II Workshop on Perspectives in Nonperturbative QCD

12-13 May, 2014 - São Paulo

Exotic States in Charmonium Spectroscopy

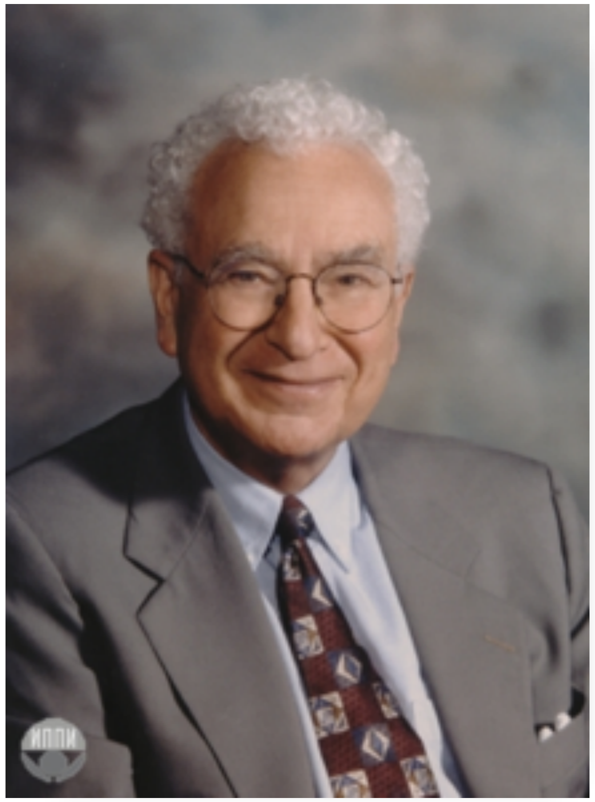
Raphael M. Albuquerque

IFT unesp

FAPESP

HADRONS

What we learned about hadronic structure with them?



Murray Gell-Mann

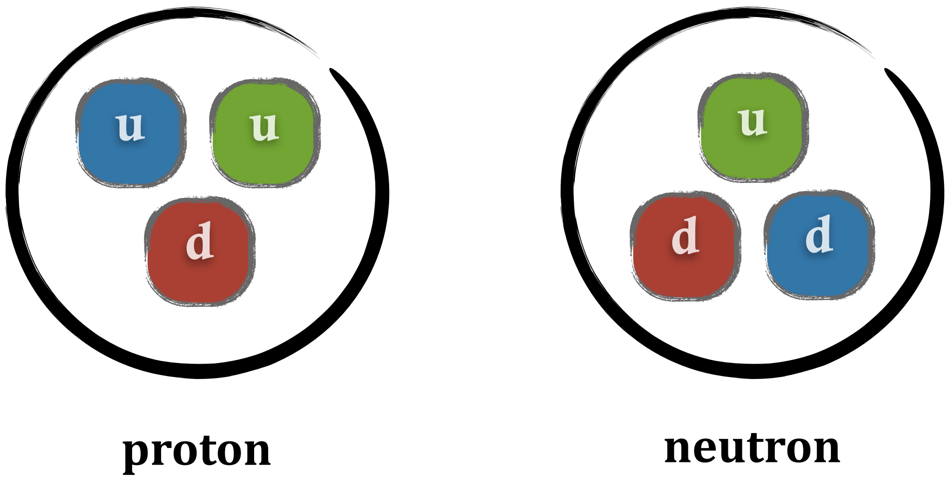
George Zweig

Introduction

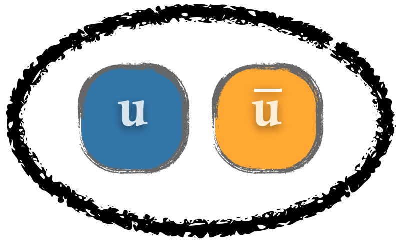
Constituent Quark Models (CQM)

- The strongly interacting particles (hadrons) have in their internal structure the so-called fundamental particles: **quarks**.

- The hadrons are formed either from three quarks (baryons):

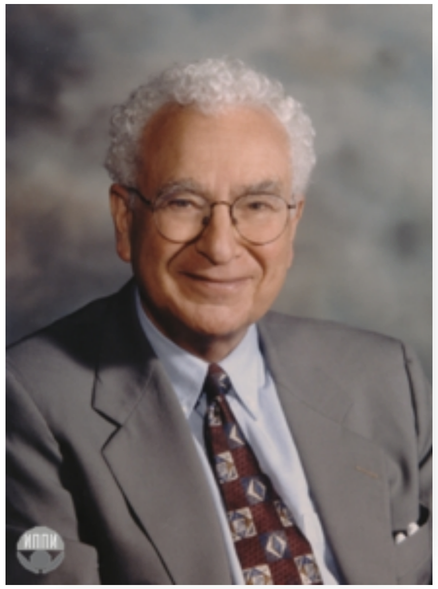


- or quark-antiquark pairs (mesons):



pion

- Only color-singlet states are observed in nature.



Murray Gell-Mann

George Zweig

Introduction

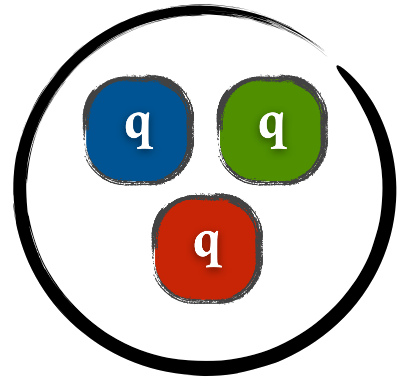
Hadrons in CQM

baryon

meson

Can we go beyond these structures?

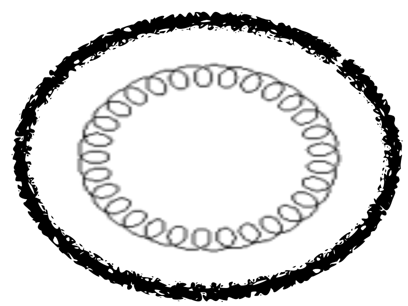
Hadrons in CQM

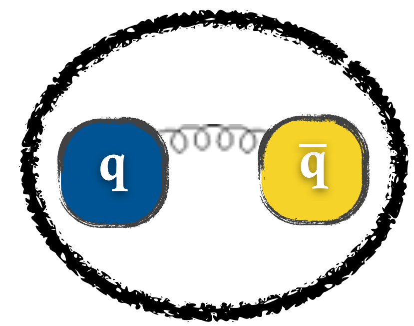


baryon

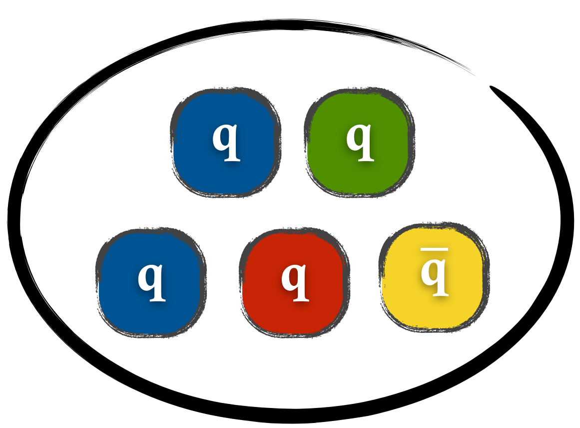
meson

Exotic Hadrons in QCD


glueballs

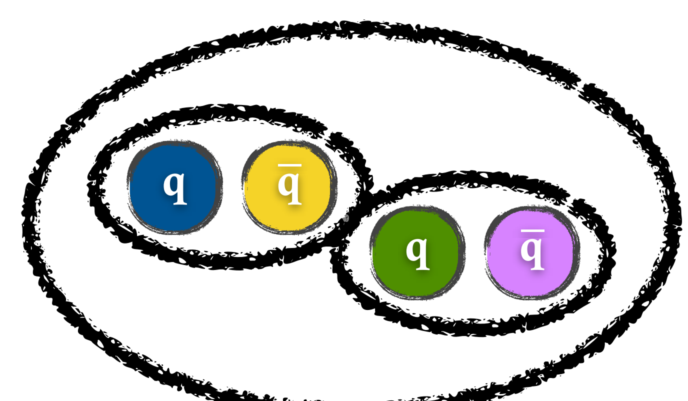


hybrids



pentaquarks

tetraquarks



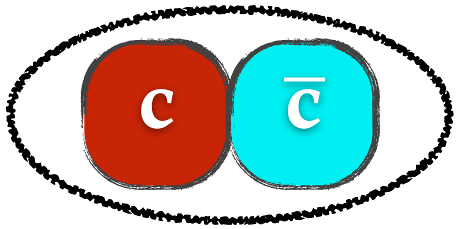
molecules

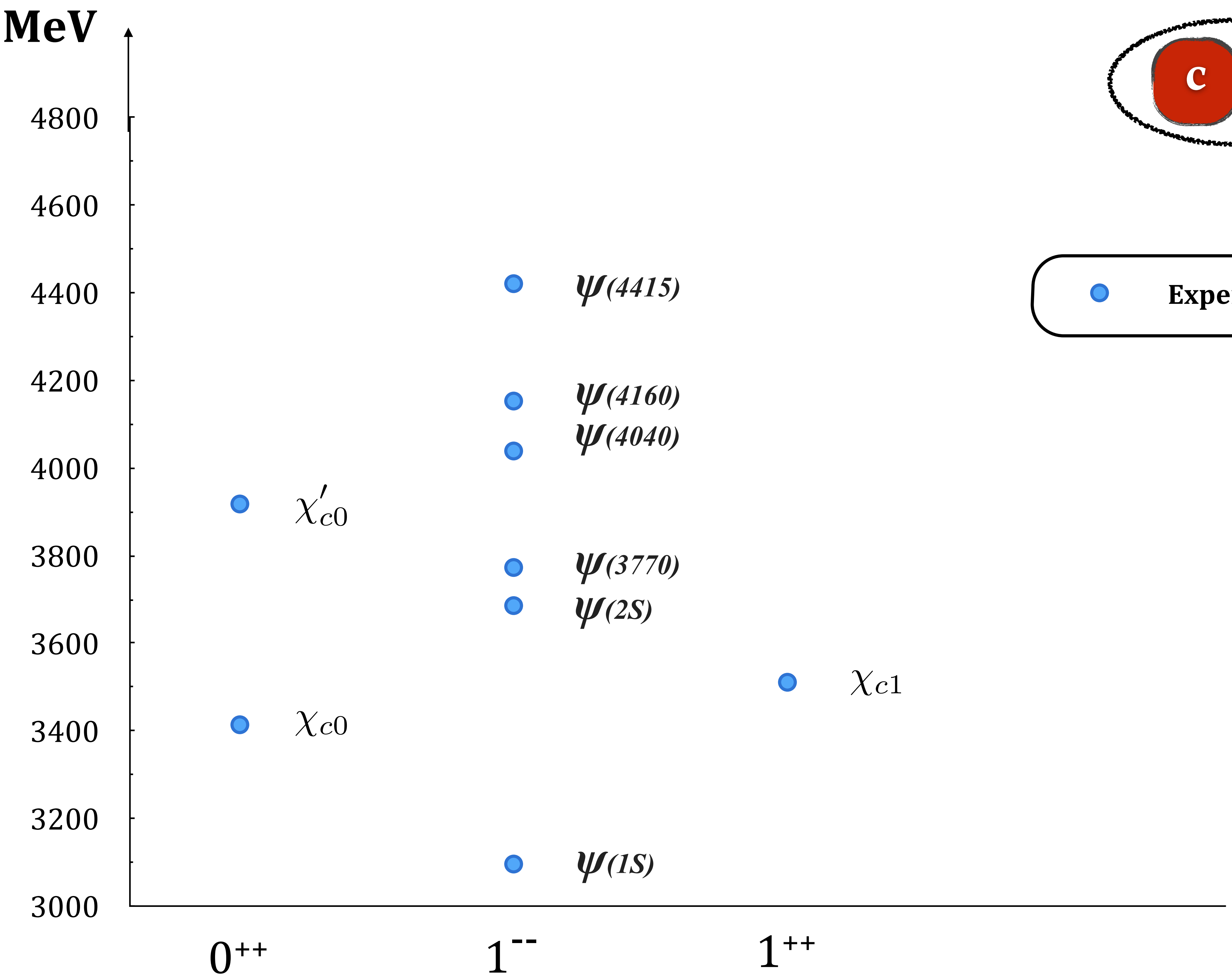
Where we could find evidences for these new hadronic structures in nature?

Where we could find evidences for these new hadronic structures in nature?

