# Status and Prospects of $e^+e^-$ hadronic cross sections at low energy

G. Venanzoni LNF/INFN

# Importance of precision R $\equiv \frac{\sigma(e^+e^- \to hadrons)}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$ measurements

- $(g\text{-}2)_\mu$ and $\alpha_{e.m.}(M_Z)$
- CVC tests between $e^+e^-$ and $\tau$
- QCD sum rules and $\alpha_S$
- Test of models and input to theory (ChPT, VDM, QCD,…)
- Search of hybrids and glueballs
- Search for hypothetical light gauge bosons

# Muon anomaly

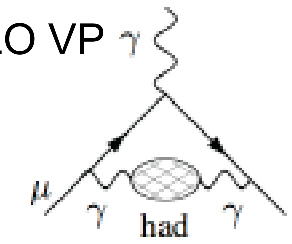
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

- Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.

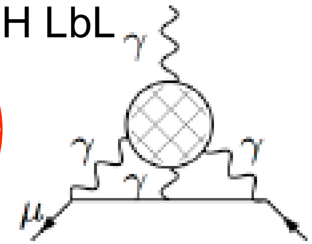
•Theoretical error $\delta a_\mu^{SM}$ (~$6\times10^{-10}$) dominated by HLO VP ($4\div5\times10^{-10}$) and HLbL ($[2.5\div4]\times10^{-10}$). A **twofold** improvement on $\delta a_\mu^{SM}$ from 2001 (thanks to new $e^+e^-$ measurements)!

•Experimental error $\delta a_\mu^{EXP}$ ~$6\times10^{-10}$(E821). Plan to reduce it to $1.5\ 10^{-10}$ by the new g-2 experiments at FNAL and J-PARC.

HLO VP




H LbL




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

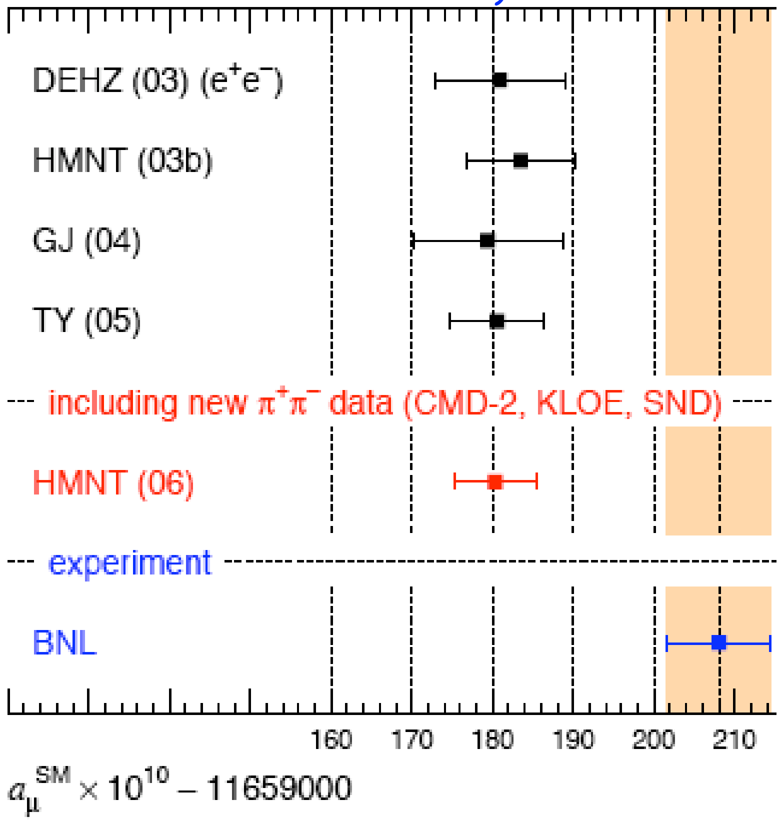
$a_\mu^{HLbL} = (10.5\pm2.6)10^{-10}$
[Prades, dR&V. 08]
$(11\pm4)10^{-10}$ (Jegerlehner, Nyffler)

**$\delta a_\mu^{HLO}$ ~0.7%**

**$\delta a_\mu^{HLbL}$ ~25-40%**

$a_\mu^{SM}$ compared to BNL world av.

*T.Teubner, PHIPSI08*




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

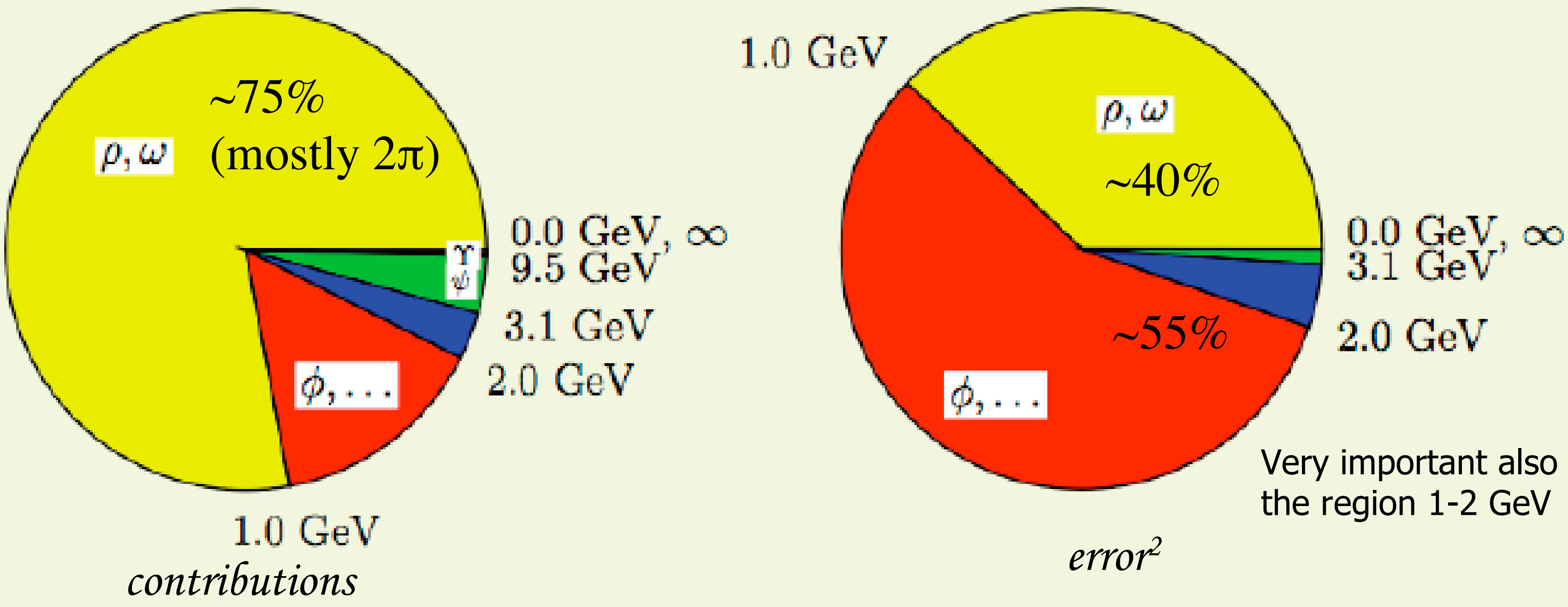
**In 2001 $a_\mu^{EXP}-a_\mu^{TH}=(23\pm16)\cdot10^{-10}$**

# Dispersion Integral: $a_\mu^{HLO} = \int_{4m_\pi^2}^{\infty} \sigma_{had}(s) K(s) ds$

K(s)~1/s

Contribution of different energy regions to the dispersion integral and the error to $a_\mu^{HLO}$

F. Jegerlehner, Talk at PHIPSI08




Experimental errors on $\sigma^{had}$ translate into theoretical uncertainty of $a_\mu^{had}$!

→ Needs precision measurements!

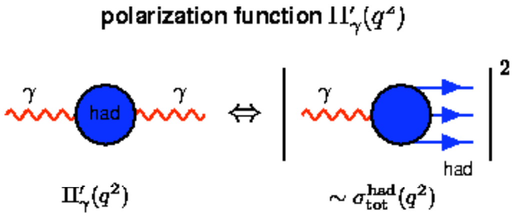
$\delta a_\mu^{exp} \rightarrow$ 1.5 $10^{-10}$ = 0.2% on $a_\mu^{HLO}$

New g-2 exp.

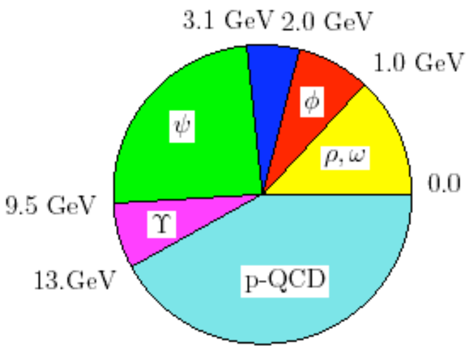
# $\alpha_{em}(M_Z)$ and EW fit of the SM ($M_{Higgs}$)

$$\alpha(M_Z) = \frac{\alpha(0)}{1-\Delta\alpha(M_Z)}$$

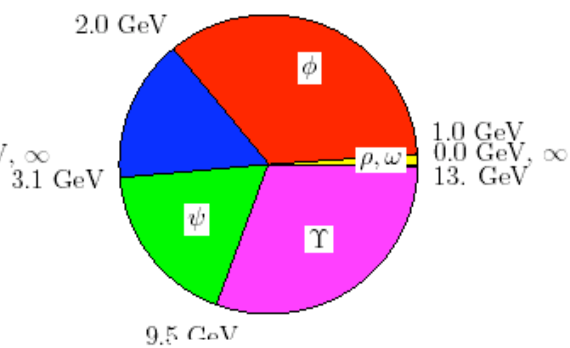
$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$



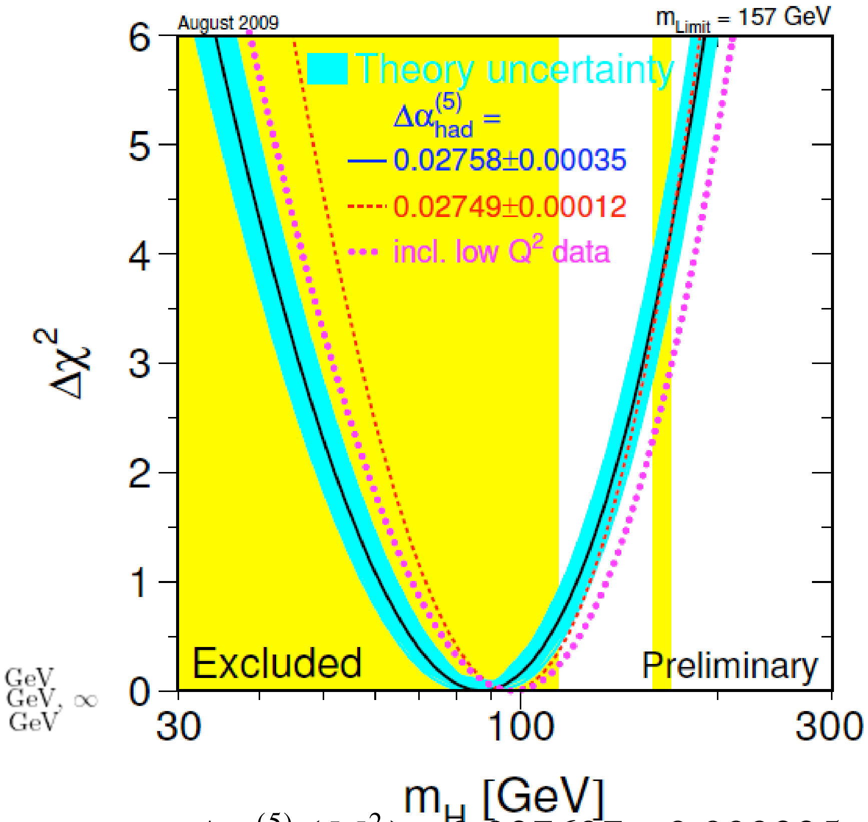

$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$




$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$




$\delta^2\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$




$$\Delta\alpha^{(5)}_{had}(M_Z^2) = 0.027607 \pm 0.000225$$

$$\alpha^{-1}(M_Z^2) = 128.947 \pm 0.035$$

$$\alpha^{-1}(0) = 137.0359895 \pm 0.0000061$$

FJ08

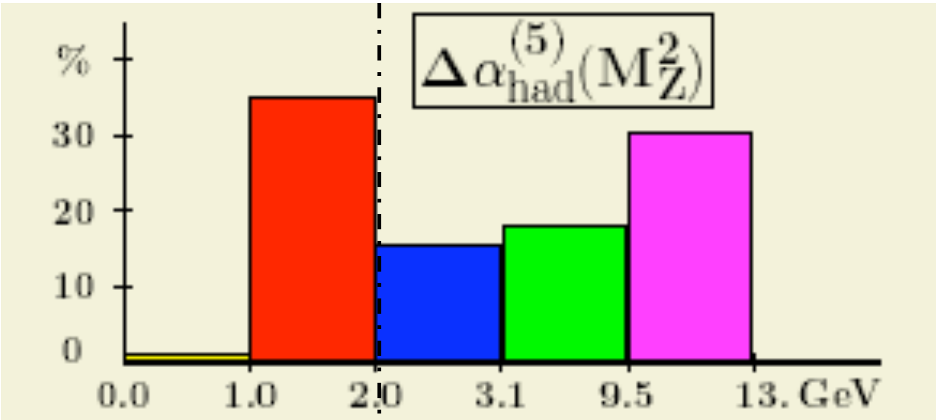
$\delta\alpha(M_Z)/\alpha(M_Z) \sim 2\times10^{-4} \rightarrow 5\times10^{-5}$

Requirement from ILC (6x improvement)

# Comparison of error profiles for $\alpha_{em}(M_Z)$

Direct integration of energy points

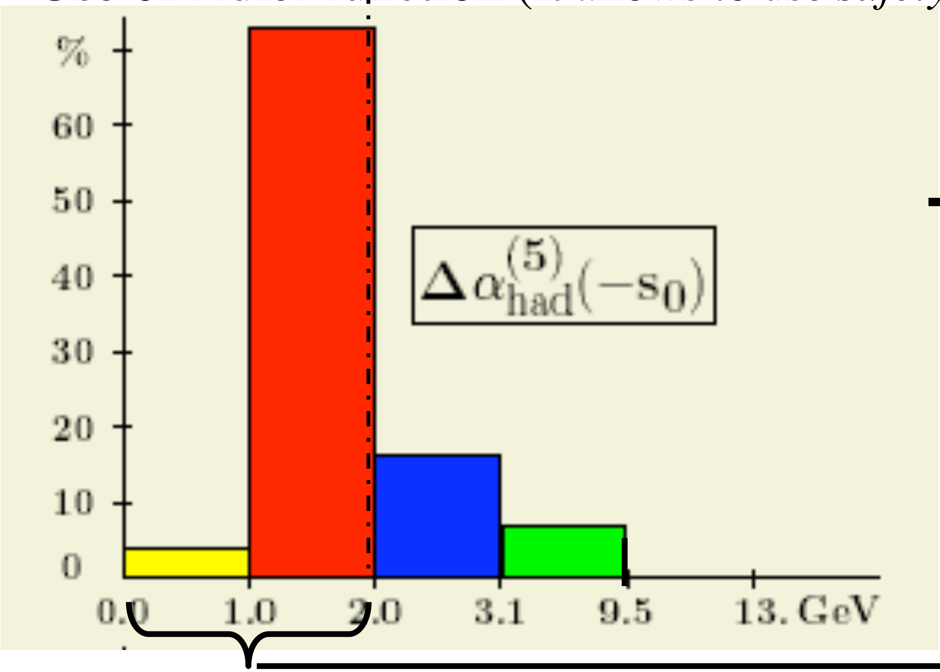
*F. Jegerlehner, Nucl. Phys. B 181-182 (2008) 135*




$\delta\sigma$ at 1% in the region **$\sqrt{s}$ < 10 GeV**

$\Rightarrow$ improvement of ~**3** in $\delta\alpha(M_Z)$

Use of Adler function (It allows to use *safely* pQCD down to 2.5 GeV)




1% in the region 1<$\sqrt{s}$ < 2.5 GeV

$\Rightarrow$ improvement of ~5 on $\delta\alpha(M_Z)$

$2m_\pi<\sqrt{s}$ < 2 GeV

**Extremely** important:

- **80%** of $\delta\Delta\alpha^{(5)}_{had}$ (using Adler function)
- **95%** of $\delta a_\mu$

# Cross section data:

Two approaches:

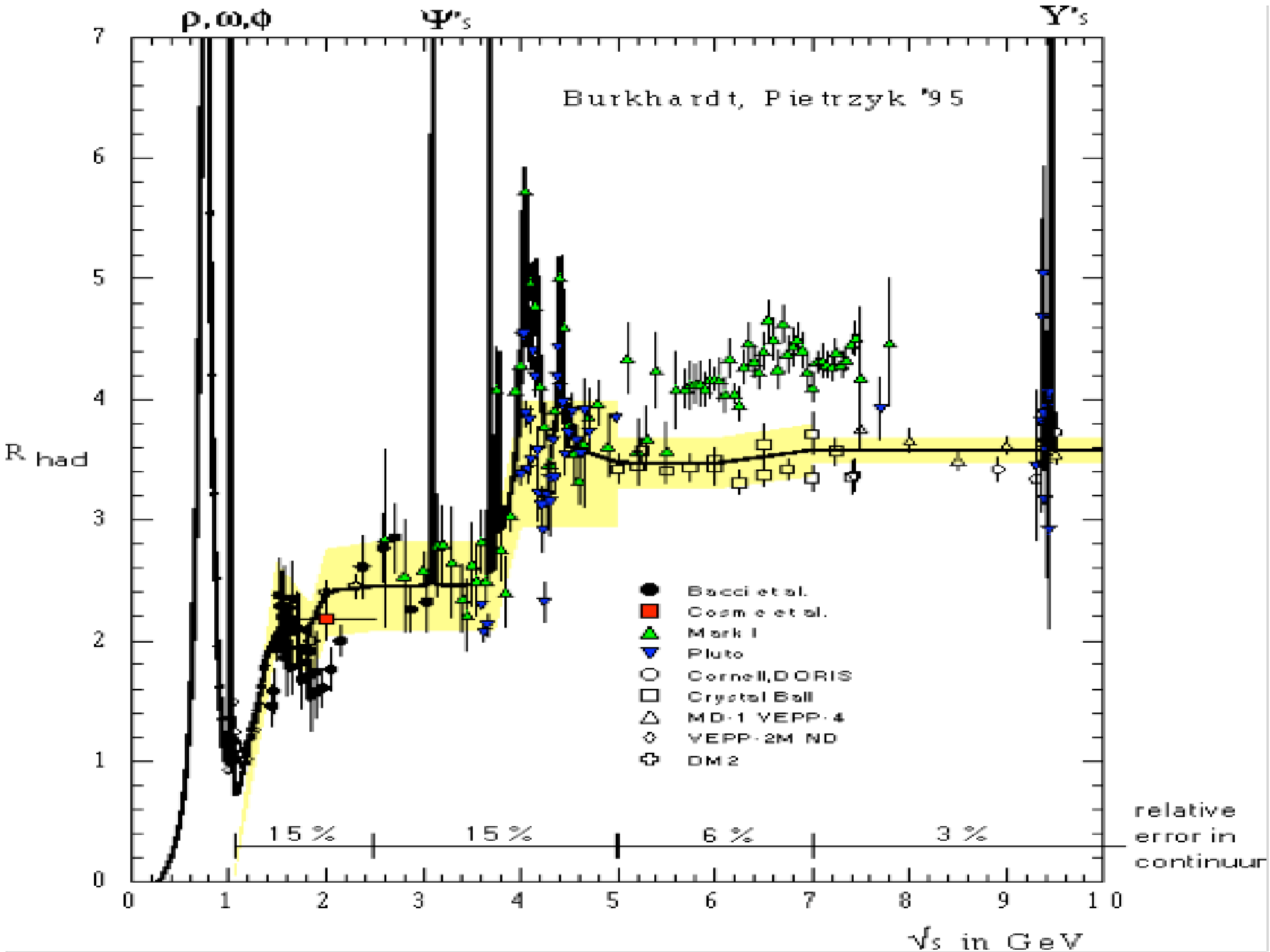
Energy scan (CMD2, SND, BES,CLEO):

