# THEORY OF XYZ

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# THE NEW HADRON RESONANCES

| State | $m$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment (#$\sigma$) | Year | Status |
|---|---|---|---|---|---|---|---|
| $X(3872)$ | 3871.52±0.20 | 1.3±0.6<br>(<2.2) | $1^{++}/2^{-+}$ | $B \to K(\pi^+\pi^- J/\psi)$<br>$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$<br>$B \to K(\omega J/\psi)$<br>$B \to K(D^{*0}\bar{D}^0)$<br>$B \to K(\gamma J/\psi)$<br>$B \to K(\gamma\psi(2S))$ | Belle [85, 86] (12.8), *BABAR* [87] (8.6)<br>CDF [88–90] (np), DØ [91] (5.2)<br>Belle [92] (4.3), *BABAR* [93] (4.0)<br>Belle [94, 95] (6.4), *BABAR* [96] (4.9)<br>Belle [92] (4.0), *BABAR* [97, 98] (3.6)<br>*BABAR* [98] (3.5), Belle [99] (0.4) | 2003 | OK |
| $X(3915)$ | $3915.6 \pm 3.1$ | 28±10 | $0/2^{?+}$ | $B \to K(\omega J/\psi)$<br>$e^+e^- \to e^+e^-(\omega J/\psi)$ | Belle [100] (8.1), *BABAR* [101] (19)<br>Belle [102] (7.7) | 2004 | OK |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^- \to J/\psi(D\bar{D}^*)$<br>$e^+e^- \to J/\psi\ (...)$ | Belle [103] (6.0)<br>Belle [54] (5.0) | 2007 | NC! |
| $G(3900)$ | $3943 \pm 21$ | 52±11 | $1^{--}$ | $e^+e^- \to \gamma(D\bar{D})$ | *BABAR* [27] (np), Belle [21] (np) | 2007 | OK |
| $Y(4008)$ | $4008^{+121}_{-49}$ | 226±97 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | Belle [104] (7.4) | 2007 | NC! |
| $Z_1(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $B \to K(\pi^+\chi_{c1}(1P))$ | Belle [105] (5.0) | 2008 | NC! |
| $Y(4140)$ | $4143.4 \pm 3.0$ | $15^{+11}_{-7}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | CDF [106, 107] (5.0) | 2009 | NC! |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $e^+e^- \to J/\psi(D\bar{D}^*)$ | Belle [103] (5.5) | 2007 | NC! |
| $Z_2(4250)^+$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | ? | $B \to K(\pi^+\chi_{c1}(1P))$ | Belle [105] (5.0) | 2008 | NC! |
| $Y(4260)$ | $4263 \pm 5$ | 108±14 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$<br><br><br>$e^+e^- \to (\pi^+\pi^- J/\psi)$<br>$e^+e^- \to (\pi^0\pi^0 J/\psi)$ | *BABAR* [108, 109] (8.0)<br>CLEO [110] (5.4)<br>Belle [104] (15)<br>CLEO [111] (11)<br>CLEO [111] (5.1) | 2005 | OK |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | CDF [107] (3.1) | 2010 | NC! |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0,2^{++}$ | $e^+e^- \to e^+e^-(\phi J/\psi)$ | Belle [112] (3.2) | 2009 | NC! |
| $Y(4360)$ | $4353 \pm 11$ | 96±42 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | *BABAR* [113] (np), Belle [114] (8.0) | 2007 | OK |
| $Z(4430)^+$ | $4443^{+24}_{-18}$ | $107^{+113}_{-71}$ | ? | $B \to K(\pi^+\psi(2S))$ | Belle [115, 116] (6.4) | 2007 | NC! |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$ | Belle [25] (8.2) | 2007 | NC! |
| $Y(4660)$ | 4664±12 | 48±15 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | Belle [114] (5.8) | 2007 | NC! |
| $Y_b(10888)$ | 10888.4±3.0 | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$ | Belle [37, 117] (3.2) | 2010 | NC! |

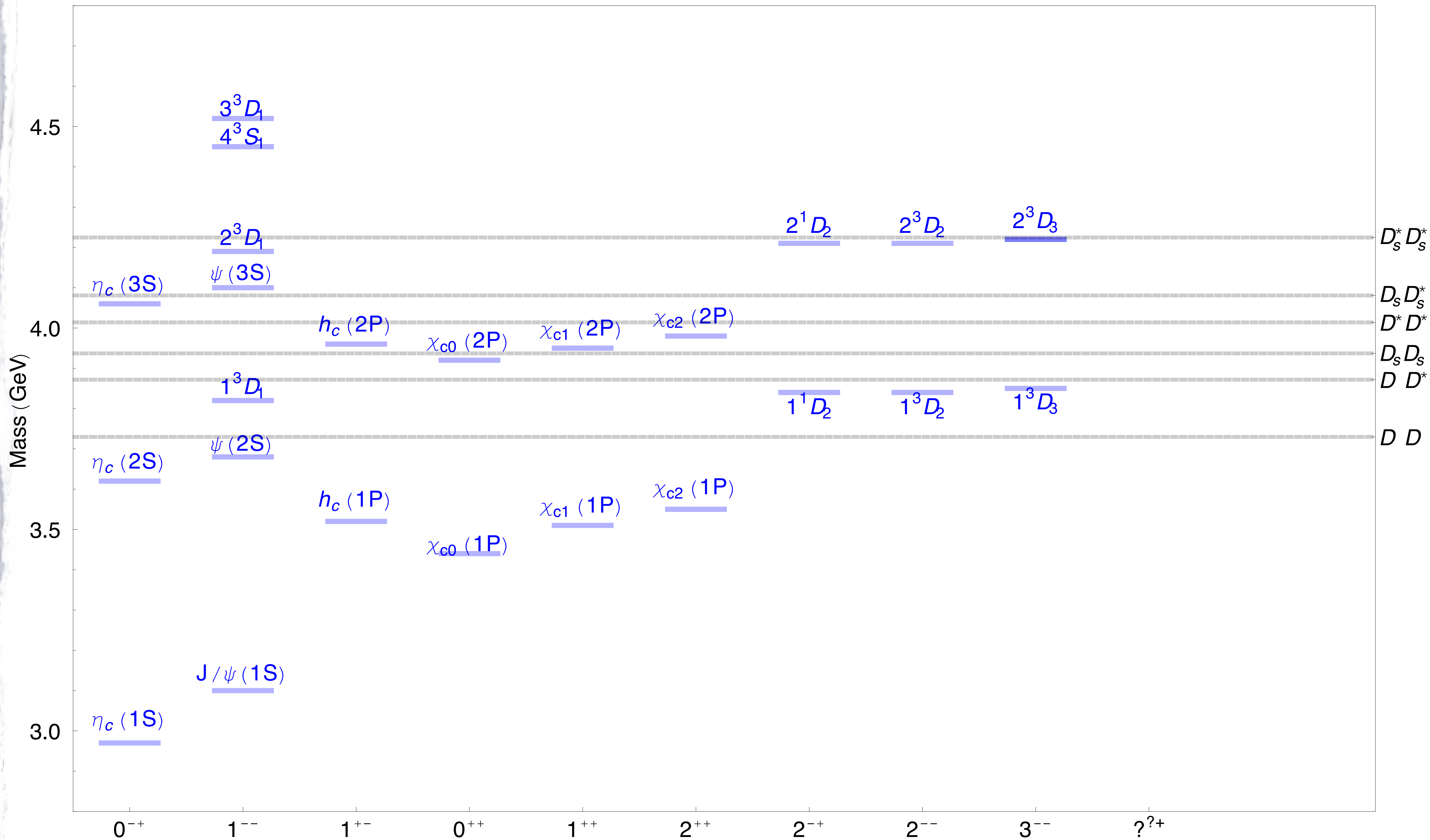
Brambilla et al. QWG, arXiv:1010.5827

*Prencipe*
*BaBar*
*Charm*
*2012*

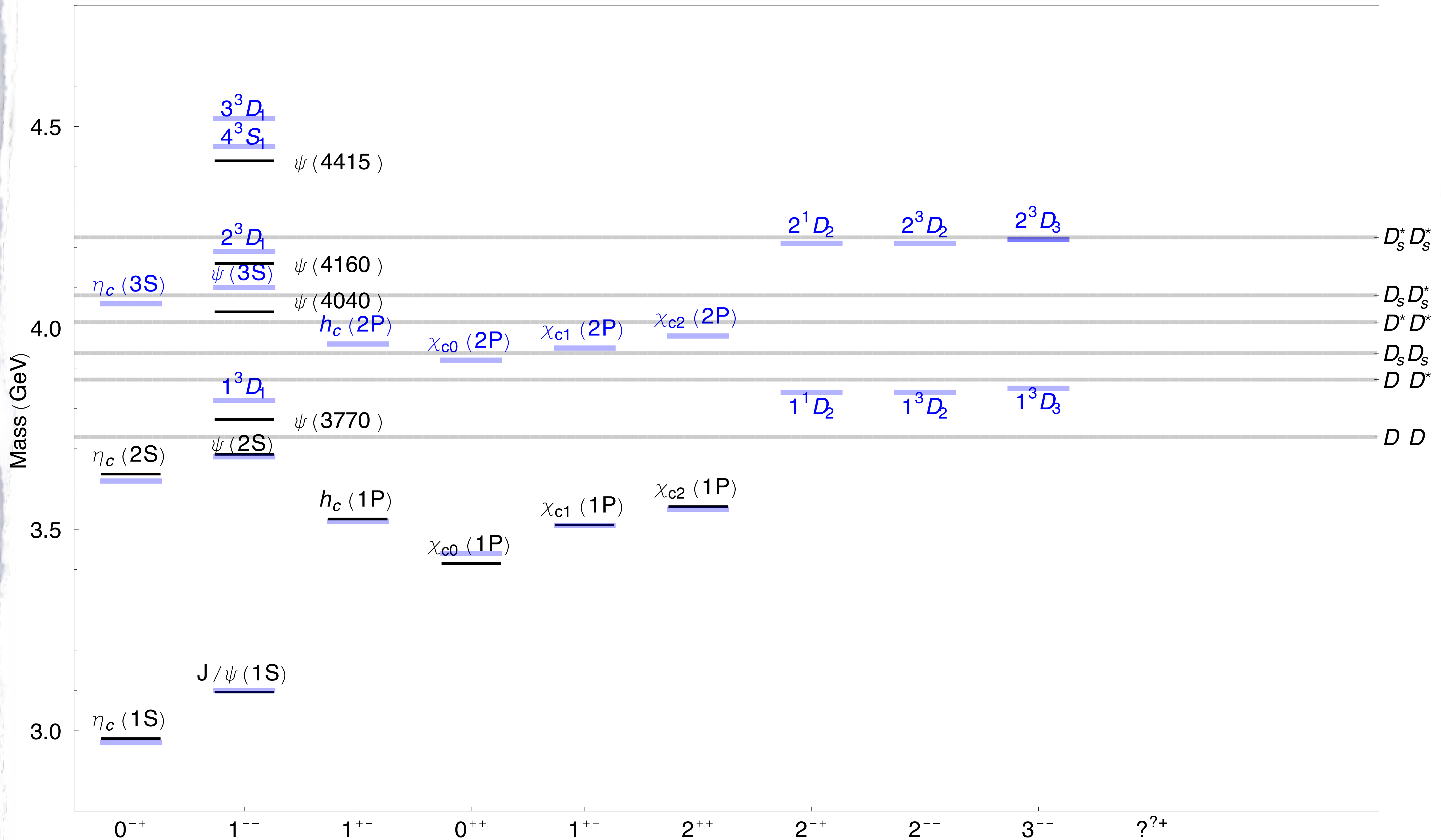
← *NO* (Y(4008))

← *YES* (Y(4660))

