LHCb results on Exotic Charmonia

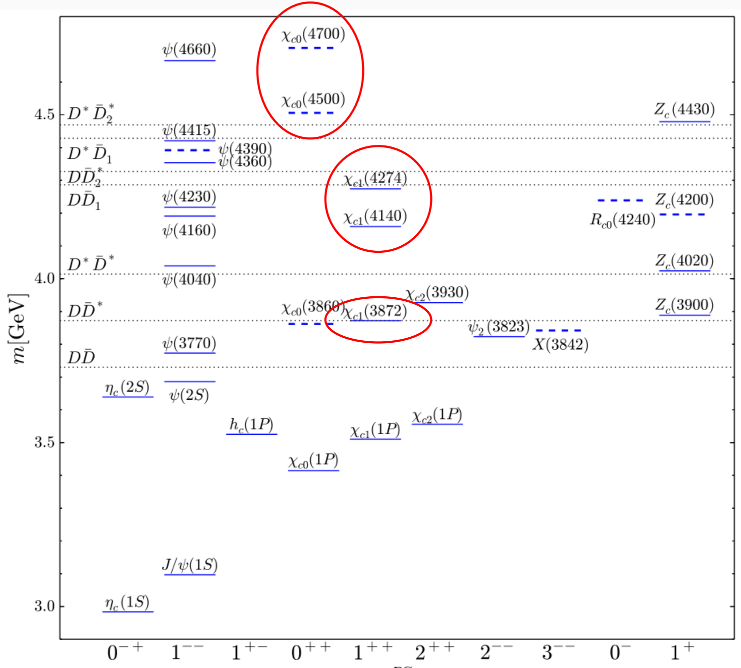
Sebastian Neubert
on behalf of the LHCb collaboration

Experimental and theoretical status of and perspectives for XYZ States,
EMMI Workshop, GSI 14.04.2021

UNIVERSITÄT BONN

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Outline: Exotic Charmonia

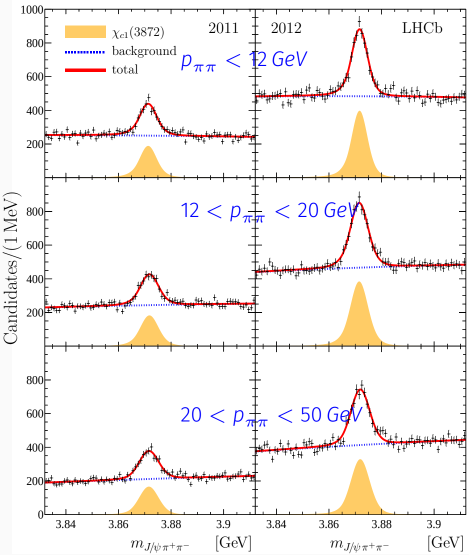


from [PR873(2020)1]

Precision measurements of mass and width of the $\chi_{c1}(3872)$ at LHCb

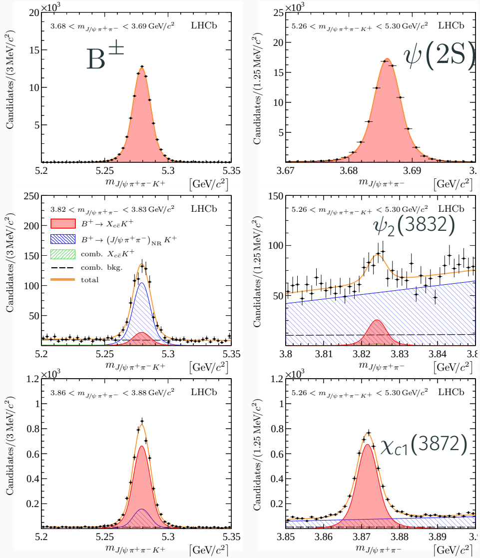
Inclusive $\chi_{c1}(3872) \to J/\psi \pi^+ \pi^-$

[PRD102(2020)092005]



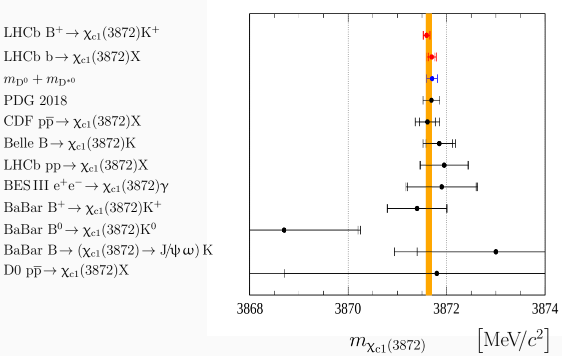
Exclusive $B^\pm \to J/\psi \pi^+ \pi^- K^\pm$

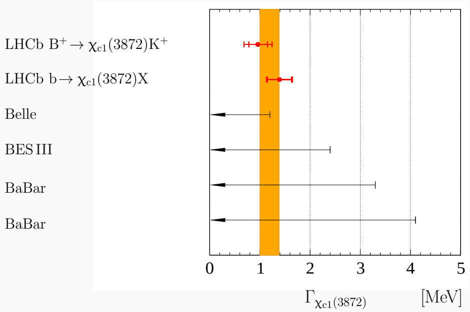
[JHEP08(2020)123]



Breit-Wigner parameters [PRD102(2020)092005][JHEP08(2020)123]

Comparison between inclusive and exclusive analysis and previous measurements





First time a width was established for this state.

Preliminary conclusion from Breit-Wigner fits

- Most precise measurements of the Breit-Wigner mass. LHCb average:

$$m_{\chi_{c1}(3872)}|_{\text{LHCb}} = 3871.64 \pm 0.06 \pm 0.01\,\text{MeV}/c$$

- Uncertainty now smaller than uncertainty of threshold location
  $m_{\mathrm{D}^0} + m_{\mathrm{D}^{0*}} = 3871.70 \pm 0.11\,MeV$

[PDG2019][JHEP08(2020)123]

- Distance to $\mathrm{D}^0\mathrm{D}^{0*}$ threshold $\delta E = m_{\mathrm{D}^0} + m_{\mathrm{D}^{0*}} - m_{\chi_{c1}(3872)}$

$$\delta E|_{\text{LHCb}} = 0.07 \pm 0.12\,MeV$$

- **First non-zero value for Breit-Wigner width**

$$\Gamma|_{\text{LHCb}} = 1.13$$

- Threshold is within the natural width
  $\Rightarrow$ Breit-Wigner is not the correct line-shape

Decay rate as function of Energy wrt to $\mathrm{D^0 D^{0*}}$ threshold

$$\frac{dR(\mathrm{J}/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{|D(E)|^2},$$

with denominator

$$D(E) = E - E_f + \frac{i}{2}\left[g\left(k_1 + k_2\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right].$$

$k1(k2)$	$\mathrm{D^0 D^{0*}}$ ($\mathrm{D^+ D^{-*}}$) momenta in $\mathrm{J}/\psi\pi^+\pi^-$ frame (imaginary below threshold)
g	coupling to $\mathrm{DD^*}$ channels
$\Gamma_\rho(E) = f_\rho \hat{\Gamma}_\rho$	dynamic width in $\mathrm{J}/\psi\pi^+\pi^-$ channel
$\Gamma_\omega(E)$	dynamic width in $\mathrm{J}/\psi\pi^+\pi^-\pi^0$ channel
Γ_0	constant width term
$E_f = m_0 - (m_{\mathrm{D^0}} + m_{\mathrm{D^{0*}}})$	Flatté mass parameter **fixed m_0 = 3864.5 MeV** to resolve Flatté scaling [EPJ.A23(2005)523]

Constraints:

branching ratios $\mathrm{D^0 D^{0*}}$ important

fit parameters in red

Taking into account the DD^* threshold: Flatté [PRD102(2020)092005]

Adding external information on branching fractions from Belle and BaBar distorts the lineshape [PRD80(2009)074004].

