Résultats récents de l'expérience BABAR sur le charmonium

Guy Wormser (LAL Orsay)

Plan de l'exposé

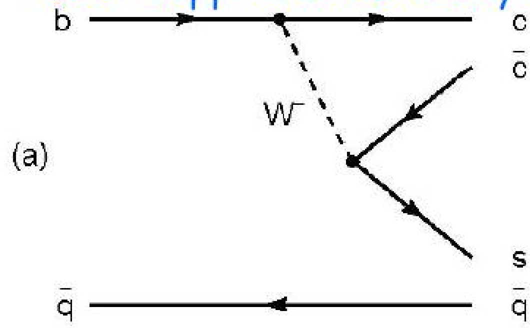
- Motivation : différents tests importants de QCD
  - Les différents modes de production
  - La spectroscopie
  - Les désintégrations
  - L'étude de la particule X(3872)
  - Les particules nouvelles de plus haute masse
- Présentation (très succincte) de BABAR
- Résultats récents sur le X(3872)
- Production de double charme
- Une méthode originale (qui apporte des informations sur tous ces aspects!) : l'étude inclusive de la désintégration des B en deux corps
- Conclusion

Intérêt renouvelé pour ce champ de physique

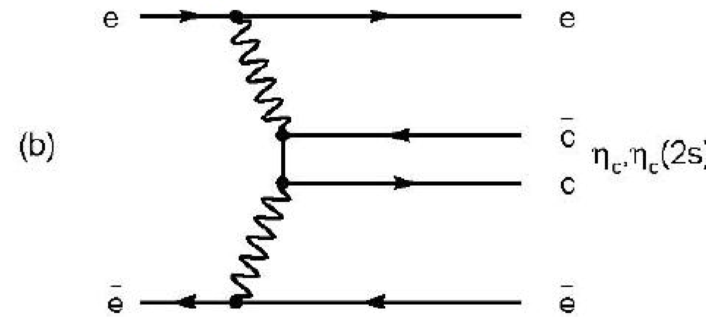
- Quarkonium workshop Octobre 2004
  - 100 expérimentateurs et 100 théoriciens
  - Quarkonium Working group, Yellow Report, (521 pages)
  - http://www.qwg.to.infn.it/YR/index.html
  - hep-ph/0412158 v1
- Séminaire de L. Maiani
  - http://www.slac.stanford.edu/exp/seminar/talks/2005/Maiani_4quarks.pdf
- Exposé de F. Close à Pékin

Charmonium production in e^+e^- collisions at 10.56 GeV

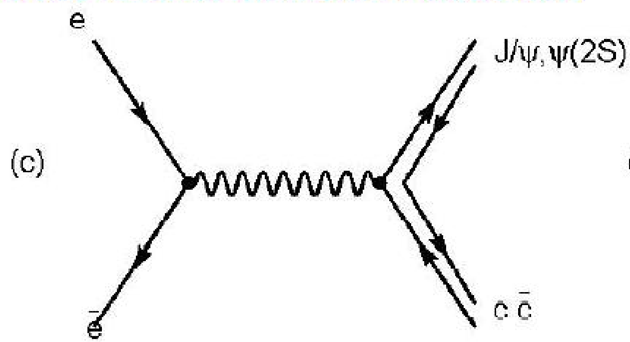
Color suppressed B decays



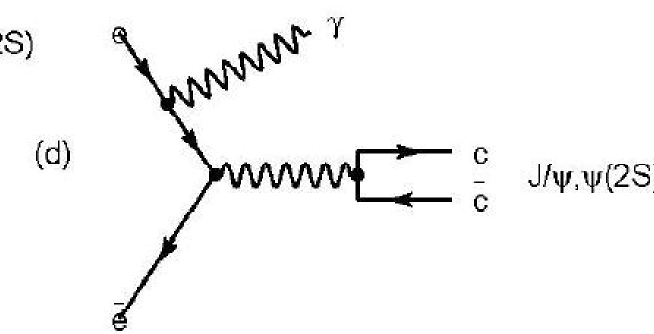
Two photon Production



Double Charmonium Production

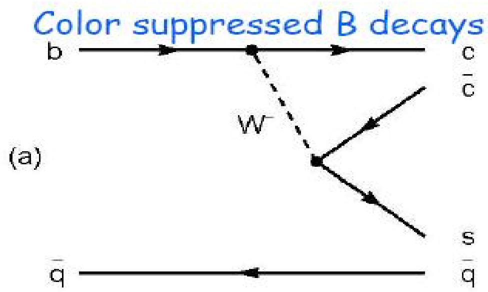


Initial State Radiation



Charmonium production in B decays

- B meson is an interesting charmonium factory



  - Large phase space, « democratic production » at zeroth order of all charmonium states
  - Selection rule : Factorisation suppression for χ_0 , χ_2 states. Is it respected? Can we undestand the source of the violations if any
  - Understand the pattern in ψ,ψ',ψ'', η_c,η'_c,χ_1 production rates

Search for Factorization-Suppressed $B \to \chi_{cJ} K^{(*)}$ Decays : Motivation

Hypothesis: Factorization of hadronic currents:

$$\langle XY|\mathcal{H}_{eff}|B\rangle = \langle X|\mathcal{J}_{EW}|0\rangle\langle Y|\mathcal{J}_S|B\rangle$$

Terms in J_{EW}:

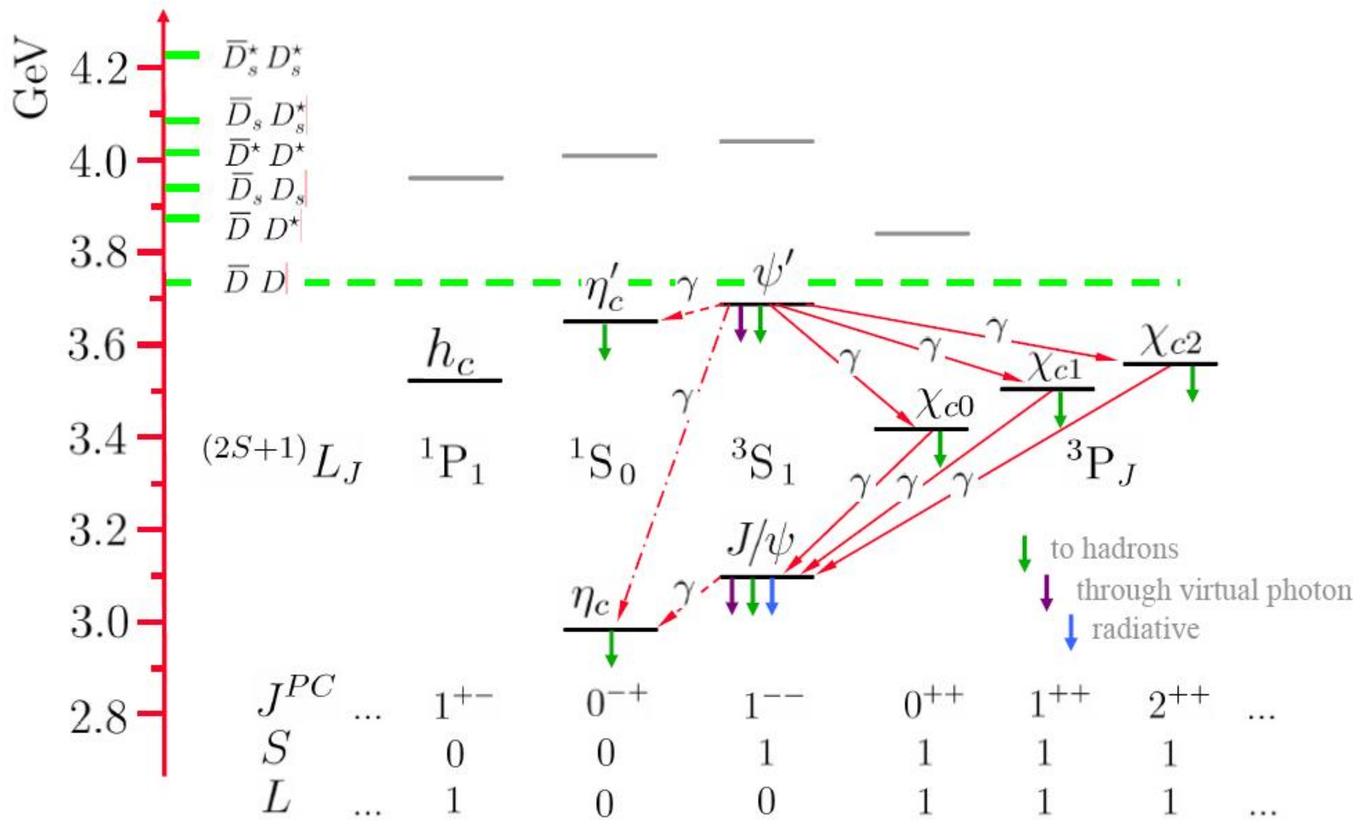
$$\begin{aligned}
\langle S(q)|\bar{c}\gamma^\mu c|0\rangle &= -if_S q^\mu \\
\langle P(q)|\bar{c}\gamma^\mu \gamma_5 c|0\rangle &= -if_P q^\mu \\
\langle V(q,\varepsilon)|\bar{c}\gamma^\mu c|0\rangle &= -if_V m_V \varepsilon^\mu \\
\langle A(q,\varepsilon)|\bar{c}\gamma^\mu \gamma_5 c|0\rangle &= -if_A m_A \varepsilon^\mu
\end{aligned}$$

- Weak current produces no $J=2$: $\Rightarrow \chi_{c2}$ suppressed.
- $J^{PC}=1^{--}$ (J/ψ, $\psi(2S)$), and $J^{PC}=1^{++}$ (χ_{c1}) allowed
- $J^{PC}=0^{++}$ (χ_{c0}) forbiden   M. Diehl, G. Hiller, JHEP 0106:067,2001, hep-ph/0105194

But sizeable $B \to \chi_{c0} K^+$ was found:

- $(6.0^{+2.1}_{-1.8} \pm 1.1) \times 10^{-4}$, Belle PRL **88** 031802 , $(2.7 \pm 0.7) \times 10^{-4}$, *BABAR* PRD **69** 071103

Charmonium spectroscopy



Interesting topics in charmonium spectroscopy

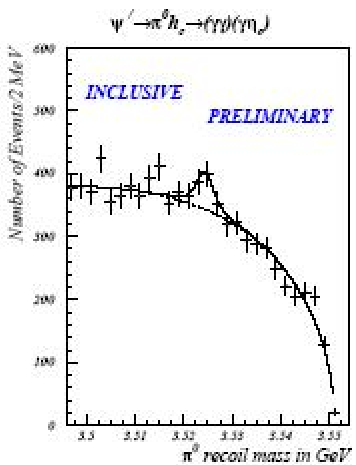
- η_c' mass to measure the (2S) hyperfine splitting
- h_c mass to compare with χ states c.o.g.
- New high mass objects
- η_c' and η_c widths

Status on h_c meson

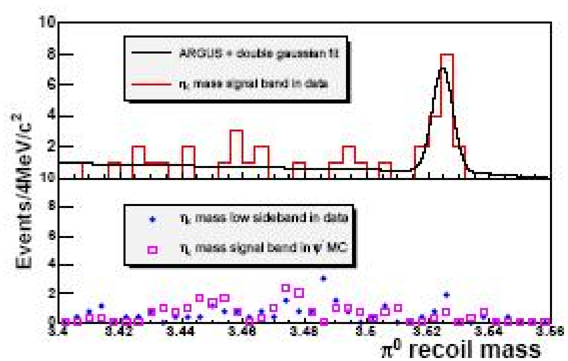
- CLEO_c recently got finally convincing (preliminary) evidence for h_c in the decay

$\psi' \rightarrow \pi^0 + h_c$; $h_c \rightarrow \gamma\eta_c$

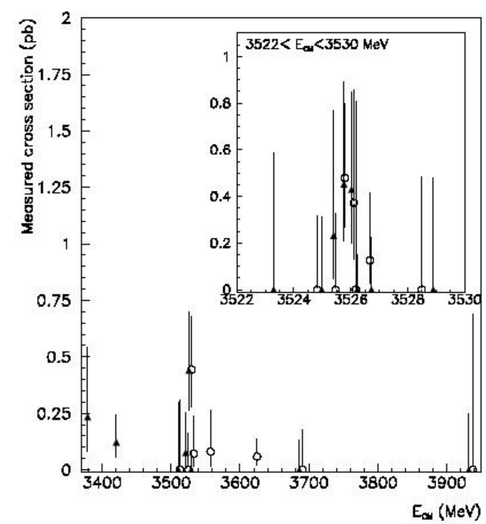
Also from E835 ($p\bar{p} \rightarrow \eta_c\gamma \rightarrow \gamma\gamma\gamma$)



hep-ex/0410090



M=3524.4 ± 0.9 MeV/c^2 right on top the c.o.g 3525.3 ± 0.1 MeV/c^2



M=3525.8 ± 0.2 ± 0.2

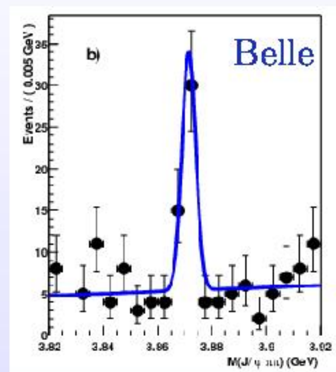
p<.001

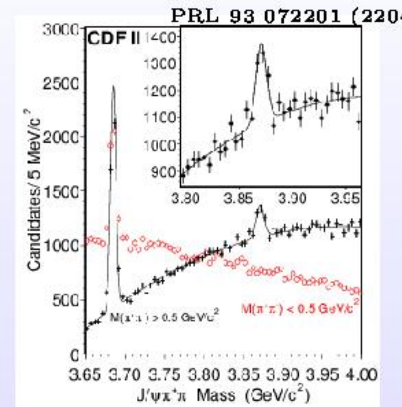
hep-ex0410085

La découverte de la particule X(3872) (Nov. 2003)

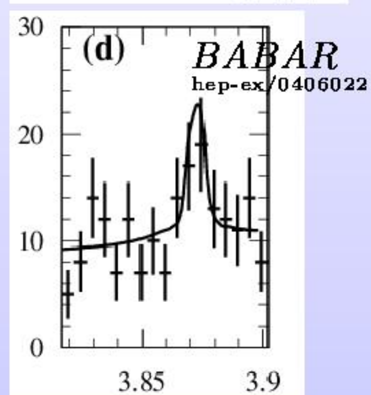
$X(3872) \to J/\psi\, \pi^+\pi^-$: discovered and confirmed

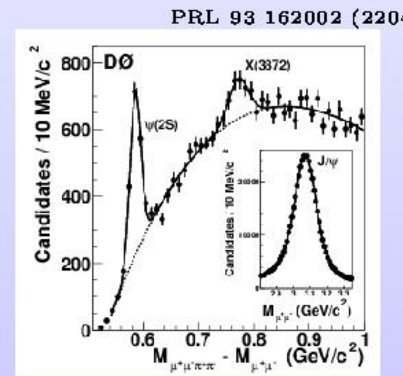
- Discovery of a narrow charmonium-like new particle X(3872) by Belle (140 fb^{-1}): (PRL 91 262001 (2003))





- Then confirmed by CDF II, D0 and BaBar





- Averaged mass = 3871.9 ± 0.5 MeV
  - within errors at the $D^0\bar{D}^{*0}$ threshold

R. Chistov XXXXth Rencontres de Moriond QCD, March 12-19 2005 p. 2

Quelle est la nature du X(3872)?

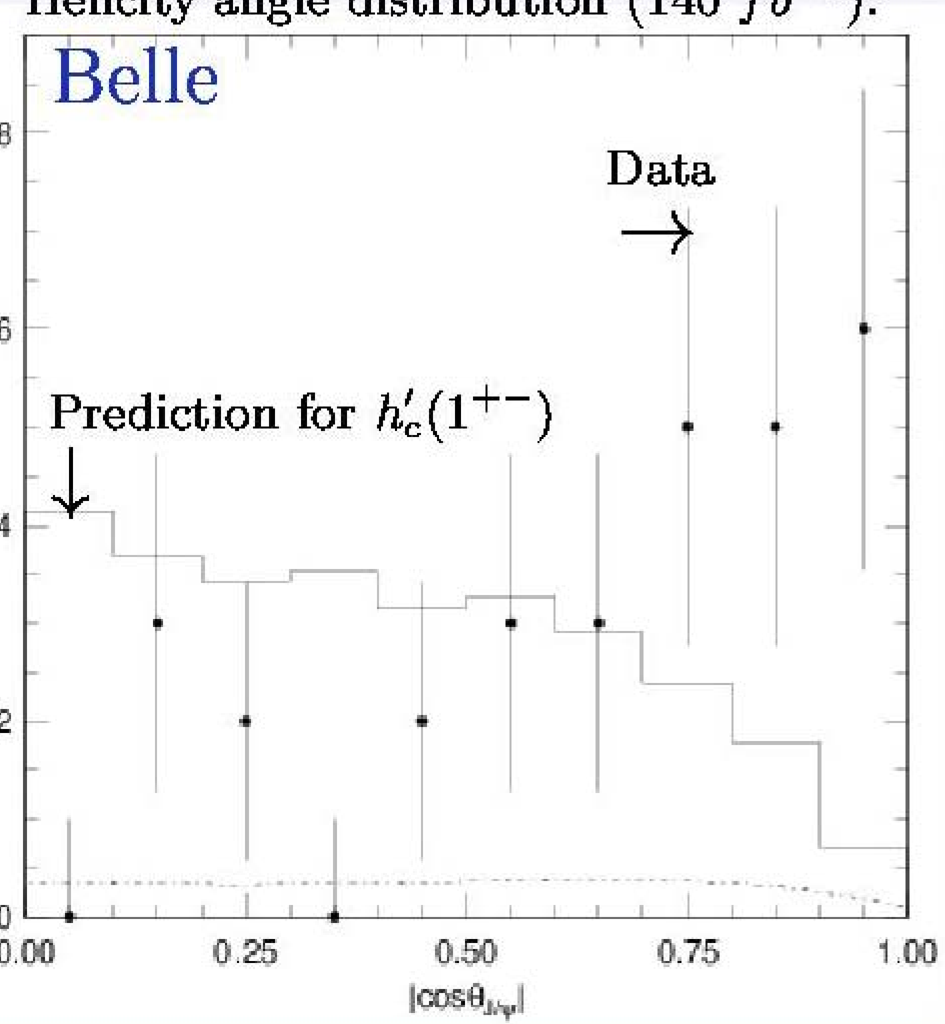
- Les différentes hypothèses
  - Etat charmonium classique
  - Molécule D-D*
  - Etat hybride
  - Etat tétra-quark
- Les informations nécessaires
  - Spin-Parité
  - Partenaire chargé
  - Modes de désintégration:
    - BR($X \rightarrow \psi\pi\pi$)
    - $\pi\pi=\rho$?
    - BR($X \rightarrow \psi\omega$)
    - Radiative decays
  - $B^0 \rightarrow X K^0$

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Measured properties of $X(3872)$ by Belle

PRL 91 262001 (2004), hep-ex/0407033, BELLE-CONF-0439

Helicity angle distribution ($140\ fb^{-1}$):



- $\Rightarrow \mathcal{B}(B^+ \to XK^+,\ X \to J/\psi\ \pi^+\pi^-)$ too high for η_{c2} $(1^1D_2, J^{PC} = 2^{-+}$ with dominant $\eta_{c2} \to \eta_c\pi^+\pi^-,\ h_c$
- $\Rightarrow$ Inconsistent ($\chi^2/ndof = 75/9$) with $h_c'(2^1P_1, J^{PC} = 1^{+-})$
- $\Rightarrow \frac{\mathcal{B}(X \to J/\psi\ \gamma)}{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-)} < 0.40$ @ 90% CL too small for χ_{c1}' $(2^3P_1,\ J^{PC} = 1$
- $\Rightarrow \frac{\mathcal{B}(X \to \chi_{c2}\gamma)}{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-)} < 1.1$ @ 90% CL too small for ψ_3 $(1^3D_3,\ J^{PC} = 3$
- $\Rightarrow \frac{\mathcal{B}(X \to \chi_{c1}\gamma)}{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-)} < 0.89$ @ 90% CL too small for ψ_2 $(1^3D_2,\ J^{PC} = 2$
- $\Rightarrow \frac{\mathcal{B}(X \to D\bar{D})}{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-)} < 7$ @ 90% CL and narrow width $\Gamma < 2.3\ MeV$ suggests $J^{PC} = 0^+, 1^-, 2^+$ are rule
- $\Rightarrow M(\pi^+\pi^-)$ tends to peak near ρ^0

- The **existence** of gluonic excitations in the hadron spectrum is one of the most important unanswered questions in hadron physics. Hybrid meson: formed by a quark-antiquark pair with an excited gluonic degree of freedom. Lattice gauge theory and hadron models predict a rich spectroscopy of charmonium hybrids i.e. states non-consistent with the constituent quark model
  - $J^{PC} = 1^{-+}$ state: $M(\psi_g) \sim 4$ GeV , lying in the vicinity of $D^{**}D$ threshold: tantalizing possibility of a relatively narrow state if below!

  Charmonium hybrids can be **produced** and detected in *B* decays:
  - $B \to \psi_g + X$, $BF[B \to \psi_g(\text{all } J^{PC})+X] \sim 1\%$ if $M < 4.7$ GeV

- There are three important **decay modes** for charmonium hybrids:
  - Decays to $D^{(*,**)} D^{(*,**)}$: the challenge is to identify decay modes which can be exp reconstructed
  - Decays to (ccbar)+(light hadrons): the cleanest signature if the BF is large enough, e.g.

    $\psi_g \to (\psi, \psi')$+(light hadrons) Kuang-Yan mechanism

    Also radiative decays may be relevant, e.g.

    $\psi_g \to (J/\psi, h_c)+\gamma$ E1 transition
  - Decays to light hadrons: Offer the possibility of producing light exotic mesons

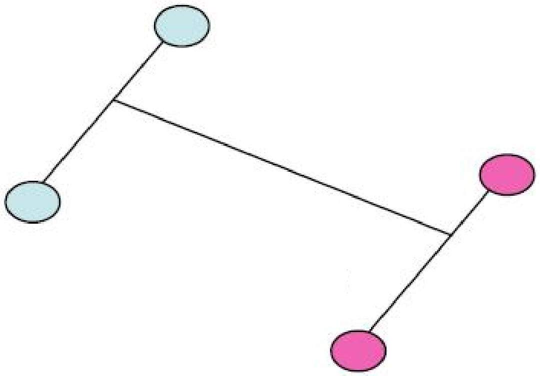
Les candidats hybrides

F. Close, et al.
Phys Lett B574 (2003) 210

ψ_g State	Final State	4.1 GeV BR (%)	4.4 GeV BR (%)
1^{-+}	D^*D	7.3	0.3
	$D^{**}(2^+)D$	-	1.3
	$D^{**}(1^+_H)D$	-	63.5
	$D^{**}(1^+_L)D$	-	9.4
	$\eta_c\pi\pi$	0.9	0.3
	light hadrons	91.7	39.4
	$\Gamma_{Total}(MeV)$	10.9	39
2^{+-}	D^*D	60	5.1
	$D^{**}(2^+)D$	-	12.8
	$D^{**}(1^+_H)D$	-	76.9
	$J/\psi\pi\pi$	20	2.6
	light hadrons	20	2.6
	$\Gamma_{Total}(MeV)$	0.5	3.9
0^{+-}	$D^{**}(1^+_L)D$	-	62.2
	$D^{**}(1^+_H)D$	-	37.3
	$J/\psi\pi\pi$	50	0.2
	light hadrons	50	0.2
	$\Gamma_{Total}(MeV)$	0.2	40.2

L'hypothèse tétraquark (Maiani et al.)