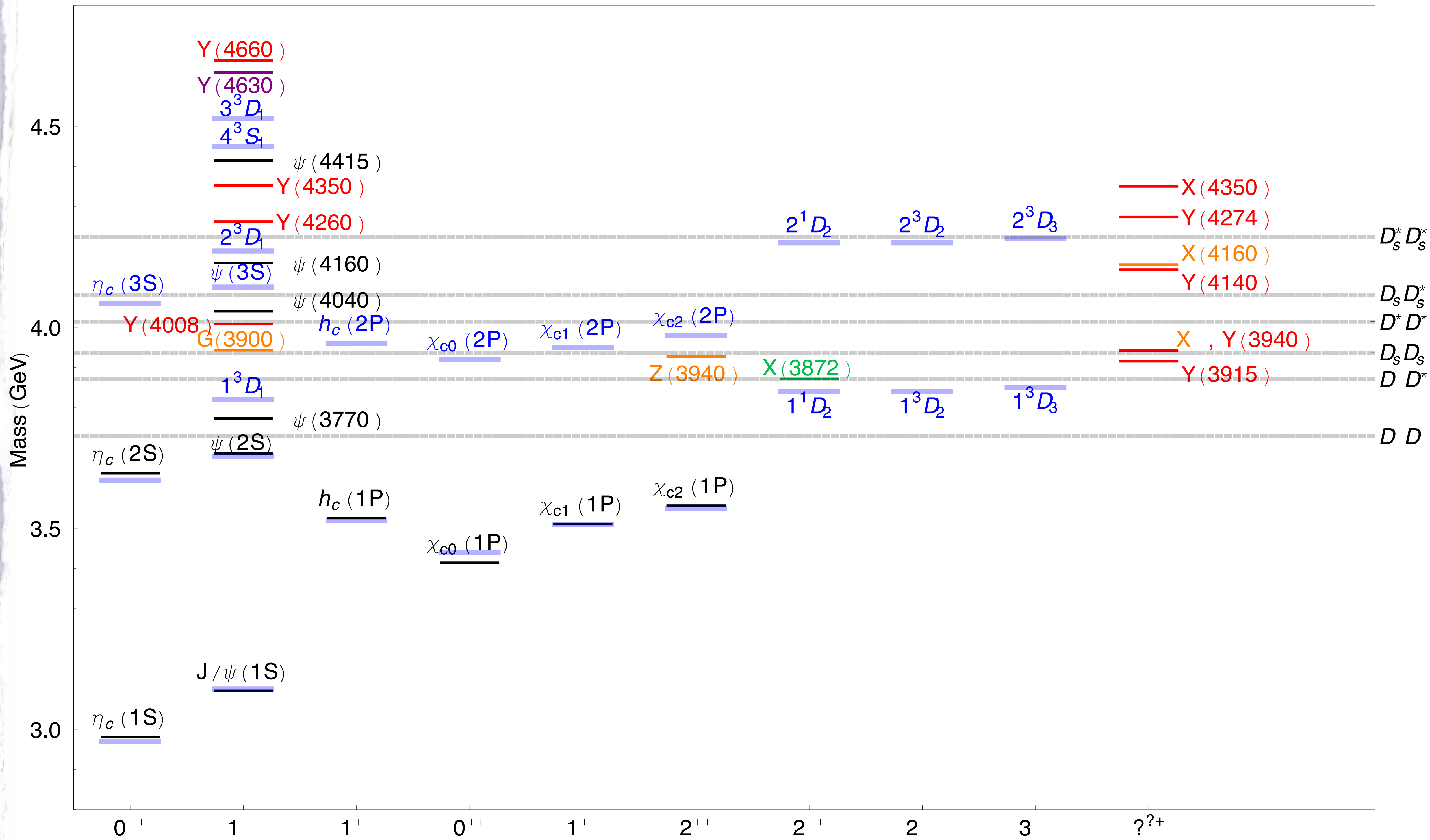
# As Predicted by Charmonium Theory



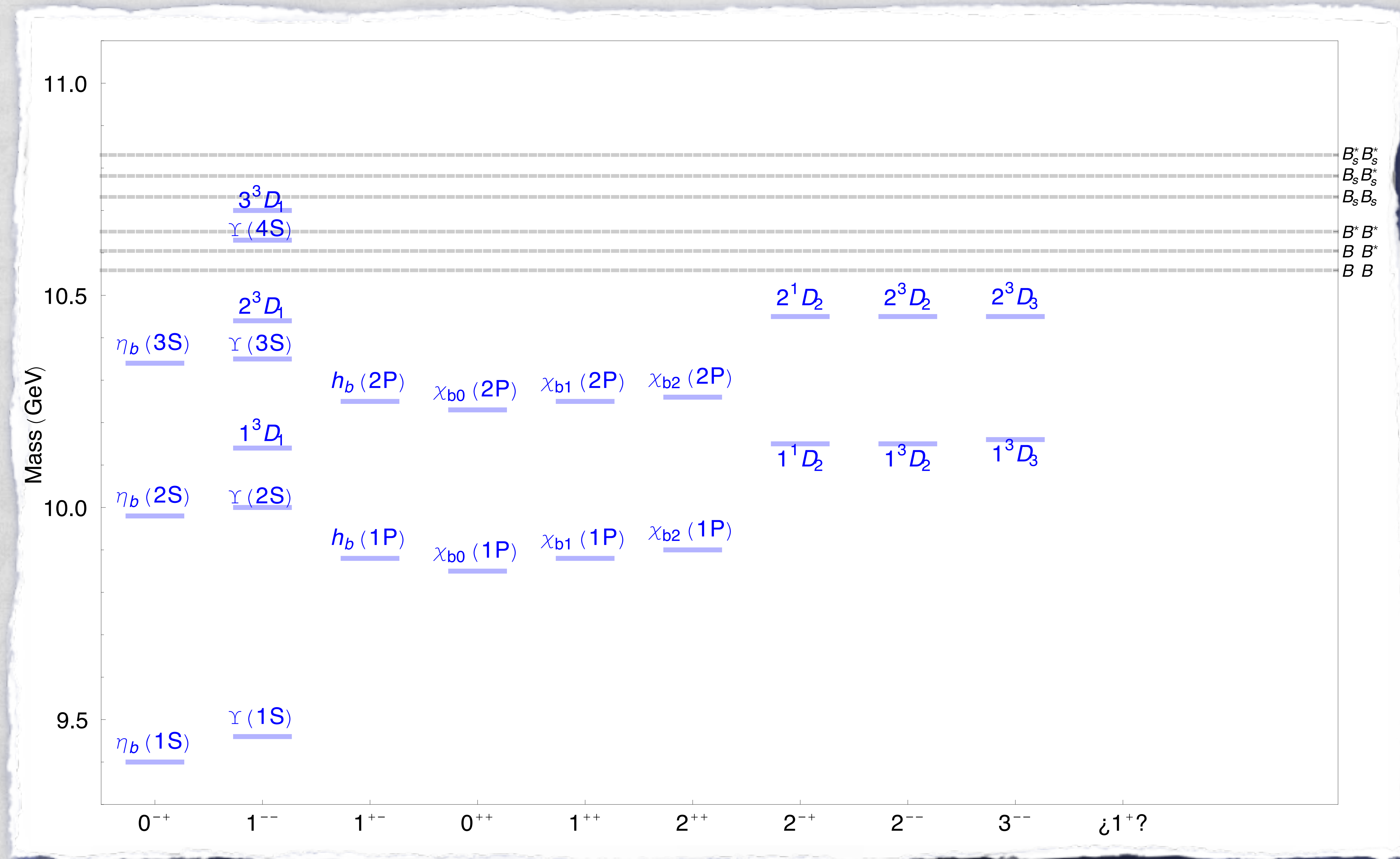
# Experimentally Observed Levels



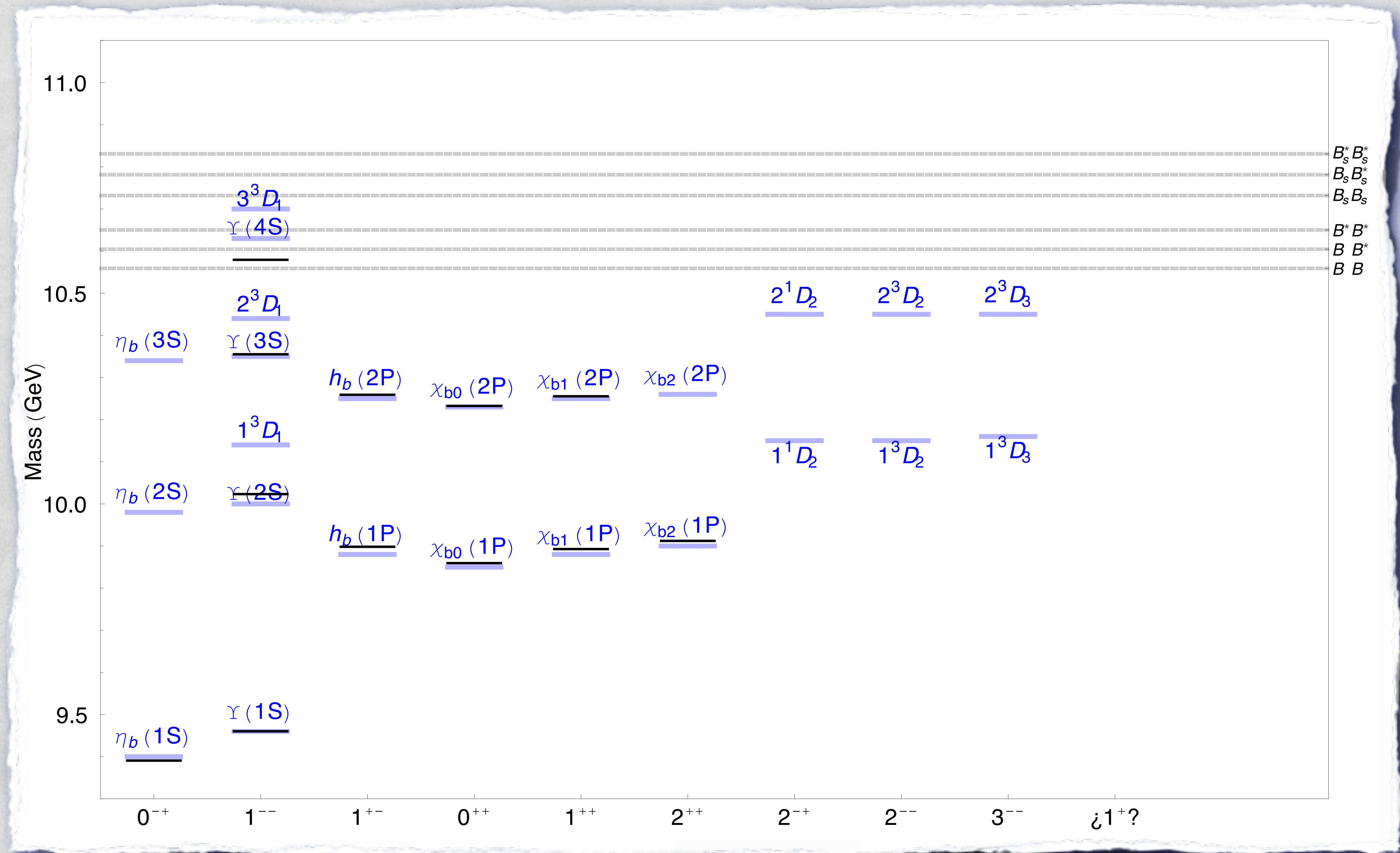
# The New States



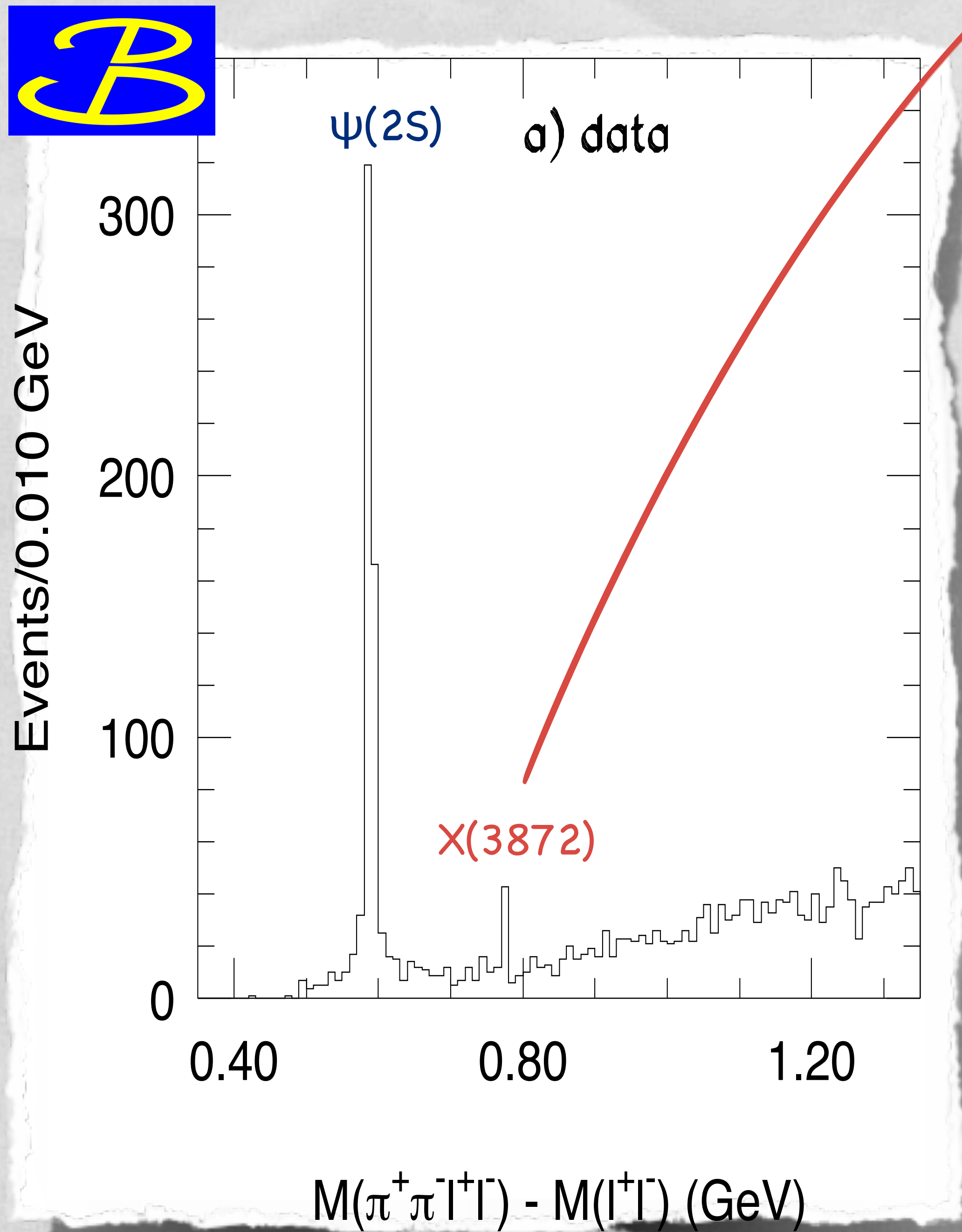
# As Predicted by Bottomonium Theory

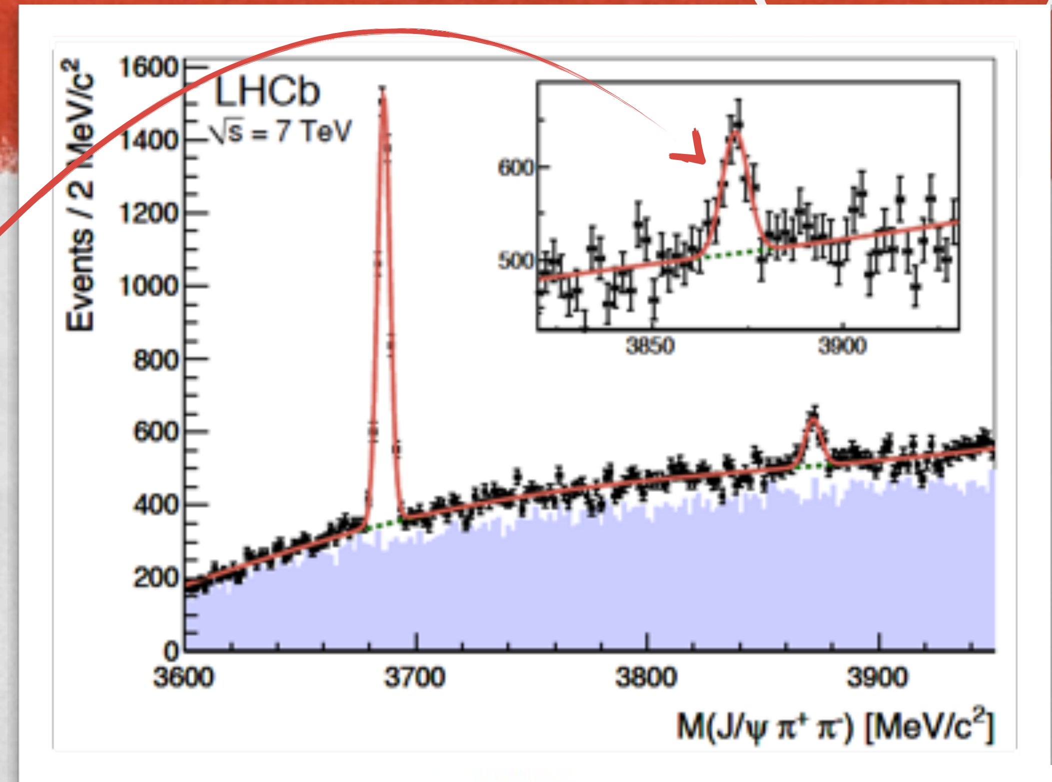


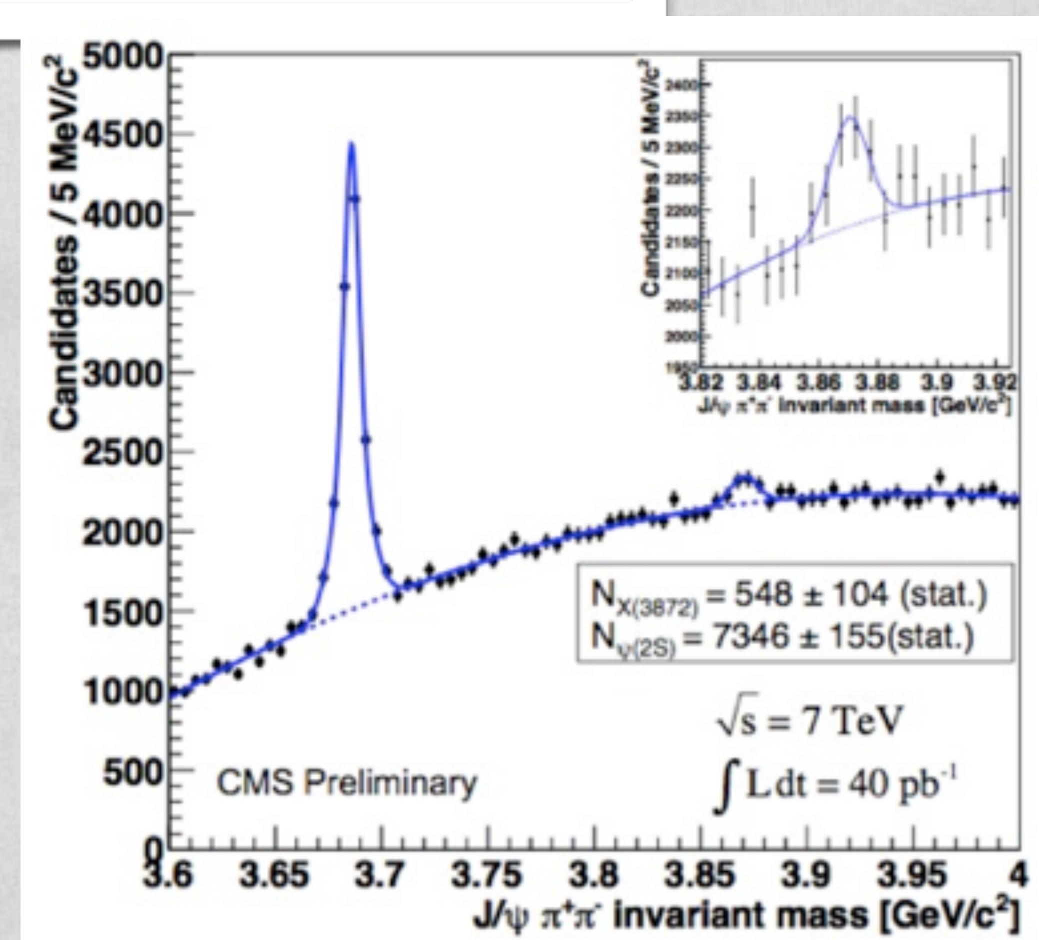
# Experimentally Observed Levels



# THE X(3872) DISCOVERY (2003)



# X : CHARMONIUM OR 'EXOTIC'?

- From the beginning it was realized that the radiative decay of $X \to J/\psi\ \gamma$ was way too small in comparison with $J/\psi+\rho$ to fit a standard charmonium picture as $2\ ^3P_1$ (Eichten, Lane and Quigg)

- $J/\psi+\rho$ and $J/\psi+\omega$ channels have very similar rates (isospin violation) - unexpected for a cc*!

- The mass of the X is almost *exactly* equal to the sum of the masses of D and D* open charm mesons

- The mass of the X does *not fit* with the expected accuracy *any of the predicted charmonium levels.*

For a rather long time the X has been supposed to be a $1^{++}$ state.

***We are now in the puzzling situation that data could (re)open the $2^{-+}$ option ...***

R. Faccini, F. Piccinini, A. Pilloni, and ADP, *'On the Spin of the X(3872)'*, arXiv:1204.1223

T. Burns, F Piccinini, ADP, C. Sabelli, *'The $2^{-}$+ assignment for the X(3872)'*, *Phys. Rev. D 2010*

# Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
*Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*
(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

## I. INTRODUCTION

IN recent years several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

It is by no means certain that nucleons, mesons, electrons, neutrinos are all elementary particles and it could be that at least some of the failures of the present theories may be due to disregarding the possibility that some of them may have a complex structure. Unfortunately, we have no clue to decide whether this is true, much less to find out what particles are simple and what particles are complex. In what follows we will try to work out in some detail a special example more as an illustration of a possible program of the theory of particles, than in the hope that what we suggest may actually correspond to reality.

We propose to discuss the hypothesis that the π-meson may not be elementary, but may be a composite particle formed by the association of a nucleon and an anti-nucleon. The first assumption will be, therefore, that both an anti-proton and an anti-neutron exist, having the same relationship to the proton and the neutron, as the electron to the positron. Although this is an assumption that goes beyond what is known experimentally, we do not view it as a very revolutionary one. We must assume, further, that between a nucleon and an anti-nucleon strong attractive forces exist, capable of binding the two particles together.

We assume that the π-meson is a pair of nucleon and anti-nucleon bound in this way. Since the mass of the π-meson is much smaller than twice the mass of a nucleon, it is necessary to assume that the binding energy is so great that its mass equivalent is equal to the difference between twice the mass of the nucleon and the mass of the meson.

According to this view the positive meson would be the association of a proton and an anti-neutron and the negative meson would be the association of an anti-proton and a neutron. As a model of a neutral meson one could take either a pair of a neutron and an anti-neutron, or of a proton and an anti-proton.

It would be difficult to set up a not too complicated scheme of forces between a nucleon and an anti-nucleon, without about equally strong forces between two ordinary nucleons. These last forces, however, would be quite different from the ordinary nuclear forces, because they would have much greater energy and much shorter range. The reason why no experimental indication of them has been observed for ordinary nucleons may be explained by the assumption that the forces could be attractive between a nucleon and an anti-nucleon and repulsive between two ordinary nucleons. If this is the case, no bound system of two ordinary nucleons would result out of this particular type of interaction. Because of the short range very little would be noticed of such forces even in scattering phenomena.

Ordinary nuclear forces from the point of view of this theory will be discussed below.

Unfortunately we have not succeeded in working out a satisfactory relativistically invariant theory of nucleons among which such attractive forces act. For this reason all the conclusion that will be presented will be

* Now at the Institute for Advanced Study, Princeton, New Jersey.

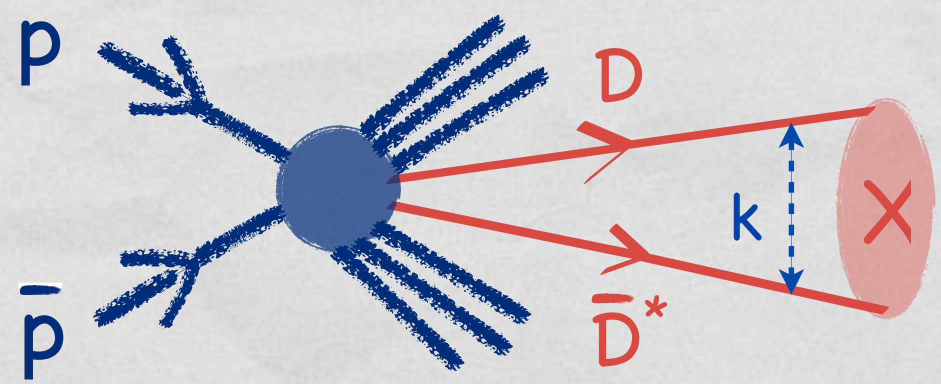


Friday, June 1, 12

# X - A DIFFERENT KIND OF MOLECULE

E. Braaten & Kusunoki, E. Swanson, F. Close and many others

The *loosely bound (~0 MeV)* molecule (DD*) interpretation is tempting - it accomodates the isospin problem. But what about production at hadron colliders?




But then, what about the high production cross sections at Tevatron and LHC?
*Computer simulations leave no space to the molecule hypothesis.*

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Rev Lett*, ***103***, *162001 (2009)*

C. Bignamini, B. Grinstein, F. Piccinini, ADP, C. Sabelli, *Phys Lett*, ***B684***, *228 (2010)*

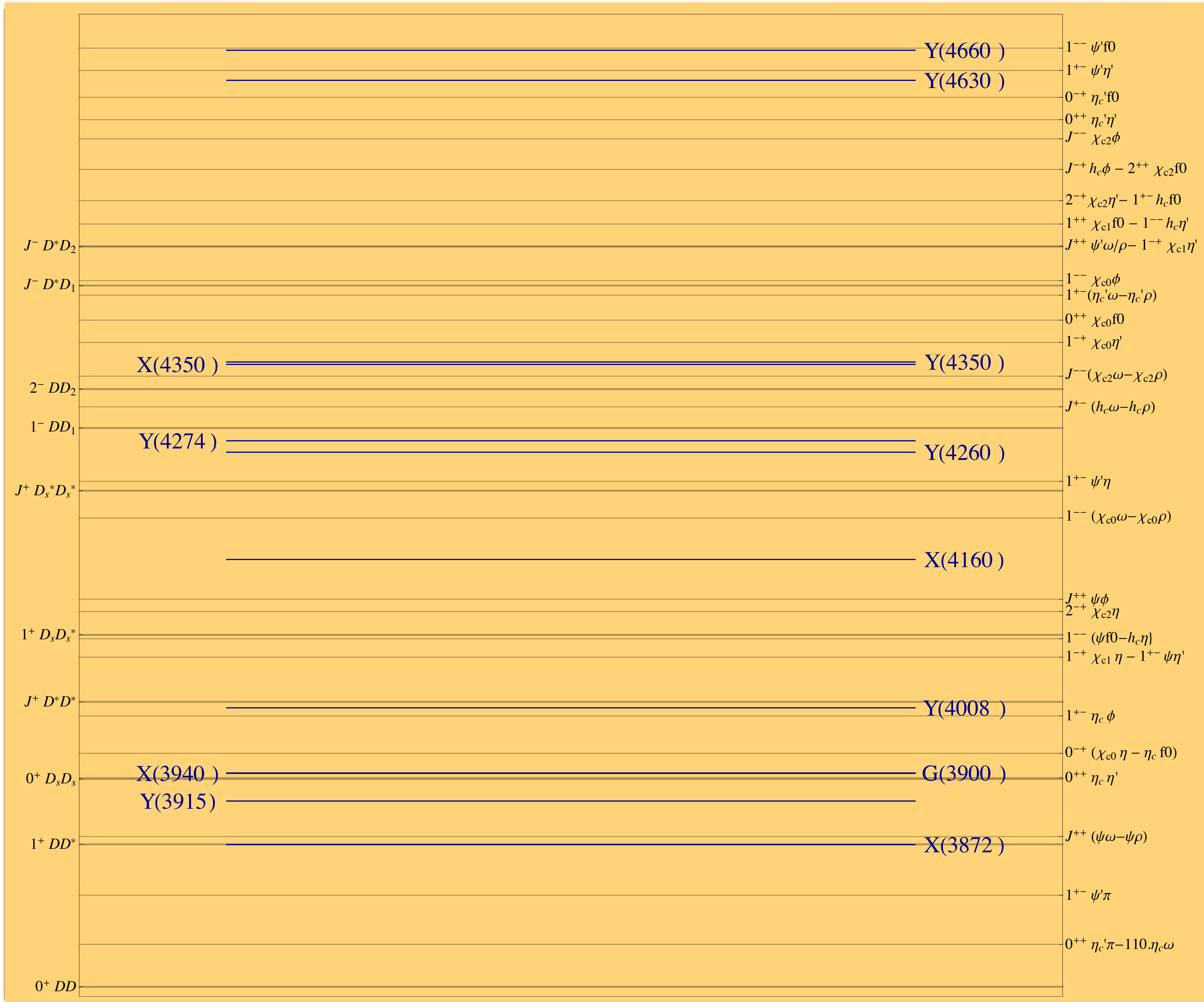
Can final state interactions allow such high production cross sections?
How can occurr the decay into J/ψ initiated by a 10 fm bound state of color neutral mesons?

P. Artoisenet and E. Braaten, *Phys Rev* ***D81***, *114018 (2010)*

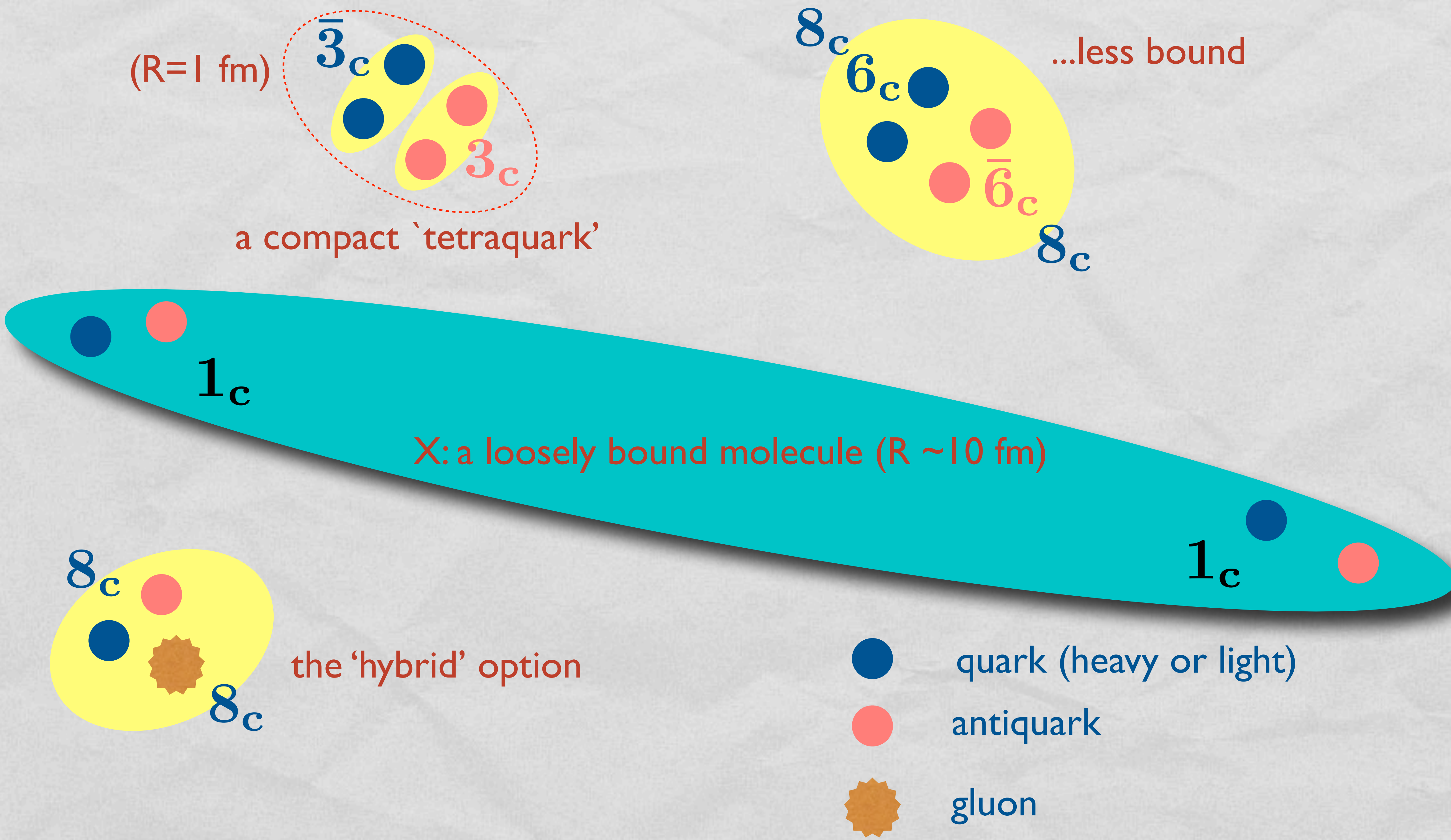
*And more: if $2^{-+}$ is confirmed the molecule hypothesis is ruled out.*

# THRESHOLDS (CHARM SECTOR)

A considerable amount of 'unoccupied' thresholds

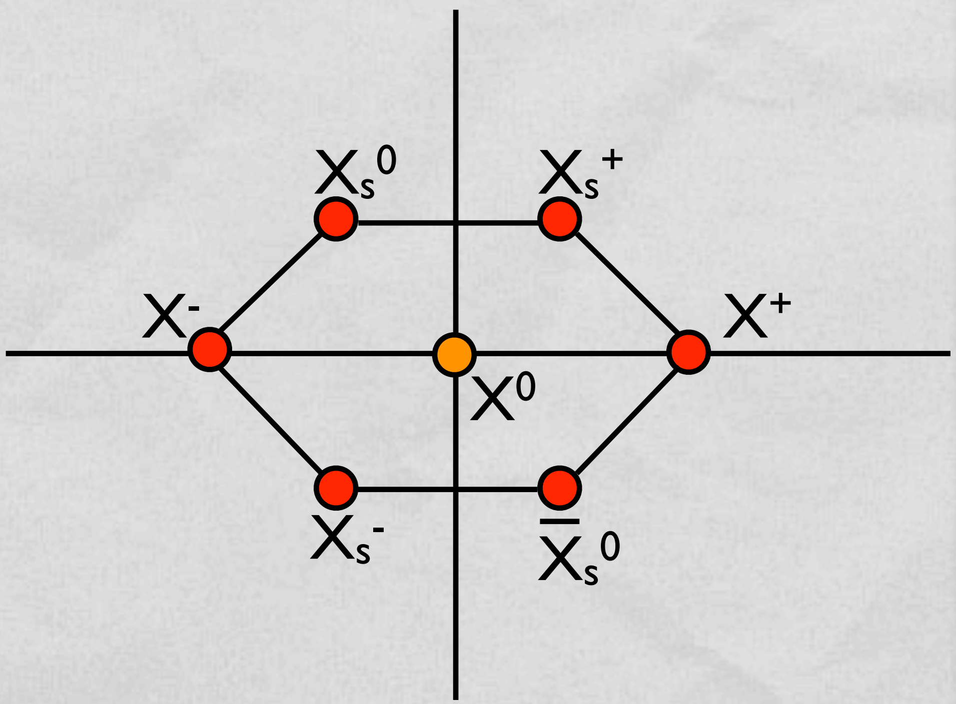


# OPTIONS FOR COLOR NEUTRAL STATES



# CHARMED DIQUARKS

The octet with diquarks - the 'azimuthal approach'




$$\mathfrak{q}_{i\alpha} = \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}\bar{q}_C^{j\beta}\gamma_5 q^{k\gamma} = [qq]_0$$

$$\mathfrak{q}_{\alpha}^{jk} = \epsilon_{\alpha\beta\gamma}\bar{q}_C^{\beta(j}\vec{\gamma}q^{k)\gamma} = [qq]_1$$

| $J^{PC}$ | dq-dq* |
|---|---|
| $0^{++}$ | $[cq]_0[\bar{c}\bar{q}]_0 \;\vee\; ([cq]_1[\bar{c}\bar{q}]_1)_0$ |
| $1^{++}$ | $\frac{[cq]_1[\bar{c}\bar{q}]_0 + [cq]_0[\bar{c}\bar{q}]_1}{\sqrt{2}}$ |
| $1^{+-}$ | $\frac{[cq]_1[\bar{c}\bar{q}]_0 - [cq]_0[\bar{c}\bar{q}]_1}{\sqrt{2}} \;\vee\; ([cq]_1[\bar{c}\bar{q}]_1)_1$ |
| $2^{++}$ | $([cq]_1[\bar{c}\bar{q}]_1)_2$ |

$$([\;]_s[\;]_s)_J$$

# ISOSPIN VIOLATIONS

We set in the flavor basis $X_u, X_d$

$$M = \begin{pmatrix} 2m_u & 0 \\ 0 & 2m_d \end{pmatrix} + \delta \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

where the mixing matrix has a diagonal structure in the Isospin $I = 0, 1$ basis, its eigenvectors being

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

At the charmonium scale we expect the annihilations to be small and quark mass to dominate - observed X -> ω/ρ isospin breaking

G.C. Rossi, G. Veneziano; L. Maiani, F. Piccinini, ADP, V.Riquer PRD 2005

# DIQUARK MODEL

Drenska, Faccini, ADP, Phys. Lett. B669, 160 (2008), Phys. Rev. D79, 077502 (2009)

$$H = 2m_{\boldsymbol{q}} + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

$$H_{SS}^{(qq)} = 2\kappa_q(\vec{S}_{q_1} \cdot \vec{S}_{q_2} + \vec{S}_{\bar{q}_1} \cdot \vec{S}_{\bar{q}_2})$$

$$H_{SS}^{(q\bar{q})} = 2\kappa_{q_1\bar{q}_2}(\vec{S}_{q_1} \cdot \vec{S}_{\bar{q}_2} + \vec{S}_{\bar{q}_1} \cdot \vec{S}_{q_2}) + 2\kappa_{q_1\bar{q}_1}\vec{S}_{q_1} \cdot \vec{S}_{\bar{q}_1} + 2\kappa_{q_2\bar{q}_2}\vec{S}_{q_2} \cdot \vec{S}_{\bar{q}_2}$$

$$H_{SL} = 2A_{\boldsymbol{q}}(\vec{S}_{\boldsymbol{q}} \cdot \vec{L} + \vec{S}_{\bar{\boldsymbol{q}}} \cdot \vec{L})$$

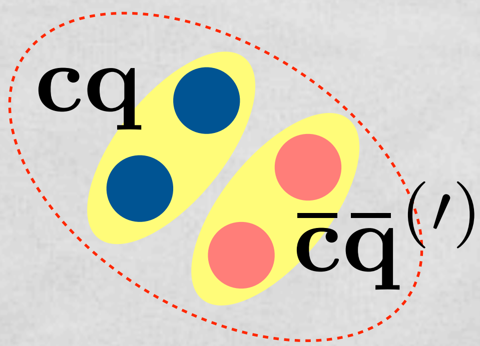
$$H_{LL} = B_{\boldsymbol{q}}\frac{L(L+1)}{2}$$

$$\kappa_{c\bar{c}}([cq][\bar{c}\bar{q}]) = \frac{1}{3}(\kappa_{c\bar{c}})_1 + \frac{2}{3}(\kappa_{c\bar{c}})_8$$

$$\kappa_{c\bar{c}} \sim (C_R^{(2)} - C_3^{(2)} - C_{\bar{3}}^{(2)})$$

# TETRAQUARKS ?

L. Maiani, F. Piccinini, ADP, V. Riquer, Phys. Rev. **D71**, 014028 (2005)




- Two neutral X predicted with an hyperfine separation in mass to accomodate isospin
- Charged partners (degenerate in mass?) with Q=±1 or even Q=2 such as in [cu][d*s*]. Not seen. Are they just too broad? (Work by Terasaki - See Bhardwaj's talk in Charm2012 - parallel session)
- The heavier partners of light tetraquarks (scalars) ...

