Exotic cc Spectroscopy

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KEK

Beyond the "standard spectroscopy"

- Search for states with 2 quarks+"something else"
  - New forms of aggregation
  - Expected but never identified!!!
- Hybrids: $q\bar{q}$+n gluons
  - Lowest state 1^{-+} (forbidden for quarkonium)
  - Dominant decay $H \rightarrow DD^{**}$
- Tetraquarks: $[q\bar{q}'][qq']$
  - Large amount of states
  - small widths also above threshold
- Molecules: $M[q\bar{q}]M[q'\bar{q}']$
  - Smaller number of states but still small widths also very close to threshold

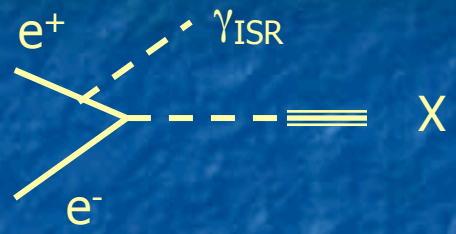
Search for resonances:
- with non-quarkonium J^{PC}
- unnaturally small widths
- not null charge: clear indication of something new going on

Building a new spectroscopy

1. Find structures
2. Measure quantum numbers (mass, JPC from production and decay properties)
3. "walks like a dog, smells like a dog …"
   - Several possible scenarios (hybrids, molecules, tetraquarks,…)
4. Quantify models and fit data to it
5. Search missing states to complete the picture

Strong interplay between theory and experiment

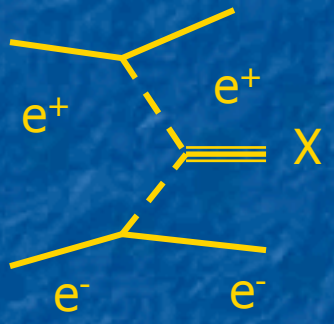
Measuring the quantum numbers



- Production:
  - ISR only produces with same quantum numbers as the photon ($J^{PC}=1^{--}$)
  - $\gamma\gamma$ only produces with C=+
  - Double charmonium production

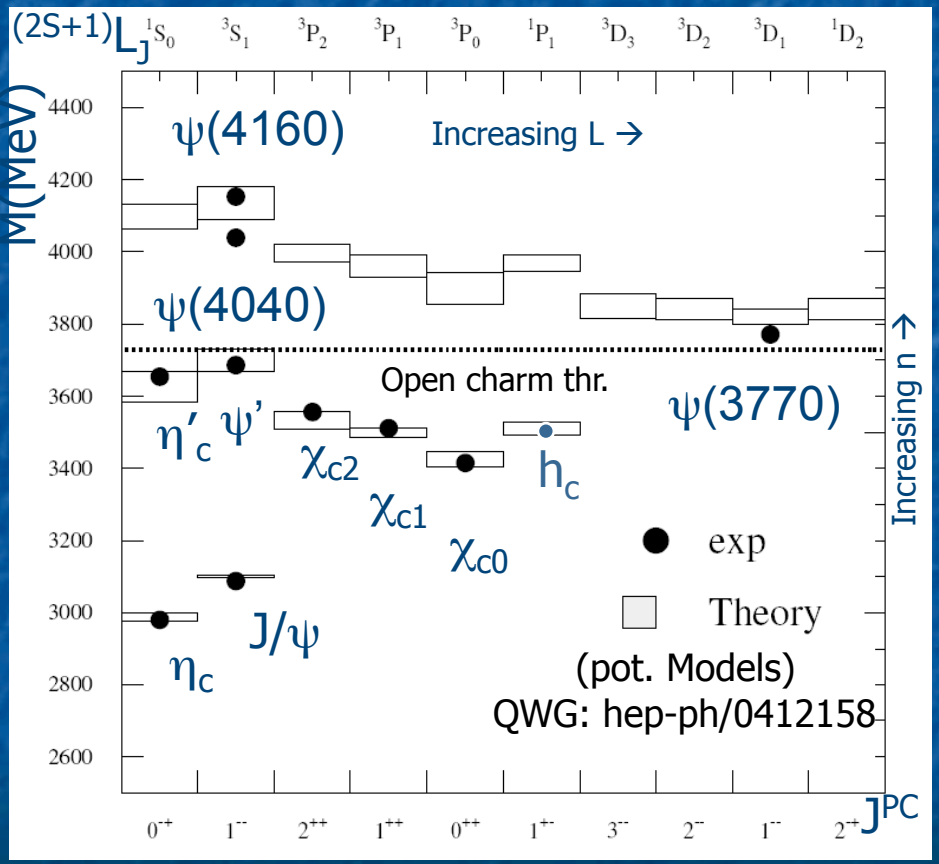
    $e^+e^- \rightarrow \gamma^* \rightarrow X_{cc}{}^1 X_{cc}{}^2$

    Possible only if quantum numbers of the two charmonia can be combined to give a 1^{--}.



- Decay:
  - Angular distributions of decay products depend on J^P.
  - Strong decay into C eigenstates (C_1 and C_2) implies $C=C_1*C_2$
  - Selection rules
    - Conservation of J
    - Conservation of P,C in strong and electromagnetic decays

Charmonium: state of the art



All states below the open charm threshold are observed and explained

Topics and open issues [exp]

- X(3872)
  - J^{PC},ΔM between $J/\psi\pi\pi$ and DD^*, width
- The 3940 Family (3 states)
  - J^{PC} of X,Y, $J/\psi\omega$ BaBar-Belle discrepancy
- The 4150 Family (3 states – one @ 4350…)
  - J^{PC}
- The 1-- family (3 states)
  - Decay modes
- The charged states (3 states)
  - Confirmation and Dalitz of Z(4050) and Z(4250)

X(3872)

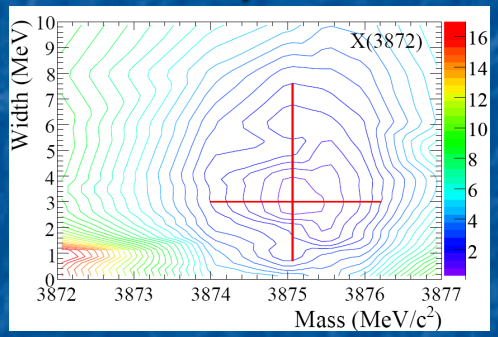
- Best known new state, M~3872 MeV, $J^{CP}=1^{++}$
- Seen mostly in B decays so far (B→XK) [CDF and D0 inclusive]
- Possiility to measure absolute BF and widths. Bayesian likelihood combination of:
  - Product BF(B→XK)xBF(X→f)
    - f=$J/\psi\pi\pi$,$D^{*0}D^0$,$J/\psi\gamma$,$\psi(2S)\gamma$,$J/\psi\pi^+\pi^-\pi^0$,$\chi_c\gamma$,$\gamma\gamma$,$J/\psi\eta$
  - Measured Γ (BaBar)

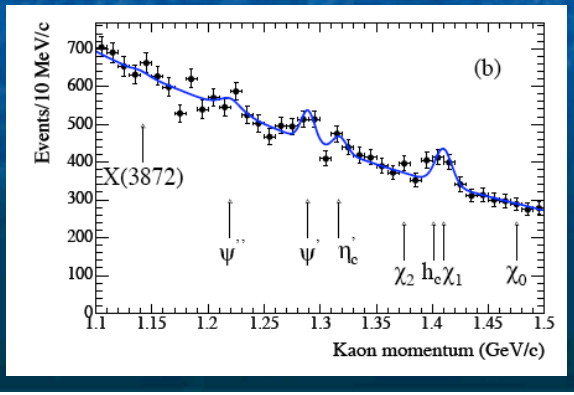
$$\Gamma = (3.6^{+4.6}_{-2.3} \pm 0.9)\,MeV$$

Original Belle paper Γ<2.3MeV@90%C.L.

