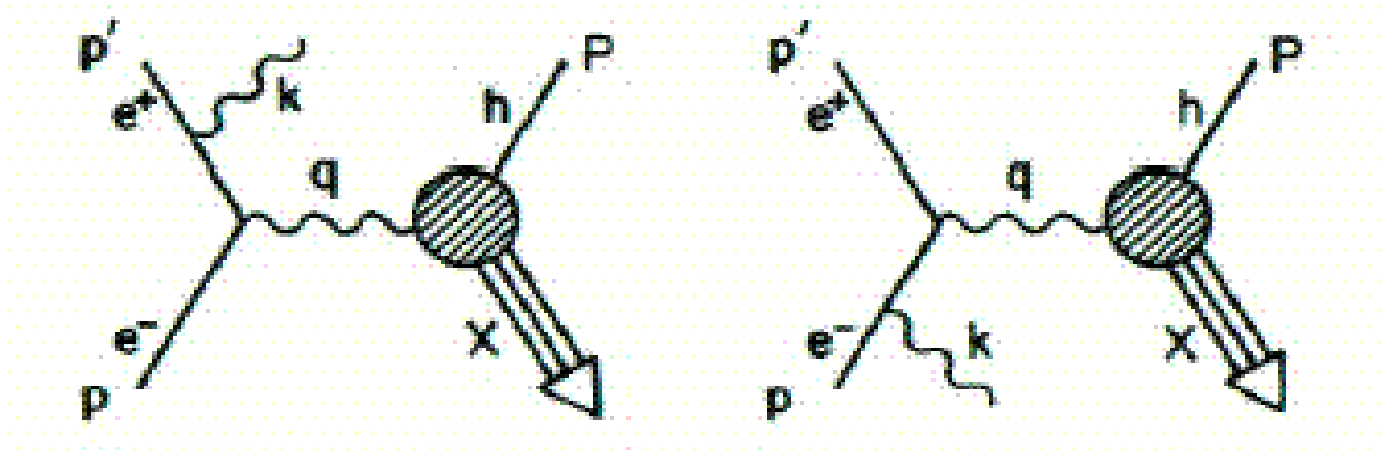
Initial State Radiation Studies at the Y(4S) in BaBar

Evgeny Solodov, Novosibirsk
on behalf of the BaBar collaboration



Motivation

Initial State Radiation Studies at the (4S) are equivalent to low-energy e+e- experiments. Due to very high luminosity of B factory it could give competitive results in various fields (e.g. spectroscopy and hadronic contributions to g_ -2 and _em) in spite of _ suppression of the ISR cross-section and (10-15)% efficiency of ISR photon reconstruction.
It is of special interest in the 1.4-3.0 GeV range of c.m. energy where few e+e- data are available.

ISR Cross Section

$$\frac{d\sigma(s,x)}{dx} = W(s,x)\sigma_f\left[s(1-x)\right]; \qquad x = \frac{2E^*_\gamma}{\sqrt{s}}$$

$$W(s,x) = \beta \cdot \left[(1+\beta)x^{(\beta-1)}\left(1+\frac{x}{2}\right)\right. \qquad (\beta \approx 0.067 \text{ at } (4S))$$

$$\beta = \frac{2\alpha}{\pi}\left(2\ln\frac{\sqrt{s}}{m_e}-1\right) \qquad (\beta \approx 0.088 \text{ at } (4S))$$

Cross Section for final state f (normalized to radiative dimuons)

$$\sigma_f(s') = \frac{dN_{f\gamma} \cdot \varepsilon_{\mu\mu} \cdot (1+\delta^{\mu\mu}_{FSR})}{dN_{\mu\mu\gamma} \cdot \varepsilon_f \cdot (1+\delta^{f}_{FSR'})} \cdot \sigma_{e^+e^-\to\mu^+\mu^-}(s')$$

"effective c.m. energy" $=M^f_{inv}= s(1-x)$

$dL(s')$

ISR luminosity

Exclude events with final state radiation

Detection efficiencies

BaBar's ISR event selection

89.4 fb-1 of BaBar data have been processed requiring:

- **E_{CM} >3 GeV photon has been found ($\sqrt{s'}$<4.68 GeV) or E_{CM} >0.5 GeV if there is □-ID for any track**
- **number of charged tracks ≥ 2**
- **even number of "good" (from IP) tracks with sum of charges=0**
- **NO electrons (radiative Bhabha events pre-scaled 1/40 for tests)**
- **ISR photon candidate is in 0.3 radian cone with axis along the missing momentum vector constructed using the other tracks in the event**

Essentially ALL exclusive ISR final states have been preliminary NTUPLEd (~2% of all events)

Current ISR Activity

□□□ -MC, IFR efficiency, luminosity

Oliver Buchmueller, Laurent Tantot, Evgeny Solodov, Vladimir Druzhinin

MC-all, J/Psi, 3pi cross section

Vladimir Druzhinin (Novosibirsk)

4pi Cross Section

Evgeny Solodov (Novosibirsk)

2K Cross Section

Peter Lukin (Novosibirsk)

2proton Form Factor

Sergey Serednyakov (Novosibirsk)

2pi Form Factor

Michel Davier (ORSAY), Laurent Tantot (ORSAY) and Oliver Buchmueller (SLAC)

Kkpi, KKeta , 6pi Study

F. Anulli, A.Zallo and R.Baldini (Frascati INFN) M.Sokoloff (SLAC)

2mu and 2hadron charge asymmetry

Eckhard Elsen (DESY,SLAC)

Inclusive R for SQRT(s')>5 GeV (photon energy)

Andreas Petzold (DRESDEN)

Inclusive R using the photon energy to define s'

Su, Dong (SLAC) and Nicolas Berger (SLAC)

Already a rather active field.
However, most of the people are not
spending 100% on their time on ISR analyses.

□ ***Still a lot of things to do and volunteers are really welcome***

ISR Monte Carlo generators

(AFKQED package)

□ **Arbuzov-Fadin-Kuraev, ISR, FSR extra photons**

simulation is based on:

"Four Pion Final State with Tagged Photon at Electron Positron Colliders", by

H. Czyz and J.H.Kuehn,

Eur.Phys.J. C18(2001)487-509 (hep-ph000826)

realistic simulation with cross sections taken from e^+e^- experiments

multiple ISR,FSR (structure functions,PHOTOS)

□+□−□

□+□−□

□+□−□, □S□L□

□+□−□0□

□+□−□+□−□

□+□−□0□0□

□+□−□□

□+□−(□)□0□

□+□−(□)□□

p+p−□

□□(892, 1410)□

□+□−□+□−□+□−□

□+□−□+□−□0□0□

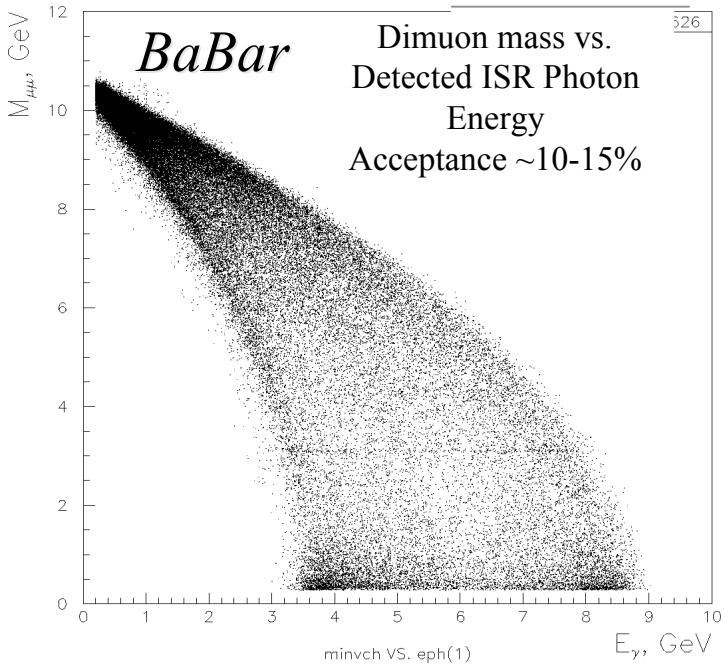
G.Bonneau and F.Martin,

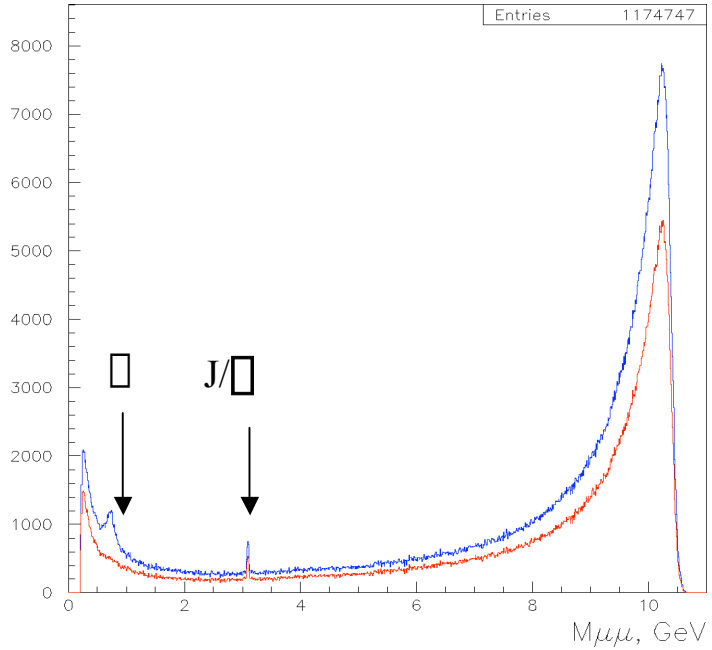
Nucl.Phys. B27(1971)381

□+□□- main test tool

-<1% accuracy in MC generator
- DATA – MC comparison
- IFR efficiency study

- $s(1-x)=M_{\square\square}$ resolution check
-comparison with BaBar Luminosity
-ISR luminosity for hadron norm-n





1 □ ID - blue, 2 □ ID - red

Radiative Dimuons: Efficiency

Very accurate knowledge of efficiency is of vital importance for a precise R measurement

 Obtain the efficiencies directly from the DATA

Example: Radiative Dimuons

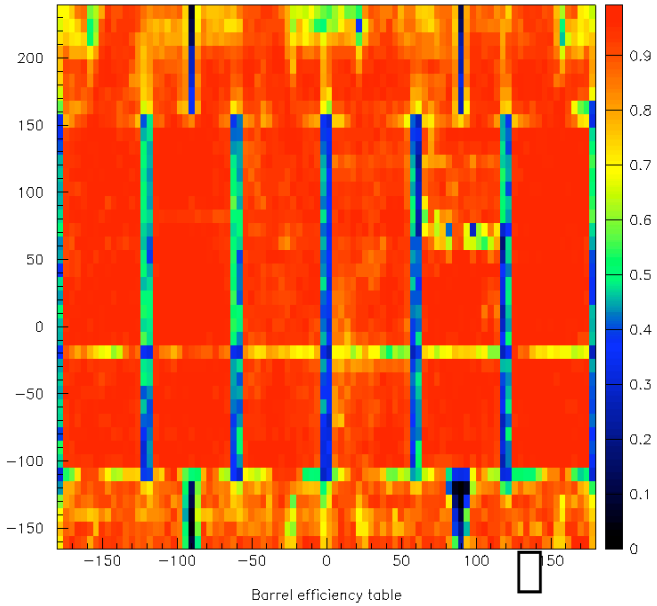
 Can be selected with very high purity ~99.99%

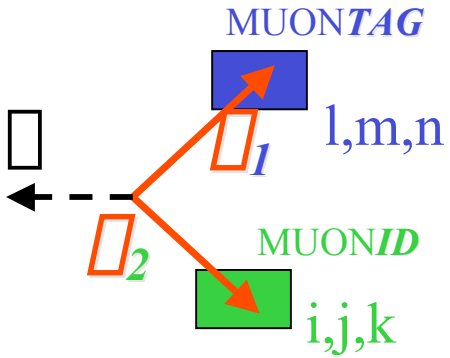
Other test samples:

Pi: events ^{0}

K: B events D^0 K

Z BARREL: Z,

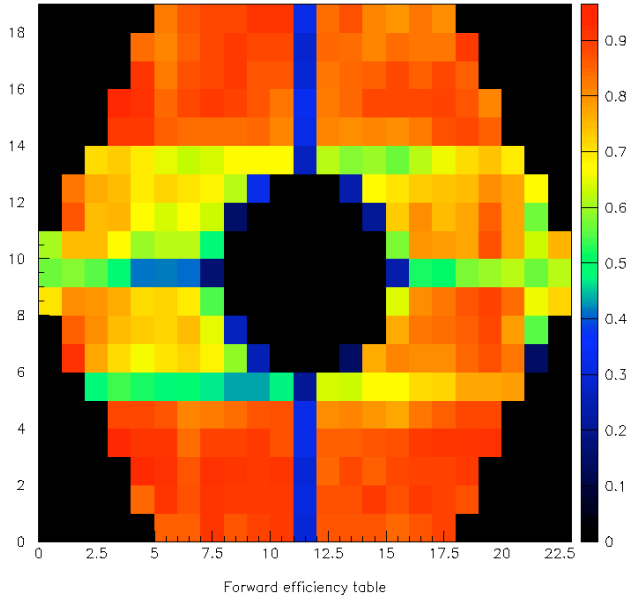




$_{i,j,k} = N_{ID}/N_{TAG}\ |_{i,j,k}$

BINS: i,j.k = P,,

FORWARD ECAP: X,Y



□+□□: Resolution

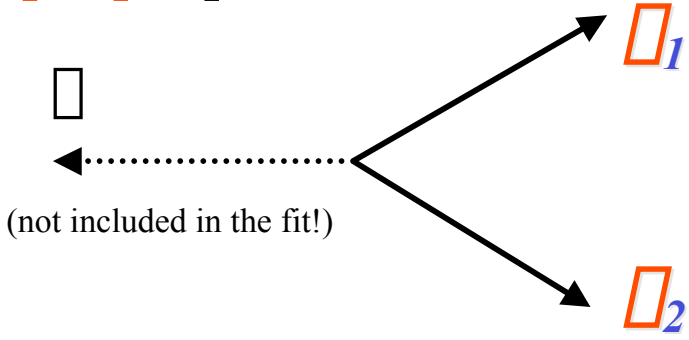
Resolution will be important for most of the measurements using the ISR sample

