X(3872) at LHCb

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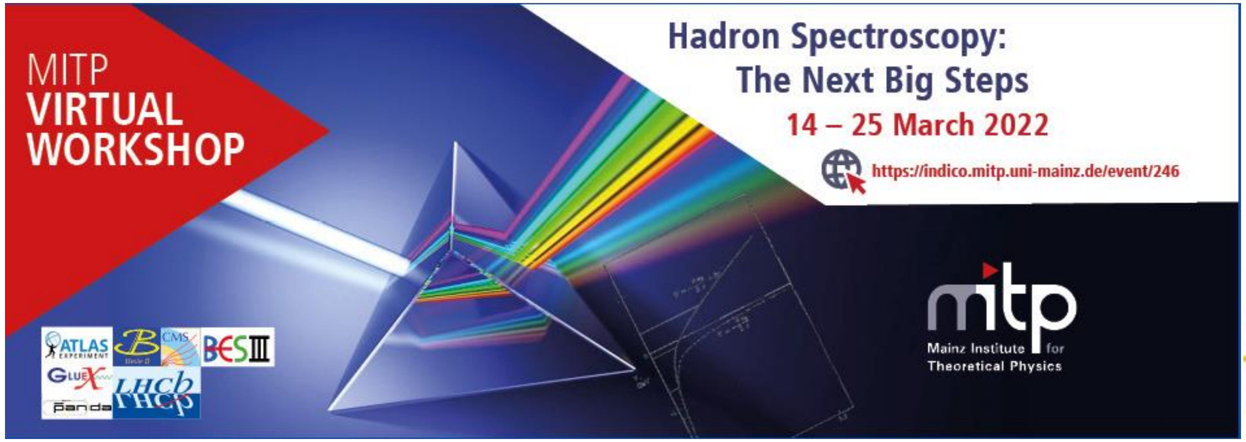


LHCb publications on X(3872)

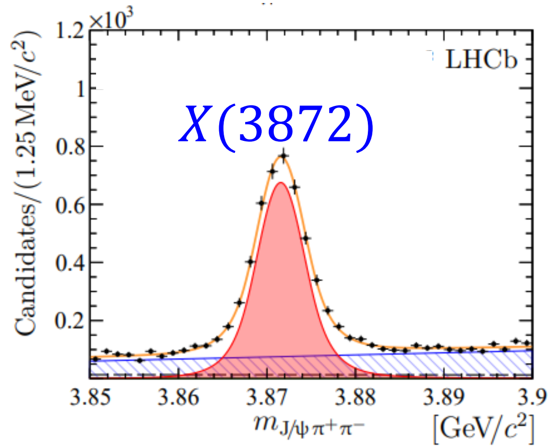
Lumi [citied]

- 9.0 fb^{-1} [-] **LHCb-PAPER-2021-045, in preparation,** ***Observation of sizeable ω contribution to $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ decays***
- 7.4 fb^{-1} [1] LHCb-PAPER-2021-026, JHEP 01 (2022) 131, *Measurement of $\chi_{c1}(3872)$ production in proton-proton collisions at $\sqrt{s}$ = 8 and 13 TeV*
- 9.0 fb^{-1} [12] LHCb-PAPER-2020-035, JHEP 02 (2021) 024, Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays
- **2.0 fb^{-1} [19] LHCb-PAPER-2020-023, Phys. Rev. Lett. 126 (2021) 092001,** ***Observation of multiplicity-dependent prompt $\chi_{c1}(3872)$ and ψ(2S) production in pp collisions***
- 9.0 fb^{-1} [43] **LHCb-PAPER-2020-009, JHEP 08 (2020) 123,** ***Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decay***
- 3.0 fb^{-1} [59] **LHCb-PAPER-2020-008, Phys. Rev. D102 (2020) 092005,** ***Study of the lineshape of the $\chi_{c1}(3872)$ state***
- 4.9 fb^{-1} [12] LHCb-PAPER-2019-023, JHEP 09 (2019) 028, *Observation of the $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ decay*
- 3.0 fb^{-1} [31] LHCb-PAPER-2016-016, Phys. Lett. B769 (2017) 305, *Observation of $\eta_c(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$ decays*
- 3.0 fb^{-1} [97] LHCb-PAPER-2015-015, Phys. Rev. D92 (2015) 011102, *Quantum numbers of the X(3872) state and orbital angular momentum in its $\rho^0 J/\psi$ decay*
- 3.0 fb^{-1} [148] LHCb-PAPER-2014-008, Nucl. Phys. B886 (2014) 665, *Evidence for the decay $X(3872) \to \psi(2S)\gamma$*
- 1.0 fb^{-1} [433] LHCb-PAPER-2013-001, Phys. Rev. Lett. 110 (2013) 222001, *Determination of the X(3872) meson quantum numbers*
- 0.03 fb^{-1} [235] LHCb-PAPER-2011-034, Eur. Phys. J. C 72 (2012) 1972, *Observation of X(3872) production in pp collisions at $\sqrt{s}$ = 7 TeV*

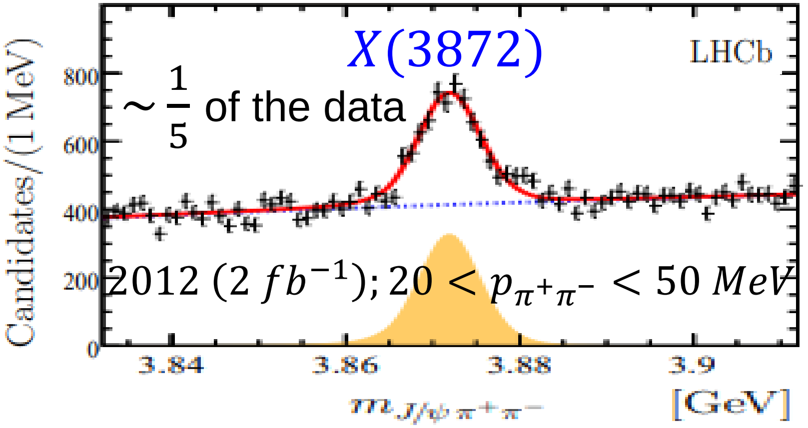
X(3872) mass and lineshape

- Use $X(3872) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$ with $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$ as the control/calibration sample
- $\pi^+\pi^-\mu^+\mu^-$ vertex detached from the primary pp collision vertex (suppression of the large prompt combinatorial background)
- Two complementary approaches:
  Full reconstruction of $B^+ \to X(3872)K^+$ [JHEP 08 (2020) 123]
  - B^+ mass cut provides further background suppression
  - Very clean, but reduced efficiency
  - $4{,}230 \pm 70$ signal events in Run 1+2 data (9 fb^{-1})

