Search for Physics beyond the Standard Model:

the muon magnetic moment and its hadronic correction

University of Tübingen

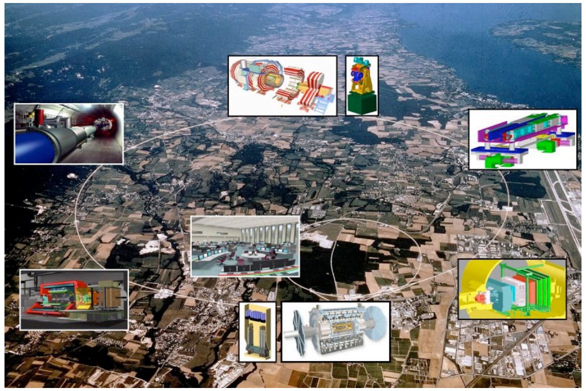
21.11.2008

Paolo Beltrame

Searching for New Physics… where?

Two complementary directions

LHC & experiments at TeV scale



➔ Very high energy physics

➔ Very precise measurements

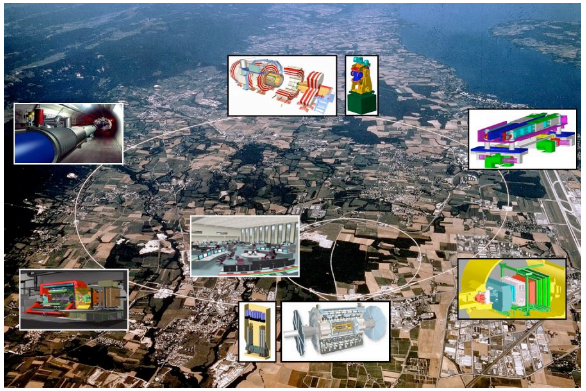
several experiments: Flavour and SuperFlavour Factories,
Neutrino experiments, Dark Matter dedicated experiments…

Searching for New Physics… where?

Two complementary directions

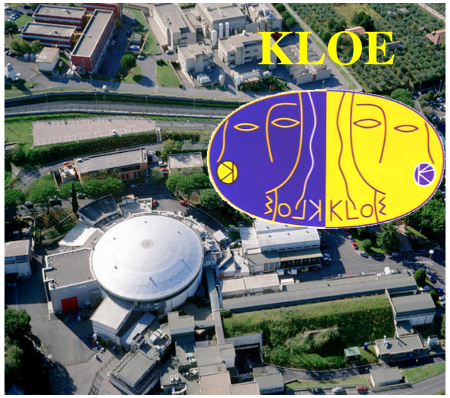
➔ Very high energy physics

LHC & experiments at TeV scale



➔ Very precise measurements

several experiments: Flavour and SuperFlavour Factories, Neutrino experiments, Dark Matter dedicated experiments…



Outlook

1. Introduction on $(g\text{-}2)_\mu$
   - Direct experimental measurement
   - Standard Model theoretical prediction

2. Radiative Return method

3. Measurements at KLOE
   - New published result
   - Ongoing analyses

4. Conclusion

1. Introduction on $(g-2)_\mu$

Lepton magnetic moment

Magnetic moment for point-like particle $\vec{\mu} = g \cdot \frac{e\hbar}{2mc} \vec{S}$

$g = 2$
Dirac (1928)

If $g \neq 2$ higher order effect… or New Physics

$g = 2 + \alpha/\pi$
Schwinger (1948)

➔ **Magnetic moment anomaly** $a_\ell = \frac{g-2}{2}$

Lepton magnetic moment

Magnetic moment for point-like particle $\vec{\mu} = g \cdot \frac{e\hbar}{2mc} \vec{S}$

$g = 2$
Dirac (1928)

If $g \neq 2$ higher order effect… or New Physics

$g = 2 + \alpha/\pi$
Schwinger (1948)

➔ **Magnetic moment anomaly** $a_\ell = \frac{g-2}{2}$

Today:
- precise prediction: a^{theo}
- precise measurement: a^{exp}

⇨ Any difference between a^{theo} and a^{exp} hints of New Physics beyond the Standard Model

Lepton magnetic moment

Magnetic moment for point-like particle $\vec{\mu} = g \cdot \frac{e\hbar}{2mc} \vec{S}$

$g = 2$
Dirac (1928)

If $g \neq 2$ higher order effect… or New Physics

$g = 2 + \alpha/\pi$
Schwinger (1948)

➔ **Magnetic moment anomaly** $a_\ell = \frac{g-2}{2}$

Today:
- precise prediction: a^{theo}
- precise measurement: a^{exp}

⇨ Any difference between a^{theo} and a^{exp} hints of
New Physics beyond the Standard Model

Why the muon?

a_μ much more sensitive to New Physics than a_e
$(m_\mu/m_e)^2 \sim 4.3 \times 10^4$

Magnetic moment anomaly **of the muon**

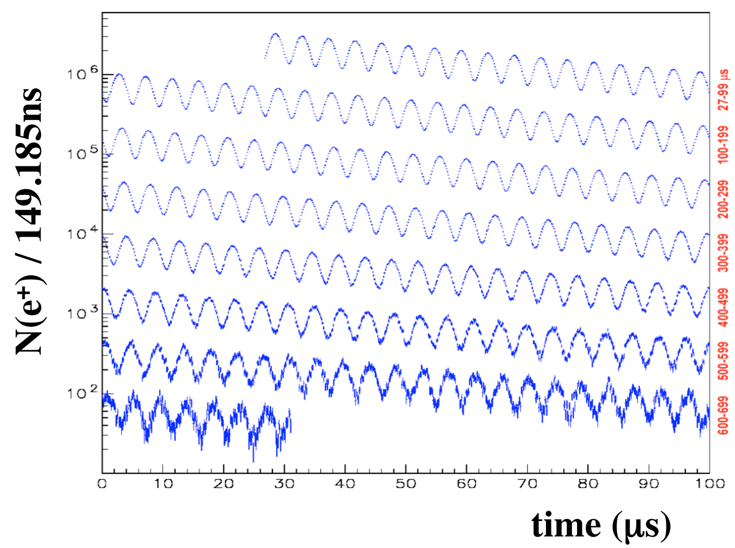
$(g\text{-}2)_\mu$ experiment: E821 at BNL

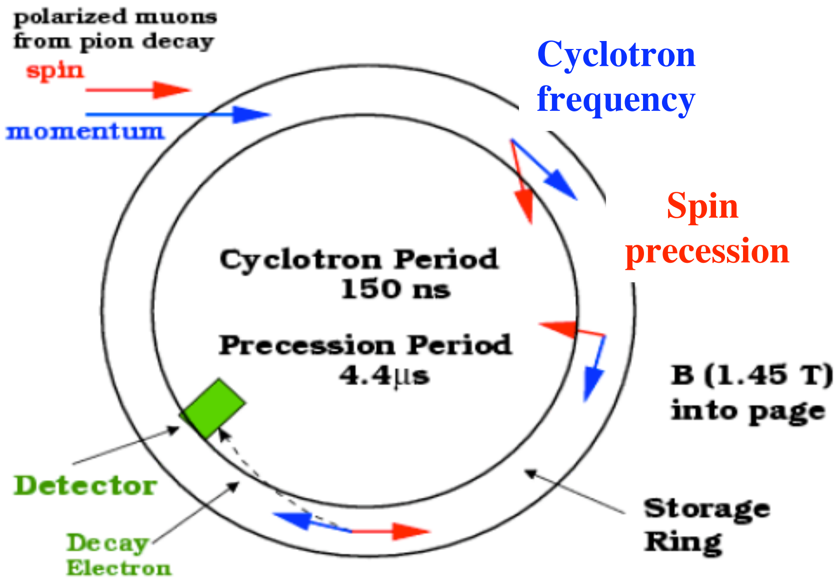
Cyclotron frequency $\omega_c = \dfrac{e \cdot B}{m}$

Spin precession $\omega_s = \dfrac{g}{2} \cdot \dfrac{e \cdot B}{m}$

Muon anomaly $$\omega_s - \omega_c = a_\mu \cdot \frac{e \cdot B}{m}$$

Positron – Yield (1999 Data)



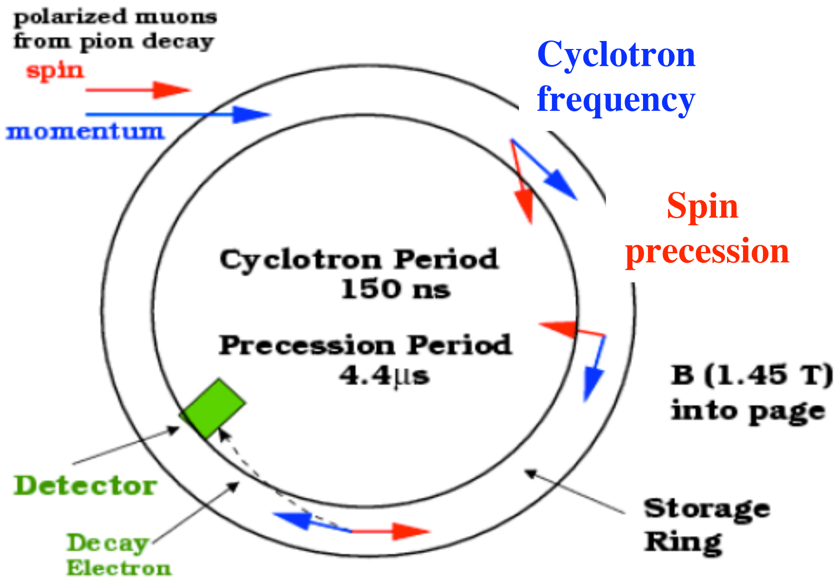


$(g\text{-}2)_\mu$ experiment: E821 at BNL

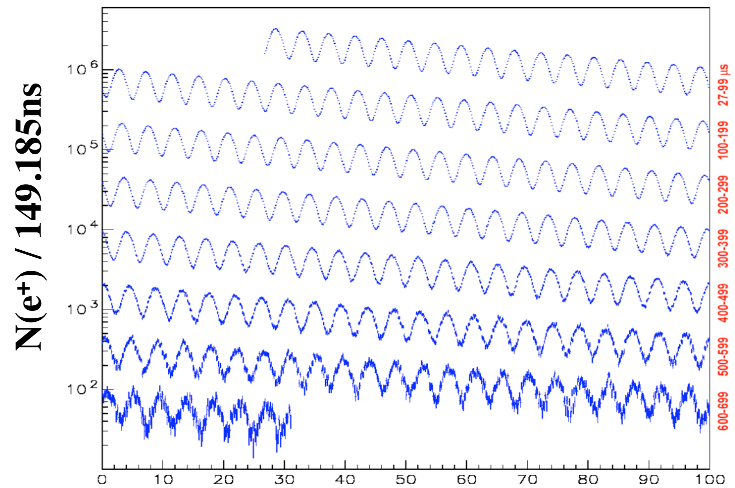
Cyclotron frequency $\omega_c = \frac{e \cdot B}{m}$

Spin precession $\omega_s = \frac{g}{2} \cdot \frac{e \cdot B}{m}$

Muon anomaly $$\omega_s - \omega_c = a_\mu \cdot \frac{e \cdot B}{m}$$



Positron – Yield (1999 Data)



$a_\mu(\mu^-) = (11\ 659\ 214 \pm 8_{stat} \pm 3_{syst}) \times 10^{-10}$

$a_\mu(\mu^+) = (11\ 659\ 204 \pm 7_{stat} \pm 5_{syst}) \times 10^{-10}$

Error a_μ (Jan 2004) = 0.5 ppm

Precise experimental measurements (0.54 ppm):

BNL/E821-Experiment => world average 2006

$$a_\mu^{exp} = (11\ 659\ 208.0 \pm 6.3) \times 10^{-10}$$

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{\text{theo}} = a^{\text{SM}}_\mu$$

$$\Rightarrow a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}$$

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{theo} = a^{SM}_\mu$$

$$\Rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

$$a_\mu^{QED} = (11\,658\,471.810 \pm 0.016) \times 10^{-10}$$

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{theo} = a^{SM}_\mu$$

$$\Rightarrow \boldsymbol{a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}}$$

$$a_\mu^{QED} = (11\ 658\ 471.810 \pm 0.016) \times 10^{-10}$$

$$a_\mu^{EW} = (15.4 \pm 0.2) \times 10^{-10}$$

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{\text{theo}} = a^{\text{SM}}_\mu$$

$$\Rightarrow \boldsymbol{a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}}$$

$$a_\mu^{\text{QED}} = (11\ 658\ 471.810 \pm 0.016) \times 10^{-10}$$

$$a_\mu^{\text{EW}} = (15.4 \pm 0.2) \times 10^{-10}$$

$$a_\mu^{\text{had}} \approx (700 \pm 7) \times 10^{-10}$$

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{theo} = a^{SM}_\mu$$

$$\Rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

$$a_\mu^{QED} = (11\,658\,471.810 \pm 0.016) \times 10^{-10}$$

$$a_\mu^{EW} = (15.4 \pm 0.2) \times 10^{-10}$$

$$a_\mu^{had} \approx (700 \pm 7) \times 10^{-10}$$

➔ 2nd largest contribution

➔ dominating error

Theoretical prediction

Standard Model theoretical prediction:

$$a_\mu^{theo} = a^{SM}_\mu$$

$$\rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$$

$$a_\mu^{QED} = (11\ 658\ 471.810 \pm 0.016) \times 10^{-10}$$

$$a_\mu^{EW} = (15.4 \pm 0.2) \times 10^{-10}$$

$$a_\mu^{had} \approx (700 \pm 7) \times 10^{-10}$$

- ➔ 2nd largest contribution
- ➔ dominating error

… so far Standard Model prediction

But if $a^{theo} - a^{exp} \neq 0$ => **New Physics**

$$a_\mu^{theo} = a^{SM}_\mu + a^{NP}_\mu$$

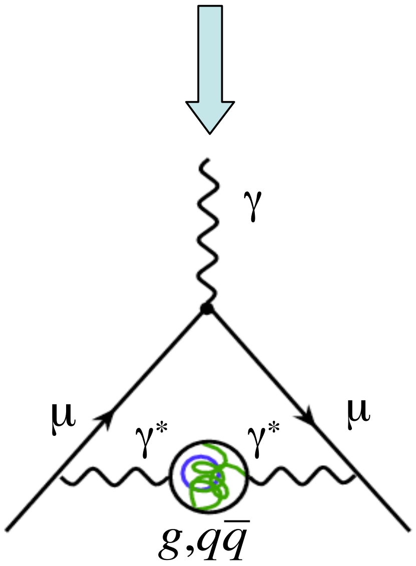
Hadronic contribution to a_μ

$$a_\mu^{\text{had}} = a_\mu^{\text{had,LO}} + a_\mu^{\text{had,HO(vp)}} + a_\mu^{\text{had,HO(lbl)}}$$

Hadronic contribution to a_μ: Leading Order

$$a_\mu^{had} = a_\mu^{had,LO} + a_\mu^{had,HO(vp)} + a_\mu^{had,HO(lbl)}$$

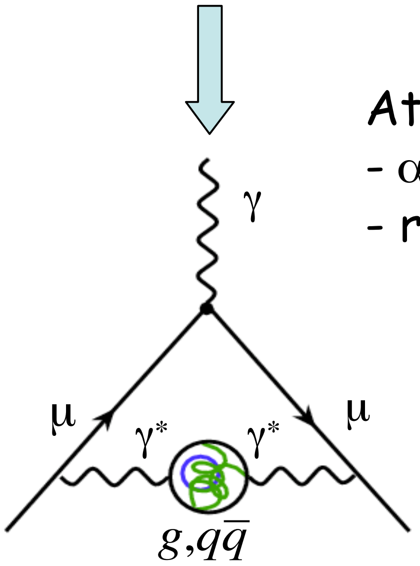
$a_\mu^{had,LO}$ Hadronic vacuum polarization



Hadronic contribution to a_μ: Leading Order

$$a_\mu^{had} = a_\mu^{had,LO} + a_\mu^{had,HO(vp)} + a_\mu^{had,HO(lbl)}$$

$a_\mu^{had,LO}$ Hadronic vacuum polarization



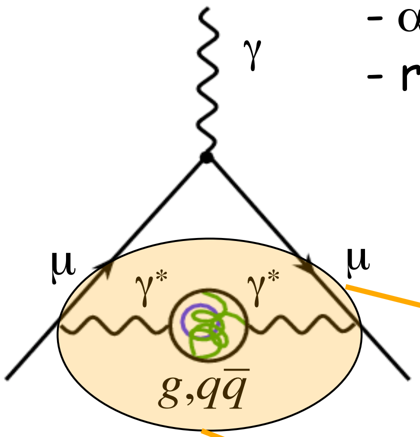
At low energy:
- α_s ~ O(1)
- resonancies

pQCD not applicable

Hadronic contribution to a_μ: Leading Order

$$a_\mu^{\text{had}} = a_\mu^{\text{had,LO}} + a_\mu^{\text{had,HO(vp)}} + a_\mu^{\text{had,HO(lbl)}}$$

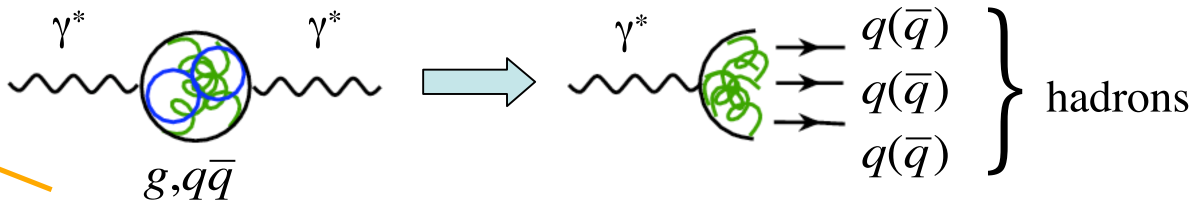
$\mathbf{a_\mu^{had,LO}}$ Hadronic vacuum polarization



At low energy:
- $\alpha_s \sim O(1)$
- resonancies

} pQCD not applicable

Optical Theorem



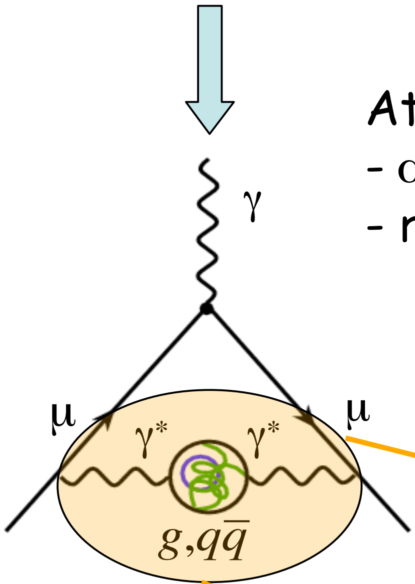
Hadronic contribution to a_μ: Leading Order

$a_\mu^{had} = a_\mu^{had,LO} + a_\mu^{had,HO(vp)} + a_\mu^{had,HO(lbl)}$

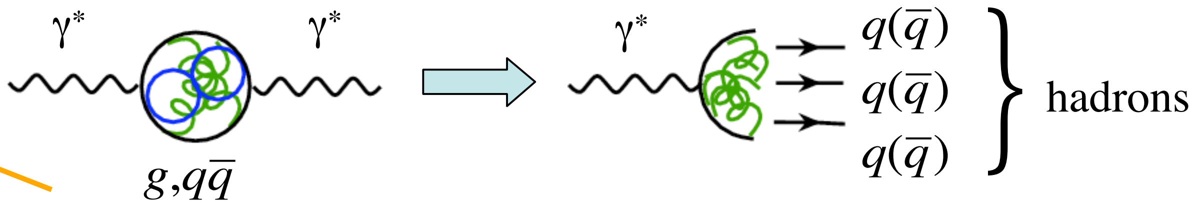
$a_\mu^{had,LO}$ — Hadronic vacuum polarization

At low energy:
- $\alpha_s \sim O(1)$
- resonancies

} pQCD not applicable



Optical Theorem



$$a_\mu^{had} = \frac{1}{4\pi^3}\left(\int_{4m_\pi^2}^{E_{Cut}^2} ds\,\sigma^{had,exp}(s)K(s) + \int_{E_{Cut}^2}^{\infty} ds\,\sigma^{had,pQCD}(s)K(s)\right)$$

Hadronic contribution to a_μ: Leading Order

Master formula for $E < E_{cut}$

$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{E_{Cut}^2} ds\, \sigma^{had}(s) K(s) = \left(\frac{\alpha \cdot m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{E_{Cut}^2} ds\, \frac{R(s) K'(s)}{s^2}$$

$$R(s) = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$

Hadronic contribution to a_μ: Leading Order

Master formula for $E < E_{cut}$

$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{Cut}^2} \mathrm{d}s\,\sigma^{had}(s)\mathrm{K}(s) = \left(\frac{\alpha\cdot m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{E_{Cut}^2} \mathrm{d}s\,\frac{R(s)K'(s)}{s^2}$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

– Needs of experimental input for $\sigma^{had}(s)$

– Great relevance of precise measurement at low energy

$$\left.\begin{array}{l}\sigma^{had}(s) \propto 1/s \\ K(s) \propto 1/s\end{array}\right\} 1/s^2$$

Hadronic contribution to a_μ: Leading Order

Master formula for $E < E_{cut}$

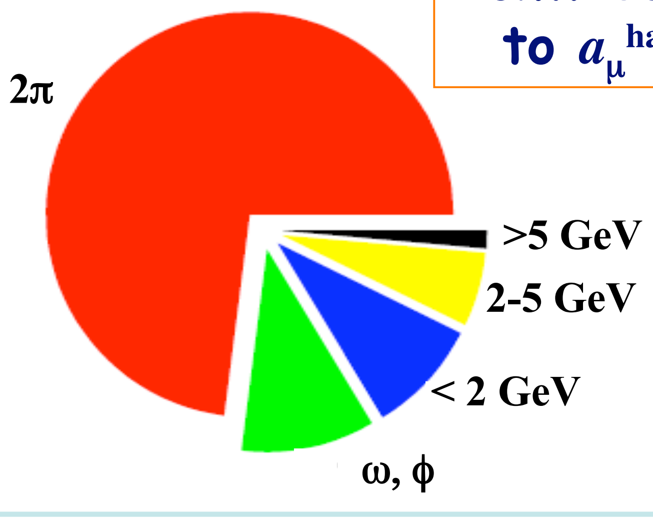
$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{Cut}^2} ds\,\sigma^{had}(s)K(s) = \left(\frac{\alpha \cdot m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{E_{Cut}^2} ds\,\frac{R(s)K'(s)}{s^2}$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

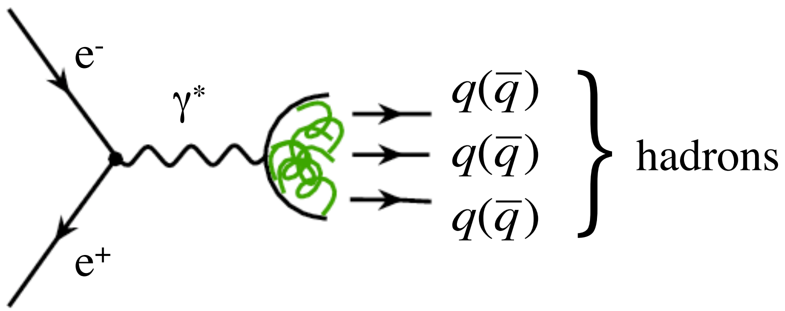
- Needs of experimental input for $\sigma^{had}(s)$
- Great relevance of precise measurement at low energy

$$\left.\begin{array}{l} \sigma^{had}(s) \propto 1/s \\ K(s) \propto 1/s \end{array}\right\} 1/s^2$$

