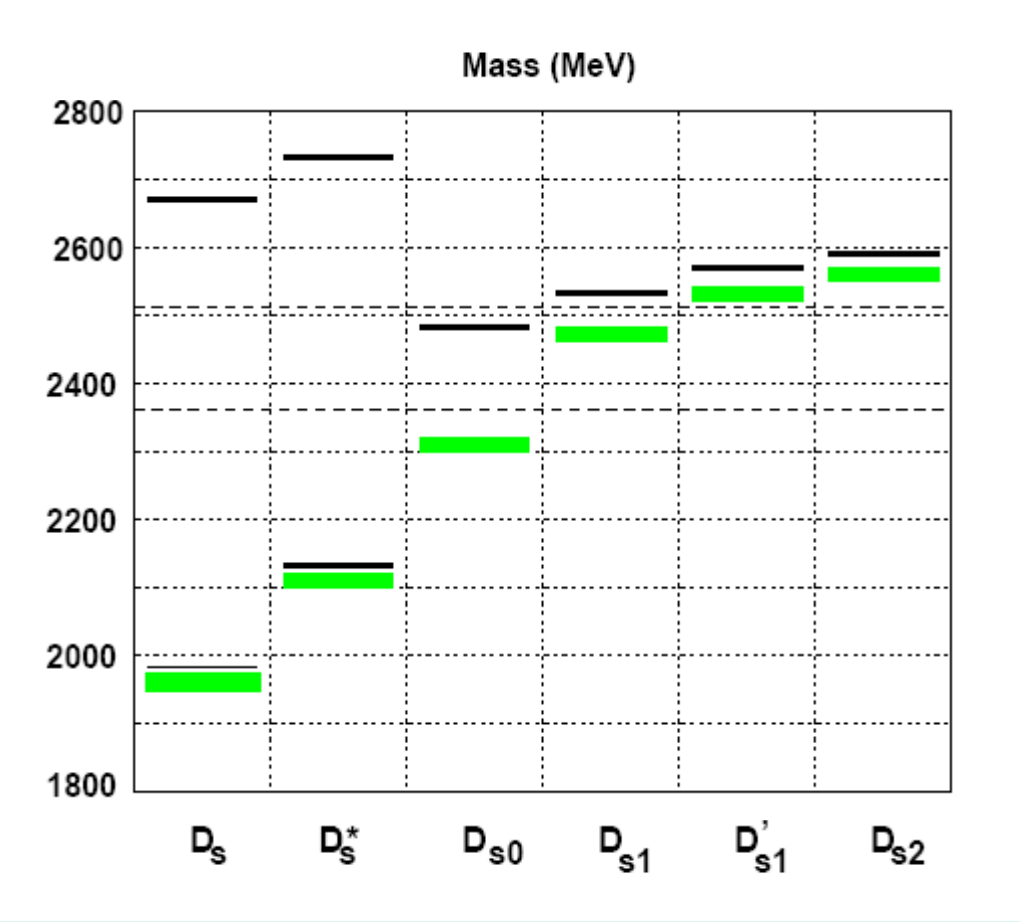
Charmed states
Old and New

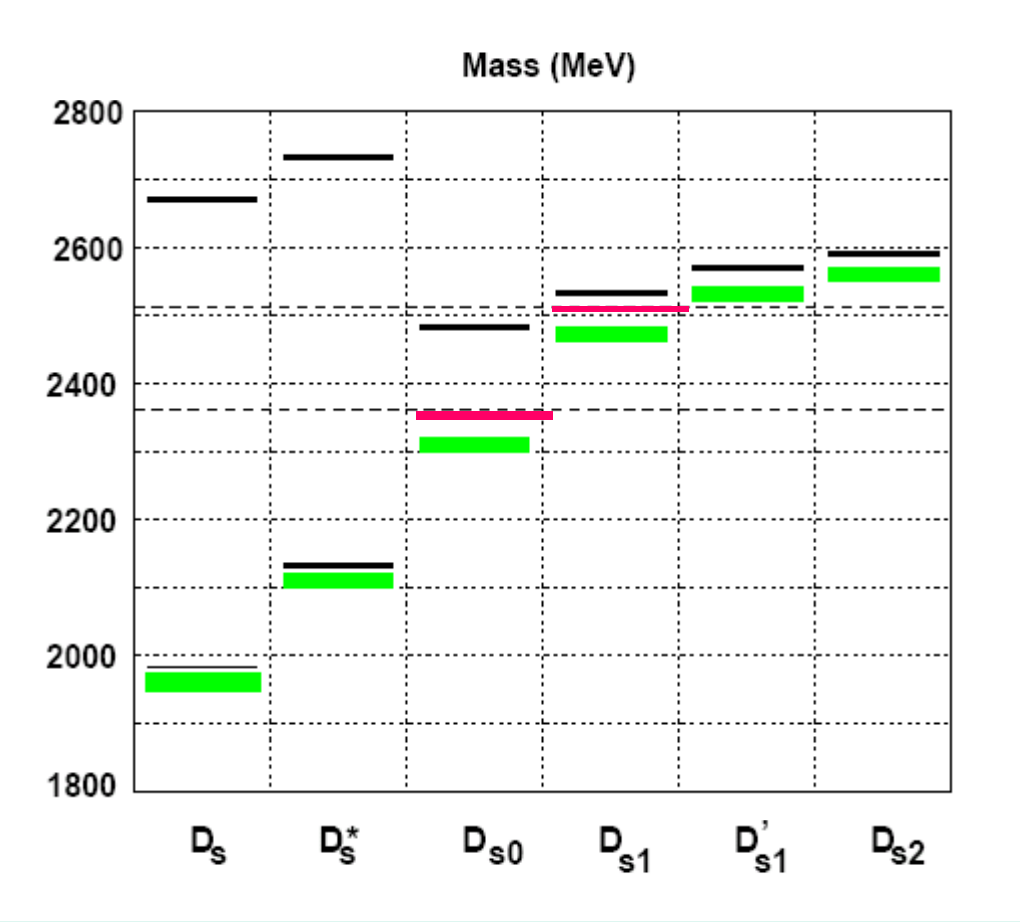
# Old D_s states




cs* model
data

FC Swanson PRD72 094004 2005

# Old D_s states



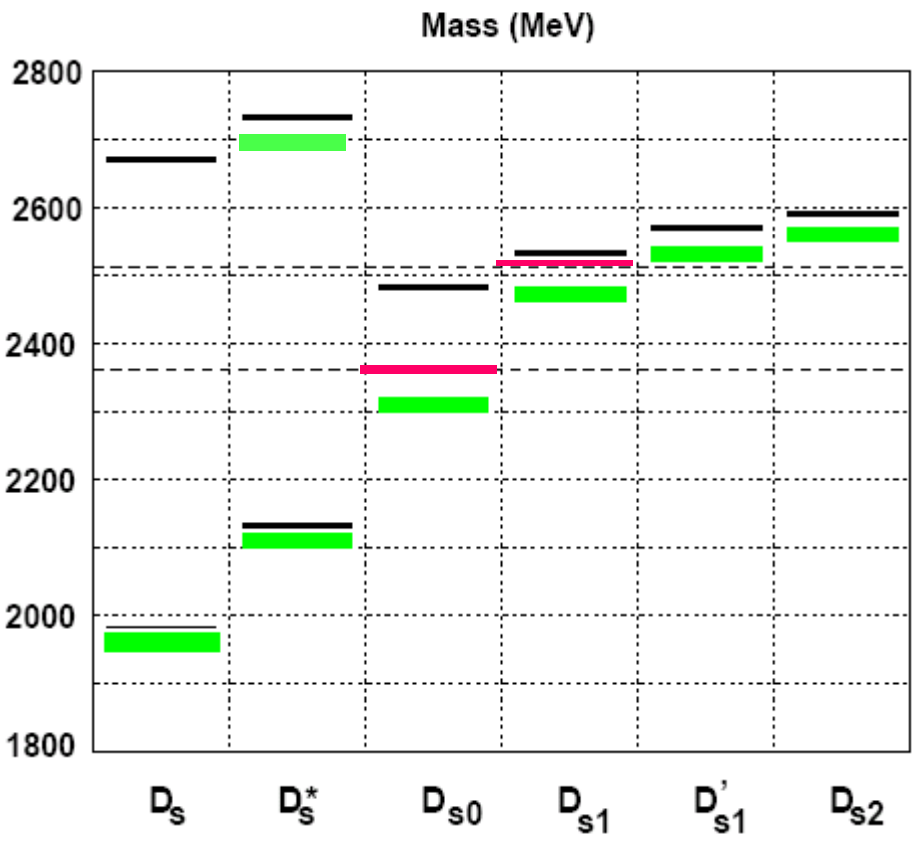

cs* model
data
D(*)K thresholds

Barnes FC Lipkin PRD68 054006 2003

**Ds*(2690)**

# New D_s state

Radial 1- looks OK



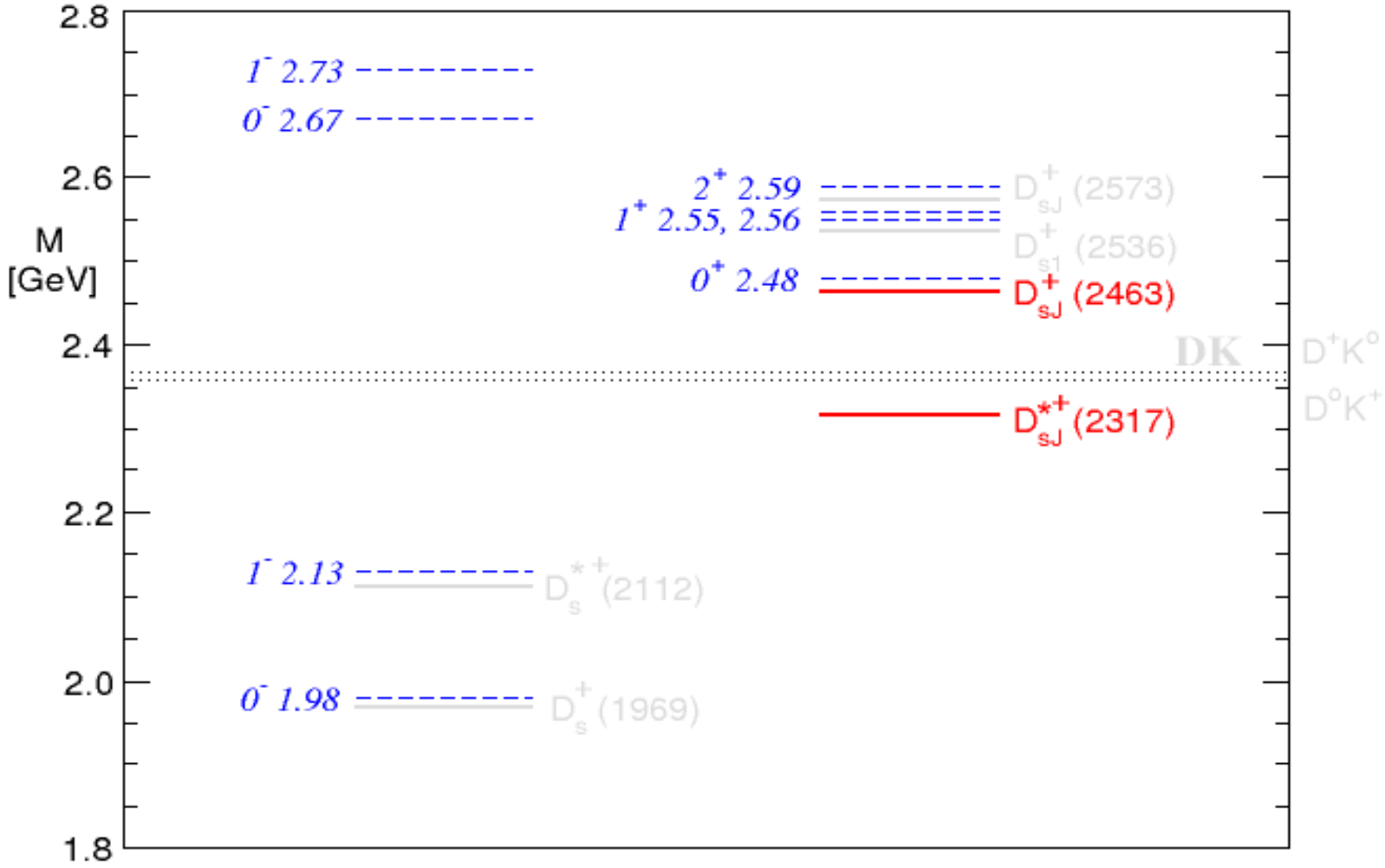

Test: B decays

$$\frac{B \to D_s(2690)D}{B \to D_s^*(2110)D} = 0.3 - 0.7$$

$$\frac{B \to D_s(2690)D^*}{B \to D_s^*(2110)D^*} = 0.5 - 1.3.$$

FC Thomas Lakhina Swanson 0608139 Phys Lett

Theory, Ds mesons (blue) and the BaBar states (red)



