Two-Photon Production of $\chi_{c2}(2P)$ at BABAR

QWG 2010, Fermilab
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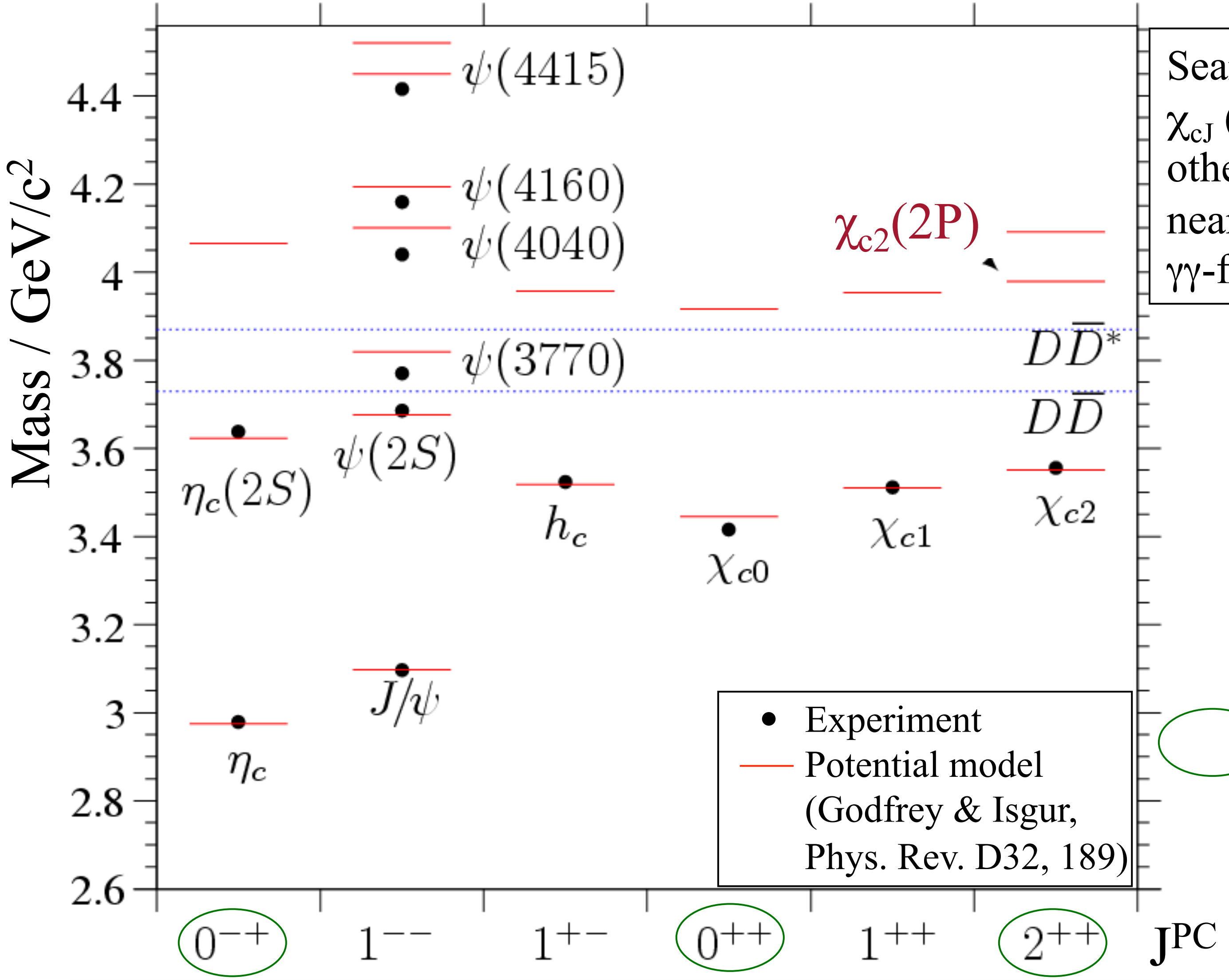
Representing the BABAR Collaboration

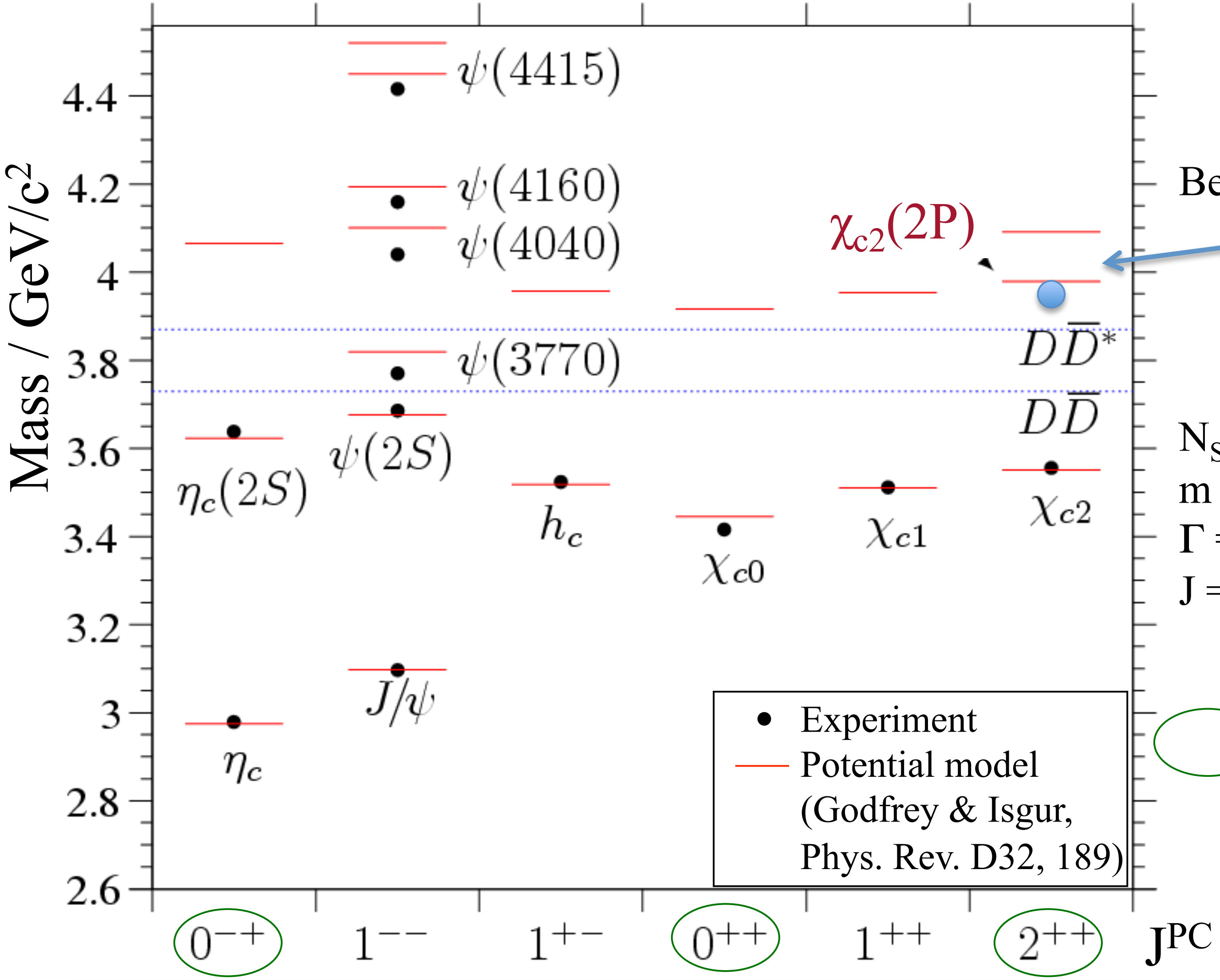
Charmonia



Search for radially excited χ_{cJ} (2^3P_J) and other new $c\bar{c}$-states near the $D\bar{D}$-threshold in $\gamma\gamma$-fusion

allowed in $\gamma\gamma$-fusion
[quasi-real photons:
J=1 forbidden (Yang)
C = +1 (two photons)]

Charmonia



$\gamma\gamma \rightarrow X \rightarrow D\bar{D}$

Belle (PRL96, 082003)

Z(3930) = χ_{c2}(2P) ?

