Theoretical aspects of XYZ states

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International Workshop on e^+e^- Collisions from Phi to Psi 2019

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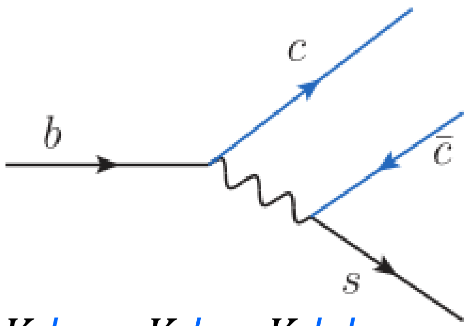
Main reactions producing XYZ

- In e^+e^- collisions
  - Energy coverage limited: $\lesssim 4.6$ GeV @BESIII, thus
    - little is known about vector states above that energy;
    - for other quantum numbers, even lower mass accessible: $e^+e^- \to X + \gamma/\text{pions}$; resonances decaying into $\psi\phi$, $\psi\omega$ cannot be studied
    - No access to charm-anticharm baryon-pair thresholds, e.g., $\Lambda_c^+\Lambda_c^-$; no access to thresholds of a pair of excited charm mesons, e.g., $D_1\bar{D}_1$
  - $e^+e^- \to \gamma_{\rm ISR}Y$: low rates due to an additional factor of α

- In weak decays $b \to [c\bar{c}]s$



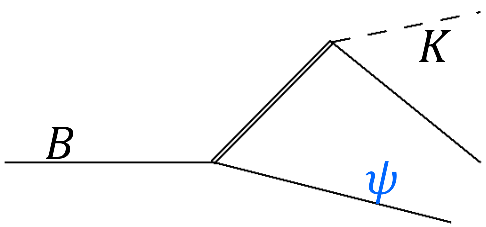
  - Energy region limited: $< m_B - m_K \approx 4.8$ GeV
  - Final states with 3 or more hadrons: $B \to K\psi\pi, K\psi\pi\pi, K\psi\omega, K\psi\phi$, …

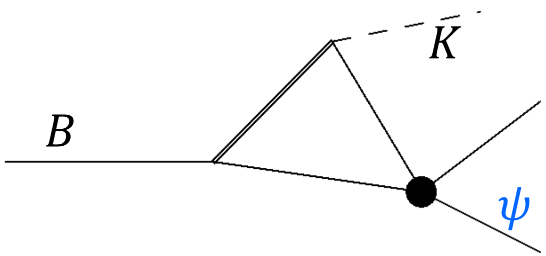
    Many states observed, e.g., X(3872), X(3915), …

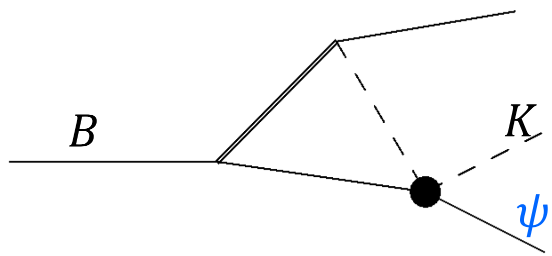
Main reactions producing XYZ

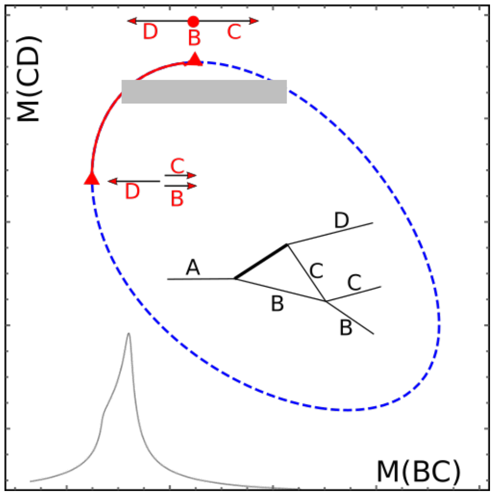
- Difficulties for multi-hadron final states
  - ✓ Many resonances from the cross channel:

    branching fractions often unknown, interference between overlapping resonances, …







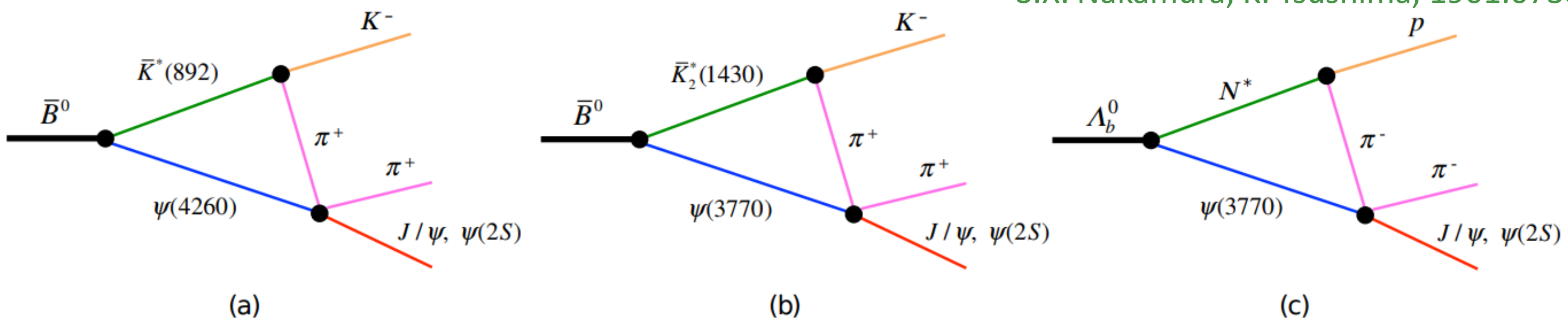


  - ✓ Complicated 3-body FSI:

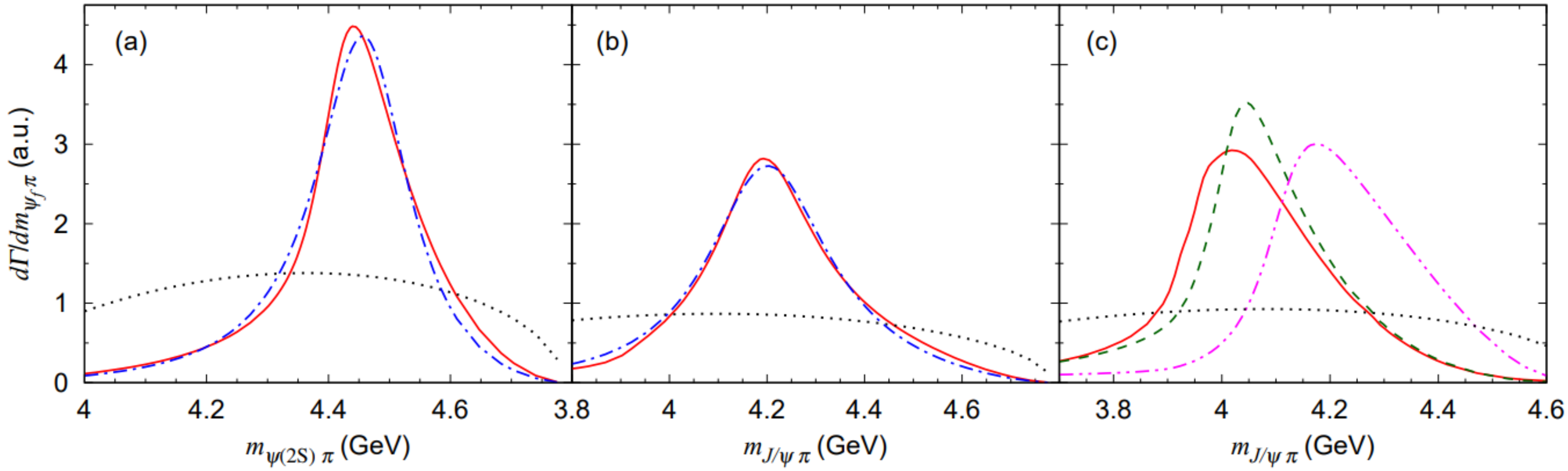
    intermediate states can be different from external ones; threshold cusps; triangle singularities (TS) singularities

