Spectroscopy and New Particles in BaBar

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Introduction

In recent years, spectroscopy has become exciting again

Many new states have been found,

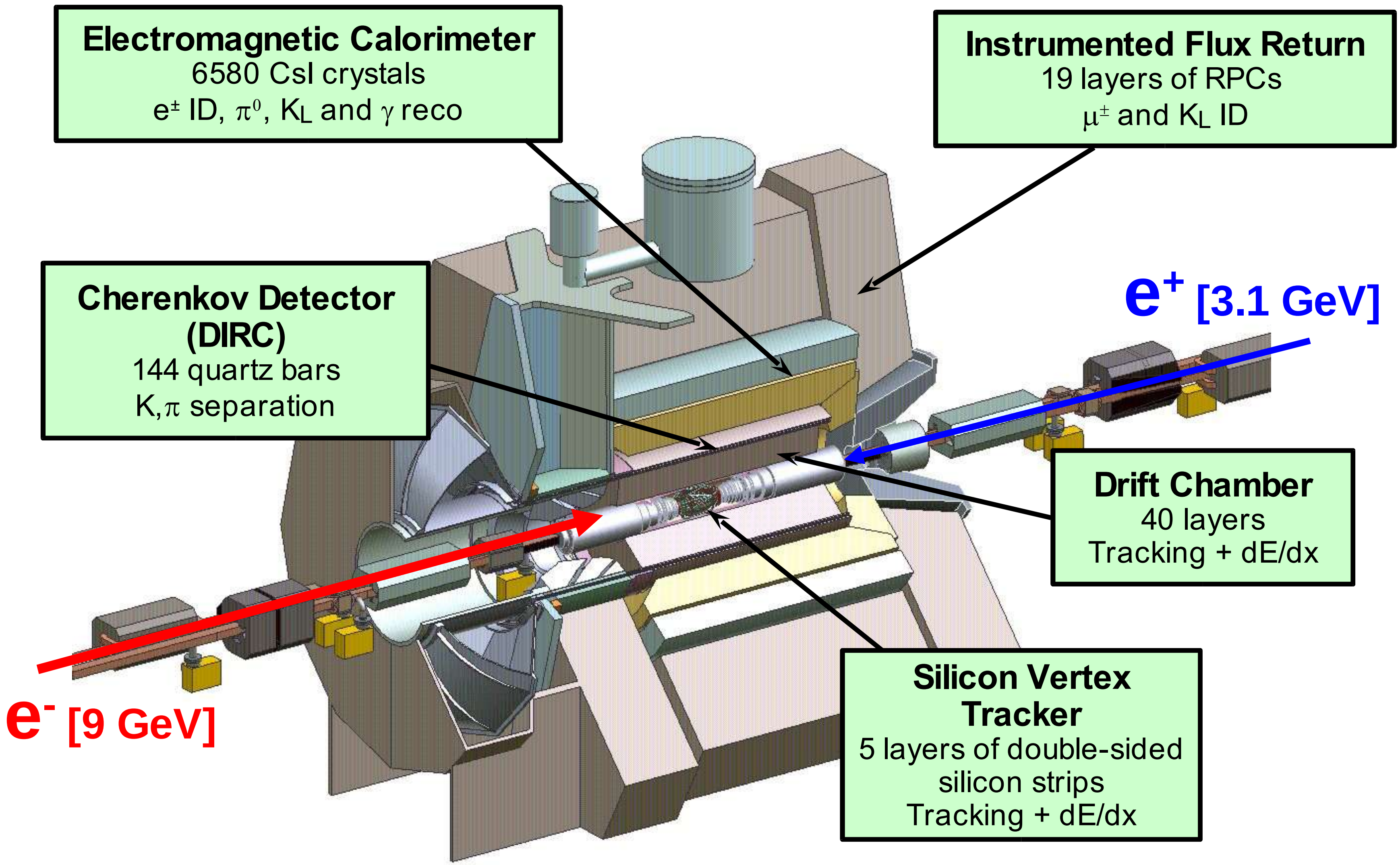
not all easily incorporated in standard $q\bar{q}/qqq$ model

- New D_{sJ} charm meson states
- New $c\bar{c}$ and $c\bar{c}$-like states such as X(3872), Y(3940)
- Candidates for pentaquark states have been reported by many experiments; still controversial since not seen by many other high statistics experiments

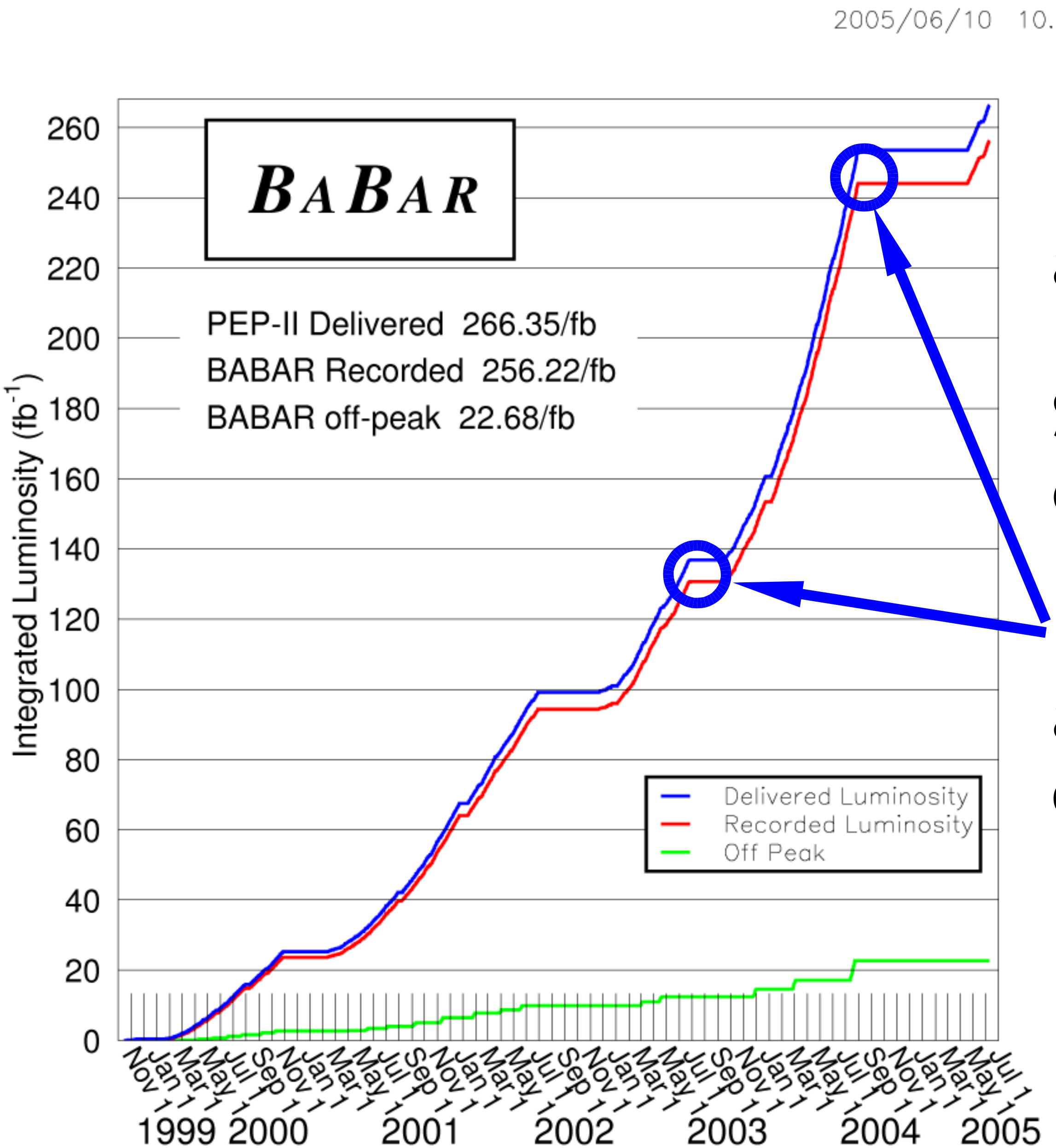
I will cover the BaBar studies of the last two subjects

The BaBar Experiment at PEP-II

e^+e^- experiment running at $\Upsilon(4S)$ resonance



BaBar Data Set



BaBar has recently restarted data-taking after long shutdown

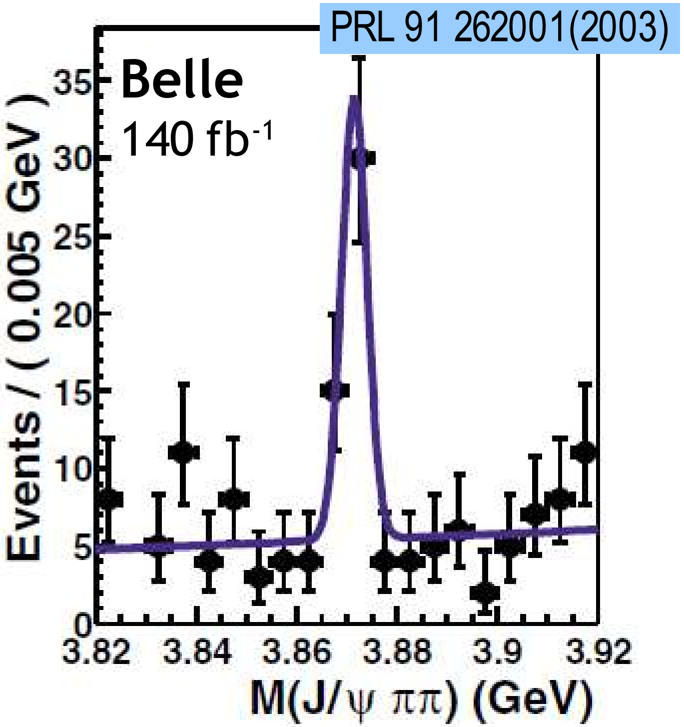
Scheduled to double dataset by next summer

