# X(YZ...) PHENOMENOLOGY

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# X(3872) AT LHC

CMS Collaboration arXiv:1302.3968



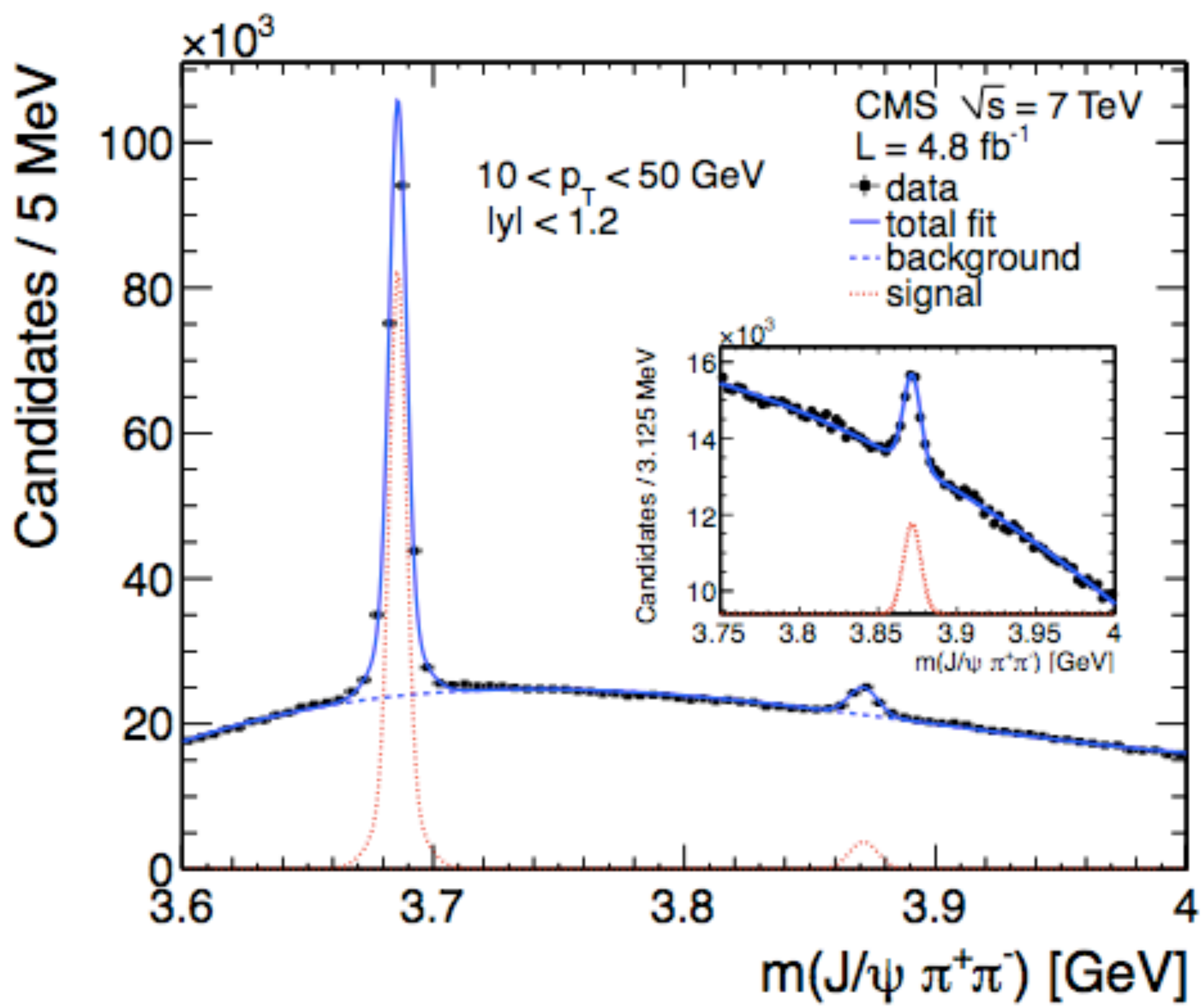


Figure 1: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum for $10 < p_T < 50$ GeV and $|y| < 1.2$. The lines represent the signal-plus-background fits (solid), the background-only (dashed), and the signal-only (dotted) components. The inset shows an enlargement of the X(3872) mass region.

# 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 quite some time the X it has not been clear from data if X were a $1^{++}$ state or a $2^{-+}$ one.


R. Faccini, F. Piccinini, A. Pilloni, and ADP, *'On the Spin of the X(3872)', Phys. Rev. D* 2012

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

# HADRON MOLECULES

# Are Mesons Elementary Particles?

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*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.

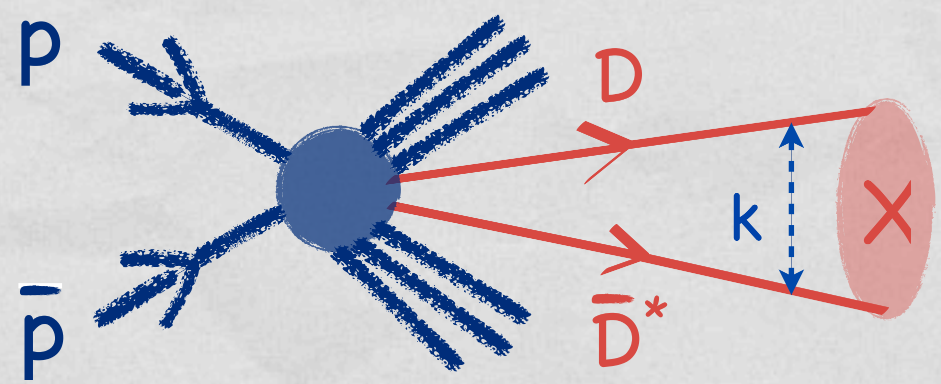


Thursday, March 7, 13

# X - A DIFFERENT KIND OF MOLECULE

N. Tornqvist, 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)*

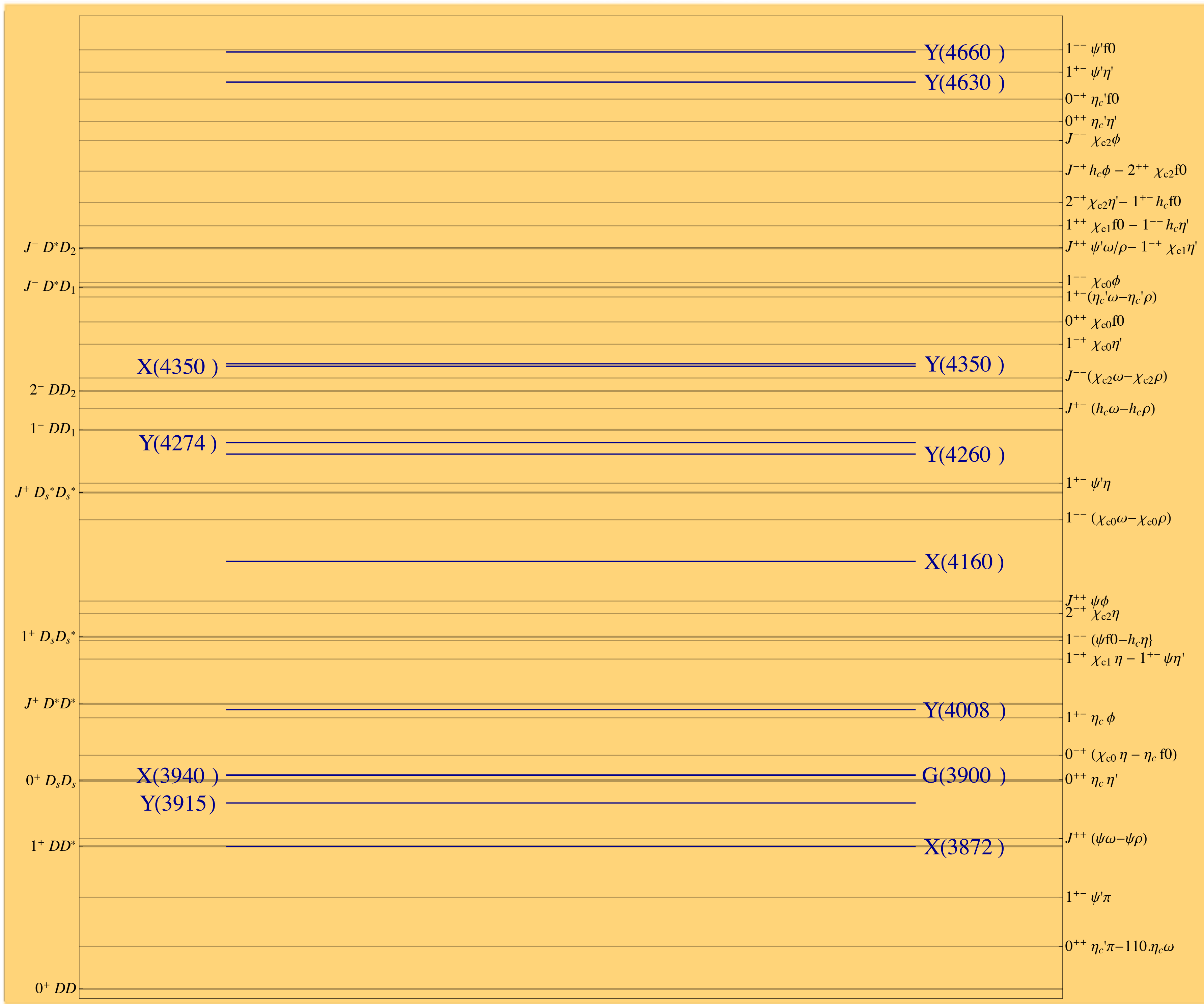
Can final state interactions allow such high production cross sections?
How can occurr the decay into J/ψ initiated by a 10 fm bound state of color neutral mesons?

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



# THRESHOLDS (CHARM SECTOR)

See E. Braaten talk at CHARM2012

- For an hadron being constituent in a hadron molecule its width has to be smaller than binding energy (e.g. ρ is just too broad)
- Close to thresholds of narrow mesons (say $DD^*$) interesting things might happen. There are several narrow charm-charm threshold one can form starting from $D$, $D^*$, $D_s$, $D_s^*$, $D_{s0}$, $D_{s1}^*$, $D_{s1}$
- Narrow light hadrons should also make up molecules (π,K,η,η',ω,φ). Similarly with light baryons.

# DEUTERIUM & X

Deuterium (spin1) has a binding energy of ~ -2.2 MeV.
Singlet deuteron (-60 keV) is a virtual particle in n-p scattering.

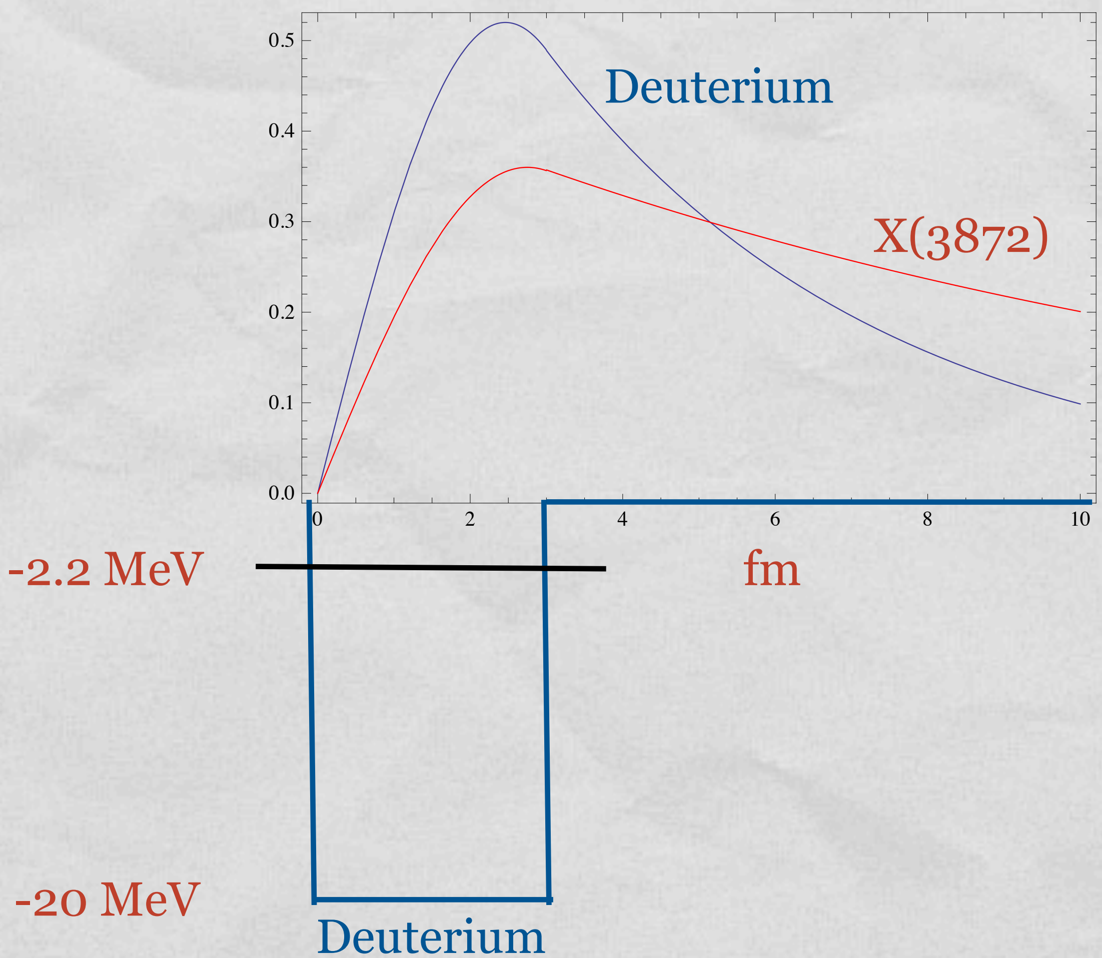
The X has ~ -0.14 MeV.

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)

N.B. The Deuterium has spin!
D and D* do not have spin-spin interactions

Production at hadron colliders?

# DEUTERIUM & X




$$k_{\rm rel} = \sqrt{2\mu\langle T\rangle_\psi^2} \approx \begin{cases} 80 \text{ MeV} & \text{for deuterium} \\ 50 \text{ MeV} & \text{for } X; \quad U_0 \approx -7 \text{ MeV} \quad \mathcal{E}_b \approx -0.14 \text{ MeV} \end{cases}$$

$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-\frac{m_\pi c}{\hbar}r_0}}{r_0} = \mathcal{E}_b = 0.14 \text{ MeV} \Rightarrow r_0 \approx 12 \text{ fm}$$

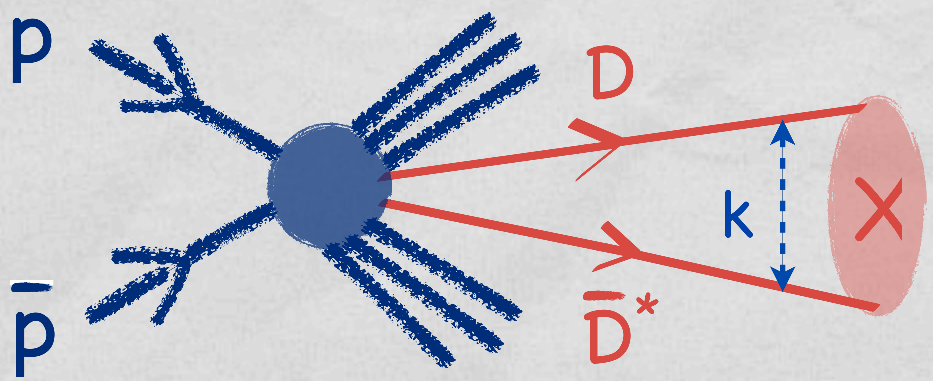
# PROMPT PRODUCTION

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

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

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

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



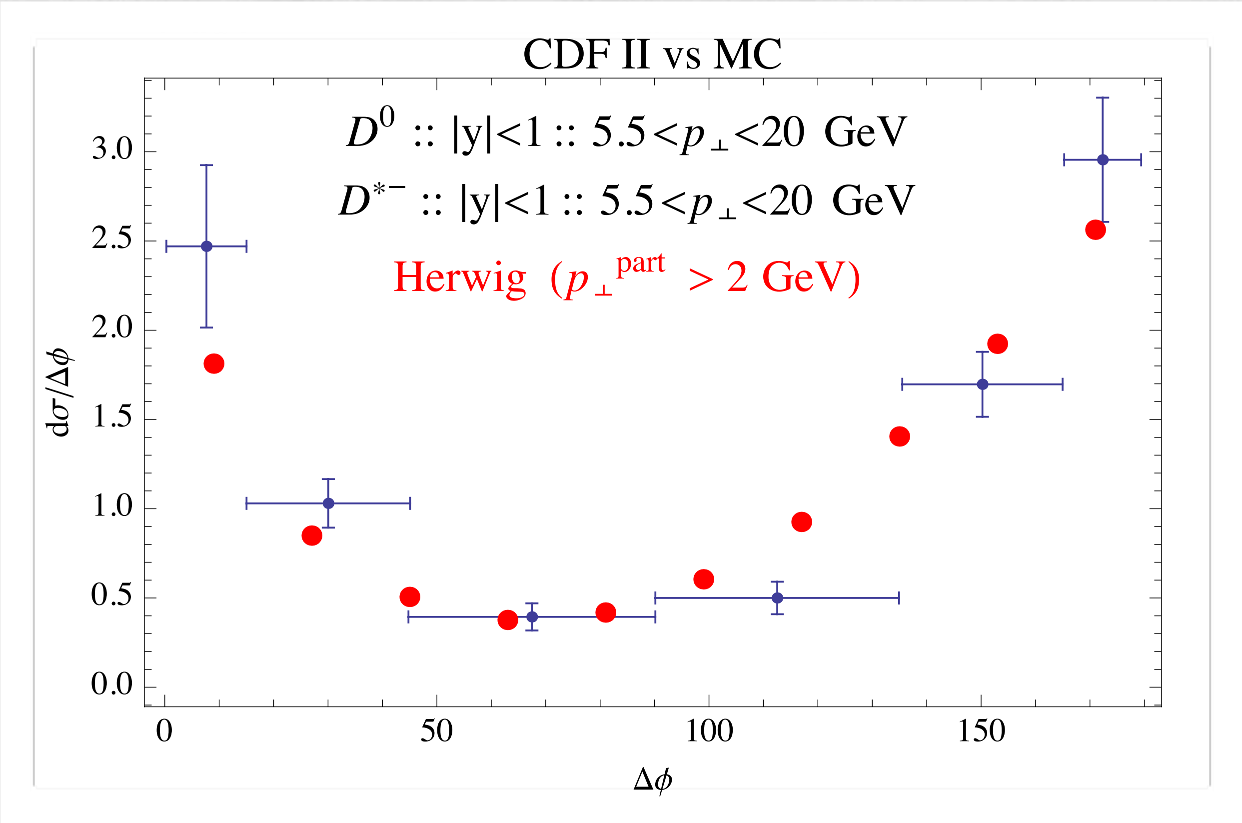

Using Pythia & Herwig we can compute

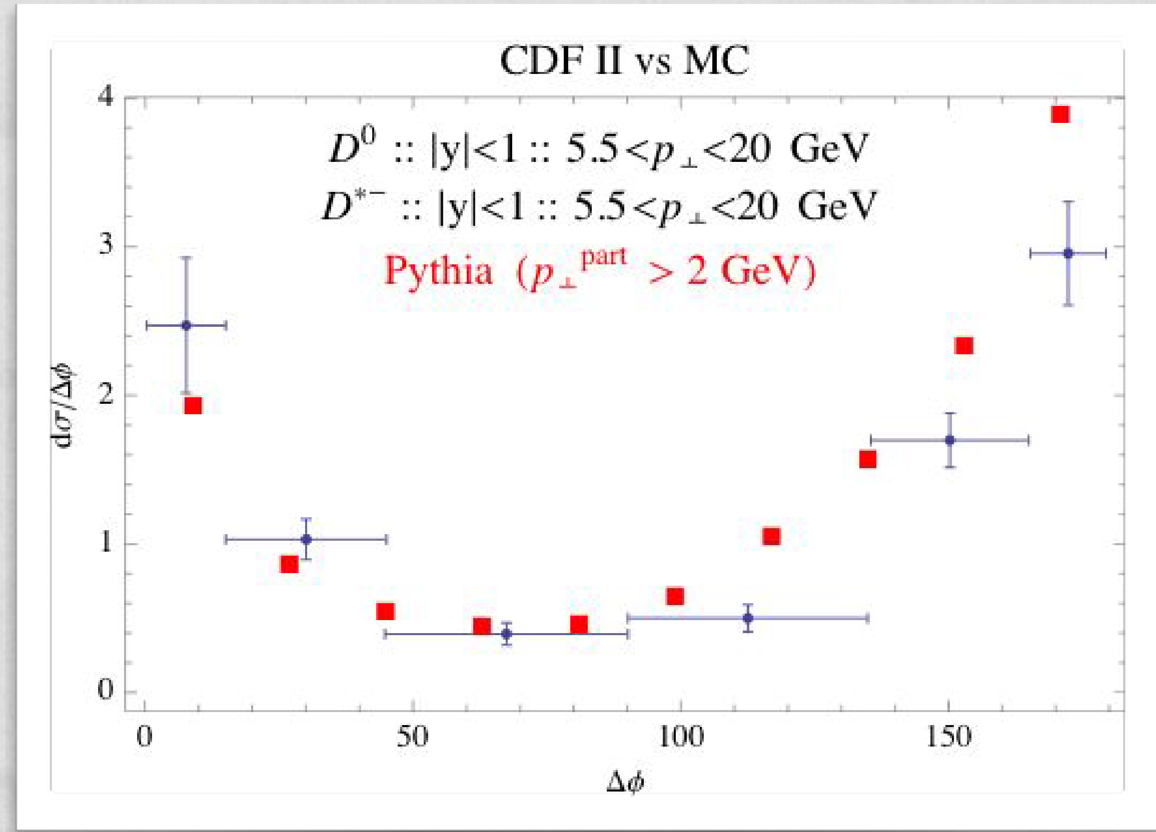
$$\sigma_{\max}(p\bar{p} \to X(3872)) = \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$$