G. 't Hooft, G. Isidori, L. Maiani, ADP, V. Riquer, *Phys Lett B 2008*

Today we have *5 charged states* - not explained by any unified picture
(to be confirmed )

$$Z(4430), Z_1(4050), Z_2(4250), Z(10610), Z(10650)$$

The decay pattern preferring a ψ(2S) (or η(2S)) is completely obscure.
The last two were found in May 2011.

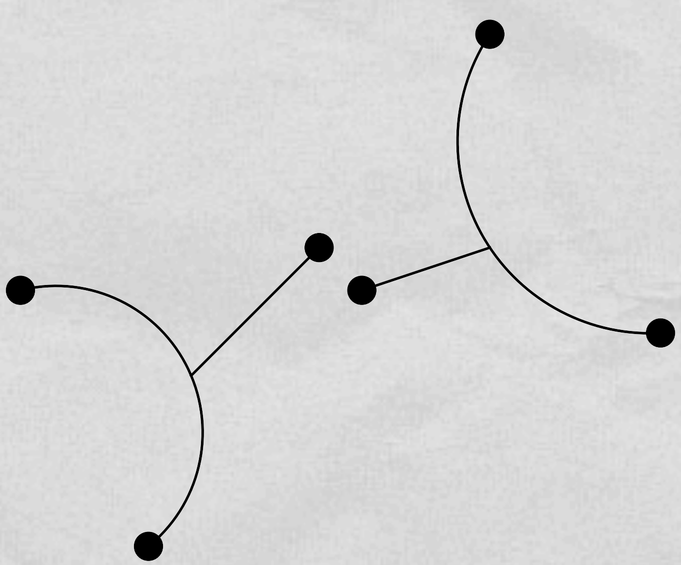
# TETRQUARKS PREFER BARYON DECAYS

G. Cotugno, R. Faccini, ADP, C. Sabelli *Phys. Rev. Lett.* ***104****, 132005 (2010)*

We observed that Y(4660) and Y(4630) might be one and the same particle ($Y_B$) showing how this hypothesis improves the fit to Belle data.

Under this hypothesis we found the remarkable ratio

$$\frac{\mathcal{B}(Y_B \to \Lambda_c \bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 24.6 \pm 6.6$$

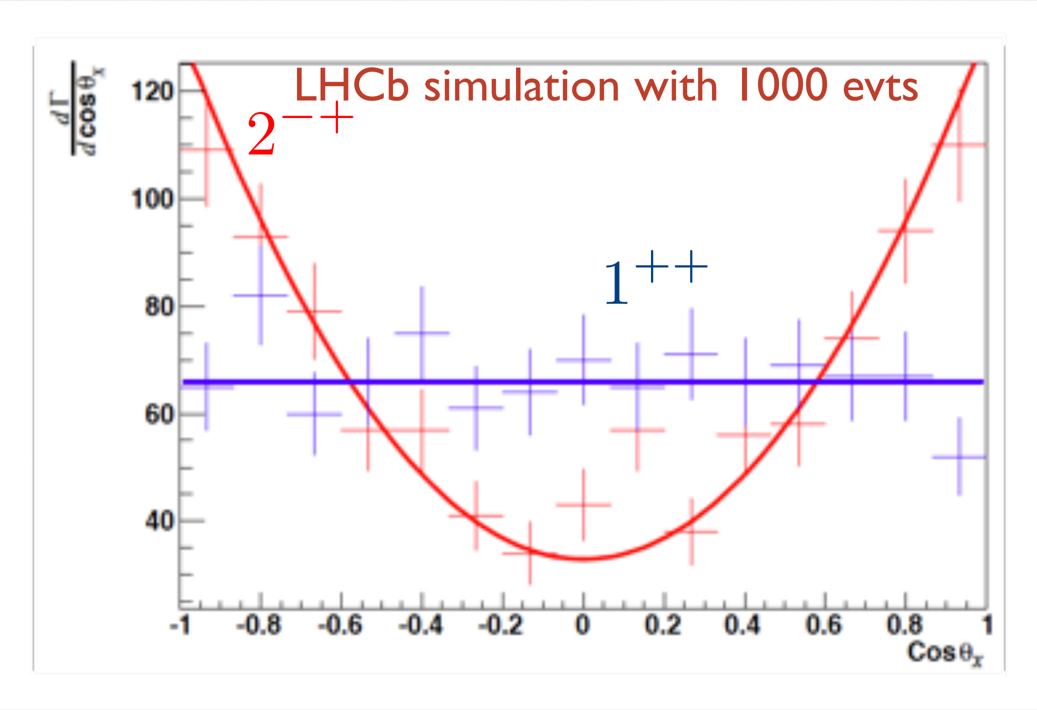


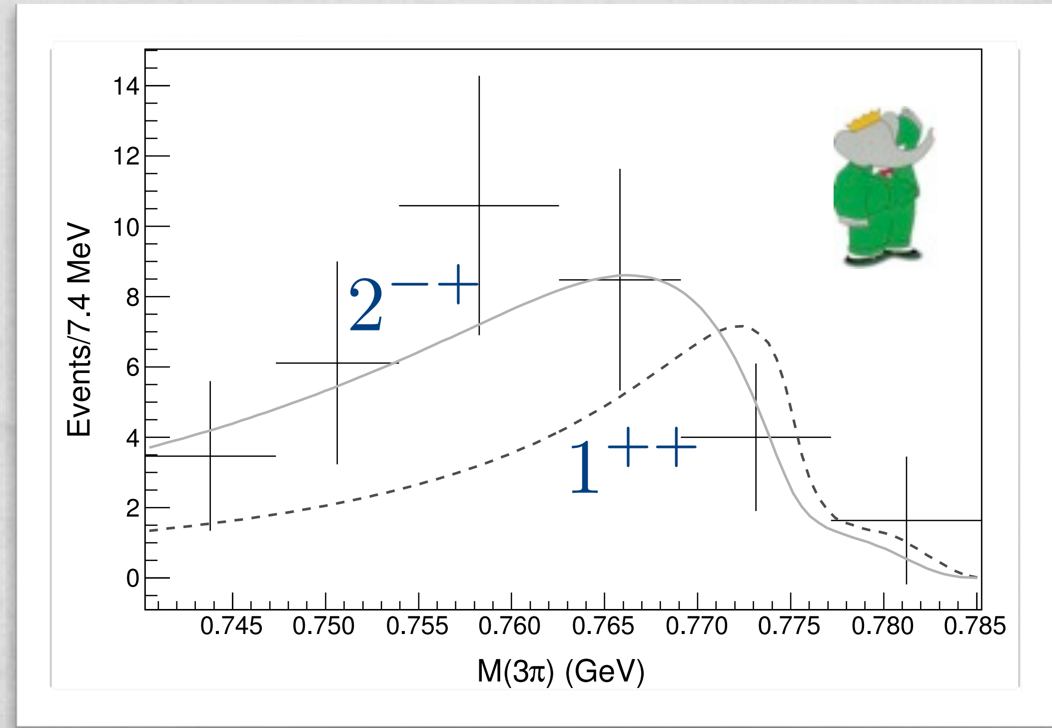
*Search for similar resonances having 'baryon affinity' in the b-system.*

# THE X(3872) SPIN

# EXPERIMENTAL RESEARCH ON SPIN

O(1000) fully reconstructed B → X(3872) $K^+$ events with X decaying into J/ψ ρ are expected at LHCb in 2013 - sufficient to have an unambiguous determination of quantum numbers performing an angular analysis. Results achievable within 2013/2014




R. Faccini, F. Piccinini, A. Pilloni, and ADP, *'On the Spin of the X(3872)'*, arXiv:1204.1223

Belle & BaBar stopped data taking in 2010 and 2008 respectively.
Ongoing analyses with low manpower but still possible and interesting.

*With 2011 ($1 fb^{-1}$), LHCb has about 15000 prompt X candidates on tape.*

# MATRIX ELEMENTS

R. Faccini, F. Piccinini, A. Pilloni, and ADP, arXiv:1204.1223

Spin 1 :: 1++

$$\langle\psi(\epsilon,p)V(\eta,q)|X(\lambda,P)\rangle = g_{1\psi V}\ \epsilon^{\mu\nu\rho\sigma}\ \lambda_\mu(P)\ \epsilon^*_\nu(p)\ \eta^*_\rho(q)\ P_\sigma$$

$V = \rho, \omega$

Spin 2 :: 2-+

$$\langle\psi(\epsilon,p)V(\eta,q)|X(\pi,P)\rangle = g_{2\psi V}\ T_A + g'_{2\psi V}\ T_B$$

$$T_A = \epsilon^{*\alpha}(p)\ \pi_{\alpha\mu}(P)\ \epsilon^{\mu\nu\rho\sigma}\ p_\nu\ q_\rho\ \eta^*_\sigma(q) - \eta^{*\alpha}(q)\ \pi_{\alpha\mu}(P)\ \epsilon^{\mu\nu\rho\sigma}\ q_\nu\ p_\rho\ \epsilon^*_\sigma(p)$$

$$T_B = Q^\alpha\ \pi_{\alpha\mu}(P)\ \epsilon^{\mu\nu\rho\sigma}\ P_\nu\ \epsilon^*_\rho(p)\ \eta^*_\sigma(q)$$

where the sum over the five polarizations is

$$\sum_{\text{pol}} \pi_{\mu\nu}(k)\pi^*_{\alpha\beta}(k) = \frac{1}{2}(P_{\mu\alpha}P_{\nu\beta} + P_{\mu\beta}P_{\nu\alpha}) - \frac{1}{3}(P_{\mu\nu}P_{\alpha\beta})$$

$$P_{\mu\nu} = -g_{\mu\nu} + \frac{k_\mu k_\nu}{m^2}$$

# CALCULATION OF WIDTHS

In our approach we do not need any orbital barrier factor (Blatt-Weisskopf) as the decay wave is fixed by the matrix elements. Instead we take into account the hadron finite sizes by introducing a 'polar' form factor (n=1,2)

$$g \to \frac{g}{(1+R^2 q^{*2})^n}$$

The *R* parameters will be fit on data. Next we compute the widths, e.g.,

$$\Gamma(X \to \psi\,\pi^+\pi^-) = \frac{1}{2J+1}\frac{1}{48\pi m_X^2}\int ds \sum_{\rm pol} |\langle \psi\;\rho(s)|X\rangle|^2 p^*(m_X^2, m_\psi^2, s)$$
$$\times \frac{1}{\pi}\frac{1}{(s-m_\rho^2)^2+(m_\rho\Gamma_\rho)^2}\int d\Phi^{(2)} \sum_{\rm pol} |\langle \pi^+\pi^-|\rho(s)\rangle|^2$$

(for ρ and ω ) in both hypotheses (spin=1,2) and compare to data.

# COMBINED FIT ANALYSIS

In the channel X → $\psi\, 2\pi$ both hypotheses J=1,2 *fit data well (no discrimination).*
*On the contrary in* X → $\psi\, 3\pi$ *the* $2^{-+}$ *hypothesis is the better one*

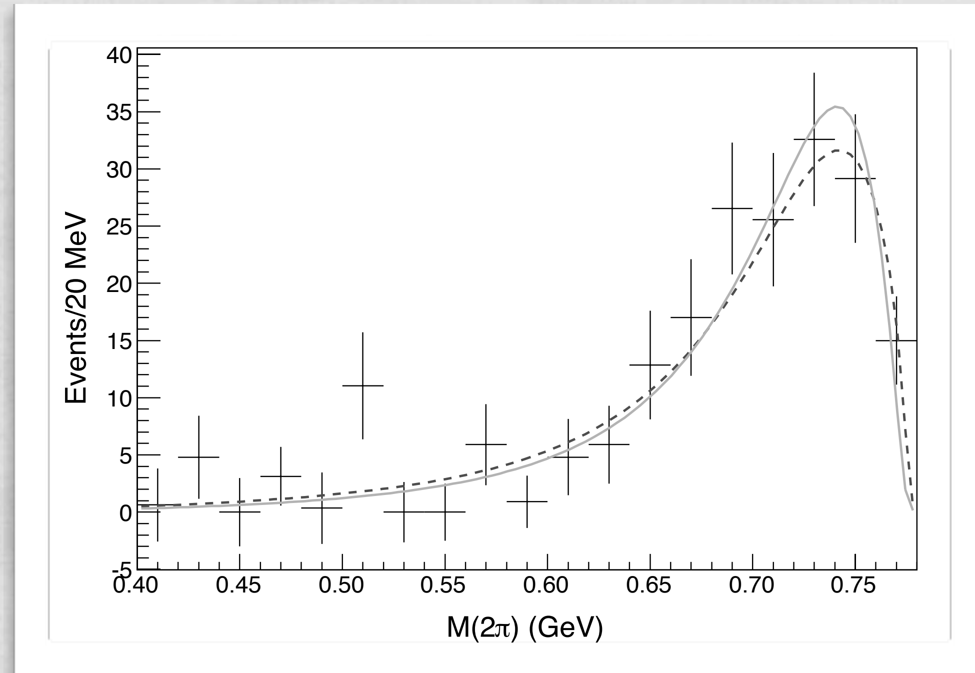
Because of this, following Hanhart et al (*Phys. Rev. D85, 011501, 2012*), we also made a combined J=1,2 fit. But our statistical analysis gives opposite results with respect to those presented in that paper

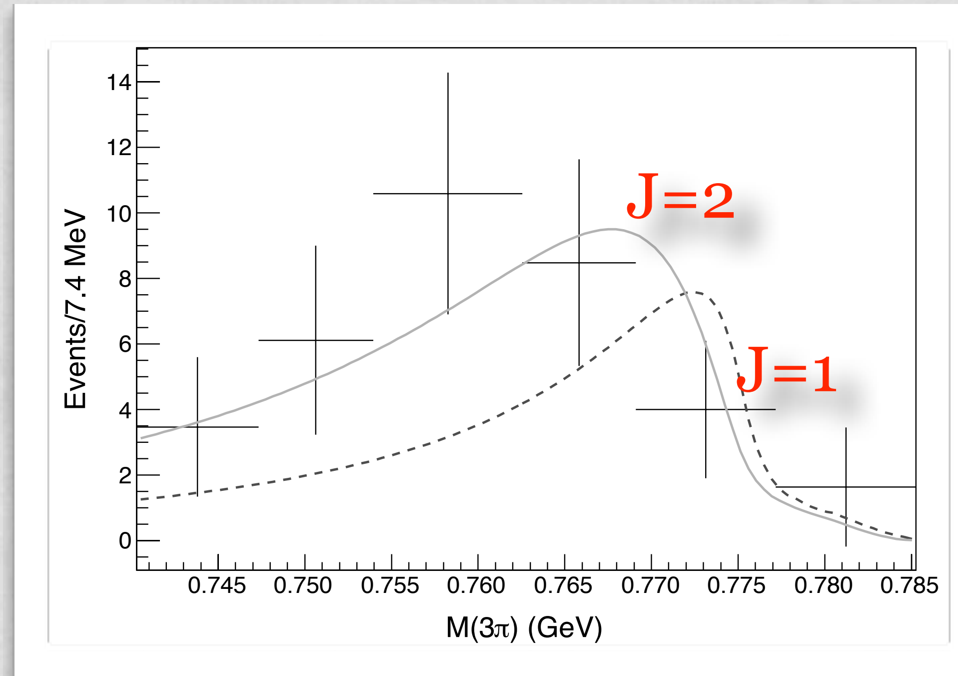
Fit parameters

$$\text{fit } J=1: R_1, g_{1\psi\rho}, g_{1\psi\omega}$$
$$\text{fit } J=2: R_2, g_{2\psi\rho}, g'_{2\psi\rho}, g_{2\psi\omega}, g'_{2\psi\omega}$$

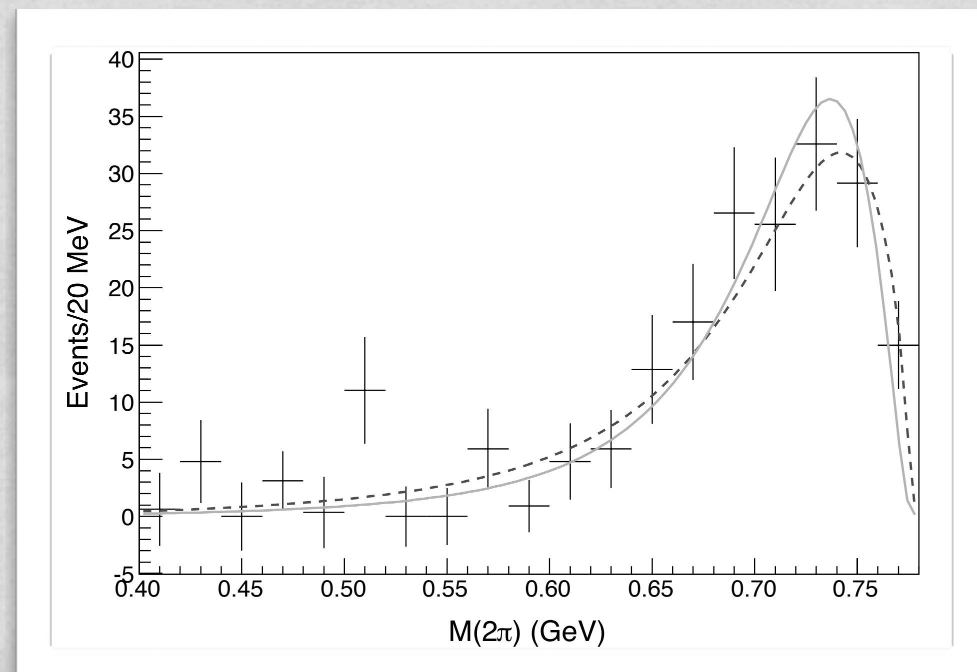
It is interesting to note that the radii, the fit parameters with a physical content, have reasonably small errors and get values consistent with 1 fm, the scale of the size of a standard hadron interaction.

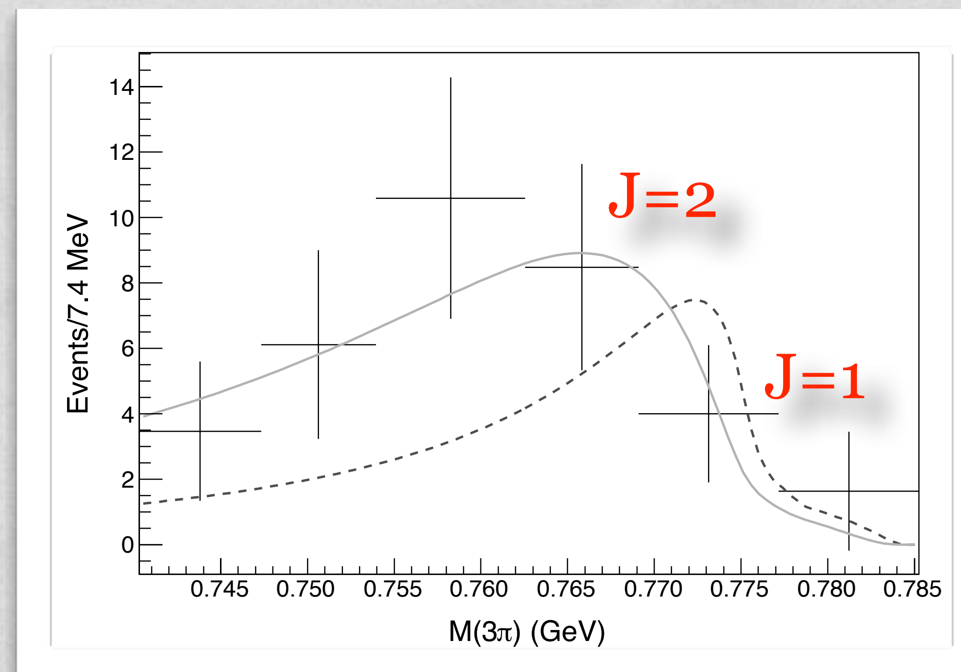
# RESULTS




n=1



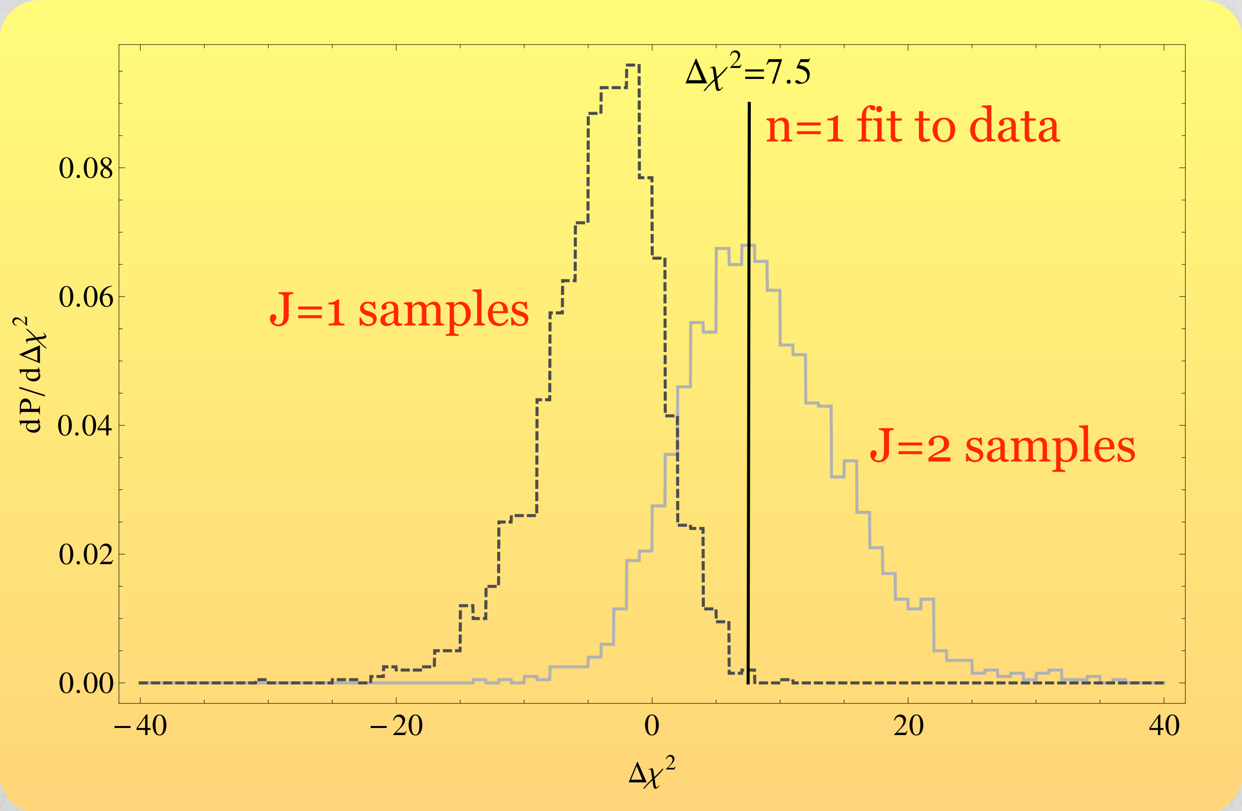

n=2

# TOY MC

We have performed a statistical analysis of data based on the Toy-MC method studying the estimator $\Delta\chi^2$

$$\Delta\chi^2 = \chi^2(1^{++}) - \chi^2(2^{-+})$$

where the $\chi^2$ are related to fits to MC samples generated under the J=1 or 2 hypothesis.
With available data there is very little room for the 1++ hypothesis




$$P(\Delta\chi^2 > 7.5\,|\,1^{++}) = 0.2\%$$

$$P(\Delta\chi^2 < 7.5\,|\,2^{-+}) = 46\%$$

(n=1)

are the probabilities for the two spin hypotheses

# (TOY MC METHOD)

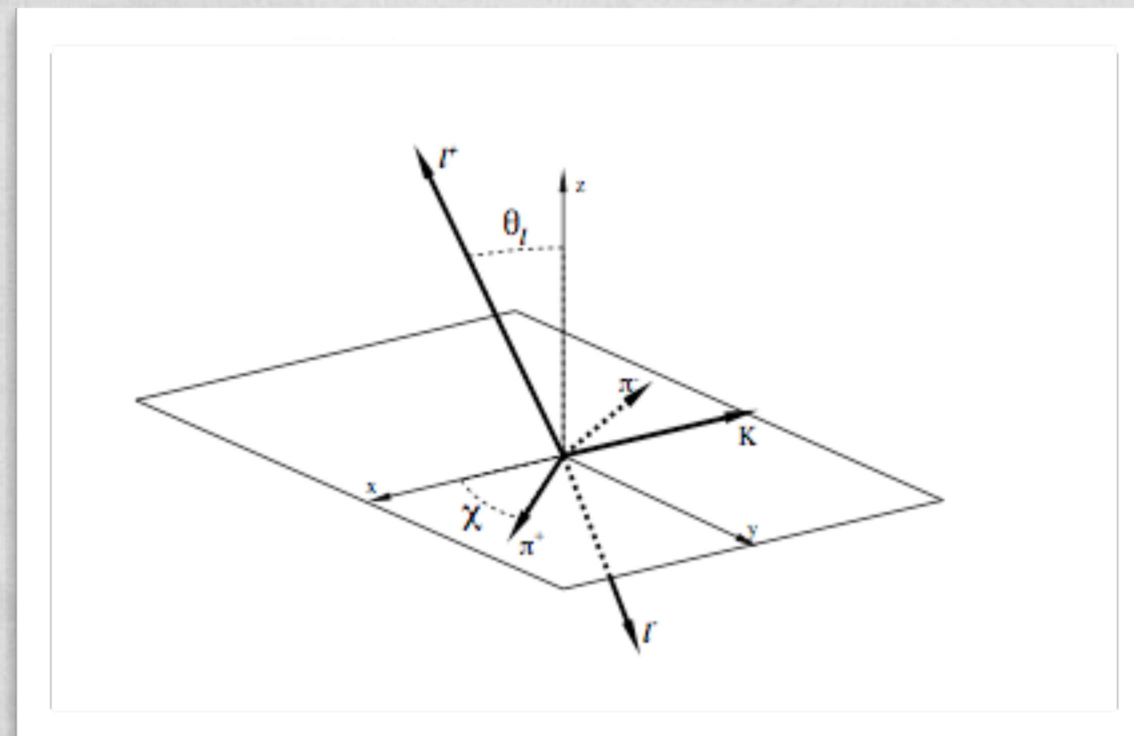
- Generate *N* MC data samples with the same # of events as real data
  - The samples can be generated using the parameters that better fit the J=1 or J=2 hypothesis (extracting, sample by sample, the parameters according to the best combined fit to data)
    - Mass bins $b_i$ are filled by extraction from Poisson distributions of mean values $\mu_i$ given, bin per bin, by the combined fit model vs data - the errors on $b_i$ are assumed to be the statistical fluctuations on $\mu_i$

