Hadron production in e^+e^- collisions at *BABAR* and implications for the muon anomalous magnetic moment

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On behalf of the *BABAR* Collaboration

ICHEP
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Institut für Kernphysik

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Outline

1. Motivation: muon-anomaly $(g-2)_\mu$
2. Initial State Radiation (ISR) analyses at *BABAR*
3. Recent results on the reactions:
   - $e^+e^- \to K^+K^-\pi^+\pi^- / K^+K^-\pi^0\pi^0$
   - $e^+e^- \to K^+K^-K^+K^-$
   - $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
4. Summary

The anomalous magnetic moment of the muon $(g-2)_\mu$

gyromagnetic ratio: g

$$\vec{\mu} = g\frac{e\hbar}{2mc} \cdot \vec{S}$$

spin $\frac{1}{2} \rightarrow$ Dirac theory: $g = 2$

QFT: $g \neq 2$

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muon anomaly: $a_\mu = (g-2)_\mu/2$

$$a_\mu^{\text{theory}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}}$$

BNL E821	11 659 208.9	± 6.4

$\cdot 10^{-10}$

Brookhaven National Laboratory (BNL)
[G.W. Bennett *et al.*, PRD**73**, 072003 (2006)]

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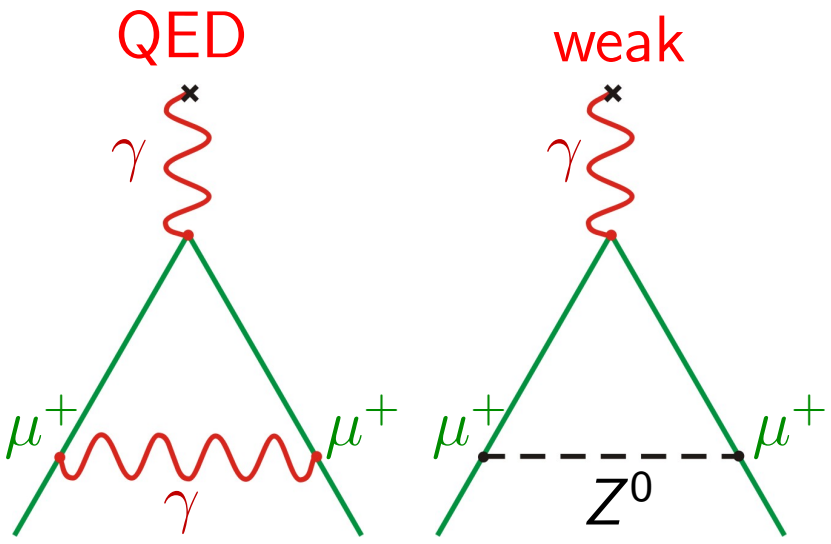

BNL E821	11 659 208.9	± 6.4
QED	11 658 471.809	± 0.015
weak	15.4	± 0.2

$\cdot 10^{-10}$

[T.Kinoshita *et al.*, PRD**73**, 013003 (2006)]

[A.Czarnecki *et al.*, PRD**67**, 073006 (2003) Erratum-ibid. D**73**, 119901 (2006)]

[M.Knecht *et al.*, JHEP 0211, 003 (2002)]

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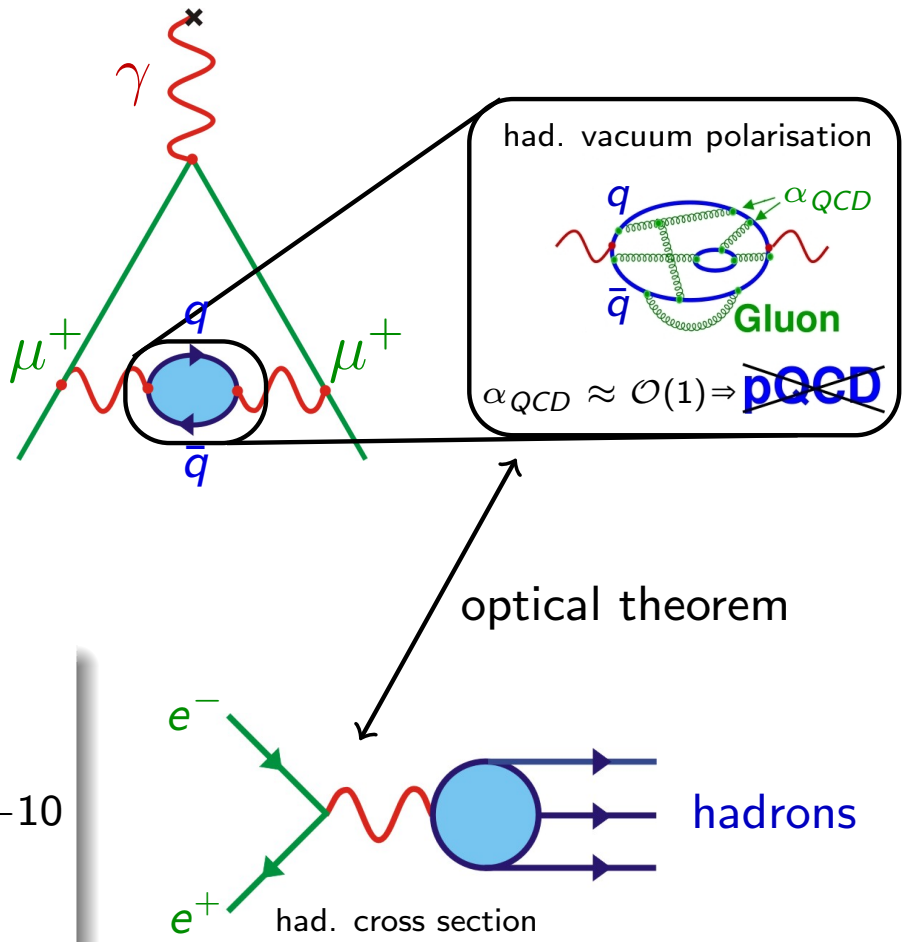
weak	15.4	± 0.2
had	693.0	± 4.9

$\cdot 10^{-10}$

hadronic



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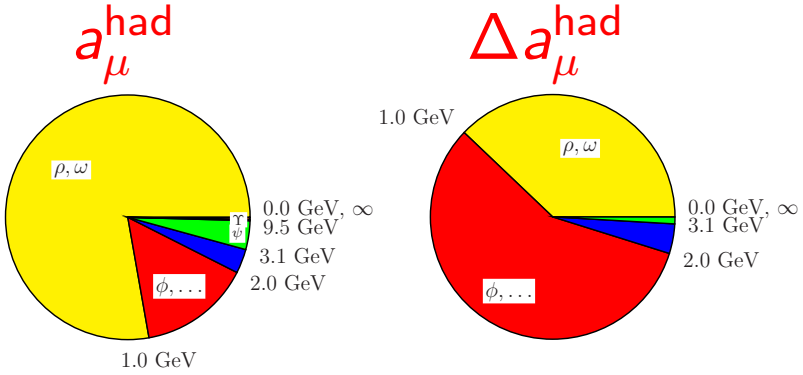
BNL−SM	28.7	± 8.0

$\cdot 10^{-10}$

$\Downarrow$

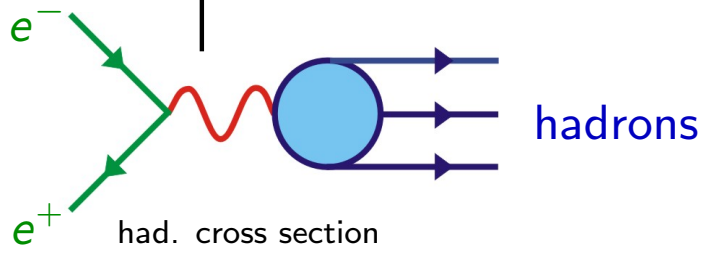
3.6σ [M. Davier *et al.*, EPJ **C**71, 1515 (2011)]

contribution to

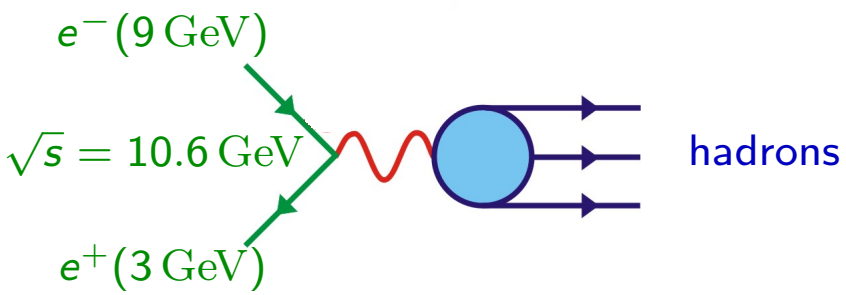


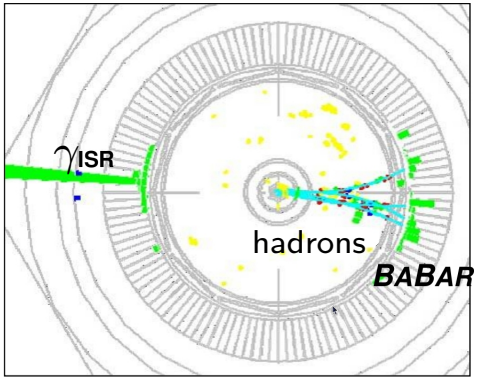
[F. Jegerlehner *et al.*, PR 477, 1 (2009)]

exp. input



Initial State Radiation (ISR) events at *BABAR*





ISR selection

- Detected high energy photon: $E_\gamma > 3\,\mathrm{GeV}$
  $\rightarrow$ defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
  $\rightarrow$ high acceptance
- Kinematic fit including γ_{ISR}
  $\rightarrow$ very good energy resolution (4 – 15 MeV)
- e^+e^--boost into the laboratory reference frame
  $\rightarrow$ high efficiency at production threshold of hadronic system
- Continuous measurement from threshold to $\sim$4.5 GeV
  $\rightarrow$ provides common, consistent systematic uncertainties

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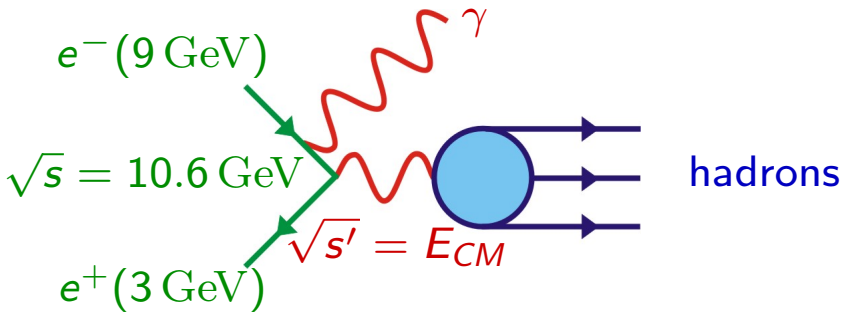