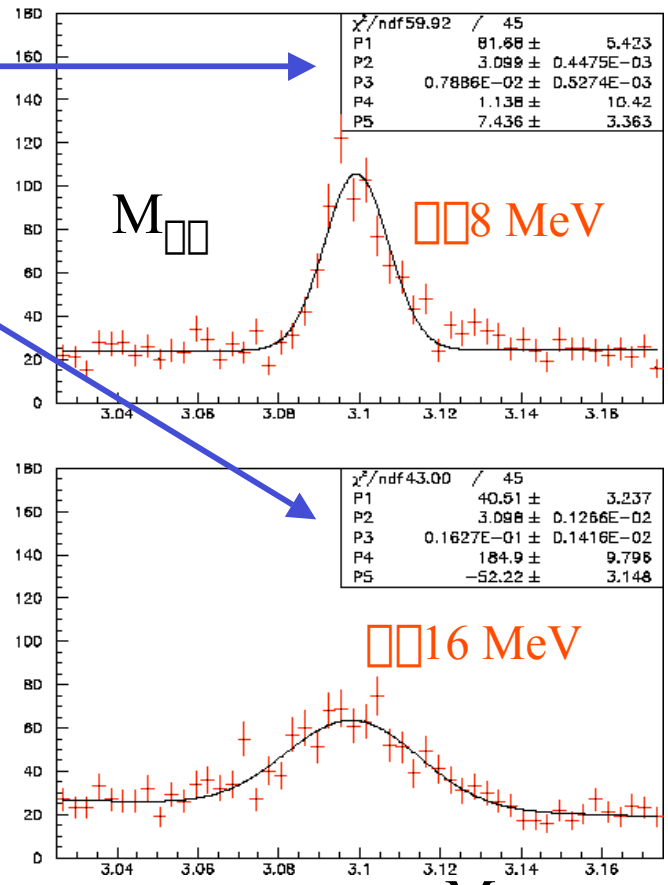
□ Use J/□ signal to monitor the resolution directly

□ Apply energy and momentum conservation using a **1C kinematic fit**

$E_{\gamma 1} + E_{\gamma 2} + E_{\gamma} - E_{ee} = 0$

$\mathbf{P}_{\gamma 1} + \mathbf{P}_{\gamma 2} + \mathbf{P}_{\gamma} - \mathbf{P}_{ee} = 0$



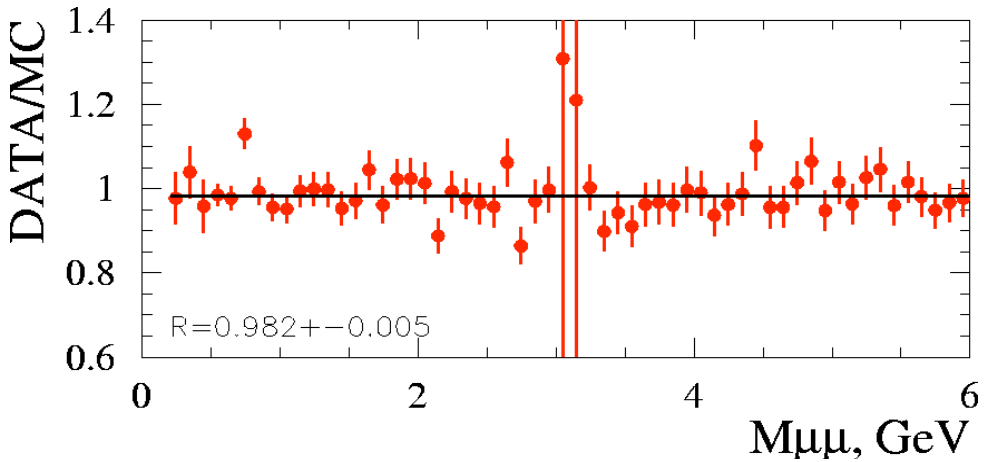


□ ***The kinematic fit is a powerful tool in order to improve the mass resolution***

□MJ/□□8 MeV

□+□□: Luminosity test

After correction for ID efficiency and acceptance from MC,
dimuon spectrum can be compared with that calculated from BaBar Luminosity



2% agreement with BaBar Luminosity

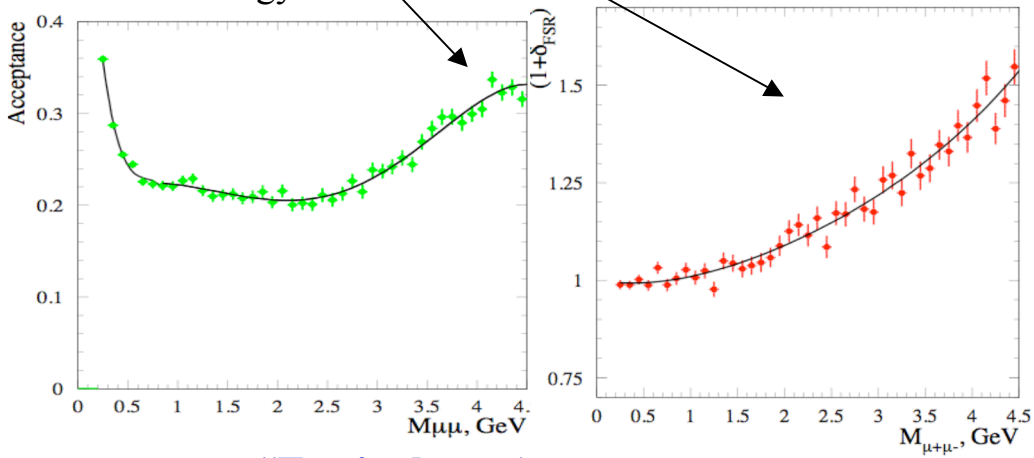
□+□-□: Luminosity

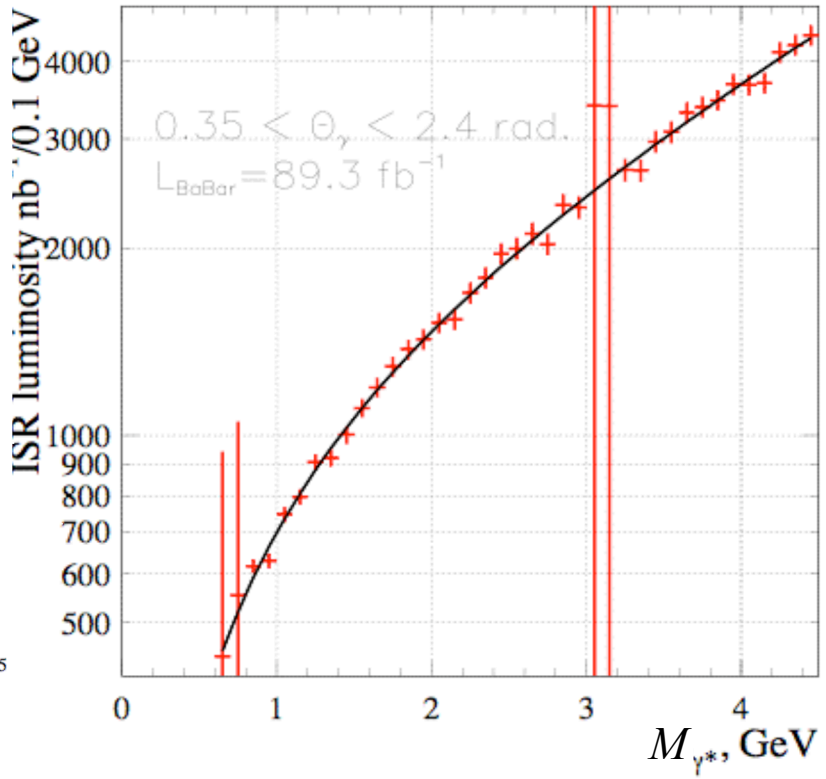
Topology: two charged tracks + hard photon + Muon ID

Luminosity from Dimuon Events

$$dL(M_{inv}^{\square\square}) = \frac{dN_{\square\square\square}(M_{inv}^{\square\square})}{\square_{\square\square}\cdot(1+\square_{FSR}^{\square\square})\cdot\square_{e^+e^-\square\ \square^+\square^-}(M_{inv}^{\square\square})}$$

"effective energy"





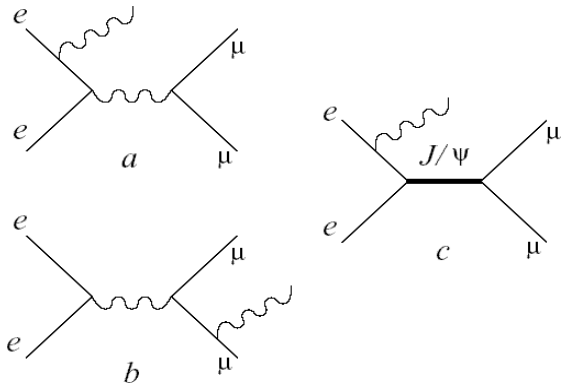
"Equivalent e+e- Luminosity"

BaBar's 90fb^{-1} corresponds to an e$^+$e$^-$ scan with ~700 nb^{-1}/0.1GeV at 1GeV and ~4 pb^{-1}/0.1GeV at 4 GeV

□ **Statistically very competitive sample**

J/_ production in e^+e^- □ □□$^+$□$^-$

$$\sigma_{J/\psi}(s) = \frac{12\pi^2\Gamma_{ee}B_{\mu\mu}}{m \cdot s} \cdot W(s, x_0),\ x_0 = (1 - \frac{m^2}{s})$$



□ J/_ cross section is proportional to □$_{ee}$ B$_{□□}$= □ B$_{ee}$ B$_{□□}$

PDG2002:

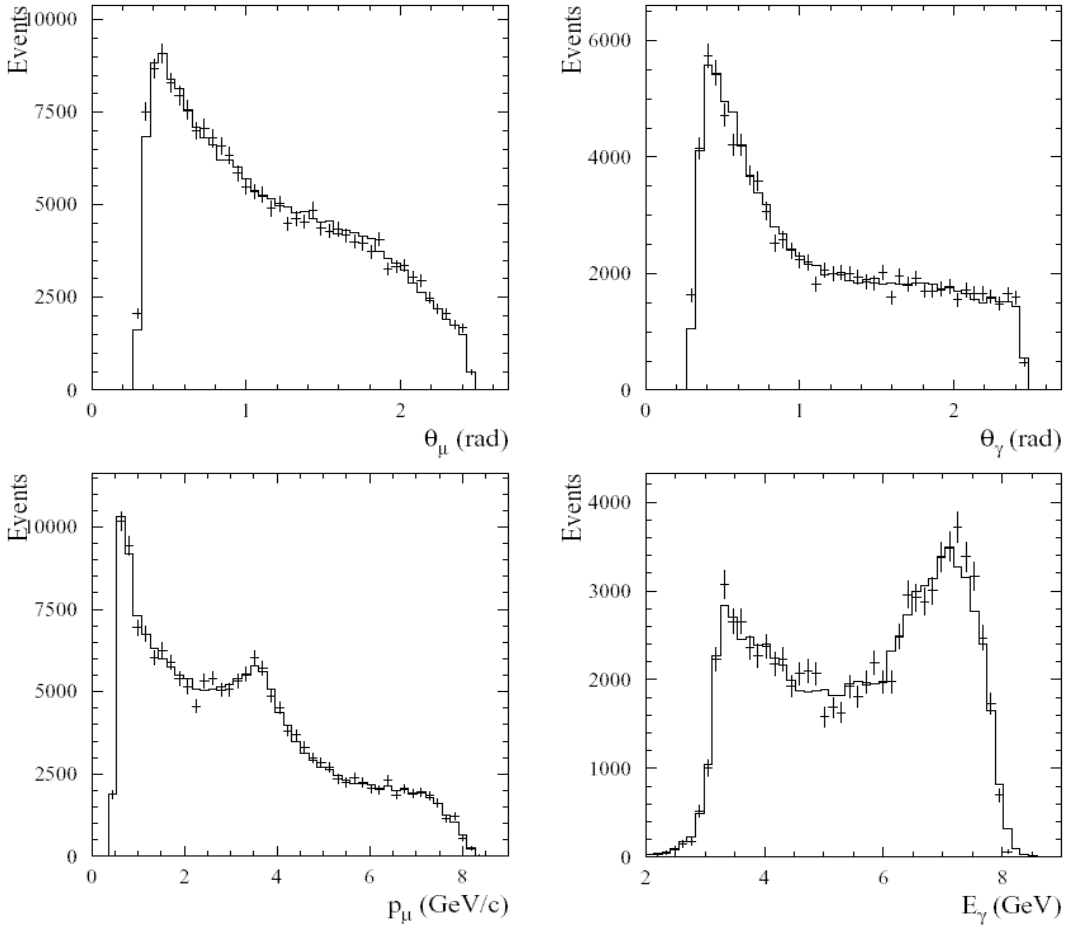
□ = 87±5 keV, B$_{ee}$ =(5.93±0.10)% and B$_{□□}$ =(5.88±0.10)%

