RADPYC 2020

The $P_c(4312)^+$ exotic

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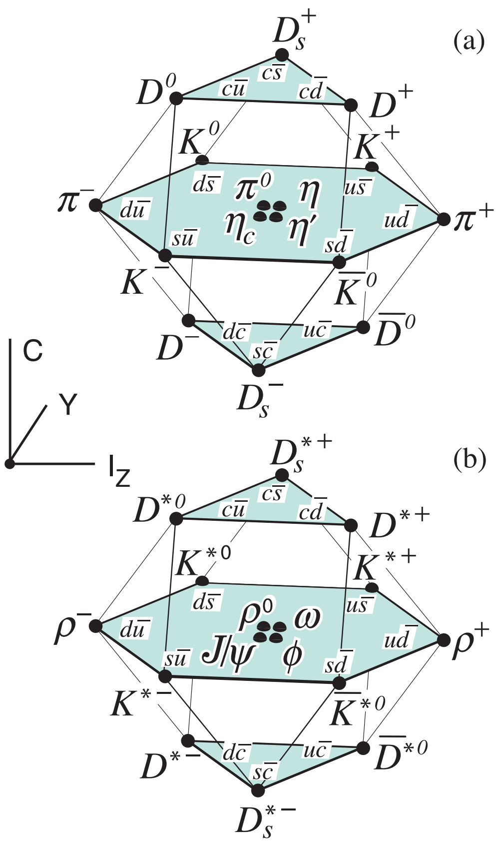
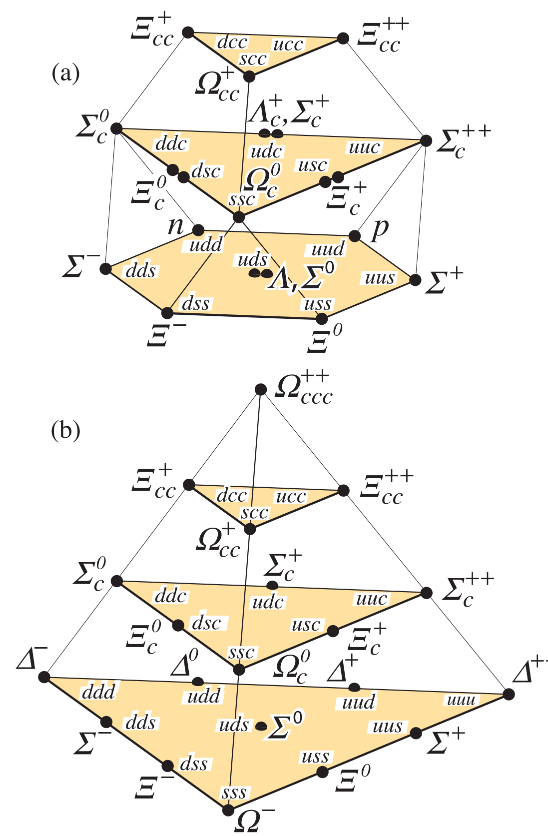
Introduction

Minimal quark model

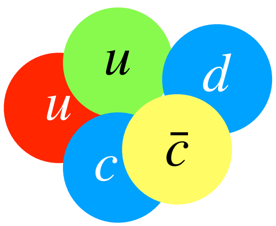


Mesons
(bosons)

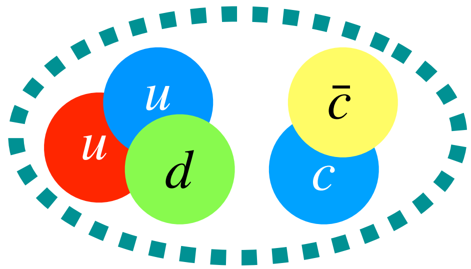
Baryons
(fermions)



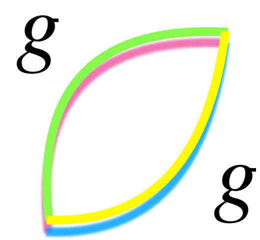
Infinite options for color singlets



Compact pentaquark



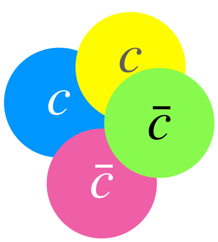
Baryon-meson molecule



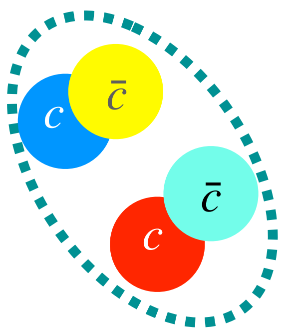
Glueball

• • •

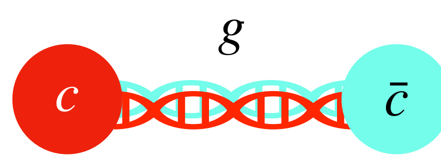
Compact tetraquark



Meson-meson molecule



Hybrid



(Multi-baryon molecules are called "nuclei")

