XII Quark Confinement & the Hadron Spectrum

X, Y, Z States

Marina Nielsen
Universidade de São Paulo

Lots of X, Y and Z states observed by BaBar, Belle, BESIII, CDF, CLEOIII, CLEO-c, CMS, D0 and LHCb Collaborations

N. Branbilla et al., arXiv:1404.3723

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5)	2005	Ok
					LHCb [1041] (> 10)		
				$B \to K(\gamma \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2)	2008	NC!
					LHCb [1041] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
					T. Xiao *et al.* [CLEO data] [1047] (>5)		
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9),	2009	NC!
					LHCb [1100] (1.4), CMS [1101] (>5)		
					D0 [1102] (3.1)		

$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$??^+$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$??^+$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11)	2005	Ok
					Belle [1046, 1094] (15), BES III [1045] (np)		
				$e^+e^- \to (f_0(980)J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$??^+$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0),	2011	NC!
					CMS [1101] (>3), D0 [1102] (np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4)	2007	Ok
					LHCb [1115] (13.9)		
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok

in 2014: 23 new states, many not confirmed

many candidates for exotic states

up to now: 9 reported charged states which are not quark-antiquark states

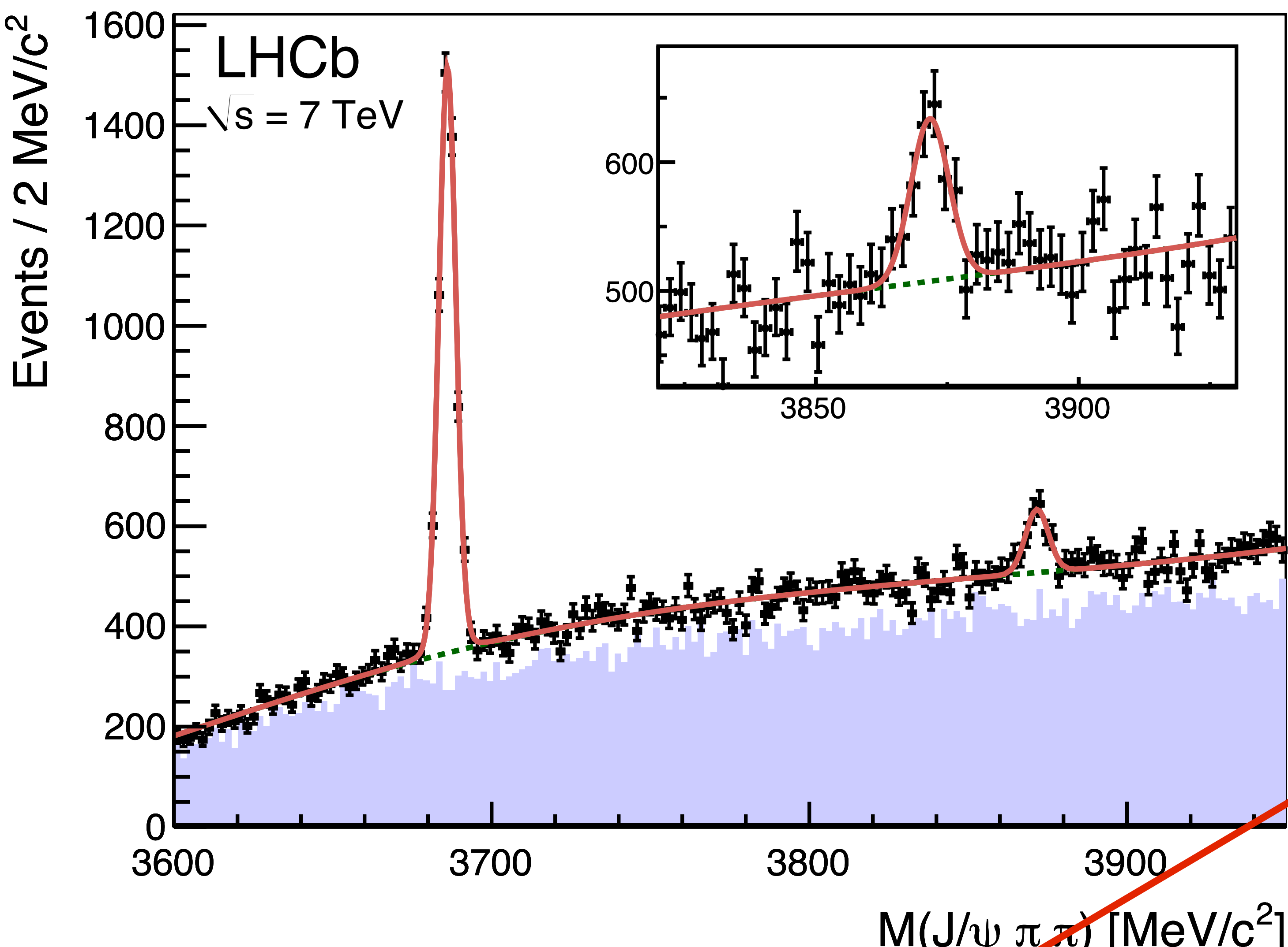
$Z^+(4430)$ 2007	$Z_1^+(4050)$ 2008	$Z_2^+(4250)$ 2008
$Z_c^+(3900)$ 2013	$Z_c^+(4025)$ 2013	$Z_c^+(4020)$ 2013
$Z_c^+(3885)$ 2013	$Z_c^+(4200)$ 2014	$X^+(5568)$ 2016

not a charmonium state

X(3872) @ KEK (PRL91(2003))

very narrow state observed in the decay: $B^{\pm} \rightarrow K^{\pm}(J/\psi\pi^{+}\pi^{-})$

best studied charmonium exotic candidate



M_X = (3872.20 ± 0.39) MeV

Γ < 2.3 MeV

$c\bar{c}$ spec. for $J^{PC} = 1^{++}$ (Barnes & Godfrey, PRD69 (2004))

$2\ ^3P_1\ (3990)$

$3\ ^3P_1\ (4290)$

$$\frac{X \to J/\psi\ \pi^+\pi^-\pi^0}{X \to J/\psi\ \pi^+\pi^-} = 0.8 \pm 0.3$$ ➡ strong isospin and G parity violation

$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

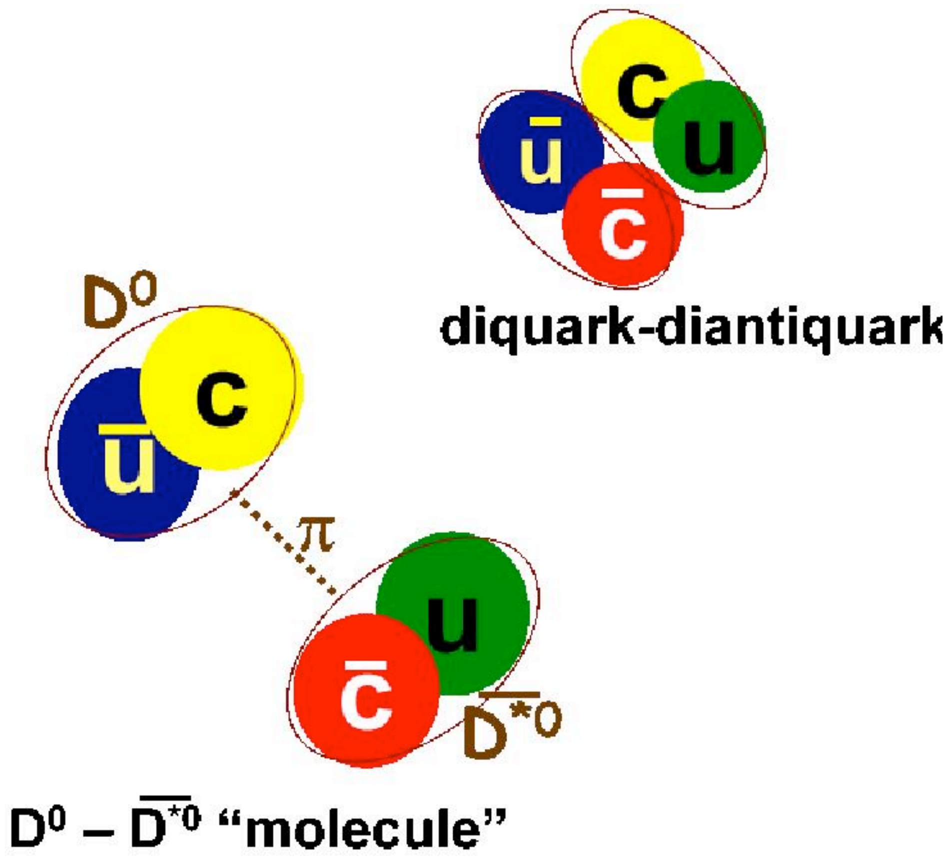
Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ state

$$\frac{X \to J/\psi\ \pi^+\pi^-\pi^0}{X \to J/\psi\ \pi^+\pi^-} = 0.8 \pm 0.3$$ ➡ strong isospin and G parity violation

$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ state



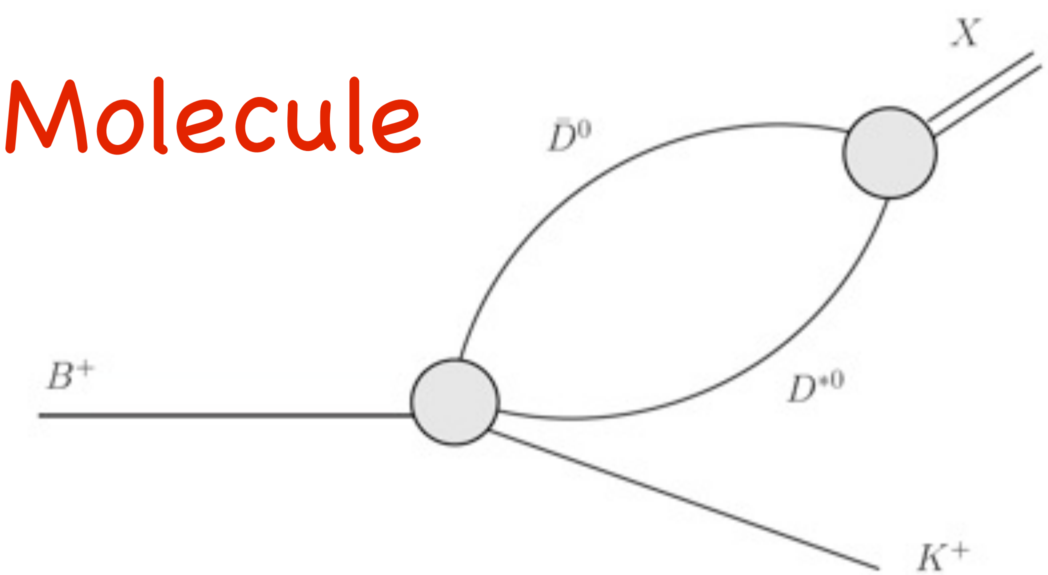
molecular and tetraquark interpretations differ by the way quarks are organized in the state

X(3872) production

B decays at B factories

$$B^{\pm} \to X(3872) K^{\pm}$$

Meson Molecule



Meson coalescence

Small binding energy

Agreement with data !

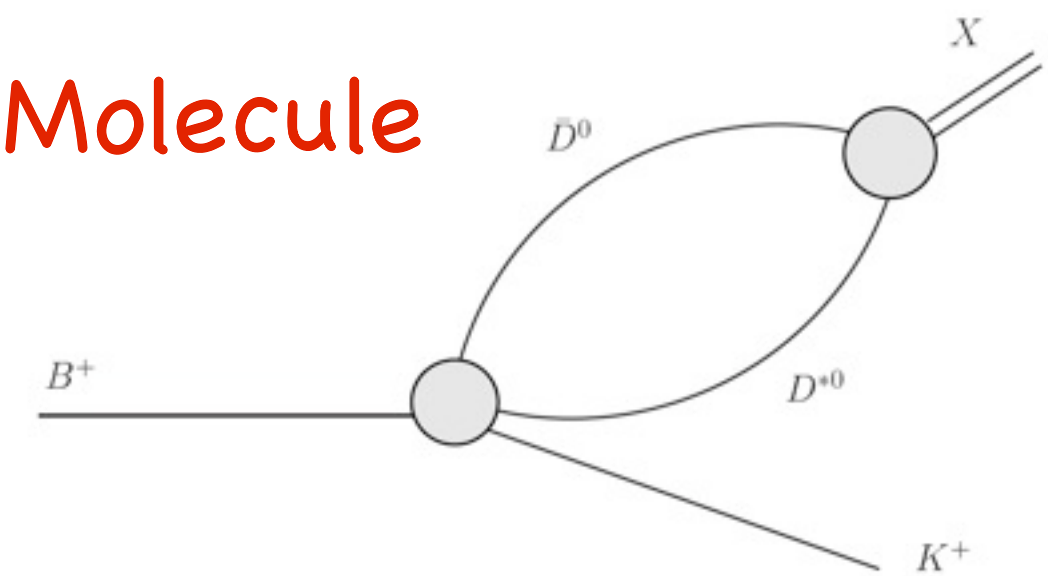
E. Braaten, M. Kusunoki, hep-ph/0404161

X(3872) production

B decays at B factories

$$B^{\pm} \to X(3872)K^{\pm}$$

Meson Molecule



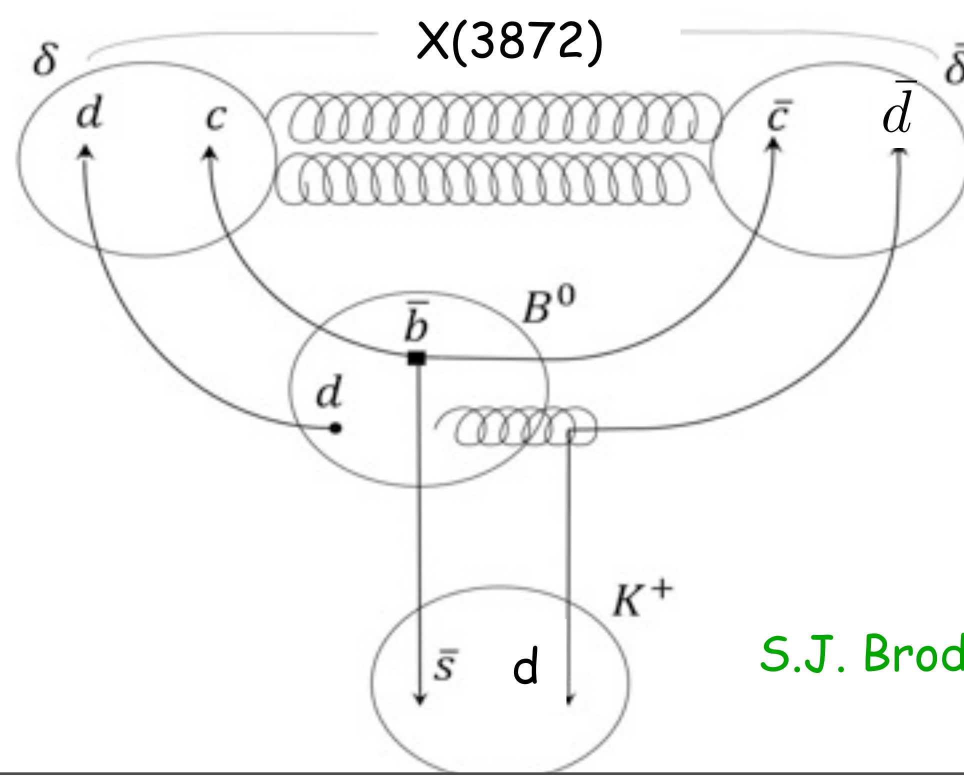
Meson coalescence

Small binding energy

Agreement with data !

E. Braaten, M. Kusunoki, hep-ph/0404161

Tetraquark



Diquark-antidiquark picture

Non-relativistic potential

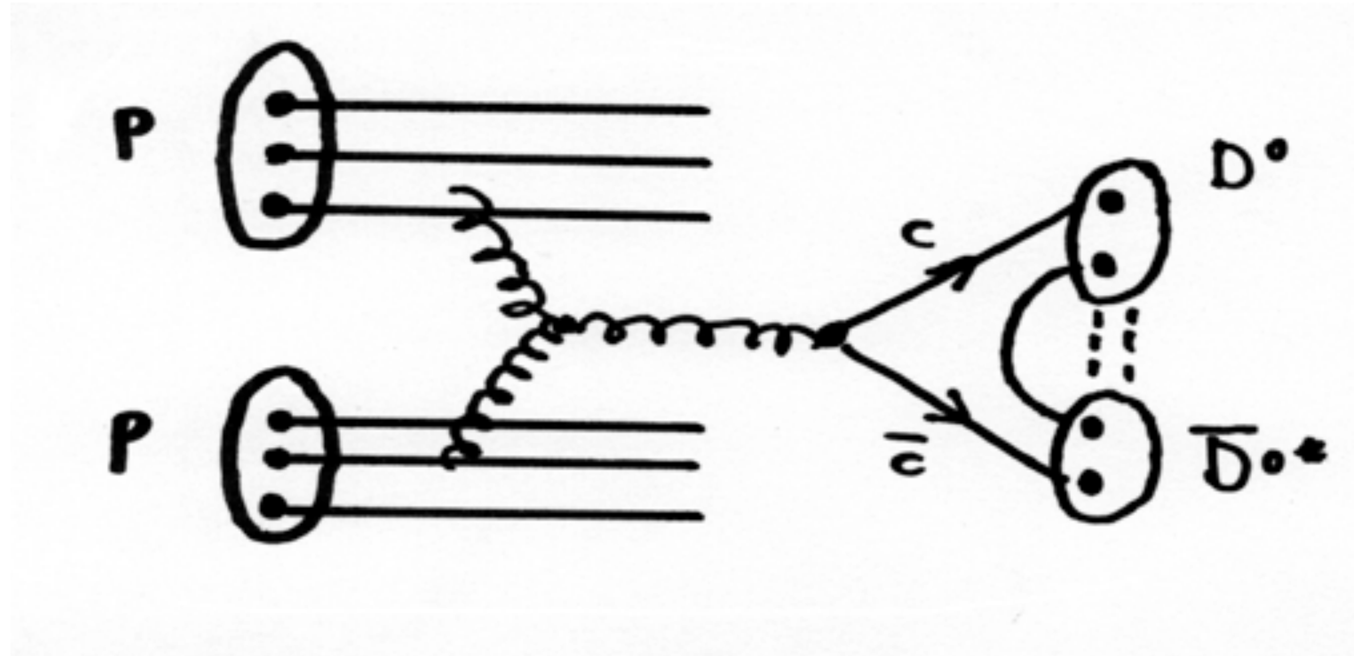
Agreement with data !

S.J. Brodsky, D.S. Hwang, R.F. Lebed, arXiv:1406.7281

Proton - (anti)Proton

$\sigma_{exp} = 30\ nb$ (CMS)

Meson molecule

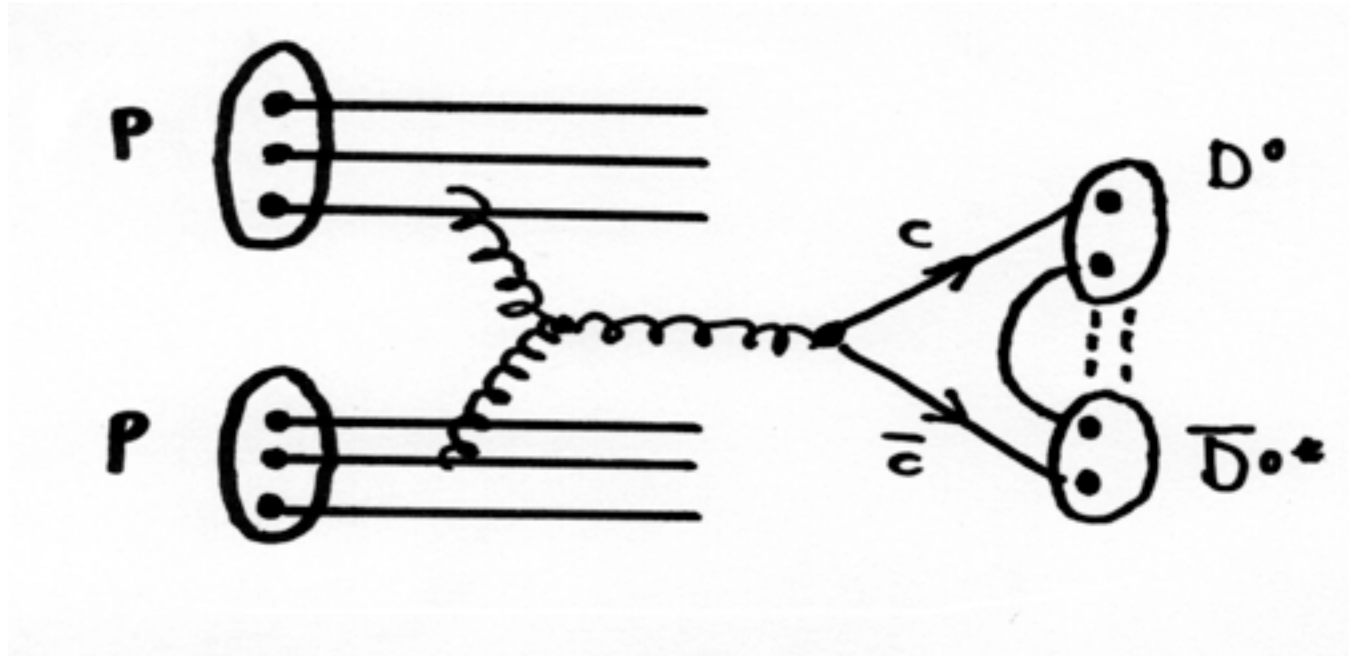


How can a molecule, with small binding energy, be produced in high energy collision with large cross section?