- Upper limit on BF(B→XK) from K inclusive spectrum on the rec of fully reconstructed B decays (BaBar).

$\Delta\chi^2$

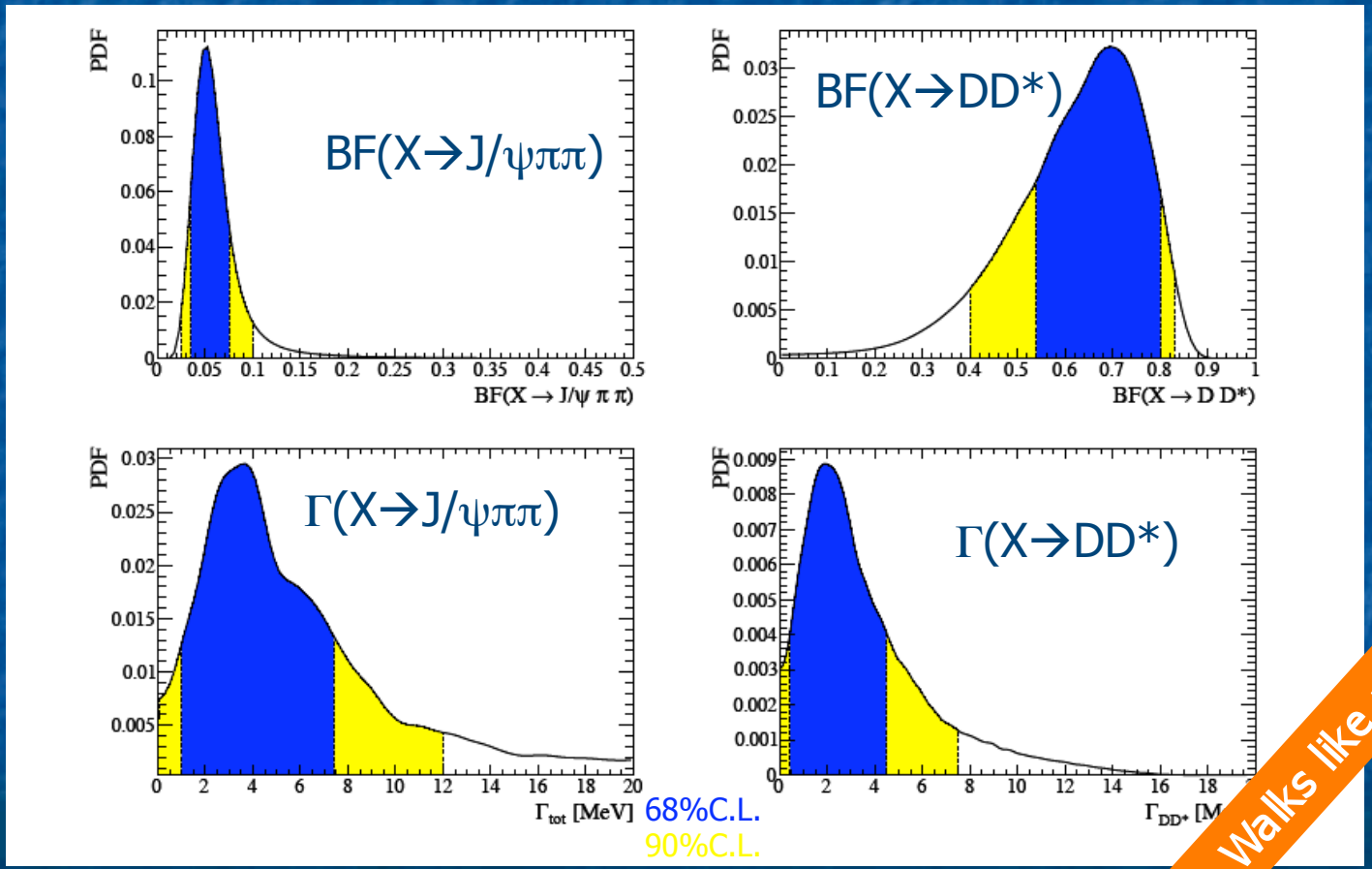




2. Measure quantum numbers

Work in progress
Drenska, RF, Piccinini, Polosa, Renga, Sabelli

Combined BF and widths



3. Walks like a duck(?)

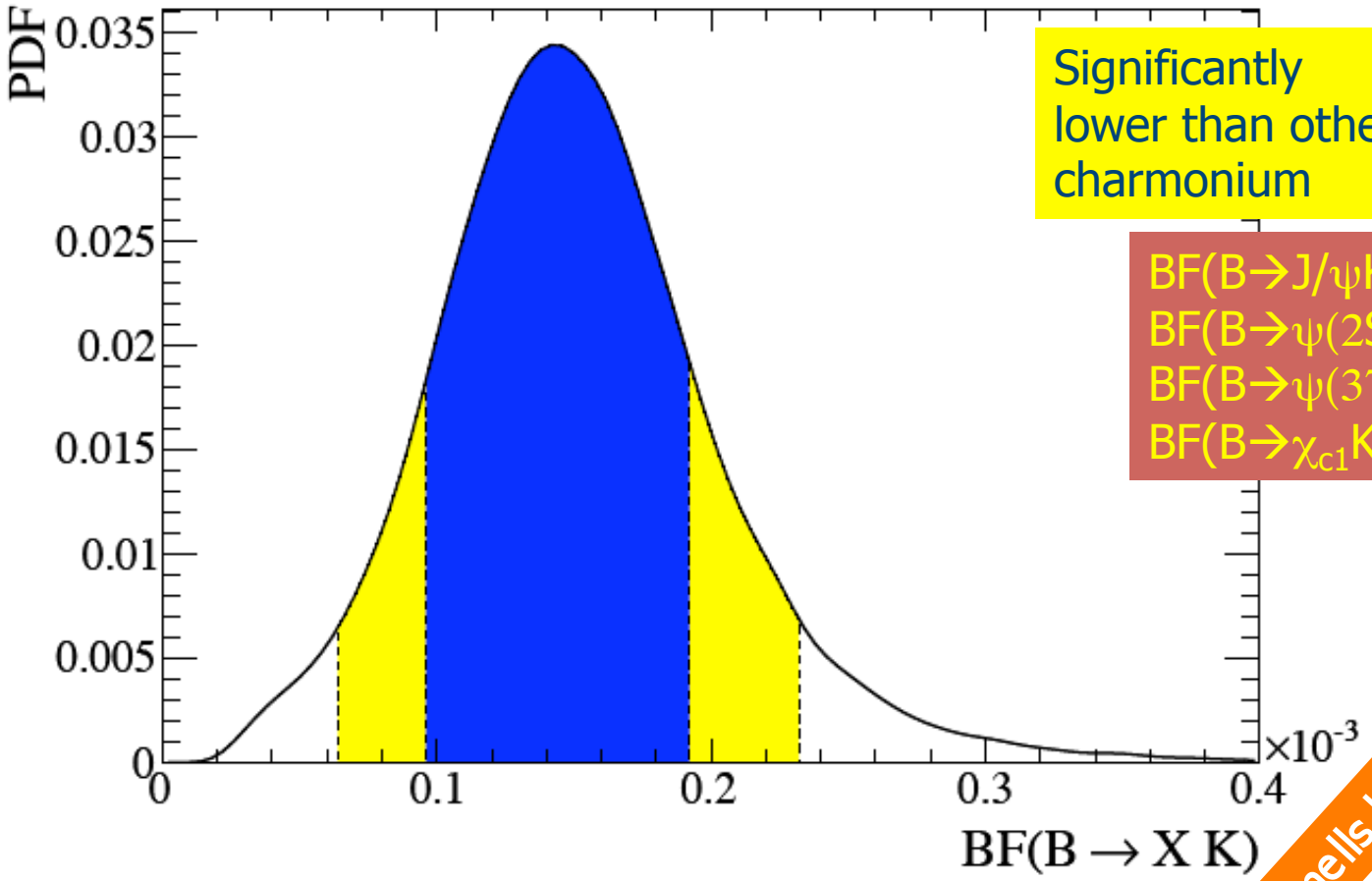
Large DD* BF and Γ : Prob(Γ(X→DD*)<Γ(D*)=0.7%

