New Results on Double Charmonium Production in e+e- Collisions with the Belle Detector

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- Introduction, Motivation
- Event selection and cross sections
- Angular distributions
- Recent update, evidence for X(3940) state
- Summary and Conclusion

Charmonium

Charmonium states as testing ground for QCD!

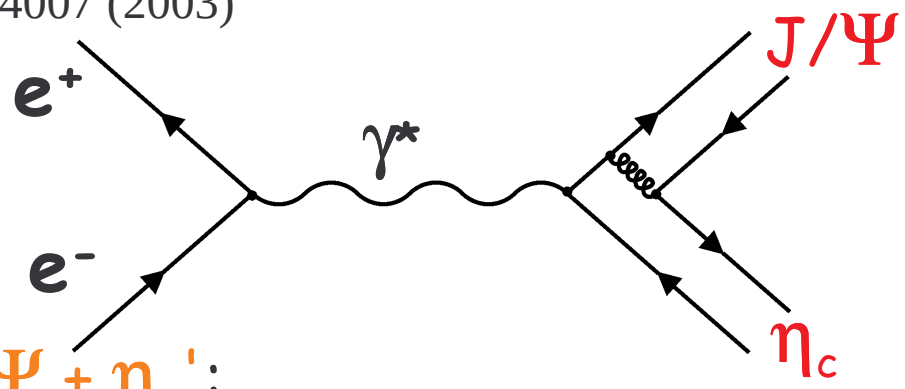
-> clear experimental signature

-> non-relativistic nature -> non-relativistic QCD (NRQCD)

-> exclusive charmonium modes even simpler

-> no unknown non-perturbative parameters

e.g. E.Braaten and J.Lee, PRD D67, 054007 (2003)



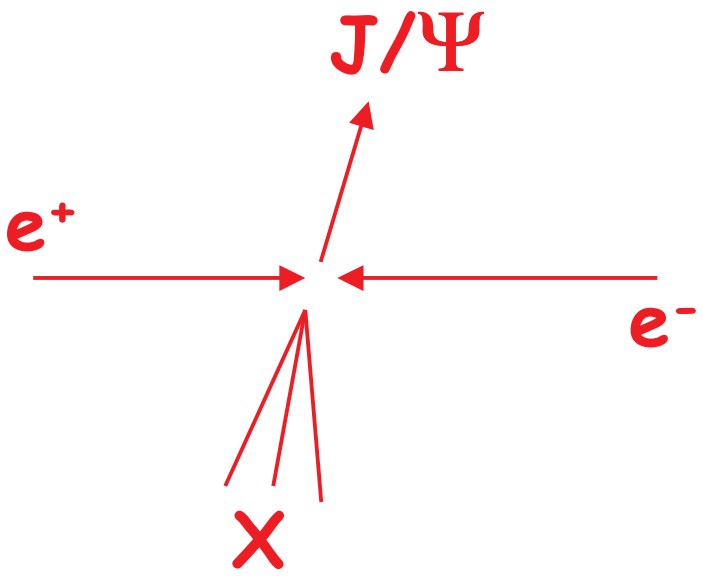
Example:

cross section for '$e^+e^- \rightarrow J/\Psi + \eta_c$':

Xsec = 2.31 ± 1.09 fb

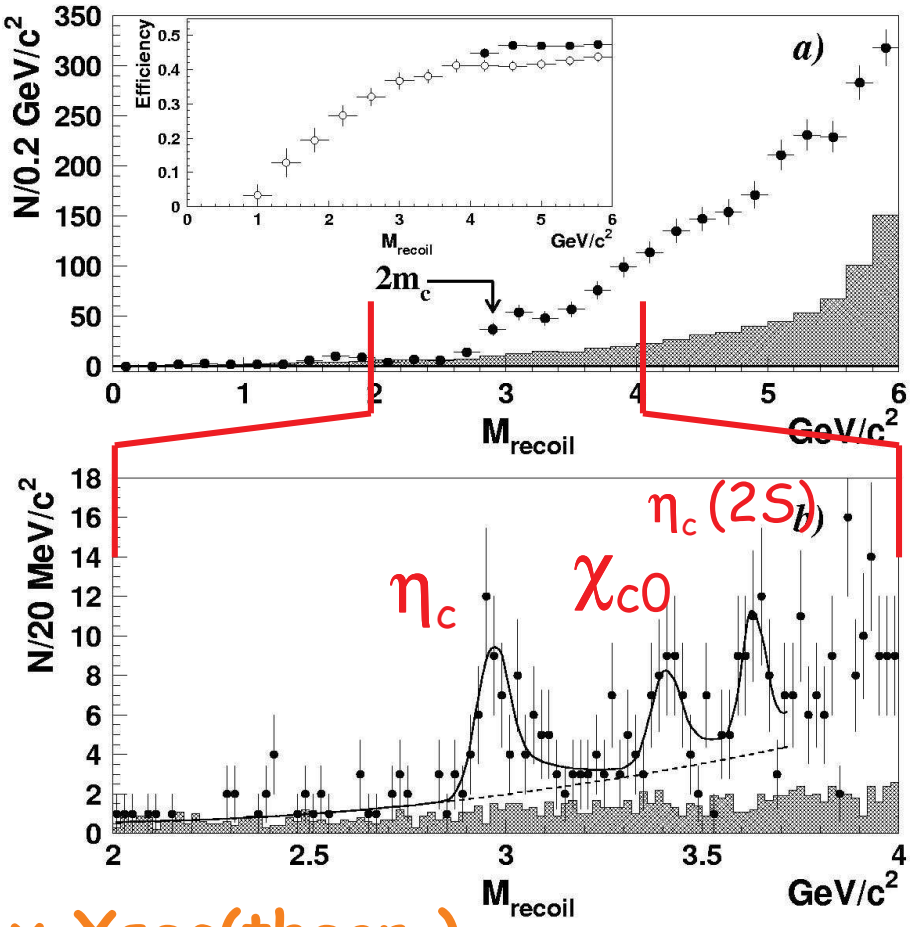
Double $c\bar{c}$ production in e^+e^- annihilation

reconstruct



Determine mass of rest of system
-> 'recoiling mass'