$Z_c(4430, 4200)$: ambiguity due to TS

S.X. Nakamura, K. Tsushima, 1901.07385



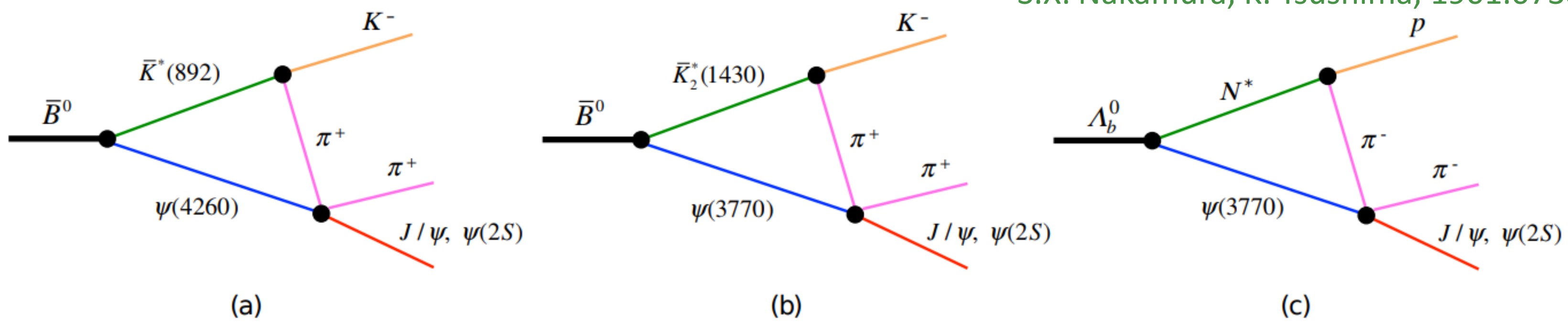
- Peaks produced at the right energy



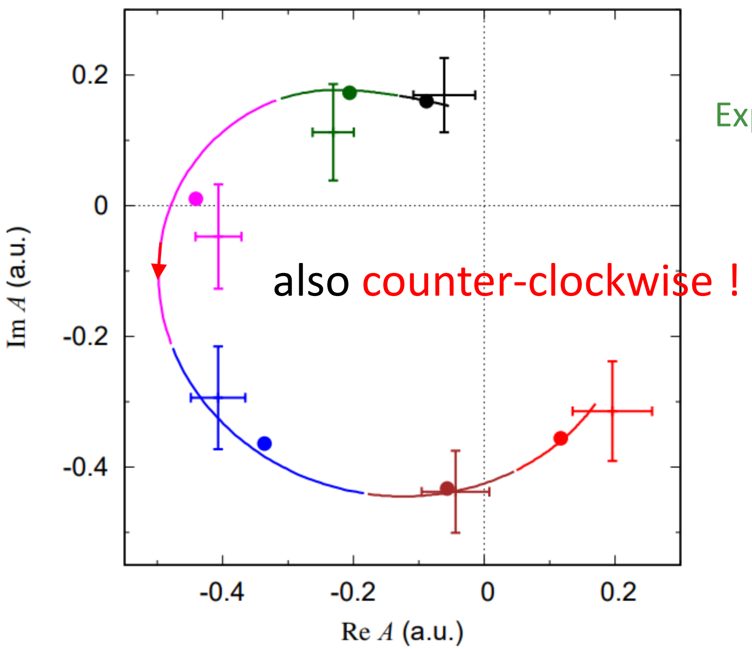
- $\mathcal{B}(Z_c(4430) \to \psi'\pi) \gg \mathcal{B}(Z_c(4430) \to J/\psi\pi)$ explained using $\frac{\mathcal{B}(\Upsilon(4260)\to\psi'\pi\pi)}{\mathcal{B}(\Upsilon(4260)\to J/\psi\pi\pi)} = 0.1 - 0.5$ From a combined fit by J. Zhang, L. Yuan, EPJC77(2017)727

$Z_c(4430, 4200)$: ambiguity due to TS

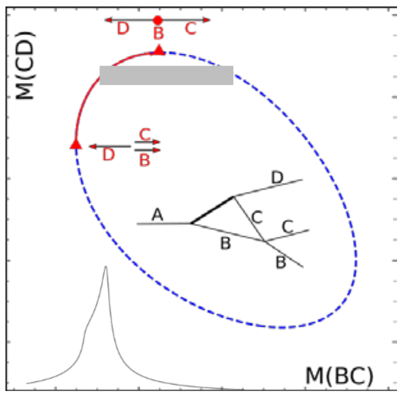
S.X. Nakamura, K. Tsushima, 1901.07385



- Argand plot for $Z_c(4430)$: diagram (a) interfered with a constant complex bg.



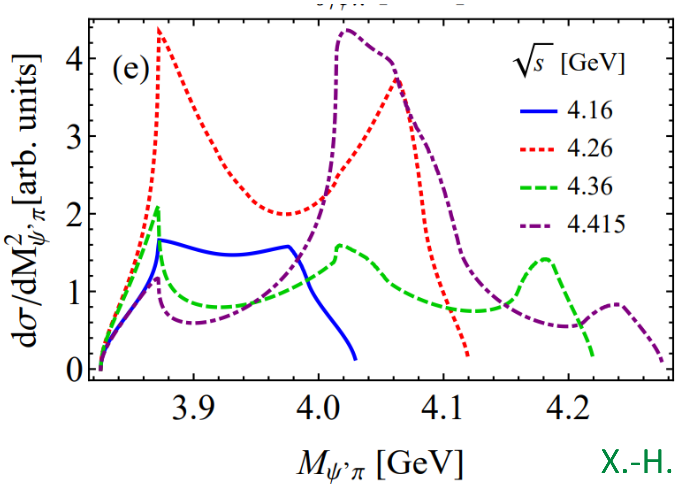
Exp. data: LHCb, PRL112(2014)222002

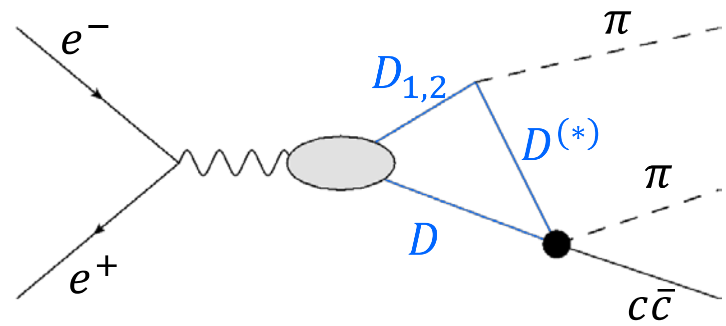


TS sensitive to kinematics!