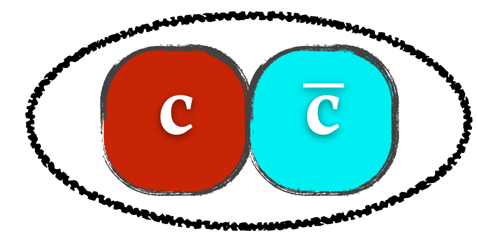
Charmonium Spectroscopy

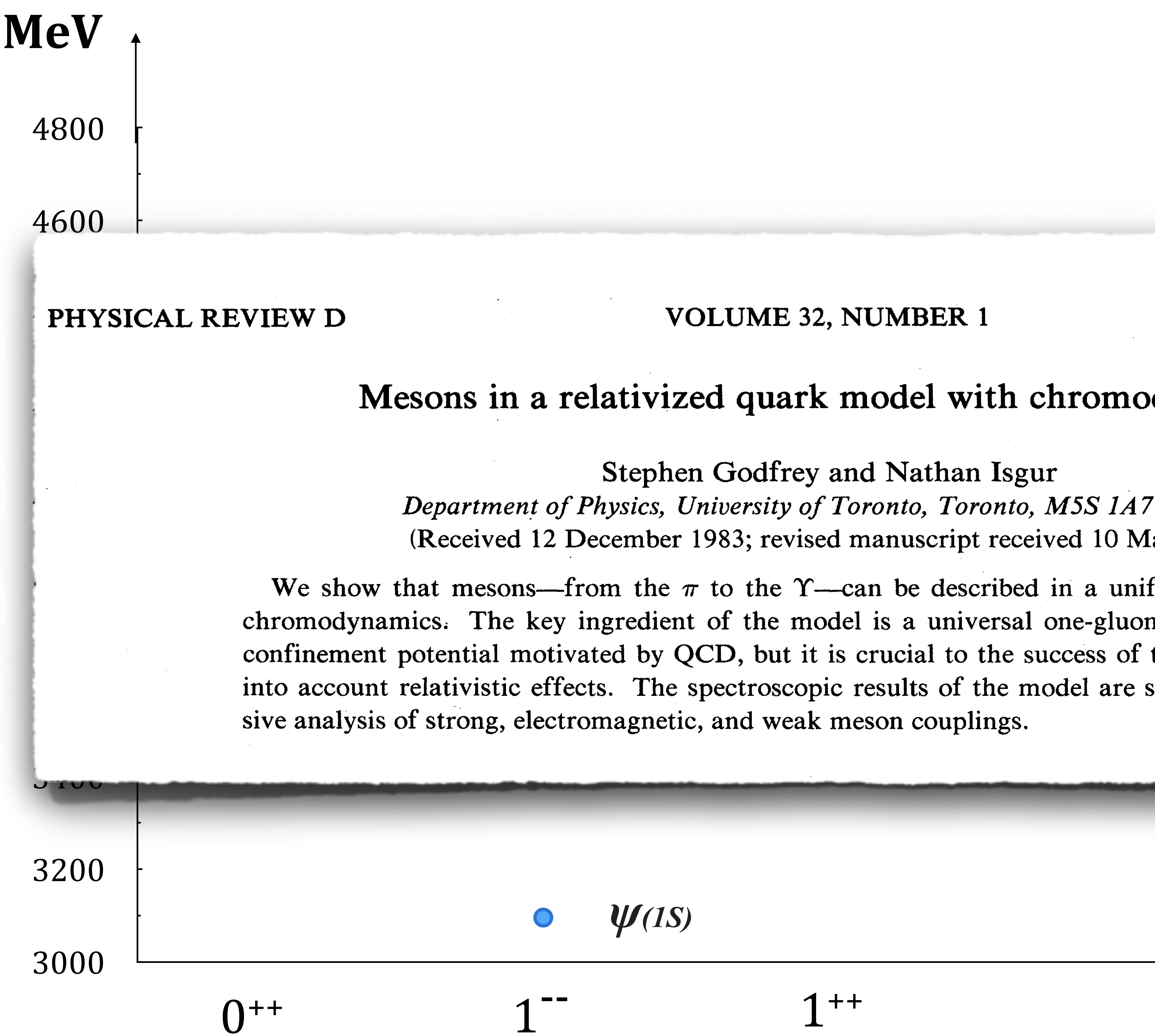
Charmonium Spectroscopy





Charmonium Spectroscopy





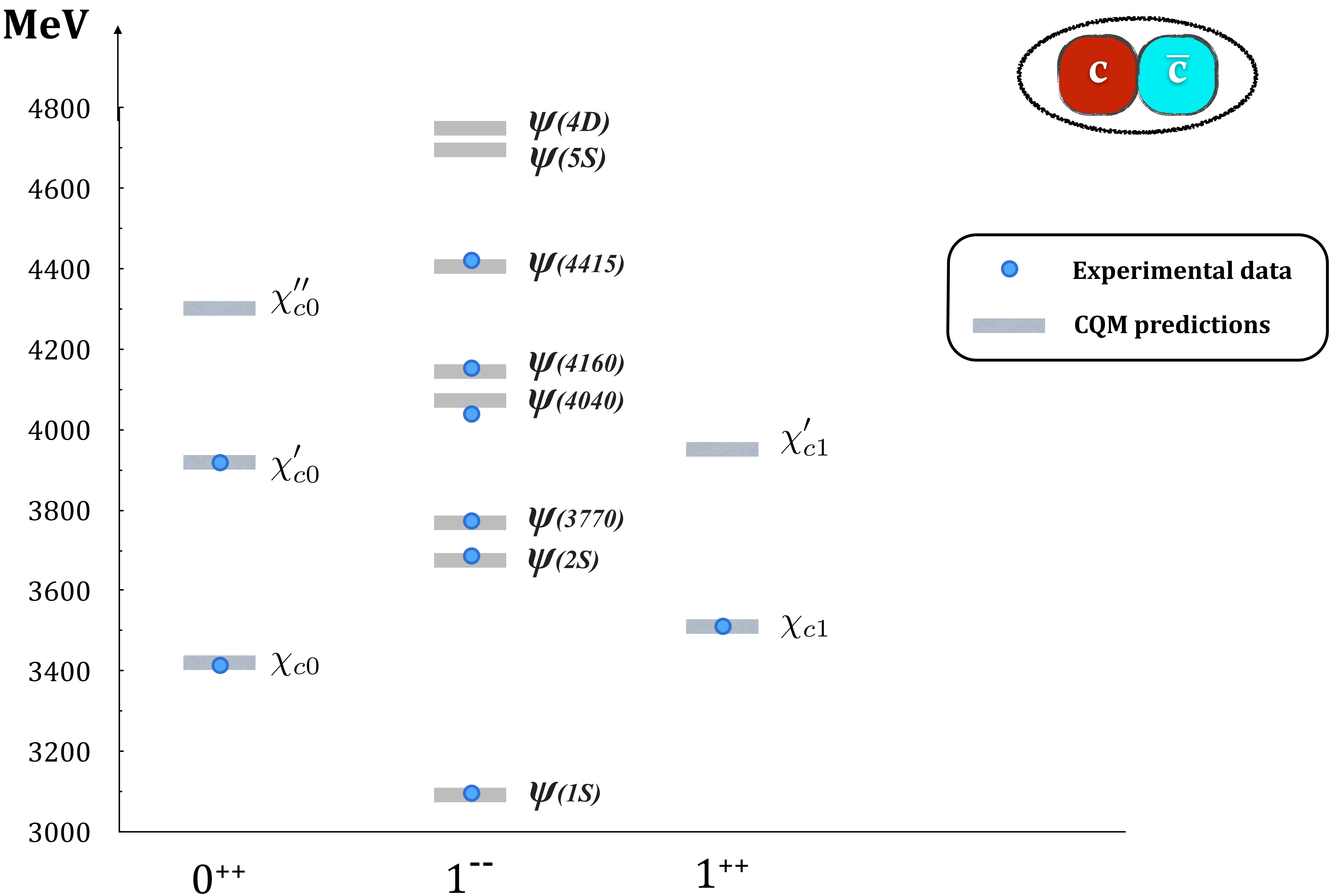
PHYSICAL REVIEW D VOLUME 32, NUMBER 1 1 JULY 1985

Mesons in a relativized quark model with chromodynamics

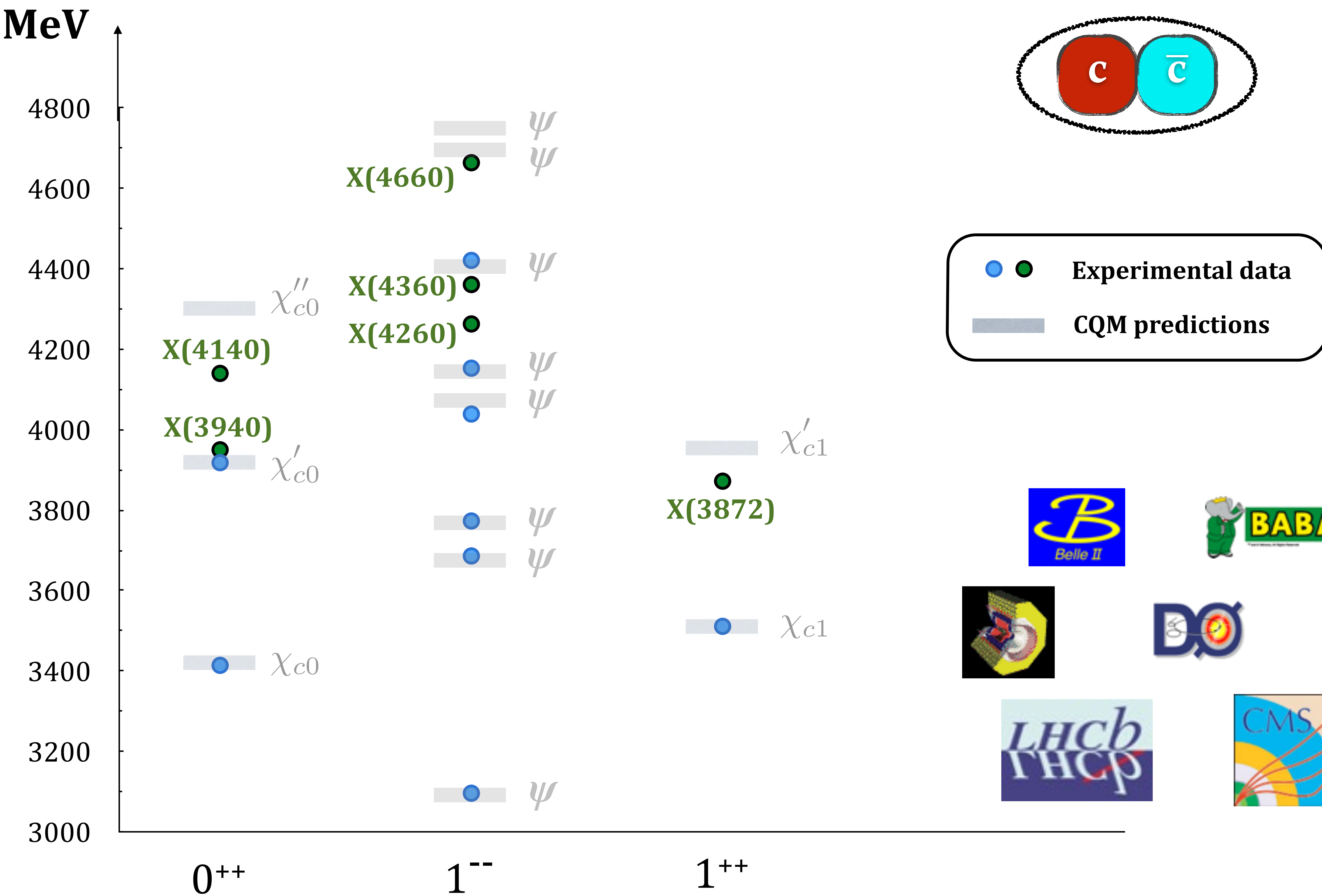
Stephen Godfrey and Nathan Isgur
Department of Physics, University of Toronto, Toronto, M5S 1A7 Canada
(Received 12 December 1983; revised manuscript received 10 May 1985)

We show that mesons—from the π to the Υ—can be described in a unified quark model with chromodynamics. The key ingredient of the model is a universal one-gluon-exchange-plus-linear-confinement potential motivated by QCD, but it is crucial to the success of the description to take into account relativistic effects. The spectroscopic results of the model are supported by an extensive analysis of strong, electromagnetic, and weak meson couplings.

Charmonium Spectroscopy

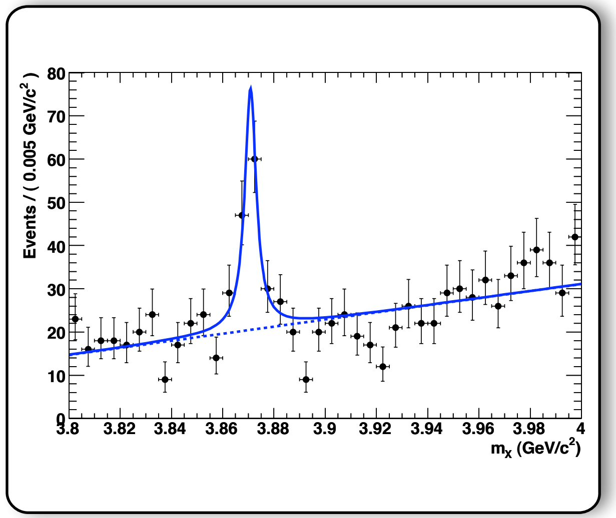


Charmonium Spectroscopy



Exotic States

X(3872)



$$M = 3871.68 \pm 0.17 \text{ MeV}$$
$$\Gamma < 1.2 \text{ MeV}$$
$$J^{PC} = 1^{++}$$

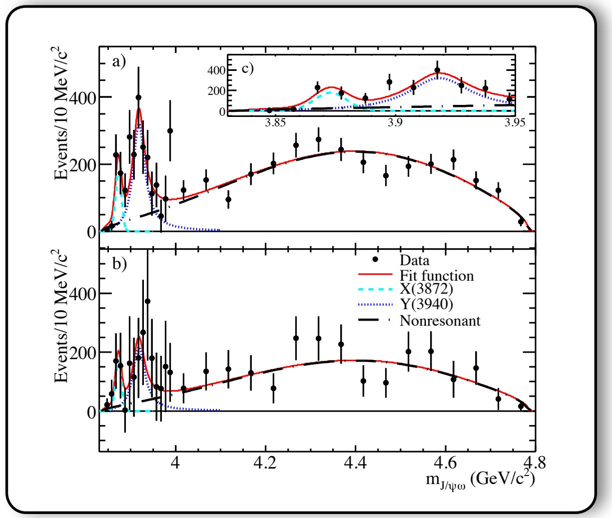
$J/\psi\,\pi^+\pi^-$ $\quad J/\psi\,\pi^+\pi^+\pi^0$

$J/\psi\,D\bar{D}\,\pi$ $\quad \gamma\gamma$

$J/\psi\,D\bar{D}\,\pi$ $\quad J/\psi\,\gamma$

$\vdots$

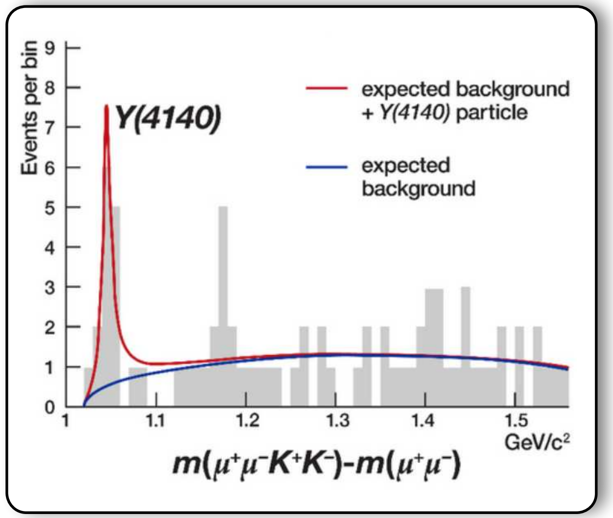
Y(3940)



$$M = 3919 \pm 4 \text{ MeV}$$
$$\Gamma = 31 \pm 10 \text{ MeV}$$
$$J^{PC} = 0^{++}$$

$J/\psi\,\omega$

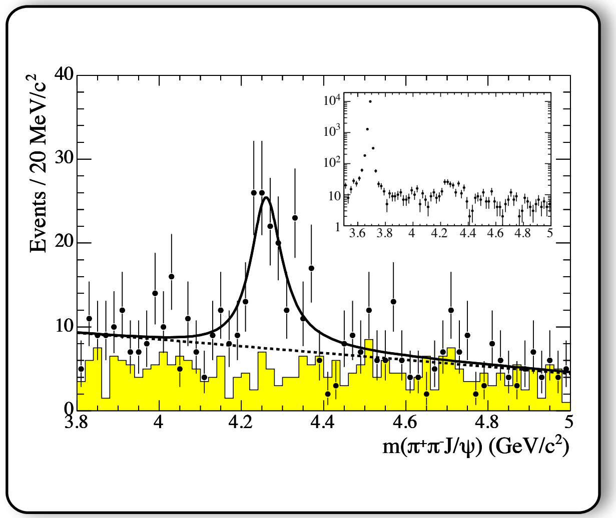
Y(4140)



$$M = 4143 \pm 3 \text{ MeV}$$
$$\Gamma = 12 \pm 8 \text{ MeV}$$
$$J^{PC} = 0^{++}$$