State superposition

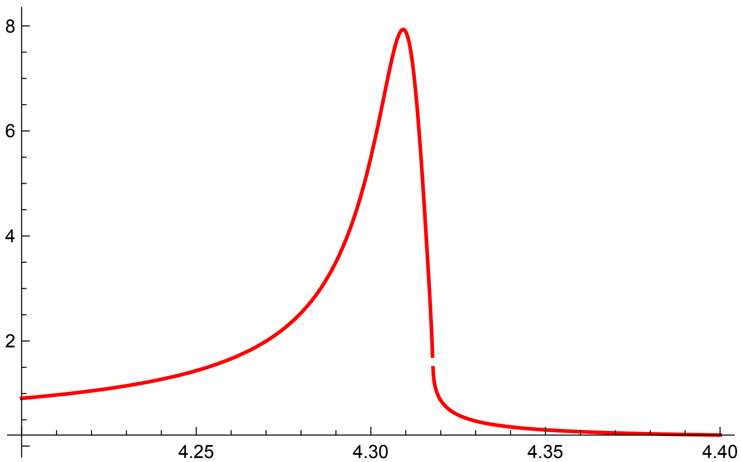
$$|M> = \alpha_0|q\bar{q}> + \alpha_1|gg> + \alpha_2|q\bar{q}g> + \alpha_3|q\bar{q}gg> + \alpha_4|q\bar{q}q\bar{q}> \ldots$$

$$|B> = \alpha_0|qqq> + \alpha_1|qqqq\bar{q}> + \alpha_2|qqqg> + \alpha_3|qqqq\bar{q}g> \ldots$$

$$\sum_i |\alpha_i|^2 = 1$$

Example: pentaquark

$$J/\psi\, p \to P_c \to J/\psi\, p$$

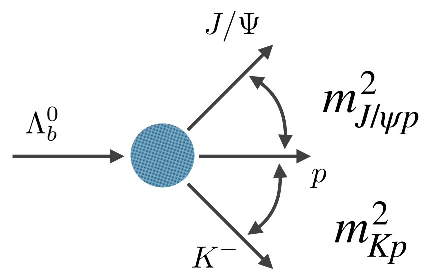


$\tau \simeq 10^{-24}\, s$

$$[c\bar{c}]\ [uud] \to [c\bar{c}uud] \to [c\bar{c}]\ [uud]$$

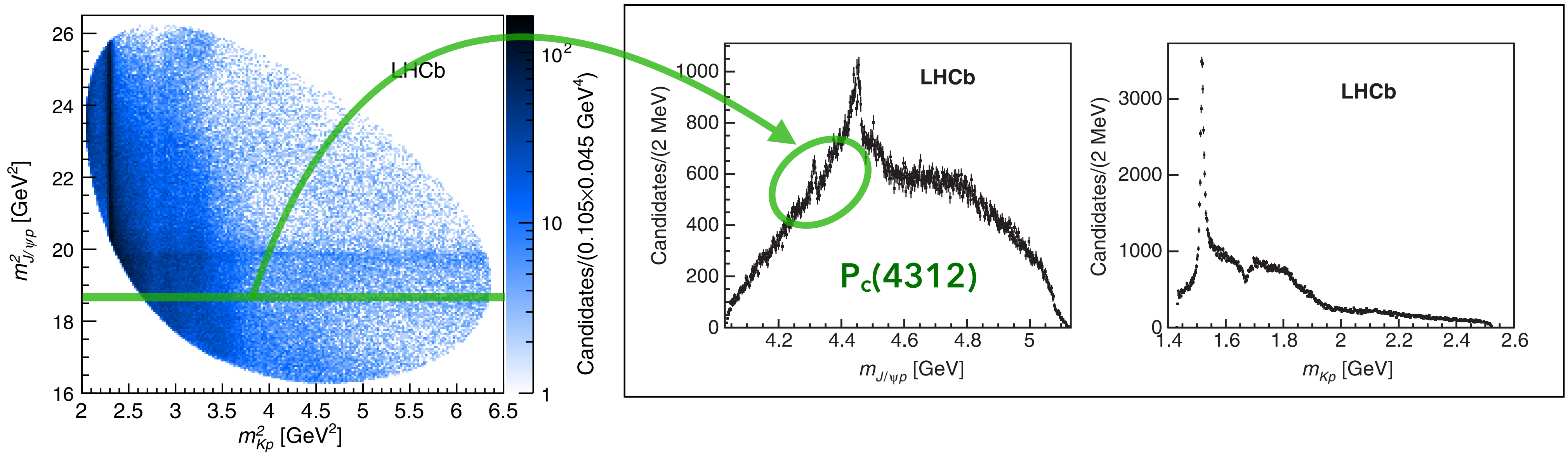
The minimal quark content is that of a pentaquark