TS: nontrivial energy dependence

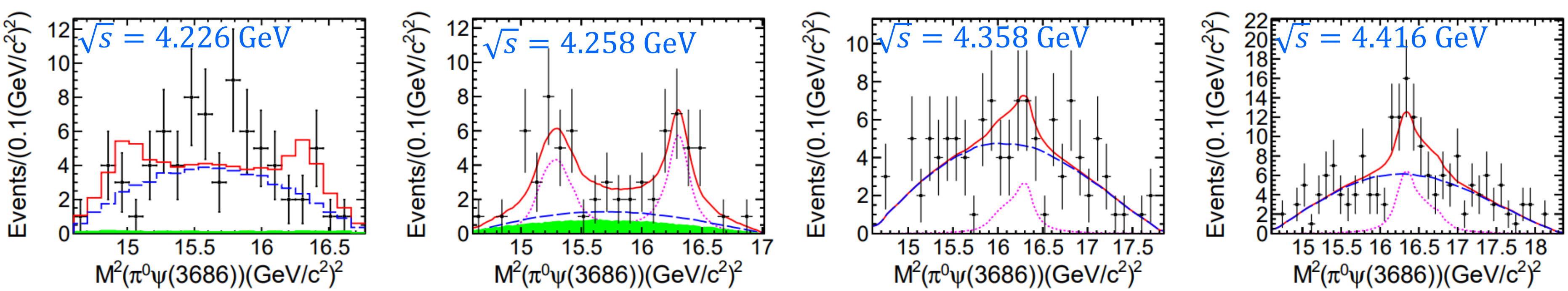
Highly nontrivial energy dependence expected, e.g. $e^+e^- \to \psi'\pi^+\pi^-$





X.-H. Liu, PRD90(2014)074004

Difficulty/opportunity of identifying Z_c



BESIII measurement of $e^+e^- \to \psi'\pi^0\pi^0$ BESIII, PRD97(2018)052001

P=+ spin multiplets

- Heavy quark spin symmetry: multiplet structure — Cleven et al., PRD92(2015)014005
  - For charmonia, spin triplet: $\chi_{cJ}(J^{++}, J = 0,1,2)$; and spin singlet: $h_c\ (1^{+-})$
  - For hadro-charmonia, similar structure as charmonia
  - For tetraquark models, controlled by $c\bar{c}$ (not necessarily color singlet) interaction
  - For hadronic molecules, controlled by meson-meson interaction. Examples:
    - For X(3872), an $X_2\ (2^{++})$ is generally expected, not identified so far
    - Existence of 0^{++} and 1^{+-} unknown
    - For Z_b states, $W_{bJ}(J^{++}, J = 0,1,2, I = 1)$ expected — Bondar et al., PRD84(2011)054010; See talk by Alexey Nefediev

    W_{bJ} not seen so far in $\Upsilon\pi\pi$ in search of X_b — CMS, PLB727(2013)57; ATLAS, PLB740(2015)199

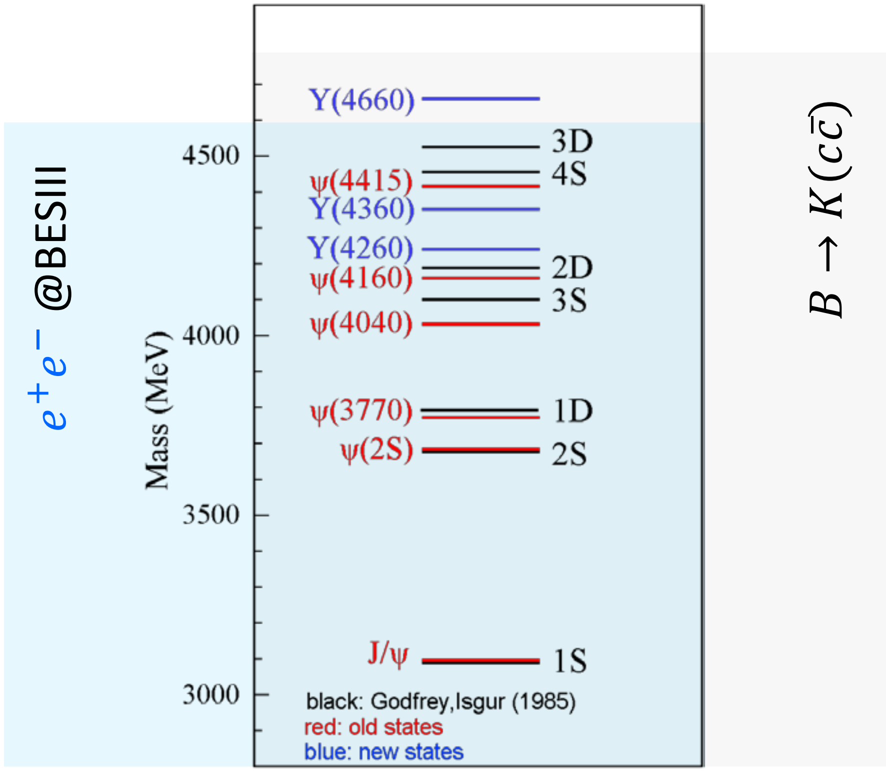
    (re-interpreted)

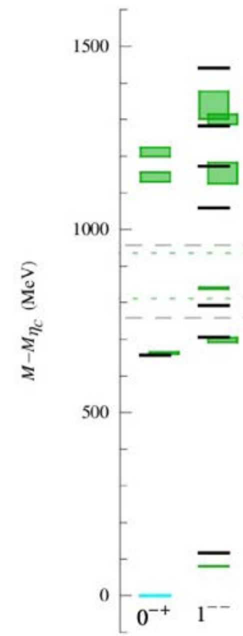
- More insights from studying states with related J^{PC} (maybe the same multiplet)
  - States with J^{++} at around 3.9 GeV: X(3860), X(3872), X(3915), $\chi_{c2}(3930)$, …
  - $\tilde{X}(3872)$ by COMPASS, consistent with 1^{+-}, better called $h_c(3860)$, relation to X?

    $M = (3860.0 \pm 10.4)$ MeV, $\Gamma < 51$ MeV — COMPASS, PLB783(2018)334

Vector charmonium(-like) states

- In e^+e^-, from decays of higher vector charmonia
- Vector charmonium(-like) states