Contribution to $a_\mu^{had,LO}$



High precision measurements



$e^+e^- \to$ hadrons

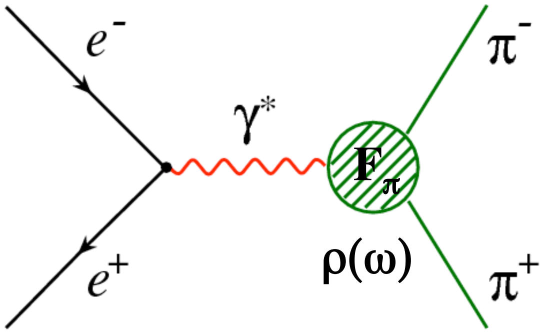
Hadronic contribution to a_μ: Leading Order

Relevance of $E < m_\phi$

➔ Channel $e^+e^- \rightarrow \rho(\omega) \rightarrow \pi^+\pi^-$

contributes to $a_\mu^{had,LO}$ of ca. 73%

Precious channel: 2π

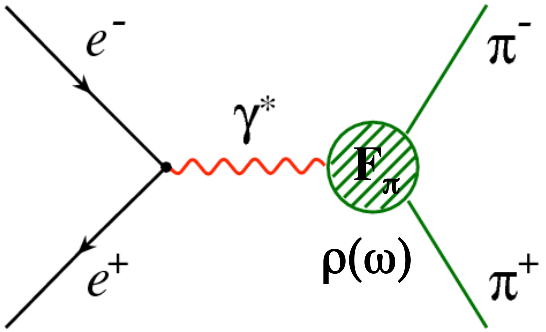


$e^+e^- \rightarrow \pi^+\pi^-$

Hadronic contribution to a_μ: Leading Order

Relevance of $E < m_\phi$
➔ Channel $e^+e^- \rightarrow \rho(\omega) \rightarrow \pi^+\pi^-$
contributes to $a_\mu^{had,LO}$ of ca. 73%

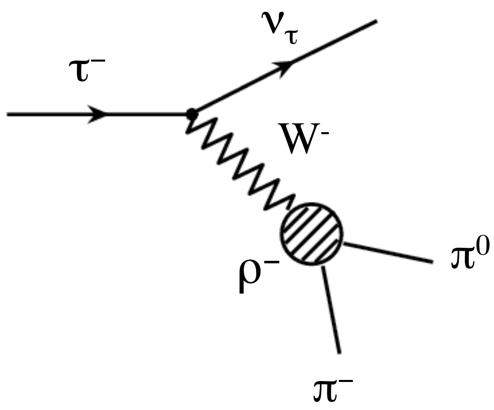
Precious channel: 2π



$e^+e^- \rightarrow \pi^+\pi^-$

CVC

+ corrections



Hadronic τ decays

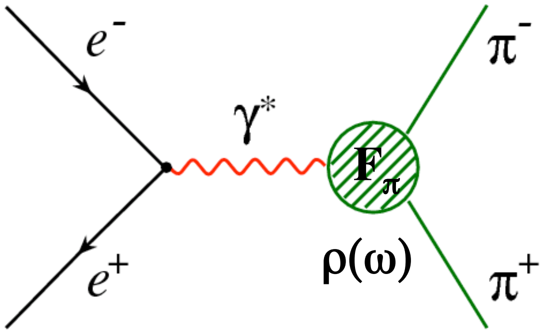
Hadronic contribution to a_μ: Leading Order

Relevance of $E < m_\phi$

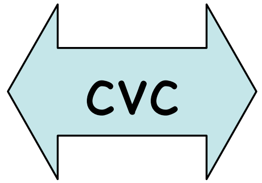
➔ Channel $e^+e^- \rightarrow \rho(\omega) \rightarrow \pi^+\pi^-$

contributes to $a_\mu^{had,LO}$ of ca. 73%

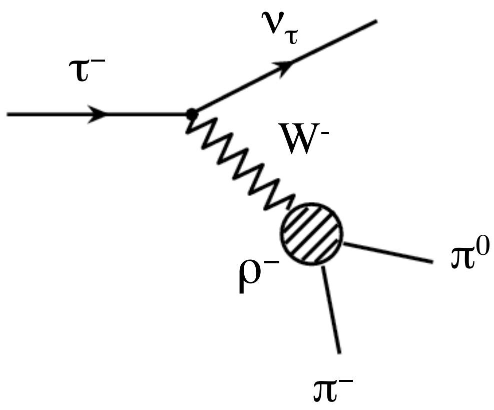
Precious channel: 2π



$e^+e^- \rightarrow \pi^+\pi^-$



+ corrections



Hadronic τ decays

"Equivalence" between $\sigma_{\pi\pi}(s)$ and $F_\pi(s)$

$$\sigma\left(e^+e^- \rightarrow \pi^+\pi^-\right) = \frac{\pi\alpha^2}{3s}\beta^3\left|F_\pi(s)\right|^2$$

Hadronic contribution to a_μ: Leading Order

Evaluations of $a_\mu^{had,LO}$
Using different experimental inputs

Calculation	$a_\mu^{had,LO} \times 10^{-10}$	$\sqrt{s}_{pQCD}$ (GeV)
DEHZ, 2003	696.3 ± 7.2	5
DEHZ, 2007	690.9 ± 4.4	5
HMNT, 2007	689.4 ± 4.6	11
J, 2008	692.3 ± 6.0	12

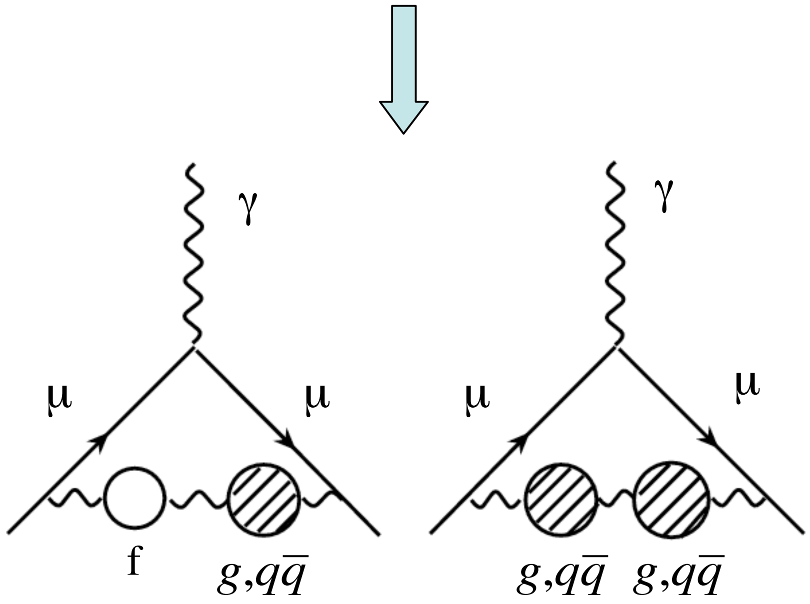
Higher accuracy of e^+e^- data
➔ uncertainty of $a_\mu^{had,LO}$ theoretical prediction: **0.63%**

Hadronic contribution to a_μ: Higher Orders I

$$a_\mu^{\text{had}} = a_\mu^{\text{had,LO}} + a_\mu^{\text{had,HO(vp)}} + a_\mu^{\text{had,HO(lbl)}}$$

$a_\mu^{\text{had,HO(vp)}}$

Higher order
hadronic vacuum polarization



$$a_\mu^{\text{had}} \Rightarrow \int \mathrm{d}s \frac{R(s)G(s)}{s^2}$$

G(s) smooth function of s
=> low energy range dominates

+ other graphs

Several calculations in agreement

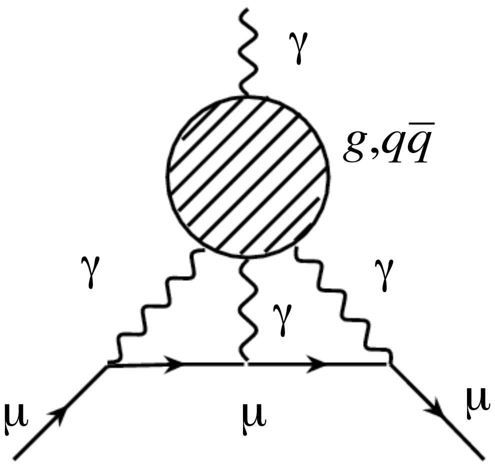
H (2003): $a_\mu^{\text{had,HO(vp)}} = (-9.8 \pm 0.1) \times 10^{-10}$

Hadronic contribution to a_μ: Higher Orders II

$$a_\mu^{had} = a_\mu^{had,LO} + a_\mu^{had,HO(vp)} + a_\mu^{had,HO(lbl)}$$

$a_\mu^{had,HO(lbl)}$

Higher order
Light by Light



- Value obtained only via theoretical calculation
- Different approaches
- Discrepancies among evaluations

Calculation	$a_\mu^{had,LbL} \times 10^{-10}$
KN (2002)	8.0 ± 4.0
MV (2004)	13.6 ± 2.5
JN (2008)	11.0 ± 4.0

Experiment vs. Theory

- BNL measurements => world average:

  $a_\mu^{exp} = (11\ 659\ 208.0 \pm 6.3) \times 10^{-10}$

Contribution	$a_\mu \times 10^{-10}$
Experiments	11 659 208.0 ± 6.3

Experiment vs. Theory

- BNL measurements => world average:

  $a_\mu^{exp} = (11\ 659\ 208.0 \pm 6.3) \times 10^{-10}$

- theoretical prediction:

  $a_\mu^{theo} \Rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$

Contribution	$a_\mu \times 10^{-10}$
Experiments	11 659 208.0 ± 6.3
QED	11 658 471.810 ± 0.016
ElectroWeak	15.4 ± 0.2
Hadronic	689.4 ± 4.6
Theory (SM)	**11 659 177.8 ± 6.1**

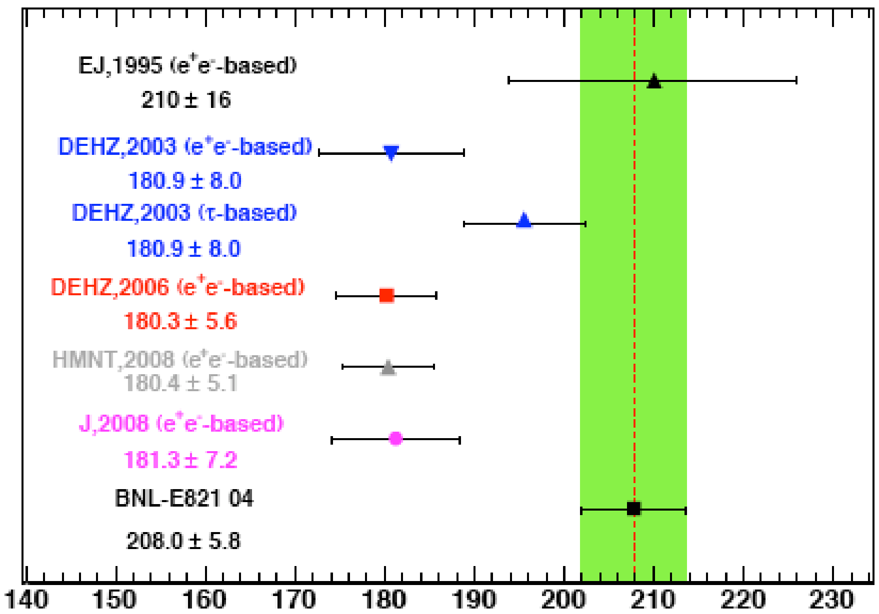
Experiment vs. Theory

- BNL measurements => world average:

  $a_\mu^{exp} = (11\ 659\ 208.0 \pm 6.3) \times 10^{-10}$

- theoretical prediction:

  $a_\mu^{theo} \Rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$



$11\ 659\ 000 \times 10^{-10}$

Contribution	$a_\mu \times 10^{-10}$
Experiments	11 659 208.0 ± 6.3
QED	11 658 471.810 ± 0.016
ElectroWeak	15.4 ± 0.2
Hadronic	689.4 ± 4.6
Theory (SM)	**11 659 177.8 ± 6.1**
Exp. - Theo.(SM)	30.2 ± 8.8 (**3.4** σ)

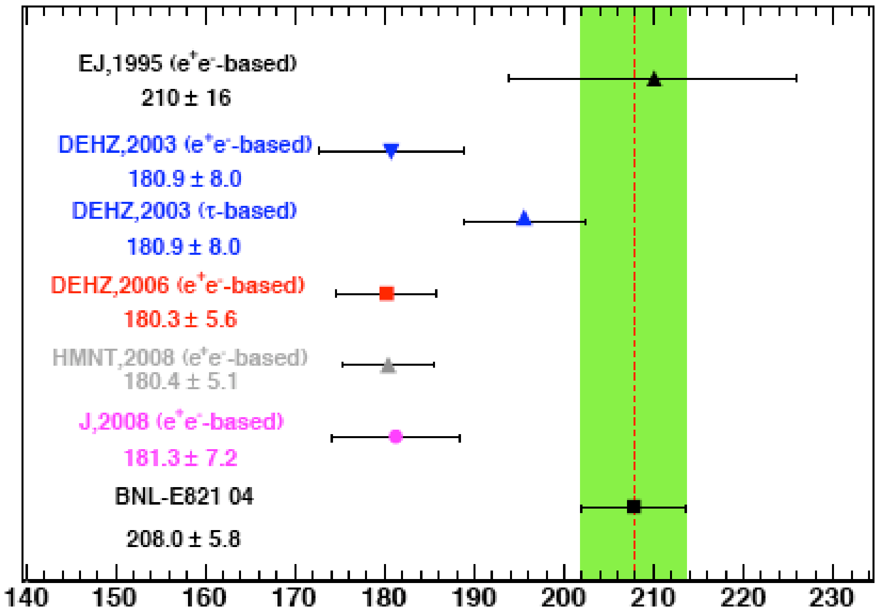
Experiment vs. Theory

- BNL measurements => world average:

  $a_\mu^{exp} = (11\,659\,208.0 \pm 6.3) \times 10^{-10}$

- theoretical prediction:

  $a_\mu^{theo} \Rightarrow a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{had}$



$11\,659\,000 \times 10^{-10}$

Contribution	$a_\mu \times 10^{-10}$
Experiments	11 659 208.0 ± 6.3
QED	11 658 471.810 ± 0.016
ElectroWeak	15.4 ± 0.2
Hadronic	689.4 ± 4.6
Theory (SM)	**11 659 177.8 ± 6.1**
Exp. - Theo.(SM)	30.2 ± 8.8 (**3.4** σ)

Using e^+e^--data based for $a_\mu^{had,LO}$

=> Experiments and Theory 3.4 σ discrepancy

- Standard Model prediction vs. direct measurements

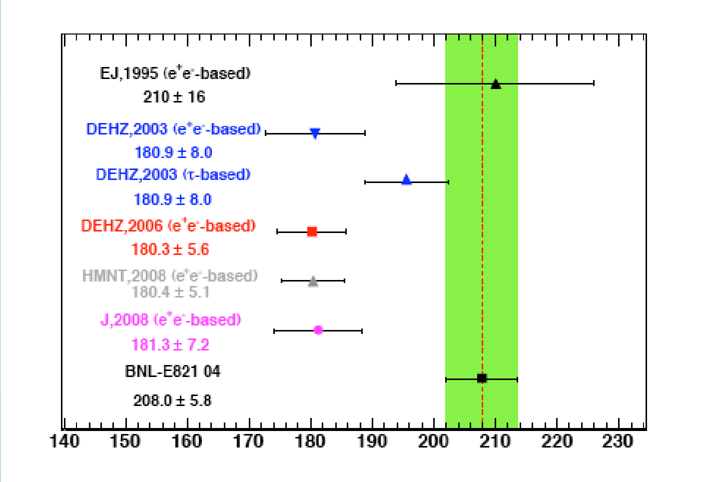
- Standard Model prediction vs. direct measurements

  3.4 σ disagreement

  … Let's look at that in deep

⇩

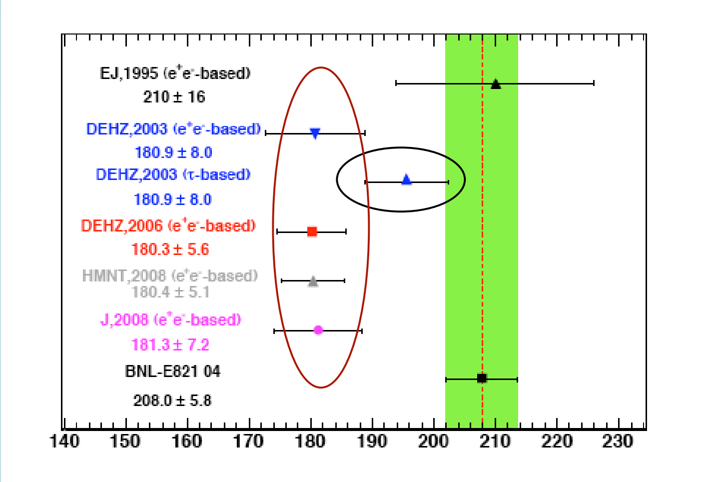
Experimental inputs to the theory



- Standard Model prediction vs. direct measurements

  3.4 σ disagreement

  ... Let's look at that in deep



↓

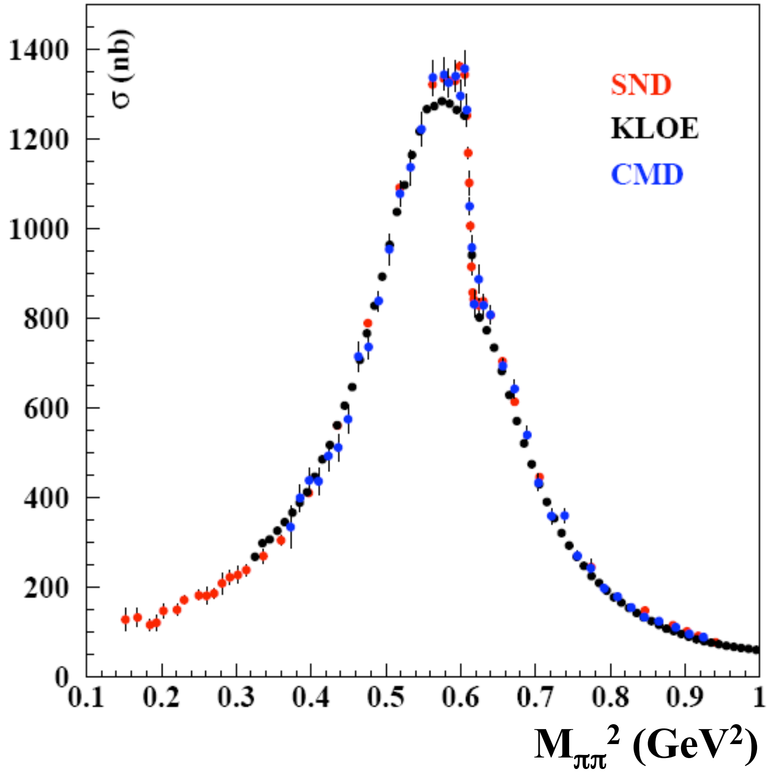
Experimental inputs to the theory

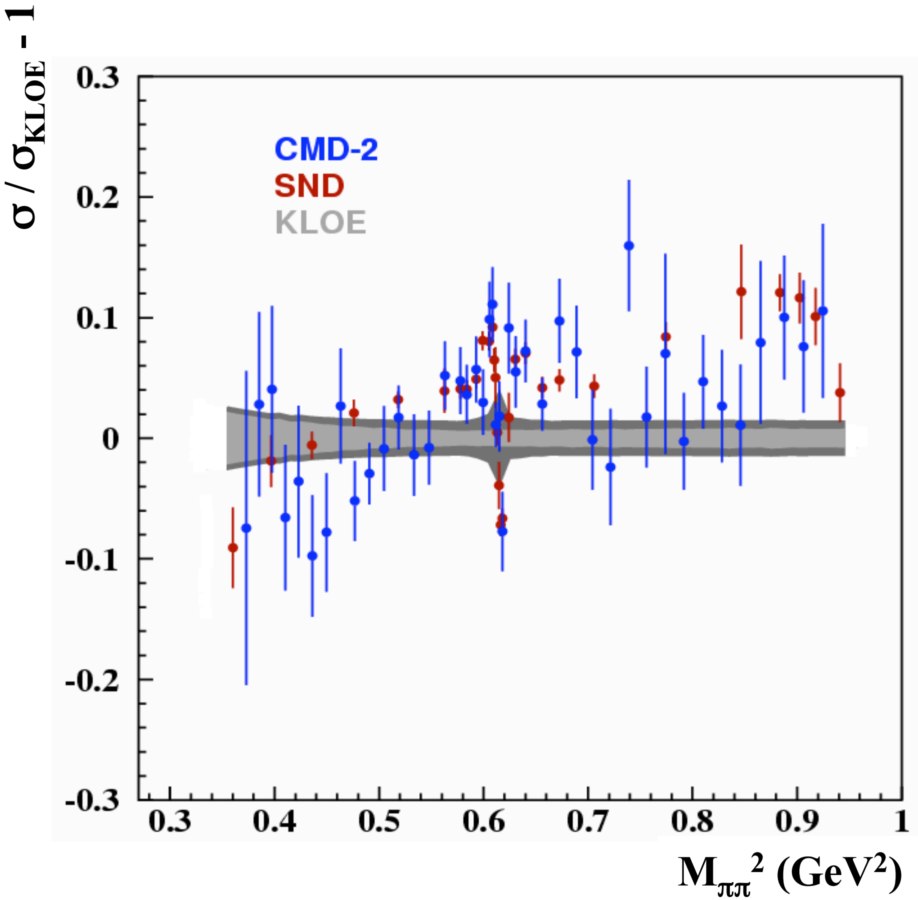
- e^+e^- & τ-data

Experimental input to $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{cut}} ds\,\sigma_{\pi\pi}(s)K(s)$$