- 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

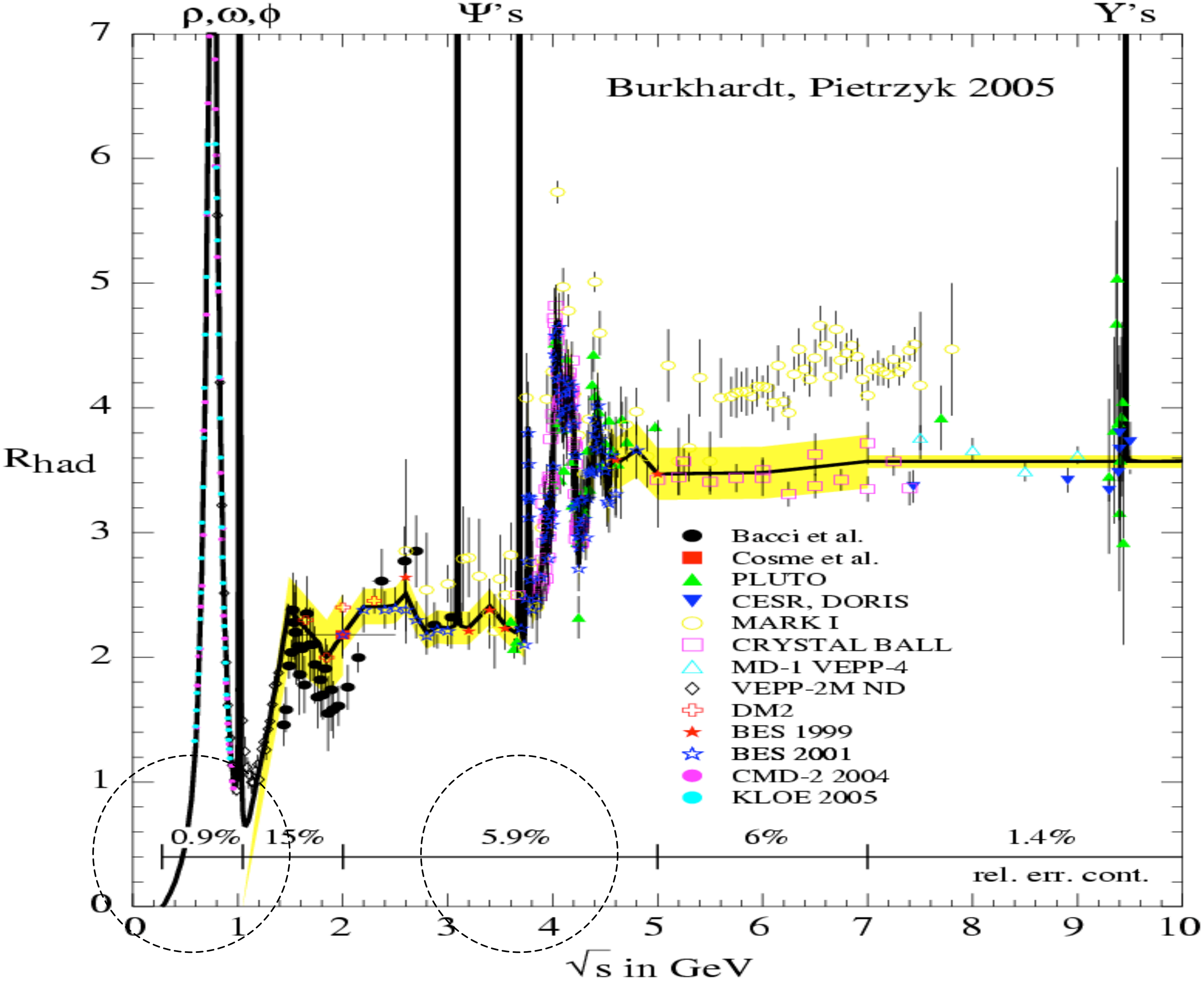
Radiative return (KLOE, BABAR, BELLE,BESIII?):

- 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

# Data at '95


ρ,ω,φ
Ψ's
Υ's
Burkhardt, Pietrzyk '95
R had
Bacci et al.
Cosme et al.
Mark I
Pluto
Cornell,DORIS
Crystal Ball
MD-1 VEPP-4
VEPP-2M ND
DM2
15 %
15 %
6 %
3 %
relative
error in
continuum
√s in GeV
0
1
2
3
4
5
6
7
8
9
10

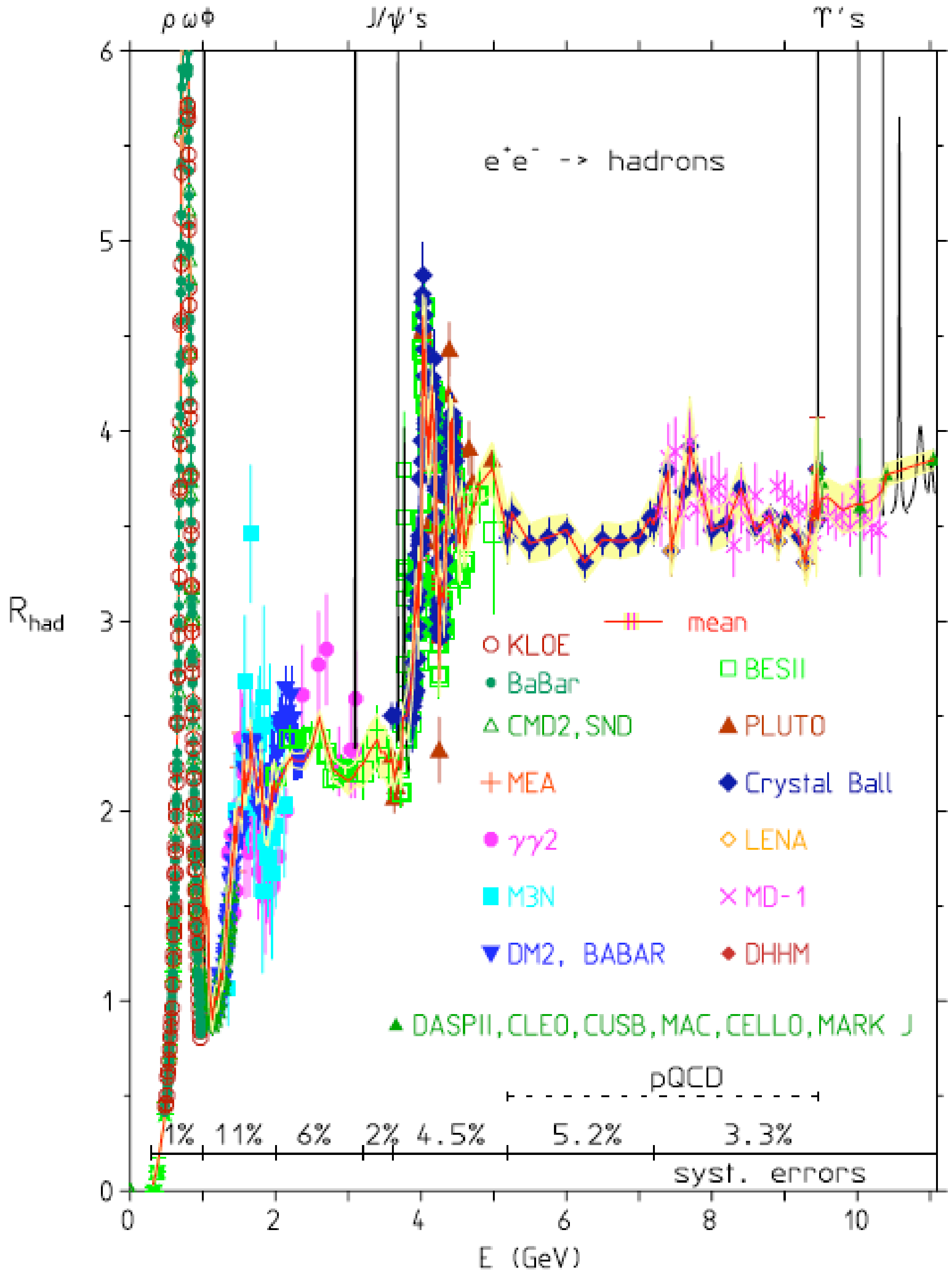
# Data at '05

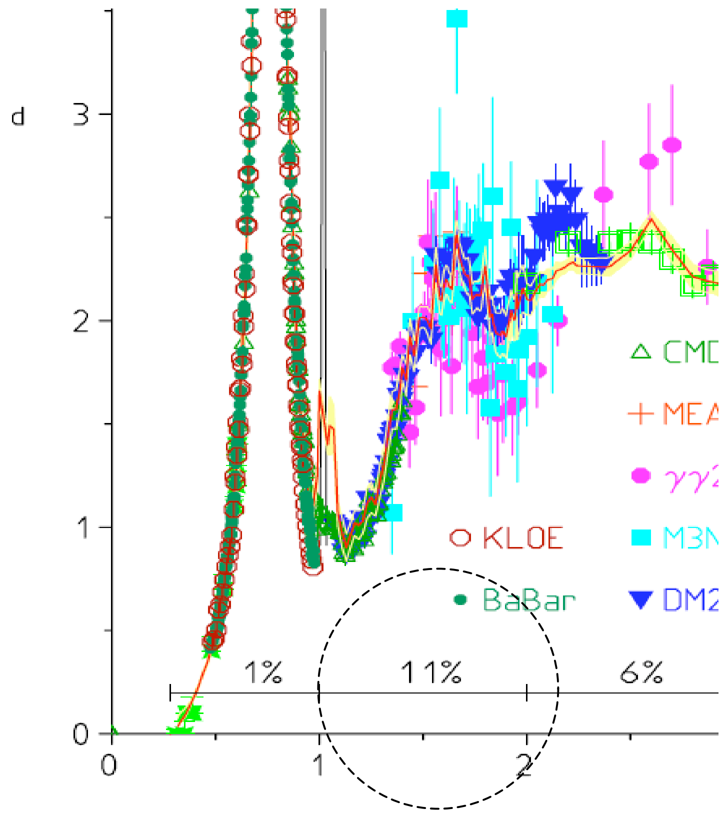


ρ,ω,φ
Ψ's
Υ's
Burkhardt, Pietrzyk 2005
Rhad
Bacci et al.
Cosme et al.
PLUTO
CESR, DORIS
MARK I
CRYSTAL BALL
MD-1 VEPP-4
VEPP-2M ND
DM2
BES 1999
BES 2001
CMD-2 2004
KLOE 2005
0.9%
15%
5.9%
6%
1.4%
rel. err. cont.
√s in GeV

# Data at 2010

Many improvements (mostly due to BaBar ISR). However the region below 2.5 GeV is still poorly known (δR~5-15%)

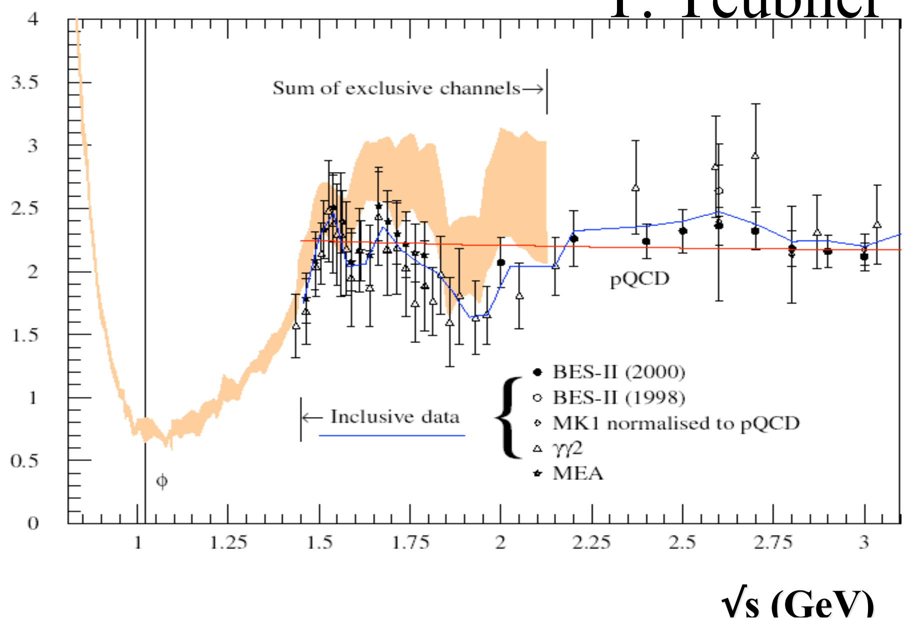


# Exclusive vs inclusive measurements?

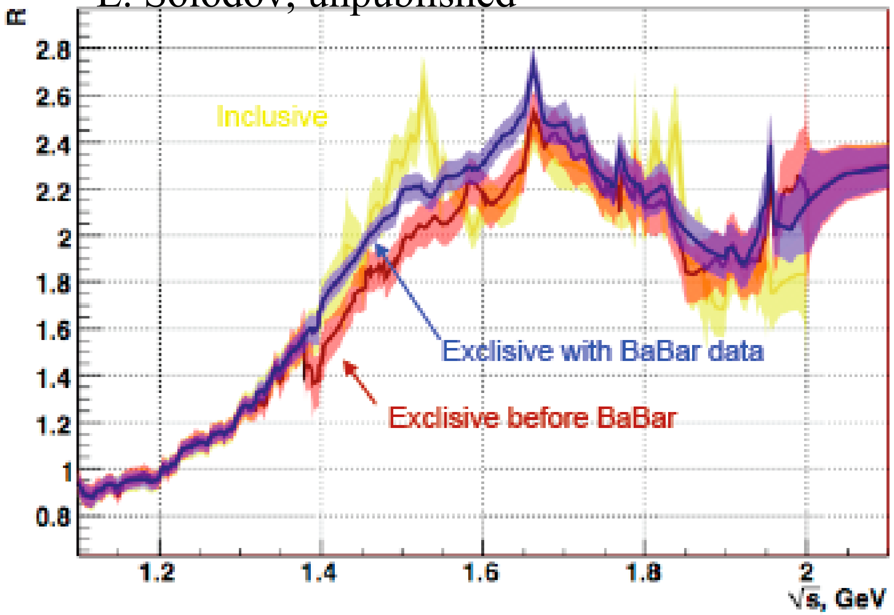
1) Most recent inclusive measurements: MEA and B antiB, with **total** integrated luminosity of **200 nb$^{-1}$** (one hour of data taking at $10^{32}$ cm$^{-2}$ sec-1).**10% stat.+ 15% syst. Errors**

T. Teubner




2) New BaBar data is improving a lot this region. However still the question on the completeness of exclusive data vs systematics of old inclusive measurements

E. Solodov, unpublished



# Radiative corrections are important!

- Unclear treatment of R.C. in old data.
- Reevaluation of RC leads to significant changes in recent data
- New data (CMD-2,SND, KLOE, Babar) paid more attention to :
  - ISR
  - Vacuum Polarization (VP)
  - FSR
- A lot of work for theorists to provide accurate MC generators (and for experimentalists to test it!)

$$\sigma_{bare} = \sigma_{dressed} |1 - \Pi(s)|^2 (1 + C_{FSR})$$

- $\sigma_{\rm dressed} = \frac{N}{\int L dt \; \varepsilon \; (1+\delta_{\rm ISR})}$
- $\Pi(s) = \Pi_{\rm lep}(s) + \Pi_{\rm had}(s)$

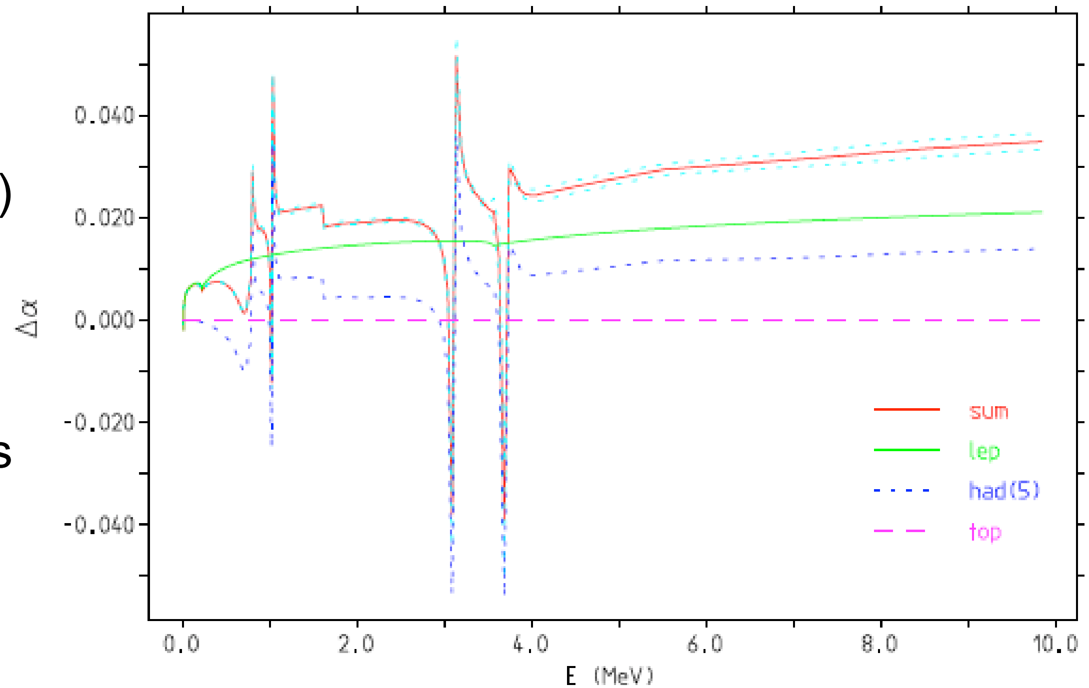



Figure from Fred Jegerlehner

# A common effort for RC and Monte Carlo tools

Eur. Phys. J. C (2010) 66: 585–686
DOI 10.1140/epjc/s10052-010-1251-4

THE EUROPEAN PHYSICAL JOURNAL C

Review

## Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[38], A. Arbuzov[9,e], G. Balossini[32,33], P. Beltrame[13], C. Bignamini[32,33], R. Bonciani[15], C.M. Carloni Calame[35], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[19,a,f,i], A. Denig[22], S. Eidelman[25,26,g], G.V. Fedotovich[25,26,e], A. Ferroglia[23], J. Gluza[19], A. Grzelińska[8], M. Gunia[19], A. Hafner[22], F. Ignatov[25], S. Jadach[8], F. Jegerlehner[3,19,41], A. Kalinowski[29], W. Kluge[17], A. Korchin[20], J.H. Kühn[18], E.A. Kuraev[9], P. Lukin[25], P. Mastrolia[14], G. Montagna[32,33,b,d], S.E. Müller[22,f], F. Nguyen[34,d], O. Nicrosini[33], D. Nomura[36,h], G. Pakhlova[24], G. Pancheri[11], M. Passera[28], A. Penin[10], F. Piccinini[33], W. Płaczek[7], T. Przedzinski[6], E. Remiddi[4,5], T. Riemann[41], G. Rodrigo[37], P. Roig[27], O. Shekhovtsova[11], C.P. Shen[16], A.L. Sibidanov[25], T. Teubner[21,h], L. Trentadue[30,31], G. Venanzoni[11,c,i], J.J. van der Bij[12], P. Wang[2], B.F.L. Ward[39], Z. Was[8,g], M. Worek[40,19], C.Z. Yuan[2]

60 participants, 13 countries

See www.lnf.infn.it/wg/sighad for more information
(next meeting April 2011, Frascati)

# Results on R from energy scan at √s<10 GeV

| Place | Ring | Detector | $E_{cm}$(GeV) | pts | Year |
|---|---|---|---|---|---|
| Novosibirsk | VEPP-2M<br>VEPP-2 | CMD2,SND<br>Olya,ND,CMD | <1.4<br><1.4 | 128 | **01-03**<br>79-85 97-99 |
| Beijing | BEPC | BESII | 2-5 | 85 | **98-99** |
| Orsay | DCI | M3N,DMI,DM2 | 1.35-2.13 | 33 | ’78 |
| Frascati | Adone | γγ2,MEA,<br>Boson,BCF | 1.42-3.09 | 31 | ’78 |
| SLAC | Spear | MarkI | 2.8-7.8 | 78 | ’82 |
| Cornell | CESR | CLEO | 3-5 | | ’05 |
| Hamburg | Doris | DASP<br>PLUTO<br>C.Ball<br>LENA | 3.1-5.2<br>3.6-4.8,9.46<br>5.0-7.4<br>7.4-9.4 | 64<br>27<br>11<br>95 | ’79<br>‘77<br>‘90<br>’82 |
| Novosibirsk | VEPP-4 | MD-1 | 7.23-10.34 | 30 | ‘91 |