Shape parameters:

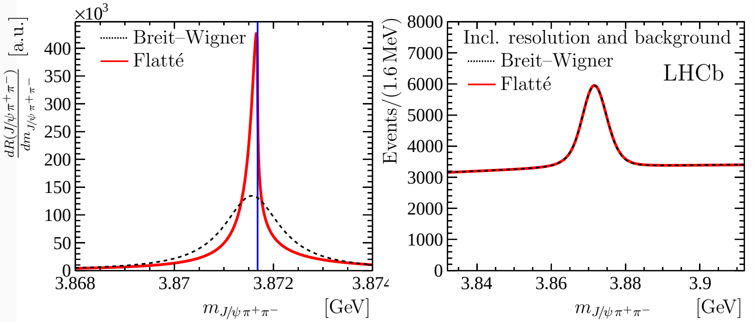
Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00}_{-0.04}{}^{+0.05}_{-0.13}$	$3871.66^{+0.07}_{-0.06}{}^{+0.11}_{-0.13}$	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$

- $J/\psi\pi\pi$ data alone cannot distinguish line shapes
- Flatté narrower than BW by factor 5

Systematic uncertainties of equal importance:

- Resolution+Bkg model
- Momentum scale
- Threshold mass

Small effect: D^{0*} width



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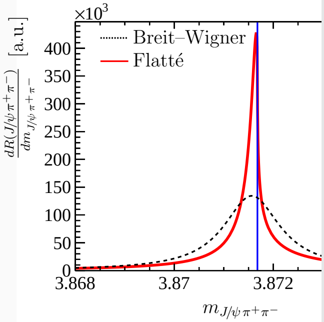
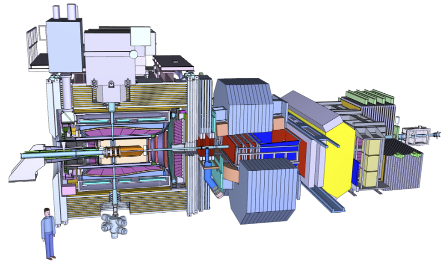


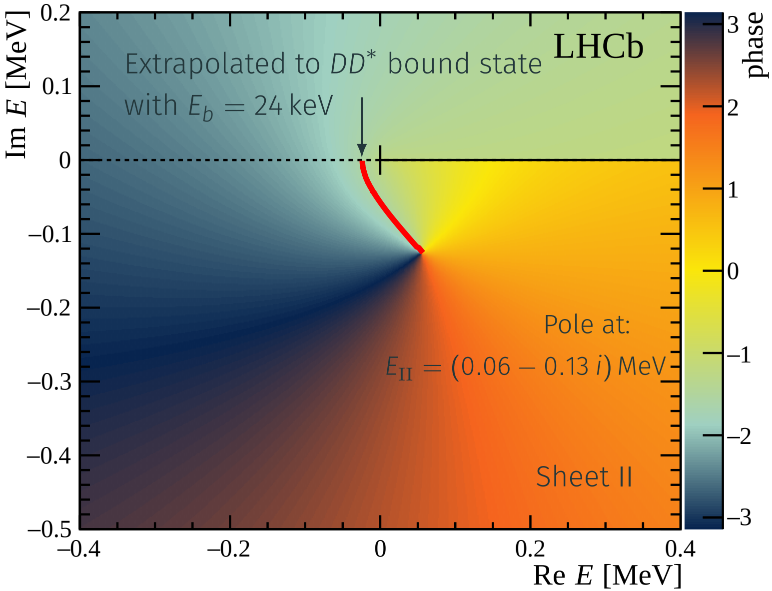
Resolve lineshape

See K. Götzen talk tomorrow



The $\bar{P}$ANDA project at FAIR

Analytic structure of the Flatté model at $D^0\bar{D}^{*0}$ threshold [PRD102(2020)092005]



Analytic structure including D^{0*} width

Simple ansatz:
[PRD76(2007)094028][PRD81(2010)094028]

$$k_1'(E) = \sqrt{-2\mu\left(E - E_R + i\Gamma_{D^{*0}}/2\right)}$$

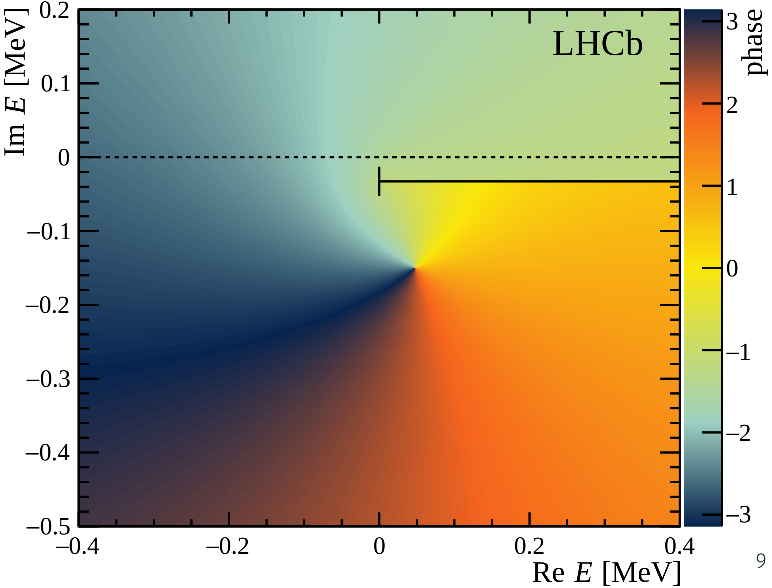
with

$E_R \equiv m_{D^{*0}} - m_{D^0} - m_{\pi^0}$

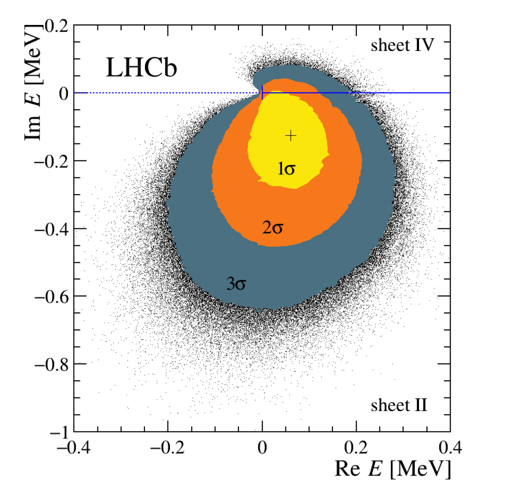
valid since D^* well separated from $D\pi$ threshold.