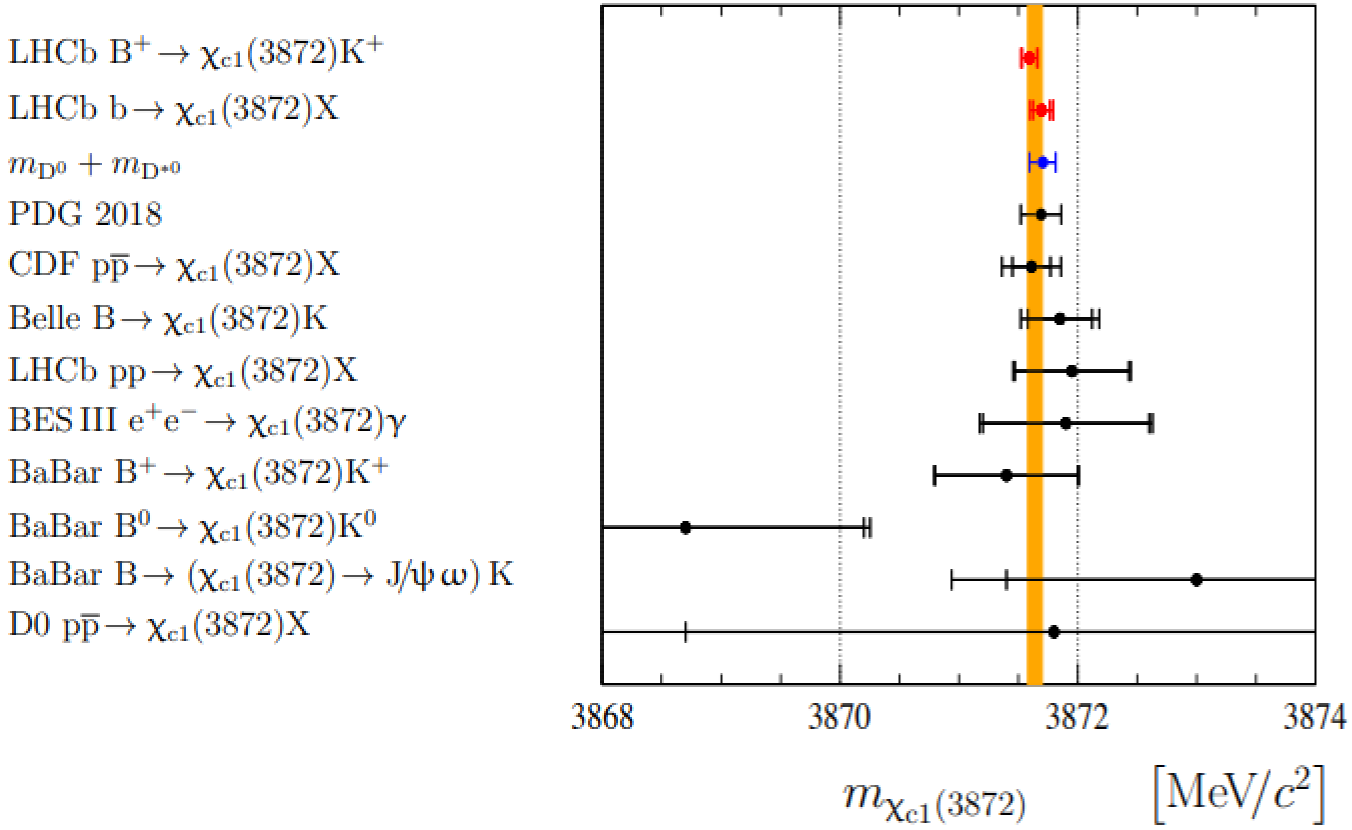
  – Just detached $X(3872)$ candidates [PRD102 (2020) 092005]
  - Larger efficiency and more sources of the signal events (e.g. $B^0 \to X(3872)K^0$, $B \to X(3872)K\pi$, $B_s \to X(3872)\phi$, $\Lambda_b \to X(3872)pK^-$, …)
  - $15{,}630 \pm 380$ signal events in Run 1 data (3 fb^{-1})
  - Fit $m_{\pi^+\pi^- J/\psi}$ in bins of $p_{\pi^+\pi^-}$ (σ_m varies: 2.4-3.0 MeV)

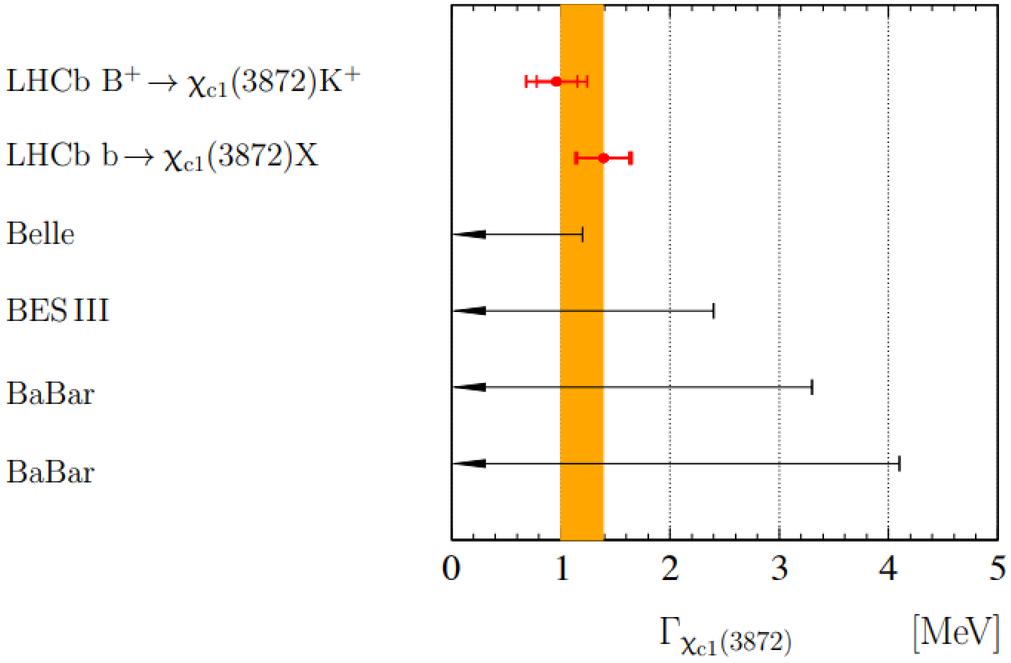


Breit-Wigner $\otimes$ σ_m



X(3872) mass and width (Breit-Wigner fits)





- The mass is still indistinguishable from the $D^0\overline{D}^{*0}$ threshold
- LHCb has reached the sensitivity to probe the natural width of $X(3872)$

Coupled-channel problem

- A resonance expected to have the Breit-Wigner shape only away from significant decay thresholds:
  - X(3872) peaks right at the $D^0\overline{D}^{*0}$ threshold, and its decay rate to $D^0\overline{D}^{*0}$ is much larger than to $\pi^+\pi^- J/\psi$

$$R_{D\bar{D}^*} = \frac{\Gamma(\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-)}{\Gamma(\chi_{c1}(3872) \to D^0\overline{D}^{*0})} = 0.11 \pm 0.03$$

Phys. Rept. **639** (2016) 1, arXiv:1601.02092

- The best determination of X(3872) lineshape would be to simultaneously fit a coupled-channel model (e.g. K-matrix) to the data from all decay channels
- Because of the proximity of the X(3872) peak to the $D^0\overline{D}^{*0}$ threshold, a simplified approach using Flatte-like formula should work well.

Flatte-like model

LHCb PRD102 (2020) 092005
based on Hanhart, Kalashnikova, Kudryavtsev, Nefediev
PRD76, 034007 (2007), PRD80, 074004 (2009)

