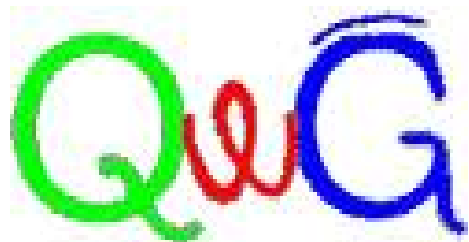# Two-Photon Physics at *BABAR*

Pietro Biassoni
Università degli Studi and INFN Milano
On behalf of the *BABAR* Collaboration
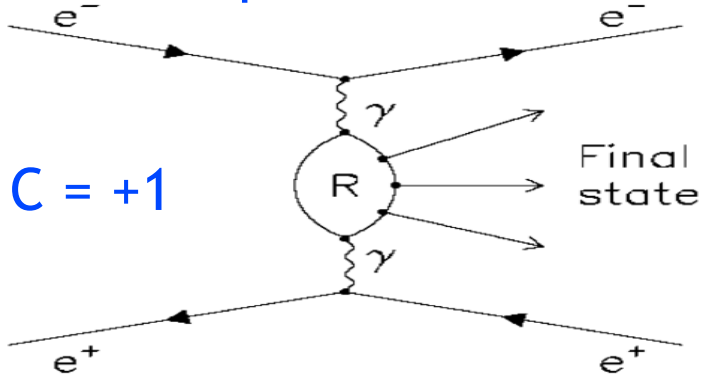
International Workshop on Heavy Quarkonium 2011
4 – 7 October 2011
GSI, Darmstadt, Germany

Why Two-Photon Physics?

Two-photon Fusion

C = +1

Two-photon collisions for $q\bar{q}$:

- No-tag events (scattered e^+e^- lost in the beampipe): quasi-real ($q^2 \sim 0$) photons
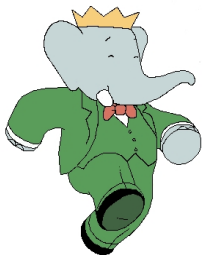- Single-tag events (either e^+ or e^- scattered at high angle): form factor measurements

Experimental features:
- Clean environment thanks to low combinatorial background
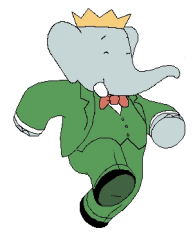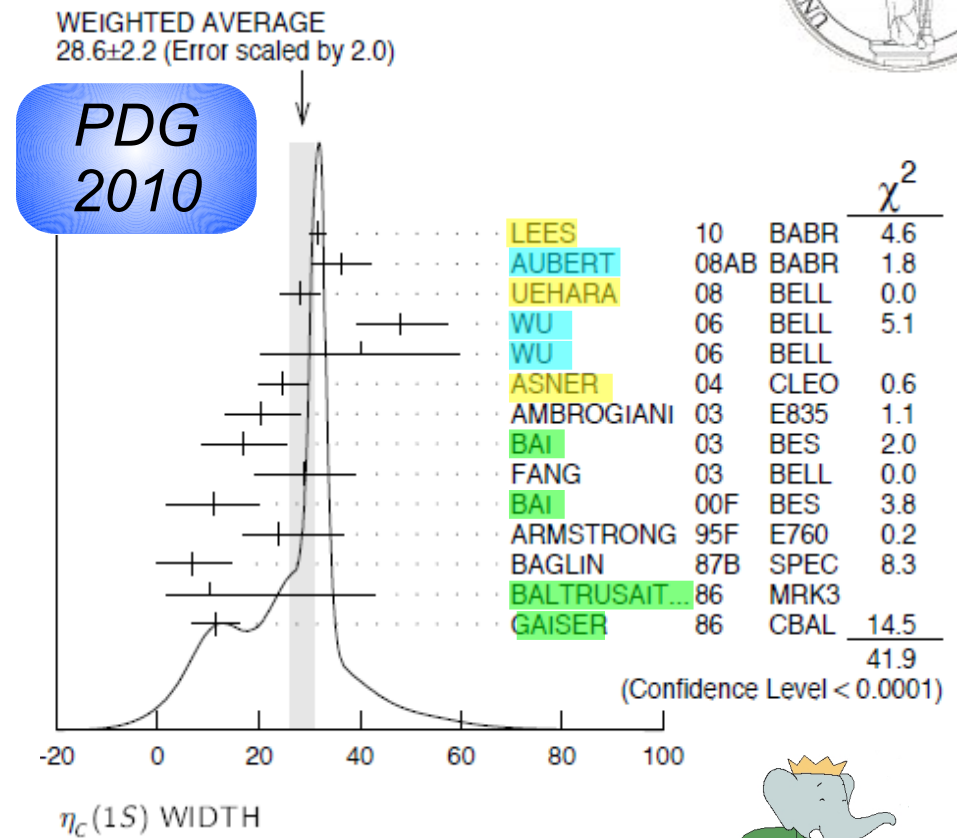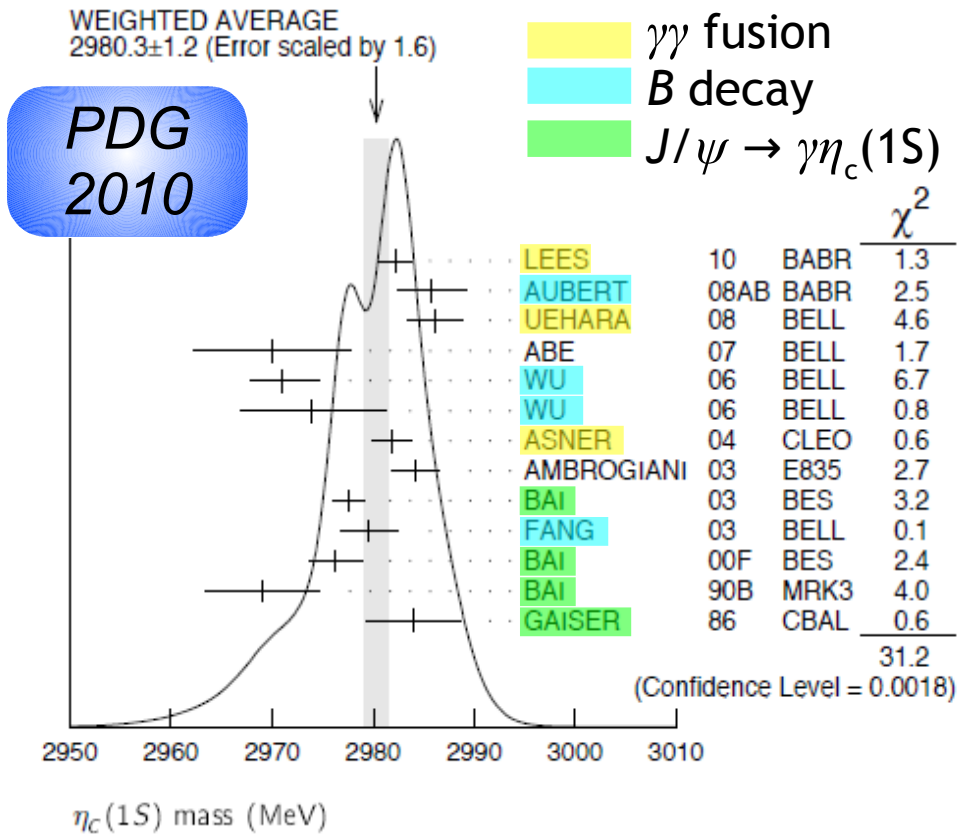- Clean signatures: missing mass and head-on collision

