Charged exotic states in charm and bottom sectors

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3rd workshop on the XYZ particles

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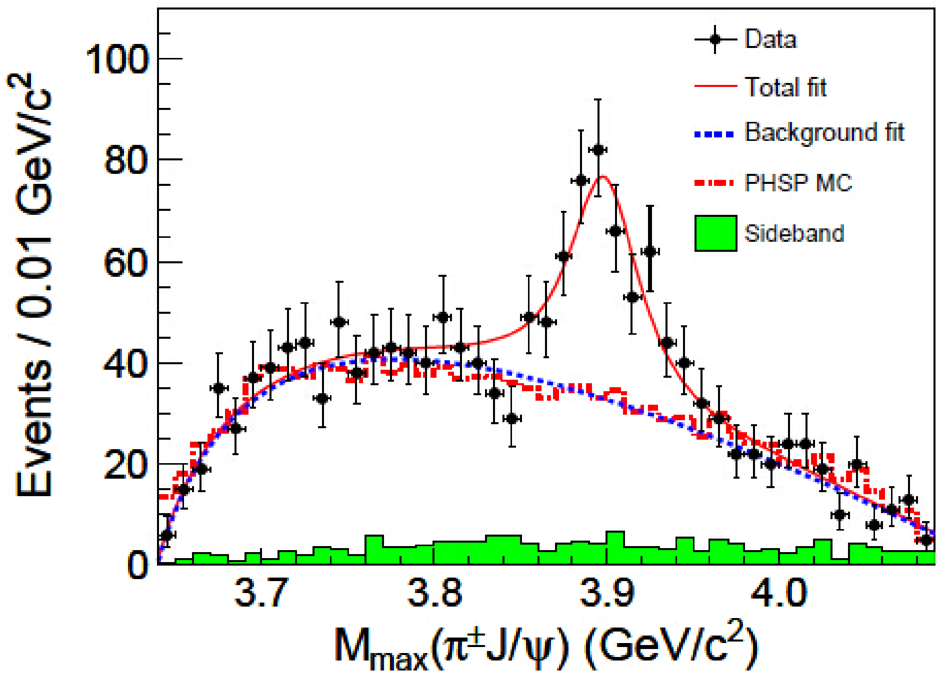
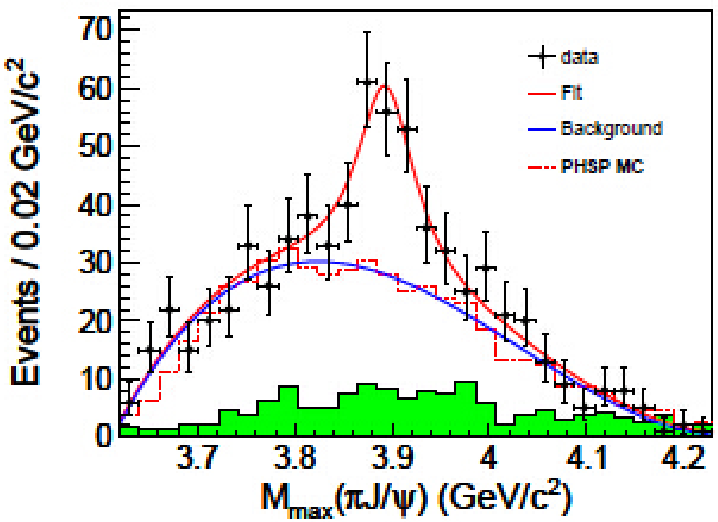
Outline

- Background
- Theoretical model
- Preliminary numerical results
- Prospection

$Z_c(3900)^\pm$

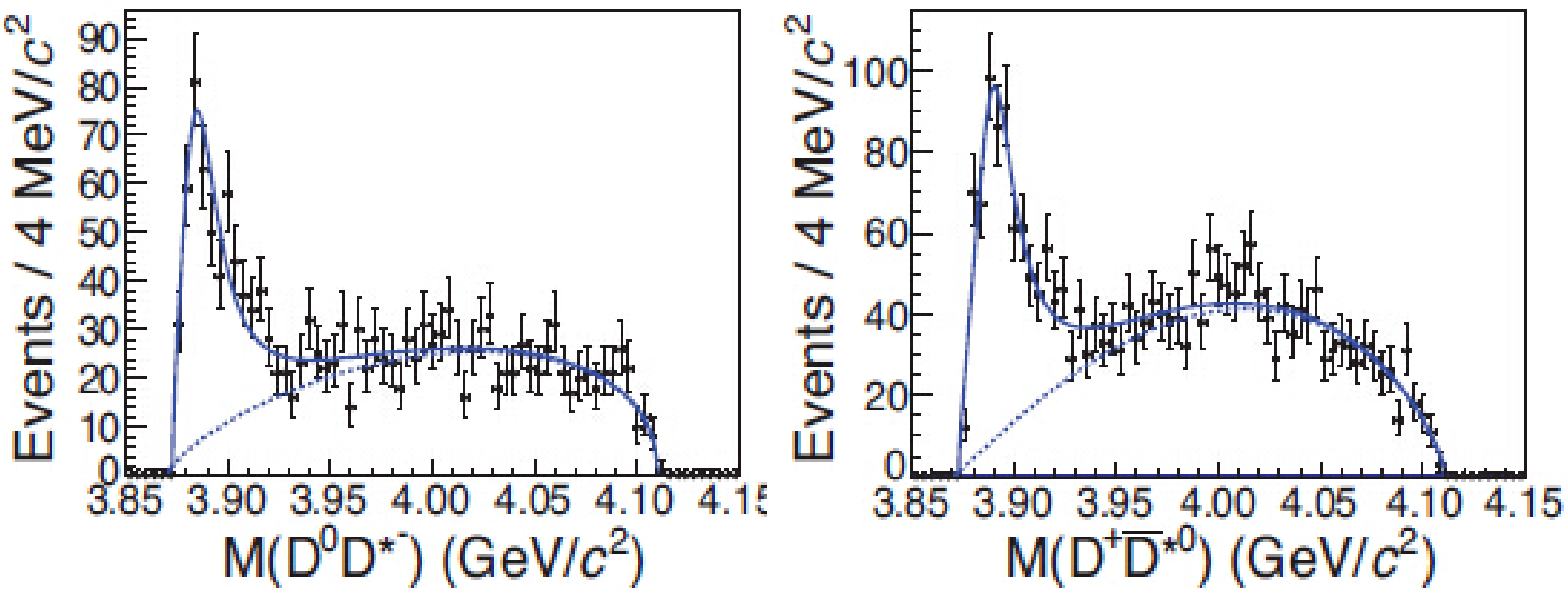
- BESIII: $e^+e^- \to \pi^+\pi^- J/\psi$[PRL 110,25001(2013)]
  $M_{Z_c} = 3899.0 \pm 3.6 \pm 4.9 MeV/c^2$,$\Gamma_{Z_c} = 46 \pm 10 \pm 20 MeV$
- Belle: $e^+e^- \to \pi^+\pi^- J/\psi$[PRL 110,25002(2013)]
  $M_{Z_c} = 3894.5 \pm 6.6 \pm 4.5 MeV/c^2$,$\Gamma_{Z_c} = 37 \pm 4 \pm 8 MeV$





