LHCb pentaquarks

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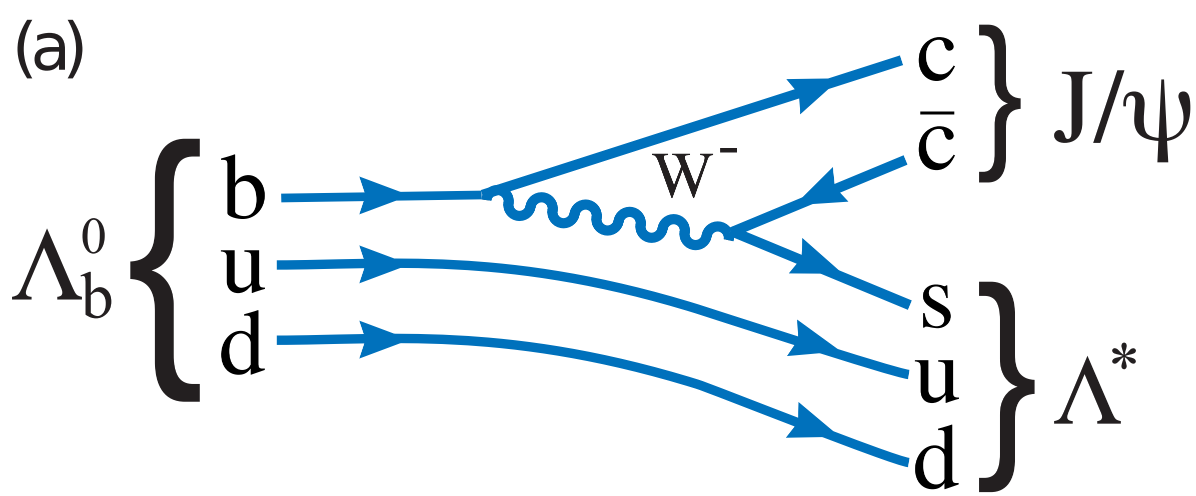
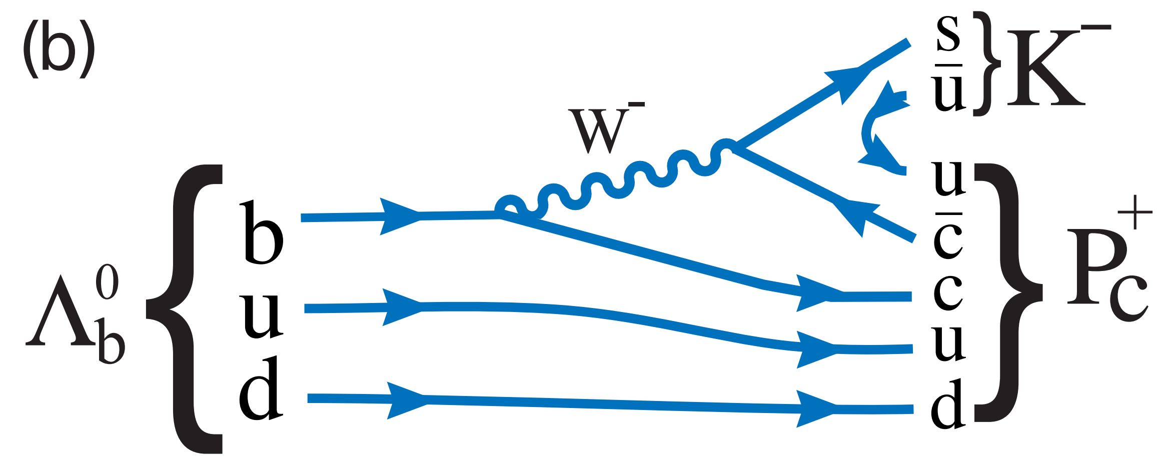
- What LHCb observed?
- Possible pictures of LHCb pentaquarks
- Interaction of charmonia with the nucleon
- Masses and width of charmonium-nucleon bound states
- Pandora box?

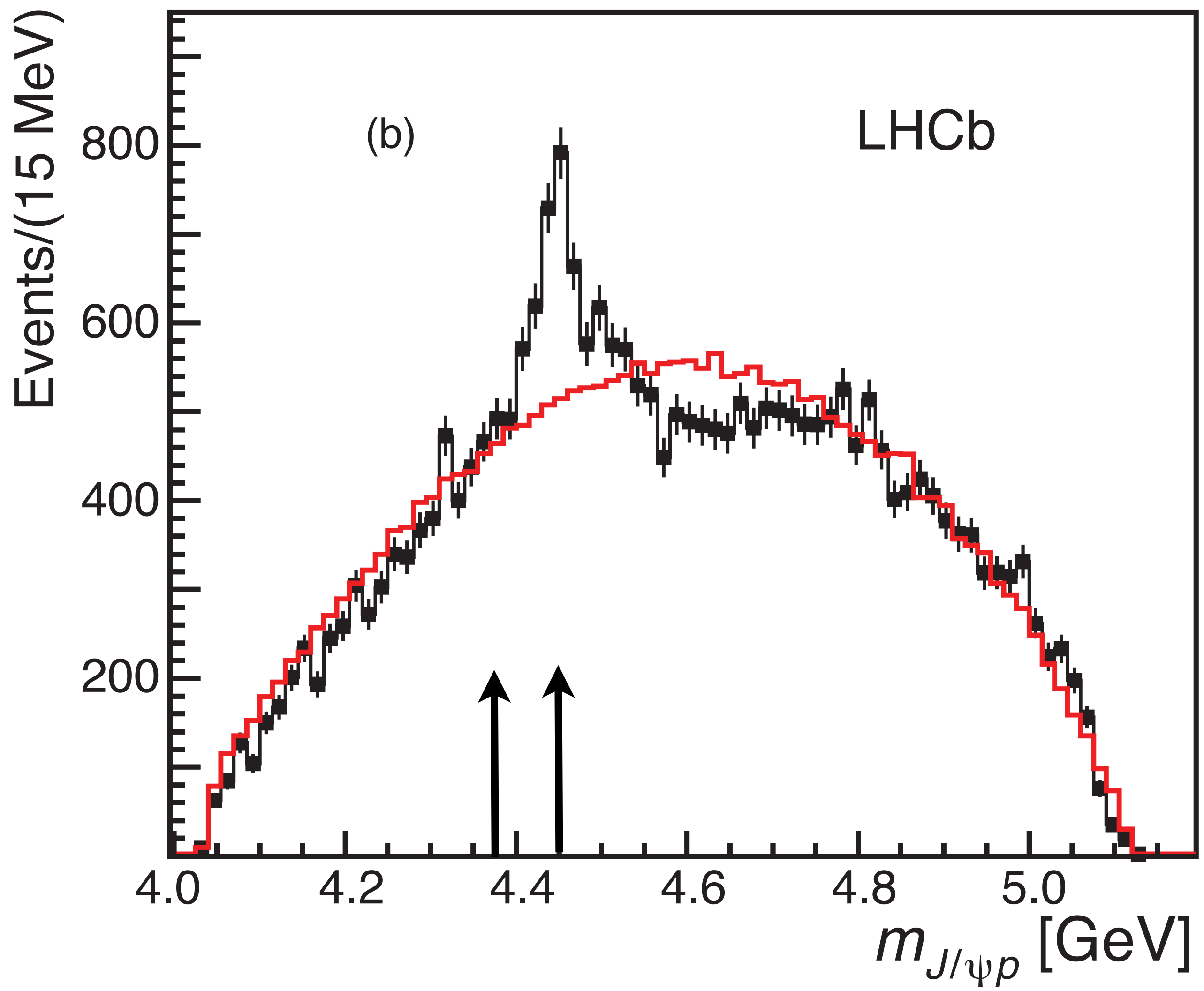
What has been observed by LHCb Phys.Rev.Lett. 115 (2015) 072001 ?

The decay $\Lambda_b^0 \to J/\psi K^- p$ was studied. Why?