Test against molecular nature

Summary of BF

B Decay mode	X decay mode	B_{fit}	$B/B_{J/\psi\pi\pi}$
$XK^{\pm}$	$X \to J/\psi\pi\pi$	$[0.035, 0.075]$	N/A
XK^{0}	$X \to J/\psi\pi\pi$	–	N/A
$XK^{\pm}$	$X \to D^{*0}D^{0}$	$[0.54, 0.8]$	$[3.9, 18.9]$
XK^{0}	$X \to D^{*0}D^{0}$	–	–
XK	$X \to J/\psi\gamma$	$[0.0075, 0.0195]$	$[0.19, 0.32]$
XK	$X \to \psi(2S)\gamma$	$[0.03, 0.09]$	$[0.75, 1.55]$
XK	$X \to \gamma\gamma$	< 0.0004	< 0.0078
XK	$X \to J/\psi\eta$	< 0.098	< 1.9
XK	$X \to J/\psi\pi\pi\pi^{0}$	$[0.015, 0.08]$	$[0.45, 1.44]$

BF(B→XK)



Significantly lower than other charmonium

BF(B→J/ψK)=10^{-3}
BF(B→ψ(2S)K)=0.65 10^{-3}
BF(B→ψ(3770)K)=0.5 10^{-3}
BF(B→χ_{c1}K)=0.5 10^{-3}

3. Smells like a duck(?)

X(3872) mass in several final states

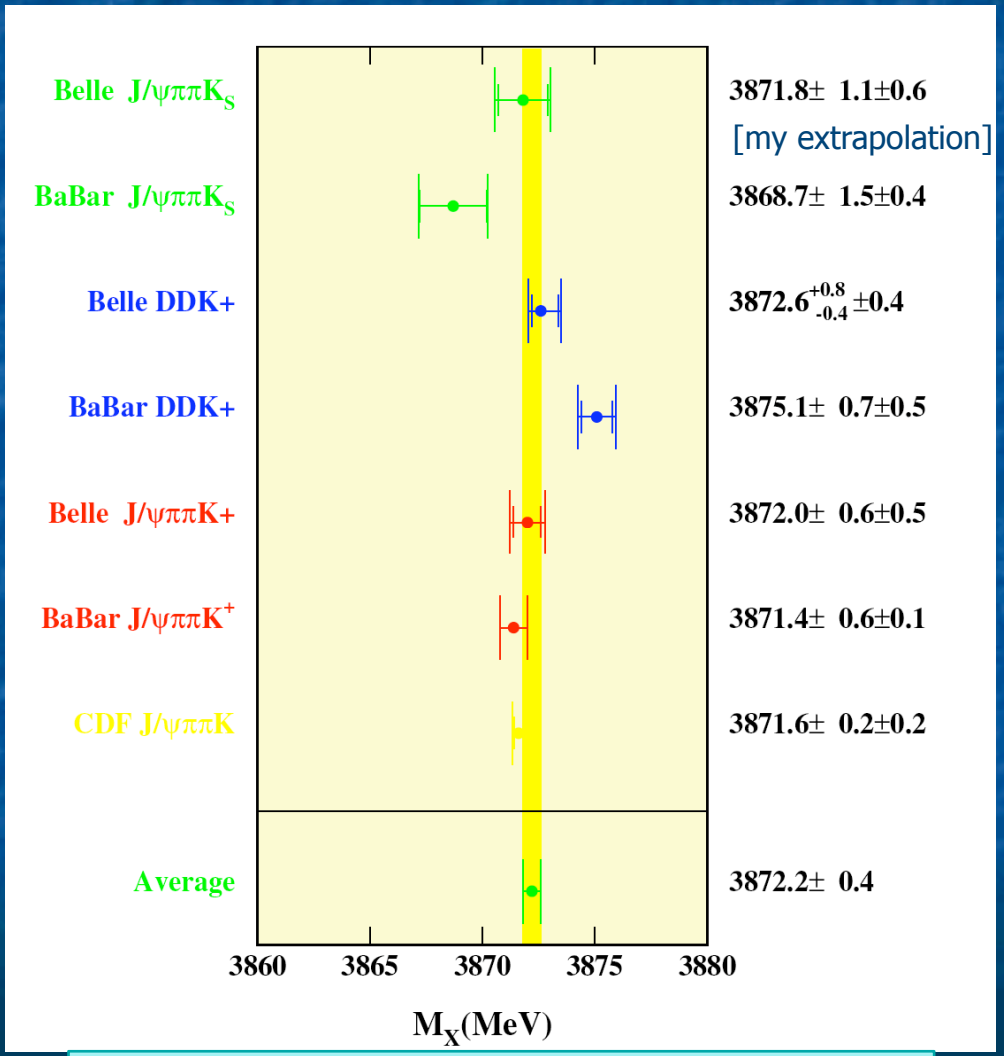
Poor agreement among mass measurements:

X→J/ψππ and X→DD(*) differ by ~3.5σ

TWO STATES? X(3872) & X(3876) ?