Proton - (anti)Proton

$\sigma_{exp} = 30\ nb$ (CMS)

Meson molecule

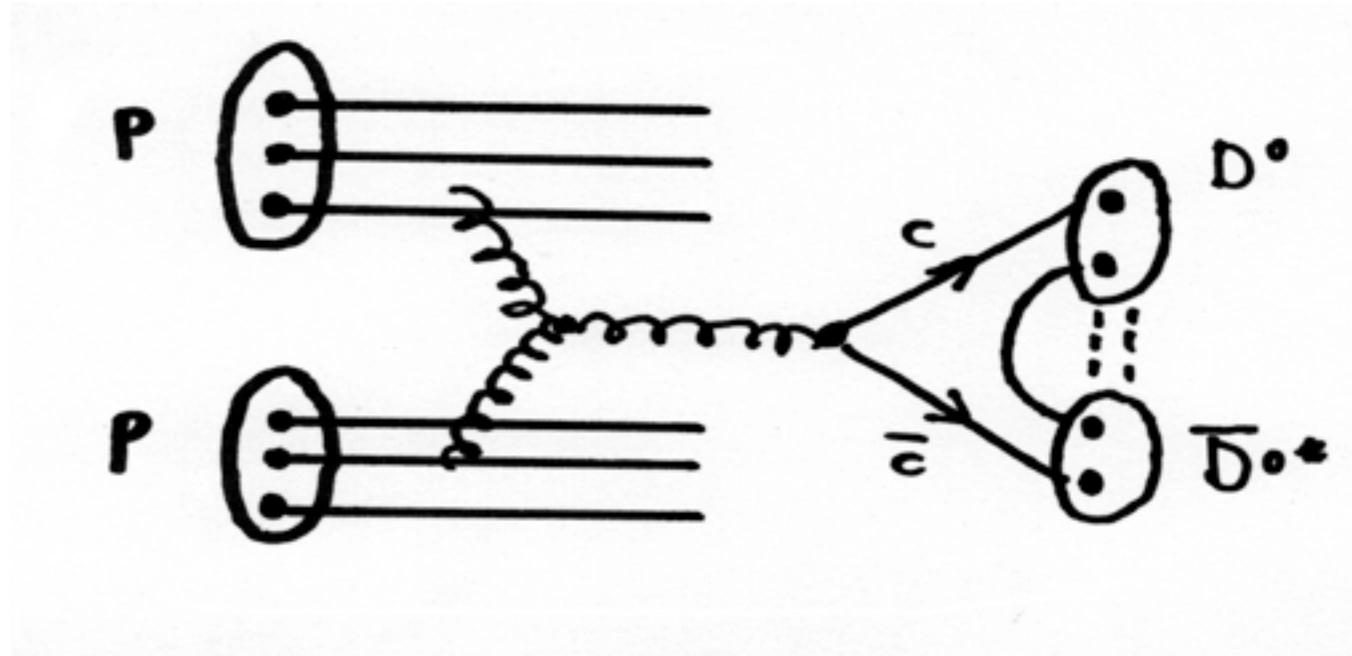


How can a molecule, with small binding energy, be produced in high energy collision with large cross section?

theoretical estimates + MC → production cross section smaller by factor 300! (Bignamini et. al., PRL103(09)162001) Problem for molecular approach

Proton - (anti)Proton $\sigma_{exp} = 30\ nb$ (CMS)

Meson molecule

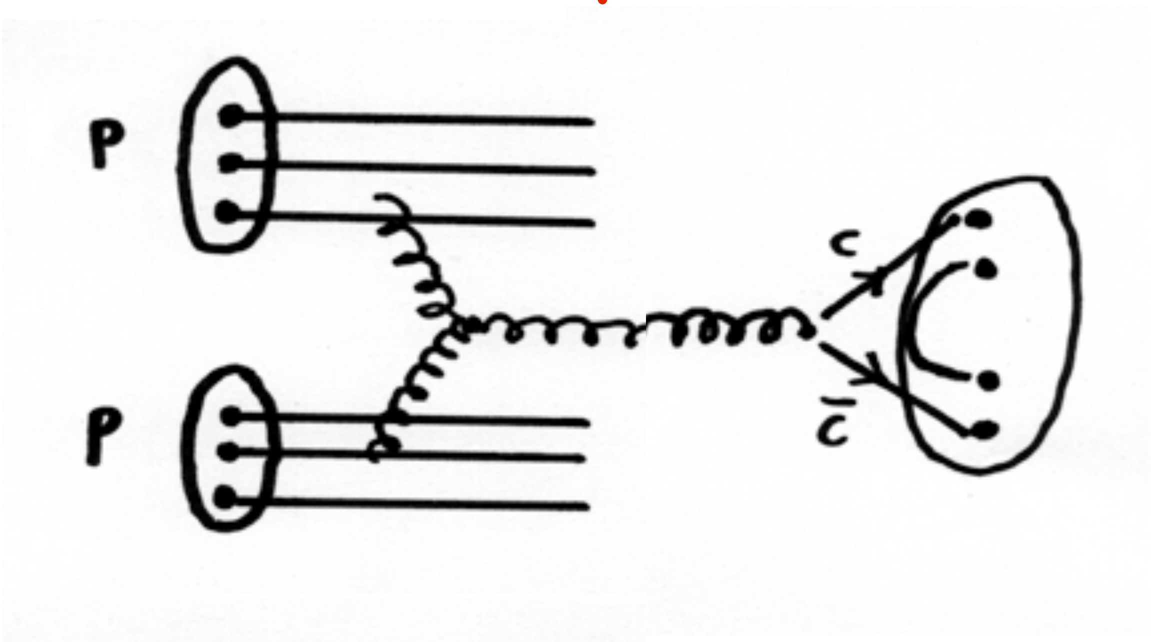


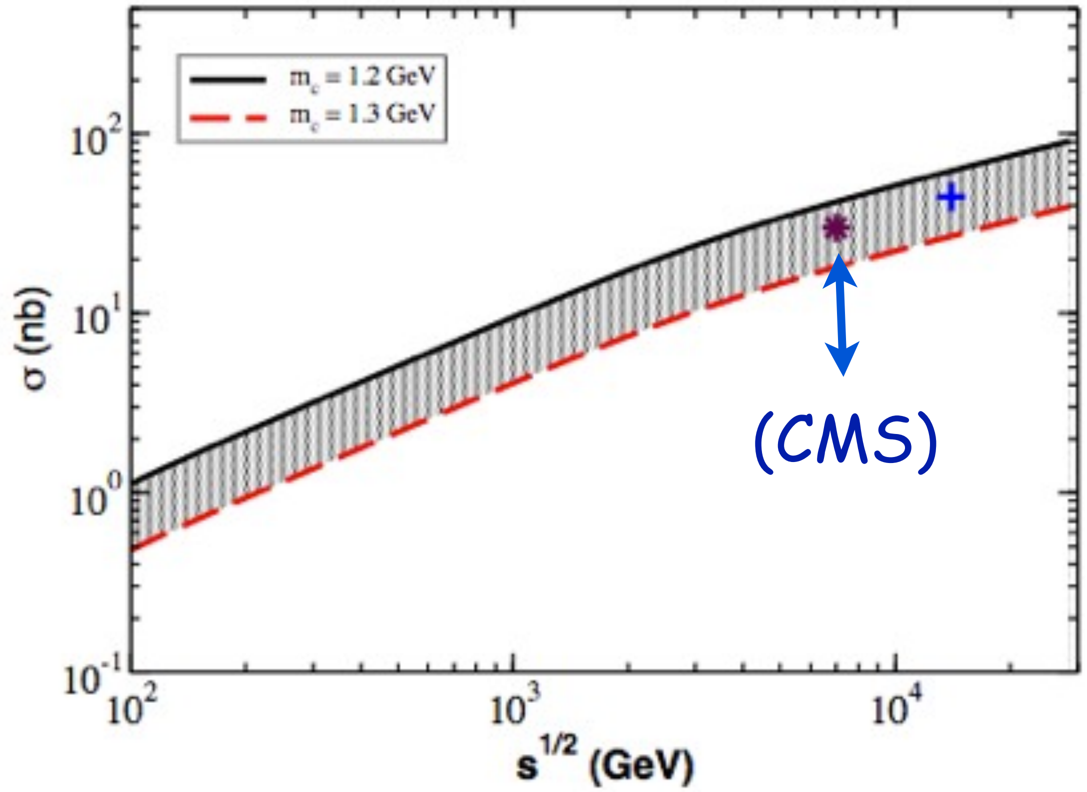
How can a molecule, with small binding energy, be produced in high energy collision with large cross section?

theoretical estimates + MC → production cross section smaller by factor 300! (Bignamini et. al., PRL103(09)162001) Problem for molecular approach

NRQCD plus rescattering in the final state: molecular approach can describe the CDF data ! P. Artoisenet, E. Braaten, arXiv:0911.2016

Tetraquark

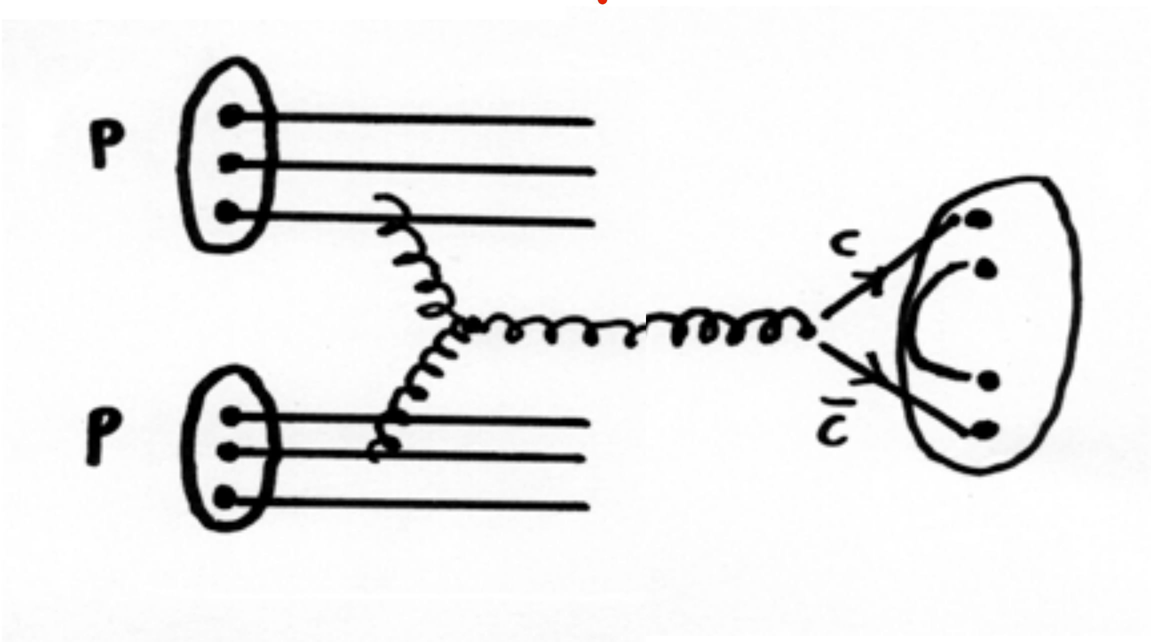


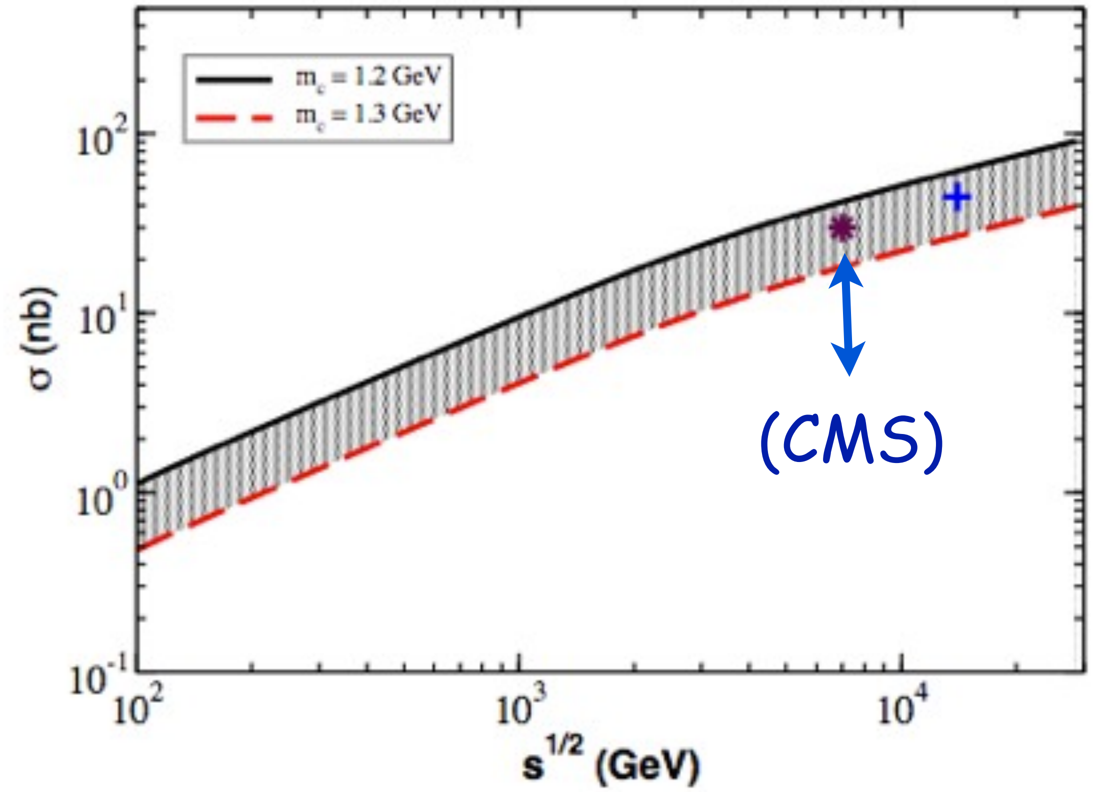


parameters fixed to reproduce CMS data

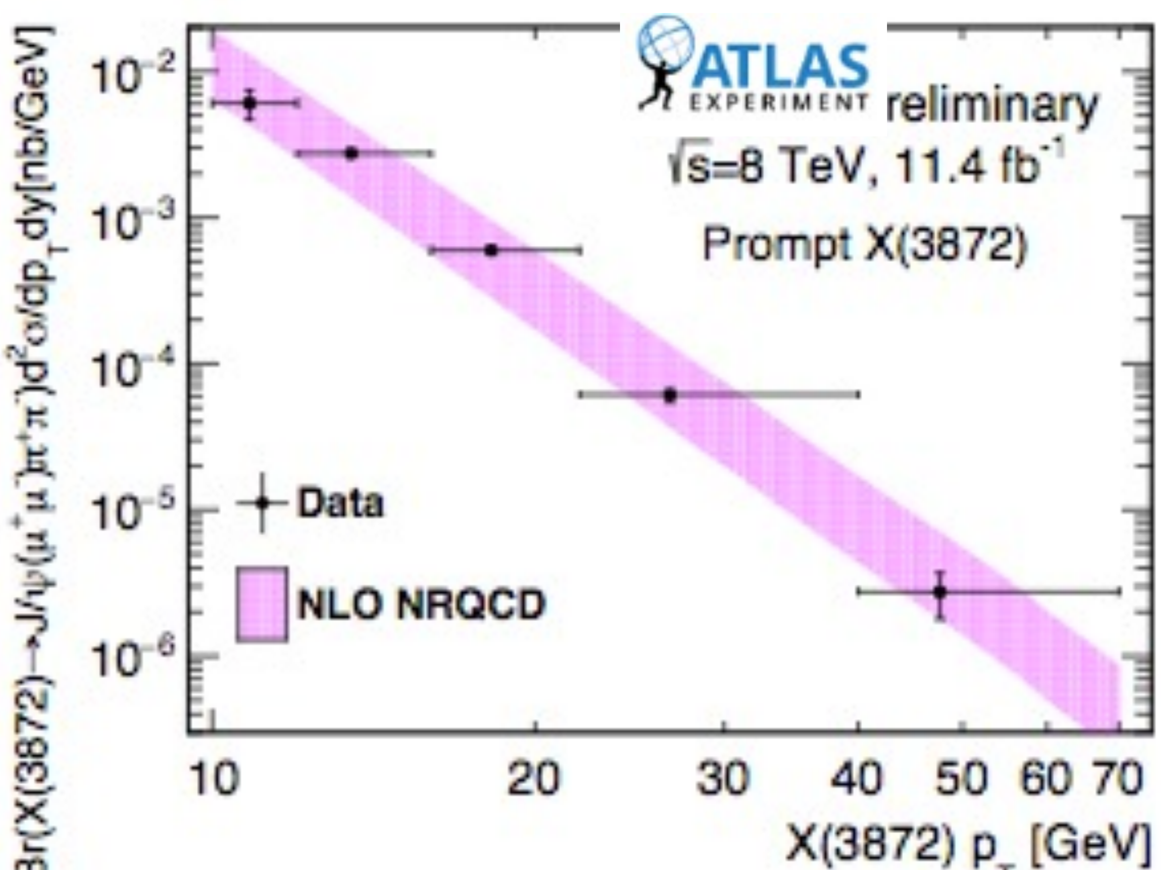
(Carvalho et al., arXiv:1511.05209)

Tetraquark





parameters fixed to reproduce CMS data
(Carvalho et al., arXiv:1511.05209)



The X(3872) is modeled as a mixture of a $\chi_{c1}(2P)$ and a $\bar{D}^0 D^{*0}$ molecular state.

from K. Toms talk ICHEP16

Theoretical calculation from Meng et al., arXiv:1304.6710

QCD Sum Rule

Fundamental Assumption: Principle of Duality

$$\Pi(q) = i \int d^4x \, e^{iq.x} \, \langle 0|T[j(x)j^\dagger(0)]|0\rangle$$

Theoretical side

- quarks and gluons degrees of freedom
- Operator Product Expansion of the correlator

Phenomenological side

- hadronic degrees of freedom
- Spectral representation for the correlator

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2)$$

valid at small Q^2

valid at large Q^2

Borel transform

s_0: continuum parameter

$$\lambda^2 e^{-m^2/M^2} = \int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ \rho^{OPE}(s)$$

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2)$$

valid at small Q^2

valid at large Q^2

Borel transform

s_0: continuum parameter

$$\lambda^2 e^{-m^2/M^2} = \int_{s_{min}}^{s_0} ds \; e^{-s/M^2} \; \rho^{OPE}(s)$$

Good Sum Rule ➡ Borel window such that:

- pole contribution > continuum contribution
- good OPE convergence
- good Borel stability

QCD sum rules calculation for $\boldsymbol{X(3872)}$

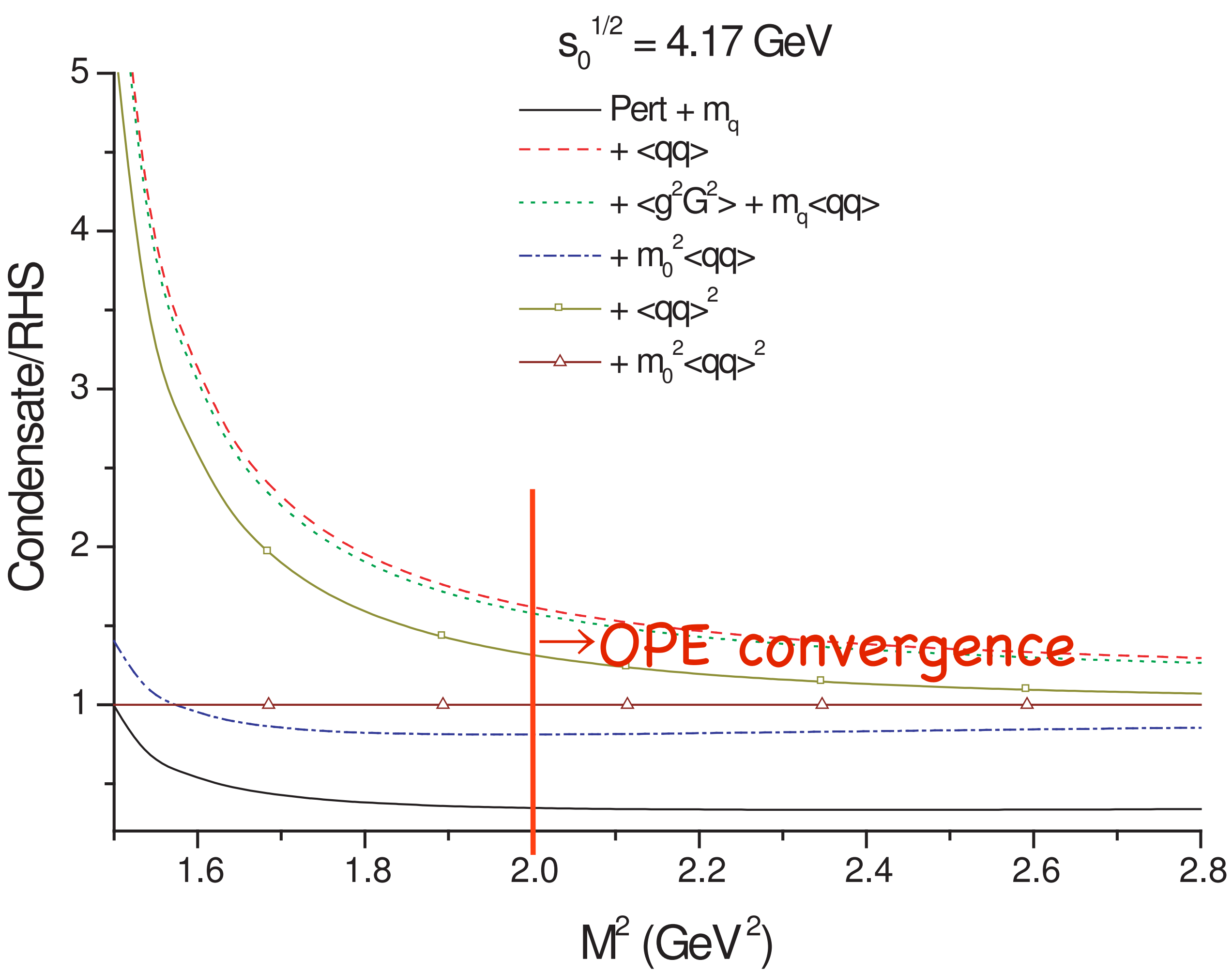
Matheus, Narison, MN, Richard: PRD75 (07)

