Carleton UNIVERSITY
Canada's Capital University

XYZ's and Charmonium Spectroscopy

Stephen Godfrey

Carleton University

(with T. Barnes, E. Eichten, H. Mahlke J. Rosner, E. Swanson)

General Comments

Charmonium spectroscopy has undergone a renaissance due to all the new experimental results

Many newly discovered states with puzzling properties

- What are they?
  - Conventional Quarkonia?
  - Hadronic Molecules?
  - Hybrids?
  - …….

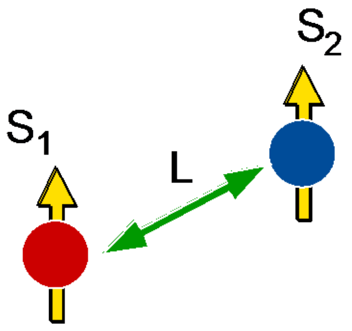
Need to measure their properties and compare to theoretical Predictions

Not all new states are exotics

Many have only been observed by one experiment and need confirmation

Conventional Mesons & Potential Models

Meson quantum numbers characterized by given J^{PC}:



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

Allowed:

$J^{PC} = 0^{-+}\ \ 1^{--}\ \ 1^{+-}\ \ 0^{++}\ \ 1^{++}\ \ 2^{++}$ …

Not allowed: exotic combinations:

$J^{PC} = 0^{--}\ \ 0^{+-}\ \ 1^{-+}\ \ 2^{+-}$ …

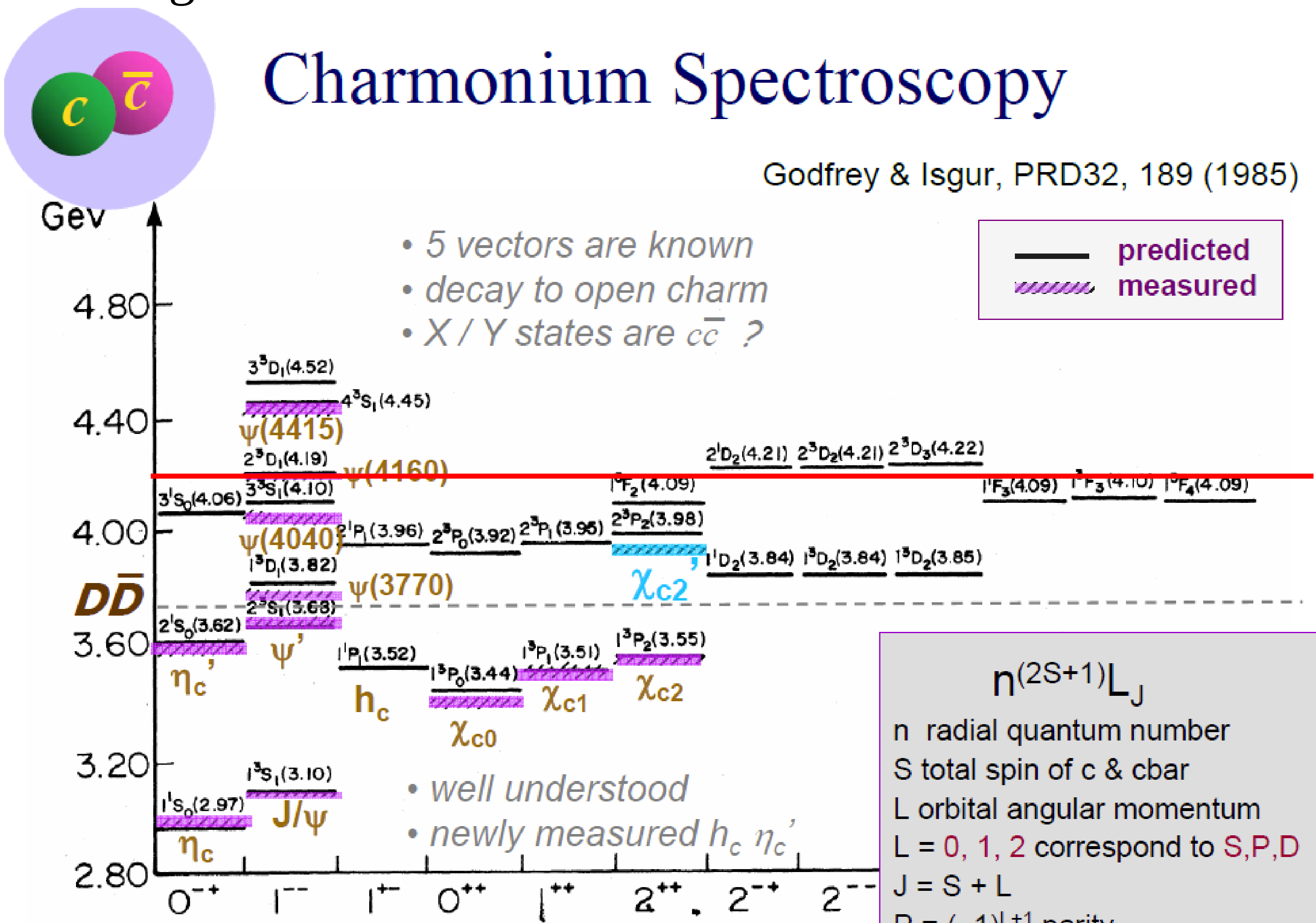
For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

Decays:

- Zweig allowed strong Decays: Well described by $^3P_0$ decay model
- Annihilation Decays
- Hadronic Transitions
- Electromagnetic Transitions: E1 & M1

Conventional Charmonium

Jingzhi Zhang PIC 2011 Vancouver



$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 correspond to S,P,D

J = S + L

P = $(-1)^{L+1}$ parity

C = $(-1)^{L+S}$ charge conj.

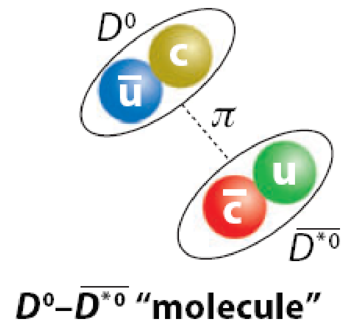
“Exotic States”

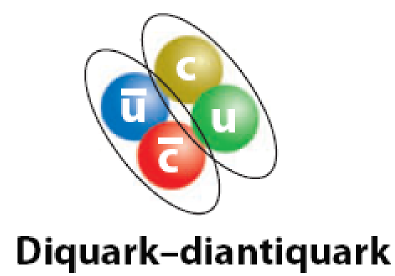
Hybrids

- States with excited gluonic degrees of freedom
- Distinctive decay modes

Multiquark States

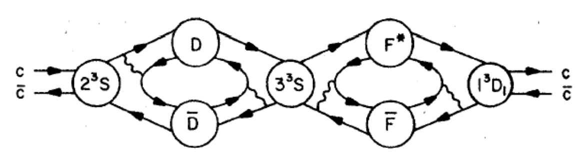
- Molecular state
  - -loosely bound pair of mesons near threshold
  - -Exhibit large isospin violations
- Tetraquarks
  - -tightly bound diquark-diantiquark states
  - -expect flavour multiplet of states