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

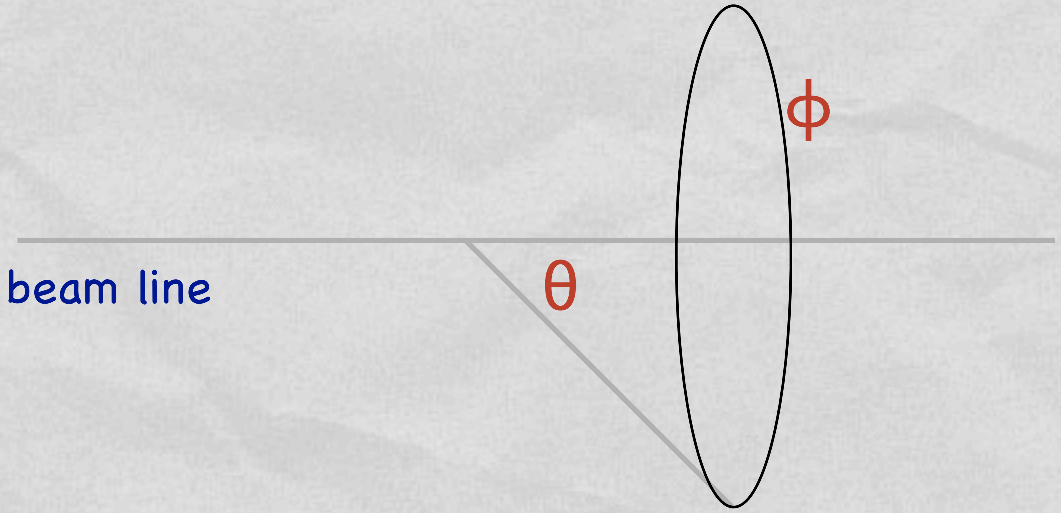
as $k \sim \sqrt{2\mu(-0.25 + 0.40)} \simeq 17$ MeV

# TUNING MC'S

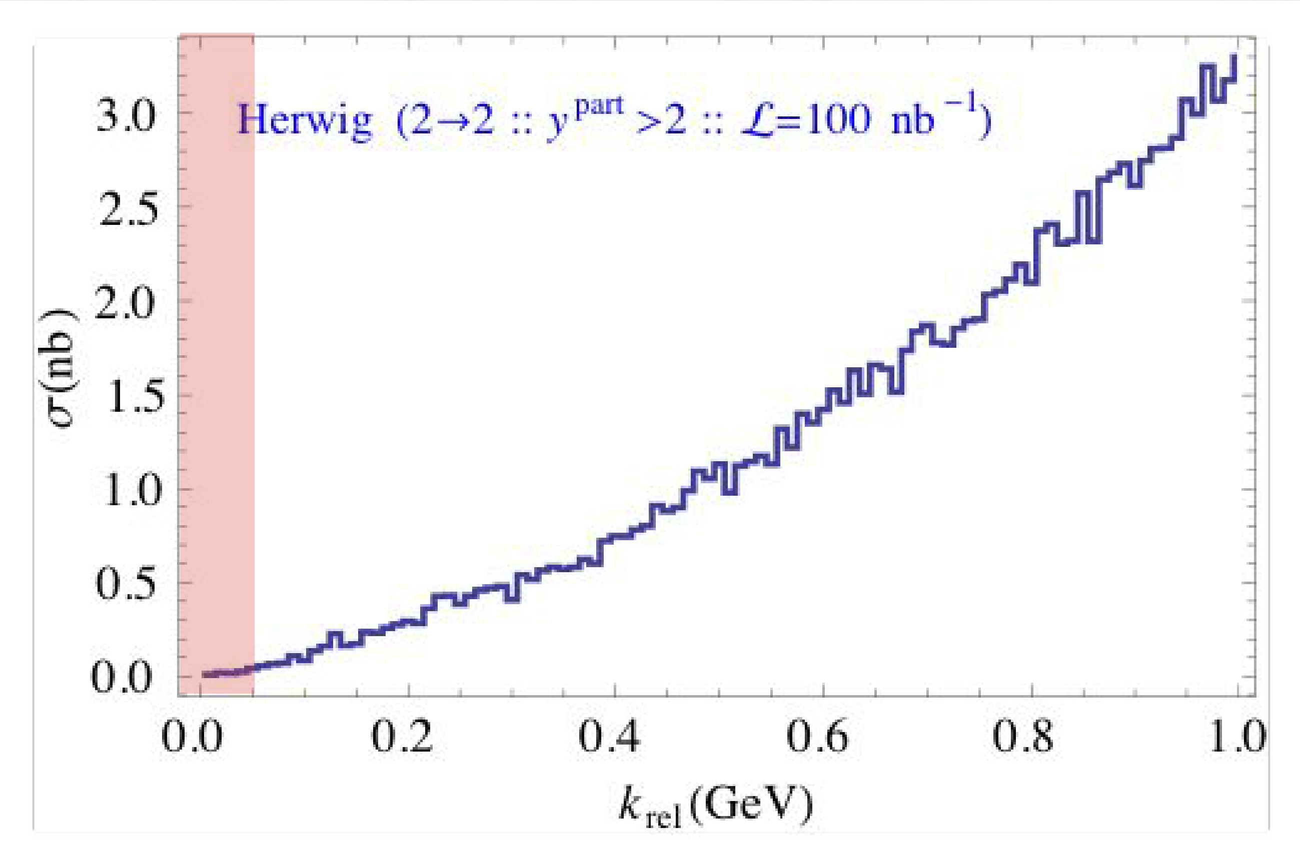


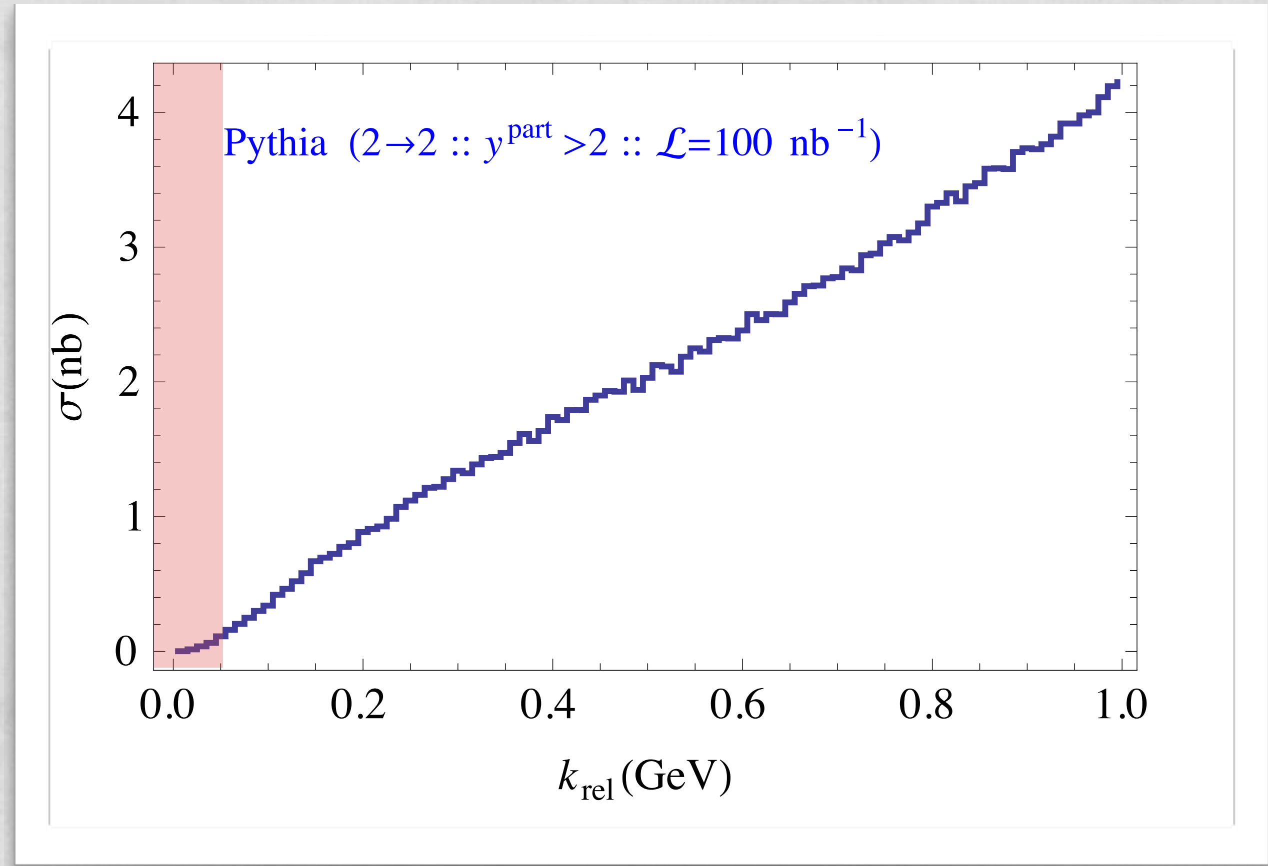




[The $D^0$ $D^{*-}$ pair cross section as function of $\Delta\varphi$ at CDF Run II. We find that we have to rescale the Herwig cross section values by a factor K= 1.8 to best fit the data on open charm production. As for Pythia we need K=0.74]



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



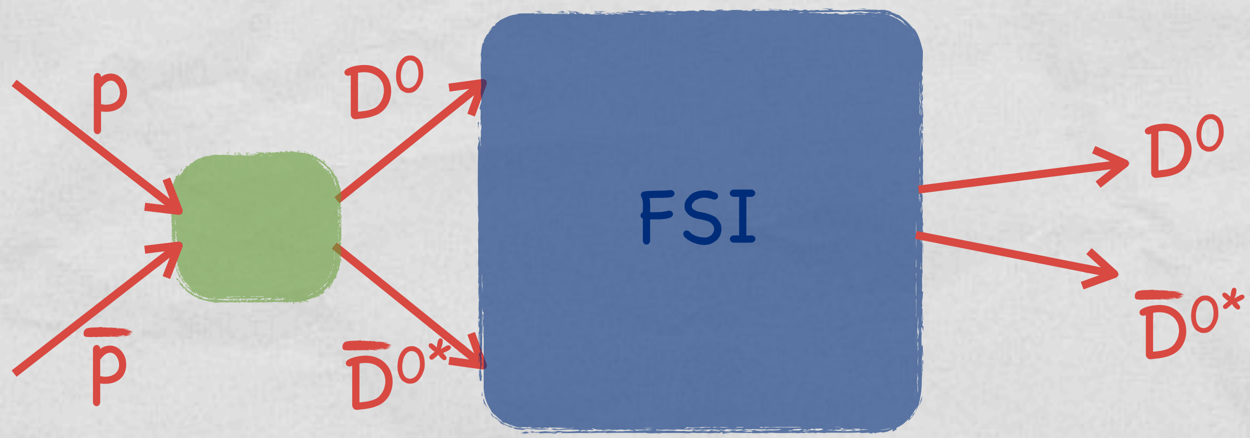

Bignamini,Grinstein, Piccinini, Polosa, Sabelli Phys Rev Lett 2009

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)



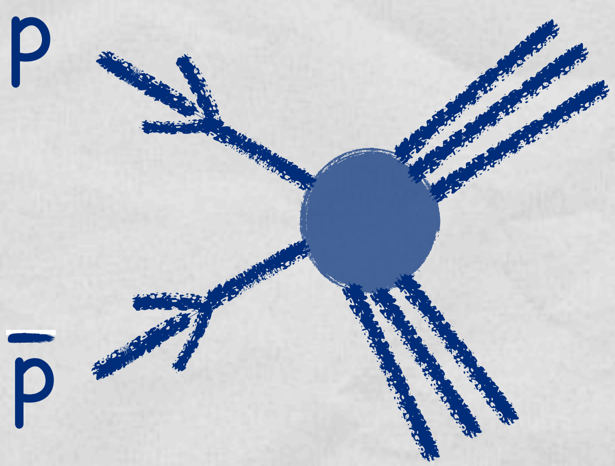

$$\sigma(p\bar{p} \to X(3872))^{\rm prompt} = \sigma(k < \Lambda) \times \frac{6\pi\sqrt{2\mu\mathcal{E}_0}}{\Lambda}$$

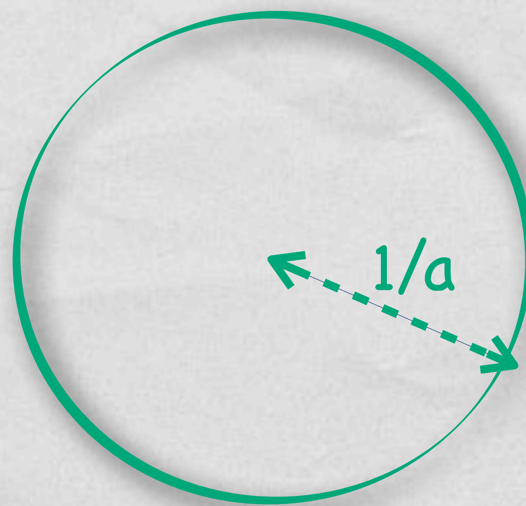
(1) FSI can make a high relative momentum pair to rescatter in a lower relative momentum pair: k can range up to $\Lambda \approx 2\text{-}3\ m_\pi$

(2) Enhancement factor

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

# FSI II

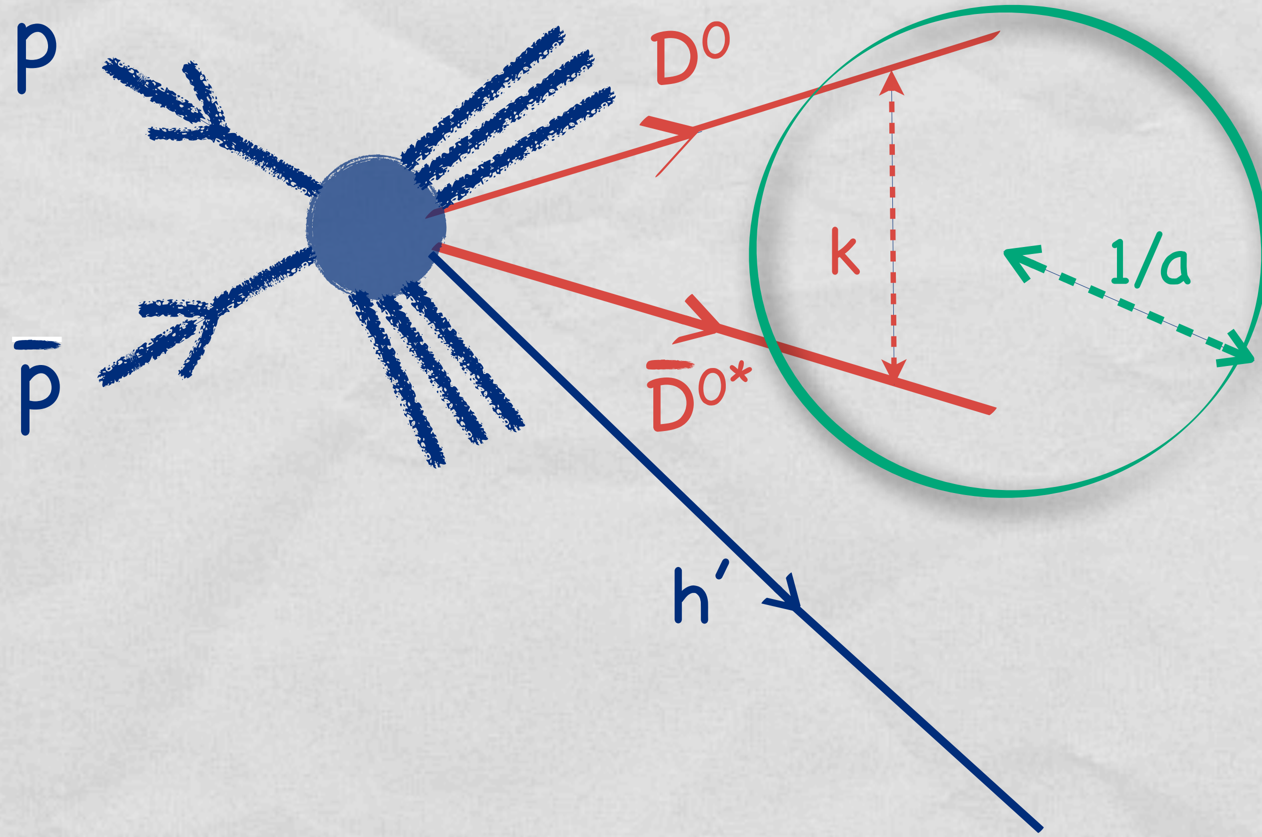



a is the range of strong interaction:
<u>a~1fm</u>
k<1/a~200MeV

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

# FSI II

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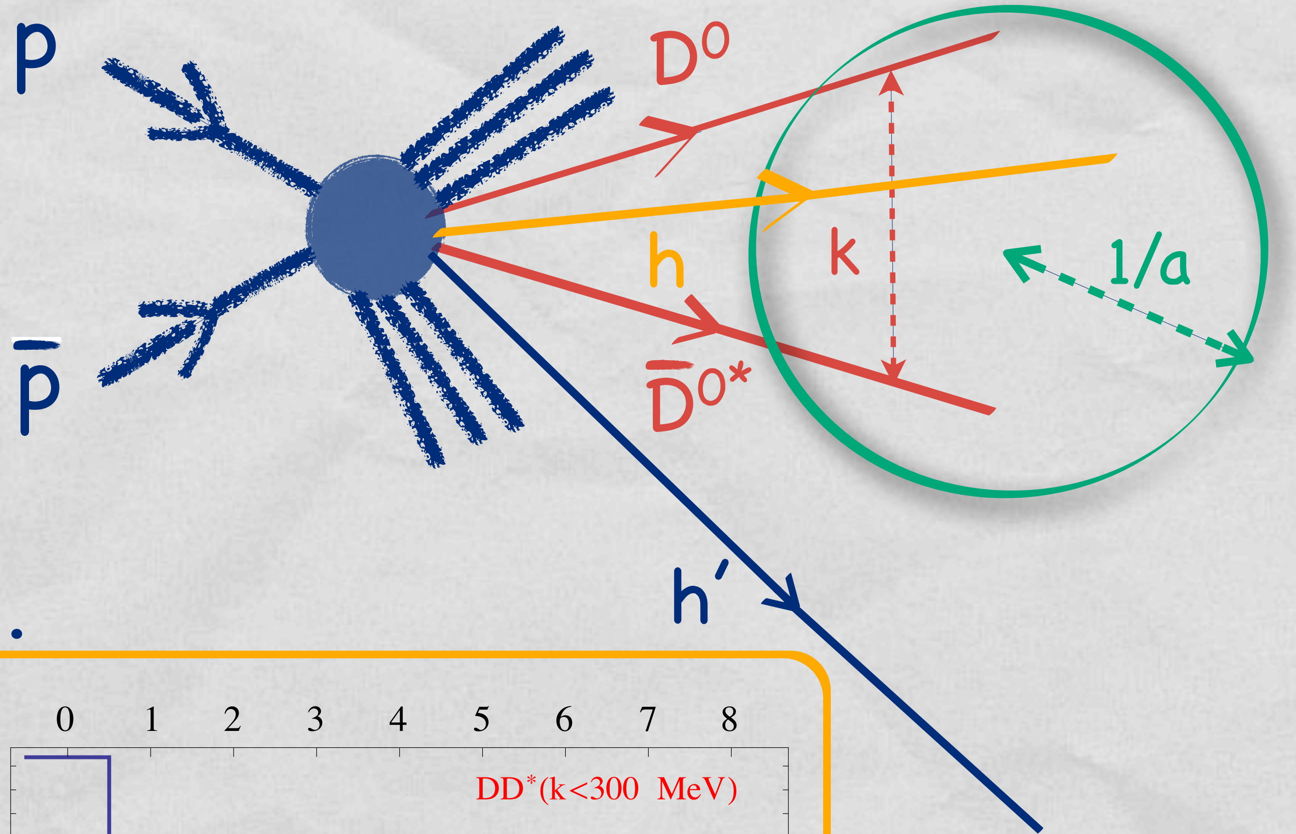


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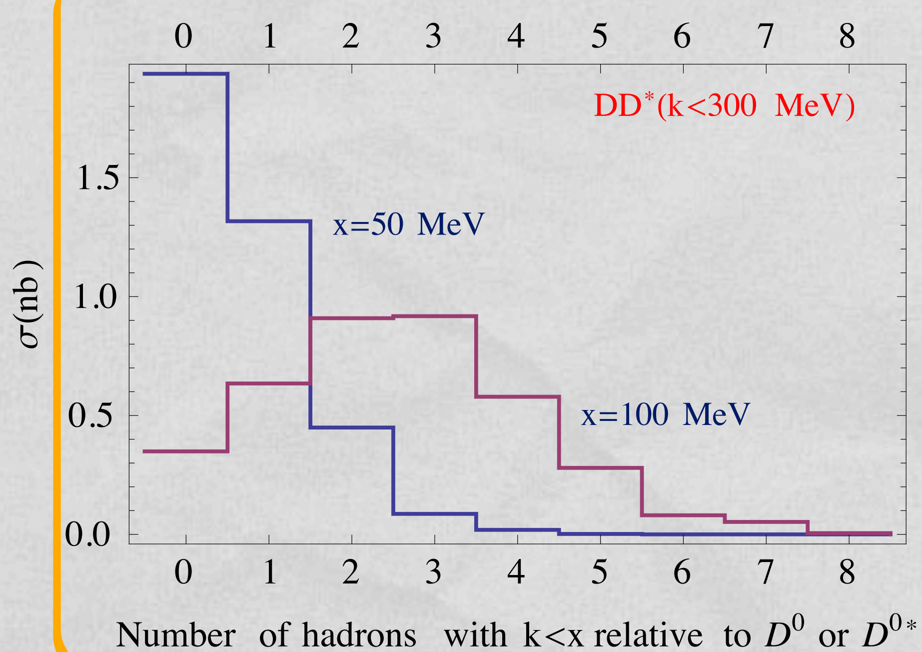
1.




