Colors of QCD:
Hadron spectroscopy and exotic states at LHCb

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June 28th, 2019

Perspective of QCD – large white space with little colorful objects

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[zoom]

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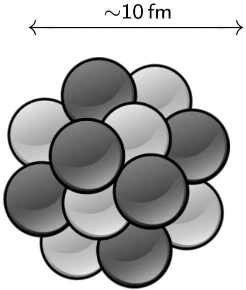
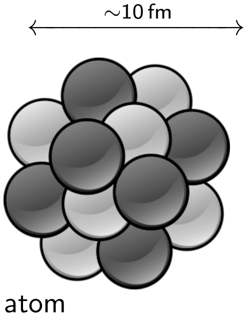


atom

Perspective of QCD – large white space with little colorful objects

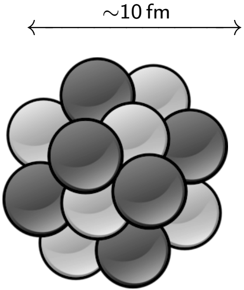
[zoom]



[zoom]

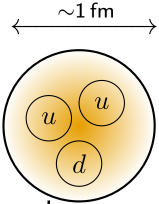
Perspective of QCD – large white space with little colorful objects

[zoom]



atom

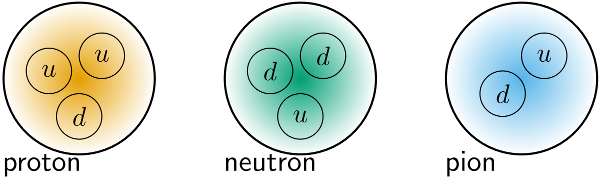
[zoom]



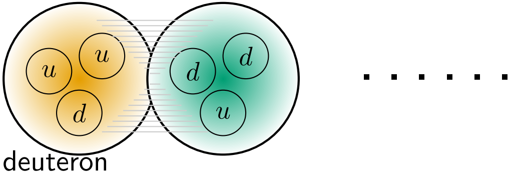
nucleon

Perspective of QCD – large white space with little colorful objects

simple hadrons (baryons, mesons)



hadronic molecules (atoms)



If that's all, who are these?

"Ok, google, show me known mesons"'...

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{π0, π-, π+, K-, K+, K0, K_L, K_S, K0-bar, η, ρ+(770), ρ0(770), ρ-(770), ω(782), f_0(600), K_0^*0(800), K_0^*+(800), K_0^*-(800), K_0^*0-bar(800), K*-(892), K*+(892), K*0(892), K*0-bar(892),
η'(958), f_0(980), a_0^-(980), a_0^0(980), a_0^+(980), ϕ(1020), X(1070), X(1110), h_1(1170), b_1^-(1235), b_1^0(1235), b_1^+(1235), a_1^-(1260), a_1^0(1260), a_1^+(1260), K_1^0(1270),
K_1^+(1270), K_1^-(1270), K_1^0-bar(1270), f_2(1270), f_1(1285), η(1295), π-(1300), π0(1300), π+(1300), a_2^-(1320), a_2^0(1320), a_2^+(1320), f_0(1370), π_1^-(1400), π_1^0(1400), π_1^+(1400),
h_1(1380), K_1^0(1400), K_1^+(1400), K_1^-(1400), K_1^0-bar(1400), η(1405), K_0^*0(1430), K_0^*+(1430), K*0(1410), K*+(1410), K_0^*-(1430), K_0^*0-bar(1430), K*-(1410), K*0-bar(1410), X(1420),
ω(1420), K_2^*+(1430), K_2^*-(1430), f_1(1420), K_2^*0(1430), K_2^*0-bar(1430), f_2(1430), ρ-(1450), ρ0(1450), ρ+(1450), K0(1460), K+(1460), K-(1460), K0-bar(1460), a_0^-(1450), a_0^0(1450),
a_0^+(1450), η(1475), f_0(1600), f_0(1500), f_1(1510), f_2'(1525), f_2(1565), K_2^0(1580), K_2^+(1580), K_2^-(1580), K_2^0-bar(1580), h_1(1595), X(1600), η_2(1645), K0(1630), K+(1630),
K-(1630), K0-bar(1630), f_2(1640), a_1^-(1640), a_1^0(1640), a_1^+(1640), K_1^0(1650), K_1^+(1650), K_1^-(1650), K_1^0-bar(1650), X(1650), π_1^-(1600), π_1^0(1600), π_1^+(1600), ω_3(1670),
ω(1650), π_2^-(1670), π_2^0(1670), π_2^+(1670), ϕ(1680), ρ_3^-(1690), ρ_3^0(1690), ρ_3^+(1690), K*0(1680), K*+(1680), K*-(1680), K*0-bar(1680), f_0(1710), ρ-(1700), ρ0(1700), ρ+(1700),
a_2^+(1700), a_2^-(1700), a_2^0(1700), X(1750), η(1760), X(1775), K_2^0(1770), K_2^+(1770), K_2^-(1770), K_2^0-bar(1770), K_3^*0(1780), K_3^*+(1780), K_3^*-(1780), K_3^*0-bar(1780), π-(1800),
π0(1800), π+(1800), f_2(1810), K_2^0(1820), K_2^+(1820), K_2^-(1820), K_2^0-bar(1820), K0(1830), K+(1830), K-(1830), K0-bar(1830), X(1835), η_2(1870), ϕ_3(1850), X(1855), ρ-(1900), ρ0(1900),
ρ+(1900), D0, D0-bar, D-, D+, a_3(1875), X(1870), π_2(1880), f_2(1910), a_1(1930), X(1935), ρ_2(1940), f_2(1950), K_0^*0(1950), K_0^*+(1950), ω_3(1945), K_0^*-(1950), K_0^*0-bar(1950),
b_1(1960), h_1(1965), ω(1960), ρ(1965), D_s, D_s-bar, X(1970), f_1(1970), K_2^*0(1980), K_2^*+(1980), X(1975), K_2^*-(1980), K_2^*0-bar(1980), ω_2(1975), ρ_3^-(1990), ρ_3^0(1990),
ρ_3^+(1990), f_0(2020), X0(2000), ρ(2000), a_4^-(2040), a_4^0(2040), a_4^+(2040), f_2(2000), a_2(1990), π_2(2005), D*(2007), D*-bar(2007), D*-bar(2010), D*(2010), η(2010), f_2(2010),
π_1(2015), X(2020), b_3(2025), f_4(2050), h_3(2025), a_0(2020), η_2(2030), K_4^*0(2045), K_4^*+(2045), K_4^*-(2045), K_4^*0-bar(2045), f_3(2050), a_2(2080), f_0(2060), a_3(2070), π(2070),
X(2075), X0(2080), π_2^-(2100), π_2^0(2100), π_2^+(2100), a_1(2095), η(2100), X(2100), f_0(2100), X(2110), D_s^*, D_s^*-bar, f_2(2140), ρ-(2150), ρ0(2150), ρ+(2150), ω(2145), X(2150),
f_2(2150), a_2(2175), f_0(2200), η(2190), ω_2(2195), ω(2205), X0(2210), η(2225), h_1(2215), f_J(2220), b_1(2240), π_2(2245), ρ_2(2240), ρ_4(2240), K_2^0(2250), K_2^+(2250), K_2^-(2250),
K_2^0-bar(2250), η_2(2250), ω_3(2255), ω_4(2250), π_4(2250), ρ_3^-(2250), ρ_3^0(2250), ρ_3^+(2250), ρ(2265), X(2260), a_2(2270), a_1(2270), h_3(2275), ω_3(2285), ρ(2280), η(2280), X(2290),
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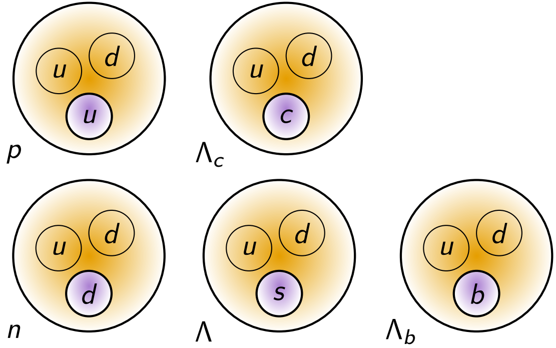
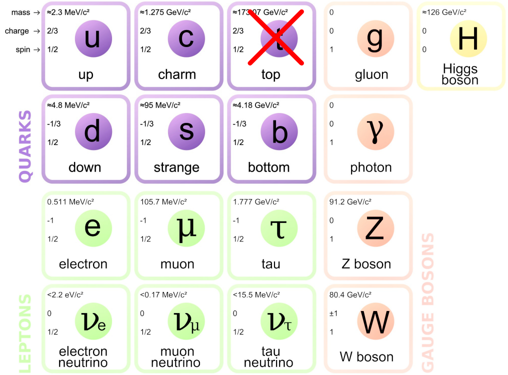
D_0^*+(2400), D_0^*-(2400), D_1^0(2420), D_1^0-bar(2420), D_1^+(2420), D_1^-(2420), D_1(2430), D_1-bar(2430), X(2440), a_6^-(2450), a_6^0(2450), a_6^+(2450), D_s1(2460), D_s1-bar(2460),
D_2^*+(2460), D_2^*-(2460), f_6(2510), D_2^*0(2460), D_2^*0-bar(2460), K_4^0(2500), K_4^+(2500), K_4^-(2500), K_4^0-bar(2500), D_s1(2536), D_s1-bar(2536), D_s2(2573), D_s2-bar(2573), X(2632),
D*(2640), D*-bar(2640), X(2680), X(2710), X(2750), η_c(1S), K(3100), J/ψ(1S), f_6(3100), X0(3250), χ_c0(1P), χ_c1(1P), h_c(1P), χ_c2(1P), η_c(2S), ψ(2S), ψ(3770), X(3872), χ_c2(2P),
Y(3940), ψ(4040), ψ(4160), X(4260), ψ(4415), B-, B+, B0, B0-bar, B*-, B*+, B*0, B*0-bar, B_s, B_s-bar, B_s^*, B_s^*-bar, B_J^*0(5732), B_J^*+(5732), B_J^*-(5732), B_J^*0-bar(5732),
B_sJ^*(5850), B_sJ^*-bar(5850), B_c, B_c-bar, η_b(1S), Y(1S), χ_b0(1P), χ_b1(1P), χ_b2(1P), Y(2S), Y(1D), χ_b0(2P), χ_b1(2P), χ_b2(2P), Y(3S), Y(4S), Y(10860), Y(11020)}