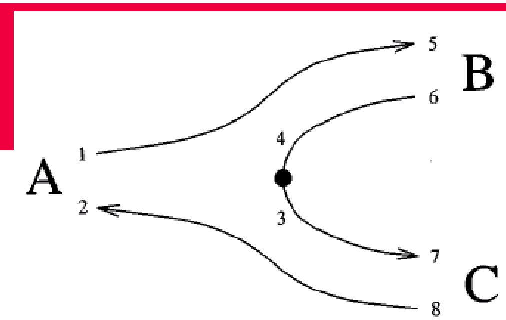


Threshold-effects

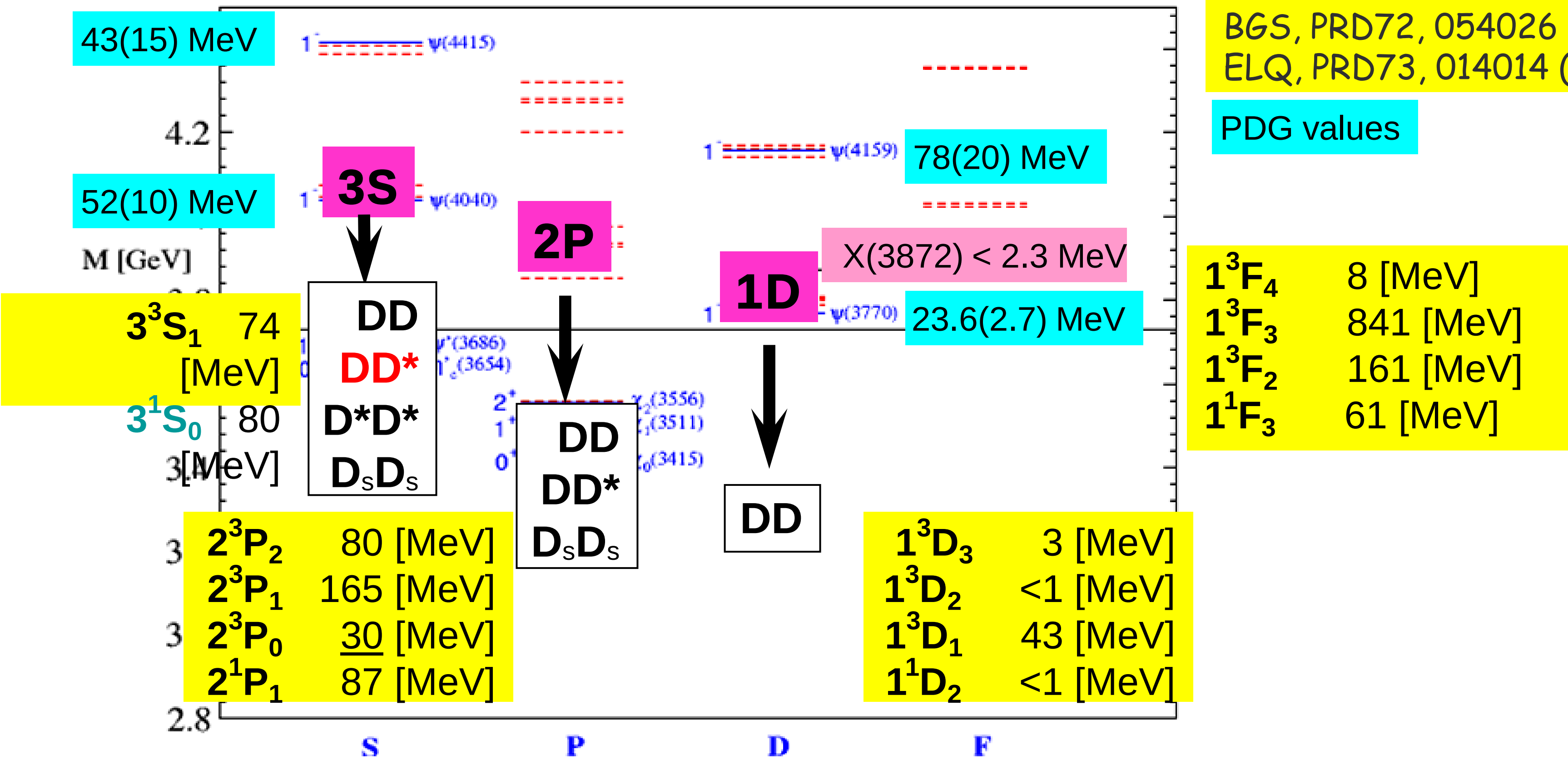
- Rescattering near threshold due to interactions between two outgoing mesons
- Mass shifts due to thresholds
- Coupled channel effects mixing 2-meson states with resonances



