



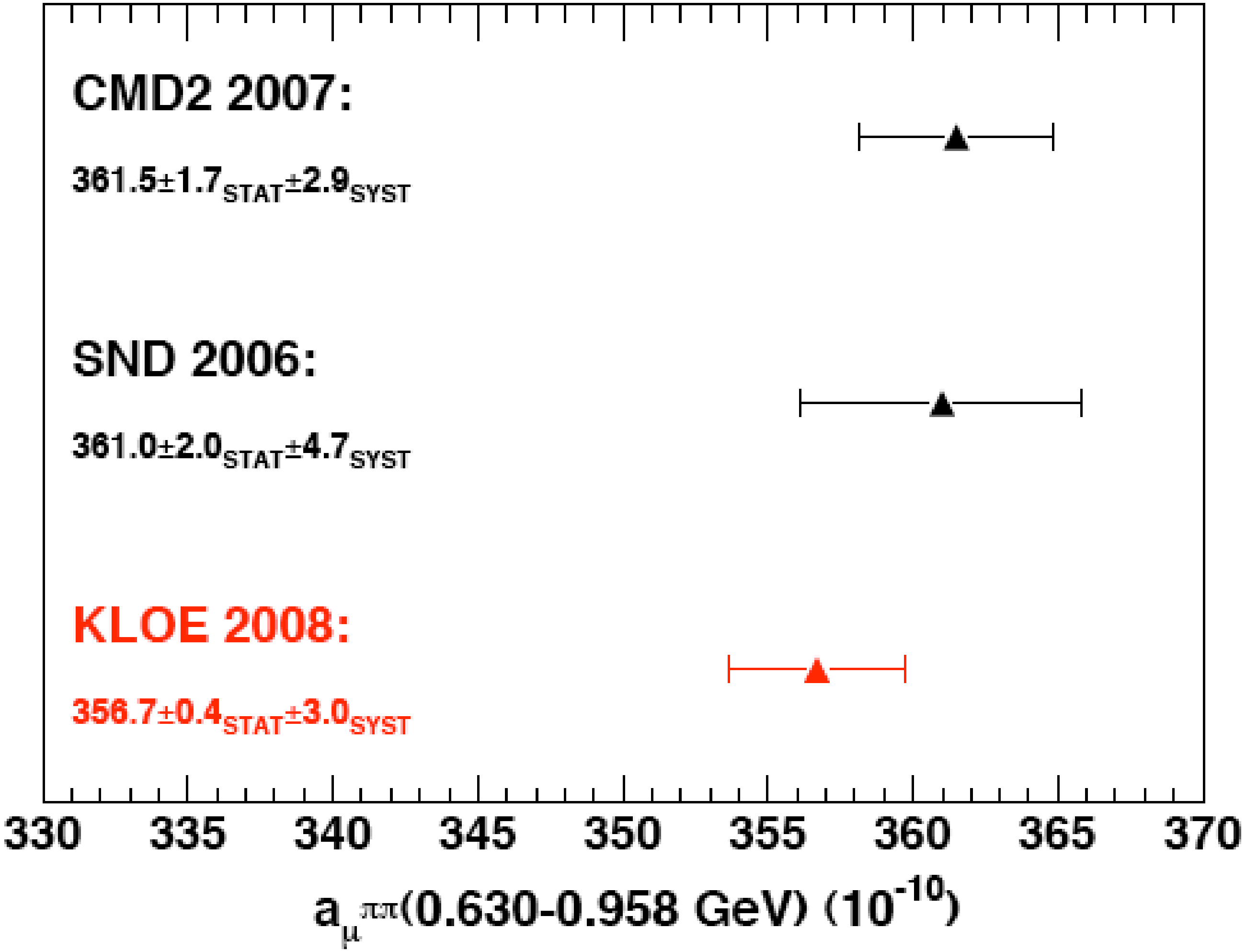
KLOE 2008

Phys. Lett. B 670 (2009) 285

● stat. error only

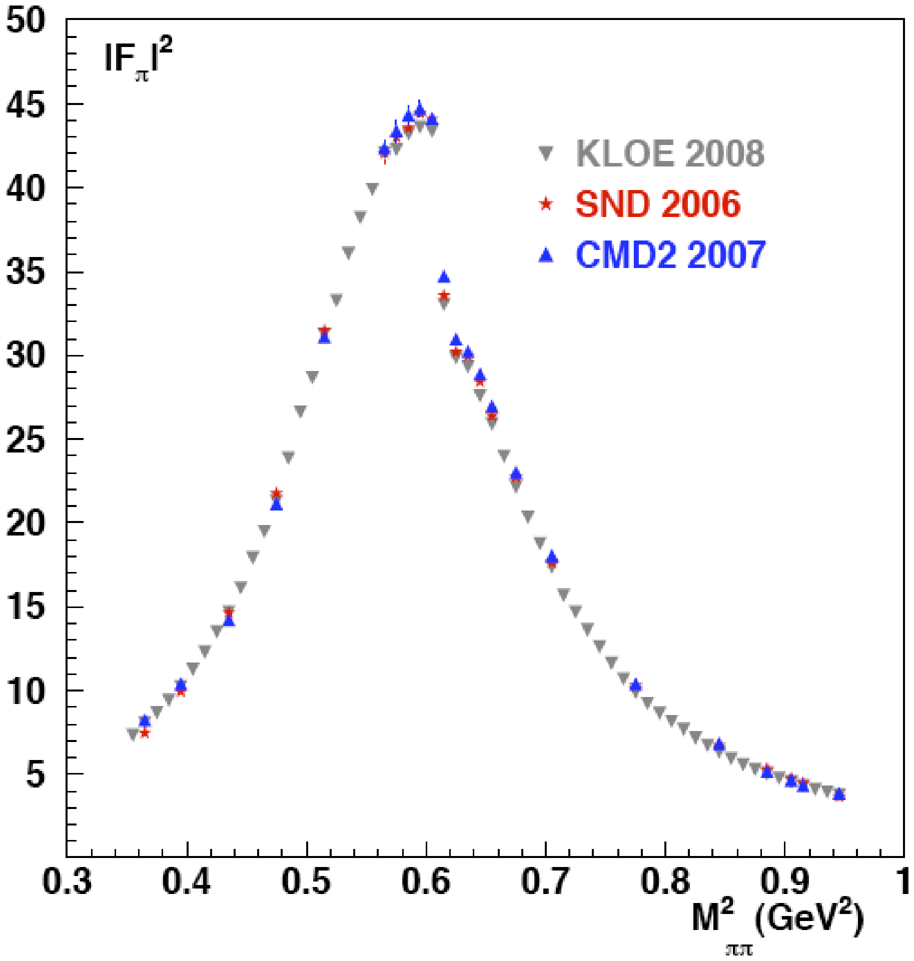
$a_\mu^{\pi\pi}(0.35\text{-}0.95\mathrm{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{sys} \pm 2.3_{theo}) \cdot 10^{-10}$

$a_\mu^{\pi\pi}$: KLOE vs CMD-2/SND

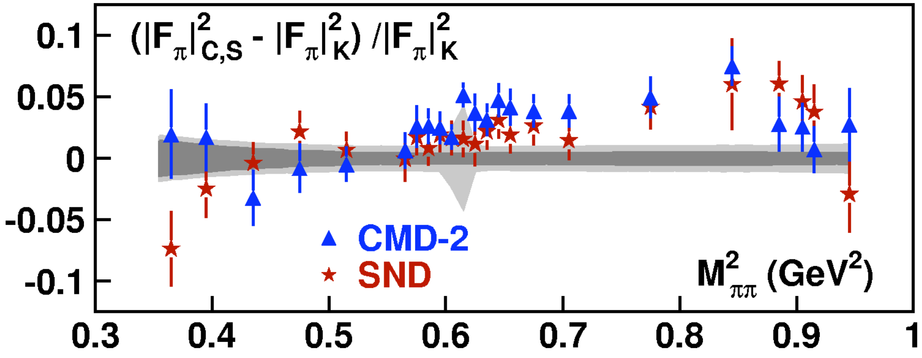


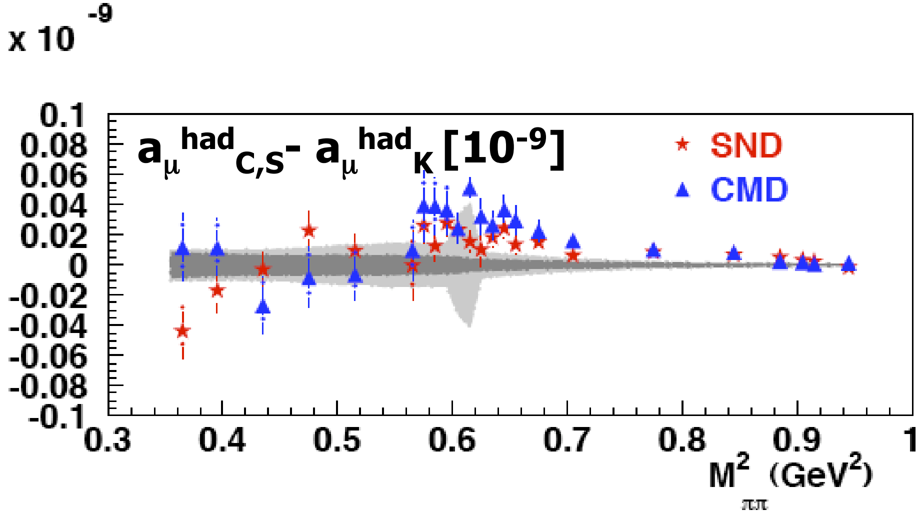
KLOE result in agreement with CMD2 and SND

Comparison with CMD2/SND



only statistical errors are shown



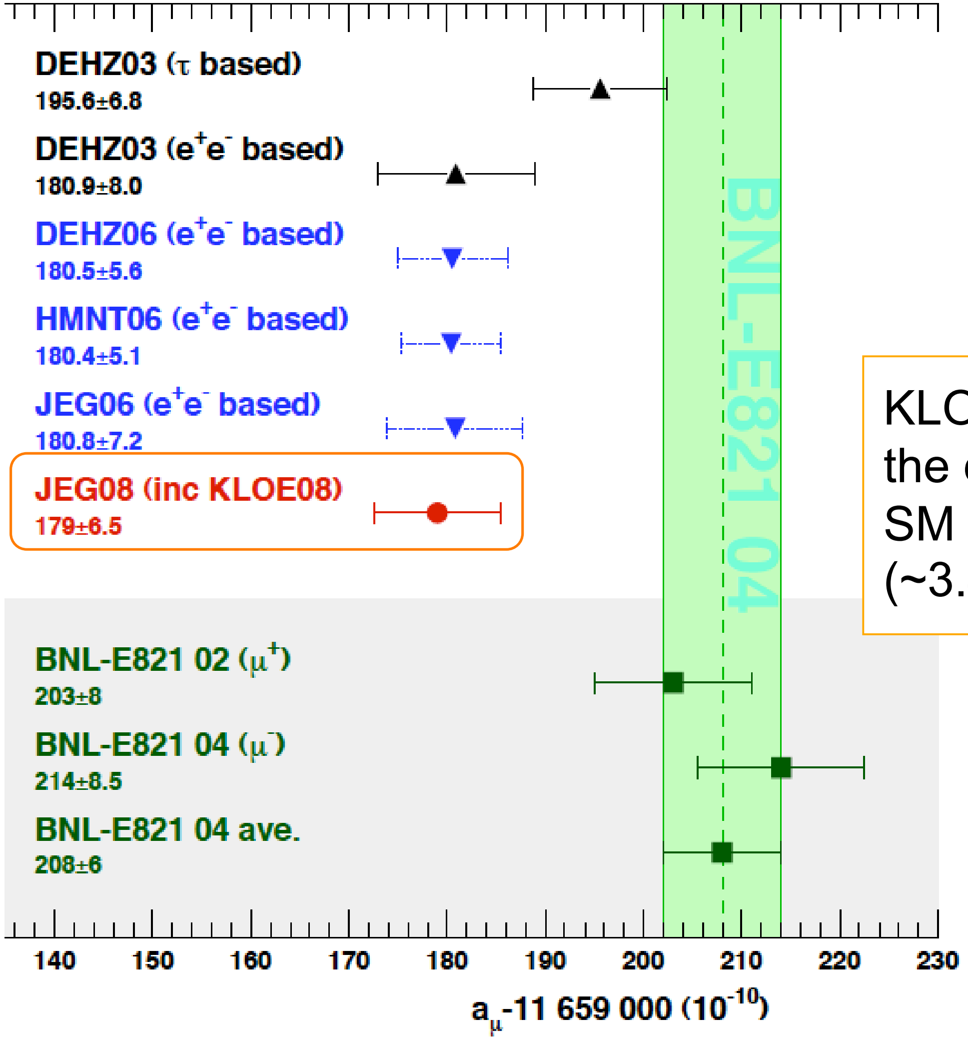


band: KLOE error
data points: CMD2/SND experiments

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

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

Theoretical predictions compared to the BNL result (in 2008):



KLOE08 confirms
the discrepancy between
SM and BNL experiment
(~3.4σ)

Measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-(\gamma))$ with photon emitted at Large Angle (“*LA Analysis*„)

New measurement based on 2006 data taken at $\sqrt{s}$=1.0 GeV, 20 MeV below the ϕ-peak (different selection!)