Results presented here are based on subsamples of the full dataset

The X(3872)^0 State

Discovered by Belle in
$B^\pm \rightarrow J/\psi\, \pi^+\pi^- K^\pm$ decays

Confirmed by BaBar,CDF and D0
Mass: 3871.4±1.4 MeV/c^2



Several interpretations of the state:

- Ordinary charmonium state
  - Mass disagrees with most potential models
- Weakly bound DD* molecule state
  - Mass very close to $D^0\bar{D}^{0*}$ threshold
  - Highly suppressed $B^0 \rightarrow X(3872)^0 K^0$ rate predicted
- Diquark-antidiquark state
  - Different mass eigenstates predicted in B^0 and B^+ decays with $|\Delta m|>5$ MeV/c^2

Exclusive $B^+ \to X(3872)^0 K^+$ Reconstruction

$B^+ \to X(3872)^0 K^+$, $X(3872)^0 \to J/\psi\pi^+\pi^-$

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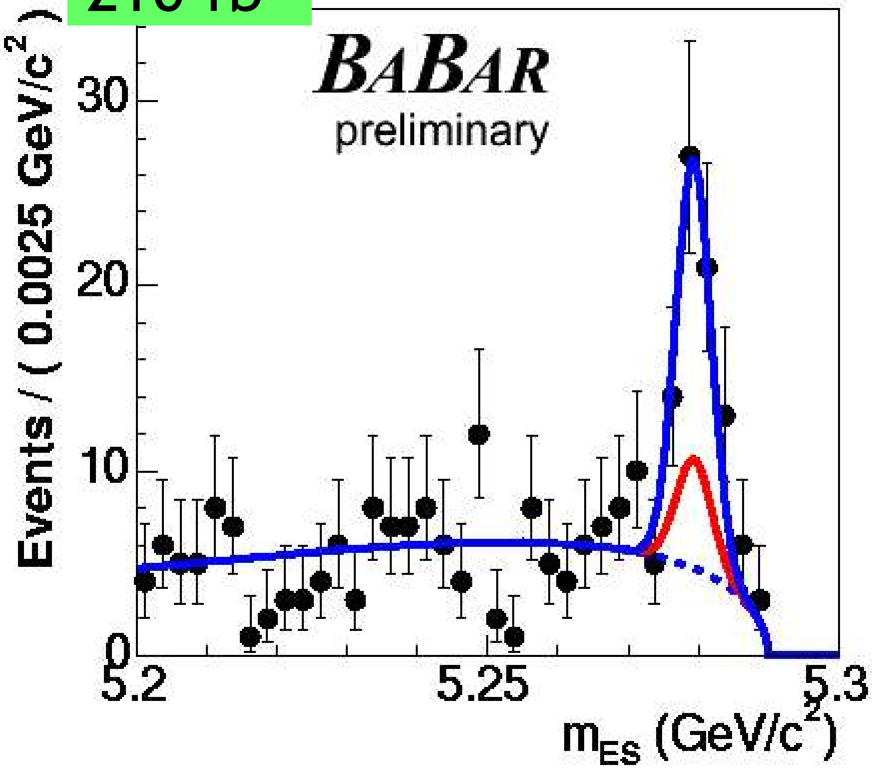
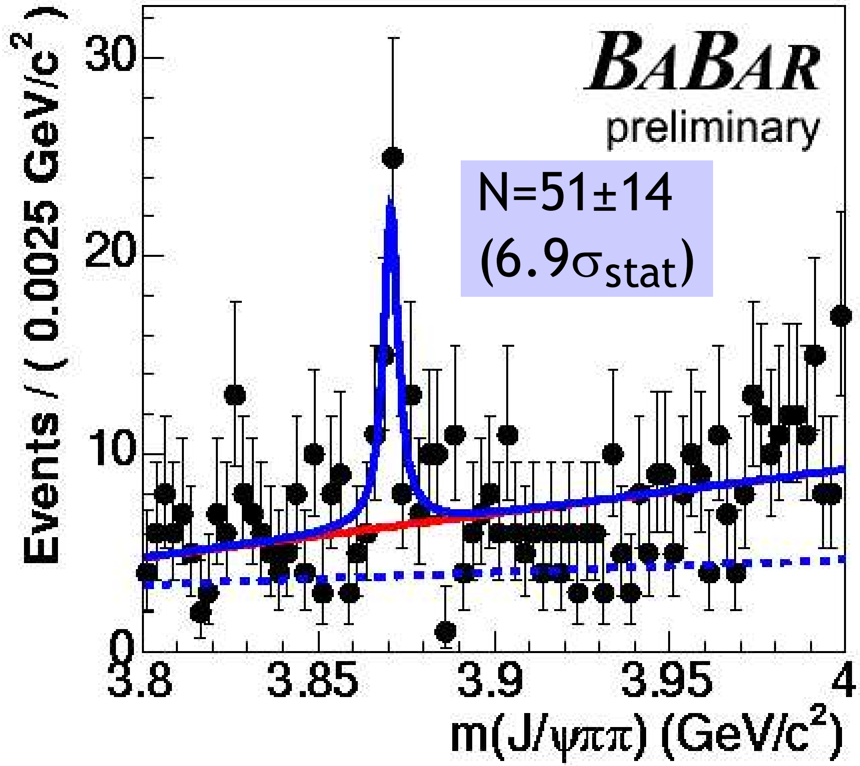




$$\left(m_{\mathrm{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2 / E_i^2 - \mathbf{p}_B^2}\right)$$

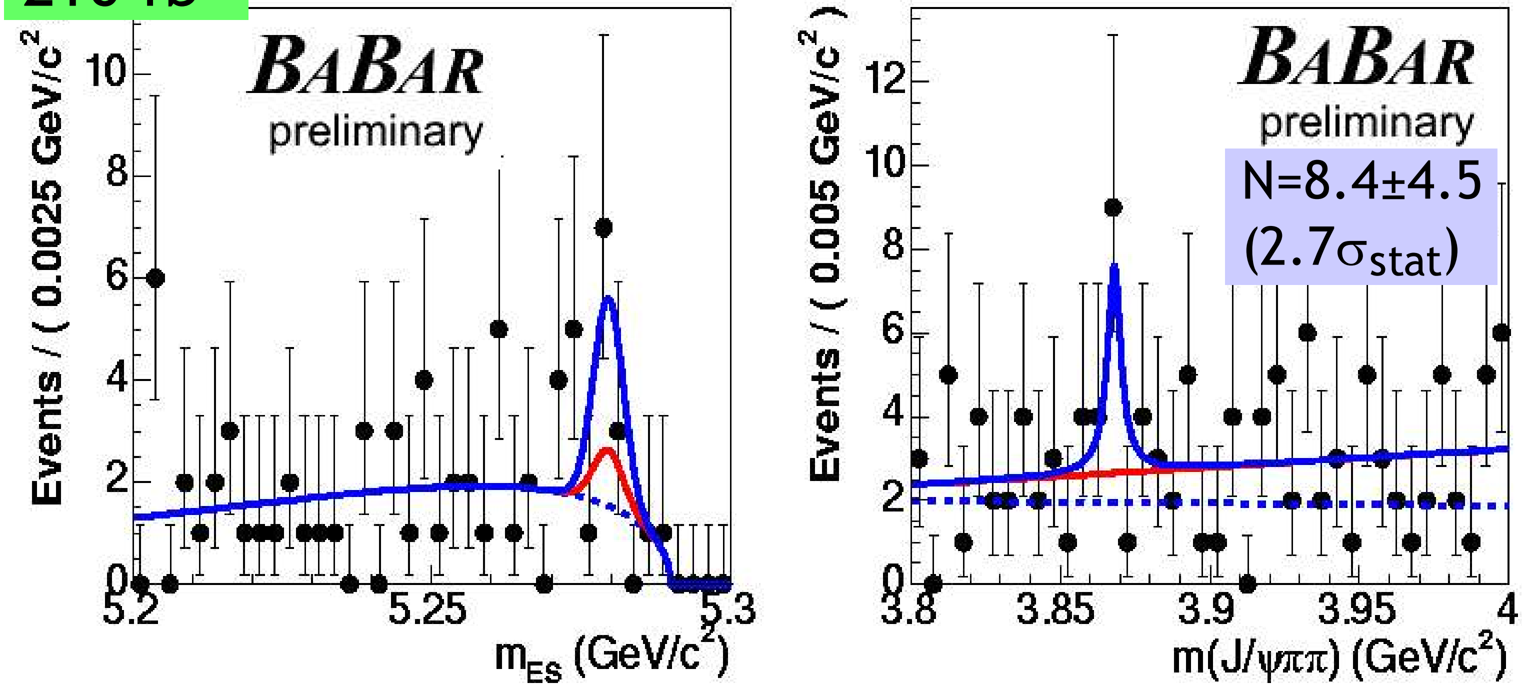
$m(X(3872)^0)$ = $3871.3 \pm 0.6 \pm 0.1$ MeV/c^2