Prediction

m = 3972-79 MeV/c^2

N_{Signal} = 64 ± 18

m = 3929 ± 5 ± 2 MeV/c^2

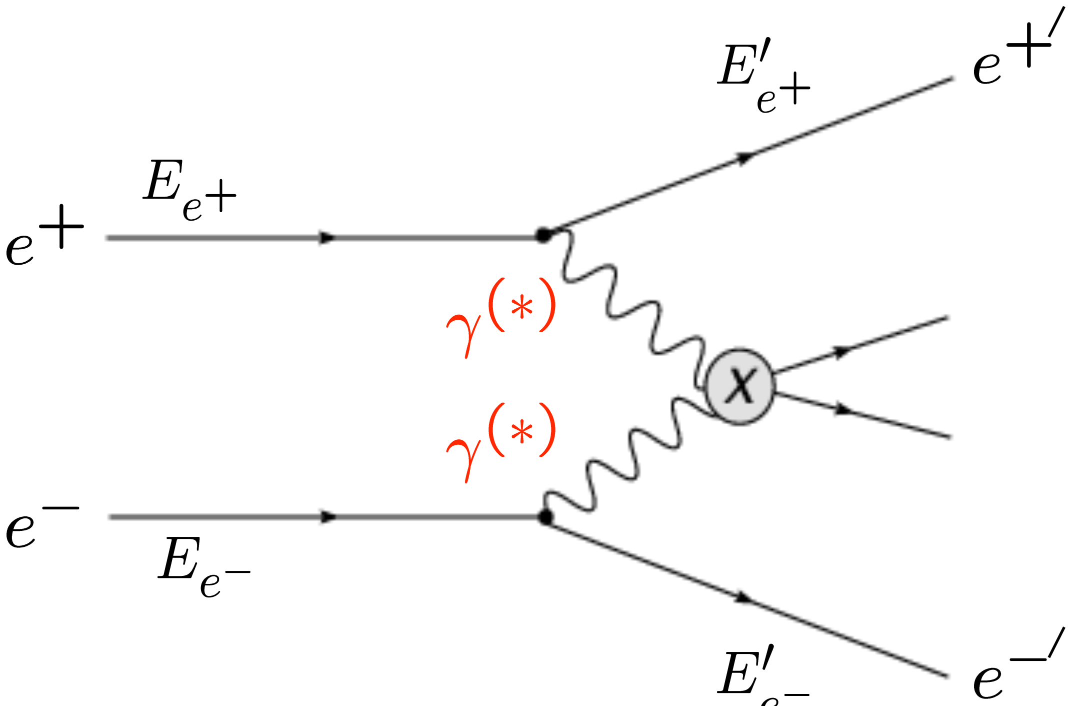
Γ = 29 ± 10 ± 2 MeV/c^2

J = 2 preferred

allowed in γγ fusion
[quasi-real photons:
J=1 forbidden (Yang)
C = +1 (two photons)]

Two-Photon Interaction

$\gamma\gamma$-fusion: clean environment to study charmonia



no-tag mode
($e^\pm$ not detected, lost in beampipe)
small $e^\pm$ scattering angles
→ quasi-real γ
→ large missing mass
$MM^2 = |p_{e^+}+p_{e^-}-p_X|^2$

X: - small transversal momentum $p_t(X)$
- Spin-parity J^P: $0^\pm$, $2^\pm$, 3^+...
- J=1 forbidden (Yang)
- Charge conj. C = +1

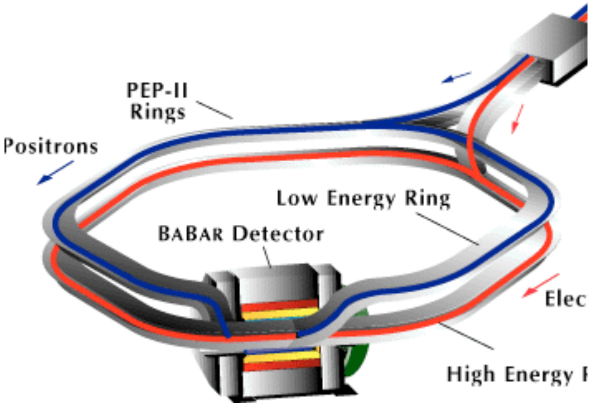
This analysis:

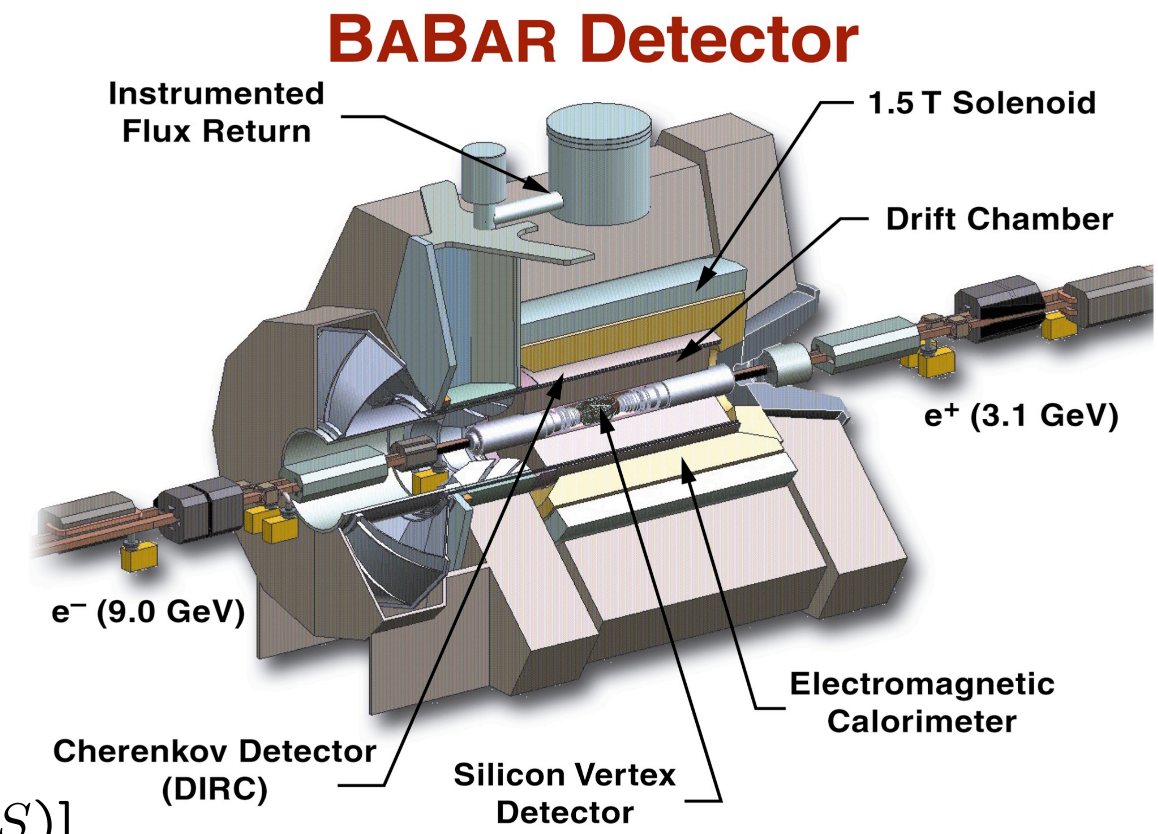
$e^+e^- \to e^+e^-\gamma\gamma$

$\gamma\gamma \to X \to D^0\bar{D}^0\ (D^+D^-)$

The BABAR Experiment

Electron-Positron Collider: PEP-II / SLAC





Integrated luminosity
1999-2008: 531 fb^{-1}

PEP-II
e^+e^- CMS energy
$\to \Upsilon(4S)$ [$\Upsilon(2S), \Upsilon(3S)$]
max. luminosity. > 1.2 x 10^{34} $cm^{-2}s^{-1}$

Analysis Overview

- Data sample

  384 fb^{-1}

  5.6 x 10^9 hadronic events

- Decay modes

$\gamma\gamma \rightarrow Z \rightarrow D^0\bar{D}^0$

N4 $D^0 \rightarrow K^-\pi^+ \quad \bar{D}^0 \rightarrow K^+\pi^-$

N5 $D^0 \rightarrow K^-\pi^+ \quad \bar{D}^0 \rightarrow K^+\pi^-\pi^0$

N6 $D^0 \rightarrow K^-\pi^+ \quad \bar{D}^0 \rightarrow K^+\pi^-\pi^-\pi^+$

N7 $D^0 \rightarrow K^-\pi^+\pi^0 \quad \bar{D}^0 \rightarrow K^+\pi^-\pi^-\pi^+$