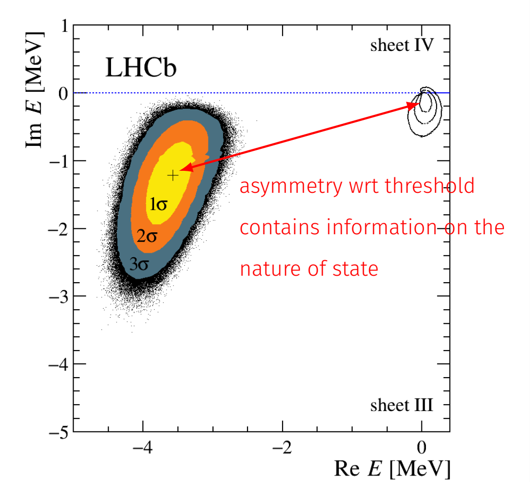
with $\Gamma_{D^{*0}} = 65.5 \pm 15.4$ keV

little impact on pole position



Statistical uncertainties + systematics from resolution & background modelling





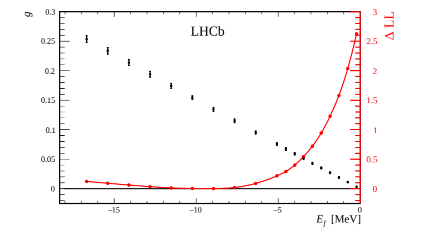
$E_b < 100$ keV at 90%CL

Best estimate: $E_{\text{II}} = (0.06 - 0.13\,i)$ MeV

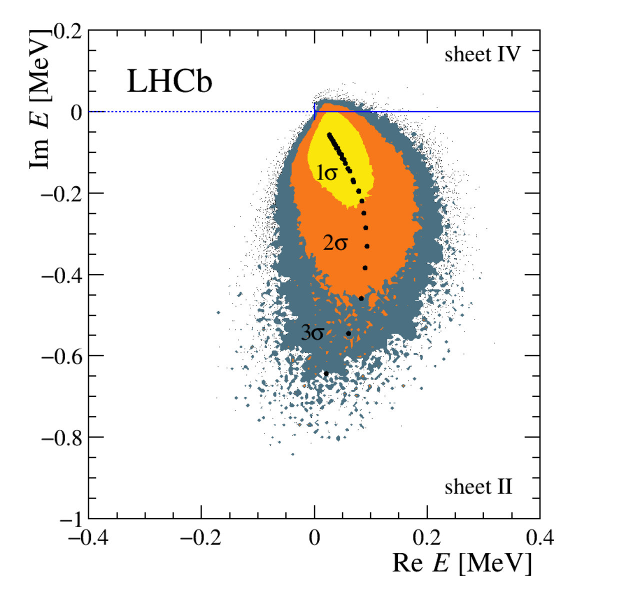
Best estimate: $E_{\text{III}} = (-3.58 - 1.22\,i)$ MeV

Impact of choice of $m_0 = 3864.5$ MeV

- Repeating the analysis with varying m_0
- As m_0 moves closer to threshold, pole moves into complex plane
- Combined confidence region (weighted with likelihood ratio)



Statistical uncertainties only



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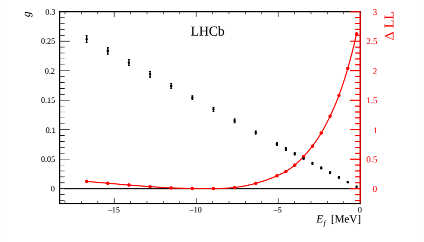

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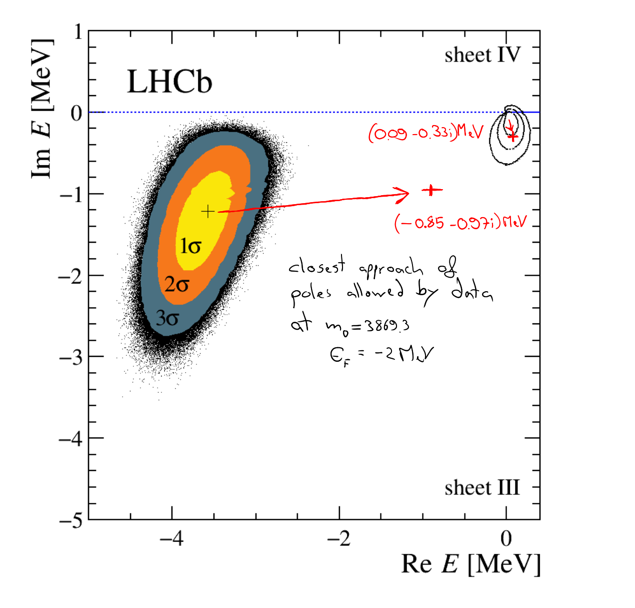


We speak of a shallow bound state of two hadrons if

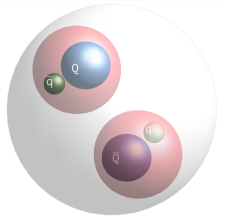
$$R > R_{\text{conf}} \qquad \Rightarrow \qquad E_b < \frac{1}{2\mu R_{\text{conf}}^2}$$

at $\mathrm{D}^0\overline{\mathrm{D}}^{0*}$ threshold, with $R_{\text{conf}} \approx 1\,\text{fm} \approx (200 MeV)^{-1}$ and $\mu_{\mathrm{DD}^*} \approx 966\,\text{MeV}$

$$E_b < 20\,\text{MeV}$$

We know they exist:

- Deuteron $E_b = 2.22\,\text{MeV}$
- Hypertriton $E_b = 0.13 \pm 0.05\,\text{MeV}$ from Λd threshold
- Not a molecule but important hadronic interaction: virtual state in nn scattering



$\chi_{c1}(3872)$ good candidate for a $\mathrm{D}\overline{\mathrm{D}}^*$ molecule!

- $E_b = 24\,\text{keV} \Rightarrow R \approx 30\ \text{fm}$!

