利用初态辐射方法对$e^+e^-\to\pi^+\pi^-(\gamma)$截面的精确测量

——第五届晨光杯报告

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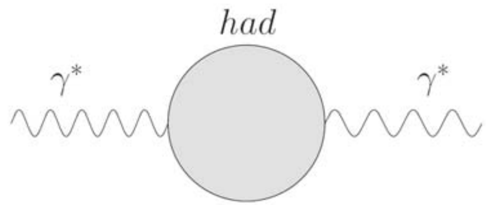
Outline

- Introduction
- PEPII and BaBar detectors
- Event selection and data samples
- Trigger, tracking and particle identification
- Kinematic fitting and backgrounds
- Important testes
- Results on $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$
- Impact on muon g –2
- Publication and citations
- Conclusions

Introduction

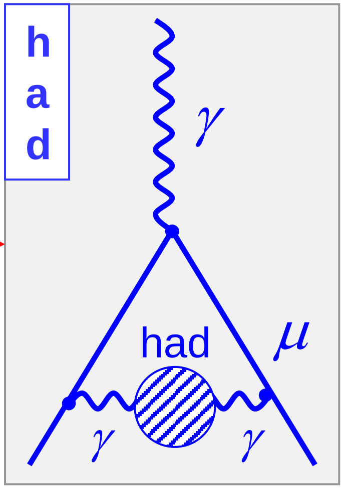
Hadronic vacuum polarization and muon $g-2$ (a_μ)

Hadronic vacuum polarization:

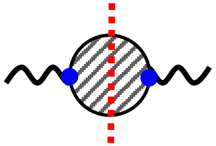
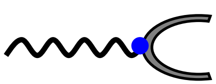


Contributions to the Standard Model (SM) Prediction for a_μ:

$$a_\mu \equiv \left(\frac{g-2}{2}\right)_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{had}} + a_\mu^{\mathrm{weak}}$$



Dominant uncertainty from lowest order hadronic piece.
Cannot be calculated from QCD ("first principles") – but:
we can use experiment!

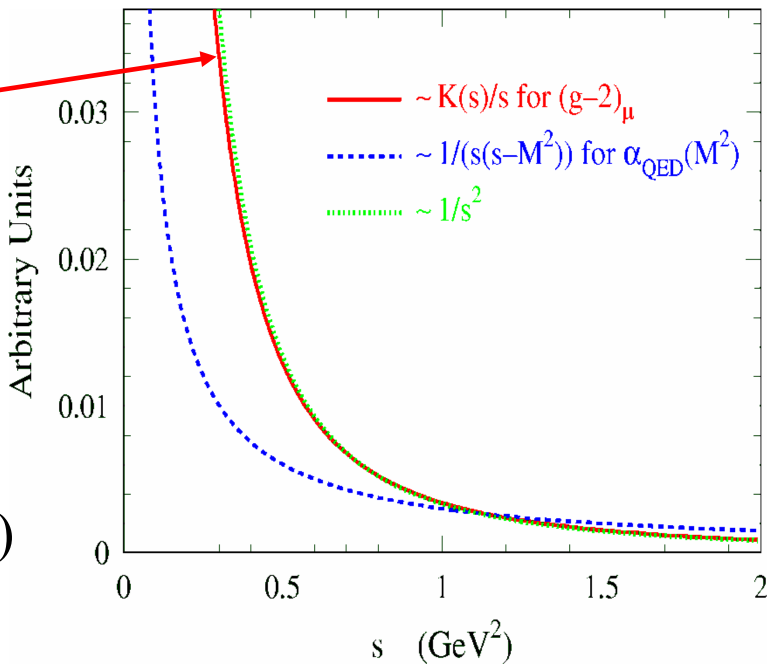
Im[] ∝ |  hadrons $|^2$

Hadronic vacuum polarization and muon *g* –2 (a_μ)

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

$$12\pi \, \mathrm{Im}\Pi_\gamma(s) = \frac{\sigma^0 [e^+e^- \to \mathrm{hadrons}(\gamma)]}{\sigma_{pt}} \equiv R(s)$$

Born: $\sigma^{(0)}(s) = \sigma(s)\left(\alpha / \alpha(s)\right)^2$



⇒ need good data on $e^+e^- \to$ hadrons at low energies where $e^+e^- \to \rho \to \pi^+\pi^-$ dominates (73% to a_μ^{had})!

Situation of a_μ

$$a_\mu^{had}[ee] = (690.9 \pm 4.4) \times 10^{-10}$$

$$a_\mu[ee] = (11\,659\,180.5 \pm 4.4_{had} \pm 3.5_{LBL} \pm 0.2_{QED+EW}) \times 10^{-10}$$

including:

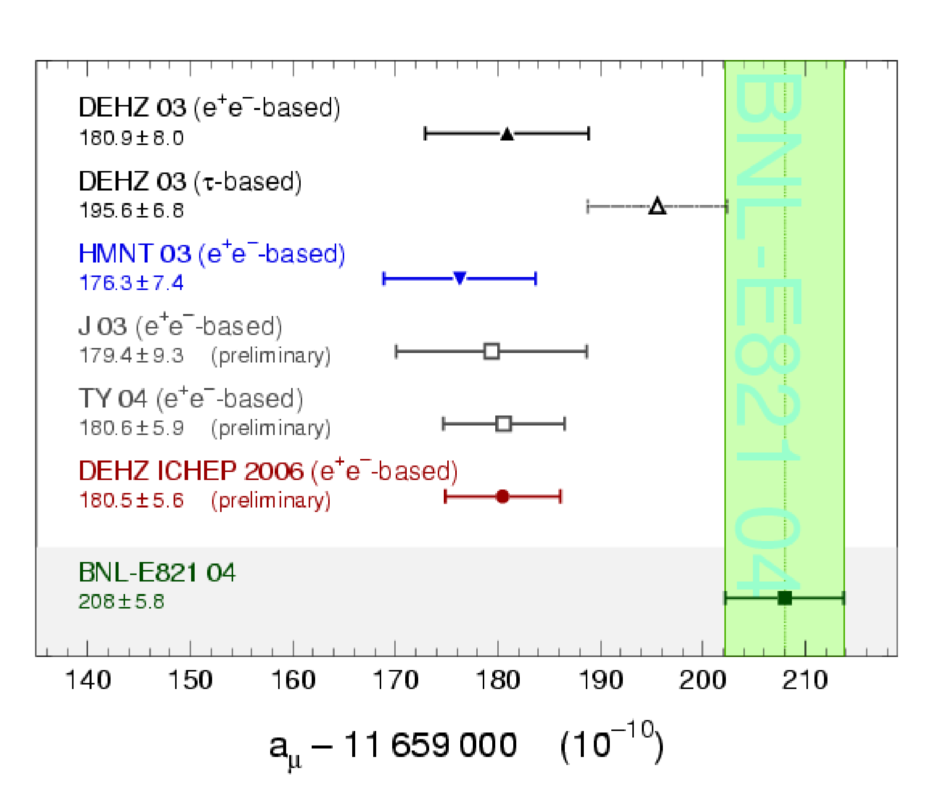
Hadronic HO	$-(9.8 \pm 0.1) \times 10^{-10}$
Hadronic LBL	$+(12.0 \pm 3.5) \times 10^{-10}$
Electroweak	$(15.4 \pm 0.2) \times 10^{-10}$
QED	$(11\,658\,471.9 \pm 0.1) \times 10^{-10}$

Knecht-Nyffeler, Phys.Rev.Lett. 88 (2002) 071802

Melnikov-Vainshtein, hep-ph/0312226

Davier-Marciano, Ann. Rev. Nucl. Part. Sc. (2004)

Kinoshita-Nio (2006)



BNL E821 (2004):

$$a_\mu^{exp} = (11\,659\,208.0 \pm 6.3)\ 10^{-10}$$

Observed Difference with BNL using e^+e^-:

$$a_\mu[exp] - a_\mu[SM] = (27.5 \pm 8.4) \times 10^{-10}$$

➡ 3.3 standard deviations

Goals of the analysis

- $\pi\pi$ channel contributes 73% of a_μ^{had}
- Dominant uncertainty also from $\pi\pi$
- Also important to increase precision on $\alpha(M_Z^2)$ (EW tests, ILC)
- Present systematic precision 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 0.8% deviation smaller
- Compare to spectral functions from τ decays

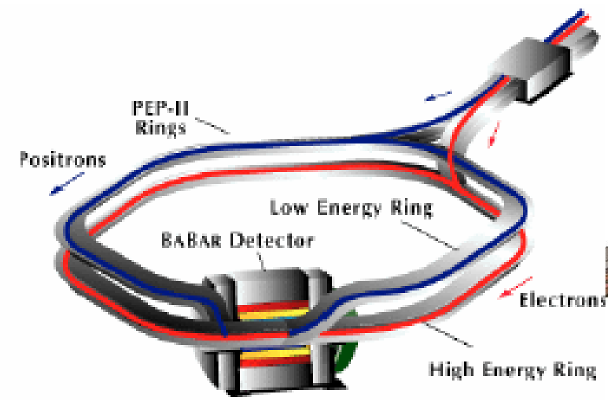
  discrepancy τ/e^+e^- evaluations $(3.0 \pm 1.1)\%$

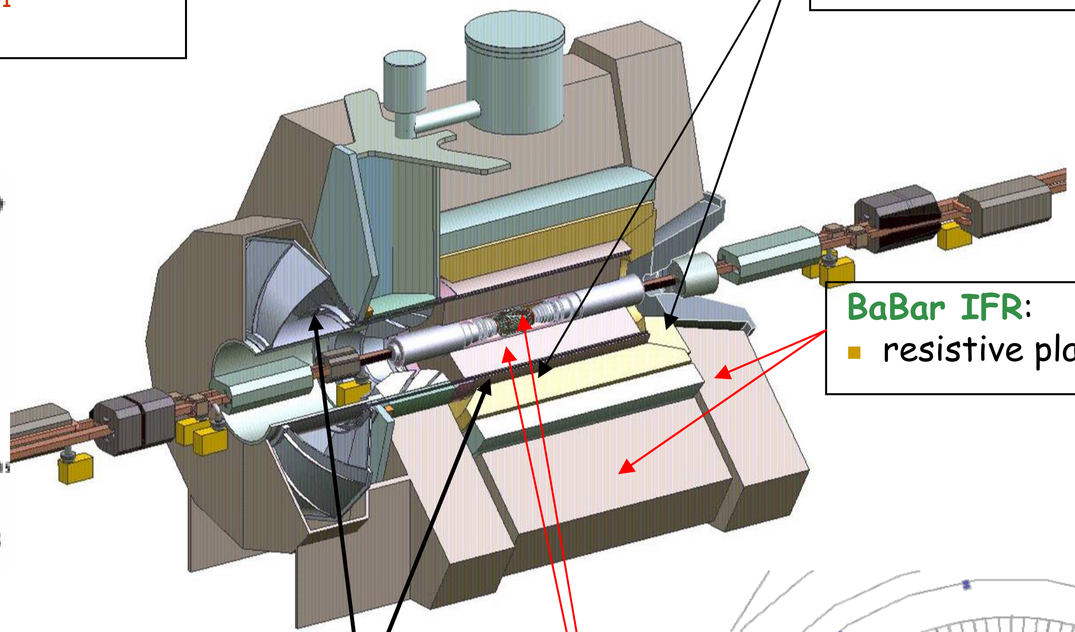
- Measure $R_{\pi\pi} = \sigma_{\pi\pi} / \sigma_{pt}$ with high accuracy for vacuum polarization calculations, using the ISR method