$\gamma\gamma \rightarrow Z \rightarrow D^+D^-$

C6 $D^+ \rightarrow K^-\pi^+\pi^+ \quad D^- \rightarrow K^+\pi^-\pi^-$

- Monte Carlo Simulation

  800000 MC events generated for each mode

  GamGam event generator

  - $\gamma\gamma \rightarrow D\bar{D}$ for mass-dependent efficiency and detector resolution
  - $\gamma\gamma \rightarrow Z \rightarrow D\bar{D}$ for resolution model verification

Selection of Two-Photon-Events

Control sample $e^+e^- \rightarrow K^-K^+\pi^+\pi^-X$

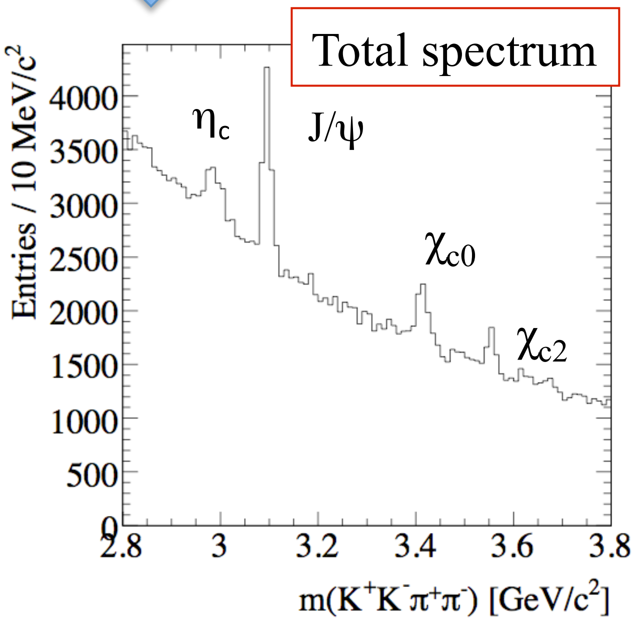
Complete data sample:

- e^+e^--annihilation
- Initial State Radiation
- Two-photon-interaction

Use J/ψ- and η_c as reference signal for definition of selection criteria for 2-photon-events

Typical for ISR: J/ψ - $J^P = 1^-$

Typical for $\gamma\gamma$: η_c - $J^P = 0^-$



Selection of Two-Photon-Events

Control sample $e^+e^- \to K^-K^+\pi^+\pi^-$

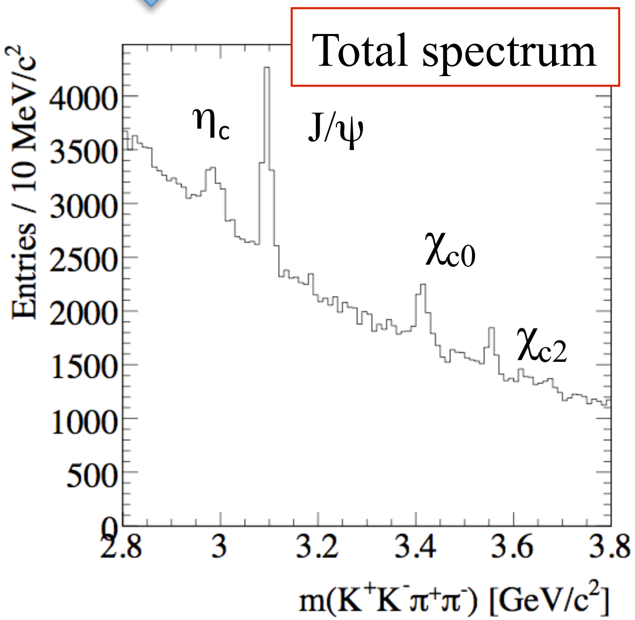
Complete data sample:

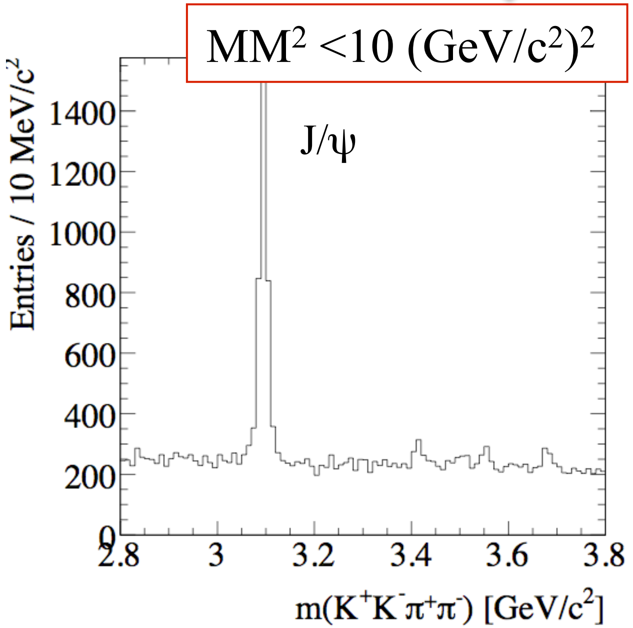
- e^+e^--annihilation
- Initial State Radiation
- Two-photon-interaction

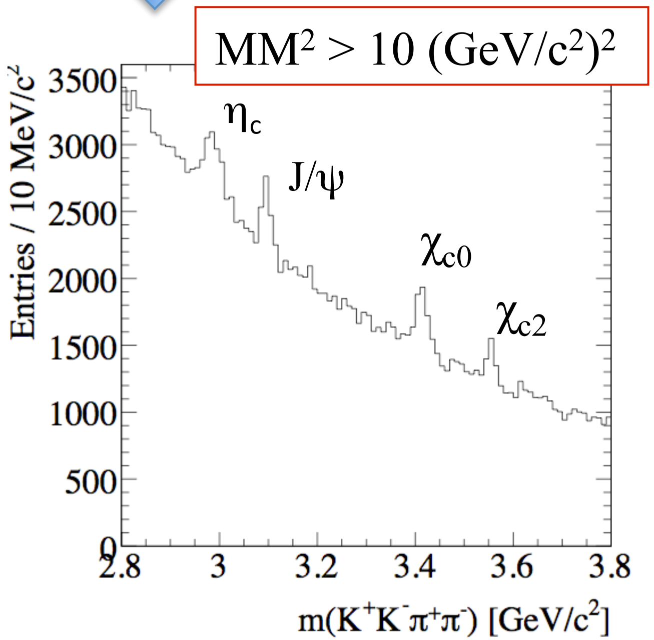
<u>1) Missing Mass</u>

$MM^2 = (p_{e^-} + p_{e^+} - p_{KK\pi\pi})^2$

→reject ISR background







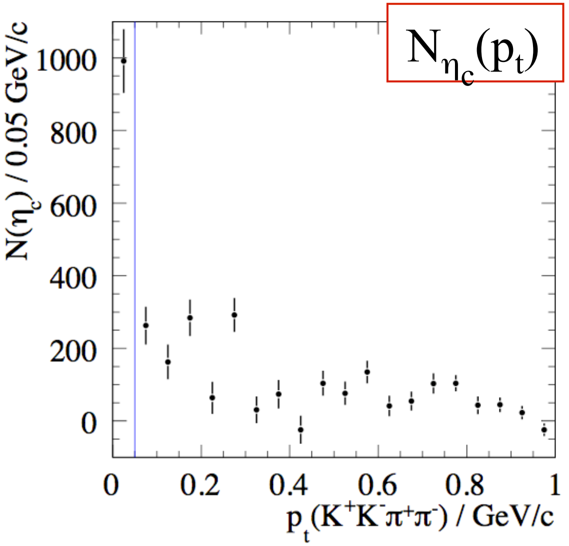
Selection of Two-Photon-Events

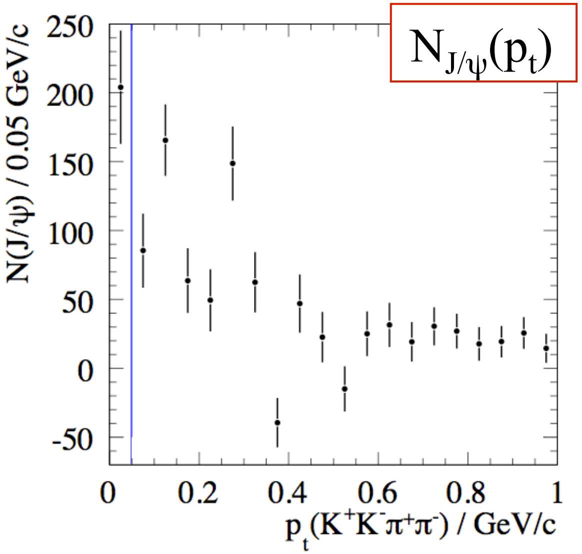
2) J/ψ and η_c signal entries dependent on <u>transversal momentum</u> $p_t(KK\pi\pi)$ (w.r.t. e^+e^- Direction)