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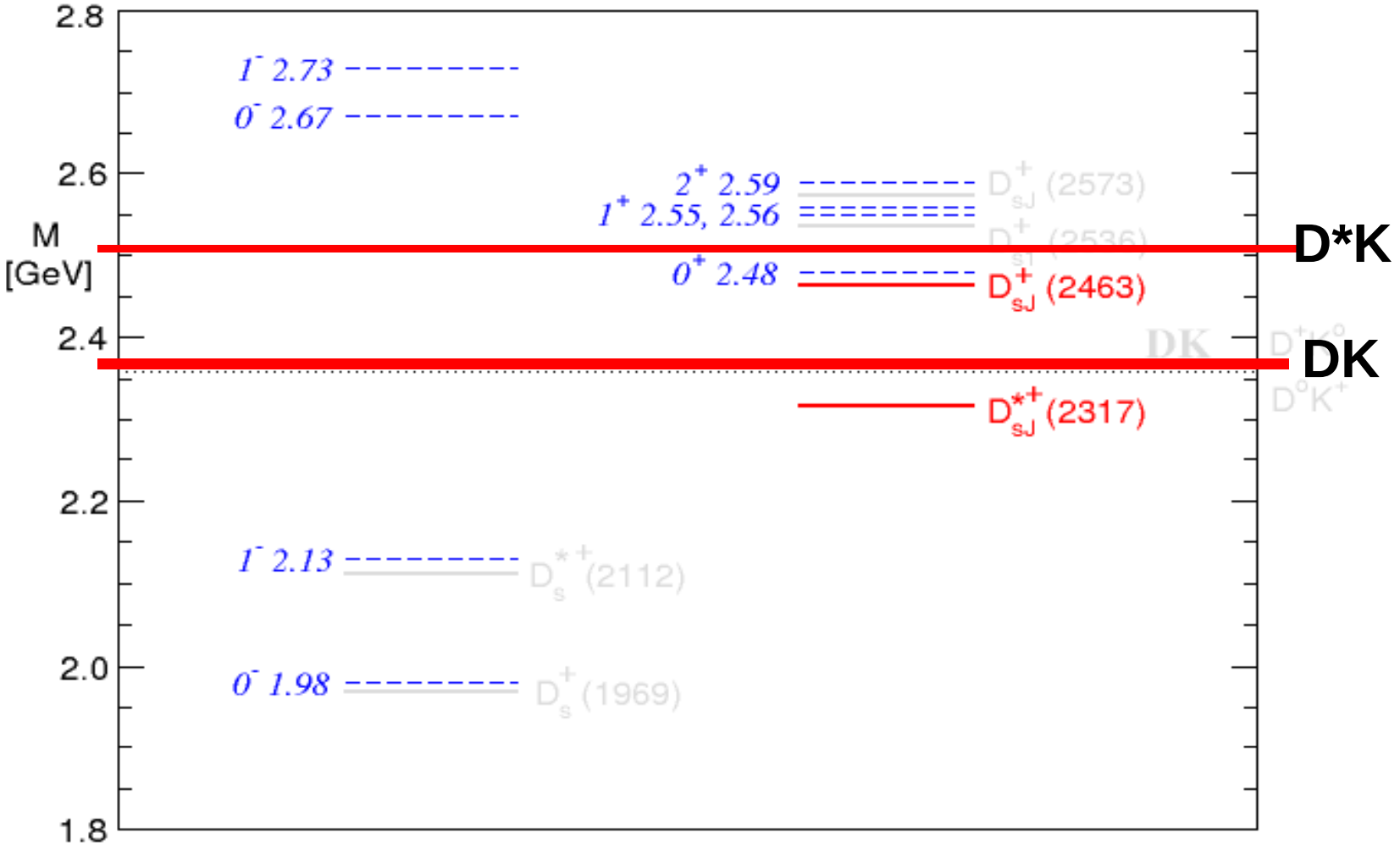
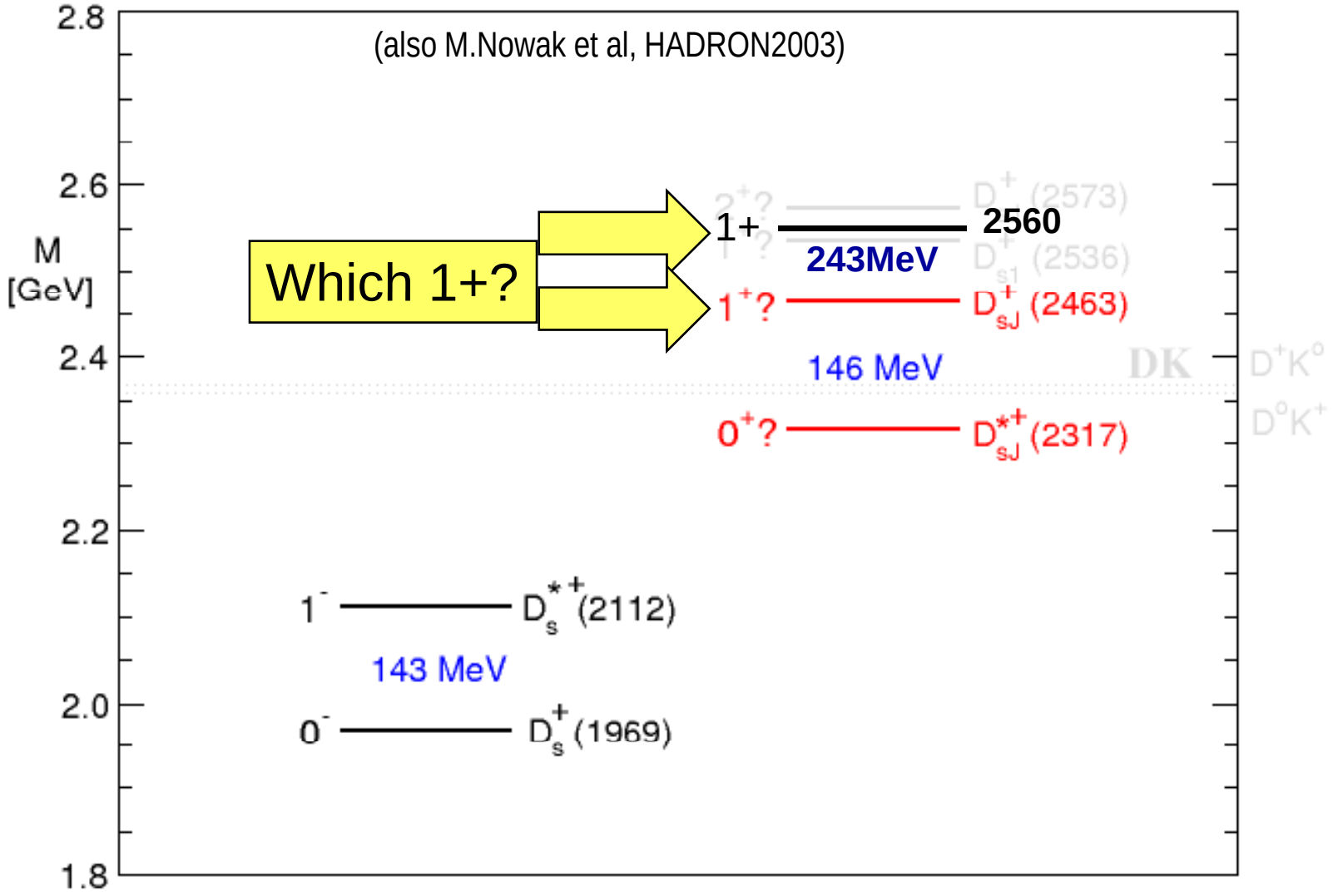


Why in cs*?

# csbar chiral partners?

*Bardeen, Eichten and Hill, hep-ph/0305049*



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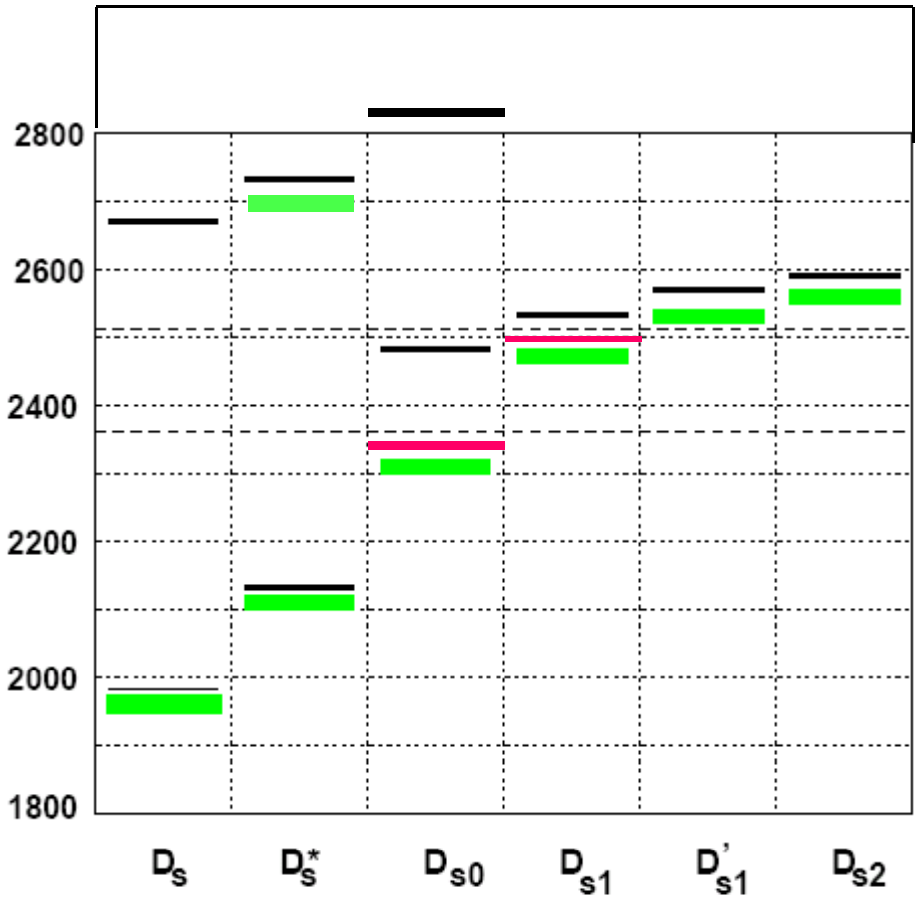
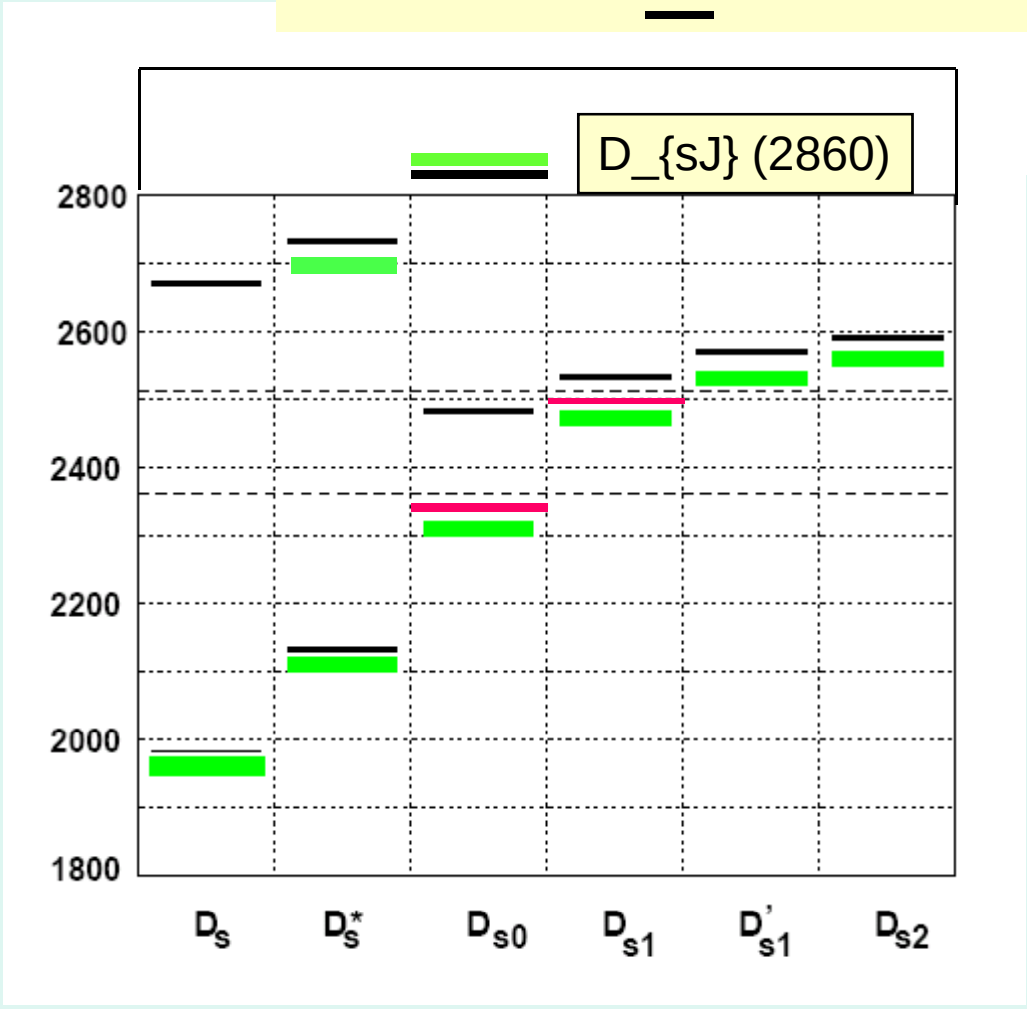


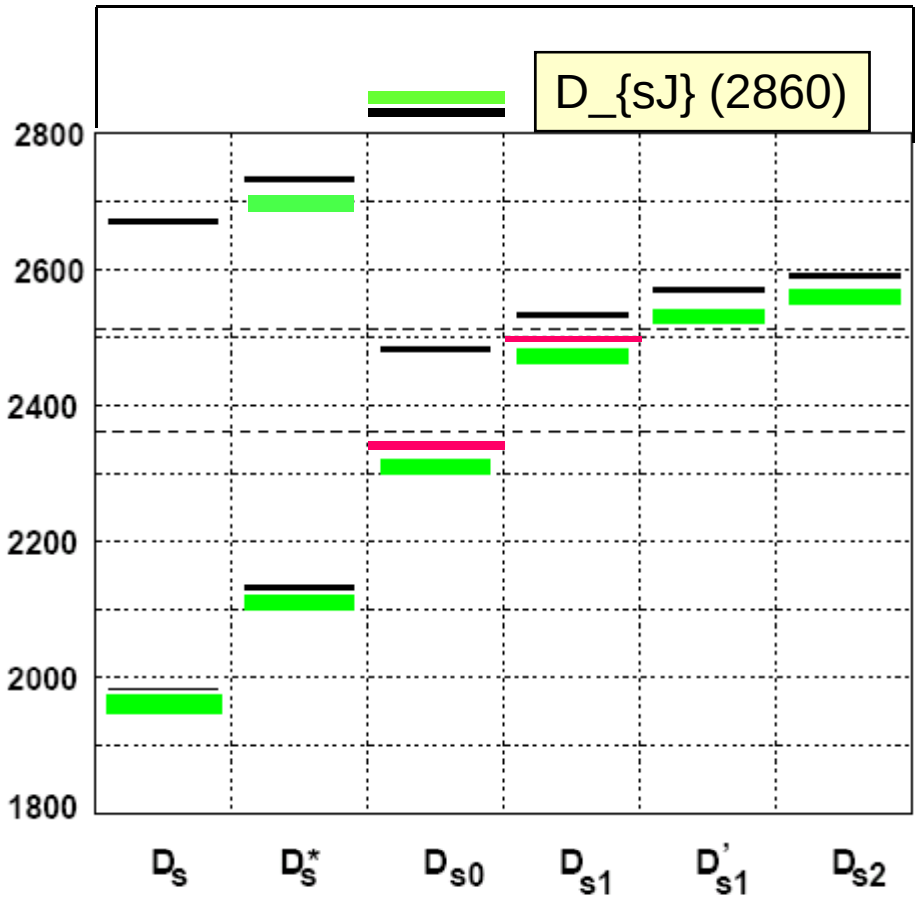

?extra 0+ 1+
or just these?