Signals



LHCb, PRL 122 (2019) 222001

Four Pc's so far: ***P_c(4312)****, P_c(4380), P_c(4440), P_c(4450)*

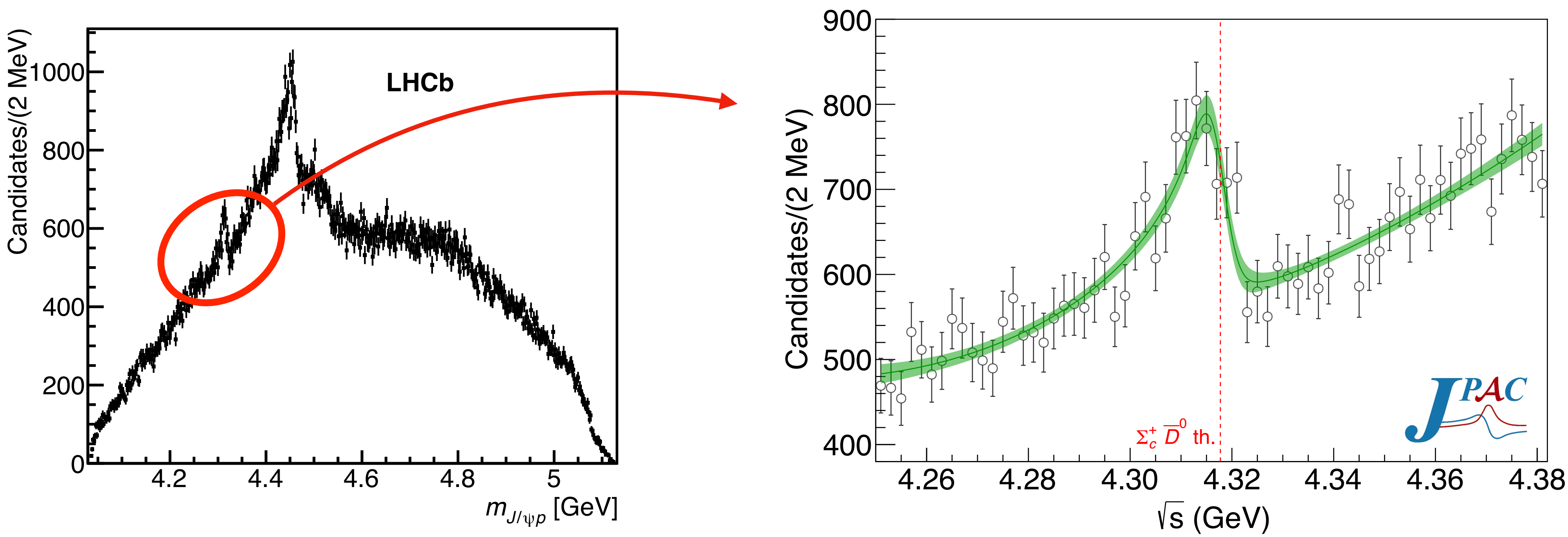


Amplitude analysis of the $P_c(4312)^+$

Joint Physics Analysis Center

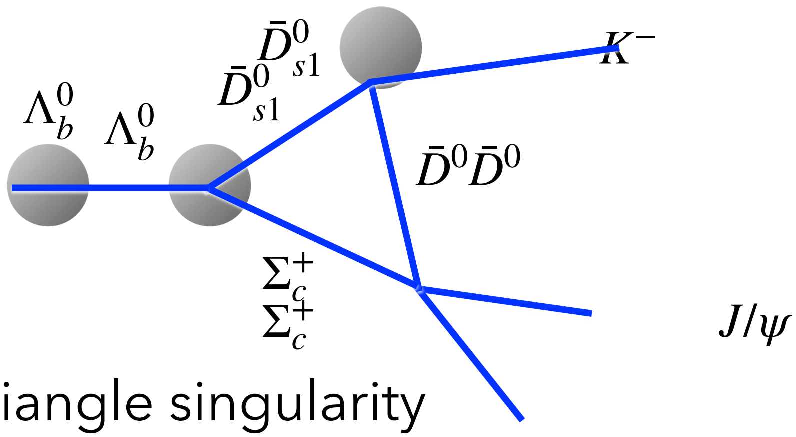
CFR et al. (Joint Physics Analysis Center), PRL 123 (2019) 092001