Pole asymmetry: mixture of molecule and compact state

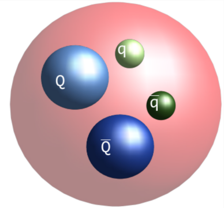
- It was shown in [PLB586(2004)53] that in the quasi-bound state szenario the asymmetry of the pole locations wrt to branch point contains information on nature of state
  - **Pure molecule (deuteron-like): second pole is far from threshold**
  - **Pure compact state: both poles close to threshold**
- analoguos to Weinberg's Composition Criterion [PR130(1963)776] and Morgan's Pole Counting approach [Nucl.Phys. A543(1992)632]
- For single channel [Rev. Mod. Phys. 90(2018)015004]:

$$\frac{|k_2| - |k_1|}{|k_1| + |k_2|} = 1 - Z\,.$$

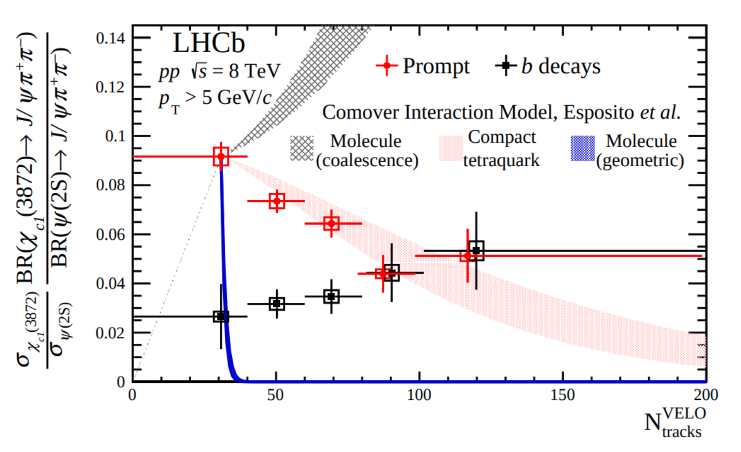
  - Z is the probability to find a compact component in the $\chi_{c1}(3872)$.
  - $k = \sqrt{-2\mu E_b}$ is purely imaginary here
- Best fit: $Z = 15\%$
- smallest asymmetry compatible with data $\boxed{\Rightarrow Z < 33\%}$

Classically one would assume a large object to be strongly affected by its production environment.

Hint for compact nature?



Molecule would be disintegrated at high multiplicity?



No rigorous theoretical treatment.

Model intriguing but hotly debated.

$$\mathrm{B} \to \mathrm{J}/\psi\phi\mathrm{K}$$

Update of amplitude analysis $\mathrm{B} \to \mathrm{J}/\psi\phi\mathrm{K}$

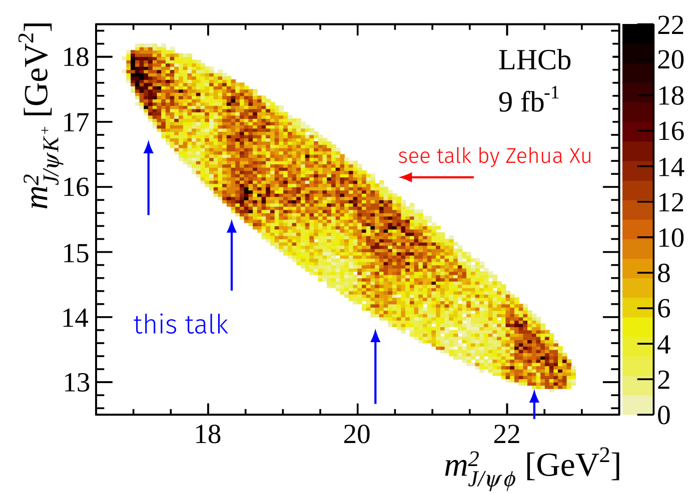
[PRL118(2017)022003][PRD95(2017)012002]

amplitude model see talk by Zehua Xu

Now: Run I+II statistics

$24\,220 \pm 170$ candidates

(6x improvement)



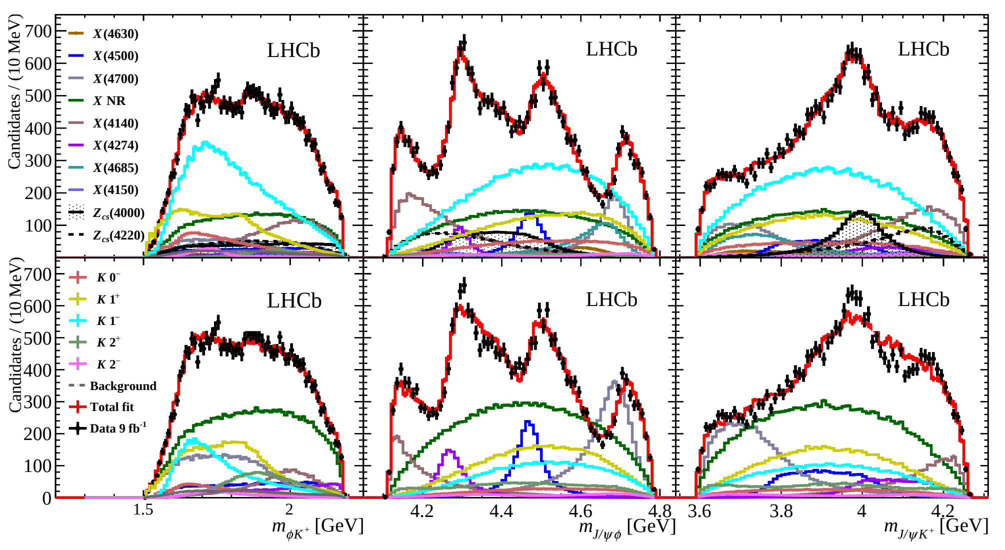
Possible contributions:

Highlying $\mathrm{K}^* \to \phi\mathrm{K}$, exotic $X \to \mathrm{J}/\psi\phi$, exotic $Z_{cs} \to \mathrm{J}/\psi\mathrm{K}$

Resonances in B $\rightarrow$ J/$\psi\phi$K at LHCb

[2103.01803] subm. to PRL

Full model: seven Breit-Wigner resonances in $\mathrm{J}/\psi\phi$ + two Z_{cs} + nine K^*

