PHIPSI08

International Workshop on $e^+ e^-$ collisions from ϕ to ψ

Laboratori Nazionali di Frascati, April 7 -10, 2008

Φ FROM TO Ψ

Initial State Radiation: A success story

W. Kluge
Institut für Experimentelle Kernphysik, Universität Karlsruhe

My message is short:

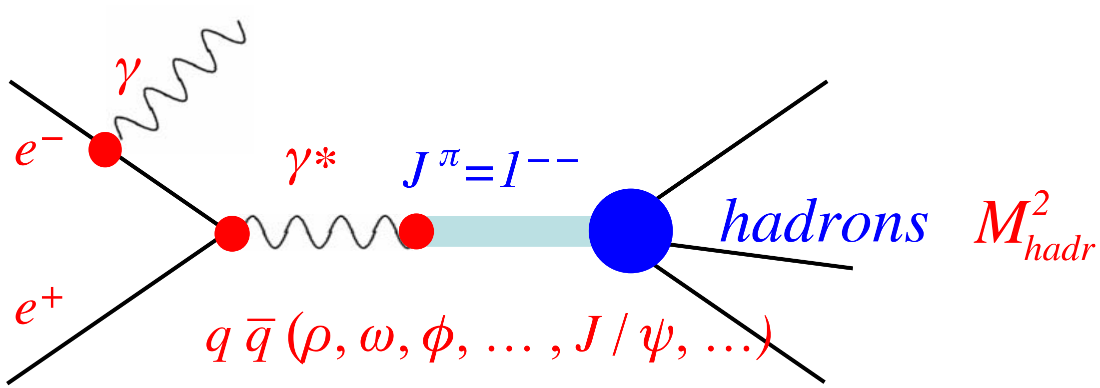
Initial State Radiation (ISR) and the subsequent *Radiative return* have become an impressively successful, powerful and guiding tool in low and intermediate energy hadron physics (competitive with and independent on an energy scan):

- to measure hadronic cross sections and the ratio *R* from the reaction threshold up to the maximum centre of mass energy of fixed energy colliders
- to clarify reaction mechanisms and reveal substructures (intermediate states)
- to detect totally new highly excited states with $J^{PC} = 1^{--}$
- to improve knowledge on the structure and decay mechanisms of those states

To add a personal remark:
While being discussed since the sixties-seventies *ISR* became a powerful tool for the analysis of experiments in low and intermediate energy hadron physics only with the development of *EVA-PHOKHARA*, a series of codes which are user friendly, flexible and easily to implement into the software of the existing detectors.

Content

1. Initial State Radiation (Radiative return): The idea



Run at fixed energy $\sqrt{s}$ and exploit the process $e^+ e^- \rightarrow hadrons + n\,\gamma$ with the γ emitted in the initial state (ISR) to reduce the centre of mass energies of the colliding $e^+ e^-$ and consequently the energy of the hadronic final state

Measurement of hadronic cross sections or $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$ with systematic errors different of those from an energy scan (e.g. no point to point errors on beam energy and luminosity)

Particularly suited for modern meson factories. The large luminosities compensate for α / π suppression of the emission of photons

$$2\,m_{\pi}^2 < M^2_{hadr} < s \qquad\qquad M^2_{hadr} = s - 2\sqrt{s}\;E_{\gamma}$$

Radiative return to ρ, ω, ϕ, … (energies below *3 GeV*)

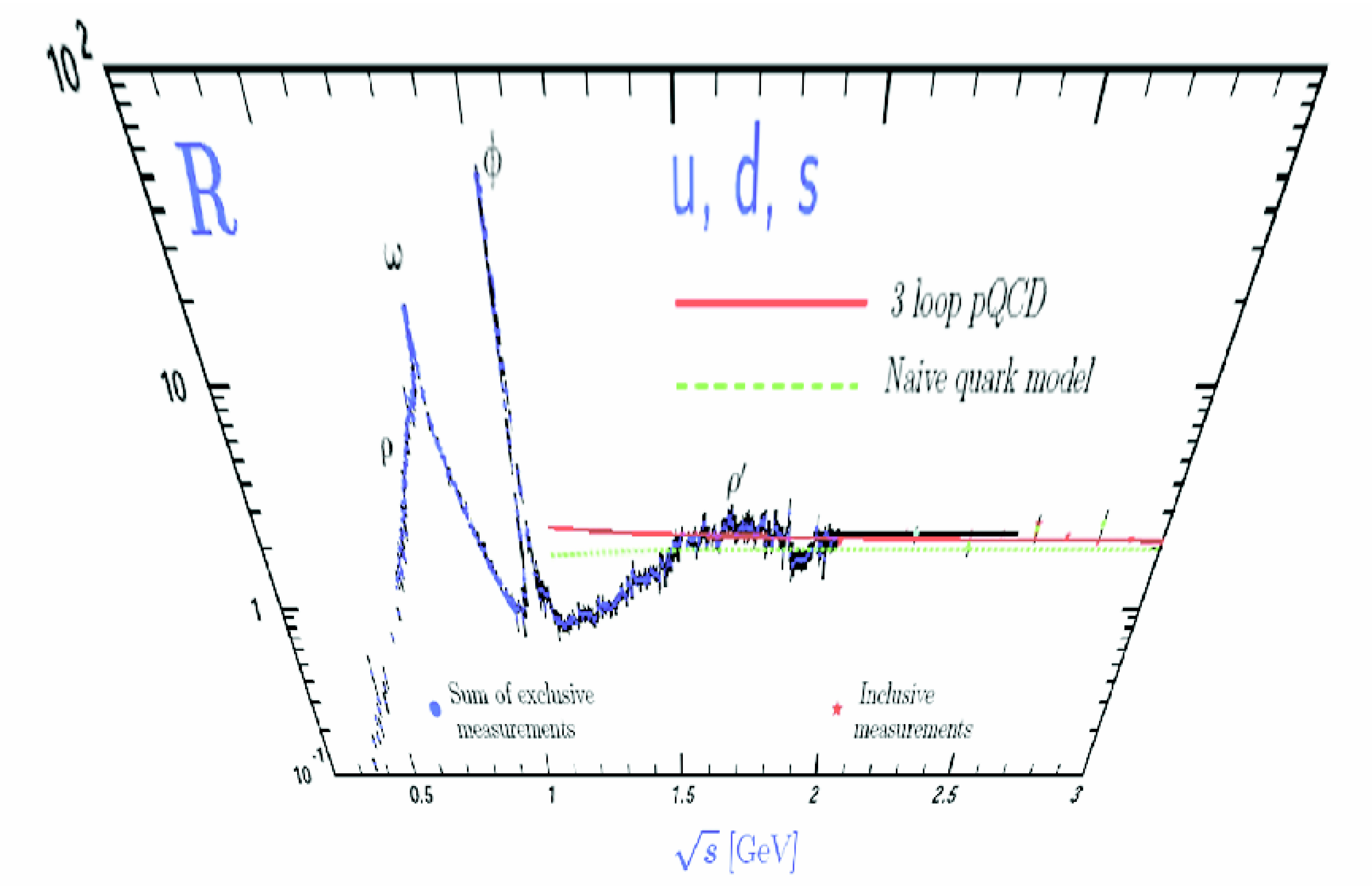


Figure elaborated artistically to become an element of the conference poster by Claudio Federici LNF

Radiative return to J/ψ, $\psi(2S)$, …(energies between *3* and *5 GeV*)

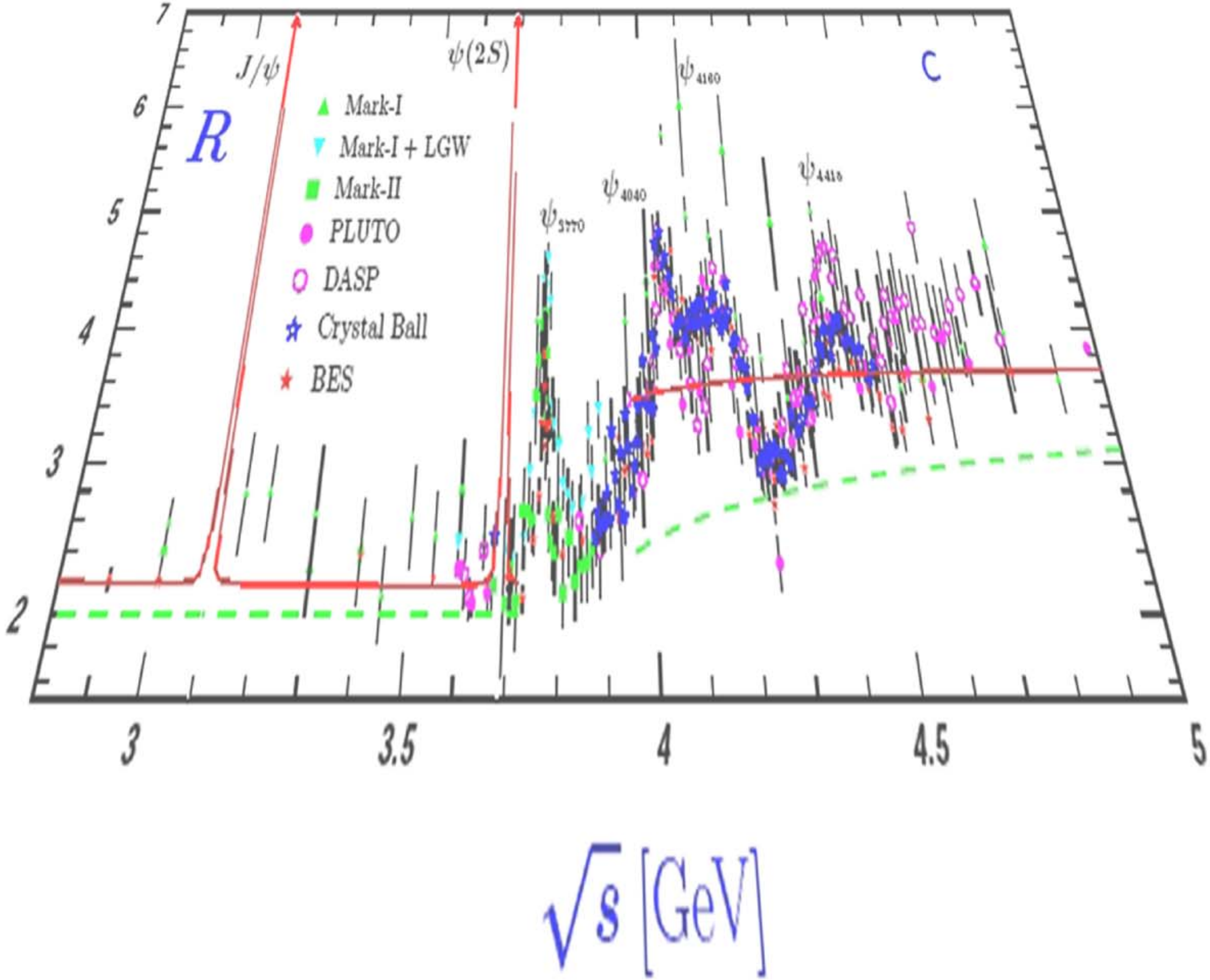
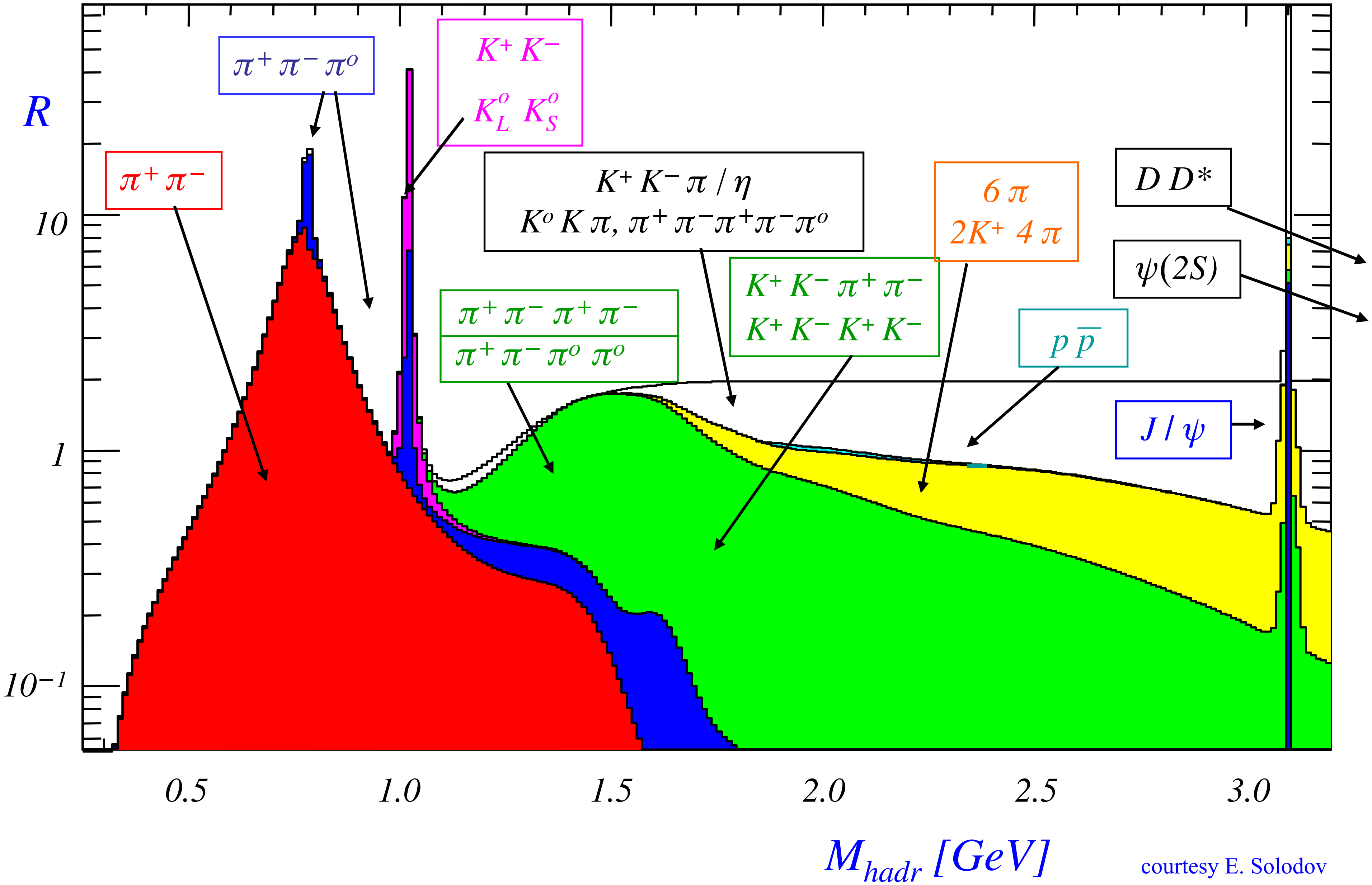


Figure elaborated artistically to become an element of the conference poster by Claudio Federici LNF