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 ::

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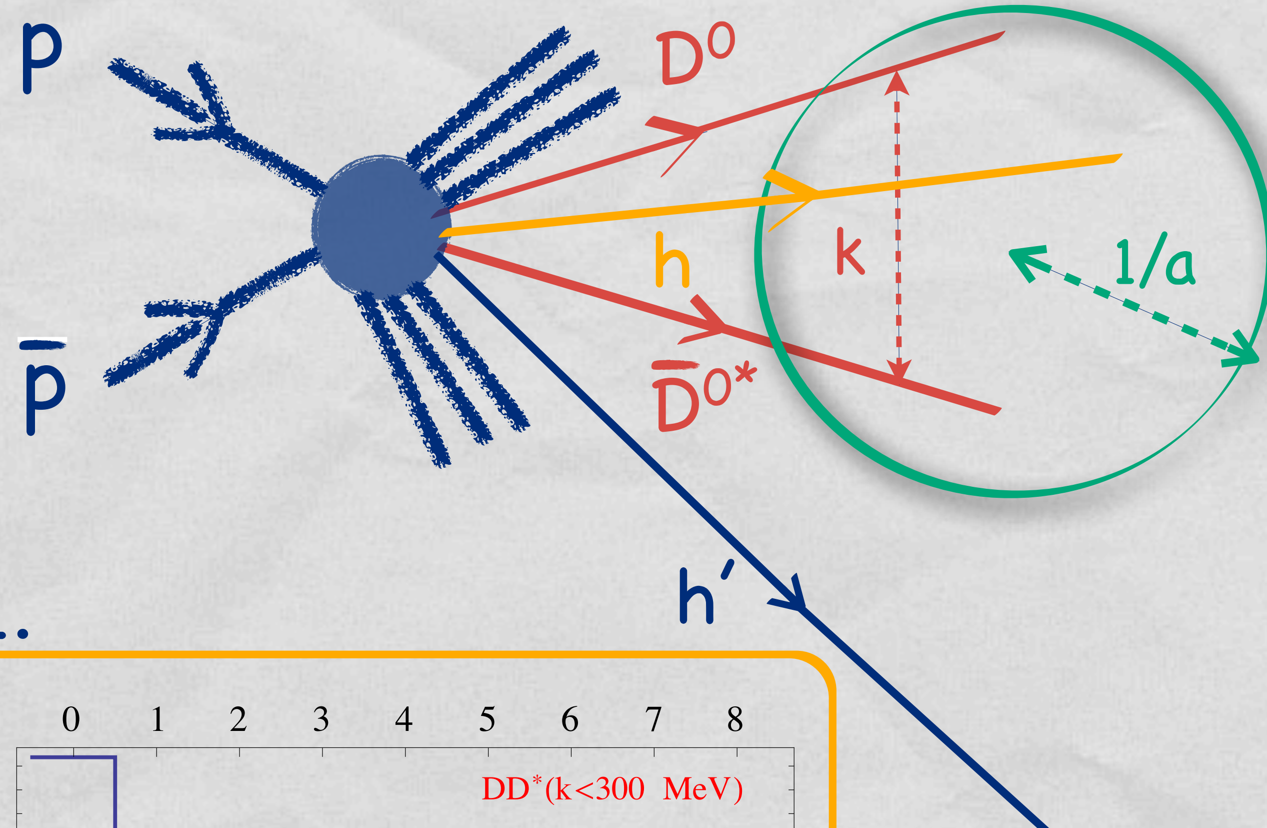
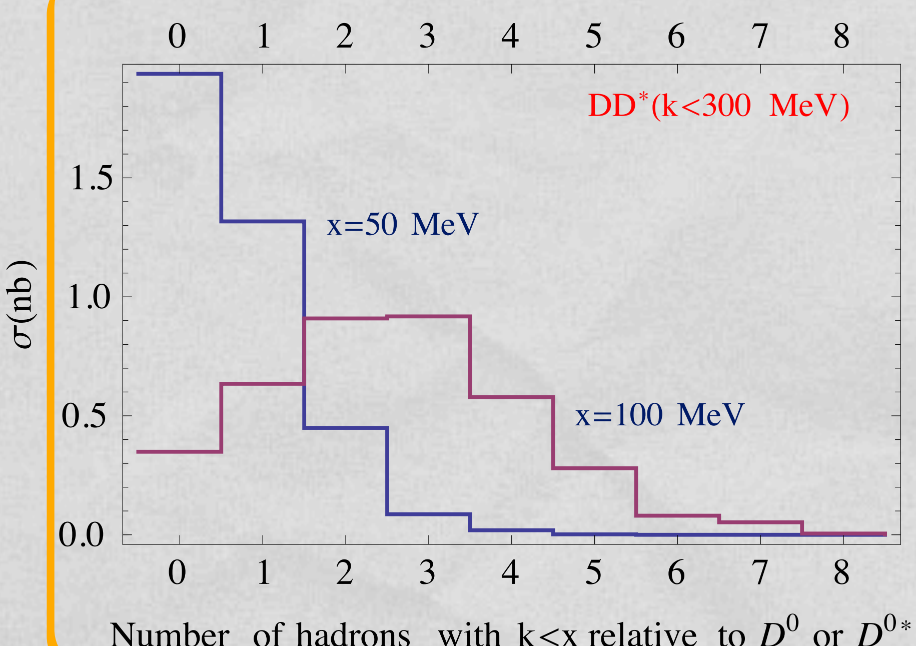



a is the range of strong interaction:
a~1fm
k<1/a~200MeV

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

1.

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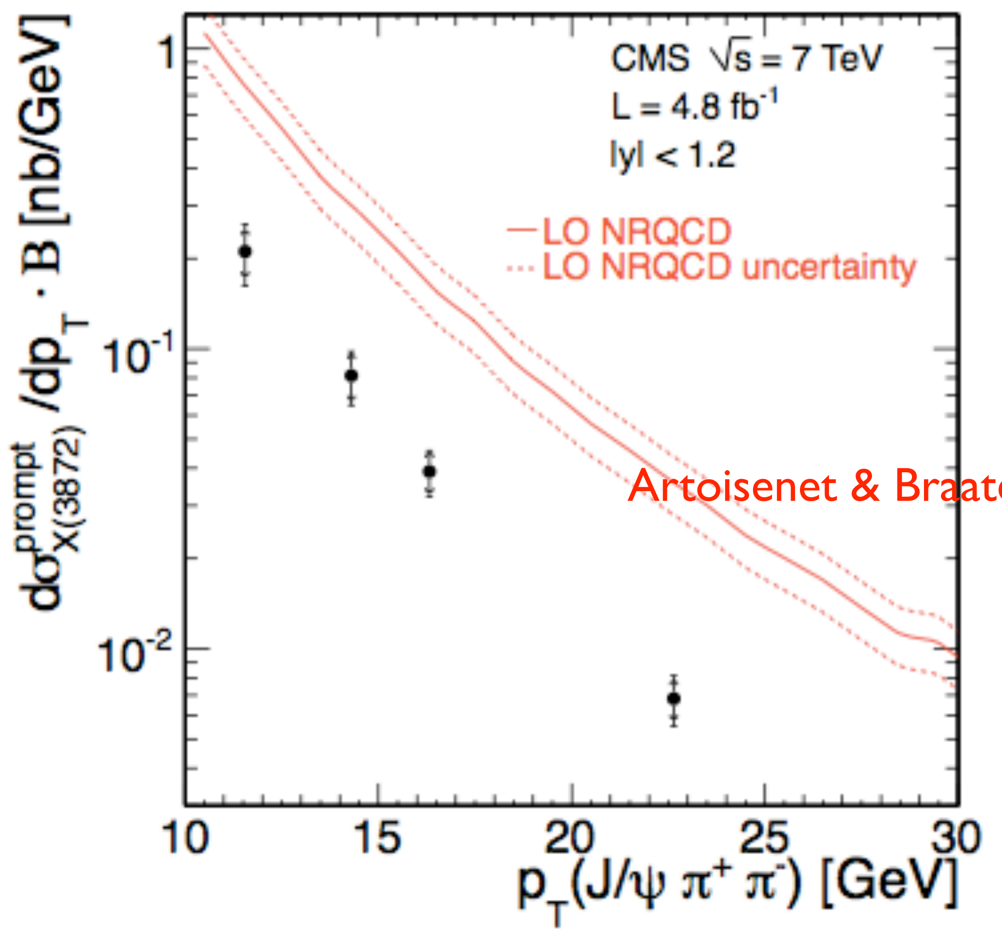
We find that this is not the case in the CDF simulation.

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

# FSI III

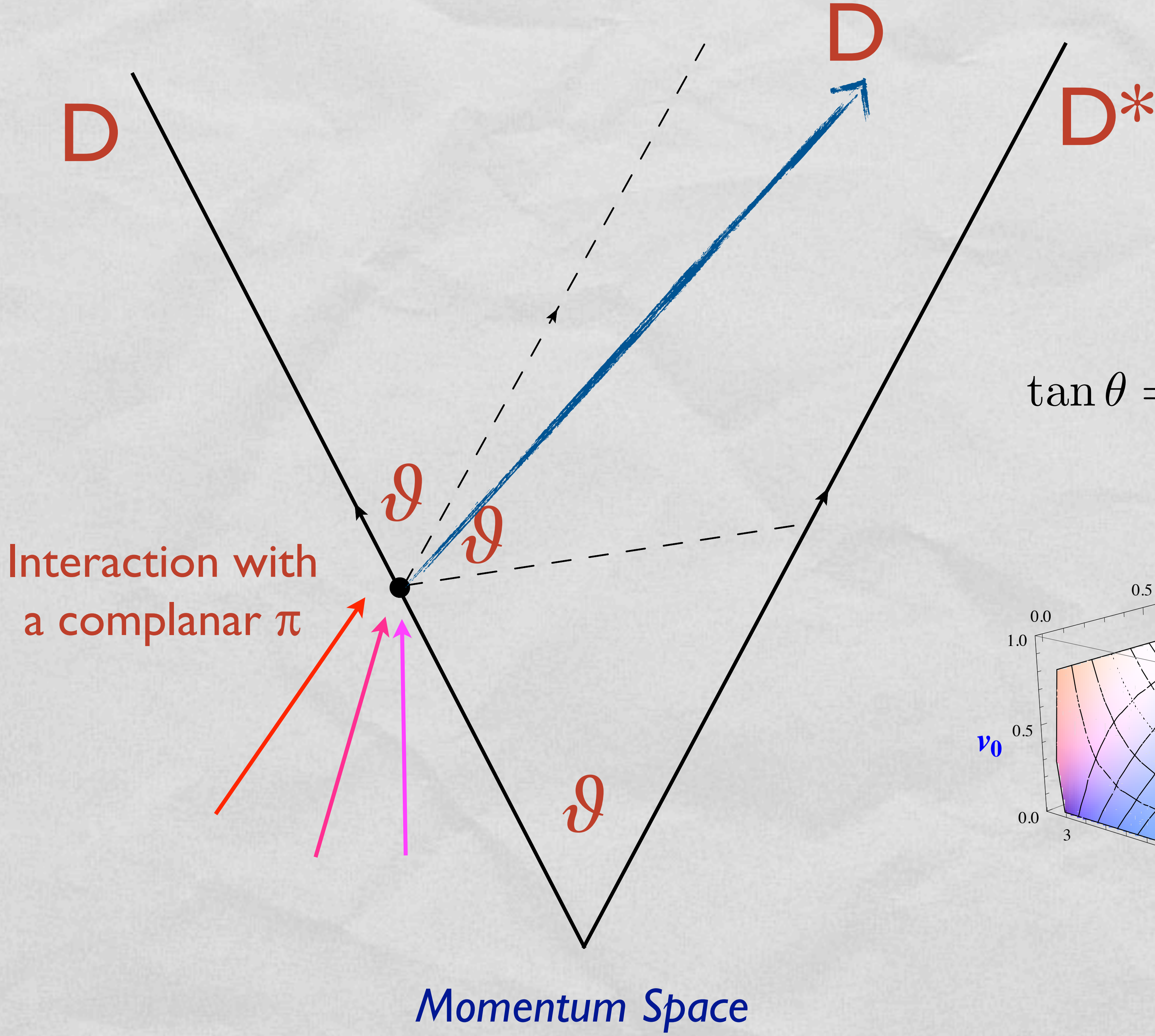
CMS Collaboration arXiv:1302.3968



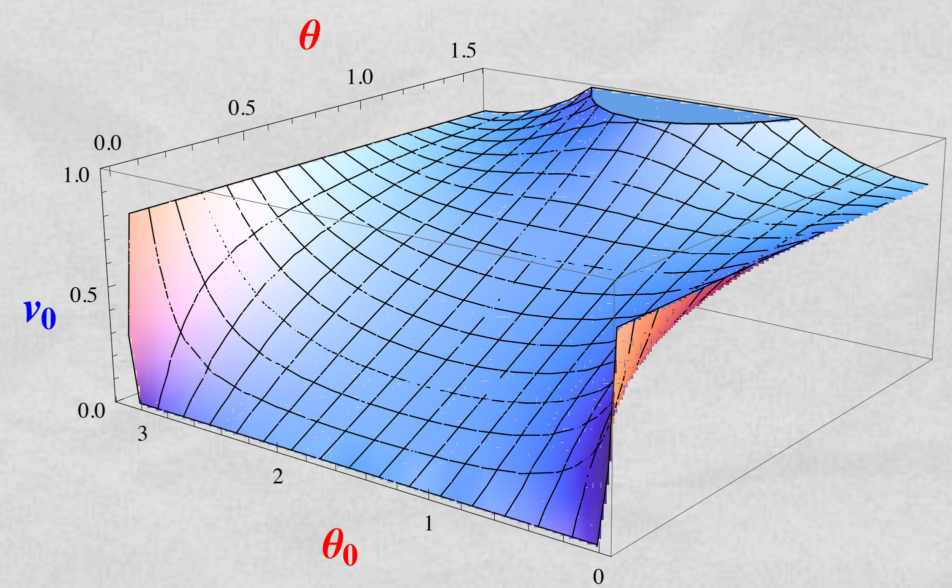

Artoisenet & Braaten: Phys Rev D81, 114018 (2010)

Figure 6: Measured differential cross section for prompt X(3872) production times branching fraction $\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ as a function of $p_T$. The inner error bars indicate the statistical uncertainty and the outer error bars represent the total uncertainty. Predictions from a NRQCD model [11] are shown by the solid line, with the dotted lines representing the uncertainty. The data points are placed where the value of the theoretical prediction is equal to its mean value over each bin, according to the prescription in [28].

# THE OPPOSITE OF FSI

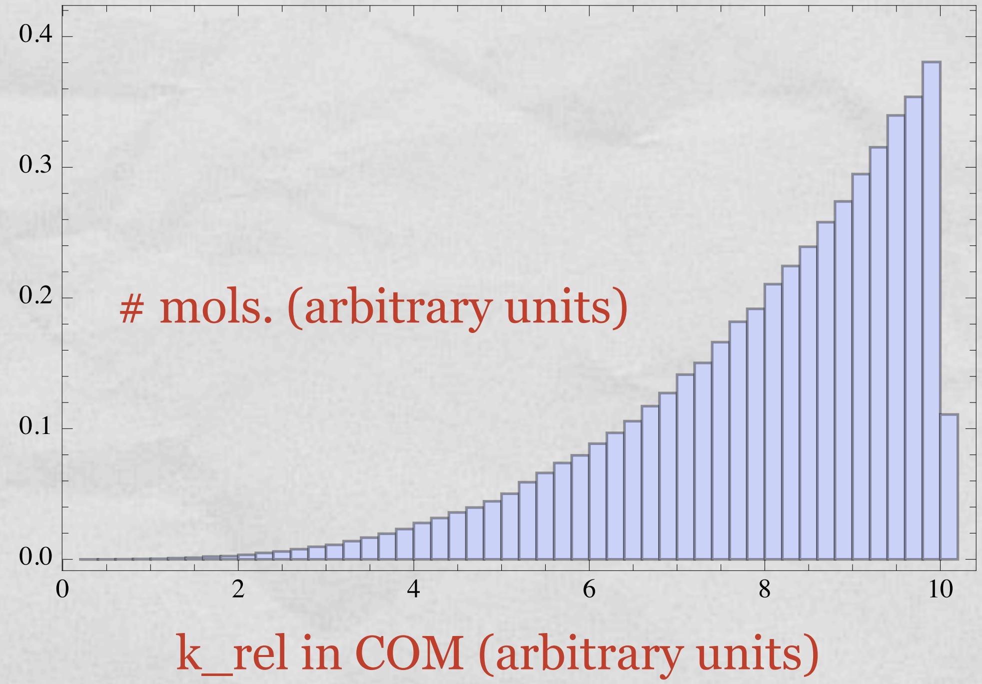



$$\tan\theta = \frac{2v_0 V\sqrt{1-V^2}\sin\theta_0}{V^2 - v_0^2 + v_0^2 V^2 \sin^2\theta_0}$$

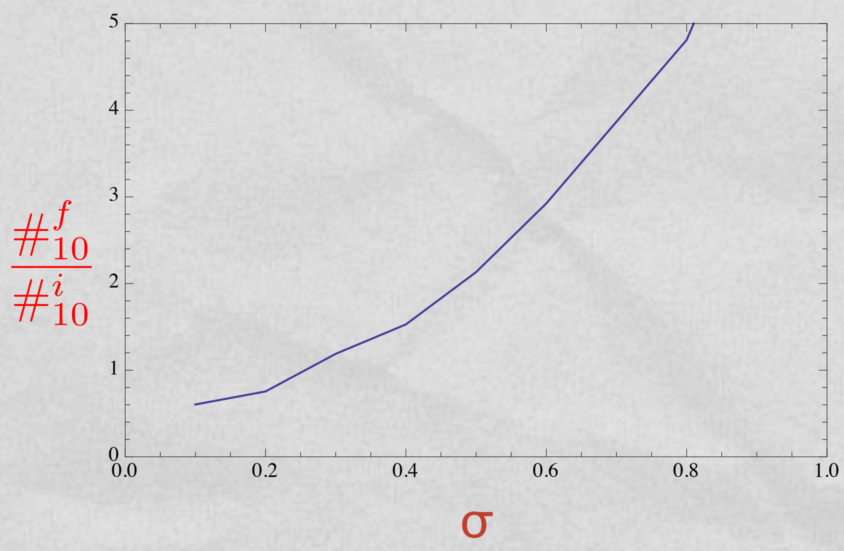


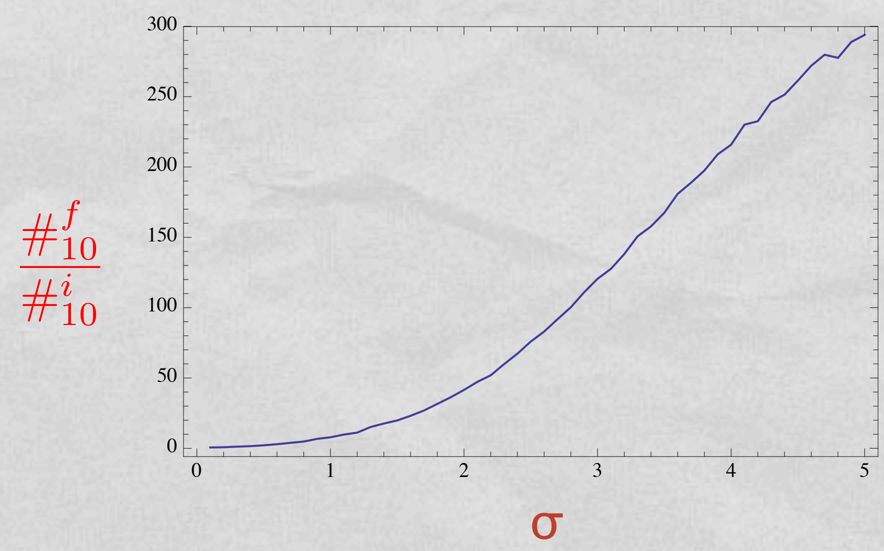

Thursday, March 7, 13

# PION RESHUFFLING




Redistribute the molecules in every bin using Gaussian random number generation for their new k_rel values. The variance is left as a parameter.

