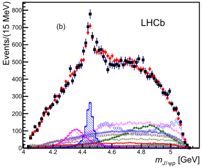


Remarks on $P_c(4450)$ and triangle singularity

Feng-Kun Guo

Institute of Theoretical Physics, Chinese Academy of Sciences

CRC110 Workshop on Nuclear Dynamics and Threshold Phenomena,
Ruhr-Universität Bochum, April 5-7, 2017

Based on:

FKG, U.-G. Meißner, W. Wang, Z. Yang, Phys. Rev. D **92**, 071502(R) (2015) [arXiv:1507.04950[hep-ph]]

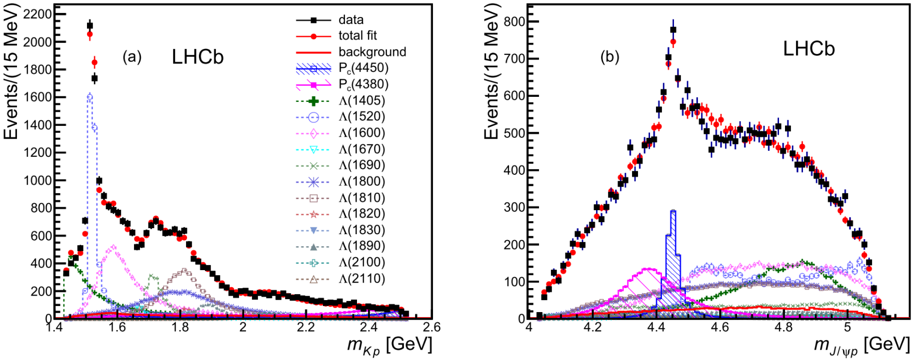
FKG, U.-G. Meißner, J. Nieves, Z. Yang, Eur. Phys. J. A **52**, 318 (2016) [arXiv:1605.05113[hep-ph]]

M. Bayar, A. Aceti, FKG, E. Oset, Phys. Rev. D **94**, 074039 (2016) [arXiv:1609.04133]

LHCb pentaquark-like structures: Big news in 2015!

PRL115(2015)072001 [arXiv:1507.03414]

submitted to PRL on 13.07, accepted on 24.07; appeared on arXiv on 14.07.2015



$M_1 = (4380 \pm 8 \pm 29)$ MeV, $\Gamma_1 = (205 \pm 18 \pm 86)$ MeV,

$M_2 = (4449.8 \pm 1.7 \pm 2.5)$ MeV, $\Gamma_2 = (39 \pm 5 \pm 19)$ MeV.

LHCb pentaquark-like structures (II)

- Quantum numbers not fully determined, for ($P_c(4380), P_c(4450)$):
  $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$
- In $J/\psi\, p$ invariant mass distribution, with hidden charm
  $\Rightarrow$ pentaquarks if they are really hadron states
- Narrow pentaquark-like structures with hidden-charm had been predicted 5 years ago (07.2010):
  Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV,
  J. J. Wu, R. Molina, E. Oset, B. S. Zou, Phys. Rev. Lett. **105** (2010) 232001.

A flood of short papers

14.07 The LHCb paper appeared on line, arXiv:1507.03414

15.07 R. Chen, X. Liu, X.-Q. Li and S.-L. Zhu, arXiv:1507.03704 [hep-ph].
H.-X. Chen, W. Chen, X. Liu, T. G. Steele and S.-L. Zhu, arXiv:1507.03717 [hep-ph].

16.07 L. Roca, J. Nieves and E. Oset, arXiv:1507.04249 [hep-ph].

17.07 A. Mironov and A. Morozov, arXiv:1507.04694 [hep-ph].

18.07 weekend,

19.07 but everybody was working hard (NOT including me)...

20.07 F.-K. Guo, U.-G. Meißner, W. Wang and Z. Yang, arXiv:1507.04950 [hep-ph].
L. Maiani, A. D. Polosa and V. Riquer, arXiv:1507.04980 [hep-ph].