$Z_c(3900)^{\pm}$

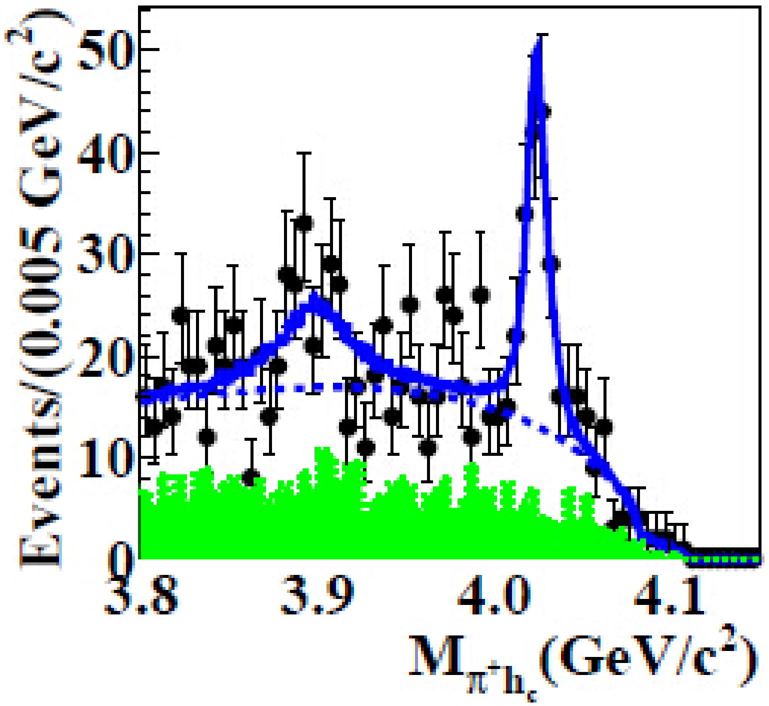
- BESIII: $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\pm}$ [PRL 112,022001(2014)]

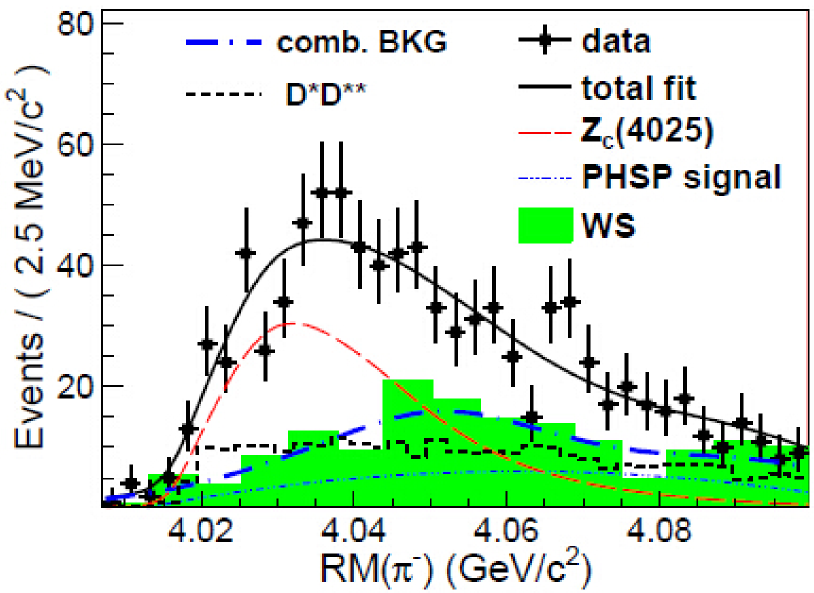


- $M_{Z_c} = 3883.9 \pm 1.5 \pm 4.2 MeV/c^2$,$\Gamma_{Z_c} = 24.8 \pm 3.3 \pm 11.0 MeV$

$Z_c(4020)^{\pm}$

- BESIII: $e^+e^- \rightarrow \pi^+\pi^- h_c$ [PRL 111,242001(2013)]; $e^+e^- \rightarrow \pi^{\pm}(D^*\bar{D}^*)^{\pm}$[PRL 112 132001]

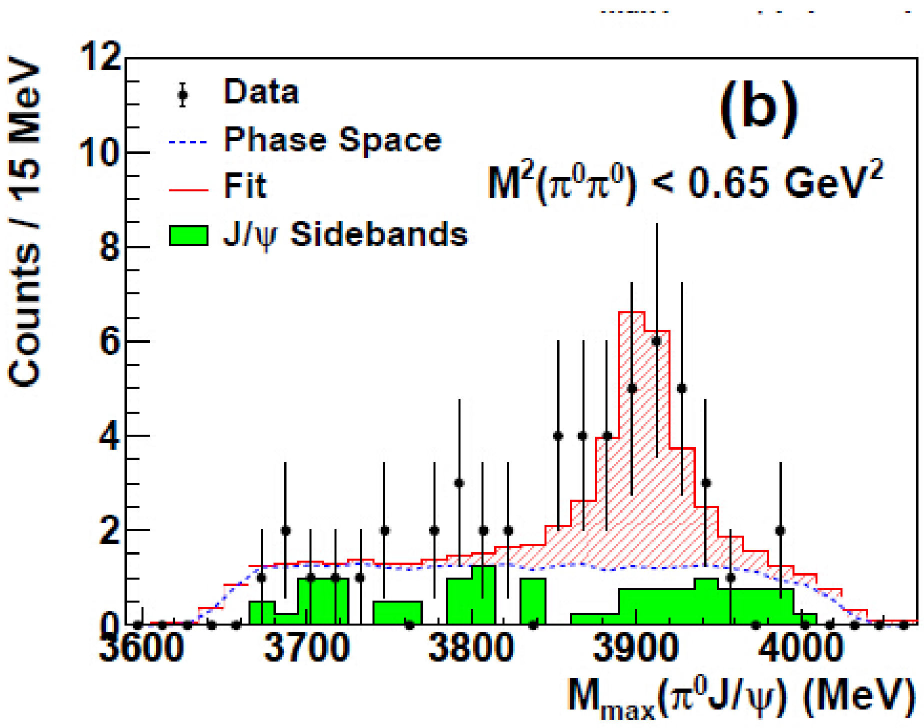




$M = 4022.9 \pm 0.8 \pm 2.7 MeV/c^2$,$\Gamma = 7.9 \pm 2.7 \pm 2.6 MeV$;
$M = 4026.3 \pm 2.6 \pm 3.7 MeV/c^2$,$\Gamma = 24.8 \pm 5.6 \pm 7.7 MeV$.