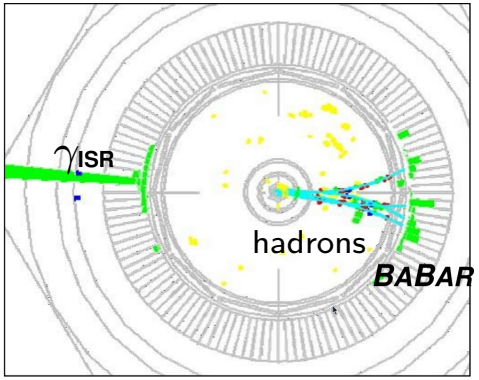

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ISR analyses at *BABAR*

published

$e^+e^- \to \pi^+\pi^-$	PRL 103 (2009) 231801, (sub. to PRD (2012) arXiv:1205.2228)
$e^+e^- \to \phi f_0(980)$	PRD 74 (2006) 091103, PRD 76 (2007) 012008
$e^+e^- \to \pi^+\pi^-\pi^0$	PRD 70 (2004) 072004
$e^+e^- \to K^+K^-\eta, K^+K^-\pi^0, K_S^0K^\pm\pi^\mp$	PRD 77 (2008) 092002, PRD 71 (2005) 052001
$e^+e^- \to 2(\pi^+\pi^-), K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PRD 76 (2007) 012008
$e^+e^- \to 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PRD 76 (2007) 092005
$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PRD 73 (2006) 052003
$e^+e^- \to p\bar{p}$	PRD 73 (2006) 012005
$e^+e^- \to \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$	PRD 76 (2007) 092006
$e^+e^- \to c\bar{c} \to \ldots$	... ...

accepted for publication by PRD

$e^+e^- \to 2(\pi^+\pi^-)$	arXiv:1201.5677
$e^+e^- \to K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	arXiv:1103.3001

ongoing analyses

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

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

accepted for publication by PRD, based on 454 fb^{-1}
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our previous publication, based on 232 fb^{-1} of the data:
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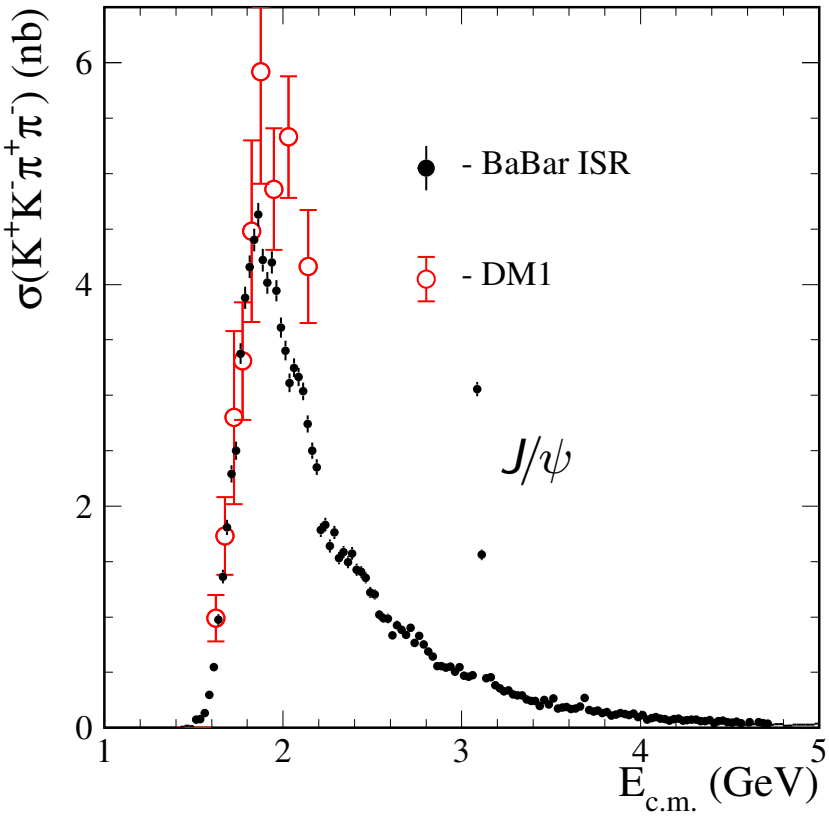
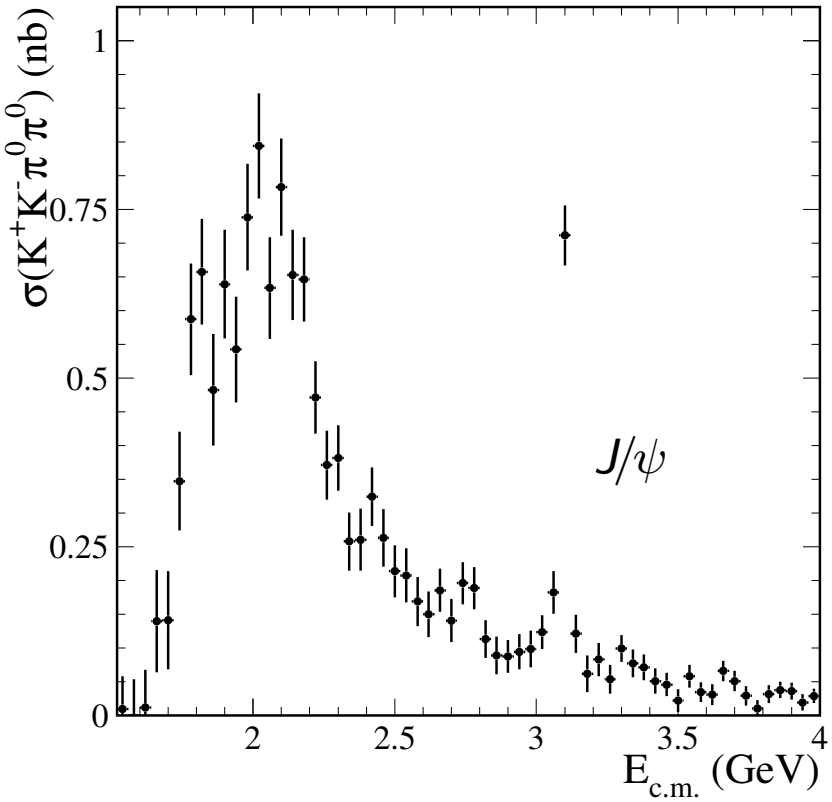
Cross section for $e^+e^- \to K^+K^-\pi\pi$

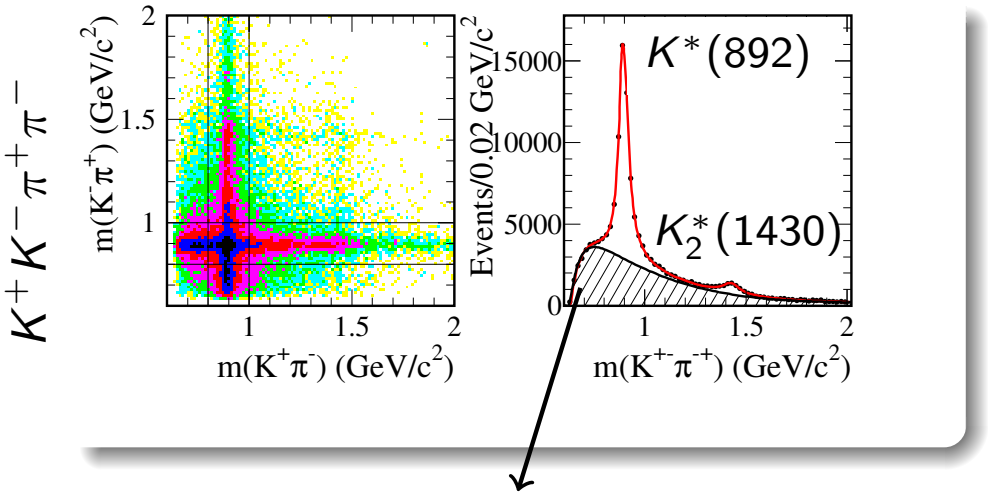


- syst. uncertainty: 4 - 11%
- resolution: 4.2 - 5.5 MeV
- J/ψ clearly visible



- syst. uncertainty: 7 - 16%
- resolution: 8.8 - 11.2 MeV
- J/ψ clearly visible

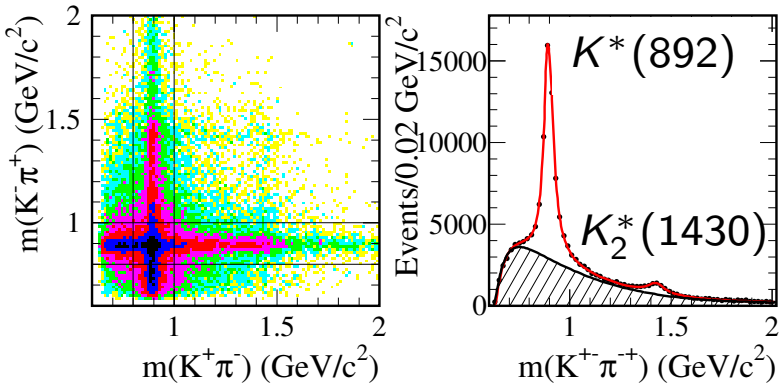
Intermediate Resonances of $e^+e^- \to K^+K^-\pi\pi$