Flavour modifications: Baryons

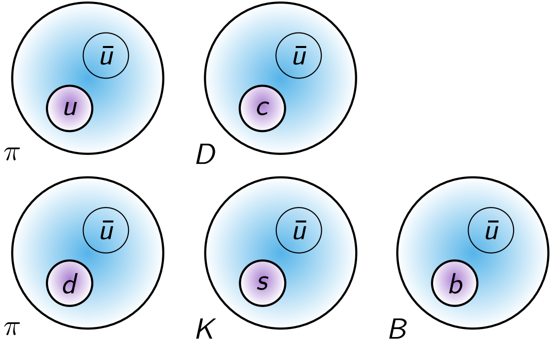


Standard Model particles

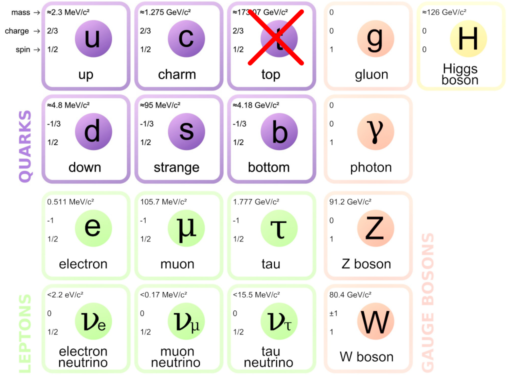


All (ground) hadrons are stable without weak interaction

Flavour modifications: Mesons

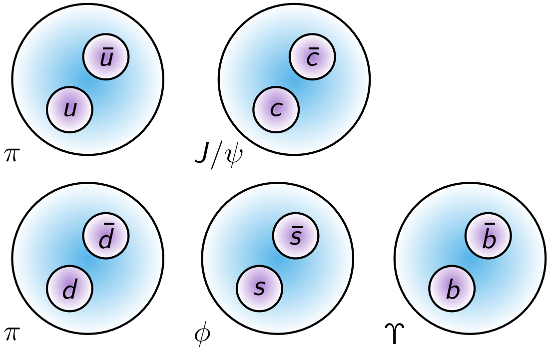


Standard Model particles

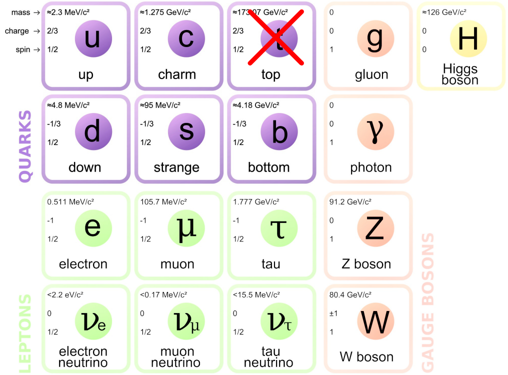


All (ground) hadrons are stable without weak interaction

Flavour modifications: Flavour-neutral Mesons

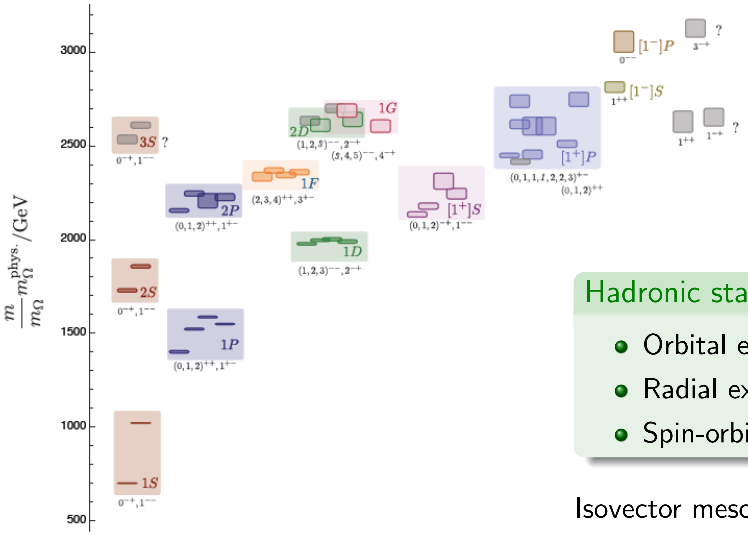


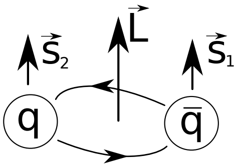
Standard Model particles



All (ground-state) hadrons are stable without the weak interaction

Conventional states: why so many hadrons





Hadronic states - energy levels

- Orbital excitation, $\vec{L}$
- Radial excitation, n
- Spin-orbit interaction, $\vec{J} = \vec{L} \oplus \vec{S}$