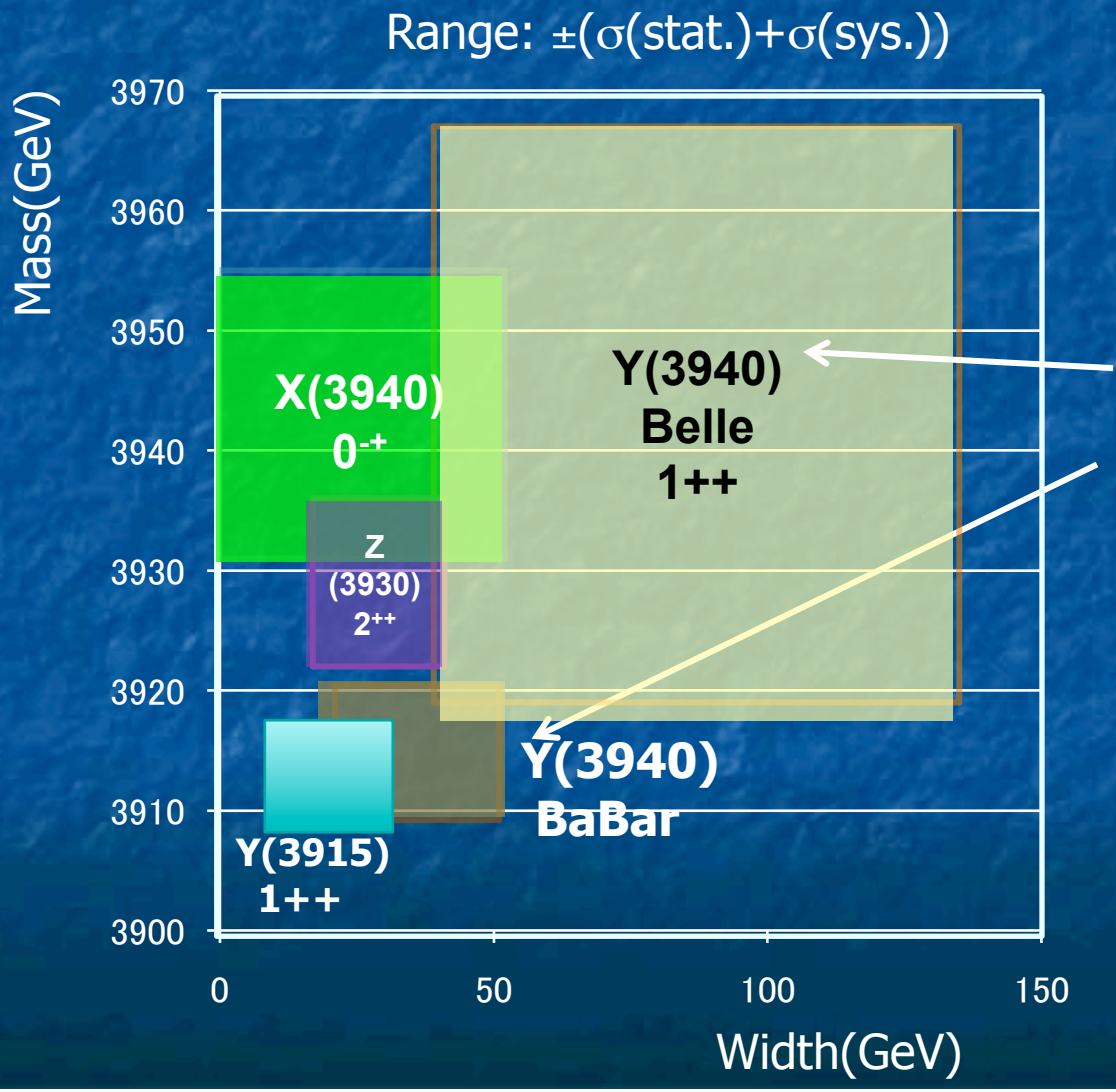
Predicted by tetraquark model
(but why so close to threshold?)

PRL 103:152001,2009
CDF inclusive J/ψππ
ΔM<3.2 MeV @90%C.L.



Issues with the fits for the DD* mode?

The 4 states near 3940

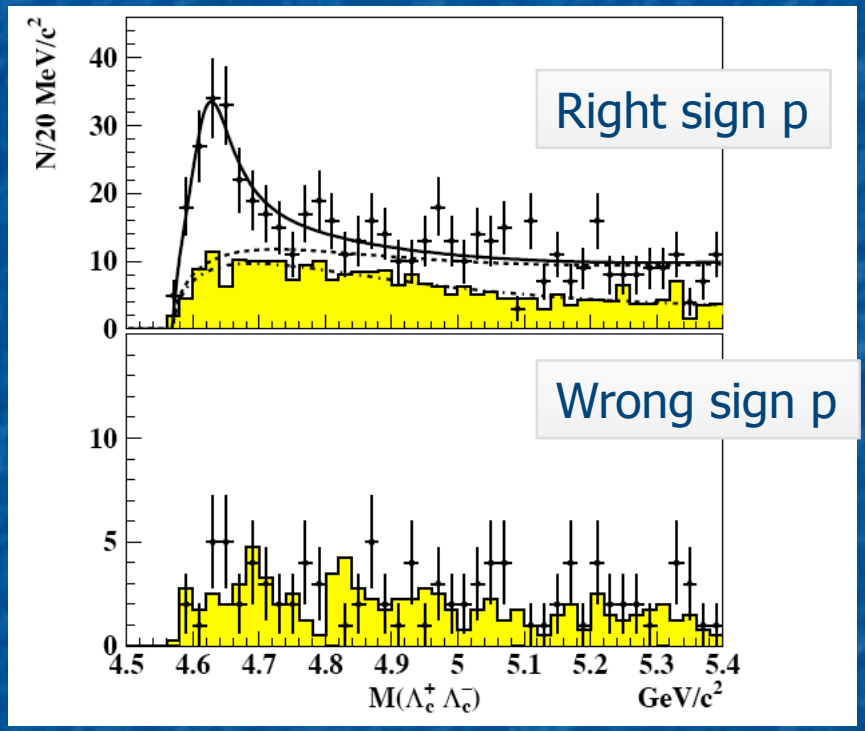


Better analysis of the J/ψ ω mass spectrum needed!!

PRL101,172001 (2008)

Y(4660)→$\Lambda_c\Lambda_c$

- Search for ISR e^+e^- → $\Lambda_c\Lambda_c\gamma$ events

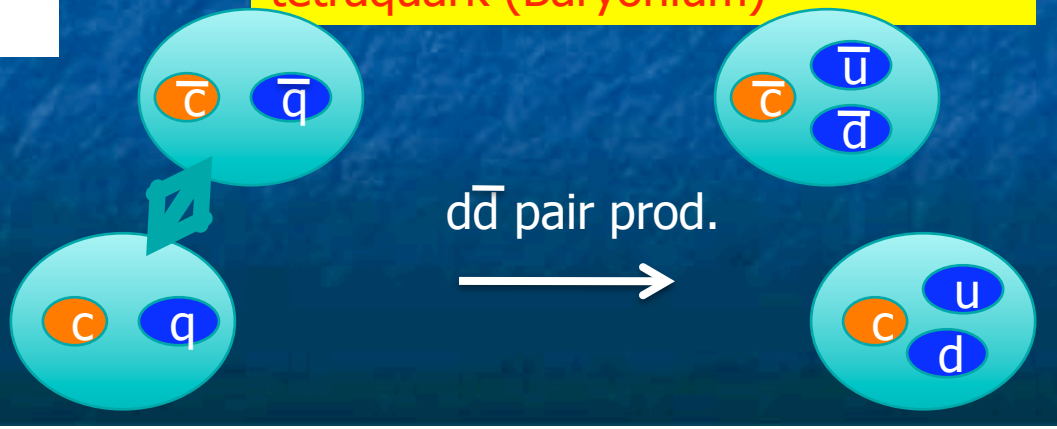


Example of global analysis

Cotugno, RF, Polosa, Sabelli
PRL104, 132005 (2010)
- simultaneous fit to $\psi(2S)\pi\pi$ and $\Lambda_c\Lambda_c$ modes has good χ^2
- M=4661±9 MeV Γ=61±23 MeV
- Large preference of the baryonic decay model!

$$\frac{\mathcal{B}(Y_B \to \Lambda_c\bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7$$

Y(4660) good candidate for a tetraquark (Baryonium)