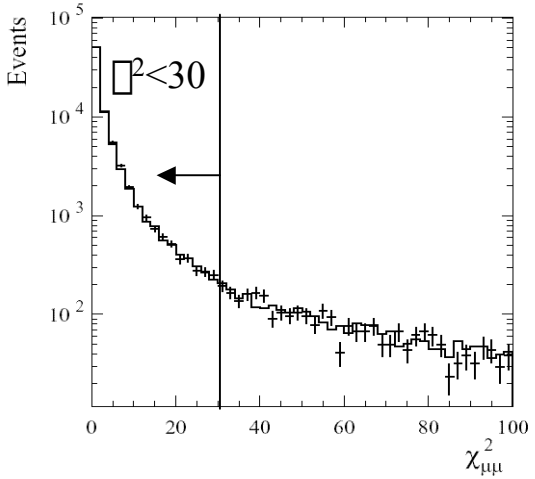
□ Measuring □$_{ee}$ B$_{□□}$ one can get:

- partial J/_ width □$_{ee}$ as □$_{ee}$ B$_{□□}$ / B$_{□□}$ (PDG)
- total J/_ width □ as □$_{ee}$ B$_{□□}$ / B$_{□□}$ (PDG) / B$_{ee}$(PDG)

Event Selection

MC vs. DATA for photon and muon parameters





χ^2 of 1C kinematic fit with acceptance cut:

$$0.35 < \theta_\gamma < 2.4$$

$$0.375 < \theta_\mu < 2.4$$

Data sample: 88.4fb^{-1} 1999-2002 runs

Analysis Procedure

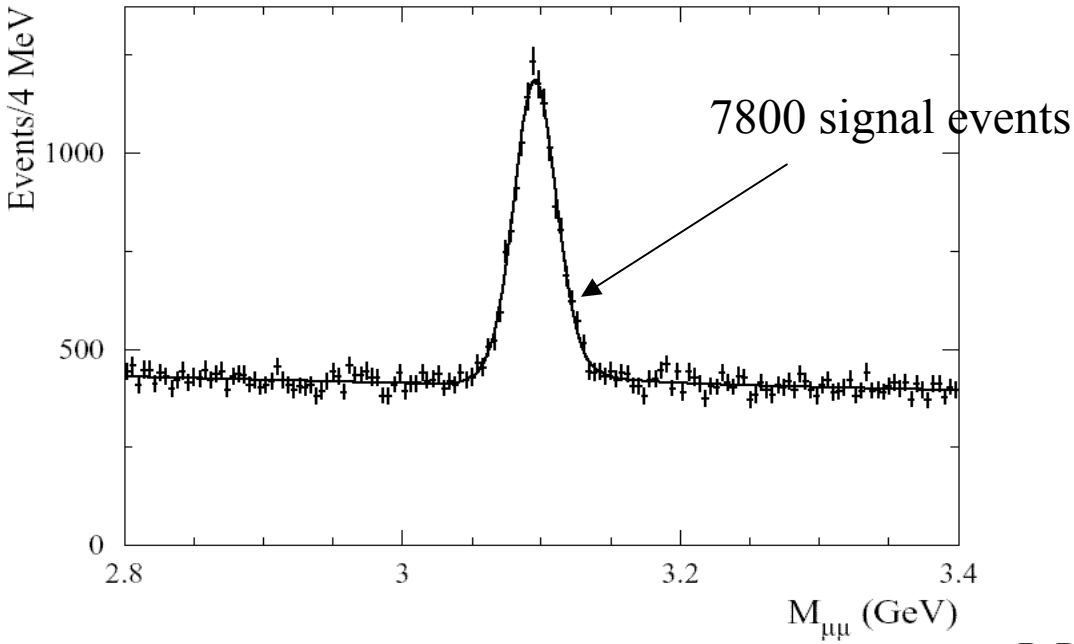
R is ratio of J/_ signal to QED background (excluding FSR) in 4 MeV bin

$$R = \frac{N_{J/\psi}}{\frac{dN}{dM} \cdot 4\ \mathrm{MeV/c^2}} =$$

← Number of Signal events

$$\frac{\sigma^{Born}_{J/\psi}}{\frac{d\sigma^{Born}_{ISR}}{dM} \cdot 4\ \mathrm{MeV/c^2}} \cdot \frac{1}{K}, \quad K = \frac{d\sigma^{vis}_{Total}/dM}{d\sigma^{vis}_{ISR}/dM}$$

According to simulation FSR correction K varies from 1.08 to 1.19 dependent of selection criteria.



Systematic Uncertainty

- interference effect - 0.3%
- J/_ line shape simulation - 1.4%
- uncertainty in background - 0.5%
- K factor cut dependence - 1.3%
- MC statistics - 0.9%

The total systematic error is - 2.2%

The statistical error is - 2.3%

Results for Γ_{ee} and Γ

$$K \cdot R = 21.03 \pm 0.49 \pm 0.46 \quad \Rightarrow \quad \sigma_{J/\psi} = (2124 \pm 49 \pm 47)\ \text{fb}$$

$$\Rightarrow \quad \Gamma_{ee} \cdot B_{\mu\mu} = 0.3301 \pm 0.0077 \pm 0.0073\ \text{keV}$$

$$B_{\mu\mu} = (5.88 \pm 0.10)\% \qquad B_{ee} = (5.93 \pm 0.10)\%$$

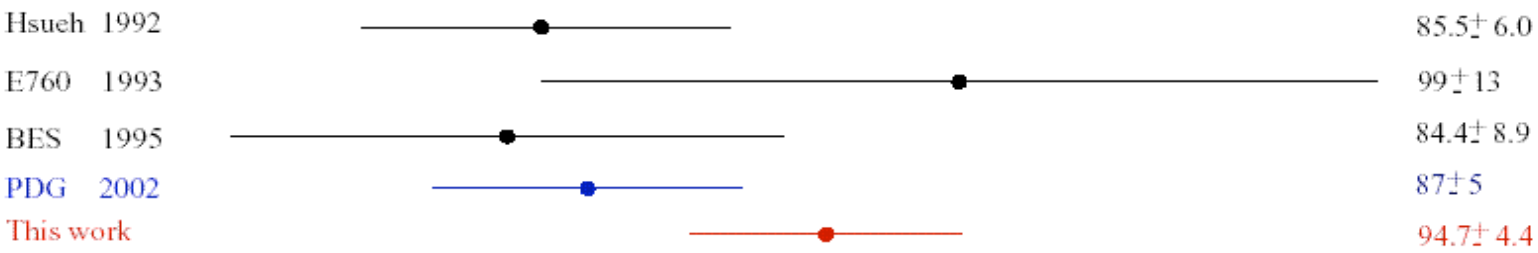
$$\Gamma_{ee} = 5.61 \pm 0.20\ \text{keV}$$

$$\Gamma = 94.7 \pm 4.4\ \text{keV}$$

5.26 ± 0.37 keV

PDG2002:

87 ± 5 keV

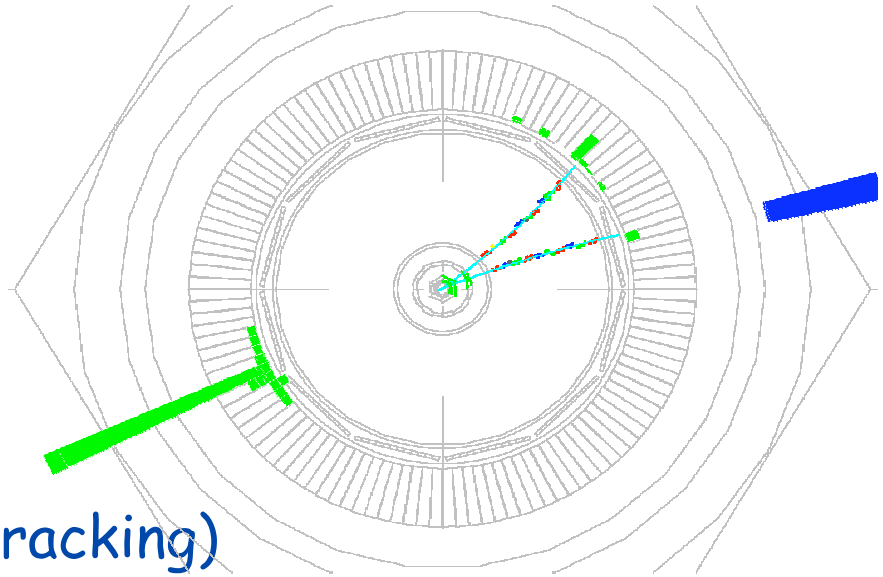


$\pi^+\pi^-\gamma$

topology: 2 charged tracks , No π ID (+ 1C fit in $\pi\pi$ hyp.)

We want to measure as a function of s' = mass^2

$$\frac{N_{\pi\pi}}{N_{\mu\mu}} \mu \left|F_\pi(s)\right|^2$$



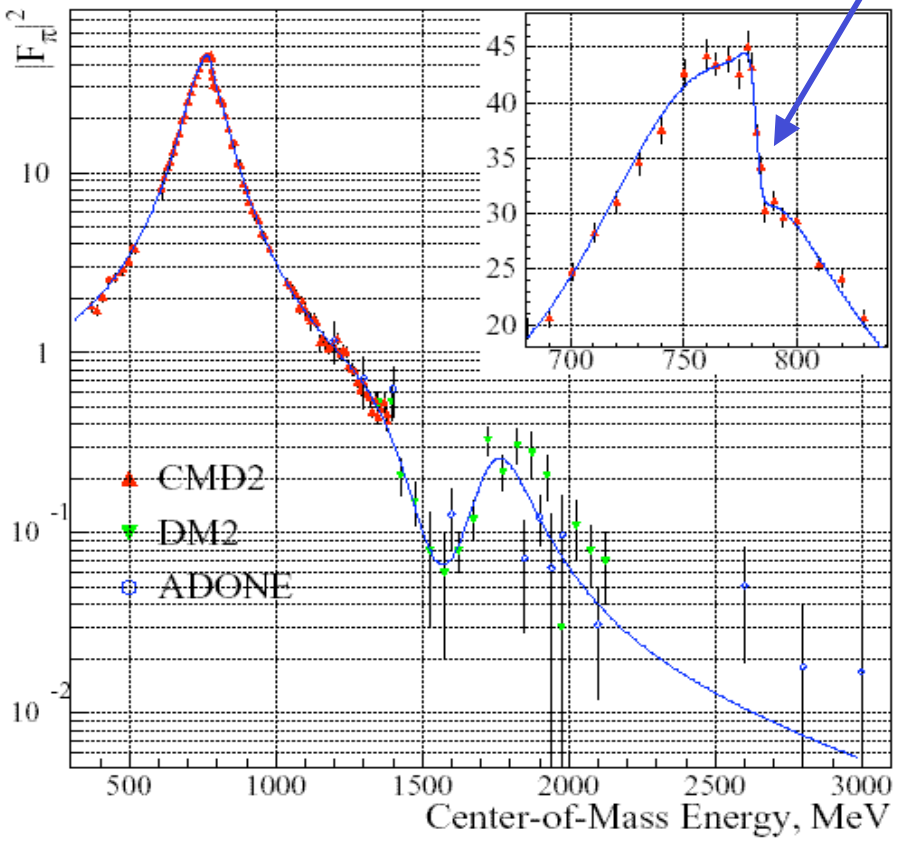
Ratio cancels:

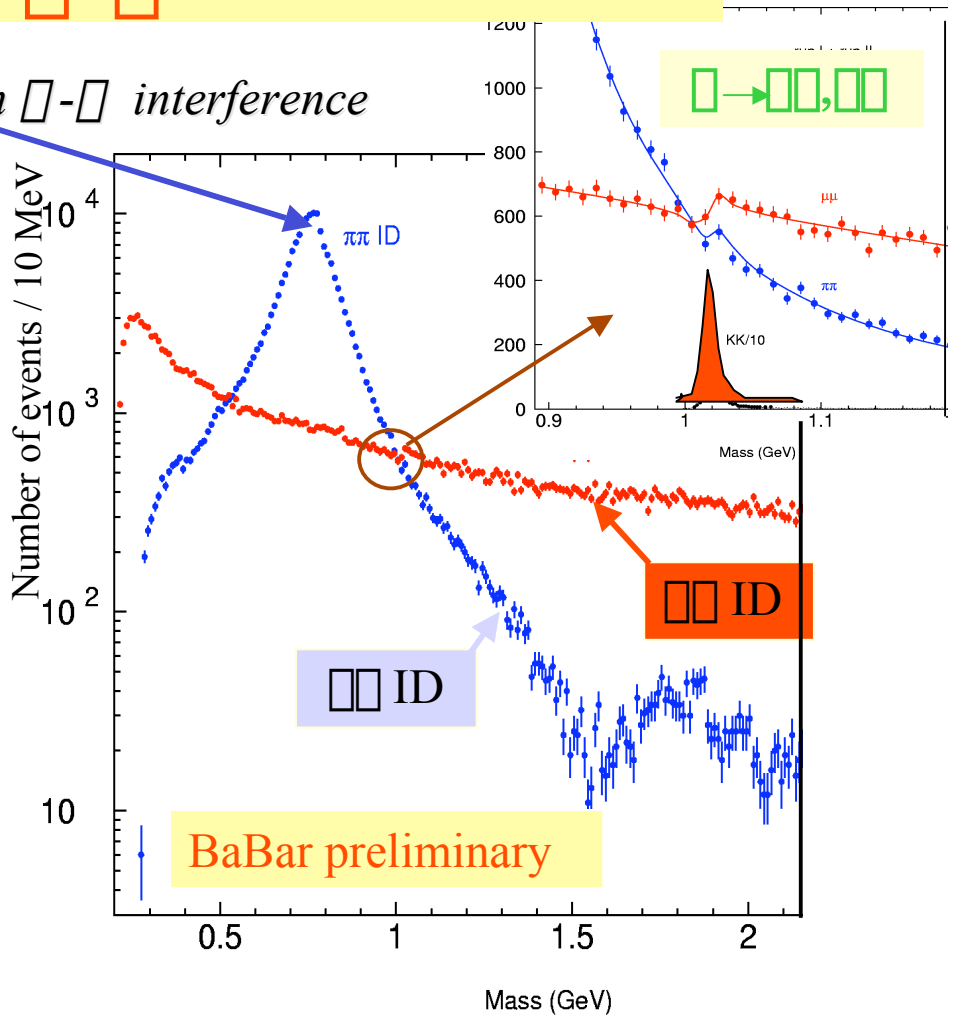
- luminosity
- radiative corrections
- efficiencies (photon, trigger, tracking)

