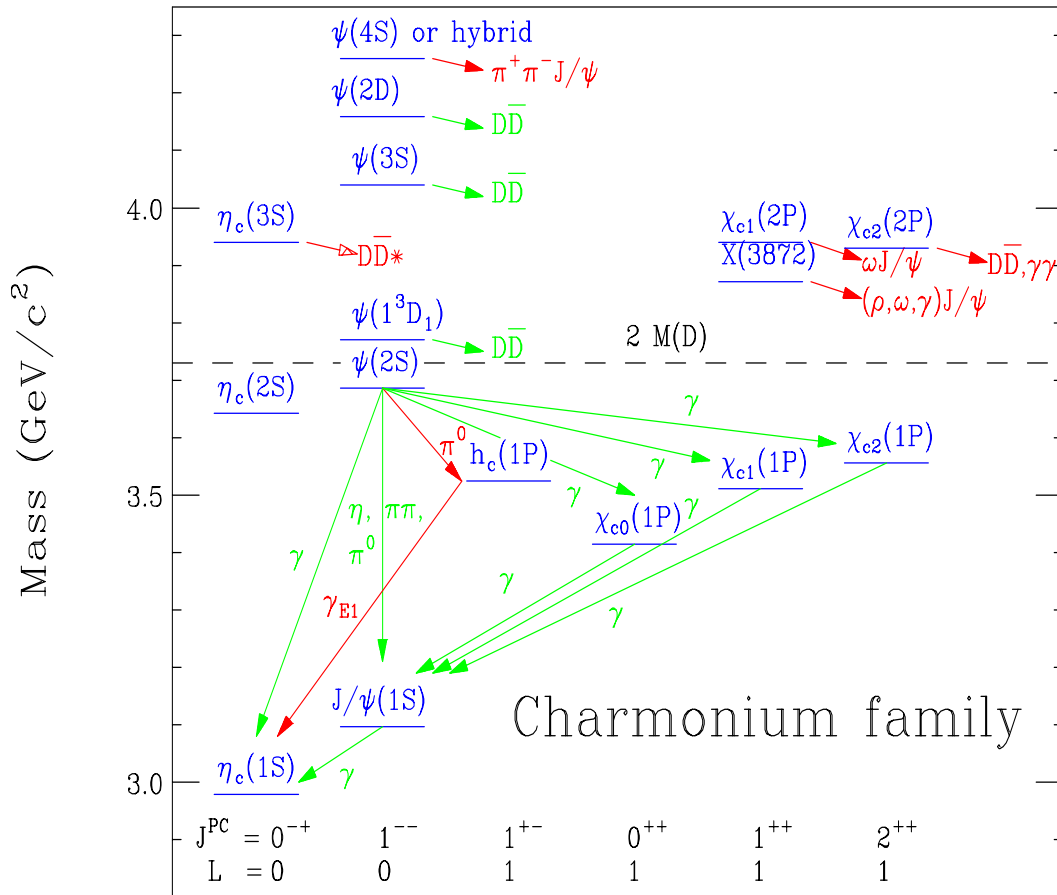


Measurement of $\text{Br}(J/\psi \rightarrow \eta_c \gamma)$ at KEDR

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J/ψ → η_cγ decay



□ M1 radiative transition

□ photon energy
 $\omega_0 = 114.2 \text{ MeV}$

□ angular distribution
 $d\Gamma/d\Omega \sim 1 + \cos^2\theta$

□ η_c- meson width (PDG)
 $\Gamma(\eta_c) = 28.6 \pm 2.2 \text{ MeV}$

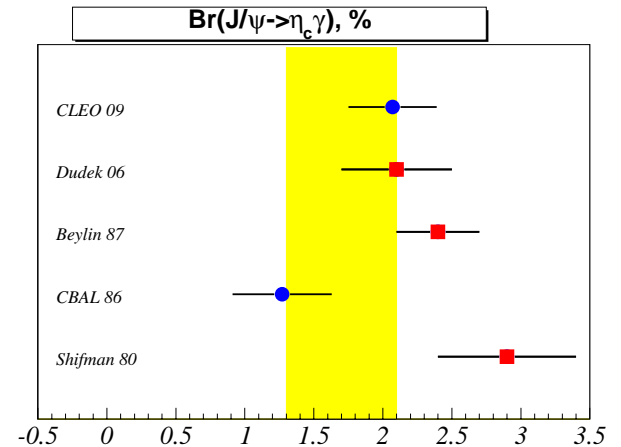
□ branching ratio (PDG)
 $B(J/\psi \rightarrow \eta_c \gamma) = (1.7 \pm 0.4)\%$

Branching ratio $B(J/\psi \rightarrow \eta_c \gamma)$

Transition between 1S states of charmonium \rightarrow rate can be easily calculated in potential models. Spatial part of wave function does not change and matrix element in leading approximation equals to one.