Invariant mass of proton and J/ψ

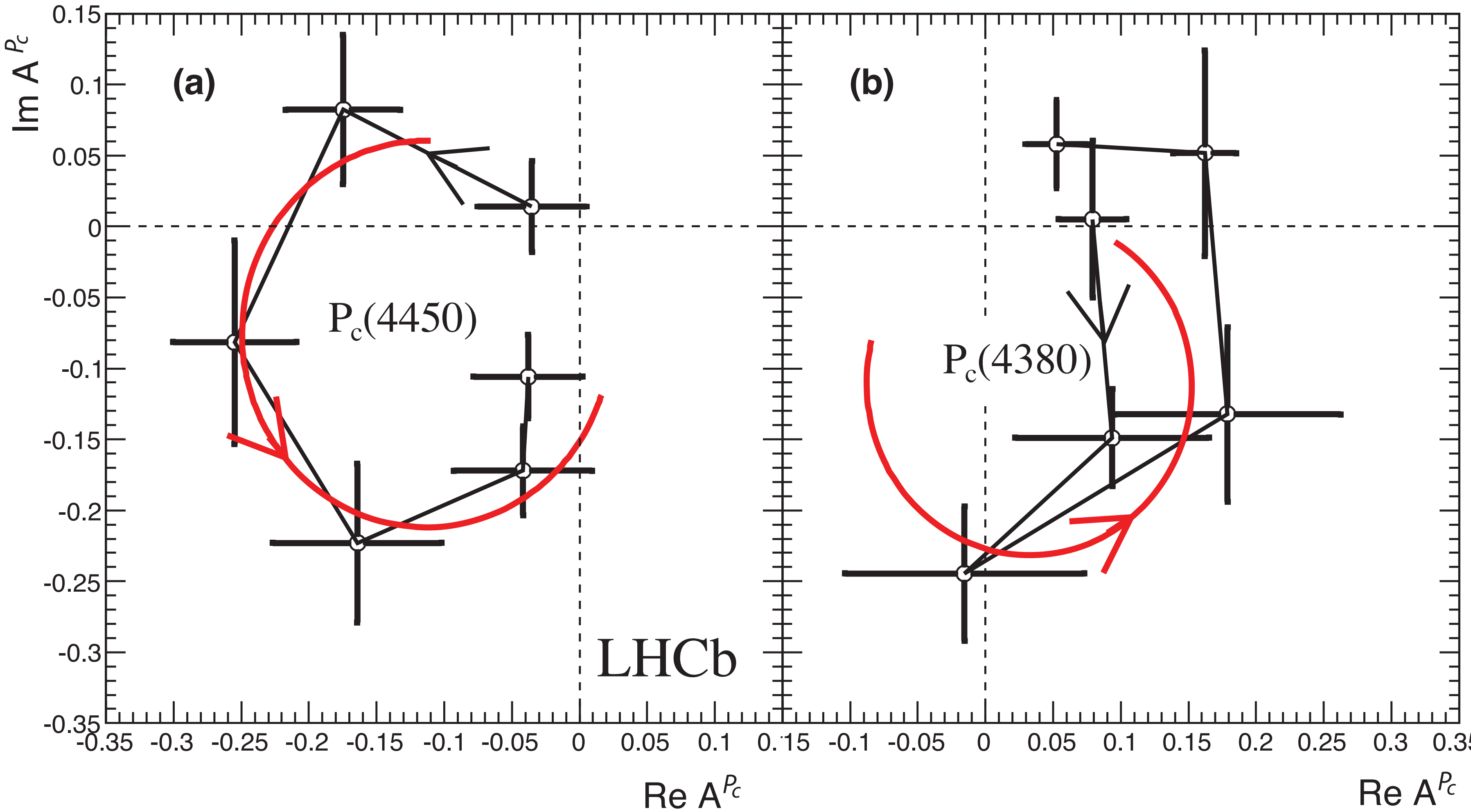


$$M_1 = 4380 \pm 37 MeV, \qquad \Gamma = 205 \pm 104 MeV$$

$$M_2 = 4450 \pm 5 MeV, \qquad \Gamma = 39 \pm 24 MeV$$

Partial wave analysis by LHCb

Argand diagramme

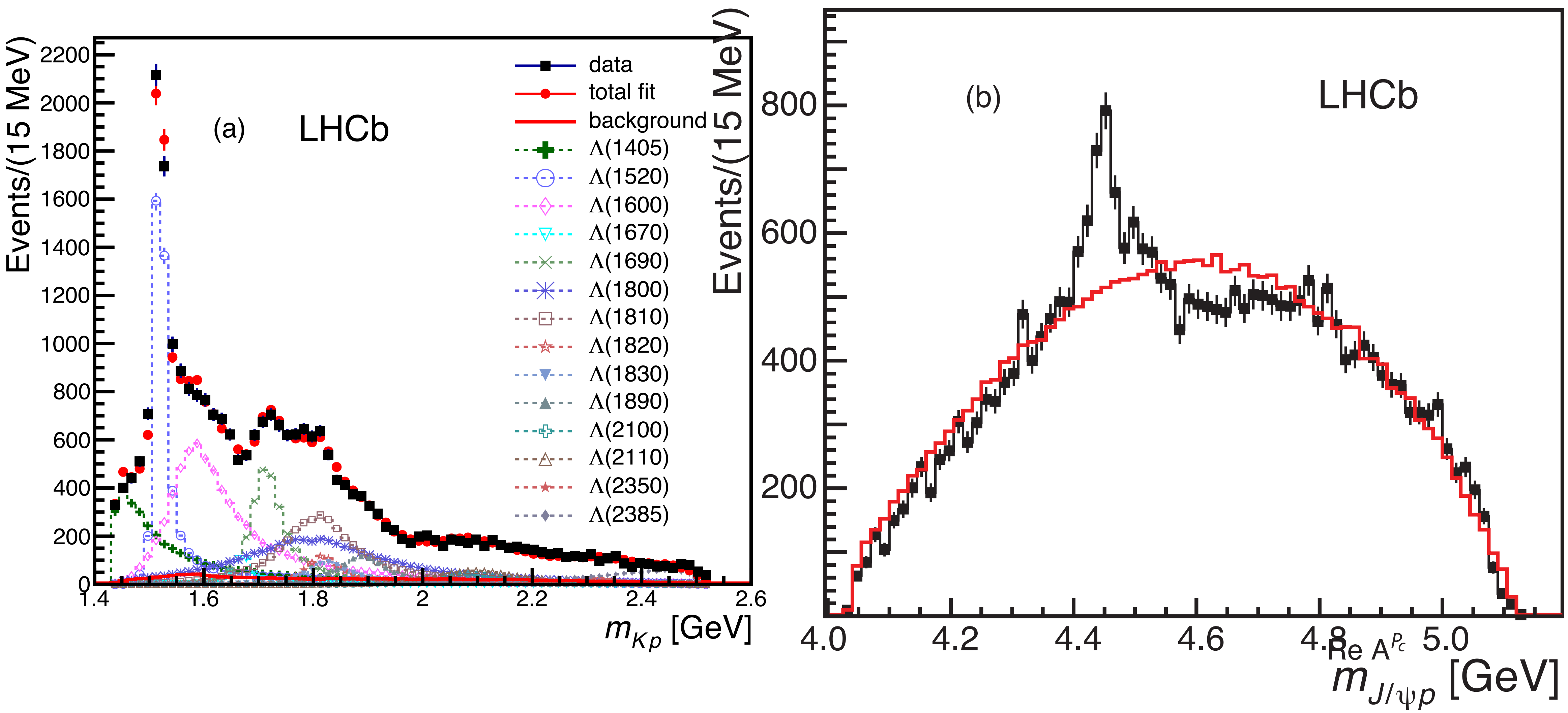


Preferable $J^p = \left(\frac{3}{2}^-, \frac{5}{2}^+\right)$ however $\left(\frac{5}{2}^+, \frac{3}{2}^-\right)$ are possible as well

significance of each of these resonances is more than 9 standard deviations.

Weak points of the analysis:

- K- p channel is enriched by hyperon resonances - danger of kinematical reflections!
- The lower mass (wide) penta can be revealed only in complicated PWA.