Problem: large e- and π-background

□+□- □

Pion Form Factor with □-□ interference

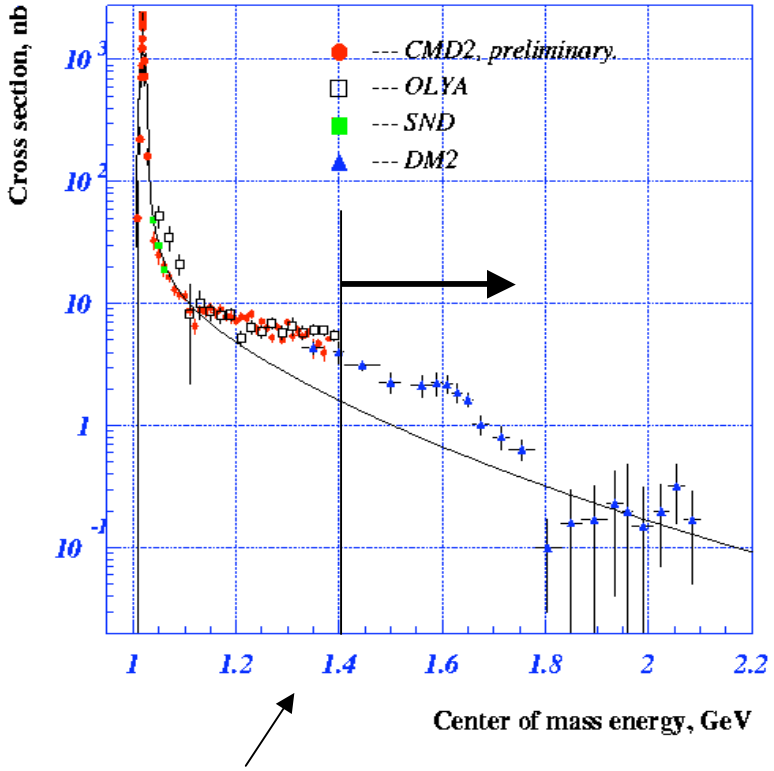




Very encouraging agreement ! Hard work! <1% systematic error is needed for g-2

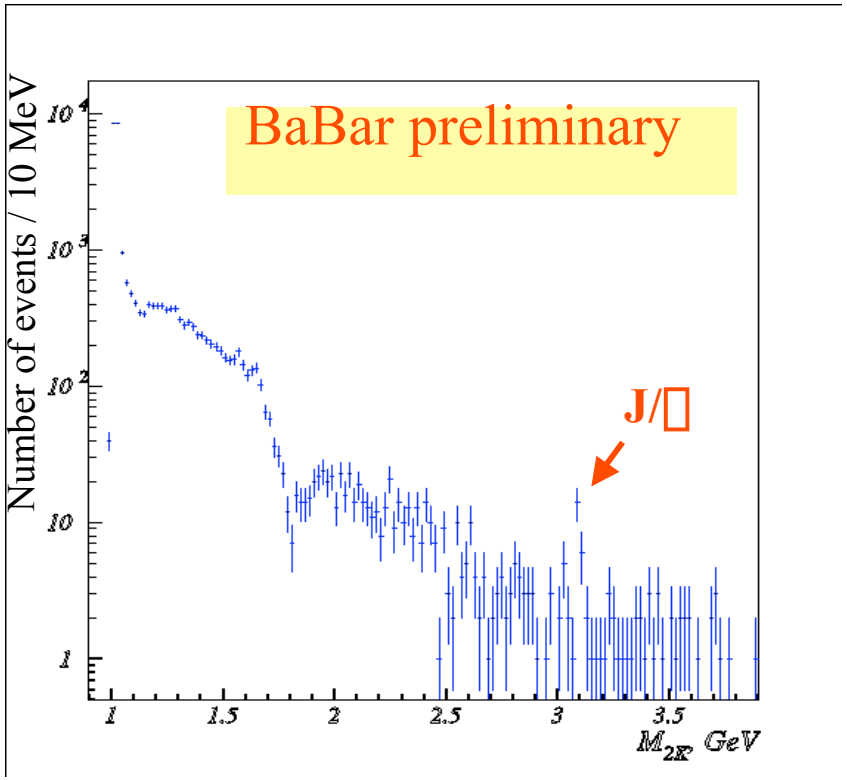
$K^+K^-\gamma$

topology: 2 charged tracks, 2 kaon ID, No γ ID (+ 1C fit in *KK* hyp.)



Above 1.4 GeV the 2*K* cross section is poorly measured. A better measurement would be very beneficial for spectroscopy of excited _-states

BaBar ISR data cover the 2*K* mass range up to 3.5 GeV



$p^+p^-\gamma$

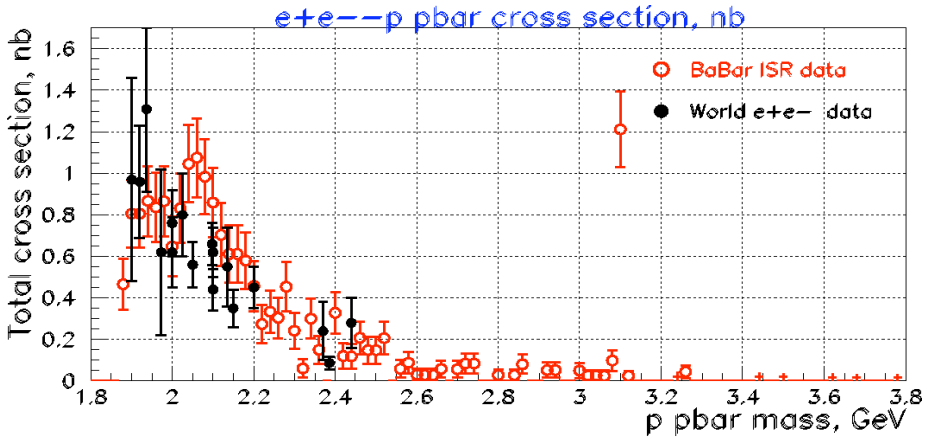
topology: 2 charged tracks, 2 proton ID, No γ ID + 1C fit in pp hyp.

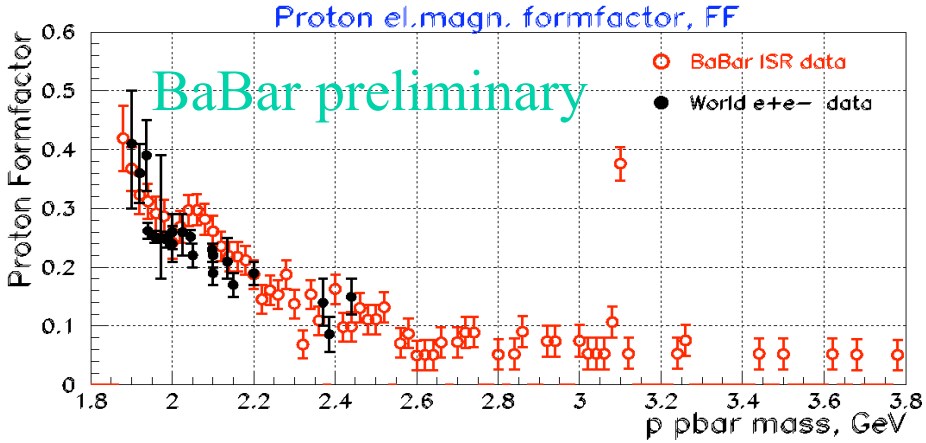
main background: $\pi\pi\gamma$, $\pi\pi(\pi)\gamma$, $KK(\pi)\gamma$

tight cuts keep background at the <5% level

$B(J/\psi \to p^+p^-) = 0.0028 \pm 0.0005$

PDG2002 -- 0.00214 ± 0.00010

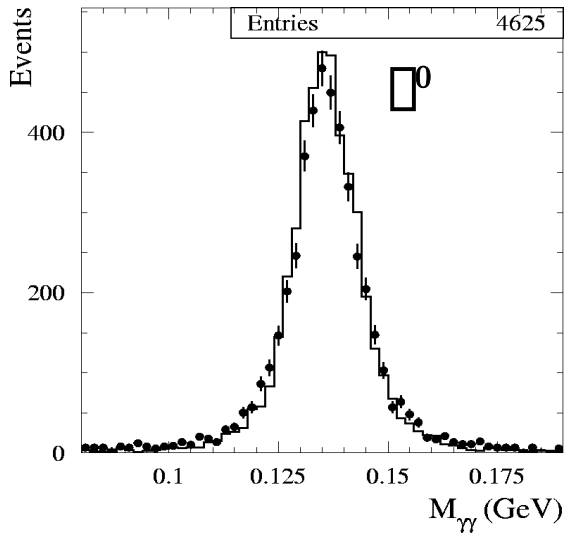


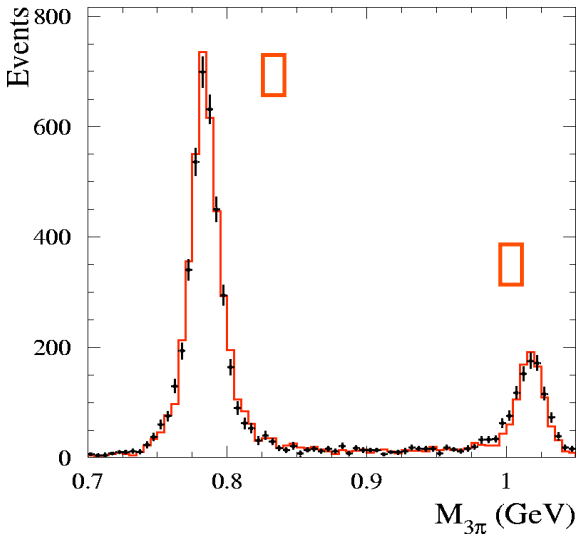


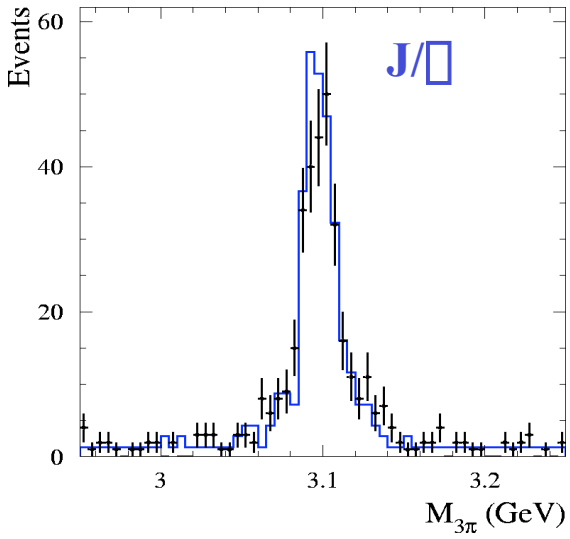
Data are not finally normalized

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

topology: 2 charged tracks+2 photons (+ 3C fit in $\pi^+\pi^-\pi^0$ hyp.)







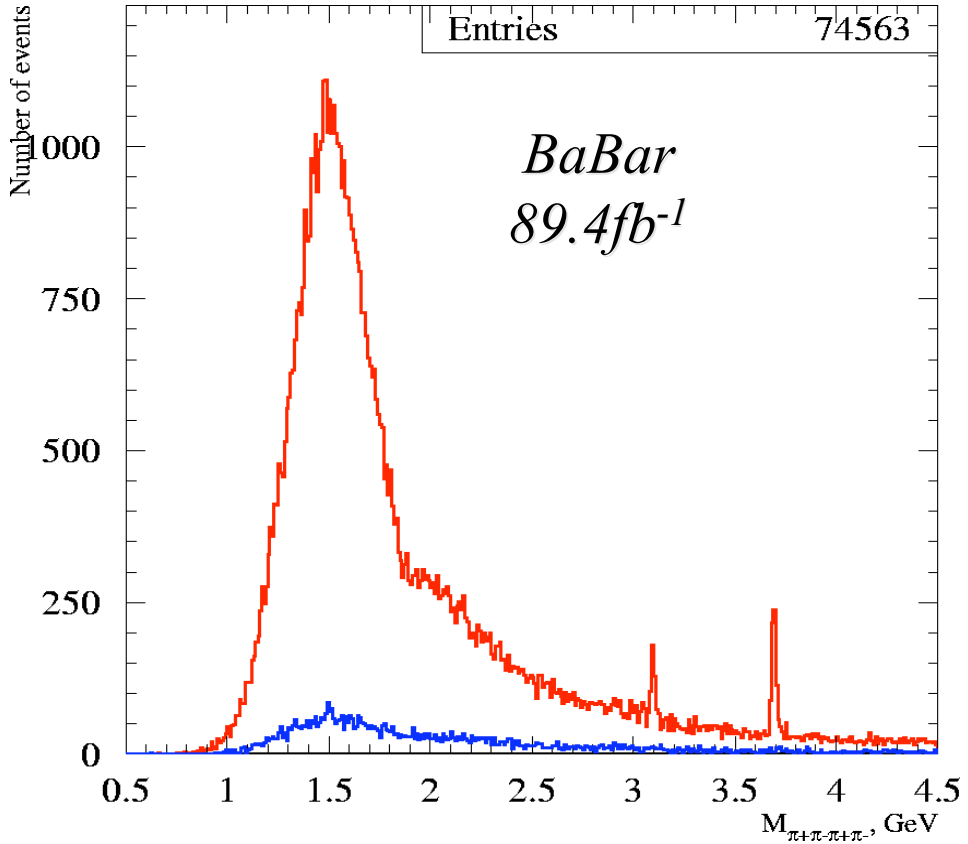
Good DATA-MC agreement. More work for background study is needed.

