International Workshop on e+e- Collisions
from Phi to Psi (PHIPSI08)
Laboratori Nazionali di Frascati
April 7 - 10, 2008

BABAR Results on Hadronic Cross Sections with Initial State Radiation (ISR)

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for the BABAR collaboration

Motivation
&
ISR - Method

Motivation: $(g_\mu\text{-}2)$ and $\alpha(M_Z)$

Motivation:
High Precision Test of the Standard Model

→ Anomalous magnetic moment of the muon

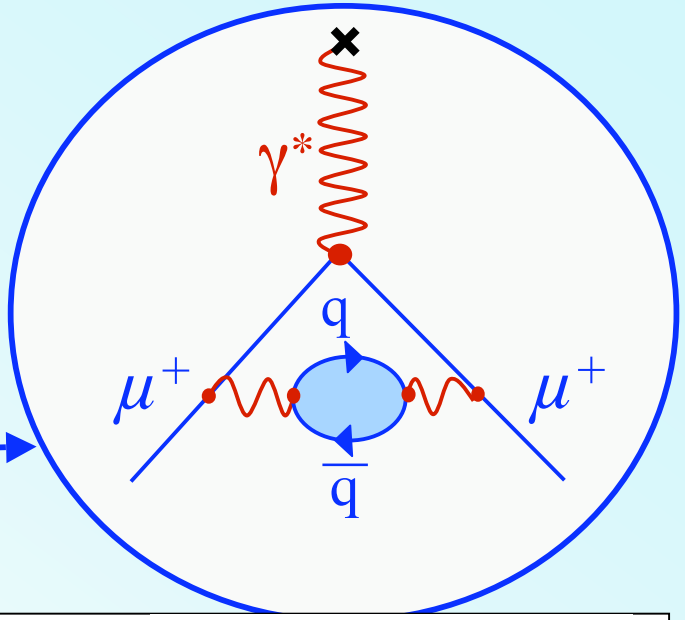
Muon-Anomaly $a_\mu = (g_\mu\text{-}2)/2 = \alpha/2\pi + \ldots.$

$$a_\mu^{\text{theo}} = a_\mu^{\text{QED}} + a_\mu^{\text{had}} + a_\mu^{\text{weak}} + a_\mu^{\text{New physics}}$$

→ Fine structure constant at Z^0-mass $\alpha_{\text{QED}}(M_Z)$

2nd largest contribution, *pQCD* not applicable
Error of hadronic contribution dominates total error of a_μ!

Hadronic Vacuum Polarization

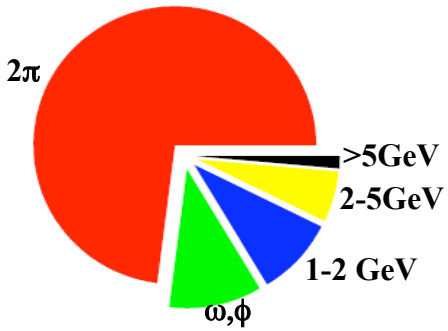


$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} \sigma_{\text{had}}(s)\, K(s)\, ds$$

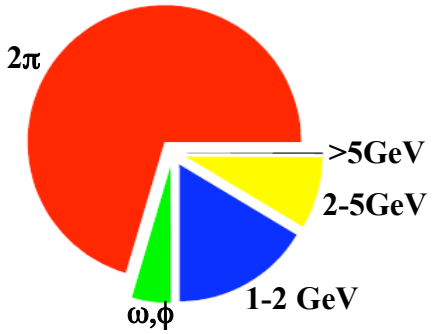
Experimental input into dispersion integral

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

Central Values

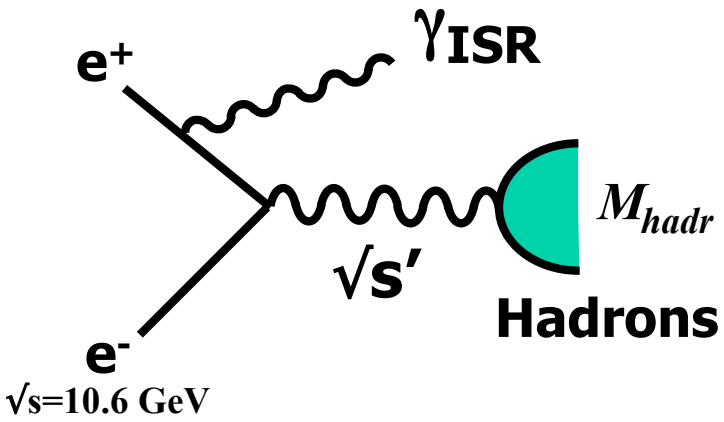


Uncertainties



from S. Eidelman

ISR at Υ(4S) Energies



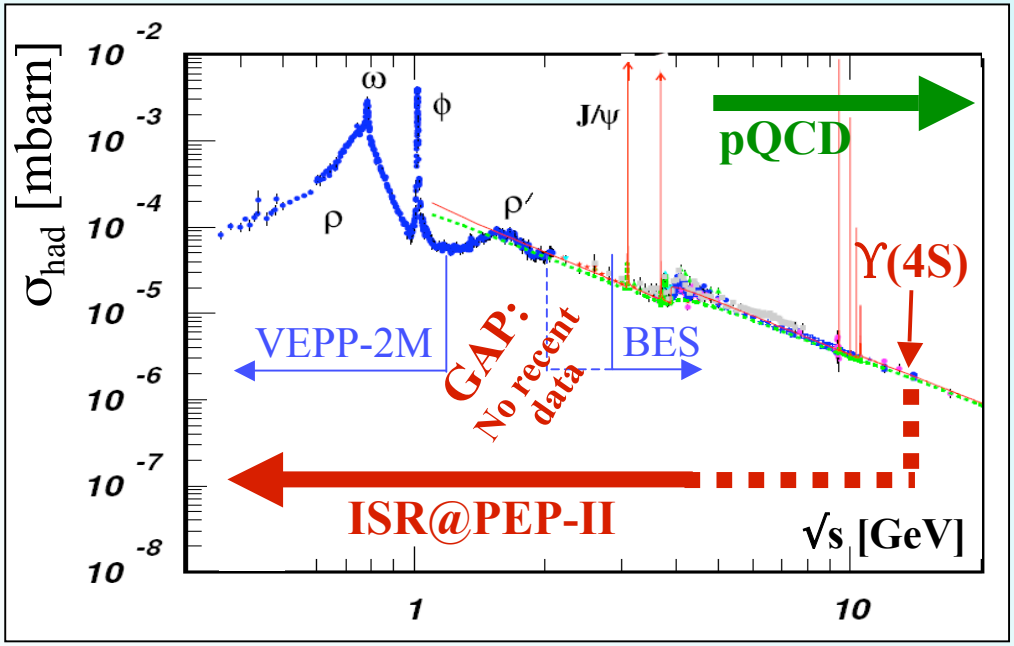
Master-Formula:

$$M_{hadr}\frac{d\sigma_{Hadr+\gamma}}{dM_{hadr}} = \sigma_{hadr}(s)\times H(s)$$

Radiator-Function (NLO)
MC-Generators EVA, Phokhara, AfkQed
J. Kühn, H. Czyż, G. Rodrigo

ISR-physics:

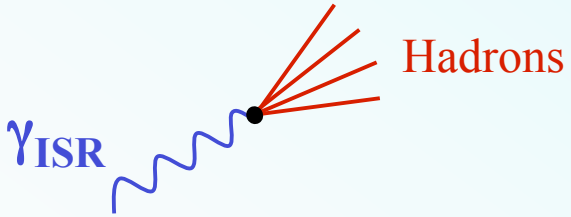
- Already used at KLOE, used at *BABAR* over a wider energy range
- Whole **√s' spectrum from threshold to ~ 4 … 5 GeV**
- Data comes as a by-product to the main physics goal of PEP-II
- Greatly **reduced point-to-point uncertainty** with ISR-program at PEP-II



ISR at Υ(4S) Energies

Features:

- Rely on **tagged (=measured) photon** for identifying ISR-events
- Excellent momentum resolution by means of **kinematic fit**
- High **fiducial efficiency** :
  wide-angle ISR-γ forces hadronic system into detector fiducial region at large polar angles



- Harder momentum spectrum due to boost
  - **fewer problems with soft particles;**
  - **allows to go down to threshold**
- Typically **systematic uncertainties ~5%** up to ~20% depending on mass and channel

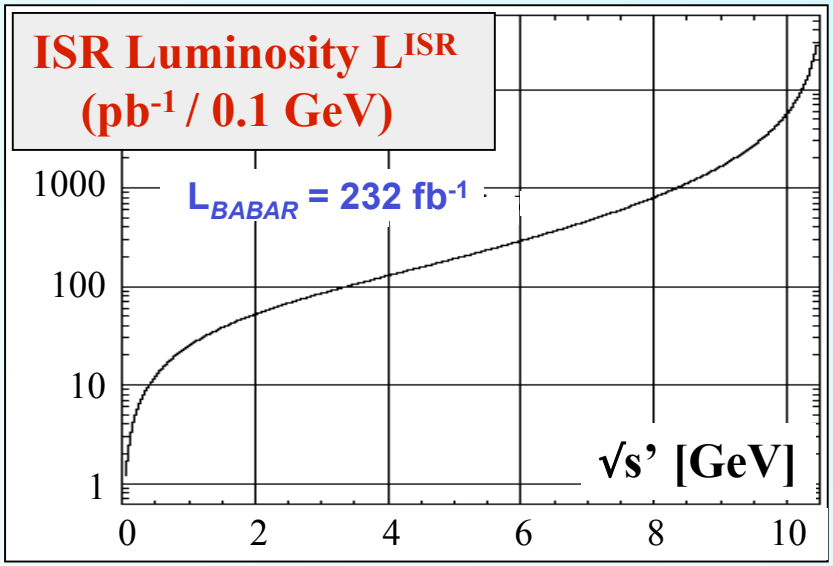
Normalitzation:

1) **Integr. Luminosity L_{int} • Radiator Function H**
   → Large angle Bhabhas → Theory

OR

2) **Or better: use $e^+e^- \to \mu^+\mu^-\gamma$ events**

$$dL^{ISR}(M) = \frac{dN_{\mu\mu\gamma}(M)}{\varepsilon_{\mu\mu\gamma}(M)(1+\delta_{FSR}(M))\sigma^{Born}_{\mu\mu}(M)} = L_{int} \cdot dH$$

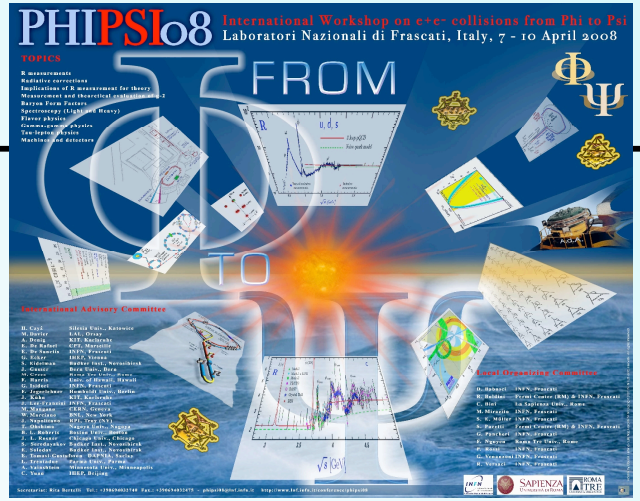


L_{ISR} = integrated luminosity in energy scan, corresponding to same statistics as the one in ISR method

International Workshop
e+e- Collisions from phi to psi
February 27 - March 2, 2006

Exclusive Hadronic Channels available at PhiPsi06 @ BINP

- $e^+e^- \to \pi^+\pi^-\pi^0$
- $e^+e^- \to 2(\pi^+\pi^-), \pi^+\pi^-K^+K^-, 2(K^+K^-)$ } 89 fb^{-1}
- $e^+e^- \to 3(\pi^+\pi^-), 3(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$ } 232 fb^{-1}
- $e^+e^- \to p\bar{p}$



Many new Results since then ....

- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$
- $e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-K^+K^-\pi^0$, $\pi^+\pi^-K^+K^-\eta$
- $e^+e^- \rightarrow K^+K^-\pi^0$, $K^+K_S\pi^-$, $K^+K_S\eta$
- $e^+e^- \rightarrow \Lambda^0\bar{\Lambda}^0$, $\Lambda^0\bar{\Sigma}^0$, $\Sigma^0\bar{\Sigma}^0$

all based on 232 fb^{-1}
now available: ~500 fb^{-1} !

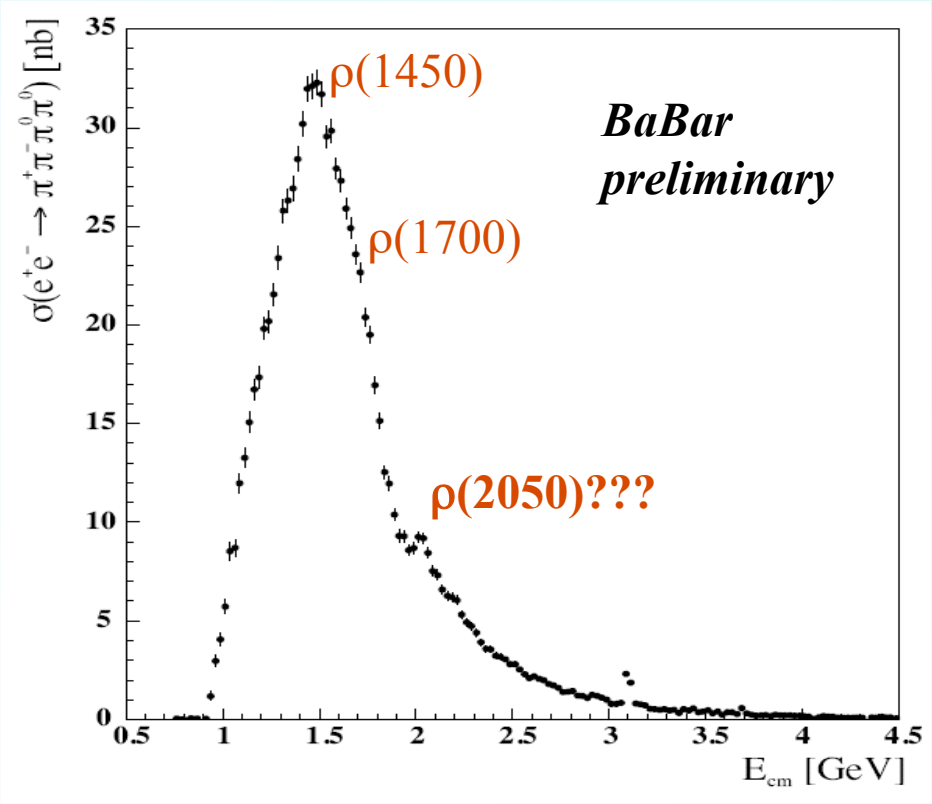
4 Hadrons:

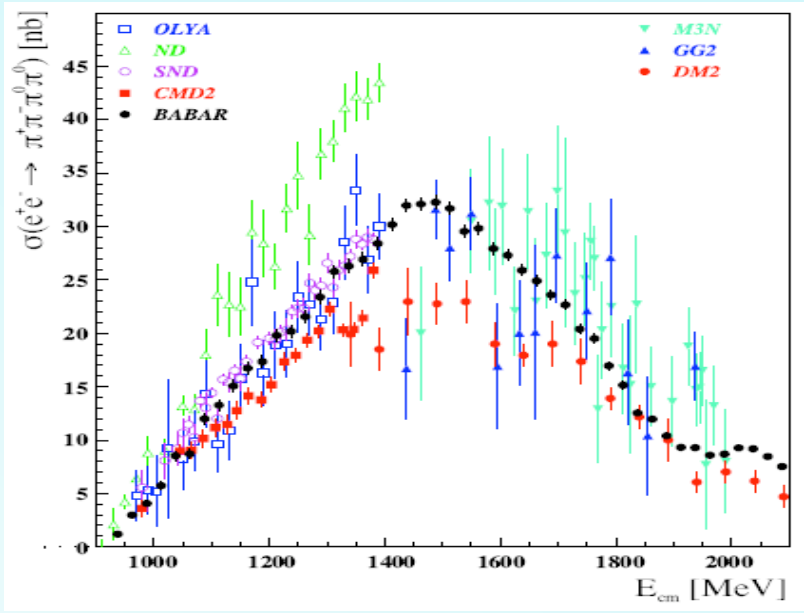
$$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$$

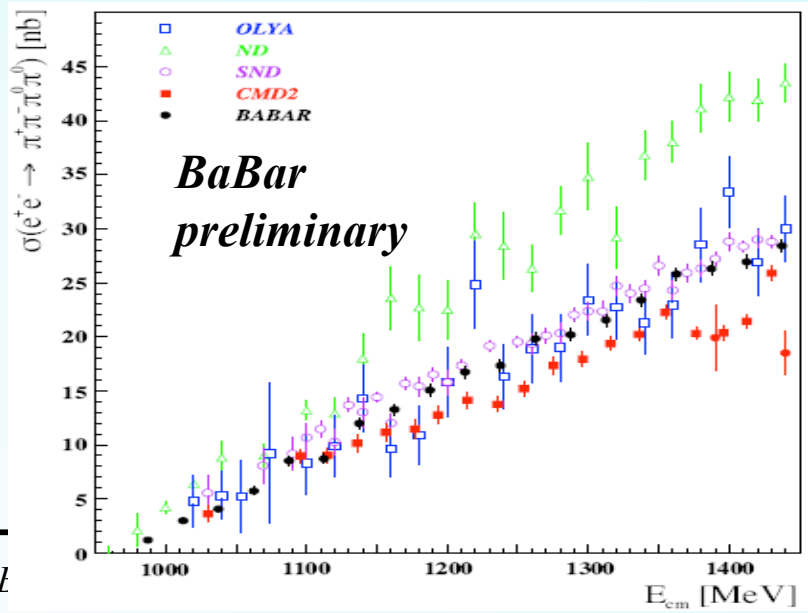
$$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$$

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

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



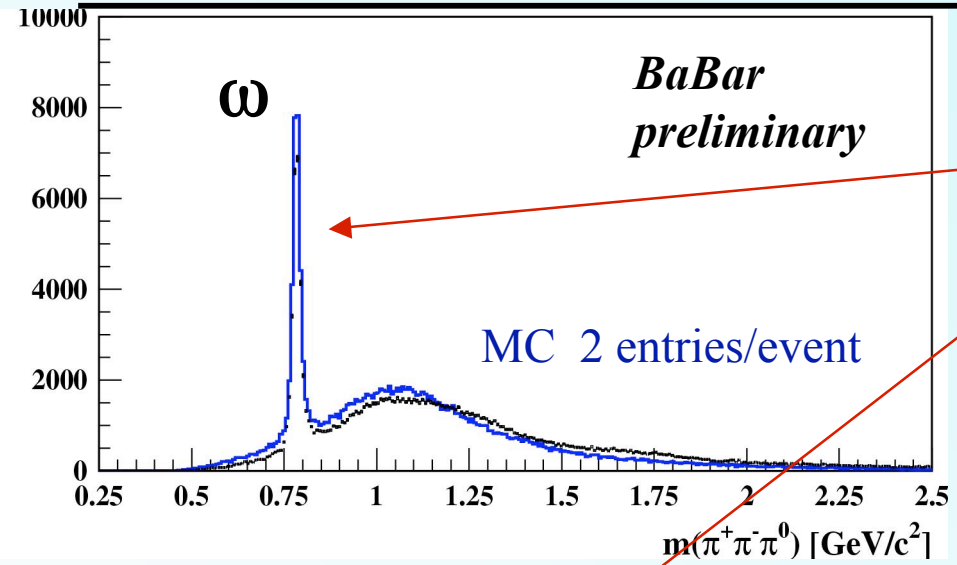




Features:

- Important mode for a_μ and α_{QED}
- Preliminary precision: 8% in peak → 5%
- Good agreement with SND <1.4 GeV
- Huge improvement >1.4 GeV
- First measurement >2.5 GeV

Substructures in $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$



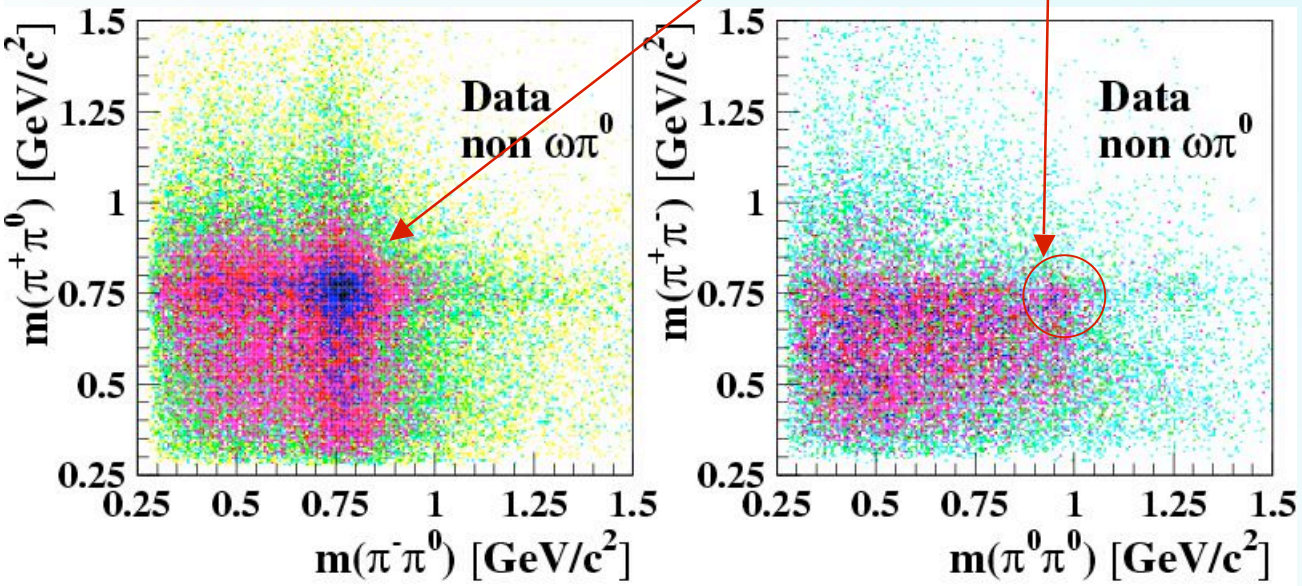
Intermediate states:

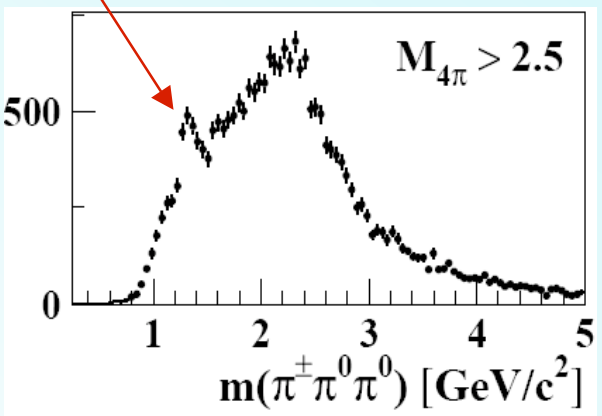
$\omega\pi^0$

$\rho^+\rho^-$, combine with meas. at 10.6 GeV

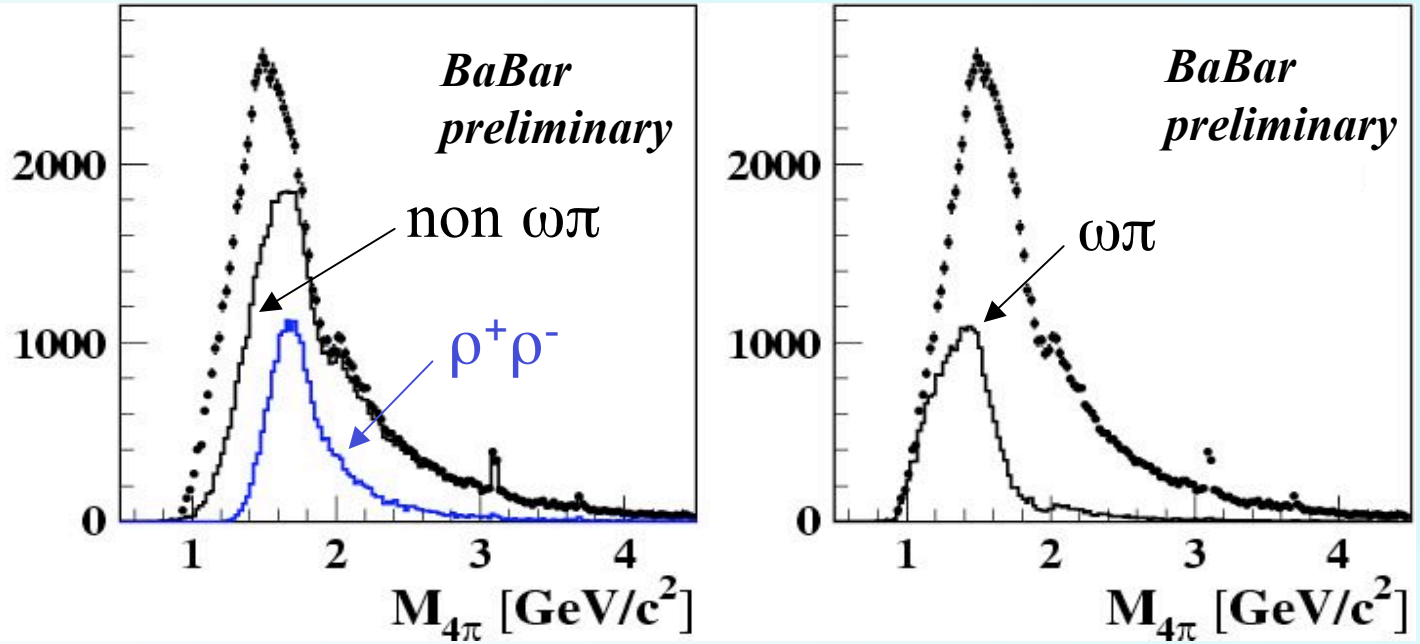
$\rho^0 f_0(980)$

$a_1(1260)\,\pi$





(Sub)structures in $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$



New 4π MC (Czyz, Kühn, Wapienik) arXiv:0804:0359

Questions:

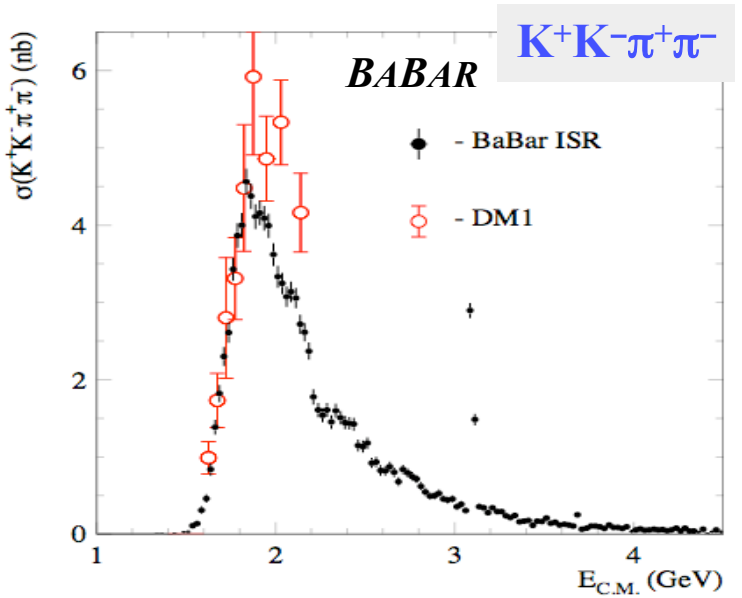
- For **first time $\rho^+\rho^-$ is seen**, it is large and even dominating the non-ω-spectrum, surprise in QCD? Combine with BABAR measurement at 10.6 GeV
- The structure at **2050 MeV is the ρ(2050)**?!

