Is $f_X(1500)$ observed in the $B \to \pi(K)KK$ decays $\rho^0(1450)$?

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Outline

- History and Questions
- 3-body decays of B meson in PQCD
- Numerical Results and discussions
- Summary

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This story begins in 2002

- In 2002, Belle studied $B^+ \to K^+K^+K^-$ decay and observed a broad structure around 1.5GeV in the invariant mass $M(K^+K^-)$ spectrum, and it is named $f_X(1500)$.

Belle, hep-ex/0201007

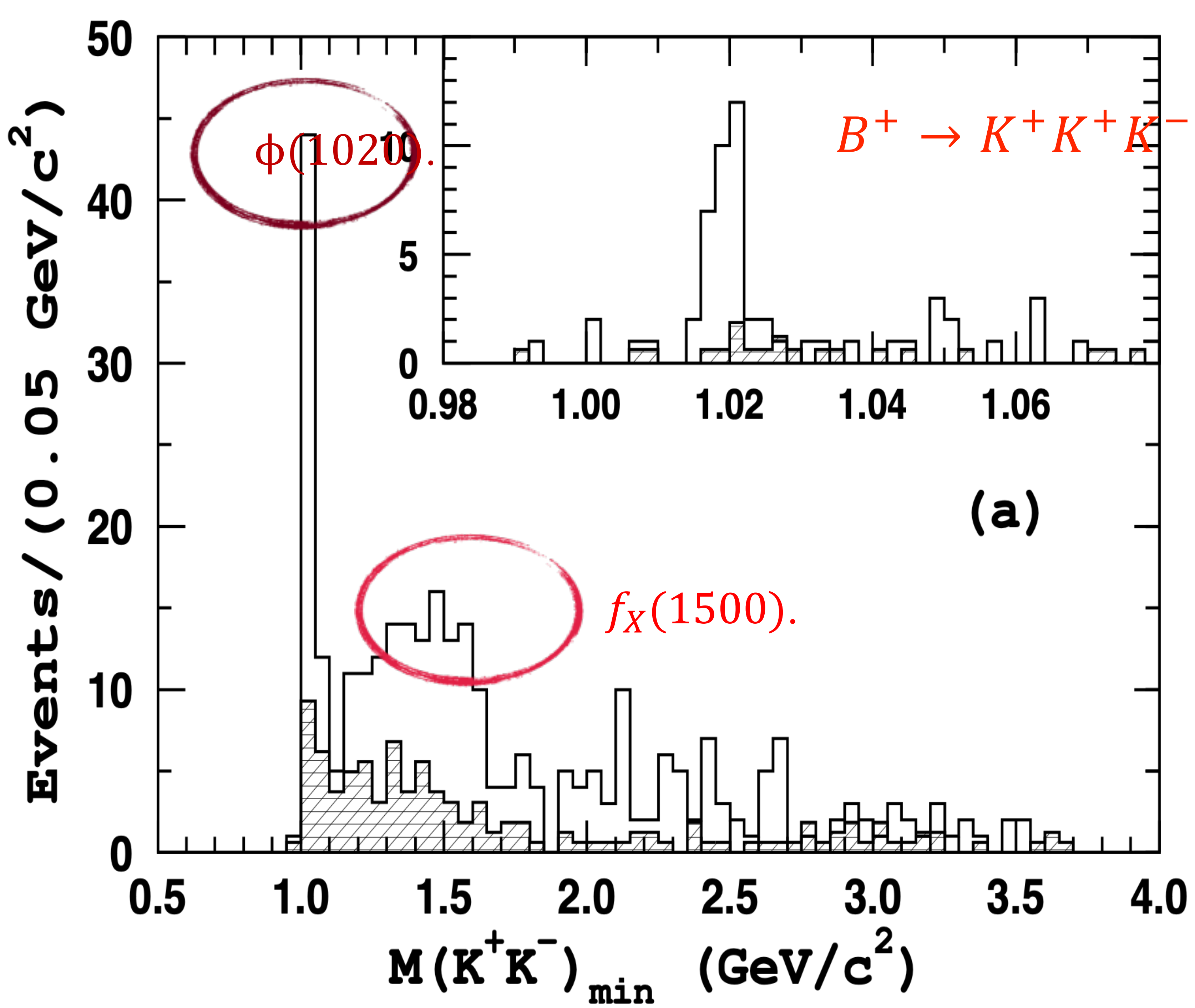
$$M(f_X) = 1500 \text{ MeV}$$

$$\Gamma(f_X) = 700 \text{ MeV}$$

$$\Gamma(f_0(1500)) = 110 \pm 7 \text{ MeV}$$

$$\Gamma(f_0(1370)) = 350 \pm 150 \text{ MeV}$$

It could be a complex superposition of several intermediate states and some contribution from the non-resonant is also possible. Belle, hep-ex/0201007



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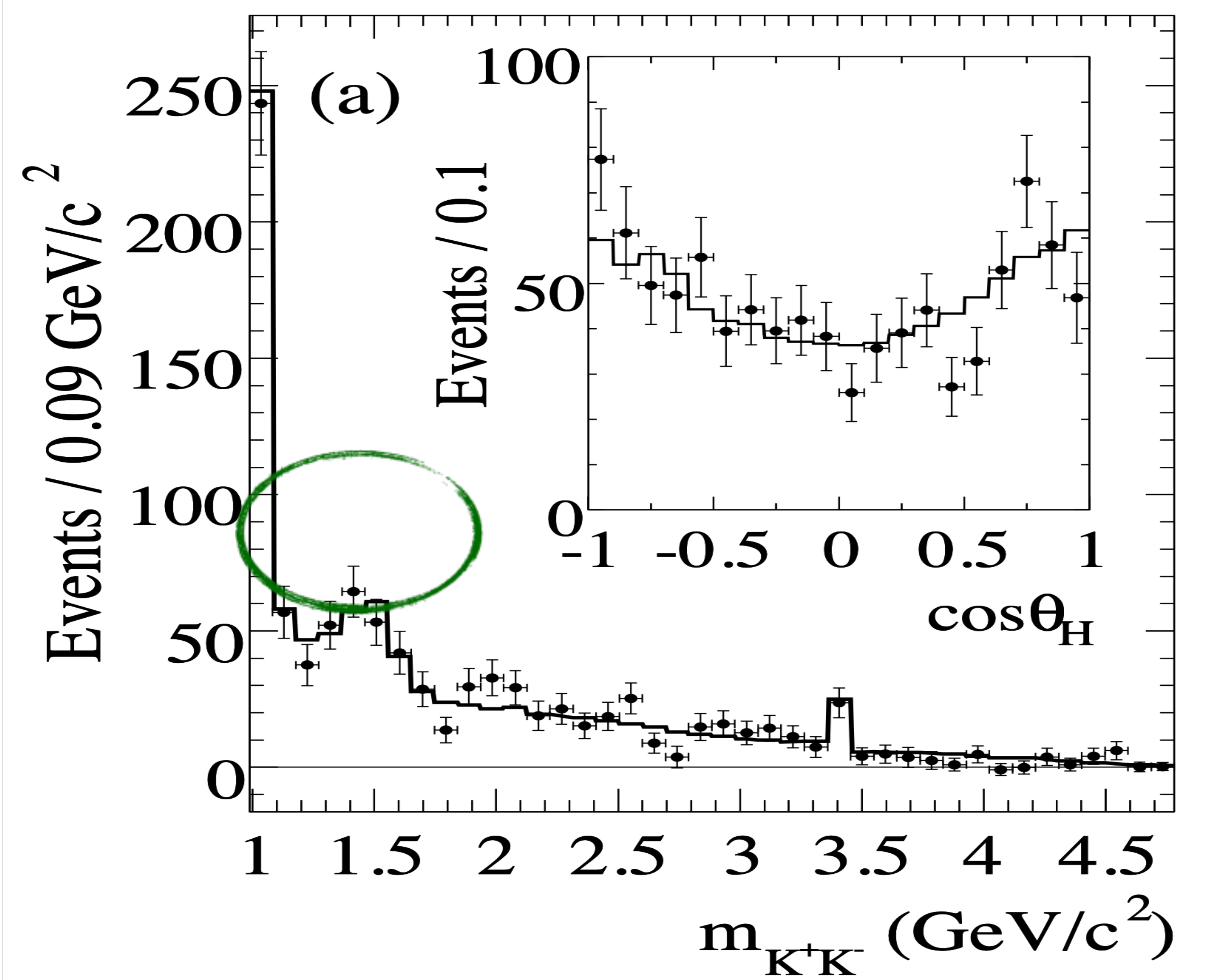
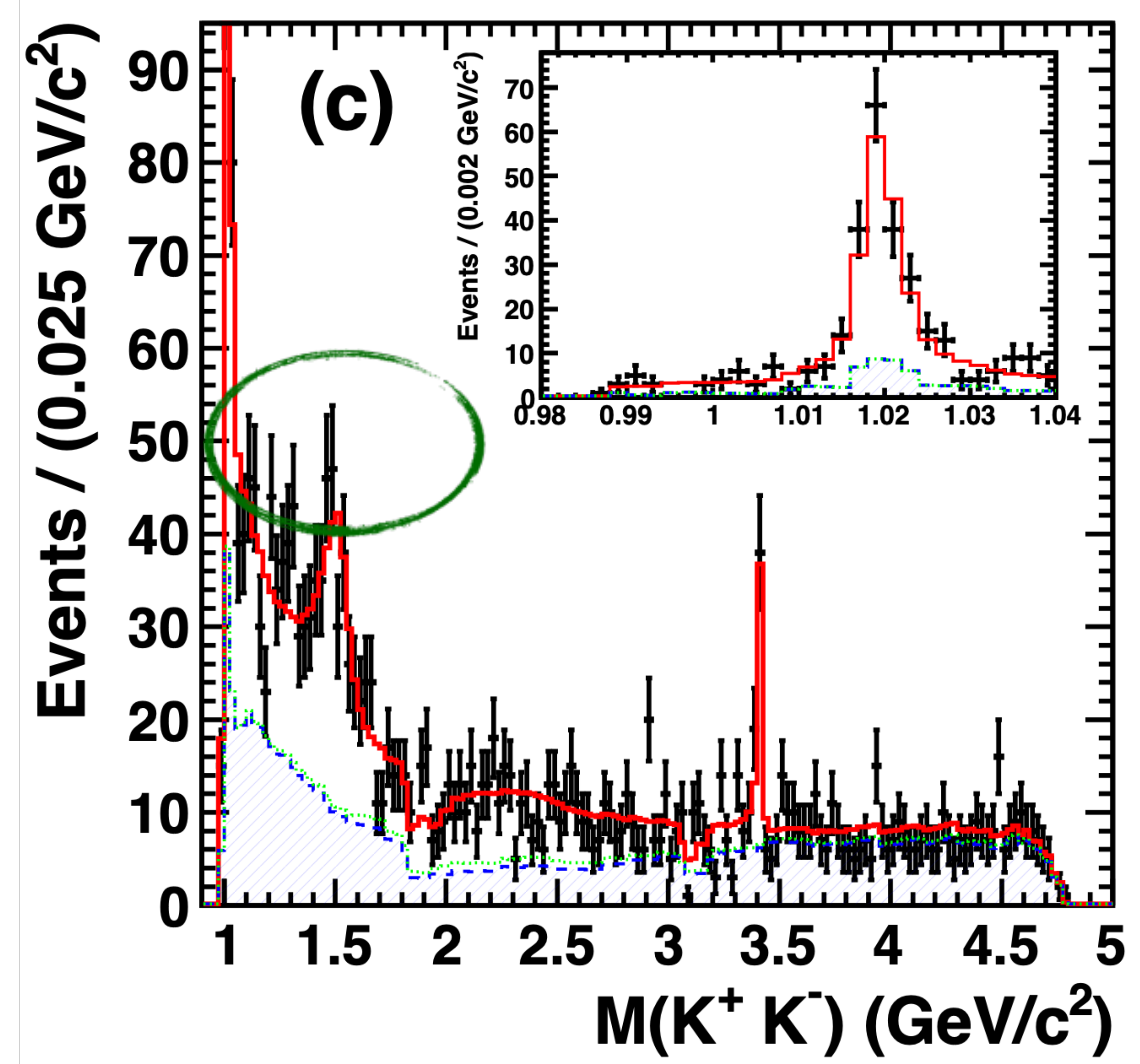
BABAR: hep-ex/0605003
0706.3885
0708.0376