# New D_s states




FC Thomas Lakhina Swanson 0608139 Phys Lett

# New D_s states

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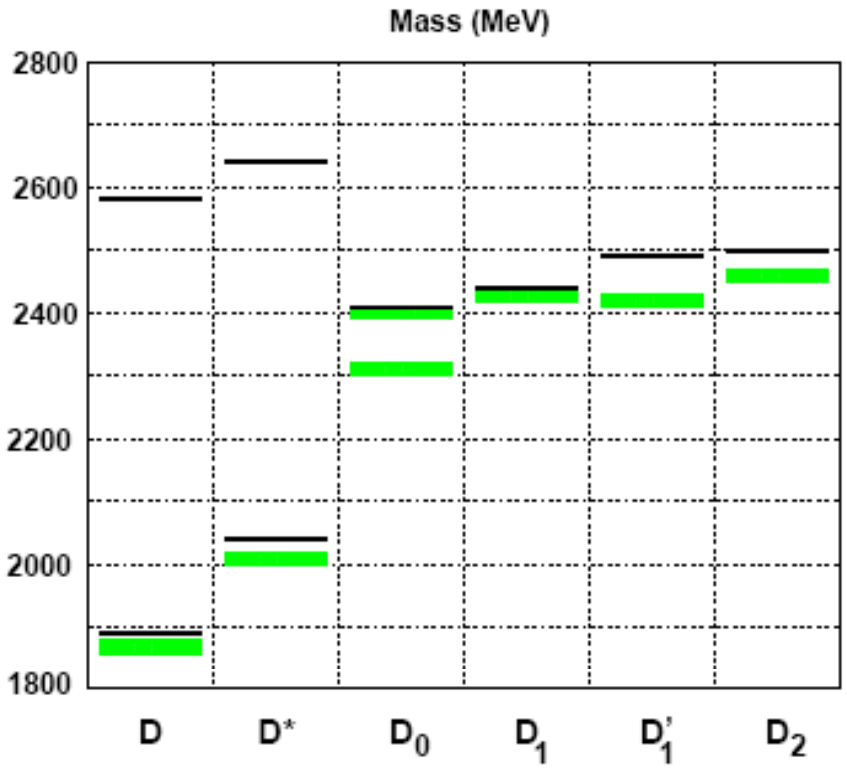
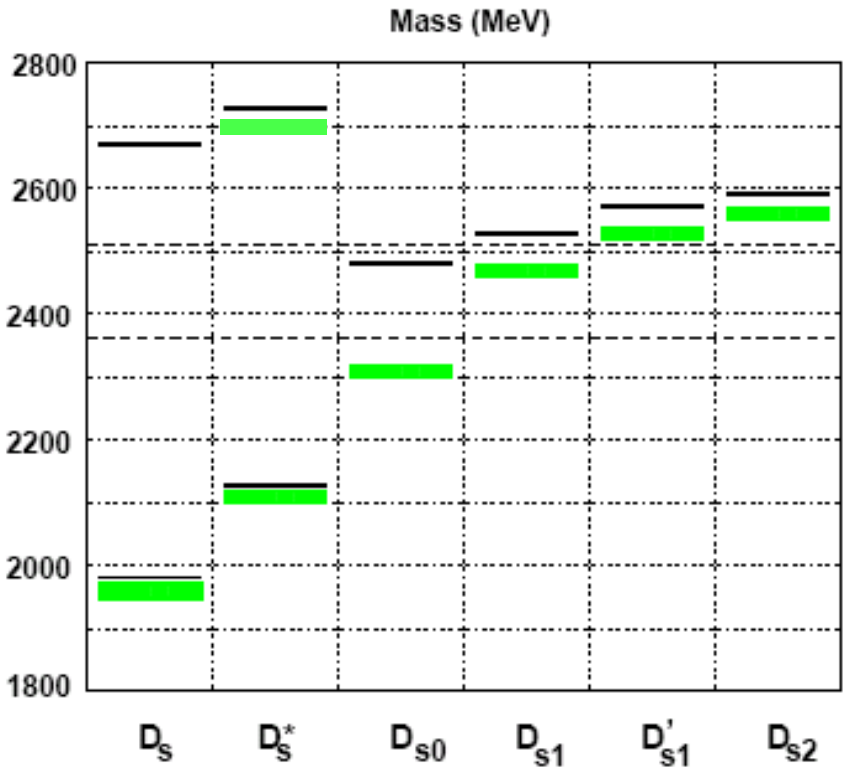
$$\frac{B \to D_s(2690)D^*}{B \to D_s^*(2110)D^*} = 0.5 - 1.3.$$

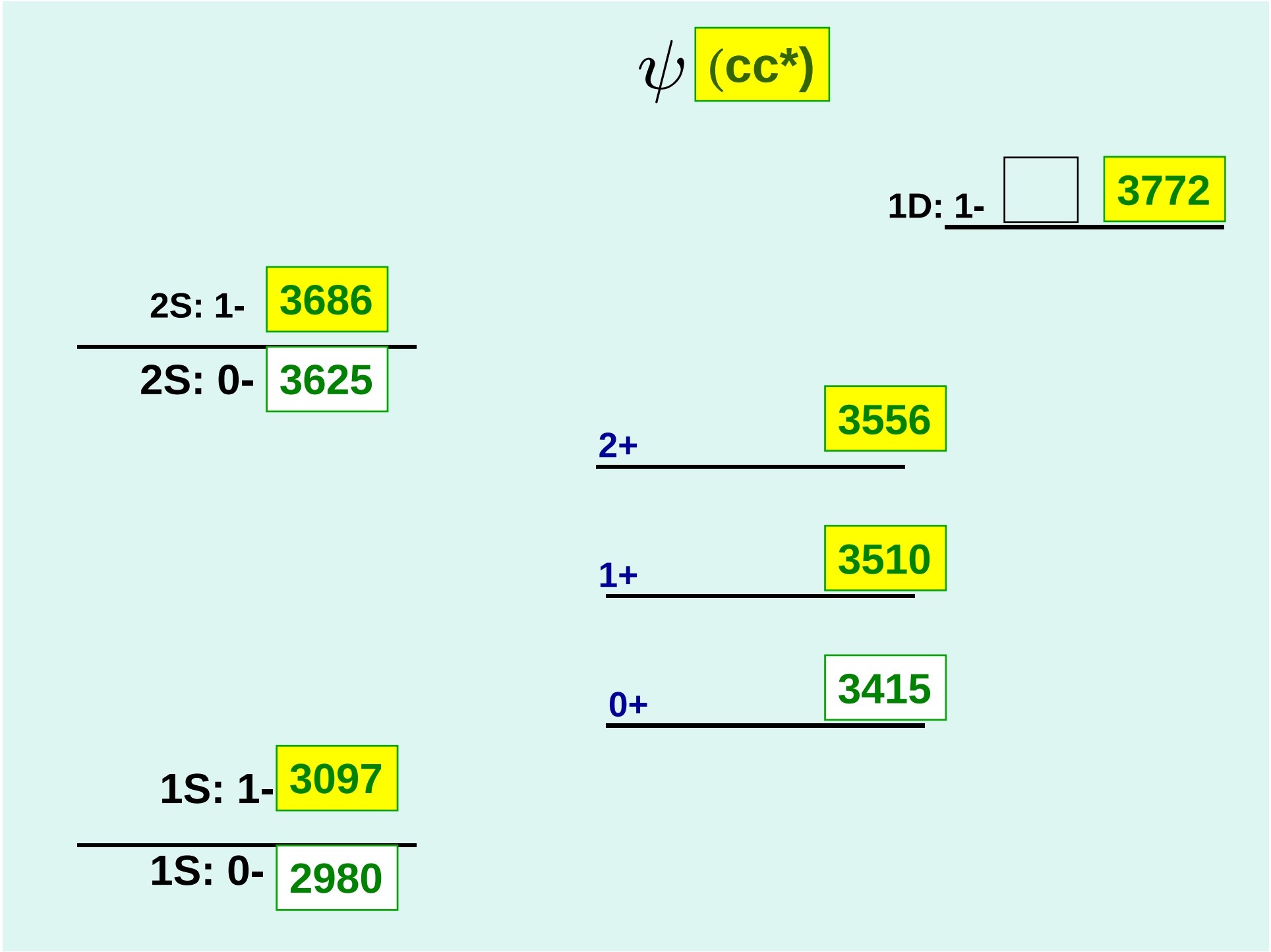
If 2P and 1P cs*

FC Thomas Lakhina Swanson 0608139 Phys Lett

# Understanding requires sorting out D and compare Ds



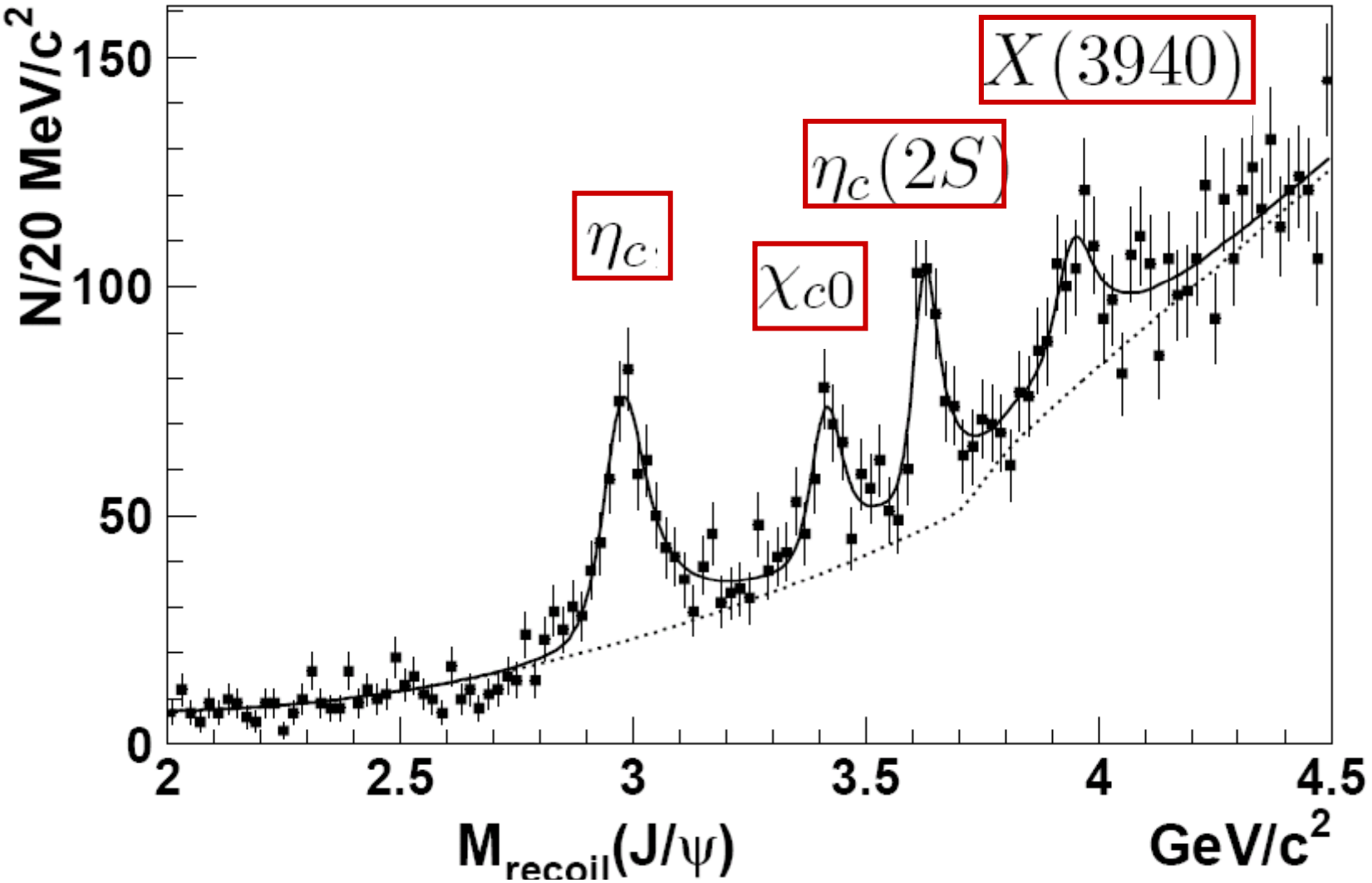




ψ (cc*)
1D: 1-
3772
2S: 1-
3686
2S: 0-
3625
2+
3556
1+
3510
0+
3415
1S: 1-
3097
1S: 0-
2980

Belle

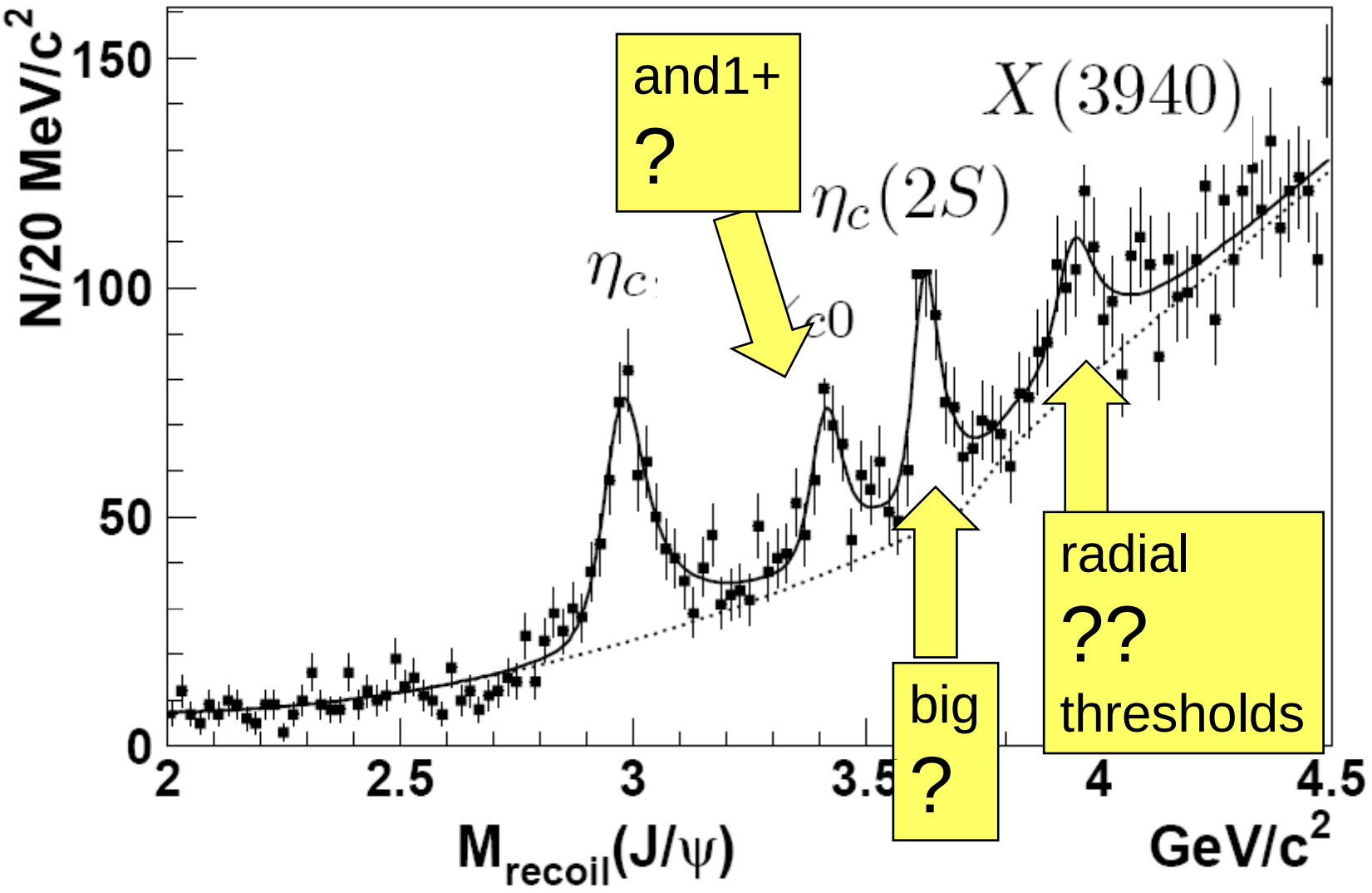
**e+e- to $\psi$ + X**

???