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

1 Assume: $g_1 = g_2 = \boldsymbol{g}$

$D^0\bar{D}^{*0}$ $D^+\bar{D}^{*-}$ $\pi^+\pi^- J/\psi$ $\pi^+\pi^-\pi^0 J/\psi$ other decay modes

$$D(E) = E - E_f + i\frac{1}{2}[\boldsymbol{g}(k_1 + k_2) + \Gamma_\rho(E) + \Gamma_\omega(E) + \boldsymbol{\Gamma_0}]$$

$$E = \boldsymbol{m}_{\pi^+\pi^- J/\psi} - (m_{D^0} + m_{D^{*0}})$$

$$E_f = \boldsymbol{m_0} - (m_{D^0} + m_{D^{*0}})$$

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

$$\mu_1 = \frac{m_{D^0} m_{D^{*0}}}{(m_{D^0} + m_{D^{*0}})} \qquad \mu_2 = \frac{m_{D^+} m_{D^{*-}}}{(m_{D^+} + m_{D^{*-}})}$$

$$\delta = 8.2\,\mathrm{MeV}$$

3 *Assume $\pi^+\pi^-$ all via ρ^0*
(not quite right – see later)

$$\Gamma_\rho(E) = \boldsymbol{f_\rho} \int_{2m_\pi}^{M(E)} \frac{dm'}{2\pi} \frac{q(m',E)\,\Gamma_\rho}{(m'-m_\rho)^2 + \Gamma_\rho^2/4},$$

$$q(m',E) = \sqrt{\frac{[M^2(E) - (m' + m_{J/\psi})^2]\,[M^2(E) - (m' - m_{J/\psi})^2]}{4M^2(E)}}$$

$$M(E) = E + (m_{D^0} + m_{D^{*0}}) - m_{J/\psi}$$

$$\Gamma_\omega(E) = f_\omega \int_{3m_\pi}^{M(E)} \frac{dm'}{2\pi} \frac{q(m',E)\,\Gamma_\omega}{(m'-m_\omega)^2 + \Gamma_\omega^2/4}$$

2 Constrain $\boldsymbol{g}$ to be large
from Belle,BaBar measurements:

$$R_{D\bar{D}^*} = \frac{BR_{\pi^+\pi^- J/\psi}}{BR_{D^0\bar{D}^{*0}}} = 0.11 \pm 0.03$$

4 f_ω constrained to f_ρ by assuming:

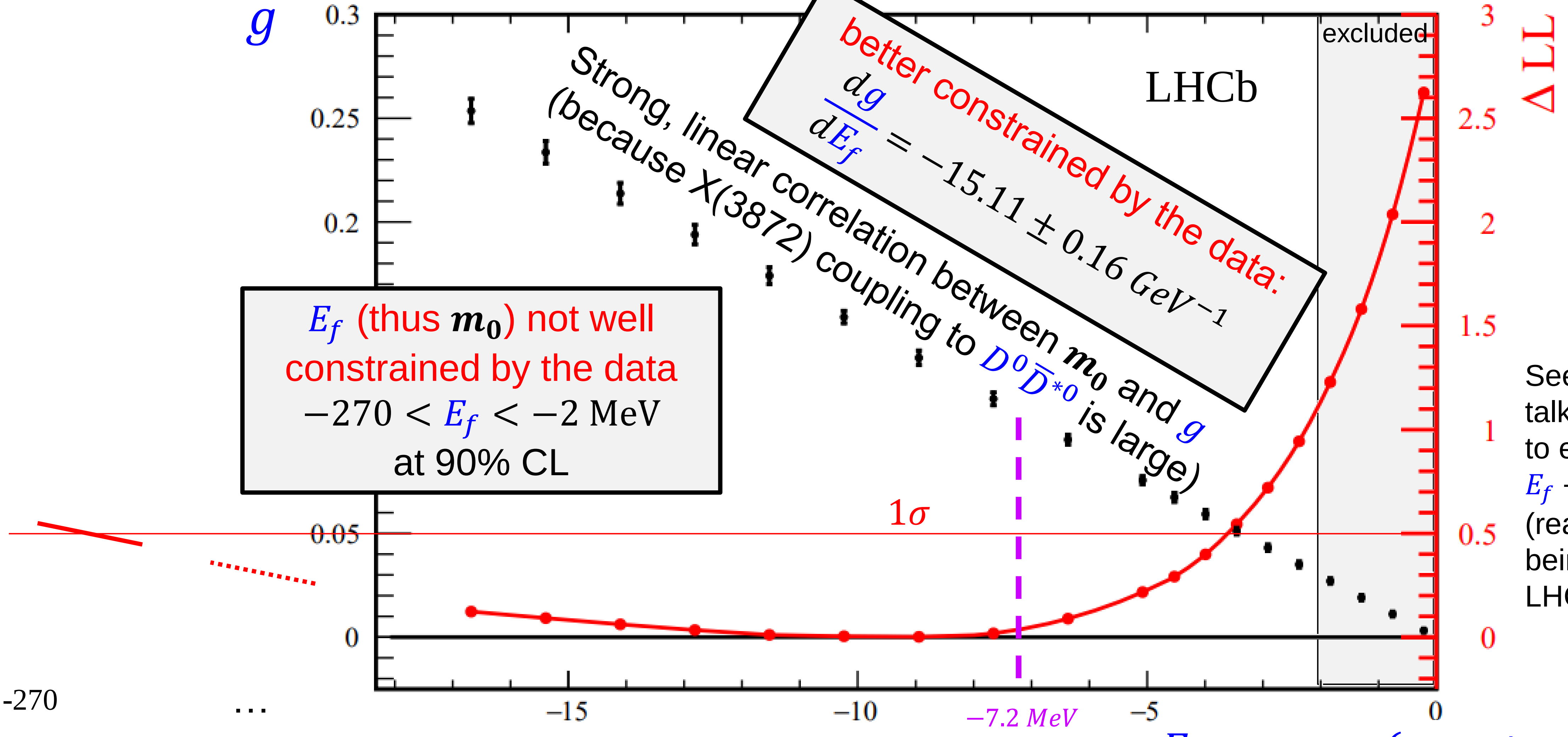
$$\frac{BR_{\omega J/\psi}}{BR_{\pi^+\pi^- J/\psi}} = 1$$

(motivated by Belle,BaBar,BESIII ave.: 1.4 ± 0.3)

Fitted parameters: $\boldsymbol{m_0}$, $\boldsymbol{g}$, $\boldsymbol{f_\rho}$, $\boldsymbol{\Gamma_0}$

Flatte-like model - fit results

[PRD102 (2020) 092005]



better constrained by the data: $\frac{dg}{dE_f} = -15.11 \pm 0.16\ GeV^{-1}$

Strong, linear correlation between m_0 and g (because X(3872) coupling to $D^0\overline{D}^{*0}$ is large)

E_f (thus m_0) not well constrained by the data
$-270 < E_f < -2$ MeV
at 90% CL

See C. Hanhart's talk yesterday how to eliminate the $E_f - g$ correlations (reanalysis is being pursued by LHCb)

$E_f = m_0 - (m_{D^0} + m_{D^{*0}})$ [MeV]

For $E_f = -7.2\ MeV$ ($m_0 = 3864.5\ MeV$):