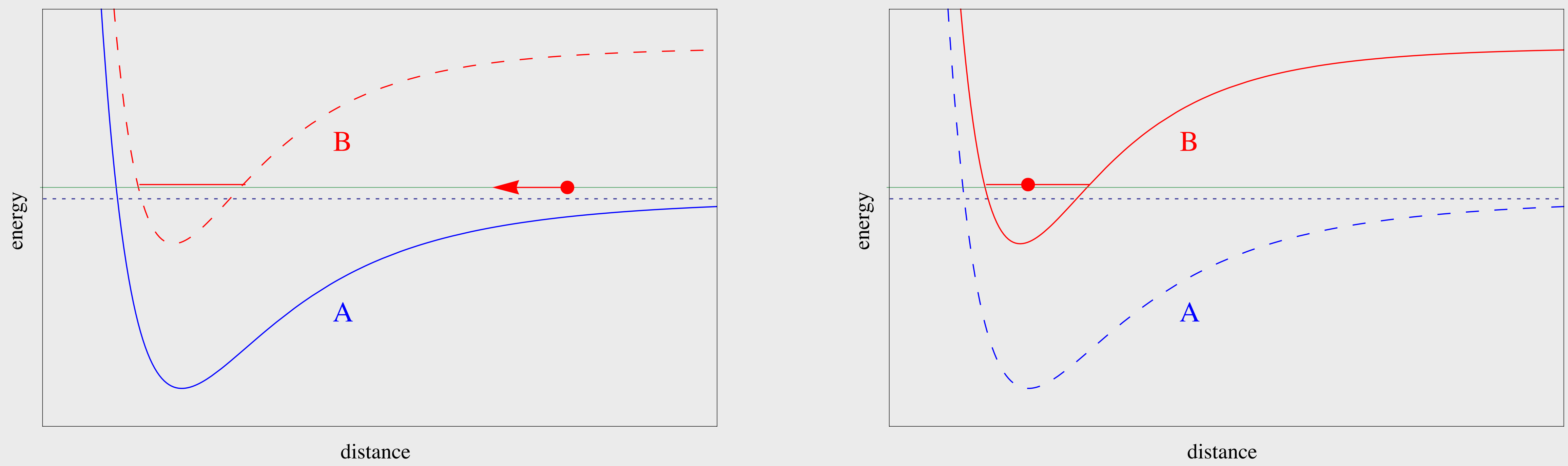


# FESHBACH MOLECULES

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]

# LOW EQUATION

(See e.g. S. Weinberg's lectures on quantum mechanics)

When *shallow* bound states  are allowed in low energy potential scattering it is possible a description of scattering leghts and phase shifts which does not require the precise knowledge of the scattering potential.

This allows to write `universal' formulae depending only on binding energies.

$$\cot\delta_{\ell=0} = -\sqrt{\frac{|E_b|}{E}} \quad \xrightarrow{\text{range expansion for k~0}} \quad a = \frac{\hbar}{\sqrt{2\mu|E_b|}}$$

$$|g|^2 = \frac{1}{\pi}\sqrt{\frac{2|E_b|}{\mu}}$$

g is for example the coupling of X to its open charm components

# LOW EQUATION

One can estimate the decay width of X into its components by

$$\Gamma\left(X(3872) \to D^0 \bar{D}^{*0} + \text{c.c.}\right) = \frac{p^*\left(M_X, M_{D^0}, M_{D^{*0}}\right)}{8\pi M_X^2} \frac{1}{3} g_{XDD^*}^2 \left(3 + \frac{p^*\left(M_X, M_{D^0}, M_{D^{*0}}\right)^2}{M_{D^{*0}}^2}\right)$$

Thus obtaining an estimate of $g$. To do so we average over a random mass of the X extracted from a Breit-Wigner distribution centered at 3871.68 MeV and having width of 1.2 MeV. The range of values is

$$M_{D^0} + M_{D^{*0}} < M_X < M_B - M_K$$

and we use the experimental estimate

$$\mathcal{B}\left(X \to D^0 \bar{D}^{*0} + \text{c.c.}\right) \approx 67\%$$

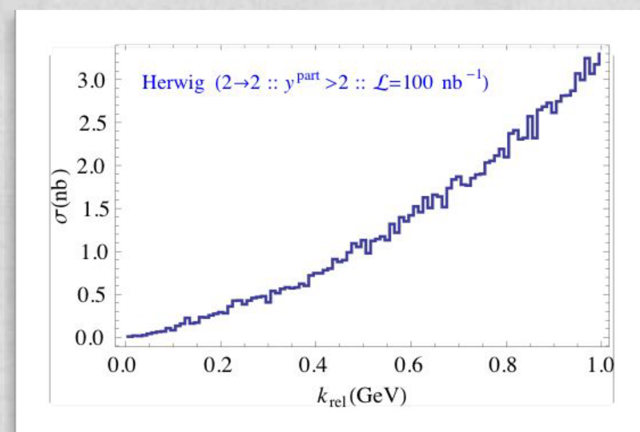
yielding

$$g_{XDD^*} = 2.5 \text{ GeV}$$

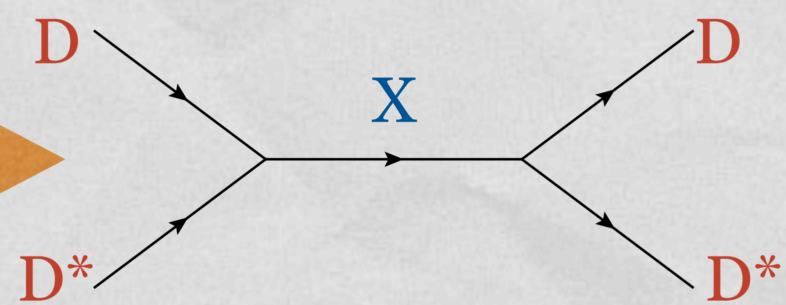
# LOW EQUATION

The coupling obtained has to be rescaled by the mass of the X to make it adimensional. Yet it is off by almost two orders of magnitude from the value computed with the binding energy - the expression of $g$ used in the Low eq.

More can be done like computing




flux function

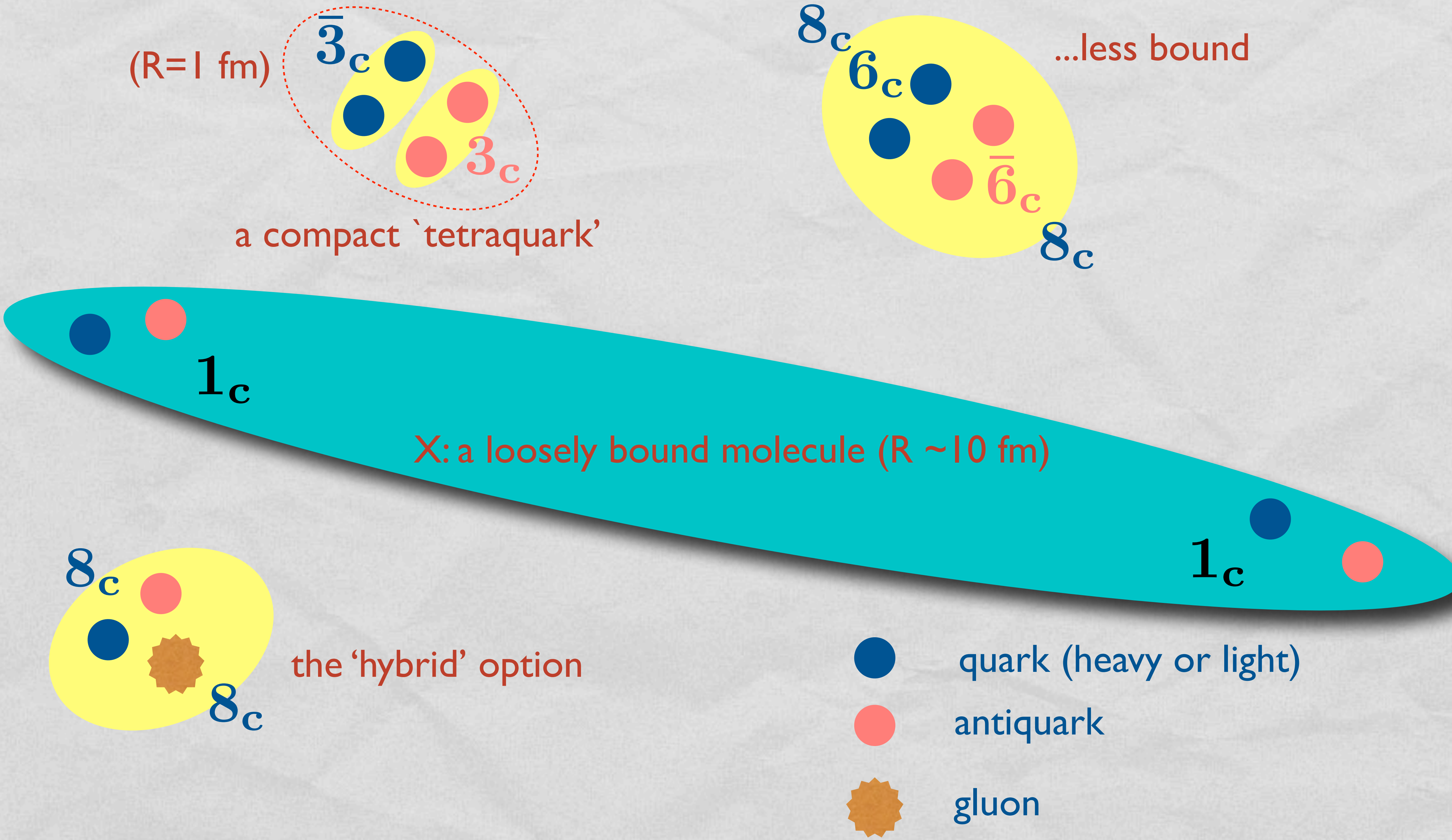



To be compared with the potential scatterig result for shallow bound states

$$\sigma_{\rm tot} = \frac{2\pi\hbar^2}{\mu|E_b|}$$

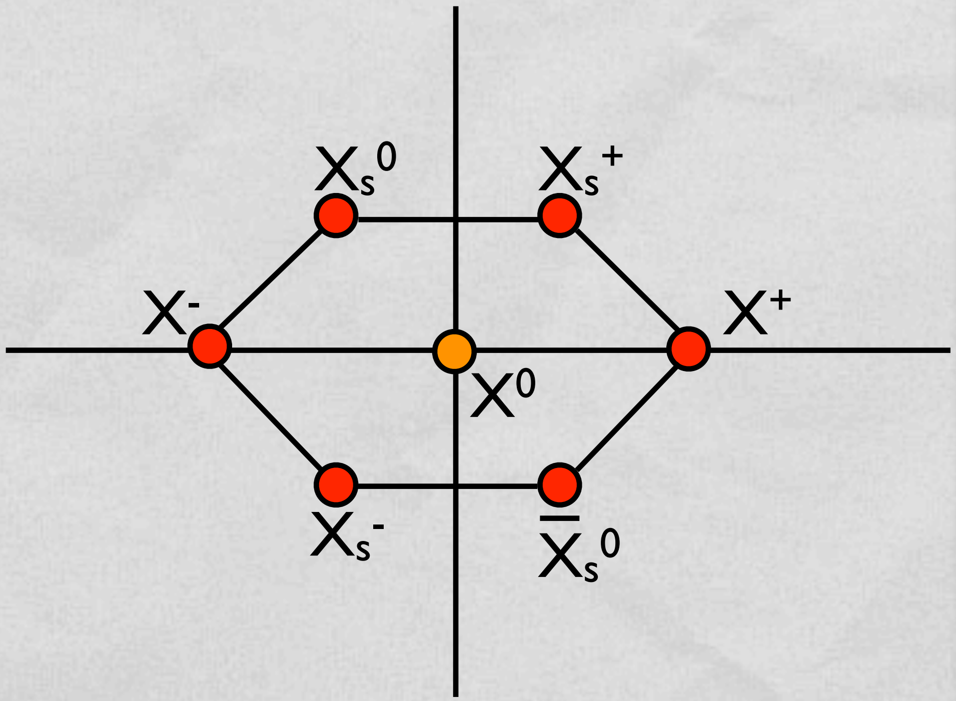
# TETRAQUARKS

# OPTIONS FOR COLOR NEUTRAL STATES



# CHARMED DIQUARKS: THE SYMMETRY APPROACH

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 -> $\omega / \rho$ isospin breaking

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

# DIQUARK MODEL

$$H = -2 \sum_{i \neq j, a} \kappa_{ij} \, \boldsymbol{S}_i \cdot \boldsymbol{S}_j \, \frac{\lambda_i^a}{2} \cdot \frac{\lambda_j^a}{2}$$

Color neutral diquark-antidiquark states can be written with a convenient notation

$$|cq_{\bar{\mathbf{3}}}, \bar{c}\bar{q}_{\mathbf{3}}\rangle = \frac{2}{3} \, \mathbb{1}_{\bar{c}c} \otimes \mathbb{1}_{\bar{q}q} - \frac{1}{2} \, \lambda^a_{\bar{c}c} \otimes \lambda^a_{\bar{q}q} = 2|\bar{c}c_{\mathbf{1}}, \bar{q}q_{\mathbf{1}}\rangle - 2\sqrt{2}|\bar{c}c_{\mathbf{8}}, \bar{q}q_{\mathbf{8}}\rangle$$

With a bit of work one finds relations like the following

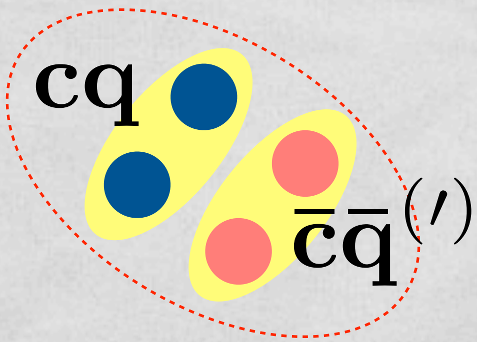
$$\langle cq_{\bar{\mathbf{3}}}, \bar{c}\bar{q}_{\mathbf{3}}|H_{c\bar{q}}|cq_{\bar{\mathbf{3}}}, \bar{c}\bar{q}_{\mathbf{3}}\rangle = \frac{1}{4}\langle \bar{c}c_{\mathbf{1}}, \bar{q}q_{\mathbf{1}}|H_{c\bar{q}}|\bar{c}c_{\mathbf{1}}, \bar{q}q_{\mathbf{1}}\rangle$$

which teach how to extract color couplings in tetraquark symmetry using info extracted from standard hadrons. On the spin side we can write

$$H_1 = 2\kappa_{\mathbb{q}}(\boldsymbol{S}_{q_1} \cdot \boldsymbol{S}_{q_2} + \boldsymbol{S}_{\bar{q}_1} \cdot \boldsymbol{S}_{\bar{q}_2})$$
$$H_2 = 2\kappa_{q_1\bar{q}_2}(\boldsymbol{S}_{q_1} \cdot \boldsymbol{S}_{\bar{q}_2} + \boldsymbol{S}_{\bar{q}_1} \cdot \boldsymbol{S}_{q_2})$$
$$H_3 = 2\kappa_{q_1\bar{q}_1}\boldsymbol{S}_{q_1} \cdot \boldsymbol{S}_{\bar{q}_1}$$
$$H_4 = 2\kappa_{q_2\bar{q}_2}\boldsymbol{S}_{q_2} \cdot \boldsymbol{S}_{\bar{q}_2}$$

# 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?
- 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.

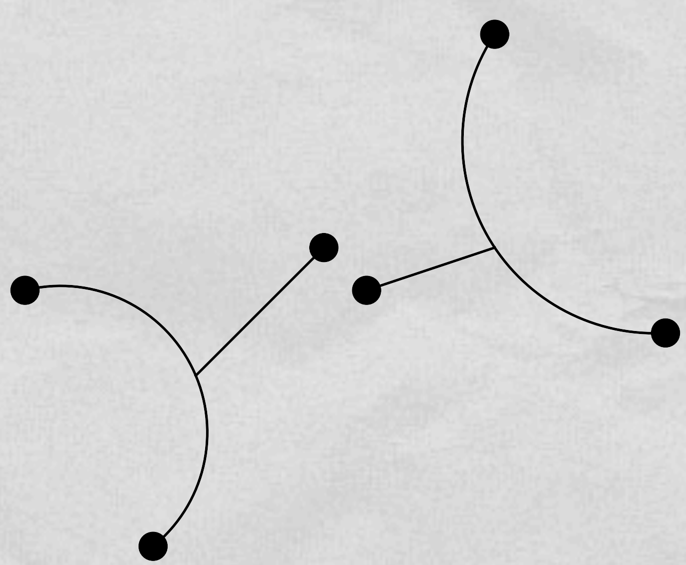
# TETRQUARKS PREFER BARYON DECAYS

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

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

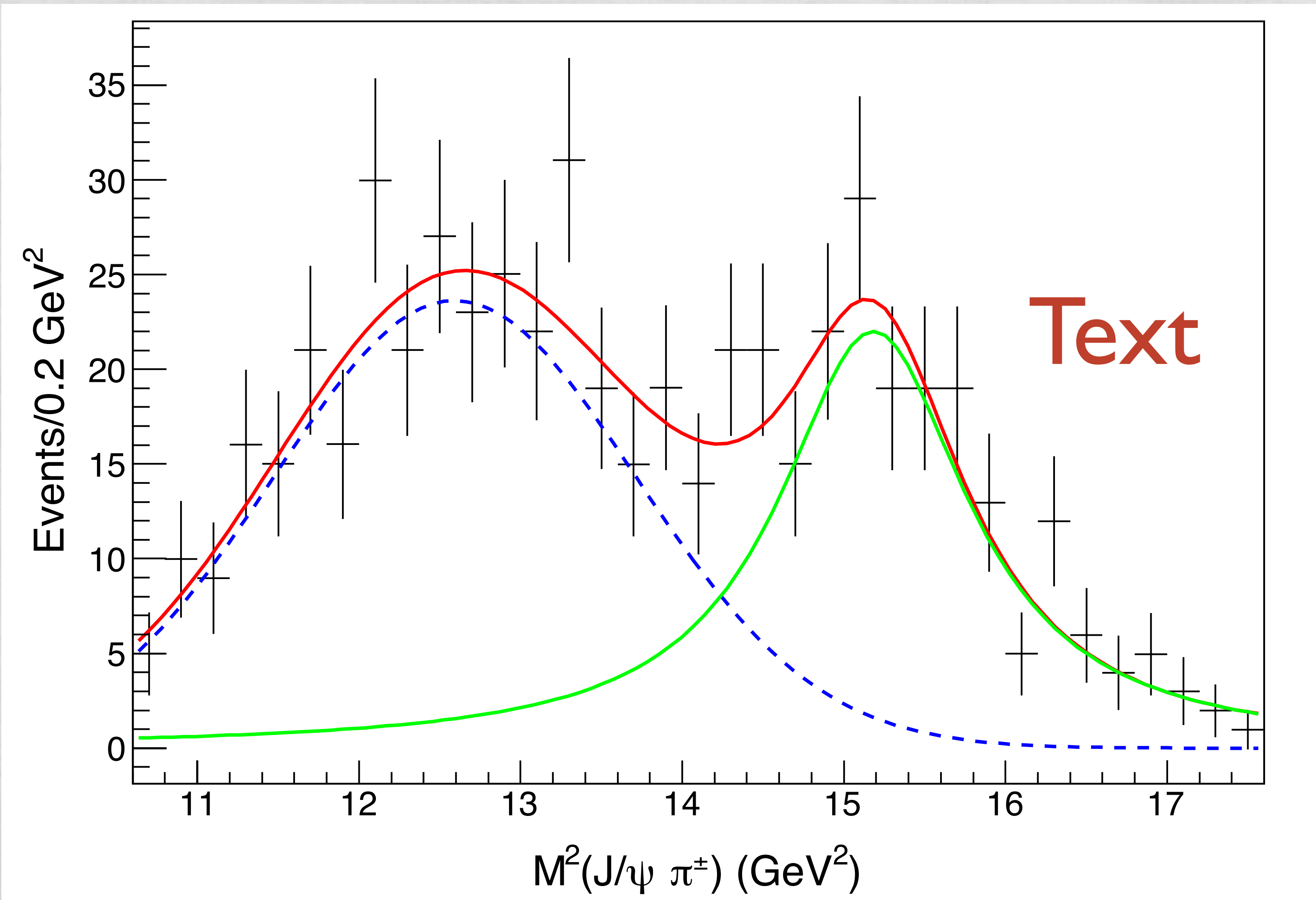


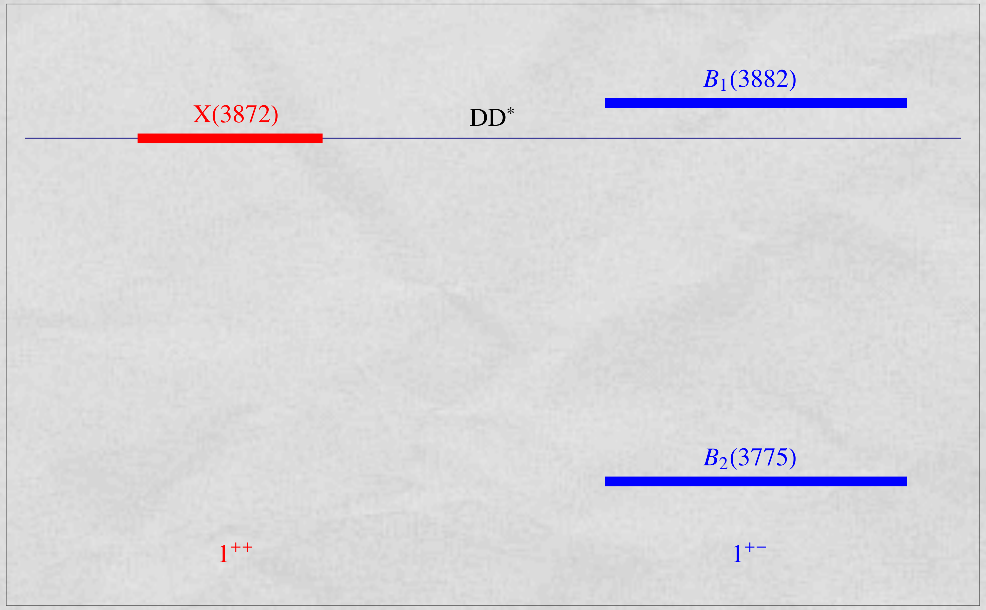
*Search for similar resonances having 'baryon affinity' in the b-system.*