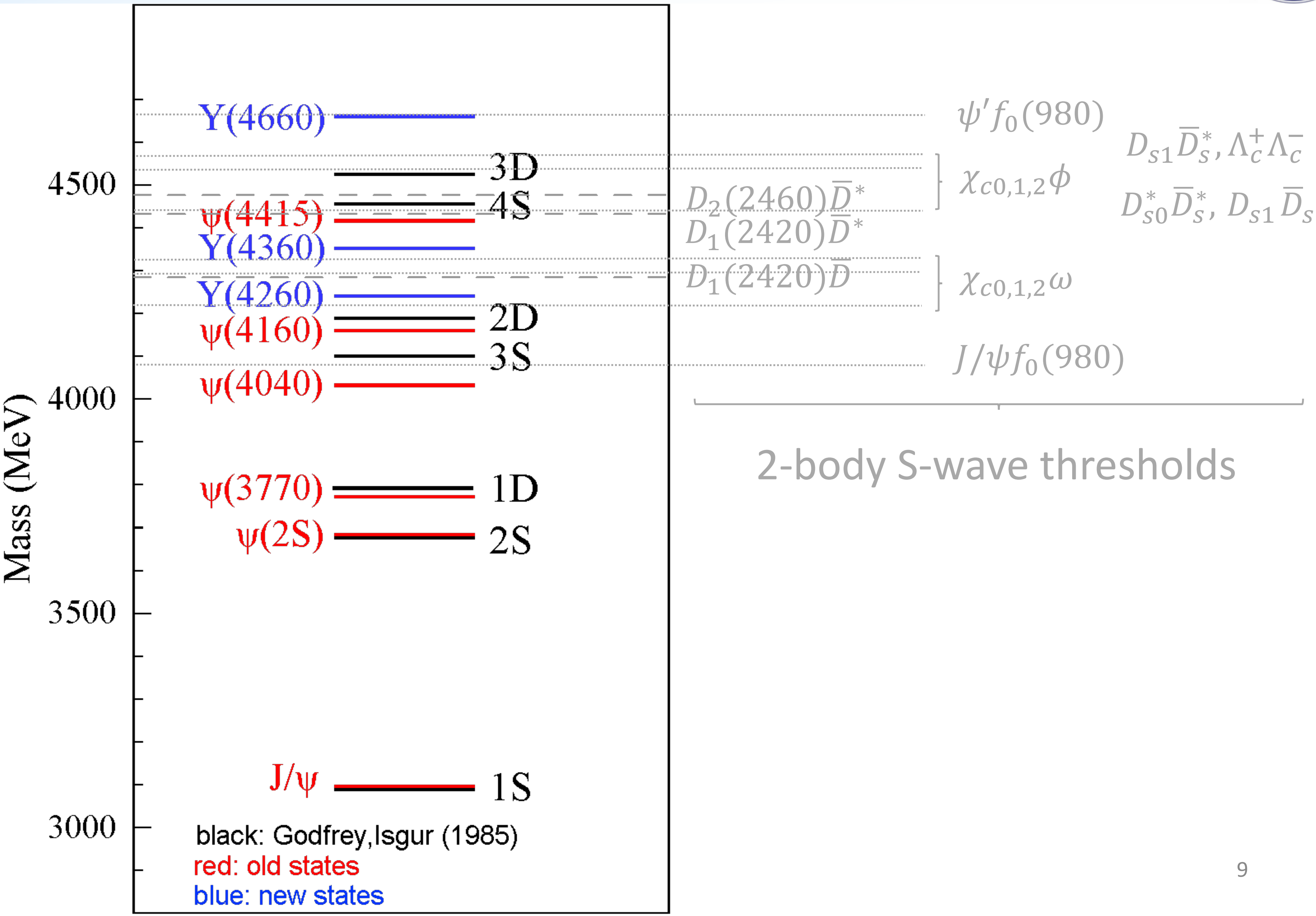




Lattice QCD, L. Liu et al., JHEP1207,126

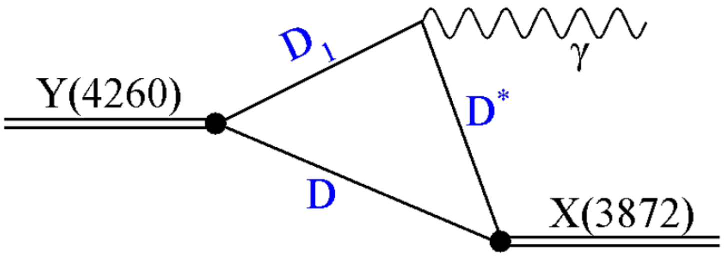
- ➢ Too many vector states (6+3) compared to potential model predictions or lattice QCD results using only $c\bar{c}$ operators
- ➢ Not seen in $D\bar{D}$, while $\mathrm{B}(\psi(3770) \to D\bar{D}) = (98^{+8}_{-9})\%$

Y: many thresholds above 4 GeV

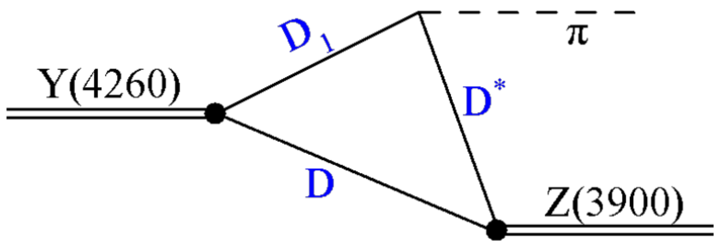


From Y to X and Z

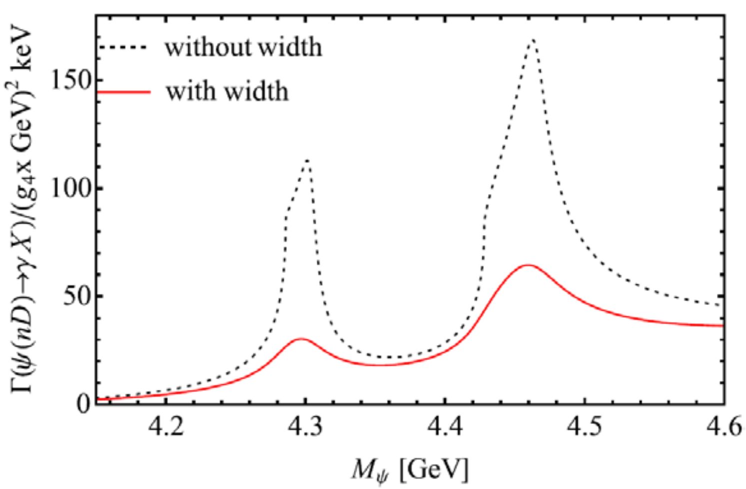
- Strong S-wave coupling of $Y(4260)$ to $D_1\bar{D} + c.c.$
- Strong S-wave coupling of $X(3872)$ and $Z_c(4020)$ to $D^*\bar{D} + c.c.$

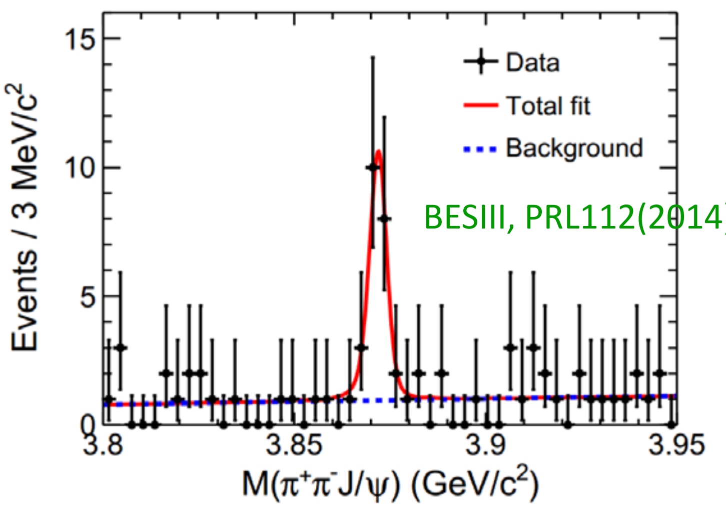


FKG et al., PLB725(2013)106



Q. Wang, C. Hanhart, Q. Zhao, PRL111(2013)132003





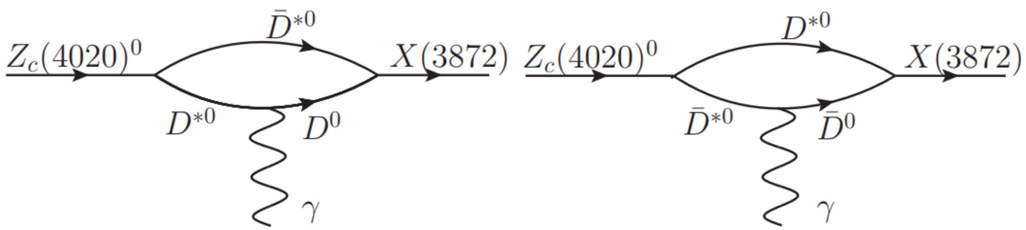
BESIII, PRL112(2014)092001

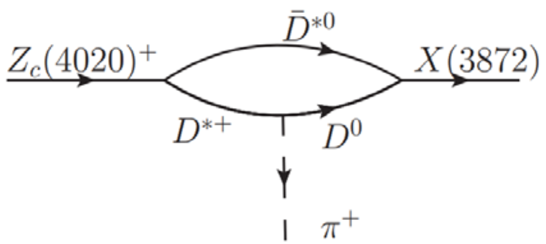
BESIII observed $e^+e^- \to \gamma X(3872)$ at $E = 4.26$ GeV

