ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

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

G. Venanzoni LNF/INFN

Scattering and annihilation electromagnetic processes
Trento 18-22 February 2013

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 τ
- QCD sum rules and α_S
- Test of models and input to theory (ChPT, VDM, QCD,…)
- Spectroscopy, search of hybrids and glueballs
- Search for hypothetical light gauge bosons
- …

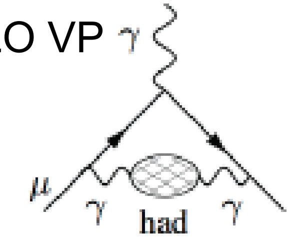
Muon anomaly

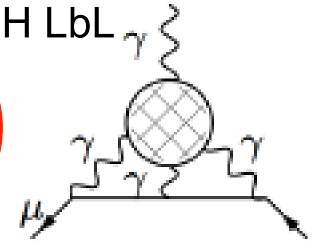
$$a_\mu = \frac{(g_\mu - 2)}{2}$$

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

•Theoretical error δa_μ^{SM} (~6x10^{-10}) dominated by HLO VP (4÷5x10^{-10}) and HLbL ([2.5÷4]x10^{-10}).
A **twofold** improvement on δa_μ^{SM} from 2001 (thanks to new e^+e^- measurements)!

•Experimental error δa_μ^{EXP} ~6 x10^{-10}(E821).
Plan to reduce it to 1.5 10^{-10} by the new g-2 experiments at FNAL and J-PARC.





a_μ^{HLO} = (690.9±**4.4**)10^{-10}
[Eidelman, TAU08]

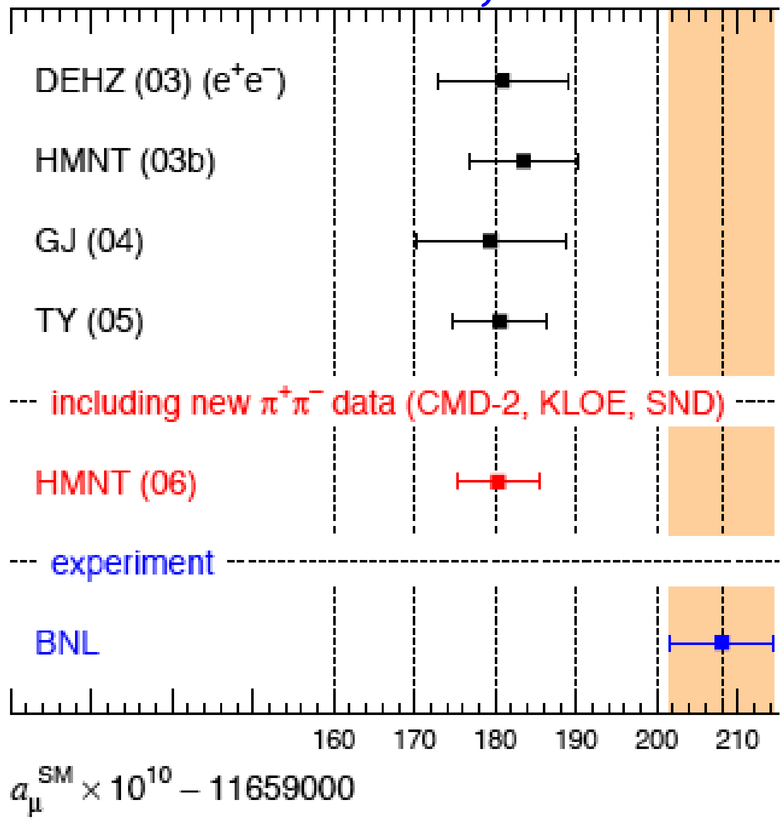
δa_μ^{HLO} ~0.7%

a_μ^{HLbL} =(10.5±2.6)10^{-10}
[Prades, dR&V. 08]
(11 ±4)10^{-10} (Jegerlehner, Nyffler)

δa_μ^{HLbL} ~25-40%

a_μ^{SM} compared to BNL world av.

T.Teubner, PHIPSI08

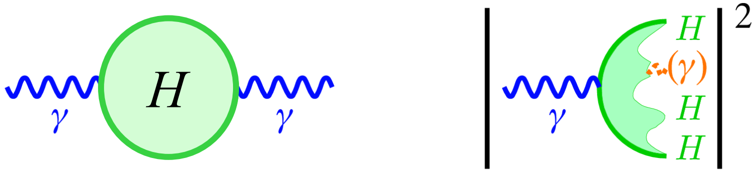


$$a_\mu^{EXP} - a_\mu^{TH} = (27.6 \pm 8.1) \cdot 10^{-10}, \ \sim 3.4\sigma$$

In 2001 a_μ^{EXP}-a_μ^{TH}=(23±16)•10^{-10}

a_μ^{HLO}:

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



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

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

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

in the range < 1 GeV contributes to 70% !

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

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

Input:

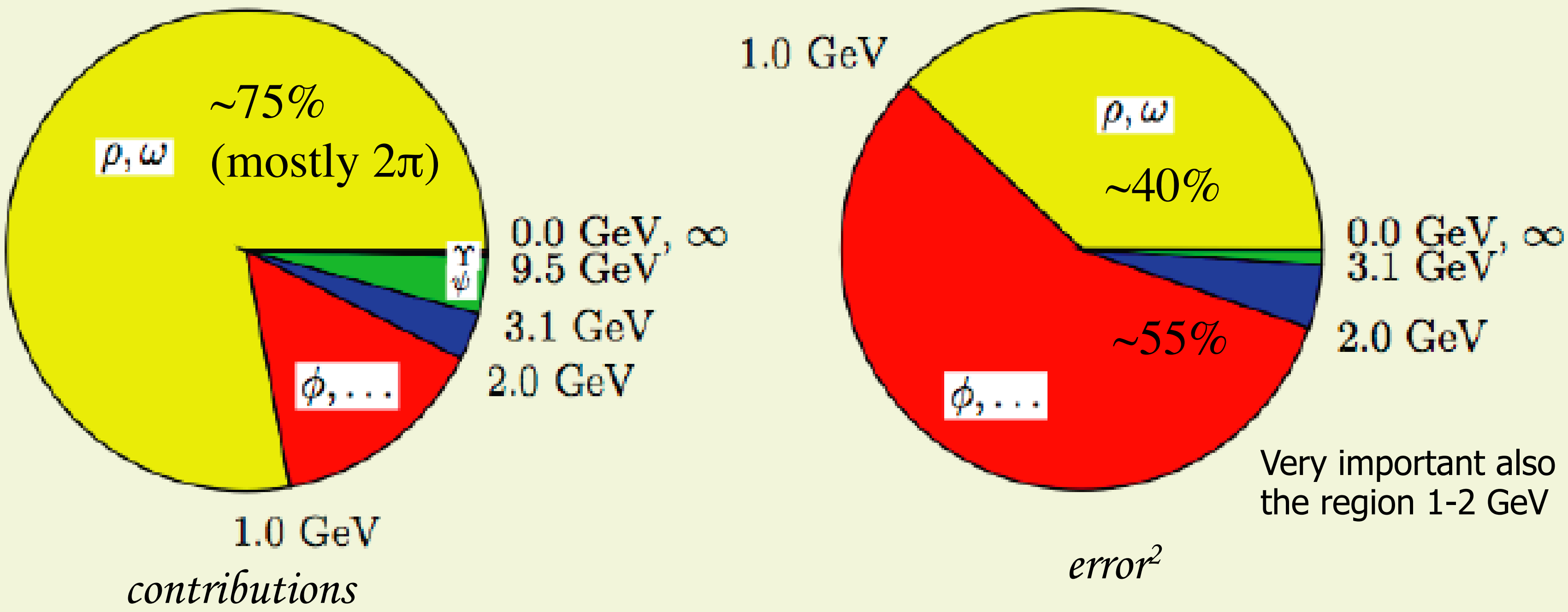
a) hadronic electron-positron cross section data (G.dR 69, E.J.95, A.D.H.'97,….)

b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections) (A., D., H. '97)

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_μ^{HLO}

F. Jegerlehner, Talk at PHIPSI08



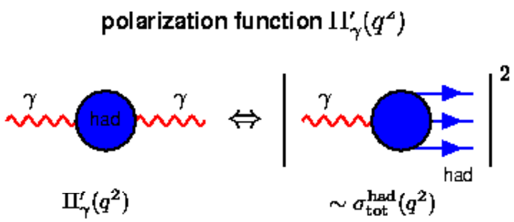
Experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{had}!
→ Needs precision measurements!

$\delta a_\mu^{exp} \rightarrow 1.5\ 10^{-10} = 0.2\%$ on a_μ^{HLO}
New g-2 exp.

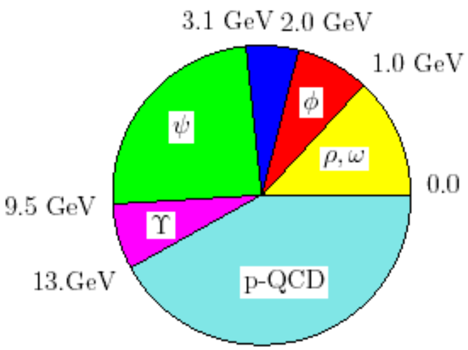
$\alpha_{em}(M_Z)$ and EW fit of the SM (M_{Higgs})

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

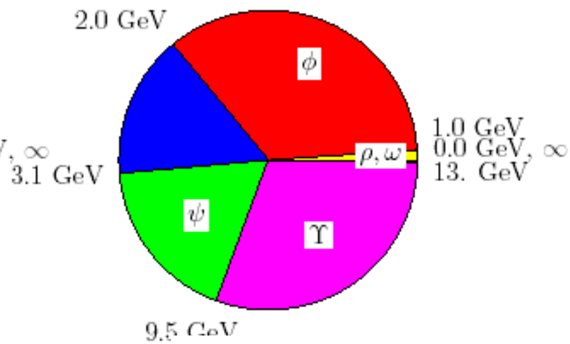
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$



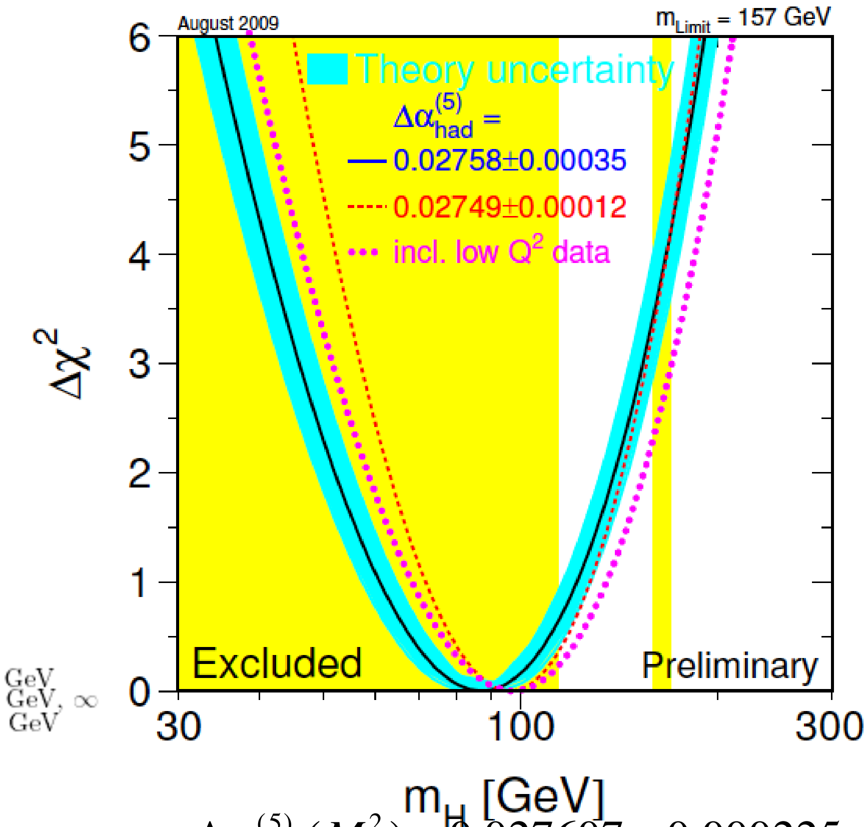
$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$



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



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



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

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

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

FJ08

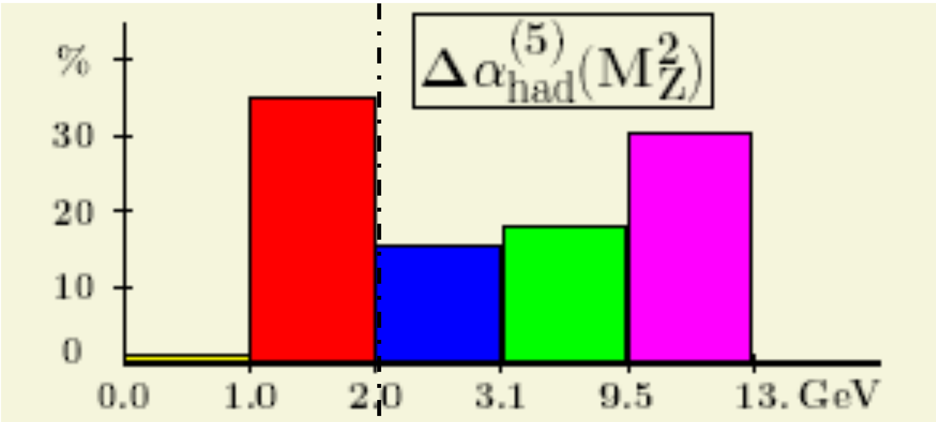
$\delta\alpha(M_Z)/\alpha(M_Z) \sim 2\times10^{-4} \rightarrow 5\times10^{-5}$

Requirement from ILC (6x improvement)

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

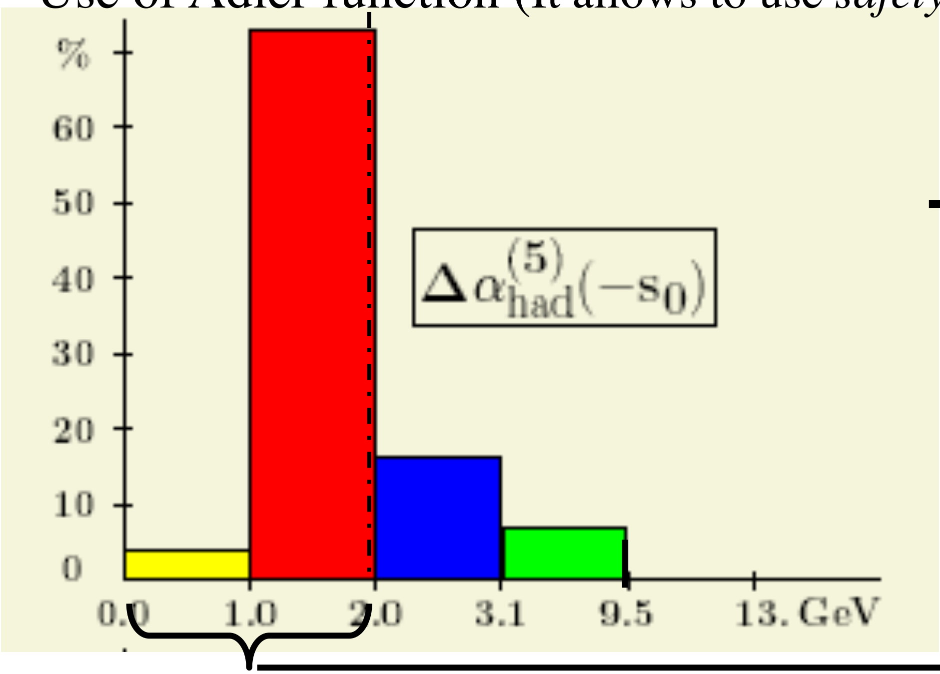
Direct integration of energy points

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



$\delta\sigma$ at 1% in the region **√s < 10 GeV**
⇒ 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<√s < 2.5 GeV
⇒ improvement of ~5 on $\delta\alpha(M_Z)$

$2m_\pi$<√s < 2 GeV
Extremely important:
- **80%** of $\delta\Delta\alpha^{(5)}_{had}$ (using Adler function)
- **95%** of δa_μ

Cross section data:

Two approaches:

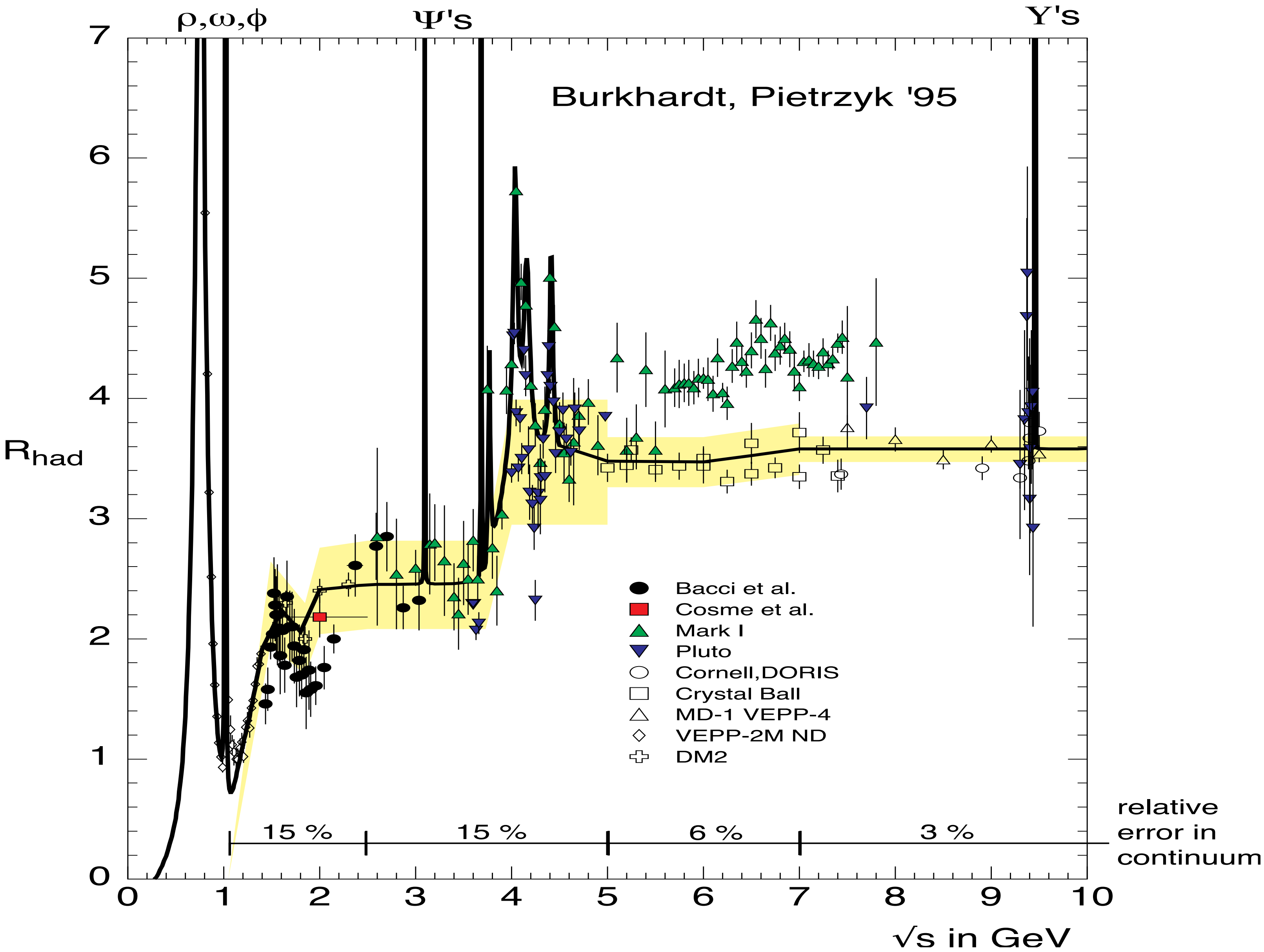
Energy scan (CMD2, SND, BES,CLEO):

- 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?):

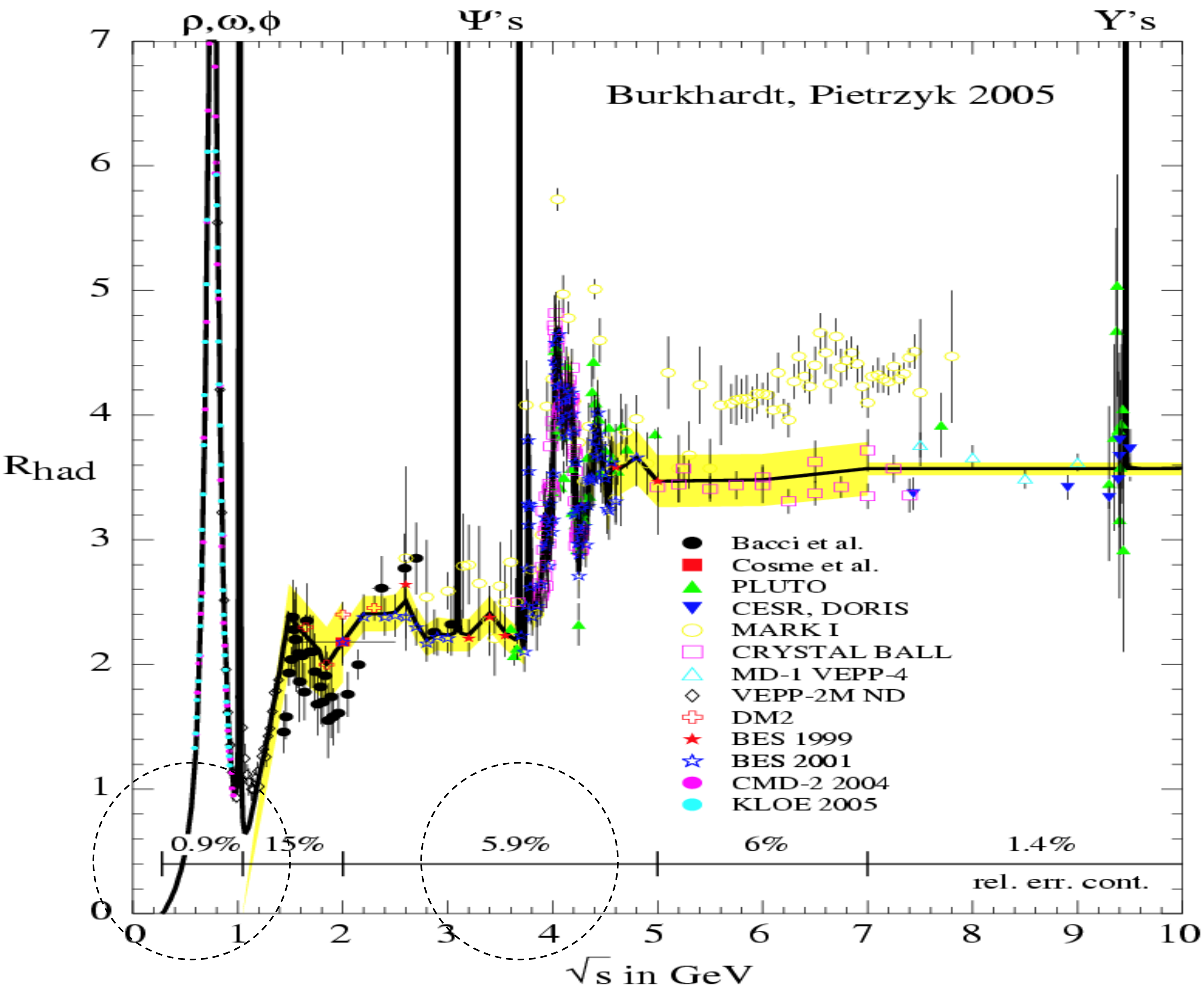
- runs at fixed-energy machines (meson factories)
- use initial state radiation process to access lower lying energies or resonances
- data come as by-product of standard physics program
- requires precise theoretical calculation of the radiator function
- luminosity and beam energy enter only once for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

Data at '95



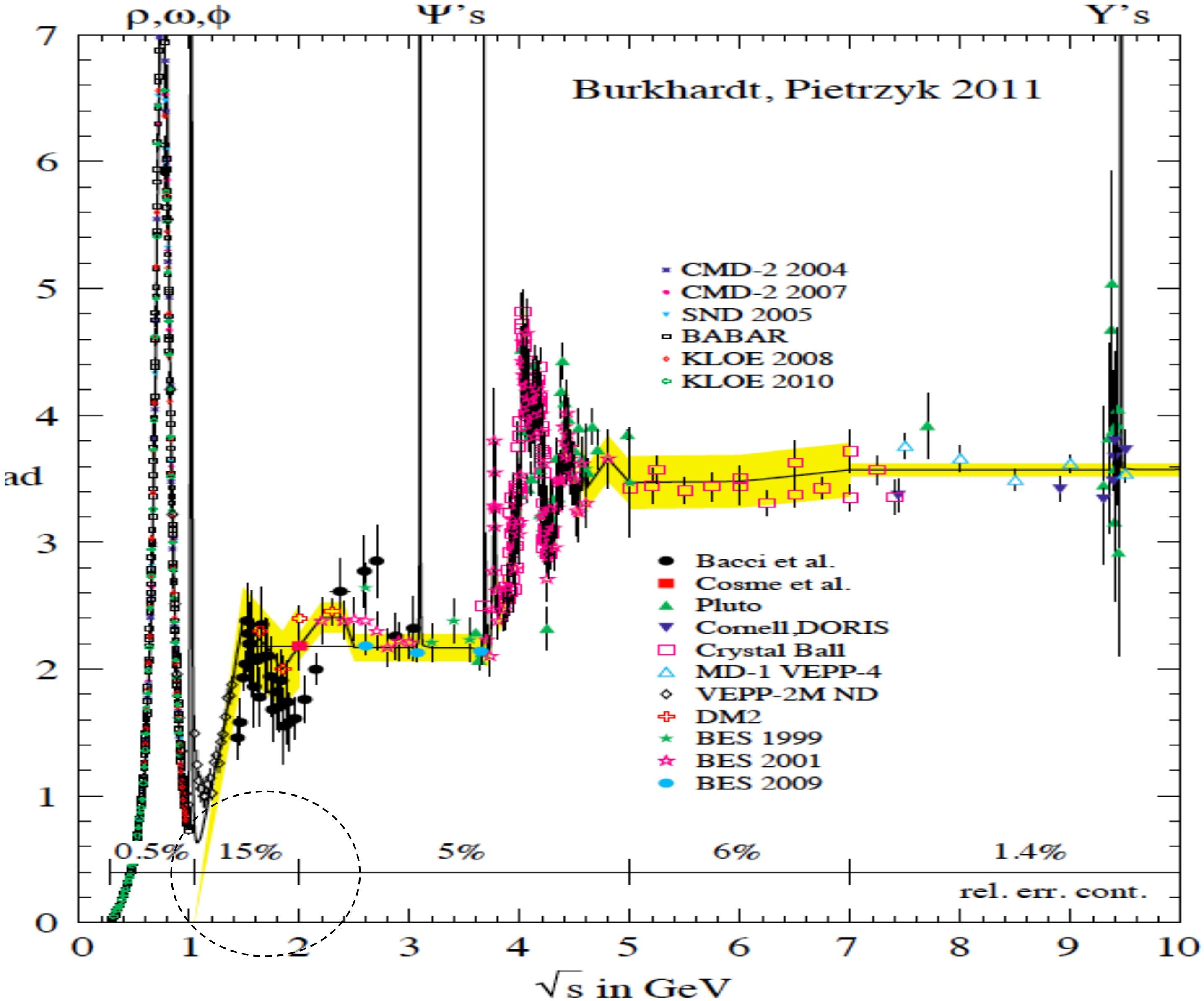
ρ,ω,ϕ
Ψ's
Υ's
Burkhardt, Pietrzyk '95
Rhad
√s in GeV
Bacci et al.
Cosme et al.
Mark I
Pluto
Cornell,DORIS
Crystal Ball
MD-1 VEPP-4
VEPP-2M ND
DM2
15 %
15 %
6 %
3 %
relative
error in
continuum
0
1
2
3
4
5
6
7
8
9
10

Data at '05



ρ,ω,φ
Ψ's
Υ's
Burkhardt, Pietrzyk 2005
Rhad
√s in GeV
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.