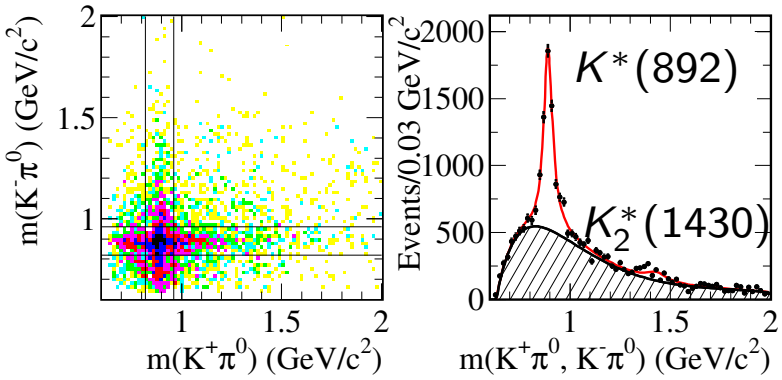
non-resonant contribution

Intermediate Resonances of $e^+e^- \to K^+K^-\pi\pi$

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

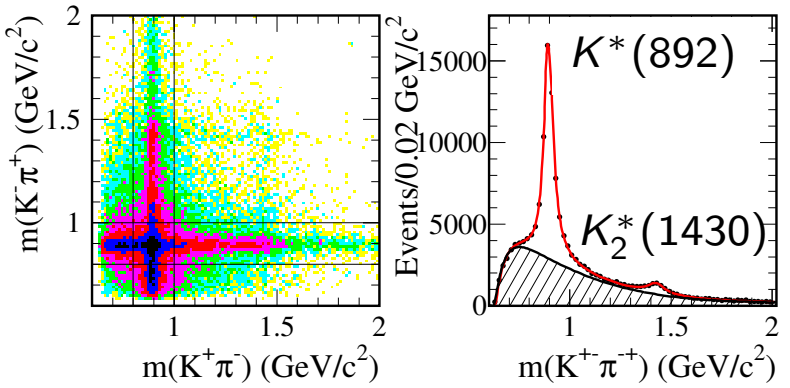


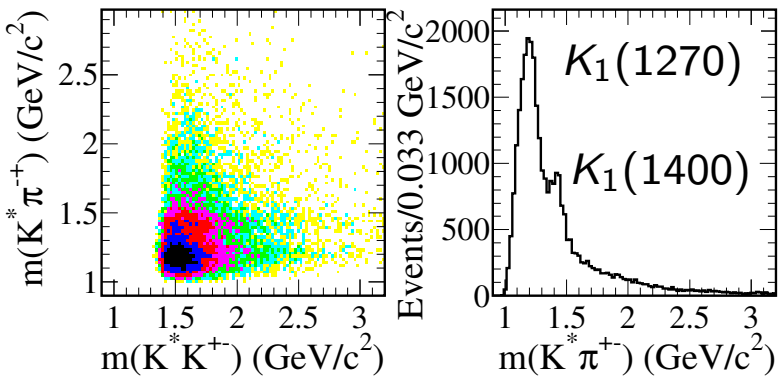
$K^+K^-\pi^0\pi^0$



Intermediate Resonances of $e^+e^- \to K^+K^-\pi^+\pi^-$

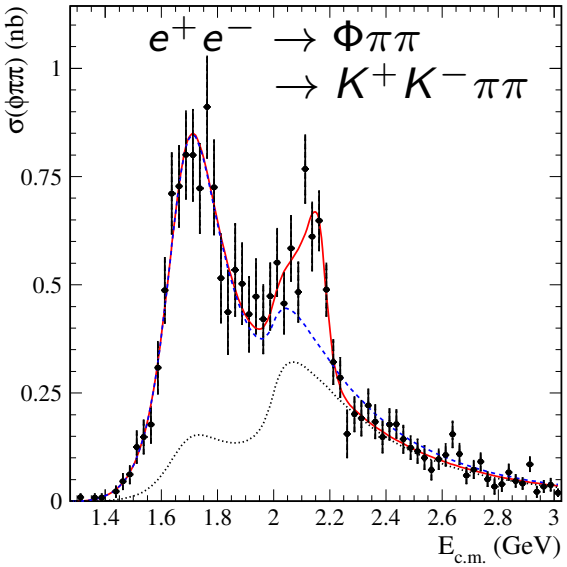
$K^+K^-\pi^+\pi^-$

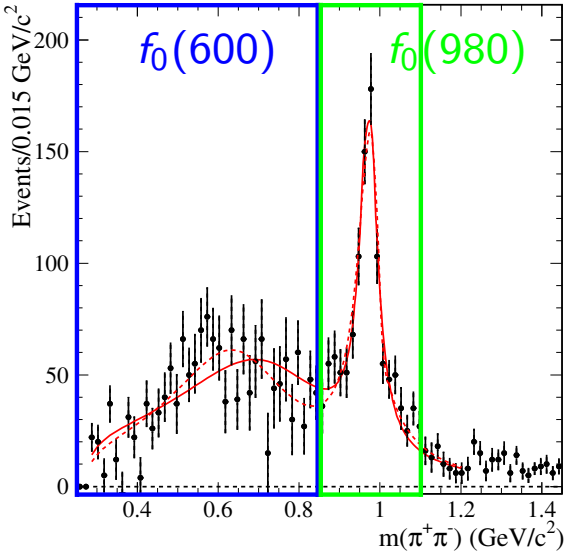


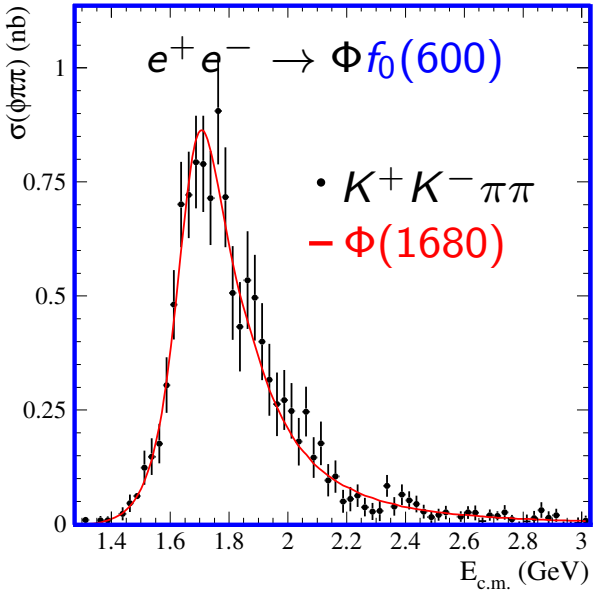


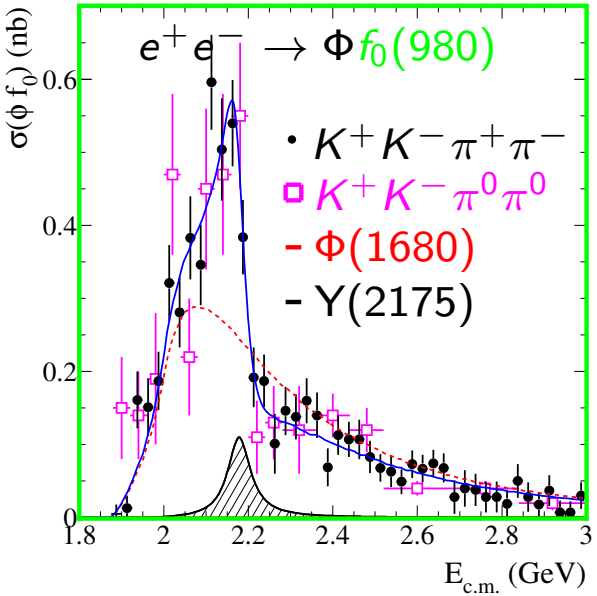
cross section dominated by $K^*(892)K^\pm\pi^\mp$ final state
$K_1(1270, 1400) \to K^*(892)\pi$ and
$K_1(1270) \to K\rho(770)$ are seen

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









- Requirement: $\phi \to K^+K^-$
- Fit assumes two resonances
- Y(2175) confirmed: $J^{PC} = 1^{--}$
  M$=2176 \pm 14 \pm 4\,\mathrm{MeV}/c^2$; $\Gamma = 90 \pm 22 \pm 10\,\mathrm{MeV}$
- Might not be a radial excitation: width too small & should also decay into $\phi f_0(600)$ as for $\phi(1680)$
- Strangeness partner of Y(4260)? Hybrid-candidate?

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

accepted for publication by PRD, based on 454 fb^{-1}
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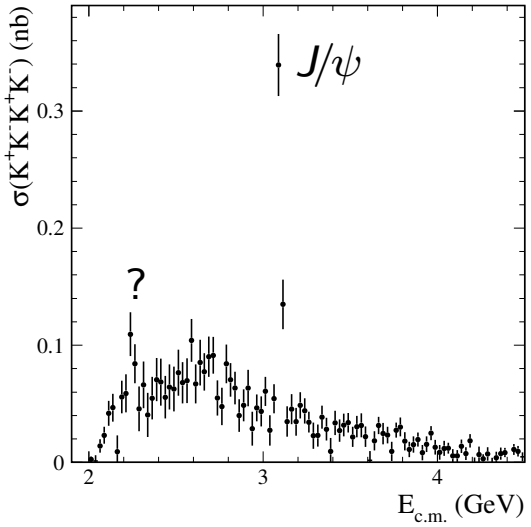
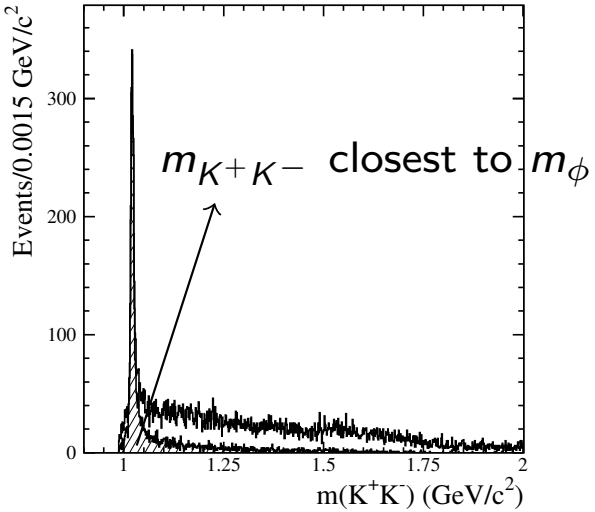
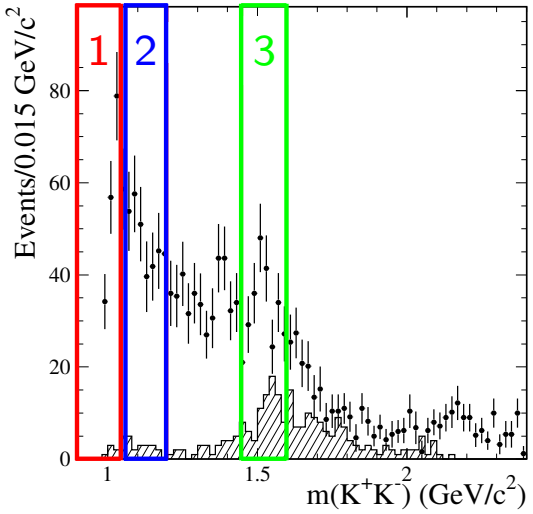






J/ψ clearly visible

Additional structure present?

