Amplitude analysis and its application in the hadrons observed by LHCb

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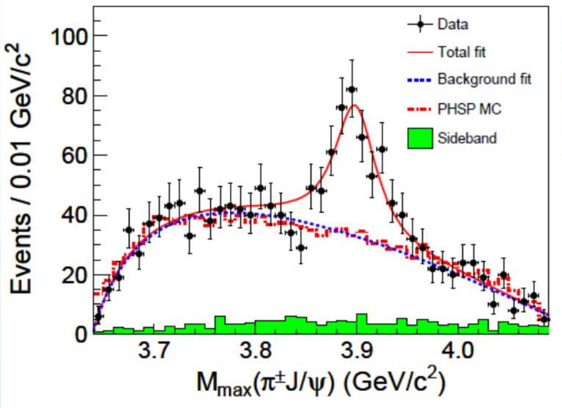
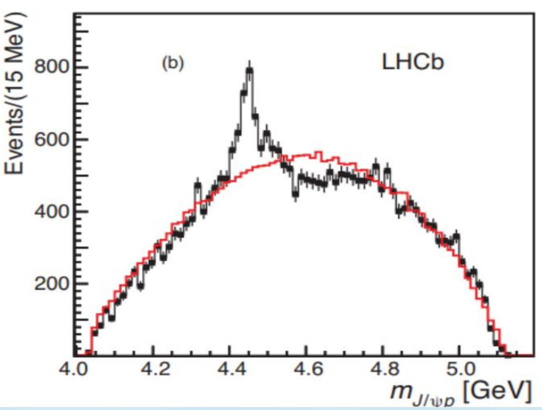
Outlines

1. Introduction
2. Formalism
3. Nature of the X(6900)
4. Some other resonances
5. Summary

Introduction

- $Z_c(3900)$ by BESIII and Belle, in 2013
- P_c states by LHCb, in2015
- ......
- Their nature?
  - Quantum number?
  - The inner structure?



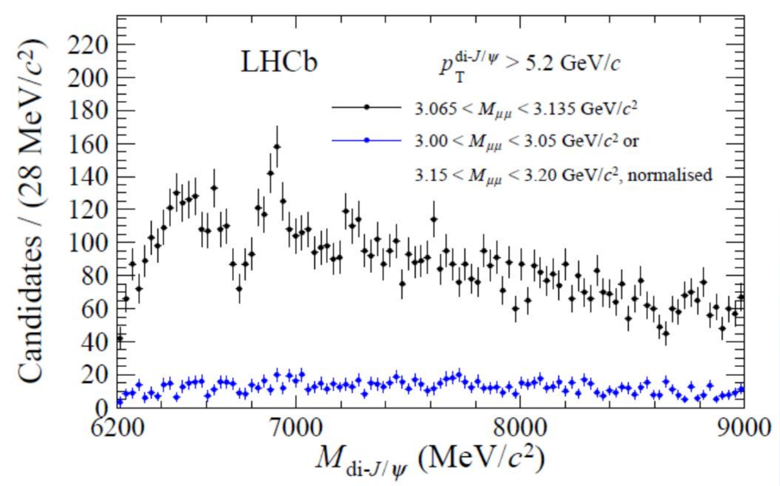


Amplitude analysis

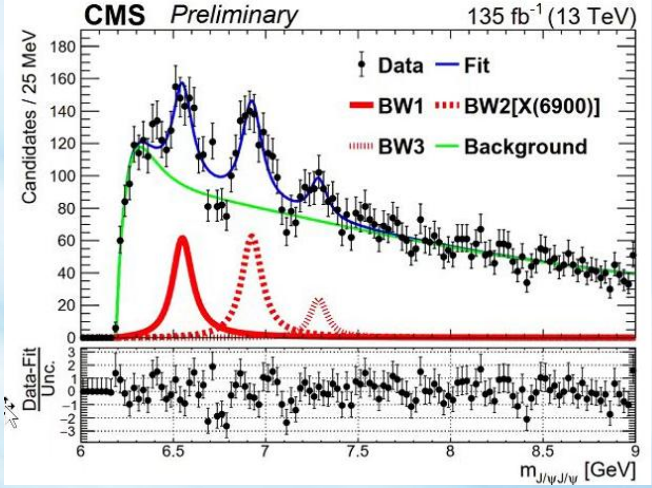
- Only one physical amplitude!
- It should satisfy the fundamental QFT principles
- It should be compatible with the data

X(6900)

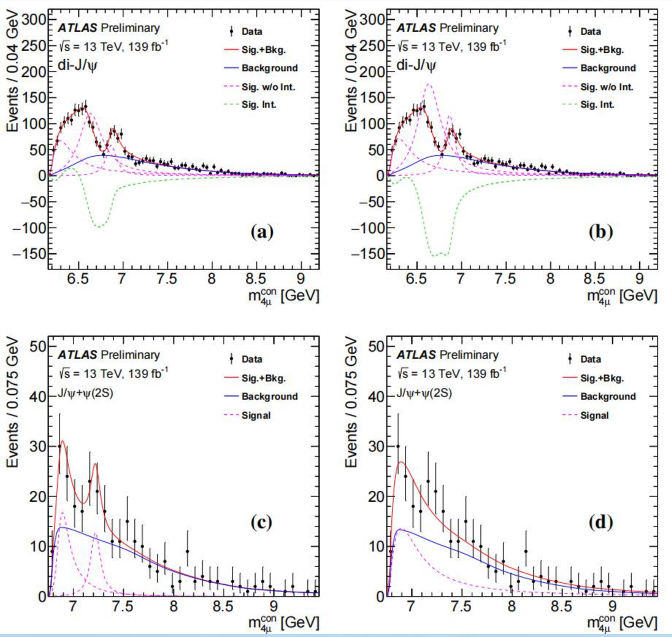
- Fully heavy tetra-quark state(s)?



LHCb, Sci.Bull. 65 (2020) 23, 1983



CMS, Kai Yi's talk at ICHEP 2022.



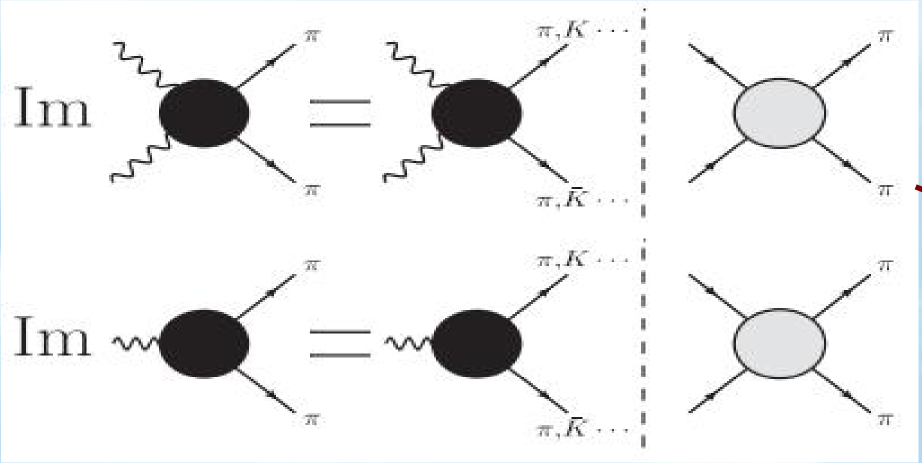
ATLAS, ATLAS-CONF-2022-040

why FSI ?

