

MENU 2026 · STONY BROOK

Exotic Hadrons at Twenty

Elementarity and Compositeness in Particle Physics

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with A. Carducci, G. Cianti, P. D'Annibali, A. Esposito, D. Germani, A. Glioti, B. Grinstein

— Graphics done with Claude

The X(3872), twenty years on

Discovered by Belle in 2003: a narrow 1^{++} state sitting *exactly* at the $D^0\bar{D}^{*0}$ threshold, decaying mostly to $D^0\bar{D}^0\pi^0$.

X(3872)

- $B = m_D + m_D^* - m_X = 0.05 \pm 0.09$ MeV
(the strongest motivation, and weakness, of the molecule interpretation)
- Size $\gtrsim 10$ fm, if a $D\bar{D}^*$ bound state
- $\Gamma \lesssim 100$ keV
- Promptly produced up to $p_T \approx 50$ GeV
- Large R_{AA} (≥ 1) in Pb–Pb collisions
- Large isospin violations ($J\rho/J\omega$)

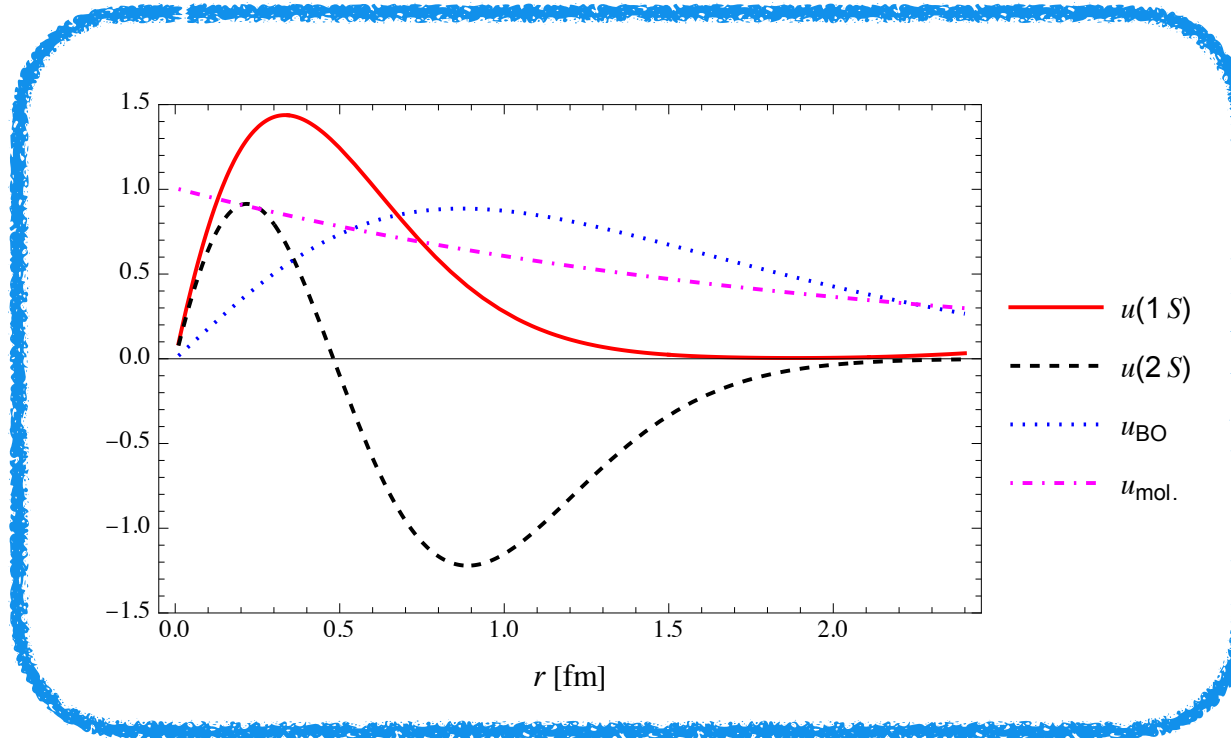
Deuteron (np)

- $B = 2.2$ MeV — the archetypal shallow bound state
- Size ≈ 4.3 fm
- Effective range $r_0 = +1.73$ fm, measured in np scattering. According to the Weinberg criterion, the deuteron is (almost) entirely a molecule.
- Never observed at high p_T

If the X is a $D\bar{D}^*$ molecule, it is like an even shallower deuteron.

The analogy can be made quantitative, studying the lineshape of the X.

The question about radiative decay



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

$$\Psi_{\mathfrak{B}}(r) = \frac{1}{\sqrt{2\pi R_0}} \frac{\exp(-r/R_0)}{r} \quad \mathcal{R}_{\mathfrak{B}}^{\text{th.}} \approx \frac{1}{30} \mathcal{R}^{\text{exp.}}$$

The argument, and the plan of the talk

1

Compositeness is a statement about the Lagrangian

Elementary or composite means: which fields appear in $\mathcal{L}_{\text{eff}}$.

The effective Lagrangian $\mathcal{L}_{\text{eff}}$ is postulated, as is the nature of the X . Test the hypothesis on data.

*Kaplan, Nucl. Phys. B 494 (1997) 471

**Carducci, Cianti, D'Annibali, Germani, ADP, arXiv:2605.12274. To appear in Phys. Rev. D

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The Weinberg criterion, as applied to LHCb data

One cannot use the universal scattering amplitude $f_{\ell=0}(\alpha \rightarrow \beta)$ reliably: too few data at $k \simeq 0$. The **Flatté amplitude** is used instead, valid at higher k values too, where the charged threshold needs to be included. But Flatté is derived from an $\mathcal{L}_{\text{eff}}$ with an *elementary* X field. *The fit is very good and the fact that it gives a negative effective range (r_0) is circular: it says little about a molecular nature, except that the opposite, compact hypothesis works!*

$$f(\alpha \rightarrow \beta) = \frac{1}{-\frac{1}{a} + \frac{1}{2} r_0 k^2 - i k}$$

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A molecular amplitude with no free coupling

Therefore we propose to change $\mathcal{L}_{\text{eff}}$. An **auxiliary field with the wrong-sign kinetic term*** (D.B. Kaplan) is introduced for the X , fixing the coupling of the would-be molecule to its constituents at the Landau value**. The method is tested on the deuteron effective range from np scattering.