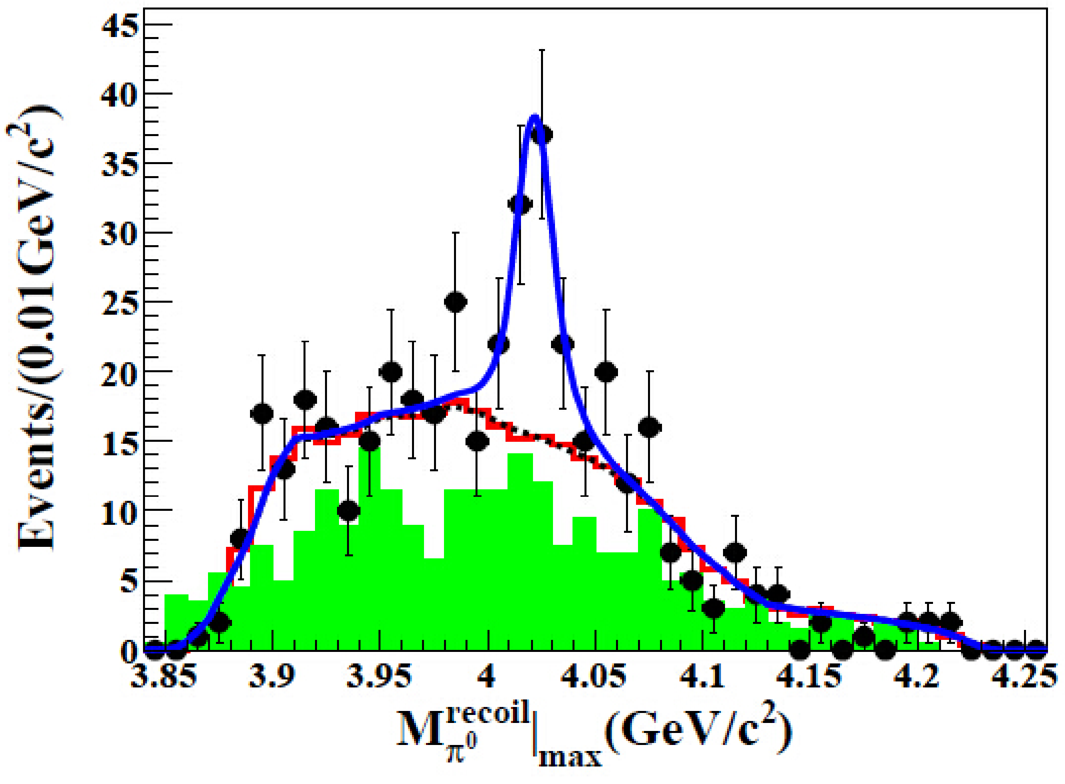
$Z_c^0(3900)$

- $I^G(J^{PC}) = 1^+(1^{+-})$
  neutral isospin partner $Z_c^0(3900)$, 3.5σ: [T. Xiao,et al.,PLB 727 366]



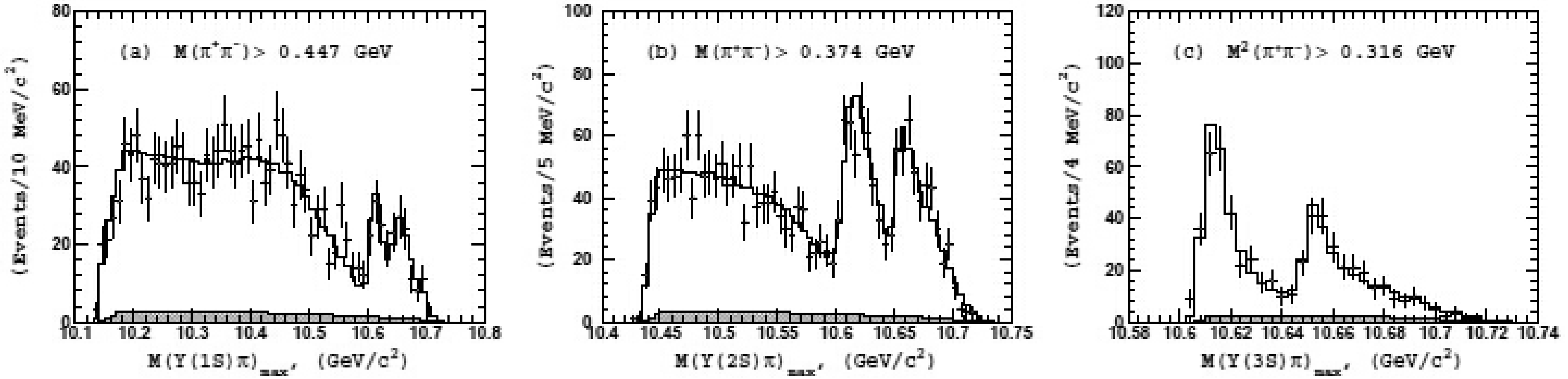
$Z_c^0(4020)$

- BESIII: $e^+e^- \to \pi^0\pi^0 h_c$: [PRL 113,212002(2014)]
  fixed $\Gamma = \Gamma_{Z_c^{\pm}(4020)}$, $M = 4023.9 \pm 2.2 \pm 3.8 MeV/c^2$



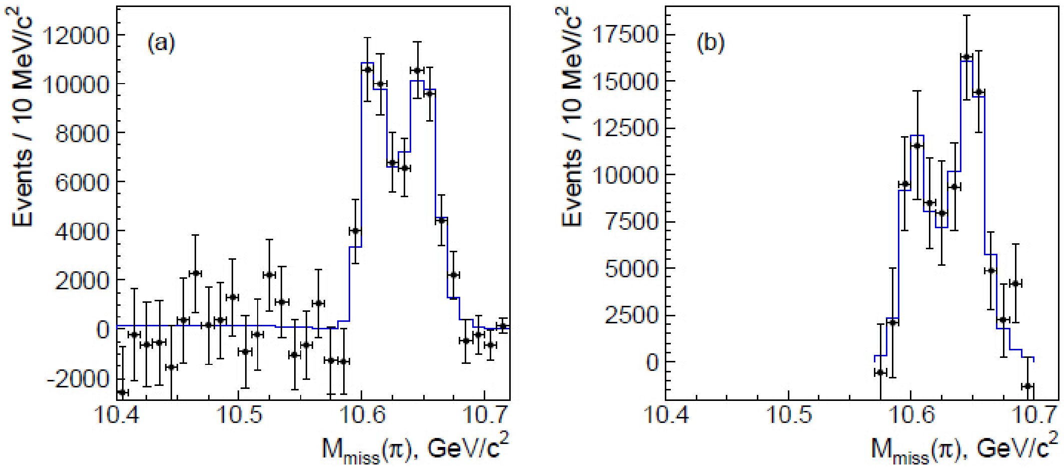
$Z_b(10610)$ and $Z_b(10650)$

- Belle observed $Z_b(10610)$ and $Z_b(10650)$ in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ channels.
  [PRL 108(2012)122001]
  - $\mathrm{M}_{Z_b} = 10607 \pm 2.0\mathrm{MeV}, \Gamma_{Z_b} = 18.4 \pm 2.4\mathrm{MeV}$,3MeV above BB^* threshold(10604).
  - $\mathrm{M}_{Z_b'} = 10652.2 \pm 1.5\mathrm{MeV}, \Gamma_{Z_b'} = 11.5 \pm 2.2\mathrm{MeV}$,2MeV above B^*B^* threshold(10650).

