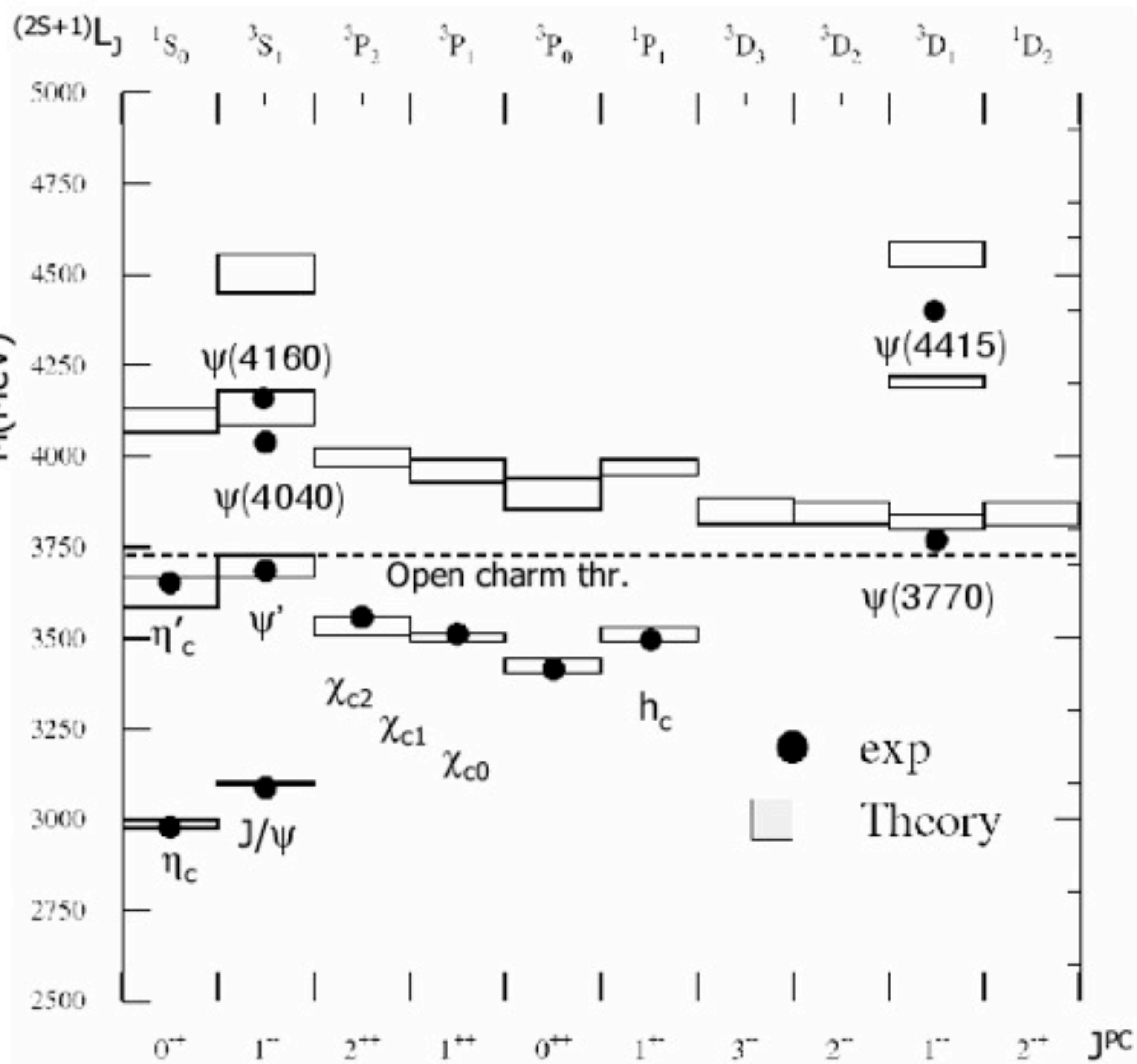
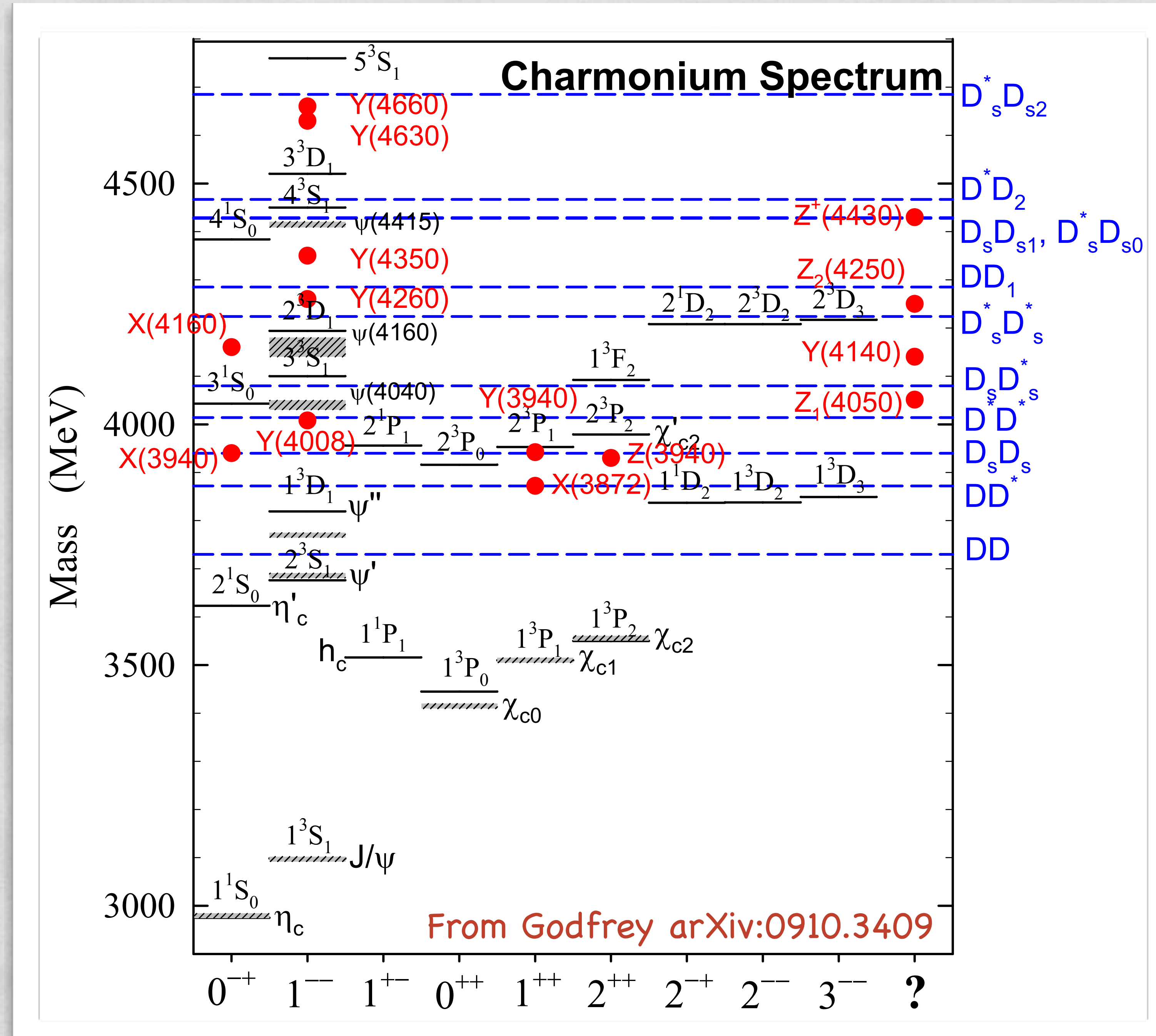
SURPRISES ON THE X(3872)

AD Polosa
INFN Roma

CHARMONIUM LEVELS



WE THOUGHT TO KNEW EVERYTHING ABOUT CHARMONIUM ...



... but then (2004/5) the red dots came about

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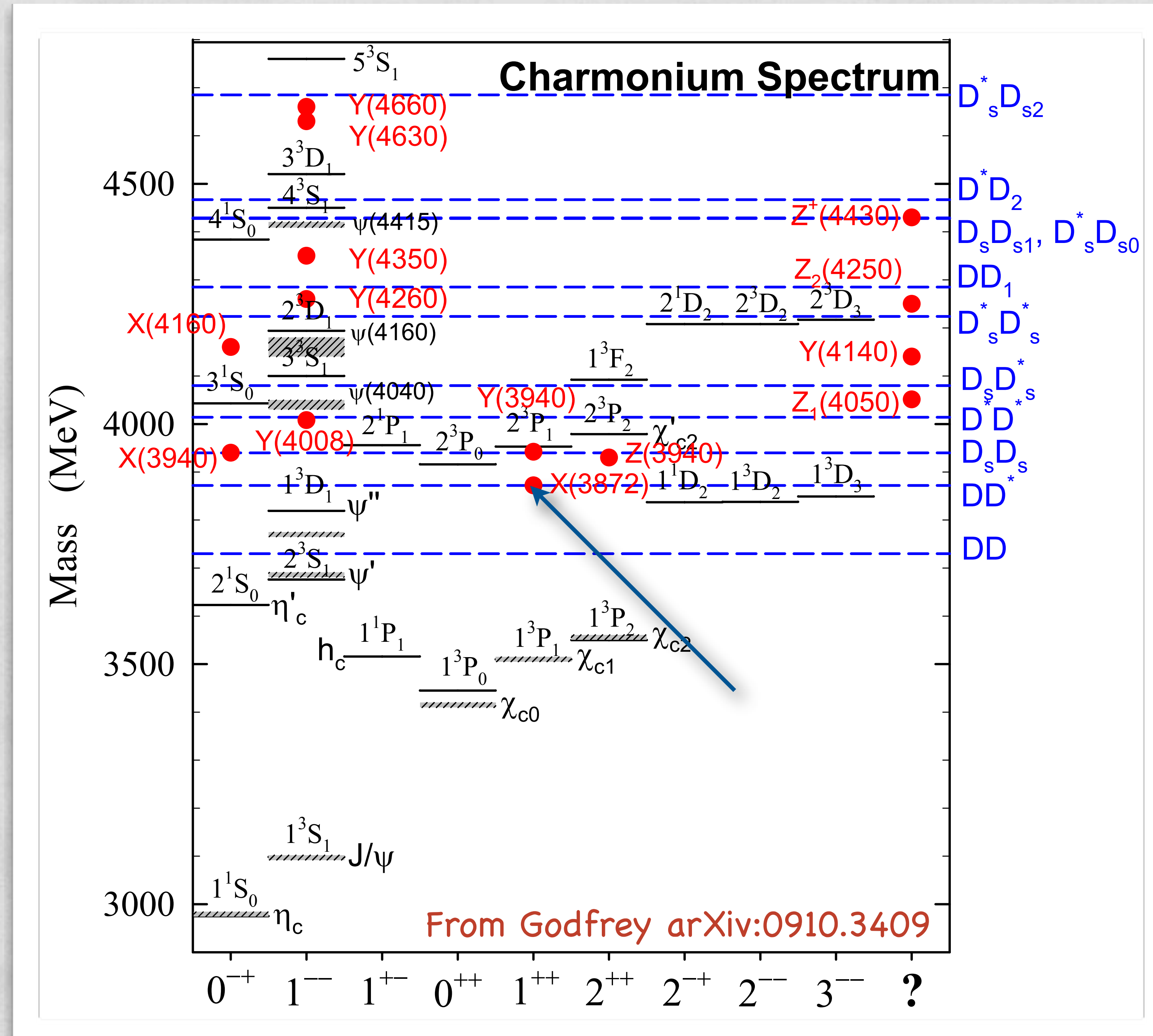