Belle: hep-ex/0412066
1007.3848

$B^0 \to K^+K^-K^0$ BaBar, 0706.3885



$B^0 \to K^+K^-K_S^0$ Belle, 1007.3848

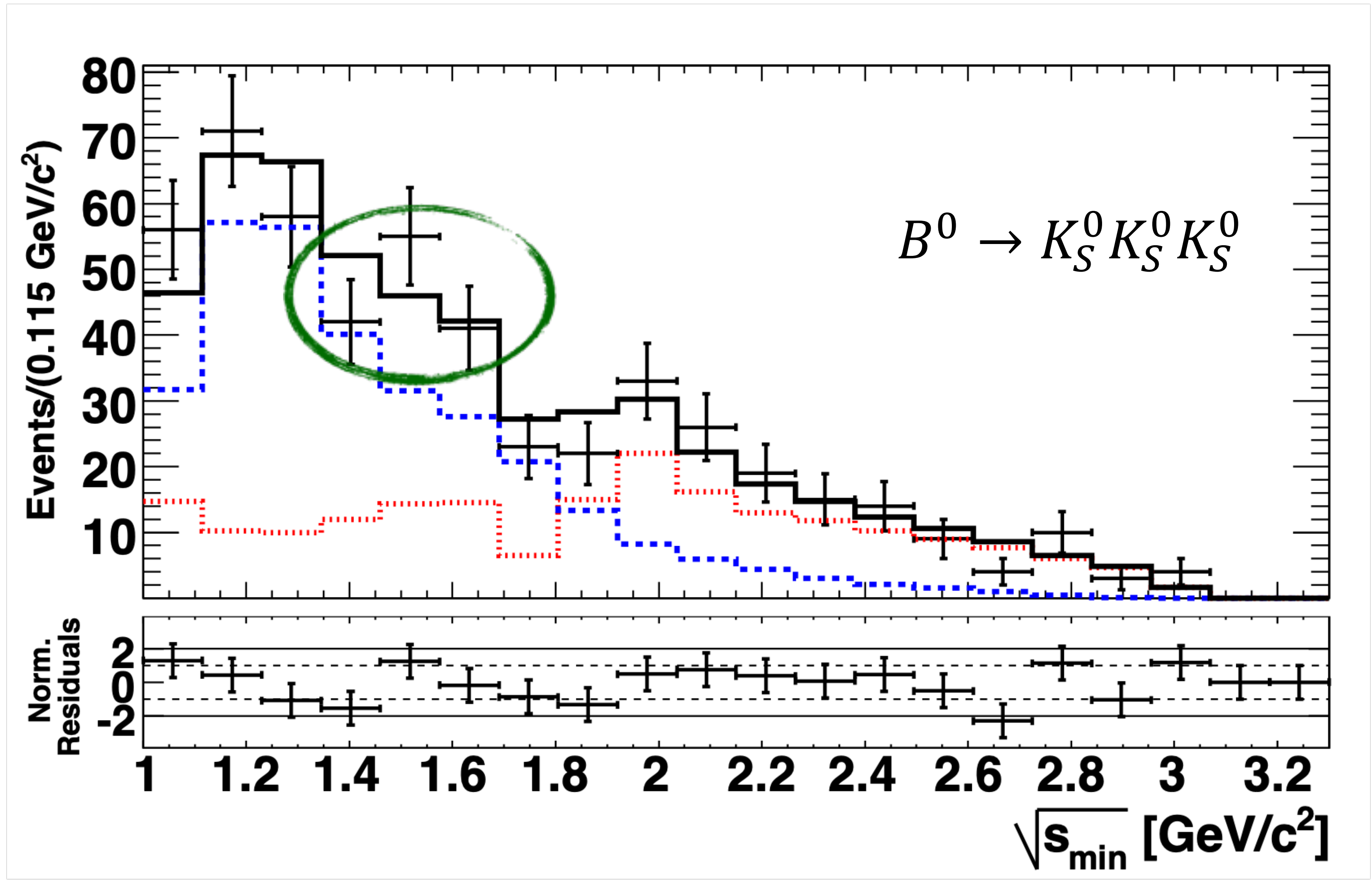


- However, BaBar analyzed the $B^{\pm} \to \pi^{\pm} K_S K_S$ decays and found no evidence of $f_X(1500)$ in the invariant mass $M(K_S K_S)$ spectrum. BaBar, 0811.1979

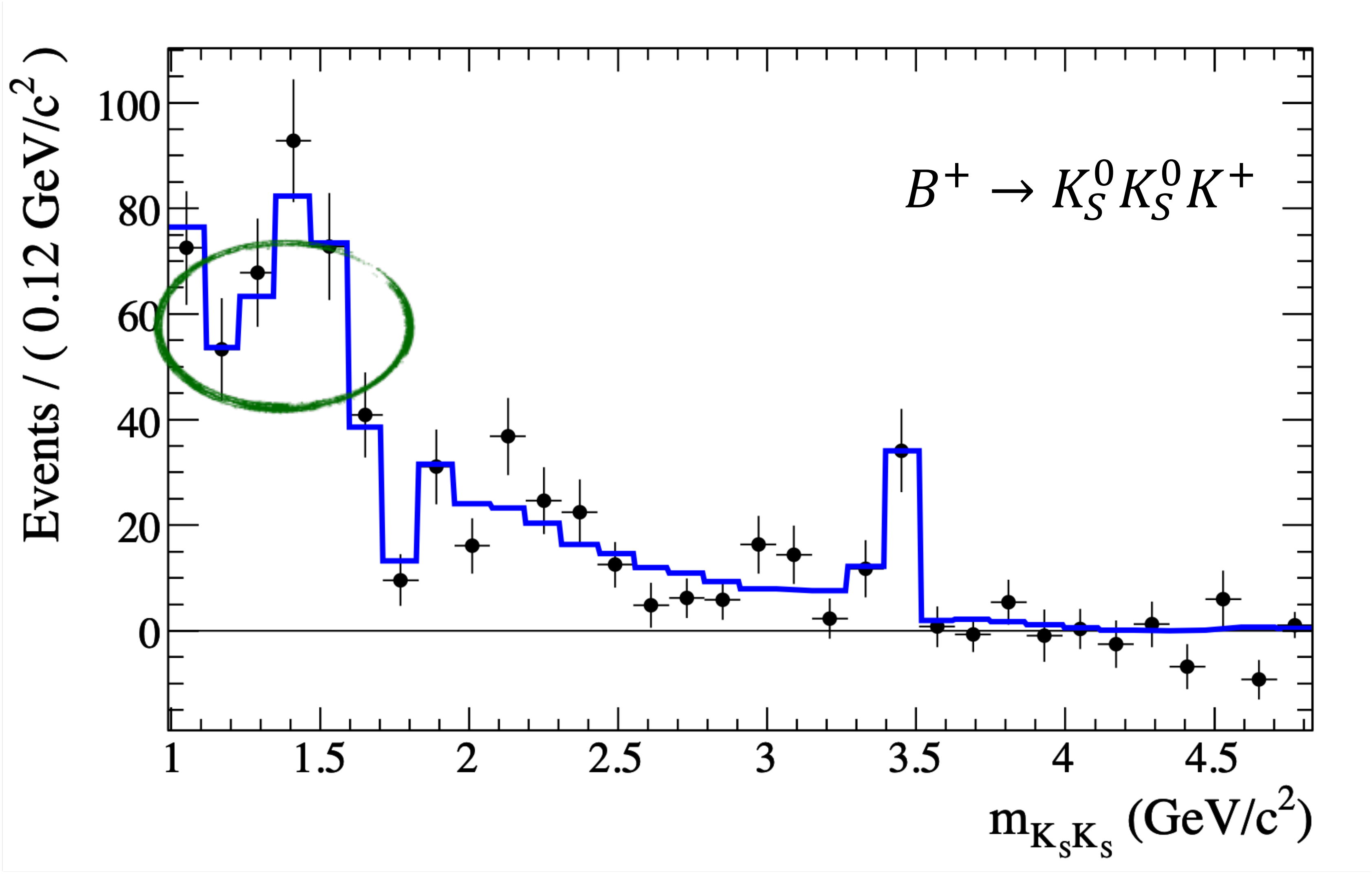
- It implies that it is either a vector meson or something exotic, because $f_X(1500)$ with an even spin, can decay into the $K_S K_S$ state in principle according to the Bose-Einstein statistics.

- So, the nature of $f_X(1500)$ has not been confirmed, though it is often viewed as a combination of narrower scalars.