- FSI needs to be taken into account to perform an amplitude analysis

- Methods: KM, N/D, AMP, Roy equation, PKU, Pade, LSE, BSE, ChEFT, *et.al.*

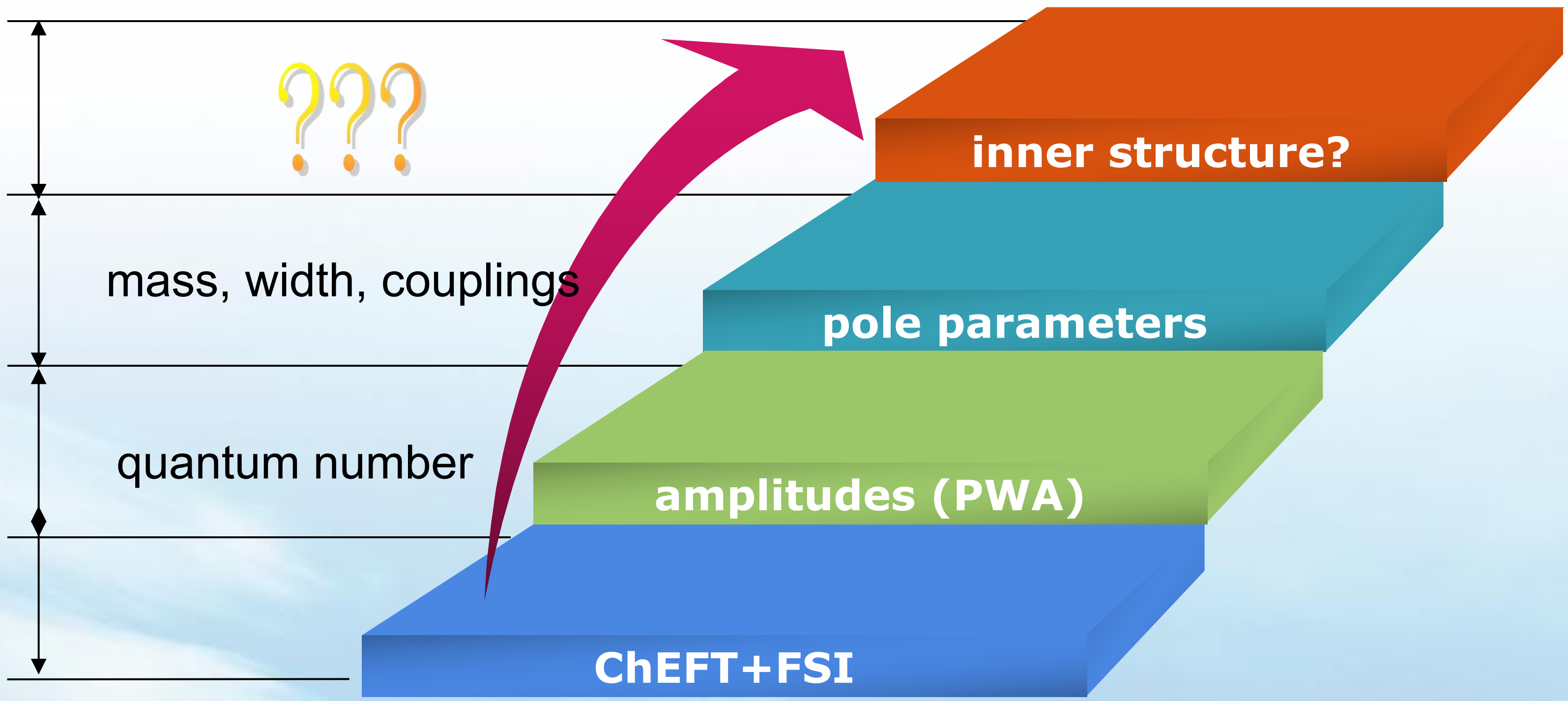
- Fixed scattering, decaying amplitudes: extracting resonance information



Yao, Dai#, Zheng, Zhou, RPP84(2021)076201

Inner structure?

- Interpretation these amplitudes, poles?



Pole counting rule

- Pole counting rule: distinguish molecule and BW resonance.
- At the very beginning, applied to light mesons

Morgan NPA543 (1992) 632.
Dai,Wang and Zheng
CTP57 (2012) 841, CTP58 (2012) 410

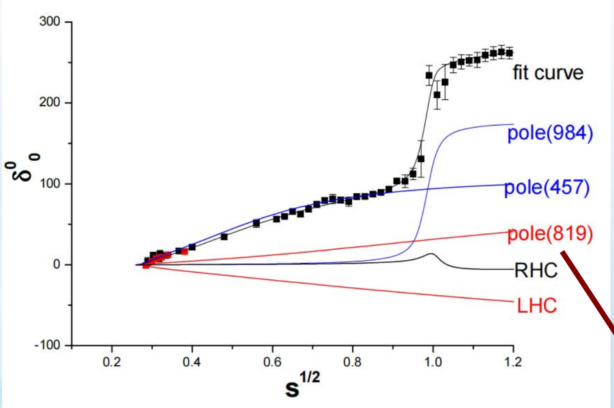
- Applied to heavier mesons

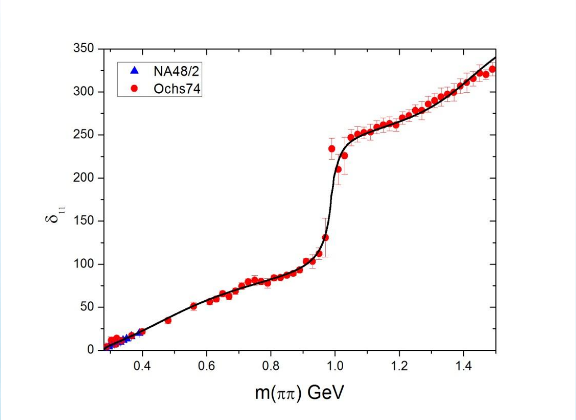
Dai, Sun, Kang, Szczepaniak, Yu,
PRD 105 (2022) 5, L051507
Kuang,**Dai**,Kang,Yao,
EPJC 80 (2020) 5, 433
Dai, Shi, Tang, Zheng,
PRD 92 (2015) 1, 014020

- Any tools else?

phase shifts?

- Phase shifts help to study hadronic scatterings and resonances therein
- Successful in study of light scalars: PKU,Roy equation, Omnes representations, etc.





Zhou, Qin, Zhang, Xiao, Zheng,JHEP 02 (2005)

Dai,Pennington, PLB736(2014)11; PRD90 (2014) 036004;

- The phase shifts of a narrow BW resonance rise from 0 to 180 degrees, crossing 90 degrees at Ecm=M

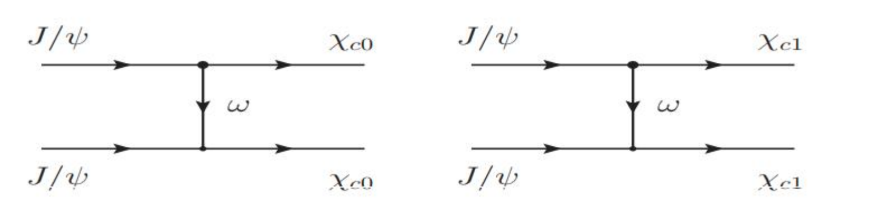
2、Formalism

- coupled channels: $J/\psi J/\psi$、$\psi(2s)J/\psi$、$\psi(3770)J/\psi$

Dong, Baru, Guo, Hanhart, Nefediev, PRL126, 132001(2021)
Gong, Du, Zhao, PRD, 106(5):054011, 2022

	J/ψ	$\psi(2s)$	$\psi(3770)$	η_c	h_c	χ_{c0}	χ_{c1}	χ_{c2}
J^{PC}	1^{--}	1^{--}	1^{--}	0^{-+}	1^{+-}	0^{++}	1^{++}	2^{++}
质量 (MeV)	3096.9	3686.1	3773.7	2983.9	3525.4	3414.7	3510.7	3556.2

- $\eta_c\eta_c$、$h_c h_c$ channels are supressed by HQSS
- $\chi_{c0}\chi_{c0}$，$\chi_{c1}\chi_{c1}$, l.h.c. are faraway



$$\begin{aligned}\mathcal{L}^{LO}_{\rm HQSS} &= g_1\langle J\bar{J}J\bar{J}\rangle \\ &= \langle \frac{1+\not{v}}{2}\not{H}\frac{1-\not{v}}{2}\not{H}^\dagger\frac{1+\not{v}}{2}\not{H}\frac{1-\not{v}}{2}\not{H}^\dagger\frac{1+\not{v}}{2}\rangle \\ &= 2N_C g_1 V_\mu V_\alpha V^\mu V^\alpha,\end{aligned}$$

- [6.2,7.2] GeV

Kuang,Zhou,Guo,Yang,Dai#, arxiv: 2302.03968 [hep-ph], accepted by EPJC
Cao, Yang, EPJC 82 (2022) 2, 161

Effective Lagrangians

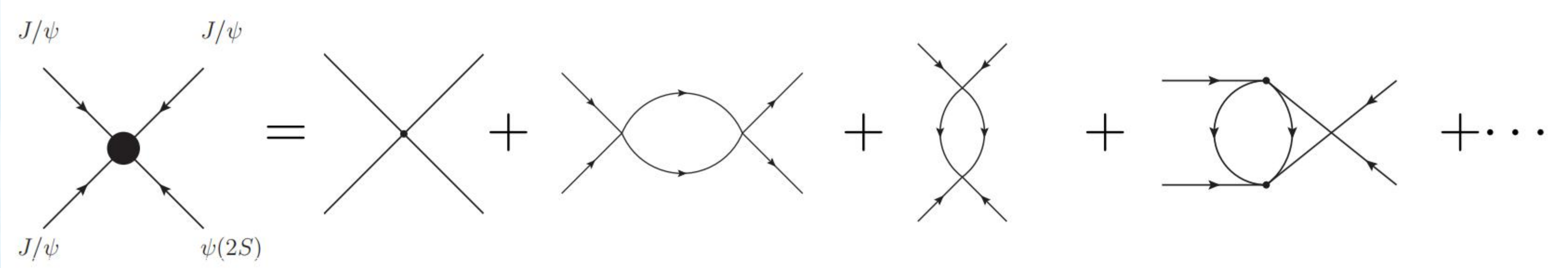
- Four vector interactions, similar to HGLS formalism