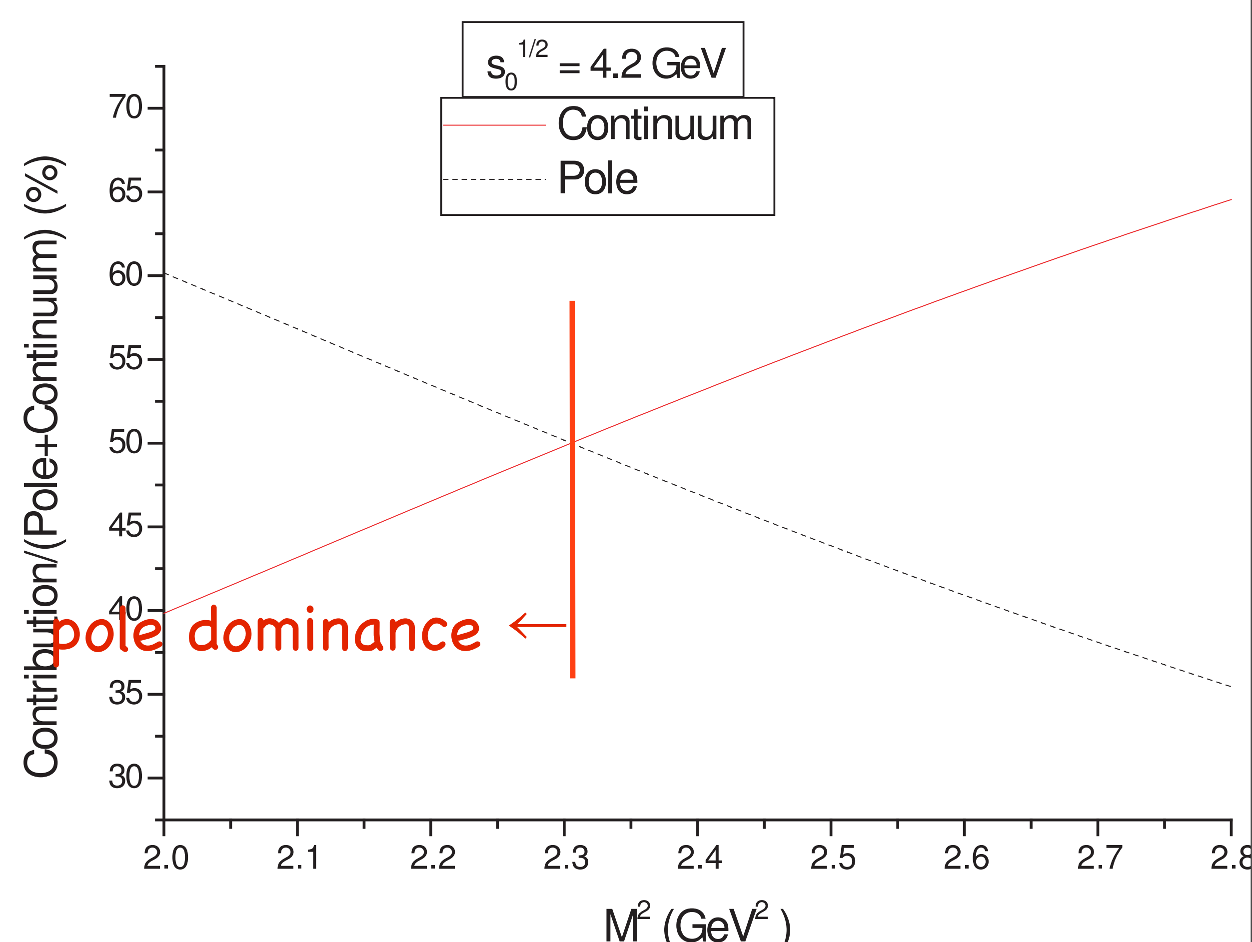
$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$

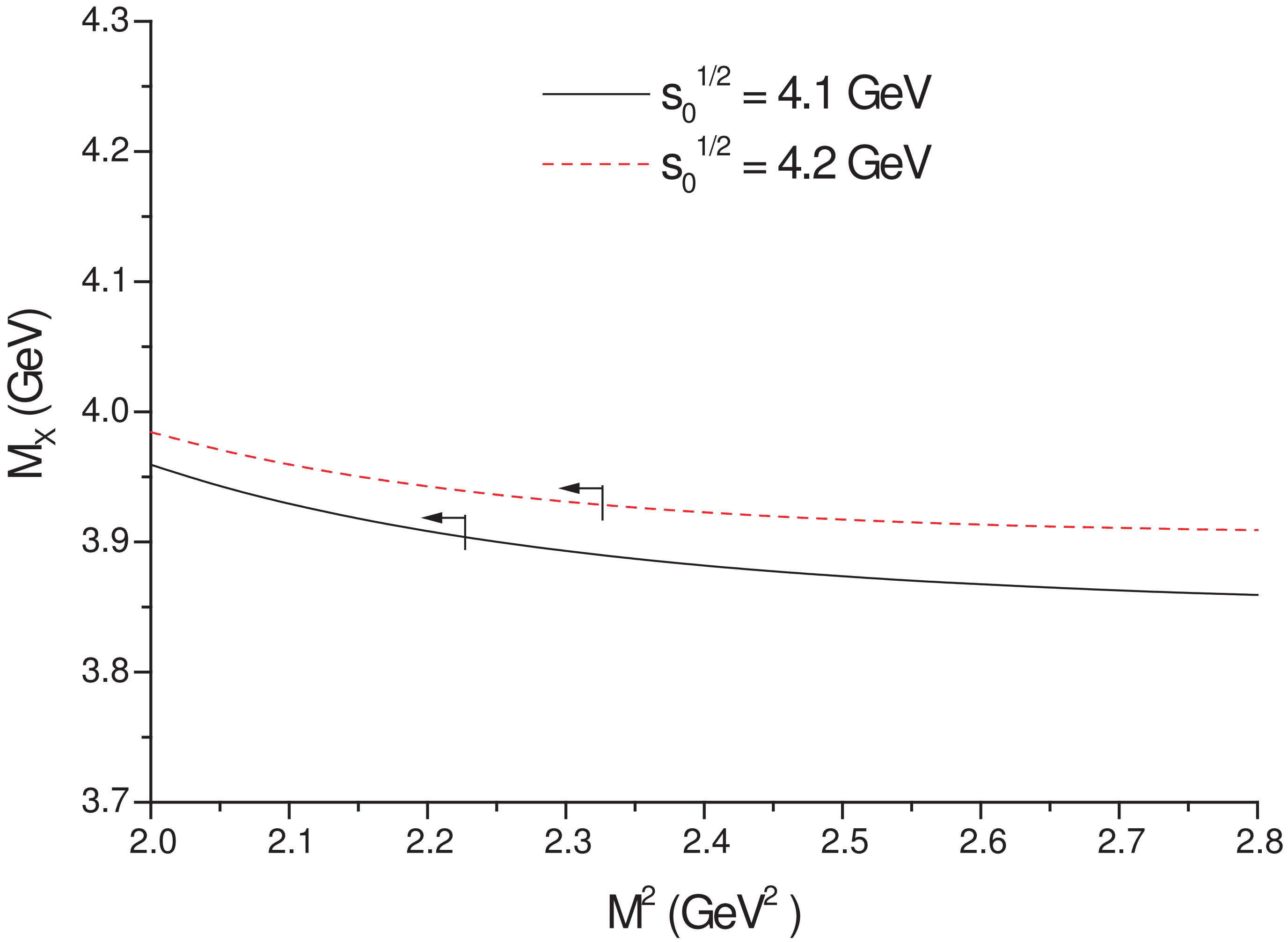
QCD sum rules calculation for $X(3872)$

Matheus, Narison, MN, Richard: PRD75 (07)

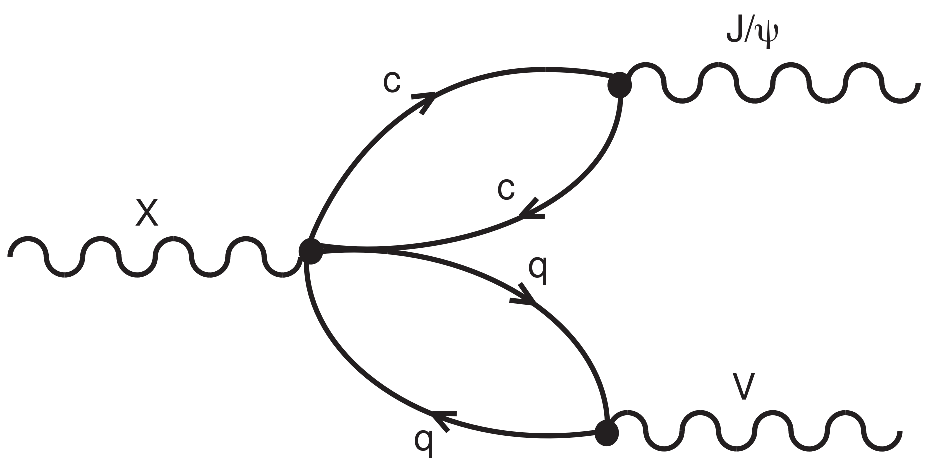
$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$







$$m_X = (3.92 \pm 0.13)\ \text{GeV}$$



Problem: decay width $X \to J/\psi\pi\pi$
~ 50 MeV (Navarra, MN, PLB639 (06)272)

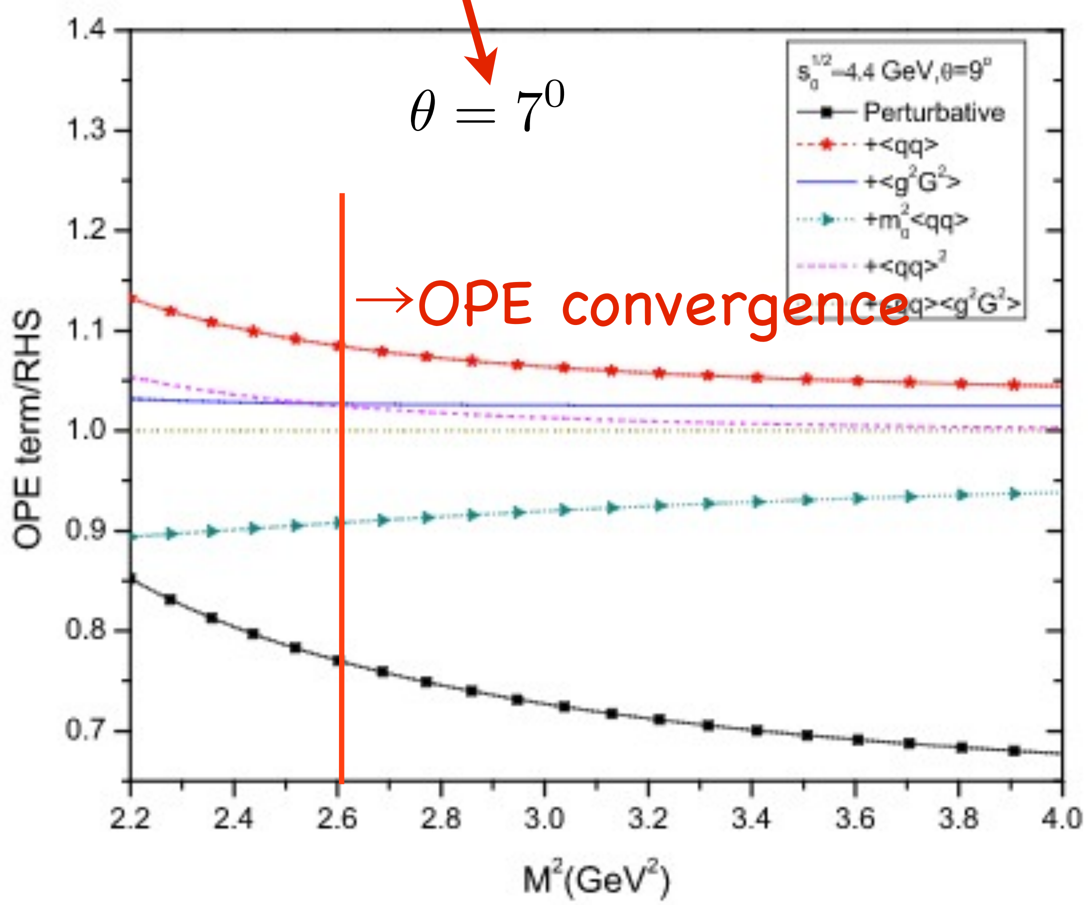
How to solve this problem?

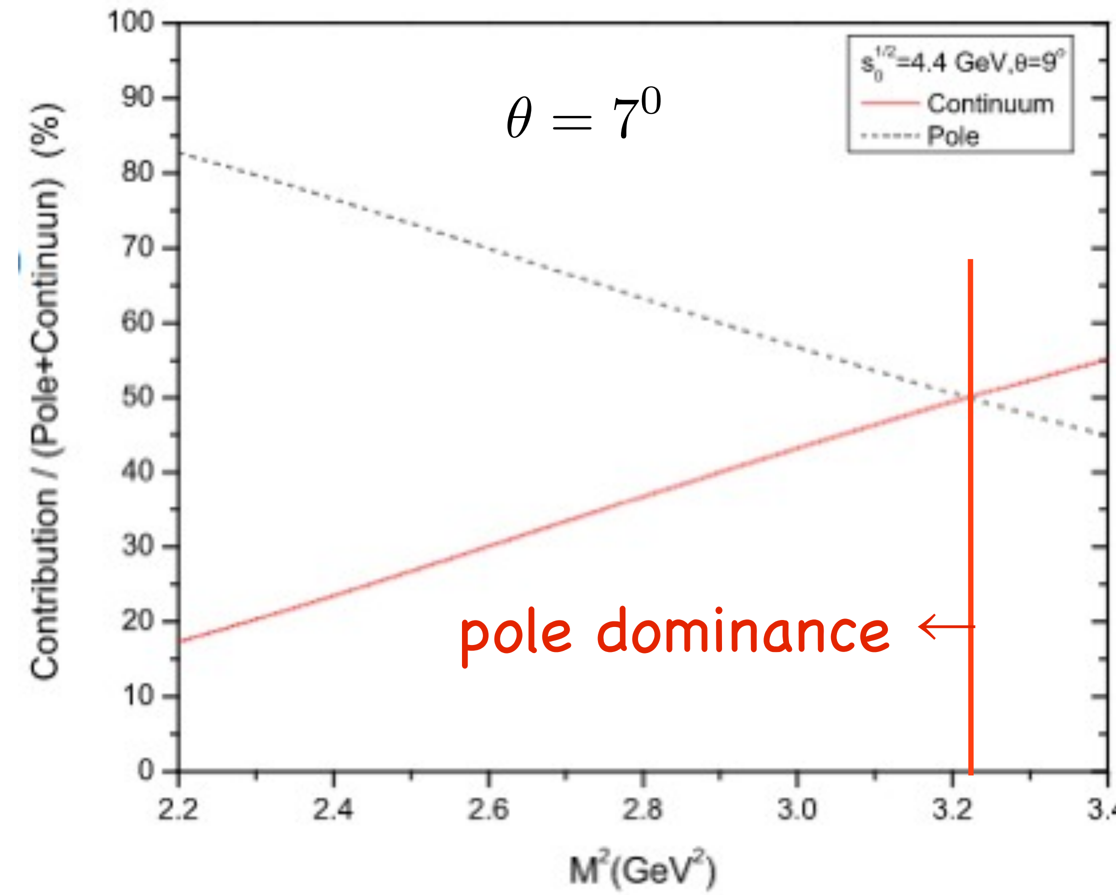
X(3872) as a mixed charmonium 4-quark state

Matheus, Navarra, MN, Zanetti: PRD80 (09)

$$J_\mu^u(x) = \sin(\theta) j_\mu^{(4u)}(x) + \cos(\theta) j_\mu^{(2u)}(x)$$

$$j_\mu^{(2u)} = \frac{1}{6\sqrt{2}} \langle \bar{u}u \rangle \, \bar{c}_a(x)\gamma_\mu\gamma_5 c_a(x)$$





$m_X = (3.77 \pm 0.18)$ GeV

$5^0 \leq \theta \leq 13^0$

Compatible with the experimental X(3872) mass

Decay width $X \rightarrow J/\psi V$

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_\nu^V(y) j_\alpha^{X\dagger}(0)]|0\rangle$$

$$j_\mu^\psi = \bar{c}_a \gamma_\mu c_a$$

$$j_\nu^V = \frac{N_V}{2}(\bar{u}_a \gamma_\nu u_a + (-1)^{I_V} \bar{d}_a \gamma_\nu d_a)$$

$N_\rho = 1, \; I_\rho = 1$

$N_\omega = 1/3$ and $I_\omega = 0$

Decay width $X \to J/\psi V$

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y}\Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_\nu^V(y) j_\alpha^{X\dagger}(0)]|0\rangle \qquad j_\mu^\psi = \bar{c}_a\gamma_\mu c_a$$

$$j_\nu^V = \frac{N_V}{2}(\bar{u}_a\gamma_\nu u_a + (-1)^{I_V}\bar{d}_a\gamma_\nu d_a)$$

$$N_\rho = 1,\; I_\rho = 1$$

$$N_\omega = 1/3 \text{ and } I_\omega = 0$$

Γ = (9.3 ±6.9) MeV, $5^0 \leq \theta \leq 13^0$

Decay width $X \to J/\psi V$

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_\nu^V(y) j_\alpha^{X\dagger}(0)]|0\rangle \qquad j_\mu^\psi = \bar{c}_a \gamma_\mu c_a$$

$$j_\nu^V = \frac{N_V}{2}(\bar{u}_a\gamma_\nu u_a + (-1)^{I_V} \bar{d}_a \gamma_\nu d_a)$$

$N_\rho = 1,\ I_\rho = 1$

$N_\omega = 1/3$ and $I_\omega = 0$

$\Gamma = (9.3 \pm 6.9)$ MeV, $5^0 \leq \theta \leq 13^0$

Decay width $X \to J/\psi\ \gamma$

MN, Zanetti: PRD82 (10)

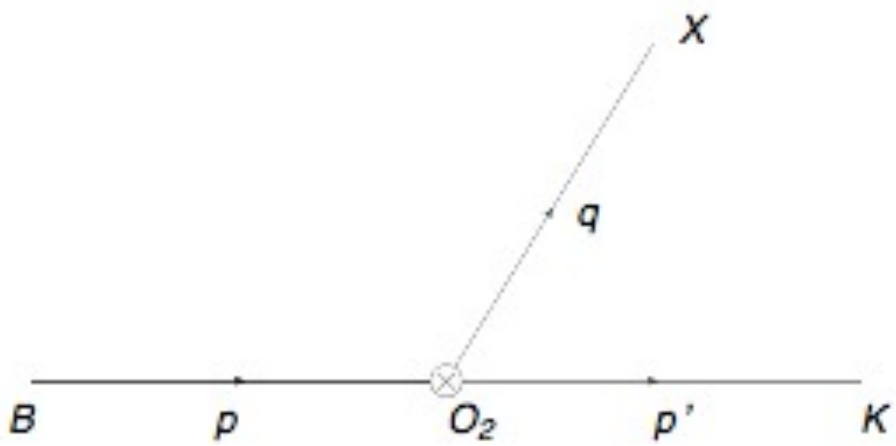
Belle II

$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} = 0.14 \pm 0.05 \qquad \frac{\Gamma(X \to J/\psi\ \gamma)}{\Gamma(X \to J/\psi\ \pi^+\pi^-)} = 0.19 \pm 0.13$$

Production rate $B^+ \to X(3872)K^+$

$$5^0 \le \theta \le 13^0$$

Matheus, MN, Zanetti: PLB702 (11)



$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left[\left(C_2(\mu) + \frac{C_1(\mu)}{3} \right) \mathcal{O}_2 + \cdots \right]$$