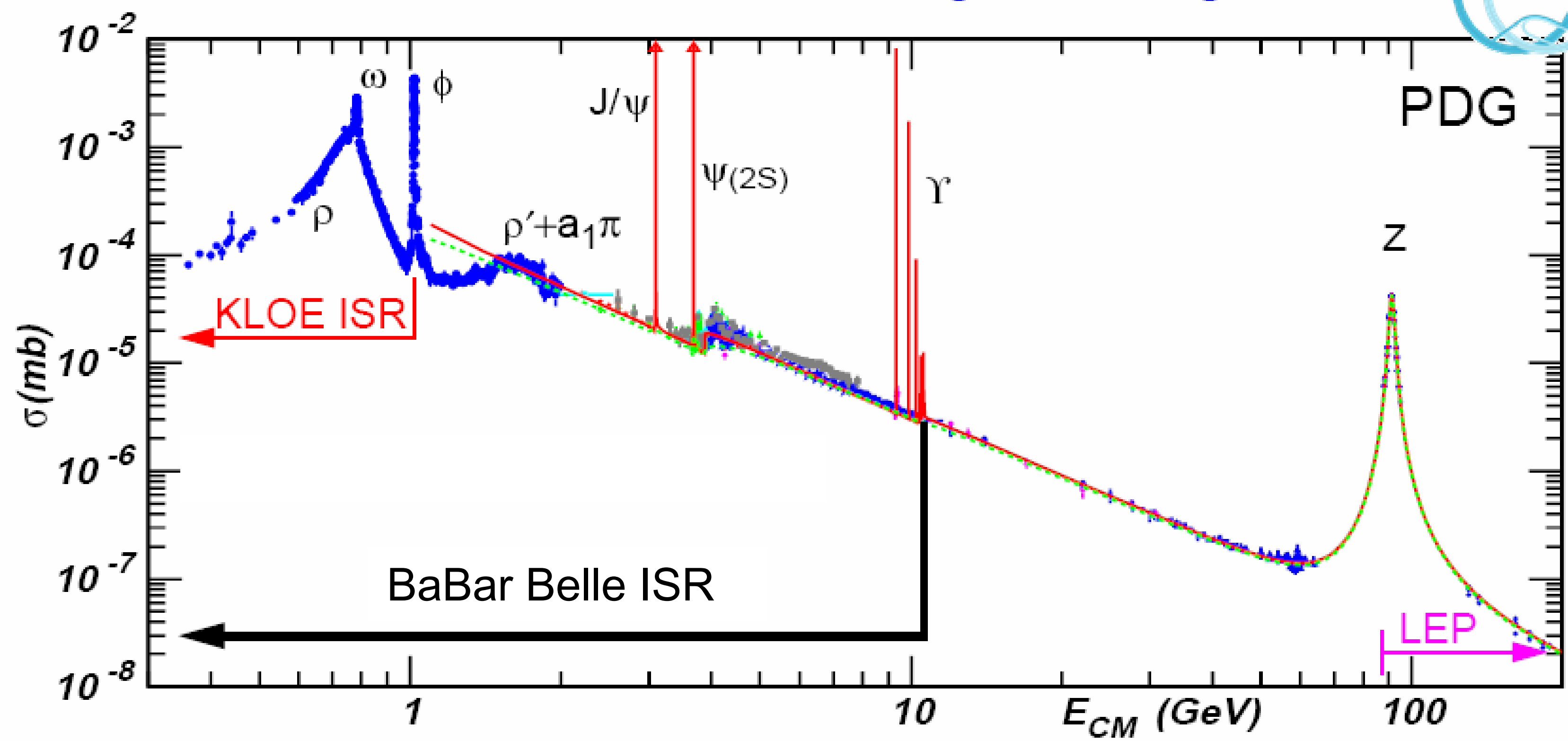
Building *R* from the sum over exclusive final states (*Monte Carlo*) (most have been studied)



courtesy E. Solodov

The hadronic cross section, resp. ratio *R*

(DAΦNE, VEPP, CESR, BES, PEP-II, KEK-, LEP-2)



studies of the energy region below ~ *4…5 GeV* by Radiative return

KLOE: energies < *1 GeV*, dominated by *2 π*-channel (*ρ*, *ω*-resonances)

BaBar, Belle: energy region *1 ... 4.5 GeV* (studies of higher multiplicities *4 π*,…
restricted by hard photon emission)

courtesy *PDG*

2. History and success of Initial State Radiation

2.1. The pre-*EVA*-*PHOKHARA* era

Early literature (selection):

Photon emission in muon pair production in electron-positron collisions
($e^+ e^- \to \mu^+ \mu^- \gamma$, σ_{tot}, *ISR*, *FSR*, interference)
V. N. Baier, V. A. Khoze, ZhETF **48** (1965) 946, Yad. Fiz. **2** (1965) 287

Radiation accompanying two particle annihilation of an electron - positron pair
(scalar final states $e^+ e^- \to \pi^+ \pi^- \gamma$, σ_{tot}, *ISR, FSR,* interference, formfactors)
V. N. Baier, V. A. Khoze, Sov. Phys. JETP **21** (1965) 629, 1145
[Zh. Eksp. Theor. Fiz. **48** (1965) 946]

Infra-red radiative corrections for resonant processes (ρ, ω, ϕ intermediate states)
G. Pancheri, Nuovo Cim. **A 60** (1969) 321

Radiative Corrections for Colliding Beam Resonances
(application to $\psi(3.1)$, $\psi'(3.7)$ intermediate states)
M. Greco, G. Pancheri, Y. N. Srivastava, Nucl. Phys. **B 101** (1975) 234

Secondary Reactions in electron - positron (electron) Collisions
(pion form factor)
M. S. Chen, P. M. Zerwas, Phys. Rev. **D 11** (1975) 58

HERA: *ISR* events used to measure the structure function $F_2(x,Q^2)$

(to reach lower Q^2 values and correspondingly lower x values)

S. Aid et al., *H1* Collaboration, Nucl. Phys. **B 470** (1996) 3

LEP 2: measurements of energies between *189* and *209 GeV*: Radiative return to the region of the *Z*- resonance with an impressive enhancement

Literature (theory)

ZFITTER: semi-analytical code

D. Bardin et al., Z. Phys. **C 44** (1989) 493

D. Bardin et al., Phys. Lett. **B 255** (1991) 290

D. Bardin et al., Nucl. Phys. **B 351** (1991) 1

D. Bardin et al., Comp. Phys. Comm. **133** (2001) 229

KK2f: Photon radiation modeled using Coherent Exclusive Exponentiation (*CEEX*) and complete $\mathcal{O}(\alpha^2)$ matrix elements for *ISR*

S. Jadach, B. F. L. Ward and Z. Wąs, Phys. Lett. **B 449** (1999) 97

S. Jadach et al., Comp. Phys. Comm. **130** (2000) 260

OPAL: $e^+ e^- \to hadrons\ \gamma$

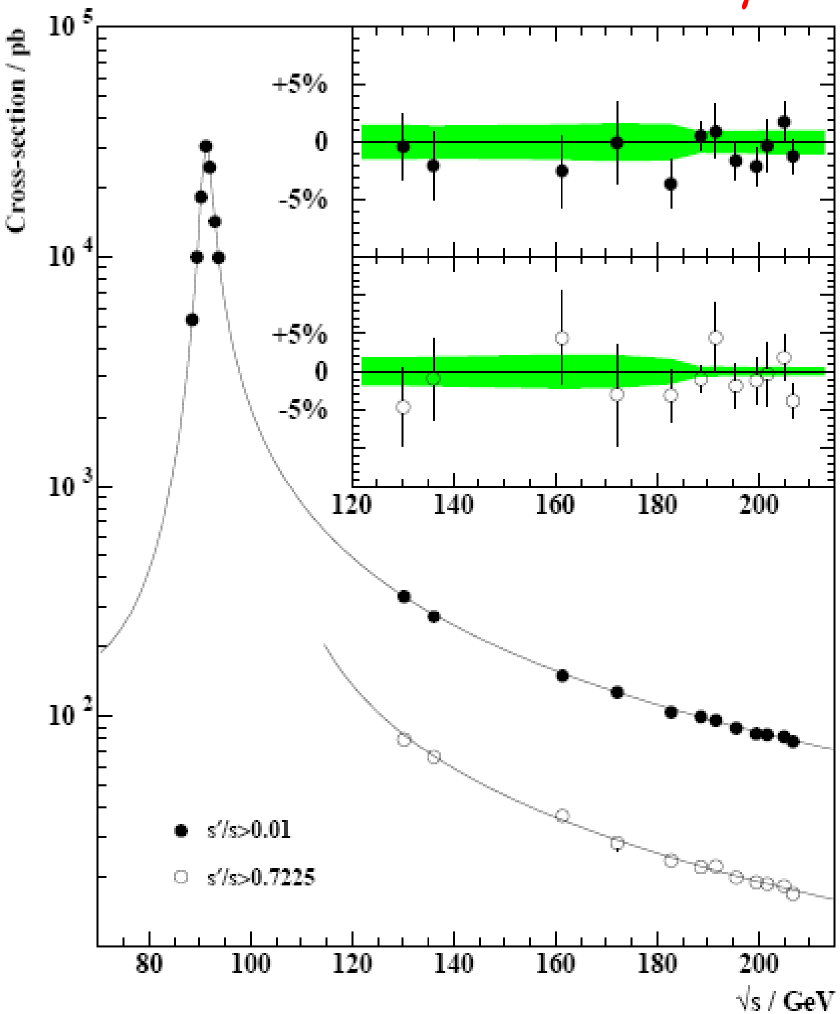


Figure 10: Measured total cross-sections ($s'/s > 0.01$) for hadronic events at lower energies [2, 3, 39] and this analysis. Cross-section measurements for $s'/s > 0.7225$ from this analysis and from [2, 3] are also shown; the values at 161 GeV and 172 GeV have been corrected from $s'/s > 0.8$ to $s'/s > 0.7225$ by adding the prediction of ZFITTER for this difference before plotting. The curves show the predictions of ZFITTER. The insets show the percentage differences between the measured values and the ZFITTER predictions for the high energy points. The error bars on the differences represent statistical errors only; the size of the experimental systematic error is indicated by the shaded band.

OPAL collaboration:
OPAL Physics Note PN 467, Nov. 2000
hep-ex/0309053v1, August 2003
Eur. Phys. J. **C 33** (2004) 173

ALEPH collaboration:
hep-ex/0609051v1, September 2006
Eur.Phys. J. **C 49 (**2007) 411

DELPHI collaboration:
hep-ex/0512012
Eur. Phys. J. **C 45** (2006) 589

L3 collaboration:
hep-ex/0603022
Eur. Phys. J. **C 47** (2006) 1

Application to low and intermediate energies (to determine hadronic cross sections): (*KLOE-DAΦNE*)

Radiative corrections for pion and kaon production of $e^+ e^-$ colliders of energies below *2 GeV*
A. B. Arbuzov, V. A. Astakhov, A. V. Fedorov, G. V. Fedotovich, E. A. Kuraev,
N. P. Merenkov, JHEP **9710**:006, 1997

Hadronic Cross Sections in Electron-Positron Annihilation with Tagged Photon
A. B. Arbuzov, E. A. Kuraev, N. P. Merenkov, L. Trentadue, JHEP **9812**:009, 1998,
hep-ph/9804430v3

Detection of hard photons (pion form factor)
S. Spagnolo, Ph. D. thesis, Univ. of Lecce, 1999, unpublished;
The hadronic contribution to the muon $g-2$ from $e^+ e^-$ annihilation at $\sqrt{s} < m_\phi$ with the *DAFNE* Collider, *KLOE* memo #139, march 1998;
LNF Spring School, Frascati, April 1998; Eur. Phys. J. **C 6** (1999) 637

Measuring $\sigma\,(e^+ e^- \rightarrow$ hadrons) using tagged photon
S. Binner, H. Kühn, K. Melnikov
Phys. Lett. **B 459** (1999) 279

Detection of charged particles (pions) by the drift chamber
(excellent energy resolution, application of *EVA*)
G. Cataldi, A. Denig, W. K., G. Venanzoni, *KLOE* memo #195, August 1999,
Frascati Physics Series (2000), p. 569

Bottomonium ϒ(ns) spectroscopy at *B*- Factories via hard photon emission
M. Benayoun, S. I. Eidelman, V. N. Ivanchenko, Z. K. Silagadze
Mod. Phys. Lett. **A 14** (1999) 2605, hep-ph/9910523, October 1999

Born cross-section and electromagnetic corrections
V. A. Khoze, M. I. Konchatnij, N. P. Merenkov, G. Pancheri, L. Trentadue, O. N. Shekhovzova,
Eur. Phys. J. **C 18** (2001) 481

2.2. A new era (since one decennium): *EVA-PHOKHARA*

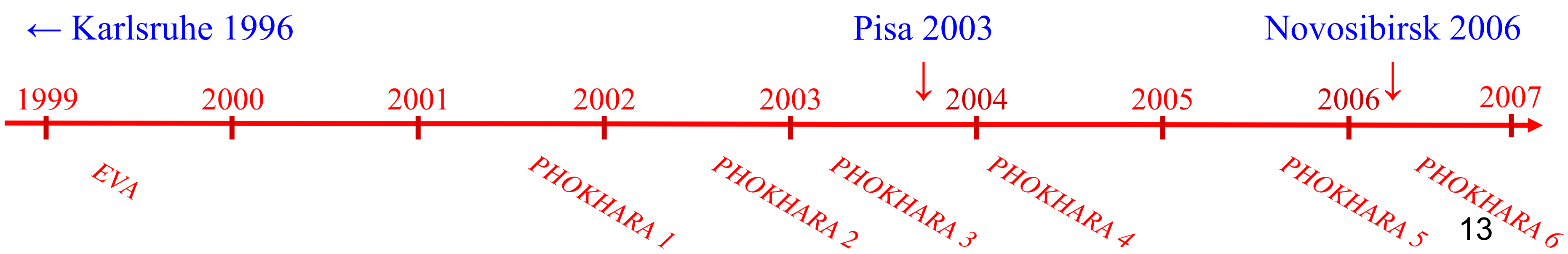
MONTE CARLO Generators *EVA, PHOKHARA, FEVA, EKHARA:* → talk of H. Czyż
measurement of hadronic cross sections by *Radiative Return*
to determine the hadronic contribution to the muon magnetic anomaly

Collaboration *ITT Karlsruhe, US Kattowice, IFIC Valencia*
(J. H. Kühn, H. Czyż, A. Grzelińska, G. Rodrigo et al.)

- developed during the last *10* years to meet the needs of the experimenters at the high luminosity meson factories *DAFNE (KLOE), CESR (CLEO), PEP-II (BaBar), KEK-B (Belle)* etc.

- implementation in Monte Carlo simulations of the detectors, for the first time realized with *KLOE*

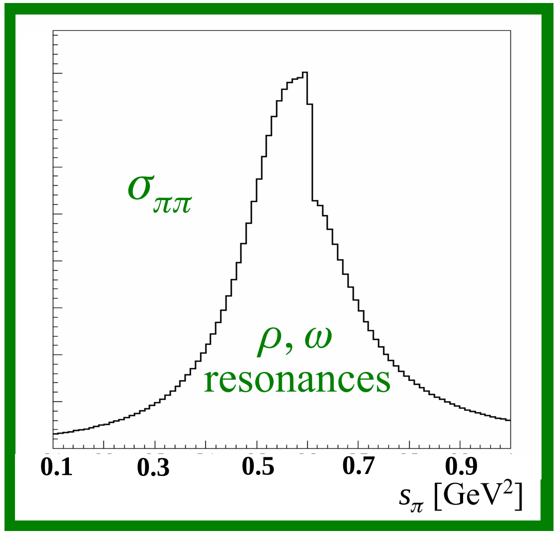
- *ISR, FSR,* and their interference
- increasing complexity due to *NLO* contributions in the initial and final states
- modular structure to implement more and more final states



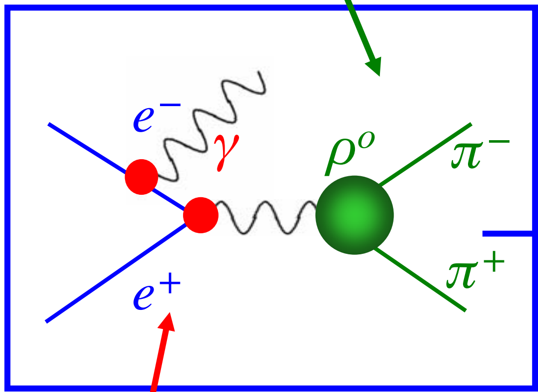
Radiative return: *PHOKHARA* for the first time applied at *DAΦNE (KLOE)*:

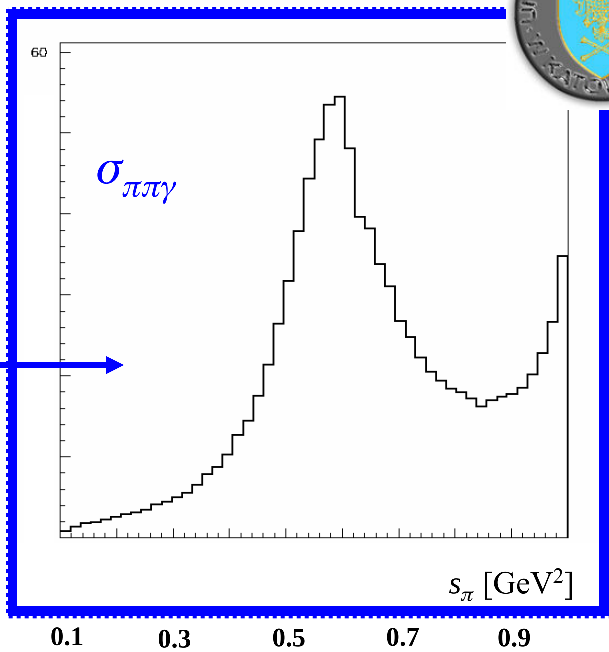
radiative return to ρ, ω : $e^+ e^- \rightarrow \gamma^* \; \gamma \rightarrow q \bar{q} \; \gamma \rightarrow \rho \; (\omega) \, \gamma \rightarrow \pi^+ \pi^- \gamma$

$$M^2_{\pi\pi} \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s) \times H(s)$$