$P_c(4312)^+$ signal



Data { LHCb }

Signal interpretation

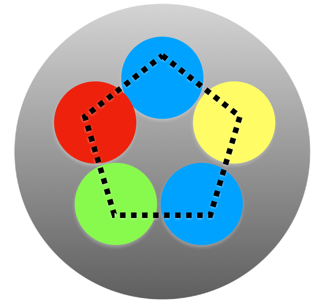


Triangle singularity

studied in LHCb 1904.03947

Compact pentaquark

Ali, Parkhomenko 1904.00446
Holma, Ohlsson 1906.08499

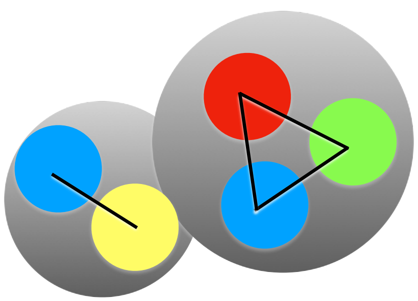


Virtual state

Burns, Swanson 1908.03528
CFR et al. 1904.10021

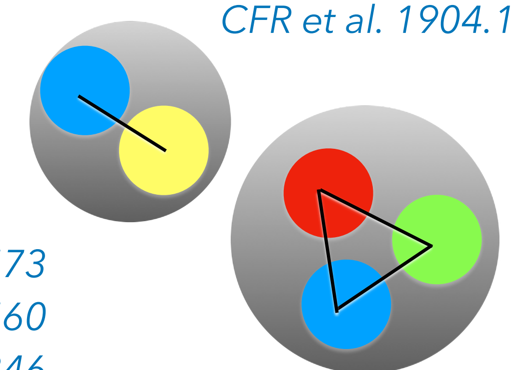
Hadrocharmonium

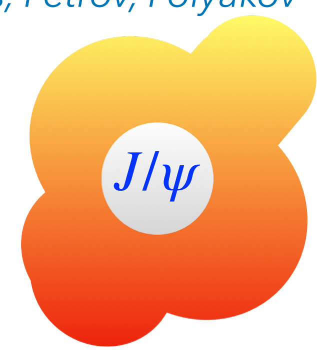
Eides, Petrov, Polyakov 1904.11616



Molecule

Wu et al. 1007.0573
Liu et al. 1903.11560
Du et al. 1910.11846

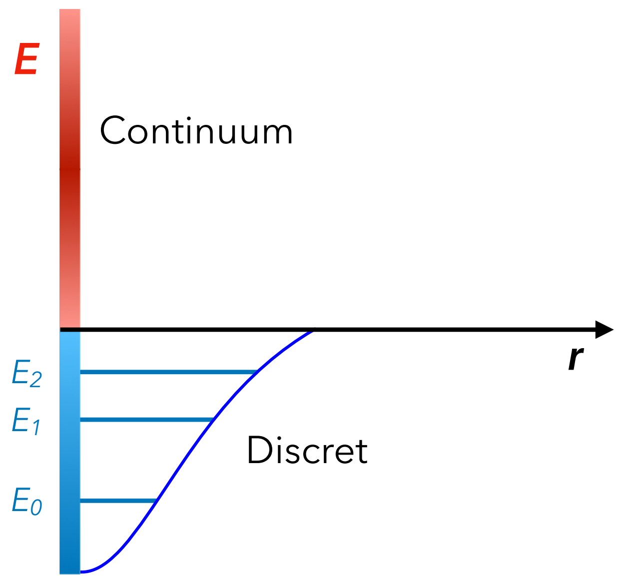




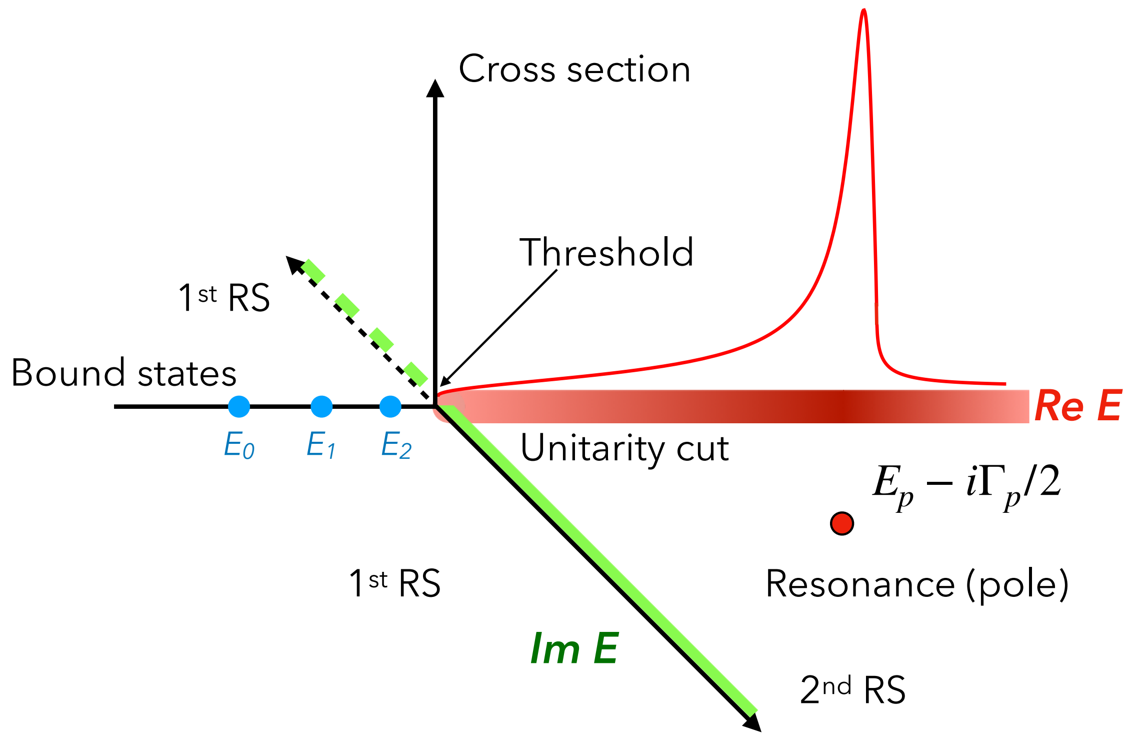
S-matrix theory

- Probability conservation ⇒ Unitarity
- Particle↔antiparticle ⇒ Crossing symmetry
- Causality ⇒ Analyticity and no poles in 1st Riemann sheet
- Additional symmetries: gauge, chiral, etc.