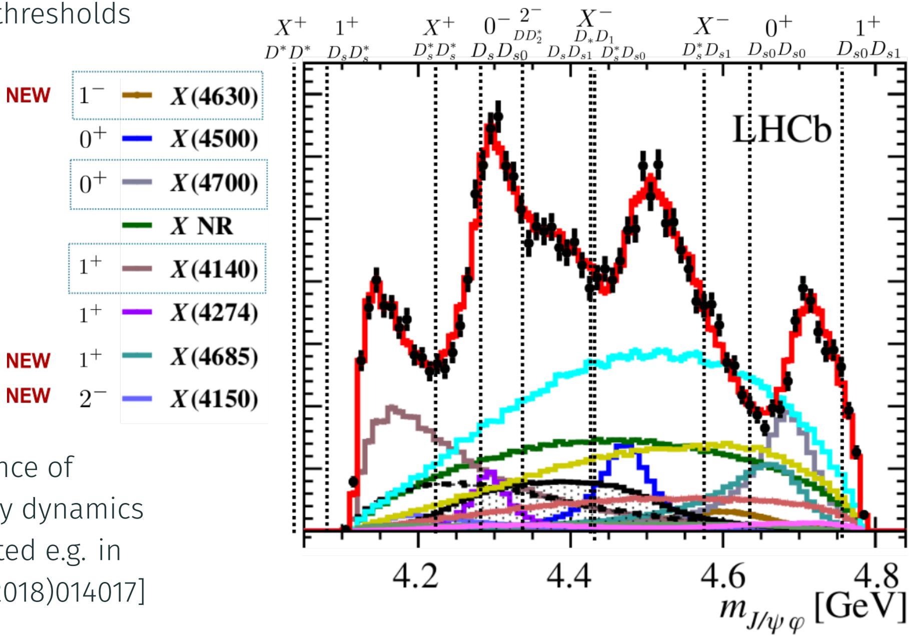


2017 model: four Breit-Wigner resonances in $\mathrm{J}/\psi\phi$ + five K^*

Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
old		$4506 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$	$6.6 \pm .4\,^{+3.5}_{-2.3}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
old		$4704 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$	$12 \pm 5\,^{+9}_{-5}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
old		$4147 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$	$13 \pm 3.2\,^{+4.7}_{-2.0}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
old		$4273.3 \pm 8\,^{+17.2}_{-3.6}$	$56 \pm 11\,^{+8}_{-11}$	$7.1 \pm 2.5\,^{+3.5}_{-2.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$

Flatté and K-matrix parameterisation have been tested where applicable

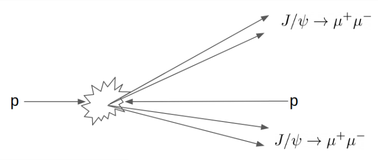
S-Wave thresholds



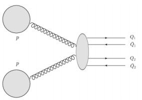
Importance of two-body dynamics highlighted e.g. in [PRD97(2018)014017]

A fully charmed $cc\bar{c}\bar{c}$ Tetraquark candidate

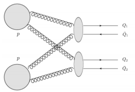
[SciB65(2020)1983]



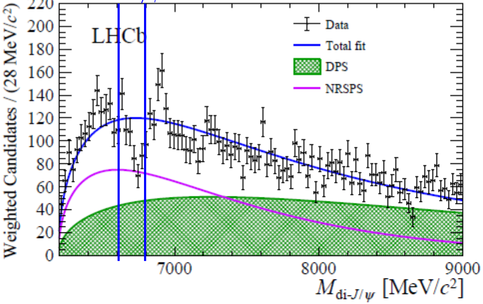
Single parton scattering (SPS)

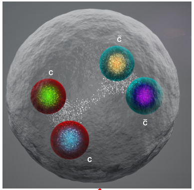


Double parton scatterings (DPS)



several J/ψ-Charmonium thresholds





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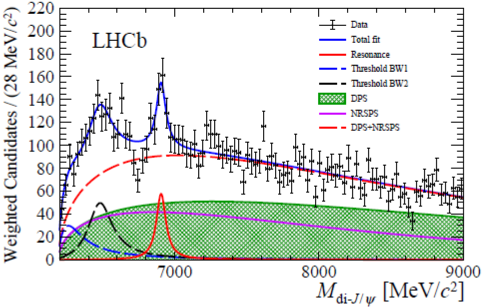
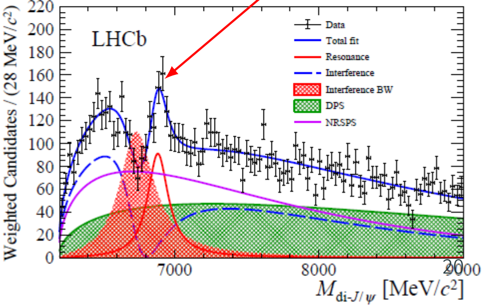
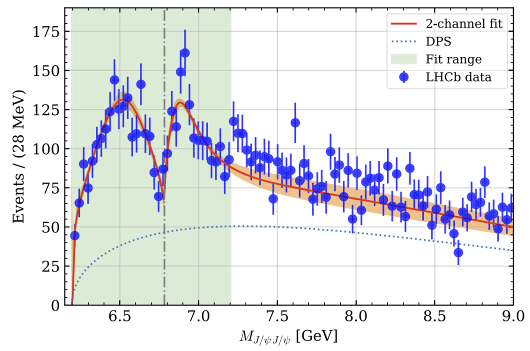


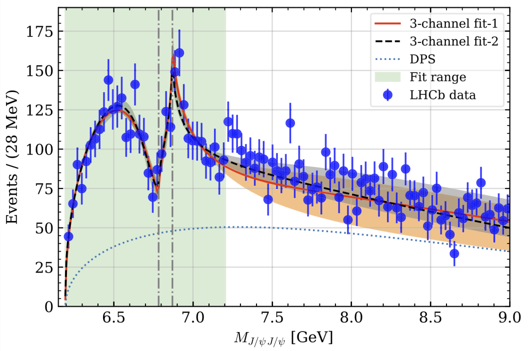


Analysis presented yesterday by Alexey Nefediev

$J/\psi J/\psi + J/\psi\psi(2S)$



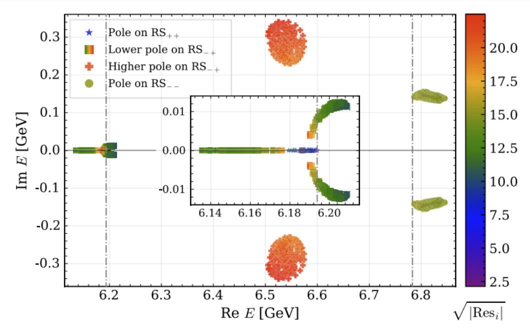
$J/\psi J/\psi + J/\psi\psi(2S) + J/\psi\psi(3770$



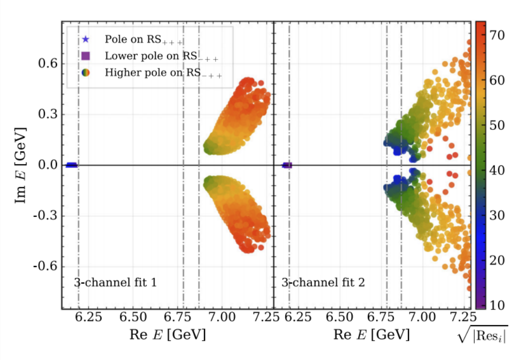
Two solutions with similar fit quality found for 3-channel fit.

In both cases a pole X(6200) very close to the $J/\psi J/\psi$ threshold is found.

$J/\psi J/\psi$ + $J/\psi\psi(2S)$



$J/\psi J/\psi$ + $J/\psi\psi(2S)$ + $J/\psi\psi(3770$



Scattering length and effective range point to a shallow bound state.

Data in the coupled channels needed!

