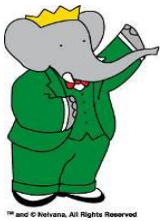
SELECTED SPECTROSCOPY RESULTS FROM THE BABAR EXPERIMENT



Veronique Ziegler

J-Lab

Theory Seminar, March 7, 2012

OUTLINE

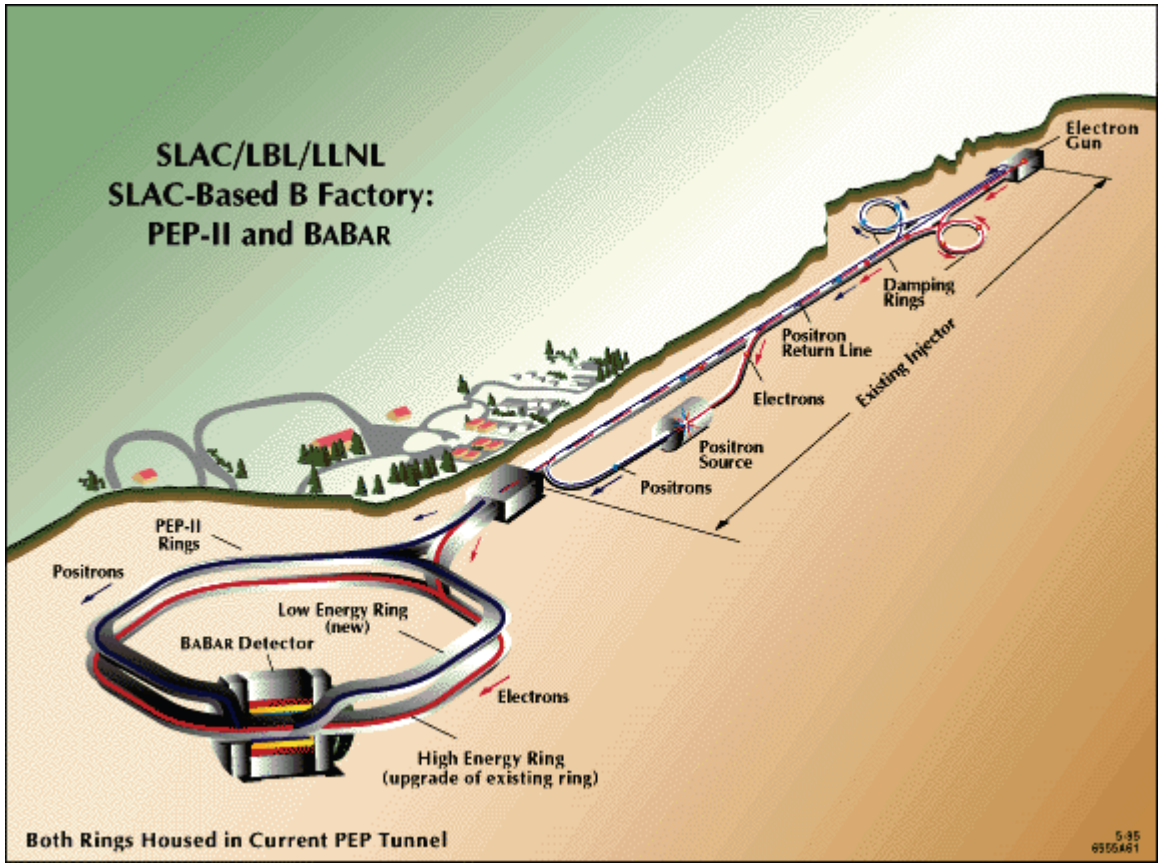
I. The BaBar Experiment

II. Selected Baryon Spectroscopy Results

III. Selected Meson Spectroscopy Results

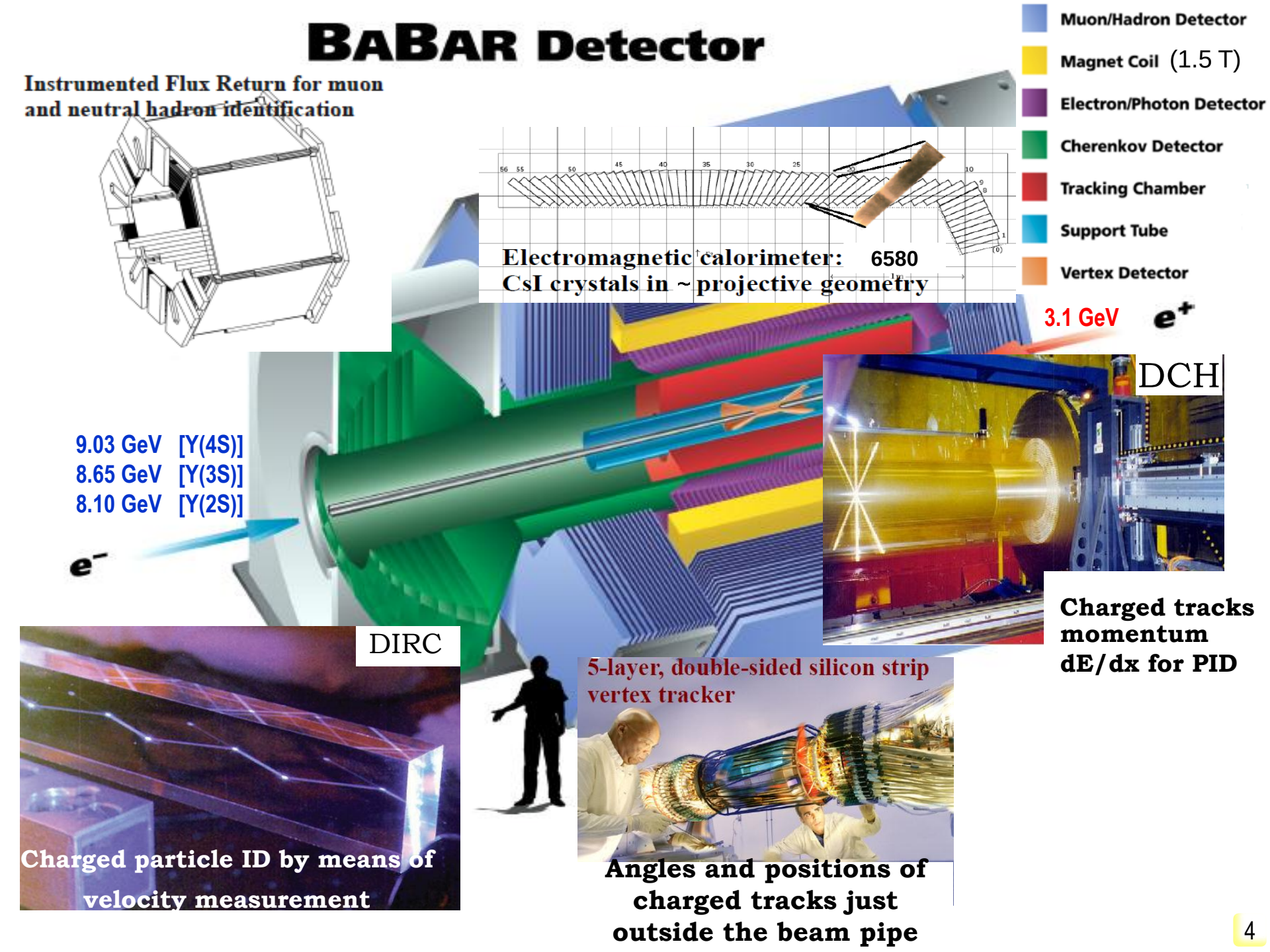
IV. Summary

THE PEP-II STORAGE RINGS AT SLAC

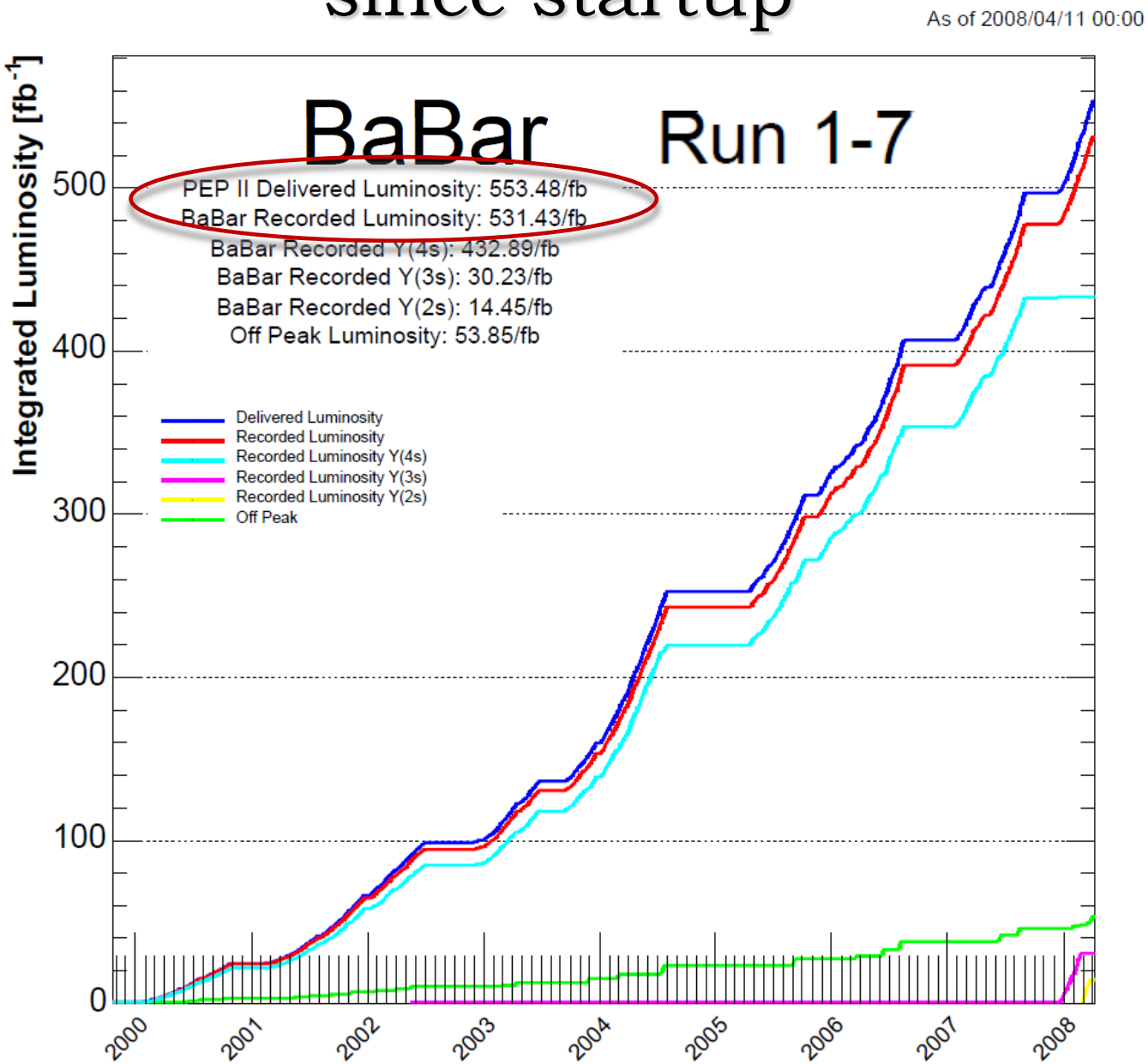


Bunches are accelerated in the SLAC Linear Accelerator and injected into the storage rings in order to collide at the BaBar detector

BABAR Detector



BaBar integrated luminosity since startup



Largest Υ(nS) Data Sets

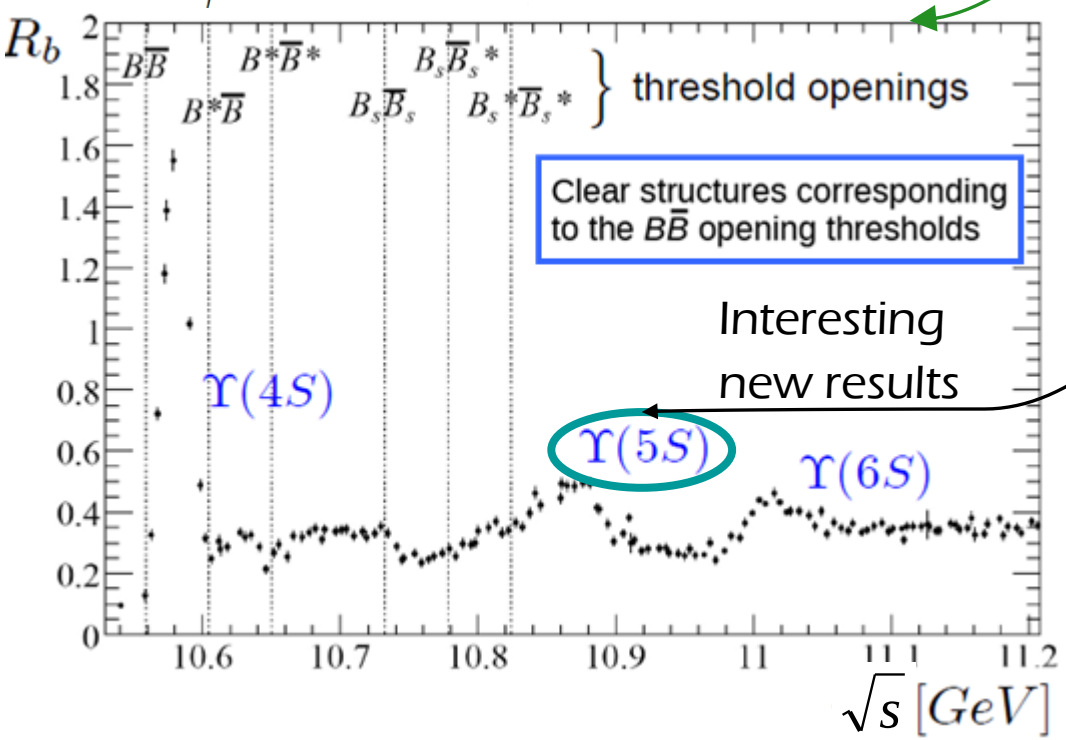
Samples	Υ(1S)	Υ(2S)	Υ(3S)	Υ(4S)	Υ(5S)
BaBar		14 fb^{-1}	**30 fb^{-1}**	433 fb^{-1}	3.2 fb^{-1} (scan)
Belle	6 fb^{-1}	24 fb^{-1}	3 fb^{-1}	**711 fb^{-1}**	**121 fb^{-1}**

e^+e^- Cross Section Scan

PRL 102, 012001 (2009)

Precision scan in E_{CM} from 10.54 GeV to 11.20 GeV

- 5 MeV steps with 25 pb^{-1} at each step ($\int \mathcal{L} \approx 3.3\, fb^{-1}$)
- 8 steps at Υ(6S) ($\int \mathcal{L} \approx 0.6\, fb^{-1}$)



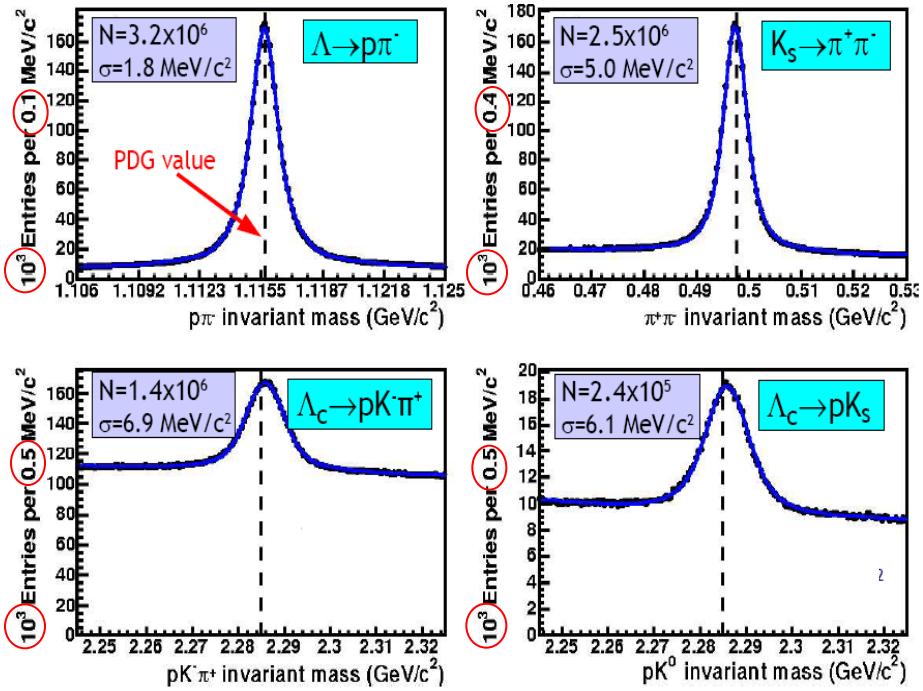
BaBar as a Charm Baryon Factory

Present data sample contains:

- **> 450 M Υ(4S) → $B\bar{B}$ events** (σ = 1.05 nb)
- **> 1600 M e^+e^- → $q\bar{q}$ events** (σ = 3.39 nb)
- **> 610 M e^+e^- → $c\bar{c}$ events** (σ = 1.30 nb)

Excellent resolution

High statistics charm baryon production



Provides access to rare decay modes &
High precision studies of charm baryon properties ...

Charm Baryon Spectroscopy

Observation of new decay modes

First observation of charm baryon to charm meson decay

Evidence for new states

Charm Baryon to Charm Meson Decay

Λ_c^+ u d c

- Observation of two states decaying to D^0 p
  - previously observed $\Lambda_c(2880)^+$ (*in* $\Lambda_c\,\pi^+\,\pi^-$) [Q~317 MeV/c^2]
  - BaBar measurements from D^0p [Q~79 MeV/c^2 ➔**much greater precision**]:

    M = 2881.9±0.1(stat)±0.5(syst) MeV/c^2

    Γ = 5.8±1.5(stat)±1.1(syst) MeV [First measurement]

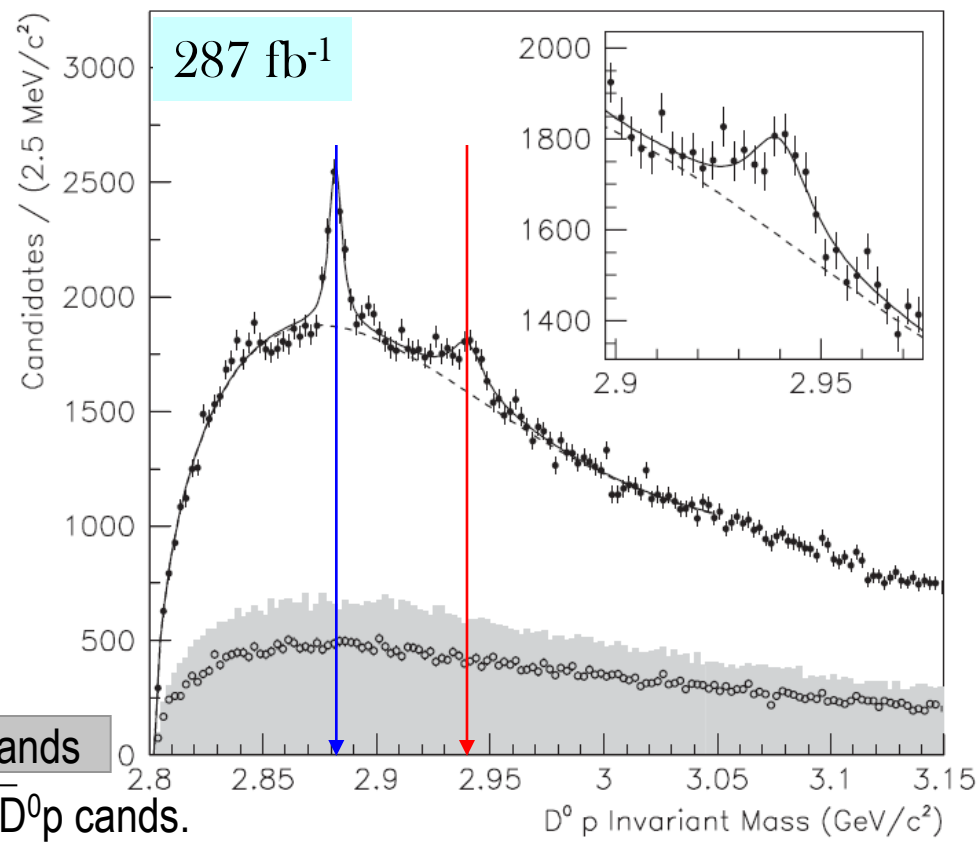
    PRL **98**, 012001 (2007)
  - **new state:**

    M = 2939.8±1.3(stat)±1.0(syst) MeV/c^2

    Γ = 17.5±5.2(stat)±5.9(syst) MeV

  ► First observation of a charm baryon decaying to a charm meson
- No evidence in D^+p of doubly charged partners

  ► Signals correspond to observation of *excited* Λ_c states, not Σ_c states



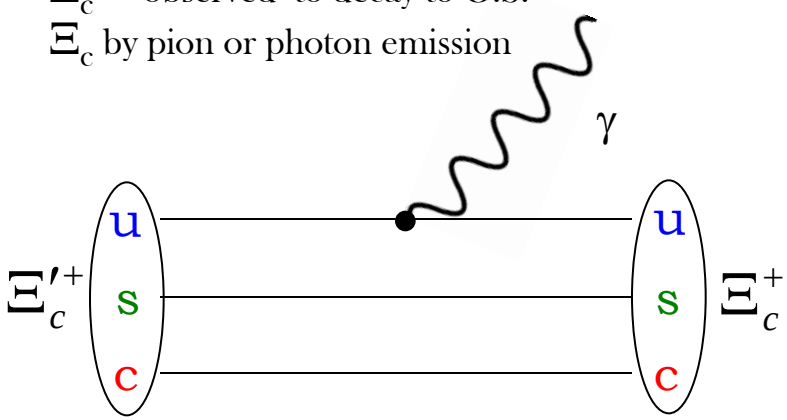
D^0 mass sidebands

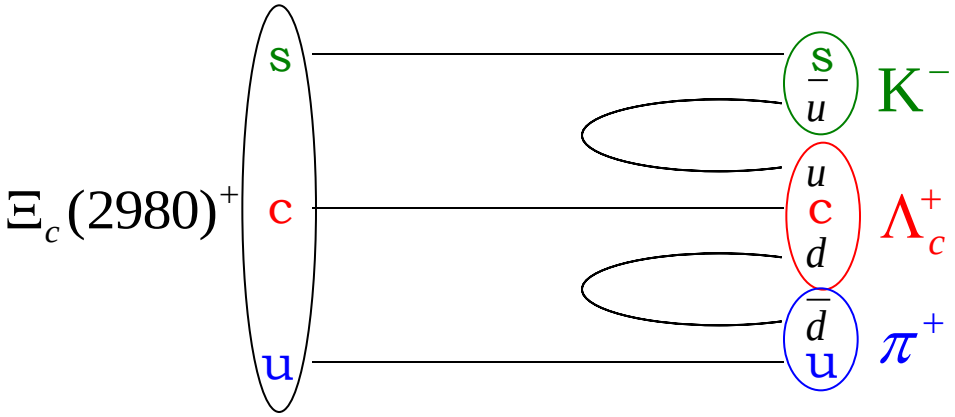
- wrong-sign $\bar{D}^0$p cands.

The Search for *charm* Cascades Decaying to $\Lambda_c^+ K^-(K_S)\ \pi^{+(-)}$ and $\Lambda_c^+ K^-(K_S)\ \pi^-\pi^+$ Final States

- Confirmation of the existence of the $\Xi_c(2980)^+$, $\Xi_c(3077)^+$ and $\Xi_c(3077)^0$
- Evidence for the $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$
  → natural widths consistent with strongly decaying states

Excited Cascade charm baryons
$\Xi_c^{\prime(*)}$ observed to decay to G.S.
Ξ_c by pion or photon emission





The $\Xi_c(2980)^{+,0}$ and $\Xi_c(3077)^{+,0}$ seen in decays in which the s and c quark are in separate hadrons

→ implications for the internal quark interactions inside these states

- predicted excited charm baryons with $J^P = 1/2^{\pm}, 3/2^{\pm}$

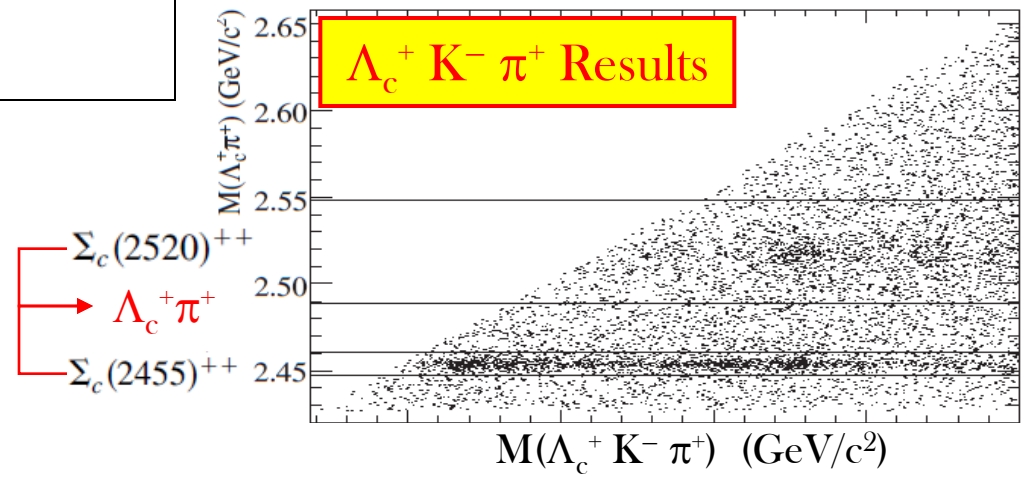
S. Migura, D. Merten, B. Metsch, and H.R. Petry, Eur. Phys. J. A **28**, 41 (2006).
H. Garcilazo, J. Vijande, and A. Valcarce, J. Phys. G **34**, 961 (2007).