$\sigma_{\pi\pi}(s)$ or $|F_\pi(s)|^2$ from e^+e^- cross section



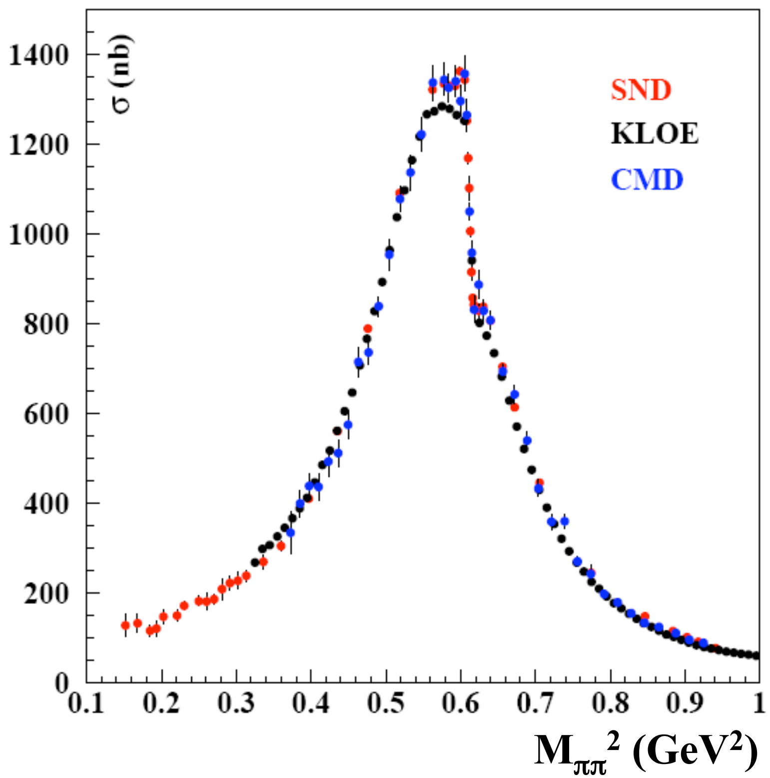


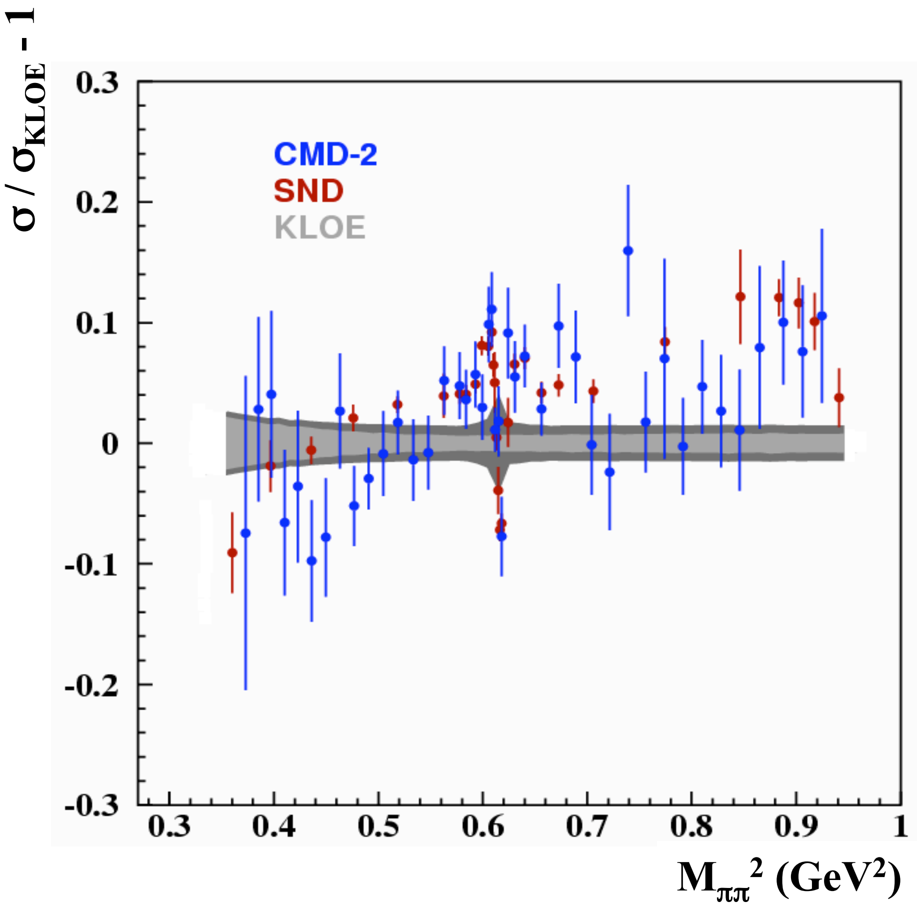
KLOE result (140 pb^{-1} of 2001)
Phys. Lett. B606 (2005) 12

Experimental input to $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{cut}} ds\, \sigma_{\pi\pi}(s) K(s)$$

$\sigma_{\pi\pi}(s)$ or $|F_\pi(s)|^2$ from e^+e^- cross section





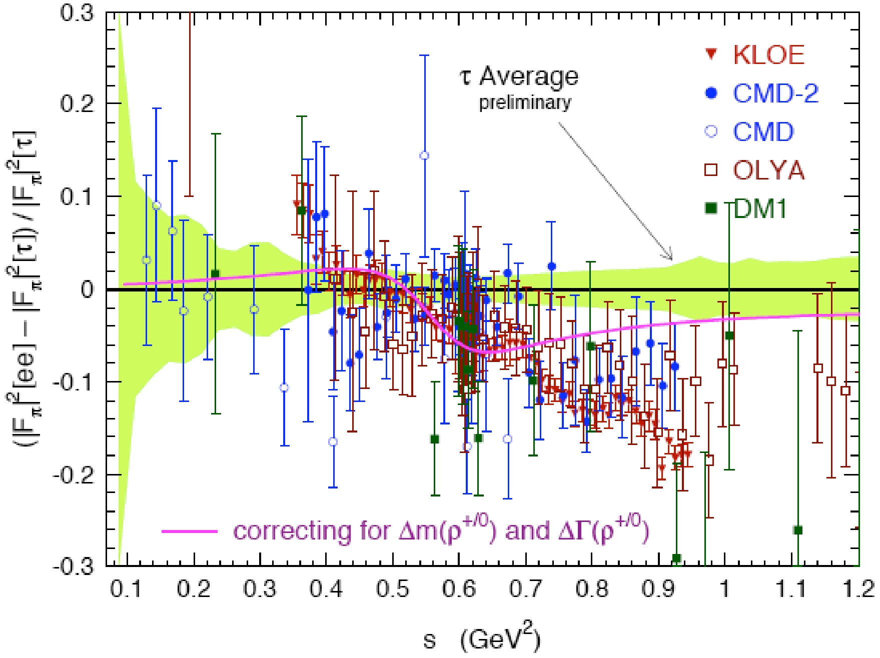
KLOE result (140 pb^{-1} of 2001)
Phys. Lett. B606 (2005) 12

Evaluation of $a_\mu^{\pi\pi}$ in agreement within 0.5 σ

Experimental input to $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{cut}} \mathrm{d}s\,\sigma_{\pi\pi}(s)K(s)$$

$\sigma_{\pi\pi}(s)$ or $|F_\pi(s)|^2$ from τ hadronic decay $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$

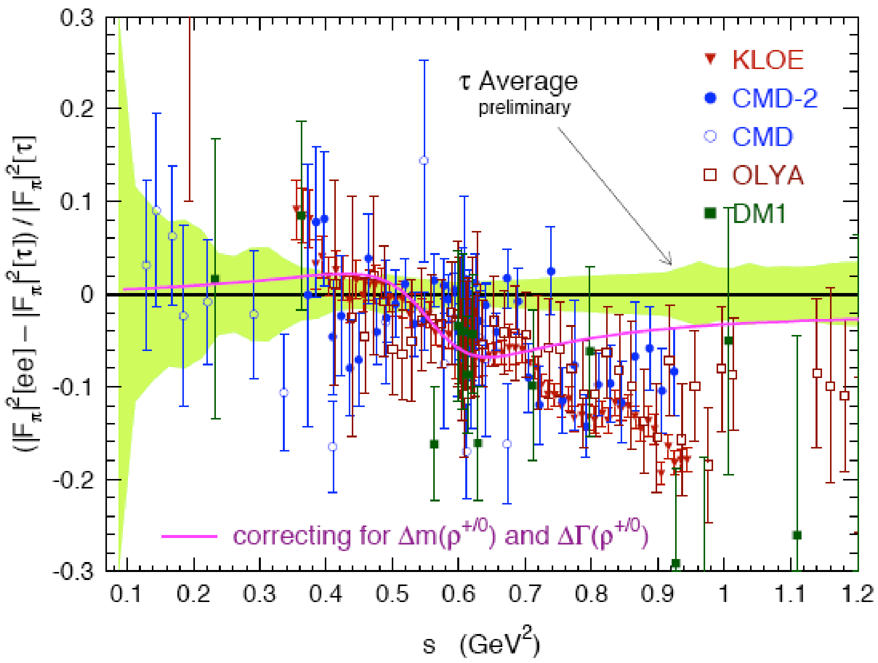


Evaluating $a_\mu^{\pi\pi}$ from τ data reduces $a_\mu^{exp}-a_\mu^{exp}$ discrepancy to ca. 1 σ

Experimental input to $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{E_{cut}} ds\,\sigma_{\pi\pi}(s)K(s)$$

$\sigma_{\pi\pi}(s)$ or $|F_\pi(s)|^2$ from τ hadronic decay $\tau^- \to \pi^-\pi^0\nu_\tau$



Evaluating $a_\mu^{\pi\pi}$ from τ data reduces $a_\mu^{exp}-a_\mu^{exp}$ discrepancy to ca. 1 σ

To get $|F_\pi(s)|^2$ from τ data requires many corrections and not all of them are completely under control

➔ To evaluate $a_\mu^{\pi\pi}$ preferentially **only inputs from e^+e^- data**

- Standard Model prediction vs. direct measurements

  3.4 σ disagreement

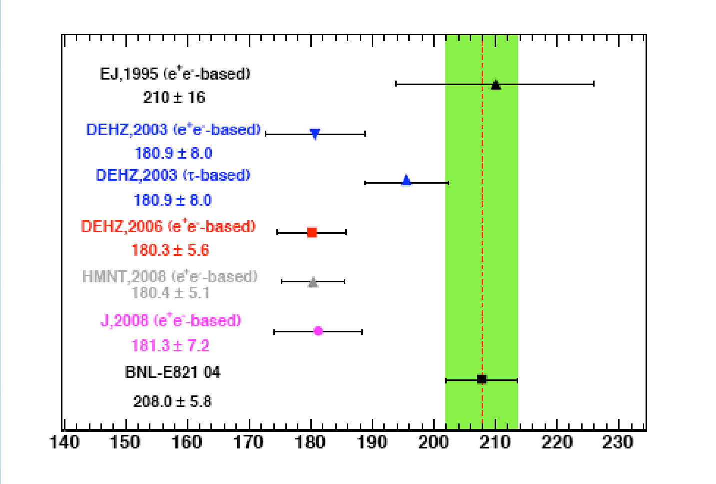
  ... Let's look at that in deep

⇓

Experimental inputs to the theory

- e^+e^- vs. τ-data

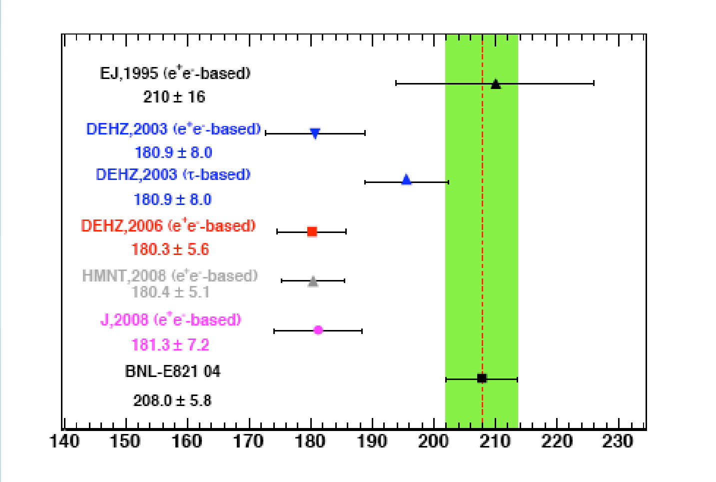
- e^+e^--data



- Standard Model prediction vs. direct measurements

  $3.4\,\sigma$ disagreement

  ... Let's look at that in deep



<u>Experimental inputs</u> to the theory

- e^+e^-- vs. τ-data

  disagreement in the spectra and in a_μ^{had}

  ... several things still to be understood in τ data

- e^+e^--data

- Standard Model prediction vs. direct measurements

  $3.4\ \sigma$ disagreement

  ... Let's look at that in deep

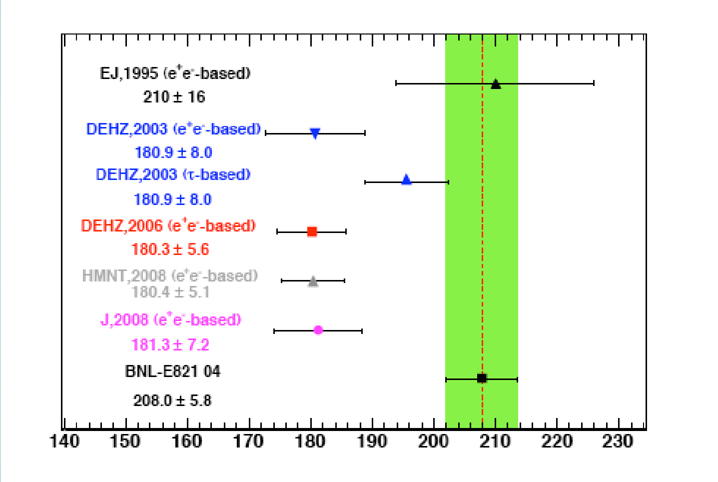
Experimental inputs to the theory

- e^+e^- vs. τ-data

disagreement in the spectra and in a_μ^{had}

... several things still to be understood in τ data

- e^+e^--data



- Standard Model prediction vs. direct measurements

  3.4 σ disagreement

  ... Let's look at that in deep

⇩

<u>Experimental inputs</u> to the theory

- e^+e^- vs. τ-data

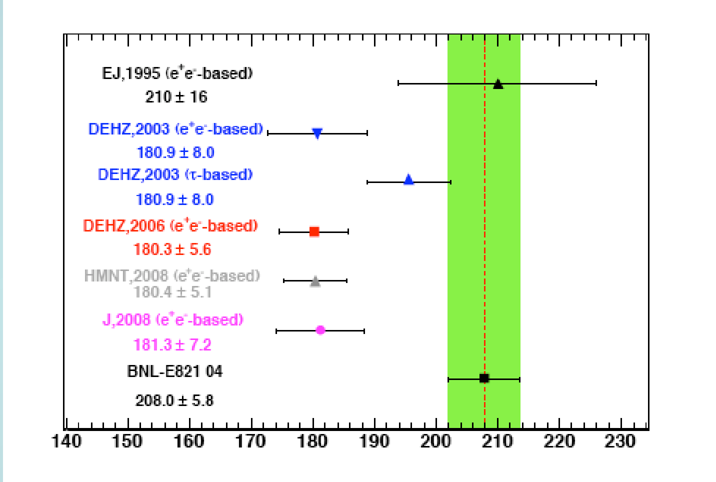
  disagreement in the spectra and in a_μ^{had}

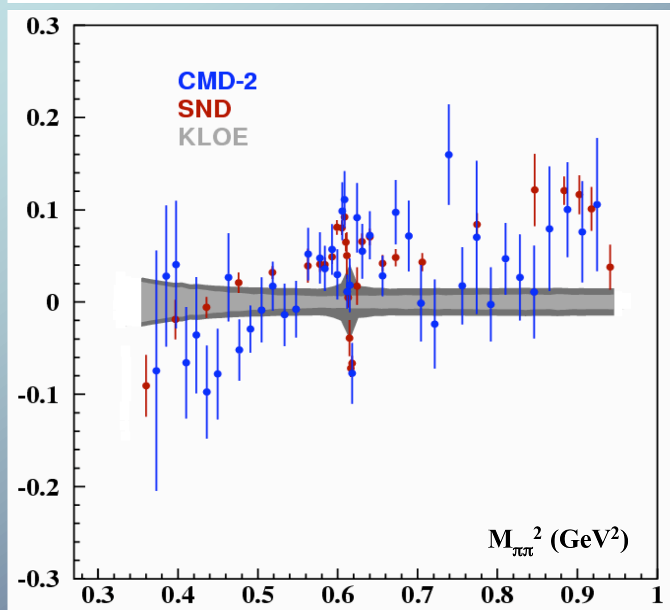
  ... several things still to be understood in τ data

- e^+e^--data

  disagreement among the spectra

  ... Let's look at that in deep

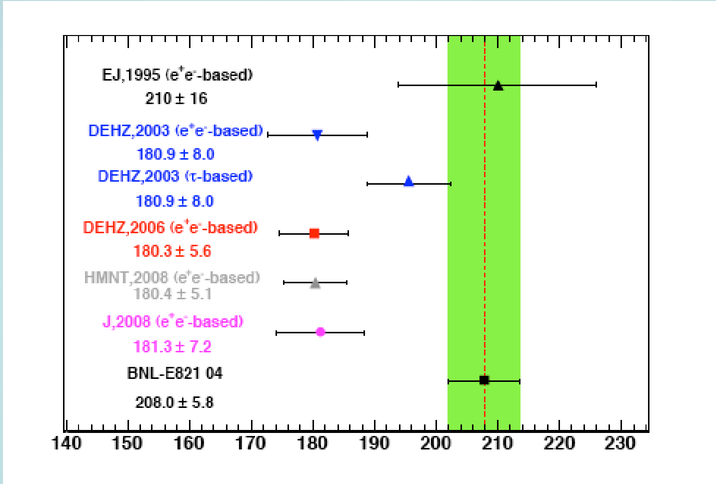




- Standard Model prediction vs. direct measurements

  3.4 σ disagreement

  ... Let's look at that in deep



Experimental inputs to the theory

- e^+e^- vs. τ-data

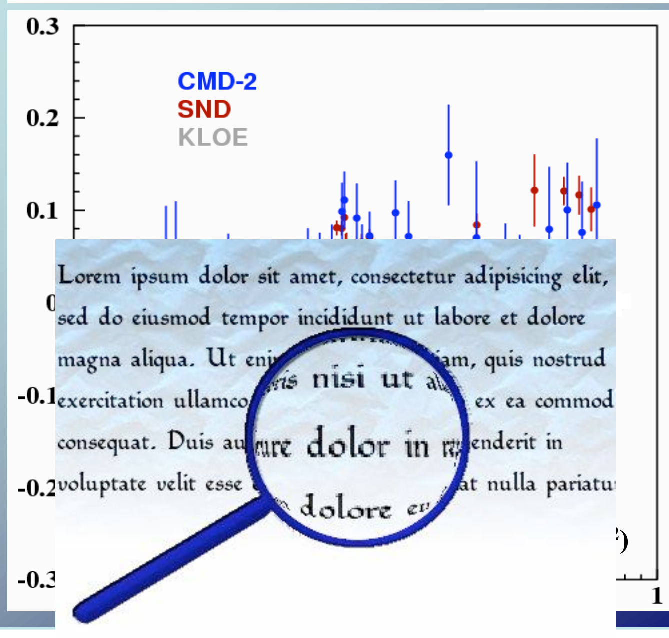
  disagreement in the spectra and in a_μ^{had}

  ... several things still to be understood in τ data

- e^+e^--data

  disagreement among the spectra

  ... Let's look at that in deep



Precise measurements of $\sigma^{had,LO}(s)$ (or $|F_\pi(s)|^2$ or $R(s)$) are needed

Precise <u>measurements</u> of $\sigma^{had,LO}(s)$ (or $|F_{\pi}(s)|^2$ or $R(s)$) are needed

1. Collisions of e^+e^- bunches

2. Hadron production at different energies

Precise <u>measurements</u> of $\sigma^{had,LO}(s)$ (or $|F_\pi(s)|^2$ or $R(s)$) are needed

1. Collisions of e^+e^- bunches

$\Rightarrow$ Collider

2. Hadron production at different energies

Precise <u>measurements</u> of $\sigma^{had,LO}(s)$ (or $|F_\pi(s)|^2$ or $R(s)$) are needed

1. Collisions of e^+e^- bunches

$\Rightarrow$ Collider

2. Hadron production at different energies

$\Rightarrow$ Changing the $\sqrt{s}$ of the bunches *

* experiments at Novosibirsk (VEPP-2M: SND and CMD-2)

Precise measurements of $\sigma^{had,LO}(s)$ (or $|F_\pi(s)|^2$ or $R(s)$) are needed

1. Collisions of e^+e^- bunches

⇒ Collider

2. Hadron production at different energies

⇒ Changing the $\sqrt{s}$ of the bunches *

⇒ Event with initial state radiated photon (ISR) **

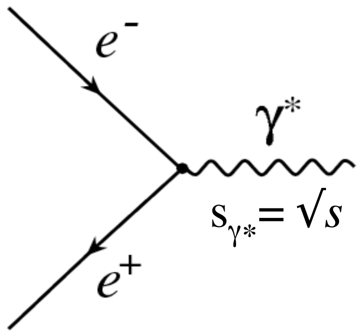
* experiments at Novosibirsk (VEPP-2M: SND and CMD-2)

** Flavor factories (PEP-II: BaBar, KEK-B: Belle, DAΦNE: KLOE)

2. Radiative Return method

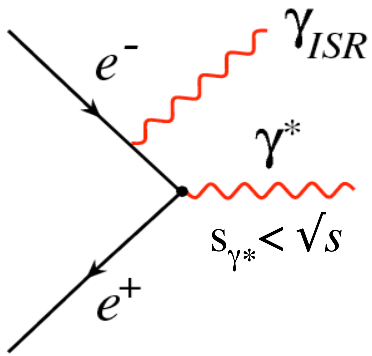
ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy



ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)

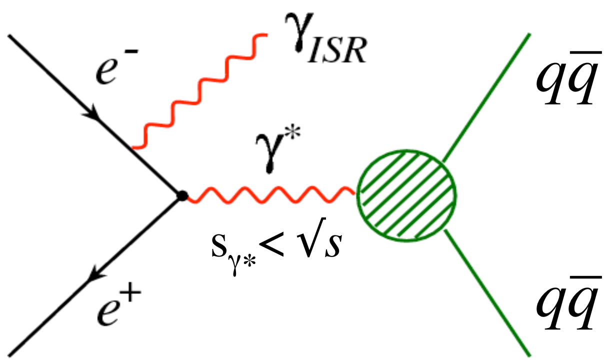


ISR events

ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

ISR events

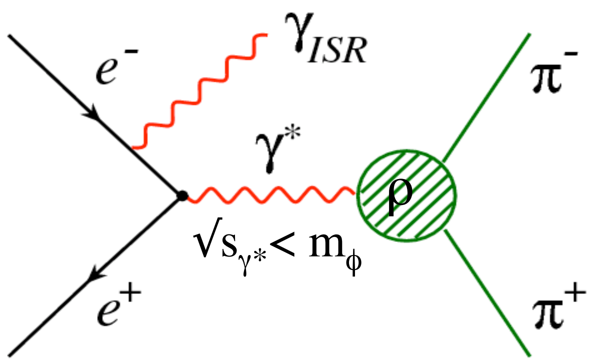


ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

DAΦNE: $\sqrt{s} = m_\phi = 1.02$ GeV ⇒ $\rho(\omega)$-resonance

ISR events



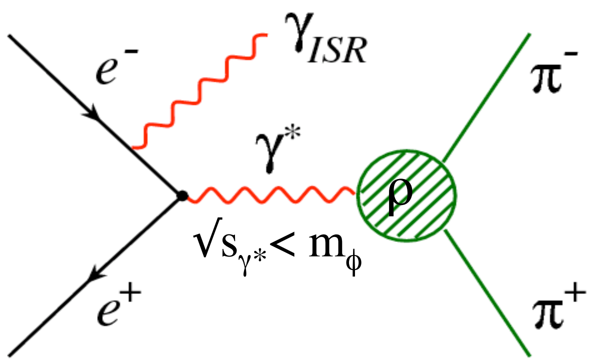
$e^+e^- \rightarrow \rho(\omega)+\gamma_{ISR} \rightarrow \pi^+\pi^- +\gamma_{ISR}$

ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

DAΦNE: $\sqrt{s} = m_\phi = 1.02$ GeV $\Rightarrow \rho(\omega)$-resonance

ISR events



$e^+e^- \rightarrow \rho(\omega)+\gamma_{ISR} \rightarrow \pi^+\pi^- +\gamma_{ISR}$

1. $\pi\pi\gamma$ spectrum as a function of pion-pair invariant mass, $M_{\pi\pi}{}^2$

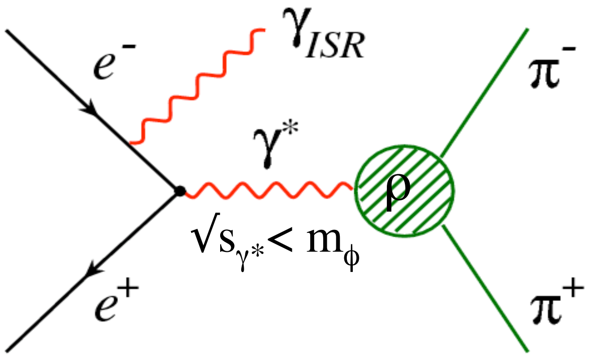
$$M_{\pi\pi}{}^2 \frac{\Delta\sigma_{\pi\pi\gamma}}{\Delta M_{\pi\pi}{}^2} = \sigma_{\pi\pi}(s) \times H(s)$$

ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

DAΦNE: $\sqrt{s} = m_\phi = 1.02$ GeV $\Rightarrow$ $\rho(\omega)$-resonance

ISR events



$e^+e^- \rightarrow \rho(\omega)+\gamma_{ISR} \rightarrow \pi^+\pi^- +\gamma_{ISR}$

1. $\pi\pi\gamma$ spectrum as a function of pion-pair invariant mass, $M_{\pi\pi}^2$

$$M_{\pi\pi}^2 \frac{\Delta\sigma_{\pi\pi\gamma}}{\Delta M_{\pi\pi}^2} = \sigma_{\pi\pi}(s) \times H(s)$$

2. Precise knowledge of radiative events

Radiator function H(s)

EVA + PHOKHARA MC generator

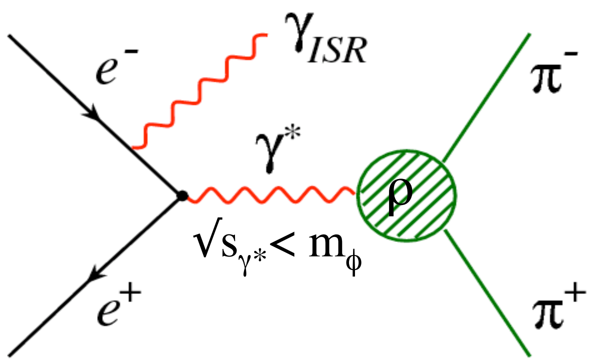
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27 (2003)

ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

DAΦNE: $\sqrt{s} = m_\phi = 1.02$ GeV $\Rightarrow \rho(\omega)$-resonance

ISR events



$e^+e^- \rightarrow \rho(\omega) + \gamma_{ISR} \rightarrow \pi^+\pi^- + \gamma_{ISR}$

1. $\pi\pi\gamma$ spectrum as a function of pion-pair invariant mass, $M_{\pi\pi}^2$

$$M_{\pi\pi}^2 \frac{\Delta\sigma_{\pi\pi\gamma}}{\Delta M_{\pi\pi}^2} = \sigma_{\pi\pi}(s) \times H(s)$$

2. Precise knowledge of radiative events

Radiator function $H(s)$

EVA + PHOKHARA MC generator

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

3. From $\sigma_{\pi\pi\gamma}(s)$ to $\sigma_{\pi\pi}(s)$

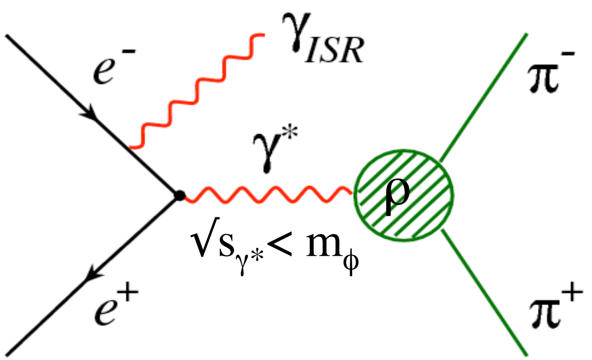
$$\sigma_{\pi\pi}(s) = \frac{\sigma_{\pi\pi\gamma}(s)}{H(s)}$$

ISR e^+e^- experiments

1. Particle factories (DAΦNE, PEP-II or KEK-B): fixed center of mass energy
2. Initial State Radiation (ISR) events (S. Binner, J.H. Kühn, K. Melnikov, Phys .Lett. B459 (1999) 279)
3. Radiative return back to a lower resonance

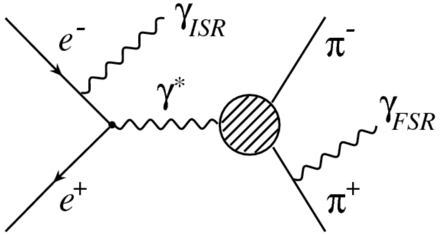
DAΦNE: $\sqrt{s} = m_\phi = 1.02$ GeV $\Rightarrow$ $\rho(\omega)$-resonance

ISR events



$e^+e^- \rightarrow \rho(\omega)+\gamma_{ISR} \rightarrow \pi^+\pi^- +\gamma_{ISR}$

Events with (FSR-NLO)
Final State Radiation Next to Leading Order



1. $\pi\pi\gamma$ spectrum as a function of pion-pair invariant mass, $M_{\pi\pi}^2$

$$M_{\pi\pi}^2 \frac{\Delta\sigma_{\pi\pi\gamma}}{\Delta M_{\pi\pi}^2} = \sigma_{\pi\pi}(s) \times H(s)$$

2. Precise knowledge of radiative events

Radiator function $H(s)$

EVA + PHOKHARA MC generator

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

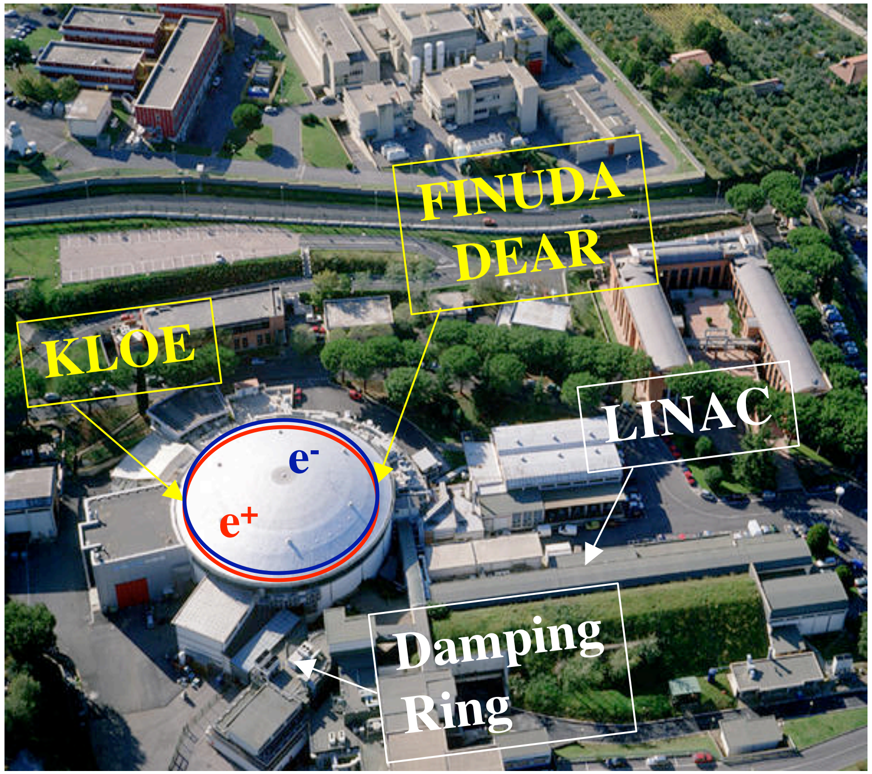
3. From $\sigma_{\pi\pi\gamma}(s)$ to $\sigma_{\pi\pi}(s)$

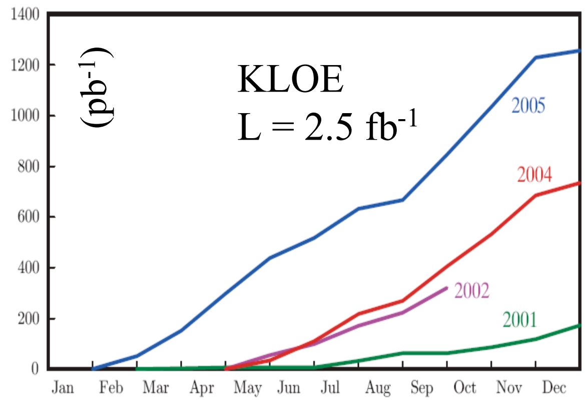
$$\sigma_{\pi\pi}(s) = \frac{\sigma_{\pi\pi\gamma}(s)}{H(s)}$$

3. Radiative Return measurements at KLOE

DAΦNE: the Frascati ϕ-factory

DAΦNE
e^+e^--collider at $\sqrt{s} = m_\phi = 1.0194$ GeV





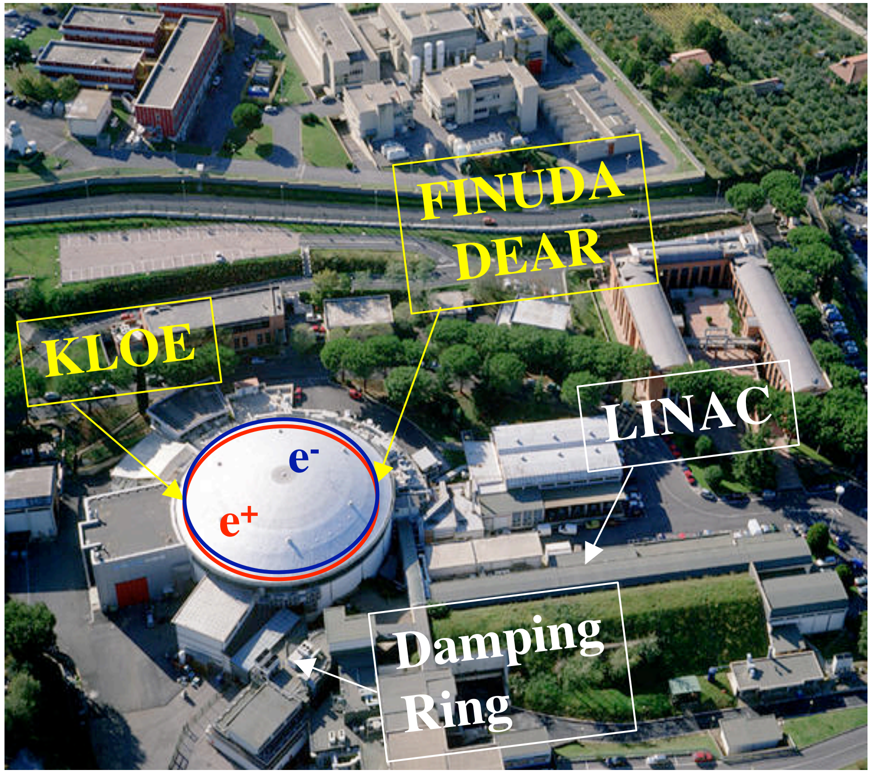
Main focus on kaon physics
> CPT test
> V_{us}, kaon form factors
> Rare kaon decays

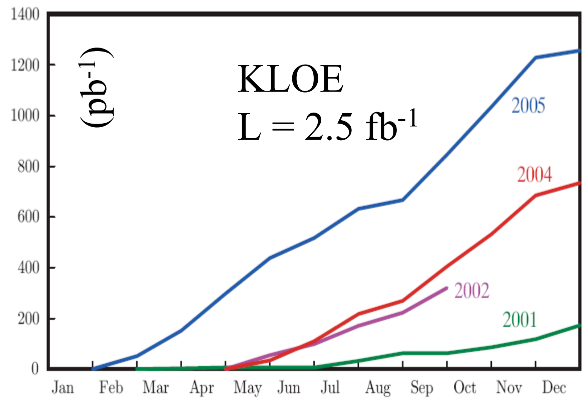
Non kaon physics
> radiative ϕ decays
> hadronic cross section
> η physics

DAΦNE: the Frascati ϕ-factory

DAΦNE

e^+e^--collider at $\sqrt{s} = m_\phi = 1.0194$ GeV



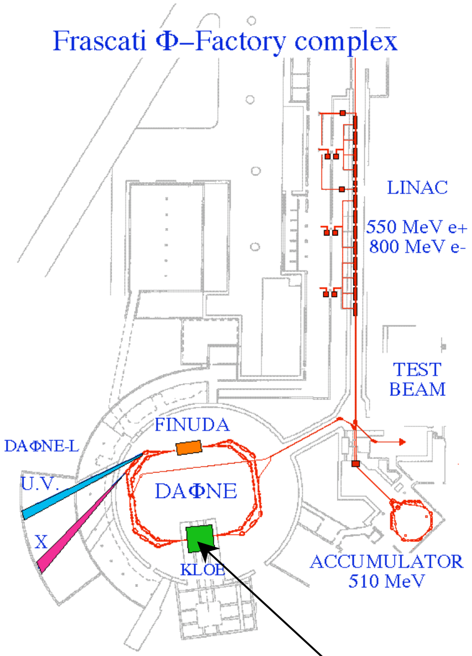


+ 225 pb^{-1} @1GeV (2006)

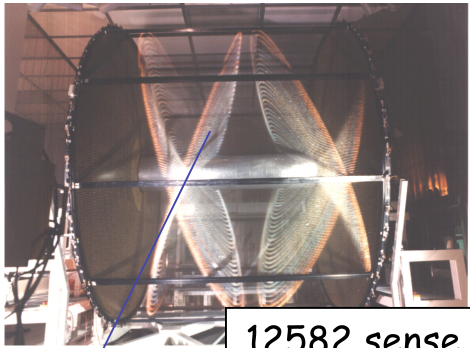
Main focus on kaon physics
> CPT test
> V_{us}, kaon form factors
> Rare kaon decays

Non kaon physics
> radiative ϕ decays
> hadronic cross section
> η physics

KLOE at DAΦNE



Drift chamber



12582 sense wires
52140 wires in total

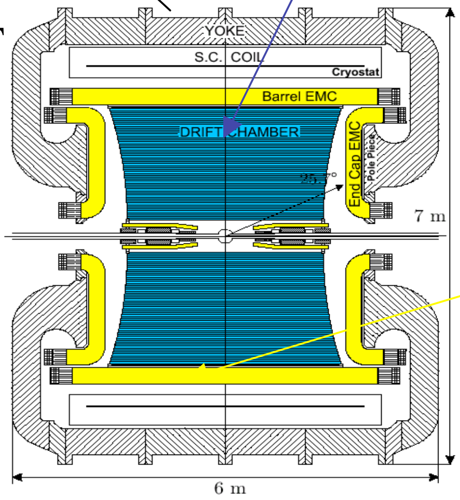
Track momentum resolution

$\sigma_p/p \approx 0.4\%$ ($\theta > 45°$)

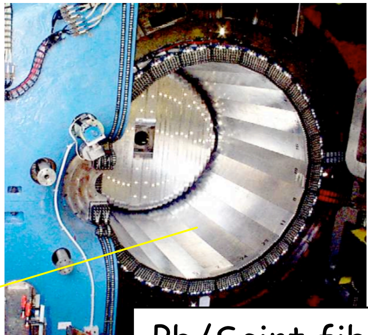
Vertex resolution

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

Magnetic Field of 0.52 T



Electro Magnetic Calorimeter



Pb/Scint fibers
4880 PM

Energy resolution

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

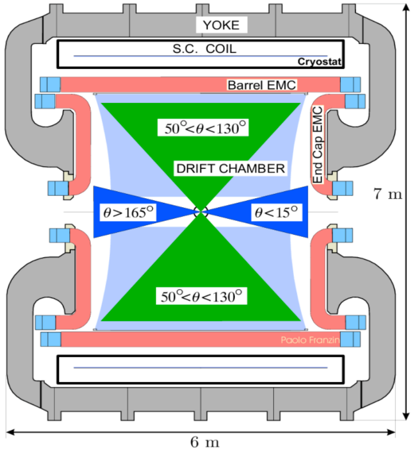
Time resolution

$\sigma_T = 57\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$

Analysis flow

$$\left|F_\pi(s)\right|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int L dt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$



$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$

Acceptance cuts

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi) \cdot \delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$

Acceptance cuts

Analysis cuts
Background subtraction
Efficiencies

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$

Acceptance cuts

Analysis cuts
Background subtraction
Efficiencies

Normalization to Luminosity

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi) \cdot \delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int L dt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

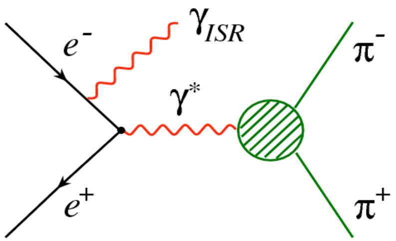
$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$

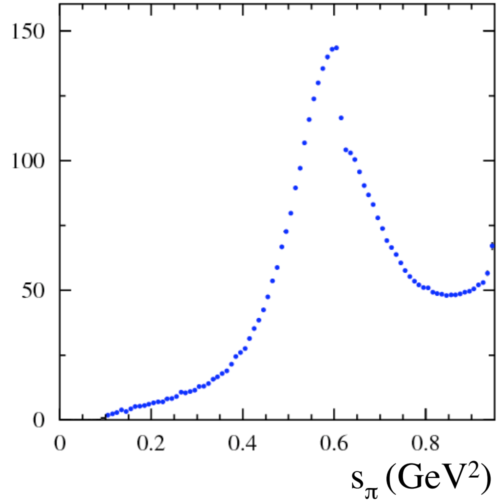
Acceptance cuts

Analysis cuts
Background subtraction
Efficiencies

Normalization to Luminosity

$d\sigma(\pi\pi\gamma(\gamma))/ds_\pi$



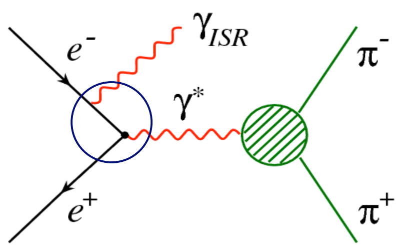


notation
$M_{\pi\pi}^2 = s_\pi$

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int L dt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$
Acceptance cuts

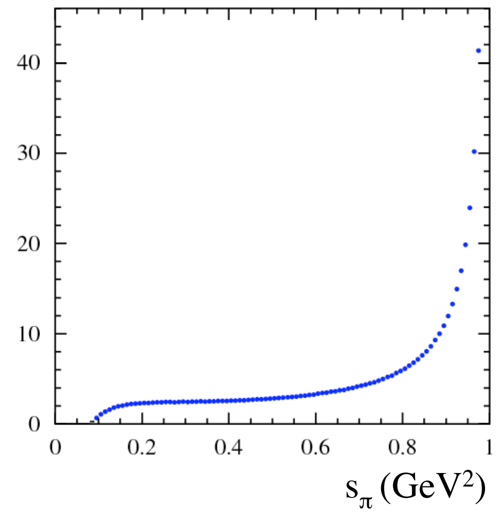
Analysis cuts
Background subtraction
Efficiencies



Normalization to Luminosity

$d\sigma(\pi\pi\gamma(\gamma))/ds_\pi$

Division by Radiator Function H(s)



notation
$M_{\pi\pi}^2 = s_\pi$

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$

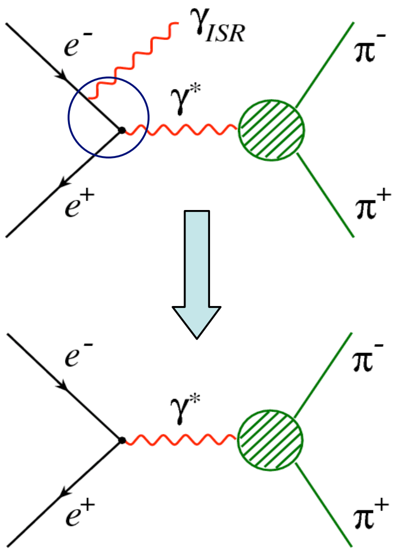
Acceptance cuts

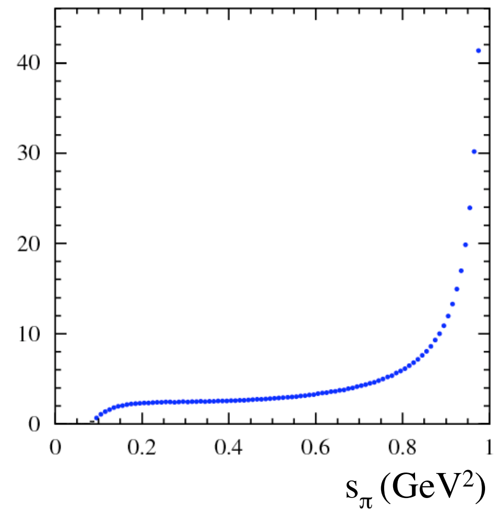
Analysis cuts
Background subtraction
Efficiencies

Normalization to Luminosity

$d\sigma(\pi\pi\gamma(\gamma))/ds_\pi$

Division by Radiator Function $H(s)$





notation
$M_{\pi\pi}^2 = s_\pi$

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi) \cdot \delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$
Acceptance cuts

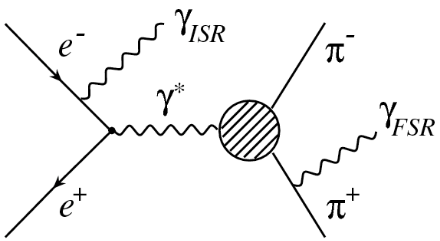
Analysis cuts
Background subtraction
Efficiencies

Normalization to Luminosity

$d\sigma(\pi\pi\gamma(\gamma))/ds_\pi$

Division by Radiator Function $H(s)$

FSR correction



notation
$M_{\pi\pi}^2 = s_\pi$

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

$\Delta N(\pi\pi\gamma(\gamma))/\Delta s_\pi$
Acceptance cuts

Analysis cuts
Background subtraction
Efficiencies

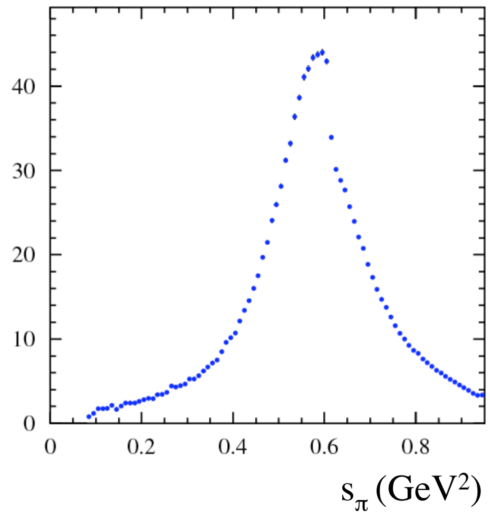
Normalization to Luminosity

$d\sigma(\pi\pi\gamma(\gamma))/ds_\pi$

Division by Radiator Function $H(s)$

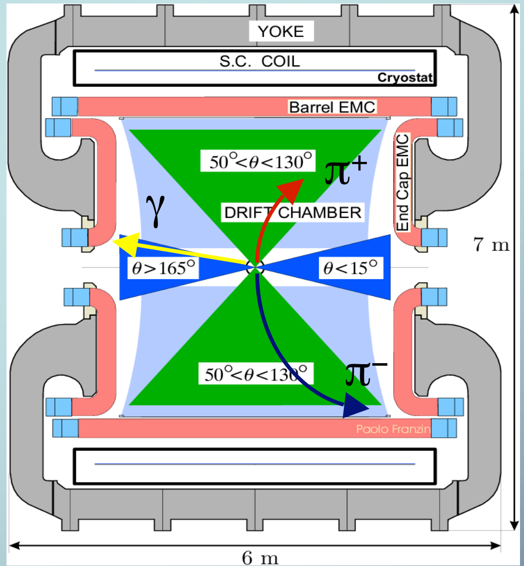
FSR correction

$|F_\pi|^2$



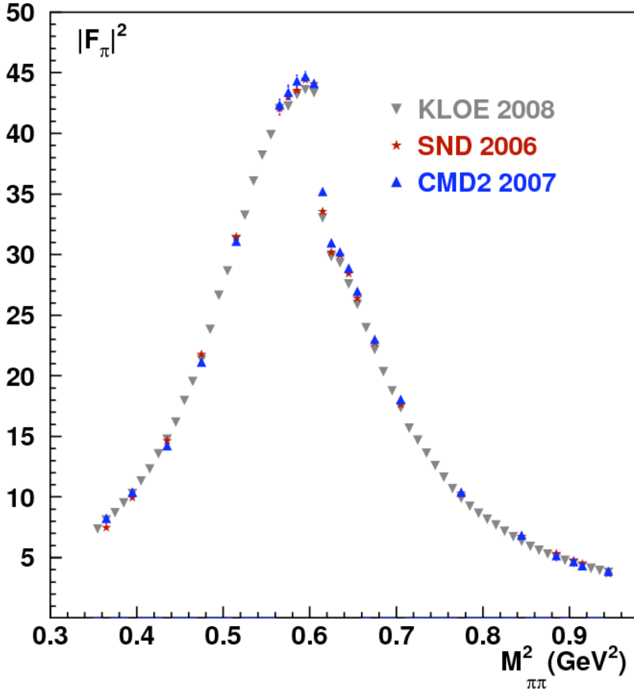
notation
$M_{\pi\pi}^2 = s_\pi$

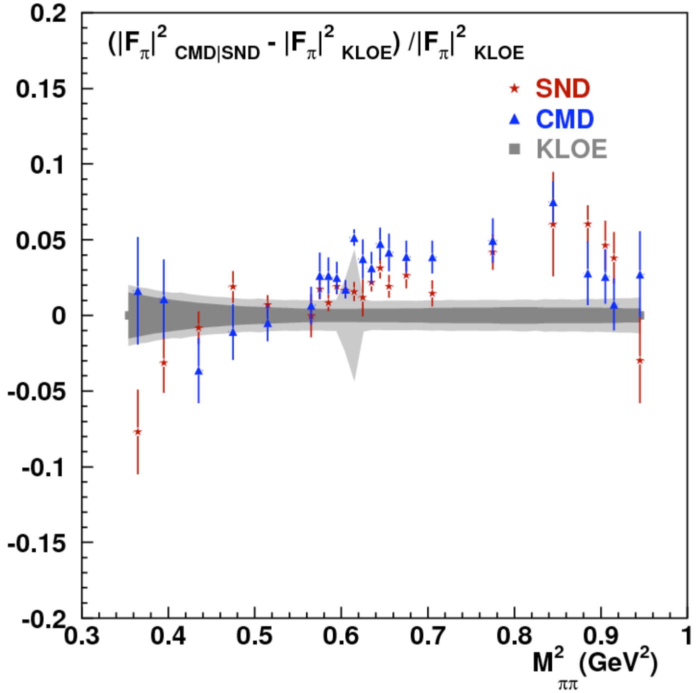
3.1 Newest KLOE published result
2002 data
w/o tagging the radiated photon
(radiated γ at small polar angle)