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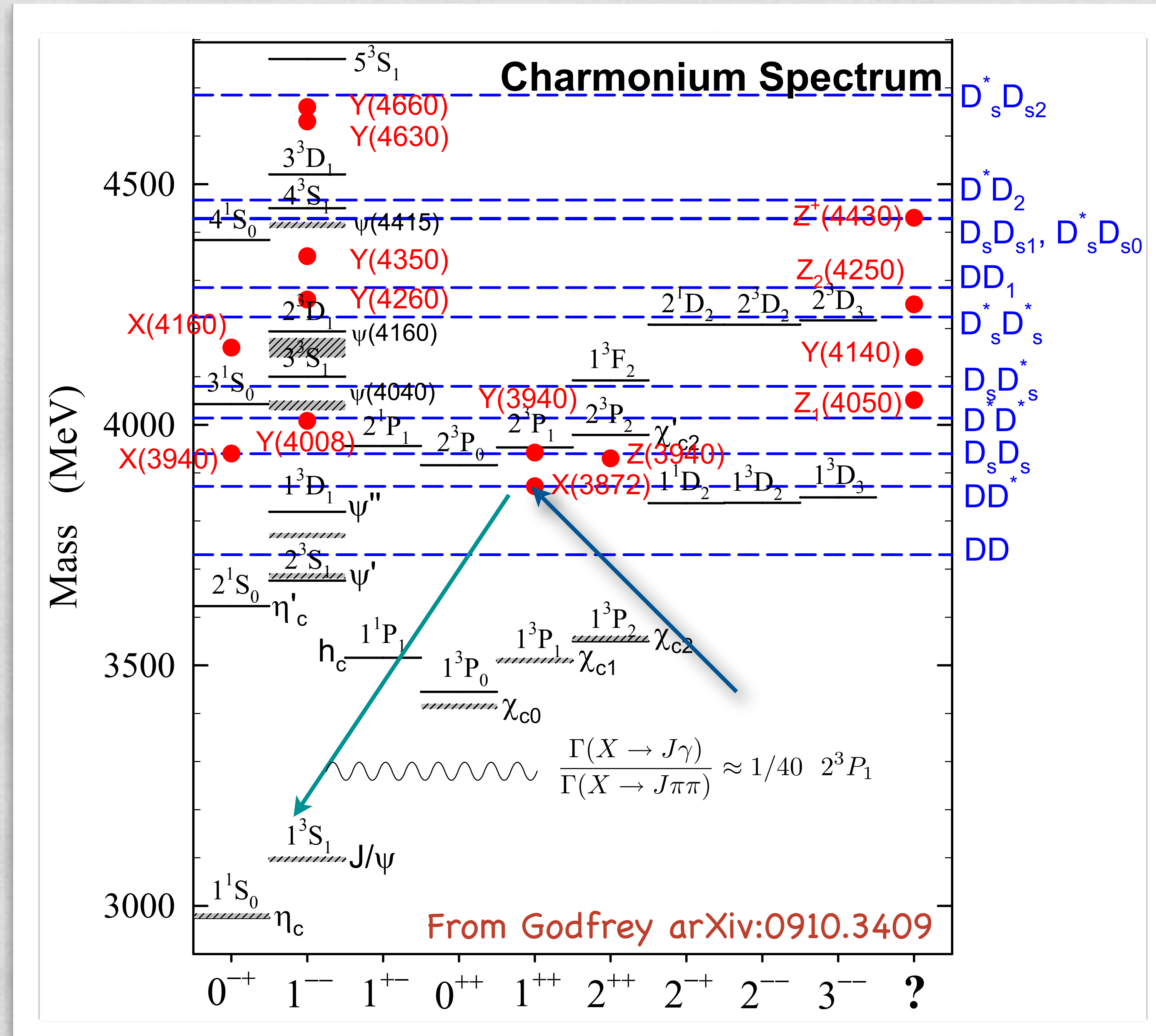
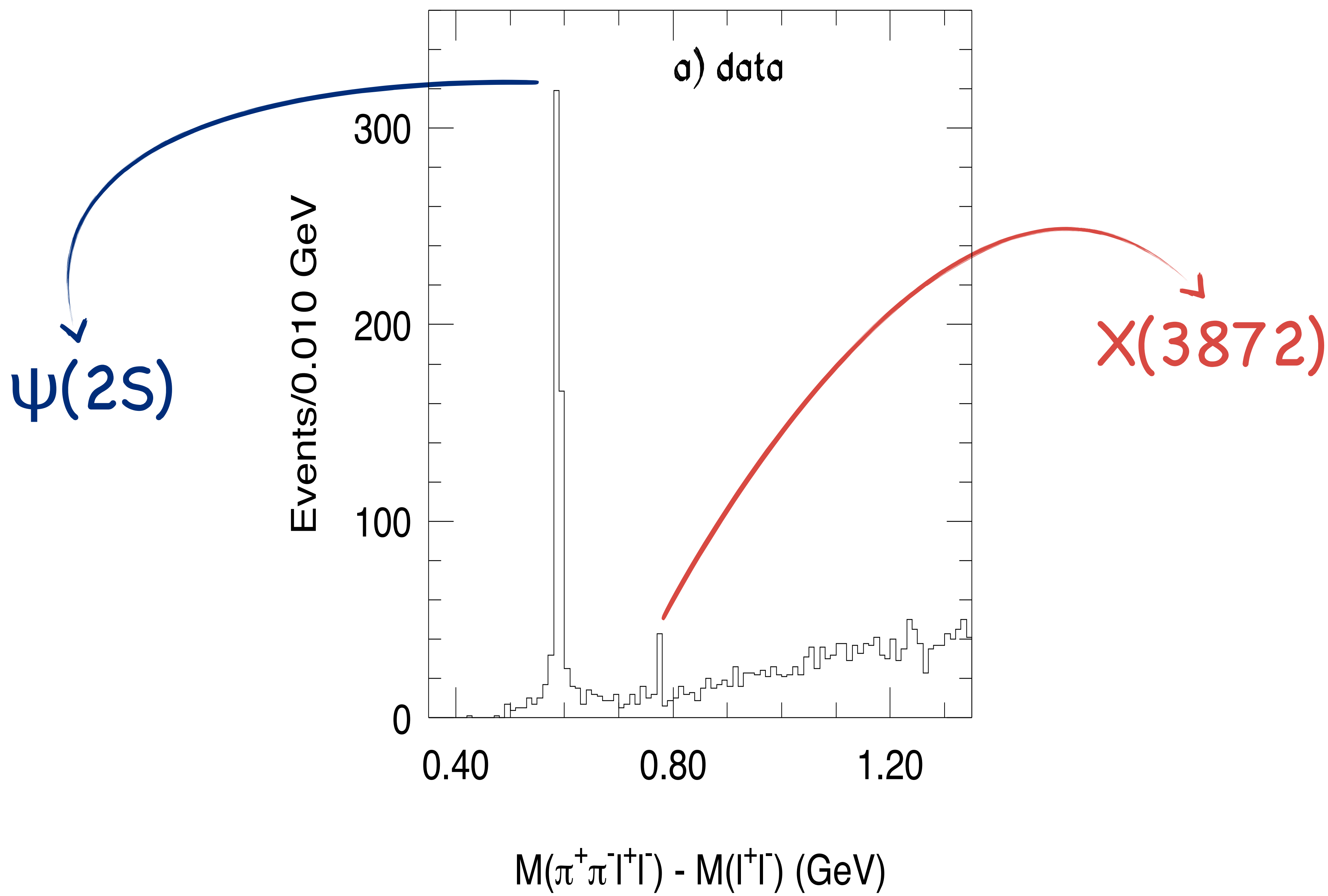


... but then (2004/5) the red dots came about

Discovery of the X(3872): B decays

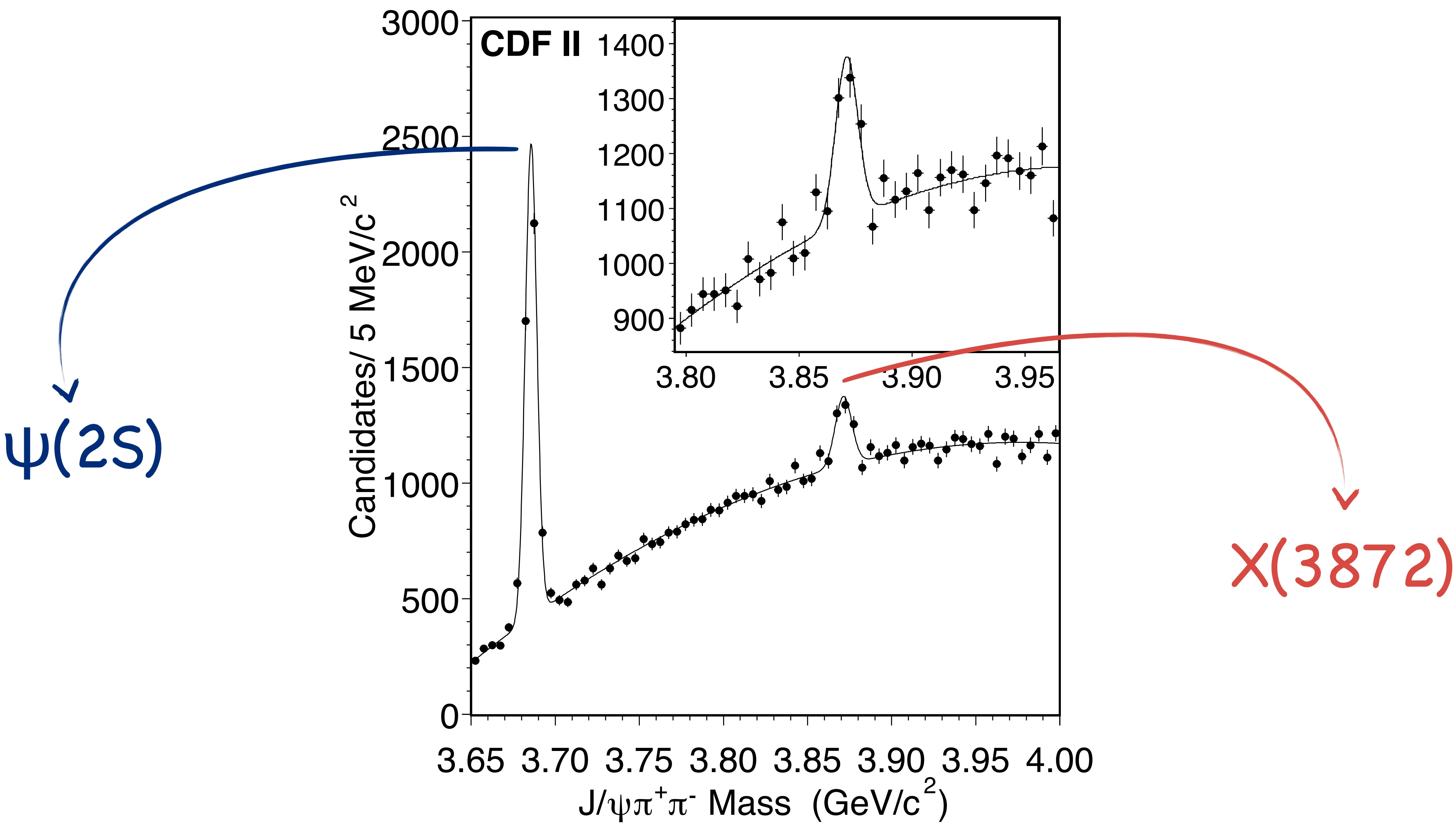
August 2003: $B^\pm \to K^\pm X \to K^\pm J/\psi\, \pi^+\pi^-$