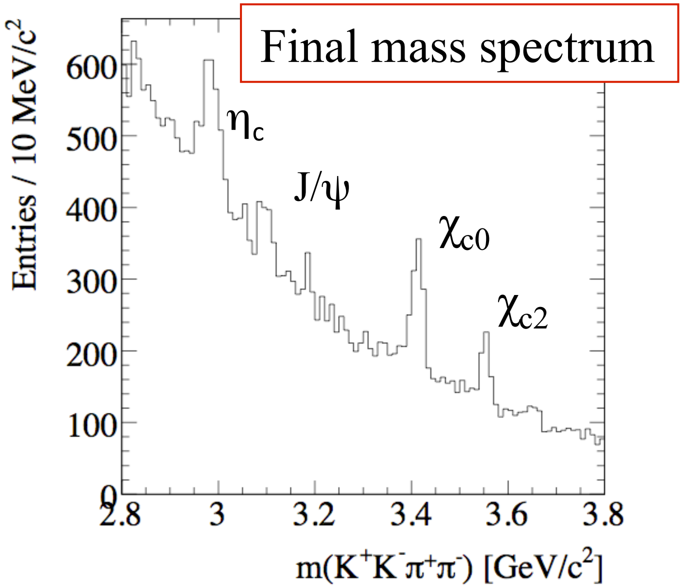
3) Quasi-exclusive reconstruction: Total <u>energy deposit in calorimeter</u> $E_{cal} < 0.4$ GeV (except photons belonging to final state)

Selection criteria:

- $\mathrm{MM}^2 = (p_{e^-} + p_{e^+} - \sum_i k_i)^2 > 10\ (\mathrm{GeV}/c^2)^2$
- $p_t < 0.05$ GeV/c
- $E_{cal} < 0.4$ GeV







→reject annihilation background

D mass spectra

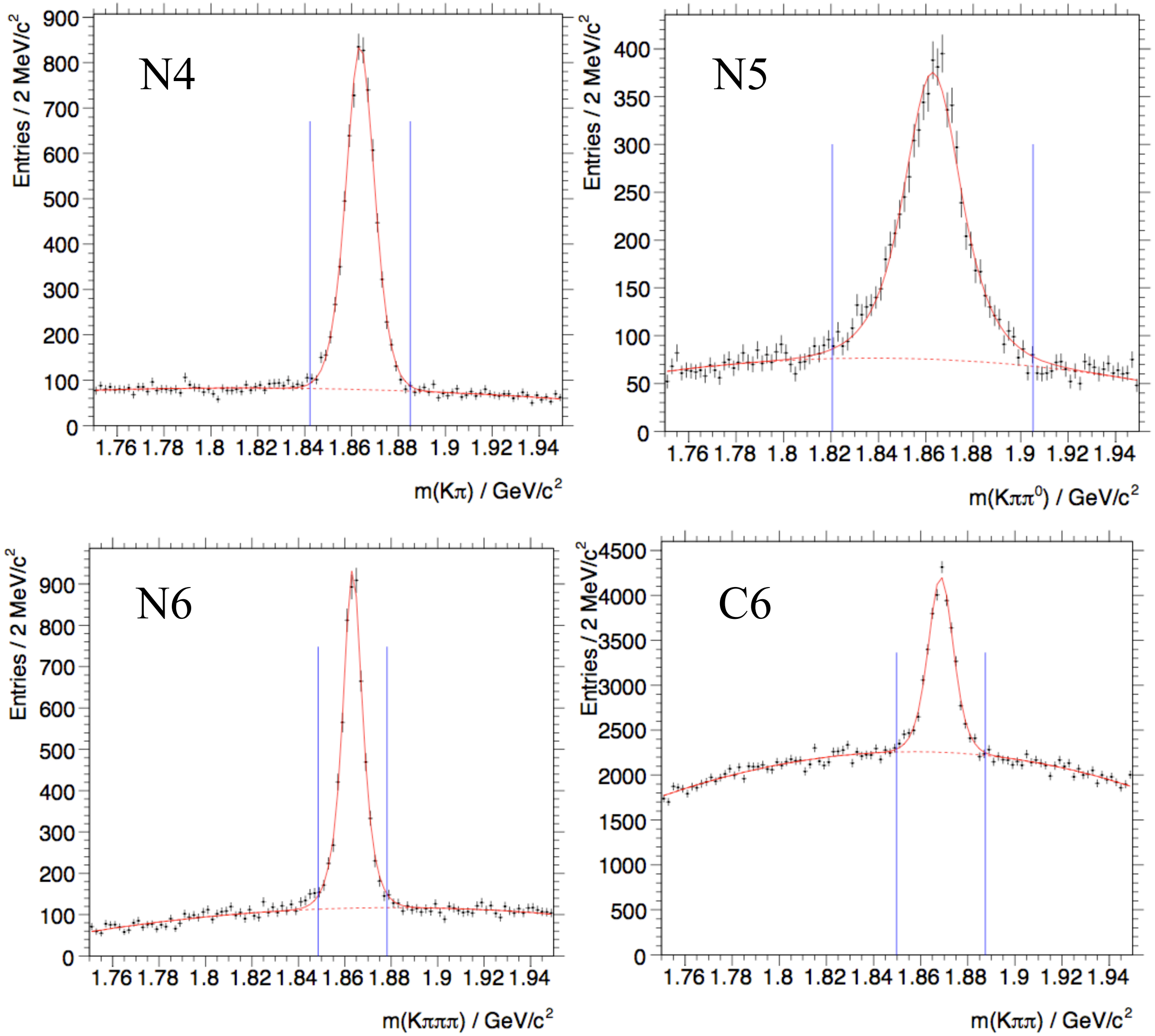
Exclusive decays
- exact number of final state particles
- reconstructed π^0: allow 0/1 depending on decay mode

$D/\bar{D}/D\bar{D}$ vertex fit probability > 0.001

Complete data set
(no two-photon selection)
Fit: Gaussian + Polynomial (background)

Define signal regions
(±1.5xFWHM; blue lines)

(mass of other D-candidate within signal region)



Summary of selection criteria

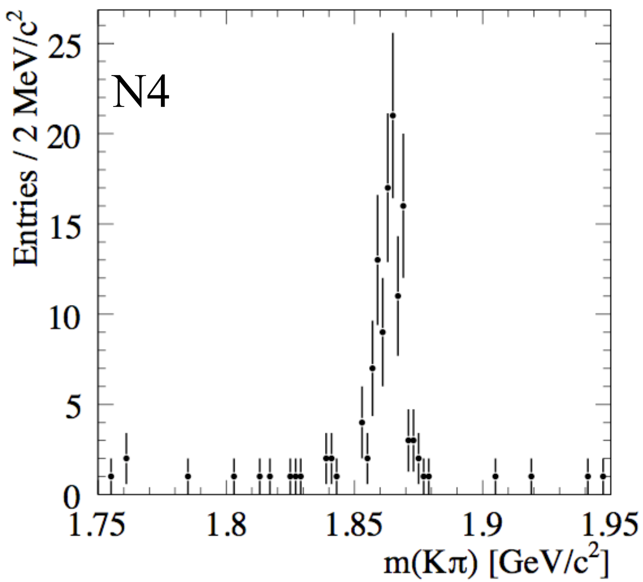
- $D\overline{D}$ Event selection
  - Exact number final state particles ($K^{\pm}$, $\pi^{\pm}$, π^0)
  - $D/\overline{D}/D\overline{D}$ vertex fit probability > 0.001
  - $D/\overline{D}$ signal regions

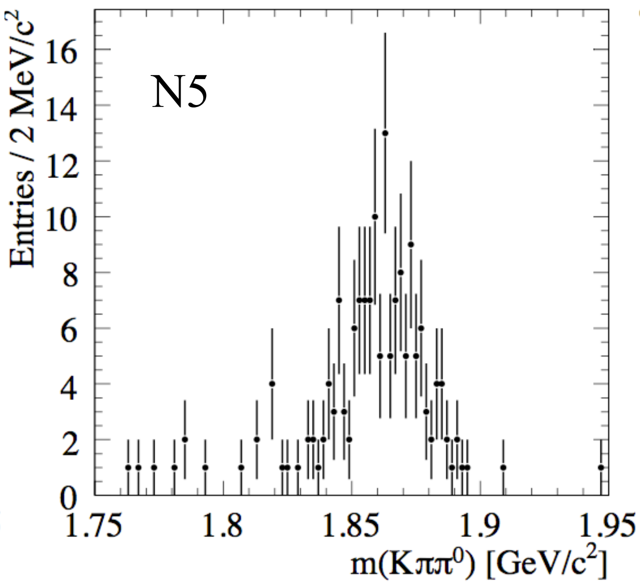
Decay mode	number of π^0	D mass window MeV/c^2	$\overline{D}$ mass window MeV/c^2
N4	0	1863.4 ± 22	1863.4 ± 22
N5	1	1863.4 ± 22	1863.4 ± 43
N6	0	1863.4 ± 22	1863.4 ± 16
N7	1	1863.4 ± 16	1863.4 ± 43
C6	0	1868.6 ± 19	1868.6 ± 19