$\Rightarrow$ aim for a measurement with <1% accuracy

BaBar at PEP II

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



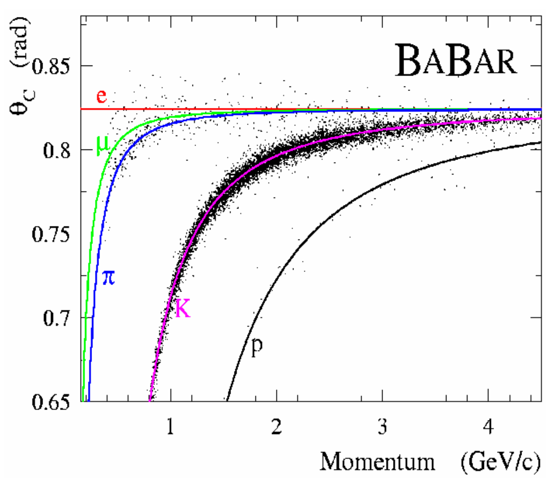


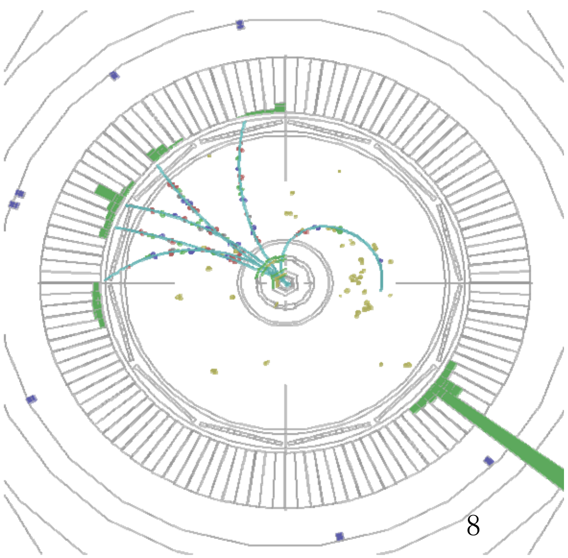
BaBar EMC:
- 6580 CsI(Tl) crystals, resolution ~1-2 % high E.

BaBar IFR:
- resistive plate chambers

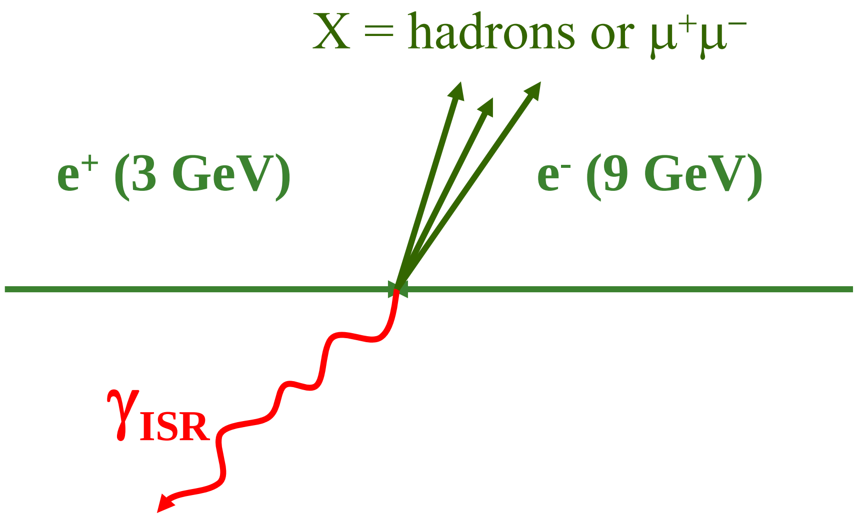
BaBar DIRC
- particle ID up to 4-5 GeV/c

BaBar SVT and DCH
- precision tracking





ISR method at BaBar : e+e- → γ X



γ detected at large angle in BaBar

Arbuzov 98', Binner 99', Benayoun 99' …

$$\frac{d\sigma(s,x)}{dx} = W(s,x)\sigma_X\left[s(1-x)\right]$$

$$x = \frac{2E^*_{\gamma_{ISR}}}{\sqrt{s}} \qquad s' = s(1-x)$$

The possibility of the ISR photon emission at lowest order:

$$W(s,x) = \frac{2\alpha}{\pi \cdot x} \cdot (2ln\frac{\sqrt{s}}{m_e} - 1) \cdot (1 - x + \frac{x^2}{2})$$

Big advantage of ISR: all mass spectrum covered at once, from threshold to 4-5 GeV (at BaBar), with same detector and analysis

ISR method at BaBar : e+e- $\rightarrow \gamma$ X

The way to measure cross-section of e+e- $\rightarrow \gamma$ X in practice:

$$\sigma_X(\sqrt{s'}) = \frac{\frac{dN_{X\gamma}}{d\sqrt{s'}}}{\epsilon_{X\gamma}\,\frac{dL_{ISR}^{eff}}{d\sqrt{s'}}}$$

Overall acceptance for Xγ events

Effective ISR luminosity

Because $\sigma_{\mu\mu}$ can be well predicted by QED, the case X=$\mu\mu$ can be used to determine the effective ISR luminosity.

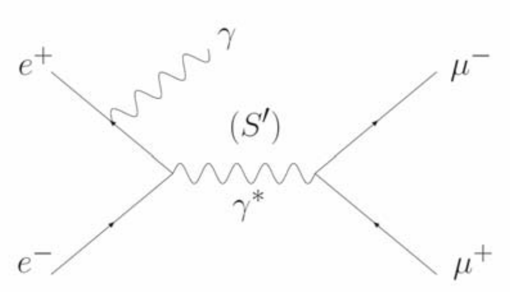
If $\mu\mu$ events are used to determine the effective ISR luminosity (i.e. $\sigma_{\pi\pi}$ obtained from $\pi\pi/\mu\mu$ ratio), several systematic errors can be cancelled: ee luminosity, additional ISR, vacuum polarization, ISR photon efficiency, otherwise there will be 2-3% more systematic error.

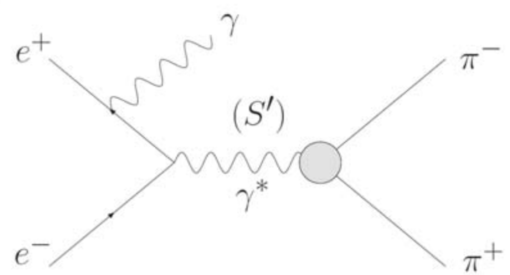
The relevant processes in this analysis

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

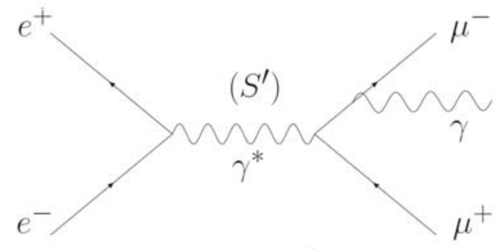
$$s' = s(1-x)$$

ISR



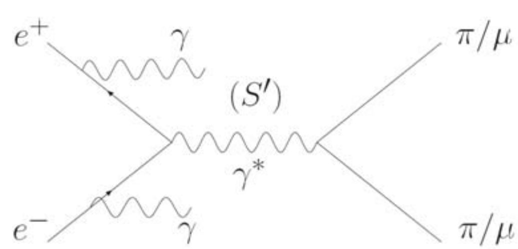


FSR

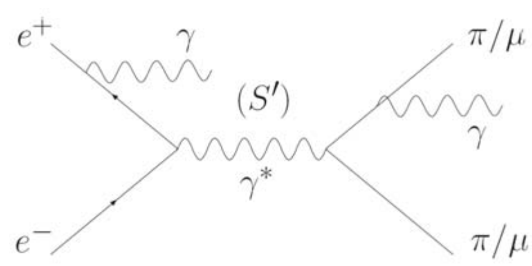


LO FSR negligible for ππ at s~(10.6 GeV)^2

ISR + additional ISR



ISR + additional FSR



The analysis steps

- Event selection
- Efficiencies studies:

  Triggers (L1 hardware, L3 software), background-filter efficiencies

  Tracking efficiency

  Particle identifications

  kinematic fit (not using ISR photon energy) including 1 additional photon
- Backgrounds study
- Acceptance study
- Consistency checks for $\mu\mu$ and $\pi\pi$ (QED test, kinematic distributions …)
- Unfolding of mass spectra
- Determination of the effective ISR luminosity
- Unblinding R: measure ratio of $\pi\pi\gamma(\gamma)$ to $\mu\mu\gamma(\gamma)$ cross sections
- Results on $\pi\pi$ cross section and calculation of dispersion integral for a_μ^{had}

Event selection and samples

Selection criteria:

- Triggers (L1 hardware, L3 software), background-filter
- 2 tracks of good quality (P>1 GeV)
- ISR photon at large angle in EMC (CM energy >3 GeV)
- Identification of the charged particles
- Pass kinematic fit (not using ISR photon energy) including 1 additional photon

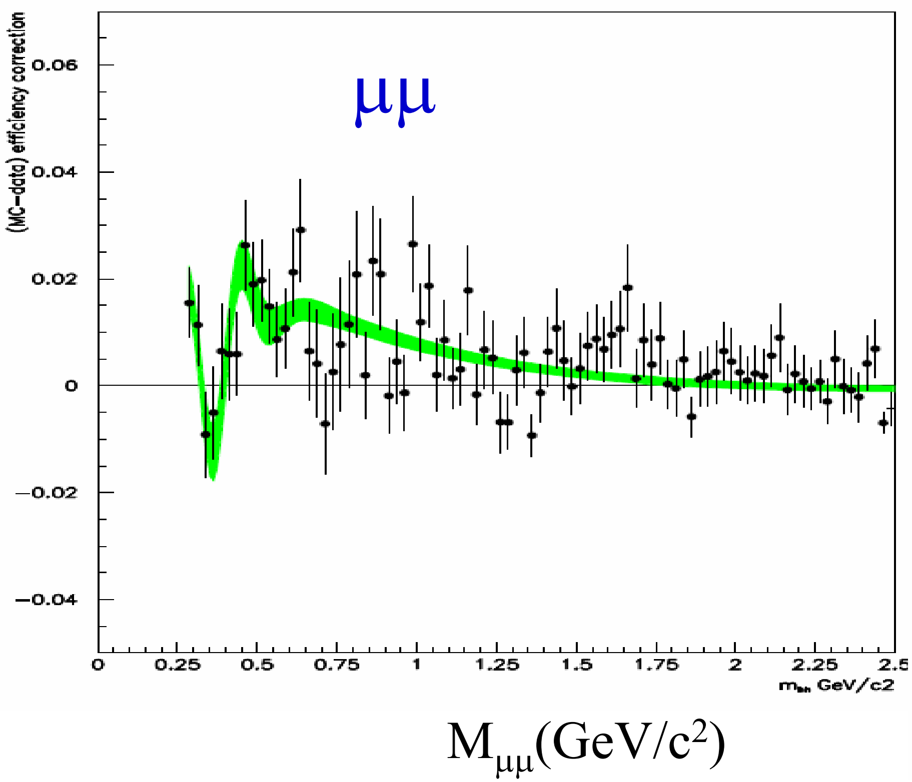
Data sample: 230.8 fb^{-1} (Y(4S) on-peak & off peak) data