However,

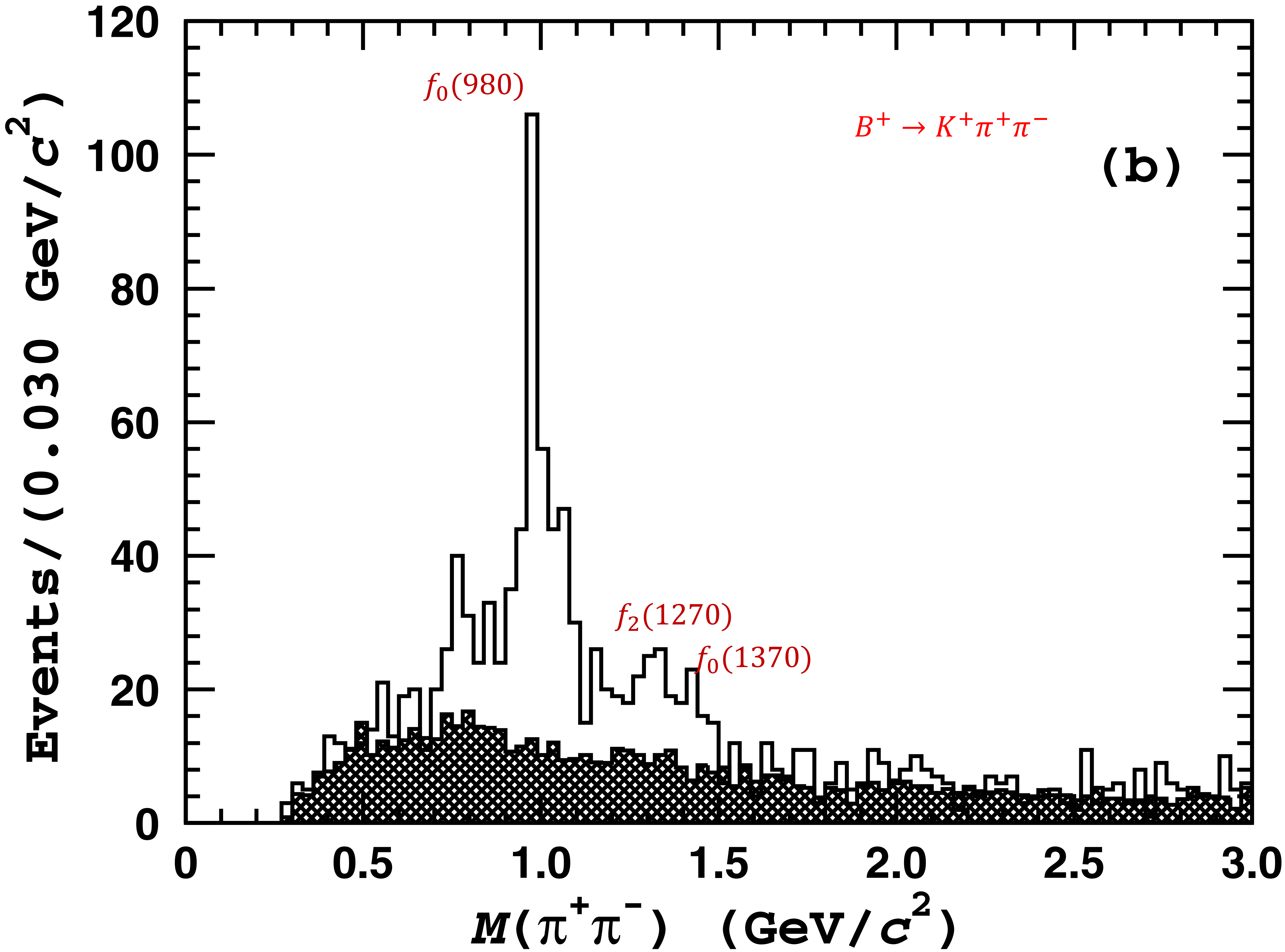


BaBar, 1111.3636 [hep-ex]



BaBar, 1201.5897 [hep-ex]

- The peak in the invariant mass between 1.5 and 1.6 GeV can be described by the interference be tween the $f_0(1710)$ resonance and the nonresonant component.

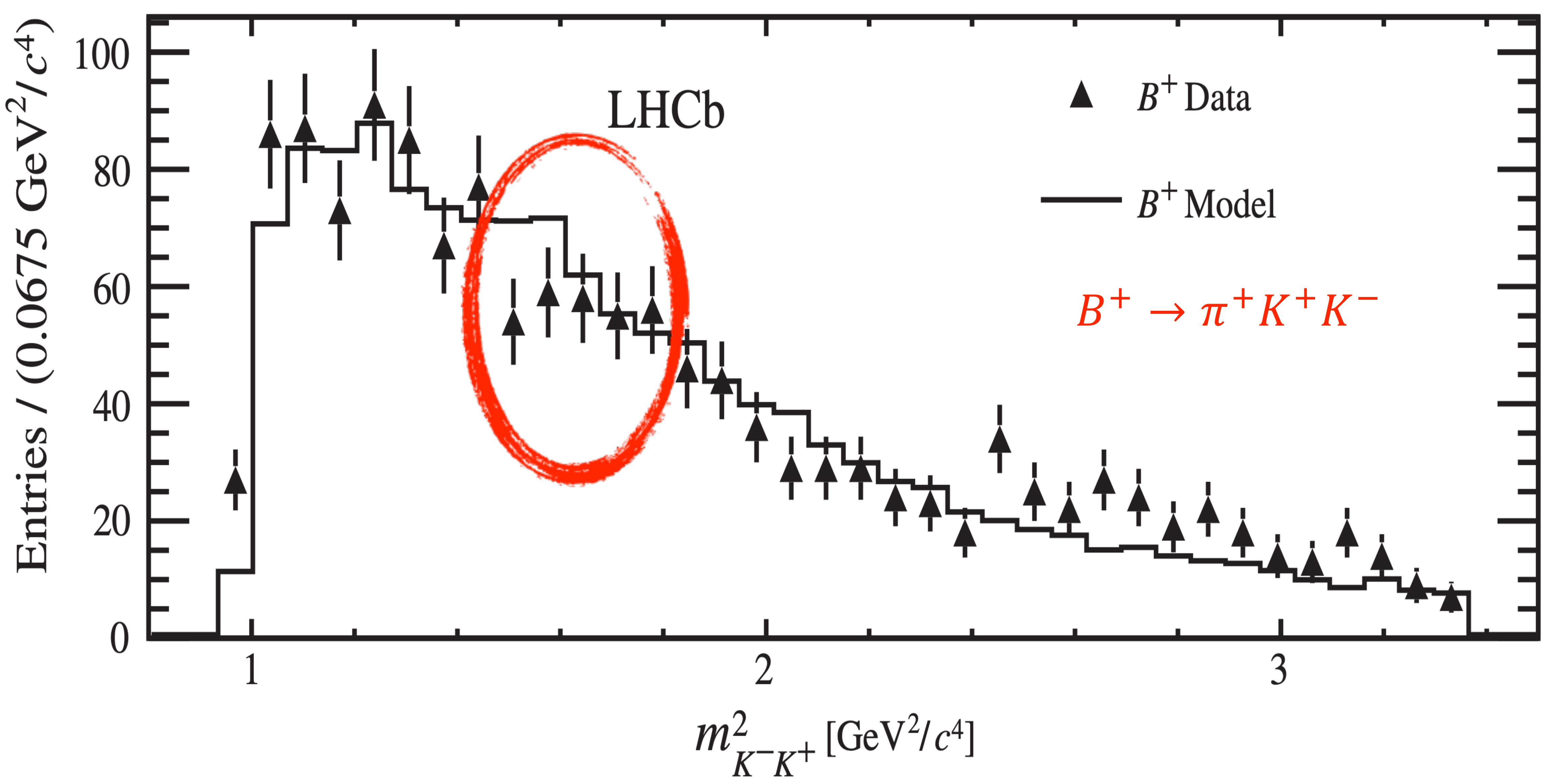


Belle: hep-ex/0412066

Very Recently

- LHCb reported an enhancement around 1.5 GeV in the invariant mass $M(K^+K^-)$ spectra of the $B^+ \to \pi^+ K^+ K^-$ decay, which could be well described by a vector resonance $\rho^0(1450)$.

LHCb, 1905.09244



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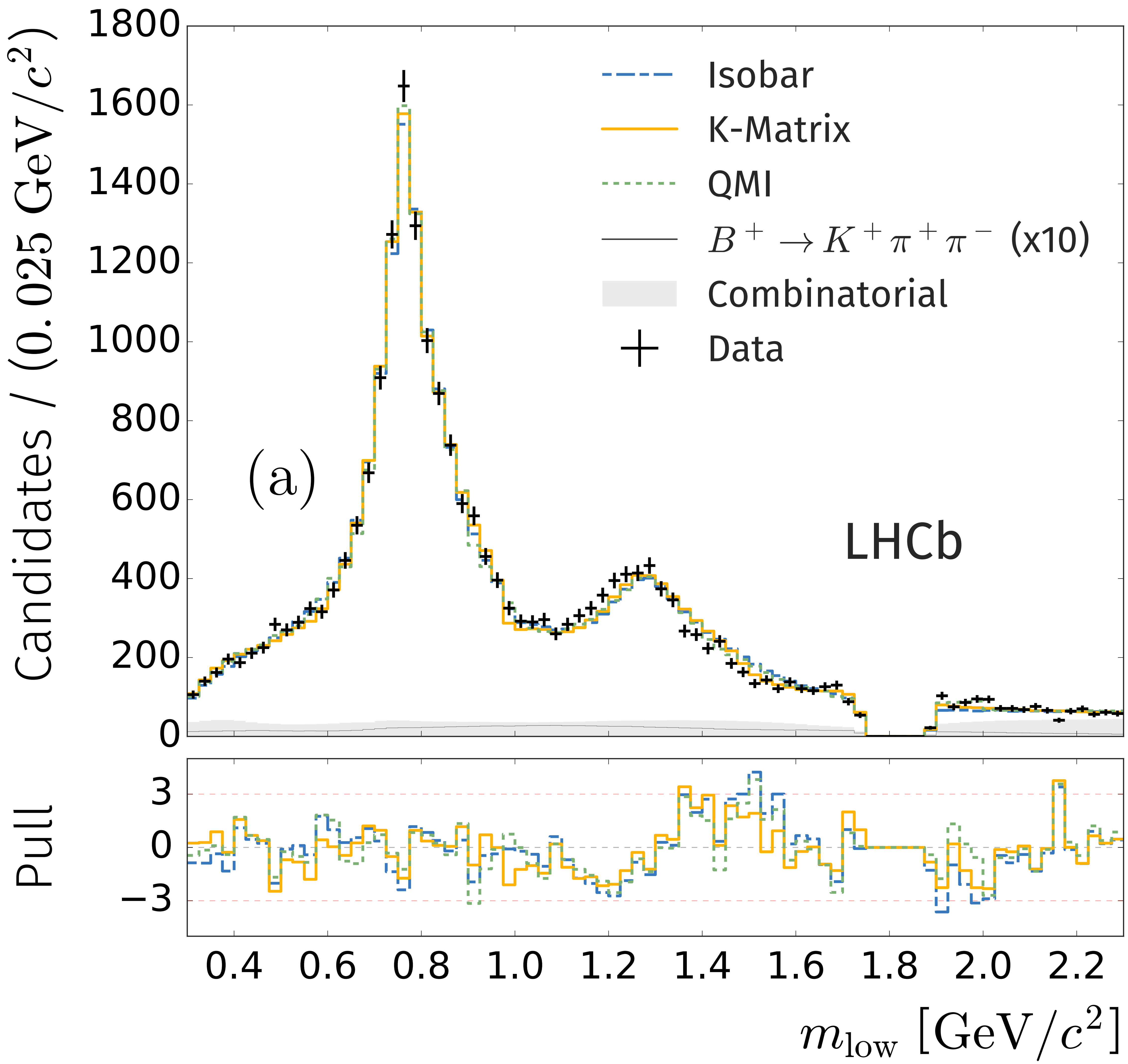

