The Compact *X* and *Z* and their *Invisible* Molecular Partners

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in collaboration with

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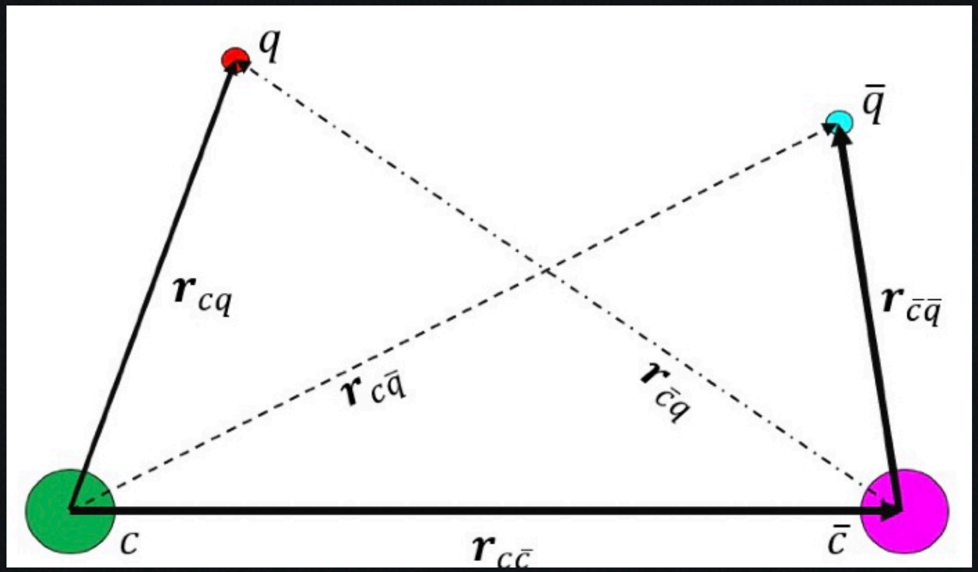
arXiv: 2512.21538

The Born-Oppenheimer Tetraquark*

A "Toy Model"



$$T \equiv |(c\bar{c})_{\mathbf{8}}\,(q\bar{q})_{\mathbf{8}}\rangle_{\mathbf{1}}$$

$$T_D = \alpha\,|(cq)_{\bar{\mathbf{3}}}(\bar{c}\bar{q})_{\mathbf{3}}\rangle + \beta\,|(cq)_{\mathbf{6}}(\bar{c}\bar{q})_{\bar{\mathbf{6}}}\rangle$$

$$T_M = \alpha'\,|(c\bar{q})_{\mathbf{1}}(\bar{c}q)_{\mathbf{1}}\rangle + \beta'\,|(c\bar{q})_{\mathbf{8}}(\bar{c}q)_{\mathbf{8}}\rangle$$

*L. Maiani, A.D.P., V. Riquer, PRD100 (2019) 1, 014002

*B. Grinstein, D. Germani, A.D.P., *JHEP* 04 (2025) 004

E. Braaten, R. Bruschini, *Phys.Lett.B* 863 (2025) 139386

N. Brambilla, A. Mohapatra, T. Scirpa, A. Vairo, *Phys.Rev.Lett.* 135 (2025) 13, 13

The Born-Oppenheimer Tetraquark

$$\Psi_T(\boldsymbol{r}_{cq}, \boldsymbol{r}_{\bar{c}\bar{q}}, \boldsymbol{R}_{c\bar{c}}) = \Psi_{c\bar{c}}(\boldsymbol{R}_{c\bar{c}}) \cdot \Psi_{q\bar{q}}(\boldsymbol{r}_{cq}, \boldsymbol{r}_{\bar{c}\bar{q}}, \boldsymbol{R}_{c\bar{c}})$$

$$\Psi_{q\bar{q}}(\boldsymbol{r}_{cq}, \boldsymbol{r}_{\bar{c}\bar{q}}, \boldsymbol{R}_{c\bar{c}}) = a_D(R_{c\bar{c}}) \underbrace{\psi_D(\boldsymbol{r}_{cq})\psi_D(\boldsymbol{r}_{\bar{c}\bar{q}})}_{T_D} + a_M(R_{c\bar{c}}) \underbrace{\psi_M(\boldsymbol{r}_{c\bar{q}})\psi_M(\boldsymbol{r}_{\bar{c}q})}_{T_M}$$

"Diquarks" $\quad V_D(\zeta) = -\frac{1}{3}\frac{\alpha_s}{\zeta} + k\zeta \quad$ where $\quad \boldsymbol{\zeta} = \boldsymbol{r}_{cq}, \boldsymbol{r}_{\bar{c}\bar{q}}$

"Mesons" $\quad V_M(\zeta) = -\frac{7}{6}\frac{\alpha_s}{\zeta} + k\zeta \quad$ where $\quad \boldsymbol{\zeta} = \boldsymbol{r}_{c\bar{q}}, \boldsymbol{r}_{\bar{c}q}$

$\psi_{\mathscr{C}} = \sqrt{\frac{\mathscr{C}^3}{\pi}} \exp(-\mathscr{C}\zeta) \quad$ where $\quad \mathscr{C} = D, M$

B. Grinstein, D. Germani, A.D.P., *JHEP* 04 (2025) 004

THE $(c\bar{c})_{\mathbf{8}}$ CONFIGURATION: CHROMO-HYDROGEN

In the one-gluon-exchange model, we can deduce the couplings

For example $\lambda_{cq} = \lambda_{\bar{c}\bar{q}} = \underbrace{\frac{2}{3}}_{|\alpha|^2} \frac{1}{2}(-\frac{4}{3}) + \underbrace{\frac{1}{3}}_{|\beta|^2} \frac{1}{2}(\underbrace{\frac{10}{3}}_{C(\mathbf{6})} - \frac{8}{3}) = -\frac{1}{3}$

Couplings are extracted by the diagonal matrix $\bigoplus_i \frac{1}{2}(C(S_i) - C(R_1) - C(R_2))\, I_i$

$$\lambda_{c\bar{c}} = \lambda_{q\bar{q}} = +\frac{1}{6}\alpha_s$$

$$\lambda_{cq} = \lambda_{\bar{c}\bar{q}} = -\frac{1}{3}\alpha_s$$

$$\lambda_{c\bar{q}} = \lambda_{\bar{c}q} = -\frac{7}{6}\alpha_s$$

L. Maiani, A.D.P., V. Riquer, Phys. Rev. D 100 (2019) 1, 014002; Phys. Rev. D 100 (2019) 7, 074002

The B.O. Potentials $\Delta E_\pm$

$$\begin{pmatrix} H_D - \Delta E & H_{DM} - S_{DM}^2 \Delta E \\ H_{DM} - S_{DM}^2 \Delta E & H_M - \Delta E \end{pmatrix} \begin{pmatrix} a_D \\ a_M \end{pmatrix} = 0 \quad \rightarrow \quad \Delta E_\pm$$

$$H_D = \langle \psi_D \psi_D | H_{q\bar{q}} | \psi_D \psi_D \rangle \quad \dots \quad S_{DM} = \int_{r_{cq}} \psi_D(r_{cq}) \psi_M(\boldsymbol{r}_{cq} - \boldsymbol{R}_{c\bar{c}})$$

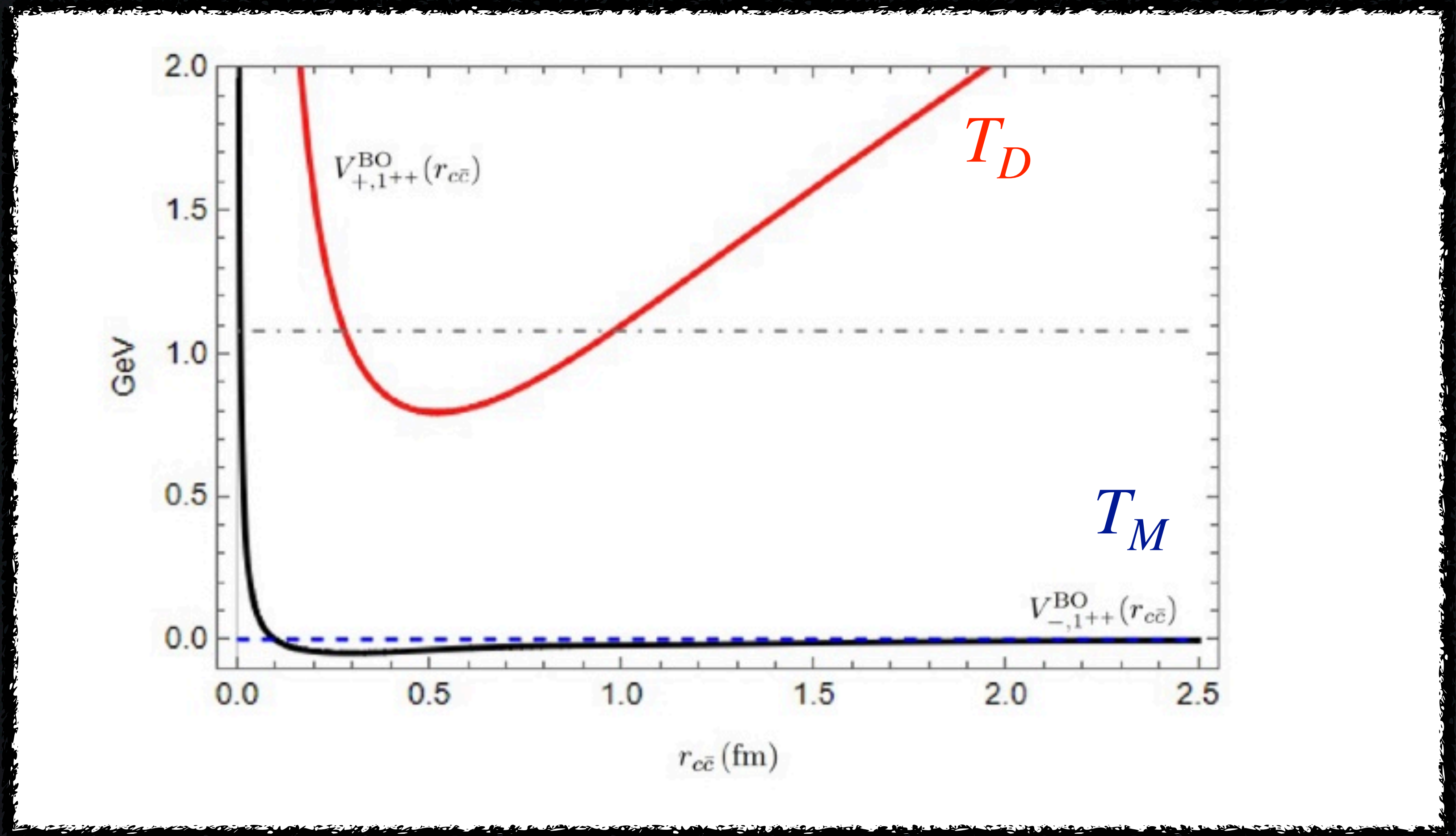
$$H_M = \langle \psi_M \psi_M | H_{q\bar{q}} | \psi_M \psi_M \rangle$$