Geng, Molina, Oset. CPC41(12):124101, 2017.

$$
\begin{aligned}
\mathcal{L} = & c_1 V_\mu V_\alpha V^\mu V^\alpha + c_2 V_\mu V_\alpha V^\mu V'^\alpha + c_3 V_\mu V'_\alpha V^\mu V'^\alpha \\
& + c_4 V_\mu V'^\mu V_\alpha V'^\alpha + c_5 V_\mu V_\alpha V^\mu V''^\alpha + c_6 V_\mu V''_\alpha V^\mu V''^\alpha \\
& + c_7 V_\mu V''^\mu V_\alpha V''^\alpha + c_8 V_\mu V'_\alpha V^\mu V''^\alpha + c_9 V_\mu V'^\mu V_\alpha V''^\alpha
\end{aligned}
$$

Zhou, Guo, Kuang, Yang, Dai, PRD106 (2022) L111502.

- Feynman diagrams up to NLO



Building amplitudes

- PWA

$$T^{ij}_{\mu_1\mu_2;\mu_3\mu_4}(s,z_s) = 16\pi N_{ij}\sum_J (2J+1) T^{J,ij}_{\mu_1\mu_2;\mu_3\mu_4}(s) d^J_{\mu\mu'}(z_s)\,.$$

- Time reversal and parity invariance reduce the amplitudes
- Tranfer amplitudes from helicity to the JMLS representation

$$T^{ij}_{\mu_1\mu_2;\mu_3\mu_4}(s,z_s) = 16\pi N_{ij}\sum_{J=M}^{\infty}(2J+1)d^J_{\mu\mu'}(z_s)\sum_{LS,L'S'}\frac{\sqrt{(2L+1)(2L'+1)}}{2J+1}\langle LS0\mu|J\mu\rangle\langle J\mu'|L'S'0\mu'\rangle$$
$$\langle s_1 s_2 \mu_1,-\mu_2|S\mu\rangle\langle S'\mu'|s_3 s_4 \mu_3,-\mu_4\rangle T^{J,ij}_{LS,L'S'}\,.$$

$$\begin{aligned}T^{ij}_{^3P_2}(s) = {}& \frac{2}{5}T^2_{++++}(s) + \frac{\sqrt{3}}{5}T^2_{+++0}(s) + \frac{\sqrt{3}}{5}T^2_{+0++}(s) + \frac{\sqrt{3}}{5}T^2_{++0+}(s) + \frac{\sqrt{3}}{5}T^2_{0+++}(s) - \frac{2}{5}T^2_{++--}(s)\\ & - \frac{\sqrt{3}}{5}T^2_{++-0}(s) - \frac{\sqrt{3}}{5}T^2_{-0++}(s) - \frac{\sqrt{3}}{5}T^2_{++0-}(s) - \frac{\sqrt{3}}{5}T^2_{0-++}(s) + \frac{3}{10}T^2_{+0+0}(s) + \frac{3}{10}T^2_{+00+}(s)\\ & + \frac{3}{10}T^2_{0++0}(s) + \frac{3}{10}T^2_{0+0+}(s) - \frac{3}{10}T^2_{0+0-}(s) - \frac{3}{10}T^2_{+00-}(s) - \frac{3}{10}T^2_{0-+0}(s) - \frac{3}{10}T^2_{-0+0}(s)\,.\end{aligned}$$

perturbation amplitudes

- LO partial wave amplitudes
- containing threshold factors and momentum dependences

$$T^{11,LO}_{^1S_0}(s) = \frac{c_1(68m_1^4 + 8sm_1^2 + 5s^2)}{144\pi m_1^4},$$

$$T^{11,LO}_{^5S_2}(s) = \frac{c_1(s + 6m_1\sqrt{s} + 14m_1^2)^2}{1800\pi m_1^4},$$

$$T^{11,LO}_{^3P_0}(s) = 0,$$

$$T^{11,LO}_{^3P_1}(s) = -\frac{c_1(s - 4m_1^2)}{12\pi m_1^2},$$

$$T^{11,LO}_{^3P_2}(s) = 0,$$

$$T^{12,LO}_{^1S_0}(s) = \frac{-10c_2(m_1^3 - m_2^2 m_1)^2 - 2s^2(3m_2^2 - 8m_2m_1 + m_1^2) + s(m_2^4 + 4m_2^2m_1^2 + 56m_2m_1^3 + 7m_1^4) + 5s^3}{288\sqrt{2}\pi m_2 m_1^3 s},$$

$$T^{12,LO}_{^5S_2}(s) = \frac{-c_2(14m_1^2 + 6m_1\sqrt{s} + s)((m_1^2 - m_2^2)^2 - 3s^{3/2}(m_1 + m_2) - 14m_1m_2s + 3\sqrt{s}(m_1 - m_2)^2(m_1 + m_2) - s^2)}{3600\sqrt{2}\pi m_1^3 m_2 s}$$

PW amplitudes

$$T^{11}_{{}^3P_2} = \frac{1}{64\pi}\int_{-1}^{1}\frac{1}{20m_1^2}\{F^{11}_{(b)}[(-3(E_1E_3-2E_1E_4+E_2E_4)+12(E_1+E_2)m_1-4m_1^2)z_s$$
$$+3(3E_1E_3-2E_1E_4+3E_2E_4-4(E_1+E_2)m_1+4m_1^2)z_s^3+6p_{cm}p'_{cm}(1-3z_s^2)]$$
$$+F^{11}_{(c)}[6p_{cm}p'_{cm}(1-3z_s^2)+z_s(-3E_1E_3+6E_1E_4-3E_2E_4+4m_1(-3(E_1+E_2)+m_1)$$
$$+3(E_1E_3-6E_1E_4+E_2E_4+4(E_1+E_2-m_1)m_1)z_s^2)]\}dz_s\,,$$

- Five PWs at last

L	$S=0$	$S=1$	$S=2$
0	$\mathbf{0^{++}}$ ($\mathbf{^1S_0}$)	1^{+-}	$\mathbf{2^{++}}$ ($\mathbf{^5S_2}$)
1	1^{--}	$\mathbf{0^{-+}}$ ($\mathbf{^3P_0}$) $\mathbf{1^{-+}}$ ($\mathbf{^3P_1}$) $\mathbf{2^{-+}}$ ($\mathbf{^3P_2}$)	1^{--} 2^{--} 3^{--}
2	2^{++}	1^{+-} 2^{+-} 3^{+-}	0^{++} 1^{++} 2^{++} 3^{++} 4^{++}
⋮	⋮	⋮	⋮

- Ignoring PWs with L>=2
- No S-D coupled channel scatterings

Unitarization

- unitarity: ignore the S-D coupled waves

$$\langle L'S'|T^J - T^{J\dagger}|LS\rangle = i\frac{4|\vec{p}\,''|}{E''_{cm}} \sum_{L''S''} \langle L'S'|T^{J\dagger}|L''S''\rangle \langle L''S''|T^J|LS\rangle$$

$$\mathrm{Im}T^{ij}_{JLS} = \sum_{k=1}^{a} T^{ik}_{JLS}\,\rho_k\,T^{kj\,*}_{JLS}$$

- Pade approximation: successful in confirming existence of light scalars, restore unitarity and perturbative amplitudes up to NLO

$$T = T^{LO} \cdot [T^{LO} - T^{NLO}]^{-1} \cdot T^{LO}$$

Dai,Wang and Zheng
CTP57 (2012) 841, CTP58 (2012) 410

Invariant mass spectra

- Each channel contributes a ratio α_i

$$\frac{d\ \text{Events}^{1,2}}{d\sqrt{s}} = \tilde{N}_{1,2}\ p_{cm}(s) \sum_{\mu_1\mu_2\mu_3\mu_4} \int_{-1}^{1} dz_s \Big| \sum_{i=1}^{a} \alpha_i T^{i1,i2}_{\mu_1\mu_2\mu_3\mu_4}(s,z_s) \Big|^2$$

