Measurements of the Absolute Branching Fractions of $B^{\pm} \rightarrow K^{\pm} X_{c\bar{c}}$

PRL 124 152001 (2020)

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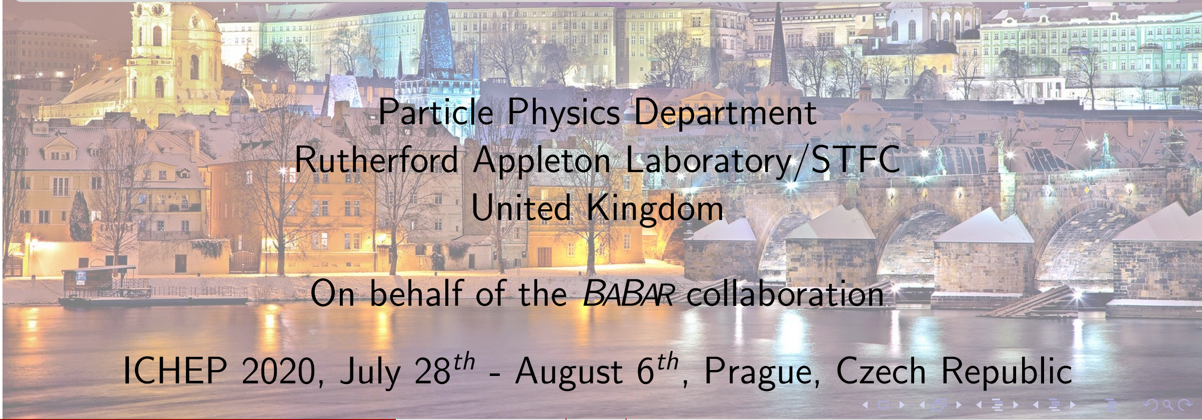

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Exotic XYZ charmonium-like states

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QCD allows for complex structure beyond $c\bar{c}$ mesons and ccc baryons.

Many "exotic" charmonium-like states have been discovered in recent years.

Some do not fit into the predicted framework of $c\bar{c}$ mesons; their masses and/or decay products do not correspond to those expected for the yet undiscovered non-exotic states.

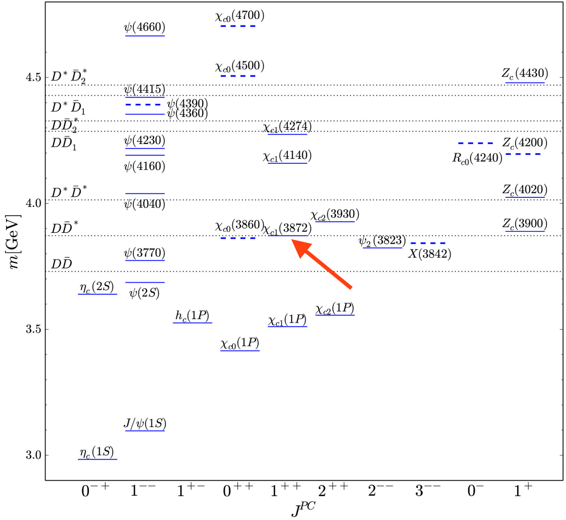
The X, Y, and Z particles

States with a $c\bar{c}$ or $b\bar{b}$:

Y mesons: $J^{PC} = 1^{--}$

Z mesons: Isospin 1 (can have $q = \pm 1$)

X mesons: all the rest

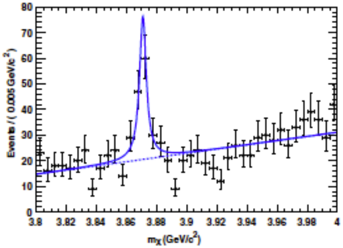


From N. Brambilla *et al.*, Physics Reports (in preparation)

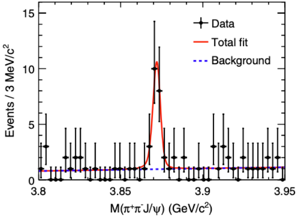
The $X(3872)$ state (also known as $\chi_{c1}(3872)$ in PDG)

This decay has been measured by many experiments: *BABAR*, Belle, CDF, BES-III, LHCb, ...