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

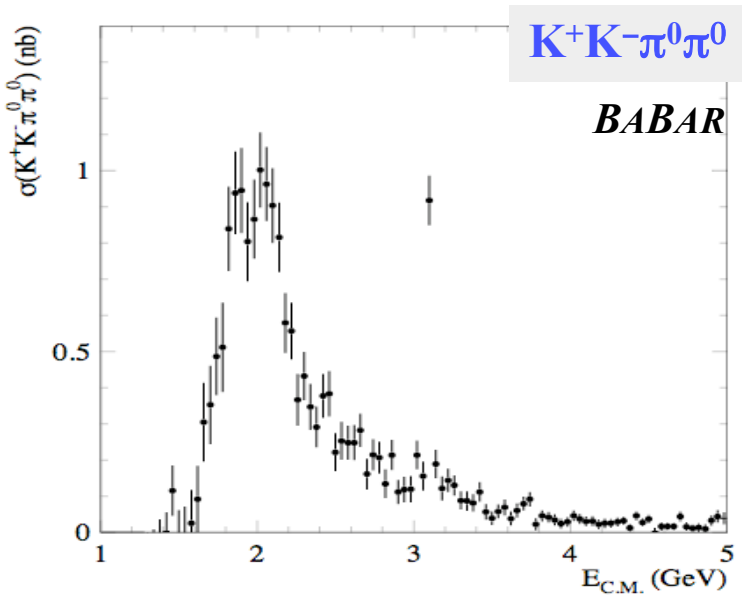
PRD-RC 74 (2006) 091103

Motivation:

- Factor 2.5 **more statistics** with respect to published result
- Search for **$\phi(1020)f_0(980)$ final state** and relation to $\phi(1020) \to f_0(980)\,\gamma$
- BR of **J/ψ and $\psi(2S)$ to $\phi(1020)\pi\pi$**
- Search for **new states**

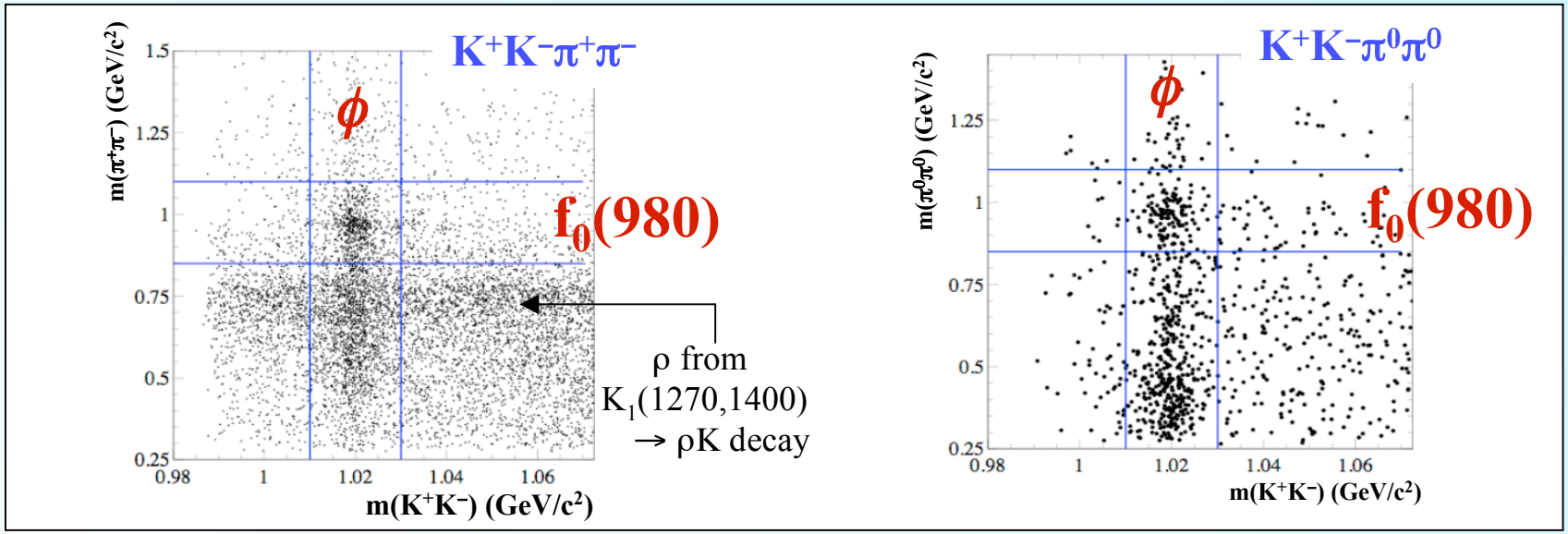


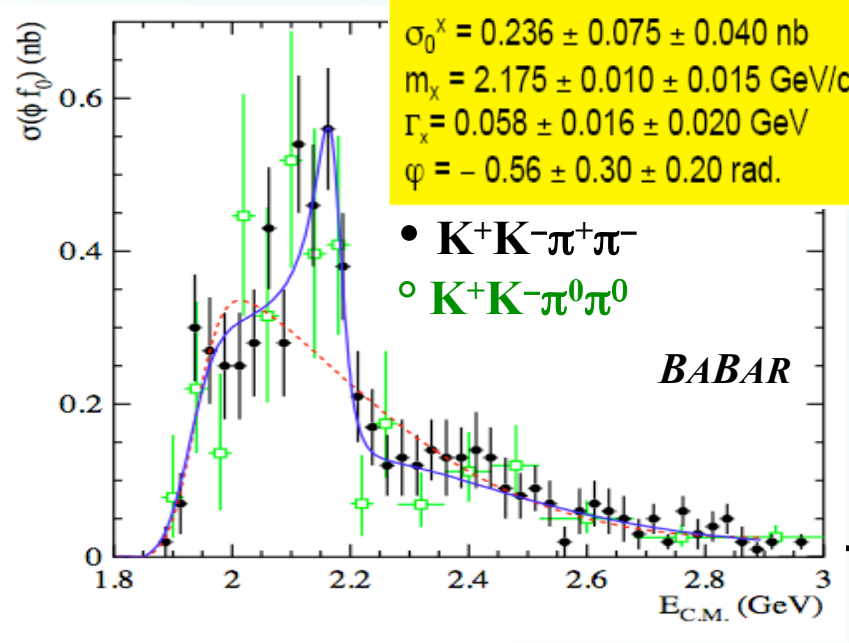
- Systematic error 8% (was 15%)
- Error dominated by acceptance



- First measurement ever !
- Systematic error 11%

Structure in $e^+e^- \to \phi\, f_0(980)$





New state with $J^{PC}=1^{--}$ with mass of 2.175 GeV and 58 MeV width ?

Fit: $\sigma(E_{c.m.}=\sqrt{s}) \sim \sqrt{1-\frac{4m^2_{f_0,\phi}}{s}} \cdot \left| \frac{\sqrt{\sigma_0}\, m_x \Gamma_x e^{i\varphi}}{m_x^2 - s - i m_x \Gamma_x} + A_{bkg.} \right|^2$

Toy MC gives $<10^{-3}$ probability for stat. fluctuation

Strangeness partner of Y(4260) ?

PRD 76 (2007) 092005

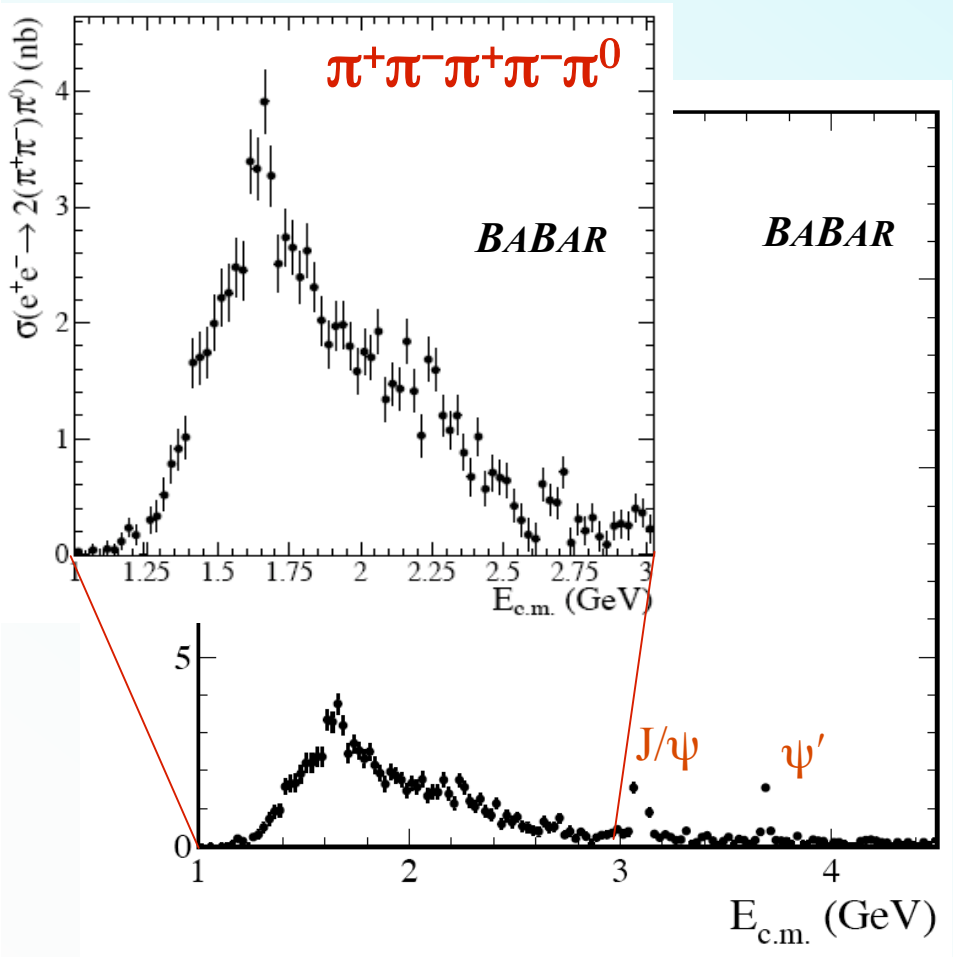
5 Hadrons:

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

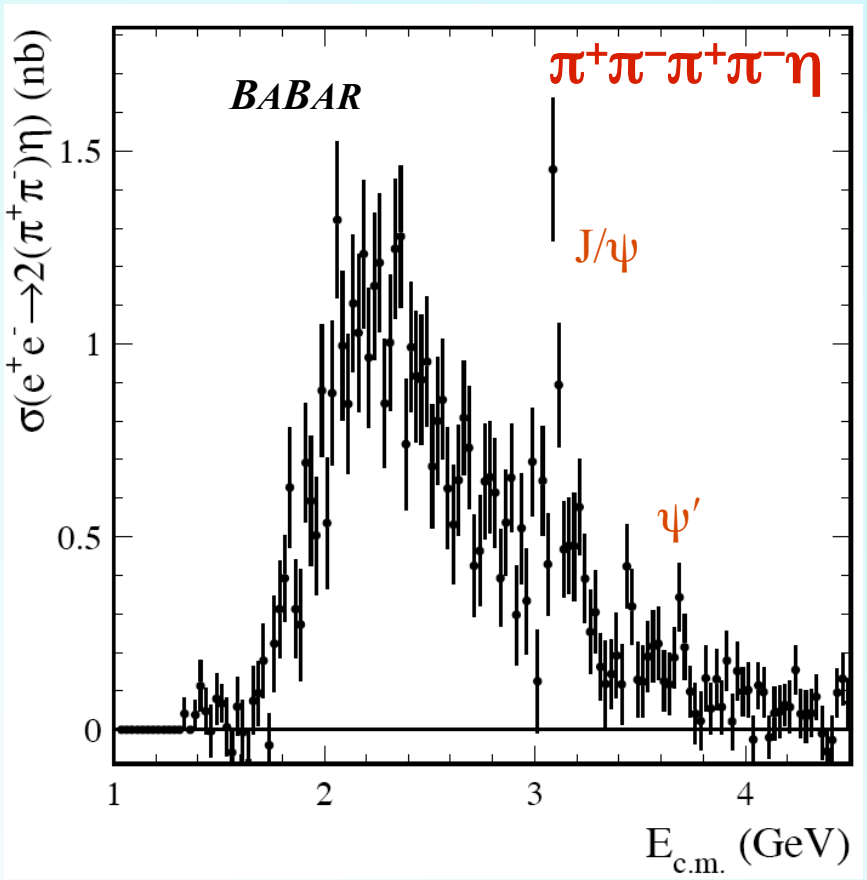
$$e^+e^- \rightarrow K^+K^-\pi^+\pi^-\pi^0,\ K^+K^-\pi^+\pi^-\eta$$

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-\eta$

First inclusive measurement of these states

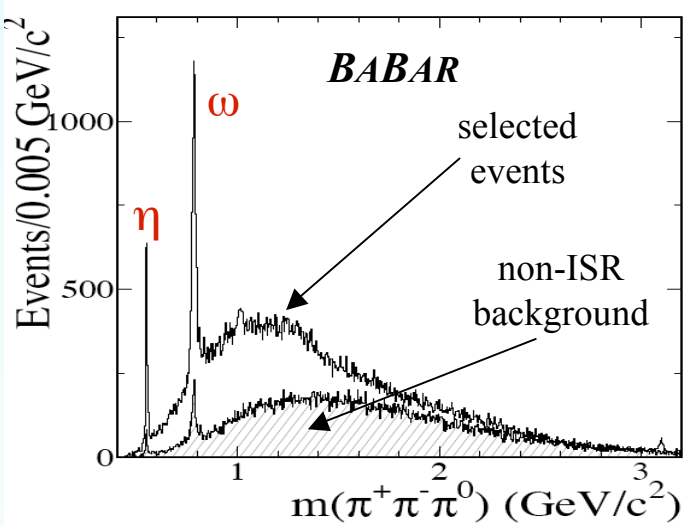


30.000 events (20% bkg. on peak)



4.300 events (20% bkg. on peak)

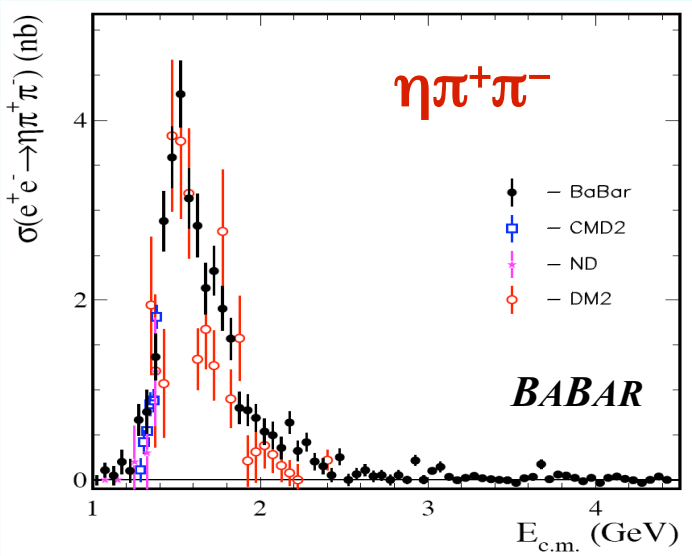
Substructures $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0$

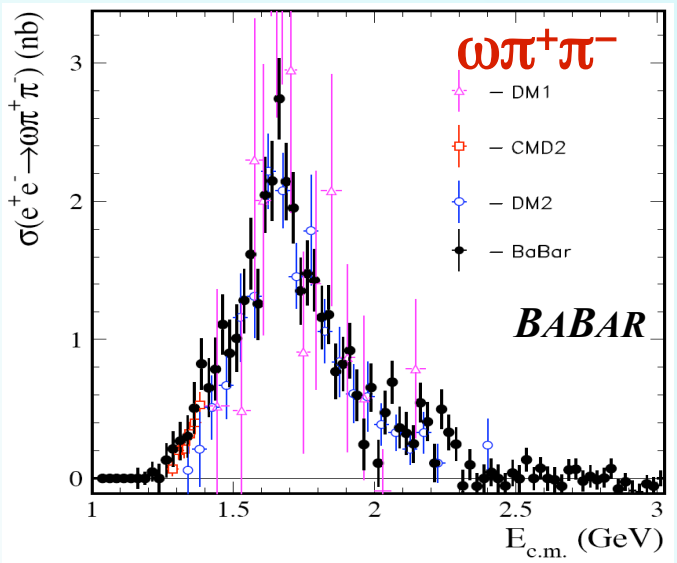


Rich structure: clear peaks are visible

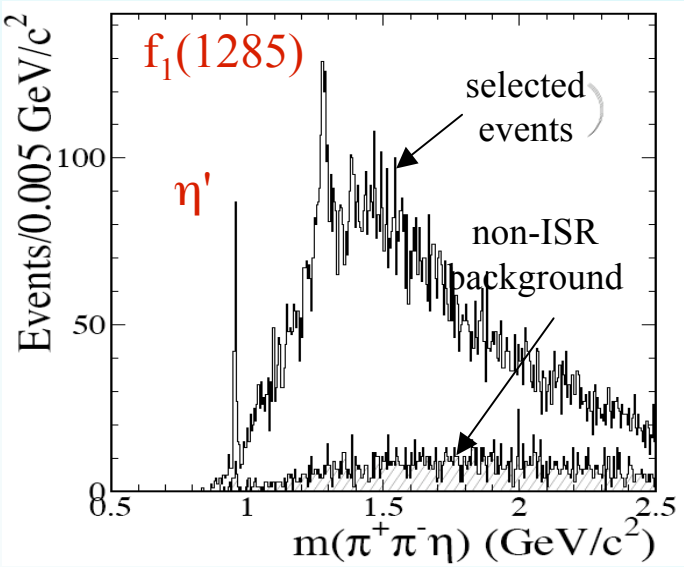
- ~20% $\eta\pi^+\pi^-$, mostly $\eta\rho^0$
- ~40% $\omega\pi^+\pi^-$, contains some ωf_0
  the rest is well described by ω' and ω''
- then almost all $\rho^0\rho^+\pi$-

$\eta\pi^+\pi^-$ and $\omega\pi^+\pi^-$ modes consistent with previous measurements, better precision





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



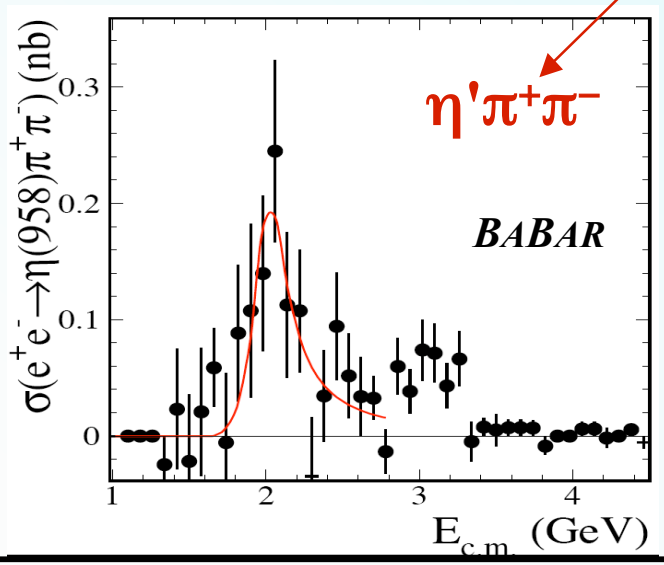
Clear evidence for η' and $f_1(1285)$, both channels showing a stracture at ~2 GeV

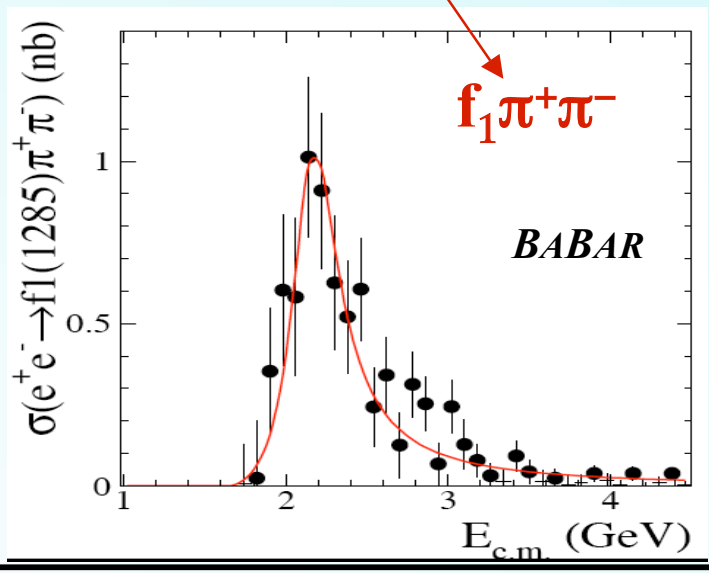
➔ Is this the $\rho(2150)$, $\rho(2050)$?