Attention:
The errors don't include the E_f error, which is large

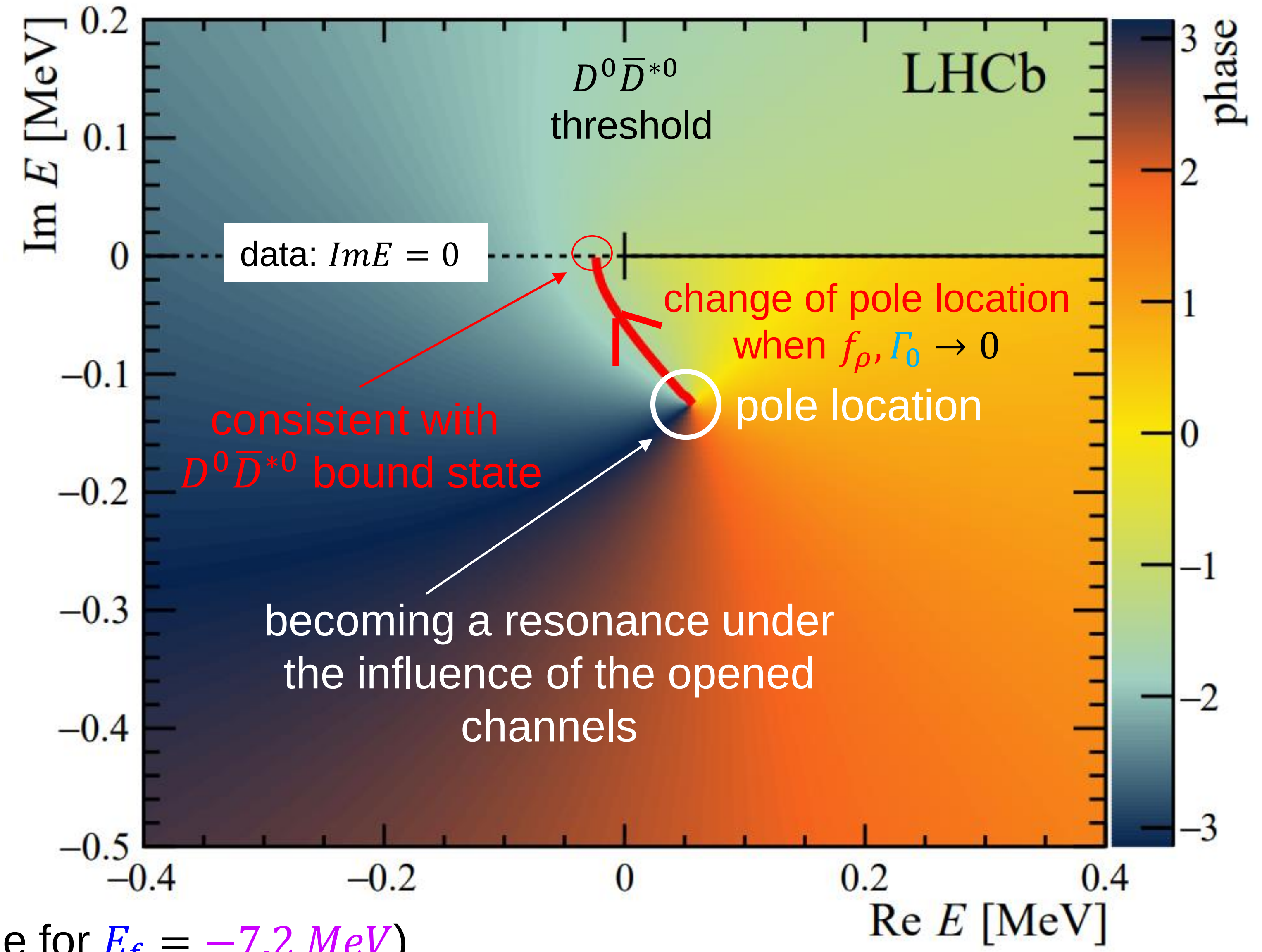
$g = 0.108 \pm 0.003^{+0.005}_{-0.006}$ $f_\rho = \left(1.8 \pm 0.6^{+0.7}_{-0.6}\right) \times 10^{-3}$ $\Gamma_0 = 1.4 \pm 0.4 \pm 0.6\ MeV$

Uncomfortably large.
Need to constrain by data on other modes?

Determination of complex poles in the Flatte amplitude obtained from the data

[PRD102 (2020) 092005]

- Analyzing pole structure in complex energy plane can help determine the nature of the singularity
- Amplitude phase becomes undetermined at the pole location – used to find poles
- Two poles found. Show the one closer to the $D^0\overline{D}^{*0}$ threshold



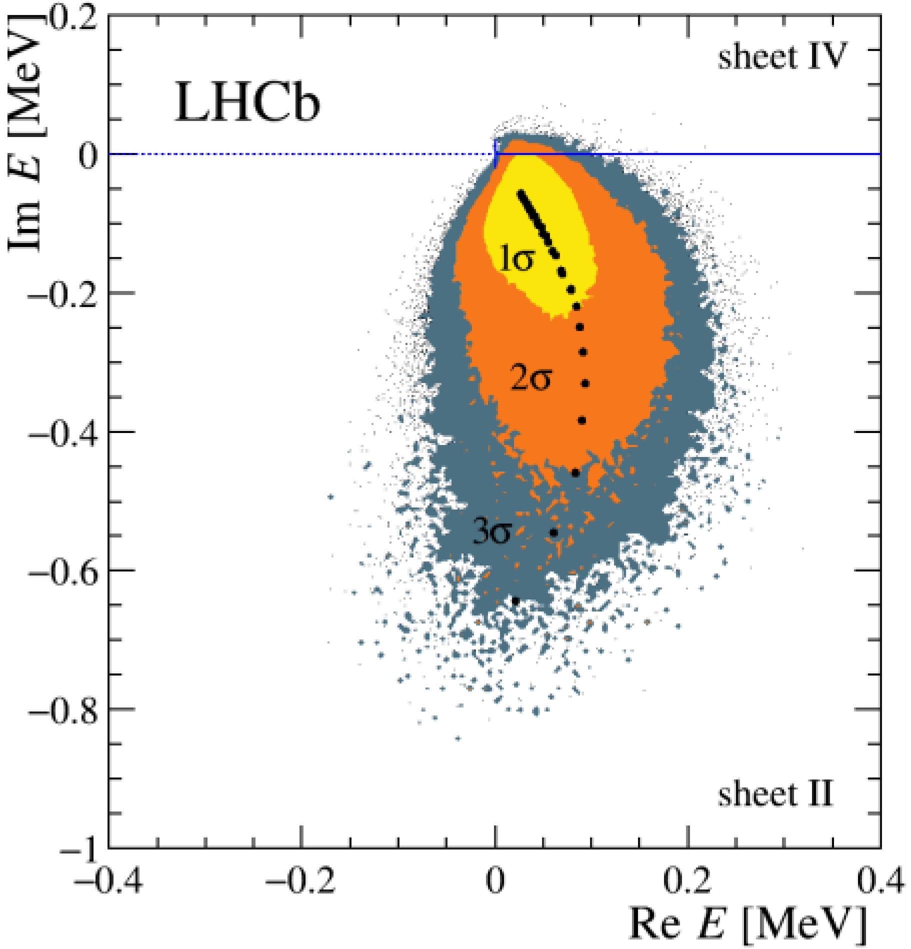
(example for $E_f = -7.2\ MeV$)

Statistical and systematic uncertainties in pole location

Statistical only, including the uncertainty in E_f
(black dots: different values of E_f)

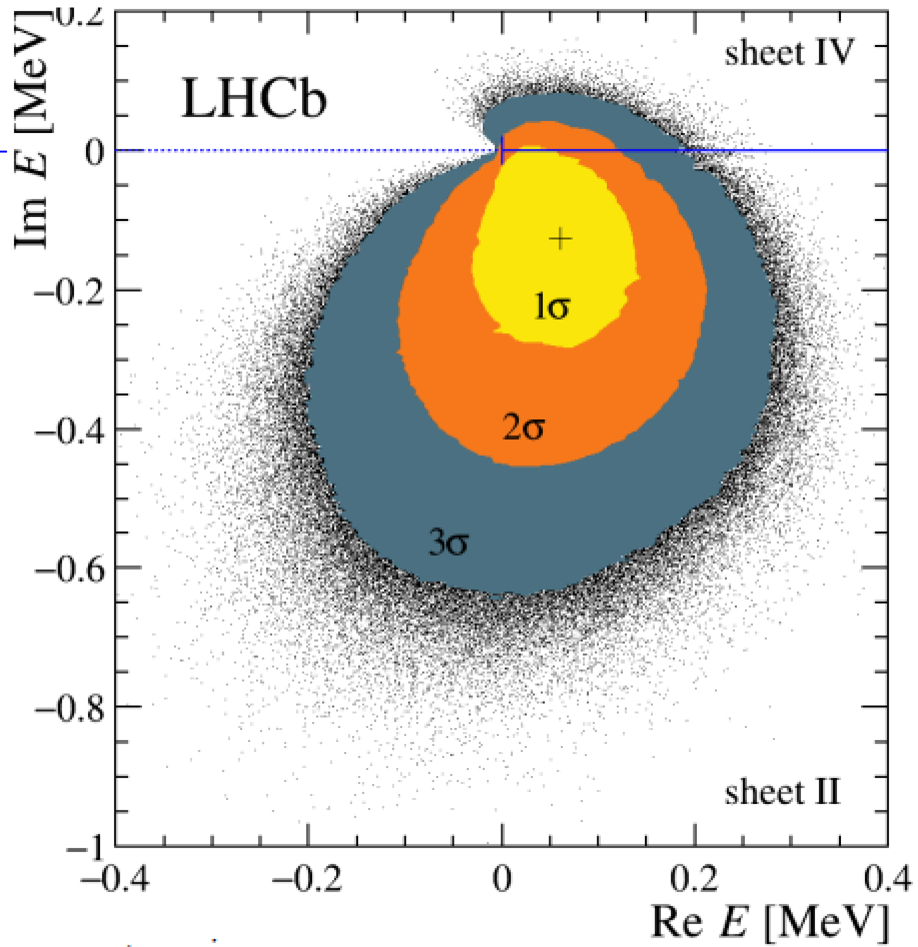
$E_f = -7.2\ MeV$
the rest of statistical plus systematic errors