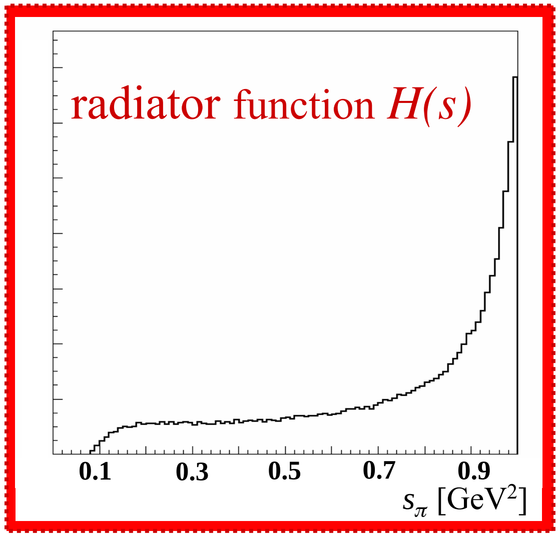


non-radiative
cross section





cross section



MC-Generator *PHOKHARA*

courtesy A. Denig

2.2.1. The hadronic contribution to the anomalous magnetic moment of the muon, running $\alpha_{QED}(M_Z)$, cross sections $e^+ e^- \rightarrow \gamma^* \rightarrow q\,\bar{q} \rightarrow hadrons$

Measurement of $\sigma(e^+ e^- \rightarrow hadrons\ \gamma)$ to determine $\sigma(e^+ e^- \rightarrow hadrons)$ and a_μ^{had} by applying *PHOKHARA*,
'Radiative return' to resonances with $J^{PC}=1^{--}$

Important motivation:

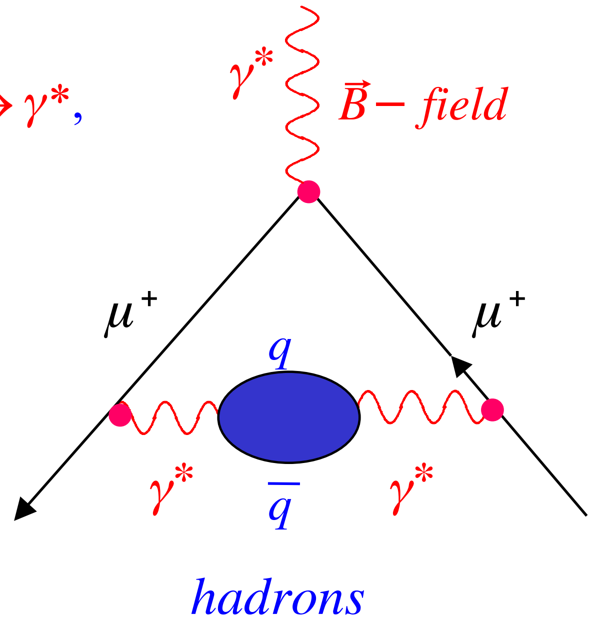
Determination of the *hadronic vacuum polarisation* $\gamma^* \rightarrow q\,\bar{q} \rightarrow \gamma^*$,
a contribution to precision tests of the *SM* of particle physics

a) Precision experiment $(g-2)_\mu$ *(Brookhaven E821)*

b) Running fine structure constant $\alpha_{QED}\ (M_Z)$

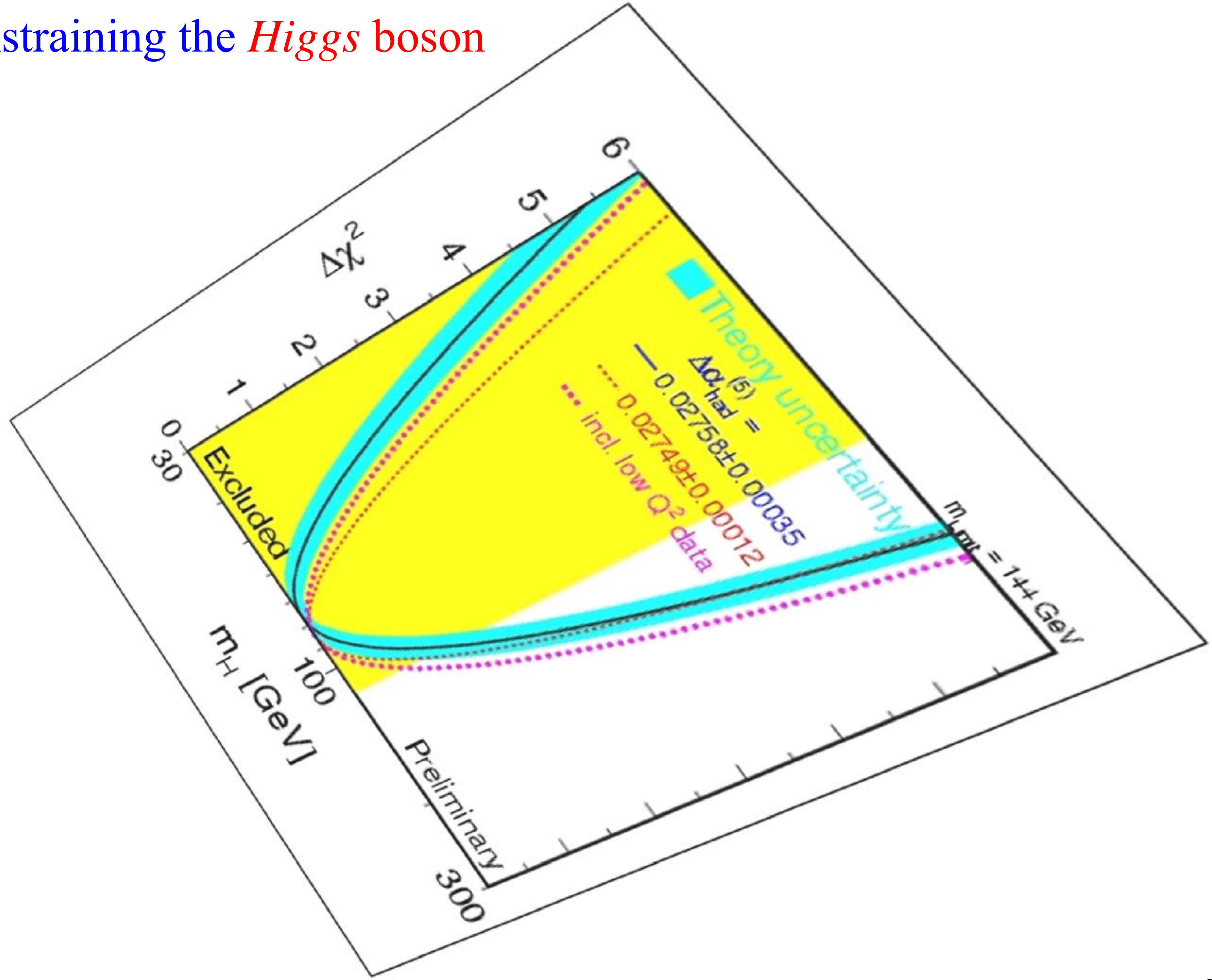
- constrains *Higgs* mass m_{Higgs}
- effective *Weinberg* angle etc.

→ major topic of this conference



See F. Jegerlehner, The Anomalous Moment of the Myon,
Springer Tracts in Mod. Phys. 226, Springer Verlag Berlin, Heidelberg 2008

Constraining the *Higgs* boson



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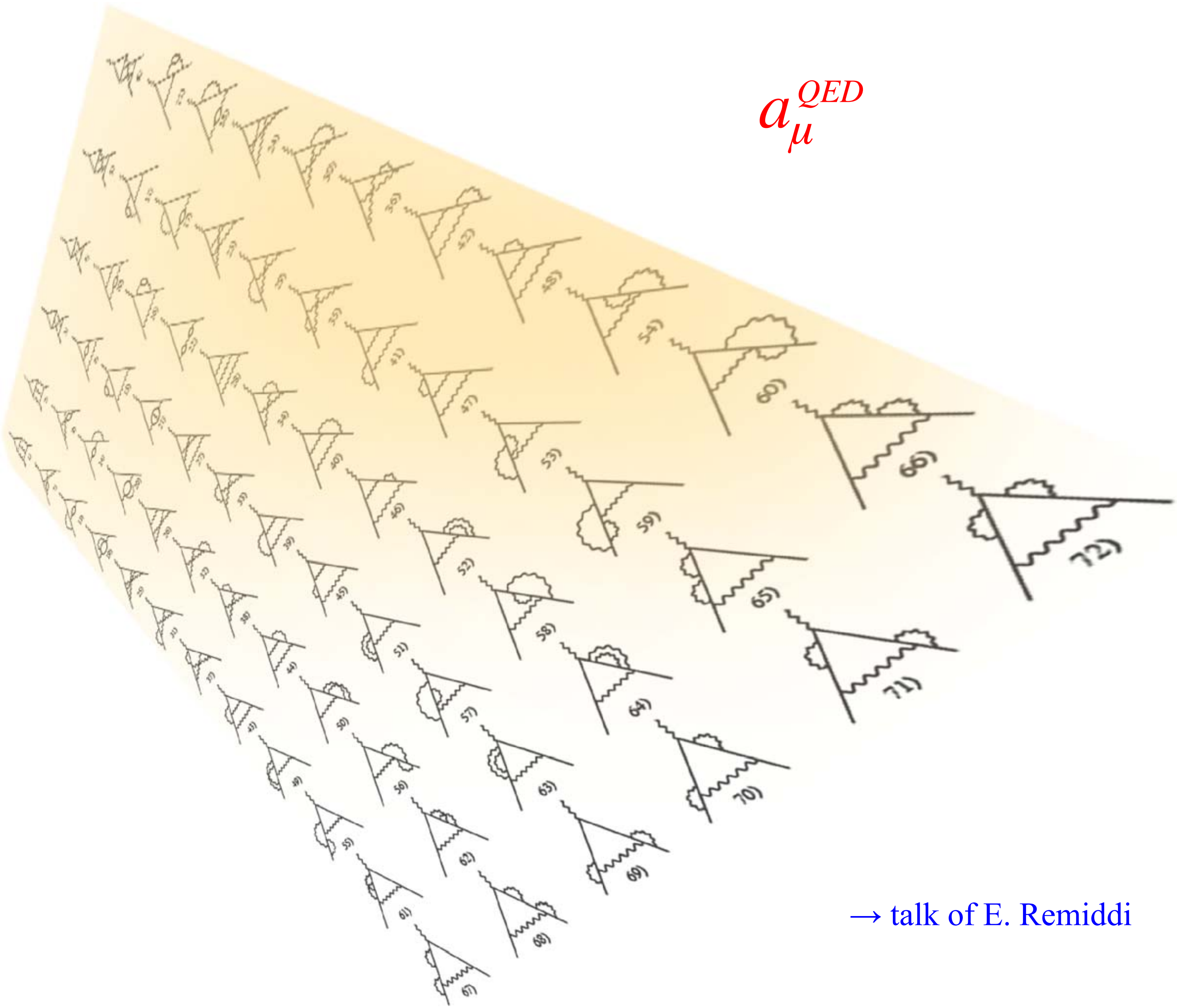
Anomalous magnetic moment of the muon

$$a_\mu = (g_\mu - 2)/2 = \alpha/2\pi + \dots$$

$$a_\mu^{theor} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak} + a_\mu^{new}$$

- *QED* a_μ^{QED}
- weak contribution a_μ^{weak}
- hadronic vacuum polarisation a_μ^{had}
- contribution beyond *SM* a_μ^{new}

a_μ^{QED}



→ talk of E. Remiddi

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Hadronic vacuum polarisation

- The hadronic contribution to vacuum polarisation is dominated by low energy effects which cannot be obtained by perturbative *QCD*

but rather

- by experimental data of $e^+ e^-$ *annihilation into hadrons* and / or by $\tau-decays$ evaluating the dispersion integral

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

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

up to some sufficiently high energies, typically *2…5 GeV*

2.2.2. *KLOE-ISR* at *DAΦNE*

Determination of $\sigma(e^+ e^- \to \pi^+ \pi^-)$ by emission of photons in the initial state $\sigma(e^+ e^- \to \pi^+ \pi^- \gamma)$ and by applying *PHOKHARA*, 'radiative return' to the resonances ρ, ω

to determine the hadronic contribution to the muon magnetic anomaly a_μ^{had} below *1 GeV* two analyses have been carried out:

Small photon angle analysis:
No photon detection, only detection of two charged pions

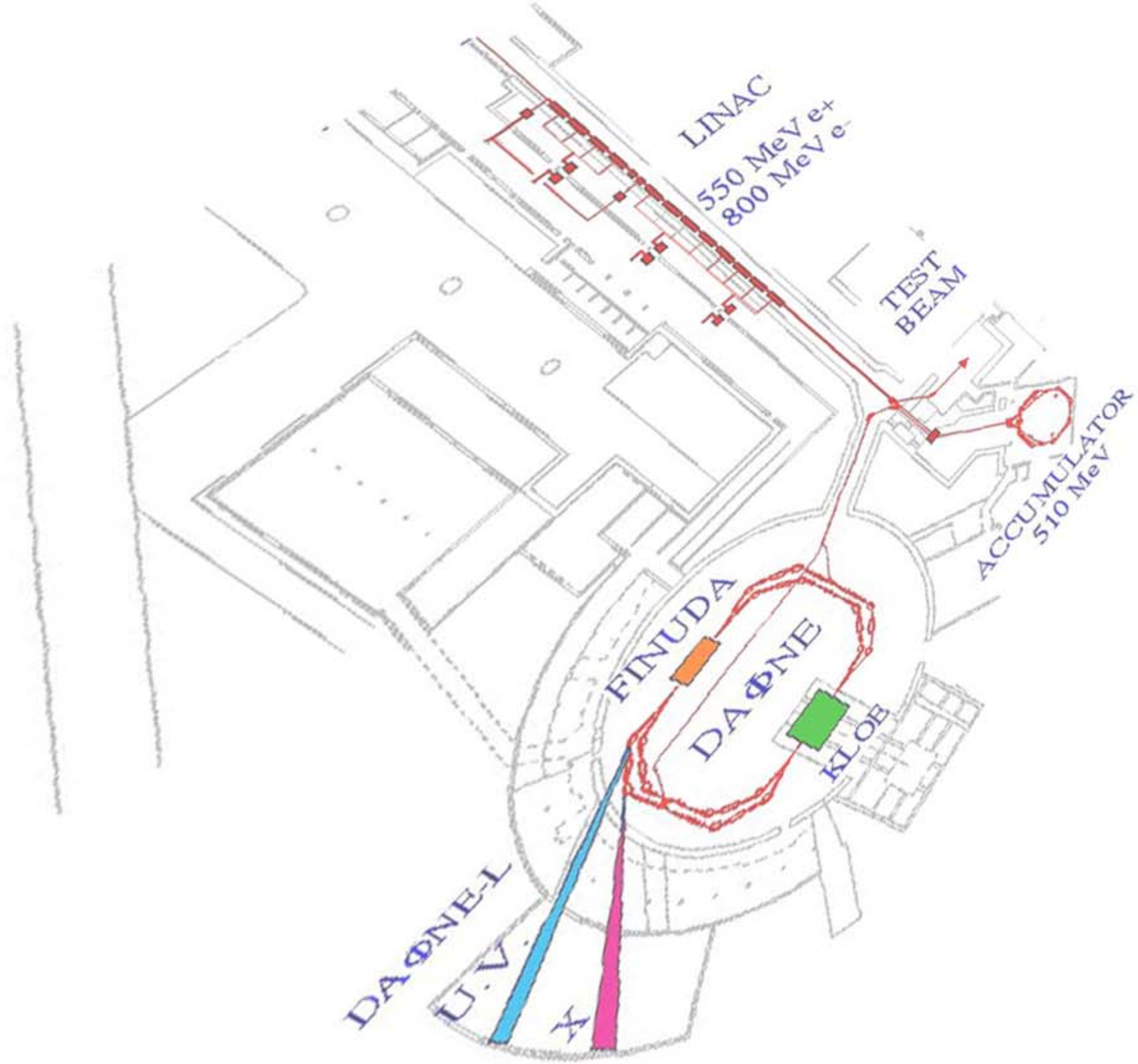
$$\theta_{\Sigma(\gamma)} < 15° \; (> 165°),\; 50° < \theta_\pi < 130°,\; E_\Sigma > 10\ MeV$$