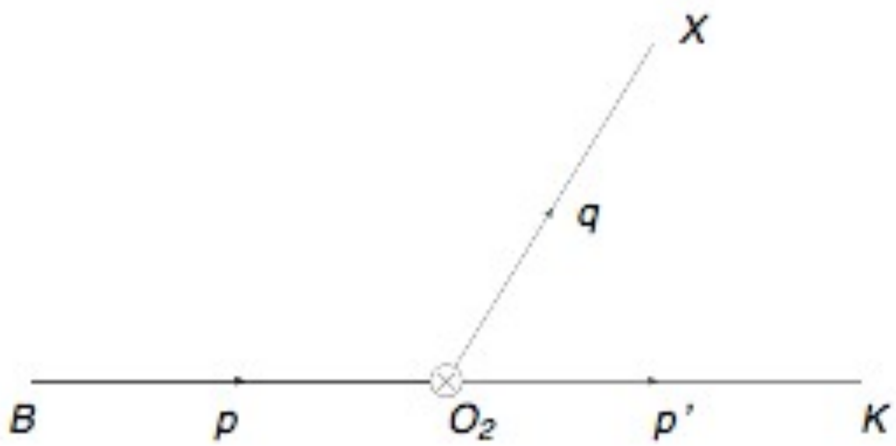
$$\mathcal{O}_2 = (\bar{c}\Gamma_\mu c)(\bar{s}\Gamma^\mu b), \text{ with } \Gamma_\mu = \gamma_\mu(1-\gamma_5)$$

$$\mathcal{B}(B \to X(3872)K) = (1.00 \pm 0.68) \times 10^{-5}$$

$$\mathcal{B}(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$$

Production rate $B^+ \to X(3872)K^+$ $5^0 \leq \theta \leq 13^0$

Matheus, MN, Zanetti: PLB702 (11)



$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left[\left(C_2(\mu) + \frac{C_1(\mu)}{3} \right) \mathcal{O}_2 + \cdots \right]$$

$$\mathcal{O}_2 = (\bar{c}\Gamma_\mu c)(\bar{s}\Gamma^\mu b), \text{ with } \Gamma_\mu = \gamma_\mu(1-\gamma_5)$$

$$\mathcal{B}(B \to X(3872)K) = (1.00 \pm 0.68) \times 10^{-5}$$

$$\mathcal{B}(B^\pm \to K^\pm X(3872)) < 3.2 \times 10^{-4}$$

Conclusions for $X(3872)$

- X(3872) is probably a mixed multiquark state with a χ_{c1} state

$Z^+(4430)$

first observed charged charmonium state ➡ not $c\bar{c}$

PRL100(08)142001

$$\bar{B}^0 \to K^{\mp} Z^{\pm}(4430), Z^{\pm}(4430) \to \psi' \pi^{\pm}$$

$Z^+(4430)$

first observed charged charmonium state ➡ not $c\bar{c}$

PRL100(08)142001

$$\bar{B}^0 \to K^{\mp} Z^{\pm}(4430),\, Z^{\pm}(4430) \to \psi' \pi^{\pm}$$

arXiv:0905.2869

searched $Z^-(4430)$ in 4 decay modes:

no conclusive evidence for the existence of $Z^+(4430)$ seen by Belle

$Z^+(4430)$

first observed charged charmonium state ➡ not $c\bar{c}$

PRL100(08)142001

$$\bar{B}^0 \to K^{\mp} Z^{\pm}(4430), Z^{\pm}(4430) \to \psi' \pi^{\pm}$$

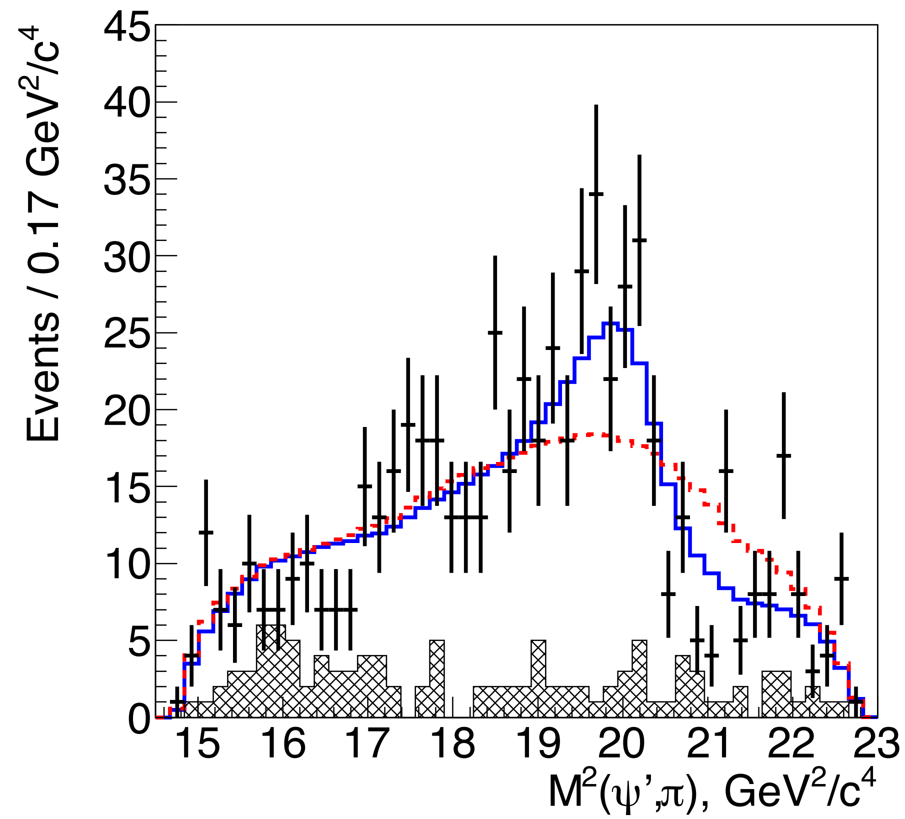
searched $Z^-(4430)$ in 4 decay modes:

arXiv:0905.2869

no conclusive
evidence for the existence of $Z^+(4430)$ seen by Belle

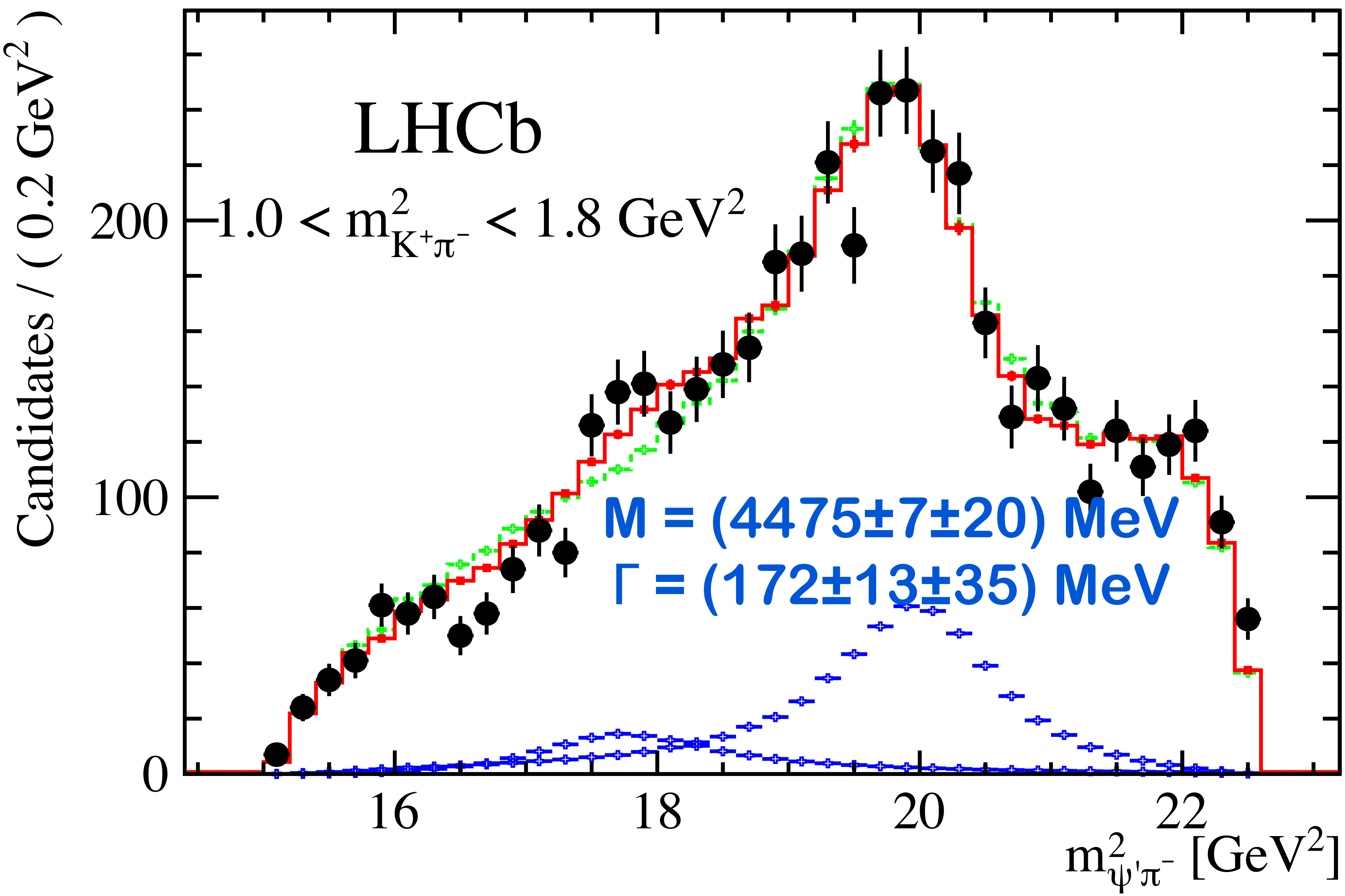
arXiv:1306.4894

confirm the observation of $Z^+(4430)$ with $6.1\,\sigma$ and $J^P=1^+$

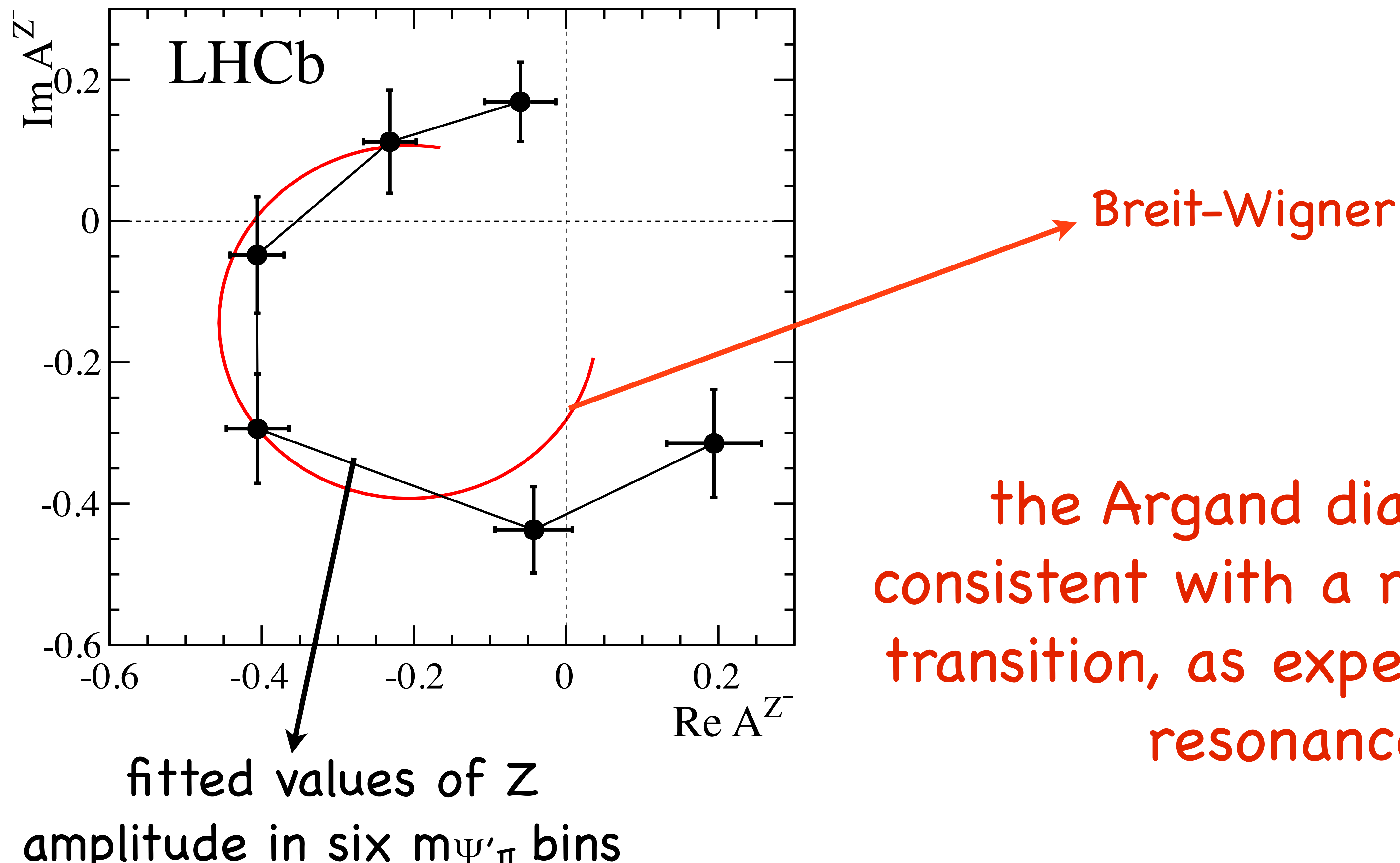


arXiv:1404.1903

has confirmed the observation of $Z^+(4430)$ with 13.9 σ and $J^+ = 1^+$



LHCB also did the first attempt to demonstrate the resonant behavior of $Z^+(4430)$ (arXiv:1404.1903): the Breit-Wigner amplitude was replaced by a combination of independent complex amplitudes at six equally spaced points in $m_{\psi'\pi}$ range covering the $Z^+(4430)$ peak region



the Argand diagram is consistent with a rapid phase transition, as expected for a resonance

$Z^+(4430)$

threshold effect in the $D_1 D^*$ channel
Rosner, arXiv:0708.3496

four-quark radial excitation with $J^{PC} = 1^{+-}$
Maiani, Polosa & Riquer, arXiv:0708.3997

radial excitation of $\Lambda_c - \Sigma_c^0$ bound state
Qiao, arXiv:0709.4066

$D_1 D^*$ molecular state with $J^P = 0^-, 1^-, 2^-$
Meng & Cheng, arXiv:0708.4222

cusp in the $D_1 D^*$ channel
Bugg, arXiv:0709.1254

$D_1 D^*$ molecular state with $J^P = 1^+$
He, arXiv:1410.8645

$D_1 D^*$ or $D_2 D^*$ molecular state with $J^P = 1^+$
Ma, Liu, Liu, Zhu, arXiv:1404.3450; Barnes, Close, Swanson, arXiv:1409.6651

$Z^+(4430)$

threshold effect in the $D_1 D^*$ channel
Rosner, arXiv:0708.3496

four-quark radial excitation with $J^{PC} = 1^{+-}$
Maiani, Polosa & Riquer, arXiv:0708.3997

radial excitation of $\Lambda_c - \Sigma_c^0$ bound state
Qiao, arXiv:0709.4066

$D_1 D^*$ molecular state with $J^P = 0^-, 1^-, 2^-$
Meng & Cheng, arXiv:0708.4222

cusp in the $D_1 D^*$ channel
Bugg, arXiv:0709.1254

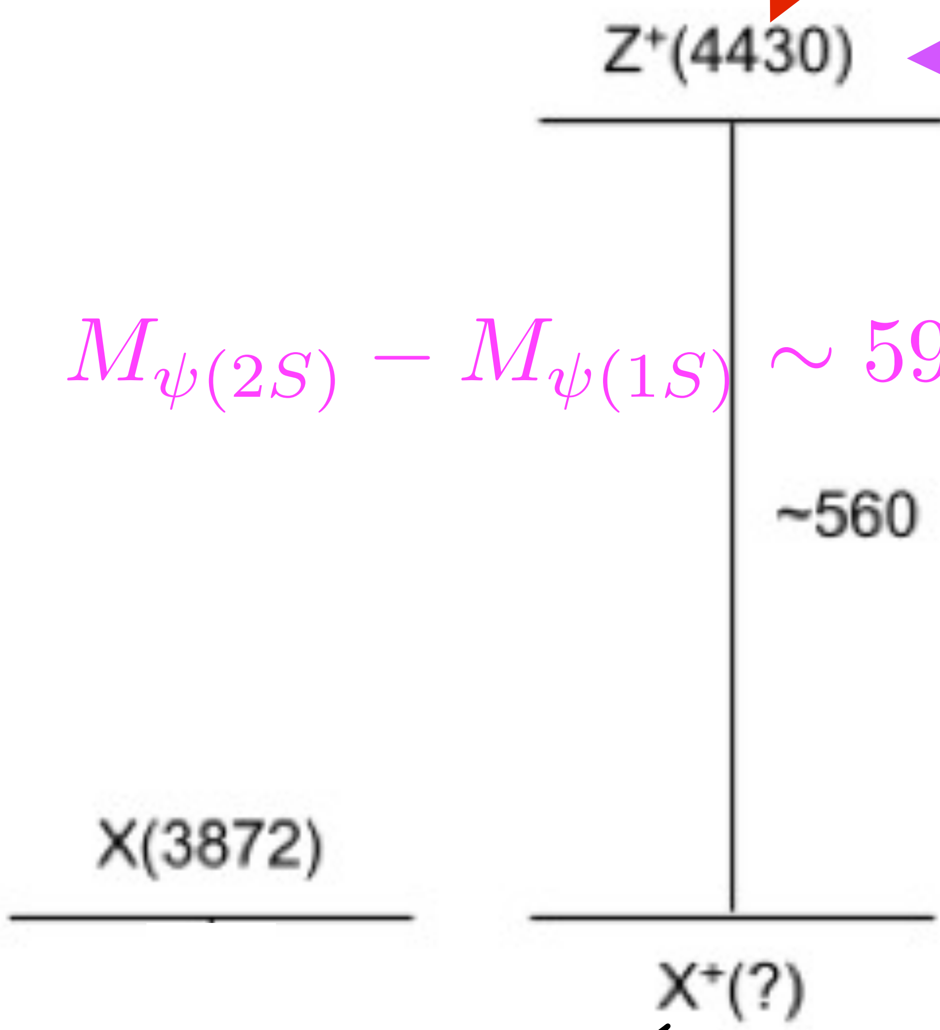
$D_1 D^*$ molecular state with $J^P = 1^+$
He, arXiv:1410.8645

$D_1 D^*$ or $D_2 D^*$ molecular state with $J^P = 1^+$
Ma, Liu, Liu, Zhu, arXiv:1404.3450; Barnes, Close, Swanson, arXiv:1409.6651

not a real state

Maiani et al. (arXiv:0708.3997) : four-quark radial excitation of the 1^+ charged state (X(3872) partner)