Theoretical predictions:

- **3.05% Potential model without relativistic corrections:** *E.E. Eichten et al., Rev. Mod. Phys., 2008, 80: 1161-1193*
- M.Shifman (*Z. Physik C, 4, 345 (1980)*): “QCD will not survive if $m(\eta_c)=2.977$ GeV and, simultaneously, the $J/\psi \rightarrow \eta_c \gamma$ decay rate is lower than 2 keV.”
- **(2.4±0.3)% QCD sum rules :** *V.A. Beilin, A.V. Radyushkin, Sov. J. Nucl. Phys., 1987, 45: 342*
- **(2.1±0.4)% Lattice QCD:** *J.J. Dudek et al., Phys. Rev. D, 2006, 73: 074507*



- experimental works
- theoretical predictions
- PDG average

Experimental results (PDG 2010):

$\Gamma(\gamma \eta_c(1S)) / \Gamma_{\text{total}}$					References	History since 1990
VALUE (10^{-2})	EVTS	DOCUMENT ID	TECN	COMMENT		Γ_{128} / Γ
1.7 ± 0.4	OUR AVERAGE			Error includes scale factor of 1.6.		
2.07 ± 0.32 ± 0.03		¹ MITCHELL	09 CLEO	$e^+ e^- \rightarrow \gamma X$		
1.27 ± 0.36		GAISER	86 CBAL	$J/\psi \rightarrow \gamma X$		

Crystal Ball measurement

- ❑ 2.2M J/ψ decays
- ❑ Inclusive photon spectrum
- ❑ E_γ^3 factor in the convolution of the detector response function with the η_c Breit-Wigner resonance shape

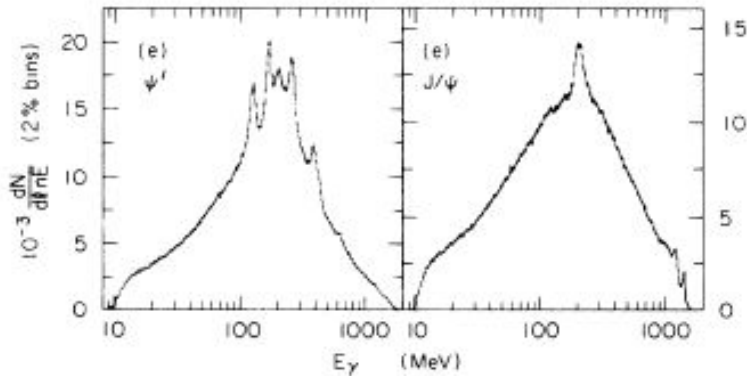


FIG. 7. Inclusive photon spectra from ψ' and J/ψ decays in 2% energy bins, obtained with the modified cut (e) on the lateral energy distribution as described in the text. This cut has less rejection power against charged particles than cut (d) as can be seen by the structure at ≈ 210 MeV, due to minimum ionizing particles.

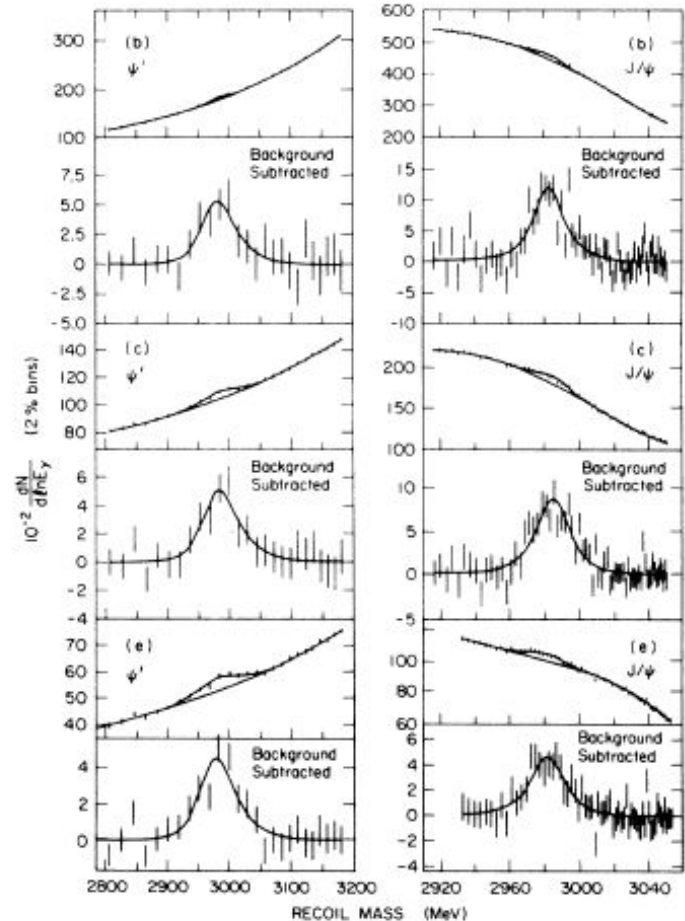
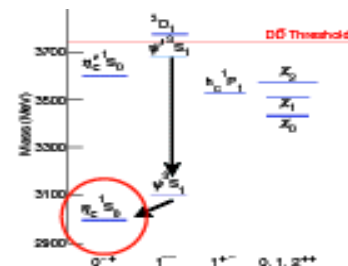