$BF(B^+ \to X^0 K^+, X^0 \to J/\psi\pi^+\pi^-)$ = $(8.5 \pm 2.3 \pm 0.8) \times 10^{-6}$

Exclusive $B^0 \to X(3872)^0 K^0$ Reconstruction

$B^0 \to X(3872)^0 K_S$, $X(3872)^0 \to J/\psi \pi^+ \pi^-$

210 fb^{-1}



$m(X(3872)^0) = 3868.6 \pm 1.2 \pm 0.2\ \mathrm{MeV}/c^2$

$BF(B^0 \to X^0 K^0,\ X^0 \to J/\psi \pi^+ \pi^-) = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$

$\Delta m = 2.7 \pm 1.3\ \mathrm{MeV}/c^2$

$0.15 < BF(B^0 \to X^0 K^0)/BF(B^+ \to X^0 K^+) < 1.34$ @ 90% CL

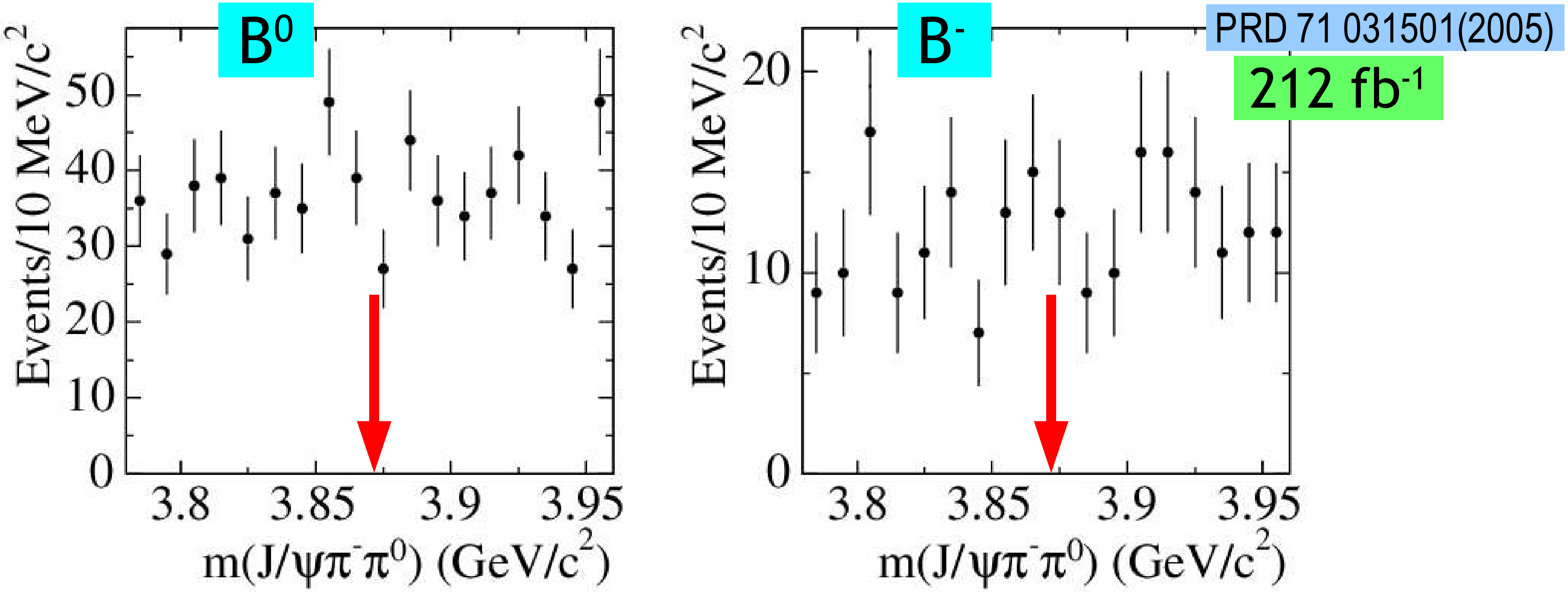
Need more statistics to discriminate among models...

Search for X(3872)$^\pm$

Data suggest X(3872)^0 decays through $J/\psi\rho^0$

- If so, $I_{X(3872)} = 1$ and we expect to find $X(3872)^- \to J/\psi\rho^-$
- Predict $BF(B\to X^-K) \sim 2\ BF(B \to X^0K)$ if isospin conserved in B decays

Search for $B^0\to X^-K^+$ and $B^-\to X^-K_S$ with $X^- \to J/\psi\rho^-$

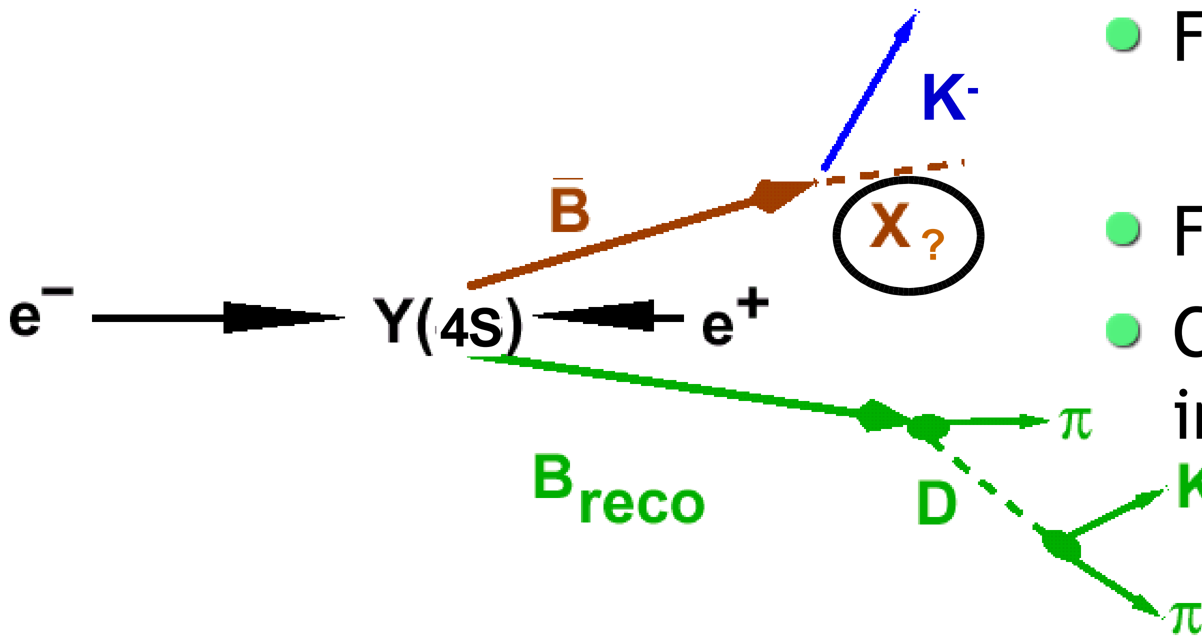


$BF(B^0\to X^-K^+,\ X^-\to J/\psi\pi^0\pi^-)<5.4\times10^{-6}$ @ 90% CL

$BF(B^-\to X^-K_S,\ X^-\to J/\psi\pi^0\pi^-)< 11\times10^{-6}$ @ 90% CL

No evidence for a X(3872)$^\pm$, isovector hypothesis excluded

Inclusive B→XK Reconstruction



- Fully reconstruct one B
  - Example: $B \to D^{(*)}\pi$
- Find recoiling kaon
- Calculate kaon momentum in other B rest frame

- Two-body B→XK decays give peaks in K momentum spectra
  - $m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B}$
- Allows measurement of absolute BF(B→XK) for any state