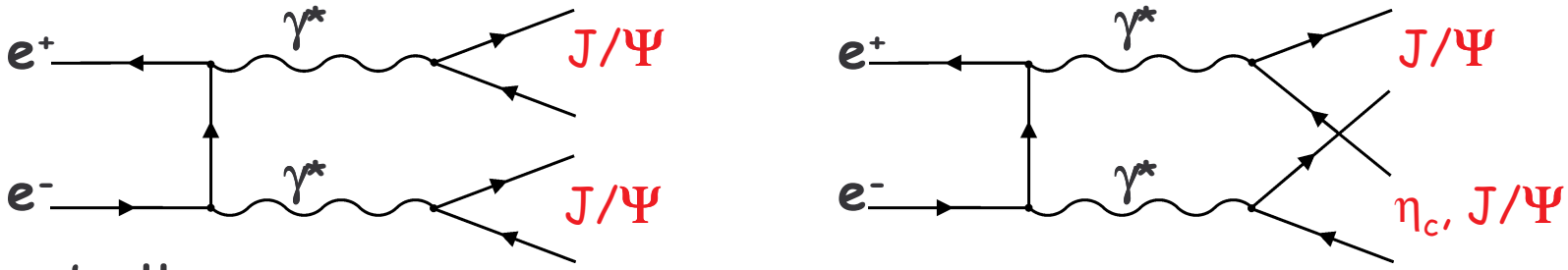
46.2 fb^{-1} -> PRL 142001-2 (2002)



Xsec(exp.) > 10 x Xsec(theor.)

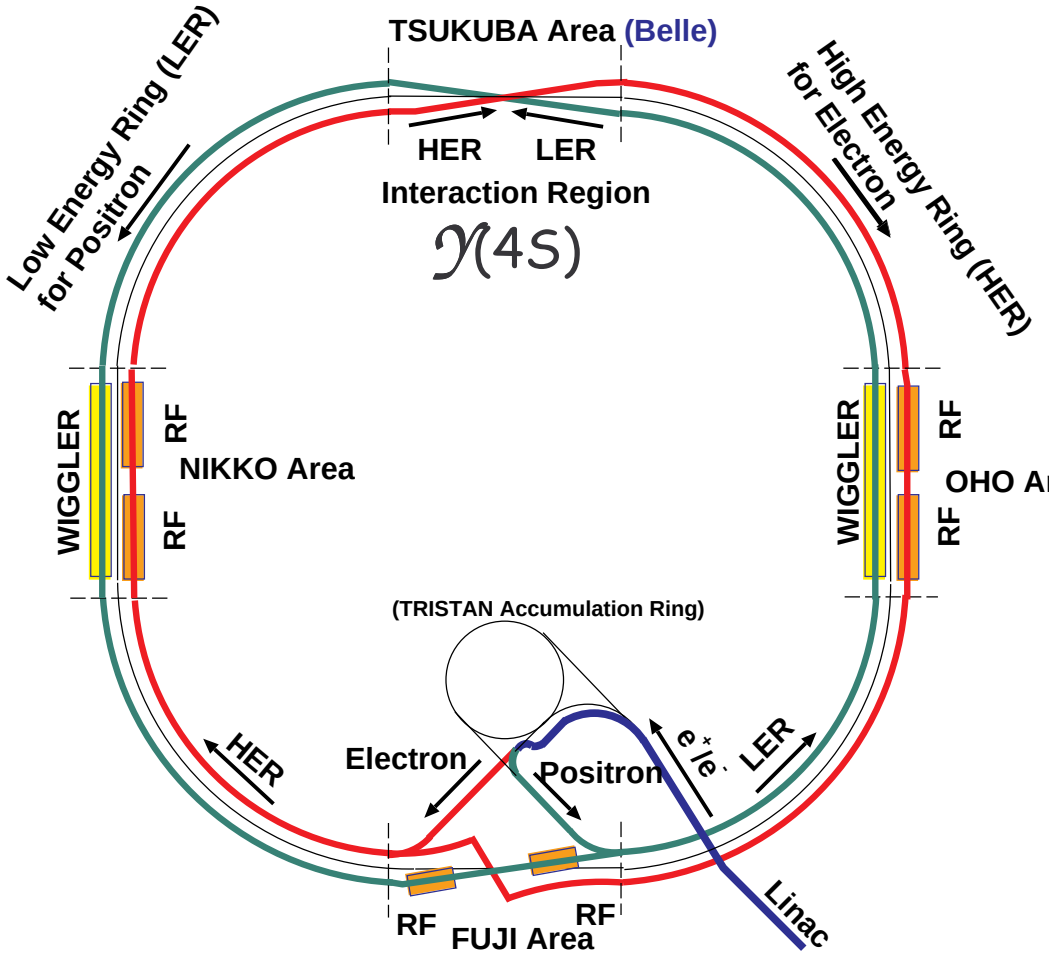
Possible explanations

- Potential problem with the momentum scale bias
  the peak is actually not η_c!
- Double J/Ψ production via 2-γ annihilation
  (this mode is forbidden by C conjugation conservation
  for 1-γ annihilation)
  => See G.T. Bodwin et al., Phys. Rev. Lett. 90, 162001 (2003)



- Glueball
  => See S.J. Brodsky et al., Phys. Rev. Lett. 91, 112001 (2003)