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Production is where the analogy ends

High- p_T yields and Pb–Pb data cannot be reproduced by counting comoving $D\bar{D}^*$ pairs — pointing to a compact core (with a molecular tail).

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Elementary or composite: ask the Lagrangian

Compact (elementary) X

$$\mathcal{L} \supset X^\dagger \left(i\partial_t + \frac{\nabla^2}{2m_X} \right) X + g X^\dagger (D\bar{D}^*) + \text{h.c.}$$

- the X is a field of the (NR)EFT, *as elementary as* $D, \bar{D}^*$
- its coupling g is purely phenomenological
- $\Rightarrow$ Flatté-type lineshape: we will call it $f_-(E)$.
The coupling g is fitted to the data

Molecular (dynamical) X

$$\mathcal{L} \supset -\frac{\lambda}{2} (D\bar{D}^*)^\dagger (D\bar{D}^*) \text{ — no } X \text{ field at all}$$

- the pole is generated by resummed $D\bar{D}^*$ bubbles
- the coupling to the constituents is fixed by the shallow pole: the Landau coupling value $g_B^2 = \frac{2\pi}{m} \sqrt{\frac{2B}{m}}$
- (we will rather introduce an auxiliary field* with a coupling to the constituents dictated by $g_B \Rightarrow$ a different lineshape.
— we call it $f_+(E)$)

We use neither of these. The derived fit function is not neutral: it encodes a structural hypothesis about the pole.

*Kaplan, Nucl. Phys. B 494 (1997) 471 · Carducci, Cianti, D'Annibali, Germani, ADP, arXiv:2605.12274. To appear in Phys. Rev. D

Weinberg's criterion and Landau's coupling (in a nutshell)

$$|X\rangle = \sqrt{Z} |\mathfrak{X}\rangle + \sqrt{1-Z} |\mathfrak{B}\rangle$$

Z = probability of finding the compact state in the physical state (QM) = the normalization constant squared of the field X (QFT). Two states are allowed here (where is the second?!)

$$g_{\mathfrak{B}D\bar{D}^*}^2 = \frac{2\pi}{m} \sqrt{\frac{2B}{m}} (1-Z)$$

Coupling of the $\mathfrak{B}$ state to its $D\bar{D}^*$ constituents (m = reduced mass, B = binding energy) in the presence of a compact state $\mathfrak{X}$. At $Z = 0$ it is Landau's universal value g_B^2 — fixed, not fitted.

$$r_0 = -\frac{Z}{1-Z} \frac{1}{\sqrt{2mB}} + O\left(\frac{1}{\Lambda}\right) \qquad a = \frac{2(1-Z)}{(2-Z)} \frac{1}{\sqrt{2mB}} + O\left(\frac{1}{\Lambda}\right)$$

Observable consequence: a bound state ($Z = 0$) has r_0 small (and positive|single channel); an elementary admixture drives r_0 large and negative.

Two measurable numbers, a and r_0 decide — **provided the amplitude** used to extract them **does not prejudge the answer** (and provided there is no more than one ‘channel’). The **universal** f at $k \rightarrow 0$ does not prejudge.

What LHCb actually fits: the Flatté amplitude

$$f_-(E) = -\frac{mg^2}{2\pi} \frac{1}{E - \Delta + i\frac{mg^2}{2\pi} \left(\sqrt{2mE} + i\sqrt{-2m(E - \delta)} \right) + i\frac{\Gamma_r}{2}}$$

Neutral and charged ($\delta \simeq 8.2$ MeV) $D\bar{D}^*$ thresholds; Γ_r = inelastic width. Derived from the EFT with an elementary X and *no* $(D\bar{D}^*)^2$ interaction.

What the fit returns

- $g_{\text{LHCb}} = 0.108 \pm 0.003$, excellent fit quality
- $r_0 \simeq -5.34$ fm $a \simeq +28$ fm
- pole counting $\Rightarrow$ “ $Z \simeq 0.15$ ”, read as a (mainly) molecular X

What the amplitude misses

- no quartic $(D\bar{D}^*)^2$ coupling $\Rightarrow$ no bound state can form
- g is not a function of B or Z
- $r_0 < 0$ is built into the parametrization, so it is no surprise that it is found negative. Some argued that the actual r_0 is smaller than the number reported by LHCb.

LHCb, Phys. Rev. D 102 (2020) 092005

A good Flatté fit is a successful test of the elementary hypothesis — not of the molecular one.

The circularity

The molecular conclusion is drawn from a fit that assumes the opposite — and the fit works well. Yet the following number has been much discussed:

$$r_0^- \simeq -\frac{2\pi}{m^2 g^2} - \frac{1}{\sqrt{2m\delta}} = (-3.84 - \cancel{1.6}) \text{ fm}$$

Negative by construction. Comparing it with Weinberg's $r_0(Z)$ reproduces the assumption; it does not test it.

Consistency check of the elementary hypothesis: taking the X purely compact, the fitted coupling $g = (1.87 \pm 0.03) \times 10^{-2} \text{ MeV}^{-1/2}$ reproduces the measured $\Gamma(X \rightarrow D^0 \bar{D}^0 \pi^0)$ for $\Gamma(D^{*0}) = 105 \pm 70 \text{ keV}$ — right where it is expected ($\Gamma(D^{*\pm}) = 83.4 \pm 1.8 \text{ keV}$).