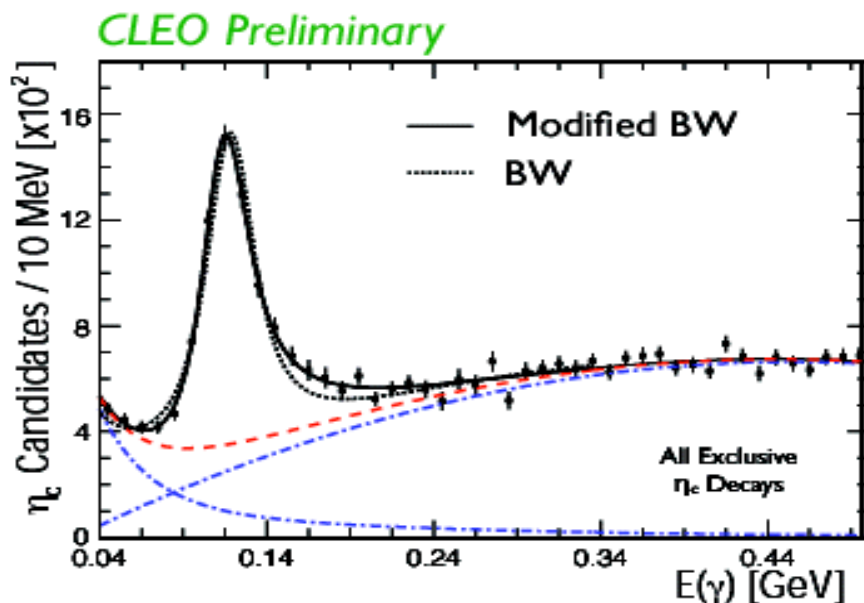
FIG. 8. Simultaneous fits to the η_c mass in the ψ' and J/ψ inclusive photon spectra. The data are plotted in 2% bins in the photon energy. The preferred resolution value of $\sigma_0=2.7\%$ is used in the fit. The spectra labeled (b) and (c) correspond to the photon selection criteria of the χ analysis. The spectra labeled (e) employ a modified cut on the lateral photon energy pattern as described in the text.

CLEO measurement

$$J/\psi \rightarrow \gamma \eta_c$$



- $J/\psi \rightarrow \gamma \eta_c$ photon line shape spectrum also shows distortion
- Constrain background shapes using MC
 - falling hadronic shower background (floating scale factor)
 - free rising polynomial background
- Breit-Wigner alone provides poor fit to data
- Nominal fit is a Breit-Wigner modified by E_γ^3 and damped by $\exp(-E_\gamma^2/\beta)$



~5.5 MeV shift in η_c mass between BW and Modified BW fits

Photon spectrum in $J/\psi \rightarrow \eta_c \gamma$ decay

- Photon spectrum can be written in the form :

$$\frac{dN_\gamma}{d\omega} = N_\psi B \int d\omega' g(\omega, \omega') \frac{d\Gamma(\omega')}{d\omega'} \frac{\varepsilon(\omega')}{\Gamma_{\eta_c \gamma}},$$

where

B – decay branching fraction,

$g(\omega, \omega')$ – calorimeter response function,

$\varepsilon(\omega)$ – photon detection efficiency,

$\Gamma_{\eta_c \gamma}$ – decay width,

$$\frac{d\Gamma(\omega)}{d\omega} = \frac{4}{3} \alpha \frac{e_c^2}{m_c^2} \omega^3 |M|^2 BW(\omega),$$

$M = \langle \eta_c | j_0(\omega r/2) | J/\psi \rangle \rightarrow 1$ when $\omega \rightarrow 0$.

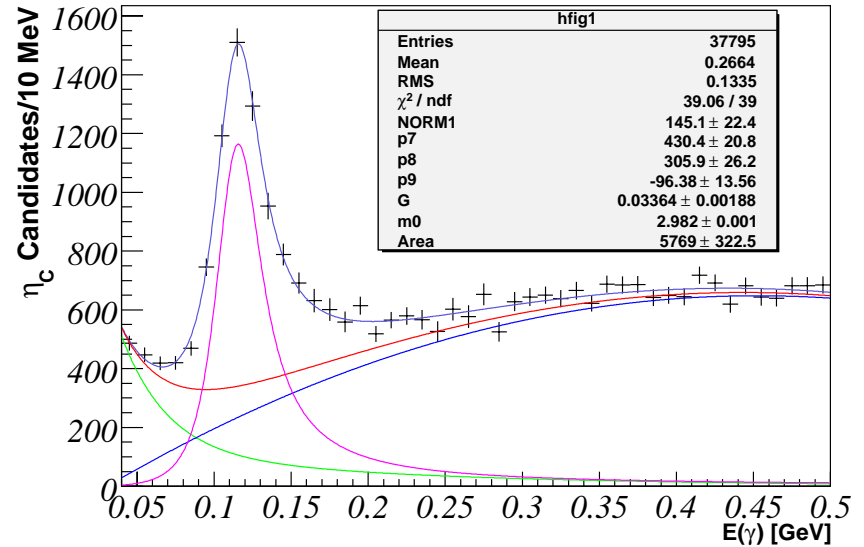
- CLEO used $|M|^2 = \exp(-\omega^2/8\beta^2)$ with $\beta = 65$ MeV, but this is valid only for harmonic oscillator wave functions. For all other potentials dependence will be $\sim \omega^{-n}$ when $\omega \rightarrow \infty$.

Our fit of CLEO data

- We tried to fit the CLEO data using another line shape :
 at small photon energy $\omega \sim \omega_0$ decay probability $d\Gamma/d\omega \sim \omega^3$;
 at $\omega \gg \omega_0$ factor $\omega^3 \rightarrow \omega$

- $d\Gamma/d\omega$ dependence can be written for example in such a form :
 $d\Gamma/d\omega \sim \omega^3 \omega_0^2 / (\omega \omega_0 + (\omega - \omega_0)^2)$.
 This function $\approx \omega^3$ at $\omega \sim \omega_0$, and
 $\sim \omega$ at $\omega \gg \omega_0$.