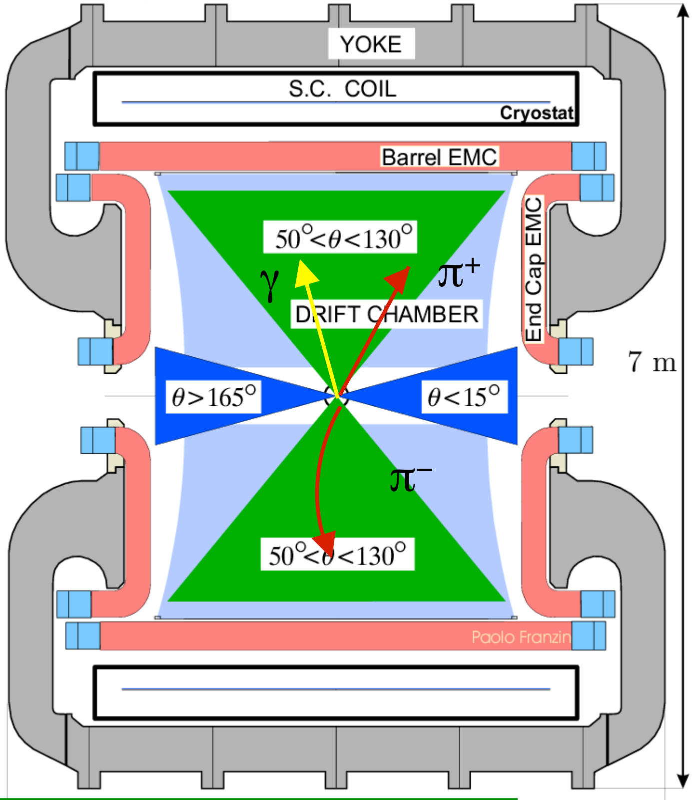
Results presented at PHIPSI09 Conference (Beijing, Oct 2009);
paper in preparation

Event Selection

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

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

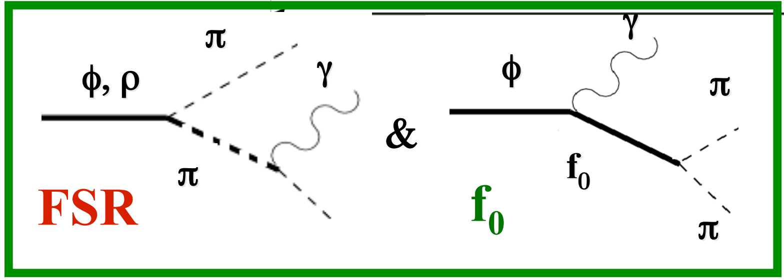
At least 1 photon with $50^o < \theta_\gamma < 130^o$ and $E_\gamma > 20$ MeV ➔ photon detected



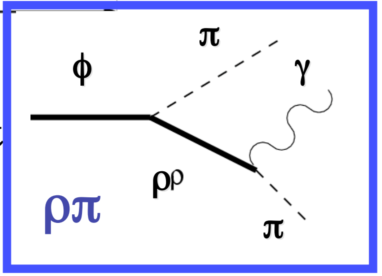
- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **γ_{ISR} photon detected (4-momentum constraints)**

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

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



&



Event Selection

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

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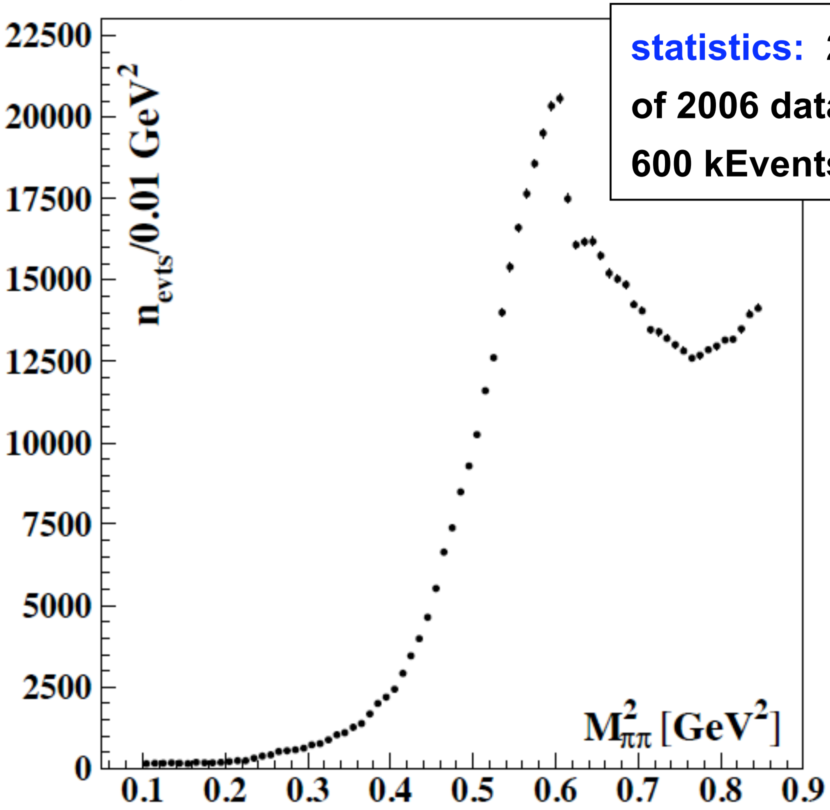
- ✓ **larger $\phi \to \pi^+\pi^-\pi^0$ background contamination**
- ✓ **irreducible background from ϕ decays ($\phi \to f_0\,\gamma \to \pi\pi\,\gamma$)**

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



statistics: **$233 pb^{-1}$**
of 2006 data
600 kEvents

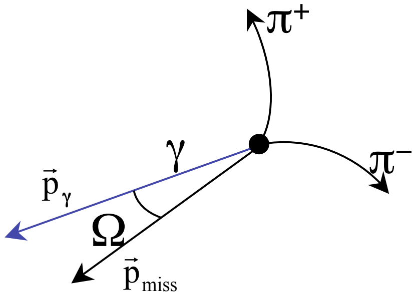
Use data sample taken at **$\sqrt{s} \cong 1000$ MeV**,
20 MeV below the ϕ–peak

Event selection

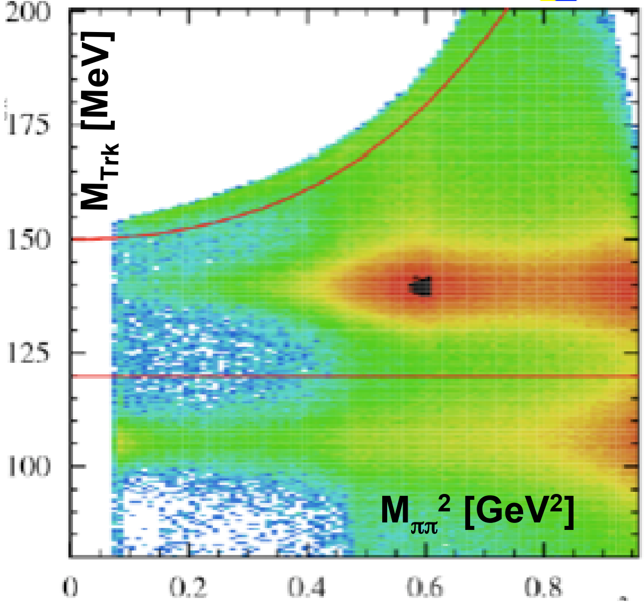
- **Experimental challenge: Fight background from**
  - $e^+e^- \rightarrow \mu^+\mu^- \gamma$,
  - $e^+e^- \rightarrow e^+e^- \gamma$
  - $\phi \rightarrow \pi^+\pi^-\pi^0$

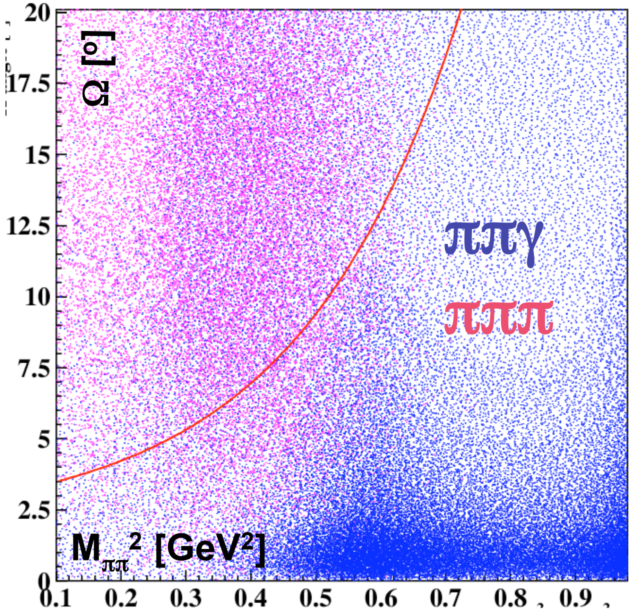
  separated by means of kinematical cuts in *trackmass M_{Trk}* and the angle Ω between the photon and the missing momentum

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



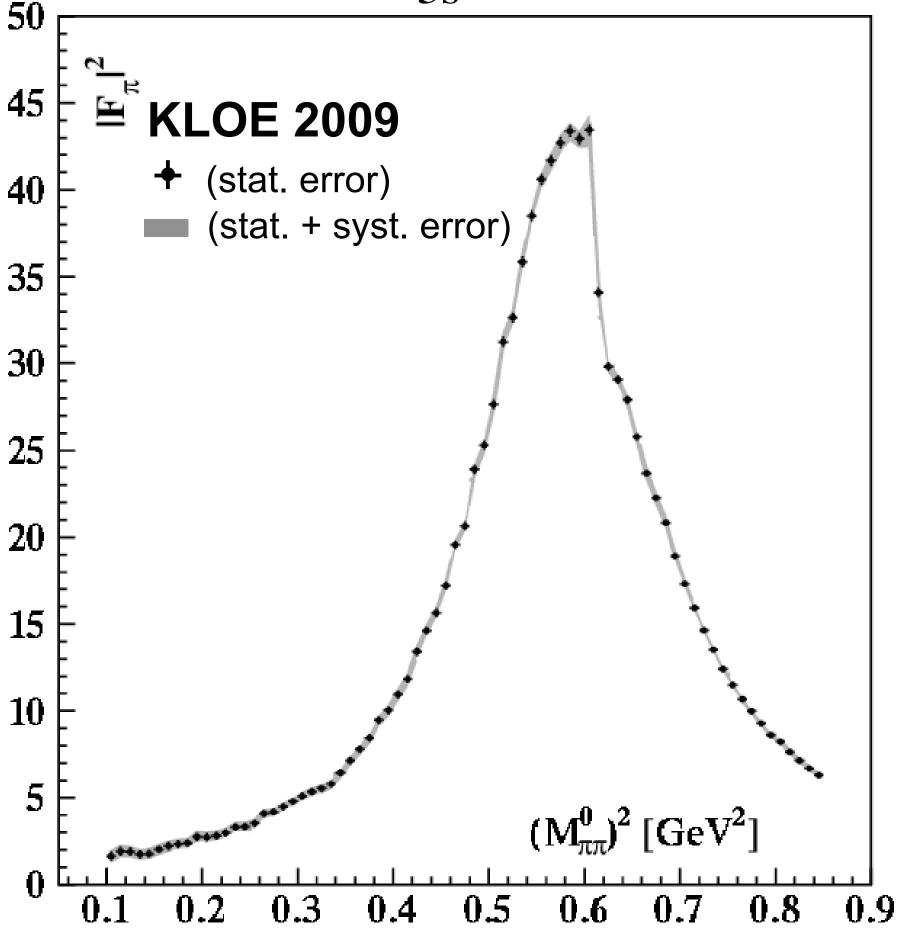
To further clean the samples from radiative Bhabha events, a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight is used.





New KLOE result (KLOE09)

$$\sigma_{\pi\pi}(s_\pi) = \frac{\pi\alpha^2\beta_\pi^3}{3s}\left|F_\pi(s_\pi)\right|^2$$



Disp. Integral:

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2}\sigma^{\text{had}}(s)\,\mathrm{K}(s)\,\mathrm{d}s$$

Table of systematic errors on $\Delta a_\mu^{\pi\pi}$(0.1-0.85 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 Δa_μ = 1.0 %

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

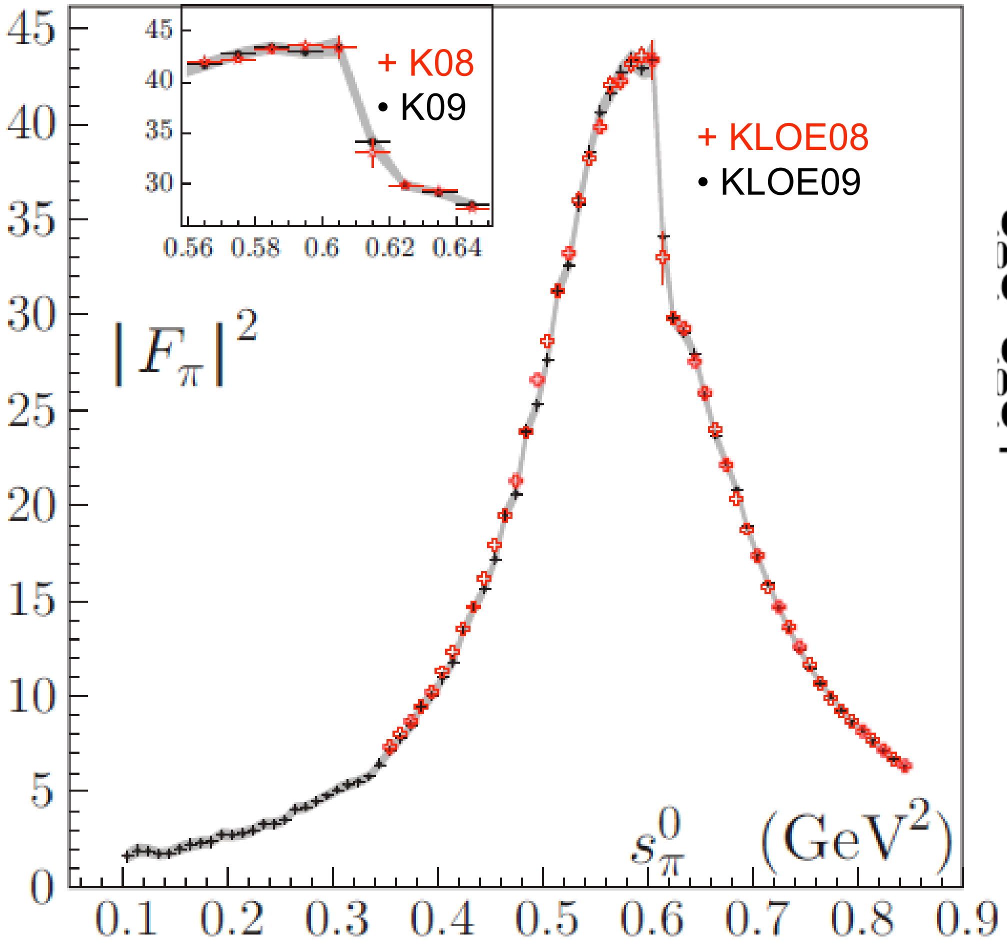
theoretical fractional error on Δa_μ = 0.6 %