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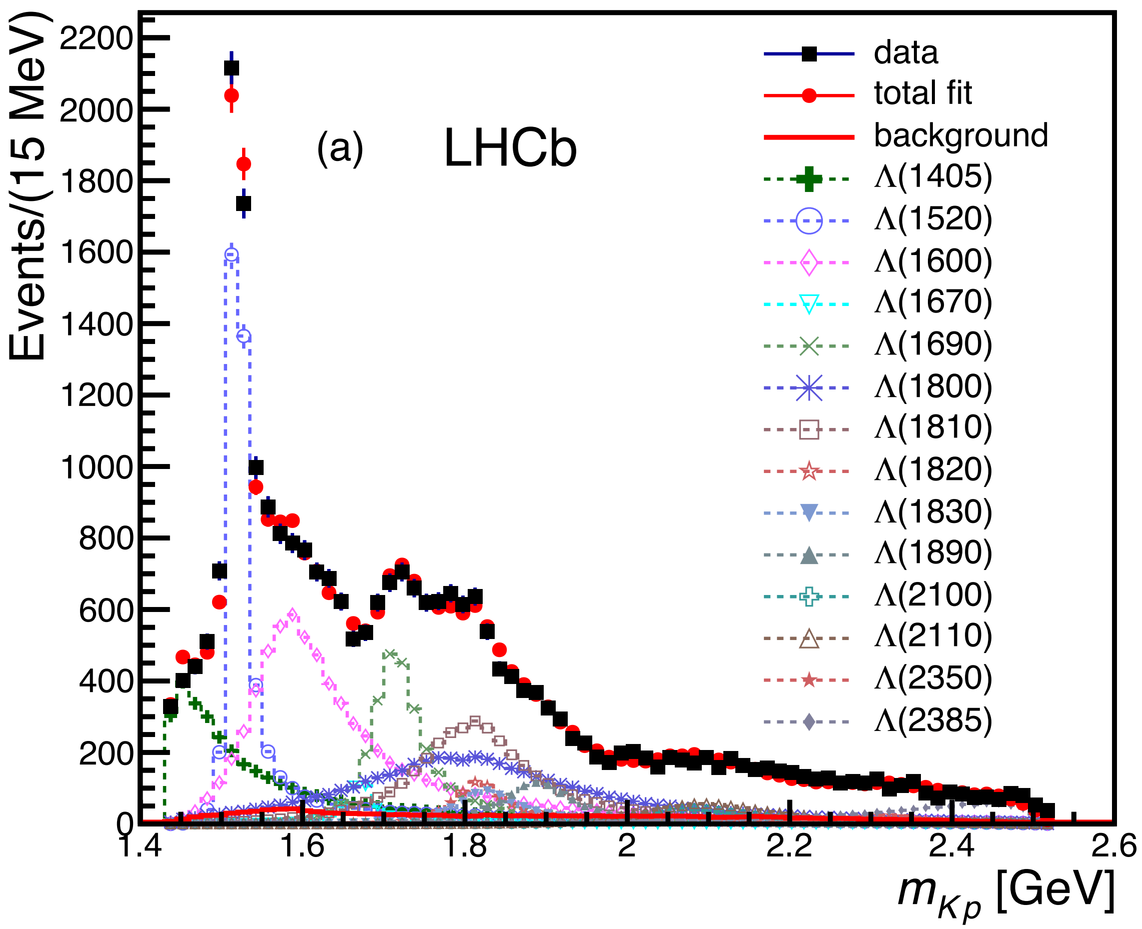
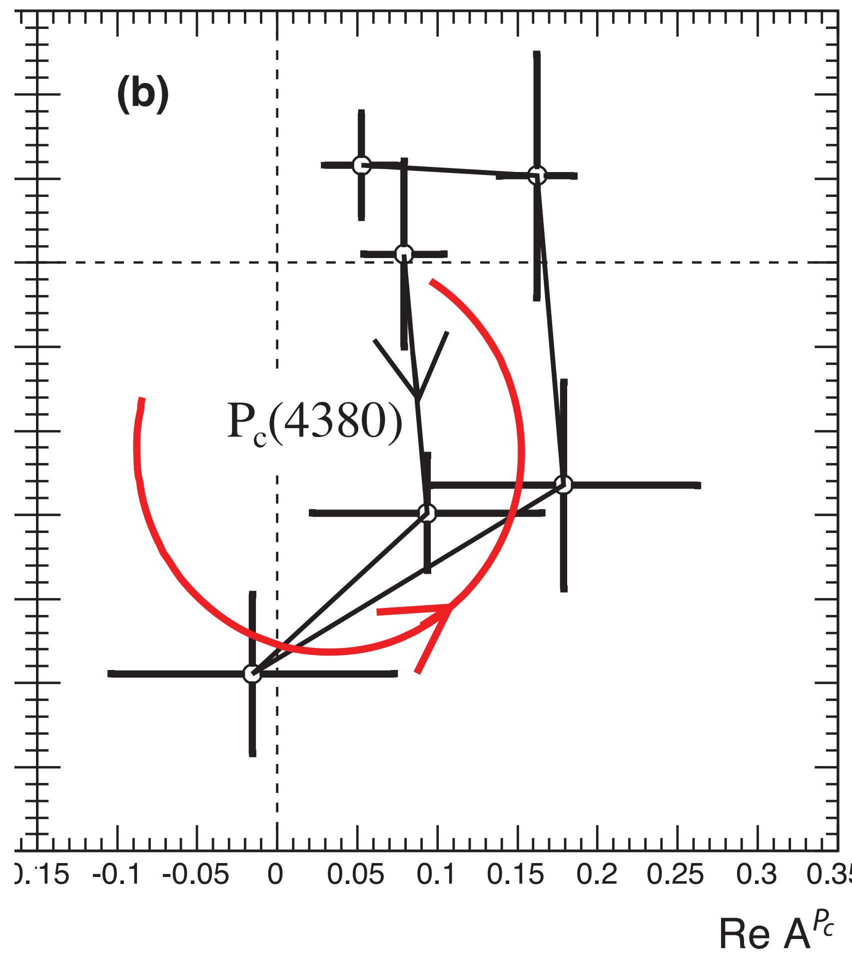
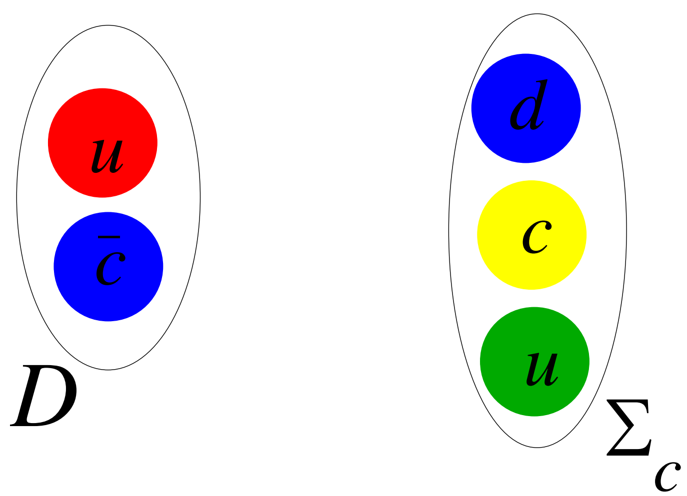


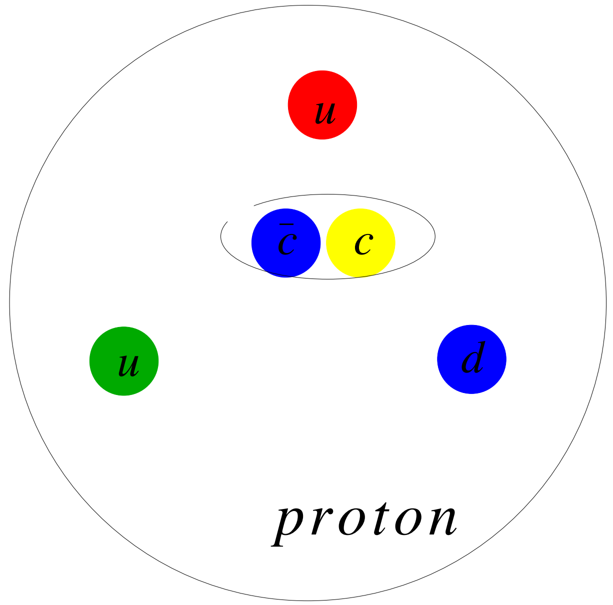


What is the nature of these pentaquark states?

- Charm quarks are far (about 1fm) from each other: molecula, diquarks
- Charm quarks are close (order 1/Mc): hadrocharmonium
- Peaks are threshold effects

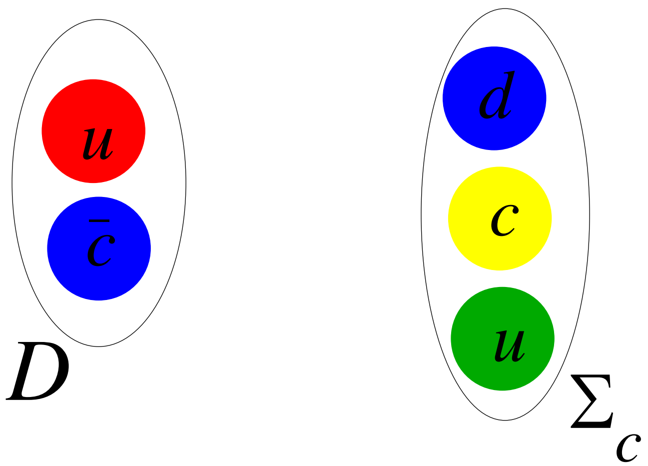


Molecula



Hadrocharmonium

Molecula



D-mesons (quark content u$\underline{c}$, d$\underline{c}$)

D_c: 0^-, $I = 1/2$, $M = 1865$ MeV
D_c^*: 1^-, $I = 1/2$, $M = 2008$ MeV

Charmed baryons (quark content udc, uuc)

Λ_c: $\frac{1}{2}^+$, $I = 0$, $M = 2286$ MeV
Σ_c: $\frac{1}{2}^+$, $I = 1$, $M = 2453$ MeV
Σ_c^*: $\frac{3}{2}^+$, $I = 1$, $M = 2517$ MeV

Suggestion by R. Chen et al. [**Phys.Rev.Lett. 115 (2015) 13, 132002**]