# Recent Results with ISR

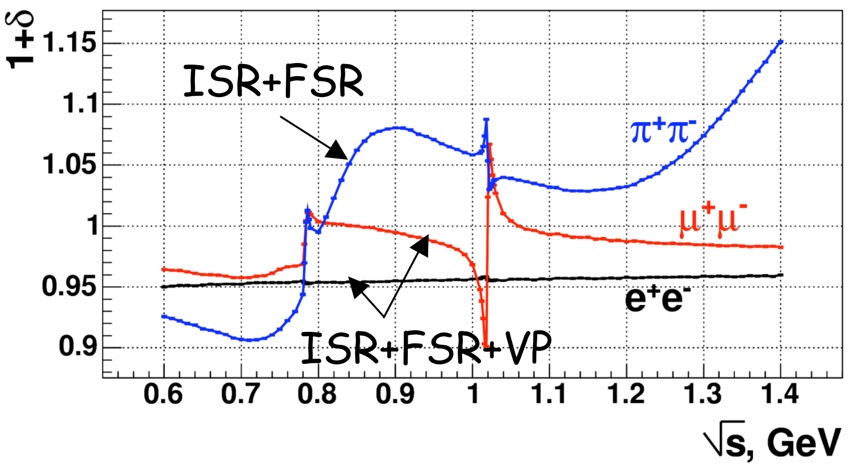
| Place | Ring | Detector | $E_{cm}$(GeV) | pts | Year |
|---|---|---|---|---|---|
| Frascati | DAΦNE | KLOE | <1 GeV | | '05-08-10 |
| SLAC | PEPII | BaBar | <5 GeV | | '05-10… |
| Tsukuba | KEKB | Belle | <5 GeV | | '08-10… |

# New Projects or Upgrades

| Place | Ring | Detector | $E_{cm}$(GeV) | pts | Year |
|---|---|---|---|---|---|
| Novosibirsk | VEPP-2000 | CMD3 and SND2 | <2 | | 10 |
| Beijing | BEPCII | BESIII | 2-4.6 (<3 with ISR) | | 10 |
| Frascati | DAΦNE | KLOE-2 | <1 (→2.5?) | | '11 |
| Tsukuba | KEKB | SuperBelle | <5 GeV | | '14? |

# Recent results with **energy scan**:

- In the last years main results were published from: CMD2 and SND @VEPP-2M, BESII@BEPC, CLEO@CESR:
- 1)VEPP-2M, Novosibirsk (exclusive measurements) $0.4 < E_{cm} < 1.4$ GeV
  - New results on $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$ ($\sigma_{syst}$~7%), $e^+e^- \to \pi^+\pi^-\pi^0$ ($\sigma_{syst}$~12%), $e^+e^- \to K_S, K_L$, $e^+e^- \to \omega\pi^+\pi^-, \eta\pi^+\pi^-$ ($\sigma_{syst}$~15%) from CMD2 and SND
  - $e^+e^- \to \pi^+\pi^-$ from CMD2 with $\sigma_{syst}$~1.% ($\sigma_{syst}$~0.6% in 0.61<E<0.96 GeV)
  - $e^+e^- \to \pi^+\pi^-$ from SND with $\sigma_{syst}$~1.3%




| Sources of errors | CMD-2 $\sqrt{s} < 1$ GeV | SND | CMD-2 $1.4 > \sqrt{s} > 1$ GeV |
|---|---|---|---|
| Event separation method | 0.2–0.4% | 0.5% | 0.2–1.5% |
| Fiducial volume | 0.2% | 0.8% | 0.2–0.5% |
| Detection efficiency | 0.2–0.5% | 0.6% | 0.5–2% |
| Corrections for pion losses | 0.2% | 0.2% | 0.2% |
| Radiative corrections | 0.3–0.4% | 0.2% | 0.5–2% |
| Beam energy determination | 0.1–0.3% | 0.3% | 0.7–1.1% |
| Other corrections | 0.2% | 0.5% | 0.6–2.2% |
| The total systematic error | 0.6–0.8% | 1.3% | 1.2–4.2% |

# How cross-section is measured

## All modes except 2π

$$\sigma\left(e^+e^- \to H\right) = \frac{N_H - N_{bg}}{L \cdot \varepsilon \cdot (1+\delta)}$$

• Luminosity L is measured using Bhabha scattering at large angles

• Efficiency ε is calculated via Monte Carlo + corrections for imperfect detector

• Radiative correction δ accounts for ISR effects only

## 2π

$$\left|F_\pi\right|^2 = \frac{N_{2\pi}}{N_{ee}} \cdot \frac{\sigma_{ee} \cdot (1+\delta_{ee})}{\sigma_{2\pi}(\text{point-like } \pi) \cdot (1+\delta_{2\pi})}$$

• Ratio N(2π)/N(ee) is measured directly ⇒ detector inefficiencies are cancelled out

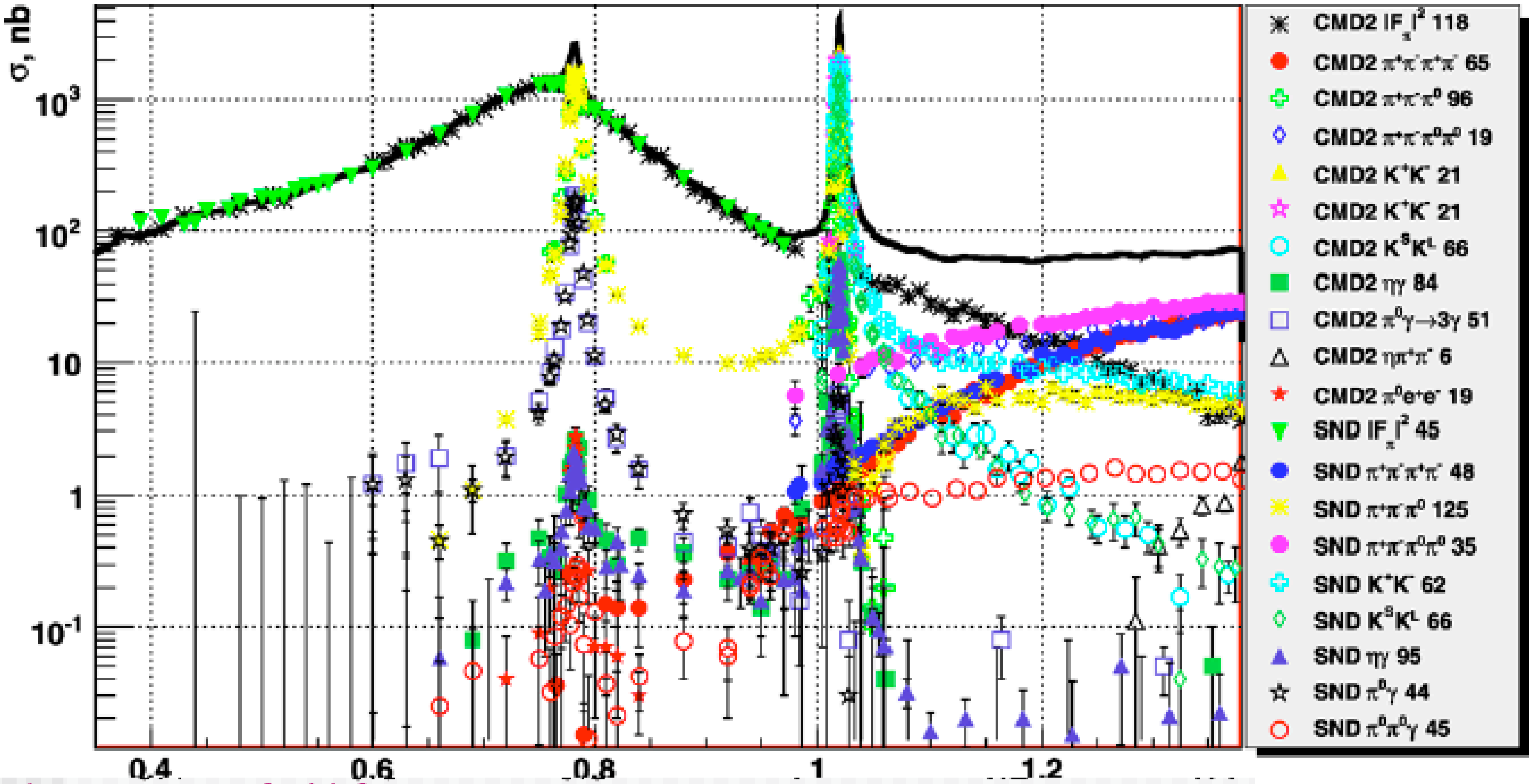
• Virtually no background

• Analysis does not rely on simulation

• Radiative corrections account for ISR and FSR effects

• Formfactor is measured to better precision than L

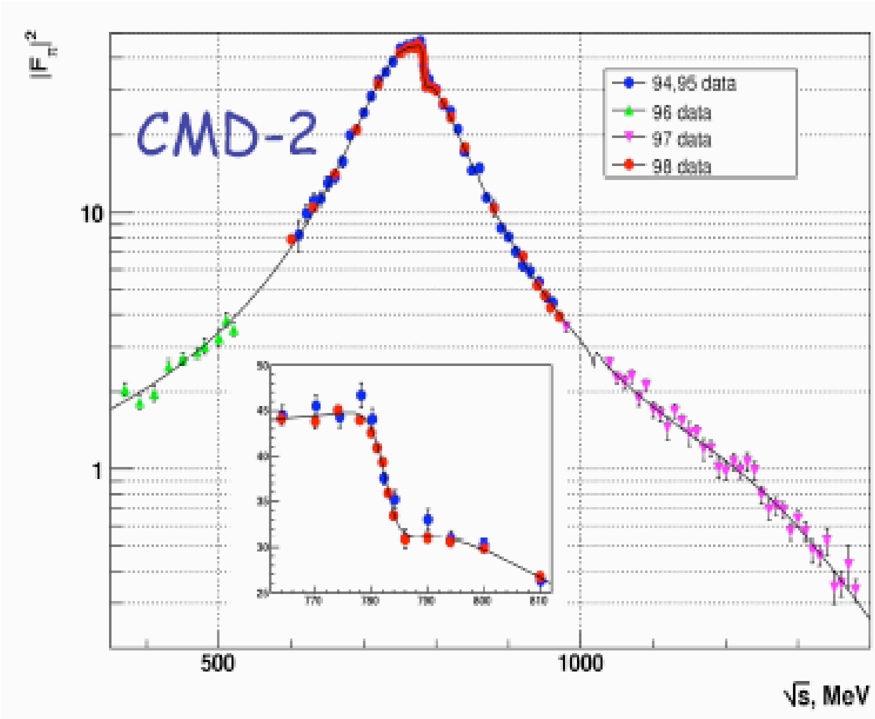
# Measurement of exclusive channels with CMD-2/SND




Combine precision of R(s) from CMD2&SND

| | | | | | |
|---|---|---|---|---|---|
| Sys. error: | ~0.6-0.7% | 1.0% | 0.6% | 1.5% | 1.5 -- 3.5 % |
| Total error: | ~ 6 -- 1% | 1.5% | 1--2% | 2.0% | 2.5 -- 3.5 % |

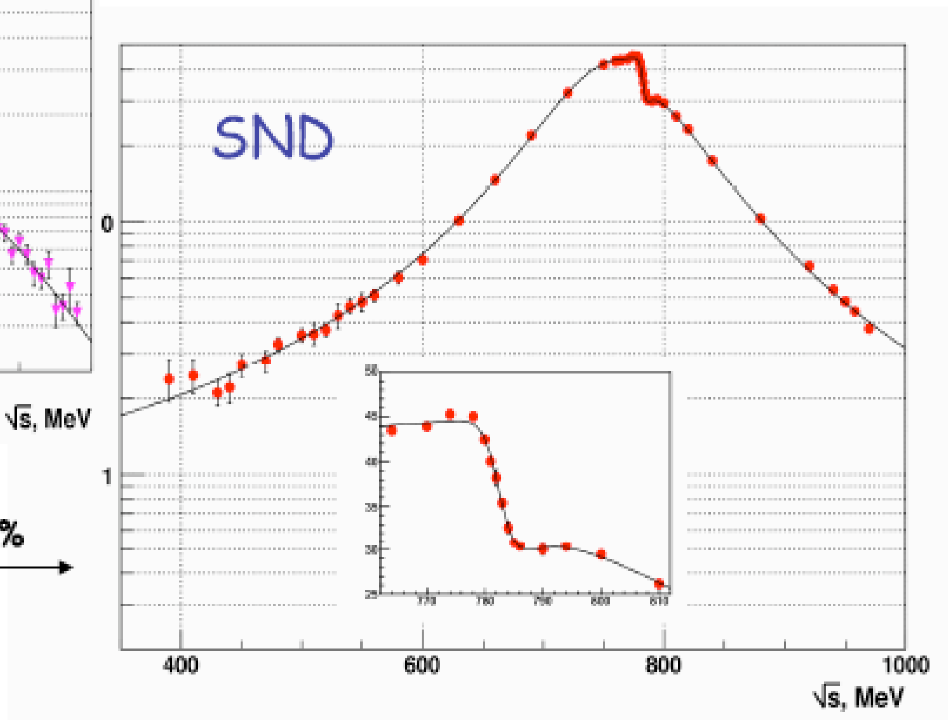
# Pion form factor @ Novosibirsk (with energy scan)




Systematic error

0.7% 0.6% / 0.8% 1.2-4.2%

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




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

Systematic error

3.2% 1.3% 8

*Good agreement between the two spectra*

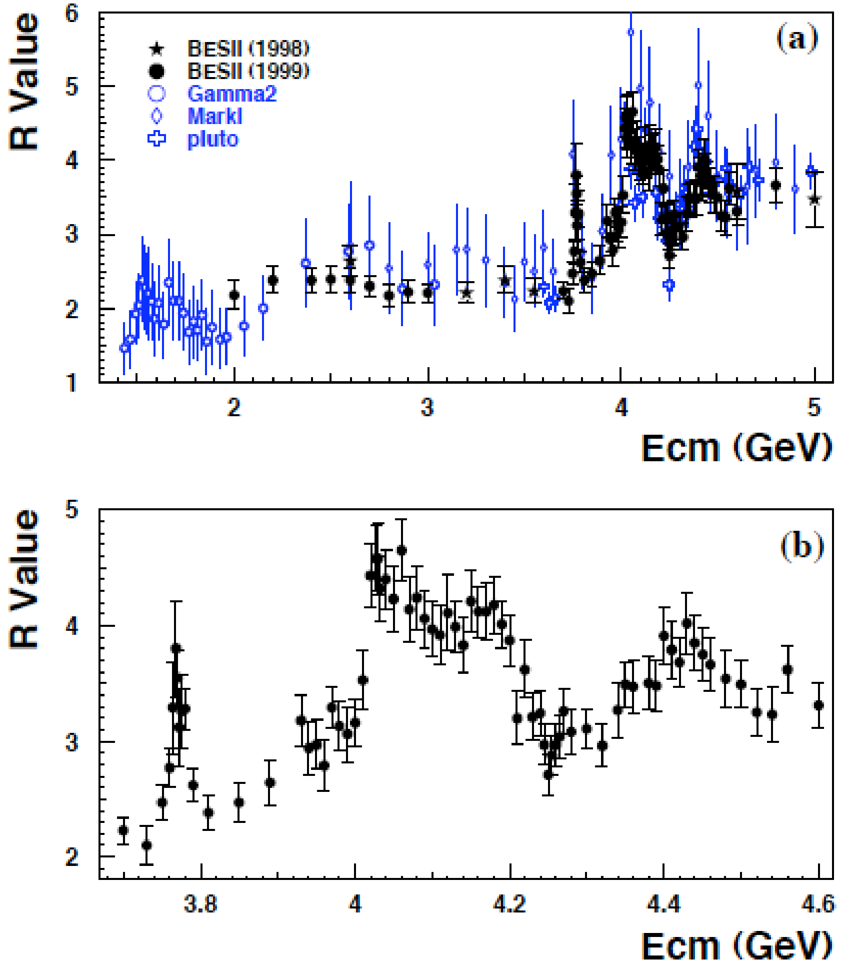
# R measurement at BESII

- BESII @ BEPC, Beijing (inclusive measurement) 2 <$E_{cm}$<5 GeV
  - New result of R in 2 <$E_{cm}$<5 GeV from BESII coll., with $\sigma_R/R$~7% (improvement of a factor **2**)

$$R = \frac{N_{had}^{obs} - N_{bg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma_{\mu\mu}^0 \cdot L \cdot \epsilon_{trg} \cdot \bar{\epsilon}_{had} \cdot (1+\delta)},$$

TABLE II. Contributions to systematic errors: experimental selection of hadronic events, luminosity determination, theoretical modeling of hadronic events, trigger efficiency, radiative corrections and total systematic error. All errors are in percentages (%).

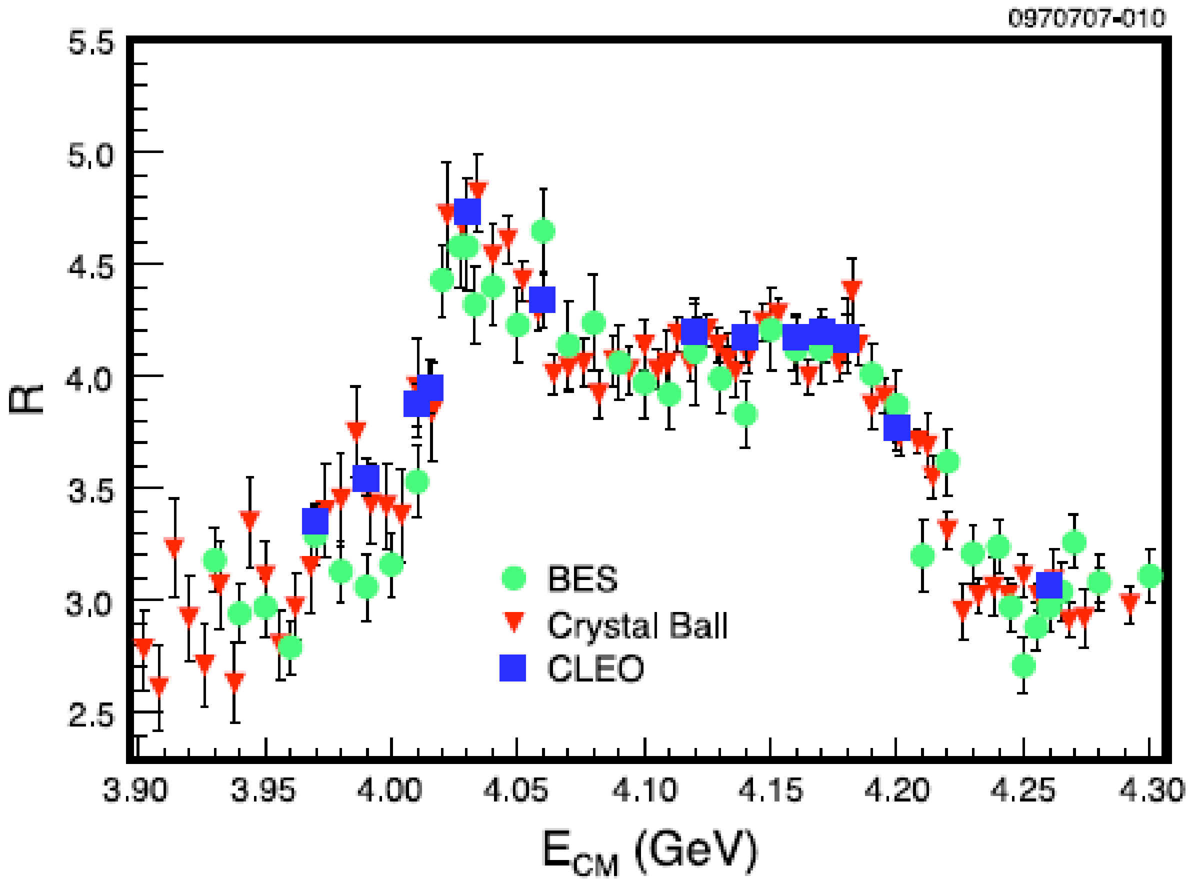
| $E_{cm}$ (GeV) | hadron selection | $L$ | M.C. modeling | trigger | radiative correction | total |
|---|---|---|---|---|---|---|
| 2.000 | 7.07 | 2.81 | 2.62 | 0.5 | 1.06 | 8.13 |
| 3.000 | 3.30 | 2.30 | 2.66 | 0.5 | 1.32 | 5.02 |
| 4.000 | 2.64 | 2.43 | 2.25 | 0.5 | 1.82 | 4.64 |
| 4.800 | 3.58 | 1.74 | 3.05 | 0.5 | 1.02 | 5.14 |



# R measurement at CLEO

- CLEO@ CESR, Ithaca (inclusive measurement) 3.9 <$E_{cm}$<4.3 GeV
  - New result on R (inclusive measurement) in 3.97<$E_{cm}$<4.26 GeV (above the open charm threshold) with a $\delta_{sys}$ between 5.2 and 6.1%. In agreement with the sum of exclusive measurement and previous experiments

| Energy (MeV) | $R$ (ISR-corrected) |
|---|---|
| 3970 | $3.36 \pm 0.04 \pm 0.05$ |
| 3990 | $3.55 \pm 0.05 \pm 0.06$ |
| 4010 | $3.88 \pm 0.04 \pm 0.08$ |
| 4015 | $3.95 \pm 0.08 \pm 0.08$ |
| 4030 | $4.74 \pm 0.07 \pm 0.12$ |
| 4060 | $4.34 \pm 0.05 \pm 0.10$ |
| 4120 | $4.21 \pm 0.06 \pm 0.10$ |
| 4140 | $4.18 \pm 0.04 \pm 0.10$ |
| 4160 | $4.18 \pm 0.03 \pm 0.10$ |
| 4170 | $4.20 \pm 0.01 \pm 0.10$ |
| 4180 | $4.17 \pm 0.04 \pm 0.10$ |
| 4200 | $3.77 \pm 0.05 \pm 0.08$ |
| 4260 | $3.06 \pm 0.02 \pm 0.04$ |