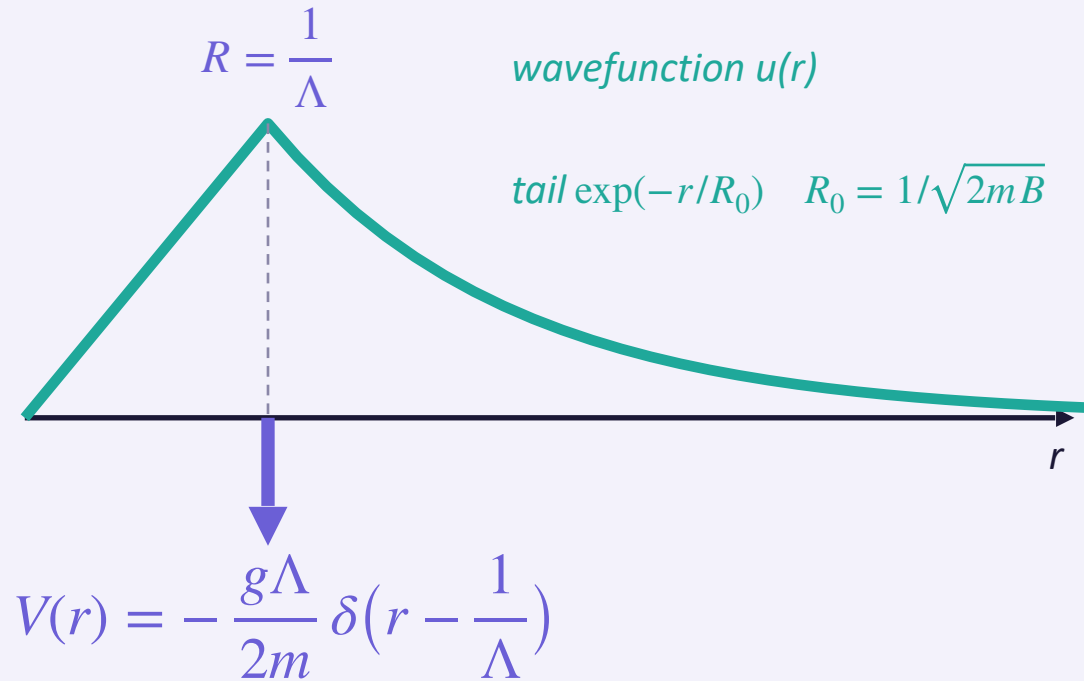
II

An amplitude for a true molecule

The deuteron as a benchmark

The delta-shell model (the QM side)

A simple quantum mechanical model: the whole interaction sits on a thin spherical shell.



Two parameters

g : strength of the attraction. $\Lambda = 1/R$: inverse range of the force. A bound state needs a deep enough shell ($g \geq 1$), like a square well.

Fixed by data

The pole sits at the binding energy B , and a_0 fixes the other parameter. Then r_0 is a prediction.

Exactly solvable

We know how to solve this exercise exactly in QM (e.g. Gottfried). **Closed-form amplitude.**

Why it is useful: Λ is a physical scale (the exchanged particle's momentum). $\Lambda \rightarrow \infty$ gives back the zero-range contact theory; finite Λ mimics pion exchange. The relation with B is $g = (\sqrt{4mB}/\Lambda)/(1 - \exp(-\sqrt{4mB}/\Lambda))$

An auxiliary field with the wrong sign (the NREFT side)

$$\mathcal{L} = N^\dagger \left(i\partial_t + \frac{\nabla^2}{2M} \right) N + \sigma \Phi^\dagger \left(i\partial_t + \frac{\nabla^2}{4M} - \Delta \right) \Phi - (y \Phi^\dagger N N + h.c.) - \frac{1}{2} C (N^\dagger N)^2 \quad (\sigma = -1)$$

Written for nucleons $N = (p \ n)$ and a Φ dibaryon/deuteron field with (bare) mass $2M + \Delta$. Replacing $n, p \rightarrow D, \bar{D}^*$ and $\Phi \rightarrow X$ gives the amplitude for a molecular X .

1

Φ is a bookkeeping device

It never appears on external legs or in loops: unitarity is safe.

Add the zero $\Delta\mathcal{L} = (\Phi - F(\Psi))^2$ at the stationary point $\Phi = F(\Psi)$ of the path integral for Φ . Define $\Delta\mathcal{L} \equiv \mathcal{L}_\Phi^{\text{free}} + \Delta\mathcal{L}_{\text{int}}$ and $\mathcal{L}_N \rightarrow \mathcal{L}_N + \Delta\mathcal{L}_{\text{int}}$

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$\sigma = -1$ is what binding requires

The wrong-sign kinetic term allows to have $y^2 > 0$ and $g > 0$ (need $g \geq 1$ to have bound states).

In addition it fixes the sign of the effective range $r_0 > 0$.

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Matching (y, Δ) with QM (g, Λ)

The coupling y and the parameter Δ are independent in $\mathcal{L}$, but matching with QM we have $y = f_1(g, \Lambda)$ and $\Delta = f_2(g, \Lambda)$.

Once the f_+ amplitude is derived on the basis of $\mathcal{L}$, we also get $a = g_1(y, \Delta)$ and $r_0 = g_2(y, \Delta)$.

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The coupling y is not free — the deuteron

The amplitude f_+ can be cast in the $(E + B)^{-1}$ polar form, with pole at $y_\star = \lambda\sqrt{2} g_B$ (with $\lambda = \sqrt{(\Delta + B)/4B}$).