Spectrum and singularities

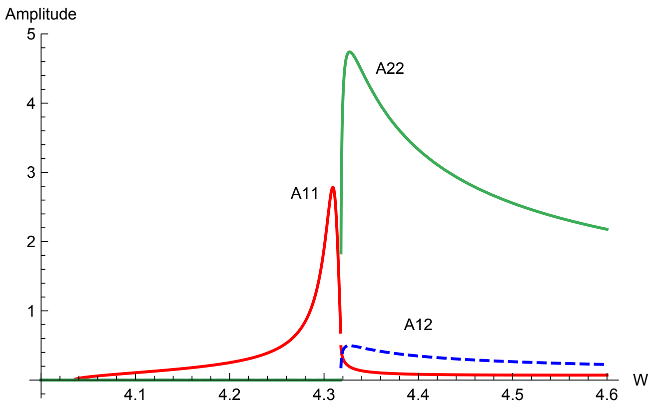


$$1 = \sum_n |E_n><E_n| + \int d\alpha |\alpha><\alpha|$$



Poles and cuts

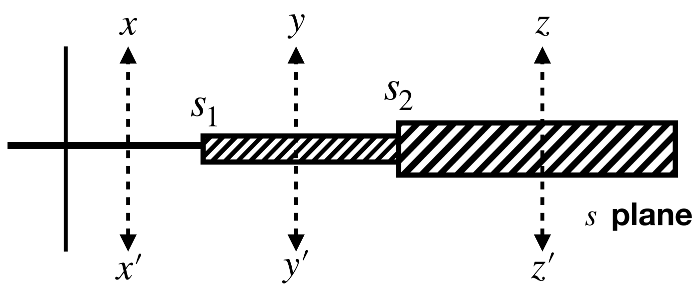
- The amplitude is an analytical function in the complex plane
- Singularities determine the amplitude (*aka* the structure)
  - Poles
  - Cuts
- Singularities are associated to the dynamics

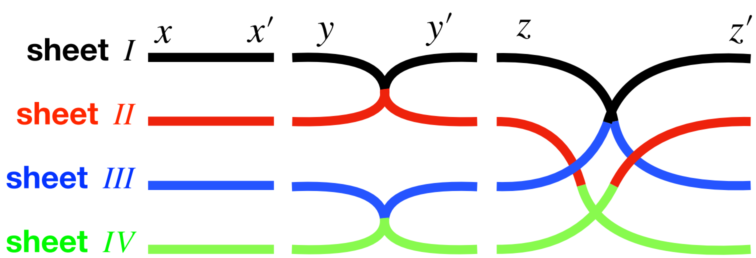


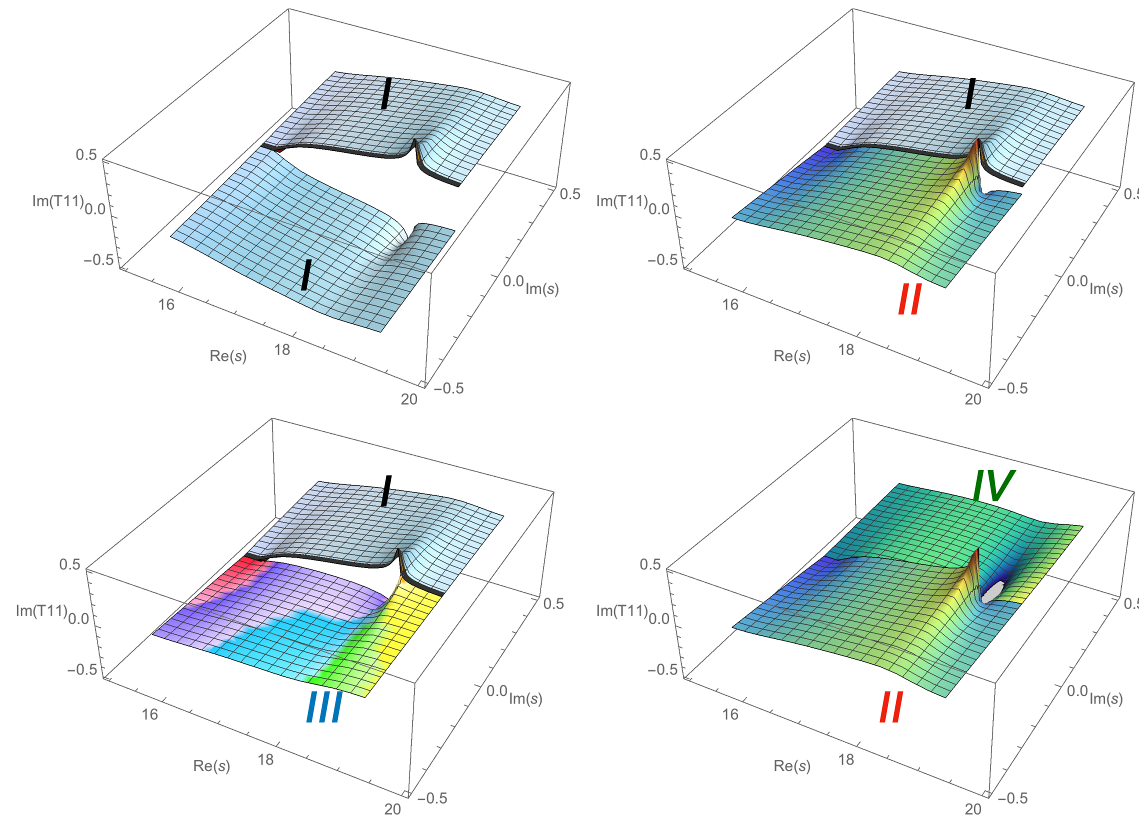
$$\begin{bmatrix} A_{11} = |p\,J/\psi > \to |p\,J/\psi > & A_{12} = |p\,J/\psi > \to |\Sigma_c^+ \bar{D}^0 > \\ A_{21} = |\Sigma_c^+ \bar{D}^0 > \to |p\,J/\psi > & A_{22} = |\Sigma_c^+ \bar{D}^0 > \to |\Sigma_c^+ \bar{D}^0 > \end{bmatrix}$$