Strong Decays

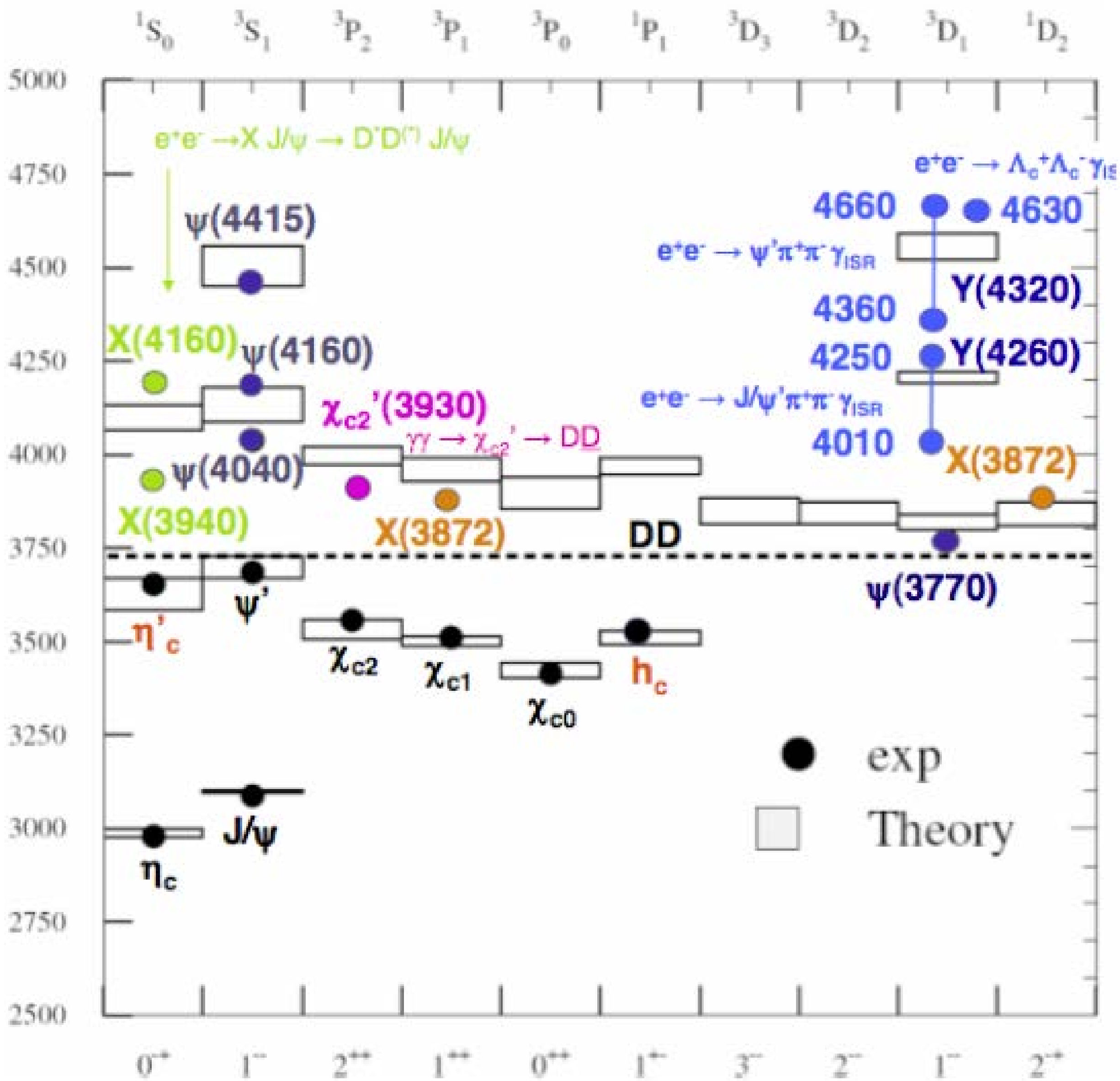


The $^3P_0$ decay model describes hadron decays reasonably well



Important to understand charmonium states to identify states that don't fit and might represent new spectroscopies

New Charmonium like "XYZ"states



M. Nielson
Charm2010

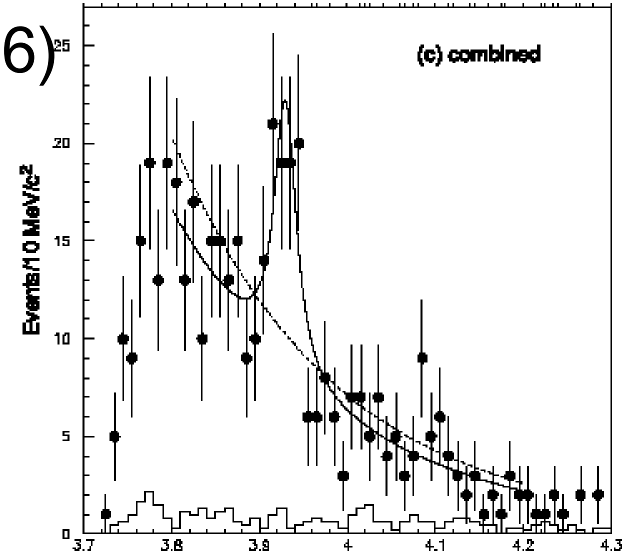
New Charmonium-like states – X, Y, Z's

Large number of charmonium-like states that are not understood

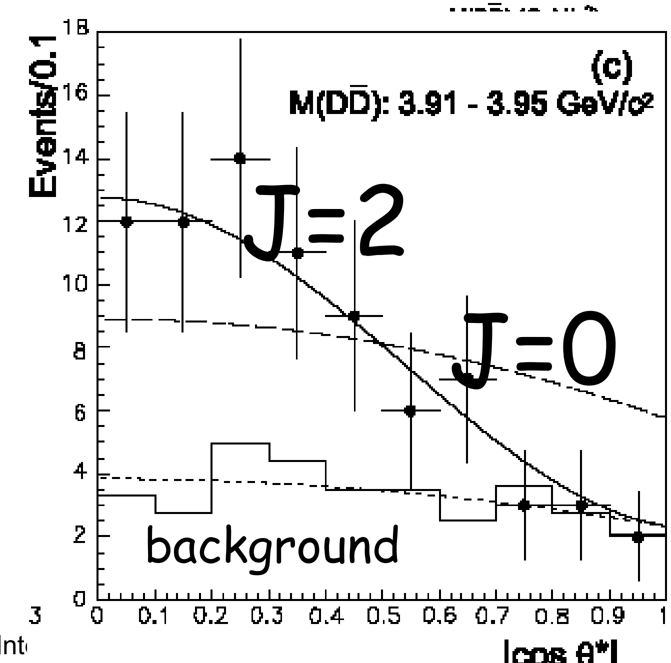
state	M (MeV)	Γ (MeV)	J^{PC}	Seen In	Observed by:	Comments
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$(e^+e^-)_{ISR}, J/\psi \to Y_s(2175) \to \phi f_0(980)$	BaBar, BESII, Belle	
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$B \to KX(3872) \to \pi^+\pi^- J/\psi, \gamma J/\psi, D\bar{D}^*$	Belle, CDF, D0, BaBar	Molecule?
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to DD$	Belle	$2^3P_2(c\bar{c})$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle	$3^1S_0(c\bar{c})$?
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar	$2^3P_1(c\bar{c})$?
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle	
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle	Hybrid?
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar, Belle	
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle	
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^\pm(4050) \to \pi^\pm \chi_{c1}$	Belle	
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^\pm(4250) \to \pi^\pm \chi_{c1}$	Belle	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^\pm(4430) \to \pi^\pm \psi'$	Belle	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^- \Upsilon(1,2,3S)$	Belle	

Z(3930)

Belle:Phys Rev Lett 96, 082003(2006)
BaBar: PRD 81, 092003



- Observed by Belle in $\gamma\gamma \to DD$
  - $M = 3929 \pm 5 \pm 2$ MeV
  - $\Gamma = 29 \pm 10 \pm 2$ MeV
- Two photon width:
  - $\Gamma_{\gamma\gamma} \bullet B_{DD} = 0.18 \pm 0.05 \pm 0.03$ keV
- DD angular distribution consistent with J=2
- Below $D^* D^*$ threshold



Z(3930)

- Obvious candidate for χ'_{c2} (the χ'_{c1} cannot decay to DD)

  Predicted χ'_{c2} mass is 3972

  $\Gamma(\chi'_{c2} \to DD)$= 21.5 MeV

  $\Gamma(\chi'_{c2} \to DD^*)$= 7.1 MeV

  Γ=47 MeV assuming $M(\chi'_{c2})$=3931

- In reasonable agreement with experiment

- Predicted $BR(\chi'_{c2} \to DD)$=70% $\Rightarrow \Gamma_{\gamma\gamma} * B_{DD} = 0.47$ keV

- Observed two-photon width about 1/2 predicted value for χ'_{c2}

  ($\Gamma_{\gamma\gamma}$ from T.Barnes, IXth Intl. Conf. on $\gamma\gamma$ Collisions, La Jolla, 1992.)