Fully reconstructed B^+ sample

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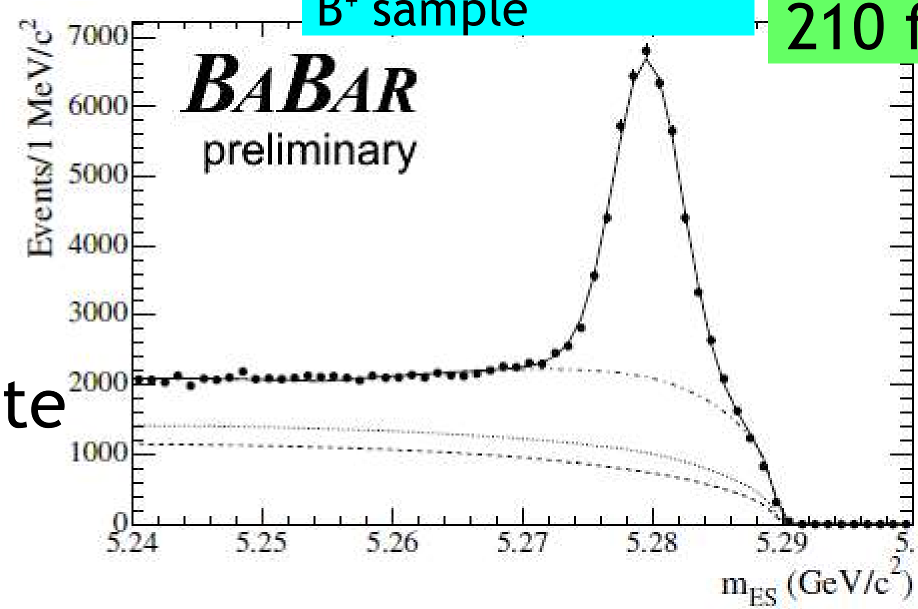
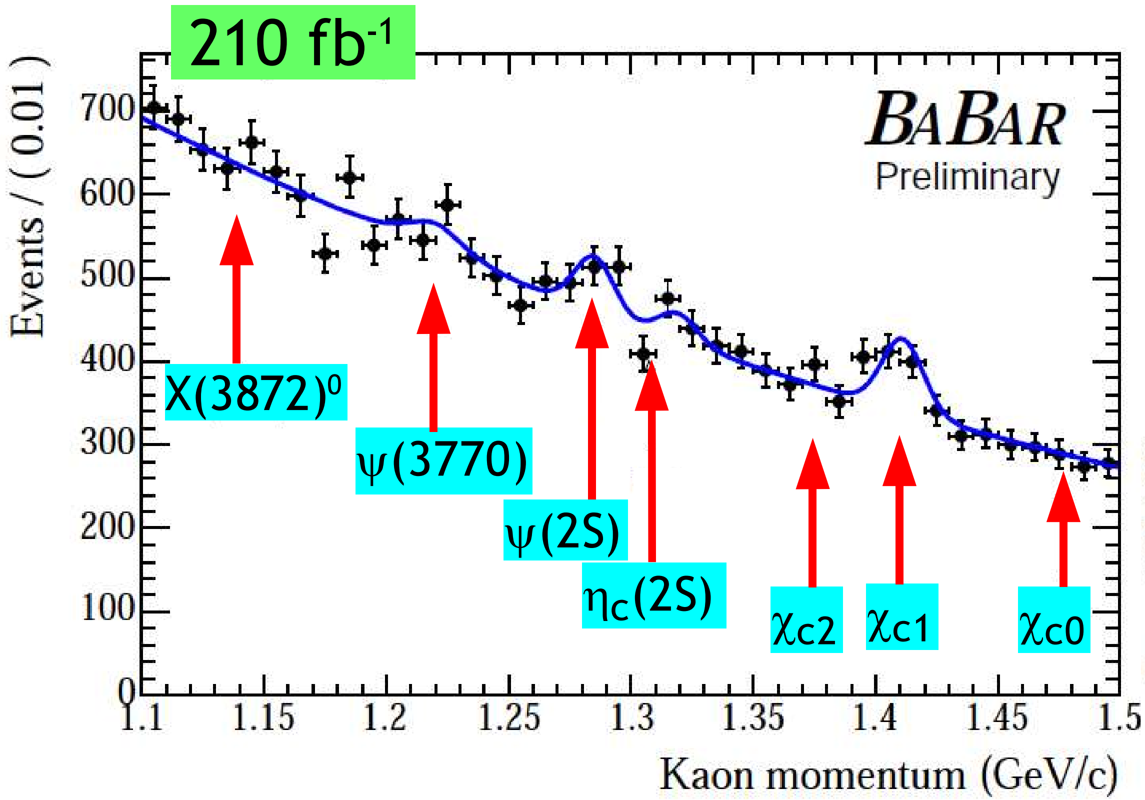
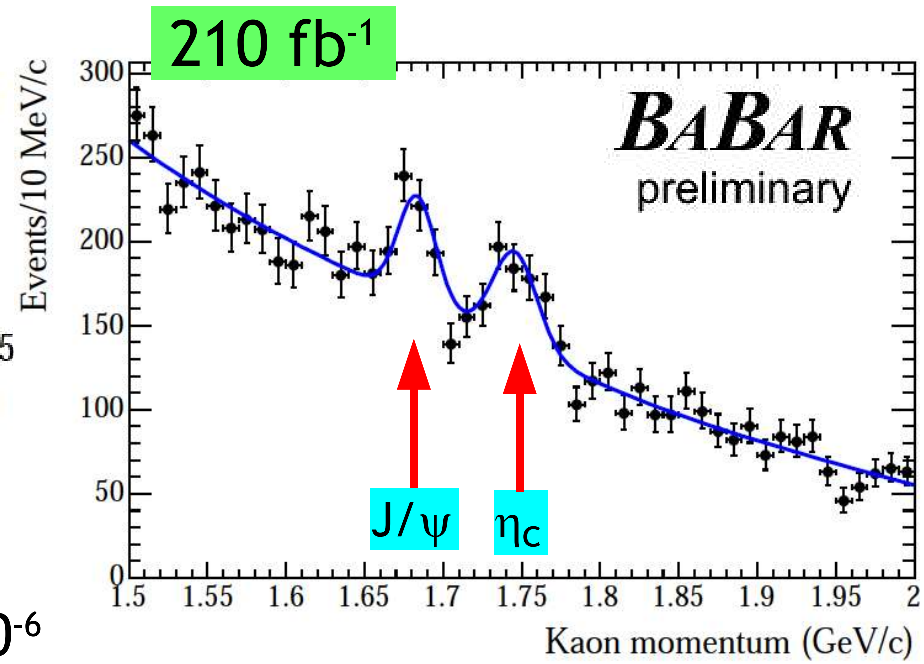


Kaon Momentum Spectrum



Clear J/ψ and η_c signals

$N(J/\psi)=258\pm42$
$N(\eta_c)\ =266\pm42$



Use non-observation of $X(3872)^0$ and BaBar-Belle average $BF(B^+\rightarrow X^0K^+,\ X^0\rightarrow J/\psi\pi^+\pi^-)=(13.7\pm2.2)\times10^{-6}$ to extract lower limit:

$BF(X(3872)^0\rightarrow J/\psi\pi^+\pi^-)>4.3\%$ at 90% CL

Branching Fractions from B→XK Study

BaBar inclusive measurements

BaBar exclusive measurements

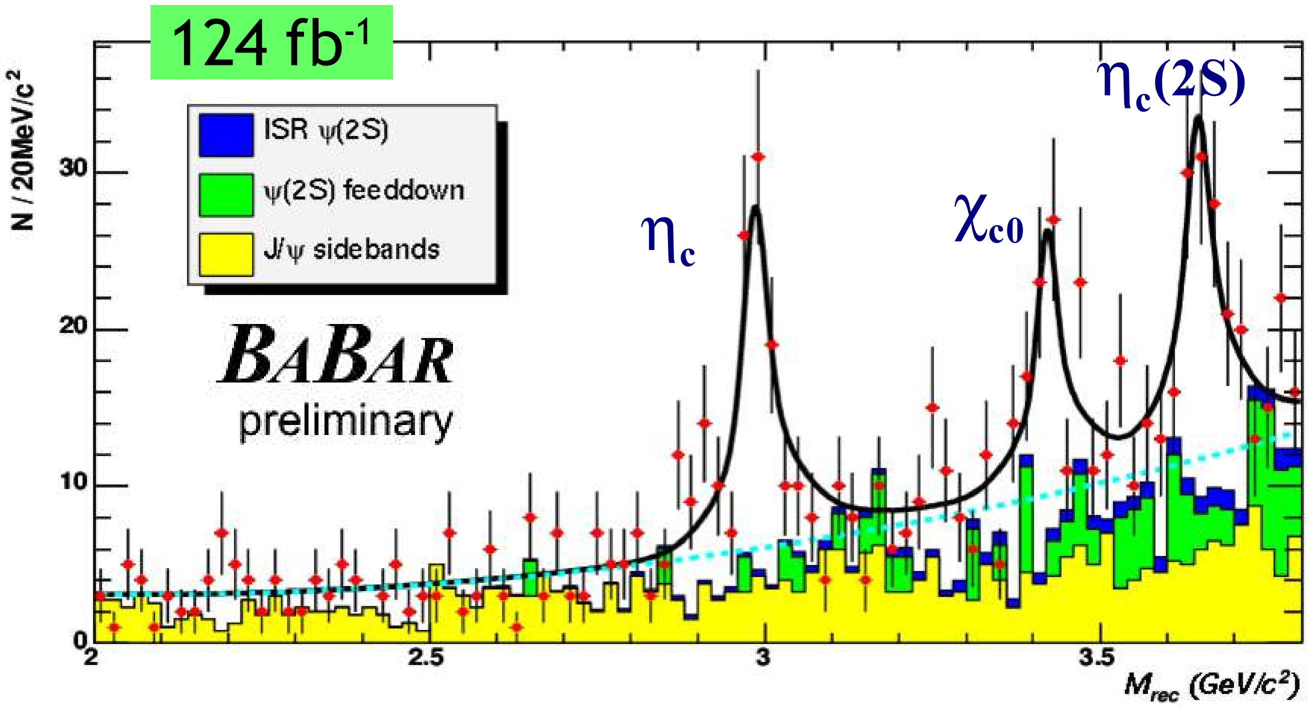
Particle	BF (10^{-4})	BF (PDG2004)	BF(BABAR)
η_c	8.9±1.5	9.0±2.7	13.4±4.4
J/ψ	8.1±1.6	10.0±0.4	10.6±0.5
χ_{c0}	<1.8	6±2.4±2.1	2.7±0.7
χ_{c1}	7.0±1.6	6.8±1.2	5.8±0.7
χ_{c2}	<2	No entry	<0.3
$\eta_c(2S)$	3.1±1.5	No entry	
$\psi(2S)$	4.2±1.4	6.8±0.4	6.2±0.5
$\psi(3770)$	3.2±2.3	No entry	
X(3872)	<3.2	No entry	