::Belle, Phys. Rev. Lett. 91 (2003) 262001 [arXiv:hep-ex/0309032] ::

Discovery of the X(3872): $p\bar{p}$ collisions

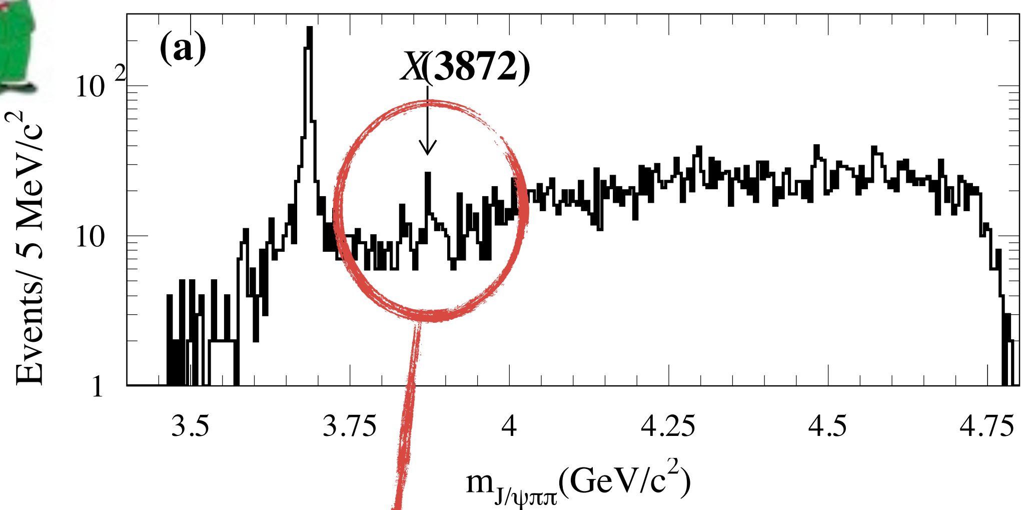
September 2003: $p\bar{p} \rightarrow X + \text{all} \rightarrow J/\psi\ \pi^+\pi^- + \text{all}$

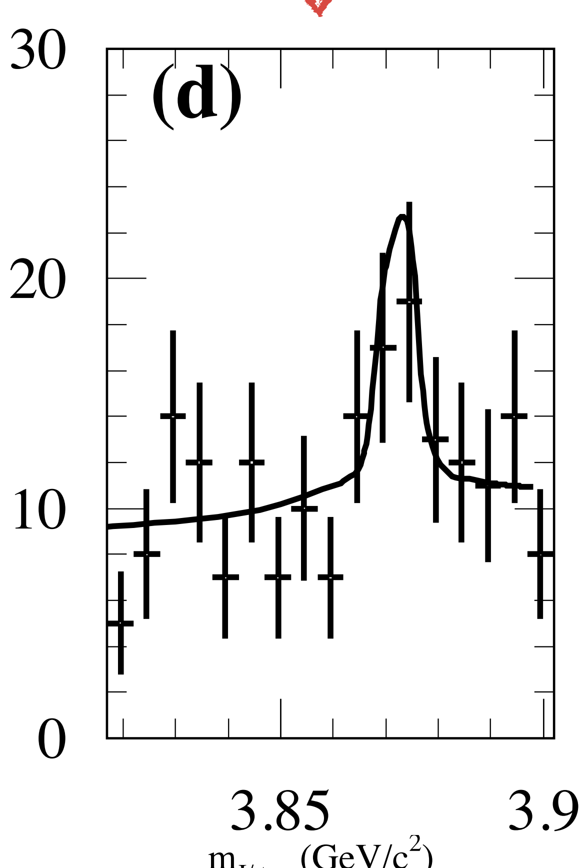


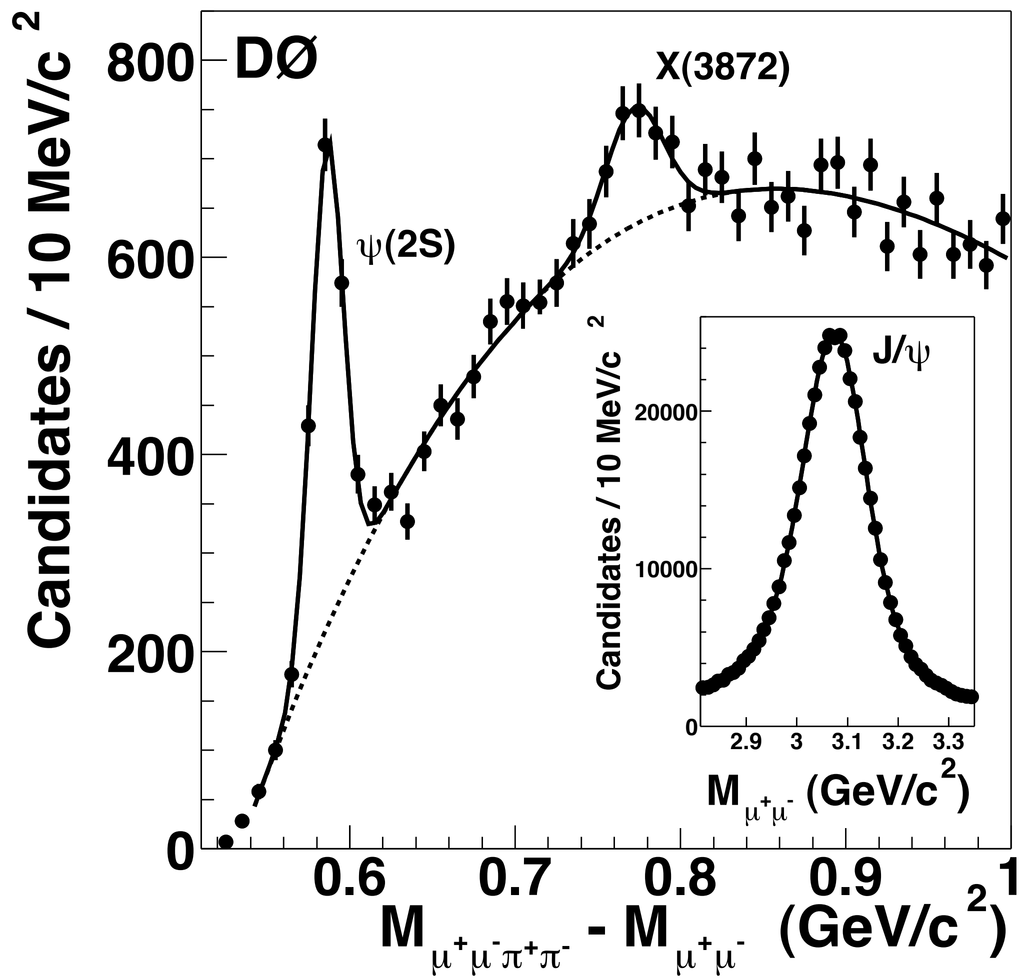
[$m(\pi^+\pi^-)$>500 MeV]

:: CDF, Phys. Rev. Lett. 93 (2004) 072001 [arXiv:hep-ex/0312021] ::

BaBar and DØ confirm the state







::BaBar, Phys. Rev. D 71 (2005) 071103 ::

:: D0, Phys. Rev. Lett. 93 (2004) 162002 ::

AFTER THE X MANY MORE

state	M (MeV)	Γ (MeV)	J^{PC}	Seen In	Observed by:	Comments
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$(e^+e^-)_{ISR}, J/\psi \to Y_s(2175) \to \phi f_0(980)$	BaBar, BESII, Belle	
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$B \to KX(3872) \to \pi^+\pi^- J/\psi, \gamma J/\psi,\ D\bar{D}^*$	Belle, CDF, D0, BaBar	Molecule?
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$?^{++}$	$\gamma\gamma \to \omega J/\psi$	Belle	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to D\bar{D}$	Belle	$2^3P_2(c\bar{c})$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle	$3^1S_0(c\bar{c})$?
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar	$2^3P_1(c\bar{c})$?
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle	
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle	Hybrid?
$Y(4350)$	4324 ± 24	172 ± 33	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar	
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	Belle	
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle	
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^\pm(4050) \to \pi^\pm \chi_{c1}$	Belle	
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^\pm(4250) \to \pi^\pm \chi_{c1}$	Belle	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^\pm(4430) \to \pi^\pm \psi'$	Belle	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^- \Upsilon(1,2,3S)$	Belle	

From Godfrey arXiv:0910.3409

$$X \to \gamma J/\psi \mapsto C = +1 \quad \text{and} \quad X \to \rho^0 J/\psi \to (\pi^+\pi^-)_S J/\psi \mapsto P = 1$$

Radiative decays

:: BaBar, Phys.Rev.Lett.102:132001,2009. ::

$$\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8(\mathrm{stat}) \pm 0.1(\mathrm{syst})) \times 10^{-6}$$

:: BaBar, Phys. Rev.D, 77 (2008) 111101 ::

$$\mathcal{B}(B^{\pm} \to X(3872)K^{\pm}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.4 \pm 1.5(\mathrm{stat}) \pm 0.7(\mathrm{syst})) \times 10^{-6}$$

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

$$\boxed{\Gamma(2^3P_1 \to \psi\gamma)/\Gamma(2^3P_1 \to \psi\pi\pi) \sim 40}$$

Charmonium predictions: :: Eichten, Lane and Quigg, Phys. Rev. D 69, 094019 (2004) ::
:: Barnes and Godfrey, Phys. Rev. D, 69, 054008 (2004) ::

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not $c\bar{c}$

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THE MOLECULE EXPLANATION

A way for accomodating isospin violations is to suppose that X(3872) is a DD* **molecule**

$$|X\rangle = \frac{|D^0\bar{D}^{0*}\rangle + |\bar{D}^0 D^{0*}\rangle}{\sqrt{2}}$$

So that one can produce both the I=0 or I=1 combinations.
In $B \rightarrow KX$ decay indeed can have both

Braaten; Mehen; Swanson; Hanhart; Tornqvist; Voloshin (hadrocharmonium)

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THE MOLECULE EXPLANATION

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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 have a characteristic size

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

which could either be infinity(!) as

$$\mathcal{E} = 0.25 \pm 0.40 \text{ MeV}$$

SOME PROBLEMS

- Such a large state must spend part of its time in a very tight configuration to allow $J/\psi\ \rho$ and $J/\psi\ \omega$ decays - one can model this but it is difficult to 'reliably' calculate...