$J/\psi\,\phi$

X(4260)



$$M = 4250 \pm 9 \text{ MeV}$$
$$\Gamma = 108 \pm 12 \text{ MeV}$$
$$J^{PC} = 1^{--}$$

$J/\psi\,\pi^+\pi^-$ $\quad J/\psi\,\pi^0\pi^0$

$J/\psi\,f_0(980)$ $\quad J/\psi\,K^+K^-$

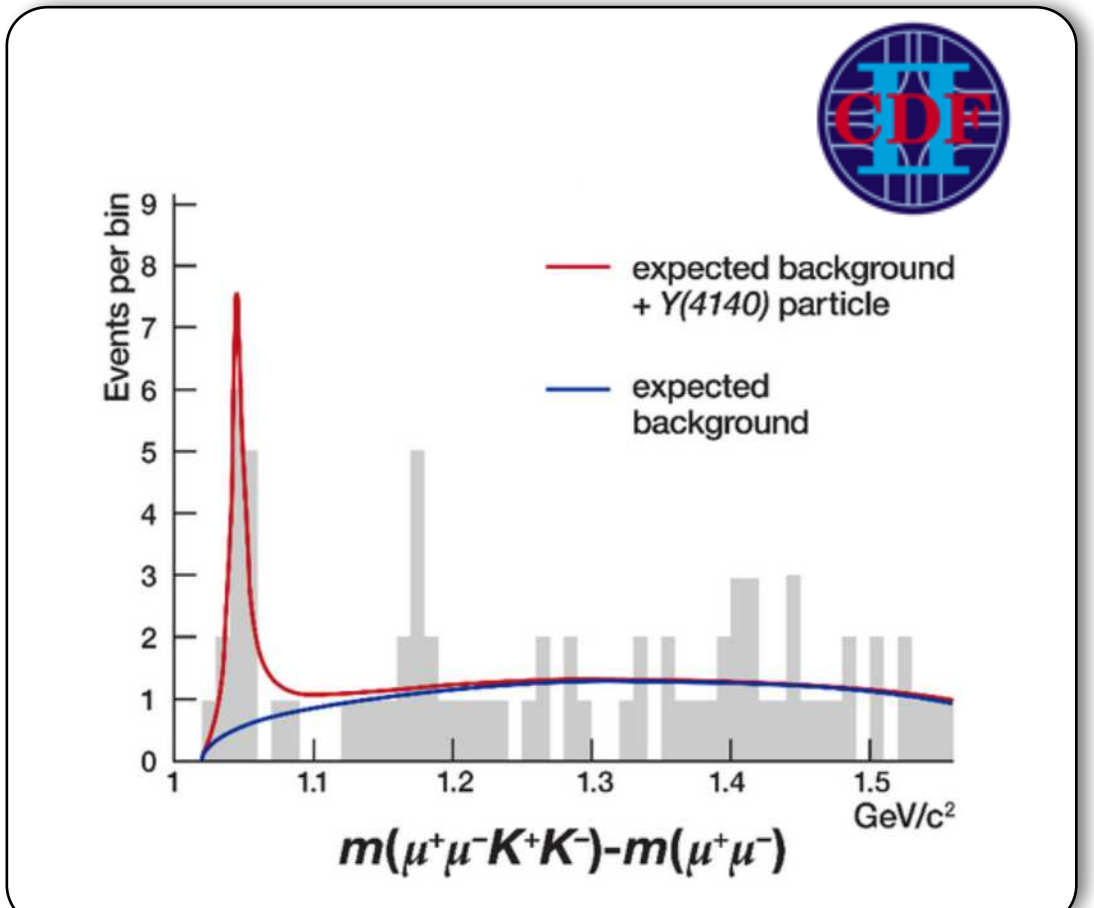
Strong evidences for the existence of Four-quark States!

Y(4140)

- In 2009, CDF collaboration announces the first observation of this possible exotic state.

$$Y \rightarrow J/\psi\, \phi$$

$$J^{PC} = ?^{?+}$$



Y(4140)

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- Afterwards, Belle collab. searched for this state in two photons collision and found no evidence of the Y(4140) signal.

$$\gamma\gamma \to J/\psi\, \phi$$

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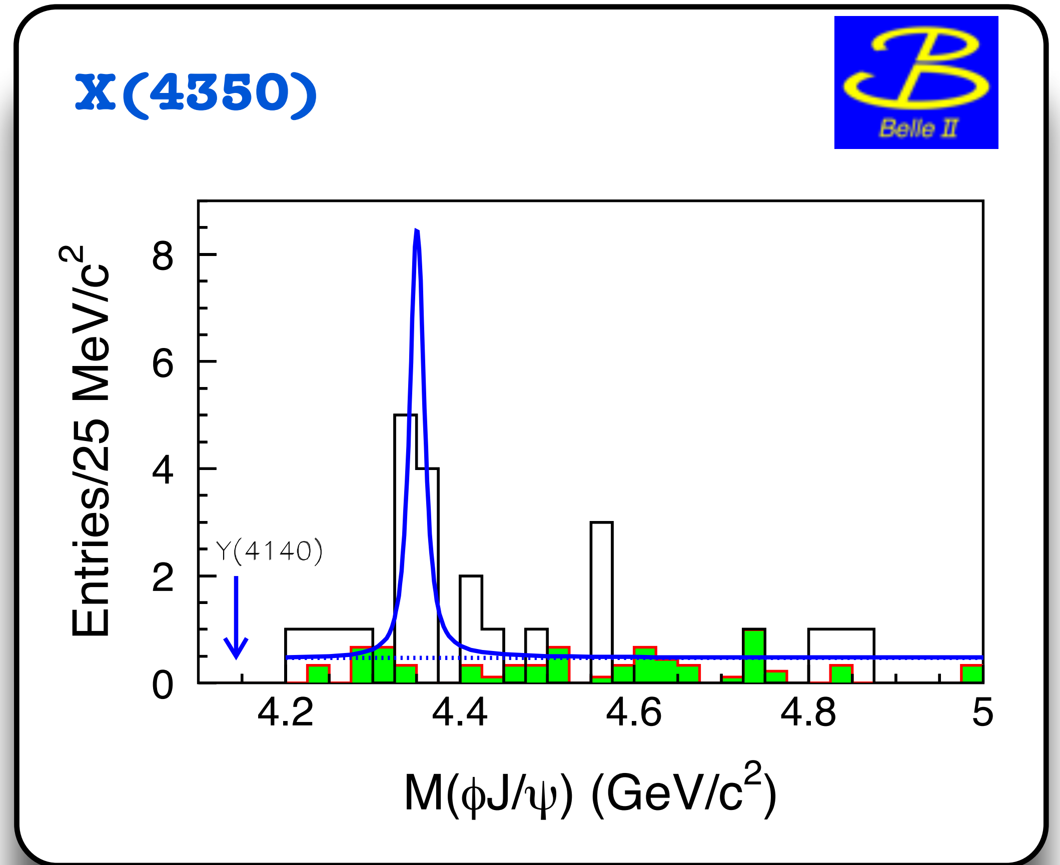

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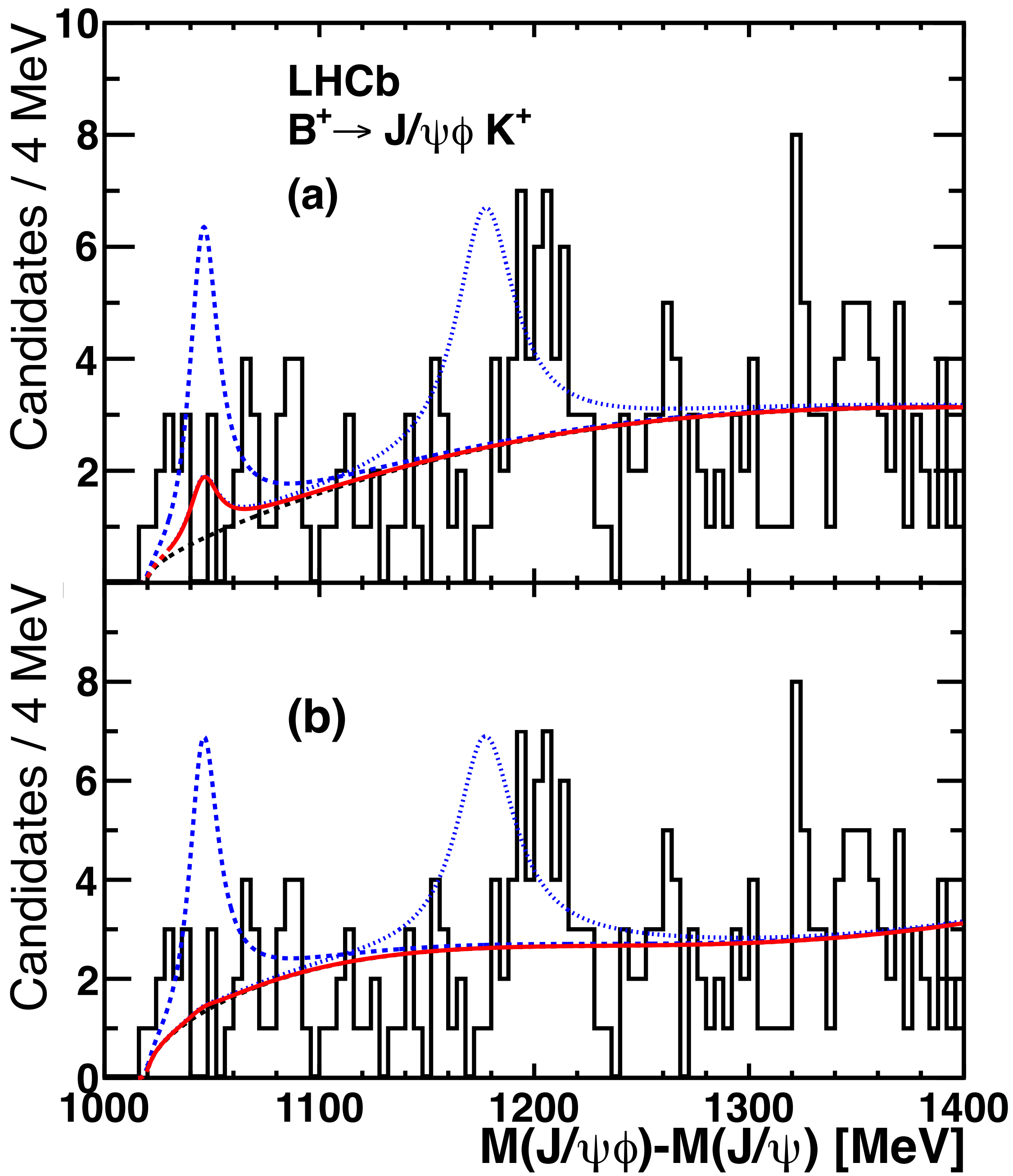
- In 2012, LHCb collab. announced new searches for the Y(4140) state which disfavored the experimental data obtained by CDF.
  The Y(4140) could no longer exists.



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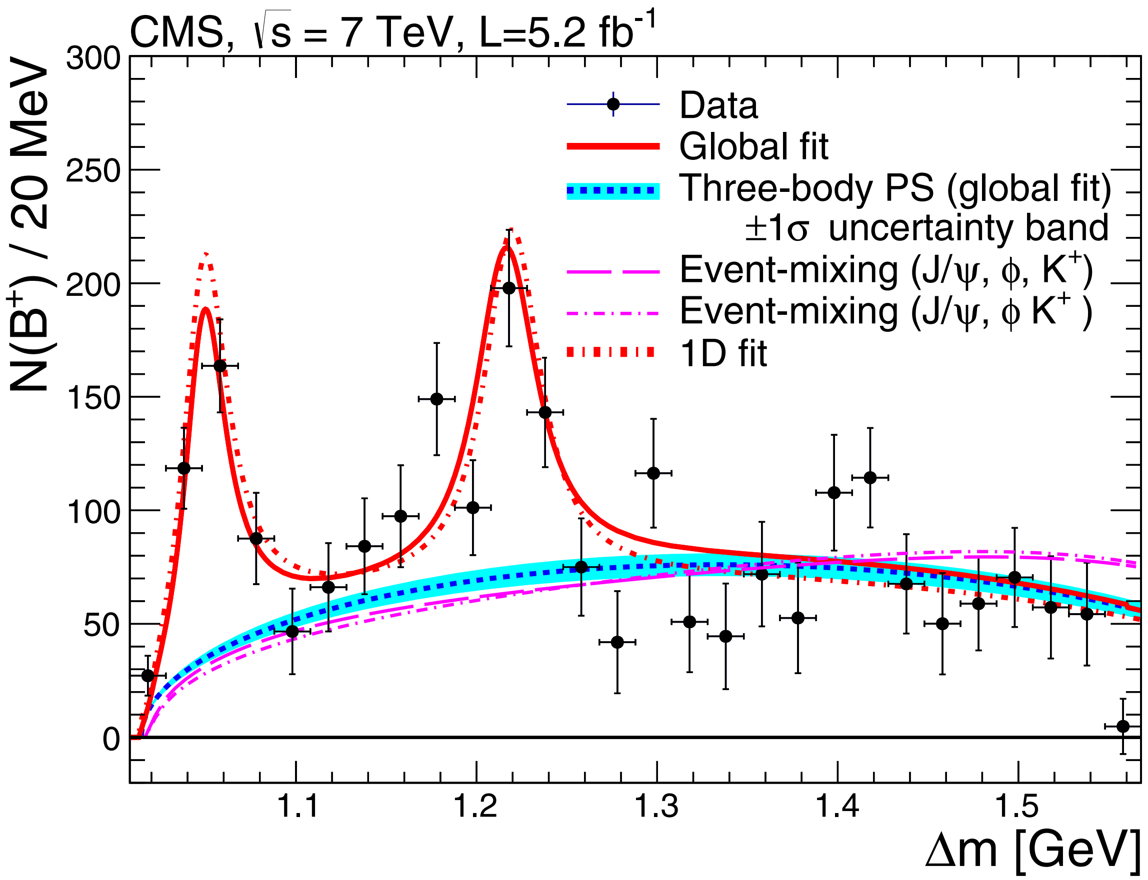
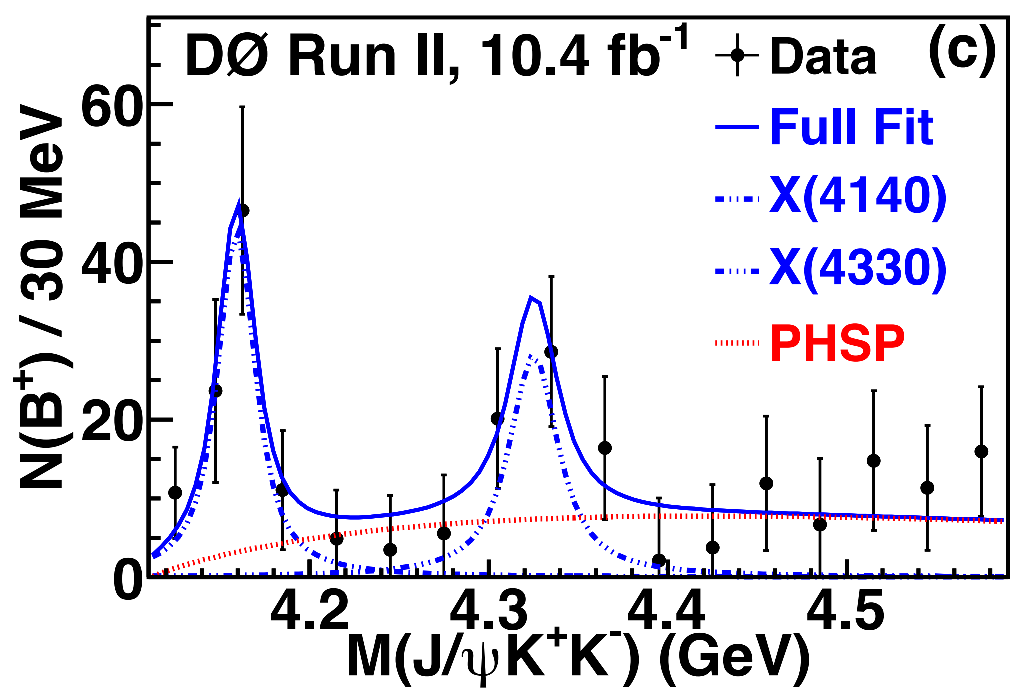
  The Y(4140) could no longer exists.
- However, new 2013 experimental findings from CMS and D0 support the CDF data and consequently the existence of the Y(4140) signal.