# BELLE ANGULAR CORRELATIONS

Belle, arXiv:1107.0613

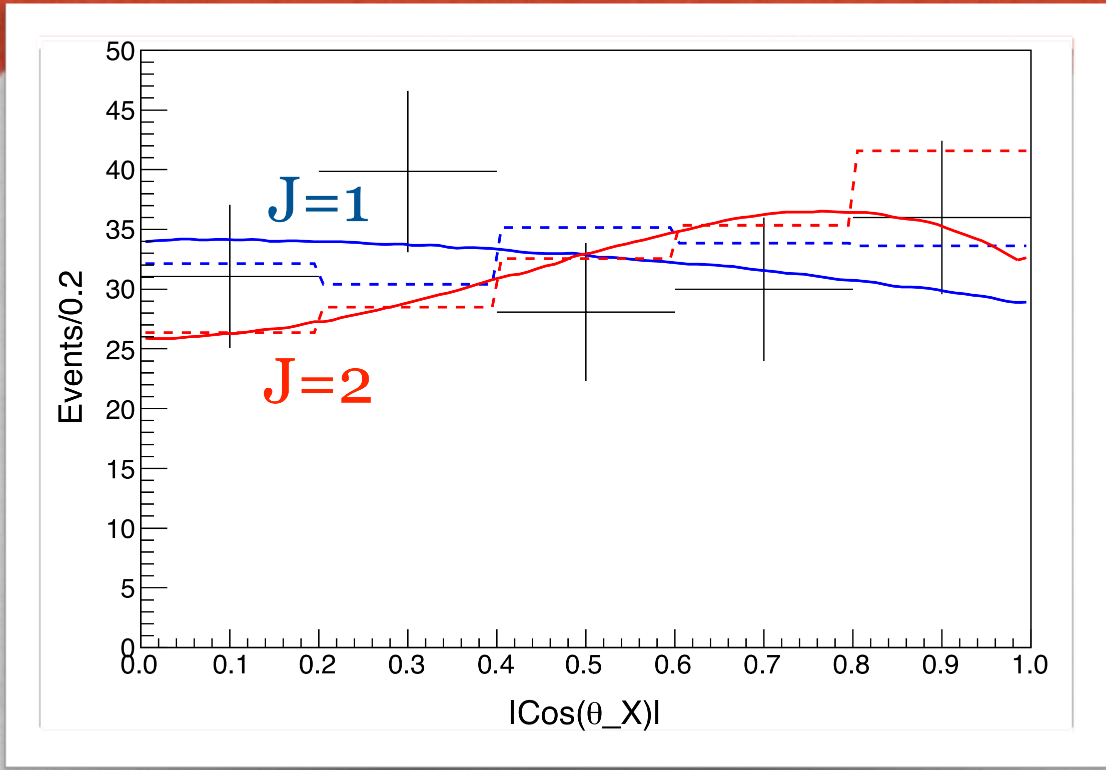
The angle $\theta_X$ is measured. It is the angle between the $J/\psi$ and the direction opposite to the K (from $B \to K X$) in the X rest frame (the resulting decay distribution is flat in S-wave and $\sim(1 + 3\cos^2\theta_X)$ in P-wave)

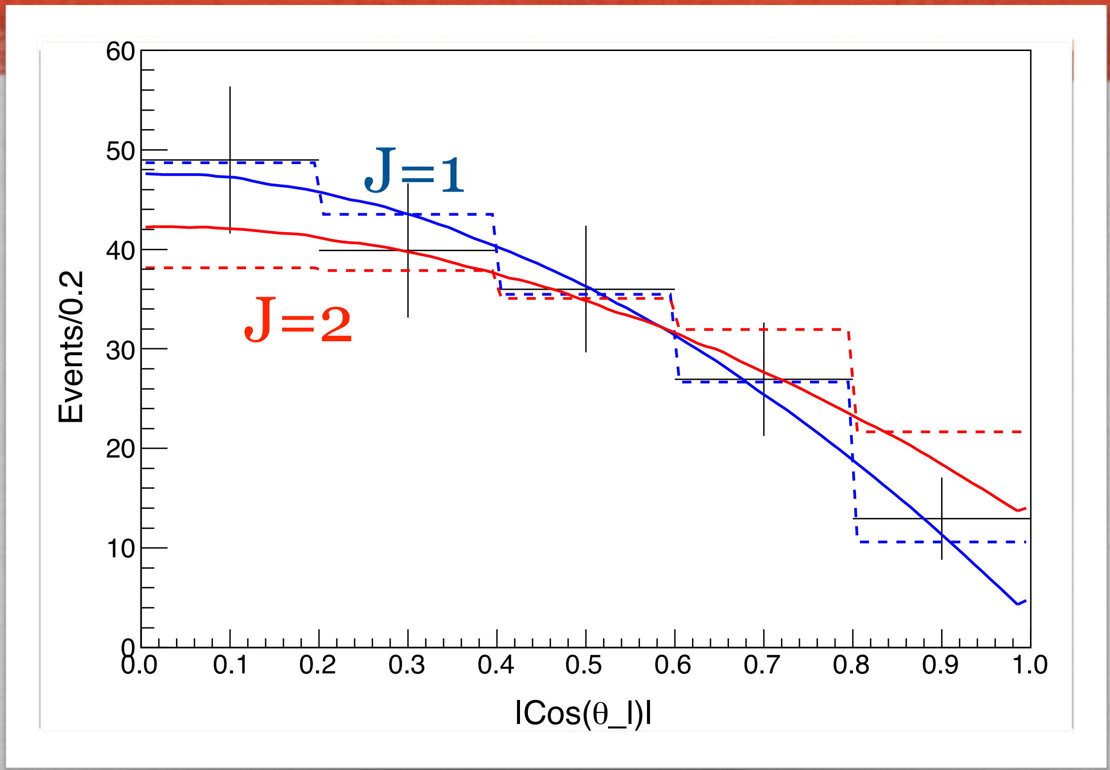
Two more angles $\theta_l$ and $\chi$ are introduced according to the definition

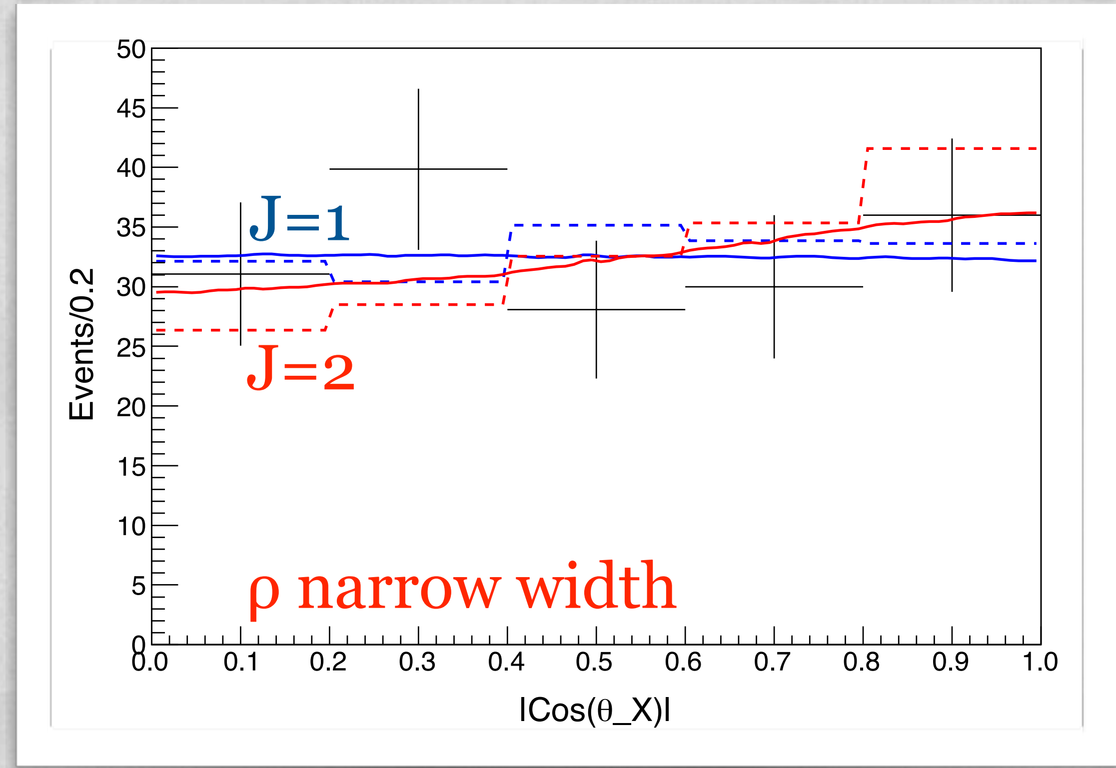


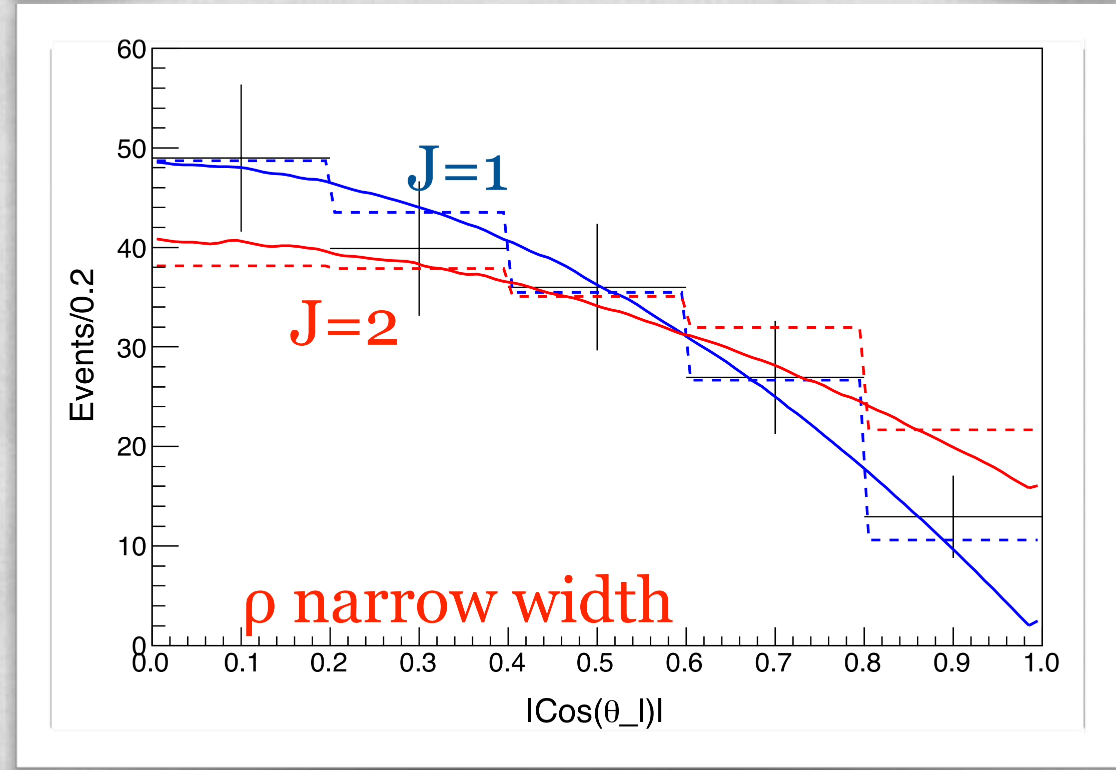

In the next slide our distributions for $\cos\theta_X$ and $\cos\theta_l$

# BELLE ANGULAR CORRELATIONS (PRELIMINARY)



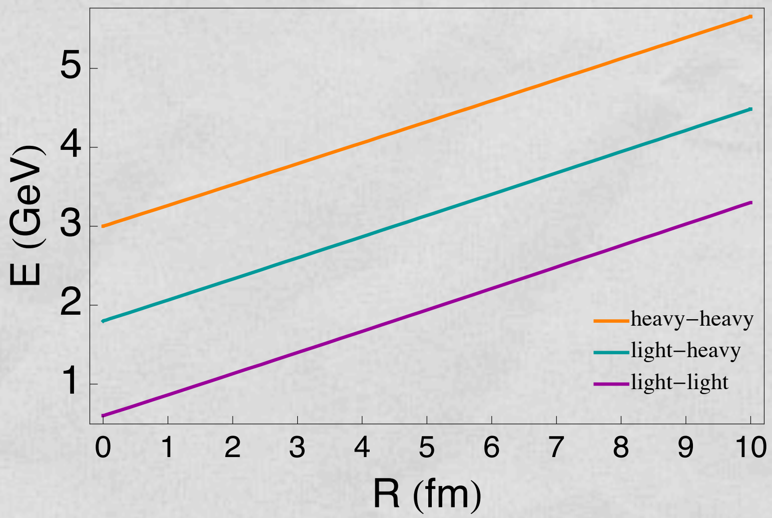



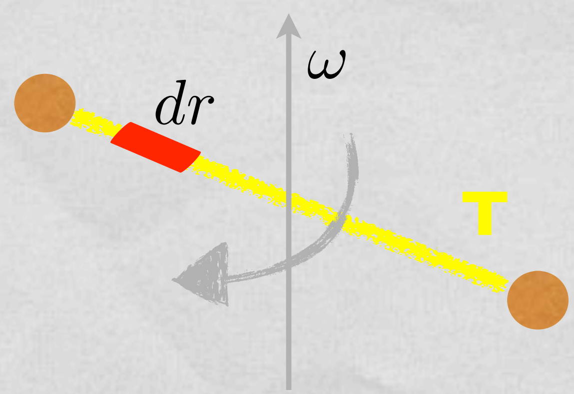
WHAT IF $2^{-+}$ ??

# THE SIMPLEST QCD STRING

Selem and Wilczek hep-ph/0602128 (on the Chew-Frautschi model)

## Charmonia with hadron strings?




$$\mathcal{E} = \frac{m_1}{\sqrt{1-(\omega r_1)^2}} + \frac{m_2}{\sqrt{1-(\omega r_2)^2}} + \frac{\sigma}{2\pi\omega}\int_0^{\omega r_1} \frac{dv}{\sqrt{1-v^2}} + \frac{\sigma}{2\pi\omega}\int_0^{\omega r_2} \frac{dv}{\sqrt{1-v^2}}$$

$$\ell = \frac{\omega r_1^2 m_1}{\sqrt{1-(\omega r_1)^2}} + \frac{\omega r_2^2 m_2}{\sqrt{1-(\omega r_2)^2}} + \frac{\sigma}{2\pi\omega^2}\int_0^{\omega r_1} \frac{dv\, v^2}{\sqrt{1-v^2}} + \frac{\sigma}{2\pi\omega^2}\int_0^{\omega r_2} \frac{dv\, v^2}{\sqrt{1-v^2}}$$

$\sigma \sim 1\ \mathrm{GeV}^2$ from Regge slopes and $d\mathcal{E}'/dr' = T = \sigma/2\pi$ and $T = \frac{d\boldsymbol{p}}{ds}\cdot\hat{\boldsymbol{u}} = m\omega^2\gamma^2 r$

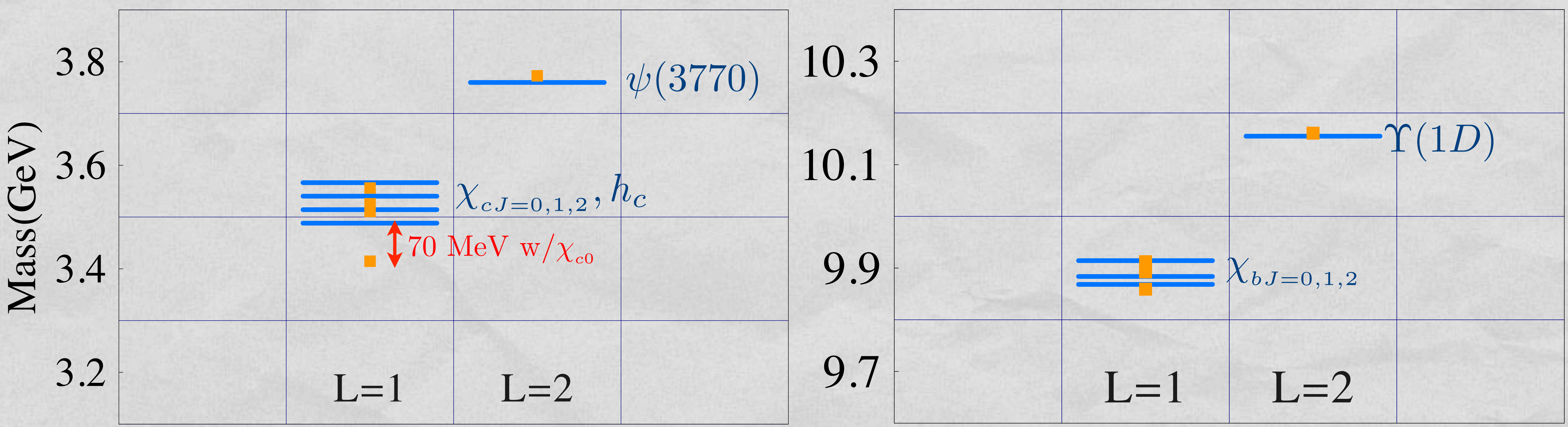
# THE SIMPLEST QCD STRING II

Cotugno, Faccini, Polosa, Sabelli, *Phys. Rev. Lett.* **104**, 132005 (2010)

We take the limit in which the mass attached to the ends of the string is the largest scale in the problem

$$\mathcal{E}(r)_{\mathrm{TOT}} \simeq \underbrace{2M + \frac{3}{(16\pi^2 M)^{1/3}}(\sigma\ell)^{2/3}}_{\mathcal{E}(r)\ \text{as}\ T/(M\omega)\to 0} + A\left(\vec{S}\cdot\vec{\ell}\right)\frac{1}{r}\frac{d}{dr}\mathcal{E}(r)$$

No spin-spin because of large r and M

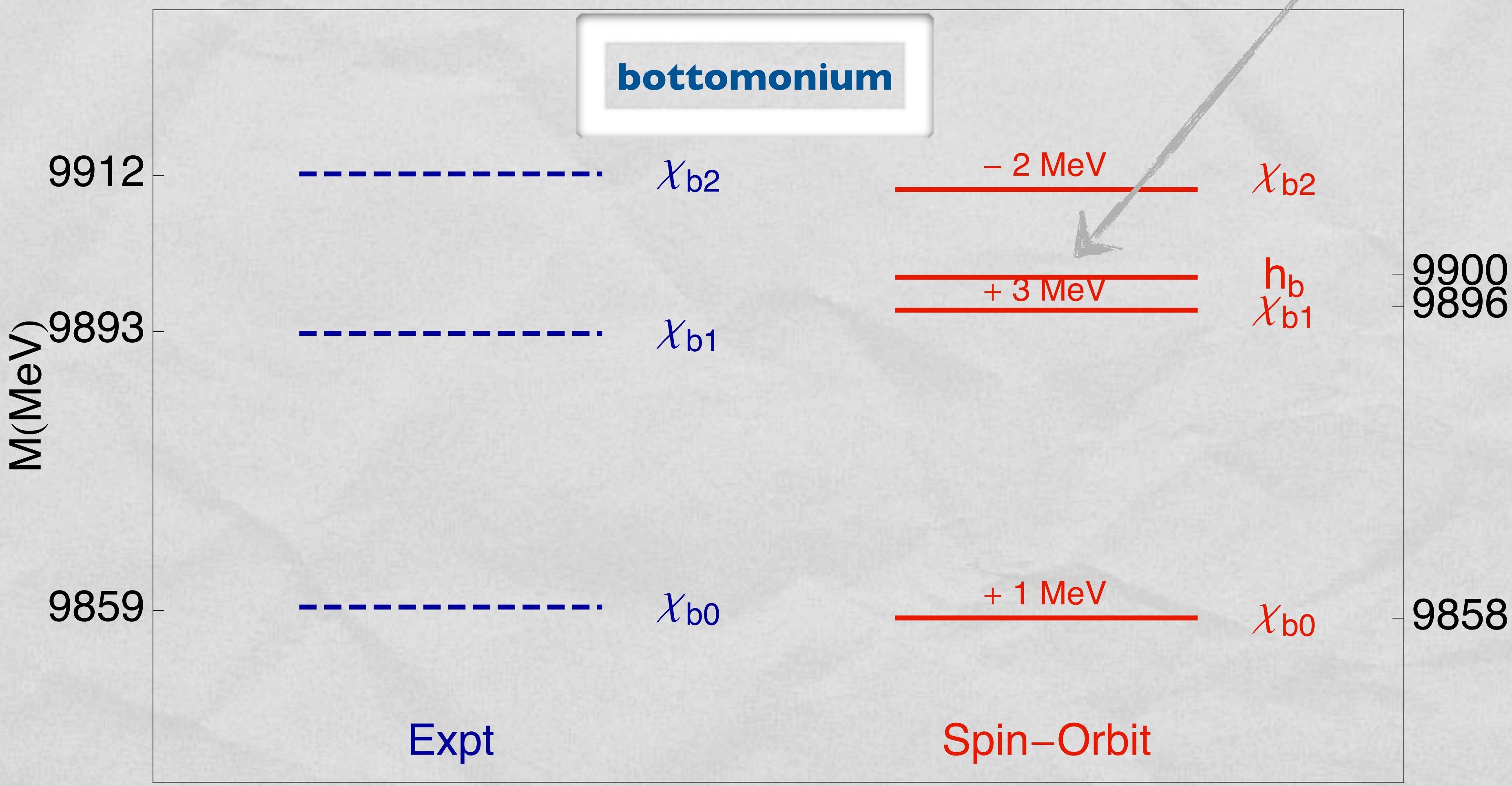



(charm) (beauty)