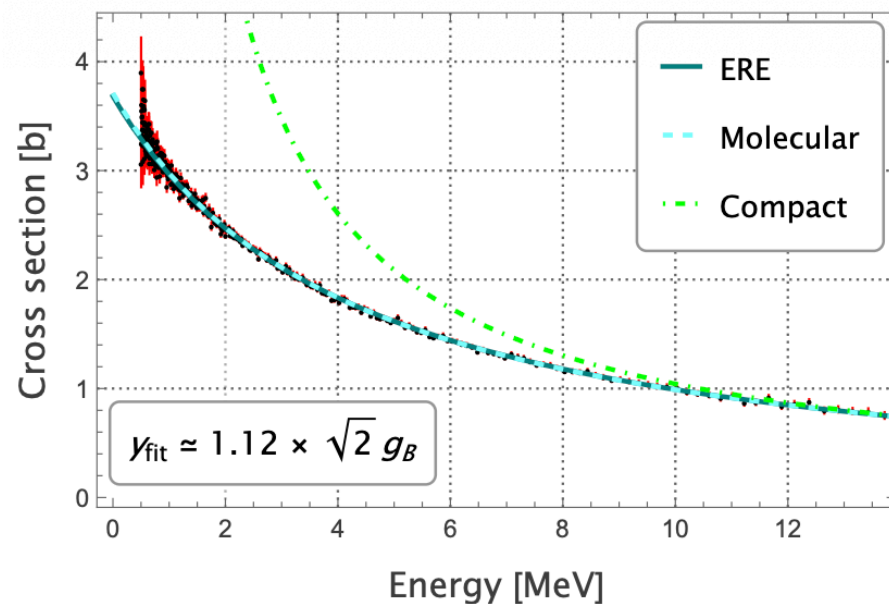
The residue at the pole is $(\alpha\sqrt{2} g_B)^2$ (with $\alpha = \lambda/\sqrt{2\lambda^2 - 1}$).

Δ can be expressed in terms of y and a (g_1 —matching with QM). From a_{exp} we find $\lambda = 1.12$ and $\alpha = 0.9$.

The deuteron passes, with no free parameters

Input: only $a_{\text{exp}} = 5.42$ fm and $B = 2.22$ MeV.

Fitting np spin-triplet cross sections with the molecular amplitude f_+ :



predicted

$$r_0 = \frac{2\pi}{m^2 y_{\star}^2} = +1.73 \text{ fm}$$

measured in np scattering

$$r_0^{\text{exp}} = +1.73 \text{ fm}$$

*the canonical signature of a bound state,
obtained with the coupling fixed at the Landau value*

The same test for the X(3872)

$$f_+(E) = -\frac{my^2}{2\pi} \frac{1}{E - \Delta - i\frac{my^2}{2\pi} \left(\sqrt{2mE} + i\sqrt{-2m(E - \delta)} \right) - i\frac{\Gamma_r}{2}}$$

Same structure as Flatté up to signs — but a different EFT: the pole is dynamically generated, and y is constrained, not free.

$$r_0^+ = \frac{2\pi}{m^2 y^2} - \frac{1}{\sqrt{2m\delta}} \implies r_0^+ \geq -1.58 \text{ fm}$$

The sign of the effective range follows from the parametrization itself: compositeness inference must be tied to the chosen amplitude.

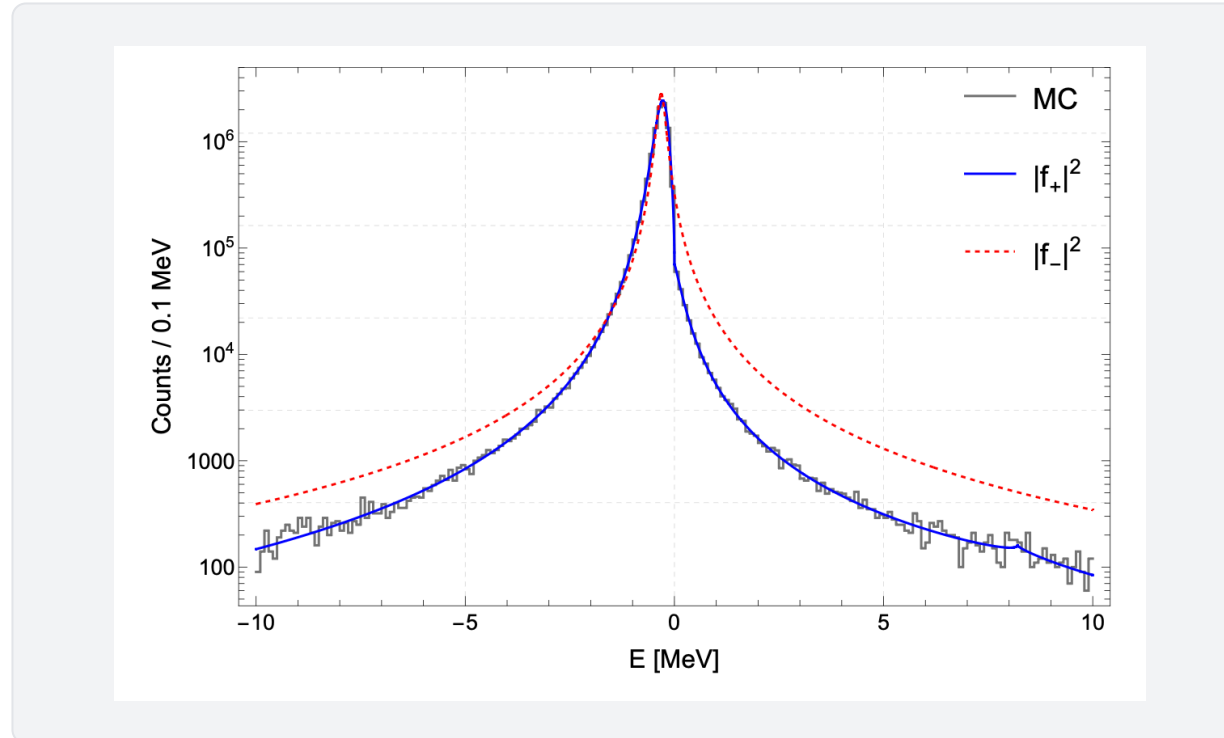
The proposal: fit the LHCb lineshape with f_+ , requiring y matching the Landau value g_B . If X is deuteron-like, a good fit at that coupling is unavoidable — its failure would disfavor the molecule. Not yet performed on data. (It has been argued that such a fit should not even be tried (it amounts to changing a sign!), because of the “clockwise rotation of the phase shift in the Argand diagram”. Indeed, the deuteron itself rotates clockwise!)