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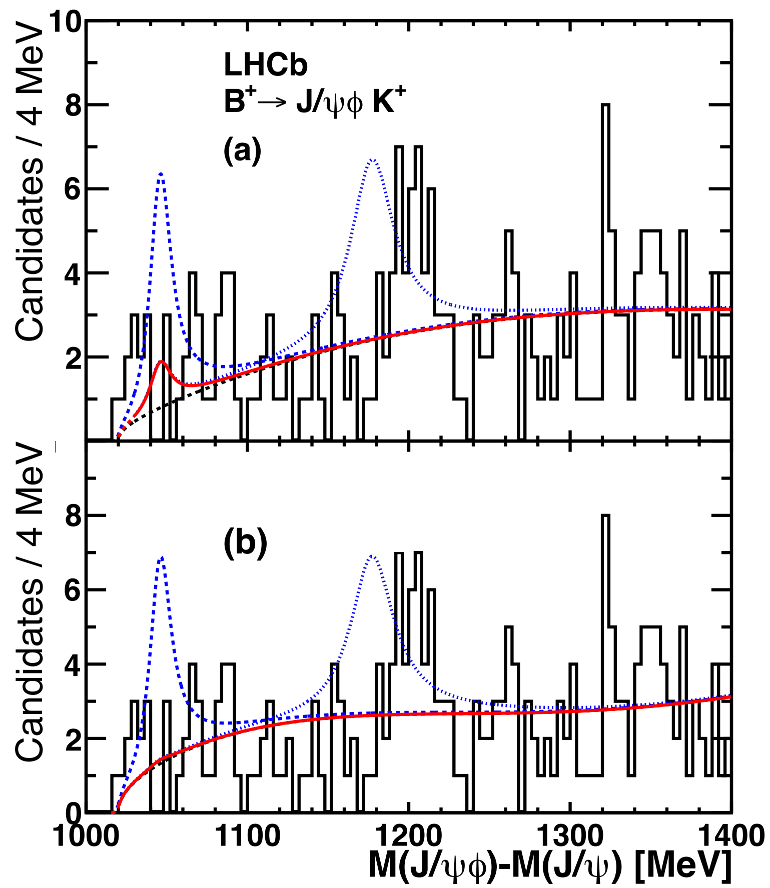
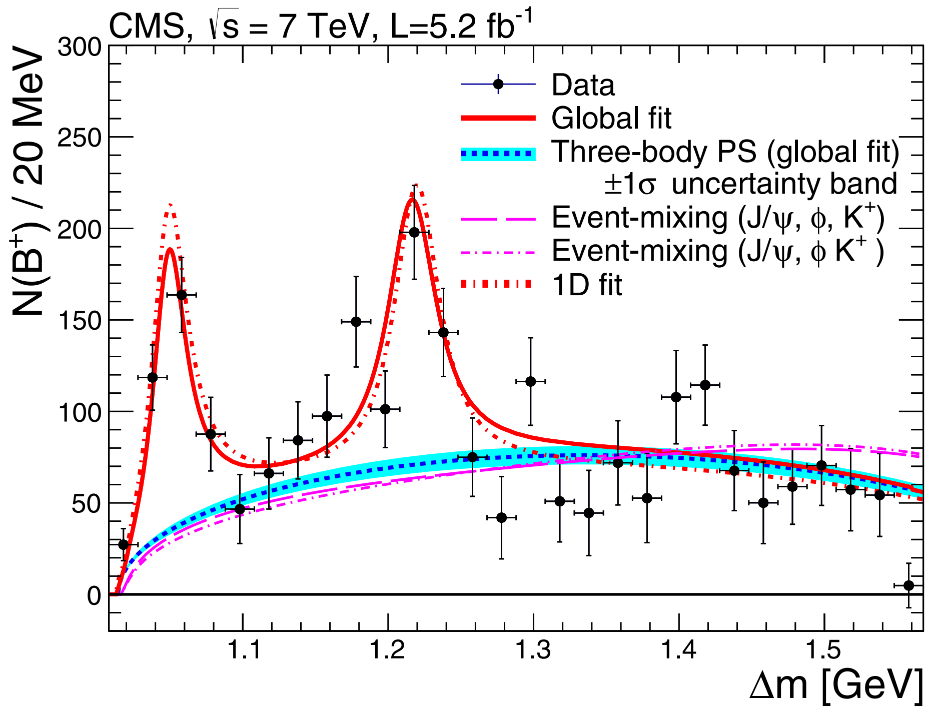
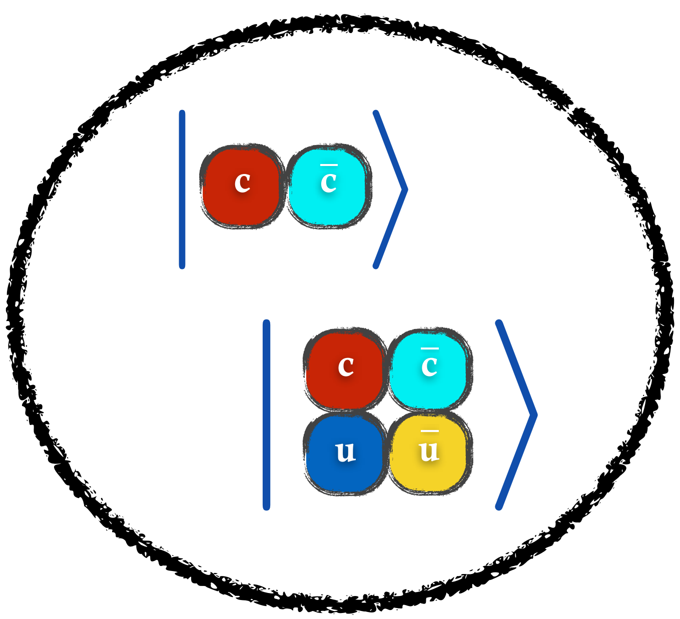
  The Y(4140) could no longer exists.
- However, new 2013 experimental findings from CMS and D0 support the CDF data and consequently the existence of the Y(4140) signal.
- Future experimental data can clarify this intriguing discrepancy between the LHCb and CMS data.





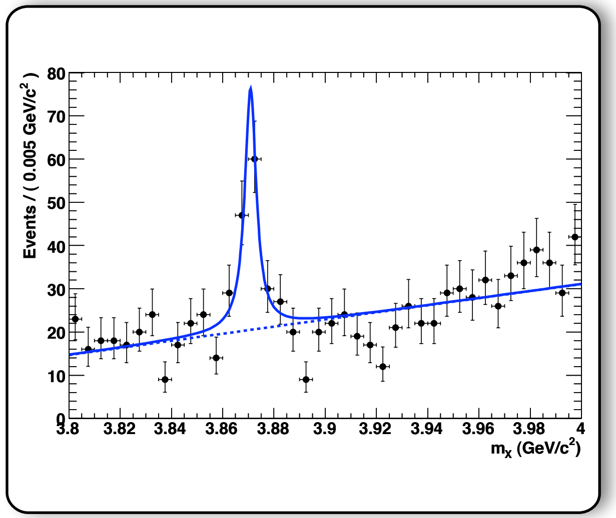
Among the possible exotic structures which one could better explain the experimental data?

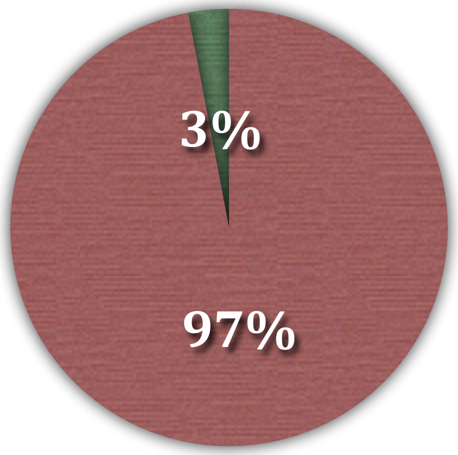
Admixture of
Charmonium and **Four-quark** states



Exotic States

X(3872)

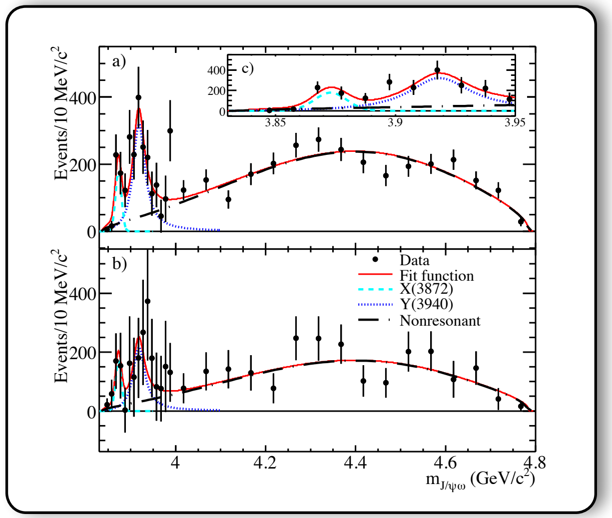


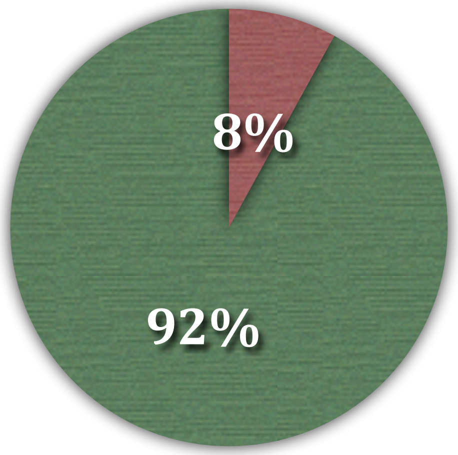


$$|c\bar{c}\rangle \oplus |D\bar{D}^*\rangle$$

PRD 80 (2009)
Matheus, Navarra, Nielsen, Zanetti

Y(3940)

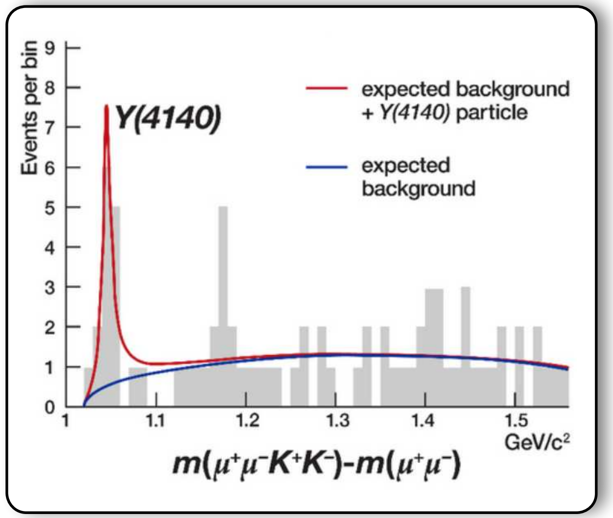




$$|c\bar{c}\rangle \oplus |D^*\bar{D}^*\rangle$$

PRD 89 (2014)
Albuquerque, Dias, Nielsen, Zanetti

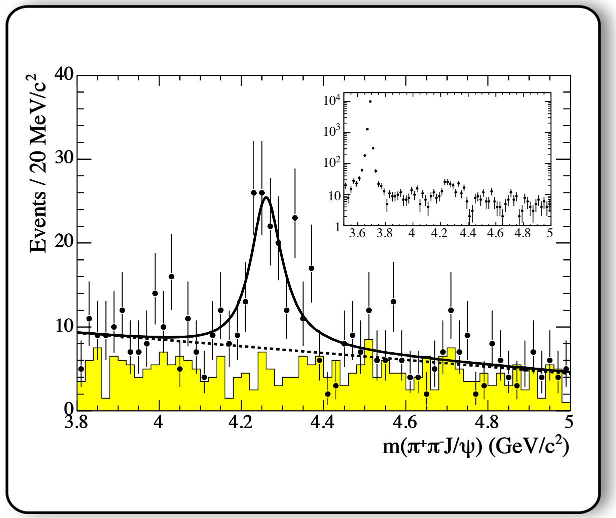
Y(4140)

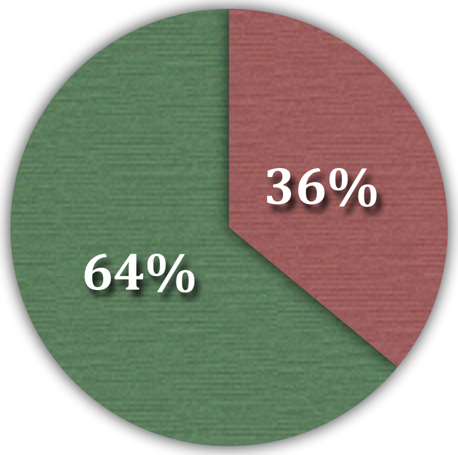


$$|D_s^*\bar{D}_s^*\rangle$$

PLB 678 (2009)
Albuquerque, Bracco, Nielsen

X(4260)

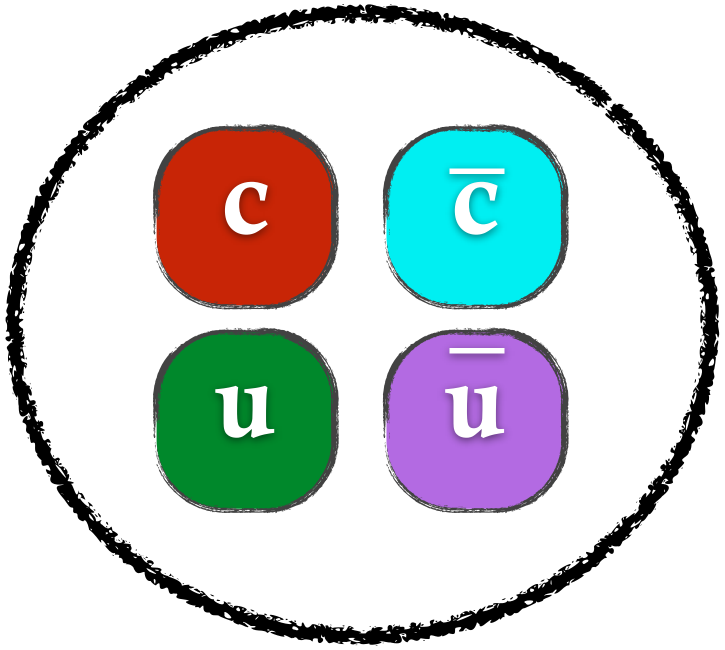




$$|c\bar{c}\rangle \oplus |cq\bar{c}\bar{q}\rangle$$

PRD 86 (2012)
Albuquerque, Dias, Nielsen, Zanetti

Four-quark neutral states



could provide explanations for ...