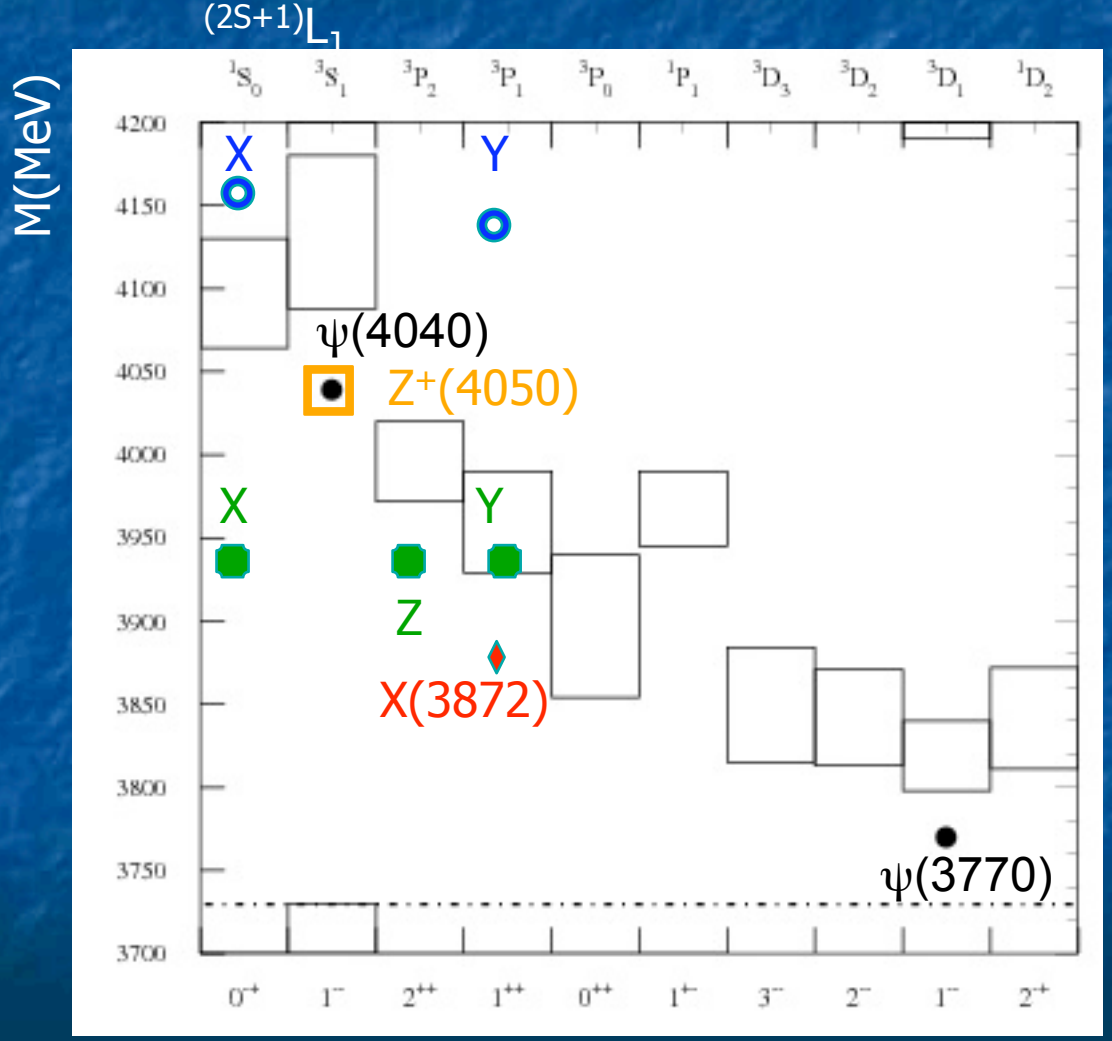
Summary (I)

ψ(4040) and Z±(4050) and isospin triplet?!?

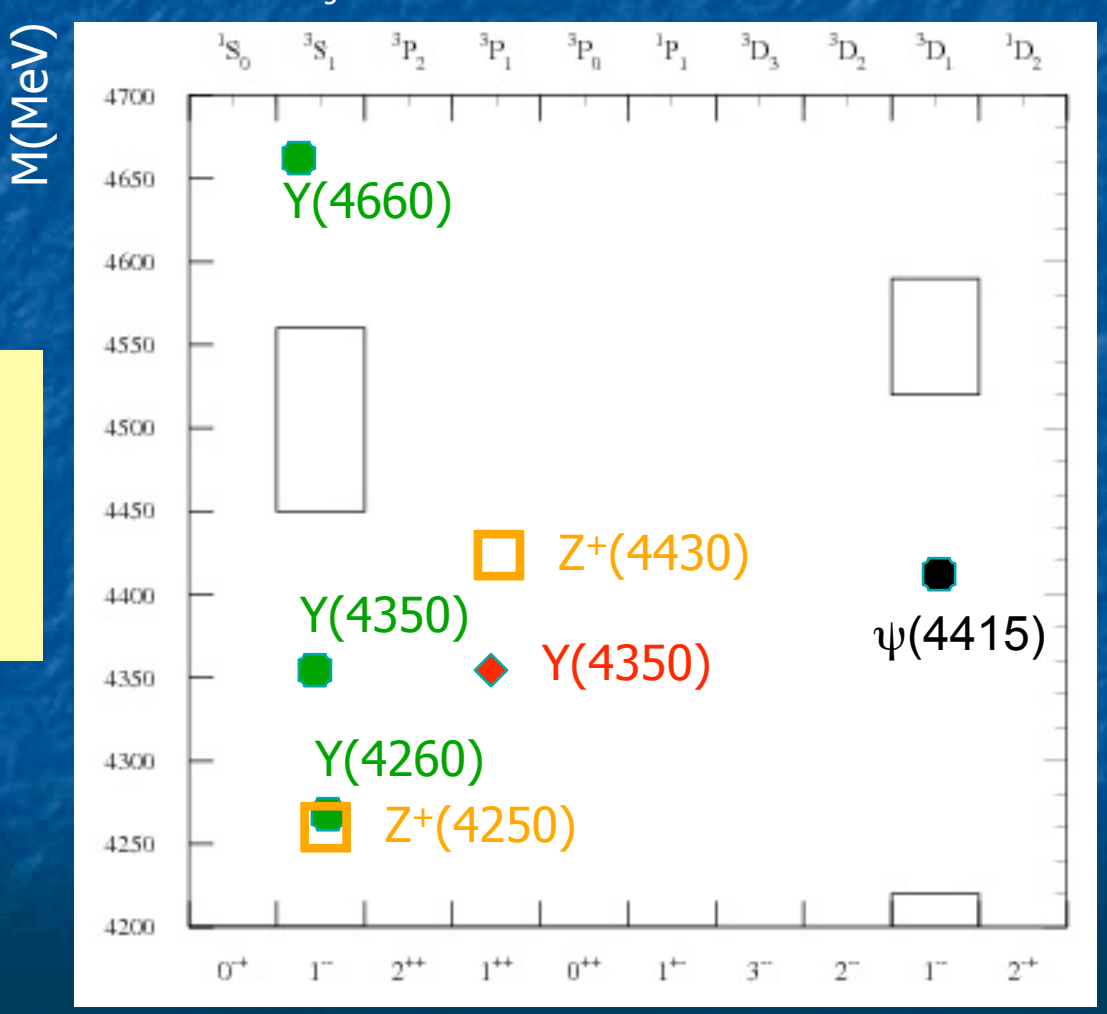
X(4160): candidate $\eta_c(3S)$
Y(4160): candidate hybrid

3940 family:
X candidate tetraquark
Y,Z candidate $\chi(2P)_{1,2}$

X: the most debated (tetraquark vs DD* molecule)



Summary (II)

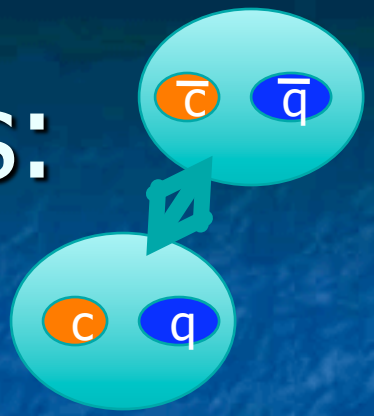


1^{--} family:
Y(4660) best tetraquark candidate
Y(4260) and Z±(4250) an isospin triplet?!?