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

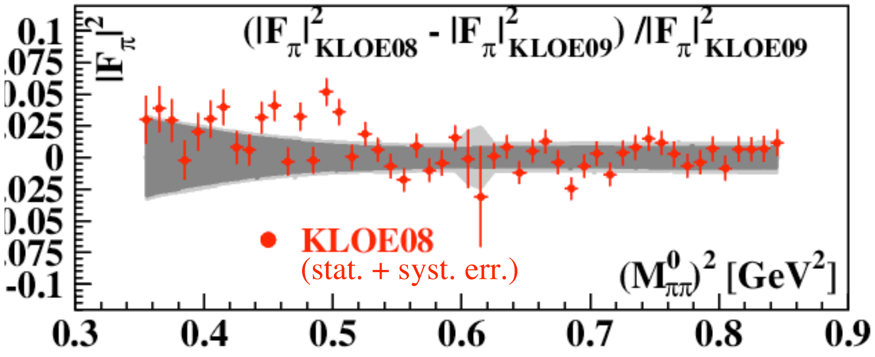
0.4% 1.0% 0.6%

Comparison of results: KLOE09 vs KLOE08

KLOE08 result compared to KLOE09:



Fractional difference:



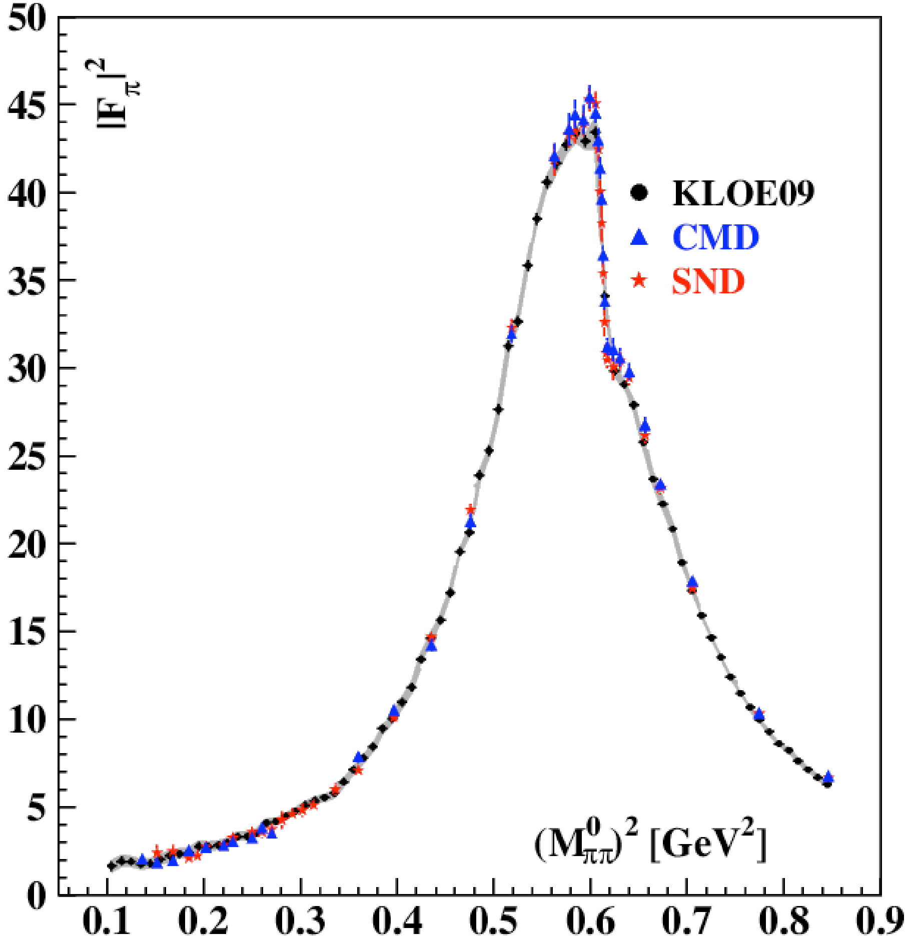
band: KLOE09 error

Excellent agreement with KLOE08, expecially above 0.5 GeV^2

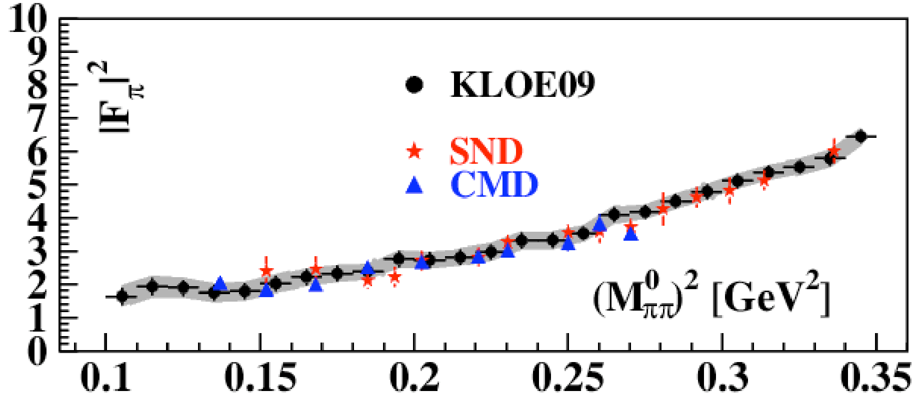
Combination of the two measurements in progress

Comparison of results: KLOE09 vs CMD-2/SND

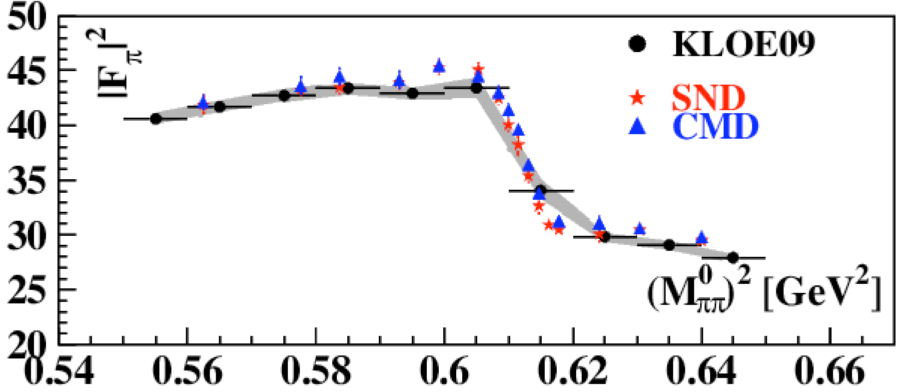
CMD and SND results compared to KLOE09:



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



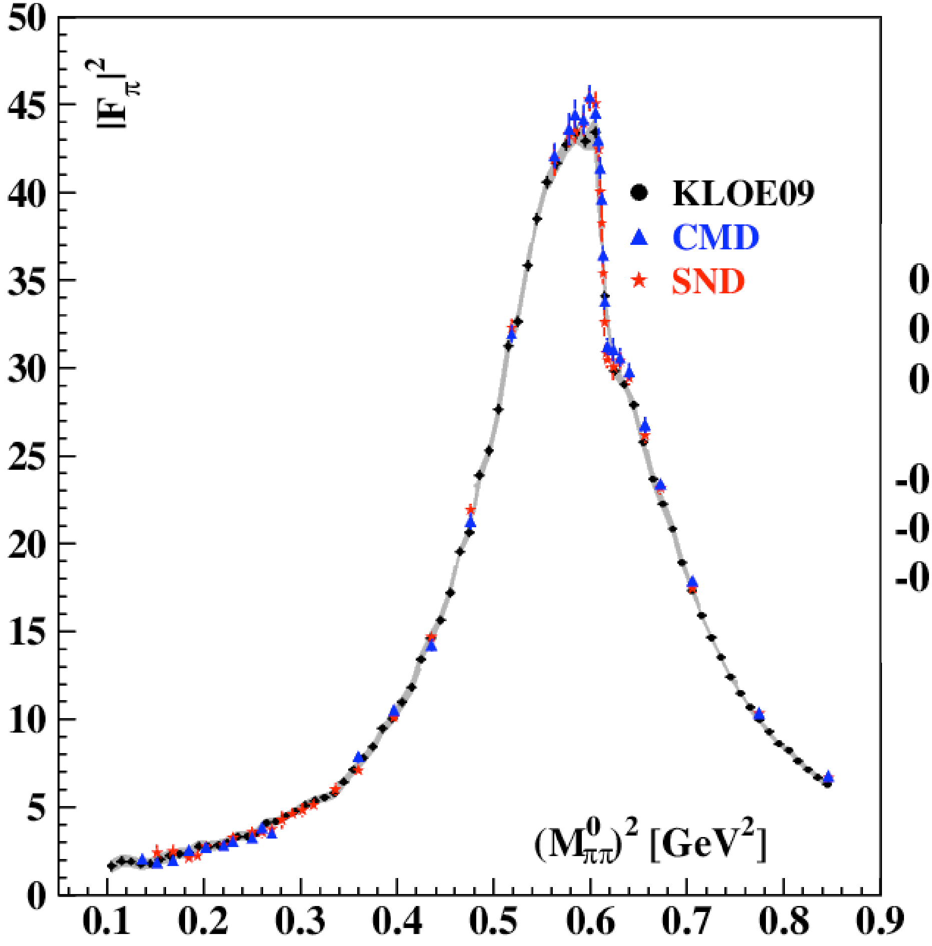
Region around ρ-peak:

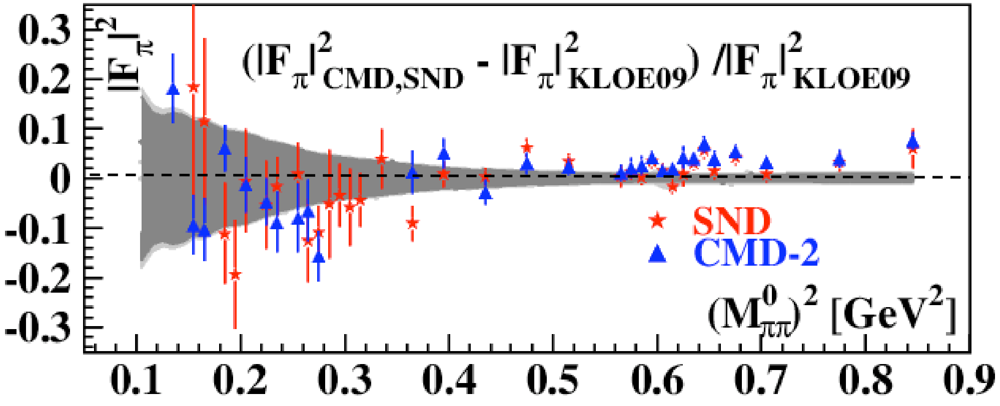


band: KLOE09 error

Comparison of results: KLOE09 vs CMD-2/SND

CMD and SND results compared to KLOE09: Fractional difference



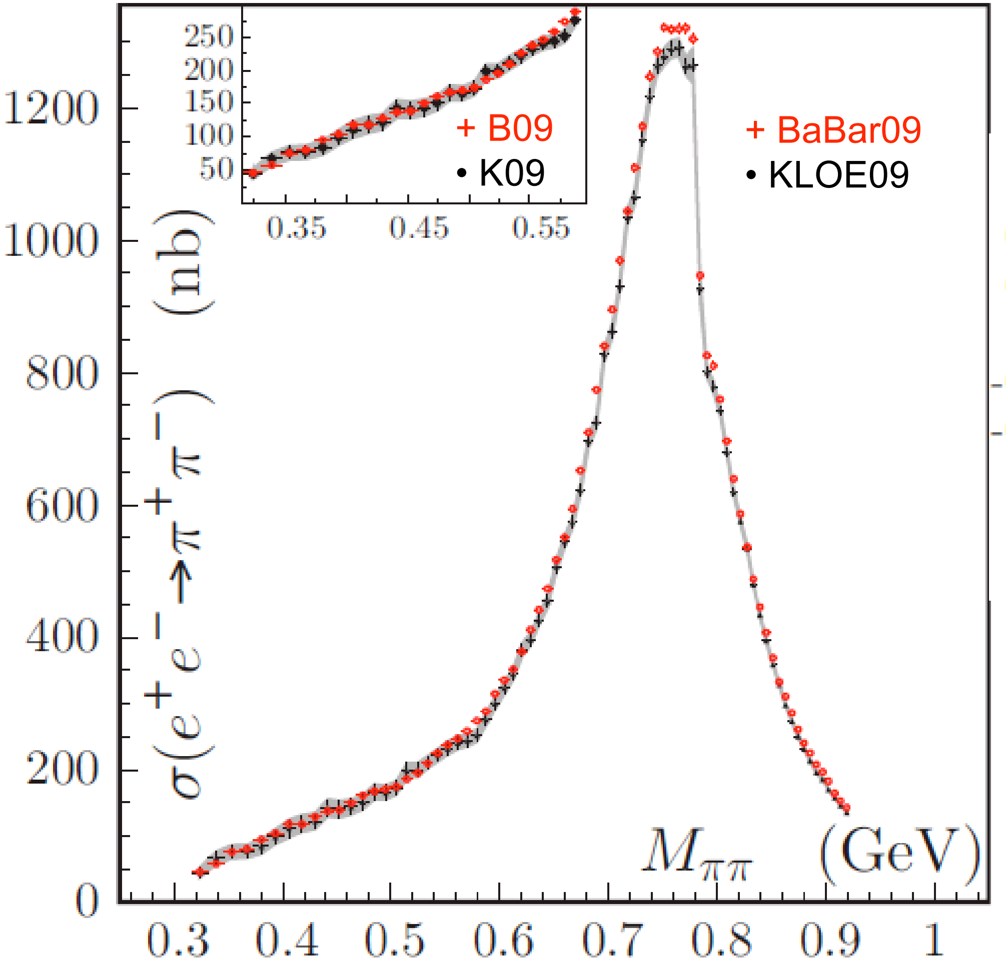


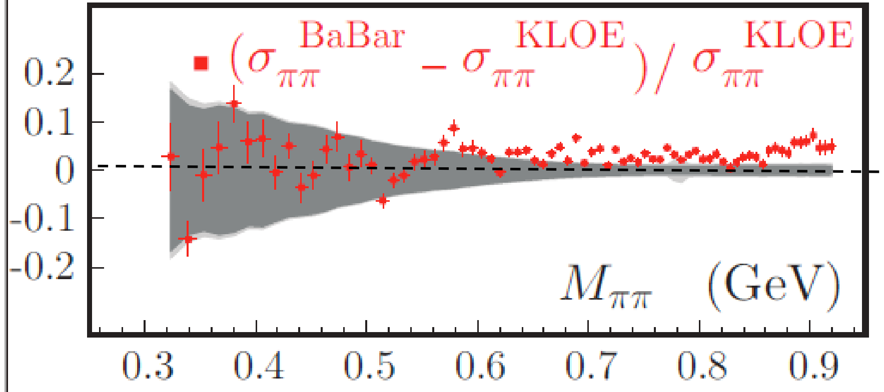
band: KLOE09 error

Below the ρ peak good agreement with CMD-2/SND.
Above the ρ peak KLOE09 slightly lower (as KLOE08)

