Measurement of $e^+e^- \rightarrow$ hadron cross-section at low energy with ISR events at BABAR

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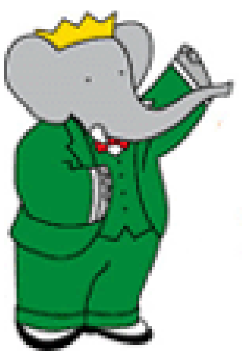

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Outlook

- The BaBar ISR (Initial State Radiation) $\pi\pi$ analysis
- Test of the method: $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
- Results on $e^+e^- \rightarrow \pi^+ \pi^-(\gamma)$

} PRL 103, 231801 (2009)

- Other ISR results on multihadronic cross sections

- Conclusion and perspectives

Goals of the BaBar Analysis

- Measure $\sigma[e^+e^- \to \pi^+\pi^-(\gamma_{FSR})]$ with high accuracy for vacuum polarization calculations, using the ISR method $e^+e^- \to \pi^+\pi^-\gamma_{ISR}(\gamma_{add.})$
- $\pi\pi$ channel contributes 73% of a_μ^{had} (see Andreas' talk)
- Dominant uncertainty also from $\pi\pi$
- Previous systematic precision (on cross section) of e^+e^- experiments

CMD-2 0.8%	SND 1.5%			in agreement
KLOE (ISR from 1.02 GeV)		2005	1.3%	some deviation in shape
		2008	0.9%	better agreement

- Big advantage of ISR: all mass spectrum covered at once (from threshold to 3 GeV in BABAR), with same detector and analysis
- Measure simultaneously $\pi^+\pi^-\gamma_{ISR}(\gamma_{add.})$ and $\mu^+\mu^-\gamma_{ISR}(\gamma_{add.})$
- Compare the measured $\mu^+\mu^-\gamma_{ISR}(\gamma_{add.})$ spectrum with QED prediction
- Compare to spectral functions from previous e^+e^- data and τ decays

$\Rightarrow$ aim for a measurement with <1% accuracy (syst. errors at per mil level)

great interest to clarify the situation as magnitude of possible discrepancy with SM is of the order of SUSY contributions with masses of a few 100 GeV

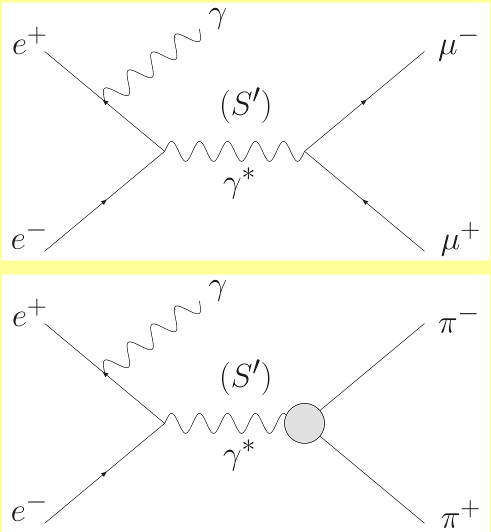
The Relevant Processes

$e^+ e^- \to \mu^+ \mu^- \gamma_{ISR} (\gamma_{add.})$ and $\pi^+ \pi^- \gamma_{ISR} (\gamma_{add.})$ measured simultaneously

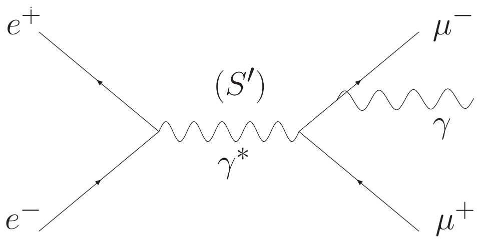
$$x = 2E^*_\gamma / \sqrt{s}$$

$$s' = s(1-x)$$

ISR

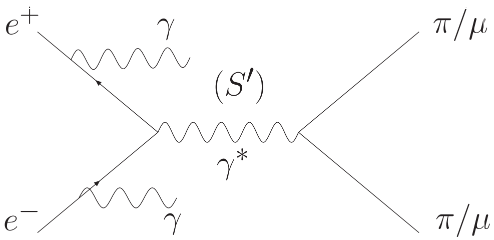


FSR

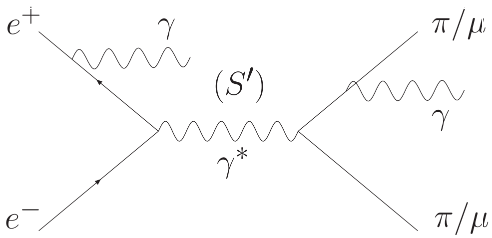


LO FSR negligible for ππ at $s \sim (10.6\ \mathrm{GeV})^2$

ISR + add. ISR



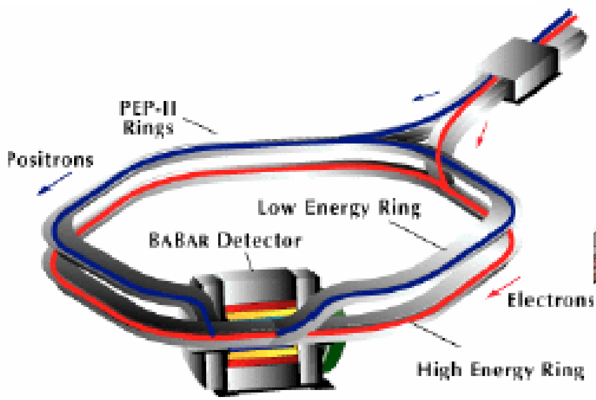
ISR + add. FSR

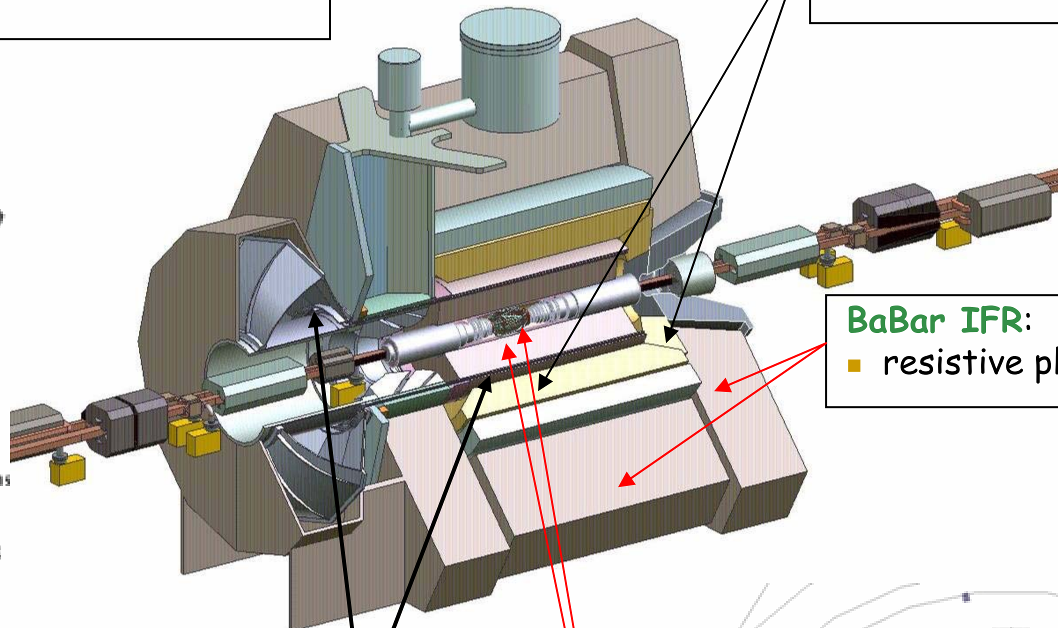


BaBar / PEP II

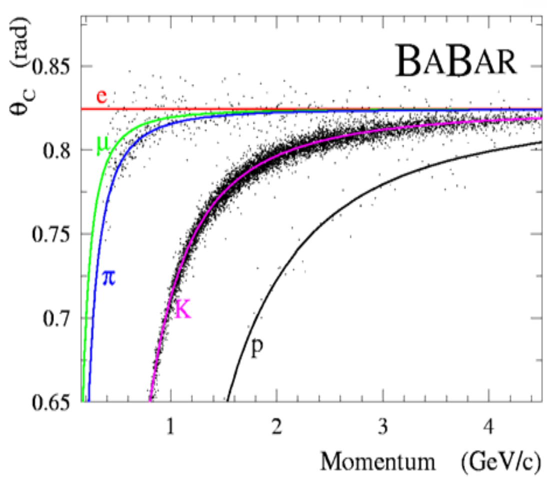
- **PEP-II** is an asymmetric e^+e^- collider operating at CM energy of $\Upsilon(4S)$.
- Integrated luminosity = 531 fb^{-1}, 232 fb^{-1} used here

BaBar EMC:
- 6580 CsI(Tl) crystals, resolution ~1-2 % high E.