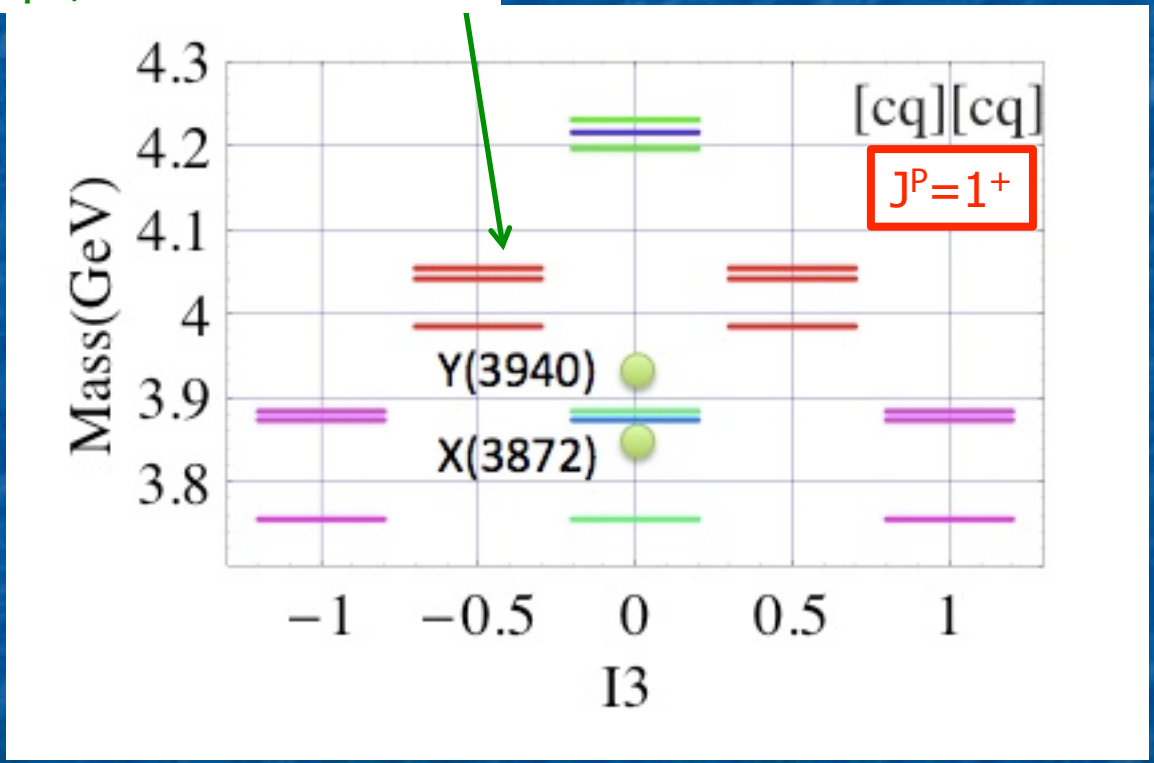
Towards a global picture

" 'tis a long way to go! "

Interpretative hazards: tetraquarks



States decaying into ψK, never looked for !



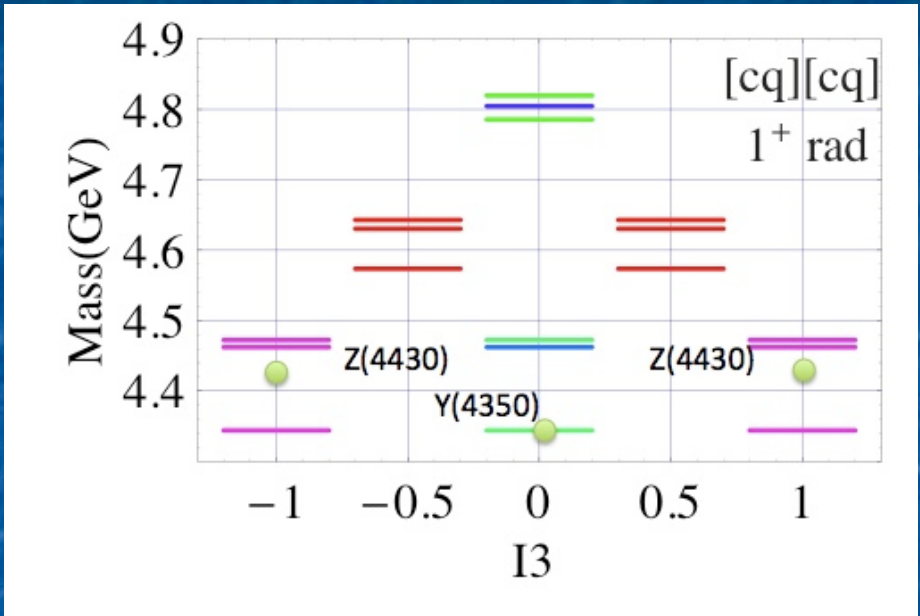
Spectra based on :

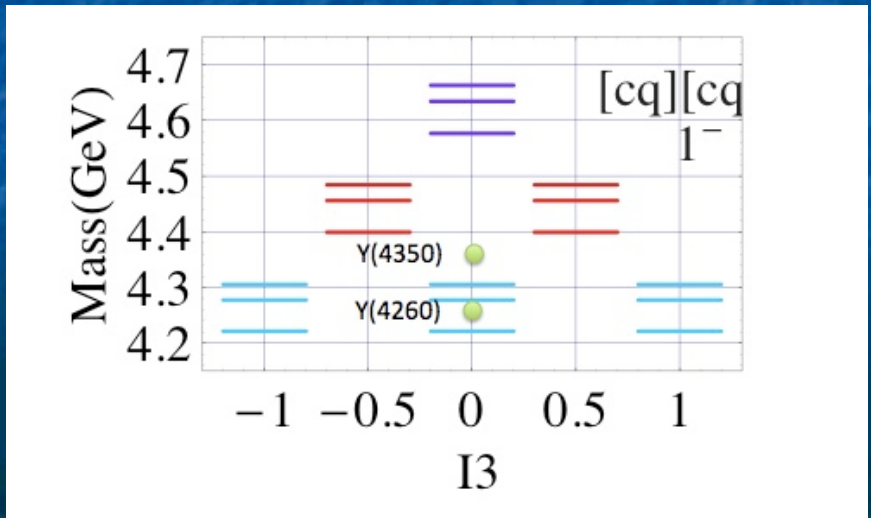
1. Quark constituent model (as in Maiani et al,
2. orbital excitations based on Chew-Frautschi as in hep-ph/0602128
3. radial excitations taken from standard charmonium