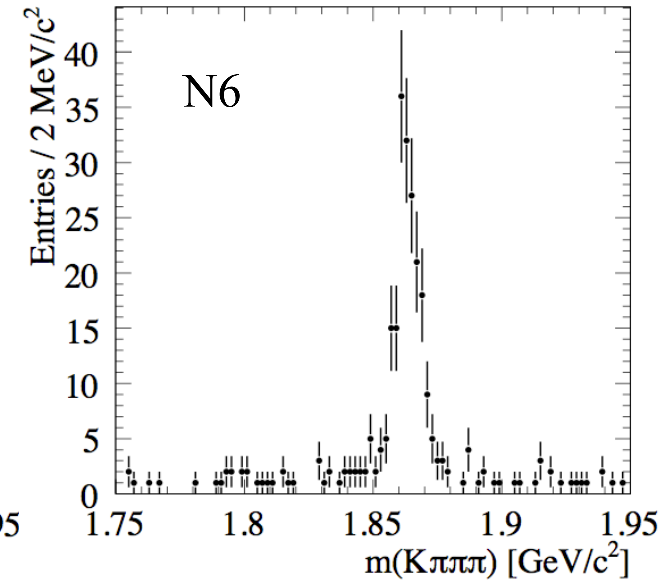
- Two Photon event selection
  - Missing mass $MM^2 > 10\ (GeV/c^2)^2$
  - Transversal momentum $p_t(D\overline{D}) < 0.05$ GeV/c
  - Total energy in calorimeter $E_{cal} < 0.4$ GeV
    (without energy of γ used for π^0 in N5,N7)

- check for multiple candidates per event
  select best one via $D\overline{D}$ vertex fit probability

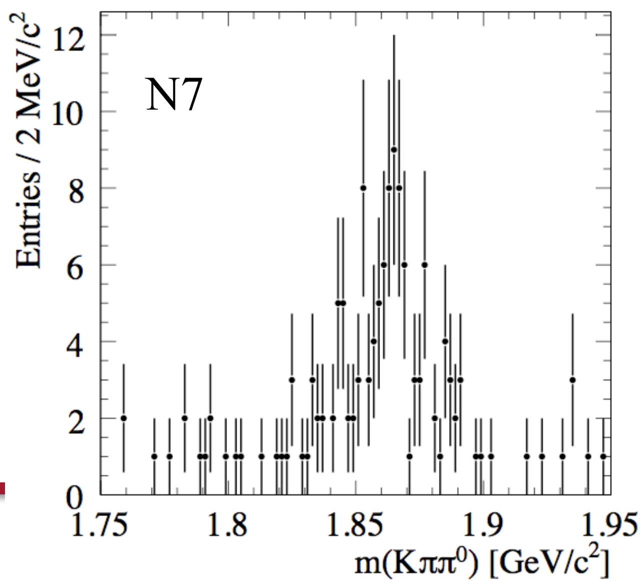
D mass spectra (final selection)

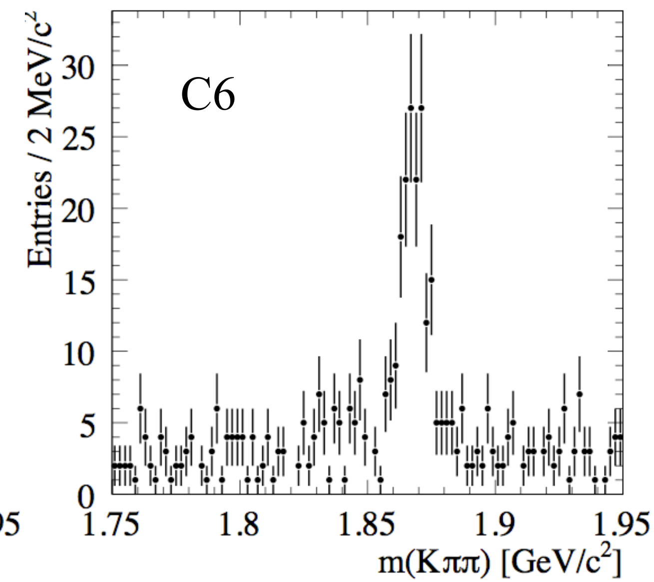




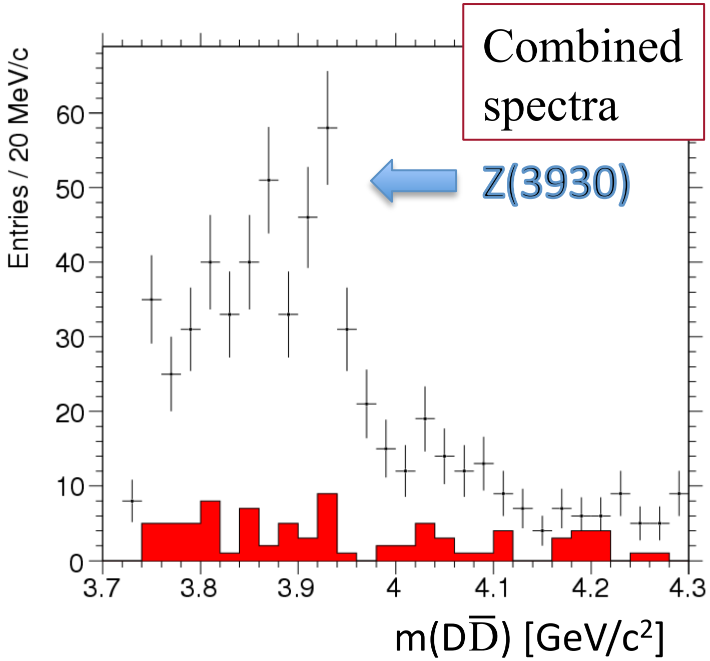


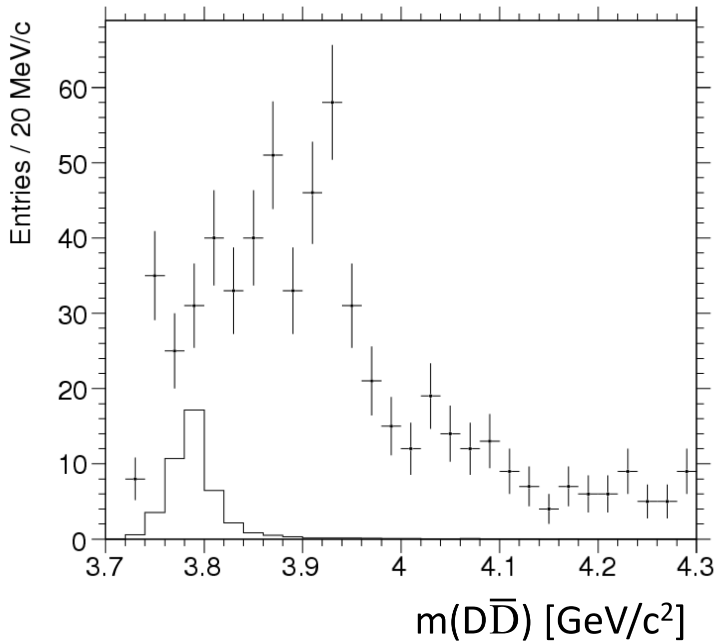
spectra shown with other
D candidate
mass within signal region