Z(3930)

- Can confirm χ'_{c2} by searching for DD^*

  χ'_{c0} only decays to DD

  χ'_{c2} decays to DD and DD^* in ratio of $DD^*/DD \sim 1/3$

- Largest radiative transition is

  BGS, PRD72, 054026 (2005)

  $\Gamma(\chi'_{c2} \to \gamma\,\psi')\sim 200$ keV vs $\Gamma(\chi'_{c0} \to \gamma\,\psi')\sim 130$ keV

(ELQ find decays are suppressed due to coupled channel effects PRD73 014014(2006))

X(3940)

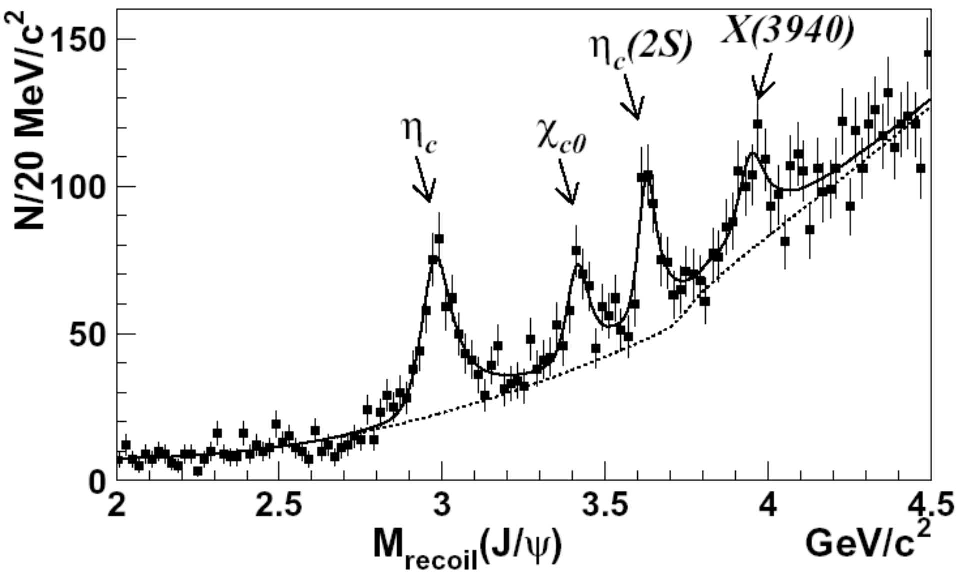
Seen by Belle in $e^+e^- \to J/\psi\, DD^*$ (recoiling against J/ψ)

PRL 98, 082001(2007).
PRL 100, 202001(2008)

$M=3943 \pm 6 \pm 6$ MeV
$\Gamma < 52$ MeV

$BR(X \to DD^*)=96^{+45}_{-32} \pm 22\%$

$BR(X \to DD) < 41\%$ (90% CL)



Decay to DD^* but not DD suggests unnatural parity state

- Belle speculates that X is 3^1S_0 given the 3^3S_1 $\psi(4040)$
    - Mass is roughly correct
    - . η_c and η_c' are also produced in double charm production

X(3940)

- Predicted width for 3^1S_0 with M=3943 ~ 50 MeV close to Γ(X(3943)) upper bound

See also Eichten Lane Quigg PRD73 014014(2006)

- Identification of ψ(4040) as 3^3S_1 state implies hyperfine splitting 88 MeV with X(3943)

- Larger than the 2S splitting and larger than predicted in potential models

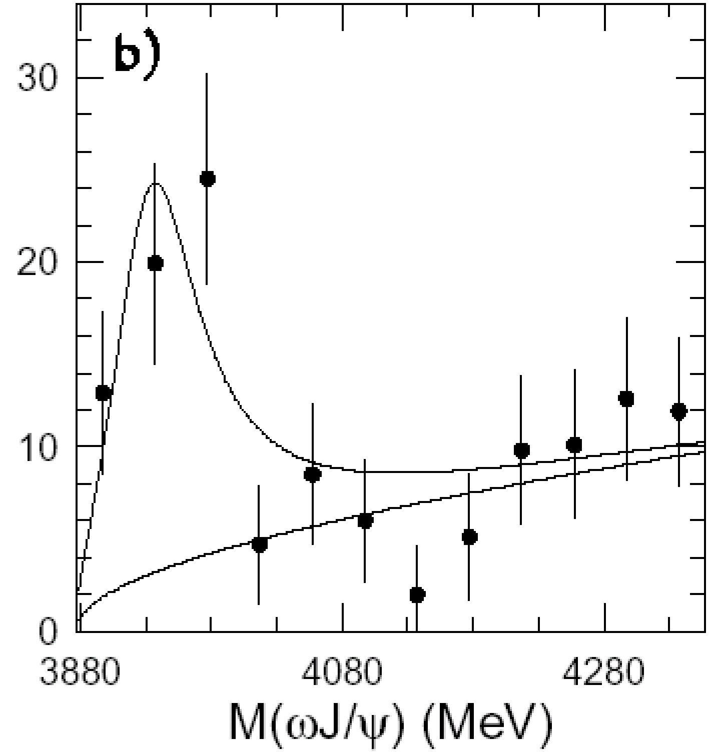
- Discrepancy could be due to:
  - Difficulty in fitting true pole position of 3^3S_1 state
  - Nearby thresholds with s-wave + p-wave charm mesons so possibly stronger threshold effects

- Test of 3^1S_0 η_c assignment is search for this state in $\gamma\gamma \rightarrow DD^*$

Y(3940)

See in $\omega J/\psi$ subsystem of the decay $B \to K \pi\pi\pi J/\psi$

Belle: Phys. Rev. Lett. 94, 182002 (2005)



$M = 3943 \pm 11 \pm 13$ MeV
$\Gamma = 87 \pm 22 \pm 26$ MeV
Not seen in $Y \to DD$ or DD^*

Mass and width suggest radially excited P-wave charmonium

But $\omega J/\psi$ decay mode is peculiar:
$BR(B \to KY) \bullet BR(Y \to \omega J/\psi) = 7.1 \pm 1.3 \pm 3.1 \bullet 10^{-5}$
where one expects $BR(B \to K\chi'_{cJ}) < BR(B \to K\chi_{cJ}) = 4 \bullet 10^{-4}$
Implies $BR(Y \to \omega J/\psi) > 12\%$ which is unusual for state above open charm threshold

Y(3940)

- Large width to $\omega J/\psi$ led Belle to suggest Y(3943) might be hybrid
- But mass is 500 MeV below LGT estimates making hybrid assignment unlikely