LHCb, 1909.05212

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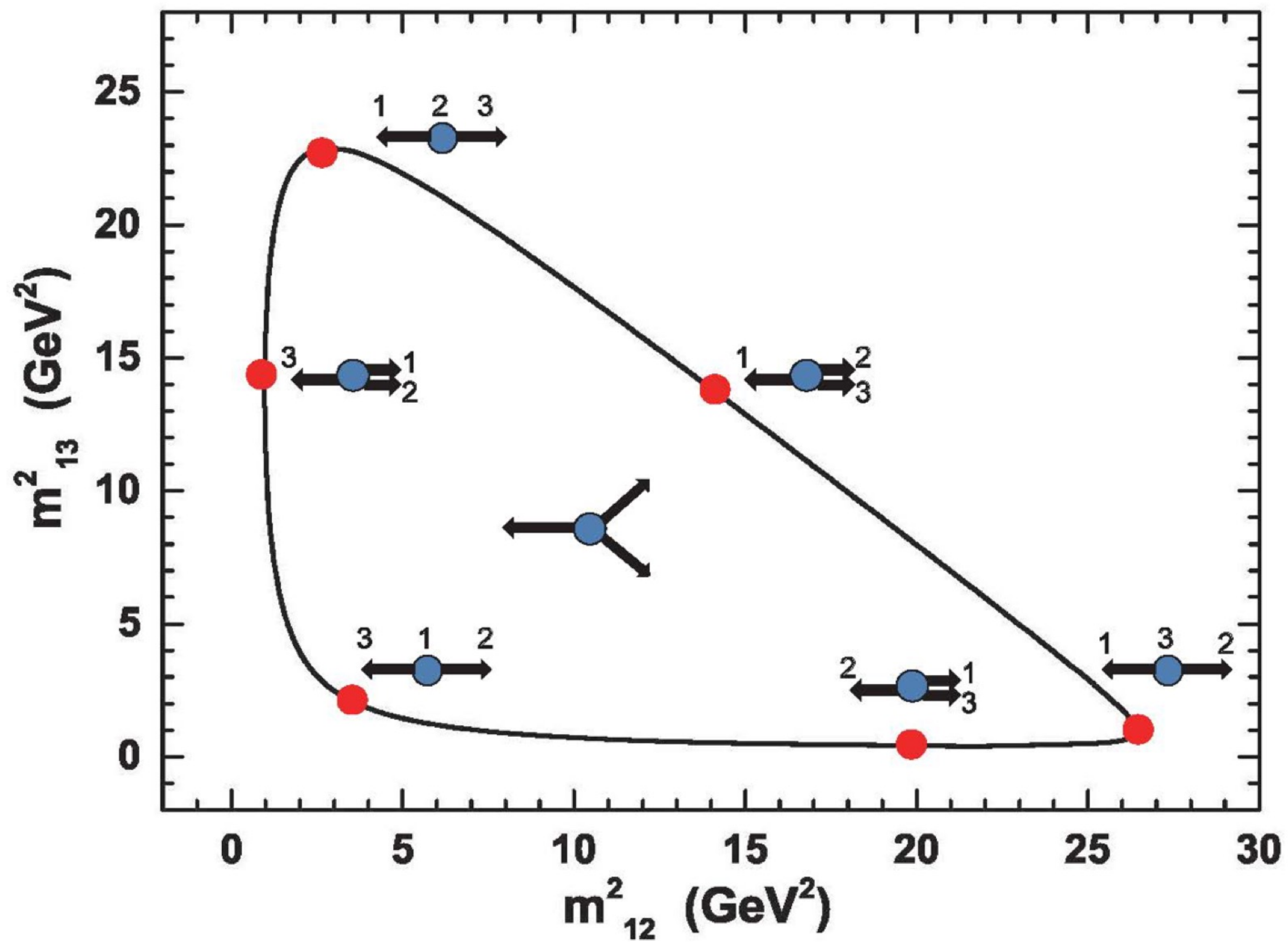
Questions

- Since the mass of $\rho^0(1450)$ is very close to that of $f_X(1500)$ and it has a rather large width, we suspect $f_X(1500)$ observed by BaBar and Belle in the $B \to K(\pi)K^+K^-$ decays is $\rho^0(1450)$.
- If it is, the interpretation for the broad structure in the $M(K^+K^-)$ spectra does not require a combination of several f_0 mesons with narrower widths.
- Besides, the $B^\pm \to \pi^\pm\rho^0(1450)$channel has been identified in the $B^\pm \to \pi^\pm\pi^+\pi^-$ decays with a small finite fit fraction. Note that the relative $\rho^0(1450) \to \pi\pi$ and $\rho^0(1450) \to K\overline{K}$ branching fractions are still uncertain, so our hypothesis is not inconsistent with the above data.
- According to the Bose-Einstein statistics, a vector meson $\rho^0(1450)$ does not decay into the K_SK_S state. A challenge to our postulation is then how to understand the broad structure in the $M(K_SK_S)$ spectra observed by BaBar.
- Recent studies within QCDF and PQCD showed that the nonresonant contributions are dominate in $B \to KKK$ decays. We therefore guess that the broad structure in the $M(K_SK_S)$ spectra is attributed to a nonresonant S-wave contribution, though a small component of scalar resonances cannot be excluded.

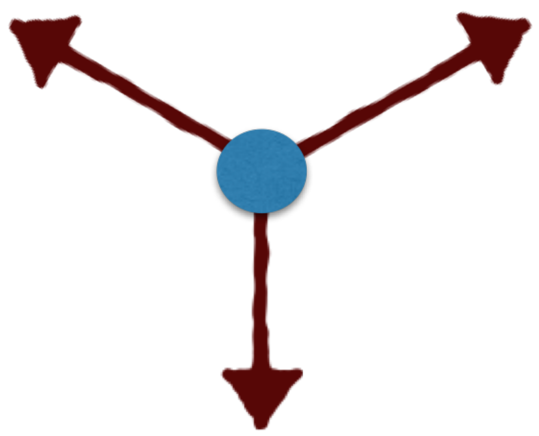
3-body Decays of B meson

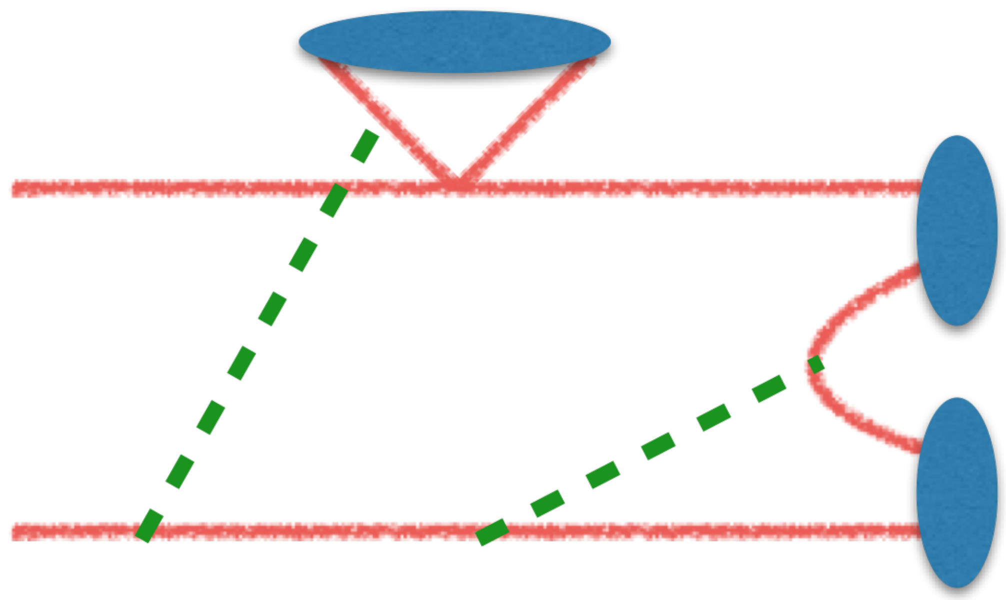
$$p_B \rightarrow p_1 + p_2 + p_3$$

$$m_{12}^2 = (p_1 + p_2)^2 \qquad m_{13}^2 = (p_1 + p_3)^2$$



3-body Decays of B meson



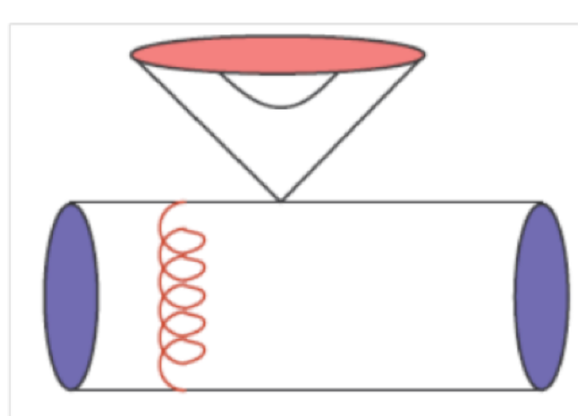


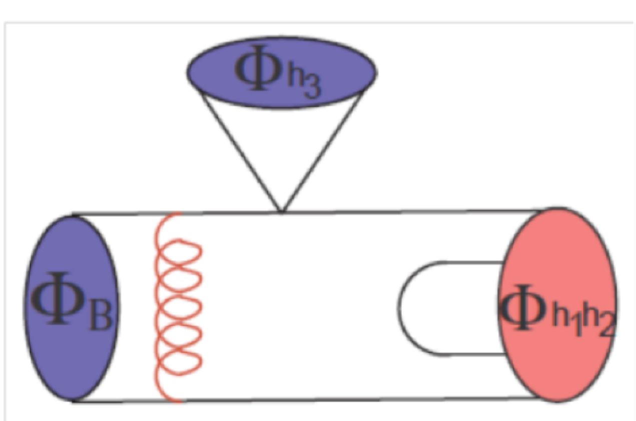
$$\langle P_1 P_2 P_3 | \mathcal{O}_i | B \rangle_c = T_i^I \otimes F^{B\to P_1} \otimes \Phi_{P_2} \otimes \Phi_{P_3} + T_i^{II} \otimes \Phi_B \otimes \Phi_{P_1} \otimes \Phi_{P_2} \otimes \Phi_{P_3}$$

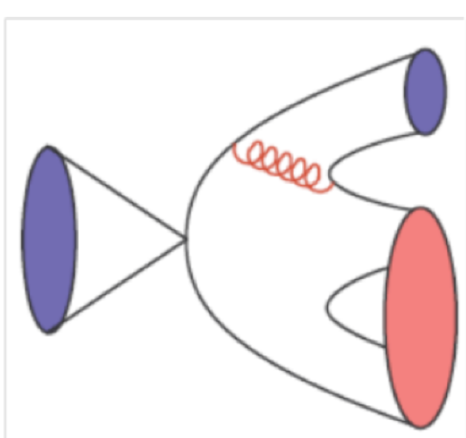
- In this region, two hard gluons are needed, so this contributions should be α_s or power suppressed.