21.07 J. He, arXiv:1507.05200 [hep-ph]; X. H. Liu, Q. Wang, Q. Zhao, arXiv:1507.05359 [hep-ph].

22.07 R. F. Lebed, arXiv:1507.05867 [hep-ph].

23.07 Exotic! why no new papers?

24.07 M. Mikhasenko, arXiv:1507.06552 [hep-ph].

28.07 U.-G. Meißner and J. A. Oller, arXiv:1507.07478 [hep-ph].

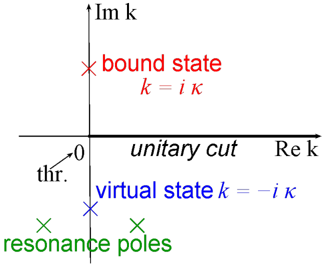
29.07 V. V. Anisovich *et al.*, arXiv:1507.07652 [hep-ph].

30.07 G.-N. Li, M. He, X.-G. He, arXiv:1507.08252 [hep-ph].

... .

Two kinds of singularities of the S matrix

- Poles in the S-matrix: dynamics
  - ☞ bound states (real axis, 1st Riemann sheet (RS) of the complex energy plane)
  - ☞ virtual states (real axis, 2nd RS)
  - ☞ resonances (2nd RS)



- Landau singularities: kinematics
  - ☞ (a): two-body threshold cusp
  - ☞ (b): triangle singularity

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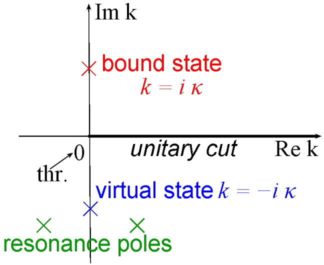

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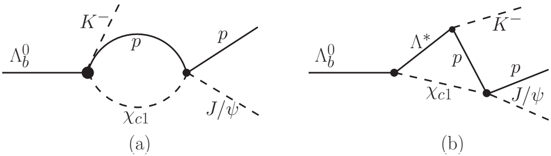

$P_c(4450)$ is at the $\chi_{c1}p$ threshold

- Mass: $M = (4449.8 \pm 1.7 \pm 2.5)$ MeV

  The LHCb paper says:

  the closest threshold is at (4457.1 ± 0.3) MeV $[\Lambda_c(2595)\bar{D}^0]$

  $\Rightarrow$ difficult to explain with threshold effect

  but, in fact, much more complicated!

- It is located *exactly* at the $\chi_{c1}p$ threshold:

$$M_{P_c(4450)} - M_{\chi_{c1}} - M_p = (0.9 \pm 3.1)\ \text{MeV}$$

  and at a triangle singularity at the same time!

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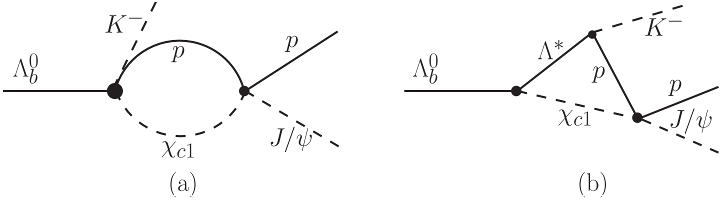
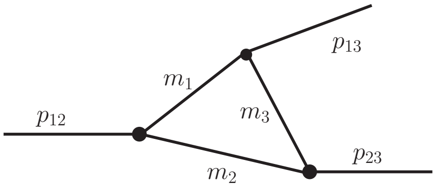


Landau equation



- Triangle singularity: leading Landau singularity for a triangle diagram, anomalous threshold

  studied extensively in 1960s

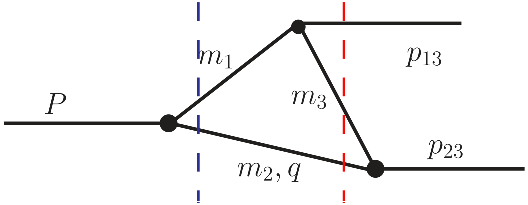
- Solutions of Landau equation for a triangle diagram: Landau (1959)

$$1 + 2\, y_{12}\, y_{23}\, y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2, \qquad y_{ij} \equiv \frac{m_i^2 + m_j^2 - p_{ij}^2}{2\, m_i\, m_j}$$

  quadratic equation of y_{ij}, always two solutions

- Do they affect the physical amplitude?

