

Colors of QCD: Hadron spectroscopy and exotic states at LHCb

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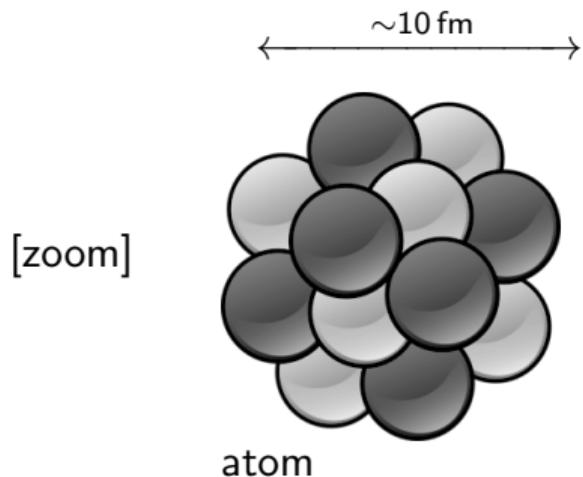
June 28th, 2019

Perspective of QCD – large white space with little colorful objects

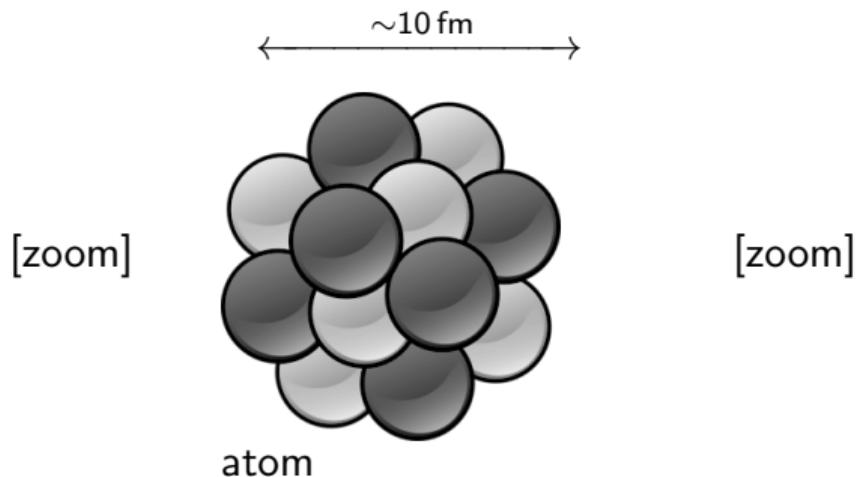
Perspective of QCD – large white space with little colorful objects

[zoom]

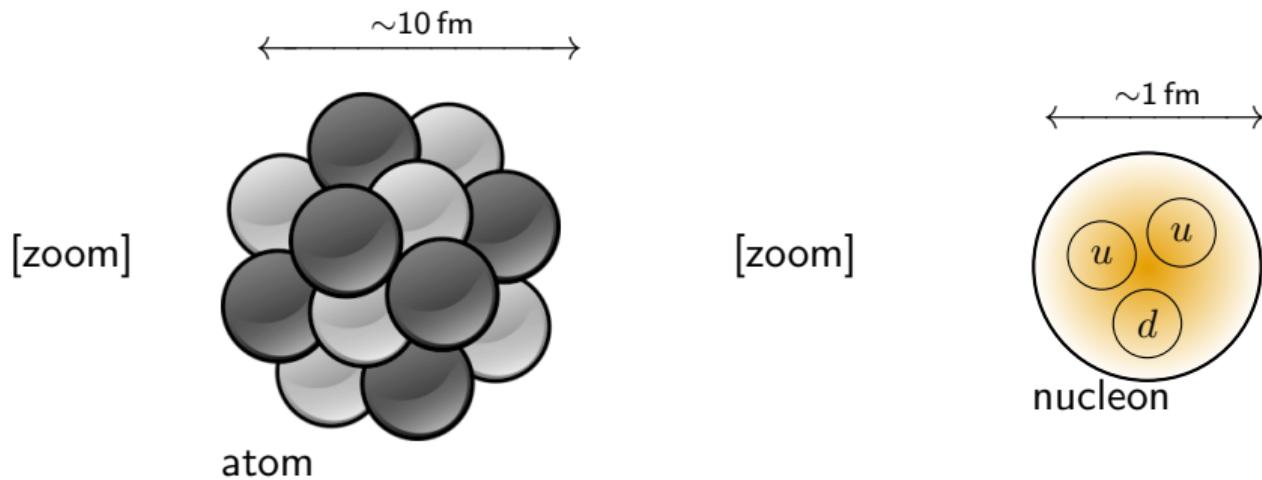
Perspective of QCD – large white space with little colorful objects



Perspective of QCD – large white space with little colorful objects

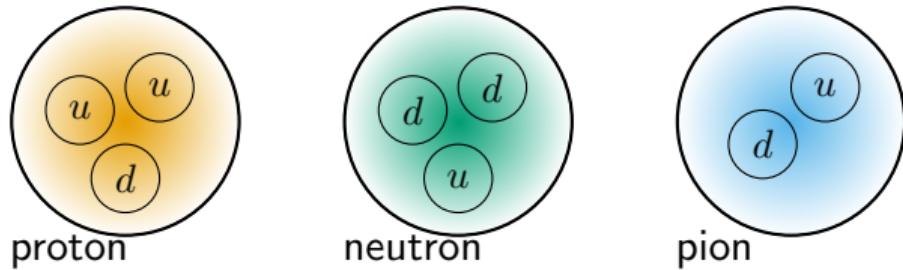


Perspective of QCD – large white space with little colorful objects

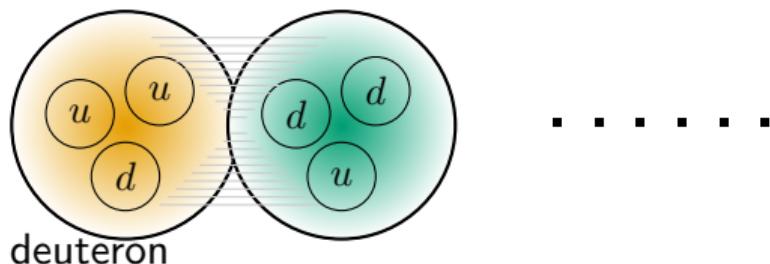


Perspective of QCD – large white space with little colorful objects

simple hadrons (baryons, mesons)



hadronic molecules (atoms)



If that's all, who are these?

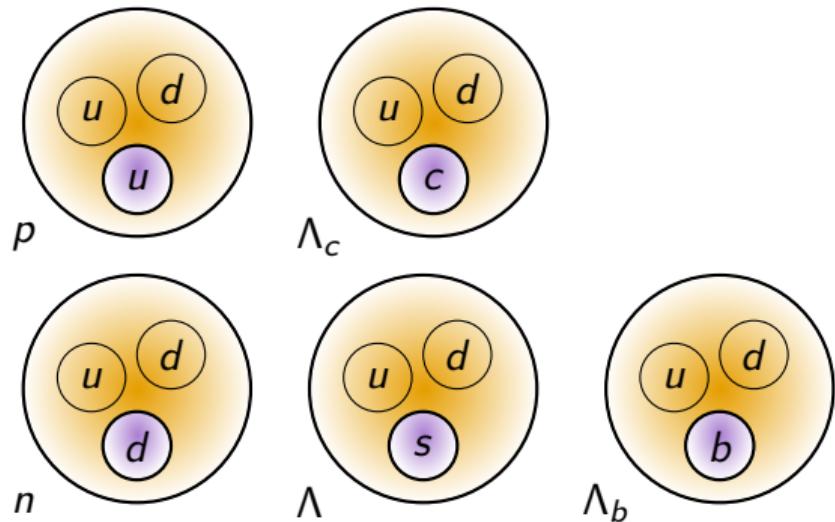
"Ok, google, show me known mesons" ...

If that's all, who are these?

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

{
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^*(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),
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π0(1800), π+(1800), I_2(1810), K_2^0(1820), K_2^2(1820), K_2^-0-bar(1820), K0(1830), K+(1830), K-(1830), K0-bar(1830), X(1835), π_2(1870), φ(1850), X(1855), ρ-(1900), ρ0(1900),
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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_2^2(1980), X(1975), K_2^-0-bar(1980), ω_2(1975), ρ_3^-(1990), ρ_3^0(1990),
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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-bar(2430), X(2440), a_6^-(2450), a_6^0(2450), a_6^+(2450), D_s1(2460), D_s1-bar(2460),
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Y(3940), ψ(4040), ψ(4160), X(4260), ψ(4415), B-, B+, B0, B0-bar, B^-, B^0, B^0-bar, B_s, B_s-bar, B_s^*, B_s^-bar, B_J^*(5732), B_J^**-(5732), B_J^**+(5732), B_J^-0-bar(5732),
B_sJ^*(5850), B_sJ^-0-bar(5850), B_c, B_c-bar, π_b(1S), Y(1S), χ_b0(1P), χ_b1(1P), χ_b2(1P), Y(2S), Y(1D), χ_b0(2P), χ_b1(2P), Y(3S), Y(4S), Y(10860), Y(11020)}

Flavour modifications: Baryons

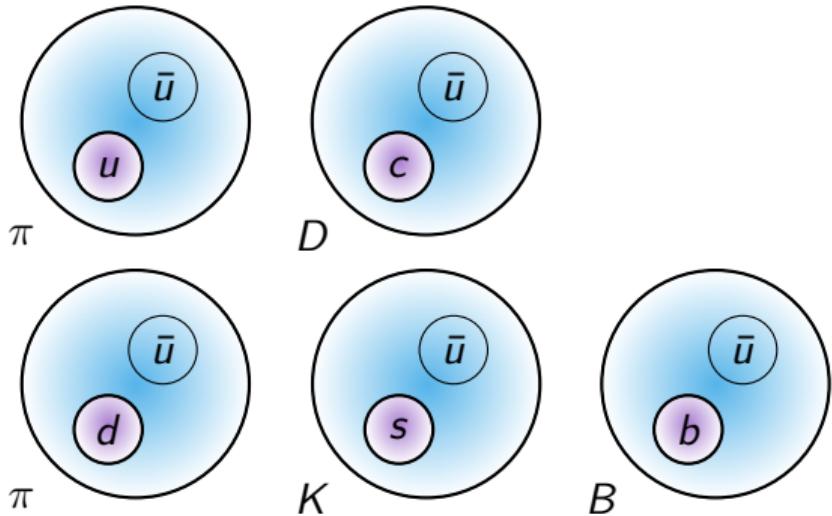


Standard Model particles

QUARKS		GAUGE BOSONS	
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	0
spin →	1/2	1/2	0
	u	c	H
	up	charm	Higgs boson
$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 91.2 \text{ GeV}/c^2$
-1/3	-1/3	-1/3	0
1/2	1/2	1/2	1
d	s	b	Z
down	strange	bottom	W
$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$80.4 \text{ GeV}/c^2$
-1	-1	-1	± 1
1/2	1/2	1/2	1
e	μ	τ	W
electron	muon	tau	boson
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
0	0	0	
1/2	1/2	1/2	
ν_e	ν_μ	ν_τ	
electron neutrino	muon neutrino	tau neutrino	