$$H_{DM} = \langle \psi_D \psi_M | H_{q\bar{q}} | \psi_D \psi_M \rangle \quad \dots \quad H_{q\bar{q}} = -\frac{\Delta_{\boldsymbol{r}_{cq}}}{2m_{cq}} - \frac{\Delta_{\boldsymbol{r}_{\bar{c}\bar{q}}}}{2m_{\bar{c}\bar{q}}} + V_{\text{Coul}} + V_{\text{Conf}} + V_{\text{Spin}}$$

$$\Delta E_\pm(r_{c\bar{c}}) = \frac{1}{2(1 - S_{DM}^4)} \Big(H_D + H_M - 2S_{DM}^2 H_{DM} \pm \sqrt{(H_D + H_M - 2S_{DM}^2 H_{DM})^2 - 4(1 - S_{DM}^4)(H_D H_M - H_{DM}^2)} \Big)$$

$$\left(H_{c\bar{c}} + \Delta E_\pm(R_{c\bar{c}}) \right) \Psi_{c\bar{c}}(\boldsymbol{R}_{c\bar{c}}) = E\, \Psi_{c\bar{c}}(\boldsymbol{R}_{c\bar{c}})$$

The B.O. Potentials

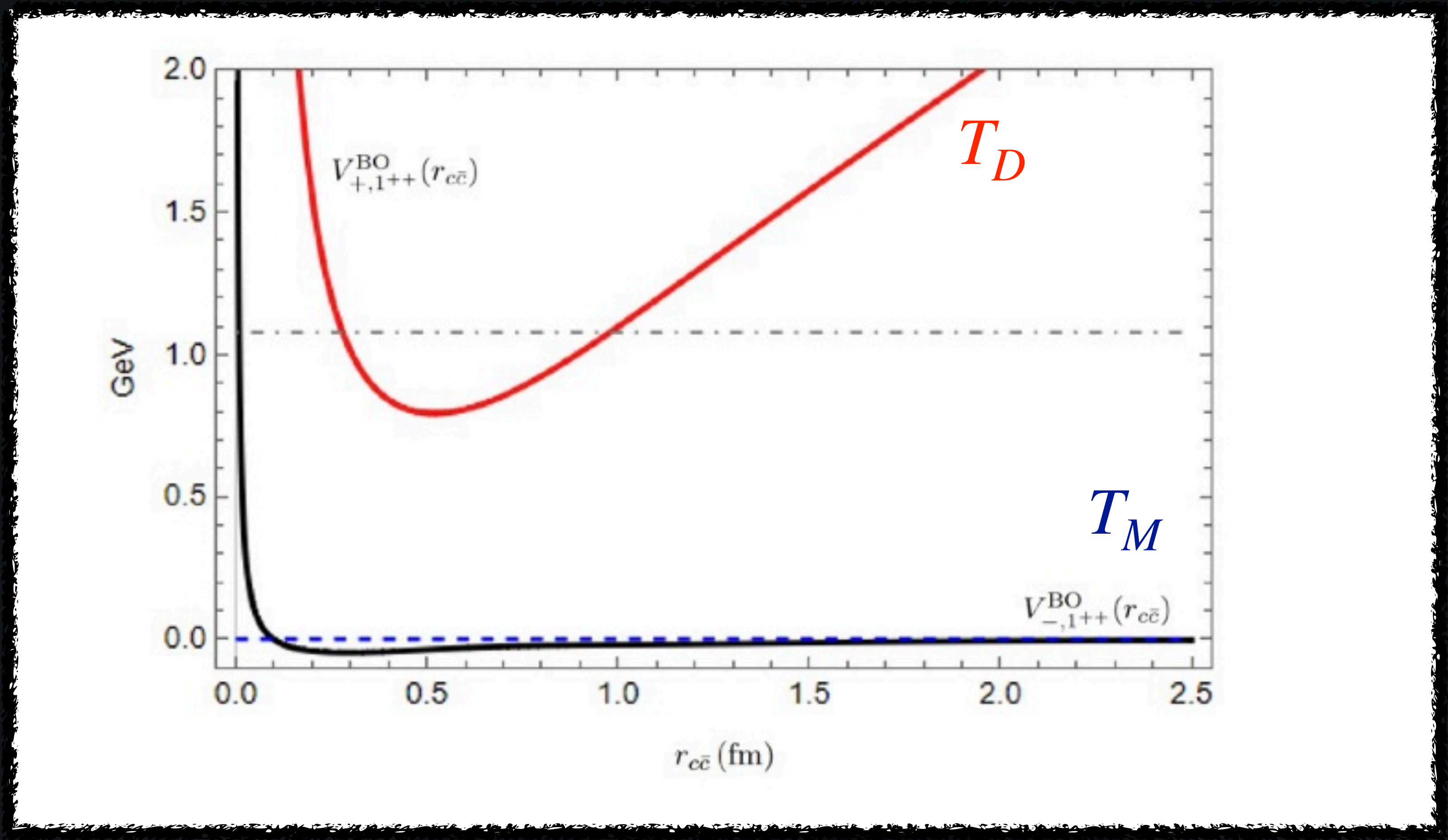


$$V_-(R_{c\bar c}) = \frac{1}{6}\frac{\alpha_s}{R_{c\bar c}} + \Delta E_-$$

$$V_+(R_{c\bar c}) = \frac{1}{6}\frac{\alpha_s}{R_{c\bar c}} + \Delta E_+ + k\,R_{c\bar c}$$

B. Grinstein, D. Germani, A.D.P., *JHEP* 04 (2025) 004

The B.O. Potentials



Shallow, **compact**, bound states, superpositions of color $(\mathbf{1},\mathbf{1})+(\mathbf{8},\mathbf{8})$ with a **size closer to the typical hadron size**. Distinct from true molecules since defined by color forces and spin-interactions.

Their wavefunctions do not match the universal form predicted for a shallow molecular bound states.

B. Grinstein, D. Germani, A.D.P., *JHEP* 04 (2025) 004

Compact and molecular states

Together with the B.O. state, in the lower potential, there could be a *truly molecular state* — which is *not* contained in the B.O. description.

We assume that this molecular state belongs to a isotriplet so that:

X_S^0	$(\mathbf{1}, \mathbf{1} + \mathbf{8}, \mathbf{8})$	isosinglet/compact
$X_T^{0,\pm}$	$(\mathbf{1}, \mathbf{1})$	isotriplet/molecular/no B.O.

$X_S\ (= X_S^0\ )$ can mix with $X_T\ (= X_T^0\ )$

A. Carducci, D. Germani, B. Grinstein, A.D.P., arXiv: 2512.21538

X_S and X_T

We argue that $X(3872) = X_S$

The loosely bound isotriplet is **not efficiently produced** at colliders: production rates are very much suppressed in high energy prompt collisions and even in B decays.

X_S can oscillate in the invisible X_T

We assume that:

$i)$ X_T quasi-degenerate with X_S

$ii)$ X_T is a shallow bound state with $B \ll M$

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

A. Carducci, D. Germani, B. Grinstein, A.D.P., arXiv: 2512.21538

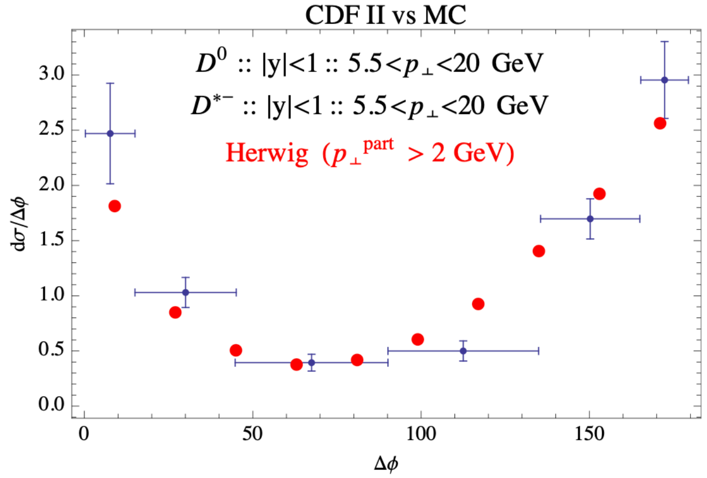


FIG. 1: The $D^0 D^{*-}$ pair cross section as function of $\Delta\phi$ at CDF Run II. The transverse momentum, $p_\perp$, and rapidity, y, ranges are indicated. Data points with error bars, are compared to the leading order event generator Herwig. The cuts on parton generation are $p_\perp^{\rm part} > 2$ GeV and $|y^{\rm part}| < 6$. We have checked that the dependency on these cuts is not significative. We find that we have to rescale the Herwig cross section values by a factor $K_{\rm Herwig} \simeq 1.8$ to best fit the data on open charm production.