Comparison of results: KLOE09 vs BaBar

BaBar results compared to KLOE09: Fractional difference





band: KLOE09 error

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

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$\Delta a_\mu^{\pi\pi}(0.35\text{-}0.85\,\mathrm{GeV}^2)$:

$$a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{\mathrm{had}}(s)\,\mathrm{K}(s)\,\mathrm{d}s$$

KLOE08 (small angle)	$\boxed{a_\mu^{\pi\pi} = (379.6 \pm 0.4_{\mathrm{stat}} \pm 2.4_{\mathrm{sys}} \pm 2.2_{\mathrm{theo}}) \cdot 10^{-10}}$
KLOE09 (large angle)	$\boxed{a_\mu^{\pi\pi} = (376.6 \pm 0.9_{\mathrm{stat}} \pm 2.4_{\mathrm{sys}} \pm 2.1_{\mathrm{theo}}) \cdot 10^{-10}}$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$\Delta a_\mu^{\pi\pi}$(0.35-0.85GeV²):

$$a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{\mathrm{had}}(s)\,\mathrm{K}(s)\,\mathrm{d}s$$

KLOE08 (small angle)

$$a_\mu^{\pi\pi} = (379.6 \pm 0.4_{stat} \pm 2.4_{sys} \pm 2.2_{theo}) \cdot 10^{-10}$$

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (376.6 \pm 0.9_{stat} \pm 2.4_{sys} \pm 2.1_{theo}) \cdot 10^{-10}$$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}$(0.152-0.270 GeV²):

KLOE09 (large angle)

$$a_\mu^{\pi\pi} = (48.1 \pm 1.2_{stat} \pm 1.2_{sys} \pm 0.4_{theo}) \cdot 10^{-10}$$

CMD-2

$$a_\mu^{\pi\pi} = (46.2 \pm 1.0_{stat} \pm 0.3_{sys}) \cdot 10^{-10}$$

$\Delta a_\mu^{\pi\pi}$ for different exp.:

$\Delta a_\mu^{\pi\pi}(0.35\text{-}0.85\,\mathrm{GeV}^2)$:

$$a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{x_1}^{x_2} \sigma^{\mathrm{had}}(s)\,\mathrm{K}(s)\,\mathrm{d}s$$

KLOE08 (small angle) $a_\mu^{\pi\pi} = (379.6 \pm 0.4_{\mathrm{stat}} \pm 2.4_{\mathrm{sys}} \pm 2.2_{\mathrm{theo}}) \cdot 10^{-10}$

KLOE09 (large angle) $a_\mu^{\pi\pi} = (376.6 \pm 0.9_{\mathrm{stat}} \pm 2.4_{\mathrm{sys}} \pm 2.1_{\mathrm{theo}}) \cdot 10^{-10}$

0.2% 0.6% 0.6%

$\Delta a_\mu^{\pi\pi}(0.152\text{-}0.270\,\mathrm{GeV}^2)$:

KLOE09 (large angle) $a_\mu^{\pi\pi} = (48.1 \pm 1.2_{\mathrm{stat}} \pm 1.2_{\mathrm{sys}} \pm 0.4_{\mathrm{theo}}) \cdot 10^{-10}$

CMD-2 $a_\mu^{\pi\pi} = (46.2 \pm 1.0_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}}) \cdot 10^{-10}$

$\Delta a_\mu^{\pi\pi}(0.397\text{-}0.918\,\mathrm{GeV}^2)$:

KLOE08 (small angle) $a_\mu^{\pi\pi} = (356.7 \pm 0.4_{\mathrm{stat}} \pm 3.1_{\mathrm{sys}}) \cdot 10^{-10}$

CMD-2 $a_\mu^{\pi\pi} = (361.5 \pm 1.7_{\mathrm{stat}} \pm 2.9_{\mathrm{sys}}) \cdot 10^{-10}$

SND $a_\mu^{\pi\pi} = (361.0 \pm 2.0_{\mathrm{stat}} \pm 4.7_{\mathrm{sys}}) \cdot 10^{-10}$

BaBar $a_\mu^{\pi\pi} = (365.2 \pm 1.9_{\mathrm{stat}} \pm 1.9_{\mathrm{sys}}) \cdot 10^{-10}$

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

Theoretical predictions compared to the BNL result (2009)

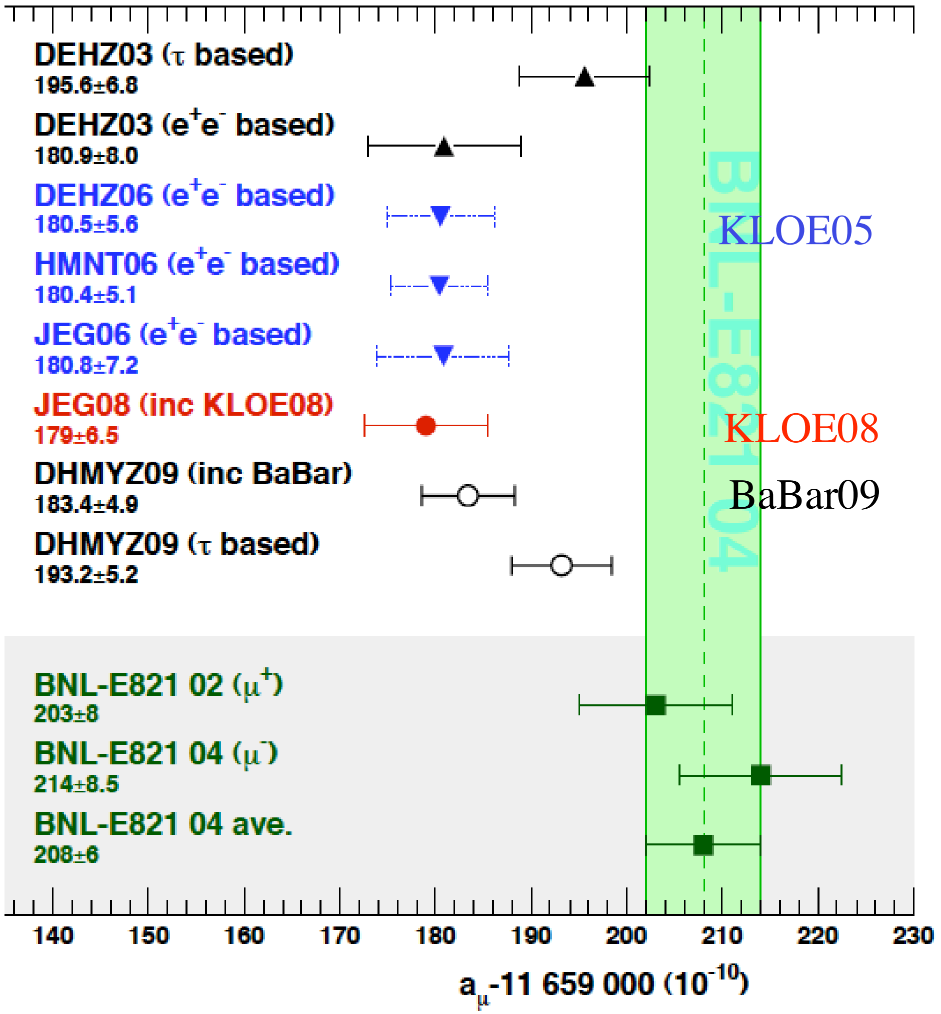
- **The latest inclusion of all e^+e^- data (DHMYZ09) gives a discrepancy btw a_μ^{SM} and a_μ^{EXP} of 3.2σ**

- **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 I. corr.,ee,τ data) [a_μ^{ee} - $\Delta a_\mu^{\tau}=1.4\sigma$]**

KLOE09 is not yet in.



ISR: KLOE vs BaBar 2π

KLOE:

- The photon is “soft” (detected or not)
- No Kinematic fit
- Bin of 0.01 GeV^2 (~8 MeV at ρ peak) >> $\delta M_{\pi\pi}^2 \sim 2\ 10^{-3}$ GeV^2

⇒ Unfolding only relevant at low $M_{\pi\pi}^2$ (up to 4%) and at ρ–ω cusp,

- Negligible contribution of LO FSR, and <2% contribution of NLO FSR($1\gamma_{ISR}+1\gamma_{FSR}$) only at low $M_{\pi\pi}^2$
- Normalize to **Luminosity** (=Bhabha)
- Use **Phokhara** for acceptance, radiator and additional-photon effects

BaBar:

- The photon is “hard” and detected
- Kinematic fit to improve resolution
- Bin of 2 MeV in the region 0.5-1 GeV

⇒ Larger effects on the unfolding

- Negligible contribution of LO FSR, % contribution of NLO FSR($1\gamma_{ISR}+1\gamma_{FSR}$)
- Normalize to μμγ
- Interplay btw **Phokhara** and **AfkQED** to estimate additional-photon effects

Different selections and use of theoretical ingredients (R.C., Luminosity, Radiator). Additional cross checks are possible (and needed)

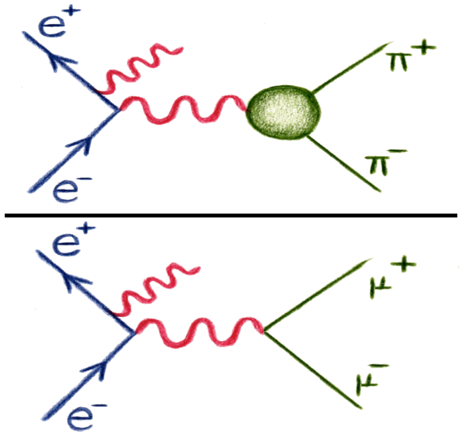
KLOE Measurement of $\sigma(e^+e^-\longrightarrow\pi^+\pi^-(\gamma))$ by $\pi\pi\gamma/\mu\mu\gamma$ ratio

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).

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



Many radiative corrections drop out:

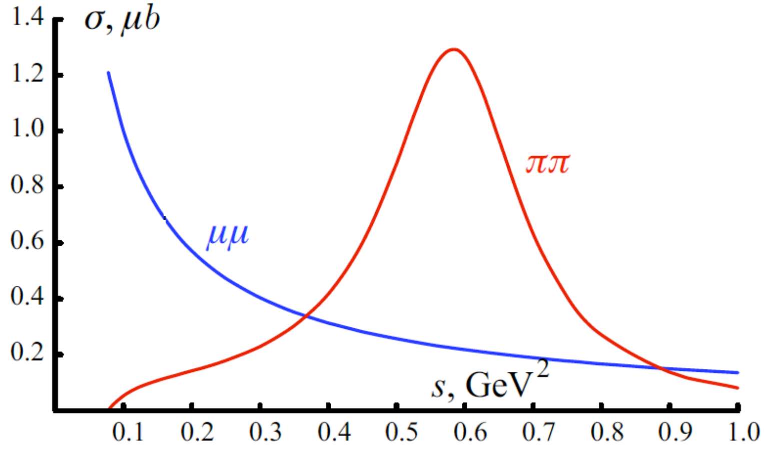
- *radiator function*
- *int. luminosity from Bhabhas*
- *Vacuum polarization*

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 $\pi/\mu \sim 10$ (see later)

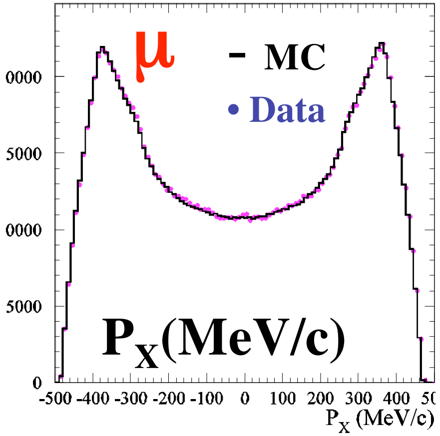
- We have achieved an excellent Data/MC agreement for muons in many kinematic variables (as we did for pions)

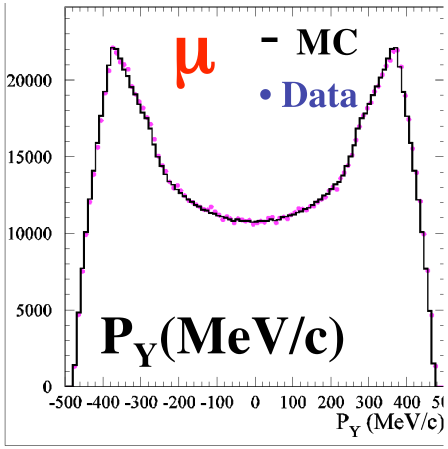
- Most of efficiencies for muons have been done and are ~100%

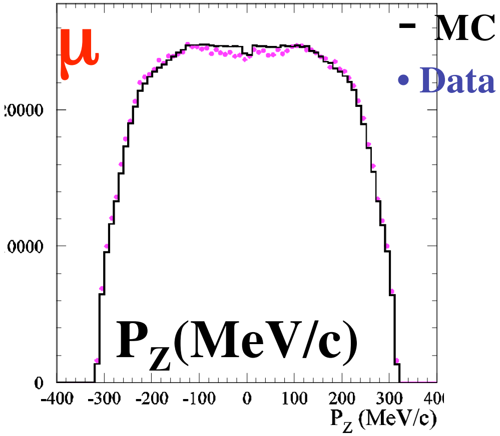
- We have not yet performed the absolute ratio $\mu\mu\gamma_{DATA}/\mu\mu\gamma_{MC}$ (test of QED) to check Radiator, Luminosity, FSR, etc…