$D\bar{D}$ Mass Spectra





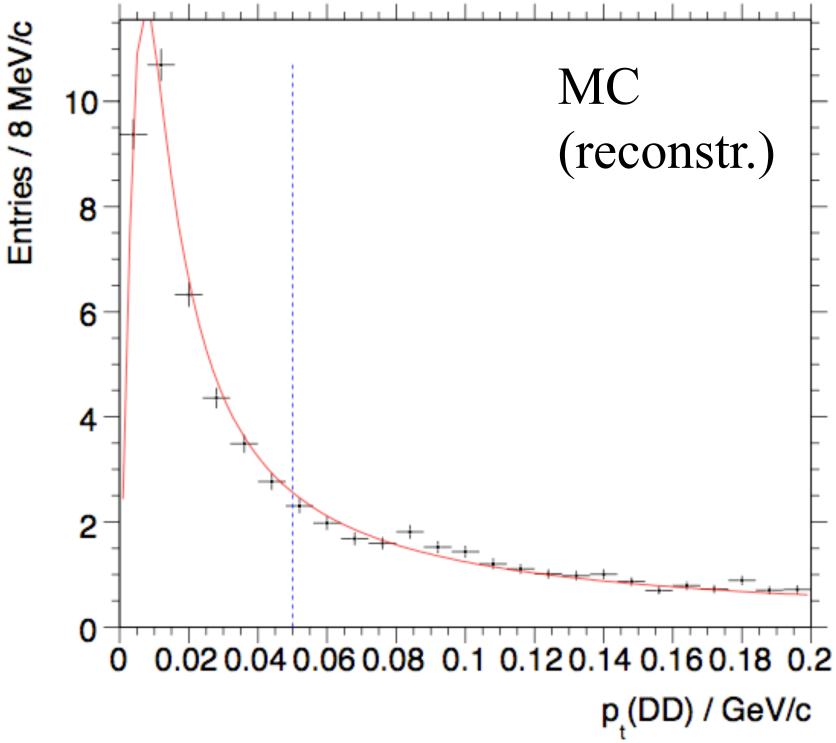
Estimation of background

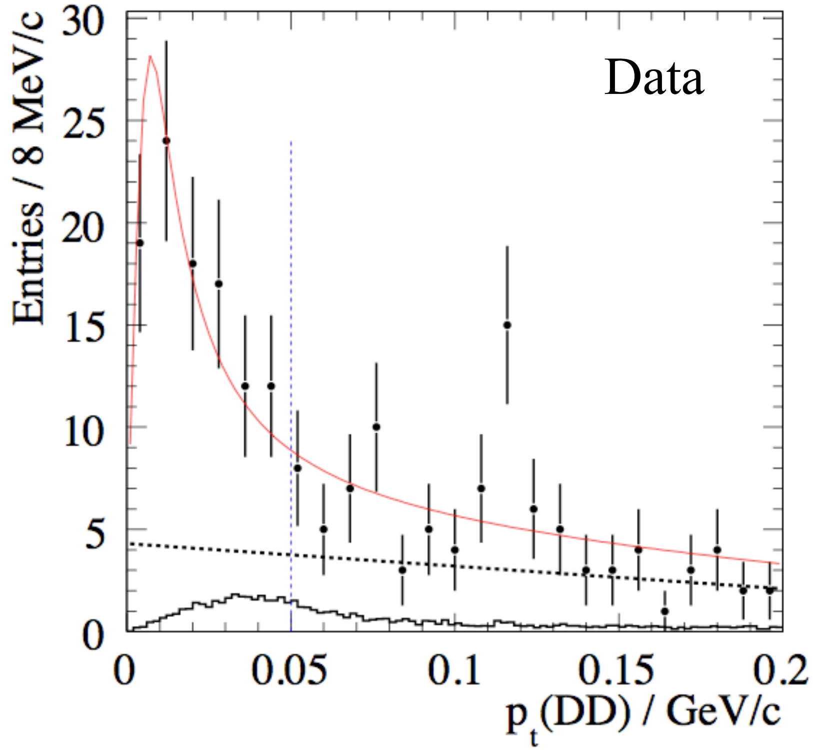
- Combinatoric background: obtained from $D,\bar{D}$ sideband regions
  →Signal region (3.91 – 3.95 GeV/c^2) dominated by real $D\bar{D}$-events

- Contribution of $D^*\bar{D} \to D\gamma\bar{D}$ / $D\pi^0\bar{D}$ (Monte Carlo simulation, arbitrary scaling)

$p_t(D\bar{D})$ distribution

Check for non-2photon contribution in Z(3930) signal region

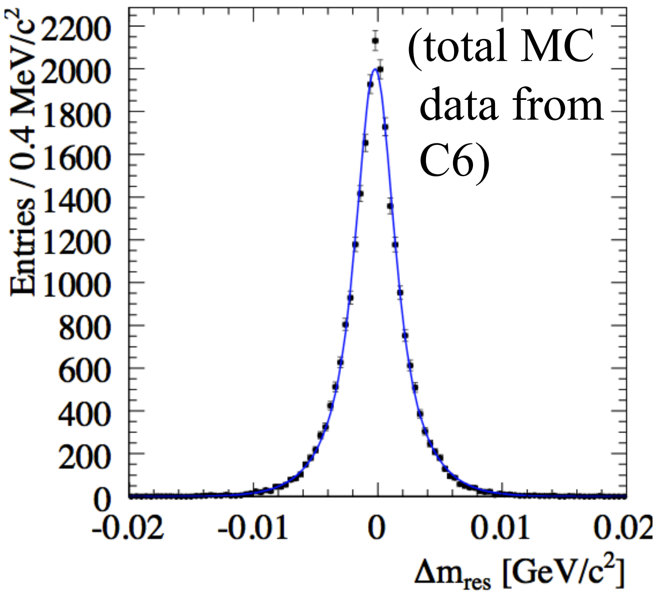


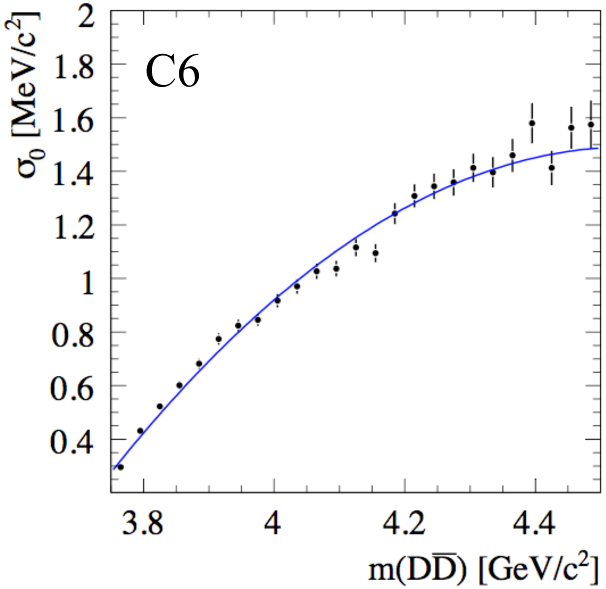


- all selection criteria but $p_t(D\bar{D})$
- events in Z(3930) signal region
  3.91 – 3.95 GeV/c^2

- Fit: MC lineshape with fixed parameters
  (red line) plus polynomial background (···)
  $D^*\bar{D}$ contribution (missing γ or π^0) (solid hist.)

Detector resolution





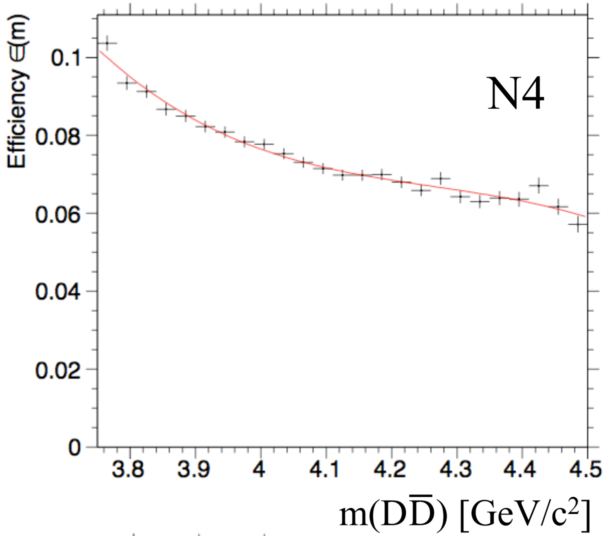
Mass-dependent resolution function:
Multi-Gaussian distribution

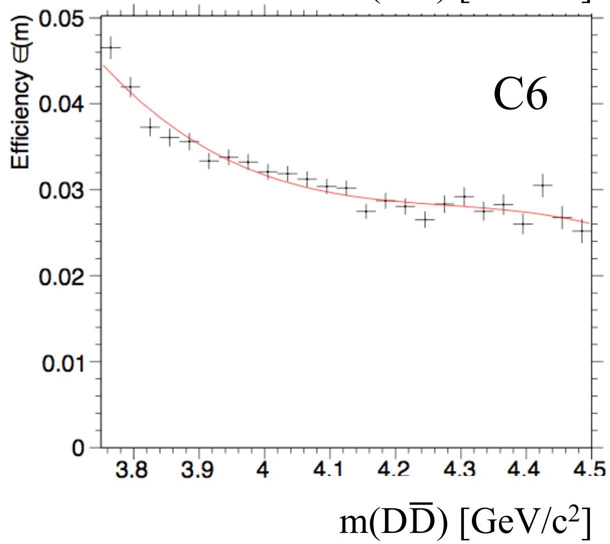
$$\int_{\sigma_0}^{r\sigma_0} \frac{1}{r\sigma^2} exp[-\frac{(\Delta m_{res} - \Delta m_{res,0})^2}{2\sigma^2}] d\sigma$$