Carducci, Cianti, D’Annibali, Germani, ADP, arXiv:2605.12274. To appear in Phys. Rev. D

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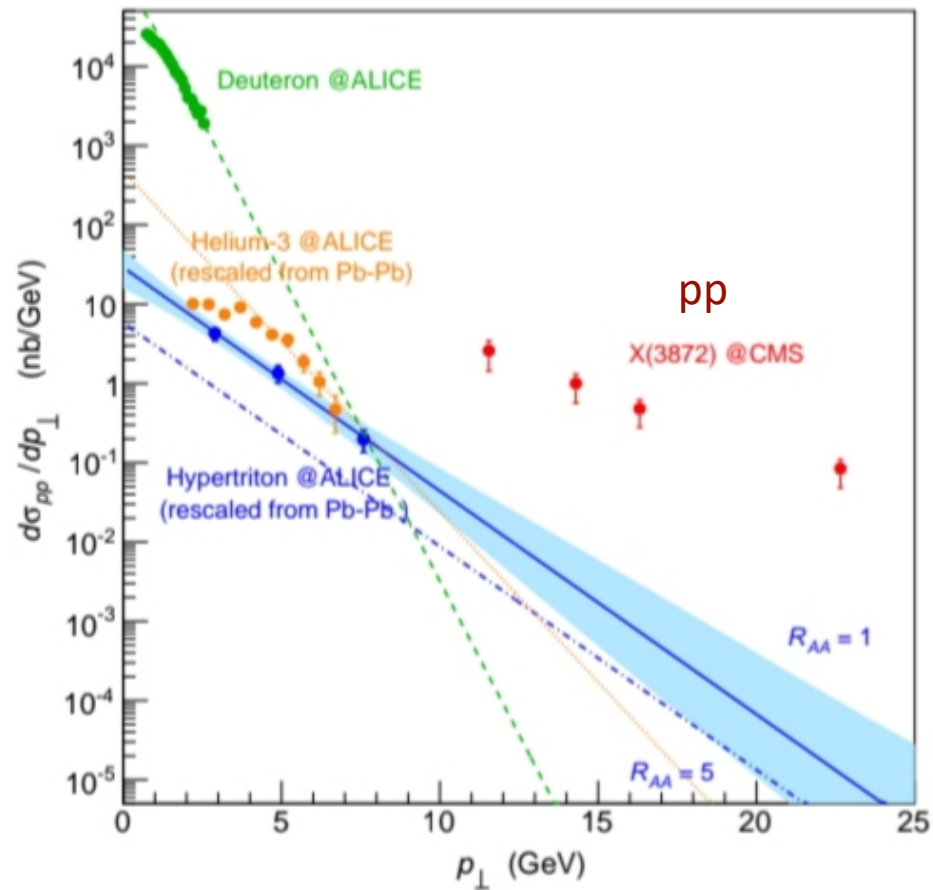


III

Production: where the analogy ends

High transverse momentum, and the Pb–Pb counting problem

The production test



Prompt production vs transverse momentum $p_{\perp}$ in pp collisions
[a brief story about Tom Mehen]

Deuteron and light nuclei

Loosely bound objects are easily broken at high momentum: the yield falls exponentially.

X(3872) at CMS

The yield decreases slowly, just like $\psi(2S)$, a genuine elementary charmonium.

Numerical simulations do not support it either

Even allowing very high relative momenta in the center of mass.

A shallow molecule at $p_T = 15 - 50$ GeV? (News from Pb–Pb)

A molecule bound by $B \leq 0.1$ MeV holds its constituents at

$$p \simeq \sqrt{2\mu B} \simeq 14 \text{ MeV}$$

a fragile, ≈ 10 fm object. No mechanism can assemble it copiously — indeed, no deuteron has ever been seen promptly at these p_T .

In Pb–Pb collisions the constituents N pairs of the would-be molecule can come from the *same* pp vertex or from two *different* vertices.

They bind with probability P

$$N_X^S = P N_{\text{thr}}^S \quad (S = \text{PbPb}, pp)$$

$$N_{\text{thr}}^{\text{PbPb}} = R_{AA}^{\text{pair}} (N_{\text{coll}} N_{\text{thr}}^{pp}) + N^{\text{comb}}$$

Yet CMS, in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV:

$$\rho \equiv \frac{\sigma(X) \mathcal{B}(X \rightarrow 2\pi J)}{\sigma(\psi(2S)) \mathcal{B}(\psi(2S) \rightarrow 2\pi J)}$$

$$\rho^{pp} \approx 0.08 \quad \text{and} \quad \rho^{\text{PbPb}} = 1.08 \pm 0.71$$

an order-of-magnitude enhancement of prompt X over $\psi(2S)$,
implying

$$R_{AA}(X) \equiv \frac{N_X^{\text{PbPb}}}{N_{\text{coll}} N_X^{pp}} = \frac{\rho^{\text{PbPb}}}{\rho^{pp}} R_{AA}(\psi(2S))$$

which is 2–3, using $R_{AA}(\psi(2S)) \approx 0.2 - 0.3$

$$N_X^S \mathcal{B}_X = \rho^S (N_{\psi(2S)}^S \mathcal{B}_{\psi(2S)})$$

If molecular, the X forms after freeze-out

formation time of the molecule

$$\tau \simeq \frac{\gamma}{2B} \geq 10^4 \text{ fm}$$

$$\gamma = \frac{p_T}{m_X} \simeq 4 - 13 \text{ in the CMS window}$$

$\gg$

lifetime of the fireball

$$\tau_F \approx 10\text{--}20 \text{ fm}$$

hadronic phase included!

Resolving a state bound by B takes one orbital period, $T \sim R/v = (1/\underbrace{\sqrt{2\mu B}}_p)(\mu/\sqrt{2\mu B}) = 1/2B$, dilated by the boost.

The medium is gone three orders of magnitude before the molecule exists: the D and $\bar{D}^*$ leave the fireball as ordinary mesons and bind in vacuum, *with the same probability P as in pp .*

$\implies P$ cancels in the $Pb\text{--}Pb / pp$ ratio: the comparison becomes a counting of near-threshold $D\bar{D}^*$ pairs.