All (ground) hadrons are stable without weak interaction

Flavour modifications: Mesons

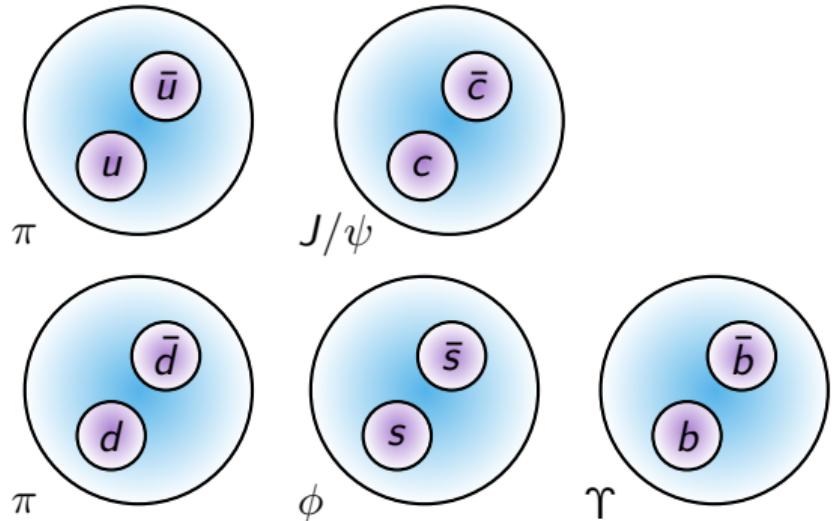


Standard Model particles

QUARKS		GAUGE BOSONS	
mass →	$\approx 2.3 \text{ MeV}/c^2$	mass →	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	charge →	0
spin →	1/2	spin →	0
	u	c	g
	up	charm	gluon
$\approx 4.8 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$
-1/3	2/3	2/3	0
1/2	1/2	1/2	0
d	s	t	H
down	strange	top	Higgs boson
$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 91.2 \text{ GeV}/c^2$	
-1/3	-1/3	0	
1/2	1/2	1	
e	b	Z	
electron	bottom	Z boson	
$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	
-1	-1	-1	
1/2	1/2	1/2	
μ	τ	W	
muon	tau	W boson	
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
0	0	0	
1/2	1/2	1/2	
ν_e	ν_μ	ν_τ	
electron neutrino	muon neutrino	tau neutrino	
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
0	0	0	
1/2	1/2	1/2	
ν_e	ν_μ	ν_τ	
electron neutrino	muon neutrino	tau neutrino	
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
0	0	0	
1/2	1/2	1/2	
ν_e	ν_μ	ν_τ	
electron neutrino	muon neutrino	tau neutrino	

All (ground) hadrons are stable without weak interaction

Flavour modifications: Flavour-neutral Mesons

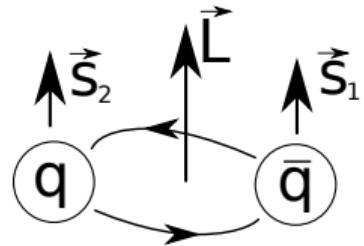
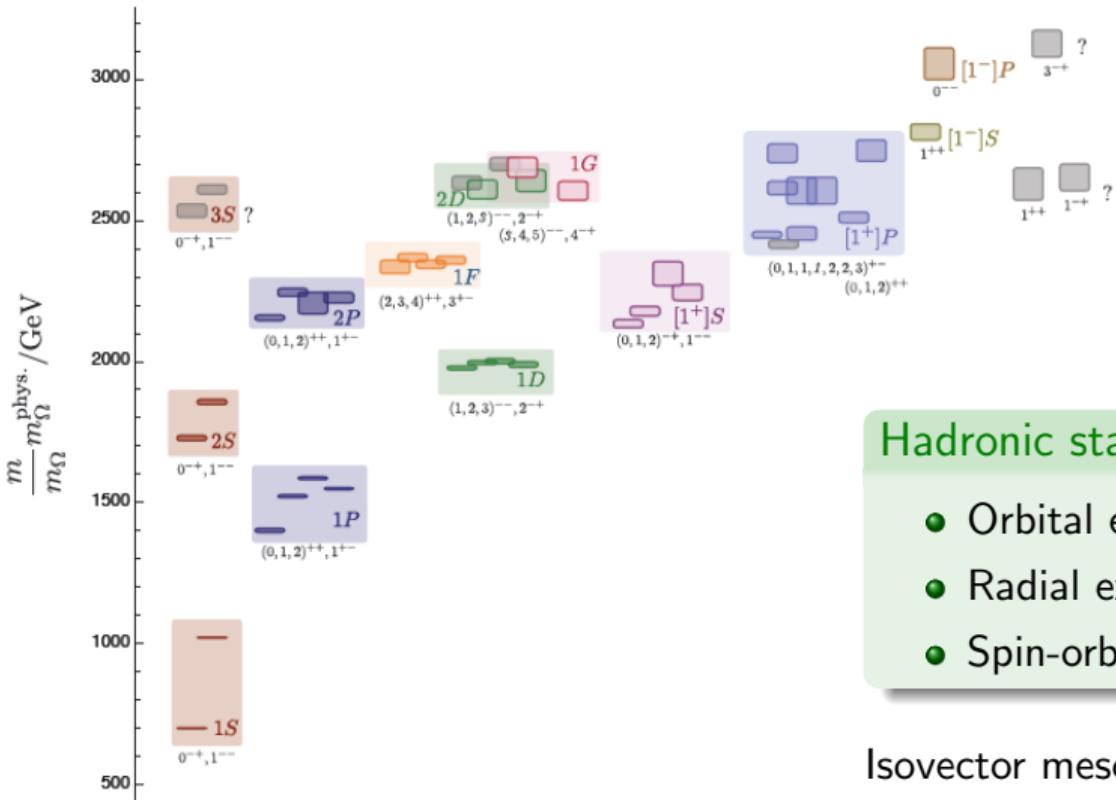


Standard Model particles

QUARKS		GAUGE BOSONS	
mass \rightarrow	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$
charge \rightarrow	2/3	2/3	0
spin \rightarrow	1/2	1/2	0
	u	c	g
	up	charm	gluon
$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$
-1/3	-1/3	-1/3	0
1/2	1/2	1/2	0
d	s	b	H
down	strange	bottom	Higgs boson
$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$
-1	-1	-1	0
1/2	1/2	1/2	1
e	μ	τ	Z
electron	muon	tau	Z boson
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$
0	0	0	± 1
1/2	1/2	1/2	1
ν_e	ν_μ	ν_τ	W
electron neutrino	muon neutrino	tau neutrino	W boson

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

Conventional states: why so many hadrons

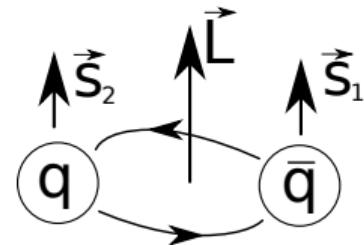
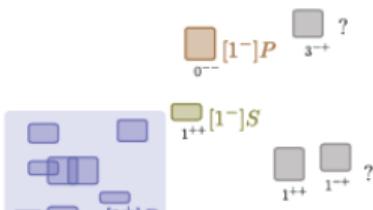
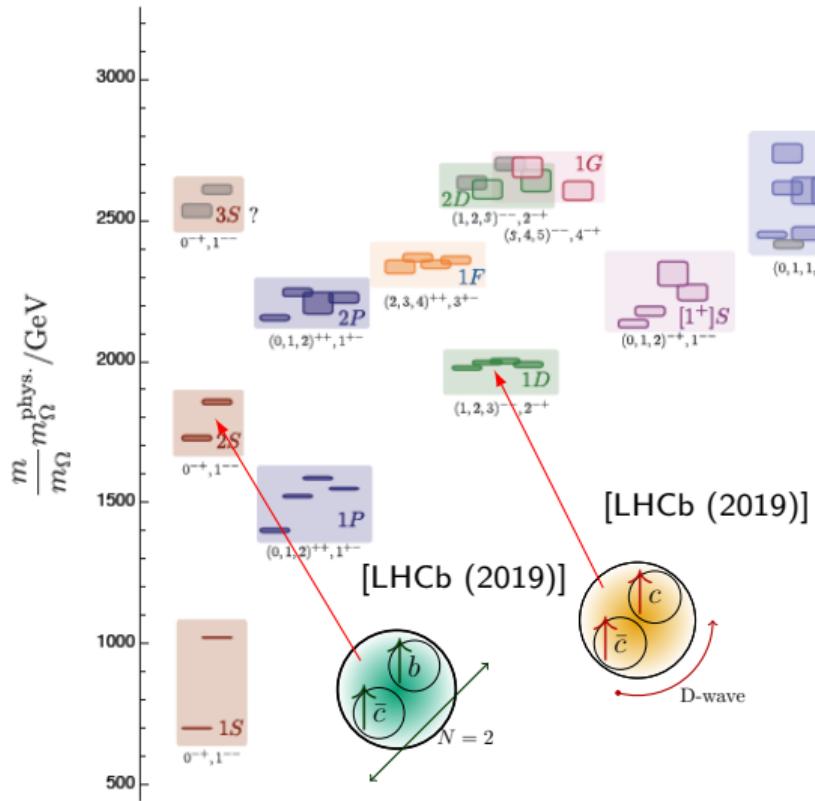


Hadronic states - energy levels

- 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)]

Conventional states: why so many hadrons



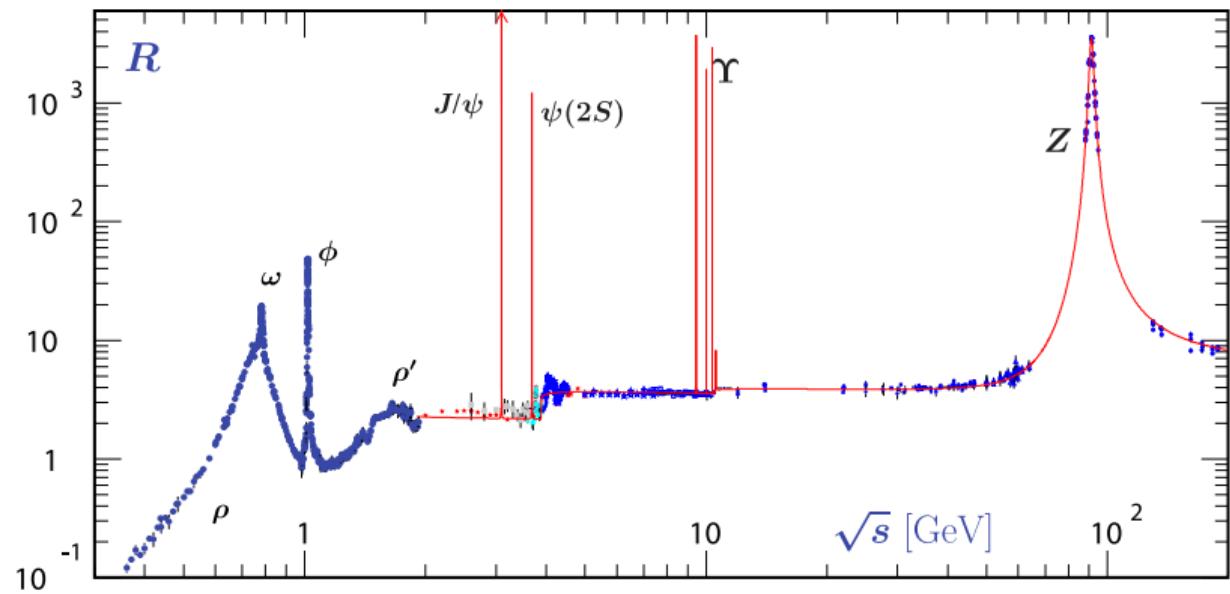
Hadronic states - energy levels

- Orbital excitation, \vec{L}
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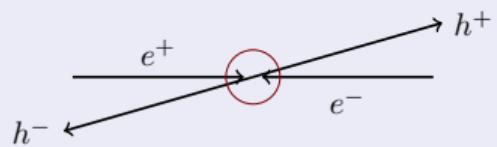
Isovector meson spectrum with $m_\pi \sim 800$ MeV [J. Dudek et al., PRD82 034508 (2010)]

Hadrons: every flavour gets its energy range

[PDG2019]