2008 published result: $|F_\pi(s)|^2$

arXiv:0809.3950v1, submitted and accepted by PLB



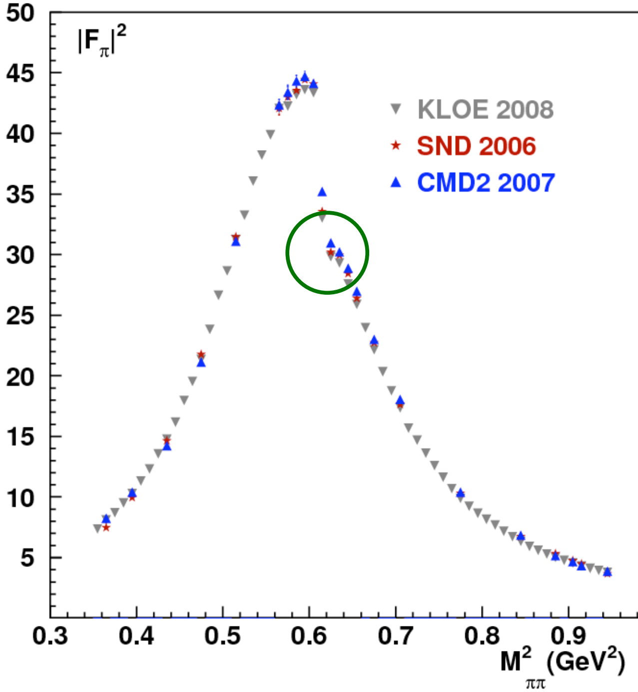


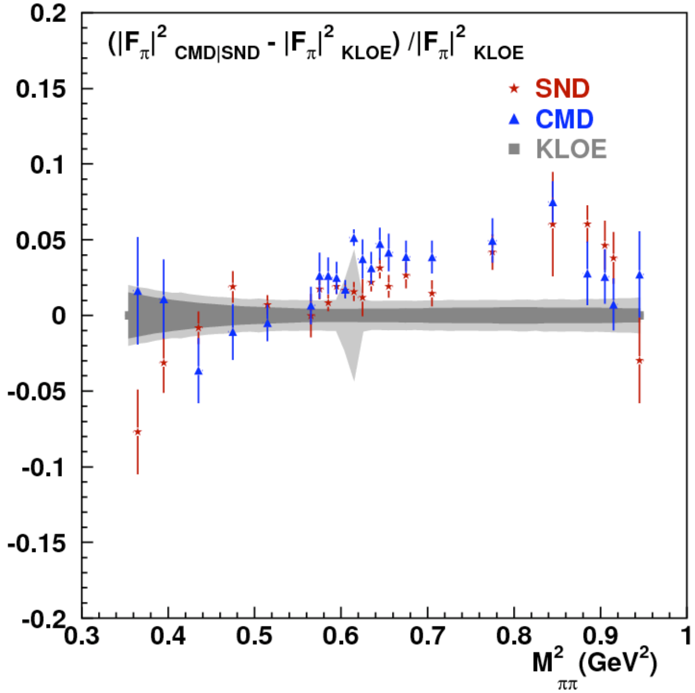
$$a_\mu^{\pi\pi} = 1/4\pi^3 \int_{0.35\mathrm{GeV}^2}^{0.95\mathrm{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = (387.6 \pm 0.5_{stat} \pm 2.5_{syst,\,exp} \pm 2.5_{sys,theo}) \times 10^{-10}$$

2008 published result: $|F_\pi(s)|^2$

arXiv:0809.3950v1, submitted and accepted by PLB





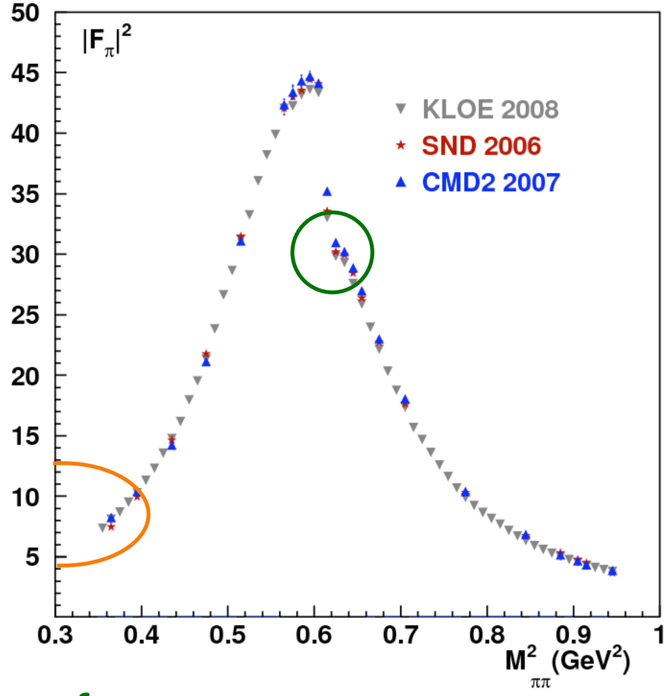
- ρ–ω interference

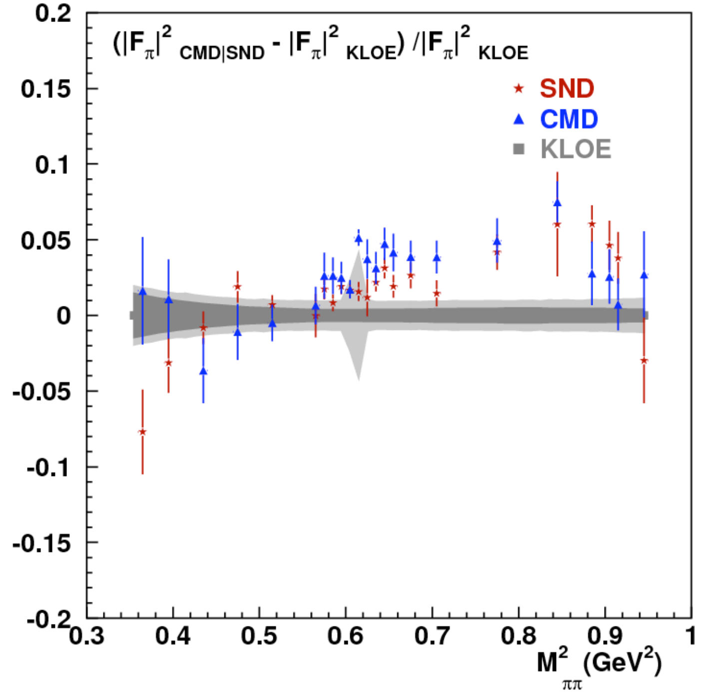
$$a_\mu^{\pi\pi} = 1/4\pi^3 \int_{0.35\mathrm{GeV}^2}^{0.95\mathrm{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = (387.6 \pm 0.5_{stat} \pm 2.5_{syst,\,exp} \pm 2.5_{sys,theo}) \times 10^{-10}$$

2008 published result: $|F_\pi(s)|^2$

arXiv:0809.3950v1, submitted and accepted by PLB





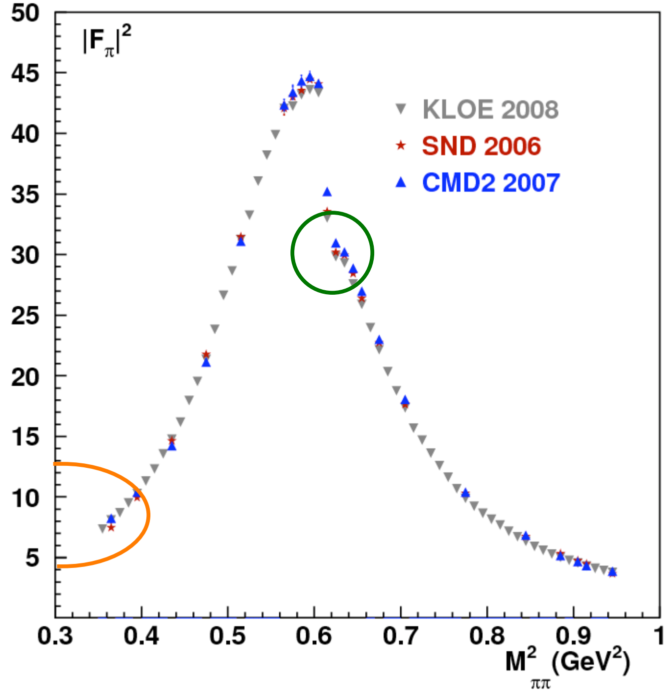
- $\rho-\omega$ interference
- threshold = $4m_\pi^2$ ($\approx 0.08\text{GeV}^2$) not reachable

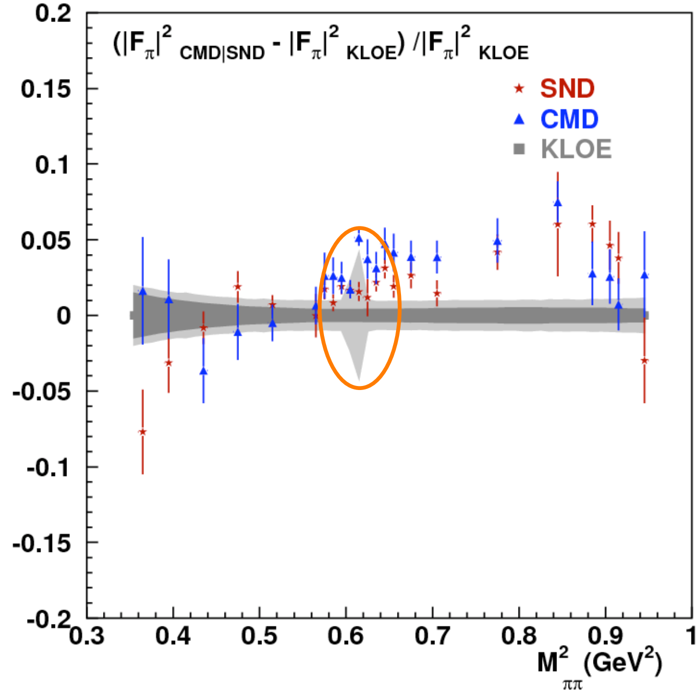
$$a_\mu^{\pi\pi} = 1/4\pi^3 \int_{0.35\text{GeV}^2}^{0.95\text{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ \text{GeV}^2) = (387.6 \pm 0.5_{stat} \pm 2.5_{syst,\,exp} \pm 2.5_{sys,theo}) \times 10^{-10}$$

2008 published result: $|F_\pi(s)|^2$

arXiv:0809.3950v1, submitted and accepted by PLB





- ρ–ω interference
- threshold = $4m_\pi^2$ (≈ 0.08GeV^2) not reachable

- increasing of the systematic error due to "unfolding" (from detector resolution) procedure

$$a_\mu^{\pi\pi} = 1/4\pi^3 \int_{0.35\mathrm{GeV}^2}^{0.95\mathrm{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = (387.6 \pm 0.5_{stat} \pm 2.5_{syst,\,exp} \pm 2.5_{sys,theo}) \times 10^{-10}$$

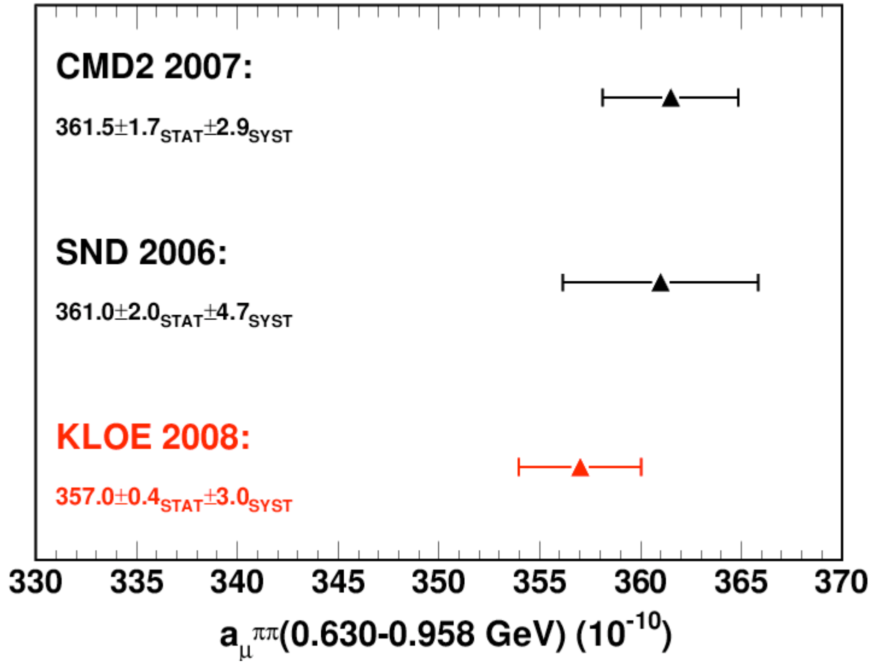
2008 published result: $a_\mu^{\pi\pi}$

Coll.	Year	$a_\mu^{\pi\pi}(0.630 < \sqrt{s}\ (GeV) < 0.958)$
SND	2006	$(361.0 \pm 2.0_{stat} \pm 4.7_{sys}) \times 10^{-10}$
CMD2	2007	$(361.5 \pm 1.7_{stat} \pm 2.9_{sys}) \times 10^{-10}$
KLOE	2008	$(357.0 \pm 0.4_{stat} \pm 3.0_{sys}) \times 10^{-10}$

Phys. Lett. B648 (2007) 28

arXiv:0809.3950v1

KLOE result based on 2002 data



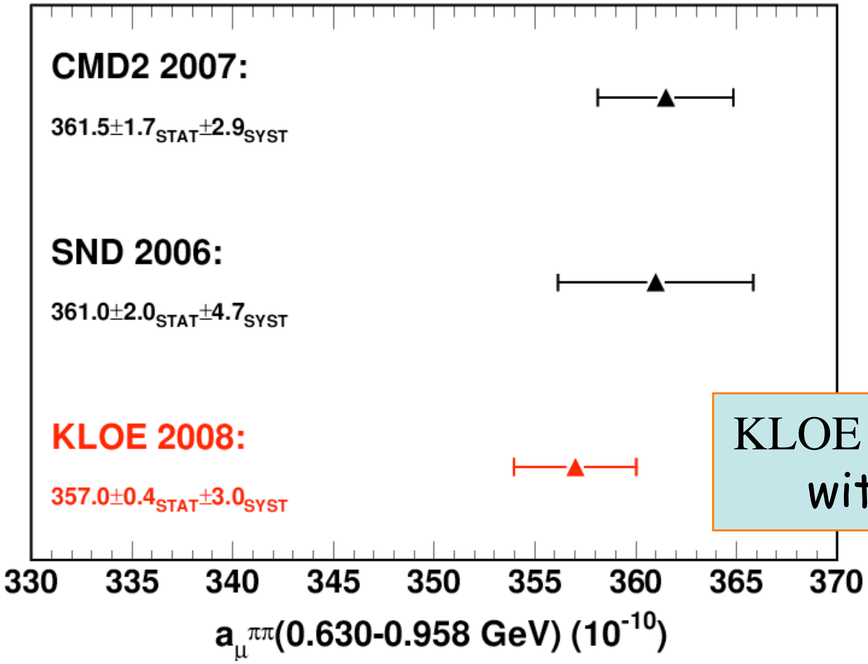
2008 published result: $a_\mu^{\pi\pi}$

Coll.	Year	$a_\mu^{\pi\pi}(0.630 < \sqrt{s}\ (GeV) < 0.958)$
SND	2006	$(361.0 \pm 2.0_{stat} \pm 4.7_{sys}) \times 10^{-10}$
CMD2	2007	$(361.5 \pm 1.7_{stat} \pm 2.9_{sys}) \times 10^{-10}$
KLOE	2008	$(357.0 \pm 0.4_{stat} \pm 3.0_{sys}) \times 10^{-10}$

Phys. Lett. B648 (2007) 28

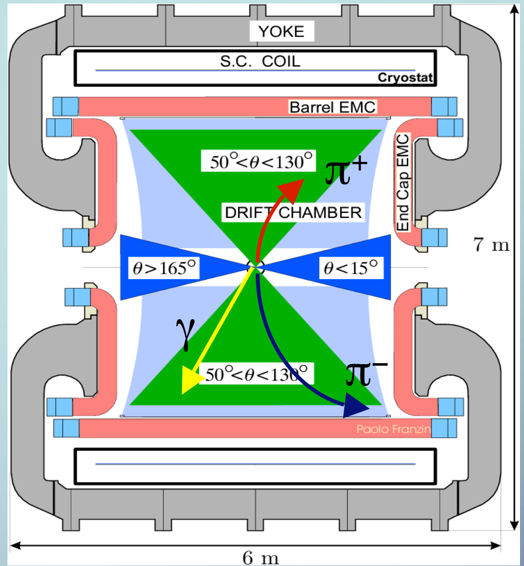
arXiv:0809.3950v1

KLOE result based on 2002 data



KLOE result in agreement with CMD2 and SND

3.2 Ongoing KLOE analyses 2002 and 2006 data tagging the radiated photon (radiated γ at large polar angle)



Large Angle analyses data samples

> "On Peak":
  2002 (ca. 240 pb^{-1}): $\sqrt{s} = m_\phi = 1.0194$ GeV

> "Off Peak":
  2006 (ca. 225 pb^{-1}): $\sqrt{s} = 1$ GeV

Large Angle analyses data samples

> "On Peak":
  2002 (ca. 240 pb^{-1}): $\sqrt{s} = m_\phi = 1.0194$ GeV

> "Off Peak":
  2006 (ca. 225 pb^{-1}): $\sqrt{s} = 1$ GeV
  -> reduced background from ϕ decays

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

Large Angle analyses data samples

> "On Peak":

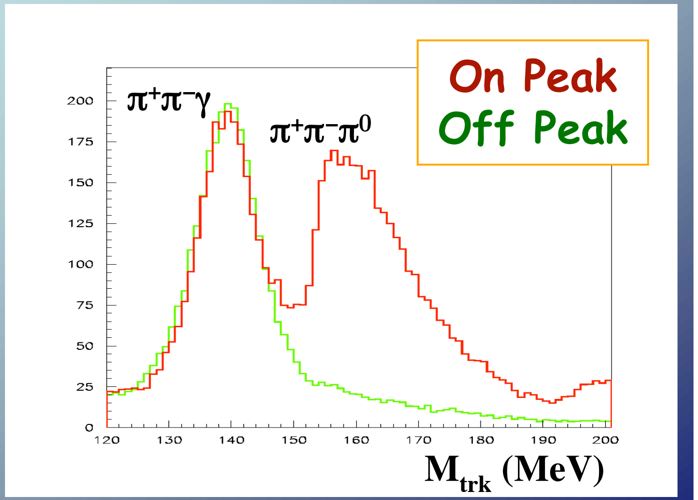
2002 (ca. 240 pb^{-1}): $\sqrt{s} = m_\phi = 1.0194$ GeV

> "Off Peak":

2006 (ca. 225 pb^{-1}): $\sqrt{s} = 1$ GeV

-> reduced background from ϕ decays

~~$\phi \to \pi^+\pi^-\pi^0$~~



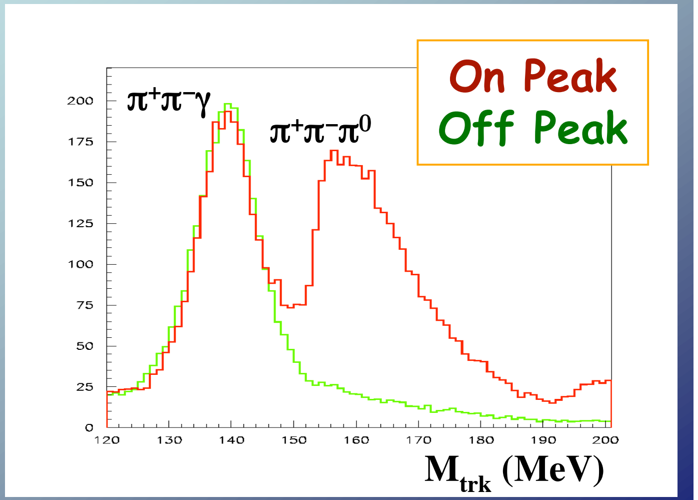
Large Angle analyses data samples

> "On Peak":
   2002 (ca. 240 pb^{-1}): $\sqrt{s} = m_\phi = 1.0194$ GeV

> "Off Peak":
   2006 (ca. 225 pb^{-1}): $\sqrt{s} = 1$ GeV
   -> reduced background from ϕ decays