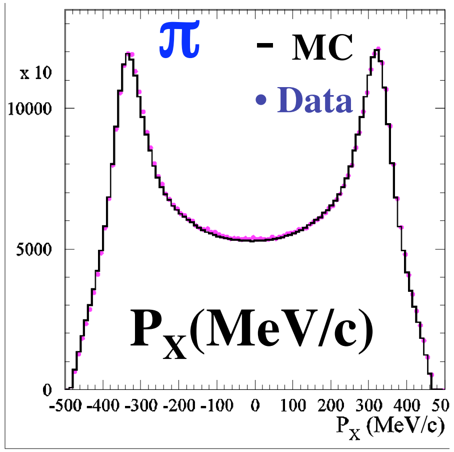
Results are expected for Summer conferences (if everything goes smoothly)

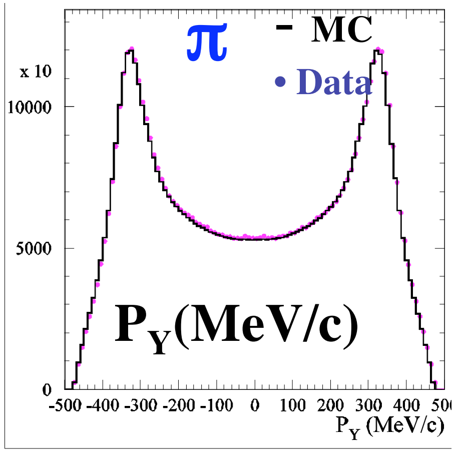
Example of data/MC comparison for $\mu\mu\gamma$ and $\pi\pi\gamma$: momentum components of μ and π

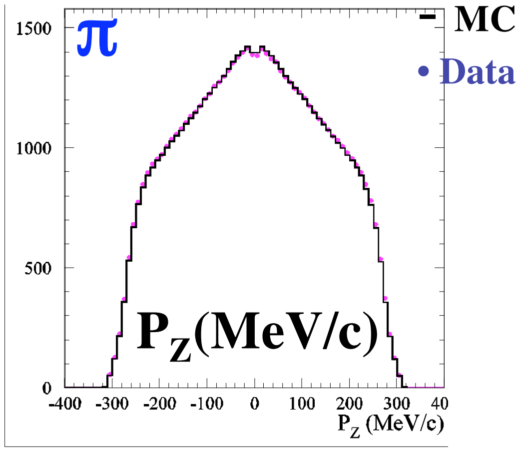






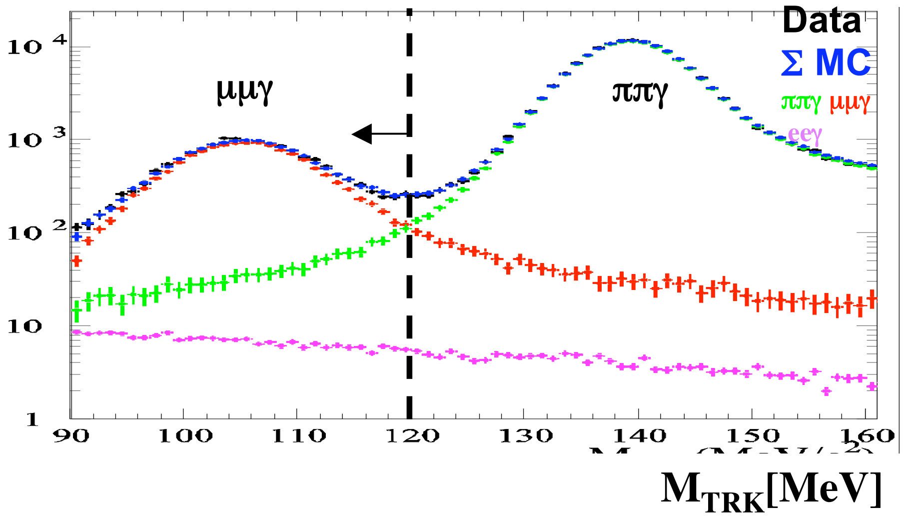




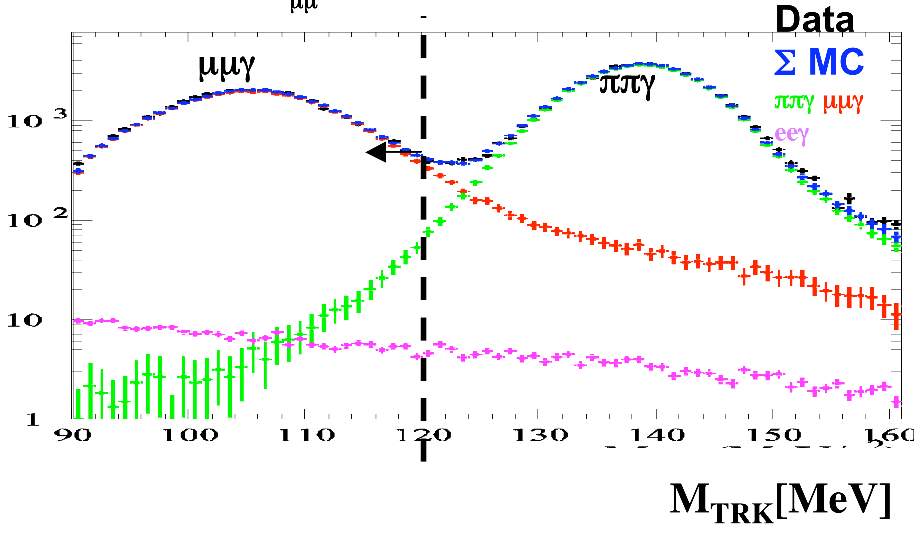


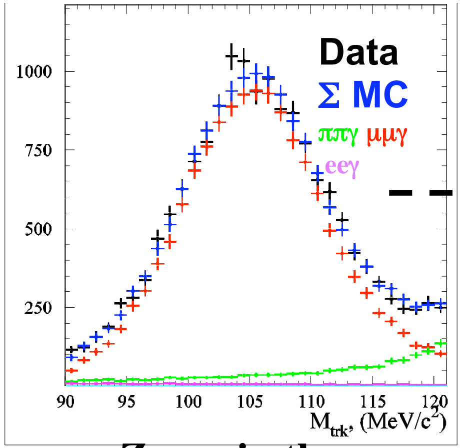
Example of μμγ selection via M_{TRK}

$0.59 < M_{\mu\mu}^2 < 0.61$ GeV^2

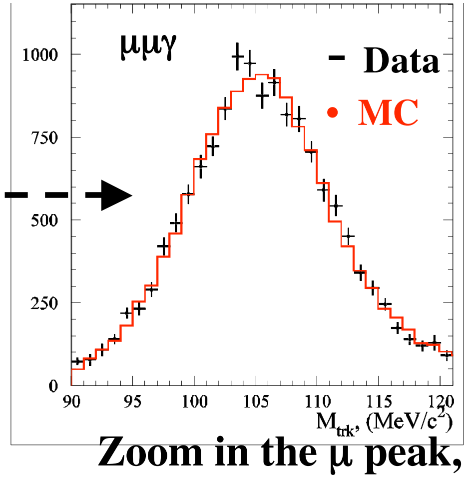


$0.93 < M_{\mu\mu}^2 < 0.95$ GeV^2

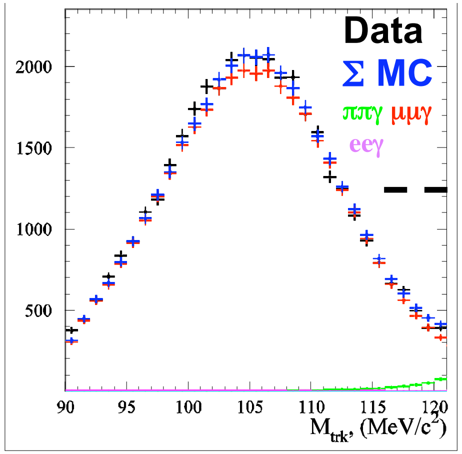




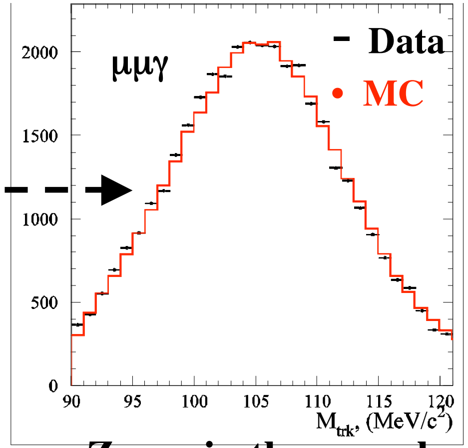
Zoom in the μ peak



Zoom in the μ peak, after background subtraction



Zoom in the μ peak



Zoom in the μ peak, after background subtraction

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

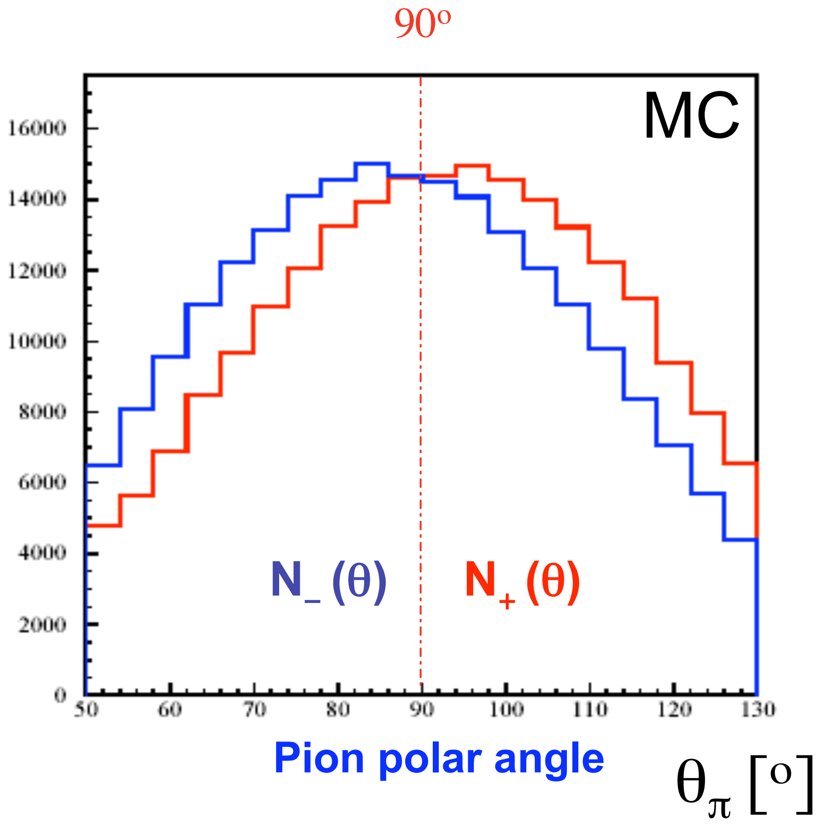
Forward-backward asymmetry:

In the case of a non-vanishing FSR contribution, the interference term between ISR and FSR is odd under exchange $\pi^+ \leftrightarrow \pi^-$ .This gives rise to a non-vanishing ***asymmetry****:*

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

Forward-backward asymmetry:

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

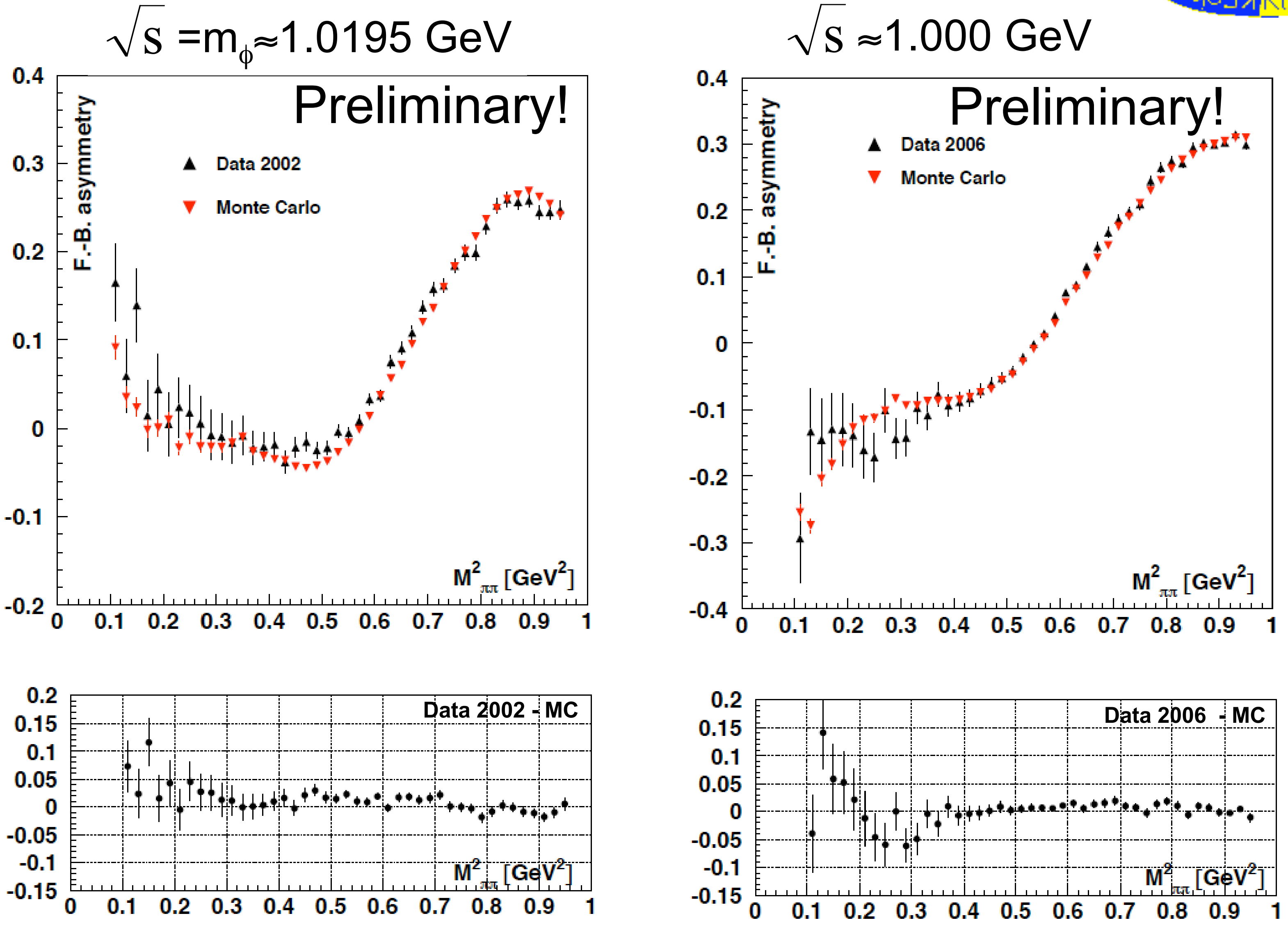


Ideal tool to test the validity of models used in Monte Carlo to describe the pionic final state radiation (point-like pion assumption, RχT, etc.)