- $J^P = 5/2^+$
- radial excitations

J.L. Rosner, J. Phys. G **34**, S127 (2007).
C. Chen, X.L. Chen, X. Liu, W.Z. Deng, and S.L. Zhu, Phys. Rev. D **75**, 094017 (2007).

Results on excited charm Cascades decaying to $\Lambda_c^+ K \pi$

PHYSICAL REVIEW D **77,** 012002 (2008)



Mode
$\Lambda_c^+ \to pK^-\pi^+$
$\Lambda_c^+ \to pK_S^0$
$\Lambda_c^+ \to pK_S^0\pi^+\pi^-$
$\Lambda_c^+ \to \Lambda\pi^+$
$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$

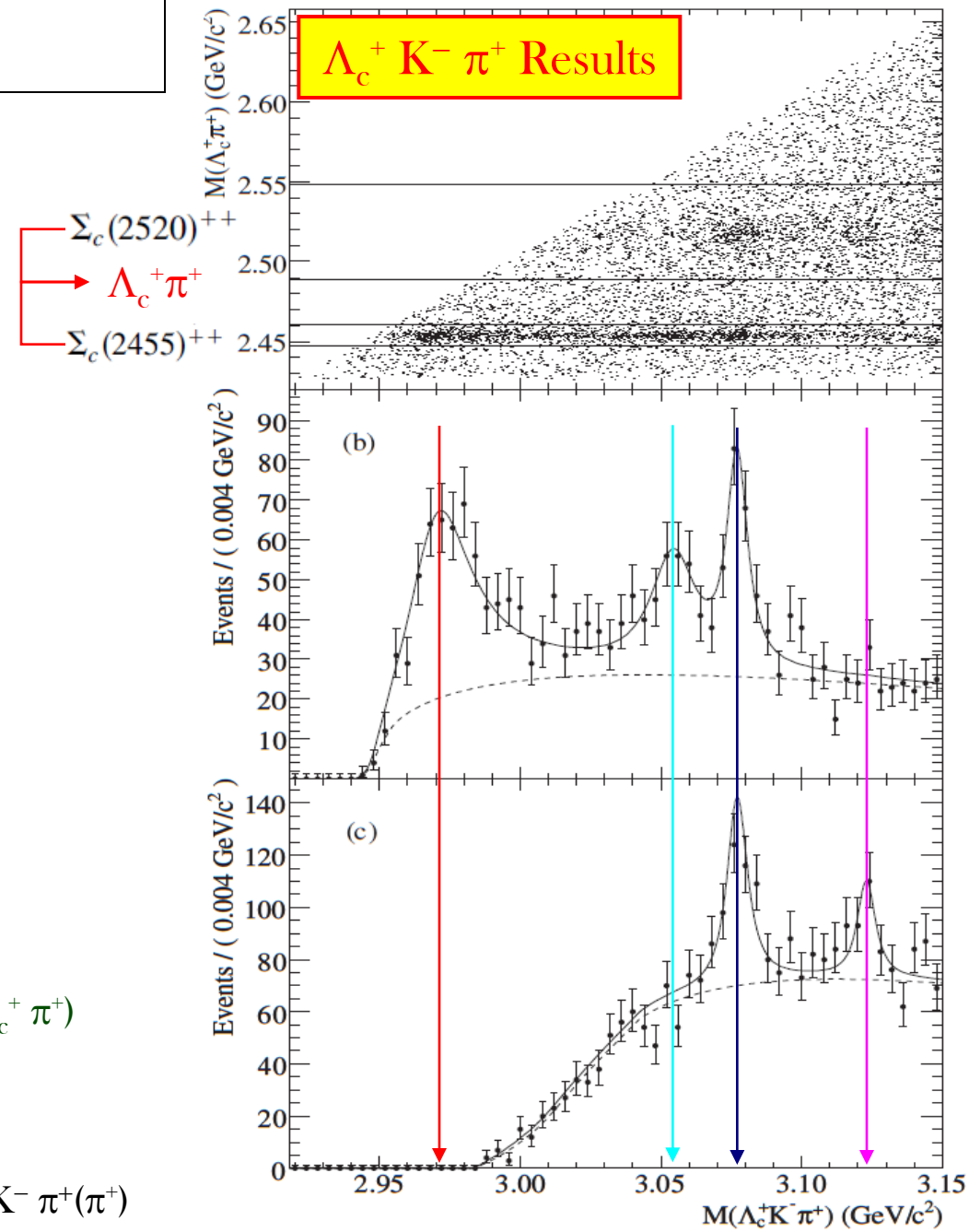
- Fit to two-dimensional invariant mass distribution $M(\Lambda_c^+ K^- \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$
  - ➢ incorporate intermediate resonances $\Sigma_c(2520)^{++}$ and $\Sigma_c(2455)^{++}$ in the fit
  - ➢ show the $M(\Lambda_c^+ K^- \pi^+)$ distribution for $M(\Lambda_c^+ \pi^+)$ ranges w/in 3-σ of the $\Sigma_c(2455)^{++}$ and 2-σ of the $\Sigma_c(2520)^{++}$

Results on excited charm Cascades decaying to $\Lambda_c^+ K \pi$

Very close to threshold
→ very important to take account of phase space

	$\Xi_c(2980)^+$	$\Xi_c(2980)^0$
Mass (MeV/c^2)	$2969.3 \pm 2.2 \pm 1.7$	$2972.9 \pm 4.4 \pm 1.6$
Width (MeV)	$27 \pm 8 \pm 2$	$31 \pm 7 \pm 8$
Yield	$756 \pm 178 \pm 104$	$67 \pm 33 \pm 29$
Resonant (%)	$55 \pm 7 \pm 13$	...
Significance	$>9.0\sigma$	1.7σ
	$\Xi_c(3077)^+$	$\Xi_c(3077)^0$
Mass (MeV/c^2)	$3077.0 \pm 0.4 \pm 0.2$	$3079.3 \pm 1.1 \pm 0.2$
Width (MeV)	$5.5 \pm 1.3 \pm 0.6$	$5.9 \pm 2.3 \pm 1.5$
Yield	$403 \pm 54 \pm 27$	$90 \pm 22 \pm 15$
Resonant (%)	>80	$78 \pm 21 \pm 5$
$\Sigma_c(2455)$ (%)	$45 \pm 5 \pm 5$	$44 \pm 12 \pm 7$
Significance	$>9.0\sigma$	4.5σ
	$\Xi_c(3055)^+$	$\Xi_c(3123)^+$
Mass (MeV/c^2)	$3054.2 \pm 1.2 \pm 0.5$	$3122.9 \pm 1.3 \pm 0.3$
Width (MeV)	$17 \pm 6 \pm 11$	$4.4 \pm 3.4 \pm 1.7$
Yield	$218 \pm 53 \pm 79$	$101 \pm 34 \pm 9$
Significance	6.4σ	3.6σ (3.0σ)

PHYSICAL REVIEW D 77, 012002 (2008)



- Similar results for $M(\Lambda_c^+ K_S \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$ although more statistically limited
- No evidence for structure in $(\Lambda_c^+ K_S \pi^+\pi^+)$ nor $(\Lambda_c^+ K^- \pi^+\pi^+)$
- No evidence for Ξ_{cc} seen by SELEX in $\Lambda_c^+ K^- \pi^+(\pi^+)$

The Search for the Ω_c^* ($J^P=3/2^+$)

PRL **97**, 232001 (2006)

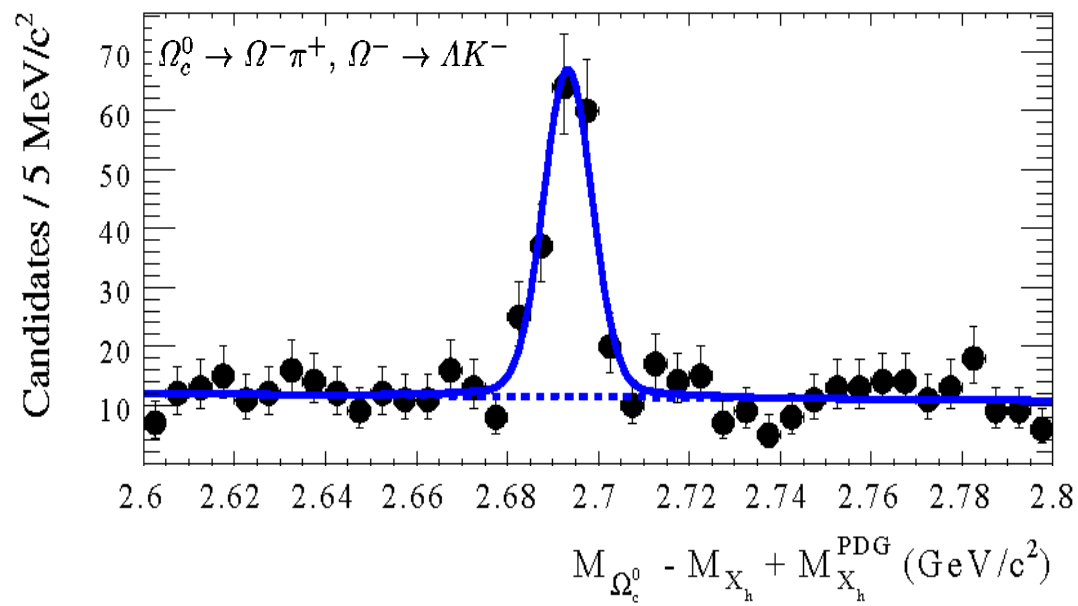
- All L=0 singly-charm baryons discovered, $J^P=3/2^+$ Ω_c^* (*css*) state missing
- Splitting $M(\Omega_c^*)$-$M(\Omega_c)$ predictions range from ~70 -100 MeV/c^2
- Search for Ω_c^* in $e^+e^- \rightarrow \Omega_c^*$ X processes

$$\boxed{\Omega_c^0 \rightarrow \Omega^-\pi^+,\ \Omega^- \rightarrow \Lambda K^-}$$

$$\Omega_c^0 \rightarrow \Omega^-\pi^+\pi^0,\ \Omega^- \rightarrow \Lambda K^-$$

$$\Omega_c^0 \rightarrow \Omega^-\pi^+\pi^-\pi^+,\ \Omega^- \rightarrow \Lambda K^-$$

$$\Omega_c^0 \rightarrow \Xi^-K^-\pi^+\pi^+,\ \Xi^- \rightarrow \Lambda\pi^-$$



Observation of $\Omega_c^* \to \Omega_c^0 \gamma$

- Splitting $M(\Omega_c^*)$-$M(\Omega_c^0)$
  $= 70.8 \pm 1.0(stat) \pm 1.1(syst)$ MeV/c^2

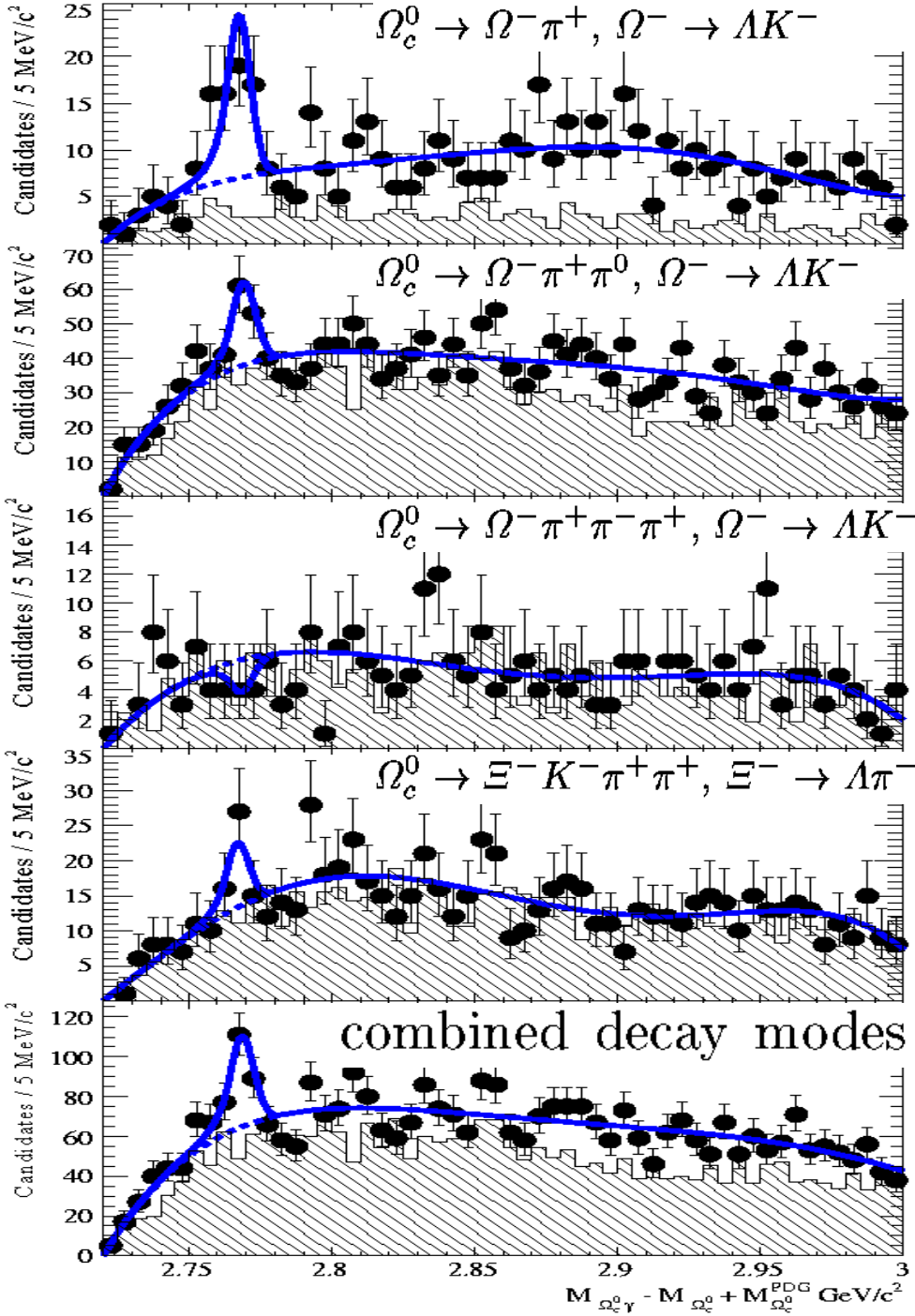
➢ **consistent with pQCD predictions**

➔ $M(\Omega_c^*)$=2768.3±3.0 MeV/c^2

- Ratio of the inclusive production cross sections

$$R = \frac{\sigma\left(e^+e^- \to \Omega_c^* X, x_p(\Omega_c^* > 0.5)\right)}{\sigma\left(e^+e^- \to \Omega_c^0 X, x_p(\Omega_c^0 > 0.5)\right)}$$

$$= 1.01 \pm 0.23(stat) \pm 0.11(syst)$$



Charm Baryon Spectroscopy

Insight into Light Baryon Spectroscopy

Study of Cascade baryons

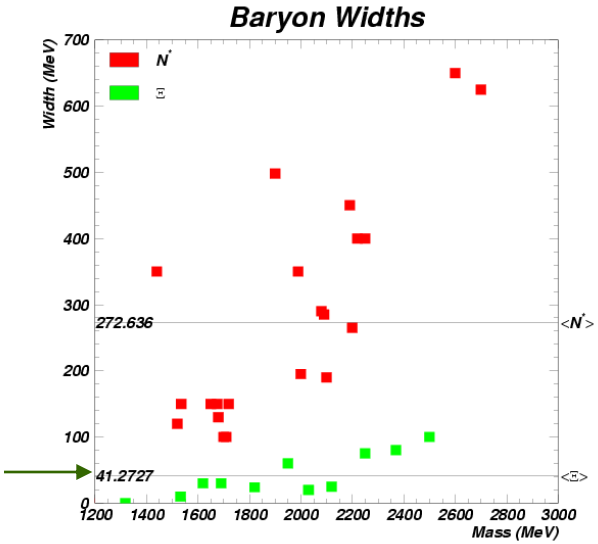
Relevance of Cascades to Baryon Spectroscopy

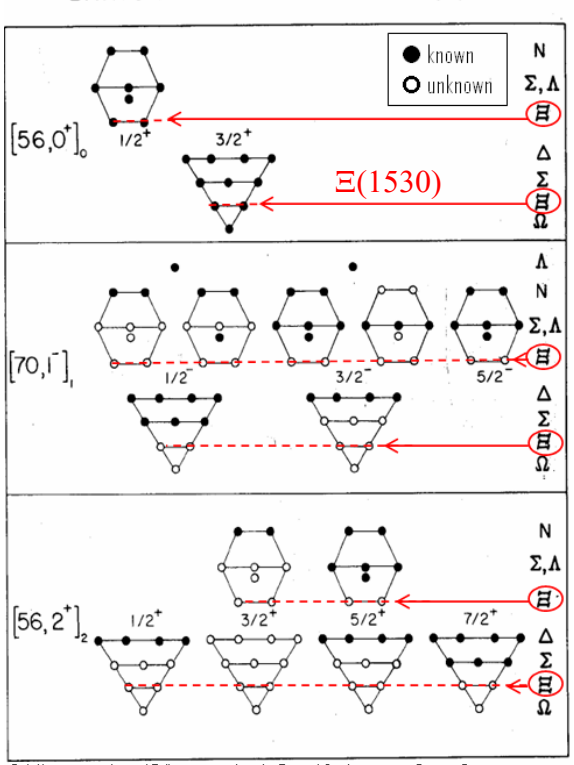
- Quark content (u or d, s, s)
  - QCD calculations easier to handle
  - Developments in fast algorithms raised expectations from Lattice QCD

- Narrow widths
  - reduces potential overlap with neighboring states

$\langle\Gamma(N)\rangle$

$\langle\Gamma(\Xi)\rangle$





- Predictions of mass, width, spin/parity rely on model-based calculations
  - Experimental validations are essential
  - Very little known about Ξ states which might populate the $[70, 1^-]_1$ and $[56, 2^+]_2$ of SU(6) X O(3)
  - Properties of Ξ(1690) are crucial: first excited state not used as input in predictions

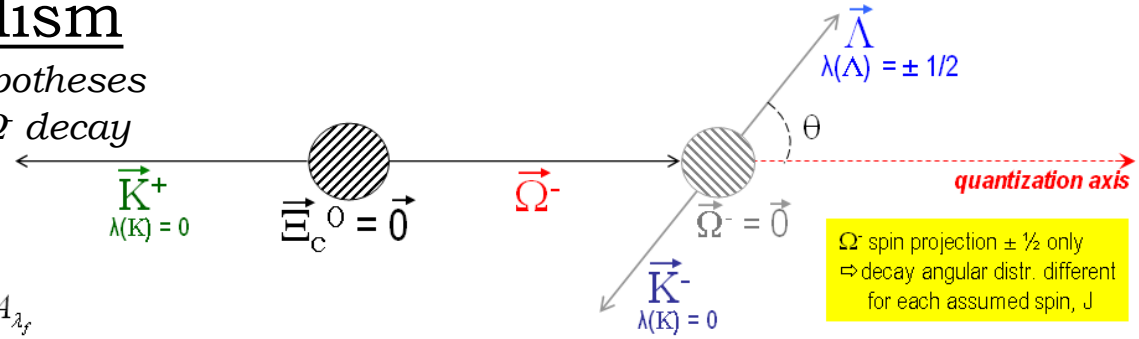
R.J. Hemingway, Invited Talk presented at the Topical Conference on Baryon Resonances.

Cascade Physics from Charm Baryon Decay

Spin measurement of Ω^- from $\Xi_c^0 \to \Omega^- K^+$, $\Omega^- \to \Lambda K^-$ decays

Helicity Formalism

▷ *Examine implications of Ω^- spin hypotheses for angular distribution of Λ from Ω^- decay*

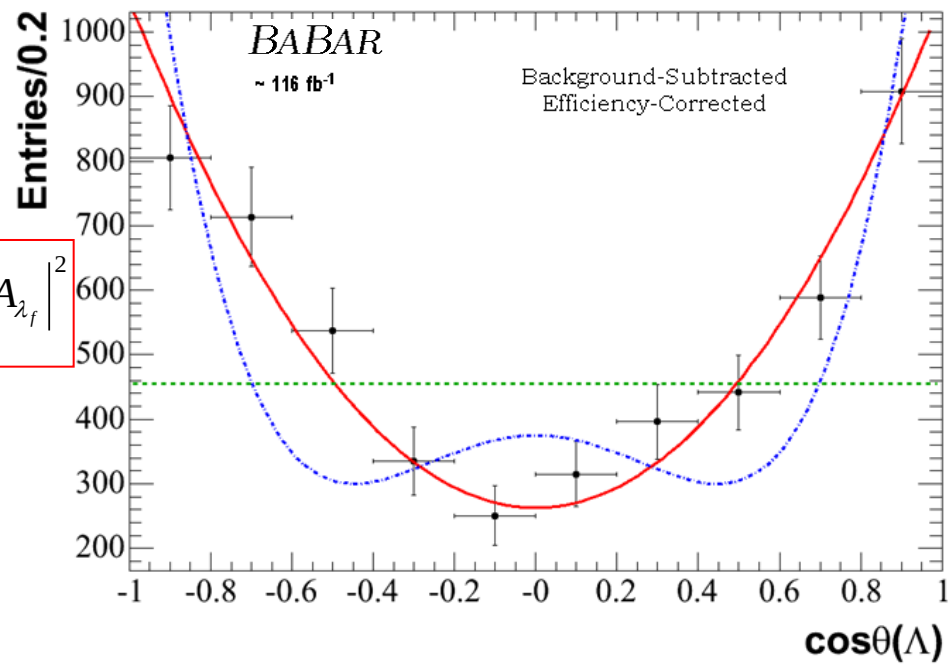


Ω^- spin projection ± ½ only
⇨ decay angular distr. different for each assumed spin, J

- Initial helicity, $\lambda_i = \lambda(\Omega) = \pm 1/2$
- Final state helicity, $\lambda_f = \lambda(\Lambda)$ - λ(pseudoscalar) = ± 1/2
- Decay amplitude for $\Omega^- \to \Lambda K^-$: $A^J_{\lambda_i \lambda_f} = D^{J*}_{\lambda_i \lambda_f}(\phi,\theta,0) A_{\lambda_f}$

$$I \propto \frac{1}{2}\sum_{\lambda_i,\lambda_f} \rho_{\lambda_i} \left| A^J_{\lambda_i \lambda_f} \right|^2 = \frac{1}{2}\sum_{\lambda_i,\lambda_f} \rho_{\lambda_i} \left| D^{J*}_{\lambda_i \lambda_f}(\phi,\theta,0) A_{\lambda_f} \right|^2$$

[density matrix element for Ω^- spin projection λ_i
= density matrix element for charm baryon parent]

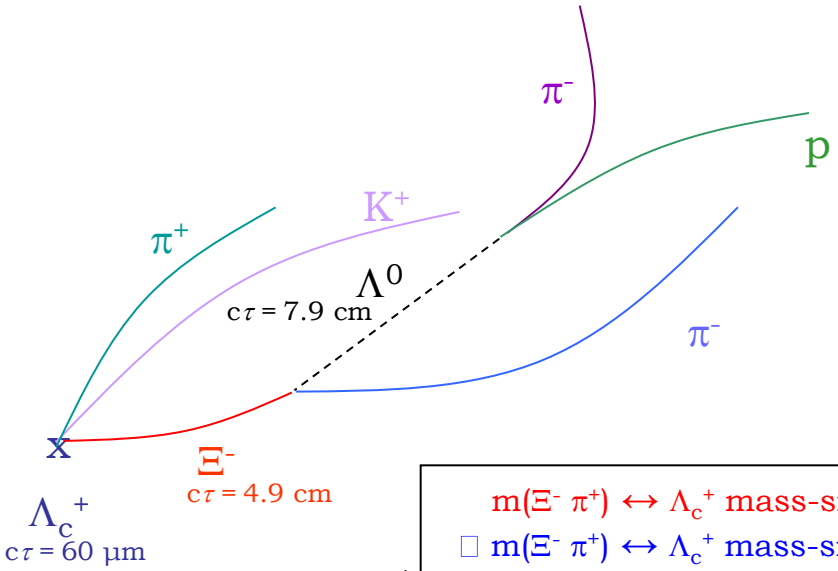


····· $J_\Omega = 1/2$	$\Rightarrow I \propto 1$	→ Fit Prob = 10^{-17}
—— $J_\Omega = 3/2$	$\Rightarrow I \propto (1+3\cos^2\theta)$	→ Fit Prob = 0.64
- - - $J_\Omega = 5/2$	$\Rightarrow I \propto (1-2\cos^2\theta+5\cos^4\theta)$	→ Fit Prob = 10^{-7}

$J_\Omega \geq 7/2$ **also excluded**: angular distribution increases more steeply near cosθ ~ ±1 and has (2 J_Ω -2) turning points.