→ talk of F. Nguyen

Large photon angle analysis:
Photon detection (tagging) and detection of two charged pions

at least one photon with $50° < \theta_\gamma < 130°$ and $E_\gamma > 50\ MeV$, $50° < \theta_\pi < 130°$

DAΦNE



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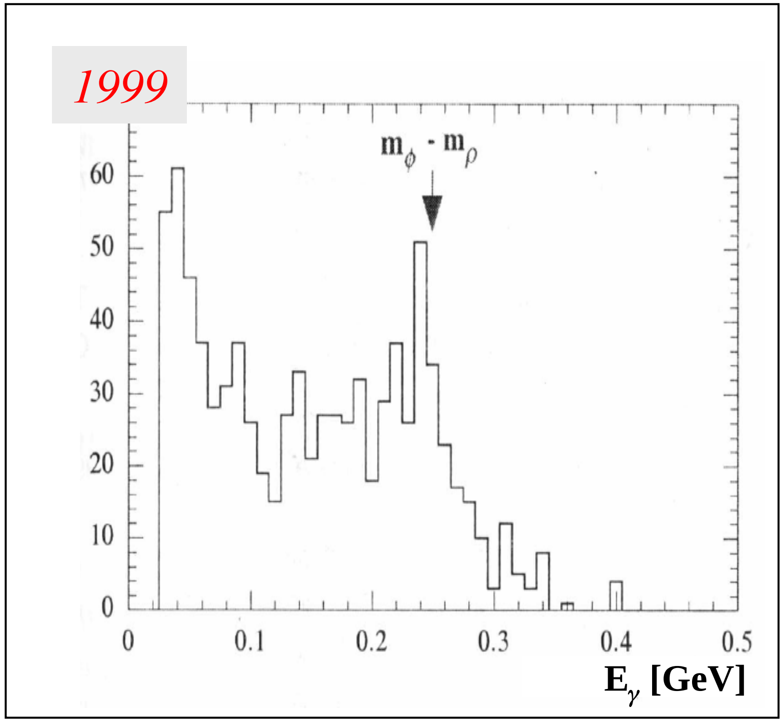
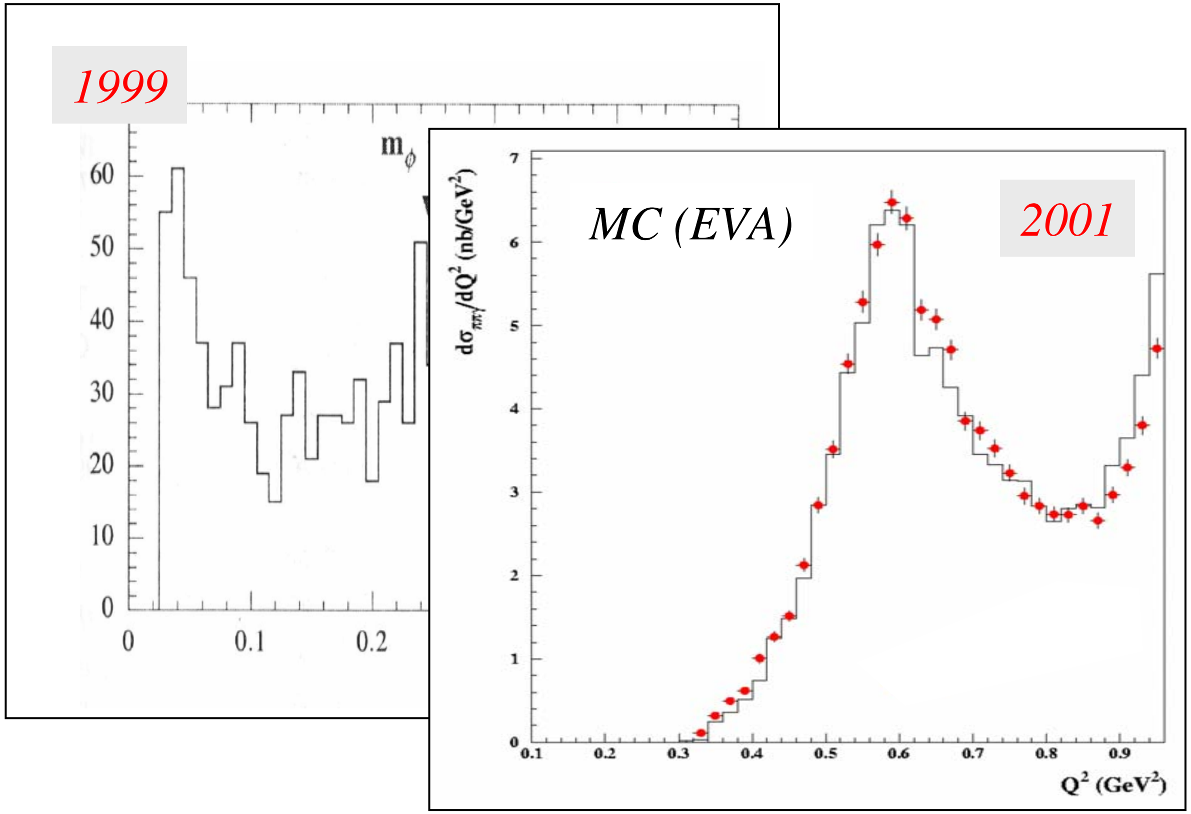
KLOE-ISR small photon angle analysis:



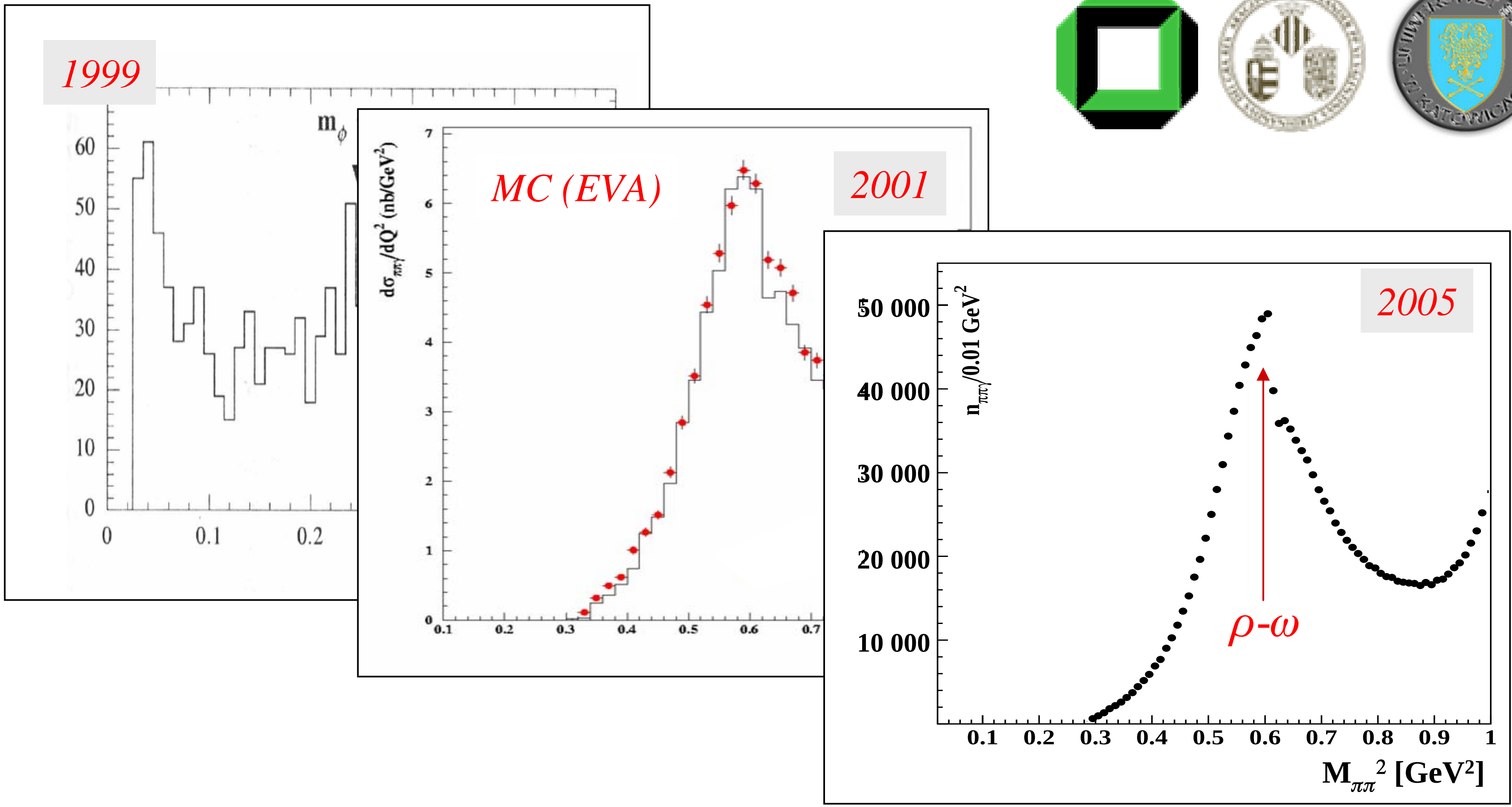
G. Cataldi, A. Denig, W. K., G. Venanzoni, *KLOE* memo #195, August 1999, Frascati Physics Series (2000), p. 569
hep-ex/0106100, hep-ex/0107023, hep-ex/0205046, hep-ex/0210013, hep-ex/0211024
KLOE note # 189, July 2003, hep-ex/0312056, Eur. Phys.J. **C 33** (2004) 656, Phys. Lett. **B 606** (2005) 12 (hep-ex/0407048)

KLOE-ISR small photon angle analysis:



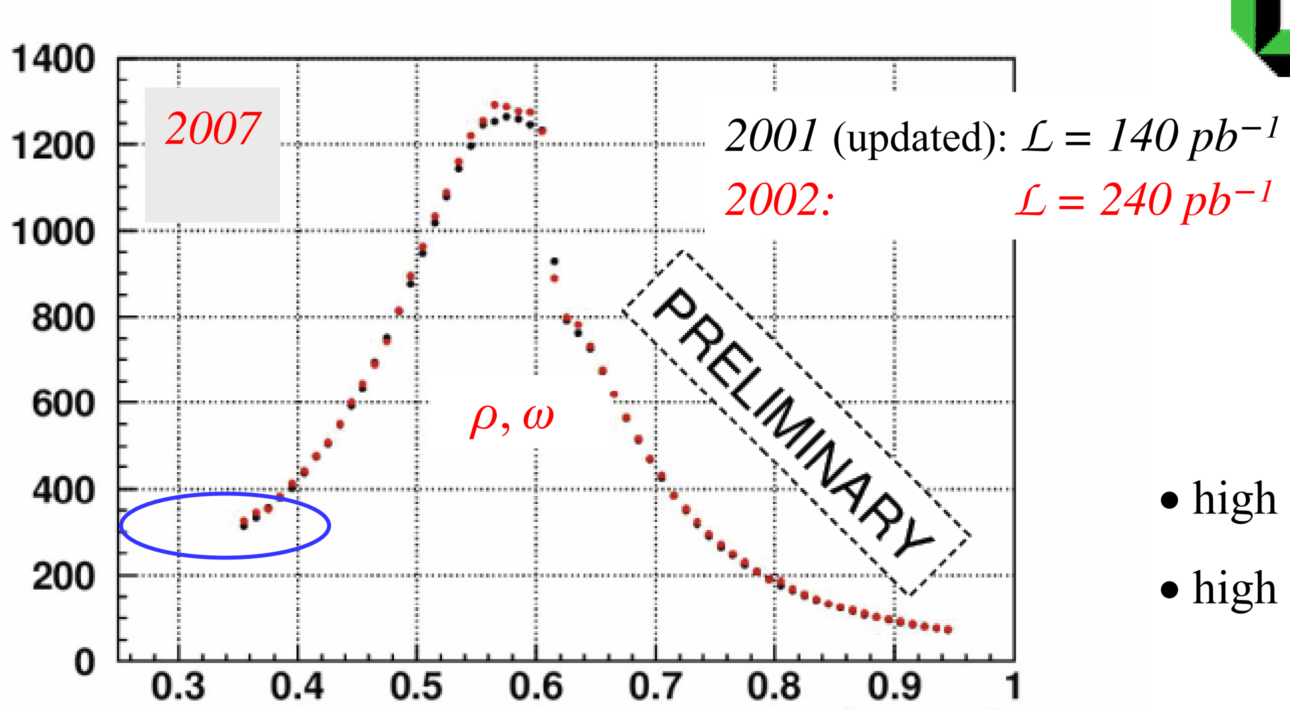
G. Cataldi, A. Denig, W. K., G. Venanzoni, *KLOE* memo #195, August 1999, Frascati Physics Series (2000), p. 569
hep-ex/0106100, hep-ex/0107023, hep-ex/0205046, hep-ex/0210013, hep-ex/0211024
KLOE note # 189, July 2003, hep-ex/0312056, Eur. Phys.J. **C 33** (2004) 656, Phys. Lett. **B 606** (2005) 12 (hep-ex/0407048)

KLOE-ISR small photon angle analysis:



G. Cataldi, A. Denig, W. K., G. Venanzoni, *KLOE* memo #195, August 1999, Frascati Physics Series (2000), p. 569
hep-ex/0106100, hep-ex/0107023, hep-ex/0205046, hep-ex/0210013, hep-ex/0211024
KLOE note # 189, July 2003, hep-ex/0312056, Eur. Phys.J. **C 33** (2004) 656, Phys. Lett. **B 606** (2005) 12 (hep-ex/0407048)

KLOE-ISR small photon angle analysis:

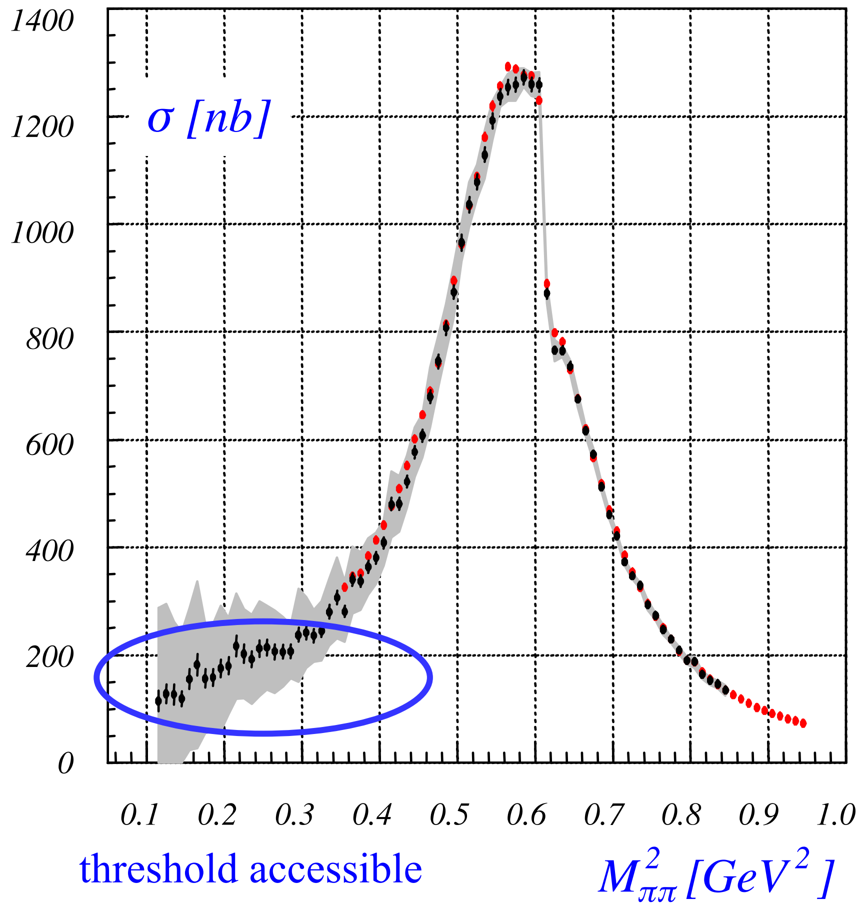


low $M^2_{\pi\pi}$ kinematically suppressed $M^2_{\pi\pi}\,[GeV^2]$

- high statistics
- high resolution

→ talk of F. Nguyen

KLOE-ISR large photon angle analysis: $\mathcal{L} = 240\ pb^{-1}$



- *2002* data (small angles)
- *2002* data (large angles)

grey error band: statistical and systematic errors, the latter dominated by the contribution of f_o

$e^+ e^- \to \phi \to f_o \gamma \to \pi^+ \pi^- \gamma$

Results for $a_\mu^{\pi\pi}$:

→ talk of F. Nguyen

published results (small angle analysis):

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ GeV^2) = (388.7 \pm 0.8_{stat} \pm 4.9_{syst})\cdot 10^{-10}$$

Phys. Lett. **B 606** (2005) 12

updated for trigger efficiency and revised Bhabha cross section* (small angles):

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ GeV^2) = (384.4 \pm 0.8_{stat} \pm 4.9_{syst})\cdot 10^{-10}$$

this conference (small angles):

$$a_\mu^{\pi\pi}(0.35\text{-}0.95\ GeV^2) = (389.2 \pm 0.8_{stat} \pm 3.0_{syst} \pm 3.5_{th})\cdot 10^{-10}$$

EPS Manchester 2007 (small angles)

$$a_\mu^{\pi\pi}(0.50\text{-}0.85\ GeV^2) = (255.4 \pm 0.4_{stat} \pm 2.5_{syst})\cdot 10^{-10}$$

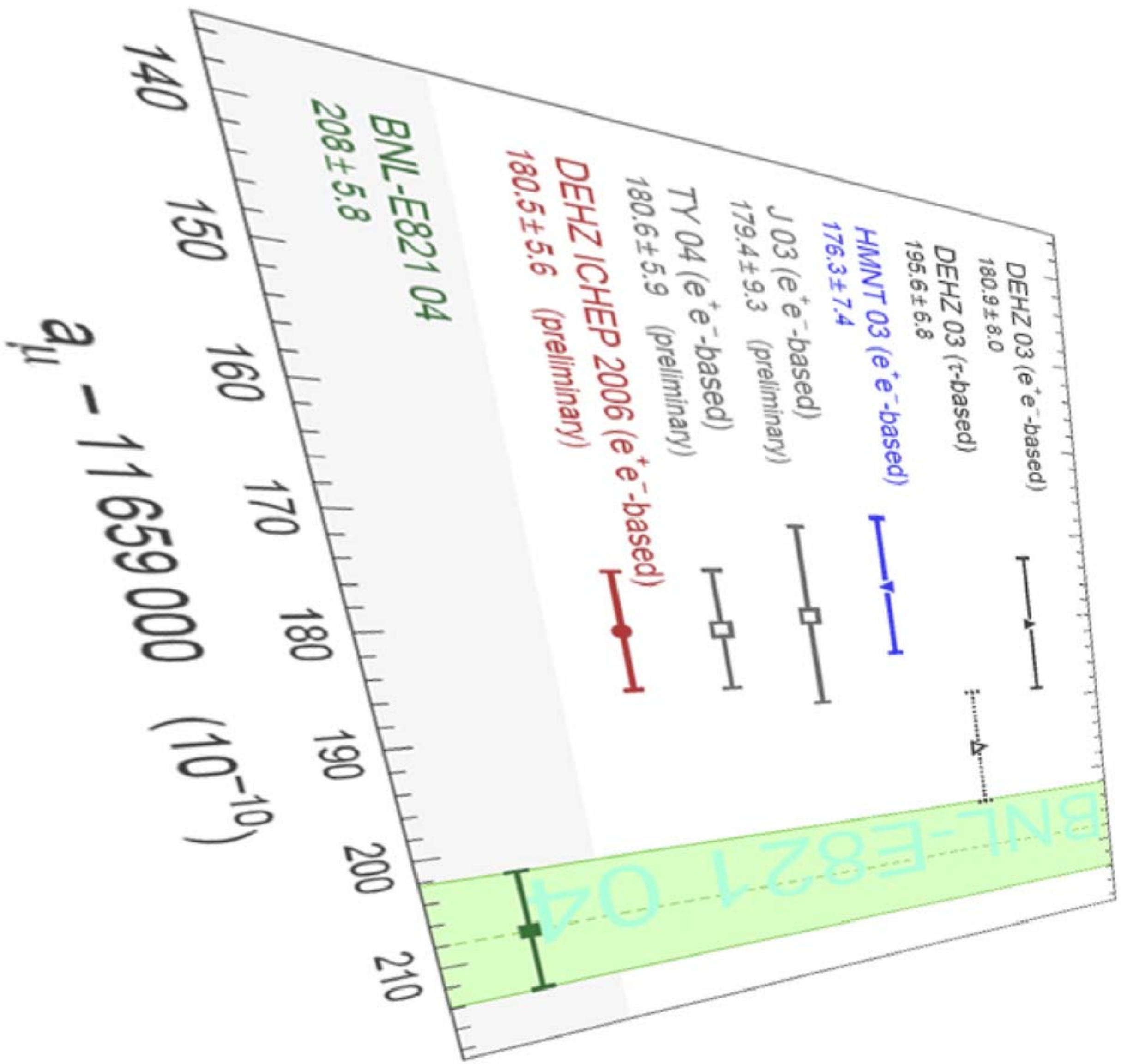
preliminary analysis of 2002 data (large angle analysis):

$$a_\mu^{\pi\pi}(0.50\text{-}0.85\ GeV^2) = (252.5 \pm 0.6_{stat} \pm 2.0_{syst} \pm 3.1_{syst,\ fo})\cdot 10^{-10}$$

in agreement with results from energy scan *(CMD-2* and *SND)*

BABAYAGA*: Nucl. Phys. **B 758 (2006) 227, → talk of C. Calame

Hadronic contribution to the vacuum polarisation



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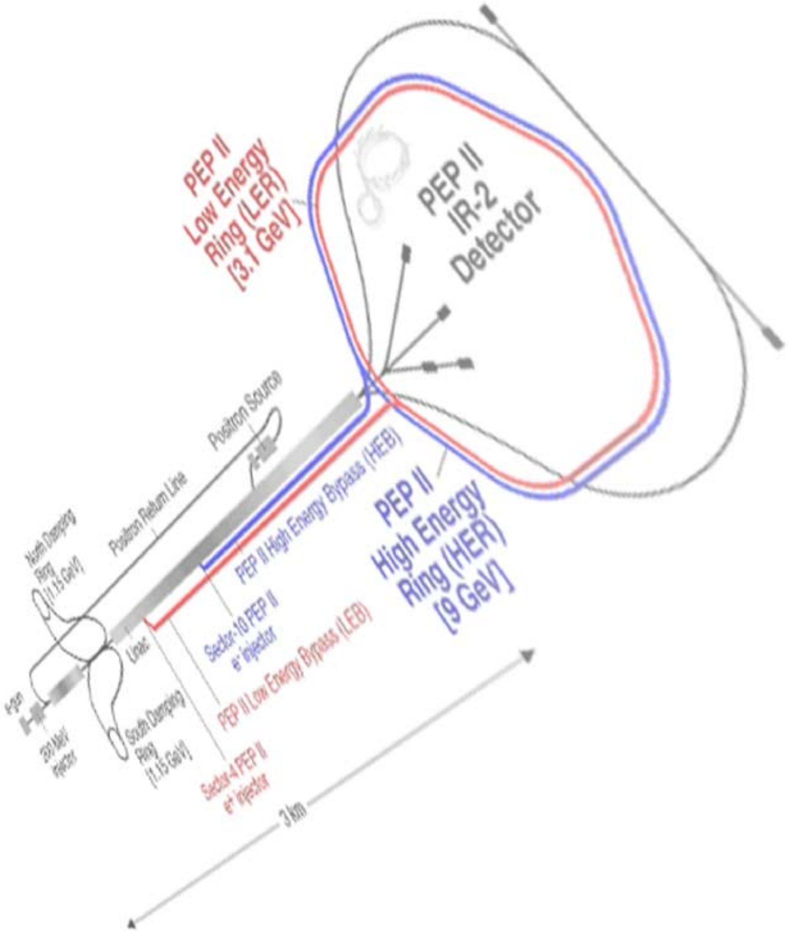
2.2.3. *BaBAR-ISR*, *Belle-ISR*: Determination of $\sigma\ (e^+ e^- \rightarrow hadrons)$ emission of photons in the initial state $e^+ e^- \rightarrow hadrons\ \gamma$, 'radiative return' to $\rho, \omega, \phi, \ldots, J/\psi, \ldots$

PEP-II



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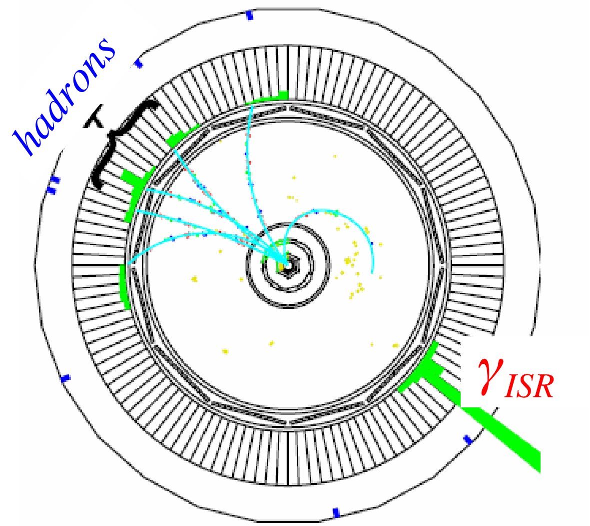
BaBAR-ISR

Study of $e^+ e^-$ collisions in the *1.5 - 3 GeV* c.m. energy region using *ISR* at *BaBar*

E. P. Solodov, *SLAC*, April 2001 hep-ex/0107027

$e^+ e^- \to \mu^+ \mu^- \gamma,\ \pi^+ \pi^- \gamma,\ K^+ K^- \gamma,\ 3\pi\,\gamma,\ 4\pi\,\gamma,\ 5\pi\,\gamma,\ 6\pi\,\gamma,\ 7\pi\,\gamma,$ etc.



$e^+ e^- \to J/\psi\,\gamma \to \mu^+ \mu^- \gamma$ Phys. Rev. **D 69** (2004) 011103

final hadronic states < *4.5 GeV:*

$e^+ e^- \to \pi^+ \pi^- \pi^o \gamma$ Phys. Rev. **D 70** (2004) 072004

$e^+ e^- \to \pi^+ \pi^- \pi^+ \pi^- \gamma,\ \pi^+ \pi^- K^+ K^- \gamma,\ K^+ K^- K^+ K^- \gamma$

Phys. Rev. **D 71** (2005) 052001

$e^+ e^- \to \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^- \gamma,\ \pi^+ \pi^- \pi^o \pi^+ \pi^- \pi^o \gamma,\ \pi^+ \pi^- \pi^+ \pi^- K^+ K^- \gamma$

Phys. Rev. **D 73** (2006) 052003

$e^+ e^- \to \phi\, f_o(980)\,\gamma$ Phys. Rev. **D 74** (2006) 091103

$e^+ e^- \to J/\psi\,\pi^+ \pi^- \gamma,\ J/\psi\,K^+ K^- \gamma,\ J/\psi\,\gamma\,\gamma\,\gamma$ (search for $c\bar{c}$ states)

hep-ex/0608004v1

→ talk of A. Denig

BaBAR-ISR

More final hadronic states < *4.5 GeV:*

$e^+ e^- \to \pi^+ \pi^- K^+ K^- \gamma, \pi^o \pi^o K^+ K^- \gamma, K^+ K^- K^+ K^- \gamma$ Phys. Rev. **D 76** (2007) 012008

$e^+ e^- \to \pi^+\pi^-\pi^+\pi^-\pi^o \gamma, \pi^+\pi^-\pi^+\pi^- \eta \gamma, \pi^+\pi^-\pi^o K^+ K^- \gamma, \pi^+\pi^- \eta K^+ K^- \gamma$

Phys. Rev. **D 76** (2007) 092005

$e^+ e^- \to \Lambda \bar{\Lambda} \gamma, \Lambda \bar{\Sigma}^o \gamma, \Sigma^o \bar{\Sigma}^o \pi^o \gamma$ Phys. Rev. **D 76** (2007) 092006

$e^+ e^- \to D \bar{D} \gamma$ Phys. Rev. **D-RC 76** (2007) 111105

$e^+ e^- \to \pi^- K^+ K_S \gamma, \pi^o K^- K^+ \gamma, \eta K^+ K^- \gamma$ hep-ex/07104451, Phys. Rev. **D**

$e^+ e^- \to p \bar{p} \gamma$ Phys. Rev. **D 73** (2006) 012005

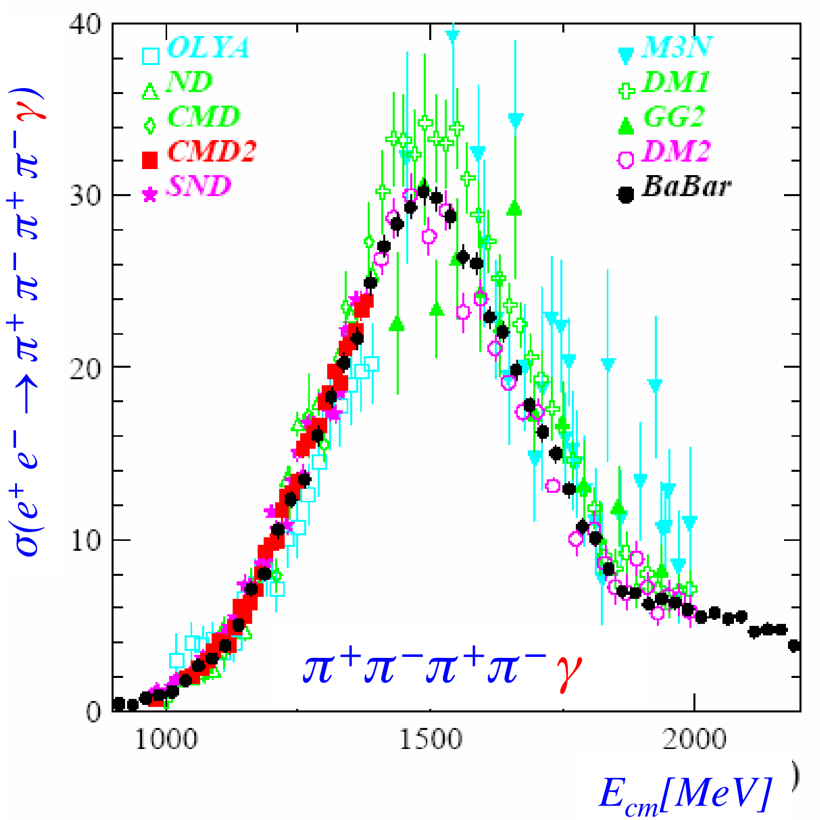
$e^+ e^- \to \pi^+ \pi^- \pi^o \pi^o \gamma, \pi^+ \pi^+ \pi^- \pi^- \pi^o \gamma$

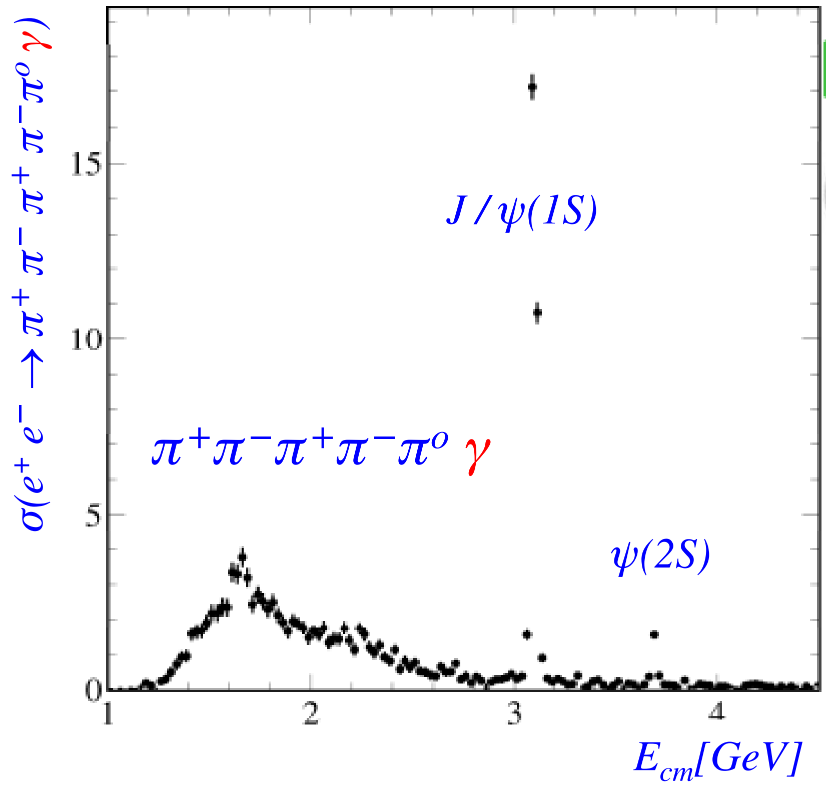
$e^+ e^- \to \pi^+ \pi^- \gamma, K^+ K^- \gamma, \pi^+ \pi^- \pi^o \pi^o \pi^o \gamma$ in preparation