Data at '11

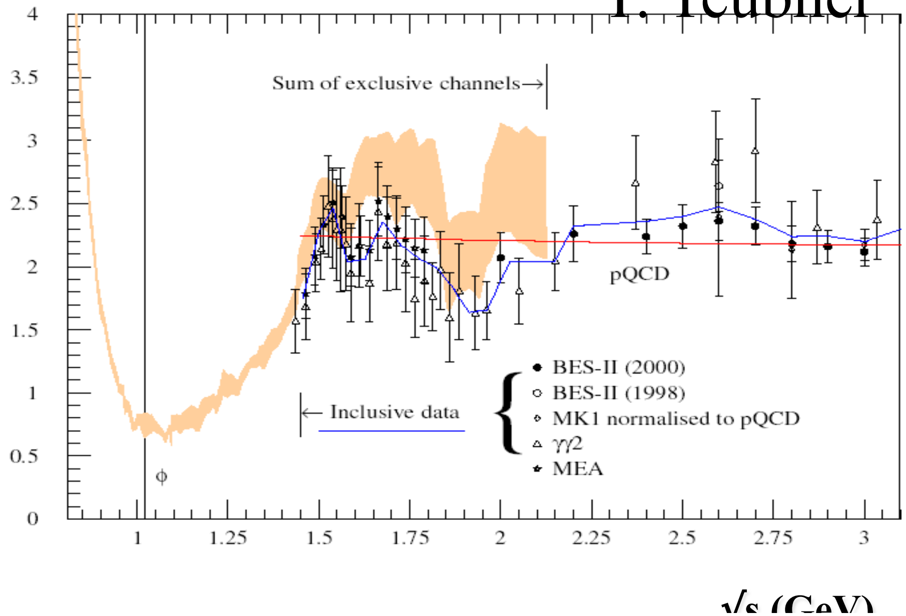


ρ,ω,φ
Ψ's
Y's
Burkhardt, Pietrzyk 2011
CMD-2 2004
CMD-2 2007
SND 2005
BABAR
KLOE 2008
KLOE 2010
Bacci et al.
Cosme et al.
Pluto
Cornell,DORIS
Crystal Ball
MD-1 VEPP-4
VEPP-2M ND
DM2
BES 1999
BES 2001
BES 2009
0.5%
15%
5%
6%
1.4%
rel. err. cont.
ad
√s in GeV

Exclusive vs inclusive measurements?

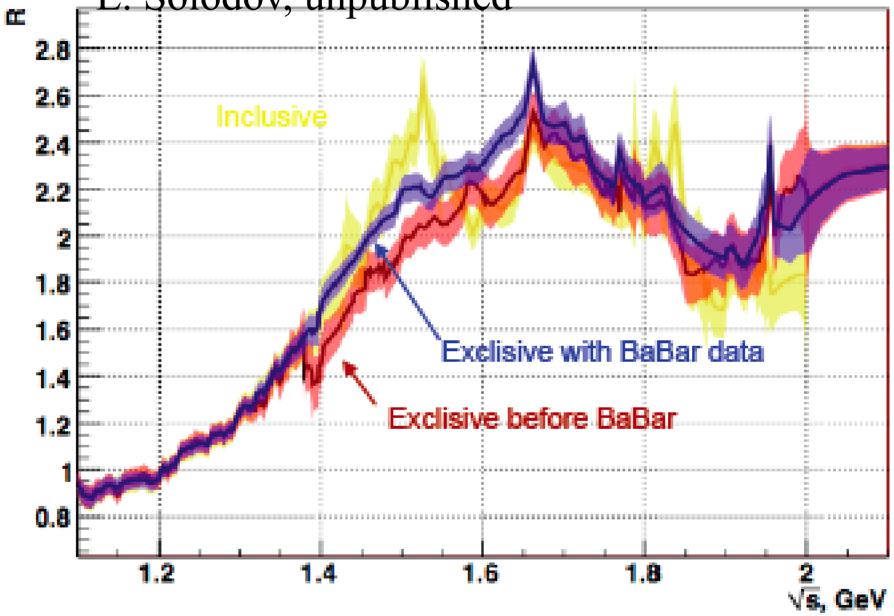
1) Most recent inclusive measurements: MEA and B antiB, with **total** integrated luminosity of **200 nb^{-1}** (one hour of data taking at 10^{32} cm^{-2} sec-1).**10% stat.+ 15% syst. Errors**

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!)

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

- $\sigma_{\text{dressed}} = \frac{N}{\int Ldt \ \varepsilon \ (1+\delta_{\text{ISR}})}$
- $\Pi(s) = \Pi_{\text{lep}}(s) + \Pi_{\text{had}}(s)$

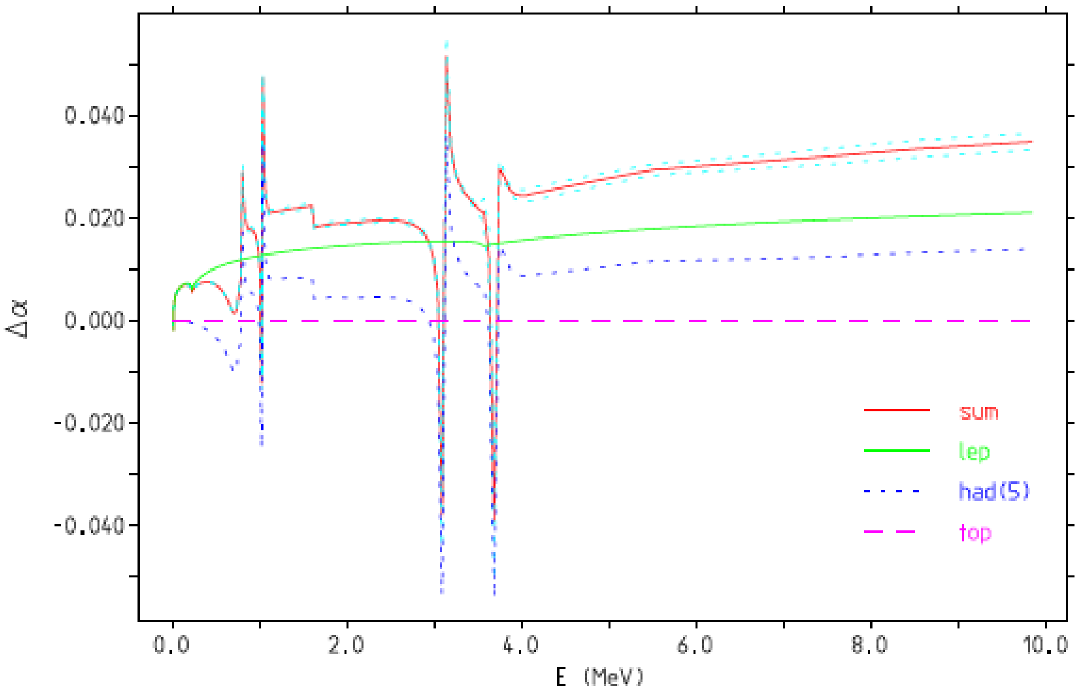


Figure from Fred Jegerlehner

A common effort for RC and Monte Carlo tools

Eur. Phys. J. C (2010) 66: 585–686
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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 11-12 April 2013, ECT*)

"Old" Results on R from energy scan at $\sqrt{s}$<10 GeV

Place	*Ring*	*Detector*	*E_{cm}(GeV)*	*pts*	*Year*
Novosibirsk	VEPP-2M VEPP-2	CMD2,SND Olya,ND,CMD	<1.4 <1.4	128	**01-03** 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, 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 PLUTO C.Ball LENA	3.1-5.2 3.6-4.8,9.46 5.0-7.4 7.4-9.4	64 27 11 95	'79 '77 '90 '82
Novosibirsk	VEPP-4	MD-1	7.23-10.34	30	'91

Recent Results with ISR

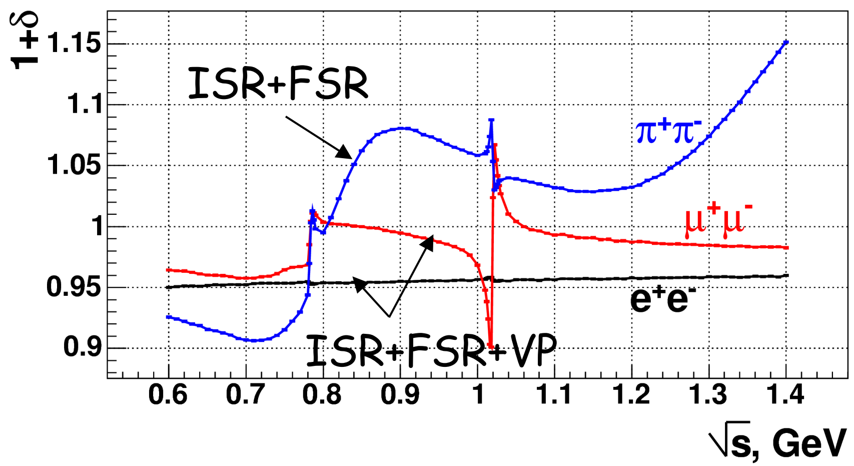
Place	*Ring*	*Detector*	*E_{cm}(GeV)*	*pts*	*Year*
Frascati	DAΦNE	KLOE	<1 GeV		'05-08-10
SLAC	PEPII	BaBar	<5 GeV		'05-10…
Tsukuba	KEKB	Belle	<5 GeV		'08-10…

New Results 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?)		'12
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 $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$ (σ_{syst}~7%), $e^+e^- \to \pi^+\pi^-\pi^0$ (σ_{syst}~12%), $e^+e^- \to K_S, K_L$, $e^+e^- \to \omega\pi^+\pi^-, \eta\pi^+\pi^-$ (σ_{syst}~15%) from CMD2 and SND
  - $e^+e^- \to \pi^+\pi^-$ from CMD2 with σ_{syst}~1.% (σ_{syst}~0.6% in 0.61<E<0.96 GeV)
  - $e^+e^- \to \pi^+\pi^-$ from SND with σ_{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

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

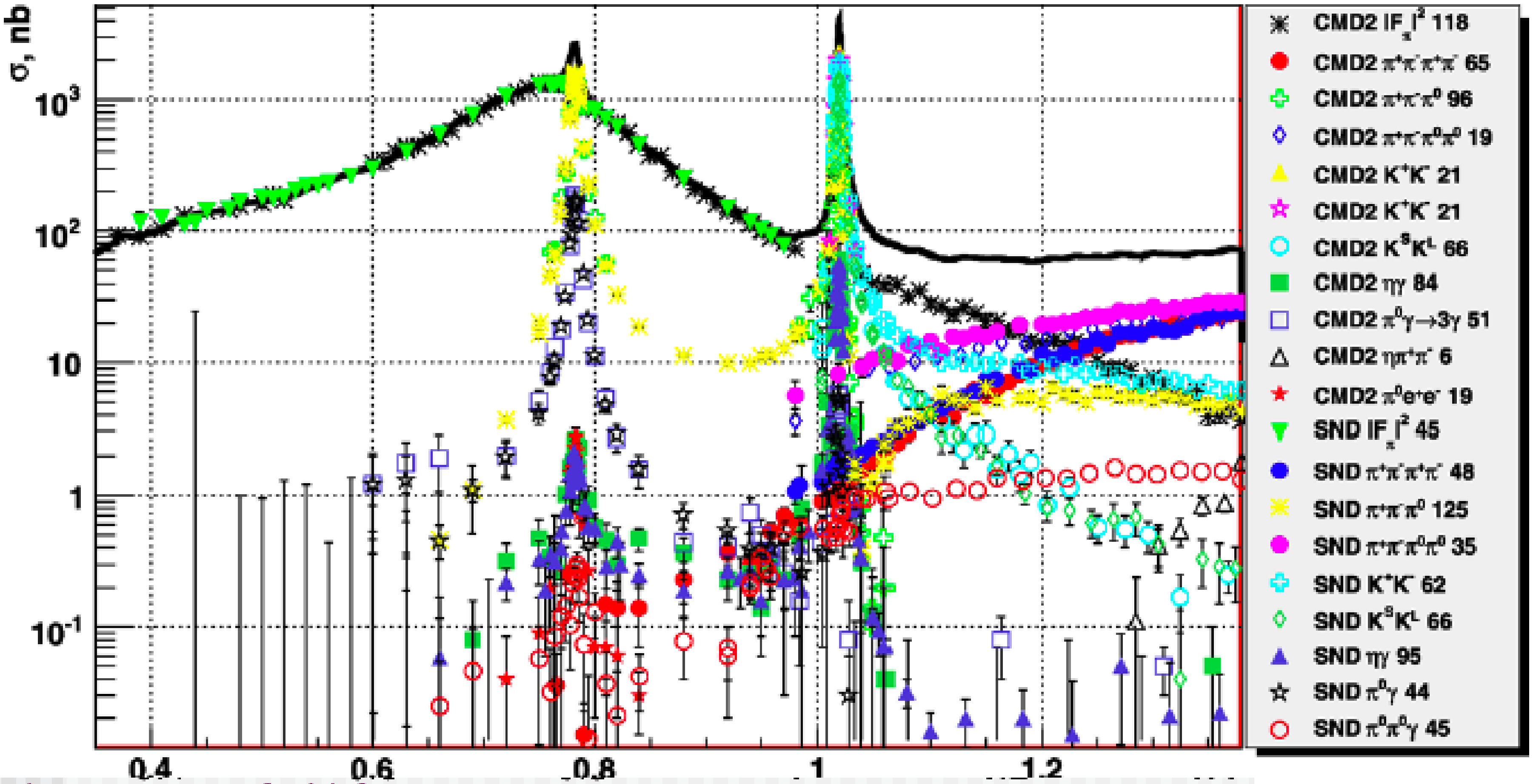
- Luminosity L is measured using Bhabha scattering at large angles
- Efficiency ε is calculated via Monte Carlo + corrections for imperfect detector
- Radiative correction δ accounts for ISR effects only

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

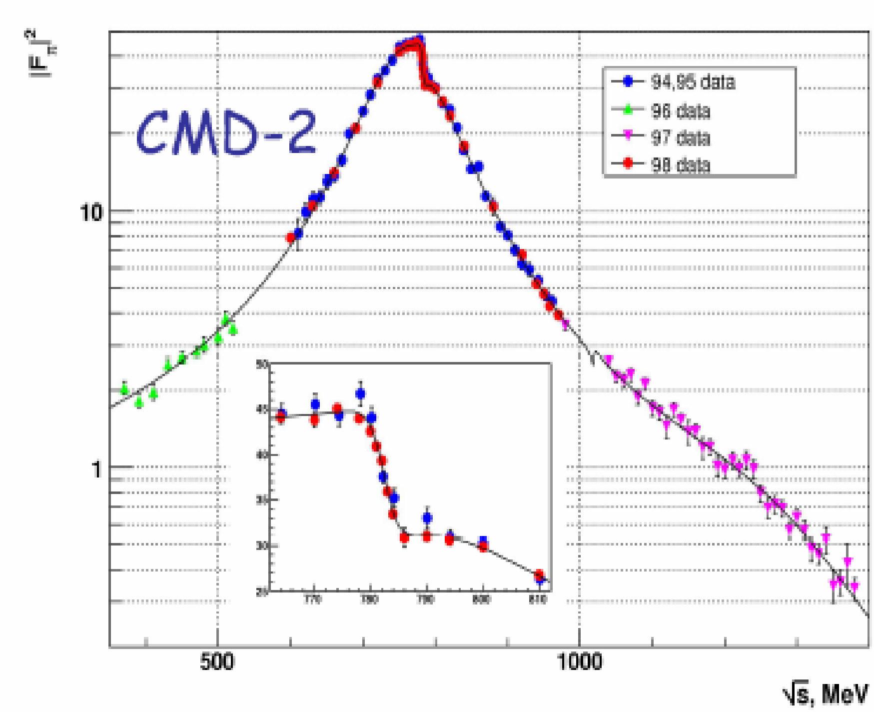
Measurement of exclusive channels with CMD-2/SND



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)

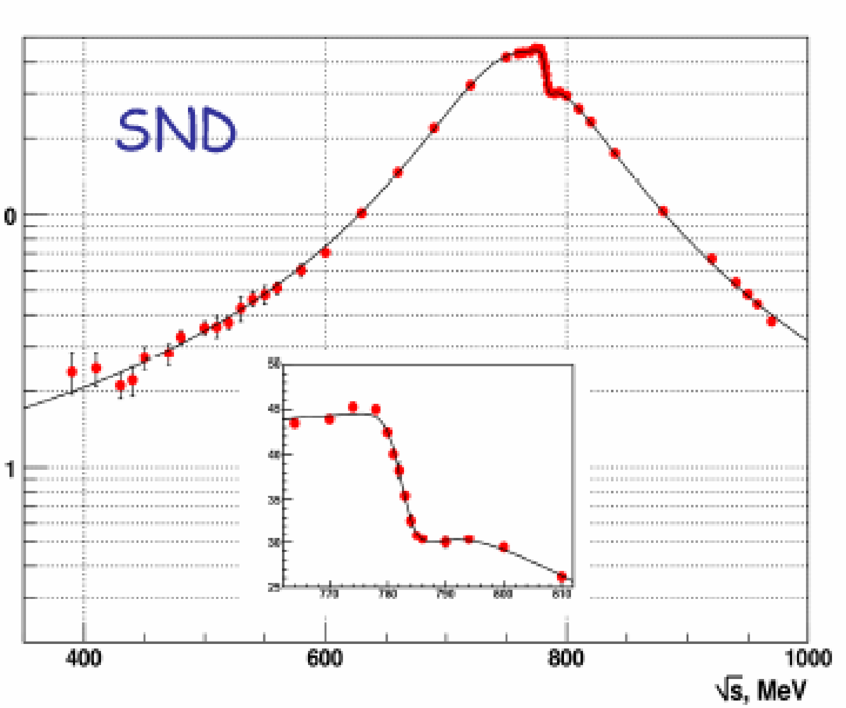


Systematic error

0.7% | 0.6% / 0.8% | 1.2-4.2%

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

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



Systematic error

3.2% | 1.3% | 8

Good agreement between the two spectra

R measurement at BESII

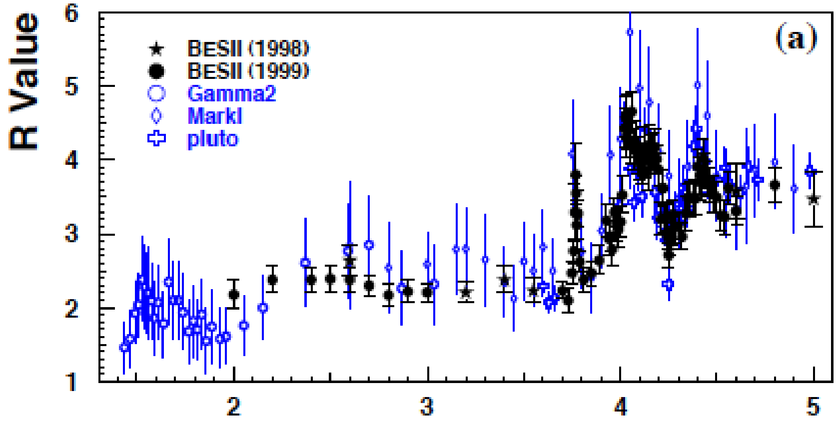
- BESII @ BEPC, Beijing (inclusive measurement) 2 <E_{cm}<5 GeV
  - 1998/99 new result of R in 2 <E_{cm}<5 GeV from BESII, 91 points with σ_R/R~7% (improvement of a factor **2**)

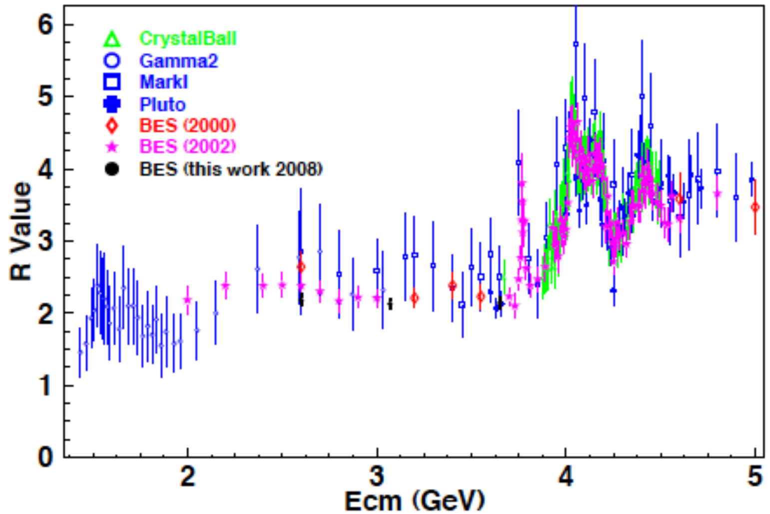
  2008: 3 points (2.6, 3.07 and 3.65 GeV) with 3.5% precision

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

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

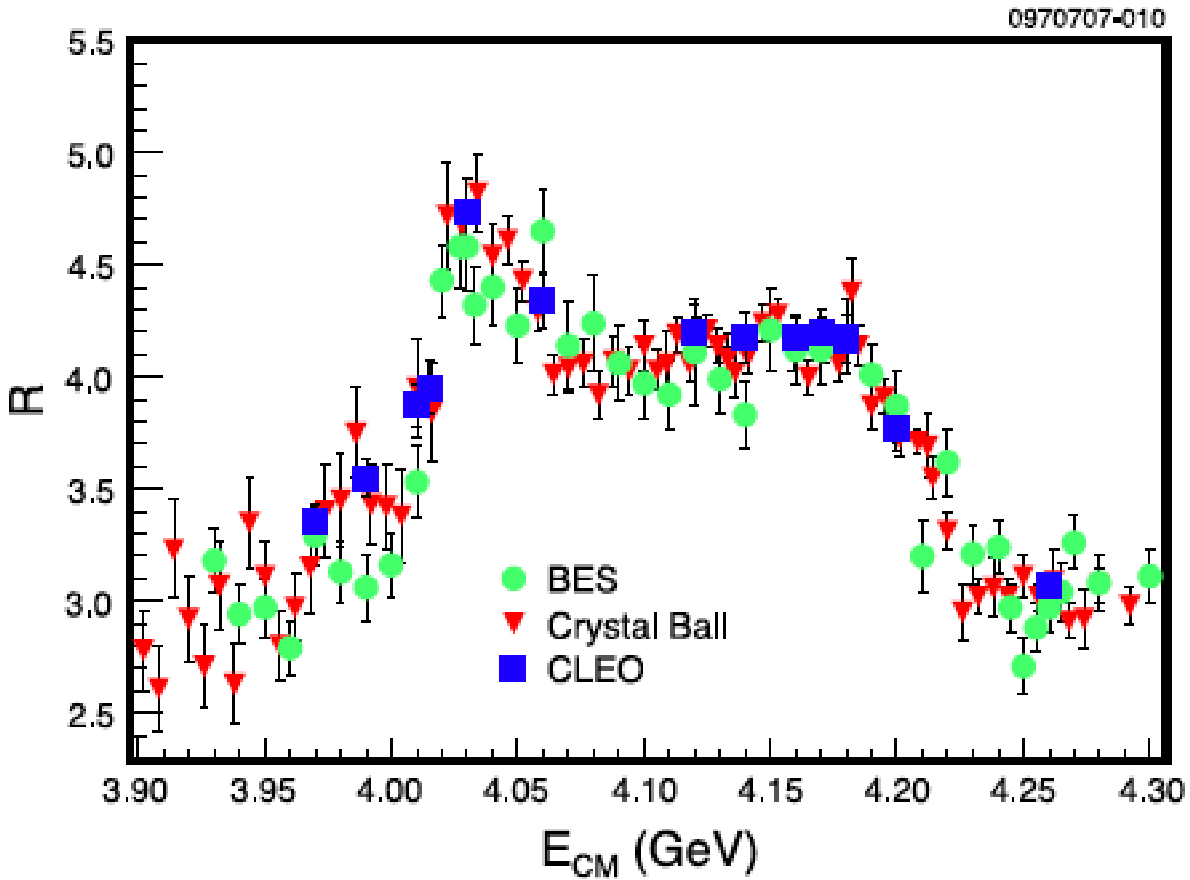




R measurement at CLEO

- 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 δ_{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	$3.06 \pm 0.02 \pm 0.04$



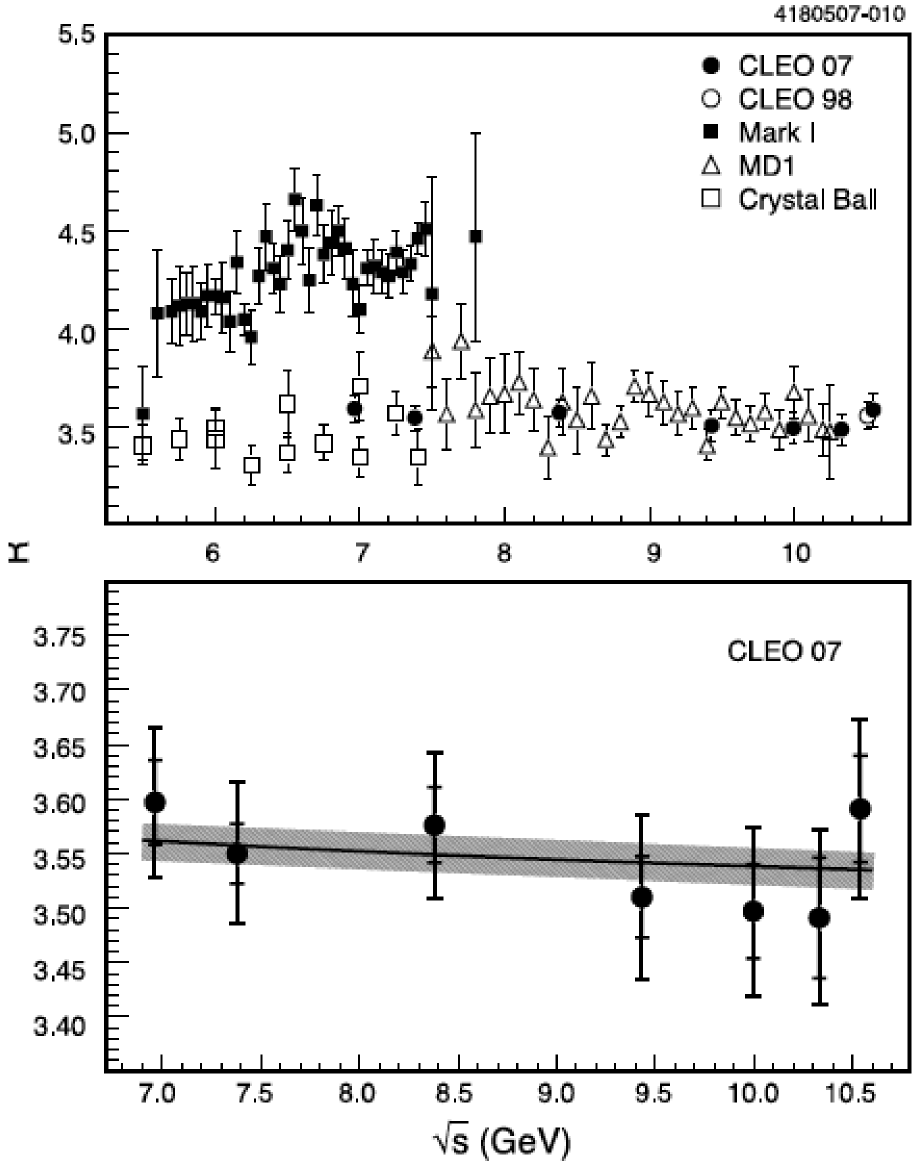
R measurement at CLEO

- 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)