Preliminary upper limits given at 90%CL

Double Charmonium Production

Can study $c\bar{c}$ states in $e^+e^-\to J/\psi c\bar{c}$ events

- Reconstruct $J/\psi\to ll$
- Suppress ISR events
- Look at recoil mass



Only observe states with even C-parity: $\eta_c(1S)$, χ_{c0}, $\eta_c(2S)$

$\Rightarrow$ Production mechanism is

$e^+e^- \to \gamma^* \to J/\psi c\bar{c}$ not $e^+e^- \to \gamma^*\gamma^* \to J/\psi c\bar{c}$

Double Charmonium Production

Extract production cross section for $e^+e^- \to J/\psi c\bar{c}$:

$J/\psi + c\bar{c}(\to > 2\,charged)$	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)	$2984.8 \pm 4.0^{+4.5}_{-5.0}$	$3420.5 \pm 4.8^{+11.5}_{-9.5}$	$3645.0 \pm 5.5^{+4.9}_{-7.8}$

Theoretical predictions are based on Nonrelativistic QCD:

	η_c	χ_{c0}	$\eta_c(2S)$
Braaten and Lee	2.31±1.09	2.28±1.03	0.96±0.45
Liu, He and Chao	5.5	6.9	3.7

Cross sections significantly larger than NRQCD prediction
Possibly because relativistic corrections not included?

Search for X(3872)^0 in ISR Events

Look for $e^+e^- \rightarrow X(3872)^0\gamma$,

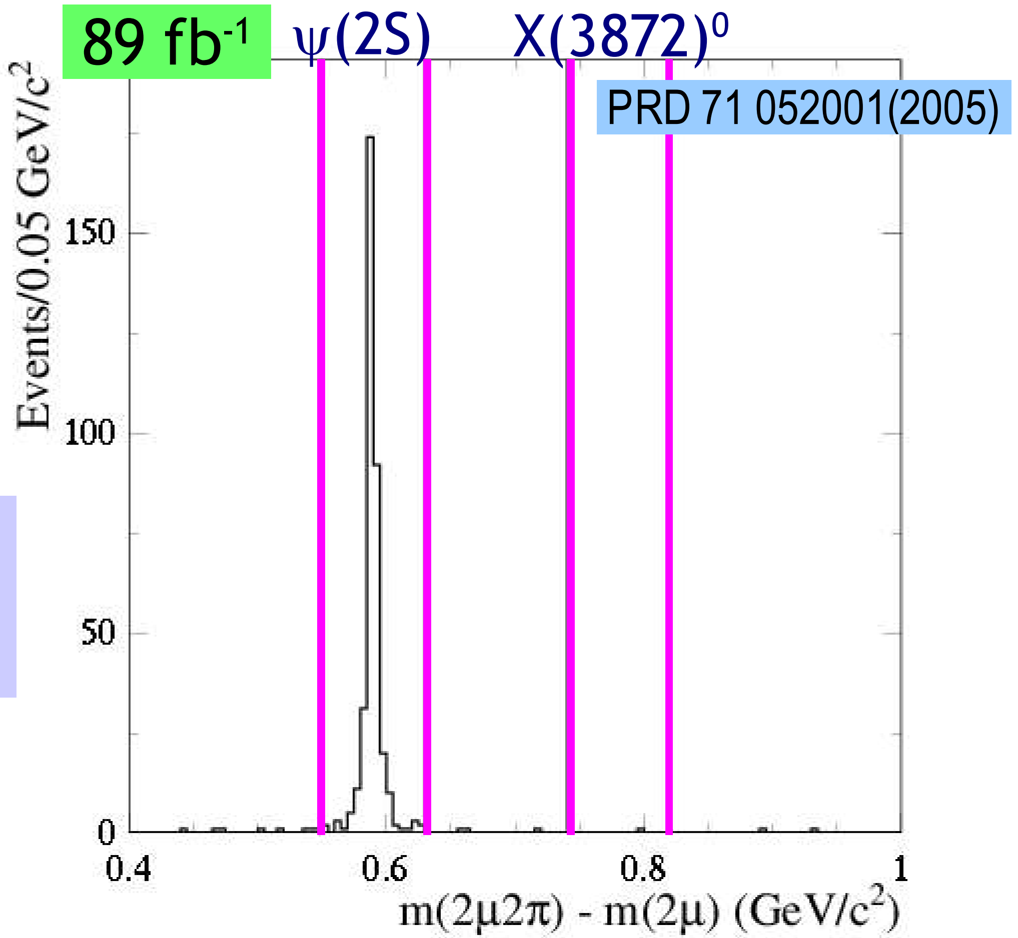
$X(3872)^0 \rightarrow J/\psi\ \pi^+\pi^-$,

$J/\psi \rightarrow \mu\mu$

Only observable if
X(3872)^0 is $J^{PC}=1^{--}$ state

No signal is observed

Set an UL @ 90% CL:
$BF(X(3872) \rightarrow J/\psi\ \pi^+\pi^-) \cdot \Gamma^X_{ee} < 6.2$ eV



Pentaquark Controversy?

Since first reported by LEPS, many experiments have reported evidence of possible pentaquark states

Experiment	State	Production	Decay	Significance
LEPS		γC_{12}	K^+n	$4.6\ \sigma$
CLAS		γd	K^+n	5.2σ
CLAS		γp	K^+n	7.8σ
SAPHIR		γp	K^+n	4.8σ
COSY		pp	$K^0_s p$	3.7σ
JINR	Θ_5^+	$p(C_3H_8)$	$K^0_s p$	5.5σ
SVD		pA	$K^0_s p$	5.6σ
DIANA		K^+Xe	$K^0_s p$	4.4σ
nBC		νA	$K^0_s p$	6.7σ
NOMAD		νA	$K^0_s p$	4.3σ
HERMES		ed	$K^0_s p$	5.8σ
ZEUS		ep	$K^0_s p$	4.6σ
NA49	Z_5^{--}	pp	$\Xi\pi$	5.8σ
H1	Θ_{5c}	ep	D^*p	5.4σ

Contradicted by high statistics CLAS measurement

$\Theta_5(1540)^+$ $[uudd\bar{s}]$

$\Xi_5(1860)^{--}$ $[ddss\bar{u}]$

$\Theta_{5c}(3100)^0$ $[uudd\bar{c}]$

Many other high statistics experiments report no evidence for pentaquark states – existence is still being debated