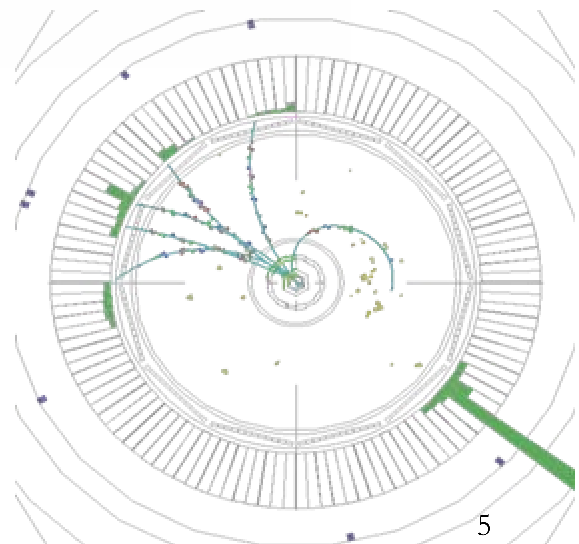


BaBar IFR:
- resistive plate chambers



BaBar DIRC
- particle ID up to 4-5 GeV/c

BaBar SVT and DCH
- precision tracking



The Measurement

- ISR photon at large angle, detected in the EMC
- detected tracks of good quality: 1 (for efficiency) or 2 (for physics)
- identification of the charged particles (DIRC, DCH)
- separate ππ/KK/μμ event samples
- kinematic fit (not using ISR photon energy) including 1 additional photon: reduce non 2-body backgrounds (discussed later)
- obtain all efficiencies (trigger, filter, tracking, ID, fit) from same data
- measure ratio of ππγ(γ) to μμγ(γ) cross sections to cancel:
  - ee luminosity
  - additional ISR
  - vacuum polarization
  - ISR photon efficiency

  } otherwise ~1-2% syst error for the ππ channel
- correct for LO FSR ($|FSR|^2$) contribution in μμγ(γ) (QED, <1% below 1 GeV)
- additional FSR photons measured

$$R_{\exp}(s') = \frac{\sigma_{[\pi\pi\gamma(\gamma)]}(s')}{\sigma_{[\mu\mu\gamma(\gamma)]}(s')} = \frac{\sigma^0_{[\pi\pi(\gamma)]}(s')}{(1+\delta^{\mu\mu}_{\rm FSR})\sigma^0_{[\mu\mu(\gamma)]}(s')} = \frac{R(s')}{(1+\delta^{\mu\mu}_{\rm FSR})(1+\delta^{\mu\mu}_{add,FSR})}$$

MC Generators

- Acceptance and efficiencies determined initially from simulation, with data/MC corrections applied
- Large simulated samples, typically 10 × data, using AfkQed generator

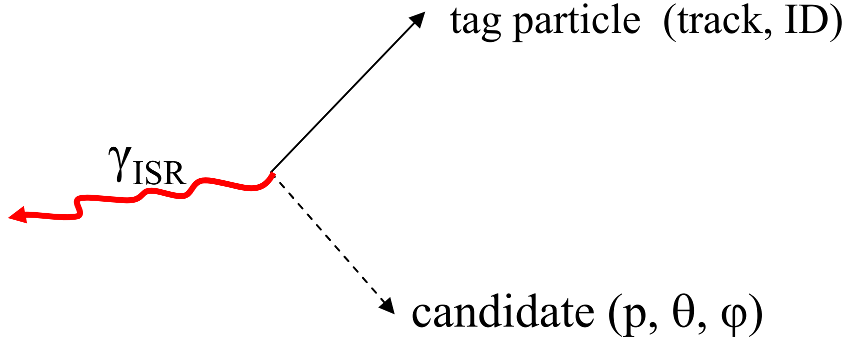
- AfkQed: lowest-order (LO) QED with additional radiation:
  - ISR with structure function method, γ assumed collinear to the beams and with limited energy
  - FSR using PHOTOS
- Phokhara 4.0: (almost) exact second-order QED matrix element, limited to NLO

- Studies comparing Phokhara and AfkQed at 4-vector level with fast simulation

- QED test with $\mu\,\mu\,\gamma\,(\gamma)$ cross section requires reliable NLO generator

- $\pi\pi(\gamma_{FSR})$ cross section obtained through $\pi\pi\gamma(\gamma)$ / $\mu\mu\gamma(\gamma)$ ratio, rather insensitive to detailed description of radiation in MC

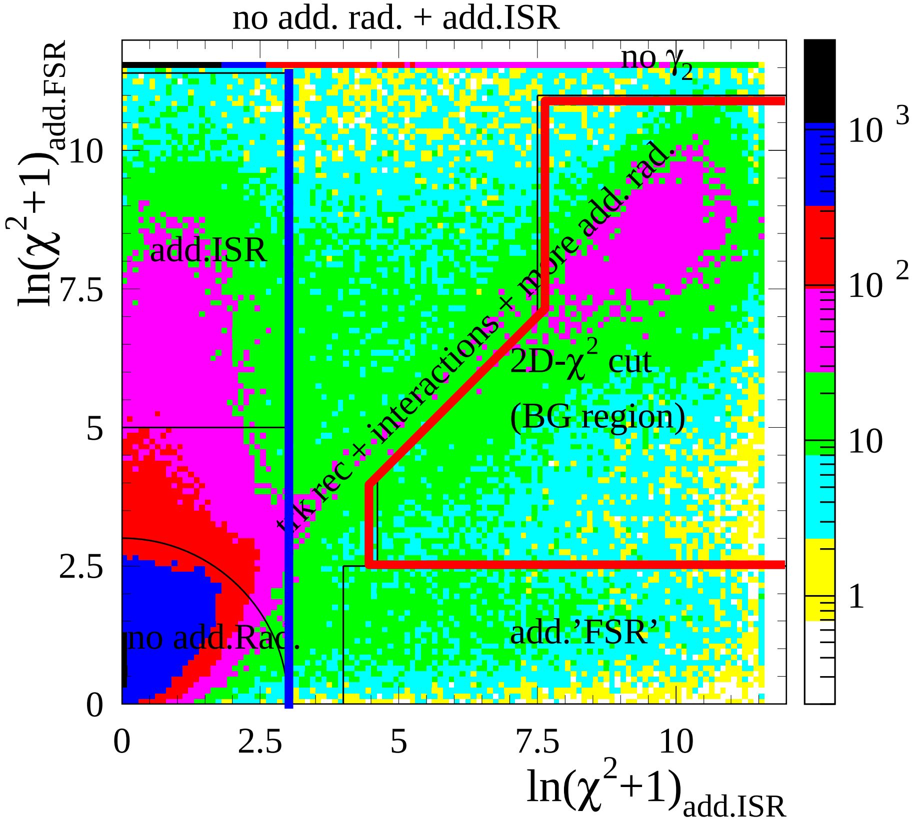
Particle-related Efficiency Measurements



- benefit from pair production for tracking and particle ID
- kinematically constrained events
- efficiency automatically averaged over running periods
- measurement in the same environment as for physics, in fact same events!
- applied to particle ID with $\pi/K/\mu$ samples, tracking…
- assumes that efficiencies of the 2 particles are uncorrelated
- in practice not true $\Rightarrow$ study of 2-particle overlap in the detector (trigger,tracking, EMC, IFR) required a large effort to reach per mil accuracies

Kinematic Fitting: First NLO Cross Section Measurement

$\pi\pi\gamma(\gamma)$



- Two kinematic fits to X X $\gamma_{ISR}\,\gamma_{add}$ (ISR photon defined as highest energy)

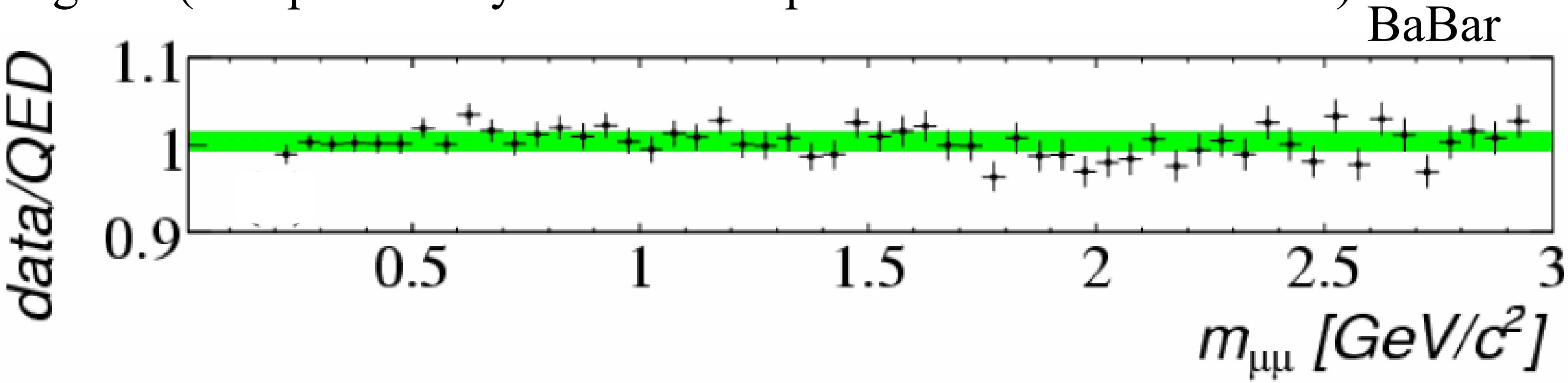
  Add. ISR fit: γ_{add} assumed along beams
  Add. 'FSR' if γ_{add} detected

- Loose χ^2 cut (outside BG region in plot) for $\mu\mu$ and $\pi\pi$ in central ρ region
- Tight χ^2 cut ($\ln(\chi^2+1)_{add.ISR}<3$) for $\pi\pi$ in ρ tail region
- χ^2 efficiency measurement: effects of add. radiation and secondary interactions

- q $\bar{q}$ and multi-hadronic ISR background from MC samples + normalization from data using signals from $\pi^0 \rightarrow \gamma_{ISR}\gamma$ ($q\bar{q}$), and ω and ϕ ($\pi\pi\pi^0\gamma$)

QED Test with $\mu\mu\gamma$ sample

- absolute comparison of $\mu\mu$ mass spectra in data and in simulation
- simulation corrected for data/MC efficiencies
- AfkQed corrected for incomplete NLO using Phokhara
- strong test (ISR probability function drops out for $\pi\pi$ cross section)



$$\frac{\sigma^{data}_{\mu\mu\gamma(\gamma)}}{\sigma^{NLO\ QED}_{\mu\mu\gamma(\gamma)}} = 1 + (4.0 \pm 1.9 \pm 5.5 \pm 9.4) \mathrm{x} 10^{-3}$$

(0.2 – 3 GeV)