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

Forward-backward asymmetry:


$\sqrt{s} = m_\phi \approx 1.0195$ GeV

$\sqrt{s} \approx 1.000$ GeV

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

Conclusions

❑ KLOE has performed the first precision measurement of $\sigma_{\pi\pi}$ in the region 0.35 - 0.95 GeV^2 with ISR → 1.3% systematic error (KLOE05, ***PLB 606, 12 (2005)***)

*- **discrepancy** between a_μ^{SM} and BNL experiment (~3σ)*

❑KLOE has presented a new measurement in 2008 (KLOE08, ***Phys. Lett. B 670, 285 (2009)***) with a different data sample using the same selection of KLOE05 (photon at small angle) →0.9% systematic error

- *KLOE08 confirms the **discrepancy** of ~3σ between a_μ^{SM} and a_μ^{EXP}*
- *KLOE08 $\boldsymbol{a_\mu^{\pi\pi}}$ agrees with recent results from CMD2 and SND experiments. Reasonable agreement on $\sigma_{\pi\pi}$ shapes*

❑KLOE has presented a new measurement of $\sigma_{\pi\pi}$ in 2009 (KLOE09) 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 in progress*
- *Agreement within errors with BaBar below 0.6 GeV; BaBar lies higher (2-3%) above*

Outlook

☐ Measurement of $\sigma_{\pi\pi}$ from $\pi\pi\gamma/\mu\mu\gamma$ ratio (as done by BaBar) well advanced.

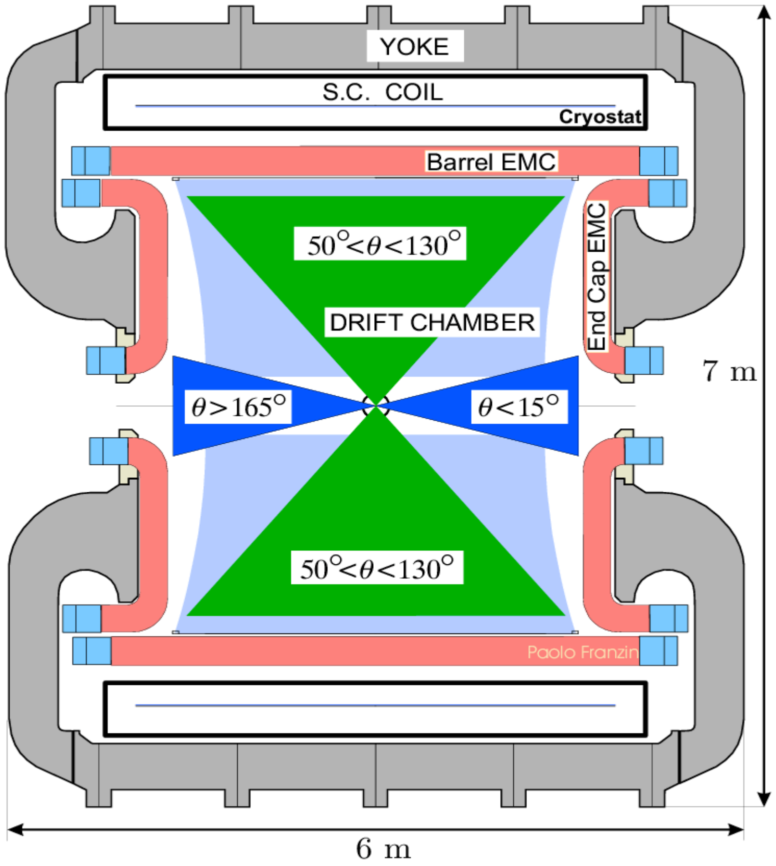
- Comparison of $\mu\mu\gamma_{DATA}/\mu\mu\gamma_{MC}$ will provide a consistency test for Radiatior, Luminosity, FSR etc…
- Results are expected for Summer conferences

☐ Check of FSR by Forward-Backward asymmetry (in progress)

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

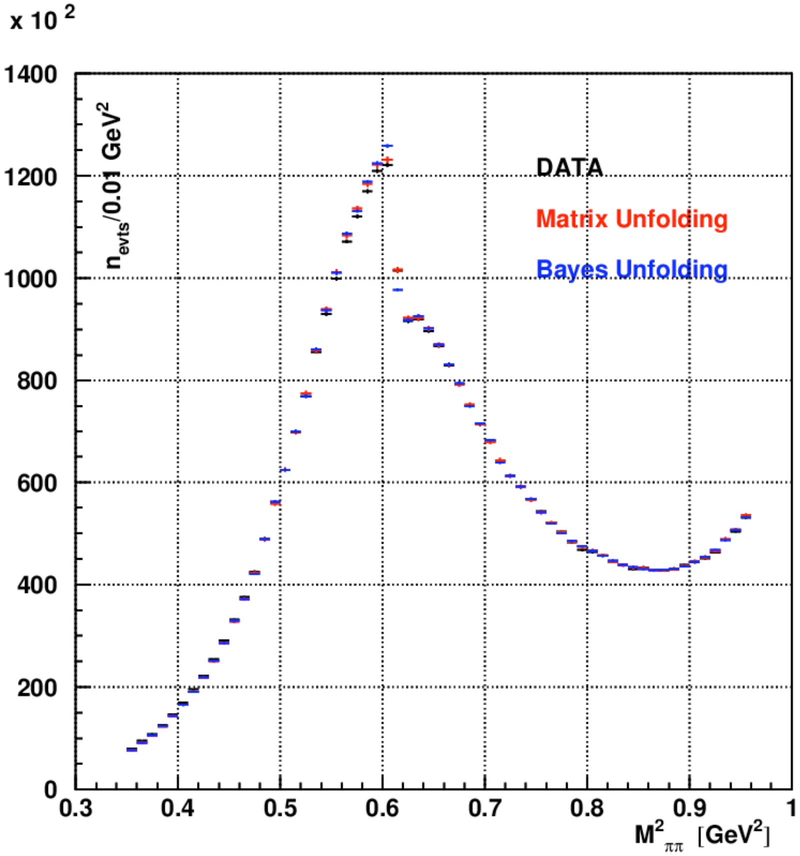
☐Very important for a_μ also the region between 1 and 2 GeV. Already a lot has been done from BaBar and Belle with ISR, and more will come also from BES-III. To reach the ultimate precision of 1% projects like VEPP2000 and DAFNE-2 (DAFNE upgraded in energy) will be essential.

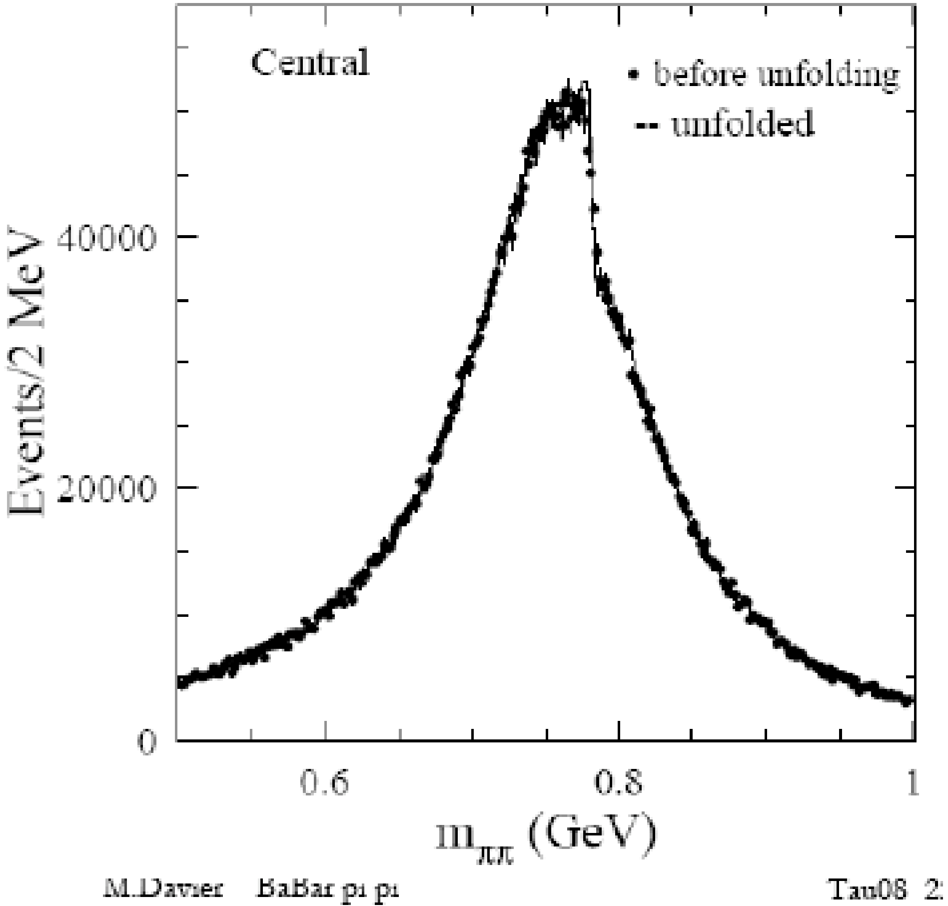
Stay Tuned!



SPARE SLIDES

Unfolding: KLOE vs BaBar 2π



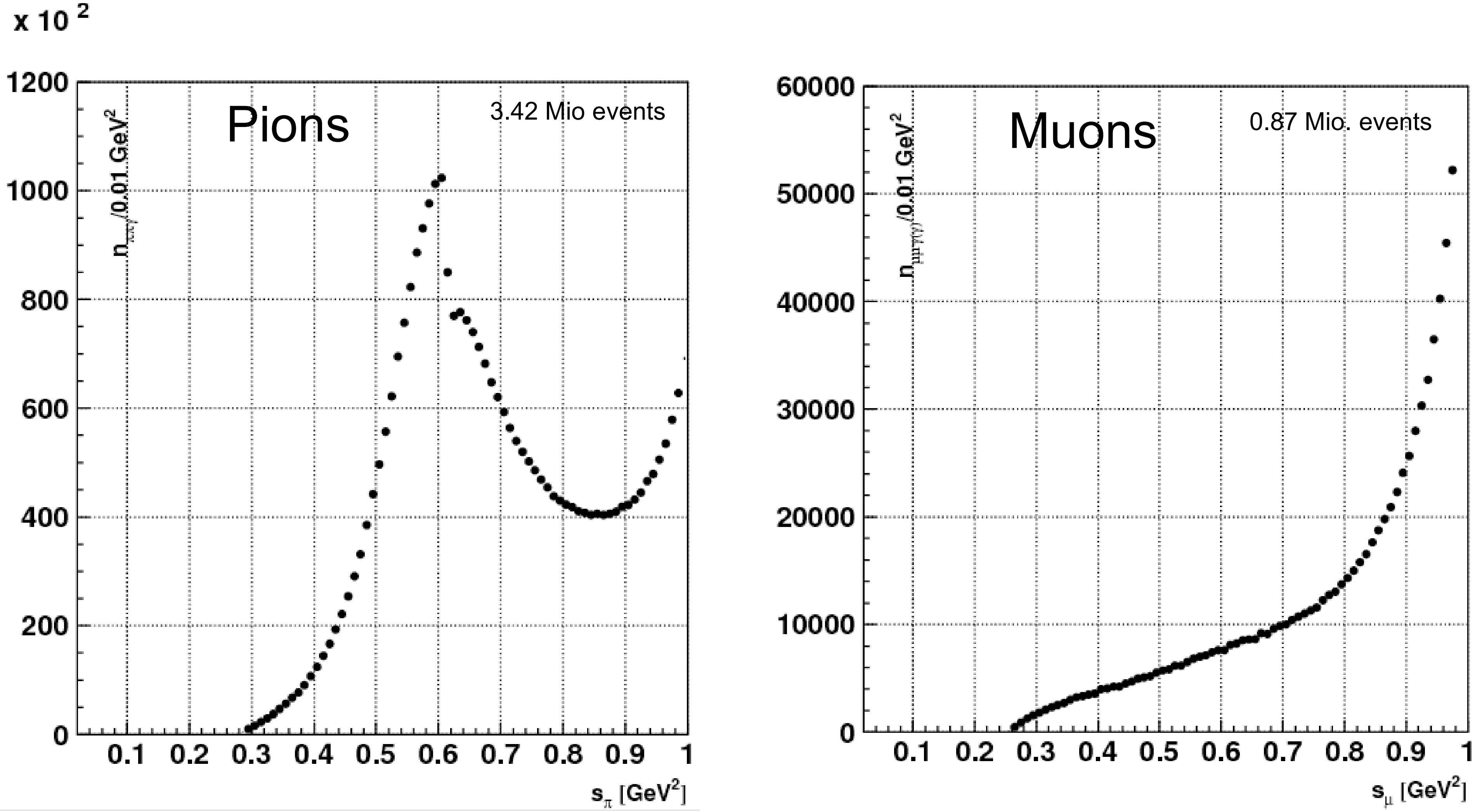


Large effect for BaBar especially in the ρ peak.