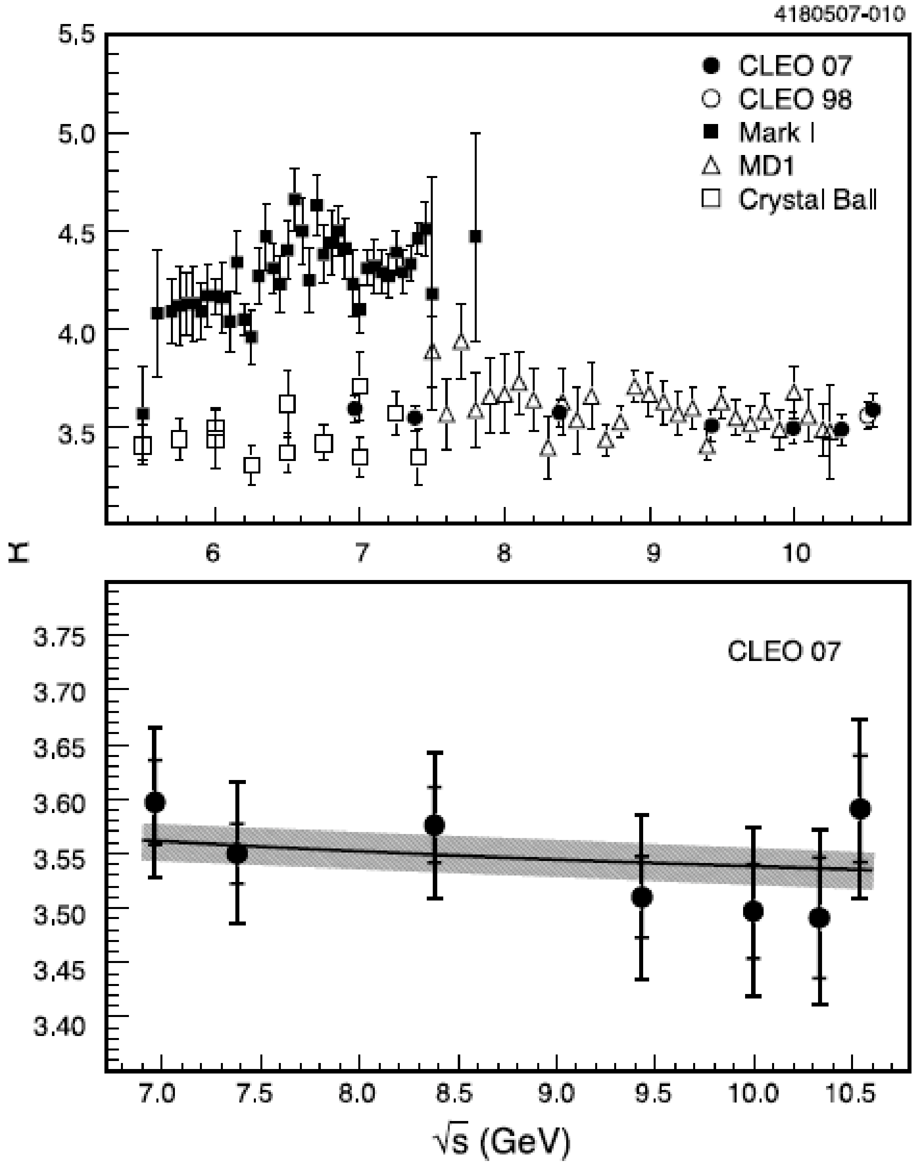
# R measurement at CLEO

- CLEO@ CESR, Ithaca (inclusive measurement) $6.9 < E_{cm} < 10..5$ GeV

  - New result on R (inclusive measurement) in $6.964 < E_{cm} < 10.538$ GeV (7 points) with a δsys of ~ 2%. In agreement with previous experiments (but MARKI) and pQCD (Λ=0.31 GeV)

$$R = \frac{N_{had}(1-f)}{\mathcal{L}\epsilon_{had}(1+\delta)\sigma^0_{\mu\mu}},$$

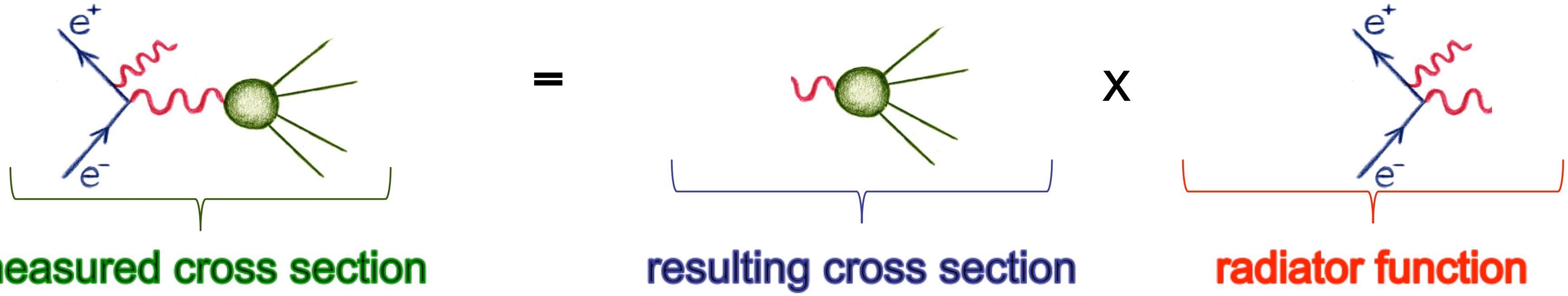
| | |
|---|---|
| ε(1+δ) | 1% |
| L | 1% |
| Bckg/Hadr Modeling | 0.7% |
| Dataset variation | 0.3% |
| TOTAL | 1.8% |



# ISR: Initial State Radiation

Neglecting final state radiation (FSR):

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




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

➔ **EVA + PHOKHARA MC Generator**

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

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

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

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

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

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

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

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

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

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

## b) Via bin-by-bin Normalisation to rad. Muon events

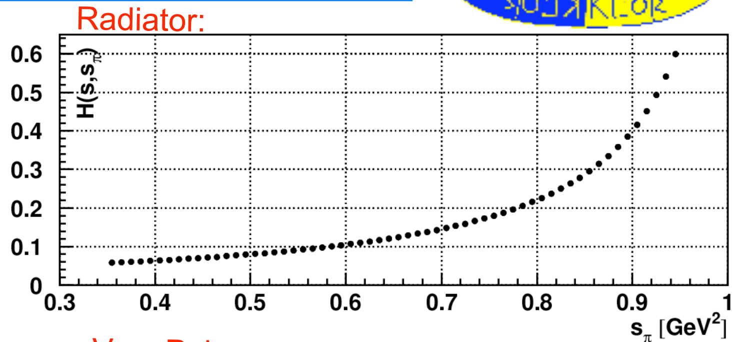
# Radiative Corrections

## 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%**

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

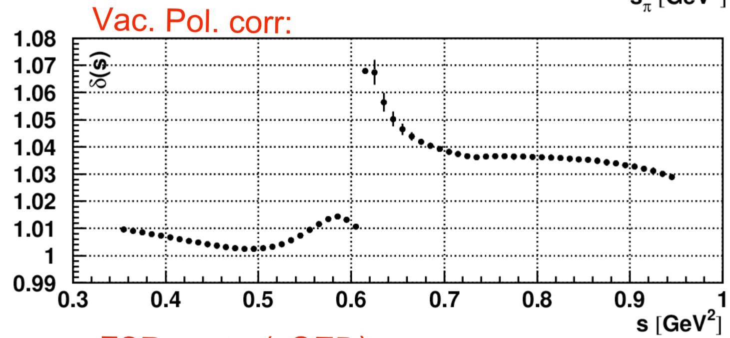



## Radiative Corrections:

**i) Bare Cross Section**

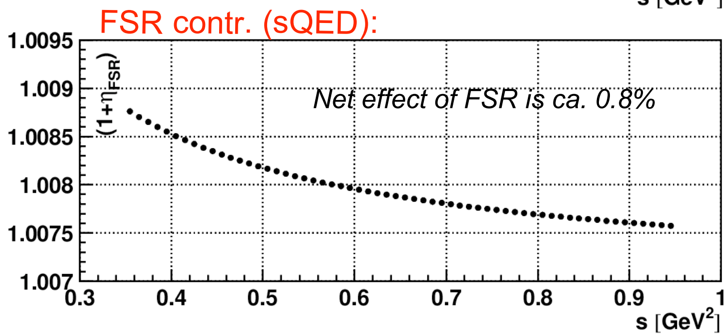
divide by Vacuum Polarisation $\delta(s)=(\alpha(s)/\alpha(0))^2$

➔ from F. Jegerlehner

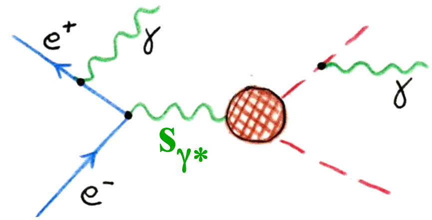



**ii) FSR**

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


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




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

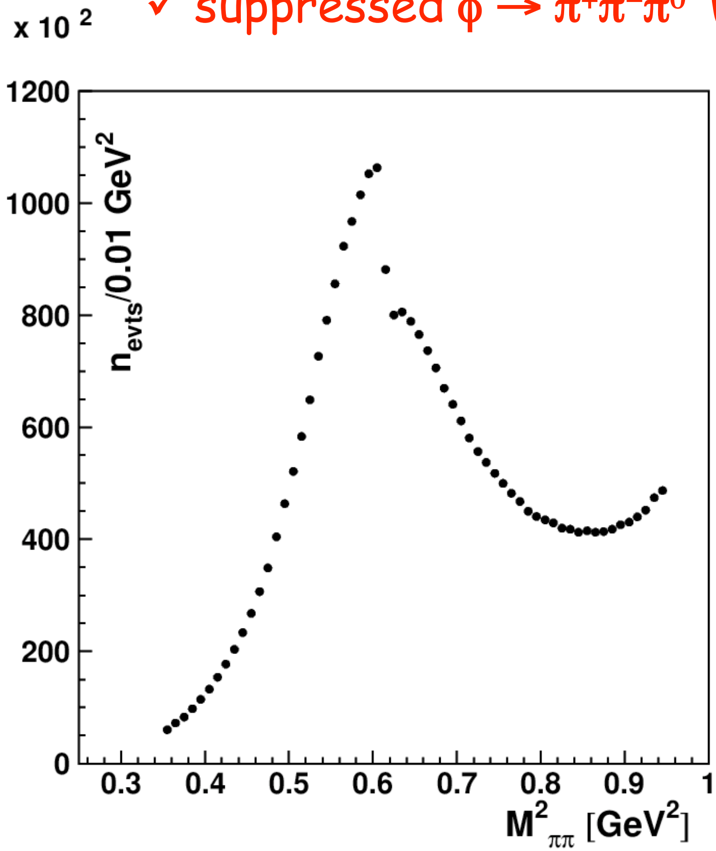
(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)

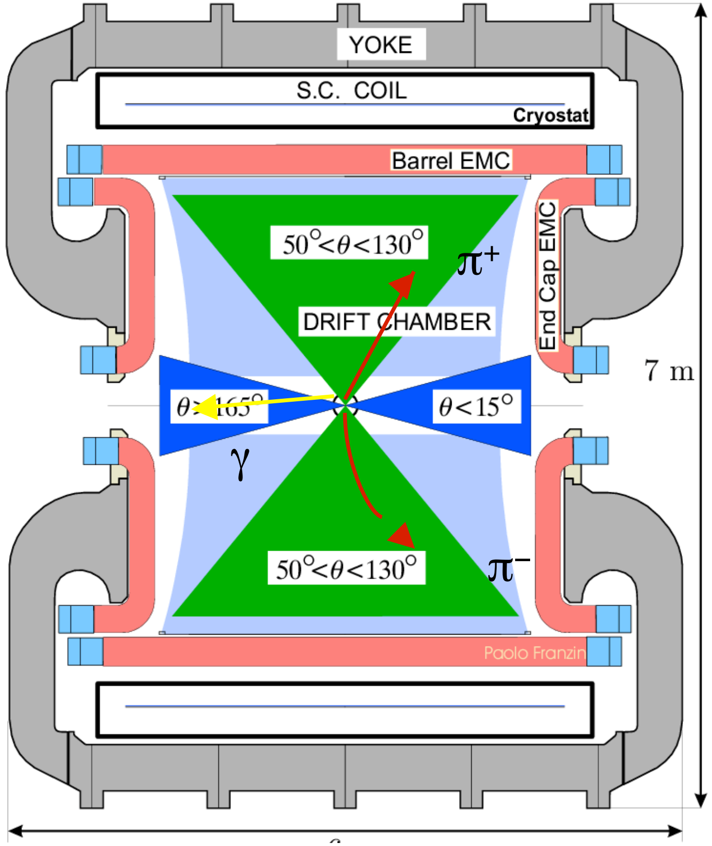
# SA Event Selection (KLOE08)

a) 2 tracks with $50^{o} < \theta_{track} < 130^{o}$
b) small angle (not detected) $\gamma$
( $\theta_{\pi\pi} < 15^{o}$ or $> 165^{o}$)

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

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




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

**3.1 Mill. Events between 0.35 and 0.95 GeV$^2$**

# Luminosity:

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

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

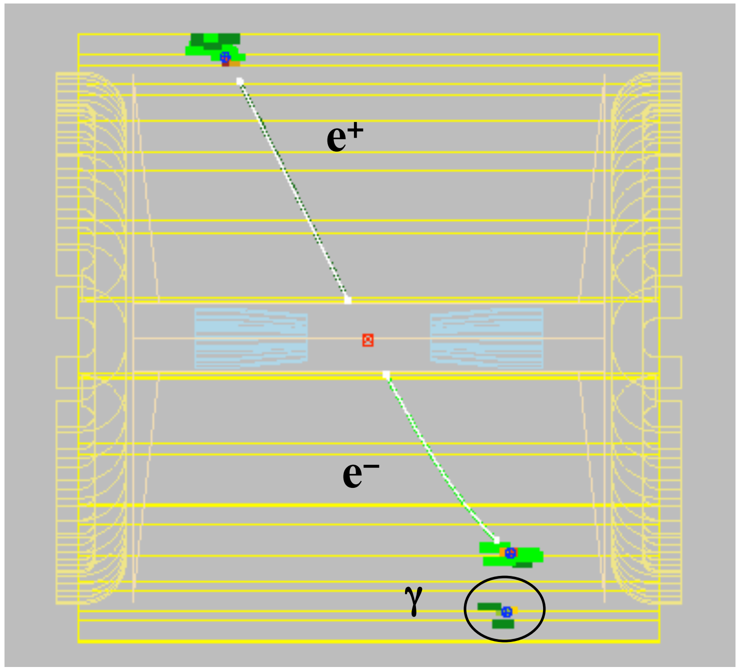
$55° < \theta < 125°$

acollinearity $< 9°$

$p \geq 400$ MeV

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

generator used for $\sigma_{eff}$
**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:

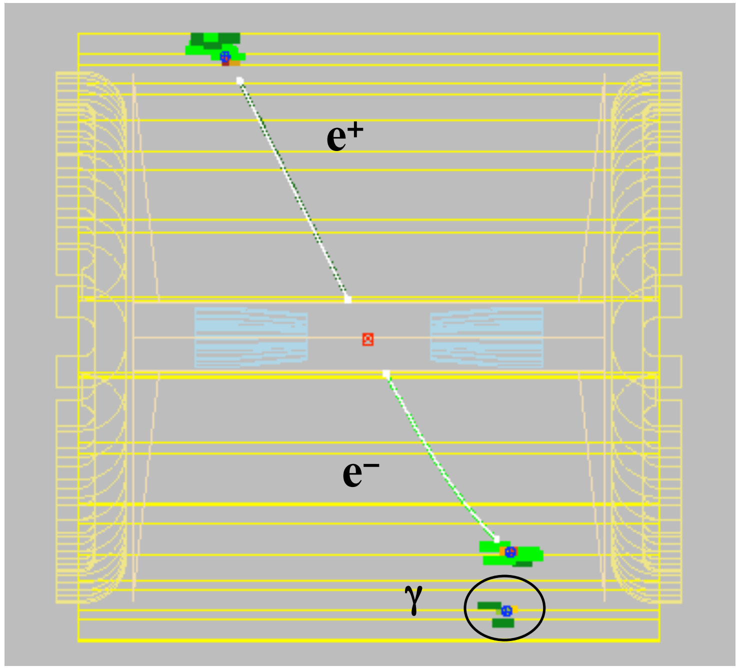
KLOE measures $L$ with Bhabha scattering

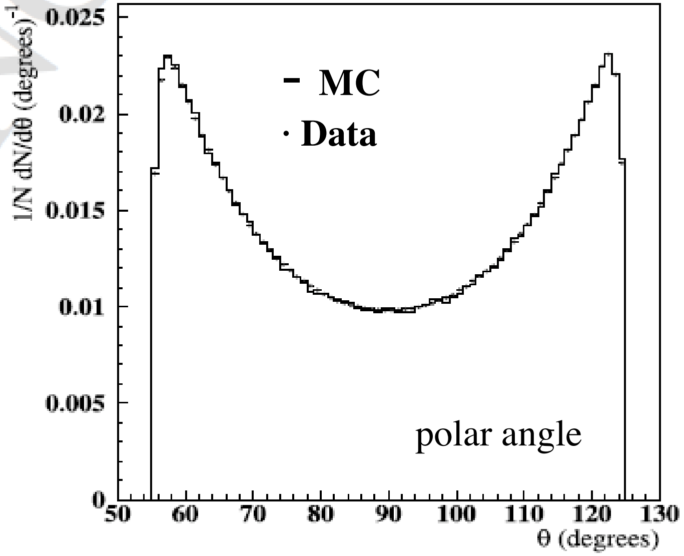
**$55° < \theta < 125°$**

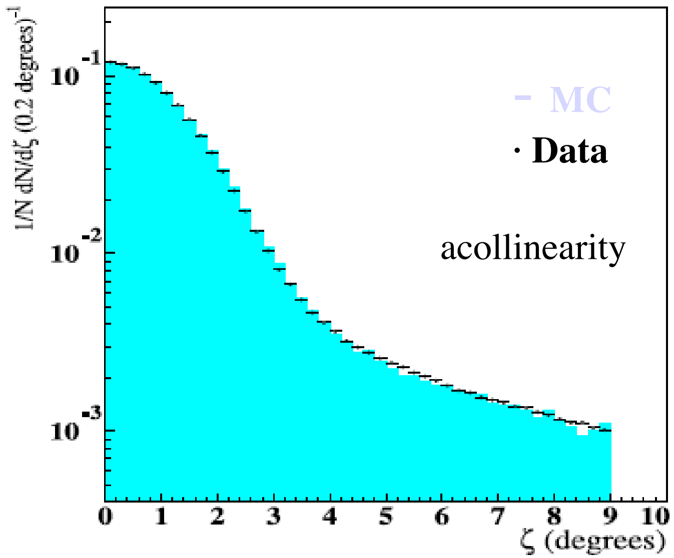
**acollinearity $< 9°$**

**p $\geq$ 400 MeV**

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



# KLOE result (KLOE08)

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

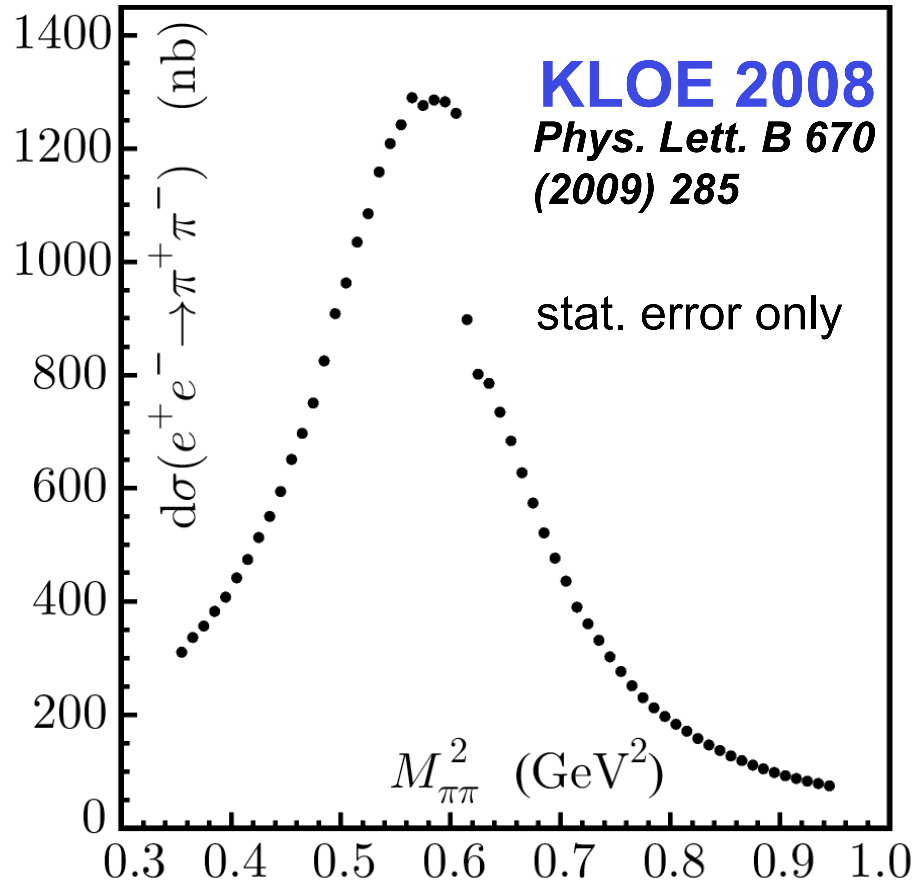
| | |
|---|---|
| Reconstruction Filter | negligible |
| Background | 0.3% |
| Trackmass/Miss. Mass | 0.2% |
| π/e-ID and TCA | negligible |
| Tracking | 0.3% |
| Trigger | 0.1% |
| Acceptance ($\theta_{\pi\pi}$) | 0.1% |
| Acceptance ($\theta_\pi$) | negligible |
| Unfolding | negligible |
| Software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