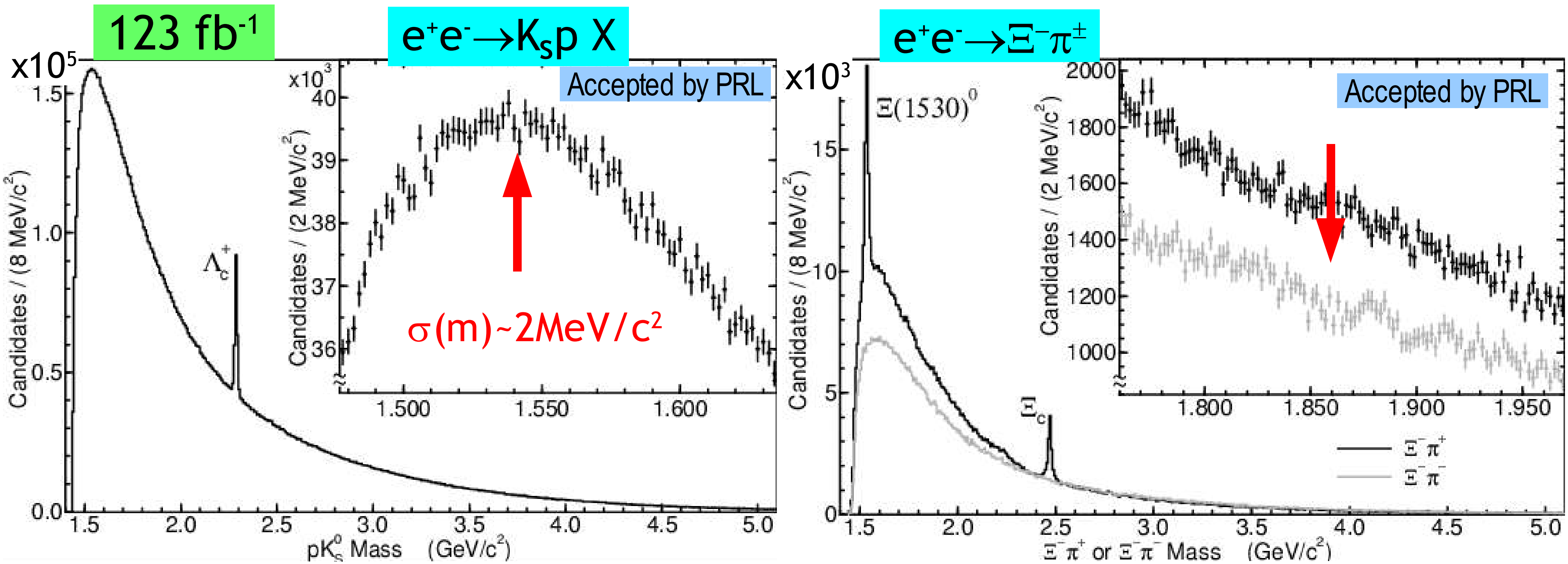
Pentaquark Searches in BaBar

BaBar has searched for pentaquarks in several places:

- In inclusive production in e^+e^- interactions:
  - Searched for: $\Theta_5(1540)^+ \to pK_S$, $\Xi_5(1860)^{--} \to \Xi^- \pi^-$
  - Also searched for other pentaquark states
- In electro- and hadro-production
  - Use inner detector as target for off-momentum beam electrons and hadrons from e^+e^- interactions
  - Searched for $\Theta_5(1540)^+ \to pK_S$

Inclusive e^+e^- Production

Large signals for $\Lambda_c \to pK_s$, $\Xi(1530)^0 \to \Xi^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$



No pentaquark signals seen

Production Cross Section

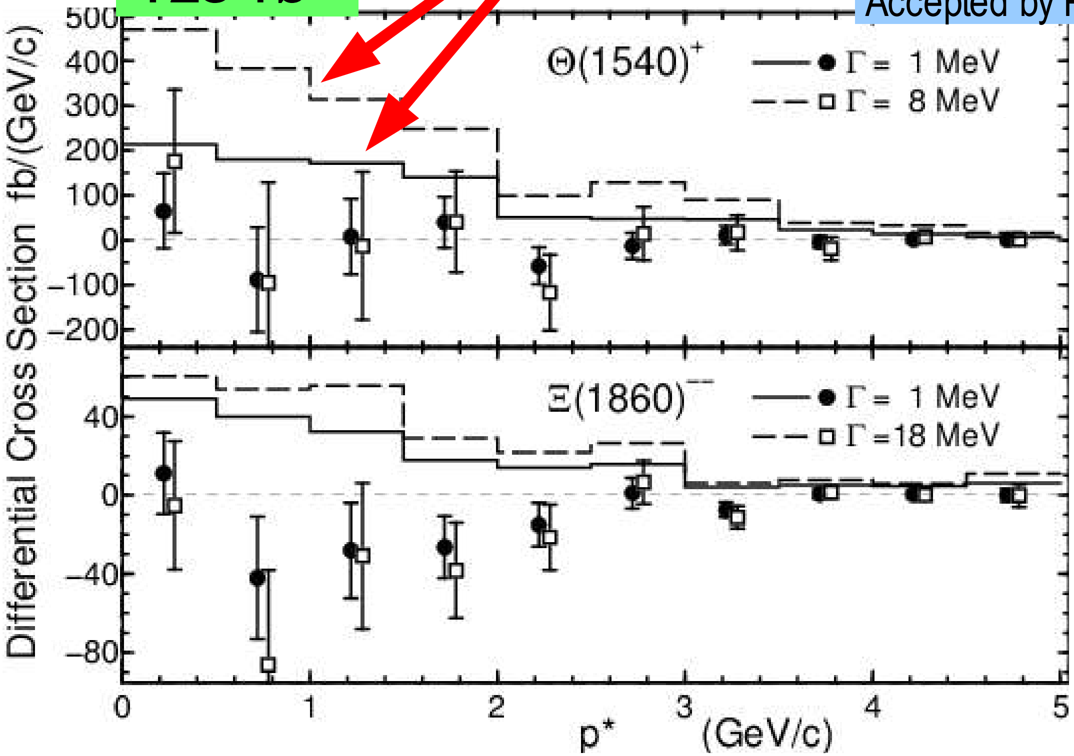
Non-observation converted to production cross section limits

Assume BF($\Theta_5(1540)^+ \to pK_S$)=25% and BF($\Xi_5(1860)^{--} \to \Xi^- \pi^-$)=50%

Upper limits with different width assumptions

123 fb^{-1}

Accepted by PRL



Limits on total cross sections:

For Γ=1 MeV:

$\sigma(\Theta_5(1540)^+)$ <171 fb @ 95% CL

$\sigma(\Xi_5(1860)^{--})$ < 25 fb @ 95% CL

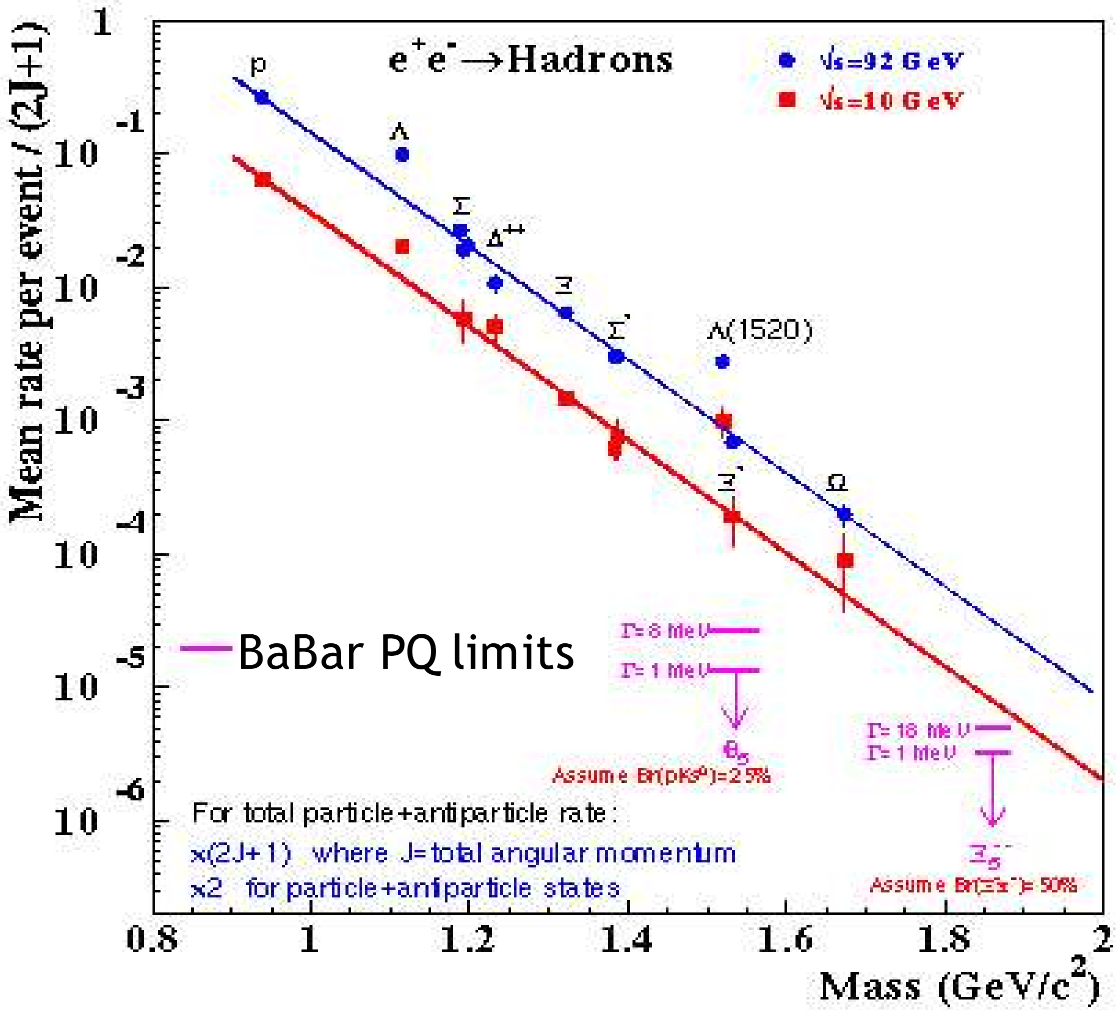
For Γ=8(18) MeV:

$\sigma(\Theta_5(1540)^+)$ <363 fb @ 95% CL

$\sigma(\Xi_5(1860)^{--})$ < 36 fb @ 95% CL

Pentaquark Cross Sections Comparison

Compare rate limits to "normal baryons"



Limits are well below rate observed for "normal" baryons

What rate to expect for pentaquarks?