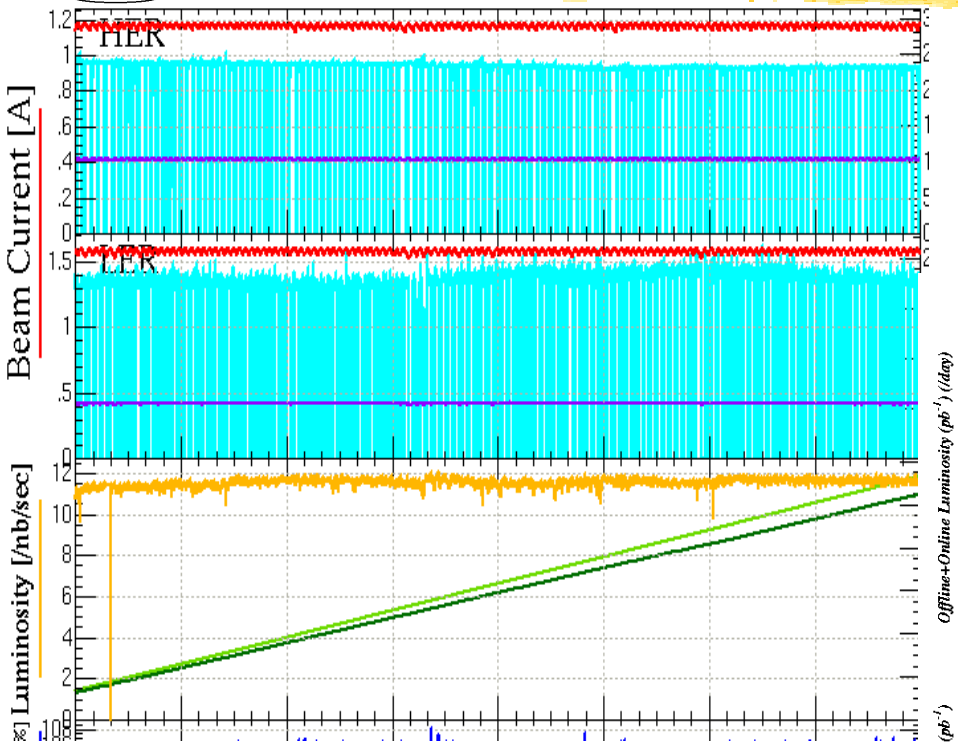
The KEK-B collider



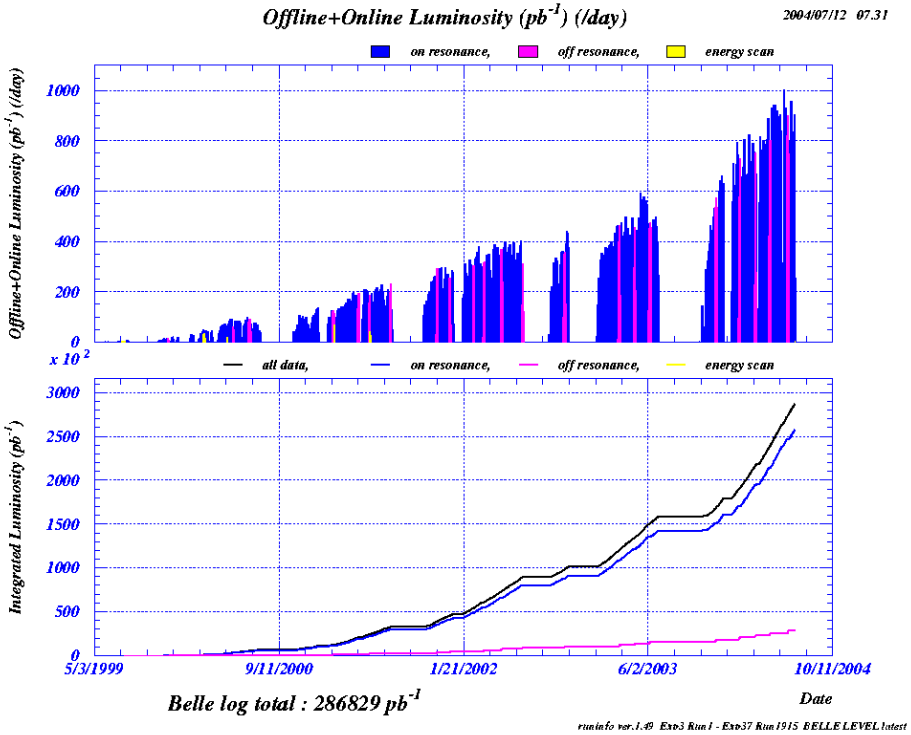
3.5 GeV e^+ on 8 GeV e^-
11 mrad crossing angle
1.6 A x 1.2 A

Excellent operation:

Peak luminosity:
$1.39\ 10^{34}\ cm^{-2}\ s^{-1}$
June 3rd, 2004



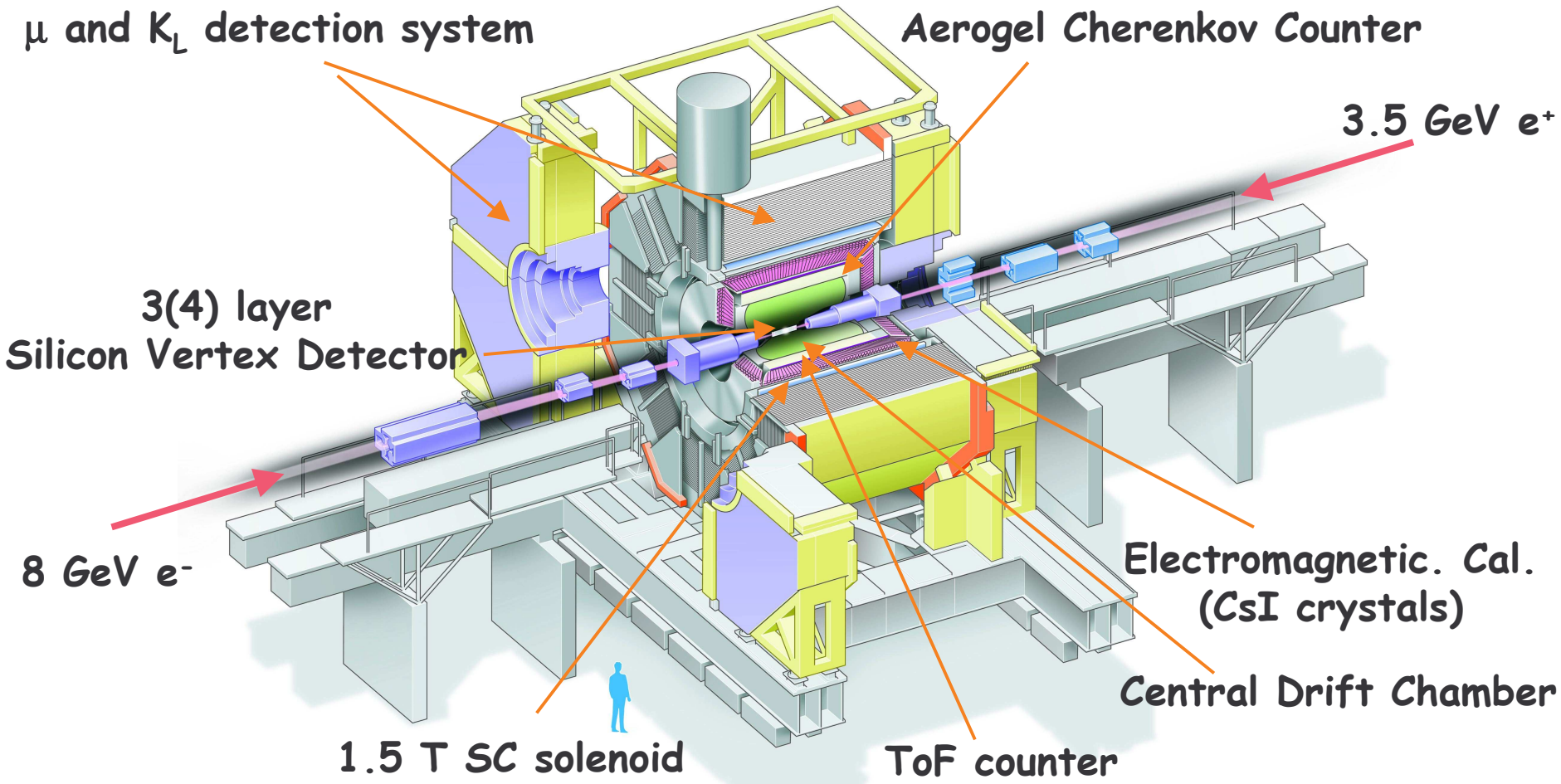
Integrated luminosity per day:
$944.2\ pb^{-1}/day$
May 23rd, 2004