The $\Xi(1530)^0$ From $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Decay

Reconstructed $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$, $\Xi^- \rightarrow \Lambda \pi^-$ Events



- PID Information
  - →Proton
  - →Kaon
  - →π^+, π^-

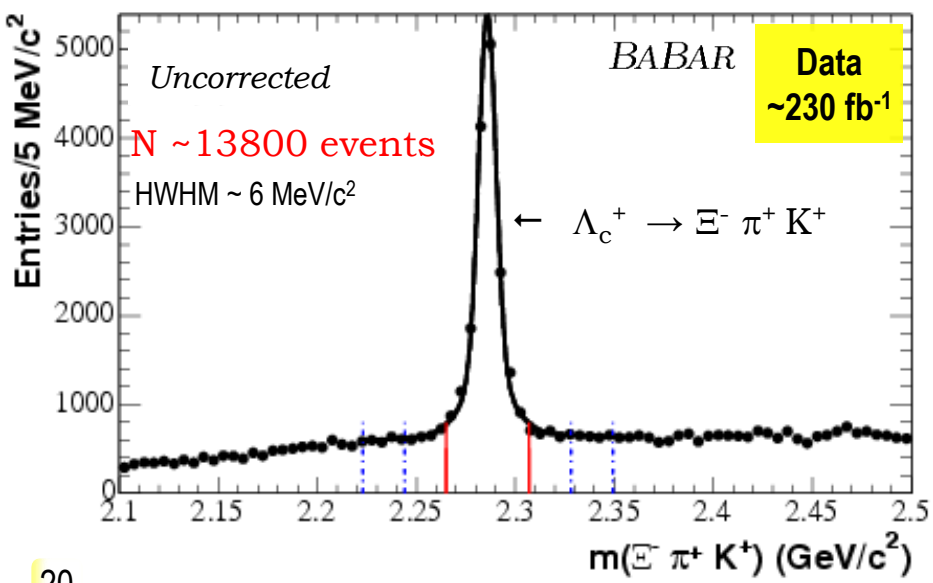
  } dE/dx & Cherenkov info (DIRC)
- 3-σ mass cut on intermediate states
- interm^d. states *mass-constrained [Λ, Ξ⁻]*
- $p^* > 2.0$ GeV/c *[reduces background].*
- $L_\Lambda > 2.0$ mm $r_\Xi > +1.5$ mm *[outgoing].*

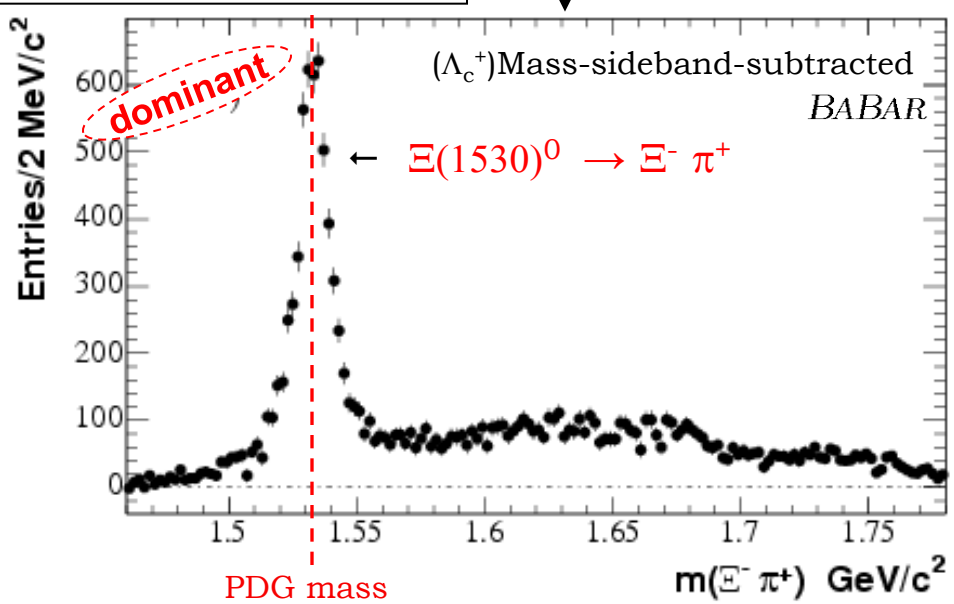
$m(\Xi^- \pi^+) \leftrightarrow \Lambda_c^+$ mass-signal region

$m(\Xi^- \pi^+) \leftrightarrow \Lambda_c^+$ mass-sideband region

---

$m(\Xi^- \pi^+) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted





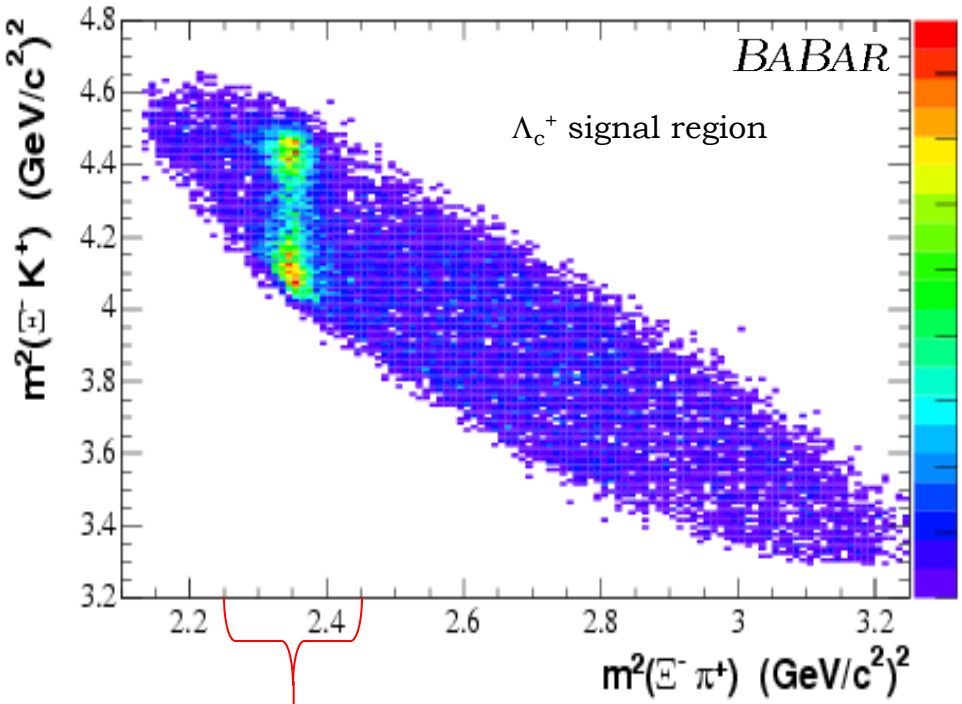
Resonant Structures in the $\Lambda_c^+ \to \Xi^- \pi^+ K^+$ Signal Region

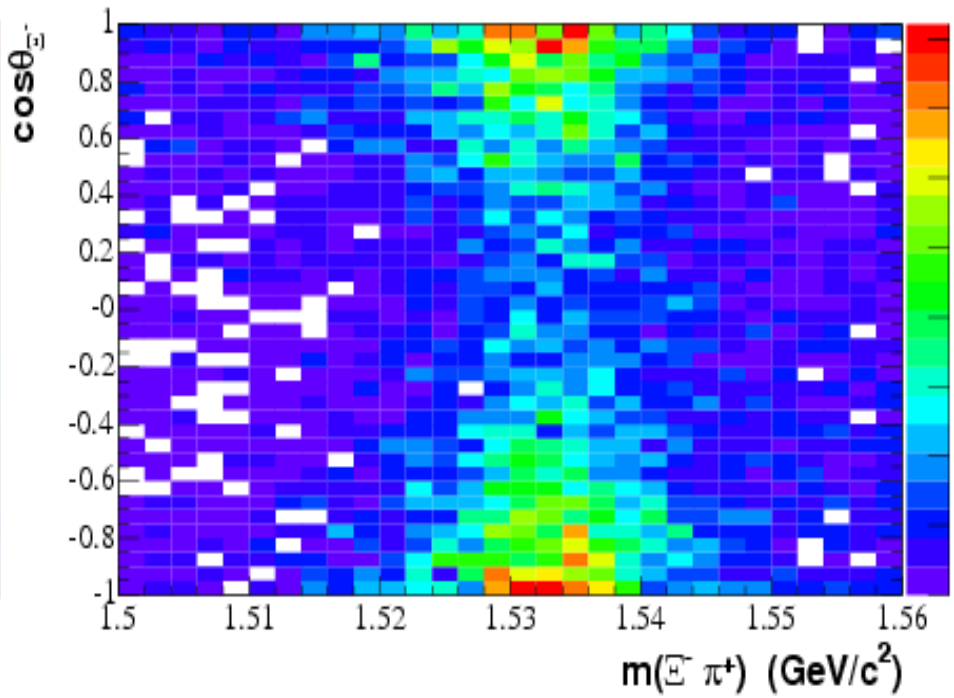
Phys.Rev.D78:034008,2008

Only ***obvious*** structure:

$\Xi(1530)^0 \to \Xi^- \pi^+$

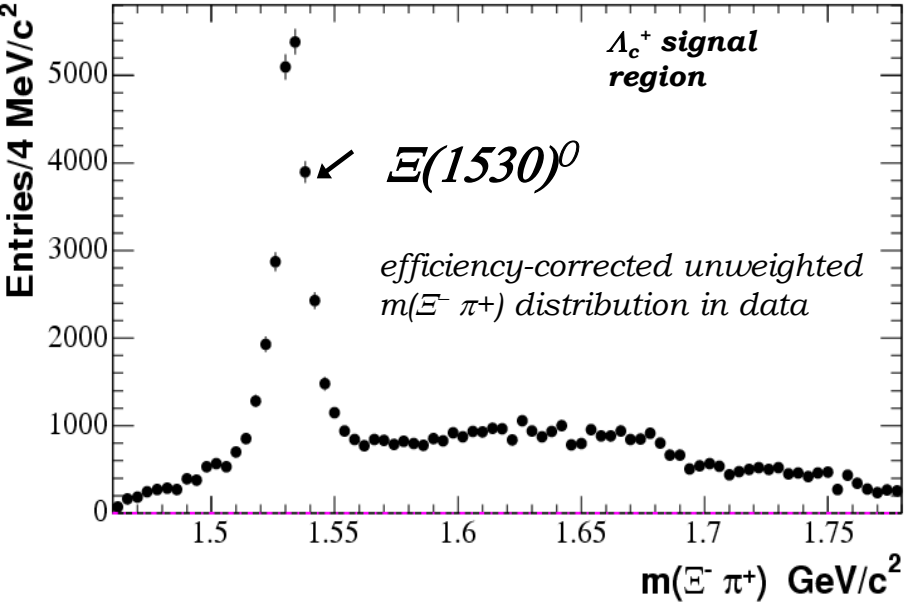
Rectangular Dalitz plot

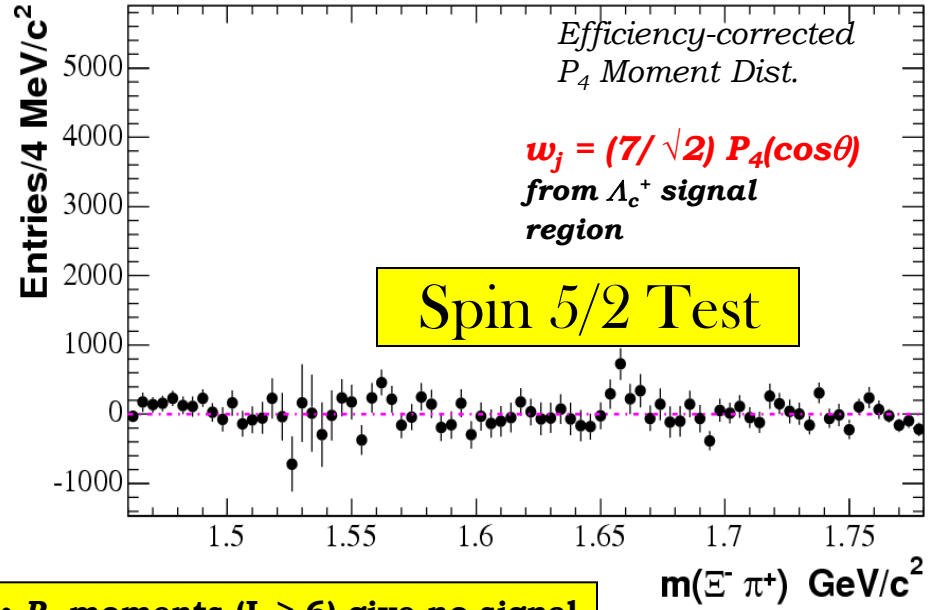




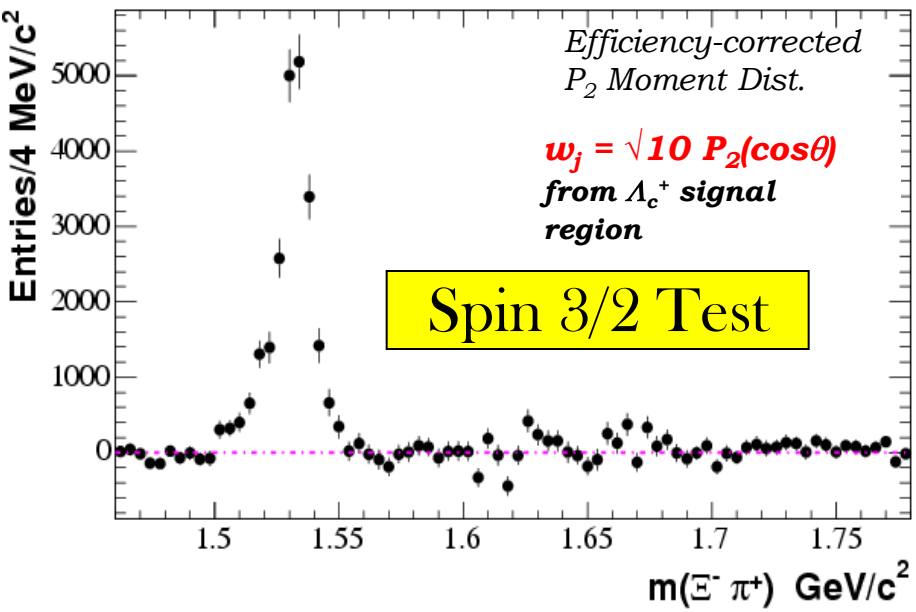
Note: $m^2(\Xi^- K^+)$ depends linearly on $\cos\theta_\Xi$

Using Legendre Polynomial Moments to Obtain Ξ(1530) Spin Information





- **P_L moments (L ≥ 6) give no signal**



⇨ spin 3/2 *clearly* established

⇨ spin 5/2 ruled out

Schlein et *al.* showed $J^P = 3/2^+$ or $J^P = 5/2^-$, and claimed J>3/2 *not required.*
[Phys.Rev.Lett.11, 167 (1963), Phys.Rev.142,883 (1966)]

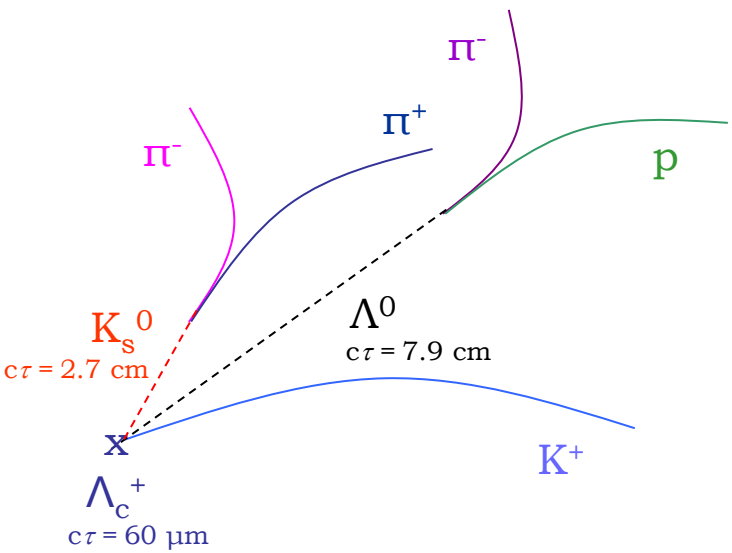
" Spin-parity $3/2^+$ is favored by the data" [PDG (2006)]

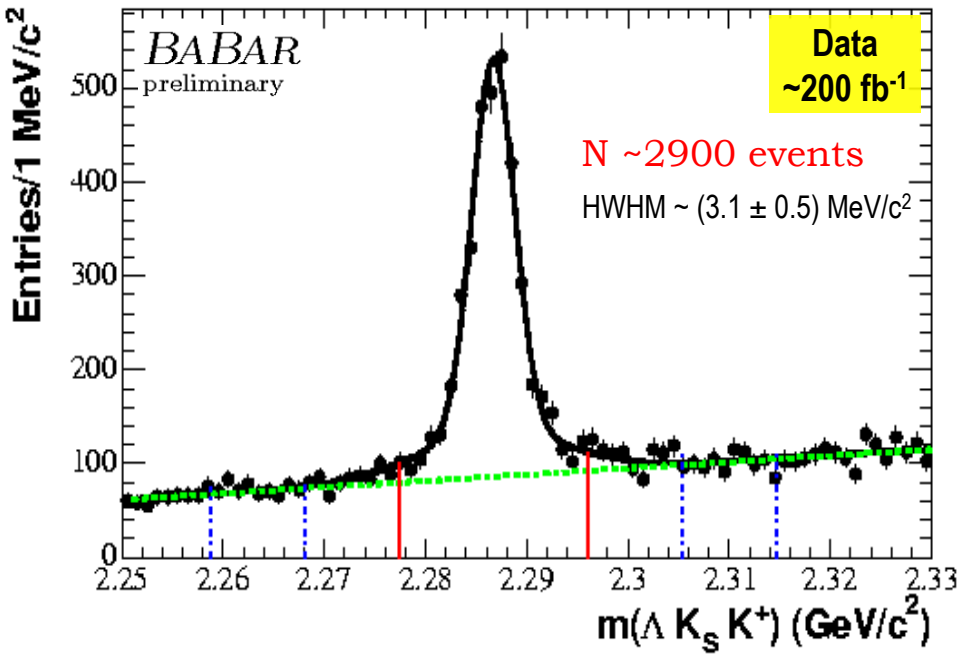
⇨ Present analysis by establishing J=3/2 also establishes positive parity *by implication* **[i.e. P-wave resonance]**

- *Other interesting aspects of Dalitz plot – not as simple as it first appears !*

The $\Xi(1690)^0$ From $\Lambda_c^+ \to \Lambda\ \overline{K}^0\ K^+$ Decay

Reconstructed $\Lambda_c^+ \rightarrow \Lambda\ K_S\ K^+$ Events





Selection Criteria:

- PID Information
  - →Proton
  - →Kaon
  - →π^+, π^-

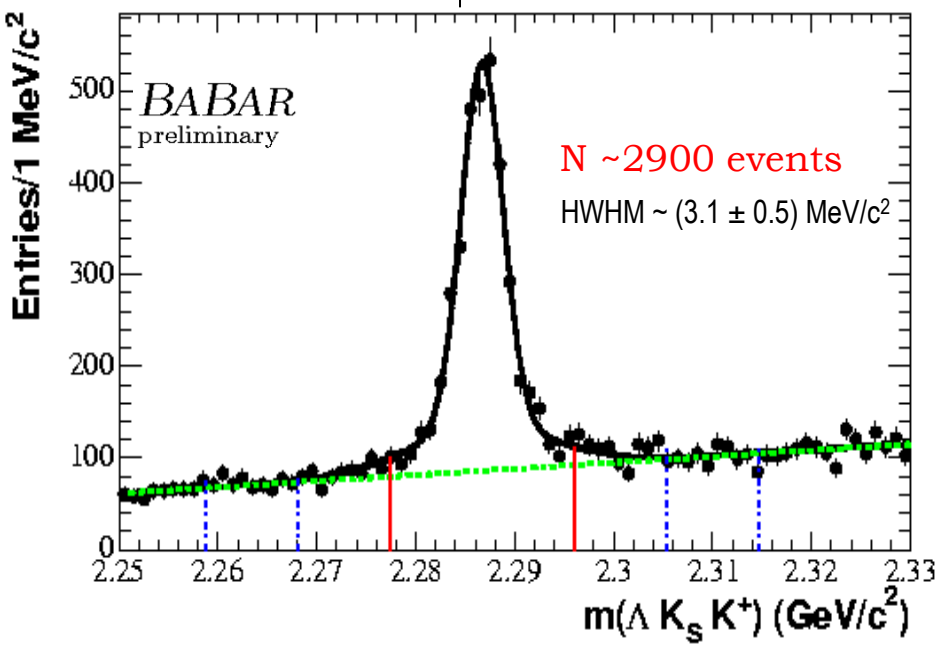
  } dE/dx & Cherenkov info (DIRC)
- 3-σ mass cut on intermediate states
- interm^d. states *mass-constrained [Λ , K_S]*
- **$p^*(\Lambda_c^+)$ > 1.5 GeV/c (reduces background)**
- **L_Λ, L_{Ks} > *+2.0, +1.0* mm *[sign ⇨ outgoing].***

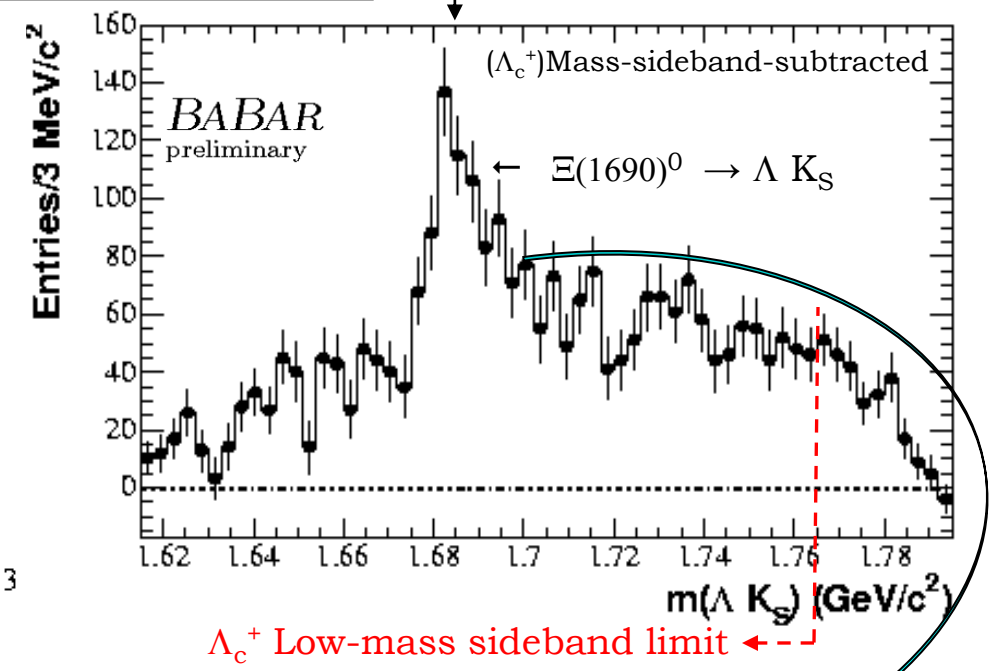
The $\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda\ K_S)\ K^+$ Decay