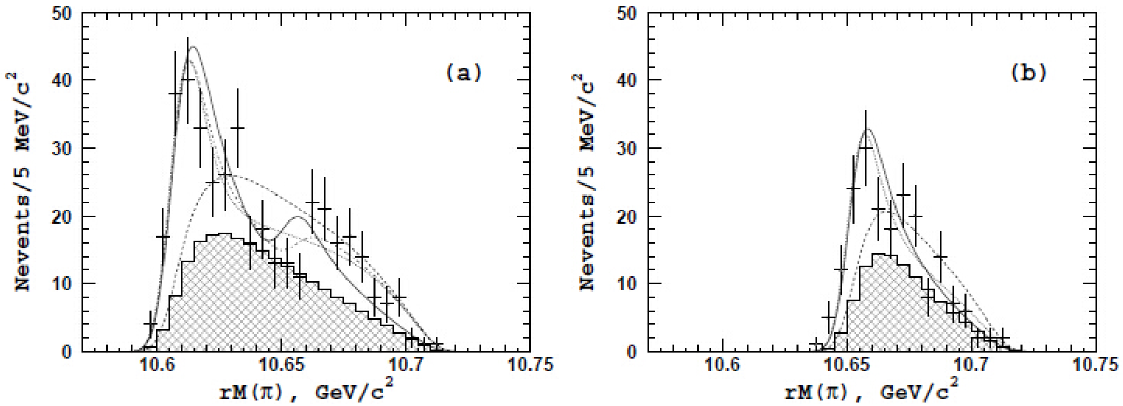


$Z_b(10610)$ and $Z_b(10650)$

- $\Upsilon(5S) \to h_b(nP)\pi\pi(n = 1, 2)$channel: [PRL 108(2012)122001]



- $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$ channel:[ArXiv:1209.6450[hep-ex]][$a : B^*\bar{B}$,$b : B^*\bar{B}^*$]

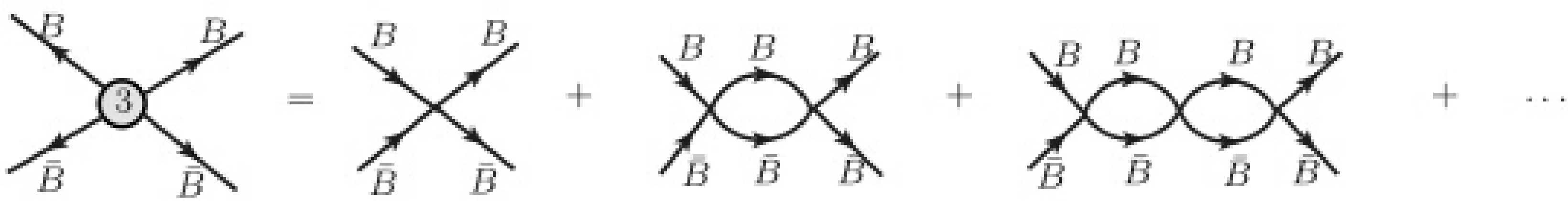


$Z_c(3900)$ and $Z_b(10610)$

- Quantum number: $I^G(J^{PC}) = 1^+(1^{+-})$

$M_{Z_b(10650)} - (M_B + M_{\bar{B}^*}) \simeq$ 3MeV
$M_{Z_c(3900)} - (M_D + M_{\bar{D}^*}) \simeq$ 23MeV

- For Z_b: molecule test
  Shi' talk



$$T_Z = \frac{4\pi}{M}\begin{pmatrix} \frac{\triangle_1-\gamma_+}{(\gamma_+-\triangle_1)(\gamma_+-\triangle_2)-\gamma_-^2} & \frac{\gamma_-}{(\gamma_+-\triangle_1)(\gamma_+-\triangle_2)-\gamma_-^2} \\ \frac{\gamma_-}{(\gamma_+-\triangle_1)(\gamma_+-\triangle_2)-\gamma_-^2} & \frac{\triangle_2-\gamma_+}{(\gamma_+-\triangle_1)(\gamma_+-\triangle_2)-\gamma_-^2} \end{pmatrix} \quad (1)$$

$Z_c(3900)$

- picture about $Z_c(3900)$
  - Hadronic molecules:
    E. Wilbring, et al., PRB 726.08059(2013), J. R. Zhang, PRD 87.116004, $\cdots$
  - Tetraquarks:
    J. M. Dias, et al., PRD 88.016004(2013),
    Y. Chen, et al., PRD 89.094506(2014), $\cdots$
  - Cusp effects:
    Adam P. Szczepaniak, arXiv:1501.01691, $\cdots$
  - $\cdots$

- molecule? tetraquark?
  pure molecule test
  pure breit-wigner test
  mixing with two components

  which is better fit with experimental data?

Effective Lagrangian

- For $X(4260) \to J/\psi(h_c)\pi\pi$ channel

$$\mathcal{L}_{XJ/\psi\pi\pi} = g_1 X_\mu \psi_\nu < u^\mu u^\nu > + g_2 X_\mu \psi^\mu < u^\nu u_\nu > + g_3 X_\mu \psi^\mu < \chi_+ > + \cdots \quad (2)$$

$$\mathcal{L}_{XZ_c\pi} = g_4 \nabla_\nu X_\mu < Z_c^\mu u^\nu > + \cdots \quad (3)$$

$$\mathcal{L}_{ZcJ/\Psi\pi} = g_7 \nabla_\nu \psi_\mu < Z_c^\mu u^\nu > + \cdots \quad (4)$$

$$\mathcal{L}_{Xh_c\pi\pi} = f_8 \nabla^\lambda \nabla_\rho X_\mu H_\nu < u_\lambda u_\sigma > \epsilon^{\mu\nu\rho\sigma} + \cdots \quad (5)$$

$$\mathcal{L}_{Z_c h_c \pi} = f_9 \nabla_\alpha H_\nu < Z_{c\mu} u_\beta > + \cdots \quad (6)$$

- Field Operator:
$X : X(4260)$; $\psi : J/\psi$; $Z_c : Z_c(3900)$; $H : h_c$, $\nabla^\mu X = \partial^\mu X + [\Gamma^\mu, X]$
$\chi_\pm = u^+ \chi u^+ \pm u \chi^+ u$, $u_\mu = i\{u^+ \partial_\mu u - u \partial_\mu u^+\}$, $\Gamma^\mu = \frac{1}{2}[u^+(\partial^\mu - i r^\mu) u + u(\partial^\mu - i l^\mu) u^+]$
$\chi = 2B(s + ip)$,$u = exp(\frac{i\Phi}{\sqrt{2}F})$

Effective Lagrangian

- For $X(4260) \to DD^*\pi$ channel

$$\begin{aligned}\mathcal{L}_{XDD^*\pi} = & f_1 \nabla^\nu X^\mu < \bar{D}^*_\mu D u_\nu > + f_2 X^\mu < \nabla^\nu \bar{D}^*_\mu D u_\nu > \\ & + f_3 \nabla^\nu X^\mu < \bar{D}^*_\nu D u_\mu > + f_4 X^\mu < \nabla_\mu \bar{D}^{*\nu} D u_\nu > + \cdots\end{aligned} \tag{7}$$

$$\mathcal{L}_{ZcDD*} = f_7[(\bar{D}^{*0}_\mu D^+ + D^{*+}_\mu \bar{D}^0) Z_c^{-\mu} + (D^{*-}_\mu D^0 + D^{*0}_\mu D^-) Z_c^{+\mu}] \tag{8}$$

$$\begin{aligned}\mathcal{L}_{D\bar{D}^*D\bar{D}^*} = & \lambda_1 (D^{*+\mu} \bar{D}^0 D^{*-}_\mu D^0 + D^+ \bar{D}^{*0\mu} D^- D^{*0}_\mu + D^{*-\mu} D^0 D^{*+}_\mu \bar{D}^0 + D^- D^{*0\mu} D^+ \bar{D}^{*0}_\mu) \\ & + \lambda_2 (D^{*+\mu} \bar{D}^0 D^- D^{*0}_\mu + D^+ \bar{D}^{*0\mu} D^{*-}_\mu D^0 + D^{*-\mu} D^0 D^+ \bar{D}^{*0}_\mu + D^- D^{*0\mu} D^{*+}_\mu \bar{D}^0)\end{aligned} \tag{9}$$

$$\begin{aligned}\mathcal{L}_{DD^*J/\psi\pi} = & \lambda_3 \nabla^\nu \psi^\mu < \bar{D}^{*\mu} D u_\nu > + \lambda_4 \psi^\mu < \nabla^\nu \bar{D}^{*\mu} D u_\nu > \\ & + \lambda_5 \nabla^\nu \psi^\mu < \bar{D}^{*\nu} D u_\mu > + \lambda_6 \psi^\mu < \nabla^\mu \bar{D}^{*\nu} D u_\nu > + \cdots\end{aligned} \tag{10}$$

$$\mathcal{L}_{D\bar{D}^*h_c\pi} = \lambda_9 \nabla^\alpha H^\nu < \bar{D}^{*\mu} D u^\beta > + \lambda_{10} H^\nu < \nabla^\alpha \bar{D}^{*\mu} D u^\beta > + \cdots \tag{11}$$