- Possibility is 2^3P_1 cc state: identifies Y(3943) as 2P χ'_{c1}
    - DD^* is the dominant decay mode
    - Width consistent with Y(3943): Γ=135 MeV
    - . χ_{c1} is seen in B decays

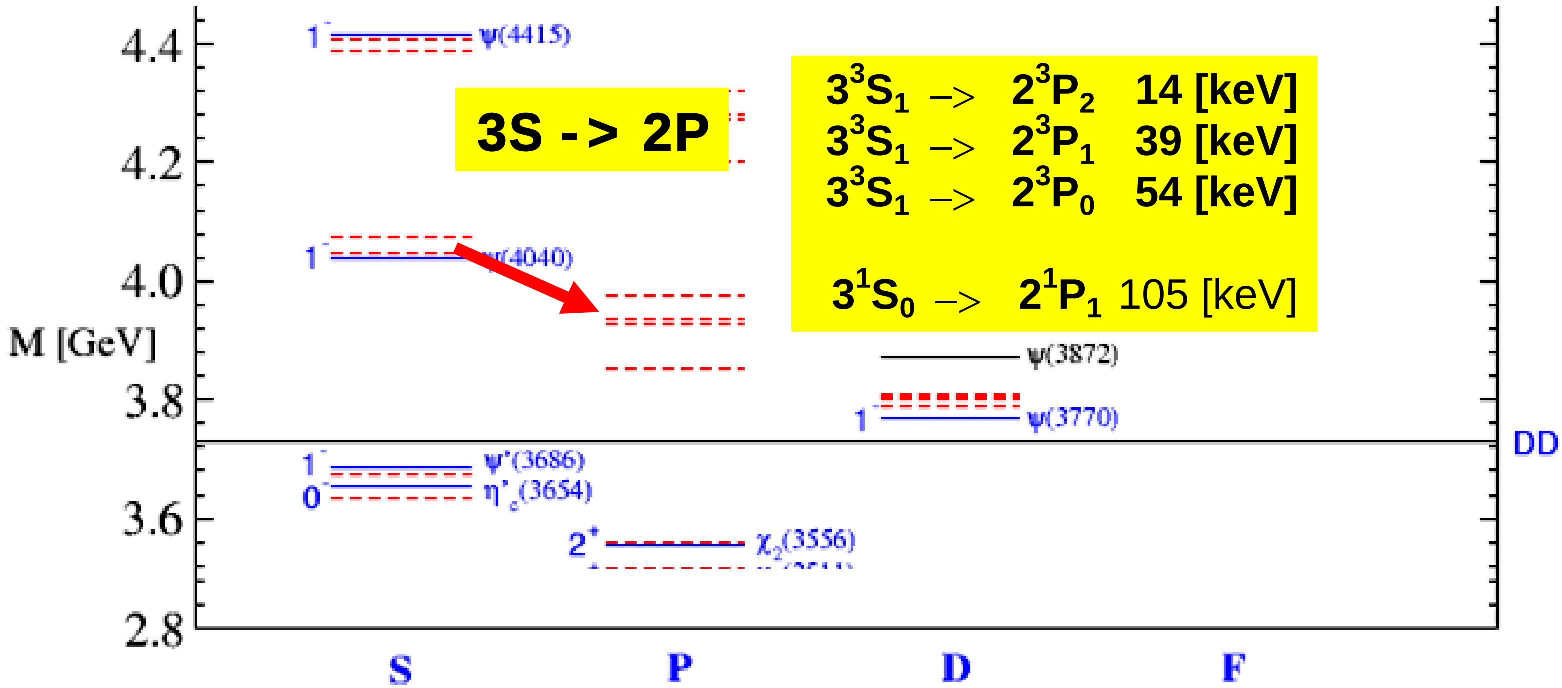
- $1^{++} \rightarrow \omega J/\psi$ is unusual
    - but corresponding $\chi'_{b1,2} \rightarrow \omega\Upsilon(1S)$ also seen
    - Maybe rescattering: $1^{++} \rightarrow DD^* \rightarrow \omega J/\psi$
    - Maybe due to mixing with 1^{++} molecular state X(3872)?
- Important to - look for DD and DD*
  - study angular distributions to DD and DD*

Could further study 2^3P_J states via radiative transitions:

- Can *find* all three $^3 2P_J$ $c\bar{c}$ states using

$$\psi(4040) \text{ and } \psi(4160) \to \gamma DD, \gamma DD^*$$

- All three E1 rad BFs of the $\psi(4040)$ are ~$0.5 * 10^{-3}$.
- These would further test whether the *Z,X,Y (3.9)* are 2P cc



X(3872)

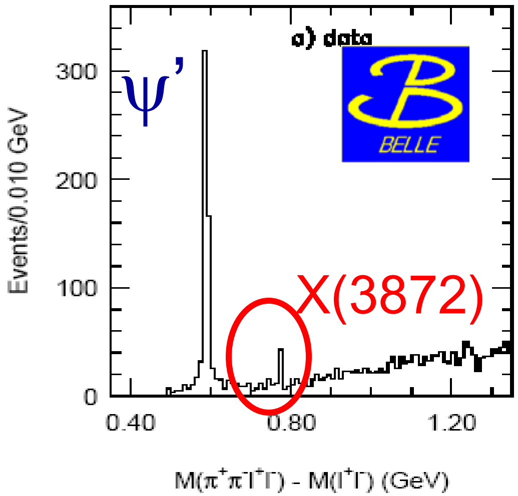
First observed by Belle PRL 91, 262001(2003)

Confirmed by:

CDF PRL 93, 072001 (2004)

D0 PRL 93, 162002 (2004)

BABAR PR D71, 071103 (2005)



M=3871.67 ± 0.17 MeV

$\Gamma < 1.2$ MeV at 90% C.L. consistent with detector resolution.

- $X(3872) \to \gamma J/\psi$ implies C=+ Belle [hep-ex/0505037]
  BaBar PR D74, 071101 (2006)

Angular distributions favour $J^{PC}=1^{++}$ Belle [hep-ex/0505038]

Higher statistics by CDF allow $J^{PC}=1^{++}$ or 2^{-+} PRL 98, 132002 (2007)

Babar in $X(3872) \to J/\psi\, \omega$ favours $J^{PC} = 2^{-+}$ PRD 82, 011101

- $X(3872) \to D^0 \bar{D}^0 \pi^0$ seen [Belle PRL 97, 162002 (2006)]
- $X(3872) \to D^0 \bar{D}^0 \gamma$ seen [BaBar PR D77, 011102R (2008)]
- Implies decays predominantly to $D^0 \bar{D}^{*0}$

X(3872)

Conventional Charmonium

Barnes, Godfrey, PR D69, 050400 (2004)
Eichten, Lane, Quigg, PR D69, 094019 (2004)
Barnes, Godfrey, Swanson, PR D 054026 (2005)