Riemann sheets structure

Physical axis







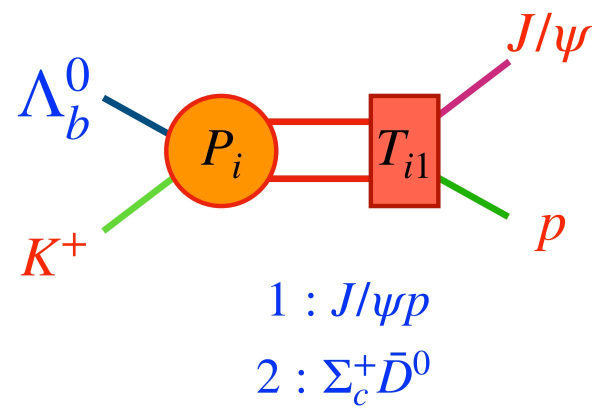
Near-threshold theory: hypotheses

- Hypotheses:
  - Only one partial wave contributes to the signal
  - The threshold drives the physics (tested)
  - Further singularities are irrelevant (tested)
- Caveat:
  - We fit the $J/\psi\, p$ projection (no info on quantum numbers)

Near-threshold theory: equations

$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[\,|F(s)|^2 + B(s)\right]$$

$$F(s) =$$



$$F(s) = P_1(s) T_{11}(s) \qquad \left(T^{-1}\right)_{ij} = M_{ij} - i k_i \delta_{ij}$$

$$M_{ij}(s) = m_{ij} - c_{ij} s$$

Matrix elements M_{ij} are singularity free and can be Taylor expanded

Frazer, Hendry PR134 (1964) B1307

Near-threshold amplitude

$$\frac{dN}{d\sqrt{s}} = \rho(s)\Big[\,|F(s)|^2 + B(s)\Big]$$

Production, hyperons and effects due to further singularities

$$B(s) = b_0 + b_1 s$$

$$F(s) = (p_0 + p_1 s)\frac{[m_{22} - c_{22}s - ik_2]}{[m_{22} - c_{22}s - ik_2][m_{11} - c_{11}s - ik_1] - m_{12}^2}$$

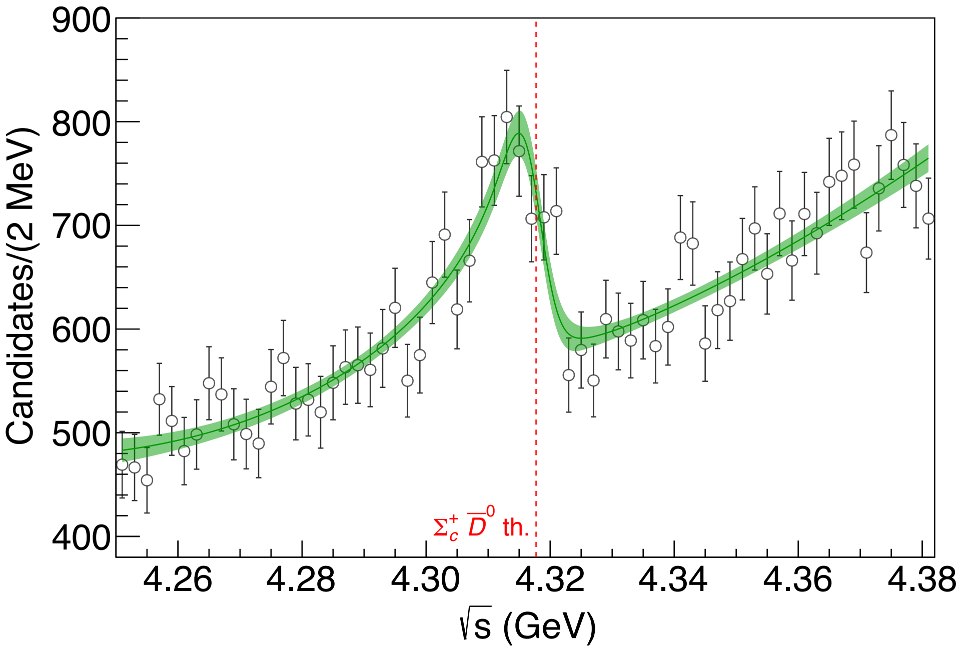
Channel coupling

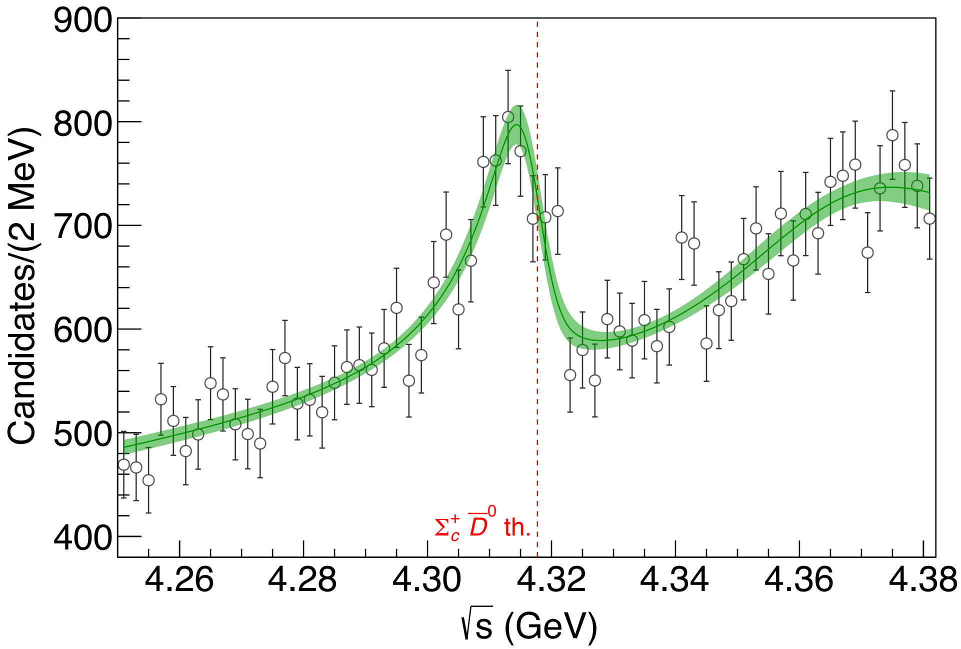
Scattering length approximation if c_{ij}=0