Counting comoving $D\bar{D}^*$ pairs

1

The pp benchmark

Data give $R_{pp} = N(X)/N(D\bar{D}^*) \approx 10^{-2}$ at $p_T > 15$ GeV — one X per ~ 100 pairs, with no near-threshold selection. This helps estimate the cross-vertex combinatorial contribution to R_{AA} which is ($P \leq 1$)

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Cross-vertex pairs in Pb–Pb

Cross-vertex pairs give no advantage: using a toy MC to enumerate N^{comb} (using a Lévy–Tsallis distribution in p_T for the open charm) we find $\Delta R_{AA} \lesssim 2 \times 10^{-2}$ for $Q \leq 0.6$ GeV — a window $20 \times$ beyond the binding scale — and $\lesssim 10^{-5}$ in the molecular window $Q \lesssim 0.05$ GeV.

$$\Delta R_{AA} = \frac{N^{\text{comb}}}{N_{\text{coll}} N_{\text{thr}}^{pp}} \leq \frac{N^{\text{comb}}}{N_{\text{coll}} N_X^{pp}} = \frac{N^{\text{comb}}}{N_{\text{coll}} R^{pp} N^{pp}(D\bar{D}^*)} \simeq \frac{N^{\text{comb}}}{N_{\text{coll}} R^{pp} 0.44 \times N^{pp}(D)}$$

Pairs from different hard vertices cannot build the X .

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3

Same-vertex pairs

Can only be depleted by the medium — shadowing, energy loss, smearing of the near-threshold peak. We estimate $R_{AA}^{\text{pair}} \lesssim R_{AA}(D)$ at the pair p_T .

Pairs from one vertex can only be lost.

Same-vertex pairs (Anderson inequality)

$$R_{AA}^{\text{pair}} = R_{AA}(D\bar{D}^*) \times \frac{p^{\text{PbPb}}}{p^{pp}}$$

The p are the probabilities that a $D\bar{D}^*$ pair is a near-threshold, single-vertex pair.

The medium affects the number of pairs in the window (first factor) as well as the near-threshold probabilities (second factor)

$$R_{AA}(D\bar{D}^*) \lesssim [R_{AA}(D^0)]_{p_T=p_T^{\text{pair}}}$$

A single charm quark carrying p_T^{pair} loses less energy by radiation (multiple-scattering color bremsstrahlung), hence depletes the window less, than a coherent/incoherent $c\bar{c}$ pair. So this is a **conservative upper bound**.

Armesto, Cianti, Escobedo, Ferreiro, Germani, Nebbia, ADP in preparation.

$$\begin{aligned} p^{\text{PbPb}} &\equiv \int_{\mathbf{Q}' \in B} w^{\text{PbPb}}(\mathbf{Q}') = \int_{\mathbf{Q}' \in B} \int_{\mathbf{y}} k(\mathbf{y}) w^{pp}(\mathbf{Q}' - \mathbf{y}) \\ &= \int_{\mathbf{y}} k(\mathbf{y}) \int_{\mathbf{Q} \in B - \mathbf{y}} w^{pp}(\mathbf{Q}) \leq \int_{\mathbf{y}} k(\mathbf{y}) \underbrace{\int_{\mathbf{Q} \in B} w^{pp}(\mathbf{Q})}_{\equiv p^{pp}} \\ &= p^{pp} \implies p^{\text{PbPb}} \leq p^{pp} \end{aligned}$$

This is an application of Anderson's theorem, which holds if $w^{pp}(\mathbf{Q}) = w^{pp}(-\mathbf{Q})$ and its superlevel sets $w^{pp} \geq t$ are convex (e.g. balls) and centered at $\mathbf{Q} = 0$.

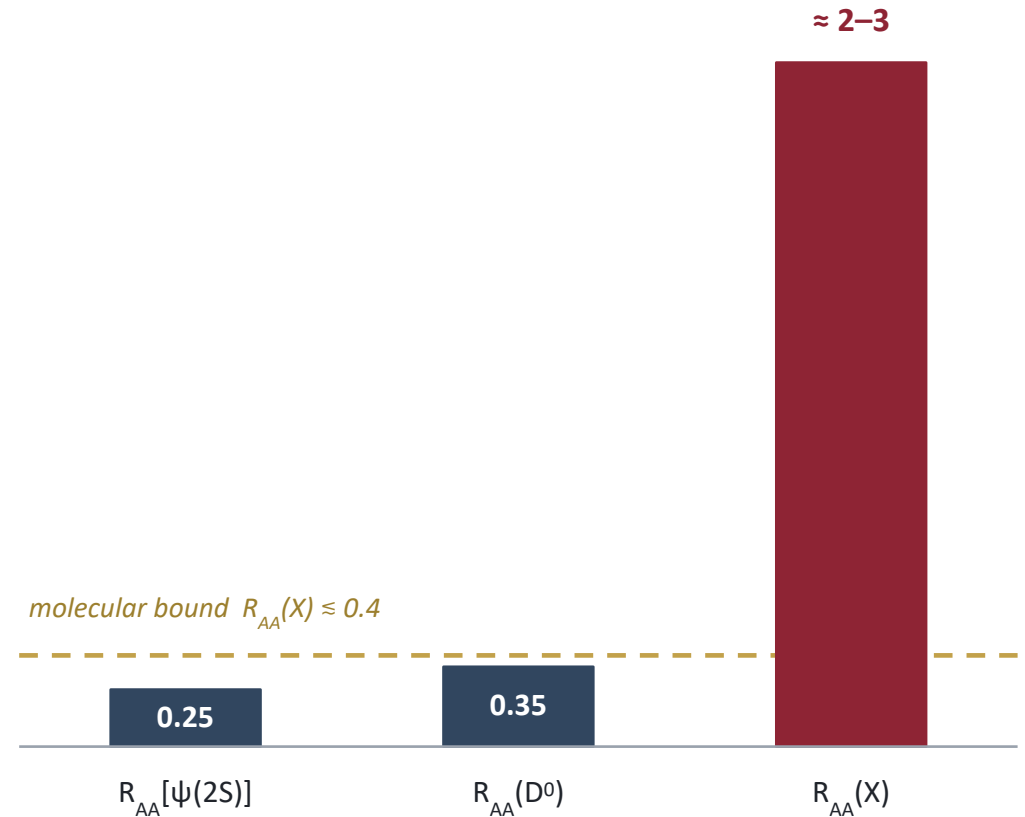
The bound — and the data

$$R_{AA}^{\text{pair}} = R_{AA}(D\bar{D}^*) \times \frac{p^{\text{PbPb}}}{p^{pp}} \lesssim R_{AA}(D^0) \Big|_{p_T=p_T^{\text{pair}}}$$

A molecular X is suppressed at least as much as open charm: $R_{AA}(X) \lesssim R_{AA}(D^0) \approx 0.3 - 0.4$.