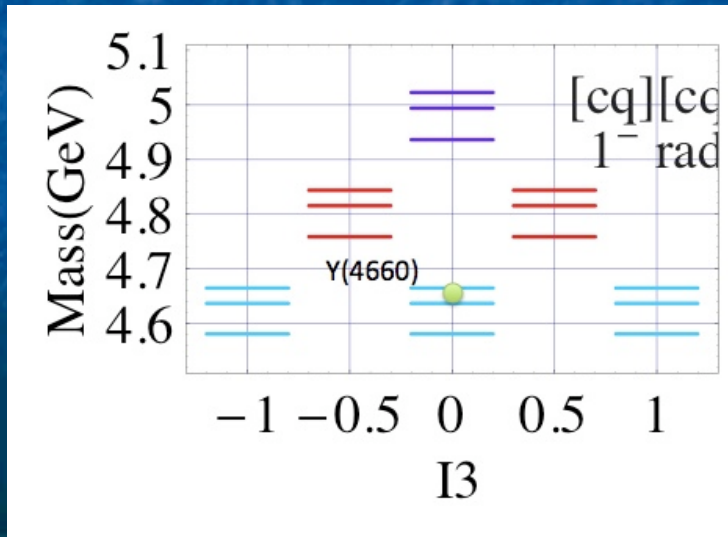
O(100 MeV) uncertainties

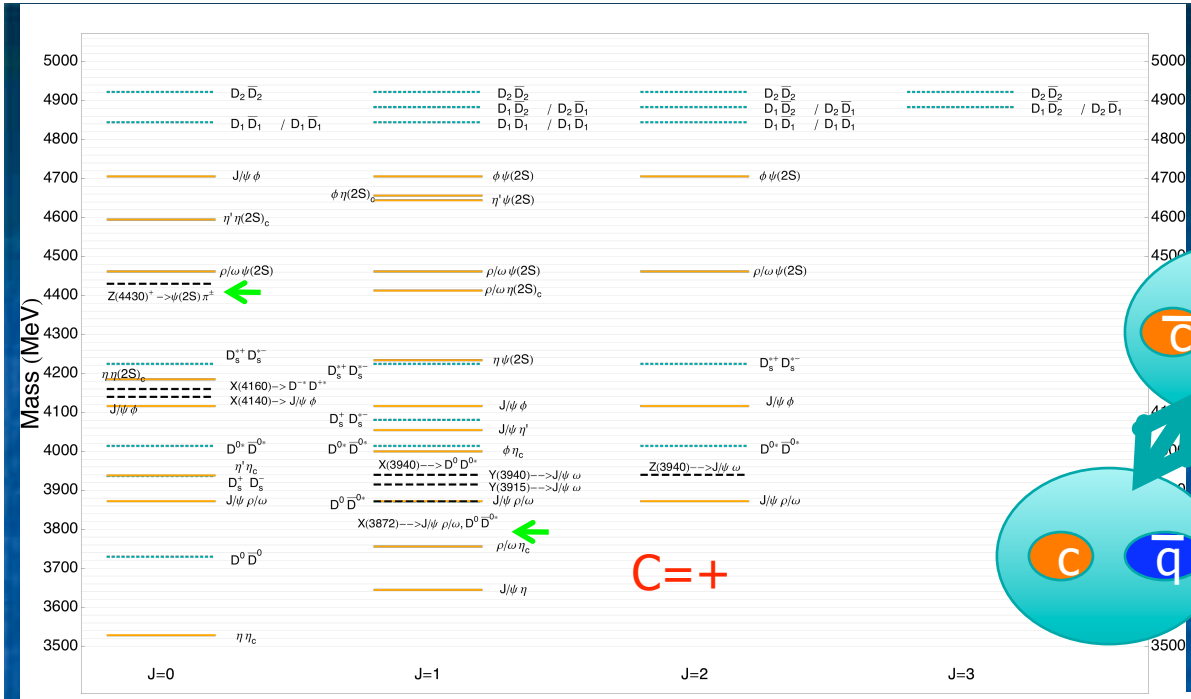
Work in progress
Drenska, RF, Piccinini, Polosa, Renga, Sabelli

More tetraquark spectra

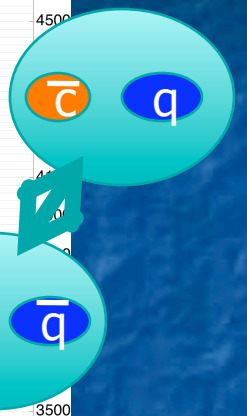








Interpretative hazards: molecules



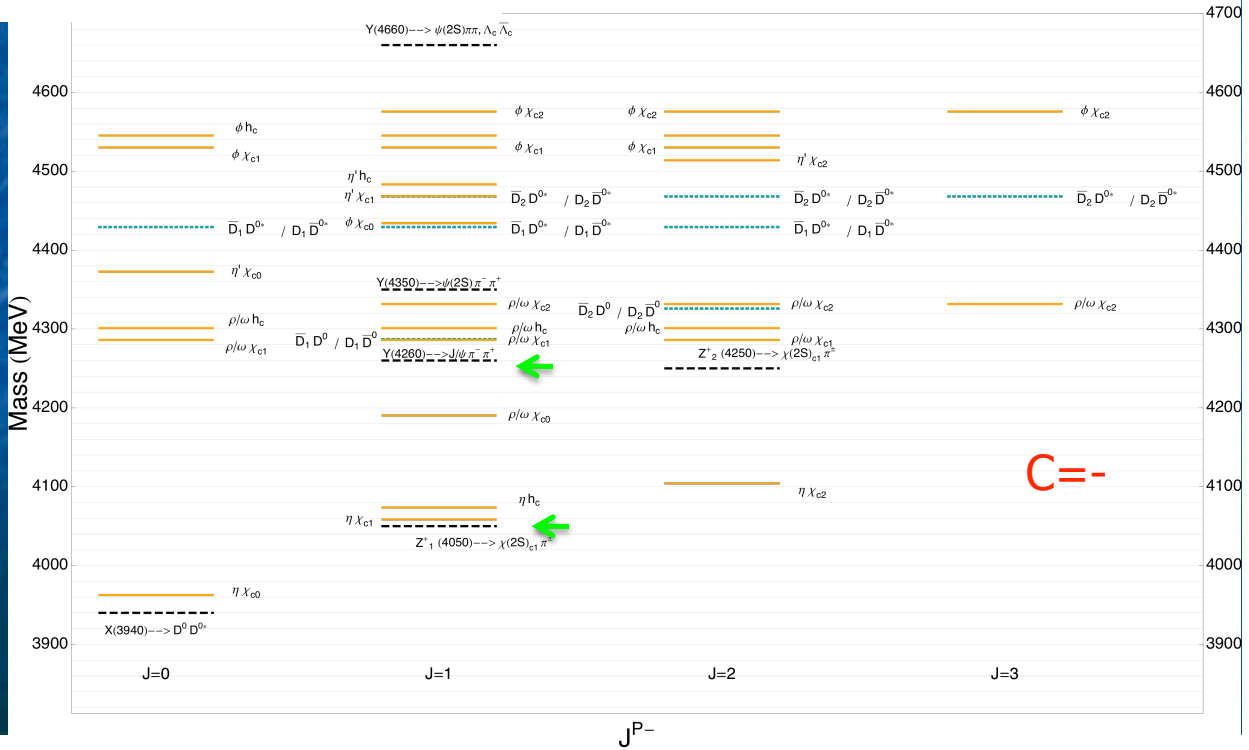
Legenda

------- charm – charm

_____ charmonium - light

- - - - - data

Interesting states: right below a threshold (→)



Outlook (I)

legenda

- S: seen
- M/F: missing fit
- N/S: not seen
- N: not searched
- N/A: not applicable
- N/F: not feasible

B decays	J/ψππ	J/ψω	J/ψγ	J/ψφ	J/ψη	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)	γγ
X(3872)	S	S	S	N/A	N/S	N/A	N/A	S	N/S	M/F	M/F	N/A	N/A	S	N/A	N/A	N/S
X,Y (3940)	M/F	S	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	N/S	N/A	N	N
Z(3940)	M/F	M/F	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	M/F	N/A	N	N
Y(4140)	M/F	M/F	N	S	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
X(4160)	M/F	M/F	N	M/F	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
Y(4260)	S	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
X(4350)	M/F	M/F	N	M/F	N/A	N	N	N	N/A	M/F	M/F	N/A	N	N	N	N	N
Y(4350)	M/F	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
Y(4660)	N	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	M/F	N	N	N	N	N/A