Only poles on sheets II and IV

If $c_{ij} \neq 0$ (effective range approximation); poles in any sheet

Fits: scattering length vs effective range





2 channel scattering length approximation

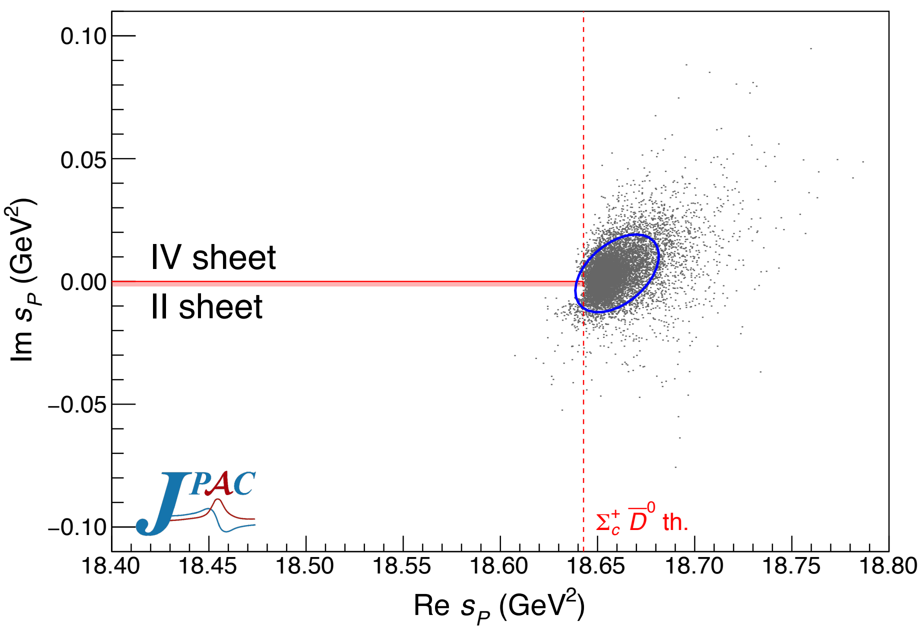
$$\chi^2/dof = 48.1/(66-7) = 0.82$$

2 channel effective range approximation

$$\chi^2/dof = 43/(66-9) = 0.75$$

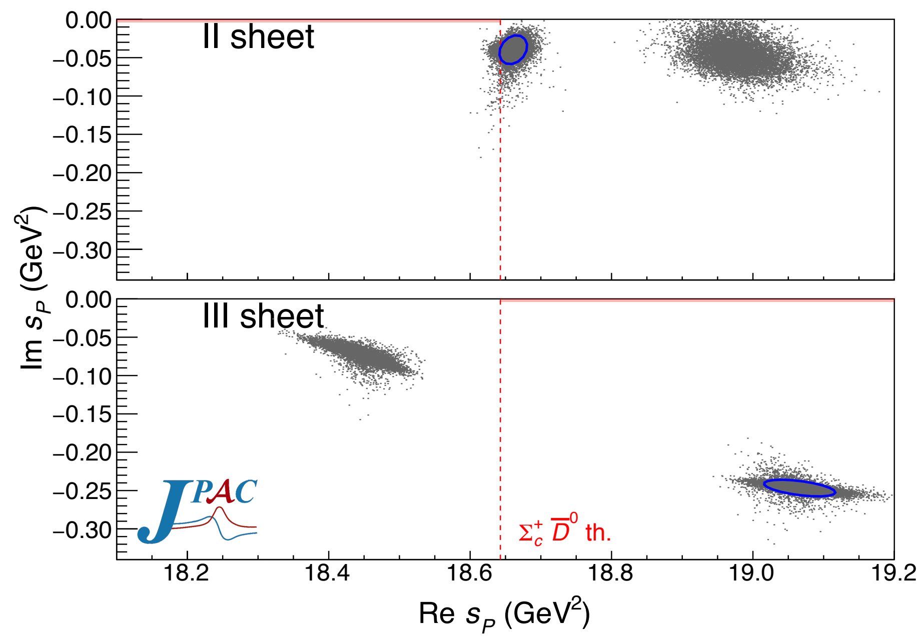
Poles

Scattering lenght



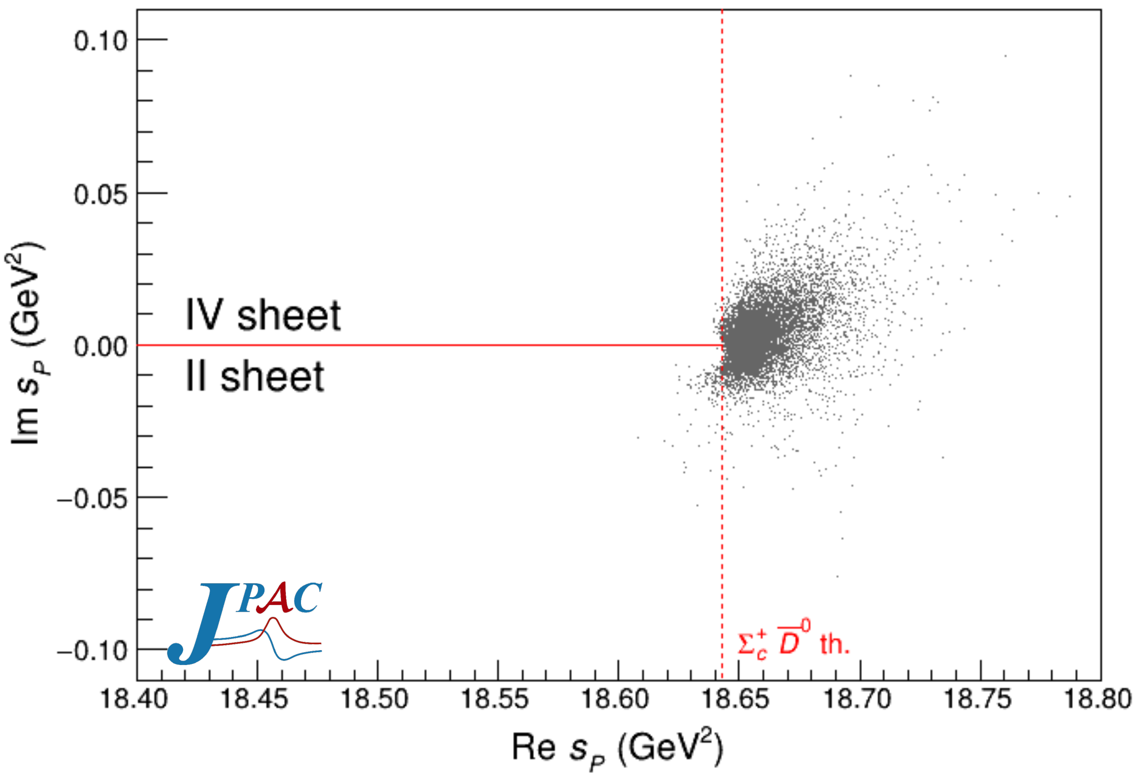
M= 4319.7±1.6 MeV | Γ= −0.8±2.4 MeV

Effective range



M= 4319.8±1.5 MeV | Γ= 9.2±2.9 MeV

Pole movement: scattering length



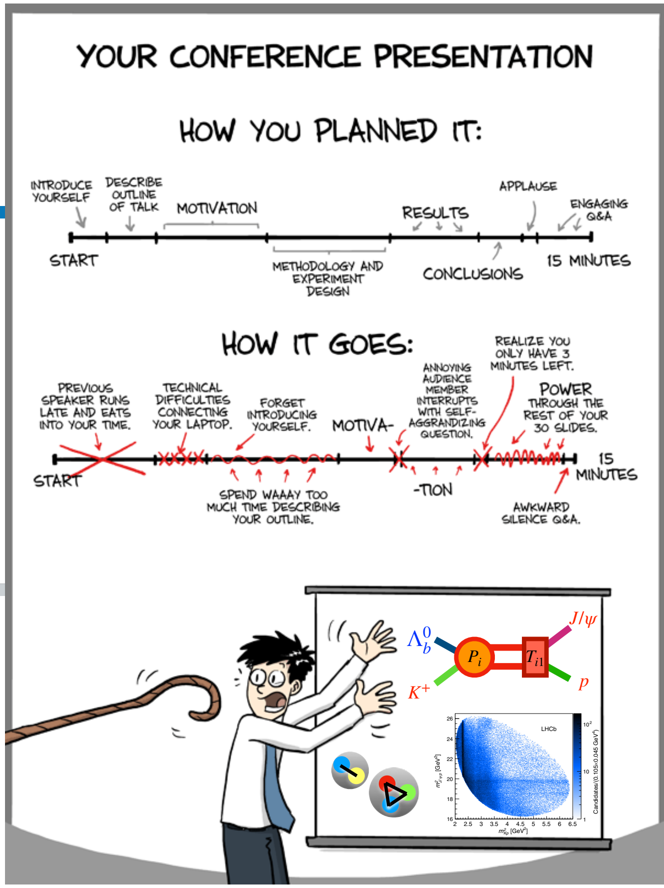
Conclusions

Summary of the current consensus

- Universally accepted by the hadron molecule community that *the P_cs are hadron molecules*
- Universally accepted by the quark model community that *the P_cs are compact pentaquarks*
- Universally accepted by the hadrocharmonium community that *the P_cs are hadrocharmonia*
- The triangles community is universally dissapointed because LHCb rules them out for two of the states

Conclusions

- Seems that $P_c(4312)$ dynamics is driven by the threshold
- Molecule? Virtual state?
- We favor the virtual state explanation
- We have to wait for the quantum numbers, although a lot of (sensible) especulation is already in the market



PhD comics

Thanks.