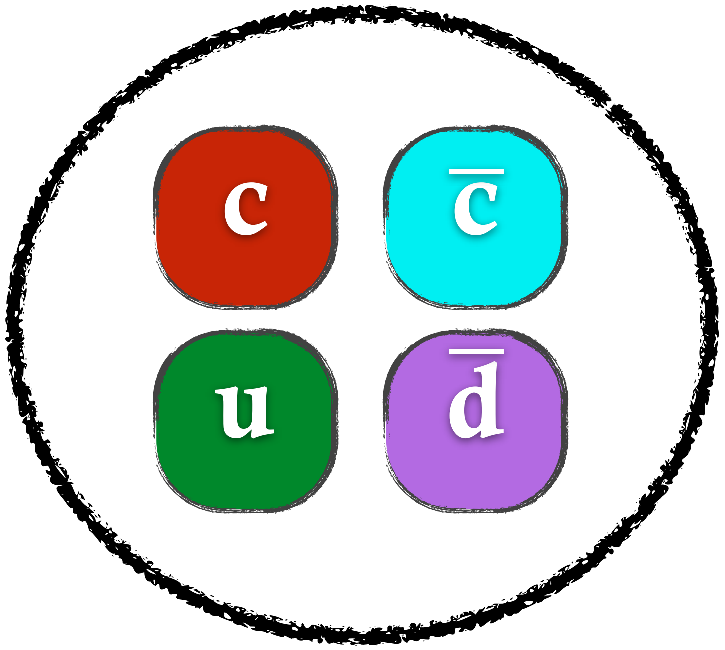
- the new states observed in the charmonium spectra
- the dominant decays into $J/\psi + (\pi, \rho, \omega, \dots)$
- in some cases, the absence of open-charm decay channels
- charmonia decays with a strong isospin violation, e.g.

$$\frac{\mathcal{B}\left[X(3872) \to J/\psi\, \pi^+\pi^-\pi^0\right]}{\mathcal{B}\left[X(3872) \to J/\psi\, \pi^+\pi^-\right]} \sim 1$$

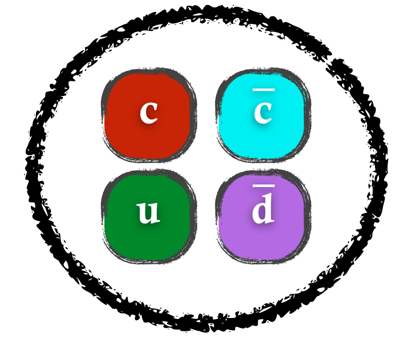
Exotic States

However, evidence of an exotic particle can be established unambiguously by detection of the so-called

Four-quark charged states



$\mathbf{Z(4430)^+}$



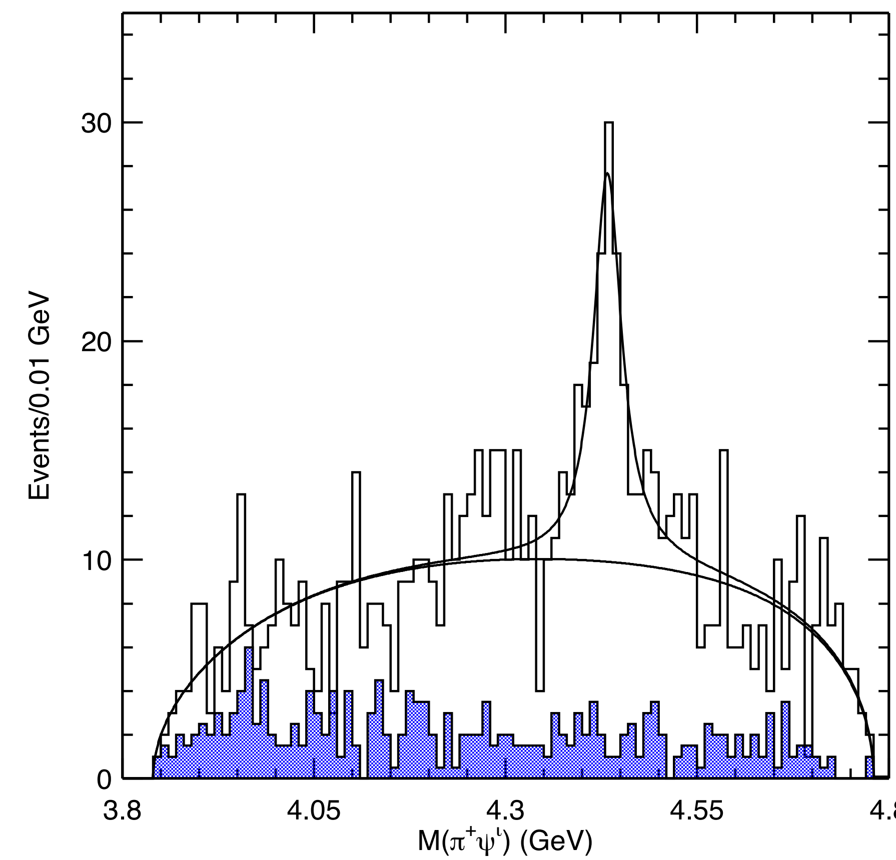
Threshold effects in the $D_1 D^*$ channel
J.L. Rosner, PRD 76, 114002 (2007)

Four-quark radial excitation with $J^{PC} = 1^{+-}$
L. Maiani, A.D. Polosa & V. Riquer, arXiv:0708.3997

Radial excitation of $\Lambda_c - \Sigma_c^0$ bound state
C-F. Qiao, J.Phys. G 35, 075008 (2008)

$D_1 D^*$ molecular state in QCD sum rules
Lee, Mihara, Navarra & Nielsen, PLB 661 (2008)

Tetraquark states with $J^P = 0^-$ or 1^-
Bracco, Lee, Nielsen & Silva, PLB 671 (2009)



Belle II: PRL 100, 142001 (2008)

BABAR: PRD 80, 031104 (2009)

No conclusive evidence for a particle in the signal seen by Belle Collaboration.

Exotic States

arXiv: 1404.1903

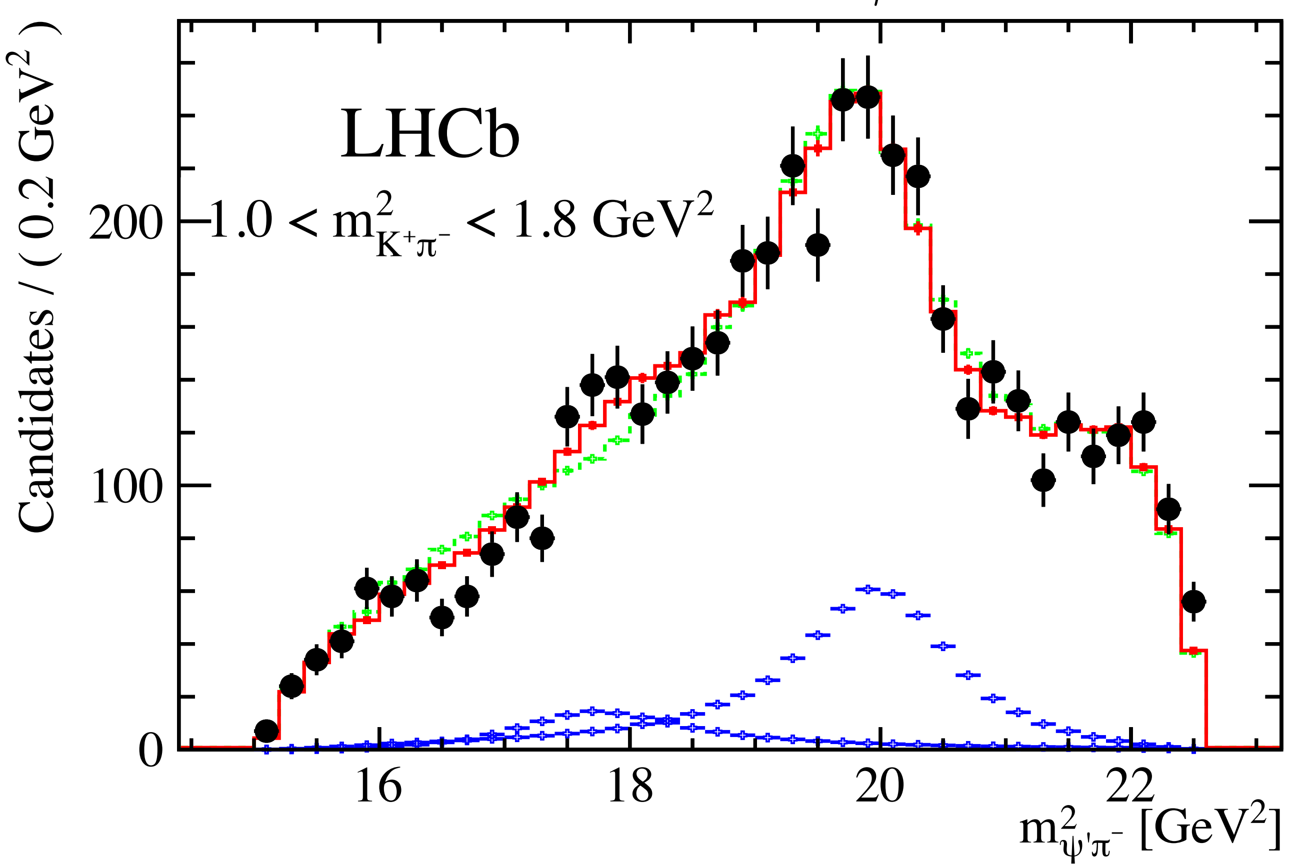
CERN-PH-EP-2014-061
LHCb-PAPER-2014-014
7 April 2014

Observation of the resonant character of the $Z(4430)^-$ state

The LHCb collaboration†

unambiguous observation of an exotic particle

$$B^+ \to K^+ \, \psi' \, \pi^-$$



- first independent confirmation of the $Z(4430)^-$ resonance.
- significance $> 15\sigma$.
- $J^P = 1^+$
- the minimal quark content of such a particle is $c\bar{c}d\bar{u}$.

Once established the existence of new states in charmonium spectroscopy, how can we study them?

QCD-BASED MODEL

QCD Sum Rules

Nuclear Physics B147 (1979) 385–447

QCD AND RESONANCE PHYSICS. THEORETICAL FOUNDATIONS

M.A. SHIFMAN, A.I. VAINSHTEIN * and V.I. ZAKHAROV
Institute of Theoretical and Experimental Physics, Moscow, 117259, USSR

Received 24 July 1978

QCDSR

- **more than 4000 citations!**
- among the all-time top cited papers in HEP.

- **Correlation Functions**

$$\Pi_{\mu\nu}(q) = i \int d^4x \, e^{iq\cdot x} \langle 0 | T[j_\mu(x) j_\nu^\dagger(0)] | 0 \rangle$$

- **Principle of duality quark-hadron**
  - The fundamental assumption in the sum rule is that the correlation function can be evaluated in two ways:
  - **OPE side:** quark and gluon fields, Wilson OPE, condensates, ...
  - **Phenomenological side:** complete set of intermediate states, hadronic fields
  - Thus, the hadronic parameters are obtained comparing both descriptions of the correlation function.