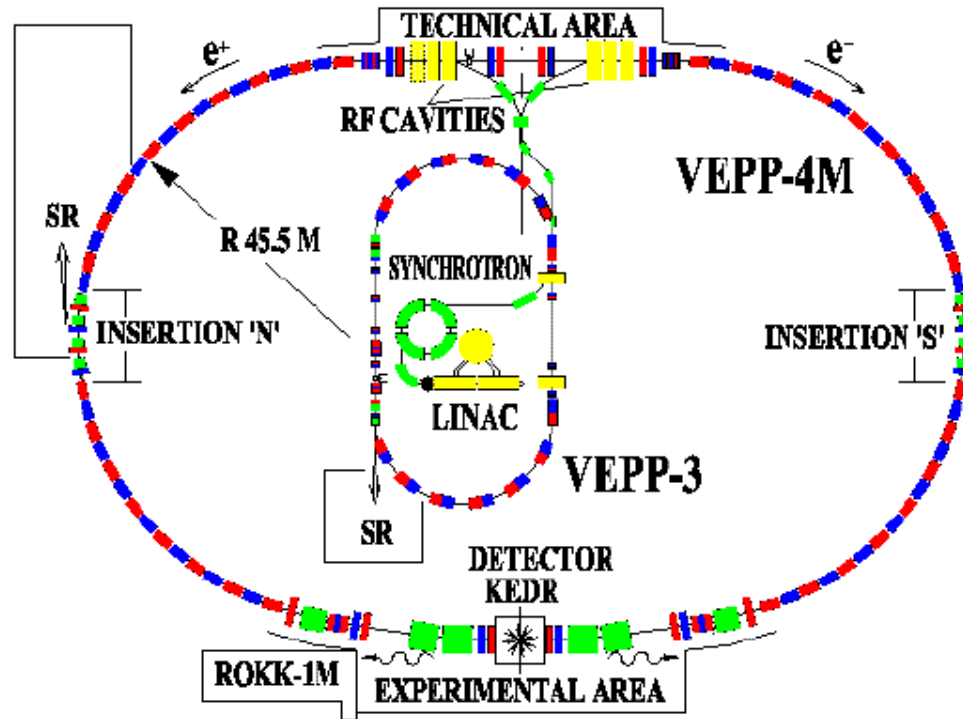
- We found that this line shape is also suitable.



Fit of CLEO data with $\omega_0^2/(\omega \omega_0 + (\omega - \omega_0)^2)$ function

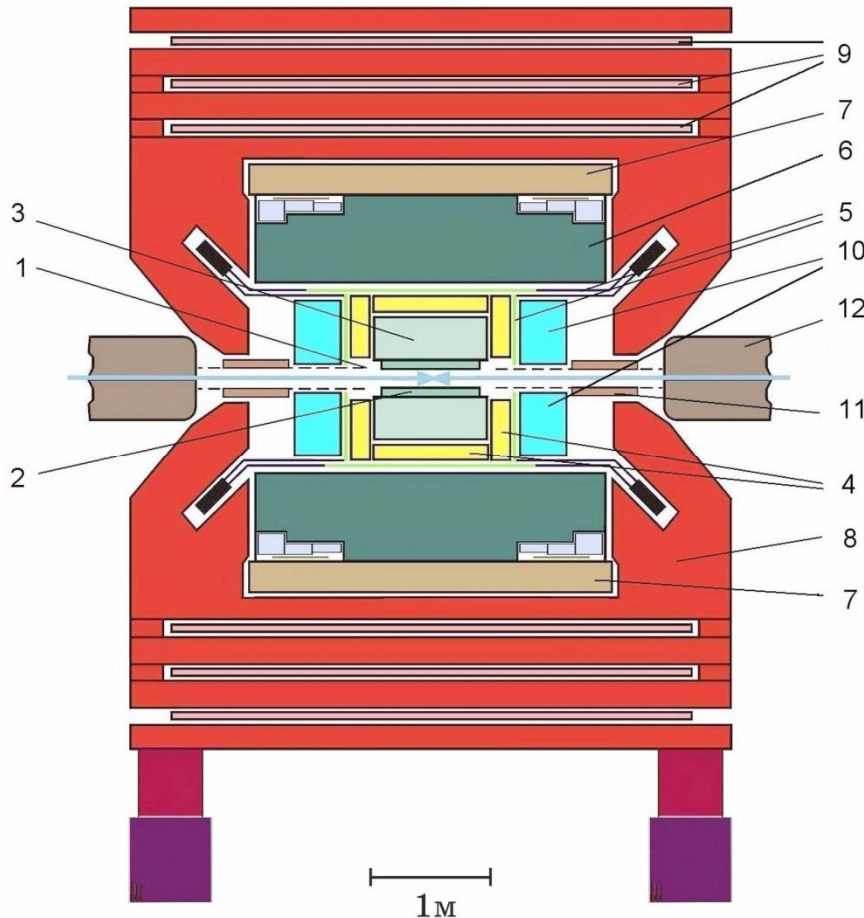
Function	$M(\eta_c)$, MeV	$\Gamma(\eta_c)$, MeV	N_{IS}^{EXC}	χ^2/NDF (C.L.)
$\omega^3 \exp(-\omega^2/8\beta^2)$, $\beta=65\text{MeV}$	2982.4 ± 0.7	32.5 ± 1.8	6142 ± 430	$38.0/38$ (0.47)
$\omega^3 \omega_0^2 / (\omega_0 \omega + (\omega - \omega_0)^2)$	2981.8 ± 0.5	33.6 ± 1.9	6494 ± 362	$39.1/39$ (0.47)