- Into the forms of PWs

$$\sum_{\mu_1\mu_2\mu_3\mu_4} \int_{-1}^{1} \Big| \sum_{i=1}^{a} \alpha_i T^{i1,i2}_{\mu_1\mu_2\mu_3\mu_4}(s,z_s) \Big|^2 dz_s = 512\pi^2 \Big[\ |F^{1,2}_{{}^1S_0}(s)|^2 + 5|F^{1,2}_{{}^5S_2}(s)|^2 + |F^{1,2}_{{}^3P_0}(s)|^2 + 3|F^{1,2}_{{}^3P_1}(s)|^2 + 5|F^{1,2}_{{}^3P_2}(s)|^2\ \Big]$$

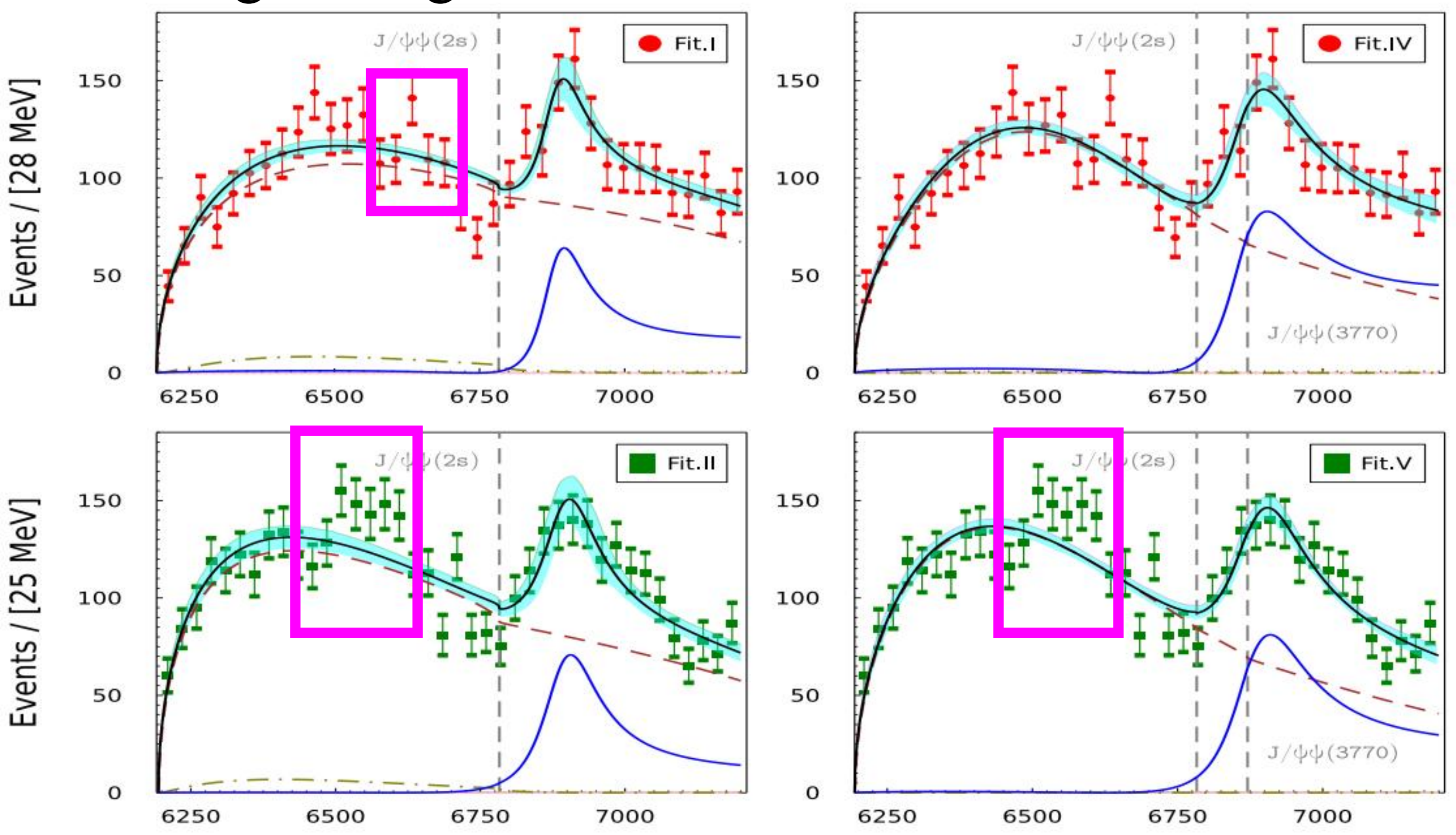
- Compatible with AMP method
  - absorbing l.h.c. and distant r.h.c.
  - Fulfill FSI theorem

$$F^{1,2}_{JLS}(s) = \sum_{i=1}^{a} \alpha_i N_i T^{i1,i2}_{JLS}(s)$$

Dai,Pennington, PLB736(2014)11; PRD90 (2014) 036004;
Dai, Shi, Tang, Zheng,PRD 92 (2015) 1, 014020

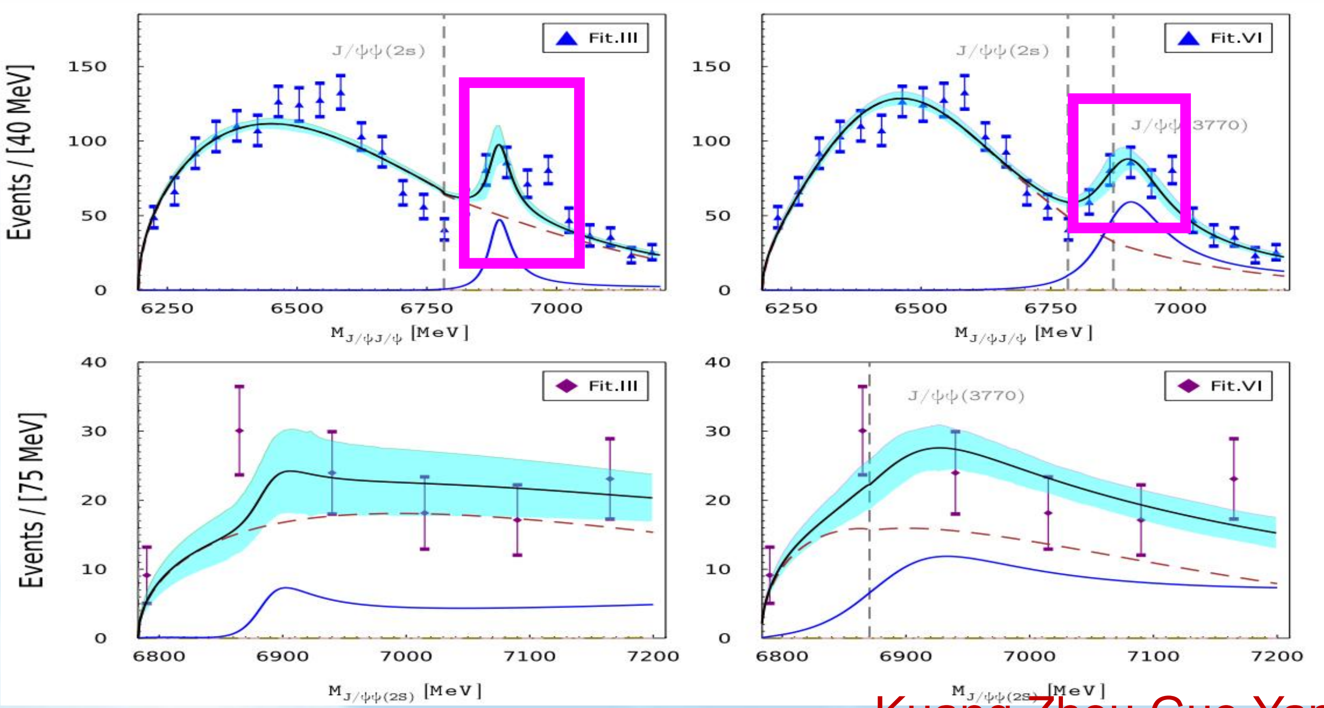
3. Nature of the X(6900)

- High quality Fits for all the data-sets
- Individual contributions of each PW
- $^1S_0$ dominates around 6900 MeV
- $^5S_2$ Contributes a large background



Fits

- Coupled channe fits on the data-sets of ATLAS,better constrains on coupled channel scattering