Isovector meson spectrum with $m_\pi \sim 800$ MeV

[J. Dudek et al., PRD82 034508 (2010)]

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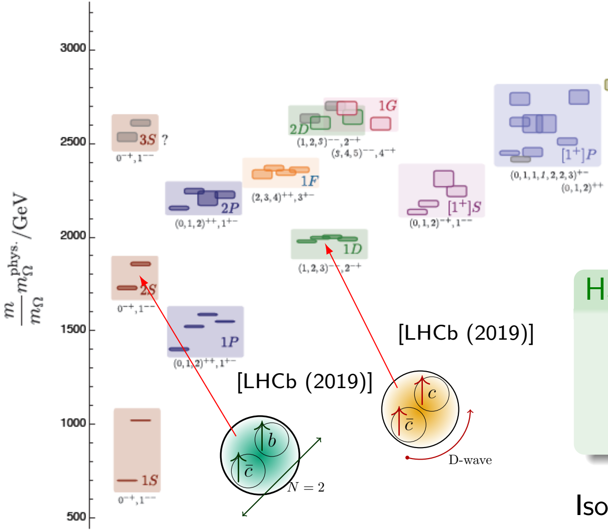

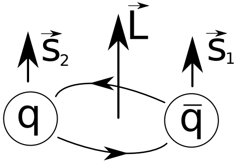

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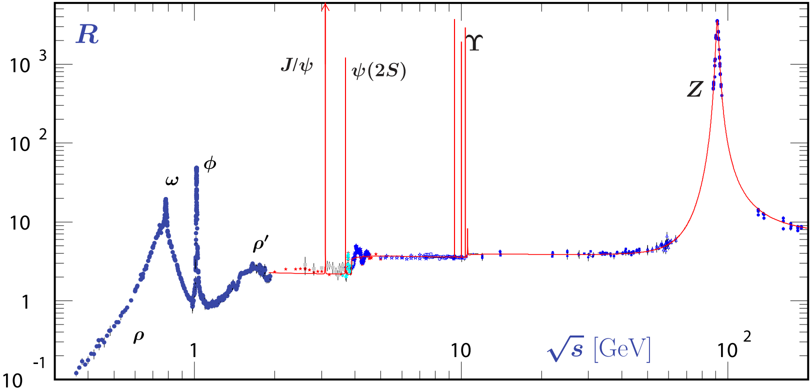
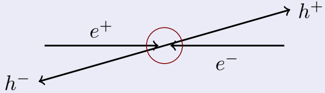
Hadrons: every flavour gets its energy range

[PDG2019]



R-ratio

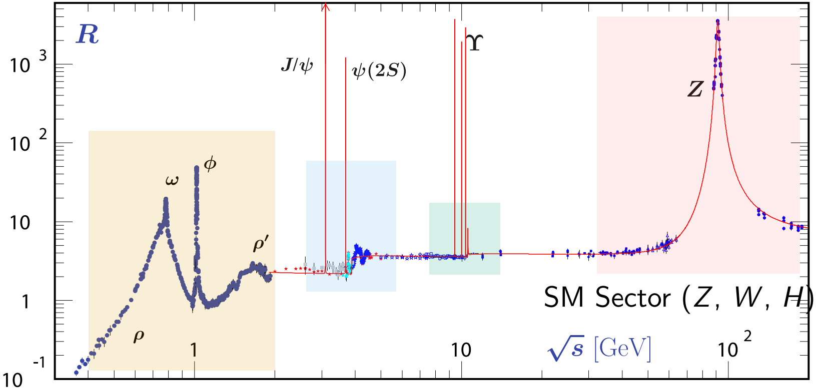


$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$

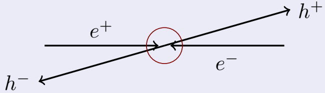
hadrons : $h^+h^-, \ldots$

Hadrons: every flavour gets its energy range

[PDG2019]



R-ratio



$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$

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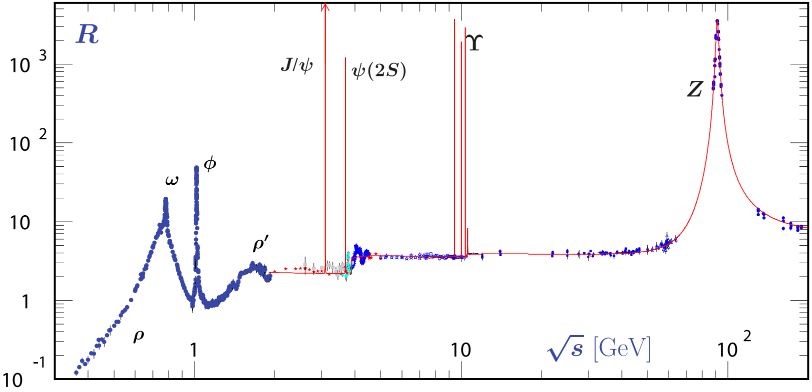
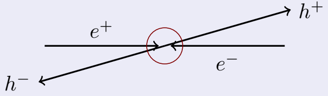
- Light (contain u,d,s) Hidden charmed ($c\bar{c}$) Hidden beauty ($b\bar{b}$)

Hadrons: every flavour gets its energy range

[PDG2019]



R-ratio



$$R = \frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-}$$

hadrons : $h^+h^-, \ldots$

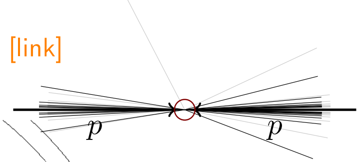
- Light (contain u,d,s) Hidden charmed ($c\bar{c}$) Hidden beauty ($b\bar{b}$)
- Energy ranges do not overlap

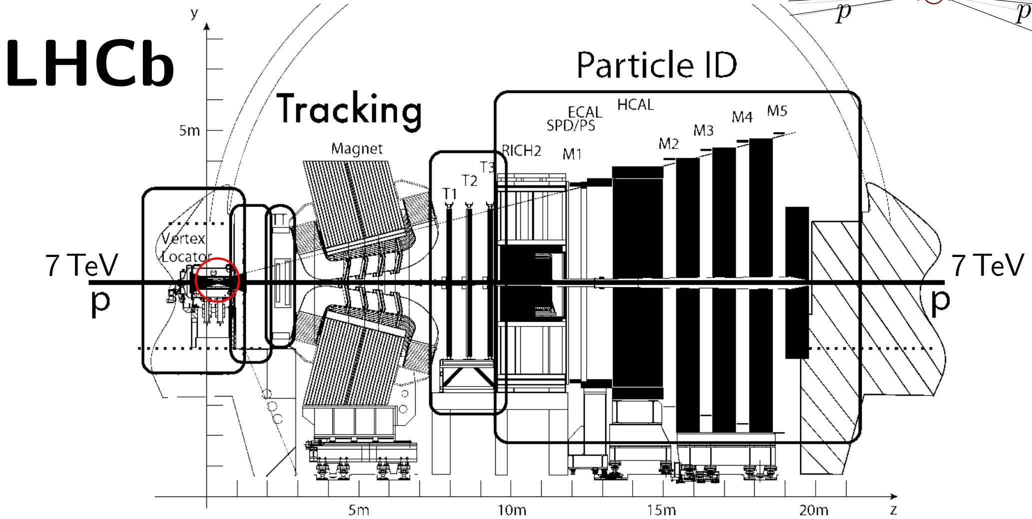
$\Rightarrow$ Energy range tells the flavour

Search for the new type of matter

[link]