ISR	J/ψππ	ψ(2S)ππ	J/ψη	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*)Ds(*)
Y(4260)	S	N/S	N/S	N/S	N/S	M/F	N/A	N/S	N/S	N/S	N
Y(4350)	N/S	S	M/F	M/F	M/F	M/F	N/A	M/F	M/F	M/F	N
Y(4660)	N/S	S	M/F	M/F	M/F	M/F	S	M/F	M/F	M/F	N

J/Psi recoil	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*
X(3872)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
X,Y (3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	S	M/F	N/A
Z(3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
Y(4140)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	M/F
X(4160)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	S	M/F
X(4350)	N/F	N	N/F	N	N/F	N	N/F	N/F	N/F	N/F	N/F	M/F	M/F	M/F

γγ	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*) Ds(*)
X(3872)	N	N/F	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	M/F	N	N/A	N/A
X,Y (3940)	N	S	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S?^	N	N/A	N
Z(3940)	N	S?^	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S	N	N/A	N
Y(4140)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4160)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4350)	N	N	N/F	S	N	N	N/F	N	N	N	N	N	N	N

B decays	J/ψπ	J/ψππ0	ψ(2S)π	ψ(2S)ππ0	χcπ	DD	DD*	D*D*
Z+(3870)	M/F	N/S	M/F	N	M/F	N	N	N/A
Z+(3940)	M/F	N	M/F	N	M/F	N	N	N/A
Z+(4050)	M/F	N	M/F	N	S	N	N	M/F
Z+(4140)	M/F	N	M/F	N	M/F	N	N	M/F
Z+(4250)	M/F	N	M/F	N	S	N	N	M/F
Z+(4350)	M/F	N	M/F	N	M/F	N	N	M/F
Z+(4430)	N/S	N	S	N	M/F	N	N	M/F
Z+(4660)	M/F	N	M/F	N	M/F	N	N	M/F

Charged states

legenda

- S: seen
- M/F: missing fit
- N/S: not seen
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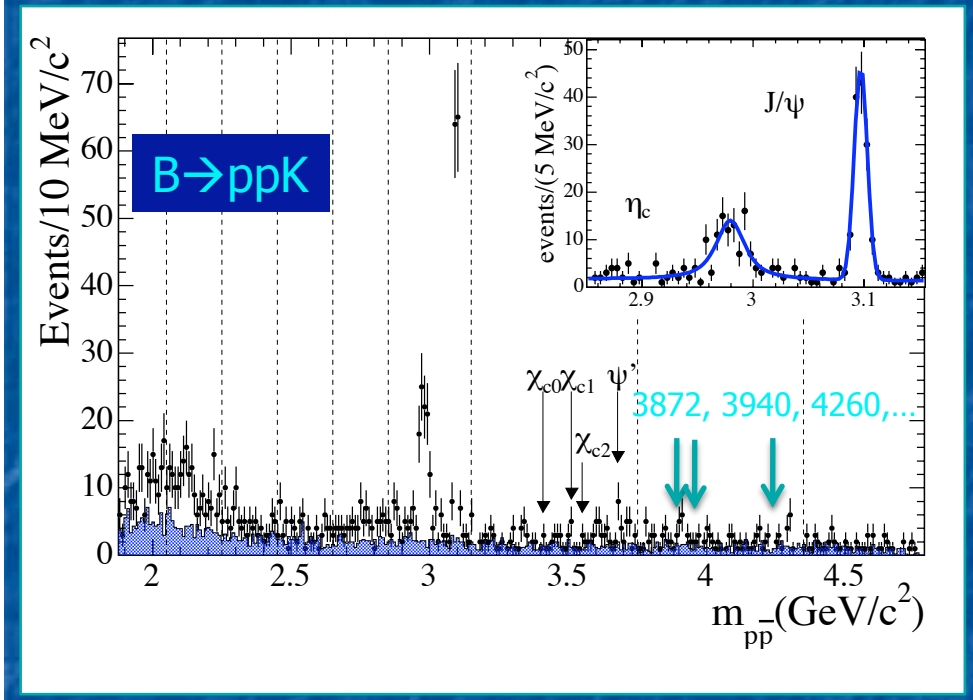
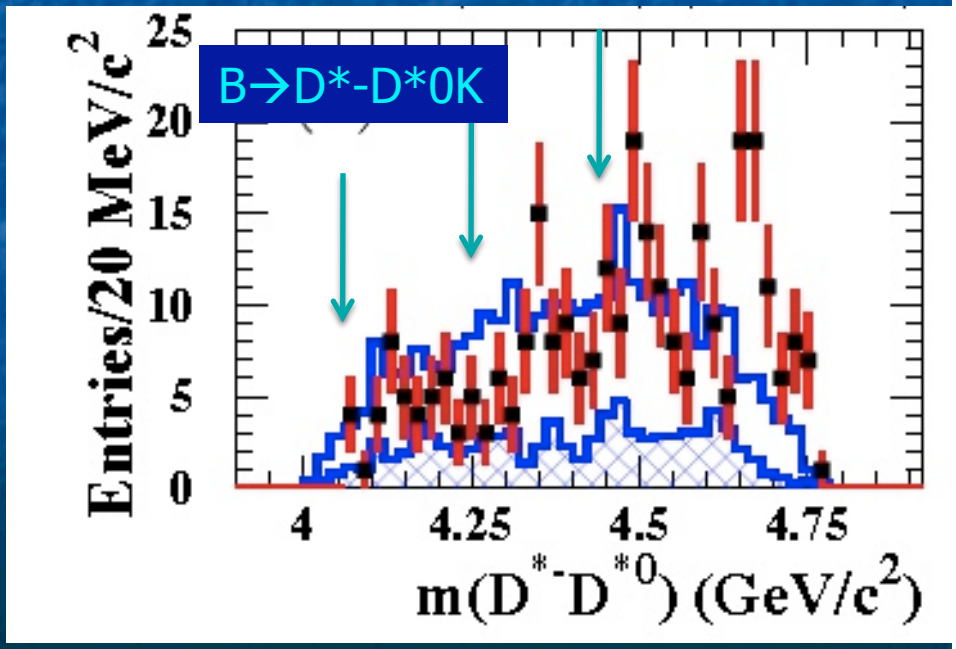
Example of missing Fits



4050, 4250, 4430



To Do (?)

- Systematic fit to invariant mass spectra with all expected states
- Systematic combination of experiments
- Room for missing analyses?
  - E.g. $B \rightarrow X\omega/\phi$ with $X \rightarrow J/\psi$ K, recoil to chi_c, analyses involving Ds partial reco?)
  - Is there manpower to make it worth making a list of modes?

Table of contents [#pages]

- Theory overview [5/8]
  - Four-quark states (tetraquarks and molecules)
  - Hybrids
- Determining particle properties:[3/5]
  - Mass and width
  - J^{CP}
- The X(3872) [5/8]
- The 3940 family [3/5]
- Other C=+ states [3/5]
- The $J^{CP}=1^{--}$ states [4/6]
- The charged states [4/6]
- Summary and global picture [3/5]

Exp results and main interpretations (?)

30/48 pages total
30 needs more work but might be nicer. Which best fits general scheme?

Interplay with other sections

- Assume that ISR, $\gamma\gamma$ and B reconstruction will be described in detail in corresponding sections (just refer to them in introduction of "measuring particle properties")