Kuang,Zhou,Guo,Yang,Dai#, arxiv: 2302.03968 [hep-ph], accepted by EPJC

- $^1S_0$ dominates around 6900 MeV for both J/ψJ/ψ、ψ(2S)J/ψ channels

Couplings

- Couplings are reasonable
- So far, so good....

parameter	**Fit.I(LHCb)**	Fit.II(CMS)	Fit.III(ATLAS)
c_1	$-0.1236^{+0.0001}_{-0.0001}$	$-0.1504^{+0.0001}_{-0.0002}$	$-0.0618^{+0.0001}_{-0.0001}$
c_2	$-0.5336^{+0.0021}_{-0.0001}$	$-0.6203^{+0.0001}_{-0.0001}$	$-0.3369^{+0.0004}_{-0.0001}$
c_3	$-0.3180^{+0.0171}_{-0.0001}$	$-0.3492^{+0.0004}_{-0.0001}$	$-0.3171^{+0.0091}_{-0.0003}$
c_4	$-0.6178^{+0.0234}_{-0.0002}$	$-0.6835^{+0.0004}_{-0.0001}$	$-0.5386^{+0.0078}_{-0.0001}$
$\tilde{N}_1$	$1.5600^{+0.6284}_{-0.0850}$	$0.5336^{+0.1404}_{-0.0193}$	$0.1888^{+0.1109}_{-0.1934}$
$\tilde{N}_2$	$\cdots$	$\cdots$	$0.2200^{+0.0721}_{-0.0198}$
α_1	$0.3831^{+0.0104}_{-0.0052}$	$0.3510^{+0.0012}_{-0.0001}$	$0.1812^{+0.0473}_{-0.0032}$
α_2	$-0.9237^{+0.0089}_{-0.0022}$	$-0.9364^{+0.0001}_{-0.0009}$	$0.9834^{+0.1861}_{-0.0088}$
$\chi^2_{d.o.f.}$	1.31	1.77	2.53

- Lack of angular distributions!

Pole analysis

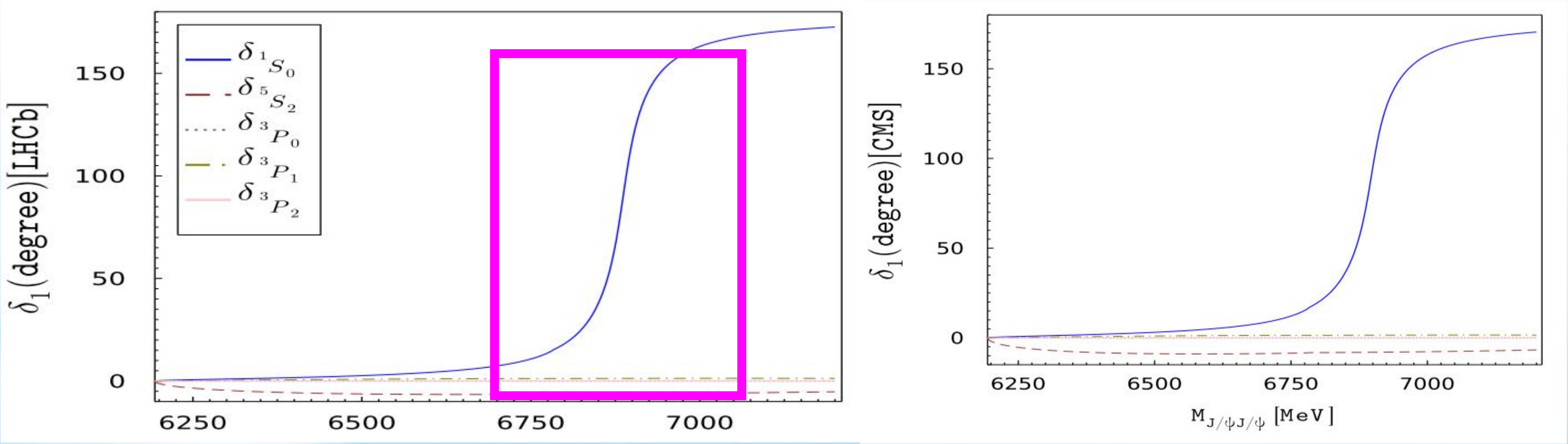
- One resonace found in $^1S_0$ wave: X(6900)----0^{++}
- Couple channels case: a pair of accompanying poles
- Triple channels case: Four poles in unphysical sheets, implying the BW origin.

pole counting rule:
Morgan,
NPA543 (1992) 632.
Dai,Wang and Zheng
CTP57 (2012) 841

Data	RS	pole location (MeV)	$g_{J/\psi J/\psi}=\vert g\vert e^{i\varphi}$		$g_{J/\psi\psi(2S)}=\vert g\vert e^{i\varphi}$		$g_{J/\psi\psi(3770)}=\vert g\vert e^{i\varphi}$	
			$\vert g_1\vert$(MeV)	$\varphi_1(^\circ)$	$\vert g_2\vert$(MeV)	$\varphi_2(^\circ)$	$\vert g_3\vert$(MeV)	$\varphi_3(^\circ)$
LHCb(Fit.IV)	II(- + +)	$6874.8^{+5.0}_{-5.8}$-$i50.4^{+1.7}_{-1.1}$	$1398.5^{+21.6}_{-15.8}$	$85.9^{+0.3}_{-0.1}$	$962.1^{+14.9}_{-10.9}$	$84.6^{+0.1}_{-0.1}$	$18.2^{+0.7}_{-0.4}$	$-79.9^{+1.2}_{-0.2}$
	III(- - +)	$6862.0^{+4.3}_{-6.2}$ -$i68.9^{+1.9}_{-2.0}$	$1364.7^{+20.1}_{-12.2}$	$80.6^{+0.3}_{-0.1}$	$927.4^{+13.4}_{-8.3}$	$77.5^{+0.5}_{-0.1}$	$19.3^{+0.7}_{-0.4}$	$-79.0^{+0.6}_{-0.3}$
	IV(- - -)	$6862.0^{+4.3}_{-6.2}$ -$i68.9^{+1.9}_{-2.0}$	$1361.6^{+19.0}_{-12.4}$	$80.7^{+0.2}_{-0.1}$	$925.3^{+12.5}_{-8.7}$	$77.5^{+0.4}_{-0.1}$	$19.4^{+0.7}_{-0.4}$	$-78.6^{+0.5}_{-0.2}$
	VII(- + -)	$6874.8^{+5.0}_{-5.8}$ -$i50.4^{+1.7}_{-1.1}$	$1394.3^{+17.7}_{-17.5}$	$85.9^{+0.2}_{-0.1}$	$959.2^{+11.7}_{-12.1}$	$84.5^{+0.1}_{-0.1}$	$18.4^{+0.7}_{-0.4}$	$-79.2^{+1.0}_{-0.3}$
CMS(Fit.V)	II(- + +)	$6888.4^{+11.3}_{-7.2}$-$i59.4^{+1.7}_{-0.5}$	$1452.8^{+23.1}_{-6.8}$	$85.6^{+0.1}_{-0.1}$	$795.8^{+12.2}_{-4.3}$	$83.3^{+0.1}_{-0.1}$	$38.8^{+2.1}_{-0.1}$	$82.2^{+0.3}_{-0.1}$
	III(- - +)	$6878.9^{+11.3}_{-7.4}$ -$i73.1^{+2.6}_{-1.1}$	$1430.3^{+29.4}_{-5.7}$	$82.0^{+0.1}_{-0.1}$	$773.9^{+15.5}_{-4.2}$	$77.8^{+0.2}_{-0.1}$	$36.4^{+2.2}_{-0.1}$	$65.0^{+1.6}_{-0.4}$
	IV(- - -)	$6878.9^{+11.3}_{-7.4}$ -$i73.1^{+2.6}_{-1.1}$	$1430.5^{+18.8}_{-5.0}$	$82.0^{+0.1}_{-0.1}$	$773.8^{+8.7}_{-3.1}$	$77.8^{+0.2}_{-0.1}$	$36.7^{+2.1}_{-0.1}$	$65.6^{+1.6}_{-0.4}$
	VII(- + -)	$6888.4^{+11.5}_{-7.2}$ -$i59.4^{+1.7}_{-0.5}$	$1452.3^{+24.4}_{-5.6}$	$85.6^{+0.1}_{-0.1}$	$795.4^{+13.6}_{-3.4}$	$83.3^{+0.1}_{-0.1}$	$39.4^{+2.2}_{-0.1}$	$83.4^{+0.4}_{-0.2}$
ATLAS(Fit.VI)	II(- + +)	$6897.7^{+19.1}_{-4.3}$-$i50.9^{+0.9}_{-0.2}$	$1409.8^{+12.0}_{-1.9}$	$86.2^{+0.1}_{-0.1}$	$997.0^{+8.8}_{-1.8}$	$85.0^{+0.1}_{-0.1}$	$5.7^{+0.1}_{-0.1}$	$56.7^{+0.8}_{-0.3}$
	III(- - +)	$6883.8^{+18.3}_{-4.0}$ -$i73.4^{+2.8}_{-0.7}$	$1373.6^{+7.3}_{-2.7}$	$80.8^{+0.1}_{-0.1}$	$960.0^{+5.6}_{-1.3}$	$77.5^{+0.1}_{-0.2}$	$7.2^{+0.1}_{-0.1}$	$21.6^{+1.1}_{-1.0}$
	IV(- - -)	$6883.8^{+18.3}_{-4.0}$ -$i73.4^{+2.8}_{-0.7}$	$1379.0^{+10.0}_{-2.0}$	$80.8^{+0.1}_{-0.1}$	$963.8^{+7.1}_{-1.2}$	$77.5^{+0.1}_{-0.1}$	$7.3^{+0.1}_{-0.1}$	$22.1^{+1.1}_{-1.0}$
	VII(- + -)	$6897.7^{+19.1}_{-4.3}$ -$i50.9^{+0.9}_{-0.2}$	$1406.7^{+10.4}_{-2.0}$	$86.2^{+0.1}_{-0.1}$	$994.9^{+7.4}_{-2.3}$	$85.0^{+0.1}_{-0.1}$	$5.8^{+0.2}_{-0.1}$	$57.6^{+0.9}_{-0.2}$