**experimental fractional error on $a_\mu$ = 0.6 %**

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

**theoretical fractional error on $a_\mu$ = 0.6 %**

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




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

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

# LA Event Selection (KLOE10)

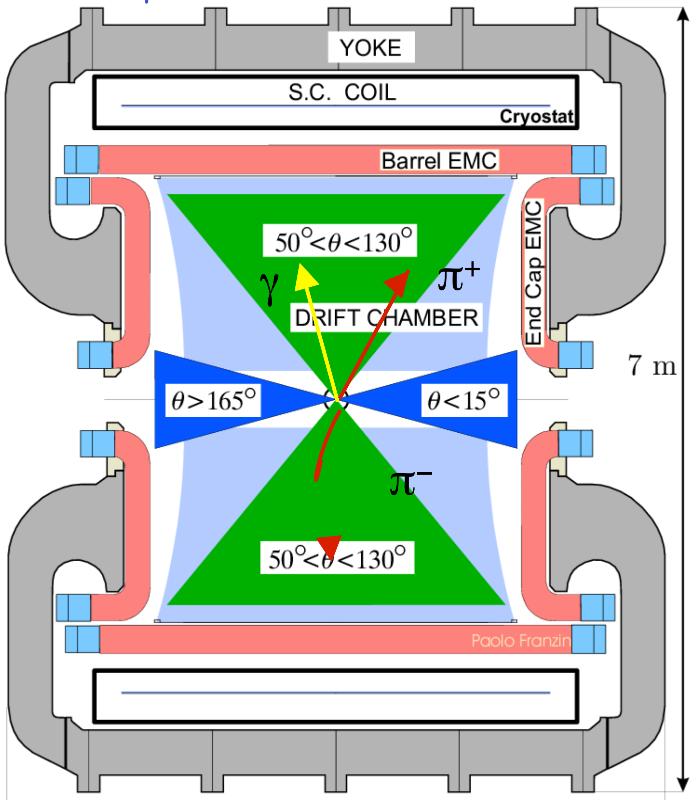
**2 pion tracks at large angles**
$50^o < \theta_\pi < 130^o$

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

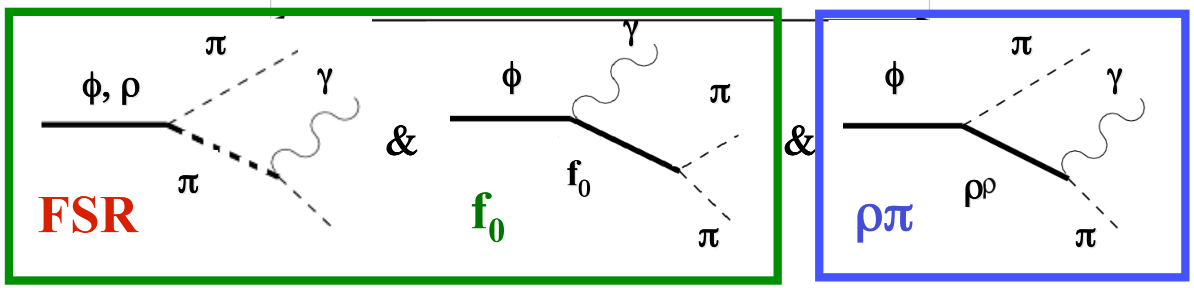
✓ **independent complementary analysis**
✓ **threshold region $(2m_\pi)^2$ accessible**
✓ **$\gamma_{ISR}$ photon detected (4-momentum constraints)**

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

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




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



# KLOE10 result: Pion Form Factor

arXiv:1006.5313

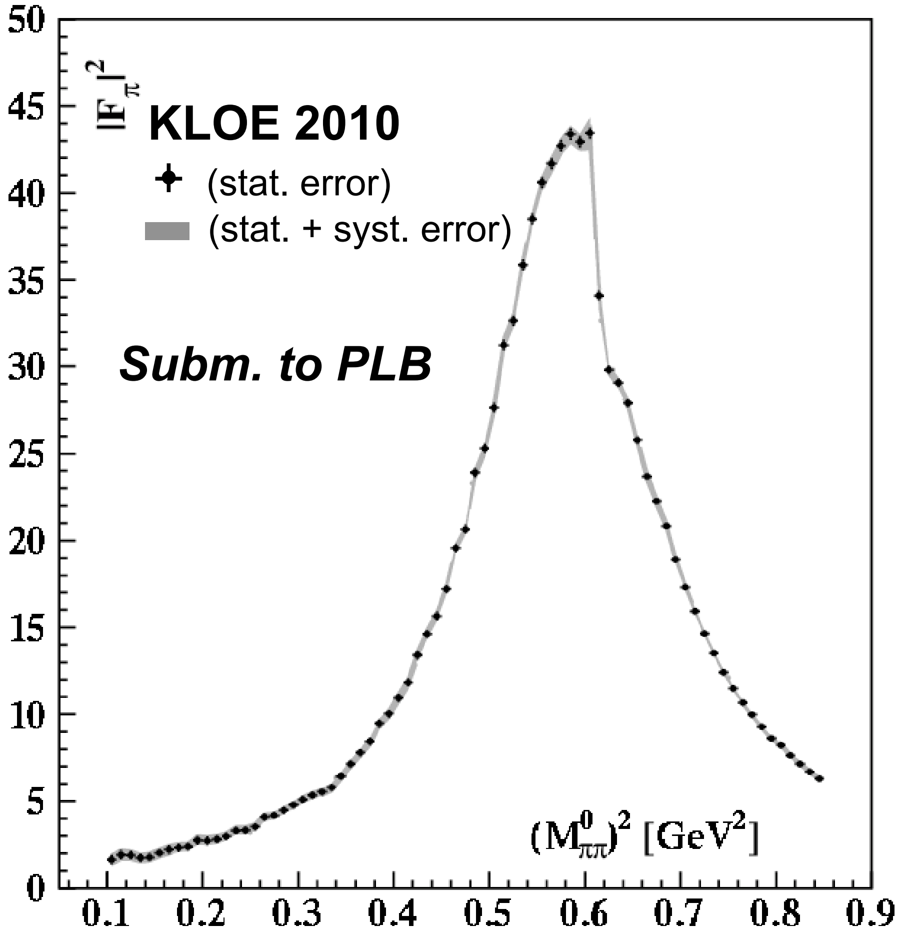



Table of systematic errors on $a_\mu^{\pi\pi}$(0.1-0.85 GeV$^2$):

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

experimental fractional error on $a_\mu$ = 1.0 %

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

theoretical fractional error on $a_\mu$ = 0.6 %

Disp. Integral:

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

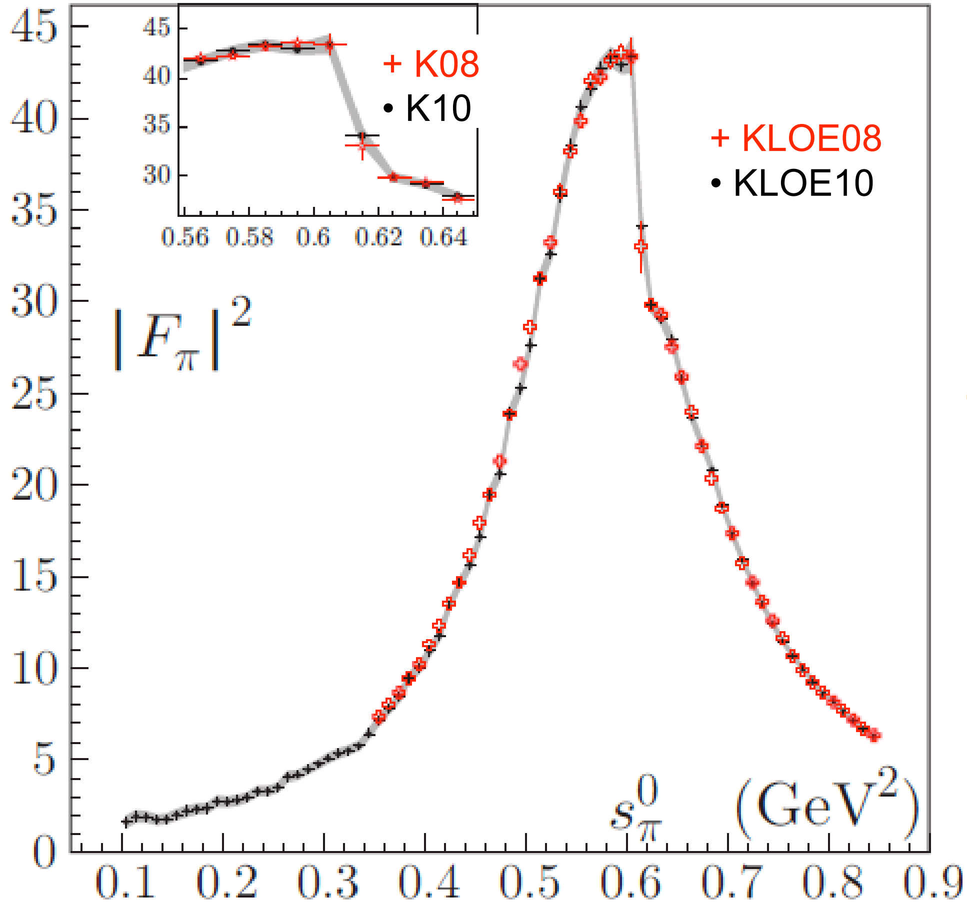
**$a_\mu^{\pi\pi}$(0.1-0.85 GeV$^2$) = (478.5 ± $2.0_{stat}$ ±$4.8_{sys}$ ±$2.9_{theo}$) · $10^{-10}$**

0.4% 1.0% 0.6%

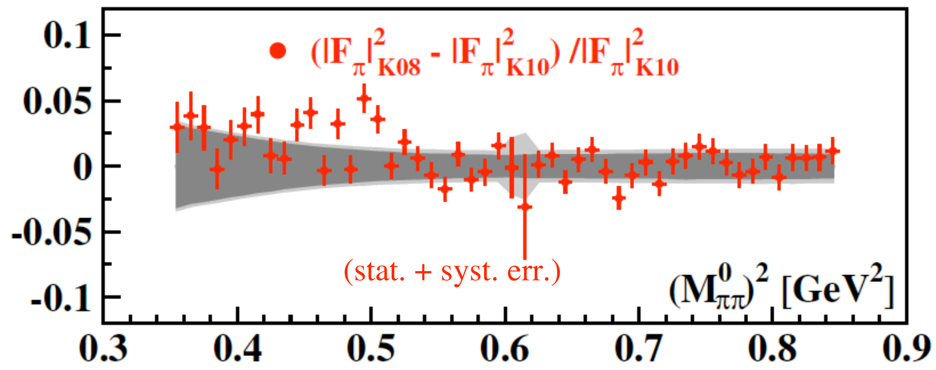
# Comparison of results: KLOE10 vs KLOE08



KLOE08 result compared to KLOE10:




Fractional difference:




*band: KLOE10 error*

**Excellent agreement with KLOE08, expecially above 0.5 GeV$^2$**

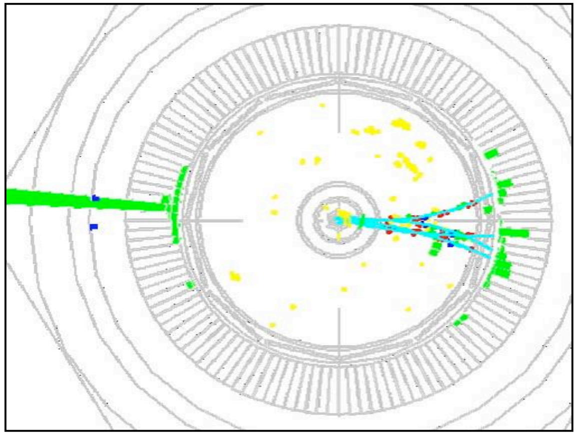
Combination of KLOE08 and KLOE10:

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

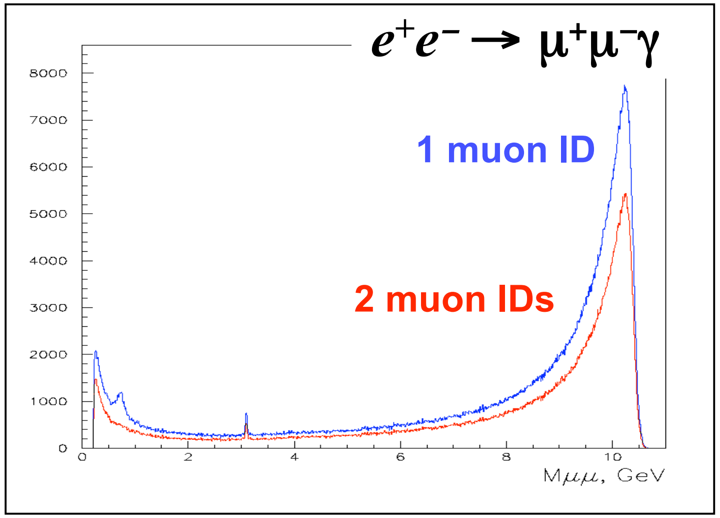
**KLOE covers ~70% of total $a_\mu^{HLO}$ with a fractional error of 1.0%**

# BABAR results on R using ISR:

• Center-of-mass energy of machine PEP-II ($\sqrt{s}=m_{\Upsilon(4s)}$=10.6 GeV) far from mass range of interest (ca. < 4 GeV )
→ requires high energy photon $E_\gamma^*$=(3 - 5.3) GeV
→ requires high integrated luminosity of PEP-II



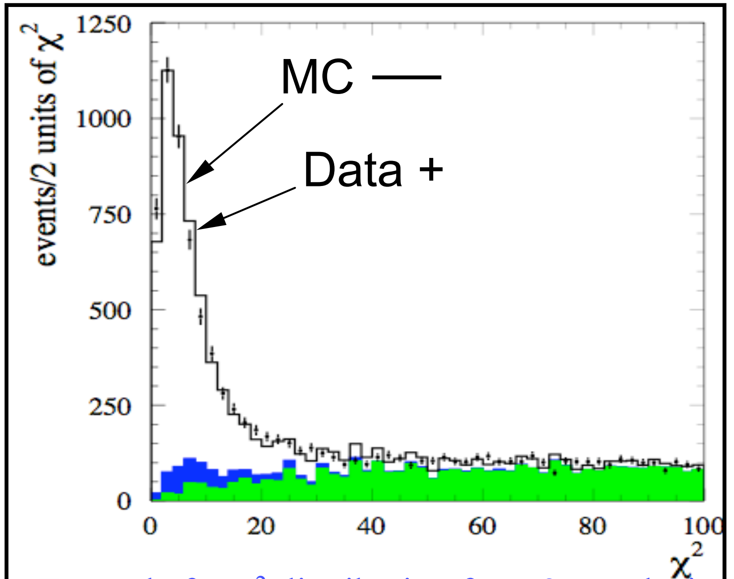

• Hard ISR-photon back-to-back to hadrons
→ only acceptance for large angle photons
→ photon tagging!




• Normalisation:
→ to integrated luminosity and radiator function (not for 2π mode)
→ to radiative muon pairs, which are selected with high precision (for 2π mode)

# BABAR results on R using ISR:

- Mass resolution of hadronic system improved by means of a kinematic fit
  → Input to the fit: Momentum and direction of ISR-photon (not energy!)
  → Constraints: energy and momentum conservation (and $\pi^0$ mass)




Example for $\chi^2$ distribution from $3\pi$ analysis

- $\chi^2$-distribution of kinematic fit is the main tool for background subtraction
  → long tail due radiative corrections (NLO)
  → remaining background obtained from MC (for q$\bar{q}$ events) or from data with sideband technique (for ISR events)

- Background from $\Upsilon(4s)$ and from B-decays is very small ($E_\gamma > 3$ GeV)
  → main backgroud from other ISR-events
  → background from continuum processes $e^+e^- \to q\bar{q}$

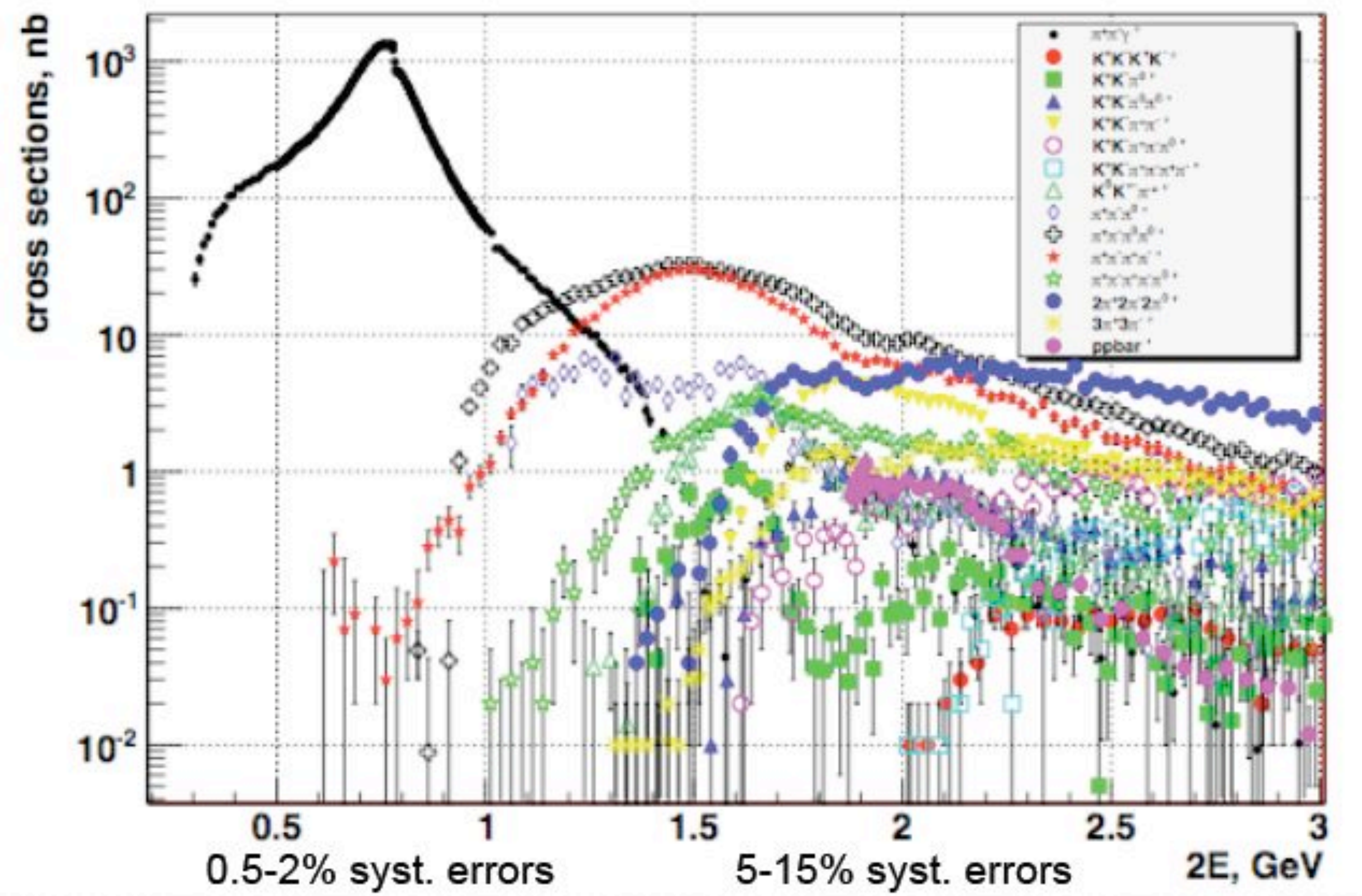
*From A.Denig, Phipsi06*

# BaBar results with ISR: an incomplete list

- $e^+e^- \to \pi^+ \pi^- \pi^0$ between 1. and 3 GeV with $\sigma_{syst}$~5%-10%
- $e^+e^- \to$ 4h ($\pi^+ \pi^- \pi^+ \pi^-$, $\pi^+ \pi^- K^+ K^-$, $K^+ K^- K^+ K^-$) between 0.6 and 4.5 GeV
  - $\sigma_{syst}(\pi^+ \pi^- \pi^+ \pi^-)$ is 12% (<1GeV), 5%(1.-3 GeV), 16% (>3 GeV)
  - $\sigma_{syst}(\pi^+ \pi^- K^+ K^-)$ is 15% (1.5-4.5 GeV)
  - $\sigma_{syst}(K^+ K^- K^+ K^-)$ is 20% (2.0-4.5 GeV)
- $e^+e^- \to$ 6h ($3(\pi^+ \pi^-)$, $2(\pi^+ \pi^-) \pi^0 \pi^0$, $2(\pi^+ \pi^-) K^+ K^-$) between 1.5 and 4.5 GeV with $\sigma_{syst}$ between 6 and 10%
- $e^+e^- \to \pi^+ \pi^-$ with $\sigma_{sys}$ ~0.6% (around the $\rho$)

| Process | Systematic accuracy |
|---|---|
| $\pi^+\pi^-\pi^0$ | (6-8)% |
| $2\pi^+2\pi^-$ | 5% |
| $2\pi 2\pi^0$ | (8-14)% |
| $2\pi^+2\pi^-\pi^0$ | (8-11)% |
| $2\pi^+2\pi^-\eta$ | 7% |
| $3\pi^+3\pi^- + 2\pi^+2\pi^-2\pi^0$ | (6-11)% |
| $KK\pi$ | (5-6)% |
| $K^+K^-\pi\pi$ | (8-11)% |