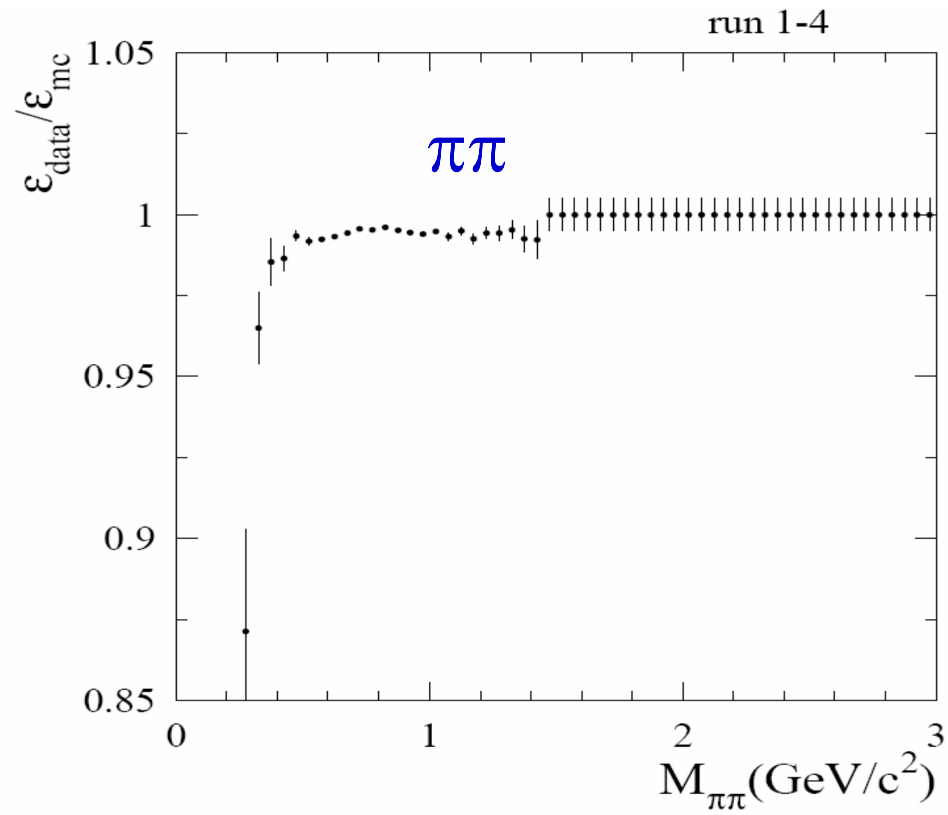
MC samples: $\mu\mu\gamma(\gamma)$ MC (~5 times of data) by AfkQED
$\pi\pi\gamma(\gamma)$ MC (~10 times of data) by AfkQED
Other BG MC

Trigger

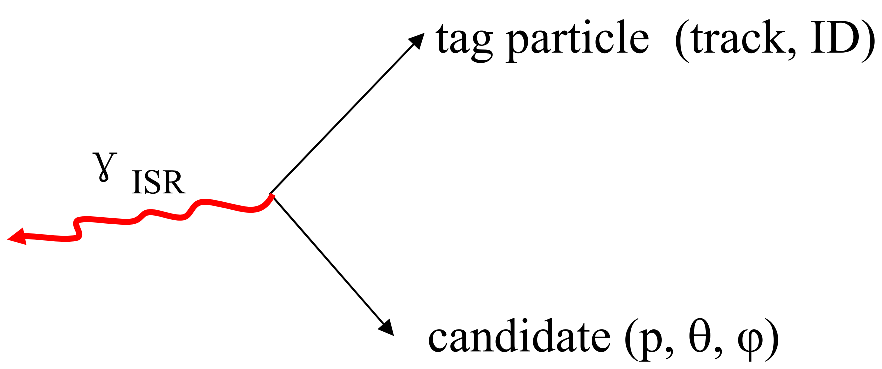
Basic idea: if T1 and T2 are two sets of trigger lines without correlations between them, T1 and T2 can be measured with the other satisfied, then

$$\varepsilon_T = 1-(1-\varepsilon_{T1})(1-\varepsilon_{T2})$$





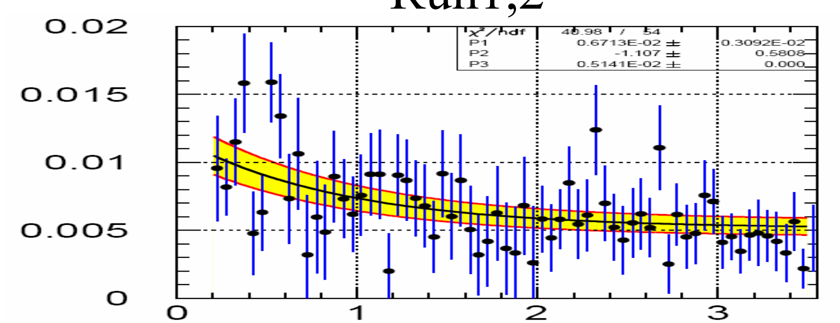
Tracking

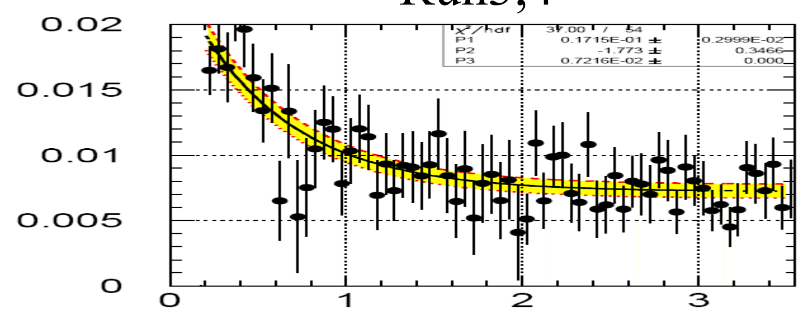


Run1,2

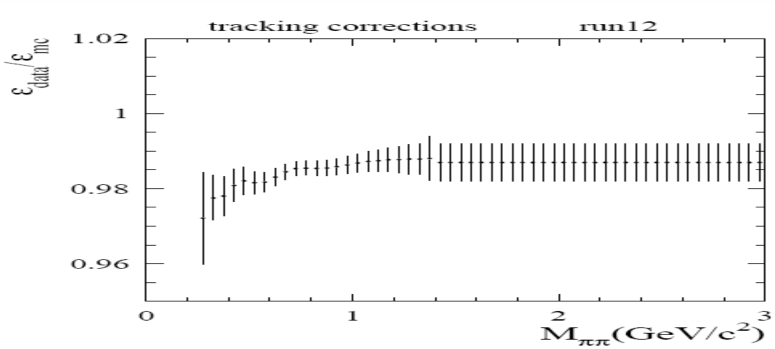
Run3,4

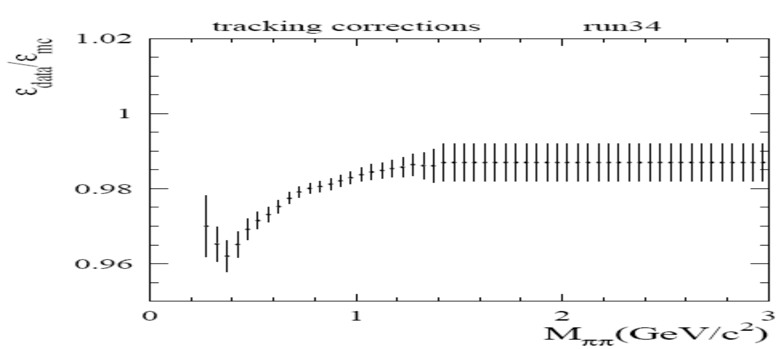
μμ:





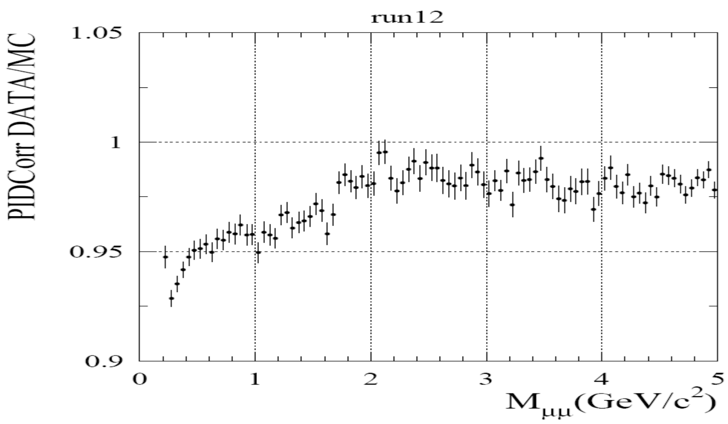
ππ:

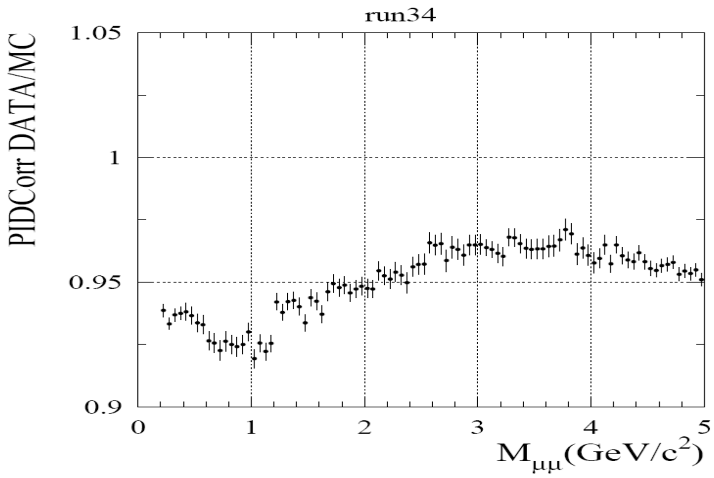




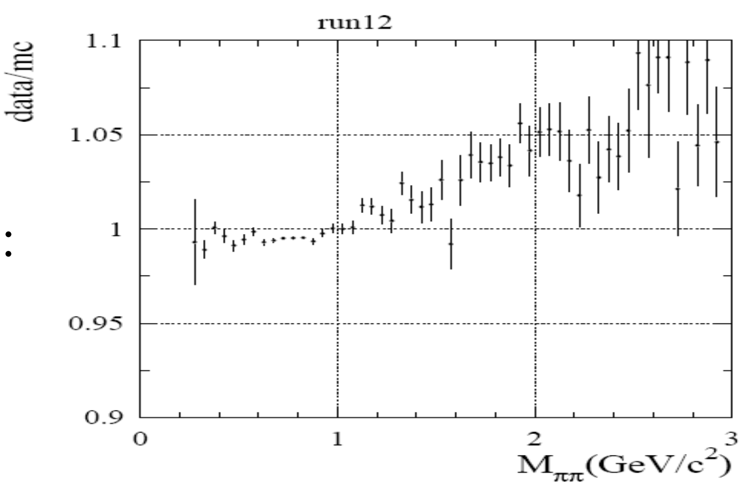
Particle ID

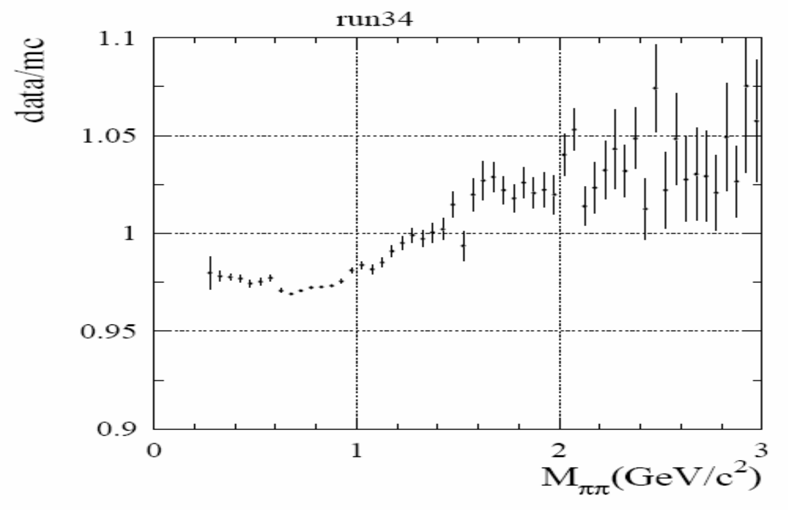
μμ:



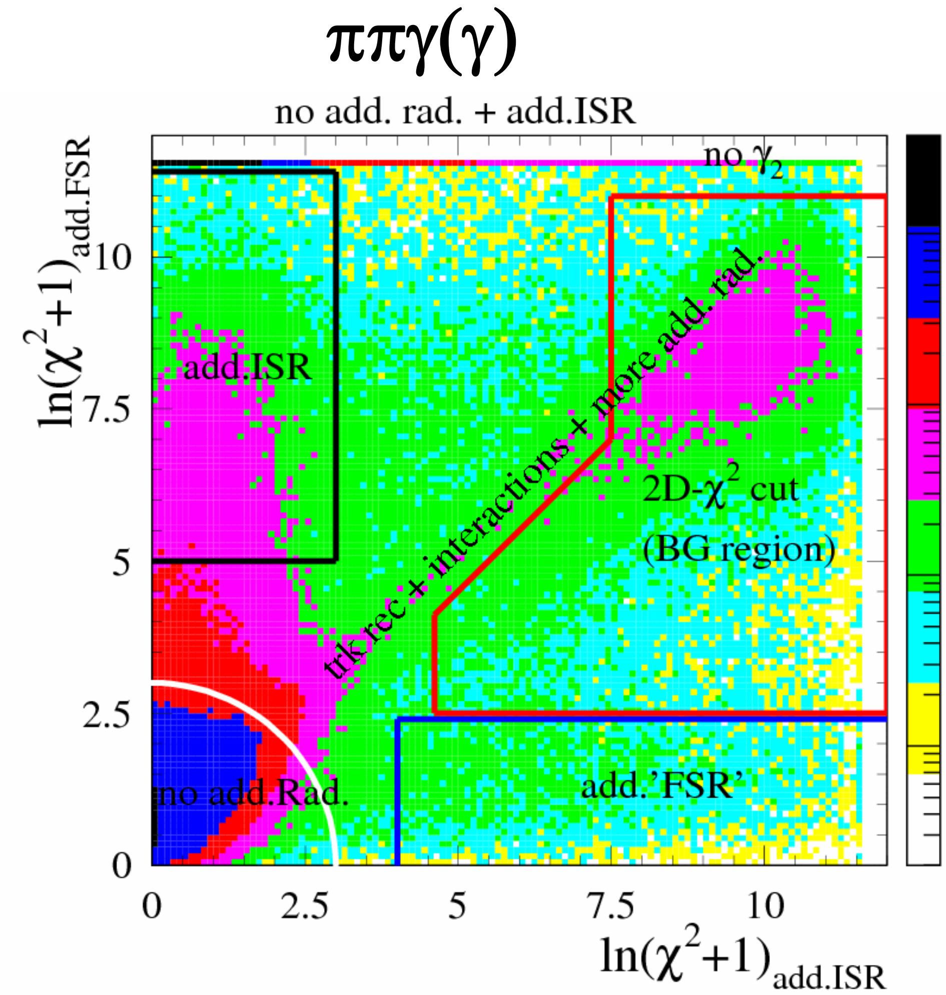


ππ:





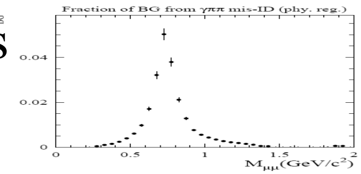
Kinematic fitting

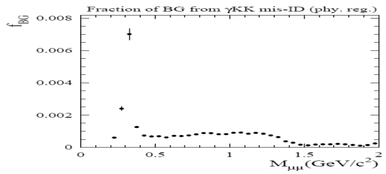


- kinematic fits to X X $\gamma_{ISR}\, \gamma_{add}$
- ISR photon defined as highest energy
- Add. ISR fit: γ_{add} assumed along beams
- Add. 'FSR' if γ_{add} detected
- Each event recorded on 2D plot
- Typical regions defined
- Loose χ^2 cut (outside BG region in plot)
  for μμ and ππ in central ρ region
- Tight χ^2 cut ($\ln(\chi^2+1)<3$)
  for ππ in ρ tail region

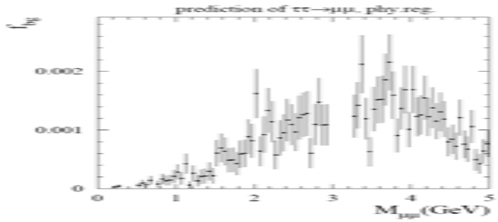
Backgrounds

- For μμ:
  1. ‘ππ’ & ‘KK’ + mis-ID ⟹ BG from hadrons

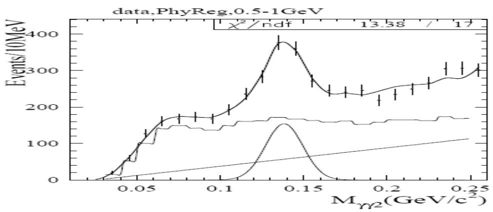


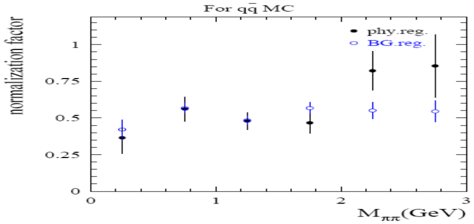


  2. Reconstructed μμ mass not in (3.0, 3.2)GeV remove BG from J/ψ
  3. ττ MC   BG from τ decay to μ

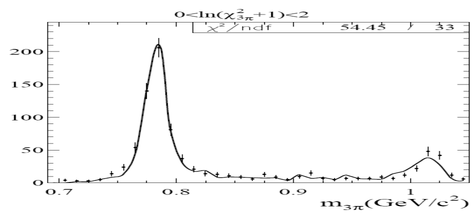


- For ππ
  1. $q\bar{q}$ BG





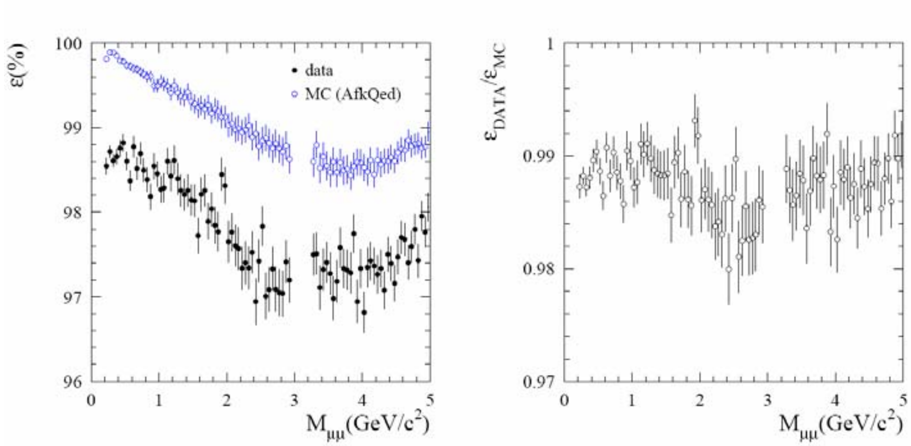
  2. $\gamma_{ISR}3\pi$



  3. Other ISR BG (other measurement)
  4. Global test

χ^2-cut efficiency determination

For μμ, almost free of BG => χ^2-cut efficiency can be determined from 'μμ' data:



Source of χ^2-cut inefficiency:

- bad input to the kinematic fits, mostly from the direction of the ISR photon,
- tails of the 2 distributions of events with additional ISR or additional FSR,
- more than one additional photon (mostly ISR),
- secondary interactions.