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

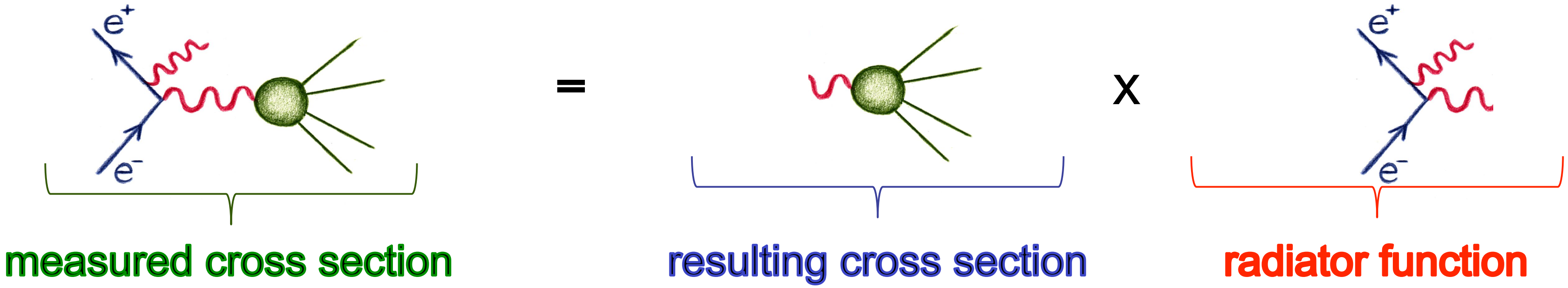
ε(1+δ)	1%
L	1%
Bckg/Hadr Modeling	0.7%
Dataset variation	0.3%
TOTAL	**1.8%**



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

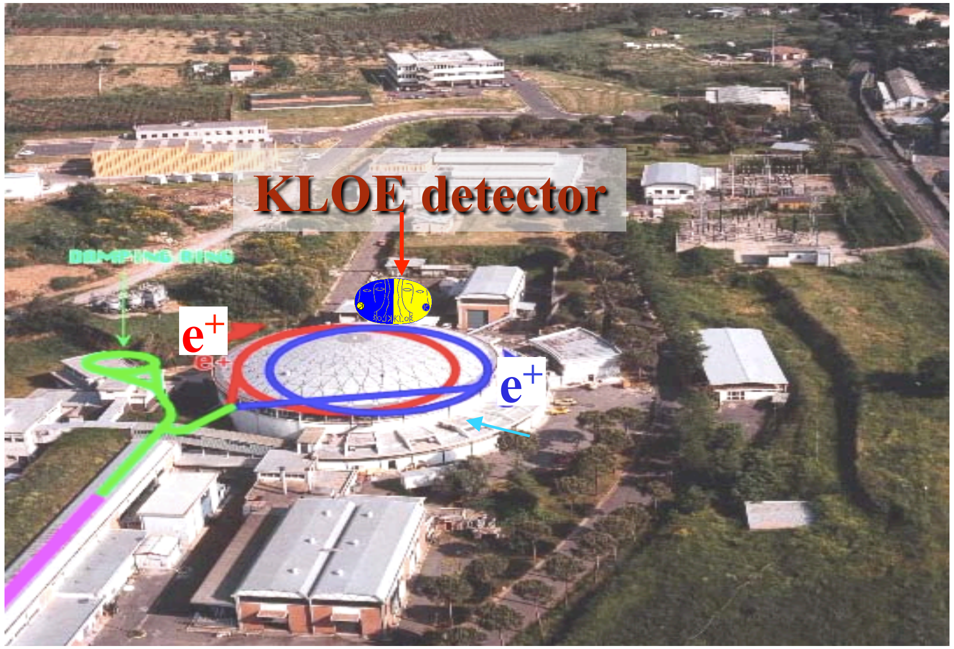
(exact next-to-leading order QED calculation of the radiator function)

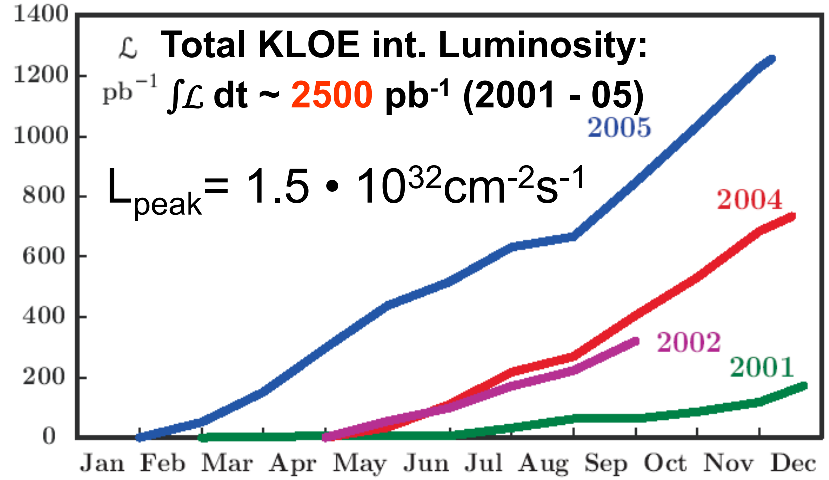
IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^-\to\pi^+\pi^-)$ with ISR using 2001 data ($140 pb^{-1}$) PLB606(2005)12 $\Rightarrow$ ~3σ discrepancy btw a_μ^{SM} and a_μ^{exp}

DAΦNE: A Φ-Factory in Frascati (near Rome)

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

Integrated Luminosity





2006

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

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

KLOE10 measurement (PLB700 (2011) 102) based on 233 pb^{-1} of 2006 data (at 1 GeV, different event selection)

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

NEW: KLOE12 measurement (submitted to PLB) based on 240 pb^{-1} of 2002 data from $\pi\pi\gamma/\mu\mu\gamma$ ratio

KLOE result (KLOE08)

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

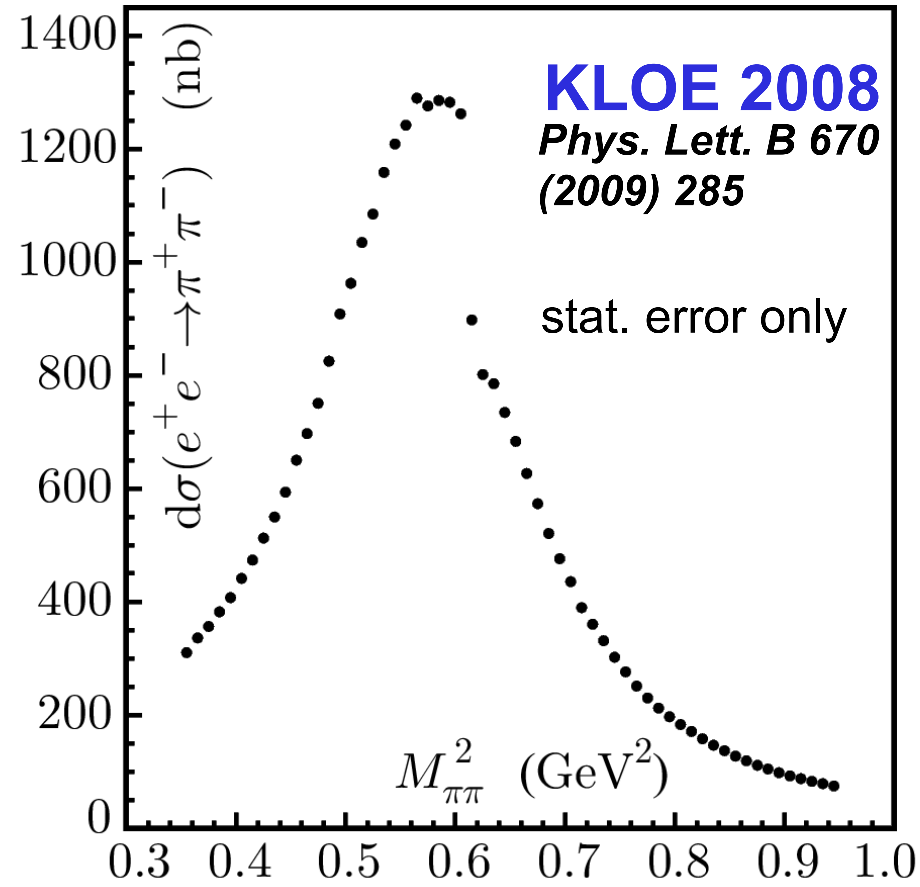
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
p/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ([illegible]$_{\pi\pi}$)	0.1%
Acceptance ([illegible])	negligible
Unfolding	negligible
Software Trigger	0.1%
√s dep. Of H	0.2%
Luminosity$(0.1_{th} \oplus 0.3_{exp})$%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

experimental fractional error on a_μ = 0.6 %

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

theoretical fractional error on a_μ = 0.6 %

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



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

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

KLOE10 result: Pion Form Factor

arXiv:1006.5313

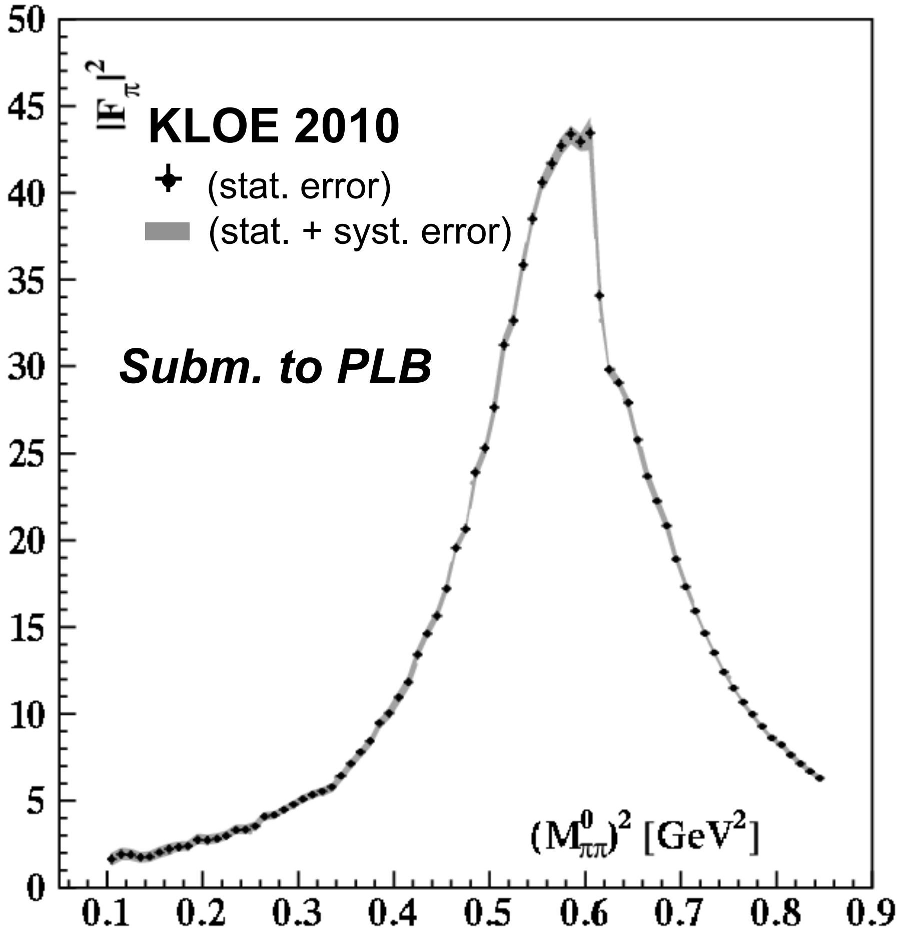


Table of systematic errors on a_m^{pp}(0.1-0.85 GeV^2):

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

experimental fractional error on a_μ = 1.0 %

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

theoretical fractional error on a_μ = 0.6 %

Disp. Integral:

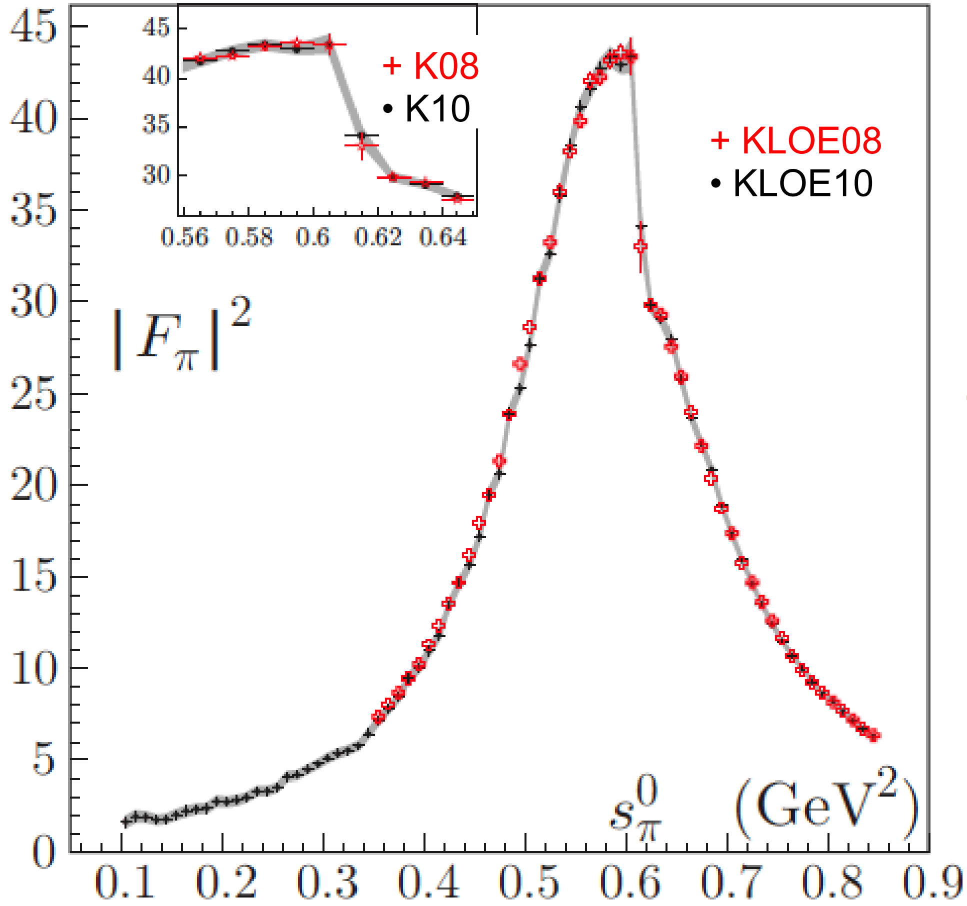
$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

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

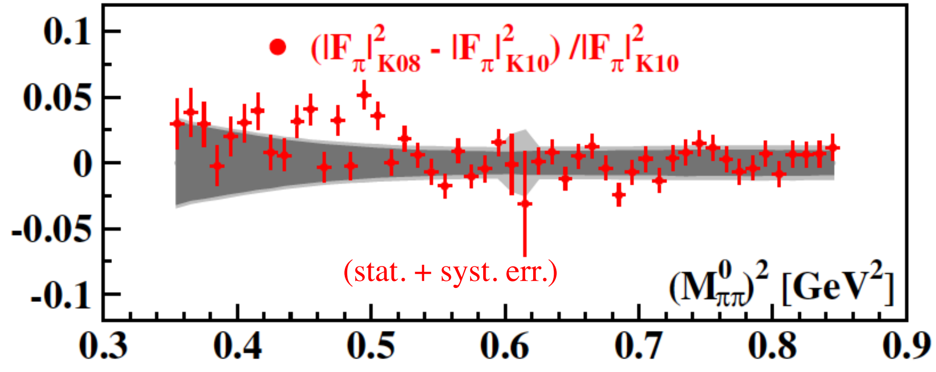
0.4% 1.0% 0.6%

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

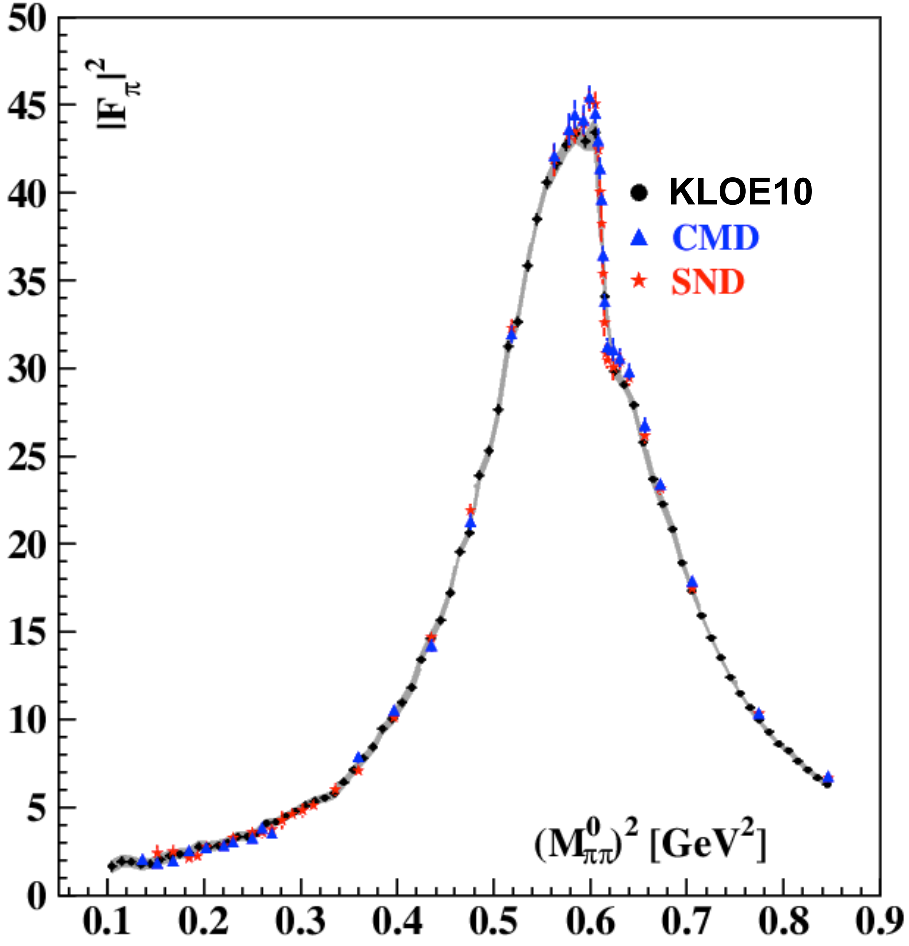
Combination of KLOE08 and KLOE10:

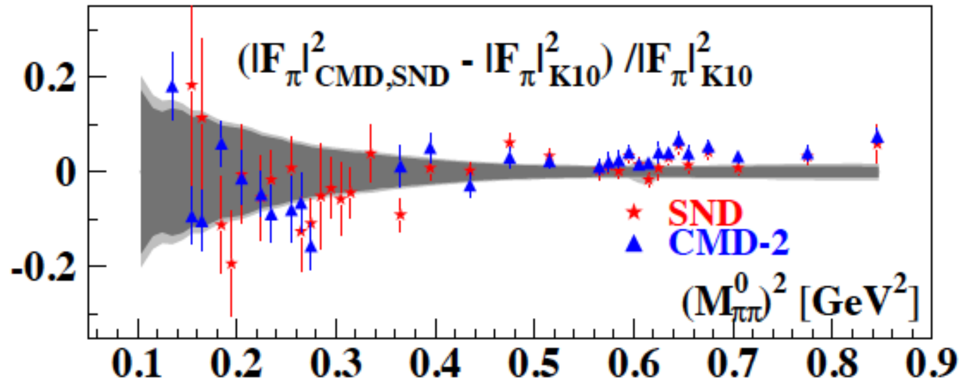
$a_\mu^{\pi\pi}(0.1\text{-}0.95\ \text{GeV}^2) = (488.6 \pm 5.0) \cdot 10^{-10}$

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

Comparison of results: KLOE10 vs CMD-2/SND

CMD and SND results compared to KLOE10: Fractional difference



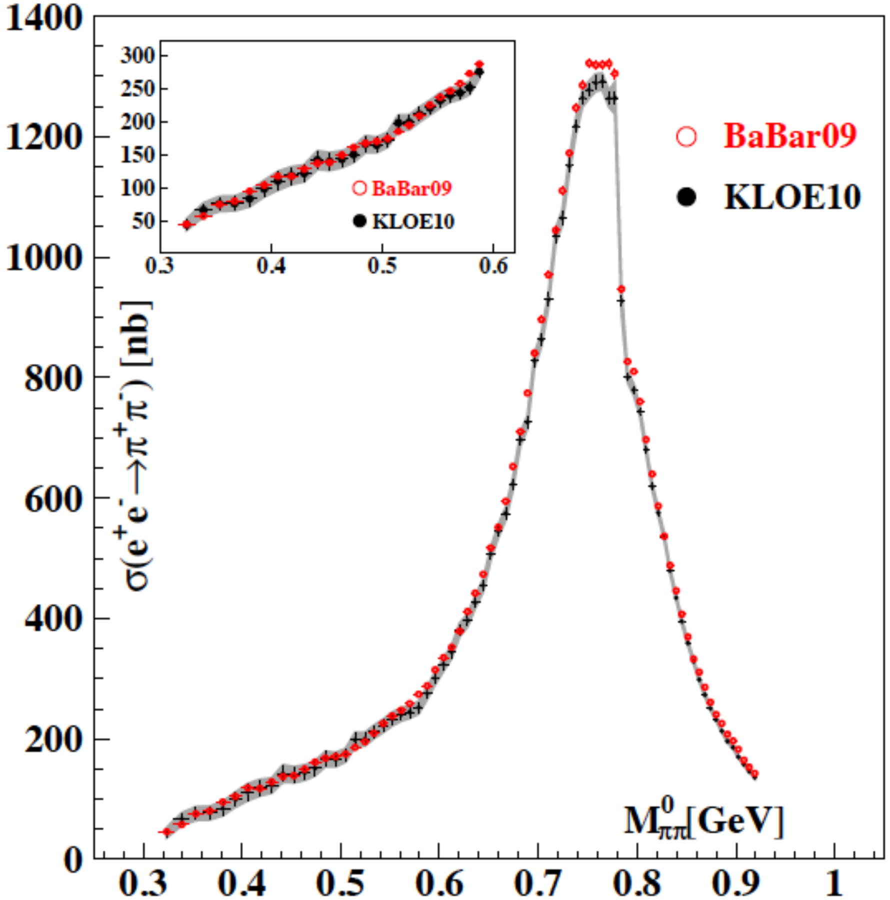


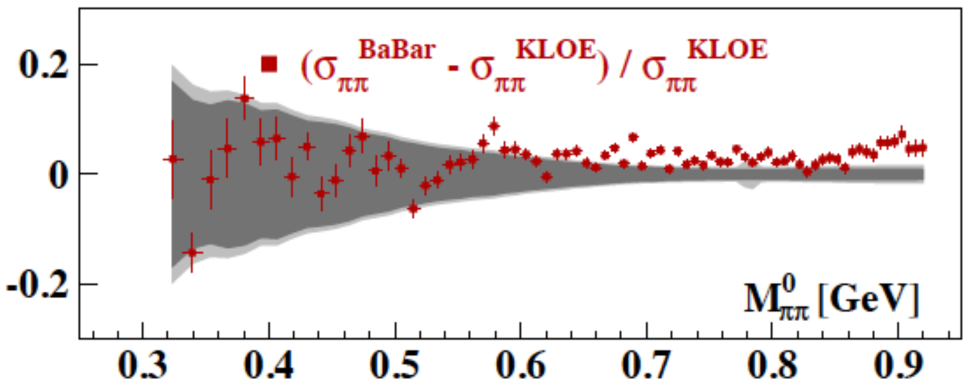
band: KLOE10 error

Below the ρ peak good agreement with CMD-2/SND.
Above the ρ peak KLOE10 slightly lower (as KLOE08)

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference





band: KLOE10 error

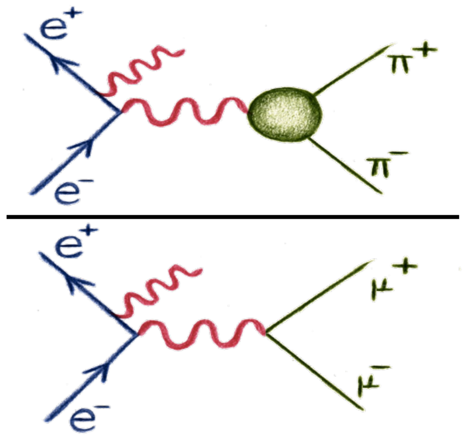
Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above

New $\sigma_{\pi\pi}$ measurement from $\pi\pi\gamma/\mu\mu\gamma$

An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

$$|F_\pi(s')|^2 \approx \frac{4(1+2m_\mu^2/s')\beta_\mu}{\beta_\pi^3} \frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

kinematical factor (s_{mm}^{Born} / s_{pp}^{Born}) — meas. quantities



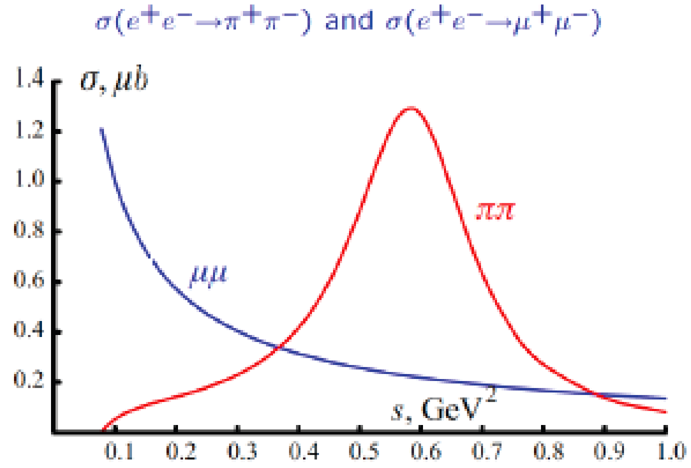
Many radiative corrections drop out:

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

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

- *muons:* $M_{Trk} < 115$ *MeV*
- *pions :* $M_{Trk} > 130$ *MeV*

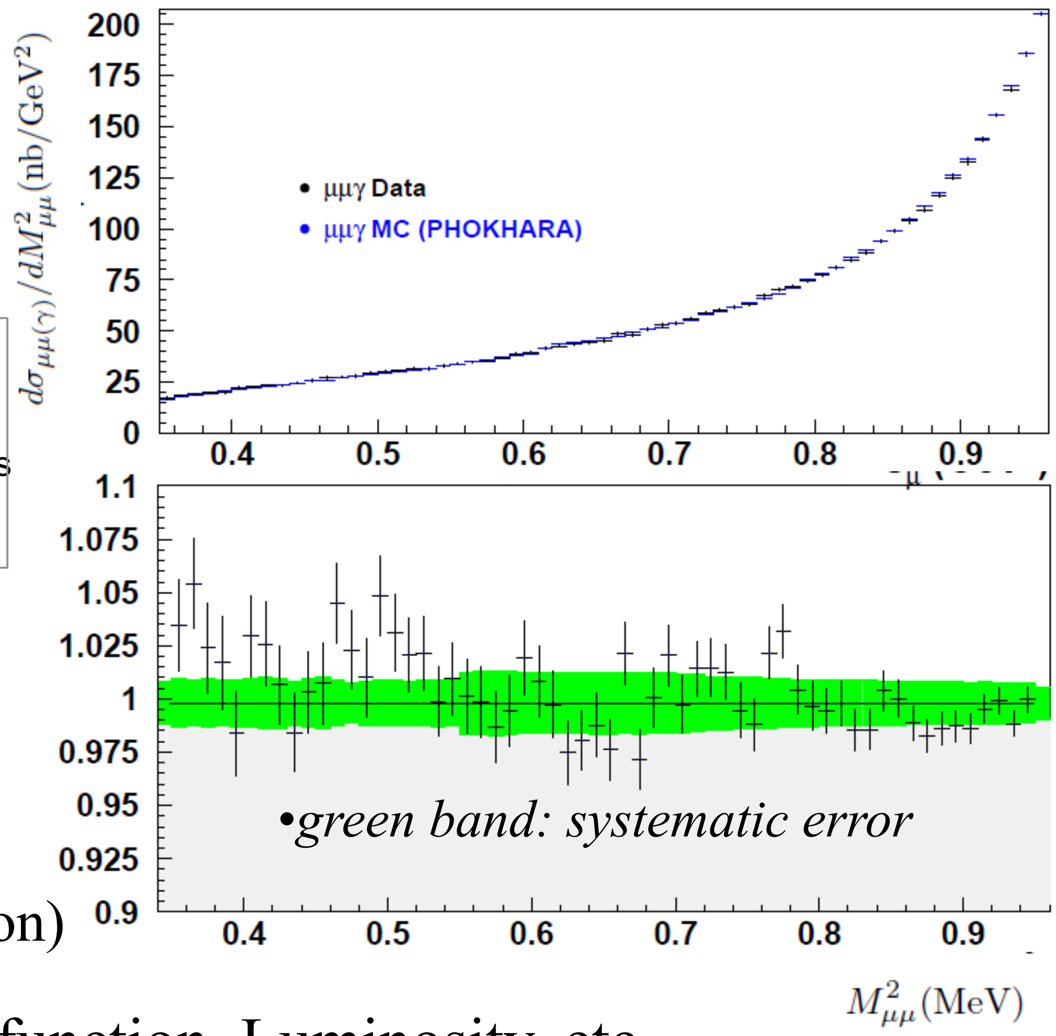
Very important control of π/μ separation in the ρ region! ($\sigma_{\pi\pi} >> \sigma_{\mu\mu}$)



μμγ cross section: data/MC comparison

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

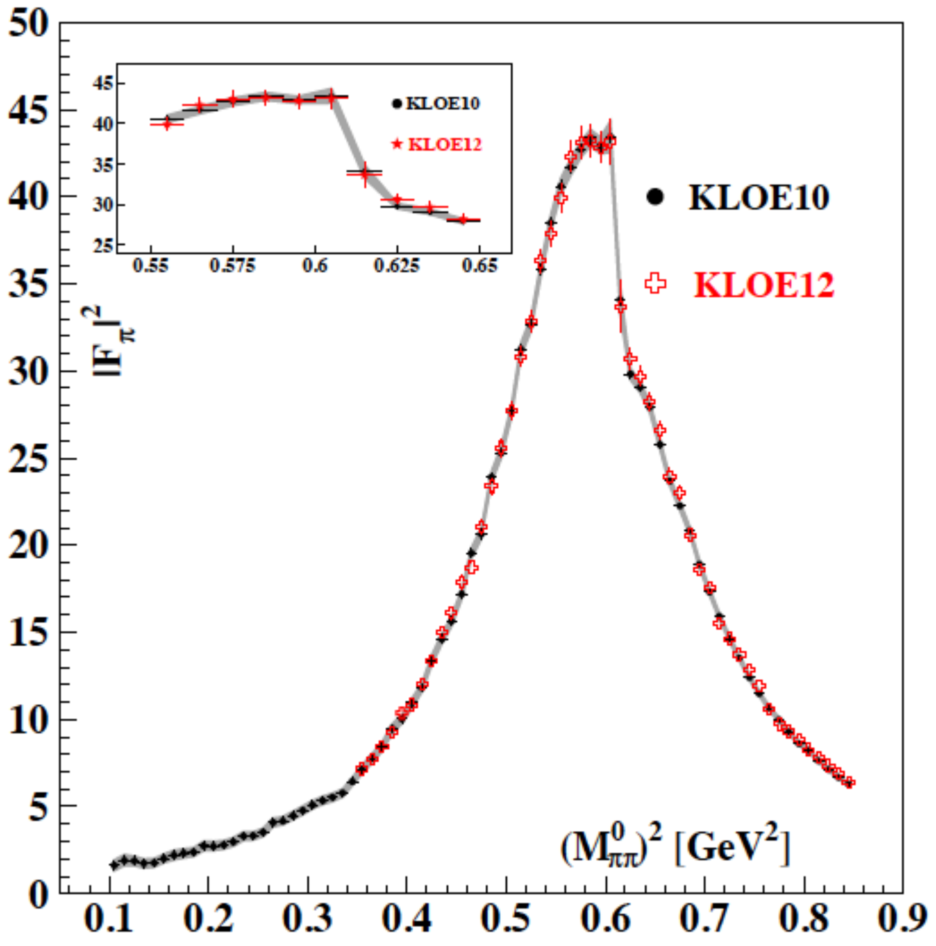
$$\frac{d\sigma^{DATA}_{\mu\mu\gamma(\gamma)}}{d\sigma^{MC}_{\mu\mu\gamma(\gamma)}} = 0.998 \pm 0.001_{stat} \pm 0.011_{sys}$$



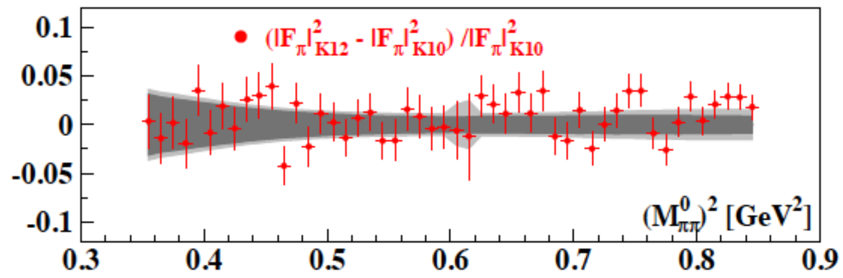
- The systematic error has been averaged on $M^2_{\mu\mu}$
- Good agreement with PHOKHARA MC (NLO Calculation)
- Consistency check of Radiator function, Luminosity, etc…

Comparison of results: KLOE12 vs KLOE10

KLOE12 result compared to KLOE10:



Fractional difference:



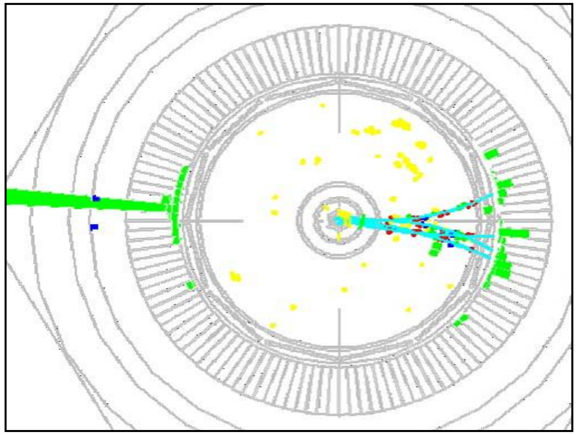
band: KLOE10 error

Excellent agreement between the two independent measurements!

Analysis	$a_\mu^{\pi\pi}(0.35 - 0.85\ \mathrm{GeV}^2) \times 10^{10}$
KLOE12	$377.4 \pm 1.1_{\mathrm{stat}} \pm 2.7_{\mathrm{sys+theo}}$
KLOE10	$376.6 \pm 0.9_{\mathrm{stat}} \pm 3.3_{\mathrm{sys+theo}}$

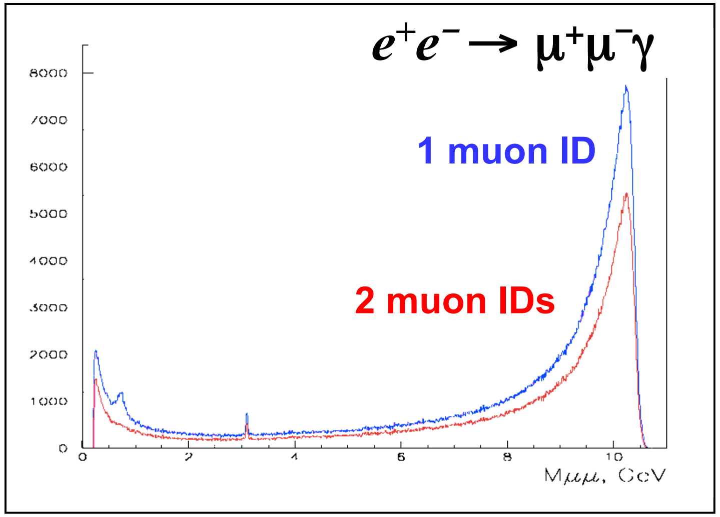
BABAR results on R using ISR:

- 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_γ^*=(3 - 5.3) GeV
  → requires high integrated luminosity of PEP-II



Event-Display of an ISR-Event in transversal plane

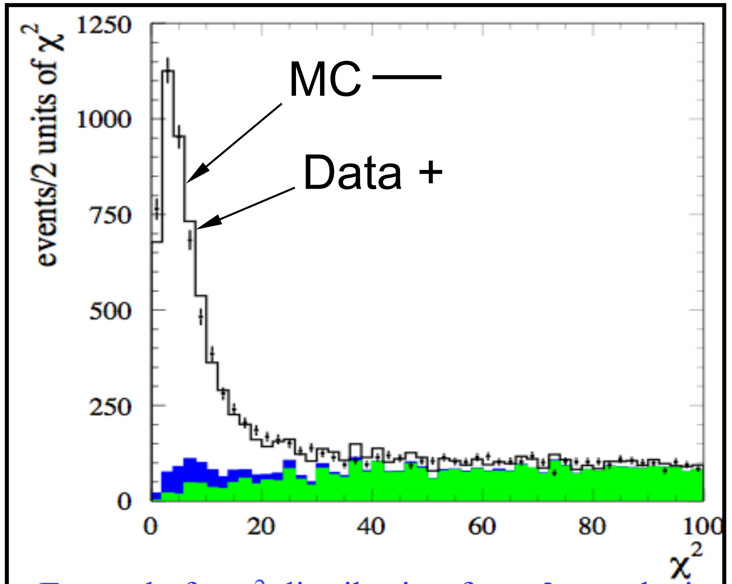
- Hard ISR-photon back-to-back to hadrons
  → only acceptance for large angle photons
  → photon tagging!



- 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 π^0 mass)



Example for χ^2 distribution from 3π analysis

- χ^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

The BaBar ISR program

- cover an almost complete set of significant exclusive e^+e^- annihilation channels up to 2 GeV

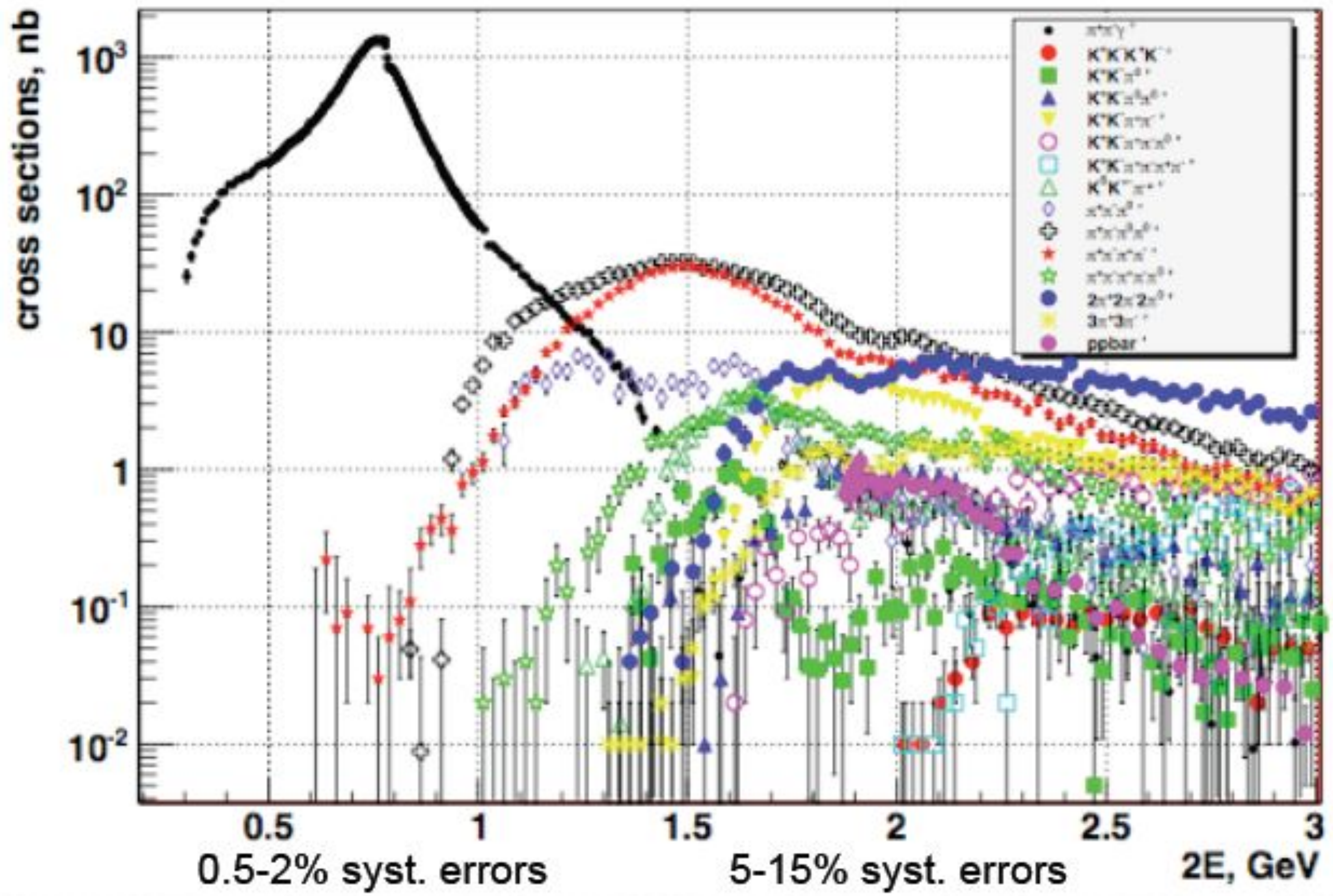
- published:

$\pi^+\pi^-$	PRL 2009; PRD 2012
$\pi^+\pi^-\pi^0$	PRD 2004
$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-2\pi^0$, $2(K^+K^-)$	PRD 2007; PRD 2012; PRD 2012
$K^0_S K^{+-}\pi^{-+}$, $K^+K^-\pi^0$, $K^+K^-\eta$	PRD 2005; PRD 2008
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	PRD 2007
$3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$	PRD 2006
$\Phi f^0(980)$	PRD 2006; PRD 2007
$p\bar{p}$	PRD 2006
$\Lambda\Lambda$, $\Lambda\Sigma^0$, $\Sigma^0\Sigma^0$	PRD 2007

- preliminary results at this workshop:
  K^+K^-

- in progress:
  $\pi^+\pi^-2\pi^0$, $K^0_S K^0_L$, $K^0_S K^0_L \pi^+\pi^-$, $K^0_S K^{+-}\pi^{-+}\pi^0$, $K^0_S K^{+-}\pi^{-+}\eta$

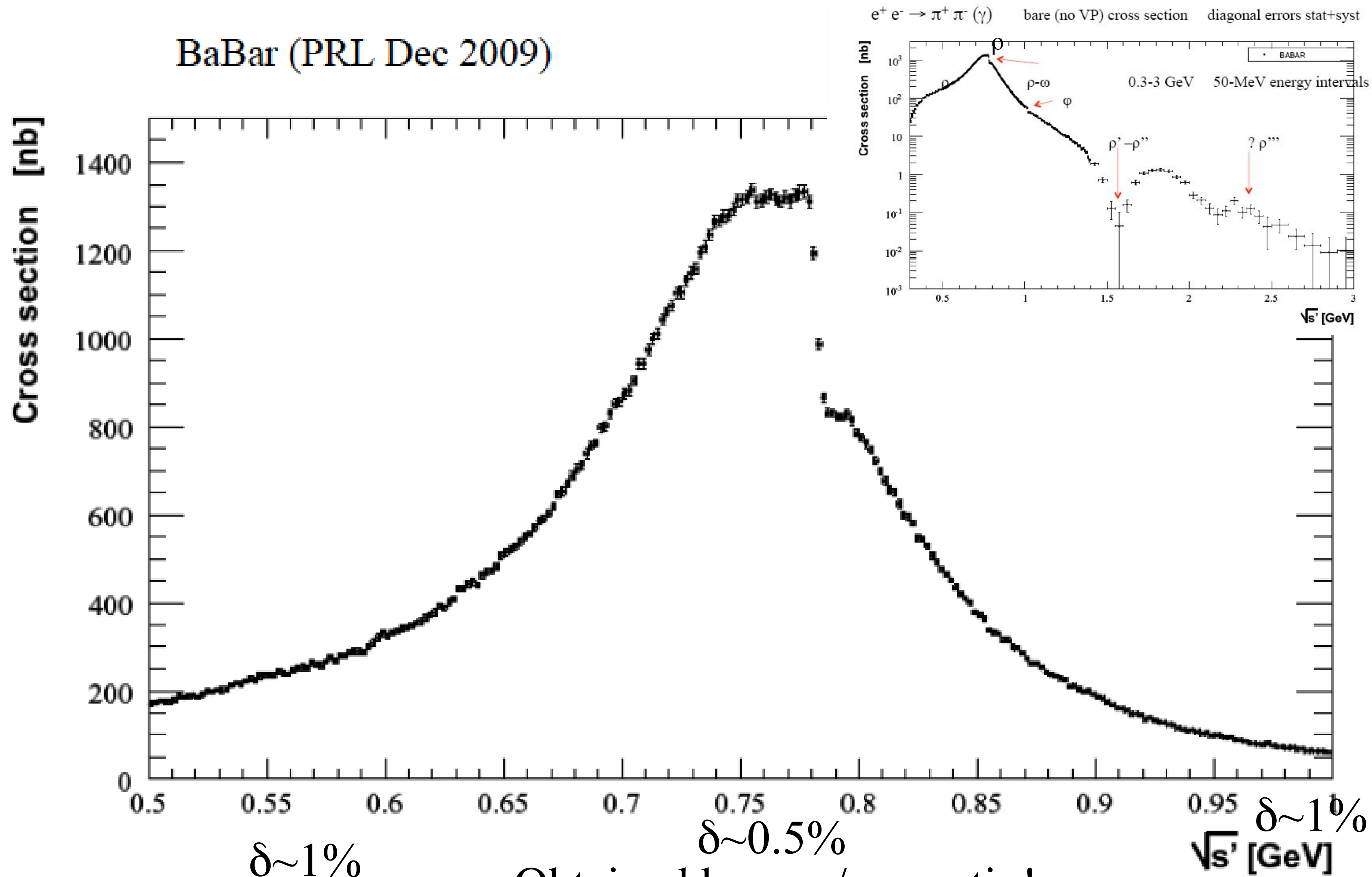
BaBar results on R using ISR:



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

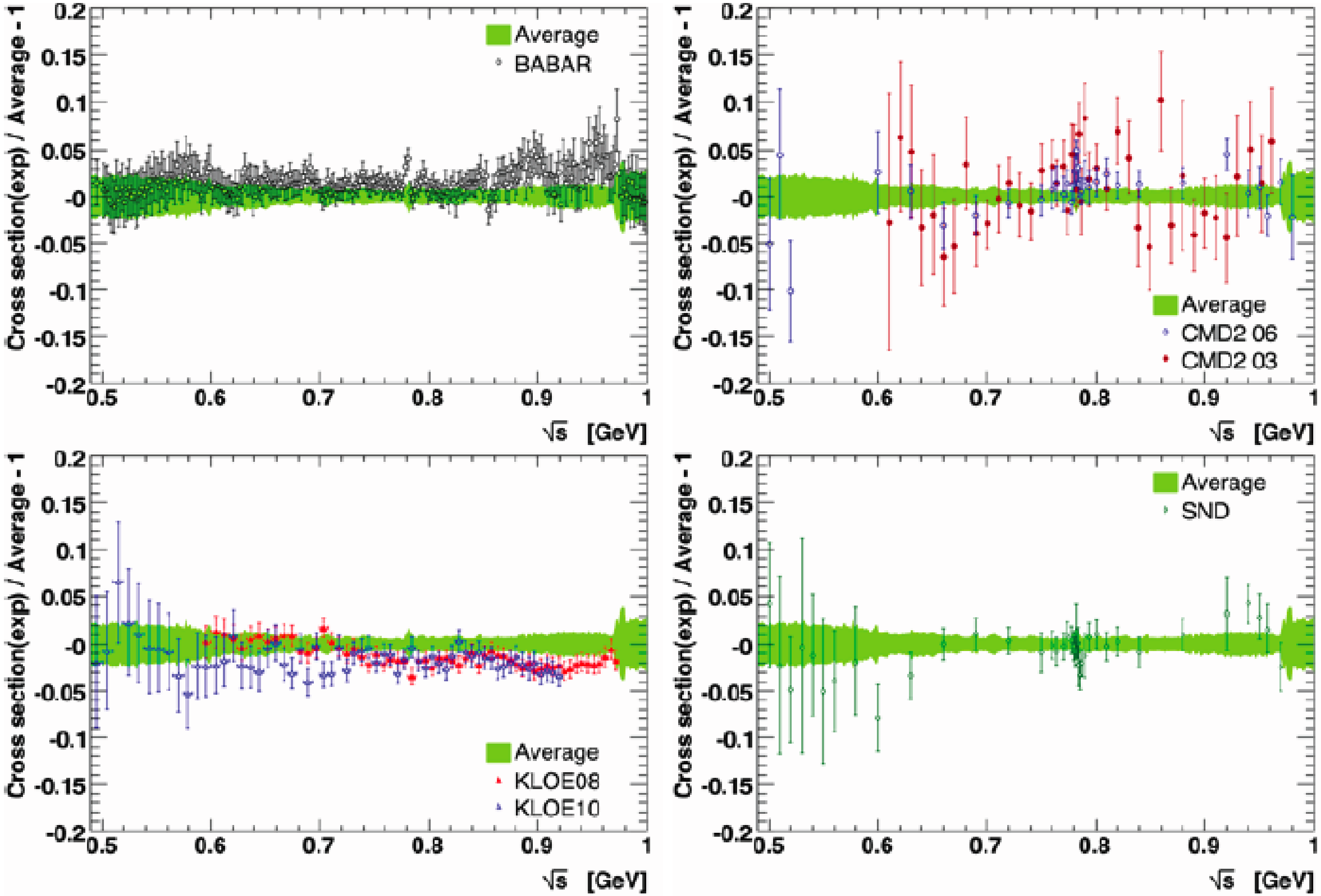
BaBar (PRL Dec 2009)



$\delta \sim 1\%$ $\delta \sim 0.5\%$ $\delta \sim 1\%$

Obtained by $\pi\pi\gamma/\mu\mu\gamma$ ratio!