ISR γ efficiency 3.4 syst.
trig/track/PID 4.0

BaBar ee luminosity

Obtaining the $\pi\pi(\gamma_{FSR})$ cross section

$$\frac{dN_{\pi\pi\gamma(\gamma)}}{d\sqrt{s'}} = \frac{dL_{ISR}^{eff}}{d\sqrt{s'}} \varepsilon_{\pi\pi\gamma(\gamma)}(\sqrt{s'}) \; \sigma^0_{\pi\pi(\gamma)}(\sqrt{s'})$$

Unfolded spectrum

Acceptance from MC + data/MC corrections

Effective ISR luminosity from $\mu\mu\gamma(\gamma)$ analysis (similar equation + QED)

$\pi\pi$ mass spectrum unfolded (B. M. arXiv:0907.3791) for detector response

Additional ISR almost cancels in the procedure ($\pi\pi\gamma(\gamma)$ / $\mu\mu\gamma(\gamma)$ ratio)
Correction $(2.5 \pm 1.0) \times 10^{-3}$ $\Rightarrow$ **$\pi\pi$ cross section does not rely on accurate description of NLO in the MC generator**

ISR luminosity from $\mu\mu\gamma(\gamma)$ in 50-MeV energy intervals
(small compared to variation of efficiency corrections)

Systematic uncertainties

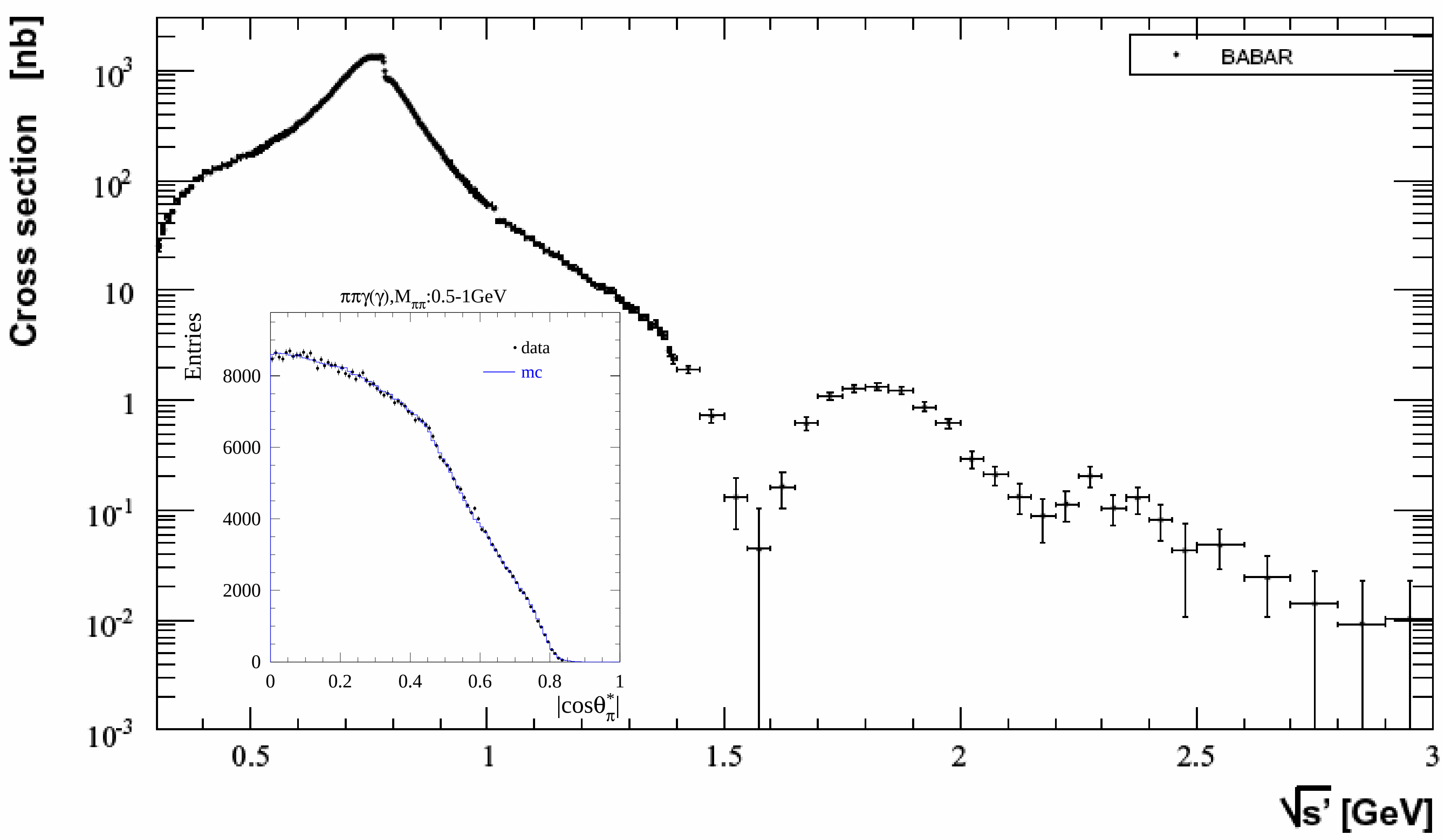
√s` intervals (GeV) errors in 10^{-3}

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)

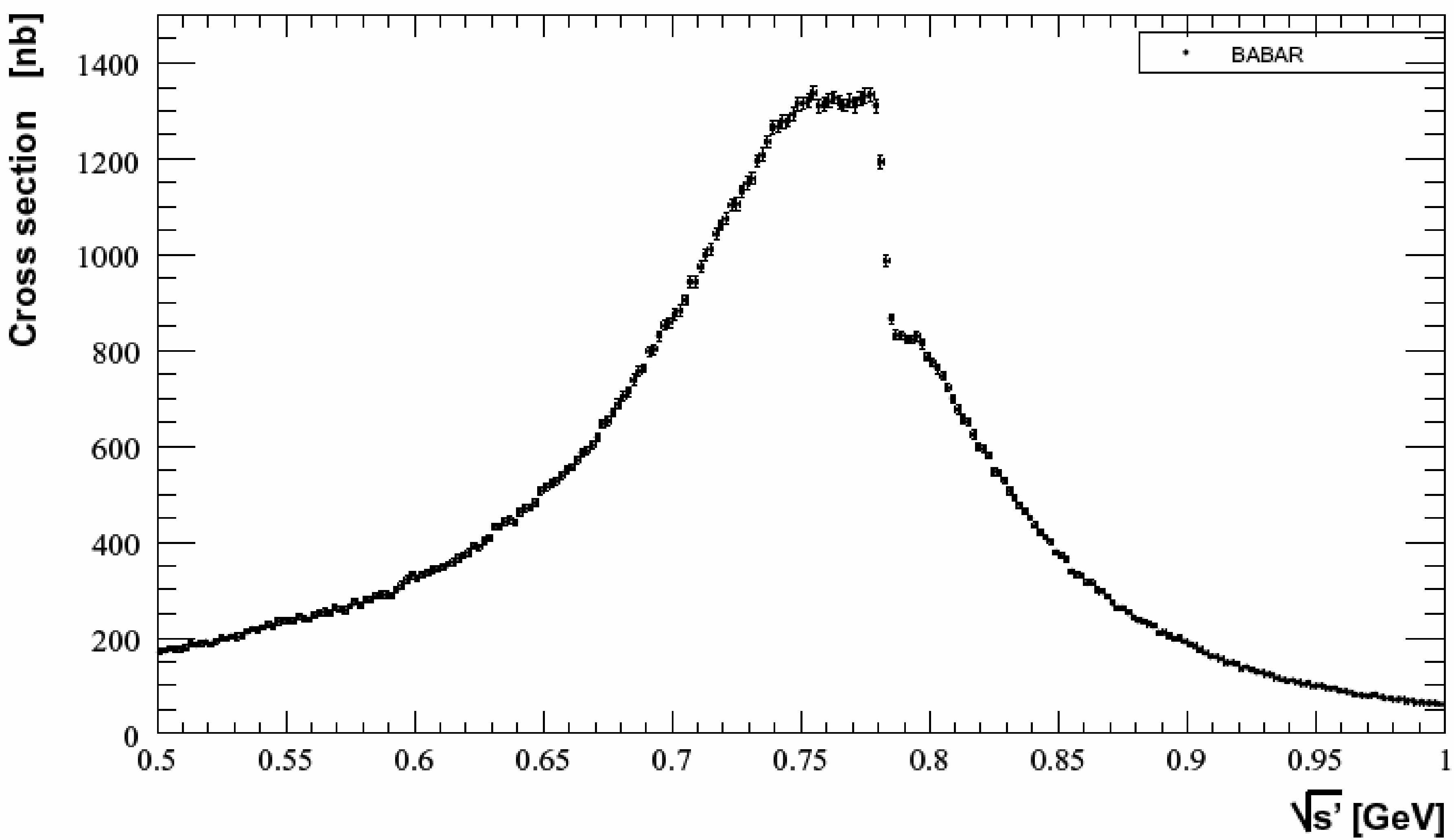
BaBar results (arXiv:0908.3589, PRL 103, 231801 (2009))

$e^+ e^- \to \pi^+ \pi^- (\gamma_{FSR})$ bare (no VP) cross section diagonal errors (stat+syst)