=> Additional corrections

Checking Known Distributions

Cosθ* in XX CM /γ

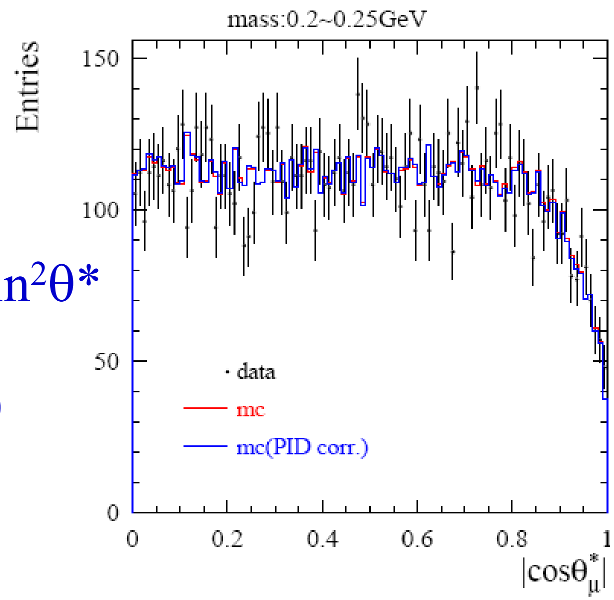
μμ

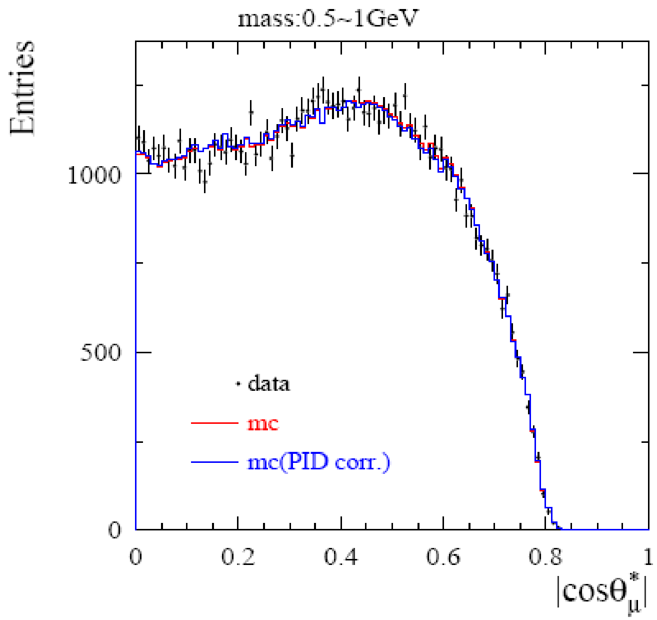
~1+cos²θ*+(1- β²$_\mu$) sin²θ*

=>

flat at threshold $\beta_\mu \rightarrow 0$

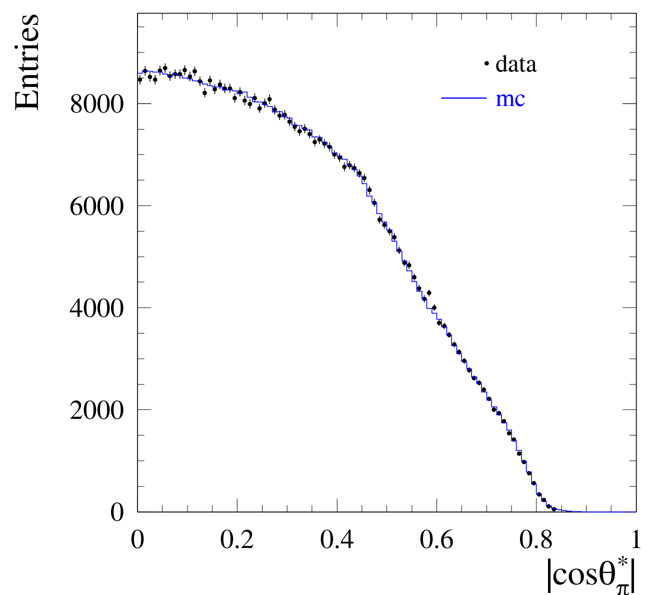
1+cos²θ* $\beta_\mu \rightarrow 1$





ππ

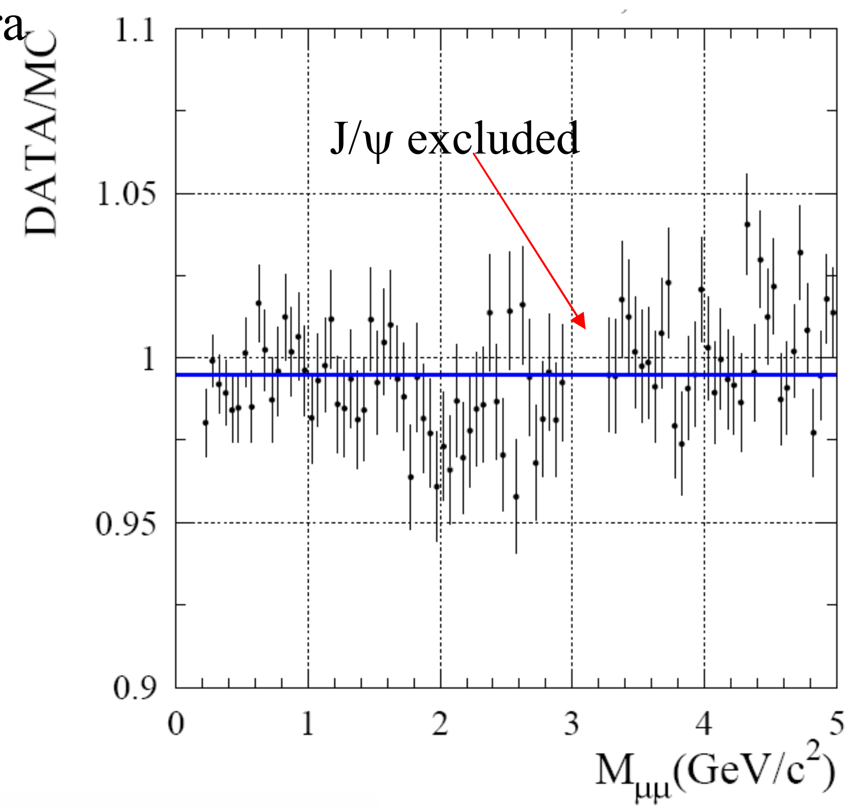
sin²θ*   ∀ β_π



P>1 GeV track requirement ⇒ loss at cosθ*~1

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 incorrect NLO using Phokhara
- results for different running periods consistent: $(7.9 \pm 7.5)\ 10^{-3}$
- agreement with QED within 1.1%

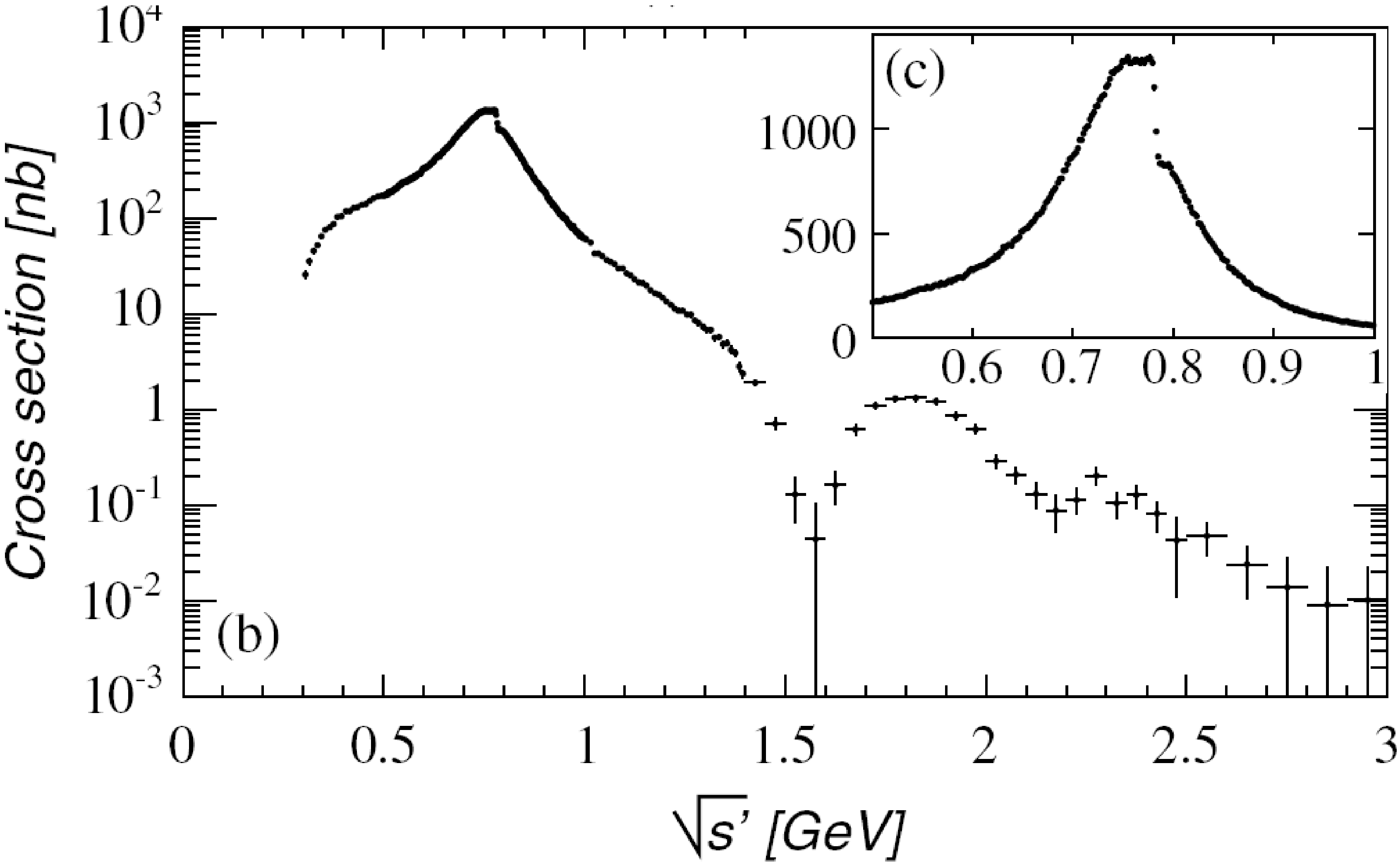


$$\frac{\sigma^{\text{data}}_{\mu\mu\gamma(\gamma)}}{\sigma^{\text{NLO QED}}_{\mu\mu\gamma(\gamma)}} - 1 = (40 \pm 20 \pm 55 \pm 94) \times 10^{-4}$$ (0.2 – 5.0 GeV)

ISR γ efficiency 5.2 syst.
trig/track/PID 4.0

BaBar ee luminosity

BaBar results



Systematic Uncertainties (10^{-3})

Source of uncertainty	$\sqrt{s'}$ (GeV) 0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.9	0.9–1.2
Trigger/filter	5.3	2.7	1.9	1.0	0.5
Tracking	3.8	2.1	2.1	1.1	1.7
π-ID	10.1	2.5	6.2	2.4	4.2
Background	3.5	4.3	5.2	1.0	3.0
Acceptance	1.6	1.6	1.0	1.0	1.6
Kinematic fit (χ^2)	0.9	0.9	0.3	0.3	0.9
Correlated $\mu\mu$ ID loss	3.0	2.0	3.0	1.3	2.0
$\pi\pi/\mu\mu$ noncancel.	2.7	1.4	1.6	1.1	1.3
Unfolding	1.0	2.7	2.7	1.0	1.3
ISR luminosity ($\mu\mu$)	3.4	3.4	3.4	3.4	3.4
Total uncertainty	13.8	8.1	10.2	5.0	6.5

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

$a_\mu^{\pi\pi(\gamma),LO}$ $(\times 10^{-10})$			
$m_{\mu\mu(\gamma)}(\mathrm{GeV}/c^2)$	BaBar	Previous e^+e^-	τ
0.28~1.8	514.1±2.2±3.1	503.5±3.5	515.2±3.4

Publication and citations

PRL **103,** 231801 (2009) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2009

Precise Measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ Cross Section with the Initial State Radiation Method at *BABAR*

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- Results reported in *Physical Review Letters 103, 231801 (Dec 4, 2009)*
- Cited 17 times (SLAC-SPIRES HEP)
- Detailed work is going to be reported in PRD
- Recalculation of a_μ using this measurement (*Eur. Phys. J. C 66, 1 (2010)*) cited 38 times.