$\int \mathcal{L}\, dt = 285\ fb^{-1}$

255 fb-1 on-resonance
30 fb-1 off-resonance

The Belle Detector



Event selection

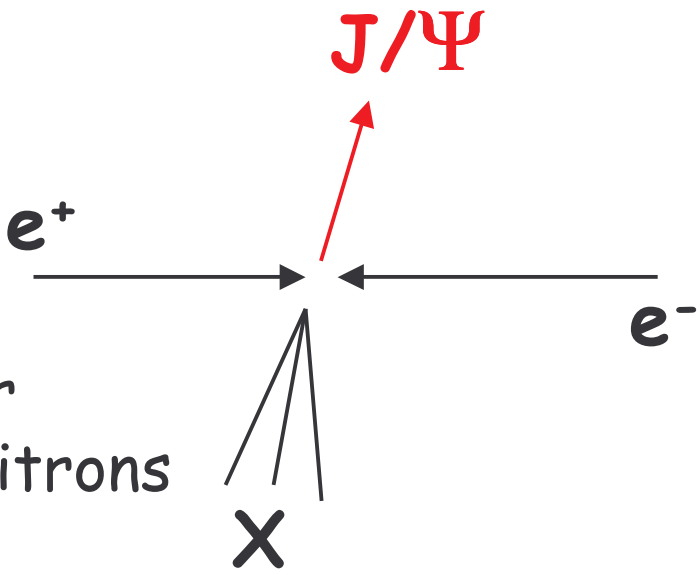
Use all SVD1 data

- 140 fb^{-1} on-resonance
- 15 fb^{-1} off-resonance

} => 155 fb^{-1} total

J/Ψ reconstruction:

- dr < 2 cm, dz < 4 cm
- $P_\mu = \mathcal{L}_\mu / (\mathcal{L}_\mu + \mathcal{L}_K + \mathcal{L}_\pi) > 0.5$
- $P_e = \mathcal{L}_e / (\mathcal{L}_e + \mathcal{L}_{non\text{-}e}) > 0.01$
- Add Bremsstrahlungsphotons closer than 50 mrad around electrons/positrons
- $|M_{ll} - M_{J/\Psi}| < 30$ MeV => 2.5 σ (sidebands = 100-400 MeV)



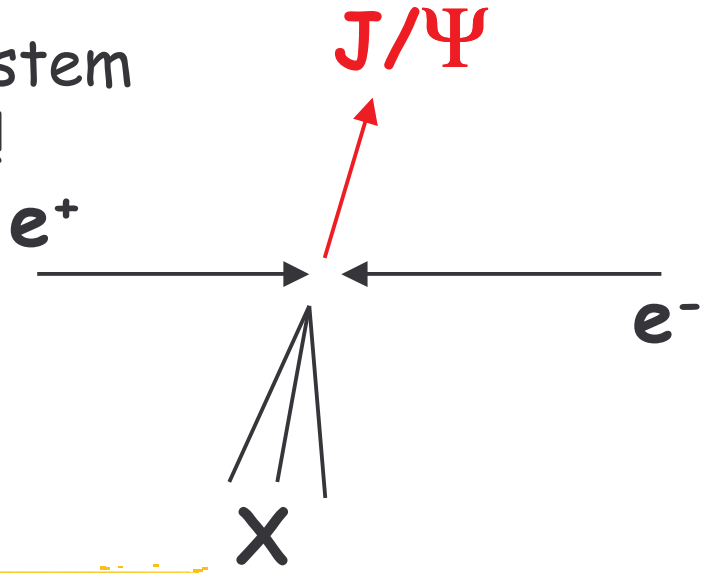
Recoiled mass

- Nch >= 4 suppresses QED background
- $P^*_{J/\Psi} > 2$ GeV suppresses BB background

Define the 'recoil mass':

$$M_{recoil} = \sqrt{(E_{CMS} - E^*_{J/\Psi})^2 - p^{*2}_{J/\Psi}}$$

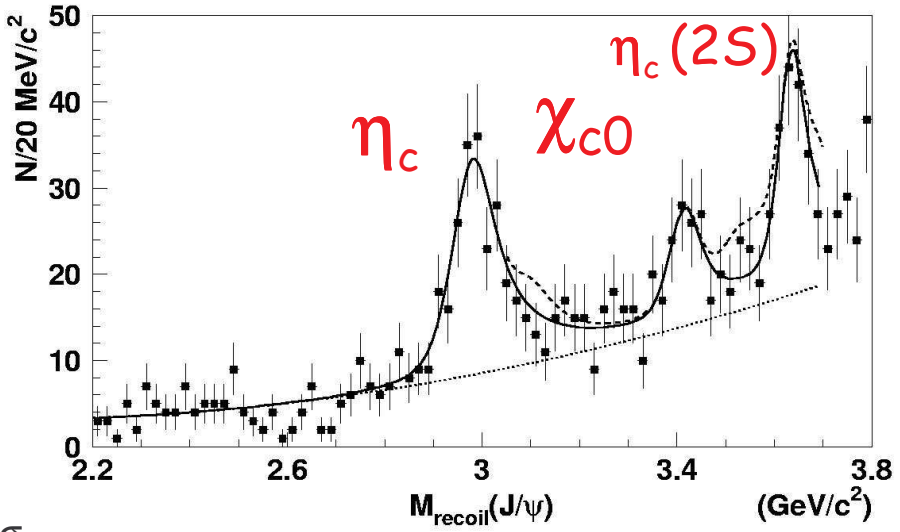
Invariant mass of the rest of the system is taken from kinematics of the J/Ψ!