Belle

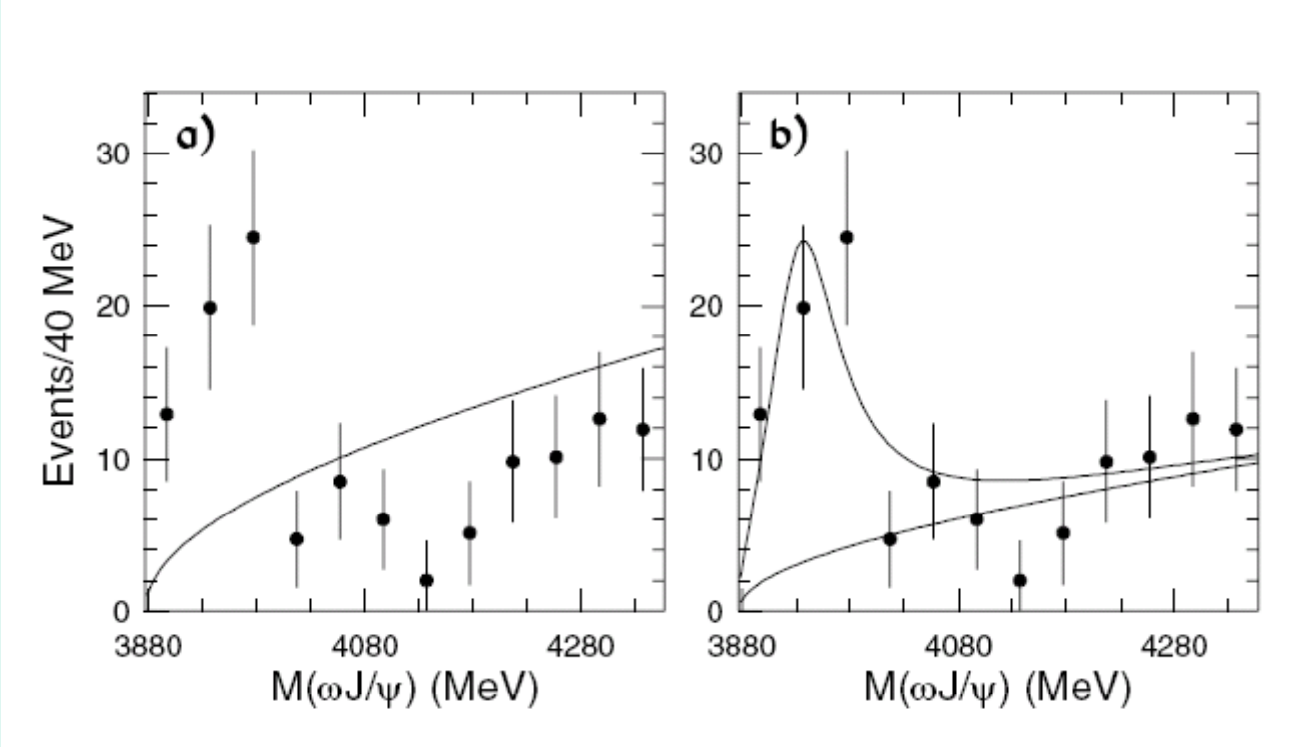
# Inconsistent strengths?



# New Charmonium

| Name | Mass (MeV) | Width (MeV) | comments | What is it? |
|---|---|---|---|---|
| X(3872) | 3871.9±0.6 | narrow | J/ψππ, D pair | $1^{++}$,DD* |
| X(3940) | 3943±6 ±6 | <52 | Recoil mass<br>ωJ/ψ not seen | $\eta_c(3S)$?<br>hybrid? |
| Y(3940) | 3943±11±13 | 87±22±26 | ωJ/ψ | hybrid? |
| Y(4260) | $4259\pm8\ \pm^{2}_{6}$ | $88\pm23\ \pm^{6}_{4}$ | $J/\psi\pi^+\pi^-$,<br>D pair not seen | $1^{--}$,hybrid? |
| Z(3930) | 3931±4±2 | 20±8±3 | D pair | $\chi'_{c2}$? |

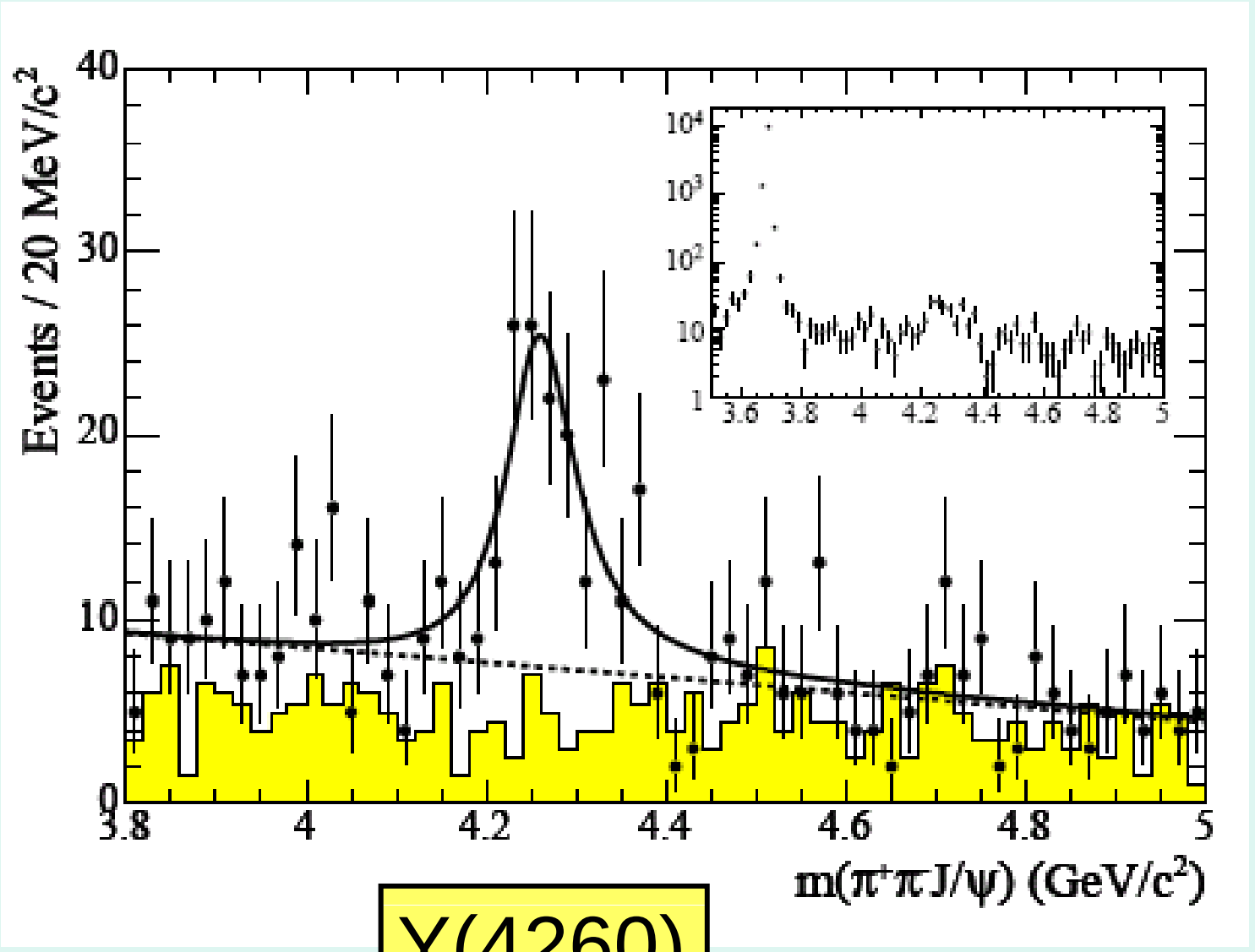
**Claim of Hybrid Charmonium at 3940 by BELLE in B decays**




$$\mathcal{B}(B \to KY(3940))\mathcal{B}(Y(3940) \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5},$$

Is this the same as X(3940)?
Is it hybrid charmonium as claimed?
….

# e+e- \to psi pi pi BaBar sees new vector cc*



Y(4260) Three Possibilities

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\mathrm{P-wave}}$$

$Y(4260)$ **as hybrid charmonium**

**Y(4260) = S-wave threshold attraction**

Experimental distinctions….later this talk

# New Charmonium

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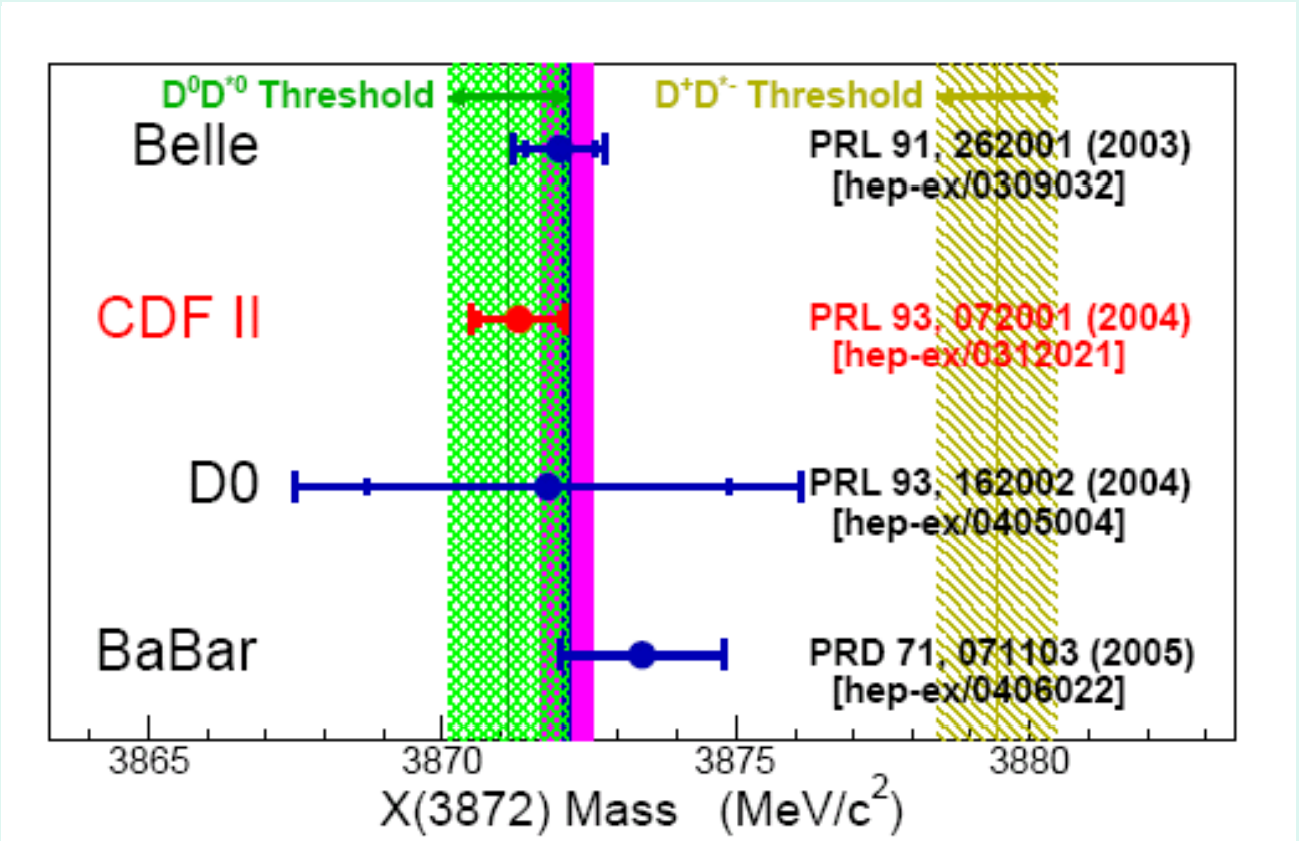
| Z(3930) | 3931±4±2 | 20±8±3 | D pair | $\chi'_{c2}$? |

# Charmonium Tetraquark:

## 1++ cc* X(3872)

# X(3872) mass compared with DD* thresholds



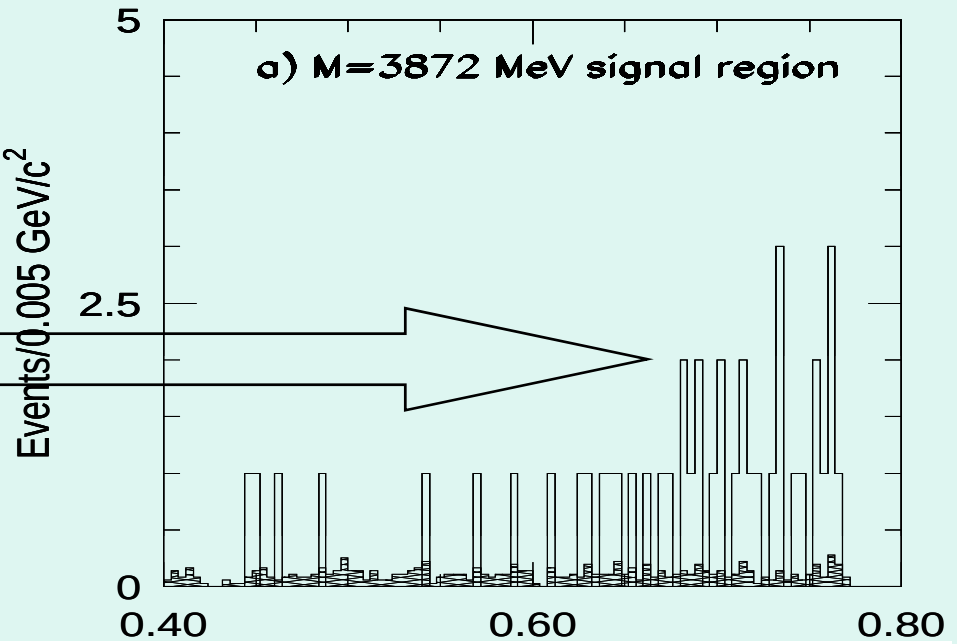

**DD* molecule "tetraquark"** Mass = neutral threshold to better than 1 in 10,000

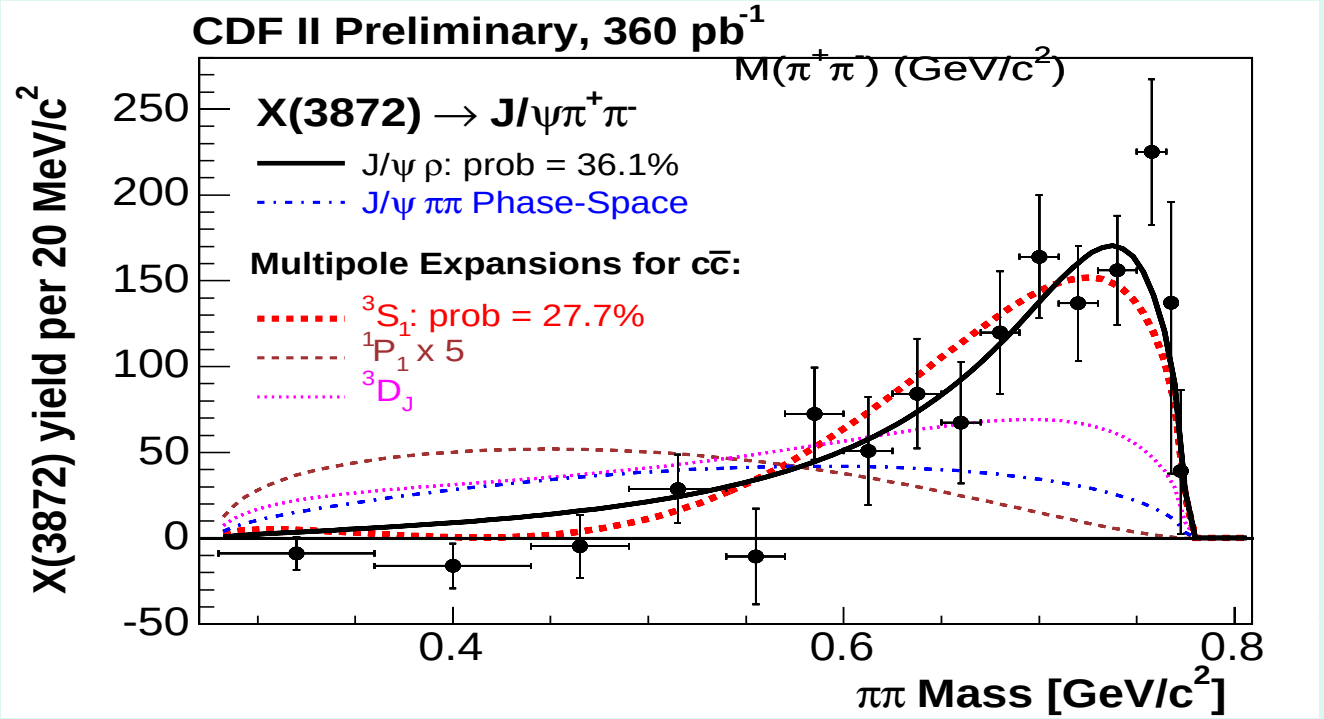
**cuc*u* S-wave $J^{PC} = 1^{++}$** **isospin maximally broken**

$X \to \psi\pi\pi$ is really

$X \to \psi\rho$ !!!