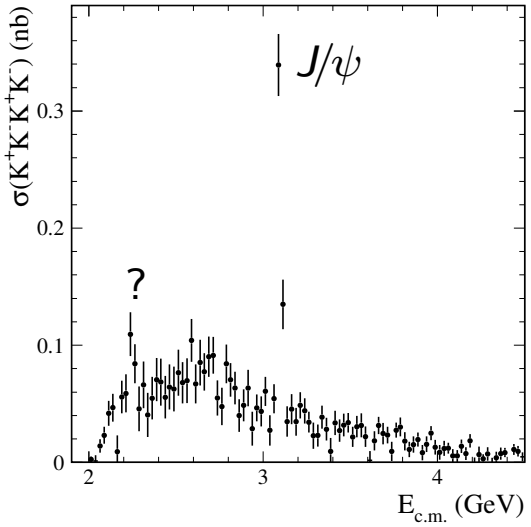
Systematic uncertainty: $9 - 13\%$

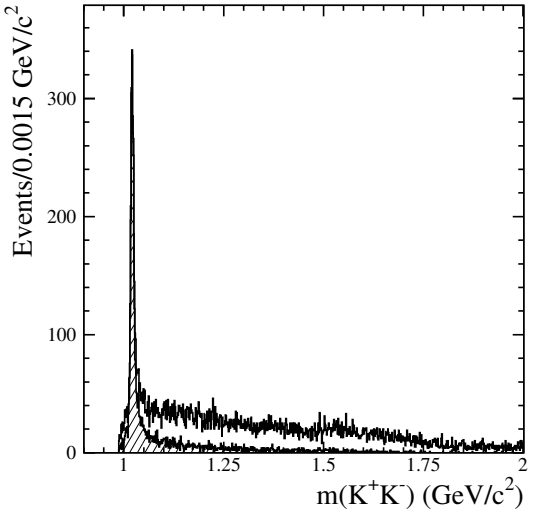
Resolution: $3 - 6.5\,\mathrm{MeV}$

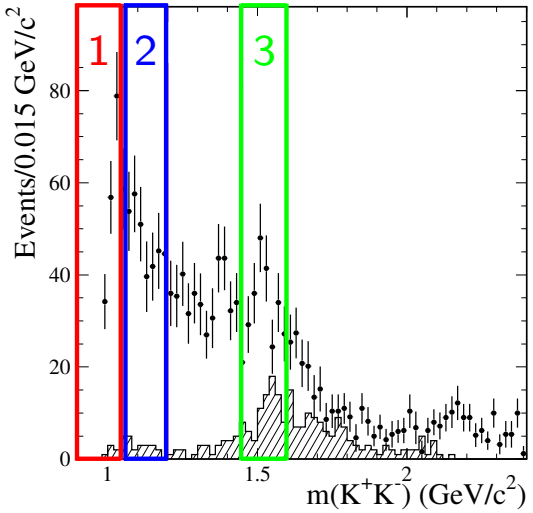
ϕK^+K^- dominant

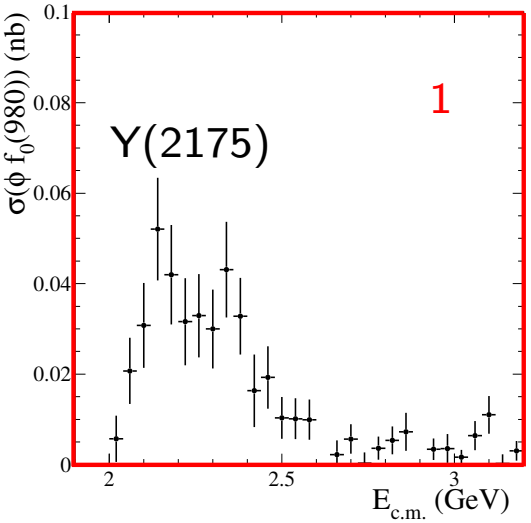
Non-ϕ K^+K^--combination

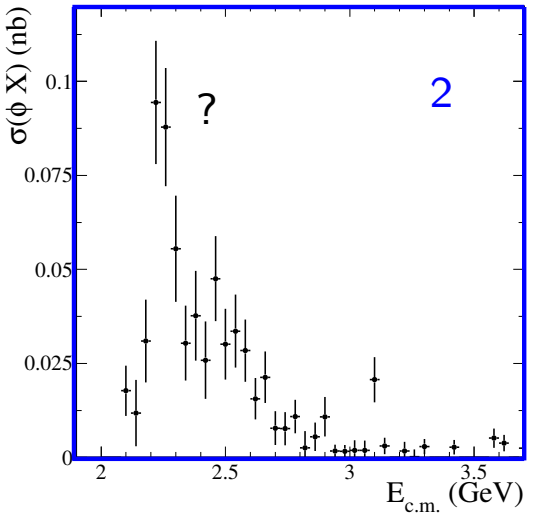
Cross section for $e^+e^- \to K^+K^-K^+K^-$

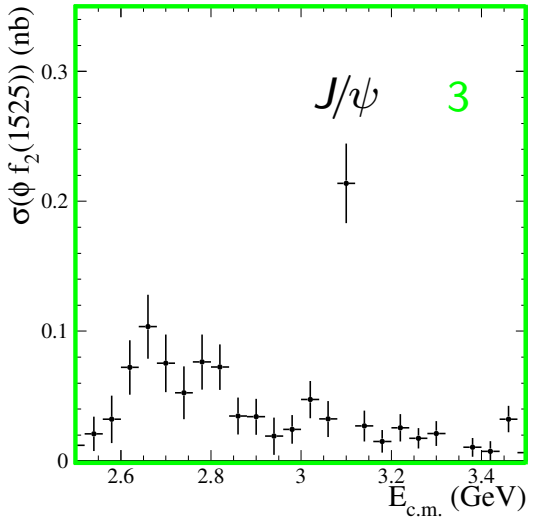












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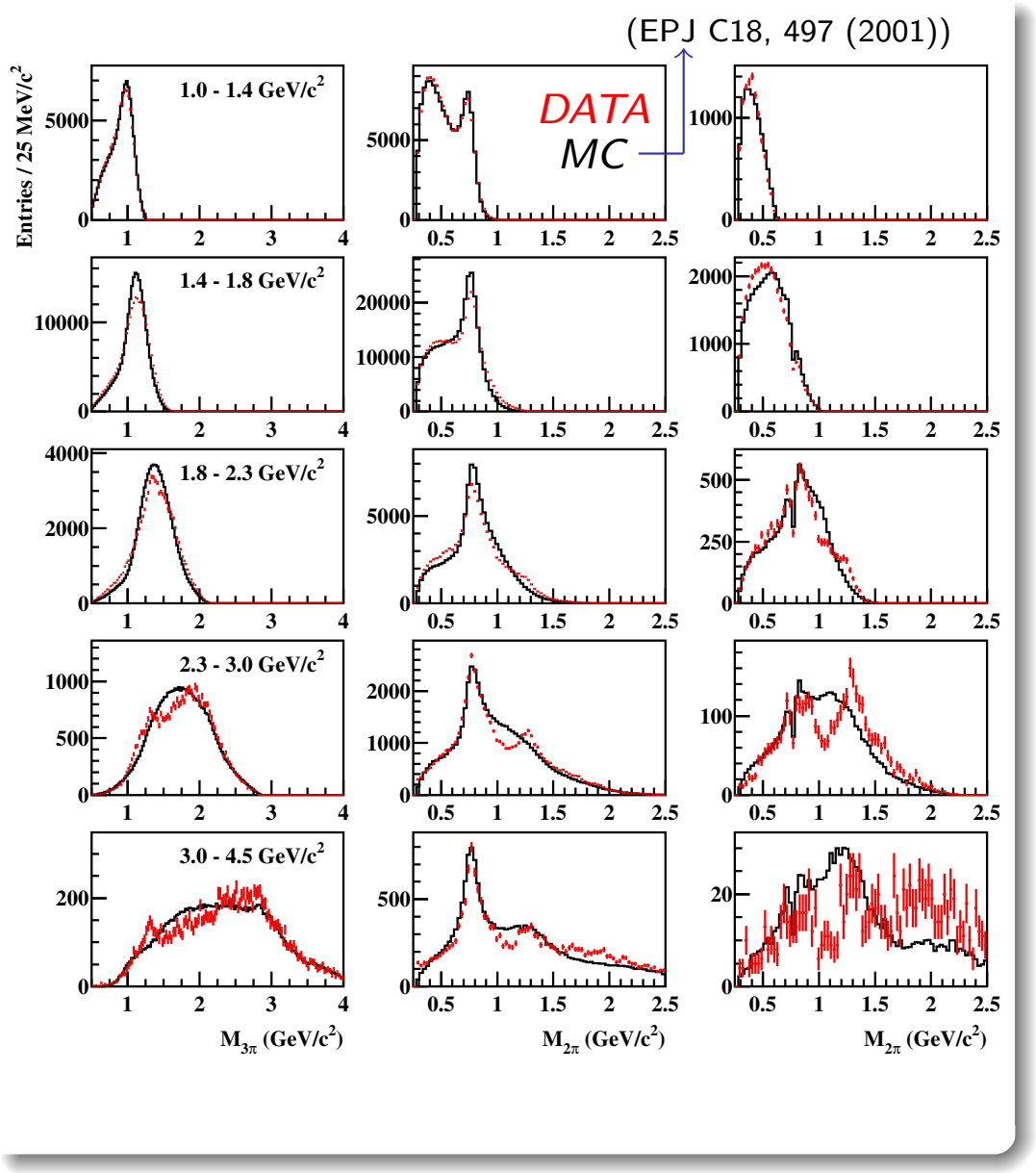
Phys. Rev. D**71**, 052001 (2005).

