

The $P_c(4450)$ pentaquark-like structure and triangle singularity

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Based on:

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

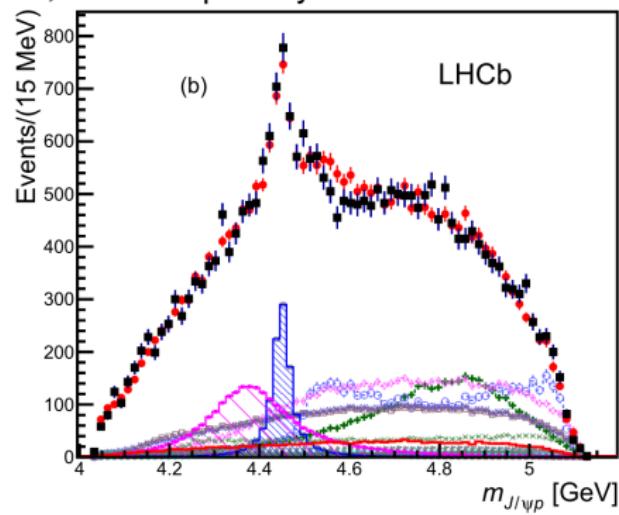
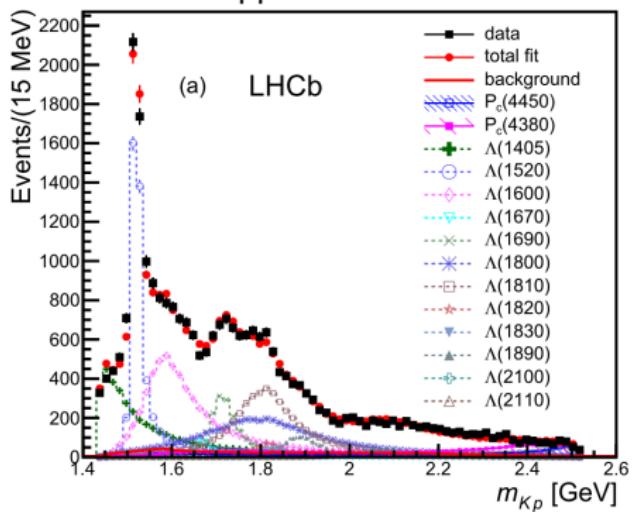
FKG, U.-G. Meißner, J. Nieves, Z. Yang, arXiv:1605.05113[hep-ph]

A. Aceti, M. Bayar, FKG, E. Oset, in preparation

LHCb pentaquark-like structures: Big news one year ago!

PRL115(2015)072001 [arXiv:1507.03414]

appeared on arXiv on 14.07.2015, and accepted by PRL on 24.07.2015!



$$M_1 = (4380 \pm 8 \pm 29) \text{ MeV},$$

$$M_2 = (4449.8 \pm 1.7 \pm 2.5) \text{ MeV},$$

$$\Gamma_1 = (205 \pm 18 \pm 86) \text{ MeV},$$

$$\Gamma_2 = (39 \pm 5 \pm 19) \text{ MeV}.$$

Quantum numbers not fully determined, for ($P_c(4380)$, $P_c(4450)$):

$$(3/2^-, 5/2^+), (3/2^+, 5/2^-), (5/2^+, 3/2^-)$$

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 Guan-Nan Li, Min He, Xiao-Gang He, arXiv:1507.08252 [hep-ph].



... [238 citations up to 01.09.2016]

Two kinds of singularities of S matrix

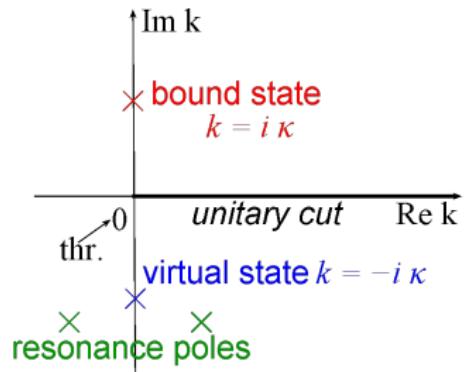
- Poles in the S -matrix: dynamics

- ☒ physical states

- Landau singularities: kinematics

- ☒ (a): two-body threshold cusp
 - ☒ (b): triangle singularity

...