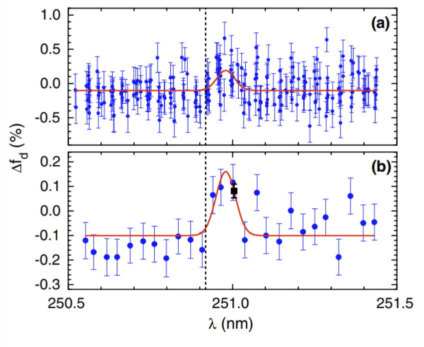
	2-channel fit	3-channel fit 1	3-channel fit 2
a_0(fm)	≤ -0.49 or ≥ 0.48	$-0.61^{+0.29}_{-0.32}$	≤ -0.60 or ≥ 0.99
r_0(fm)	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}_A$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$

Final Note: Di-Positronium Molecules

Stable molecules of Positronium Ps_2 can be created by impinging an intense positron beam on a porous silica substrate [Nature449(2007)195].

Decays via annihilation $\tau(Ps_2) < \tau(Ps)$. Detection through density/temperature dependent annihilation rates.

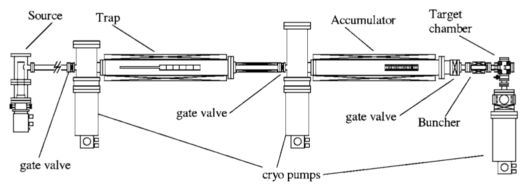
Radiative transition observed



[PRL108(2012)133402]

Positron Accumulator

[Rev. Sci. Inst.77(2006)073106]



Sub ns pulses of $3 \times 10^{10} \mathrm{cm}^2 \mathrm{s}^{-1}$ positrons ($> 10m$ A)

Summary – Exotic Charmonia at LHCb

- Precision measurement of $\chi_{c1}(3872)$ lineshape
  - Quasi-bound state preferred, virtual state cannot be ruled out
  - Significant asymmetry of pole locations points towards composite nature
- Three new structures in $\mathrm{J}/\psi\phi$
  - Need 7 Breit-Wigner resonances to describe data
  - in addition: resonant structures in $Z_c s$ - see Zehua Xu's talk
- First candiate for a $\mathrm{J}/\psi\mathrm{J}/\psi$ resonance

Backup

Breit-Wigner masses:

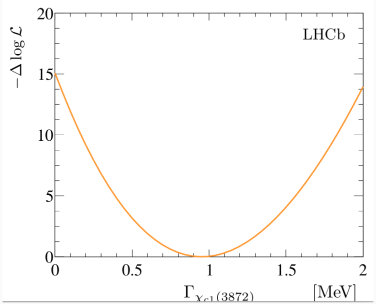
$$m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01\,\mathrm{MeV}/c$$

$$m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01\,\mathrm{MeV}/c$$

Breit-Wigner widths:

$$\Gamma_{\psi_2(3823)} < 5.2(6.6)\mathrm{MeV} \quad \text{at} \quad 90(95)\%\mathrm{CL}.$$

$$\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\,\mathrm{MeV}$$



Dominant systematic uncertainty: signal and background shapes
(does not include the systematic of choosing a Breit-Wigner parameterization)

Factsheet $\chi_{c1}(3872)$

- $J^{PC} = 1^{++}$ established $\Rightarrow$ PDG nomenclature $\chi_{c1}(3872)$
  LHCb [PRL110(2013)222001][PRD92(2015)011102]

- Mass $m = 3871.69 \pm 0.17\,MeV$ (in $\mathrm{X}(3872) \to \mathrm{J}/\psi\ X$ decays)
- $D\bar{D}^*$ threshold: $3871.70 \pm 0.11\,MeV$
- Mass difference $m_X - m_{\mathrm{J}/\psi} = 775 \pm 4\,MeV$
- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

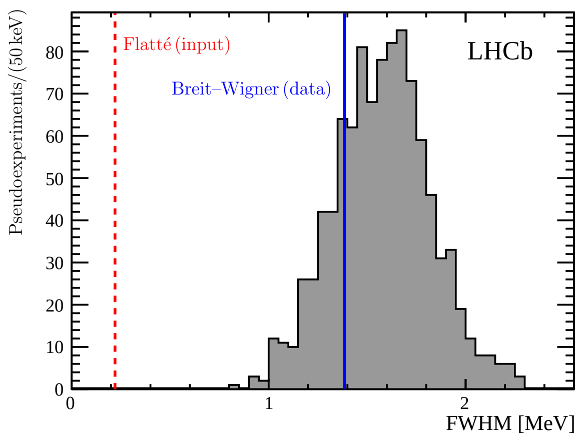
- Observed in Charmonium-like decay modes:
  $\mathrm{D}^{*0}\overline{\mathrm{D}}^0$, $\mathrm{J}/\psi\pi\pi$, $\mathrm{J}/\psi\omega$, $\mathrm{J}/\psi\gamma$, $\psi(2\mathrm{S})\gamma$, $\chi_{c1}\pi^0$
- Mass and decay modes disfavour pure $\mathrm{c}\bar{\mathrm{c}}$ state.
  $\chi_{c1}(2P)$ predicted to be few 10 MeV higher in mass

- No charged partner, no $C = -1$ partner found
  - $X \to \mathrm{J}/\psi\pi^+\pi^0$ Belle[PRL111(2013)032001],BaBar[PRD71(2005)031501]
  - $X \to \mathrm{J}/\psi\eta$ Belle[PTEP(2014)043C01],Belle[PRL111(2013)032001]

Are these measurements consistent?

- Start with Flatté line shape
- Fold with resolution
- Generate synthetic dataset
- Fit pseudo data with Breit-Wigner
- $\Rightarrow$ **yes, consistent**

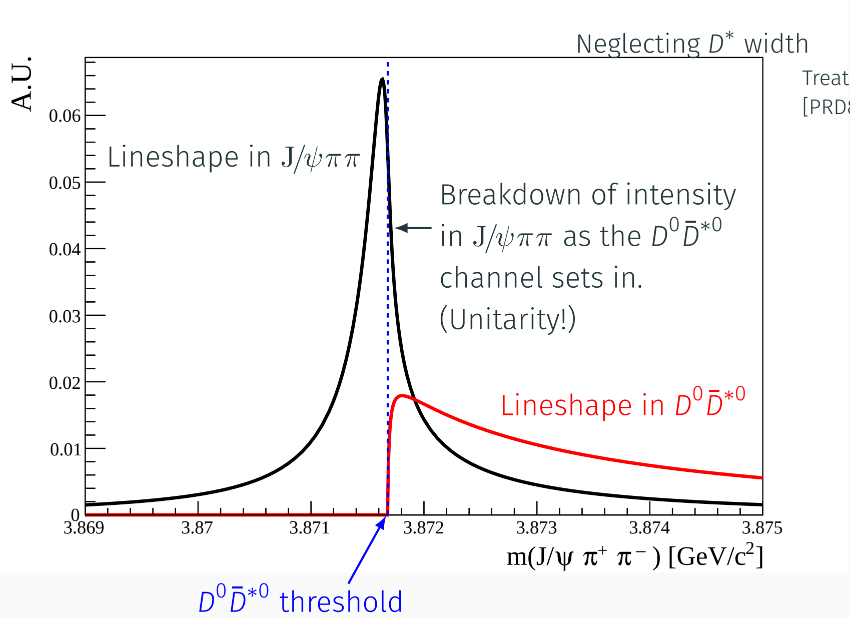
Breit-Wigner width is biased



$\Rightarrow$ physical quantity is the pole location (which comes as no surprise)

This result illustrates the importance of a well motivated line-shape model, especially near thresholds.