The present work (1)



Recent evidence for σ at low energy led us to reconsider the case of sub-GeV scalar mesons.
Many previous investigations (Joffe, Close&Tornqvist, Schecter and coll...).

We propose:

- ***all scalars below 1 GeV are diquark-antidiquark bound states (1 nonet),***
- ***the q-qbar scalar nonet (L=1, S=1, J=0) has to be above.***

Results:

• Low energy states show inverted mass spectrum, consistent with "perfect mixing";
• Strong decays are reasonably accounted for;
• Relations with ealier proposal by Rossi&Veneziano suggests connection to baryon-antibaryon, rather than meson-meson states (or molecule)

PRL **93**, 212002 (2004), hep-ph/0407017

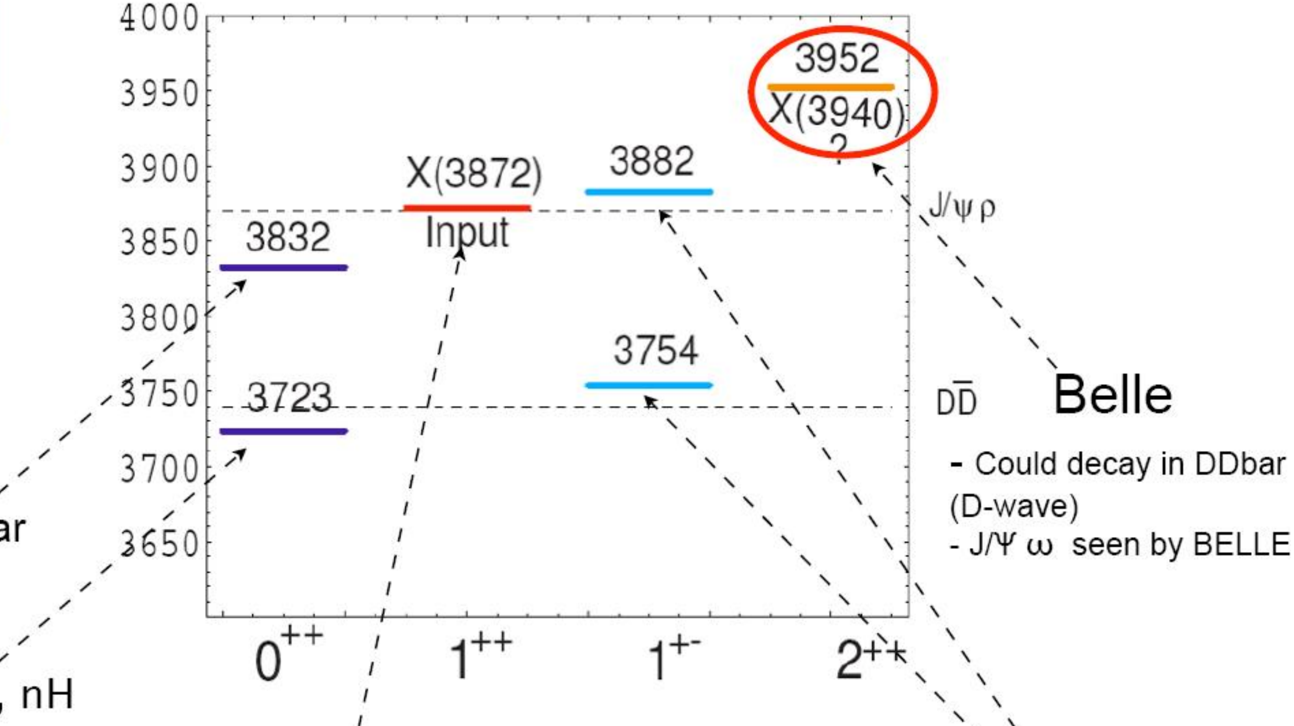
SLAC. 25/02/05 L.MAIANI. Scalar Mesons & 4-quarks 7

The present work (2)

PR D70 054009 (2004), hep-ph/0407028; hep-ph/0412098 (PR D71, 014028, 2005)

- Heavy quark interactions are spin independent: new spin states?
  - We propose that X(3872) observed by Belle and by Babar ***is a diquark-antidiquark bound state and estimate the spectrum of states of the spin multiplet with the same flavors:***
  - X(3872)=(J=1^{++})= $(cq)_{col=\bar{3},S=1}(\bar{c}\bar{q})_{col=3,S=1}$
  - with the same parameters, we can accommodate the X(2632) observed by SELEX:
  - X(2632)=(J=2^{++}) = $(cq)_{col=\bar{3},S=1}(\bar{s}\bar{q})_{col=3,S=1}$
- ***we predict X(3872) is made by two states with Δm = (5-8) MeV ≈ 2 (m_d - m_u)***
- ***if one state only in the decay: $B^+ \to K^+ X(3872)$, the other must appear in $B^0 \to K_S X(3872)$***
- ***a charged partners must exist:*** $X^+ = (cu)_{col=\bar{3},S=1}(\bar{s}\bar{d})_{col=3,S=1}$
- ***bounds to the production of X^+ are close but not in contradiction with BaBar.***

X-states



$$[cq]_{S=1}(\bar{c}\bar{q})_{S=0}+(cq)_{S=0}[\bar{c}\bar{q}]_{S=1}$$

-Unnatural spin-parity forbids decay in DDbar
Consistent with observed decays in J/Ψ+V.
-It decays both to ρ and ω due to isospin breaking in its wave function.

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D-D* molecule

- one state only: D^0-D^{*0}
- ... and very extended:
- $$R = \frac{1}{\sqrt{2M_D E_{bind}}} \sim 4\ fm$$
- most of the time (70-80%), D and D* are too far to exchange a c-quark and form a J/Ψ;
- for a tight state: $BR(\Psi' \to \Psi\pi^+\pi^-) \approx 0.3$, maybe: $BR(X \to \Psi\ \pi^+\pi^-) \approx 0.03$
- the measure of inclusive $B(B^+ \to XK^+)$ determines the X BR from the overall ratio:
- $$R = \frac{B(B^+ \to XK^+)B(X \to J/\Psi\ \pi^+\pi^-)}{B(B \to \Psi' K^+)B(\Psi' \to J/\Psi\ \pi^+\pi^-)} = 0.063 \pm 0.014$$
- and give an important clue (G. Wormser, yesterday talk).

Towards a new spectroscopy(?)

Recent observations of new states (D_{sJ}, X(3872)...)

- several models have been developed
- Are we at a stage where we can start to discriminate among them?

e.g molecular model predicts highly suppressed $B^0 \rightarrow X(3872) K_s$

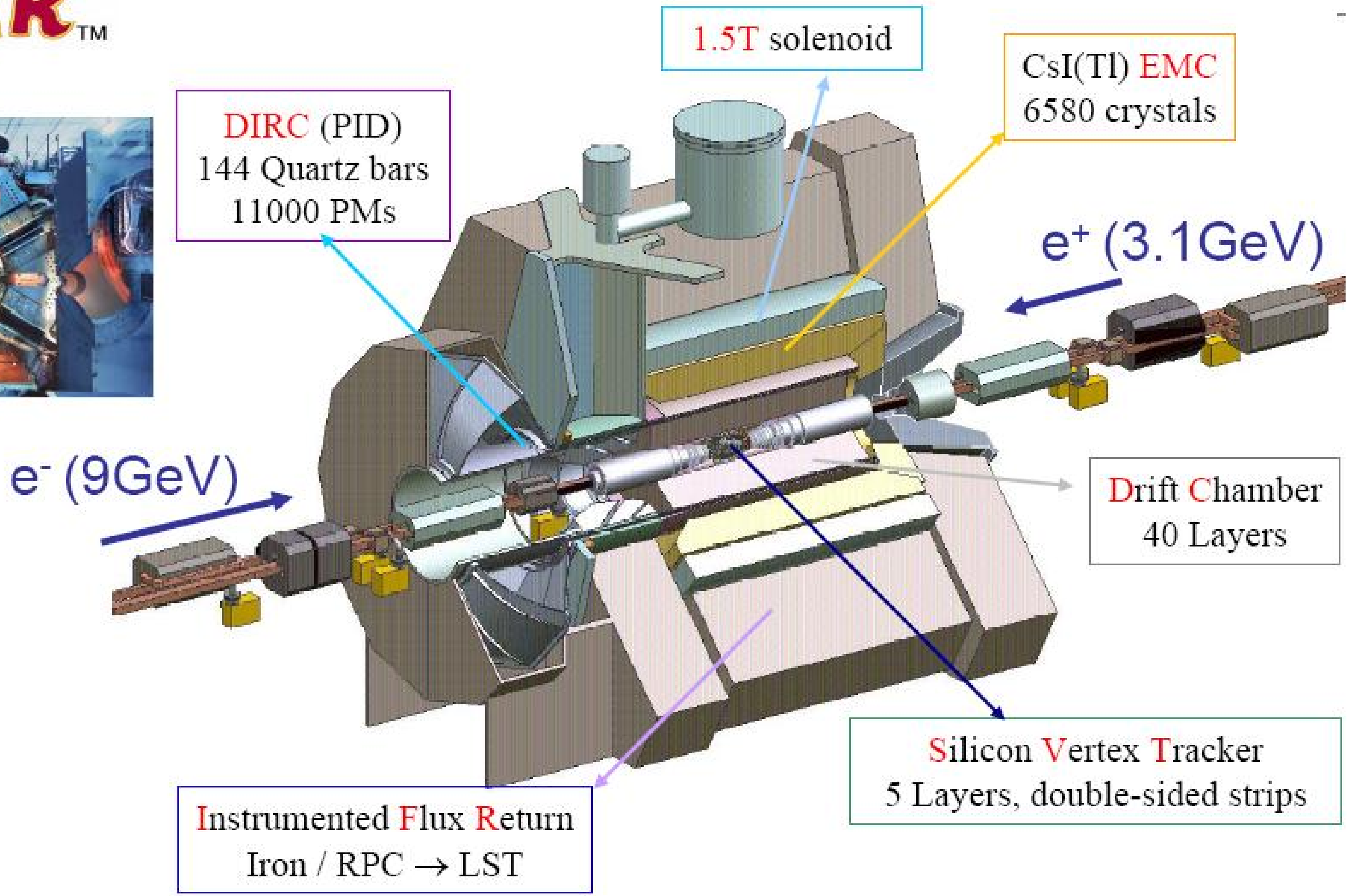
E. Braaten, M. Kusunoki
hep-ph/0412268

4-quark model predicts different masses between X(3872) in B^0 and B^+ decays

$$|\Delta M| > 5 \text{ MeV}/c^2$$

L. Maiani, F. Piccinini.
A.D. Polosa, V. Riquer
PRD 71 (2005) 014028

BABAR™



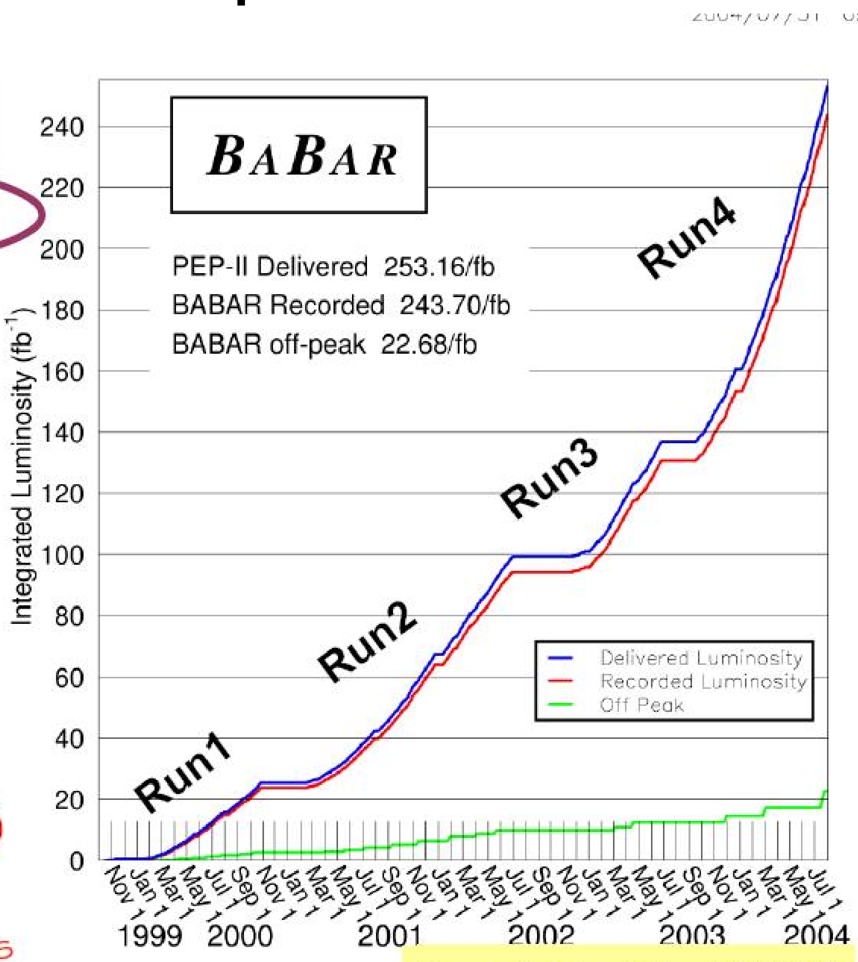
11 countries, 80 Institutes, 600 physicists

La statistique accumulée par BABAR

PEP-II Records	
Peak luminosity	0.923×10^{34} $cm^{-2}\ s^{-1}$
Best shift	246.3 pb^{-1}
Best day	710.5 pb^{-1}
Best 7 days	4.464 fb^{-1}
Best week	4.464 fb^{-1}
Best month	16.72 fb^{-1}
Best 30 days	17.04 fb^{-1}
BABAR logged	246.4 fb^{-1}

lumi: 3x design

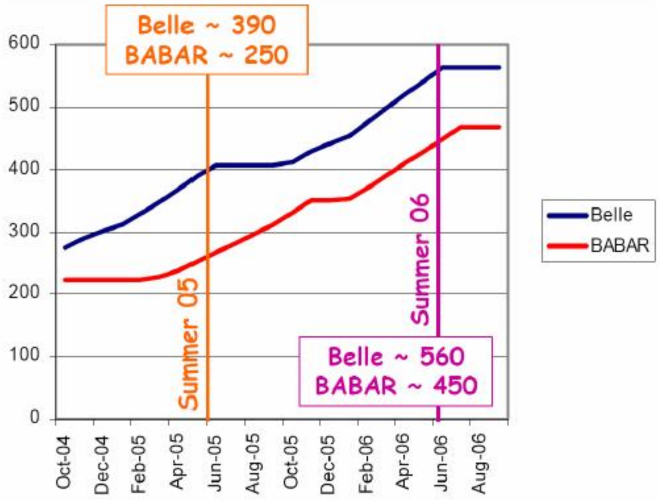
~245 million $B\bar{B}$ pairs



(as of July 31, 2004)

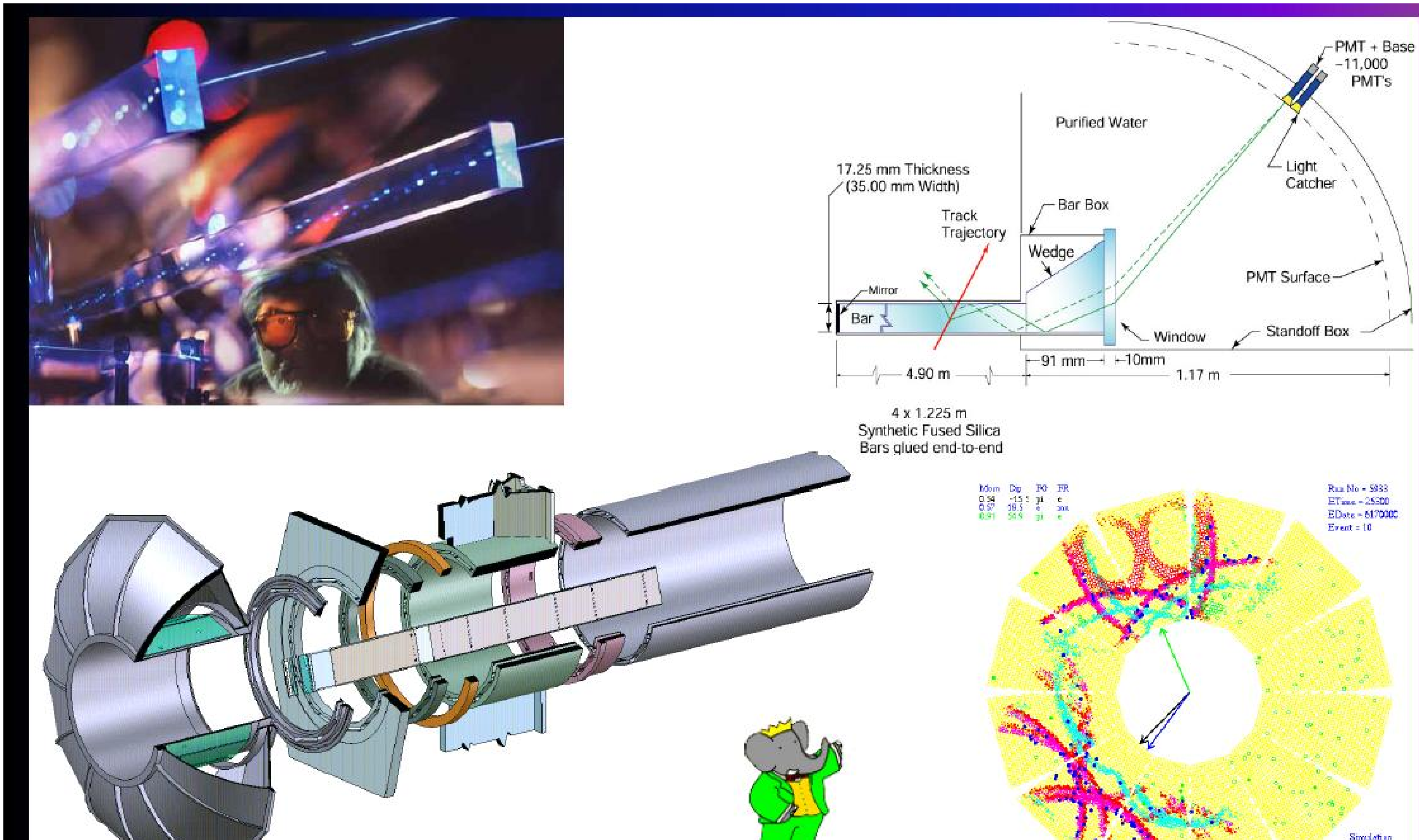
Les conséquences de l’accident de sécurité du 11/10/2004

- Short-term scenario
  - resume data taking this month (mid-March 2005)
  - continuous running (except short break in December 2005)
  - goal of doubling the data sample by Summer 2006



- Longer-term goal
  - doubling again the data sample by Summer 2008
- Future of BABAR *after* 2008 is uncertain
  - competitiveness once ultimate PEP-2 luminosity is reached?

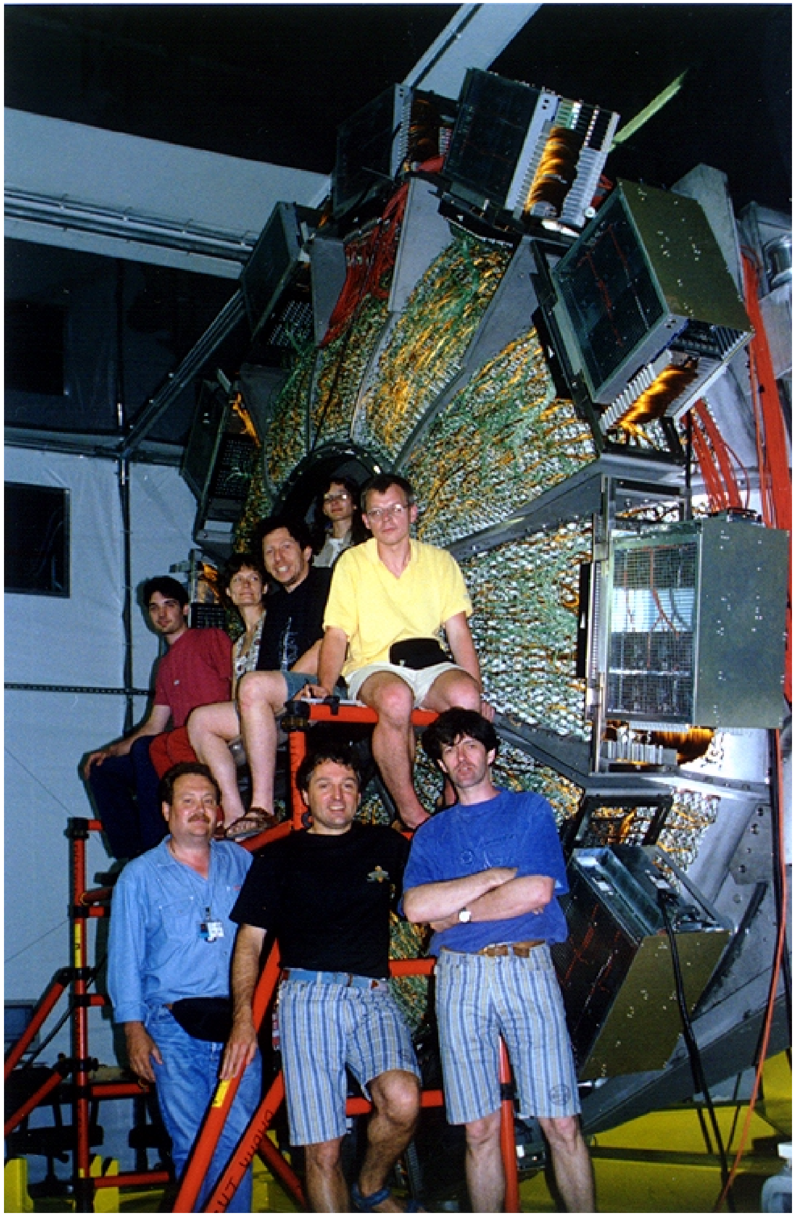
Le DIRC, compteur Cerenkov de BABAR



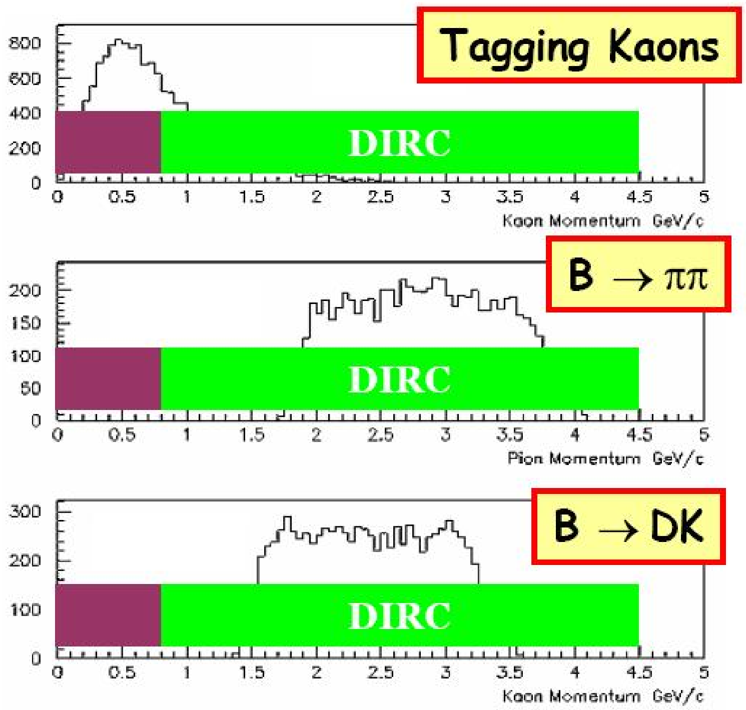
Une très grande partie de l’électronique a été construite au LAL (chips front-end, cartes de lecture, cables, chassis,..)