Some details (I)



Consider the scalar three-point loop integral

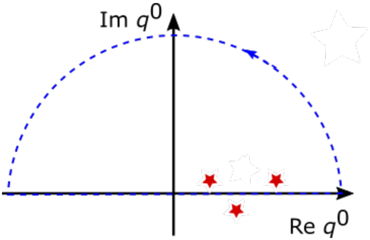
$$I = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{[(P-q)^2 - m_1^2 + i\epsilon]\,(q^2 - m_2^2 + i\epsilon)\,[(p_{23}-q)^2 - m_3^2 + i\epsilon]}$$

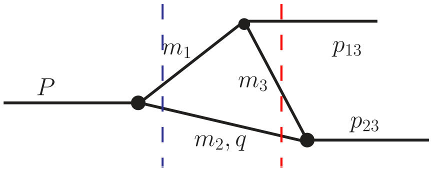
Rewriting a propagator into two poles:

$$\frac{1}{q^2 - m_2^2 + i\epsilon} = \frac{1}{(q^0 - \omega_2 + i\epsilon)\,(q^0 + \omega_2 - i\epsilon)} \quad \text{with} \quad \omega_2 = \sqrt{m_2^2 + \vec{q}^{\,2}}$$

focus on the positive-energy poles

$$I \simeq \frac{i}{8m_1m_2m_3} \int \frac{dq^0 d^3\vec{q}}{(2\pi)^4} \frac{1}{(P^0 - q^0 - \omega_1 + i\epsilon)\,(q^0 - \omega_2 + i\epsilon)\,(p_{23}^0 - q^0 - \omega_3 + i\epsilon)}$$





Contour integral over $q^0 \Rightarrow$

$$I \propto \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{1}{[P^0 - \omega_1(q) - \omega_2(q) + i\,\epsilon][p_{23}^0 - \omega_2(q) - \omega_3(\vec{p}_{23} - \vec{q}\,) + i\,\epsilon]}$$

$$\propto \int_0^\infty dq\, \frac{q^2}{P^0 - \omega_1(q) - \omega_2(q) + i\,\epsilon} f(q)$$

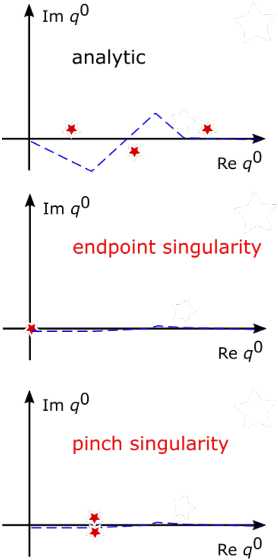
The second cut:

$$f(q) = \int_{-1}^{1} dz\, \frac{1}{p_{23}^0 - \omega_2(q) - \sqrt{m_3^2 + q^2 + p_{23}^2 - 2p_{23}qz} + i\,\epsilon}$$

Some details (III)

Relation between singularities of integrand and integral

- singularity of integrand does not necessarily give a singularity of integral: integral contour can be deformed to avoid the singularity
- Two cases that a singularity cannot be avoided:
  - ☞ endpoint singularity
  - ☞ pinch singularity