VEPP-4M collider



- ❑ Wide energy range $E_{\text{beam}} = 1 \div 6 \text{ GeV}$
- ❑ Peak luminosity $1.5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ at J/ψ
- ❑ Precise beam energy determination :
 - Resonant Depolarization Method, $\sigma_E \approx 1.5 \text{ keV}$
 - Interpolation for DAQ runs $\sigma_E \approx 8 \div 30 \text{ keV}$
 - IR-light Compton BackScattering, $\sigma_E < 100 \text{ keV}$

KEDR detector



1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Threshold aerogel counters
5. ToF-counters
6. Liquid krypton calorimeter
7. Superconducting coil (0.65 T)
8. Magnet yoke
9. Muon tubes
10. CsI-calorimeter
11. Compensation solenoid
12. VEPP-4M quadrupole

☐ Luminosity is measured by single Bremsstrahlung in e^+ and e^- directions and by Bhabha scattering

☐ Scattering electron tagging system for two-photon studies

KEDR data

- ❑ Data were taken during 2007-2009 years :
 - Integrated luminosity at J/ψ peak $L = 1.52 \pm 0.08 \text{ pb}^{-1}$ is collected.
 - 3 J/ψ scans were performed; measured beam energy spread was used for calculation of the number of J/ψ produced : $N_{\psi} = 6.3 \pm 0.3 \text{ M}$

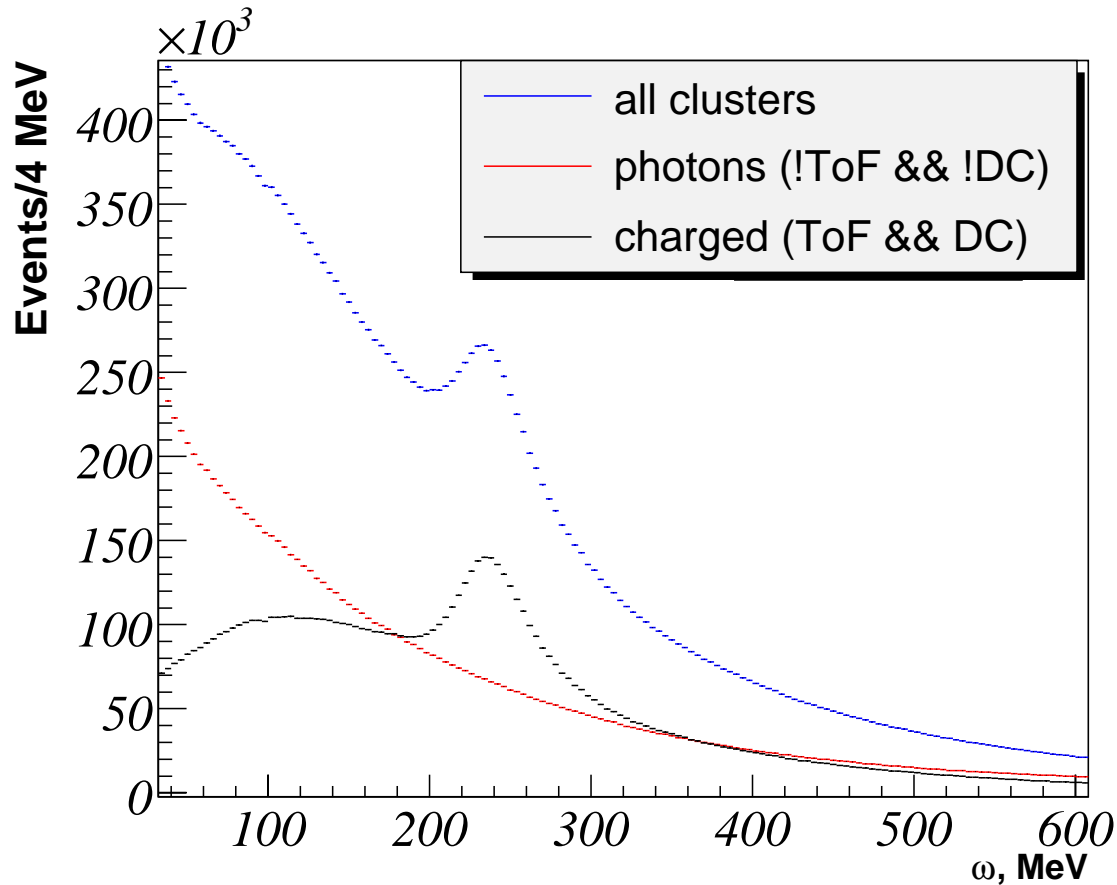
- ❑ At the first step multihadron decays of J/ψ were selected. These cuts effectively suppress background from cosmic rays, beam-gas interactions and QED events :
 - Total energy in clusters $E_{\Sigma} > 0.8 \text{ GeV}$
 - Number of clusters with $E_{cl} > 30 \text{ MeV}$ $N_{cl} > 3$
 - Number of central DC tracks $N_{trackIP} > 0$
 - No muon tubes activated in 3-rd layer $N_{MU3} = 0$