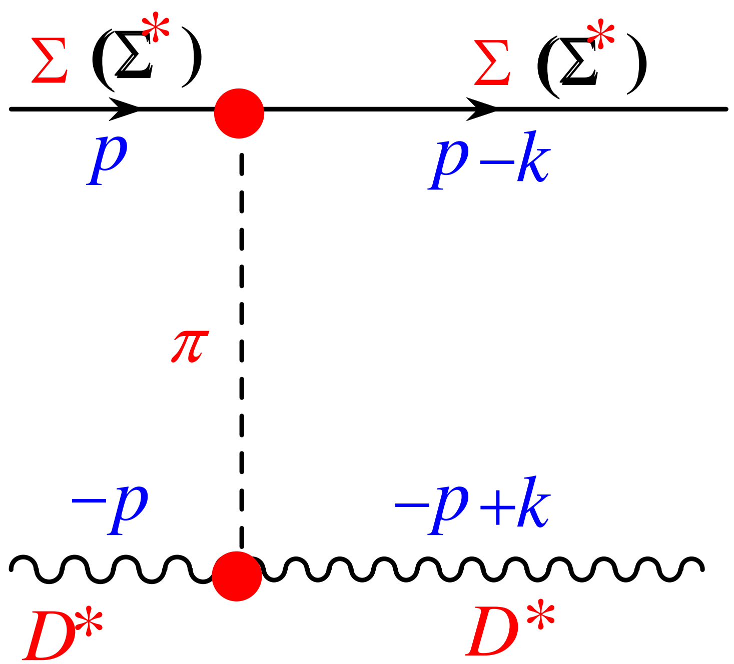
Light (and wide) penta: $\Sigma + D^*$, $\varepsilon_{bound} = -81$ Mev

Heavy (and narrow) penta: $\Sigma^* + D^*$, $\varepsilon_{bound} = -75$ Mev

Binding mechanism ?

Molecula

Idea: to bind by one-pion exchange:



Coupling constants

$$g_{D^*D^*\pi} = 0.59$$

$$g_{D^*D^*\pi} = 0.94$$

fixed from decays+heavy quark symmetry

The potential $V = \nabla^2 Y$ with $Y = \int d^3q e^{-i\vec{q}\cdot\vec{r}} \frac{1}{q^2+m_\pi^2} \frac{\Lambda^2}{q^2+\Lambda^2}$

cutoffs are fitted to get correct masses for penta. The results:

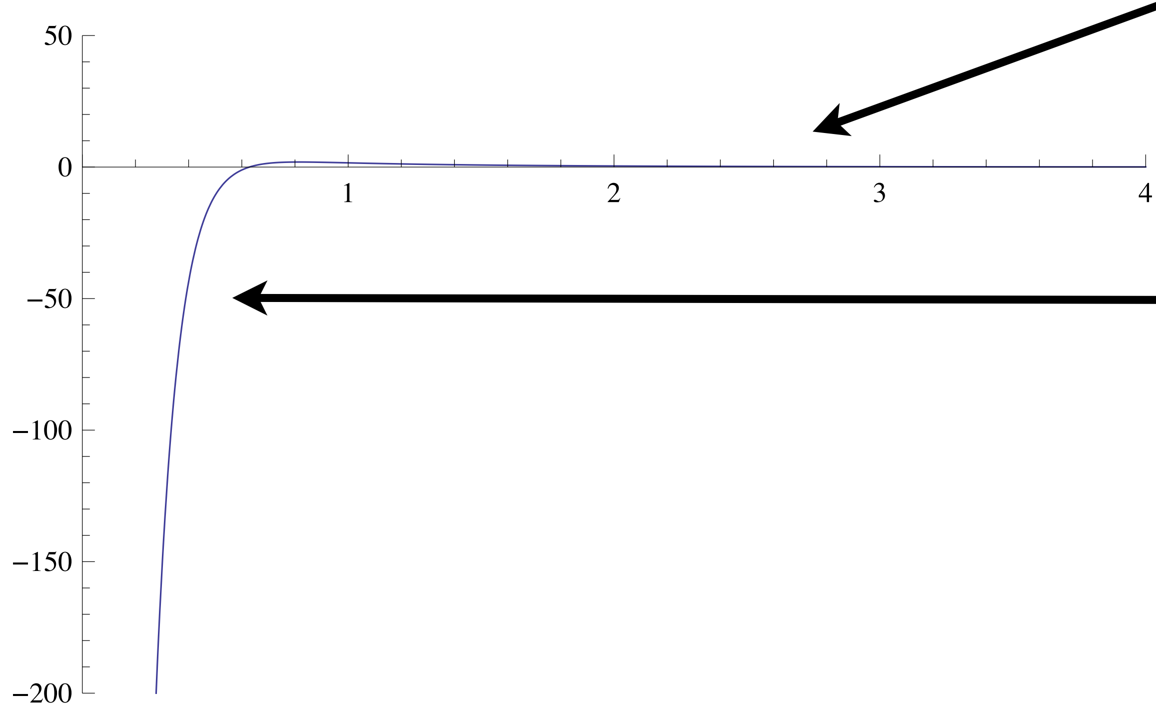
$\Lambda = 2.35$ Gev (!) (ΣD^*), $\Lambda = 1.77$ Gev (!) $(\Sigma^* D^*)$

One would expect $\Lambda \leq 1$ GeV

Molecula - problems

In model of Chen et al the potential looks like:

1-pion exchange tale



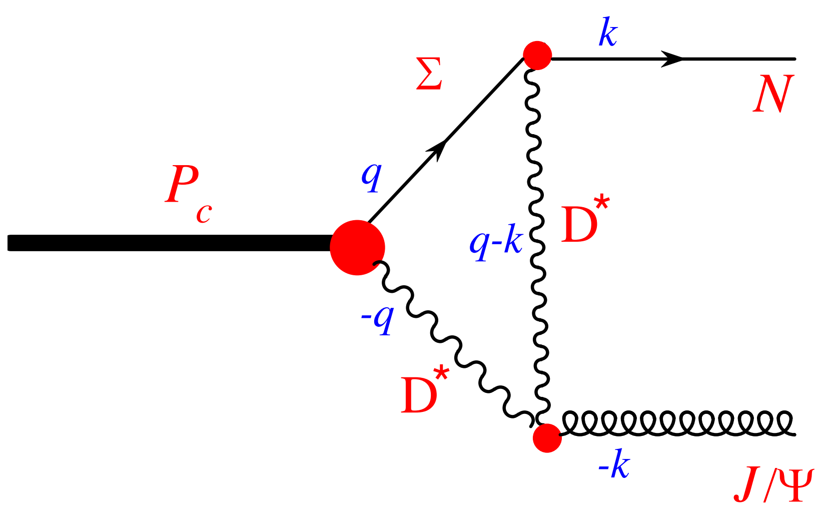
short range core = effect of the cutoff

Binding is due to very strong short-range core !!! Cutoff effect!

Molecula size = 0.3 fm !!!

Molecula - general problem

Main general problem of molecula picture is small $J/\Psi + p$ partial decay width