QCD Sum Rules

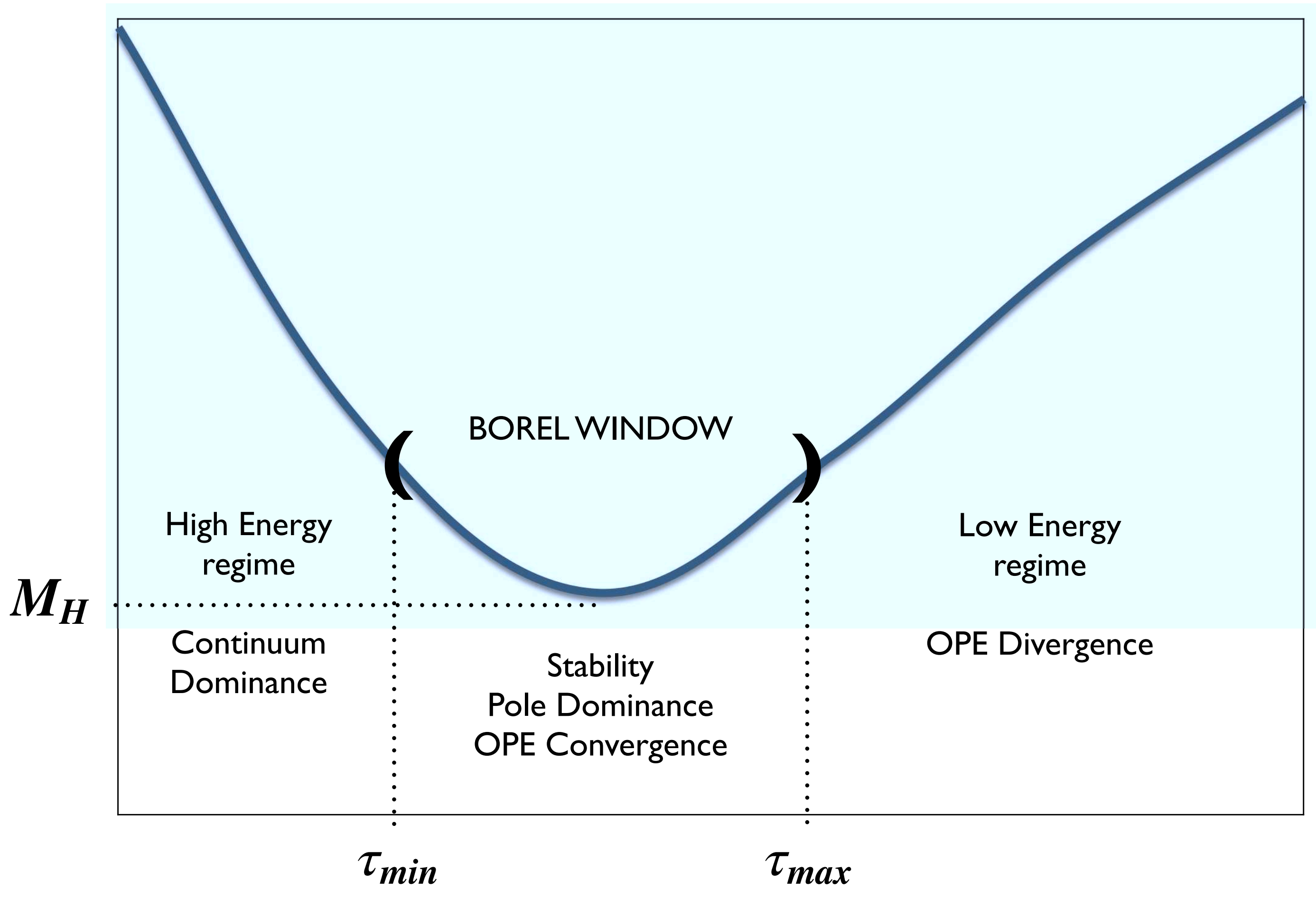
- **Optimal tuning of QCDSR parameters**

  ❖ A reliable sum rule implies that we can establish a region in the Borel parameter, such that we have:

  ❖ **Good OPE convergence**

  ❖ **Pole dominance over the continuum contributions**

  ❖ **Good Borel stability**



X(4260) state

X(4260)

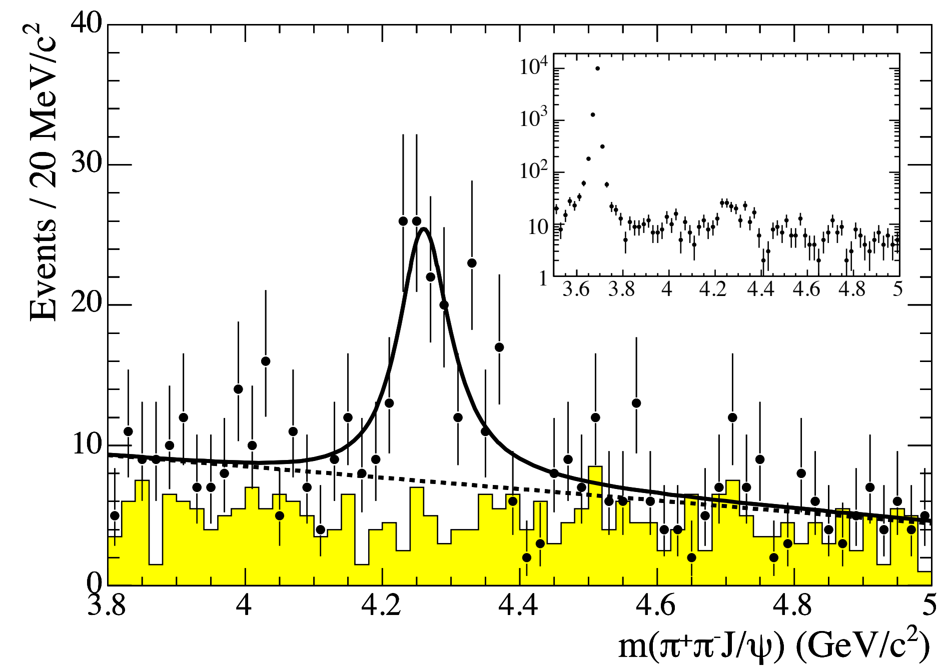
- seen in the ISR process with E$_{cm}$ $\sqrt{s} \sim 10.6\ \mathrm{GeV}$
- decay channel: $e^+ e^- \longrightarrow \gamma_{ISR}\, Y(4260) \longrightarrow \gamma_{ISR}\, J/\psi\, \pi^+ \pi^-$
- Significance $> 10\sigma$.
- PDG:

$$
\begin{aligned}
M &= 4263 \pm 9\ \ \mathrm{MeV} \\
\Gamma &= 95 \pm 14\,\mathrm{MeV} \\
J^{PC} &= (1^{--})
\end{aligned}
$$

- $J/\psi\, \pi\pi$ decay mode is unusual for a conventional charmonium.

PRL 95 (2005)

BABAR



also confirmed by

CLEO Collab, PRD 74 (2006)

Belle Collab, PRL 99 (2007)

X(4260)

- **Tetraquark:** Maiani *et al,* PRD 72. Albuquerque *et al* , NPA 815
- **Molecules:**

  D_1D, D_0D^* - Ding, PRD 79 (2009)

  $\chi_{c1}\,\omega$: Yuan, Wang, Mo, PLB 634 (2006)

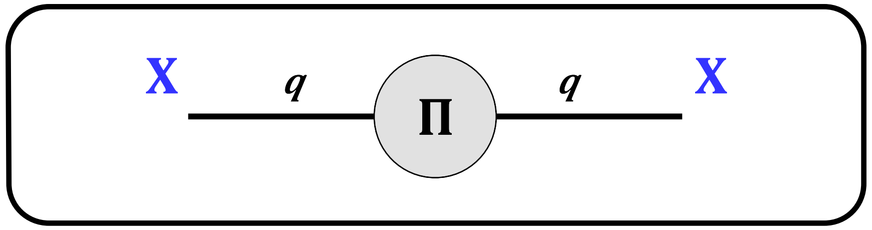
  $\chi_{c1}\,\rho$: Liu, Zeng & Li, PRD 72 (2005)

  $J/\psi\ f_0$: Oset et al, PRD 80. Albuquerque *et al, PRD 84 (2011)*

- **Hybrids:** Zhu, PLB 625 (2005)
- **ψ(4S):** Llanes-Estrada, PRD 72 (2005)
- **Charmonium-Tetraquark:** Albuquerque *et al, PRD 86 (2012)*

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**



$$\left(J^{PC} = 1^{--}\right)$$

$$\Pi_{\mu\nu}(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|\, T[\, j_\mu^X(x) j_\nu^{X\dagger}(0)\,]\,|0\rangle$$

$$j_\mu^X = \sin\theta\, j_\mu^{\mathbf{4}} + a\cos\theta\, j_\mu^{\psi}$$

$$j_\mu^{\mathbf{4}} = \frac{\epsilon_{abc}\,\epsilon_{dec}}{\sqrt{2}}\left[\left(\boldsymbol{q}_a^T\, C\gamma_5\, \boldsymbol{c}_b\right)\left(\bar{\boldsymbol{q}}_d\, \gamma_\mu\gamma_5 C\, \bar{\boldsymbol{c}}_e^T\right) + \left(\boldsymbol{q}_a^T\, C\gamma_5\gamma_\mu\, \boldsymbol{c}_b\right)\left(\bar{\boldsymbol{q}}_d\, \gamma_5 C\, \bar{\boldsymbol{c}}_e^T\right)\right]$$

$$j_\mu^{\psi} = \bar{\boldsymbol{c}}_a\gamma_\mu\boldsymbol{c}_a$$

$$\Pi_{\mu\nu}^{PH} = \frac{\lambda_X^2}{M_X^2 - q^2}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) + \ldots$$

$$\Pi_{\mu\nu}^{OPE} = -g_{\mu\nu}\int_{4m_c^2}^{\infty} ds\, \frac{\rho^{OPE}(s)}{s - q^2}$$

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**

TABLE I. QCD input parameters.

Parameters	Values
$\bar{m}_c$	$(1.23 - 1.47)$ GeV
$\langle\bar{q}q\rangle$	$-(0.23 \pm 0.03)^3$ GeV^3
$\langle g_s^2 G^2\rangle$	(0.88 ± 0.25) GeV^4
$\langle g_s^3 G^3\rangle$	(0.58 ± 0.18)GeV^6
$m_0^2 \equiv \langle\bar{q}Gq\rangle/\langle\bar{q}q\rangle$	(0.8 ± 0.1) GeV^2
$\rho \equiv \langle\bar{q}q\bar{q}q\rangle/\langle\bar{q}q\rangle^2$	$(0.5 - 2.0)$

One calculates the sum rule at leading order in α_S in the operators and considers the contributions from the condensates up to dimension eight in the OPE

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**

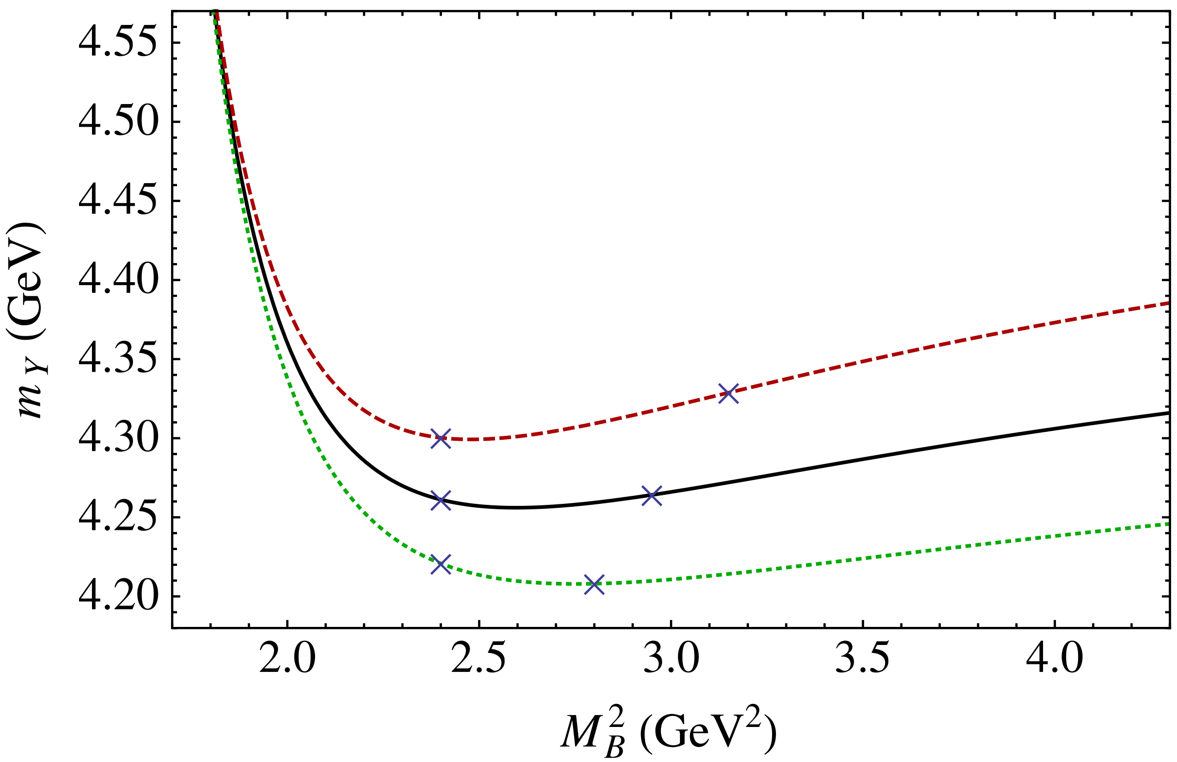
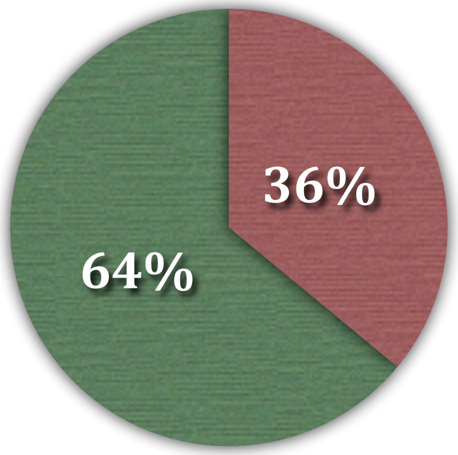


FIG. 3 (color online). The mass as a function of the sum rule parameter M_B^2 for $\sqrt{s_0} = 4.60$ GeV (dotted line), $\sqrt{s_0} = 4.70$ GeV (solid line), $\sqrt{s_0} = 4.80$ GeV (long-dashed line). The crosses indicate the valid Borel window.

$$
\begin{aligned}
M_X &= (4.26 \pm 0.13)\ \mathrm{GeV} \\
\lambda_X &= (2.00 \pm 0.23) \times 10^{-2}\ \mathrm{GeV}^5 \\
\theta &= (53.0 \pm 0.5)^0 \\
\sqrt{t_c} &= (4.70 \pm 0.10)\ \mathrm{GeV}
\end{aligned}
$$

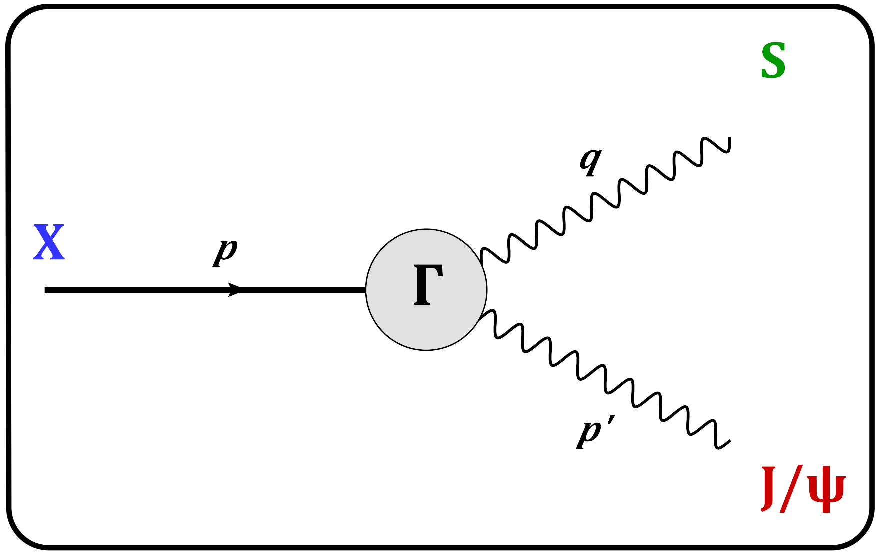


$|c\bar{c}\rangle \oplus |cq\bar{c}\bar{q}\rangle$

- ☑ **the mass value is in a good agreement with the experimental data.**
- ☑ **Optimal SR conditions satisfied.**