- D^* has a width of about 70 keV. Why the $X \to DD\pi$ decay rate is ~3 MeV then? In other words, which is the mechanism accelerating the D^* decay into the molecule?

X PROMPT CROSS SECTION

At the moment CDF (which has performed the most precise determination of the X(3872) mass) measures a prompt X production cross section of about 30-70 nb.

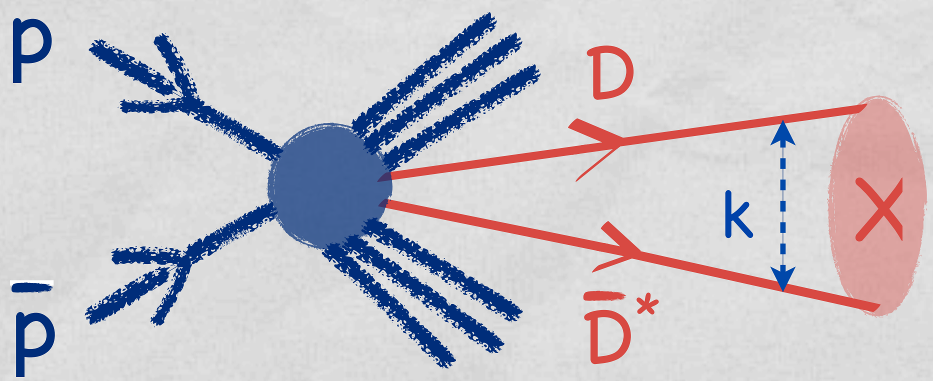
We find that the prompt production cross section is an important table test of the molecule interpretation.

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

How can a loosely bound state (almost zero binding energy) be poduced in the wild environment of hadronic collisions?

Beppe Nardulli once told me:
“Sometimes it is more profitable to have important enemies than important friends...”

PROMPT PRODUCTION



$$
\begin{aligned}
\sigma(p\bar{p} \to X(3872)) \quad &\sim \quad \left| \int d^3k \langle X | D\bar{D}^*(\mathbf{k})\rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle \right|^2 \\
&\simeq \quad \left| \int_{\mathcal{R}} d^3k \langle X | D\bar{D}^*(\mathbf{k})\rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle \right|^2 \\
&\leq \quad \int_{\mathcal{R}} d^3k |\psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2 \\
&\leq \quad \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2
\end{aligned}
$$

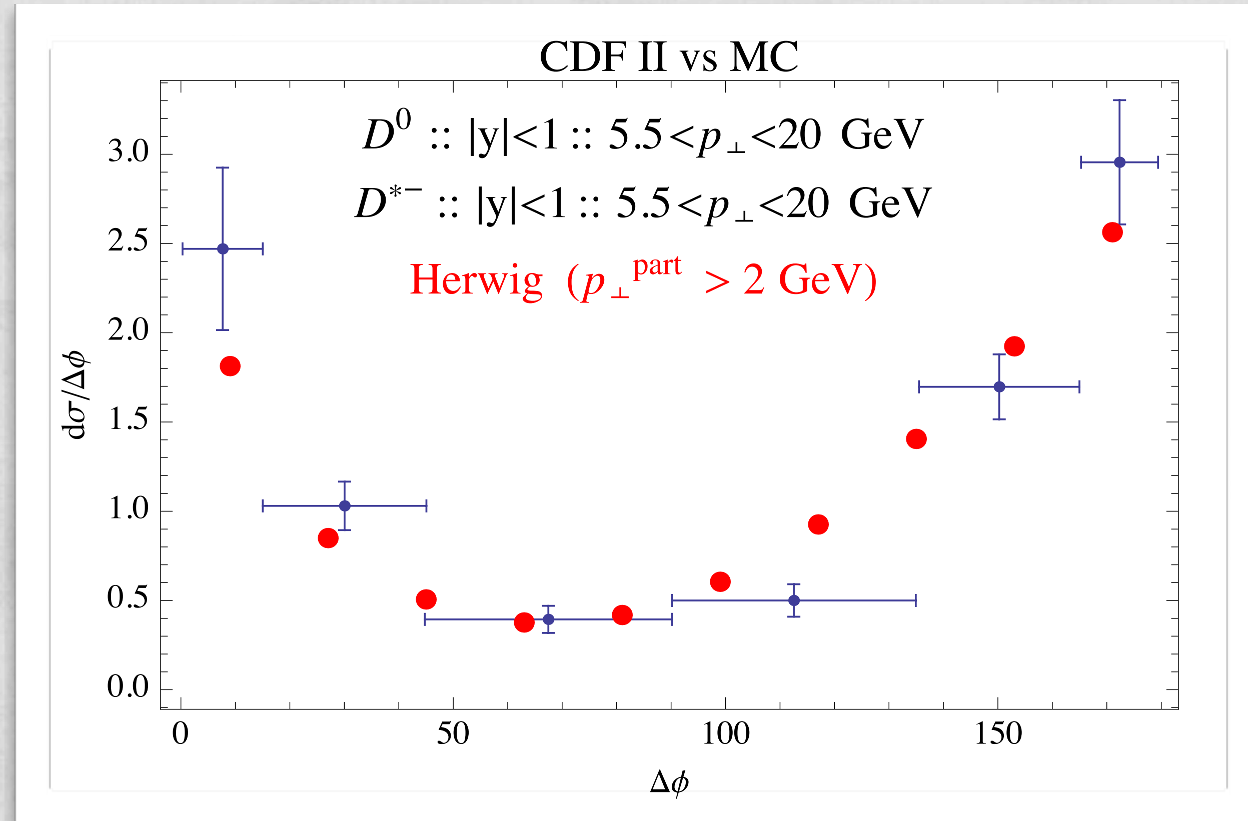
Using Pythia & Herwig we can compute

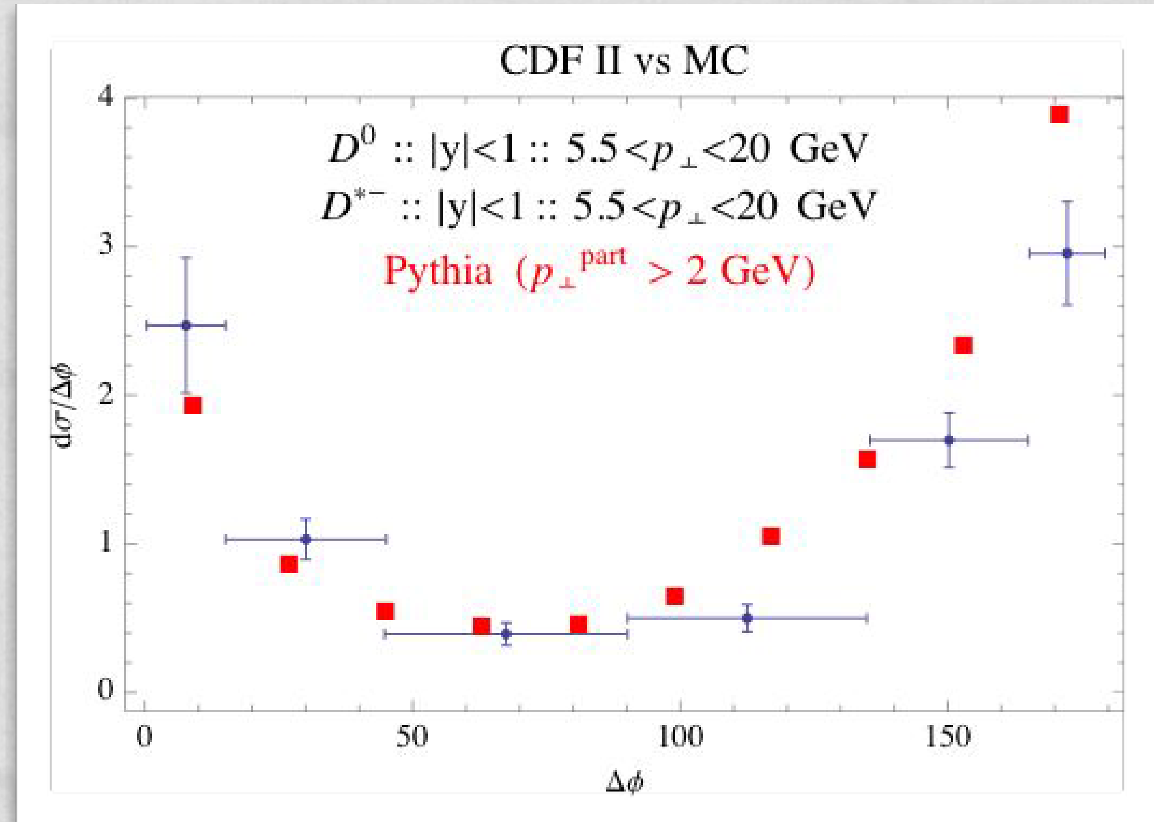
$$\sigma_{\max}(p\bar{p} \to X(3872)) = \int_{\mathcal{R}} d^3k |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p}\rangle|^2$$

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

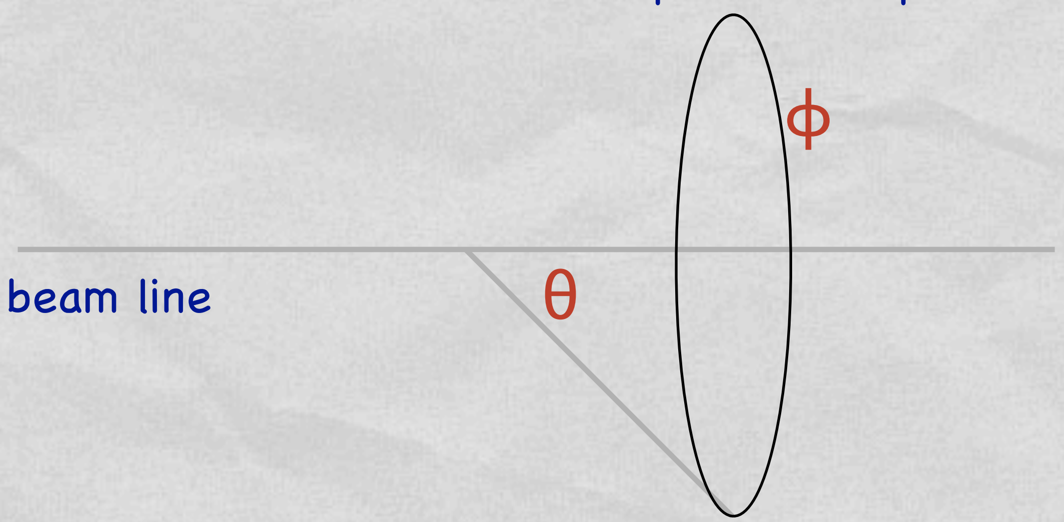
as $\quad k \sim \sqrt{2\mu(-0.25 + 0.40)} \simeq 17$ MeV