Internal structure in various E_{CM} energy slices



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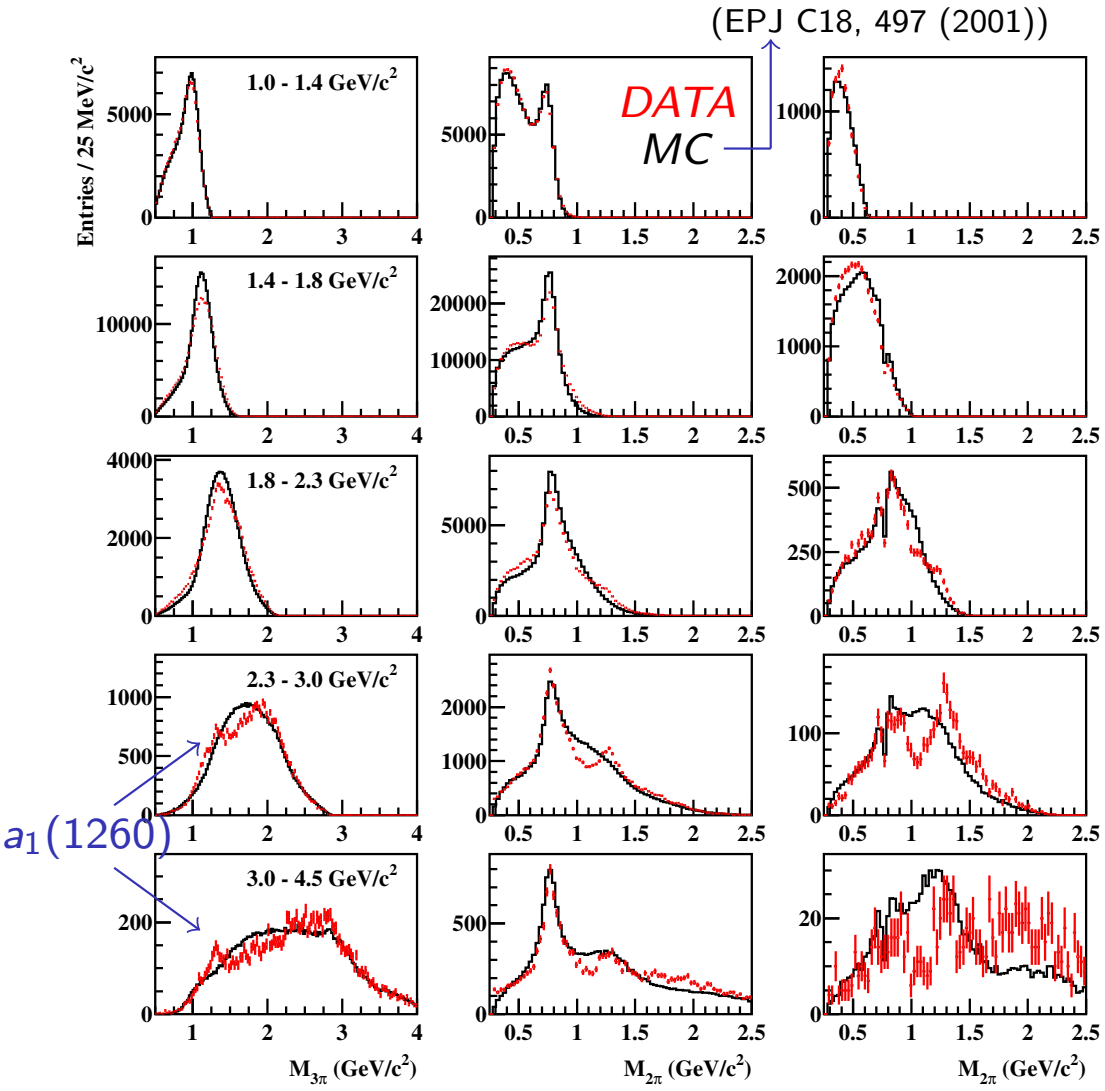

First column (4 entries/event):

$a_1(1260)$

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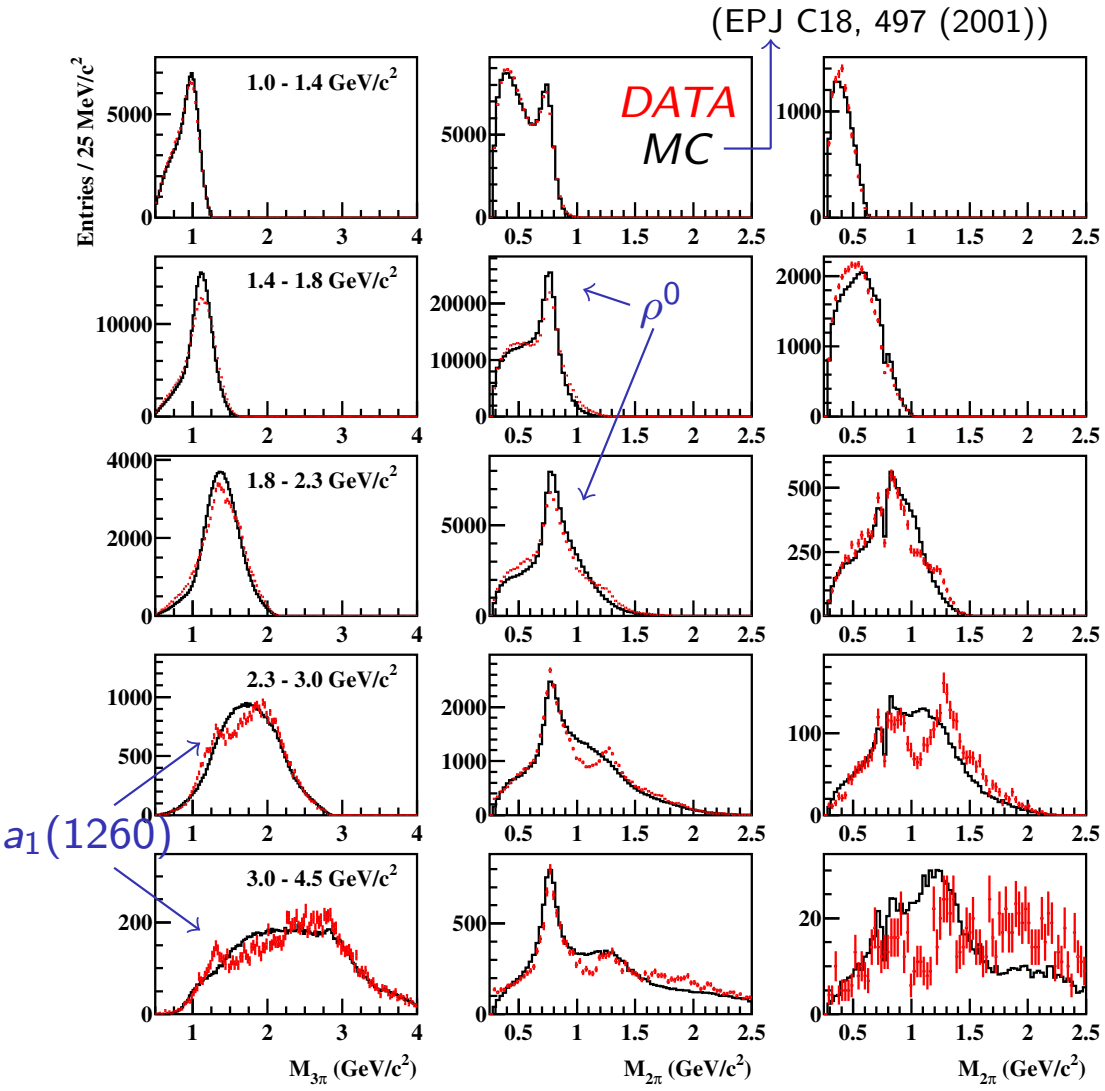


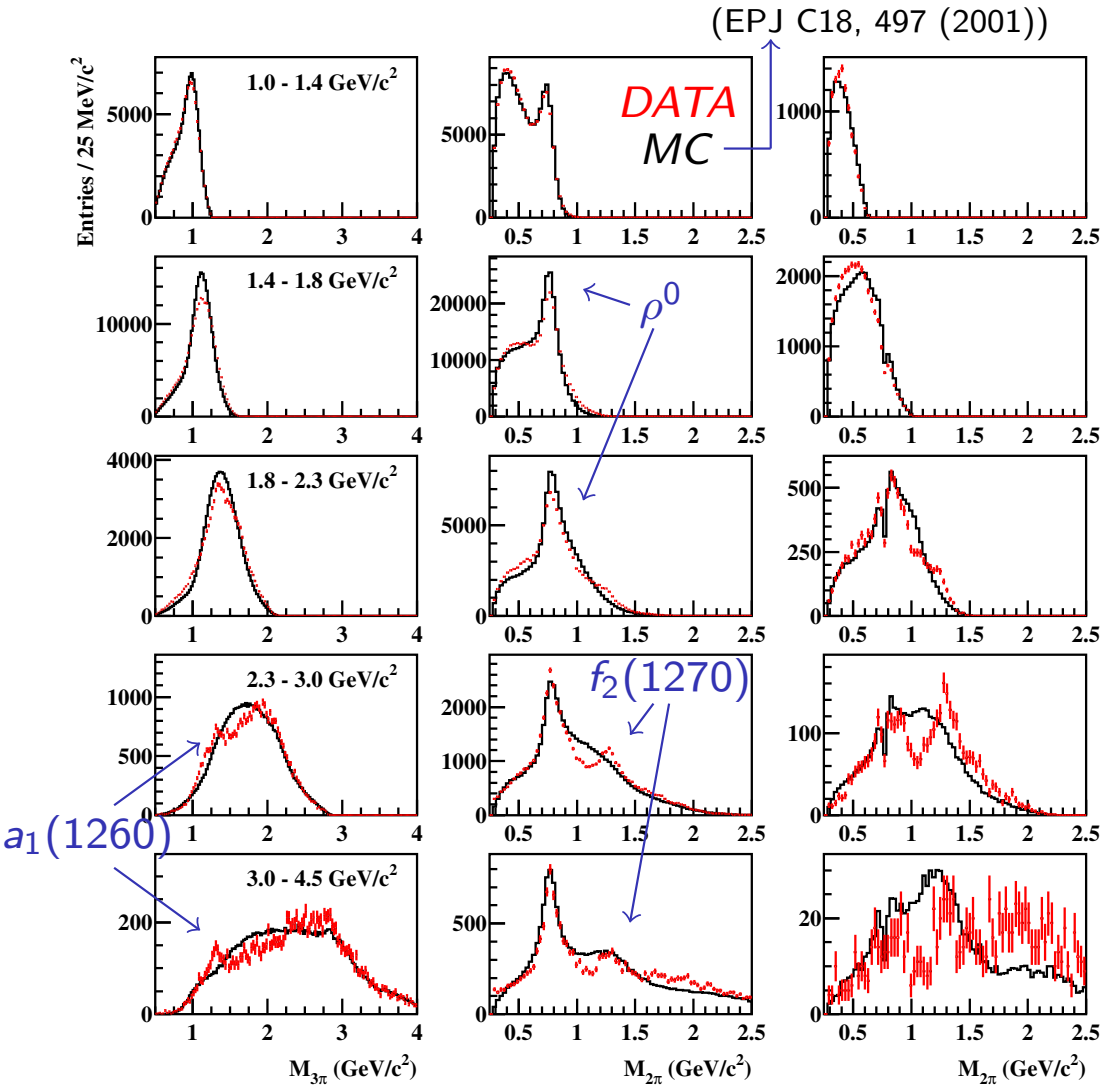
First column (4 entries/event):

$a_1(1260)$

Second column (4 entries/event):

strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4\,\mathrm{GeV}/c^2$:
$1/4th$ of entries in ρ^0 peak
$\rho^0\rho^0$ is forbidden
$\to \rho^0$ in each event!