Close+Page
Tornqvist
Swanson

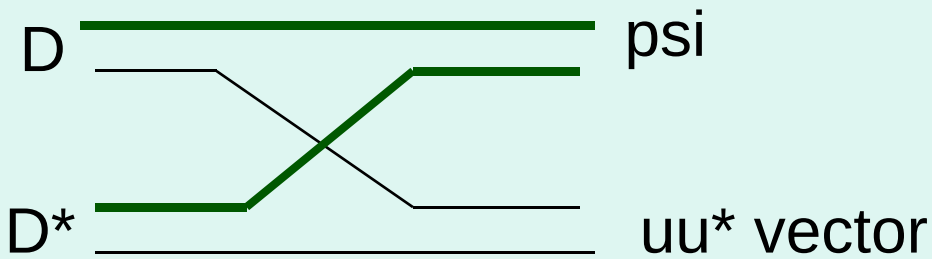


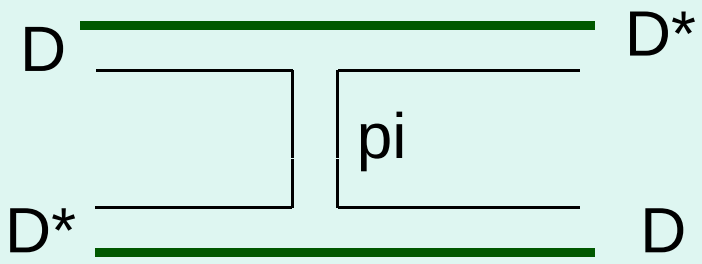



cc*1++ 3550; 1++* 3950: P-wave cc*

DD* (neutral) threshold
Psi rho; psi omega
} S-wave 1++ mesons

Mass coincidence only happens with Charm, not strange or bottom




Energy degeneracy

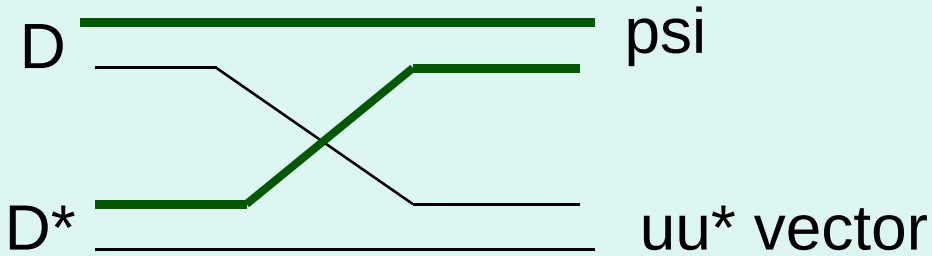
Psi rho:psi omega \sim 1

Specific model: Swanson

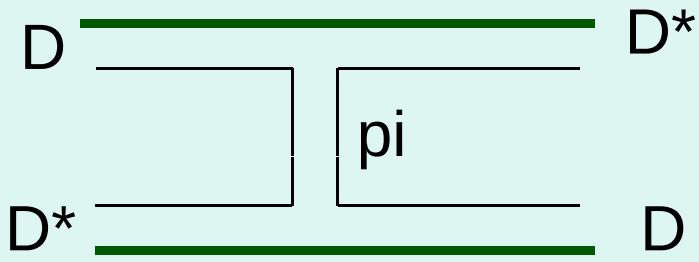
(Recall for Y(4260) later)

DD* (neutral) threshold
Psi rho; psi omega

S-wave 1++ mesons




Q exch not enough




Pi exchange drives attraction

## An extra narrow charmonium state

$$X(3872) \rightarrow \psi\pi\pi$$

Current opinion:
1++ cc* with large tetraquark cc*uu* admixture:
Test: produce in B+ > B0

**X \to K+K-\pi>> K0K0\pi**

**CLEOc/BES precision test for 1++ 3550 also**

# New Charmonium

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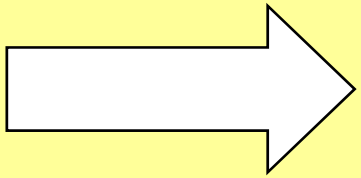


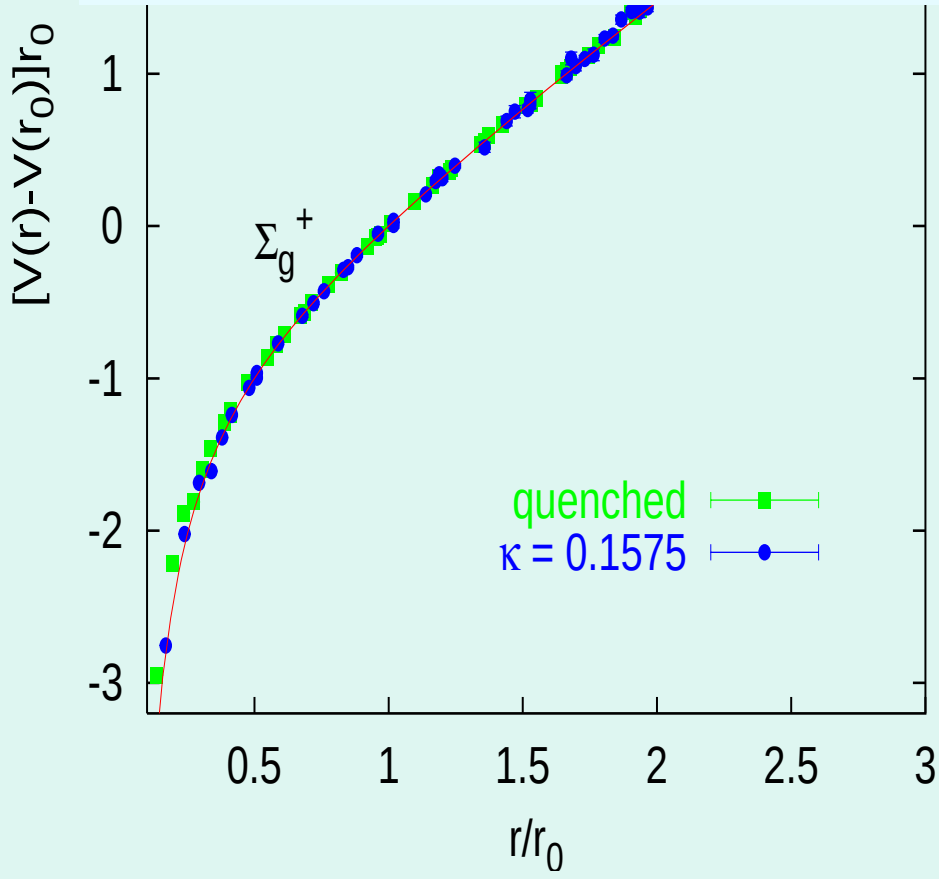
**New states outside the quark model:**

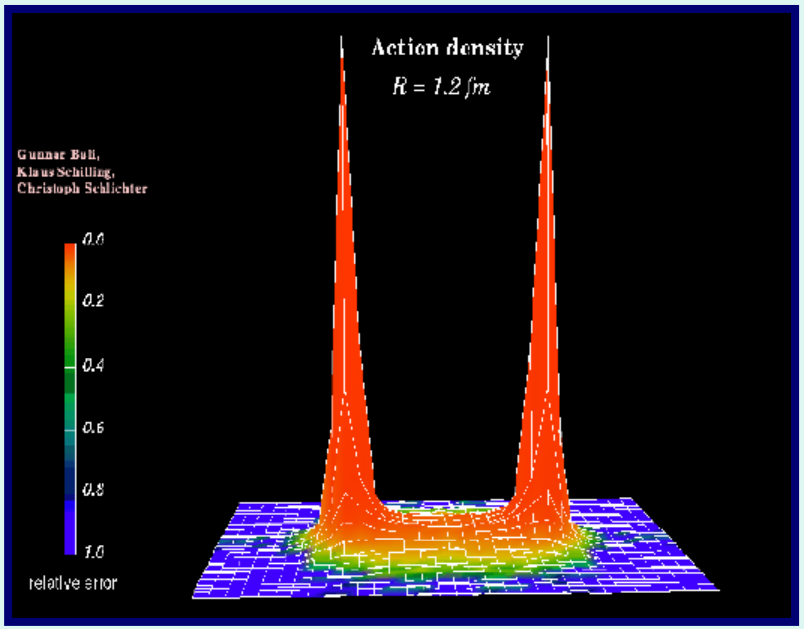
**Gluonic Hybrid Mesons**

# Lattice Linear Potential

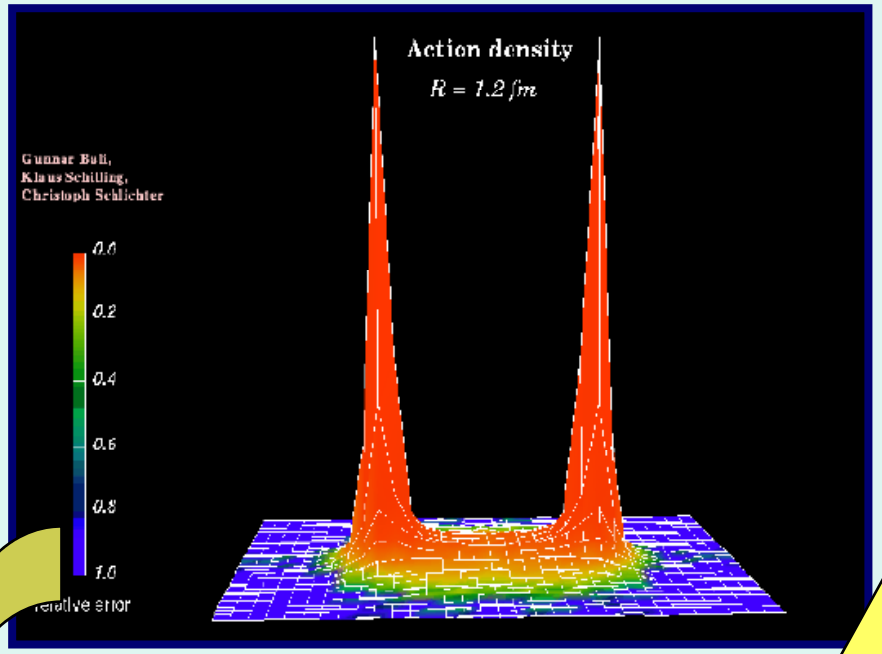
Linear flux tube model Isgur

Linear flux tube (lattice) Bali…

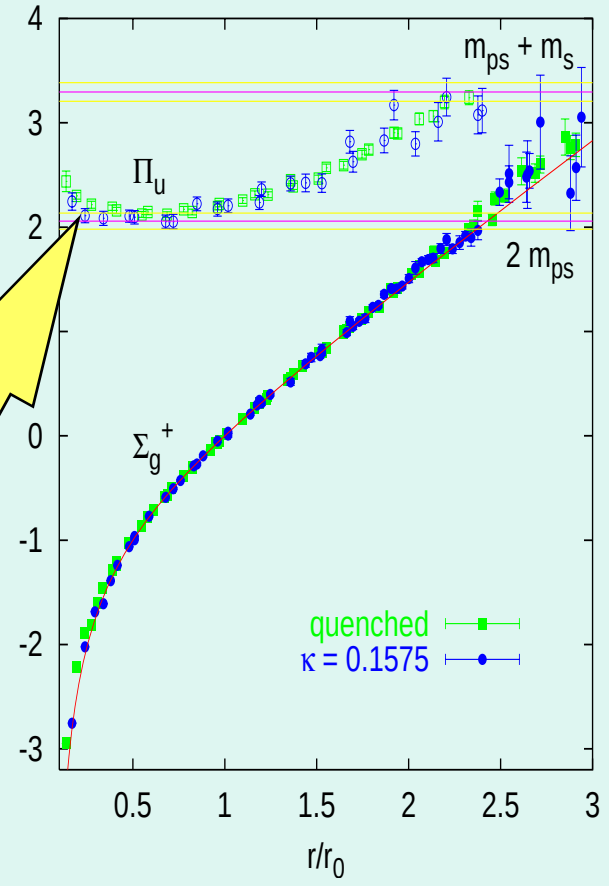


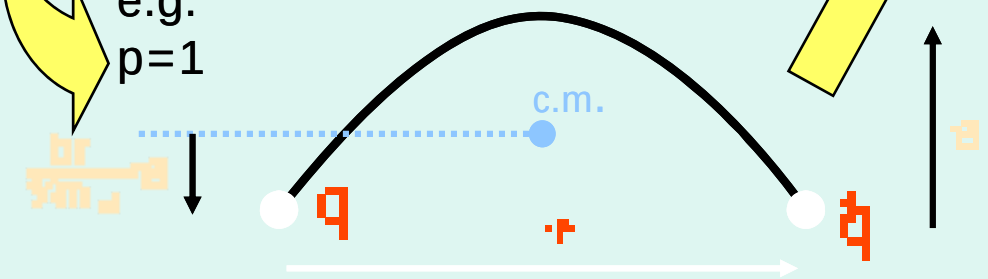
# Gluonic hybrid mesons




UKQCD



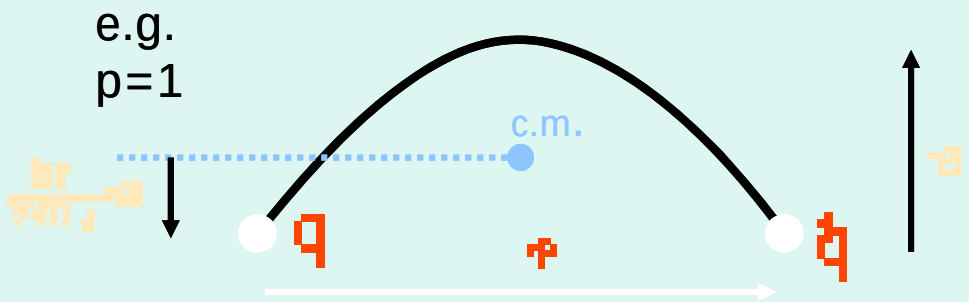

e.g.
p=1




**Exciting the flux tube**

Lattice and model agree spectrum; decays in FT, new = lattice

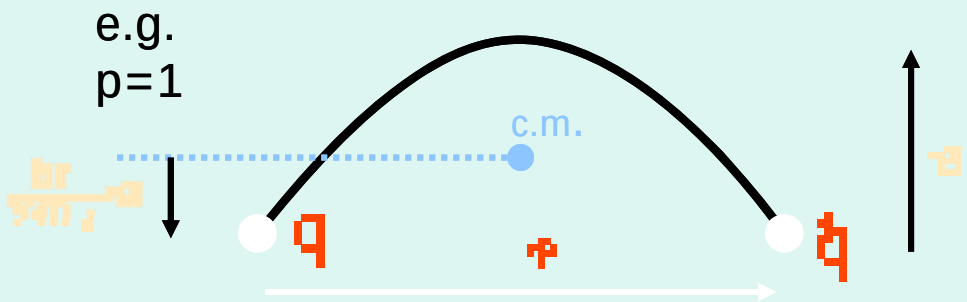
# flux-tube degrees-of-freedom




**Costs about 1 to 1.5GeV energy to excite phonon "pi/R"**
**Hybrid qq* @ 2GeV; Hybrid cc* @ 4-4.5GeV**

Barnes FC Swanson 93

# flux-tube degrees-of-freedom

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Barnes FC Swanson 93

Ted Barnes (Soton) FC (RL); **mass/splitting; light exotic 1-+**

TABLE I. Predicted $1^{-+}$ Hybrid Masses.

| state | mass (GeV) | model |
|---|---|---|
| $H_{u,d}$ | 1.3-1.8 | bag model |
| | 1.8-2.0 | flux tube model |

\sim 2.2 GeV ss* quarks LGT
\sim 2 GeV ud flavours

LGT: Michael…

Spin hyperfine splittings pattern

Barnes FC 82
Chanowitz Sharpe

2-+
1- -
1- + HQLGT
0- +

# Predicted 1-+ Hybrid masses (without spin splittings)

| | | |
|---|---|---|
| $H_c$ | $\approx 3.9$ | adiabatic bag model |
| | 4.2-4.5 | flux tube model |
| | 4.1-5.3 | QCD sum rules (most after 1984) |
| | 4.19(3) $\pm$ sys. | HQLGT |

# Predicted 1-+ Hybrid masses (with spin splittings)

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Spin hyperfine splittings

Barnes FC 82
Chanowitz Sharpe

1- - (4.25) Y(4260?)