Phase shifts

- Phase shifts of $^1S_0$ is very likely to the one generated by a narrow BW resonacne: tetra-quark
- Other waves should contribute backgrounds



- other points of view.
  - excited tetraquark?

Zhang, Li, Xie et.al.,
EPJC 82 (2022) 1126

4、Some other resonances：Tcc

- Obviously contain four quarks
- Chew-Mandelstam K-matrix

$$T^{-1}(s) = K^{-1}(s) - C(s) \qquad C_i(s) = \frac{s}{\pi}\int_{s_{th_i}}^{\infty} ds' \frac{\rho_i(s')}{s'(s'-s)}$$

- D^{*+}, unstable particles

$$C_2(s) \to \frac{1}{\pi}\int_{s_{tr,D\pi}}^{\infty} ds' C(s;\sqrt{s'},m_2)\mathrm{Im} f_{D\pi}(s')$$

- FSI: AMP method

$$F_i(s) = \sum_{k=1}^{2} \alpha_k(s) T_{ki}(s),$$

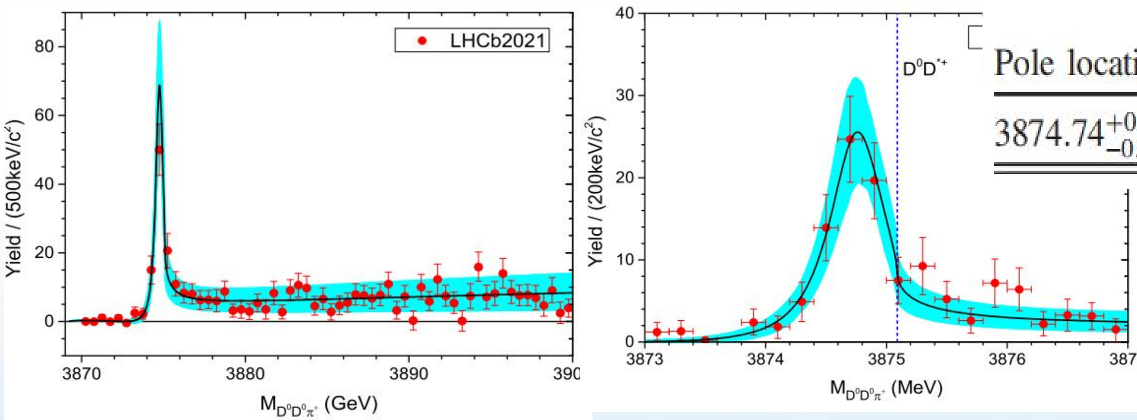
$$K_{11} = -0.01204 \pm 0.00691^{+0.03280}_{-0.07039}$$
$$K_{12} = K_{21} = 0.5080 \pm 0.0025^{+0.0348}_{-0.0700}$$
$$K_{22} = 1.4447 \pm 0.0015^{+0.0235}_{-0.0477}$$
$$\alpha_2 = -0.3024 \pm 0.0016^{+0.0261}_{-0.0583}$$
$$N_a = 1434.0 \pm 129.8^{+662.0}_{-964.8}\ \mathrm{GeV}^{-2}$$
$$N_b = 516.0 \pm 49.3^{+225.6}_{-363.4}\ \mathrm{GeV}^{-2}$$
$$\chi^2_{\mathrm{d.o.f.}} = 0.92$$

- one term in K-matrix: similar to effective range expansion

Dai, Sun, Kang, Szczepaniak, Yu, PRD105 (2022) L051507

Tcc: virtual state origin?

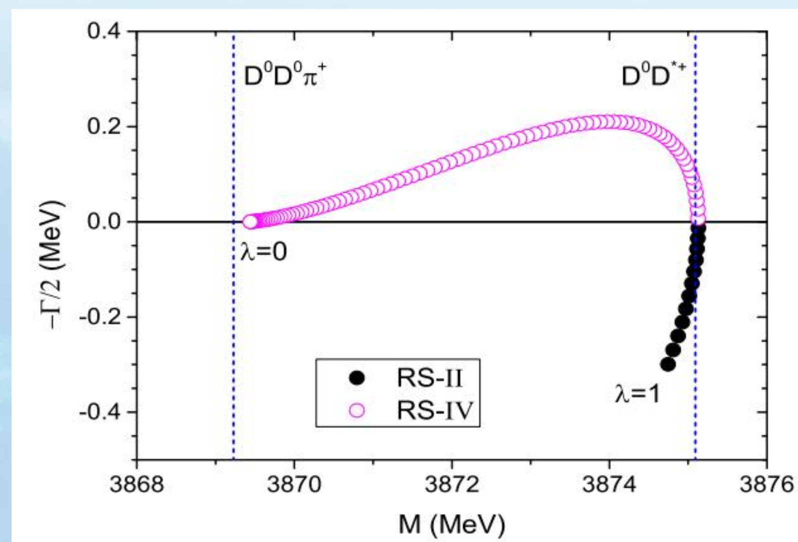
- Pole parameters extracted



	$g^{II}_{D^0D^0\pi^+} = \vert g\vert e^{i\varphi}$		$g^{II}_{D^0D^{*+}} = \vert g\vert e^{i\varphi}$	
Pole location (MeV)	$\vert g_1\vert$ (GeV)	φ_1 (°)	$\vert g_2\vert$ (GeV)	φ_2 (°)
$3874.74^{+0.11}_{-0.04} - i0.30^{+0.05}_{-0.09}$	$0.22^{+0.03}_{-0.04}$	9^{+11}_{-5}	$0.69^{+0.04}_{-0.02}$	10^{+11}_{-5}

- Pole analysis by switching the inelastic channel
- pole-counting, one pole,molecule?
- λ=0 RS-IV corresponds to RS-II in D^0D^{*+} single channel, virtual state origin!