~~$\phi \to \pi^+\pi^-\pi^0$~~

$\phi \to f_0(980)\,\gamma \to \pi^+\pi^-\gamma$



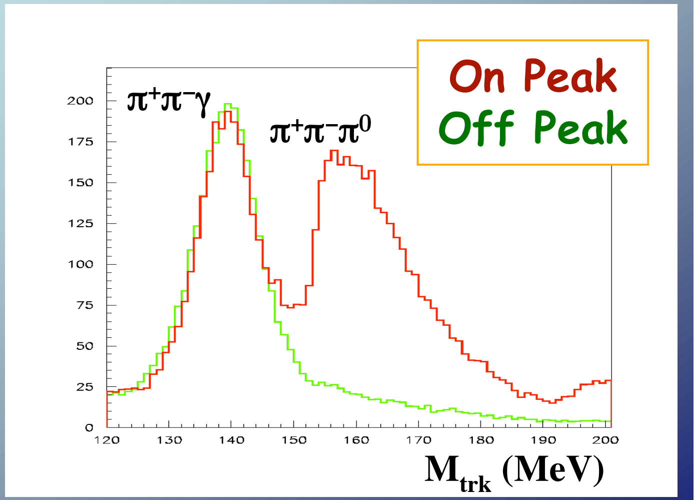
Large Angle analyses data samples

> "On Peak":
  2002 (ca. 240 pb^{-1}): $\sqrt{s} = m_\phi = 1.0194$ GeV

> "Off Peak":
  2006 (ca. 225 pb^{-1}): $\sqrt{s} = 1$ GeV
  -> reduced background from ϕ decays

~~$\phi \rightarrow \pi^+\pi^-\pi^0$~~

~~$\phi \rightarrow f_0(980)\,\gamma \rightarrow \pi^+\pi^-\gamma$~~



Signal selection

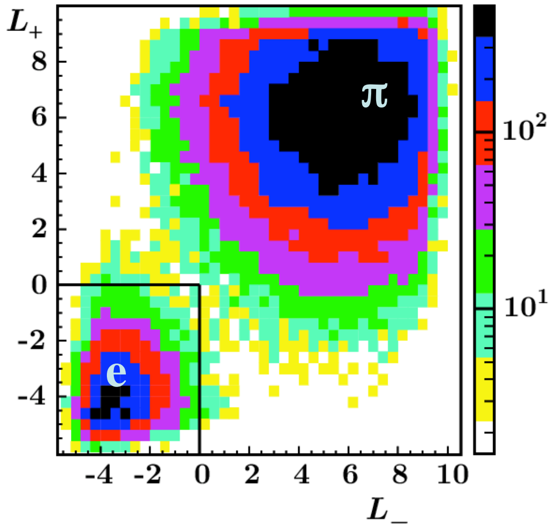
Background sources

$e^+e^- \rightarrow e^+e^-\gamma, \mu^+\mu^-\gamma$

$\phi \rightarrow \pi^+\pi^-\pi^0$ (strongly reduced in 2006 DATA)

$\phi \rightarrow f_0(980)\,\gamma \rightarrow \pi^+\pi^-\gamma$ (strongly reduced in 2006 DATA)

- Likelihood function for e-π separation: calorimeter and time of flight information used for each track



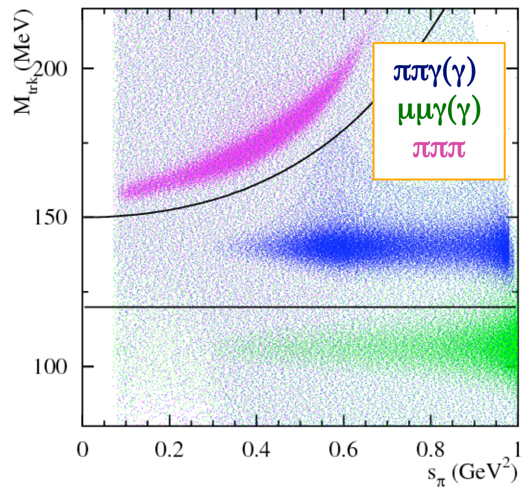
- Kinematic cuts:
  - Trackmass: 4-momenta conservation under the hypothesis of $e^+e^- \rightarrow x^+x^-\gamma$

$$\left(\sqrt{s} - \sqrt{\vec{p}_{x+}^{\,2} + M_{trk}^2} - \sqrt{\vec{p}_{x-}^{\,2} + M_{trk}^2}\right)^2 - (\vec{p}_{x+} + \vec{p}_{x-})^2 = q_\gamma^2 = 0$$

  - Omega angle: angle between the missing momentum and the momentum of the tagged photon

$$\Omega = \mathrm{acos}(\vec{p}_\gamma \cdot \vec{p}_{miss})$$

  - (2002) Kinematic fit: under the hypothesis of $e^+e^- \rightarrow 3\pi$, selecting $\chi^2 > \chi^2_{cut}$

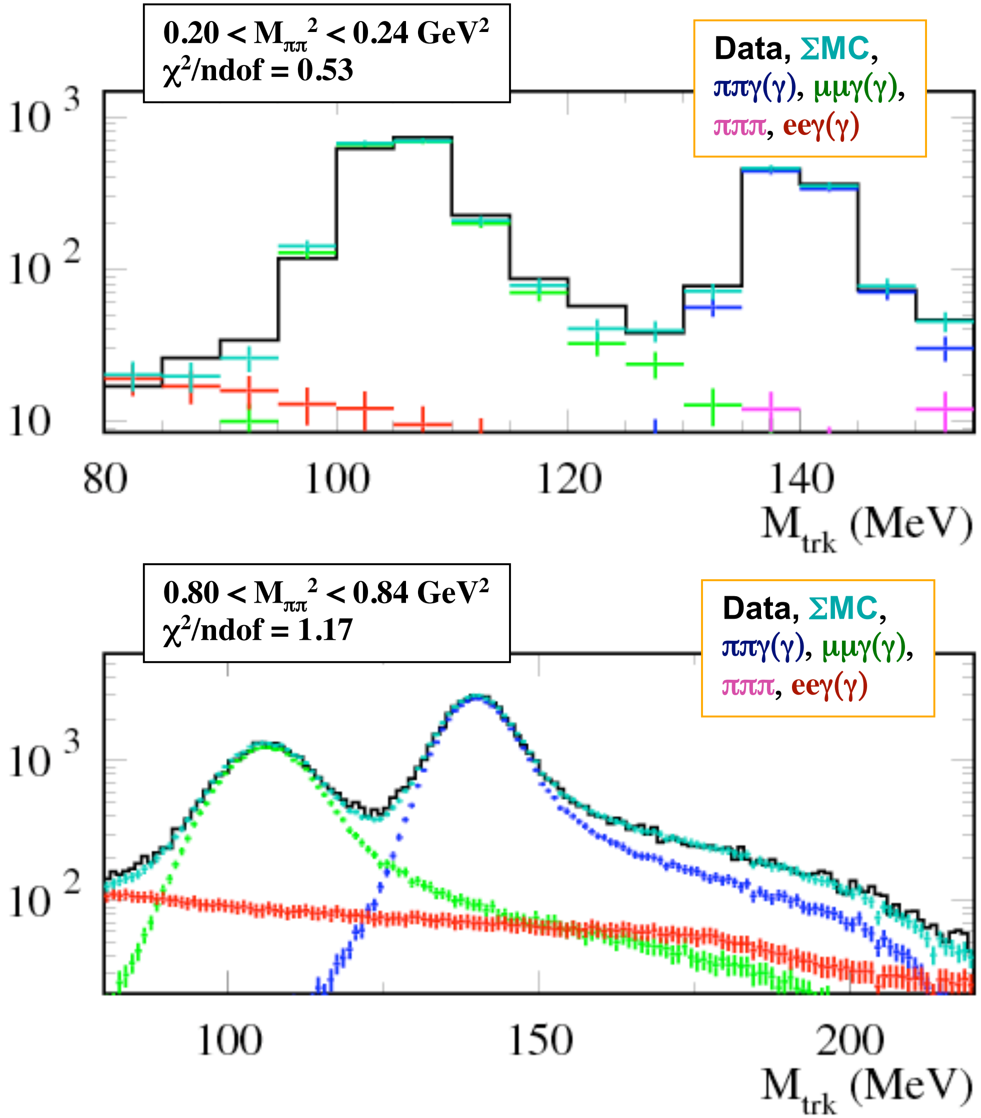


Background subtraction

2006 DATA sample

-> looser analysis cuts

-> background estimated and subtracted with sophisticate fit procedure



Pion Form Factor extraction (2006 data)

$$\left|F_{\pi}(s)\right|^{2} = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_{\pi}} \times \frac{1}{\varepsilon_{Select}(s_{\pi}) \cdot \delta_{rad}(s_{\pi}, s_{\gamma*})} \times \frac{1}{\int L dt} \times \frac{1}{H(s_{\pi}, s_{\gamma*})}$$

Pion Form Factor extraction (2006 data)

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

- Main challenge: **systematic errors** to be reduced down to **per-mil level**

Pion Form Factor extraction (2006 data)

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi) \cdot \delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

- Main challenge: **systematic errors** to be reduced down to **per-mil level**

=> Analysis cuts and background subtraction
- in "safe" regions
- best possible DATA-MC agreement

< 0.35 GeV^2	0.35-0.5 GeV^2	0.5-0.7 GeV^2	0.7-0.85 GeV^2
1%	0.3%	0.1%	0.2%

Pion Form Factor extraction (2006 data)

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi) \cdot \delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int Ldt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

- Main challenge: **systematic errors** to be reduced down to **per-mil level**

=> Analysis cuts and background subtraction
- in "safe" regions
- best possible DATA-MC agreement

< 0.35 GeV^2	0.35-0.5 GeV^2	0.5-0.7 GeV^2	0.7-0.85 GeV^2
1%	0.3%	0.1%	0.2%

=> Efficiencies
- from MonteCarlo
- correct by means of $\varepsilon_{DT}/\varepsilon_{MC}$ ratio

< 0.35 GeV^2	0.35-0.5 GeV^2	0.5-0.7 GeV^2	0.7-0.85 GeV^2
0.5%	0.4%		0.1%

Pion Form Factor extraction (2006 data)

$$|F_\pi(s)|^2 = \frac{\Delta N^{obs} - \Delta N^{bkg}}{\Delta s_\pi} \times \frac{1}{\varepsilon_{Select}(s_\pi)\cdot\delta_{rad}(s_\pi, s_{\gamma*})} \times \frac{1}{\int L dt} \times \frac{1}{H(s_\pi, s_{\gamma*})}$$

- Main challenge: **systematic errors** to be reduced down to **per-mil level**

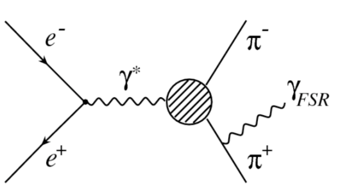
=> Analysis cuts and background subtraction
- in "safe" regions
- best possible DATA-MC agreement

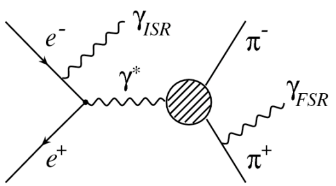
< 0.35 GeV²	0.35-0.5 GeV²	0.5-0.7 GeV²	0.7-0.85 GeV²
1%	0.3%	0.1%	0.2%

=> Efficiencies
- from MonteCarlo
- correct by means of $\varepsilon_{DT}/\varepsilon_{MC}$ ratio

< 0.35 GeV²	0.35-0.5 GeV²	0.5-0.7 GeV²	0.7-0.85 GeV²
0.5%	0.4%		0.1%

=> Radiative corrections
- experimental and theoretical errors





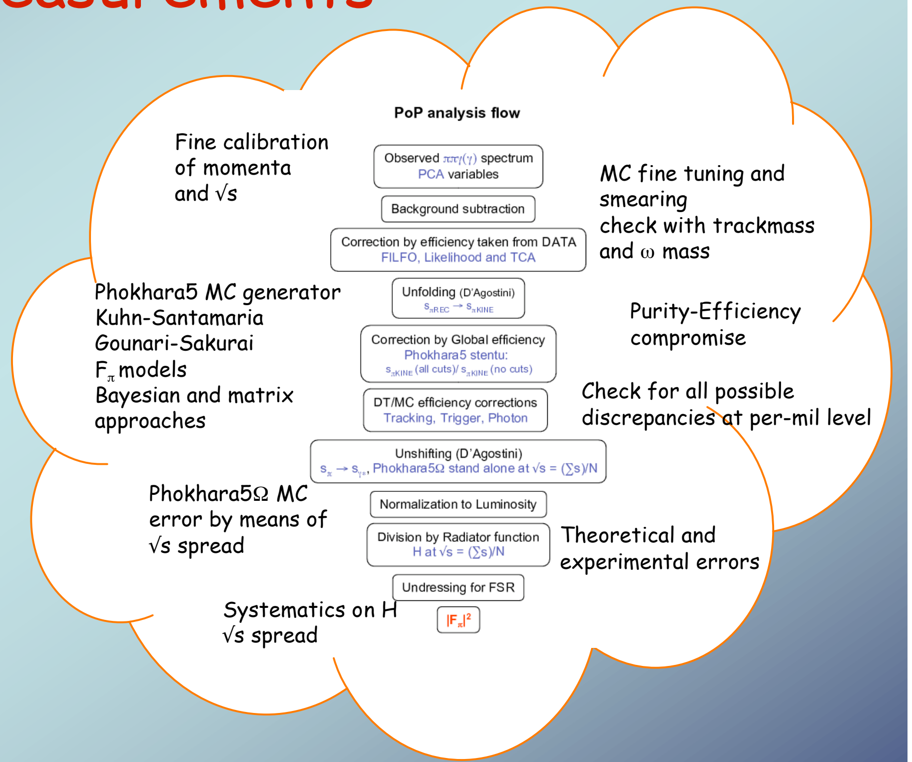
Unshifting from s_π to $s_{\gamma*}$	0.1%
Radiator function	0.5%
FSR and NLO radiation	0.3%

Searching for New Physics
via
high precision measurements

First…

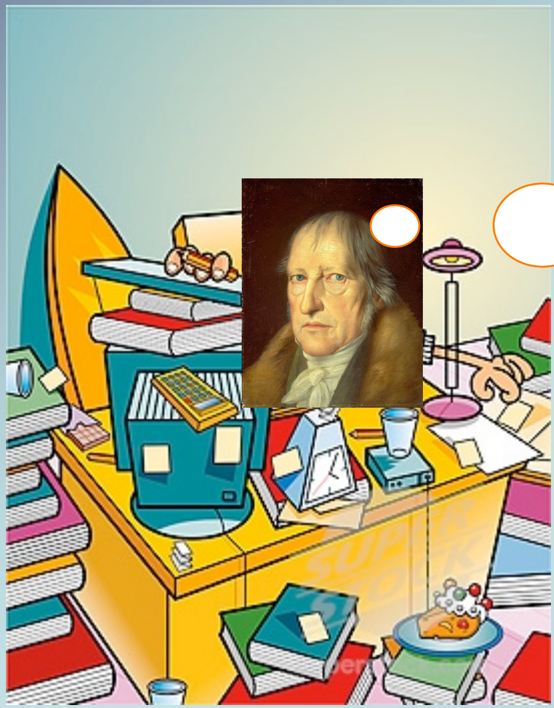
Searching for New Physics via high precision measurements

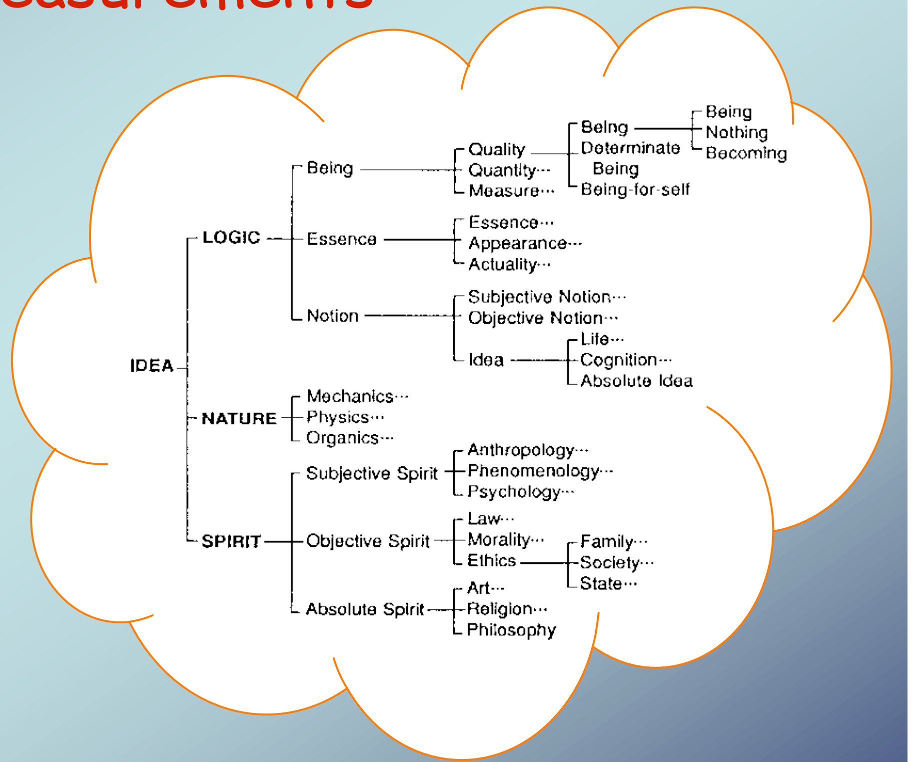
First…



Searching for New Physics
via
high precision measurements

First…





Searching for New Physics
via
high precision measurements

First…

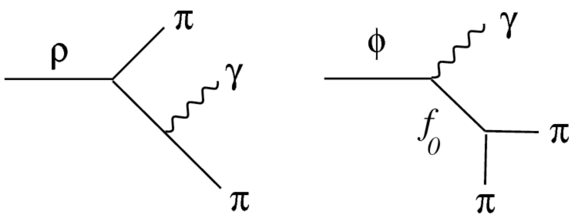
precision,
accuracy,
patience,
bit of "pathology"
…

… and then giving some contribution may be possible

Large Angle 2002

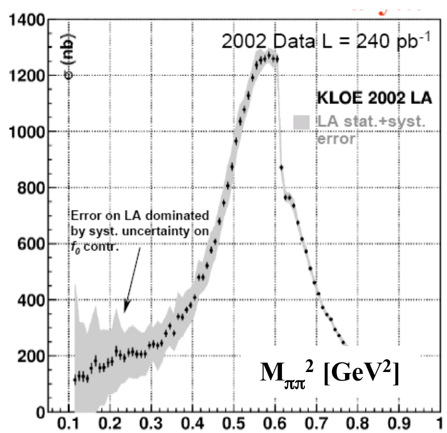
Scalar background from $f_0(980)$ large also at low masses due to non-Breit-Wigner shape of mass distribution in ϕ radiative decays

➔ **Precise phenomenological model still missing**



Dedicated KLOE analysis on $f_0(980) \to \pi^0\pi^0$, $f_0(980) \to \pi^+\pi^-$

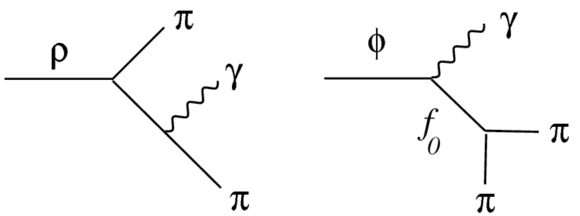
Systematic errors due to f_0 and $\rho\pi\gamma$ contribution:
-> absolute difference between two different models



Large Angle 2002

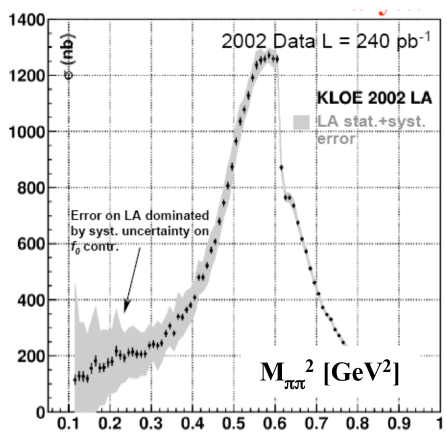
Scalar background from $f_0(980)$ large also at low masses due to non-Breit-Wigner shape of mass distribution in ϕ radiative decays

➔ **Precise phenomenological model still missing**

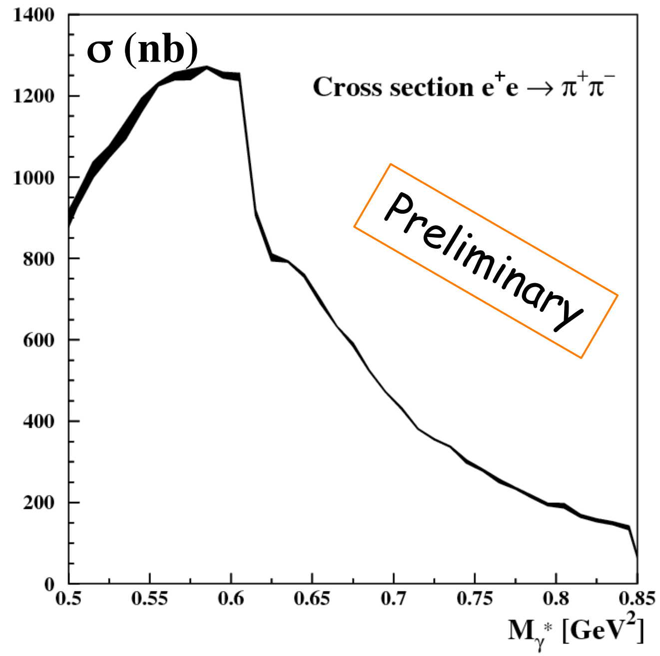


Dedicated KLOE analysis on $f_0(980) \to \pi^0\pi^0$, $f_0(980) \to \pi^+\pi^-$

Systematic errors due to f_0 and $\rho\pi\gamma$ contribution:
-> absolute difference between two different models



Spectrum extended down to $0.5\ \mathrm{GeV}^2$



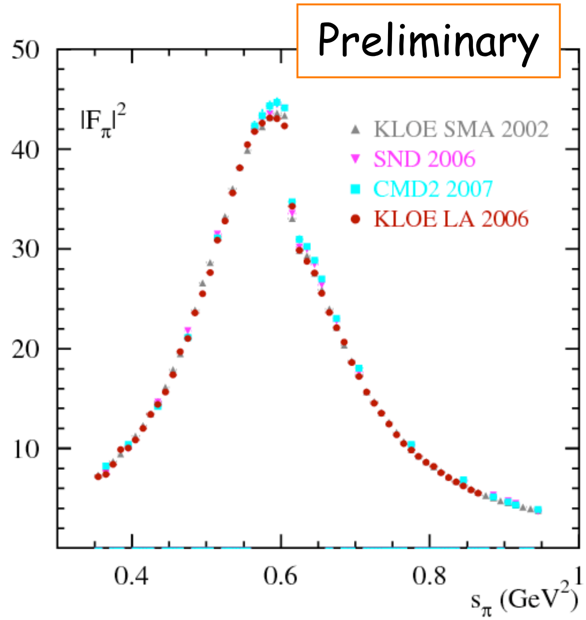
Preliminary

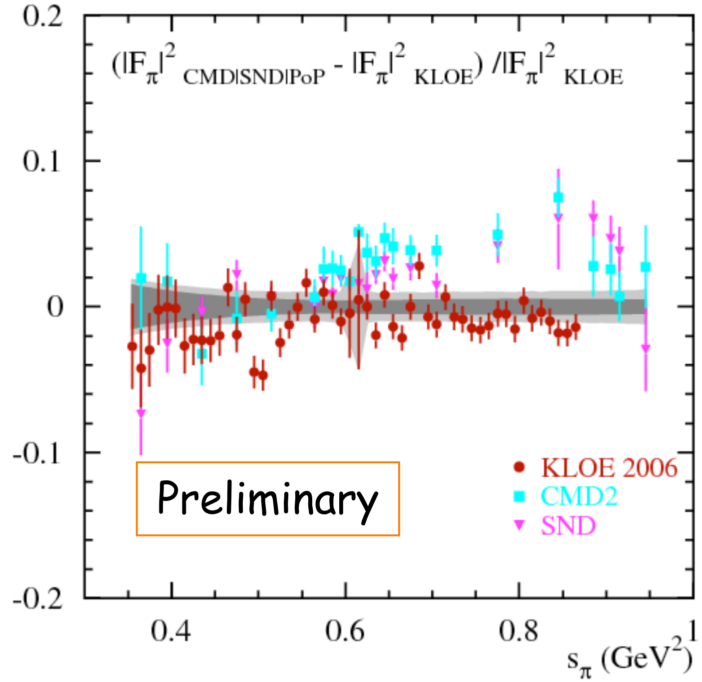
$$a_\mu^{\pi\pi}(0.50\text{-}0.85\mathrm{GeV}^2) = (\mathbf{252.5} \pm \mathbf{0.6}_{stat} \pm \mathbf{5.1}_{styst}) \times 10^{-10}$$

Large Angle 2006

Exploiting 2006 data: almost free from non-reducible background sources

-> Spectrum can be extended **down to the threshold**
-> Threshold effects carefully studied
-> NLO and NNLO radiative events need precise evaluation
-> Statistics becomes an issue





Large Angle analyses 2002 and 2006 very close to be finalized
> Result based on 2006 off peak data: ultimate KLOE measurement on $a_\mu^{\pi\pi}$

4. Conclusion

$(g\text{-}2)_\mu$ Error or New Physics?