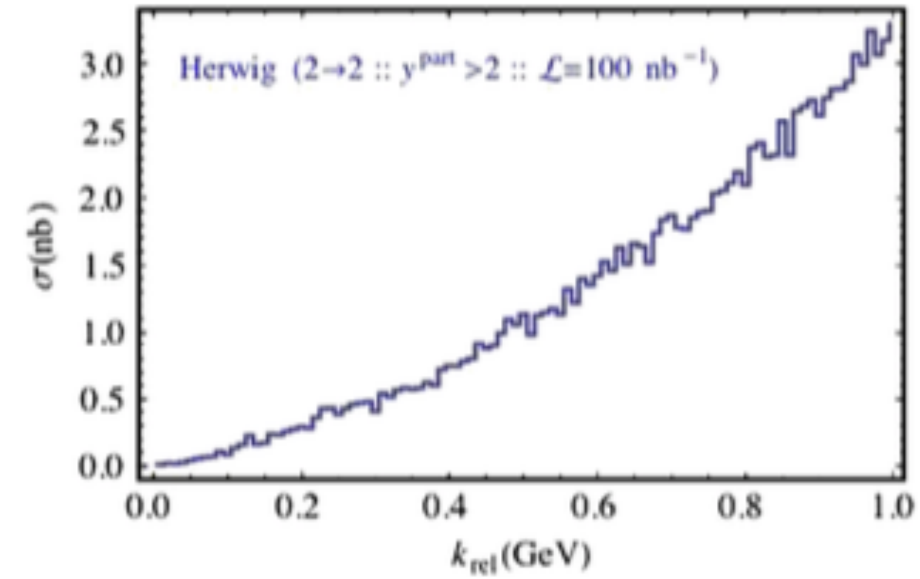
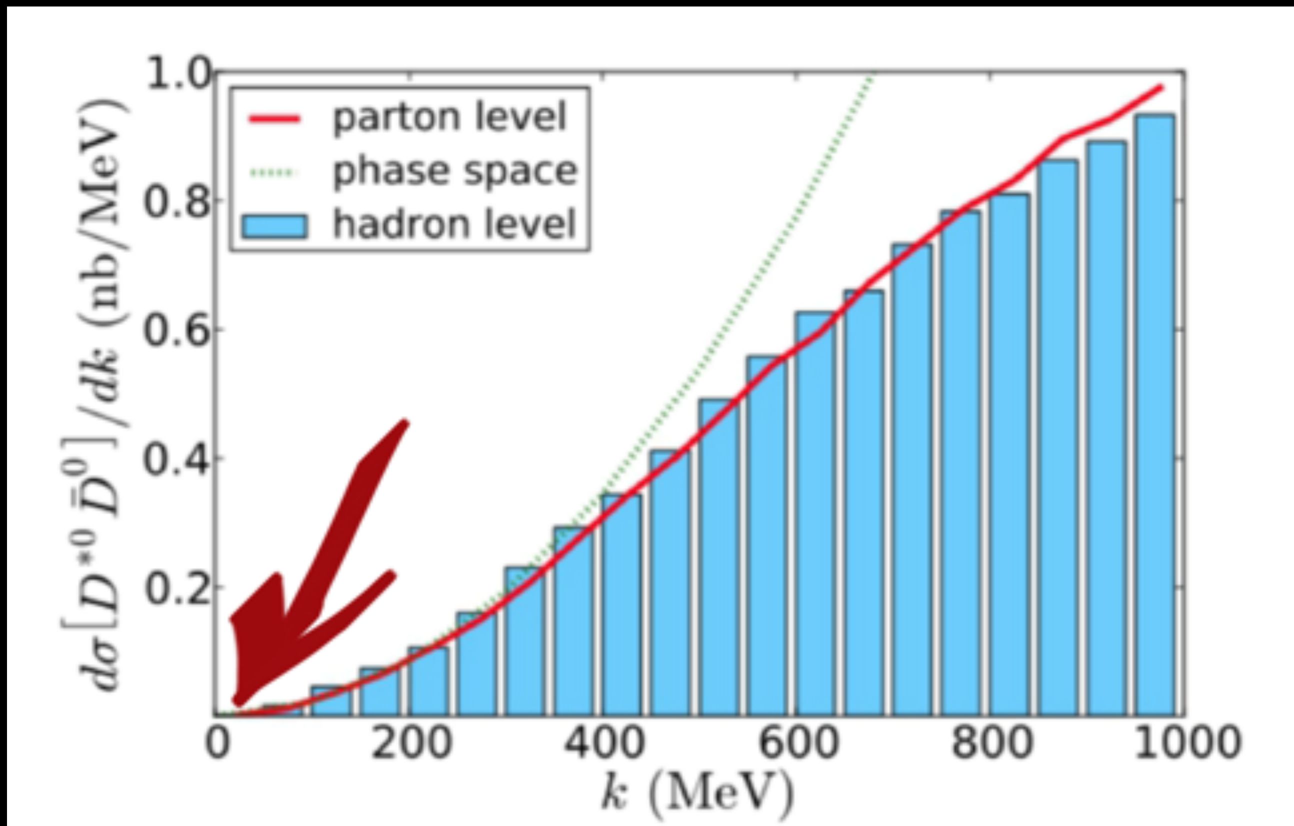


FIG. 3 (color online). The integrated cross section obtained with HERWIG as a function of the center of mass relative momentum of the mesons in the $D^0\bar{D}^{*0}$ molecule. This plot is obtained after the generation of 55×10^9 events with parton cuts $p_\perp^{\rm part} > 2$ GeV and $|y^{\rm part}| < 6$. The cuts on the final D mesons are such that the molecule produced has a $p_\perp > 5$ GeV and $|y| < 0.6$.