For no-tag events: Yang's theorem holds [Yang, Phys. Rev. 77,242 (1950)]

$$J^P = 0^+, 0^-, 2^+, 2^-, 3^+, 4^-, 4^+$$

$J > 2$ suppressed by available phase-space

$\eta_c(1S)$ Open Issues

WEIGHTED AVERAGE
2980.3±1.2 (Error scaled by 1.6)

PDG 2010

- $\gamma\gamma$ fusion (yellow)
- B decay (cyan)
- $J/\psi \to \gamma\eta_c(1S)$ (green)

			χ^2
LEES	10	BABR	1.3
AUBERT	08AB	BABR	2.5
UEHARA	08	BELL	4.6
ABE	07	BELL	1.7
WU	06	BELL	6.7
WU	06	BELL	0.8
ASNER	04	CLEO	0.6
AMBROGIANI	03	E835	2.7
BAI	03	BES	3.2
FANG	03	BELL	0.1
BAI	00F	BES	2.4
BAI	90B	MRK3	4.0
GAISER	86	CBAL	0.6
			31.2

(Confidence Level = 0.0018)

$\eta_c(1S)$ mass (MeV)
2950 2960 2970 2980 2990 3000 3010

WEIGHTED AVERAGE
28.6±2.2 (Error scaled by 2.0)

PDG 2010

			χ^2
LEES	10	BABR	4.6
AUBERT	08AB	BABR	1.8
UEHARA	08	BELL	0.0
WU	06	BELL	5.1
WU	06	BELL	
ASNER	04	CLEO	0.6
AMBROGIANI	03	E835	1.1
BAI	03	BES	2.0
FANG	03	BELL	0.0
BAI	00F	BES	3.8
ARMSTRONG	95F	E760	0.2
BAGLIN	87B	SPEC	8.3
BALTRUSAIT...	86	MRK3	
GAISER	86	CBAL	14.5
			41.9

(Confidence Level < 0.0001)

$\eta_c(1S)$ WIDTH
-20 0 20 40 60 80 100
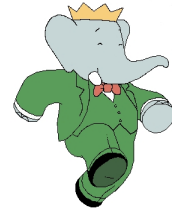
$\eta_c(1S)$ firmly established, but some issues:

- Large spread in mass and width measurements
- Recent CLEO paper suggests that previous measurements in J/ψ and $\psi(2S)$ radiative decays can be biased because of the neglected energy dependence of the M1 transition [PRL 102, 011801 (2009)]
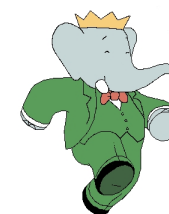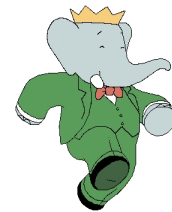- Sum of observed decay modes BFs is less than 50%

$\eta_c(2S)$ Open Issues

$\eta_c(2S)$ discovered in 2002 by Belle:

- Current PDG width average has 50% uncertainty
- Particularly elusive particle: just one decay mode observed

$\eta_c(2S)$ discovered in 2002 by Belle:

- Current PDG width average has 50% uncertainty
- Particularly elusive particle: just one decay mode observed

PDG 2010

$\eta_c(2S)$ DECAY MODES

Mode		Fraction (Γ_i/Γ)
Γ_1	hadrons	not seen
Γ_2	$K\bar{K}\pi$	(1.9 ± 1.2) %
Γ_3	$2\pi^+ 2\pi^-$	not seen
Γ_4	$3\pi^+ 3\pi^-$	not seen
Γ_5	$K^+ K^- \pi^+ \pi^-$	not seen
Γ_6	$K^+ K^- \pi^+ \pi^- \pi^0$	not seen
Γ_7	$K^+ K^- 2\pi^+ 2\pi^-$	not seen
Γ_8	$K_S^0 K^- 2\pi^+ \pi^- + $ c.c.	not seen
Γ_9	$2K^+ 2K^-$	not seen
Γ_{10}	$p\bar{p}$	not seen
Γ_{11}	$\gamma\gamma$	$< 5 \quad \times 10^{-4}$
Γ_{12}	$\pi^+ \pi^- \eta$	not seen
Γ_{13}	$\pi^+ \pi^- \eta'$	not seen
Γ_{14}	$K^+ K^- \eta$	not seen
Γ_{15}	$\pi^+ \pi^- \eta_c(1S)$	not seen

Not seen by DELPHI in $e^+ e^- \to e^+ e^-$ + hadrons [PLB 441, 479 (1998)]

BABAR observes it in $B^\pm \to K^\pm X_{c\bar{c}}$ [PRL 96, 052002 (2006)]

Only decay mode observed until 2011

$\eta_c(2S)$ discovered in 2002 by Belle:

- Current PDG width average has 50% uncertainty
- Particularly elusive particle: just one decay mode observed