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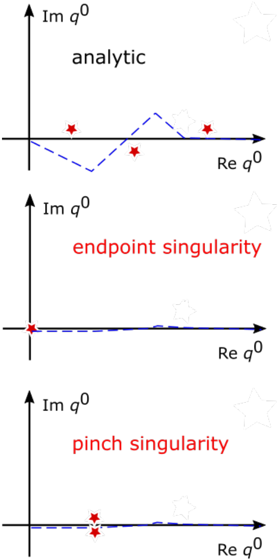
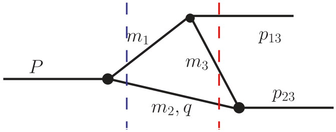




$$I \propto \int_0^\infty dq \, \frac{q^2}{P^0 - \omega_1(q) - \omega_2(q) + i\,\epsilon} f(q)$$

$$f(q) = \int_{-1}^{1} dz \, \frac{1}{A(q,z)} \equiv \int_{-1}^{1} dz \, \frac{1}{p_{23}^0 - \omega_2(q) - \sqrt{m_3^2 + q^2 + p_{23}^2 - 2p_{23}qz} + i\,\epsilon}$$

Singularities of the **integrand of I** in the rest frame of initial particle:

- 1st cut: $M - \omega_1(l) - \omega_2(l) + i\,\epsilon = 0 \Rightarrow$

$$q_{\text{on}\pm} \equiv \pm \left(\frac{1}{2M} \sqrt{\lambda(M^2, m_1^2, m_2^2)} + i\,\epsilon \right)$$

- 2nd cut: $A(q, \pm 1) = 0 \Rightarrow$ endpoint singularities of $f(q)$

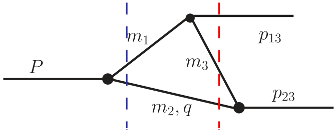
$$z = +1: \quad q_{a+} = \gamma\,(\beta\, E_2^* + p_2^*) + i\,\epsilon\,, \qquad q_{a-} = \gamma\,(\beta\, E_2^* - p_2^*) - i\,\epsilon\,,$$

$$z = -1: \quad q_{b+} = \gamma\,(-\beta\, E_2^* + p_2^*) + i\,\epsilon\,, \quad q_{b-} = -\gamma\,(\beta\, E_2^* + p_2^*) - i\,\epsilon$$

$$\beta = |\vec{p}_{23}|/E_{23}, \qquad \gamma = 1/\sqrt{1-\beta^2} = E_{23}/m_{23}$$

$E_2^*(p_2^*)$: energy (momentum) of particle-2 in the cmf of the (2,3) system

Some details (IV)



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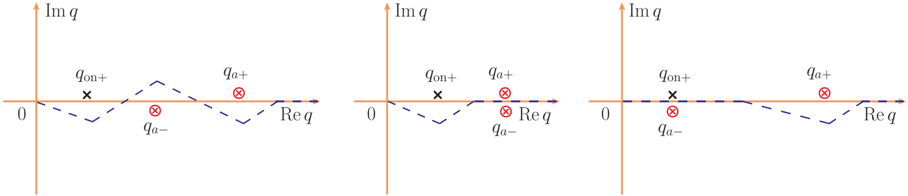
Some details (V)

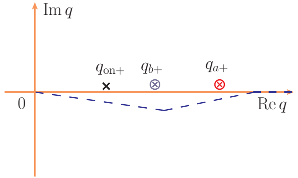
All singularities of the integrand:

$$q_{\text{on}+}, \qquad q_{a+} = \gamma\,(\beta\, E_2^* + p_2^*) + i\,\epsilon, \qquad q_{a-} = \gamma\,(\beta\, E_2^* - p_2^*) - i\,\epsilon,$$

$$q_{\text{on}-} < 0, \quad q_{b-} = -q_{a+} < 0 \text{ (for } \epsilon = 0), \qquad q_{b+} = -q_{a-},$$



(a) (b) (c)



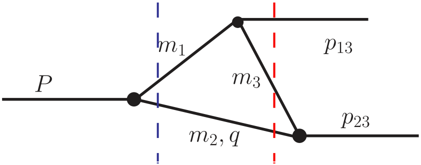
2-body threshold singularity at

$m_{23} = m_2 + m_3$

triangle singularity at

$\boxed{q_{\text{on}+} = q_{a-}}$

Some details (VI)