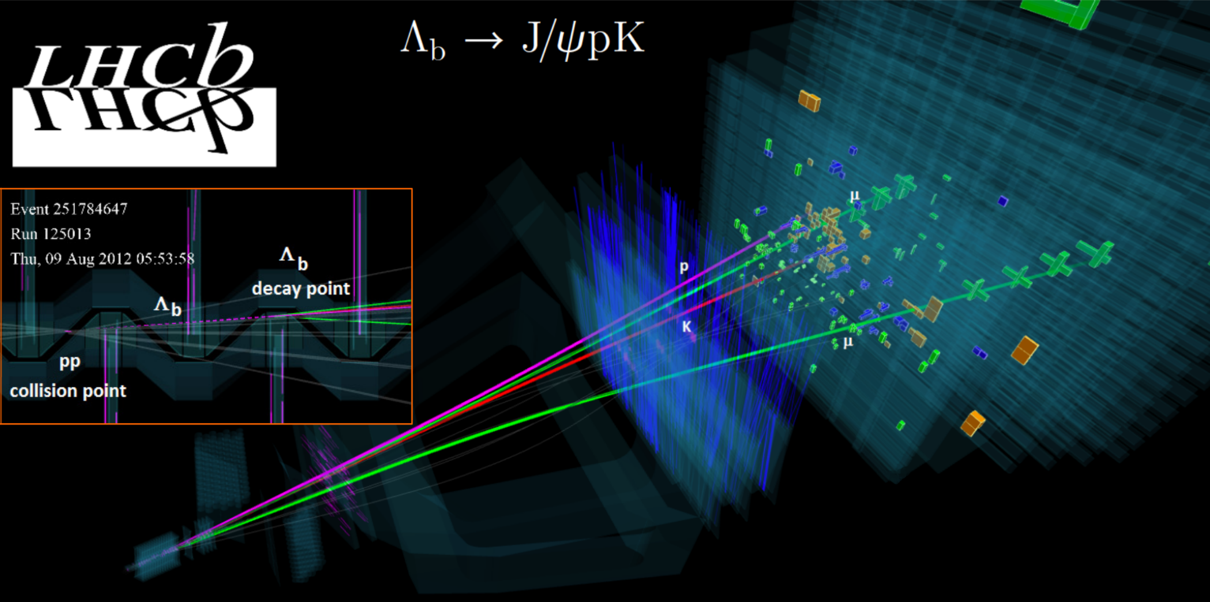
How to search for color physics with colorless environment?





modification of a plot from [INT. J. MOD. PHYS. A 30, 1530022]

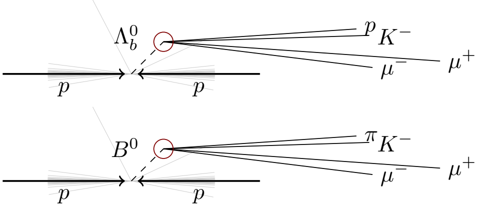
$\Lambda_b \rightarrow J/\psi p K$



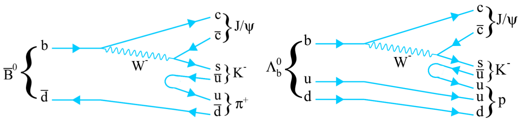
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



- similar decay chains



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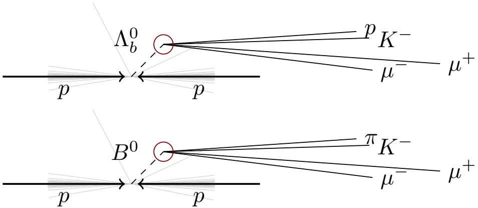

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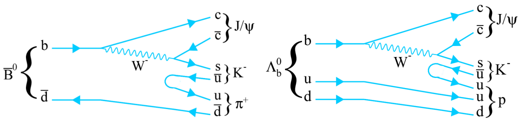
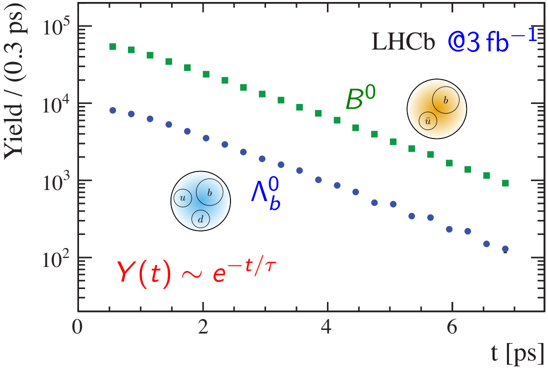


[PLB734 (2014) 122]



$$\tau_{\Lambda_b^0}/\tau_{B^0} = 0.974 \pm 0.006 \pm 0.004,$$

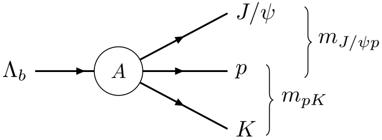
$$\boxed{\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010\,\text{ps},}$$

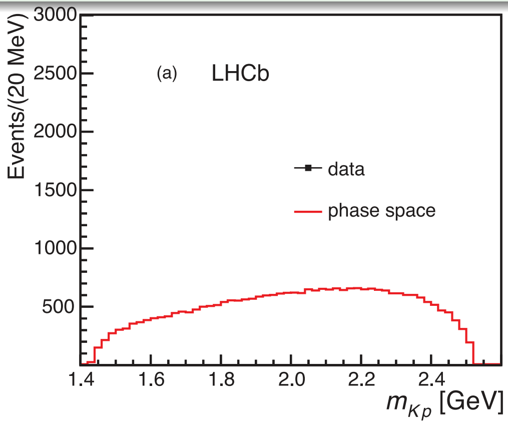
Dynamics of the decay $\Lambda_b^0 \to J/\psi\, p\, K$,

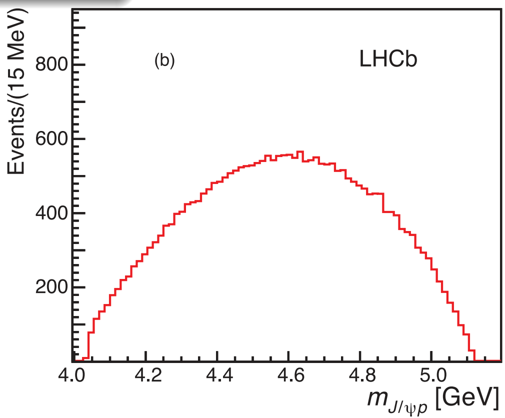
[PRL 115, 072001 (2015)]

Highly non-trivial transition amplitude

- interaction in pK subsystem
- something in $J/\psi p$ subsystem (!?)