Parameters
- minimum width σ_0
- maximum width $r\sigma_0$
- $\Delta m_{res} = m_{rec}(D\bar{D}) - m_{gen}(D\bar{D})$

- fit to complete dataset → Parameter r
- divide MC data into mass dep. subsets
- repeat fit with r set to constant value
  → parameterize $\sigma_0[m(D\bar{D})]$

Reconstruction efficiency





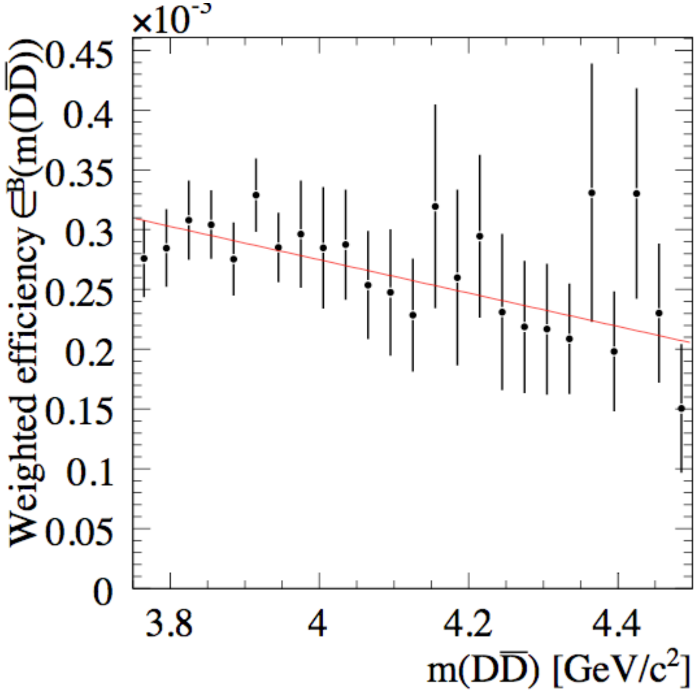
MC: divide reconstructed/generated mass spectra

→ $\varepsilon_i(m)$

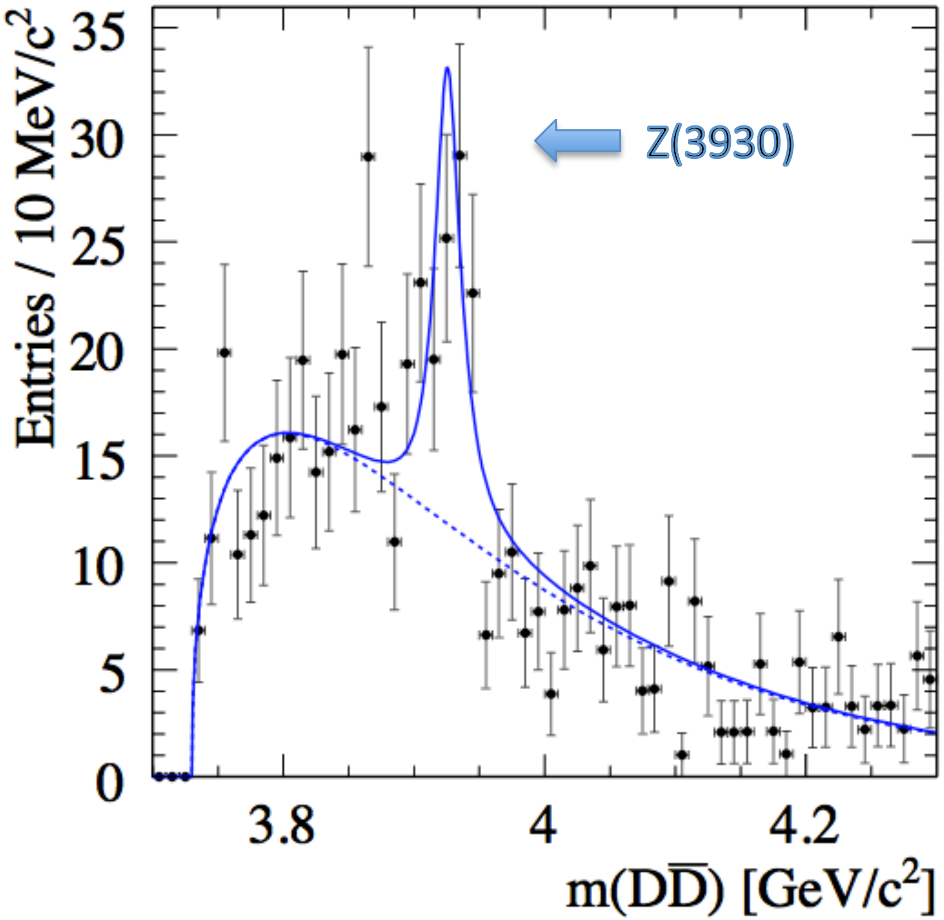
$\varepsilon_{B,i} = \varepsilon_i \times BF_i$ → combined efficiency ε_B

$$\epsilon_B = \frac{5}{2} \frac{\sum_i N_i}{\sum_i N_i/\epsilon_{B,i}}$$

N_i: entries in histogram (data)



Fit to Data



Belle: $m = 3929 \pm 5 \pm 2$ MeV/c^2
$\Gamma = 29 \pm 10 \pm 2$ MeV
$N_{Signal} = 64 \pm 18$

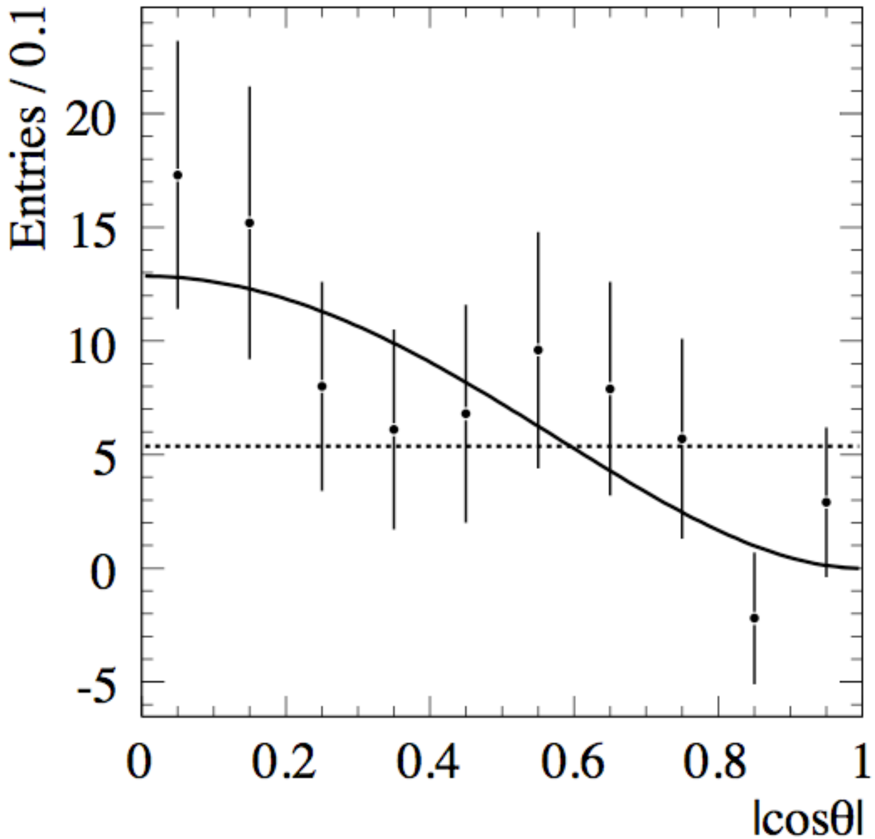
Unbinned Maximum Likelihood fit
- data corrected by mass-dependent reconstruction efficiency
- Signal: relativistic Breit-Wigner
- Convolution with detector resolution parameterization
- Background model