Bignamini, Grinstein, Piccinini, ADP, Sabelli, PRL103 (2009) 162001

$$p \sim \Delta p \sim \sqrt{2mB} \sim$$

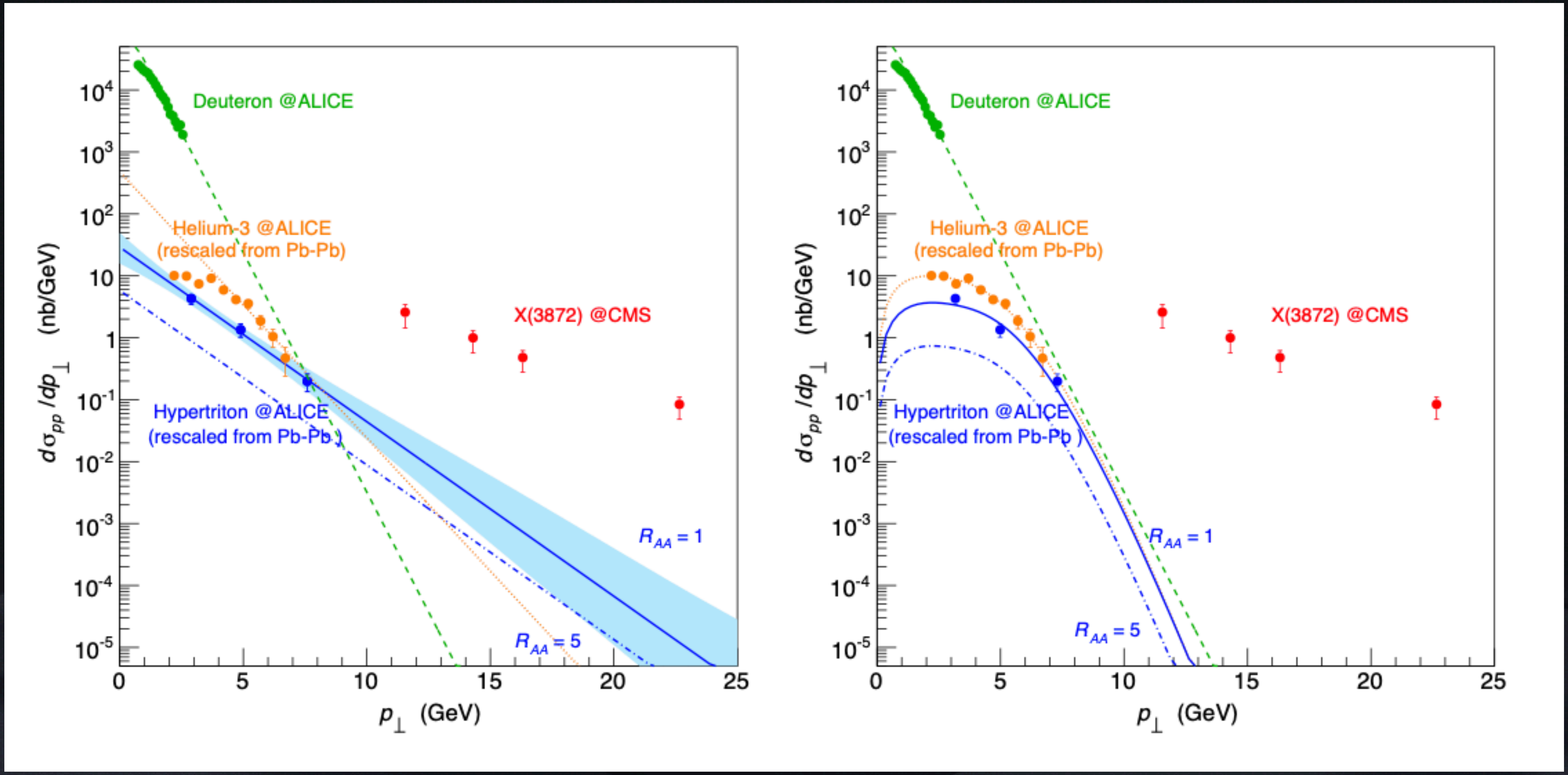
~ 14 MeV



Braaten and Artoisenet, PRD81103 (2010) 114018

The most fine tuned bound state

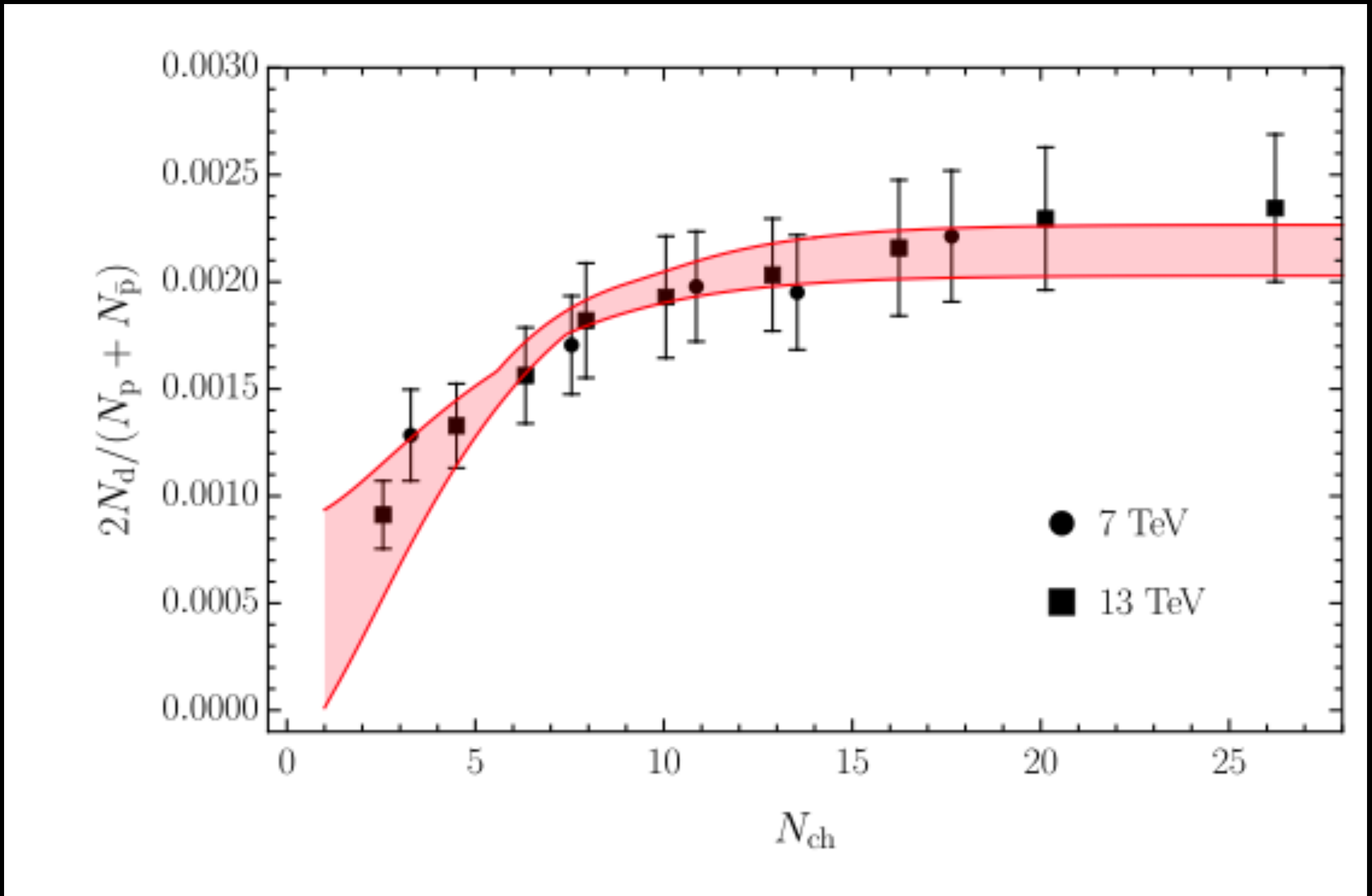
...ever seen. Too weakly bound to be a final state in ***pp*** collisions.



Esposito, Guerrieri, Maiani, Piccinini, Pilloni, ADP, Riquer, Phys. Rev. D 92 (2015) 3, 034028

DOES THE X(3872) BEHAVE AS THE DEUTERON?

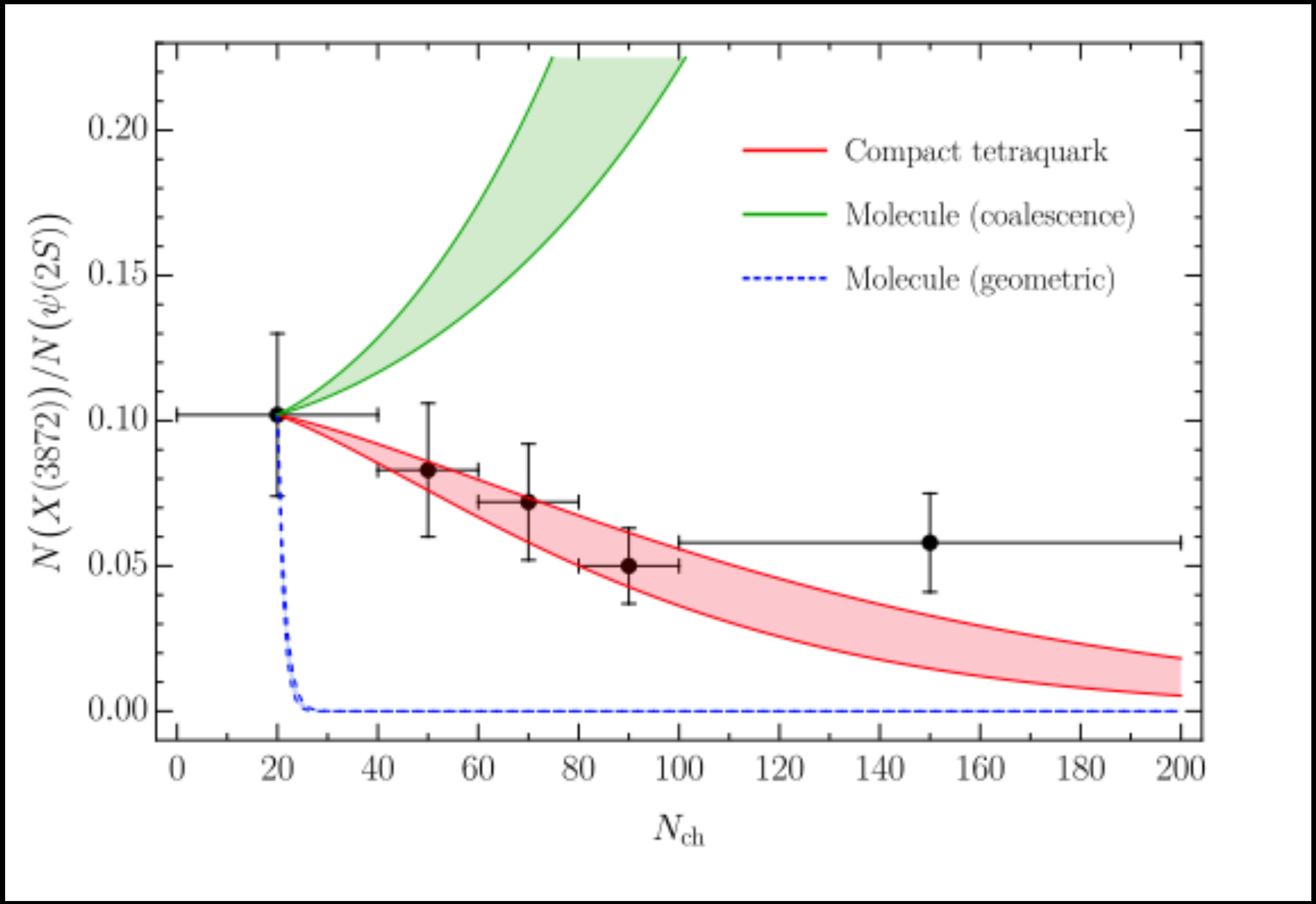
ALICE: 1902.09290; 2003.03184



Esposito, Ferreiro, Pilloni, ADP, Salgado *Eur. Phys. J. C* 81 (2021) 669

Number of deuterons as a function of the multiplicity computed with kinetic theory (coalescence momentum varied between $50 < k < 250$ MeV – up to 360 MeV for X)

DOES THE X(3872) BEHAVE AS THE DEUTERON?



Esposito, Ferreiro, Pilloni, ADP, Salgado *Eur. Phys. J. C* 81 (2021) 669

The coalescence picture predicts a behavior (green band) qualitatively different from data – see talk by M Durham

X_S and X_T

problems potentially solved within this scheme

1) Reconcile with the sizable isospin violations observed

$$\mathcal{I} = \frac{\text{Br}(X \to J/\psi\, \pi^+\pi^-\pi^0)}{\text{Br}(X \to J/\psi\, \pi^+\pi^-)} = \begin{cases} 1.0 \pm 0.4\,(\text{stat}) \pm 0.3\,(\text{syst}) & [\text{Belle}] \\ 0.8 \pm 0.3 & [\text{BABAR}] \\ 1.43^{+0.28}_{-0.23} & [\text{BESIII}] \end{cases}$$

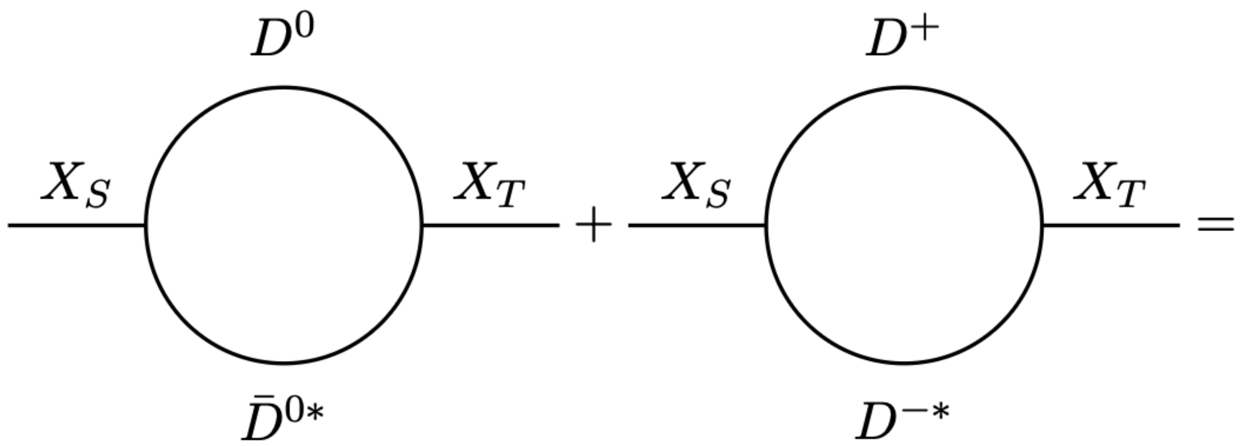
2) As of today *no charged partners of the* $X(3872)$ have been discovered *nor extra neutral states*: in the quark model we should have two neutral X particles (within a few MeV).

3) A triplet of states $Z^{0,\pm}$, slightly heavier, is observed with opposite charge conjugation with respect to the X. These three particles are all **compact** quark states. No isospin violations are expected in this system.

The mixing mechanism

Both X_S and X_T couple to $D\bar{D}^*$

$(-ig_{\mathrm{mix}}) =$



$$= (-ig_S)(ig_T)i\frac{m}{\pi^2}\left(-\Lambda + \sqrt{-2mE}\arctan\left(\frac{\Lambda}{\sqrt{-2mE}}\right)\right) +$$

$$+ (ig_S)(ig_T)i\frac{m_+}{\pi^2}\left(-\Lambda + \sqrt{-2m_+(E-\Delta)}\arctan\left(\frac{\Lambda}{\sqrt{-2m_+(E-\Delta)}}\right)\right)$$

where $E = m_X - m_D - m_{D^*} \neq B$.