Electro- and Hadro-Production of pK_s

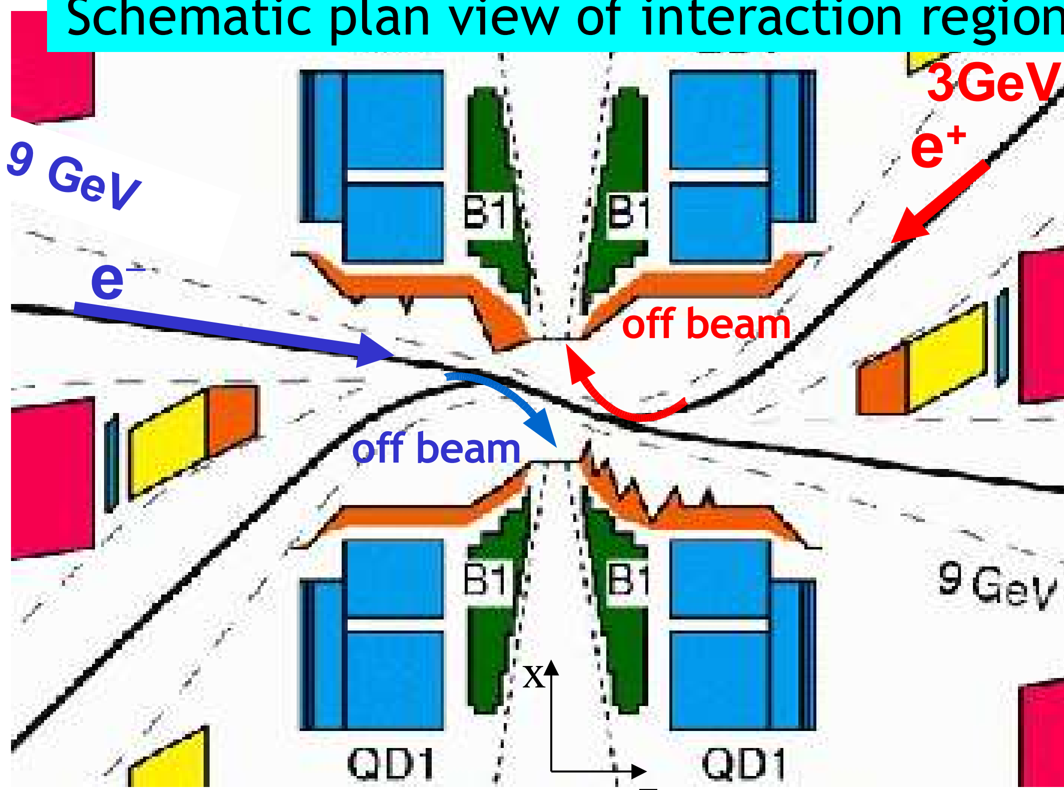
Hadroproduction:

- Secondary interactions in detector material of hadrons produced in e^+e^- annihilations

Electroproduction:

- Off-beam e^- and e^+ bent into Be beam pipe in horizontal plane by final focusing magnets

Schematic plan view of interaction region

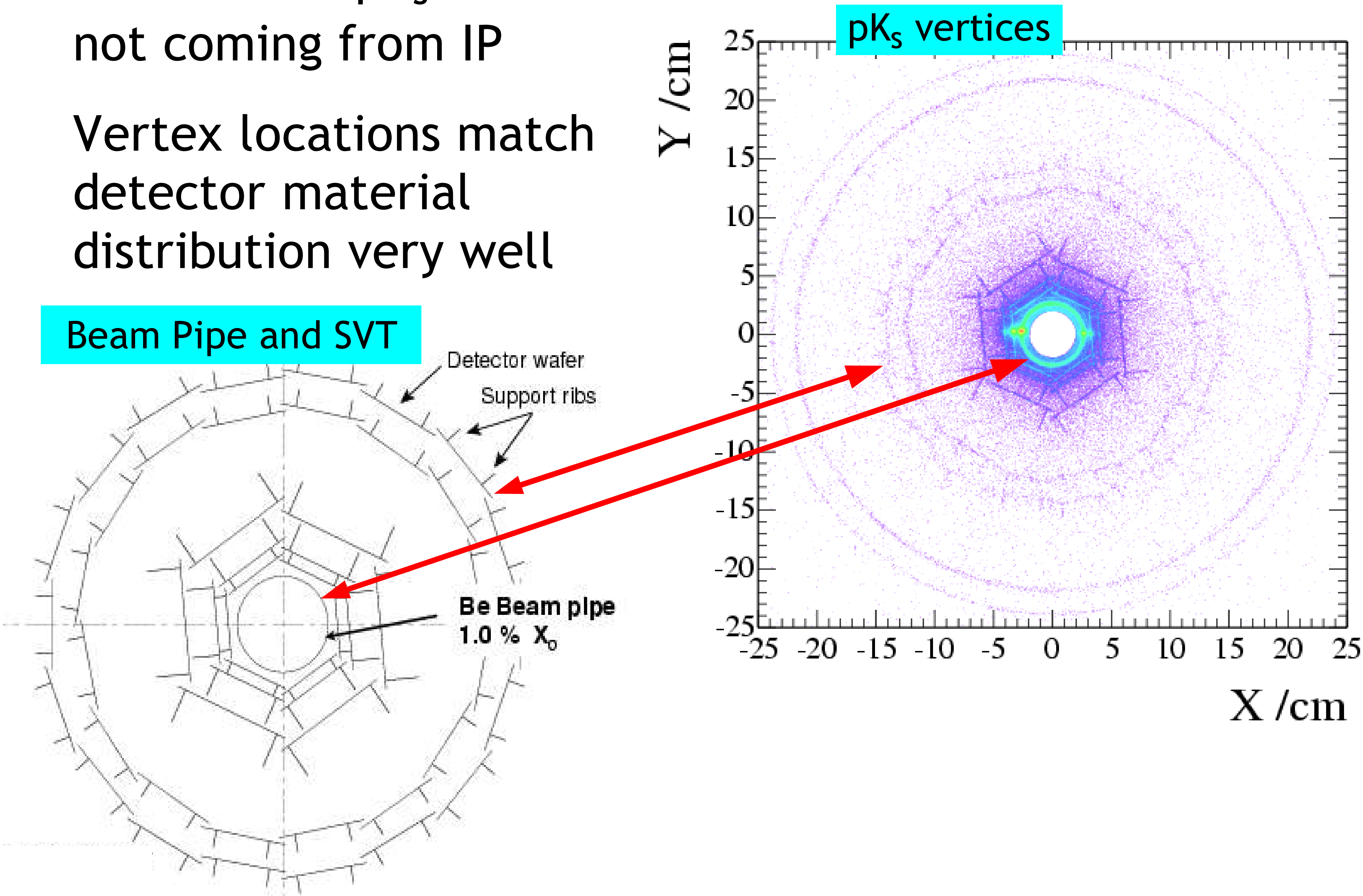


different x and z scales

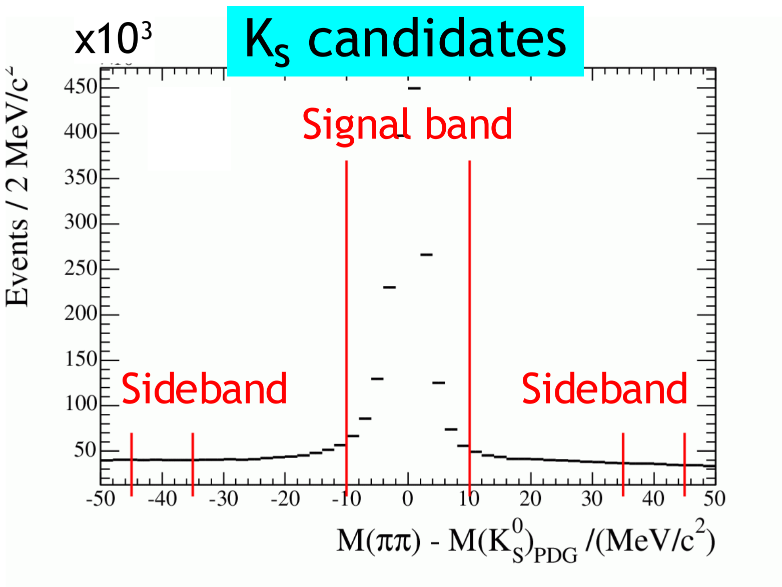
Detector Tomography

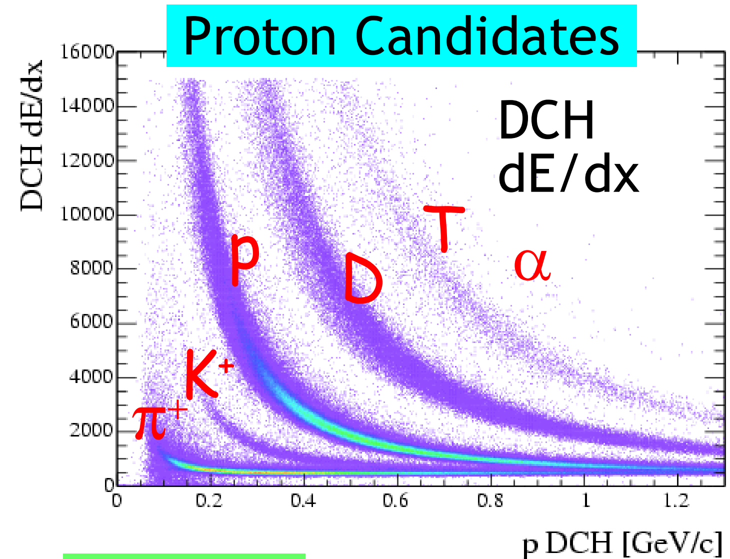
Reconstruct pK_s vertices not coming from IP