PDG 2010

$\eta_c(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	not seen
Γ_2	$K\overline{K}\pi$	$(1.9\pm1.2)\%$
Γ_3	$2\pi^+2\pi^-$	not seen
Γ_4	$3\pi^+3\pi^-$	not seen
Γ_5	$K^+K^-\pi^+\pi^-$	not seen
Γ_6	$K^+K^-\pi^+\pi^-\pi^0$	not seen
Γ_7	$K^+K^-2\pi^+2\pi^-$	not seen
Γ_8	$K_S^0K^-2\pi^+\pi^- +$ c.c.	not seen
Γ_9	$2K^+2K^-$	not seen
Γ_{10}	$p\overline{p}$	not seen
Γ_{11}	$\gamma\gamma$	$< 5 \times 10^{-4}$
Γ_{12}	$\pi^+\pi^-\eta$	not seen
Γ_{13}	$\pi^+\pi^-\eta'$	not seen
Γ_{14}	$K^+K^-\eta$	not seen
Γ_{15}	$\pi^+\pi^-\eta_c(1S)$	not seen

Unsuccessful searches for $\eta_c(2S)$:

$\gamma\gamma \rightarrow 4$ prongs
[EPJ C53, 1 (2008)]
$p\overline{p} \rightarrow \gamma\gamma$
[PRD 64, 052003 (2001)]
$B^\pm \rightarrow K^\pm \gamma\gamma$
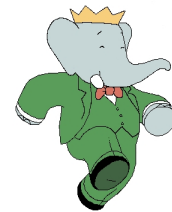[PLB 662, 323 (2008)]

$\psi(2S) \rightarrow \gamma\eta_c(2S)$
[PRD 81, 052002 (2010)]
Probably not observed due to small production rate

$\eta_c(2S)$ Open Issues

$\eta_c(2S)$ discovered in 2002 by Belle:

- Current PDG width average has 50% uncertainty
- Particularly elusive particle: just one decay mode observed

PDG 2010

$\eta_c(2S)$ **DECAY MODES**

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	not seen
Γ_2	$K\overline{K}\pi$	(1.9 ± 1.2) %
Γ_3	$2\pi^+ 2\pi^-$	not seen
Γ_4	$3\pi^+ 3\pi^-$	not seen
Γ_5	$K^+ K^- \pi^+ \pi^-$	not seen
Γ_6	$K^+ K^- \pi^+ \pi^- \pi^0$	not seen
Γ_7	$K^+ K^- 2\pi^+ 2\pi^-$	not seen
Γ_8	$K_S^0 K^- 2\pi^+ \pi^- +$ c.c.	not seen
Γ_9	$2K^+ 2K^-$	not seen
Γ_{10}	$p\overline{p}$	not seen
Γ_{11}	$\gamma\gamma$	$< 5 \times 10^{-4}$
Γ_{12}	$\pi^+ \pi^- \eta$	not seen
Γ_{13}	$\pi^+ \pi^- \eta'$	not seen
Γ_{14}	$K^+ K^- \eta$	not seen
Γ_{15}	$\pi^+ \pi^- \eta_c(1S)$	not seen

New searches for $\eta_c(2S)$:

$\gamma\gamma$ collisions:
- *BABAR* observation in $K^+K^-\pi^+\pi^-\pi^0$ (this talk) [PRD 84, 012004 (2011)]
- Belle observation in 6 prong final state [Nakazawa @ ICHEP2010]

$\psi(2S) \rightarrow \gamma\eta_c(2S)$

Recent observation by BESIII with BF two times smaller with respect to previous CLEO UL [arXiv: 1108.5789]

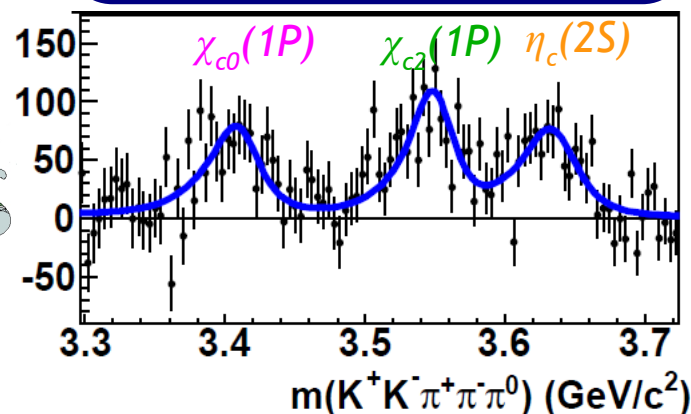# Recent Two-Photon Physics Results at *BABAR*

$\gamma\gamma \to K^0_S K\pi$, $K^+K^-\pi^+\pi^-\pi^0$ no tag

- Observation of $K^+K^-\pi^+\pi^-\pi^0$ decay of $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ and $\eta_c(2S)$
- Measurement of $\eta_c(1S)$ and $\eta_c(2S)$ mass and width in both decays
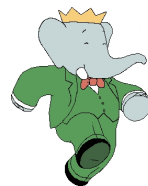- Search for $\chi_{c2}(2P)$ [also dubbed Z(3930)]
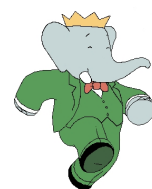
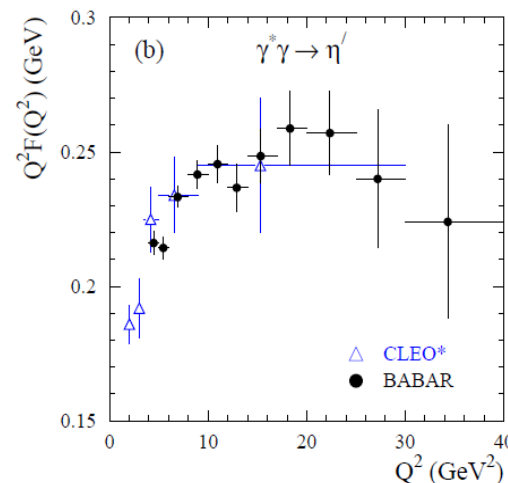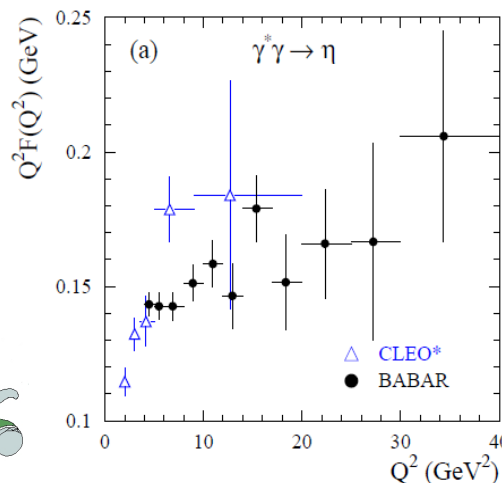$\gamma^*\gamma \to \eta$, η' single tag