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**



$$\Gamma_{\mu\nu}(p,p',q) = \int d^4x\, d^4y\, e^{ip'\cdot x}\, e^{iq\cdot y}\langle 0|\, T[\, j_\mu^{\psi}(x) j^{S}(y) j_\nu^{X\dagger}(0)\,]\,|0\rangle$$

$$\begin{aligned} j^{\sigma} &= \frac{1}{\sqrt{2}}(\bar{u}_a u_a + \bar{d}_a d_a) \\ j^{f_0} &= \bar{s}_a s_a \end{aligned}$$

$$\begin{aligned} \langle 0|j_\mu^{\psi}|J/\psi(p')\rangle &= m_\psi f_\psi \epsilon_\mu(p'), \\ \langle 0|j^{\sigma}|\sigma(q)\rangle &= A_\sigma, \\ \langle Y(p)|j_\nu^{Y}|0\rangle &= \lambda_Y \epsilon_\nu^{*}(p), \end{aligned}$$

$$\Pi_{\mu\nu}^{PH} = -q_\mu p'_\nu\, \frac{\lambda_X\, m_\psi f_\psi A_S\, g_{X\psi S}(q^2)}{(p^2 - M_X^2)(p'^{\,2} - m_\psi^2)(q^2 - m_S^2)} + \ldots$$

$$\Pi_{\mu\nu}^{OPE} = q_\mu p'_\nu \int_{4m_c^2}^{\infty} ds\, \frac{\rho^{OPE}(s)}{s - q^2}$$

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**

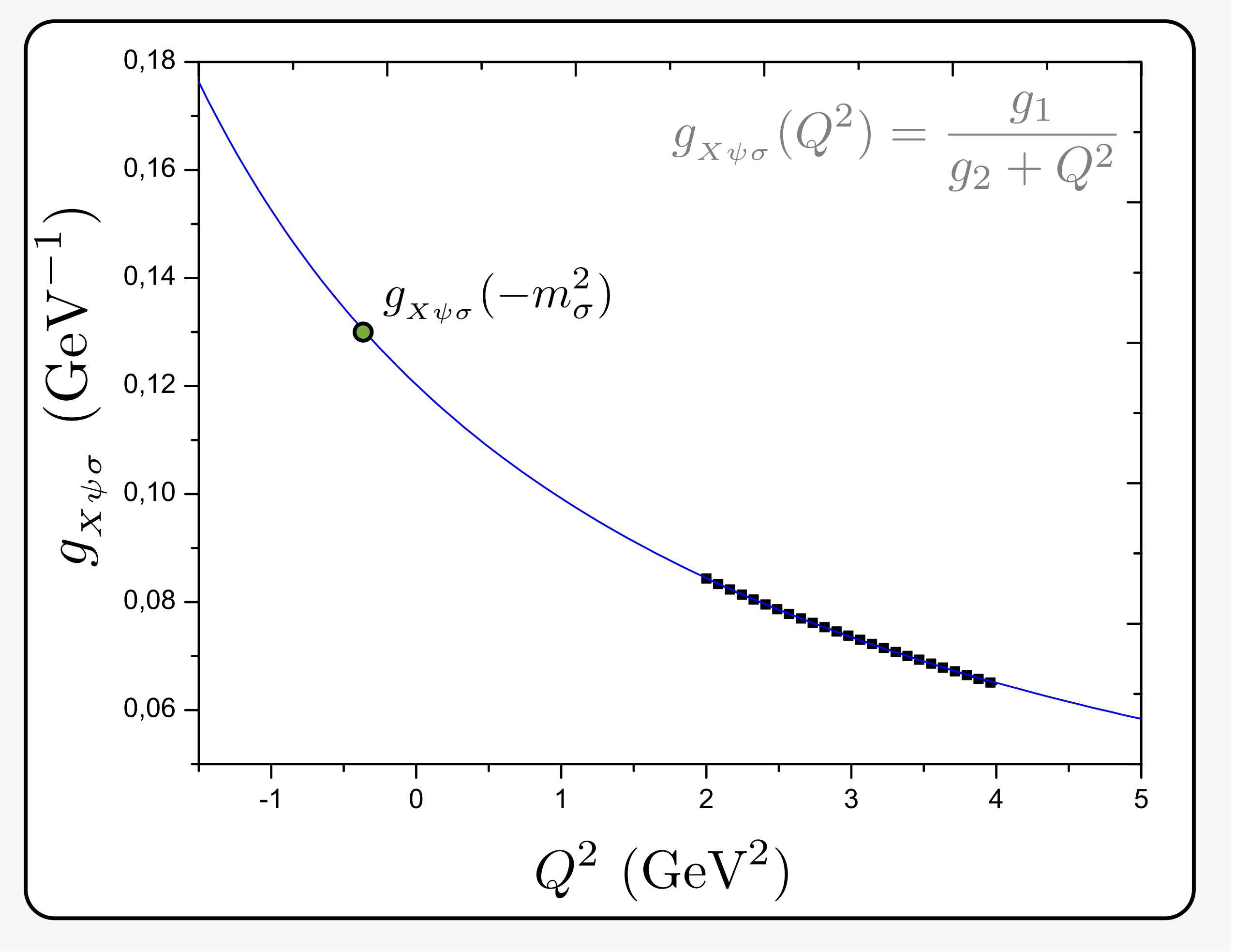
- Assuming that $\pi^+\pi^-$ and K^+K^- in the final states come from intermediate resonances, namely $\sigma(500)$ and $f_0(980)$, we can estimate the coupling constants associated with the processes:

$$X(4260) \to J/\psi\,\sigma \to J/\psi\,\pi\pi$$

$$g_{X\psi\sigma}(-m_\sigma^2) = (0.13 \pm 0.01)\ \mathrm{GeV}^{-1}$$

$$\begin{aligned} X(4260) \;\to\; J/\psi\, f_0(980) \;&\to\; J/\psi\,\pi\pi \\ &\to\; J/\psi\,KK \end{aligned}$$

$$g_{X\psi f_0}(-m_{f_0}^2) = (0.26 \pm 0.01)\ \mathrm{GeV}^{-1}$$



Results

- The decay for the process $X(4260) \to J/\psi\, \sigma \to J/\psi\, \pi\pi$ can be evaluated in the narrow width approximation

$$\frac{d\Gamma}{ds}(X \to J/\psi\pi\pi) = \frac{|\mathcal{M}|^2}{8\pi M_X^2} \cdot \frac{(M_X^2 - m_\psi^2 + s)}{2M_X^2} \cdot \frac{\Gamma_\sigma(s) m_\sigma}{2\pi M_X} \cdot \frac{\sqrt{\lambda(M_X^2, m_\psi^2, s)}}{(s - m_\sigma^2)^2 + m_\sigma^2\, \Gamma_\sigma(s)^2}$$

- where $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc$, is the s-dependent width of an off-shell meson:

$$\Gamma_\sigma(s) = \frac{m_\sigma^2\, \Gamma_{0\sigma}}{s} \sqrt{\frac{\lambda(s, m_\pi^2, m_\pi^2)}{\lambda(m_\sigma^2, m_\pi^2, m_\pi^2)}}$$

- and $\Gamma_{0\sigma}$ is the experimental value for the decay of meson into two pions.

- The invariant amplitude squared is given by

$$|\mathcal{M}|^2 = \frac{1}{3} g_{X\psi\sigma}^2 \left[M_X^2 m_\psi^2 + \frac{1}{2}(M_X^2 + m_\psi^2 - s)^2 \right]$$

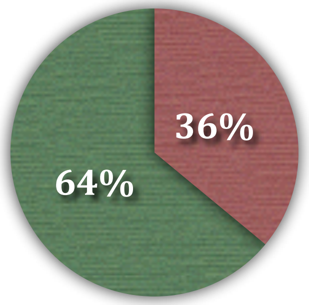
- Hence, we obtain the value for the decay width

$$\Gamma_\sigma(X \to J/\psi\, \pi\pi) = (1.0 \pm 0.4)\ \mathrm{MeV}$$

X(4260) as a Mixed Charmonium-Tetraquark state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 88, 076001 (2013)**

Channel	Intermediate Process	Decay Width (MeV)
$X \to J/\psi\, \pi^+\pi^-$	$\sigma \to \pi^+\pi^-$	1.0 ± 0.4
	$f_0 \to \pi^+\pi^-$	3.1 ± 0.2
$X \to J/\psi\, K^+K^-$	$f_0 \to K^+K^-$	1.3 ± 0.4



$|c\bar{c}\rangle \oplus |cq\bar{c}\bar{q}\rangle$

- Our estimation for the total width is $\Gamma_{\rm total} \simeq (5.4 \pm 1.0)$ MeV, which is much smaller than the experimental data: ∼108 MeV.
- Possibly the main decay channel of the X(4260) should be into D mesons, mostly due to the presence of charmonium in its internal structure. These channels would increase the value estimated for $\Gamma_{\rm total}$.
- The dominance of the tetraquark state could be an explanation to the preferable hidden-charm decay modes for this particle.

Y(3940) state

Y(3940) as a Mixed Charmonium-Molecule state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 89, 076007 (2014)**

$$\left(J^{PC} = 0^{++}\right)$$

$$j^{Y} = \sin\theta\ j^{D^* D^*} + a\cos\theta\ j^{\chi_{c0}}$$

$$j^{D^* D^*} = (\bar{q}_a\, \gamma_\mu\, c_a)\,(\bar{c}_b\, \gamma^\mu\, q_b)$$

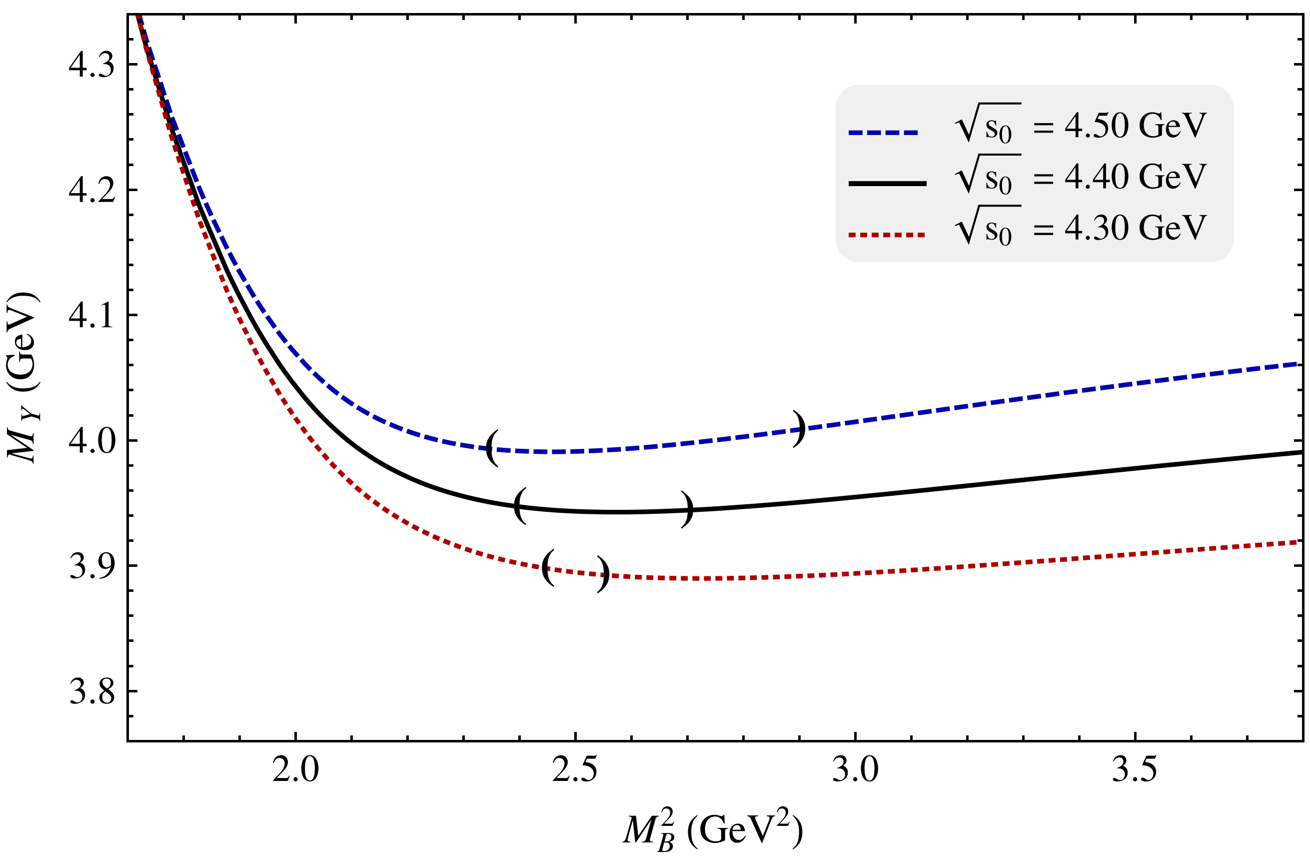
$$j^{\chi_{c0}} = \bar{c}_a c_a$$

$$\Pi^{PHEN}(q) = \frac{\lambda_Y^2}{M_Y^2 - q^2} + \int_0^\infty ds\, \frac{\rho^{\mathrm{cont}}(s)}{s - q^2}$$

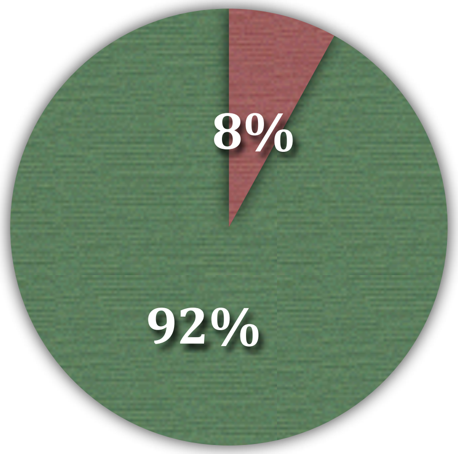
$$\Pi^{\mathrm{OPE}}(q^2) = \int_{4m_c^2}^\infty ds\, \frac{\rho^{\mathrm{OPE}}(s)}{s - q^2}$$

Y(3940) as a Mixed Charmonium-Molecule state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 89, 076007 (2014)**



$$
\begin{aligned}
M_Y &= (3.95 \pm 0.11)\ \text{GeV} \\
\lambda_Y &= (2.1 \pm 0.6)\ \text{GeV}^5 \\
\theta &= (76.0 \pm 5.0)^0 \\
\sqrt{t_c} &= (4.40 \pm 0.10)\ \text{GeV}
\end{aligned}
$$



$$|c\bar{c}\rangle \oplus |D^*\bar{D}^*\rangle$$

- ☑ **the mass value is in a good agreement with the experimental data.**
- ☑ **Optimal SR conditions satisfied.**