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



quasi-virtual $D^0\bar{D}^{*0}$ state

quasi-bound $D^0\bar{D}^{*0}$ state

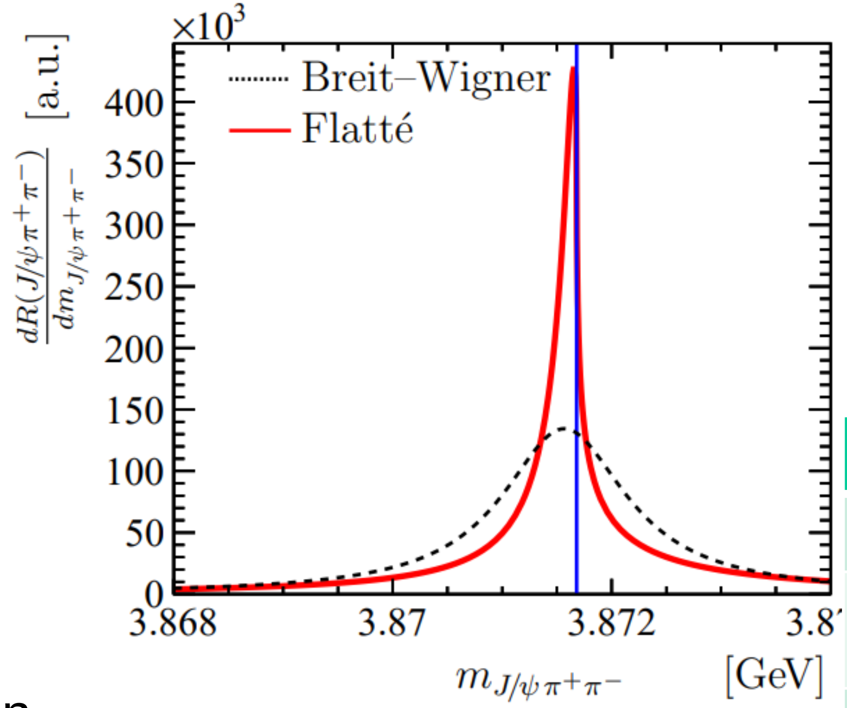


$$\text{II:}\ \ E - E_f - \frac{g}{2}\left(+\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E)\ \text{with}\ \mathrm{Im}\,E < 0\,,$$

Limitation on sensitivity

[PRD102 (2020) 092005]

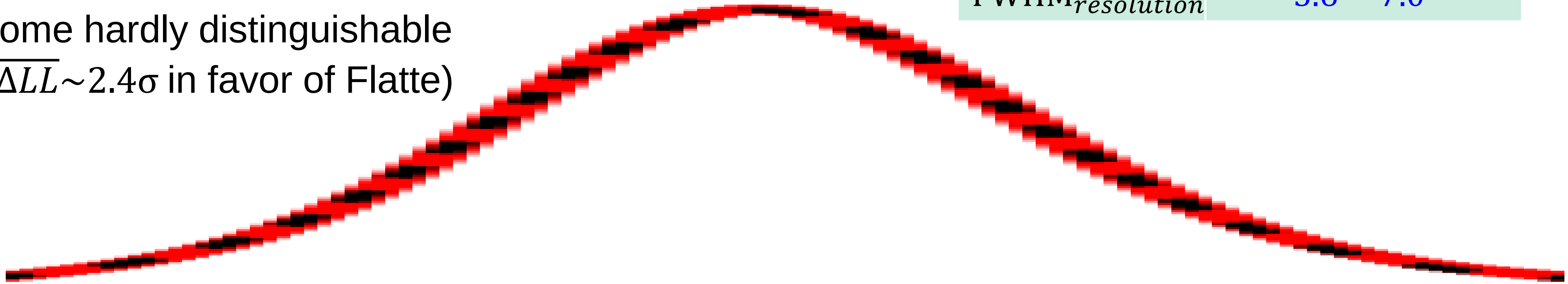
Underlying lineshapes



Quantity	Value in MeV
Γ_{BW}	$1.39 \pm 0.24 \pm 0.10$
FWHM_{Flatte}	$0.22^{+0.06\,+0.25}_{-0.08\,-0.17}$
$\mathrm{FWHM}_{resolution}$	$5.6 - 7.0$

Attention:
The errors don't include the E_f error,

After mass resolution become hardly distinguishable ($\sqrt{2\Delta LL}$~2.4σ in favor of Flatte)



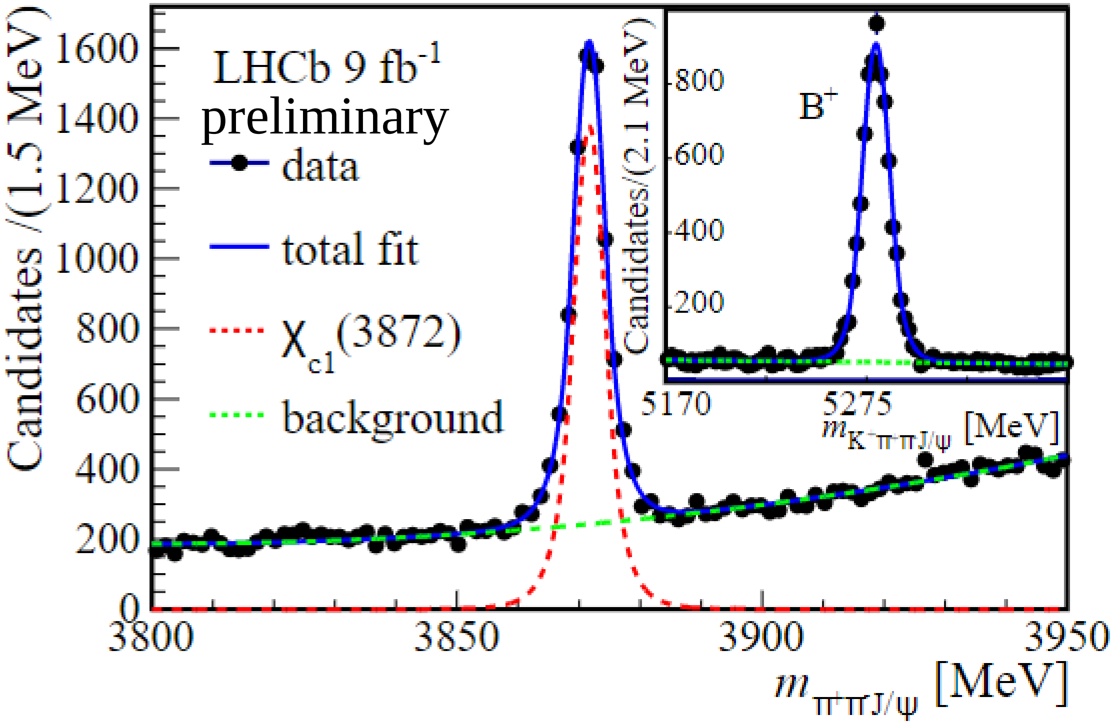
Sensitivity to the underlying lineshape is mostly washed out by the mass resolution.