Conclusions

- The $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ cross-section has been measured in the energy range 0.3 to 3.0GeV/c^2 in one experiment (BaBar) with the ISR method.
- Efficiencies are studied intensively in real data and the differences between data and MC are taken as corrections.
- Absolute μμ cross section agrees with NLO QED within 1.1%
- Structures observed in pion form factor at large masses
- This measured result has the best precision in the world! ($a_\mu^{\pi\pi(\gamma),LO}$ based on our result can comparable to the combined value from all the other existing e^+e^- experiments.)
- Contribution to a_μ from BaBar agrees better with τ results
- Deviation between BNL measurement and theory prediction would be reduced using BaBar ππ data

$$a_\mu[\exp] - a_\mu[SM] = (27.5 \pm 8.4) \times 10^{-10} \Rightarrow (14.0 \pm 8.4) \times 10^{-10}$$

谢谢

Backup Slides

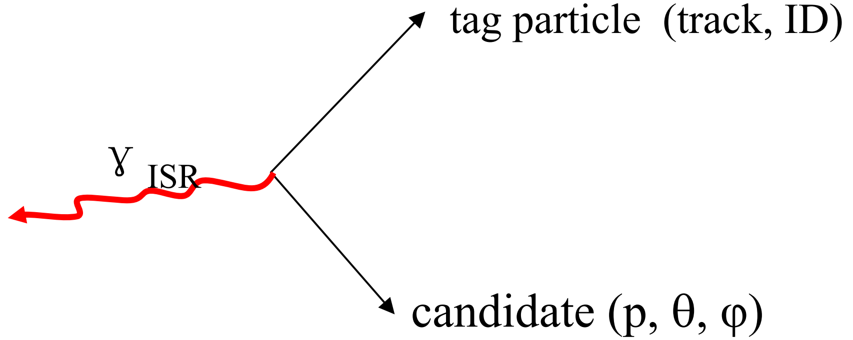
MC generators

- Acceptance and efficiencies determined initially from simulation, with data/MC corrections applied

- AfkQed: lowest-order QED with additional radiation:
  - ISR with structure function method, γ assumed collinear to the beams and with limited energy
  - FSR using PHOTOS
  - similar to EVA (Phokhara ancestor)
- Phokhara 4.0: (almost) exact second-order QED matrix element (2 FSR missing), limited to one extra photon

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

Particle-related efficiency measurements



- benefit from pair production for 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, study of secondary interactions…
- assumes that efficiencies of the 2 particles are uncorrelated
- in practice not true $\Rightarrow$ this is where 95% of the work goes!
  study of 2-particle overlap in the detector (trigger,tracking, EMC, IFR) required a large effort to reach per mil accuracies (hence the duration of the analysis)

PID separation and Global Test

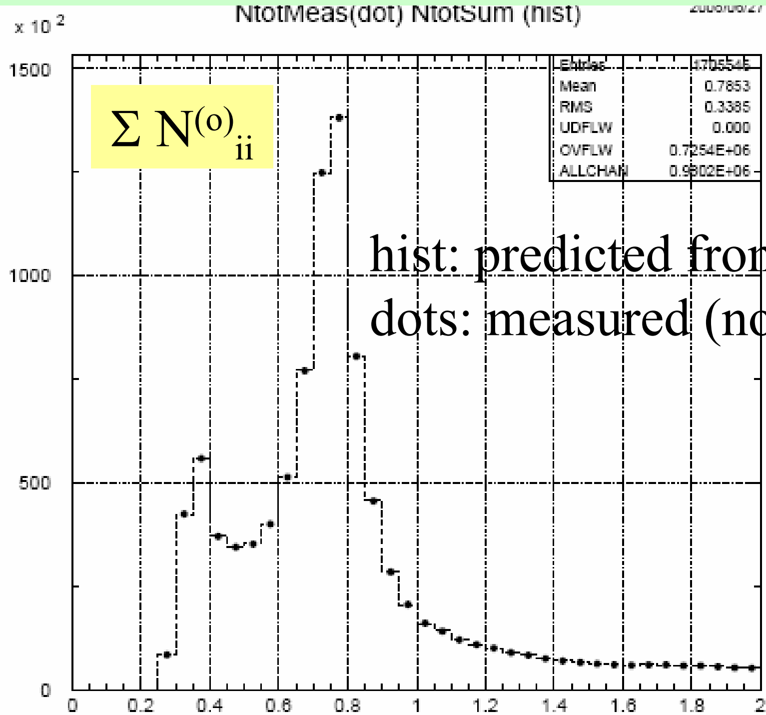
$$N_{'\pi\pi'} = N^{(0)}_{\mu\mu}\varepsilon_{\mu\mu\to'\pi\pi'} + N^{(0)}_{\pi\pi}\varepsilon_{\pi\pi\to'\pi\pi'} + N^{(0)}_{KK}\varepsilon_{KK\to'\pi\pi'} + N_{ee/'\pi\pi'}$$

$$N_{'\mu\mu'} = N^{(0)}_{\mu\mu}\varepsilon_{\mu\mu\to'\mu\mu'} + N^{(0)}_{\pi\pi}\varepsilon_{\pi\pi\to'\mu\mu'} + N^{(0)}_{KK}\varepsilon_{KK\to'\mu\mu'}$$

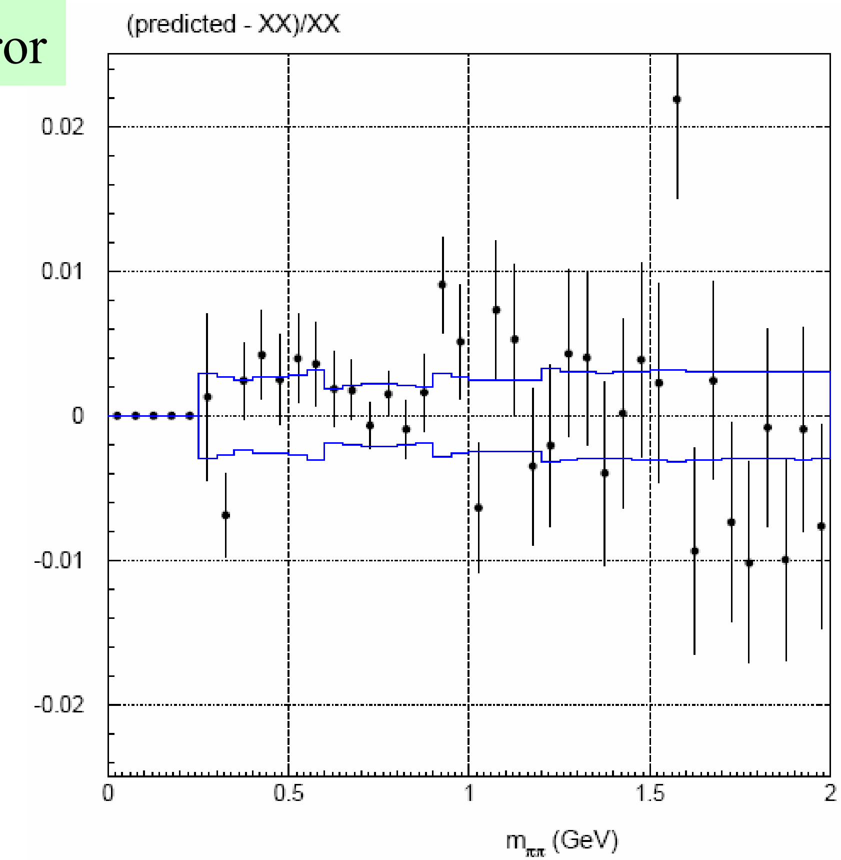
$$N_{'KK'} = N^{(0)}_{\mu\mu}\varepsilon_{\mu\mu\to'KK'} + N^{(0)}_{\pi\pi}\varepsilon_{\pi\pi\to'KK'} + N^{(0)}_{KK}\varepsilon_{KK\to'KK'}$$

All ‘xx’ ⇒ solve for all $xx^{(0)}$ and compare with no-ID spectrum and estimated syst. error

(small $p\bar{p}$ contribution subtracted statistically)



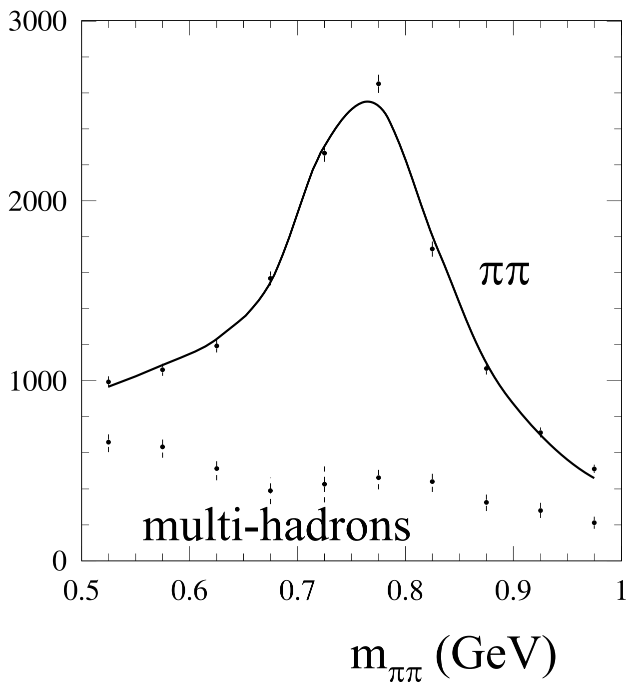
$m_{\pi\pi}$ (GeV)



Backgrounds in $\pi\pi\gamma$

- background larger with loose χ^2 cut used in 0.5-1.0 GeV mass range
- $q\bar{q}$ and multi-hadronic ISR background from MC samples + normalization from data using signals from $\pi^0 \to \gamma_{ISR}\gamma$ ($q\bar{q}$), and ω and ϕ ($\pi\pi\pi^0\gamma$)
- global test in background-rich region near cut boundary

Fitted BG/predicted = 0.968±0.037

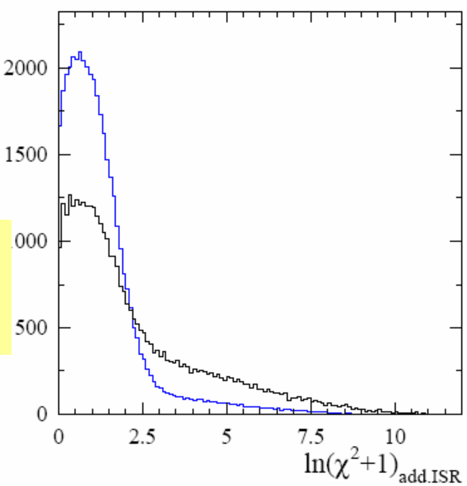


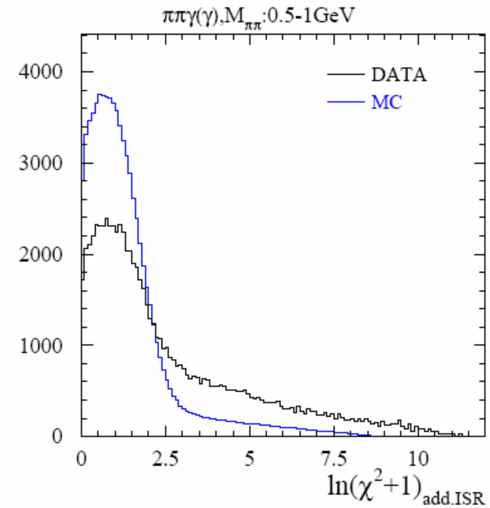
BG fractions in 10^{-3} at $m_{\pi\pi}$ values

process	0.525 GeV	0.775 GeV	0.975 GeV
$\mu\mu$	2.98 ± 0.16	0.25 ± 0.01	1.95 ± 0.11
KK	0.08 ± 0.01	0.01 ± 0.01	0.08 ± 0.01
$\gamma 2\pi\pi^0$	8.04 ± 0.41	0.39 ± 0.05	0.88 ± 0.19
$q\bar{q}$	1.11 ± 0.17	0.26 ± 0.03	1.81 ± 0.19
$\gamma 2\pi 2\pi^0$	1.29 ± 0.16	0.06 ± 0.01	0.46 ± 0.09
$\gamma 4\pi$	0.20 ± 0.04	0.09 ± 0.01	0.24 ± 0.06
$\gamma p\bar{p}$	0.22 ± 0.02	0.04 ± 0.01	0.52 ± 0.06
$\gamma\eta 2\pi$	0.02 ± 0.01	0.03 ± 0.01	0.09 ± 0.01
$\gamma K_S K_L$	0.18 ± 0.03	0.01 ± 0.01	0.10 ± 0.02
$\gamma 4\pi 2\pi^0$	< 0.01	< 0.01	< 0.01
$\tau\tau$	0.17 ± 0.03	0.04 ± 0.01	0.31 ± 0.05
γee	0.63 ± 0.63	0.03 ± 0.03	0.27 ± 0.27
total	14.88 ± 0.81	1.19 ± 0.07	6.61 ± 0.42