# THE NEXT-TO-SIMPLEST QCD STRING

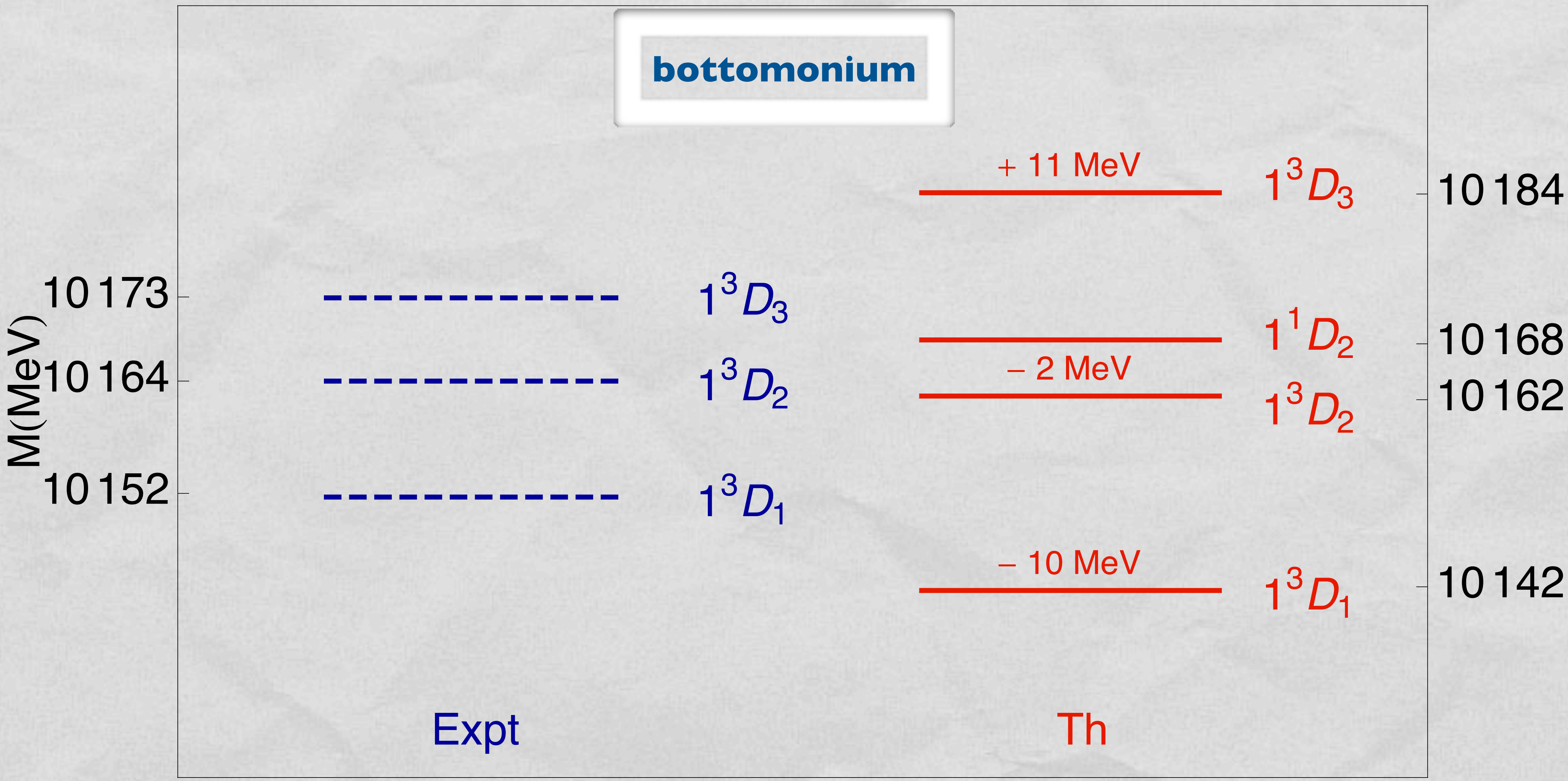
$$\mathcal{E}(r)_{\rm TOT} \simeq \underbrace{2M + \frac{3}{(16\pi^2 M)^{1/3}}(\sigma\ell)^{2/3}}_{\mathcal{E}(r)\ \text{as}\ T/(M\omega)\to 0} + A\left(\vec{S}\cdot\vec{\ell}\right)\frac{1}{r}\frac{d}{dr}\mathcal{E}(r) + B\left[\vec{S}^2 - 3\left(\vec{S}\cdot\vec{n}\right)^2\right]$$

**Prediction +1MeV**




Burns, Piccinini, Polosa, Sabelli, *Phys Rev D* 2010

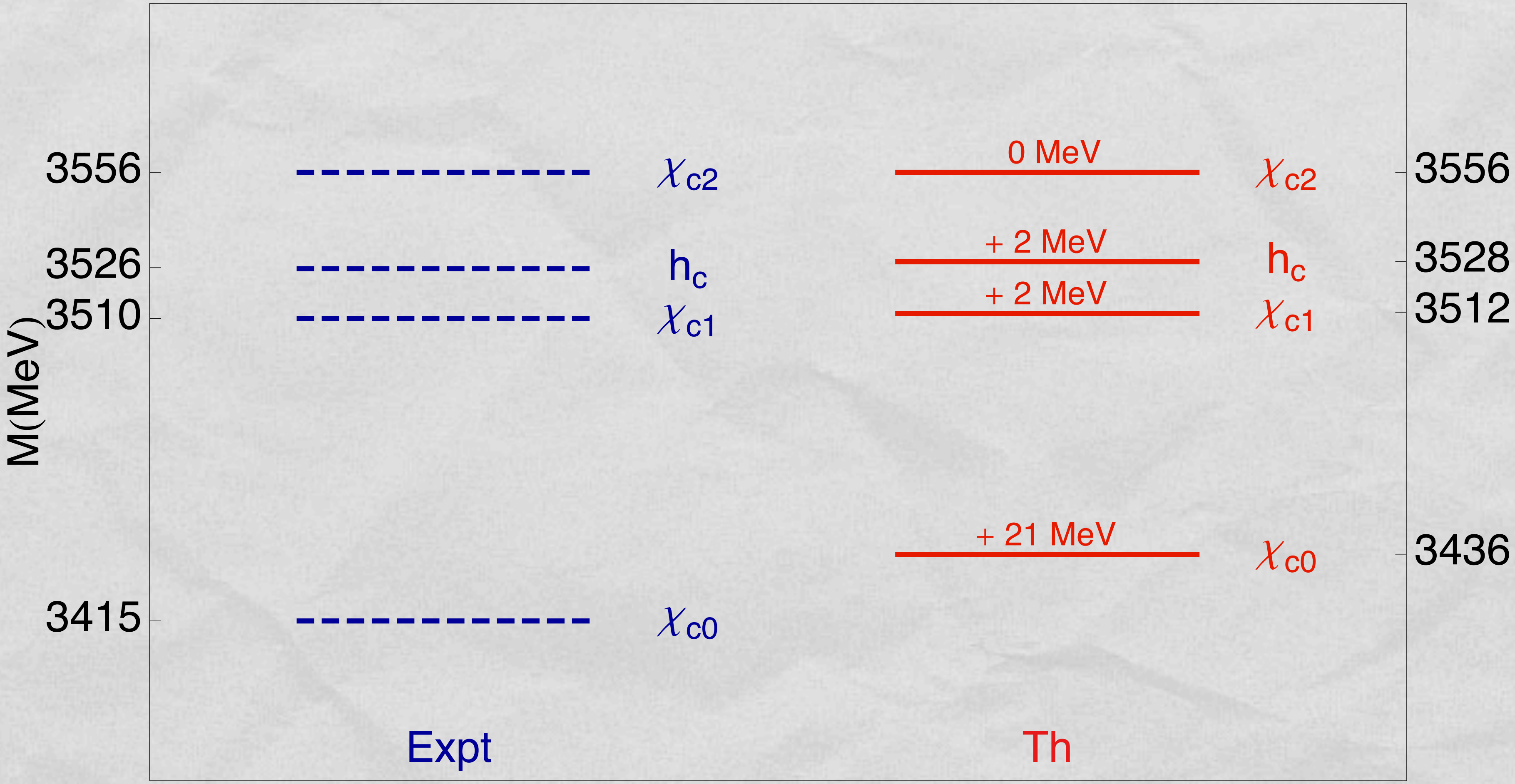
# D-WAVE BOTTOMONIUM



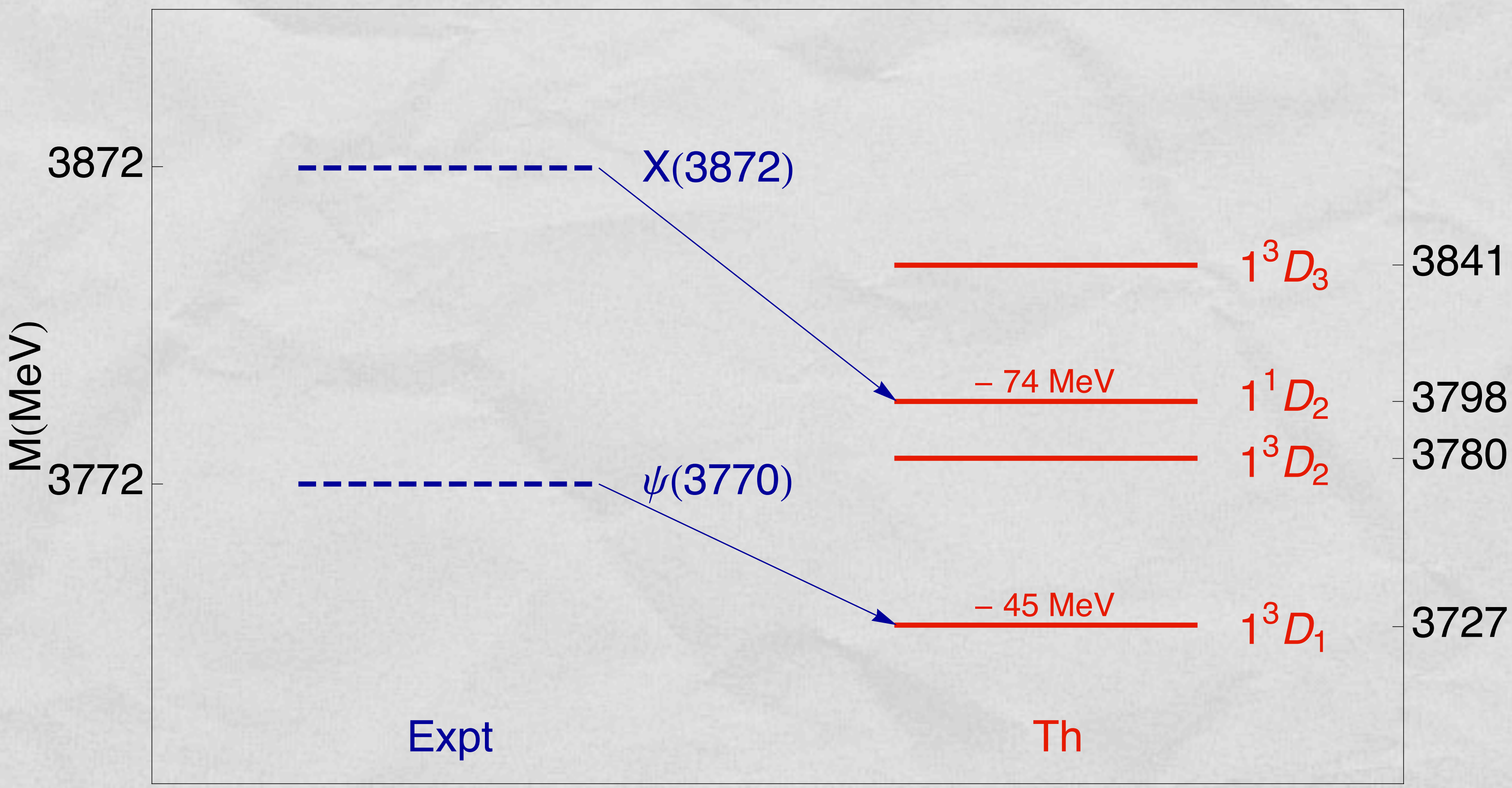

Based on BaBar data

# CHARMONIUM L=1

The situation for charmonium is a bit more tricky since the `infinite` mass limit is less appropriate here.



# IS THE X(3872) A $^1D_2$ ($2^{-+}$)CHARMONIUM?!




Maybe isospin violations mentioned are not the main problem,

But what about radiative decays?

J/ψγ and J/ψρ would be P-wave decays - but then why

$$\frac{\mathcal{B}(X(3872) \to J/\psi\gamma)}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} = (0.3 \pm 0.1)$$

# FRAGMENTATION OF A GLUON IN A $^1D_2$

Cho and Wise hep-ph/9410214

$$\frac{d\sigma}{dp_\perp}(p\bar{p} \to 1^1 D_2 + \text{All}) = \sum_{h=0}^{2} \int_0^1 dz \frac{d\sigma}{dp_\perp}(p\bar{p} \to g(p_\perp/z) + \text{All}; \mu) \times D_{g \to 1^1 D_2^{(h)}}(z; \mu)$$

$x \simeq \sqrt{M_\perp^2/1960^2} \simeq 0.02$

$p_\perp \gtrsim 5$ GeV

$|y| \leq 6$

factorization scale $\mu \simeq M_\perp$

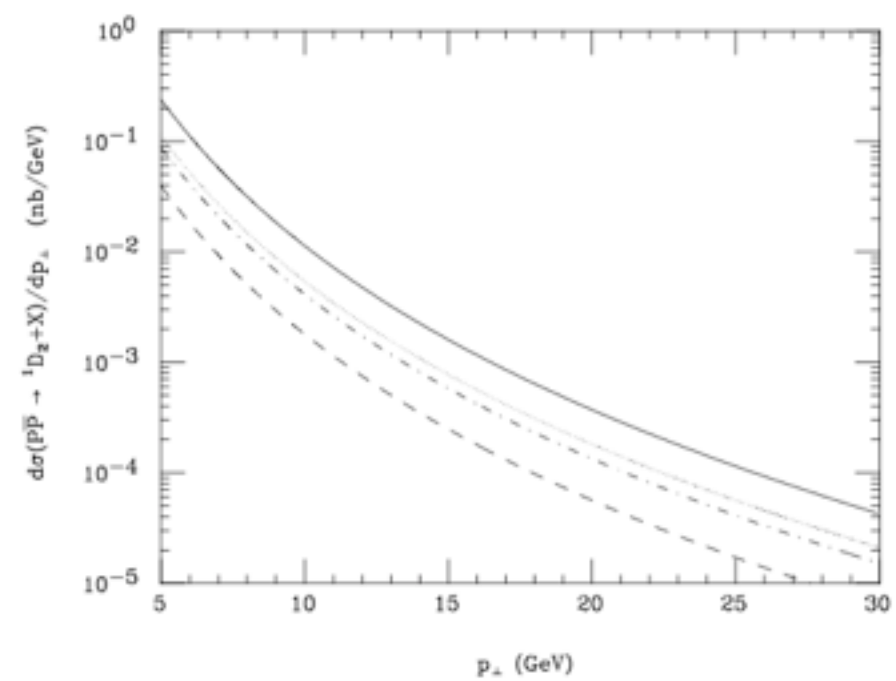



Figure 4

Updating the pdf's we find

$$\sigma(p\bar{p} \to 1^1 D_2) = 0.6 \text{ nb}$$

**Still very small w/ respect to the prompt production at CDF**

# BARYONS STRING AND DIQUARKS

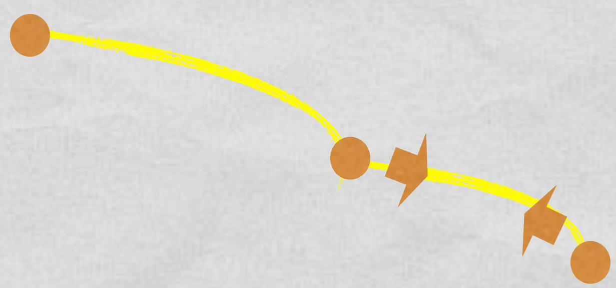
't Hooft hep-th/0408148


$$X^{\mu,1}(\sigma = 0, \tau) = X^{\mu,2}(\sigma = 0, \tau) = X^{\mu,3}(\sigma = 0, \tau)$$

$$\sigma \in [0, L^i(\tau)] \text{ variable length in time}$$

$$S = -\sum_{i=1}^{3} \int d\tau \int_0^{L^i(\tau)} d\sigma \sqrt{(\partial_\sigma X^i_\mu \cdot \partial_\tau X^{\mu i})^2 - (\partial_\sigma X^i_\mu)^2 (\partial_\tau X^i_\nu)^2}$$

It is found that one of the three harms will soon (τ) disappear shedding its energy into the excitation modes of the two other harms:
we end up with a single open string connecting three quarks.

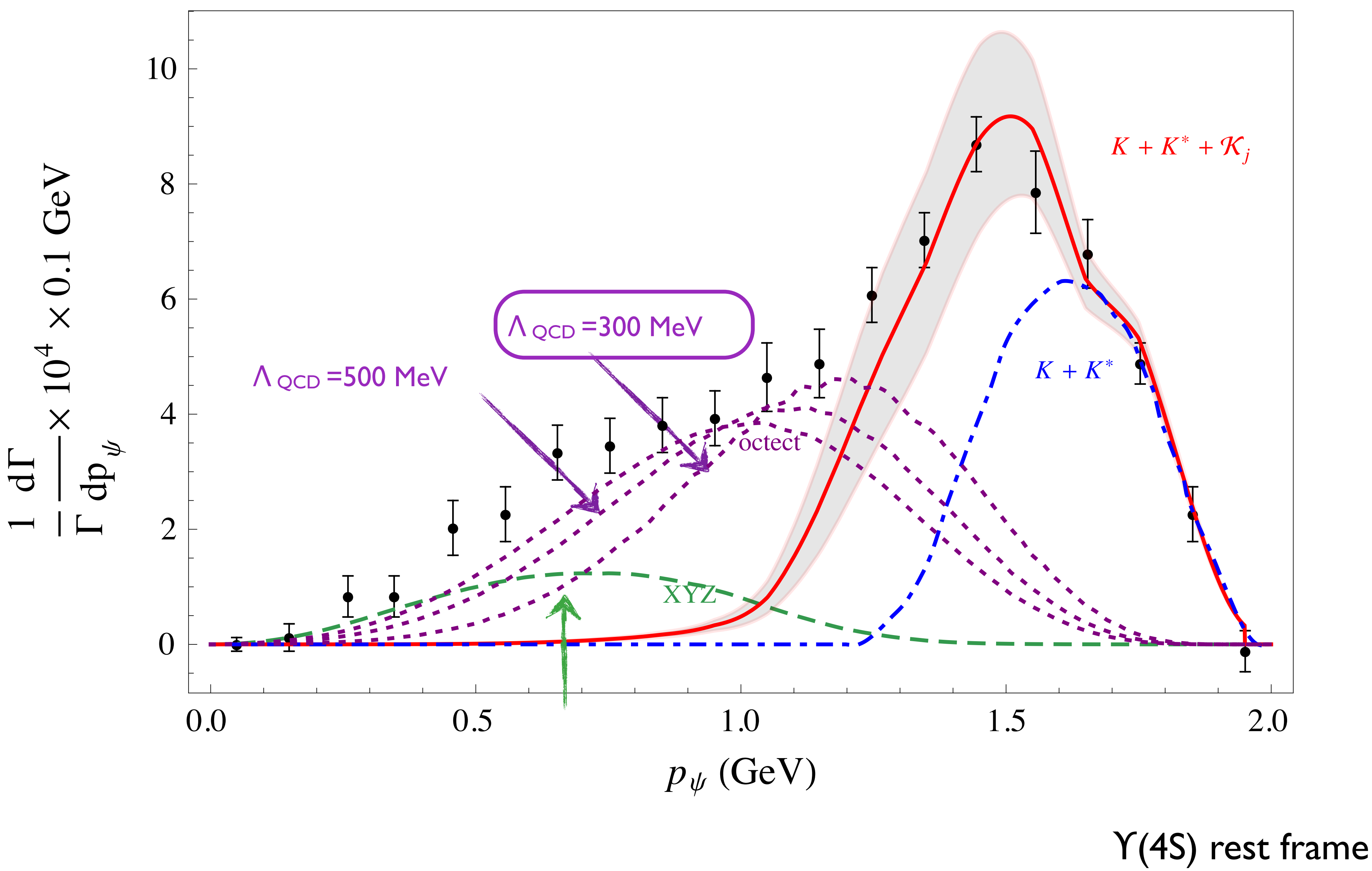


Quantum effects will then favor the configuration with one quark at one end and a diquark at the other hand. Baryons are like mesons as in Regge trajectories

# 2-+ OPTION

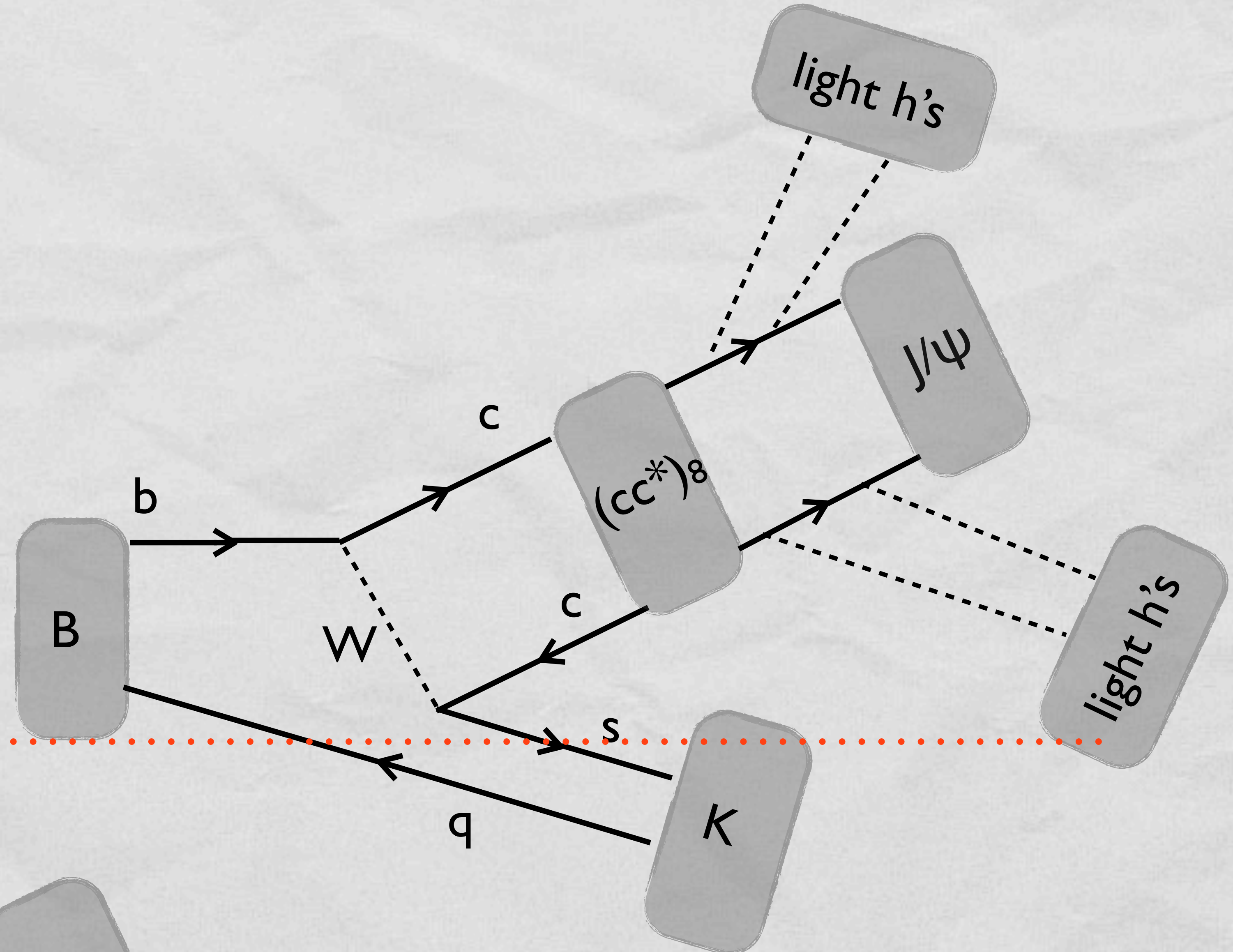
- Molecule ruled out
- Standard charmonium suffers
- Tetraquarks can be but, again - more states required -
- Are there reasons to expect more states? In the following we give one of the possible ones

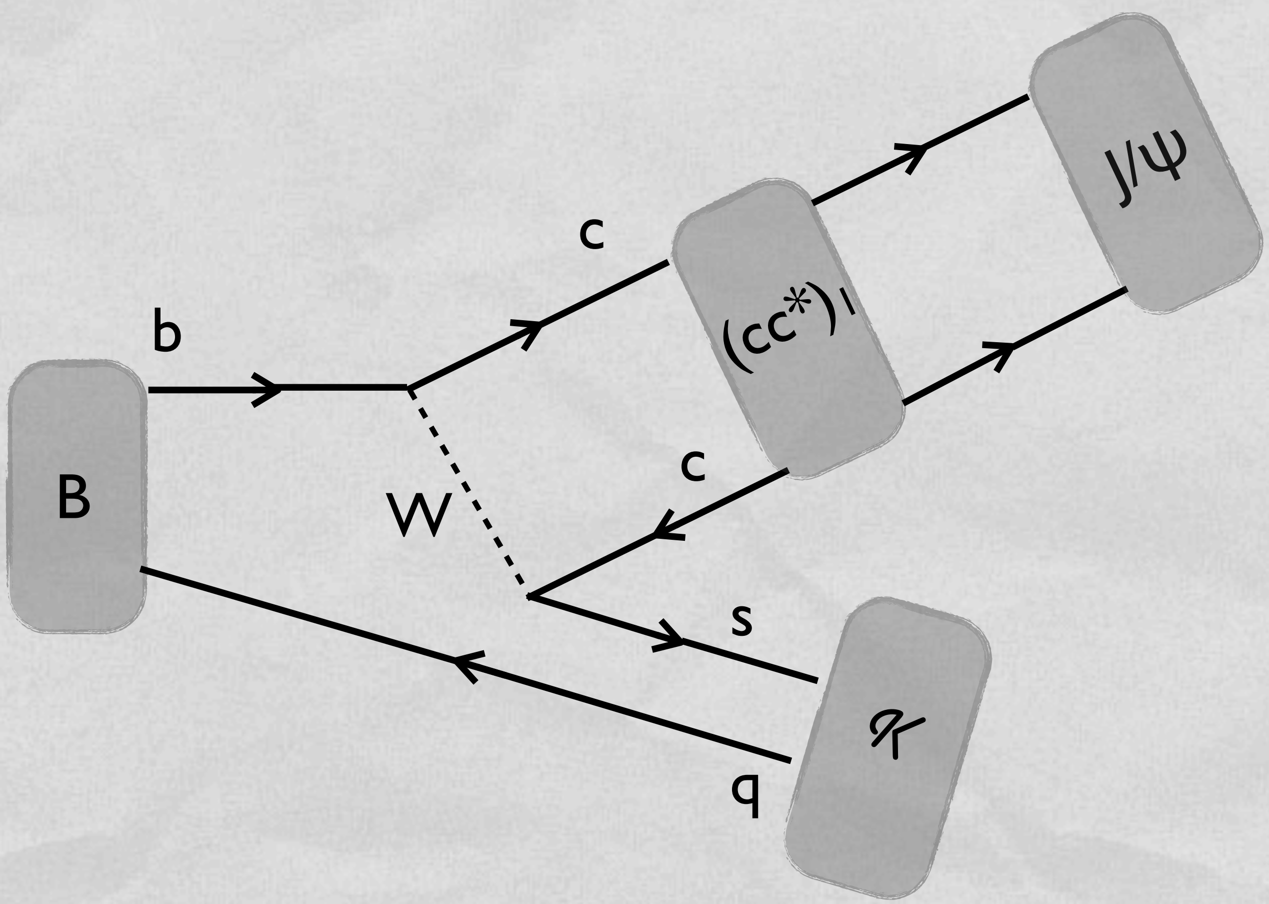
Having more XYZ (or having underestimated their br's) would improve on a old puzzle about the momentum decay of J/ψ in B → J/ψ+ All decays observed by BaBar




T. Burns, F. Piccinini, ADP, V. Prosperi, C. Sabelli, *Phys Rev* ***D83,*** *114029 2011*

Hypothesis:
no interaction between the hard part and soft part of the process.