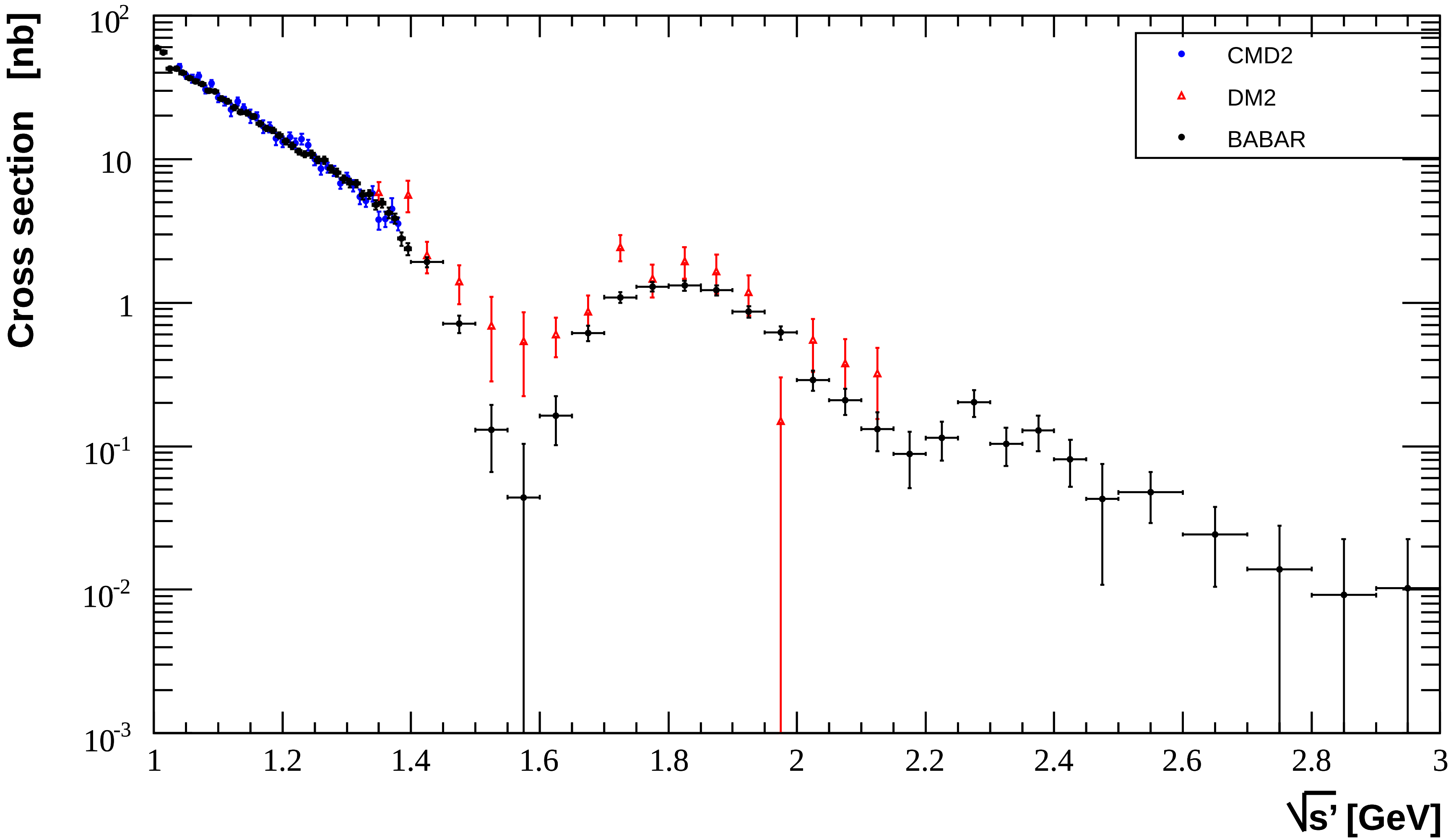


BaBar results in ρ region

2-MeV energy intervals



BaBar vs. other experiments at larger mass



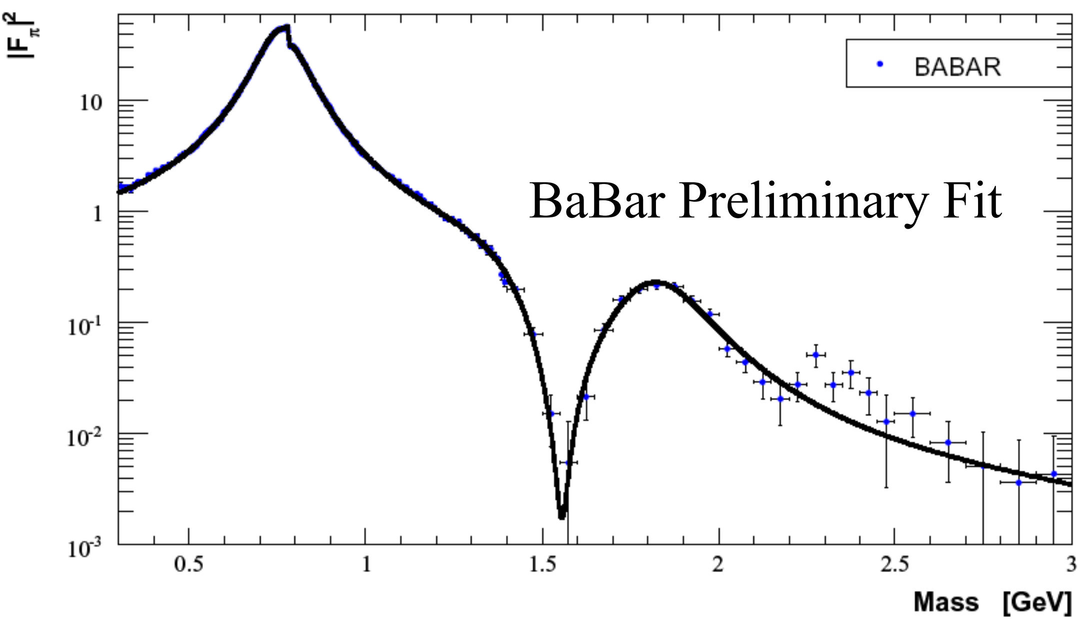
VDM fit of the pion form factor

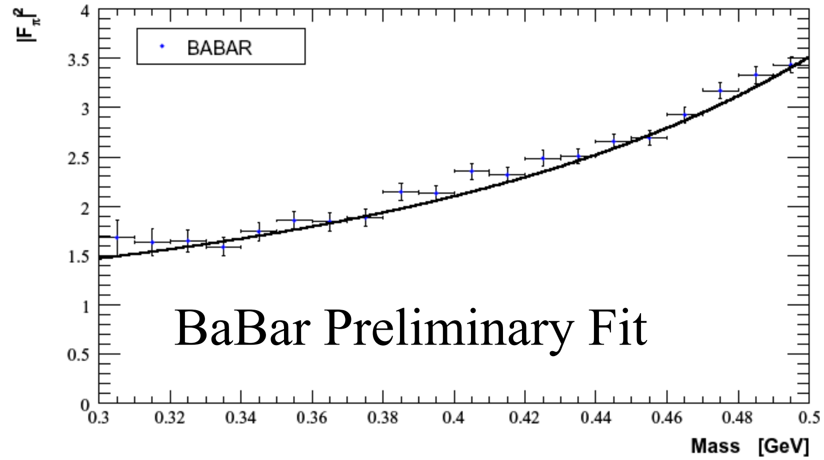
$$F_\pi(s) = \frac{BW_\rho^{GS}(s, m_\rho, \Gamma_\rho)\frac{1+\alpha BW_\omega^{KS}(s, m_\omega, \Gamma_\omega)}{1+\alpha} + \beta BW_{\rho'}^{GS}(s, m_{\rho'}, \Gamma_{\rho'}) + \gamma BW_{\rho''}^{GS}(s, m_{\rho''}, \Gamma_{\rho''})}{1+\beta+\gamma}$$

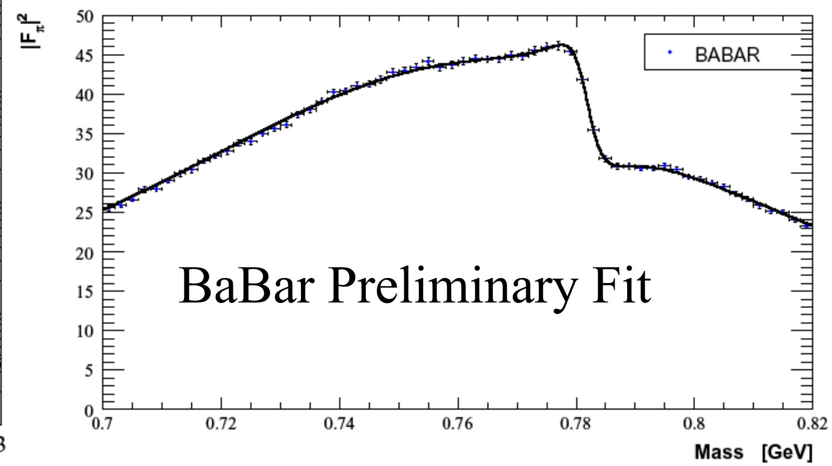
$$|F_\pi|^2(s') = \frac{3s'}{\pi\alpha^2(0)\beta_\pi^3}\,\sigma_{\pi\pi}(s')$$

$$\sigma_{\pi\pi}(s') = \frac{\sigma^0_{\pi\pi(\gamma)}(s')}{1+\frac{\alpha}{\pi}\eta(s')} \quad \left(\frac{\alpha(s')}{\alpha(0)}\right)^2$$

add. FSR $\quad$ α Running (VP)