Two kinds of singularities of S matrix

- Poles in the S -matrix: **dynamics**

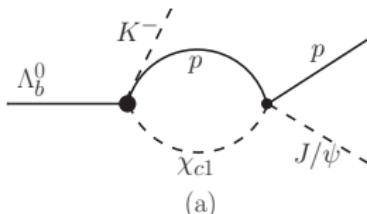
☞ physical states

- Landau singularities: **kinematics**

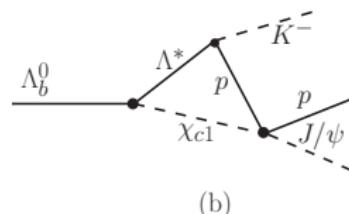
☞ (a): two-body threshold cusp

☞ (b): triangle singularity

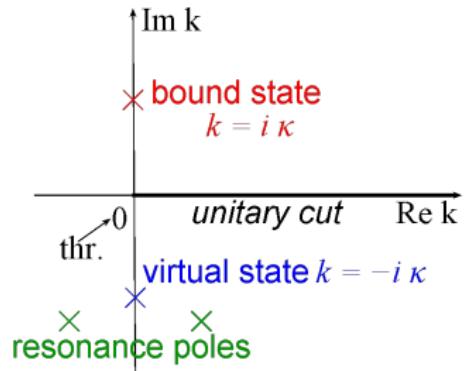
...



(a)



(b)



Triangle singularity – literature

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

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];
.....

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

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

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

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

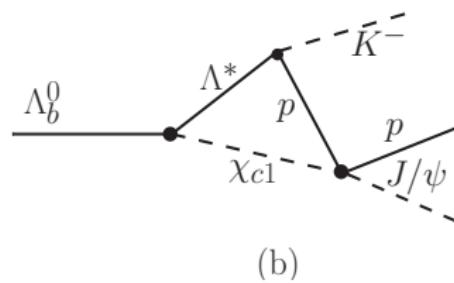
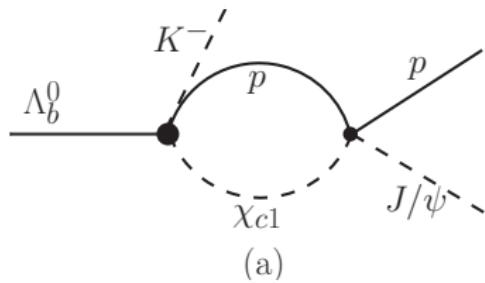
- Landau singularities from loop diagrams:

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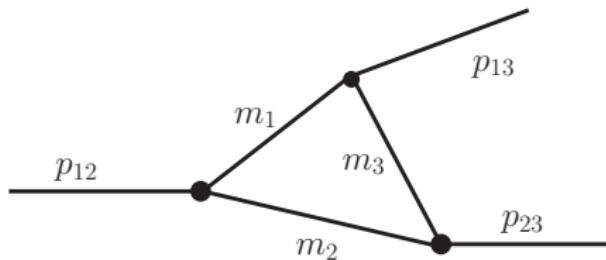
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- Landau singularities from loop diagrams:



Landau equation



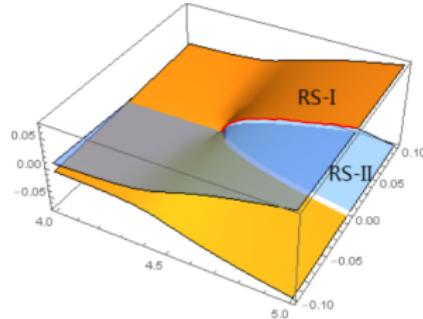
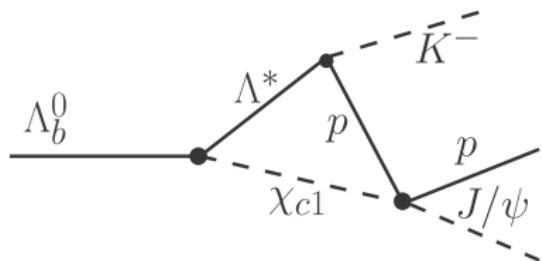
- Triangle singularity: leading Landau singularity for a triangle diagram, anomalous threshold
studied extensively in 1960s
- Solutions of Landau equation: Landau (1959)

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

quadratic equation of y_{ij} , always two solutions

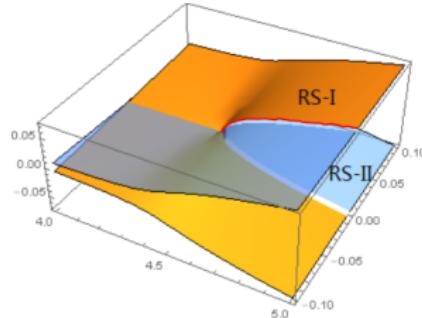
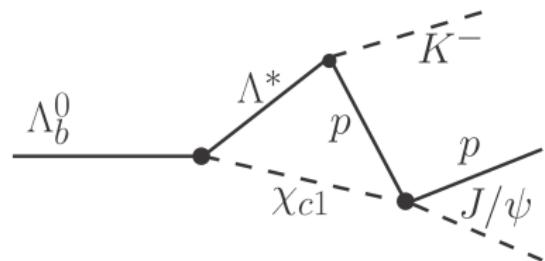
- Do they affect the physical amplitude?

Special kinematics for triangle singularity (I)



- 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

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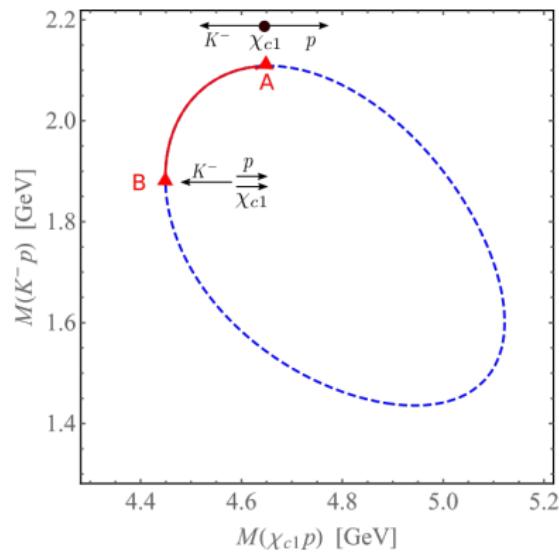
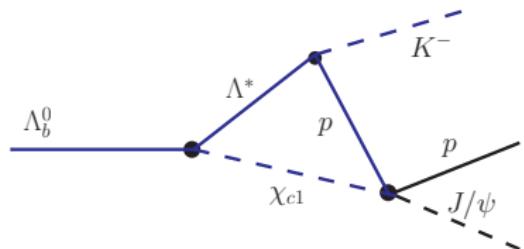
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Special kinematics for triangle singularity (II)