Ainsi que des parties importantes de la mécanique (embases des phototubes, réflecteurs de lumière)

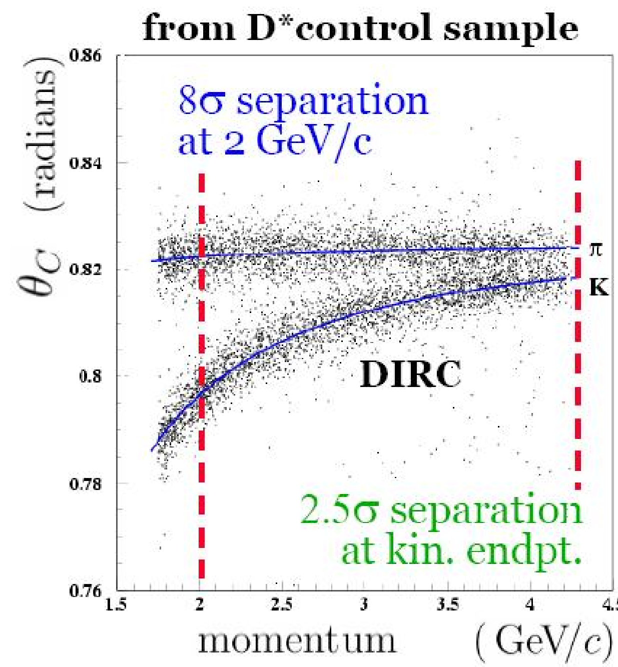
Le DIRC dans sa zone d’assemblage en 1998



Les performances du DIRC



Note: in two-body decays, full dip angle/momentum correlation due to boost



★ Simulateous $\pi\pi/K\pi$ analysis

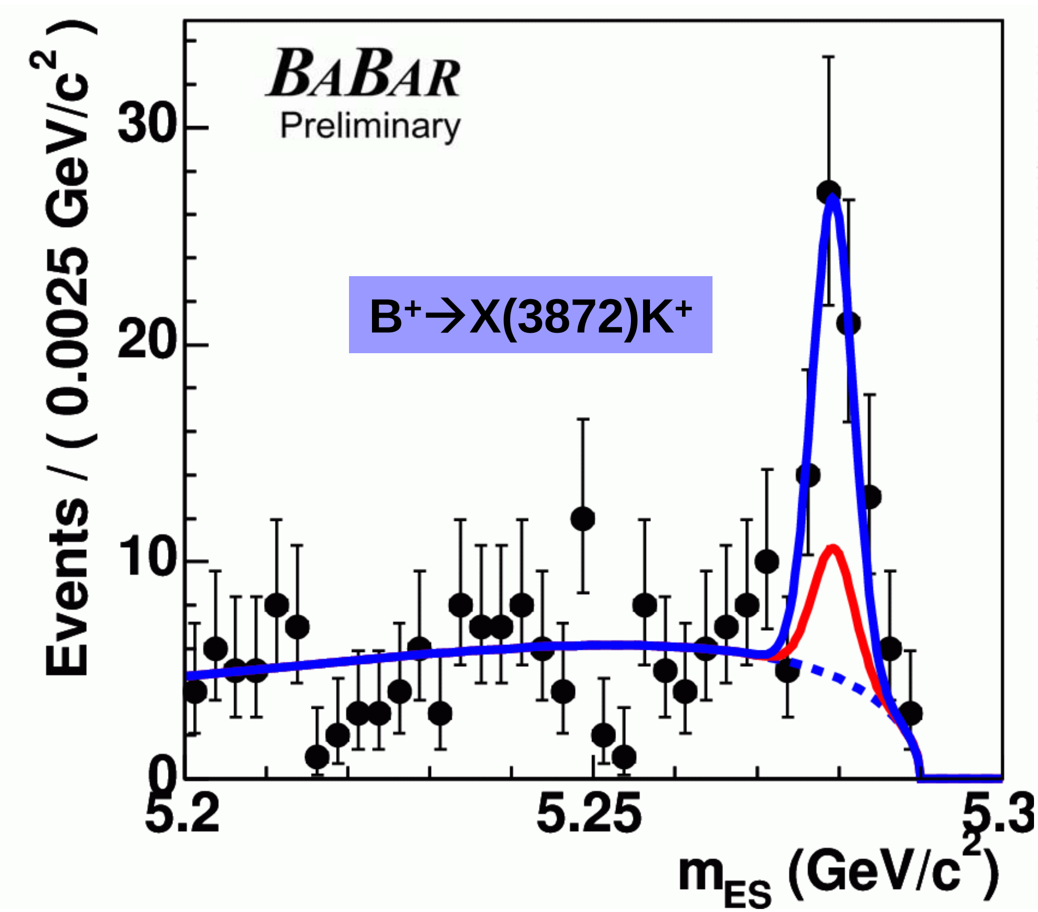
Cherenkov angle as a discriminating variable in the Maximum Likelihood Fit

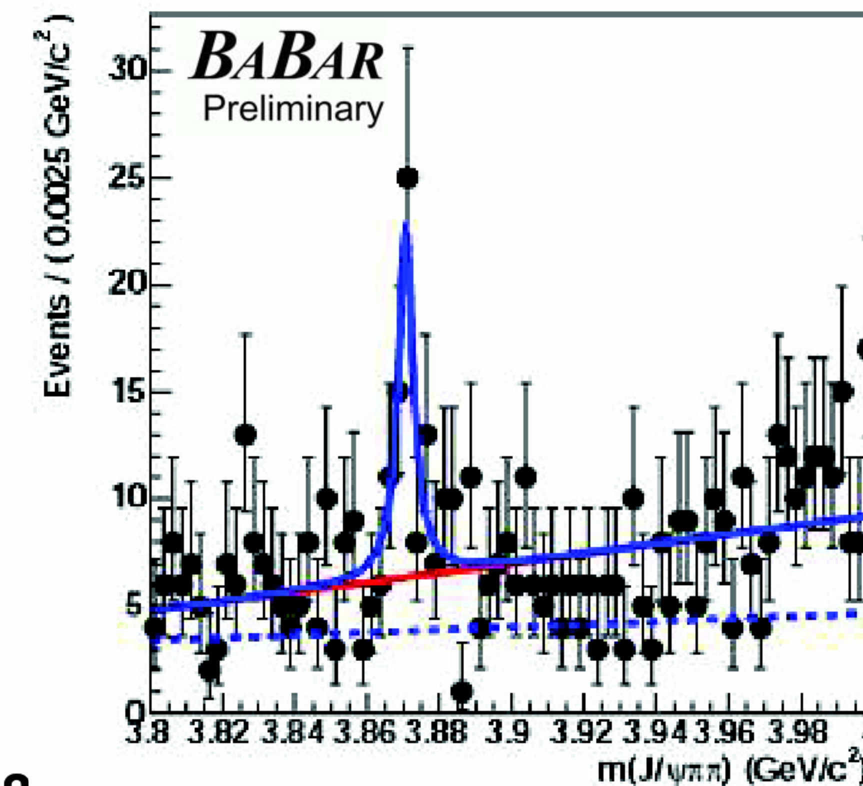
Nouveaux résultats de BABAR concernant le X(3872)

- Mesure du canal $X \rightarrow \psi\pi\pi$ avec toute la statistique disponible dans les deux canaux:
  - $B^+ \rightarrow X\, K^+$
  - $B^0 \rightarrow X\, K^0$

$B^+ \to X(3872)K^+$ with $X \to J/\psi\ \pi\pi$

244 fb^{-1}





$N=51\pm14$ 6.9σ

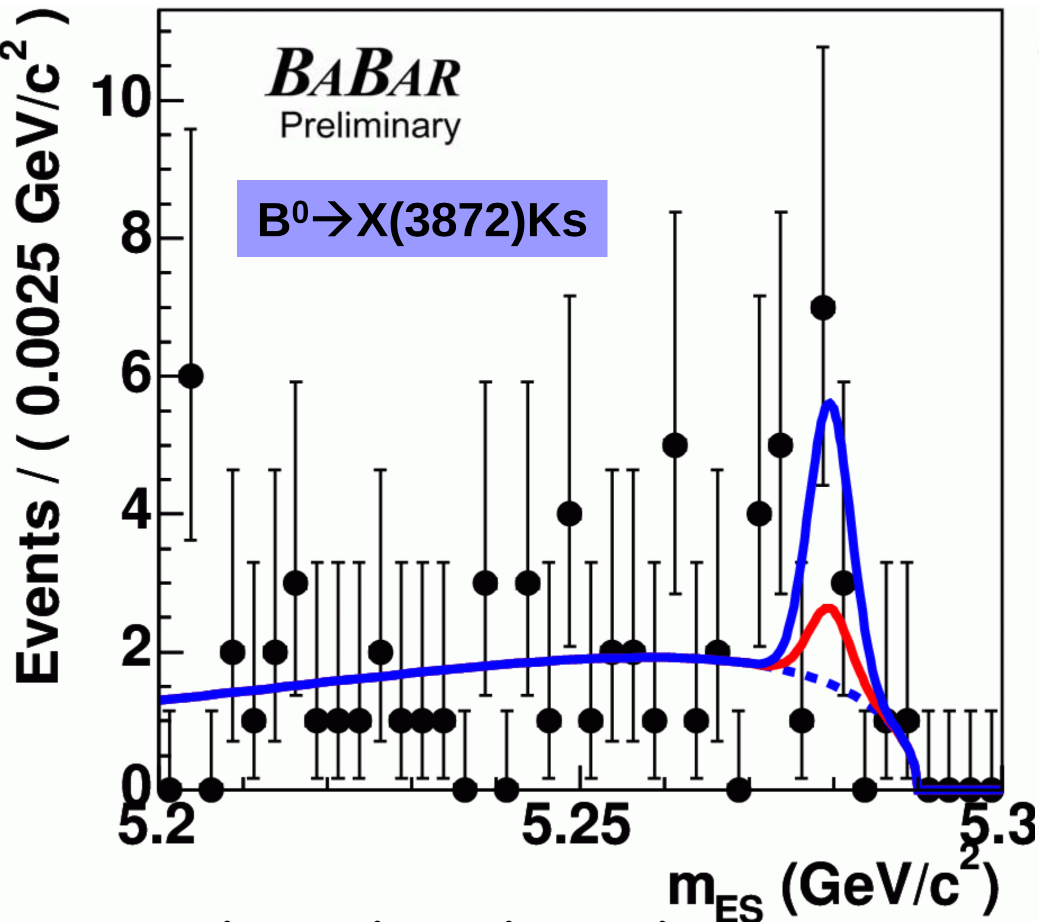
$m_X=(3871.3\pm0.6)\,MeV/c^2$

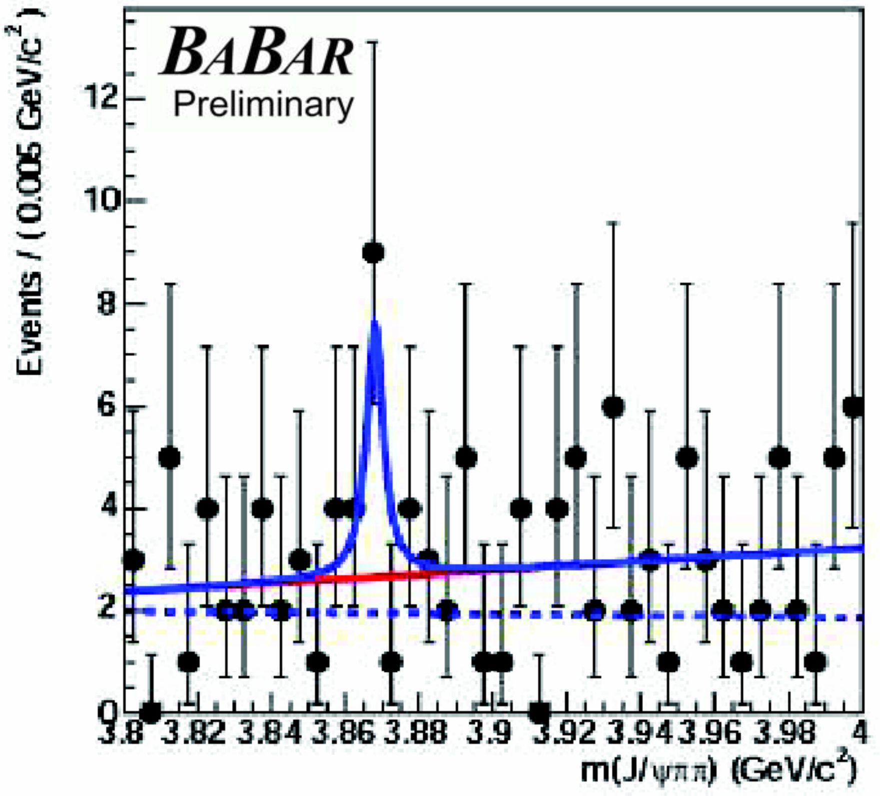
- $B \to J/\psi\ \pi\pi\ K$ Signal + non B-background
- Non-resonant $J/\psi\ \pi\pi$ background + Non-B background
- Non-B background

• Statistical errors only

Search for $B^0 \rightarrow X(3872)K_s$

NEW





$N = 8.4 \pm 4.5 \quad 2.7\sigma$

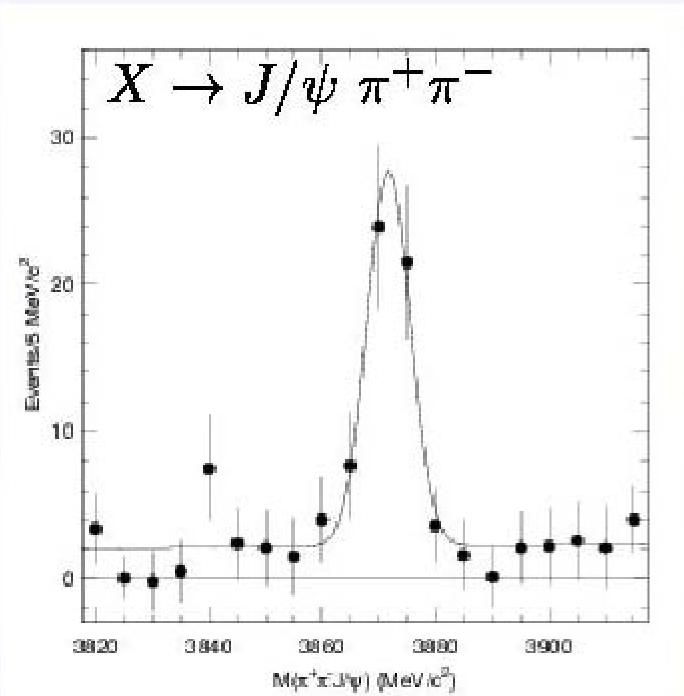
$m_X = (3868.6 \pm 1.2) MeV/c^2$

$\Delta M = M(X,K^+) - M(X,K_S)$

$\Delta M = (2.7 \pm 1.3)\ MeV/c^2$

Promising… Needs more data

$X(3872)$: Belle update $(253 fb^{-1})$

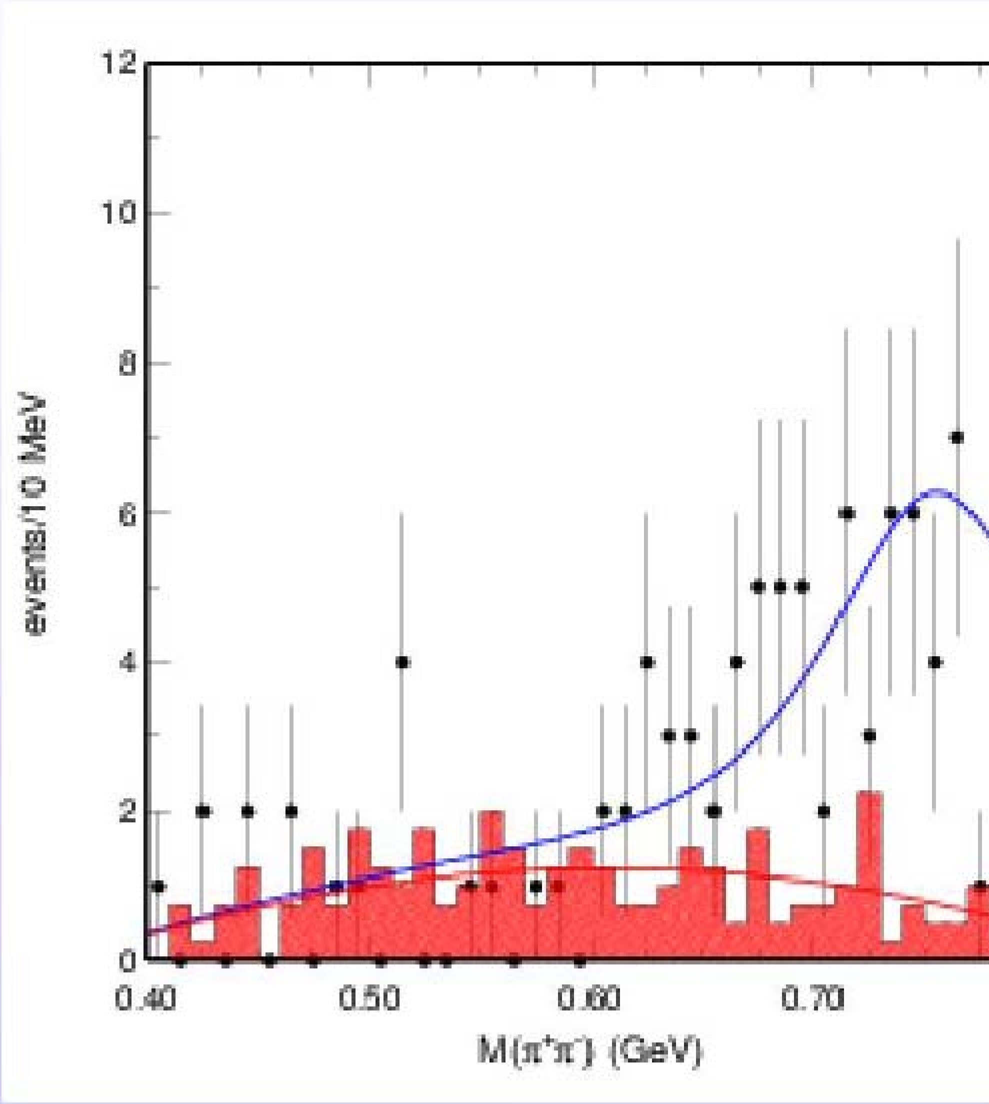


$N = 46.6 \pm 7.8$ events

MASS(X)$= 3872.4 \pm 0.7$ MeV

$M(\pi^+\pi^-)$ is consistent with ρ^0!

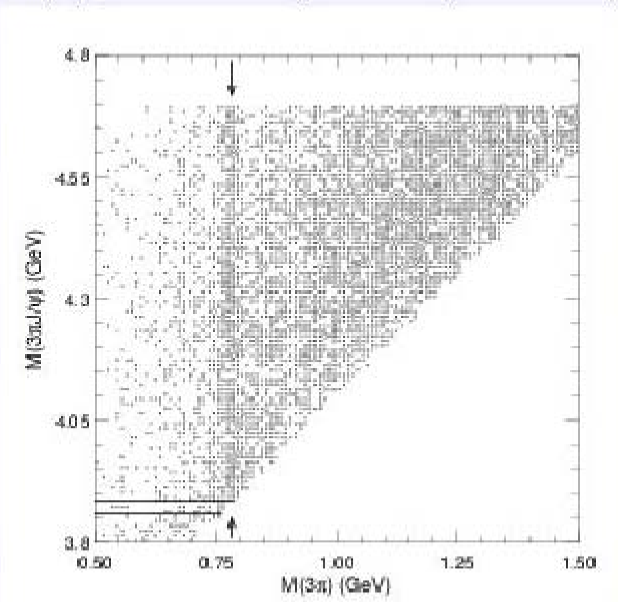
C(X(3872))=+1



Belle: Evidence for $X(3872) \to J/\psi\ \omega\ (253\ fb^{-1})$

$B \to K J/\psi\ \pi^+\pi^-\pi^0$ signal region:

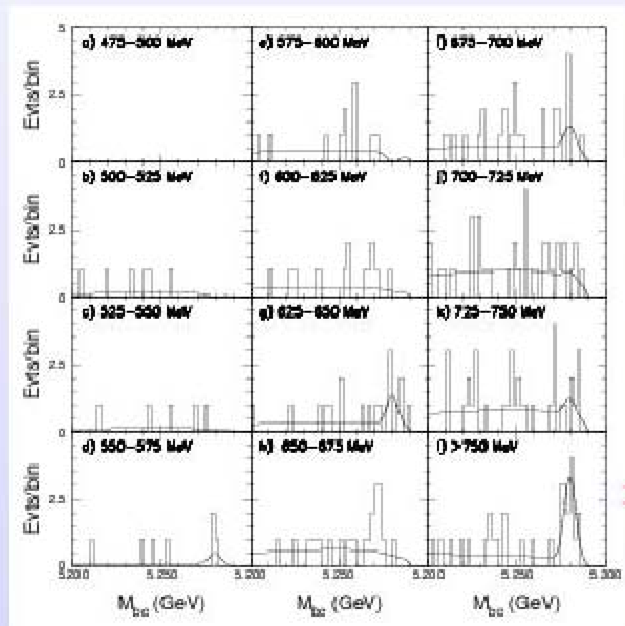
$M(J/\psi\ \ \pi^+\pi^-\pi^0)$ vs $M(\pi^+\pi^-\pi^0)$



Require

$M(J\psi\ \pi^+\pi^-\pi^0)$ around $M(X)$:

fit M_{bc} in $M(\pi^+\pi^-\pi^0)$ bins

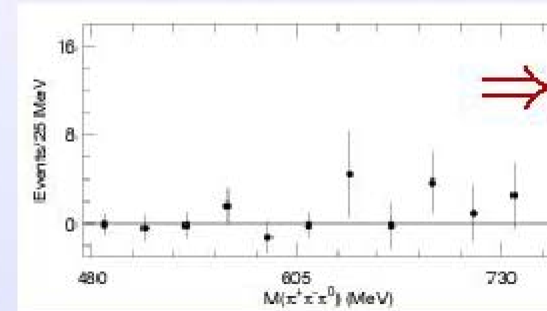


$\Rightarrow$ 12.4 ± 4.2 events

$\sim 4\ \sigma$ signif.