# $Y(4260) \rightarrow J/\psi + \pi^+\pi^-$

J. Zhang (Belle) 'Study of XYZ particles at BESIII'

Workshop on New Hadron Spectroscopies, November 2012, Seoul http://q2c.snu.ac.kr/indico/conferenceDisp

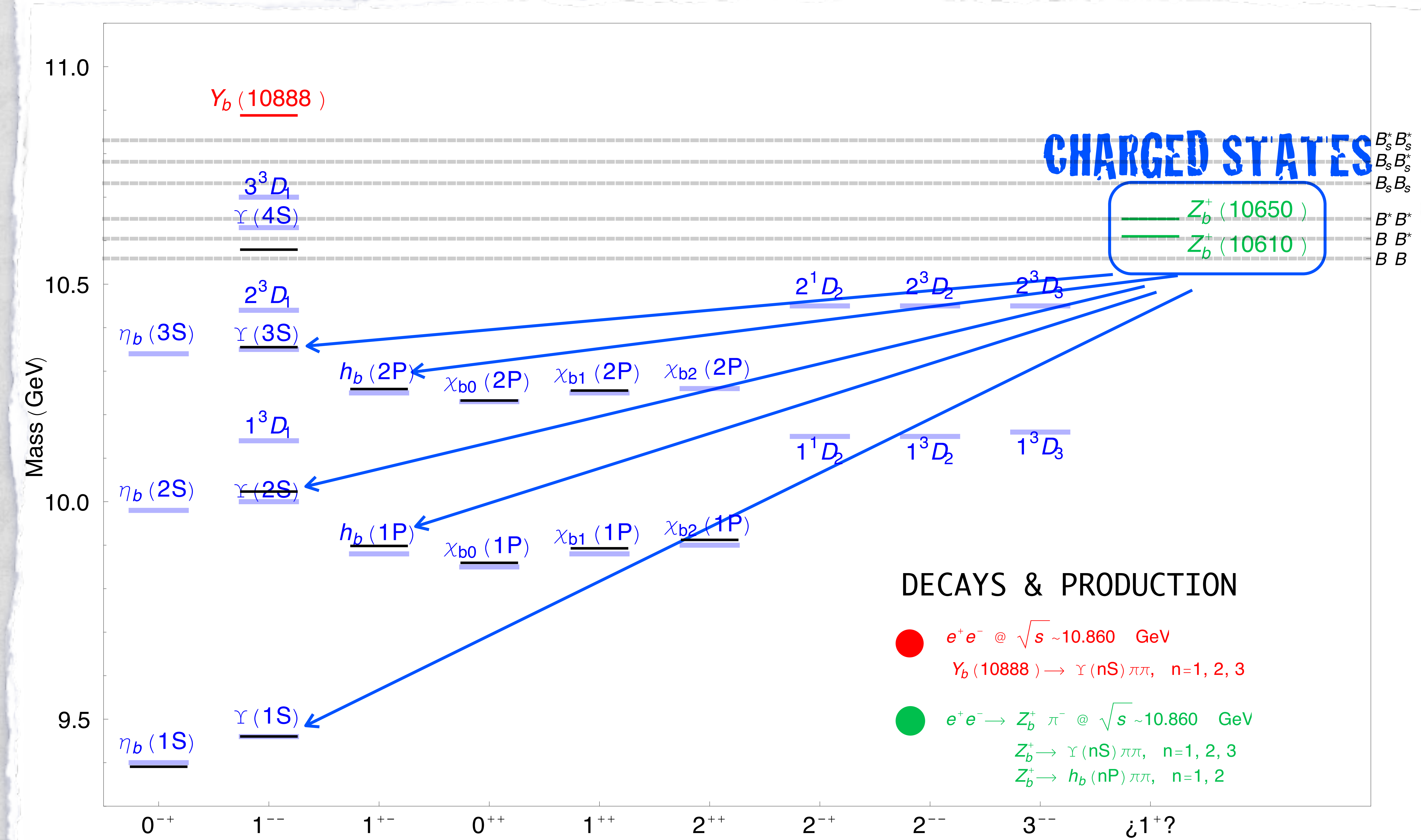



Tetraquark prediction: 2005
Maiani et al. Phys. Rev. D71 (2005) 014028

A $1^{+-}$ state at about 3880 MeV?

# Newcomers in the b-System



# 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

# BACK UP

# THE 'NEW' HADRON RESONANCES

Brambilla et al. QWG, arXiv:1010.5827

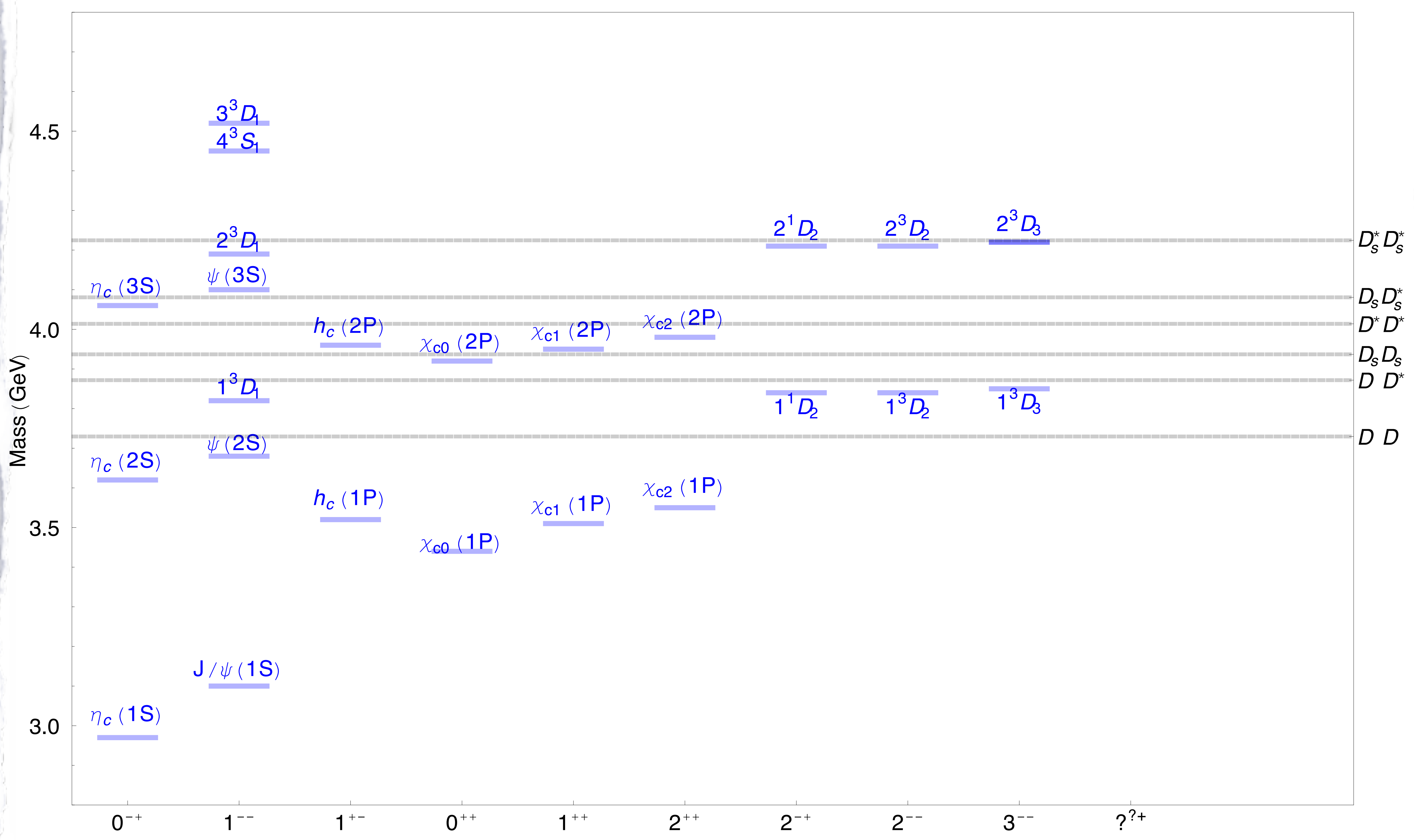
| State | $m$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment (#$\sigma$) | Year | Status |
|---|---|---|---|---|---|---|---|
| $X(3872)$ | 3871.52±0.20 | 1.3±0.6 | $1^{++}/2^{-+}$ | $B \to K(\pi^+\pi^- J/\psi)$ | Belle [85, 86] (12.8), *BABAR* [87] (8.6) | 2003 | OK |
| | | (<2.2) | | $p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$ | CDF [88–90] (np), DØ [91] (5.2) | | |
| | | | | $B \to K(\omega J/\psi)$ | Belle [92] (4.3), *BABAR* [93] (4.0) | | |
| | | | | $B \to K(D^{*0}\bar{D}^0)$ | Belle [94, 95] (6.4), *BABAR* [96] (4.9) | | |
| | | | | $B \to K(\gamma J/\psi)$ | Belle [92] (4.0), *BABAR* [97, 98] (3.6) | | |
| | | | | $B \to K(\gamma\psi(2S))$ | *BABAR* [98] (3.5), Belle [99] (0.4) | | |
| $X(3915)$ | $3915.6 \pm 3.1$ | 28±10 | $0/2^{?+}$ | $B \to K(\omega J/\psi)$ | Belle [100] (8.1), *BABAR* [101] (19) | 2004 | OK |
| | | | | $e^+e^- \to e^+e^-(\omega J/\psi)$ | Belle [102] (7.7) | | |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^- \to J/\psi(D\bar{D}^*)$ | Belle [103] (6.0) | 2007 | NC! |
| | | | | $e^+e^- \to J/\psi\ (...)$ | Belle [54] (5.0) | | |
| $G(3900)$ | $3943 \pm 21$ | 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 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | *BABAR* [108, 109] (8.0) | 2005 | OK |
| | | | | | CLEO [110] (5.4) | | |
| | | | | | Belle [104] (15) | | |
| | | | | $e^+e^- \to (\pi^+\pi^- J/\psi)$ | CLEO [111] (11) | | |
| | | | | $e^+e^- \to (\pi^0\pi^0 J/\psi)$ | CLEO [111] (5.1) | | |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | CDF [107] (3.1) | 2010 | 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! |

*BaBar Charm 2012*

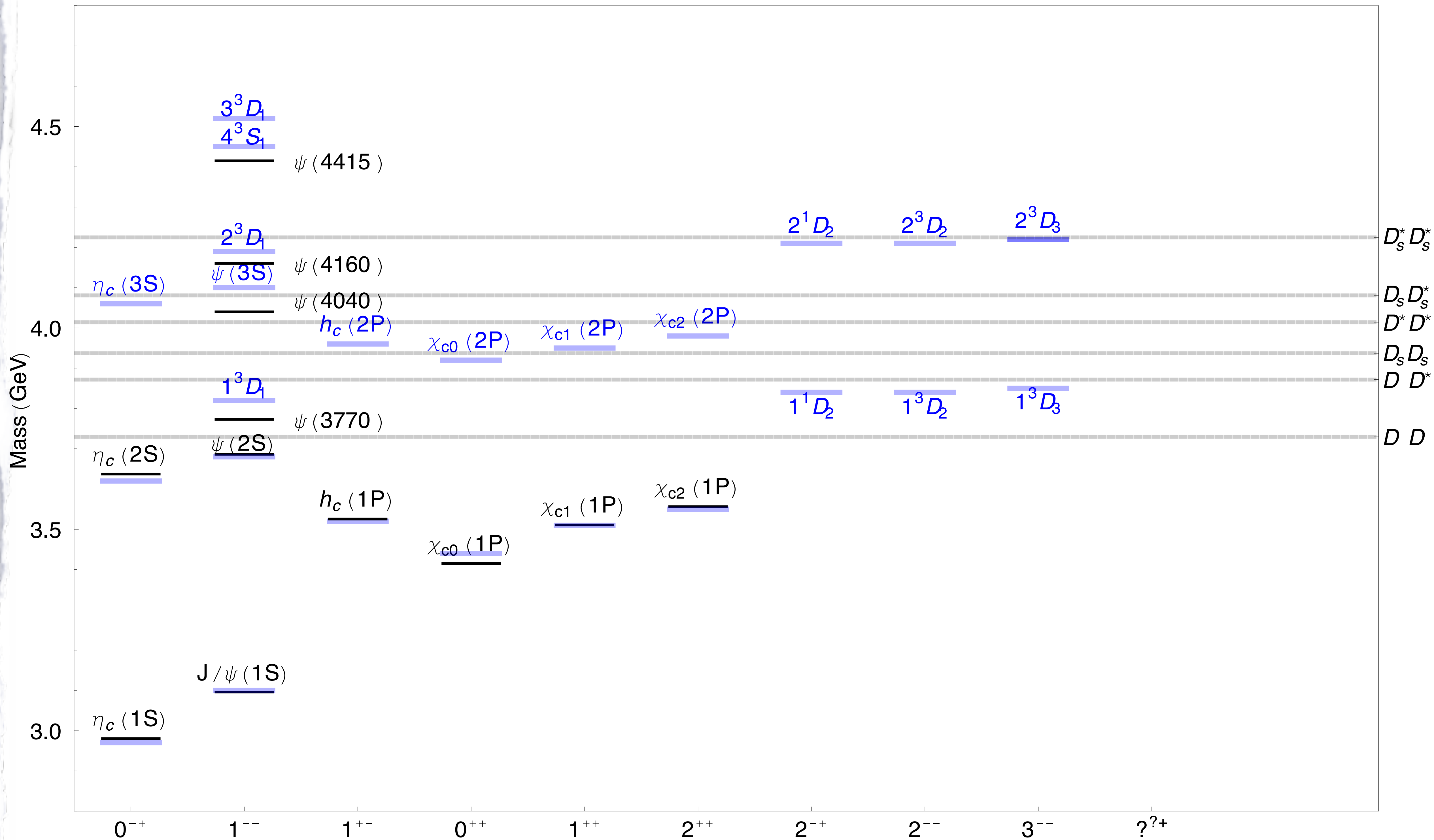
*NO* (← $Y(4008)$)

*YES* (← $Y(4660)$)