$m(\Lambda\ K_S) \leftrightarrow \Lambda_c^+$ mass-signal region

$m(\Lambda\ K_S) \leftrightarrow \Lambda_c^+$ mass-sideband region

$m(\Lambda\ K_S) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted

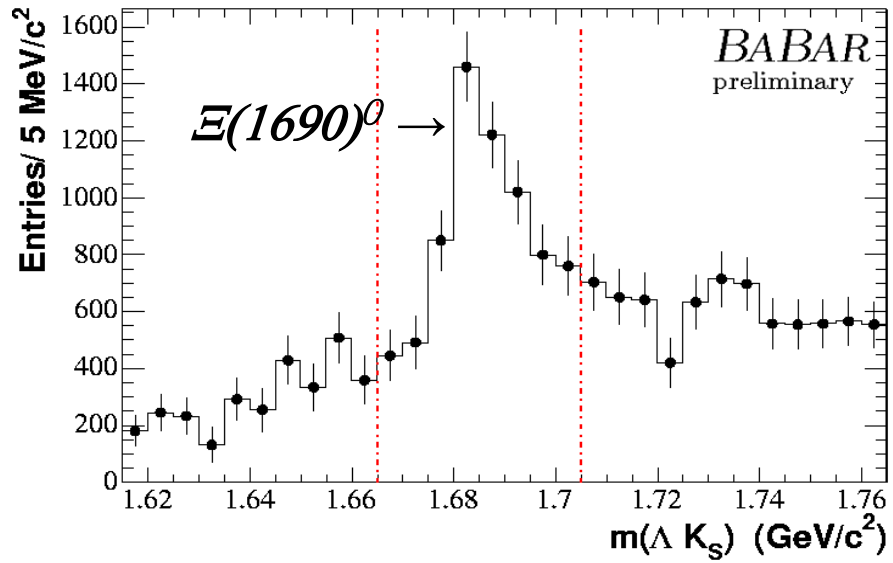


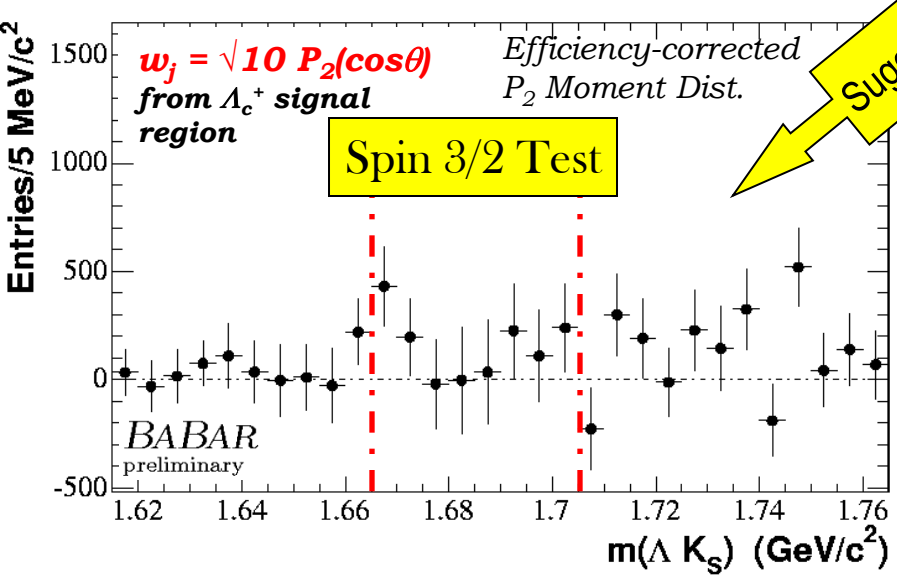


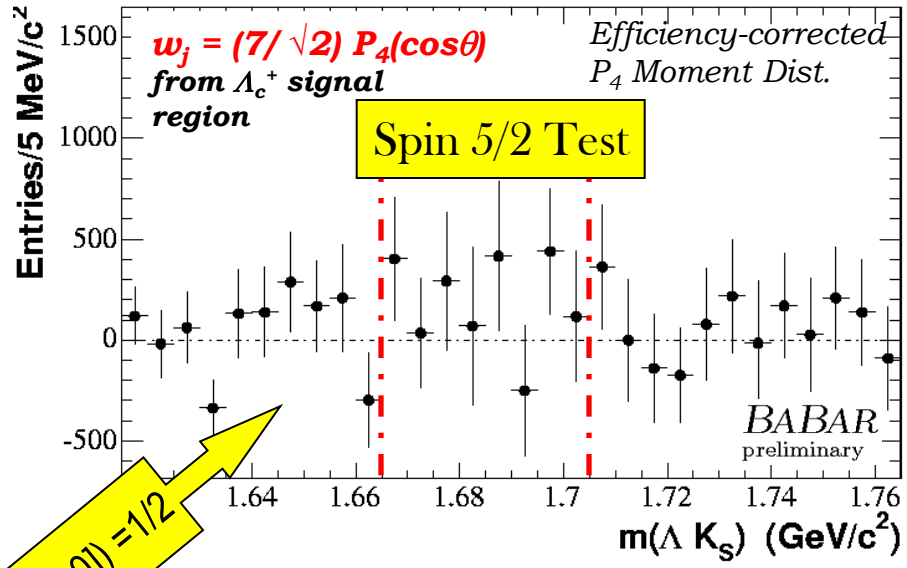
Note skewing

Using Legendre Polynomial Moments to Obtain Ξ(1690) Spin Information

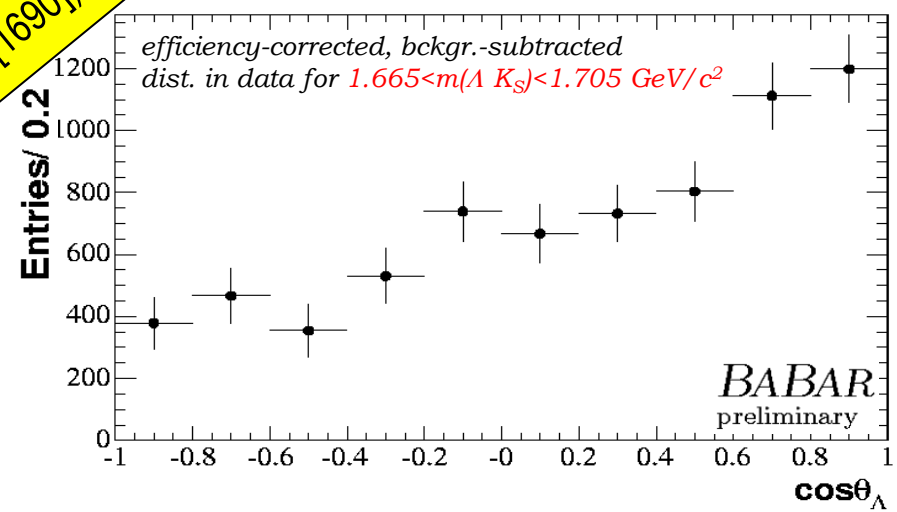
— ***efficiency-corrected, background-subtracted unweighted m(Λ K_S) distribution in data***







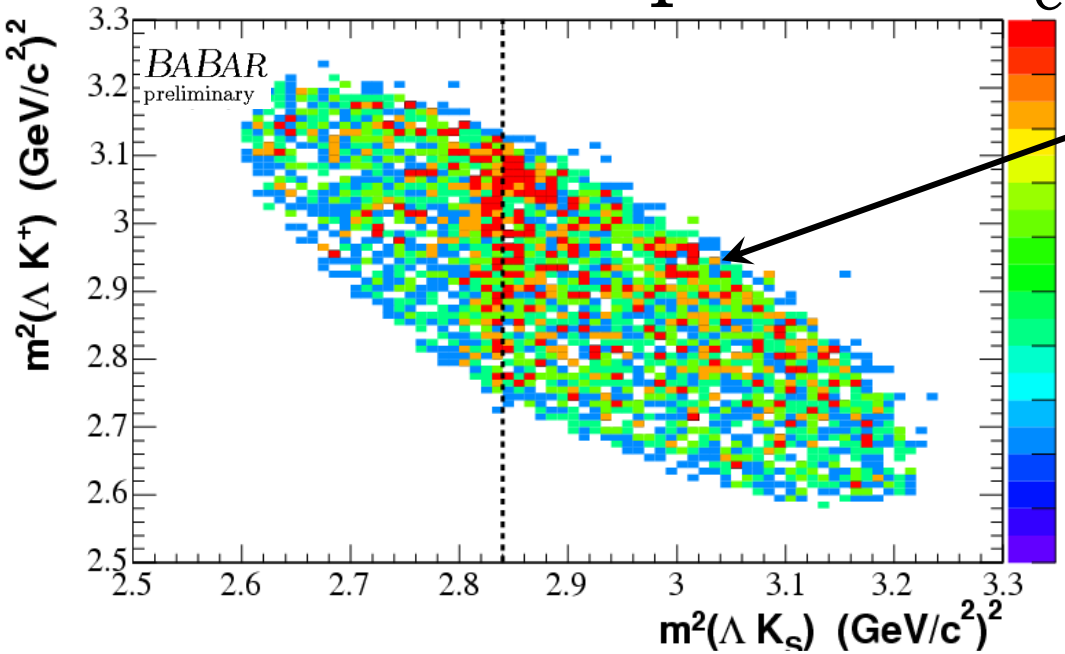
Suggest J(Ξ[1690]) =1/2



…however $\cos\theta_\Lambda$ clearly not flat *as expected for J = 1/2*

WHY?

Dalitz plot for $\Lambda_c^+ \rightarrow \Lambda K_S K^+$



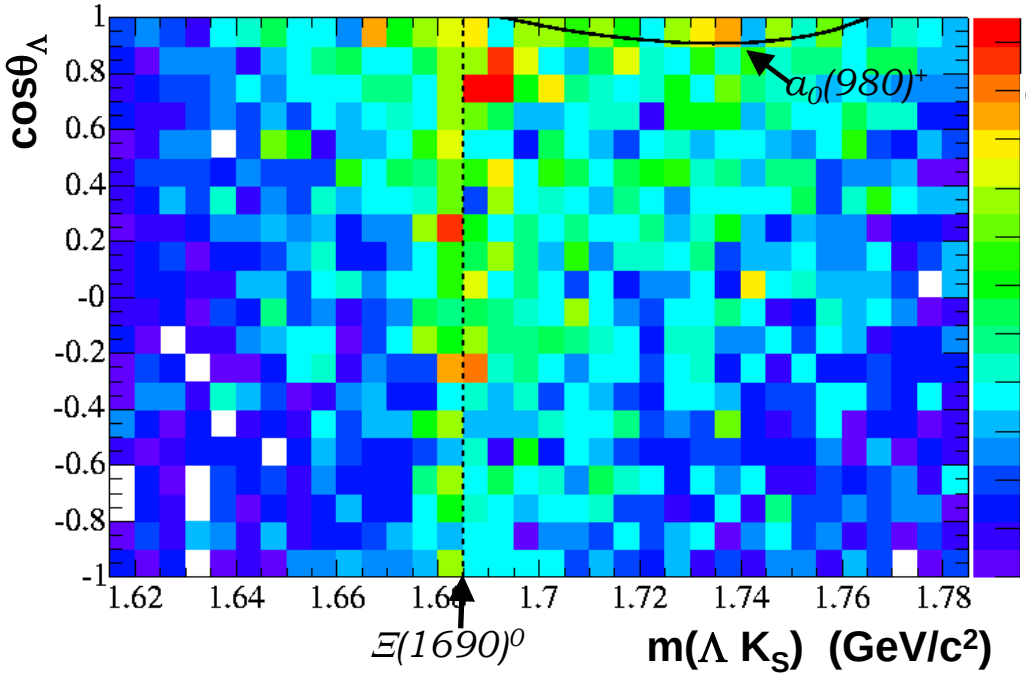
Accumulation of events in $K_S K^+$ near threshold ⇨ evidence of $a_0(980)^+$

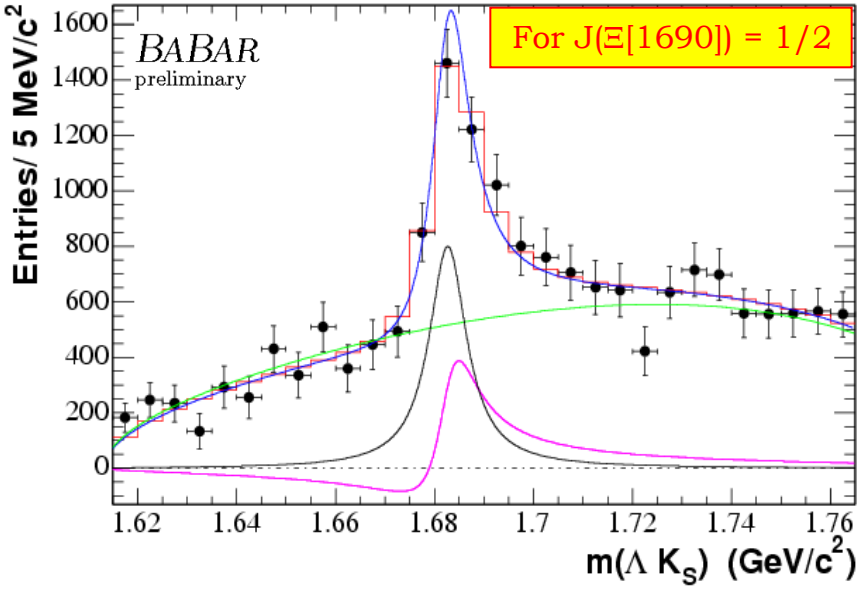
$m = 1682.9 \pm 0.9(stat) \pm 0.8(syst)$ MeV/c^2

$\Gamma = 9.3^{+2.0}_{-1.7}(stat) \pm 0.4(syst)$ MeV

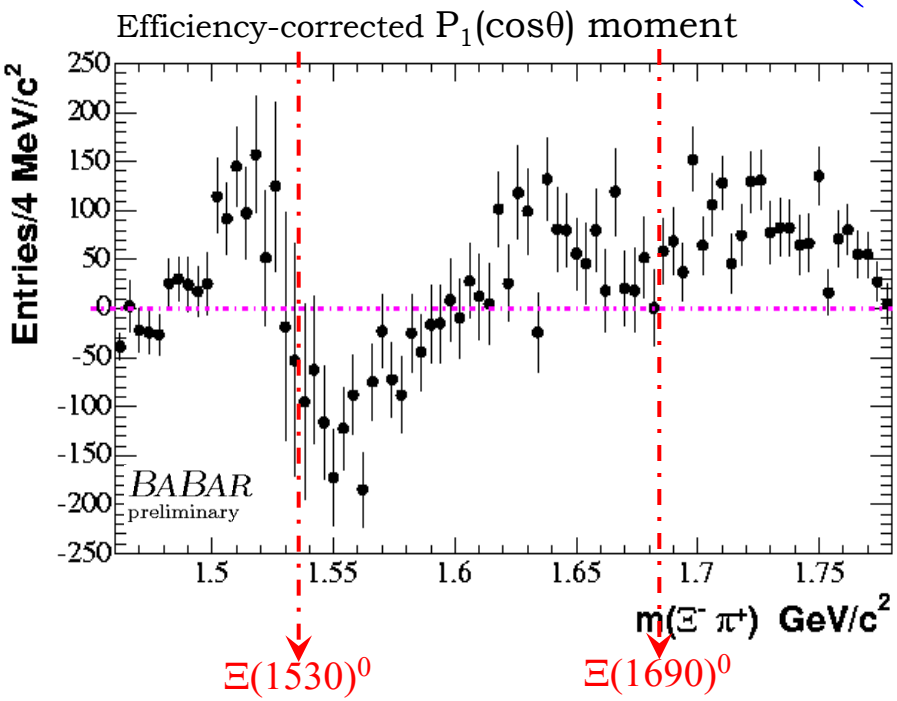
J = 1/2 favored

- ● Background-subtracted, efficiency-corrected data
- — Integrated signal function ***smeared*** by mass resolution [Histogram]
- — Signal function with no ***resolution smearing***
- — $|A(a_0(980)|^2$ contribution
- — $|A(\Xi(1690)|^2$ contribution
- — *Interference* term contribution



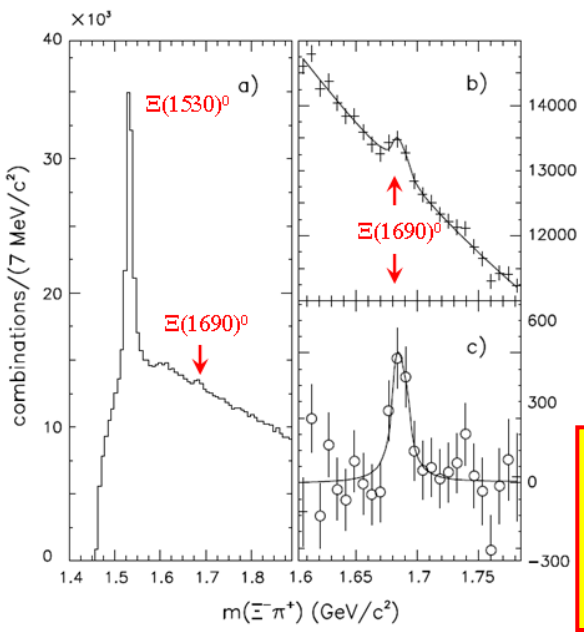


Evidence for the $\Xi(1690)$ in $\Lambda_c^+ \to \Xi^- \pi^+ K^+$



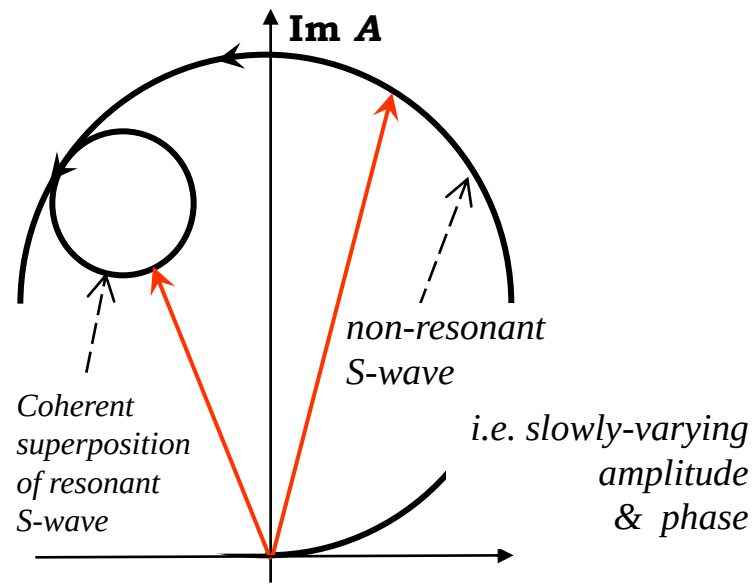
$\Xi(1690)$ seen in inclusive environment in hyperon beam expt. M.I. Adamovich *et al.* Eur.Phys.J. C**5**, 621 (1998)

S-P interference -- dip at 1690 MeV/c



Speculation:

Dip (~1680 MeV/c²) may be due to *resonant* $\Xi(1690)^0$ S-wave

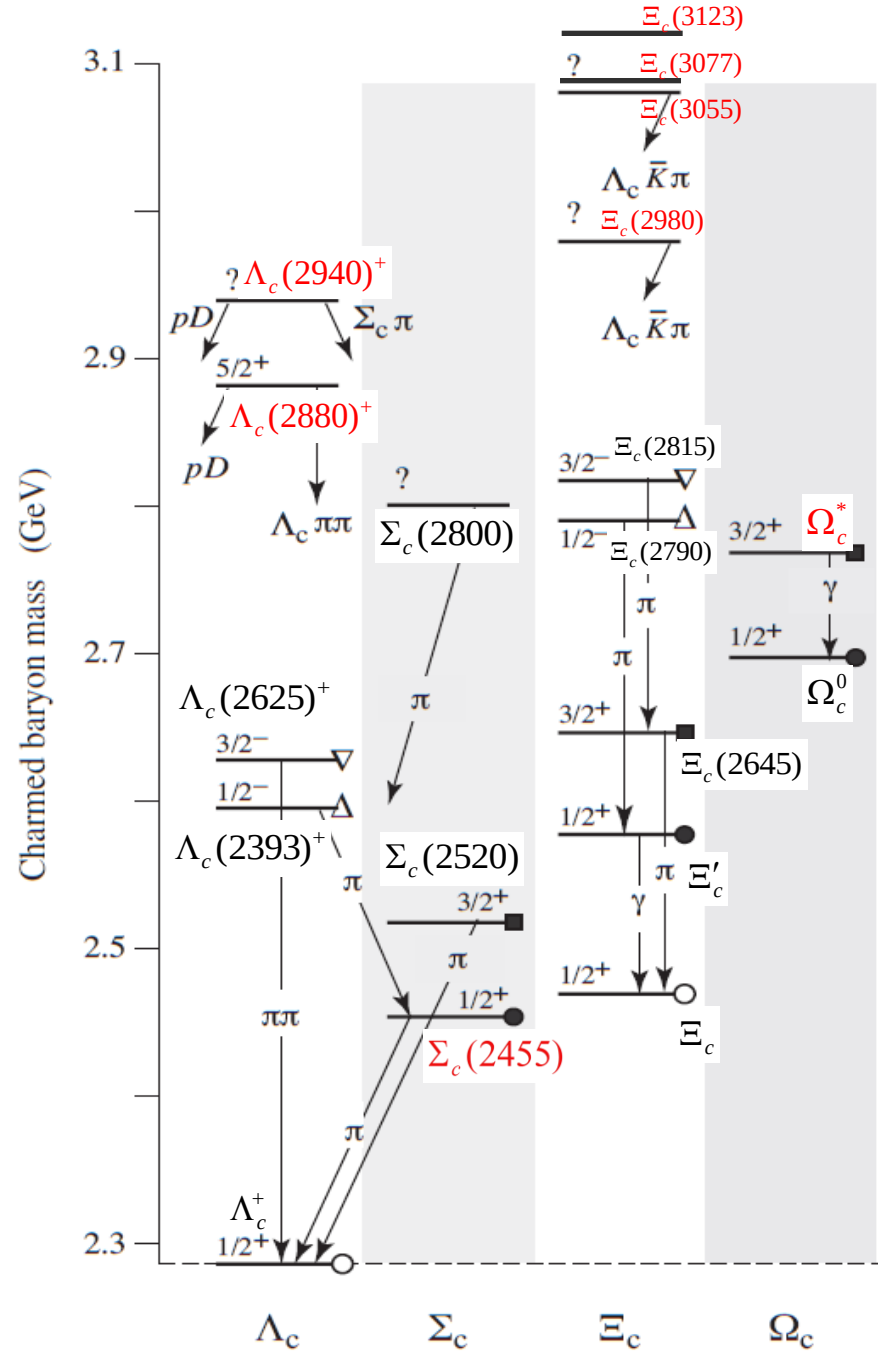


⇨ *negative parity for* $\Xi(1690)$

Implications for Lattice calculations and models of level structure of Ξ excited states

Remarks

- Lots of progress in charm baryon spectroscopy
- Insight into charm baryon production
- Measurements of charm baryon spin from exclusive B decay processes
- Insight into light quark spectroscopy from hyperon resonances produced in charm baryon decay



Possible Similar Ξ Studies in Photoproduction

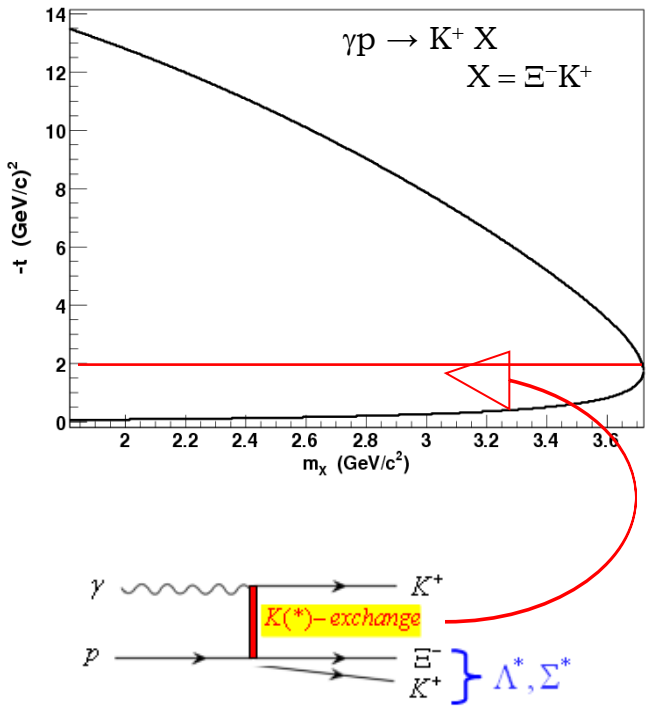
- Exclusive t-channel (i.e. meson exchange) Processes
  - Production of two-body systems with a Ξ

    e.g. $\gamma\, p \rightarrow K^+\ (\Xi^- K^+)$

    $\rightarrow K^+\ (\Xi^0 K^0)$

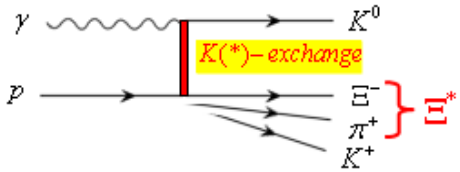
    $\rightarrow K^0\ (\Xi^0 K^+)$

    would enable the study of high mass Λ* and Σ* states decaying via these Ξ modes.