Internal structure in various E_{CM} energy slices



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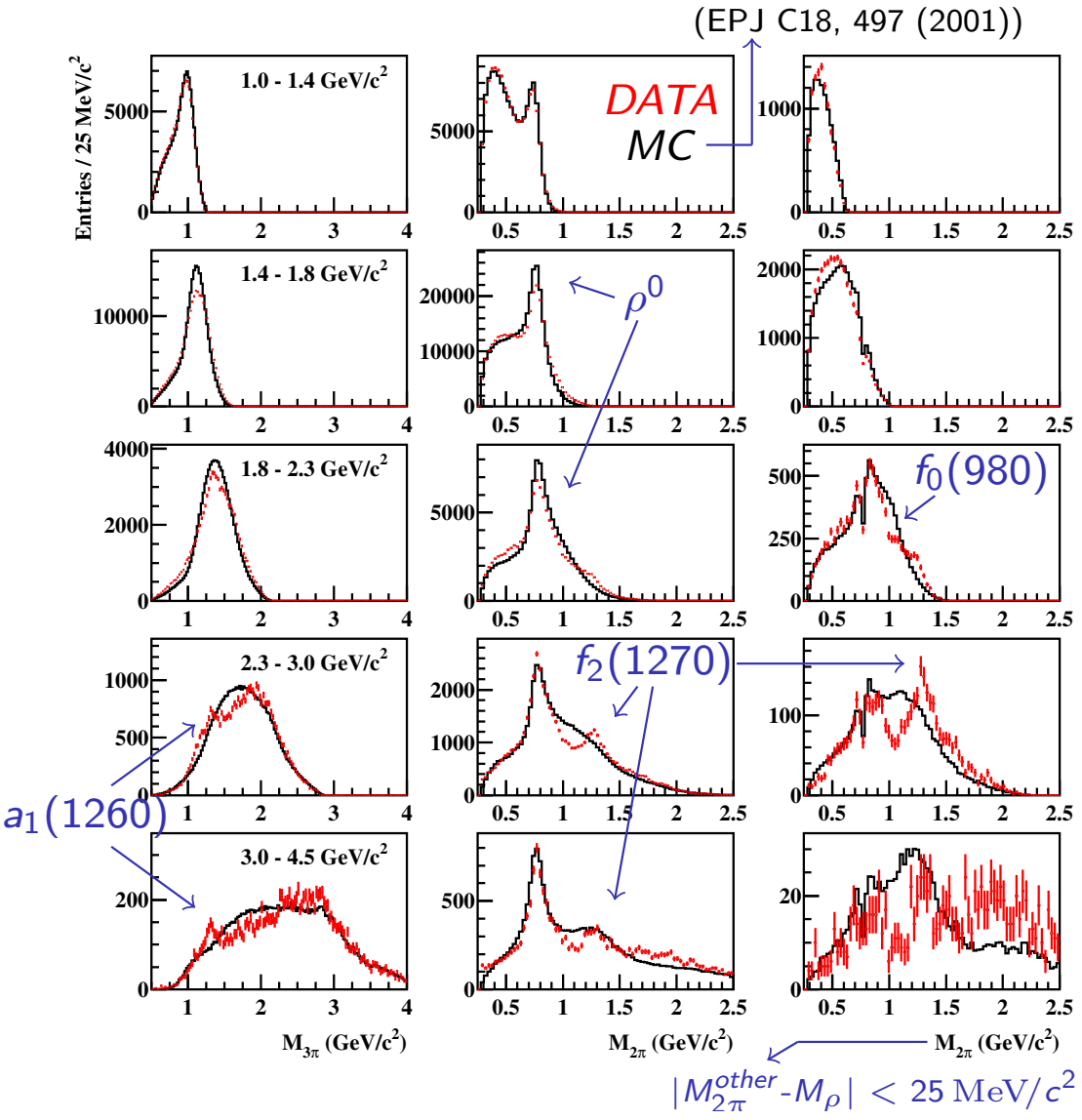

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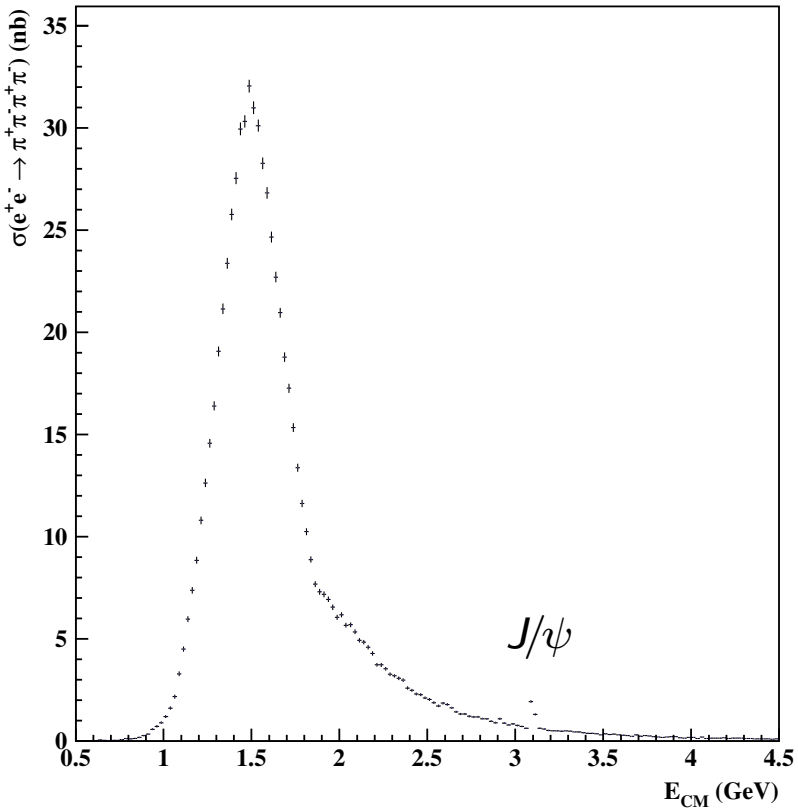
Third column (1 entry/event):

2π lie within ρ^0 mass
$\to$ other $\pi^+\pi^-$'s mass plotted

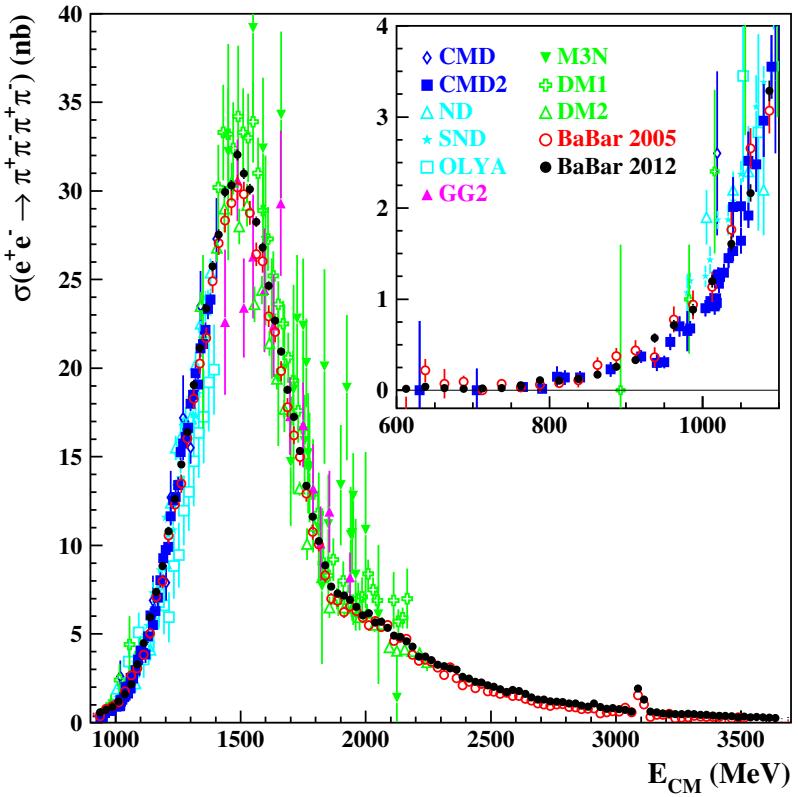
$f_2(1270)$, $a_1(1260)$, $f_0(980)\ldots$?

$\to$ Partial Wave Analysis needed

Cross section for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$



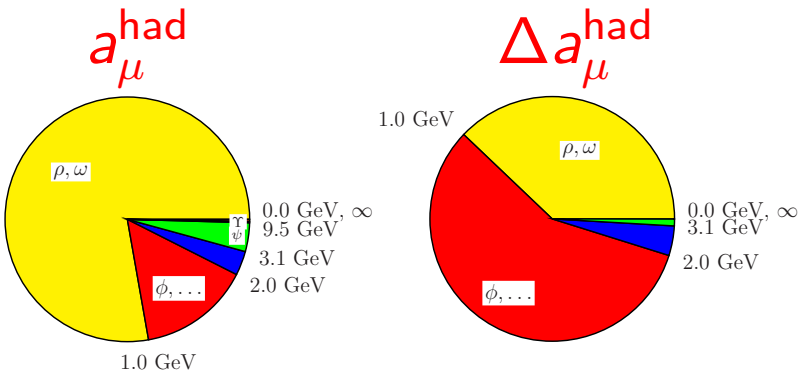
- Systematic uncertainties
  2.4% in peak region (1.1-2.8 GeV)
  11% (0.6-1.1 GeV)
  4% (2.8-4.0 GeV)
- J/ψ visible



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

Impact on $(g-2)_\mu$

contribution to



[PR 477, 1 (2009).]