PANDA will have mass resolution an order of magnitude better than LHCb (see talk by Nerling)

Dipion mass spectrum in $X(3872) \to \pi^+\pi^- J/\psi$

[LHCb-PAPER-2021-045, in preparation]

Full reconstruction of
$B^+ \to X(3872)K^+$, $X(3872) \to \pi^+\pi^- J/\psi$
6788 ± 117 signal events



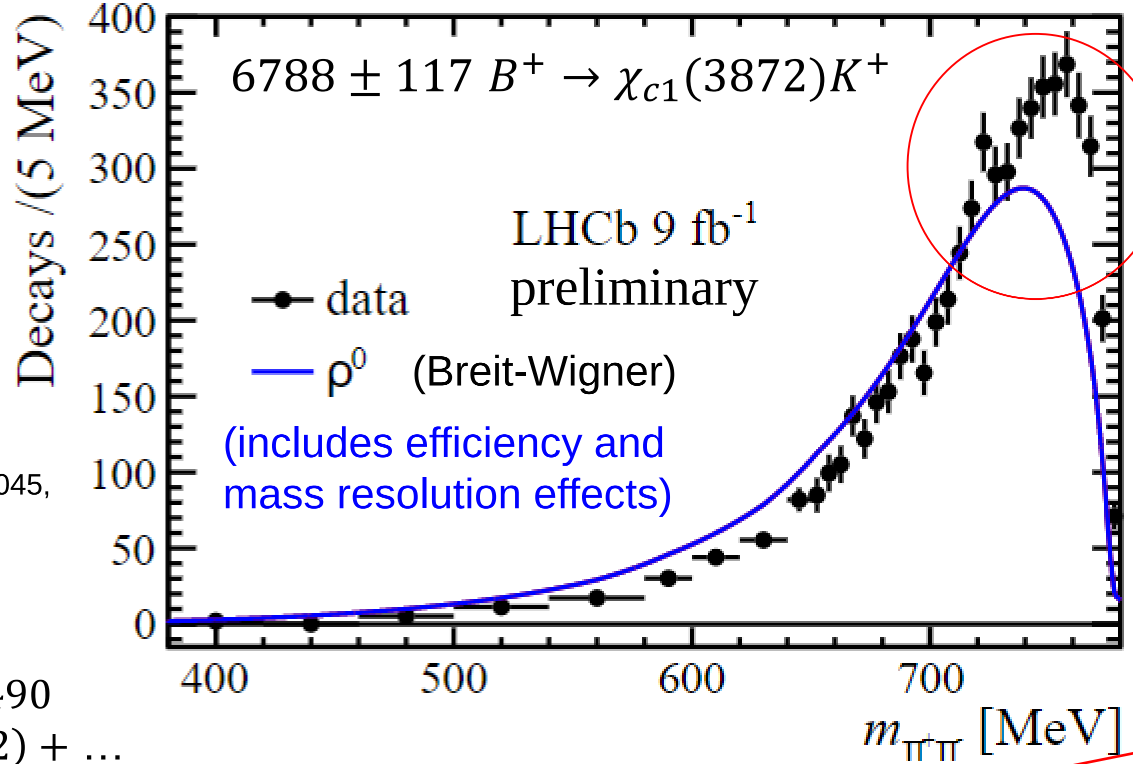
- The $m_{\pi^+\pi^-}$ distribution is obtained by 2D unbinned fits of the $X(3872)$ signal yields to the $m_{\pi^+\pi^- J/\psi}$ data in $m_{\pi^+\pi^-}$ intervals – the result on the next slide (dependence of the signal and background shapes on $m_{\pi^+\pi^-}$ via the phase-space factor $p_{J/\psi}$ in $\pi^+\pi^- J/\psi$ rest frame)

Is it all $X(3872) \to \rho^0 J/\psi$?

No!

$$\chi^2/NDF = 366.6/34$$

[LHCb-PAPER-2021-045, in preparation]



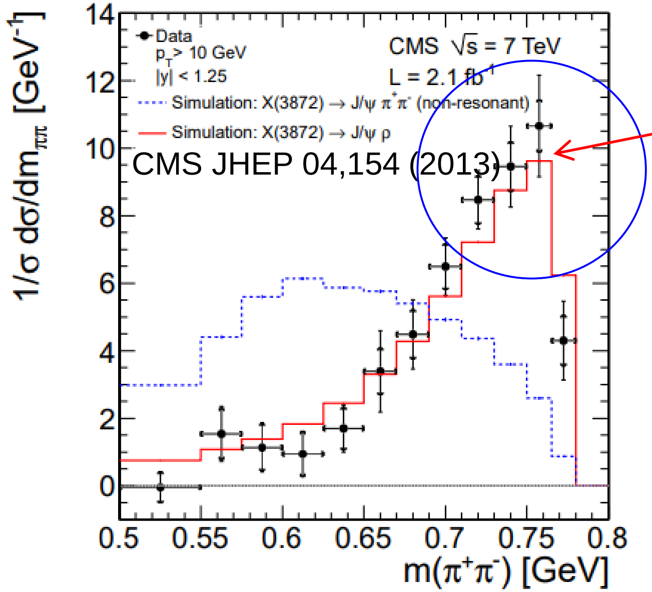
How did we miss it before?

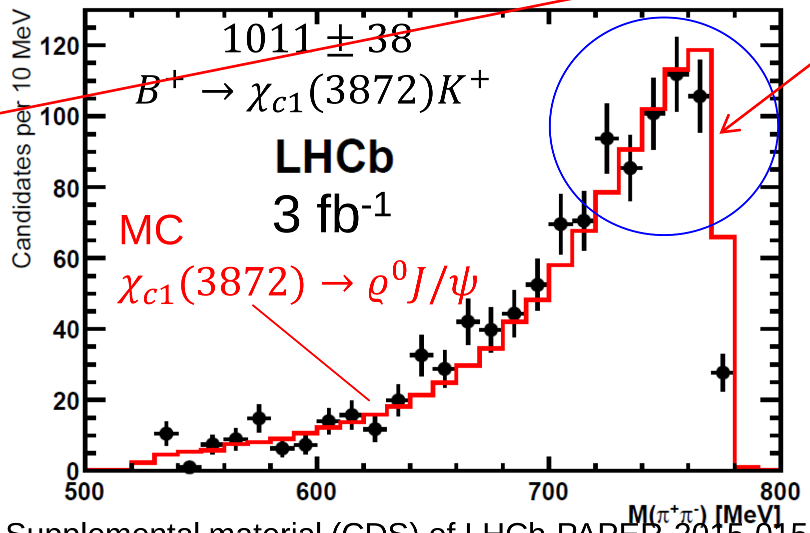
The previous comparisons of the data from CMS, LHCb and ATLAS with the $X(3872) \to \rho^0 J/\psi$ simulations (see below) used **EvtGen** which **does not simulate the effects of phase space on resonance masses in a decay sequence**

$p_{J/\psi}$ suppression factor missing in the simulations!