$X \to J/\psi\ \omega$ goes via

virtual ω



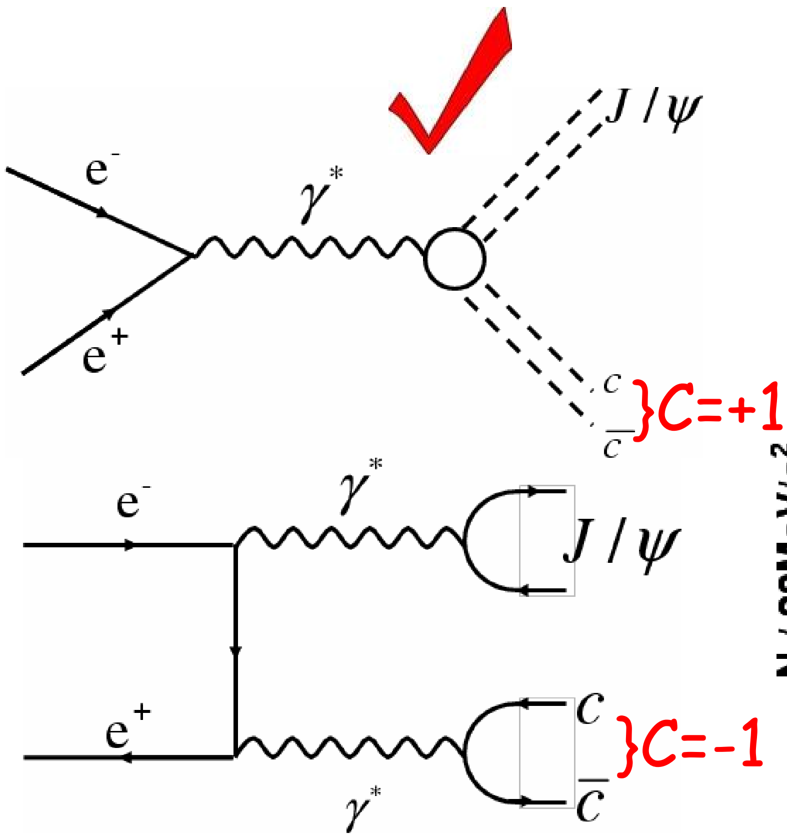
$\Rightarrow$

$$\frac{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\ \pi^+\pi^-)} = 1.1 \pm 0.4 \pm 0.3 \Rightarrow$$ in agreement with Swanson's $D^0\bar{D}^{0*}$ bound-state model for the X(3872) [PLB 588, 189 (2004)]

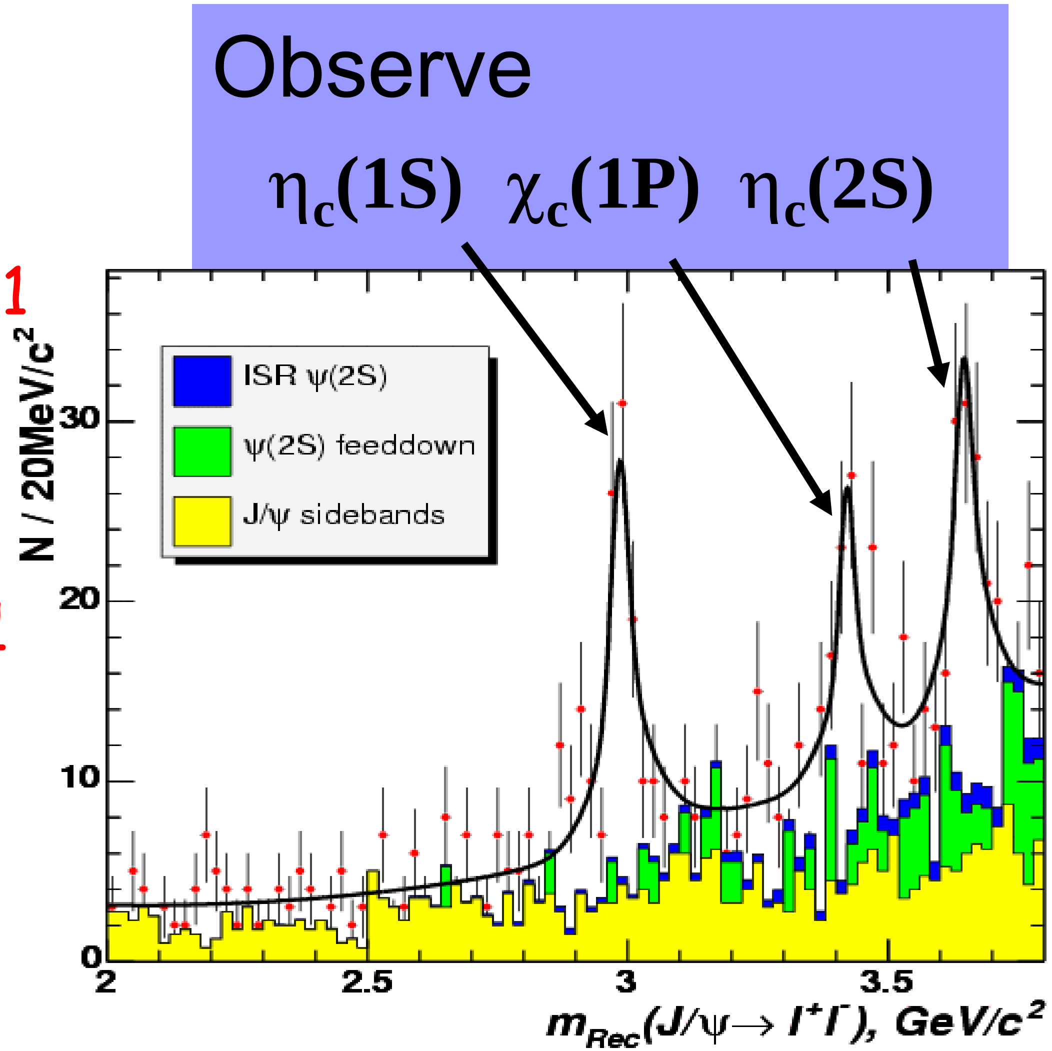
$\Rightarrow$ Intriguing indications that X(3872) may be a $D^0\bar{D}^{0*}$ molecular!

Recoil Mass Spectrum

124 fb $^{-1}$



observe only C=+1 states!



Preliminary Results

124 fb $^{-1}$

$J/\psi + c\bar{c}(\rightarrow > 2\,charged)$	η_c	χ_{c0}	$\eta_c(2S)$
N(signals)	127 ± 20	81 ± 16	121 ± 20
Efficiency (%)	29.5 ± 0.7	32.2 ± 0.7	30.2 ± 0.8
Born Cross-section (fb)	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Mass (MeV/c^2)	$2984.8 \pm 4.0^{+4.5}_{-5.0}$	$3420.5 \pm 4.8^{+11.5}_{-9.5}$	$3645.0 \pm 5.5^{+4.9}_{-7.8}$

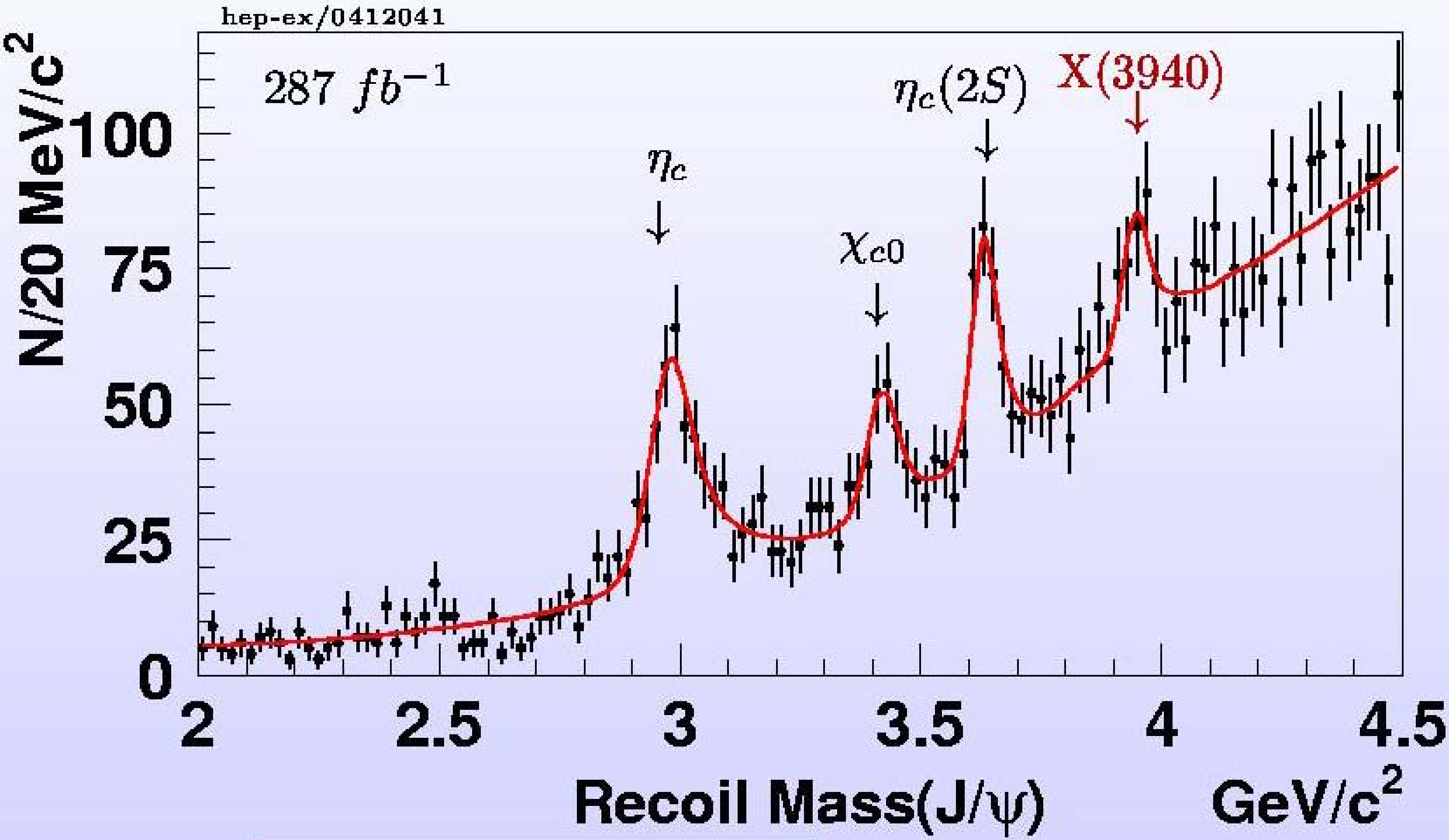
Comparison to Belle & Theory

$J/\psi\, c\bar{c}$	η_c	χ_{c0}	$\eta_c(2S)$
Nevt, BaBar ($124.4\, fb^{-1}$)	127 ± 20	81 ± 16	121 ± 20
Nevt, Belle ($155\, fb^{-1}$) (*)	235 ± 26	89 ± 24	164 ± 30
(+) $\sigma_{Born} \times \mathcal{B}_{>2}$, BaBar	$17.6 \pm 2.8 \pm 2.1$	$10.3 \pm 2.5 \pm 1.8$	$16.4 \pm 3.7 \pm 3.0$
$\sigma_{Born} \times \mathcal{B}_{>2}$, Belle (*)	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
(+) NRQCD by Braaten and Lee [1]	2.31 ± 1.09	2.28 ± 1.03	0.96 ± 0.45
(+) NRQCD by Liu, He and Chao [2]	5.5	6.9	3.7

(+) cross sections in fb , (*) hep-ex/0412041, hep-ex/0407009

[1] PRD 67, 054007 (2003), [2] hep-ph/0408141

Belle: Evidence for $X(3940)$ in double $c\bar{c}$ producti

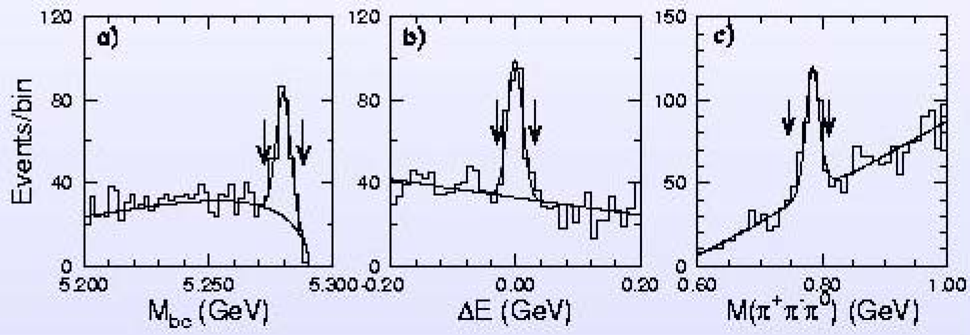


$M(X(3940)) = 3940 \pm 12\ MeV$

$\Gamma(X(3940)) < 96\ MeV$ @ 90% CL

Belle: Observation of $Y(3940) \to J/\psi\ \omega\ (253\ fb^{-1})$

$B \to J/\psi\ \omega K$ signal:



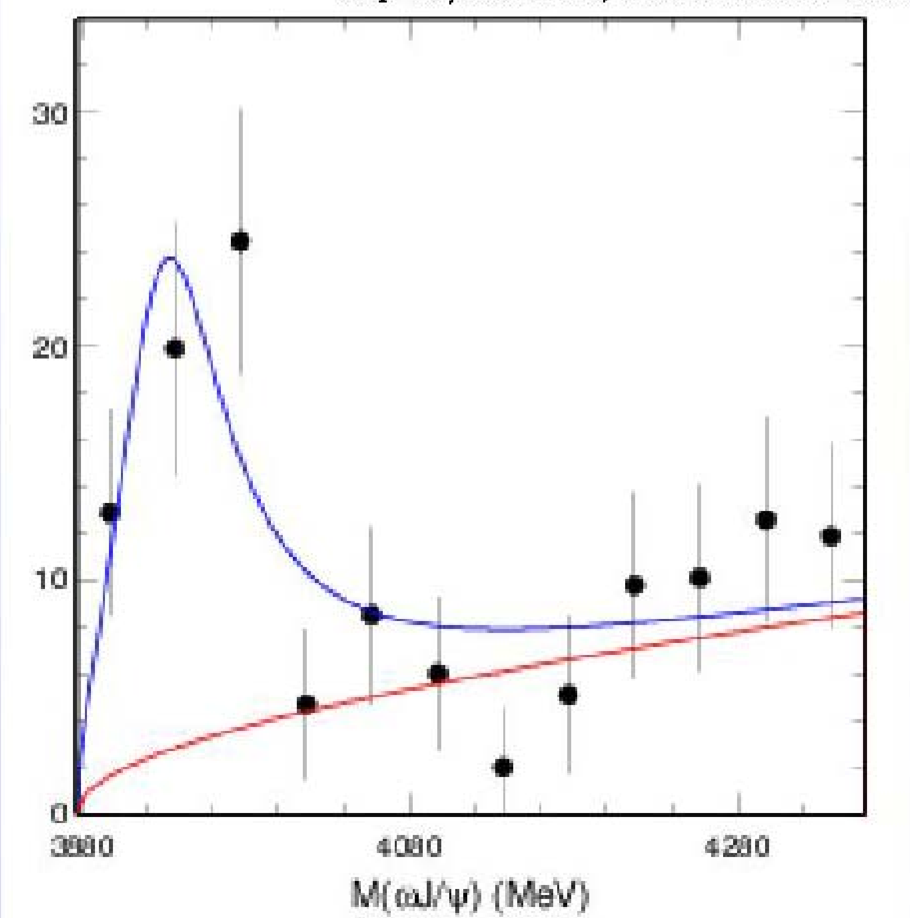
$M(K\ \omega) > 1.6$ GeV to avoid $K^{**} \to K\ \omega$

Fit M_{bc} in $M(J/\psi\,\omega)$ bins ⇒

$M(Y(3940)) = 3943 \pm 11 \pm 13$ MeV

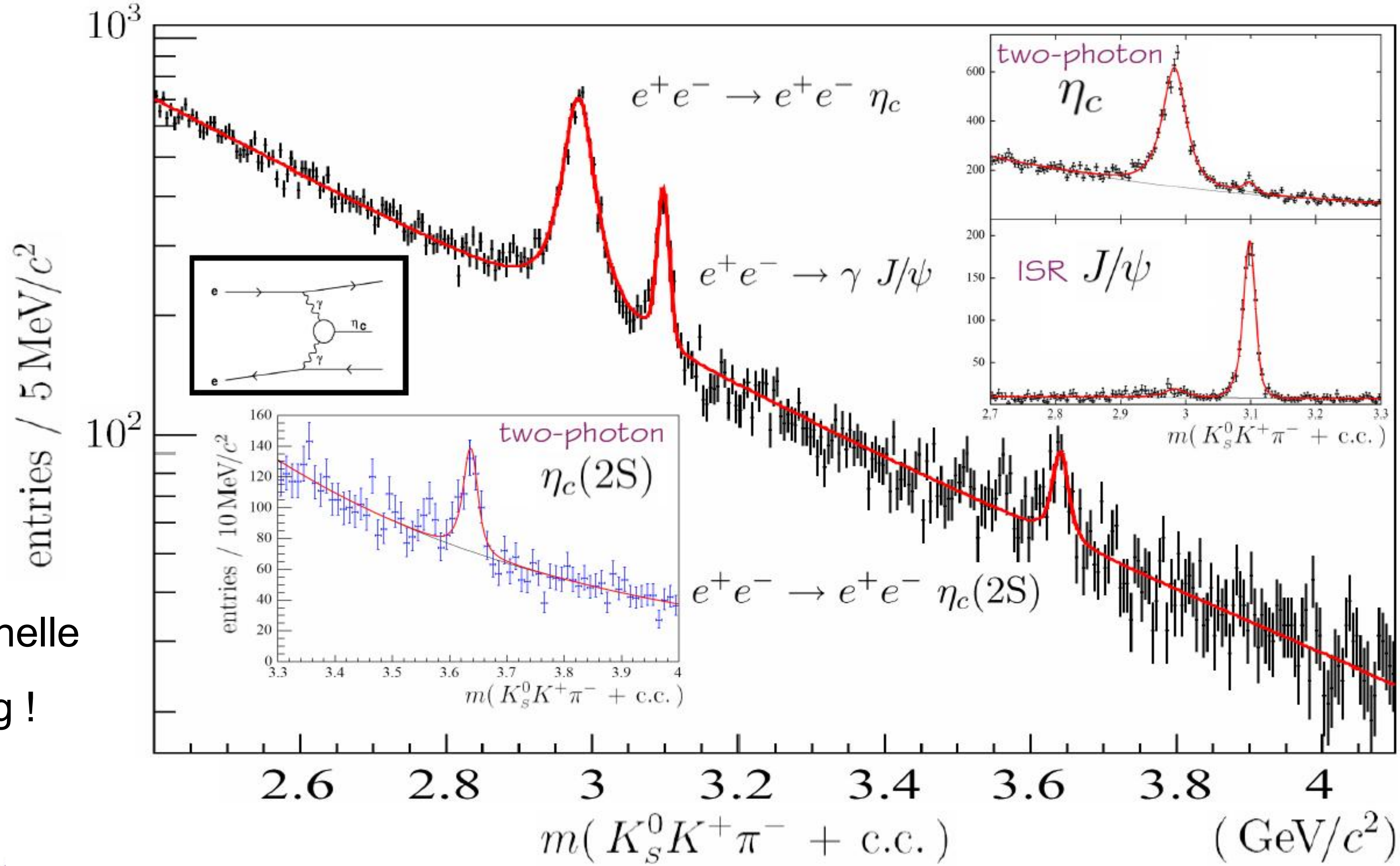
$\Gamma(Y(3940)) = 87 \pm 22 \pm 26$ MeV

hep-ex/0408126, submitted to PRL



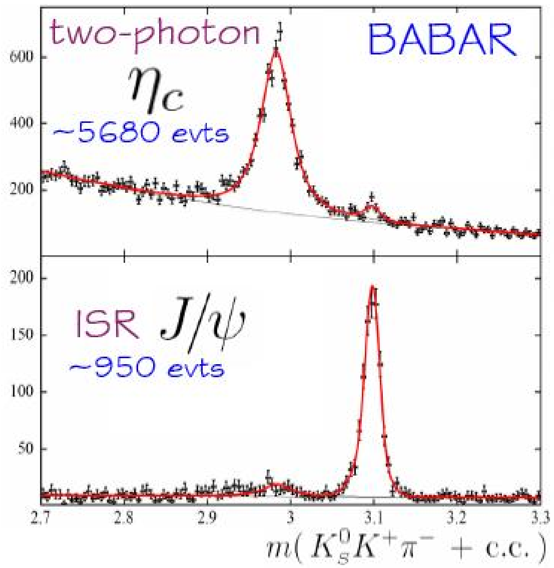
What is it?: Charmonium $c\bar{c}$? $J/\psi - \omega$ threshold interaction? $c\bar{c}$-gluon hybrid ?