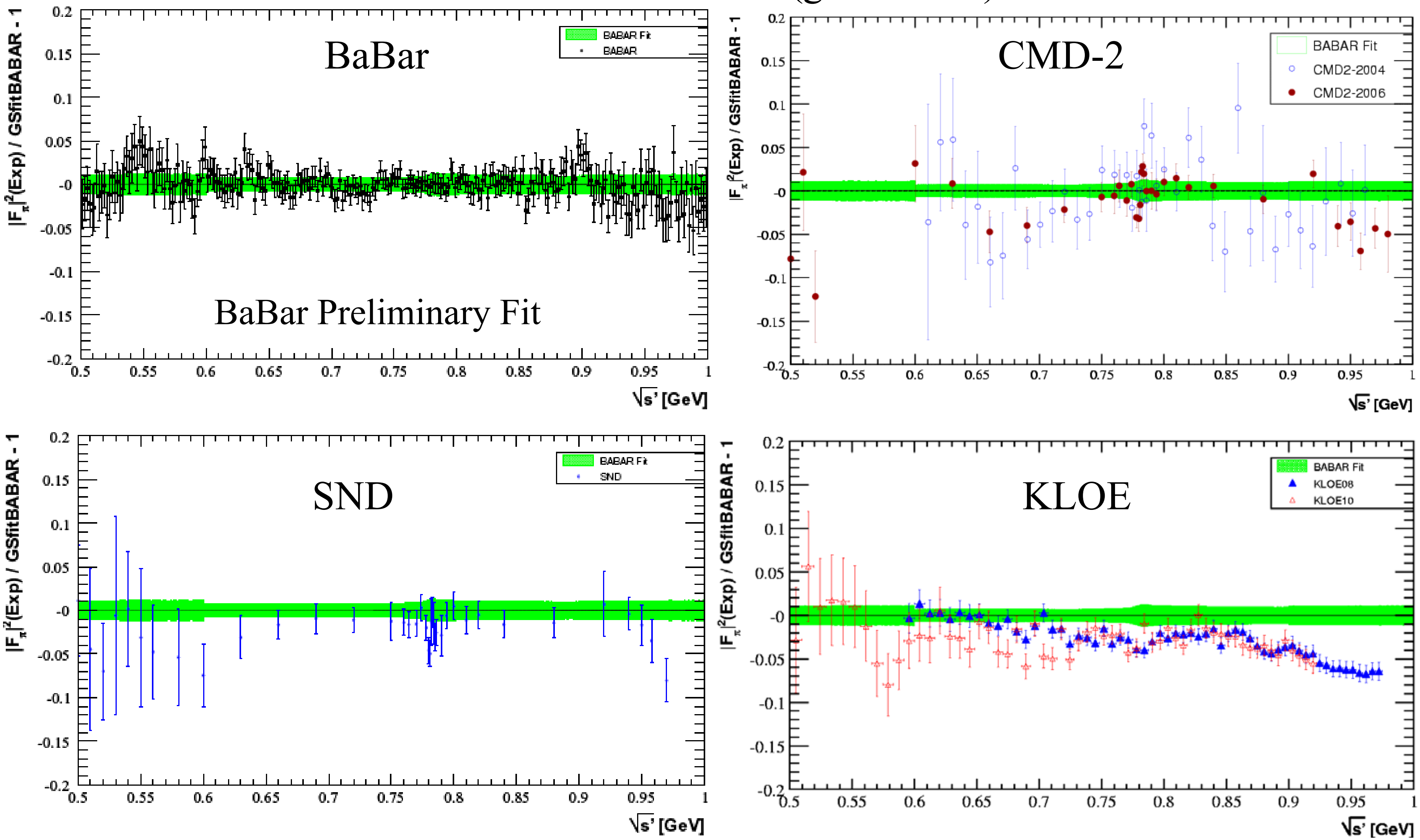






BaBar vs.other ee data (0.5-1.0 GeV)

direct relative comparison of cross sections with BaBar fit (stat + syst errors included)
(green band)



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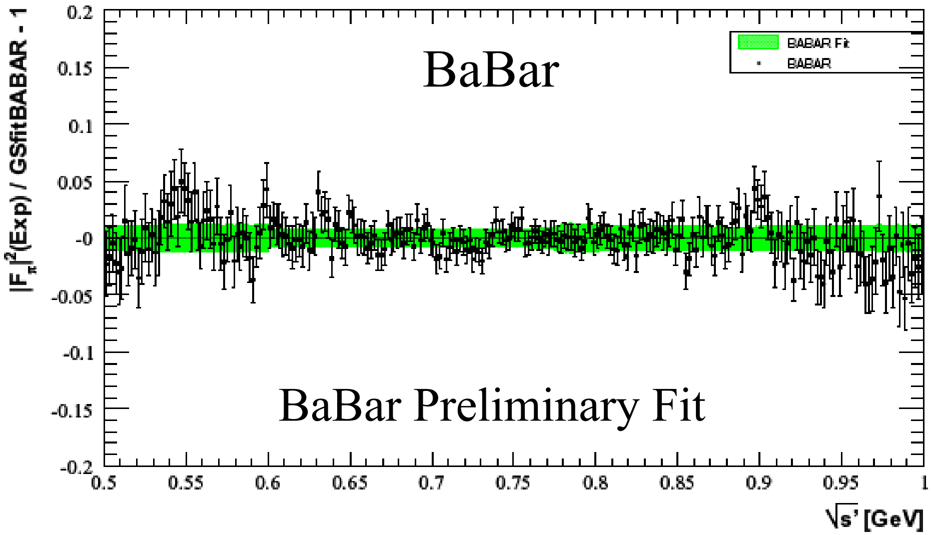
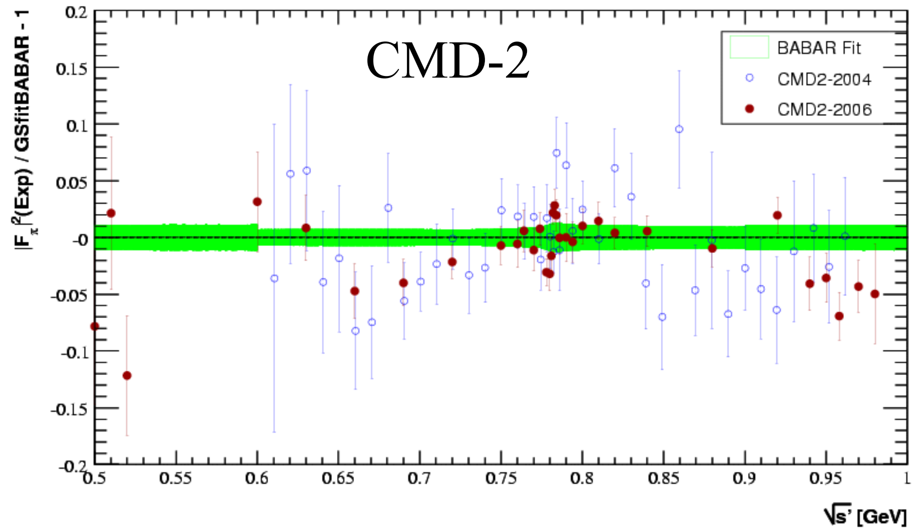
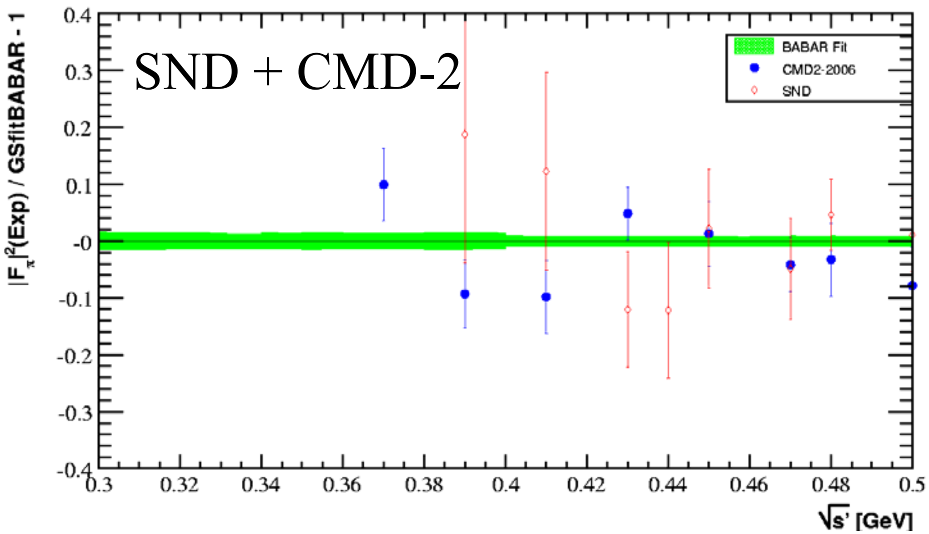
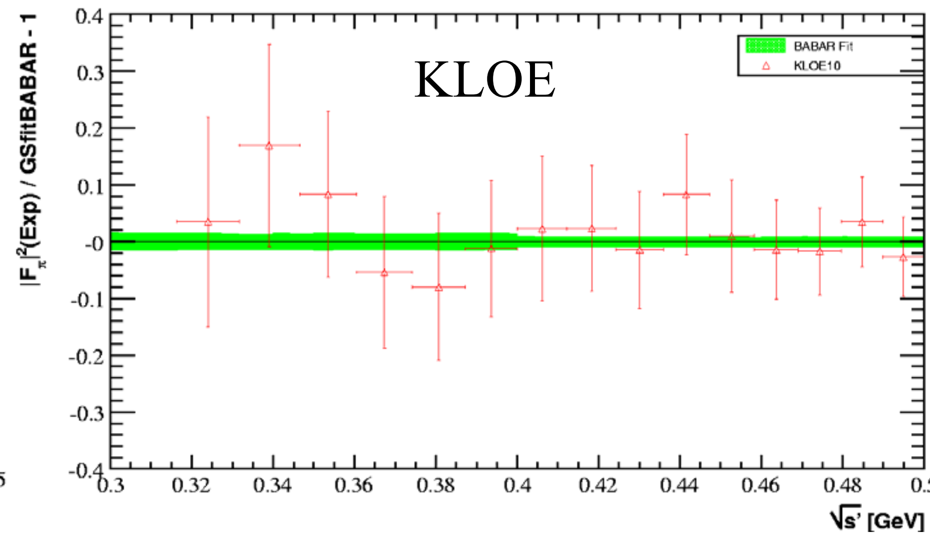
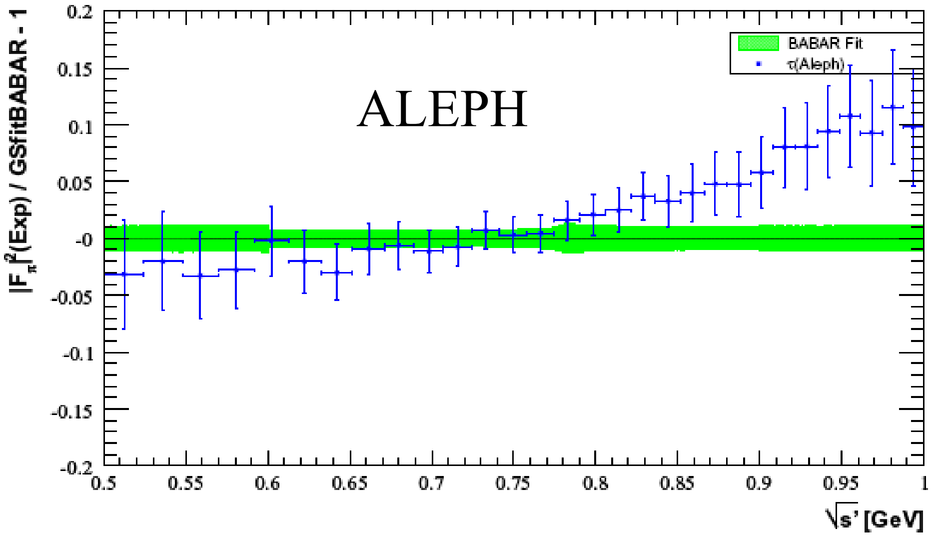