R-ratio

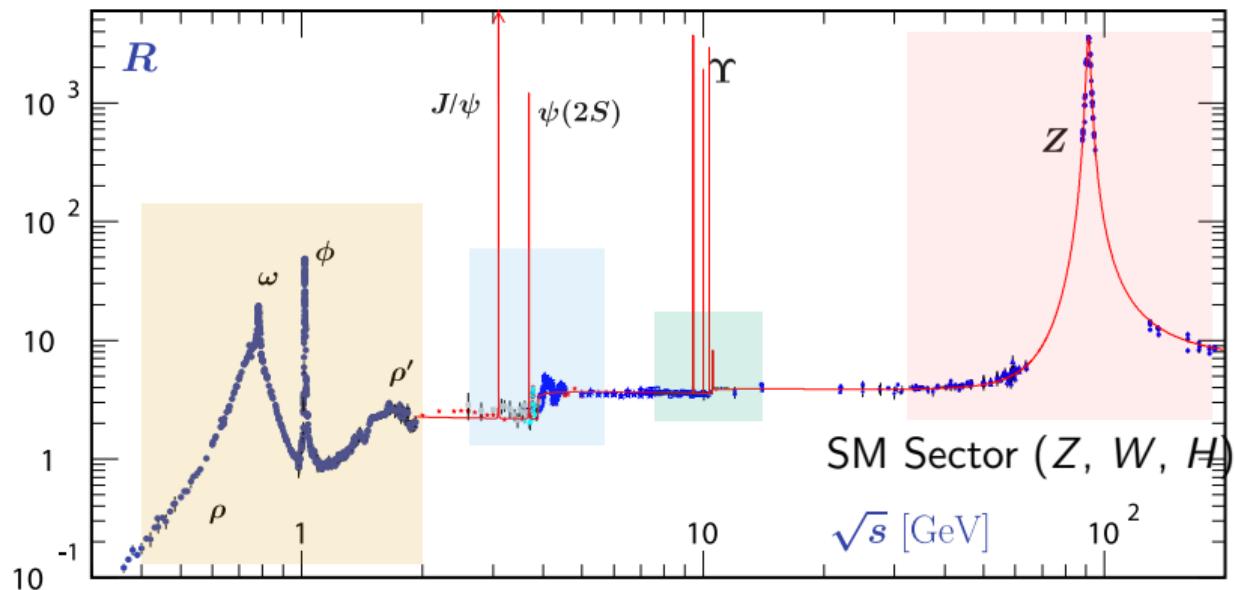


$$R = \frac{e^+e^- \rightarrow \text{hadrons}}{e^+e^- \rightarrow \mu^+\mu^-}$$

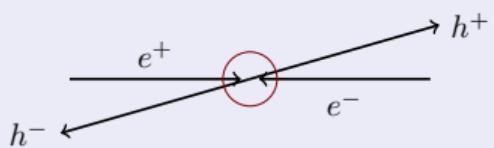
hadrons : h^+h^- , ...

Hadrons: every flavour gets its energy range

[PDG2019]



R -ratio



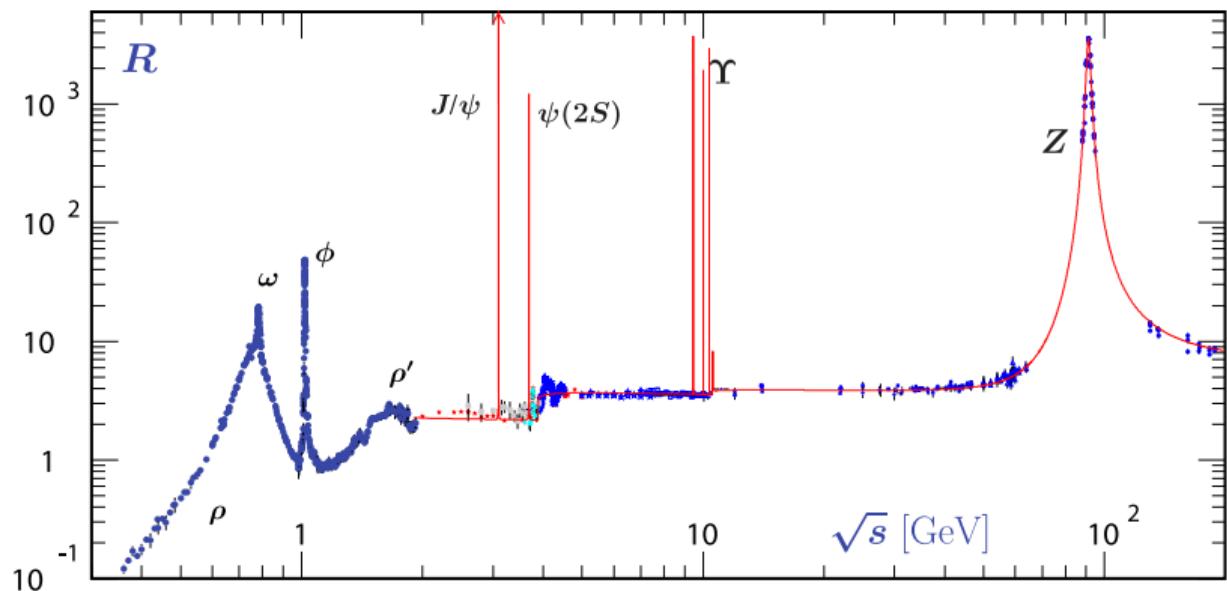
$$R = \frac{e^+ e^- \rightarrow \text{hadrons}}{e^+ e^- \rightarrow \mu^+ \mu^-}$$

hadrons : $h^+ h^-$, ...

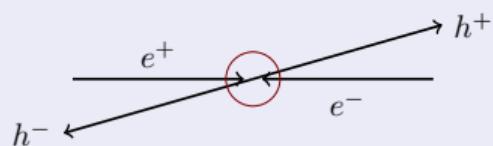
- Light (contain u,d,s) Hidden charmed ($c\bar{c}$) Hidden beauty ($b\bar{b}$)

Hadrons: every flavour gets its energy range

[PDG2019]



R -ratio



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

hadrons : $h^+ h^-$, ...

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

⇒ Energy range tells the flavour

Search for the new type of matter

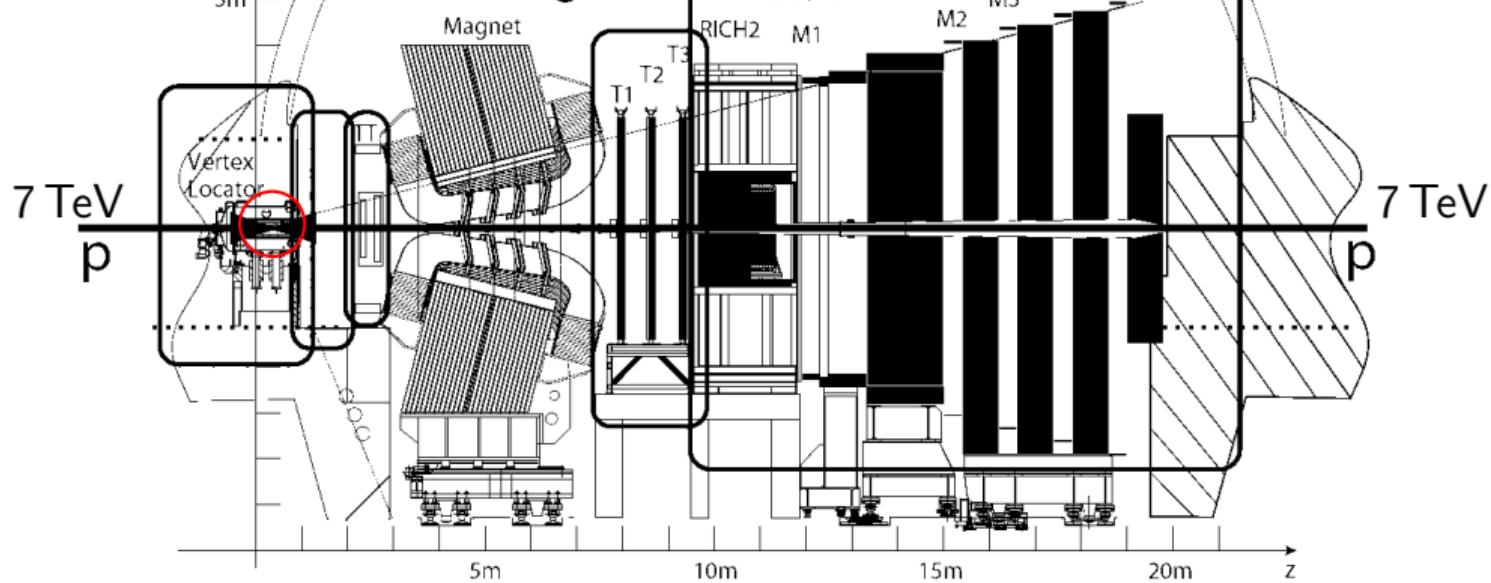
How to search for color physics with colorless environment?

[link]

LHCb

Tracking

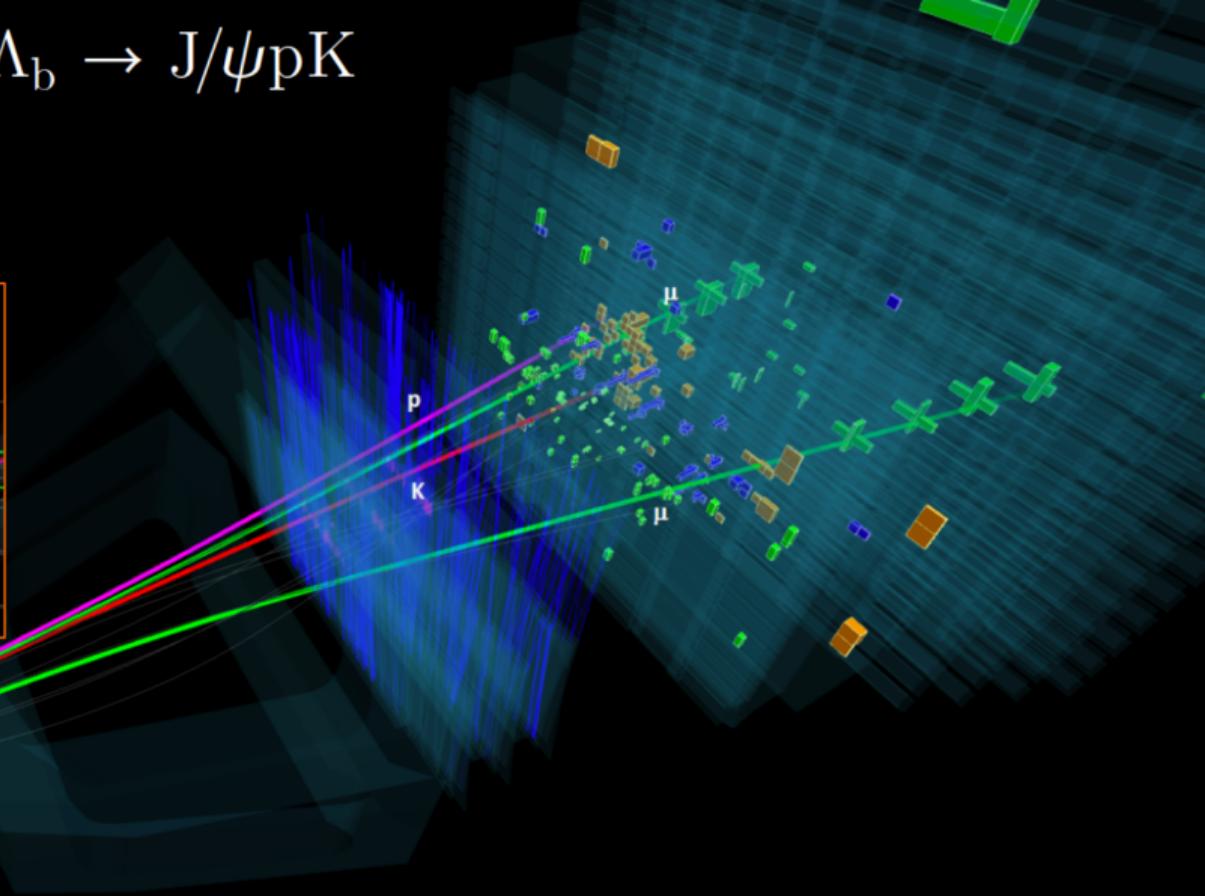
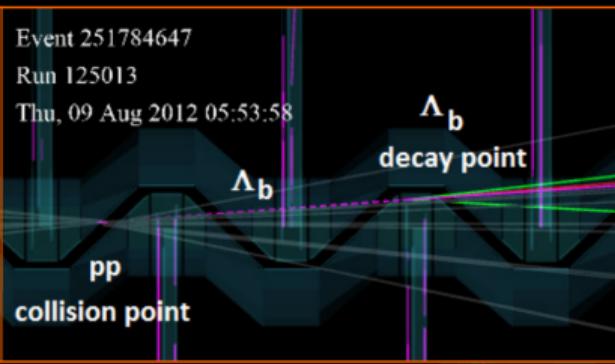
Particle ID