[EPJ C66, 1 (2011).] a_μ units in 10^{-10}

$$a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-) = 13.35 \pm 0.10 \pm 0.52$$

$$\Downarrow$$

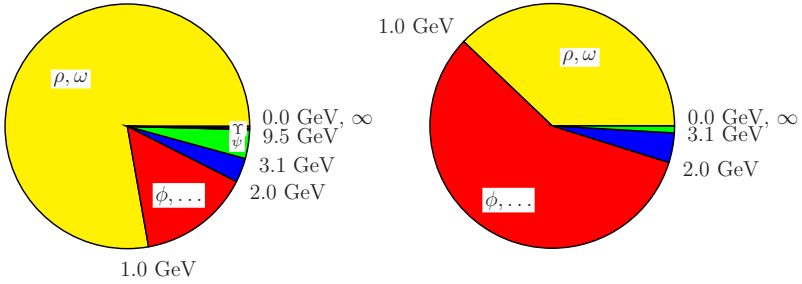
$$a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-) = 13.64 \pm 0.03 \pm 0.36$$

calculation only based on *BABAR* 2012 data!

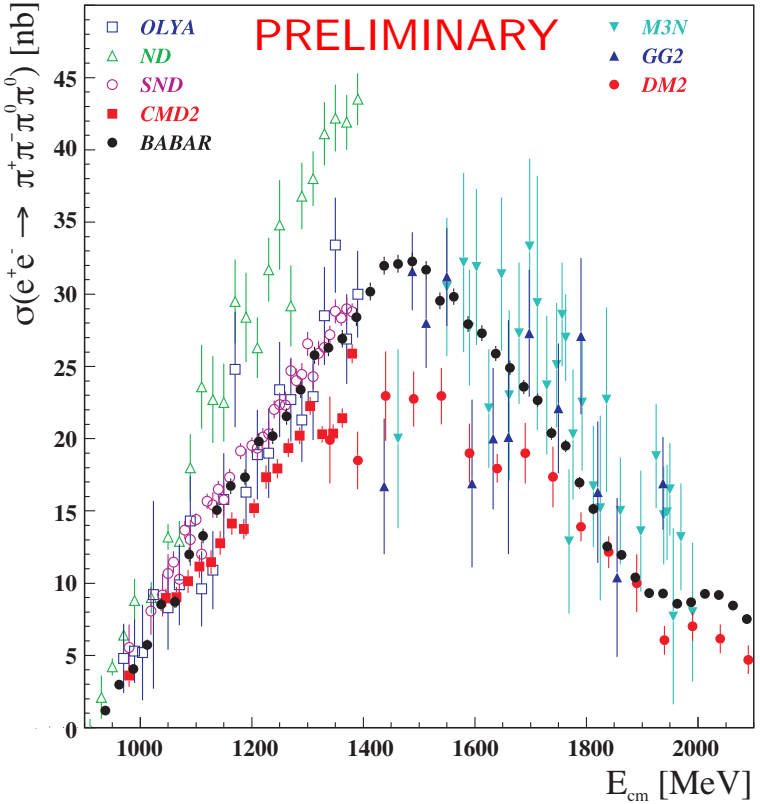
Impact on $(g-2)_\mu$

contribution to

a_μ^{had} Δa_μ^{had}



[PR 477, 1 (2009).]



[EPJ C66, 1 (2011).]

a_μ units in 10^{-10}

$$a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-) = 13.35 \pm 0.10 \pm 0.52$$
$$\Downarrow$$
$$a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-) = 13.64 \pm 0.03 \pm 0.36$$

calculation only based on *BABAR* 2012 data!

dominant contribution to Δa_μ^{had}:

$$a_\mu^{had}(\pi^+\pi^-\pi^0\pi^0) = 18.01 \pm 0.03 \pm 1.24$$
$$\Downarrow$$

BABAR analysis in progress

Summary

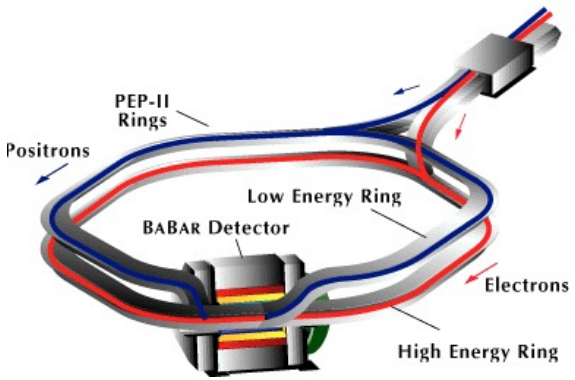
Measurement of hadronic cross sections via ISR is a very productive field in addition to B-physics at *BABAR*

- Measurements from threshold of the invariant mass up to $4.5\,\mathrm{GeV}/c^2$
- Many measurements for the first time with high accuracy
- Hadron spectroscopy
- Important for theoretical predictions of $(g_\mu - 2)$
  $\rightarrow$ hint for new physics? (3.6σ)
- Implications on the running of α_{QED} and predictions for the Higgs mass

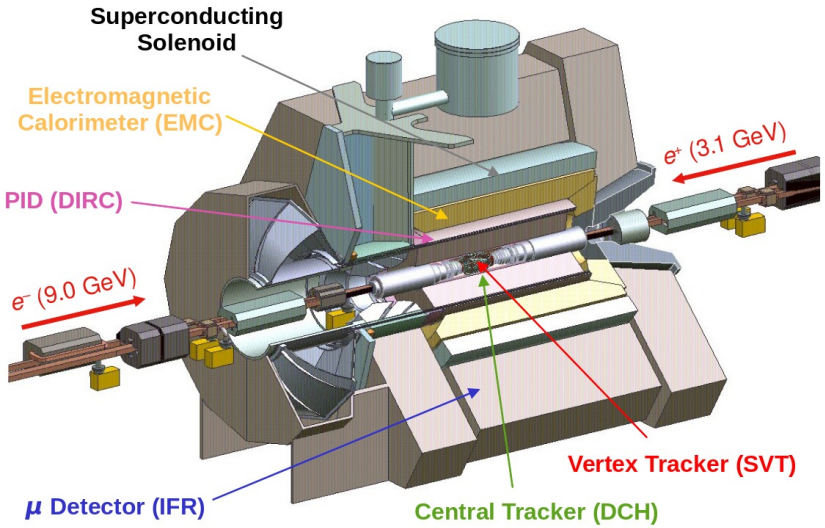
backup slides

PEP-II and the *BABAR* detector at SLAC

- asymmetric e^+e^--collider:
  $9\,\mathrm{GeV}$ (e^-) and $3.1\,\mathrm{GeV}$ (e^+)
- $\sqrt{s} = 10.58\,\mathrm{GeV} \Rightarrow \Upsilon(4S)$
  $\Rightarrow$ above $B\overline{B}$-threshold

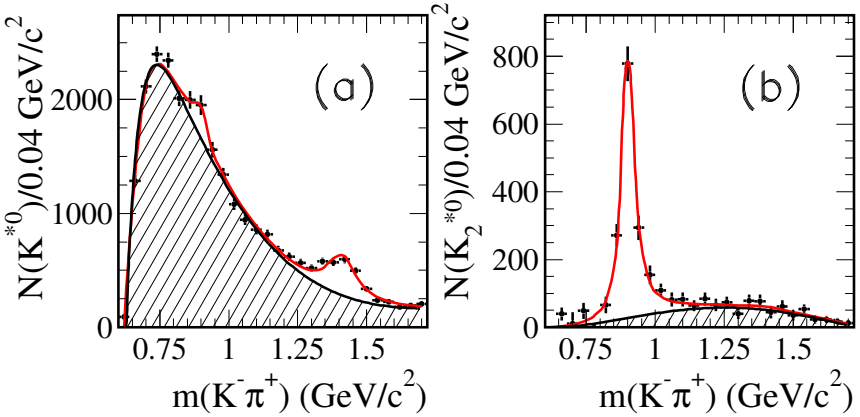


- main purpose: B-physics
- multi purpose detector
- data taken from 1999 – 2008
- integrated luminosity: $531\,\mathrm{fb}^{-1}$
  on $\Upsilon(4S)$: $454\,\mathrm{fb}^{-1}$
  $\approx 600 \cdot 10^6$ $B\overline{B}$-pairs



Coherent K^*K^* contribution in $e^+e^- \to K^+K^-\pi\pi$

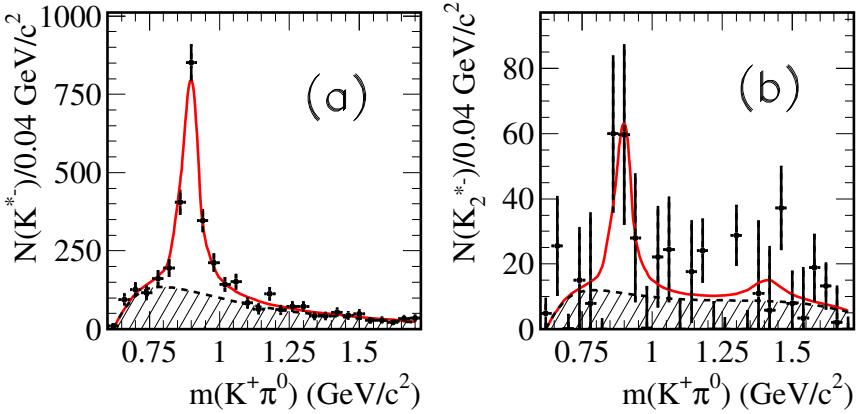
$K^+K^-\pi^+\pi^-$



Extract number of $K^*(892)^0$ and $K_2^*(1430)^0$ by fitting $K^+\pi^-$ mass in every $40\,\mathrm{MeV}/c^2$ bin of $K^-\ \pi^+$ mass