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

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

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

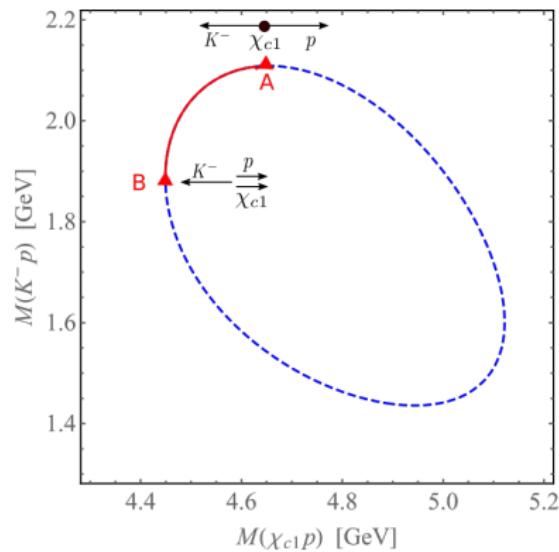
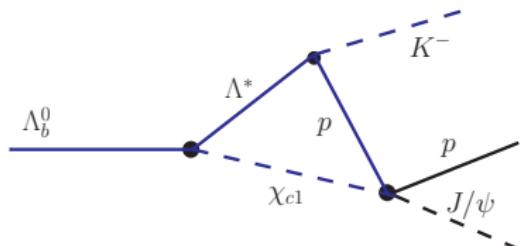


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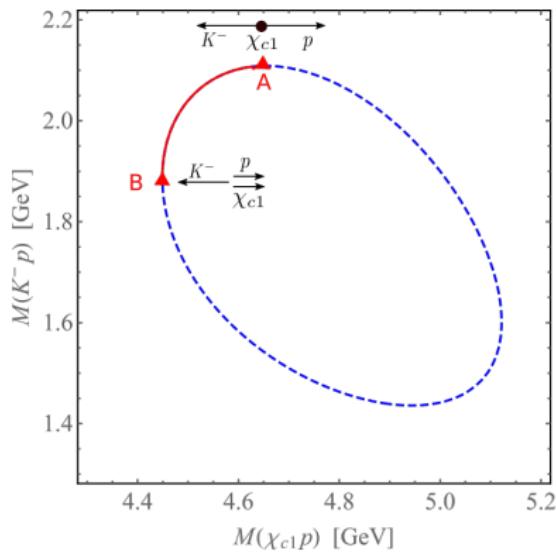
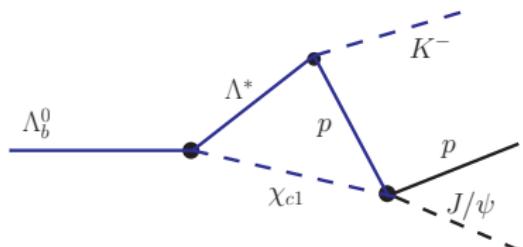


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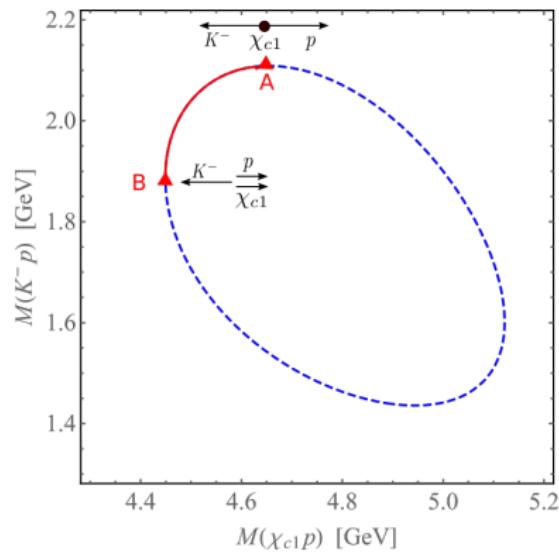
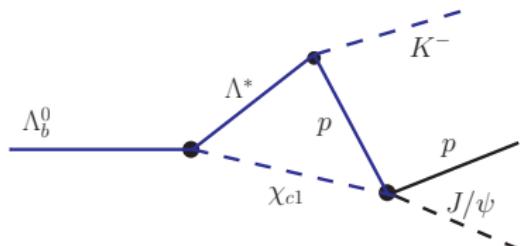