The recoiled mass spectrum

—— set * to 0

----- set * to 90% C.L. upper limits



Yields for J/Ψ, χ_{c1} and $\Psi(2S)$ are compatible with 0!

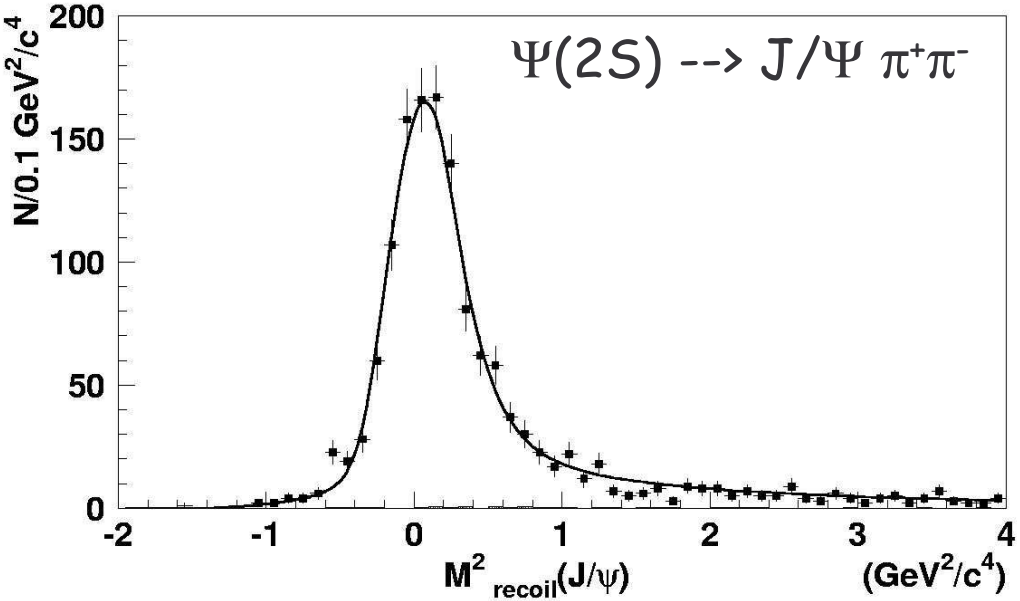
CC	M_{recoil}	N_{evt}	σ
η_c	2.972 ± 0.007	235 ± 26	10.7
J/Ψ	Fixed @ PDG	-14 ± 20	*
χ_{c0}	3.407 ± 0.011	89 ± 24	3.8
$\chi_{c1}+\chi_{c2}$	Fixed @ PDG	10 ± 27	*
$\eta_c(2S)$	3.630 ± 0.008	164 ± 30	6.0
$\Psi(2S)$	Fixed @ PDG	-26 ± 29	*

*: masses fixed at PDG value

$$\sigma = \sqrt{-\ln(\mathcal{L}_0/\mathcal{L}_{max})}$$

Calibrate M_{recoil} with e^+e^- -> $\Psi(2S)\,\gamma$

Fit $M^2_{recoil}(\Psi(2S))$
with free peak position



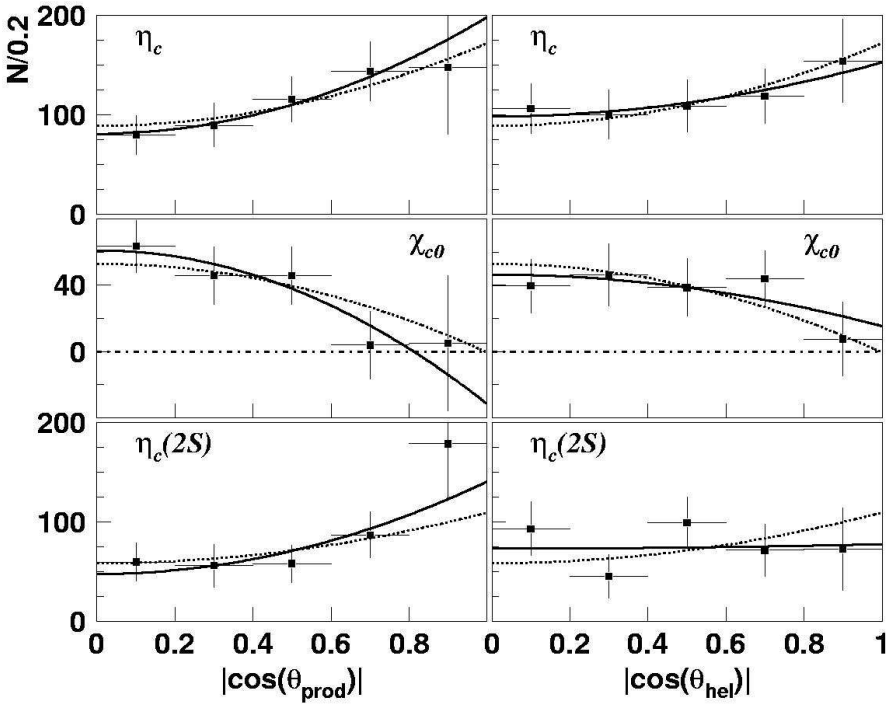
Very clean sample
-> <1% background
from non-$\Psi(2S)$

-> ΔM^2_{recoil} = 0.010 ± 0.009 GeV2/c4 (data/MC)

-> ΔM_{recoil} (J/Ψ) < 3 MeV/c for M_{recoil} (J/Ψ) = 3 GeV/c

=> Momentum scale is OK!