3-body Decays of B meson

Resonant and Nonresonant

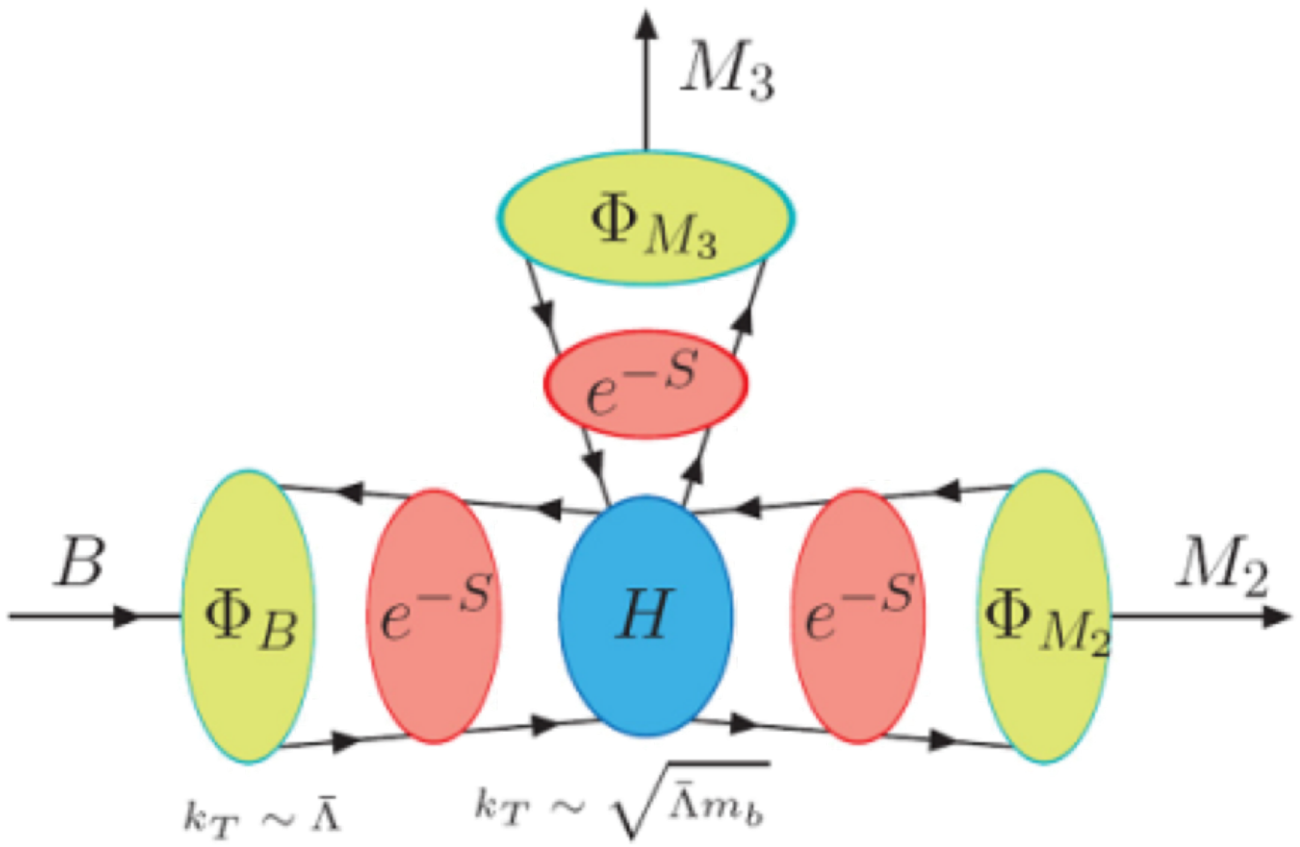






$$\langle P_1P_2P_3|\mathcal{O}_i|B\rangle_c = T_i^I \otimes F^{B\to P_1} \otimes \Phi_{P_2P_3} + T_i^{II} \otimes F^{B\to P_1P_2} \otimes \Phi_{P_3} + T_i^{III} \otimes \Phi_B \otimes \Phi_{P_1} \otimes \Phi_{P_2P_3}$$

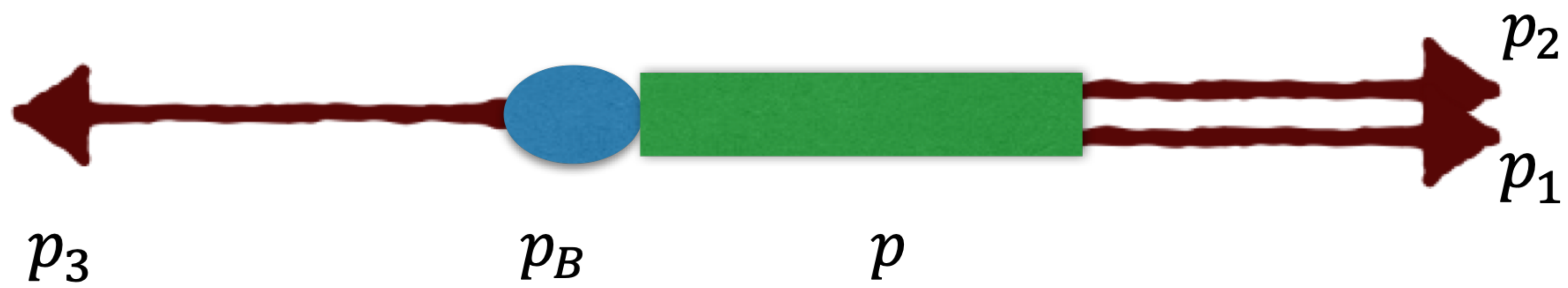
PQCD Approach



$$\mathcal{A} \sim C(t)\Phi(x)H(t)\exp\left\{-s(s,p) - 2\int_{1/b}^{t} \frac{d\mu}{\mu}\gamma_q(\alpha_s(\mu))\right\}$$

- **Nonperturbative parts are factorized into universal wave functions**
- **The hard part can calculated perturbatively.**
- **Parton kT smears end-point singularity**

Introduction to PQCD



- Meson momenta in light-cone coordinates

$$p_B = \frac{m_B}{\sqrt{2}}(1, 1, 0_{\rm T}), \quad p = \frac{m_B}{\sqrt{2}}(1, \eta, 0_{\rm T}), \quad p_3 = \frac{m_B}{\sqrt{2}}(0, 1-\eta, 0_{\rm T})$$

- Two-hadron invariant mass

$$\omega^2 = p^2 \qquad p = p_1 + p_2 \qquad \eta = \frac{\omega^2}{m_B^2}$$

- pi+ momentum fraction

$$p_1^+ = \zeta\frac{m_B}{\sqrt{2}}, \quad p_1^- = (1-\zeta)\eta\frac{m_B}{\sqrt{2}}, \quad p_2^+ = (1-\zeta)\frac{m_B}{\sqrt{2}}, \quad p_2^- = \zeta\eta\frac{m_B}{\sqrt{2}}$$

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PQCD Calculations

$$\phi^I_{v\nu}(z,\zeta,w^2)=\frac{1}{2\sqrt{2N_c}}\int\frac{dy^-}{2\pi}e^{-izp^+y^-}\langle K^+(p_1)K^-(p_2)|\bar\psi(y^-)\gamma_\nu T\psi(0)|0\rangle,$$
$$\phi^I_{s}(z,\zeta,w^2)=\frac{1}{2\sqrt{2N_c}}\frac{p^+}{w}\int\frac{dy^-}{2\pi}e^{-izp^+y^-}\langle K^+(p_1)K^-(p_2)|\bar\psi(y^-)T\psi(0)|0\rangle,$$
$$\phi^I_{t\nu}(z,\zeta,w^2)=\frac{1}{2\sqrt{2N_c}}\frac{p^+f^{\perp}_{2K}}{w^2}\int\frac{dy^-}{2\pi}e^{-izp^+y^-}\langle K^+(p_1)K^-(p_2)|\bar\psi(y^-)i\sigma_{\mu\nu}n^\mu_- T\psi(0)|0\rangle,$$

The wave function of P-wave KK-pair **[1609.04614,1704.07566]**

$$\Phi_{KK,P}=\frac{1}{\sqrt{2N_c}}\left[\not p\phi_v(z,\zeta,\omega^2)+\omega\phi_s(z,\zeta,\omega^2)+\frac{\not p_1\not p_2-\not p_2\not p_1}{\omega(2\zeta-1)}\phi_t(z,\zeta,\omega^2)\right]$$
$$\phi_v(z,\zeta,\omega^2)=\frac{3\mathcal{F}_v(\omega^2)}{\sqrt{2N_c}}z(1-z)\left[1+a_vC_2^{3/2}(2z-1)\right]P(\zeta),$$
$$\phi_s(z,\zeta,\omega^2)=\frac{3\mathcal{F}_s(\omega^2)}{2\sqrt{2N_c}}(1-2z)\left[1+a_s(1-10z+10z^2)\right]P(\zeta),$$
$$\phi_t(z,\zeta,\omega^2)=\frac{3\mathcal{F}_t(\omega^2)}{2\sqrt{2N_c}}(2z-1)^2\left[1+a_tC_2^{3/2}(2z-1)\right]P(\zeta),$$

$$\mathcal{F}_i(\omega^2)=\mathcal{F}_i^R(\omega^2)+\mathcal{F}_i^{NR}(\omega^2).$$

The relativistic Breit-Wigner (RBW) model 1711.09854

$$\mathcal{F}_v^R(\omega^2)=\frac{m^2_{\rho^0(1450)}e^{i\beta}}{m^2_{\rho^0(1450)}-\omega^2-im_{\rho^0(1450)}\Gamma(\omega)}.$$

$$\mathcal{F}_v^{NR}(\omega^2)=\frac{m_P^2}{\omega^2+m_P^2}$$

$$\frac{\mathcal{F}^R_{s,t}(\omega^2)}{\mathcal{F}^R_v(\omega^2)}=\frac{f^T_{\rho^0(1450)}}{f_{\rho^0(1450)}},$$

$$\mathcal{F}_{s,t}^{NR}(\omega^2)=\frac{m_0m_P^2}{\omega^3+m_0m_P^2}$$

hep-ph/0209043

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PQCD Calculations

Cheng, Chua, 1308.5139

$B^- \to K^- K_S K_S$			
Decay mode	BaBar [12]	Belle [11]	Theory
$f_0(980)K^-$	$14.7 \pm 2.8 \pm 1.8$		$8.7^{+0.0+2.1+0.0}_{-0.0-1.6-0.0}$
$f_0(1500)K^-$	$0.42 \pm 0.22 \pm 0.58$		$0.59^{+0.00+0.10+0.00}_{-0.00-0.09-0.00}$
$f_0(1710)K^-$	$0.48^{+0.40}_{-0.24} \pm 0.11$		$1.08^{+0.00+0.18+0.00}_{-0.00-0.17-0.00}$
$f_2'(1525)K^-$	$0.61 \pm 0.21^{+0.12}_{-0.09}$		
NR	$19.8 \pm 3.7 \pm 2.5$		$11.3^{+0.2+3.7+0.0}_{-0.3-3.0-0.0}$
Total	$10.1 \pm 0.5 \pm 0.3$	$13.4 \pm 1.9 \pm 1.5$	$15.1^{+0.0+3.7+0.0}_{-0.0-3.2-0.0}$
$\overline{B}^0 \to K_S K_S K_S$			
Decay mode	BaBar [21]	Belle [11]	Theory
$f_0(980)K_S$	$2.7^{+1.3}_{-1.2} \pm 0.4 \pm 1.2$		$2.4^{+0.0+0.6+0.0}_{-0.0-0.5-0.0}$
$f_0(1500)K_S$			$0.15^{+0.00+0.03+0.00}_{-0.00-0.02-0.00}$
$f_0(1710)K_S$	$0.50^{+0.46}_{-0.24} \pm 0.04 \pm 0.10$		$0.28^{+0.00+0.05+0.00}_{-0.00-0.04-0.00}$
$f_2(2010)K_S$	$0.54^{+0.21}_{-0.20} \pm 0.03 \pm 0.52$		
NR	$13.3^{+2.2}_{-2.3} \pm 0.6 \pm 2.1$		$6.58^{+0.09+2.04+0.01}_{-0.12-1.70-0.01}$
Total	$6.19 \pm 0.48 \pm 0.15 \pm 0.12$	$4.2^{+1.6}_{-1.3} \pm 0.8$	$6.19^{+0.01+1.62+0.01}_{-0.02-1.42-0.01}$