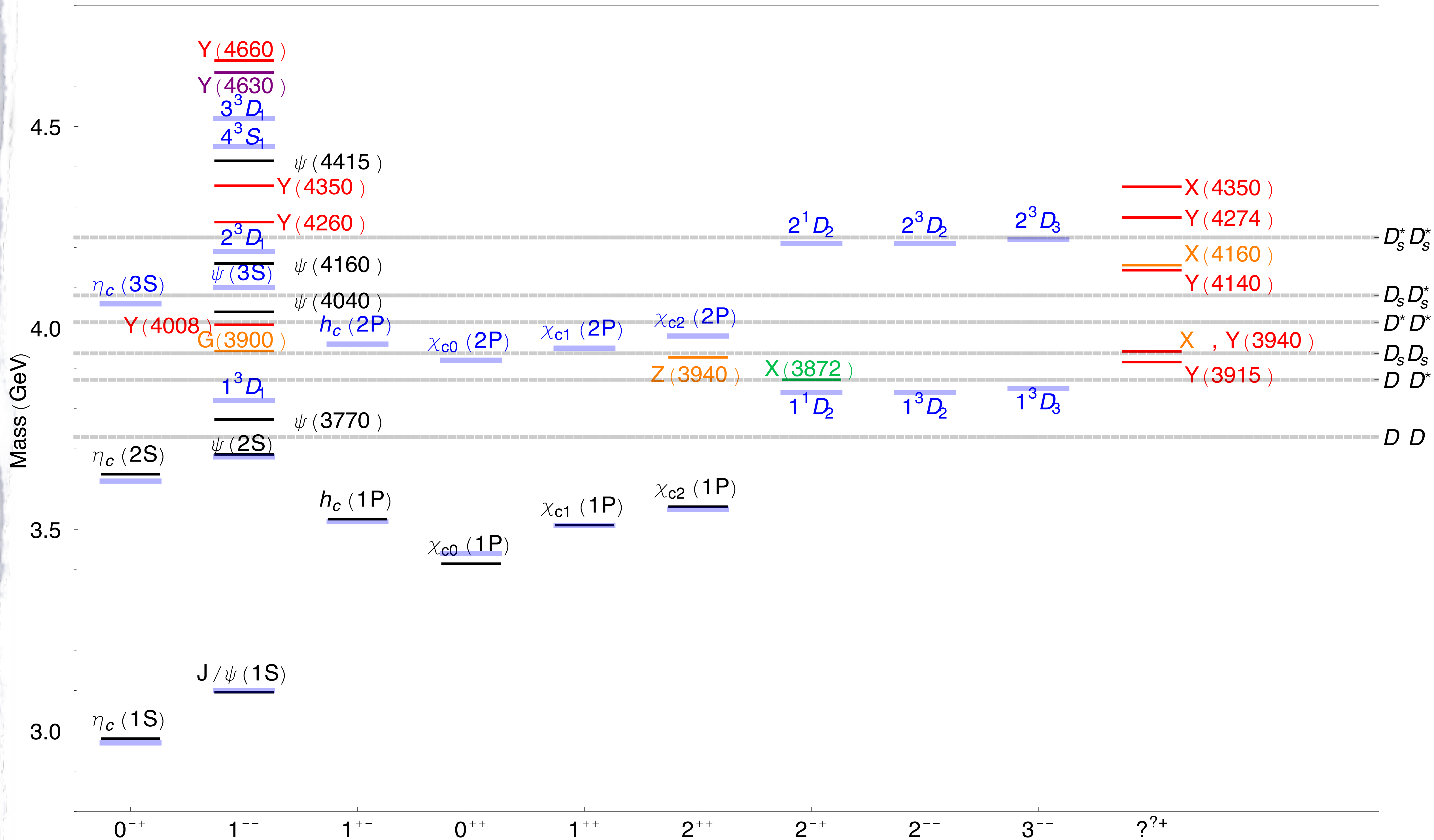
# As Predicted by Charmonium Theory



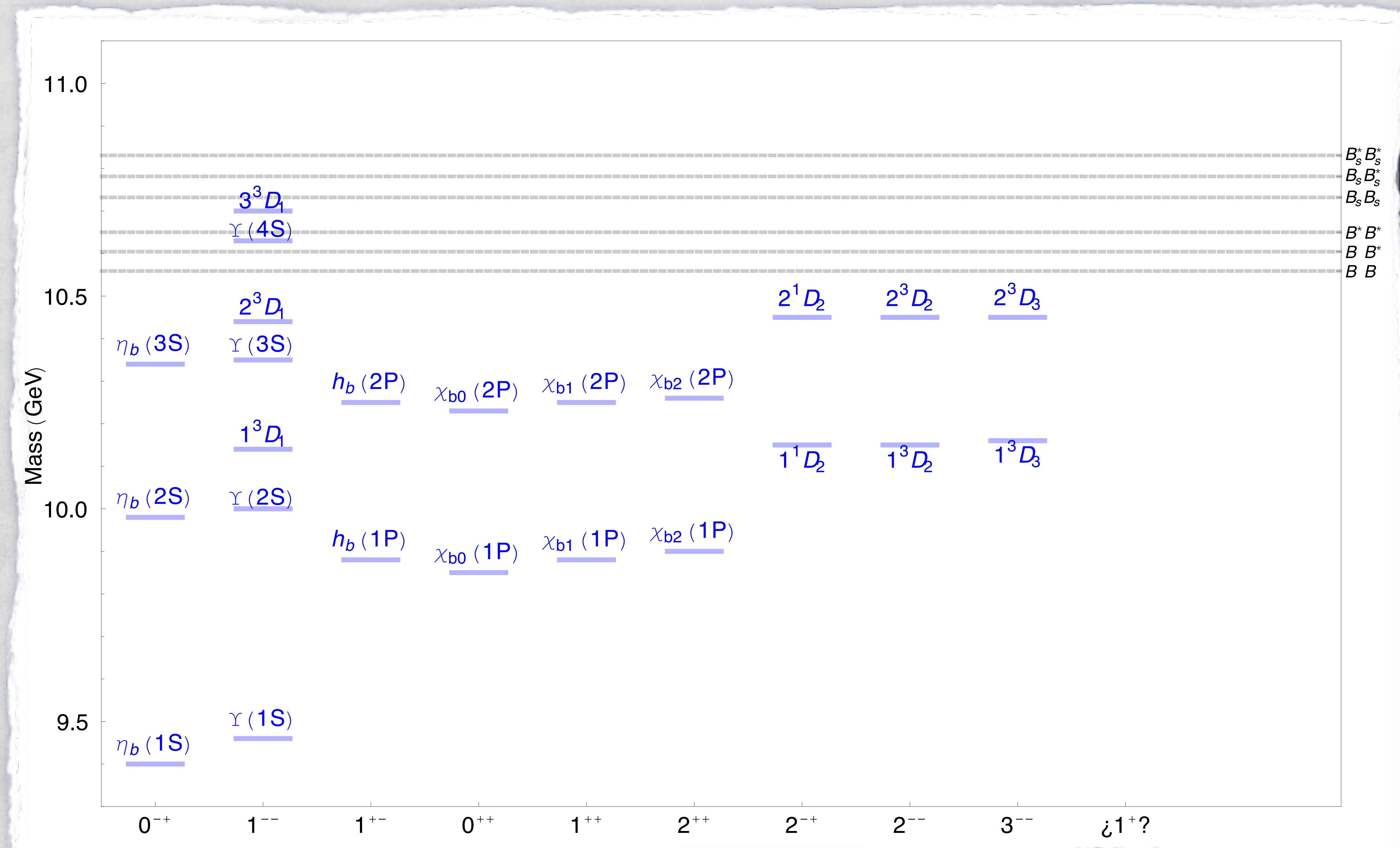
# Experimentally Observed Levels



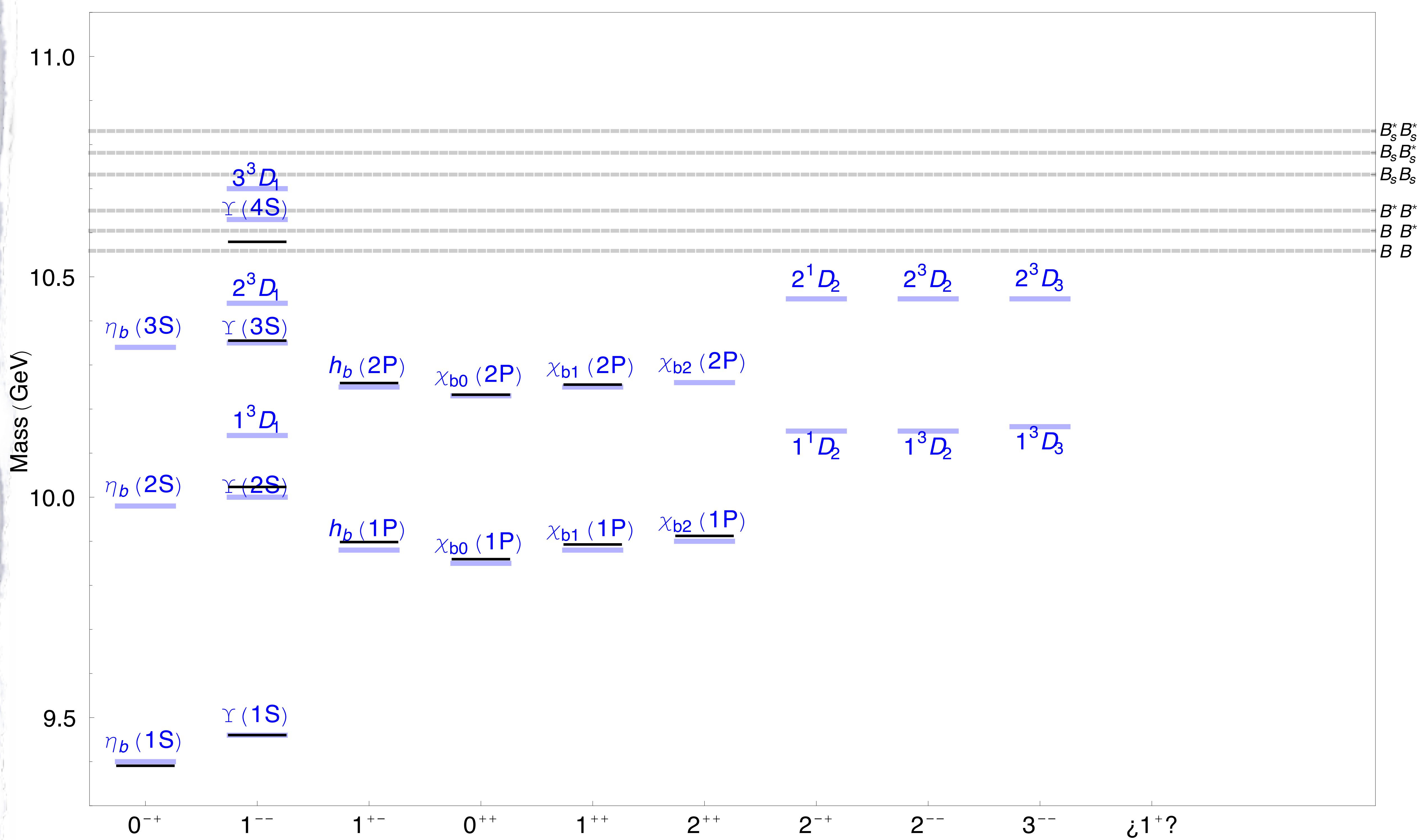
# The New States



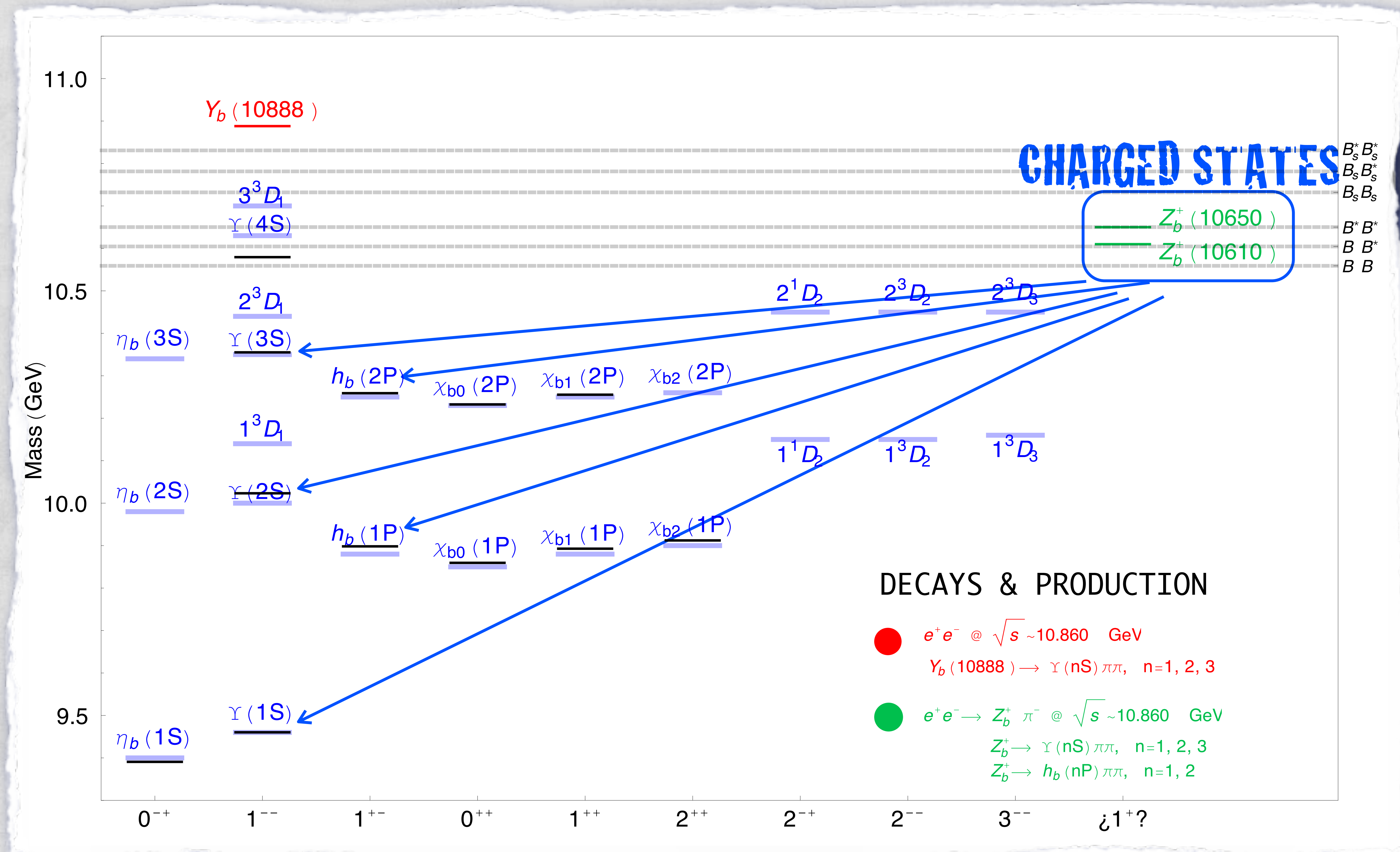
# As Predicted by Bottomonium Theory



# Experimentally Observed Levels



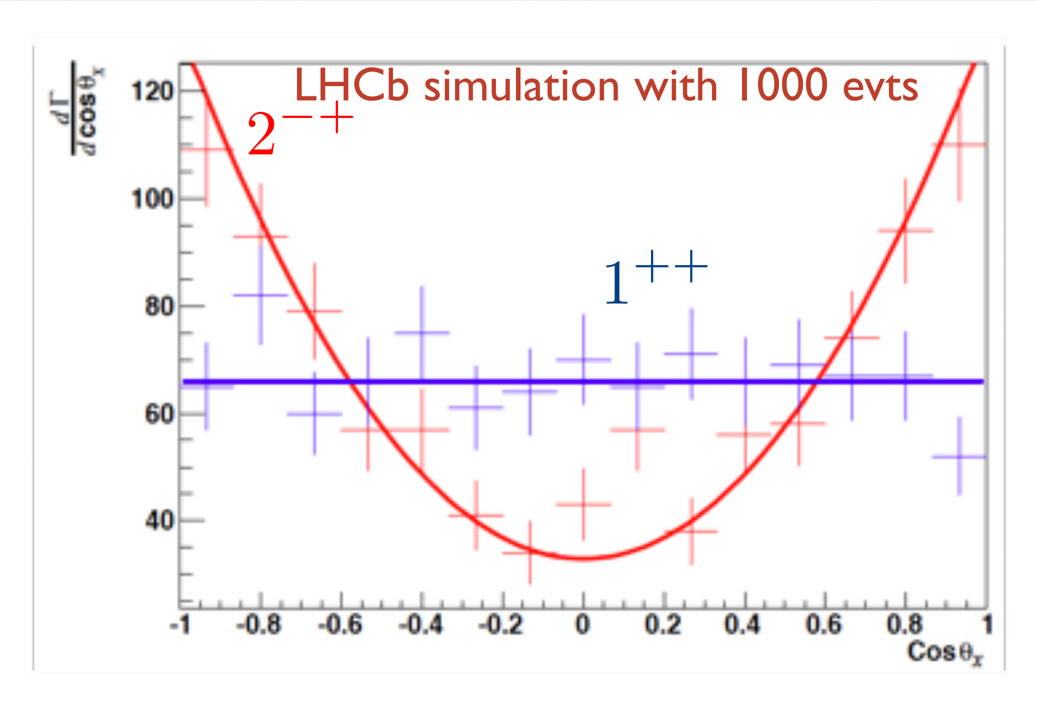
# Newcomers in the b-System

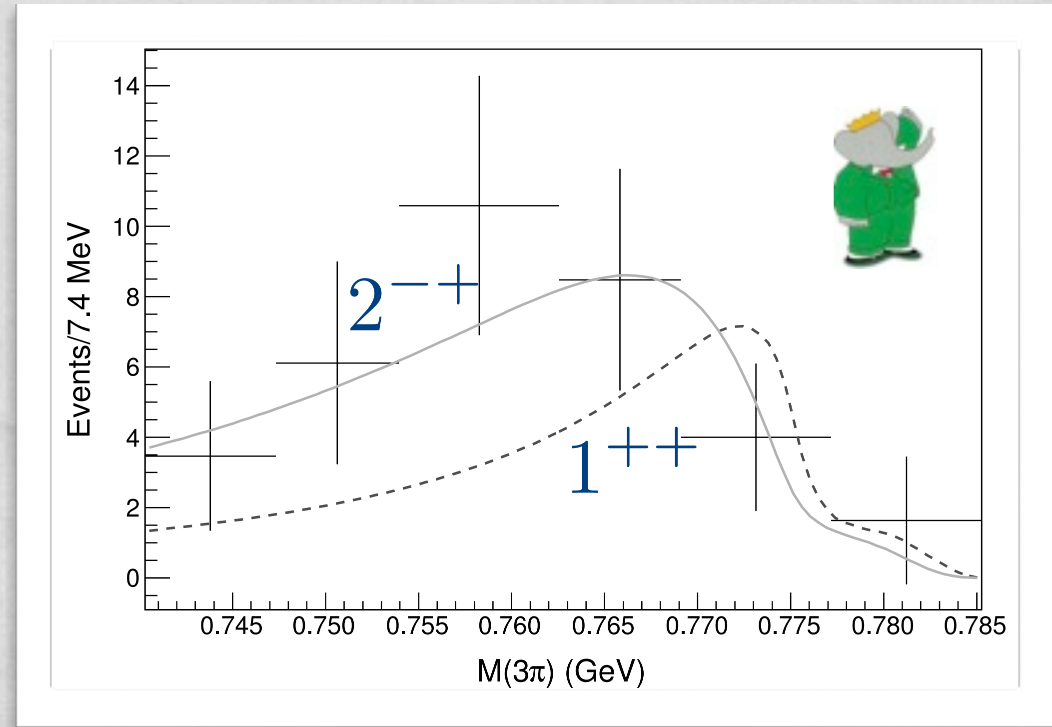


# THE X(3872) SPIN

# 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

# MATRIX ELEMENTS

R. Faccini, F. Piccinini, A. Pilloni, and ADP, Phys Rev. D86 (2012)

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

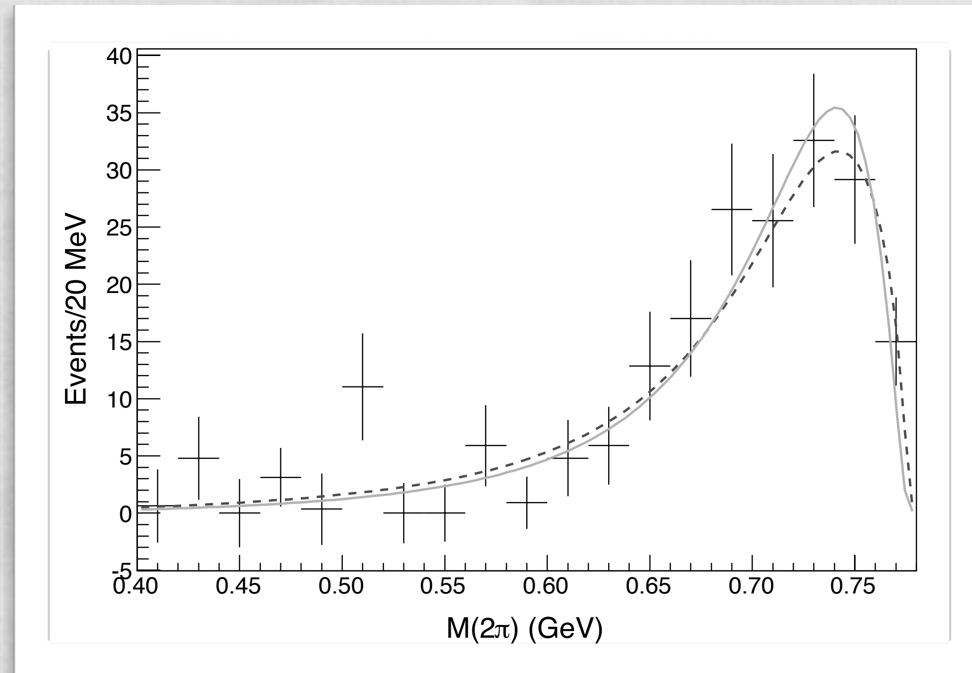
Because of this, following Hanhart et al (*Phys. Rev. D85, 011501, 2012*), we also made a combined J=1,2 fit. But our statistical analysis gives opposite results with respect to those presented in that paper

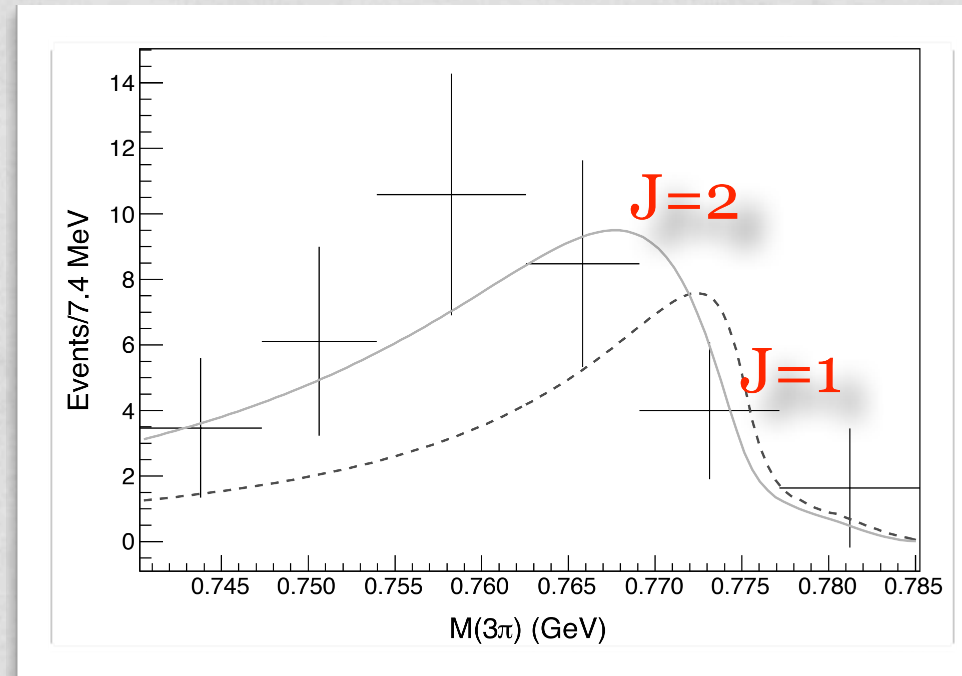
Fit parameters

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

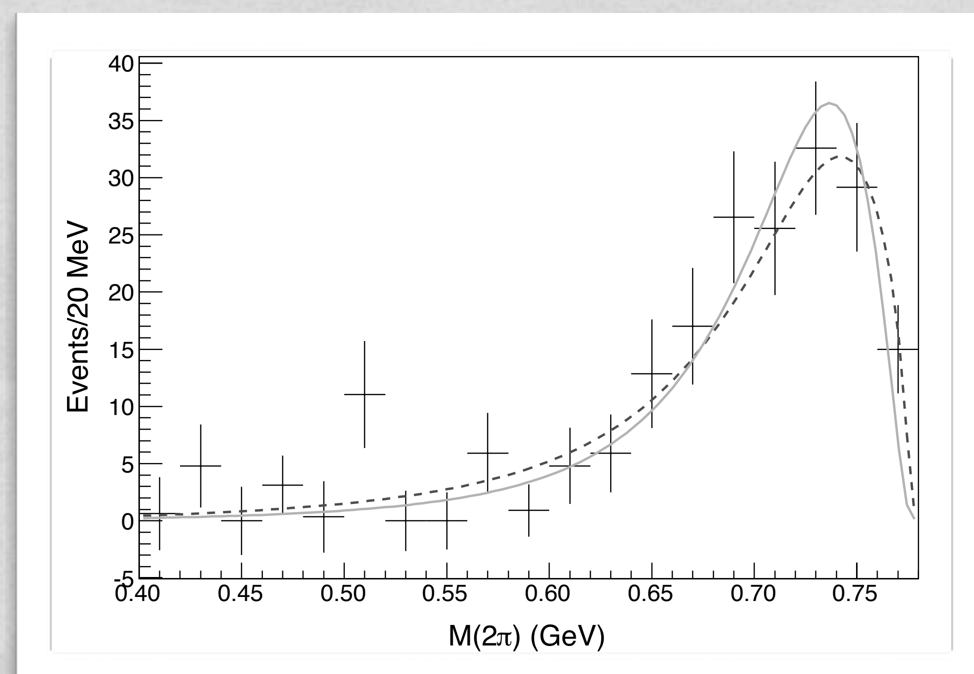
It is interesting to note that the radii, the fit parameters with a physical content, have reasonably small errors and get values consistent with 1 fm, the scale of the size of a standard hadron interaction.