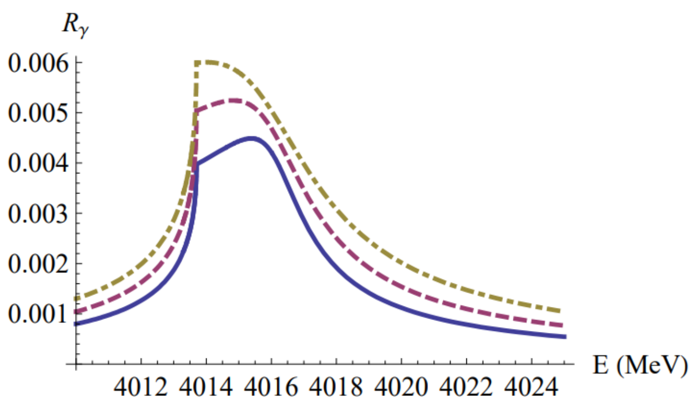
From Z to X ?

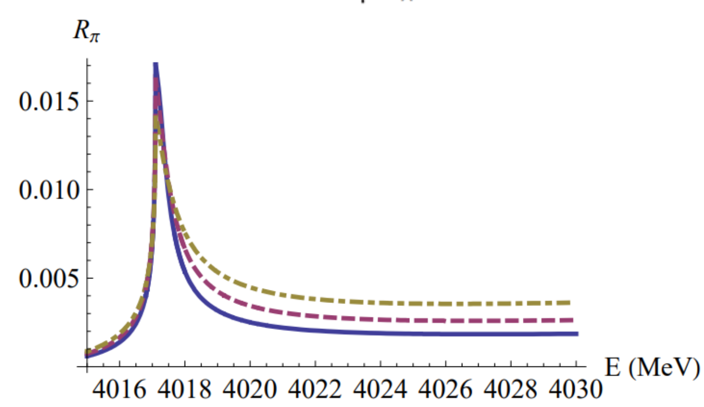
- Similarly, strong S-wave coupling of $Z_c(4020)$ to $D^*\bar{D}^*$; strong S-wave coupling of $X(3872)$ to $D^*\bar{D} + c.c.$
- $Z_c(4020)^0 \to X(3872)\gamma$ and $Z_c(4020)^{\pm} \to X(3872)\pi^{\pm}$

M. Voloshin, 1902.01281









- Branching fractions strongly energy-sensitive, ~ permil to percent level
- Reason: triangle singularity close to the physical region

From Y to X_2?

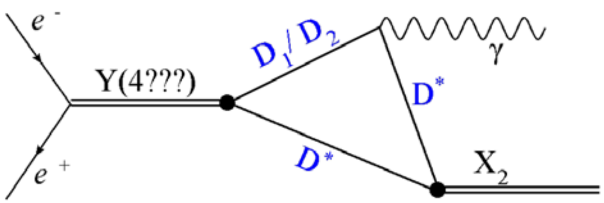
- X_2: $2^{++}, M \approx 4$ GeV, $D^*\bar{D}^*$, spin partner of $X(3872)$ in hadronic molecular model

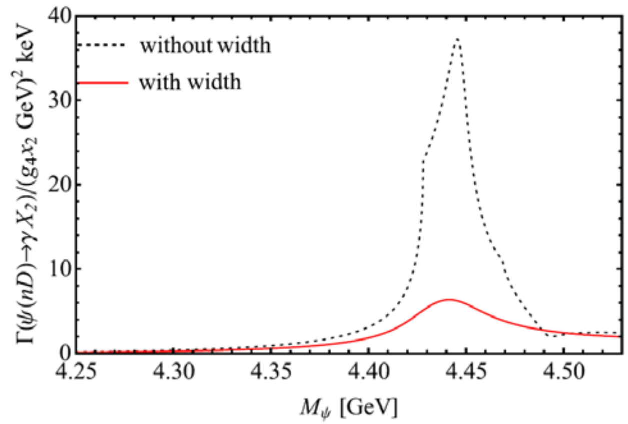
  Nieves, Pavon Valderrama, PRD86(2012)056004

  Small width $\lesssim 50$ MeV   Albaladejo et al., EPJC75(2014)547; Baru et al., PLB763(2016)20

- Methods of producing X_2 in e^+e^-:
  - $e^+e^- \to \gamma X_2$, $X_2 \to D\bar{D}, D\bar{D}^*, J/\psi\omega$

    FKG, Meißner, Yang, PLB740(2015)42

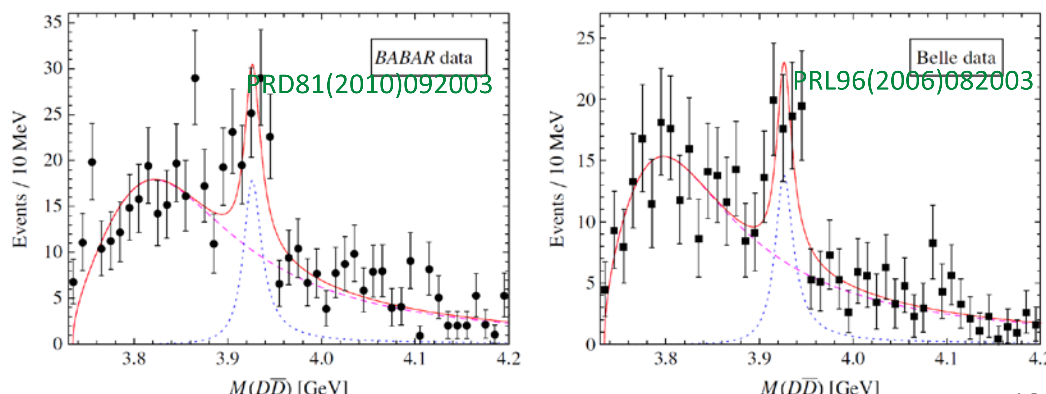




$$\sqrt{s} \sim 4.26 \text{ GeV} + (M_{D_1/D_2} + M_{D^*}) - (M_{D_1} + M_D) \sim [4.4, 4.5] \text{ GeV}$$