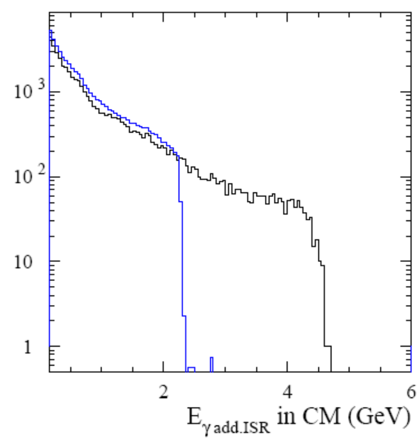
Additional radiation

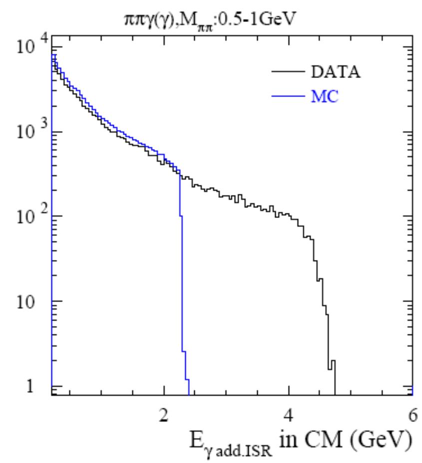
Angular distribution of add. ISR /beams!



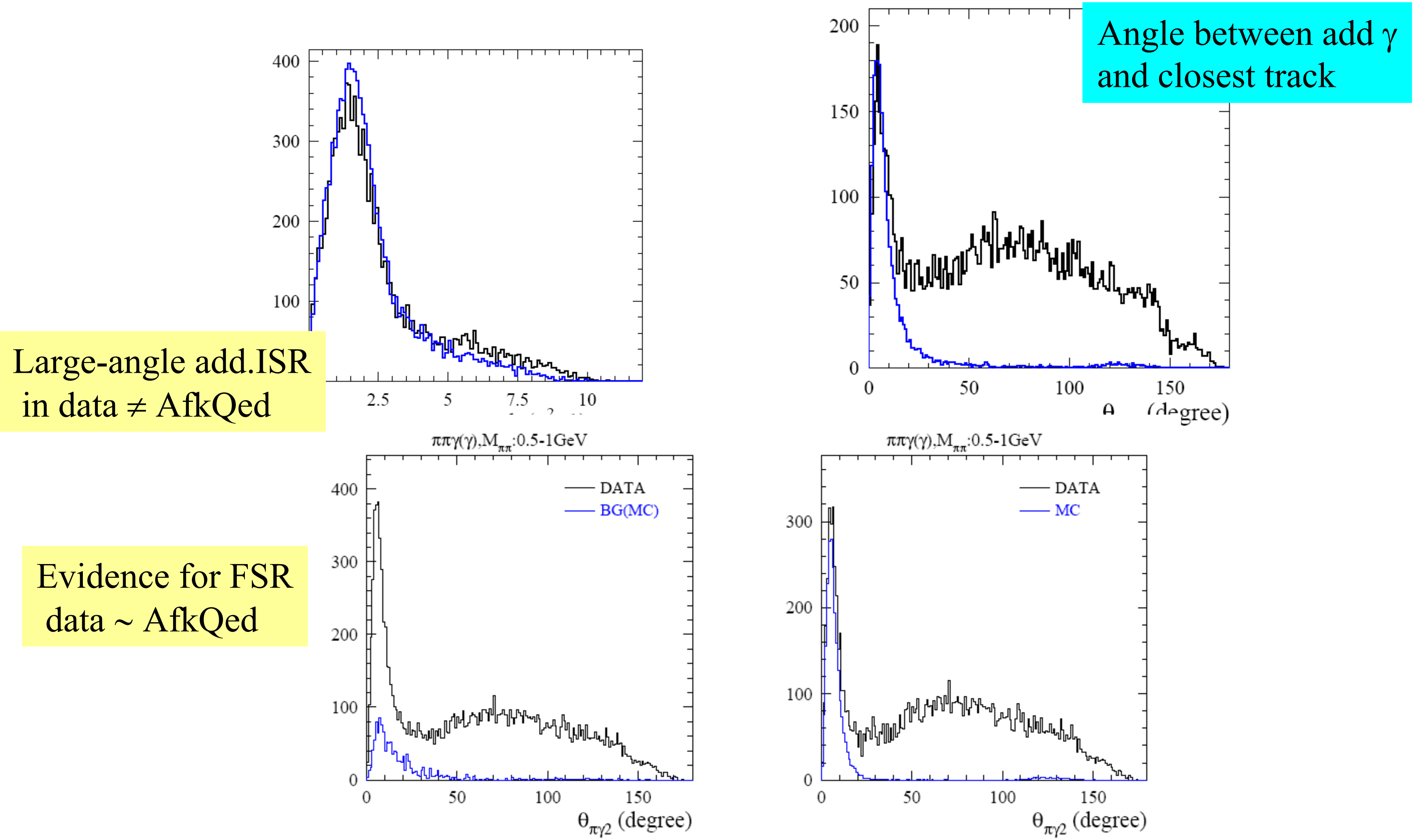


Energy cut-off for add. ISR in AfkQed

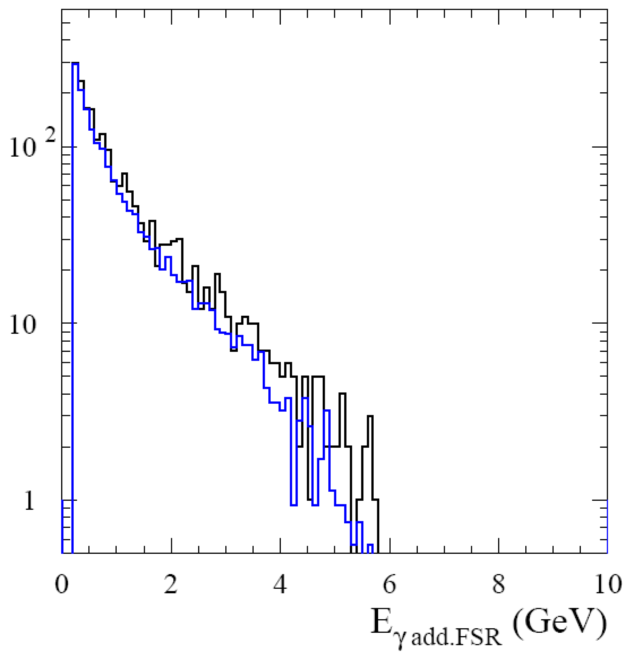


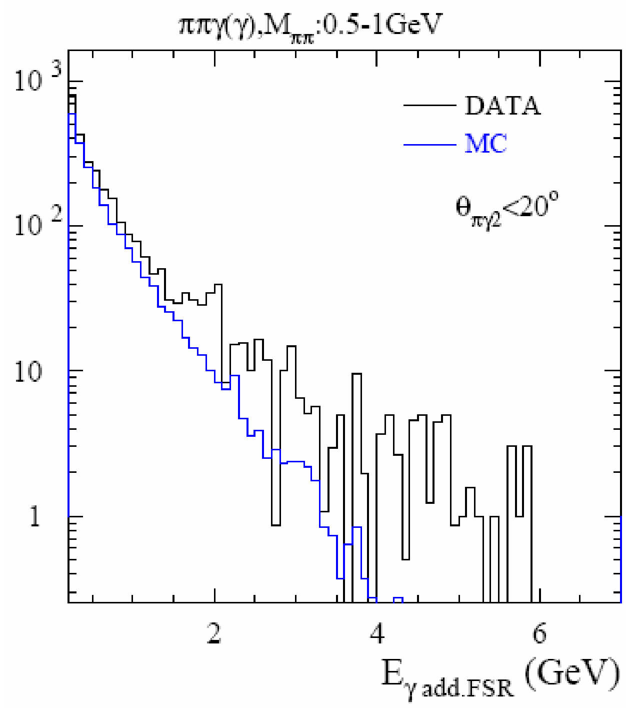


Additional 'FSR'