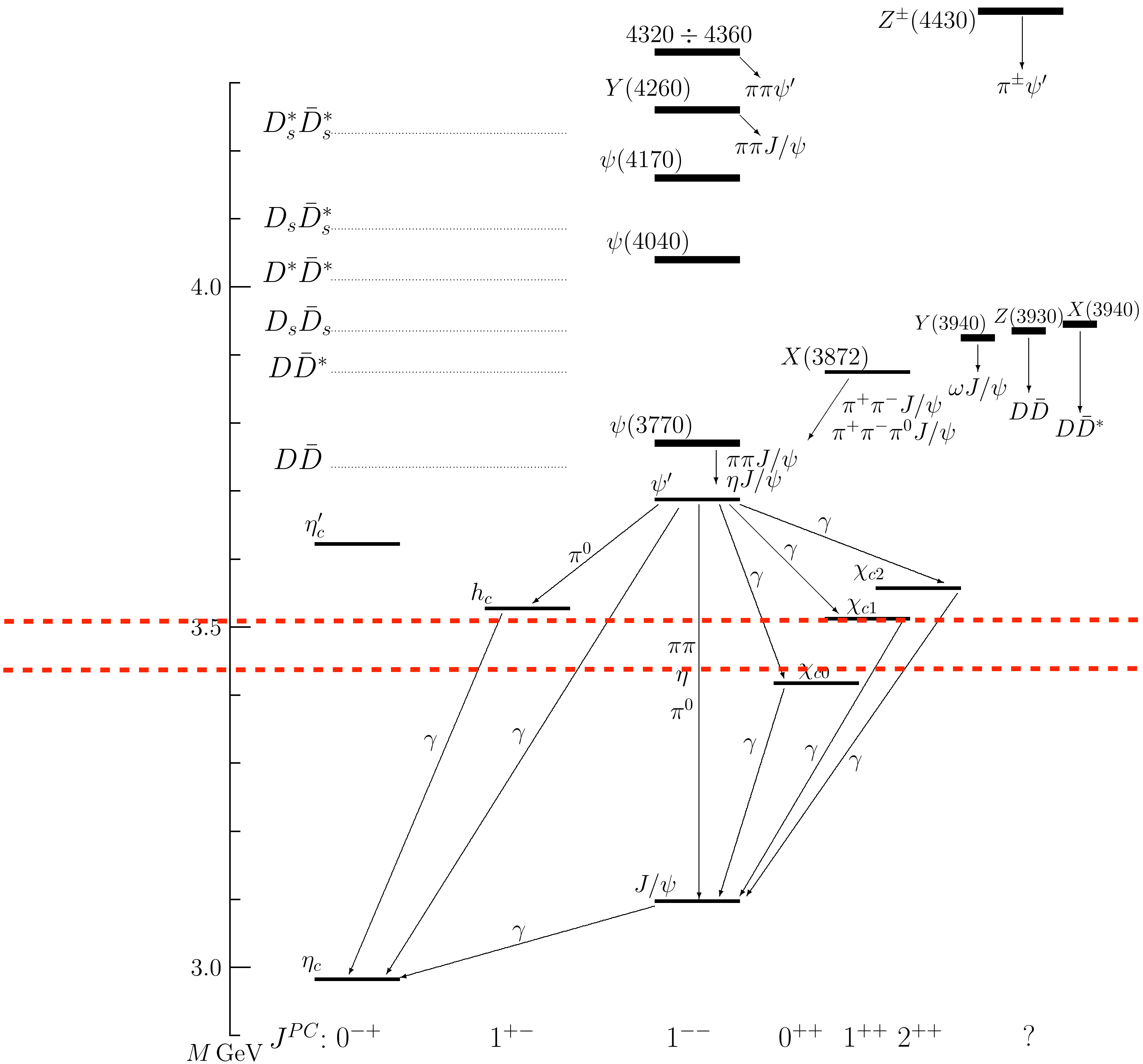


Exchange by heavy D-meson in t-channel

$$\Gamma_{P_c \to J/\psi N} \sim |\Psi(0)|^2$$

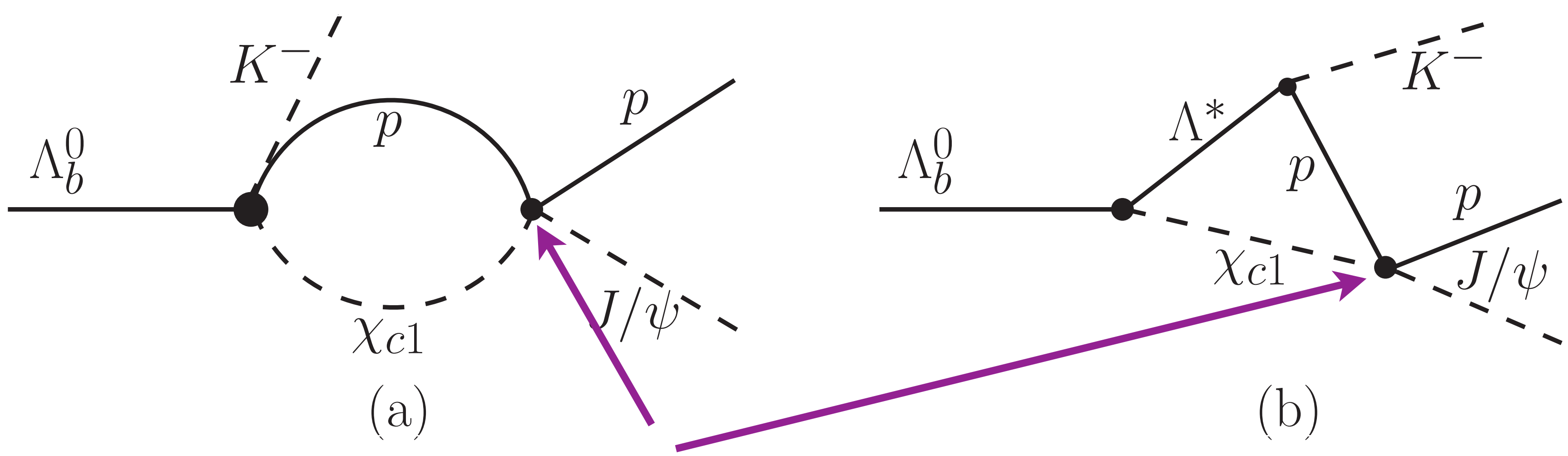
at the best tens of KeV !

LHCb structures as threshold effects



LHCb structures as a threshold effects

Guo, Meissner, Wang, Yang, arXiv:1507.0495

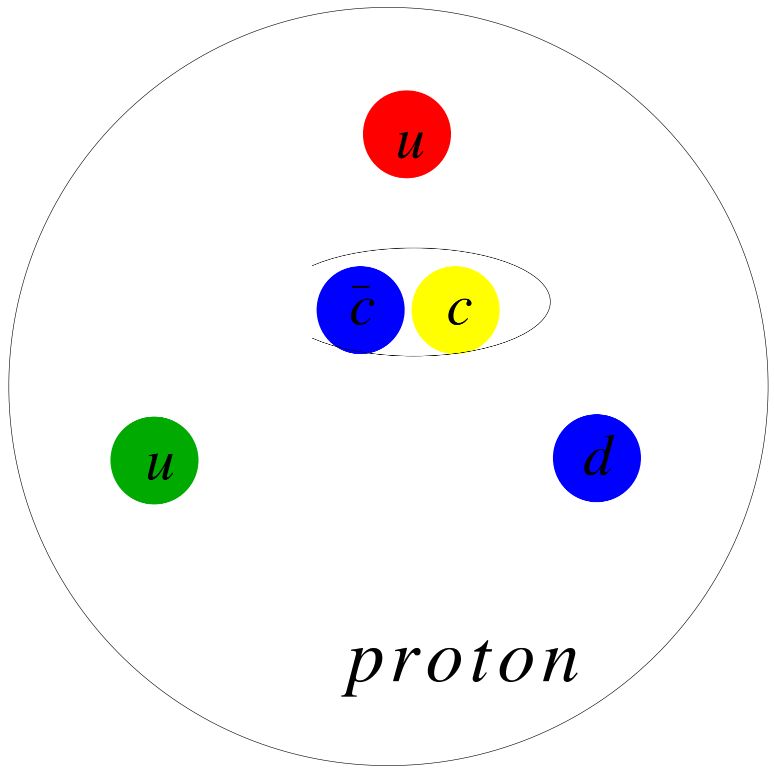


Value is fitted to LHCb peak at 4450 MeV

Huge value was obtained! It seems in contradiction with QCD multipole expansion !
In QCD that coupling is proportional to $\langle N'|G\tilde{G}|N\rangle$ which is computable (axial anomaly) and turned out to be small!

Our approach (M. Eides, V. Petrov +M.V.P.)

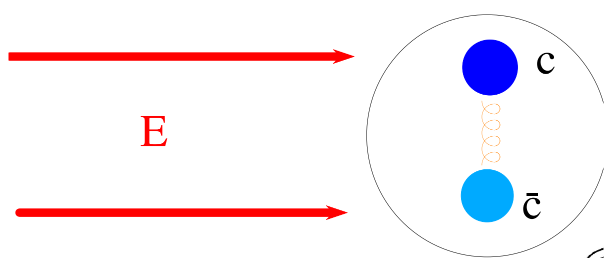
Main idea - to what decays = consist of



Small size charmonium "seats" inside the proton surrounded by light quarks

Small size charmonium interacts with light degrees of freedom via 2-gluon exchange (Voloshin, Shifman et a.):

$$V = \frac{1}{2}\alpha\ \mathbf{E^a}\cdot\mathbf{E^a}$$



Chromoelectric polarizability

Chromoelectric field. Its source are light quarks and gluons in the proton

Small size charmonium as a probe of energy-momentum density in the proton

$$E^2 = \frac{E^2 + H^2}{2} + \frac{E^2 - H^2}{2} = \Theta_{00}^{(G)} + G_{\mu\nu}^2$$

$\Theta_{\mu\nu}$ is the total (quarks+gluons) energy momentum tensor, $\Theta_{\mu\nu}^{(G)}$ its gluon part

Conformal anomaly: $\Theta_\mu^\mu = \frac{bg_s^2}{8\pi^2} G_{\mu\nu}^2$ with $b = \frac{11}{3}N_c - \frac{2}{3}N_f$ (Gell-Mann Low coef)

Effective potential: $$V(x) = \frac{1}{2} \alpha \left[\Theta_{00}^{(\mathbf{G})}(\tilde{\mathbf{x}}) + \frac{8\pi^2}{\mathbf{bg_s^2}}\Theta_\mu^\mu(\tilde{\mathbf{x}})\right]$$

g_s is normalized at the proton size. In the instanton vacuum $\frac{8\pi^2}{g_s^2} \approx 11 - 12$

For gluon EMT we use $\Theta_{00}^{(G)} = \xi\Theta_{00}$, where $\xi \approx 0.4$ is the momentum fraction carried by gluons in the proton

Effective proton-charmonium potential in other form:

$$V(\vec{x}) = -\frac{4\pi^2}{b}\alpha\left(\rho_E(\vec{x})\left[1+\xi\frac{bg_s^2}{8\pi^2}\right] - 3p(\vec{x})\right)$$

Total energy density in the proton

Pressure in the proton

Normalizations: $\int d^3x \rho_E(\vec{x}) = M_N$ total energy = nucleon mass

$\int d^3x p(\vec{x}) = 0$ stability of the nucleon

From here we obtain the normalization of the potential:

$$\int d^3x V(\vec{x}) = -\alpha\frac{4\pi^2}{b}M_N\left[1+\xi\frac{bg_s^2}{8\pi^2}\right]$$

Normalization is known (upto value of chromoelectric polarizability)!