Possible Similar Ξ Studies in Photoproduction (ctd.)

- Production of three-body systems with a Ξ, or a Ξ* system with two-body decay:



with a forward K^0:

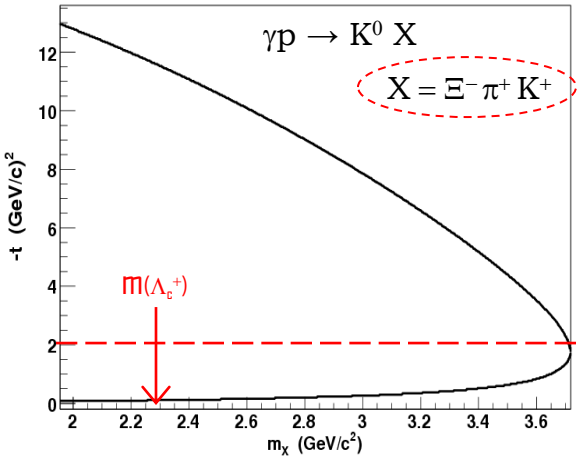
Σ*, Λ*

e.g. $\gamma\, p \to K^0\, (\Xi^-\pi^+)\, K^+$, $K^0\, (\Xi^0\pi^0)\, K^+$, $K^0\, (\Xi^0 K^0)$

States analyzed in Λ_c^+ decay

$\to K^0\, (\Lambda\, \overline{K^0})\, K^+$

- can observe in a totally different context



with a forward K^+:

e.g. $\gamma\, p \to K^+\, (\Xi^-\pi^+)\, K^0$, $K^+\, (\Xi^-\pi^0)\, K^+$

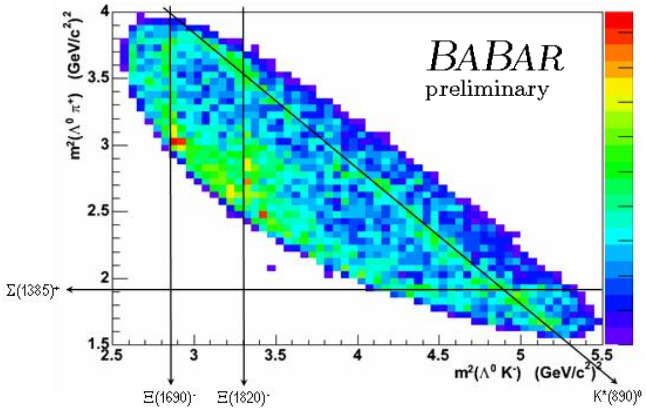
$\to K^+\, (\Xi^0\pi^-)\, K^+$, $K^+\, (\Xi^0\pi^0)\, K^0$

$\to K^+\, (\Lambda\, K^-)\, K^+$

- Interesting four-body possibilities when add pion

e.g. $\gamma\, p \to K^+\, (\Lambda\, K^-\pi^+)\, K^+$,

- accessible at BaBar via $\Xi_c^0 \to \Lambda K^-\pi^+$, complicated Dalitz plot

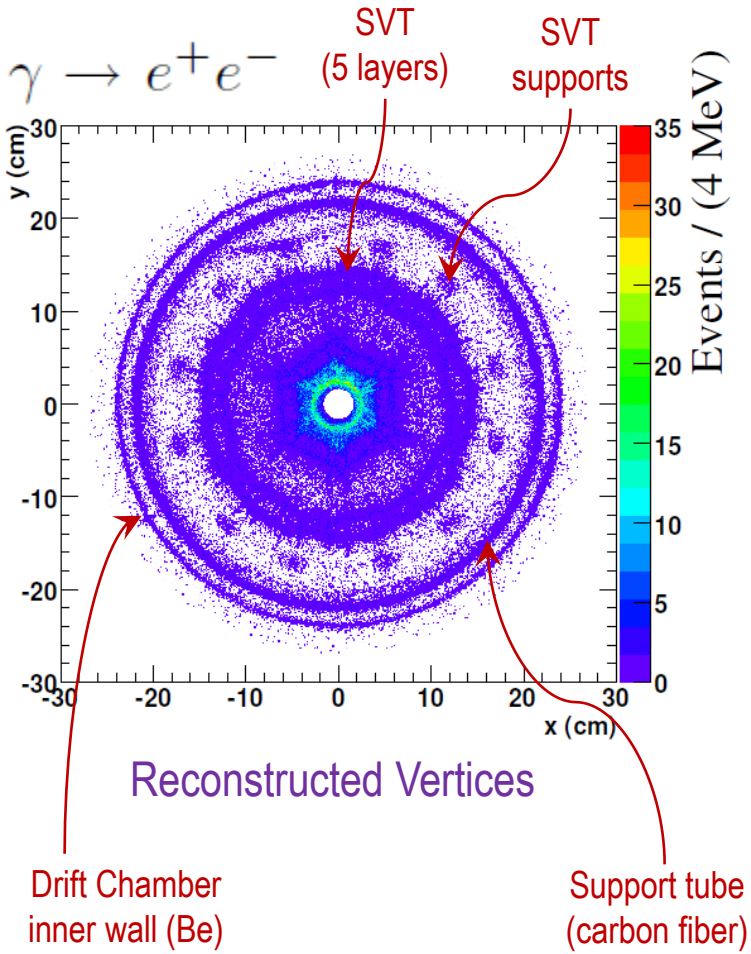


Quarkonium Spectroscopy

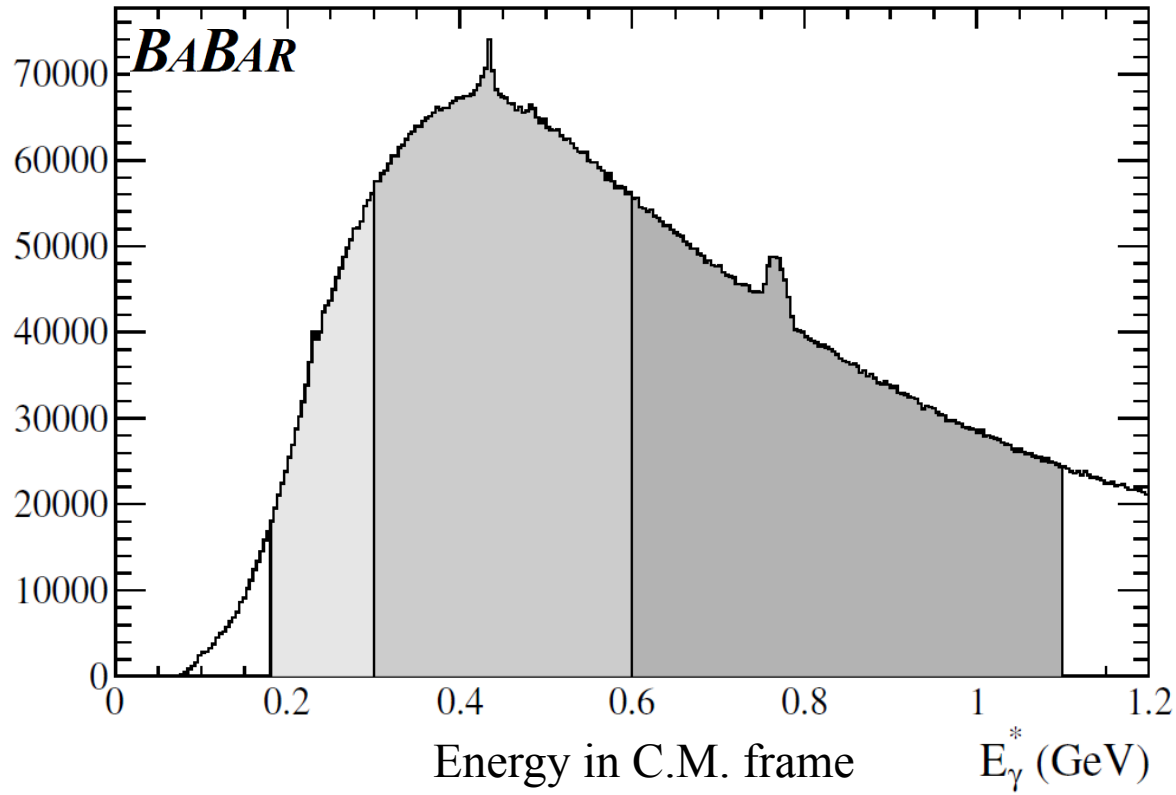
Insight into Bottomonium Spectroscopy

Searches for missing states

Radiative bottomonium transitions from Υ(3S) events using $\gamma \to e^+e^-$ conversions



Phy.Rev. D 84, 072002(2011)

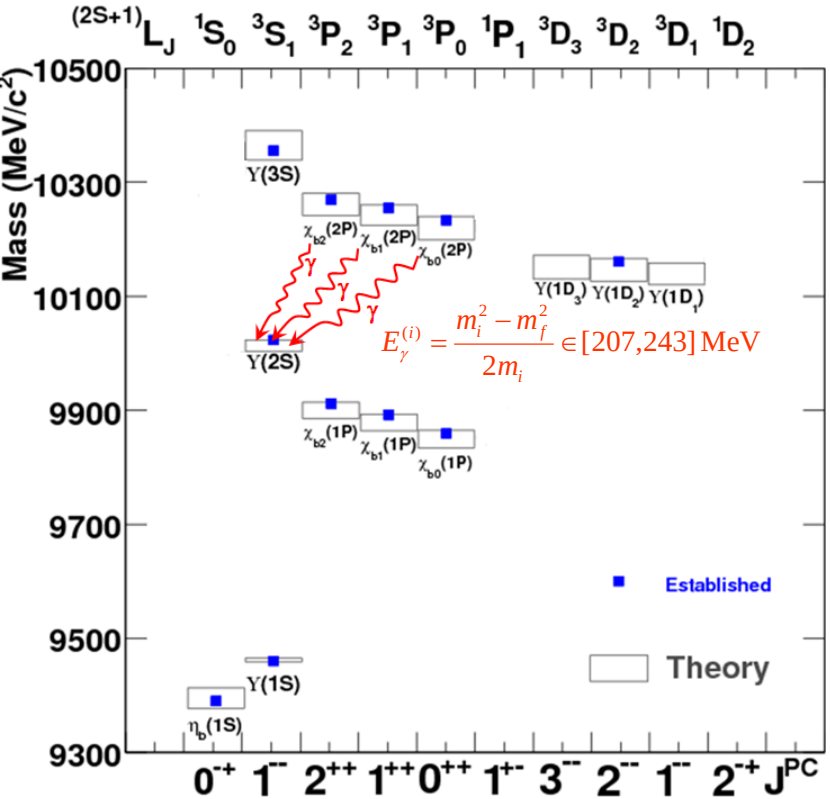


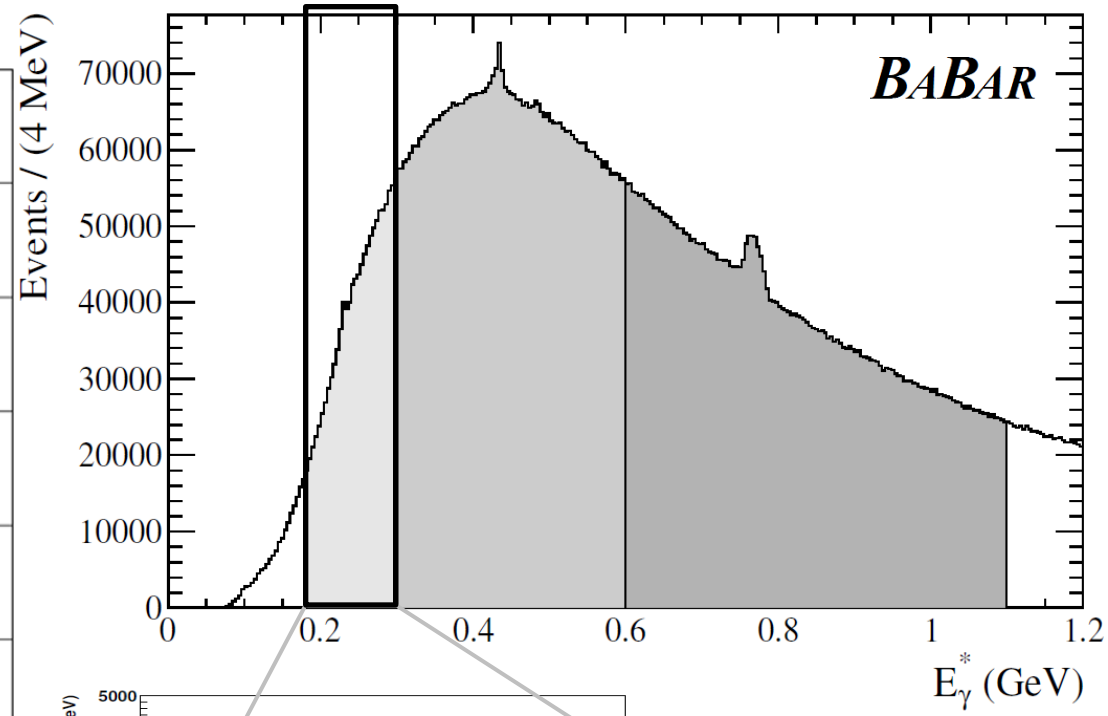
Significantly improves energy resolution [see later]

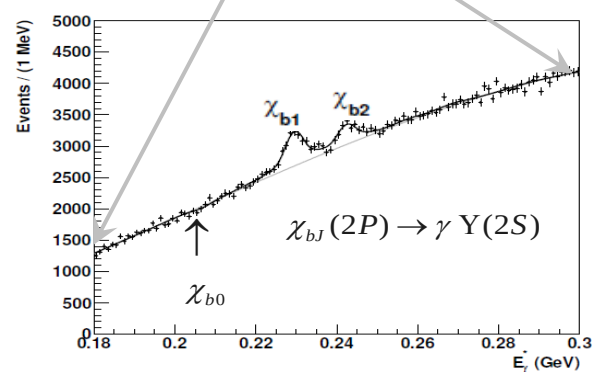
➔ Precise BF Measurements

Efficiency ~(0.1 – 1)%

Inclusive photon energy regions for Υ(3S) events



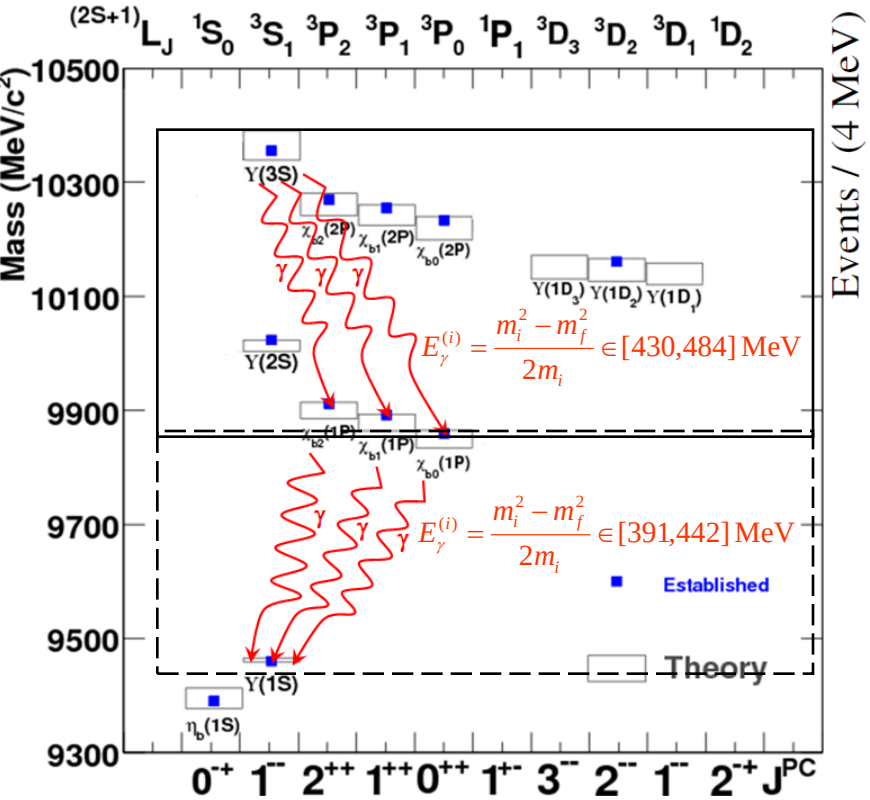


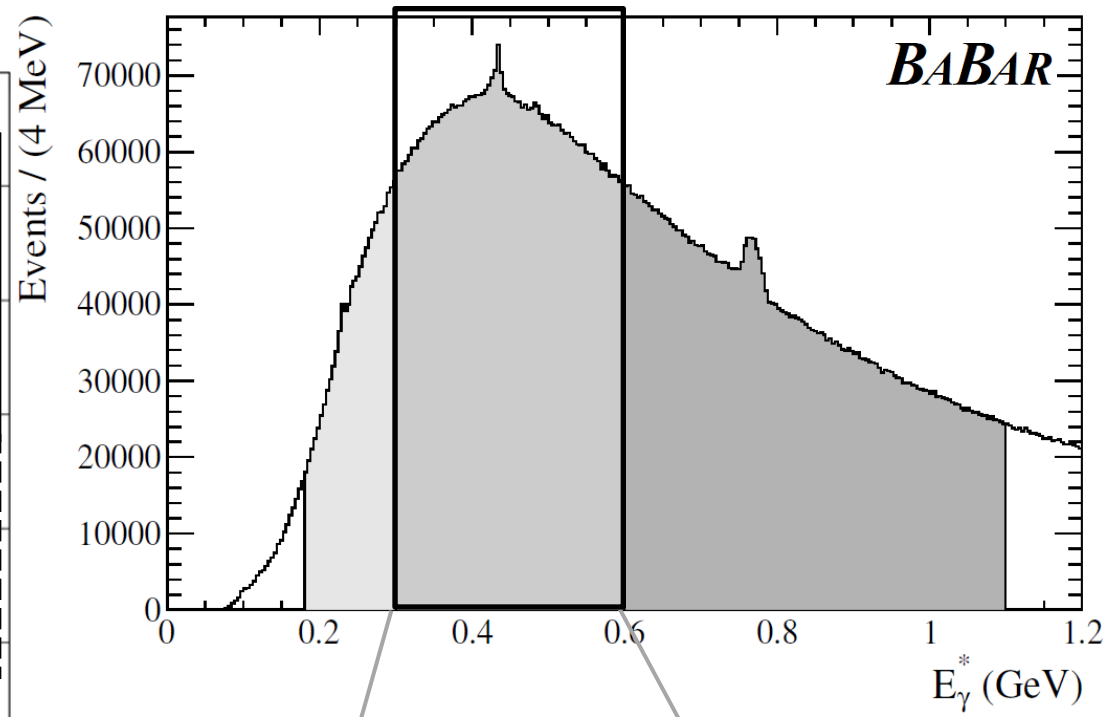


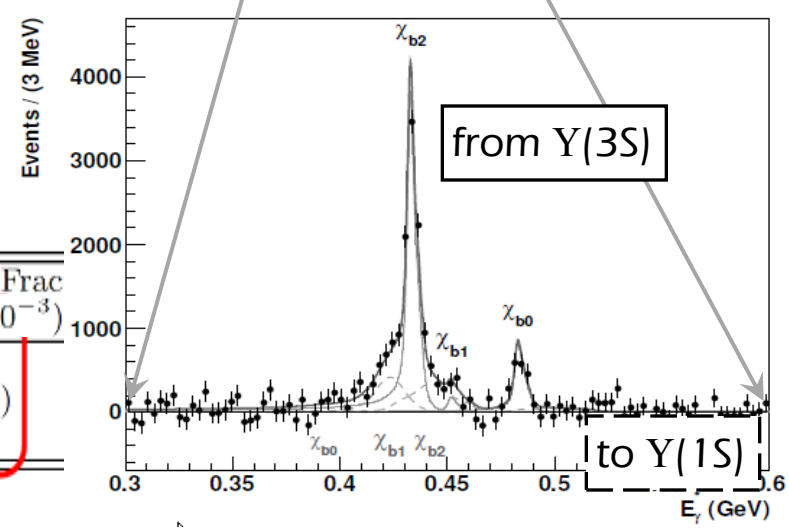
- Resolution dominated
- Small Doppler broadening

Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Fraction (%) *BABAR*	CUSB	CLEO
$\chi_{b0}(2P) \to \gamma\Upsilon(2S)$	205.0	-347 ± 209	0.105	$-4.9 \pm 2.9^{+0.7}_{-0.8} \pm 0.5$ (< 2.9)	3.6 ± 1.6	< 5.2
$\chi_{b1}(2P) \to \gamma\Upsilon(2S)$	229.7	4294 ± 251	0.152	$19.5 \pm 1.1^{+1.1}_{-1.0} \pm 1.9$	13.6 ± 2.4	21.1 ± 4.5
$\chi_{b2}(2P) \to \gamma\Upsilon(2S)$	242.3	2462 ± 243	0.190	$8.6^{+0.9}_{-0.8} \pm 0.5 \pm 1.1$	10.9 ± 2.2	9.9 ± 2.7

Inclusive photon energy regions for Υ(3S) events

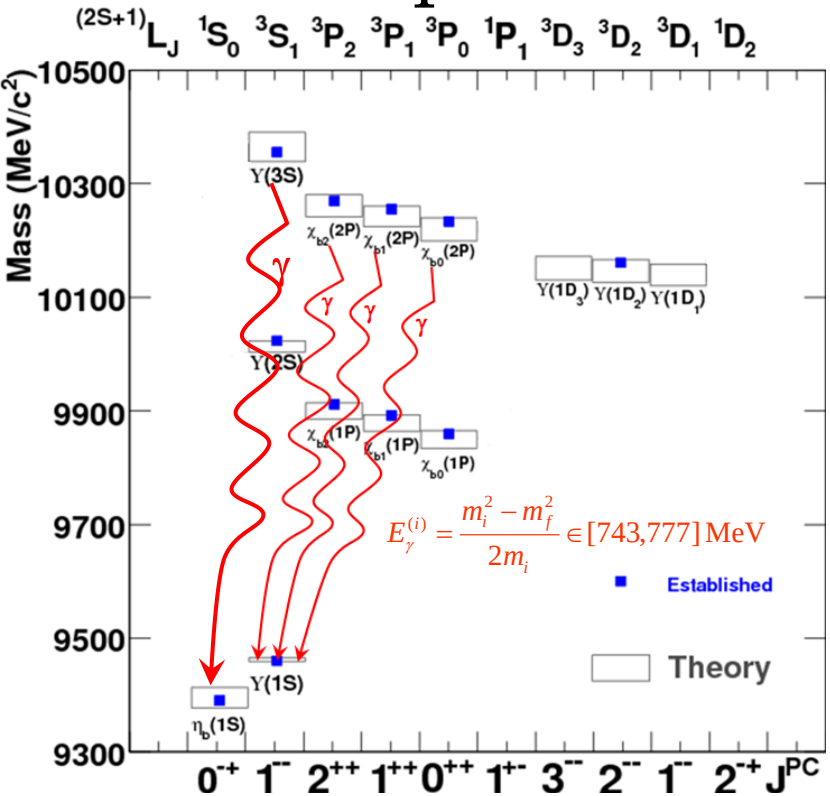




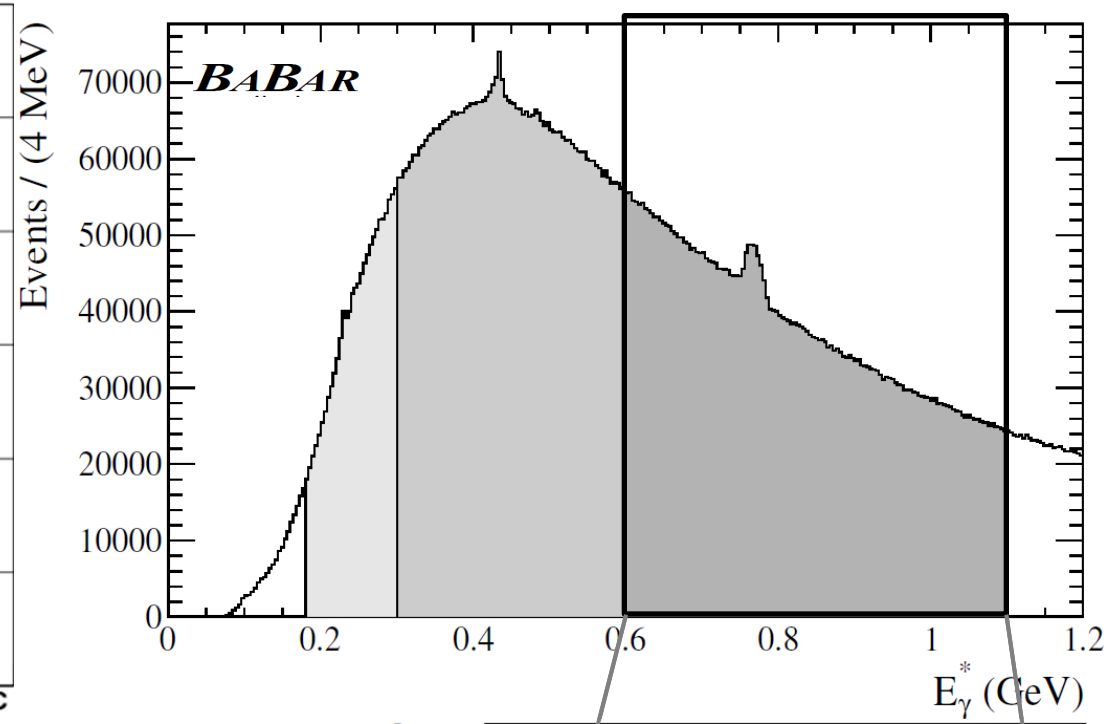


Transition	E_γ^* (MeV)	Yield	ϵ (%)	Derived Branching Frac *BABAR* ($\times 10^{-3}$)
$\Upsilon(3S) \to \gamma\chi_{b2}(1P)$	433.1	9699 ± 318	0.794	$10.6 \pm 0.3 \pm 0.6$
$\Upsilon(3S) \to \gamma\chi_{b1}(1P)$	452.2	483 ± 315	0.818	$0.5 \pm 0.3^{+0.2}_{-0.1}$ (< 1.1)
$\Upsilon(3S) \to \gamma\chi_{b0}(1P)$	483.5	2273 ± 307	0.730	$2.7 \pm 0.4 \pm 0.2$