  - $\gamma\gamma \to X_2 \to D\bar{D}, D\bar{D}^*, J/\psi\omega$

    No signal in existing data for $\gamma\gamma \to D\bar{D}$

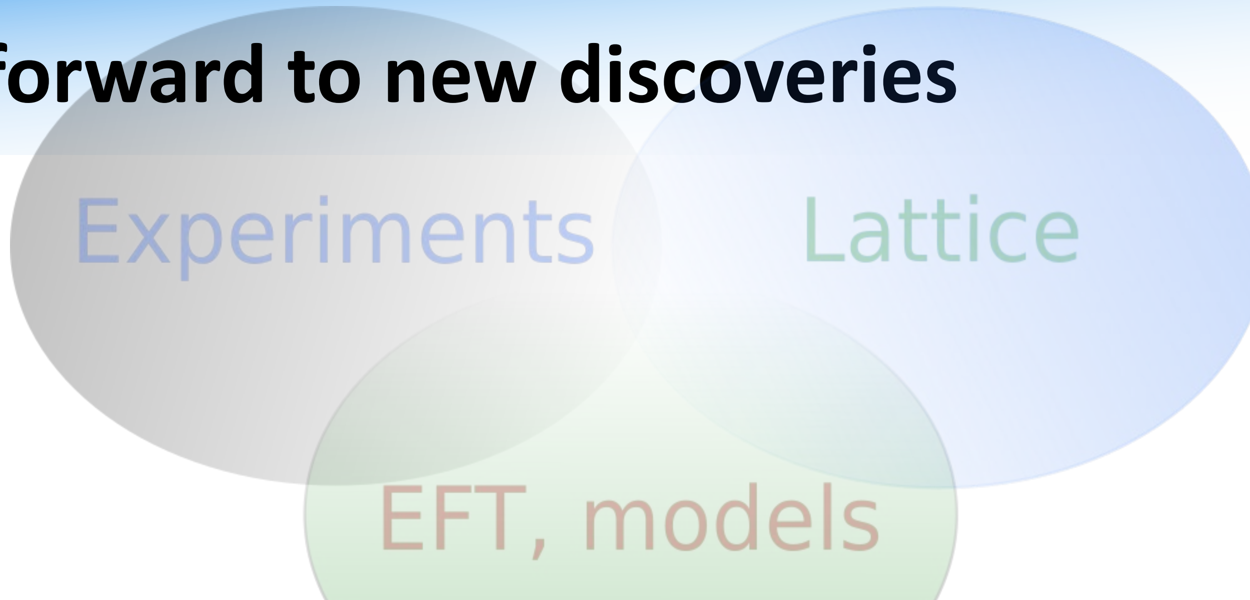


FKG, Meißner, PRD86(2012)091501

XYZ at SCTF/STCF

- No clear pattern for XYZ so far: to establish the hidden-charm spectrum far beyond 4 GeV, necessary to establish a pattern
- To study the known vector states and Z_c in much more detail; higher vector spectrum
- For J^{++} excited states with masses about 3.8-4 GeV: At SCTF/STCF, hadronic channels: $E \gtrsim 4.7\ \mathrm{GeV}, e^+e^- \to \omega X(J^{++})$
- To study the heavier PC=++ states observed in $\phi\, J/\psi$, $E > 5\ \mathrm{GeV}, e^+e^- \to \phi X(J^{++})$
- $E > 5\ \mathrm{GeV}$, to reveal expected rich phenomena above charm baryon-antibaryon thresholds; also above thresholds of excited charm-meson pairs; physics of excited charm mesons
- $E > 5\ \mathrm{GeV}$, $J/\psi p\bar{p}, \Lambda_c \bar{D} \bar{p}$, … accessible, hidden-charm pentaquarks, rich spectrum above $\Lambda_c \bar{D}$ threshold
- Energy can vary $\Longrightarrow$ handle of kinematic singularities in multi-hadron final states

Looking forward to new discoveries

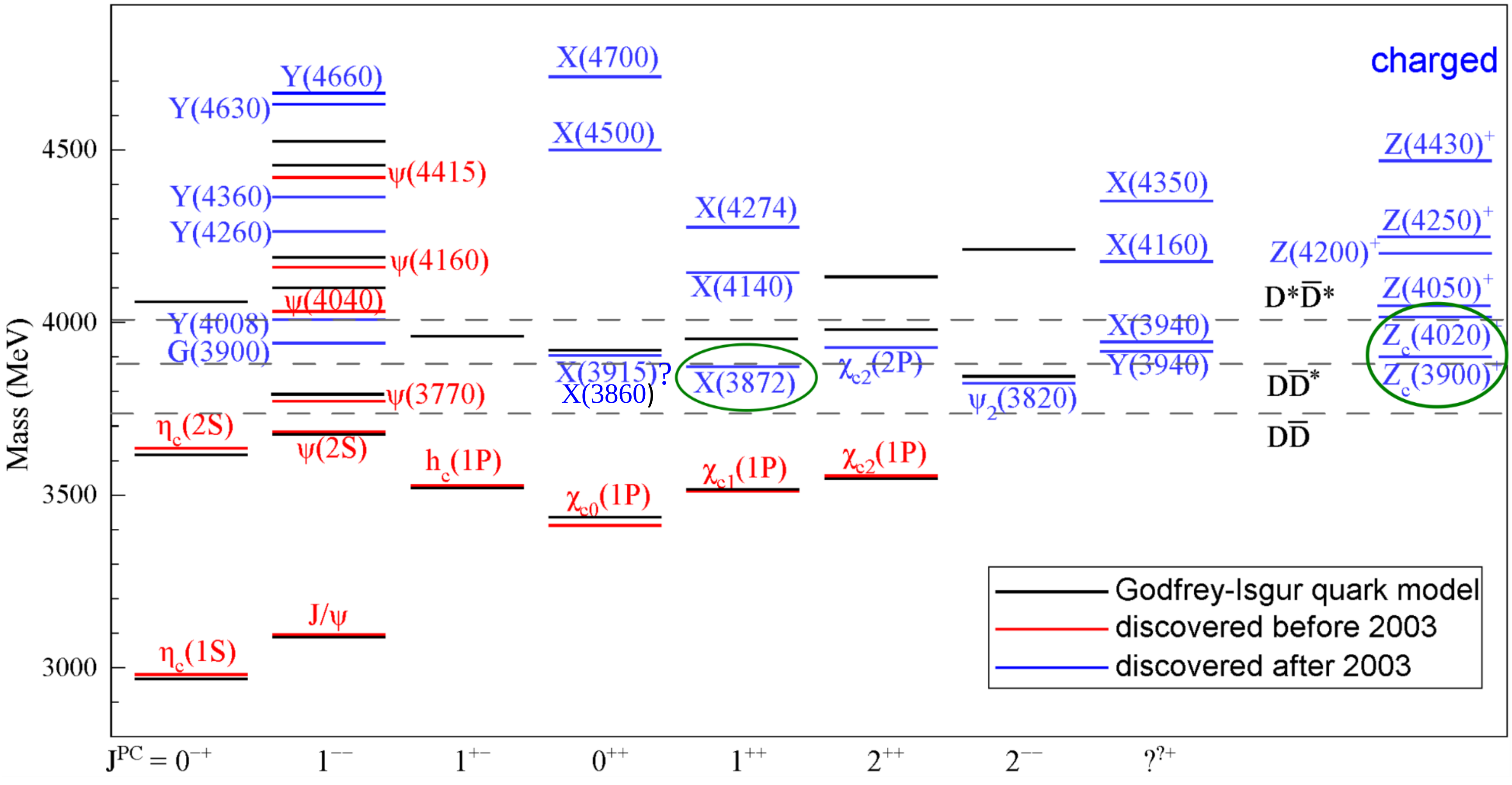


HADRON2019: August 16-21, 2019, Guilin, China

http://hadron2019.csp.escience.cn https://indico.ihep.ac.cn/event/9119

Thank you for your attention!