TUNING MC'S

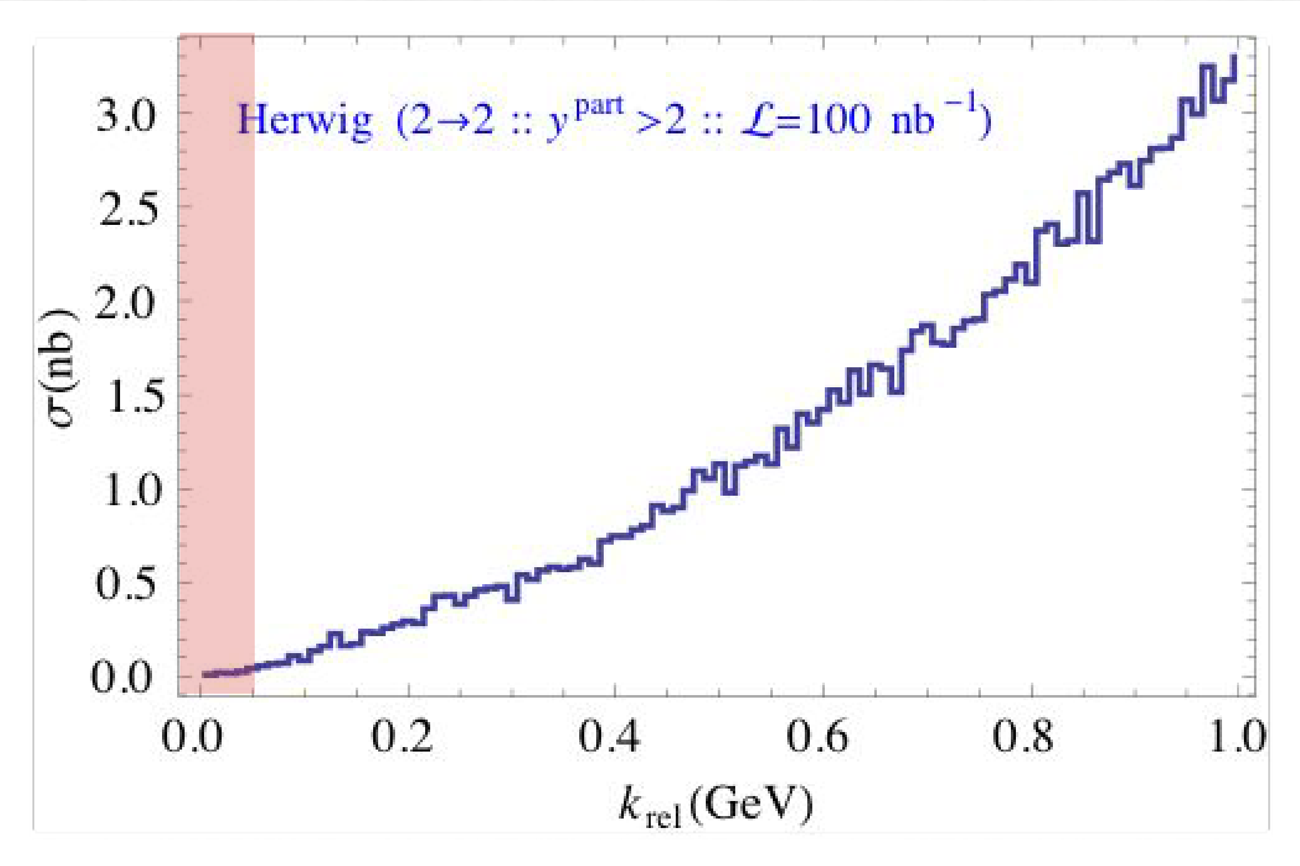


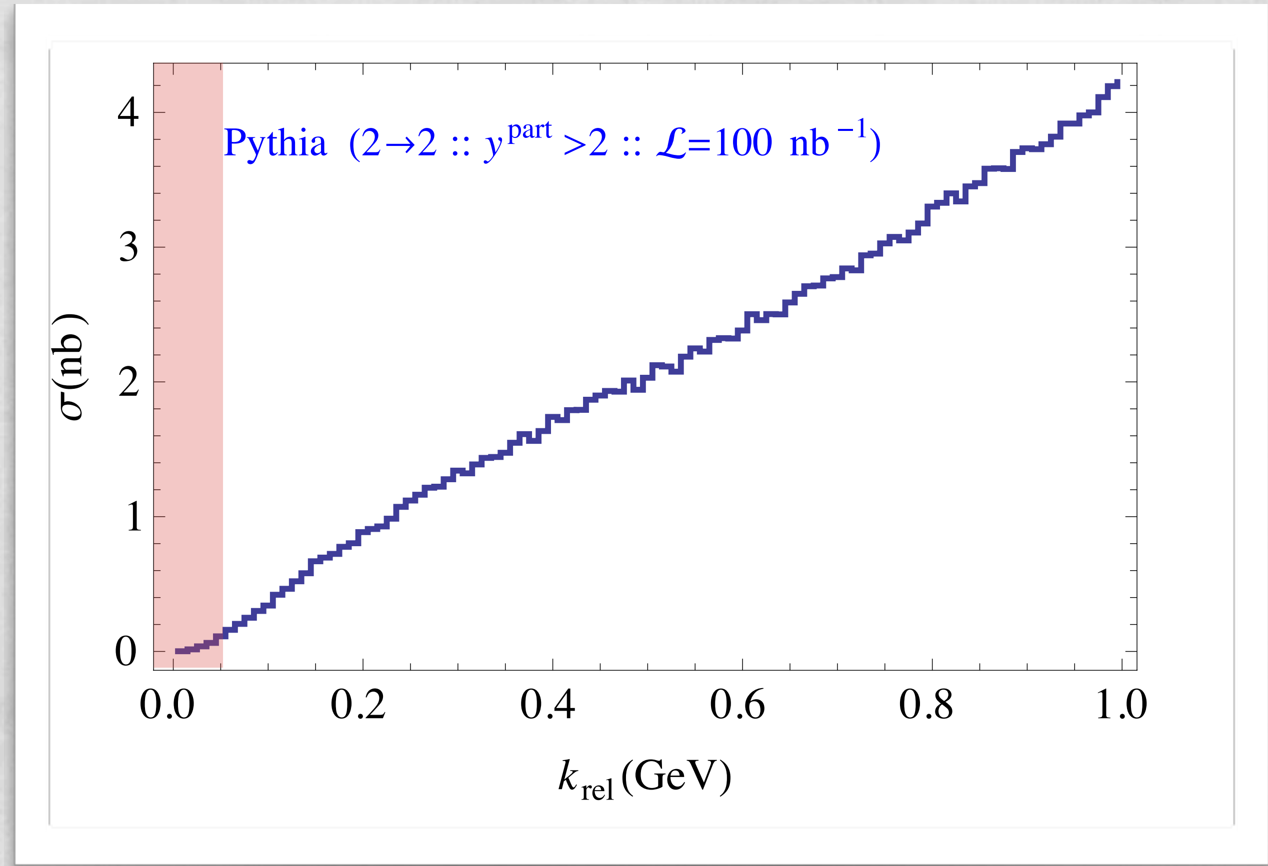


[The D^0 D^{*-} pair cross section as function of $\Delta\phi$ at CDF Run II. We find that we have to rescale the Herwig cross section values by a factor K= 1.8 to best fit the data on open charm production. As for Pythia we need K=0.74]



COUNTING PAIRS OVER 5*10**9 SIMULATED EVENTS





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

$$\sigma_{\rm TH} \sim 1/300\ \sigma_{\rm EXP}$$

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)**.

ARE XYZ DIQUARK-ANTIDIQUARK PARTICLES?

Suppose that X(3872) is a new type of meson with a body-plan different from standard ones, namely a diquark-antidiquark meson

Maiani, Piccinini, Polosa, Riquer Phys Rev D 2005

A diquark qq has the same color as an antiquark
(there is attraction between two quarks in this color channel)

- This would explain easily $J/\psi\ \rho$ and $J/\psi\ \omega$ decays
- With a bit more effort it would also explain the observed isospin violations
- $J/\psi\ \gamma$ is understood! (only with 4q!)

THE MOST CHALLENGING PREDICTIONS

TWO NEUTRAL X are PREDICTED with a separation in mass of few MeV (of the order of m_u-m_d)

All the mesons (red dots) found in the first table are NEUTRAL particles whereas the tetraquark model predicts also the existence of CHARGED particles like

$$[cu][\bar{c}\bar{d}] \quad Q = +1$$

$$[cu][\bar{d}\bar{s}] \quad Q = +2$$

Light states like

$$[uu][\bar{d}\bar{s}] \quad Q = +2$$

are disfavored as the spin one light diquark is itself disfavored

BUT THEN A NEW PAPER BY BABAR CAME...

arXiv:1005.5190

The quantum numbers of the X are
not 1^{++} but 2^{-+} !!

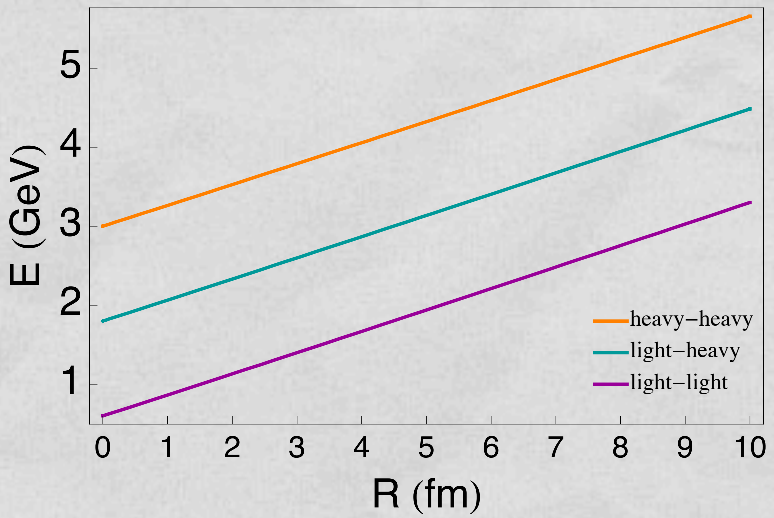
This is why we cannot justify the prompt production of X at CDF. There is no 1++ (DD*) molecule.