Why does this happen? Competing decay channels



Treatment of width [PRD81(2010)094028]

Fitting the Flatté model

[PRD102(2020)092005]

- Constraints on partial widths, consistent with existing data

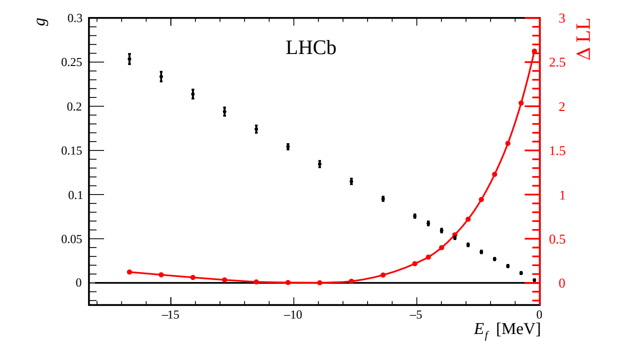
$$\Gamma(\mathrm{J}/\psi\rho) = \Gamma(\mathrm{J}/\psi\omega)$$

$$\frac{\Gamma(\mathrm{J}/\psi\rho)}{\Gamma(\mathrm{D}^0\mathrm{D}^{0*})} = 0.11 \pm 0.03$$

- Will cause shape to be different from Breit-Wigner
- 4 fit parameters: m_0, g, f_ρ, Γ_0
- **Fix $m_0 = 3864.5$ MeV**

Flatté exhibits scaling behaviour [EPJ.A23(2005)523]

$$\frac{dg}{dE_f} = (-15.11 \pm 0.16)\mathrm{GeV}^{-1}$$



Very shallow likelihood minimum at $E_f \approx -10\,MeV$

Riemann Sheets of the Flatté model

Denominator in the Flatté model:

$$D(E) = E - E_f + \frac{i}{2}\left[g\left(k_1 + k_2\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right].$$

with

$$k_1 = \sqrt{2\mu_1 E} \qquad k_2 = \sqrt{\mu_2(E-\delta)}.$$

where μ is the reduced mass of the two-body system.

Sheet I: $E - E_f - \frac{g}{2}\left(+\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E)$. with $\mathrm{Im}(E) > 0$

Sheet II: $E - E_f - \frac{g}{2}\left(+\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E)$. with $\mathrm{Im}(E) < 0$

Sheet III: $E - E_f - \frac{g}{2}\left(-\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E)$. with $\mathrm{Im}(E) < 0$

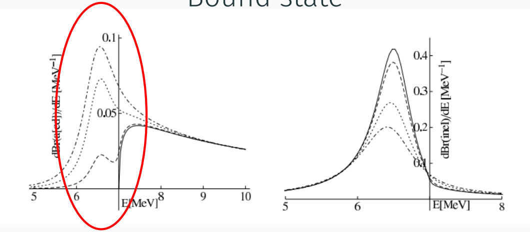
Sheet IV: $E - E_f - \frac{g}{2}\left(-\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E)$. with $\mathrm{Im}(E) > 0$

We only consider branch cuts from the two nearby thresholds.

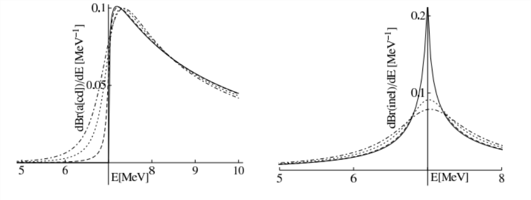
Open channels: Riemann sheets change when crossing the real axis.

Lineshapes with finite D^* width [PRD81(2010)094028]

Bound state



Virtual state



$\mathrm{D\overline{D}}^*$ $\quad$ $\mathrm{J}/\psi\pi\pi$ $\quad$ $\mathrm{D\overline{D}}^*$ $\quad$ $\mathrm{J}/\psi\pi\pi$

Different curves correspond to different D^* widths.

Lineshape in the $\mathrm{D\overline{D}}^*$ channel with a finite width D^* most sensitive signature

Isospin of the $\chi_{c1}(3872)$ aka X(3872)

Decays of the $\chi_{c1}(3872)$:

Approx. product branching fractions	
$\mathcal{B}(\mathrm{B} \to \mathrm{K}X) \times \mathcal{B}(X \to \mathrm{D}^{*0}\overline{\mathrm{D}}^0)$	$\sim 1 \times 10^{-4}$
$\mathcal{B}(\mathrm{B} \to \mathrm{K}X) \times \mathcal{B}(X \to \mathrm{J}/\psi \underbrace{\pi\pi}_{\rho})$	$\sim 1 \times 10^{-5}$
$\mathcal{B}(\mathrm{B} \to \mathrm{K}X) \times \mathcal{B}(X \to \mathrm{J}/\psi\omega)$	0.6×10^{-5}
$\frac{\mathcal{B}(X \to \chi_{c1}\pi^0)}{\mathcal{B}(X \to \mathrm{J}/\psi\pi\pi)}$	$0.88^{+0.33}_{-0.27} \pm 0.1$
$\mathcal{B}(\mathrm{B} \to \mathrm{K}X) \times \mathcal{B}(X \to \mathrm{J}/\psi\gamma)$	$\sim 2 \times 10^{-6}$
$\frac{\mathcal{B}(X \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(X \to \mathrm{J}/\psi\gamma)}$	$\sim 2 - 3$
$\frac{\mathcal{B}(\mathrm{B}^+ \to X\mathrm{K}^+) \times \mathcal{B}(X \to \mathrm{p}\overline{\mathrm{p}})}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+) \times \mathcal{B}(\mathrm{J}/\psi \to \mathrm{p}\overline{\mathrm{p}})}$	$< 0.25 \times 10^{-2}$
$\mathcal{B}(\mathrm{B}^+ \to X\mathrm{K}^+) \times \mathcal{B}(X \to \mathrm{p}\overline{\mathrm{p}})$	$< 6 \times 10^{-9}$

$X \to \mathrm{J}/\psi\rho$, $X \to \mathrm{J}/\psi\omega$ and $X \to \chi_{c1}\pi^0$ all equally important.

Isospin violation?

Consider a $\mathrm{D}^0\overline{\mathrm{D}}^{0*}$ molecule.
What is the Isospin?

$$|\,\bar{u}c\rangle \otimes |\,u\bar{c}\rangle$$

is a **mixture of isospin singlet and triplet!**

To build isospin eigenstates we need the charge conjugate mode $\mathrm{D}^+\mathrm{D}^{-*}$.

So $\mathrm{D}^0\overline{\mathrm{D}}^{0*}$ would be 50% I=0 and 50% I=1.