$\to$ less than 1% $K^*(892)^0K^*(892)^0$

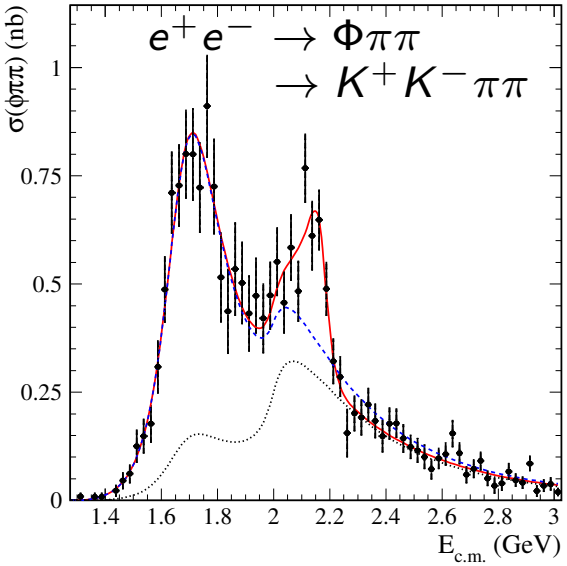
$K^+K^-\pi^0\pi^0$

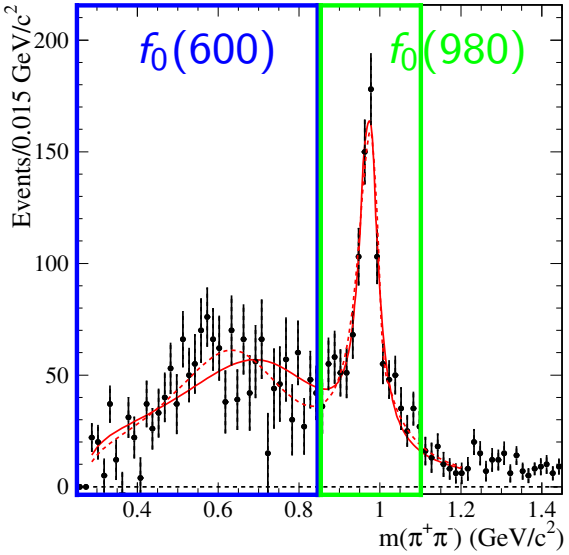


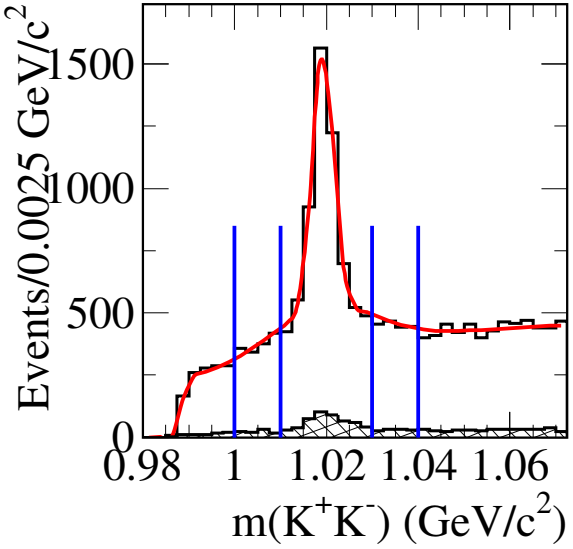
Extract number of $K^*(892)^+$ and $K_2^*(1430)^+$ by fitting $40\,\mathrm{MeV}/c^2$ bins of $K^-\pi^0$ mass

$\to$ 30% $K^*(892)^\pm K^*(892)^\mp$

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

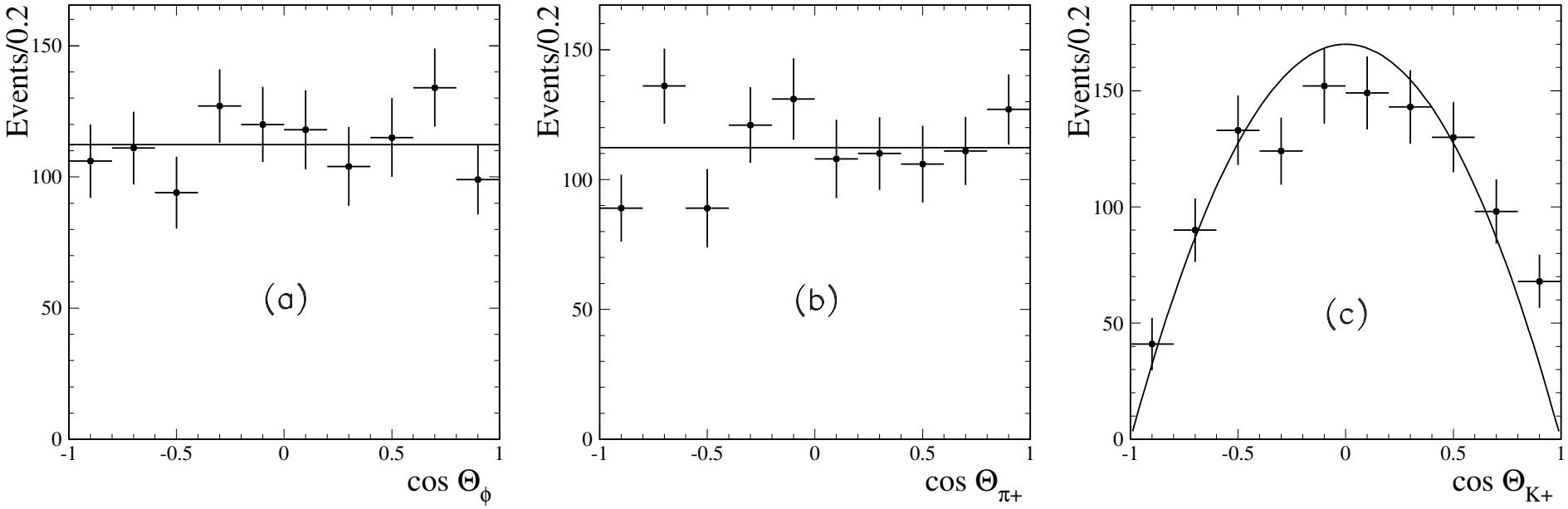


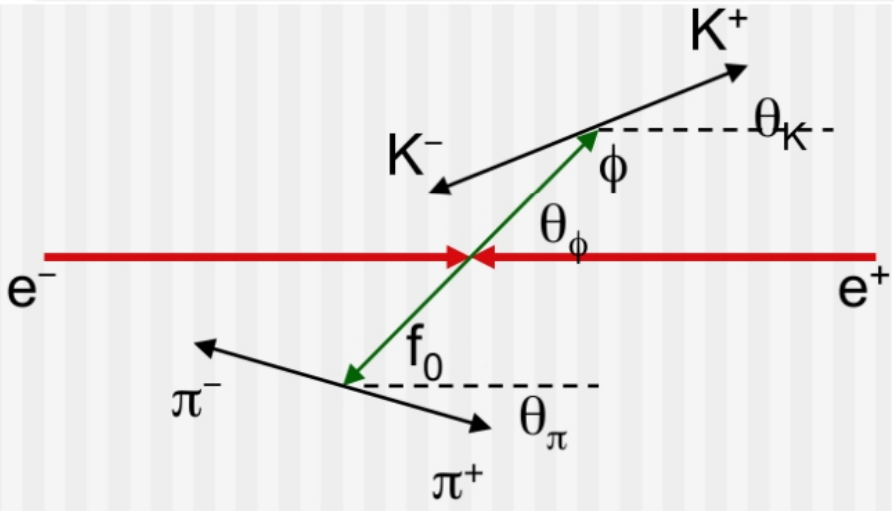




- minimum 2 peaks!
- resonance confirmed: $J^{PC} = 1^{--}$
  M=$2176 \pm 14 \pm 4\,\mathrm{MeV}/c^2$; $\Gamma = 90 \pm 22 \pm 10\,\mathrm{MeV}$

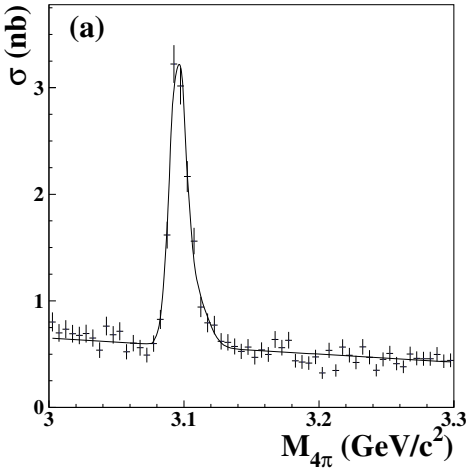
$e^+e^- \to \phi\pi^+\pi^- \to K^+K^-\pi^+\pi^-$





- ϕ and $\pi^+\pi^-$ system are in S-wave
- pions in $\pi^+\pi^-$ system are in S-wave
- kaons from ϕ are in P-wave (as expected)

charmonium branching ratios

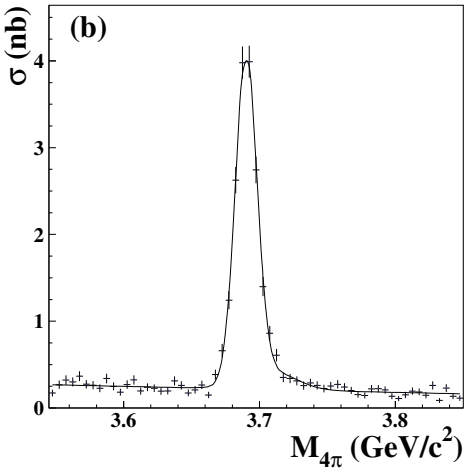


$$\mathcal{B}_{J/\psi \to 2(\pi^+\pi^-)} \cdot \sigma_{int}^{J/\psi} = \frac{N(J/\psi \to 2(\pi^+\pi^-))}{d\mathcal{L}/dE \cdot \epsilon_{MC}} = (48.9 \pm 2.1_{stat} \pm 1.0_{syst})\,\mathrm{MeV}/c^2\,\mathrm{nb}$$

$$\mathcal{B}_{J/\psi \to 2(\pi^+\pi^-)} = (3.67 \pm 0.16_{stat} \pm 0.08_{syst} \pm 0.09_{ext}) \cdot 10^{-3}$$

$$\mathcal{B}^{PDG}_{J/\psi \to 2(\pi^+\pi^-)} = (3.55 \pm 0.23) \cdot 10^{-3}$$

→ agrees with PDG, higher in precision



$$\mathcal{B}_{\psi(2S) \to J/\psi\,\pi^+\pi^-} \cdot \mathcal{B}_{J/\psi \to \mu^+\mu^-} \cdot \sigma_{int}^{\psi(2S)} = \frac{N(\psi(2S) \to \pi^+\pi^-\mu^+\mu^-)}{d\mathcal{L}/dE \cdot \epsilon_{MC}} = (84.7 \pm 2.2_{stat} \pm 1.8_{syst})\,\mathrm{MeV}/c^2\,\mathrm{nb}$$

$$\mathcal{B}_{\psi(2S) \to J/\psi\,\pi^+\pi^-} = 0.354 \pm 0.009_{stat} \pm 0.007_{syst} \pm 0.007_{ext}$$

$$\mathcal{B}^{PDG}_{\psi(2S) \to J/\psi\,\pi^+\pi^-} = 0.336 \pm 0.004$$

$$\mathcal{B}^{CLEO}_{\psi(2S) \to J/\psi\,\pi^+\pi^-} = 0.3504 \pm 0.0007_{syst} \pm 0.0077_{ext}$$

→ agrees with recent CLEO result (PRD 78, 011102 (2008))