Angular analysis



Correct for efficiency and fit $1 + \alpha \cdot \cos^2\theta$

NRQCD (s-/d-wave):

*) α_{prod} / α_{hel} = +0.25/+0.25

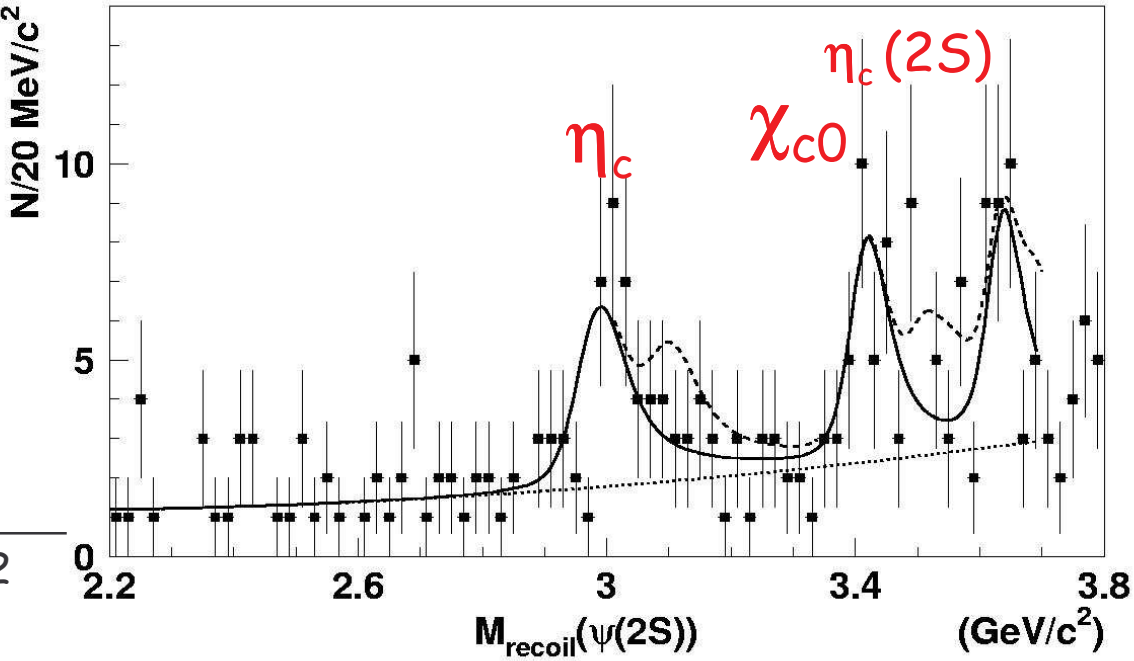
Glueball:

α_{prod} / α_{hel} = -0.9 /-0.9

	α_{prod}	α_{hel}	α_{prod}	α_{hel}	$\alpha_{prod} = \alpha_{hel}$
η_c	+1.4 +1.1/-0.8	+0.5 +0.7/-0.5	+1	+1	+0.93 +0.57/-0.47
χ_{c0}*	-1.7 +0.5/-0.5	-0.7 +0.7/-0.5	-1	-1	-1.01 +0.38/-0.33
$\eta_c(2S)$	+1.9 +2.0/-1.2	+0.3 +1.0/-0.7	+1	+1	+0.87 +0.86/-0.63

Look for e^+e^- -> $\Psi(2S)$ $c\bar{c}$

Reconstruction same as above,
$\Psi(2S)$ --> J/Ψ π^+ π^-



$c\bar{c}$	N_{evt}	σ
η_c	36.7 ± 10.4	4.2
J/Ψ	6.9 ± 8.9	*
χ_{c0}	35.4 ± 10.7	3.5
$\chi_{c1} + \chi_{c1}$	6.6 ± 8.0	*
$\eta_c(2S)$	36.0 ± 11.4	3.4
$\Psi(2S)$	-8.3 ± 8.5	*

5.3 σ observation of sum of η_c, χ_{c0}, $\eta_c(2s)$

Cross sections for J/Ψ and Ψ(2s)

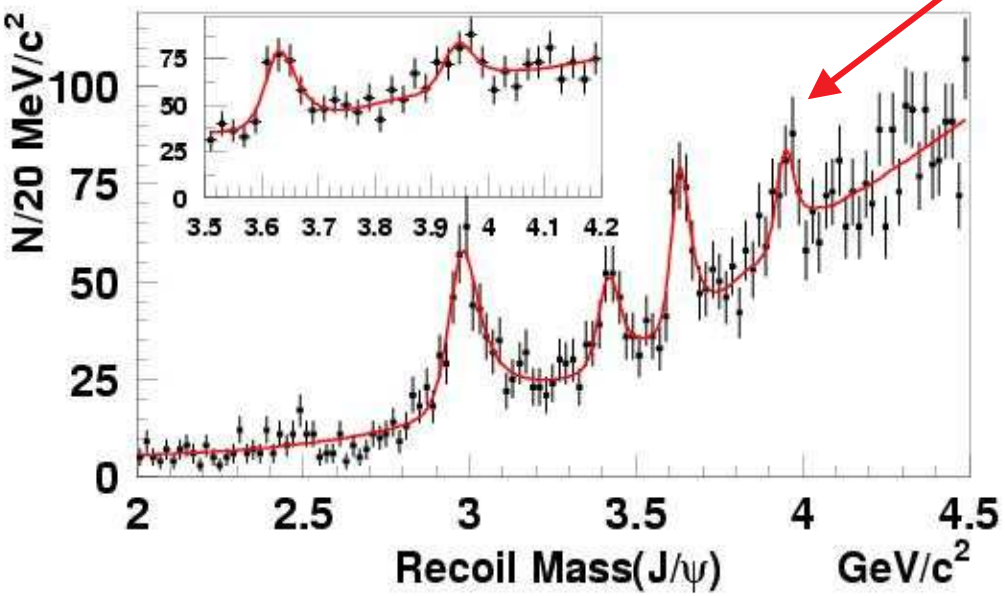
$C\bar{C}$	$\sigma_{Born} \times B((c\bar{c})_{res} \to$ J/ Ψ	> 2 charged [fb] Ψ(2s)
η_c	25.6 ± 2.8 ± 3.4	16.3 ± 4.6 ± 3.9
J/Ψ	< 9.1	< 16.9
χ_{c0}	6.4 ± 1.7 ± 1.0	12.5 ± 3.8 ± 3.1
$\chi_{c1} + \chi_{c2}$	< 5.3	< 8.6
$\eta_c(2S)$	16.5 ± 1.7 ± 0.4	16.3 ± 4.6 ± 3.9
Ψ(2S)	< 9.1	< 16.