- Precise measurement of $\eta^{(')}$ FF
- Extension of Q^2 range previously measured by CLEO
- Not covered in this talk

Event Selection

Reconstruct $K^0_S K\pi$ and $K^+K^-\pi^+\pi^-\pi^0$ with $K^0_S \to \pi^+\pi^-$

Require no additional tracks and limited number of neutral particles

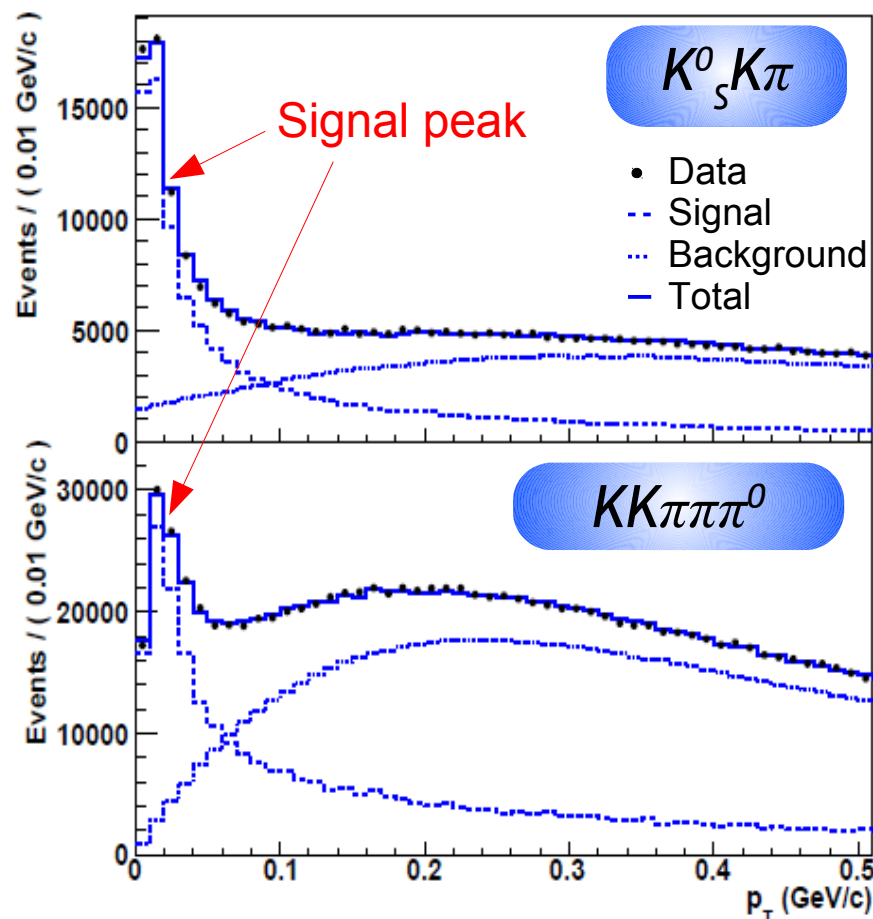- There are two characteristic signatures for two-photon production:
  - Small value of the transverse momentum p_T with respect to the beam axis. Require $p_T < 0.15$ GeV/c
  - High value of the missing mass.

$$M^2_{miss} = (p_{e+e-} - p_{rec})^2$$

Require $M^2_{miss} > 2$ (GeV/c^2)^2

PRD 84, 012004 (2011)

M^2_{miss} (GeV/c^2)^2

MC simulation

MC $\gamma\gamma \to KK\pi\pi\pi^0$ Signal
MC ISR $KK\pi\pi\pi^0$ background

M^2_{miss} (GeV/c^2)^2

$K^0_S K\pi$

Signal peak

- Data
- - Signal
- Background
- Total

$KK\pi\pi\pi^0$

Fit Strategy
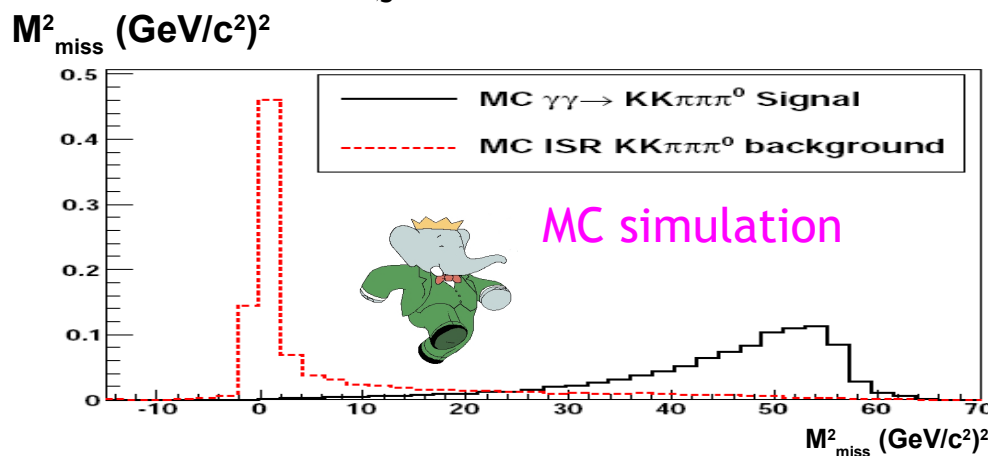
Binned extended ML fit to the $K^0_S K\pi$ $KK\pi\pi^0$ invariant mass distribution to extract the yields and resonances parameters.