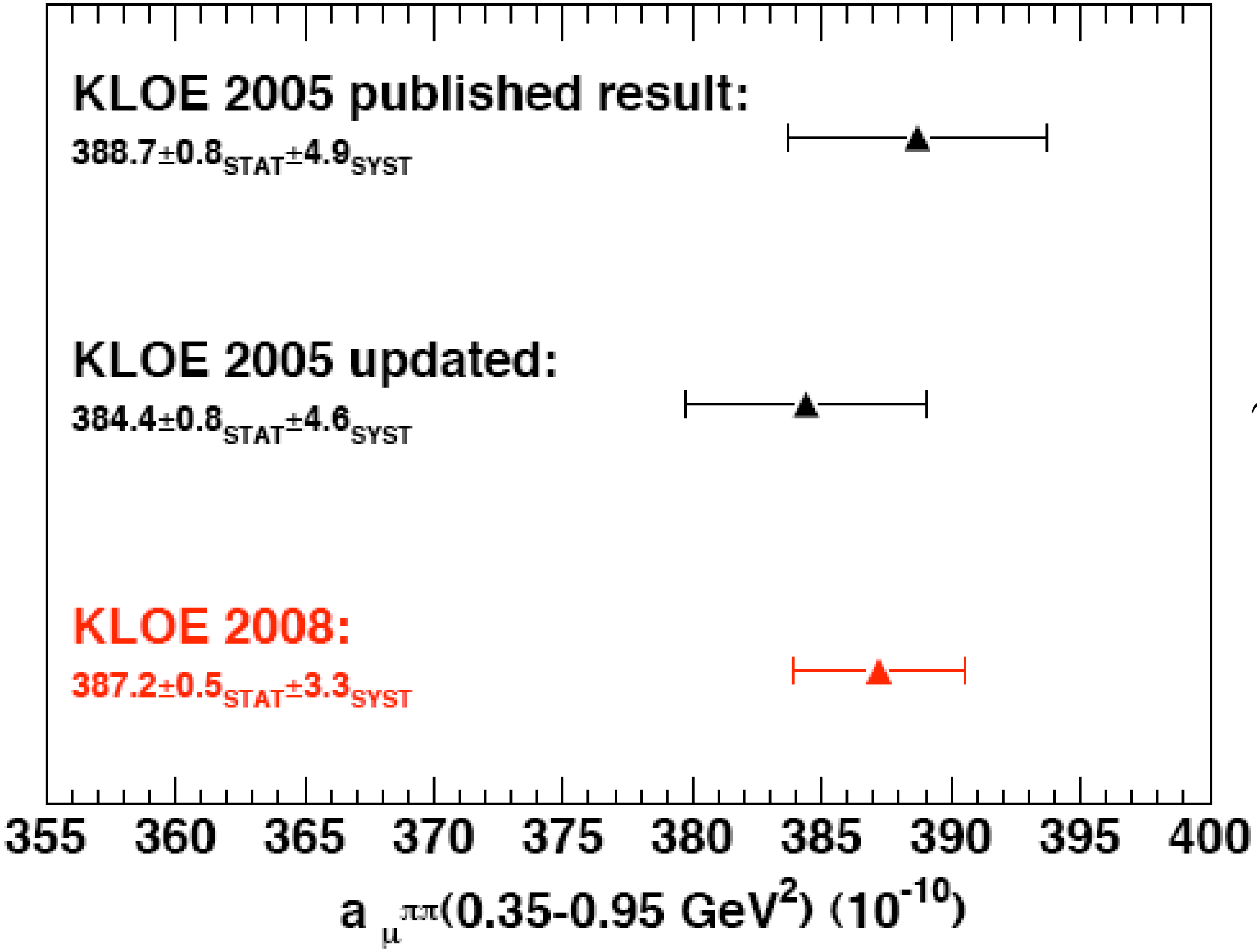
Essentially no effect for KLOE

Spectra after SMA selection:

The spectra of selected events for the small angle analysis from 242.62 pb^{-1} of data taken in 2002:



$a_\mu^{\pi\pi}$ from KLOE:



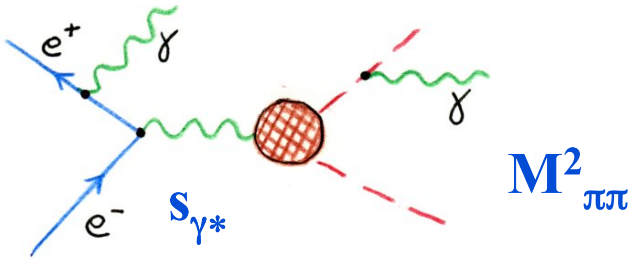
$\sim 1.3\%_{\mathrm{SYST}}$

$\sim 0.9\%_{\mathrm{SYST}}$

All results are in good agreement. New result has 30% better accuracy

Correcting for γ_{FSR} energy:

Go from $M^2_{\pi\pi} \rightarrow s_{\gamma*}$



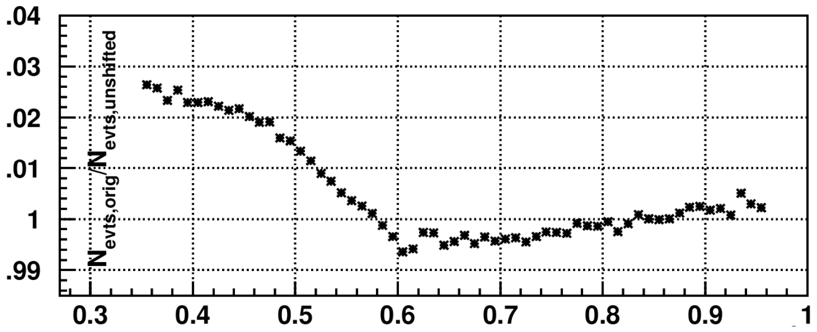
The presence of γ_{FSR} results in a shift of the measured quantity $M^2_{\pi\pi}$ towards lower values:

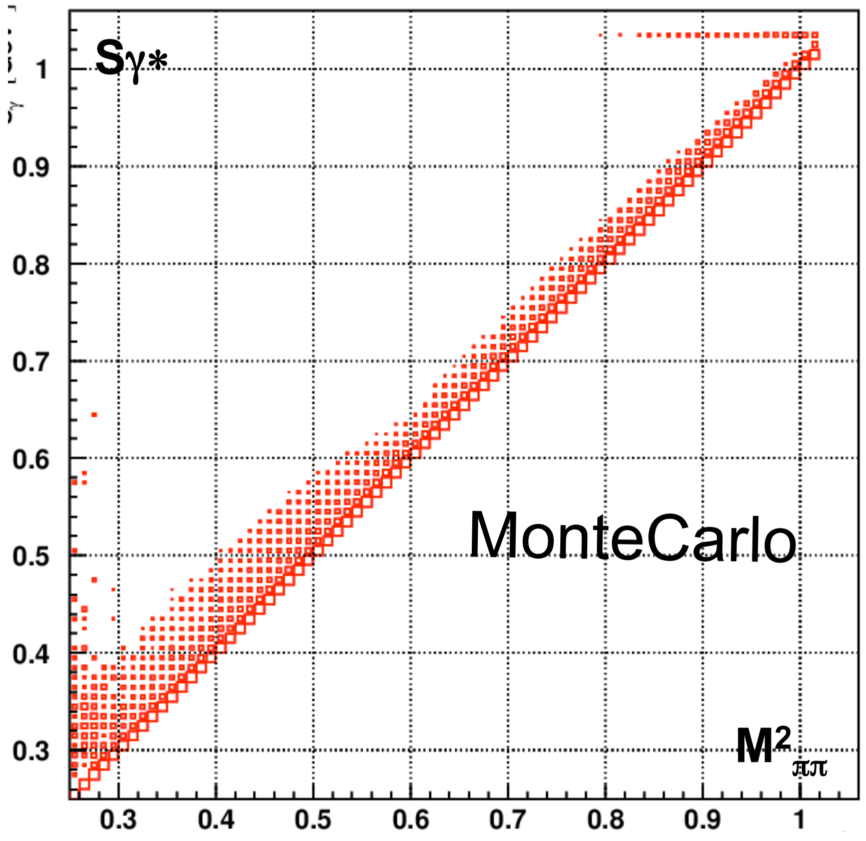
$$\boxed{M^2_{\pi\pi} < S_{\gamma*}}$$

Use special version of PHOKHARA which allows to determine whether photon comes from initial or final state → build matrix which relates $M^2_{\pi\pi}$ to $M^2_{\gamma*}$.

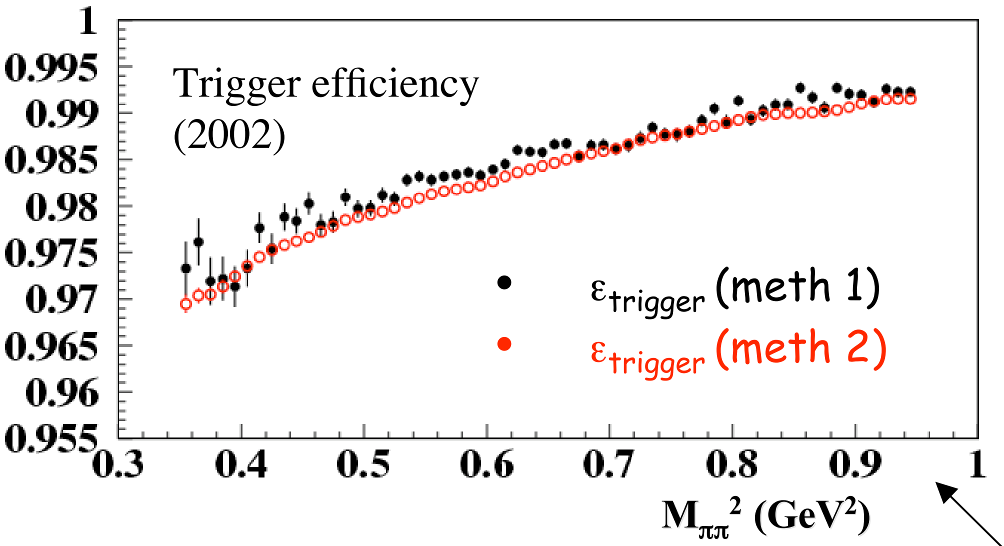
ISR only: $s_{\gamma*} = M^2_{\pi\pi}$

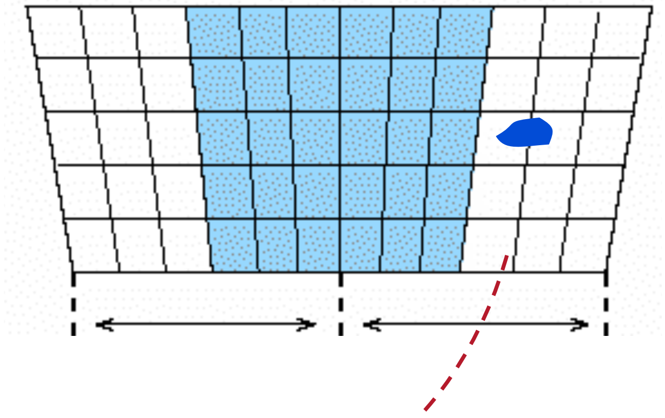
FSR photon present: $s_{\gamma*} = M^2_{\pi\pi\gamma(FSR)}$

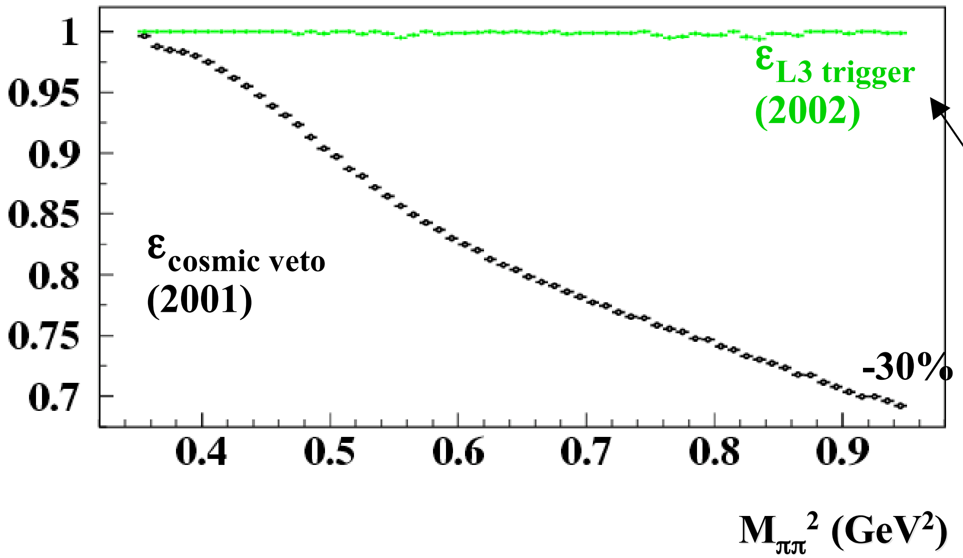




Trigger







~99.9%

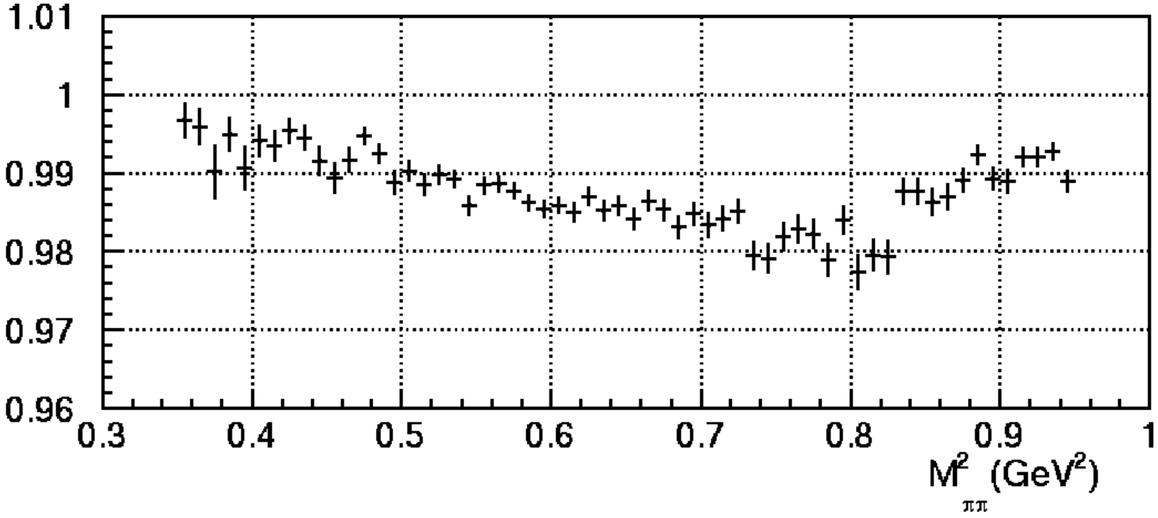
~70.%

- The event is **triggered** by the (pion) tracks only which deposit E>50 MeV in 2 sectors of the calorimeter
- trigger efficiency evaluated on data by 2 independent methods.
- Error is the fractional difference of the 2 methods: 0.1%
- The main source (**hardware** veto of cosmic rays) of inefficiency in the published result **has been replaced by an online filter (L3)**