Next after $\pi\pi$ contribution to g-2. Analysis is in progress.

2□+2□- □□ 4□ Cross Section

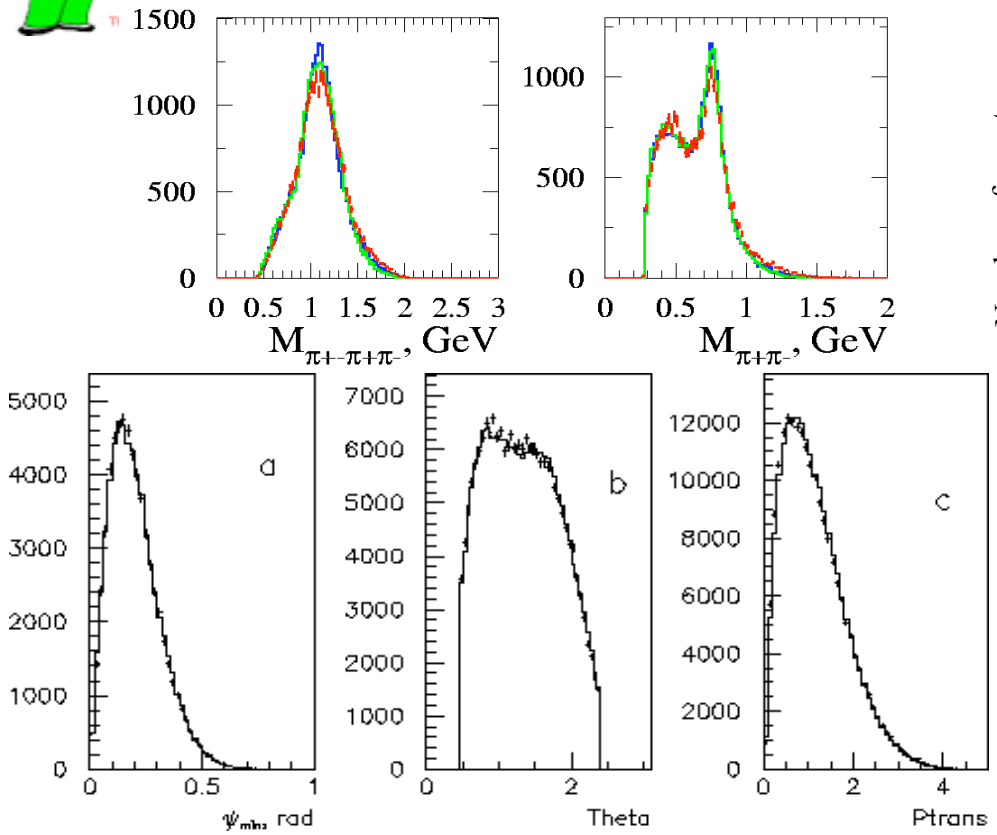
Topology: four charged tracks + hard photon (+ 1C fit in 4□ hyp.)

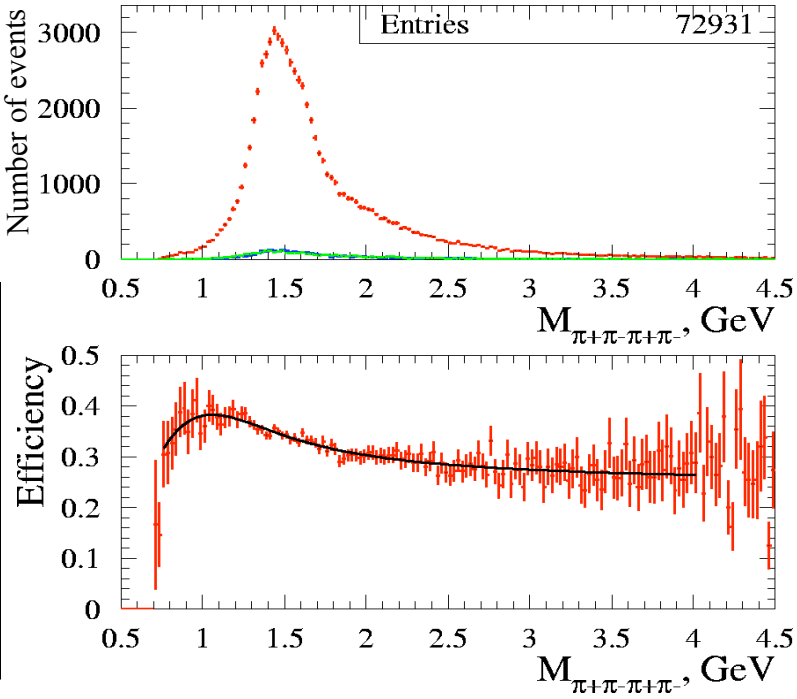
- **very clean sample (~2% background)**
- **whole mass range is covered**
- **large statistic (~75k events)**



□ Analysis is almost ready – BAD is in preparation

4$\pi^{\pm}$ acceptance from simulation



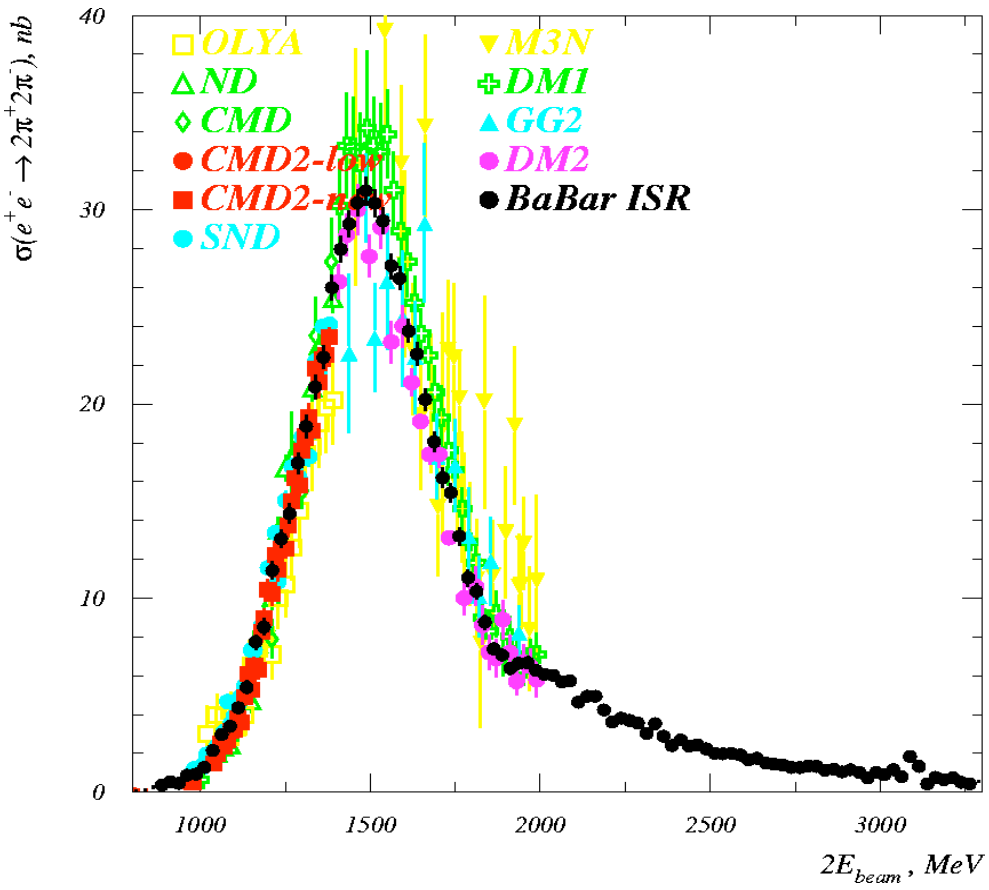


Comparison of data (points) with simulation (histogram). Simulation assumes $a_1(1260)\pi$ dominance.

Model parameter variation (including PointLike coupling) gives less than 3% change of acceptance

4□ Cross Section (preliminary)

Normalization to □□□ISR luminosity



Systematic errors count

- □□□ISR luminosity - 3%
- background subtraction -1%
  (10-15% for $M_{4\pi}$<1.0 GeV)
- □² MC-DATA cut difference -2%
- radiative corr. accuracy -1%
- MC-DATA track losses diff. -2%
- model dependent acceptance -2%

Expected total systematic error 5%

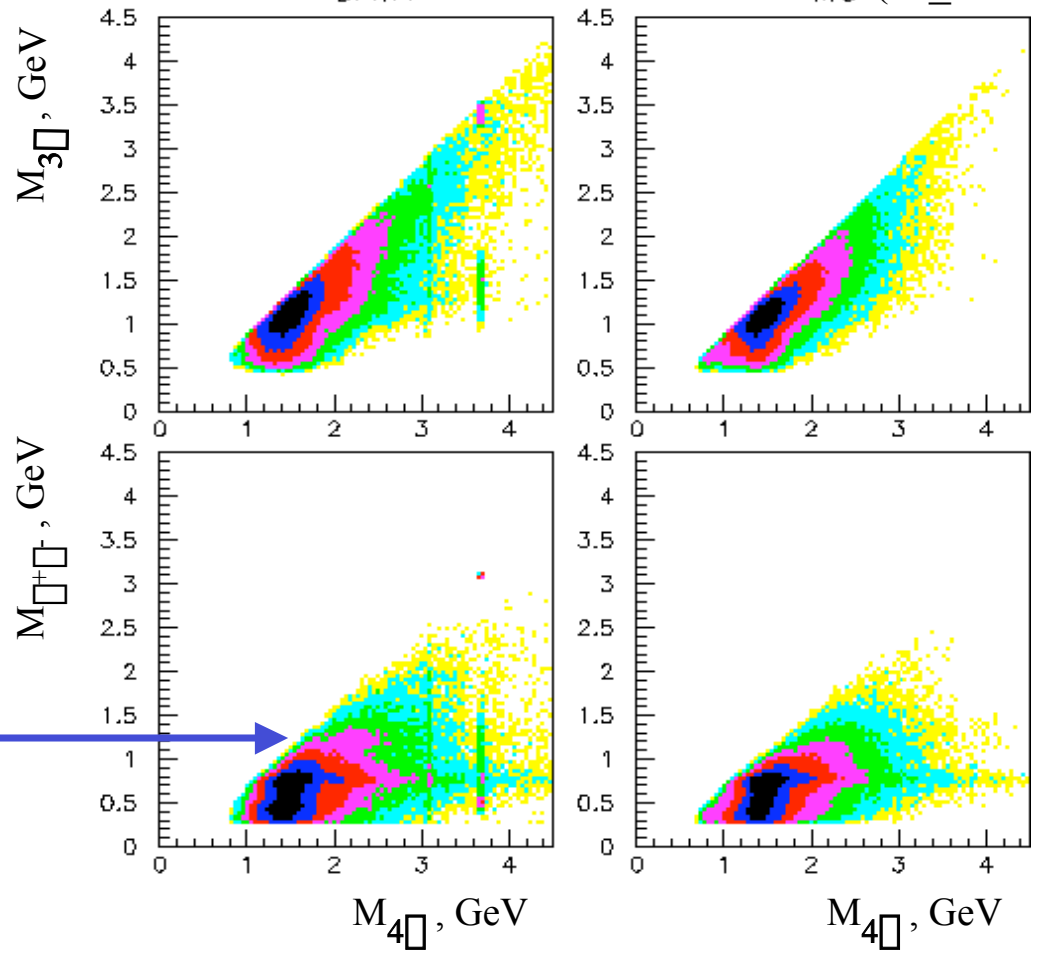
- **Very competitive statistical uncertainties**
- **Babar is the only experiment which covers whole range**