- Consider all 1D and 2P cc possibilities
- Assume M=3872 MeV
  - calculate radiative widths and
  - strong decay widths

- 1^1D_2 or 2^3P_1 only possible conventional states with correct quantum numbers close enough in mass
- But identification of Z(3931) with 2^3P_2 implies 2P mass ~ 3940 MeV
- Expect 1^1D_2 to be narrow because can't decay to DD due to parity and below DD^* threshold
- mass higher than predictions: $M(1^1D_2)$=3837 MeV
- $X(3872) \to \gamma J/\psi, \gamma\psi'$ disfavours 1^1D_2

X(3872)

$D^0 D^{*0}$ molecule

Close, Page PLB 578, 119 (2004)
Voloshin PLB 579, 316(2004)
Swanson PLB 588, 189(2004)
Braaten Kusunoki PR D72 054022(2005

- Close to $D^0 D^{*0}$ threshold so might be S-wave $D^0 D^{*0}$ bound state "molecule"

$$X(3872) \to \rho J/\psi \sim X(3872) \to \omega J/\psi$$

So large isospin violation indicative of molecule

But decays $X(3872) \to \gamma J/\psi$ & $X(3872) \to \gamma \psi'$ implies ccbar content

BaBar: PRL 102,132001(2009)

Probably mixing with χ'_{c1} explains both X(3872) and Y(3940) properties as admixtures of molecule and 2^3P_1 states

Danilin & Simonov, 0907.1088; SG hep-ph/0605152;
Ortega et al, 0907.3997, Matheus et al 0907.2683

Y states in ISR: What are they?

- Conventional states?
  - Don't match the peaks in $D^{(*)}D^{(*)}$ cross-sections
  - No room unless predictions way off
- Are Y states threshold effects?
  - Opening up of channels
  - Coupled-channel effects
  - rescattering of charmed meson pairs could shift masses, cause binding and account for observed spectrum

Voloshin hep-ph/0602233; Close & Downum, PRL 102, 242003(2009); Danilin & Simonov, 0907.1088; van Beveren & Rupp 0904.4351

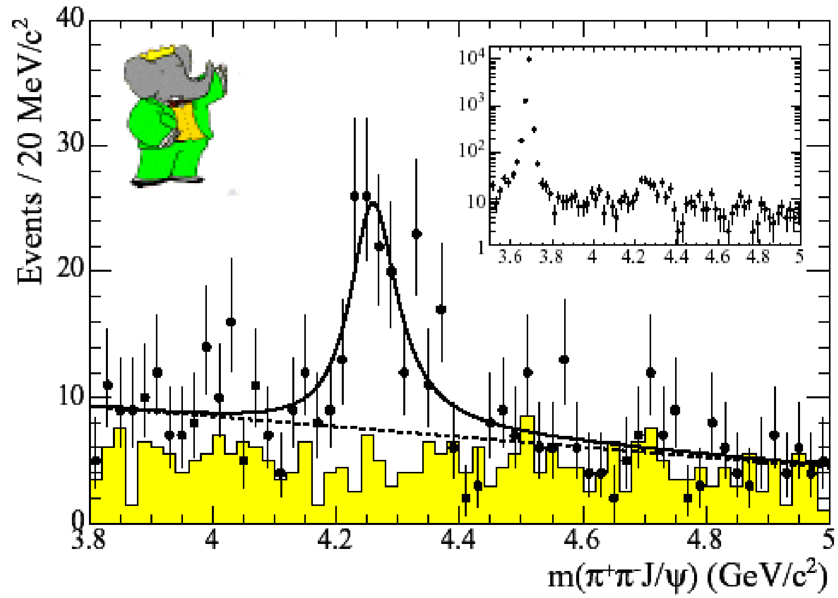
- Charmonium hybrids
- Multiquark states

Most need to be confirmed

The Y(4260) is the most robust and might be hybrid

Y(4260)

Discovered by Babar as enhancement in $\pi\pi\ J/\psi$ subsystem in $e^+e^- \to \gamma_{ISR}\ \psi\pi\pi$ PRL 95, 142001(2005)



$M=4259 \pm 8 \pm 4$ MeV

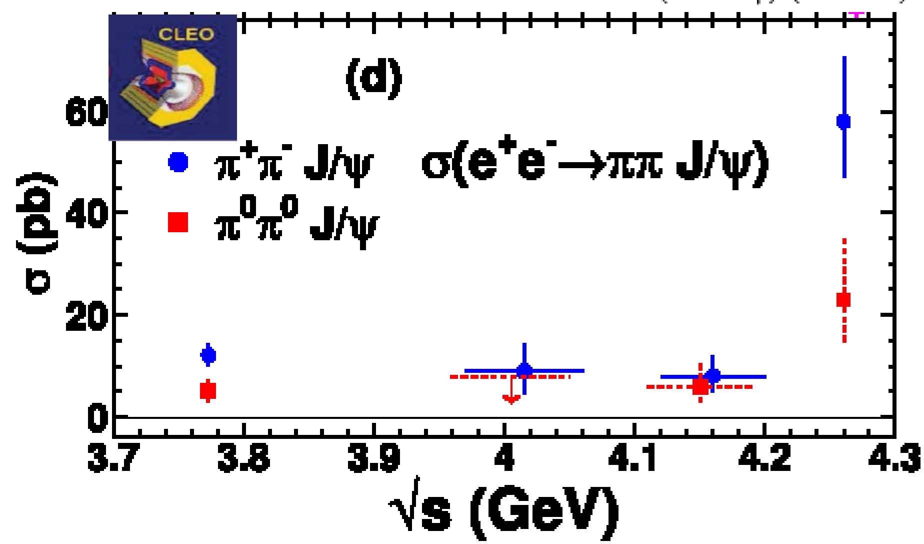
$\Gamma = 88 \pm 23 \pm 5$ MeV

$\Gamma_{ee} \times BR(Y \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.0 \pm 0.8$ eV

ISR production tells us $J^{PC}=1^{--}$

Further evidence in

$B \to K(\pi^+\pi^- J/\psi)$ PR D73, 011101(2006)



Confirmed by

CLEO PRL 96, 162003 (2006)

Belle PRL 99, 182004 (2007)