M. Passera, W. J. Marciano, A. Sirlin

To get agreement between a_μ^{exp} and $a_\mu^{theo,SM}$ (w/o New Physics)

- Wrong value of $a_\mu^{had,LbL}$ => it should be moved of ca. 8-10 σ

- Errors in $\sigma(s)$ => increasing it also $\Delta\alpha_{had}(M_Z)$ increases
  -> decreasing or M_{Higgs}^{UB} restricting the allowed region into
  114 GeV < M_{Higgs} < 154 GeV

- Using τ–data => increases also $\Delta\alpha_{had}(M_Z)$
  -> setting M_{Higgs}^{UB} < 133 GeV

- Bridging the discrepancy in a_μ => $\sigma(s)$ increased by 4% from threshold to infinity
  -> M_{Higgs} < 70 GeV
  if locally increased
  -> M_{Higgs} < 130 GeV

$(g\text{-}2)_\mu$ Error or New Physics?

M. Passera, W. J. Marciano, A. Sirlin

To get agreement between a_μ^{exp} and $a_\mu^{theo,SM}$ (w/o New Physics)

- Wrong value of $a_\mu^{had,LbL}$ => it should be moved of ca. 8-10 σ

- Errors in $\sigma(s)$ => increasing it also $\Delta\alpha_{had}(M_Z)$ increases
  -> decreasing or M_{Higgs}^{UB} restricting the allowed region into
  $114\ GeV < M_{Higgs} < 154\ GeV$

- Using τ–data => increases also $\Delta\alpha_{had}(M_Z)$
  -> setting $M_{Higgs}^{UB} < 133\ GeV$

- Bridging the discrepancy in a_μ => $\sigma(s)$ increased by 4% from threshold to infinity
  -> $M_{Higgs} < 70\ GeV$
  if locally increased
  -> $M_{Higgs} < 130\ GeV$

All scenarios rather unlikely
=> Strong suggestion that New Physics is playing role in $(g\text{-}2)_\mu$

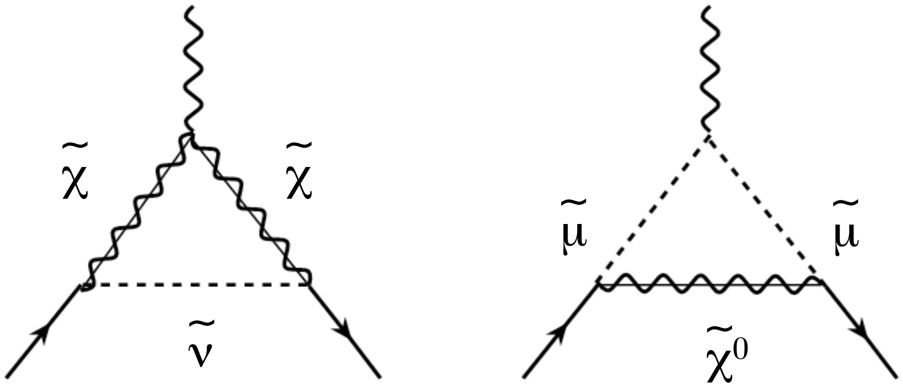
New Physics in $(g\text{-}2)_\mu$

Several scenarios from New Physics

One of the most accredited is **SUSY** contribution to a_μ

$a_\mu^{\text{theo}} = a^{\text{SM}}_\mu + a^{\text{SUSY}}_\mu$

sneutrino-chargino
+
smuon-neutralino



M_{SUSY} in the range [100 - 500] GeV^2, tanβ above ca. 5, μ>0
➔ coverage of the $(g\text{-}2)_\mu$ discrepancy

For high tanβ ⇒ $\left|a_\mu^{SUSY}\right| \approx 123 \times 10^{-11} \left(\frac{100\ GeV^2}{M_{SUSY}}\right) \tan\beta$

$M_{SUSY} \approx \left(65.5\ GeV^2\right)\sqrt{\tan\beta}$

$\tan\beta \sim 2 - 40$

Fit with SUSY particle expectation

Future of $(g\text{-}2)_\mu$

- More ISR analyses (from KLOE, BaBar, Belle) still at preliminary phase close to be finalize

- Better R(s) below 4.3 GeV from CLEO-c

- Experiments at VEP-2000 up to $\sqrt{s} = 2$ GeV

- Similar machine at LNF (DAΦNE II) under discussion

- τ-c factory in commissioning in Beijing

- By 2012 total error limited by LBL term

- New $(g\text{-}2)_\mu$ experiment at FLAB. Expected accuracy of 0.1 ppm (stat) and 0.1 ppm (syst)

  -> Corresponds to accuracy on $a_\mu^{had,LO}$ 0.2%

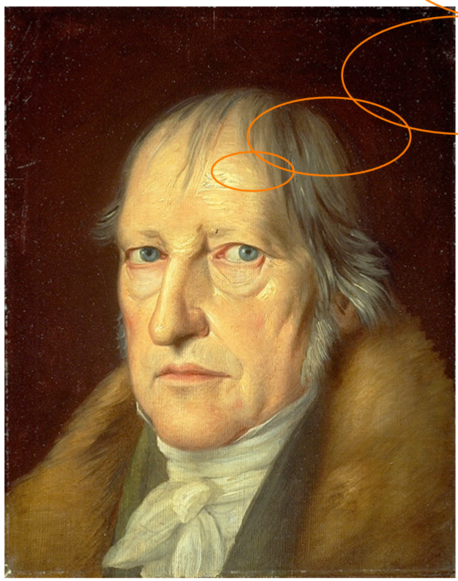
    -> hardly ever achievable using absolute measurement of $\sigma(e^+e^- \rightarrow hadrons)$

From a student of Tübingen

Thesis, Antithesis, Synthesis…
everything goes through this path.

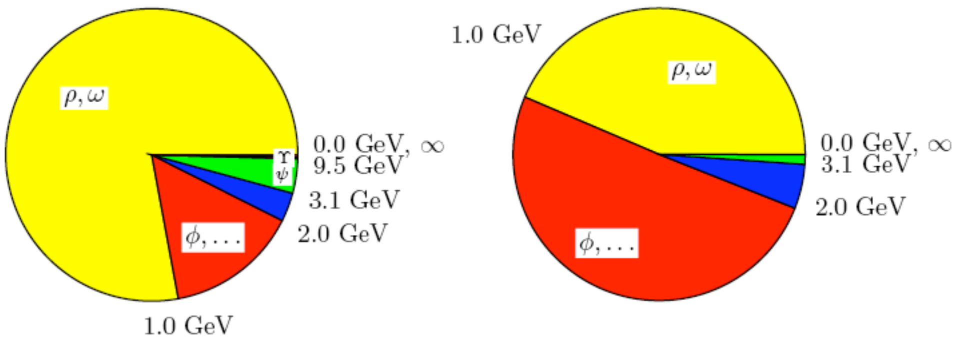
$(g\text{-}2)_\mu$ *too: it cannot escape from this Law.*

The Spirit will find the reason to manifest itself
into a New Synthesis
… ehm, entschuldigen, or into New Physics?!



Backup slides

Contributions to $a_\mu^{\text{had,LO}}$



$\sqrt{s}$, GeV	$a_\mu^{\text{had,LO}}, 10^{-10}$	$\delta a_\mu^{\text{had,LO}}$, %
2π	$504.6 \pm 3.1 \pm 1.0$	73.0
ω	$38.0 \pm 1.0 \pm 0.3$	5.5
ϕ	$35.7 \pm 0.8 \pm 0.2$	5.2
$0.6 - 1.8$	$54.2 \pm 1.9 \pm 0.4$	7.8
$1.8 - 5.0$	$41.1 \pm 0.6 \pm 0.0$	6.0
$J/\psi, \psi'$	$7.4 \pm 0.4 \pm 0.0$	1.1
> 5.0	$9.9 \pm 0.2 \pm 0.0$	1.4
Total	$690.9 \pm 3.9_{\text{exp}} \pm 1.9_{\text{rad}} \pm 0.7_{\text{QCD}}$	100.0

Experimental Status of a_l

$$a_e = 1159652180.73(28) \times 10^{-12} \quad 0.24\text{ppt}$$

D. Hanneke et al., PRL 100, 120801 (2008)
QED test or α determination

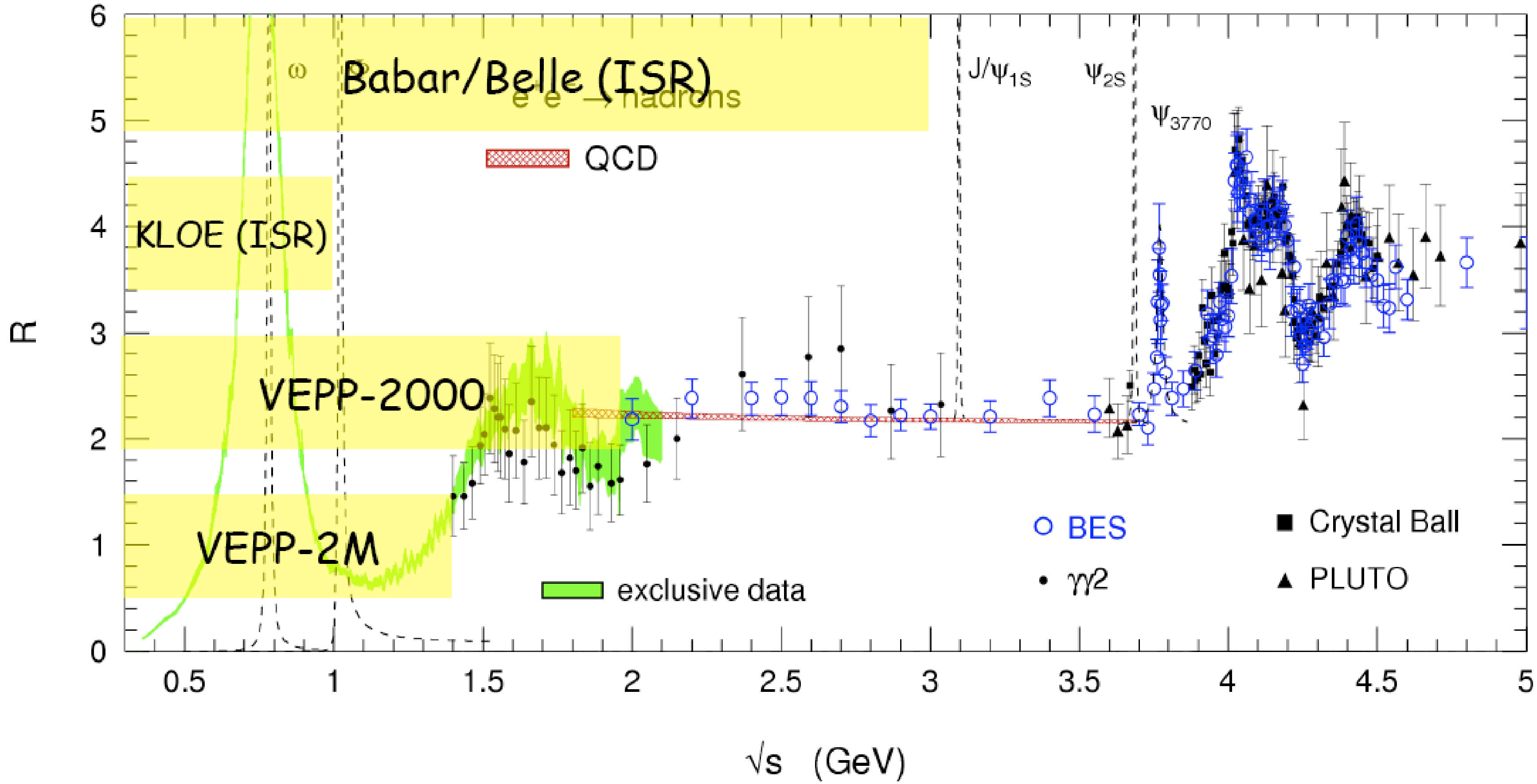
$$a_\mu = 116592080(63) \times 10^{-11} \quad 0.54\text{ppb}$$

G.W. Bennett et al. (E821), PRD 73, 072003 (2006)
Sensitive test of the Standard Model

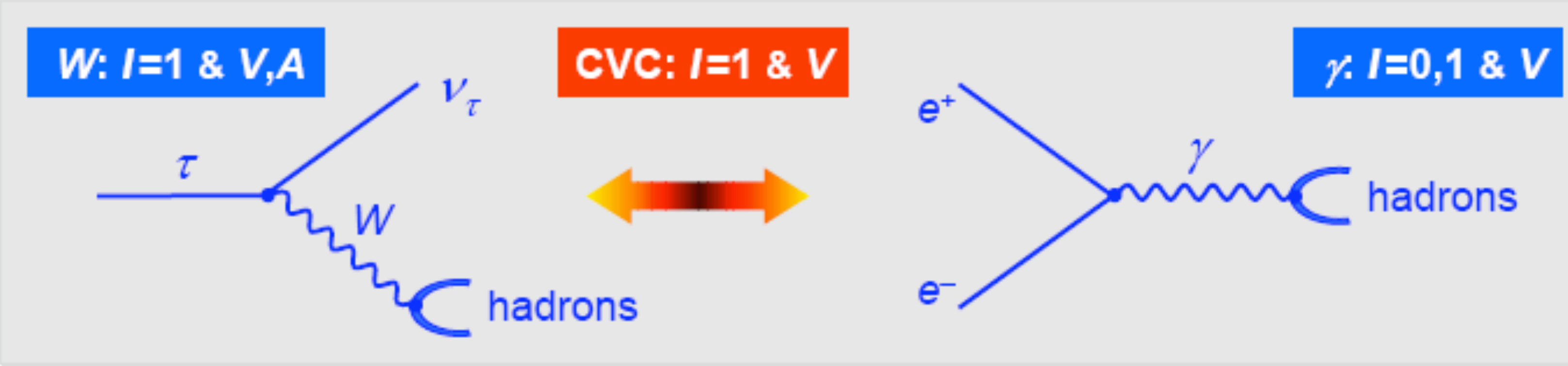
$$a_\tau = -0.018(17) \quad \text{or} \quad -0.052 < a_\tau < 0.013 \quad 95\%\text{CL}$$

J. Abdallah et al. (DELPHI), EPJ C 35, 159 (2004)
Theory: $117721(5) \times 10^{-8}$, SE, M. Passera, MPL A 22, 159 (2007)

Energy ranges



The Conserved Vector Current – SU(2)



Hadronic physics factorizes in *Spectral Functions*:

fundamental ingredient relating long distance (resonances) to short distance description (QCD)

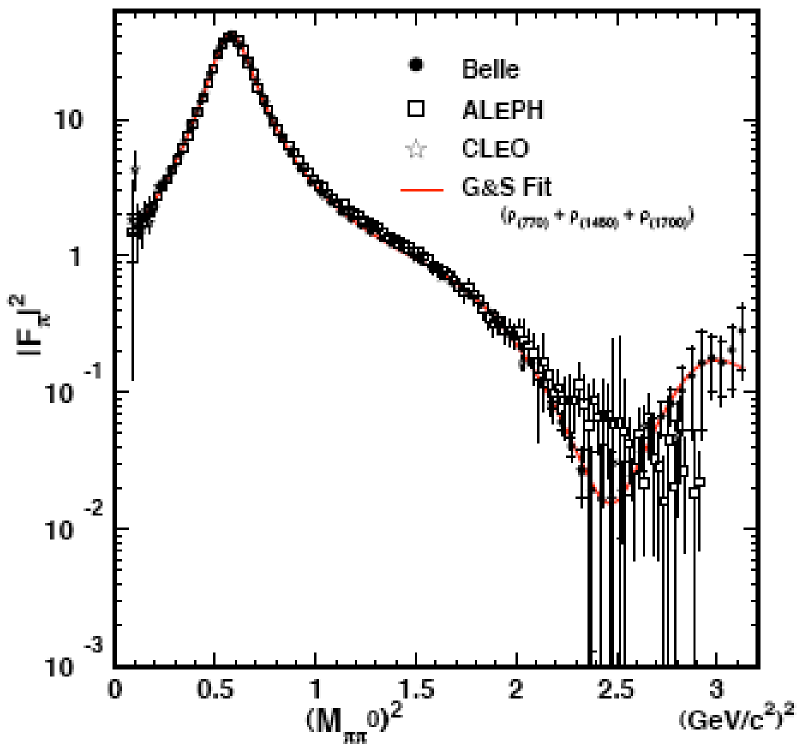
Isospin symmetry (CVC) connects I=1 e^+e^- cross section to vector τ spectral functions:

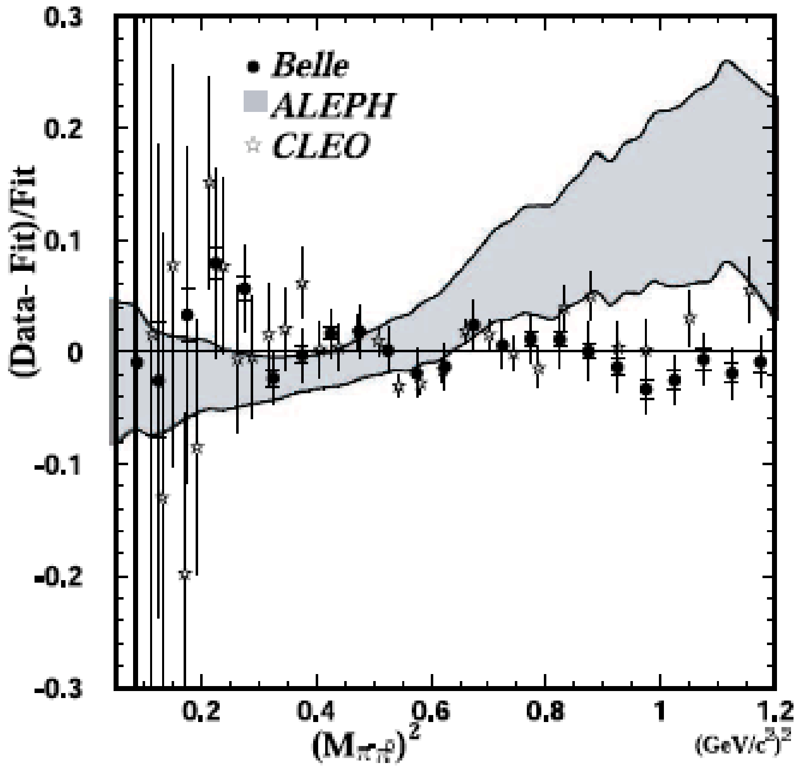
$$\sigma^{(I=1)}\left[e^+e^- \rightarrow \pi^+\pi^-\right] = \frac{4\pi\alpha^2}{s}\upsilon\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right]$$

$$\upsilon\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right] \propto \frac{BR\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right]}{BR\left[\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau\right]} \frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds} \frac{m_\tau^2}{\left(1-s/m_\tau^2\right)^2\left(1+s/m_\tau^2\right)}$$

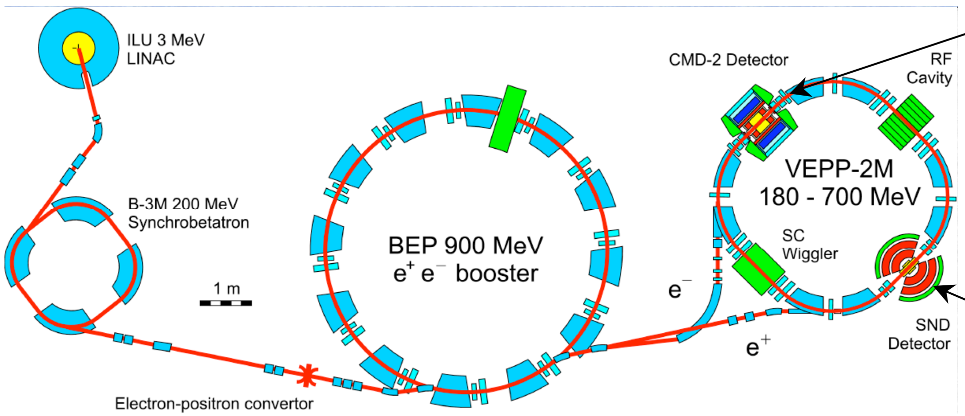
branching Fractions | mass spectrum | kinematic factor (PS)

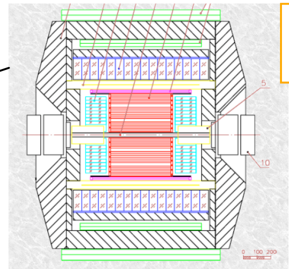
$|F_\pi(s)|^2$ from τ. News from Belle





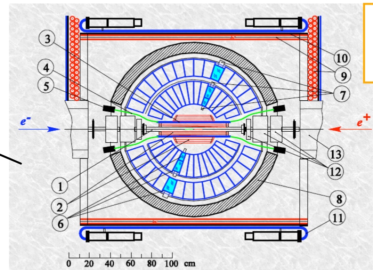
CMD2 and SND at VEP-2M





CMD2

Cryogenic
Magnetic Detector 2



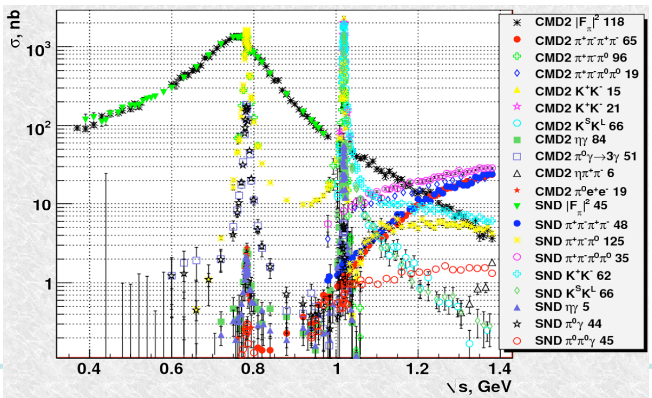
SND

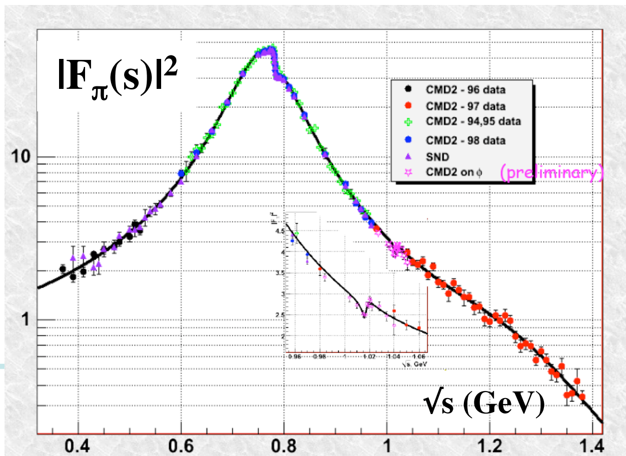
Spherical
Neutral Detector

- VEP-2M collider: 0.36-1.4 GeV, $dL/dt \approx 10^{30}$ $1/cm^2 s$ at 1 GeV
- Detectors CMD2 and SND: integrated luminosity of $L \approx 60\ pb^{-1}$ (1993-2000)
- All the most relevant hadronic modes measured:

  $e^+e^- \to \pi^+\pi^-, 3\pi, 4\pi, KK, \ldots$

  $e^+e^- \to \rho, \omega, \phi$



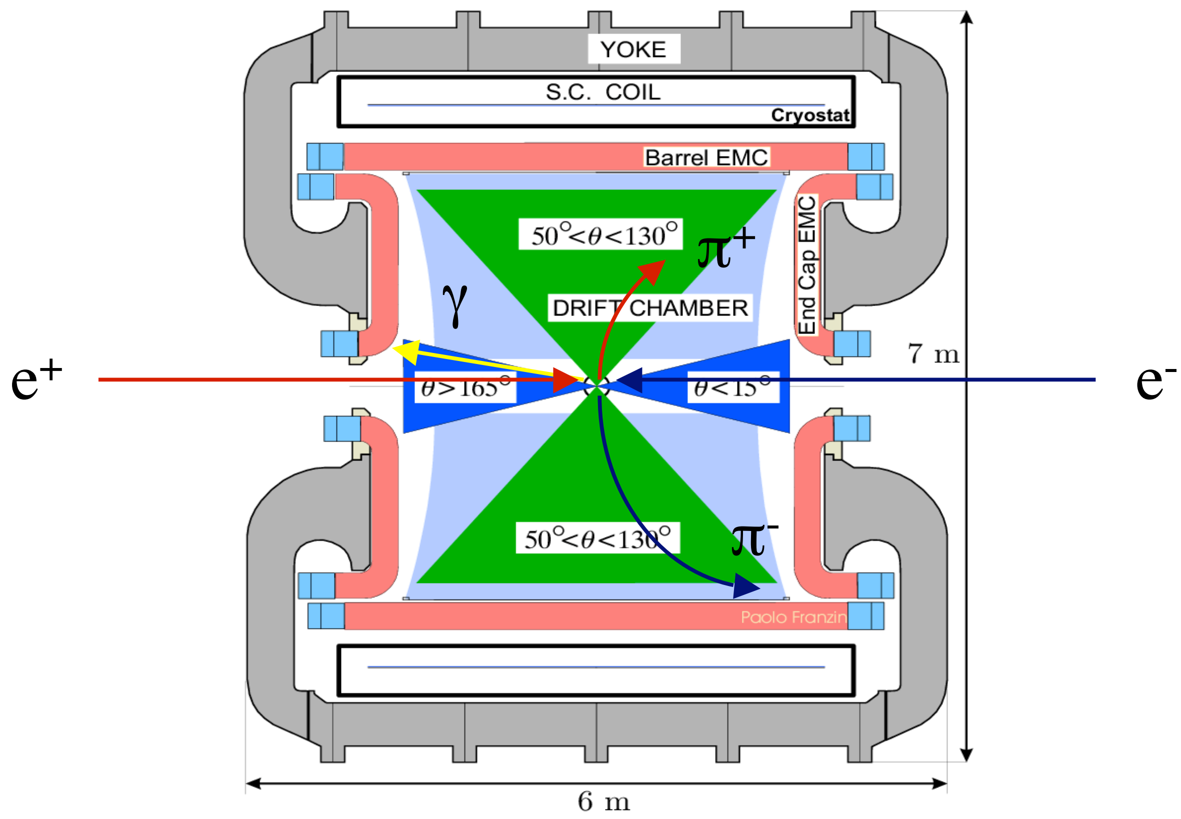


Analysis with γ at small polar angle

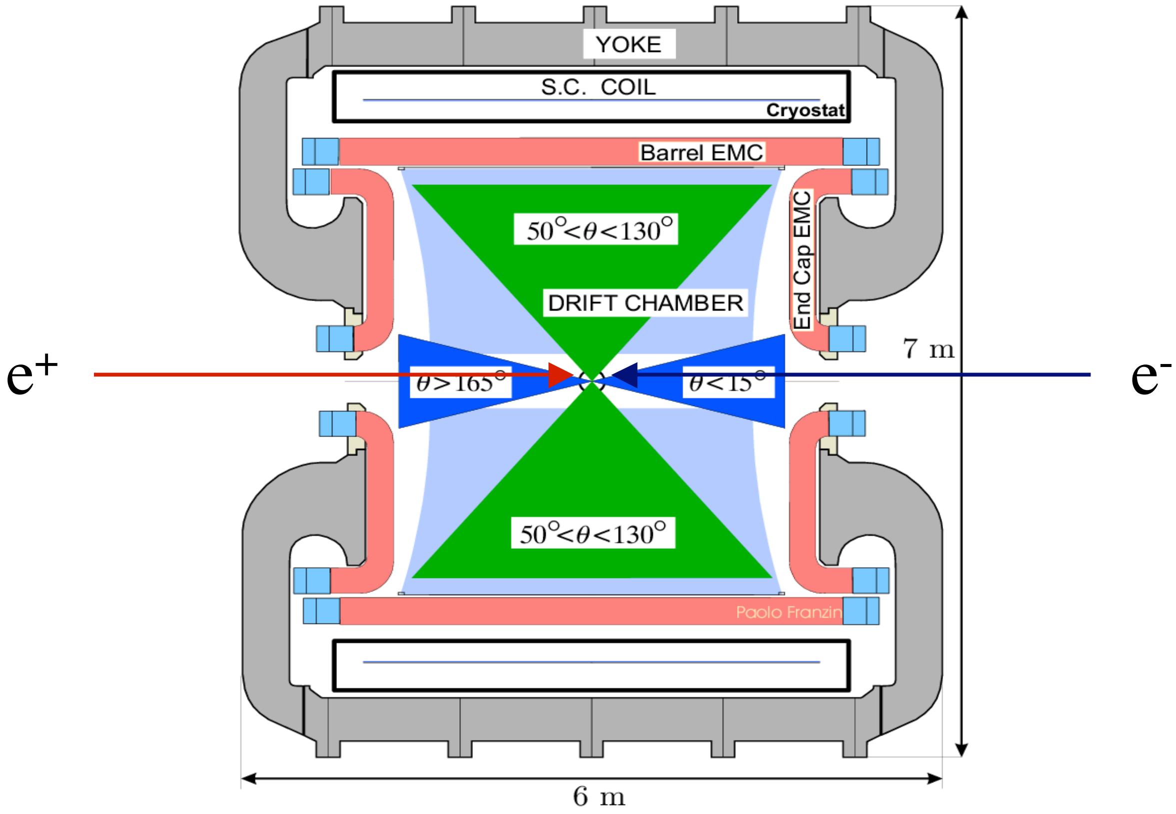
Pion tracks at LARGE ANGLE
$50° < \theta_\pi < 130°$

w/o tagging the photon
Photon at SMALL ANGLE
$\theta_{miss} < 15°, \theta_{miss} > 165°$

- No kinematic closure of the events
- High statistic for ISR photons
- Negligible contribution of FSR
- Reduced background
- $4m_\pi^2$ threshold not reachable



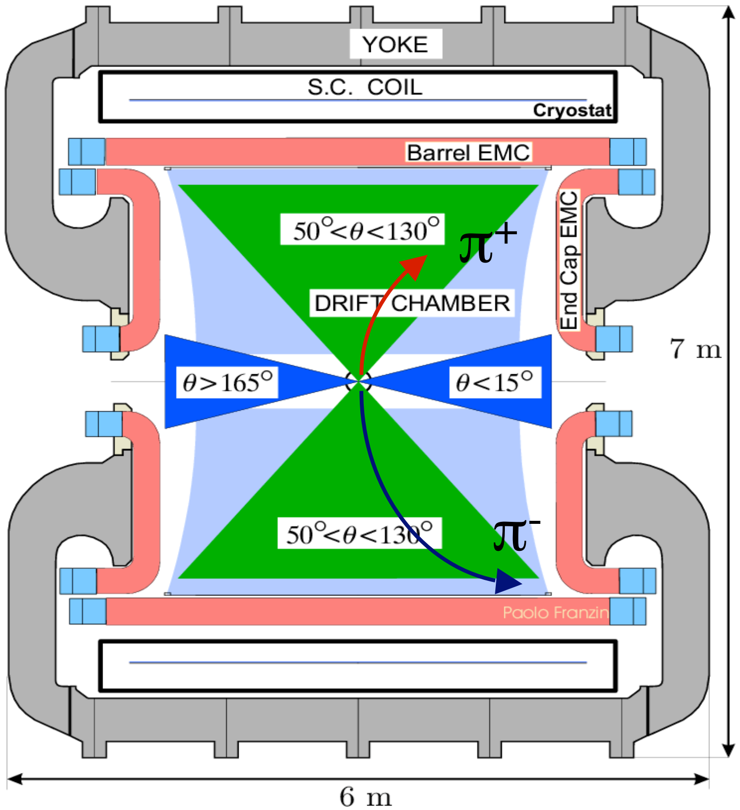
Analysis with γ at large polar angle



Analysis with γ at large polar angle

Pion tracks at LARGE ANGLE

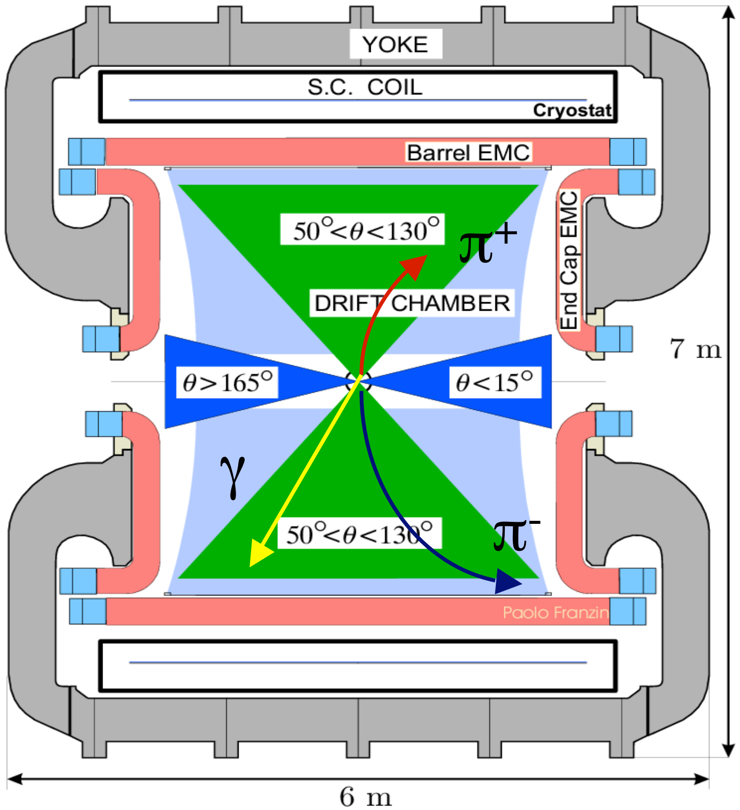
$50° < \theta_\pi < 130°$



Analysis with γ at large polar angle

Pion tracks at LARGE ANGLE
$50° < \theta_\pi < 130°$

w/ photon tagging
Photon at LARGE ANGLE
$50° < \theta_\gamma < 130°$

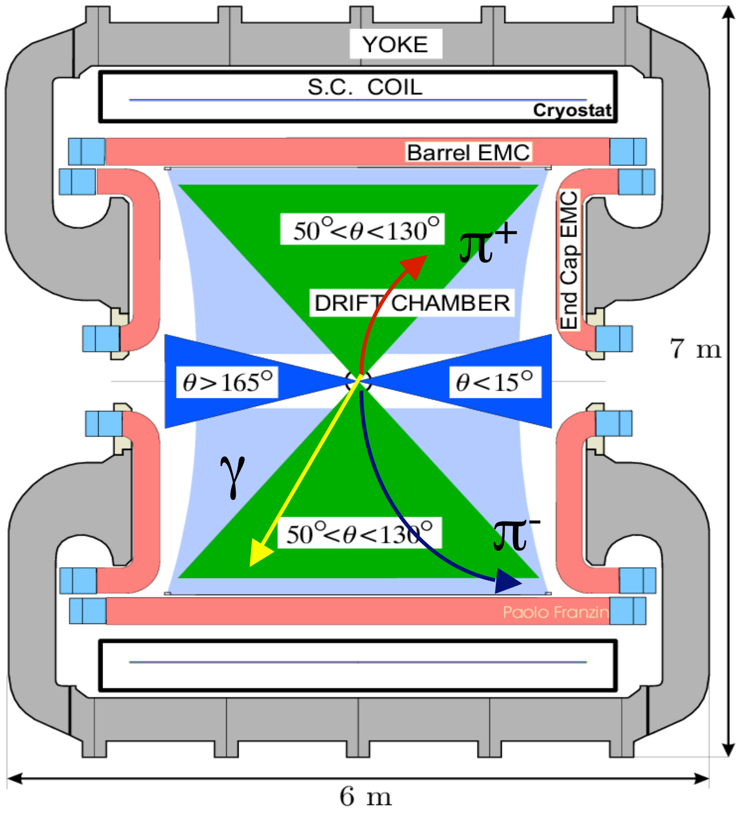


Analysis with γ at large polar angle

Pion tracks at LARGE ANGLE
$50° < \theta_\pi < 130°$

w/ photon tagging
Photon at LARGE ANGLE
$50° < \theta_\gamma < 130°$

- Kinematic closure of the events
- Increased contribution of FSR
- Higher background from ϕ decays (2002)
- Presence of $\phi \to f_0(980)\gamma \to \pi^+\pi^-\gamma$ (2002)
- $4m_\pi^2$ threshold reachable

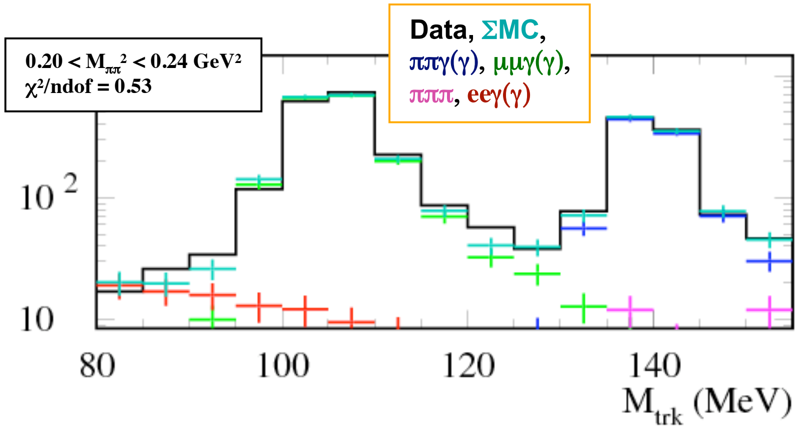


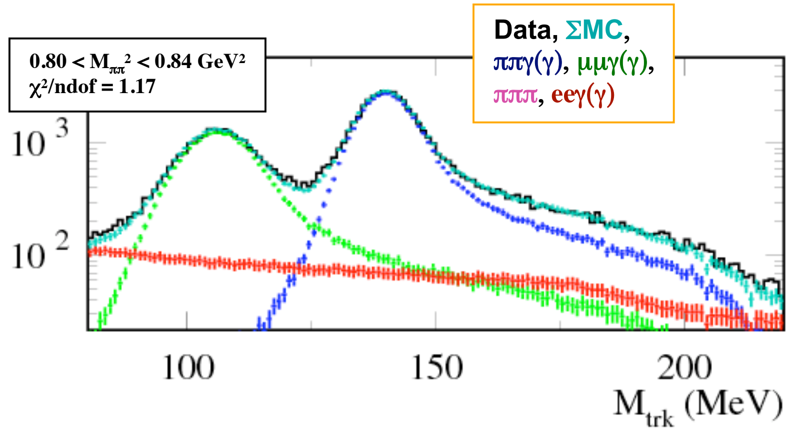
Precise background subtraction

Residual background estimation and subtraction
Excellent DATA-MC agreement thanks to

1. Tracking calibration fine tuning => uncertainty on track momentum at per-mil level

2. Accurate smearing of MC momentum => reproduce DATA resolution

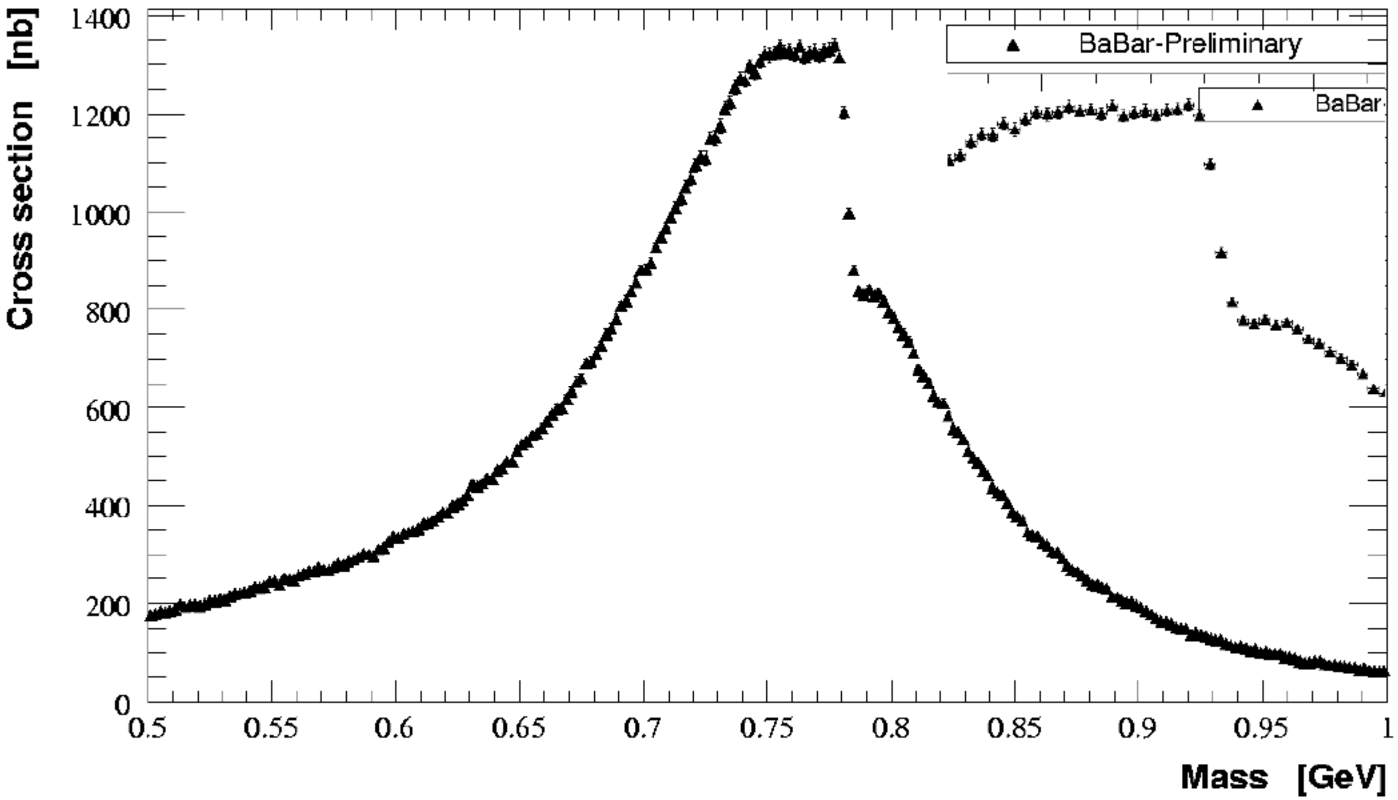




Fitting MonteCarlo distributions of signal($\pi\pi\gamma$)+background($\mu\mu\gamma$,$\pi\pi\pi$,$ee\gamma$)
to the DATA distributions in M_{trk}

➔ getting very precise agreement between DATA and MC:
needed to have precise precise background subtraction

BaBar

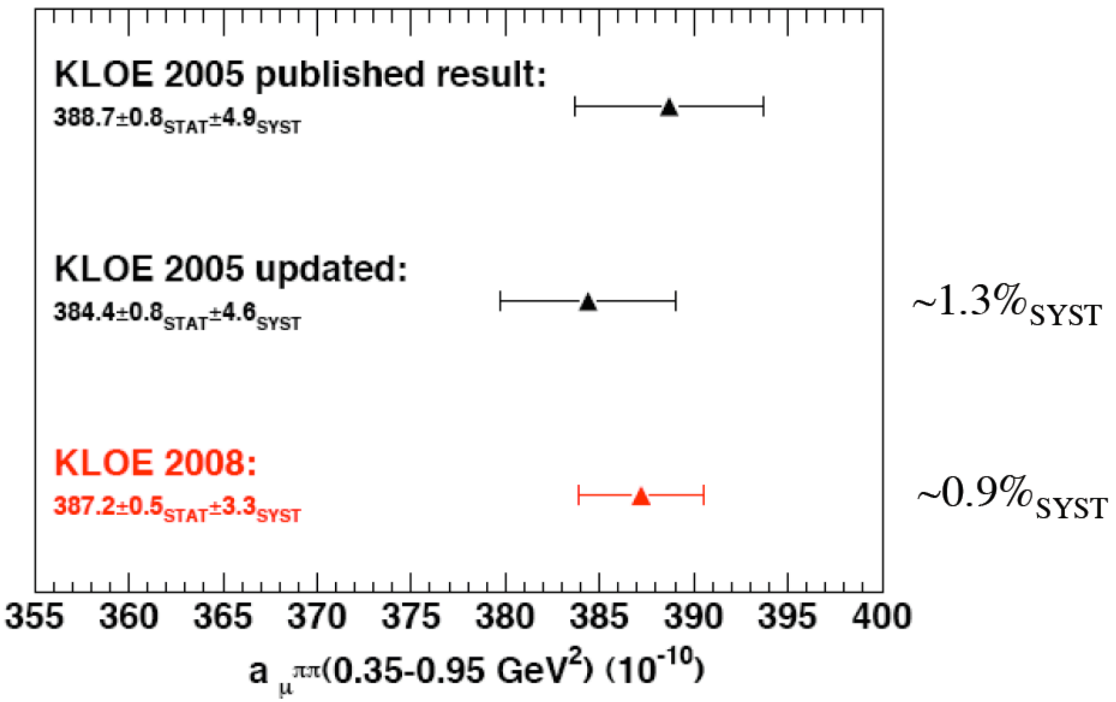


$$a_\mu^{\pi\pi}(0.630 < \sqrt{s}\ (\text{GeV}) < 0.958) = (369.3 \pm 0.8 \pm 2.2) \times 10^{-10}$$

$$a_\mu^{exp} - a_\mu^{theo} = (27.5 \pm 8.4) \times 10^{-10} \Rightarrow (14.0 \pm 8.4) \times 10^{-10}$$

=> 1.7 σ

$a_\mu^{\pi\pi}$ comparison



SMA 2005 updated $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = \mathbf{(384.9 \pm 0.8_{stat} \pm 6.6_{styst}) \times 10^{-10}}$

SMA 2008 $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = \mathbf{(387.6 \pm 0.5_{stat} \pm 2.3_{styst}) \times 10^{-10}}$

Bound on Higgs mass