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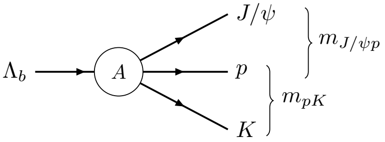
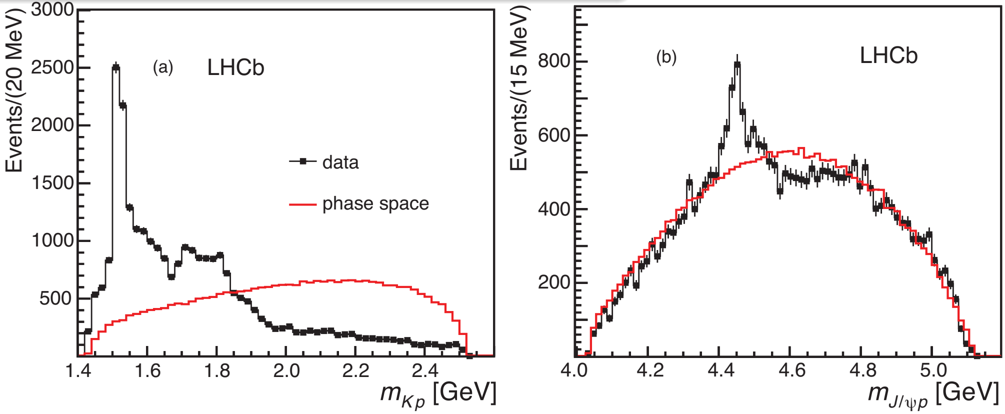


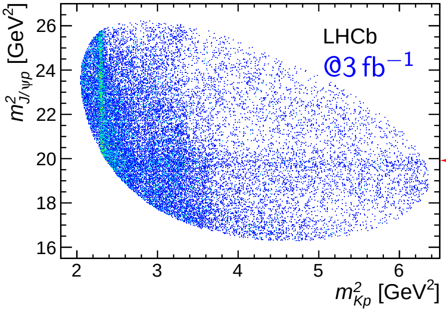


What could we expect

Example demo [link]

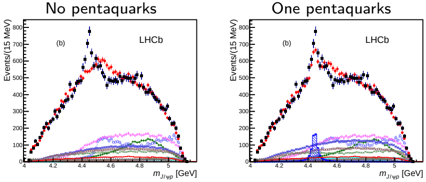
Observation of $P_c(4450)$ and $P_c(4380)$,

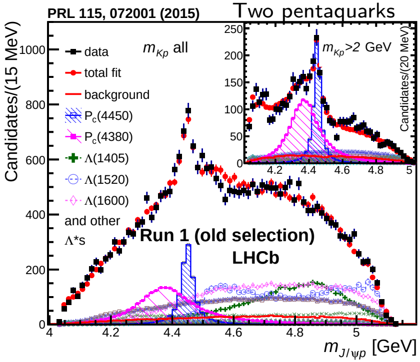
[PRL 115, 072001 (2015)]



$P_c(4450)$

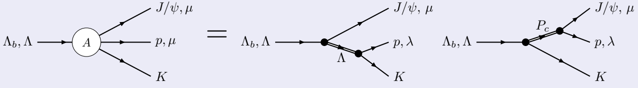
$\sim P_c(4380)$





Amplitude analysis of 2015

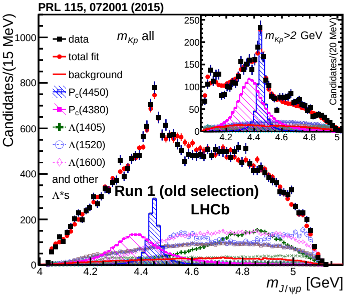
Helicity formalism, isobar model, 6-dim. analysis.

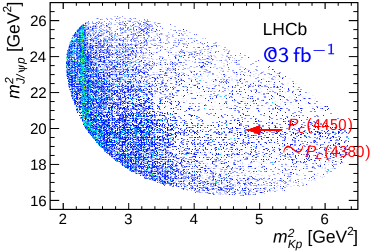


$\Rightarrow$ first ever observation of 5-quark states $[uudc\bar{c}]$.

Adding more data with Run-II (2017,2018)

[arXiv:1904.03947]





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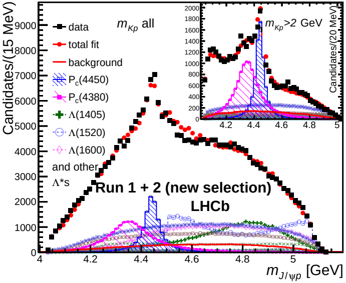

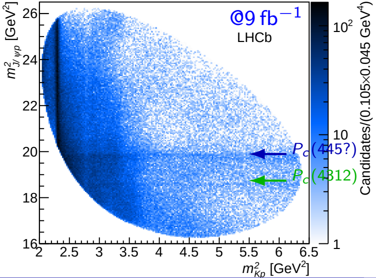

Gain in statistics $\times 9$

$26k$ events $\Rightarrow$ $246k$ events

- Luminosity: $3\,\mathrm{fb}^{-1} \oplus 6\,\mathrm{fb}^{-1}$,
- Cross section $\times 2$: 7 TeV$\rightarrow$ 13 TeV,
- Selection efficiency $\times 2$.

Amplitude Analysis

- same AA gives consistent results,
- but unacceptable quality.
  - Narrow peaks in $J/\psi p$
  - Lineshape of Λ.

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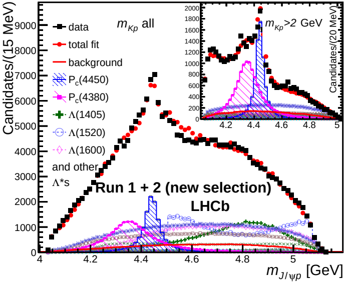

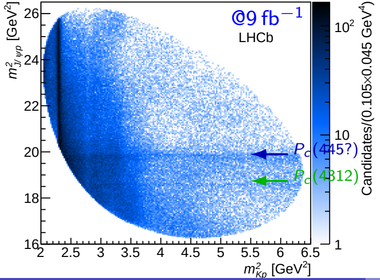

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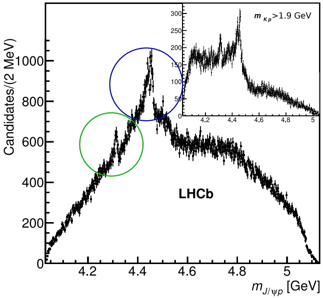


New features

- Peak at 4.312 GeV becomes significant
- Peak at 4.457 GeV got resolved in two!

Extracting resonance properties

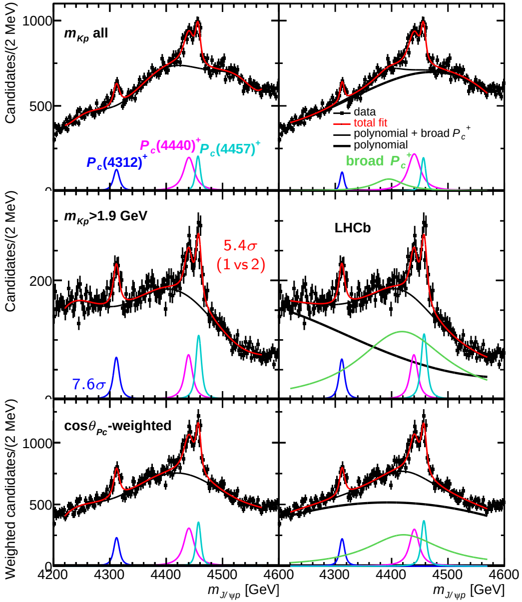
[arXiv:1904.03947]

1-dim. fit and extensive systematic studies:

- Three different projection methods
- Several background parametrization
- Interference effects
- Procedure is validated using 6-dim. MC

Mass and width of the peaks

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)
$P_c(4380)^+$	inconclusive with 1-dim. analysis		