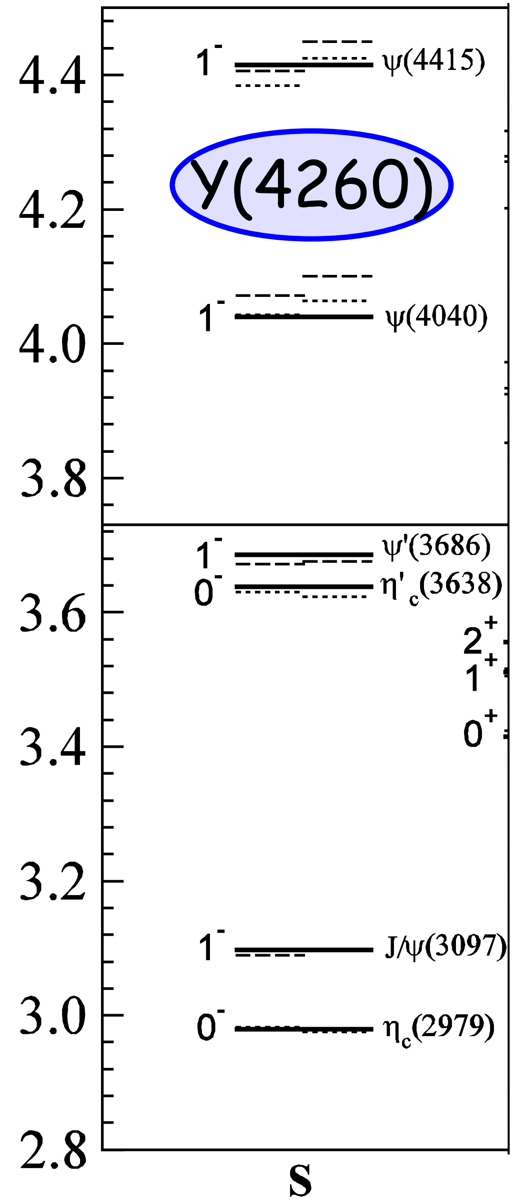
Y(4260)

Conventional Charmonium:

- The first unaccounted 1^{--} state is the $\psi(3D)$
- Quark models estimate $M(\psi(3D))$~4500 MeV much too heavy for the Y(4260)
- Y(4260) represents an overpopulation of expected 1^{-} states
- Absence of open charm production also against conventional cc state

Other explanations are:

- . $\psi(4S)$ Phys Rev D72, 031503 (2005)
- Tetraquark Phys Rev D72, 031502 (2005)
- D_1D^* Bound state PRL 102, 242003
- cc hybrid Phys Lett B625, 212 (2005); Phys Lett B628, 215 (2005) Phys Lett B631, 164 (2005)



Y(4260): Hybrid?

- Flux tube model predicts lowest $c\bar{c}$ hybrid at 4200 MeV
- LGT expects lowest $c\bar{c}$ hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]

  - LGT study suggest searching for other closed charm modes with $J^{PC}=1^{--}$ $J/\psi\eta,\ J/\psi\eta',\ \chi_J\omega\ldots$
  - The dominant decay mode expected to be $D+D_1(2420)$
    $D_1(2420)$ has width ~300 MeV and decays to $D^*\pi$
    - **Suggests search for Y(4260) in $DD^*\pi$**
  - Evidence of large $DD_1(2420)$ signal would be strong evidence for hybrid

- Search for Partner States: (fill in the multiplet)
  - Identify J^{PC} partners of the hybrid candidate nearby in mass.
  - The F-T model expects:

$$0^{+-},\ 1^{-+},\ 2^{+-},\ 0^{-+},\ 1^{+-},\ 2^{-+},\ 1^{++},\ 1^{--}$$

How can pbar-p help?

- Democratic in producing J^{PC}:
  - Produce non-exotic J^{PC} in direct s-channel annihilation

$$\bar{p}p \to c\bar{c} \to hadrons$$

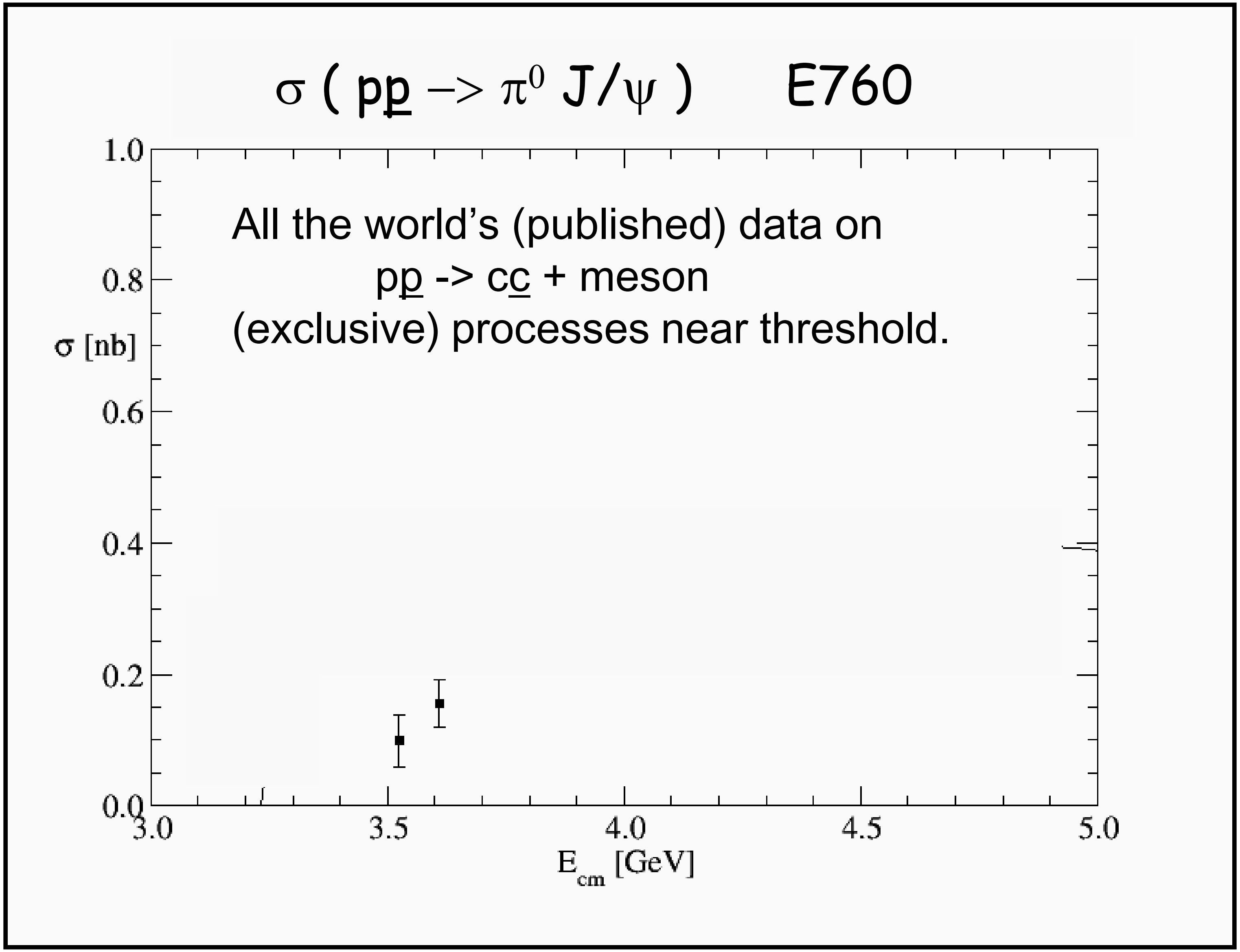
  - Can produce $c\bar{c}$ sector J^{PC}-exotics (presumably hybrids) using associated production

$$\bar{p}p \to \text{light meson} + c\bar{c}\ \text{(exotic)}$$

- High statistics
- Can do PWA to measure quantum numbers?