$m = 1.99 \pm 0.08$ GeV/c^2
$\Gamma = 0.31 \pm 0.14$ GeV

single BW fits

$m = 2.15 \pm 0.04 \pm 0.05$ GeV/c^2,
$\Gamma = 0.35 \pm 0.04 \pm 0.05$ GeV





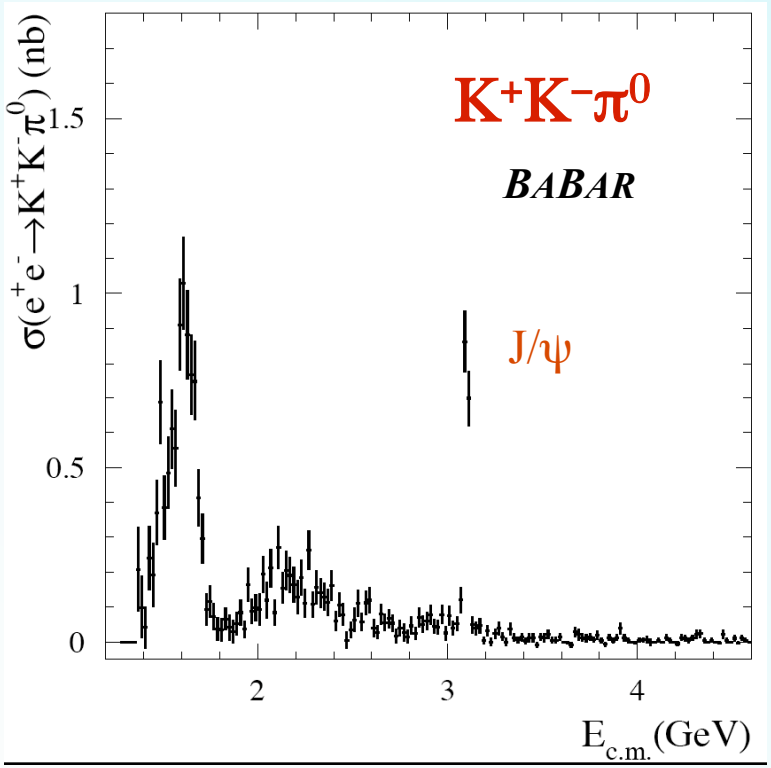
arXiv:0710.4451 submitted to PRD

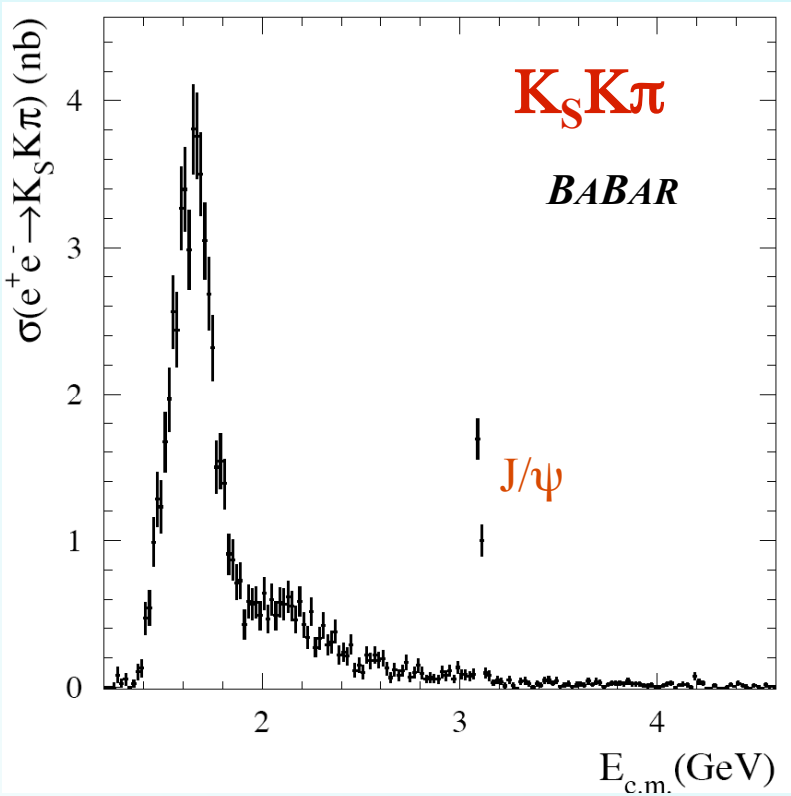
3 Hadrons including 2 Kaons:

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

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

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

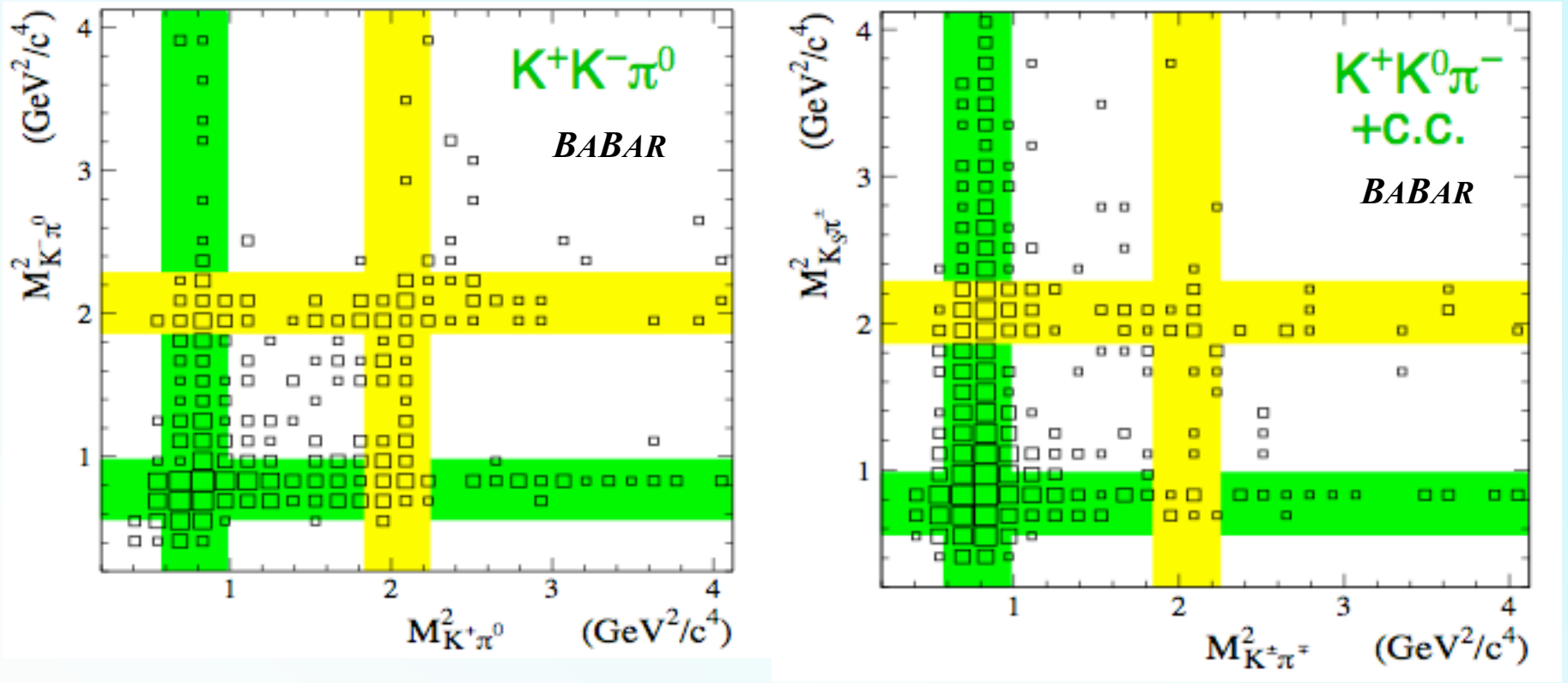




Features:

- Dominant decay mode for the **$\phi(1680)$**
- Systematic errors 5% - 6%
- Significant improvement over existing measurements from DM1, DM2