Data sit a factor 5–10 above the bound — today at $\sim 1.3 \sigma$, given the 65% uncertainty on ρ^{PbPb} .

What would decide: a $\sim 30\%$ measurement of X/D^0 , binned in centrality. For a molecule the ratio stays flat at or below one; any rise with N_{coll} excludes it.



nuclear modification factors, $15 \leq p_T \leq 50$ GeV, central Pb–Pb

One fact behind all symptoms

The X — like other exotic hadrons — has a compact tetraquark core, while ‘looking’ molecular at large distances — the picture recently emerging from the Born–Oppenheimer approach *

Lineshape

The elementary hypothesis is self-consistent on LHCb data; the molecular one is still untested — f_+ at the Landau coupling is the test.

Production

The core is produced at high p_T , where no shallow molecule can be assembled; the $D\bar{D}^*$ tail is what appears at large distances.

Isospin violation

A compact isosinglet X_S mixing with a molecular isotriplet X_T

$$\text{reproduces } \frac{\mathcal{B}(X \rightarrow J/\psi 3\pi)}{\mathcal{B}(X \rightarrow J/\psi 2\pi)} \approx 1$$

and predicts no isospin violation in Z(3900) decays, as observed.

Born–Oppenheimer QCD

Treating the heavy quarks as nuclei: a compact $(c\bar{q})(\bar{c}q)$ core whose state at large distance is the superposition $|1 \otimes 1\rangle + |8 \otimes 8\rangle$ tetraquark inside, molecule outside.

* 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) 131902

Conclusions

- 1 Elementary vs composite is decided by the fields of the effective Lagrangian. The Flatté amplitude tests the elementary X ; it cannot test the molecule.
- 2 The molecular amplitude f_+ , with its coupling fixed at the Landau value, reproduces the deuteron with no free parameters. Fitting the LHCb lineshape with f_+ is the decisive, still-missing test.
- 3 In Pb–Pb a molecular X must satisfy $R_{AA}(X) \lesssim R_{AA}(D^0) \approx 0.3 - 0.4$. Data are 5–10 times higher. Waiting for the analysis to be published!
- 4 Isospin violation in X decays follows from a compact X_S mixing with a molecular X_T that is never produced; the $Z(3900)$ mirror predicts none. Everything points to a compact core that looks molecular at large distances.
- 5 Everything points the same way: a compact tetraquark core that looks molecular at large distances — the picture reached independently in the Born–Oppenheimer approach.

IV

Isospin: the invisible partners

A compact X , a molecular triplet that is never produced — and the $Z(3900)$ mirror

The isospin puzzle

The X decays to $J/\psi \omega$ ($I = 0$) and to $J/\psi \rho^0$ ($I = 1$) at comparable rates.

What is measured

- $I = \mathcal{B}(J/\psi \pi^+ \pi^- \pi^0) / \mathcal{B}(J/\psi \pi^+ \pi^-)$
- $I_{\text{Belle}} = 1.0 \pm 0.5$ $I_{\text{BaBar}} = 0.8 \pm 0.3$ $I_{\text{BESIII}} = 1.43^{+0.28}_{-0.23}$
- LHCb: $G = g_{J/\psi \rho} / g_{J/\psi \omega} = 0.29 \pm 0.04$
- Charmonium benchmark, $\psi(2S)$: $g(J/\psi \pi^0) / g(J/\psi \eta) = 0.045$
(the decay with π violates isospin because $\psi(2S)$ is an isosinglet)

What a model must explain

- isospin breaking $\sim 6 \times$ larger than in charmonium
- no charged partners $X^\pm$ ever observed
- copious prompt production at high p_T (Part III)
- $D^0 \bar{D}^{*0}$ dominance of a molecule breaks isospin (but fails production)

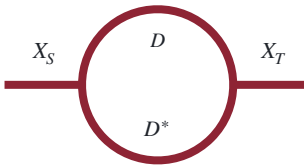
Large isospin violation, no charged partners, copious prompt production: one mechanism should account for all three.

A compact singlet mixing with an invisible triplet

$$X(3872) \simeq X_S + \left[\frac{g_{\text{mix}}}{E + B + i\Gamma_T/2} \right] X_T \quad I \propto \left[\frac{g_{\text{mix}}}{E + B + i\Gamma_T/2} \right]^{-2}$$

X_T : neutral member of a $D\bar{D}^*$ isotriplet bound by B . $E = m_X - m_D - m_{D^*} = -0.05 \pm 0.09 \text{ MeV}$; $\Gamma_T \simeq \Gamma(D^{*0}) \approx 57 \text{ keV}$

- 1 **X_S a compact isosinglet tetraquark**
The only state produced promptly and in B decays. It decays to $J/\psi \omega$ conserving isospin: $|G_\omega| = 0.11 \pm 0.02$ from $\text{Br}(X \rightarrow J/\psi \omega)$.
- 2 **X_T a molecular isotriplet, never produced**
A shallow $D\bar{D}^*$ molecule has negligible prompt yield — hence no charged partners. Its neutral member decays to $J/\psi \rho$ (vector dominance, universal wavefunction).
- 3 **Resonant amplification**
When $E + B$ and Γ_T are small compared with g_{mix} , the mixing ratio $\rightarrow 1$: a tiny isospin-breaking amplitude yields $\mathcal{O}(1)$ isospin violation.