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



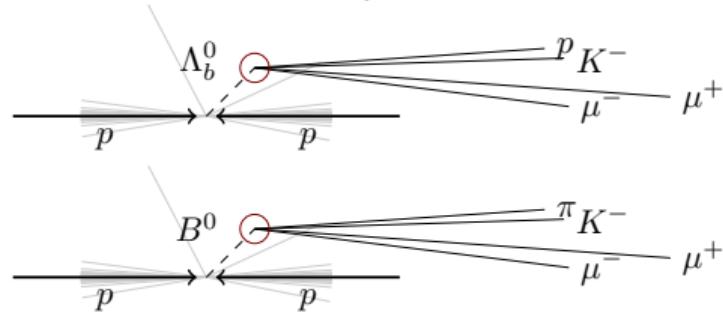
$\Lambda_b \rightarrow J/\psi p K$



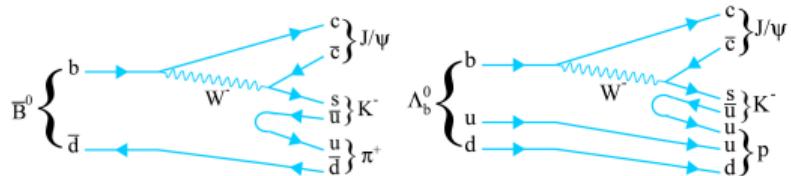
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



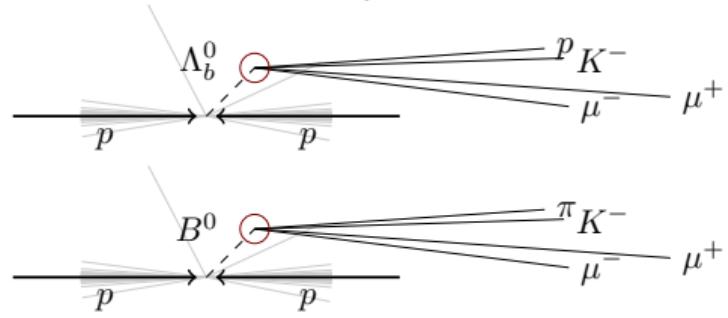
- similar decay chains



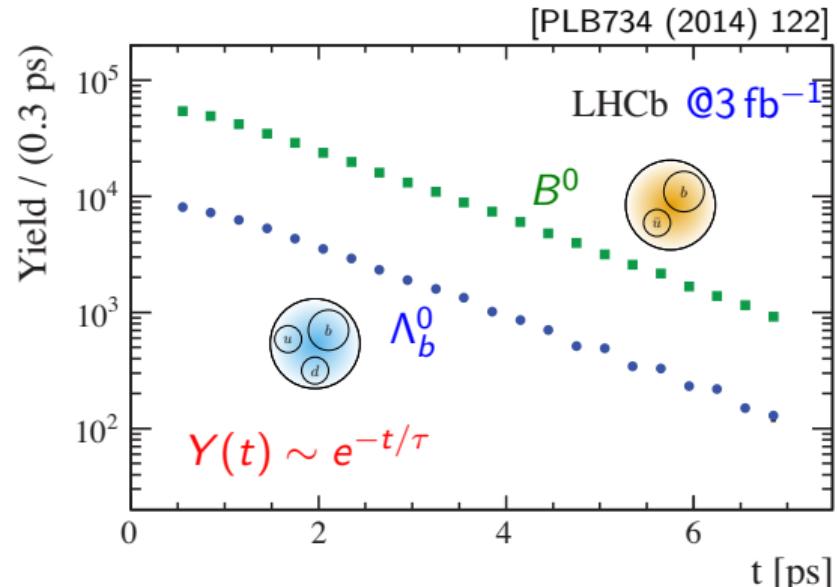
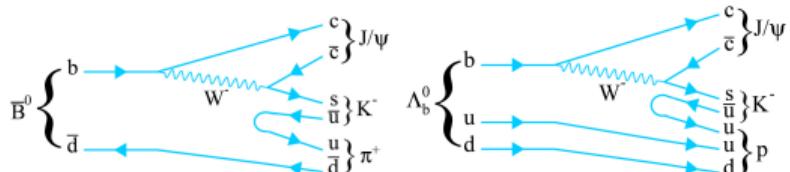
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



- similar decay chains



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

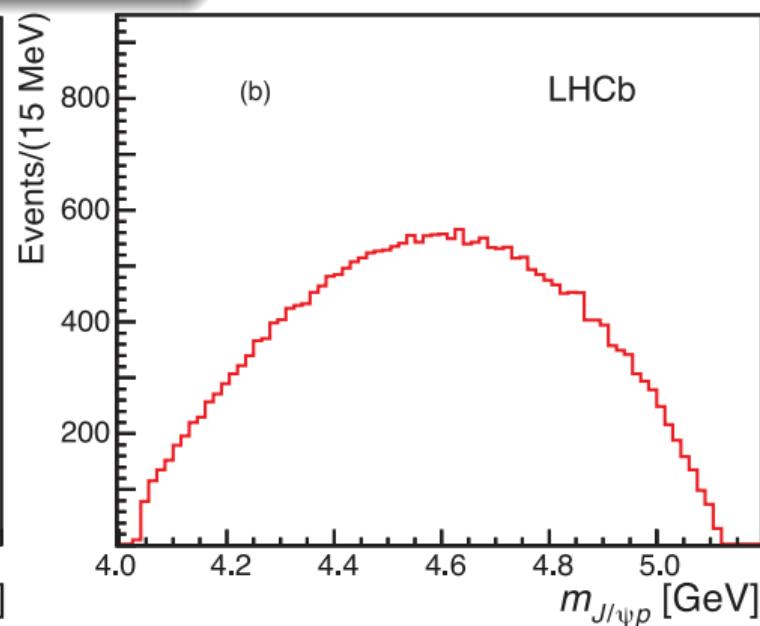
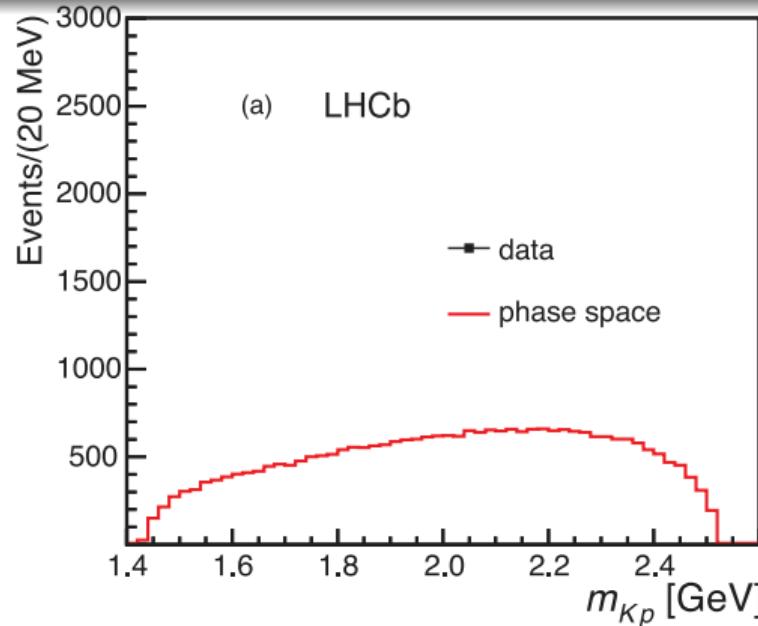
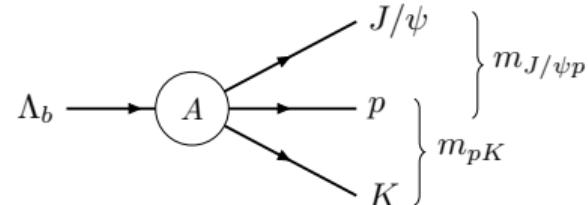
$$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010 \text{ ps},$$

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

[PRL 115, 072001 (2015)]

Highly non-trivial transition amplitude

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

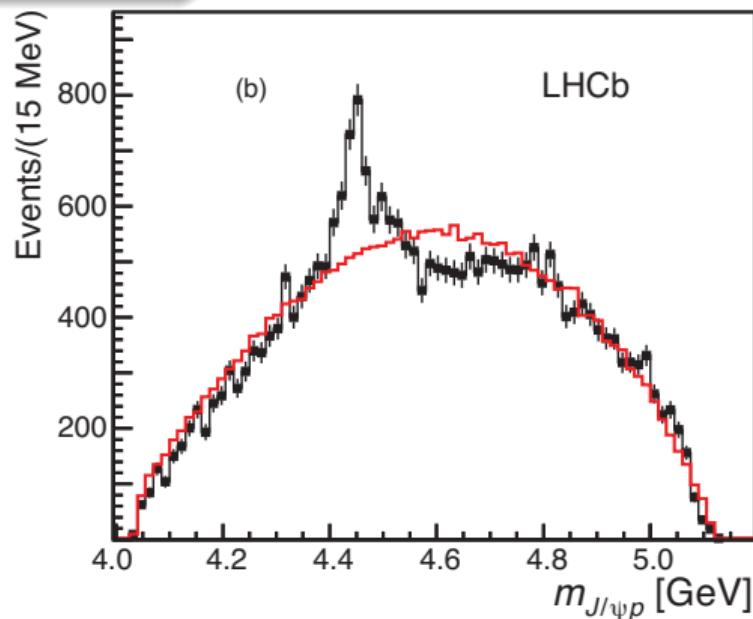
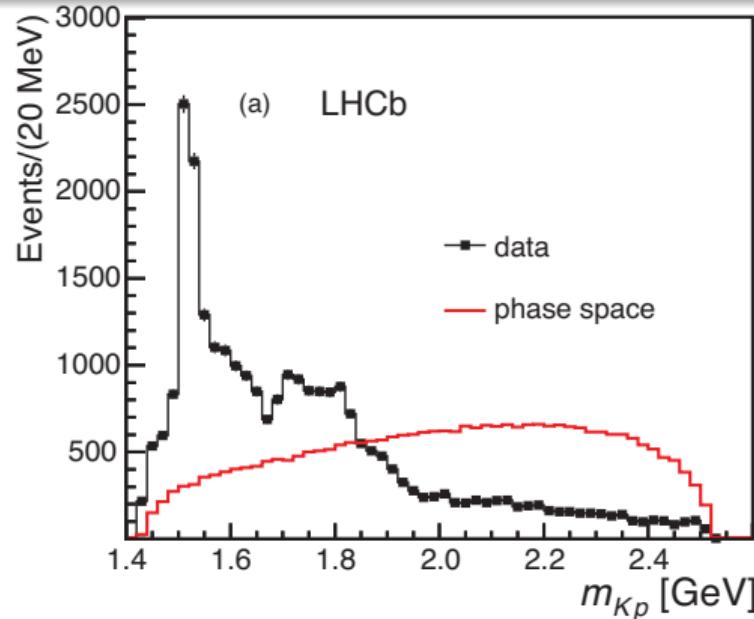
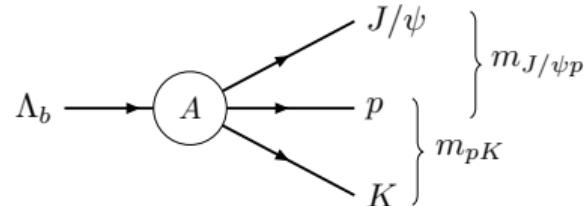