□ **no point-to-point normalization problem**

□ potential for being the world best 4□ cross section measurement

□⁺□⁻ and 3□± mass substructure

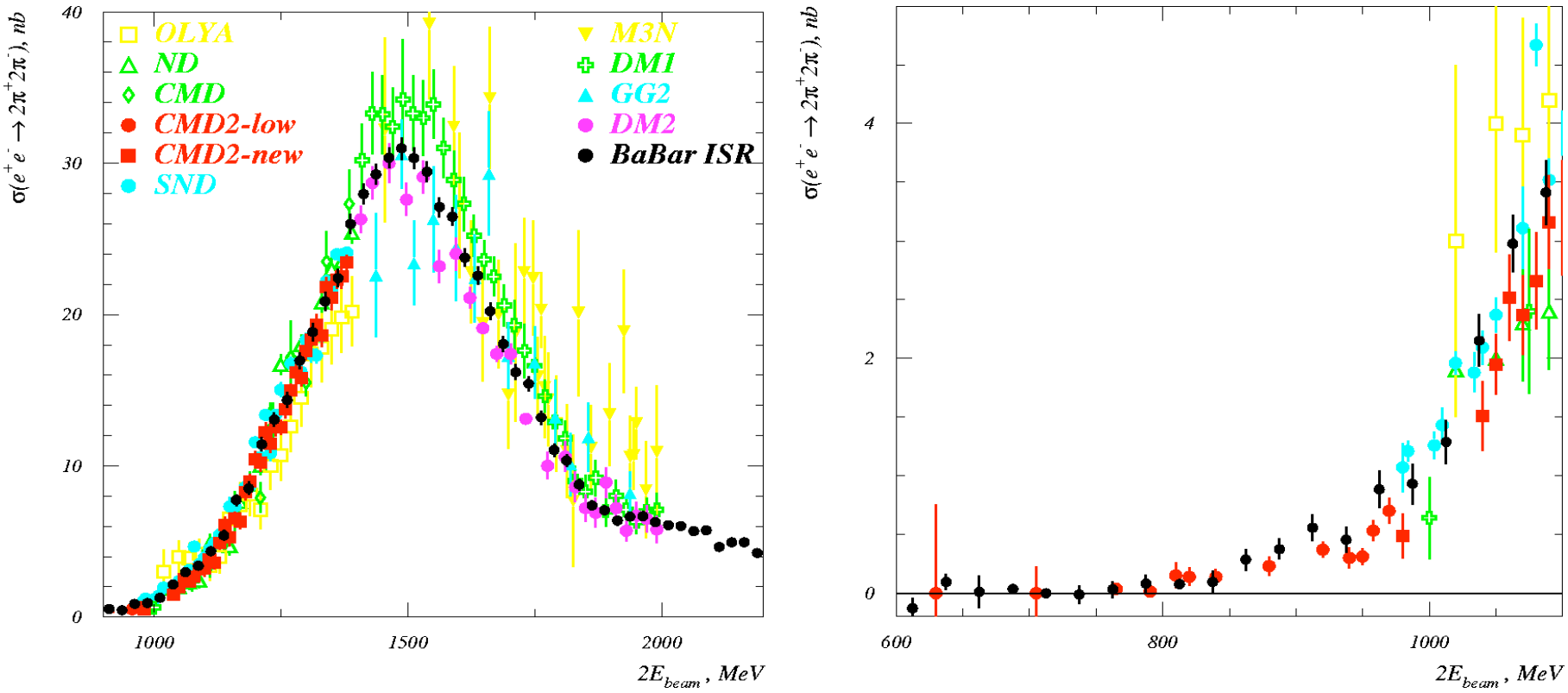
DATA MC (J/ _ and _(2S) are not included)



$f_0(1300)$?

3□ and 2□ combinations v.s. 4□ mass for data and MC.

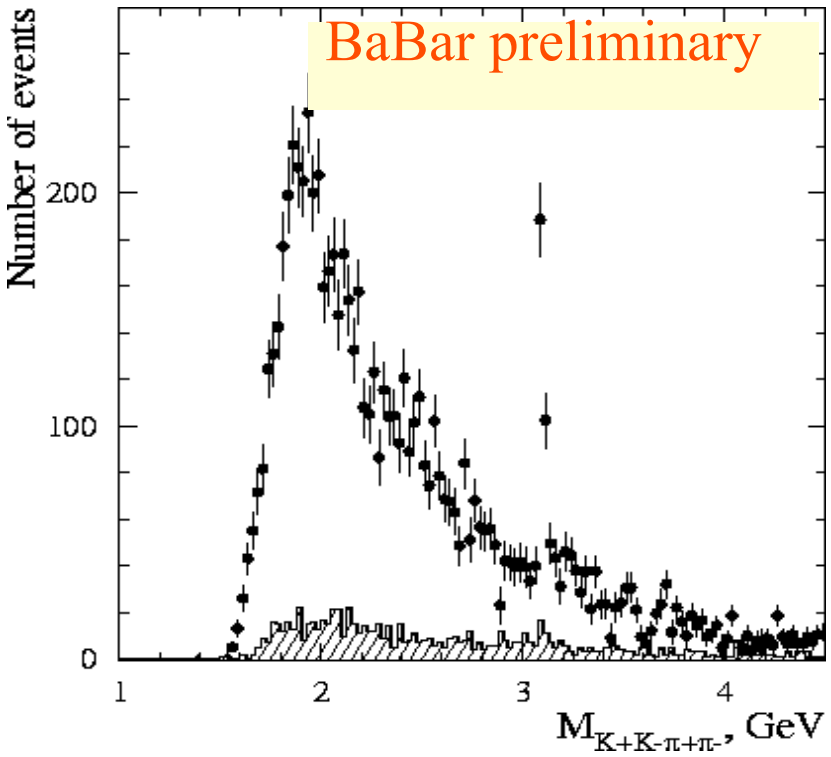
4 Cross Section –expanded view

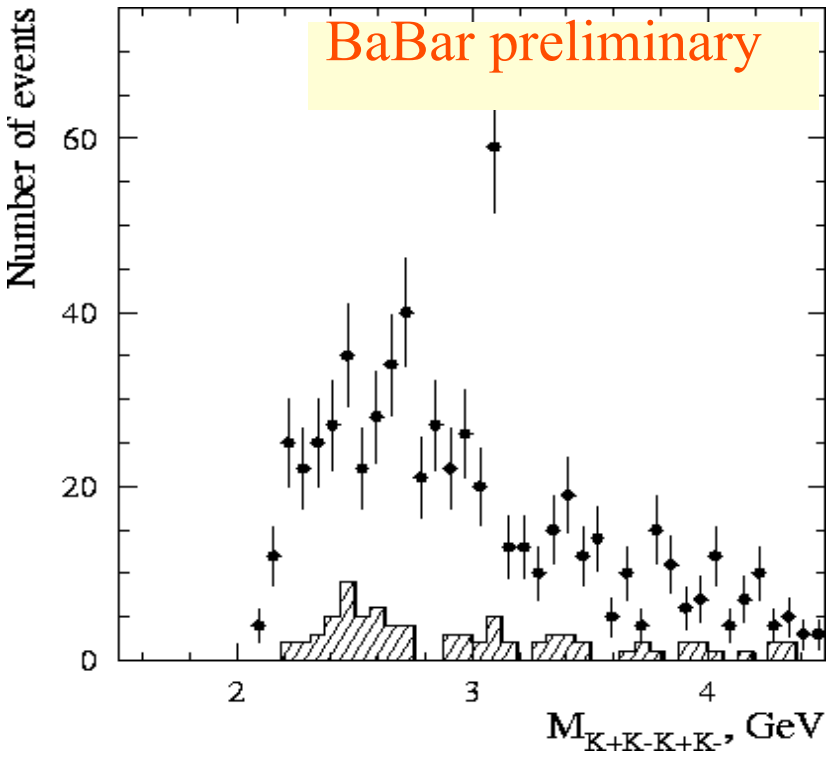


Good agreement with the most precision e^+e^- experiments

$K^+K^-\pi^+\pi^-$ and $4K^{\pm}$ production

$KK\pi\pi$ and 4K final states are easily selected by 1 or 2 kaon ID and 1C fit

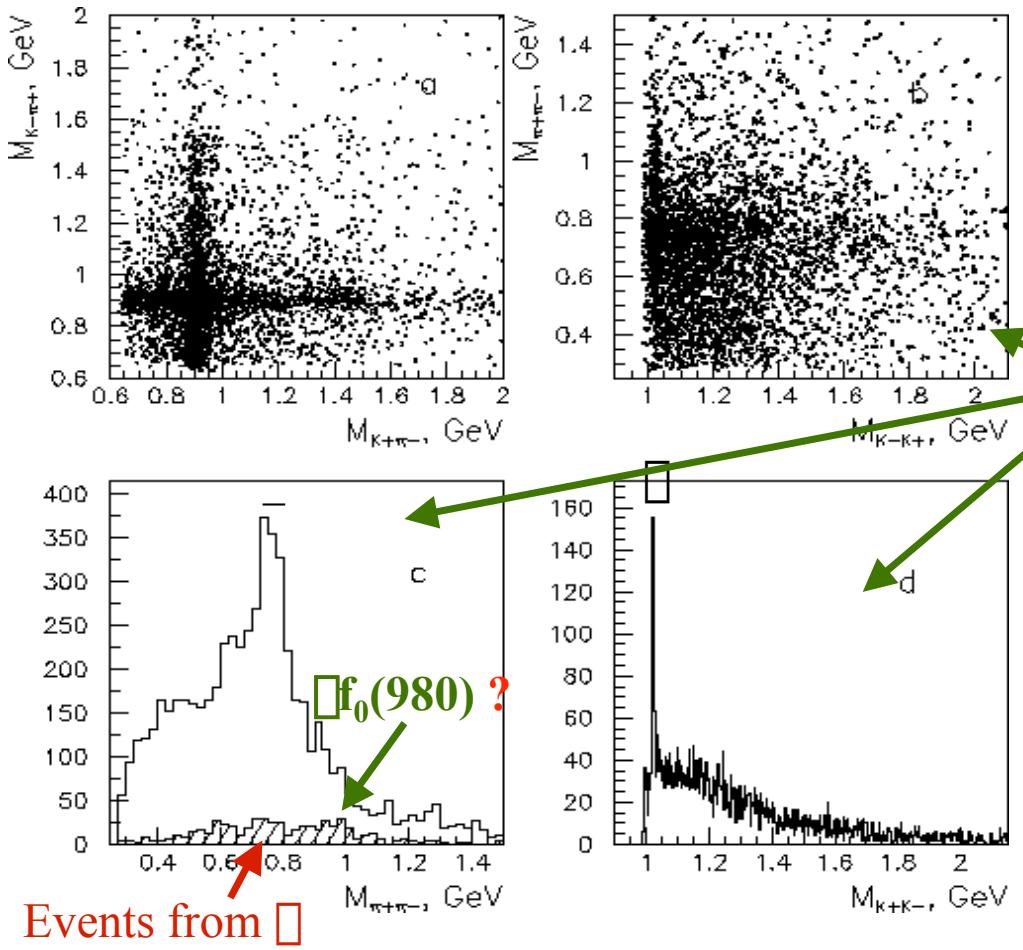




NO measurements from e^+e^- !

$K^+K^-\pi^+\pi^-$ substructures

K*K* dominated



NO measurements from e^+e^- experiments!

K*K*$\pi\pi$ MC generators are not available yet

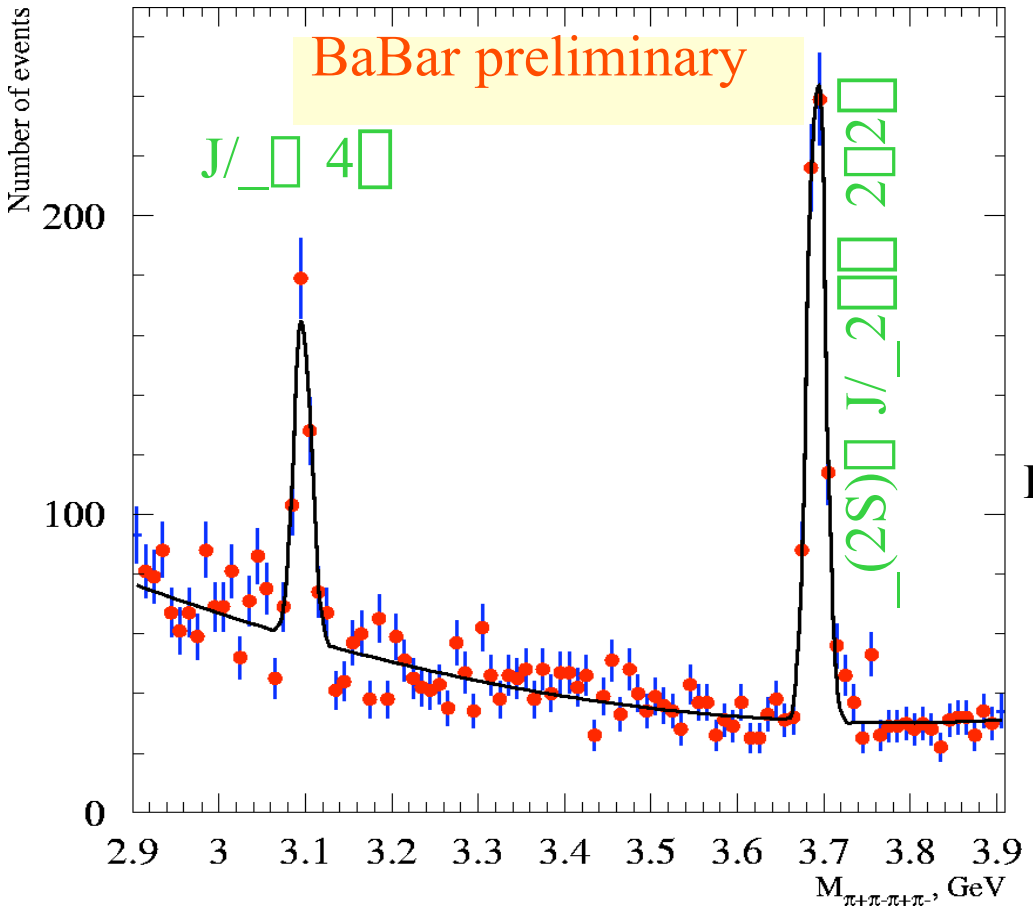
Events from NOT K*K* bands

$f_0(980)$?