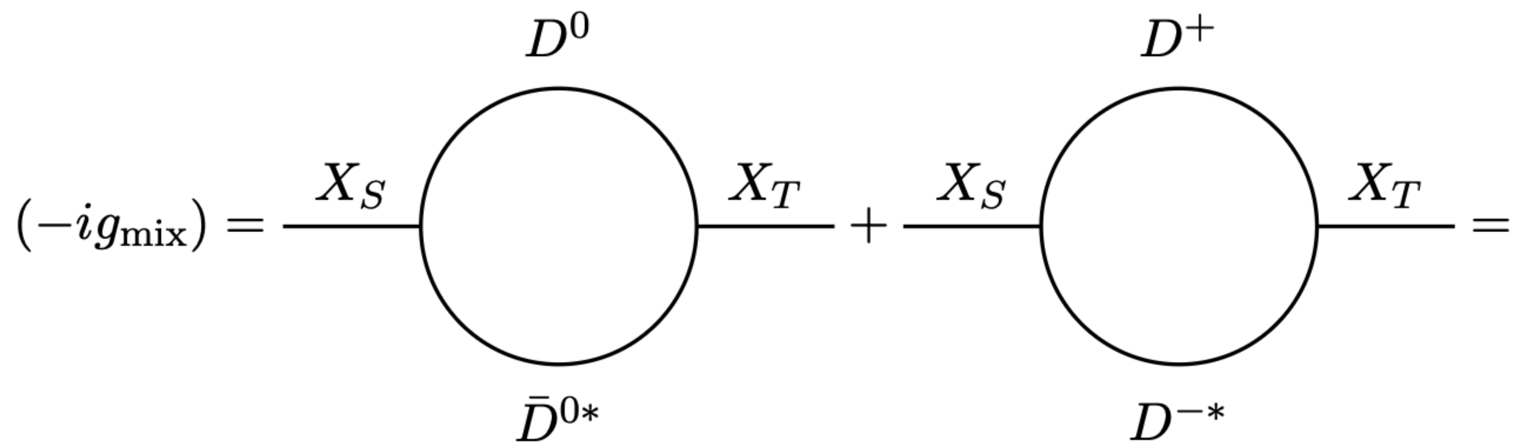
Notice that $g_{\mathrm{mix}} = 0$ in the limit $\Delta \to 0$, where

$\Delta = m_{D^{*+}} + m_{D^+} - m_{D^{*0}} - m_{D^0} \simeq 8$ MeV.

The reduced mass of the charged mesons is $m_+ \simeq m$.

The mixing mechanism

Both X_S and X_T couple to $D\bar{D}^*$



$$= (-ig_S)(ig_T)i\frac{m}{\pi^2}\left(-\Lambda + \sqrt{-2mE}\,\arctan\left(\frac{\Lambda}{\sqrt{-2mE}}\right)\right) +$$
$$+ (ig_S)(ig_T)i\frac{m_+}{\pi^2}\left(-\Lambda + \sqrt{-2m_+(E-\Delta)}\,\arctan\left(\frac{\Lambda}{\sqrt{-2m_+(E-\Delta)}}\right)\right)$$

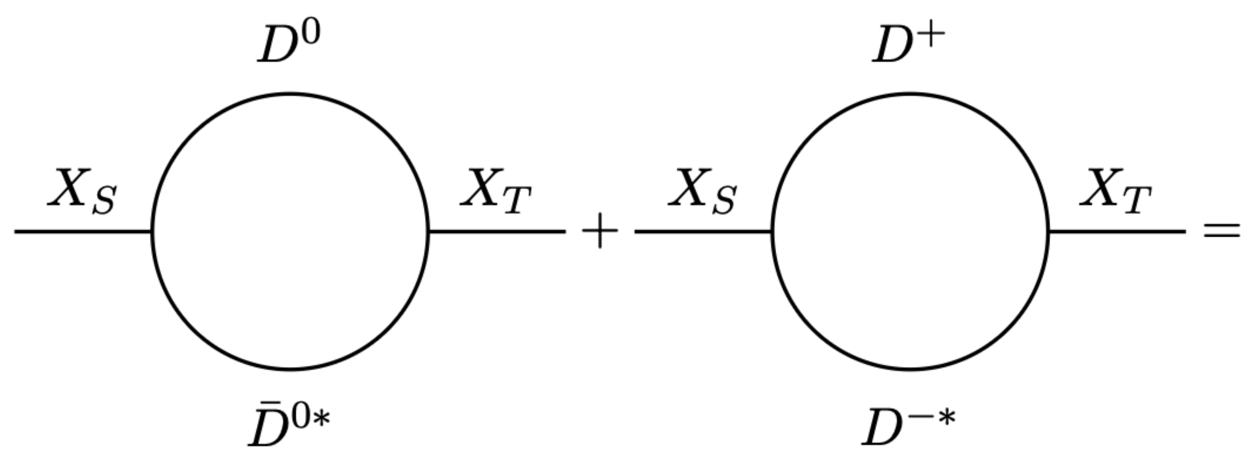
Studying the Flatte` lineshape of the $X = X_S$ at the LHCb allows to measure the coupling g_S.

As for g_T : it can be estimated theoretically — we will use an argument due to Landau and Weinberg.

The mixing mechanism

Both X_S and X_T couple to $D\bar{D}^*$

$(-ig_{\text{mix}}) =$



$$= (-ig_S)(ig_T)i\frac{m}{\pi^2}\left(-\Lambda + \sqrt{-2mE}\arctan\left(\frac{\Lambda}{\sqrt{-2mE}}\right)\right) +$$

$$+ (ig_S)(ig_T)i\frac{m_+}{\pi^2}\left(-\Lambda + \sqrt{-2m_+(E-\Delta)}\arctan\left(\frac{\Lambda}{\sqrt{-2m_+(E-\Delta)}}\right)\right)$$

We have to introduce a physical cutoff Λ in this calculation if we want to use the Landau* coupling g_T, which is defined for meson pairs recoiling at very low energy (this introduces a dependency of g_{mix} on B)

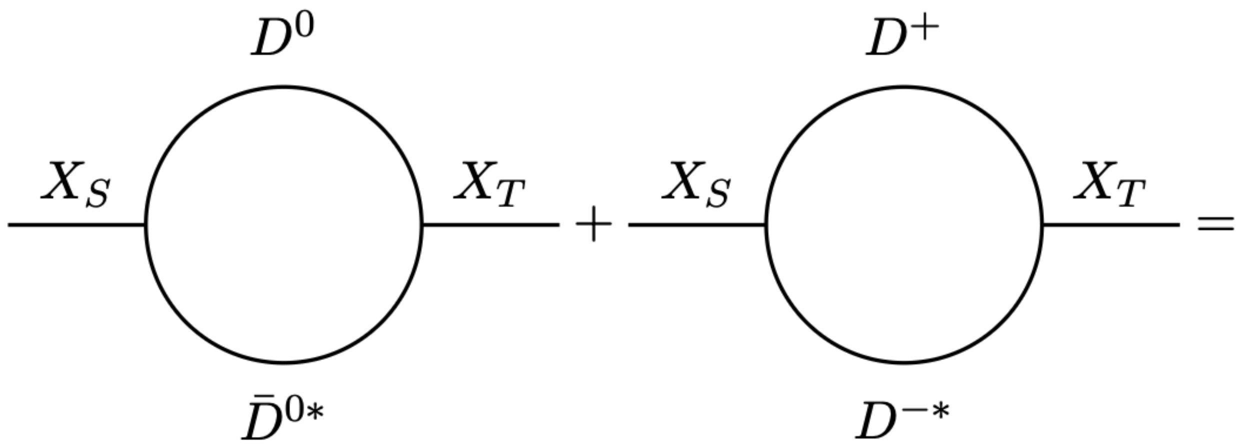
$$g_T^2 = \frac{2\pi}{m}\sqrt{\frac{2B}{m}}$$

*Esposito, Germani, Glioti, ADP, 2502.02505 (review); and ADP *Phys.Lett.B* 746 (2015) 248-250

The mixing mechanism

Both X_S and X_T couple to $D\bar{D}^*$

$(-ig_{\text{mix}}) =$



$$= (-ig_S)(ig_T)i\frac{m}{\pi^2}\left(-\Lambda + \sqrt{-2mE}\,\arctan\left(\frac{\Lambda}{\sqrt{-2mE}}\right)\right) +$$
$$+ (ig_S)(ig_T)i\frac{m_+}{\pi^2}\left(-\Lambda + \sqrt{-2m_+(E-\Delta)}\,\arctan\left(\frac{\Lambda}{\sqrt{-2m_+(E-\Delta)}}\right)\right)$$

As for Λ we expect

$$\Lambda \simeq k_{\text{max}} \sim \langle k \rangle + \Delta k = \sqrt{2mB} + \Delta k = \frac{3}{2}\sqrt{2mB}$$

We will compare this with the what obtained from the loop calculation and $g_{\text{mix}}(B)$

Isospin violating decays

The role of X_S and X_T

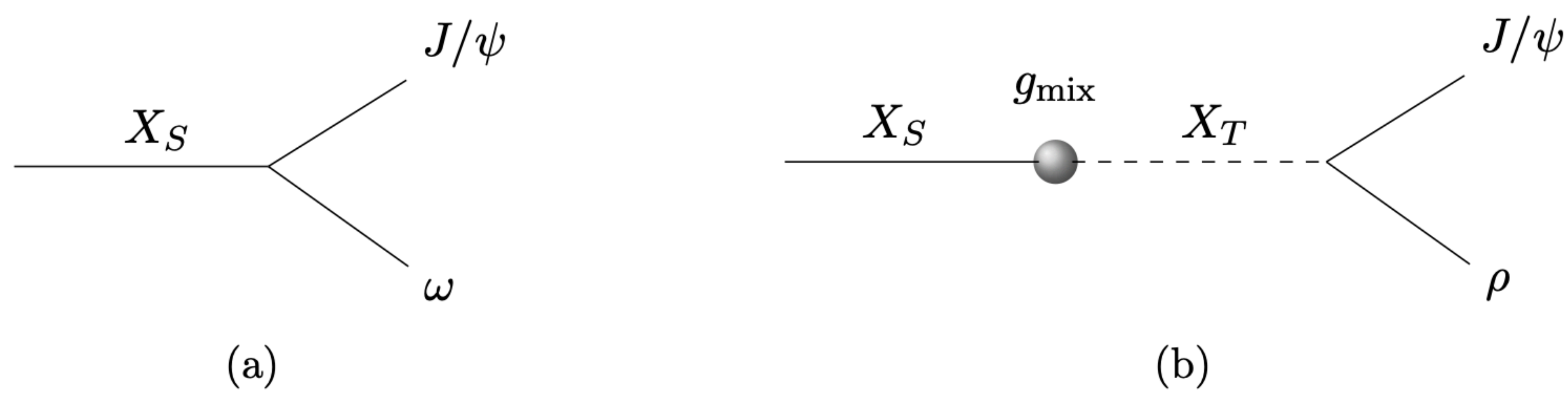


Figure 1: Decay mechanisms for $X(3872) \to J/\psi V$ with $V = \rho, \omega$. (a) Isospin-conserving decay. (b) Isospin-violating decay induced by mixing with the isotriplet.