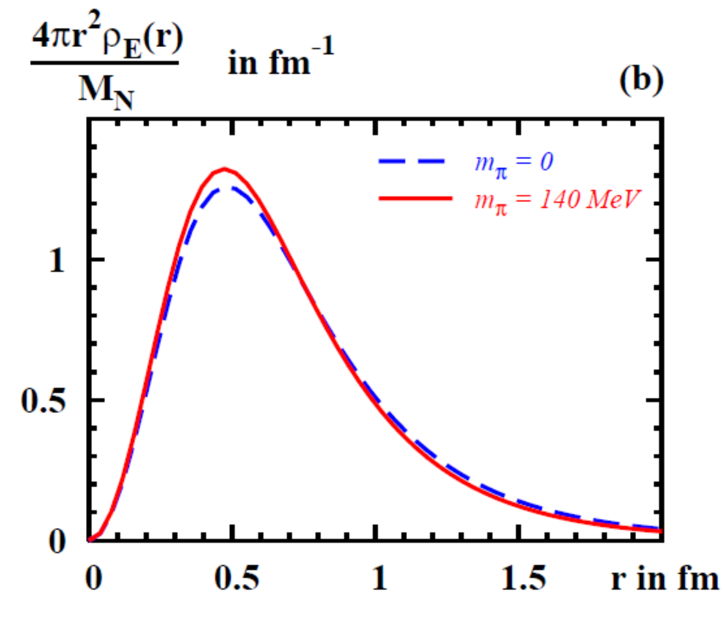
Effective proton-charmonium potential at all distances

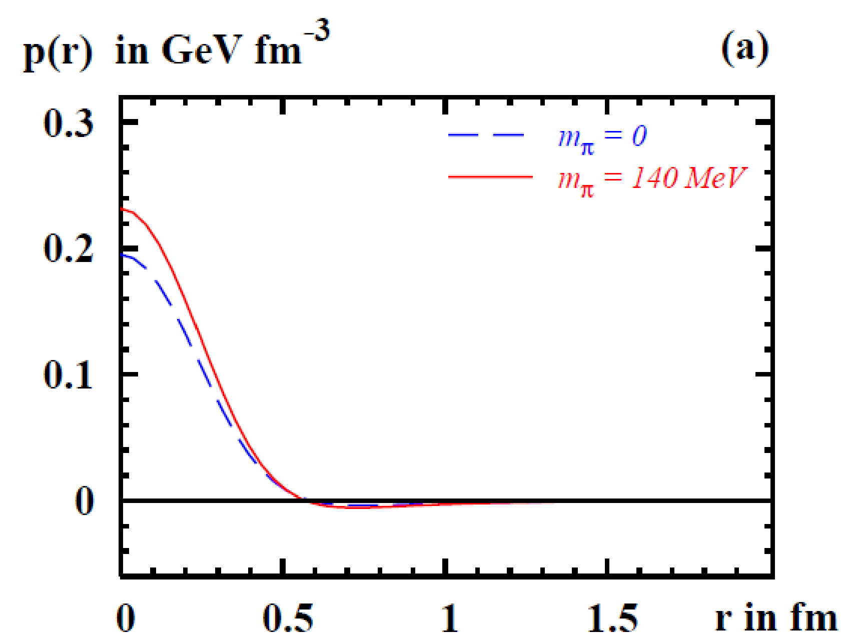
At large distances the chiral perturbation theory can be applied:

$$V(\boldsymbol{x}) \sim -\alpha \frac{27(1+\nu)}{16b} \frac{g_A^2}{F_\pi^2 |\boldsymbol{x}|^6}.$$

$\nu = 1 + \xi(bg_s^2/8\pi^2) \qquad \nu \sim 1.5$

Energy density and pressure in N were computed in ChQSM (Goeke, Schweitzer, M.V.P)





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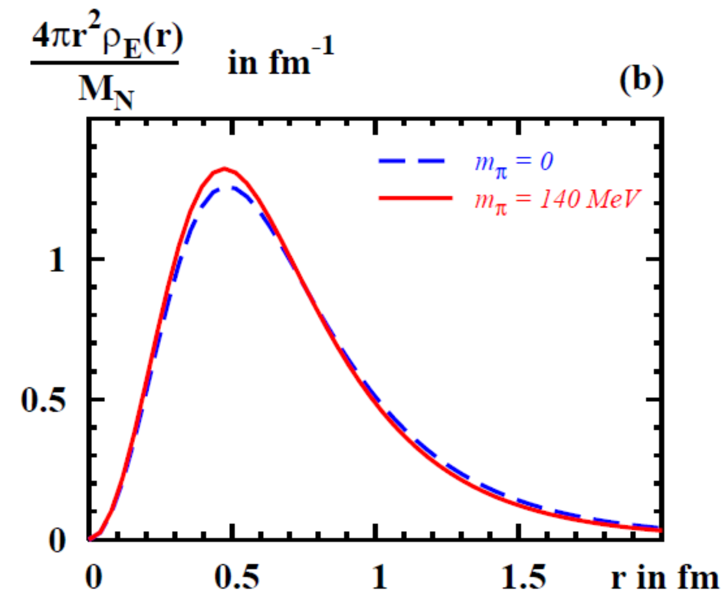
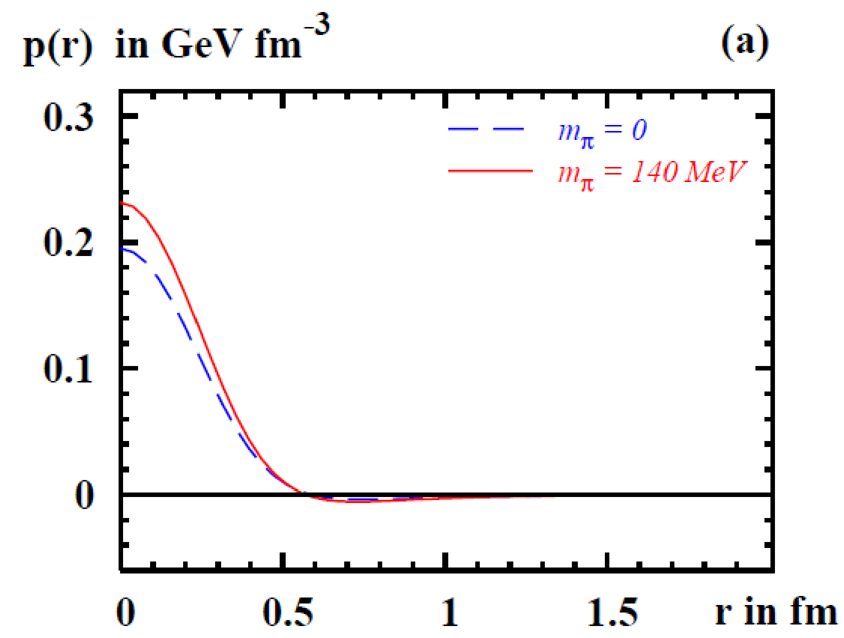
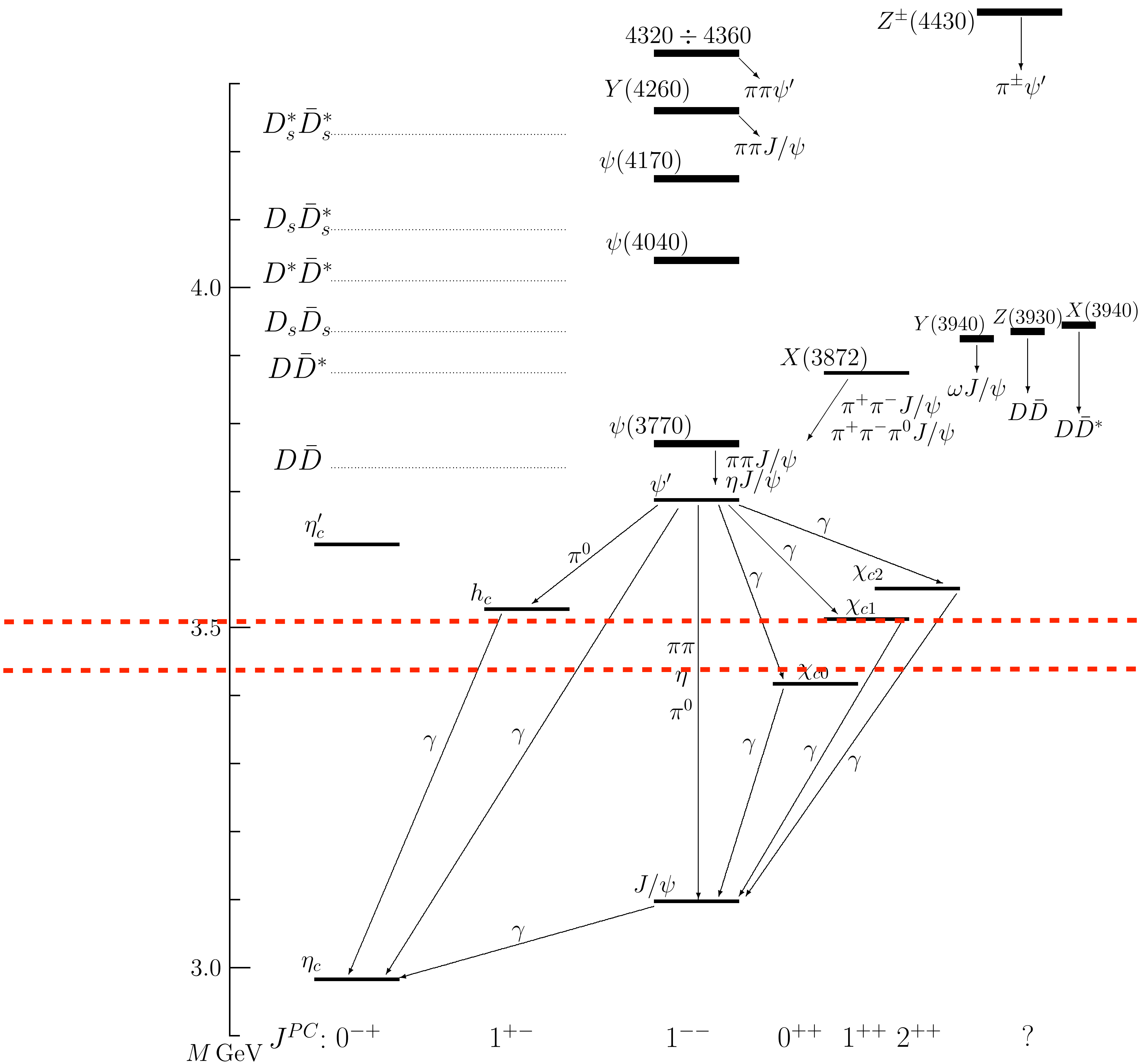