Events from $\pi\pi$

How $\pi\pi f_0(980)$ production is Related to $\pi\pi$->$f_0(980)\pi\pi$?

4□± in the J/_ and _(2S) regions



$N_{J/\_\square 4\square} = 303 \pm 23$

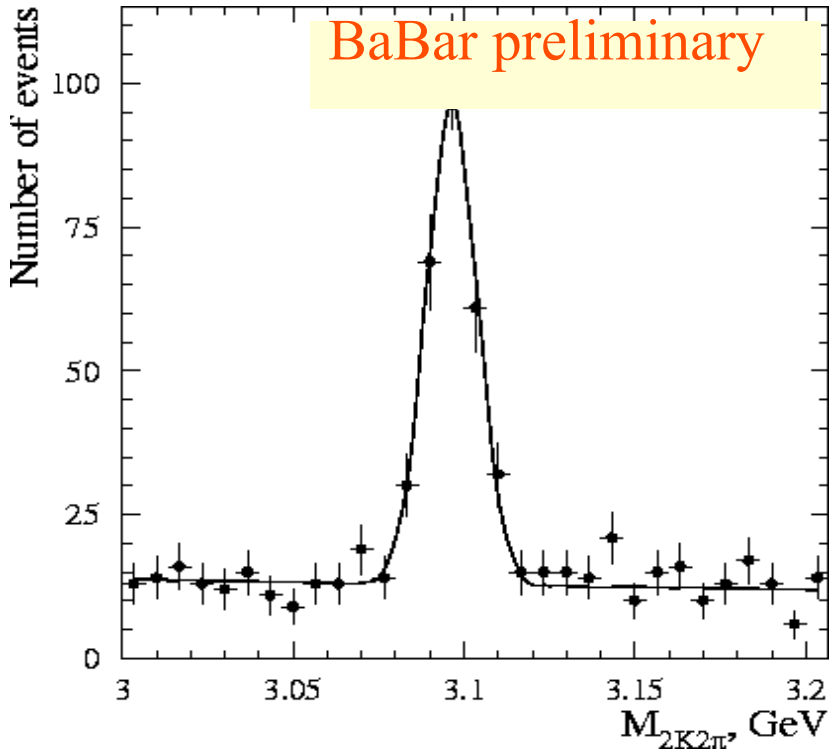
$N_{\_(2S)\square 2\square 2\square} = 611 \pm 30$

$B_{J/\_\square 4\square}(PDG) = (4.0 \pm 1.0) \times 10^{-3}$

□ factor of 2.5 better error

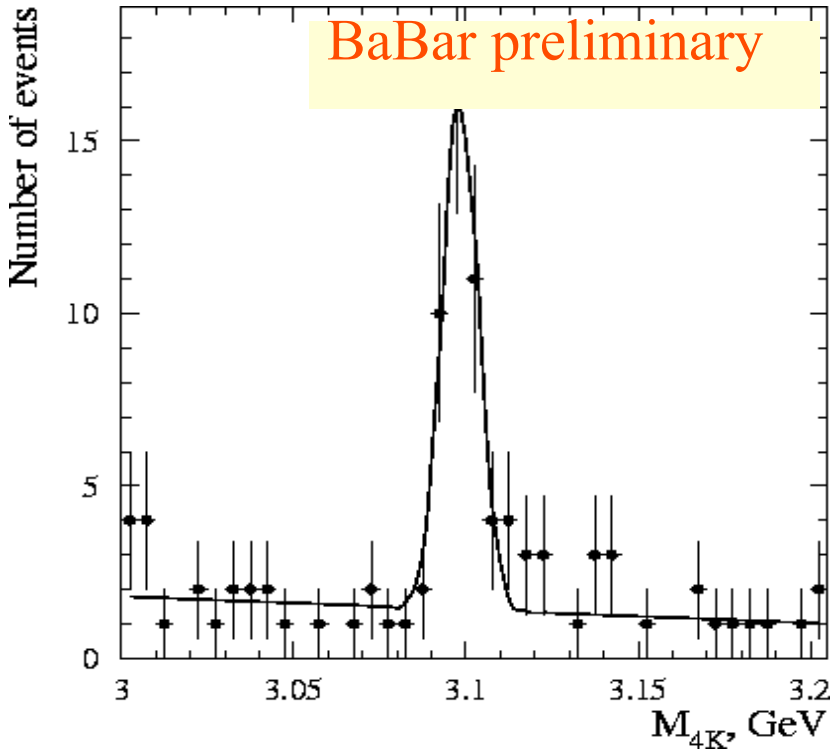
□ potential for the world best measurement

$K^+K^-\pi^+\pi^-$ and $4K^{\pm}$ in the J/ψ region



$N_{J/\psi\ 2K2\pi} = 262 \pm 21$

$B_{J/\psi\ 2K2\pi}$(PDG) $= (7.2 \pm 2.3) \times 10^{-3}$



$N_{J/\psi\ 4K} = 43 \pm 7$

$B_{J/\psi\ 4K}$(PDG) $= (7.0 \pm 3.0) \times 10^{-4}$

$K_S K^{\pm}\pi^{\mp}$, $K^+K^-\pi^0$

- Study ϕ resonance
  - ✓ $K_S K^+\pi^-$
  - ✓ $K^-K^+\pi^0$

observed by DM2 Collaboration
Z.Phys.C –Particle and Fields 52, 227-230 (1991)

- Look at $e^+e^- \to \phi(\to) + \gamma$

for the first time

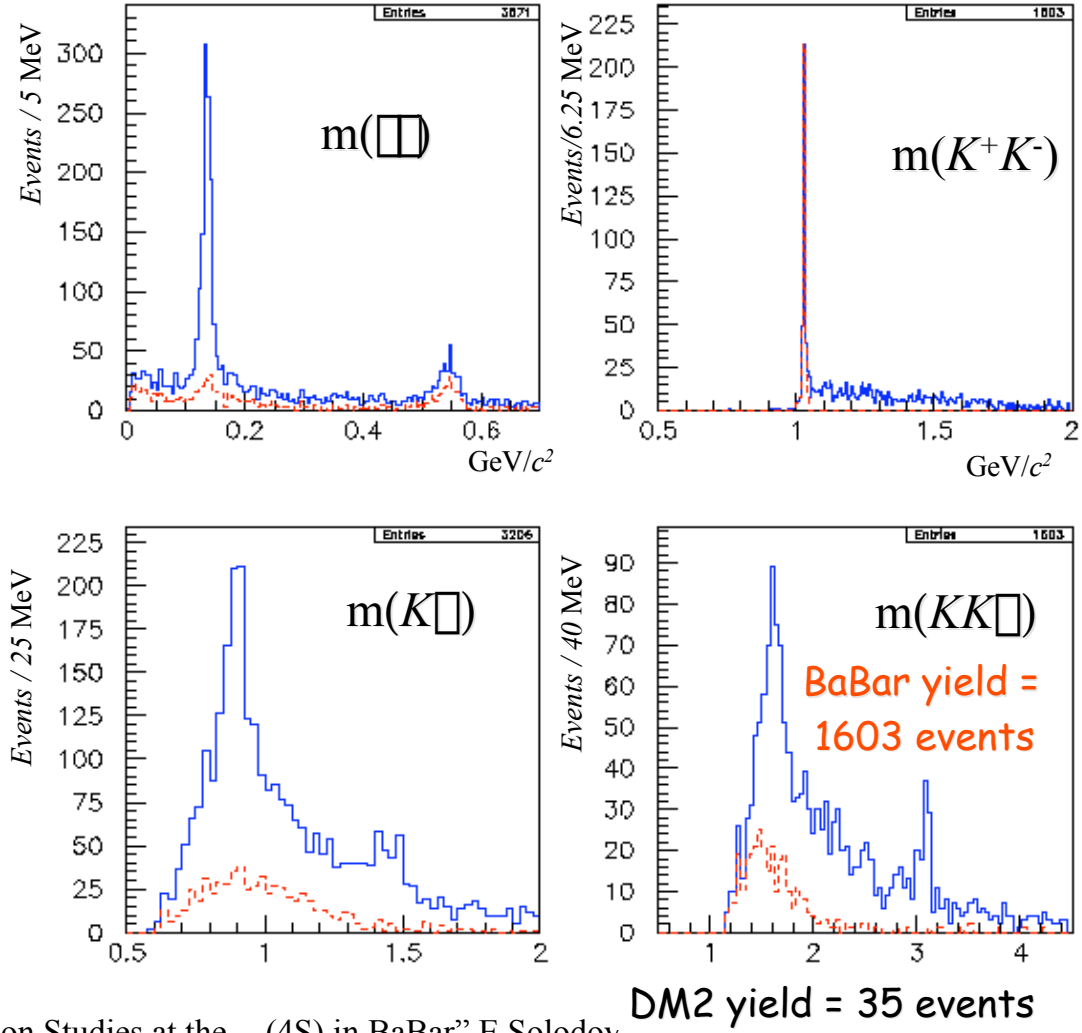
- Data samples:
  - RUNII
  - 80k MC events $K_S K^+\pi^-$
  - 80k MC events $K^+K^-\pi^0$

Special MC generator with $K^*(892)$, $K^*(1410)$, $K^*_2(1430)$ has been developed with all interferences included

$K^+K^-\pi^0(\gamma)$

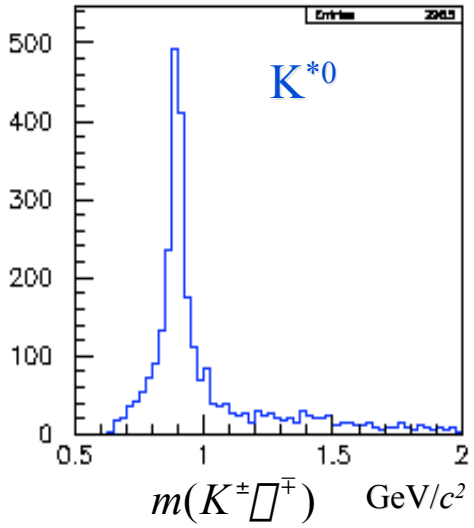
topology: 2 charged tracks with kaon ID + ≥2 photons

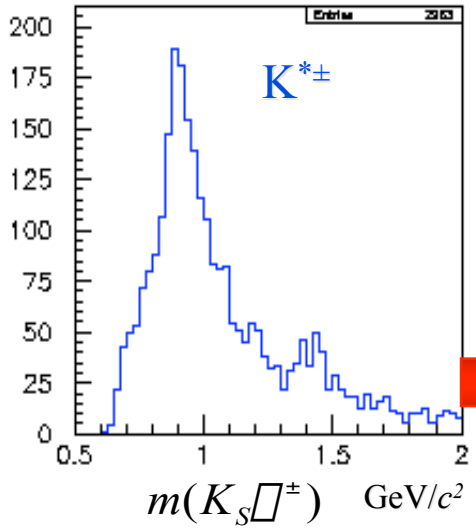
- a clear ϕ peak in m(K^+ K^-) can be seen
- no evidence of contribution from $\phi\pi^0$ events to the ϕ resonance
  (red histograms:
  $1.00 < m(K^+ K^-) < 1.04$ GeV/c^2)
- very clean ϕ signal corresponding to the ϕ peak

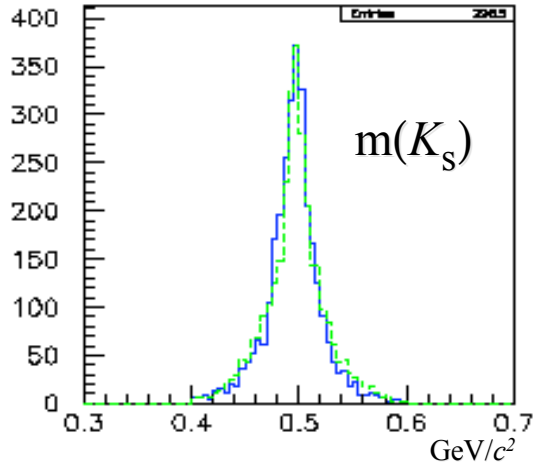


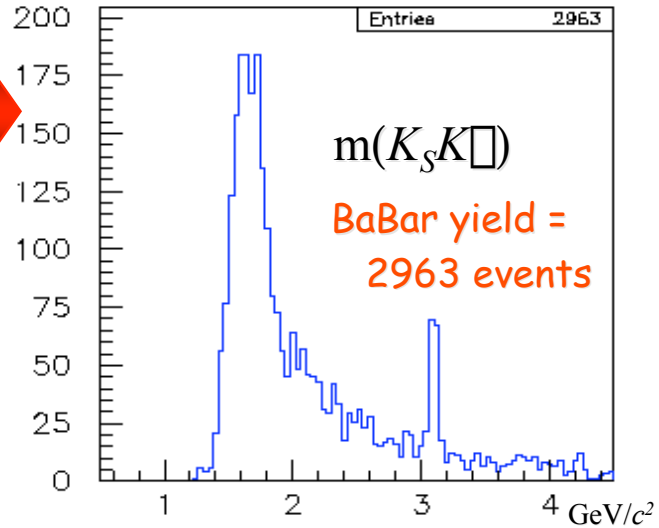
$K_S K^{\pm}\pi^{\mp}$

topology: 2 charged tracks + K_S







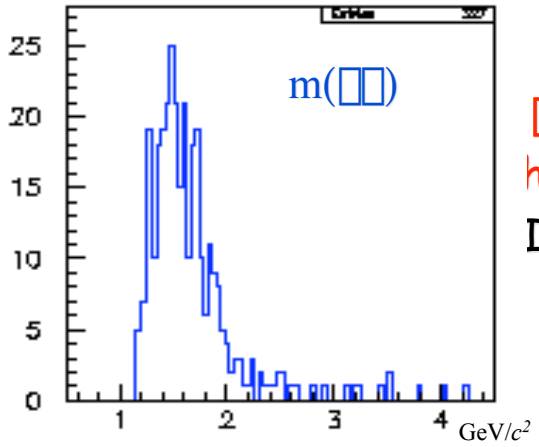


DM2 yield = 367 events

✓ $K^{*0}\,K^{0}$ decay mode is clearly favored over $K^{*\pm}\,K^{\mp}$. K^{*0} dominance can be explained by interference between isovector (ρ-like) and isoscalar (ω-like) amplitudes