# BaBar results on R using ISR:




**To calculate R in 1 – 2 GeV the processes $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, $K^+K^-$, $K_LK_S$, $K_LK_S\pi\pi$, $K_SK^+\pi^-\pi^0$ must be measured. The work is in progress.**

# BABAR RESULTS being updated

$e^+e^- \rightarrow 2\mu\gamma,\ 2\pi\gamma,\ 2K\gamma,\ 2p\gamma,\ 2\Lambda\gamma,\ 2\Sigma\gamma,\ \Lambda\Sigma\gamma$

$e^+e^- \rightarrow 3\pi\gamma$

$e^+e^- \rightarrow 2(\pi^+\pi^-)\gamma,\ K^+K^-\pi^+\pi^-\gamma,\ K^+K^-\pi^0\pi^0\gamma,\ 2(K^+K^-)\gamma$

$e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0\pi^0\gamma,\ 3(\pi^+\pi^-)\gamma,\ K^+K^-2(\pi^+\pi^-)\gamma$

$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma,\ \pi^+\pi^-\pi^0\pi^0\pi^0\gamma,\ \pi^+\pi^-\pi^0\eta\gamma\ \ldots$

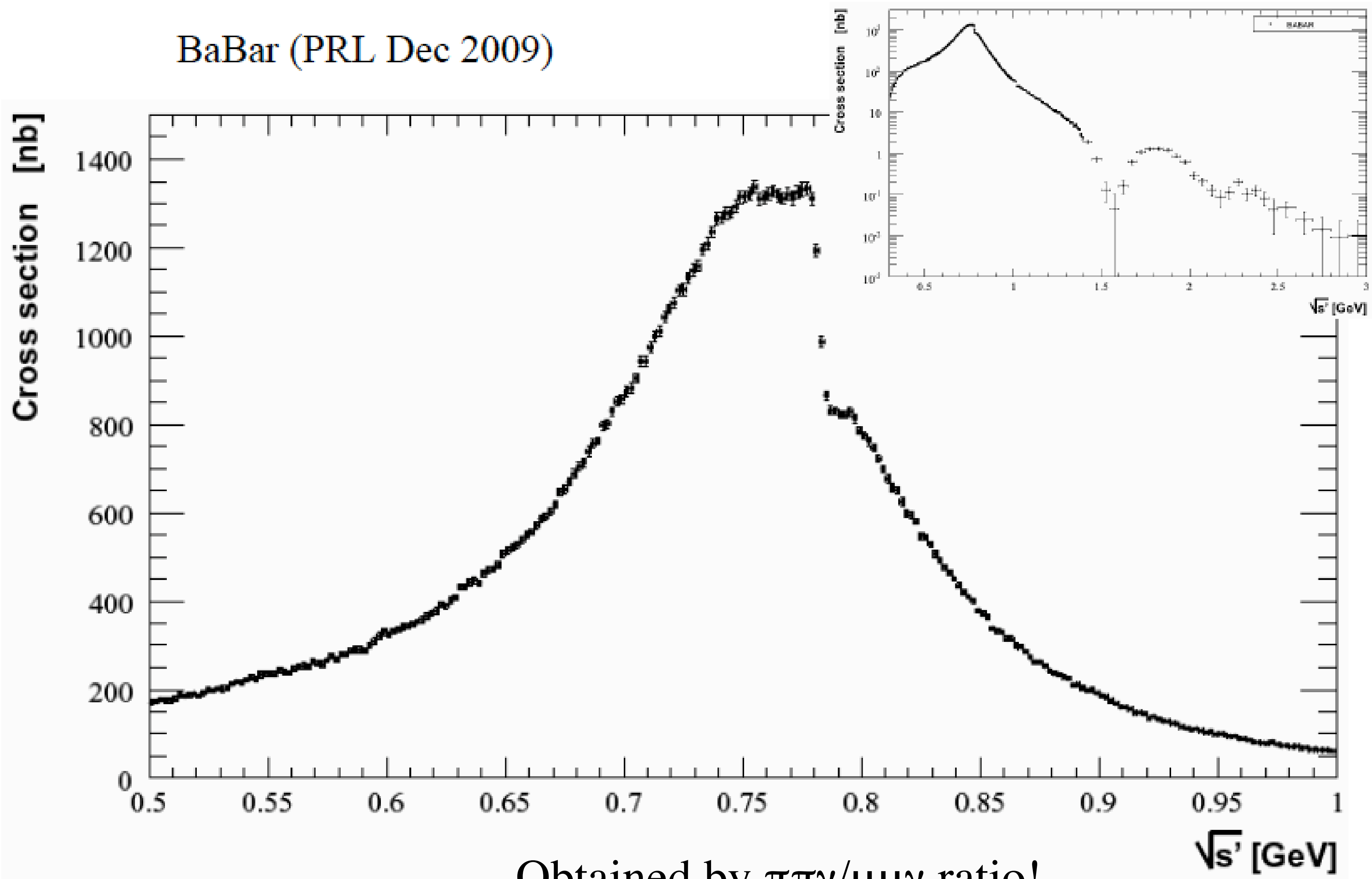
$e^+e^- \rightarrow K^+K^-\pi^0\gamma,\ K^+K^-\eta\gamma\ (KK^*\gamma,\ \phi\pi^0\gamma,\ \phi\eta\gamma\ \ldots)$

$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0/\eta\gamma,\ K^+K^-\pi^+\pi^-\pi^0/\eta\gamma$

Are being updated to full BaBar data with ~500fb$^{-1}$

# BaBar results on $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ using ISR:

BaBar (PRL Dec 2009)




Obtained by ππγ/μμγ ratio!

# PION FORM FACTOR AT BABAR

## SYSTEMATIC ERRORS

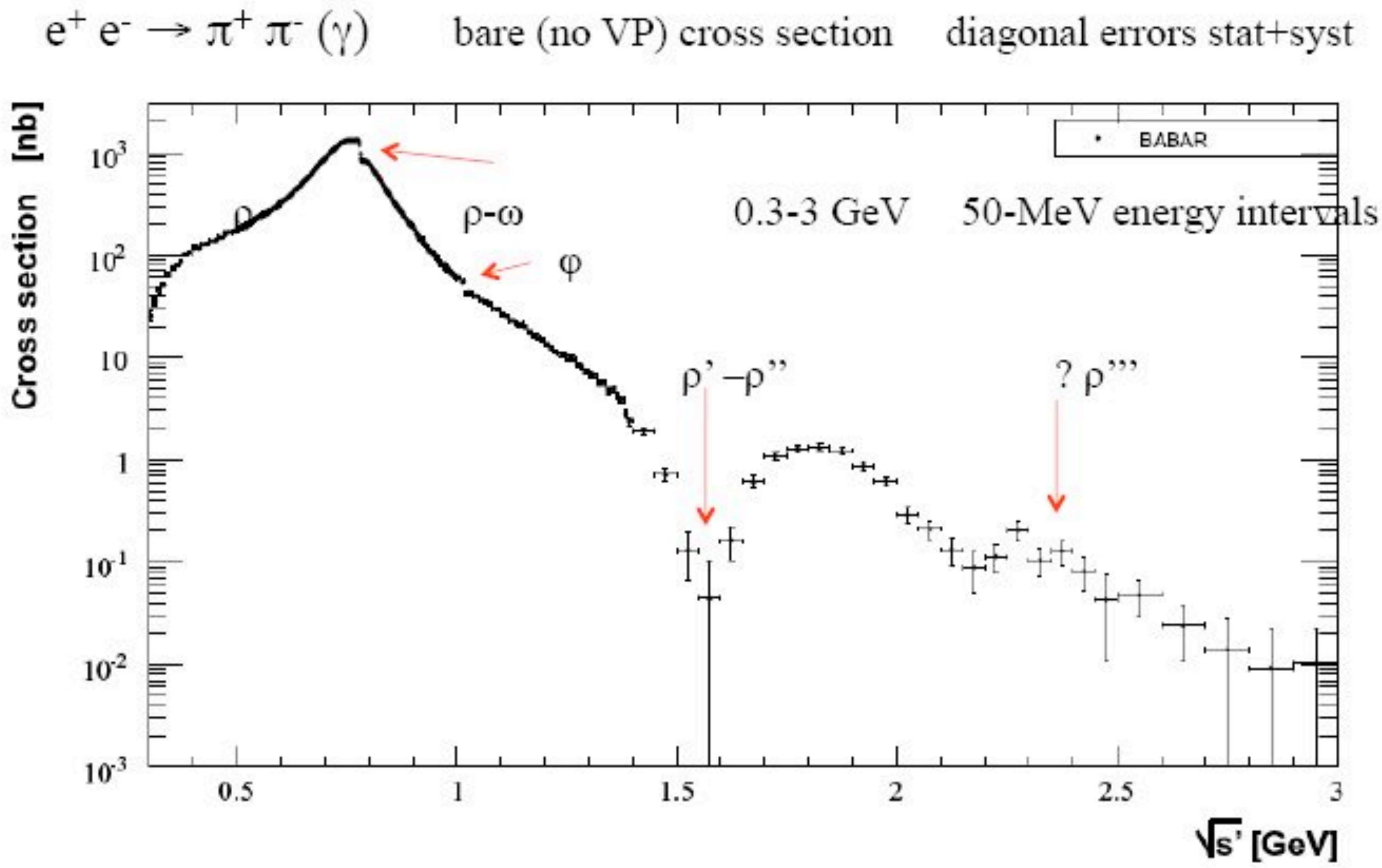
√s' intervals (GeV) errors in $10^{-3}$

| sources | 0.3-0.4 | 0.4-0.5 | 0.5-0.6 | 0.6-0.9 | 0.9-1.2 | 1.2-1.4 | 1.4-2.0 | 2.0-3.0 |
|---|---|---|---|---|---|---|---|---|
| trigger/ filter | 5.3 | 2.7 | 1.9 | 1.0 | 0.5 | 0.4 | 0.3 | 0.3 |
| tracking | 3.8 | 2.1 | 2.1 | 1.1 | 1.7 | 3.1 | 3.1 | 3.1 |
| $\pi$-ID | 10.1 | 2.5 | 6.2 | 2.4 | 4.2 | 10.1 | 10.1 | 10.1 |
| background | 3.5 | 4.3 | 5.2 | 1.0 | 3.0 | 7.0 | 12.0 | 50.0 |
| acceptance | 1.6 | 1.6 | 1.0 | 1.0 | 1.6 | 1.6 | 1.6 | 1.6 |
| kinematic fit ($\chi^2$) | 0.9 | 0.9 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.9 |
| correl $\mu\mu$ ID loss | 3.0 | 2.0 | 3.0 | 1.3 | 2.0 | 3.0 | 10.0 | 10.0 |
| $\pi\pi/\mu\mu$ cancel. | 2.7 | 1.4 | 1.6 | 1.1 | 1.3 | 2.7 | 5.1 | 5.1 |
| unfolding | 1.0 | 2.7 | 2.7 | 1.0 | 1.3 | 1.0 | 1.0 | 1.0 |
| ISR luminosity | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| sum (cross section) | 13.8 | 8.1 | 10.2 | 5.0 | 6.5 | 13.9 | 19.8 | 52.4 |

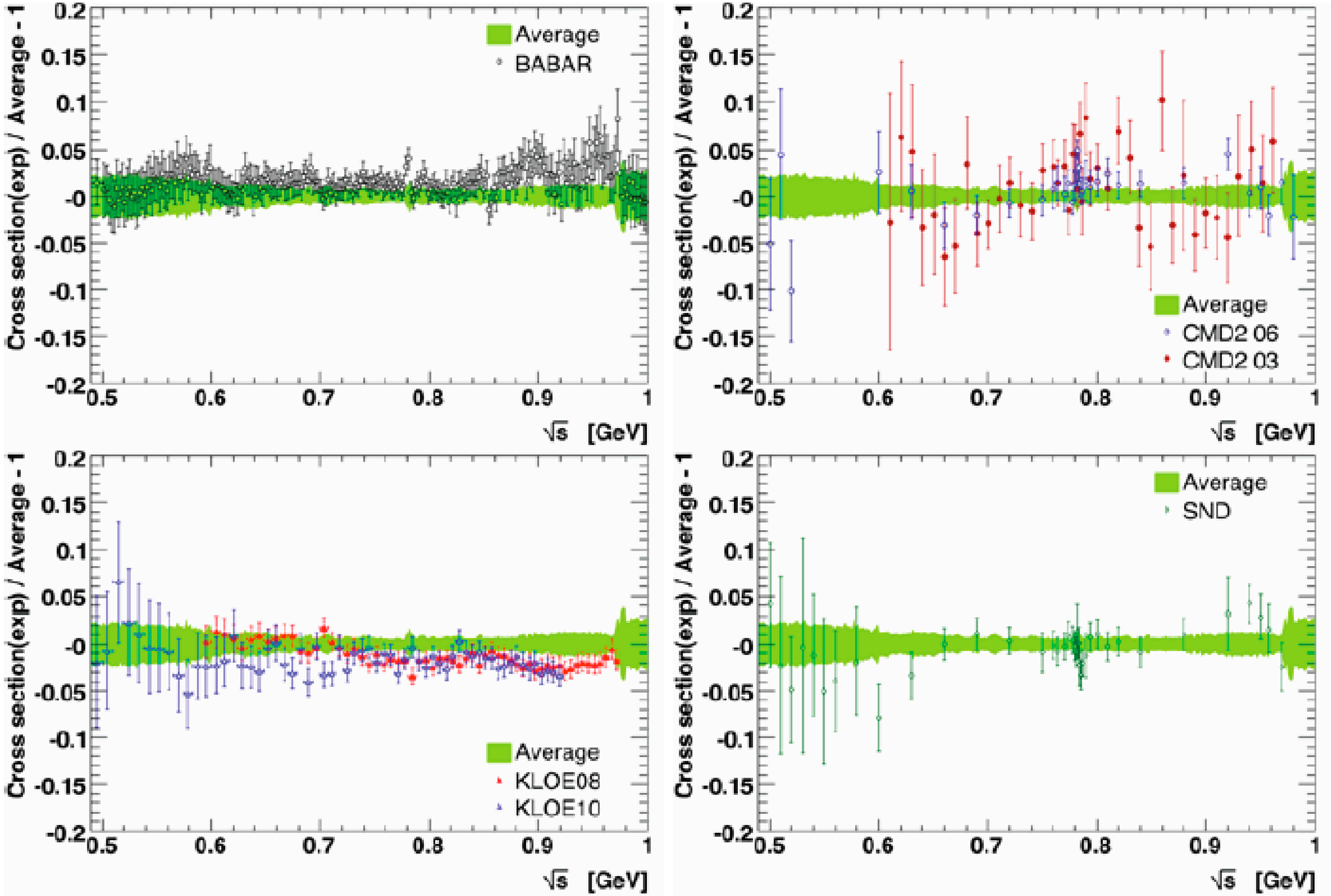
Dominated by particle ID (π-ID, correlated μμ→'ππ', μ-ID in ISR luminosity)