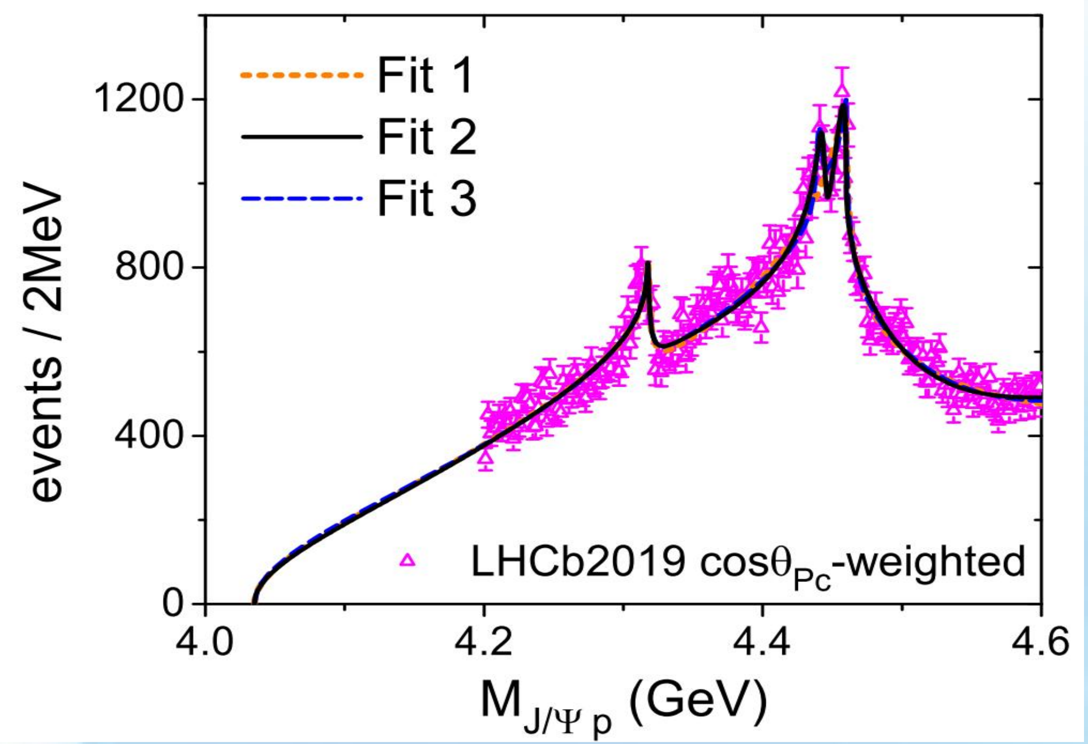
Ling, Geng, Xie *et.al.*, PLB 826 (2022) 136897



Pc states

- Candidates for pentaquarks
- CM K-matrix+AMP
- $J/\psi p - \bar{D}^0\Sigma_c^+ - \bar{D}^{*0}\Sigma_c^+$ triple channels
- Fit 1: no pole in KM
- Fit 2: a pole in KM around Pc(4440)
- Fit 3: P-wave instead of KM pole around Pc(4440)

Kuang, Dai#, Kang, Yao,
EPJC 80 (2020) 433



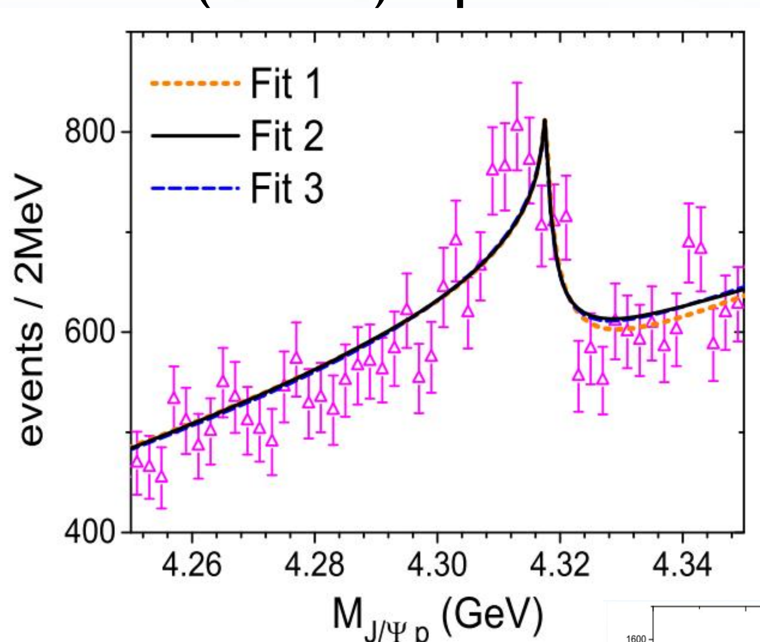
Pc states

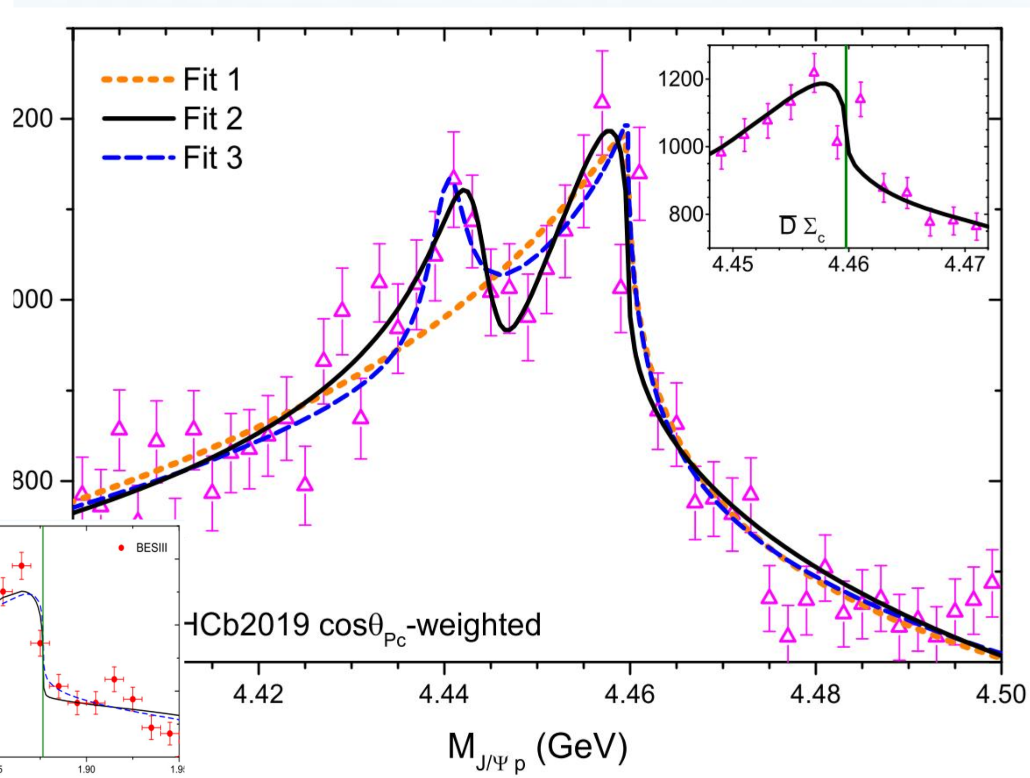
- pole parameters
- pole counting rule
- Pc(4312): molecule?
- Pc(4440): compact tetraquark
- Pc(4457): threhold effect?

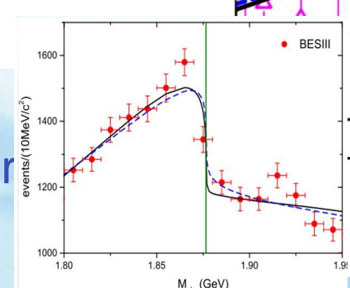
State	Pole locations (MeV)					
	RS	Fit.1	RS	Fit.2	RS	Fit.3
$P_c(4312)$	III	$4296.93^{+2.48}_{-3.00}$	III	...	**V***	$4313.38^{+2.52}_{-5.73}$
		$-i5.12^{+2.44}_{-1.06}$		...		$-i2.05^{+1.65}_{-0.75}$
	V*	$4312.74^{+1.69}_{-0.67}$	**V***	$4314.31^{+2.06}_{-1.10}$	VIII	$4313.11^{+3.86}_{-4.76}$
		$-i3.33^{+2.91}_{-1.25}$		$-i1.43^{+1.50}_{-0.57}$		$-i3.11^{+1.63}_{-2.02}$
$P_c(4440)$	...	...	**III***	$4444.09^{+2.53}_{-1.48}$	**III***	$4440.53^{+0.47}_{-0.31}$
		...		$-i3.10^{+0.53}_{-1.33}$		$-i2.42^{+0.22}_{-0.22}$
	...	...	IV	$4443.69^{+2.89}_{-1.34}$	IV	$4440.38^{+0.41}_{-0.19}$
		...		$-i0.32^{+1.23}_{-0.04}$		$-i1.40^{+0.59}_{-0.50}$
	...	...	V	$4444.22^{+2.72}_{-1.41}$	V	$4440.53^{+0.37}_{-0.30}$
		...		$-i2.48^{+0.57}_{-0.67}$		$-i2.32^{+0.27}_{-0.61}$
	...	...	VII	$4443.84^{+1.93}_{-1.91}$	VIII	$4440.38^{+3.31}_{-0.52}$
		...		$-i1.02^{+1.05}_{-0.92}$		$-i1.30^{+4.45}_{-0.50}$
$P_c(4457)$	...	...	III	$4466.53^{+2.13}_{-4.75}$	...	...
		...		$-i3.88^{+6.95}_{-0.93}$		...
	...	...	VII	$4456.77^{+3.10}_{-8.89}$	VIII	$4453.44^{+7.11}_{-3.34}$
		...		$-i7.77^{+11.07}_{-4.41}$		$-i21.58^{+8.01}_{-6.36}$

Pc states: inner structure?