→ talk of A. Denig

BaBar-ISR: $e^+ e^- \to pions\ \gamma$ (study of reaction mechanisms, identification of intermediate states)

PHOKHARA





- consistent with previous results
- best measurement for $E_{cm} < 0.75\ GeV$
- competitive for $0.75 - 1.4\ GeV$
- best for $1.4 - 2.0\ GeV$
- only measurement for $E_{CM} > 2.0\ GeV$

$\sim 20\ \%\ \pi^+\pi^-\eta$, mostly $\rho^o\eta$
$\sim 40\ \%\ \pi^+\pi^-\omega$, rest $\rho^o\rho^\pm\pi^\mp$

$\psi(2S)$ due to $\mu^\pm$ misidentified as $\pi^\pm$

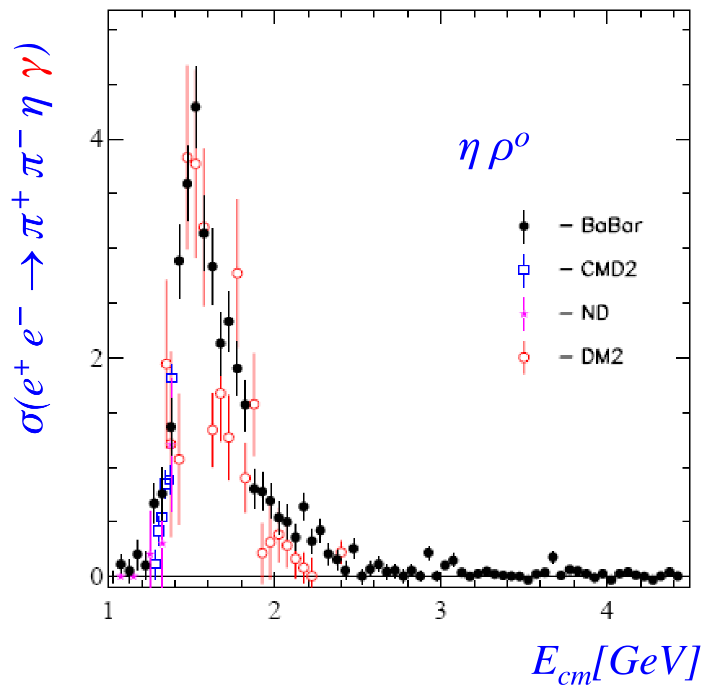
Phys. Rev. **D 71** (2005) 052001

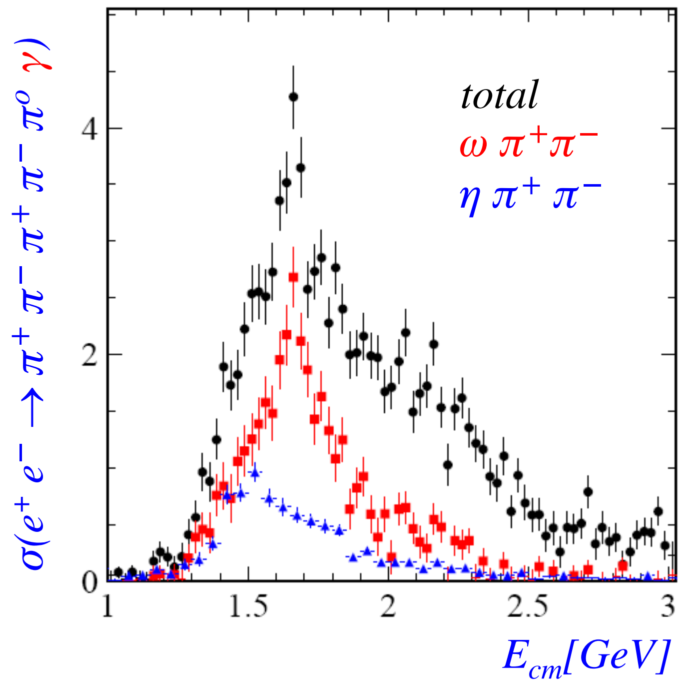
Phys. Rev. **D 76** (2007) 092005

BaBar-ISR: $e^+ e^- \to pions\ \gamma$ (study of reaction mechanisms, identification of intermediate states)

PHOKHARA

$$\left.\begin{array}{l} e^+ e^- \to \eta\ (\rho^o \to \pi^+\pi^-)\ \gamma \\ \quad\quad \omega\ \pi\ \pi\ \gamma \\ \quad\quad a_1(1260)\ \rho\ \gamma \text{ or } \pi(1300)\ \rho\ \gamma \end{array}\right\} \to \pi^+\pi^-\pi^+\pi^-\pi^o\ \gamma$$



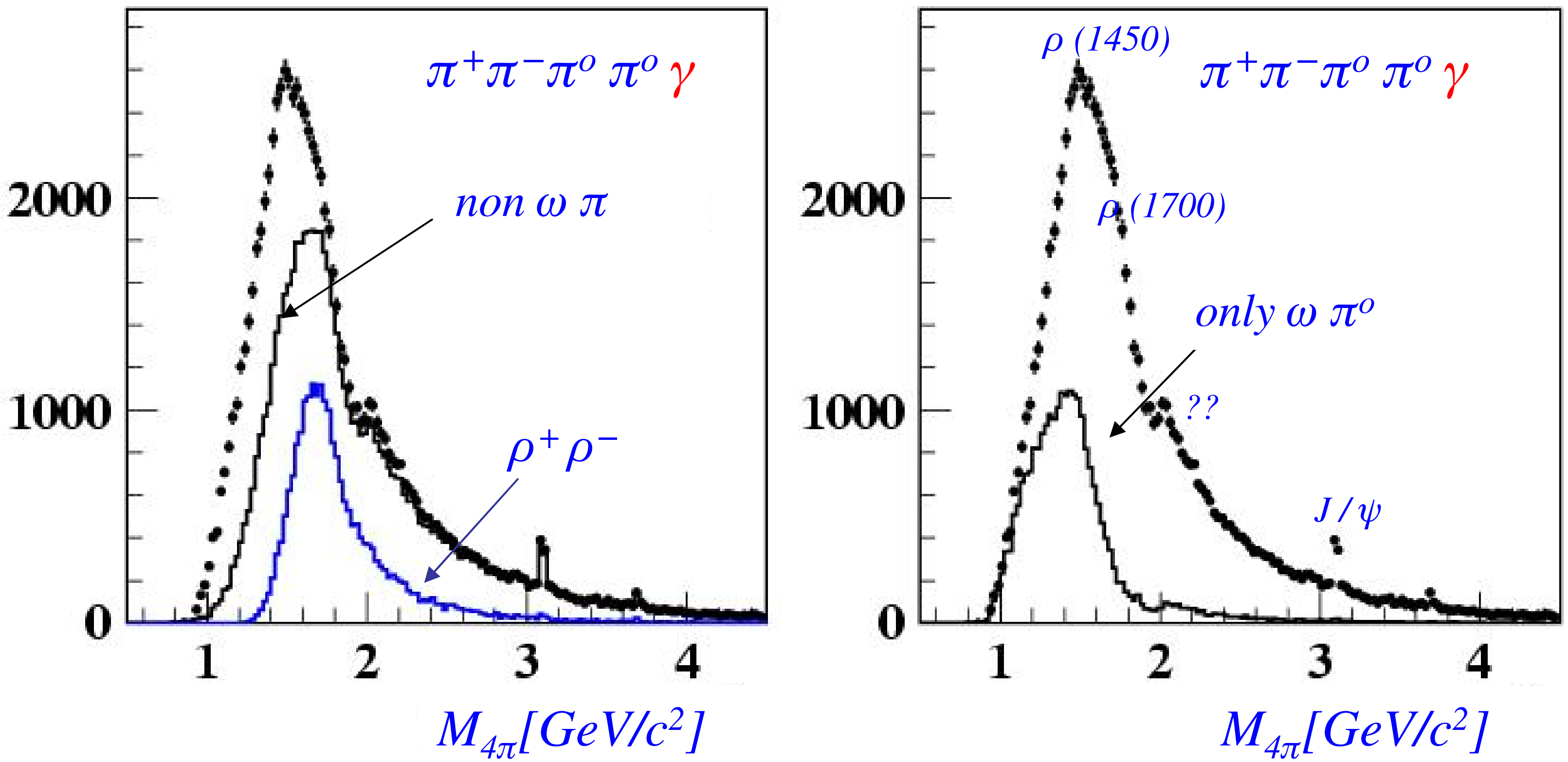


Phys. Rev. **D 76 (**2007) 092005

BaBar-ISR: $e^+ e^- \rightarrow pions\ \gamma$ (study of reaction mechanisms, identification of intermediate states)

PHOKHARA

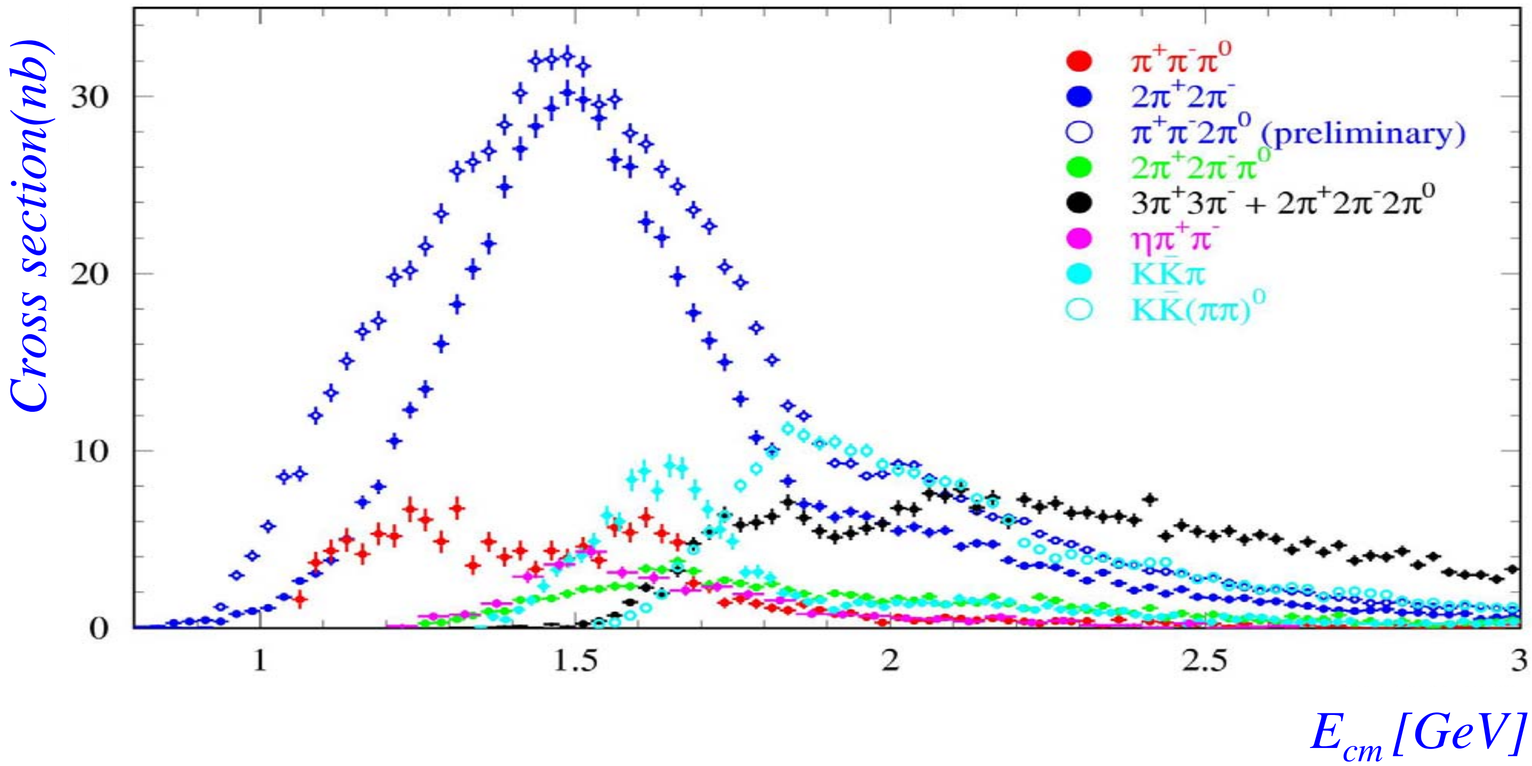
$$e^+ e^- \longrightarrow \left.\begin{array}{l} \omega\, \pi^o\, \gamma \\ a_1(1260)\, \pi\, \gamma \\ \rho^+ \rho^- \gamma \\ \rho^o f_o(980)\, \gamma \end{array}\right\} \rightarrow \pi^+\pi^-\pi^o\,\pi^o\,\gamma$$



competitive / best / first measurement for $E_{CM} < 1.4 / < 2.4 / > 2.4$ GeV

PHOKHARA

Summary *BaBar*- *ISR*



→ talk of A. Denig

KEK-B

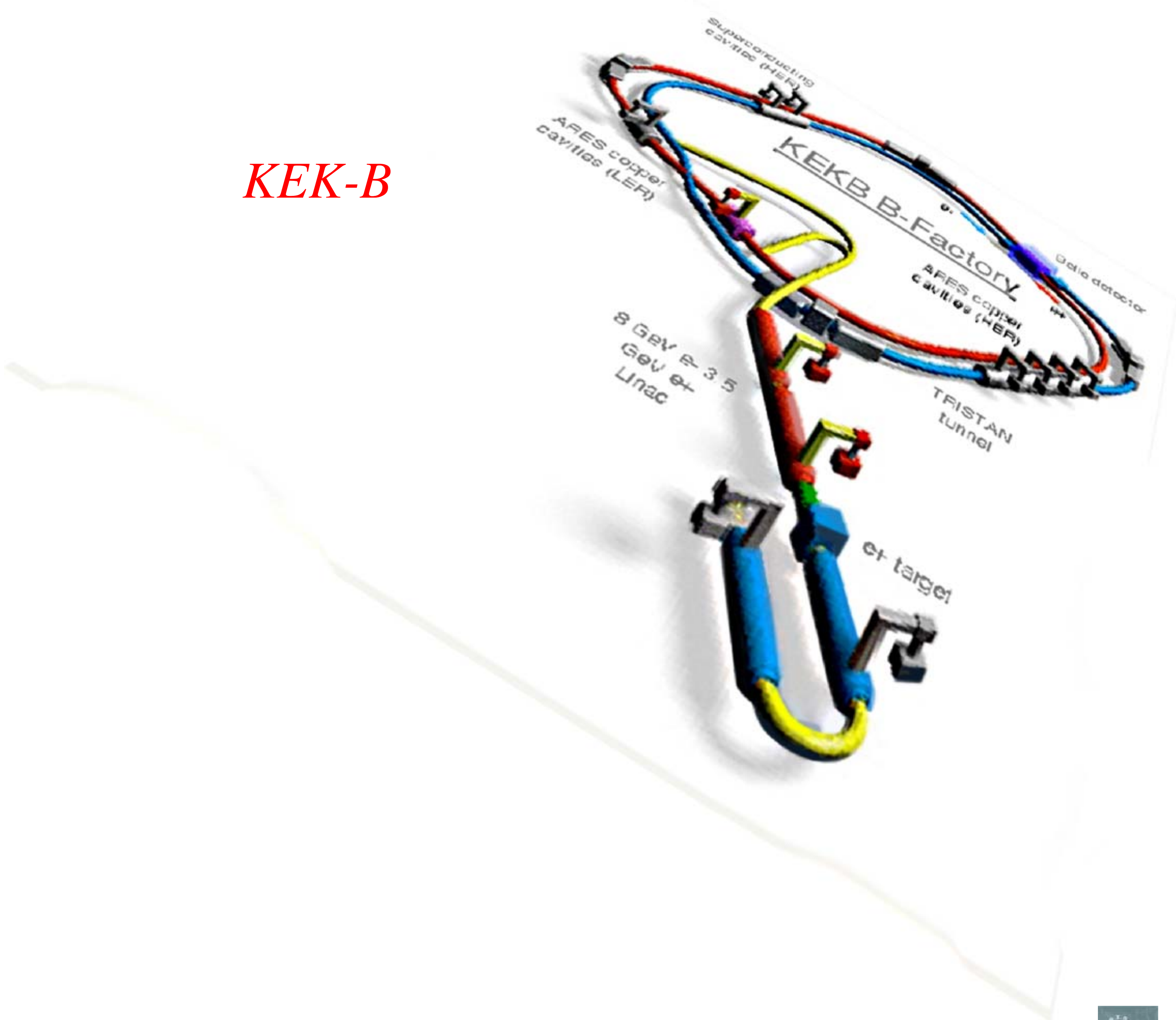


Figure elaborated artistically to become an element of the conference poster by Claudio Federici LNF