- Non-relativistic BW convolved with mass resolution function obtained from fit to signal MC samples

PDFs

- Free parameters: signal and background yields, $\eta_c(1S)$, $\eta_c(2S)$ mass and width, background shape parameters
- $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ parameters are fixed to PDG values
- $\eta_c(2S)$ width in $KK\pi\pi^0$ mode is fixed to the value found in $K^0_S K\pi$
- $\chi_{c2}(2P)$ parameters fixed to values found in $BABAR$ $\gamma\gamma \to D\overline{D}$ analysis
  [PRD 81, 092003 (2010)]

Parameters

$\chi_{c0}(1P) \to K^0_S K\pi$ is forbidden

PRD 84, 012004 (2011)
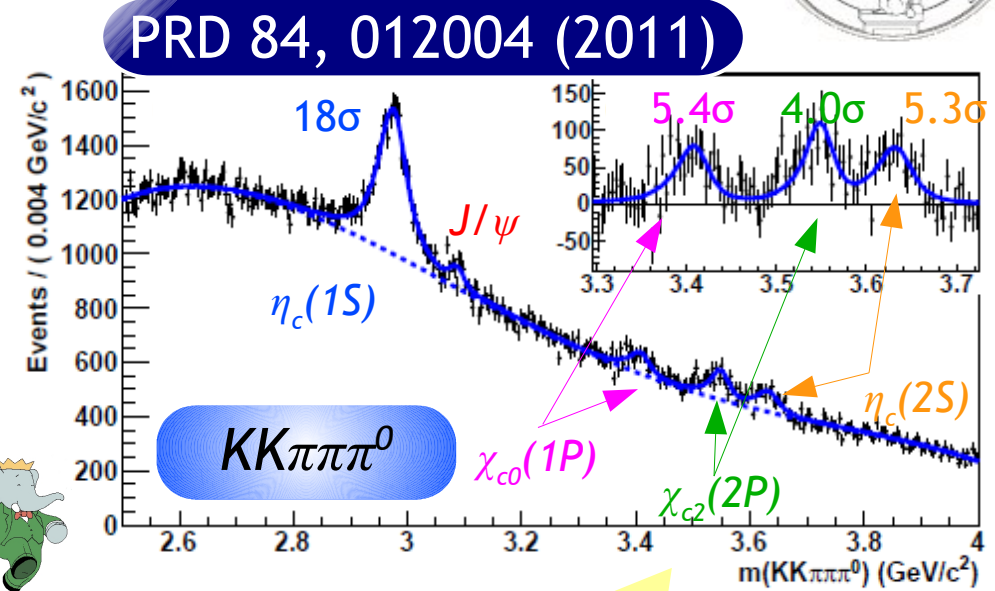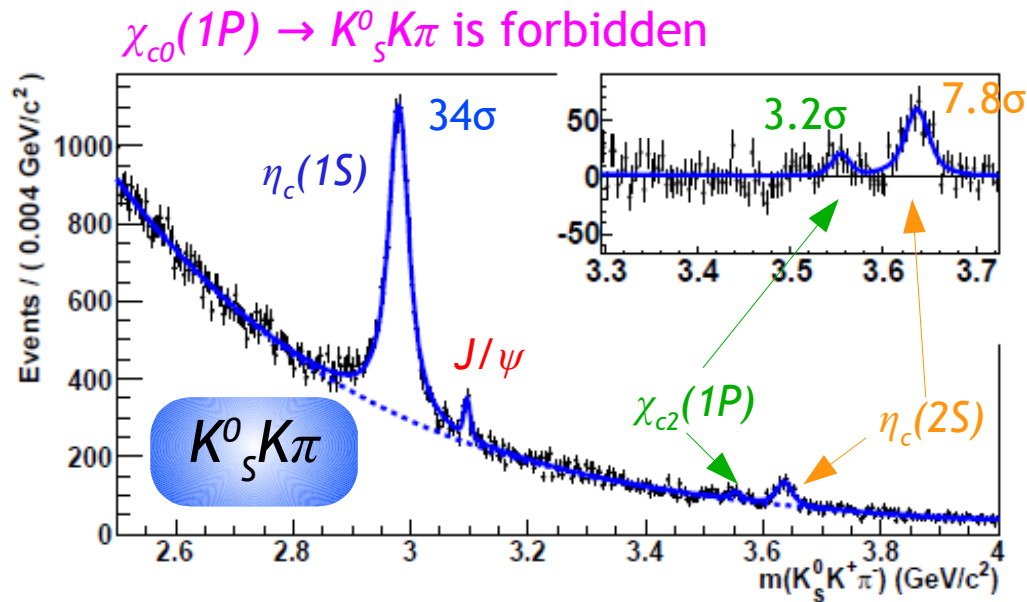
$$m(\eta_c(2S)) = 3638.5 \pm 1.5 \pm 0.8 \text{ MeV}/c^2$$
$$\Gamma(\eta_c(2S)) = 13.4 \pm 4.6 \pm 3.2 \text{ MeV}$$

Most precise single measurement of η_c(2S) parameters

- **Correct mass** measurement for the mass shift observed for J/ψ in ISR enriched sample
- **First observation** of η_c(1S), χ_{c0}(1P), η_c(2S) and evidence for χ_{c2}(1P) in $KK\pi\pi^0$
- No evidence for χ_{c2}(2P) in both decay modes

Peaking Background Estimation

Several processes can produce real $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ and $\eta_c(2S)$, thus originating irreducible peaking background

Radiative J/ψ and $\psi(2S)$ decays

- Estimated using the number of J/ψ and $\psi(2S)$ fitted in data, known BFs, and MC detection efficiencies
- Correct the $\eta_c(1S)$ yield and take a systematic for other resonances

Two-photon processes with extra particle (such as $\gamma\gamma \to \eta_c(1S)\pi^0$)

- Signal is expected to show a peak at $p_T \sim 0$ GeV/c, background is almost flat in p_T
- Fit the spectrum in slide 12 in intervals of p_T: obtain yield distribution as a function of p_T
- Fit such distribution with MC signal + flat background p_T shape and give a systematic
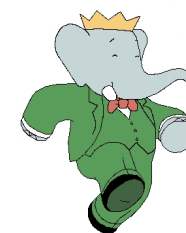
# Branching Fraction Measurement

Two-photon coupling ($\Gamma_{\gamma\gamma}$) times the final state BF is proportional to the ratio between the signal yield N and the reconstruction efficiency ε.

- N/ε extracted by using an unbinned maximum likelihood fit where each event is given a weight proportional to ε^{-1}. So, reduced dependence on MC sub-resonant decay model.

- Take into account ε dependence on the decay kinematics.