$$\mathcal{I} = \frac{\Gamma(X \to J/\psi\, \pi^+\pi^-\pi^0)}{\Gamma(X \to J/\psi\, \pi^+\pi^-)} = \left| \frac{g_{\rm mix}}{E_T + i\frac{\Gamma_T}{2}} \right|^{-2} \frac{\alpha\, |G_\omega|^2}{\Gamma(X_T \to J/\psi \pi^+\pi^-)}$$

$$E_T = m_{X_S} - m_{X_T} \equiv m_X - (m_D + m_D^* - B) = (m_X - m_D - m_D^*) + B \equiv E + B$$

$\alpha =$ 3-body $(\omega \to 3\pi)$ phase space factor

Determination of g_{mix}

The role of X_S and X_T

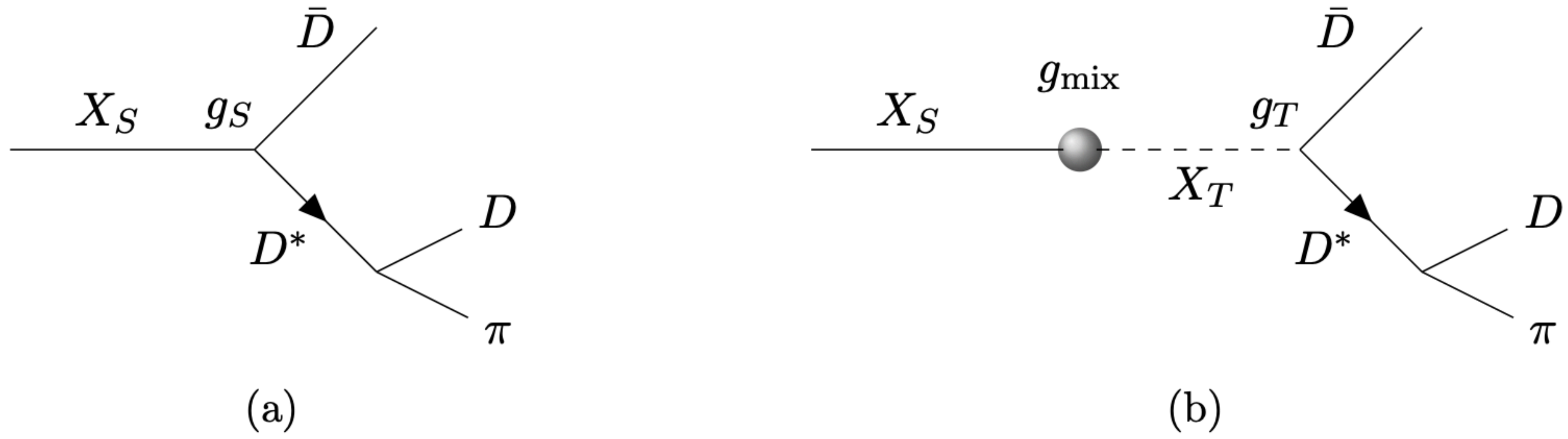


Figure 4: Decay diagrams for $X_S \to D\bar{D}\pi$. (a) Direct decay. (b) Decay via isospin mixing through X_T.

$$g^2 \propto \left| g_S - \frac{g_{\text{mix}}\, g_T}{E + B + i\Gamma_T/2} \right|^2$$

Two solutions for $g_{\text{mix}}(B)$

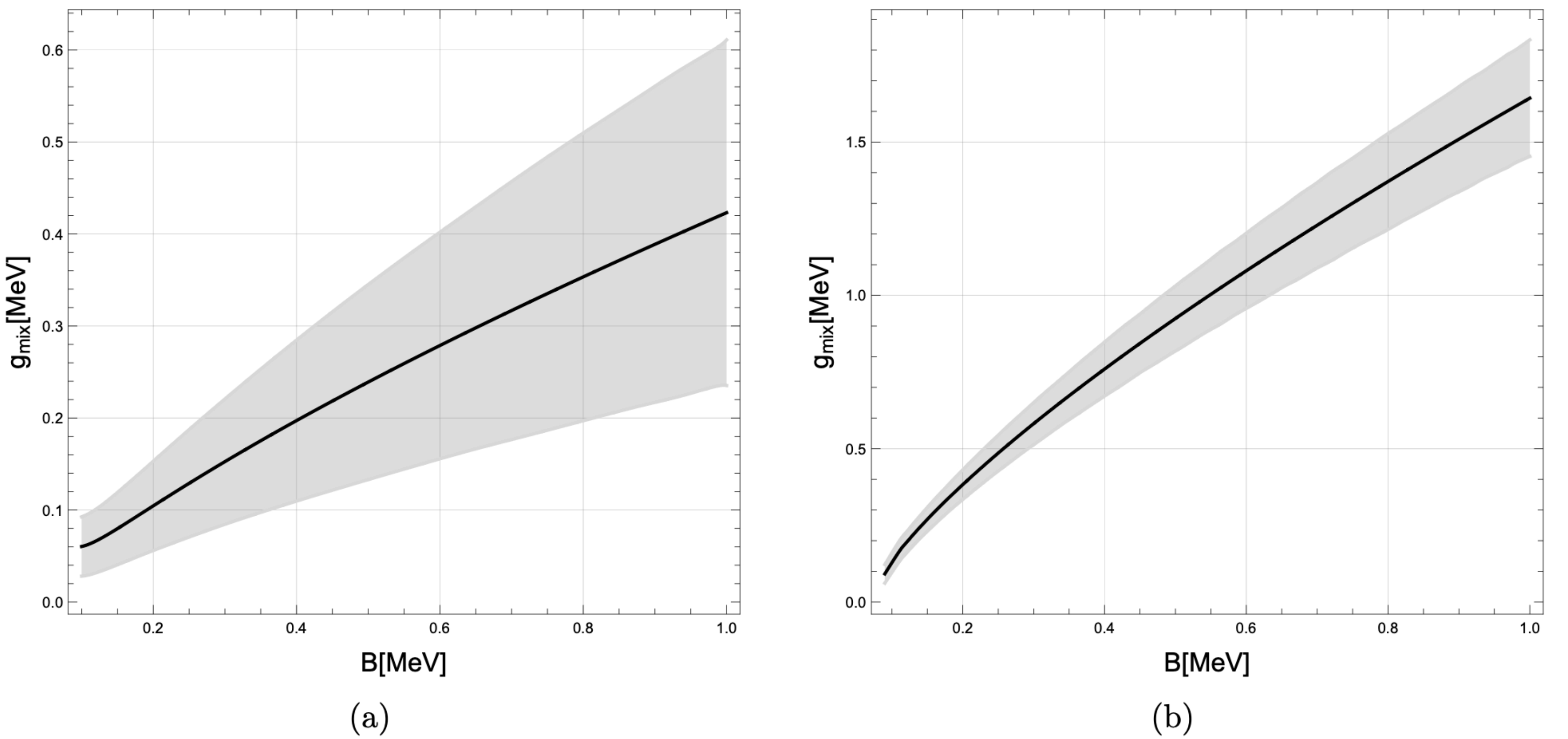


Figure 5: g_{mix} as a function of B for the two solutions found. The black line represents the central value of g_{mix} and the gray region contains the values within one sigma.

Two solutions for g_{mix}, as a function of the unknown parameter B, are possible from $X \to DD\pi$ — we will use the r.h.s. $g_{\text{mix}}(B)$.

Two solutions for $g_{\text{mix}}(B)$

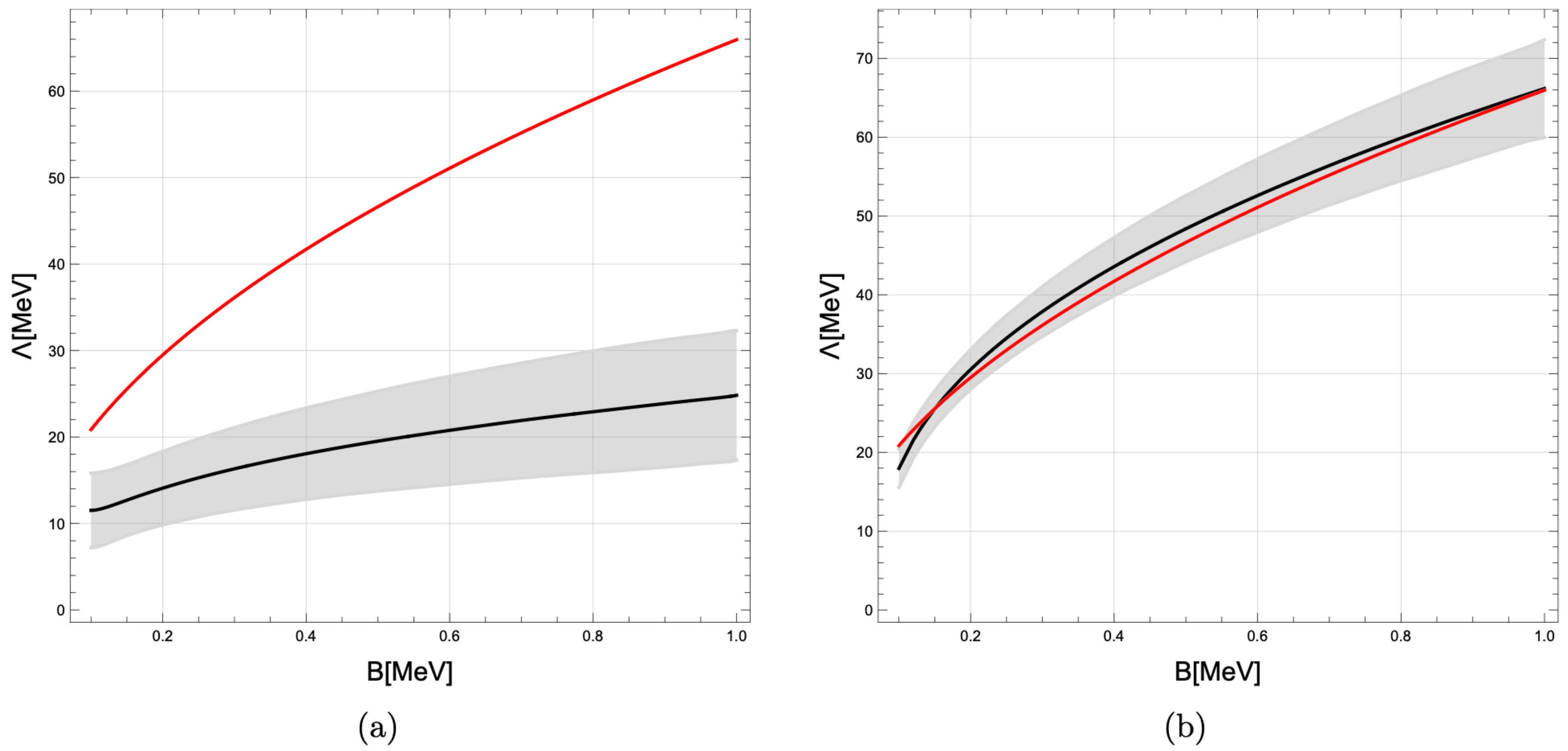


Figure 10: Λ as a function of B for the two solutions of g_{mix}. The black line represents the central value of Λ and the gray region contains the values within one sigma. The red line marks the values obtained through the estimate in Eq. (42).