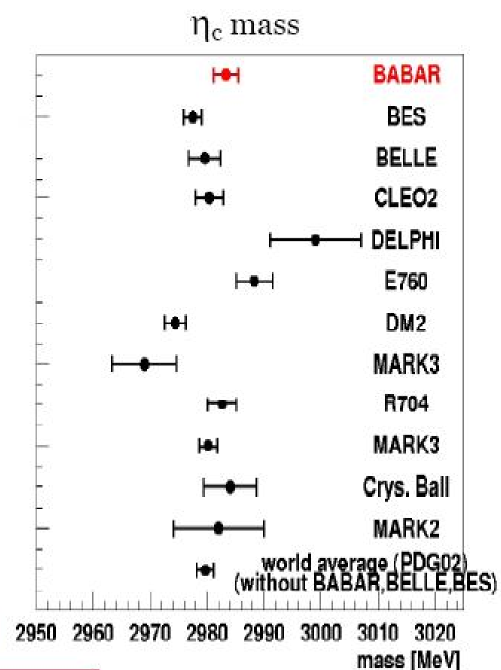
Résultats de BABAR sur le η_c

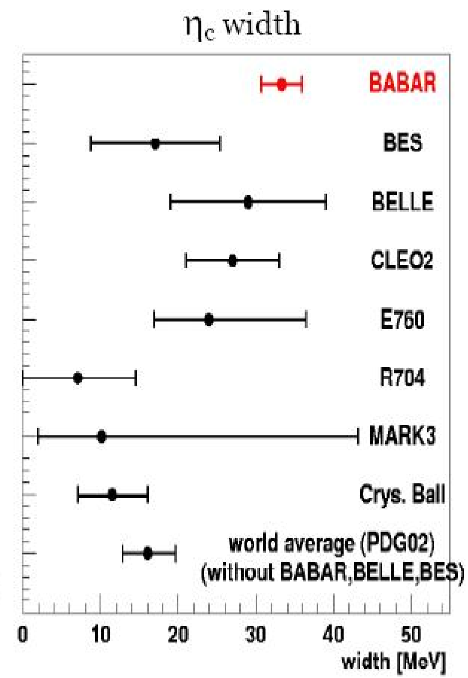


Echelle

Log !







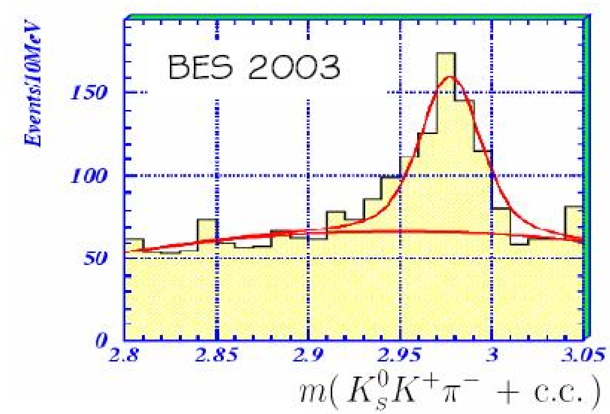
★ η_c mass and total width (88 fb^{-1})

Phys. Rev. Lett 92, 142002 (2004)

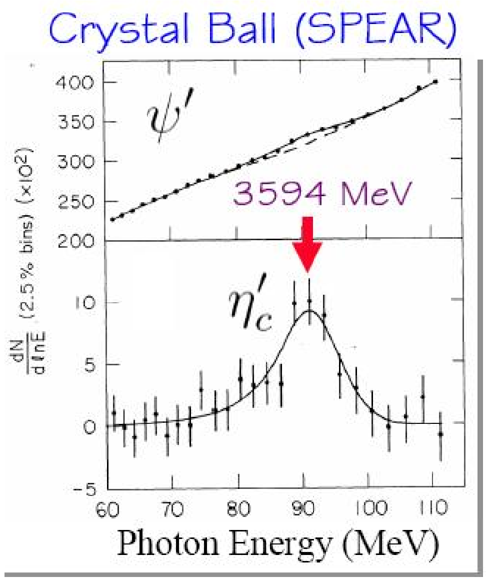
$$m_{\eta_c} = 2982.5 \pm 1.1(stat) \pm 0.9(syst)\,\text{MeV}/c^2$$

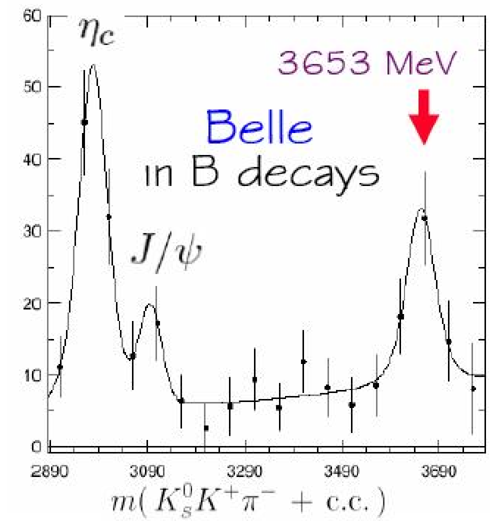
$$\Gamma^{\eta_c}_{tot} = 34.3 \pm 2.3(stat) \pm 0.9(syst)\,\text{MeV}/c^2.$$

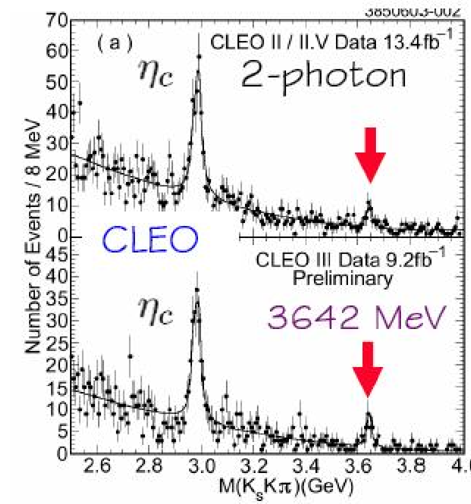
- significantly larger width than previous average
  dominated by BES 2003 measurement
- main uncertainty: experimental resolution function
  ISR-J/ψ as control sample

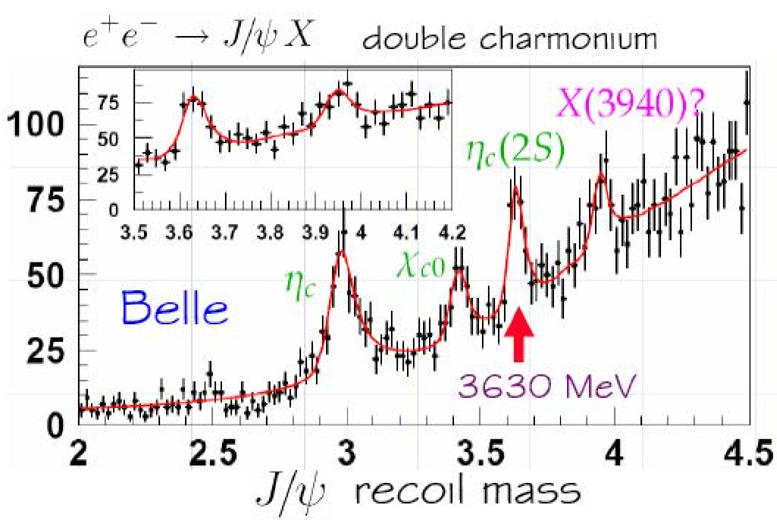


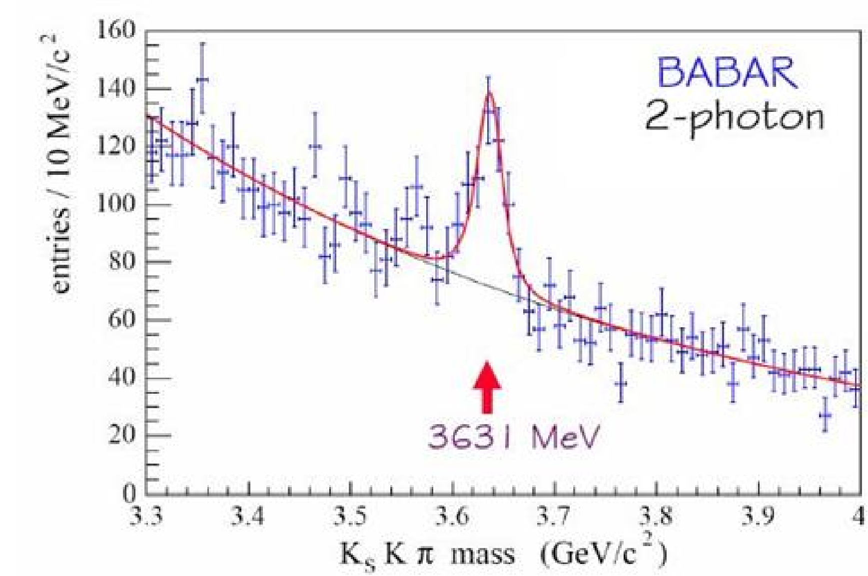
Les observations du $\eta_c(2S)$



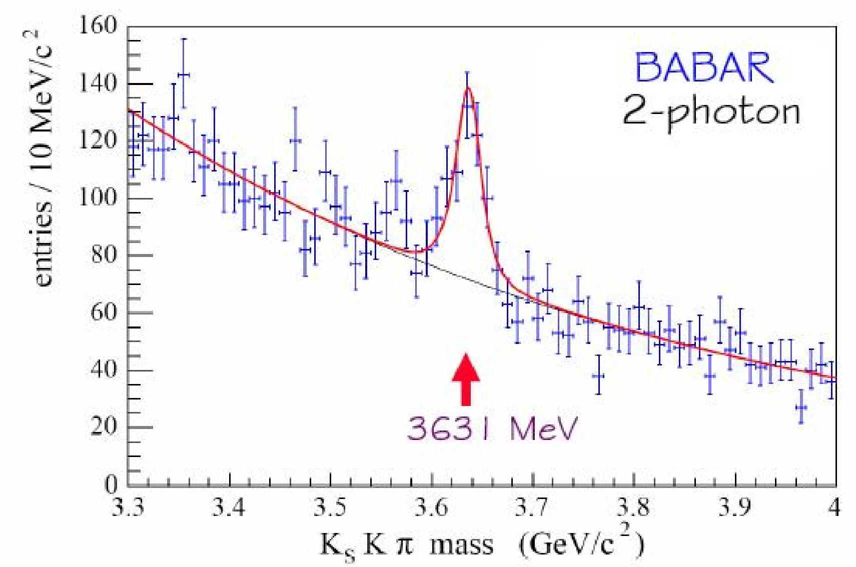


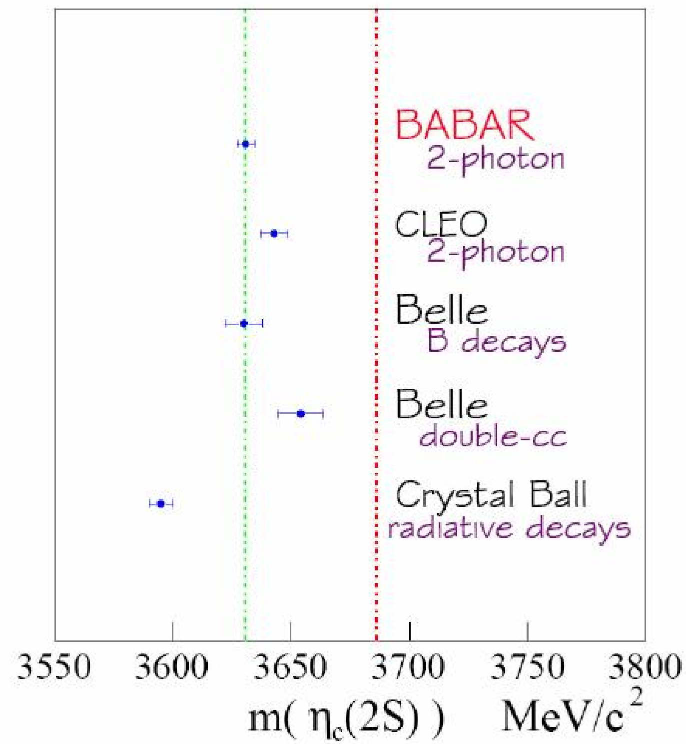






Recent BABAR $\eta_c(2S)$ result in $\gamma\gamma$





★ $\eta_c(2S)$ mass and total width

Phys. Rev. Lett 92, 142002 (2004)

$$m_{\eta_c(2S)} = 3630.8 \pm 3.4(stat) \pm 1.0(syst)\ \mathrm{MeV}/c^2$$

$$\Gamma_{tot}^{\eta_c(2S)} = 17.0 \pm 8.3(stat) \pm 2.5(syst)\ \mathrm{MeV}/c^2$$

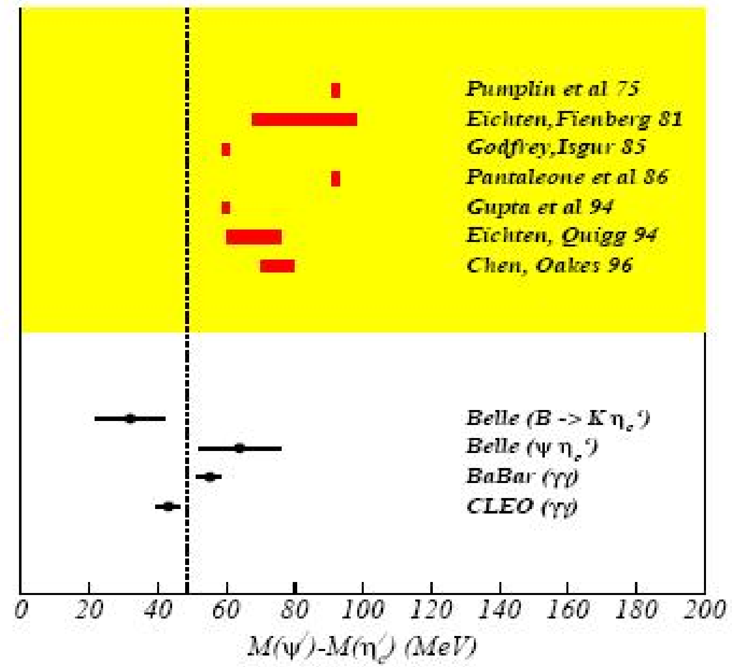
★ excluding Crystal Ball
$\Delta m(2S) = 47 \pm 4$ MeV

splitting in better agreement with NR potential models

Résumé de la spectroscopie du η_c et du $\eta_c(2S)$

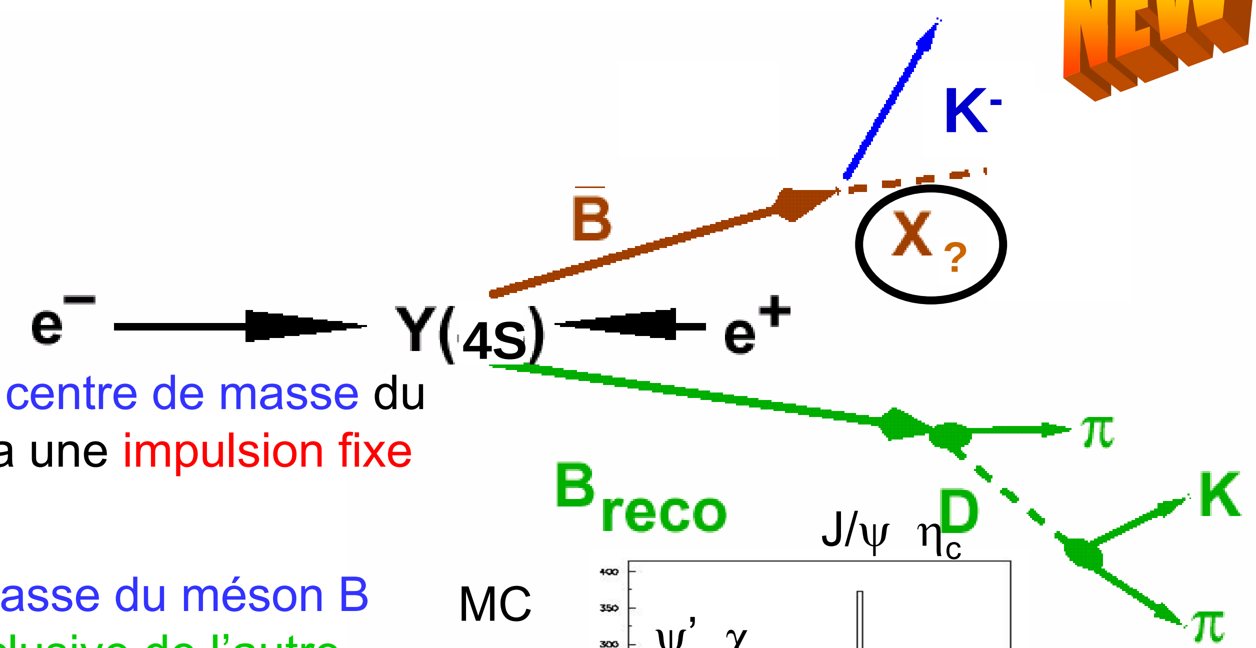
	$\eta_c(1S)$	$\eta_c(2S)$
Mass (MeV/c^2)	2982.5±1.1± 0.9	3630.8 ± 1.2
Δm (MeV/c^2)	117 ± 1	47 ± 4
Width (MeV/c^2)	34.3 ±2.3± 0.9	17.0 ±8.3± 2.5

$\Delta m(2S)$: Comparison with some theoretical predictions



hep-ex/0408001

Etude de la réaction $B^+ \rightarrow K^+ X_{c\bar{c}}$

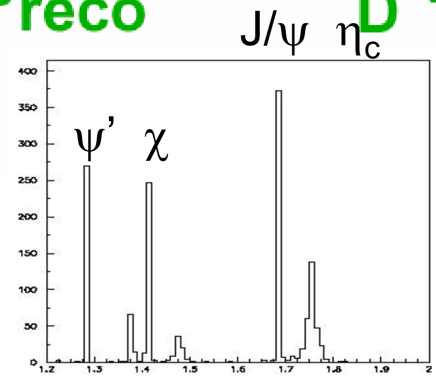


Dans le référentiel du centre de masse du méson B, le kaon aura une impulsion fixe pour chaque $X_{c\bar{c}}$

Accès au centre de masse du méson B par reconstruction exclusive de l'autre méson B

Les états $X_{c\bar{c}}$ sont mesurés indépendamment de leurs propriétés de désintégration

MC



Each peak is expected to be ~10 MeV wide

The case of the η_c meson

- Measure the absolute $BR(B^+ \to \eta_c K^+)$, only known today with a 30% error:

  PDG2004: $BR(B^+ \to \eta_c K^+) = (9 \pm 2.7)10^{-4}$

- This will in turn gives better measurements of the η_c BR decay into $KK\pi$
- This will in turn give a better measurement of the $BR(J/\psi \to \gamma\ \eta_c)$ previously used to normalize the exclusive η_c decays.

Physics motivation (2): More information about X(3872)

- Measure the absolute BR ($B^+ \rightarrow X(3872)\, K^+$) (or get an upper limit)
- Deduce the BR($X(3872) \rightarrow J/\psi\, \pi^+\pi^-$)
  (or get a LOWER limit)
- Look for a charged partner, irrespective of its decay modes
- These three informations are very useful to know more about the true nature of this particle

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Search for other high mass states

- Various high mass states have been reported in **BR ($B^+ \rightarrow X K^+$)** channels: X(3940), Y(3940),…
- Try to confirm their existence, measure their production rate, etc,…

Description of the analysis

- B selection
  - SemiExclusive B reconstruction sample candidate, Very high yield (~2000 B/fb^{-1}), low purity.
  - B purification: NN based on event shape variables and angular information (Breco-rest of the event, Breco-recoil Kaon)
    - NN_sel> cut_b
    - M_min<Mes<M_max
- Kaon Selection
  - Kaon Identification: Tight Kaon id (LH selector)
  - Kaon Purification:
    - Correct sign
    - Rejection of secondary kaons: NN based on energy flow around the kaon track and angular correlations
      - NN_top>cut_top
- Cuts optimization : cut_b, M_min, M_max, cut_top
- Fits to the Kaon momentum spectrum

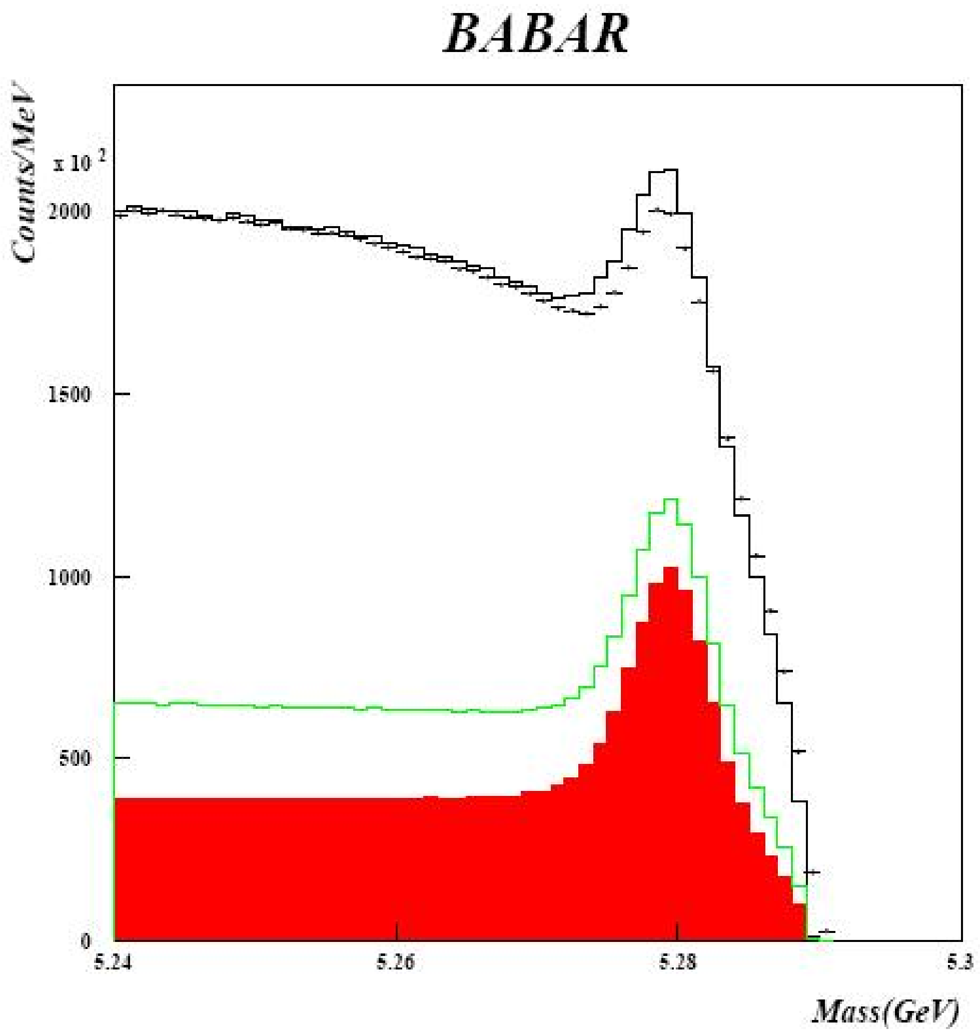
B reconstruction

- Data sample : Run1-Run4 210.5 fb^{-1}
- Use the semiexclusive B reco sample provided by the Vub group (B+ yield ~2kB/fb-1)
  - $Dn\pi$ decays with D going to $Km\pi$
- Aimed at maximum efficiency for ~50% purity