"Squared" Dalitz plot for $K^0_S K\pi$ ($K\pi$ mass and K^+ helicity angle)

8D parameterization for $KK\pi\pi^0$: 3 masses and 5 angles
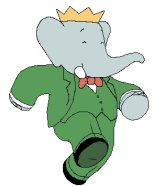
θ_K is the helicity angle of K^+
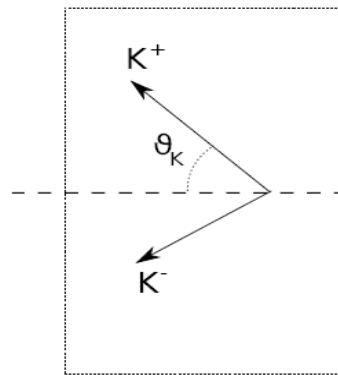
$\theta_{\pi0}$ describes the orientation of 3π system in its decay plane

and Φ describe the entation of 3π decay ne in the space
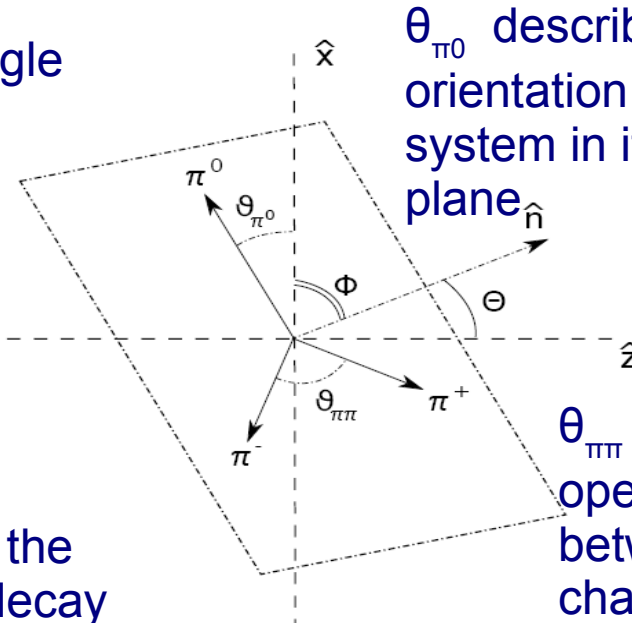
$\theta_{\pi\pi}$ is the opening angle between charged π's in 3π rest frame

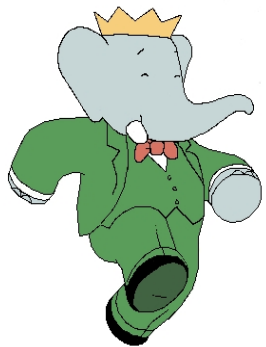# Branching Fraction Results

- The fit is performed separately in $\eta_c(1S)$ and $\eta_c(2S)$ mass regions to take into account kinematics dependence on invariant mass.

- Resonances parameters are fixed to values reported at slide 12.

Process	$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (keV)
$\eta_c(1S) \to K\overline{K}\pi$	$0.386 \pm 0.008 \pm 0.021$
$\chi_{c2}(1P) \to K\overline{K}\pi$	$(1.8 \pm 0.5 \pm 0.2) \times 10^{-3}$
$\eta_c(2S) \to K\overline{K}\pi$	$0.041 \pm 0.004 \pm 0.006$
$\chi_{c2}(2P) \to K\overline{K}\pi$	$< 2.1 \times 10^{-3}$
$\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.190 \pm 0.006 \pm 0.028$
$\chi_{c0}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$0.026 \pm 0.004 \pm 0.004$
$\chi_{c2}(1P) \to K^+K^-\pi^+\pi^-\pi^0$	$(6.5 \pm 0.9 \pm 1.4) \times 10^{-3}$
$\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0$	$0.030 \pm 0.006 \pm 0.005$
$\chi_{c2}(2P) \to K^+K^-\pi^+\pi^-\pi^0$	$< 3.4 \times 10^{-3}$

$$\frac{\mathcal{B}(\eta_c(1S) \to K^+K^-\pi^+\pi^-\pi^0)}{\mathcal{B}(\eta_c(1S) \to K_S^0 K^\pm \pi^\mp)} = 1.42 \pm 0.06 \pm 0.27$$

$$\frac{\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^+\pi^-\pi^0)}{\mathcal{B}(\eta_c(2S) \to K_S^0 K^\pm \pi^\mp)} = 2.2 \pm 0.4 \pm 0.5$$

Systematics

- Shape of the combinatorial background
- Peaking background contribution

Yields

Effect of the interference with non-resonant background taken as systematic for $\eta_c(1S)$, not accounted for $\eta_c(2S)$ do to small signal size and poor signal to noise ratio

Mass

- Shape of the combinatorial background
- Differences in data/MC resolution
- Distortion arising from efficiency dependence on invariant mass and decay dynamics

Width
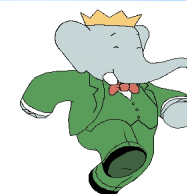
Efficiency parameterization: estimated with toy experiments taking into account MC statistical uncertainty

BF

Conclusions

We provide a measurement of the $\eta_c(2S)$ parameters in the $K^0_S K\pi$ channel with an uncertainty lower than the PDG average:

	BABAR $\gamma\gamma$ fusion PRD **78**, 012004	Belle B decays arXiv:1105.0978	BESIII $\psi(2S)$ Radiative arXiv:1108.5789	PDG2010
η_c Mass (MeV/c^2)	$2982.5 \pm 0.4 \pm 1.4$	$2985.4 \pm 1.5^{+0.2}_{-2.0}$	$2984.4 \pm 0.5 \pm 0.6$	2980.3 ± 1.2
η_c Width (MeV)	$32.1 \pm 1.1 \pm 1.3$	$35.1 \pm 3.1^{+1.0}_{-1.6}$	$30.5 \pm 1.0 \pm 0.9$	28.6 ± 2.2
$\eta_c(2S)$ Mass (MeV/c^2)	$3638.5 \pm 1.5 \pm 0.8$	$3636.1^{+3.9+0.5}_{-1.5-2.0}$	$3638.5 \pm 2.3 \pm 1.0$	3637 ± 4
$\eta_c(2S)$ Width (MeV)	$13.4 \pm 4.6 \pm 3.2$	$6.6.^{+8.4+2.6}_{-5.1-0.9}$	12 (fixed)	14 ± 7

We first observe $\eta_c(1S)$, $\chi_{c0}(1P)$ $\eta_c(2S)$ in $KK\pi\pi\pi^0$ decay.

This is the first observation (with Belle's preliminary in 6 prongs) of an $\eta_c(2S)$ exclusive decay other than $K\bar{K}\pi$.