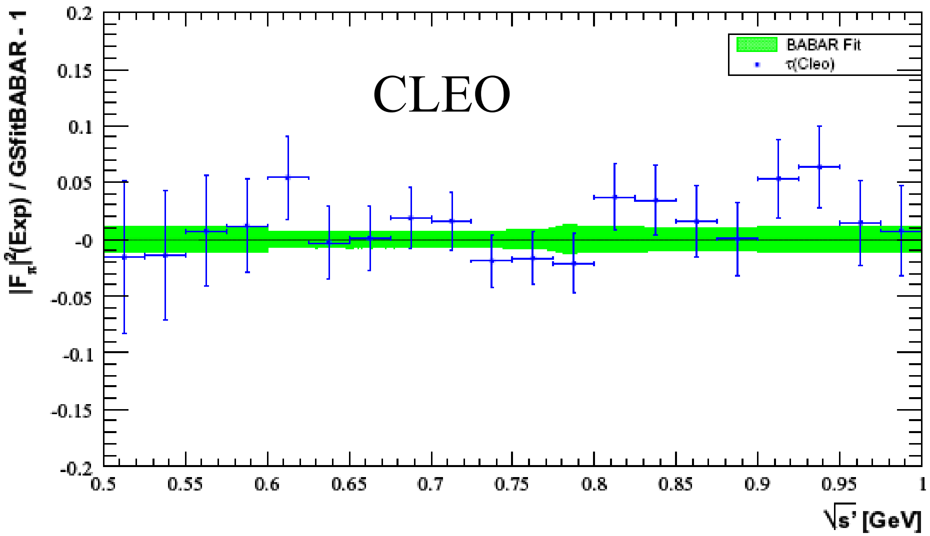
BaBar vs. IB-corrected τ data (0.5-1.0 GeV)

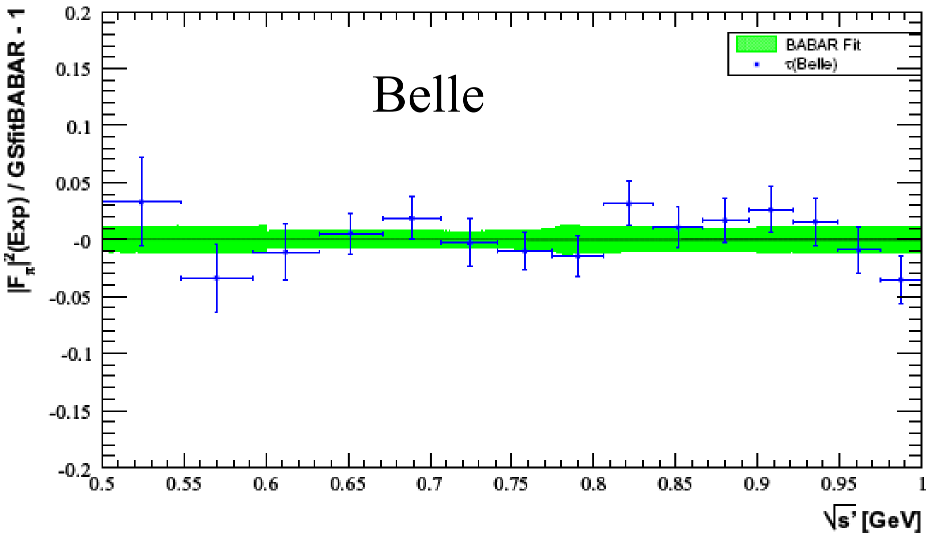


relative comparison w.r.t. BaBar of τ spectral functions corrected for isospin-breaking(IB)

IB corrections: radiative corr., π masses, ρ-ω interference, ρ masses/widths

each τ data normalized to its own BR





Computing $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi(\gamma),LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\pi\pi(\gamma)}(s)\ ,$$

where $K(s)$ is the QED kernel,

$$K(s) = x^2\left(1-\frac{x^2}{2}\right) + (1+x)^2\left(1+\frac{1}{x^2}\right)\left[\ln(1+x) - x + \frac{x^2}{2}\right] + x^2\frac{1+x}{1-x}\ln x\ ,$$

with $x = (1-\beta_\mu)/(1+\beta_\mu)$ and $\beta_\mu = (1-4m_\mu^2/s)^{1/2}$.

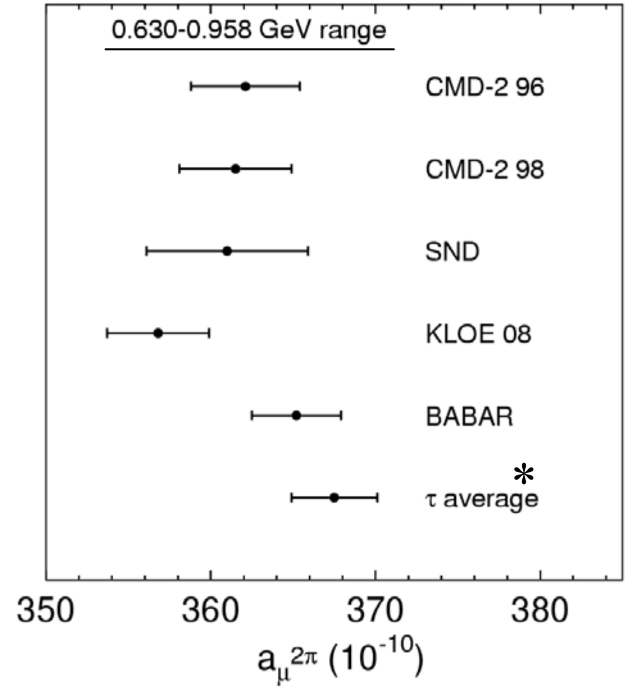
0.28–1.8 (GeV)

BABAR	$(514.1 \pm 3.8) \times 10^{-10}$
previous e^+e^- combined	$(503.5 \pm 3.5) \times 10^{-10}$ *
τ combined	$(515.2 \pm 3.5) \times 10^{-10}$ *

Deviation between BNL measurement and theory prediction reduced using BaBar $\pi^+\pi^-$ data

$a_\mu[\exp] - a_\mu[SM] = (19.8 \pm 8.4)\times 10^{-10}$ (2.4σ)

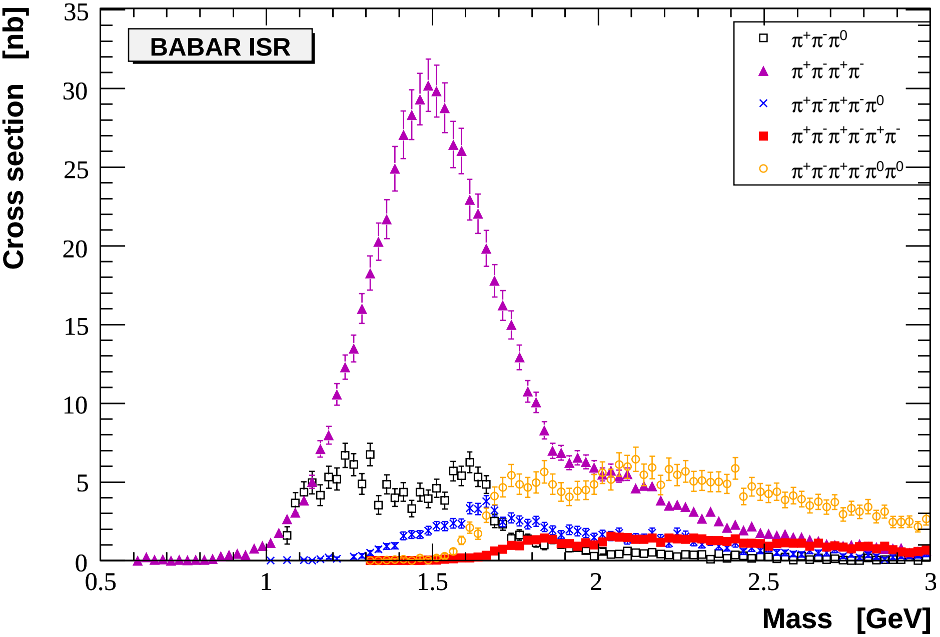
$\pi^+\pi^-$ from BaBar only

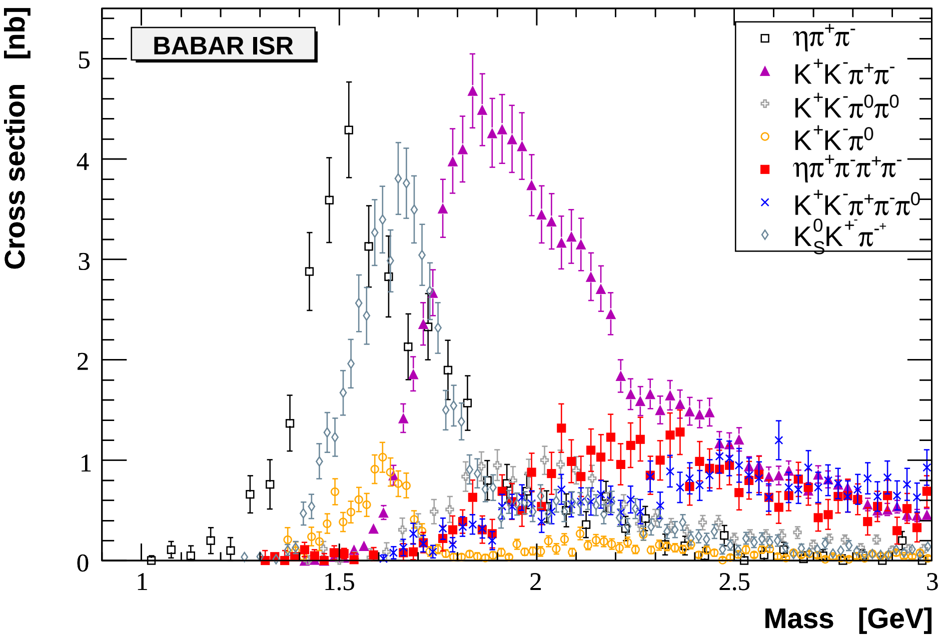


* arXiv:0906.5443 M. Davier et al.