If the $cc^\star$ pair is produced in color singlet configuration one has a two body decay: $B \to J/\psi\ \mathcal{K}$.

# MANY STATES...STATISTICAL METHODS?

E.N.M. Cirillo, M. Mori and A.D.P., *Phys. Lett.* ***B705***, *498 (2011)*

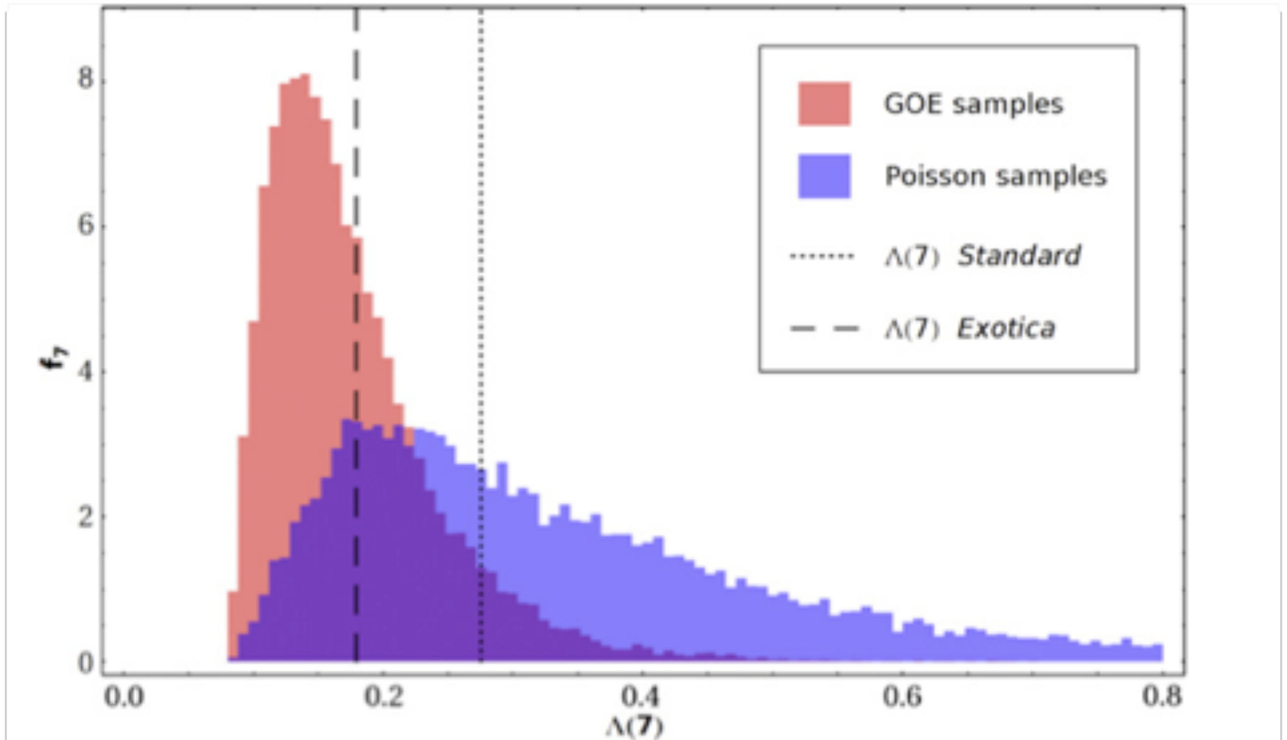
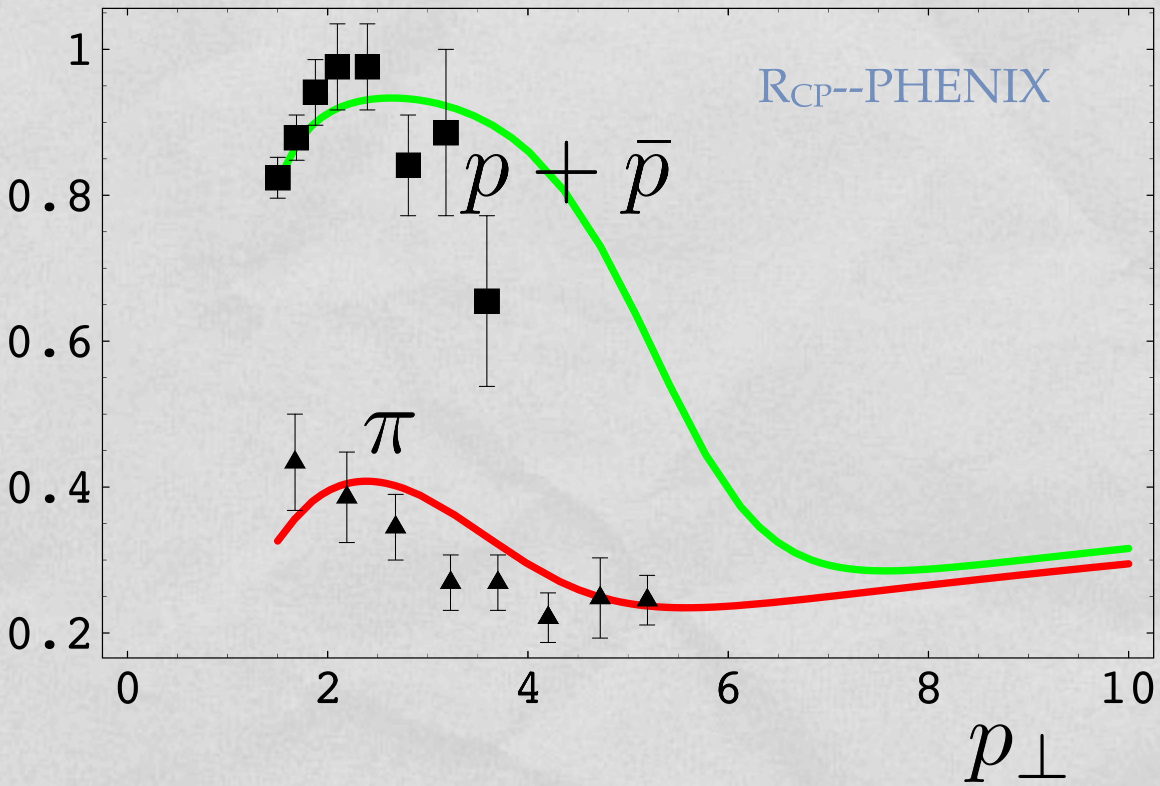



**Fig. 4.** Sampled distributions for $\Lambda(7)$. The histograms are obtained with 19 980 GOE samples and 20 000 Poisson samples and rescaled to unit area. The vertical lines indicate the $\Lambda(7)$ value for the *standard* and the *exotica* series. The bin width is equal 0.008.

***Hamiltonian classically chaotic*** → quantum level repulsion, Wigner law of GOE eigenvalues
***Hamiltonian classically integrable*** → Poisson distribution
Study done with **six $1^{--}$ charmonia *vs.* six $1^{--}$ possible exotic hadrons**

# EXOTIC HADRONS AND HIC

- What are the fragmentation functions of diquark-antidiquark mesons? Could they be modeled and confronted with data from ALICE and CMS/ATLAS?




$$R_{CP} = \frac{N_{\rm coll}(b)}{N_{\rm coll}(b=0)} \left( \frac{dN_H/d^2p_\perp(b=0)}{dN_H/d^2p_\perp(b)} \right)$$

$$R_{AA} = \frac{1}{N_{\rm coll}(b=0)} \left( \frac{dN_H/d^2p_\perp(b=0)}{dN_H/d^2p_\perp|pp} \right)$$

The numerators are dominated by the 'coalescence' mechanism (B. Muller et al). Molecule and tetraquark denominators should also be different

L. Maiani, A.D. Polosa, V. Riquer, C. Salgado, *Phys Lett B 2007* (light mesons)

# EXOTIC HADRONS AND HIC

I - The transverse momentum of partons is steeply falling with *pT (assume exp.)*
II - Fragmentation functions favor the situation where the energy of the fragmenting parton is democratically distributed amid all the radiated partons

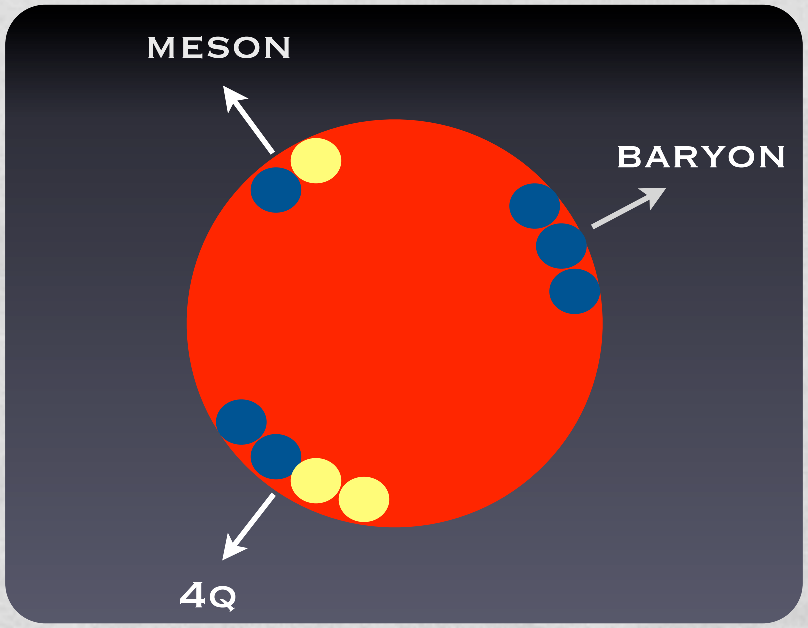
For this reason fragmentation is inefficient at producing high pT hadrons.
In particular pions are produced more efficiently with respect to baryons.
But what if the phase space is densely populated with partons?

$$P_\pi = p_u + p_{\bar{d}} \sim 2\,p$$
$$P_p = p_u + p_u + p_d \sim 3\,p$$

$$\#(\text{protons}) \sim \exp(-3\,p) \sim \exp(-P_p)$$
$$\#(\text{pions}) \sim \exp(-2\,p) \sim \exp(-P_\pi)$$

$$\#(\text{protons})/\#(\text{pions}) \sim 1 \quad \text{if} \quad P_\pi \sim P_p$$

$$\#(X_{4q}) \sim \exp(-P_X)$$
$$\#(X_{\text{mol}}) \sim C\exp(-P_X)$$




C = Combinatorial factor of producing a (almost non relatively recoiling) pair (D,D*)

# CONCLUSIONS

- We have spent quite some time debating about which is the correct description of these resonances.
  - The models presented all have pros/cons but none of them has -the- solution
    - Hopefully a new bunch of results from the LHC will revitalize the field

# BACKUP SLIDES

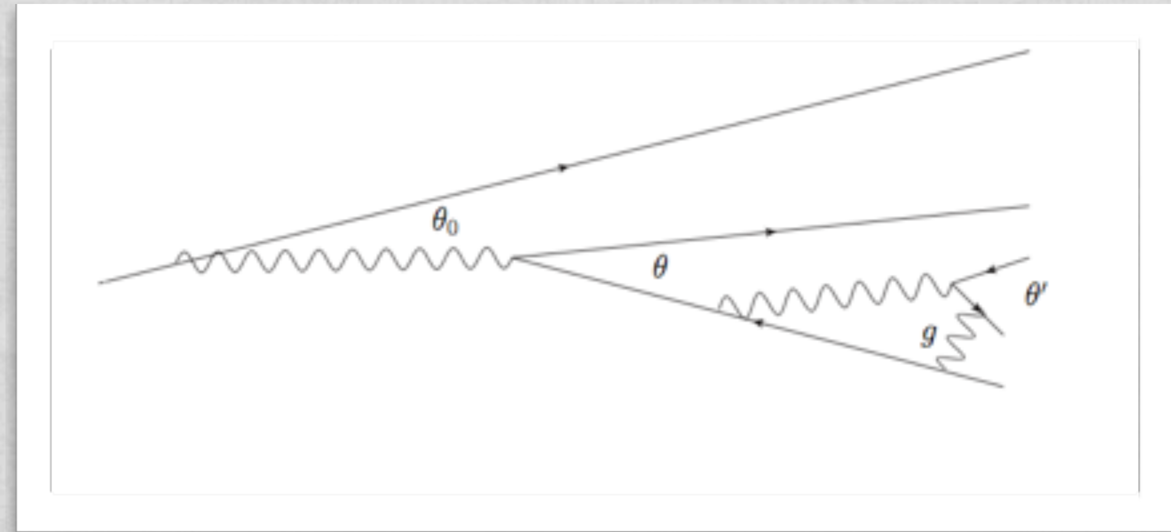
# DEUTERIUM & X

Deuterium has a binding energy of ~2.2 MeV.
The X has ~ -0.14 MeV.

For Deuterium one can make a square well potential model with a depth of ~ 20 MeV
For the X the depth could be of about 7 MeV.
The *expectation* for the X to be found outside 3 fm is 77%
(~72% to be within [3,20] fm and only 20% to be in [0,3] fm)

The Deuterium has spin
D and D* do not have spin-spin interactions

Production at hadron colliders?



# HOW LARGE IS A MOLECULE?

Using the indetermination principle

$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-\frac{m_\pi c}{\hbar} r_0}}{r_0} = \mathcal{E} = M_D + M_{D^*} - M_X \sim 0.25 \text{ MeV}$$

and the fact that $g^2/4\pi \sim 10$ we find a characteristic size

$$r_0 \sim 8 \text{ fm}$$

which could either be infinity(!) as

$$\mathcal{E} = -0.12 \pm 0.35 \text{ MeV}$$

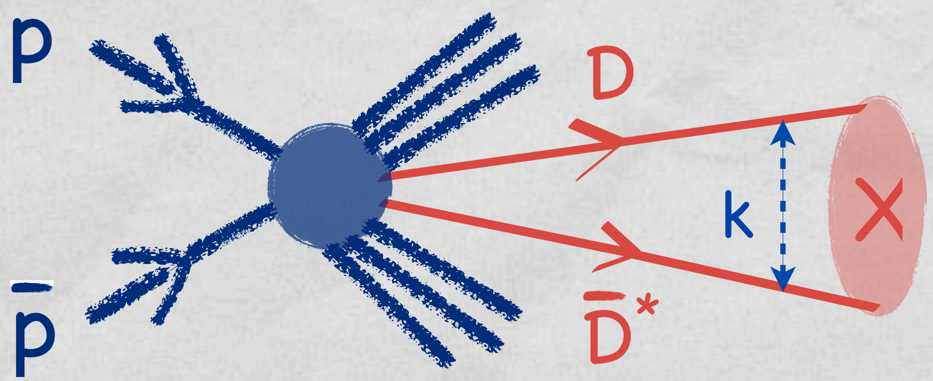
# PROMPT PRODUCTION

$$\sigma(p\bar{p} \to X(3872)) \sim \left| \int d^3k \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2$$

$$\simeq \left| \int_{\mathcal{R}} d^3k \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2$$

$$\leq \int_{\mathcal{R}} d^3k |\psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$

$$\leq \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$



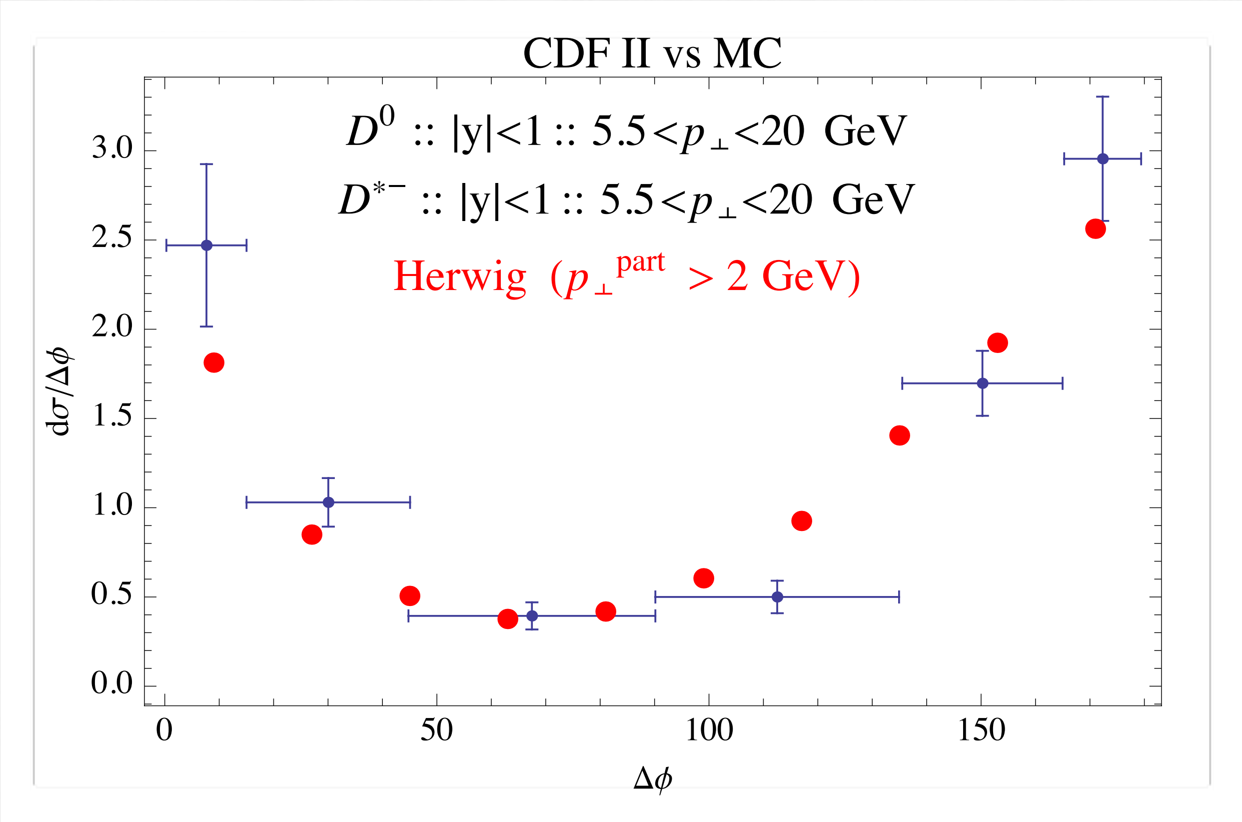

Using Pythia & Herwig we can compute

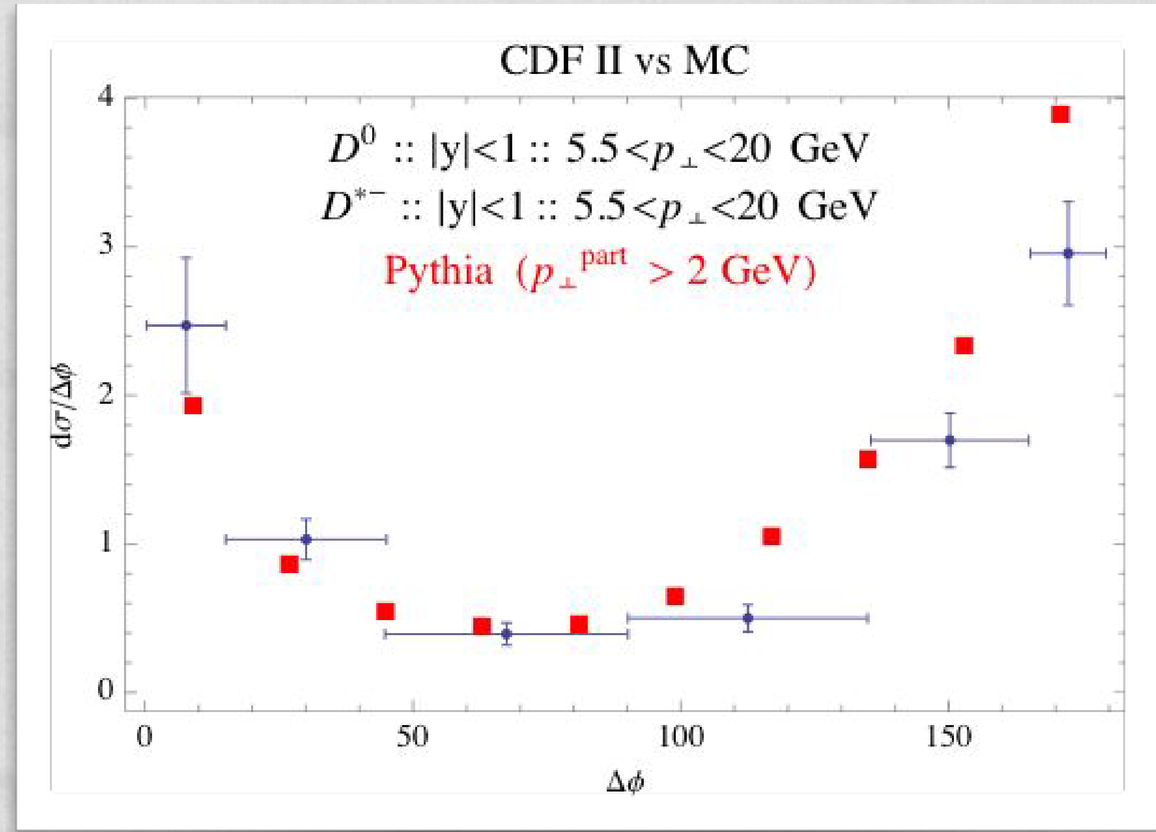
$$\sigma_{\max}(p\bar{p} \to X(3872)) = \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$

where $\mathcal{R} \sim [0.40]$ MeV

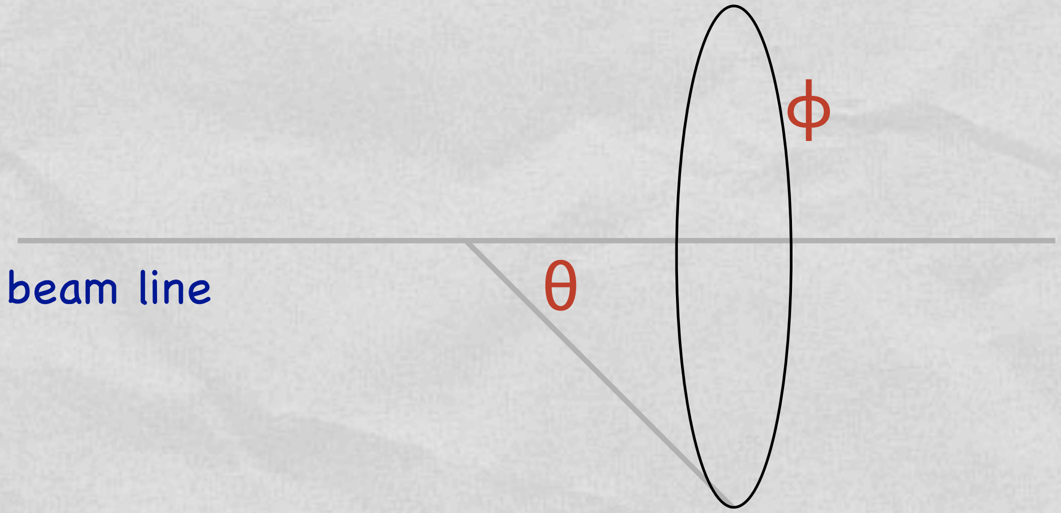
as $k \sim \sqrt{2\mu(-0.25 + 0.40)} \simeq 17$ MeV