# PION FORM FACTOR AT BABAR

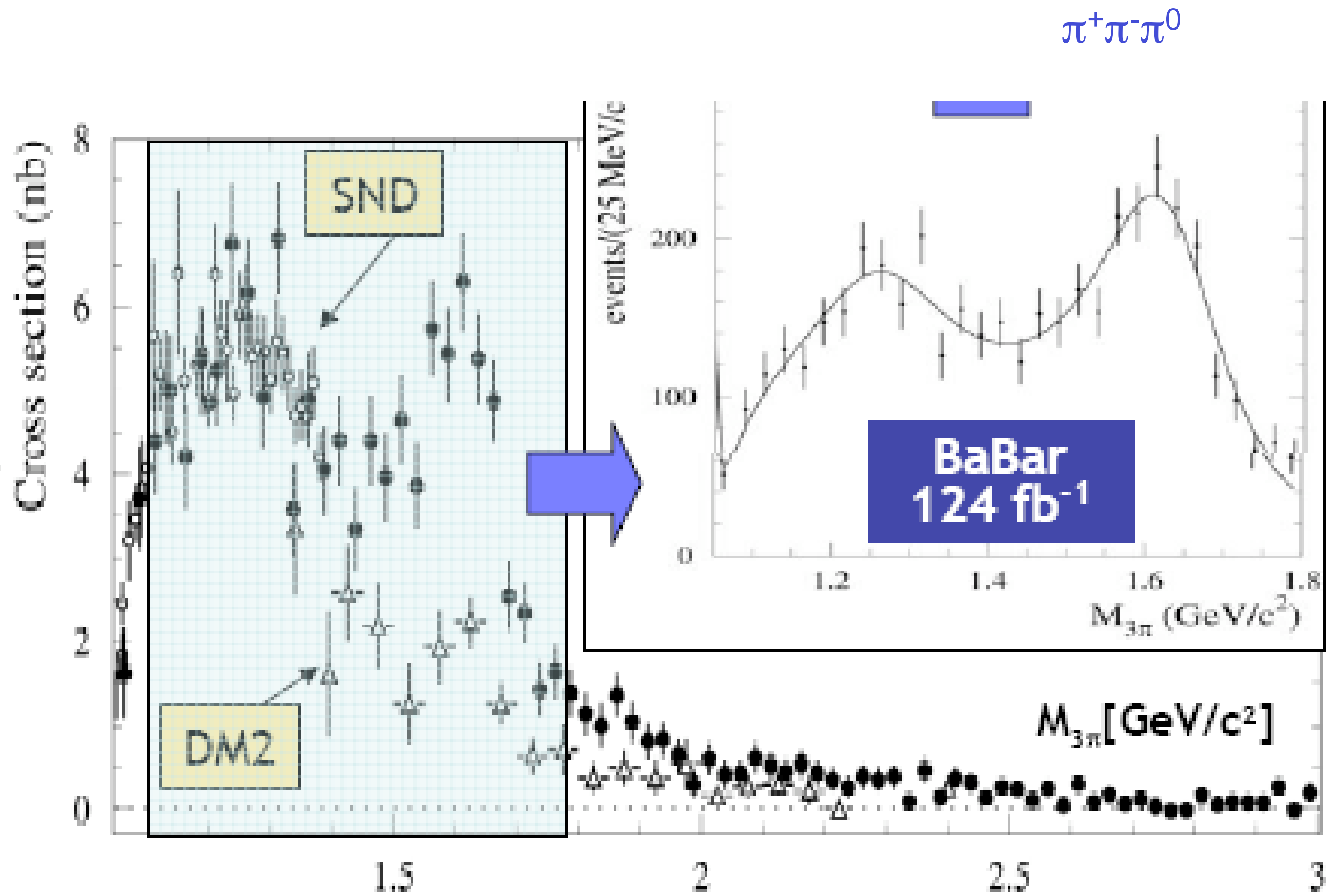
CROSS SECTION



# Comparison of input ee→ππ data

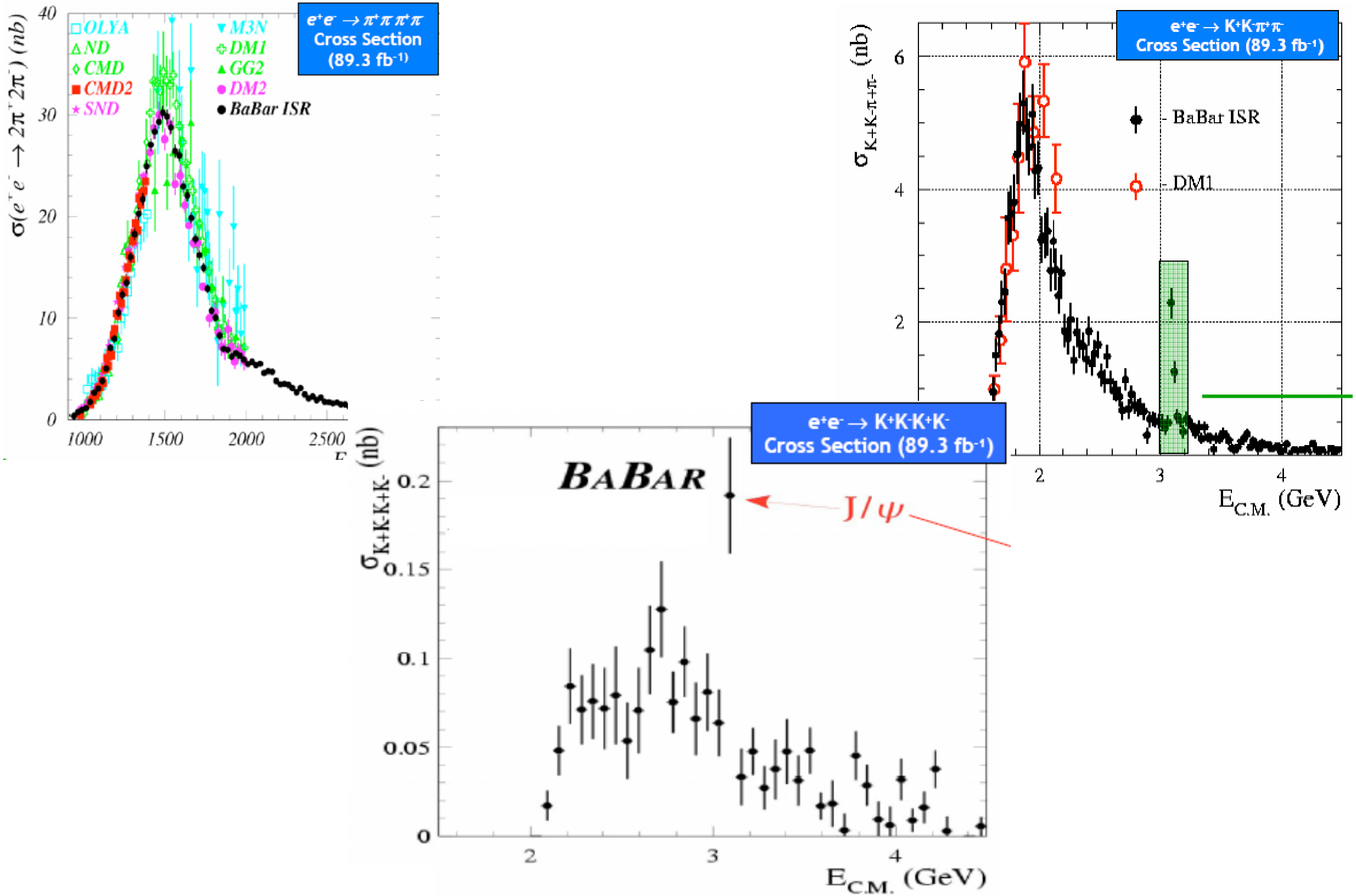


# Babar: 3π



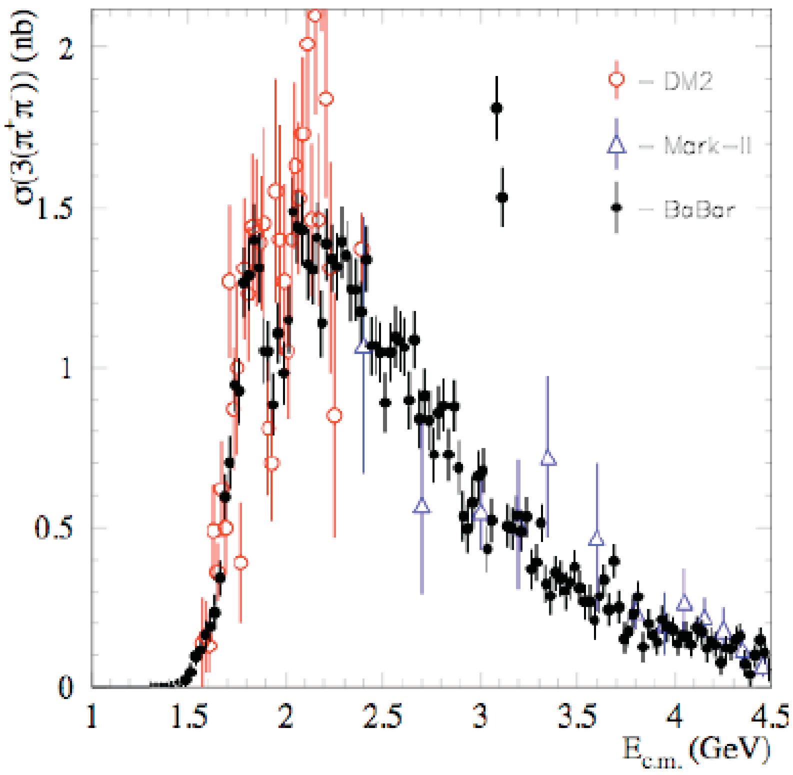
π+π-π0
Cross section (nb)
SND
DM2
events/(25 MeV/c
BaBar
124 fb-1
M3π (GeV/c2)
M3π[GeV/c2]

# Babar: 4h



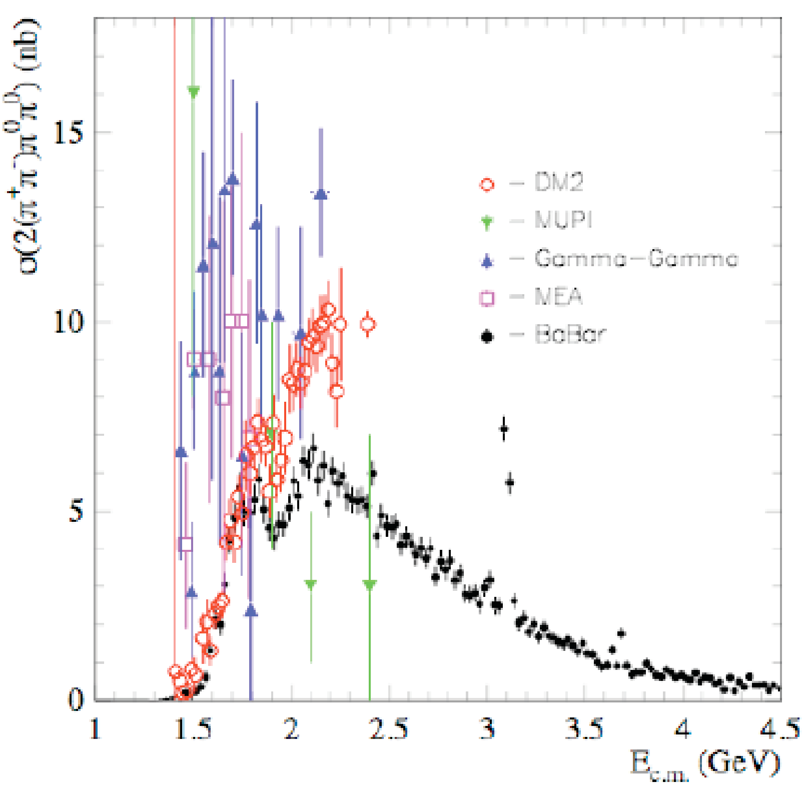
e+e- → π+π-π+π-
Cross Section
(89.3 fb-1)
OLYA
ND
CMD
CMD2
SND
M3N
DM1
GG2
DM2
BaBar ISR
e+e- → K+K-π+π-
Cross Section (89.3 fb-1)
BaBar ISR
DM1
e+e- → K+K-K+K-
Cross Section (89.3 fb-1)
BABAR
J/ψ
E_C.M. (GeV)

# Babar: 6π




$3(\pi^+\pi^-)$

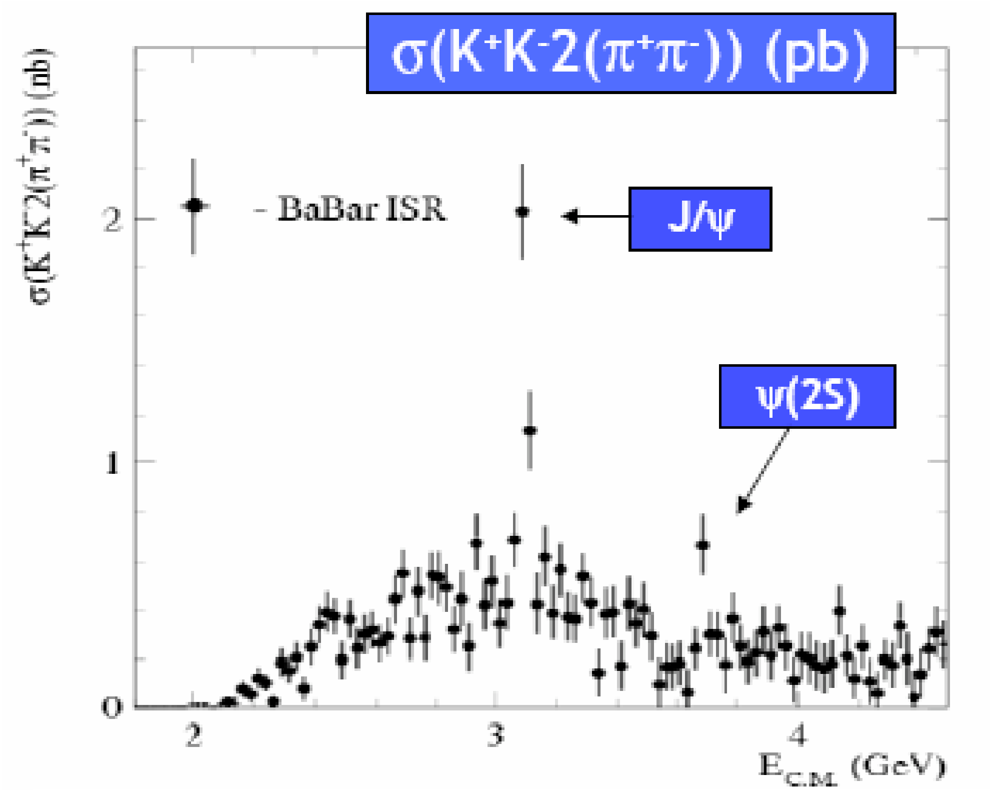
Total systematic: ~6-8%




$2(\pi^+\pi^-)\pi^0\pi^0$

Total systematic: ~11%

# Babar: 2K4π




$2(\pi^+\pi^-)K^+K^-$

Total systematic: ~7%

# Prospects on R?

- An significant improvement on $\delta\alpha_{em}(M_Z^2)$ would require 1% up to 10 GeV (using the standard integration method of data ) or up to ~3 GeV using the Adler function (+ improvements from Theory)
- But how realistic is this possibility?
- Remember the error is:

*F. Jegerlehner*

| **Energy (GeV)** | **< 1** | **1-2** | **2-3** | **3-9.5 (exc.J/ψ and ϒ)** | **9.5-13** |
|---|---|---|---|---|---|
| $\delta_{tot}R/R$ | ~0.5% | 6% | 4% | 0.7% | 5.5% |
| $\delta^2\Delta\alpha_{had}^{(5)}(M_Z^2)$ | ~1% | **36%** | 11% | 2% | **31%** |
| $\delta^2\Delta\alpha_{had}^{(5)}(-2.5GeV)$ | ~4% | **75%** | 12% | <1% | <1% |

•(Super)B factories will continue to improve the region below 5 GeV with ISR. BESIII will also enter in the game both with a scan above 2-3 GeV and with ISR below. However not easy to keep the systematic error at 1% level using ISR (FSR, RC?).

# Prospects on R?

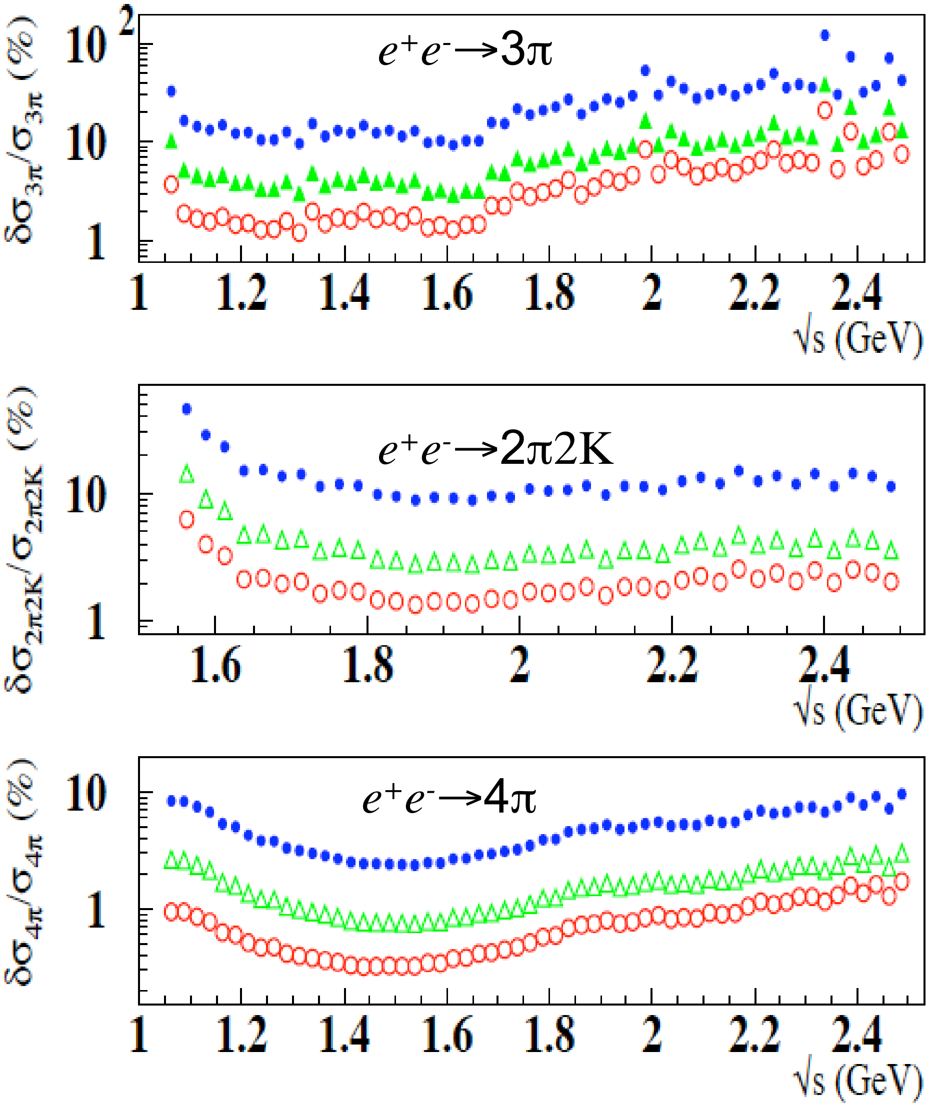
- VEPP2000 could improve the situation below 2 GeV by a direct scan
- An energy upgrade of Dafne would improve the region below 2/3 GeV as well
- This would allow to matches the request in precision using the Adler function method.
- However in the direct integration not clear how to reduce the error in the region 9.5 -13 GeV (unless using theory?)

| **Energy (GeV)** | **< 1** | **1-2** | **2-3** | **3-9.5 (exc.J/ψ and ϒ)** | **9.5-13** |
|---|---|---|---|---|---|
| $\delta_{tot}R/R$ | ~0.5% | 6% | 4% | 0.7% | 5.5% |
| $\delta^2\Delta\alpha^{(5)}_{had}(M_Z^2)$ | ~1% | **36%** | 11% | 2% | **31%** |
| $\delta^2\Delta\alpha^{(5)}_{had}(-2.5GeV)$ | ~4% | **75%** | 12% | <1% | <1% |

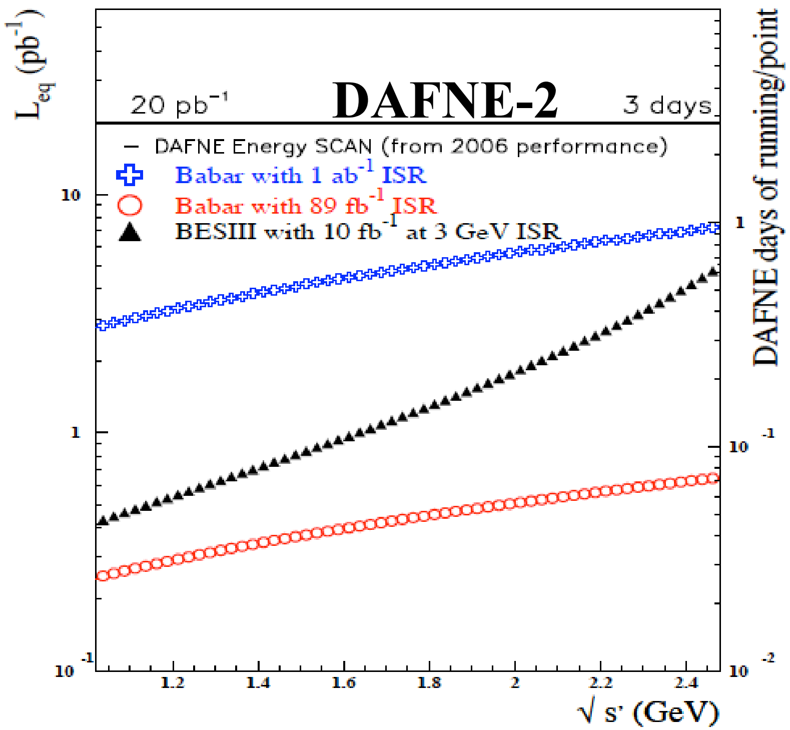
*F. Jegerlehner*

Thanks!