The B mass spectrum

Very good agreement with the MC on the side bands

MC overestimates B reco efficiency by 8.5%



Red B+

Green B0

White : udcs

Black: Full MC

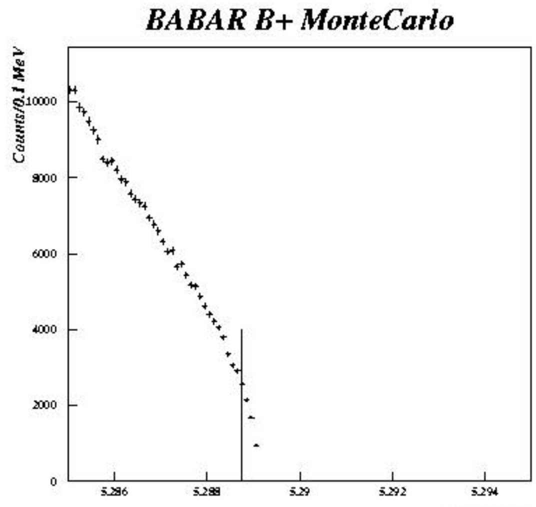
Dots: Data

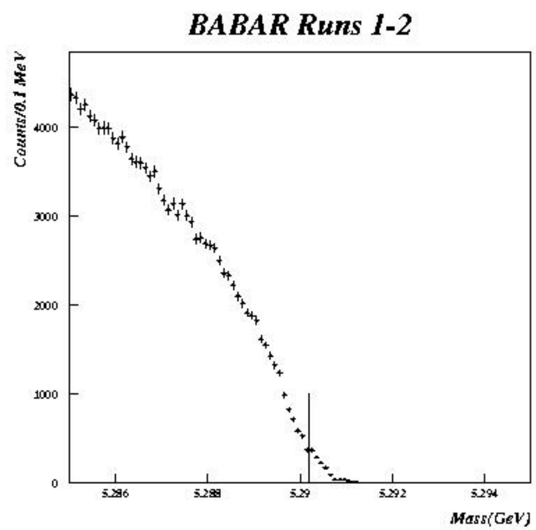
Counting reconstructed B

- The number of reconstructed B is the normalization of this analysis
- We expect a ~15% precision on the number of reconstructed J/Ψ, the goal is to count B with a precision significantly better than 10%
- Signal description: Crystal Ball shape, variation of energy end-point and reconstructed B mass as function of run periods
- Background description: B^+ , B^0 and udcs background components described by distinct Argus-like functions

End point determination

- For each sample, fix the average endpoint





	Av. end point	Diff wrt MC (MeV)
MC	5.28876	0
Runs 1-2	5.2902	1,44
Run 3	5.28985	1,09
Run4	5.28925	0,5

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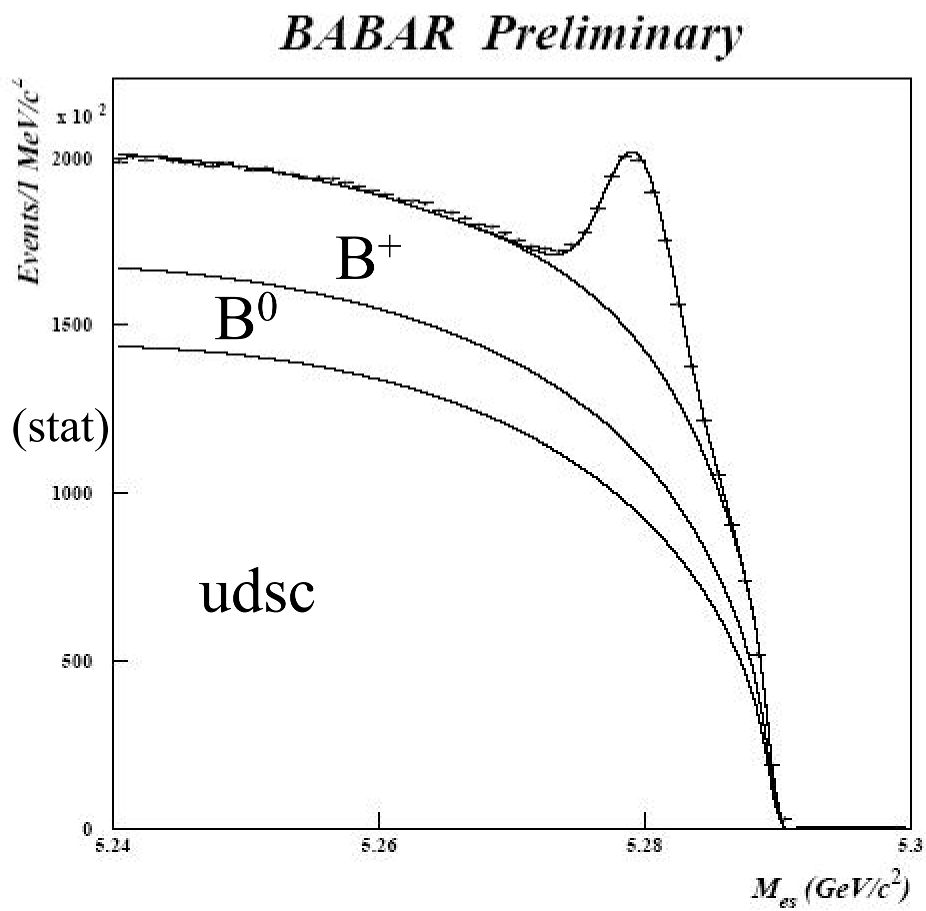
The fit to the B mass spectrum

Data B^+ :378530 ± 1110 (stat)

Normalized MC B+: 413693 ± 680 (stat)

Data B^0 :245597 ± 719(stat)



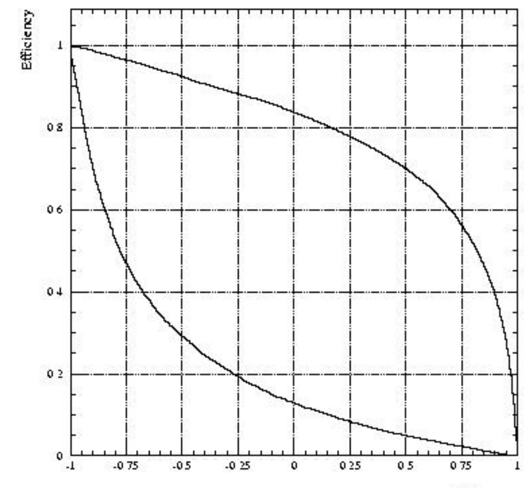
B counting results

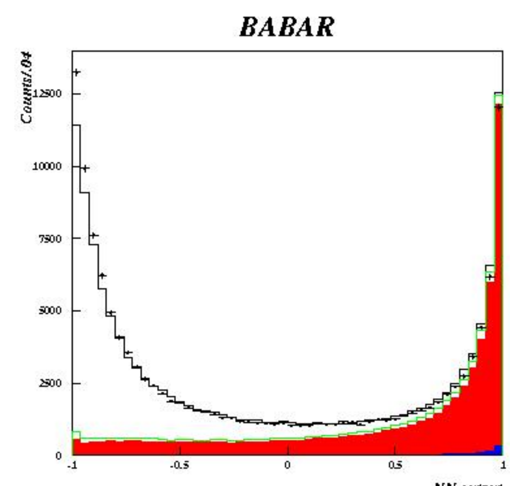
Parameter	MC	Runs 1-2	Run3	Run4	Total Data	Typical error
Endpoint (MeV)	5288.76	5290.20	5289.85	5289.25		0.05
Peak Mass(MeV/c^2)	5279.42	5279.83	5279.67	5279.42		0.05
Peak Width (MeV/c^2)	2.50	2.69	2.65	2.615		0.06
α Cristal Ball	1.41	1.7	2.9	1.67		0.13
N Cristal Ball	19.9	27.8	48	23.9		6
High purity $B^{\pm}$ (kB/fb^{-1})	0.173	0.133	0.147	0.125	0.131	0.01
High purity $B^{\pm}$ MC-truth (kB/fb^{-1})	0.173	0.179	0.169	0.168		0.004
$B^{\pm}$	1313311	145789	56499	176292	378580	800
$B^{\pm}$ (kB/fb^{-1})	1.97	1.83	1.88	1.76	1.80	0.007
$B^{\pm}$ MC truth (kB/fb^{-1})	2.06	2.11	1.99	2.04		
MC $B^{\pm}$ only fits (kB/fb^{-1})	2.01	2.05	1.97	1.99		

Table 1: Summary of all $B^{\pm}$ mass fit results.

B purification

- NN based on
  - usual cocktail of discriminating variables between BB and continuum (thrust, R_2, Wolfram moments,etc)
  - $\cos(B_1\text{-}B_2)$
  - $\cos(B_{reco}\text{-}K)$

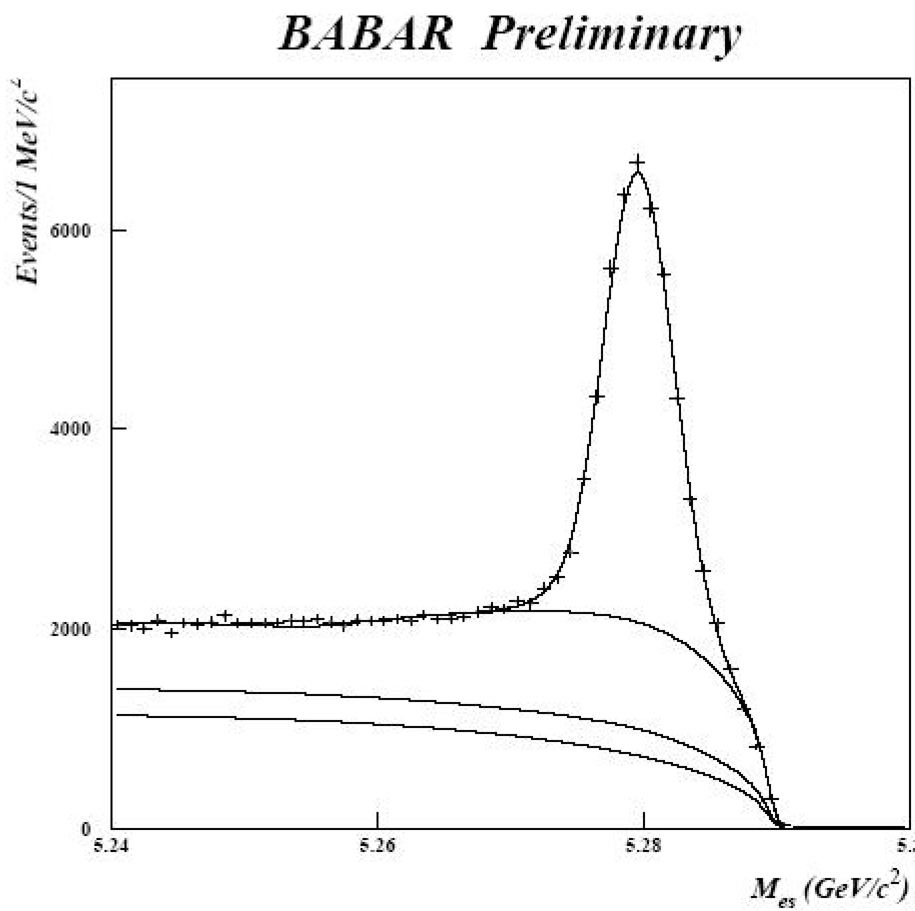




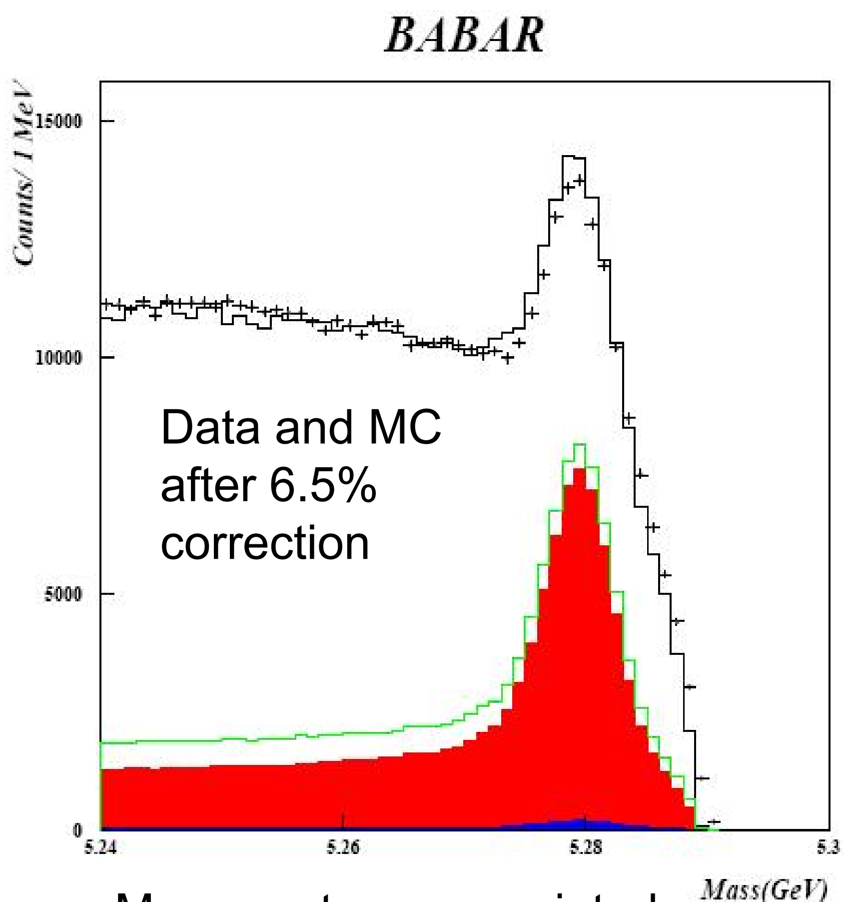
B mass spectrum after NN cut

A kaon with momentum above 1 GeV/c is required to present int he recoil system

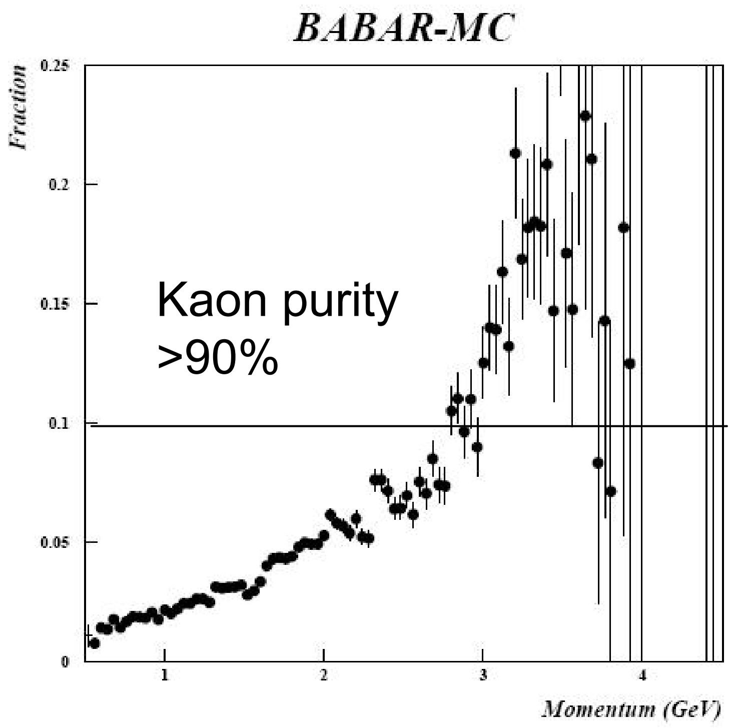
NN output>0.1



Kaon Selection



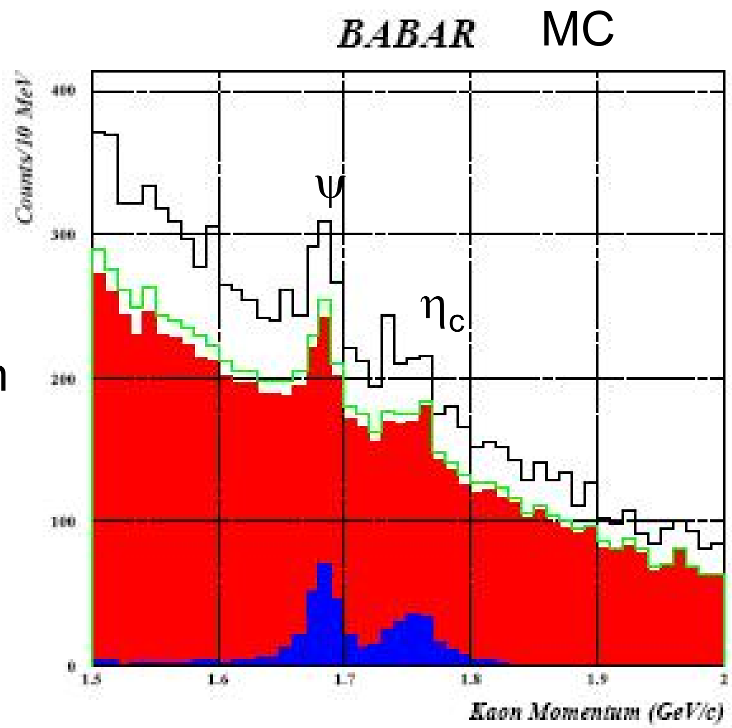
Mes spectrum associated with a Kaon above 1 GeV/c



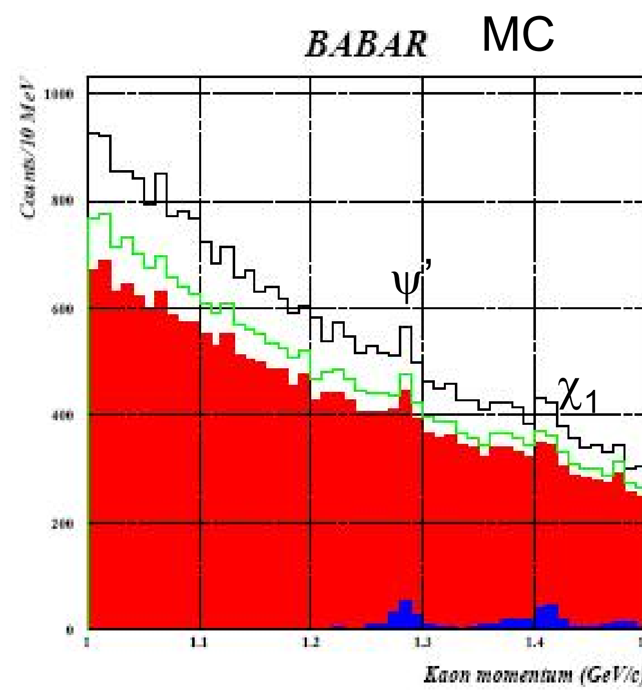
Fraction of MisID Kaons as function of Kaon momentum

MC expectations for the kaon spectrum

ψ-η_c region



High mass region



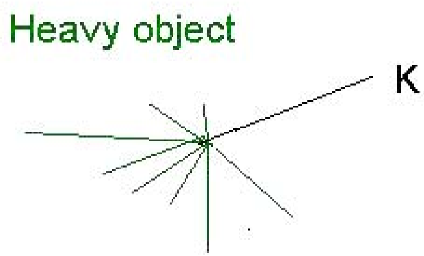
Blue : two-Bodydecays

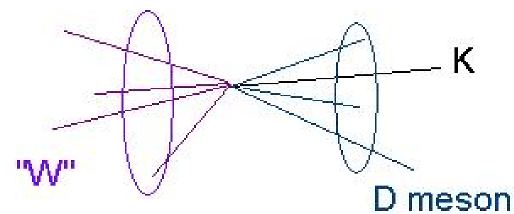
Red B+

Green B0

Black Full MC

Performance of the topology NN selector

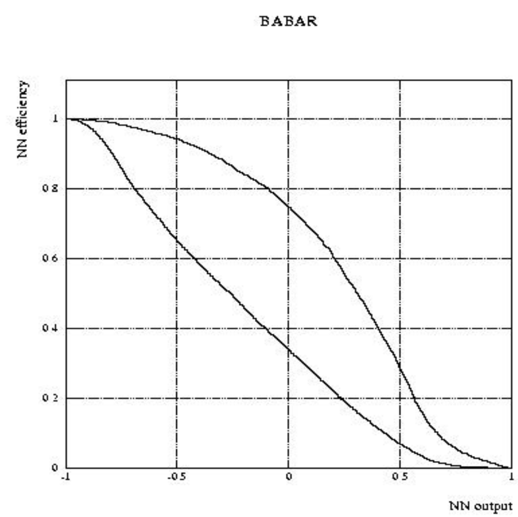




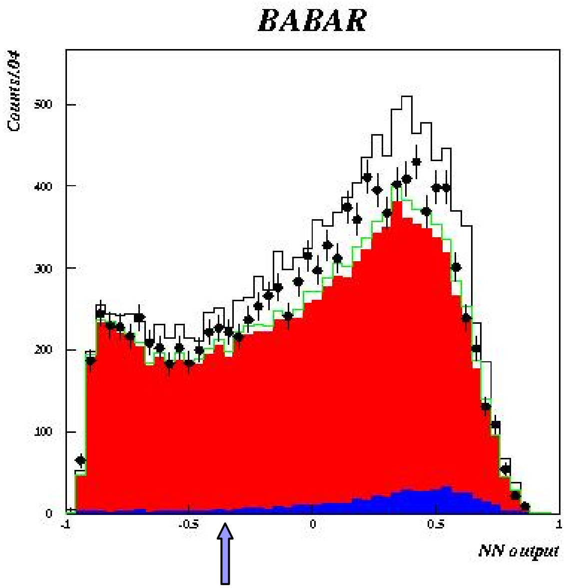
Training done with B+ MC: Primary K from charmonia (signal), K from D decays (background) in two kinematic regions m>3.2 GeV and below