Dynamics of the decay $\Lambda_b^0 \rightarrow J/\psi p K$,

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- interaction in pK subsystem
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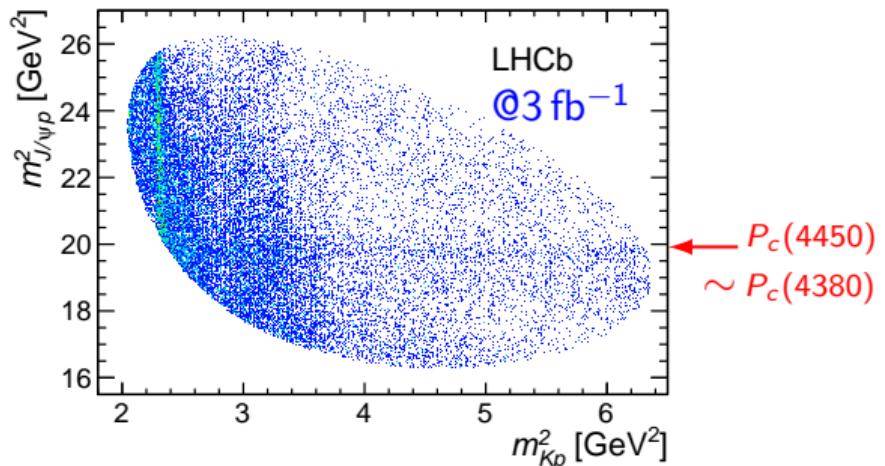


What could we expect

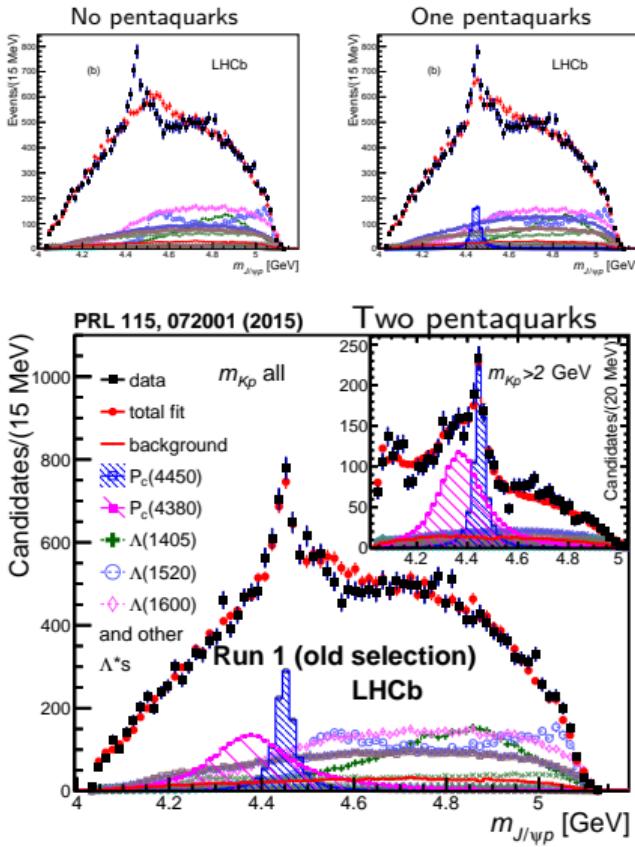
Example demo [\[link\]](#)



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

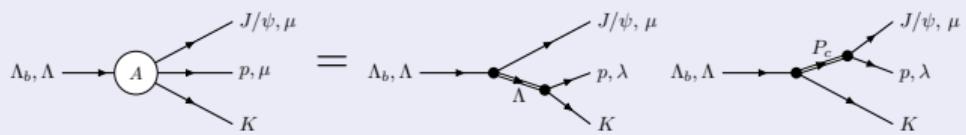


[PRL 115, 072001 (2015)]



Amplitude analysis of 2015

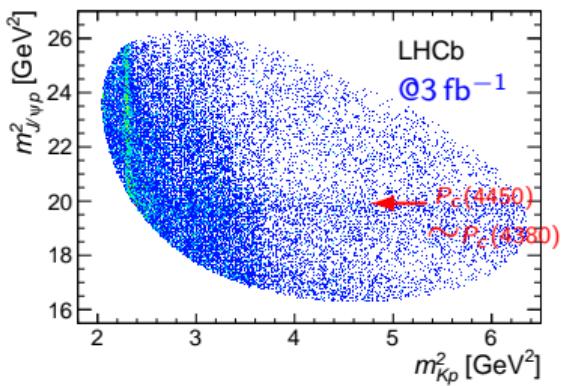
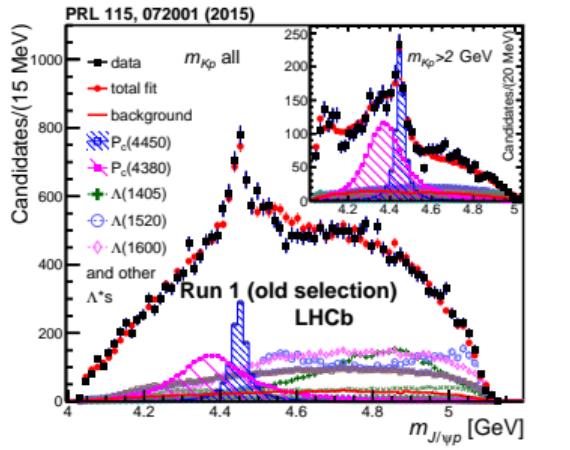
Helicity formalism, isobar model, 6-dim. analysis.



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

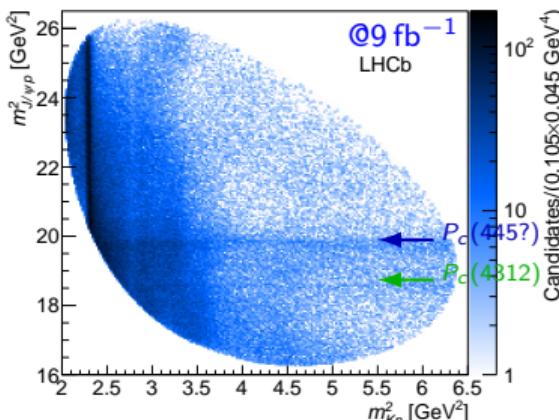
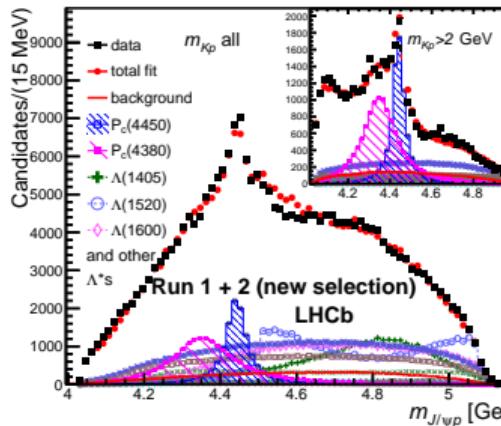
Adding more data with Run-II (2017,2018)

[arXiv:1904.03947]



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Gain in statistics $\times 9$

26k events \Rightarrow 246k events

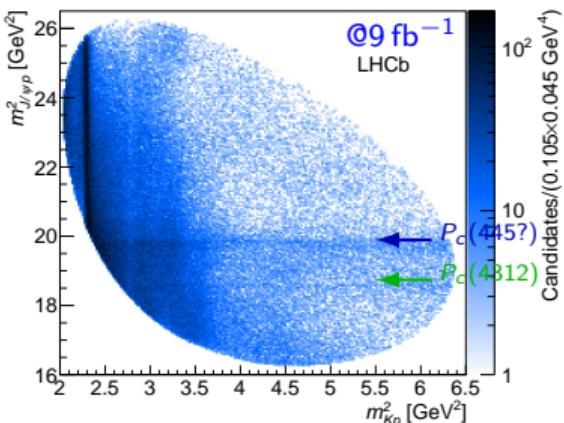
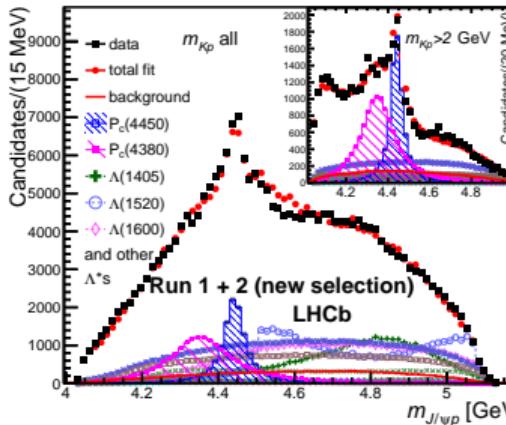
- Luminosity: $3 \text{ fb}^{-1} \oplus 6 \text{ fb}^{-1}$,
- Cross section $\times 2$:
 $7 \text{ TeV} \rightarrow 13 \text{ TeV}$,
- Selection efficiency $\times 2$.

Amplitude Analysis

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

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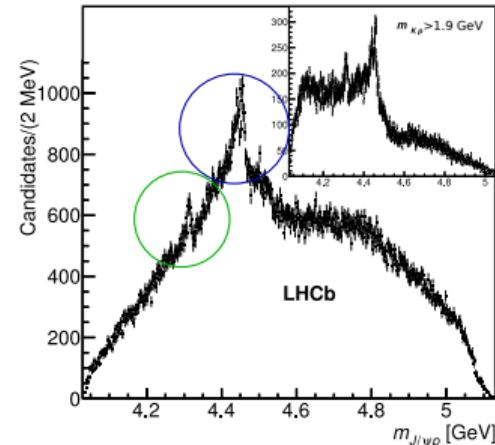
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New features

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

Extracting resonance properties

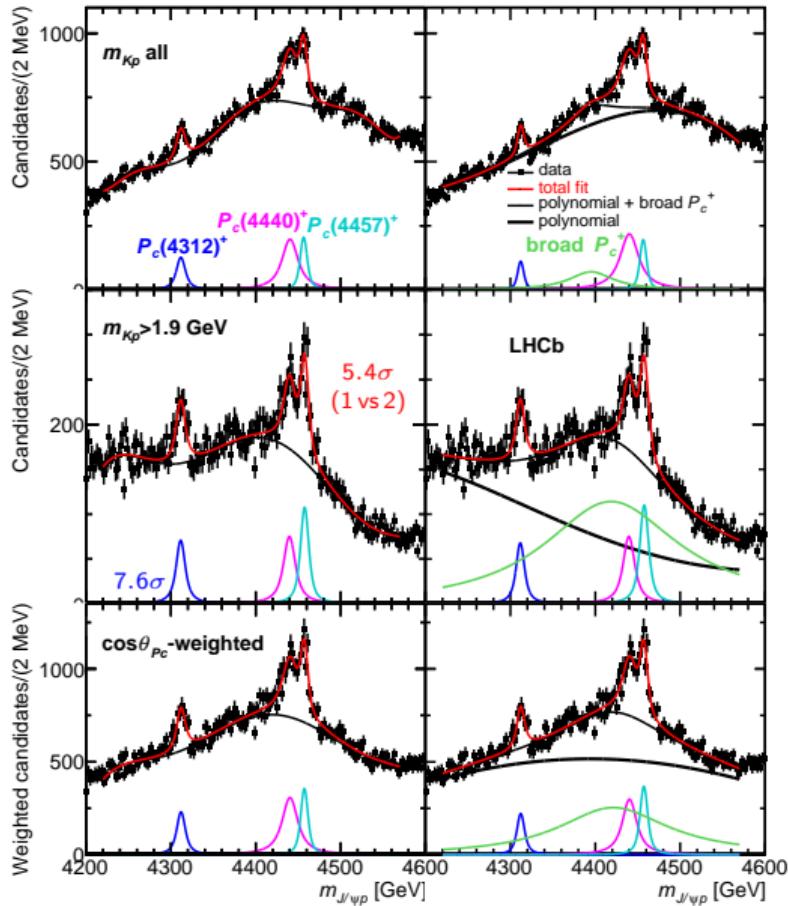
[arXiv:1904.03947]