- pole-counting, one pole is molecule type
- Fit 2 better than Fit 3, Pc(4440) prefers to be S-wave
- Pc(4457): quite similar to ppbar threshold behaviour



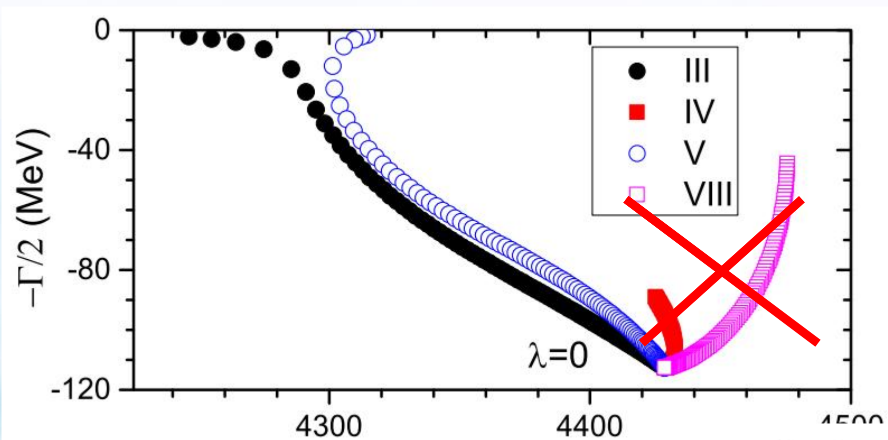


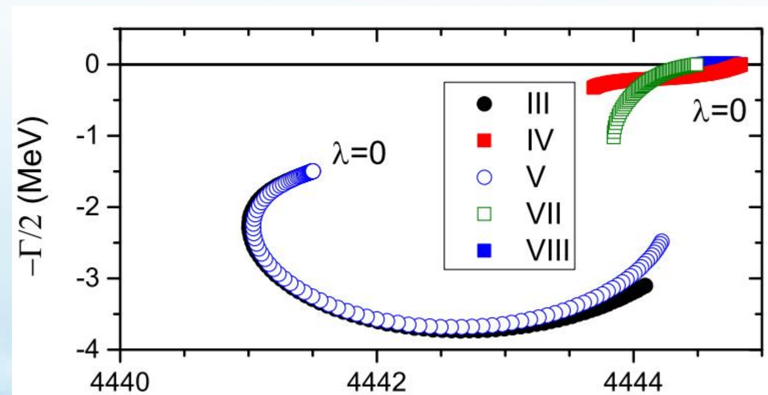


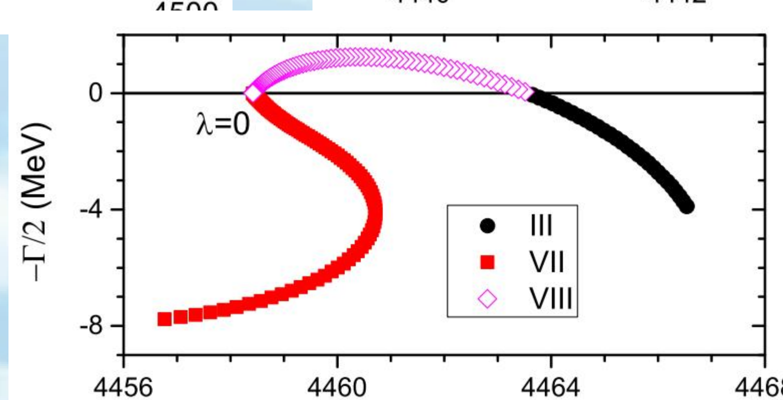
Dai, Haidenbauer, Meissner
PRD 98 (2018) 1, 014005

Pole trajectories?

- Pc(4312): support molecule.
- Pc(4440): compact tetraquark
- Pc(4457): threshold behaviour

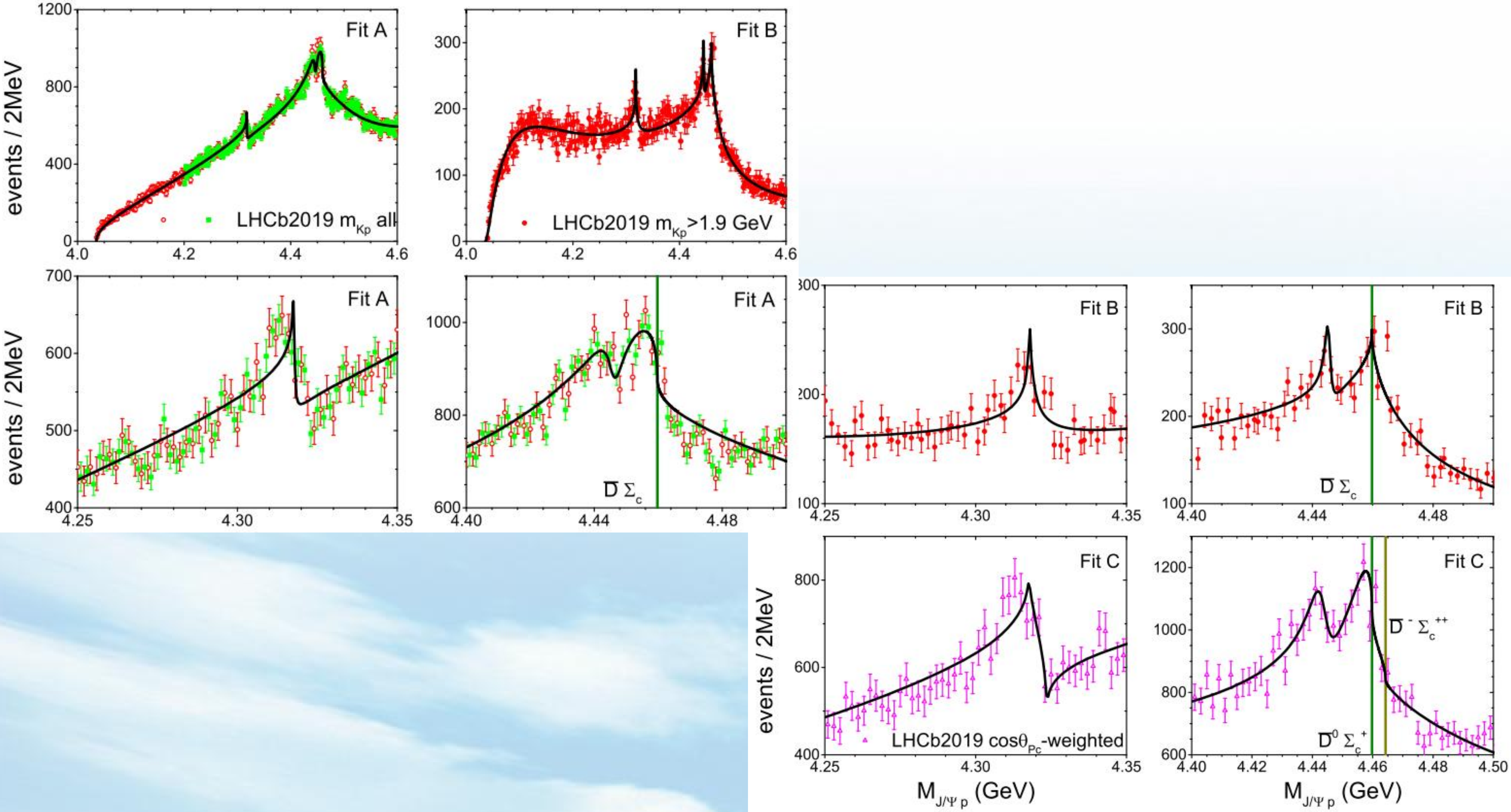






other datasets

- The same conclusion as the previours analysis



4、Summary

PWA

One needs PWA to extract pole parameters for the resonance: quantum number, mass, width, residues...

FSI

Amplitude analsysis connects QFT principles and Exp. FSI needs to be considered when performing amplitude analysis.

structure

X6900: 0^{++}, likely to be a compact tetraquark;
Tcc: virtual state origin; Pc(4312): molecule, Pc(4440): pentaquark, Pc(4457): threshold behaviour.

Next?

Angular distribution? Being essential to separate the partial waves. Other scatterings? Better method to classify nature of hadrons?

Thank You For your patience !