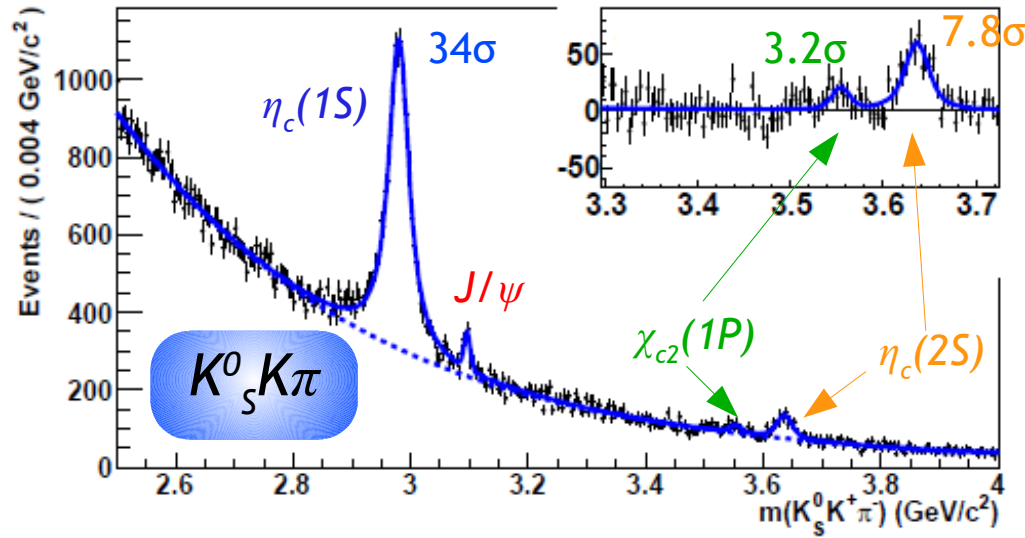The $\chi_{c2}(2P)$ resonance is searched for in both final states, but no significant signal is found.
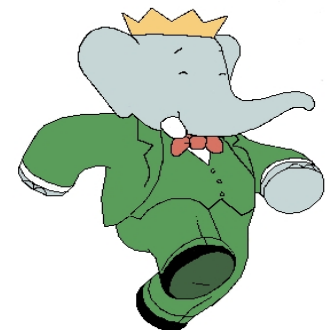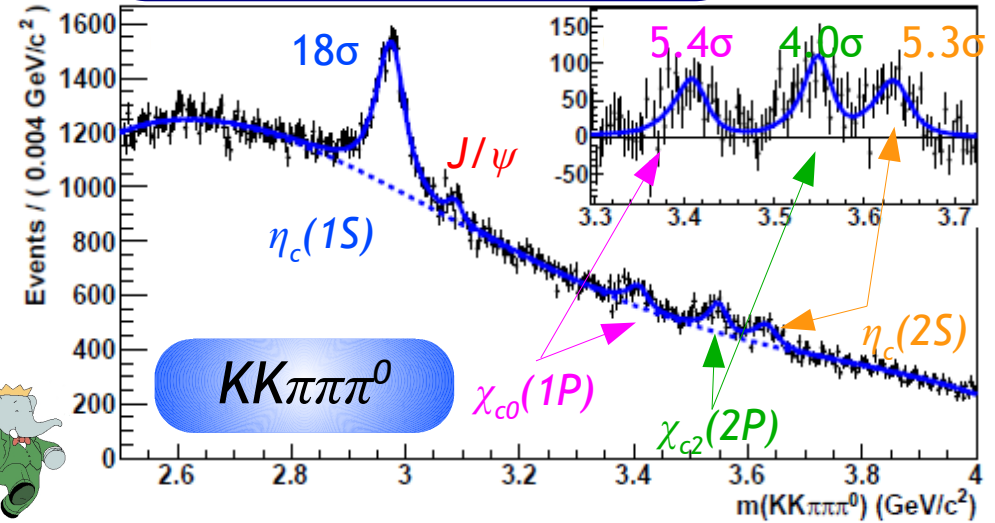
Backup slides

Results

$\chi_{c0}(1P) \to K^0_S K\pi$ is forbidden

PRD 84, 012004 (2011)

Decay Mode	Efficiency (%)	Corrected Yield (Evts.)	N_{peak} (Evts.)	N_ψ (Evts.)	Significance (σ)	Corrected Mass (MeV/c^2)	Fitted Width (MeV)
$\eta_c(1S) \to K^0_S K^\pm \pi^\mp$	10.7	$12096 \pm 235 \pm 274$	189 ± 18	214 ± 82	33.5	$2982.5 \pm 0.4 \pm 1.4$	$32.1 \pm 1.1 \pm 1.3$
$\chi_{c2}(1P) \to K^0_S K^\pm \pi^\mp$	13.1	$126 \pm 37 \pm 14$	-45 ± 11	–	3.2	3556.2 (fixed)	2 (fixed)
$\eta_c(2S) \to K^0_S K^\pm \pi^\mp$	13.3	$624 \pm 72 \pm 34$	25 ± 5	–	7.8	$3638.5 \pm 1.5 \pm 0.8$	$13.4 \pm 4.6 \pm 3.2$
$\eta_c(1S) \to K^+ K^- \pi^+ \pi^- \pi^0$	4.2	$11132 \pm 430 \pm 442$	118 ± 32	26 ± 9	18.1	$2984.5 \pm 0.8 \pm 3.1$	$36.2 \pm 2.8 \pm 3.0$
$\chi_{c0}(1P) \to K^+ K^- \pi^+ \pi^- \pi^0$	5.6	$1094 \pm 143 \pm 143$	-39 ± 19	75 ± 21	5.4	3415.8 (fixed)	10.2 (fixed)
$\chi_{c2}(1P) \to K^+ K^- \pi^+ \pi^- \pi^0$	5.8	$1250 \pm 118 \pm 290$	14 ± 24	233 ± 73	4.0	3556.2 (fixed)	2 (fixed)
$\eta_c(2S) \to K^+ K^- \pi^+ \pi^- \pi^0$	5.9	$1201 \pm 133 \pm 185$	-46 ± 17	–	5.3	$3640.5 \pm 3.2 \pm 2.5$	13.4 (fixed)