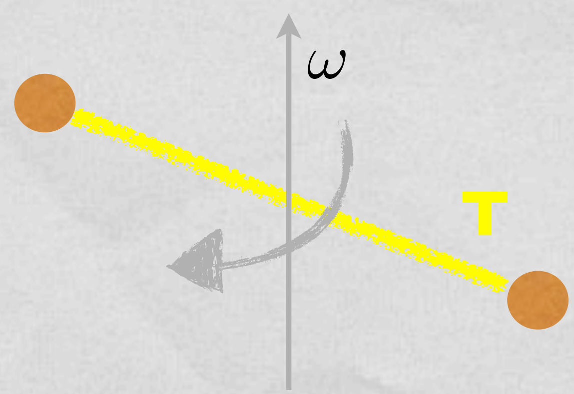
O(200) papers on the molecular interpretation...

THE SIMPLEST QCD STRING

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

Loosely bound (S-wave) molecules cannot have orbital or radial excitations. Two diquarks bound by a string can.





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

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

$\sigma \sim 1\ \mathrm{GeV}^2$ from Regge slopes and $d\mathcal{E}'/dr' = T = \sigma/2\pi$ and $\dfrac{m_i \omega^2 r_i}{1-(\omega r_i)^2} = T$

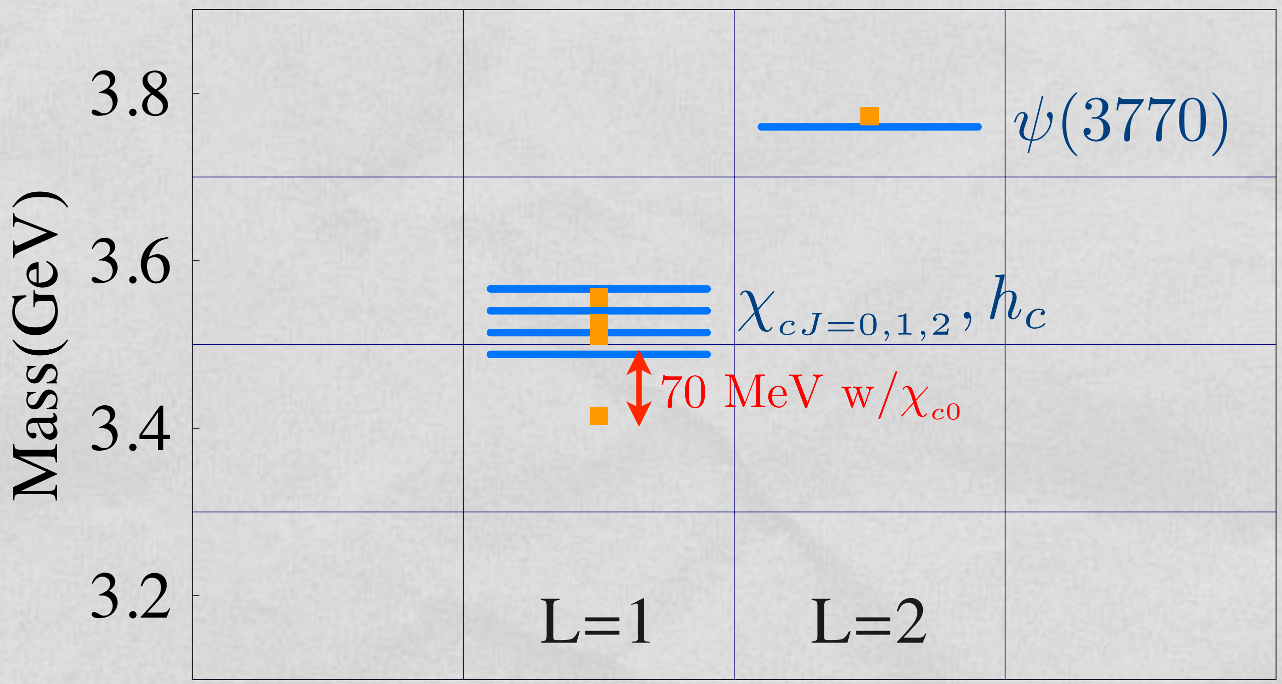
THE SIMPLEST QCD STRING II

Cotugno, Faccini, Polosa, Sabelli Phys Rev Lett 2010

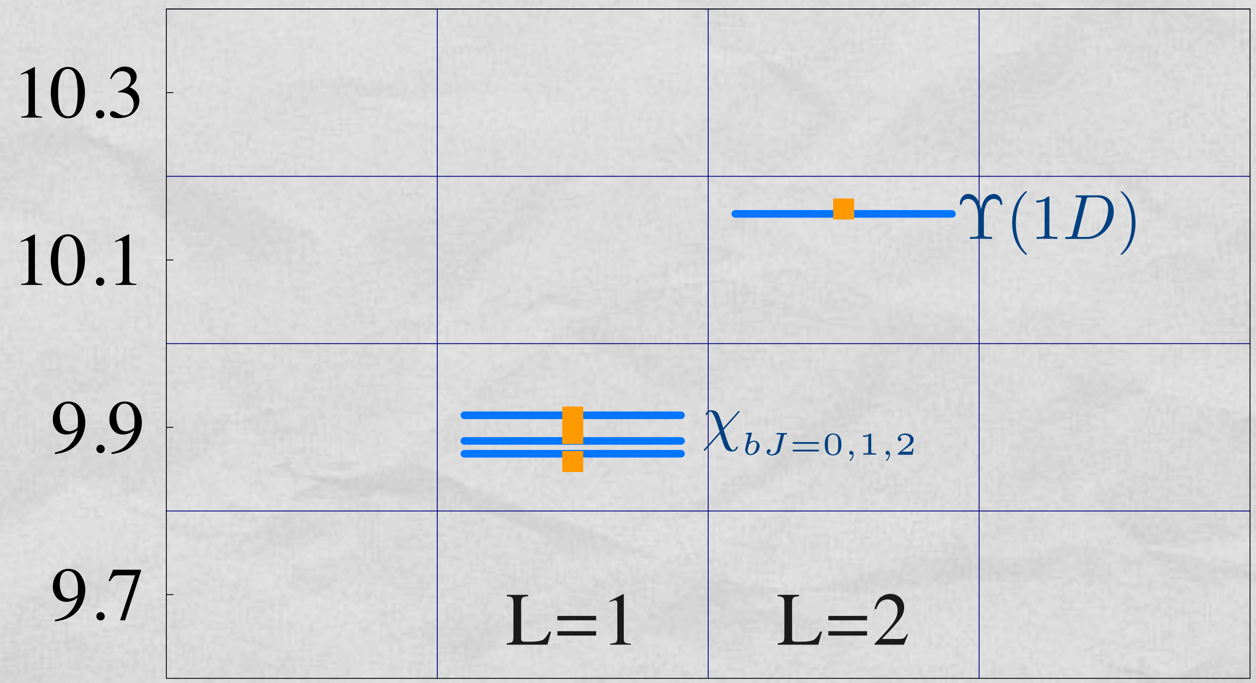
In the limit of infinite (heavy-light) quark mass we find

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

No spin-spin because of large r and M



(charm)

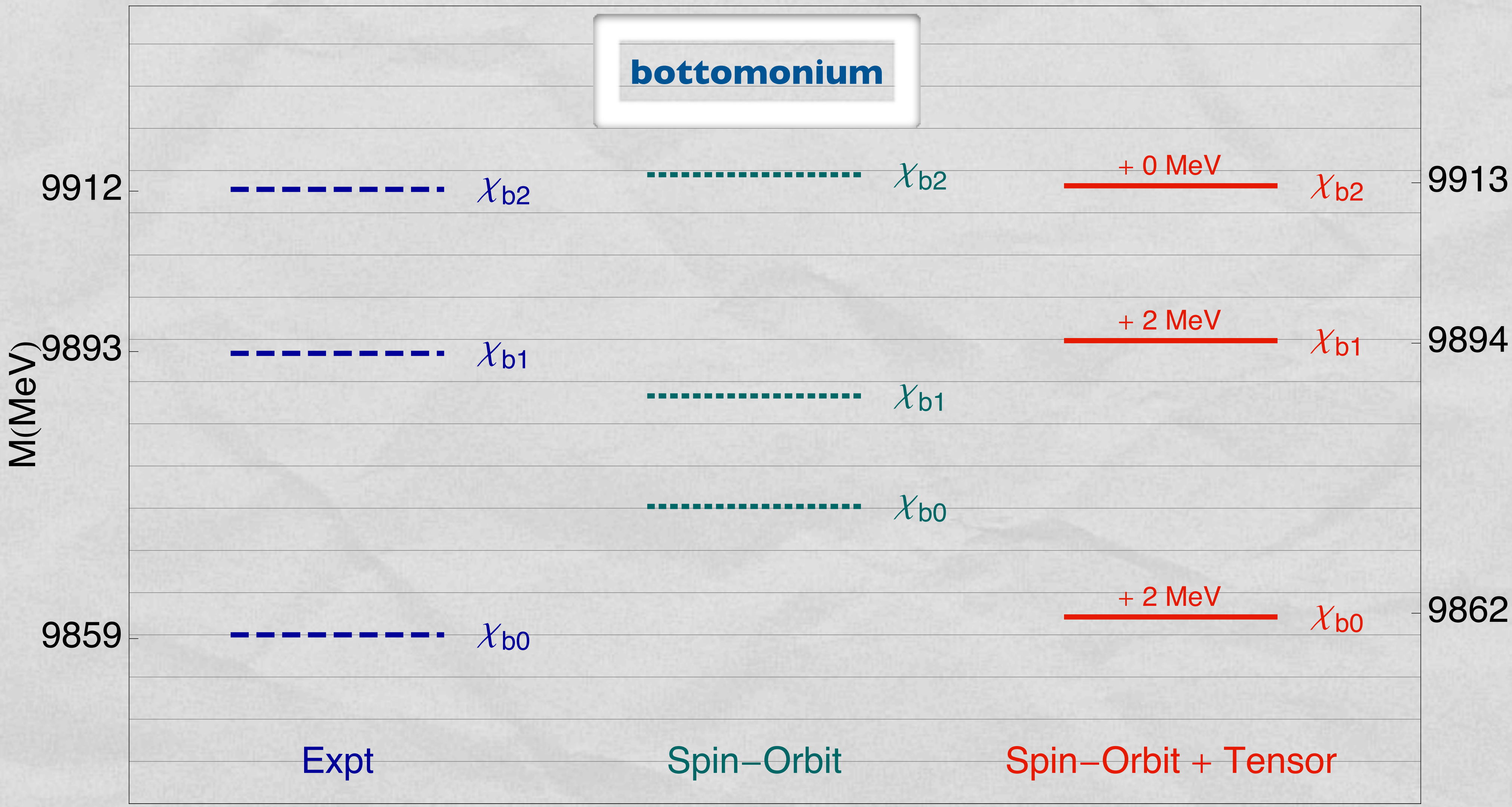


(beauty)