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)
inconclusive with 1-dim. analysis			



Extracting resonance properties

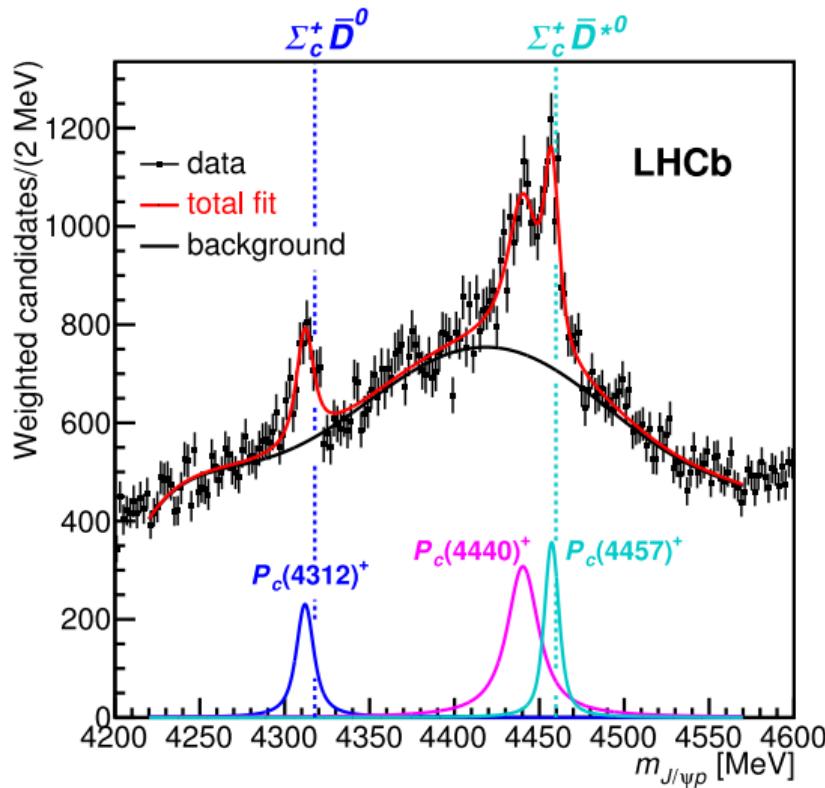
[arXiv:1904.03947]

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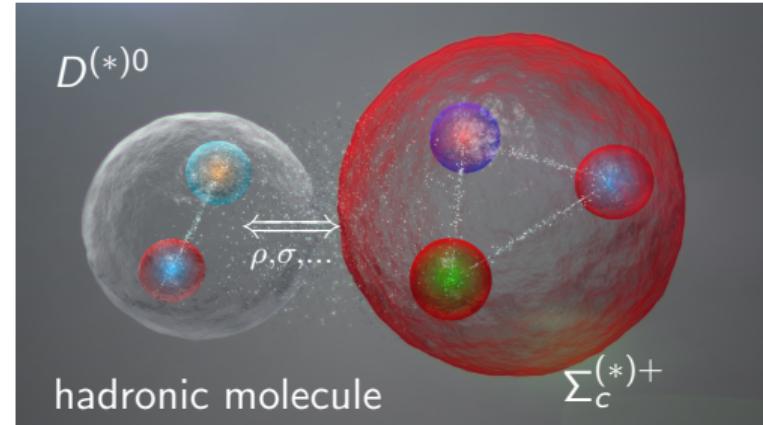
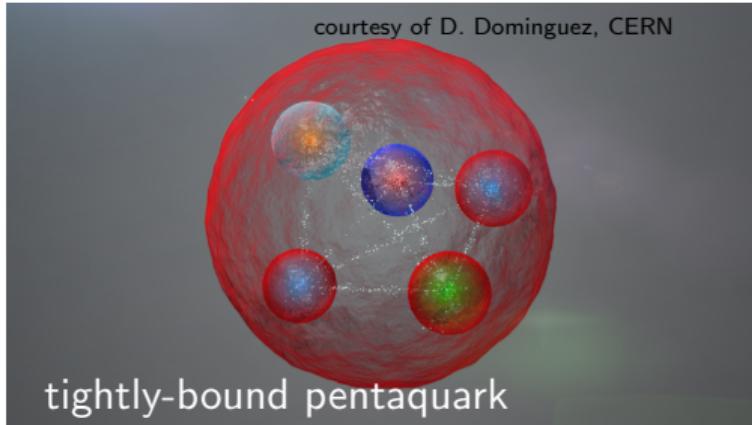
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Two main interpretations of P_c states



- The state should have high probability 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]

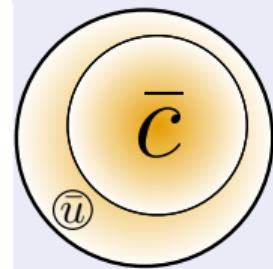
[J.-J. Wu et al., Phys. Rev. C85 (2012) 044002]

Pattern of states in the Heavy-Quark limit

[arXiv:1904.03947]

States counting

Heavy Quark Spin Symmetry



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

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

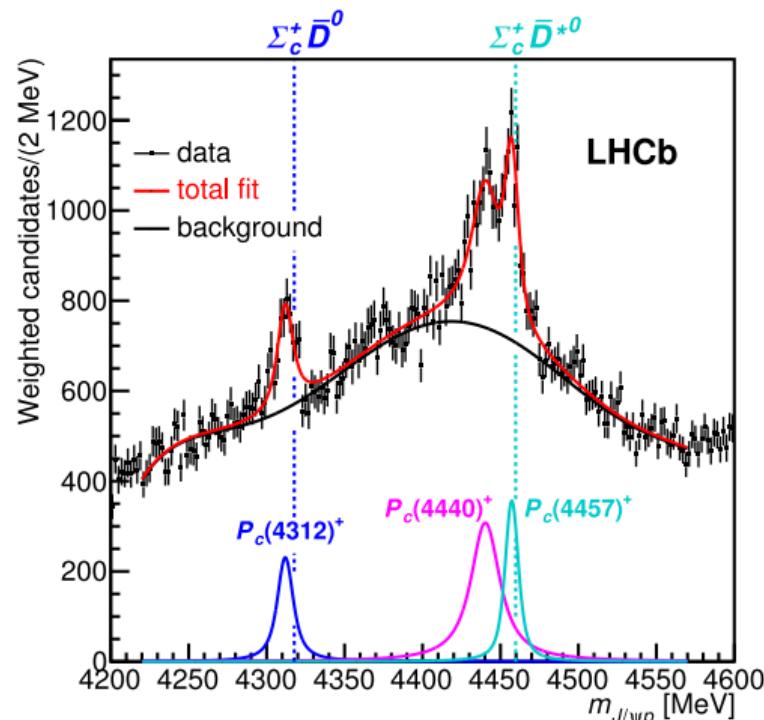
Pattern of $\Sigma_c \bar{D}$ molecules

$$\Sigma_c^+ \bar{D}^0 \quad 1/2^+ \otimes 0^- \xrightarrow{\text{S-wave}} \quad J^P : 1/2^-$$

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



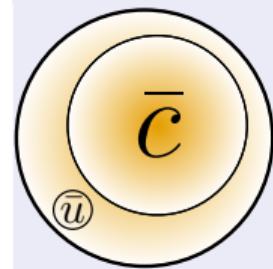
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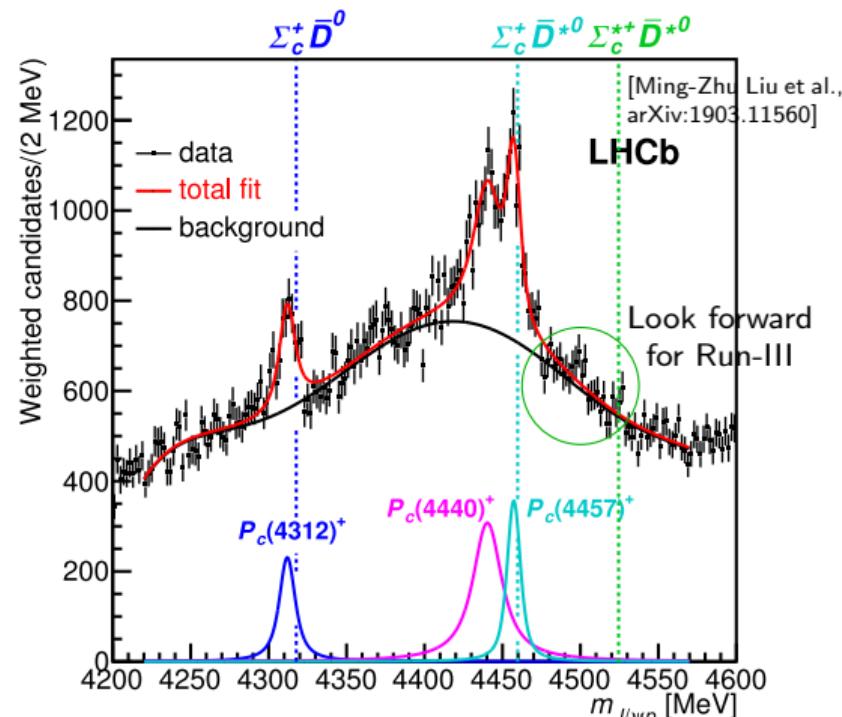
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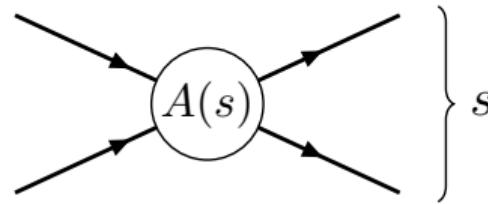


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Basics of amplitude analysis

aka S-matrix theory

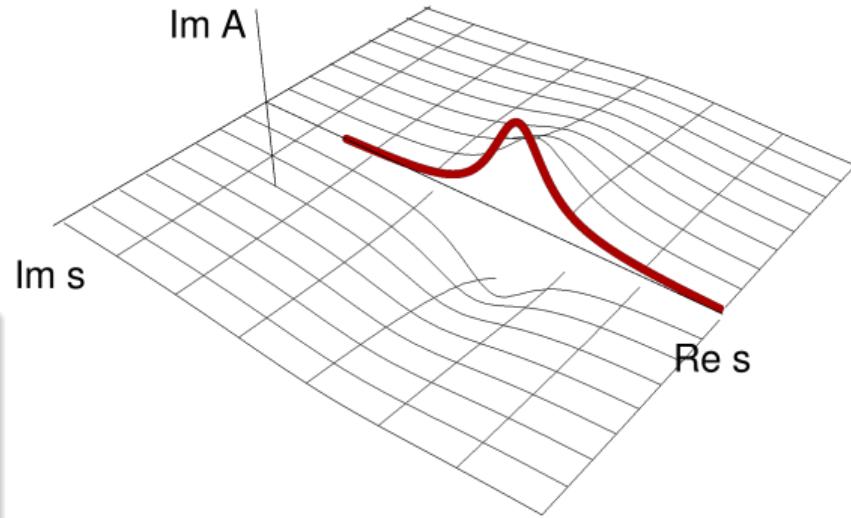
[see great books by Gribov, Collins, Martin-Spearman]



Scattering PW-amplitude

$A(s)$ is a transition amplitude

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

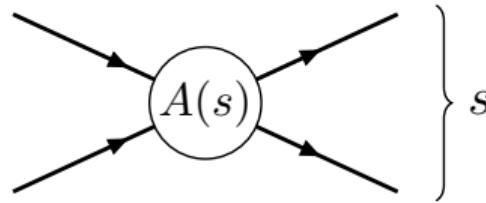


- All structures in the energy spectrum have origin in the complex plane
- Hadronic resonances - complex **poles!**
- Production thresholds - branching points.