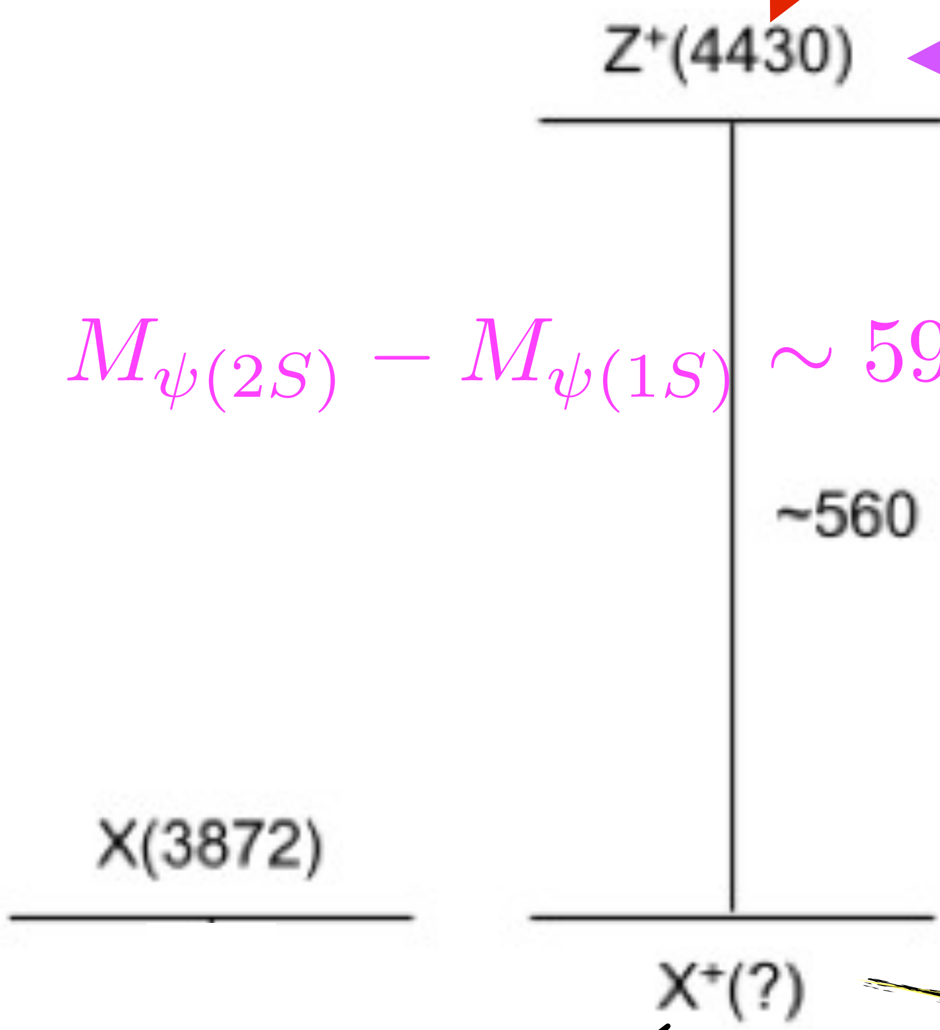
$$Z^+(4430) \to \psi(2S)\pi^+$$



$$M_{\psi(2S)} - M_{\psi(1S)} \sim 590 \text{ MeV} \sim M_{Z^+} - M_X$$

should be seen in J/ψπ decay mode

Maiani et al. (arXiv:0708.3997) : four-quark radial excitation of the 1^+ charged state (X(3872) partner)



$$Z^+(4430) \to \psi(2S)\pi^+$$

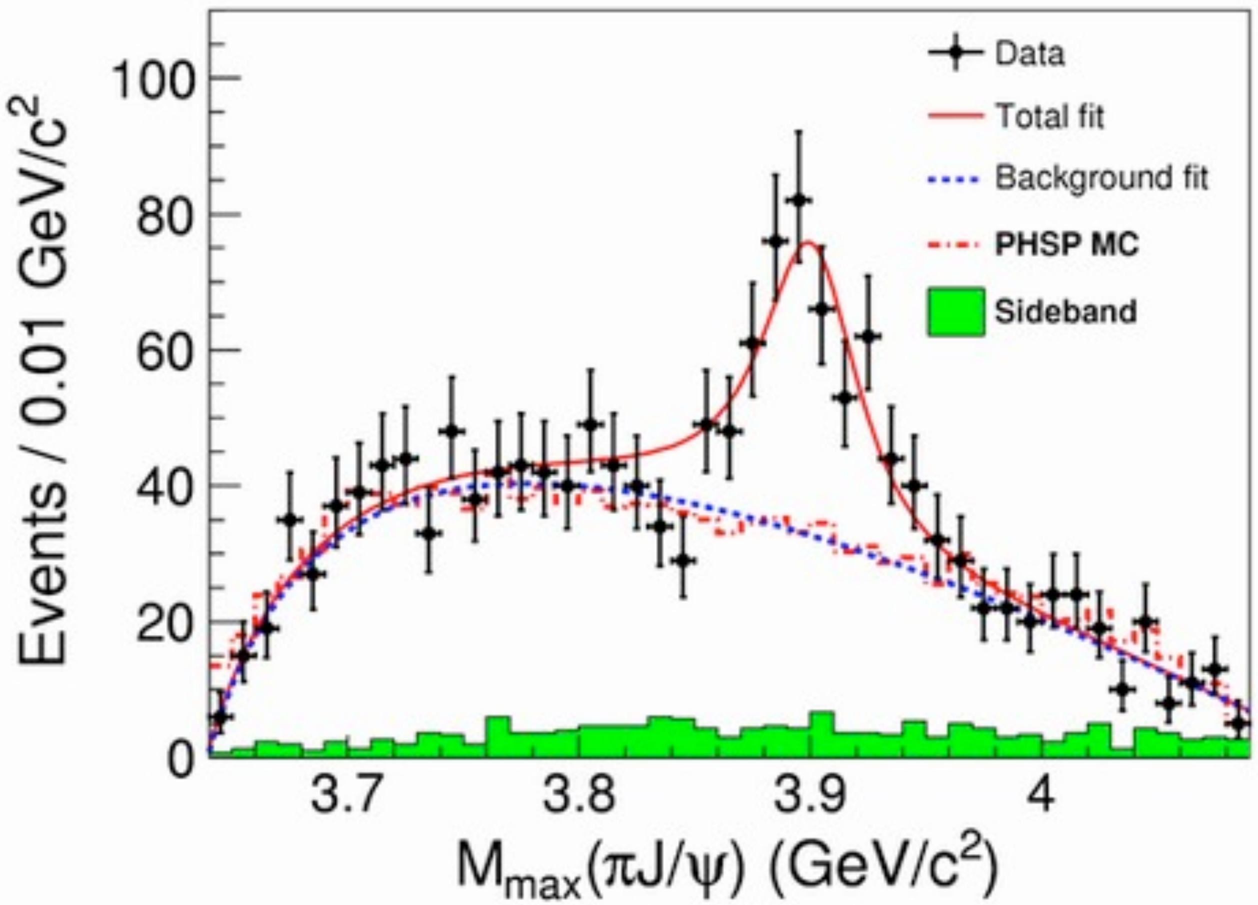
$$M_{\psi(2S)} - M_{\psi(1S)} \sim 590 \text{ MeV} \sim M_{Z^+} - M_X$$

should be seen in $J/\psi\pi$ decay mode

discovered in 2013

$Z_c^+(3900)$

Charged Charmonium states discovered in 2013



$Z_c^+(3900)$ BES III BELLE

arXiv:1303.5949 arXiv:1304.0121

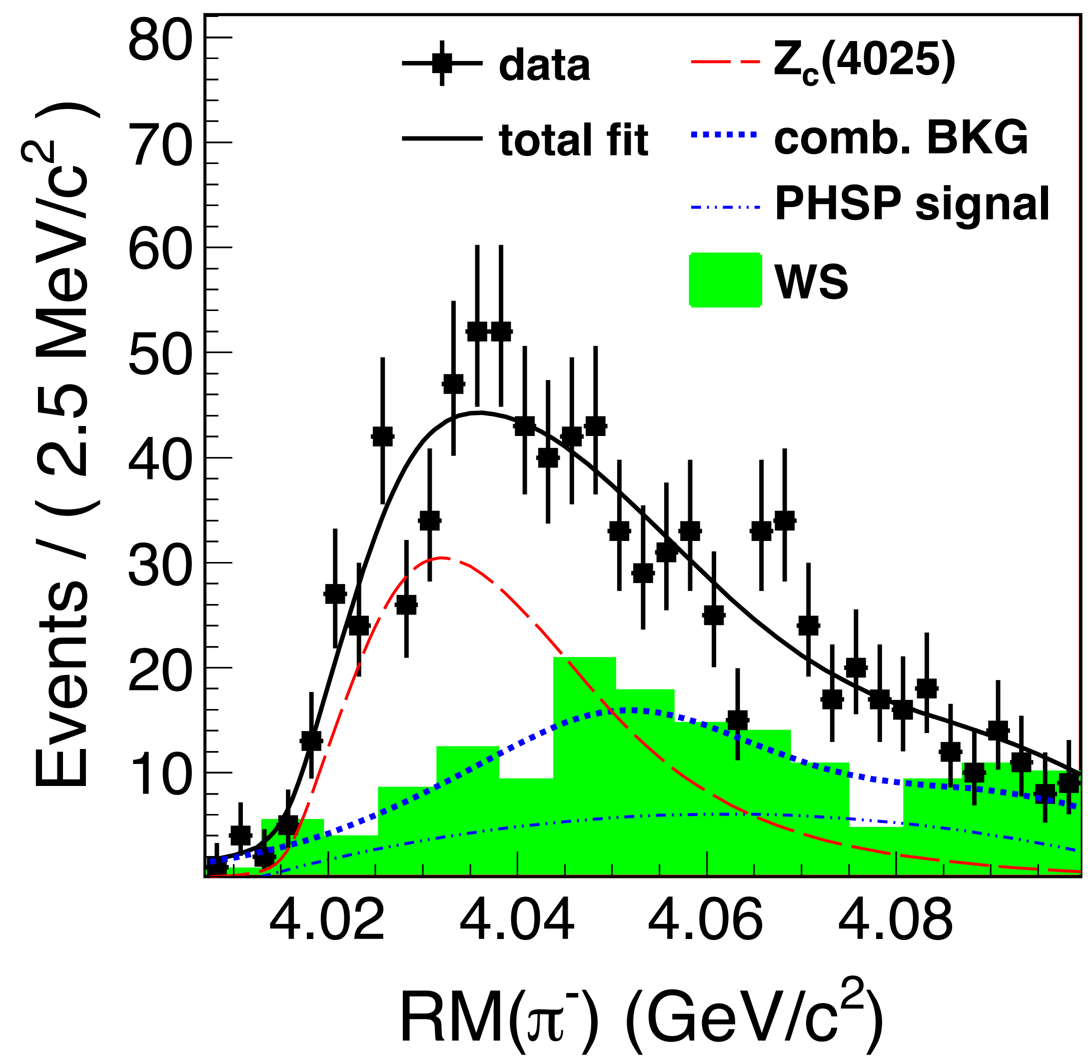
$$Y(4260) \to (J/\psi\pi^+)\pi^-$$

$Z_c^+(4025)$ BES III

arXiv:1308.2760

$$e^+e^- \to (D^*\overline{D}^*)^\pm\pi^\mp$$

$$\sqrt{s} = 4.26 \text{ GeV}$$

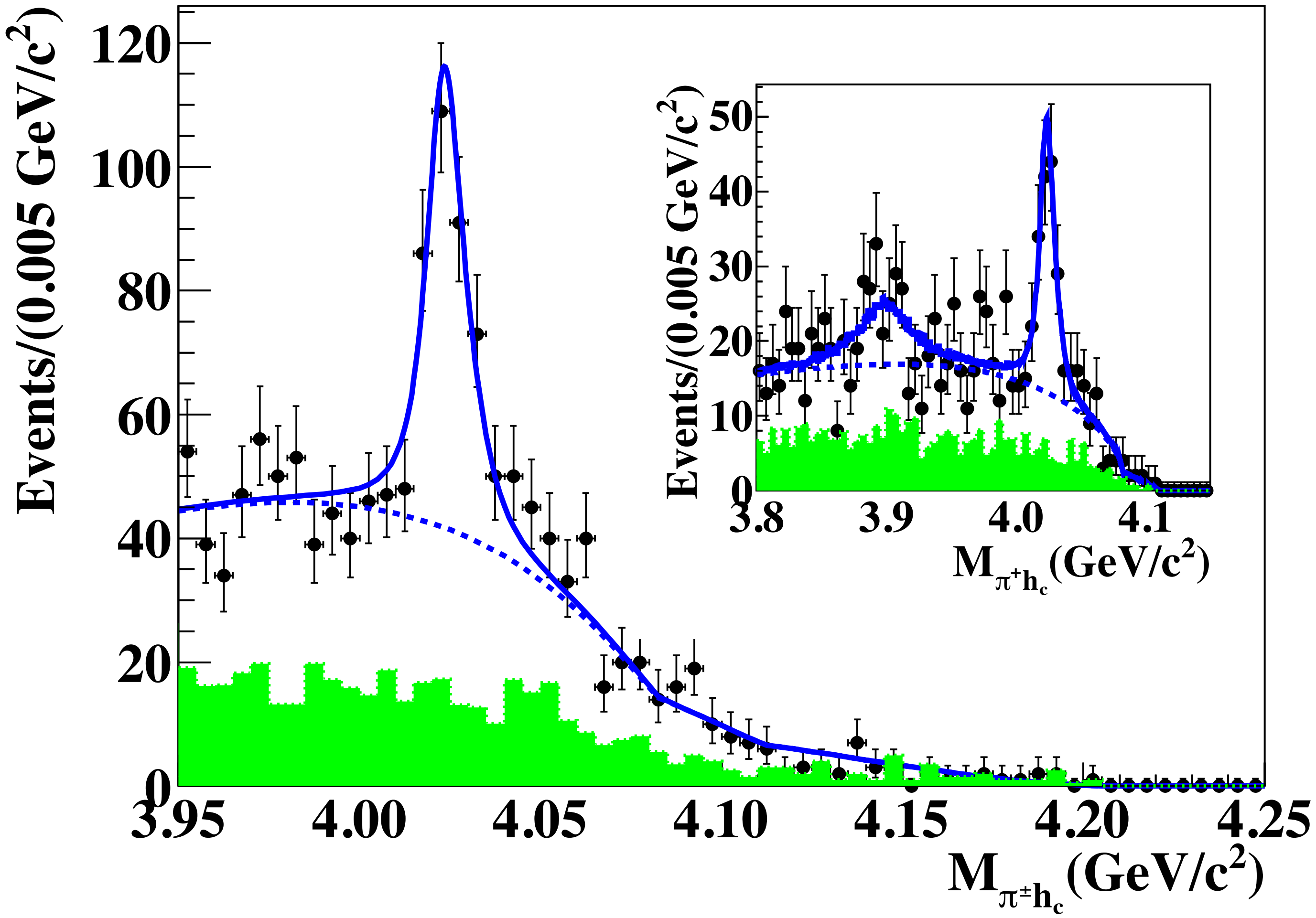


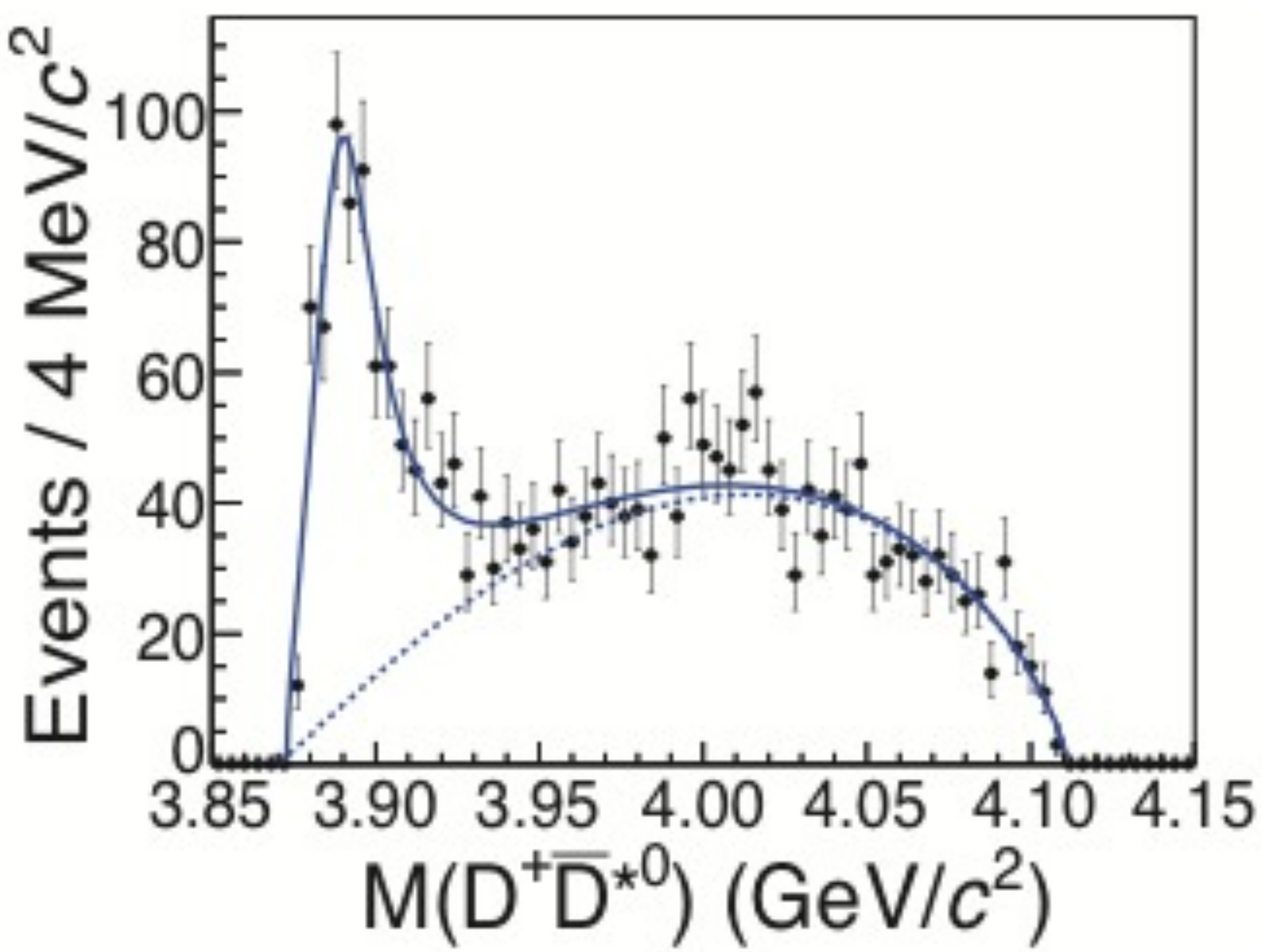
$Z_c^+(4020)$ BES III

arXiv:1309.1896

$$e^+e^- \rightarrow \pi^+\pi^- h_c$$

$$\sqrt{s} = (3.90 - 4.42)\ \text{GeV}$$





$Z_c^+(3885)$ BES III

arXiv:1310.1163

$$e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp \ @ \ \sqrt{s} = 4.26\ \text{GeV}$$

BESIII: a summary of Z_c observations

Zc	Mass (MeV/c²)	Width (MeV)	Decay	Process	[Ref]
$Z_c(3900)^\pm$	3899.0±3.6±4.9	46±10±20	$\pi^\pm J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$	[1]
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$	[2]
$Z_c(3885)^\pm$	3883.9±1.5±4.2 Single D tag	24.8±3.3±11.0 Single D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$	[3]
	3881.7±1.6±2.1 Double D tag	26.6±2.0±2.3 Double D tag	$(D\bar{D}^*)^\pm$	$e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$	[4]
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$	[5]
$Z_c(4020)^\pm$	4022.9±0.8±2.7	7.9±2.7±2.6	$\pi^\pm h_c$	$e^+e^- \to \pi^+\pi^- h_c$	[6]
$Z_c(4020)^0$	4023.9±2.2±3.8	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$	[7]
$Z_c(4025)^\pm$	4026.3±2.6±3.7	24.8±5.6±7.7	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$	[8]
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	23.0±6.0±1.0	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$	[9]

[1] PRL 110,252001; [2] PRL 115, 112003; [3] PRL 112, 022001; [4] PRD 92, 092006
[5] PRL 115, 222002; [6] PRL110, 252001; [7] PRL 113,212002; [8] PRL 112, 132001
[9] PRL 115, 182002

- Mass and widths of $Z_c(3900)$ and $Z_c(3885)$ (also $Z_c(4020)$ and $Z_c(4025)$) are consistent within 2σ → the same states?

from Shan Jin talk ICHEP16

$Z_c^+(3900)$

Tetraquark state

Maiani et al., PRD87(13); Dias et al., arXiv:1304.6433; Wang & Huang, arXiv:1310.2412; Braaten, arXiv:1305.6905,...

$D^*\bar{D}$ molecular state

Sun et al., arXiv:1106.2968; Guo et al., arXiv:1303.6608; Voloshin, arXiv:1304.0380; Wang et al., arXiv:1303.6355; Cui et al., arXiv:1304.1850; Zhang, arXiv:1304.5748; Dong et al., arXiv:1306.0824; Ke et al., arXiv:1307.2414; Prelovsek et al., arXiv:1308.2097

to reproduce the measured width $\Rightarrow$ $\langle r_{eff}\rangle \simeq 0.4$ fm $\Rightarrow$

disfavors molecular interpretation

(Mahajan, arXiv1304.1301)

$D^*\bar{D}$ molecule with $\langle r^2\rangle \simeq 0.11$ fm^2 (Wilbring et al., PLB726(13))

hard to understand since $\langle r_\psi{}^2\rangle \simeq 0.16$ fm^2

QCDSR calculation for $Z_c^+(3900)$

two-point calculation for $Z_c^+(3900)$ with a tetraquark current gives the same result as for X(3872)

Decay width $Z^+ \to J/\psi\,\pi^+$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_{5\nu}^\pi(y) j_\alpha^\dagger(0)]|0\rangle$$

$$j_\alpha = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(u_a^T C\gamma_5 c_b)(\bar{d}_d\gamma_\alpha C\bar{c}_e^T) - (u_a^T C\gamma_\alpha c_b)(\bar{d}_d\gamma_5 C\bar{c}_e^T)]$$

tetraquark current

QCDSR calculation for $Z_c^+(3900)$

two-point calculation for $Z_c^+(3900)$ with a tetraquark current gives the same result as for X(3872)

Decay width $Z^+ \to J/\psi\,\pi^+$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_{5\nu}^\pi(y) j_\alpha^\dagger(0)]|0\rangle$$

$$j_\alpha = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(u_a^T C\gamma_5 c_b)(\bar{d}_d\gamma_\alpha C\bar{c}_e^T) - (u_a^T C\gamma_\alpha c_b)(\bar{d}_d\gamma_5 C\bar{c}_e^T)]$$

tetraquark current

$$\Gamma(Z_c^+(3900) \to J/\psi\pi^+) = (29.1 \pm 8.2)\ \mathrm{MeV}$$

QCDSR Results for decay widths of the $Z_c^+(3900)$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900) J/\psi \pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900) \eta_c \rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900) D^+ \bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900) \bar{D}^0 D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

$$\Gamma_{Z_c^+} = (63 \pm 18)\ \mathrm{MeV}$$

QCDSR Results for decay widths of the $Z_c^+(3900)$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900)\bar{D}^0D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

$$\Gamma_{Z_c^+} = (63 \pm 18)\ \mathrm{MeV}$$

$$\Gamma_{Z_c^+}^{BES} = (46 \pm 22)\ \mathrm{MeV} \quad \Gamma_{Z_c^+}^{BELLE} = (63 \pm 35)\ \mathrm{MeV}$$

Very good agreement

$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 0.22 \pm 0.12$$

BES III

arXiv:1310.1163

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

QCDSR $\Rightarrow$ not the same state!