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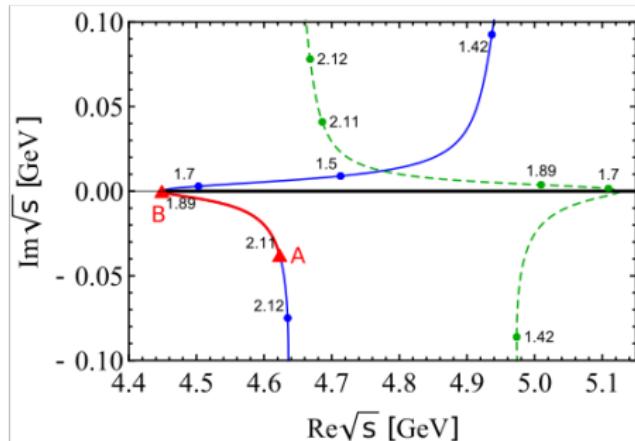
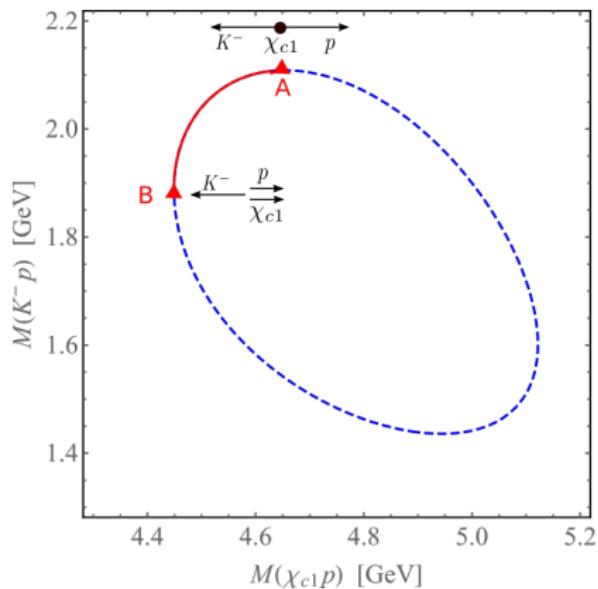
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Trajectories of triangle singularities in complex energy plane



numbers: assumed masses for Λ^*

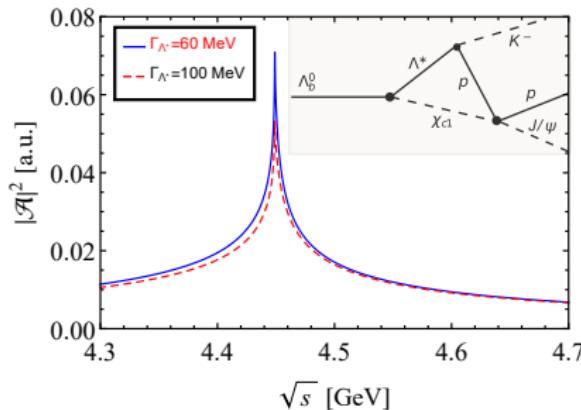
- ☞ blue: proton and χ_{c1} are parallel, in the 2nd Riemann sheet
- ☞ green: proton and χ_{c1} are anti-parallel