However ....

Isospin of the $\chi_{c1}(3872)$ aka X(3872)

What Branching fractions would be expected for decays into $\mathrm{J}/\psi\,\rho$ and $\mathrm{J}/\psi\,\omega$ from a state with equal amounts of I=0 and I=1 ?

Take into account phase space:

- $\mathrm{J}/\psi\pi\pi$ opens 500 MeV below X.
- $\mathrm{J}/\psi\omega$ opens 8 MeV above X.

$\Rightarrow$ for 50/50 isospin mixture, the $\mathrm{J}/\psi\omega$ would be completely suppressed by phasespace compared to $\mathrm{J}/\psi\,\rho$

BUT $\mathcal{B}(\mathrm{J}/\psi\omega) \approx \mathcal{B}(\mathrm{J}/\psi\,\rho)$

$\Rightarrow$ **X(3872) should be considered as Isospin singlet.**

with no charged partners!

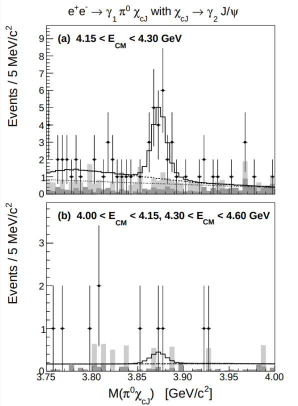
I=0 : Evidence from EFT and $X \to \chi_{cJ}\pi^0$ decays [PRD92(2015)034019]

For I=1 component the decay width into this channel would be larger than the total allowed width of the X(3872).

If both $\mathrm{D}^0\overline{\mathrm{D}}^{0*}$ and $\mathrm{D}^+\mathrm{D}^{-*}$ are included in the EFT, then the two corresponding loops enter with opposite sign and (almost) cancel each other.

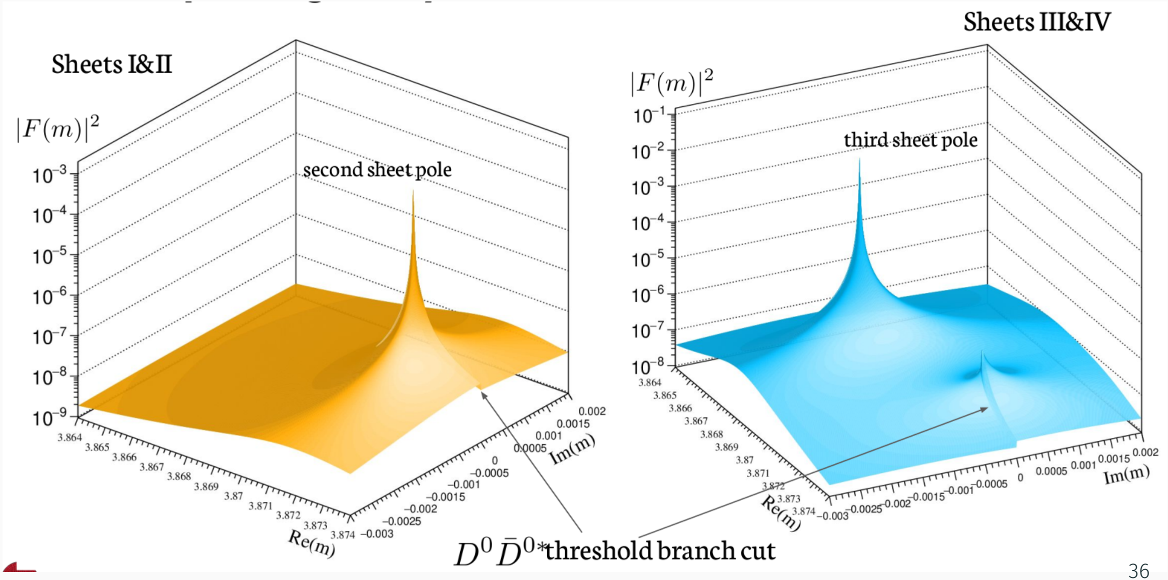
The isospin violation is then driven by the $\sim 8\,\mathrm{MeV}$ mass difference between those two channels.

New BESIII result on the $\chi_{cJ}\pi^0$ branching fraction [PRL122(2019)202001] will allow to constrain the couplings.



Analytic Structure of the Flatté Model: Example

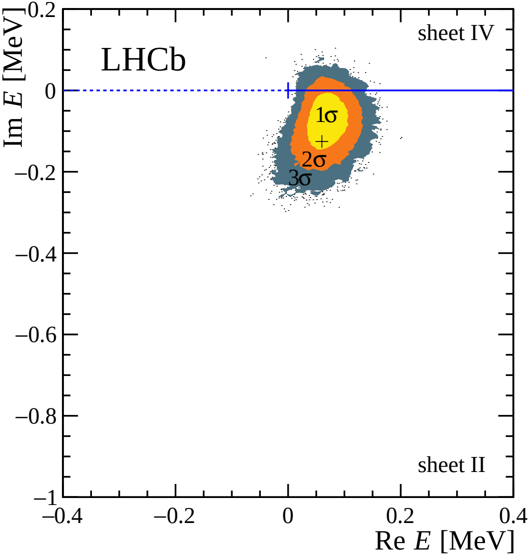
Sheets II and IV analytically connected above threshold

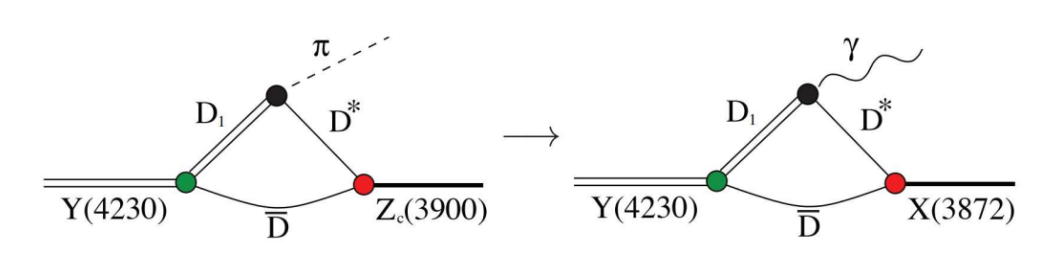


Impact of uncertainty of threshold location

- Threshold mass and mass scale uncertainty equal magnitude
- Repeat pole search with mass scale shifted by 0.066 MeV closer to threshold
- **Pole still favored to ly on sheet II**
- systematically limited by knowledge of threshold mass
  $\Rightarrow$ investigate $\mathrm{D}^0\overline{\mathrm{D}}^0\pi^0$ channel

Statistical uncertainties only





The assignment of $\psi(4230)$ (formerly known as Y(4260) as a DD_1 molecule explains the decays into $Z_c(3900) + \pi$ and $\chi_{c1}(3872) + \gamma$ as seen by BESIII [PRL112(2014)092001.]

In the quark model D_1 is expected to undergo both decays, providing for the opposite C-parity.