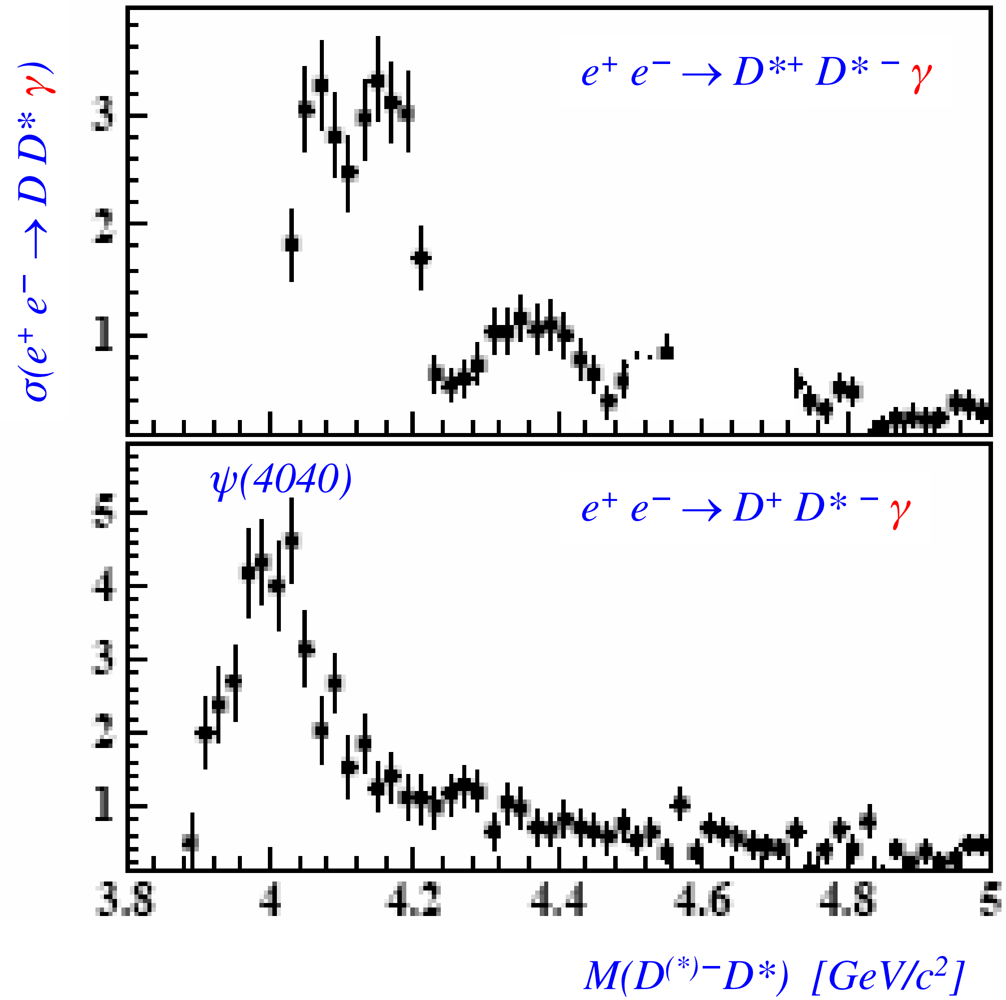
Belle-ISR

Determination of $\sigma(e^+ e^- \to hadrons)$ by emission of photons in the initial state $e^+ e^- \to hadrons\ \gamma$ and by applying *PHOKHARA, 'radiative return'* to $\rho, \omega, \phi, \dots, J/\psi, \dots$

$e^+ e^- \to J/\psi\ K^+ K^- \gamma$	Phys. Rev. **D-RC**, hep-ex/07092565
$e^+ e^- \to D\,\bar{D}\,\gamma\ (D^+ D^- \gamma)\ (D^o\,\bar{D}^o \gamma)$	Phys. Rev. **D 77** (2008) 011103, hep-ex/07080082
$e^+ e^- \to \pi^+ \pi^-\ \psi(2S)\gamma$	hep-ex/07073699
$e^+ e^- \to \pi^+ \pi^-\ J/\psi\ \gamma$	hep-ex/07072541
$e^+ e^- \to D^{*\pm}\,\bar{D}^{*\mp}\ \gamma$	Phys. Rev. Lett. **98** (2007) 092001, hep-ex/0608018
$e^+ e^- \to D^o\,D^-\,\pi^+\,\gamma$	Phys. Rev. Lett. **100** (2008) 062001

$\to$ talk of G. Pakhlova

Belle-ISR



→ talk of G. Pakhlova

Phys. Rev. Lett. **98** (2007) 092001, hep-ex/0608018

2.3. *PHOKHARA* and hadron spectroscopy

(search for new hadronic states)

2.3.1. *KLOE*

(structure studies of light scalar mesons $\sigma(500)$, $f_o(980)$, $a_o(980)$
by their decay into pairs of pseudoscalars)

example: $e^+ e^- \rightarrow f_o \gamma \rightarrow \pi^+ \pi^- \gamma$

large irreducible backgrounds from *ISR, FSR* determined by *PHOKHARA*

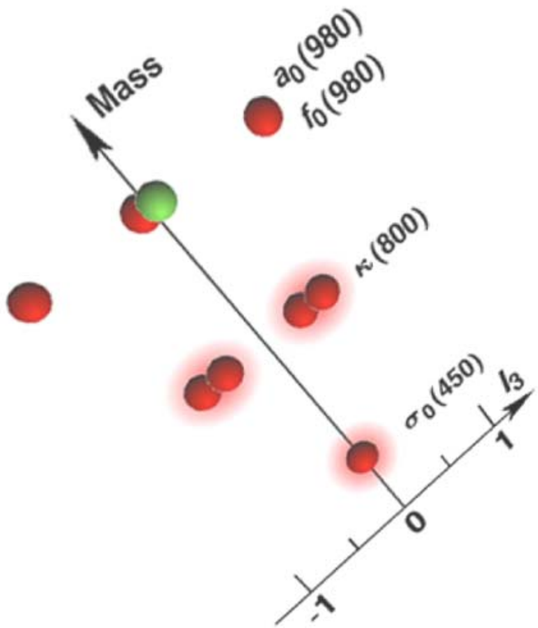
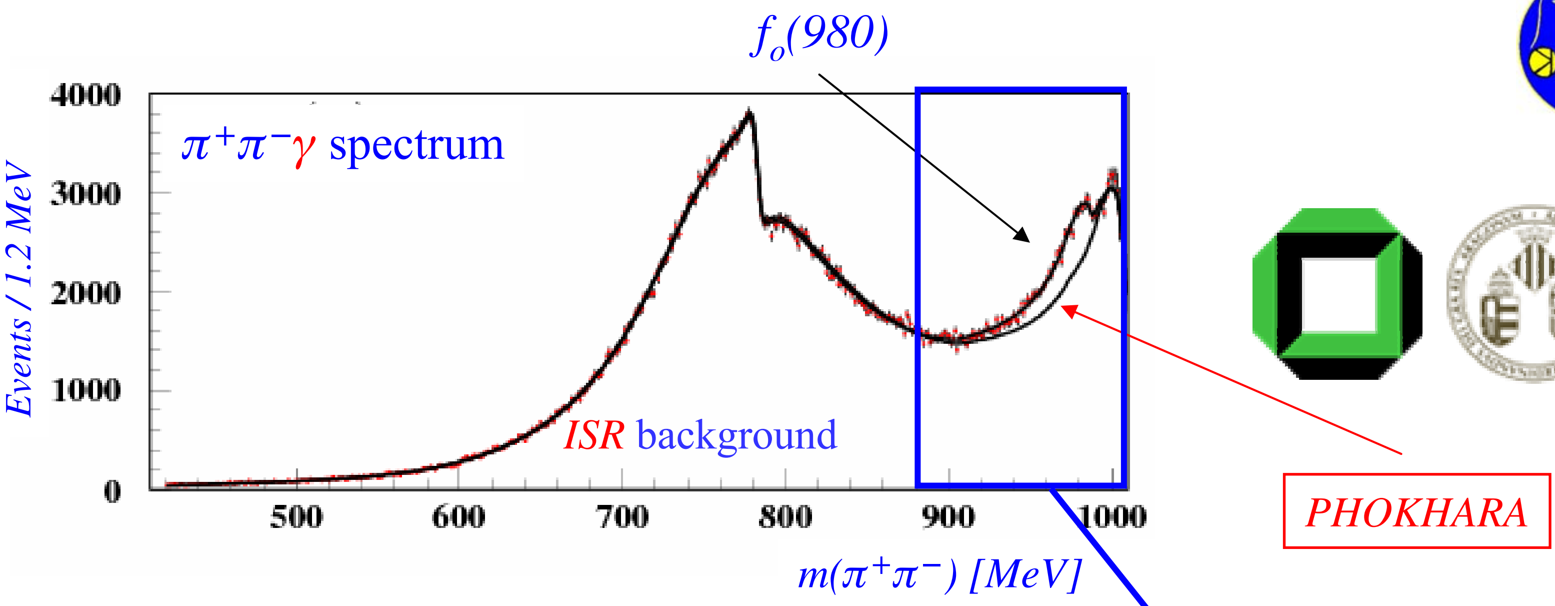
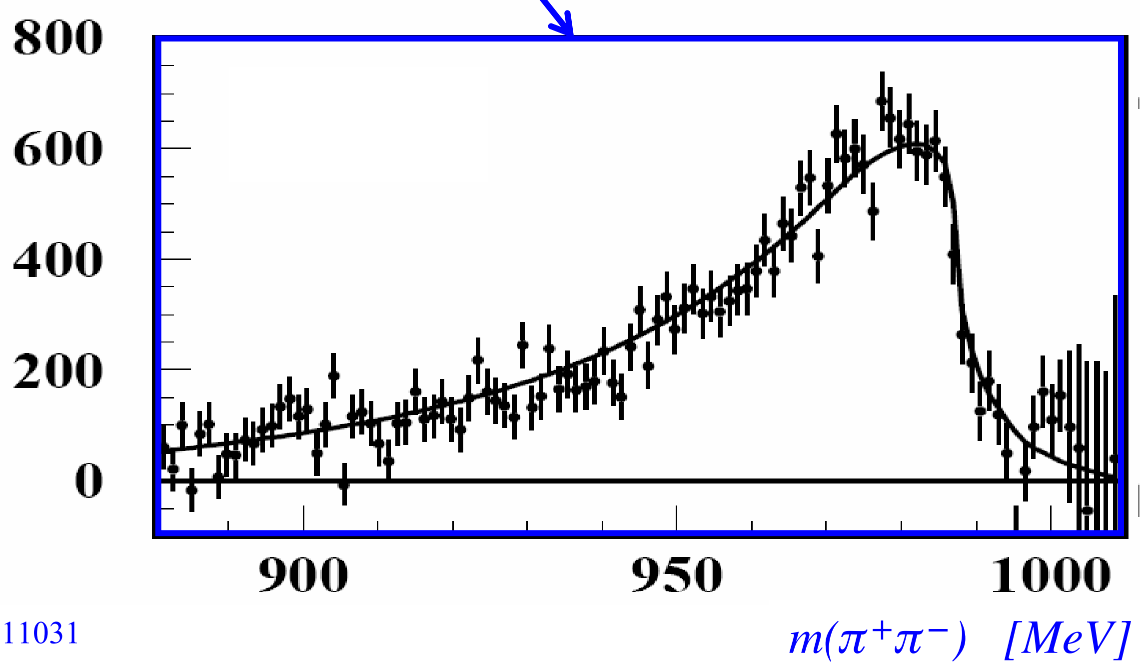


Figure elaborated artistically to become an element of the conference poster by Claudio Federici LNF



$$f_o(980) \to \pi^+ \pi^-$$
$$\to \pi^o \ \pi^o$$



$\pi^o \pi^o \gamma$: Phys. Lett. **B 537** (2002) 21;
Eur. Phys. J. **C 49** (2006) 433

$\pi^+ \pi^- \gamma$: Phys. Lett. **B 634** (2006) 148, hep-ex/0511031

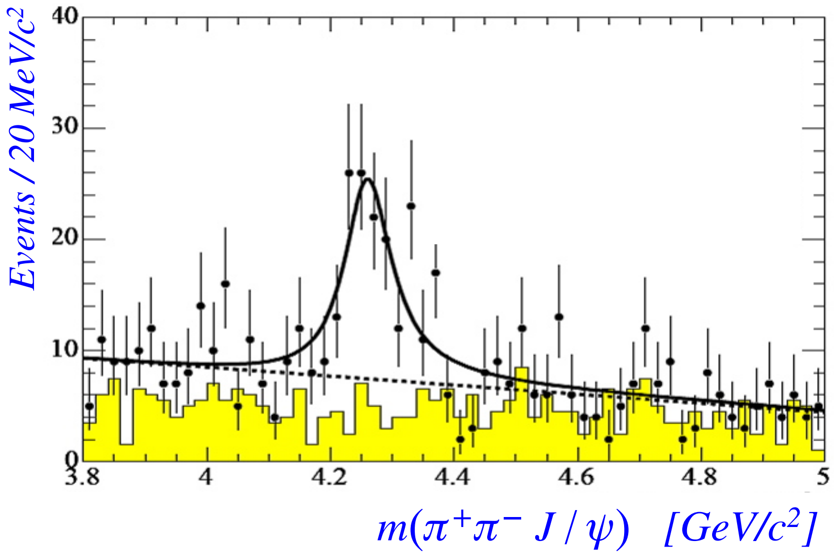
2.3.2. *BaBar, Belle-ISR, CLEO-c :*

New neutral meson states with $J^{PC} = 1^{--}$

Y(4050)
Y(4260)
Y(4360)
Y(4660)
…

Charmonium spectroscopy $c\bar{c}$*:*
first discovery with ISR by BaBar

$$e^+ e^- \rightarrow Y(4260)\,\gamma \rightarrow J/\psi\, \pi^+ \pi^- \gamma$$



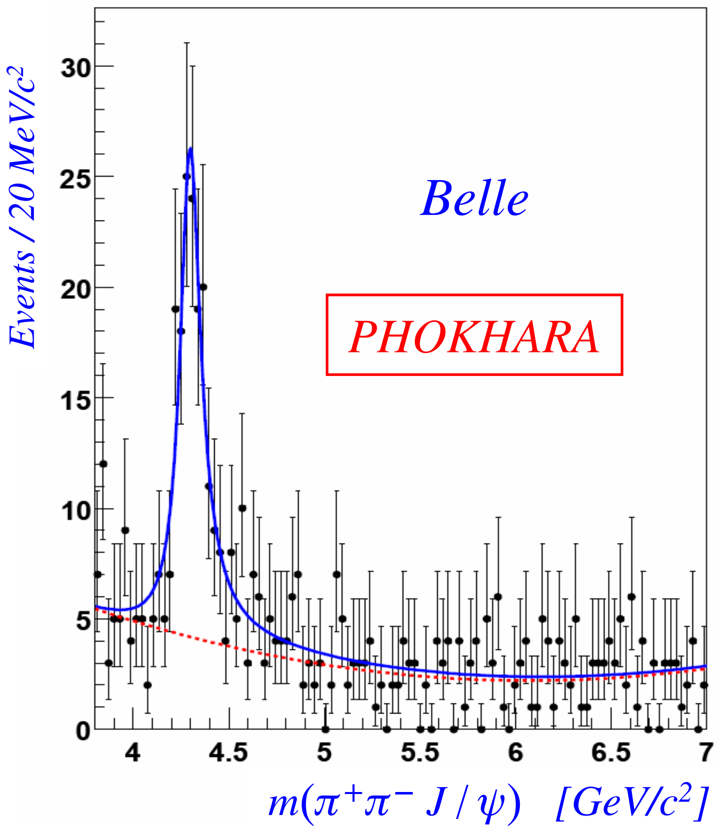
$M = 4259.2 \pm 8$ *MeV*
$\Gamma = 88 \pm 8$ *MeV*

Phys. Rev. Lett. **95** (2005) 142001

no $c\bar{c}$ assignment, probably not a glueball, because no decay into $\phi\, \pi^- \pi^+$,
4 quark $[cs][\bar{c}\bar{s}]$, hybrid meson, $\omega\chi_{c1}$ molecule ?