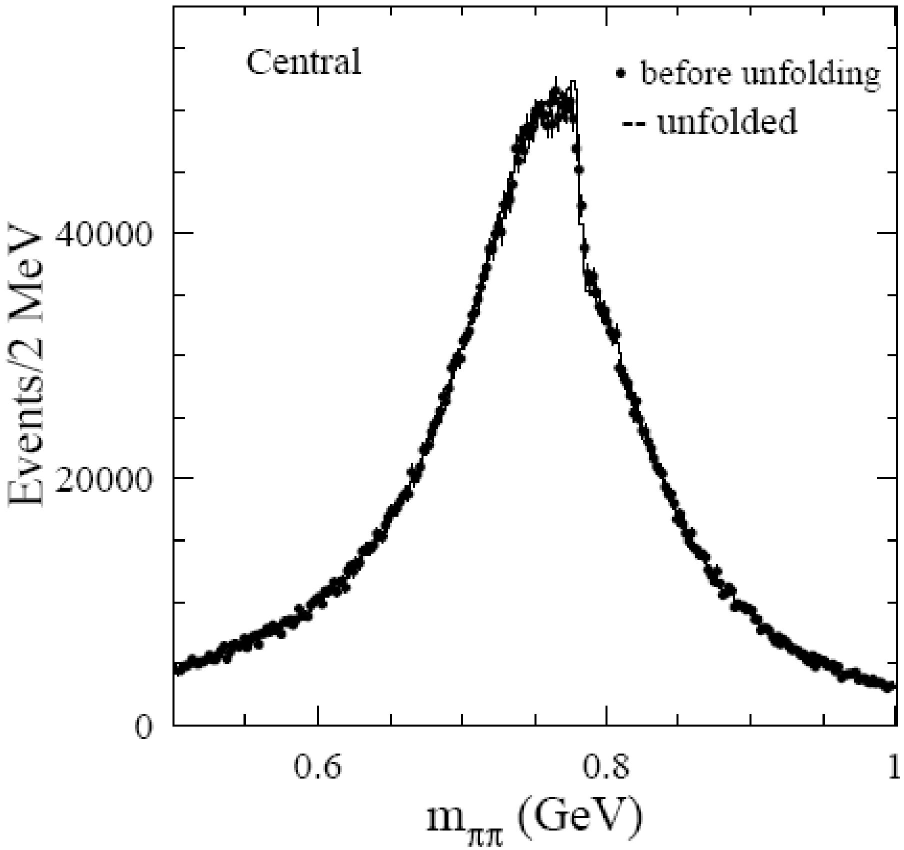
Energy distribution for additional FSR

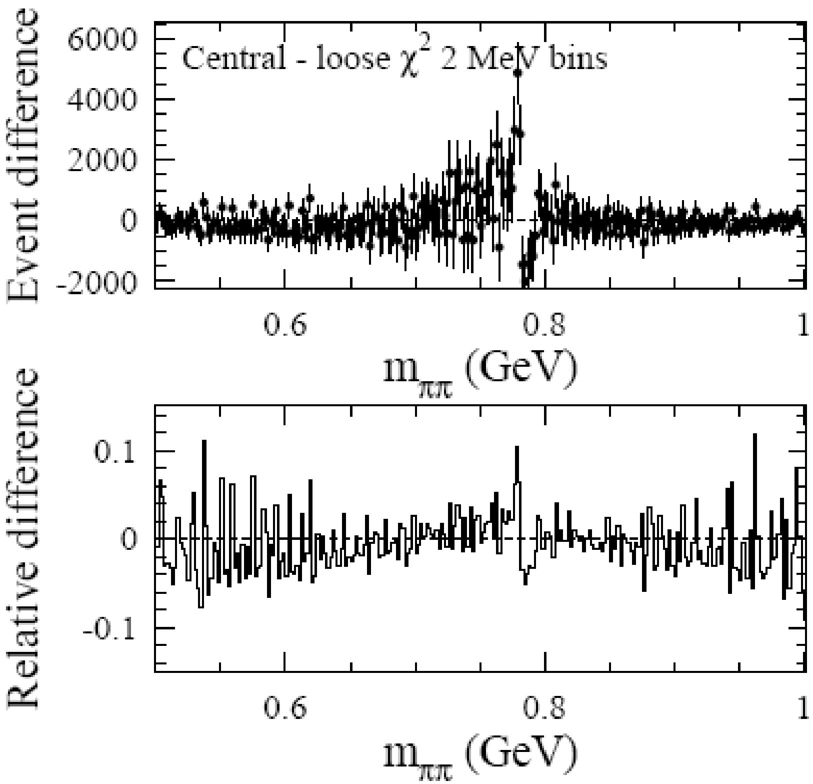




Unfolding the $\pi\pi$ mass spectrum

- measured mass spectrum distorted by resolution effects and FSR ($m_{\pi\pi}$ vs. s')
- unfolding uses mass-transfer matrix from simulation
- 2 MeV bins in 0.5-1.0 GeV mass range, 10 MeV bins outside
- most salient effect in ρ-ω interference region (little effect on $a_\mu^{\pi\pi}$)

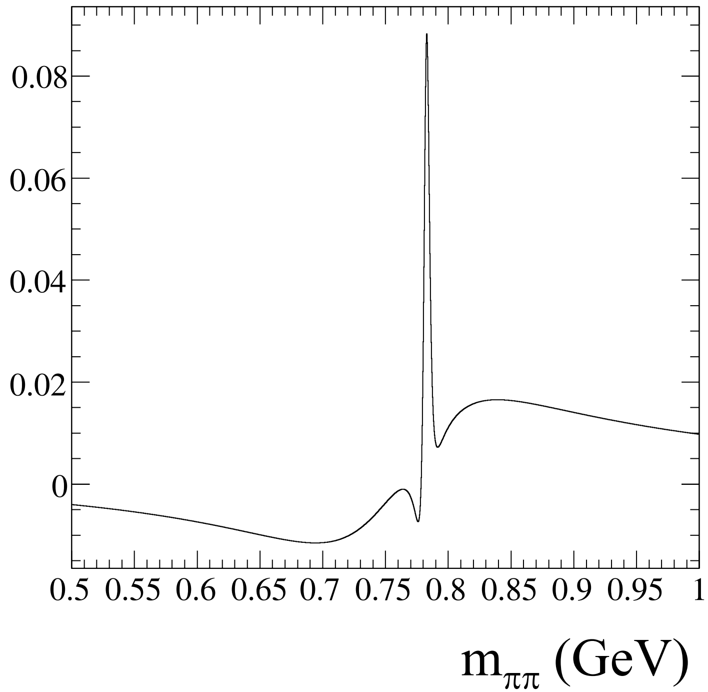




Mass calibration

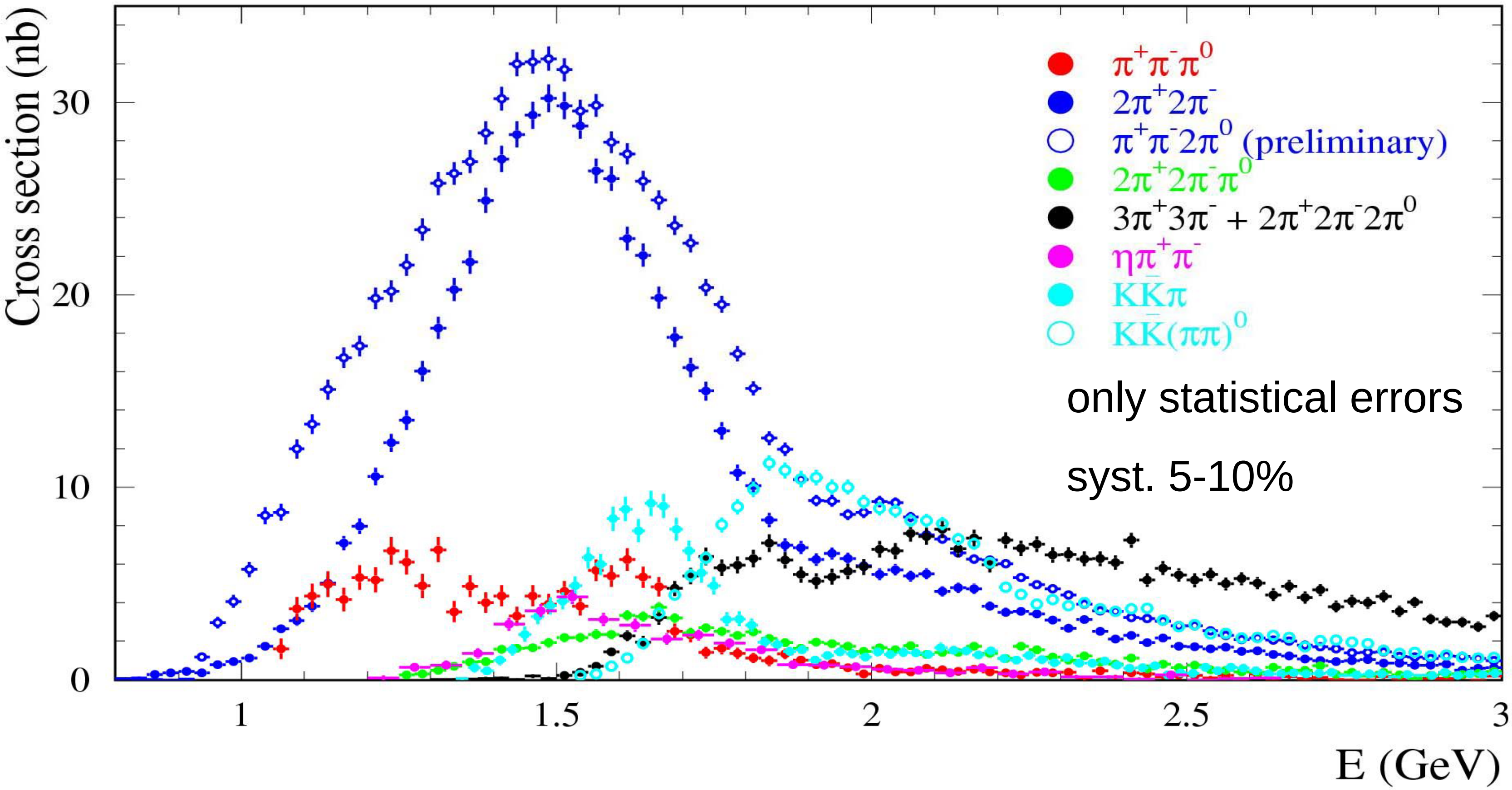
mass calibration using $J/\psi \longrightarrow \mu\mu$, scaled to ρ region : (0.16 ± 0.16) MeV)
mass resolution 6 MeV

effect of a 1 MeV mass scale shift



Multihadronic channels: BaBar ISR measurements

many ISR BaBar results already published on $e^+e^-\rightarrow$hadrons for larger multiplicities



to complete the R measurement in the energy range 1-2 GeV
the processes $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$, K^+K^-, K_SK_L, $K_SK_L\pi\pi$, $K_SK^{+-}\pi^{-+}\pi^0$
are being measured

Contributions to a_μ^{had} from multihadronic modes

- The BaBar results are the most precise measurements to date for CM energies greater than 1.4 GeV.

- Examples: contributions to a_μ^{had} ($\times 10^{-10}$) from $2\pi^+ 2\pi^-$ (0.56 – 1.8 GeV)

from all $e^+ e^-$ exp.	$14.21 \pm 0.87_{exp} \pm 0.23_{rad}$
from all τ data	$12.35 \pm 0.96_{exp} \pm 0.40_{SU(2)}$
from BaBar	$12.95 \pm 0.64_{exp} \pm 0.13_{rad}$

from $\pi^+ \pi^- \pi^0$ (1.055 – 1.8 GeV)

from all $e^+ e^-$ exp.	$2.45 \pm 0.26_{exp} \pm 0.03_{rad}$
from BaBar	$3.31 \pm 0.13_{exp} \pm 0.03_{rad}$

reminder: total 690.9 ± 4.4 (DEHZ 2006)

Outlook for muon g–2 SM prediction

Hadronic LO contribution

- potentially existing e+e– data can reach a precision $\Delta a_\mu^{had} = 2.5\ (10^{-10})$
- hopeful that remaining discrepancies will be brought close to quoted systematic uncertainties
- use of τ data limited by knowledge of isospin-breaking corrections: present precision $2.5\ (10^{-10})$, total error $3.9\ (10^{-10})$, work in progress
- new data expected from VEPP-2000 with CMD-2 and SND

Hadronic LBL contribution

- relies only on phenomenological estimates, precision $\Delta a_\mu^{hadLBL} = 3.5\ (10^{-10})$
- more progress? lattice?

Other contributions

- QED, electroweak, HO hadronic: $\Delta a_\mu^{others} = 0.2\ (10^{-10})$

g–2 experimental error

- BNL E821 (2004) $\Delta a_\mu^{exp} = 6.3\ (10^{-10})$
- a new measurement will be needed to match the 'theory' uncertainty