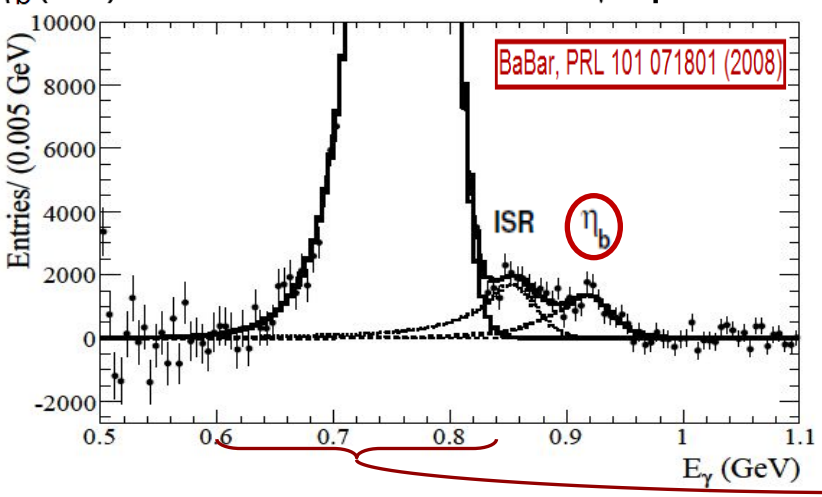
Inclusive photon energy regions for Υ(3S) events



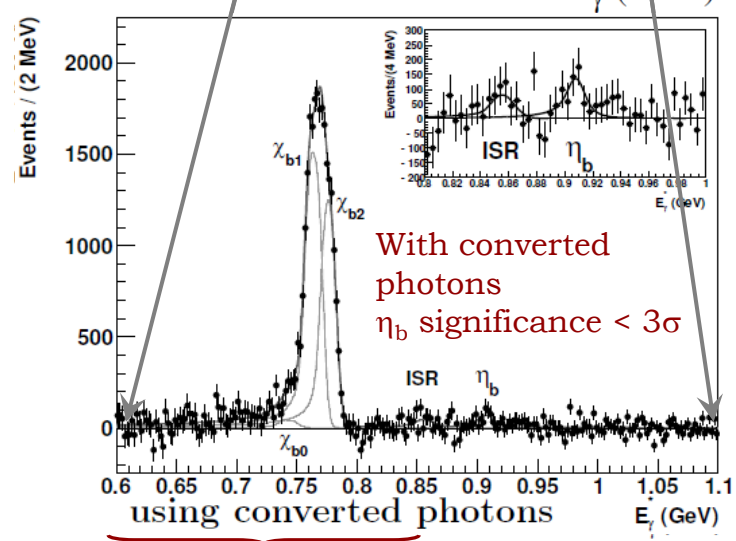
Search for the Bottomonium Ground State η_b(1S)



η_b(1S) observed in inclusive γ spectrum



Υ(3S)→ γ η_b(1S) photons from calorimeter



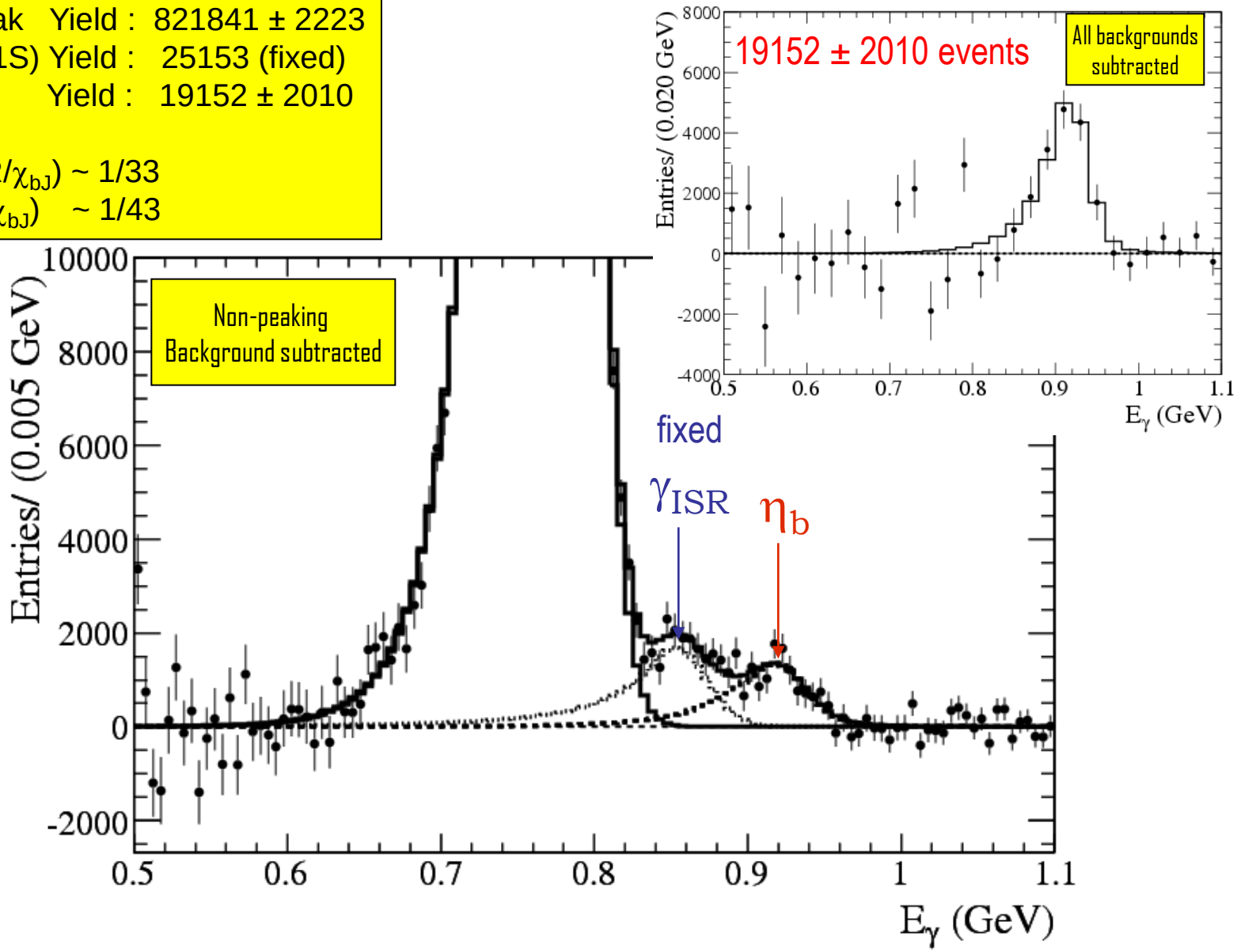
With converted photons
η_b significance < 3σ

using converted photons

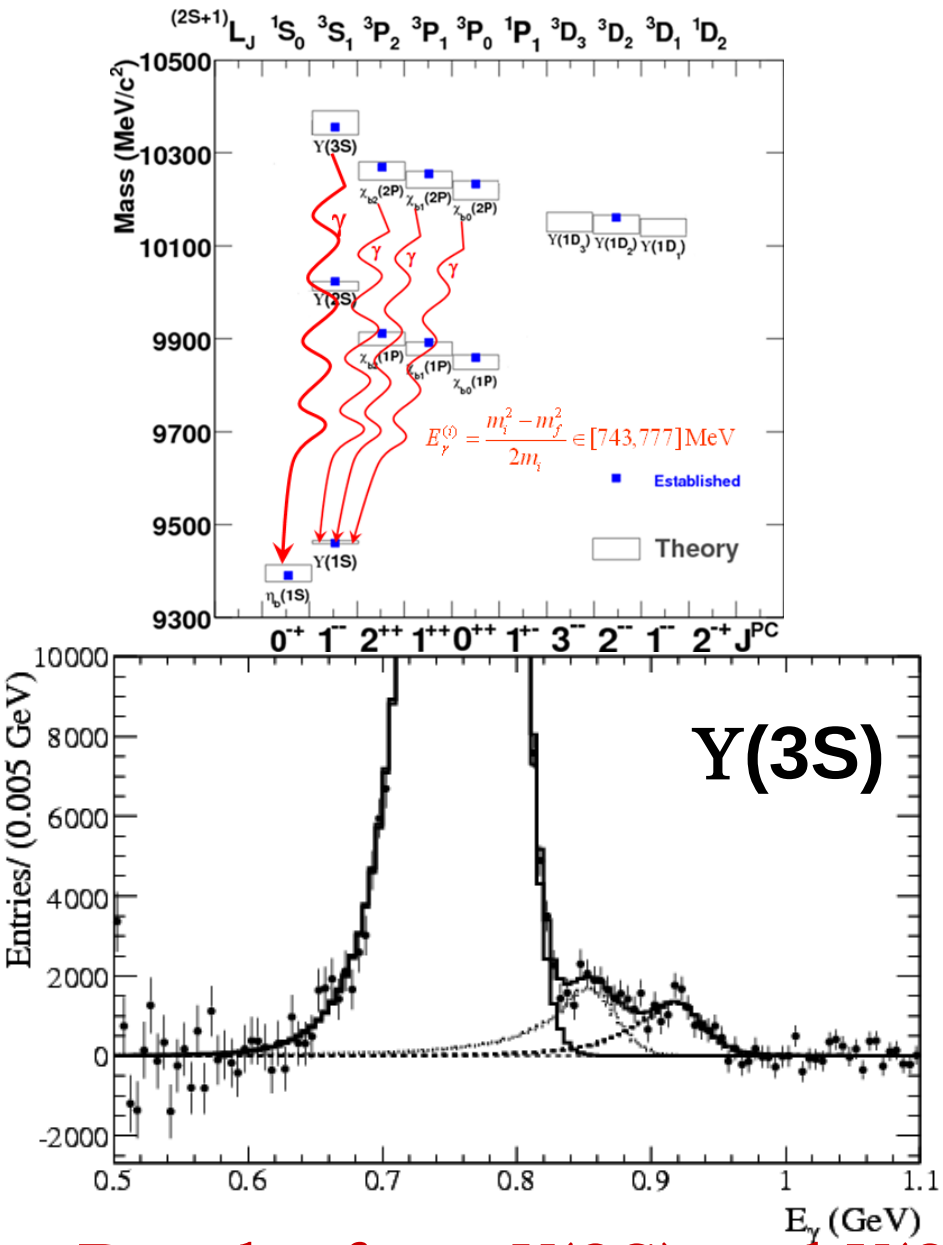
The BaBar Observation of the η_b

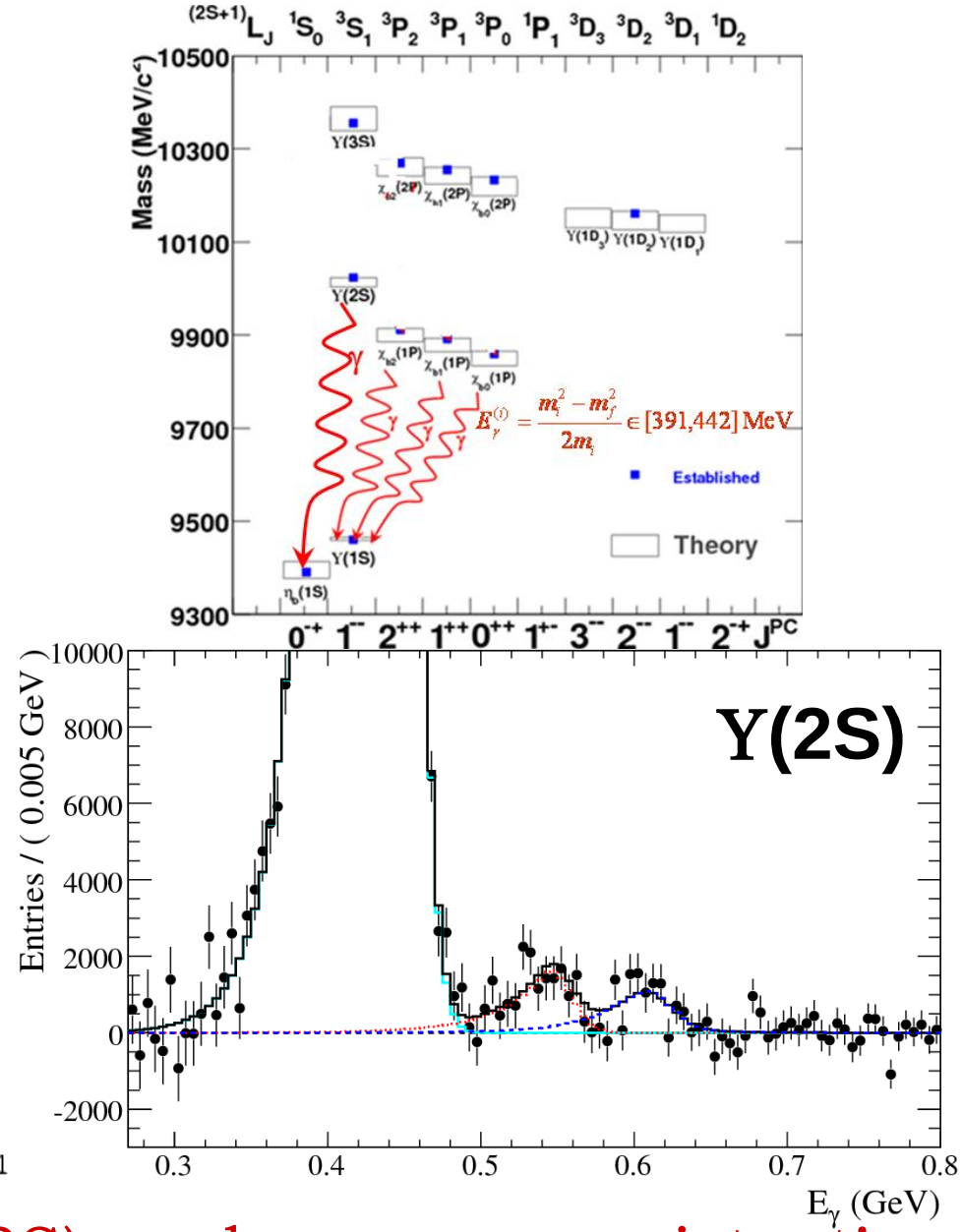
- χ_{bJ} Peak Yield : 821841 ± 2223
- γ_{ISR} Y(1S) Yield : 25153 (fixed)
- η_b Yield : 19152 ± 2010

➢ R(ISR/χ_{bJ}) ~ 1/33
➢ R(η_b/χ_{bJ}) ~ 1/43



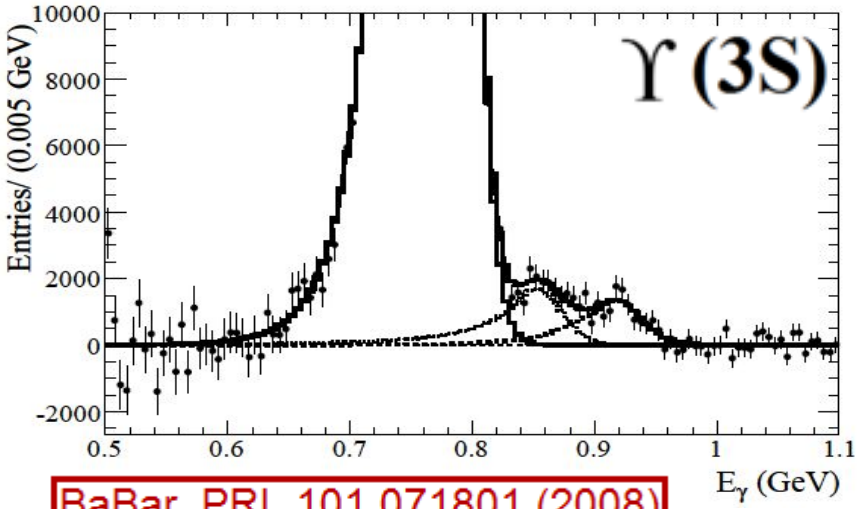
Comparison of E_γ Spectra for Υ(3S) and Υ(2S) Events



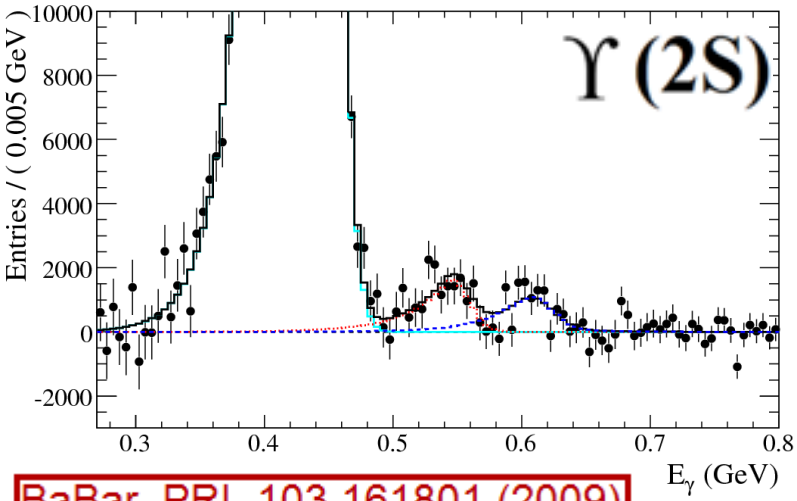


Results from Υ(2S) and Υ(3S) analyses are consistent!

Summary of Results



BaBar, PRL 101 071801 (2008)



BaBar, PRL 103 161801 (2009)

- BF measurements:

  B$(\Upsilon(3S) \to \gamma\eta_b(1S)) = (5.1 \pm 0.7) \times 10^{-4}$ **B**$(\Upsilon(2S) \to \gamma\eta_b(1S)) = (3.9 \pm 1.5) \times 10^{-4}$

  ☞ Compatible with predictions

  S. Godfrey, J.L. Rosner PRD 64 074011 (2001)

- Combined values of mass and HF splitting:
  - $m_{\eta_b(1S)} = 9390.9 \pm 2.8$ MeV/c^2 ($\Gamma_{\eta_b(1S)} \approx 10$ MeV)
  - $(m_{\Upsilon(1S)} - m_{\eta_b(1S)}) = 69.3 \pm 2.8$ MeV/c^2

  ☞ Unquenched lattice QCD calculations (~50-60 MeV/c^2) agree better than NRQCD predictions (~40 MeV/c^2)

  HPQCD, PRD 72 094507 (2005)
  Fermilab & MILC, PRD 81 034508 (2010)

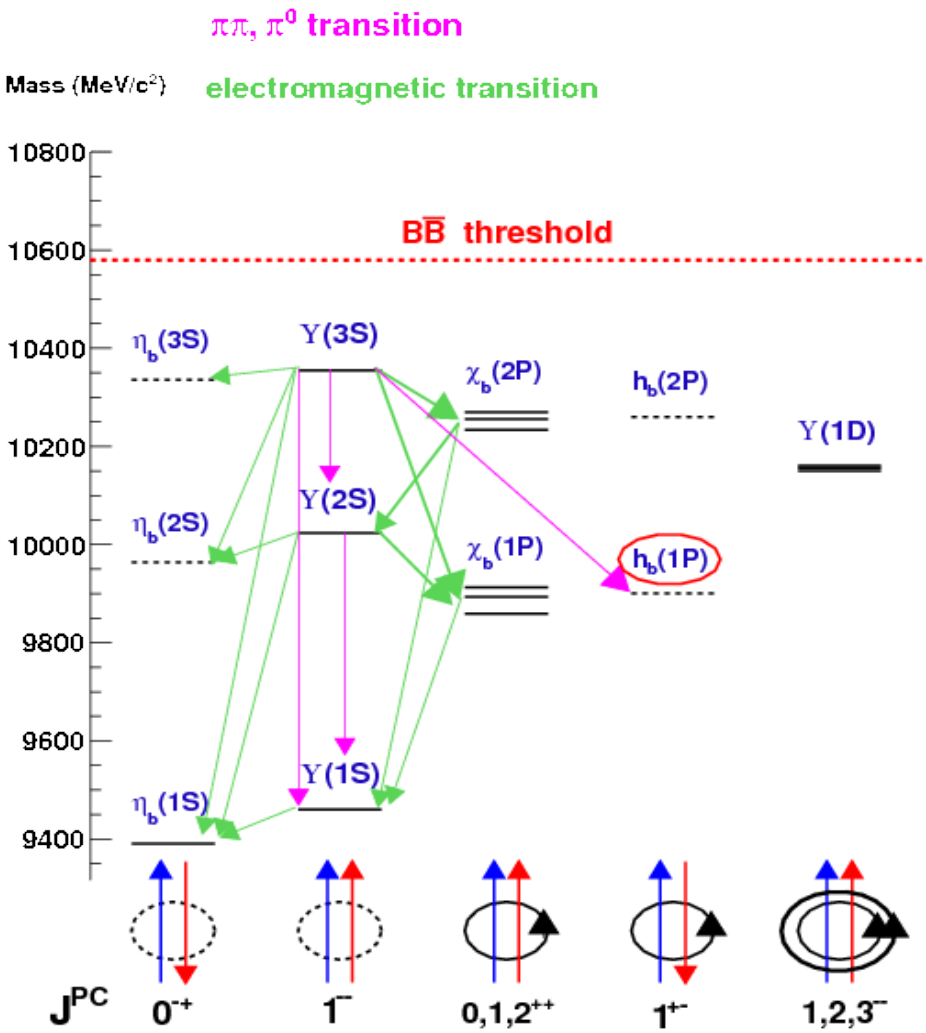
  Kniehl et al., PRL 92 242001 (2004)

  - Tension with Belle measurement in $\Upsilon(5S) \to \pi\pi\, h_b(1P) \to \gamma\eta_b(1S))$:

    $(m_{\Upsilon(1S)} - m_{\eta_b(1S)}) = 59.3 \pm 1.9\,^{+2.4}_{-1.4}$ MeV/c^2

    arXiv:1110.3934v1

Searches for the $h_b(1P)$ State of Bottomonium at BaBar



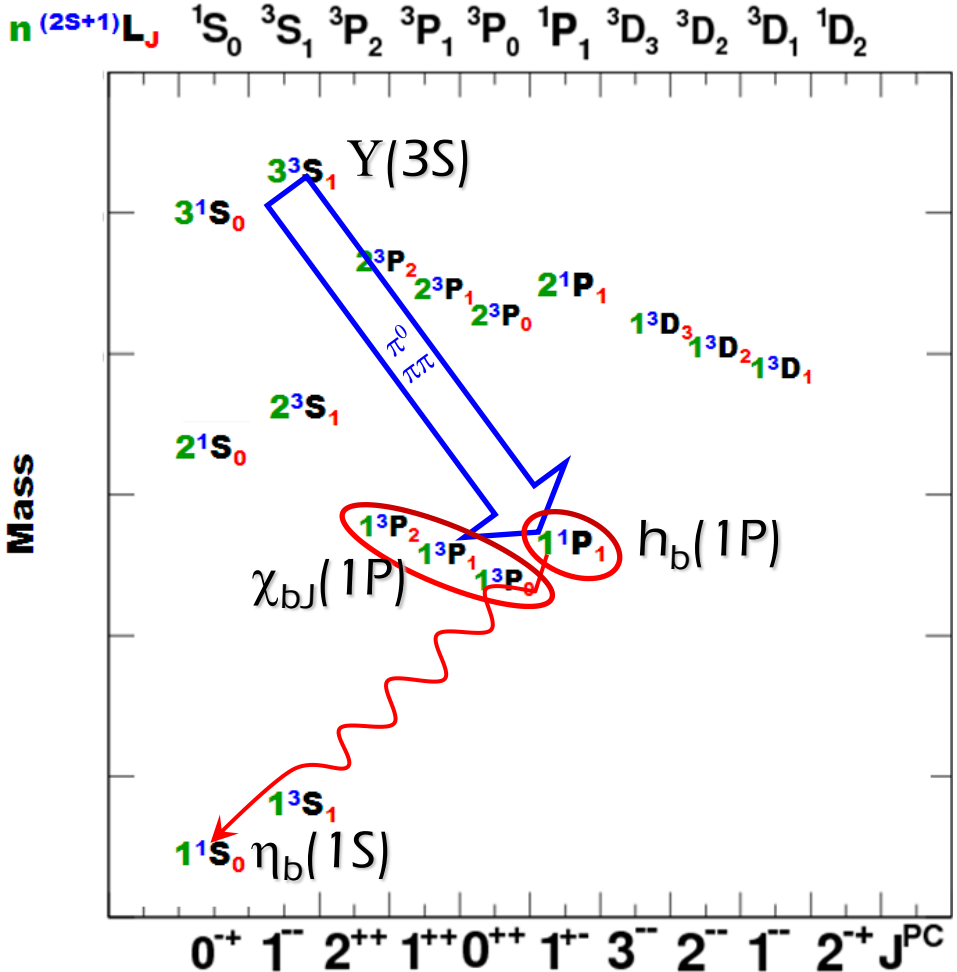
- Essential to measure the hyperfine mass splitting for *P*-wave states to understand the spin dependence of $q\bar{q}$ potentials for heavy quarks.
- Hyperfine splitting between $h_b(1P)$ mass & spin-weighted center of gravity of the $\chi_{bJ}(1P)$ states (9899.87±0.27 MeV/c^2) expected to be ~0 [confirmed for h_c].
- Hyperfine mass splitting larger than 1 MeV/c^2 might be indicative of a vector component in the confinement potential.
- BaBar searched for the $h_b(1P)$ meson in the transitions:
  - $\Upsilon(3S)\to\pi^+\pi^- h_b(1P)$
  - $\Upsilon(3S)\to\pi^0 h_b(1P)$ (requiring a photon consistent with subsequent $h_b\to\gamma\eta_b(1S)$ decay)

Expected Mass of the $h_b(1P)$ State

Hyperfine splitting for L=1 states ☞ M [c.o.g.(1^3P_J)] – M(1^1P_1)

$$\Delta M_{HF}(nL) = \underbrace{\langle M(n^3L_J)\rangle}_{\sum_J (2J+1)M_J / \sum_J (2J+1)} - M(n^1L_{J=L}) \sim 0$$

$$\Rightarrow M(1^1P_1) \sim \left(M(1^3P_0) + 3M(1^3P_1) + 5M(1^3P_2)\right)/9 = 9899.87 \pm 0.27\ \mathrm{MeV}/c^2$$

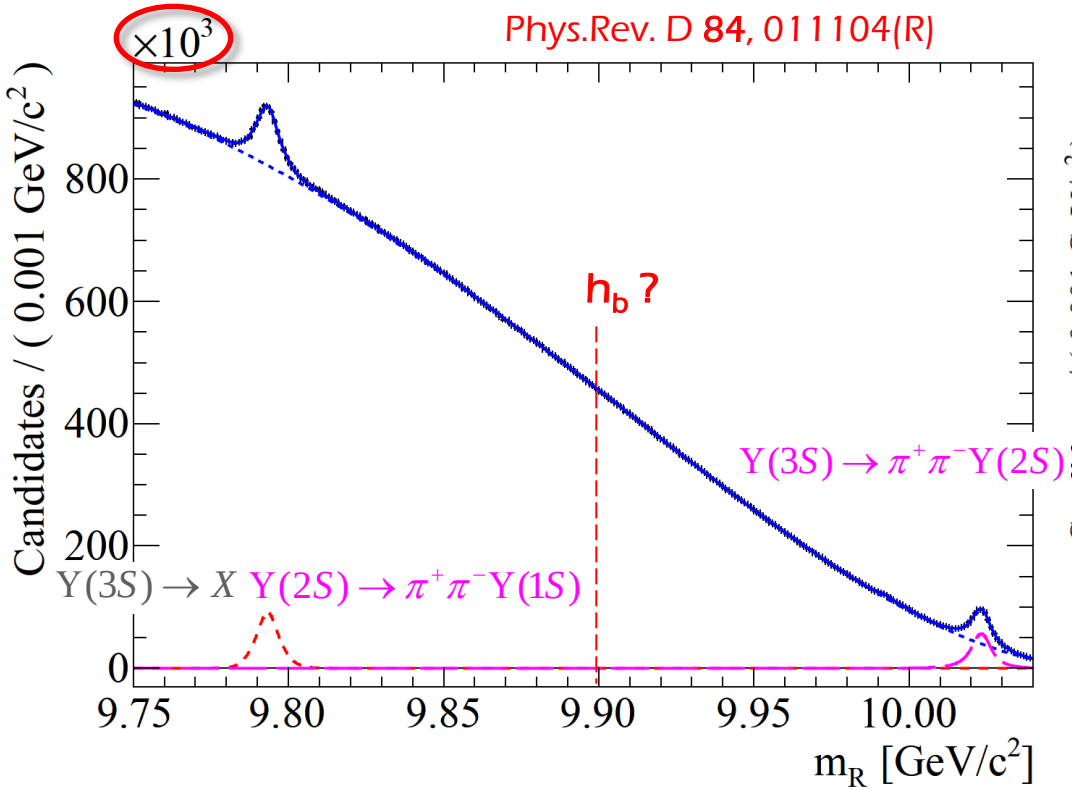


Search for a peak in invariant mass of system recoiling against $\pi^+\pi^-$ or π^0

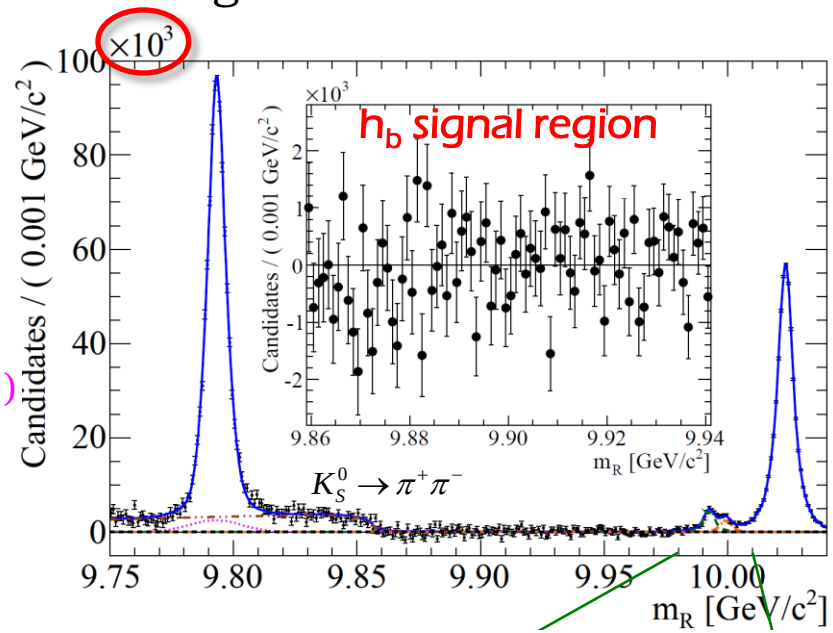
$$m_{recoil}(X) \equiv \sqrt{(E^*_{\Upsilon(3S)} - E^*_X)^2 - (\vec{p}^{\,*}_X)^2}$$

Search for the $h_b(1P)$ in the decay $\Upsilon(3S)\to\pi^+\pi^-h_b$

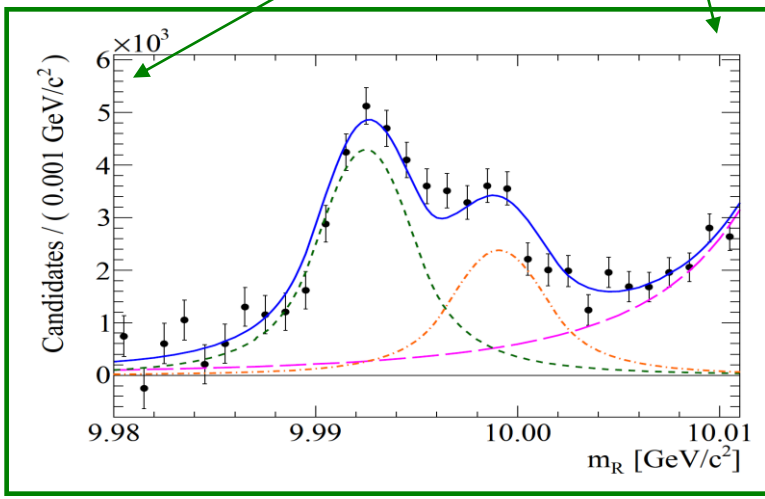
Phys.Rev. D **84**, 011104(R)



background-subtracted result:



$\chi_{b1,2}(2P)\to\pi^+\pi^-\chi_{b1,2}(1P)$

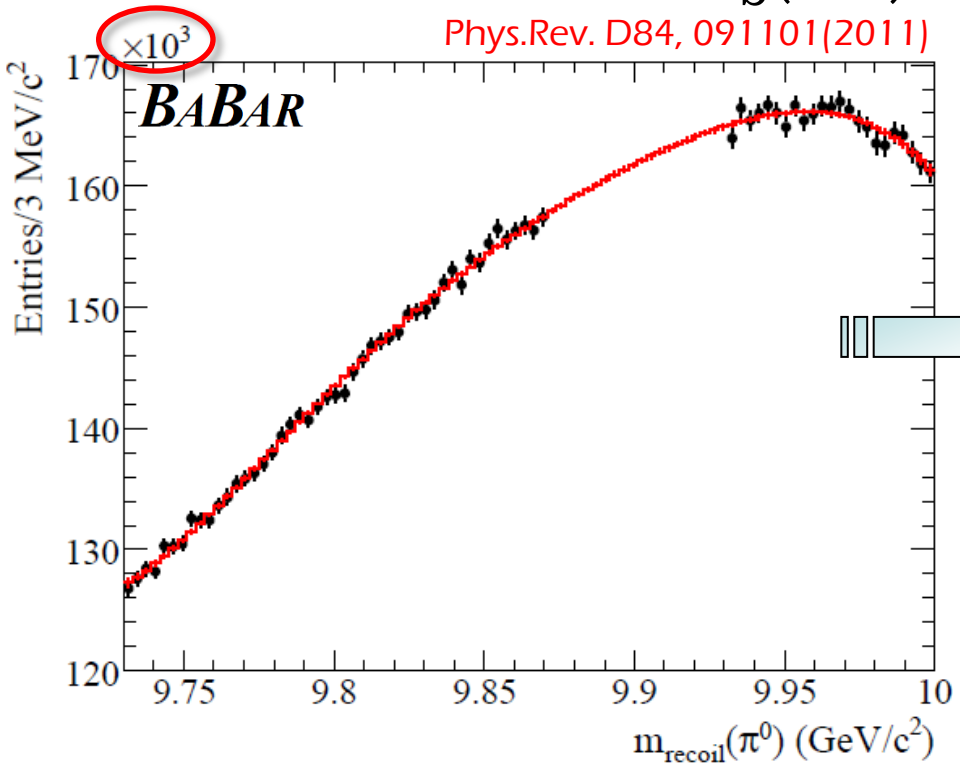


- No h_b observation: -1106 ± 2432(stat.) signal events (mass fixed at 9.9 GeV/c²)
- BF($\Upsilon(3S)\to\pi^+\pi^-h_b$)<1.0x10^{-4} (@90% C.L.)

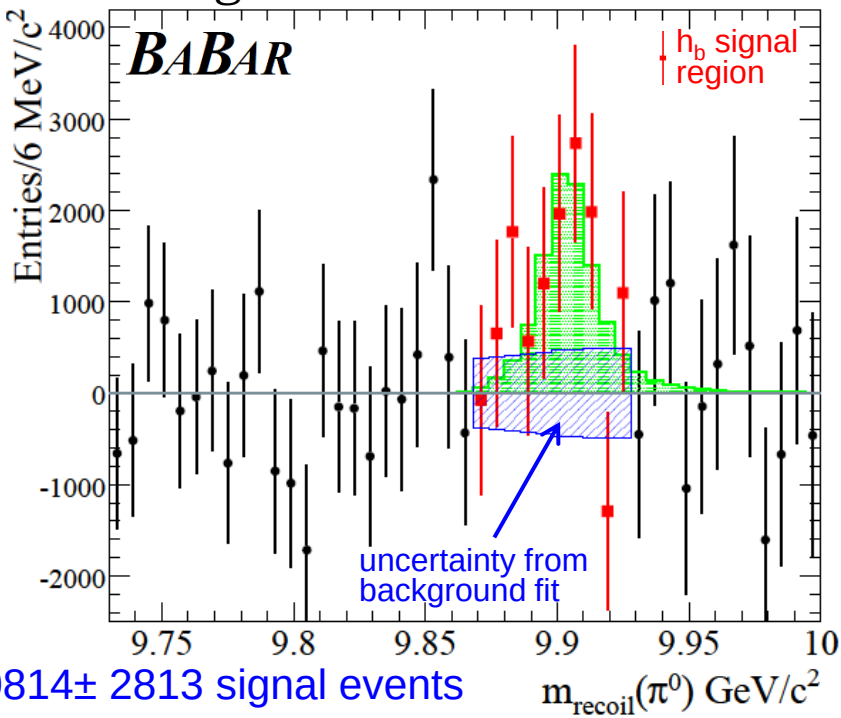
  --suppressed by a factor >3 compared to π^0 mode (see later)
- First separate observation of $\chi_{b1,2}(2P)\to\pi^+\pi^-\chi_{b1,2}(1P)$ transitions and BF measurements:
  - BF($\chi_{b1}(2P)\to\pi^+\pi^-\chi_{b1,2}(1P)$) = (9.2±0.6±0.9)×10^{-3}
  - BF($\chi_{b2}(2P)\to\pi^+\pi^-\chi_{b1,2}(1P)$) = (4.9±0.4±0.6)×10^{-3}

Evidence for the $h_b(1P)$ in the decay $\Upsilon(3S) \to \pi^0 h_b$

Phys.Rev. D84, 091101(2011)



background-subtracted result:



- χ^2 fit of $m_{recoil}(\pi^o)$ distribution:
  - $h_b(1P)$ signal: **Double Crystal Ball** function
  - Background: 5th order polynomial
    - Parameters determined with h_b signal region excluded (i.e. blind analysis strategy)

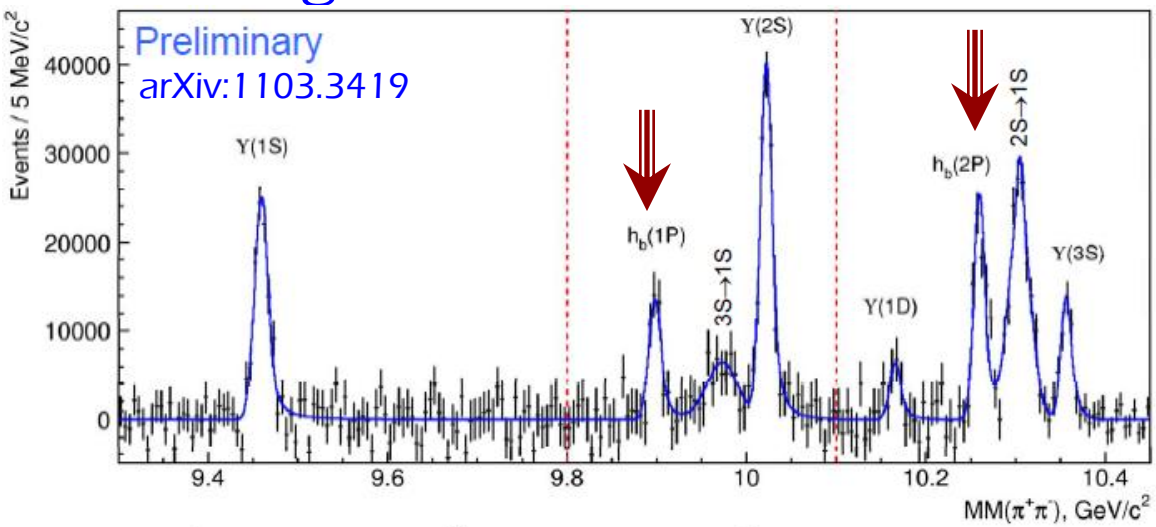
- 10814± 2813 signal events
- $M(h_b)$ = 9902±4 ±2 MeV/c^2 (C.G.=9899.87±0.27 MeV/c^2)
- Stat. Signif. = 3.8σ ($\sqrt{\Delta\chi^2}$); including systematic errors = **3.3σ**
- $B(\Upsilon(3S) \to \pi^0 h_b(1P)) = (4.1 \pm 1.1 \pm 0.9) \times 10^{-4}$
  $< 6.1 \times 10^{-4}$ (@ 90% CL)
- Existence subsequently confirmed by Belle in $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$ (arXiv:1103.3419 (*)) with combinatorial bkg. 2X BaBar $\Upsilon(3S)$ search —also observe $h_b(2P)$

(*) La Thuille 2011)

Confirmation of the existence of the $h_b(1P)$ by Belle in $e^+e^- \to \pi^+\pi^-$ transitions at the $\Upsilon(5S)$

Observation of the $h_b(1P)$ and $h_b(2P)$ states

background subtracted results



	Yield, 10^3	Mass, MeV/c^2	Signif.
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	$6.2\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	$16.6\,\sigma$
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	$12.4\,\sigma$
$2S \to 1S$	$151.6 \pm 9.7^{+9.0}_{-20.}$	$10304.57 \pm 0.61 \pm 1.03$	$15.7\,\sigma$
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	$8.5\,\sigma$

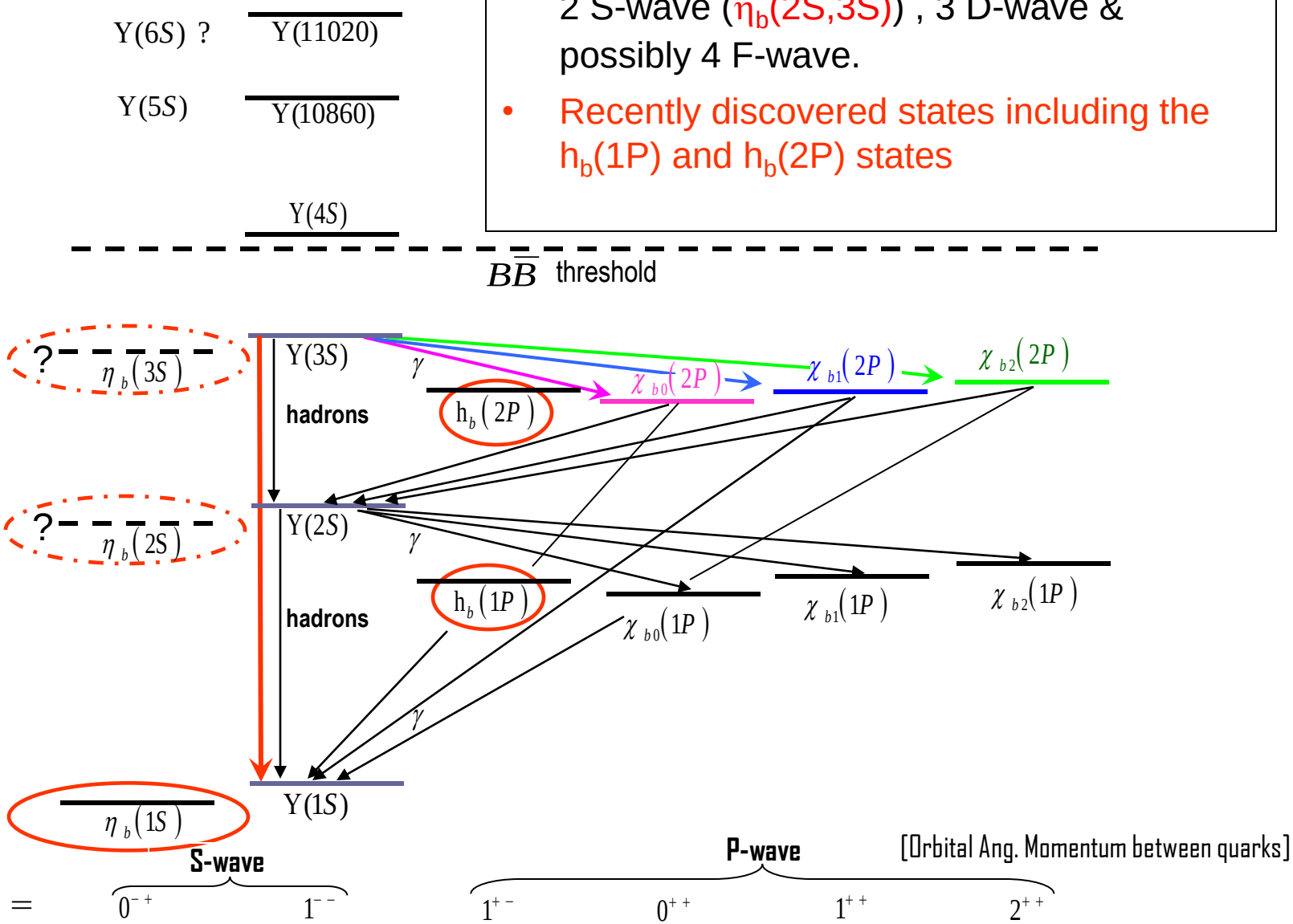
→ Consistent with BaBar measmt.

- Measured $h_b(1,2P)$ mass values consistent with predictions
- Observed h_b production rate enhancement may be indicative of exotic process violating HQ spin-flip suppression
- Resonant structures in $h_b(1P, 2P)\,\pi$ seen in $\Upsilon(5S) \to h_b(1P, 2P)\,\pi^+\pi^-$ events (also in $\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$)

→ **charged exotic** candidates $\mathbf{Z_{b1}}$, $\mathbf{Z_{b2}}$

2011 Picture of the Bottomonium Spectrum

- $b\bar{b}$ states below Υ(3S) not yet discovered: 2 S-wave (η_b(2S,3S)) , 3 D-wave & possibly 4 F-wave.
- Recently discovered states including the h_b(1P) and h_b(2P) states



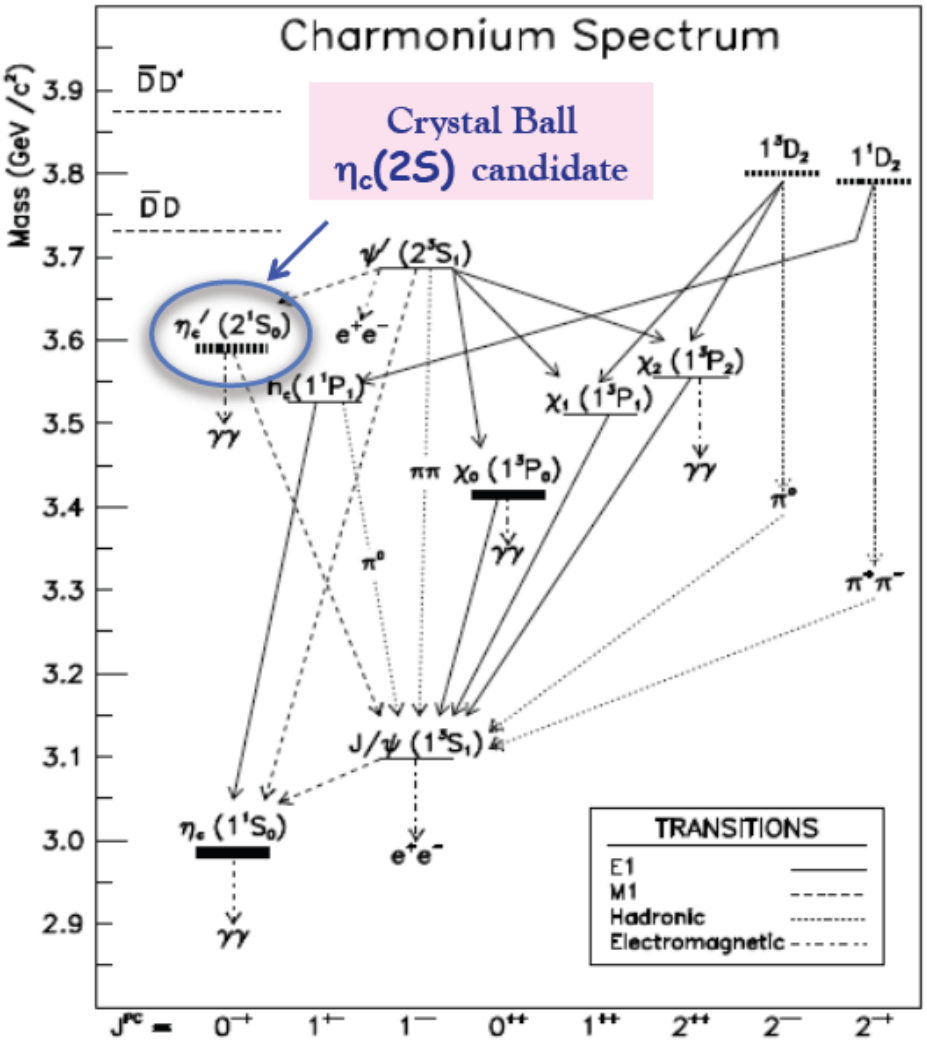
(nL) where n is the principal quantum number and L indicates the $b\bar{b}$ angular momentum in spectroscopic notation (L=S, P, D,...)