Rewrite $q_{a-} = p_2 - i\,\epsilon, \quad p_2 \equiv \gamma\,(\beta\,E_2^* - p_2^*)$

Kinematics for $p_2 > 0$, which is relevant to triangle singularity:

- $p_3 = \gamma\,(\beta\,E_3^* + p_2^*) > 0 \Rightarrow$
  particles 2 and 3 move in the same direction in the rest frame of initial particle
- velocities in the rest frame of the initial particle: $v_3 > \beta > v_2$

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

particle 3 moves faster than particle 2 in the rest frame of initial particle

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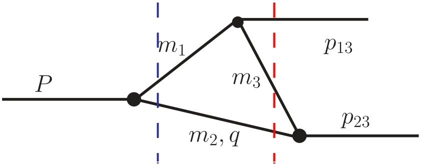

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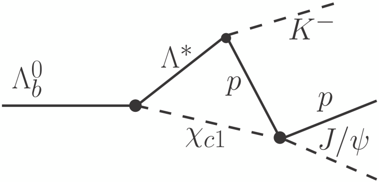
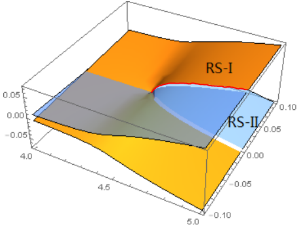
Coleman-Norton theorem





- Coleman–Norton theorem: S. Coleman and R. E. Norton, Nuovo Cim. 38 (1965) 438

  The singularity is on the physical boundary if and only if the diagram can be interpreted as a classical process in space-time.

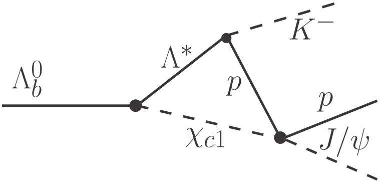
  ☞ physical boundary: upper edge (lower edge) of the unitary cut in the first (second) Riemann sheet

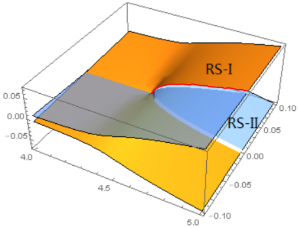
- Translation:

  ☞ all three intermediate states can go on shell

  ☞ $\vec{p} \parallel \vec{p}_{\chi_{c1}}$, the proton can catch up with the χ_{c1} to rescatter

Coleman-Norton theorem





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Analysis of the kinematics

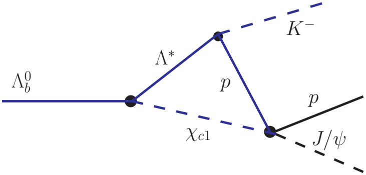
Dalitz plot for $\Lambda_b \to \chi_{c1}\Lambda^* \to \chi_{c1} p \bar{K}$:

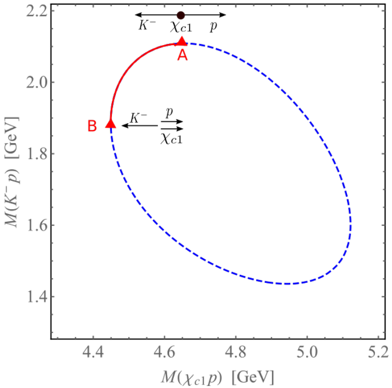
Starting from a large Λ^* mass, in Λ_b rest frame