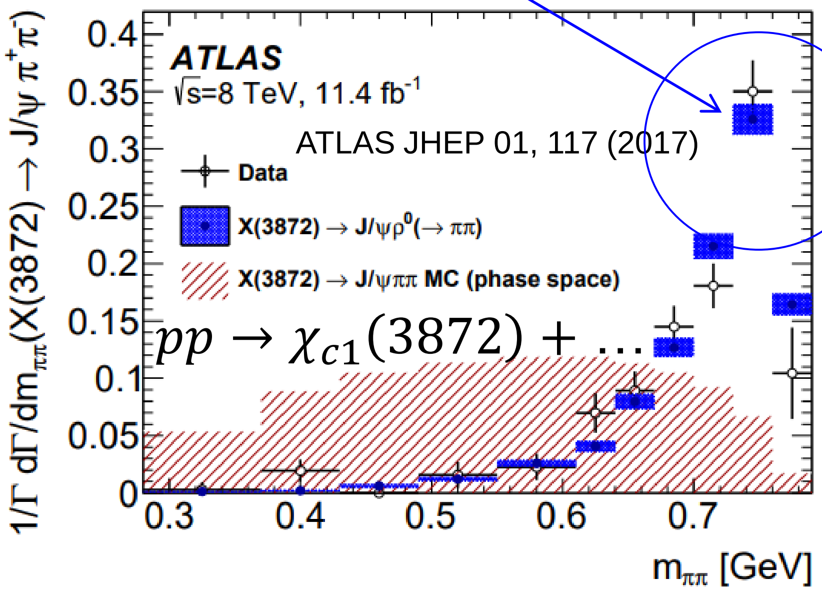
11910 ± 490

$pp \to \chi_{c1}(3872) + \ldots$



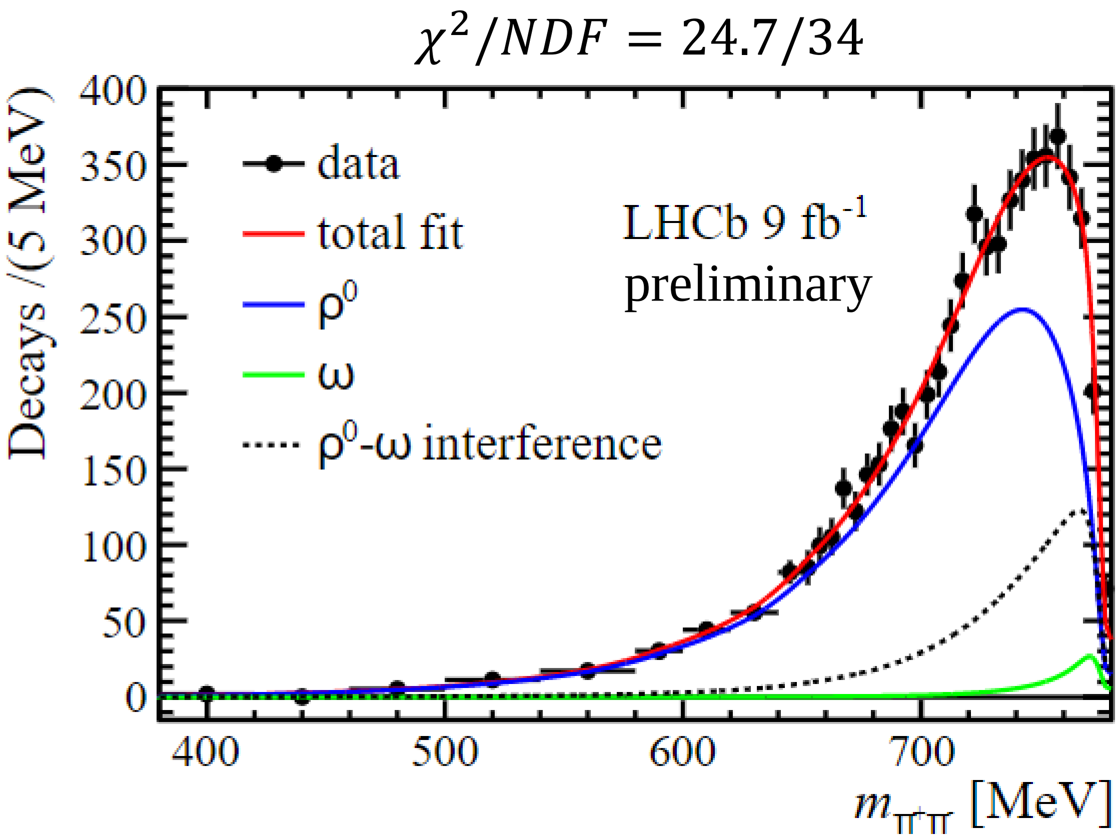


Supplemental material (CDS) of LHCb-PAPER-2015-015
PRD92, 011102 (2015)



What is missing in the model?

[LHCb-PAPER-2021-045, in preparation]



$\boldsymbol{\omega}$, which is small on its own, but is enhanced to a sizeable contribution via $\boldsymbol{\rho}-\boldsymbol{\omega}$ interference!

Significance of $\boldsymbol{\omega}$ contributions is 7.1σ

$\boldsymbol{\rho}$ ~ 79%

$\boldsymbol{\rho}-\boldsymbol{\omega}$ ~ 19% $\quad (\mathbf{21.4} \pm \mathbf{2.3} \pm \mathbf{2.0})\%$

$\boldsymbol{\omega}$ ~ 2%

$(\mathbf{1.9} \pm \mathbf{0.4} \pm \mathbf{0.3})\%$

In agreement with the expectations from the

$\Gamma(X(3872) \to \omega\, J/\psi,\ \omega \to \pi^+\pi^-\pi^0)$ / $\Gamma(X(3872) \to \pi^+\pi^- J/\psi)$

measurements by Belle, BaBar and BESIII

Proper coupled-channel model is necessary for a successful fit to the data:

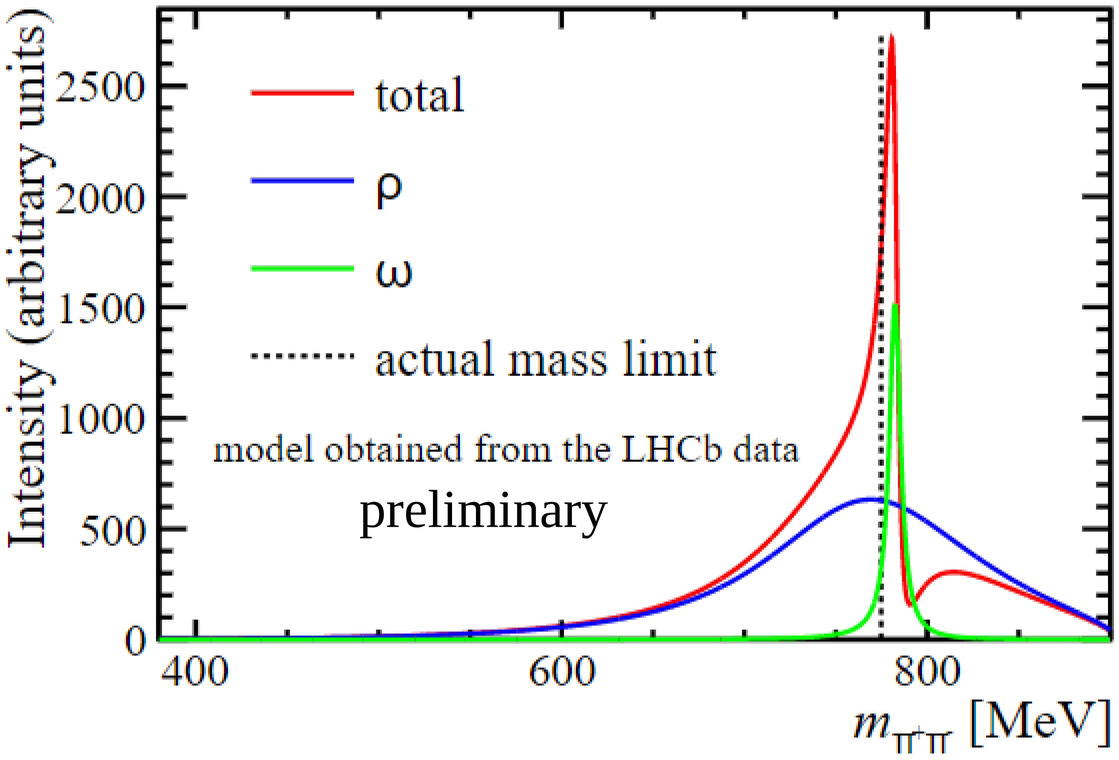
2-channel K-matrix: $$K = \frac{1}{m_\rho^2 - s}\begin{pmatrix} g^2_{\rho\to2\pi} & 0 \\ 0 & 0 \end{pmatrix} + \frac{1}{m_\omega^2 - s}\begin{pmatrix} g^2_{\omega\to2\pi} & g_{\omega\to2\pi}\, g_{\omega\to3\pi} \\ g_{\omega\to2\pi}\, g_{\omega\to3\pi} & g^2_{\omega\to3\pi} \end{pmatrix} \quad \begin{array}{c} \pi^+\pi^- \\ \pi^+\pi^-\pi^0 \end{array}$$