# TUNING MC'S

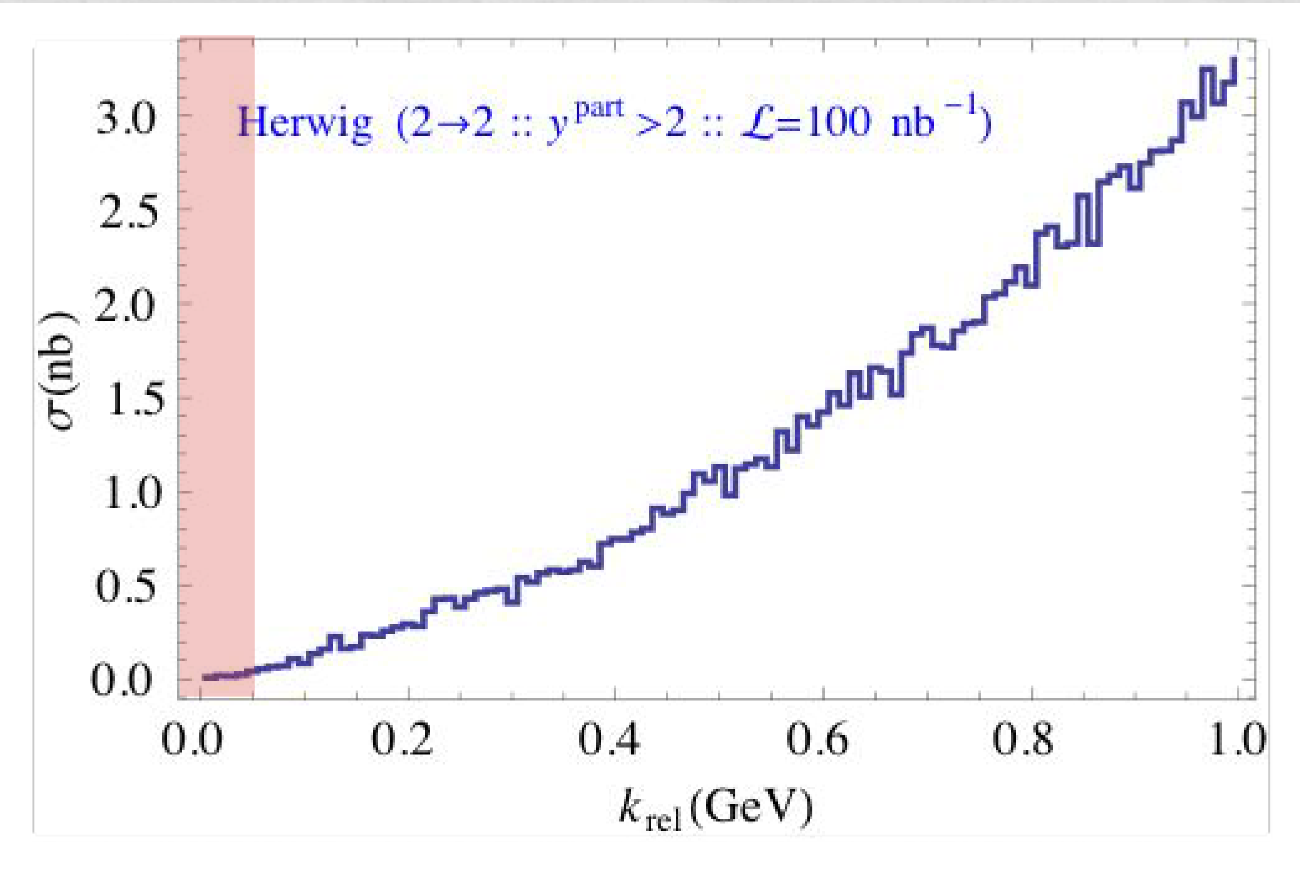


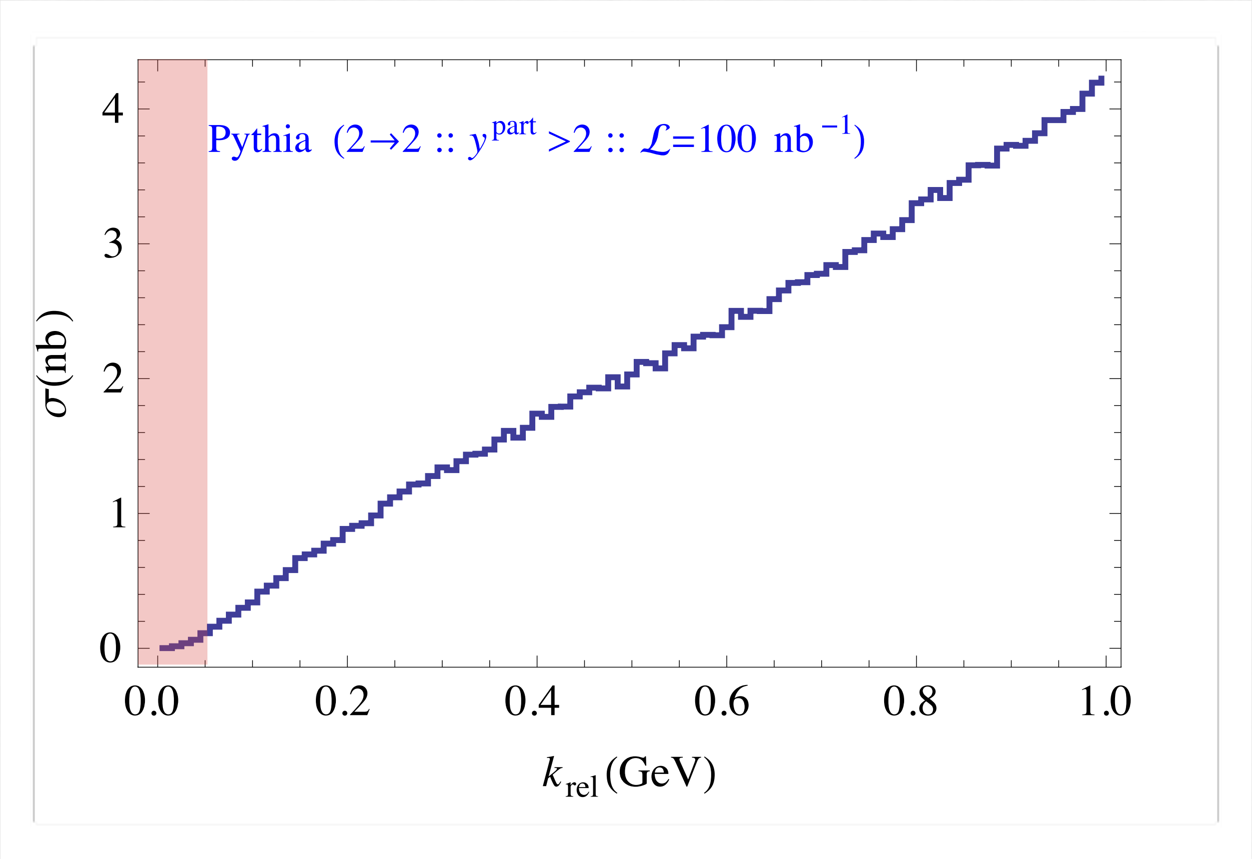




[The $D^0$ $D^{*-}$ pair cross section as function of Δϕ at CDF Run II. We find that we have to rescale the Herwig cross section values by a factor K= 1.8 to best fit the data on open charm production. As for Pythia we need K=0.74]



# COUNTING PAIRS OVER 5*10**9 SIMULATED EVENTS



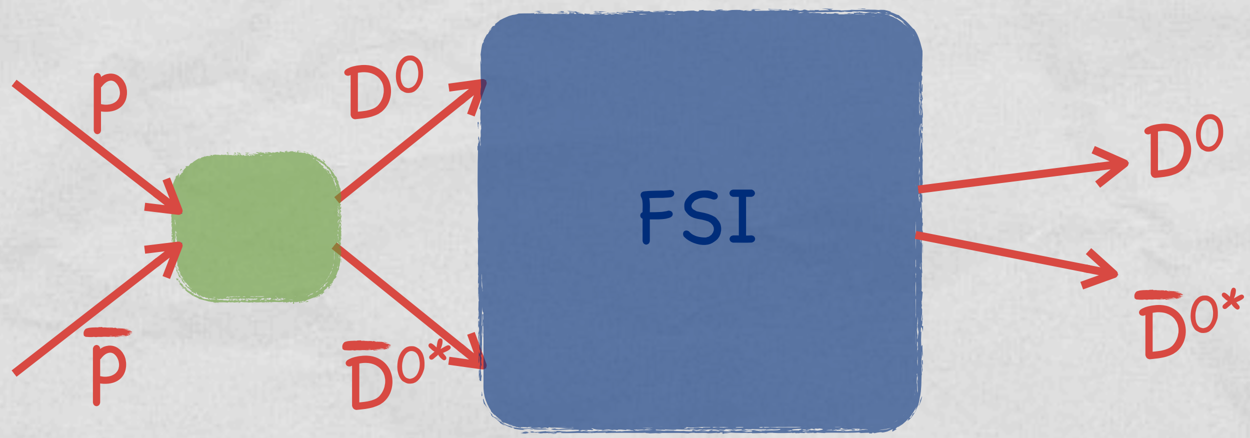

Bignamini,Grinstein, Piccinini, Polosa, Sabelli Phys Rev Lett 2009

In the Ball R of relative momenta found above the cross section turns out to be 0.07-0.11 nb, about **300 times smaller** than the minimum experimental value found by CDF data (~30nb).

**One needs to integrate cross section up to about 205 MeV with Herwig and 130 MeV with Pythia** in order to reach the experimental value. We thus **EXCLUDE any molecular interpretation of X(3872)**.

# FSI

Artoisenet & Braaten: Phys Rev D81, 114018 (2010)



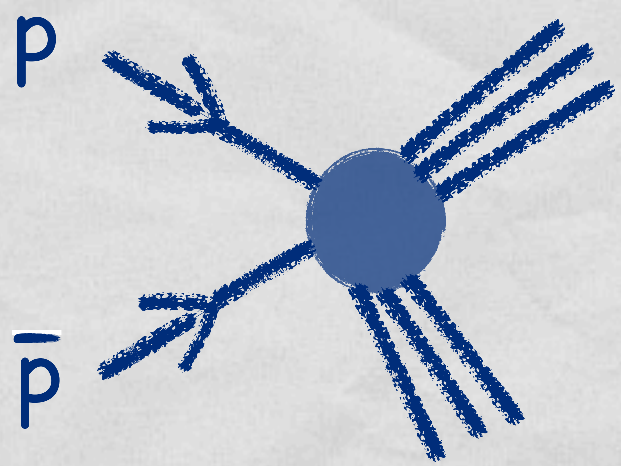

$$\sigma(p\bar{p} \to X(3872))^{\text{prompt}} = \sigma(k < \Lambda) \times \frac{6\pi\sqrt{2\mu\mathcal{E}_0}}{\Lambda}$$

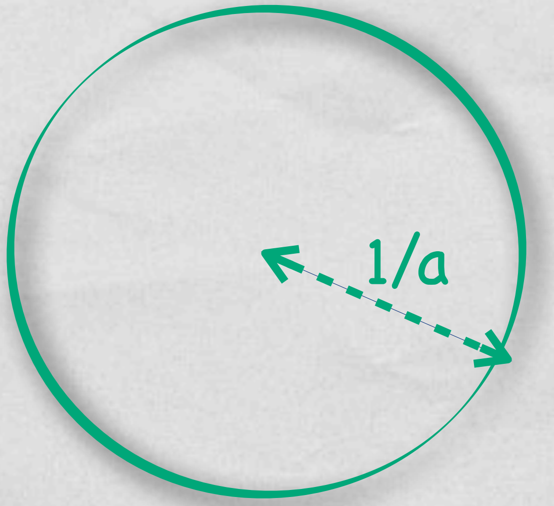
(1) FSI can make a high relative momentum pair to rescatter in a lower relative momentum pair: $k$ can range up to $\Lambda \approx 2m_\pi$

(2) Enhancement factor

In this way $\sigma^{th}$ and $\sigma^{exp}$ can be reconciled

# FSI II

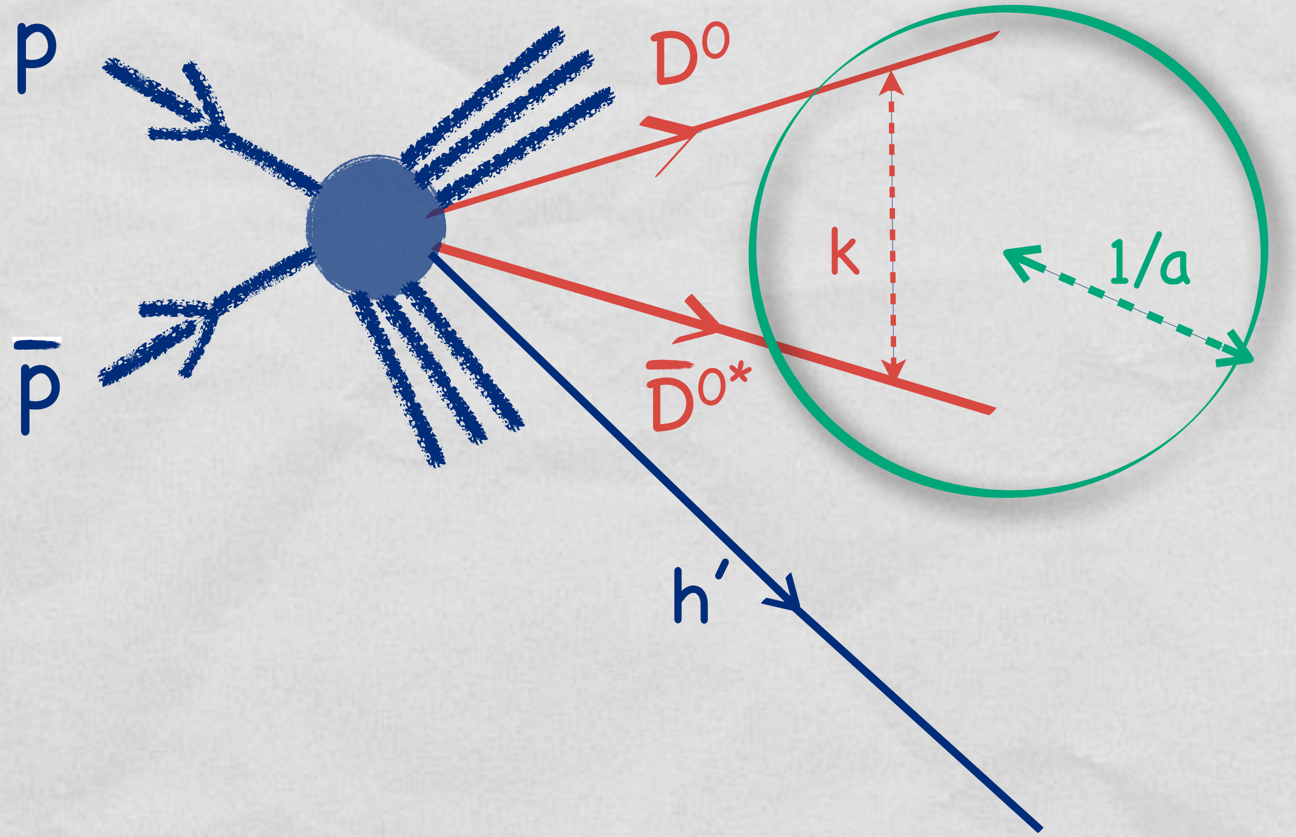



a is the range of strong interaction:
<u>a~1fm</u>
k<1/a~200MeV

:: Bignamini, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::

# FSI II

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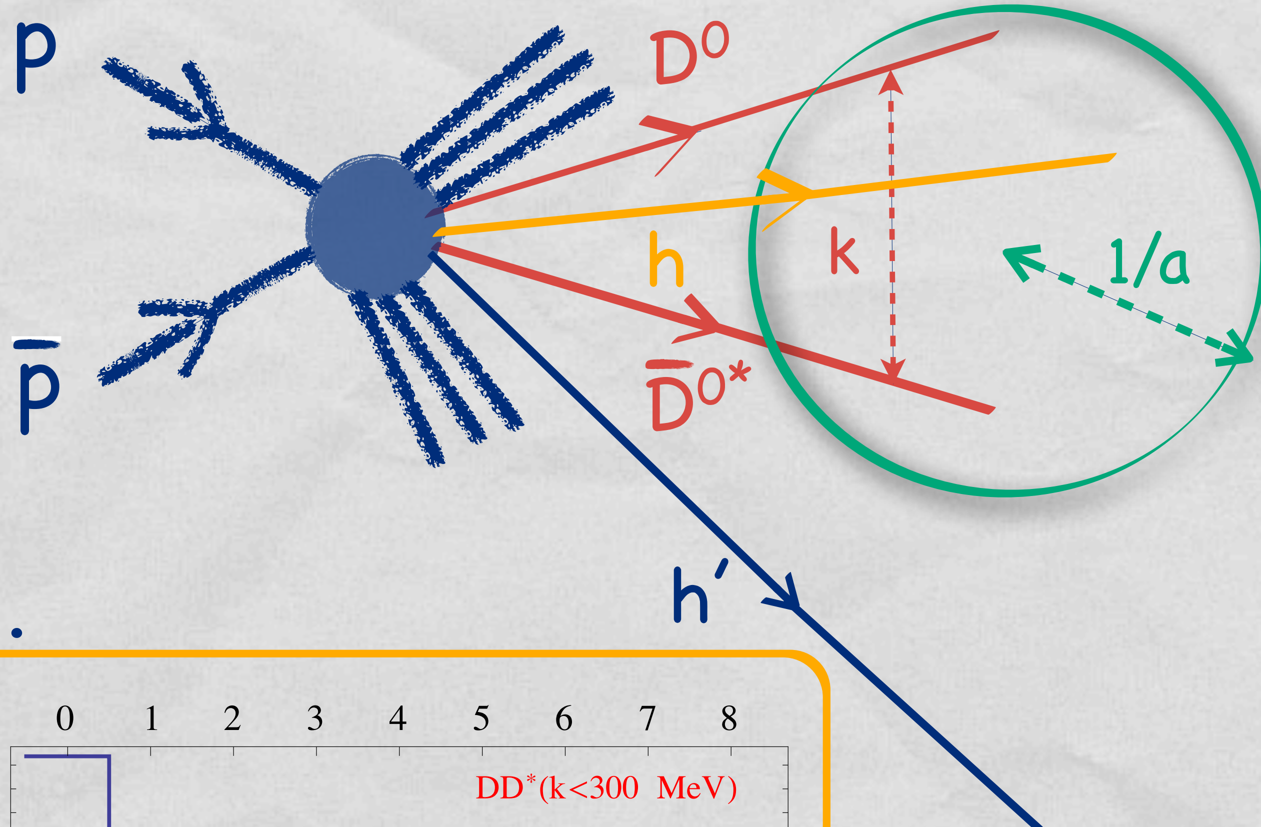
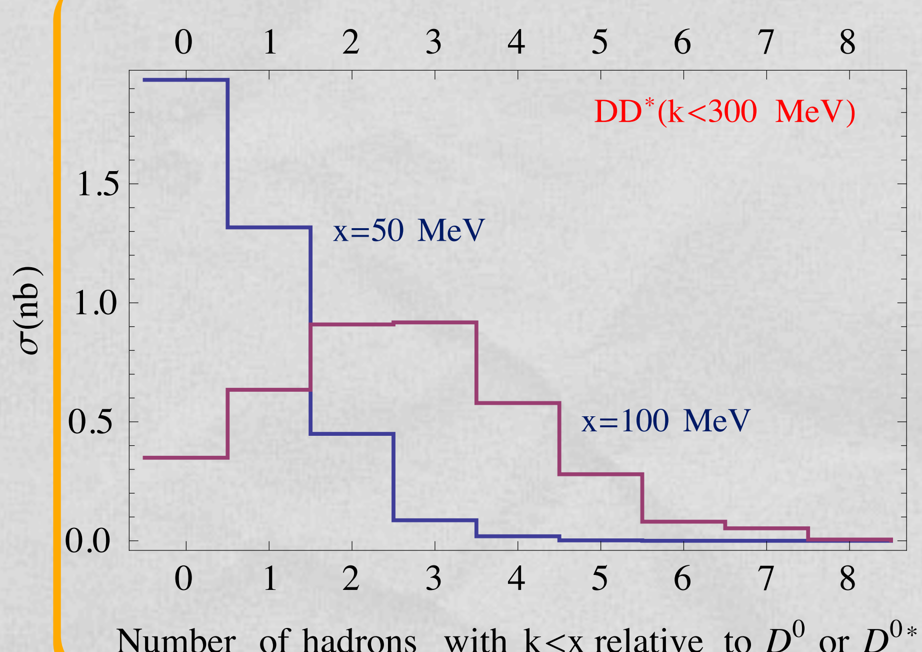
:: Bignamini, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::

# FSI II




a is the range of strong interaction:
a~1fm
k<1/a~200MeV

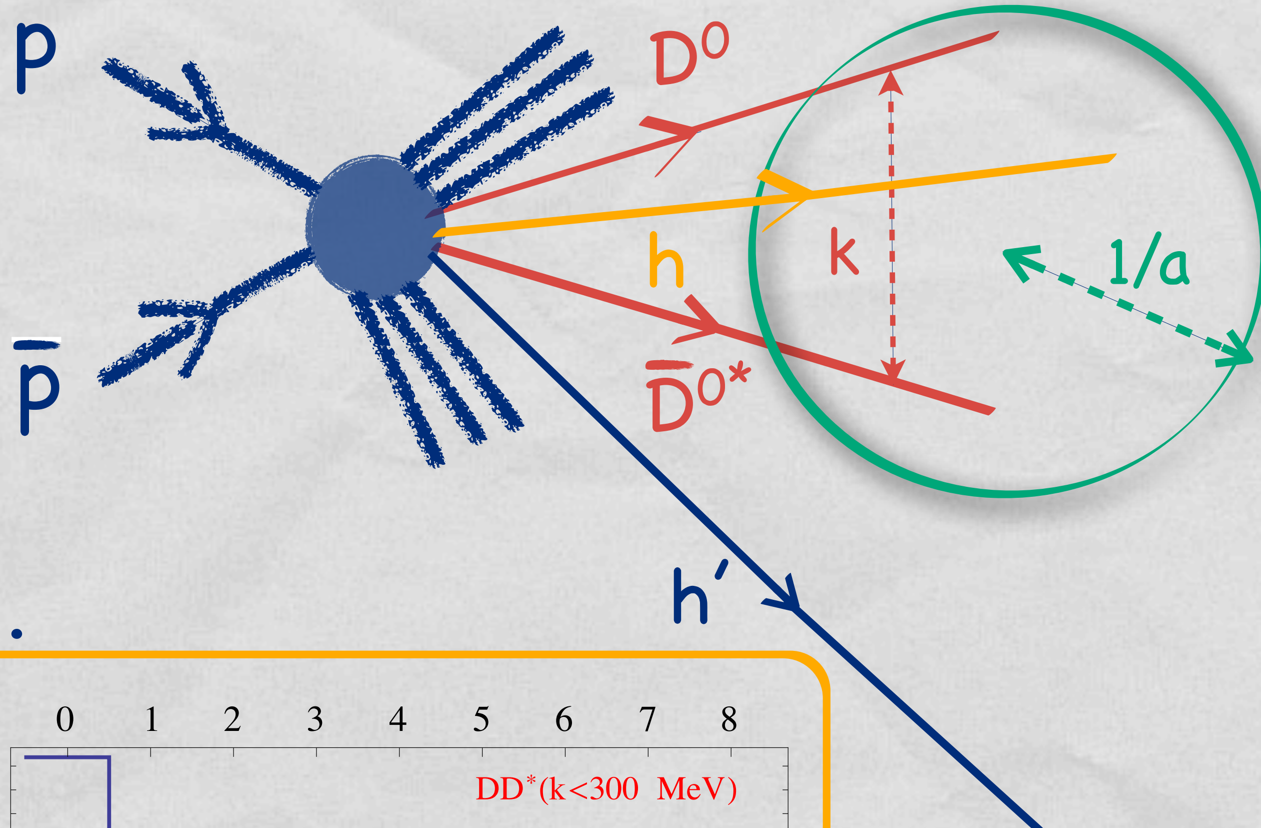
1.




In the standard treatment of FSI (Watson Theorem) one should have no more than two particles rescattering in the final state.
We find that this is not the case in the CDF simulation.