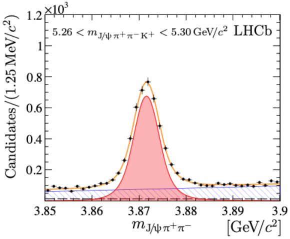
Belle 2003



BES-III (2014)



LHCb (2020)

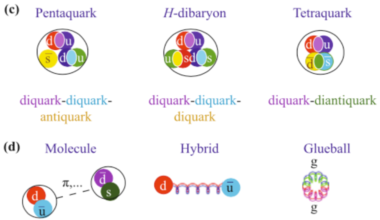


- Belle PRD 97, (2018) 012005 [1]: $\mathcal{B}(B^{\pm} \to K^{\pm}X(3872)) < 2.6 \times 10^{-4}$
- $X(3872)$ has a much narrower width ($\Gamma = 0.96^{+0.19}_{-0.18} \pm 0.21\,\mathrm{MeV}$ [2]) than other XYZ states ($\Gamma = [40 - 180]\,\mathrm{MeV}$).
- Narrowness of the $X(3872)$ makes it an excellent candidate for a missing mass analysis

Interpretation of the XYZ and $X(3872)$ states

Possible XYZ explanations

- Tetraquarks: $(qq)(\overline{qq})$ mesons; Pentaquarks: $(qq)(qq)\overline{q}$ baryons; H-dibaryon: $(qq)(qq)(\overline{qq})$ mesons
- Molecule: bound states of color-singlet standard hadrons
- Glueballs: mesons composed of gluons only.
- Hybrid: q, $\overline{q}$, and gluon.



$X(3872)$ explanations and predictions

- Options: hybrids, glueball, and charmonium-molecule
- D^0–$\overline{D}^{*0}$ molecule: $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) \approx 10\%$ [3]
- Tetraquark: $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) \geq 50\%$ [4]

Reviews

N. Brambilla *et al.*, Phys. Reports 2020 (in preparation), J. S. Olsen *et al.*, Mod Phys 90 (2018) 015003,

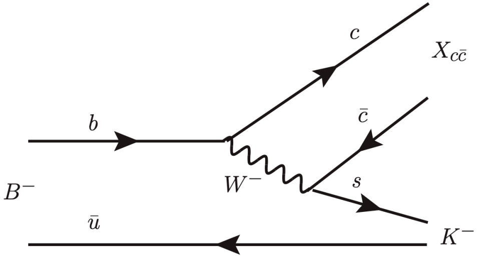
H. X. Chen *et al.*, Phys. Report. 639 (2016) 1

Absolute branching fraction $\mathcal{B}(B^\pm \to K^\pm X(3872))$

Exclusive 2-body B-meson decays of the form $B^\pm \to K^\pm X_{c\bar{c}}, X_{c\bar{c}} \to f$ have been published:

- Measure the product $\mathcal{B}(B^\pm \to K^\pm X_{c\bar{c}}) \times \mathcal{B}(X_{c\bar{c}} \to f)$
- Do not measure $\mathcal{B}(B^\pm \to K^\pm X_{c\bar{c}})$ or $\mathcal{B}(X_{c\bar{c}} \to f)$

Knowledge of exotic decay $\mathcal{B}(X(3872) \to f)$ would help in $X(3872)$ interpretation.



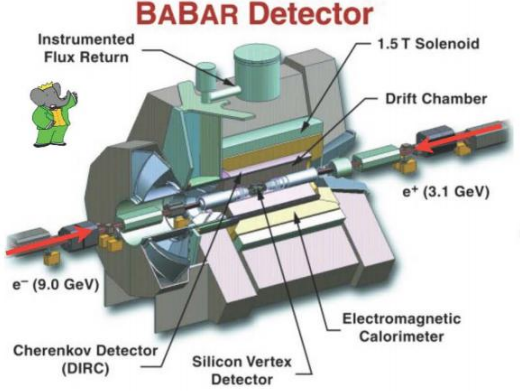
$X_{c\bar{c}} = J/\psi, \chi_{cJ}(1P), \eta_c, \eta_c(2S), \psi(2S), \phi(3770), X(3872), \ldots$

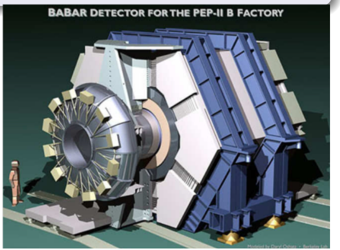
- J/ψ: $f = e^+e^-, \mu^+\mu^-$
- $\chi_{cJ=0,1,2}(1P)$: $f = J/\psi\pi^+\pi^-$, $J/\psi\gamma$
- η_c: $f = K^+K^-\pi^0$, etc.
- $X(3872)$: $f = J/\psi\pi^+\pi^-$, etc.
- ...