PQCD Calculations

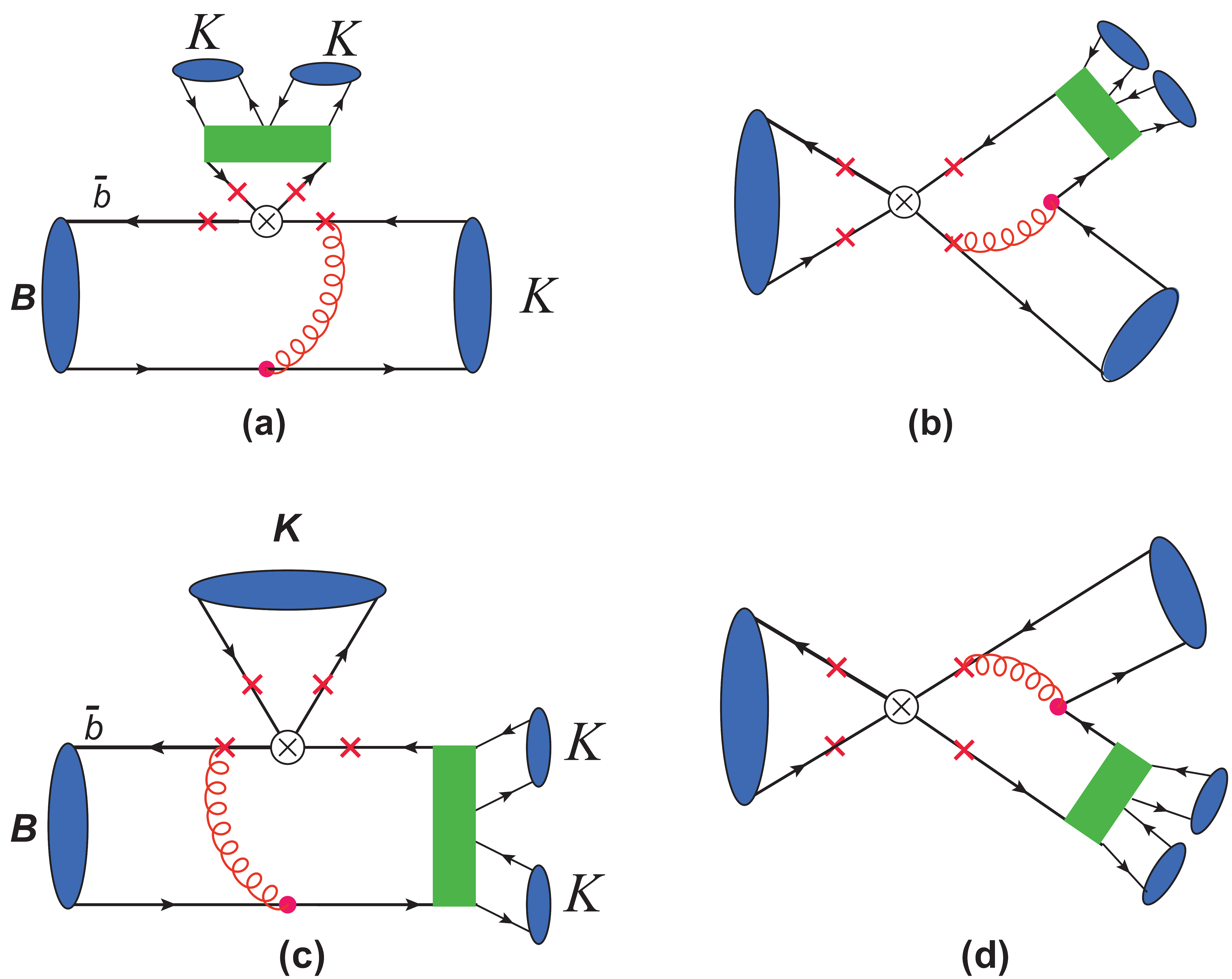
The wave function of S-wave KK-pair **[2003.03754]**

$$\Phi_{KK,S} = \frac{1}{\sqrt{2Nc}}[\not{P}\phi_S(z,\zeta,\omega^2) + \omega\phi_S^s(z,\zeta,\omega^2) + \omega(\not{n}\not{v} - 1)\phi_S^t(z,\zeta,\omega^2)].$$

$$\begin{aligned}
\phi_S(z,\zeta,\omega^2) &= \frac{9}{\sqrt{2Nc}}F_S(\omega^2)a_S z(1-z)(2z-1), \\
\phi_S^s(z,\zeta,\omega^2) &= \frac{1}{2\sqrt{2Nc}}F_S(\omega^2), \\
\phi_S^t(z,\zeta,\omega^2) &= \frac{1}{2\sqrt{2Nc}}F_S(\omega^2)(1-2z),
\end{aligned}$$

$$F_S(\omega^2) = \frac{m_S^2}{\omega^2 + m_S^2}$$

PQCD Calculations



Numerical Results and Discussions

- The Gegenbauer moments $a_{v,s,t}$ in the distributions amplitudes of $\phi_{v,s,t}$ can be derived in nonperturbative methods in principle, but they are not yet available.

- LHCb reported an unexpected $\rho^0(1450)$ resonance, which contributes to the $M(K^+K^-)$ channel with the fit fraction as large as $(30.7 \pm 1.2 \pm 0.9)\%$. Using the $B^\pm \to \pi^\pm K^+K^-$ branching fraction in PDG, we deduce the observed branching fraction of the quasi-two-body decay $B^\pm \to \pi^\pm \rho^0(1450)$ $\to \pi^\pm K^+K^-$ as

$$\mathcal{B}(B^\pm \to \pi^\pm \rho^0(1450) \to \pi^\pm K^+K^-) = (1.60^{+0.21}_{-0.20})\times 10^{-6}.$$

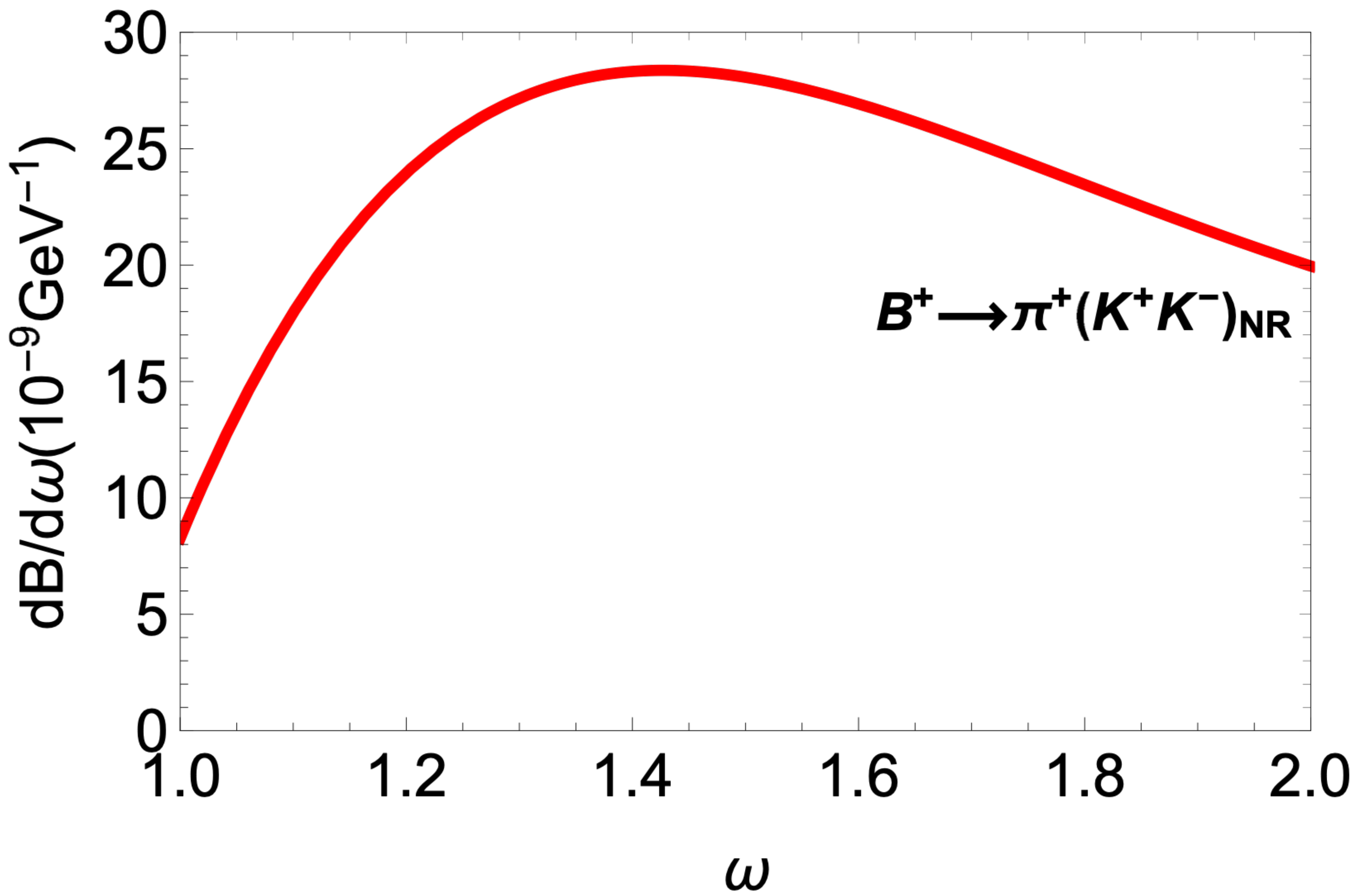
1905.09244

- If we choice

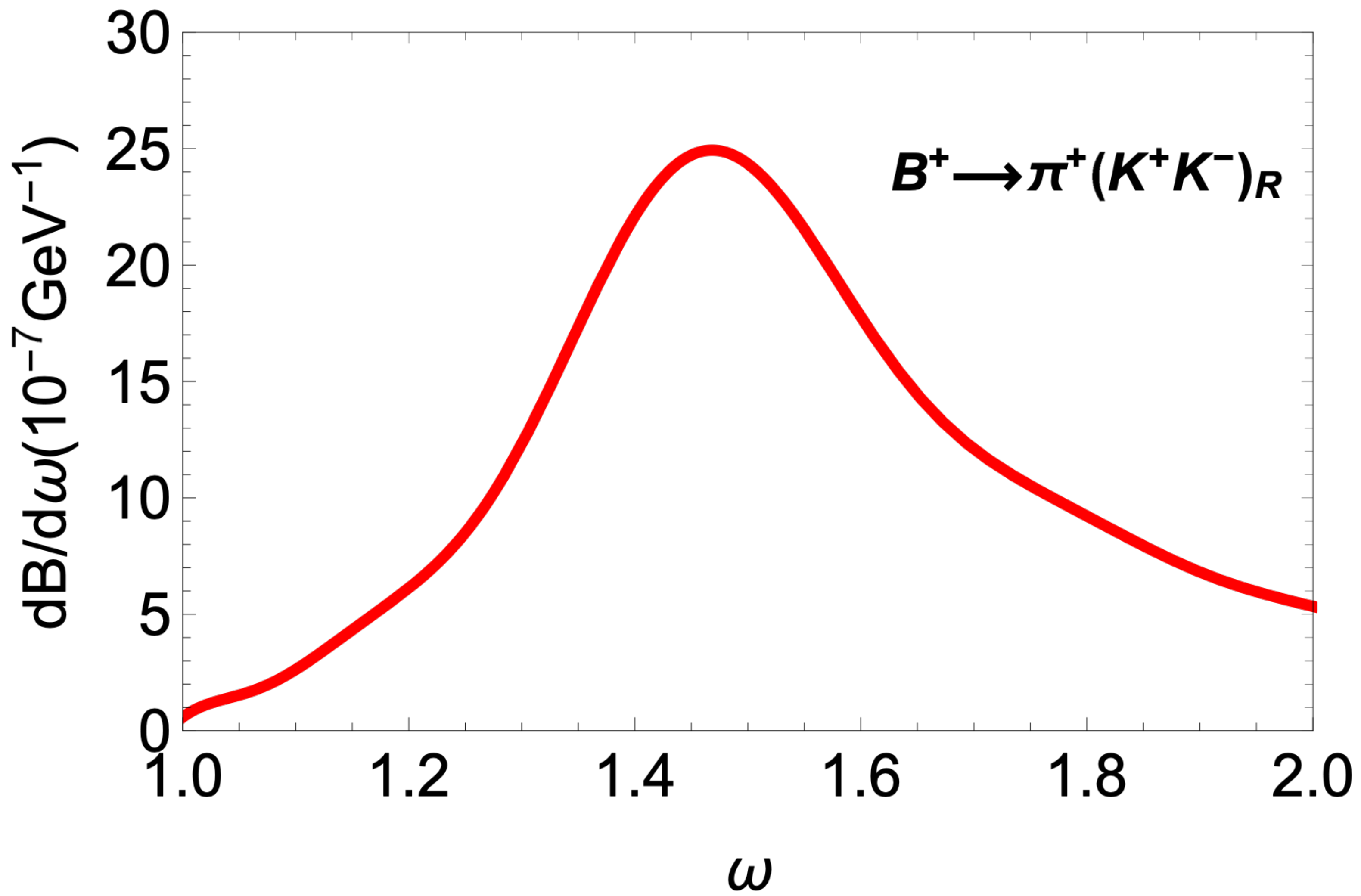
$$a_v = -0.70 \pm 0.14, a_s = -0.50 \pm 0.10, a_t = -0.60 \pm 0.12,$$