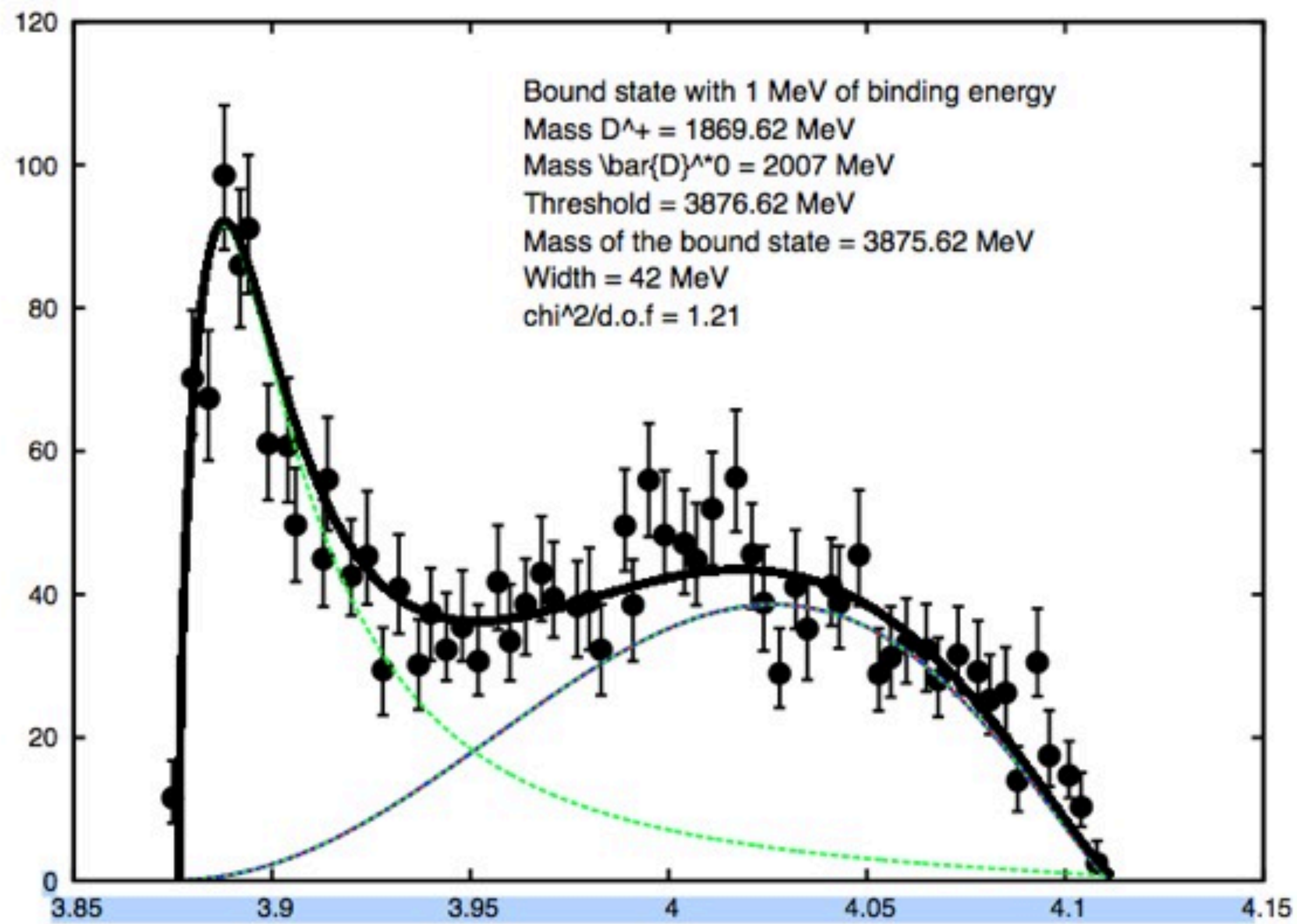
$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 0.22 \pm 0.12$$

BES III

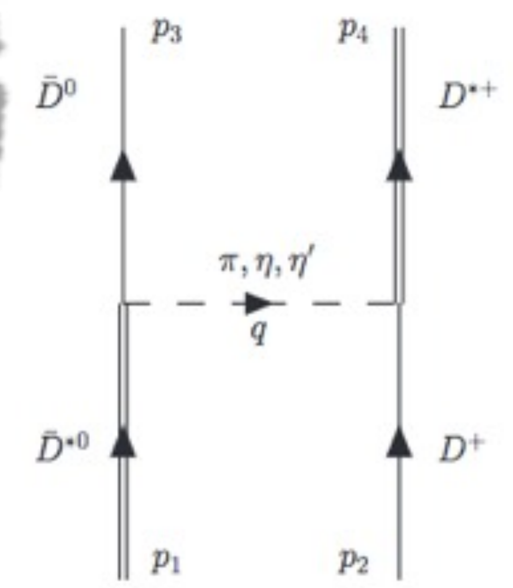
arXiv:1310.1163

$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

QCDSR $\Rightarrow$ not the same state!



Aceti et al.,
arXiv:1401.8216



$Z_c^+(3885)$
can be explained as
a 1^+ $D\bar{D}^*$ state below
the threshold

Conclusions for $Z_c^+(3900)$ and $Z_c^+(3885)$

- $Z_c^+(3900)$ is probably a 1^+ tetraquark state

- $Z_c^+(3885)$ is probably a DD^* 1^+ state below threshold

Conclusions for $Z_c^+(3900)$ and $Z_c^+(3885)$

- $Z_c^+(3900)$ is probably a 1^+ tetraquark state

- $Z_c^+(3885)$ is probably a DD^* 1^+ state below threshold

QCDSR for $Z_c^+(4025)$ as a $D^*\bar{D}^*$ molecule

Khemchandani, Martínez, Navarra, MN: arXiv:1310.0862

$$M^{S=1} = (3950 \pm 105)\ \text{MeV}$$

$$M^{S=2} = (3946 \pm 104)\ \text{MeV}$$

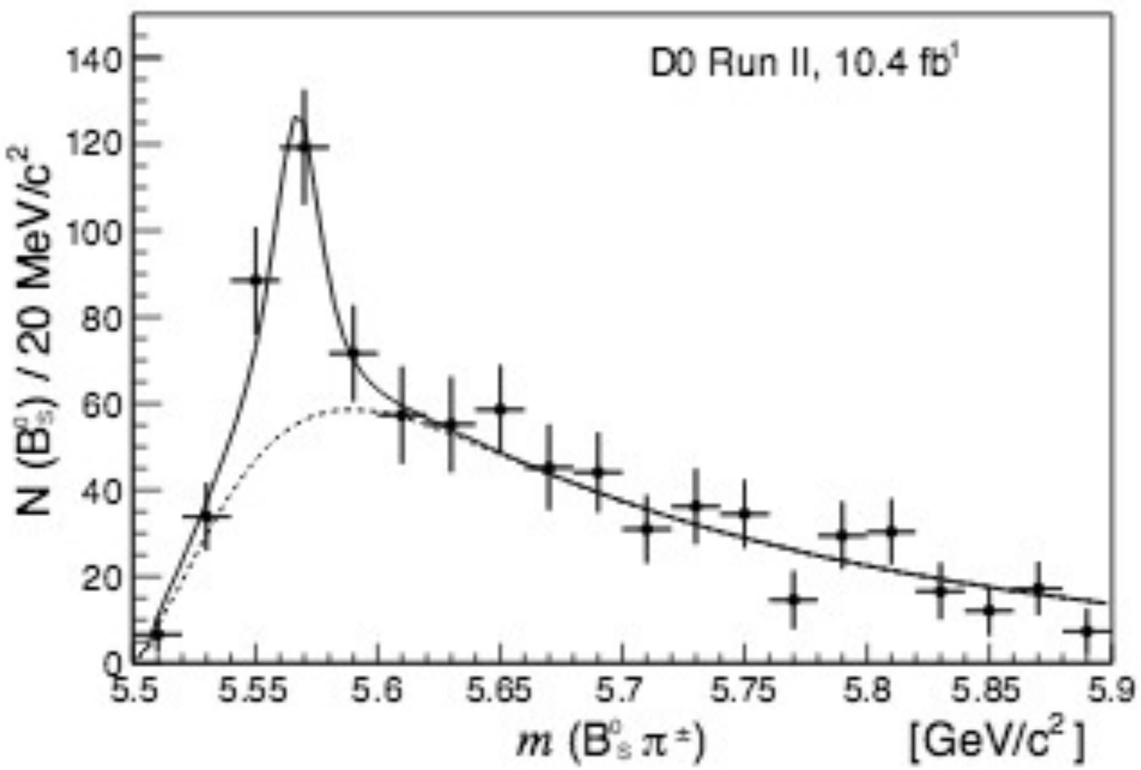
Both compatible with $Z_c(4025)$

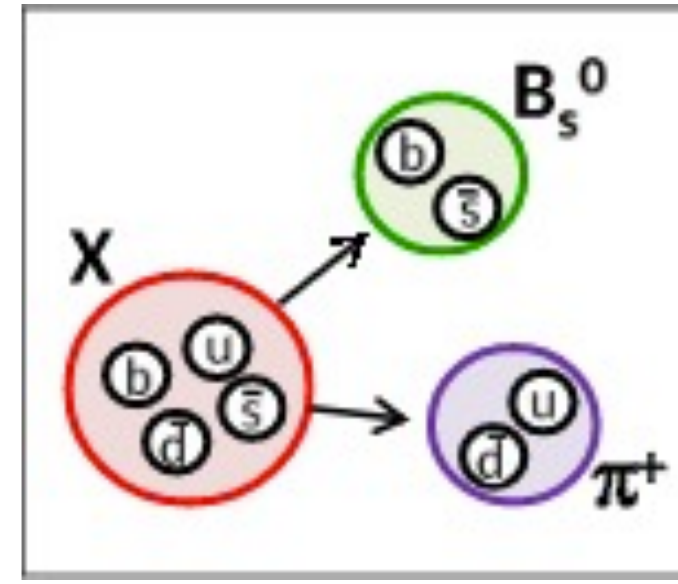
$$M^{exp} = (4026.3 \pm 2.6 \pm 3.7)\ \text{MeV}$$

results are also compatible with a spin 2 $D^*\bar{D}^*$ state below threshold (arXiv:1310.1119), consistent with prediction from Molina & Oset (PRD80(2009)114013) doing a coupled channel analysis

$X^{\pm}(5568)$: most recent acquisition

arXiv:1602.07588





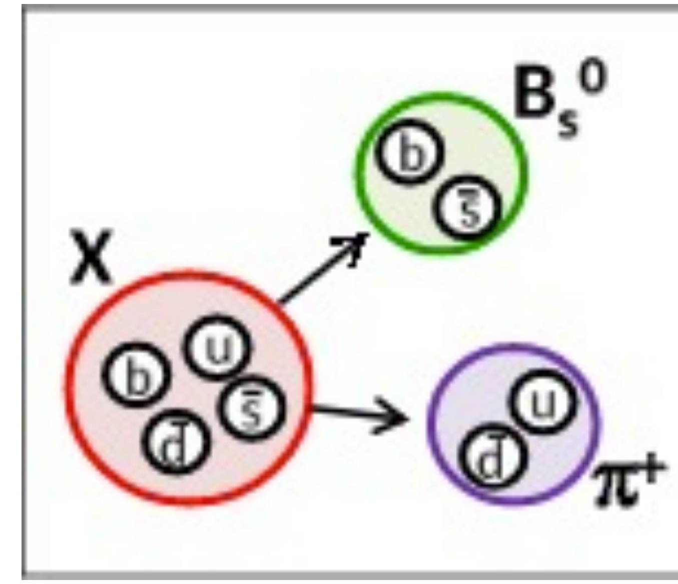
M = (5567.8±2.9±1.2) MeV

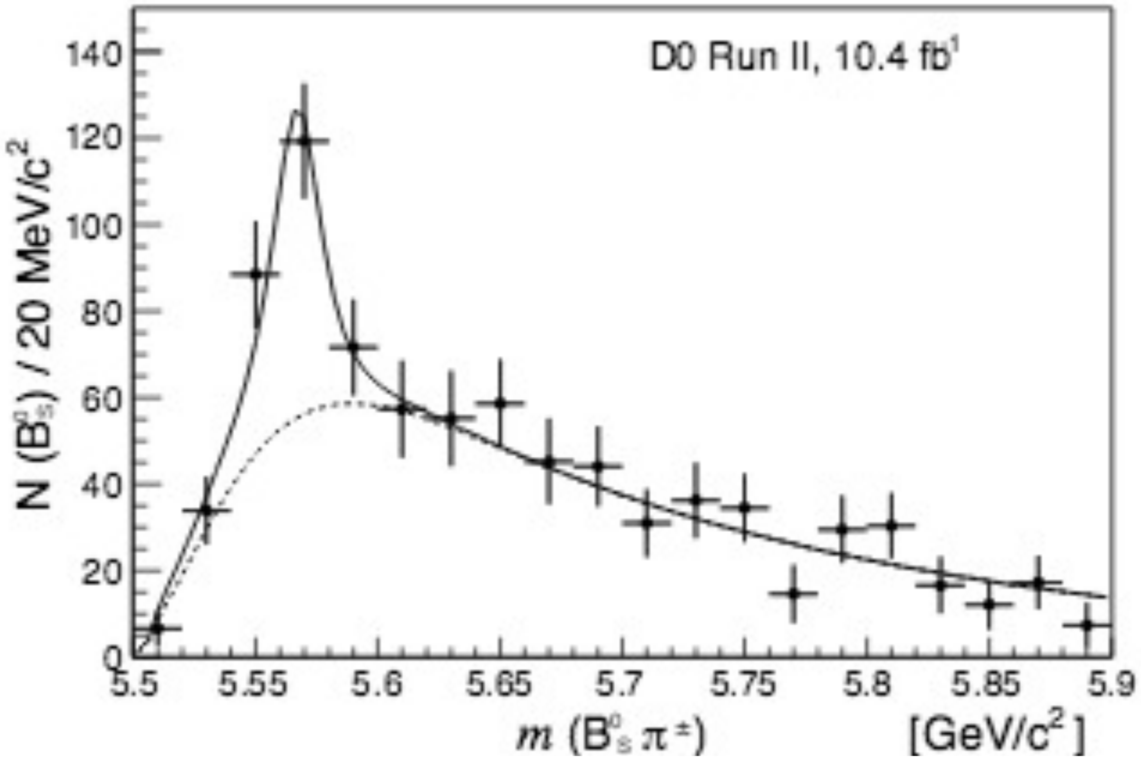
Γ = (21.9±6.4±3.5) MeV

stat. significance 5.1σ

$X^{\pm}(5568)$: most recent acquisition

arXiv:1602.07588

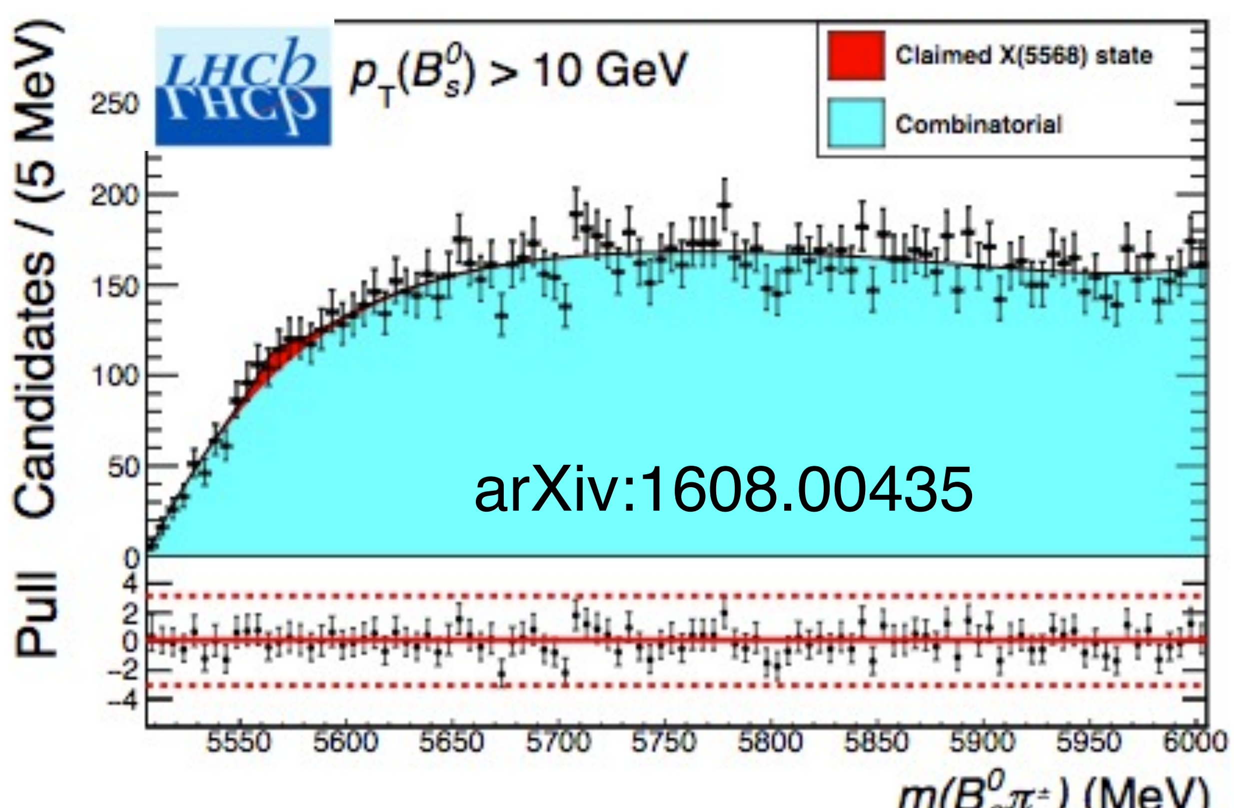


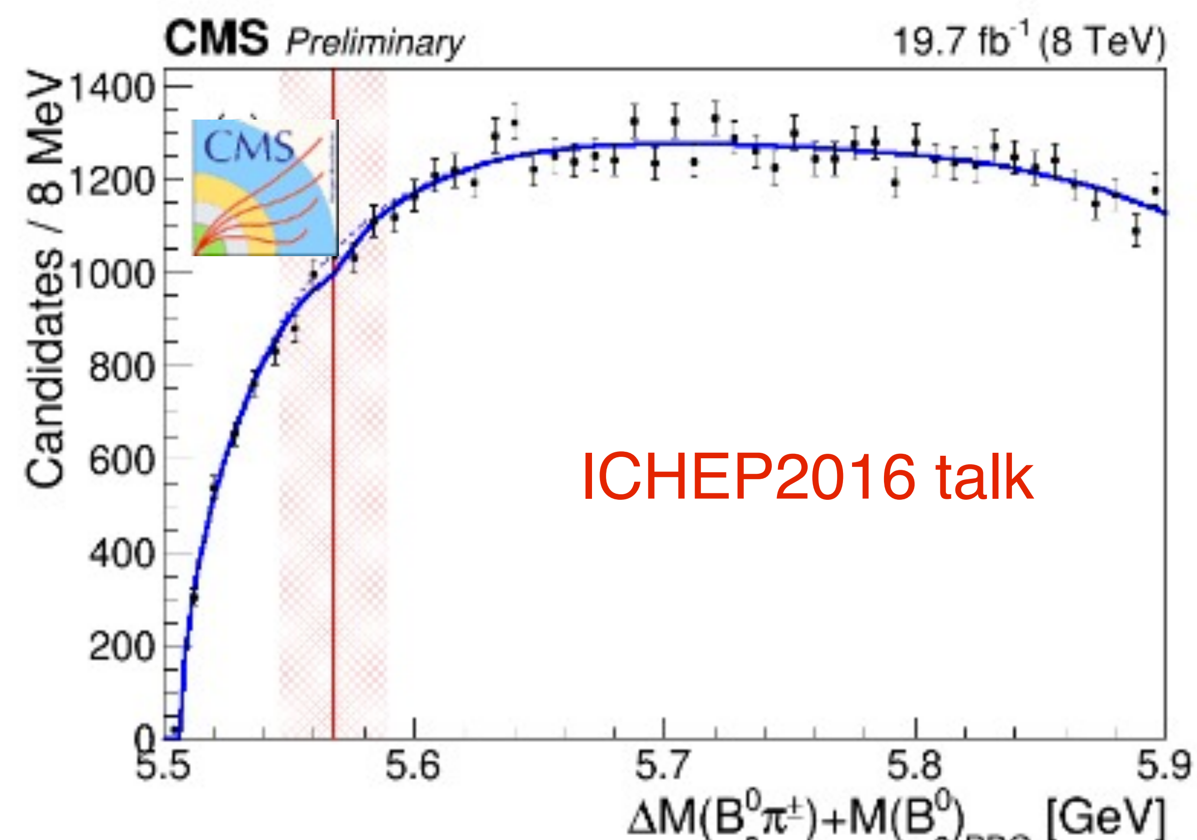


M = (5567.8±2.9±1.2) MeV

Γ = (21.9±6.4±3.5) MeV

stat. significance 5.1σ





$X^+(5568)$

Tetraquark state

Agaev et al., arXiv:1602.08642; Chen et al., arXiv:1602.08916; Wang, arXiv:1602.08711; Tang & Qiao, arXiv:1603.04761