- Heavy quark limit $\to$ heavy quark spin symmetry $\to$ D and D^* are degenerate so $\lambda_1 = \lambda_2$

Symmetry

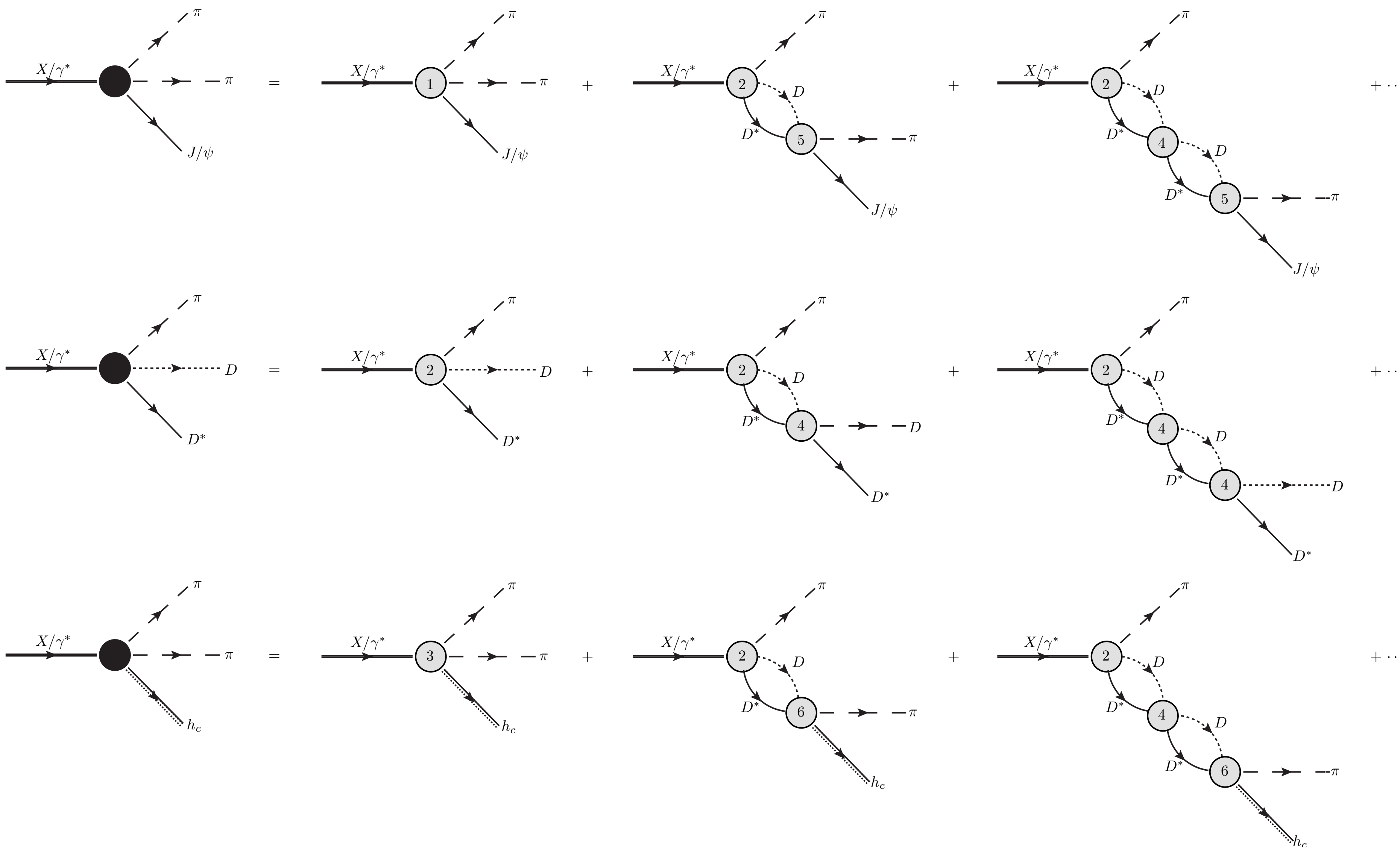
- chiral building block: [JHEP 9902,020(1999)]

operator	P	C	h.c.
u_μ	$-\varepsilon(\mu)u_\mu$	u_μ^T	u_μ
$h_{\mu\nu}$	$-\varepsilon(\mu)\varepsilon(\nu)h_{\mu\nu}$	$h_{\mu\nu}^T$	$h_{\mu\nu}$
$\chi_\pm$	$\pm\chi_\pm$	$\chi_\pm^T$	$\pm\chi_\pm$
$f_\pm^{\mu\nu}$	$\pm\varepsilon(\mu)\varepsilon(\nu)f_\pm^{\mu\nu}$	$\mp f_\pm^{\mu\nu T}$	$f_\pm^{\mu\nu}$