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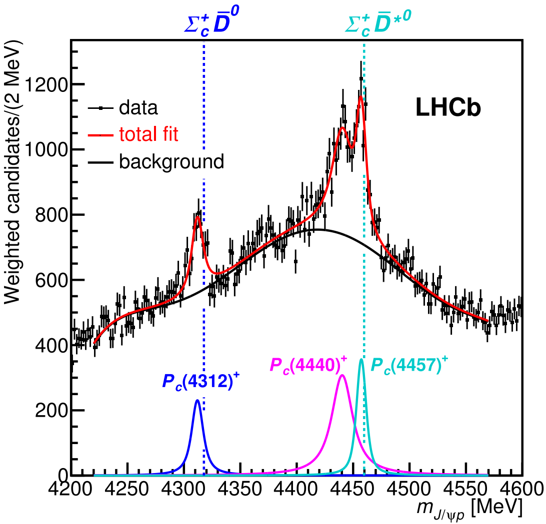
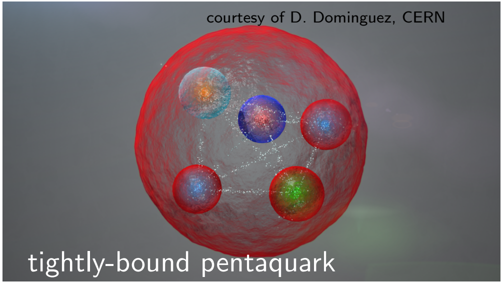
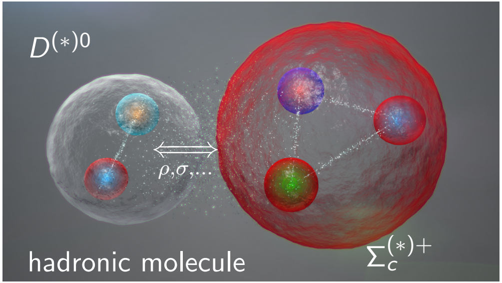


Two main interpretations of P_c states



- The state should have high probably to disintegrate to $J/\psi(c\bar{c})\ p(uud)$
- Diquark picture with a potential barrier
  [Maiani et al., PLB778, 247 (2018)]
- Does not relate appearance to the thresholds

[see Ref. in arXiv:1904.03947]



- Masses are near threshold of $\overline{D}^{0(*)}\Sigma_c^+$,
- Natural mechanism to separate charm quarks,
- Suggest importance of ρ/σ exchanges.

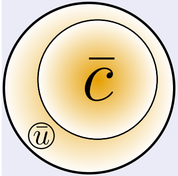
[W. L. Wang et al., Phys. Rev. C84 (2011) 015203]
[Z.-C. Yang et al., Chin. Phys. C36 (2012) 6]
[J.-J. Wu et al., Phys. Rev. C85 (2012) 044002]

Pattern of states in the Heavy-Quark limit

[arXiv:1904.03947]

States counting

Heavy Quark Spin Symmetry



Main interaction of $\overline{Q}q$ is strong

- Not sensitive to fravor
- Spin-spin interaction is suppressed

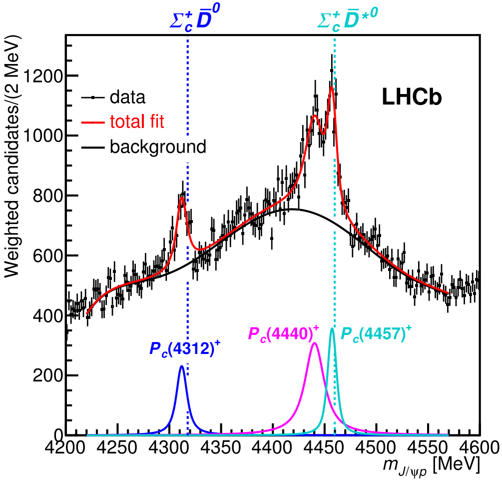
Pattern of $\Sigma_c\overline{D}$ molecules

$$\Sigma_c^+\overline{D}^0 \qquad 1/2^+ \otimes 0^- \xrightarrow{S-\mathrm{wave}} J^P : 1/2^-$$

$$\Sigma_c^+\overline{D}^{*0} \qquad 1/2^+ \otimes 1^- \xrightarrow{S-\mathrm{wave}} J^P : 1/2^- \oplus 3/2^-$$

$$\Sigma_c^{*+}\overline{D}^{*0} \qquad 3/2^+ \otimes 1^- \xrightarrow{S-\mathrm{wave}} J^P : 1/2^- \oplus 3/2^- \oplus 5/2^-$$

Many theoretical predictions of $\Sigma_c\, D$ binding published before 2015 (see backup).



- Important check is J^P of states!

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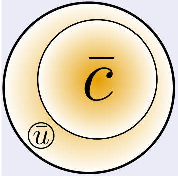

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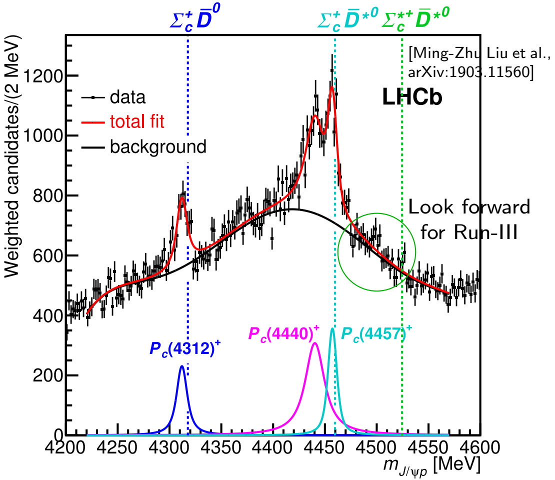

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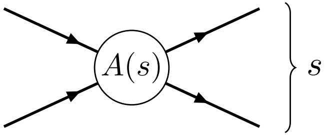
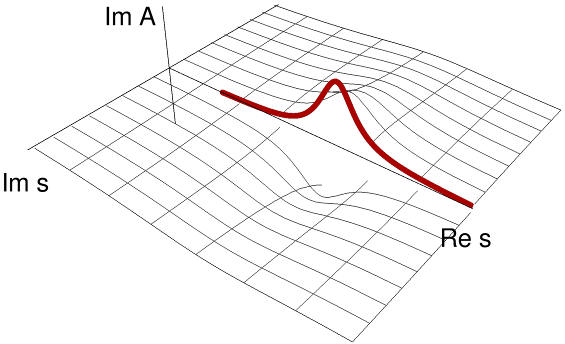
Basics of amplitude analysis

[see great books by Gribov, Collins, Martin-Spearman]

aka S-matrix theory





Scattering PW-amplitude

$A(s)$ is a transition amplitude

- Complex analytic function,
- Can be analytically continued to the complex energy plane, i.e. $A(\mathrm{Re}\, s + i\, \mathrm{Im}\, s)$
- The observed projection, $A(\mathrm{Re}\, s + i0)$

- All structures in the energy spectum have origin in the complex plane
- Hadronic resonances - complex **poles**!
- Production thresholds - branching points.