Belle-ISR, CLEO-c : New neutral meson states with $J^{PC} = 1^{--}$

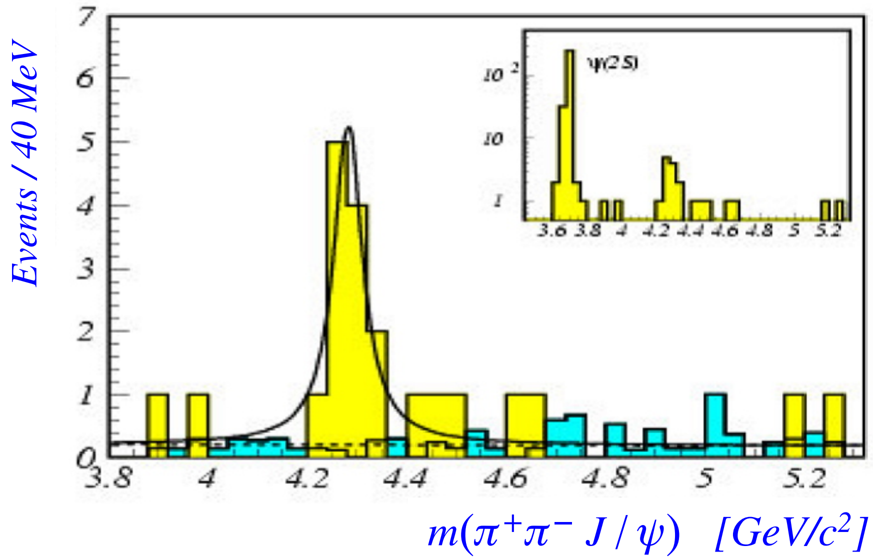
$e^+ e^- \to Y(4260)\,\gamma \to J/\psi\,\pi^+\pi^-\,\gamma$



$M = 4295 \pm 15$ MeV
$\Gamma = 133 \pm 30$ MeV

hep-ex/0612006v1, hep-ex/0707.2541v2

CLEO-c
scan around *4.26 GeV*, no *ISR*

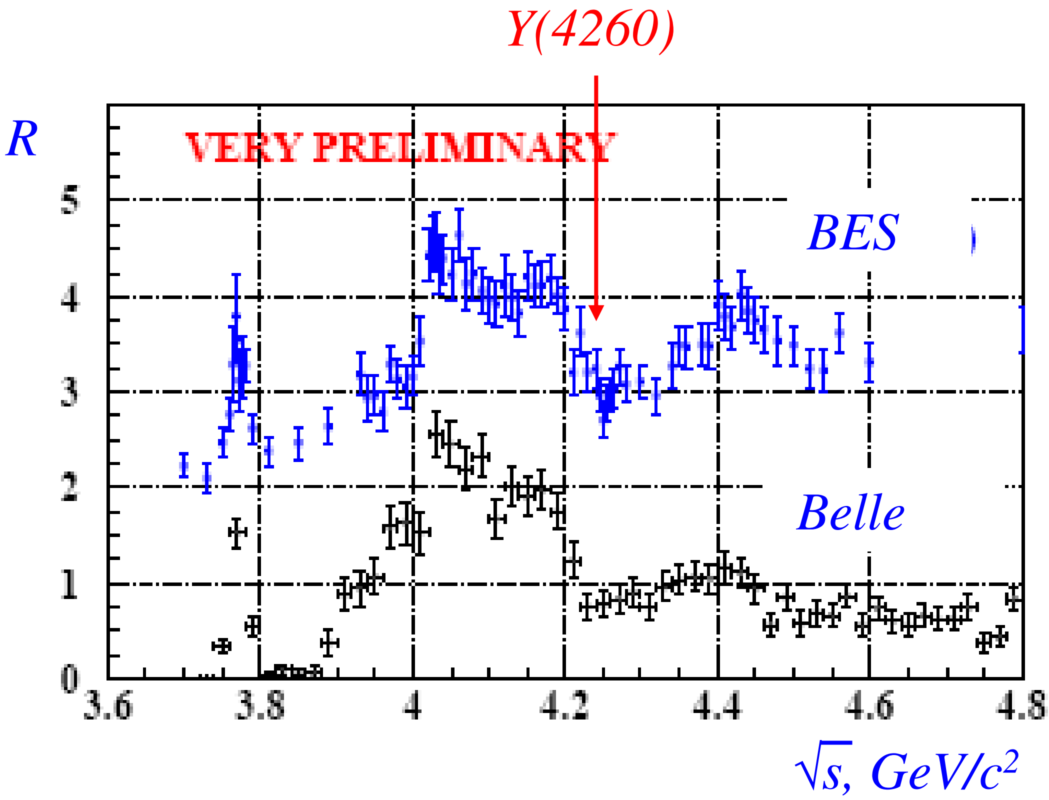


$M = 4284 \pm 18$ MeV
$\Gamma = 73 \pm 40$ MeV

Phys. Rev. **D 74** (2006) 091104

Belle-ISR: total exclusive cross section

impressive parallelism between *ISR (Belle)* and energy scan *(BES)*



→ talks of G. Pakhlova, P. Wang

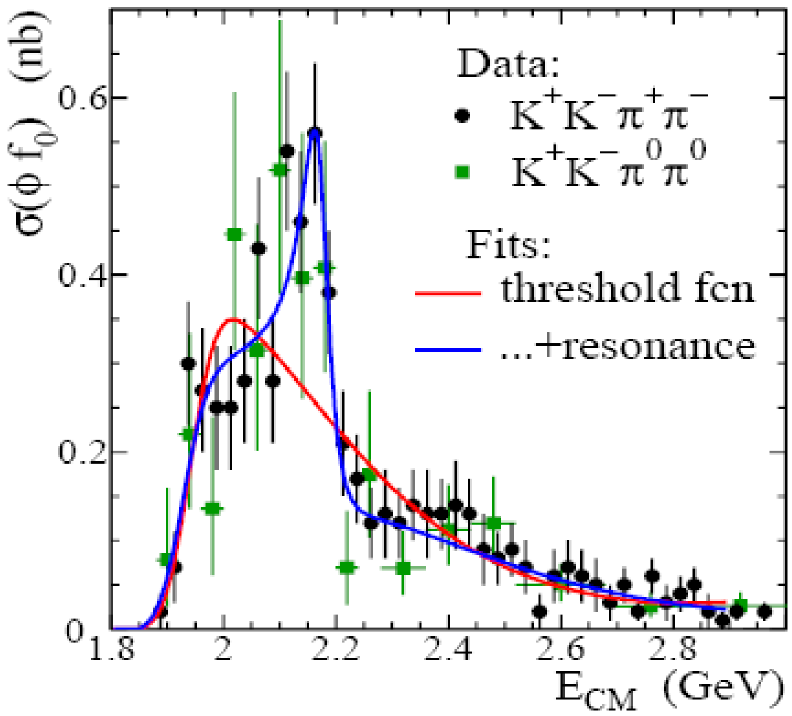
BaBar-ISR: new neutral meson state *Y(2175)* with $J^{PC} = 1^{--}$

PHOKHARA

$e^+ e^- \to Y(2175)\,\gamma \to \phi\, f_o(980)\,\gamma$

$M = 2175 \pm 10 \pm 15\ MeV$

$\Gamma = 58 \pm 16 \pm 20\ MeV$

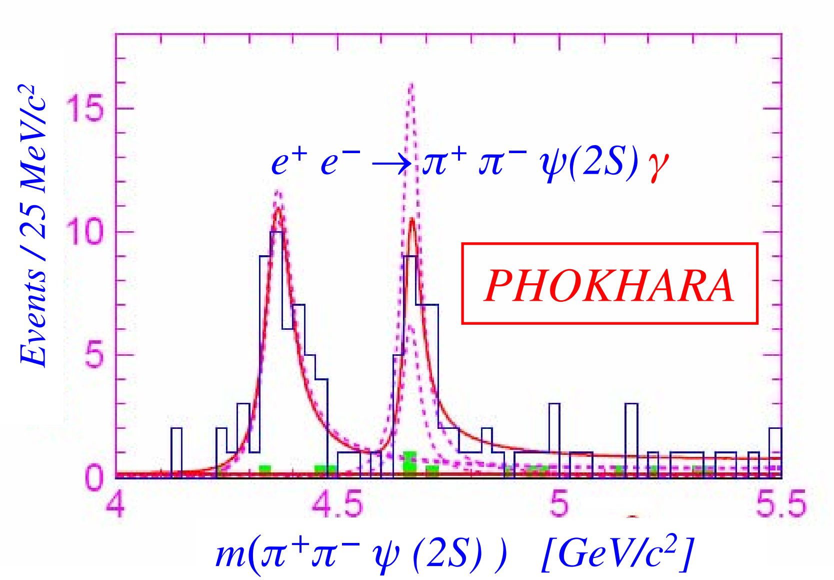


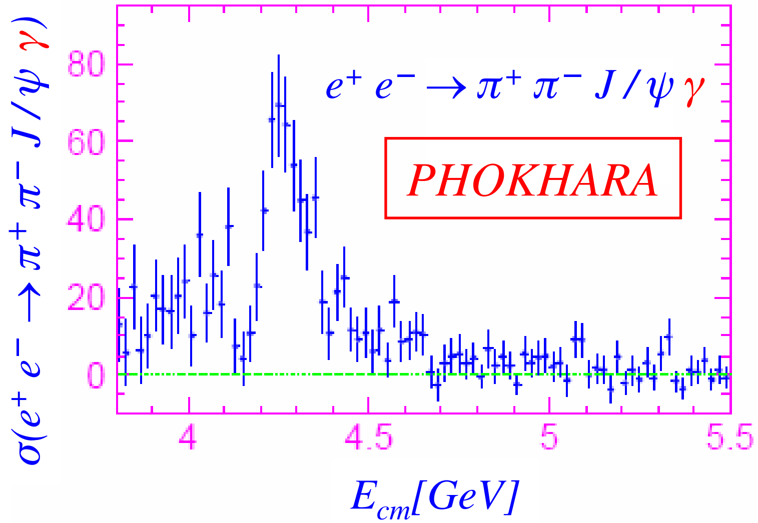
- a new state ?
- to be interpreted as a "strange" partner of *Y(4260)* with c-quark replaced by s-quark? or it is a $s\,s\,\bar{s}\,\bar{s}$-state?

Phys. Rev. **D 74** (2006) 091103, Shan Jin, Hadron07

Belle-ISR: New neutral meson states with $J^{PC} = 1^{--}$

Belle:	$M = 4080 \pm 40$ MeV	$\Gamma = 226 \pm 44 \pm 87$ MeV
(BaBar)	$M = 4247 \pm 12$ MeV	$\Gamma = 108 \pm 19 \pm 10$ MeV
	$M = 4361 \pm 9 \pm 9$ MeV	$\Gamma = 74 \pm 15 \pm 10$ MeV
	$M = 4664 \pm 11 \pm 5$ MeV	$\Gamma = 48 \pm 15 \pm 3$ MeV





$e^+ e^- \to Y(4360,4660)\, \gamma \to \psi(2S)\, \pi^+ \pi^- \gamma$
distinct peaks at *4.36* and *4.66 GeV*

$e^+ e^- \to Y(4050, 4250)\, \gamma \to J/\psi\, \pi^+ \pi^- \gamma$
distinct peaks at *4.05* and *4.25GeV*

Phys. Rev. Lett. **99** (2007) 142002, hep-ex/07073699

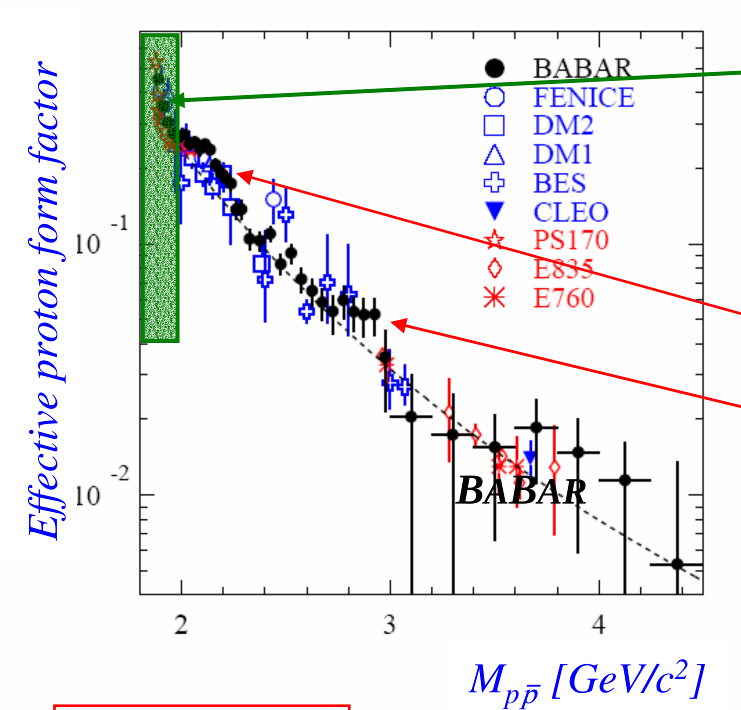
Phys. Rev. Lett. **99** (2007) 182004, hep-ex/07072541v2

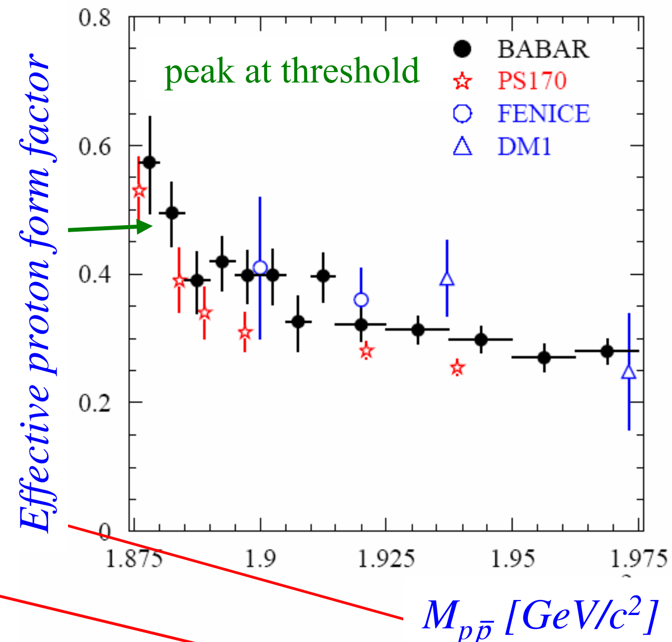
2.4. *BaBar-ISR*: Formfactors $e^+ e^- \to N\bar{N}\gamma$

$$\sigma(e^+e^- \to N\bar{N}\gamma) = \frac{4\pi\alpha^2\beta_N C}{3\, m^2_{p\bar{p}}}\left(|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right) \quad \beta_N = \sqrt{1 - \frac{4\, m_N^2}{m^2_{p\bar{p}}}} \quad \tau = \frac{m^2_{p\bar{p}}}{4 m_N^2}$$

C Coulomb correction factor

nontrivial structure observed:





thresholds (cusps) at *2.25 GeV* and at *3.0 GeV ?*

Phys. Rev. **D 73** (2006) 012005

PHOKHARA

→ talk of F. Maas

3. Summary and outlook

- *ISR* was originally thought to be an alternative (to energy scans) to determine hadronic cross sections from the reaction threshold up to the maximum centre of mass energy of fixed energy meson (ϕ, τ/*charm*, *B*) factories in order to determine the hadronic contribution to the muon magnetic anomaly and to the running fine structure constant $\alpha_{QED}(m_Z)$, and it was very successful in that respect

- But being more than a *poor man's* alternative to scan energies is turned out to be an extremely competitive tool to clarify reaction mechanisms and to reveal substructures (intermediate states and their decay mechanisms) leading to hadronic final states

- Finally it opened a totally new and unexpected access to highly excited states (with $J^{PC} = 1^{--}$) the structure of many of them is still to be determined

Again my personal remark:

While being discussed since the sixties/seventies *ISR* became a powerful tool for the analysis of experiments in low and intermediate energy hadron physics only with the development of *EVA/PHOKHARA*, a series of codes which are user friendly, flexible and easily to implement into the software of the existing detectors.

Thanks to *Claudio Federici*, *LNF,* for the permission to use elements of the conference poster designed by him showing figures related to this talk and well known to the community of this conference in an artistically elaborated manner.