- ❑ At the second step photons in these events were identified. Photon is a cluster in liquid krypton calorimeter without tracks in DC attached to it and without TOF scintillator counters activated before cluster :
 - Angle between cluster and beam direction $\Theta > 45^{\circ}$
 - No tracks in drift chamber (DC) attached to cluster
 - No time of flight (ToF) scintillator counters activated before cluster

- ❑ Selection efficiency (MC) :
 - J/ψ decays $\epsilon, \%$
82
 - $J/\psi \rightarrow \eta_c \gamma$ decays 89
 - Photon in $J/\psi \rightarrow \eta_c \gamma$ decay 28

- ❑ Number of signal photons detected 46k

Inclusive spectra



Inclusive spectra: blue - spectrum of all clusters; red - photon spectrum; black - spectrum of charged particles, when ToF scintillator counter is activated before cluster and DC track is attached to cluster. The last was used for elimination of charged particles which were detected as neutral from the photon spectrum.

KEDR data fit

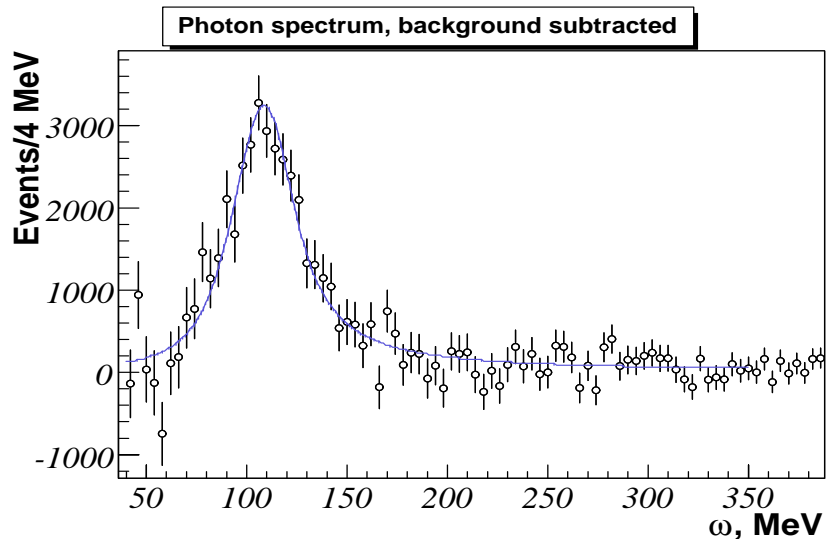
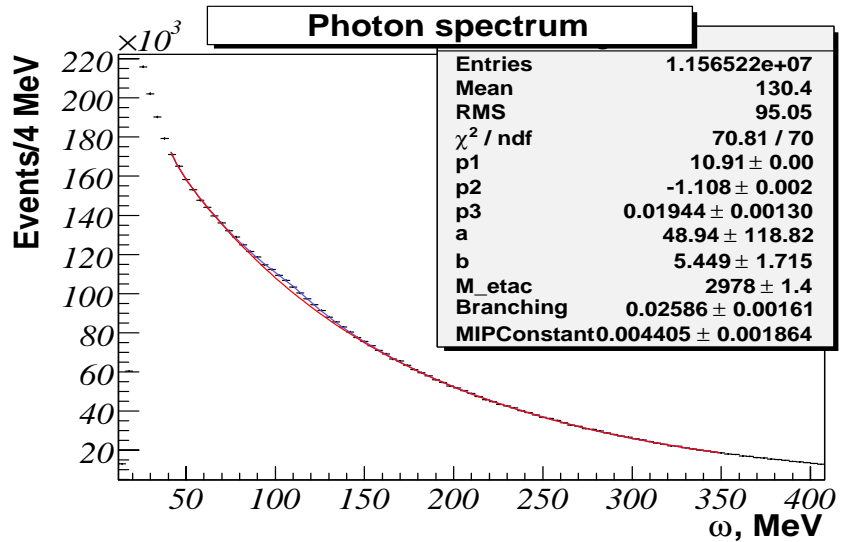
☐ Inclusive photon spectrum was fit by the sum of the signal having a shape

$$\frac{d\Gamma}{d\omega} \sim \frac{\omega^3 \omega_0^2}{\omega \omega_0 + (\omega - \omega_0)^2} BW(\omega),$$

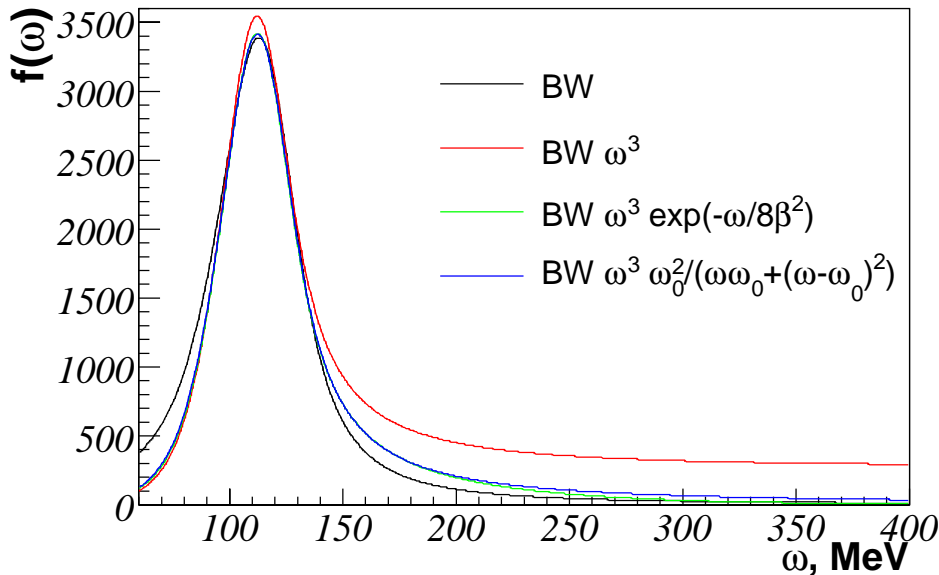
convolved with calorimeter response function (Novosibirsk PDF - asymmetric Gaussian with $\sigma_E=7.4$ MeV at 110 MeV and $a=-0.33$) and background