Reminder from theory:

σ(e+e- --> J/Ψ η_c) ≈ 2 fb, see E.Braaten and J.Lee, PRD D67, 054007 (2003)

Very recent update

Whole Belle data set collected by
July 2004 L=285 fb^{-1}



Extend the studied region

- No signal of X(3872)
- Significant peak at M=3.940±0.011 GeV/c^2
- N=148±33 (4.5σ)
- The width is surprisingly narrow <~ resolution (= 32 MeV)

Summary and conclusion

- $e^+e^- \rightarrow J/\Psi\ (c\bar{c})_{res}$ was studied in detail:
  - $(c\bar{c})_{res} = \eta_c, \chi_{c0}, \eta_c(2s)$ are confirmed; angular analysis is done
  - $(c\bar{c})_{res} = J/\Psi, \chi_{c1}, \chi_{c2}, \Psi(2S)$ not seen Xsec 1 order of magnitude larger than theor. pred

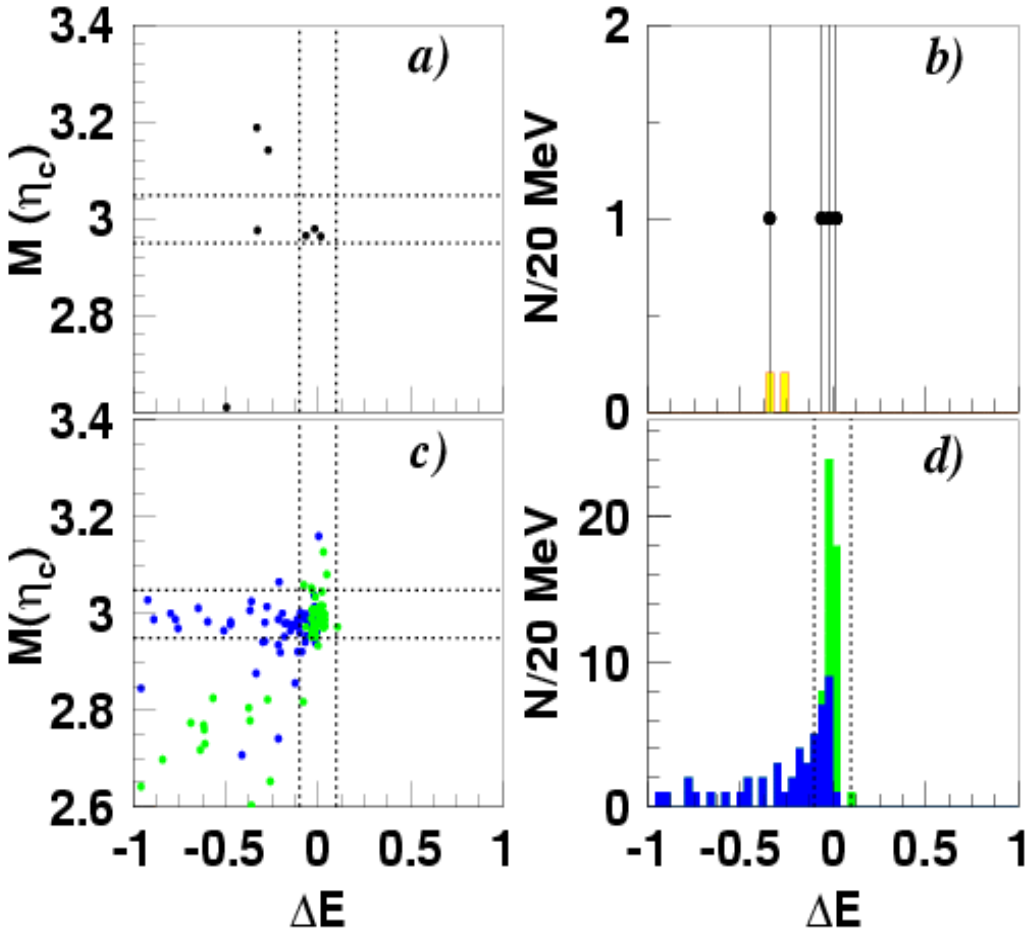
- 'e^+e^- --> $\Psi(2s)\ (c\bar{c})$' seen for first time, Xsection has same order of magnitude as for $J/\Psi\ (c\bar{c})$

- Strong evidence for new charmonium state @ 3.94 GeV with a small width

Some more details

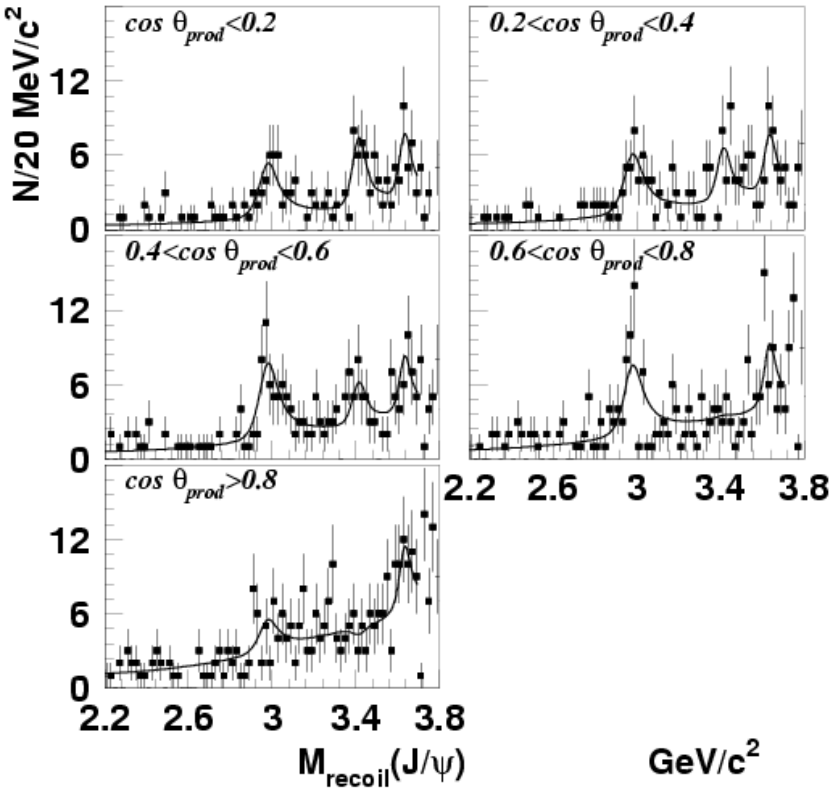
$e^+e^- \to J/\Psi(2S)\,\eta_c$ full reconstruction