Quarkonium Spectroscopy

Insight into Charmonium Spectroscopy

Evidence for <u>unconventional</u> states

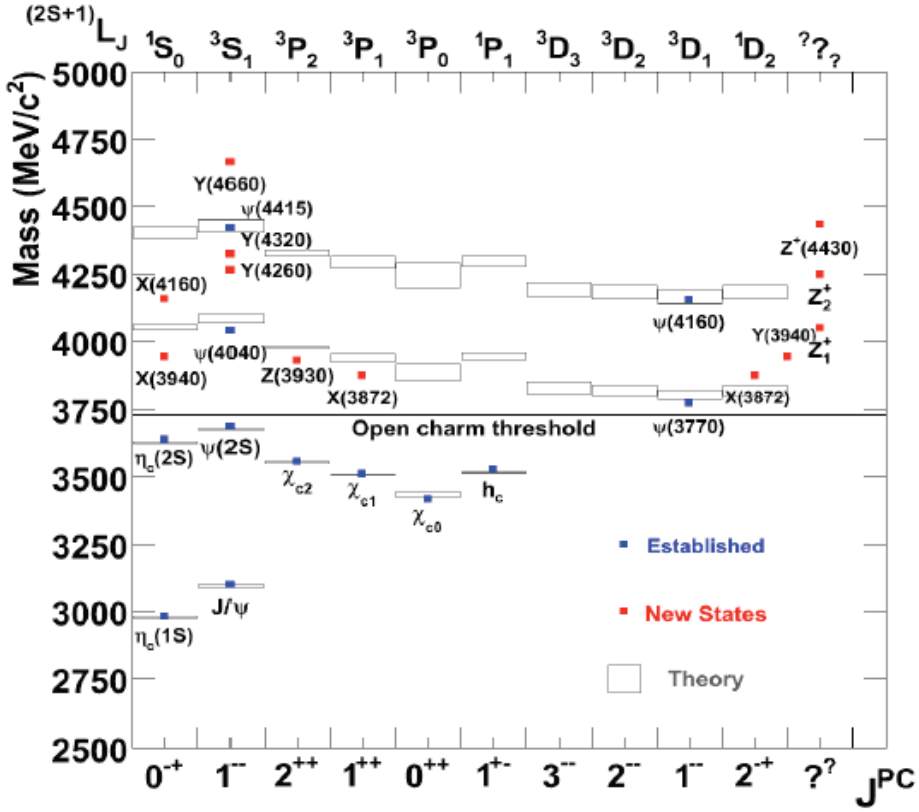
Charmonium Spectrum (year 2000)



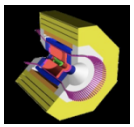
(E835 experiment - year 2000) in the same year -B factories started to take data

- ✓ Charmonium properties were well understood up to $\psi(3770)$ (i.e. about the $D\bar{D}$ threshold) with some missing pieces (like the $\eta_c(2S)$)
- ✓ No new $c\bar{c}$ states were discovered between 1980 and 2002
- ✓ $c\bar{c}$ states above open charm threshold are expected to have significant width values and to decay mainly to open charm Channels
- ✓ Contributions of B factories to charmonium spectroscopy…

Charmonium Spectrum (year 2012)



State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$h_c(1P)$	3525.45 ± 0.15	0.73 ± 0.53 (<1.44)	1^{+-}	$\psi(2S) \to \pi^0(\gamma\eta_c(1S))$ $\psi(2S) \to \pi^0(\gamma...)$ $p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$ $\psi(2S) \to \pi^0(...)$
$\eta_c(2S)$	3637 ± 4	14 ± 7	0^{-+}	$B \to K(K_S^0 K^- \pi^+)$ $e^+e^- \to e^+e^-(K_S^0 K^- \pi^+)$
Z(3930) $\chi_{c2}(2P)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$e^+e^- \to J/\psi\ (...)$ $e^+e^- \to e^+e^-(D\bar{D})$



- In a few years the situation changed rapidly
- There were discoveries of new charmonium states like the $h_c(1P)$, $\eta_c(2S)$ and $\chi_{c2}(2P)$
- And several new "charmonium-like" states

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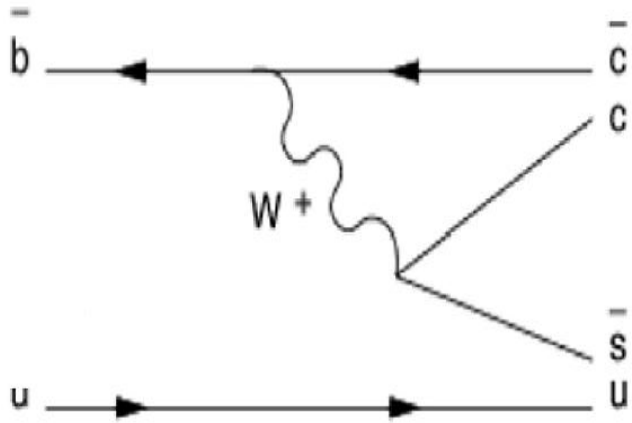
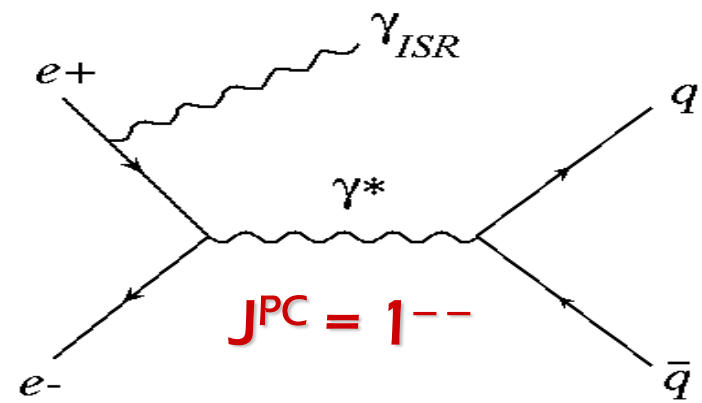
Charmonium production mechanisms at the B-factories

$B \to c\bar{c}\, K(*)$ decay

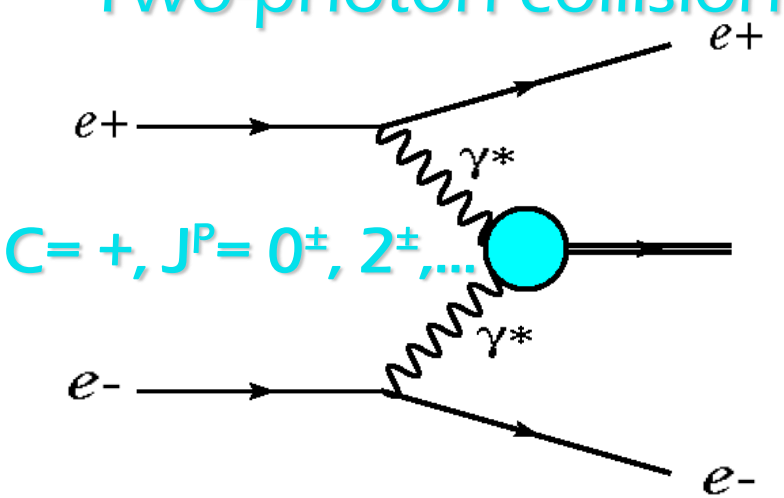


States of any Quantum Number can be formed

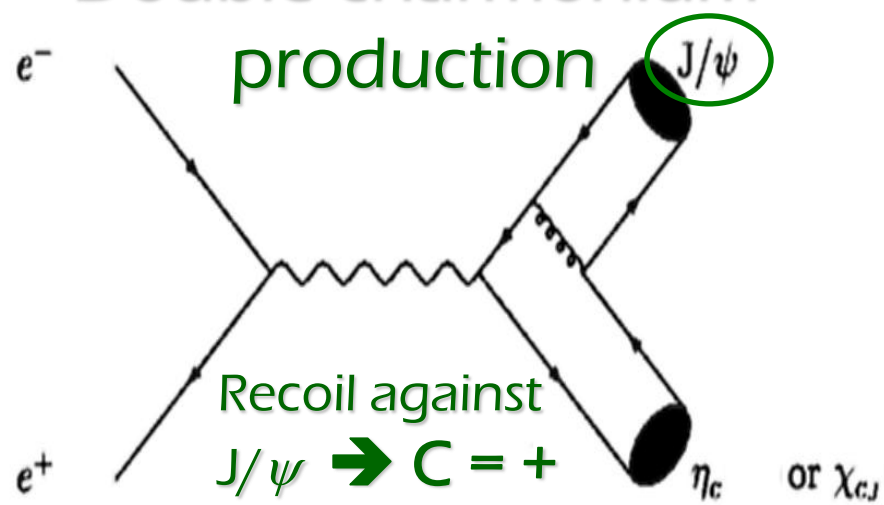
Initial state radiation



Two-photon collision

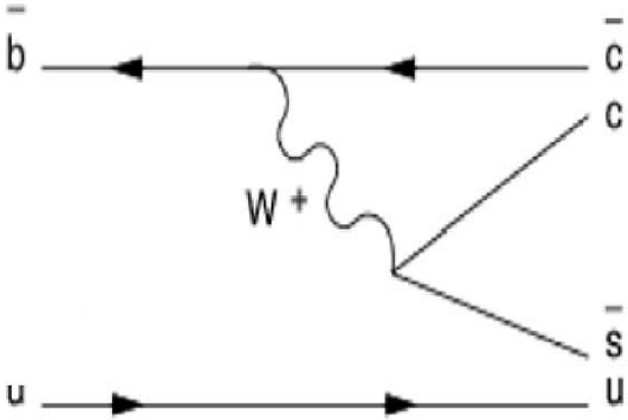


Double charmonium production



Some *Unconventional* States

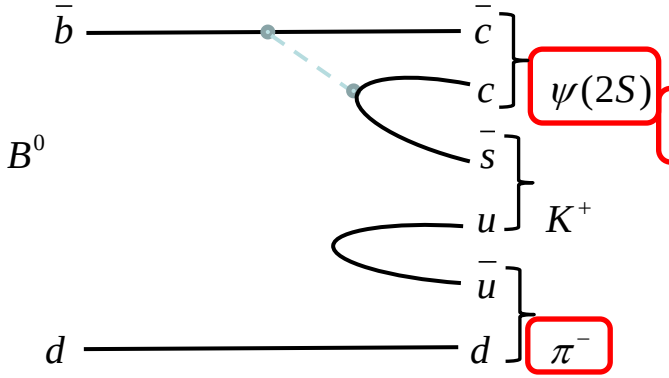
$B \to c\bar{c}\, K(*)$ decay



- **X(3872)**
  - Narrow state above $D\bar{D}$ threshold
  - First Observed by Belle in **J/ψ π π**
  - Confirmed by BaBar, CDF, D0, LHCb
  - **Measured width much smaller than that expected for a conventional charmonium state**
  - Seen in J/ψ γ, ψ(2S) γ decay → C=+
  - Angular analyses inconclusive: $J^P = 1^+$, <u>OR</u> 2^-

Some *Unconventional* States

$B \to c\bar{c}\, K(*)$ decay



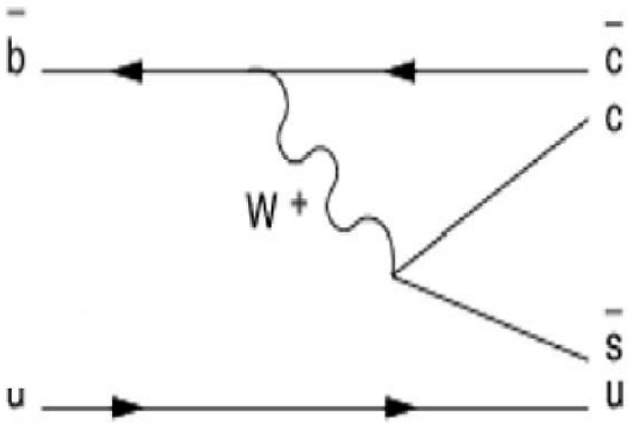
- **X(3872)**
- **Y(3940)**
- **Z(4430)$^-$**
- **Z_1(4050)$^-$**
- **Z_2(4250)$^-$**
- **Y(4140)**

A state $Z^- \to \psi' \pi^-$ would have hidden charm & charge

☞ candidate for $\bar{c}c\bar{u}d$ tetraquark

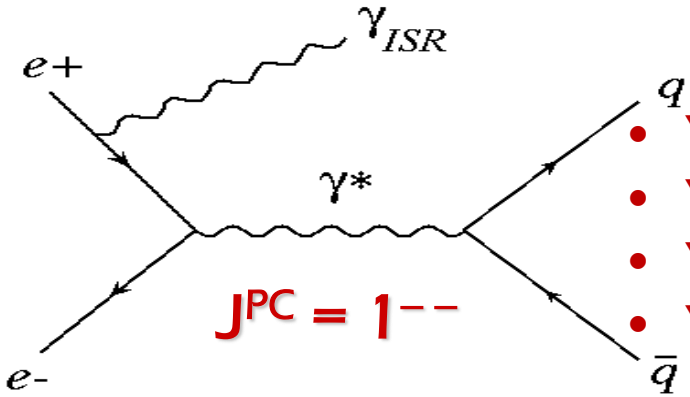
Some *Unconventional* States

$B \to c\bar{c}\, K(*)$ decay



- X(3872)
- Y(3940)
- $Z(4430)^-$
- $Z_1(4050)^-$
- $Z_2(4250)^-$
- Y(4140)

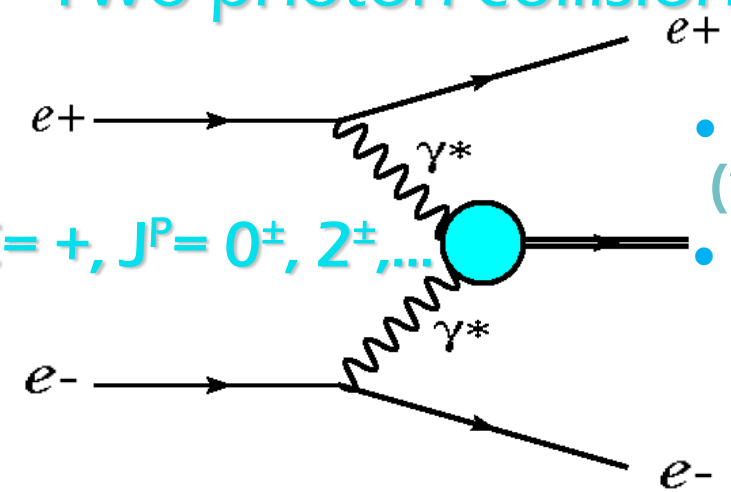
Initial state radiation



$J^{PC} = 1^{--}$

- Y(4260)
- Y(4008)
- Y(4350)
- Y(4660)

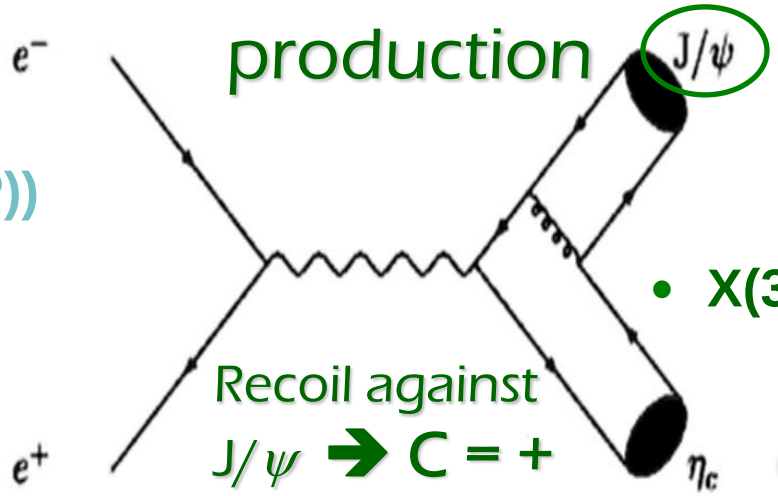
Two-photon collision



$C = +,\ J^P = 0^{\pm}, 2^{\pm}, \ldots$

- Z(3930) (?=$\chi_{c2}(2P)$)
- Y(3915)

Double charmonium production



- X(3940)

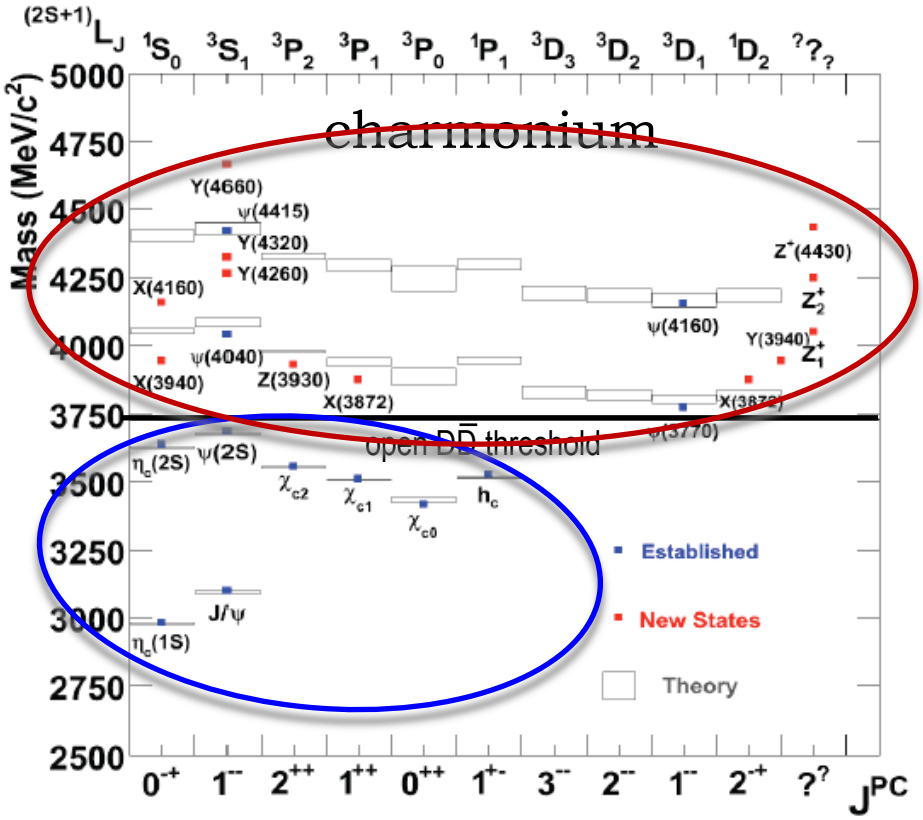
Recoil against J/ψ ➔ C = +

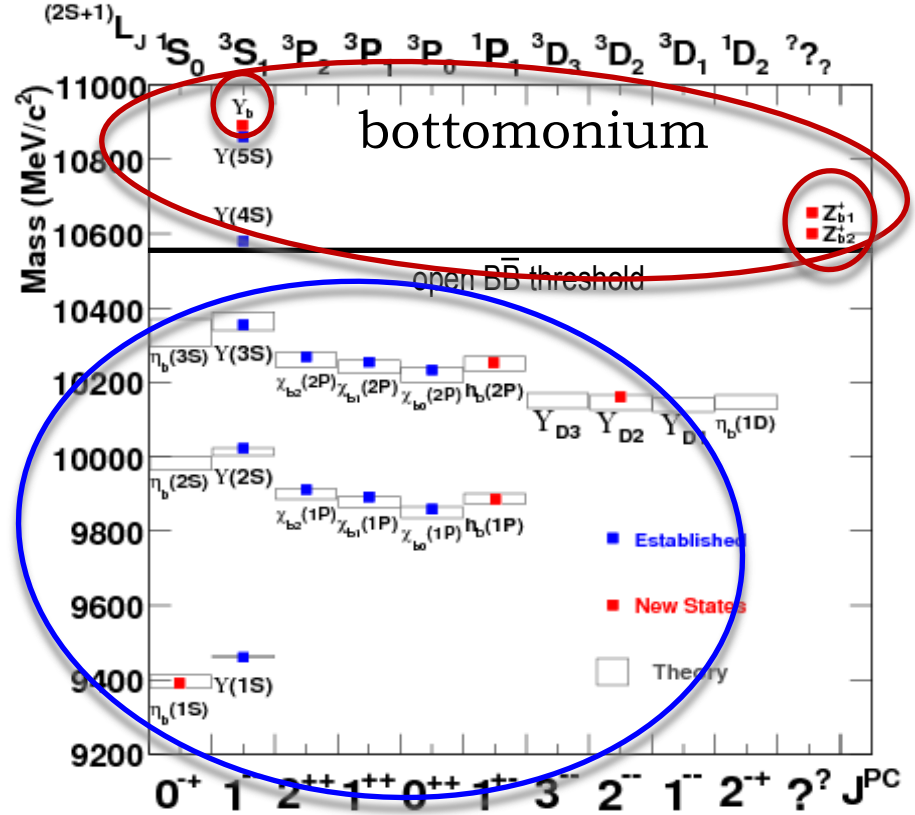
Topics not covered today

EPJC 71 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year
$\eta_c(2S)$	3637 ± 4	14 ± 7	0^{-+}	$B \to K(K_S^0 K^- \pi^+)$	Belle [49] (6.0)	2002
				$e^+e^- \to e^+e^-(K_S^0 K^- \pi^+)$	BABAR [50] (4.9), CLEO [51] (6.5), Belle [52] (6)	
				$e^+e^- \to J/\psi\ (...)$	BABAR [53] (np), Belle [54] (8.1)	
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6 (<2.2)	$1^{++}/2^{-+}$	$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)	2003
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)	
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)	
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)	
$\chi_{c2}(2P)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [55] (5.3), BABAR [56] (5.8)	2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)	
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [108, 109] (8.0)	2005
					CLEO [110] (5.4)	
					Belle [104] (15)	
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)	
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [113] (np), Belle [114] (8.0)	2007
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007
$\eta_b(1S)$	9390.7 ± 2.9	?	0^{-+}	$\Upsilon(3S) \to \gamma + (...)$	BABAR [59] (10), CLEO [60] (4.0)	2008
				$\Upsilon(2S) \to \gamma + (...)$	BABAR [61] (3.0)	
$\Upsilon(1^3D_2)$	10163.8 ± 1.4	?	2^{--}	$\Upsilon(3S) \to \gamma\gamma(\gamma\gamma\Upsilon(1S))$	CLEO [62] (10.2)	2004
				$\Upsilon(3S) \to \gamma\gamma(\pi^+\pi^-\Upsilon(1S))$	BABAR [63] (5.8)	
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010

Current Status





- All states below **open flavor threshold** well understood & conform to quark model $q\bar{q}$ interpretation
  - Region above open $c\bar{c}$ flavor more complicated
- Little exploration of the region above Υ(4S)
  - Recent Belle evidence for Z_b^+ states (structures in Υ(nS)π and h_b(1P,2P)π from Υ(5S))
  - No analogues to the X,Y states found yet
- Much higher statistics needed:
  - Spin-parity information from charmonium decays to exclusive final states
  - Information in the bottomonium sector in the region above the Υ(4S)