Vertex locations match detector material distribution very well



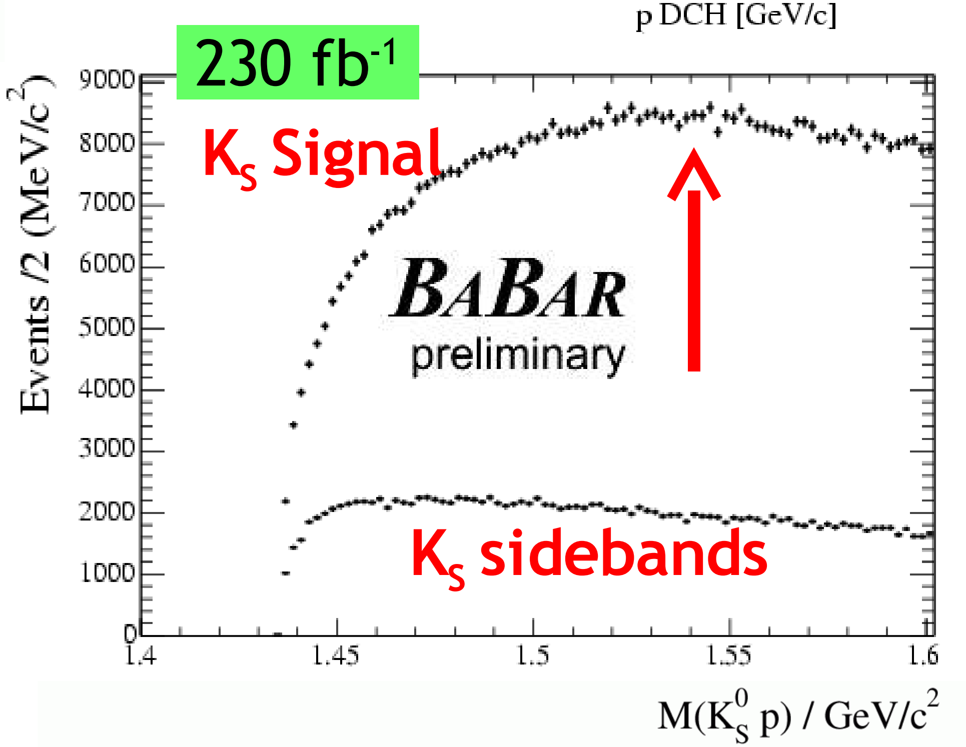
Search in Hadro-Production



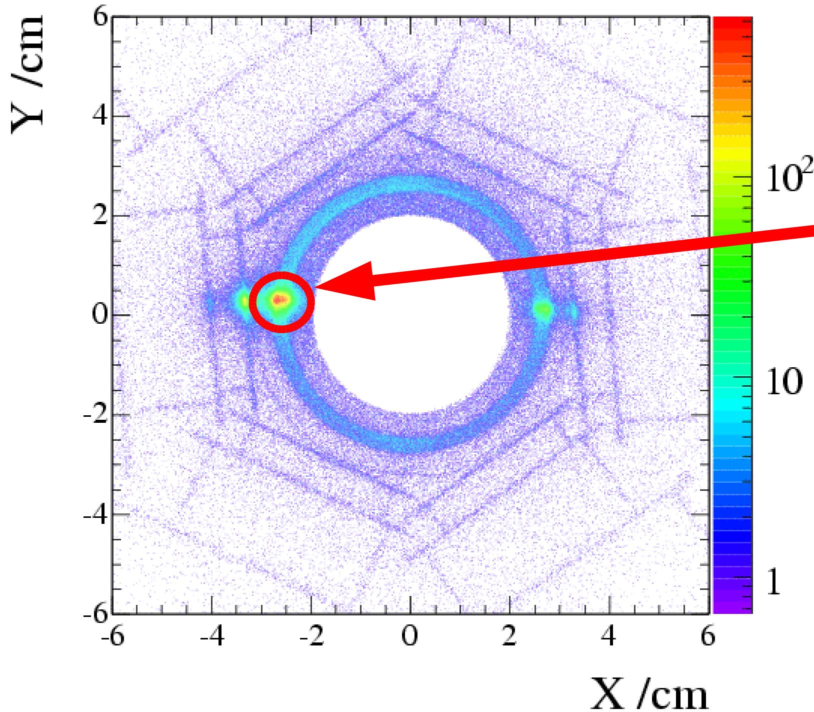


Protons and kaons are cleanly selected

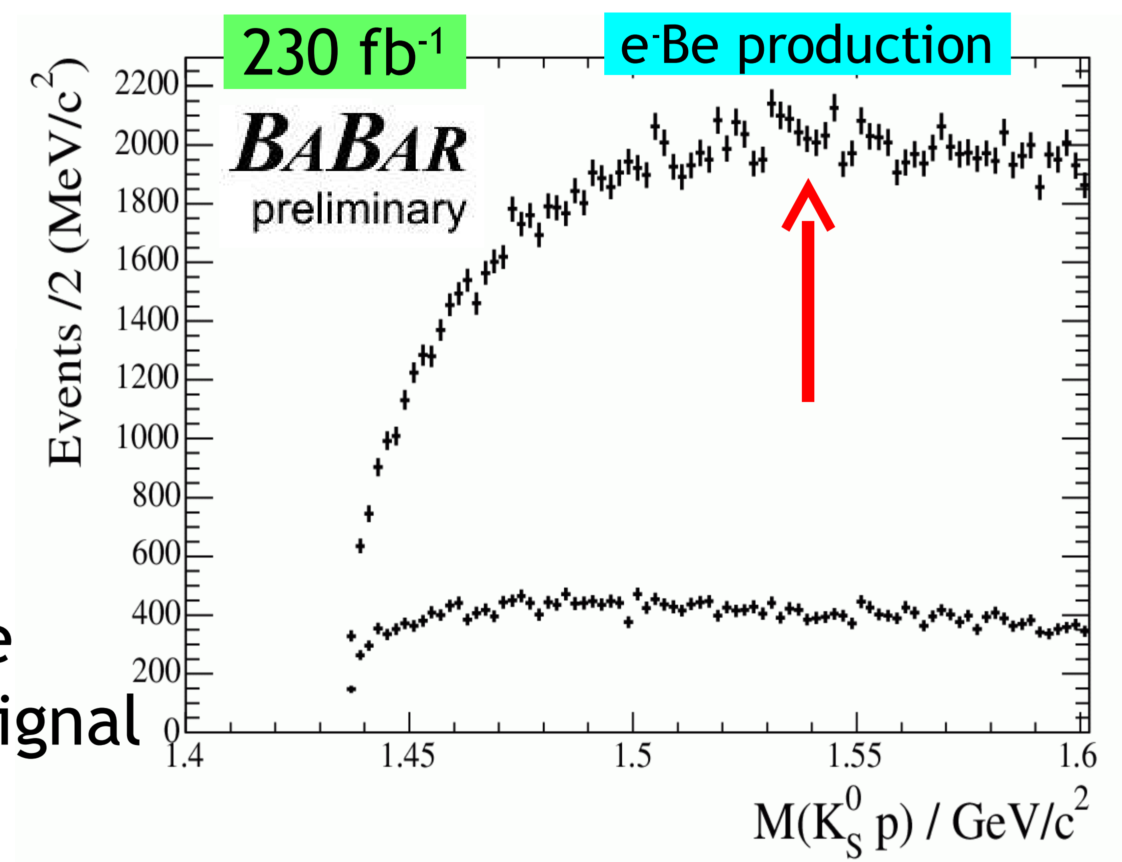
Searching in all events (mainly hadro-production) no pentaquark signal is observed



Search in Electro-Production



Electro-production studied by selecting region where most off-momentum electrons hit Beryllium beam pipe



Again no pentaquark signal is observed

Requiring a third particle also does not show any signal

Summary

X(3872) state

- Clear $X(3872)^0$ signal observed in $B^+ \to XK^+$ decays
  - Measured $m(X(3872)^0) = 3871.3 \pm 0.6 \pm 0.1$ MeV/c^2
- No charged state $X(3872)^+$ has been found
- No signal is observed in ISR events
- Recoil B analysis puts lower limit on $X(3872)^0$ BF
- More statistics needed to definitively discriminate among X(3872) models

Pentaquarks

- No signal in e^+e^- production – limits are well below normal baryon production cross sections
- No signal for $\Theta_5(1540)^+$ in electro- and hadro-production in detector material