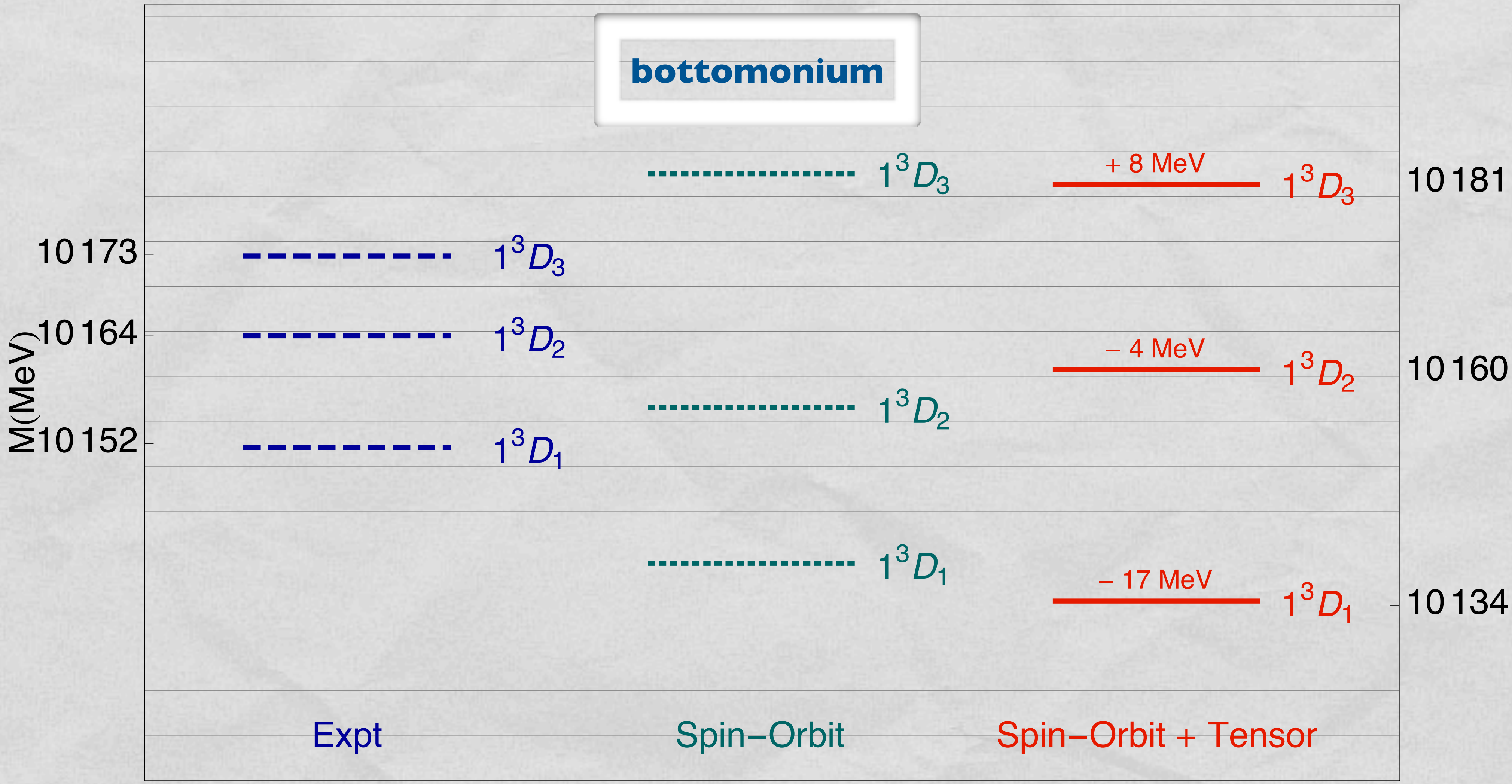
THE NEXT-TO-SIMPLEST QCD STRING

Burns, Piccinini, Polosa, Sabelli -w.i.p.-

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



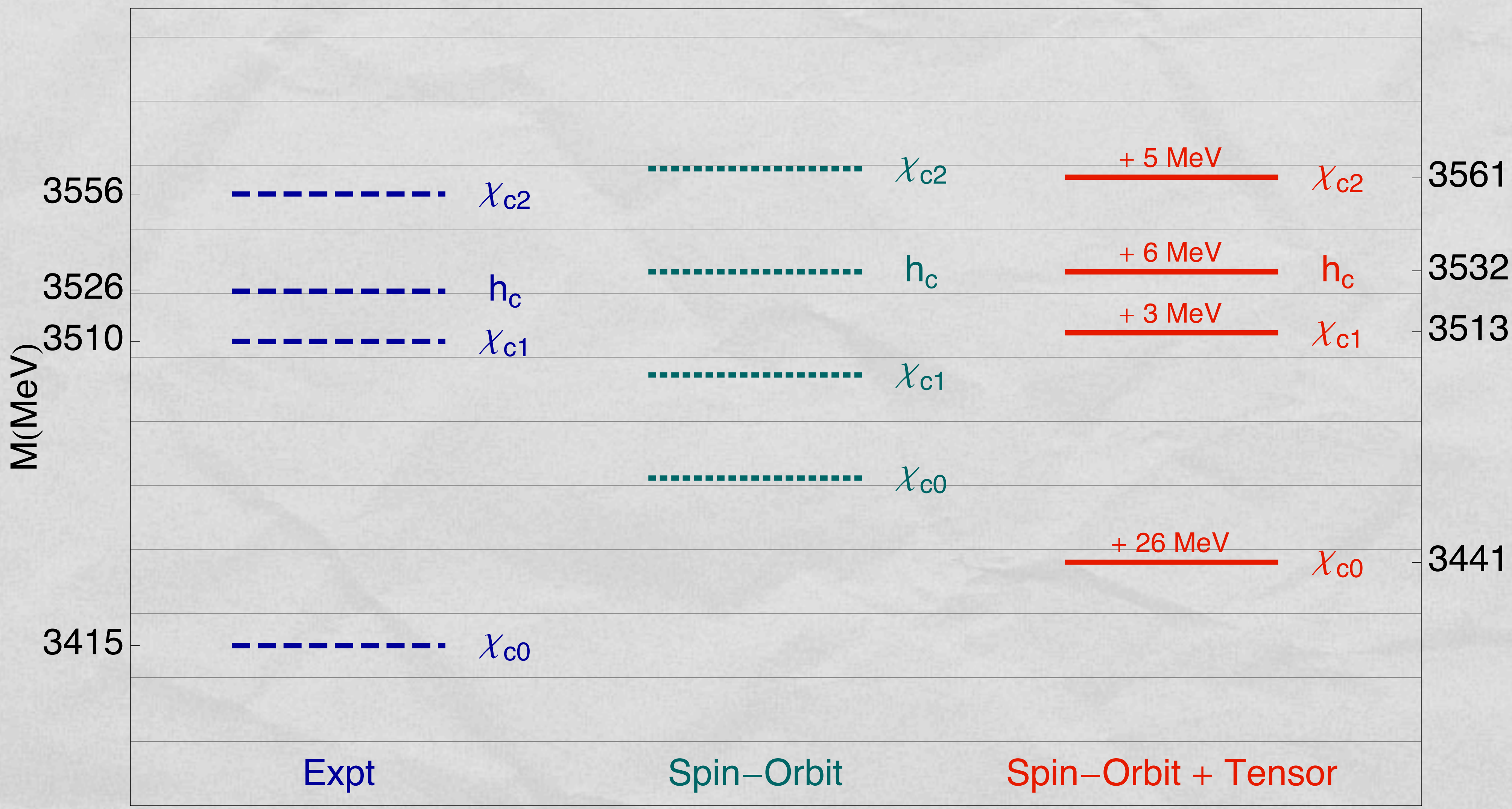
D-WAVE BOTTOMONIUM



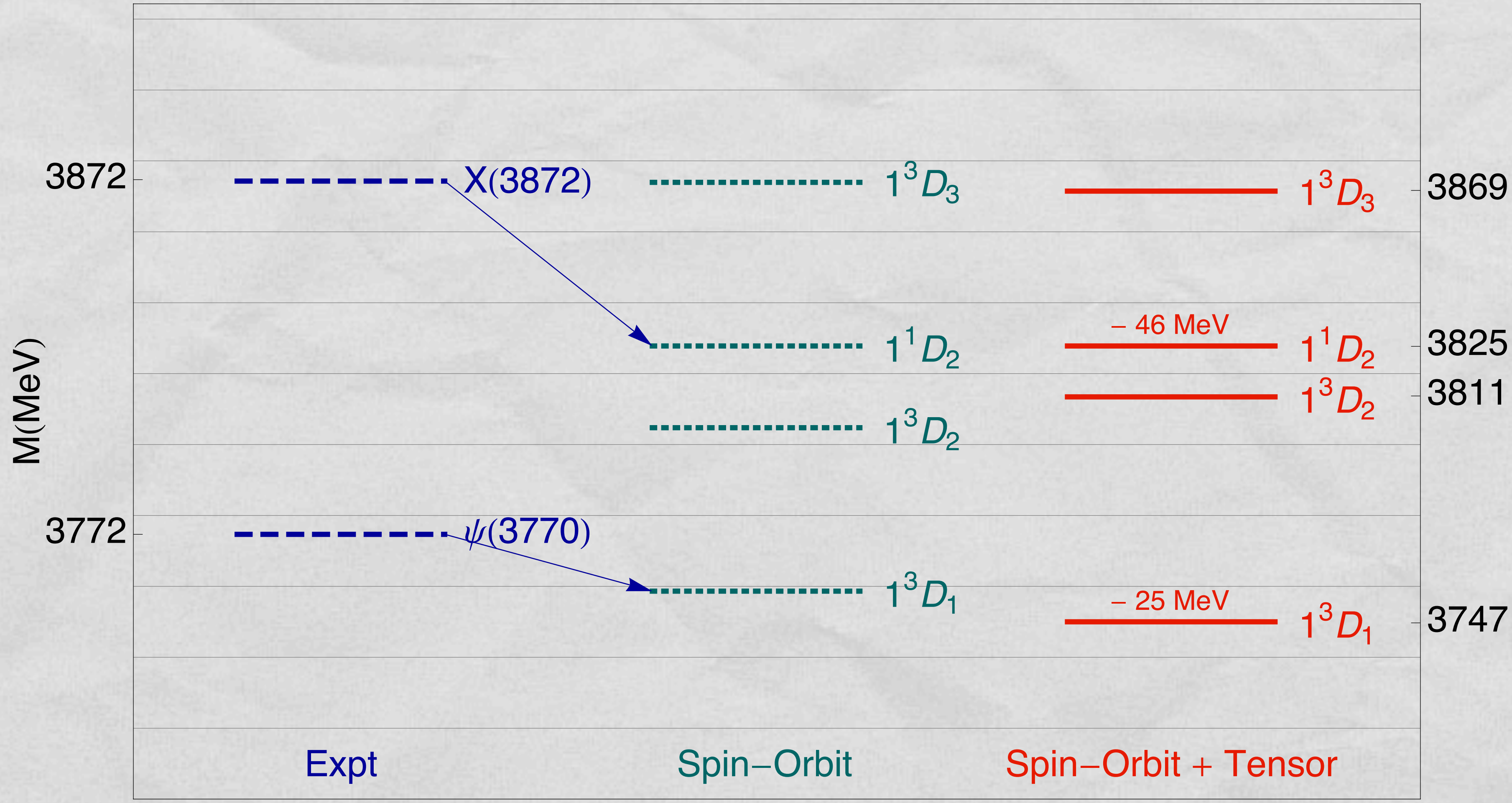
BaBar :: Moriond 2010

CHARMONIUM

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?