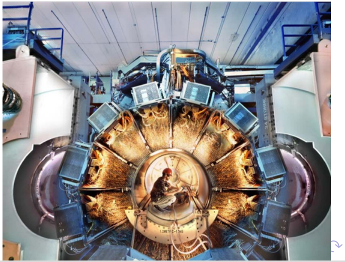
BABAR Detector at PEP-II

Asymmetric beam momenta, $E_{\mathrm{CM}} = 10.58\,\mathrm{GeV}$, low multiplicity, low background, K/π particle identification, good μ and e identification.

Data sample: $\sim 424\,\mathrm{fb}^{-1}$ at $\Upsilon(4S)$ resonance
$\Upsilon(4S)$ decays to $B^{+}B^{-}$ or $B^{0}\overline{B}^{0}$ $\sim 100\%$





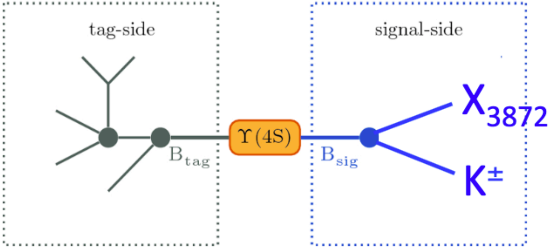


Method - Hadronic Tagging

- "Hadronic Tag": Fully reconstruct a B meson in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ ("$B_{\rm tag}$").
- $B_{\rm tag} \to SY$ with

  $S = D^{(*)0}, D^{(*)\pm}, D_s^{(*)\pm}, J/\psi$

  $Y =$ combinations of $\pi^\pm, K^\pm, \pi^0$ and K_S^0
- Accept $B_{\rm tag} \to SY$ channels with purity > 0.08
- Select events with an identified $K^\pm$ in the other B meson decay ("$B_{\rm sig}$").



Method and Improvements

1. Boost to center-of-mass (CM) of the "B_{sig}"
2. Plot $K^{\pm}$ momentum in the 2-body $B \to K^{\pm} X_{c\bar{c}}$ decay; related to the missing mass m_X

$$m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B} \qquad E_K = \text{energy of } K^{\pm} \text{ in } B_{\mathrm{sig}}\ CM.$$

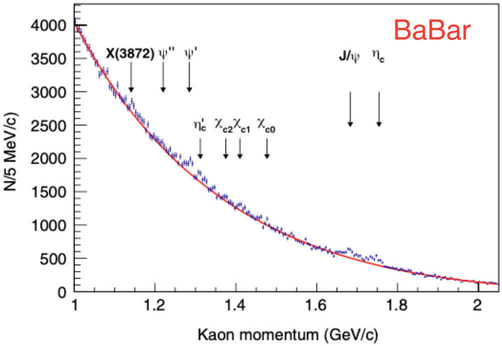
3. $X_{c\bar{c}}$ resonances appear as peaks in the $K^{\pm}$ momentum distribution
4. Search for $X(3872)$ in $K^{\pm}$ momentum distribution and determine absolute $\mathcal{B}(B^{\pm} \to K^{\pm} X(3872))$ directly; no knowledge of the $X(3872) \to f$ decay needed
5. Use already known product $\mathcal{B}(B^{\pm} \to K^{\pm} X(3872)) \times \mathcal{B}(X(3872) \to f)$ to determine $\mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)$

Improvements over earlier *BABAR* analysis (PRL 96 052002 (2006))

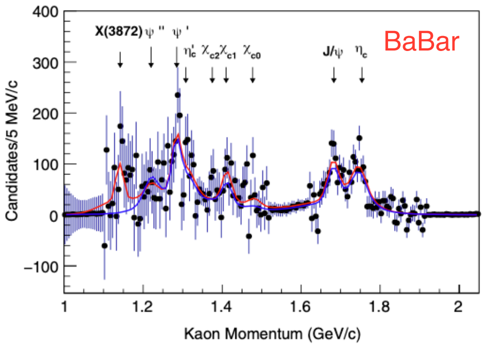
- A factor 2 increase in data sample size ($211\,\mathrm{fb}^{-1} \to 424\,\mathrm{fb}^{-1}$).
- A factor 3 increase in $X(3872)$ signal reconstruction efficiency:
  - Mainly by keeping all B_{tag} candidates in an event (not just one)
  - Also improved hadronic tagging algorithm and background evaluation