Comparison of input $ee \to \pi\pi$ data



ISR: KLOE vs BaBar 2π

KLOE:

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

$\Rightarrow$ Unfolding only relevant at low $M_{\pi\pi}^2$ (up to 4%) and at $\rho-\omega$ cusp,

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

BaBar:

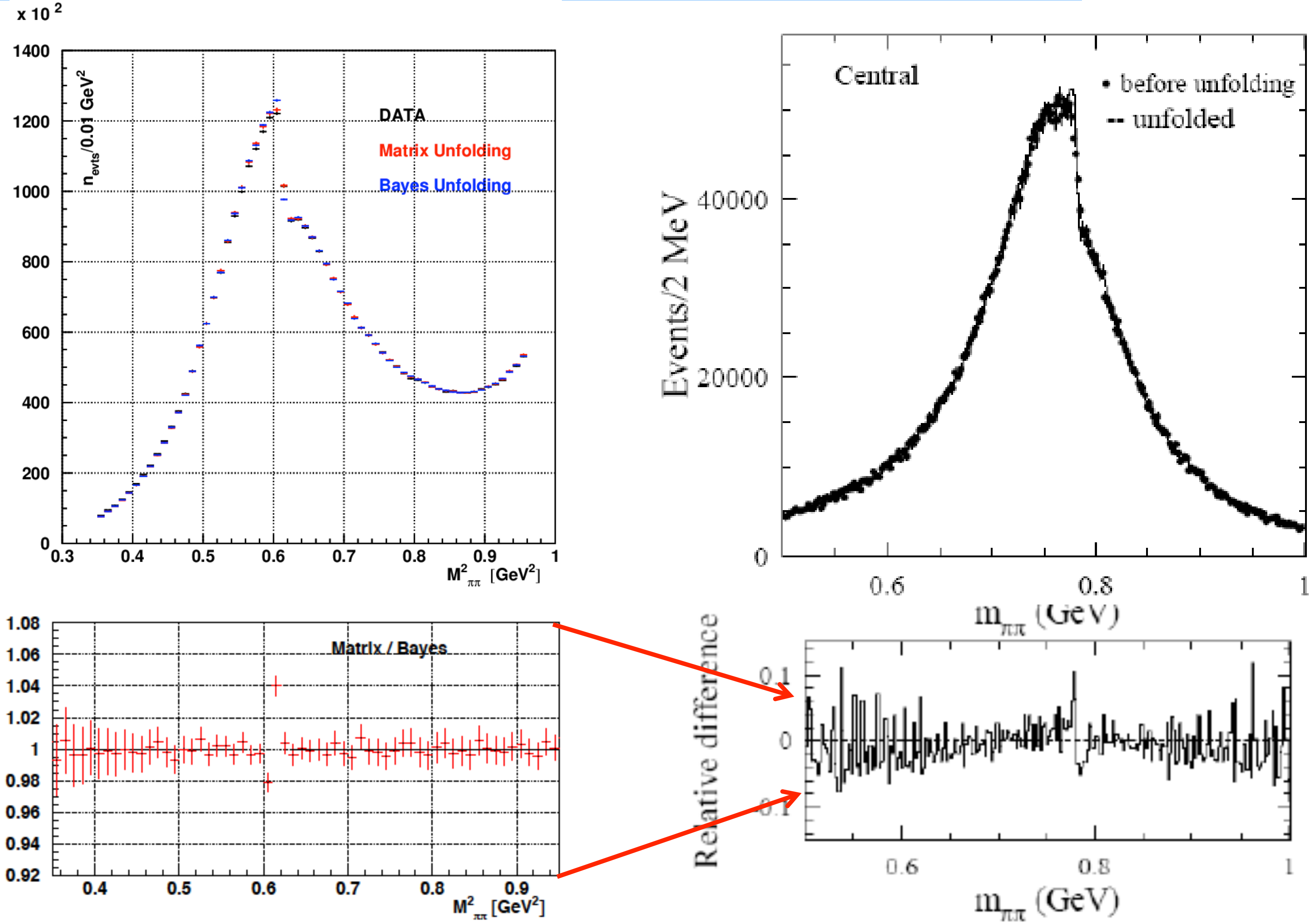
- The photon is "hard" and detected
- Kinematic fit to improve resolution
- Bin of 2 MeV in the region 0.5-1 GeV

$\Rightarrow$ Larger effects on the unfolding

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

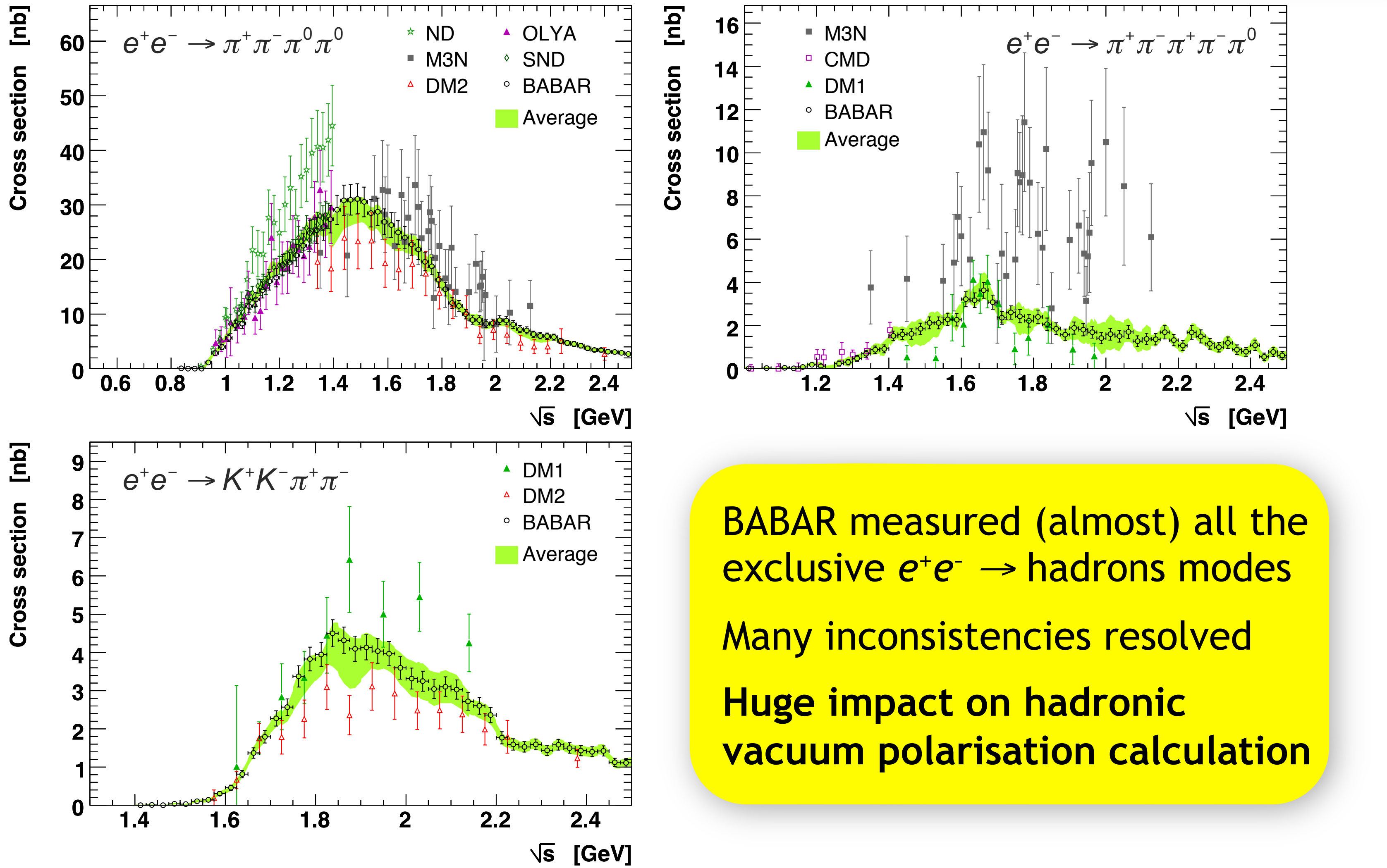
Different selections and use of theoretical ingredients (R.C., Luminosity, Radiator).
Additional cross checks are possible (and needed)

Unfolding: KLOE vs Babar 2π:



Multihadron channels between 1 and 2.5 GeV

Davier *et al.*, EPJ C 71, 1515 (2011)



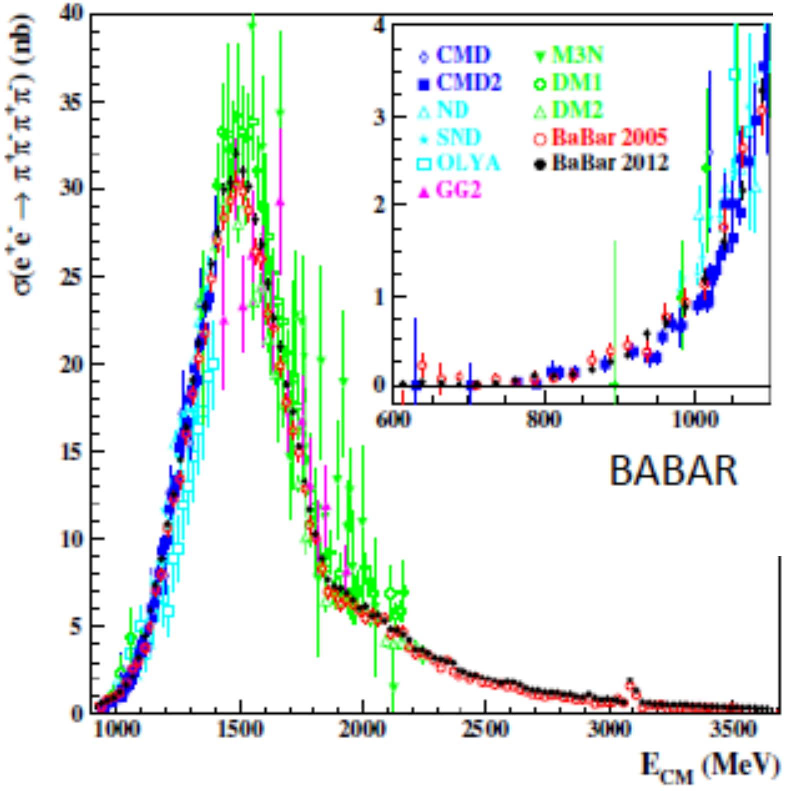
BABAR measured (almost) all the exclusive $e^+e^- \to$ hadrons modes

Many inconsistencies resolved

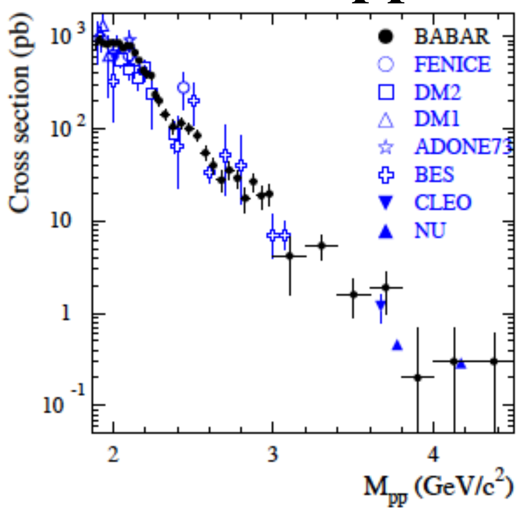
Huge impact on hadronic vacuum polarisation calculation

New cross section results

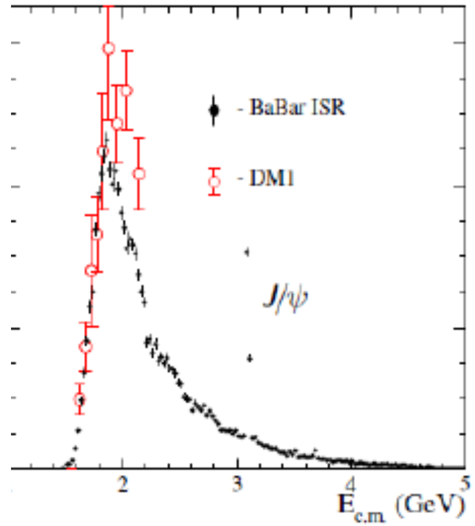
$e^+e^- \to \pi^+\pi^-\pi^+\pi^-(\gamma)$



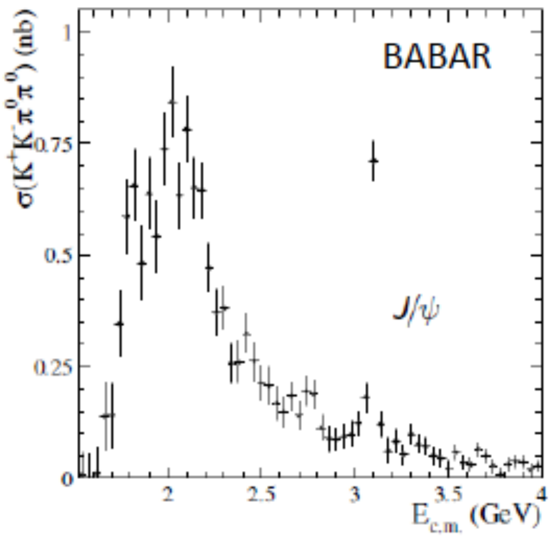
$e^+e^- \to p\bar{p}$



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



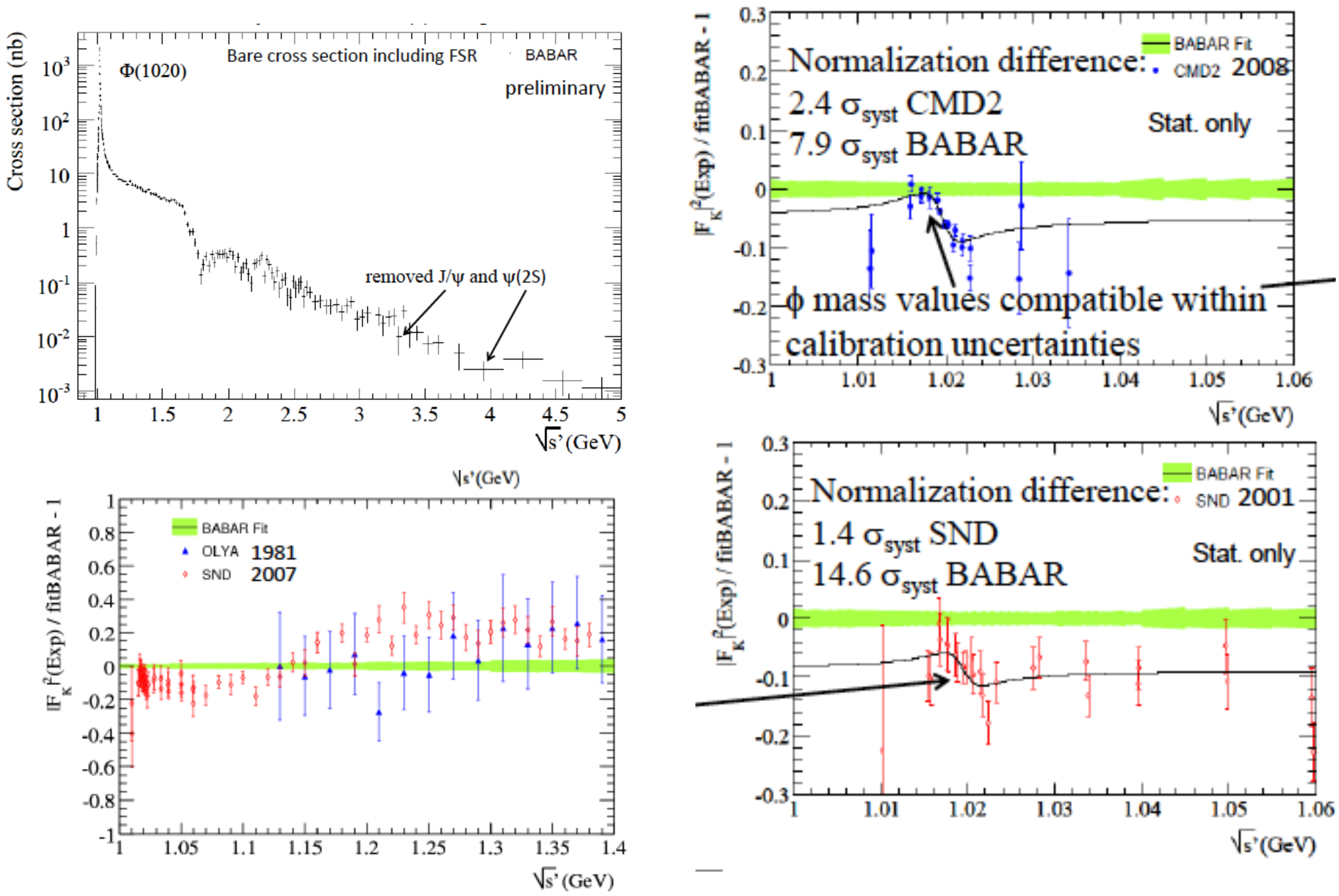
Systematic uncertainties btw 2-15%



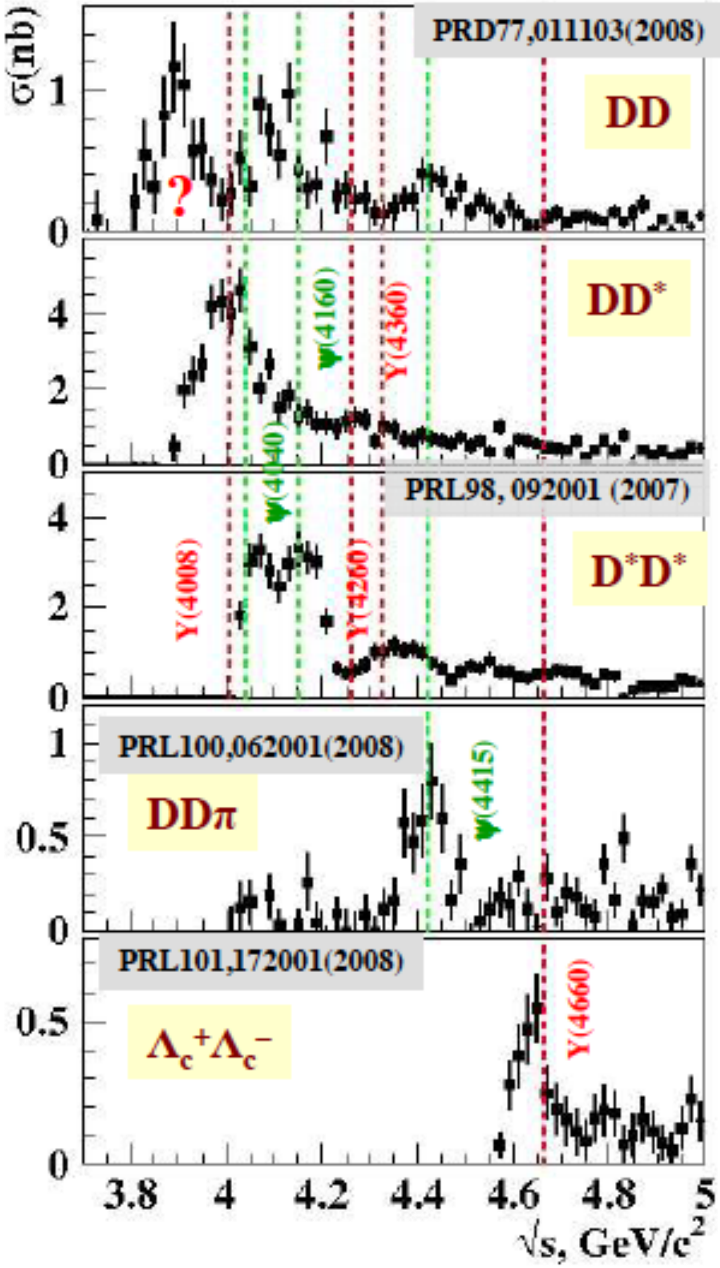
$e^+e^- \to K^+K^-\pi^0\pi^0$

- < 1.4 GeV: agreement with previous *BABAR* results, SND and CMD-2 data
- > 1.4 GeV: highest precision (DM2, 20%)

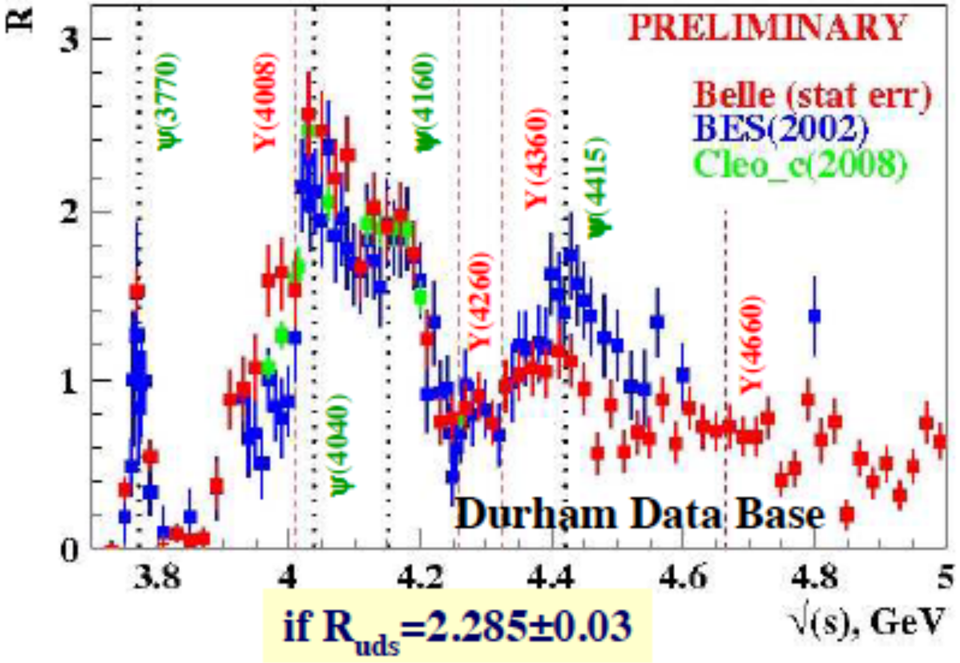
New: $e^+e^- \to K^+K^-(\gamma)$ cross section (preliminary)



σ(e+e-→open charm) at Belle



Belle: Sum of all measured exclusive contributions



Y states vs exclusive cross sections

- Y(4008) mass coincides with DD^* peak
- Y(4260) mass corresponds to dip in D^*D^* cross-sect
- Y(4660) mass is close to $\Lambda_c^+\Lambda_c^-$ peak
- Enhancement near 3.9 GeV in ee→DD
  coupled channel effect?

ψ(4415) still some unaccounted-for decay channels

Charm strange final states contribution to be factor of 10 less

Galina Pakhlova

σ(e+e-→open charm) at Belle

Six exclusive open charm final states were measured

$$DD, DD\pi, DD^*\pi, D^*D, D^*D^*, \Lambda_c\Lambda_c$$

- Their sum is close to $e^+e^- \to$ hadrons
- Belle & BaBar & Cleo_c cross section measurements are consistent with each other in corresponding energy ranges

- D^*D^* (main contribution)
  - complicated shape of cross section
  - clear dip at $M(D^*D^*) \sim 4260$GeV (similar to inclusive R)
- DD^* (main contribution)
  - broad peak at threshold (shifted relative to 4040 GeV)
- DD
  - complicated shape of cross section
  - broad enhancement ~ 3.9 GeV – coupled channel effect?
- $DD\pi$
  - ψ(4415) signal observed, dominated by $\psi(4415) \to DD_2\,(2460)$
- $DD^*\pi$
  - No evidend structures observed

  <u>In charm meson final states no evident peaks corresponding to members of charmoniumlike 1^{--} family are found !</u>
- $\Lambda_c\Lambda_c$
  - *Enhancement at threshold, quantum numbers, mass and width are consistent with Y(4660)*

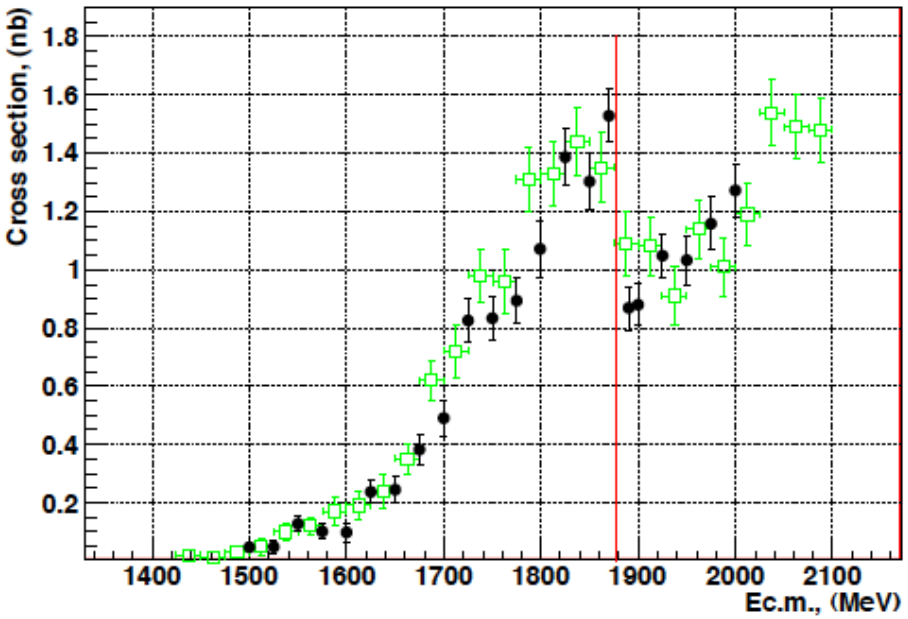
New data at the horizon:

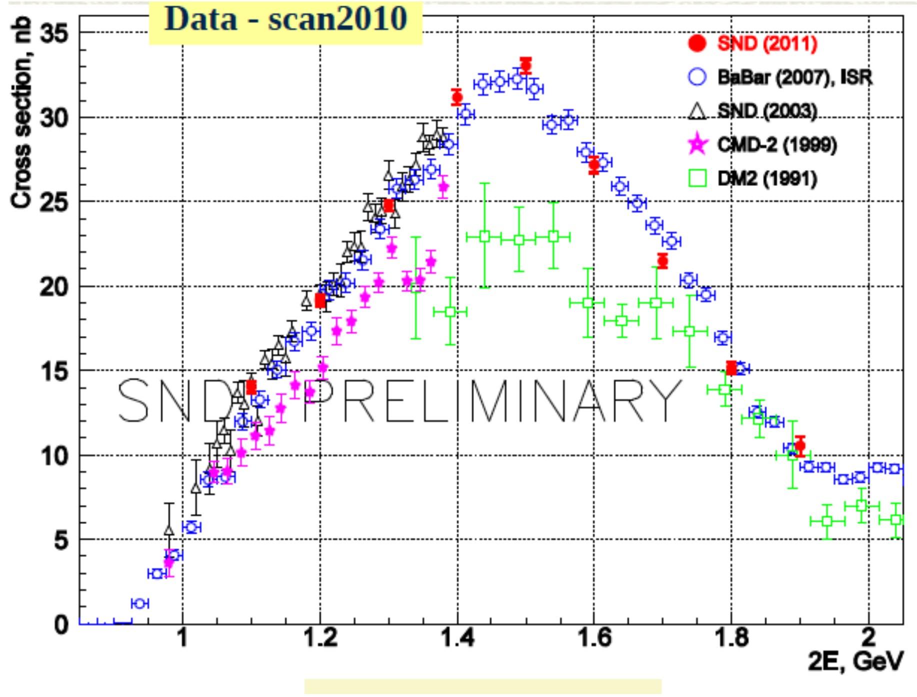
First data from VEPP-2000 @Novosibirsk
(L ~ 10^{31} cm^{-2} sec^{-1})

$\int L \sim 30\ pb^{-1}$

$e^+e^- \to 2\pi^+2\pi^0$ SND

CMD3 $e^+e^- \to 3\pi^+3\pi^-$



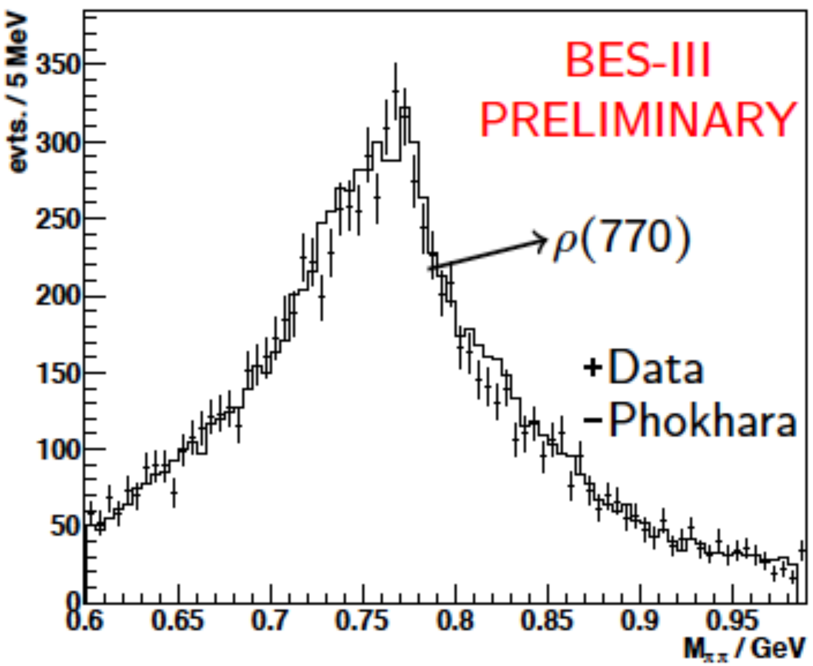


Additional results also from BaBar, Belle,BES with ISR, and possibly with DAFNE upgraded in energy (DAFNE-2, see **arXiv:1007.521**)

Feasibility study of ISR analyses at BES-III on Ψ''

$e^+e^- \to \pi^+\pi^-\gamma_{ISR}$:

- Phokhara event generator (within BES simulation framework)
- Data: pre-analysis (tagged) on $400\,\text{pb}^{-1}$ performed

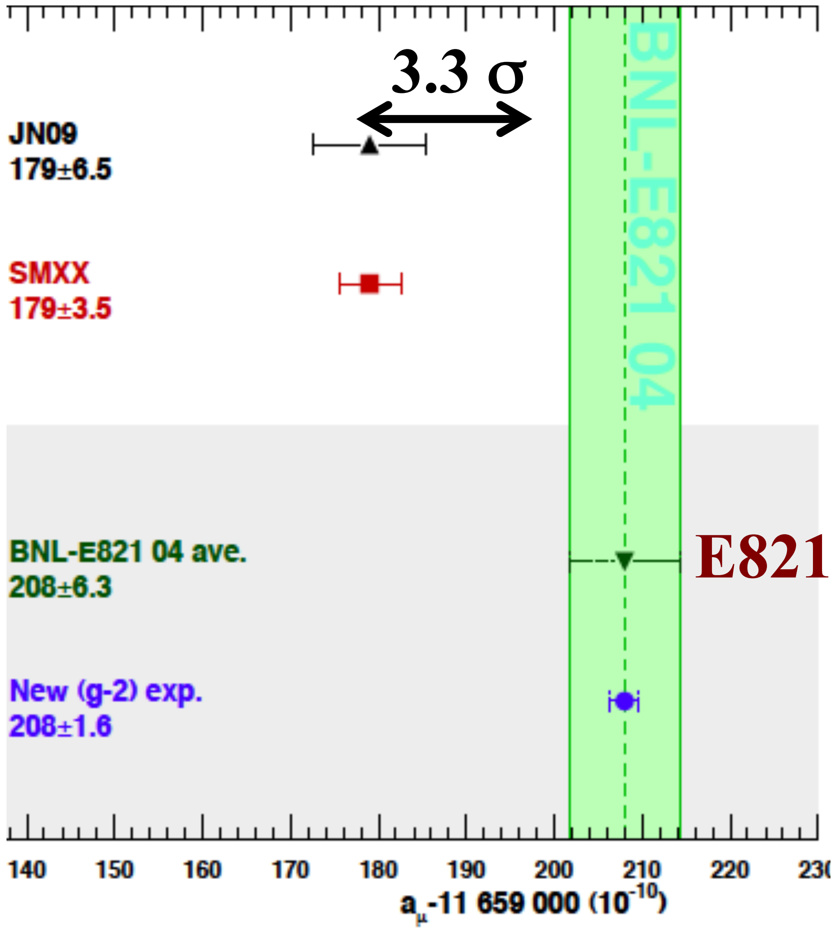


Diploma Thesis Zimmermann

A rough estimate for g-2: now

$a_\mu^{exp} - a_\mu^{theo,SM} = (27.7 \pm 8.4)10^{-10}$ (3.3σ)

$8.4 = \sim 5_{HLO} \oplus \sim 3_{HLbL} \oplus 6_{BNL}$



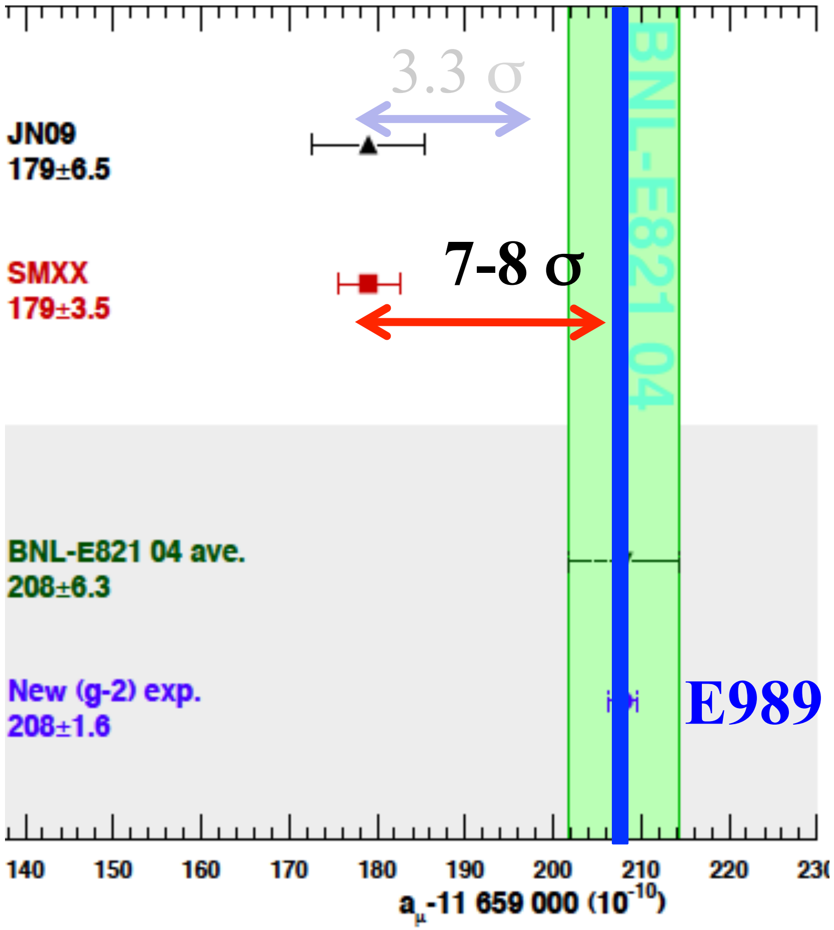
$\delta a_\mu^{HLO} = 5.3 = 3.3(\sqrt{s}<1\text{GeV}) \oplus 3.9(1<\sqrt{s}<2\text{GeV}) \oplus 1.2(\sqrt{s}>2\text{GeV})$

A rough estimate for g-2: …and (possible) future

$a_\mu^{exp} - a_\mu^{theo,SM} = (27.7 \pm 8.4)10^{-10}$ (3.3σ)

$8.4 = \sim 5_{HLO} \oplus \sim 3_{HLbL} \oplus 6_{BNL}$

4 3 3 1.6 NEW G-2



$a_\mu^{exp} - a_\mu^{theo,SM} = (XXX \pm 3.8)10^{-10}$

If central value is the same → 7-8σ

(if no progress on theory → 5 σ)

$\delta a_\mu^{HLO} \rightarrow 2.6 = 1.9\ (\sqrt{s}<1\text{GeV}) \oplus 1.3\ (1<\sqrt{s}<2\text{GeV}) \oplus 1.2(\sqrt{s}>2\text{GeV})$

This is possible if:

- **$\delta\sigma_{HAD} \sim 0.4\%$ $\sqrt{s}<1$GeV (instead of 0.7% as now)**

- **$\delta\sigma_{HAD} \sim 2\%$ $1<\sqrt{s}<2$GeV (instead of 6% as now)**

(Possible with direct scan or ISR at Flavour factories)

→ **$\delta a_{\mu}^{HLO} = 2.6\ 10^{-10}$ (instead of ~5 as now)**

A similar improvement on $\delta\alpha_{em}(Mz)$ using Adler function method

Conclusion

- Significant improvement on R measurement in the last 15 years due to more precise data. Interplay with theorists for the control of RC and development of MC
- ISR opened a new way to precisely measure the hadronic cross sections
- New data are expected from DAFNE, VEPP2000, BESIII and (Super)B factories which will continue to improve the region below 5 GeV with ISR.
- These data would allow to reduce of a factor ~2 the uncertainty on the hadronic contribution to g-2 to match the request from the next g-2 experiments (at FNAL and J-PARC). A similar improvement is expected on α_{em}(Mz).

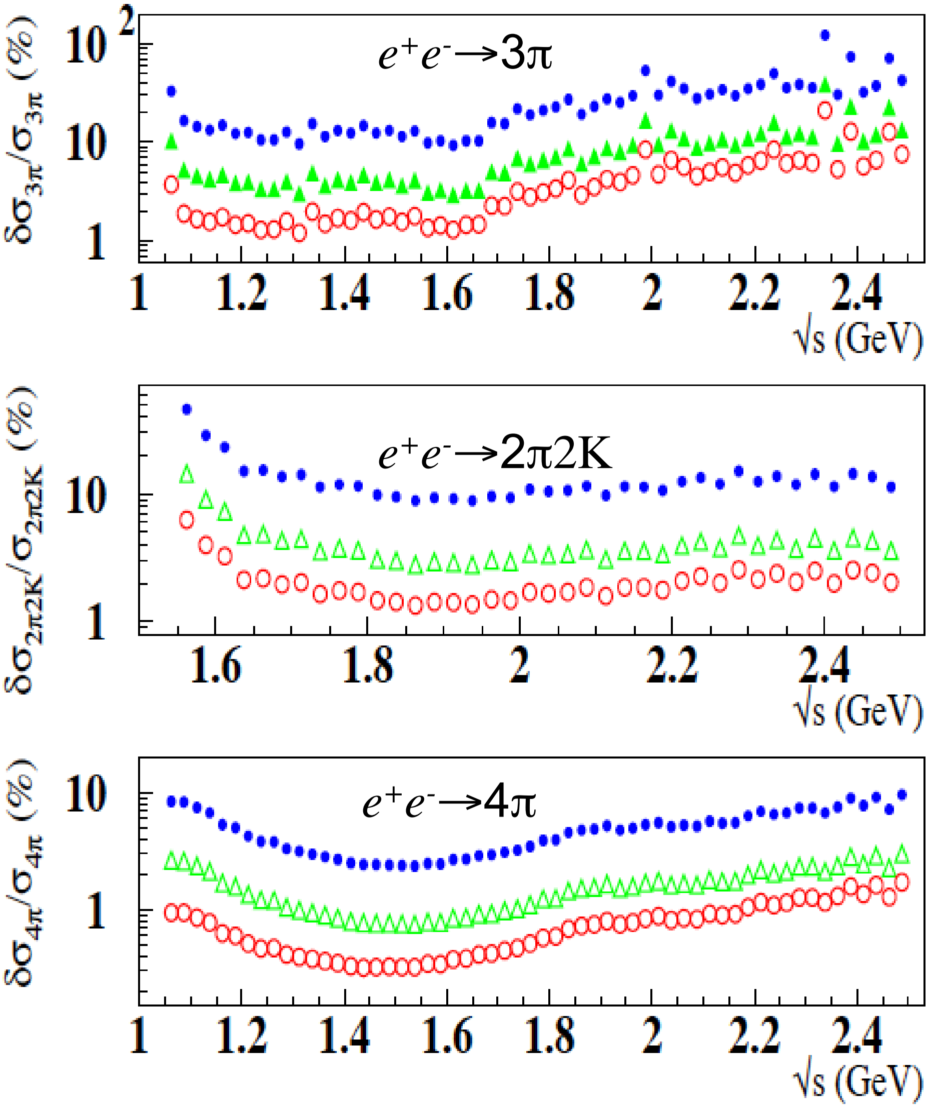
Stay tuned!

Thanks!

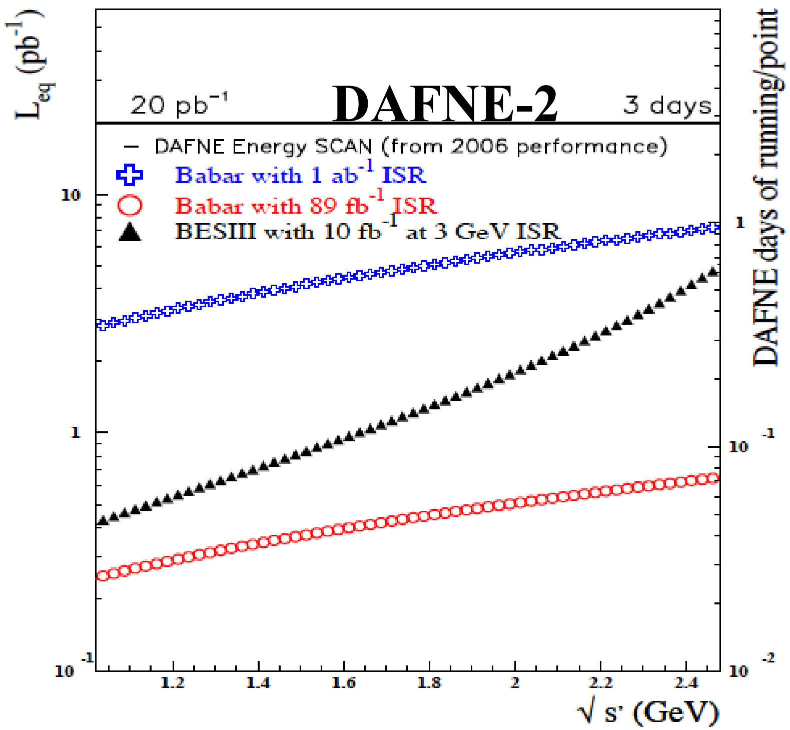
SPARE

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

arXiv:1007.521



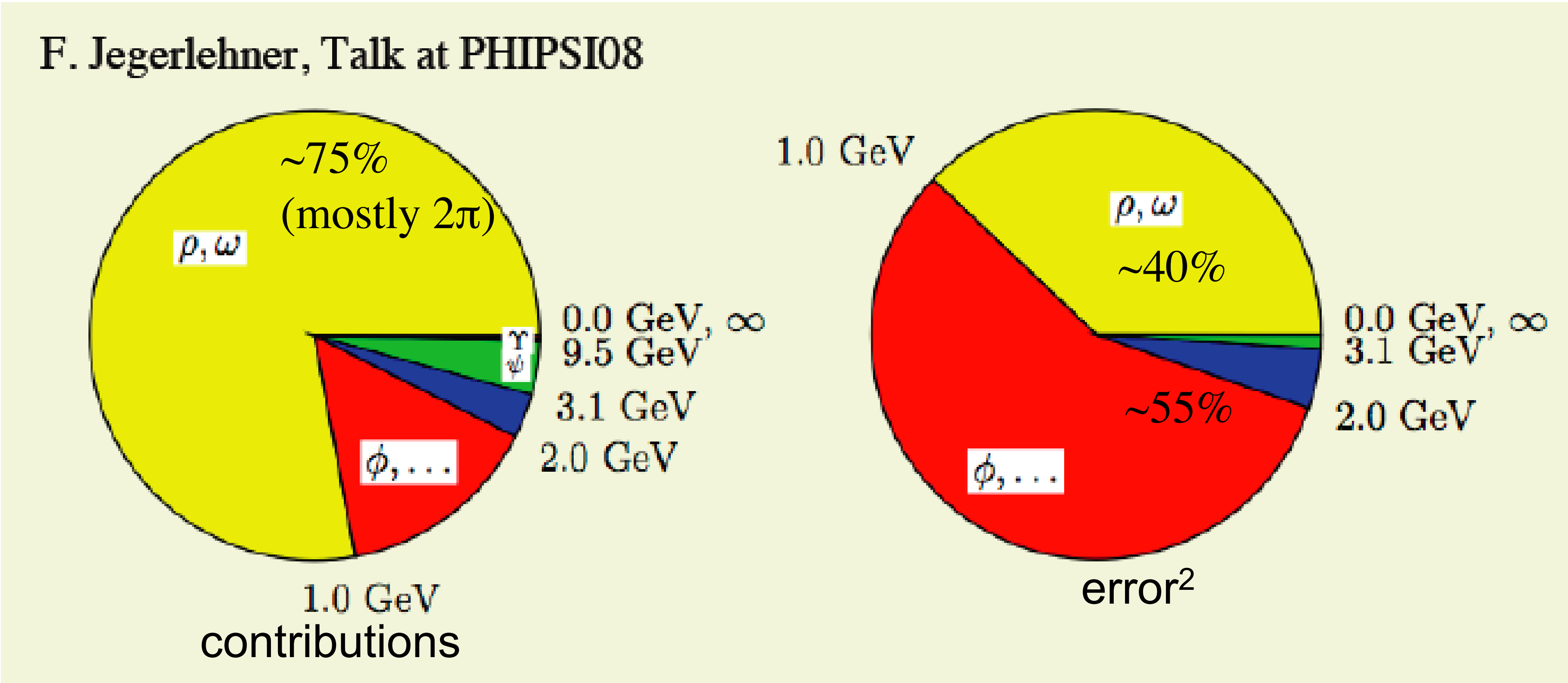
- **Published BaBar results: 89 fb^{-1} (ISR)**
- ▲ **"BaBar" × 10 (890 fb^{-1})**
- o **KLOE-2 energy scan: 20 pb^{-1}/point @ L= 10^{32} cm^{-2} s^{-1}, 25 MeV bin ⇒ 1 year data-taking**



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

Error budget on a_μ^{HLO}

δa_μ^{HLO}=5.3=3.3($\sqrt{s}$<1GeV) ⊕**3.9**(1< $\sqrt{s}$<2GeV)) ⊕1.2($\sqrt{s}$>2GeV)



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

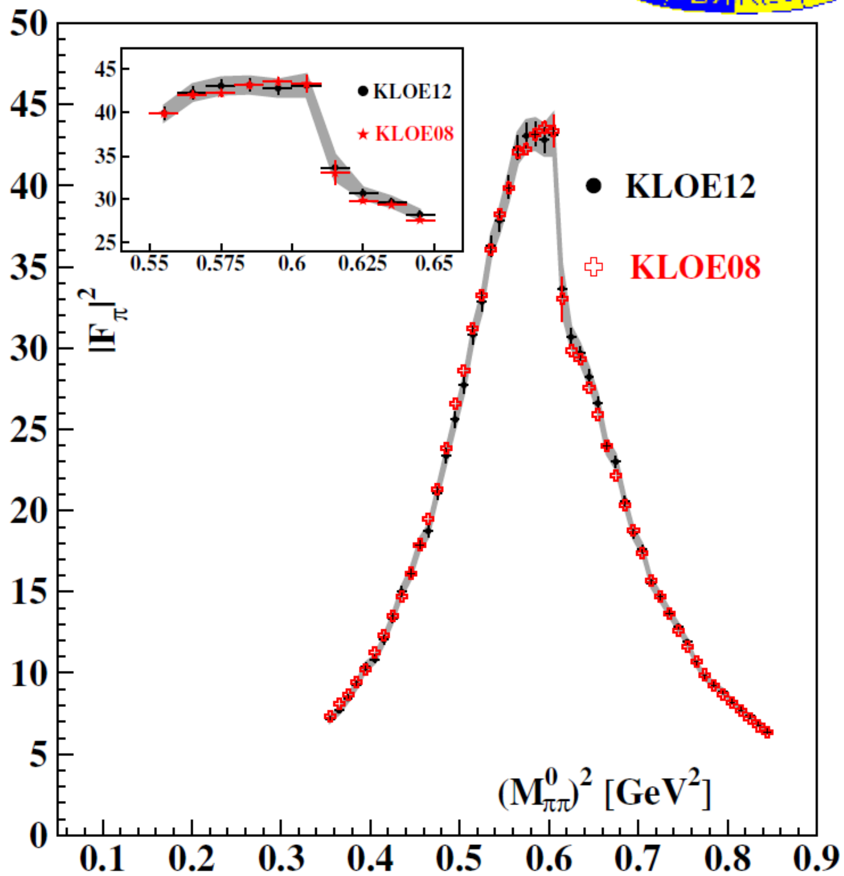
in the range < 1 GeV contributes to 70% !

But

Very important also the region 1-2 GeV !!!

KLOE12 result on $|F_\pi|^2$ and comp. with KLOE08

Syst. errors (%)	KLOE08 $\Delta^{\pi\pi}a_\mu$ abs	KLOE12 $\Delta^{\pi\pi}a_\mu$ ratio
Reconstruction Filter	negligible	negligible
Background subtraction	0.3	0.6
Trackmass	0.2	0.2
Particle ID	negligible	negligible
Tracking	0.3	0.1
Trigger	0.1	0.1
Unfolding	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1
Luminosity	0.3 ($0.1_{th} \oplus 0.3_{exp}$)	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	0.7
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.2
Rad. function H	0.5	-
Total theory systematics	0.6	0.2
Total systematic error	0.9	0.7



	$a_\mu^{\pi\pi}(0.35 - 0.95\ \mathrm{GeV}^2) \times 10^{10}$
KLOE12	$385.1 \pm 1.1_{\mathrm{stat}} \pm 2.7_{\mathrm{sys+theo}}$
KLOE08	$387.2 \pm 0.5_{\mathrm{stat}} \pm 3.3_{\mathrm{sys+theo}}$

- Good agreement btw the two measurements, especially in the ρ region.
- Improved syst. error in KLOE12. Theoretical error strongly reduced
- The two measurements are not independent (ππγ sample is the same)…

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?)

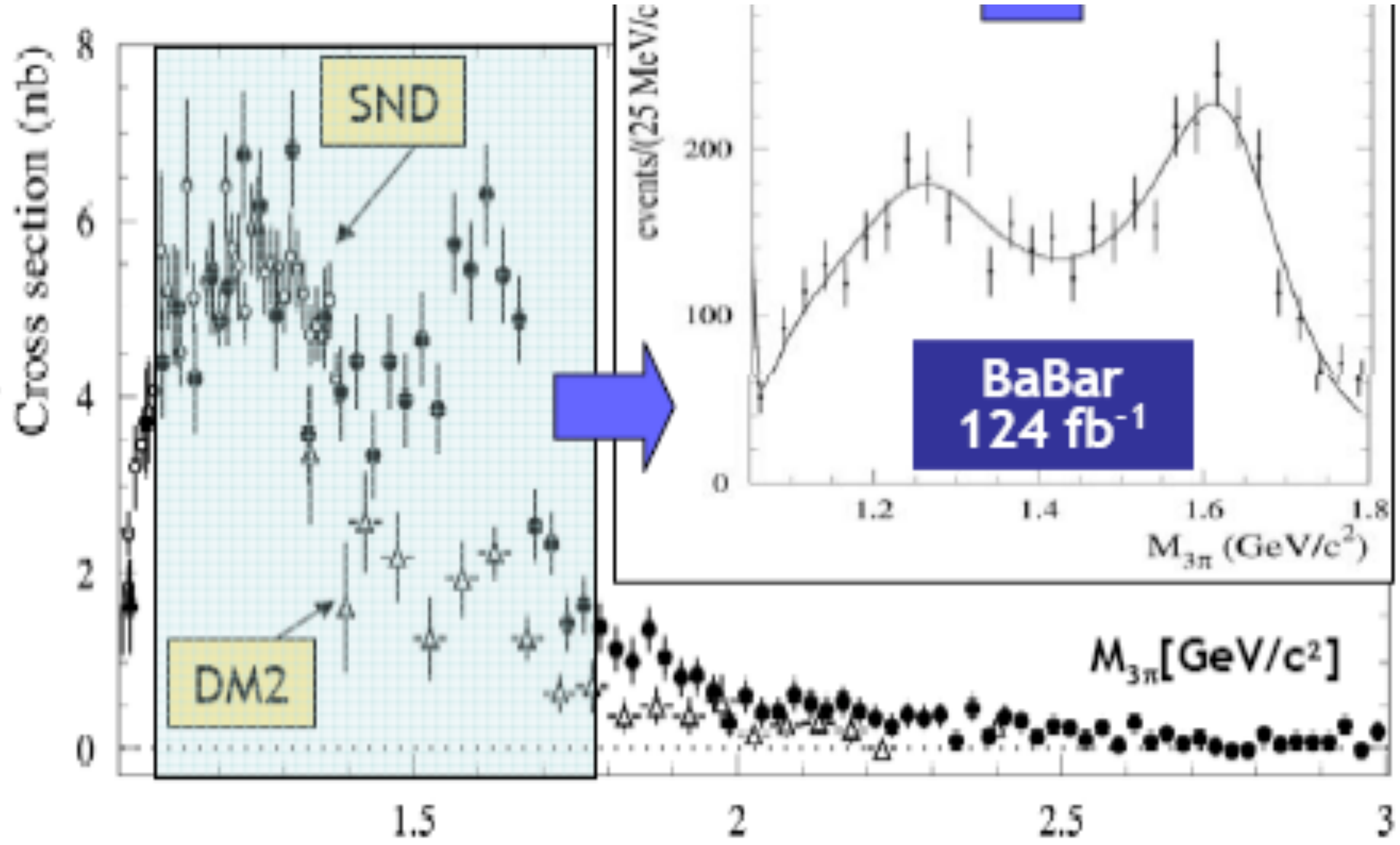
Energy (GeV)	**< 1**	**1-2**	**2-3**	**3-9.5 (exc.J/ψ and Υ)**	**9.5-13**
$\delta_{tot}R/R$	~0.5%	6%	4%	0.7%	5.5%
$\delta^2\Delta\alpha_{had}^{(5)}(M_Z^2)$	~1%	**36%**	11%	2%	**31%**
$\delta^2\Delta\alpha_{had}^{(5)}(-2.5GeV)$	~4%	**75%**	12%	<1%	<1%

F. Jegerlehner

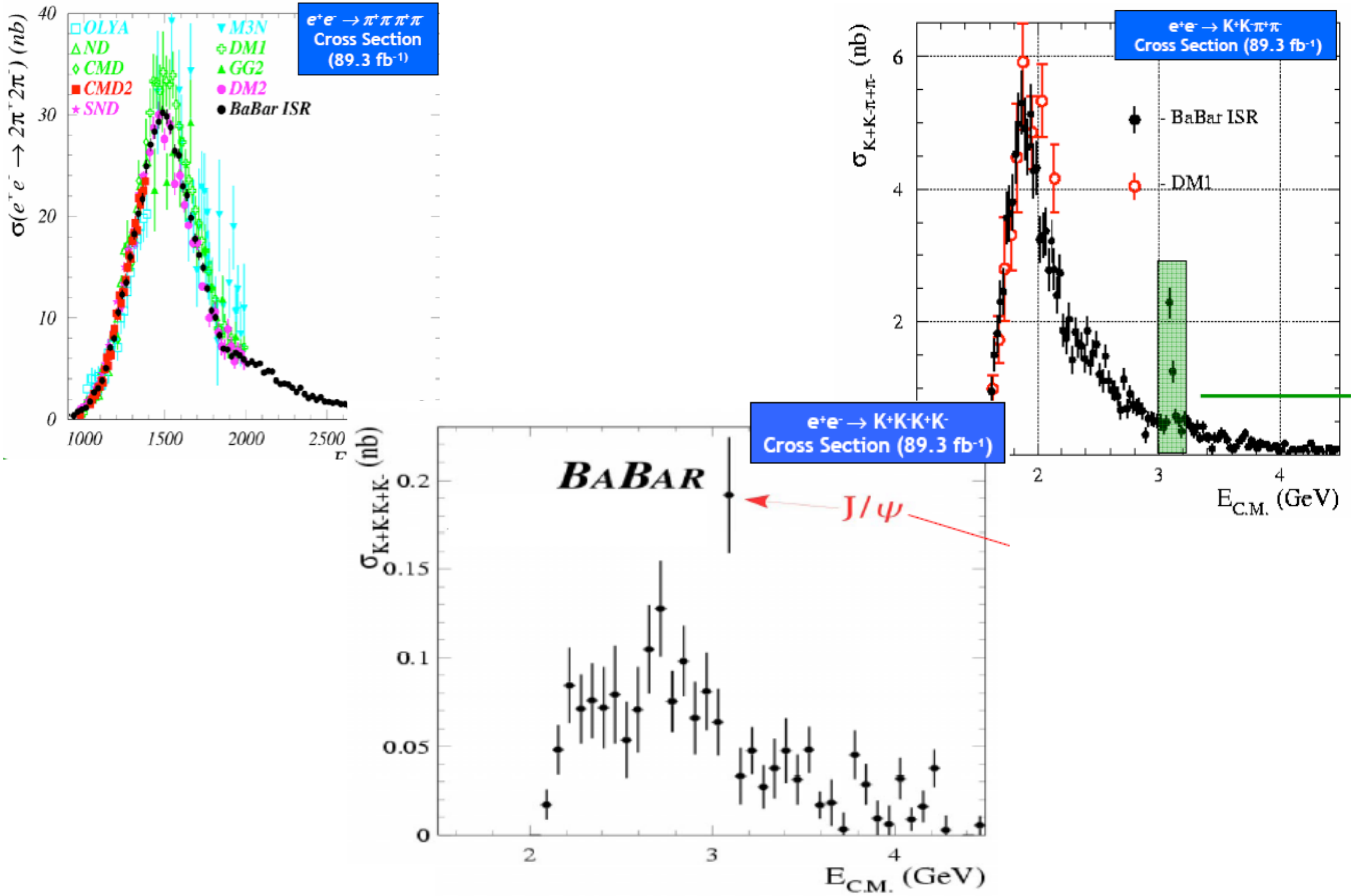
Thanks!