Breit-Wigner-sum model of ρ^0 and $\boldsymbol{\omega}$ fails to describe the data well ($\chi^2/NDF = 102.9/33$) !

Determination of isospin violating and conserving couplings in $X(3872) \to \pi^+\pi^- J/\psi$

[LHCb-PAPER-2021-045, in preparation]

(efficiency or mass resolution not included in the display)



Set $m_{X(3872)} = 4000\ MeV$ in the obtained $X(3872) \to \pi^+\pi^- J/\psi$ model to contain ρ^0 and $\boldsymbol{\omega}$ resonances.

From the ratio of the integrals in the extended phase space determine:

$$\frac{g_{X(3872)\to\rho^0 J/\psi}}{g_{X(3872)\to\omega J/\psi}} = 0.29 \pm 0.04$$

Isospin violation an order of magnitude larger than expected for a pure charmonium state:

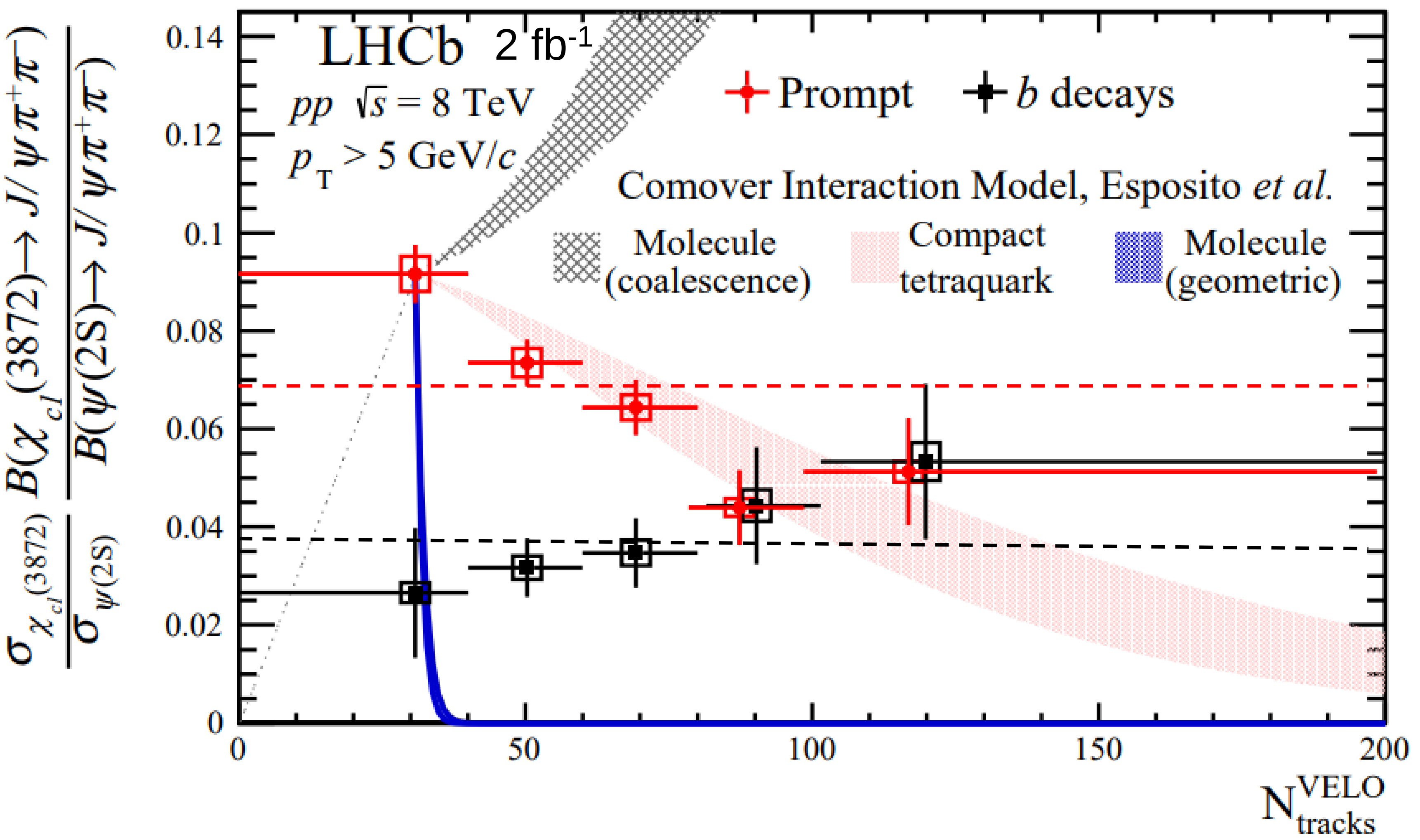
$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

Natural explanation via large $D^0\bar{D}^{*0}$ component (the mass 8 MeV below $D^+\bar{D}^{*-}$)

(mixing of two degenerate compact tetraquark states can also lead to the large isospin violation)

Event multiplicity dependence of prompt production of X(3872)

PRL126 (2021) 092001



- Dependence of X(3872) prompt production cross-section on event multiplicity is significantly different (5σ) then the one for $\psi(2S)$

How $\chi_{c1}(2P) - D^0\overline{D}^{*0}$ mixture model would look like on this plot?

∝ number of particles produced in pp collision

Conclusion

- The LHCb has reached $X(3872) \to \pi^+\pi^- J/\psi$ data sample sizes sufficient to start probing natural line shape of X(3872):
  - the initial Flatte lineshape fits indicate consistency of X(3872) with weakly bound $D^0\overline{D}^{*0}$ becoming a resonance via coupling to the other lower-threshold channels (however, a virtual state not ruled out)
  - the experimental errors are large and other interpretations are also plausible
  - a lot of room for improvement in statistics (more data already available) and better constraints from the coupled channels, $D^0\overline{D}^{*0}$ in particular
  - Future measurements with improved mass resolution would be very valuable (PANDA ?)
- $X(3872) \to \pi^+\pi^- J/\psi$ is not totally dominated by $X(3872) \to \rho^0 J/\psi$, and sizeable ρ^0 – ω interference is clearly visible in the data:
  - This has consequences for determination of isospin violating to isospin conserving X(3872) couplings
- Many other interesting X(3872) papers not covered in my talk due to the time constraints (see slide 2 for the list)