1- + (4.1) HQLGT

0- + (3.95) X(3940?)

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e+e- feebly coupled

e+e- \to \psi + X?

## Spin hyperfine splittings

Barnes FC 82
Chanowitz Sharpe

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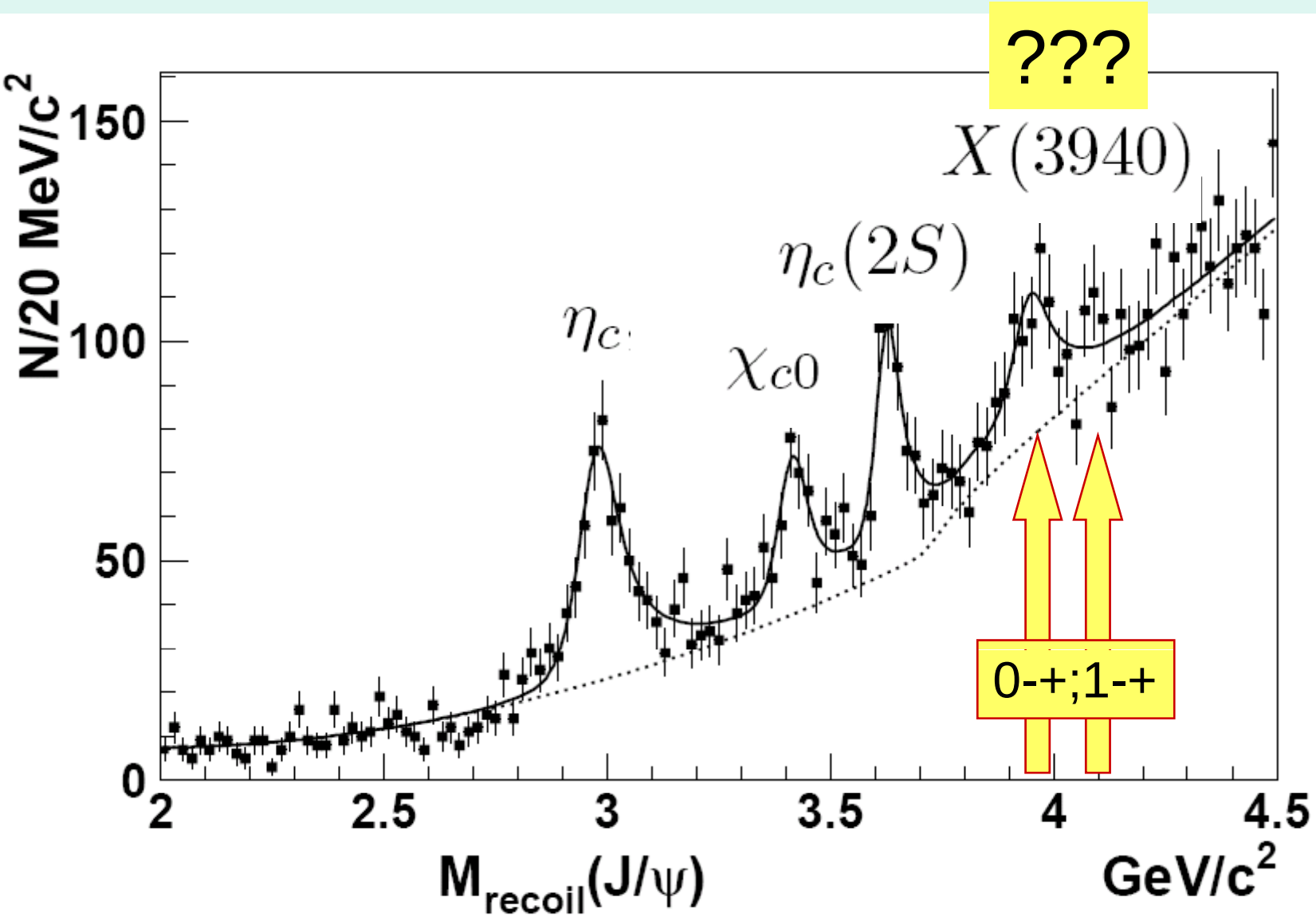
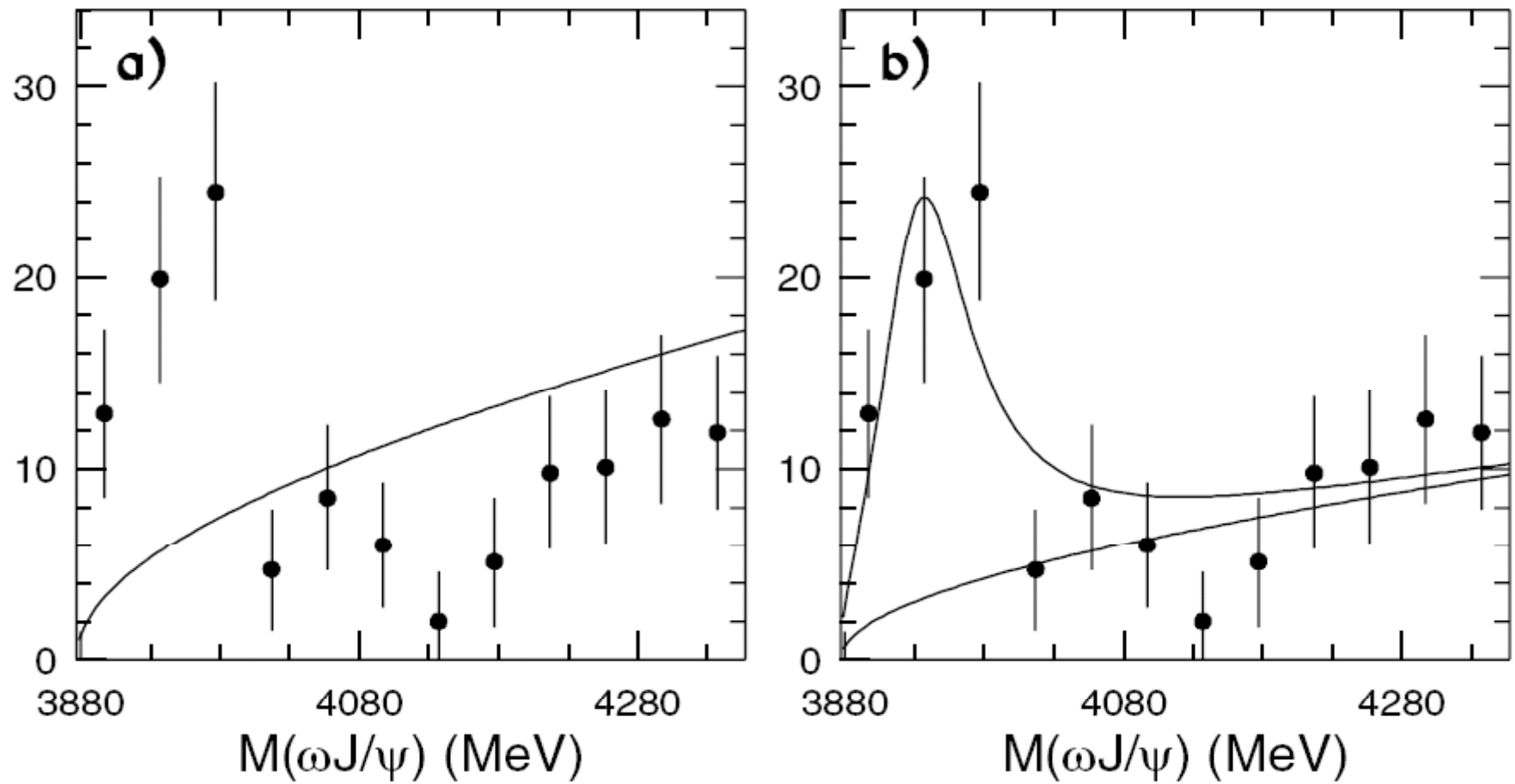
Belle

**e+e- to $\psi$ + X**

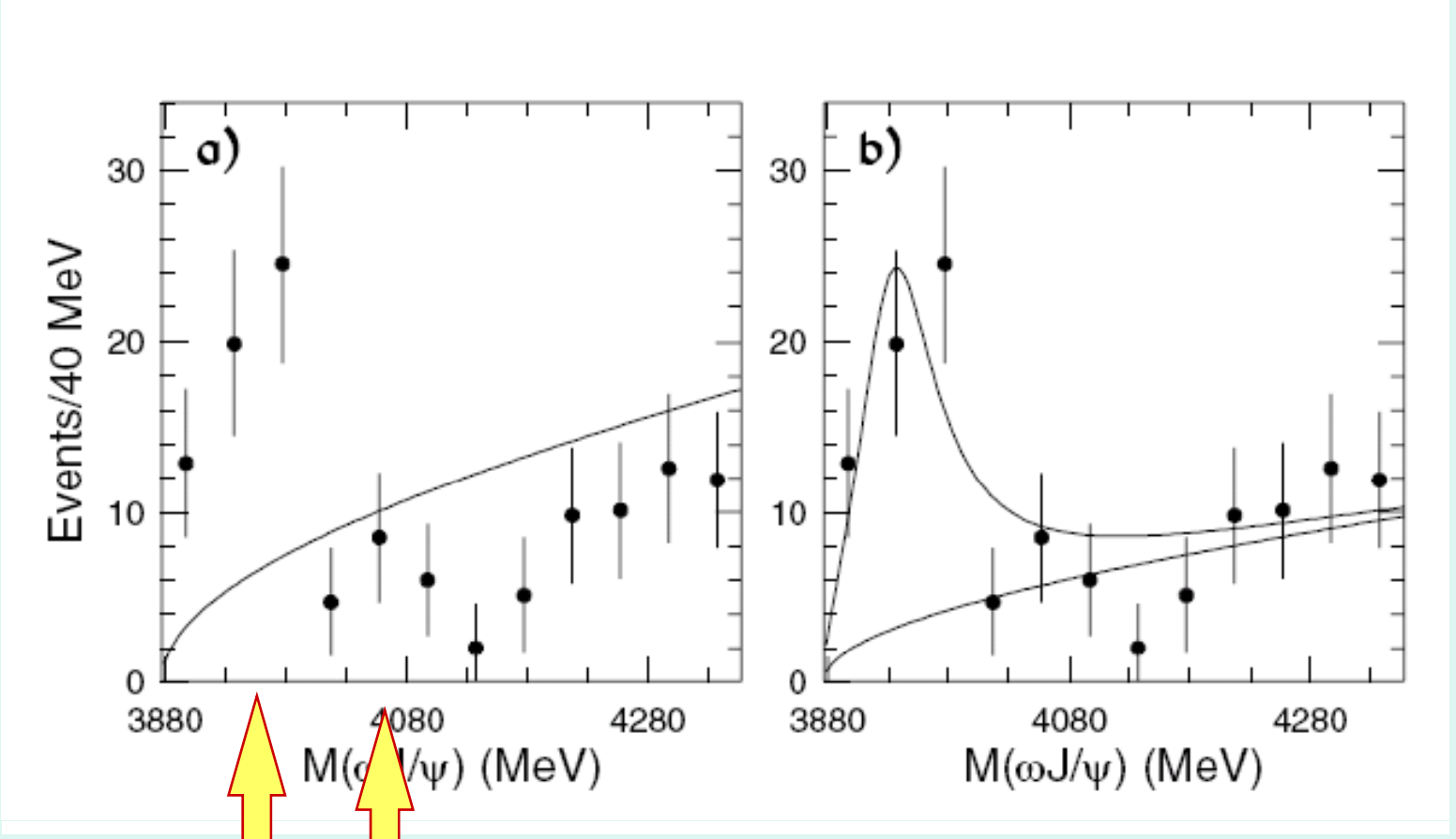


**Belle Y(3940) claimed “hybrid charmonium”**




**….but seems also to be in DD* (need to measure b.r)….**

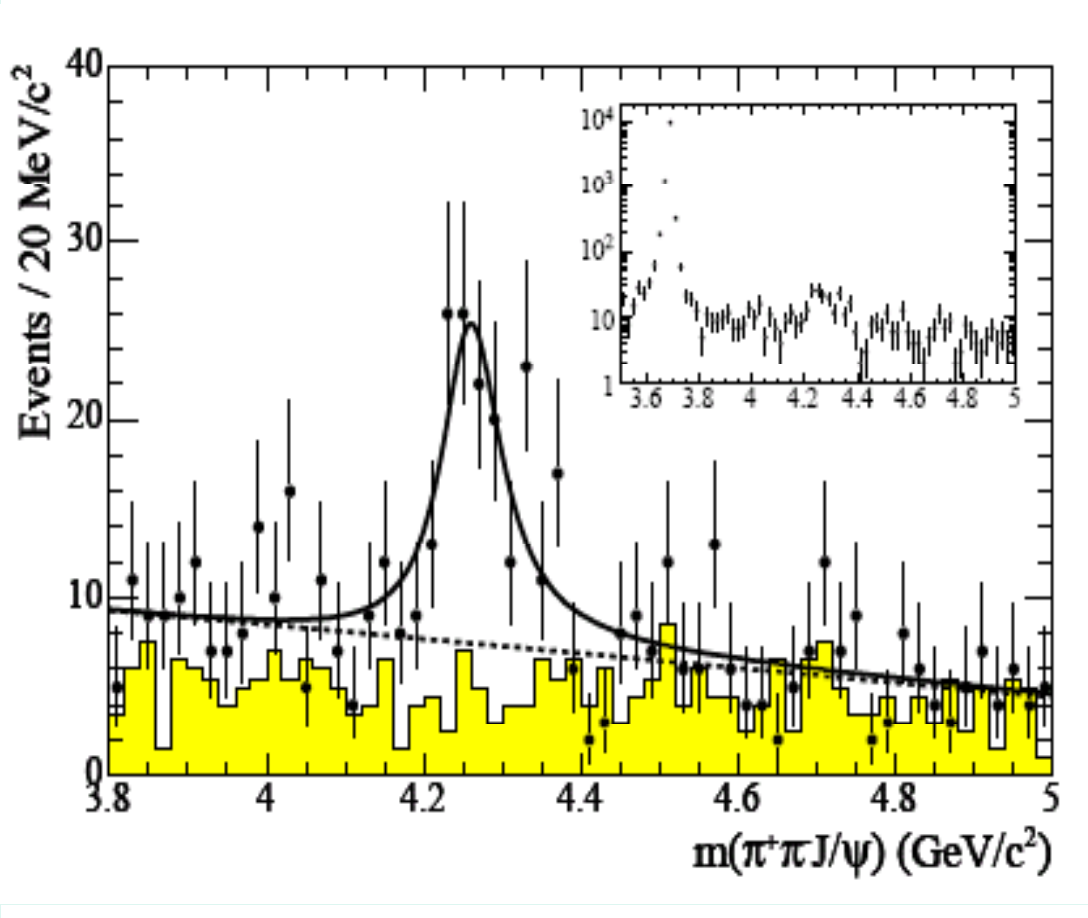
## Claim of Hybrid Charmonium by BELLE




0-+;1-+

Statistics resolve if 0,1,2 structures and J^PC

# e+e- \to psi pi pi BaBar sees new vector cc*




Y(4260)

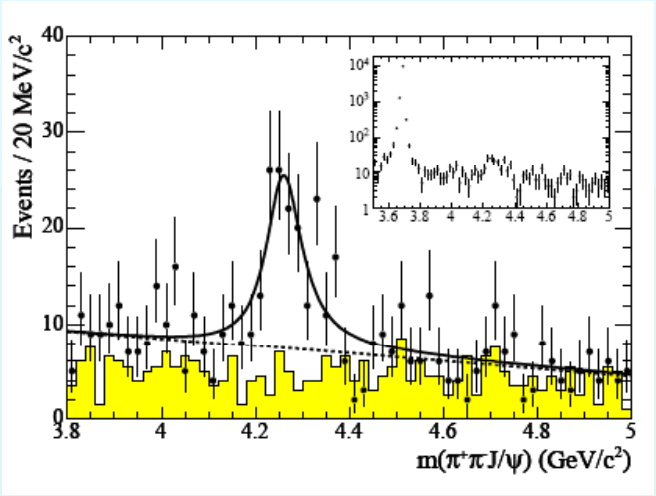
No sign of established
3S/2D(4040/4160)
4S(4400)
in the psi pipi data

Y(4260) thus seems anomalous

Also no place
for extra cc* state

\Gamma(ee) 5-80eV
Compare \sim 1 keV !!