- when $M_{\Lambda^*} > M_{\Lambda_b} - M_{\chi_c 1}$, cannot go on-shell
- at point A, $M_{\Lambda^*} = M_{\Lambda_b} - M_{\chi_c 1}$, χ_{c1} is at rest
- at point B, proton and χ_{c1} has the same velocity, $p\,\chi_{c1}$ threshold
- between A and B, $\vec{p}_p \parallel \vec{p}_{\chi_{c1}}$ and proton moves faster than χ_{c1}

$$M_{K^-p,A} = M_{\Lambda_b} - M_{\chi_{c1}},$$

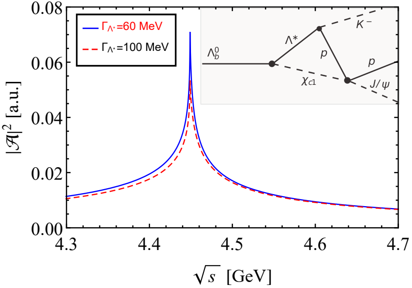
$$M_{K^-p,B} = \sqrt{\frac{M^2_{\Lambda_b} M_p + M^2_K M_{\chi_{c1}}}{M_{\chi_{c1}} + M_p} - M_{\chi_{c1}} M_p}$$

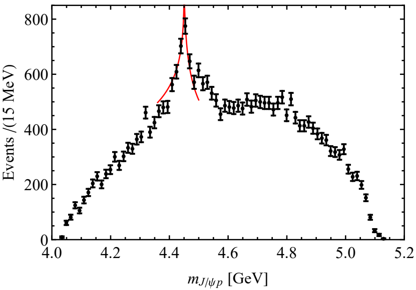




Triangle singularity for $P_c(4450)$

- At point B, the triangle singularity is exactly at the $\chi_{c1}p$ threshold, 4.449 GeV, requiring $M_{\Lambda^*} = 1.89$ GeV
- Coincidentally, four-star baryon $\Lambda(1890)$: $J^P = 3/2^+, \Gamma:\ 60 - 200$ MeV
- triangle loop with S-wave $\chi_{c1}p$: $J^P = \frac{1}{2}^+, \frac{3}{2}^+$



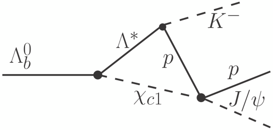


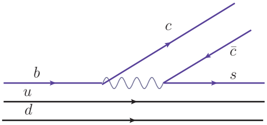
- impossible to produce a narrow peak for $\chi_{c1}p$ in other partial waves

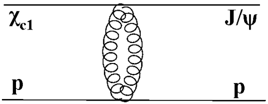
More comments

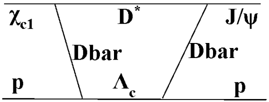
Strength of the triangle singularity is determined by

- couplings:
  - ☞ $\Lambda_b \to \Lambda^* \chi_{c1}$ is from $b \to c\bar{c}s$, not measured, but should have a sizeable branching fraction:
    Br$(B^+ \to J/\psi K^+) \simeq 1 \times 10^{-3}$,
    Br$(B^+ \to \chi_{c1} K^+) \simeq 0.5 \times 10^{-3}$
  - ☞ $\Lambda^*(1890) \to N\bar{K}$: largest branching fraction, Br$= 20 - 35\%$
  - ☞ $\chi_{c1} p \to J/\psi p$: OZI suppressed,
    $\mathcal{O}\left(1/N_c\right)$ [recall: OZI suppressed meson-meson scattering: $\mathcal{O}\left(1/N_c^2\right)$]









lattice QCD predicts possible $c\bar{c}$-nucleus bound states at $M_\pi = 805$ MeV

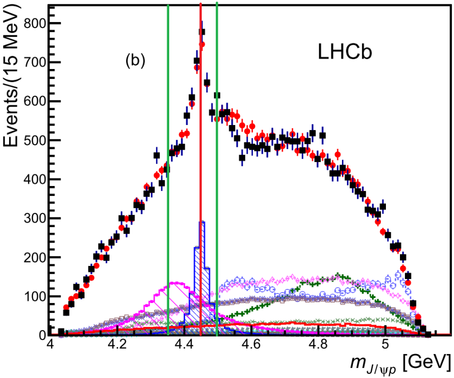
NPLQCD, PRD91(2015)114503

More triangle singularities?