Dalitz plots for the $K^+K^-\pi^0$, $K_SK\pi$



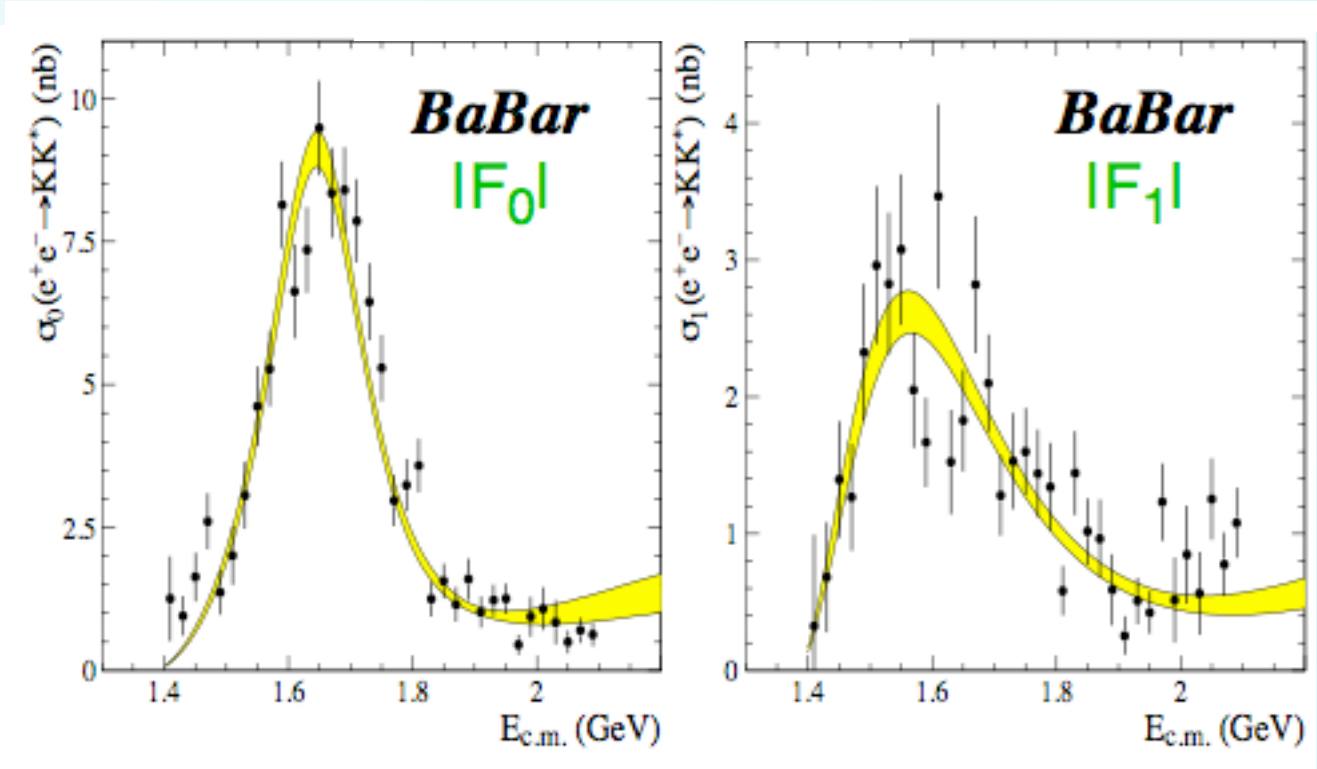
Both Dalitz plots are dominated by the K*(890), some K_2*(1430) also present

➔ Allows to extract the isospin components (isoscalar, isovector) of the KK*(890) cross section (moduli and relative phase)

➔ Allows a description in terms of vector meson resonances **without** interferences

Isospin components in K(890)K*

A global fit in $E_{c.m.}$ bins has been performed



Result: isoscalar and isovector channels are dominated by resonances

$m = 1708 \pm 47$	1505 ± 20 MeV/c^2
$\Gamma = 322 \pm 178$	418 ± 25 MeV
consistent with: $\phi(1680)$	$\rho(1500)$

to appear in PRD

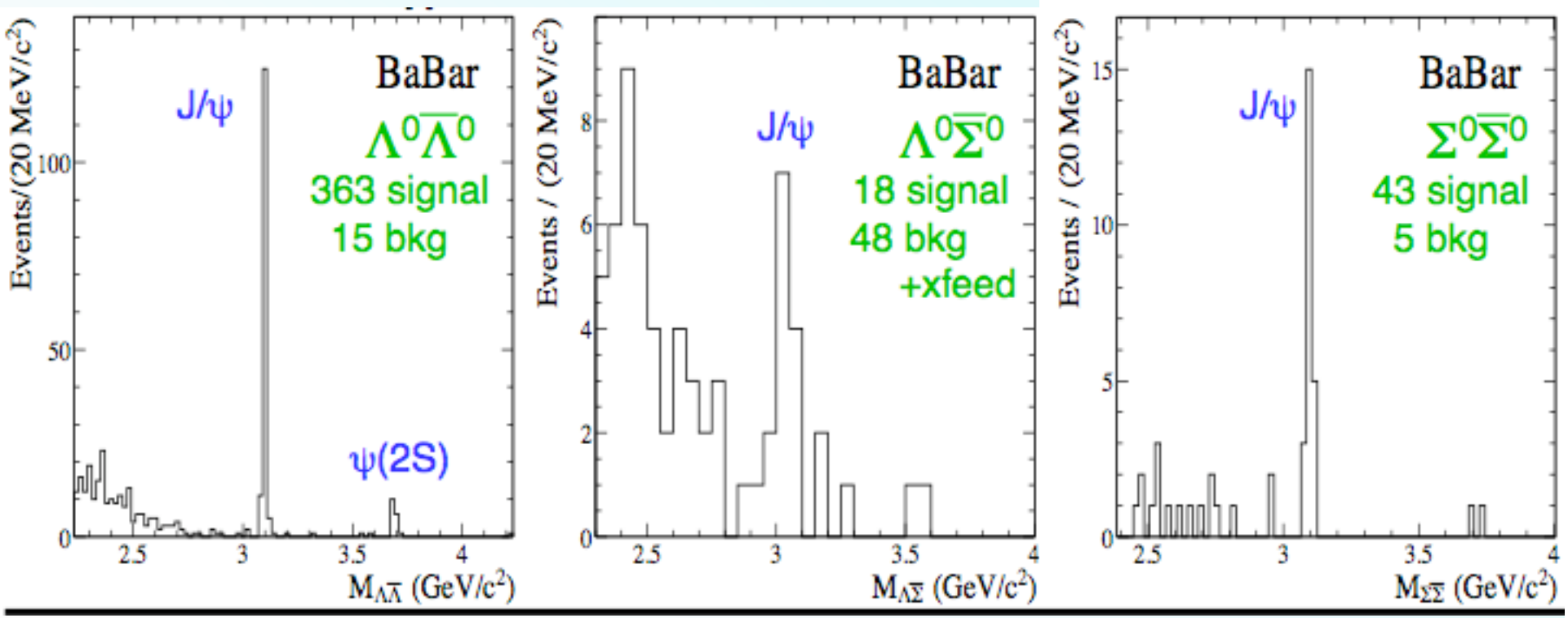
Baryons:

$$e^+e^- \rightarrow \Lambda^0\bar{\Lambda}^0,\ \Lambda^0\bar{\Sigma}^0,\ \Sigma^0\bar{\Sigma}^0$$

$e^+e^- \to \Lambda^0\overline{\Lambda^0}, \Lambda^0\overline{\Sigma^0}, \Sigma^0\overline{\Sigma^0}$

Continuation of the ISR-baryon program, which started with the measurement of the proton form factor in the time like region

Select events with $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$
Add an additional photon for the Σ candidates
Perform a kinematic fit with Λ, Σ mass constraints and distinguish channels based on best χ^2



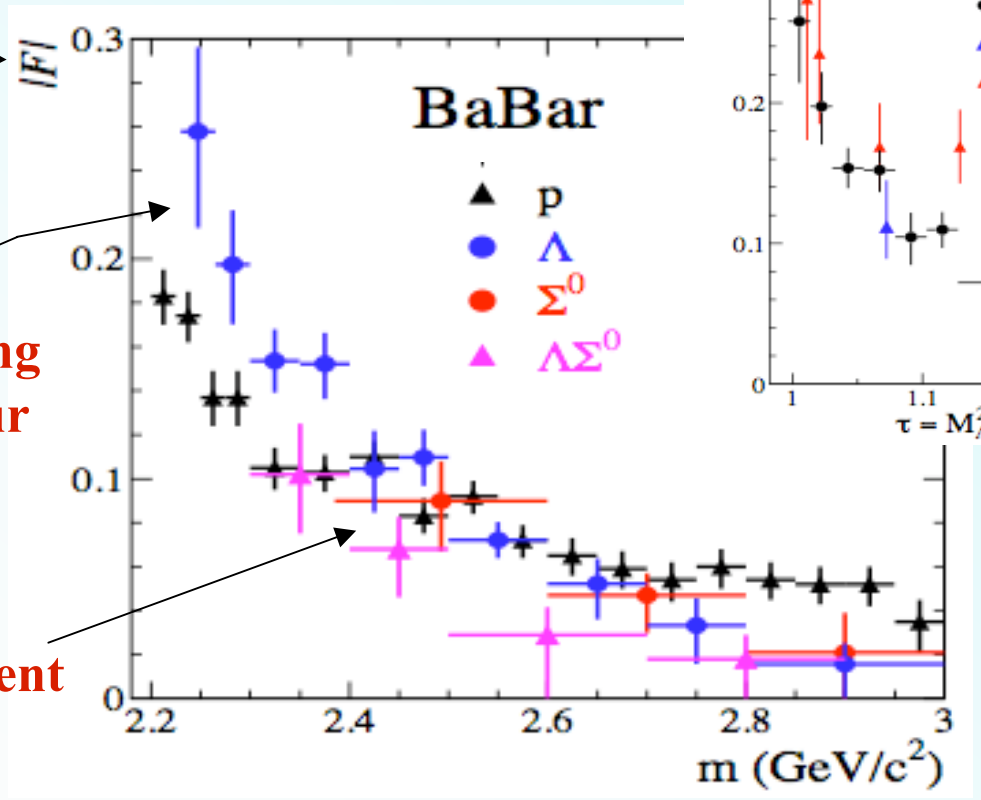
Baryon (Effective) Form Factors

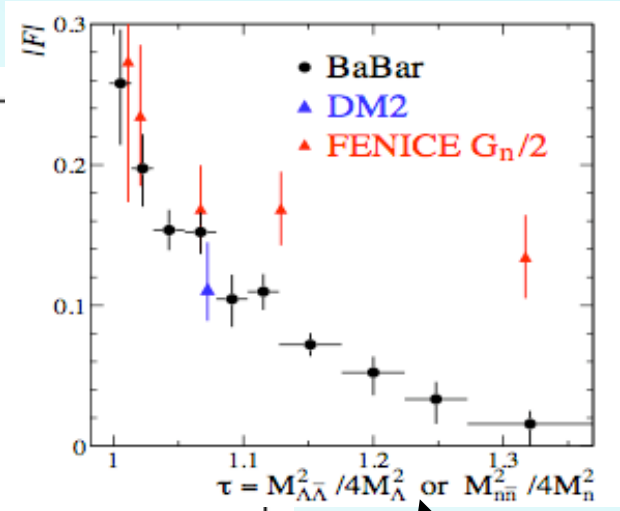
$$\sigma_{B\overline{B}}(m) = \frac{4\pi\alpha^2\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