$B\bar{K}$ molecular state

Agaev et al., arXiv:1603.02708; Xiao & Chen, arXiv:1603.00228; Albaladejo et al., PLB757

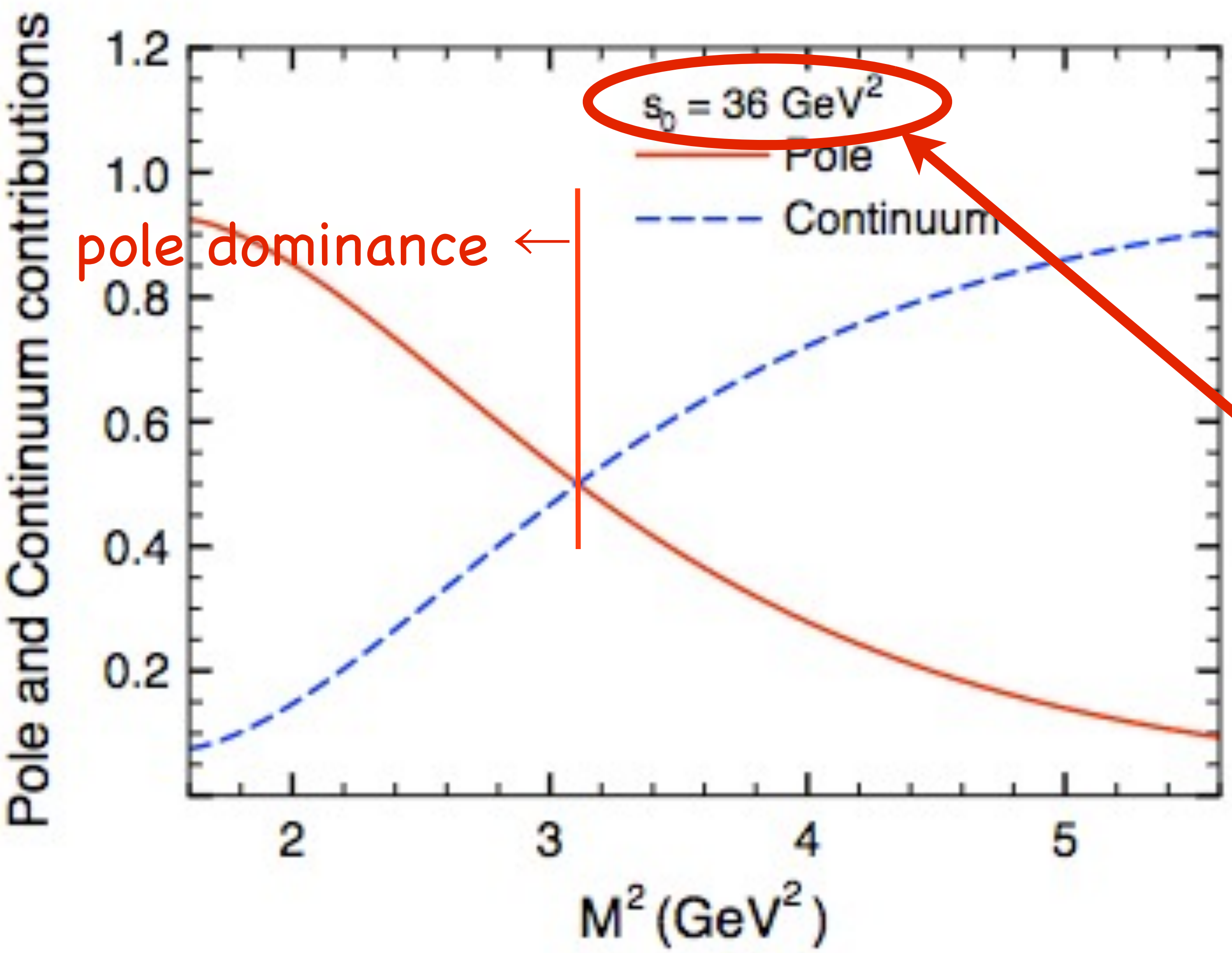
mass not compatible with 4-q or mol.

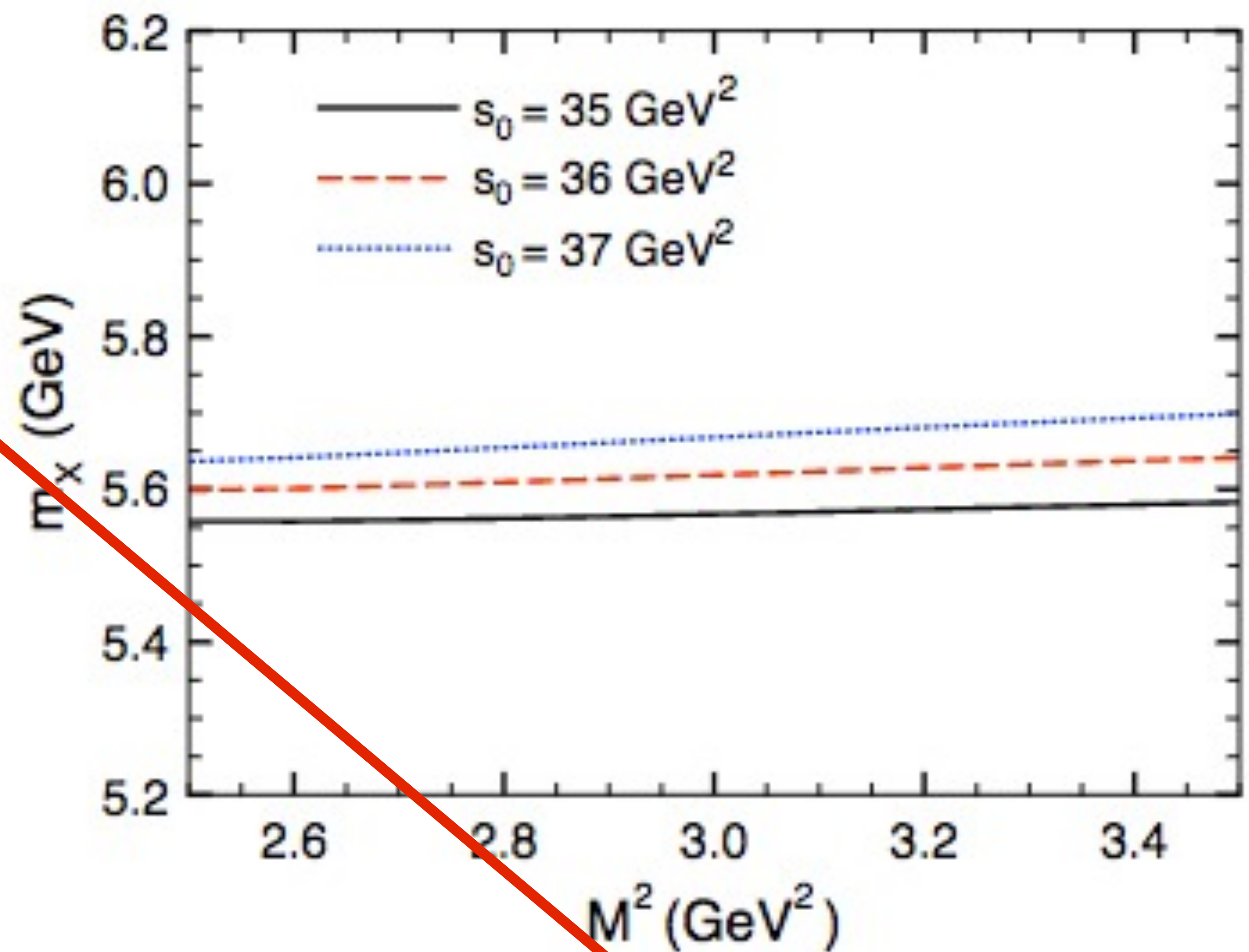
Burns & Swanson, arXiv:1603.04366; Guo et al., arXiv:1603.06316; Zanetti et al., arXiv:1602.09041; Wang & Zhu, arXiv:1602.08806; Chen & Ping, arXiv:1604.05651; Maiani et al., arXiv:1604.01731; Lu & Dong, arXiv:1603.06417; Albuquerque et al., arXiv:1604.05566

QCDSR for $X^+(5568)$ as a tetraquark state

Khemchandani, MN, Zanetti: arXiv:1602.09041

$$j_S = \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 s_b)(\bar{d}_d \gamma_5 C \bar{b}_e^T)$$





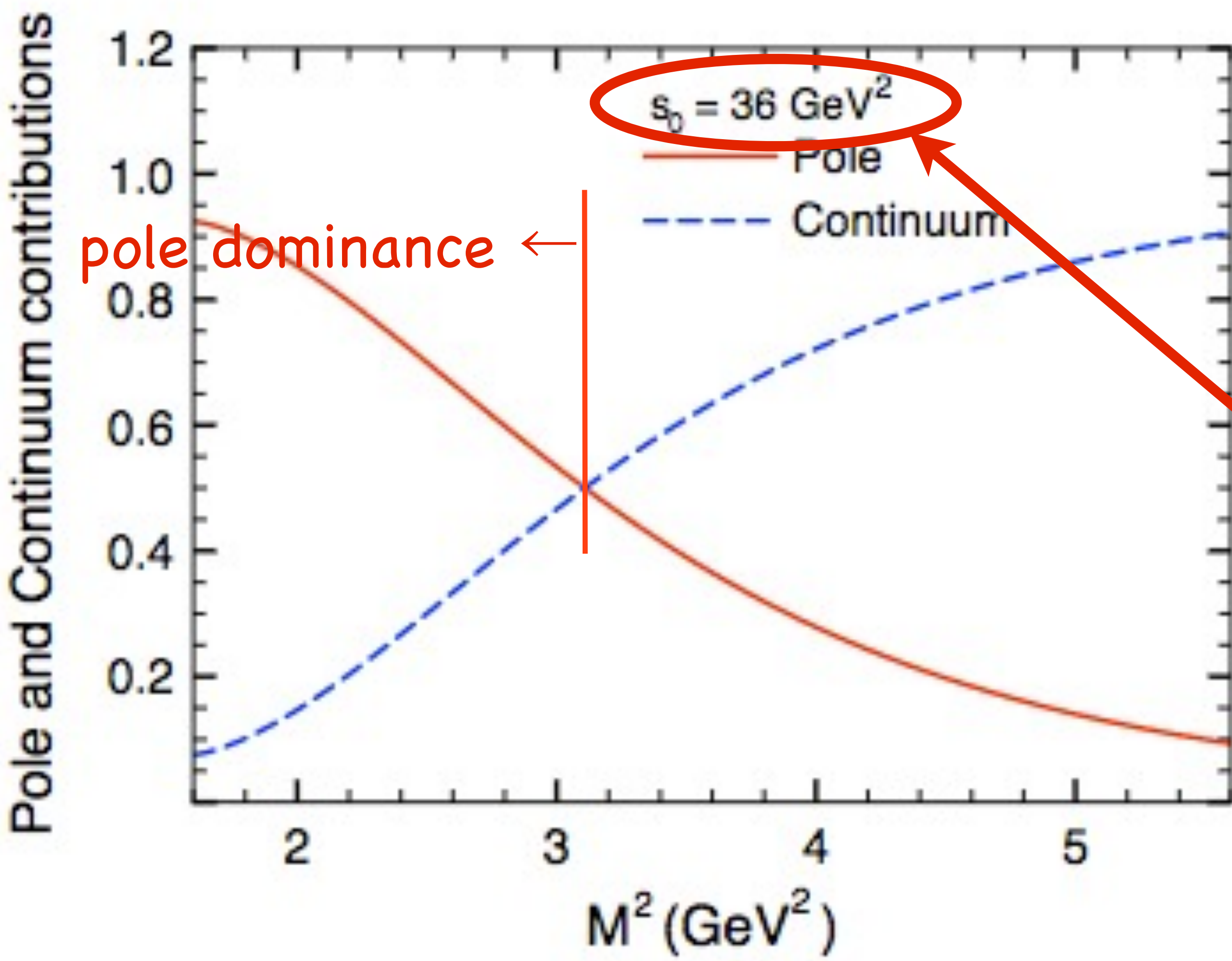
$$\boxed{m_X = (5.58 \pm 0.17)\,\text{GeV}}$$

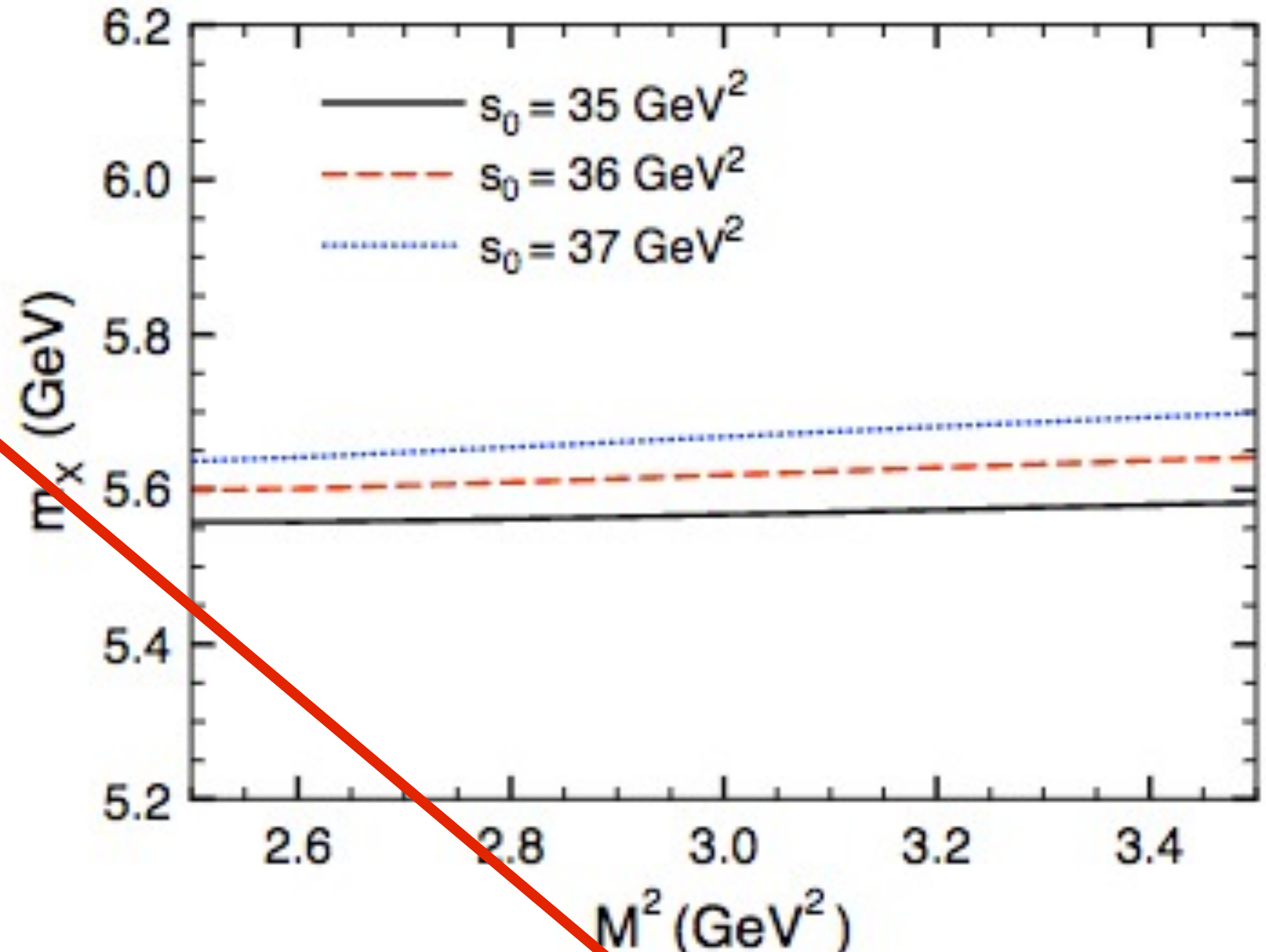
$s_0 \sim (m + 0.5 \text{ GeV})^2$

QCDSR for $X^+(5568)$ as a tetraquark state

Khemchandani, MN, Zanetti: arXiv:1602.09041

$$j_S = \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 s_b)(\bar{d}_d\gamma_5 C\bar{b}_e^T)$$

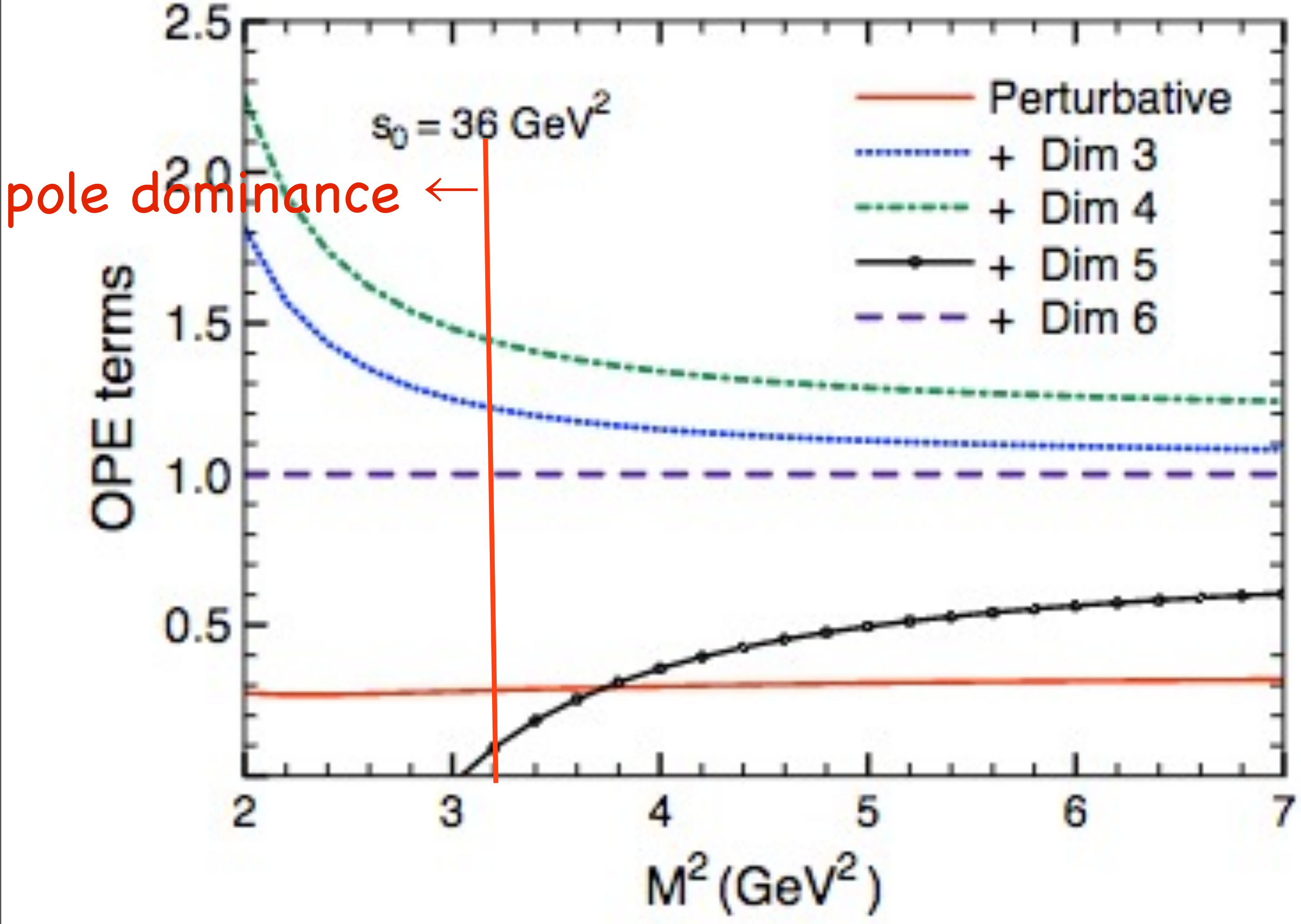




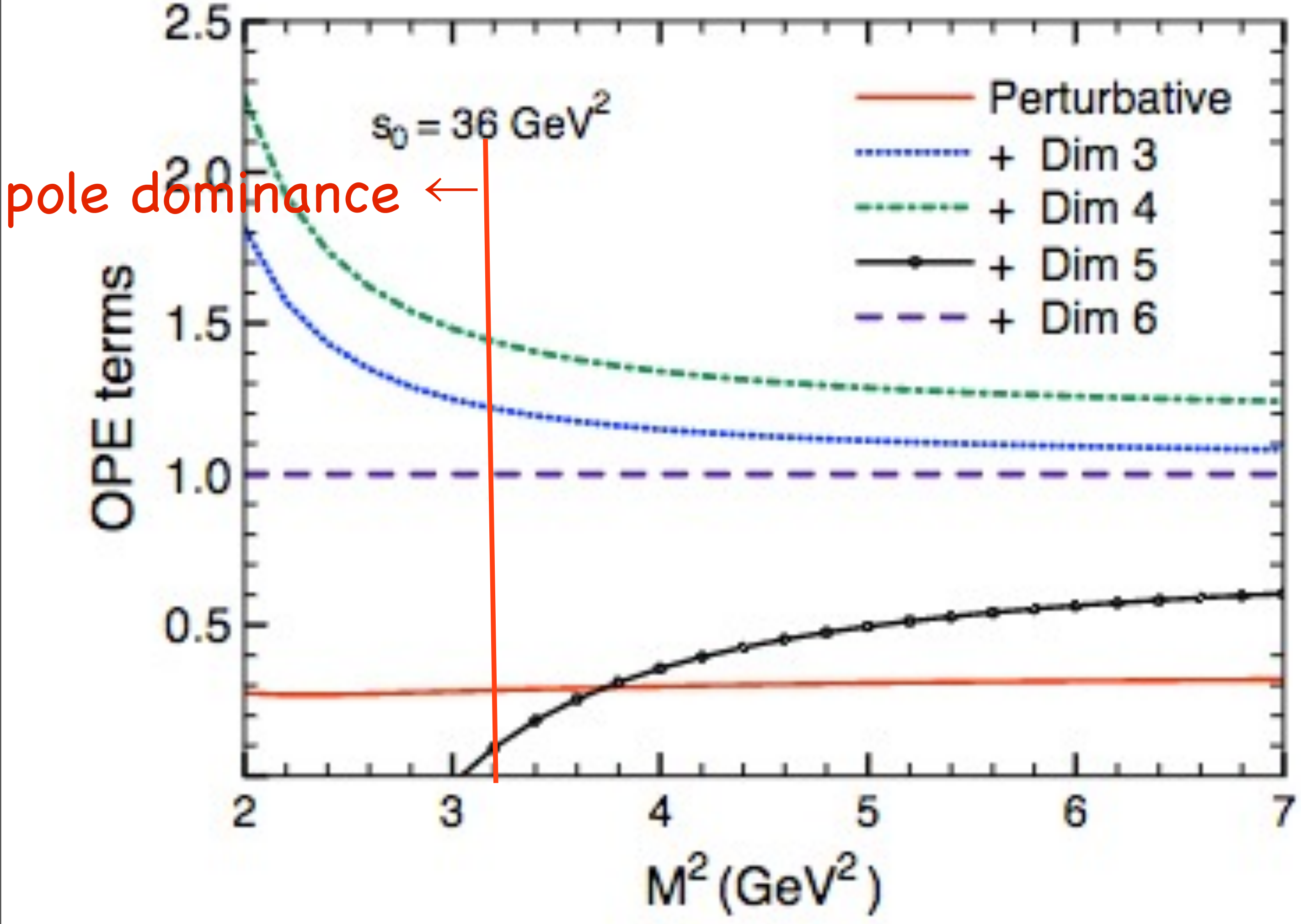
$$\boxed{m_X = (5.58 \pm 0.17)\,\mathrm{GeV}}$$

$$s_0 \sim (m + 0.5\ \mathrm{GeV})^2$$

OPE convergence?