- $\chi_{c0,c1,c2}\, p \to J/\psi\, p$ are related through heavy quark spin symmetry
- Weak decay $b \to c\bar{c}s$, $V - A \overset{\text{Fierz}}{\Rightarrow} \bar{c}\gamma^\mu(1-\gamma_5)c$
  - ☞ $\Lambda_b \to \Lambda^*\, J/\psi$ and $\Lambda_b \to \Lambda^*\, \chi_{c1}$ are easy
  - ☞ for χ_{c2}: strongly suppressed, χ_{c0}: also suppressed; for $B^+ \to \chi_{cJ} K^+$

$$\text{Br}_1 \simeq 5\times 10^{-4} > \text{Br}_0 \simeq 1.5\times 10^{-4} \gg \text{Br}_2 \simeq 1.1\times 10^{-5}$$

$\Rightarrow$ no obvious peak around the $\chi_{c0}\, p$ or $\chi_{c2}\, p$ threshold



Summary

- Two coincidences for the LHCb $P_c(4450)$ structure:
  - ☞ located exactly at the $\chi_{c1}\,p$ threshold
  - ☞ four-star $\Lambda(1890)$ makes a triangle singularity exactly at the same position
- To control the strength, we need:
  - ☞ Br$(\Lambda_b \to \Lambda^*(1890)\chi_{c1}) \Leftarrow$ LHCb
  - ☞ $\chi_{c1}p \to J/\psi p$, might get information from lattice QCD
- More measurements are necessary to reveal the nature of the $P_c(4450)$
  - ☞ J^P unambiguously
  - ☞ $\Lambda_b \to \chi_{c1}pK$
  - ☞ searching for $P_c(4450)$ in processes with a different kinematics

THANK YOU FOR YOUR ATTENTION!

Backup slides

Triangle singularity – literature

- Some recent work using triangle singularity to explain (part of) peak structures [$\eta(1405/1475)$, $a_1(1420)$, $\ldots$]:

  J. J. Wu, X. H. Liu, Q. Zhao and B. S. Zou, PRL108(2012)081803;

  X. G. Wu, J. J. Wu, Q. Zhao and B. S. Zou, PRD87(2013)014023(2013);

  Q. Wang, C. Hanhart and Q. Zhao, PLB725(2013)106;

  M. Mikhasenko, B. Ketzer and A. Sarantsev, PRD91(2015)094015;

  N. N. Achasov, A. A. Kozhevnikov and G. N. Shestakov, PRD92(2015)036003;

  X. H. Liu, M. Oka and Q. Zhao, PLB753(2016)297;

  A. P. Szczepaniak, PLB747(2015)410; PLB757(2016)61;

  F. Aceti, L. R. Dai and E. Oset, arXiv:1606.06893 [hep-ph];

  ......

Triangle singularity – literature

- Very old knowledge from 1960s:

  Classical books:

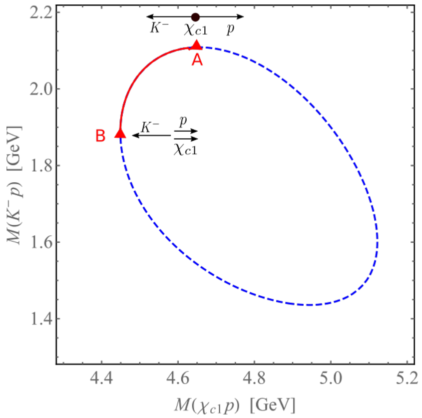
  R. J. Eden, P. V. Landshoff, D. I. Olive and J. C. Polkinghorne, *The Analytic S-Matrix* Cambridge University Press, 1966.

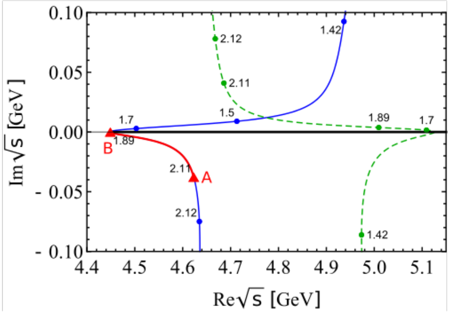
  T.-S. Chang, Introduction to Dispersion Relation (2 volumes, in Chinese, written in 1965), Science Press, Beijing 1980, 1983.