XYZ: no clear pattern



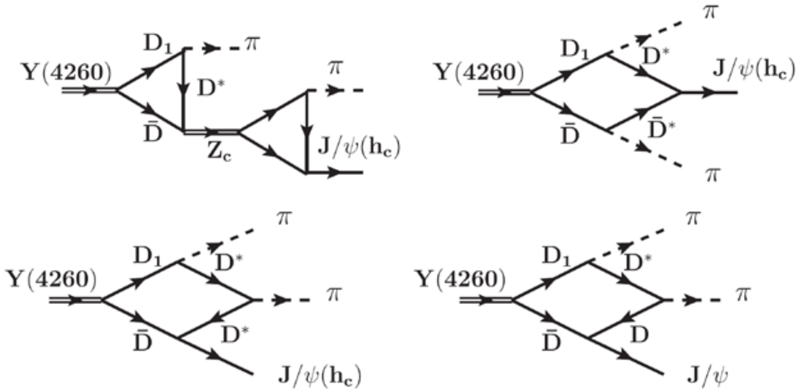
Y(4260): puzzling features

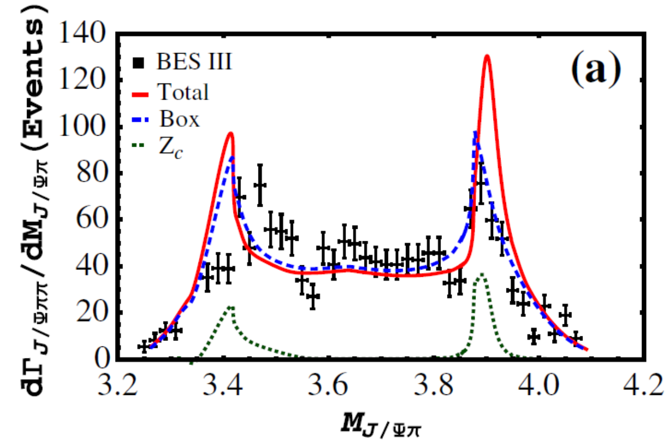
- No obvious slot in charmonium spectrum in quark model
- Not seen in R-scan
- Not seen in $D\bar{D}$, $D^*\bar{D}+c.c.$, contrary to known ψ states above the $D\bar{D}$ threshold
- The only observed open-charm channel: $D^0D^{*-}\pi^+ + c.c.$
- Similar cross sections into spin-triplet and spin-singlet final states
  - Spin-triplet: $J/\psi\pi^+\pi^-$, $\chi_{c0}\omega$
  - Spin-singlet: $h_c\pi^+\pi^-$
  - Mixture of spin-triplet and spin-singlet: $D^0D^{*-}\pi^+ + c.c.$

Y(4260): strong coupling to $D_1\bar{D}$

- Y(4260) as mainly a $D_1(2420)\bar{D}$ hadronic molecule (never purely)

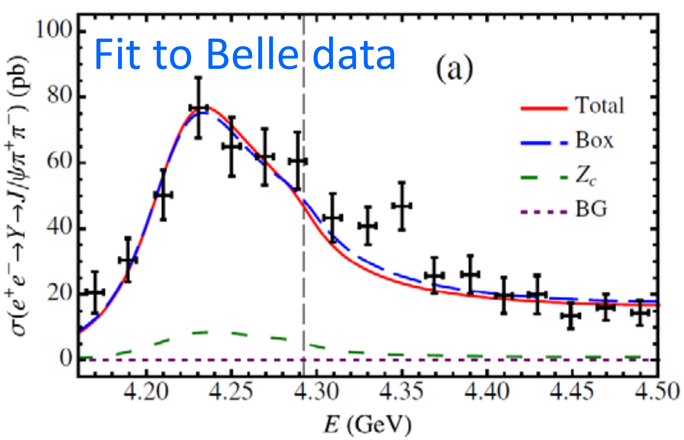
Q. Wang, C. Hanhart, Q. Zhao, PRL111(2013)132003



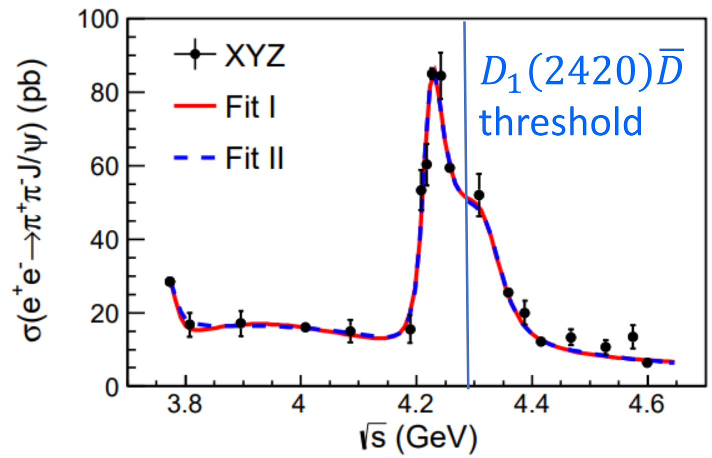


- a large coupling to $D_1\bar{D}$ $\Longrightarrow$ large impact on the line shape

M. Cleven et al., PRD90(2014)074039
see also Qin et al., PRD94(2016)054035



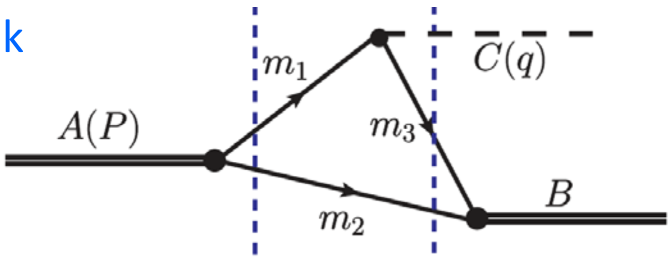
$M_Y = (4217.2 \pm 2.0)$ MeV



BESIII data PRL118(2017)092001

Triangle singularity

Logarithmic singularity ⇒ peak



$$\frac{1}{2m_A}\sqrt{\lambda(m_A^2, m_1^2, m_2^2)} \equiv \boxed{p_{2,\text{left}} = p_{2,\text{right}}} \equiv \gamma\,(\beta\, E_2^* - p_2^*)$$

on-shell momentum of m_2 at the left and right cuts in the A rest frame

$\beta = |\vec{p}_{23}|/E_{23},\ \gamma = 1/\sqrt{1-\beta^2}$ Bayar et al., PRD94(2016)074039

- $p_2 > 0,\ p_3 = \gamma\,(\beta\, E_3^* + p_2^*) > 0 \Rightarrow$ m_2 and m_3 move in the same direction
- velocities in the A rest frame: $v_3 > \beta > v_2$

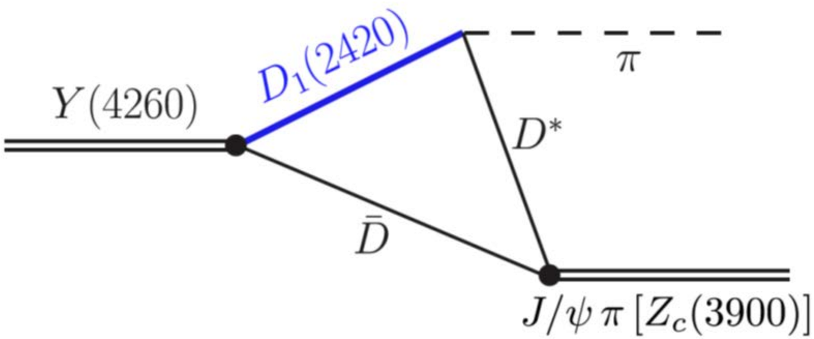
$$v_2 = \beta\,\frac{E_2^* - p_2^*/\beta}{E_2^* - \beta\, p_2^*} < \beta\,, \qquad v_3 = \beta\,\frac{E_3^* + p_2^*/\beta}{E_3^* + \beta\, p_2^*} > \beta$$