Babar: 3π

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

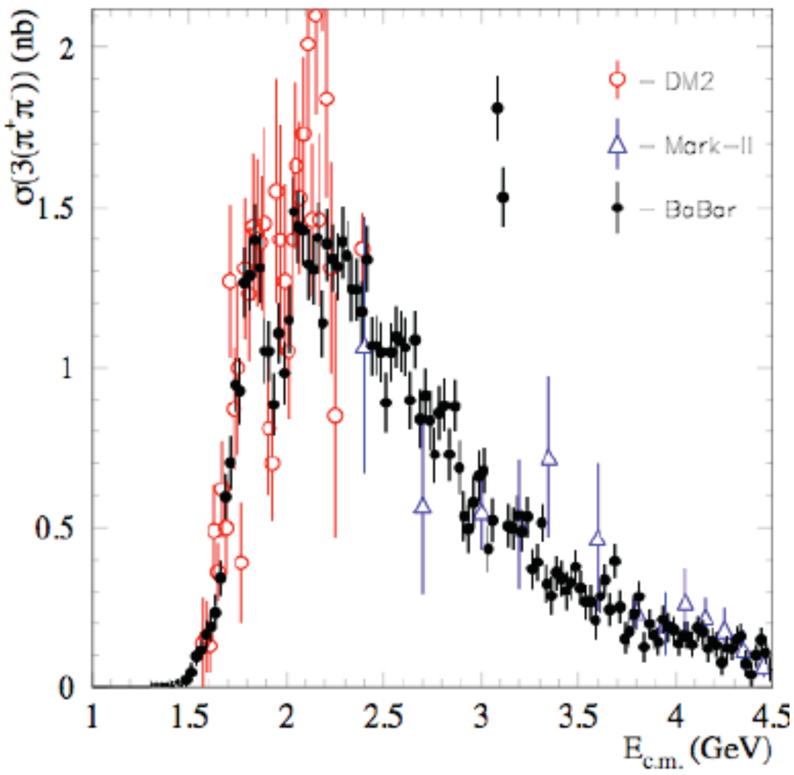


Babar: 4h



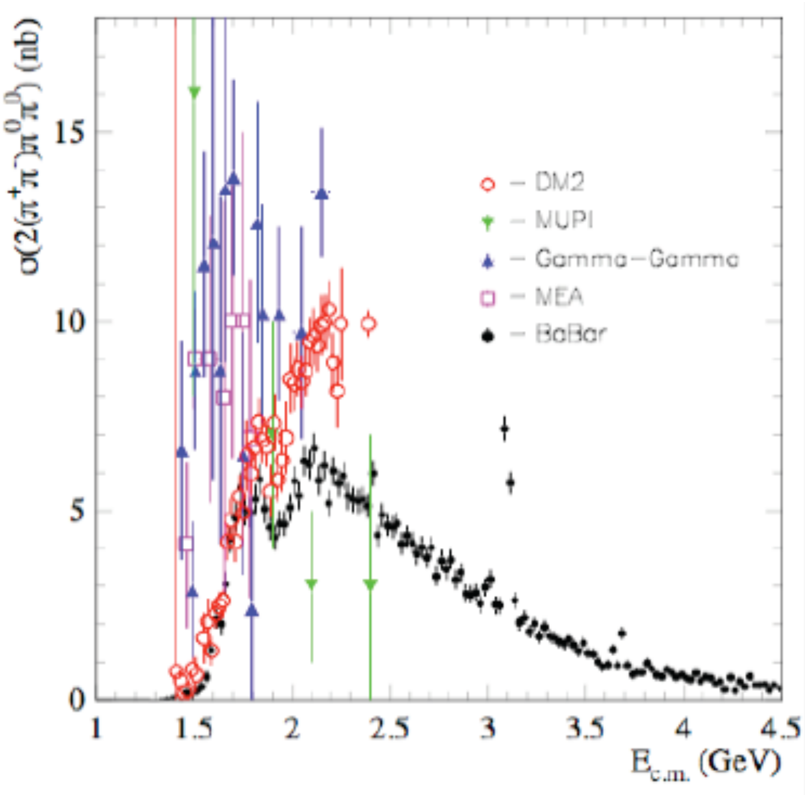
e+e- → π+π-π+π-
Cross Section
(89.3 fb-1)
σ(e+e- → 2π+2π-) (nb)
OLYA
ND
CMD
CMD2
SND
M3N
DM1
GG2
DM2
BaBar ISR
0
10
20
30
40
1000
1500
2000
2500
e+e- → K+K-π+π-
Cross Section (89.3 fb-1)
σK+K-π+π- (nb)
BaBar ISR
DM1
2
4
6
3
E C.M. (GeV)
e+e- → K+K-K+K-
Cross Section (89.3 fb-1)
BABAR
σK+K-K+K- (nb)
J/ψ
0
0.05
0.1
0.15
0.2
2
3
4
E C.M. (GeV)

Babar: 6π



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

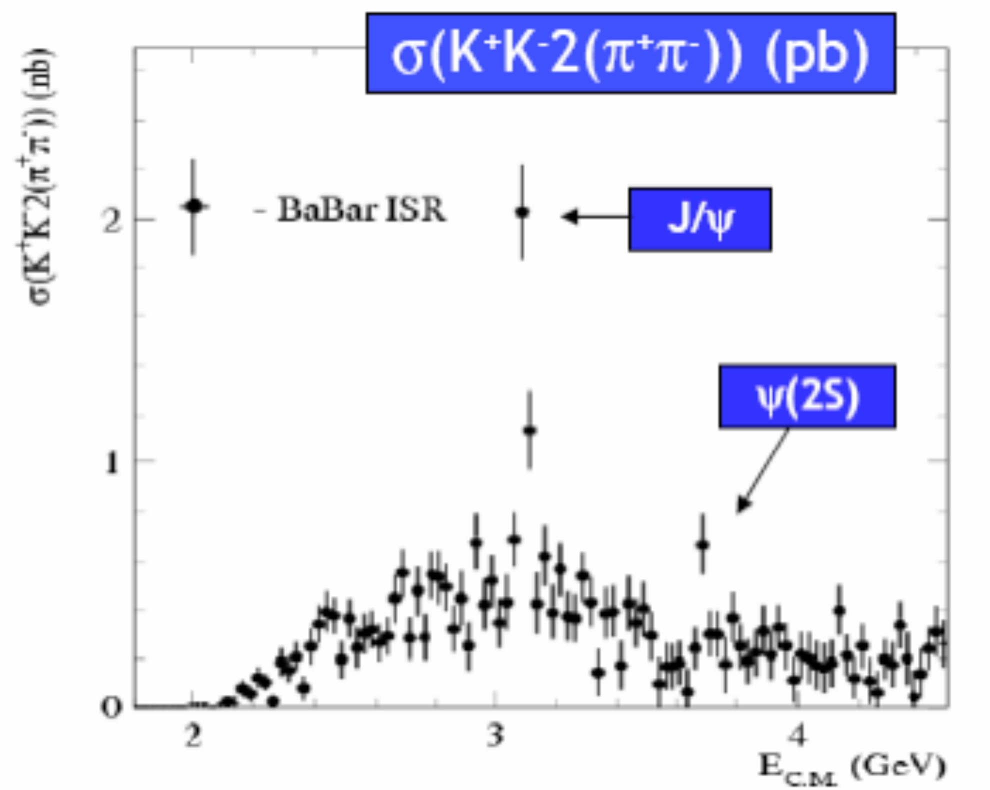
Total systematic: ~6-8%



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

Total systematic: ~11%

Babar: 2K4π



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

Total systematic: ~7%

PION FORM FACTOR AT BABAR

SYSTEMATIC ERRORS

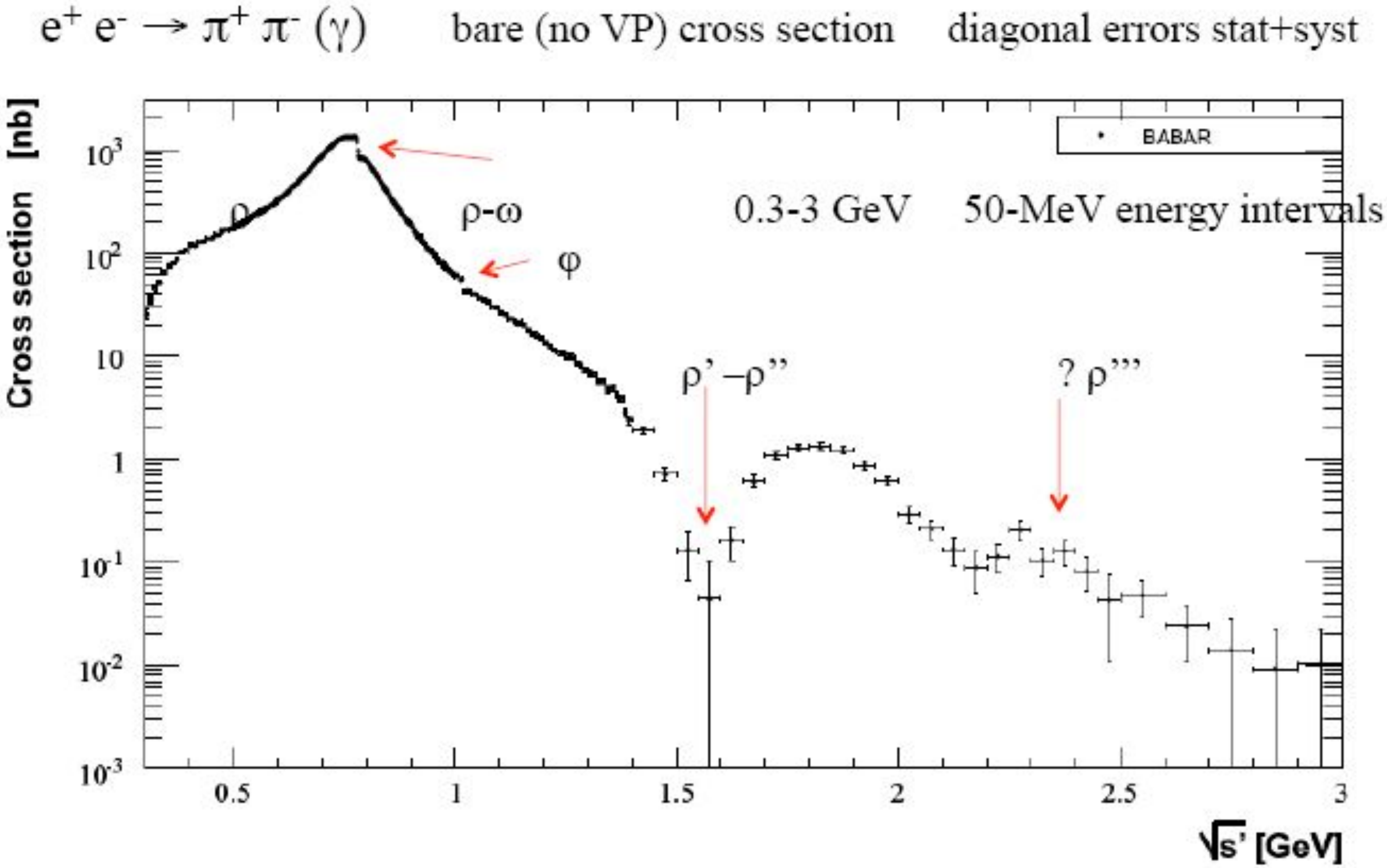
√s' intervals (GeV) errors in 10^{-3}

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
π-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 (χ^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



BaBar results with ISR: an incomplete list

- $e^+e^- \to \pi^+\pi^-\pi^0$ between 1. and 3 GeV with σ_{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 σ_{syst} between 6 and 10%
- $e^+e^- \to \pi^+\pi^-$ with σ_{sys} ~0.6% (around the ρ)

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 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}

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

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

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

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

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

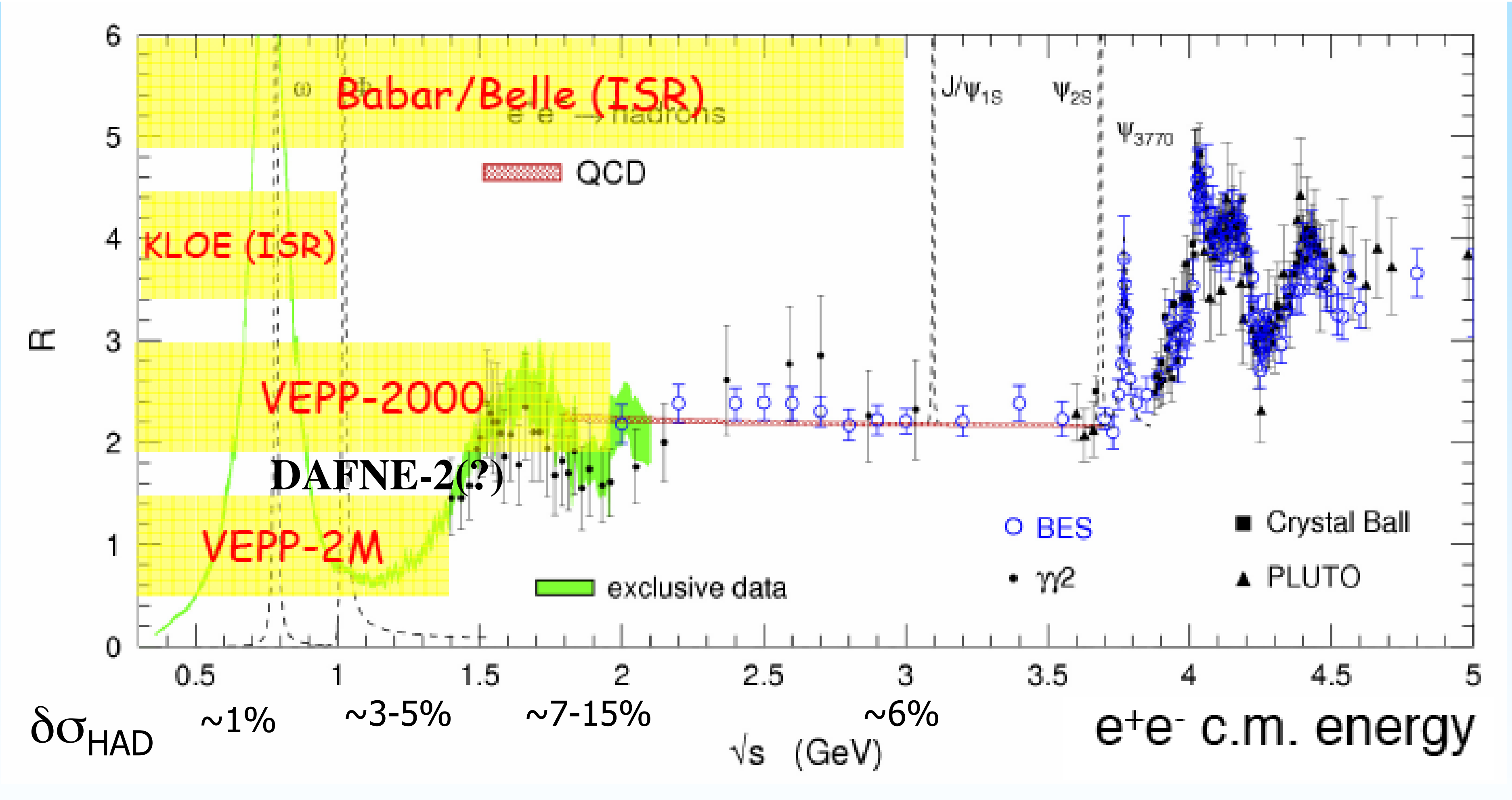
Obtain $\sigma_{\pi\pi}$ from (ISR) - radiative cross section $d\sigma_{\pi\pi\gamma(\gamma)}/dM^2$ via theoretical radiator function H(s):

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

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

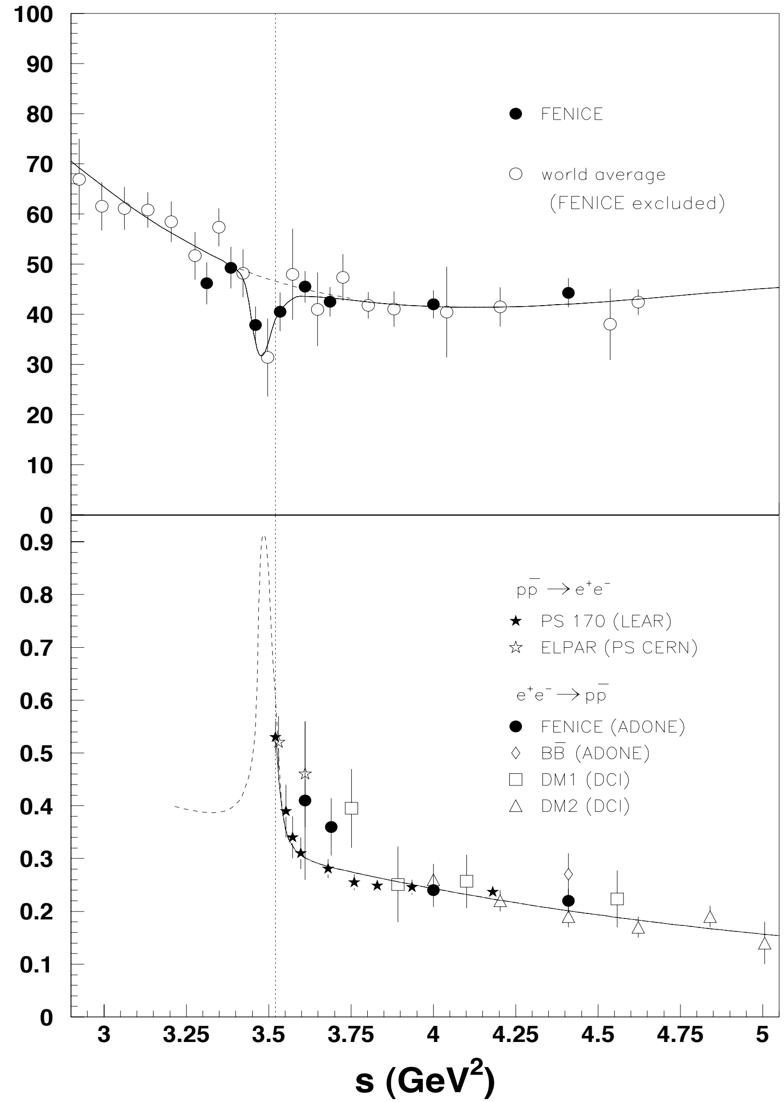
b) Via bin-by-bin Normalisation to rad. Muon events

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



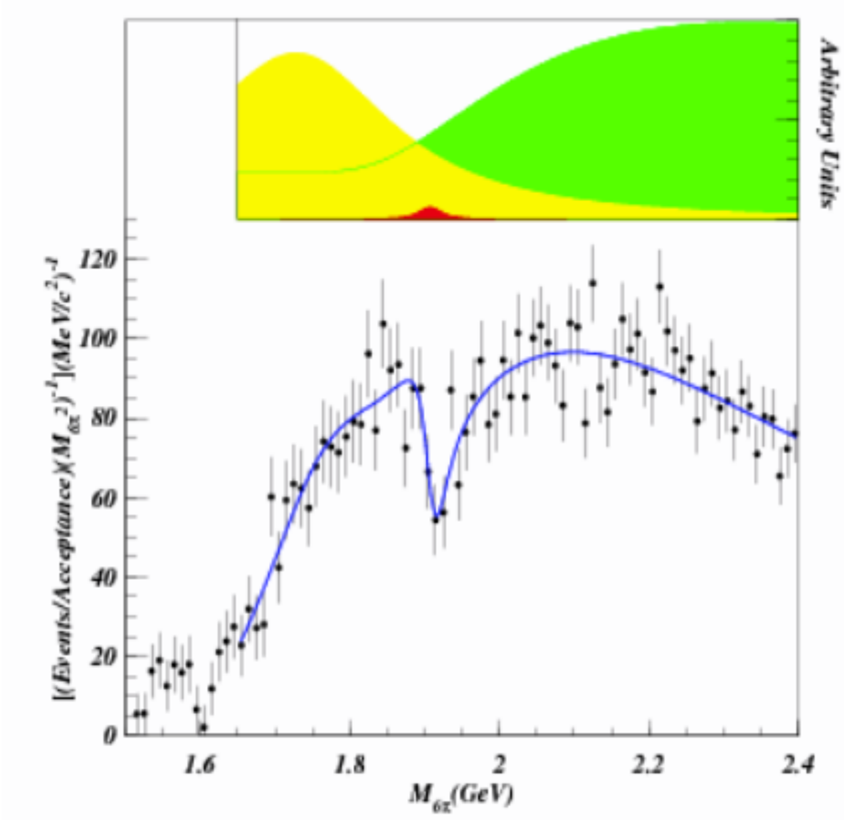
Open issues

- 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 N bar-N bound state

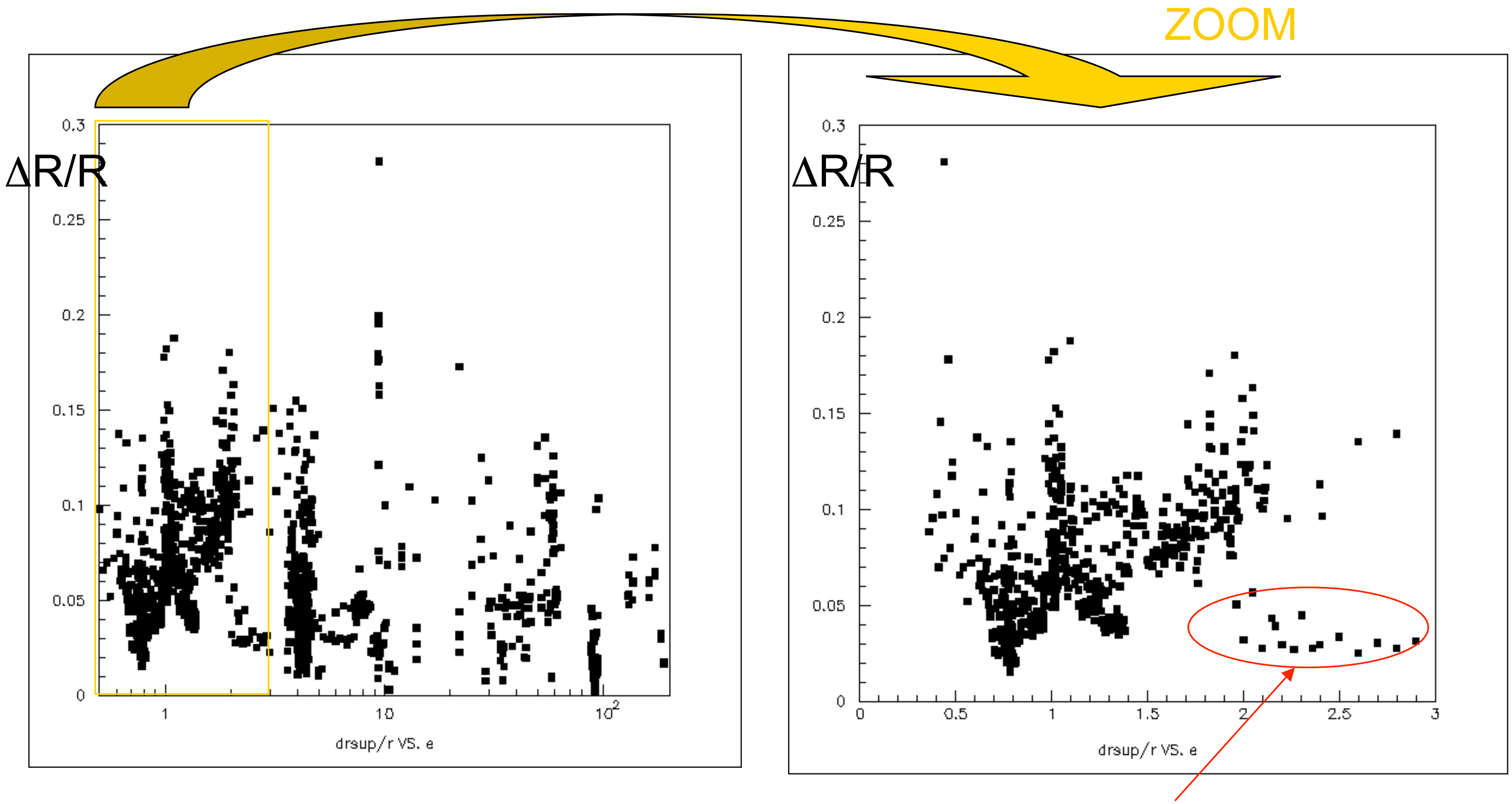


Open issues

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



Errore percentuale



Punti con errore ~3% dalla misura inclusiva di BES

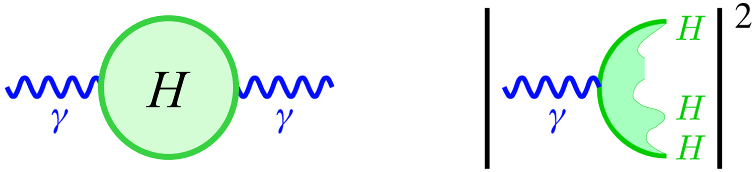
PRL 84, 594 (2000) – PRL 88, 101802 (2002)

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

$\Delta\alpha^{(5)}_{had}$	**Method**	***Ref***
0.0280 ±0.00065	data<12 GeV	S.Eidelman F.Jegerlehner '95
0.02777 ± 0.00017	data<1.8 GeV	J.H.Kuhen, 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 (new data CMD2 & BES)	H.Burkhardt,B.Pietrzyk '01 ('05)
0.00007 (0.00005)	$\delta\sigma$~1% up to J/ψ ($\delta\sigma$~1% up to Υ)	

a_μ^{HLO}:

L.O. Hadronic contribution to a_m 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 t- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

Alemany, Davier, Hoecker '97

LA Event Selection (KLOE10)