$$\mathcal{B}(B^\pm \to \pi^\pm \rho^0(1450) \to \pi^\pm K^+K^-) = (1.61^{+1.21}_{-0.87})\times 10^{-6}$$

Numerical Results and Discussions



(a)

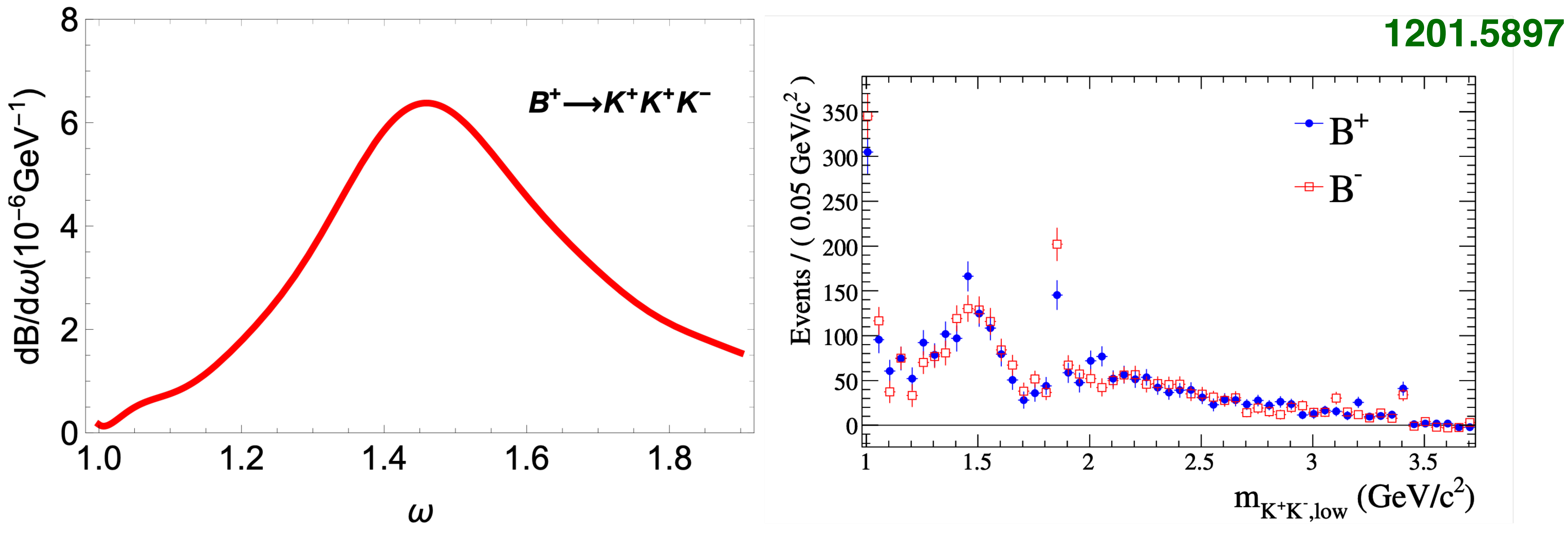


(b)

$\mathcal{B}(B^{\pm} \to \pi^{\pm} K^{+} K^{-}) = (6.84^{+0.92}_{-0.87}) \times 10^{-8}$

$\mathcal{B}(B^{\pm} \to \pi^{\pm}\rho^{0}(1450) \to \pi^{\pm}K^{+}K^{-}) = (1.60^{+0.21}_{-0.20})\times 10^{-6}.$

Numerical Results and Discussions



(a) (b)

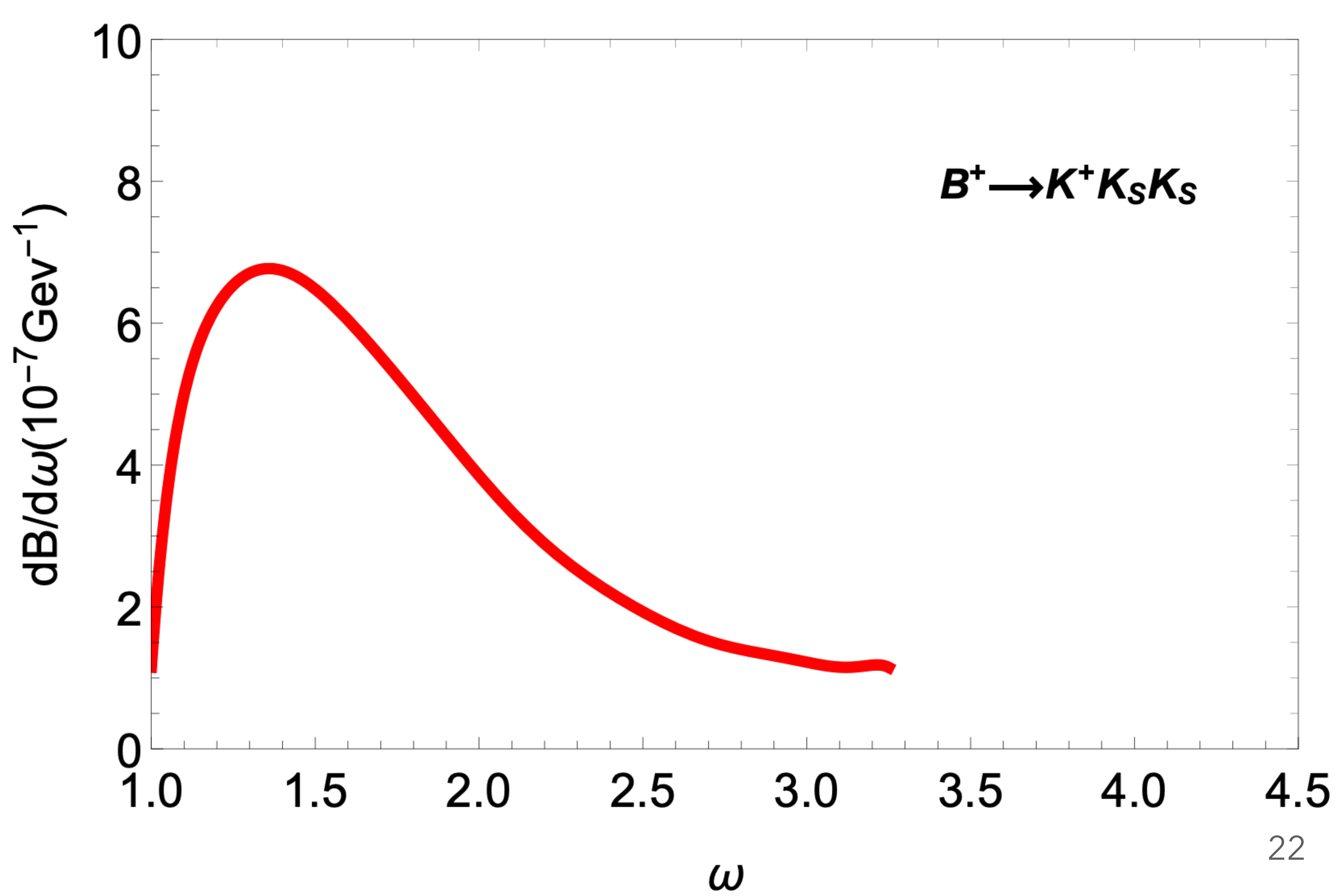
- The NR contribution amounts only up to 4% of that of $\rho^0(1450)$.

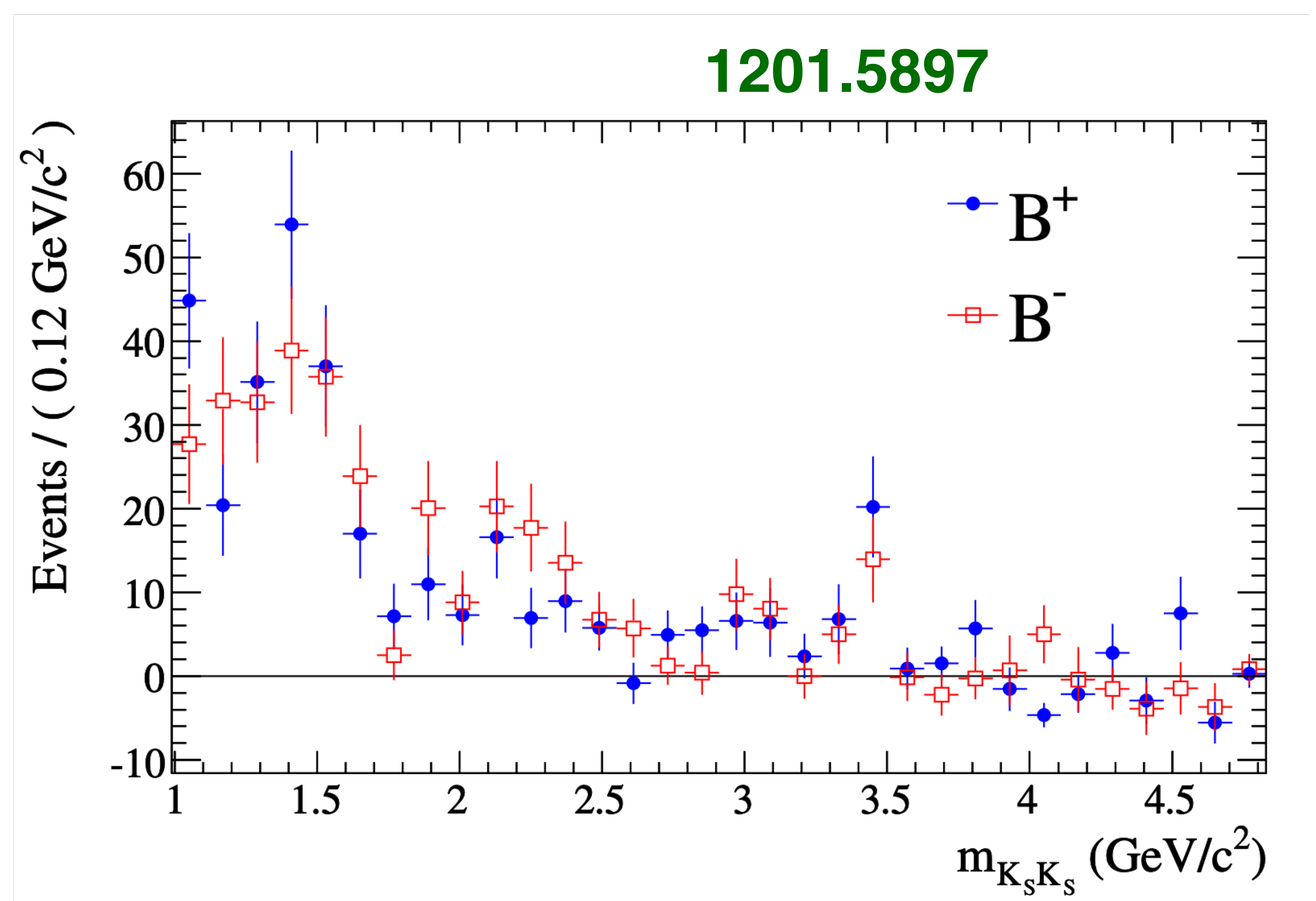
$$\mathcal{B}(B^+ \to K^+\rho^0(1450) \to K^+K^+K^-) = (3.62^{+1.33+0.87+0.18}_{-1.42-0.81-0.24})\times 10^{-6},$$