Y(3940) as a Mixed Charmonium-Molecule state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 89, 076007 (2014)**

$$Y(3940) \to J/\psi\omega$$

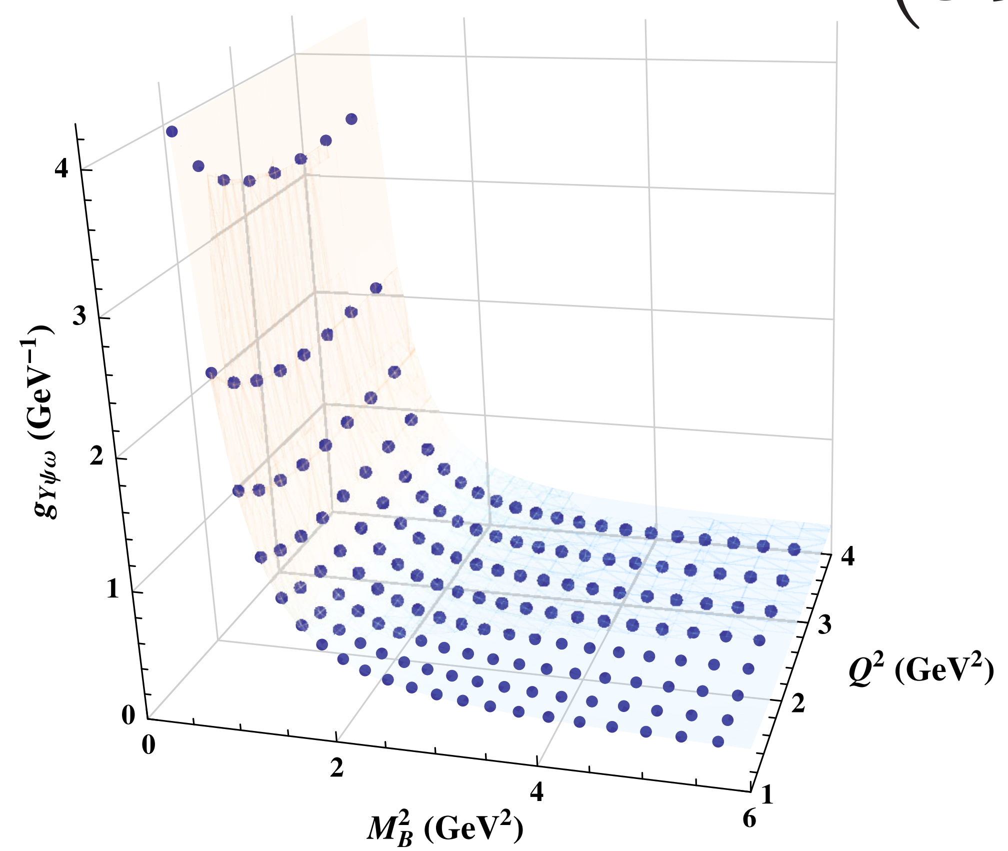
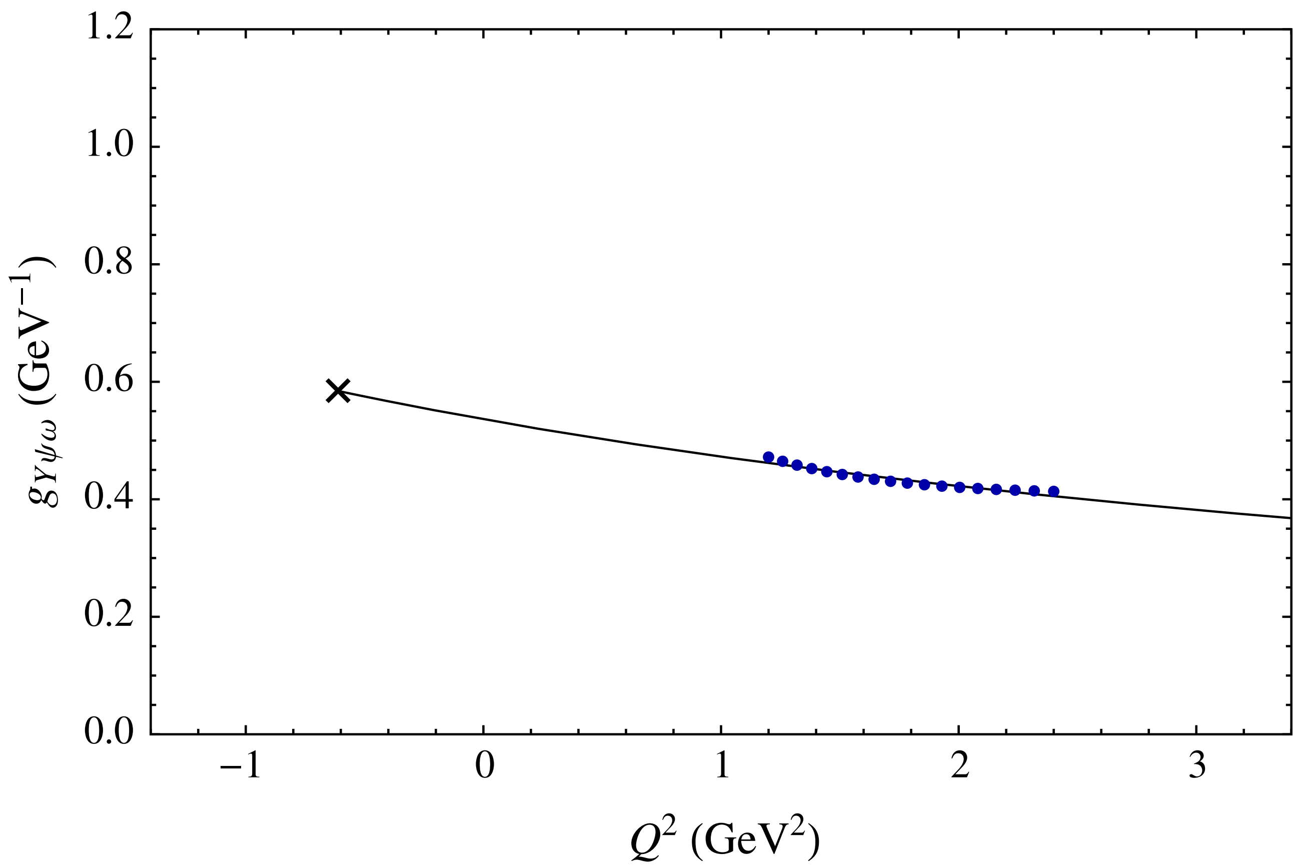


FIG. 4 (color online). The form factor $g_{Y\psi\omega}(Q^2)$ as a function of the momentum Q^2 and Borel mass parameter M_B^2.



$$g_{Y\psi\omega} = g_{Y\psi\omega}(-M_\omega^2) = (0.58 \pm 0.14)\ \text{GeV}^{-1}$$

Results

Y(3940) as a Mixed Charmonium-Molecule state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 89, 076007 (2014)**

$$Y(3940) \to \gamma\gamma$$

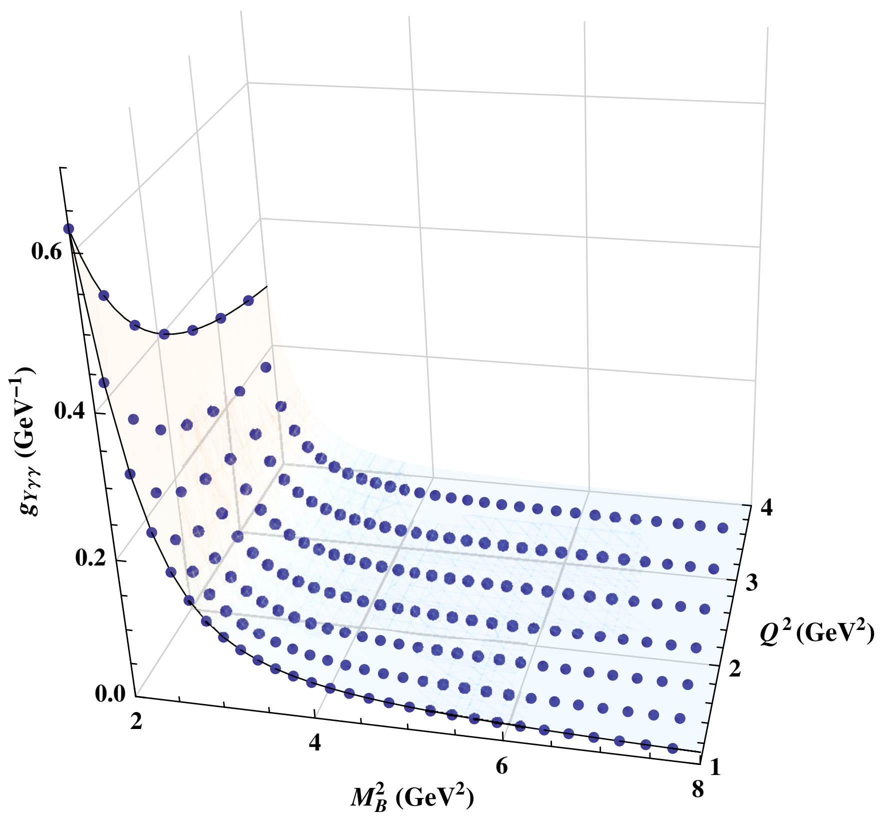
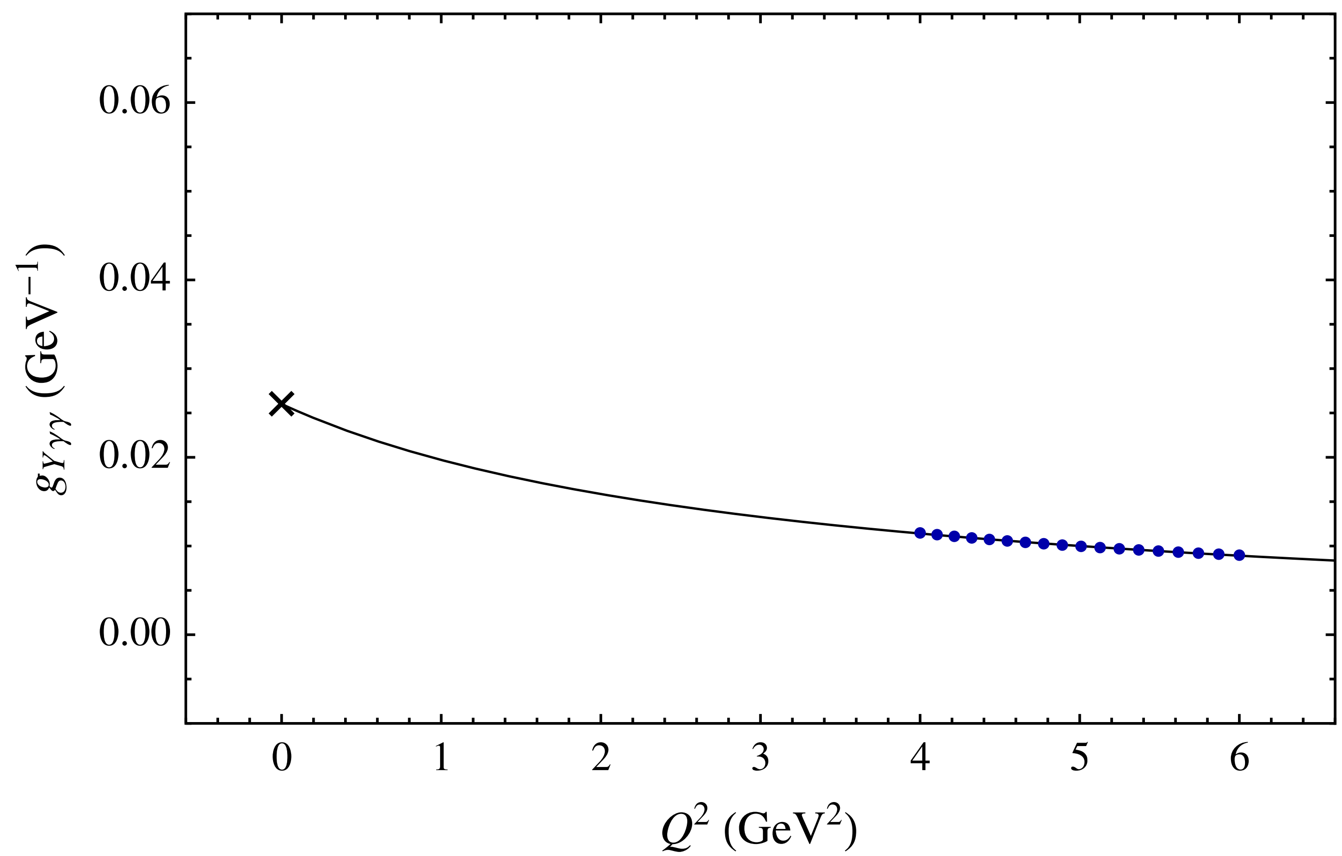


FIG. 6 (color online). The form factor $g_{Y\gamma\gamma}(Q^2)$ as a function of the momentum Q^2 and Borel mass parameter M_B^2.



$$g_{Y\gamma\gamma} = (0.025 \pm 0.010)\ \mathrm{GeV}^{-1}$$

Y(3940) as a Mixed Charmonium-Molecule state

R.M. Albuquerque, J.M. Dias, M. Nielsen & C.M. Zanetti, **PRD 89, 076007 (2014)**

Channel	Decay Width
$Y(3940) \to J/\psi\omega$	(1.7 ± 0.6) MeV
$Y(3940) \to \gamma\gamma$	(1.6 ± 1.3) KeV

- Our estimation for the width is $\Gamma_{J/\psi\omega} = (1.7 \pm 0.6)$ MeV, which is smaller than the experimental width (~30 MeV), but is consistent with the lower limit for this channel $\Gamma > 1$ MeV.

  Branz, Gutsche & Lyubovitskij, PRD 80 (2009)
  Branz, Molina & Oset, PRD 83 (2011)

- The product of the two partial widths

$$\Gamma_{\gamma\gamma} \times \Gamma_{J/\psi\omega} \sim \mathcal{O}(10^3)\ \text{KeV}^2$$

in accordance with one predicted by Belle and BaBar Collaborations.

PRL 104, 092001 (2010)   PRD 86, 072002 (2012)

Charmonium Exotic States

- The LHCb observation in the $\psi' \, \pi^-$ invariant mass has proved unambiguously that the minimal quark content of the charged Z(4430) state is $c\bar{c}d\bar{u}$.
  Therefore, it is a four-quark state.

- From a QCD sum rule calculation, we shall retain an admixture of charmonium and four-quark states as a possible hadronic structure to describe these exotic states observed recently.

- Using such a exotic structure we could explain the expected mass and decay widths obtained in the experiments.

  - ❖ X(4260) as a J/ψ - tetraquark state, with $J^{PC} = 1^{--}$.

  - ❖ Y(3940) as a χ_{c0} - $D^*\bar{D}^*$ molecule, with $J^{PC} = 0^{++}$.

- Future QCDSR estimations of the decay channels into D mesons can improve the results for the total widths.

THANK YOU!