BaBar Multi-hadronic Published Results

Statistical + systematic errors





Still more channels under analysis: K^+K^-, $KK\pi\pi$ with K^0, $\pi^+\pi^-2\pi^0$

Conclusions and Perspectives

- BaBar analysis of $\pi^+\pi^-$ and $\mu^+\mu^-$ ISR processes completed
- Precision goal has been achieved: 0.5% in ρ region (0.6-0.9 GeV)
- Absolute $\mu^+\mu^-$ cross section agrees with NLO QED within 1.1%
- $ee \rightarrow \pi^+\pi^-(\gamma)$ cross section insensitive to MC generator
- Full range of interest covered from 0.3 to 3 GeV

- Contribution to a_μ from BaBar is $(514.1 \pm 2.2 \pm 3.1) \times 10^{-10}$ in the range 0.28-1.8 GeV
- BaBar result has an accuracy (0.7%) comparable to combined previous results
- Contribution from multi-hadronic channels will continue to be updated with more results forthcoming from BaBar, particularly $\pi^+\pi^-2\pi^0$

Conclusions and Perspectives

- Comparison with data from other experiments: fair agreement with CMD-2 and SND, poor with KLOE

  →First priority is a clarification of the BaBar/KLOE discrepancy:

  - most important effect on a_μ: difference on ρ peak
  - origin of the 'slope' (was very pronounced with the 2004 KLOE results, reduced with the 2008 and 2010 results)
  - slope also seen in KLOE/τ comparison; BaBar agrees with τ
- Further checks of the KLOE results are possible: as method is based on MC simulation for ISR and additional ISR/FSR probabilities

  $\Rightarrow$ test with $\mu\mu\gamma$ analysis

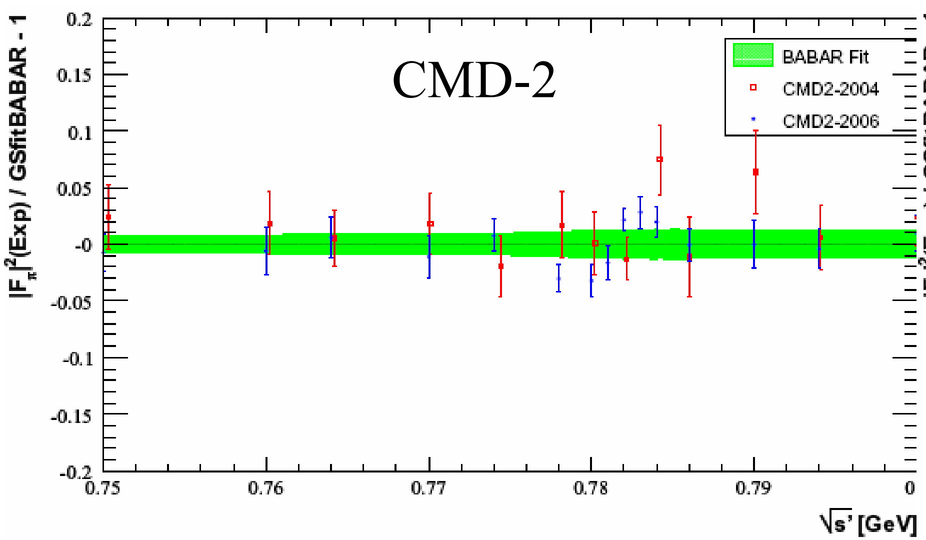
Backup Slides

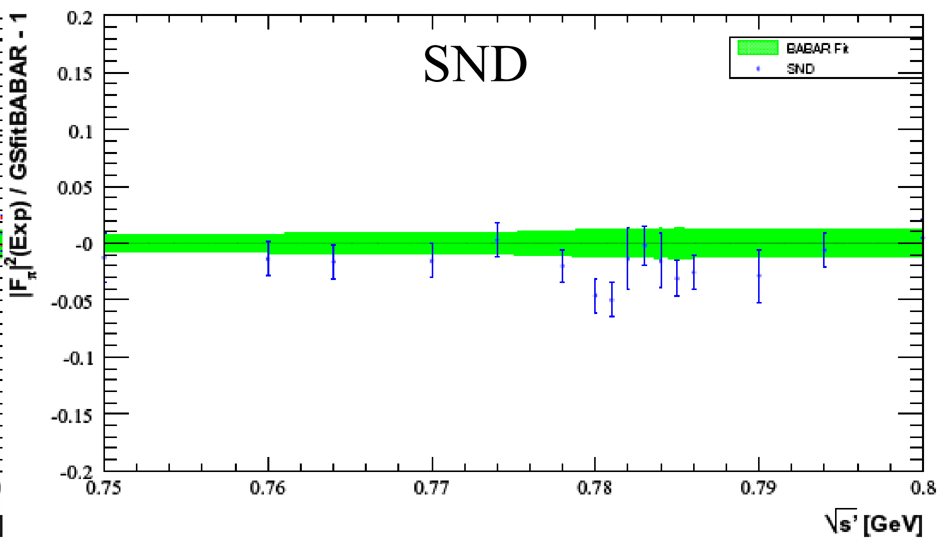
BaBar vs.other ee data ($\rho-\omega$ interference region)

- mass calibration of BaBar checked with ISR-produced $J/\psi \to \mu\mu$
- expect $-(0.16 \pm 0.16)$ MeV at ρ peak
- ω mass determined through VDM mass fit

$$m_\omega^{fit} - m_\omega^{PDG} = -(0.12 \pm 0.29)\ \text{MeV}$$

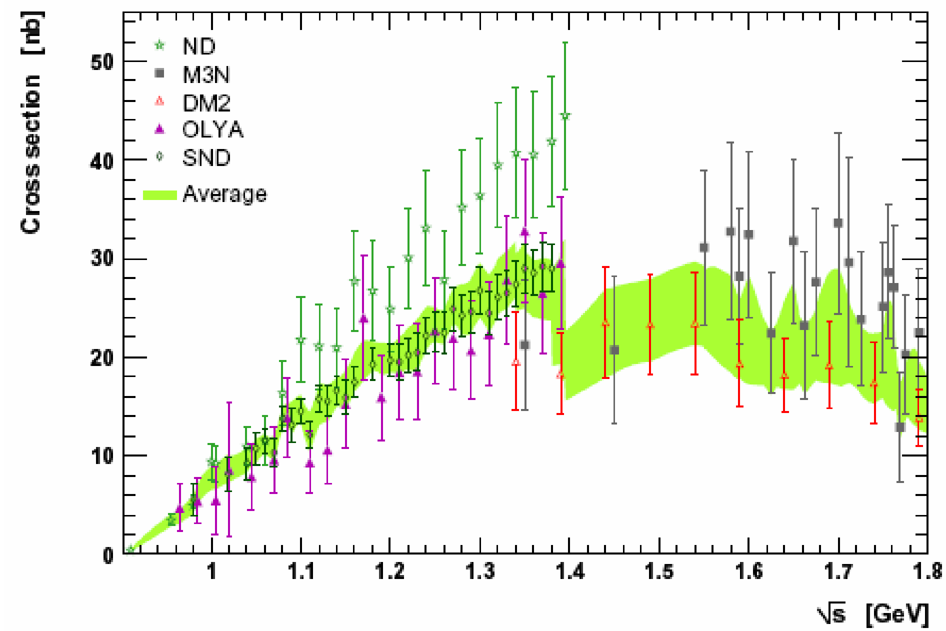
- Novosibirsk data precisely calibrated using resonant depolarization
- comparison BaBar/CMD-2/SND in ρ-ω interference region shows no evidence for a mass shift



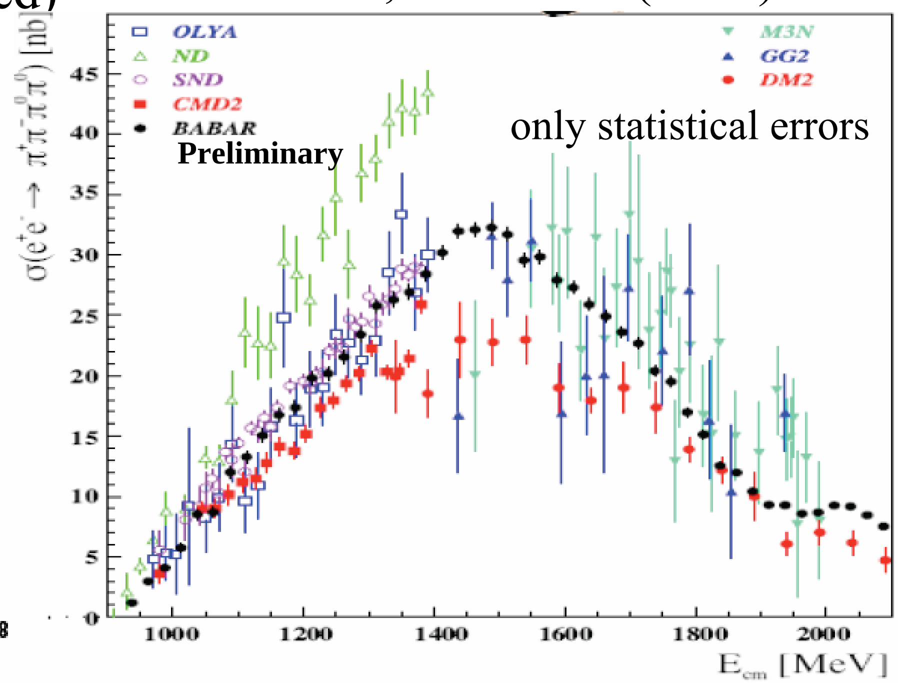


The Problematic $\pi^+\pi^-2\pi^0$ Contribution

$e^+e^- \to \pi^+\pi^-2\pi^0$ data (CMD2 discarded)