$\eta^{(')}$ Form Factor Measurement
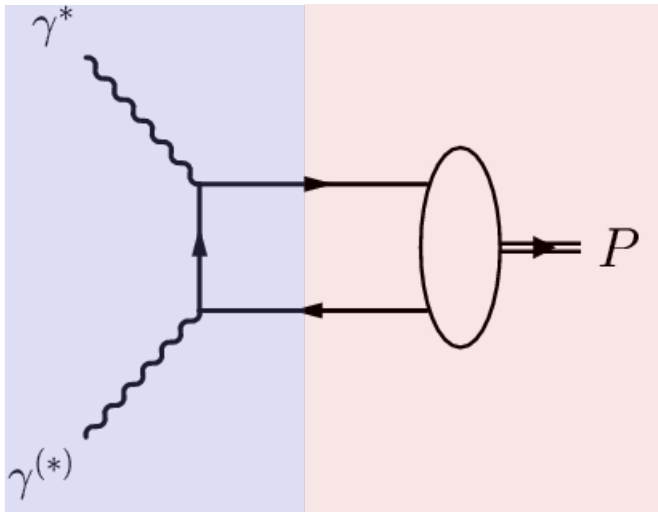
$$F(Q^2) = \int T(x, Q^2)\, \varphi(x, Q^2)\, dx$$

Hard scattering amplitude for $\gamma^*\gamma \to q\bar{q}$ transition which is calculable in pQCD

Nonperturbative meson distribution amplitude (DA) describing transition $P \to q\bar{q}$

x is the fraction of the meson momentum carried by one of the quarks

- ✓ The meson DA $\varphi(x,Q^2)$ plays an important role in theoretical descriptions of many QCD processes ($\gamma^* \to \pi^+\pi^-$, $\gamma\gamma \to \pi\pi$, $\chi_{c,0,1} \to \pi^+\pi^-$, $B \to \pi l\nu$, $B \to \pi\pi$…).
- ✓ Its shape (x dependence) is unknown, but its evolution with Q^2 is predicted by pQCD.
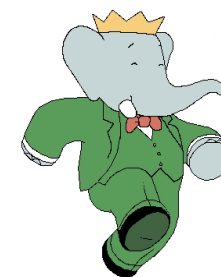- ✓ The models for DA shape can be tested using data on the form factor Q^2 dependence.
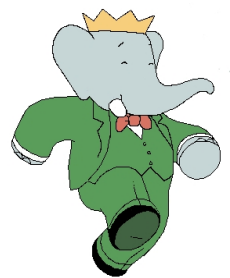
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$\eta^{(')}$ Form Factor Measurement

PRD 84,052001 (2011)
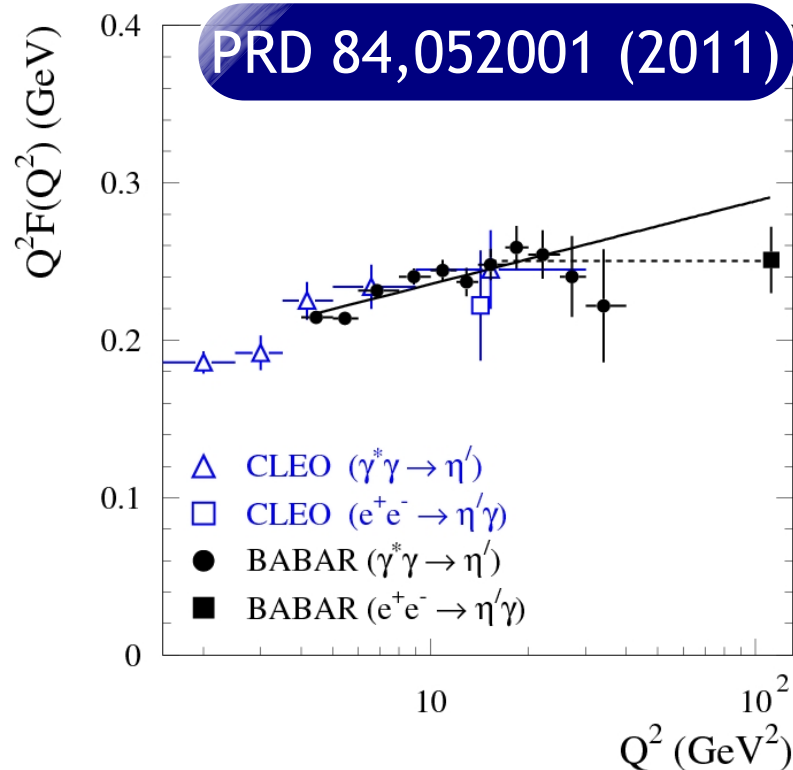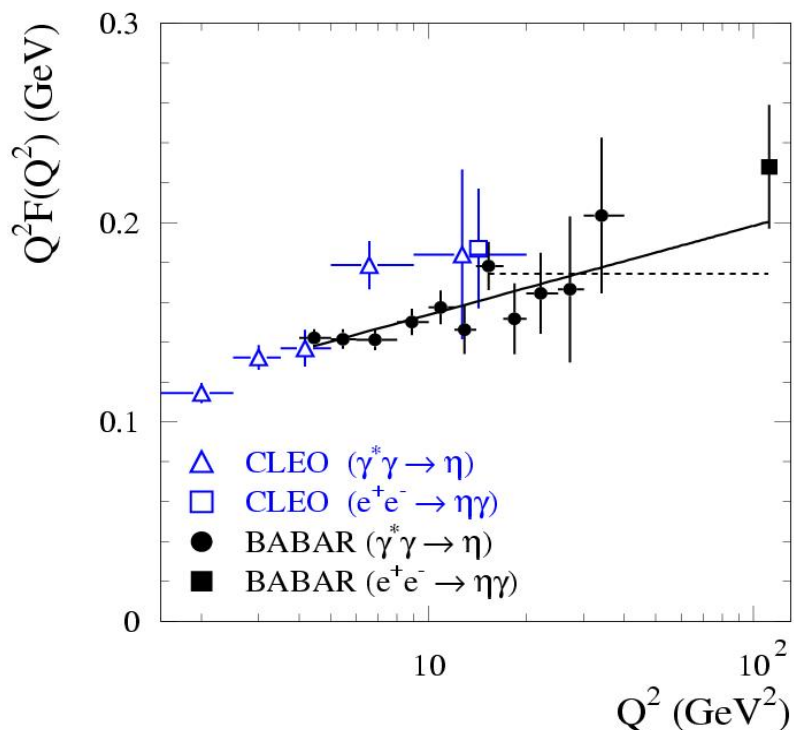
- The BABAR data are fit with $Q^2F(Q^2)=b+a \ln Q^2$ (GeV^2) with $\chi^2/n=6.7/10$ for η and $14.6/10$ for η'
- The fitted rise (a≈0.2 GeV^2) is about 3 times weaker than that for π^0.
- The fit by a constant for $Q^2>15$ GeV^2 also gives reasonable quality: $\chi^2/n=5.6/5$ for η and $2.6/5$ for η'.

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