☐ Background has a form

$\ln(dN/d\omega) \sim a \cdot \exp(-\omega/b) + p_2(\omega) + c \cdot MIP(\omega)$,
 where the first term describes nuclear interactions in the calorimeter, $p_2(\omega)$ is the second order polynomial, $MIP(\omega)$ is the spectrum of charged particles



Fits of KEDR data with various signal shapes



Resulting signal line shapes for various $d\Gamma/d\omega$ functions

- ❑ BW alone gives shifted value of η_c mass $M(\eta_c) = 2974.3 \pm 1.4$ MeV
- ❑ $BW \cdot \omega^3$ leads to a great tail at higher photon energies :
 $B(J/\psi \rightarrow \eta_c \gamma) = (7.3 \pm 0.5)\%$
- ❑ Last two functions give close results of fits, and difference can be used for estimation of systematic error appearing due to unknown line shape.

Line shape	$M(\eta_c)$, MeV*	$\Gamma(\eta_c)$, MeV	$B(J/\psi \rightarrow \gamma \eta_c)$, %*	χ^2/NDF (C.L.)*
BW	2974.3 ± 1.4	51.6 ± 12.3	2.39 ± 0.15	70.0/70 (0.48)
$BW \cdot \omega^3$	2980.2 ± 1.4	37.9 ± 6.0	7.3 ± 0.5	72.2/70 (0.40)
$BW \cdot \omega^3 \cdot \exp(-\omega^2/8\beta^2)$	2978.8 ± 1.4	41.2 ± 5.9	2.44 ± 0.16	71.0/70 (0.44)
$BW \cdot \omega^3 \cdot \omega_0^2 / (\omega_0 \omega + (\omega - \omega_0)^2)$	2978.1 ± 1.4	43.5 ± 5.4	2.59 ± 0.16	70.8/70 (0.45)

* results with fixed $\Gamma(\eta_c) = 28.6$ MeV

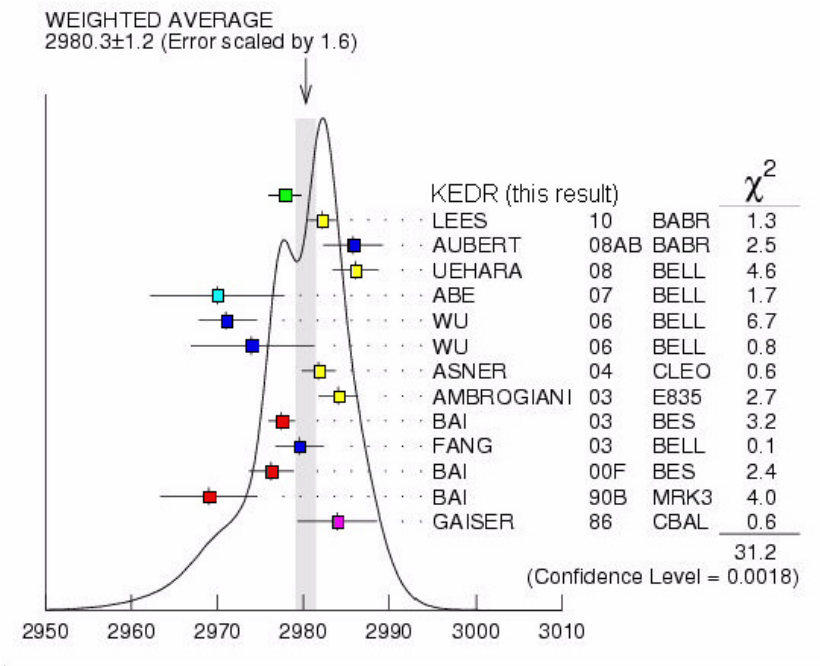
Systematic errors

Systematic error	$M(\eta_C)$, MeV	$\Gamma(\eta_C)$, MeV	$B(J/\psi \rightarrow \eta_C \gamma)$, %
Line shape	0.7	2.3	0.15
η_C width	0.4		0.15
Background subtraction	0.8	15.6	0.17
Number of J/ψ produced			0.13
Photon efficiency			0.08
Photon energy scale	0.8		
Total	1.4	15.8	0.31