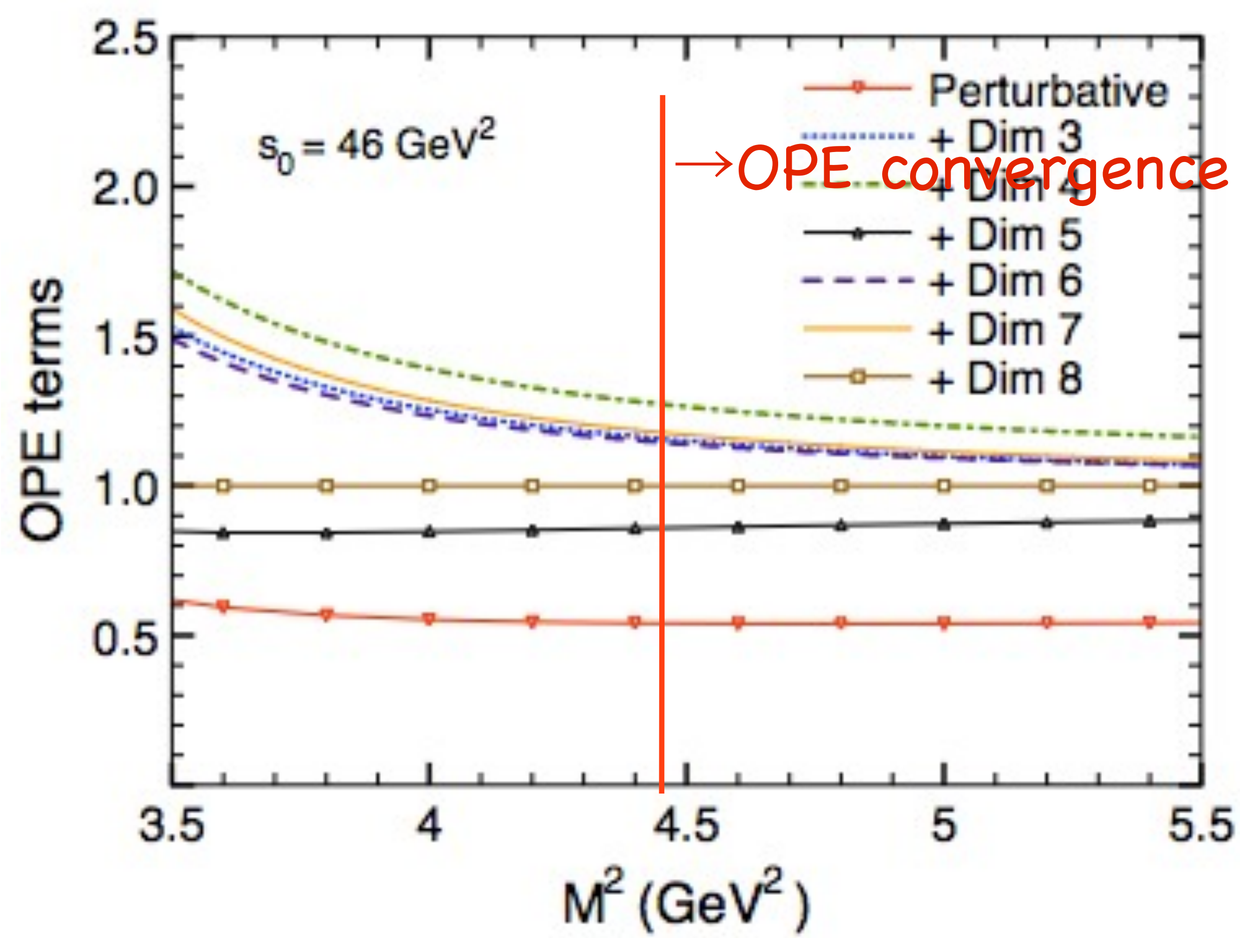


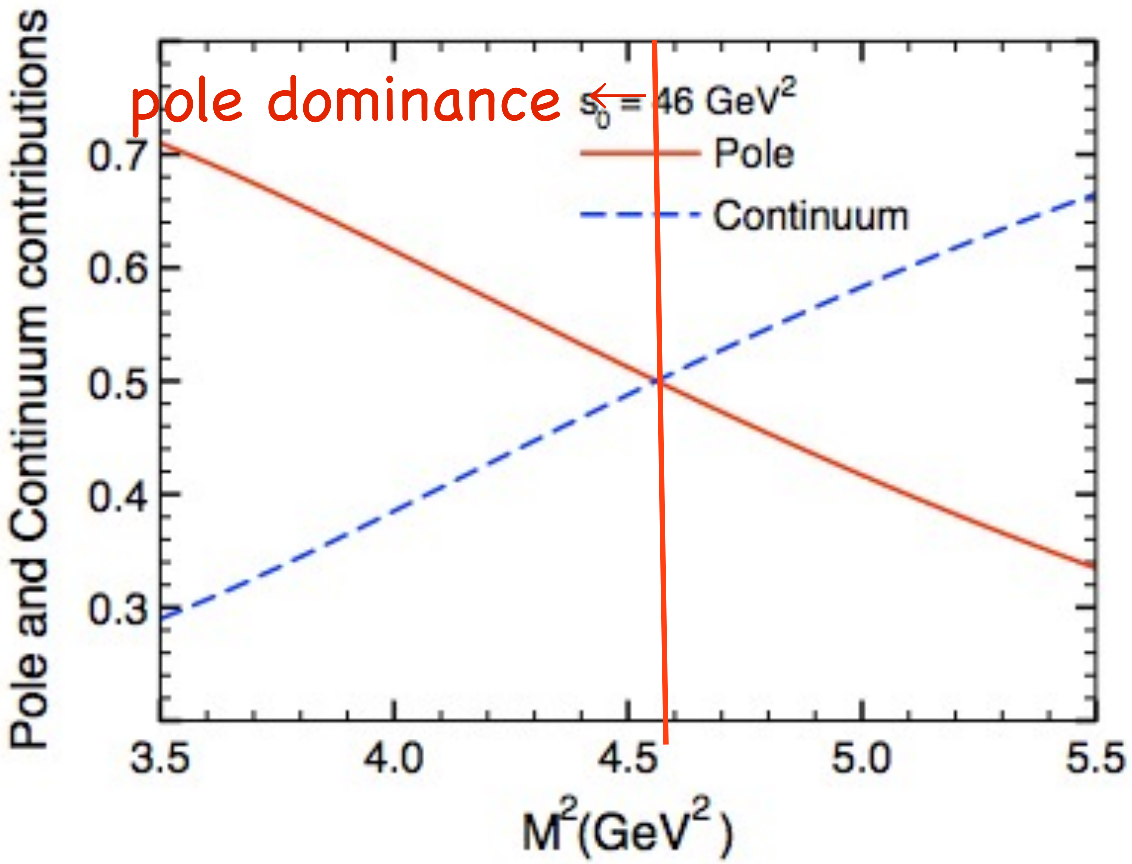
No OPE convergence for $s_0 \simeq 3.6$ GeV^2

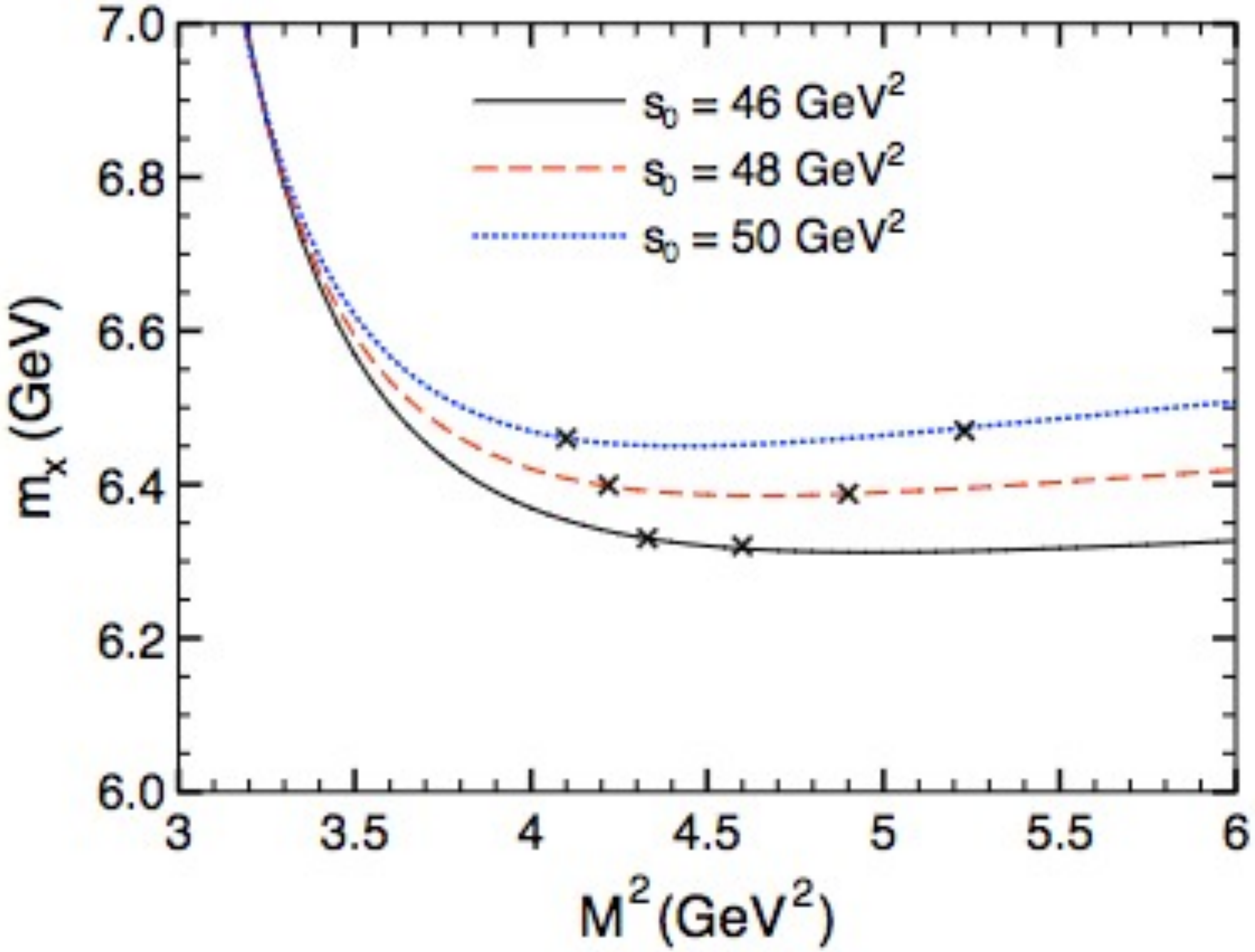


No OPE convergence for $s_0 \simeq 3.6\ GeV^2$

OPE convergence only for $s_0 \geq 46\ GeV^2$

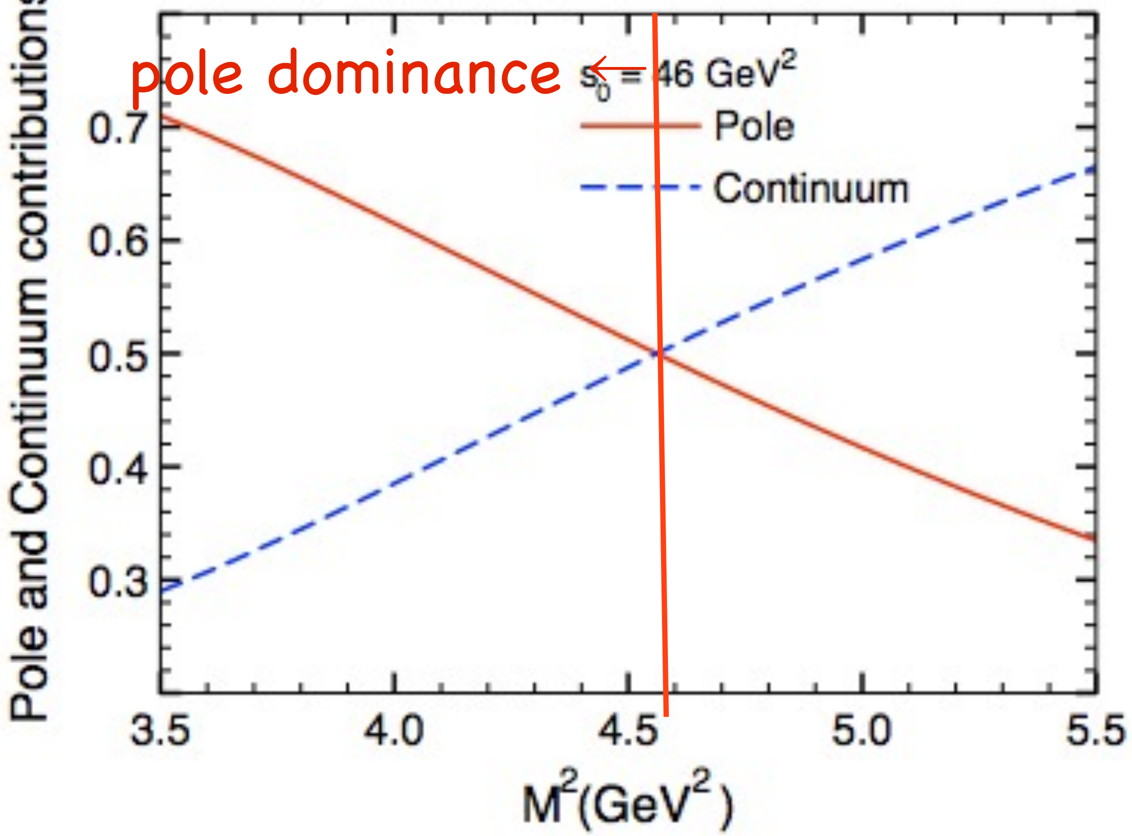


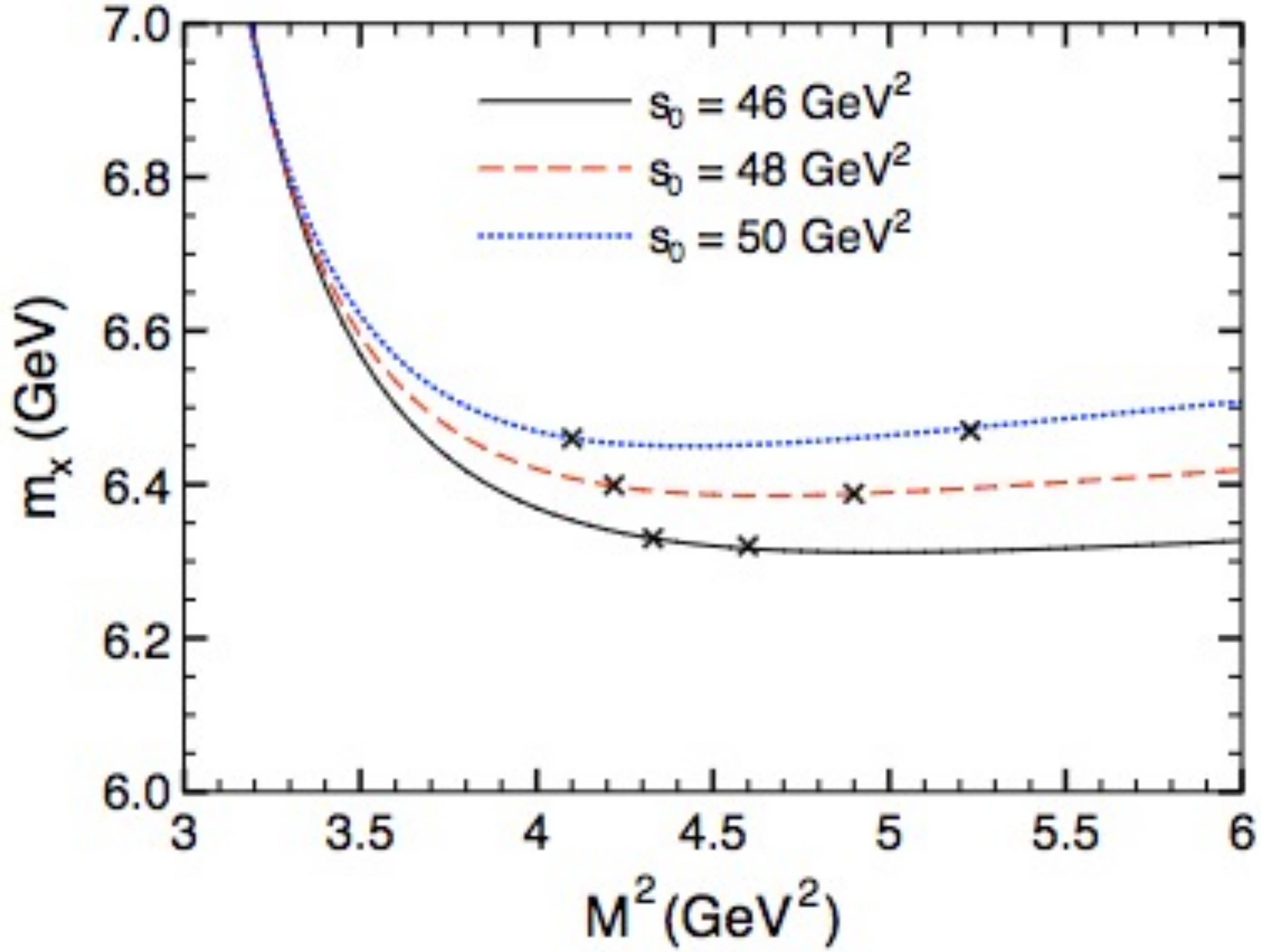




not compatible with
X^+ (5568) mass

m_X=(6.39 ± 0.10)GeV





not compatible with
X^+ (5568) mass

m_X=(6.39 ± 0.10)GeV

Conclusions for X^+(5568)

- probably not a real state

Conclusions

$X(3872) \rightarrow$ mixture χ_{c1} and a $D^*\bar{D}$ molecule

$Z_c^+(3900) \rightarrow$ $J^P=1^+$ tetraquark state

$Z_c^+(3900)$ and $Z_c^+(3885) \rightarrow$ not the same state

$Z_c^+(4025) \rightarrow$ $J^P=1^+,2^+$ $D^*\bar{D}^*$ resonance, or D-wave background

- Z^+ states need confirmation. A bump in the spectra near the threshold does not indicate, necessarily, the existence of a state

$X^+(5568) \rightarrow$ needs confirmation, probably not a real state

Thank you

$\theta \quad \varepsilon \quad \nu \quad \kappa \quad \upsilon$


Questions?