$$\mathcal{B}(B^0 \to K^0\rho^0(1450) \to K^0K^+K^-) = (7.49^{+4.36+3.76+0.35}_{-3.96-3.05-0.12})\times 10^{-7},$$

Numerical Results and Discussions

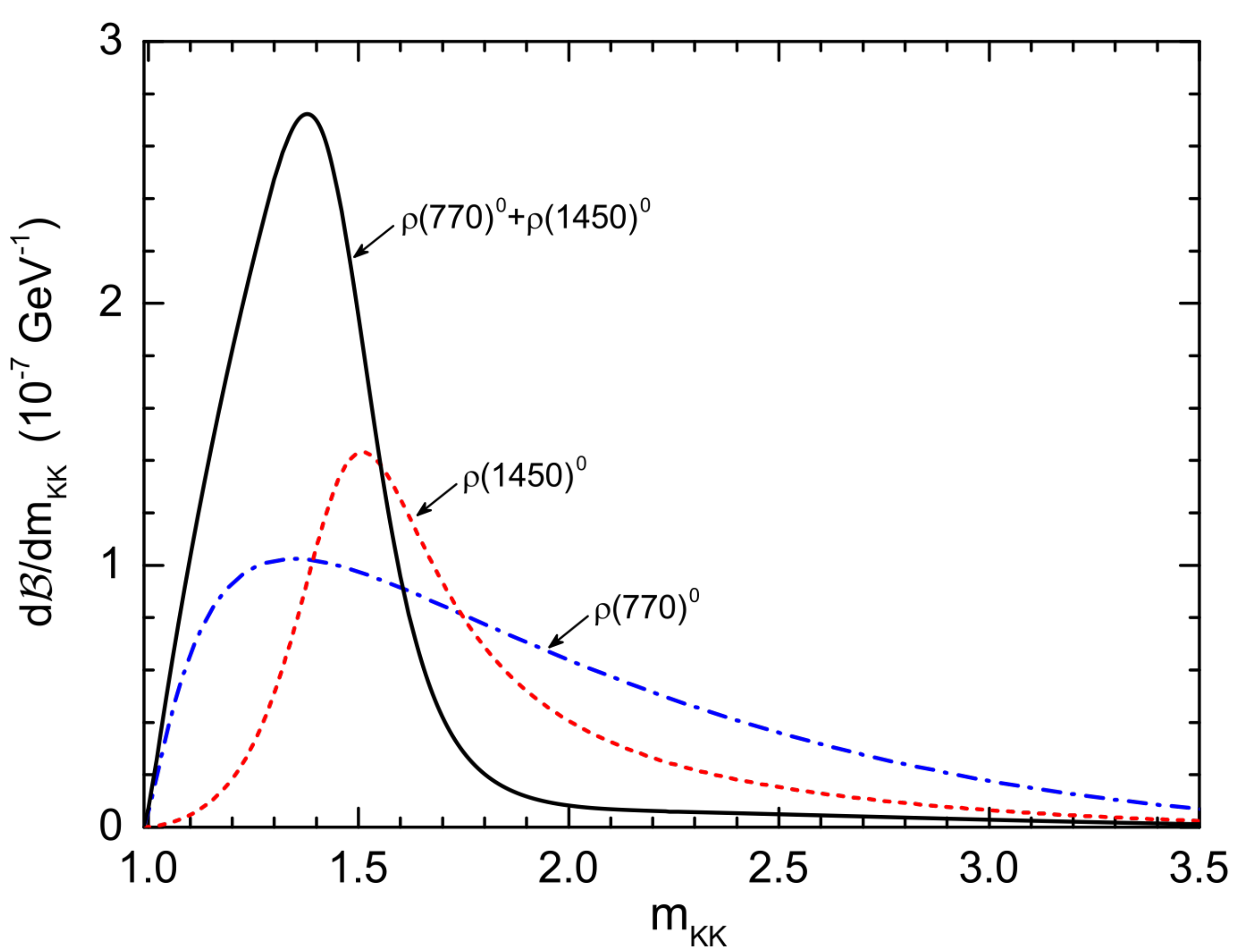
- Once $f_X(1500)$ is regarded as the vector resonance $\rho^0(1450)$, it cannot be seen in the $B^\pm \to \pi^\pm K_S K_S$ and $B^0 \to K_S K_S K_S$ decays.
- Hence, we rely on the nonresonant S-wave contribution to the $B^+ \to K^+ K_S K_S$ decay around the $M(K_S K_S) \sim 1.5$GeV region.

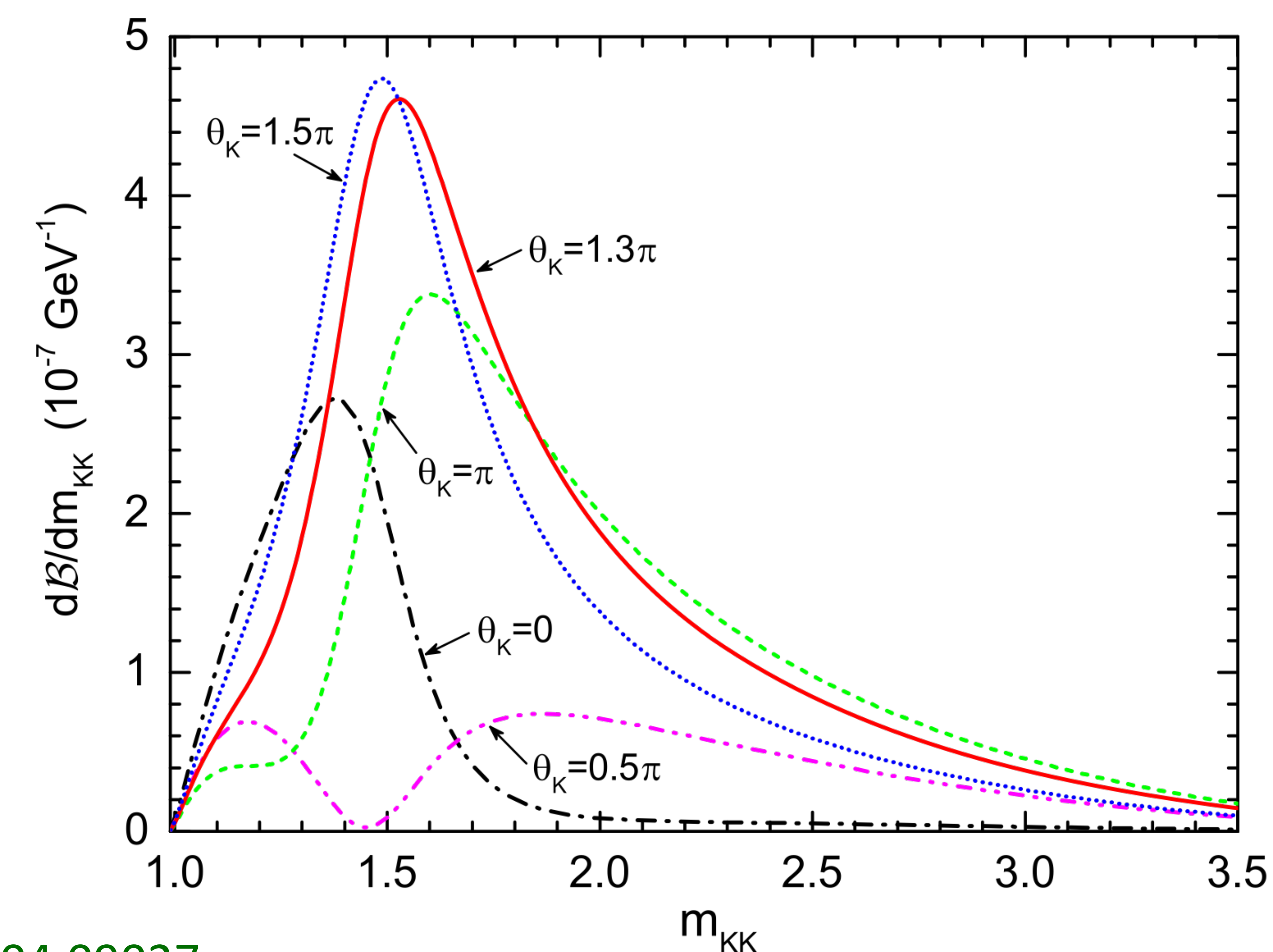




Numerical Results and Discussions

- Wang also explored this peak consider two resonances ($\rho^0(770)$ and $\rho^0(1450)$), and claimed that the tail of $\rho^0(770)$ is dominant . Wen-Fei Wang, 2004.09027
- The width of $\rho^0(770)$ is 150 MeV, We cannot understand its large effect.
- The relate phase affect his results remarkably.





Wen-Fei Wang, 2004.09027

Summary

- We examined whether the puzzling $f_X(1500)$ that has been modeled as a single scalar or a combination of several scalar resonances by BaBar and Belle for more than a decade is the vector $\rho^0(1450)$ reported by LHCb recently. YES!

- Our hypothesis is consistent with the small fit fraction of $B^\pm \to \pi^\pm \rho^0(1450)$ in the $B^\pm \to \pi^\pm \pi^+ \pi^-$ decays, because the relative $\rho^0(1450) \to \pi\pi$ and $\rho^0(1450) \to K\bar{K}$ branching fractions are still uncertain.

- To verify the above hypothesis quantitatively, we have studied the relevant three-body B meson decays in the PQCD approach. The obtained differential branching fractions agree well with the experimental data for both modes in the locations of the peaks, the widths, and the relative magnitudes between them around the invariant mass 1.5 GeV.

- We acknowledge that possible contributions from other ρ resonances like $\rho(700)$,$\rho(1250)$,... have not been excluded completely, though the single resonance parametrization was assumed in this work.


Thank you for your attentio