Primary K

Secondary K

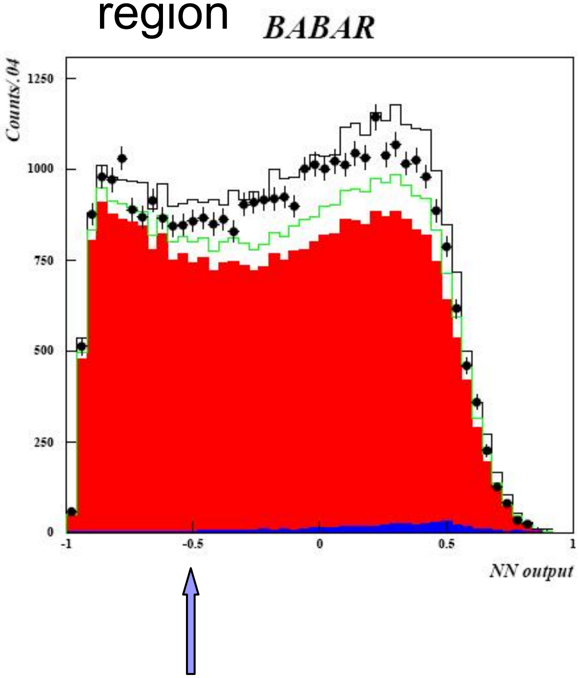


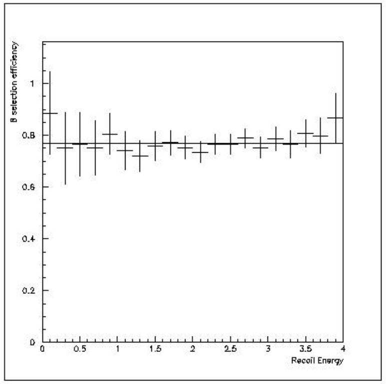
NN topology performance



Topology NN in the low mass region

Topology NN in the high mass region



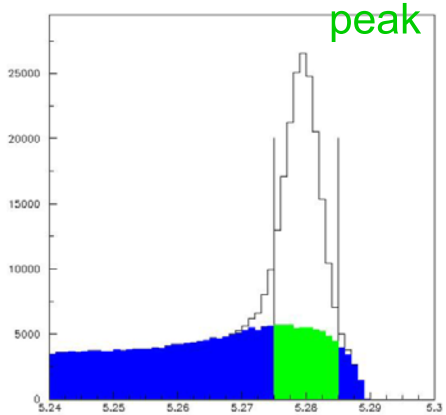


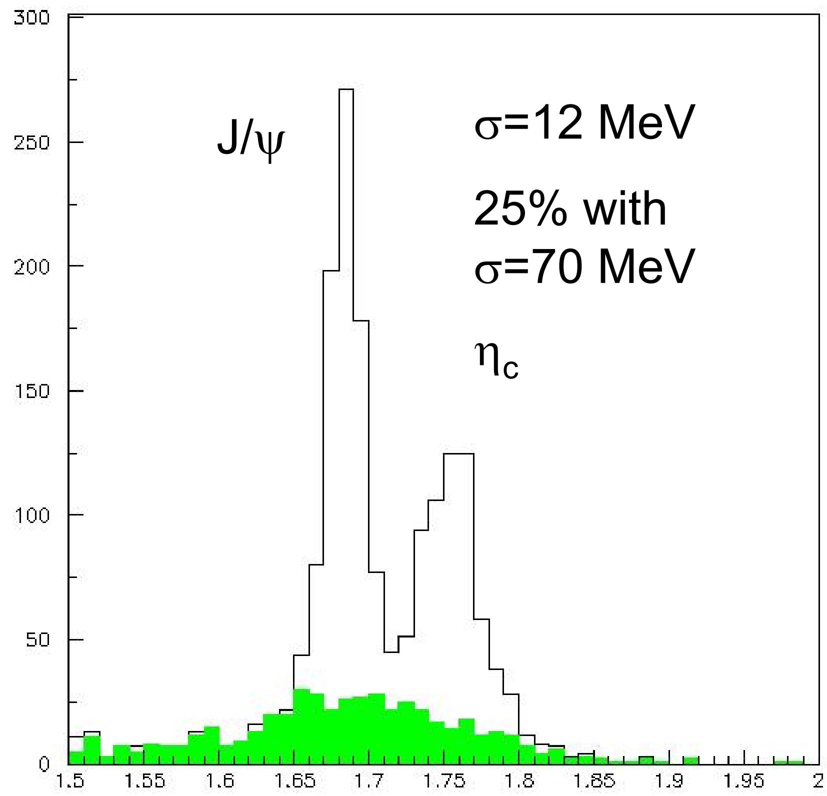
No systematic efficiency variation of function of visible energy or multiplicity

Kaon momentum spectrum in the $\psi - \eta_c$ region

Extra signal + Significant tails connected to incorrectly reconstructed B

Green: combinatoric background under the B peak





Systematic errors

	Absolute (%)		Intradata(%)	
B counting	4.5		0	
B selection	3		3	
K reconstruction	2		0	
K identification	5		5/1	
Topological selection	3		3	
Signal counting-shape	3		3	
Signal counting-background modelisation	3.5	10	3.5	10
Total	9.4	13	8/6.3	13
	Low mass	High mass	Low mass	High mass

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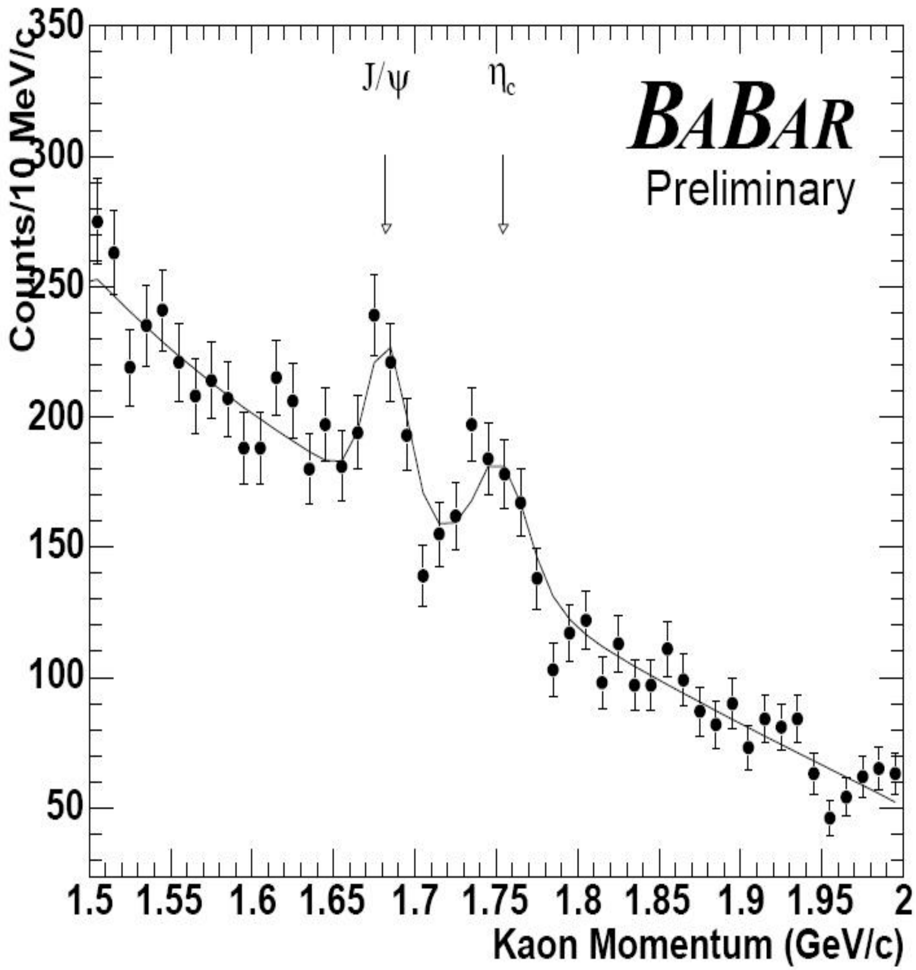
Results in the low mass region

Very clear J/ψ and
η_c signals

Significance> 6 σ
N J/ψ=258 ± 42
N_ η_c =266 ± 42



210 fb-1

Background:
Cubic
polynomial
free in the fit

Initial values
taken as in
MC

Measurement of the BR($B^+ \to \eta_c K^+$)

- N_J/ψ=258 ± 42
- N_η_c =266 ± 42

using MC efficiency

BR($B^+ \to J/\psi K^+$)= (8.1 ± 1.2(stat) ± 0.9(sys) 10^{-4}

BR($B^+ \to \eta_c K^+$)$_{MC}$=(8.3 ± 1.3(stat) ± 0.9(sys)) 10^{-4}

Using Intradata:

- BR($B^+ \to \eta_c K^+$)/BR($B \to J/\psi K^+$)=1.03 ± 0.22(stat) ± 0.06(sys)
- BR($B^+ \to \eta_c K^+$)$_{data}$=(10.3 ± 2.2(stat) ± 0.6(sys) ± 0.4(ref)) 10^{-4}

using the PDG04 BR for the J/ψ decay

→ **BR($B^+ \to \eta_c K^+$)=(8.9 ± 1.5) 10^{-4}**

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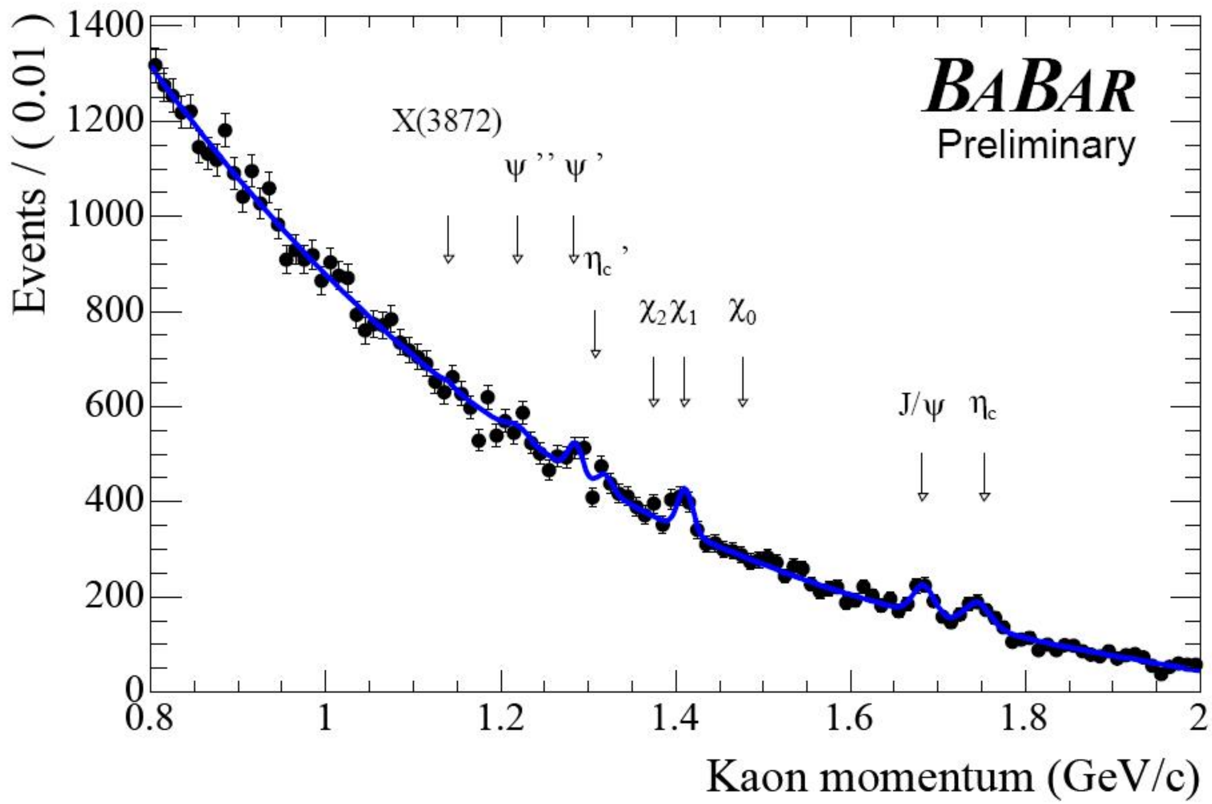
Results in the high mass region

Unbinned max. likelihood fit using ROOFIT

3rd degree polynomial free in the fit

Initial values taken from MC



9 states allowed in the fit. All the signal parameters fixed in the fit and taken from MC/PDG

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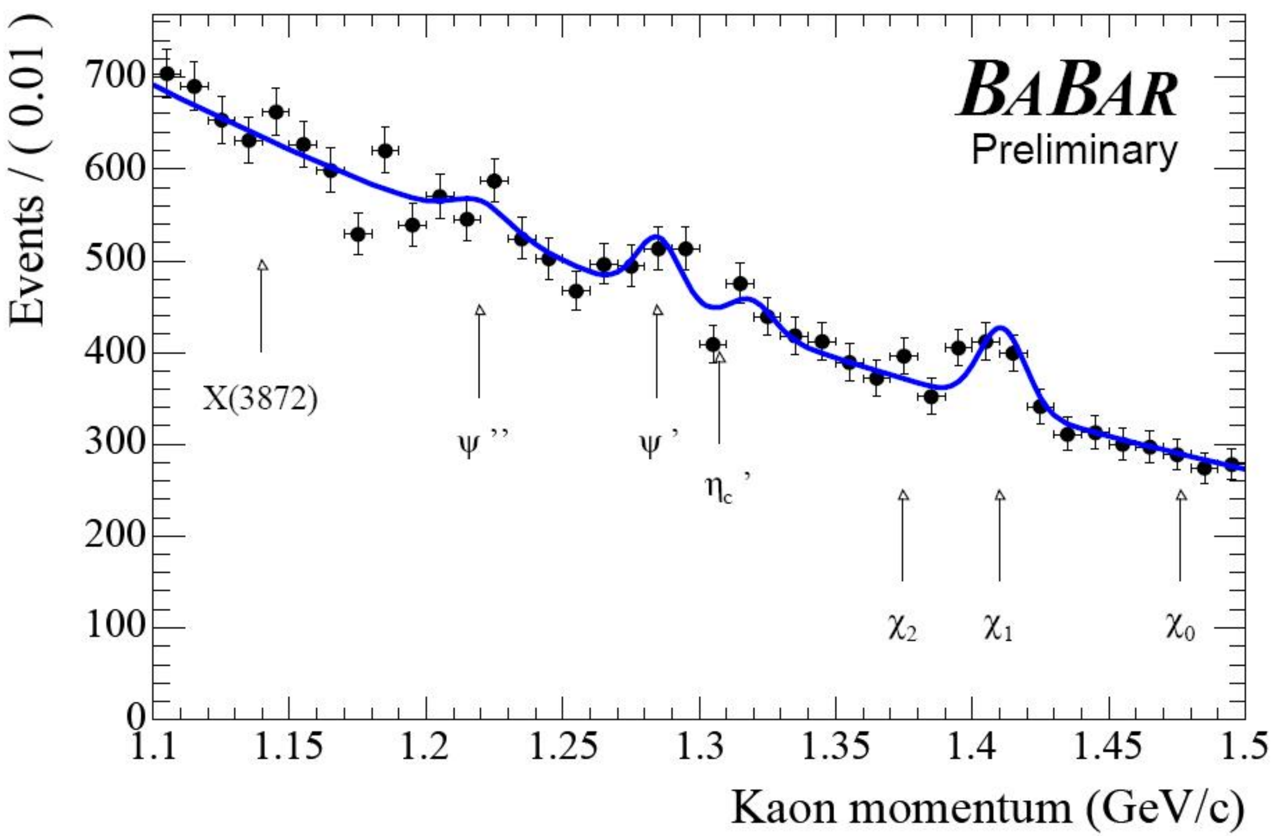
Results in the high mass region

-2 clear signals ψ' and χ_1

-2 excess of events : ψ'' and η_c'

-3 limits χ_0, χ_2 and X(3872)



Zoom in the 3.4-3.9 GeV region

Fit Results in the high mass region

Particle	Yield	Peak Position	Width	BR(10^{-4})
χ_{c0}	9±21			<1.8
χ_{c1}	192±35			7.0±1.3(stat)±1.0(sys)
χ_{c2}	0±36			<2.0
η_c (2S)	84±39	1.319±0.005	<15	3.1±1.4(stat)±0.4(sys)
ψ'	116±37			4.2±1.3(stat)±0.6(sys)
ψ''	87±60			3.2±2.2(stat)±0.5(sys)
X(3872)	10±18			<3.2

Note: χ_1 désigne en fait χ_1 + h_c

Results concerning X(3872)

- N_X(3872) = 10 ± 18
- The 90% CL on $BR(B^+ \to X(3872)\ K^+)$ is $3.2\ 10^{-4}$
- From $BR(B^+ \to X(3872)\ K^+) * BR(X(3872) \to \psi\pi\pi) = (13.7 \pm 2.2)\ 10^{-6}$ (BABAR-BELLE averaged), one gets:

$BR(X(3872) \to \psi\pi\pi) > 4.3\%$ at 90% CL

Limits were also set on the production rate of X(3940) and Y(3940) (allowing up to 100 MeV width for this last state) of respectively

3.3 and $2.4\ 10^{-4}$ at 90% CL

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Mass and width of η_c and η'_c

Part icle	Mass (MeV) This analysis	Mass (MeV) Other results	Width Limit at 90% CL (MeV) This analysis	Width Other results
η_c	2994 ± 5	PDG: 2979.6 ± 1.2 BABAR 2982± 1.1± 0.9	<43	PDG 17.3 ± 2.5 BABAR 34 ±2.5
η_c'	3639 ± 7	PDG:3654 ± 6 ± 8 BABAR 3630.8 ± 3.5	<23	PDG <55 BABAR :17.3 ± 8.3 ± 1.5

Results derived from η_c and η'_c production rates

- This analysis gives $BR(B^+ \to \eta_c K^+) = (8.9 \pm 1.5)\ 10^{-4}$
- From BABAR,

  $BR(B \to \eta_c K) * BR(\eta_c \to KK\pi) = (74 \pm 5 \pm 7)\ 10^{-6}$

  ⇒ $BR(\eta_c \to KK\pi) = (8.3 \pm 1.7)\%$

- From BES, MARKIII and DM2,

  $BR(\eta_c \to KK\pi) * BR(J/\psi \to \gamma\ \eta_c) = (6.7 \pm 0.9)\ 10^{-4}$

  ⇒ $BR(J/\psi \to \gamma\ \eta_c) = (0.81 \mp 0.17)\%$

- From PDG2004 $\Gamma(\eta_c \to \gamma\gamma) * BR(\eta_c \to KK\pi) = (0.48 \pm 0.06)$ keV

  ⇒ $\Gamma(\eta_c \to \gamma\gamma) = 5.8 \pm 1.2$ keV

Summary of results derived concerning η_c and η_c'

	BR(KKπ) (%)	$\Gamma_{\gamma\gamma}$ (KeV)	BR($J/\psi \to \gamma\, \eta_c$)(%)
η_c	8.3 ± 1.7 PDG 5.7 ± 1.6	5.8 ± 1.2 PDG 7 ± 1 ± 2	0.81 ± 0.17 PDG 1.30 ± 0.4
η_c'	9 ± 5 First meast	0.8 ± 0.5 First meast	

Precision can be further improved by combining these measurements

Table of the Branching Ratios

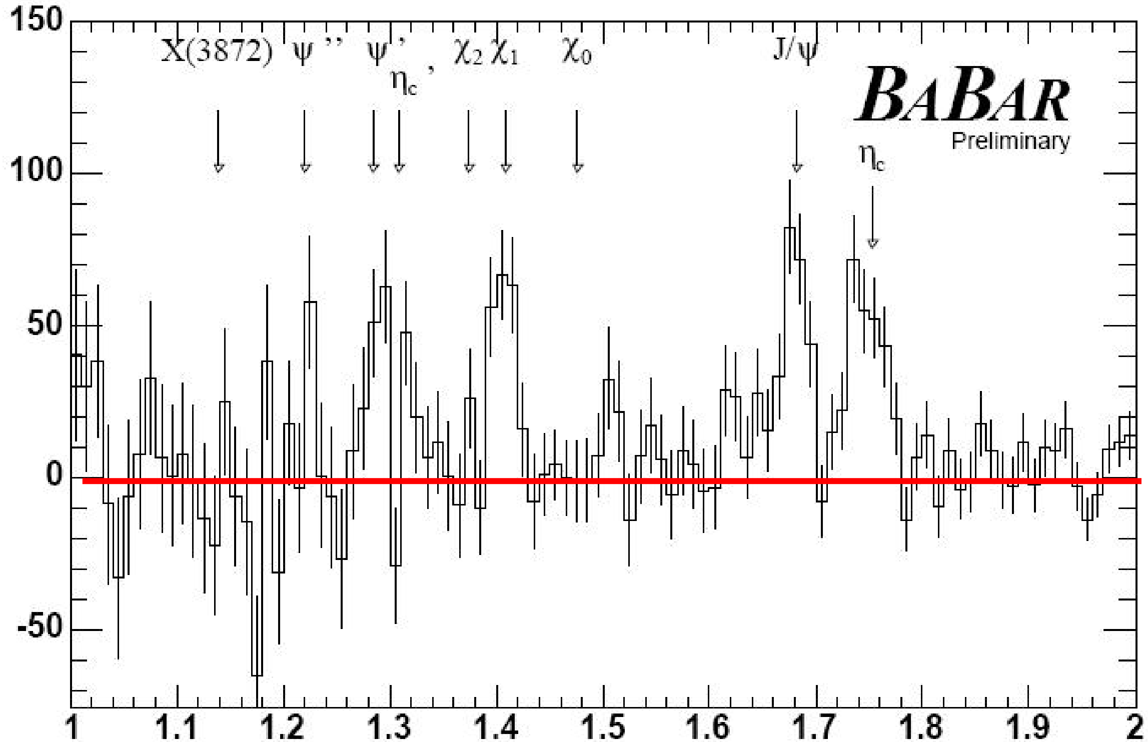
Particle	BR (10^{-4})	BR(PDG2004)	BR(BABAR)
η_c	8.9±1.5	9.0±2.7	13.4±4.4
J/ψ	8.1±1.6	10.0±0.4	10.6±0.5
χ_{c0}	<1.8	6±2.4±2.1 (*)	2.7±0.7
χ_{c1}	7.0±1.6	6.8±1.2	5.8±0.7
χ_{c2}	<2	No entry	<0.3
$\eta_c(2S)$	3.1±1.5	No entry	
ψ'	4.2±1.4	6.8±0.4	6.2±0.5
ψ''	3.2±2.3	No entry	
X(3872)	<3.2	No entry	

Many improvements compared to PDG2004

(*) based on first BELLE result.
New result :2.0± 0.3± 0.3

hep-ex/0412066

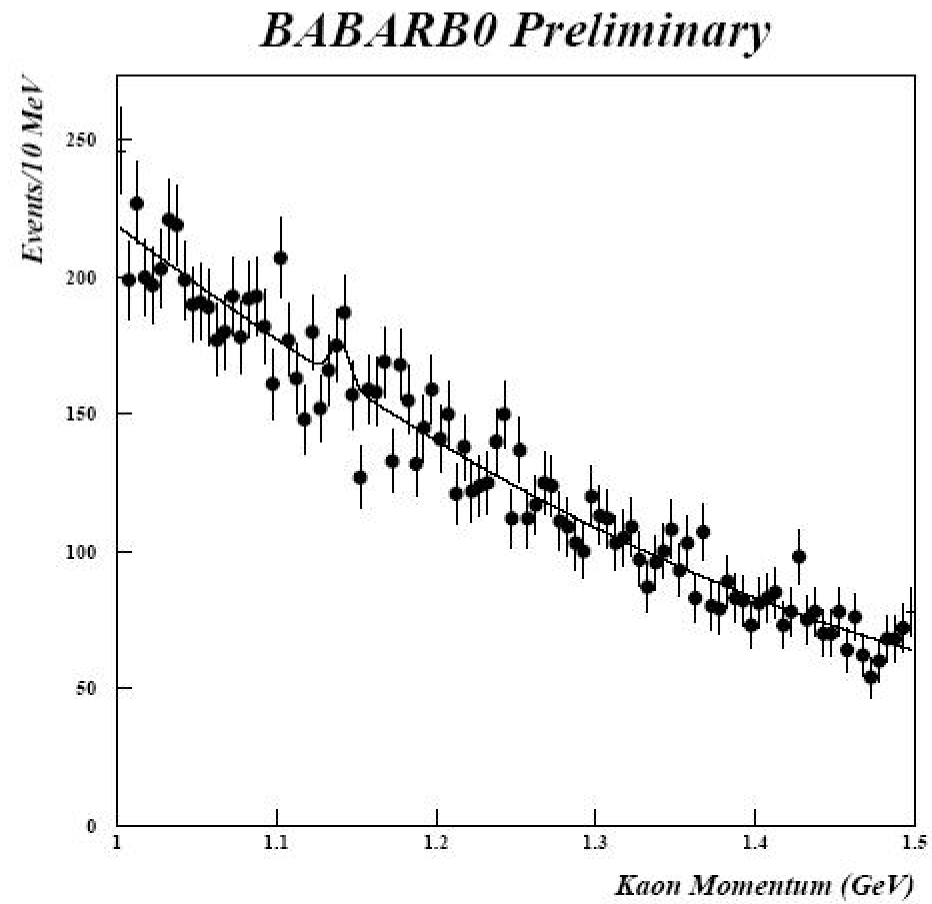
The complete charmonium spectrum from a single analysis!