  Recent lecture notes by one of the key players:
  I. J. R. Aitchison, arXiv:1507.02697 [hep-ph].
  Unitarity, Analyticity and Crossing Symmetry in Two- and Three-hadron Final State Interactions.

Tsung-Sui Chang (1915–1969)

Trajectories of triangle singularities in complex energy plane





numbers: assumed masses for Λ^*

- blue: proton and χ_{c1} are parallel, in the 2nd Riemann sheet
- green: proton and χ_{c1} are anti-parallel

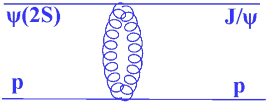
$M_{\Lambda_b} = 5.62$ GeV, $M_{\chi_{c1}} = 3.51$ GeV, $\quad \sqrt{s} \equiv M(\chi_{c1} p)$

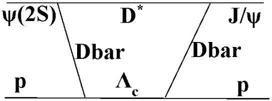
$$M_{K^-p,A} = M_{\Lambda_b} - M_{\chi_{c1}}, \qquad M_{K^-p,B} = \sqrt{\frac{M_{\Lambda_b}^2 M_p + M_K^2 M_{\chi_{c1}}}{M_{\chi_{c1}} + M_p} - M_{\chi_{c1}} M_p}$$

More triangle singularities?

Considering other possible $c\bar{c}$–Λ^* combinations:

- $h_c, \eta_c(1S, 2S)$: spin-singlet
  $\Rightarrow h_c[\eta_c(1S, 2S)]p \to J/\psi p$ breaks heavy quark spin symmetry, suppressed relative to $\chi_{c1}p \to J/\psi p$
- J/ψ:
  $J/\psi p \to J/\psi p$: elastic, no peak will show up (due to Schmid theorem)
- $\psi(2S)$: radial excitation different from J/ψ





in comparison with $\chi_{c1}p \to J/\psi p$

left: strongly suppressed; right: might be slightly suppressed, not very clear

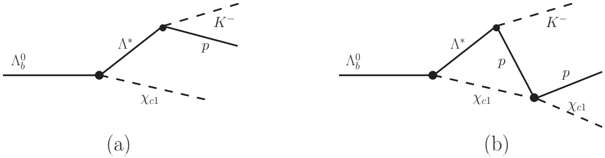
For possible triangle singularities for $\Lambda_b \to J/\psi p K$, the χ_{c1}–$\Lambda^*(1890)$ seems the most prominent one among all $c\bar{c}$–Λ^* combinations

How to distinguish triangle-singularity from genuine resonance?

- Schmid theorem: C. Schmid, Phys. Rev. 154 (1967) 1363

  see also, A. V. Anisovich, V. V. Anisovich, Phys. Lett. B 345 (1995) 321

  Triangle singularity cannot produce an additional peak in the invariant mass distribution of the elastic channel when neglecting inelasticity



  Nearby the effective singularity: $\mathcal{A}_{(a)+(b)}(s) \sim e^{2i\,\delta_{\chi_{c1}p}(s)}\mathcal{A}_{(a)}(s)$

  here $\delta_{\chi_{c1}p}$ is the elastic $\chi_{c1}p$ scattering phase shift

- corrections from coupled channels A. Szczepaniak, PLB757(2016)61

How to distinguish triangle-singularity from genuine resonance?

- Method-1: measuring the process $\Lambda_b^0 \to \chi_{c1}\, p\, K^-$
  - ☞ if a narrow near-threshold peak in $\chi_{c1}\, p \Rightarrow$ a real exotic resonance
- Method-2: processes (such as photoproduction) with a different kinematics

  Q. Wang, X.-H. Liu, Q. Zhao, PRD92(2015)034022;

  V. Kubarovsky, M. Voloshin, PRD92(2015)031502;

  M. Karliner, J. L. Rosner, PLB752(2015)329; . . .