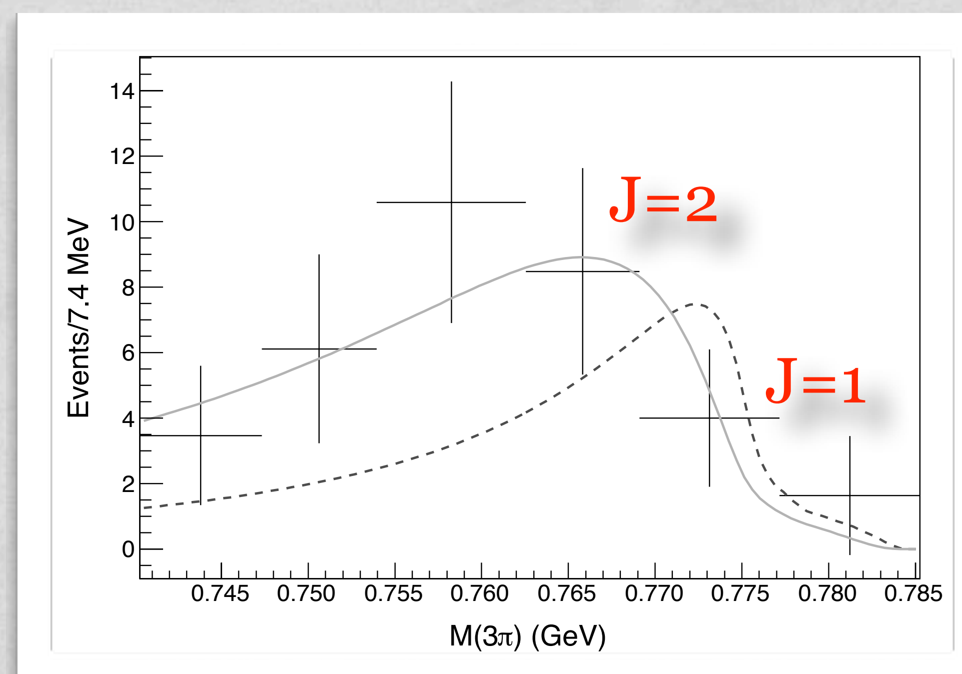
# RESULTS




n=1




n=2

# (TOY MC 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 $\mu_i$

# 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.

The 2-+ hypothesis is excluded at 99%CL but a probability of only 5.5% is obtained for the 1++ hyp.

*Separate* fits return a clear preference for 1++ in rho-channel and a clear preference for 2-+ in the omega-channel

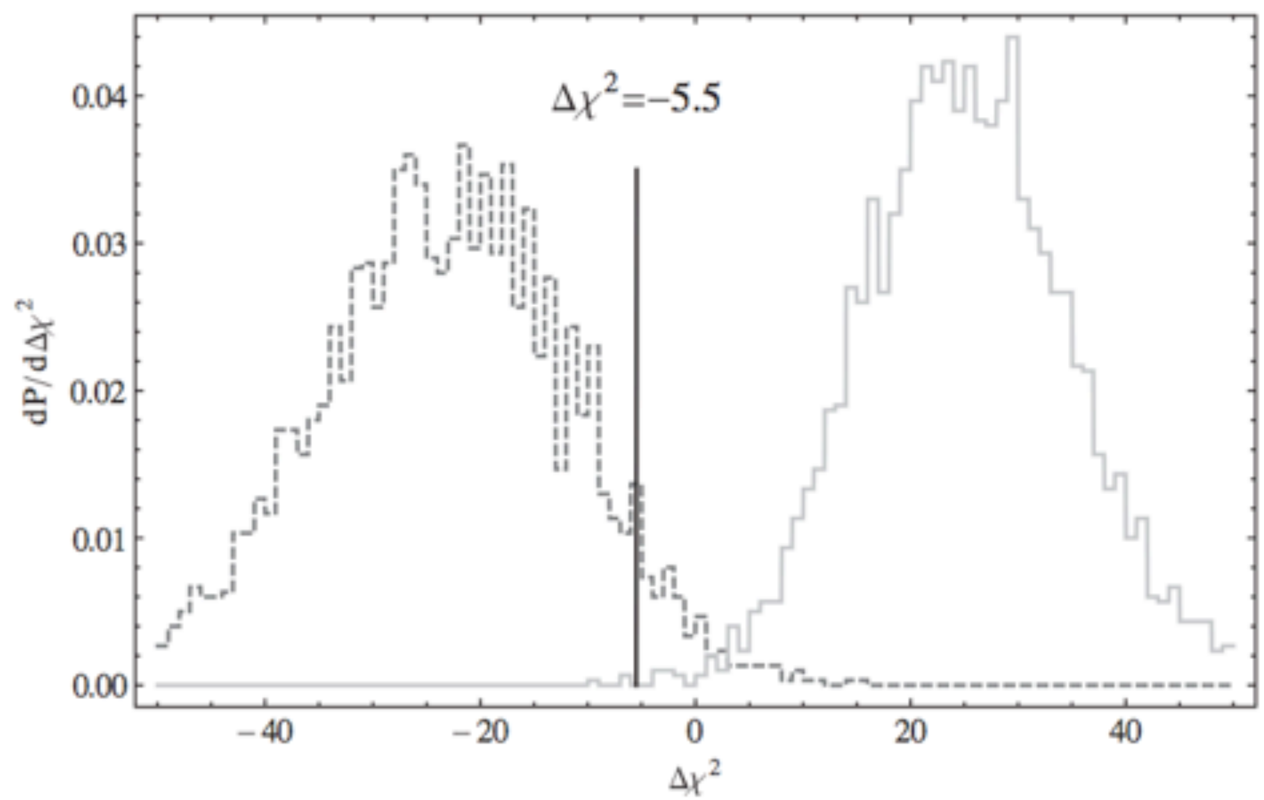


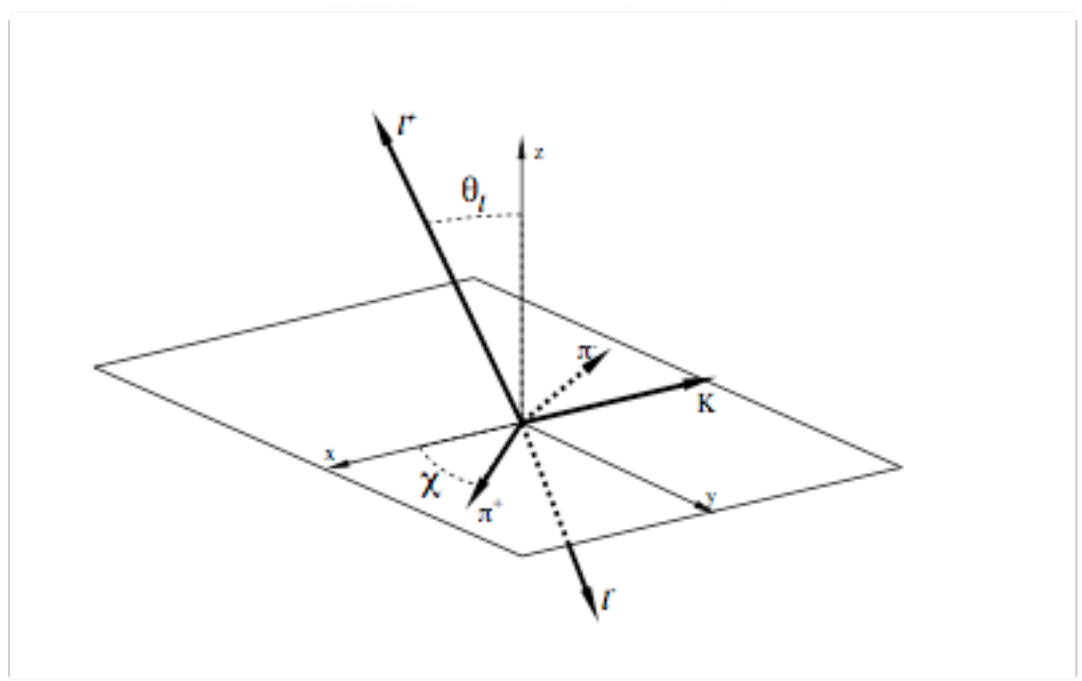

FIG. 5. Distribution of the $\Delta\chi^2 = \chi^2(1^{++}) - \chi^2(2^{-+})$ resulting from the combined fits to Monte Carlo data samples with $n = 1$. The solid (dashed) histogram corresponds to events generated assuming the $X$ to be a $2^{-+}$ $(1^{++})$ state. We mark with a line the position of the experimental $\Delta\chi^2$.

# BELLE ANGULAR CORRELATIONS

Belle, arXiv:1107.0613

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

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



# RESULTS

R. Faccini, F. Piccinini, A. Pilloni, and ADP, Phys Rev. D86 (2012)

TABLE II. Results of the Toy MC

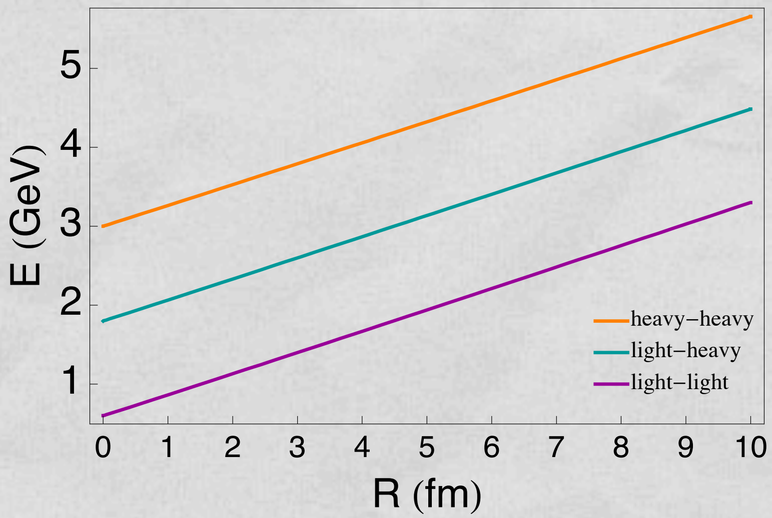
| | $1^{++}$ (dashed curve) | $2^{-+}$ (solid curve) |
|---|---|---|
| Combined | $\chi^2/\text{DOF} = 31.8/36$<br>$P(\chi^2) = 67\%$<br>$\text{CL} = 5.5\%$ | $\chi^2/\text{DOF} = 37.3/33$<br>$P(\chi^2) = 28\%$<br>$\text{CL} = 0.1\%$ |
| $2\pi$ (angular + mass) | $\chi^2/\text{DOF} = 20.9/31$<br>$P(\chi^2) = 91\%$<br>$\text{CL} = 23\%$ | $\chi^2/\text{DOF} = 34.7/29$<br>$P(\chi^2) = 21\%$<br>$\text{CL} < 0.1\%$ |
| $3\pi$ (mass) | $\chi^2/\text{DOF} = 9.9/4$<br>$P(\chi^2) = 4\%$<br>$\text{CL} = 0.1\%$ | $\chi^2/\text{DOF} = 1.5/3$<br>$P(\chi^2) = 68\%$<br>$\text{CL} = 81\%$ |
| Combined (only mass) | $\chi^2/\text{DOF} = 25.2/22$<br>$P(\chi^2) = 29\%$<br>$\text{CL} = 0.1\%$ | $\chi^2/\text{DOF} = 17.7/20$<br>$P(\chi^2) = 61\%$<br>$\text{CL} = 46\%$ |
| $2\pi$ (only angular) | $\chi^2/\text{DOF} = 6.6/14$<br>$P(\chi^2) = 95\%$<br>$\text{CL} = 27\%$ | $\chi^2/\text{DOF} = 19.6/12$<br>$P(\chi^2) = 7.6\%$<br>$\text{CL} < 0.1\%$ |

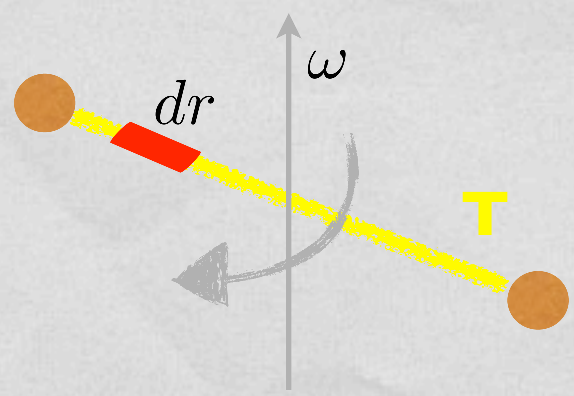
WHAT IF $2^{-+}$ ??

# 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

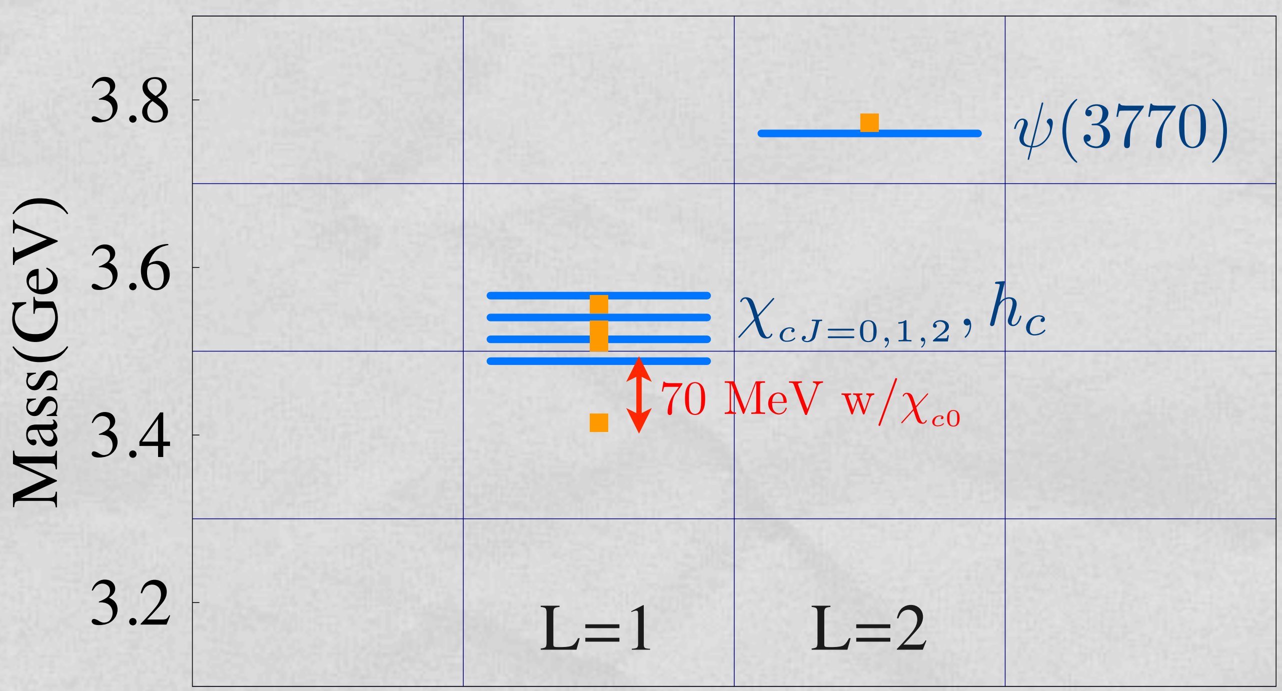
Cotugno, Faccini, Polosa, Sabelli, *Phys. Rev. Lett.* **104**, 132005 (2010)

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

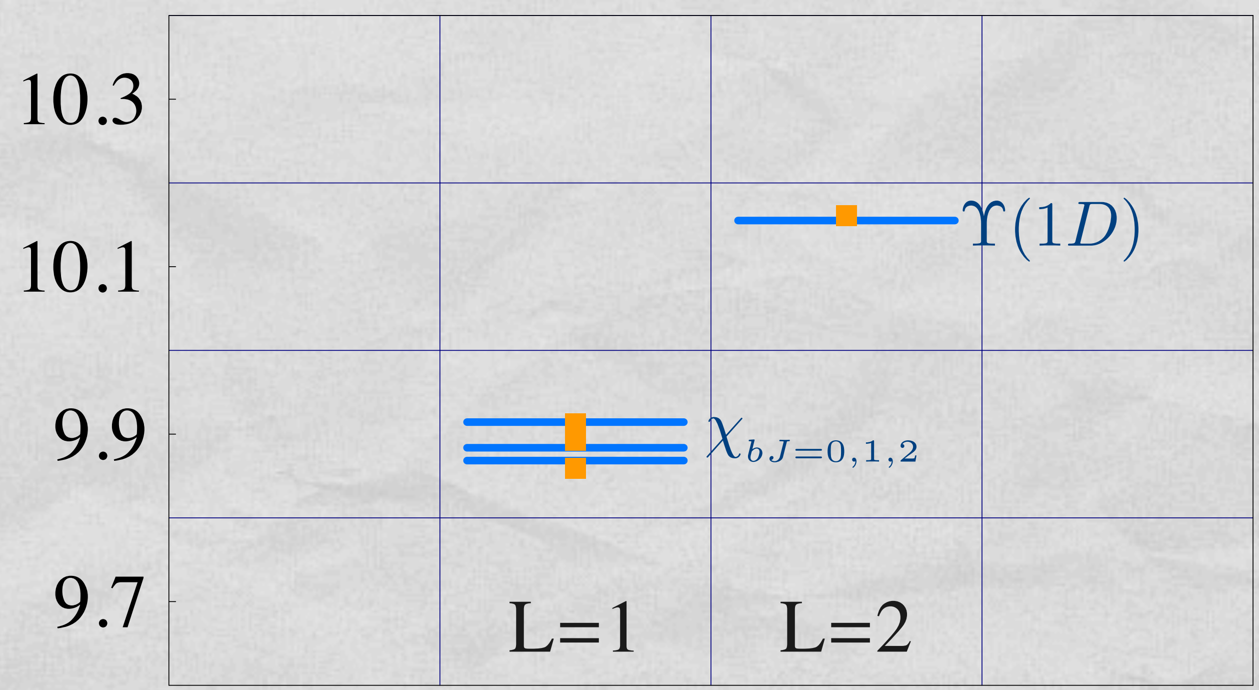
We take the limit in which the mass attached to the ends of the string is the largest scale in the problem

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

No spin-spin because of large r and M



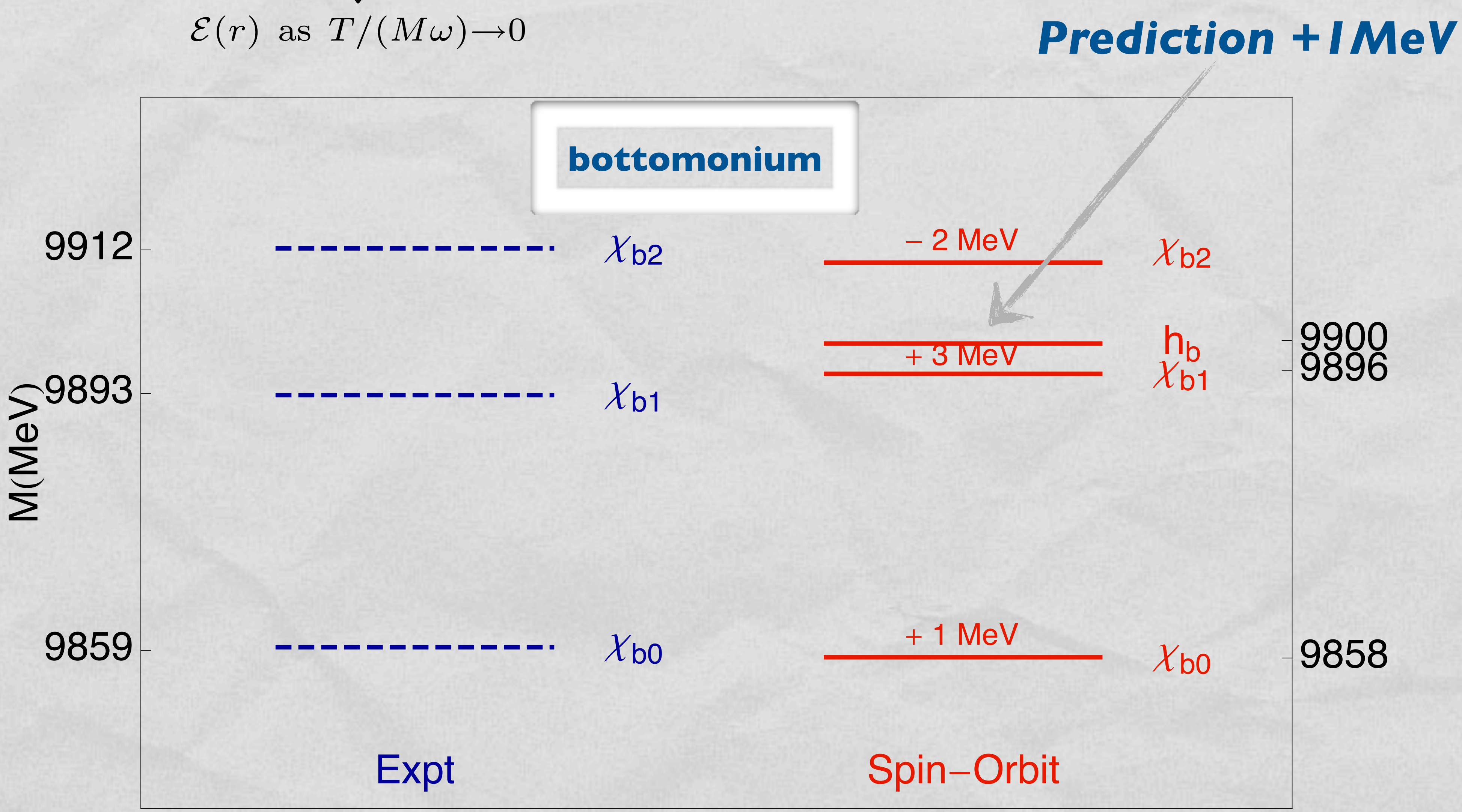

(charm)