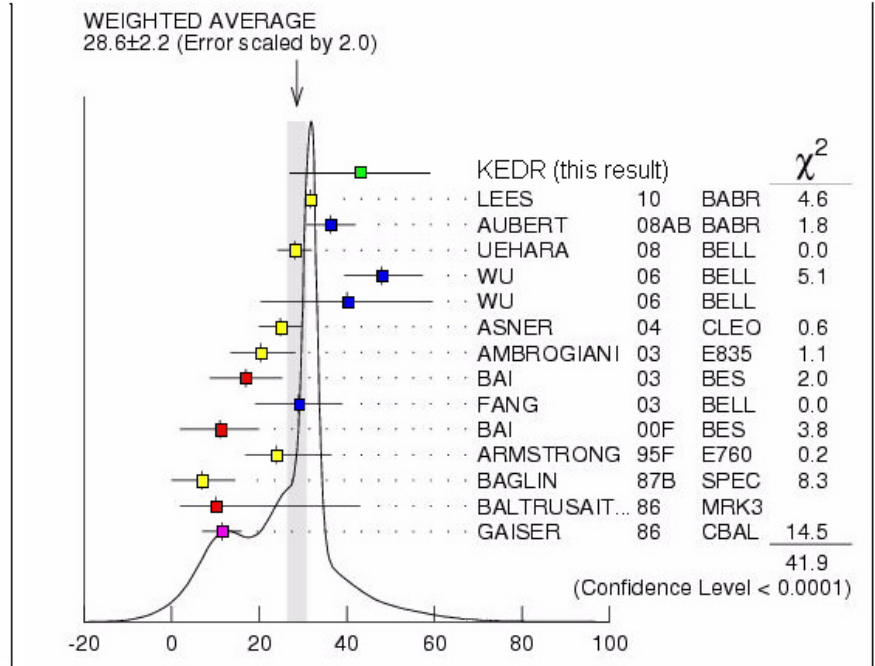
- ❑ *Line shape* : was estimated using CLEO line shape in the fit
- ❑ $\Gamma(\eta_C)$: varying 28.6 ± 2.2 MeV (PDG value)
- ❑ *Background subtraction* : was estimated taking polynomial of 3-rd order, varying ranges of the fit, using or not ToF veto in photon selection
- ❑ *Number of J/ψ produced* : estimated from the difference between measured and calculated number of multihadron J/ψ decays
- ❑ *Photon efficiency* : by changing weights of events with small track multiplicity ($n < 4$) and large ($n \geq 4$) by 25%; taking different MC generators for J/ψ decays
- ❑ *Photon energy scale* : calibration was made using $\pi^0 \rightarrow 2\gamma$ decays and $\psi' \rightarrow \gamma \chi_{C1}, \chi_{C2}; \chi_{CJ} \rightarrow \gamma J/\psi$ transitions

Results on η_c mass and width

η_c mass (MeV)



η_c width (MeV)



■ J/ψ decays ■ B decays ■ $\gamma\gamma$ or $pp \rightarrow \eta_c$ ■ $ee \rightarrow J/\psi+cc$ ■ J/ψ decays with ω^3 factor

KEDR results :

$$M(\eta_c) = 2978.1 \pm 1.4 \pm 1.4 \text{ MeV}$$

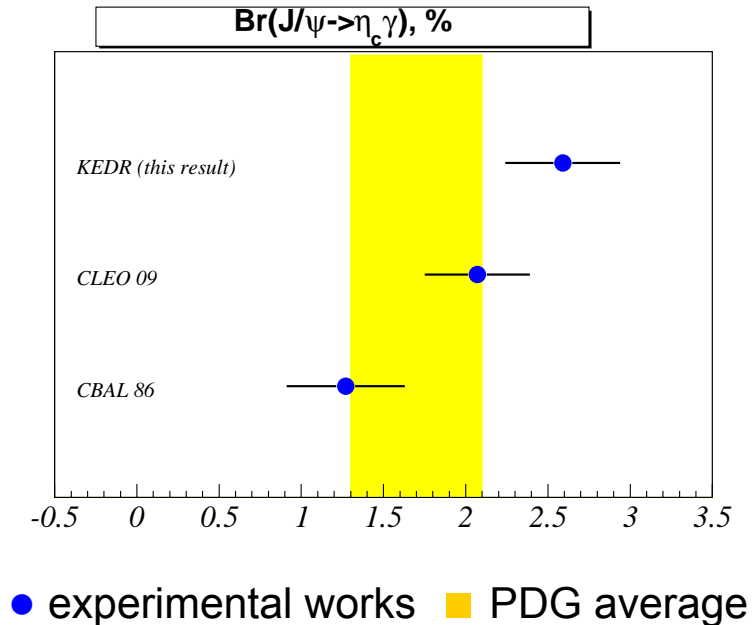
$$\Gamma(\eta_c) = 43.5 \pm 5.4 \pm 15.8 \text{ MeV}$$

$$\text{PDG } 2980.3 \pm 1.2 \text{ MeV}$$

$$\text{PDG } 28.6 \pm 2.2 \text{ MeV}$$

Result on $B(J/\psi \rightarrow \eta_c \gamma)$ and conclusions

- ❑ Photon line shape in the radiative $J/\psi \rightarrow \eta_c \gamma$ decay is asymmetric. The branching value of this decay and η_c mass are sensitive to the line shape, and it should be taken into account during measurement.
- ❑ Our result on $B(J/\psi \rightarrow \eta_c \gamma)$ is consistent with that of CLEO, is higher than the old Crystal Ball value and close to theoretical predictions.



KEDR result :

$$B(J/\psi \rightarrow \eta_c \gamma) = (2.59 \pm 0.16 \pm 0.31)\% \quad \text{PDG } (1.7 \pm 0.4)\%$$