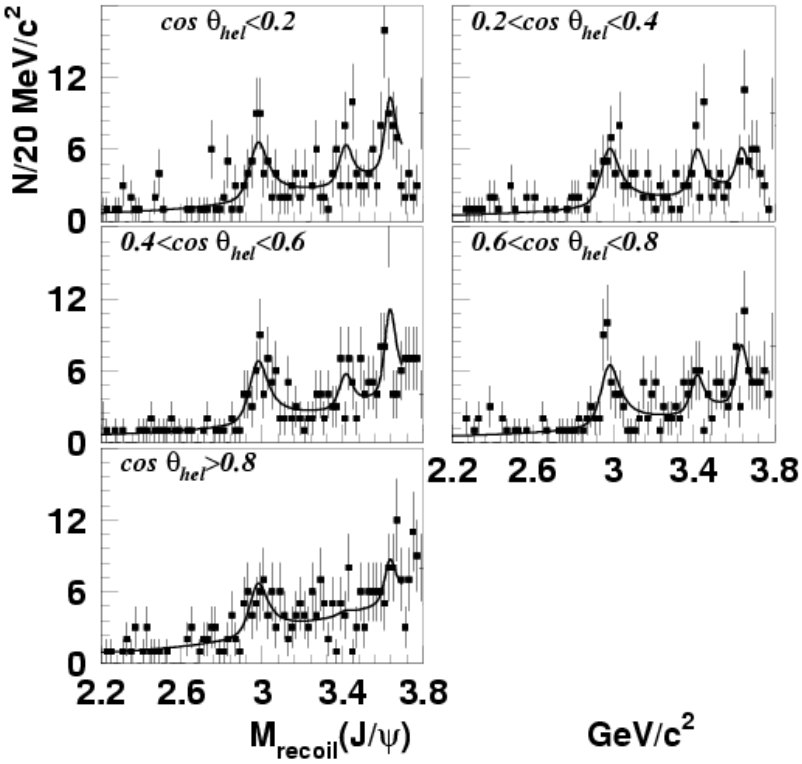
- $\eta_c \to K_s K\pi$, $KK\pi\pi$
- Require: $E_{J/\psi} + E_{\eta_c} \sim E_{cms}$
- 3 events are found in the data (>4σ)
- 2.6 events are expected from MC based on M_{recoil} fit yield



Angular anaysis

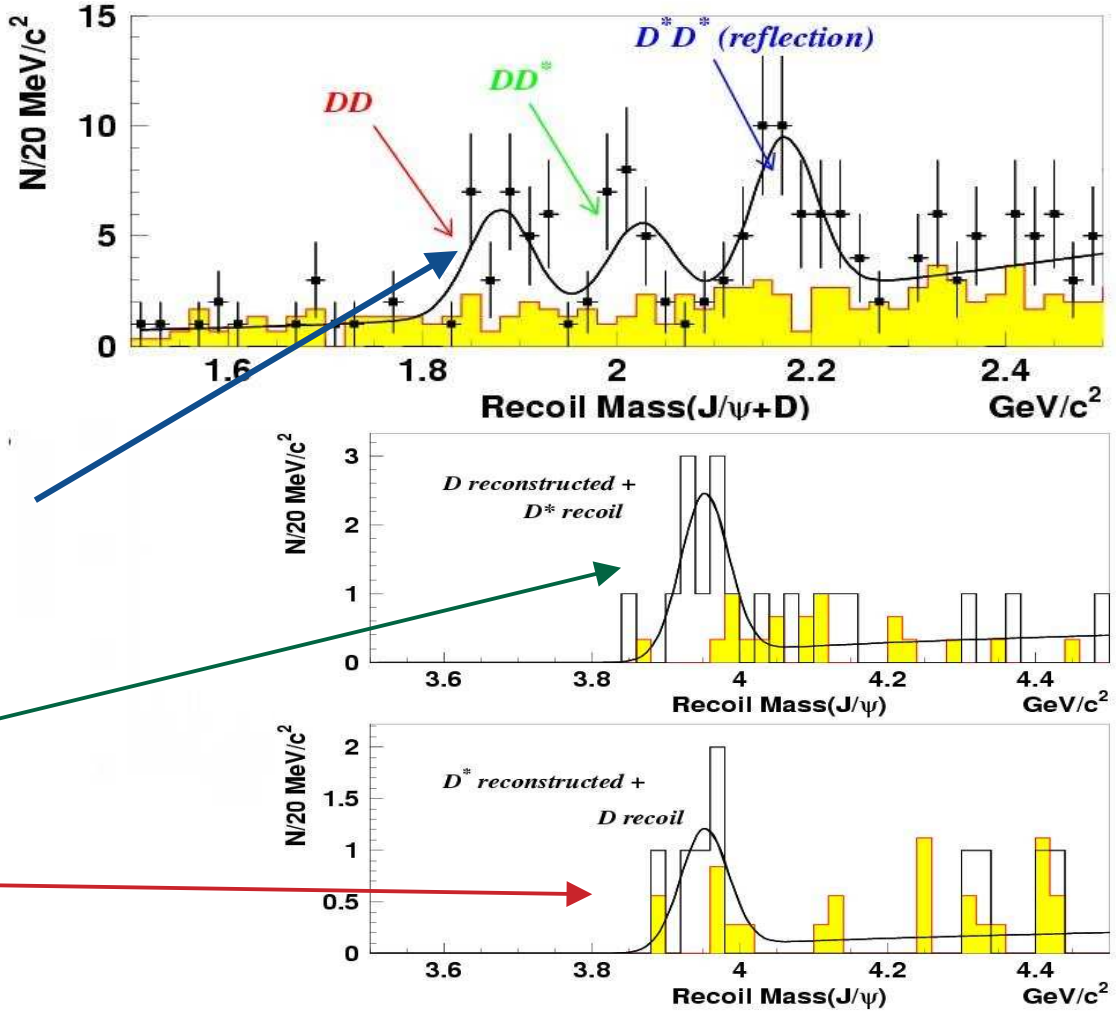
Fit $M_{recoil}(J/\psi)$ in bins of J/ψ production and helicity angles





Search for X(3940) -> DD(*)

- Idea: Reconstruct J/ψ and one D; Look for the second D(*) in the event at recoil mass against reconstructed (J/ψ D).
- Use only the cleanest $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$
- $e^+e^- \to J/\psi D^{(*)}D^{(*)}$+nothing clearly seen
- Look at M_{recoil} (J/ψ) when
  - M_{recoil} (J/ψ D) ~ M(D*) N=9.9±3.3 (4.5σ)
  - M_{recoil} (J/ψ D) ~ M(D) N=4.1±2.2 (2.1σ)



Charm physics…