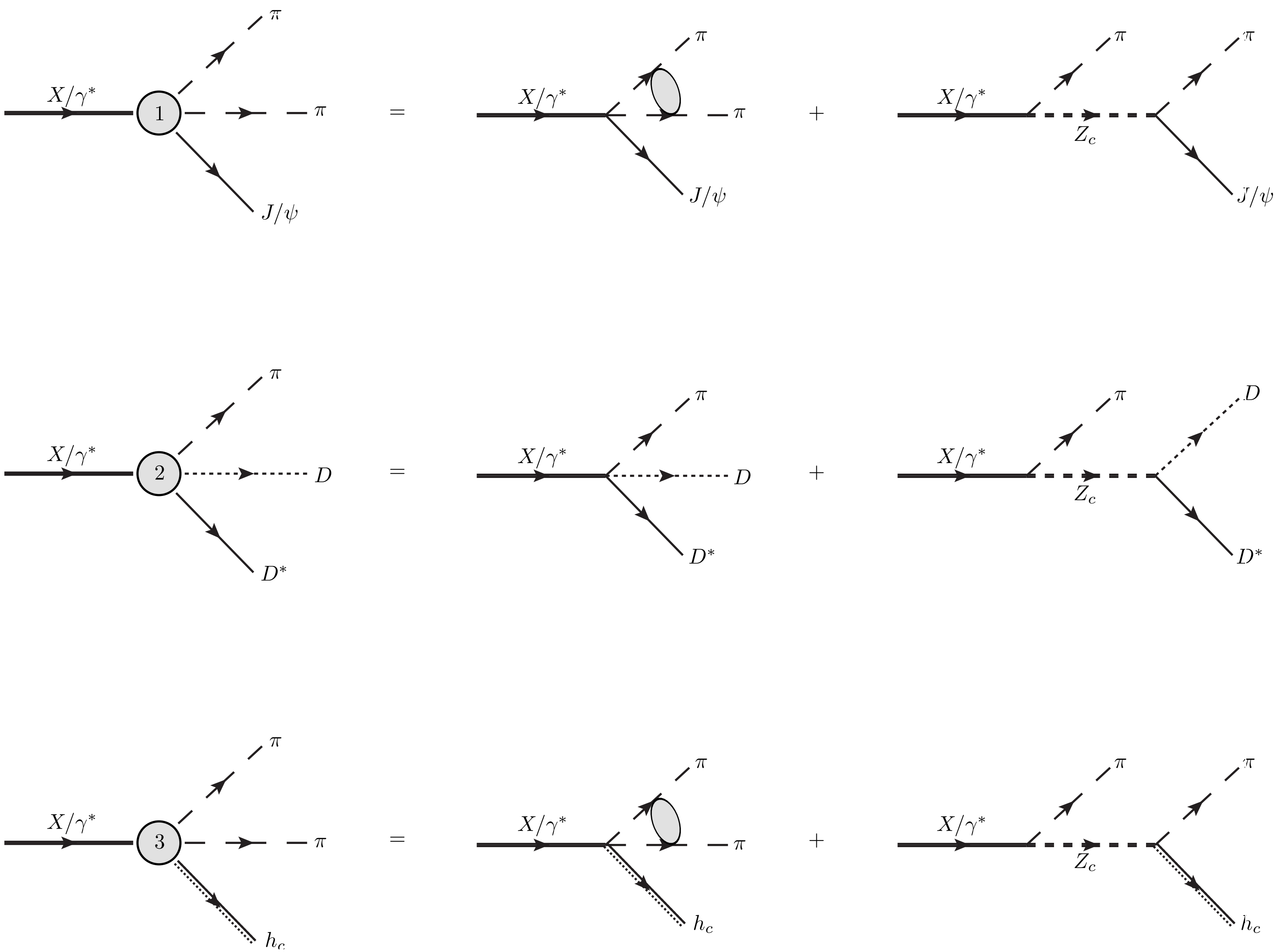
Table 1: P, C and hermiticity properties of operators contained in chiral Lagrangians. Space-time arguments are suppressed and we do not list the derivatives $\chi_{\pm\mu}$, $\nabla_\lambda f_\pm^{\mu\nu}$ separately. $\varepsilon(0) = -\varepsilon(\mu \neq 0) = 1$.

- P, C, isospin and chiral symmetry

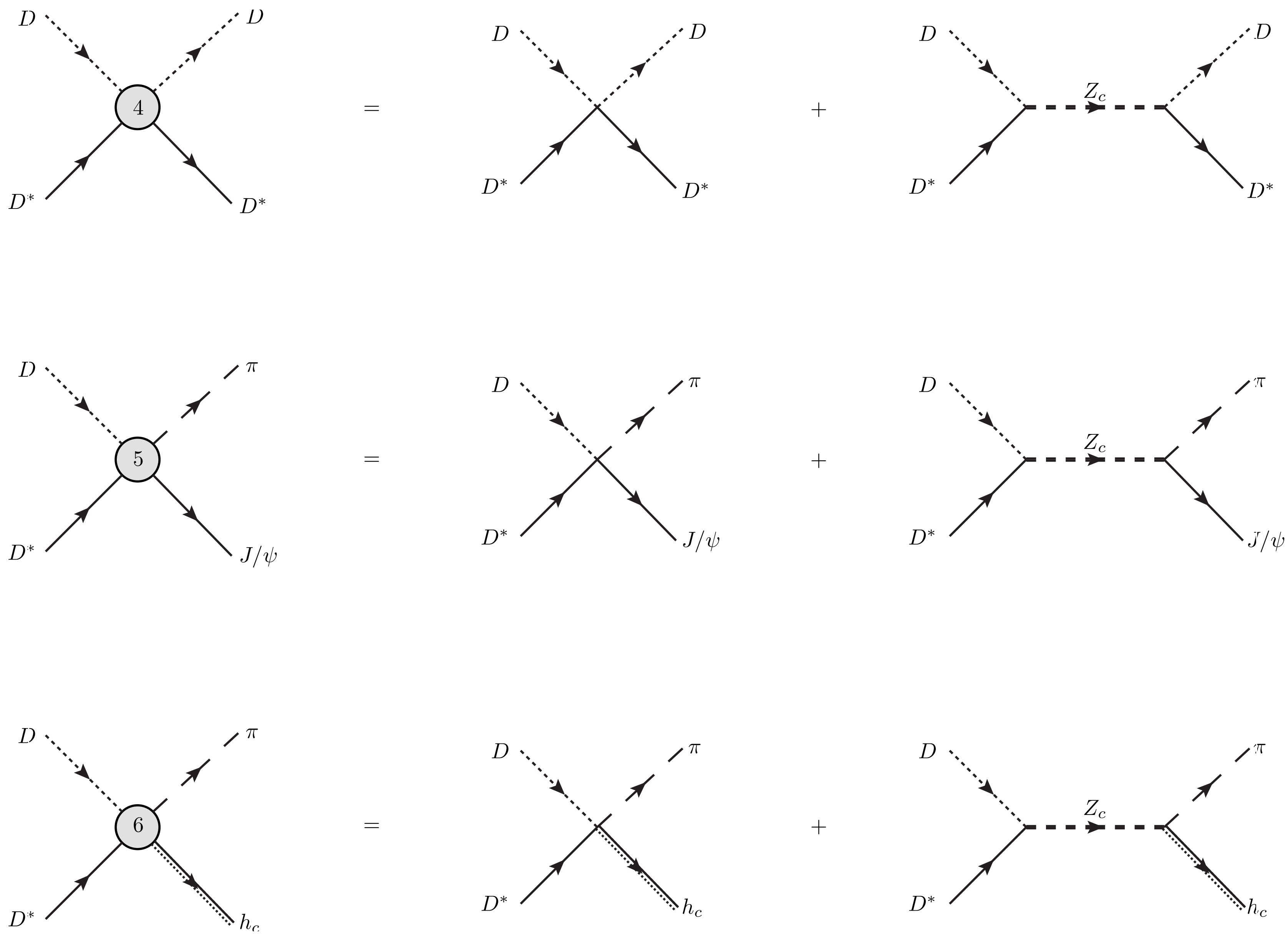
Feynman diagram



Feynman diagram



Feynman diagram



Amplitude

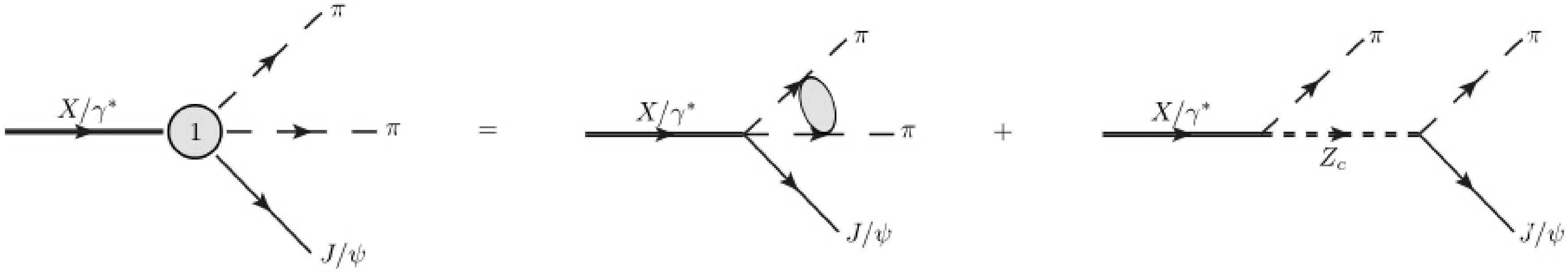
- transverse and longitudinal components repectively
  $1 - i(\lambda_1 + \frac{f_7^2}{p^2 - m_Z^2})\Pi_T$,$1 - i(\lambda_1 - \frac{f_7^2}{m_Z^2})\Pi_L$
  only focus on the pole in the transverse part, because the pole producing in the longitudinal component is very far away the energy region under study