Cross section parametrized by magnetic and electric form factors G_M and G_E

$\tau = m^2/4m_B^2$

Effective FF:
$|G_E|=|G_M|$





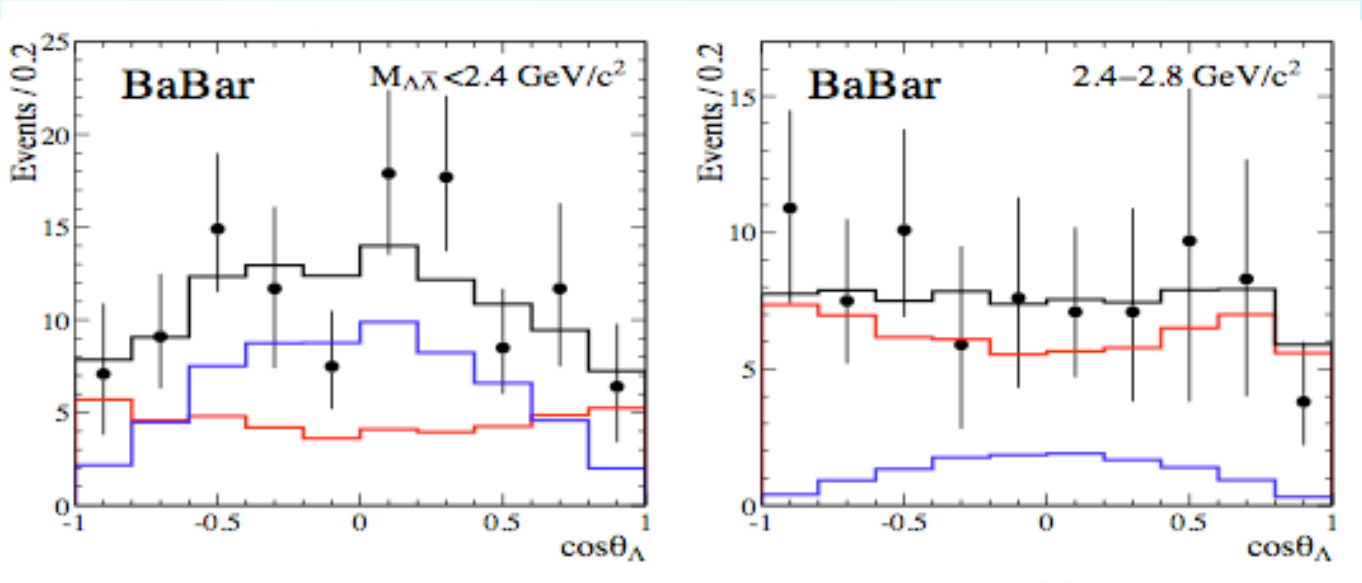
All FF's showing rising behaviour

All FF's seem to have consistent behaviour

F_Λ in agreement with the prev. measurem. (DM2) and with F_n (FENICE)

$|G_E / G_M|$ for $\Lambda^0\bar{\Lambda}^0$

- Can **measure $|G_E/G_M|$** by fitting the distribution of the cosine of helicity angle



$|G_E/G_M| < 1.73^{+0.99}_{-0.57}$ $\quad$ $|G_E/G_M| < 0.71^{+0.66}_{-0.71}$

Within large errors consistent with proton results

- Λ^0 polarization tested by fitting the slope of the angle btw. the polarization axis and the proton momentum in the Λ^0 rest frame: **$-0.22 < P_\Lambda < 0.28$ @90% C.L.**
  ➔ **tests a non-zero relative phase btw. G_E and G_M: $-0.76 < \sin\phi < 0.98$**

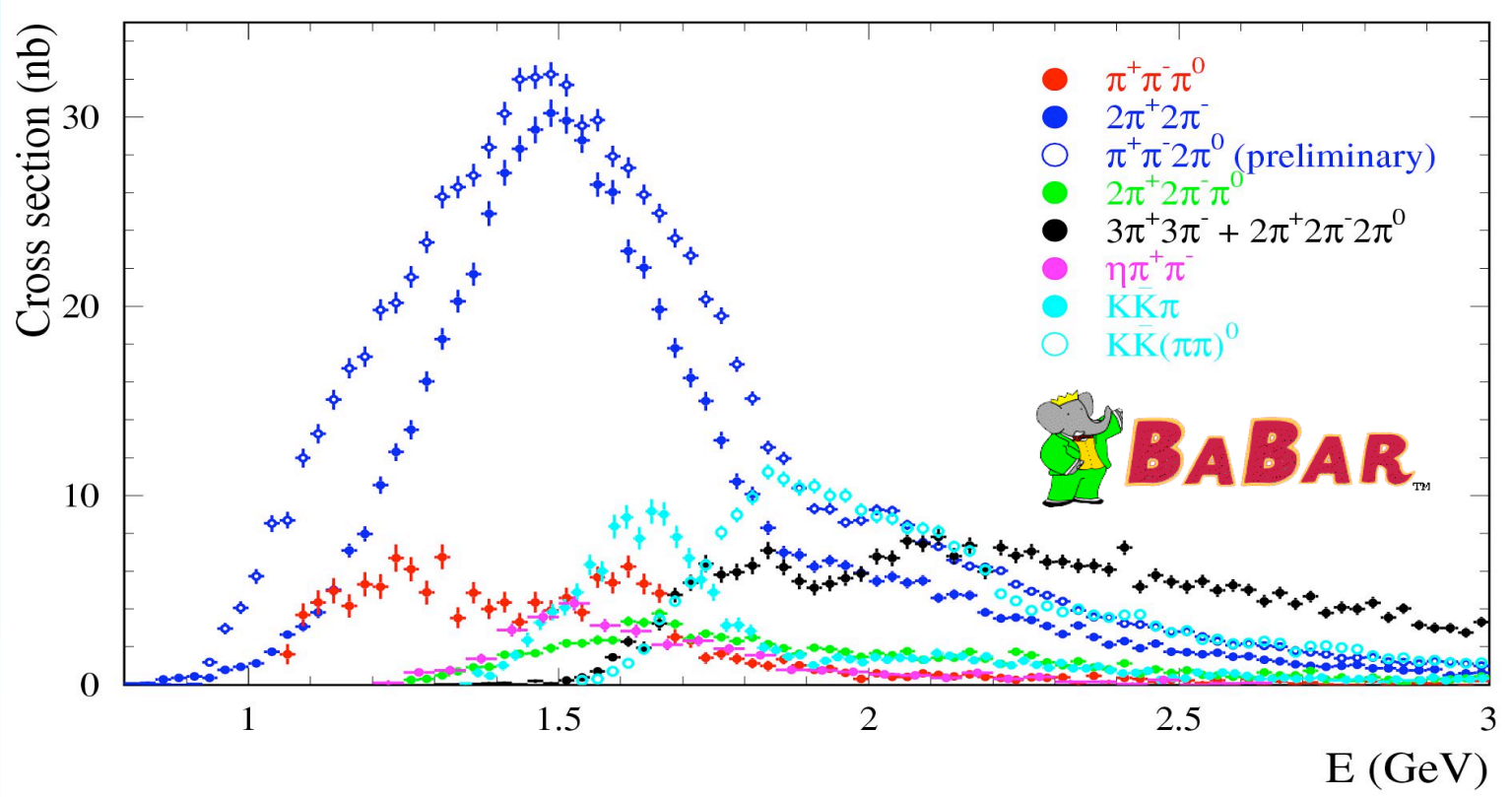
Czyz, Grzelinska, Kühn: hep-ph/0702122

Conclusions

Conclusions

- Radiative Return physics continues to be a productive field beyond B-physics at *BABAR*
- Measurements are important to improve our theoretical understanding of $(g\text{-}2)_\mu$ and $\alpha(M_Z)$
- (Sub)Structures: growing impact in the field of hadron spectroscopy
  - New structures at low energies at M~2175, 1900, 2050, ... MeV
  - *Y(4260)* discovered in ISR-events
  - 26 J/ψ and 10 ψ(2S) branching ratios measured, very competitive
- In future many new, improved studies planned
  - update current results
  - additional excl. channels under study, in particular $e^+e^- \rightarrow \pi^+\pi^-$
  - inclusive measurements of R

Conclusions



To calculate R only using *BABAR* data in the energy range <2 GeV the missing processes $\pi^+\pi^-$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, K^+K^-, K_SK_L, $K_SK_L\pi\pi$ must be measured.