(red line) $\Lambda \simeq = \frac{3}{2}\sqrt{2mB}$

Determination of $\mathscr{I}$

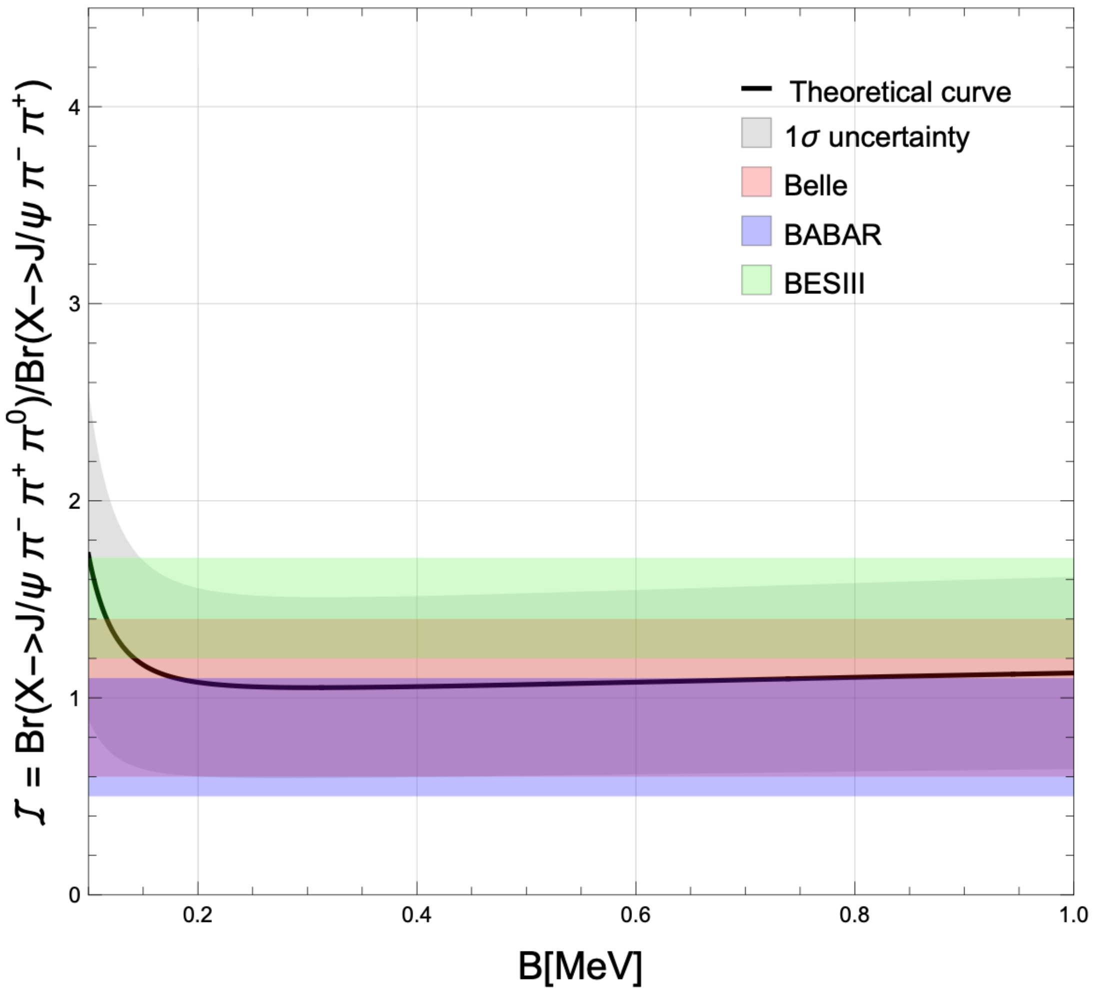


Figure 6: $\mathscr{I}$ as a function of B for the solution $g_{\rm mix}$ shown in Fig. 9b. The black line represents the central value of $\mathscr{I}$ obtained from Eq. (38), with the 1σ uncertainty band shown in gray. The horizontal bands correspond to the experimental values in Eq. (1).

One of the two $g^{II}_{\rm mix}$ works well to explain the $\mathscr{I}$ ratio as in figure.

The $X_T \to J/\psi\rho$ decay

There is no data on the X_T decay, because this particle is not produced at colliders (if not through the mixing).

We model the decay as dominantly given by the light quark-antiquark annihilation into a virtual γ which subsequently converts into ρ^0 by VMD.

We apply the same method we used to describe the $X \to \psi\gamma$ decays*

*L. Maiani, B. Grinstein, A.D.P., *Phys.Rev.D* 109 (2024) 7, 074009

The Z particles reversed pattern

In the case of the X system we have that:

X_S is a compact tetraquark state whereas X_T is a loosely bound molecule together with two charge partners — unobservable.

In the case of the Z system

Z_T are compact tetraquarks (all visible) and Z_S is a singlet molecule — unobservable.

What is the role of C in all this **?**

Isospin violations in Z decays

The Zs' feature a reversed pattern with respect to the X

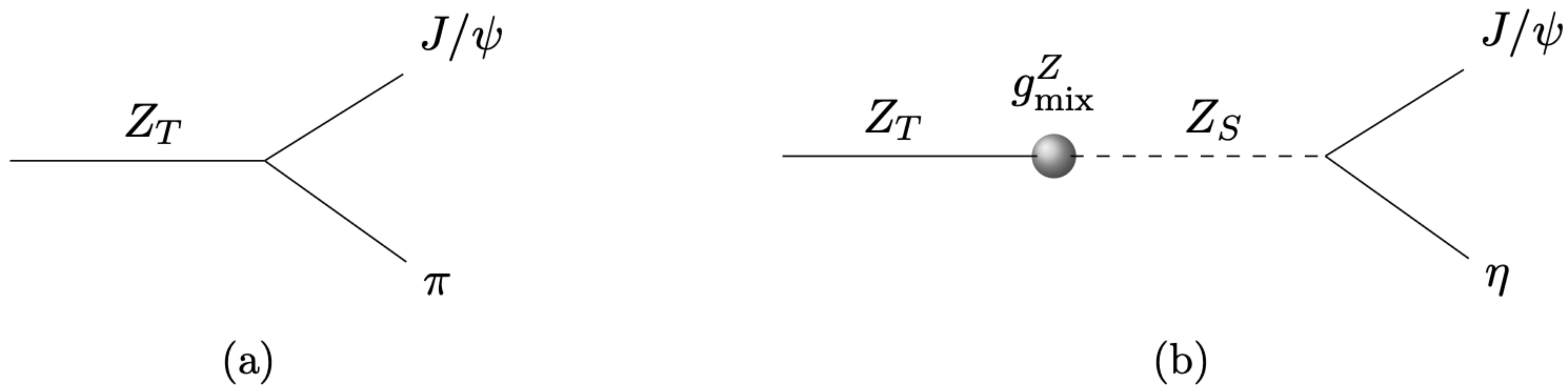


Figure 13: Decay mechanisms for $Z(3900) \to J/\psi\, P$ with $P = \pi, \eta$. (a) Isospin-conserving decay. (b) Isospin-violating decay induced by mixing with the isosinglet.

$$\mathcal{I}_Z = \frac{\text{Br}(Z(3900) \to J/\psi\, \eta)}{\text{Br}(Z(3900) \to J/\psi\, \pi)} < 0.15 \quad \text{[BESIII]}$$

Isospin violations in Z decays

The $\boldsymbol{Z}$s' feature a reversed pattern with respect to the $\boldsymbol{X}$