Where the mixing comes from: a $D\bar{D}^*$ loop 

$$g_{\text{mix}} = g_S g_T \frac{m}{\pi^2} \left[\sqrt{-2m(E - \Delta)} \arctan\left(\Lambda / \sqrt{-2m(E - \Delta)}\right) - \sqrt{-2mE} \arctan\left(\Lambda / \sqrt{-2mE}\right) \right]$$

$X_S \rightarrow D\bar{D}^* \rightarrow X_T$: neutral and charged loops cancel in the isospin limit $g_{\text{mix}} = 0$ at $\Delta = 0$. Breaking enters only through $\Delta = m_D^{*+} + m_D^+ - m_D^0 - m_D^0 \simeq 8 \text{ MeV}$

$$g_S = (1.87 \pm 0.03) \times 10^{-2} \text{ MeV}^{-1/2} \quad g_T^2 = \frac{2\pi}{m} \sqrt{\frac{2B}{m}}$$

g_S : compact coupling, from the LHCb fit (slide 7). g_T : Landau coupling of the molecule — fixed, not fitted.

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

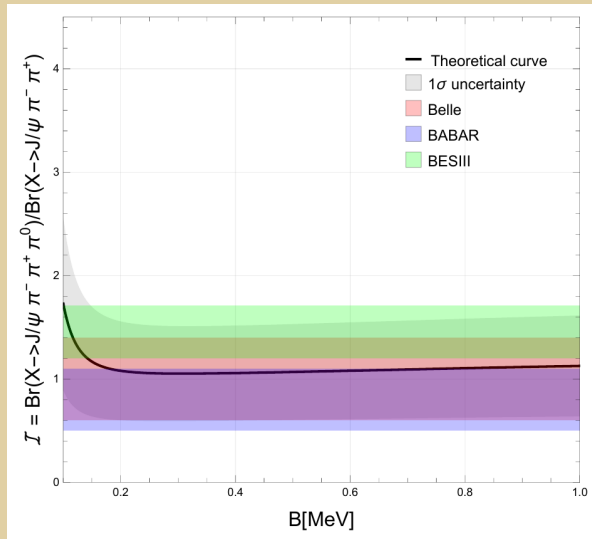
Cutoff below which the Landau coupling holds. Extracting g_{mix} from $\Gamma(X \rightarrow D\bar{D}\pi)$ returns a $\Lambda(B)$ consistent with this estimate.

The mixing is computed, not postulated: D-meson mass splittings, a compact coupling, and a Landau coupling.

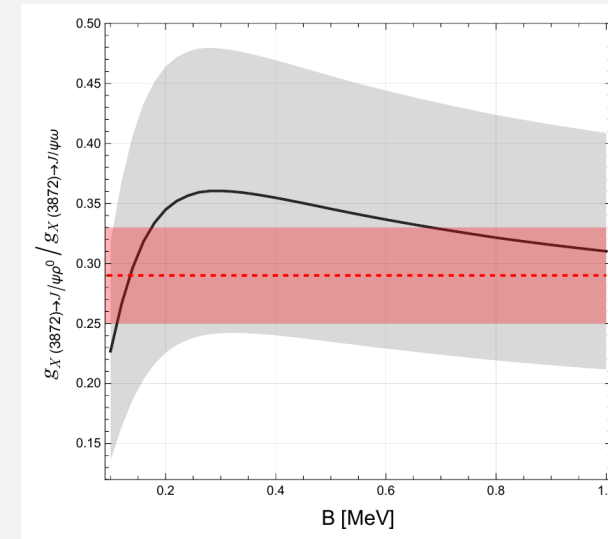
Both ratios, with the same parameters

g_{mix} is extracted from $\Gamma(X \rightarrow D\bar{D}\pi)$. I and G then follow with no further input.

$$I = \mathcal{B}(J/\psi 3\pi) / \mathcal{B}(J/\psi 2\pi)$$



$$G = g_{J/\psi\rho} / g_{J/\psi\omega}$$



Favors very small B

Belle, BaBar, BESIII and LHCb are reproduced for $0.1 \lesssim B \lesssim 1$ MeV: the isospin pattern needs a compact X — and a molecule that is never seen directly.

Figures: Carducci, Grinstein, Germani, ADP, JHEP 05 (2026) 192 [arXiv:2512.21538] · gray bands: 1σ ; coloured bands / red: data

The Z(3900): the mirror image

$X(3872) \quad 1^{++}$

X_S compact singlet $\oplus X_T$ molecular triplet

- only X_S is produced: one neutral state, no charged partners
- X_T feeds $J/\psi \rho$ through mixing $\implies$ large isospin violation

$Z(3900) \quad 1^{+-}$

Z_T compact triplet $\oplus Z_S$ molecular singlet

- $Z^\pm, Z^0$ all observed just above threshold: compact
- Fierz: Z_T rearranges only into $D^* \bar{D}^*$ — a light Z_S may not exist
- if it does: $I_Z = \mathcal{B}(J/\psi \eta) / \mathcal{B}(J/\psi \pi) \leq 10^{-7} \quad \text{vs} \quad \text{BESIII} < 0.15$

Same mechanism, reversed multiplets: no isospin violation in Z decays, no neutral doubling of either X or Z — as observed.

One fact behind all symptoms

The X — like other exotic hadrons — has a compact tetraquark core, while looking molecular at large distances.

Lineshape

The elementary hypothesis is self-consistent on LHCb data; the molecular one is still untested — f_+ at the Landau coupling is the test.

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The core is produced at high p_T , where no shallow molecule can be assembled; the $D\bar{D}^*$ tail is what appears at large distances.

Isospin violation

A compact isosinglet X_S mixing with a molecular isotriplet X_T reproduces $I(J/\psi + 3\pi / J/\psi + 2\pi) \approx 1$ — and predicts no isospin violation in $Z(3900)$ decays, as observed.

Born–Oppenheimer QCD

Treating the heavy quarks as nuclei: a compact $(c\bar{q})(\bar{c}q)$ core whose state at large distance is the superposition $|1\otimes 1\rangle + |8\otimes 8\rangle$ — tetraquark inside, molecule outside.