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

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

Triangle singularity for $P_c(4450)$

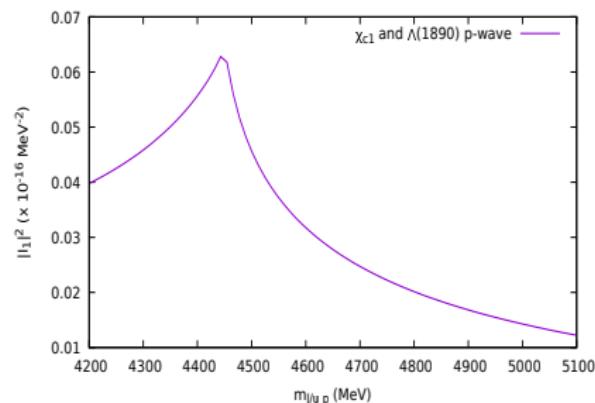
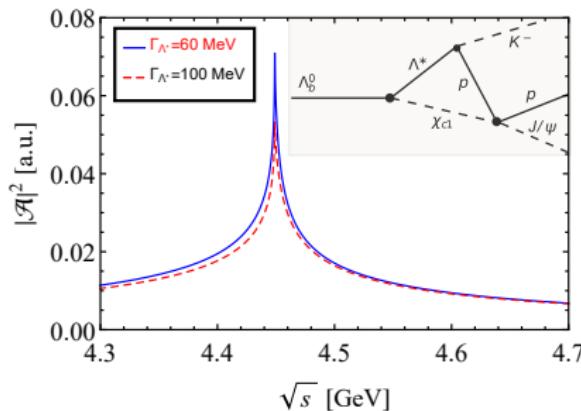
- When $M_{\Lambda^*} = 1.89$ GeV, the effective triangle singularity is located exactly at the $\chi_{c1}p$ threshold, 4.449 GeV!
- Coincidentally, four-star baryon $\Lambda(1890)$: $J^P = 3/2^+$, $\Gamma : 60 - 200$ MeV
- triangle loop with S -wave $\chi_{c1}p$



- Correction to arXiv:1507.04950: no such a prominent peak in other partial waves
⇒ the $\Lambda(1890)$ - χ_{c1} - p mechanism relevant if the quantum numbers are
 $J^P = \frac{3}{2}^+, \frac{1}{2}^+$

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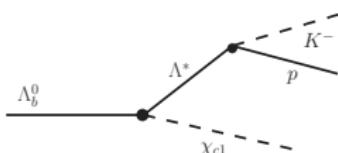
How to distinguish triangle-singularity from genuine resonance?

- Schmid theorem:

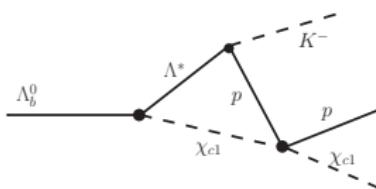
C. Schmid, Phys. Rev. 154 (1967) 1363

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



(a)



(b)

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 $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$
 - ☞ if a prominent 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. Kubarovskiy, M. Voloshin, PRD92(2015)031502;
M. Karliner, J. L. Rosner, PLB752(2015)329; ...

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:
 - ☞ $\text{Br}(\Lambda_b \rightarrow \Lambda^*(1890)\chi_{c1}) \Leftarrow \text{LHCb}$
 - ☞ $\chi_{c1} p \rightarrow J/\psi p$, might get information from lattice QCD
- More measurements are **necessary** to reveal the nature of the $P_c(4450)$
 - ☞ J^P unambiguously
 - ☞ $\Lambda_b \rightarrow \chi_{c1} p K$
 - ☞ searching for $P_c(4450)$ in processes with a different kinematics

THANK YOU FOR YOUR ATTENTION!

More comments

Strength of the triangle singularity is determined by

- couplings:

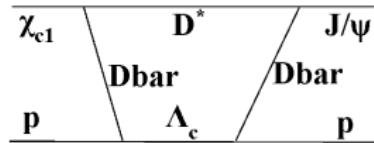
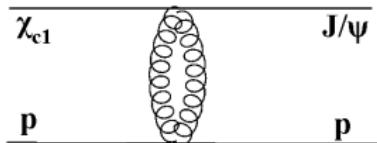
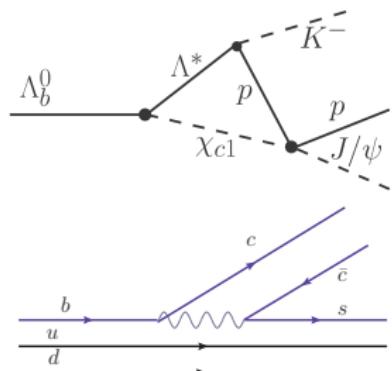
☞ $\Lambda_b \rightarrow \Lambda^* \chi_{c1}$ is from $b \rightarrow c\bar{c}s$, not measured,
but should be easy:

$$\text{Br}(B^+ \rightarrow J/\psi K^+) \simeq 1 \times 10^{-3},$$

$$\text{Br}(B^+ \rightarrow \chi_{c1} K^+) \simeq 0.5 \times 10^{-3}$$

☞ $\Lambda^*(1890) \rightarrow N\bar{K}$: largest branching
fraction, $\text{Br}= 20 - 35\%$

☞ $\chi_{c1} p \rightarrow J/\psi p$: OZI suppressed,
 $\mathcal{O}(1/N_c)$ [recall: OZI suppressed meson-meson scattering: $\mathcal{O}(1/N_c^2)$]

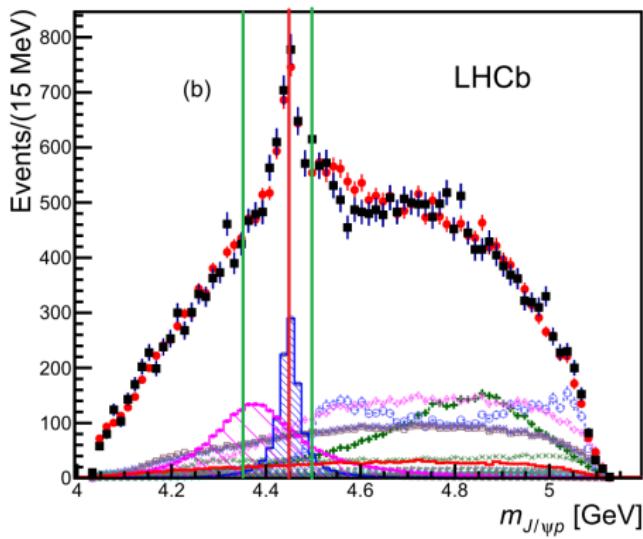


lattice QCD predicts possible $c\bar{c}$ -nucleus bound states at $M_\pi = 805$ MeV

NPLQCD, PRD91(2015)114503

More triangle singularities?

- $\chi_{c0,c1,c2} p \rightarrow J/\psi p$ are related through heavy quark spin symmetry
 - Weak decay $b \rightarrow c\bar{c}s, V - A \xrightarrow{\text{Fierz}} \bar{c}\gamma^\mu(1 - \gamma_5)c$
 - ☞ $\Lambda_b \rightarrow \Lambda^* J/\psi$ and $\Lambda_b \rightarrow \Lambda^* \chi_{c1}$ are easy
 - ☞ for χ_{c2} : strongly suppressed, χ_{c0} : also suppressed; for $B^+ \rightarrow \chi_{cJ} K^+$
 $\text{Br}_1 \simeq 5 \times 10^{-4} > \text{Br}_0 \simeq 1.5 \times 10^{-4} \gg \text{Br}_2 \simeq 1.1 \times 10^{-5}$
- ⇒ no obvious peak around the $\chi_{c0} p$ or $\chi_{c2} p$ threshold

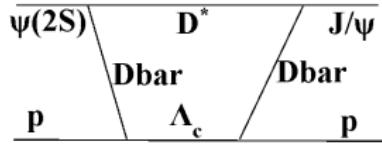
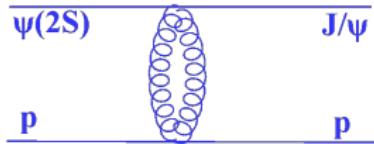


Backup slides

More triangle singularities?

Considering other possible $c\bar{c}-\Lambda^*$ combinations:

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



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

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

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