- Conditions (Coleman–Norton theorem): Coleman, Norton (1965); Bronzan (1964)
  - ☞ all three intermediate particles can go on shell simultaneously
  - ☞ $\vec{p}_2 \parallel \vec{p}_3$, particle-3 can catch up with particle-2 (as a classical process)
- needs very special kinematics ⇒ process dependent! (contrary to pole position)

For a brief review, see FKG, Hanhart, Meißner, Wang, Zhao, Zou, RMP90(2018)015004

From Y to Z

- Strong S-wave coupling of $Y(4260)$ to $D_1\bar{D} + c.c.$
- Strong S-wave coupling of $Z_c(3900)$ to $D^*\bar{D} + c.c.$
- Natural production mechanism of $Z_c(3900)$:



- Enhancement due to closeness to thresholds

$$\mathcal{A} \sim \frac{v^5}{(v^2)^3} \text{Vertex}_{D_1 D^*}(p_\pi) = \frac{1}{v} \text{Vertex}_{D_1 D^*}(p_\pi)$$

Intermediate mesons are nonrelativistic, $v \sim 0.1 \ll 1$

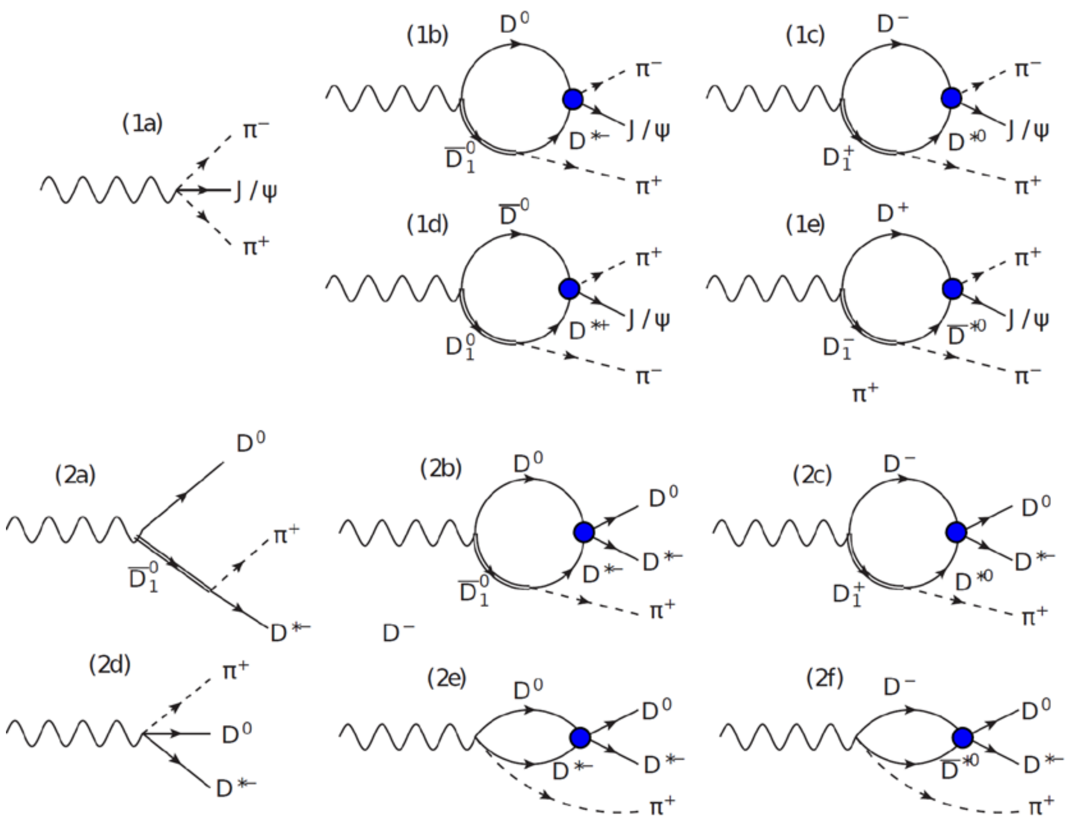
Power counting: 3-momentum $\sim \mathcal{O}(v)$, energy $\sim \mathcal{O}(v^2)$

loop integral measure $\sim \mathcal{O}(v^5)$, propagator $\sim \mathcal{O}(v^{-2})$

From Y to Z

- Coupled-channel analysis with both FSI and triangle diagrams

Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337



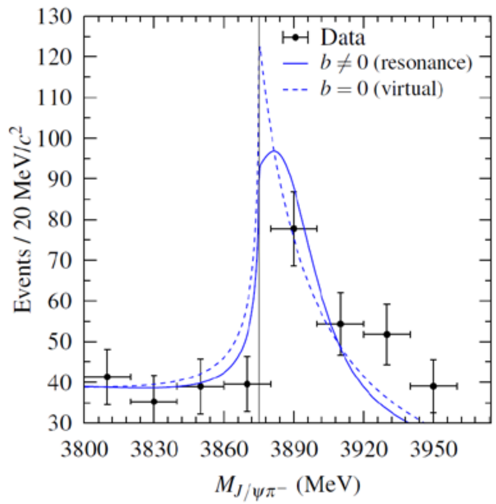
Blue bulbs: FSI T-matrix, it may or may not have a near-threshold pole (Z_c); data will tell

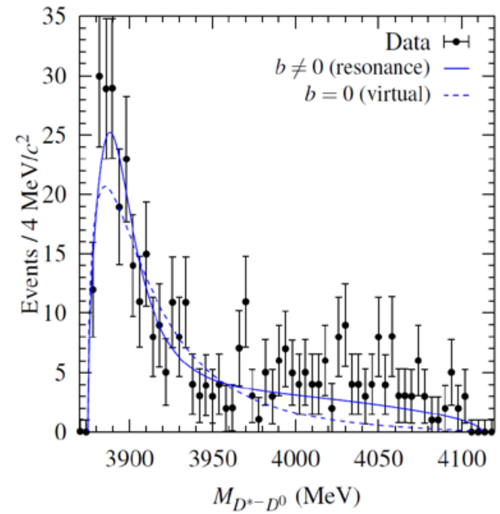
Kinematical singularities (threshold cusp, TS) and resonances are NOT exclusive

From Y to Z

Fit to BESIII data at 4.26 GeV — Albaladejo, FKG, Hidalgo-Duque, Nieves, PLB755(2016)337

$Z_c(3900)$ is needed: either a resonance or a virtual state, more precise line shape data needed





M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	[1] (BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	[2] (Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	[3] (CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	[4] (BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	[5] (BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi$, $\bar{D}^* D$
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi$, $\bar{D}^* D$
$3831 \pm 26^{+7}_{-28}$	virtual state	$\Lambda_2 = 1.0$ GeV	$J/\psi\ \pi$, $\bar{D}^* D$
$3844 \pm 19^{+12}_{-21}$	virtual state	$\Lambda_2 = 0.5$ GeV	$J/\psi\ \pi$, $\bar{D}^* D$

resonance pole $\chi^2/\text{dof} = 1.09$

or virtual state $\chi^2/\text{dof} = 1.36$