Now everything is more or less known up to overall scale given by chromoelectric polarizability



L=2 L=1 L=0 L=1

decays L

if $J^P = \frac{3}{2}^-$

Chromoelectric polarizability

If one treats a charmonium as an non-relativistic Coulomb system, the polarizability can be computed (M. Peskin '76)

$$\alpha(nS) = \frac{16\pi n^2}{3g^2 N_c^2} c_n a_0^3,$$

where $c_1 = 7/4$, $c_2 = 251/8$, $c_n(n \geq 3) = (5/16)n^2(7n^2 - 3)$, $a_0 = 16\pi/(g^2 N_c m_q)$

Rapid increase with principal quantum number n !!!

Numerically:

$$\alpha(1S) \approx 0.2\ \mathrm{GeV}^{-3}, \qquad \alpha(2S) \approx 12\ \mathrm{GeV}^{-3}, \qquad \alpha(2S \to 1S) \approx -0.6\ \mathrm{GeV}^{-3}$$

Transitional polarizability can be extracted from the decay $\Psi(2S) \to J/\psi + \pi + \pi$ with the result (M.Voloshin'06)

$$|\alpha(2S \to 1S)| \approx 2\ \mathrm{GeV}^{-3}$$

It seems charmonia are not good Coulomb systems! Let us use Coulomb values only as a guide.

Possible proton-charmonium bound states

Effective potential is attractive. Its form is fixed. The overall strength is given by the polarizability.

Let us see at which polarizability bound states and what kind are possible.
Schroedinger eq:

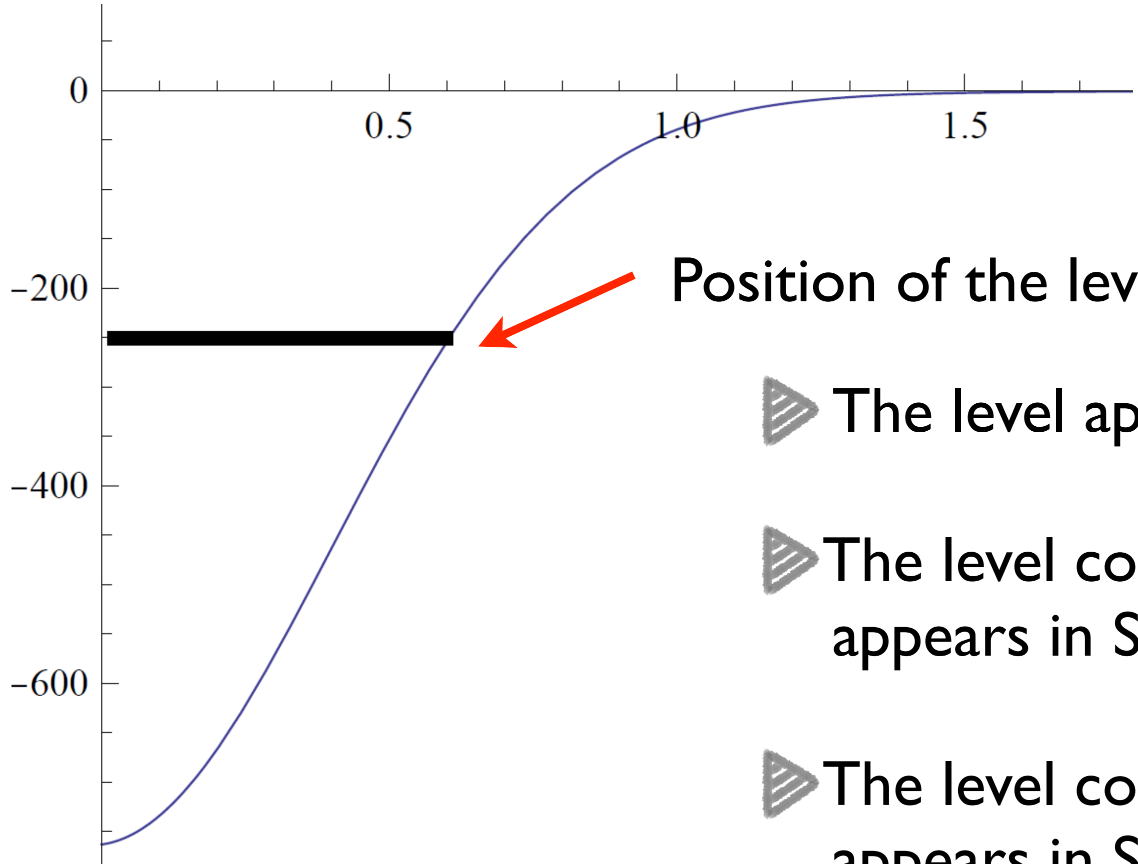
$$\left(-\frac{\boldsymbol{\nabla}^2}{2\mu_1} + V_{11}(r) - E\right)\Psi_1 + V_{12}(r)\Psi_2 = 0,$$
$$\left(-\frac{\boldsymbol{\nabla}^2}{2\mu_2} + V_{22}(r) - E + \Delta\right)\Psi_2 + V_{12}(r)\Psi_1 = 0.$$

$$V_{22}(r) \equiv V(r), \qquad V_{11}(r) = \frac{\alpha(1S)}{\alpha(2S)}V(r), \qquad V_{12}(r) = \frac{\alpha(2S \to 1S)}{\alpha(2S)}V(r)$$

$$V(\vec{x}) = -\frac{4\pi^2}{b}\alpha\left(\rho_E(\vec{x})\left[1 + \xi\frac{bg_s^2}{8\pi^2}\right] - 3p(\vec{x})\right)$$

$$\alpha = \alpha(2S)$$

Possible proton-charmonium bound states



Position of the level depends of the value of the polarizability

- The level appears first in S-wave at $\alpha = 5.6\ \mathrm{GeV}^{-3}$
- The level corresponding upper penta (E=-176 MeV) appears in S-wave at $\alpha = 17.2\ GeV^{-3}$
- The level corresponding lower penta (E=-246 MeV) appears in S-wave at $\alpha = 20.2\ GeV^{-3}$

Compare (for guidence) with the Coulomb values of the polarizabilities:

$$\alpha(1S) \approx 0.2\ \mathrm{GeV}^{-3}, \qquad \alpha(2S) \approx 12\ \mathrm{GeV}^{-3}, \qquad \alpha(2S \to 1S) \approx -0.6\ \mathrm{GeV}^{-3}$$

J/ψ does not form a bound state!

$\psi(2S)$ does it! But only one bound state is possible! Which one lower (wide) or upper (narrow) penta? Let us consider the width of the bound state.