:: Bignamini, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::

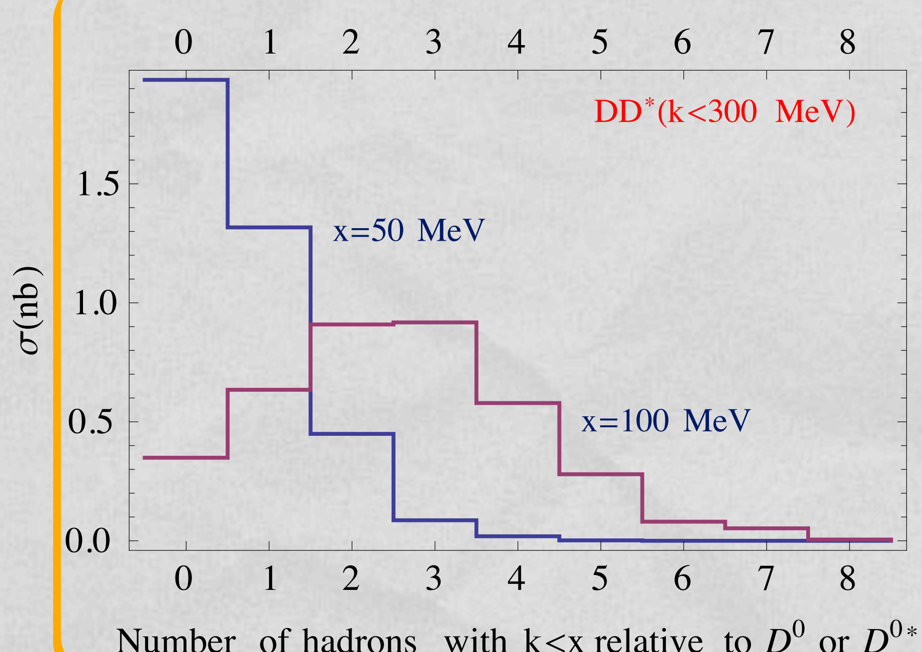
# FSI II




a is the range of strong interaction:
a~1fm
k<1/a~200MeV

S-wave scattering requires: ka<<1
k<<200 MeV

1.

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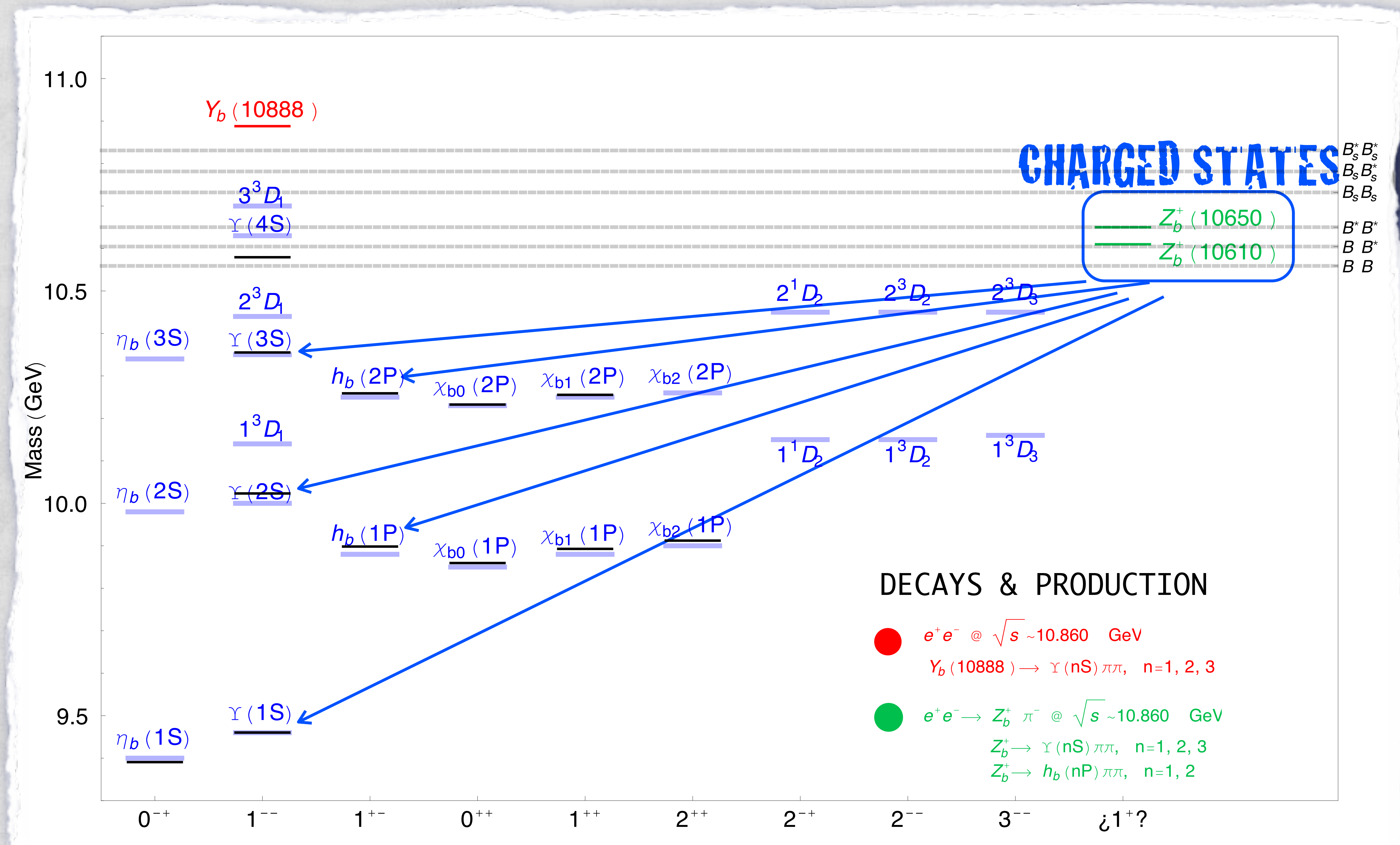
We find that this is not the case in the CDF simulation.

:: Bignamini, Piccinini, Polosa, Riquer, Sabelli, Phys.Lett.B684:228-230,2010 ::

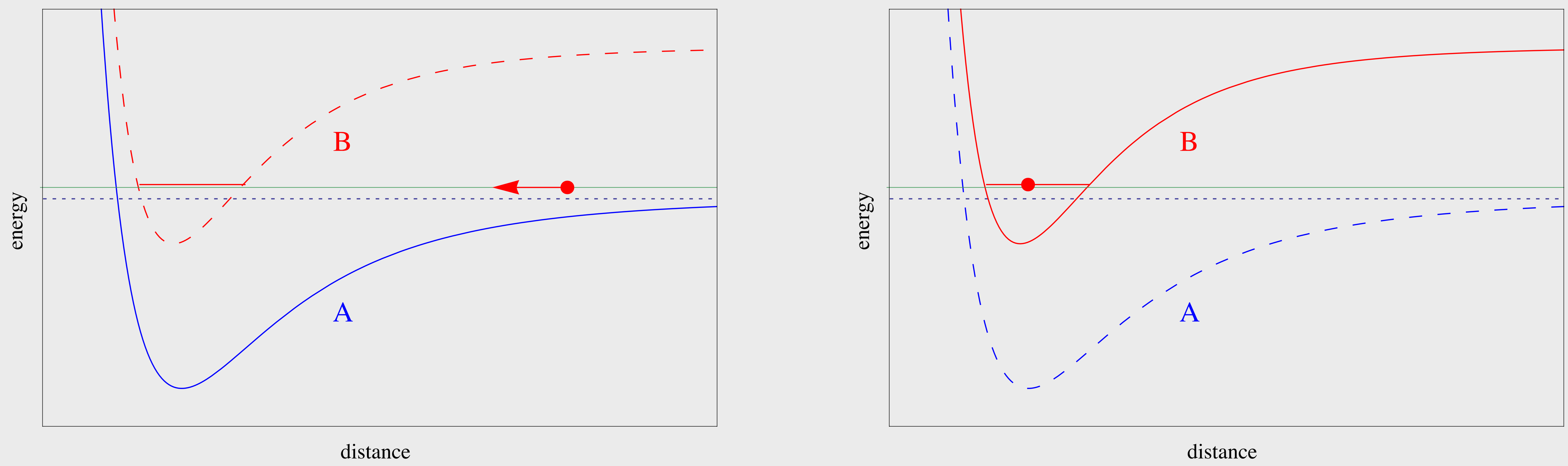
# Newcomers in the b-System



# FESHBACH MOLECULES

E. Braaten

Much studied in cold atoms physics. What about hadrons?




$$i\frac{\Gamma}{2} = \langle\psi_B|H_{BA}\frac{1}{\mathcal{E}-H_{AA}}H_{AB}|\psi_B\rangle \sim |g|^2$$

[The Breit-Wigner width of a Feshbach resonance
is proportional to the coupling squared between the open (A) and closed (B) channels]

# LIGHT SCALAR MESONS

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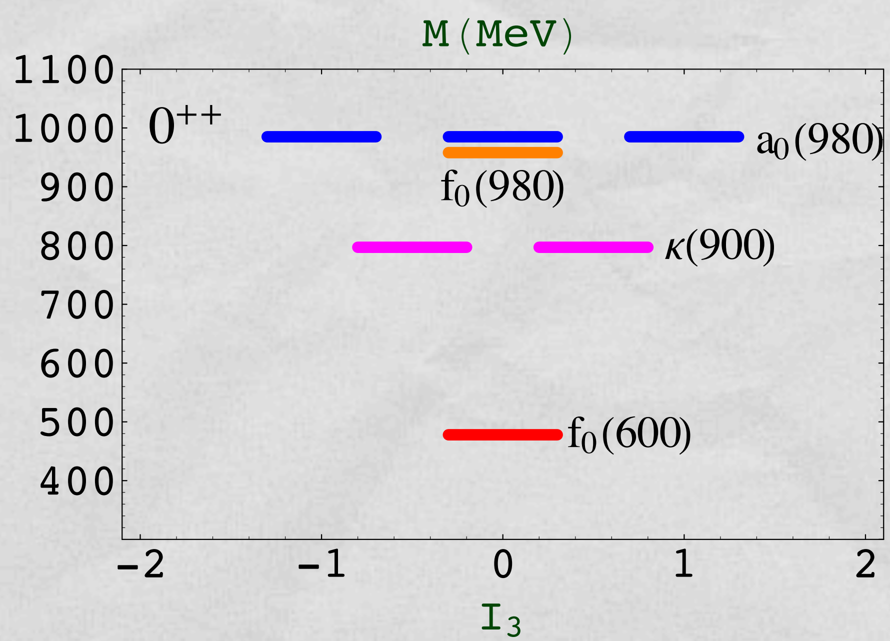
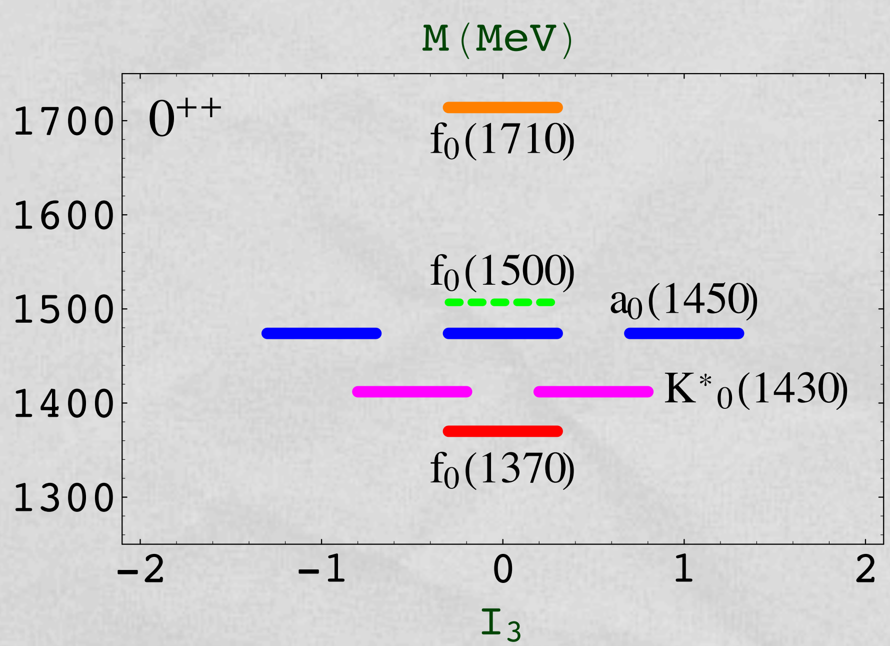
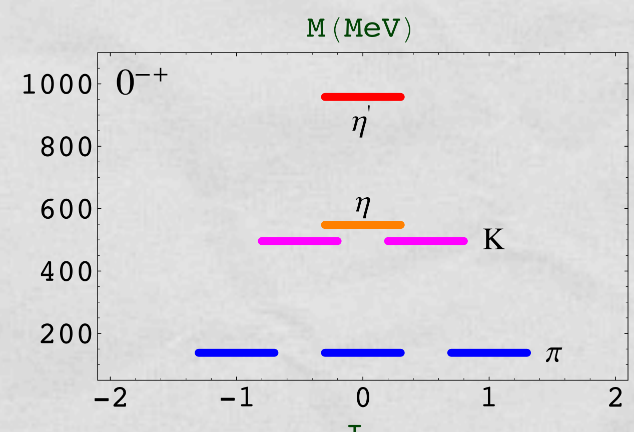
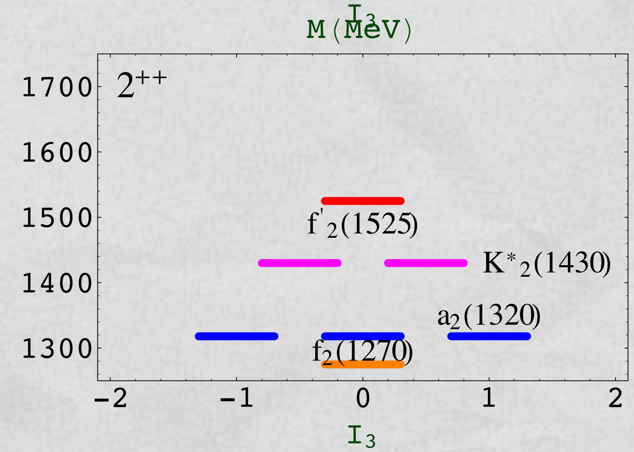
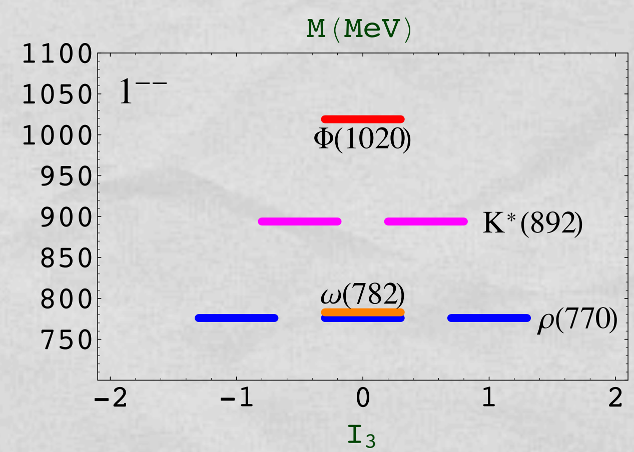



Observed by R Jaffe in several works

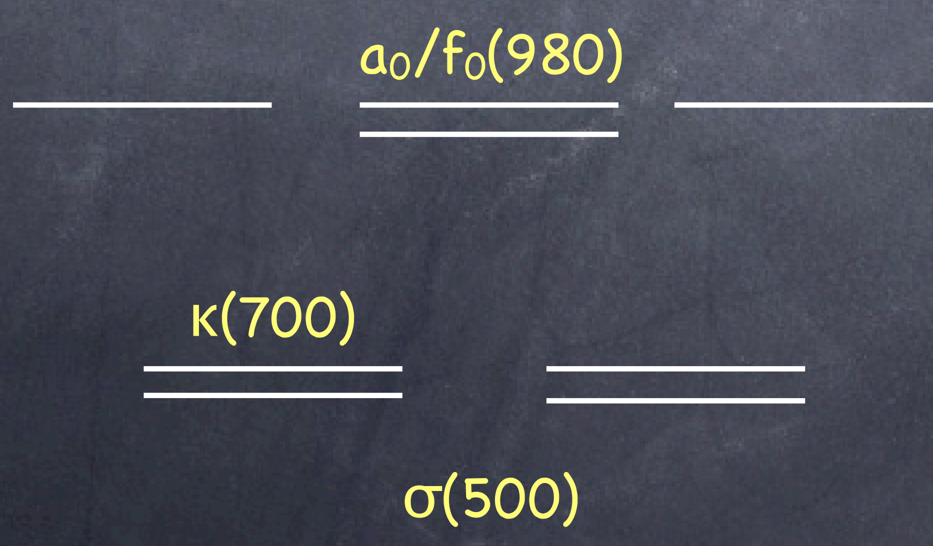
# Diquark Exoticity

$$q \mapsto \bar{\mathfrak{q}}$$
$$\bar{q} \mapsto \mathfrak{q}$$

$\mathfrak{q} = [q \uparrow q \downarrow]_{\bar{\mathbf{3}}_{\mathbf{c}}, \bar{\mathbf{3}}_{\mathbf{f}}}$ or, more precisely, $\mathfrak{q}_{i\alpha} = \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}\bar{q}_C^{j\beta}\gamma_5 q^{k\gamma}$

with such a notation we would write

$$\begin{aligned}
\sigma &= \mathfrak{q}^3\bar{\mathfrak{q}}^3;\ \text{where } 1,2,3 = u,d,s \\
\kappa &= \mathfrak{q}^2\bar{\mathfrak{q}}^3,\ \mathfrak{q}^1\bar{\mathfrak{q}}^3,\ + \text{conj. doubl.} \\
f_0 &= \frac{\mathfrak{q}^2\bar{\mathfrak{q}}^2 + \mathfrak{q}^1\bar{\mathfrak{q}}^1}{\sqrt{2}} \\
a_0 &= \mathfrak{q}^2\bar{\mathfrak{q}}^1,\ \frac{\mathfrak{q}^2\bar{\mathfrak{q}}^2 - \mathfrak{q}^1\bar{\mathfrak{q}}^1}{\sqrt{2}},\ \mathfrak{q}^1\bar{\mathfrak{q}}^2
\end{aligned}$$




$$\underbrace{[ds][\bar{u}\bar{s}]}_{I_3=-1} \quad \underbrace{[us][\bar{u}\bar{s}],[sd][\bar{s}\bar{d}]}_{I_3=0} \quad \underbrace{[us][\bar{d}\bar{s}]}_{I_3=+1}$$

$$\underbrace{[ud][\bar{u}\bar{s}],[sd][\bar{u}\bar{d}]}_{I_3=-1/2} \quad \underbrace{[ud][\bar{d}\bar{s}],[us][\bar{u}\bar{d}]}_{I_3=+1/2}$$

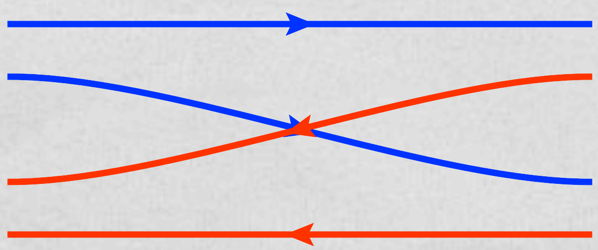
$$\underbrace{[ud][\bar{u}\bar{d}]}_{I_3=0}$$

# HOW DOES F0 DECAY?

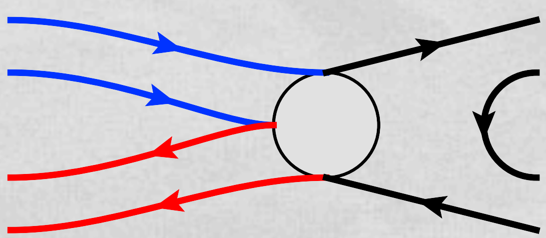
‘t Hooft, Isidori, Maiani, Polosa, Riquer, Phys Lett B 2008

The f0(980), [us][u*s*] is known to decay mostly in two pions; the kaon channel being closed by phase space.

$$\mathcal{L}_1 = g_1 S^{i}{}_{j}\epsilon_{i\ell k}\epsilon^{jmn}\partial_\mu \Pi^\ell_m \partial^\mu \Pi^k_n$$

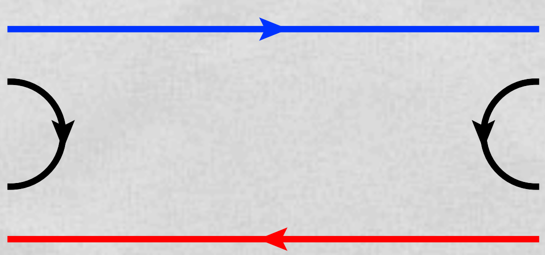


$$\mathcal{L}_2 = g_2 \mathrm{Tr}\ S\partial_\mu\Pi\partial^\mu\Pi$$



6-fermion interaction induced by instantons.

vs. double annihilation



# BEST FIT

't Hooft, Isidori, Maiani, Polosa, Riquer, *Phys Lett B 2008*

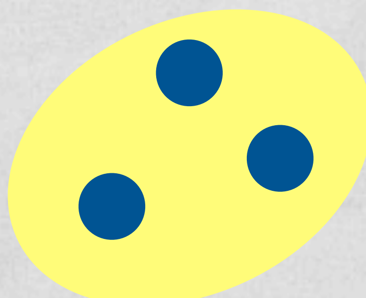
Why not simply invoking the annihilation of strange quarks?
Annihilation would mean 1-the breaking of diquarks 2-the annihilation of strange quarks.
Instantanton induced interactions proceed directly from the diquarks.
Yet the effective treatment of the problem is at the meson level.

| Processes | $\mathcal{A}_{\rm th}([qq][\bar{q}\bar{q}])$ | | | $\mathcal{A}_{\rm th}(q\bar{q})$ | | $\mathcal{A}_{\rm expt}$ |
|---|---|---|---|---|---|---|
| | with inst. | no inst. | best fit | with inst. | no inst. | |
| $\sigma \to \pi^+\pi^-$ | input | input | 1.6 | input | input | $3.22 \pm 0.04$ |
| $\kappa^+ \to K^0\pi^+$ | 7.3 | 7.7 | 3.3 | 6.0 | 5.5 | $5.2 \pm 0.1$ |
| $f_0 \to \pi^+\pi^-$ | input | [0–1.6] | 1.6 | input | [0–1.6] | $1.4 \pm 0.6$ |
| $f_0 \to K^+K^-$ | 6.7 | 6.4 | 3.5 | 6.4 | 6.4 | $3.8 \pm 1.1$ |
| $a_0 \to \pi^0\eta$ | 6.7 | 7.6 | 2.7 | 12.4 | 11.8 | $2.8 \pm 0.1$ |
| $a_0 \to K^+K^-$ | 4.9 | 5.2 | 2.2 | 4.1 | 3.7 | $2.16 \pm 0.04$ |

This is the first global fit which works.

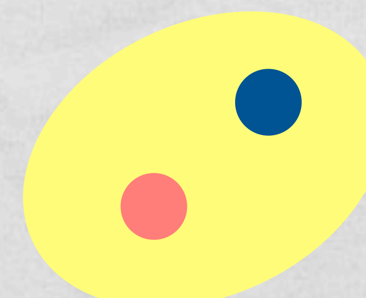
# QUARKS IN HADRONS

Quarks are the building blocks of matter.
We describe *baryons (p,n,...)* and *mesons (pions, K's, ...)* as aggregations of confined quarks

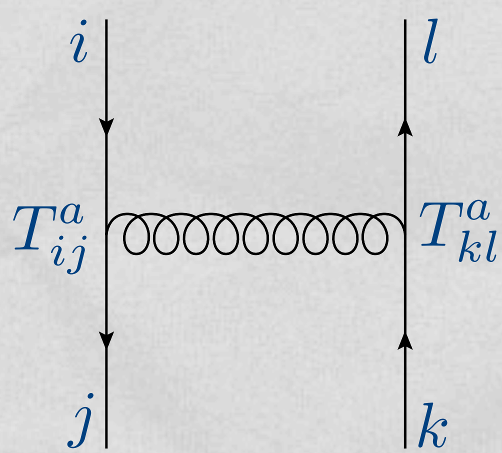


$$\text{baryon}: \quad \epsilon^{ijk} q^i q^j q^k$$

$$\text{meson}: \quad q^i \bar{q}_i$$



This is the picture since the first days of the quark model and the discovery of *color.*
Attraction and repulsion between electric charges is a matter *product* of *signs.*
In chromodynamics (color SU(3)) it is more complicated than that (matrix tensor products)




$$T^a_{R_1} \times T^a_{R_2}$$

# DIQUARKS

The 9x9 matrix obtained can be diagonalized along the Kronecker decomposition

$$R_1 \times R_2 = S_1 + S_2 + \ldots$$

For example, in the decomposition of

$$\mathbf{3} \times \bar{\mathbf{3}} = \mathbf{1} + \mathbf{8}$$

the tensor product of *T's* is negative along the singlet component (*attraction in the color neutral channel*) and positive along the eight remaining matrix entries (*repulsion*). However there is *attraction also* in the antitriplet 'channel' of the decomposition

$$\mathbf{3} \times \mathbf{3} = \bar{\mathbf{3}} + \mathbf{6}$$

**One gluon-exchange suggests that *diquarks* - qq - states might be formed as a result of this attraction (lattice confirmation!)**

# HADRONS (60s)

Exponentially rising density of hadron resonances.

$$Z = \sum \underbrace{m^{-k} e^{m/T_H}}_{\rho(m)} e^{-m/T}$$

Hadron matter cannot exist at temperatures $T > T_H$