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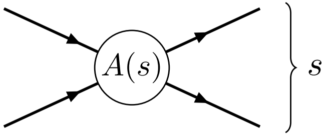

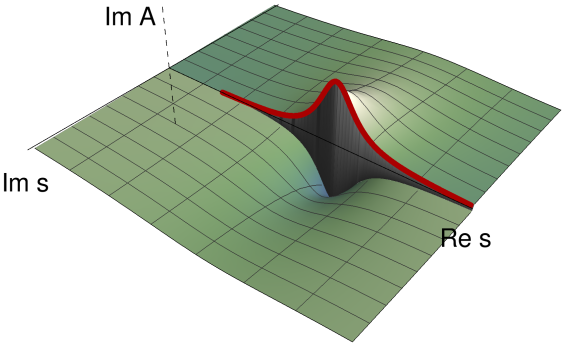

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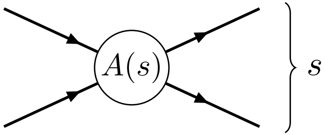

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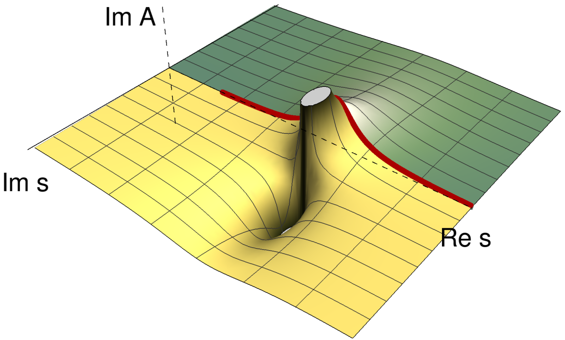

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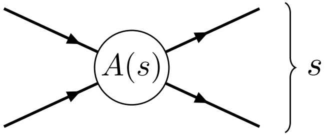

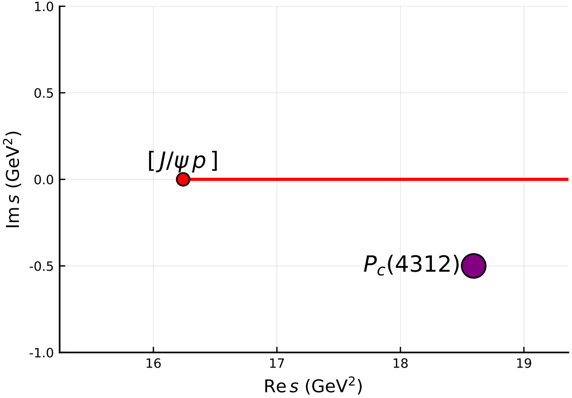

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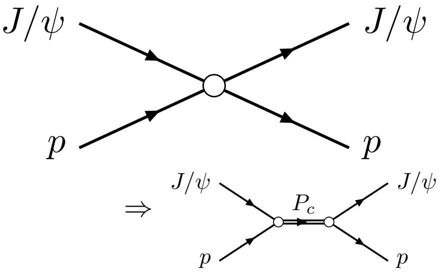
Range of interaction and different manifistation

Model statements

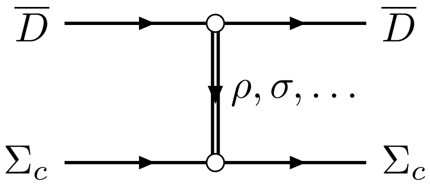
Compact state is the resonance in the $J/\psi p$ system

- Generated by the short-range QCD forces
- Potential involves contact interaction



Molecule is a bound state in the $\overline{D}^0\Sigma_c^+$

- Generated by the long-range forces
- Potential is given by exchange processes
- Small coupling to $J/\psi p$ to the inelastic channel.

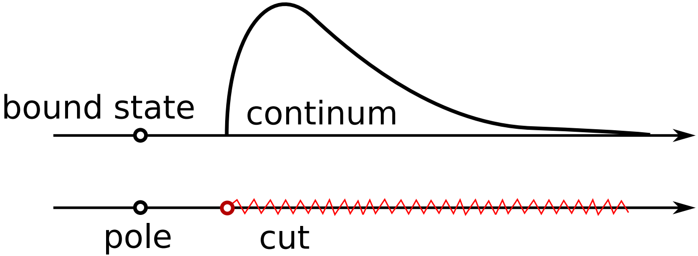


The hypothesis are difficult to separate on the model-independent way

Classical bound-state (molecular) picture

Complex energy plane

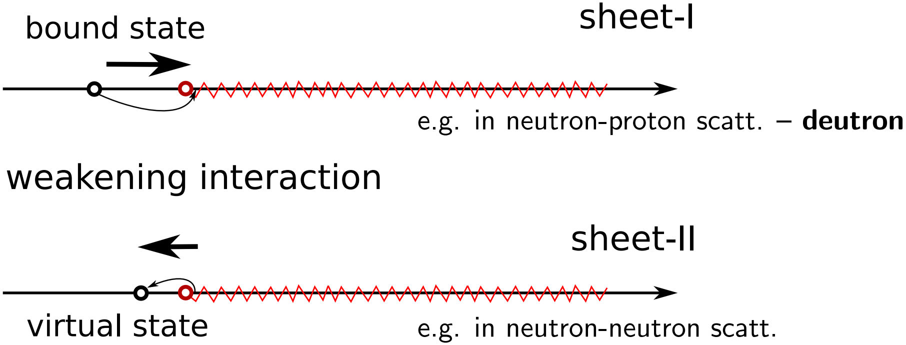
Structures of the complex scattering amplitude correspond to physical



- bound state - pole of the complex scattering amplitude
- continuum - free particles above elastic threshold (branching of the complex plane)

Strength of interaction

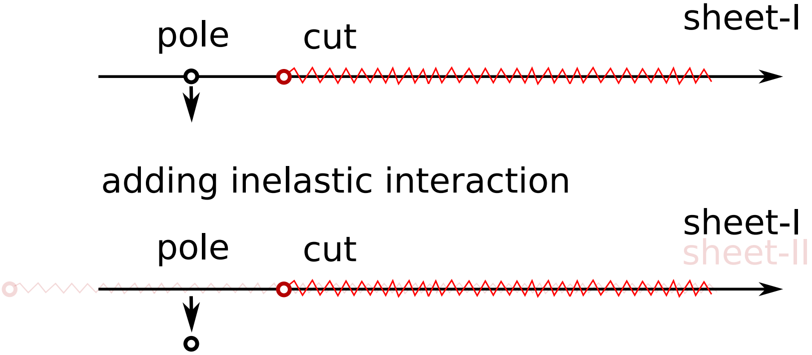
Molecular bound-state vs virtual state



- as weaker the binding as closer the pole to the threshold
- at some point moves to the unphysical sheet and leaves to $-\infty$.

Influence of the inelastic channels

Width of the molecular state



- probability to move to continuum of other channels led to shift of the pole
- lower threshold introduces the branching point and cut
  $\Rightarrow$ the pole is still on the physical sheet, causality is not violated.

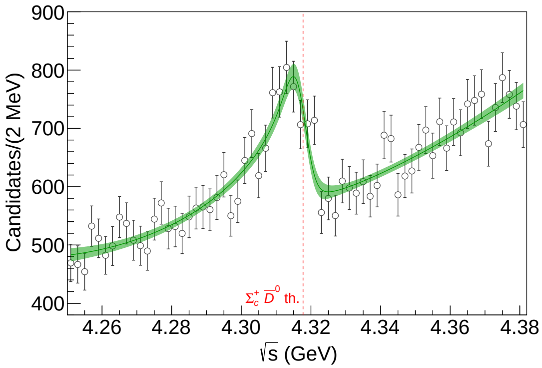
Lineshape of the spectrum in the scattering length approximation

Example demo [link]

$P_c(4312)$ in molecular picture

[C. Fernandez, A. Pilloni, MM (JPAC) arXiv:1904.10021]

Fit to the LHCb data



Fit parameters:

- m_{11}, m_{22}, $m_{12} = m_{21}$,
- p_0, p_1, b_0, and b_1.

Scattering-length approximation

$$T_{ij}^{-1} = m_{ij} - ik_i\delta_{ij},$$
$$k_i = \sqrt{s - s_i}$$

Two channels: $\Sigma_c^+ \bar{D}^0$ and $J/\psi p$.