Background Rejection and Signal Extraction

- Increase in $B^{\pm} \to K^{\pm} X_{c\bar{c}}$ reconstruction efficiency leads to more background
- Use two Neural Nets to reduce background from:
  1. Continuum events $e^{+}e^{-} \to q\bar{q}$, mainly based on event shape difference.
  2. $B^{\pm} \to K^{\pm} X_{c\bar{c}}$ signal events with a secondary $K^{\pm}$, mainly based on isolation of $K^{\pm}$ in B_{sig} CM.
- Fit a 5th order Chebychev polynomial to background, interpolating between "resonance-free" regions.
- Apply a binned maximum-likelihood fit to the background-subtracted $K^{\pm}$ distribution.
- Fitted resonances: 9 $X_{c\bar{c}}$: J/ψ, η_c, $\psi(2S)$, $\chi_{cJ=0,1,2}(1P)$, $\psi(3770)$, $\eta_c(2S)$, $X(3872)$.
- Widths from MC, position from PDG [5].



Results



Particle	Yield	$\mathcal{B}(10^{-4})$	N_σ
J/ψ	2364 ± 189	10.1 ± 0.29 (Ref. [21])	10.4
η_c	2259 ± 188	$9.6 \pm 1.2(\text{stat}) \pm 0.6(\text{syst})$	9.3
χ_{c0}	287 ± 181	$2.0 \pm 1.3(\text{stat}) \pm 0.3(\text{syst})$	1.6
χ_{c1}	1035 ± 193	$4.0 \pm 0.8(\text{stat}) \pm 0.6(\text{syst})$	2.2
χ_{c2}	200 ± 164	< 2.0	1.2
$\eta_c(2S)$	527 ± 271	$3.5 \pm 1.7(\text{stat}) \pm 0.5(\text{syst})$	2.3
ψ'	1278 ± 285	$4.6 \pm 1(\text{stat}) \pm 0.7(\text{syst})$	3.1
$\psi(3770)$	497 ± 308	$3.2 \pm 2.0(\text{stat}) \pm 0.5(\text{syst})$	1.2
$X(3872)$	992 ± 285	$2.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})$	3.0

$\mathcal{B}$ compatible with Belle [1] measurements
Main systematic: $p_{K^\pm}$ background shape

Using J/ψ and $X(3872)$ yields and reconstruction efficiencies:

$$=> \mathcal{B}(B^\pm \to K^\pm X(3872)) = (2.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-4}$$

From PDG: $\mathcal{B}(B^\pm \to K^\pm X(3872)) \times \mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) = (8.6 \pm 0.8) \times 10^{-6}$

$$=> \mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) = (4.1 \pm 1.3)\%$$

Summary

- Results published in PRL 124, 152001 (2020)
- First absolute measurement of $\mathcal{B}(B^+ \to K^\pm X(3872))$ based on a hadronic tag and missing mass:
$$\mathcal{B}(B^+ \to K^\pm X(3872)) = (2.1 \pm 0.6_{\mathrm{stats}} \pm 0.3_{\mathrm{syst}}) \times 10^{-4}$$
- First determination of $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-)$:
$$\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) = (4.1 \pm 1.3)\%$$
- Rules out simple tetraquark model, which predicts $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) \geq 50\%$
- Molecular models, which predict $\mathcal{B}(X(3872) \to J/\psi \pi^+\pi^-) \leq 10\%$, are more consistent.
- However, pure molecular models have problems with branching fractions in radiative decays. Could indicate hybrid molecular models worthwhile pursuing.
- Can combine $\mathcal{B}$ with measured $\Gamma_{X(3872)}$ [2] to extract partial widths.
- Method can be applied to other $X(3872) \to f$ final states.

References

[1] Belle Collaboration, Y. Kato *et al.*, *Measurements of the absolute branching fractions of $B^+ \to X_{c\bar{c}} K^+$ and $B^+ \to \overline{D}^{(*)0}\pi^+$ at Belle*, Phys. Rev. D **97** (2018) 012005.

[2] LHCb Collaboration, R. Aaij *et al.*, *Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays*, Tech. Rep. arXiv:2005.13422. LHCB-PAPER-2020-009, CERN, Geneva, May, 2020.

[3] E. Braaten and M. Kusunoki, *Decays of the $X(3872)$ into J/ψ and light hadrons*, Phys. Rev. D **72** (2005) 054022.

[4] N. A. Tornqvist, *Isospin breaking of the narrow charmonium state of Belle at 3872 MeV as a deuson*, Physics Letters B **590** (2004) 209 .

[5] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. D **98** (2018) 030001, and 2019 update.