Search for X(3872)$^-$ using $B^0 \to X(3872)^+ K^-$

- 90% CL set on

$B^0 \to X(3872)^+ K^-$ of 5 10^{-4}

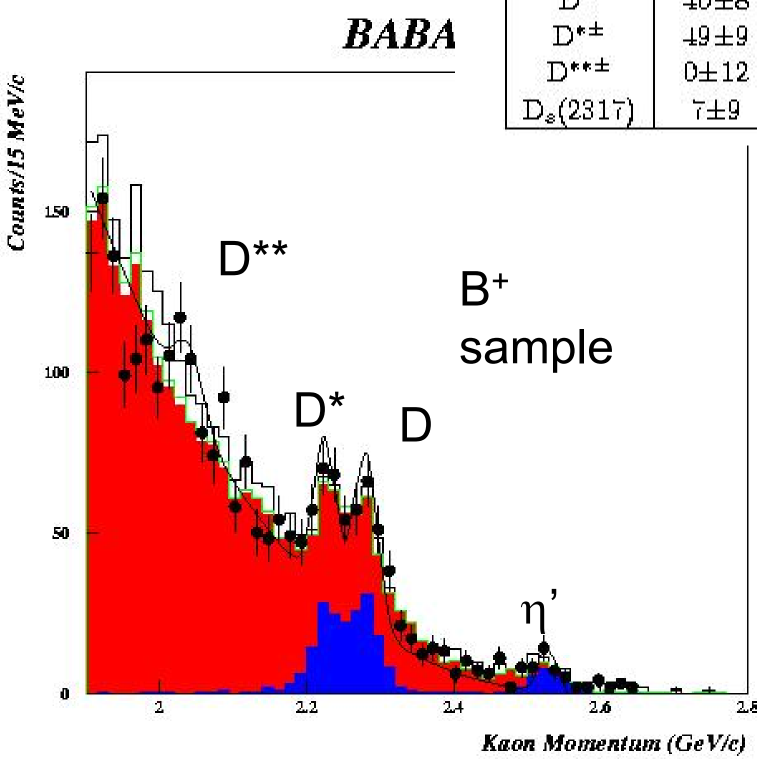


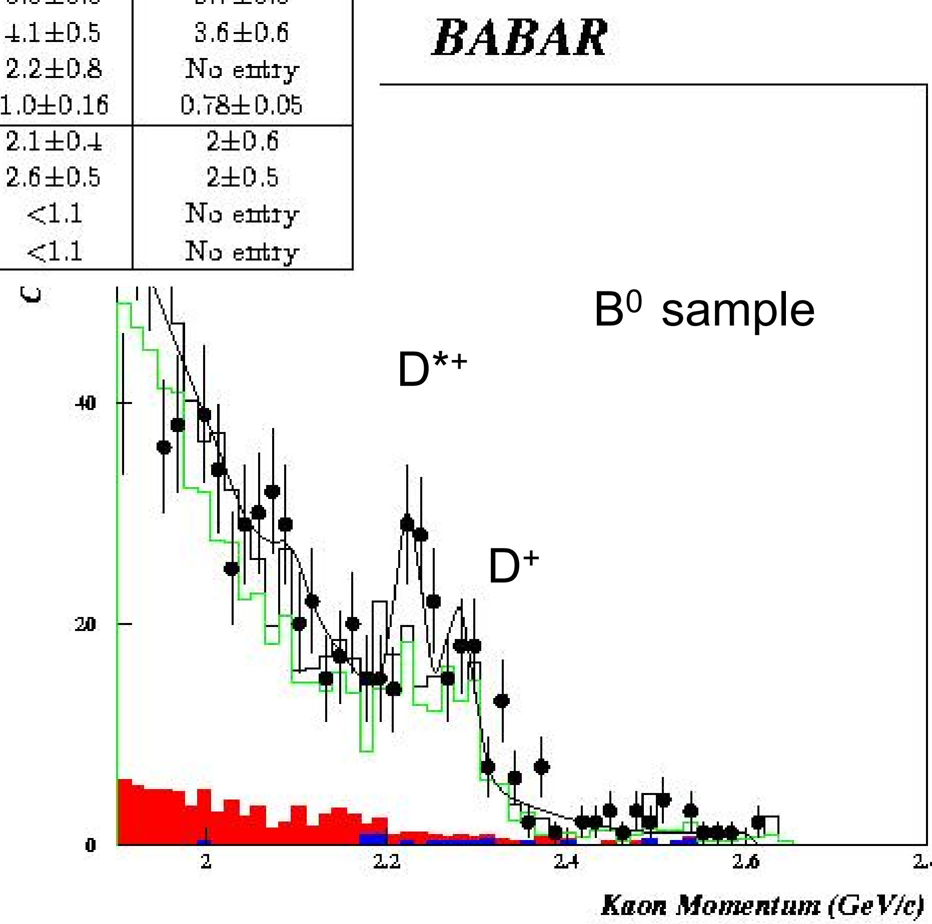
Conclusions

- An original analysis has been performed to extract informations of charmonium particles production and properties in a novel way.
- The kaon spectrum in the B rest frame, accessed thru the reconstruction of the other B, allowed to measure the production rate of 6 charmonium particles and set upper limits of 3 others
- Significant improvments over PDG were obtained in several domains, especially concerning the η_c and η_c' mesons
- New important information has been obtained on the X(3872): an upper limit on its production rate and a lower limit on its decay rate to $\psi\pi\pi$. An upper limit was set on the production rate of an hypothetical charged partner and several other hypothetical high mass states

Results in the DK region

Particle	Yield	BR(10^{-4})	BR(PDG2004)
D^0	146±14	5.0±0.5	3.7±0.6
D^{*0}	120±15	4.1±0.5	3.6±0.6
D^{**0}	63±23	2.2±0.8	No entry
η'	30±5	1.0±0.16	0.78±0.05
$D^{\pm}$	40±8	2.1±0.4	2±0.6
$D^{*\pm}$	49±9	2.6±0.5	2±0.5
$D^{**\pm}$	0±12	<1.1	No entry
$D_s(2317)$	7±9	<1.1	No entry





Future plans

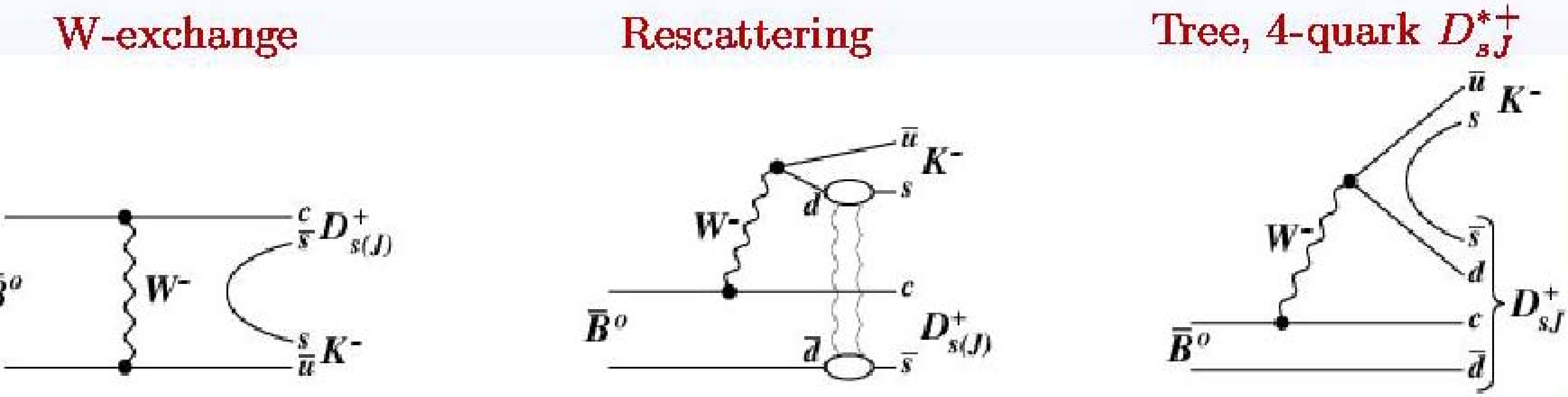
- Publication plans: PRL, before summer
- Analysis improvments
  - Reoptimize high mass cuts using our BR upper limit
  - Use Vertex informations
  - Look on Y(4S)
  - Can we use semileptonic decays
  - K^0

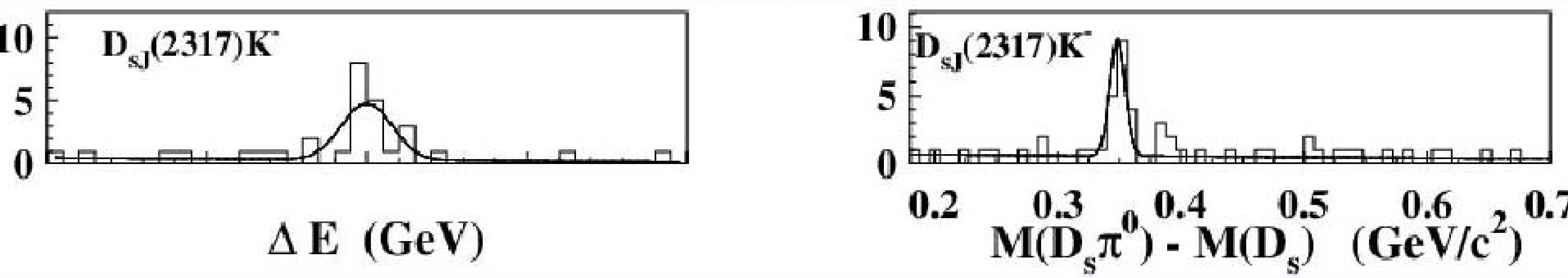
Conclusions

- Le secteur du charmonium a bénéfécié de beaucoup de très belles nouvelles mesures et offre encore de nombreux mystères
  - Production dans le continuum de double charme
  - Règle de factorisation: OK pour χ_2 , moins pour χ_0
  - Compréhension de la largeur des mésons η_c et du η_c '
  - Nature de la nouvelle particule X(3872) et des éventuelles particules X(3940) et Y(3940)
- Une nouvelle méthode originale permet d'aborder un certain nombre de réponses
  - BR absolus de tous les états charmonium produits dans le mode B->KX
  - Précision inégalée pour la mesure des BR du η_c et du η_c '
  - Amélioration de mesures importantes pour l'étude du charmonium
    - BR($\eta_c \rightarrow KK\pi$) , BR($J/\psi \rightarrow \gamma\ \eta_c$), $\Gamma(\eta_c \rightarrow \gamma\gamma)$
  - Limite inférieure sur le rapport de branchement du X(3872) en $\psi\pi\pi$ qui a tendance à défavoriser le modèle de molécule D-D*

Backup slides

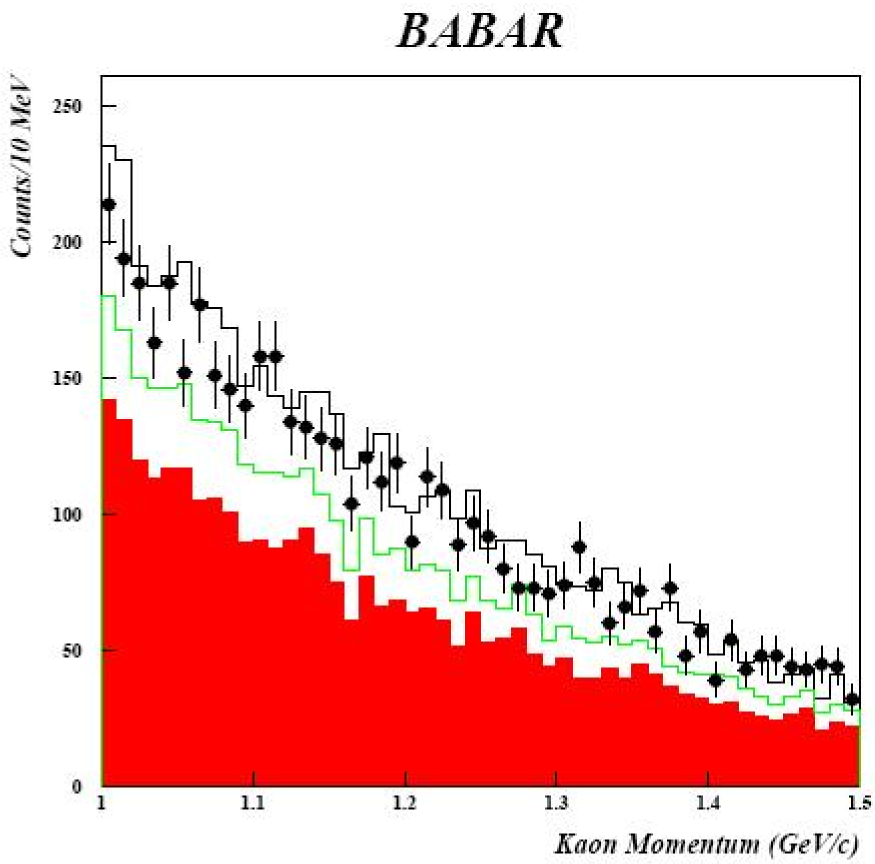
Belle: Observation of $B \to D^*_{sJ}(2317)K^+$ (PRL 94, 061802(20





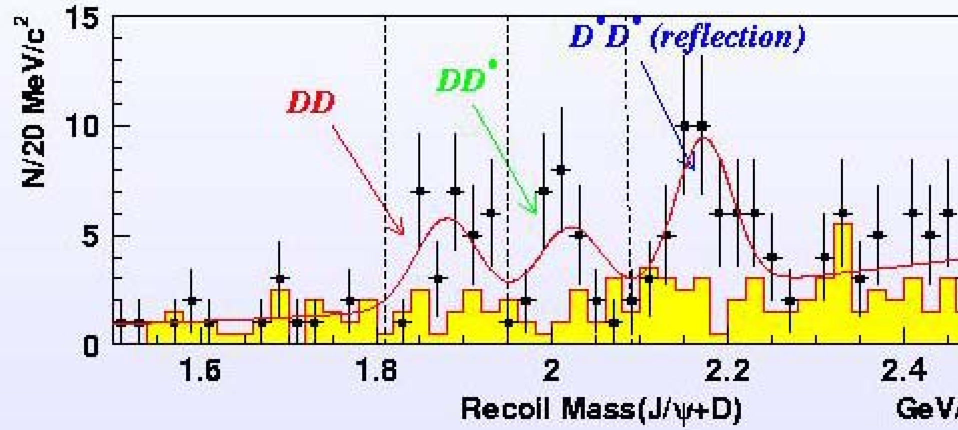
$\mathcal{B}(\bar{B}^0 \to D^*_{sJ}(2317)^+K^-) \times \mathcal{B}(D^*_{sJ}(2317)^+ \to D_s^+\pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}$ ⇒

⇒ the same order as $\bar{B}^0 \to D_s^+K^-$ with $\mathcal{B} = (3.8 \pm 1.3) \times 10^{-5}$ (PDG'04)


BABAR
Counts/10 MeV
250
200
150
100
50
0
1
1.1
1.2
1.3
1.4
1.5
Kaon Momentum (GeV/c)

Belle: $X(3940)$ decay modes

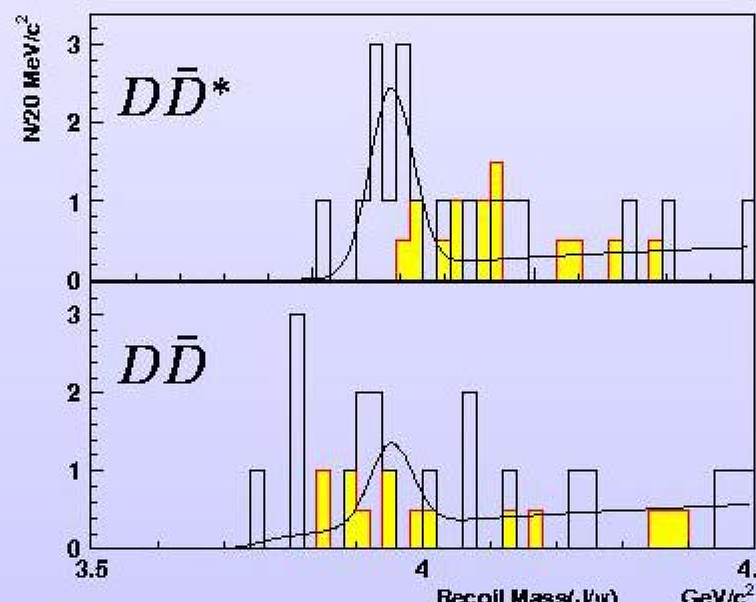
Reconstruct D and look for $(J/\psi\ D)$-recoil mass $\longrightarrow$



Require $(J/\psi + D)$-recoil mass around D or D^* $\longrightarrow$

Probably X(3940) not the Y(3940)
(different widths)

$\eta_c(3S)$?? $D\bar{D}^*$ mode rules out χ'_{c0}



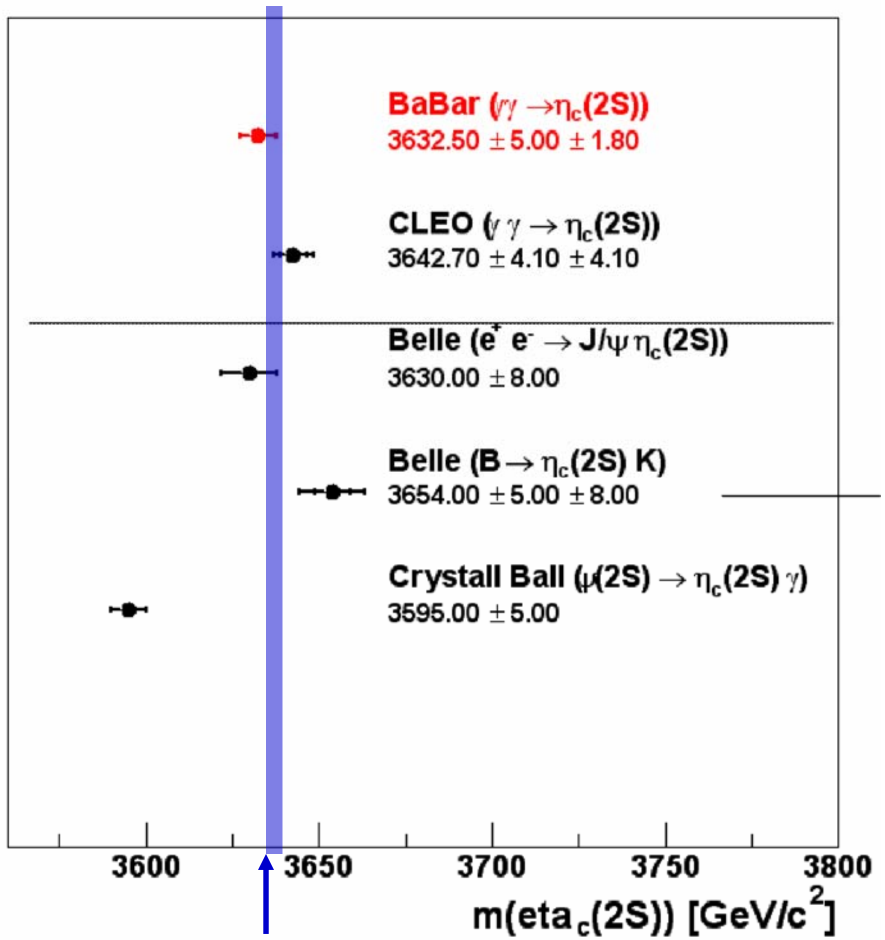
$4.5\ \sigma$

$2.1\ \sigma$

Radiative and exclusive decays (I)

- **Radiative decays** are not just useful pathways to other states but allow to probe details of quarkonium wavefunctions and intrinsic properties (e.g. magnetic moment) and velocity of heavy quarks in the bound state. Still poor known but relevant for NRQCD!
  - CLEO-c has accumulated 1.5 million $\psi(2S)$'s allowing to study the single photon spectrum and determine $BR[\psi(2S)\rightarrow\gamma\eta_c(1S)]$. A much larger sample is needed to observe the direct transition to $\eta_c(2S)$
    - the hindered transition will measure relativistic corrections (e.g. finite size), while
    - the direct M1 transition will measure the magnetic moment of the charm quark
  - Measurement of angular distributions in χ_c radiative decays gives insight into the multipolar structure of the process:
    - decay dominated by the E1 dipole term
    - higher M2 and E3 transitions arise in a relativistic treatment.
    - Comparison between E760 (χ_{c2}) and Crystal Ball (χ_{c1}) results are not consistent with theory: additional contributions? Effect also seen by E835. More statistics needed!
- Radiative decays of J/ψ into η, η' and η_c states can test the underlying dynamics:
  - assumed to be dominated by the gluonic contribution
  - of particular interest radiative quarkonium decays into scalar mesons instead of pseudoscalars (they might even be glueballs with admixtures of light quarks)

η_c': current status



M_{avg} =3637±4 MeV

(Crystal Ball excluded)