Basics of amplitude analysis

aka S-matrix theory

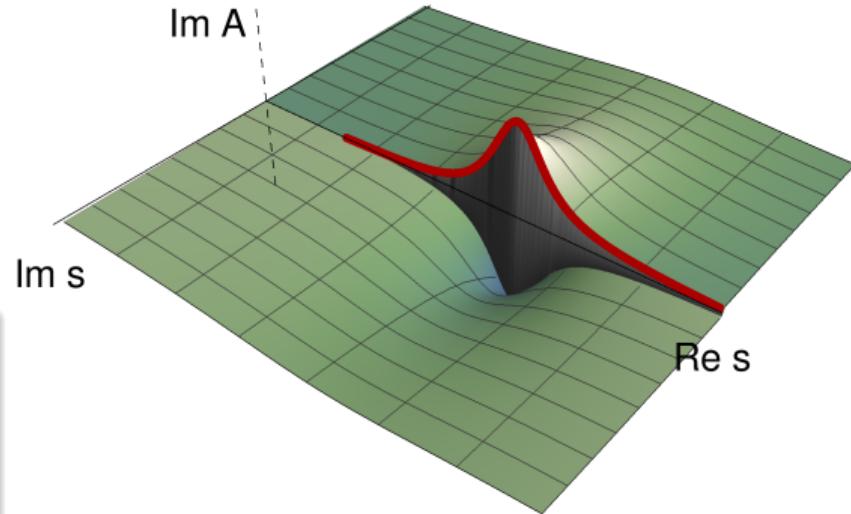
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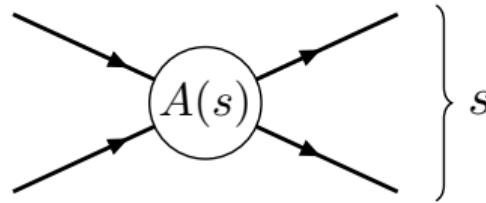


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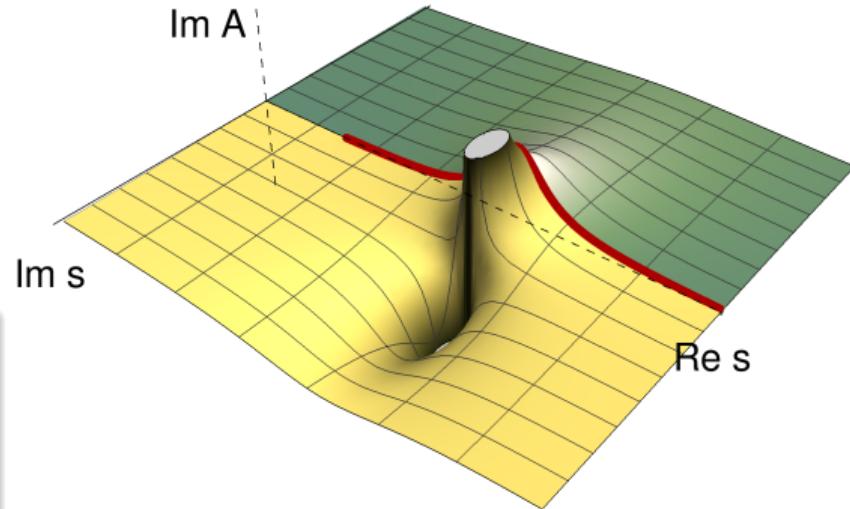
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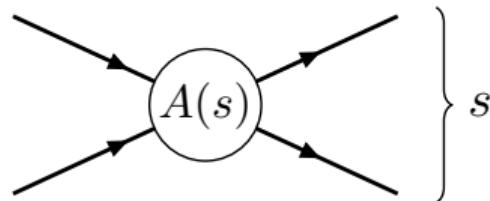
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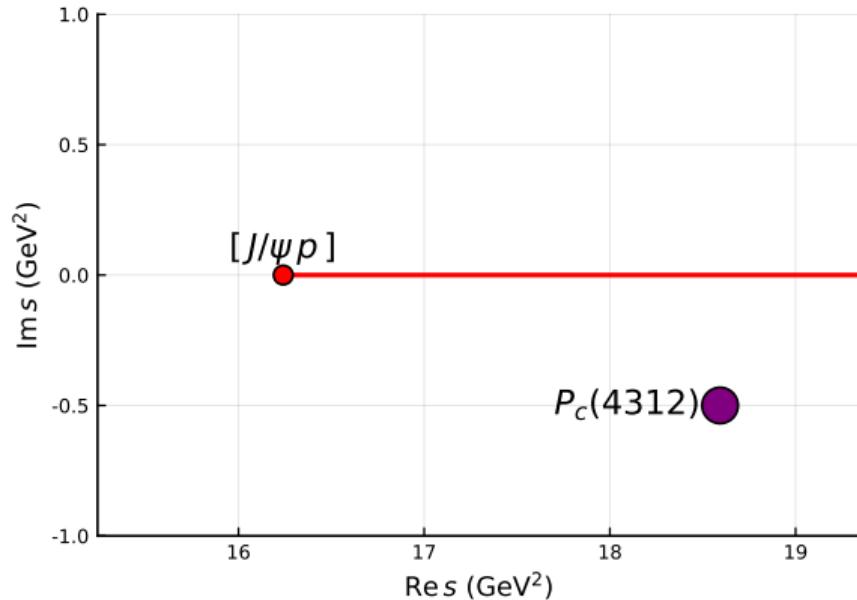


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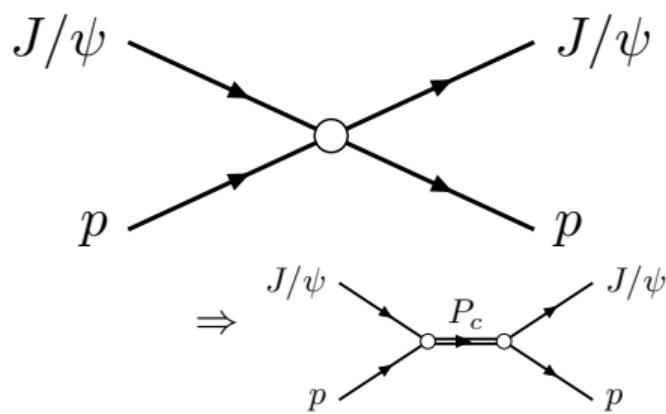
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Range of interaction and different manifestation

Model statements

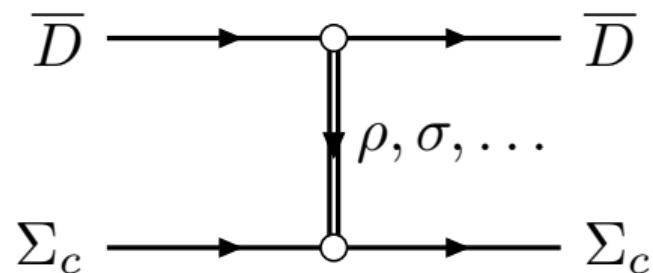
Compact state is the resonance in the $J/\psi p$ system

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



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

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

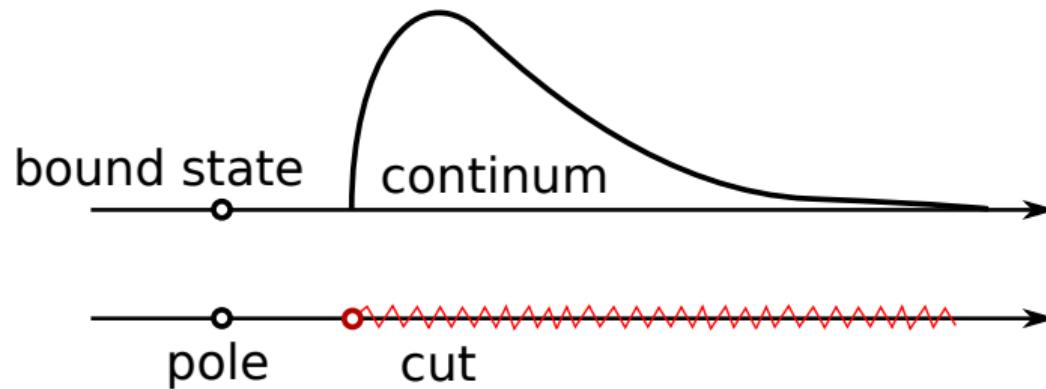


The hypothesis are difficult to separate on the model-independent way

Classical bound-state (molecular) picture

Complex energy plane

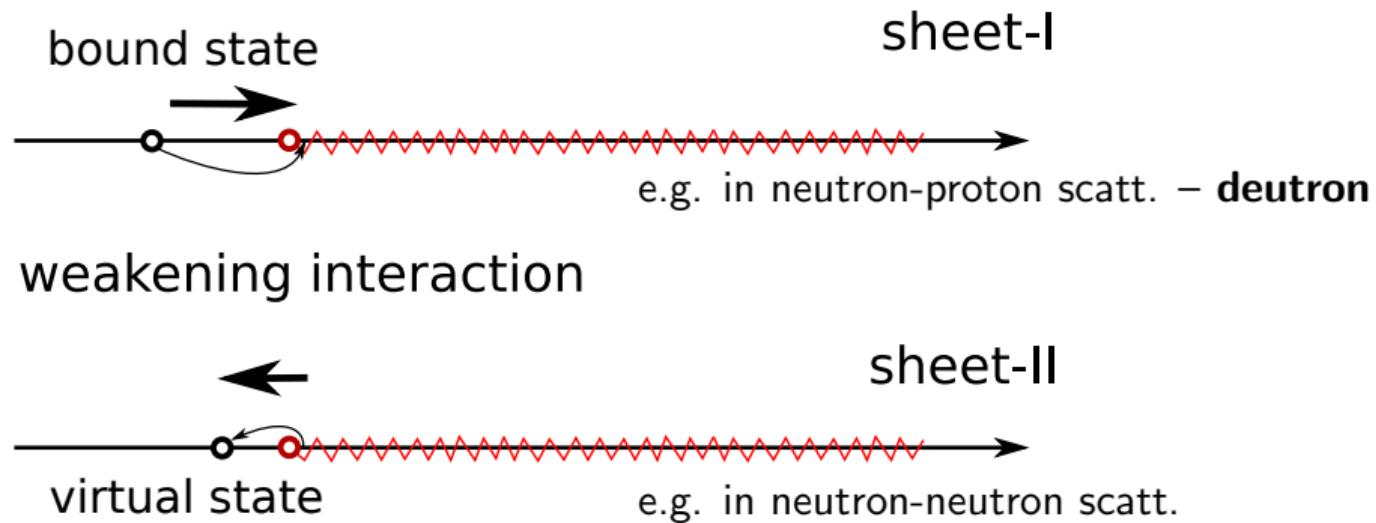
Structures of the complex scattering amplitude correspond to physical



- 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



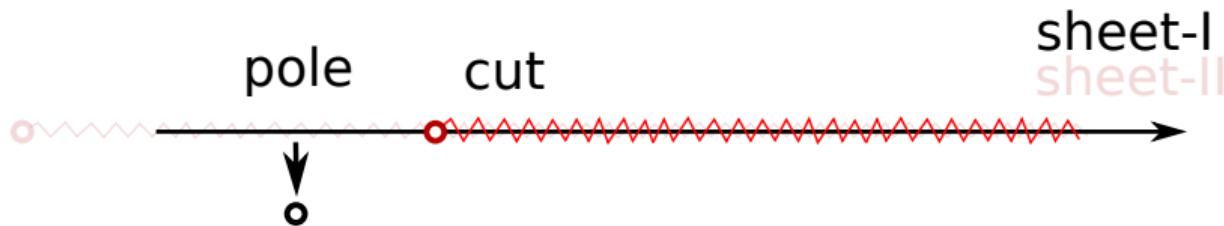
- as weaker the binding as closer the pole to the threshold
- at some point moves to the unphysical sheet and leaves to $-\infty$.