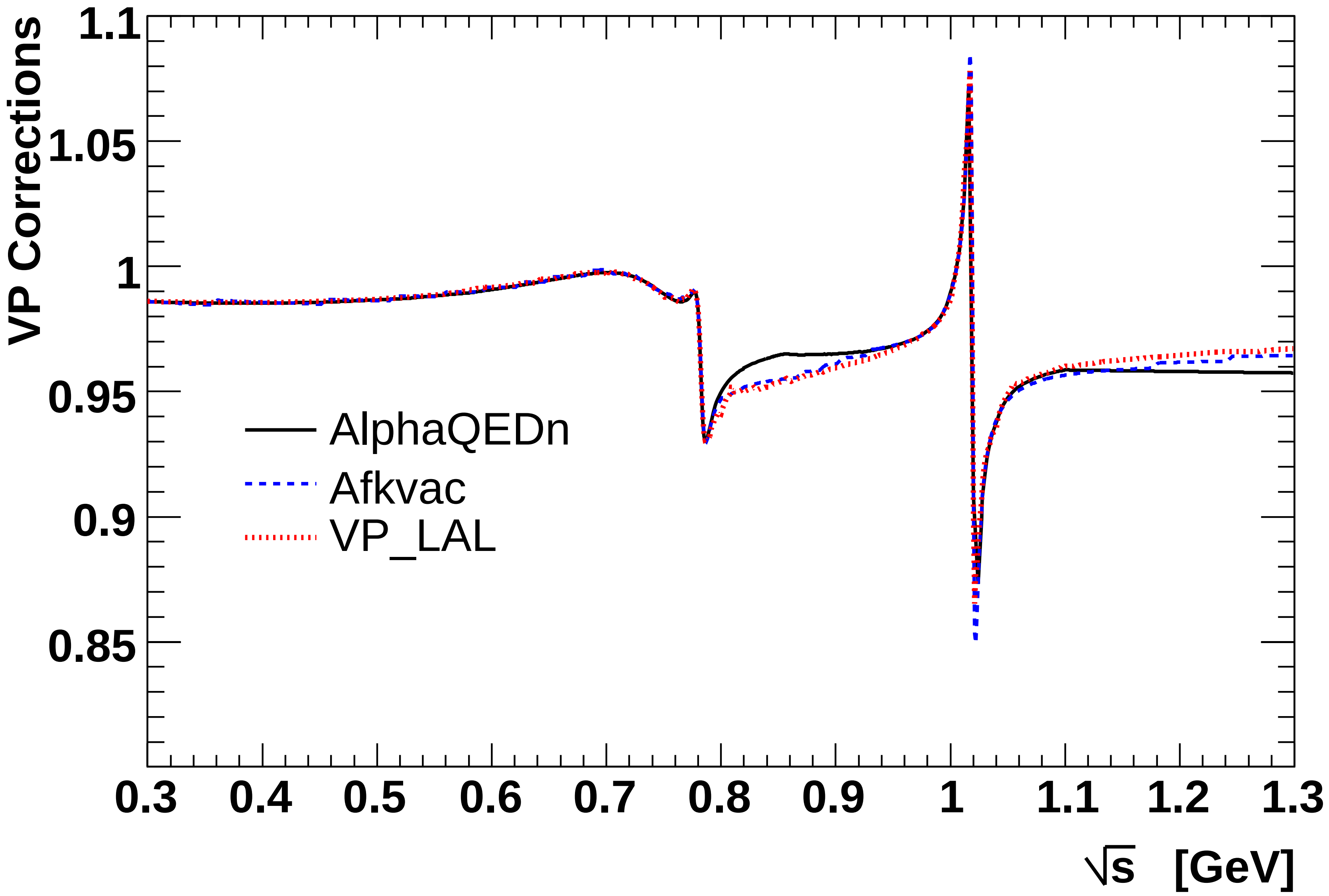


preliminary ISR BaBar data:
A. Petzold, EPS-HEP (2007)

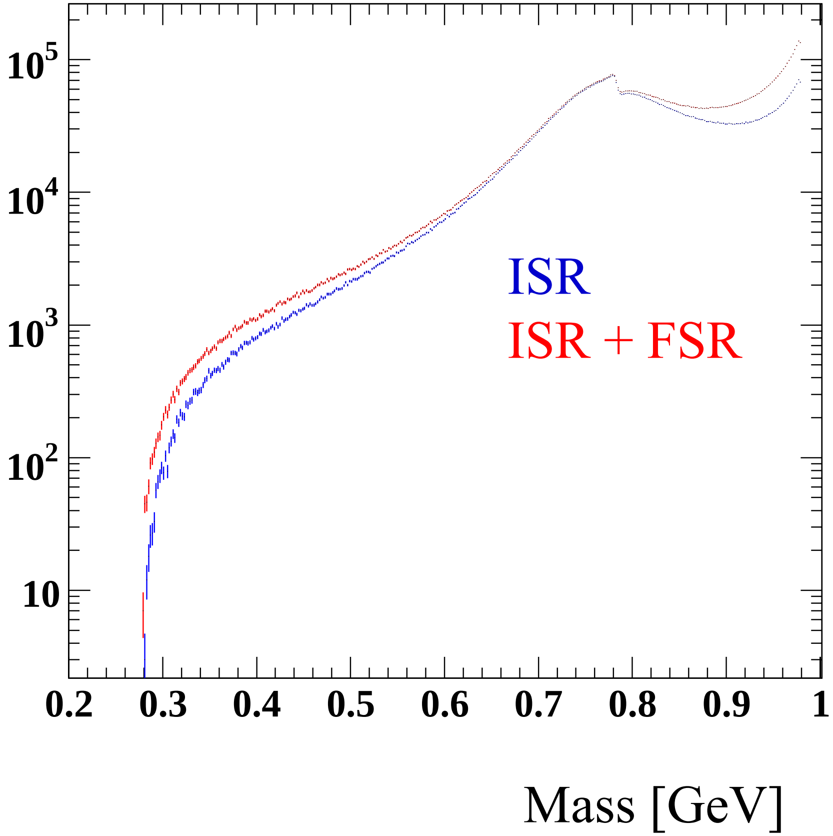


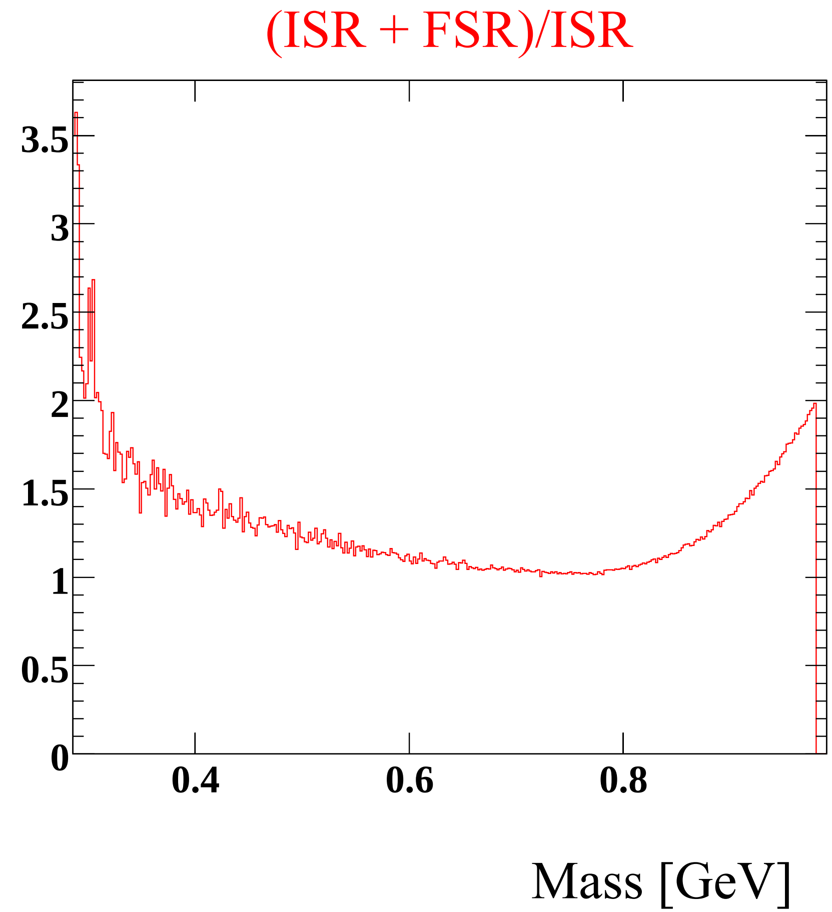
old contribution	16.8 ± 1.3	
update	17.6 ± 1.7	probably still underestimated (BaBar)
τ	21.4 ± 1.4	

Vacuum Polarization Functions



FSR Fraction for KLOE (Phokhara)





Pion Angular Distributions in $\pi\pi$ CM (Phokhara)