- one-loop integration of D and D^* propagators can be written as:
  $\Pi_{\mu\nu} = \int \frac{\mathrm{d}^\mathrm{D} k}{(2\pi)^D} \frac{g_{\mu\nu} - \frac{k_\mu k_\nu}{m_{D^*}^2}}{(k^2 - m_{D^*}^2)[(p-k)^2 - m_D^2]} = P_{T\mu\nu}\Pi_T + P_{L\mu\nu}\Pi_L$
  $P_{T\mu\nu} = g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}$,$P_{L\mu\nu} = \frac{p_\mu p_\nu}{p^2}$

- p: the momentum of $Z_c(3900)$
  pure bubble chain: $f_7 = 0$
  pure Breit-Wigner: $\lambda_1 = 0$
  including two components: $\lambda_1 \neq 0$, $f_7 \neq 0$

Partial wave analysis

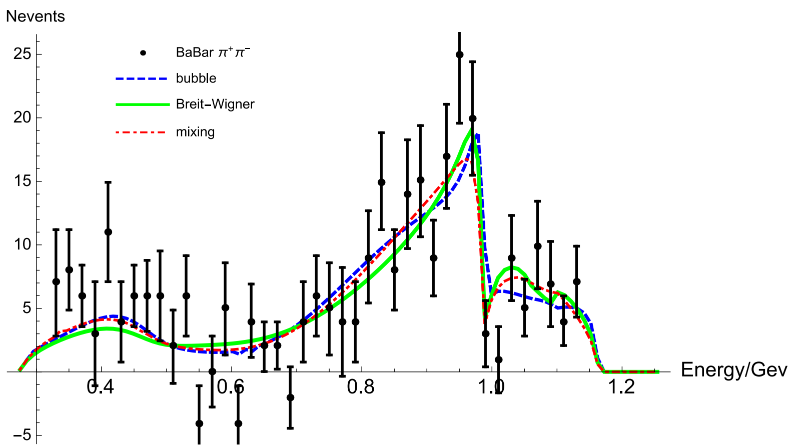
- Extract S-wave part for contact tree vertex

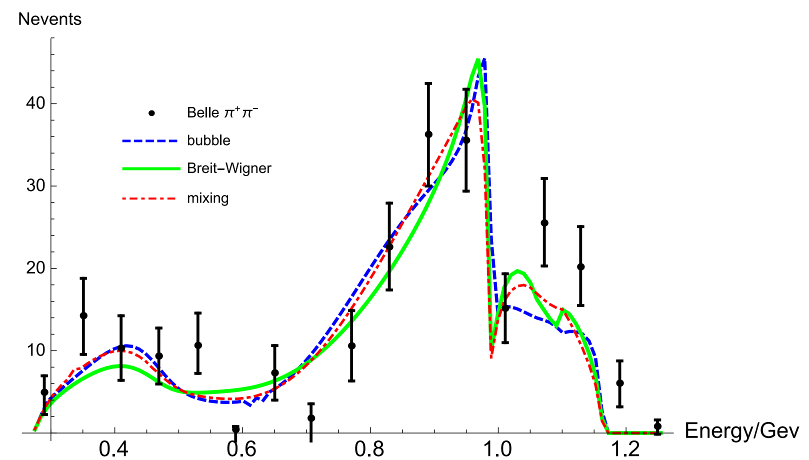


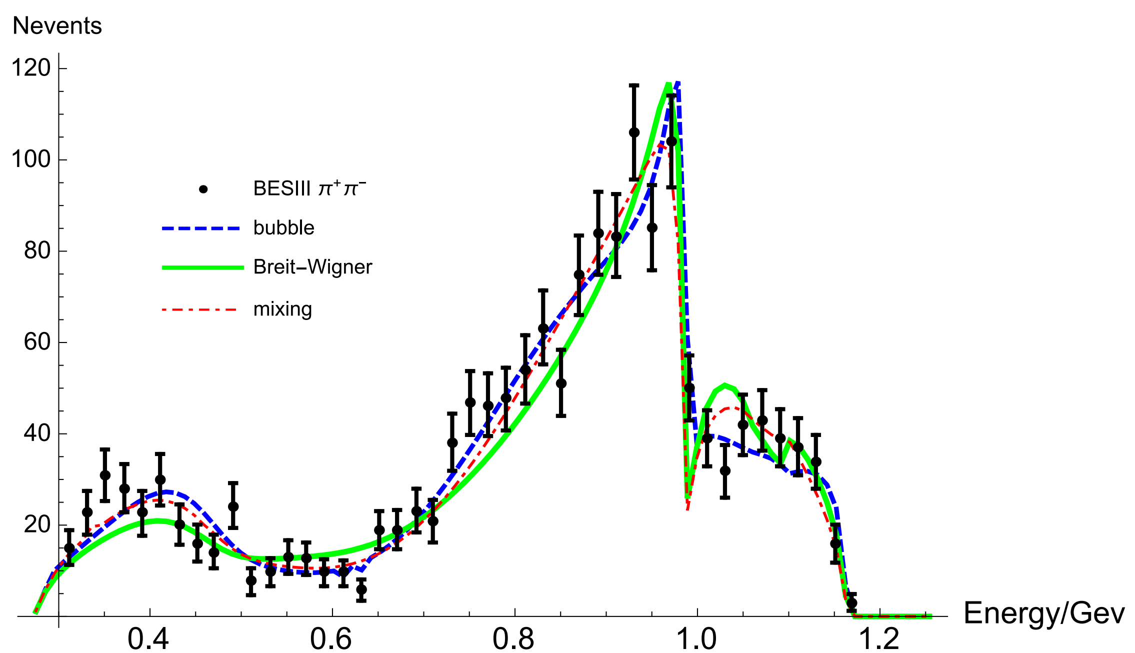
  - $\Gamma_{Z_c} \approx 40$MeV, the final state interaction of two pions in the second picture is very weak.