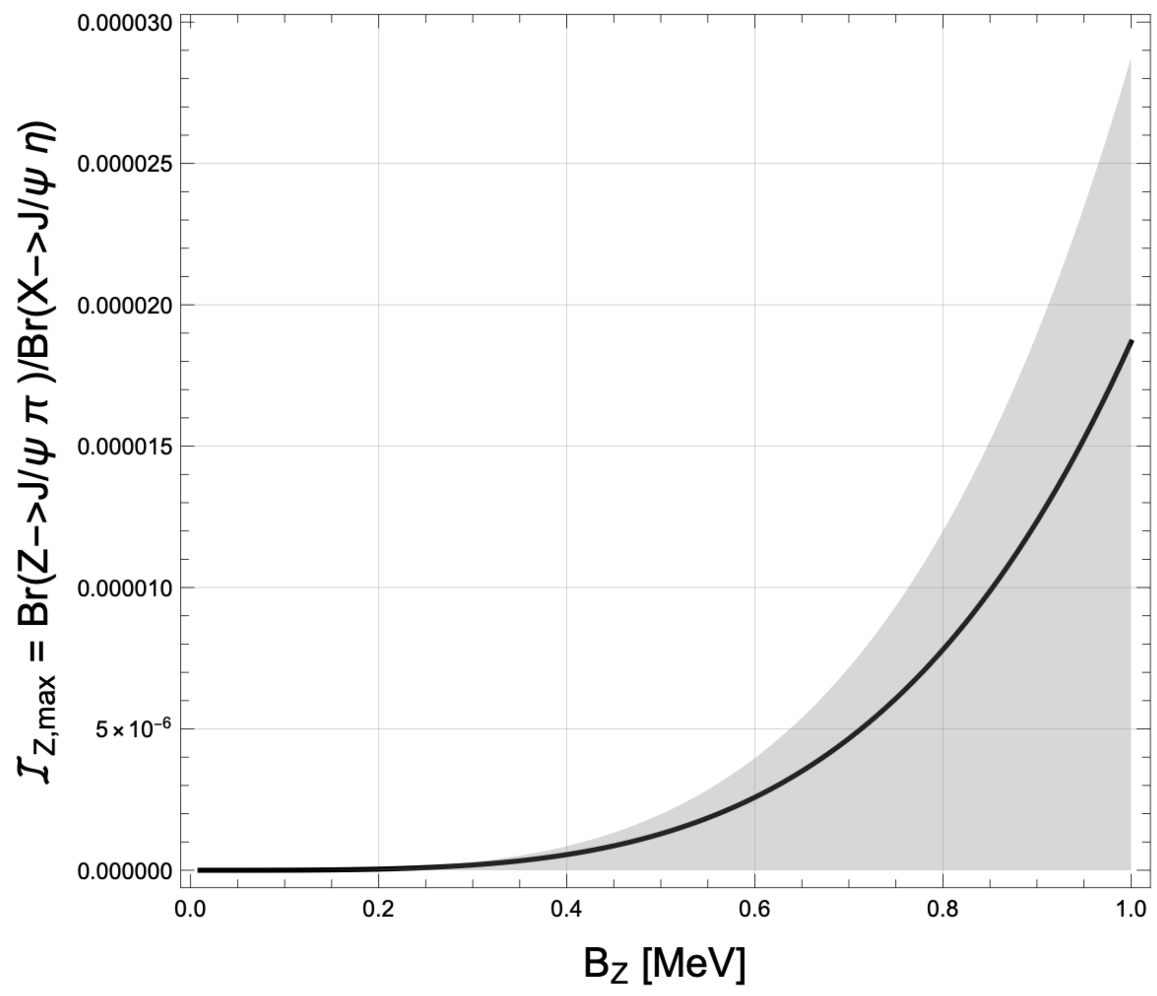


Figure 14: $\mathscr{I}_{Z,\max}$ as a function of B_Z. The black line represents the central value of $\mathscr{I}_{Z,\max}$ and the gray region contains the values within one sigma.

Conclusions

The mirroring patterns

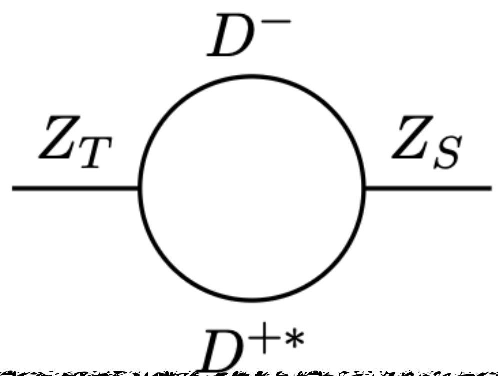
- Loosely bound molecules are not efficiently produced at high energy colliders — unobservable at high energy — what about heavy ion collisions?
- $X(3872)$ corresponds to an X_S compact iso-singlet. In the iso-triplet configurations quarks arrange into loosely bound color neutral states. The neutral component of the molecular isotriplet corresponds to the X_T.
- $X_S \to X_T$ oscillations explain the isospin violation observed. Consistency with $X_S \to D\bar{D}\pi$ decays is found.
- In the case of Z particles the pattern is reversed. The unobservable molecular component is the iso-singlet Z_S.
- No isospin violation expected in the Z system.
- This analysis can be extended to the known exotic spectroscopy.

Backup

Isospin violations in Z decays

The Zs' feature a reversed pattern with respect to the X

$g^Z_{\text{mix}} =$



$$= g^Z_T\, g^Z_S\, \frac{m_+}{\pi^2}\left(\Lambda_Z - \sqrt{-2m_+E_Z}\ \text{arctan}\frac{\Lambda_Z}{\sqrt{-2m_+E_Z}}\right)$$

$$E_Z = m_Z - m_{D^{+*}} - m_{D^-} = 7.3 \pm 2.6\ \text{MeV}$$

The close charged threshold (from below!)

$$g^Z_{\text{mix}} = g^Z_T\, g^Z_S\, \frac{m_+}{\pi^2}\left(\Lambda_Z - \sqrt{2m_+E_Z}\ \text{arctanh}\frac{\Lambda_Z}{\sqrt{2m_+E_Z}}\right).$$

THE BORN-OPPENHEIMER APPROXIMATION AND – COMPACT – TETRAQUARKS

BORN-OPPENHEIMER FOR MOLECULES

$$(T_e(p) + T_N(P) + V(x,X))\,\Psi = E\,\Psi$$

Neglect T_N. Discrete spectrum, normalizable states $(\Psi,\Psi)=1$.
Switching off T_N converts Ψ into Φ^n_X with continuum normalization.

$$\Big(T_e(p) + V(x,X)\Big)\Phi^n_X = \mathscr{E}_n(X)\,\Phi^n_X$$

$$(\Phi^n_X, \Phi^m_Y) = \delta^{nm}\prod_{N,i}\delta(X_{N,i} - Y_{N,i})$$

Eventually the solution Ψ can be expressed in terms of the Φ^n_X **complete set,** where all the electron dynamics is contained

$$\Psi = \int dX\,\Psi_n(X)\,\Phi^n_X$$

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The $\mathbf{\Phi}_X^n$ can be written in turn as

$$\Phi_X^n = \int dx\, \psi_n(x, X)\, \Phi_{x,X}$$

so as the equation to solve to construct the $\mathbf{\Phi}_X^n$ is

$$(T_e(-i\nabla_x) + V(x, X))\, \psi_n(x, X) = \mathscr{E}_n(X)\, \psi_n(x, X)$$

$\mathscr{E}_n(X)$ can be obtained by a variational principle, i.e. minimizing $\langle T_e + V(x, X) \rangle_{\psi_n}$, while holding X fixed. The $\mathscr{E}_n(X)$ obtained is then inserted back into the nuclear part **in place of** T_e and V

$$\Big(T_N(-i\nabla_X) + \mathscr{E}_n(X)\Big)\Psi_n(X) = E\, \Psi_n(X)$$

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Deducing the latter equation requires to apply T_N on Φ_X^n and in turn on $\psi_n(x, X)$ and $\Phi_{x,X}$ (where $P_{Ni}\Phi_{x,X} = i\hbar\frac{\partial}{\partial X_{Ni}}\Phi_{x,X}$)

The BO approximation consists in dropping the gradient

$$\nabla_{X_{Ni}}\psi(x, X) \simeq 0$$

which is motivated by

$$\Psi_n(X)\,\nabla_{X_{Ni}}\psi(x, X) \sim \left(\frac{m}{M}\right)^{1/4}\psi(x, X)\,\nabla_{X_{Ni}}\Psi_n(X)$$

BORN-OPPENHEIMER FOR MOLECULES

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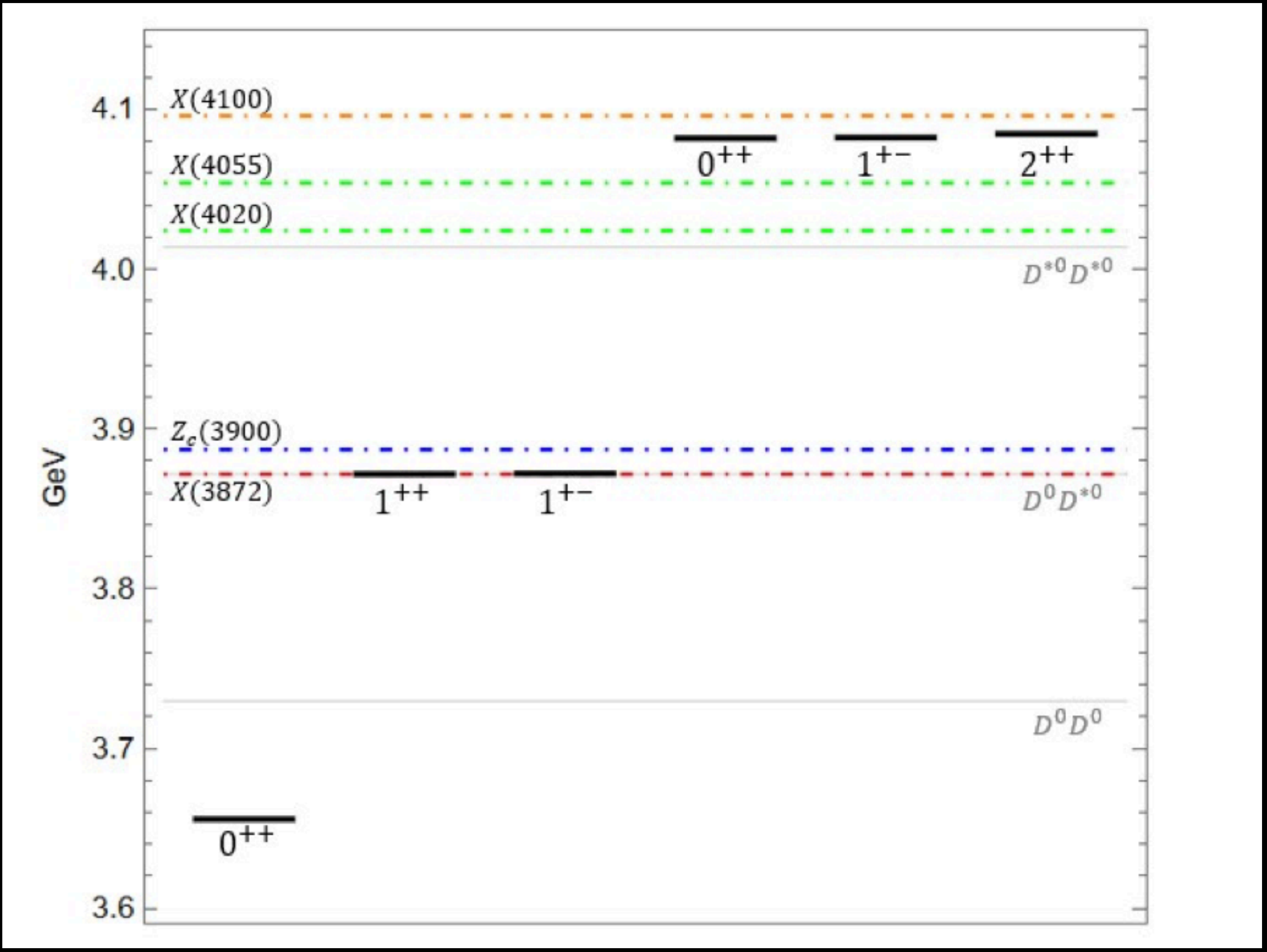
used to obtain

$$\Big(T_N(-i\nabla_X) + \mathscr{E}(X)\Big)\Psi(X) = E\,\Psi(X)$$

The B.O. Tetraquark spectrum



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