But width 90MeV dominantly psi pipi !

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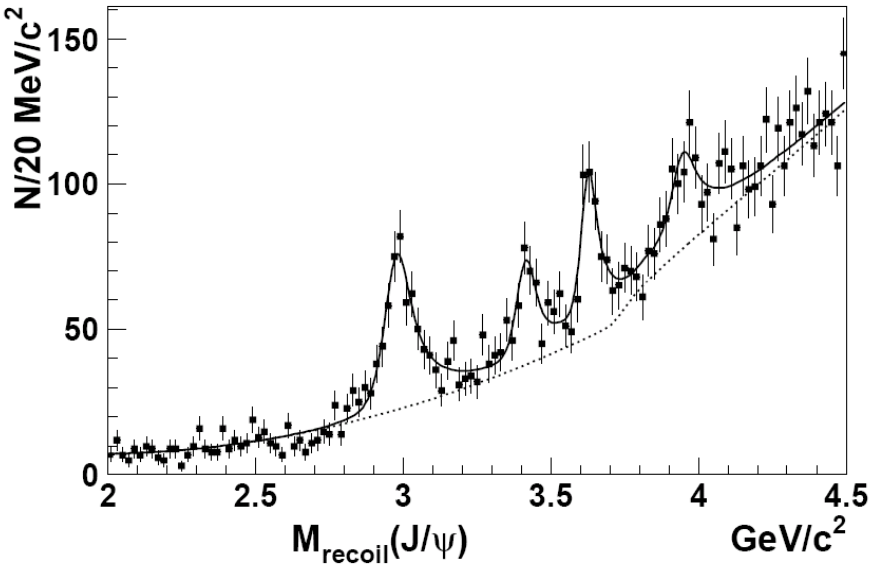
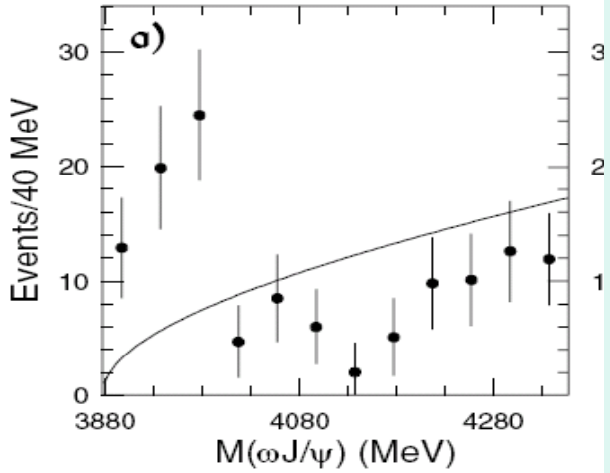
1- + (4.1) HQLGT
0- + (3.95) X(3940?)



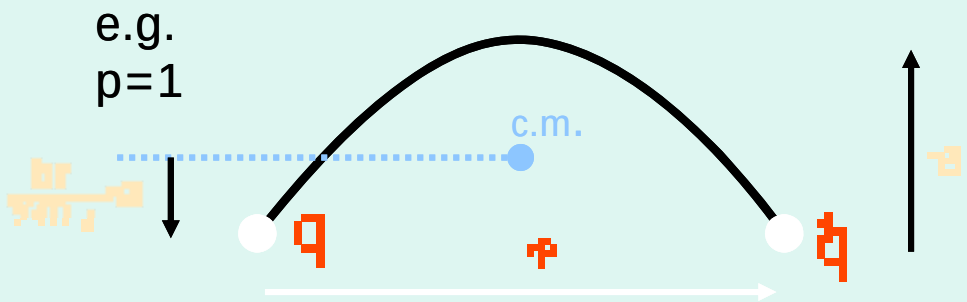



**Masses OK. Need to go**

# Beyond spectroscopy:

**Hybrid decays and production.**
**+ new insights from Lattice QCD**

# flux-tube breaking and decays




Isgur Paton 92 light exotics

FC Page 95 all

**Break tube: S+P states yes; S+S suppressed**

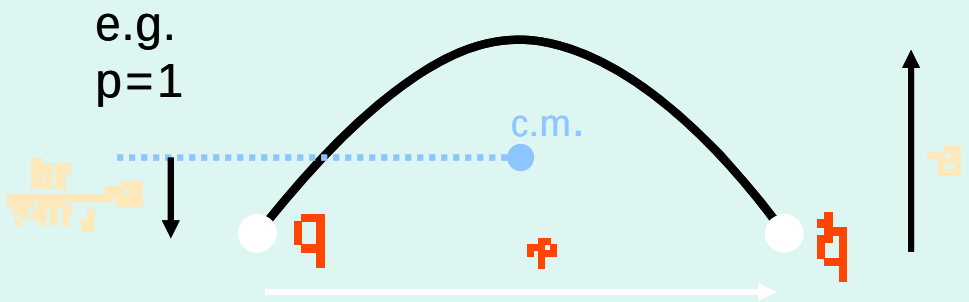
e.g. 1-+ ⇒ pi + (^1P_1) or (^3P_1)

| | $\pi_1 \to b_1(^1P_1)\pi$ | $\pi_1 \to f_1(^3P_1)\pi$ |
|---|---|---|
| Lattice | $2.9 \pm 0.4$ | $1.5 \pm 0.4$ |
| Flux tube | 2.9 | 1.4 |

Michael McNeile 06

FC Burns 06

# flux-tube breaking and decays




**Break tube: S+P states yes; S+S suppressed**

**S+S = 0 for hybrid charmonium**

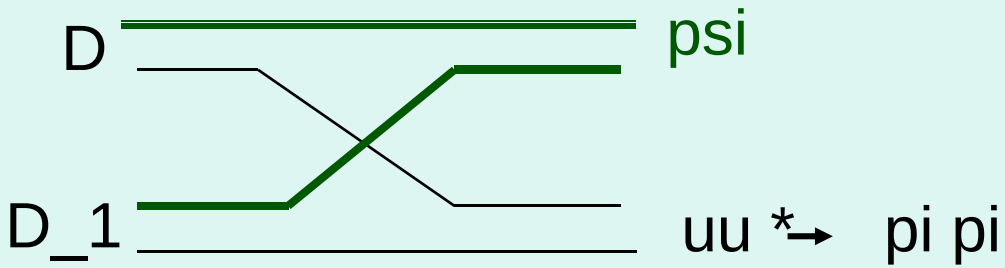
(FC + Page predictions 1995)

**Look for DD_{0,1}; a bit of DD* and absence of DD or D*D* and of DsDs or Ds*Ds***

**\psi f_0; \psi pipi; \chi \eta; h_c \eta also**

# The large psi +pi pi

S-wave, relative mom \sim 0;
DD_1 interchange constituents to make psi pipi “strongly”
(c.f. Swanson model of 3872 DD* \to psi omega)



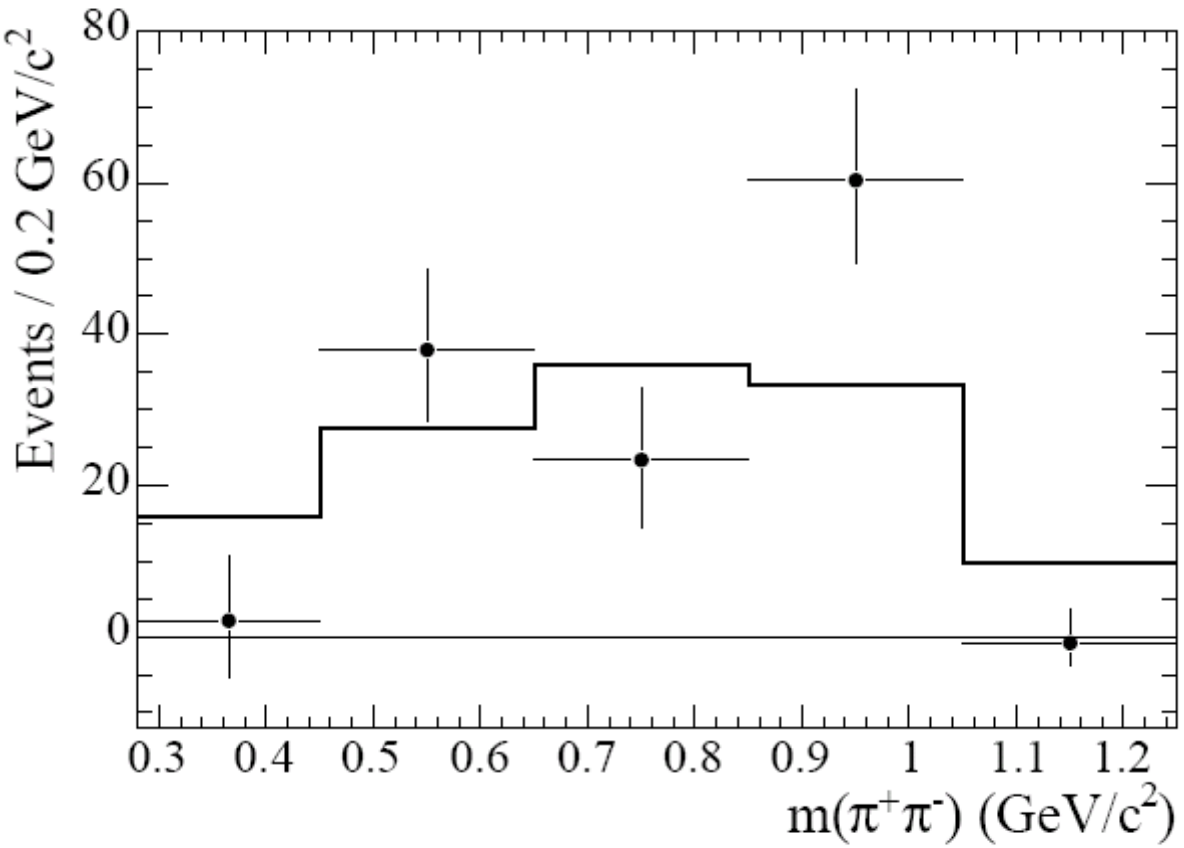



FIG. 3: The dipion mass distribution for $Y(4260) \to \pi^+\pi^- J/\psi$ data is shown as points with error bars. The histogram shows the distribution for Monte Carlo events where $Y(4260) \to \pi^+\pi^- J/\psi$ is generated according to an $S$-wave phase space model.

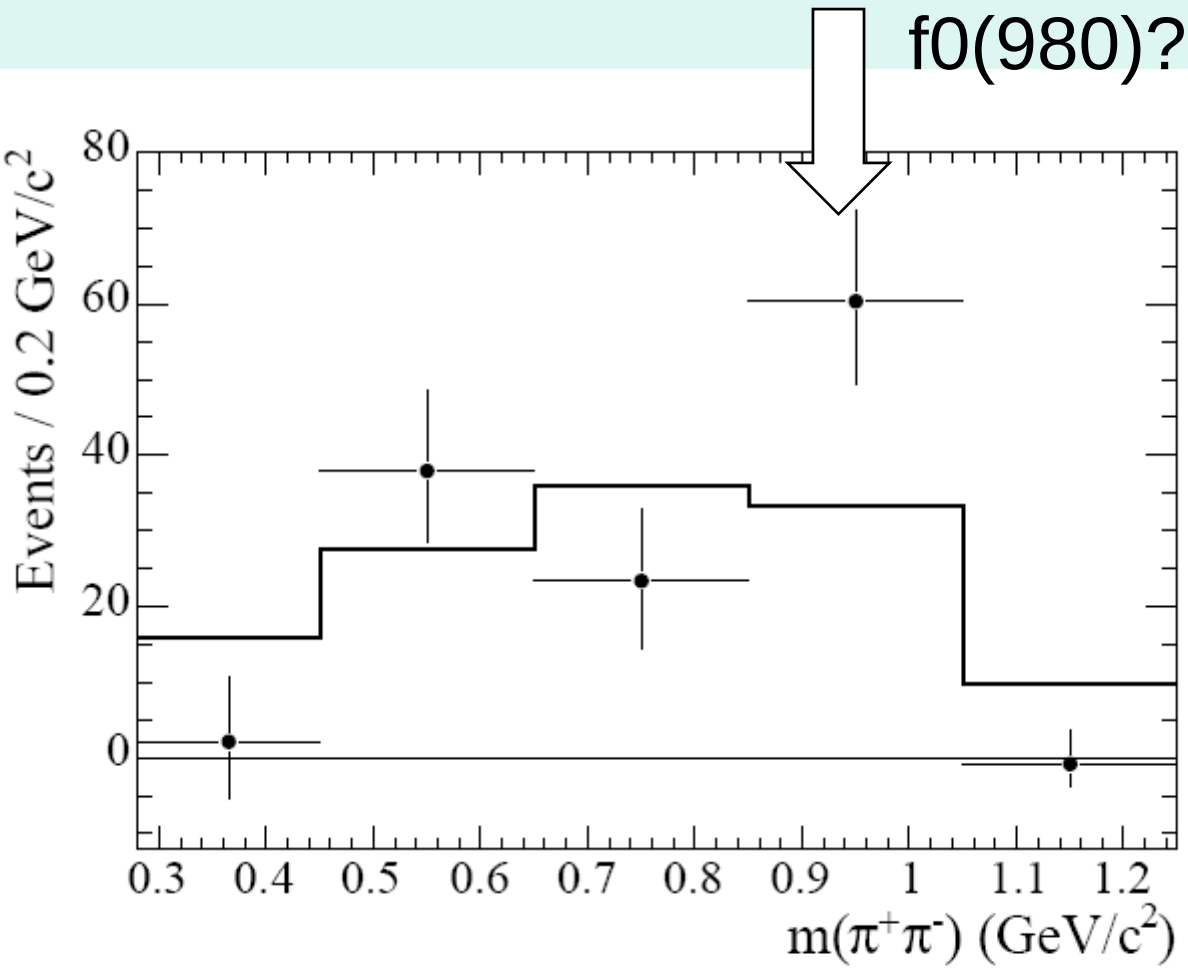



FIG. 3: The dipion mass distribution for $Y(4260) \to \pi^+\pi^- J/\psi$ data is shown as points with error bars. The histogram shows the distribution for Monte Carlo events where $Y(4260) \to \pi^+\pi^- J/\psi$ is generated according to an $S$-wave phase space model.