- For $X(4260) \to J/\psi(h_c)\pi\pi$:
  $M = M^{tree}_{\pi\pi}\alpha_1(s)T_{\pi\pi\to\pi\pi} + M^{tree}_{K\bar{K}}\alpha_2(s)T_{K\bar{K}\to\pi\pi} + M^{'}$
  $\alpha_i = \frac{c_0^i}{s-s_A} + c_1^i + c_2^i s + \cdots$($s_A$ is Adler zero)
  $M^{'}$: amplitude except for contact tree contribution

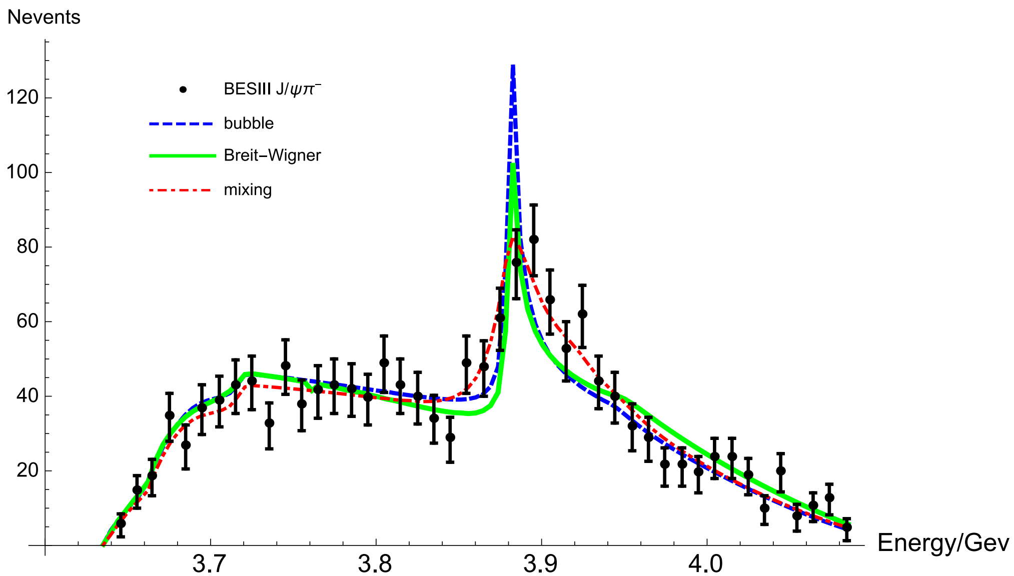
$M(\pi\pi)$ spectrum

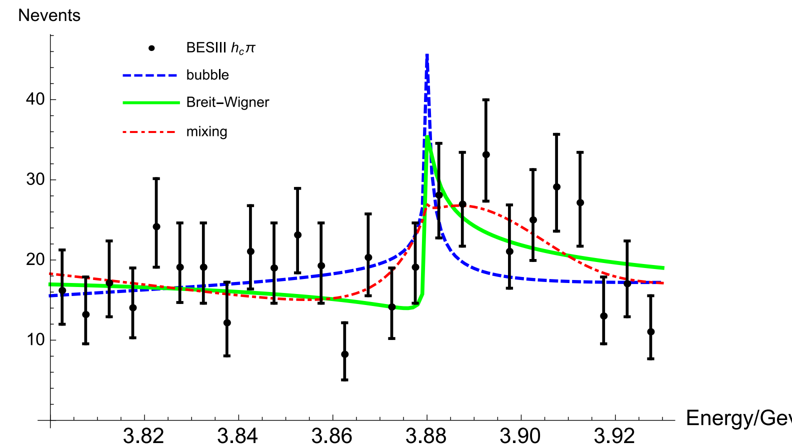


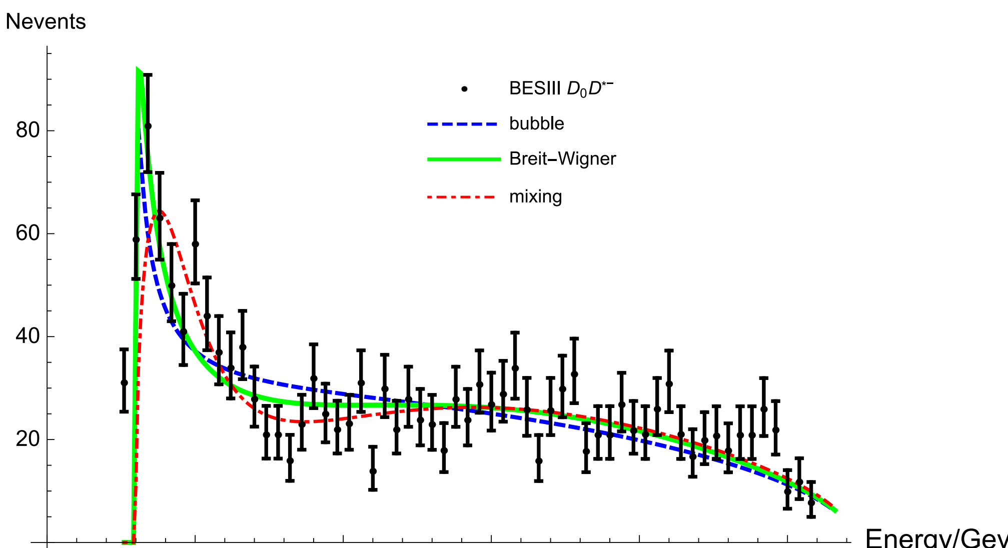


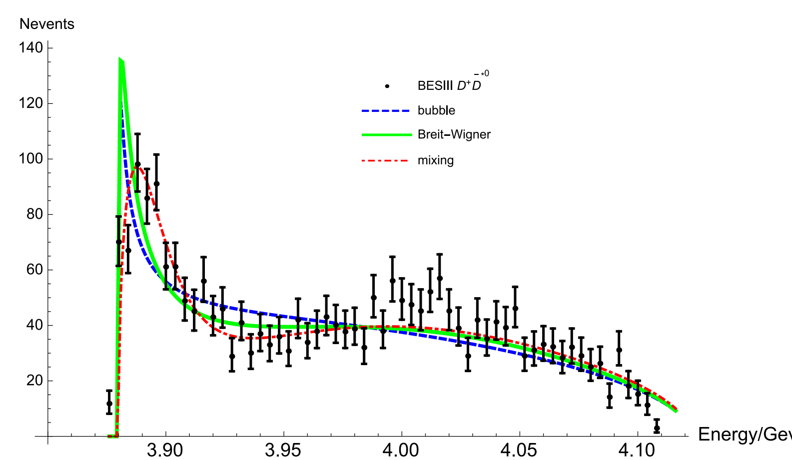


$M(J/\psi\pi)$,$M(h_c\pi)$ and $M(DD^*)$ spectrum









Preliminary numerical results

- Preliminary χ^2/dof

	pure bubble	pure breit-wigner	mixing
$Z_c(3900)$	$497/(332-28)$	$535/(332-25)$	$456/(332-32)$
$X(3872)$	$83.3/(60-12)$		$47.1/(60-17)$

$X(3872)$: arXiv:1411.3106

- $Z_c(3900)$ may be very different from $X(3872)$.

Prospection

- in the pure bubble chain fitting: $1 - i\lambda_1 \Pi_{T/L} + c_0$
  c_0 represents the contributions from $J/\psi\pi$, $h_c\pi$, $\rho\eta_c$, $\cdots$

- find pole in each Riemann Sheet

- calculate some ratios:
  $\Gamma(X(4260) \to Z_c\pi \to J/\psi\pi(h_c\pi/DD^*)\pi) : \Gamma(X(4260) \to J/\psi(h_c\pi/DD^*)\pi\pi)$

- if know the efficiency and luminosity, we can calculate the decay branching ratio of $X(4260)$ and $Z_c(3900)$

Thank you!