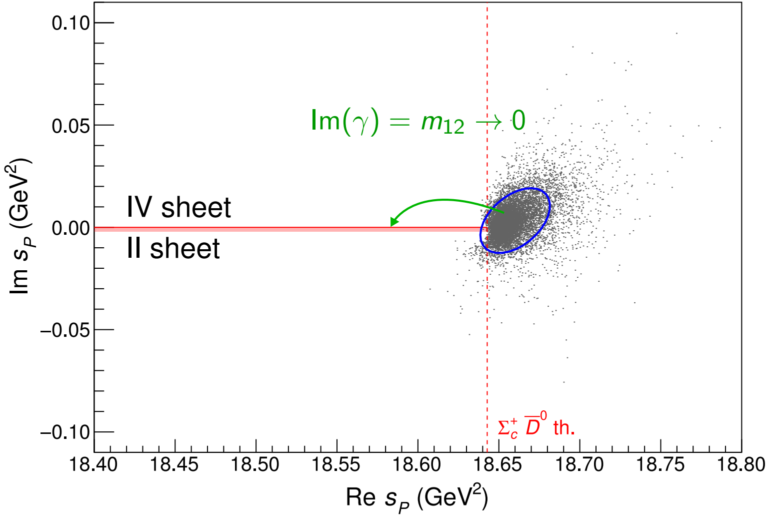
Intensity

$$I(s) = \rho(s)(|T_{11}(s)\, p(s)|^2 + b(s)),$$

- $p(s)$ and $b(s)$ are the first order polynomials.
- $\rho(s)$ is a phase-space factor.

Pole position of the $P_c(4312)$ state

[arXiv:1904.10021]



- Large uncertainties to the pole position due to statistical uncertainties
- Obtained parameters suggest $P_c(4312)$ to be a **virtual state**
- When coupling m_{12} is turned off, the pole ends up on the unphysical sheet

Hadrons are confined colors of QCD!

Hadron spectroscopy

- is an active field with ground-breaking discoveries,
- with many players and approaches:
  - Experiments (LHCb, Belle, BESIII, COMPASS, GlueX, . . .)
  - Lattice QCD (HadSpec, BMW, . . .)
  - Phenomenological potential models
  - Amplitude Analysis

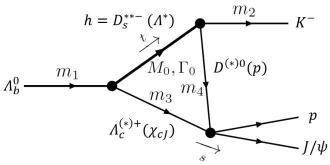
Pentaquarks are new formations of the matter

- The existence is confirmed (c) LHCb.
- A pattern of the new spectroscopy sector is emerging

Thank you for the attention

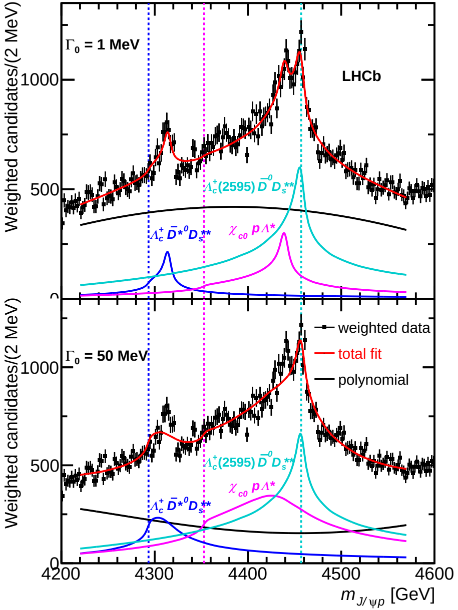
Follow the **Pentaquark** and **Tetraquark** investigation!

Rescattering interpretation



- There are many thresholds around P_c peaks
  - $\Lambda_c \bar{D}^0$, $\Sigma_c \bar{D}^0$, $\chi_c N^*$ with different exchanges as suggested in [Guo et al.(PRD92 (2015) 071502), U.-G. Meißner et al. (PLB751 (2015) 59), X.-H. Liu et al. (PLB757 (2016) 231), MM (arXiv:1507.06552)]
- An appropriate Triangle Singularity can be found for all peaks
- BUT, as soon as **width** of exchange particle is taken into account

$\Rightarrow$ no acceptable description in rescattering picture



Scattering amplitude

(see e.g. Landau and Lifshitz, Vol.III, (132.9))

$D\overline{D}^* \to D\overline{D}^*$ scattering. $T(s)$ is S-wave scattering amplitude

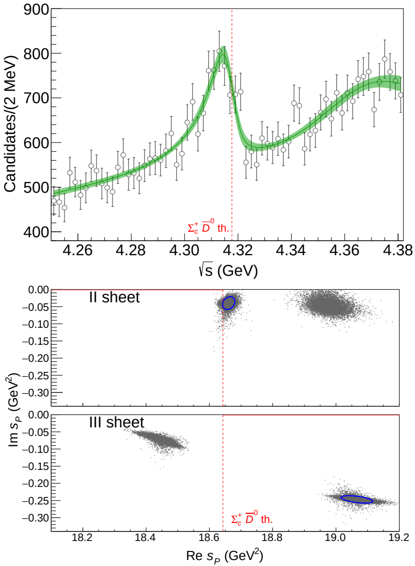
$$T(s) = \overbrace{-\alpha}^{\text{scattering length}} = \underbrace{\frac{1}{-\gamma}}_{\gamma \text{ is the inverse scattering length}}$$

Energy dependence in vicinity of threshold, $m_{\text{th}} = m_D + m_{D^*}$:

$$T(s) = \frac{1}{\underbrace{-\gamma - ik}_{\text{momentum } k=\frac{1}{2}\sqrt{s-s_{\text{th}}}}} \approx \frac{1}{-\gamma - i\sqrt{2\mu\left(\sqrt{s} - m_{\text{th}}\right)}} \xrightarrow[\text{rotate cut}]{-i\sqrt{x}=+\sqrt{-x}} \underbrace{\frac{1}{-\gamma + \sqrt{-2\mu E}}}_{\text{[used in PRD76 044028]}}$$

- μ is a reduced mass, $1\mu = 1/m_D + 1/m_{D^*}$,
- $E = \sqrt{s} - m_{\text{th}}$ is a distance from threshold

Case B: effective-range model



Effective-range approximation

$$T_{ij}^{-1} = m_{ij} + c_{ij} s - i k_i \delta_{ij},$$
$$k_i = \sqrt{s - s_i}$$

Two channels: $\Sigma_c^+ \bar{D}^0$ and $J/\psi p$.

Fit parameters

- m_{11}, m_{22}, $m_{12} = m_{21}$, c_{11}, c_{22}
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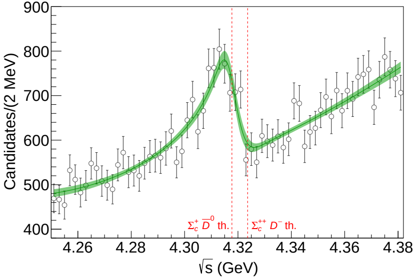
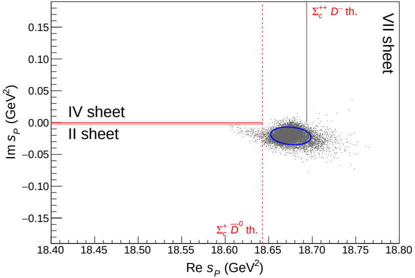
Three channels: effective-range model





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Fit parameters

- m_{11}, m_{22}, $m_{12} = m_{13}$, m_{23}, c_{11}, m is symmetric.
- p_0, p_1, b_0, and b_1.

Systematic studies

- Other data samples: cut $M_{Kp} > 1.9\,\mathrm{GeV}$, all-$Kp$.
- Extended model(see backup)
  - case B: effective-range expansion $m_{ij} \to m_{ij} + c_{ij}s$
  - including third channel $(\Sigma_c^{++}D^-$.
  - tests of K-matrix parametrization and the Flatte parametrization