Influence of the inelastic channels

Width of the molecular state



adding inelastic interaction



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

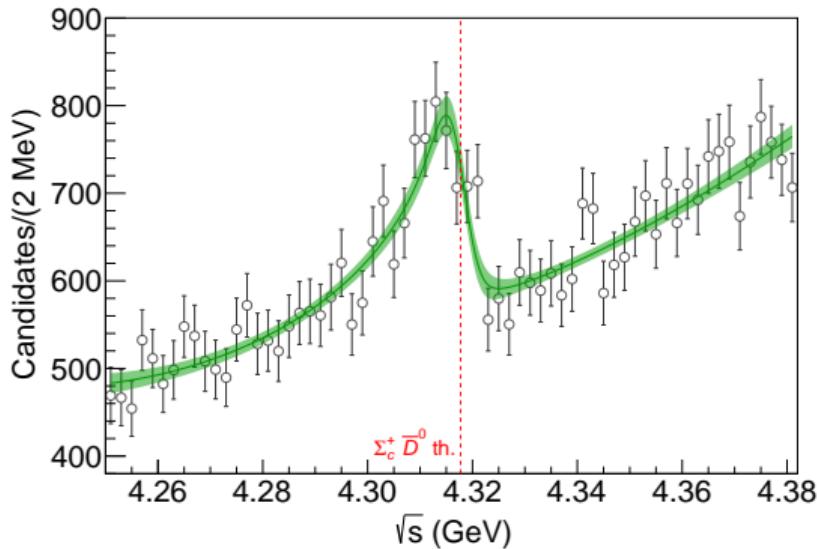
Example demo [\[link\]](#)



$P_c(4312)$ 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 $J/\psi p$.

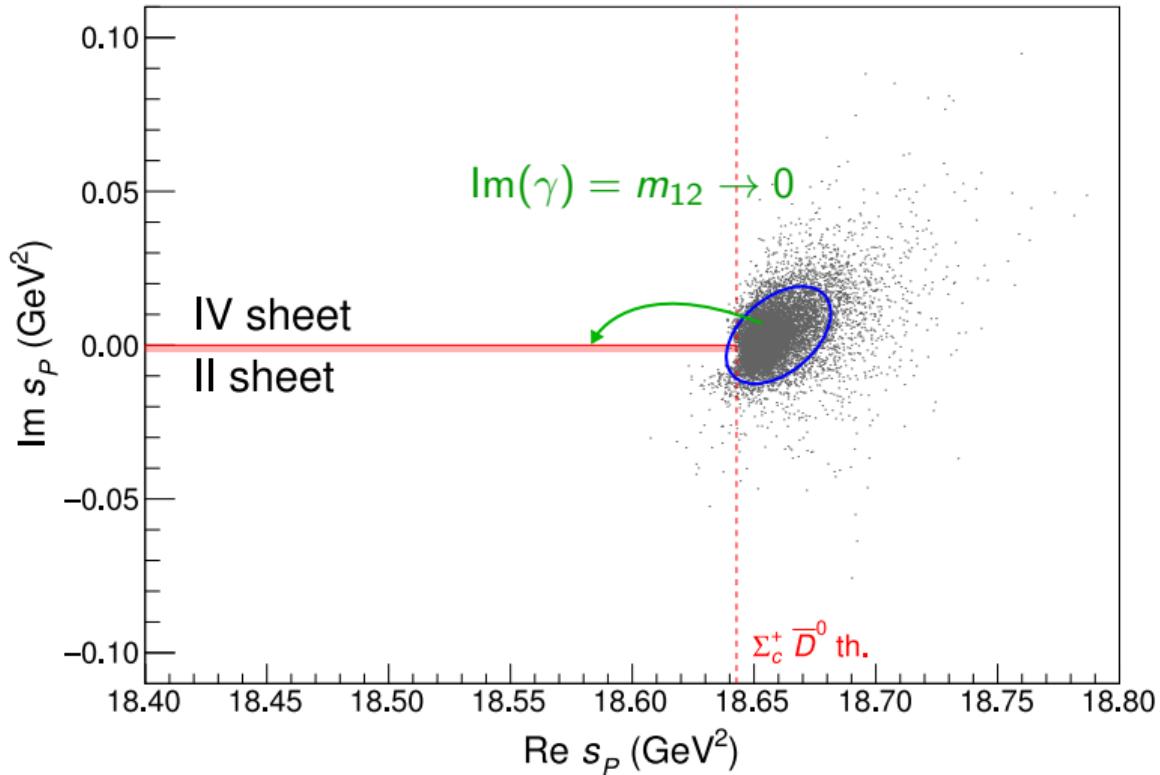
Intensity

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

- $p(s)$ 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



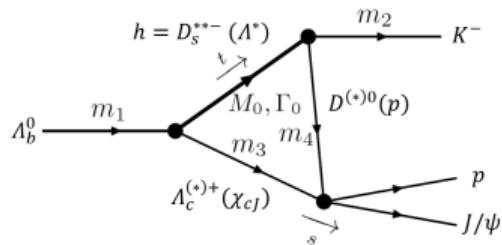
The background of the image is a vibrant, abstract composition of thick, textured paint. It features a variety of colors including bright red, yellow, green, blue, and white. The paint is applied in broad, expressive brushstrokes that overlap and blend into each other, creating a dynamic and energetic visual effect.

Thank you for the attention



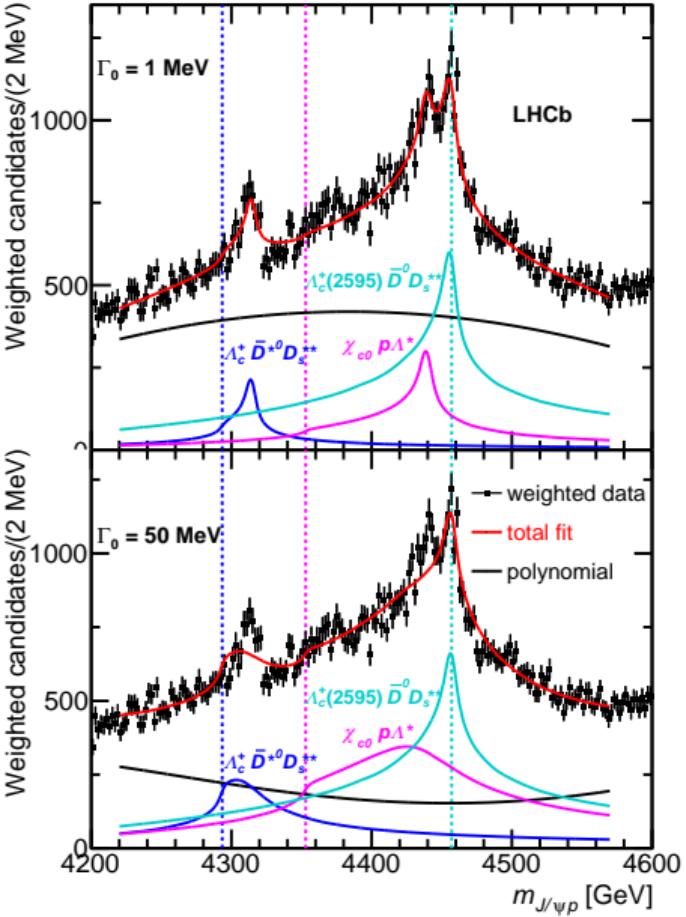
Follow the **Pentaquark** and **Tetraquark** investigation!

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

⇒ no acceptable description in rescattering picture



Scattering amplitude

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

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

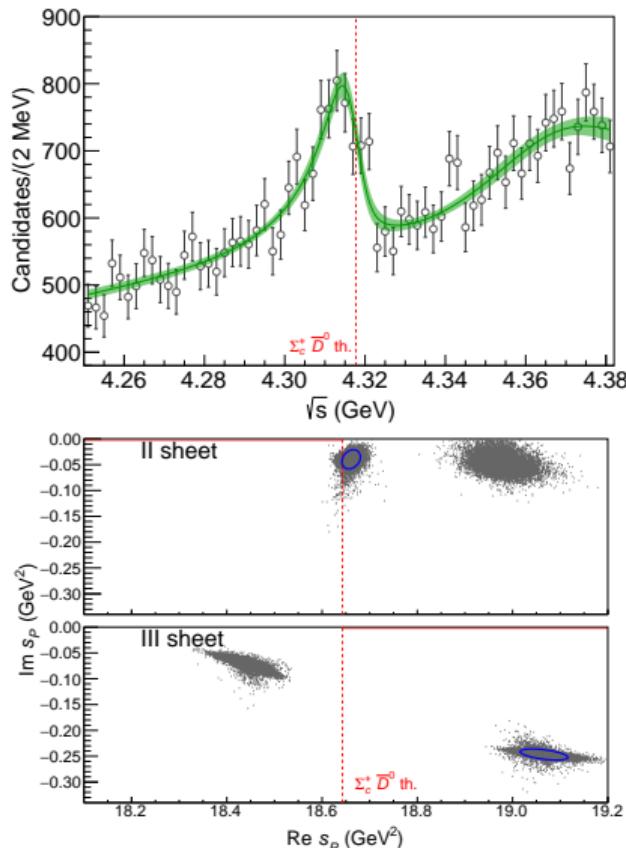
$$T(s) = \underbrace{-\alpha}_{\text{scattering length}} = \frac{1}{\underbrace{-\gamma}_{\gamma \text{ is the inverse scattering length}}}$$

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

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

- 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

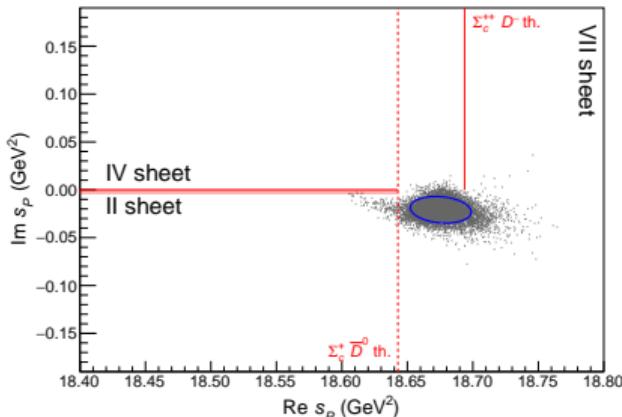
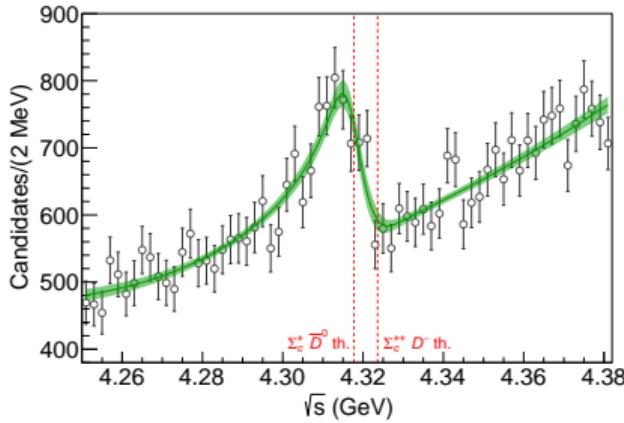
$$T_{ij}^{-1} = m_{ij} + \color{red}c_{ij}s - ik_i\delta_{ij},$$
$$k_i = \sqrt{s - s_i}$$

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

Fit parameters

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

Three channels: effective-range model



Effective-range approximation

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

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

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