*The mass coincides with the $D_1(2420)D$ threshold:*

*The decay modes $\psi\sigma/\eta$, $\psi f_0(980)/a_0(980)$ appear to dominate:*

*$\Gamma(Y(4260) \to e^+e^-)$ is much smaller than all other $1^{--}$ charmonia:*

$$5.5\ eV \leq \Gamma(Y(4260) \to e^+e^-) \lesssim 62\ eV,$$

*$\Gamma(Y(4260) \to \psi\pi^+\pi^-)$ is much larger than all $1^{--}$ charmonia:*

$$\Gamma(Y(4260) \to \psi\pi^+\pi^-) \gtrsim 7.8\ MeV.$$

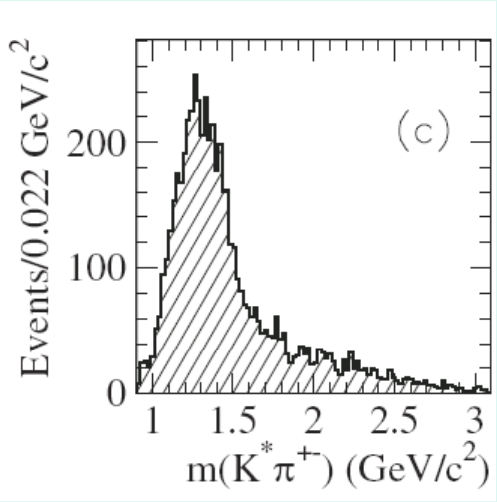
All consistent with **predictions** for hybrid charmonium

FC+Page 1995

PHYSICAL REVIEW D 71, 052001 (2005)

**$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and $K^+K^-K^+K^-$ cross sections at center-of-mass energies 0.5–4.5 GeV measured with initial-state radiation**

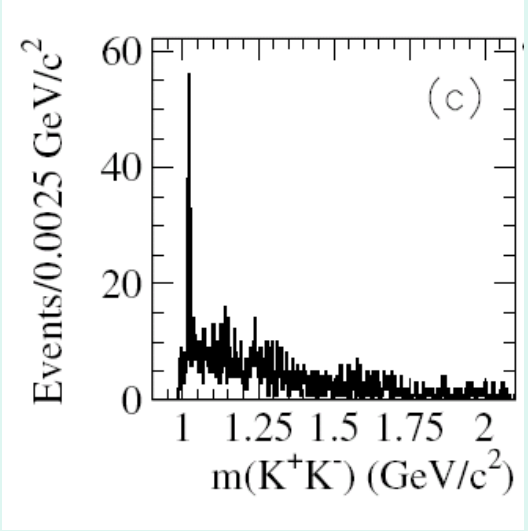
e+e- → KK_1

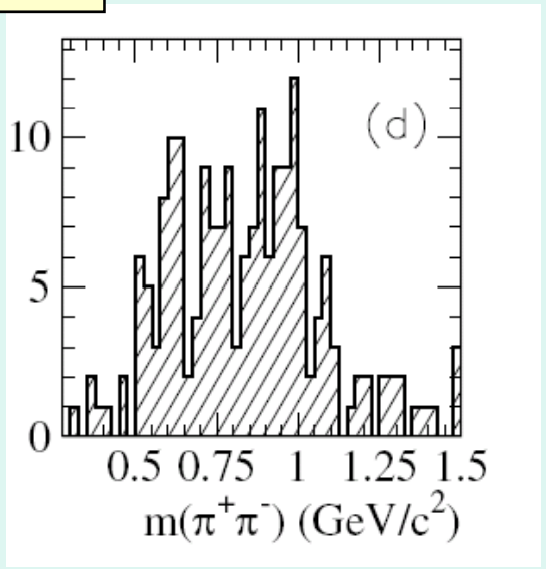



Future need to do:
Compare this with the DD_1 / psi pipi case:

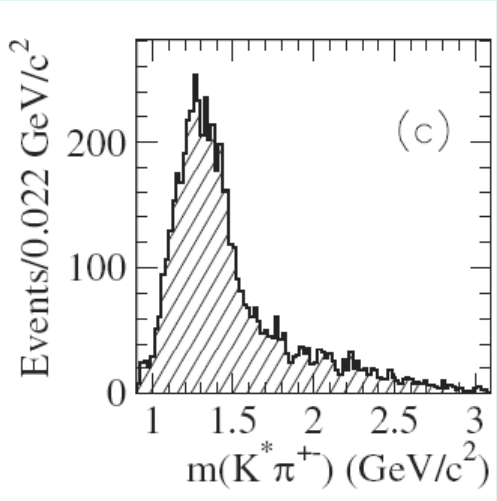
M(pipi);
phi (psi) polarisation

→ phi pi pi



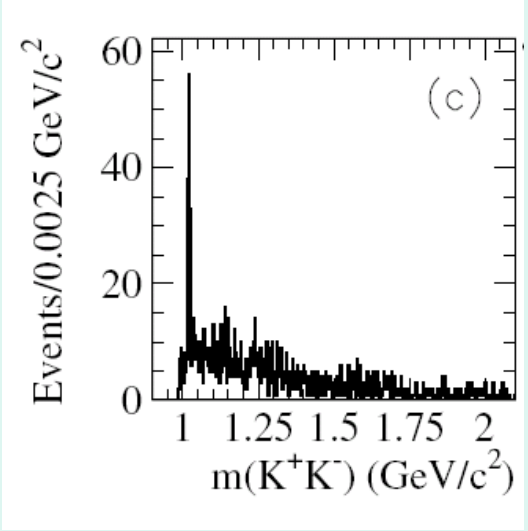
e+e- → KK_1

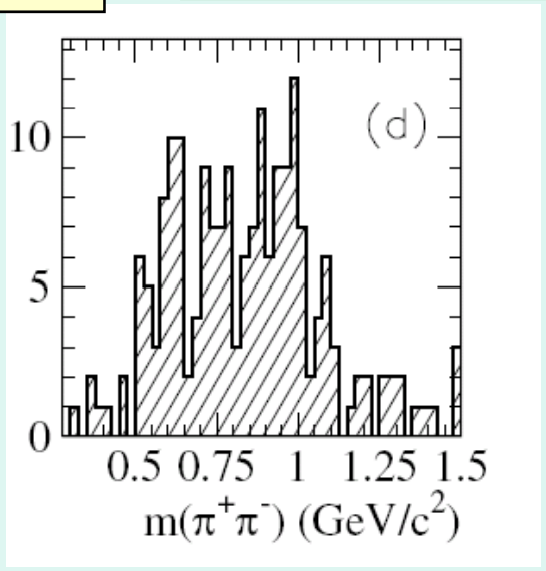



Intriguing resonant signal at 2190 = phi(hybrid)??

**2190 – m(phi) = 4265 – m(psi) !!??**

→ phi pi pi



## Four Quark Interpretation of $Y(4260)$

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*Università di Roma 'La Sapienza' and I.N.F.N., Roma, Italy*

F. Piccinini‡
*I.N.F.N. Sezione di Pavia and Dipartimento di Fisica Nucleare e Teorica, via A. Bassi, 6, I-27100, Pavia, Italy*

A.D. Polosa§
*Dip. di Fisica, Università di Bari and I.N.F.N., Bari, Italy*

$$Y(4260) = \left([cs]_{S=0}[\bar{c}\bar{s}]_{S=0}\right)_{\mathrm{P-wave}}$$

$$\Gamma_Y(D_s\bar{D}_s) >> \Gamma_Y(D\bar{D})$$

Dominant $D_s\bar{D}_s$ decay is quite a distinctive signature of the validity of the present model.

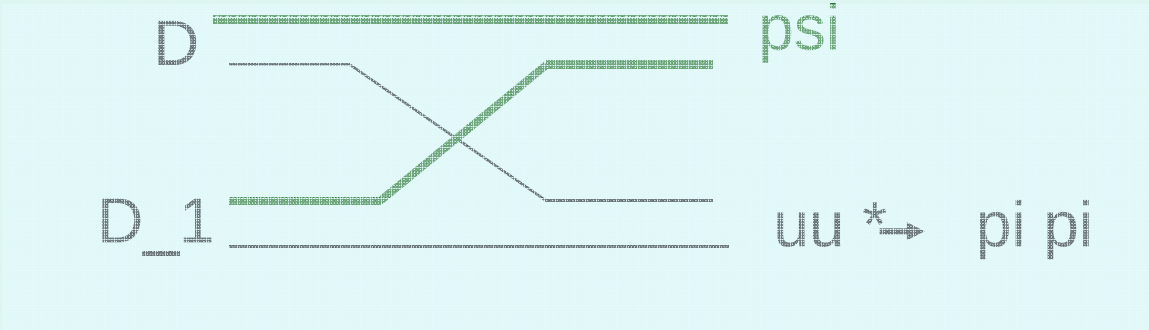
**This is a clear distinction with hybrid for which this is ~ zero**

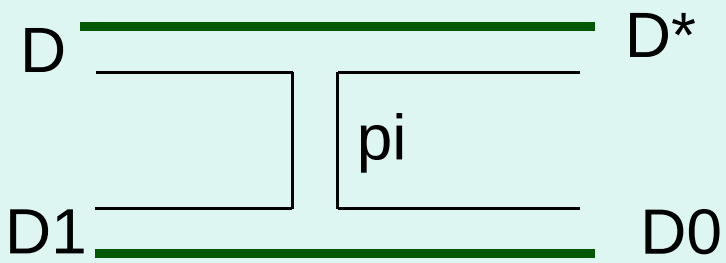
# Is it an S wave attraction?

e+e- ⇒ DD_1

**is first S-wave charm threshold and occurs \sim 4.2 GeV !**

S-wave, relative mom \sim 0;
DD_1 interchange constituents to make psi pipi “strongly”
(c.f. Swanson model of 3872 DD* \to psi omega)






Pi exchange drives attraction

1- - isoscalar: like 4260

1– +  isovector:  doubly exotic!

Y(4260) Three Possibilities

Y(4260) = S wave effect

My worry

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\mathrm{P-wave}}$$

Maiani

$$Y(4260) \textbf{ as hybrid charmonium}$$

Close

DD_1 and not DsDs for hybrid

DsDs and not DD_1 for tetraquark

→ Experiment can decide

Y(4260) Three Possibilities

Y(4260) = S wave effect

My worry

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\mathrm{P-wave}}$$

Maiani

$$Y(4260) \textbf{ as hybrid charmonium}$$

Close

**If NOT hybrid cc* then why not/where is it ?!**

DD_1 and not DsDs for hybrid

DsDs and not DD_1 for tetraquark

→ Experiment can decide

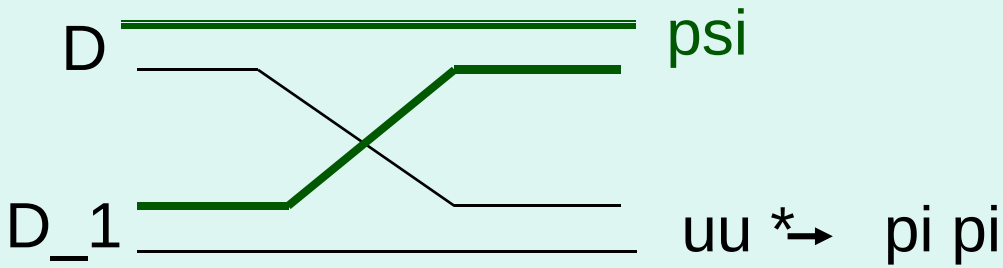
end

# Is it really a resonance?

e+e- ⇒ DD_1

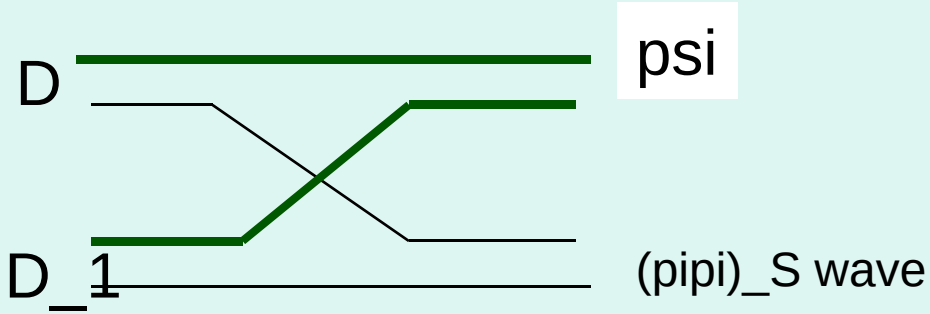
is first S-wave charm threshold and occurs \sim 4.2 GeV !

S-wave, relative mom \sim 0;
DD_1 interchange constituents to make psi pipi “strongly”
(c.f. Swanson model of 3872 DD* \to psi omega)




e+e- ⇒ Ds Ds_1 ⇒ psi KK should show similar

# Psi polarisation test in X(4260) \to psi pipi




Hybrid cc* has spin(cc*)=0 (!)
Swanson exchange model ⇨ psi polarised transverse

FC Swanson

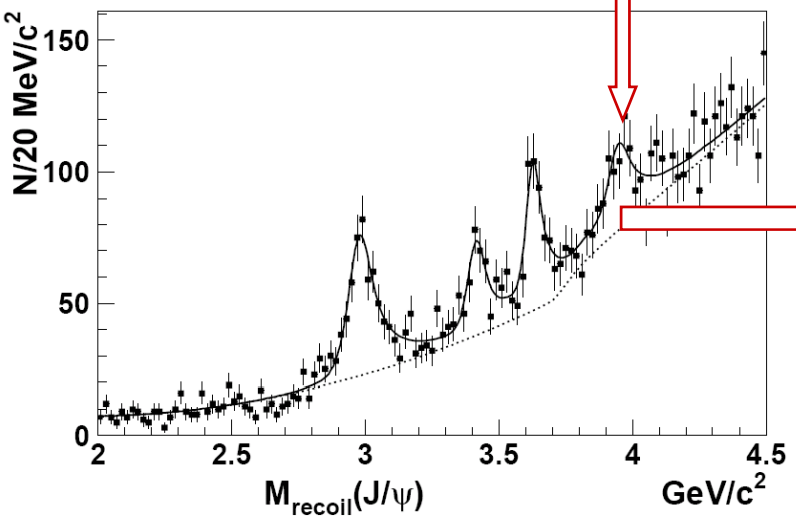
If spin cc* = 1 (conventional) psi polarisation different but model dependence to be understood

In any event, poln measure should be done and compared with phi in the KK_1 region

S=1 qq* pair creation triggers decays
+ algebraic 6j 9j factorisation

Production of: qq* + qq*
Hybrid + qq*
Hybrid + Hybrid

e+e- \to psi + (0-+ or 1-+)Hyb =0




Not hybrid!

But……