# Impact of DAFNE-2 on exclusive channels in the range [1-2.5] GeV with a scan (Statistics only)



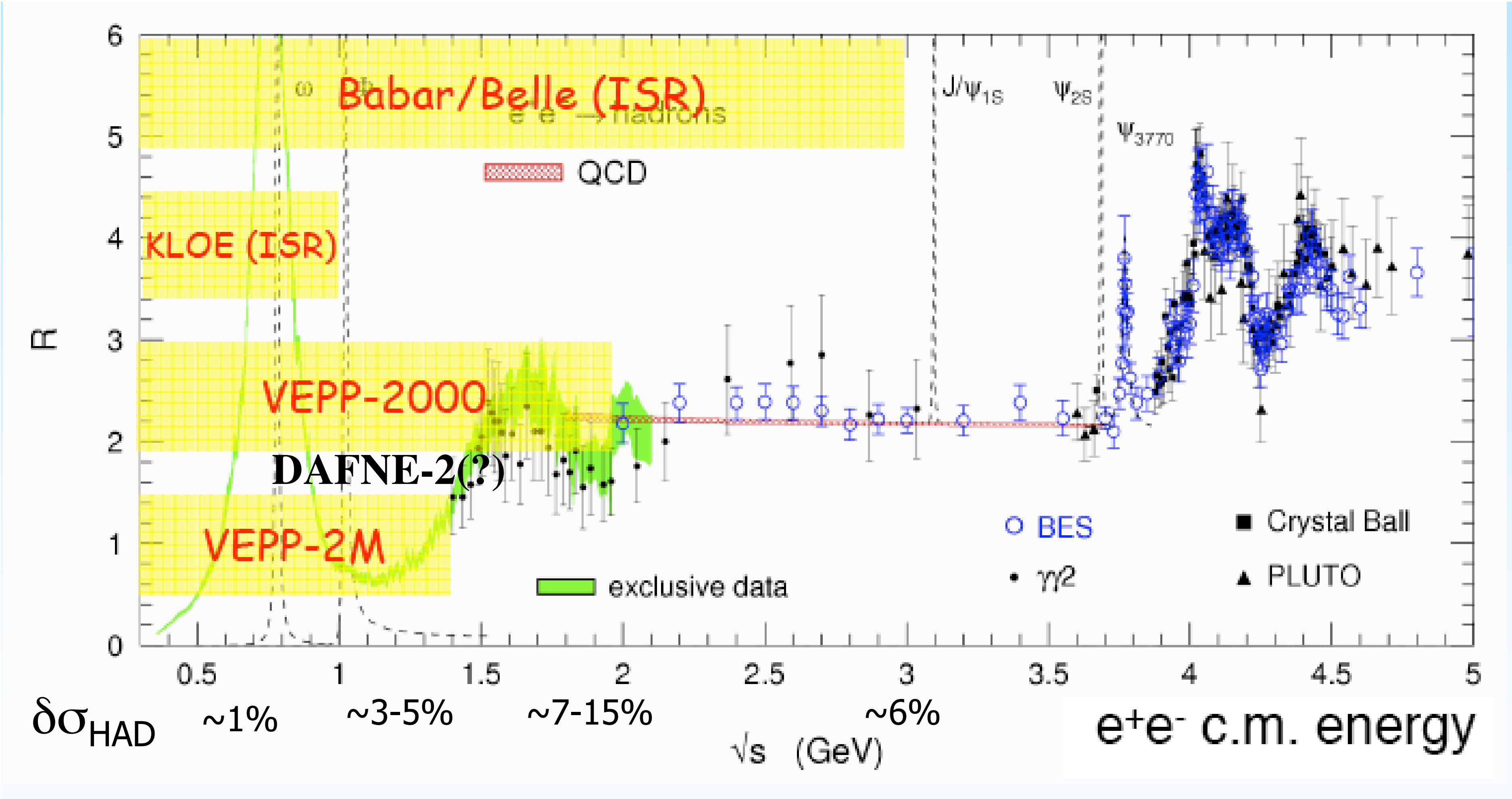

- **Published BaBar results: 89 $fb^{-1}$ (ISR)**
- ▲ **"BaBar" × 10 (890 $fb^{-1}$)**
- o **KLOE-2 energy scan: 20 $pb^{-1}$/point @ L= $10^{32}$ $cm^{-2}$ $s^{-1}$, 25 MeV bin ⇒ 1 year data-taking**




DAFNE-2 is **statistically** equivalent to 5÷10 $ab^{-1}$ (Super)B-factory

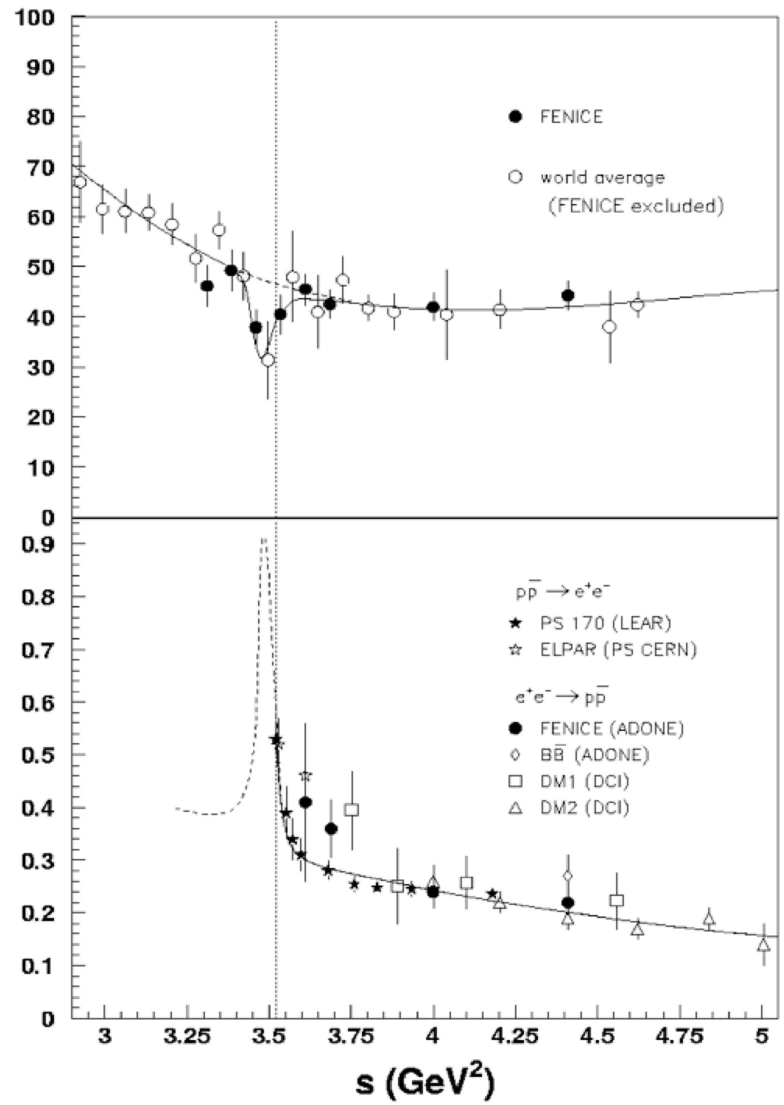
SPARE

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



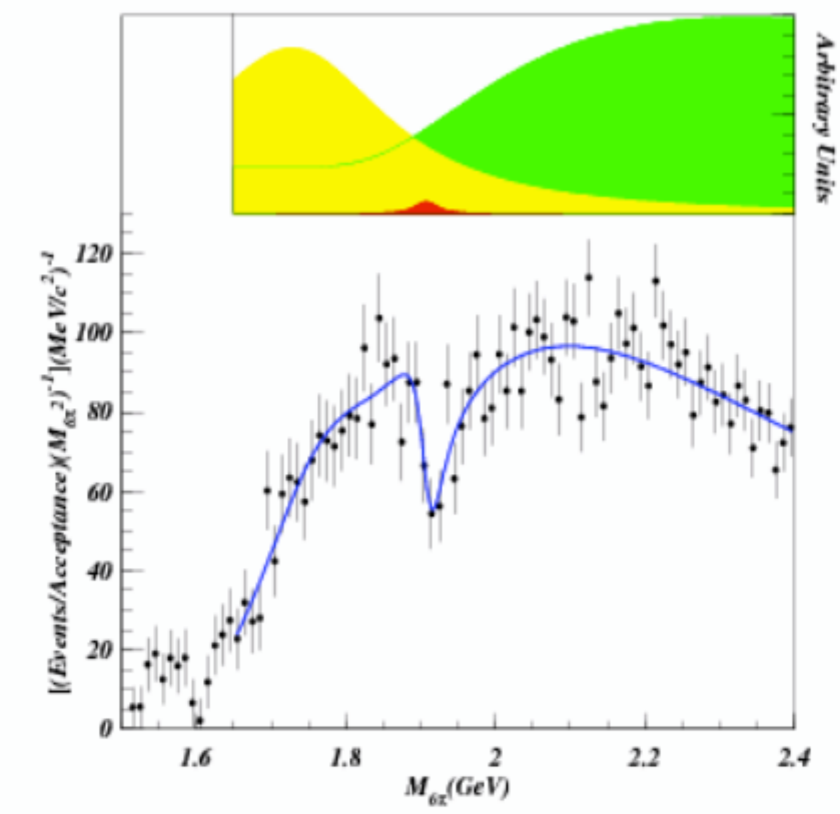
# Open issues

- Buco nella sezione d'urto multiadronica vicino a soglia p bar-b
- narrow vector meson resonance, with a mass M ~1.87 GeV and a width Γ ~ 10-20 MeV, consistent with an Nbar-N bound state

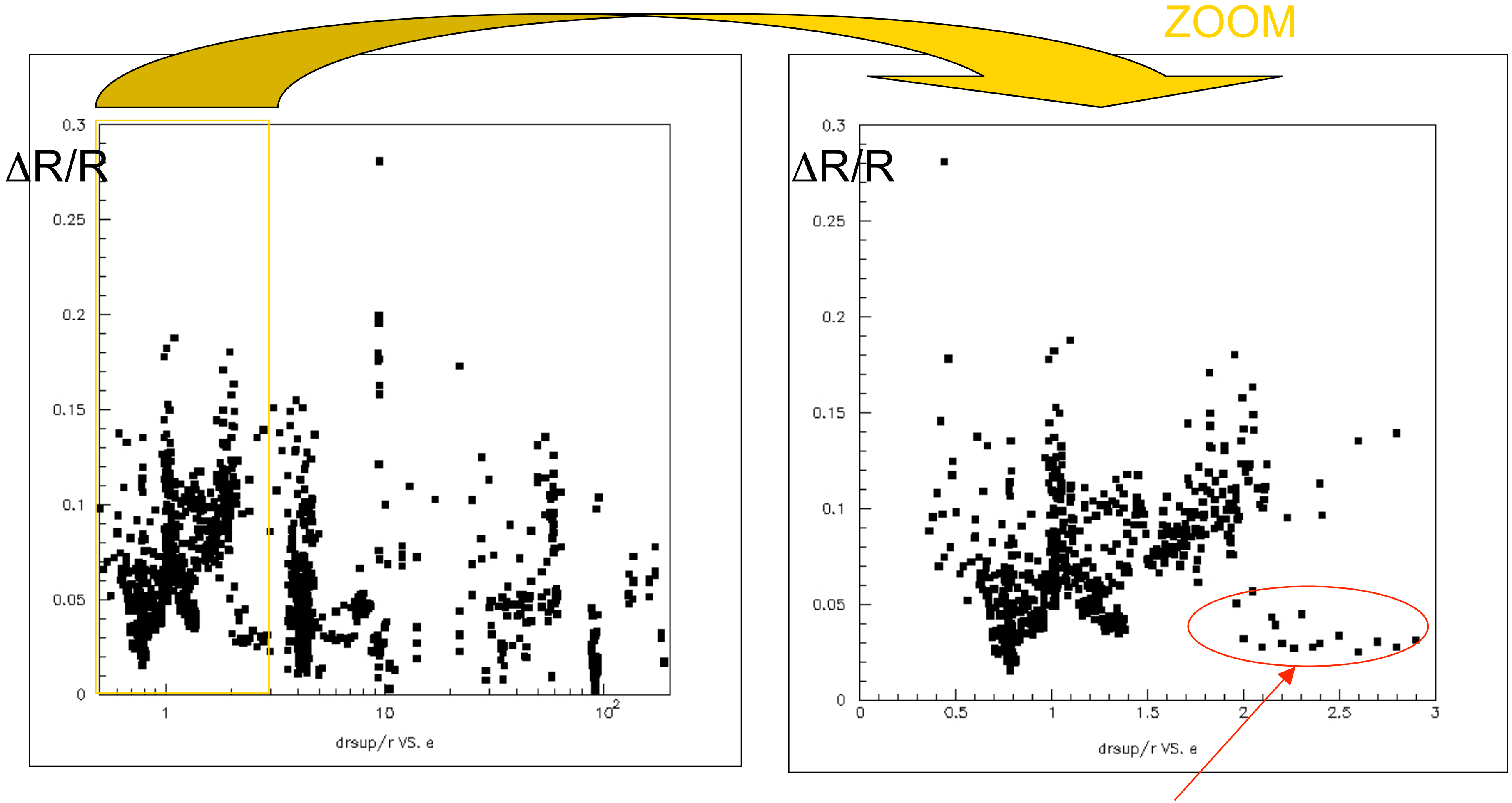


# Open issues

- Buco di FOCUS nella sezione d'urto dei $6\pi$
- Babar conferma in entrambi i canali



# Errore percentuale




Punti con errore ~3% dalla misura inclusiva di BES

PRL 84, 594 (2000) – PRL 88, 101802 (2002)

# Comparison of different evaluations of $\Delta\alpha^{(5)}_{had}$

| $\Delta\alpha^{(5)}_{had}$ | **Method** | ***Ref*** |
|---|---|---|
| 0.0280 ±0.00065 | data<12 GeV | S.Eidelman<br>F.Jegerlehner ’95 |
| 0.02777 ± 0.00017 | data<1.8 GeV | J.H.Kuhen,<br>M.Steinhauser ’98 |
| 0.02763 ±0.00016 | data<1.8GeV | M.Davier, A.Höcker ’98 |
| 0.027730±0.000148 | Euclidean>2.5 GeV | F.Jegerlehener ’99 |
| 0.027426±0.000190 | scaled data, pQCD 2.8-3.7, 5-∞ | A.D.Martin et al. ’00 |
| 0.027896±0.000391 | data<12 GeV (new data CMD2 & BES) | F.Jegerlehner ’01 |
| 0.02761 ± 0.00036 | data<12 GeV<br>(new data CMD2 & BES) | H.Burkhardt,B.Pietrzyk ’01 ( ’05) |
| 0.00007<br>(0.00005) | $\delta\sigma$~1% up to J/ψ ($\delta\sigma$~1% up to Υ) | |

# $a_\mu^{HLO}$:

L.O. Hadronic contribution to $a_\mu$ can be estimated by means of a dispersion integral:


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

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

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

$e^+e^- \to \pi^+\pi^-$

in the range < 1 GeV contributes to 70% !

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

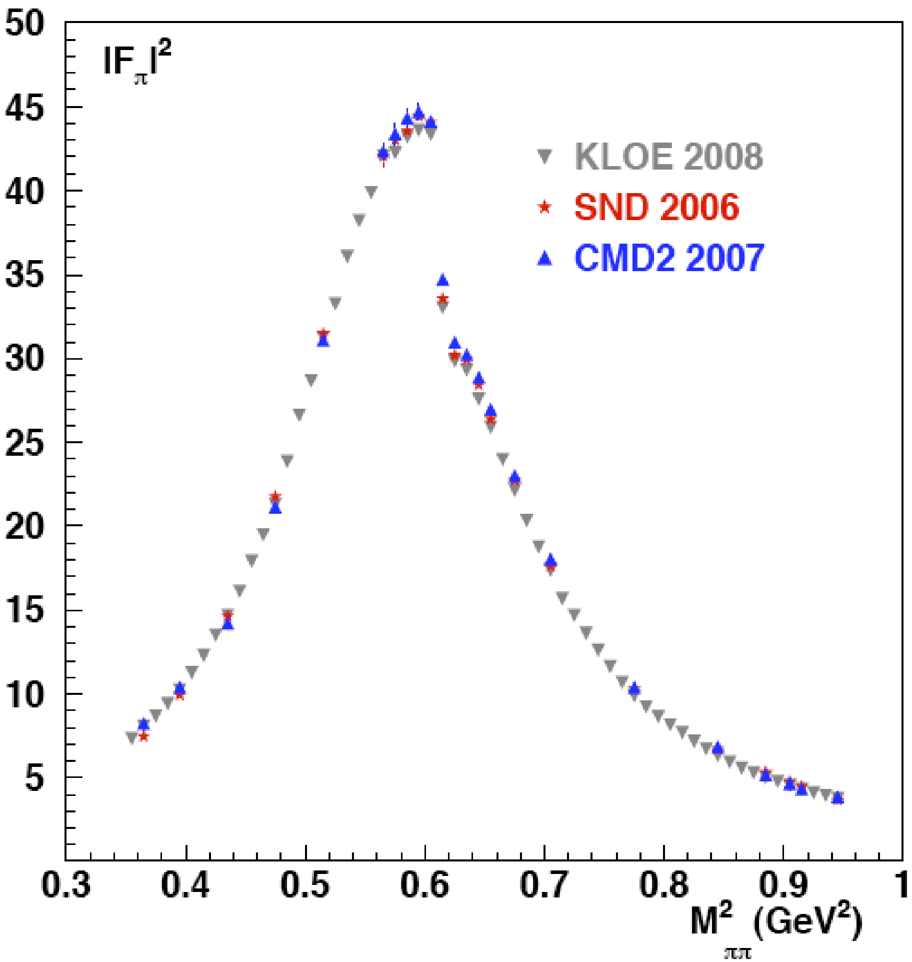
Input:

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

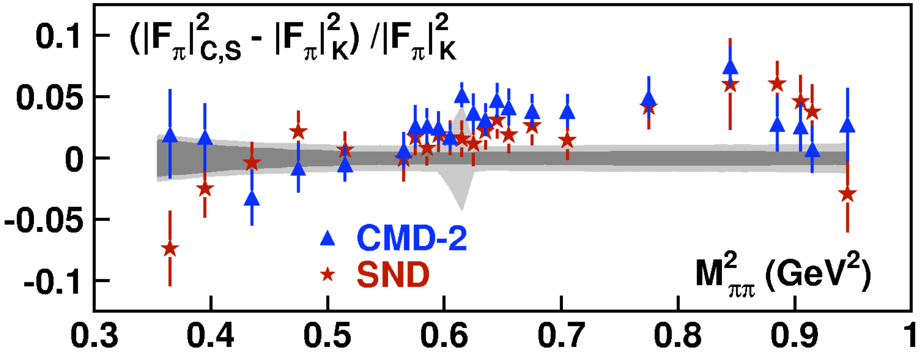
b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

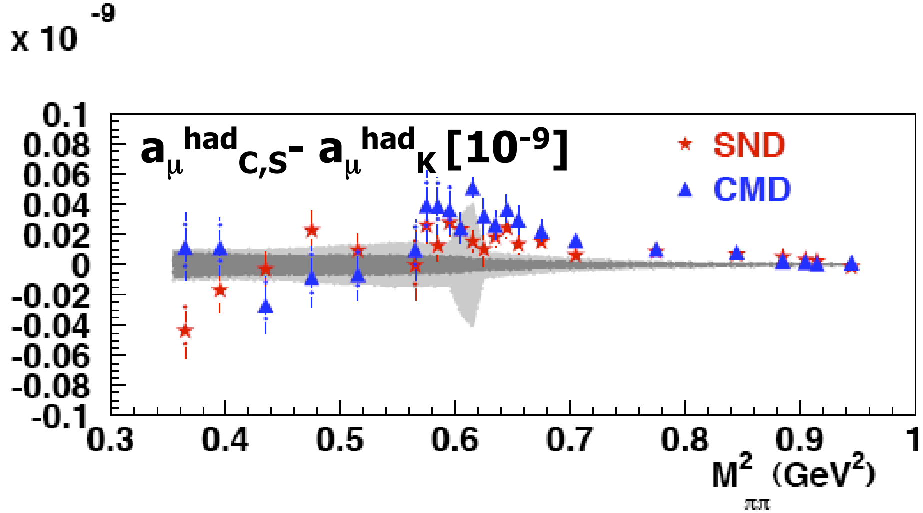
Alemany, Davier, Hoecker ‘97

# 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$^2$)

# LA Event Selection (KLOE10)

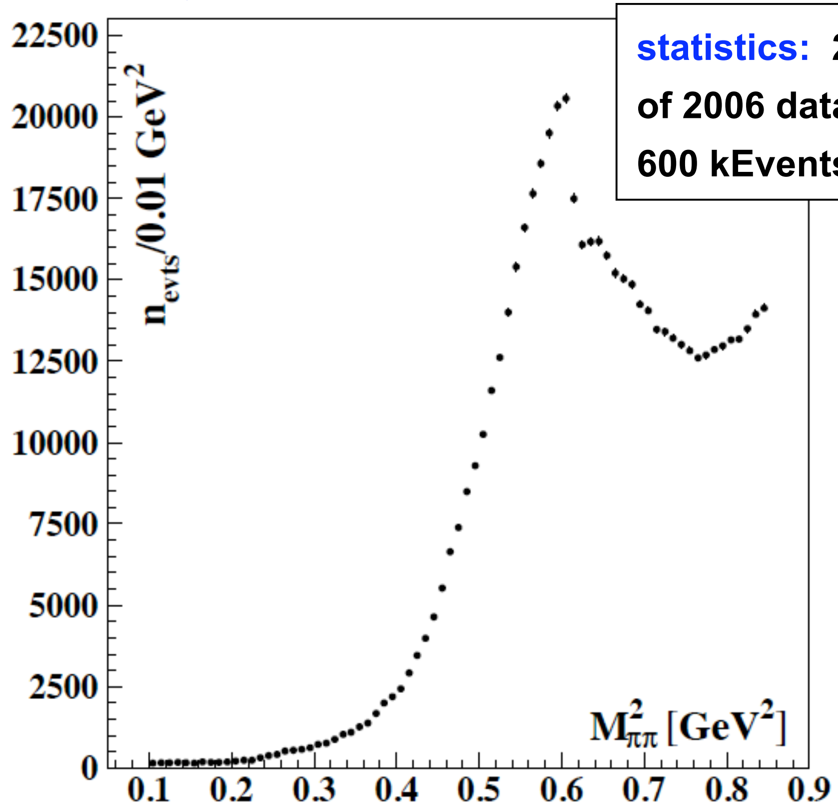
**2 pion tracks at large angles**
$50^o < \theta_\pi < 130^o$

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

- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **$\gamma_{ISR}$ 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 $\phi$ 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: 233pb[-1]**
**of 2006 data**
**600 kEvents**

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