(beauty)

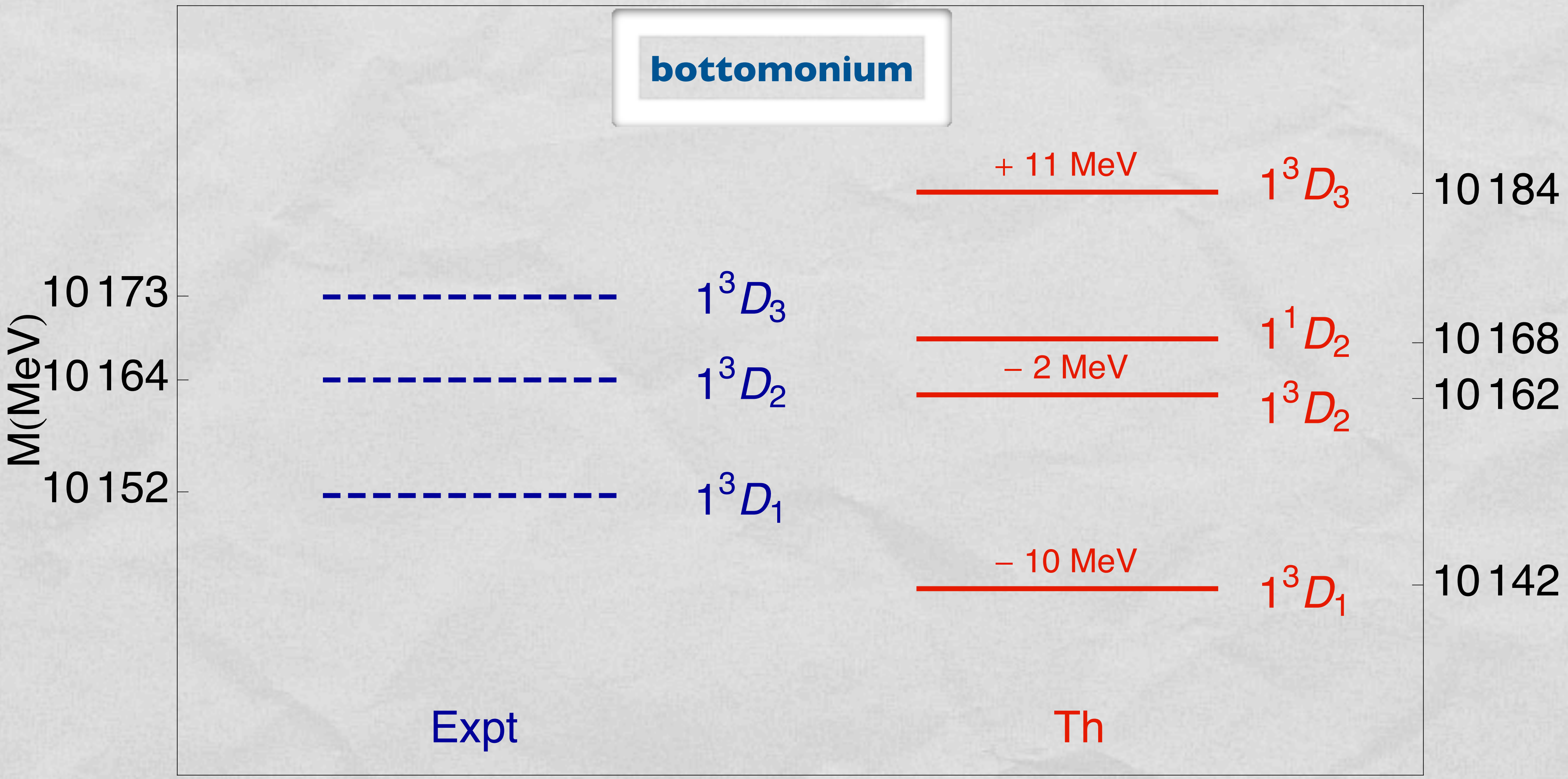
# THE NEXT-TO-SIMPLEST QCD STRING

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




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

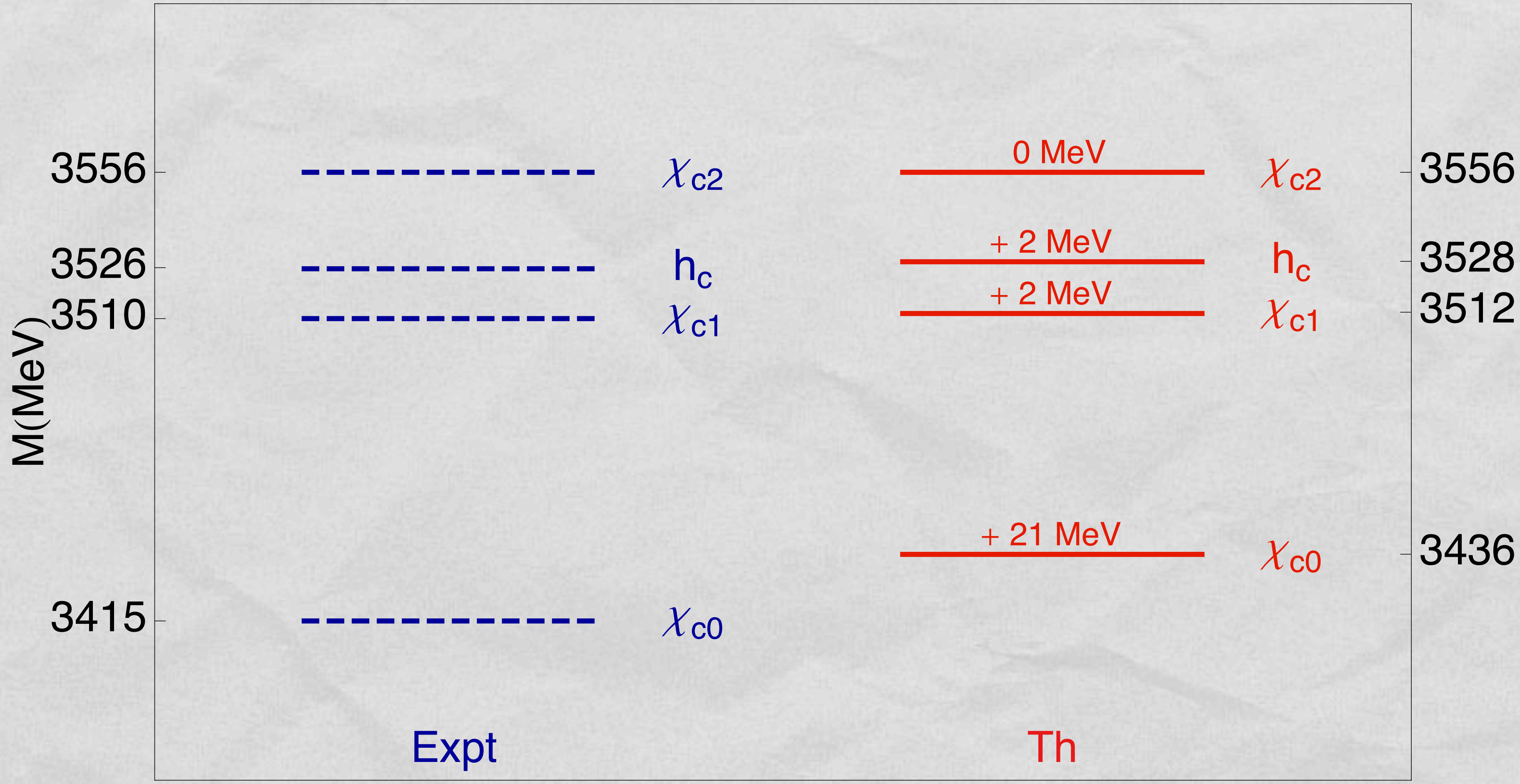
# D-WAVE BOTTOMONIUM



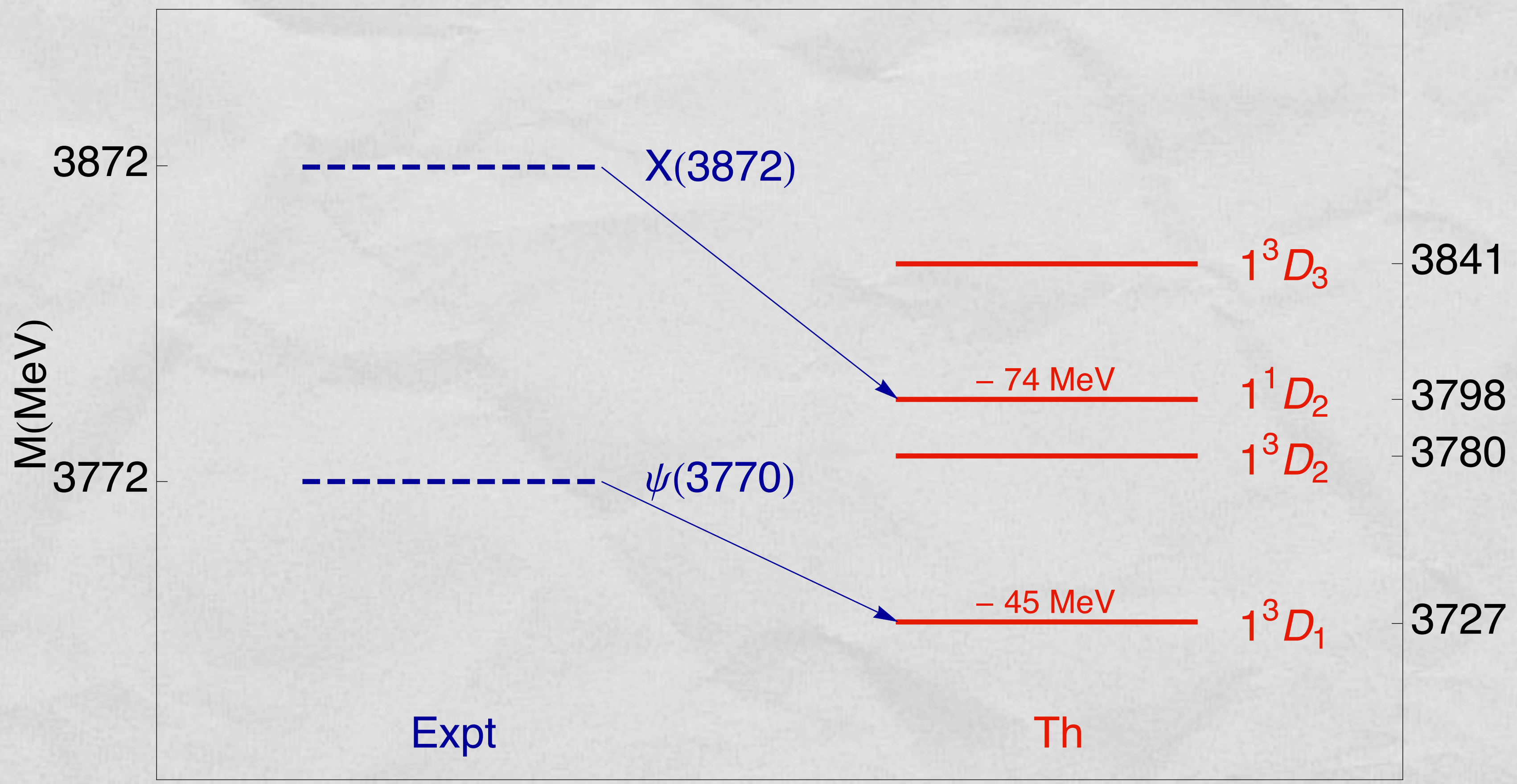

Based on BaBar data

# 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

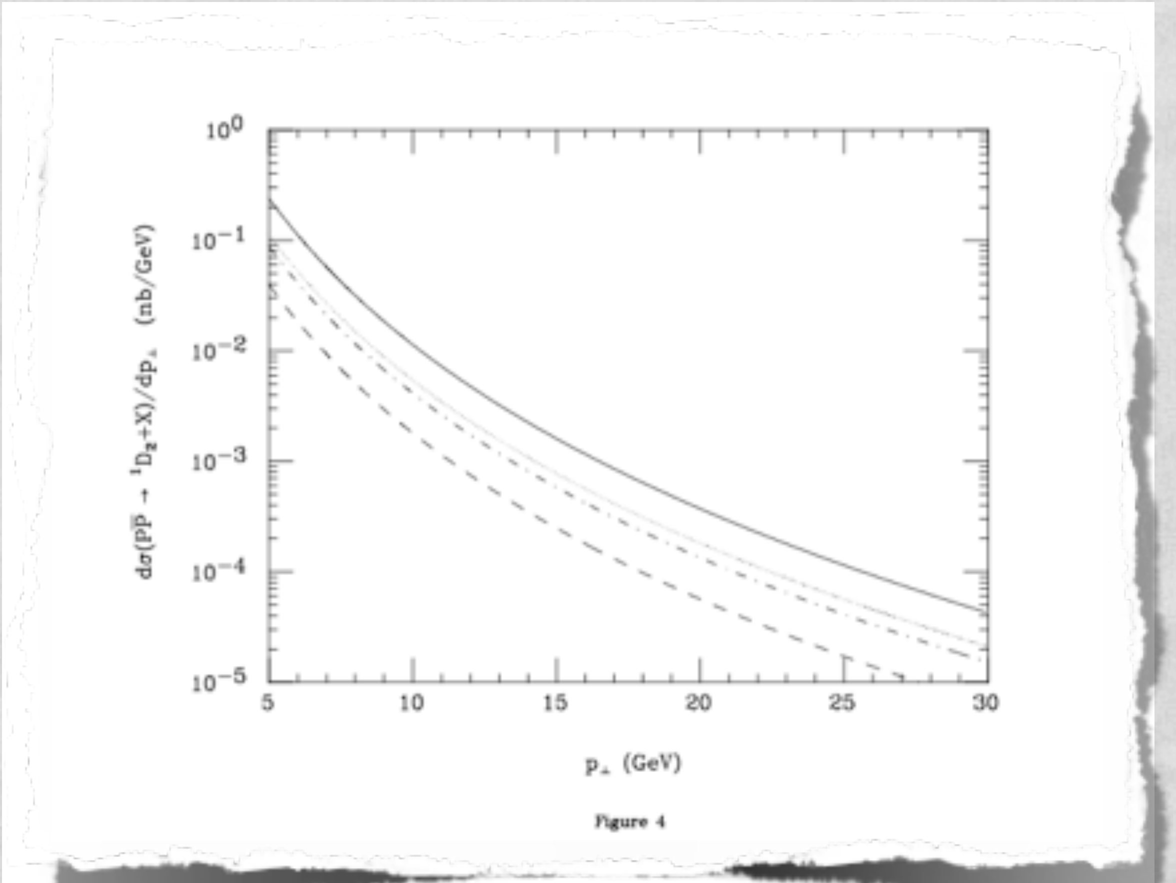
$$\frac{\mathcal{B}(X(3872) \to J/\psi\gamma)}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} = (0.3 \pm 0.1)$$

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

Cho and Wise hep-ph/9410214

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

$$x \simeq \sqrt{M_\perp^2/1960^2} \simeq 0.02$$
$$p_\perp \gtrsim 5 \text{ GeV}$$
$$|y| \leq 6$$
$$\text{factorization scale } \mu \simeq M_\perp$$




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**

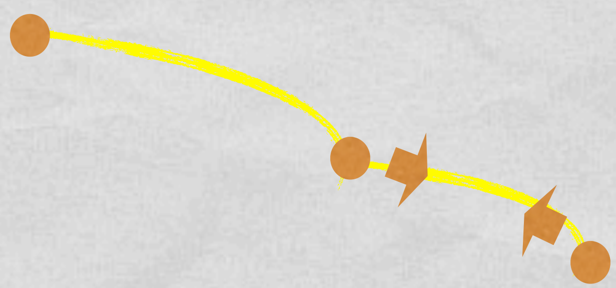
# BARYONS STRING AND DIQUARKS

'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.



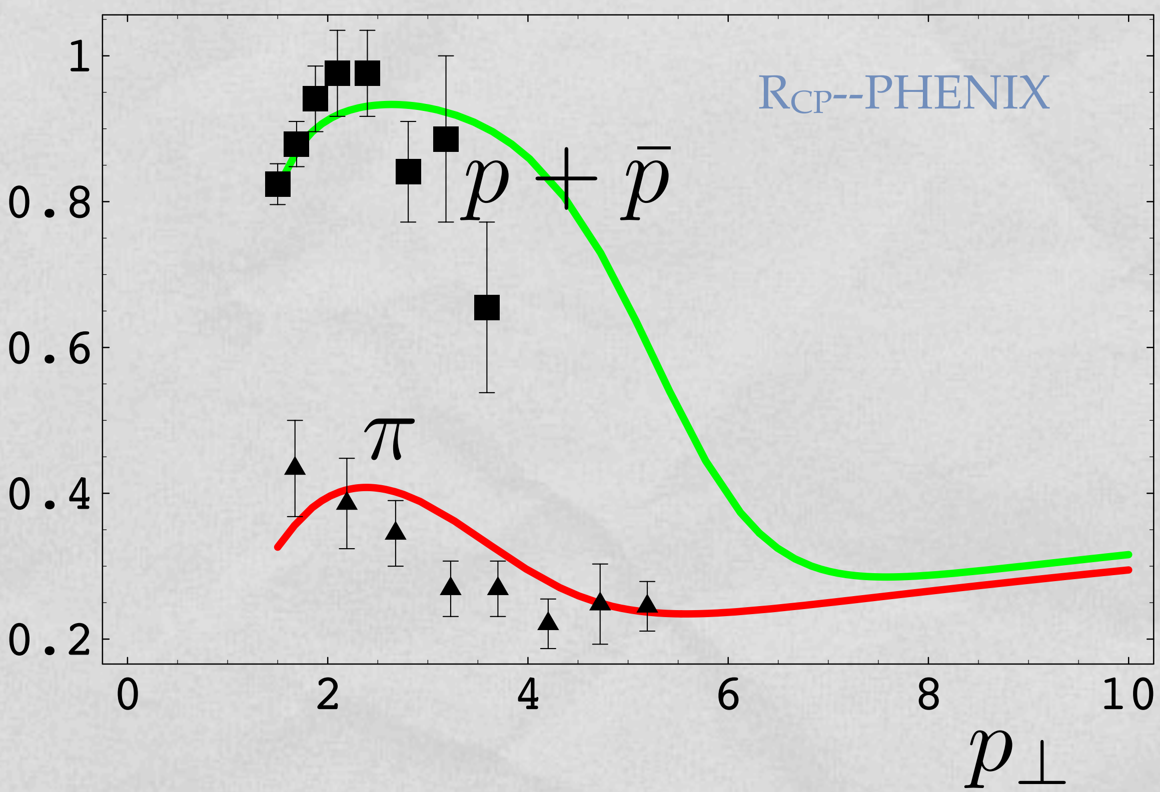
Quantum effects will then favor the configuration with one quark at one end and a diquark at the other hand. Baryons are like mesons as in Regge trajectories

# 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

# 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

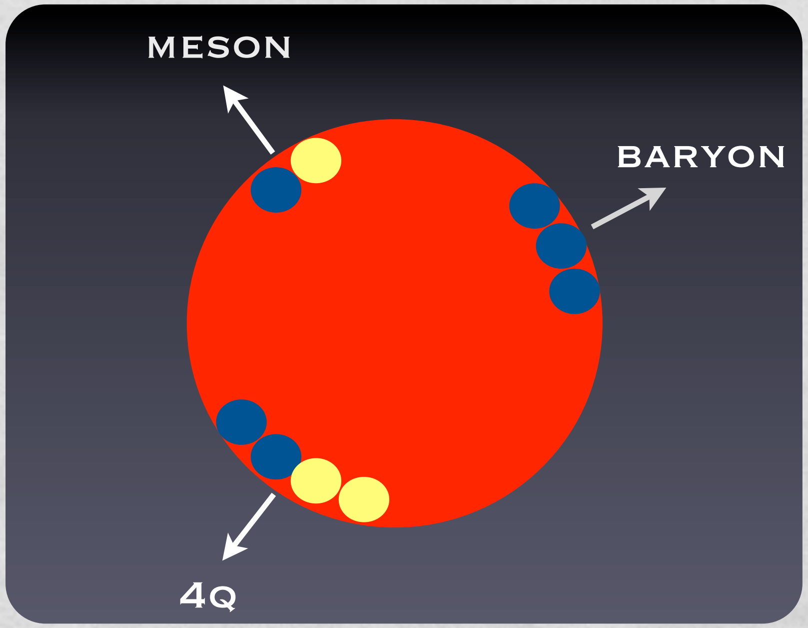
For this reason fragmentation is inefficient at producing high pT hadrons.
In particular pions are produced more efficiently with respect to baryons.
But what if the phase space is densely populated with partons?

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

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

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

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




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