- **Crucial question:** just how large are these cross sections?
- Very little relevant data exists. There is some data on the hopefully similar associated charmonium production reaction

  $p\bar{p}$ –> **J/ψ** π^0 from E760/835 at Fermilab.
- Will show all the world's data and a theoretical attempt to predict these cross sections.



Evidently 0.1–0.2 [nb] near threshold for J/ψ . Other states, other energies???

PCAC-like model of $p\bar{p} \rightarrow \Psi + \pi^0$:

T.Barnes and X.Li, hep-ph/0611340; PRD75, 054018 (2007).

Original paper by Gaillard, Maiani and Petronzio, Phys Lett 110B, 489 (1982)

Assume simple pointlike hadron vertices

Use the 2 tree-level Feynman diagrams to evaluate **dσ/dt** and **σ**.

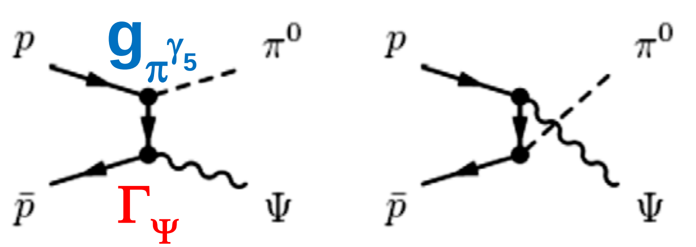


FIG.1. Feynman diagrams assumed in this model of $p\bar{p} \rightarrow \pi^0 \Psi$.

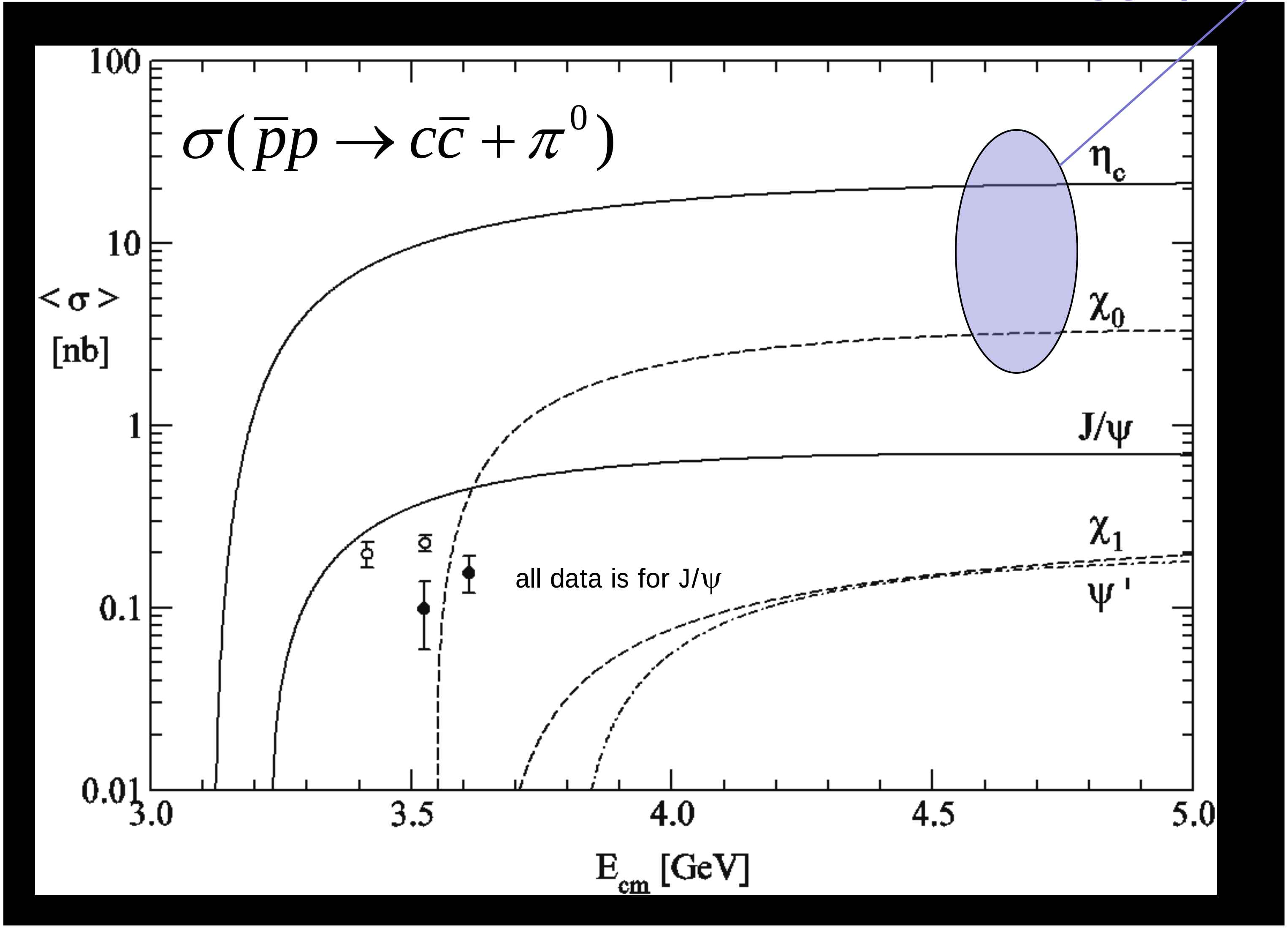
To predict numerical $p\bar{p} \rightarrow \Psi + \pi^0$ production cross sections in this model, we know $g_{p\bar{p}\pi}$ **~ 13.5** but not the { $g_{p\bar{p}\Psi}$ }.

We can get these new coupling constants from the known $\Psi \rightarrow p\bar{p}$ partial widths:

From Barnes and Li, PRD75, 054018(2007) hep-ph/0611340;
Barnes, arXiv:1003.2644

Important to add real data to this plot

gg quant. #'s.



(two E835 points (open) from a PhD thesis)

Summary

- Quarkonium spectroscopy has undergone a renaissance with many new states discovered recently

- Many new charmonium-like states, not clear how they fit
  - Most need confirmation and measure properties
  - **Not all new states are exotics**

- Many narrow states still to be found:
  - Charmonium $\eta_2(1^1D_2)$, $\psi_2(1^3D_2)$, $\psi_3(1^3D_3)$, 2^3P_2, 1^3F_4

- pbar-p can contribute to finding the missing conventional states, discovering "exotic" states, and helping to understand the enigmatic X, Y, Z states