$J/\psi\gamma$ and $J/\psi\rho$ 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

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

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

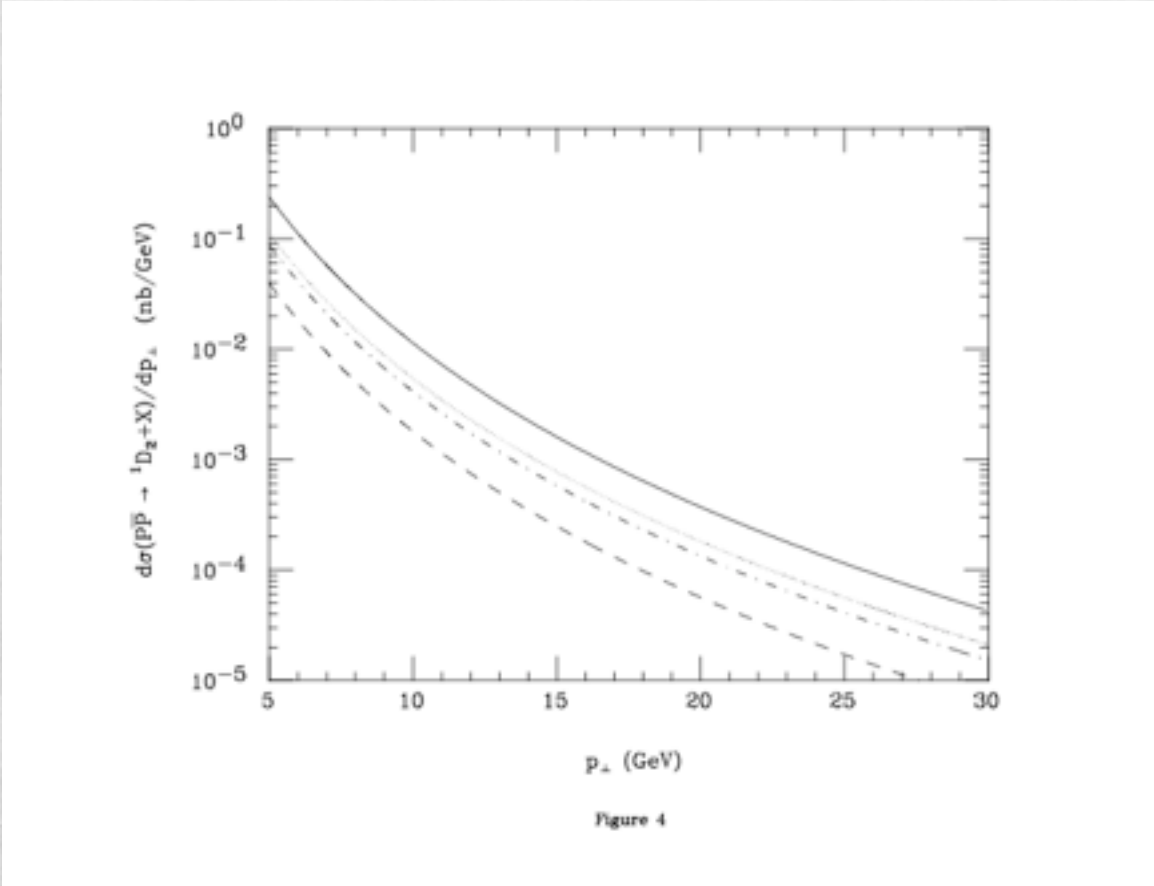
$p_\perp \gtrsim 5$ GeV

$|y| \leq 6$

factorization scale $\mu \simeq M_\perp$

Updating the pdf's we find

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



Still very small w/ respect to the prompt production at CDF (??)

OUTLOOK

- There are about 20 newly found narrow resonances resembling standard charmonia but often evading the well known charmonium features.
- Belle has observed a $Z^+(4430)$ decaying into charmonium + charged pion! This is a highly exotic state. What is it? (A Tetraquark?)
- Are we really observing hadrons with a different `body plan`? We think so.
- More urgently: is the X just D-wave charmonium?

THREE MORE (NEW) STATES

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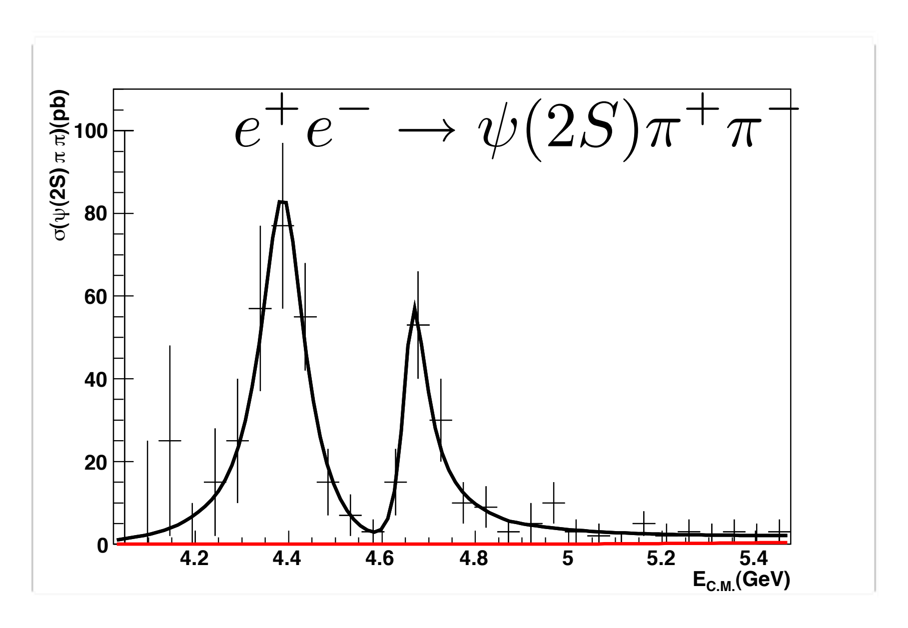
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to D\bar{D}$	Belle	$2^3P_2(c\bar{c})$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle	$3^1S_0(c\bar{c})$?
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar	$2^3P_1(c\bar{c})$?
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle	
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle	Hybrid?
$Y(4350)$	4324 ± 24	172 ± 33	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar	
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	Belle	
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle	
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^\pm(4050) \to \pi^\pm \chi_{c1}$	Belle	
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^\pm(4250) \to \pi^\pm \chi_{c1}$	Belle	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^\pm(4430) \to \pi^\pm \psi'$	Belle	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^- \Upsilon(1,2,3S)$	Belle	

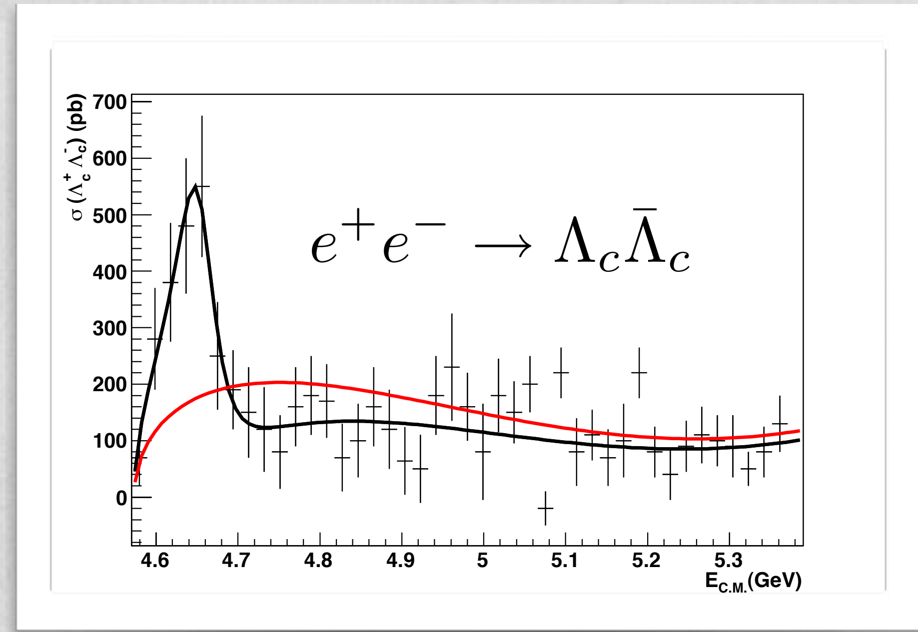
From Godfrey arXiv:0910.3409

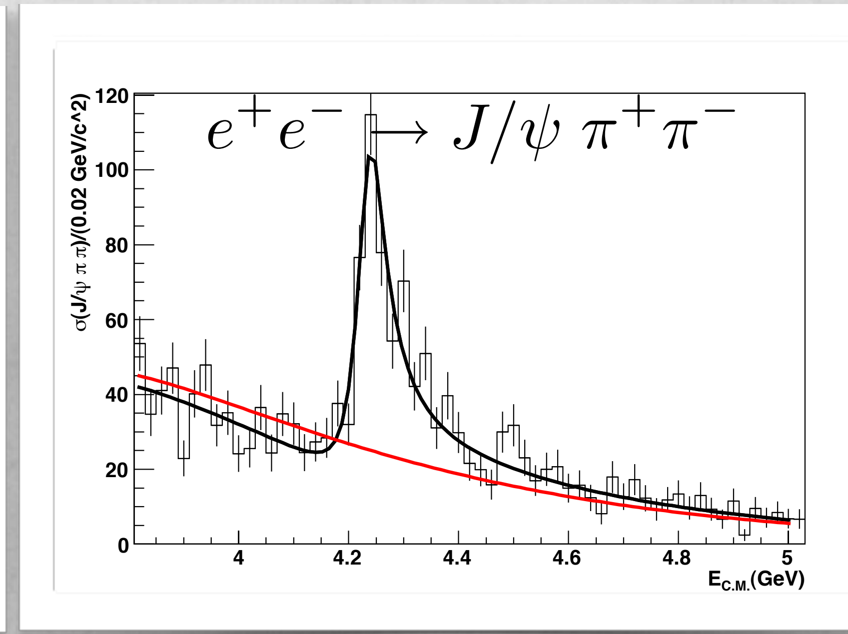
TWO ARE THE SAME: Y_B

Cotugno, Faccini, Polosa, Sabelli Phys Rev Lett 2010

We just redo the fits using Belle data under the hypothesis that Y(4660) and Y(4630) are the same (1^{--}) particle.
This hypothesis improves the fit







What we find surprising is that

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