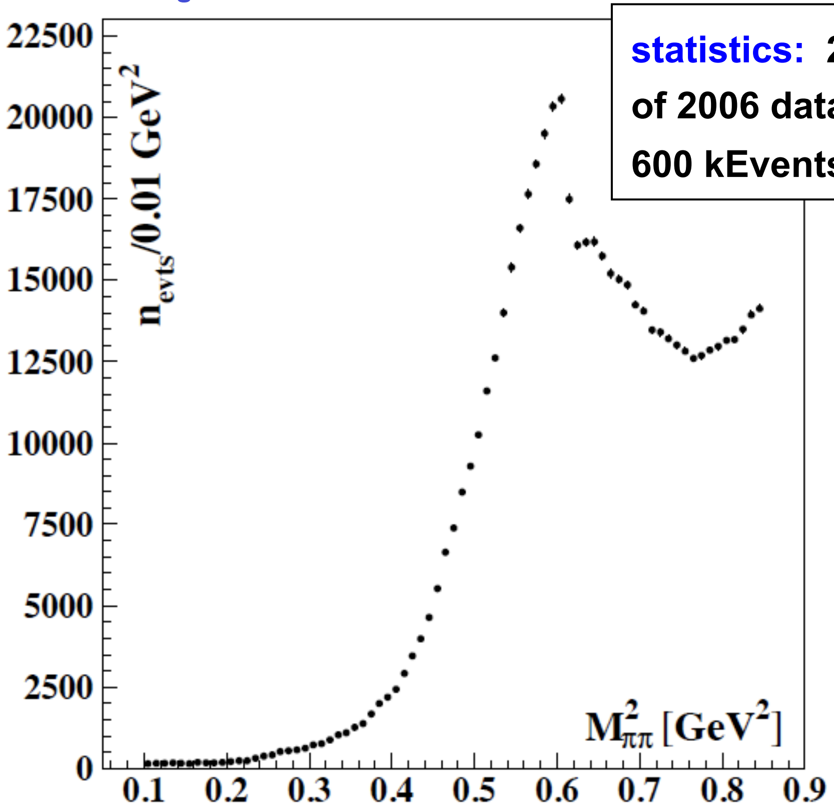
2 pion tracks at large angles
$50^o < \theta_p < 130^o$

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

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

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

At least 1 photon with $50^o < \theta_g < 130^o$ **and** $E_g > 20$ **MeV ➔ photon detected**



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

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

Impact of DAFNE-2 on $(g\text{-}2)_\mu$

arXiv:1007.521

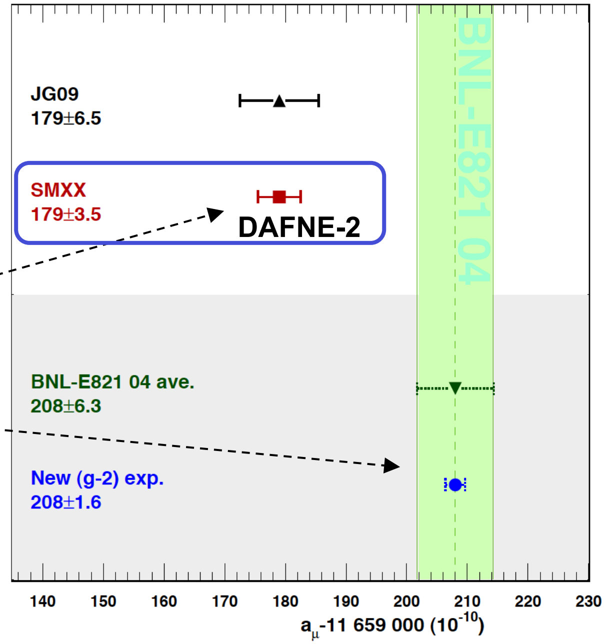
$a_\mu^{exp} - a_\mu^{theo,SM} = (27.7 \pm 8.4)10^{-10}$ (3.3σ) [Eidelman, TAU08]

$8.4 = \sim 5_{HLO} \oplus \sim 3_{HLbL} \oplus 6_{BNL}$

4 $2.6_{DAFNE\text{-}2}$ 2.5 $1.6_{NEW\ G\text{-}2}$

$7\text{-}8\sigma$

(if 27.7 will remain the same)



$\delta a_\mu^{HLO} = 5.3 = 3.3(\sqrt{s}<1\text{GeV}) \oplus 3.9(1<\sqrt{s}<2\text{GeV}) \oplus 1.2(\sqrt{s}>2\text{GeV})$

$\delta a_\mu^{HLO} \rightarrow \mathbf{2.6} = 1.9\ (\sqrt{s}<1\text{GeV}) \oplus \mathbf{1.3\ (\sqrt{s}<1GeV)} \oplus 1.2(\sqrt{s}>2\text{GeV})$

This means:

$\delta\sigma_{HAD} \sim 0.4\%$ $\sqrt{s}<1$GeV (instead of 0.7% as now) *With ISR at 1 GeV*

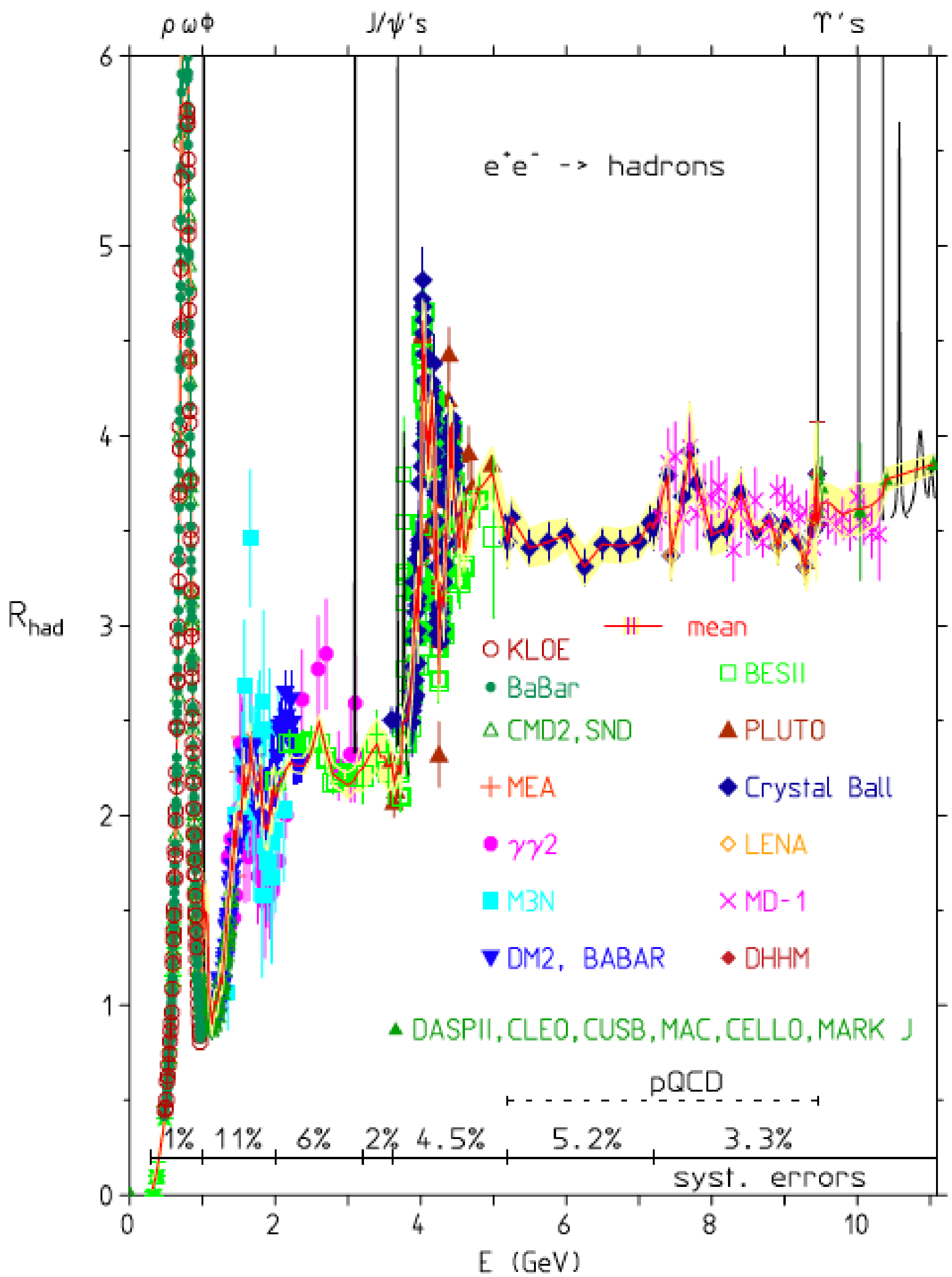
$\delta\sigma_{HAD} \sim 2\%$ $1<\sqrt{s}<2$GeV (instead of 6% as now) *With Energy Scan 1-2 GeV*

Possible at DAFNE-2!

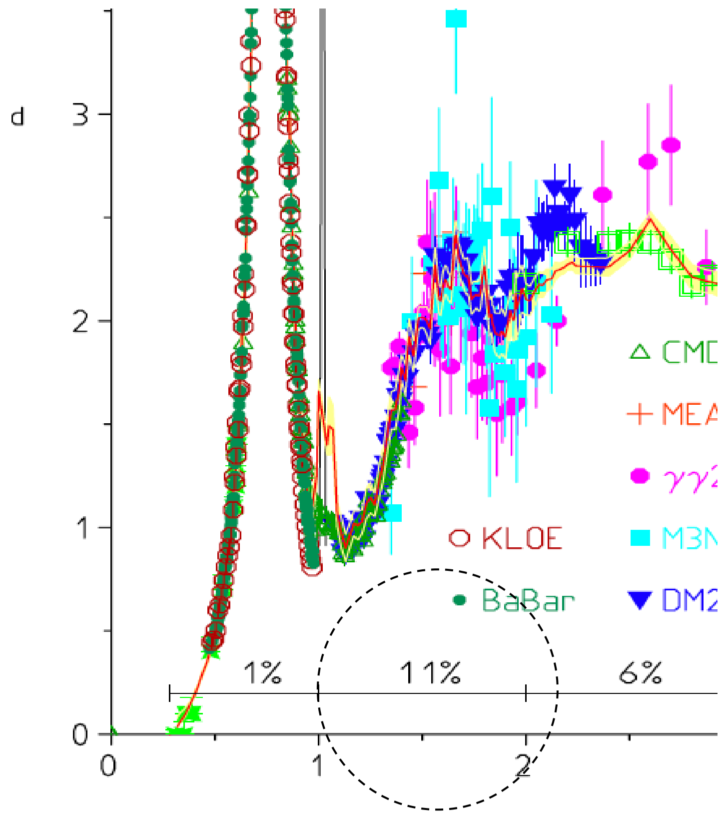
However the project is not yet approved…

Precise measurement of σ_{HAD} at low energies very important also for $\alpha_{em}(M_Z)$ (necessary for ILC) !!!

Data at 2012 (F.J.)



Many improvements (mostly due to BaBar ISR).
However the region below 2.5 GeV is still poorly known ($\delta R \sim 5$-15%)



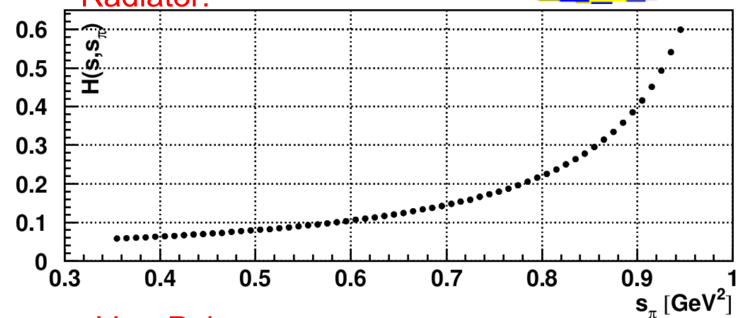
Radiative Corrections

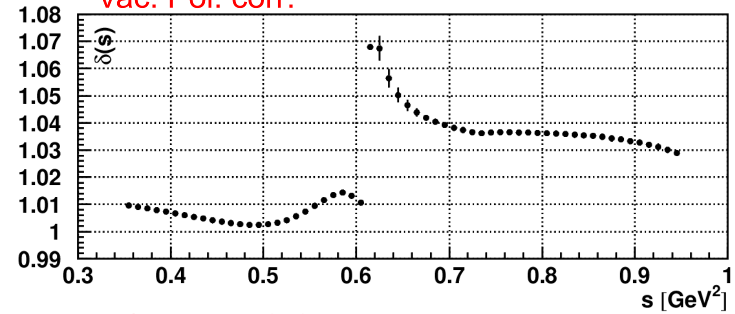
Radiator-Function $H(s,s_p)$ (ISR):

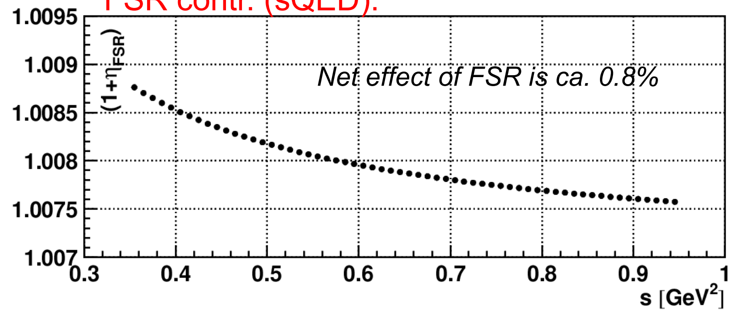
- **ISR-Process calculated at NLO-level**
  PHOKHARA generator
  (H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

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:

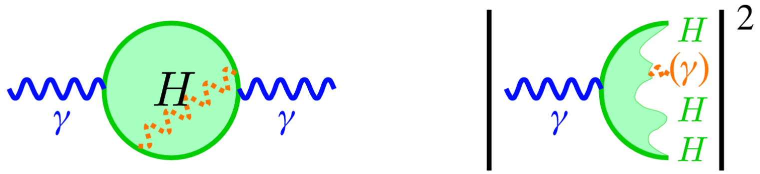
i) Bare Cross Section

divide by Vacuum Polarisation $d(s)=(a(s)/a(0))^2$

➔ from F. Jegerlehner

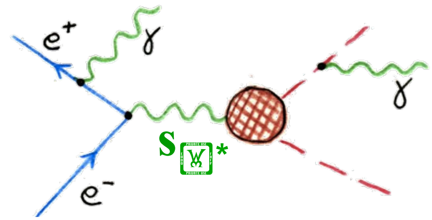
ii) FSR

Cross section s_{pp} must be incl. for FSR
for use in the dispersion integral of a_m



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

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



$s_{\gamma*} > s_p$

SA Event Selection (KLOE08)

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

b) small angle (not detected) γ

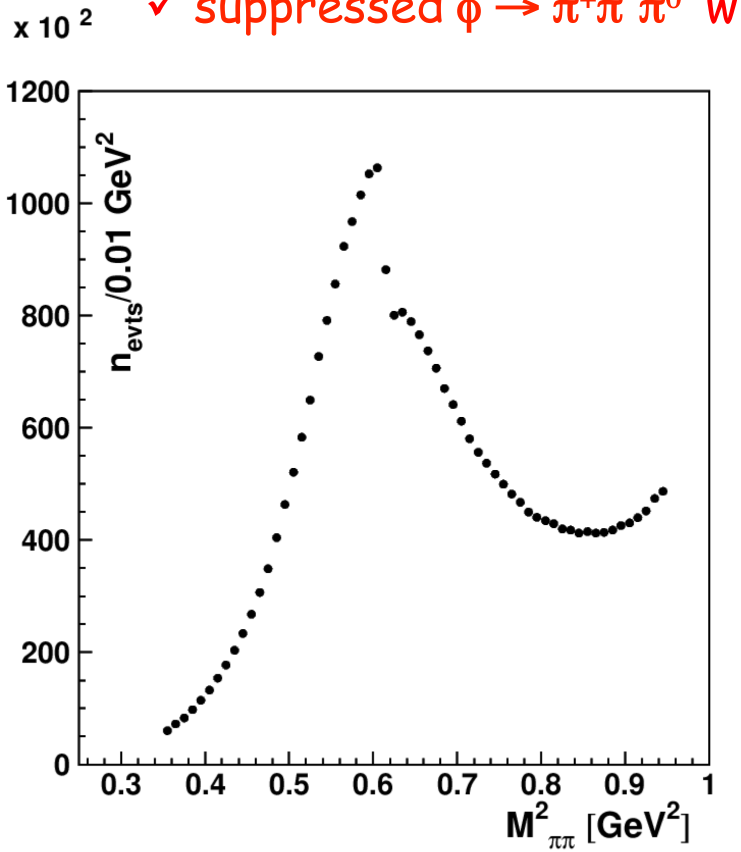
($\theta_{\pi\pi} < 15^o$ or $> 165^o$)

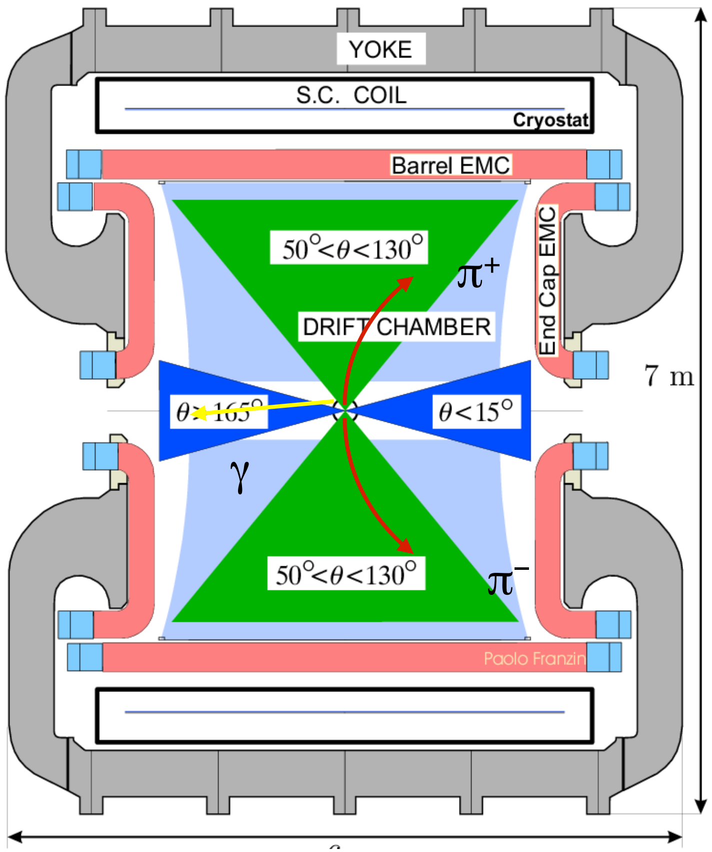
✓ high statistics for ISR

✓ low relative FSR contribution

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

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





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

3.1 Mill. Events between 0.35 and 0.95 GeV^2

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 $< 9°$

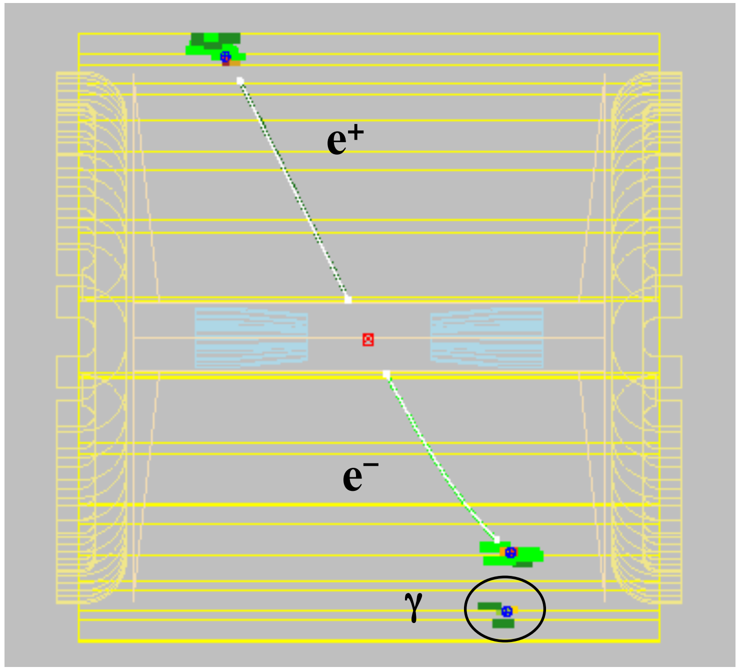
$p \geq 400$ MeV

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

generator used for σ_{eff}

BABAYAGA (Pavia group):

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



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

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

Luminosity:

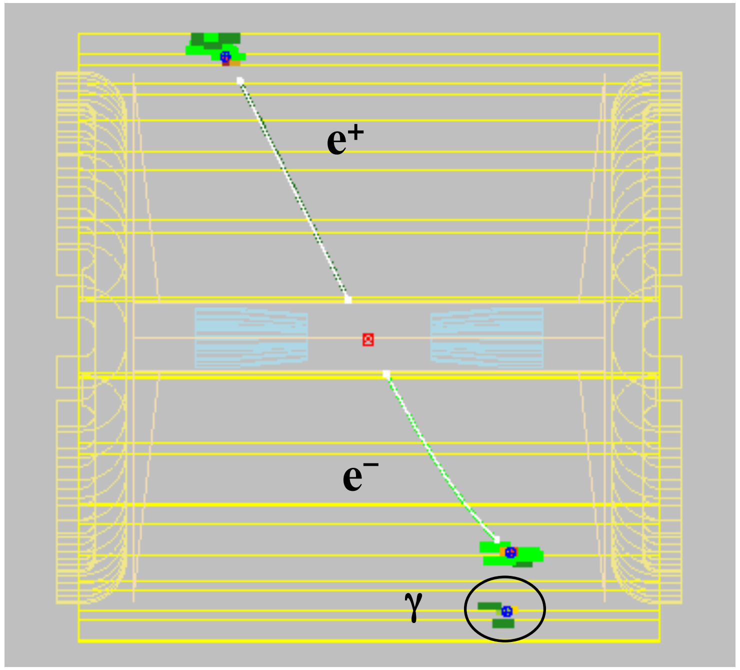
KLOE measures $\mathcal{L}$ with Bhabha scattering

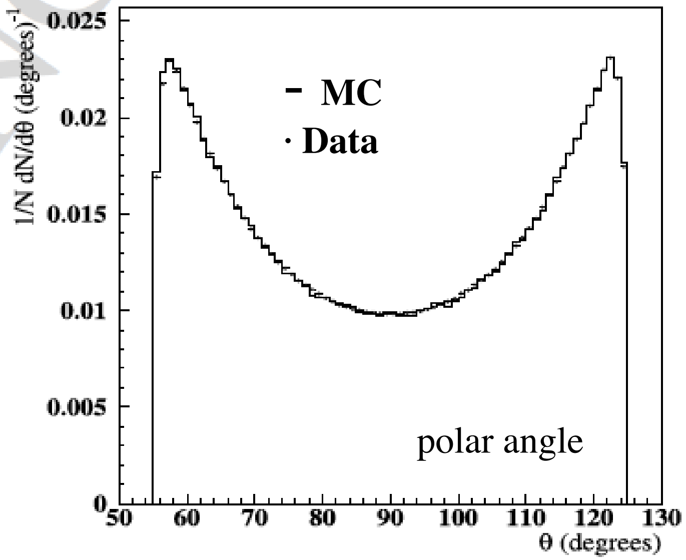
$55° < \theta < 125°$

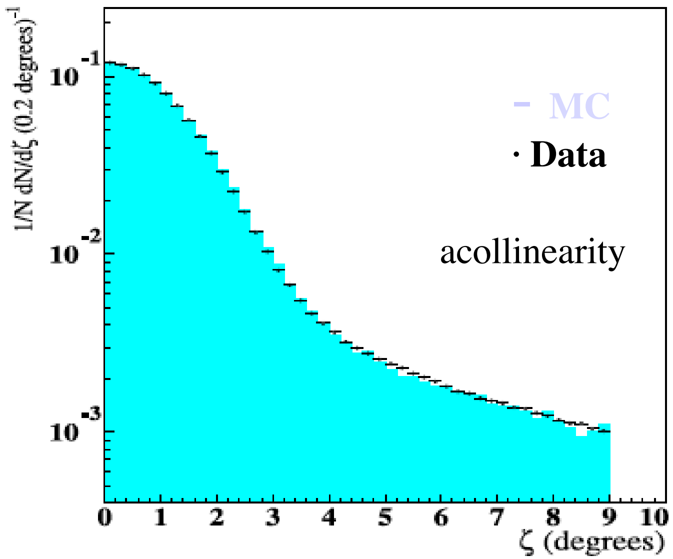
acollinearity < 9°

p ≥ 400 MeV

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







LA Event Selection (KLOE10)

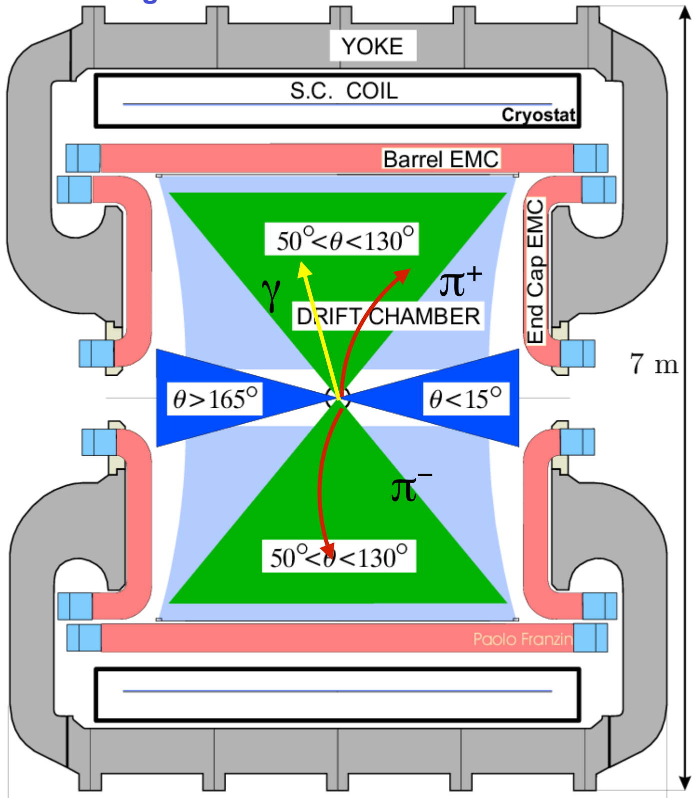
2 pion tracks at large angles
$50^o < \theta_\pi < 130^o$

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

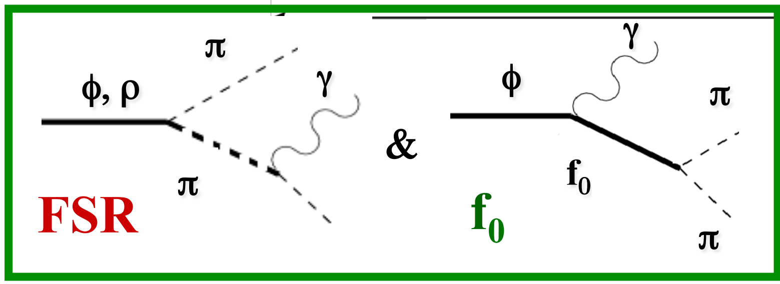
- ✓ **independent complementary analysis**
- ✓ **threshold region $(2m_\pi)^2$ accessible**
- ✓ **γ_{ISR} photon detected (4-momentum constraints)**

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

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



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



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