Width of the proton-charmonium bound states

Scattering problem for coupled channel Schroedinger eqs:

$$\left(-\frac{\boldsymbol{\nabla}^2}{2\mu_1}+V_{11}(r)-E\right)\Psi_1+V_{12}(r)\Psi_2=0,$$
$$\left(-\frac{\boldsymbol{\nabla}^2}{2\mu_2}+V_{22}(r)-E+\Delta\right)\Psi_2+V_{12}(r)\Psi_1=0.$$

Result:

$$\Gamma=\left(\frac{\alpha(2S\to 1S)}{\alpha(2S)}\right)^2(4\mu_1 q)\left|\int_0^\infty drr^2R_l(r)V(r)j_l(qr)\right|^2$$

Important: everything is fixed!! Numerically:

$$\Gamma(P_c(4450)\ \to\ N\ +\ J/\psi)\ =\ 11.2\ \text{MeV}$$

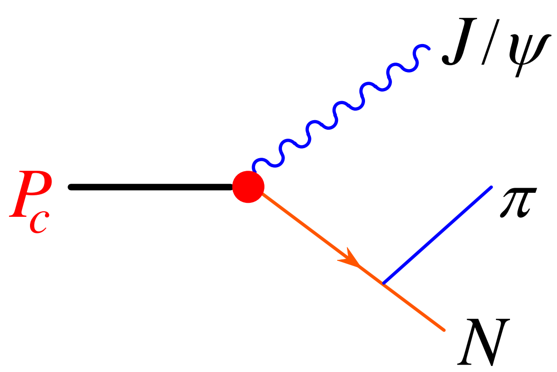
Excellent agreement with experimental width of upper (narrow) penta $\Gamma_{\text{exp}}=39\pm 5\pm 19$ MeV

Therefore we identify our bound state with $P_c(4450)$ pentaquark

Width of the proton-charmonium bound states

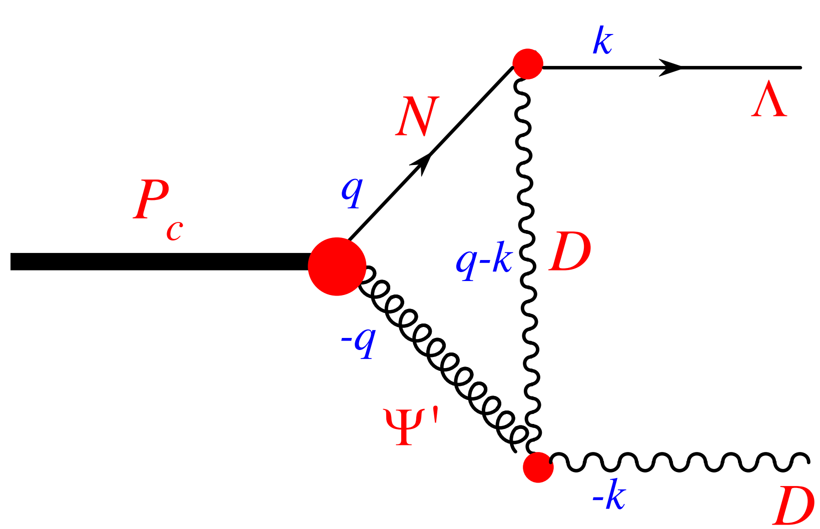
We consider only partial decay width to $J/\psi + p$

What else?



$$\frac{\Gamma_3}{\Gamma_2} = \frac{g^2_{\pi NN}}{15\pi^2}\frac{\Delta^2}{M_1^2}\frac{1}{1+\frac{M_1}{2M_{J/\psi}}}$$

40 times smaller



Exchange by heavy D-meson in t-channel
~0.1 MeV at best.

Quantum numbers

Bound state is in S-wave - there are two possibility to add 1/2-spin of proton to spin-1 of charmonium:

$$J^P = \frac{1}{2}^-, \frac{3}{2}^-$$

In leading order of the heavy quark mass expansion both states are degenerate in mass!

The degeneracy is lifted by hyperfine interaction:

$$H_{eff} = -\frac{\alpha}{4m_q} S_j \langle N | [E_i^a (D_i B_j)^a + (D_i B_j)^a E_i^a] N \rangle$$

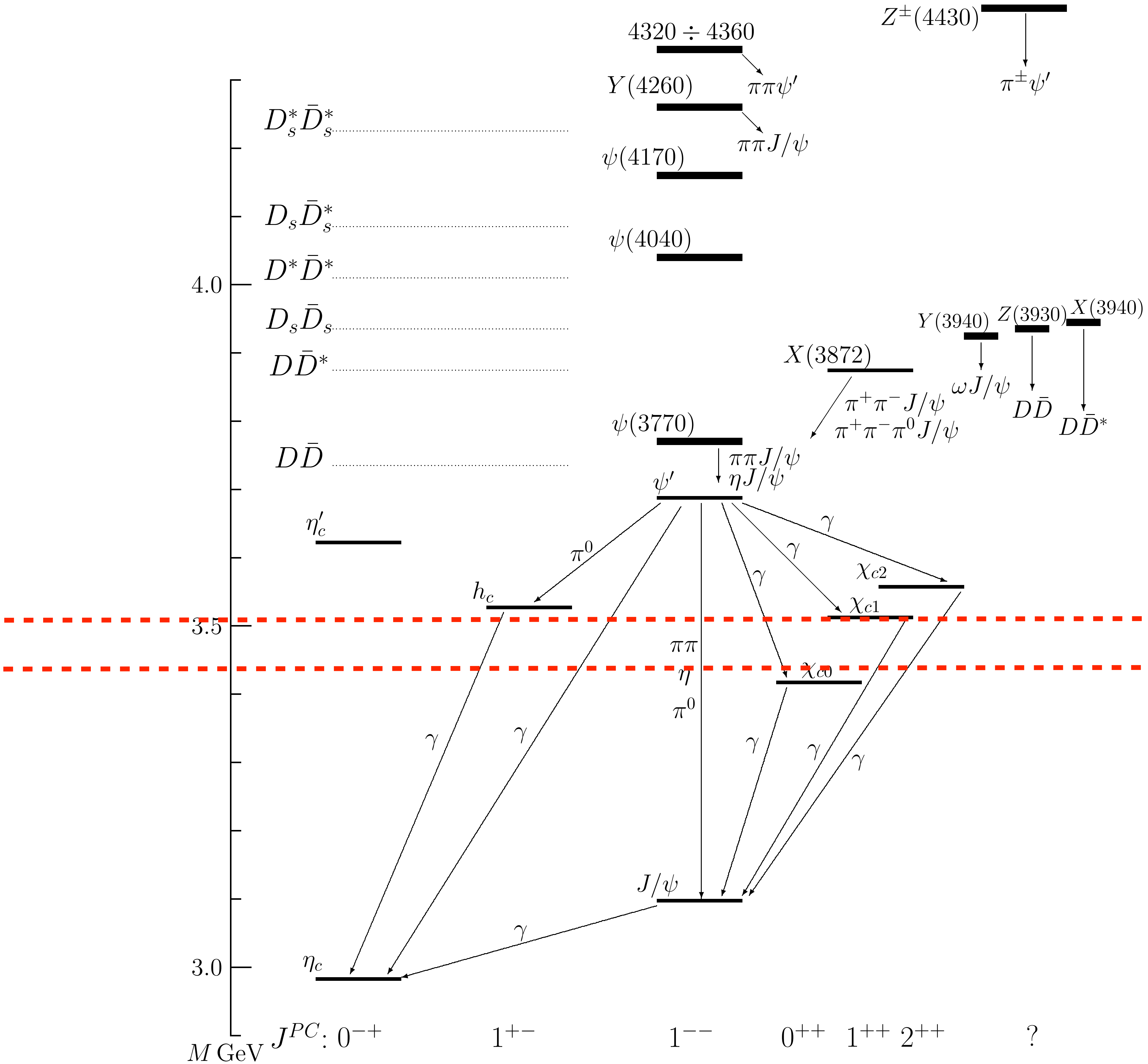
Note that polarizability is same, only QCD operator changes! This operator can be reduced (via axial anomaly) to known matrix element:

$$< N' | G\widetilde{G} | N >= \frac{32\pi^2}{12 N_f} g_a^{(0)} (\vec{S} \cdot \vec{q})$$

Numerical estimates give 10-15 MeV splitting

In our picture

- P(4450) is the bound state of the proton and the charmonium $\psi(2S)$
- The peak at 4450 MeV is the interplay of two almost degenerate resonances with quantum # 1/2- and 3/2- (at variance with LHCb PWA)
- What about bound states with other type of charmonia? Polarizabilities are increasing with principal quantum number and orbital momentum!



decays L if $J^P = \frac{3}{2}^-$

L=2 L=1 L=0 L=1

Pandora box?

- Small quarkonia almost do not disturb inner baryon structure, therefore, if bound with proton, than bound to its various excitations: hyperons, Deltas, Nstars, etc (PDG volume 2 :))

- Each pentaquark is accompanied by almost degenerate (hyperfine splitted) partners of the same parity

- Good news (no PDG v3 :)): it seems that bottomia do not bind to the nucleon -- polarizabilities are too small! Good way to falsify our picture of LHCb pentaquarks!

Hvala !