□□(□) + □

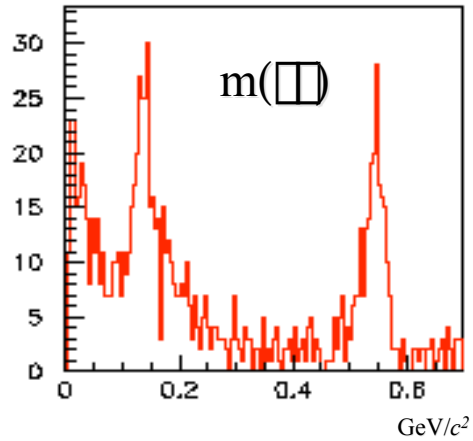
Select events with $1.0 < m(K^+K^-) < 1.04$ GeV/c^2

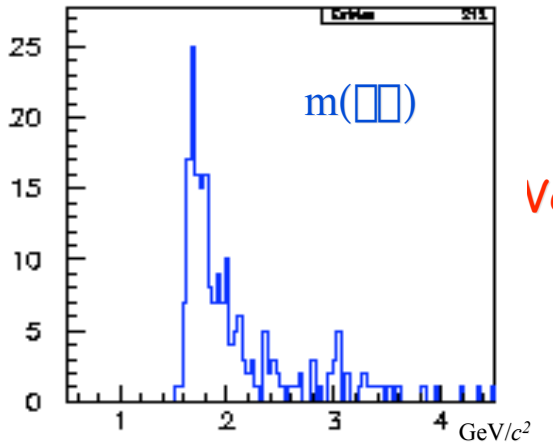


□□⁰ suppressed by Zweig rule and can have □□□⁰ mixing contribution

Interesting for exotic states

Negligible background under □ peak





Very clean □□ signal.
□□ resonance ?

Need □⁰ background suppression

How □□⁰, □□ productions are Related to □ -> □⁰□, □□?

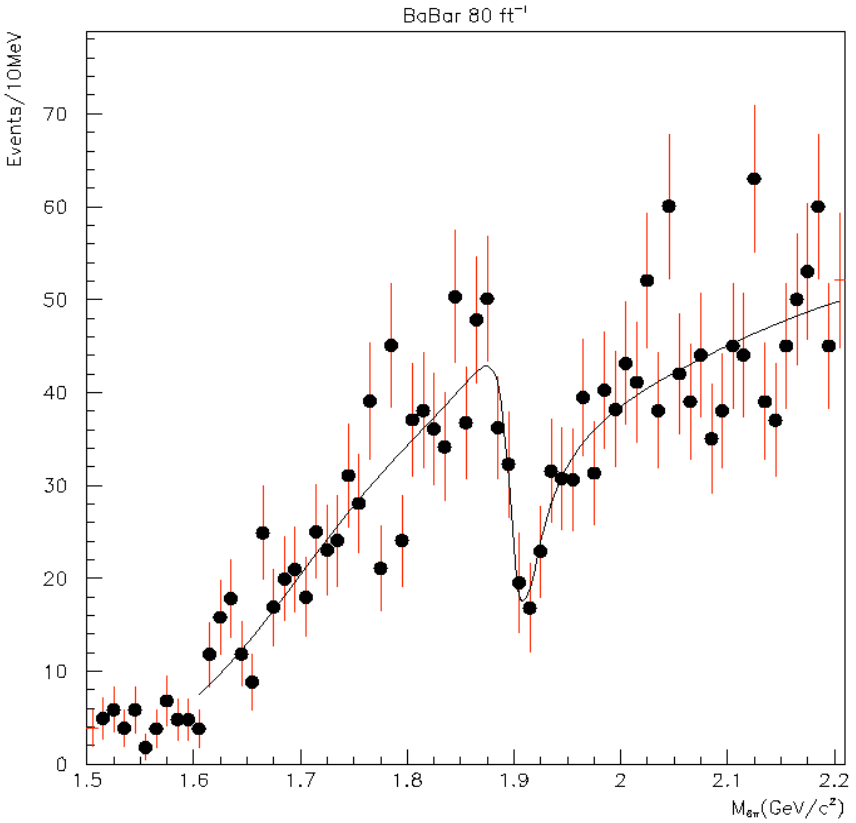
$e^+ e^- \to 3\pi^+ 3\pi^- + \pi$

(BaBar 80ft $^{-1}$)

M = 1900 ± 10 MeV

Γ = 32 ± 5 MeV

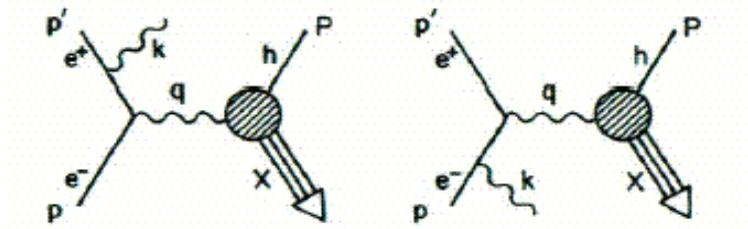
Preliminary



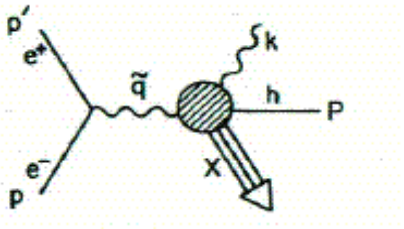
Structure has been observed by DM2 and FOCUS – no explanation!

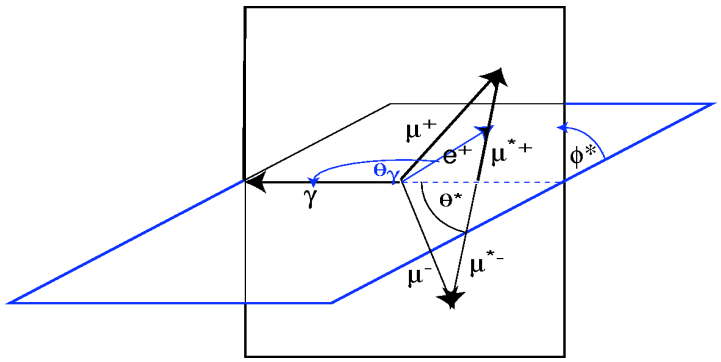
Initial and Final State Interference

ISR

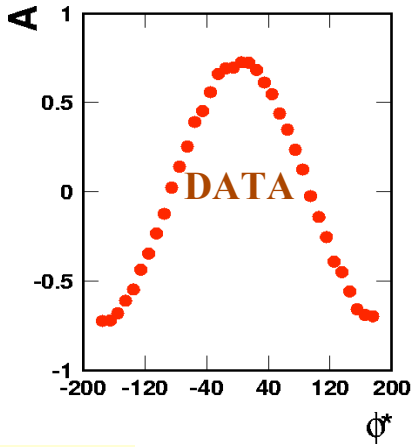


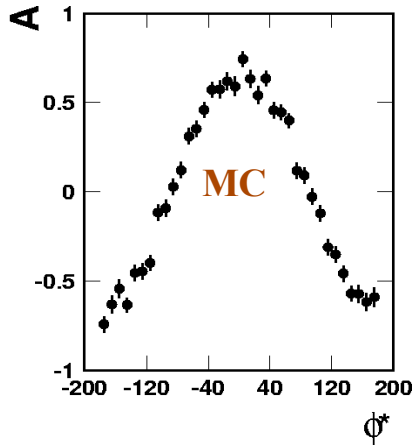
⊕ FSR





ISR-FSR interference





- QED charge asymmetry observed in the channel

What does *A* look like for or ?

- measurement of QCD phases

Inclusive R Measurements

What about using the ISR photon energy + hadrons opposite to it?
Resolution enough ? Efficiency under control? Does it matter ?

Hadronic contributions to $\Delta\alpha_{em}$:

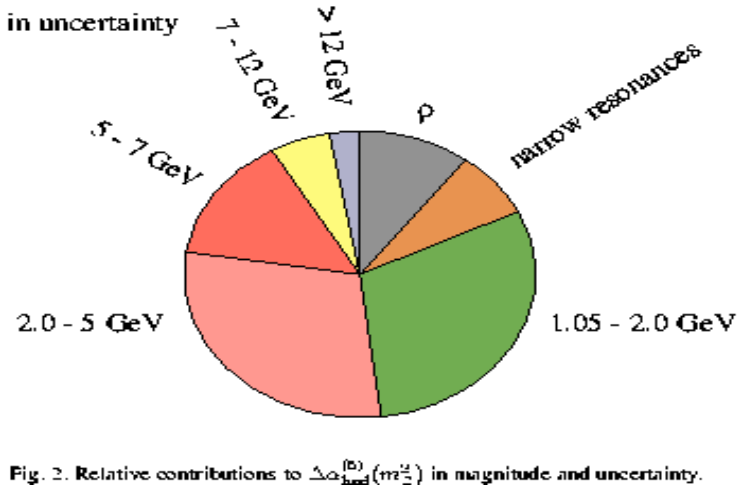
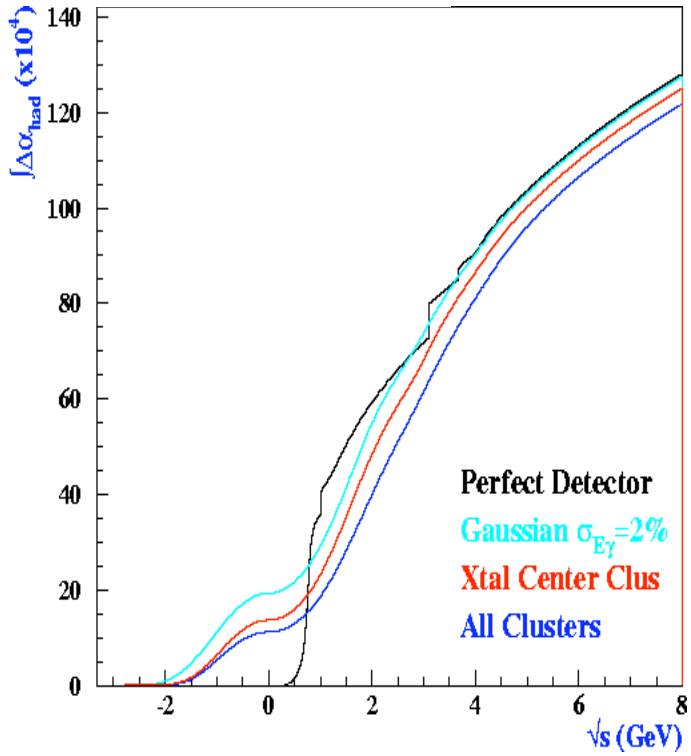


Fig. 2. Relative contributions to $\Delta\alpha^{(5)}_{had}(m_Z^2)$ in magnitude and uncertainty.



The absolute total effect of integral at 7 GeV Compared to perfect detector:
Gaussian ~0.5%
Crystal center ~3%
All clusters ~7%

We can surely calibrate From data to a small fraction of the 3% ! Looks very promising.

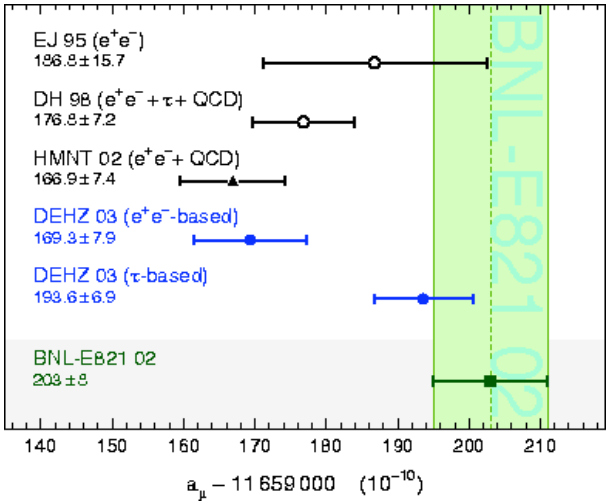
Can work for $\Delta\alpha_{had}$ up to $\sqrt{s'}$~ 7-8 GeV before photon background from normal non-radiative hadronic events becoming significant.

Conclusion

™ISR sample has an enormous potential
and should have a bright future in BaBar! (and Belle ?)

There are many channels NEVER studied at e^+e^- machines in 1-4 GeV range already available in BaBar data sample

Measurements of cross section for a few main (better all!) channels in < 3 GeV range with ~5% systematic errors (<1% needed for □□) can improve accuracy of hadronic contribution to muon g-2



Inclusive measurement up to 7-8 GeV can improve accuracy of □□$_{had}$

□ already an active field with some interesting analyses (2□, *2K*, 4□, *KK*□, Asymmetry,…) to come soon.