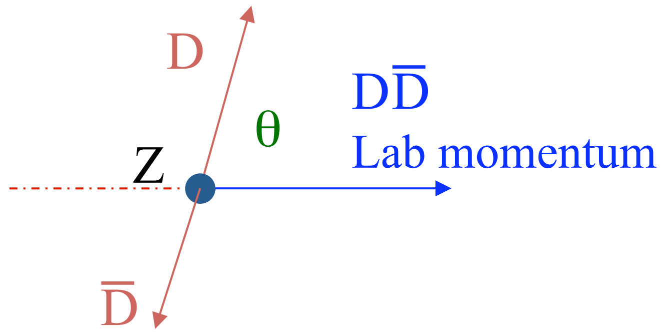
$$\propto \sqrt{m^2 - m_t^2}(m - m_t)^{\alpha} e^{[-\beta(m-m_t)]}$$

$m = 3926.7 \pm 2.7 \pm 1.1$ MeV/c^2
$\Gamma = 21.3 \pm 6.8 \pm 3.6$ MeV
$N_{Signal} = 76 \pm 17$
Significance 5.8σ

Angular Distribution

Entries in signal region
(from fit to data; m, Γ fixed)
Data efficiency corrected, ε(cosθ)





Spin 0 → Flat distribution

Spin 2, Helicity 2

$$\frac{dN}{d\cos\theta} \propto \sin^4\theta$$

Production: C = +1 Decay: J = L

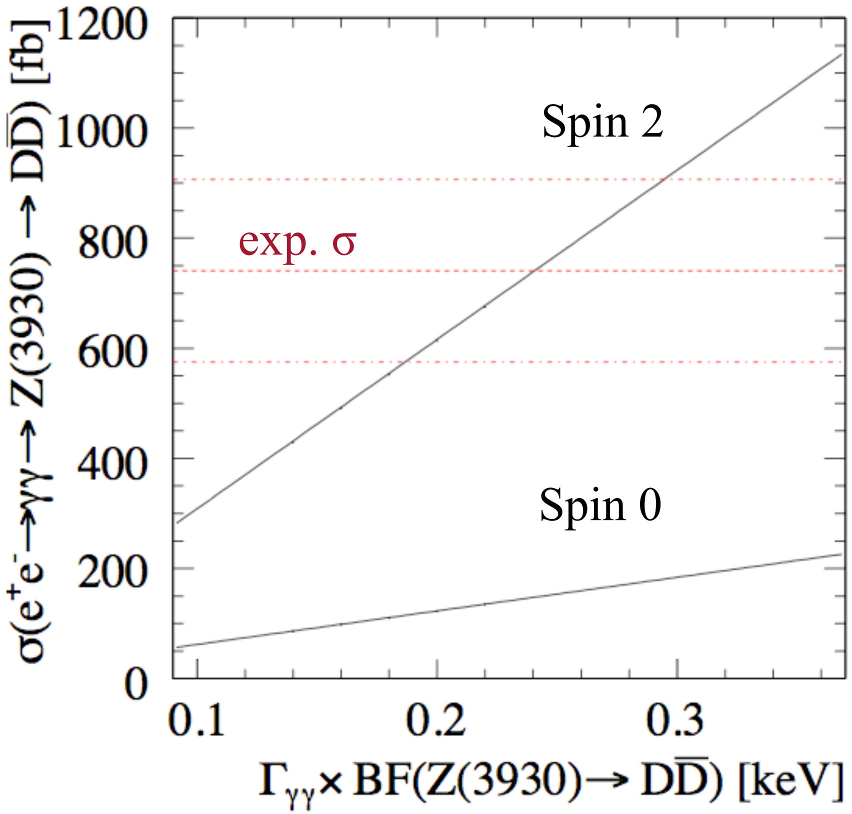
→ $J^{PC} = 2^{++}$ preferred

Consistent with Belle result

Cross Section and Two-Photon Width

Cross section: $\sigma(e^+e^- \to \gamma\gamma \to Z(3930) \to D\bar{D}) = \frac{N_{Signal}}{\epsilon_B \int L dt} = 741 \pm 166$ fb

(ε_B: mean reconstruction efficiency including D branching fractions)



Use 2-photon-generator *GamGam:*
Calculate cross-section σ
depending on two-photon width $\Gamma_{\gamma\gamma}$
Compare with data (for J = 2)

⇩

$\boxed{\Gamma_{\gamma\gamma}[Z(3930)] \times BF[Z(3930) \to D\bar{D}] = 0.24 \pm 0.05 \pm 0.04 \text{ keV}}$

Belle result
$\Gamma_{\gamma\gamma}(Z) \times BF(Z \to D\bar{D})$
$= 0.18 \pm 0.05 \pm 0.03$ keV

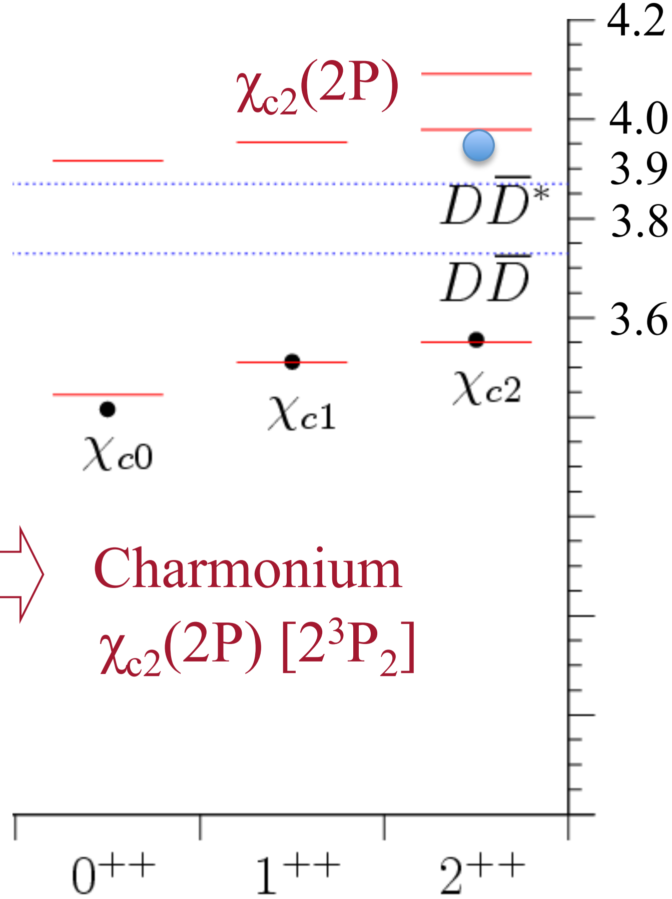
Systematic Uncertainties

	Δm [MeV/c^2]	$\Delta\Gamma$ [MeV]	$\Delta(\Gamma_{\gamma\gamma}\times B)$ [keV]
Choice of Spin J=1, J=0	< 0.05	< 0.05	-
Value of R (Breit-Wigner)	< 0.05	< 0.05	< 0.0005
Background model	0.4	3.0	0.029
Convolution steps = 35	0.2	0.2	0.003
Convolution range + 0.02 MeV/c^2	< 0.05	0.9	0.003
Resolution multi-Gauss $r \pm \delta r$	< 0.05	0.1	< 0.0005
Fit precision and mass scale	0.9	0.1	0.001
Uncertainty in D mass	0.3	-	-
Combined reconstr. effiency: polynomial	< 0.05	0.4	< 0.0005
Efficiency: angular distribution	-	-	0.018
Error in D branching fraction	< 0.05	< 0.05	0.010
PID	0.4	1.8	0.004
Tracking efficiency correction	< 0.05	< 0.05	0.022
π^0 efficiency correction	< 0.05	< 0.05	0.003
Generator precision	-	-	0.007
Choice of Form Factor	-	-	0.002
Luminosity	-	-	0.002
Quad. Sum	**± 1.1**	**± 3.6**	**± 0.04**

Summary of Results

Observation of a resonance in $\gamma\gamma \to D^0\bar{D}^0(D^+D^-)$
consistent with Z(3930) (Belle)

- Signal significance 5.8σ
- m = 3926.7 ± 2.7 ± 1.1 MeV/c^2
- Γ = 21.3 ± 6.8 ± 3.6 MeV
- N = 76 ± 17
- J = 2
  Decay → J = L → P = +1
  Production (γγ) → C = +1
  → $J^{PC} = 2^{++}$ preferred
- $\Gamma_{\gamma\gamma}\times BF[Z(3930)\to D\bar{D}]$
  = 0.24 ± 0.05 ± 0.04 keV



⇨ Charmonium
$\chi_{c2}(2P)$ $[2^3P_2]$

arXiv:1002.0281 [hep-ex] - accepted for publication in PRD