Reconstruction and L3 filters:

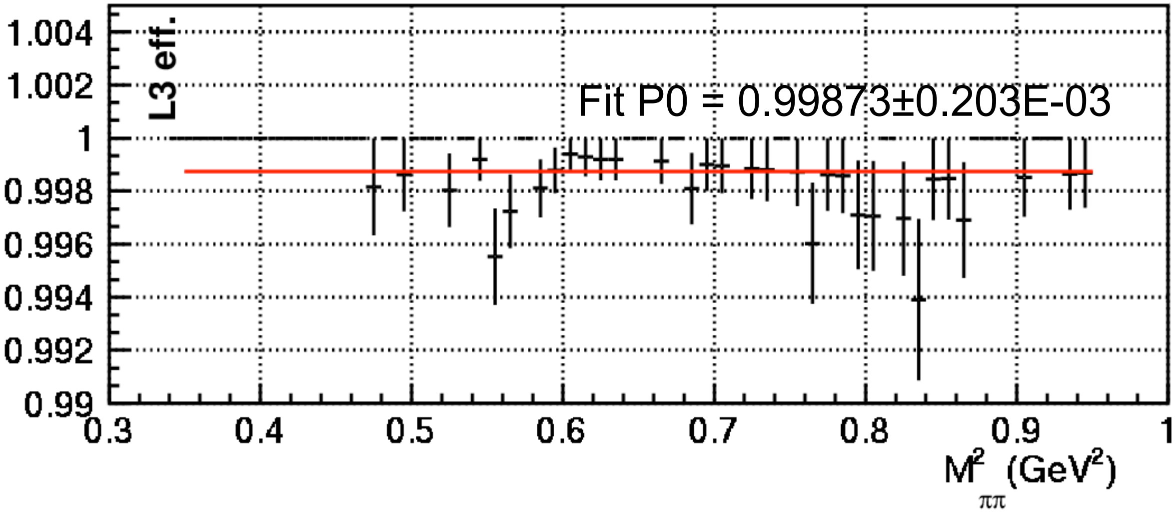
Both efficiencies estimated via downscaled control samples:

Reconstructior
Filter



~2%

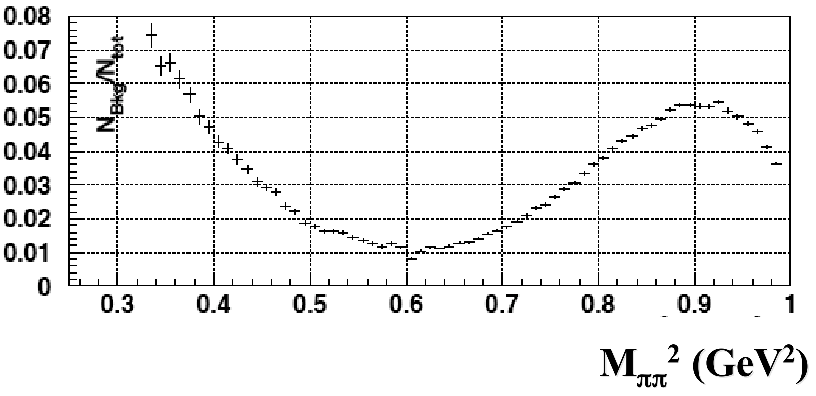
L3:



0.1% taken as uncertainty on the spectrum due to L3 trigger.

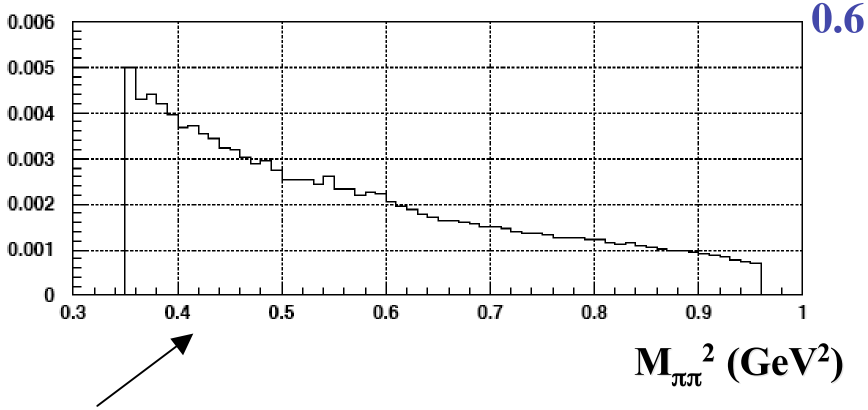
Background: total contribution and error

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



8%

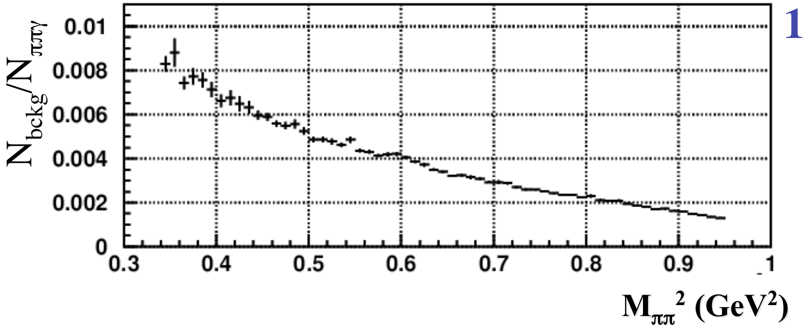
Error on bckg subtraction (in %)



0.6%

Additional bckg channels:

- $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ (Ekhara) ~ *0.8% at low $M^2_{\pi\pi}$*
- $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (Nextcalibur) *negligible*
- $\phi \rightarrow f_0\gamma \rightarrow \pi\pi\gamma$ (Phokhara,Fasterd) *negligible*
- $\phi \rightarrow \pi\rho \rightarrow \pi\pi\gamma$ (Phokhara,Fasterd) *negligible*
- $e^+e^- \rightarrow \omega\gamma_{ISR} \rightarrow \pi\pi\pi\gamma$(Phokhara) *negligible*



1%

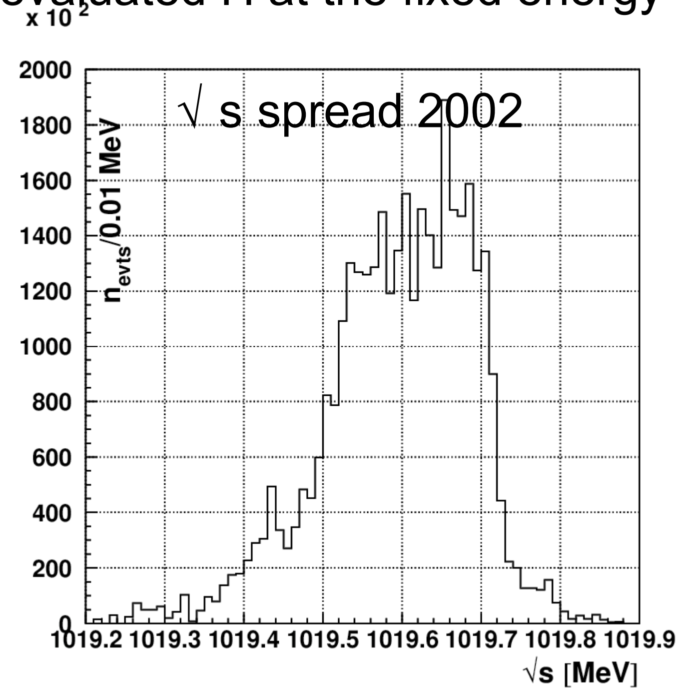
Contribution to Bckg error :

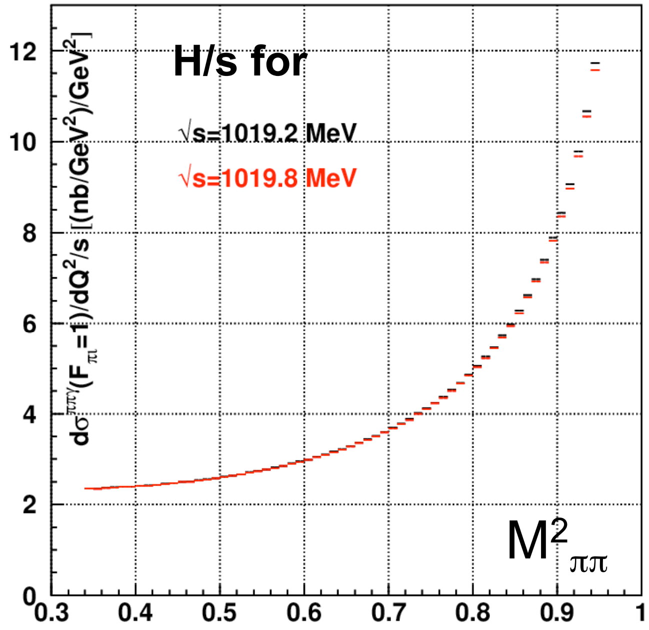
- Uncertainty on e+e- → e+e-$\pi^+\pi^-$ contribution
- Error from normalization parameters obtained from the fit

"Phokhara": see talk of A. Grzielinska
"Ekhara": C.zyz *et al*
"Nextcalibur" : *F.A. Berends et al*
"Fasterd": *O. Shekhotvsova et al*

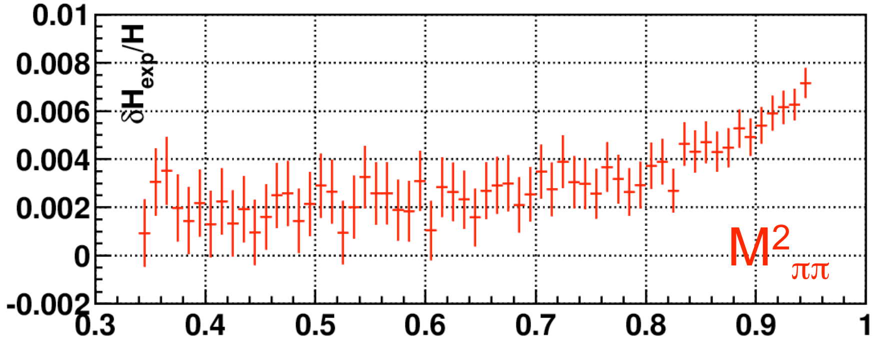
Radiator function (H)

In addition ot the 0.5% theoretical error we evaluate the experimental uncertainty due to the spread in √ s during the data taking in 2002 (since we evaluated H at the fixed energy √ s = 1.019456 GeV)





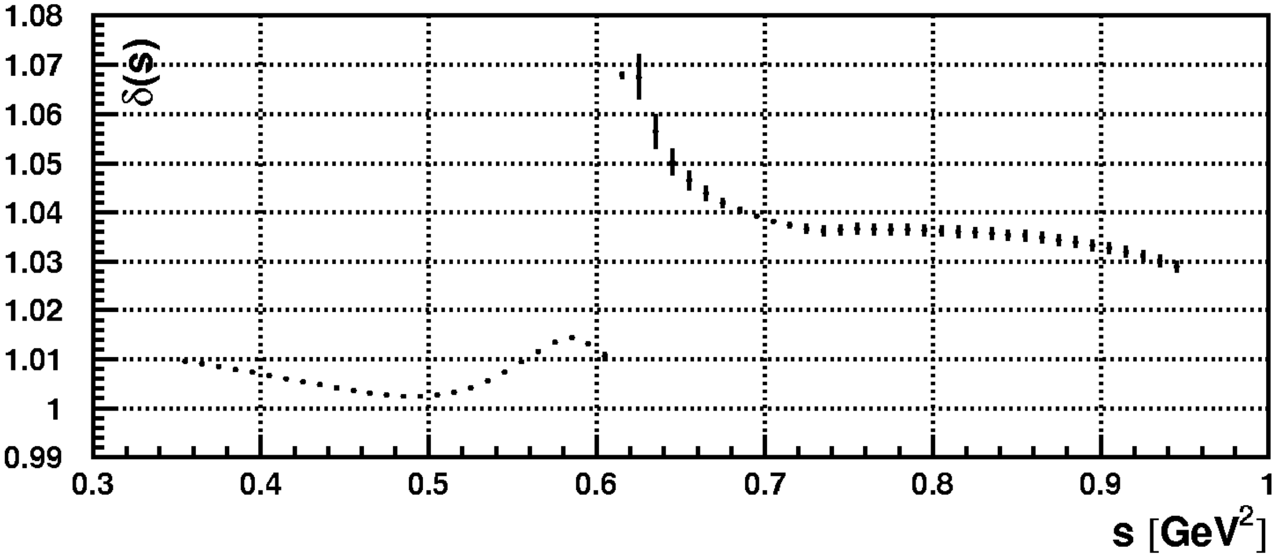
We take half the rel. difference between the radiator functions obtained at √ s = 1.0192 GeV and √ s = 1.0198 GeV as the experimental syst. uncertainty on the radiator function.



Vacuum Polarisation

For use in the dispersive integral for $\Delta^{\pi\pi}a_\mu$, one needs to subtract effects from vacuum polarization (VP) to obtain a *bare* cross section $\sigma^0_{\pi\pi}$:

$$\sigma^0_{\pi\pi}(s) = \sigma^{\text{dressed}}{}_{\pi\pi}(s)\left(\frac{\alpha(0)}{\alpha(s)}\right)^2 = \sigma_{\pi\pi}(s)/\delta(s)$$



Points obtained from F. Jegerlehner's webpage *(the only points which are publicly available!)*

Correction is applied only to the cross section $\sigma^0_{\pi\pi}$ (not on $\sigma_{\pi\pi\gamma}$ and $|F_\pi|^2$).

Error on VP points introduces an relative error on the value of $\Delta^{\pi\pi}a_\mu$ of 0.1%.