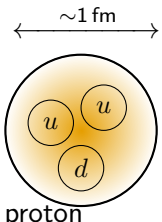
Colors of QCD: Hadron spectroscopy and exotic states at LHCb

Mikhail Mikhasenko
on behalf of LHCb Collaboration

CERN, Switzerland

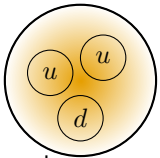
June 5th, 2019

Perspective of QCD – large white space with little colorful objects

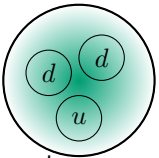


Perspective of QCD – large white space with little colorful objects

simple hadrons (baryons, mesons)

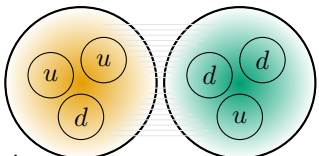


proton



neutron

hardonic molecules (atoms)

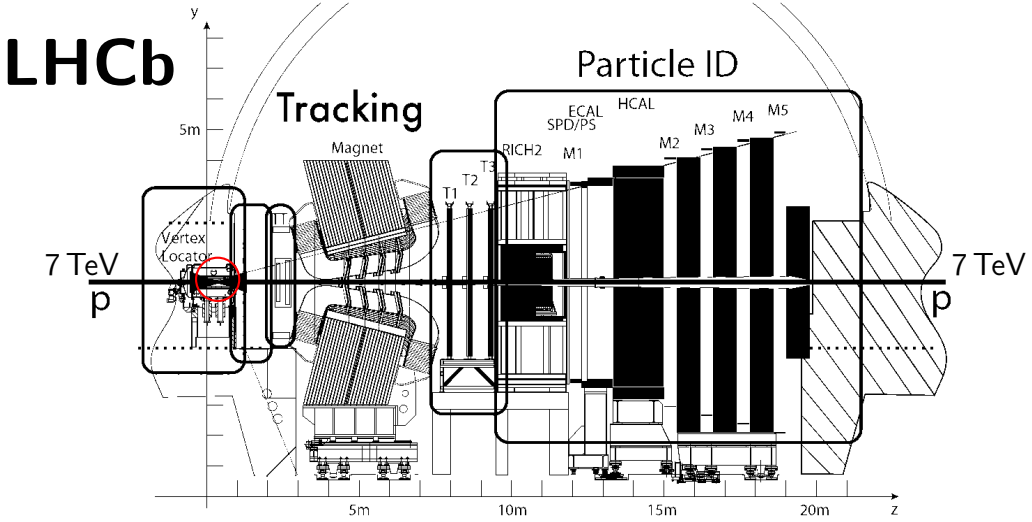


deuteron

. . . . . .

Search for the new type of matter

How to search for color physics with colorless environment?



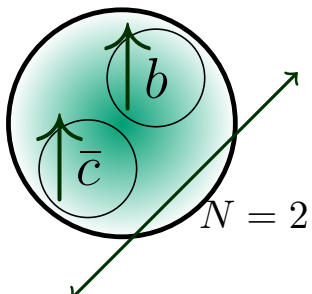
modification of a plot from [INT. J. MOD. PHYS. A 30, 1530022]

Several stories to tell

Run-II data, just-released results

1. Double heavy
2. Pentaquarks
3. Near-threshold $D\bar{D}$ spectroscopy

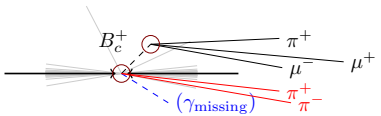
Excitation of the double-heavy double-flavor meson B_c



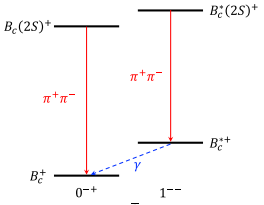
Double-flavor meson B_c and its excitations

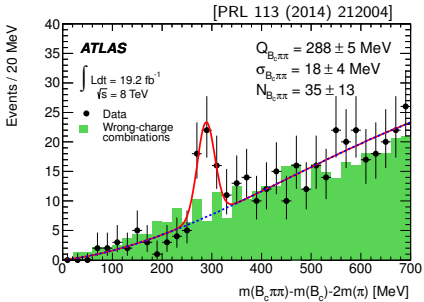
B_c spectroscopy

- (CDF1998) first observation of B_c
- (ATLAS2014) first observation of excited $B_c(2S)$
- (CMS2019) resolving two radial-excited states, $(\uparrow\downarrow)^*$ and $(\uparrow\uparrow)^*$
- (LHCb2019) confirmation of two states



- Clean B_c sample, 3785 ± 73 ev.
- Large combinatorial background





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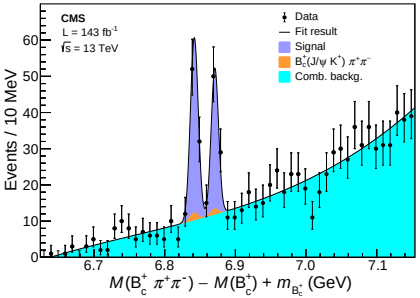
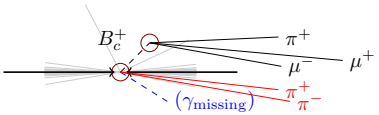
[PRL 122 (2019), 132001]





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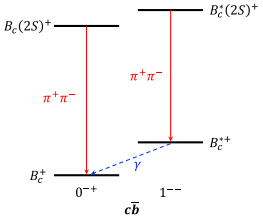

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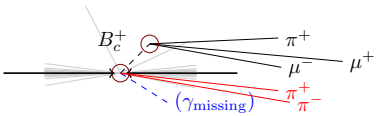

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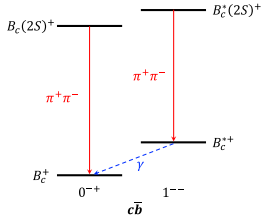
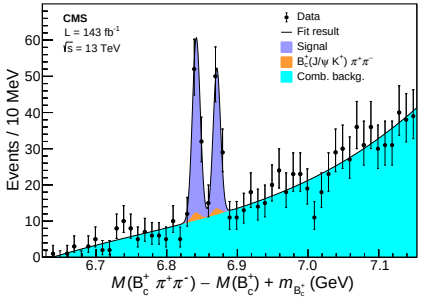
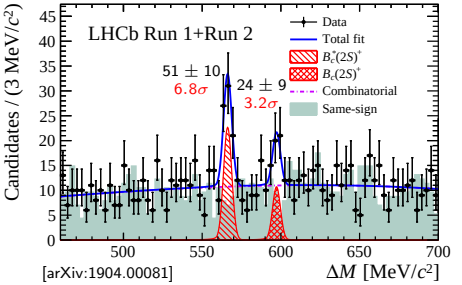


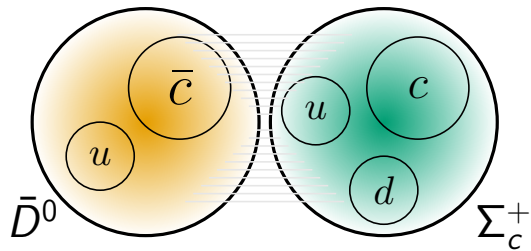
[PRL 122 (2019), 132001]





Pentaquark states P_c

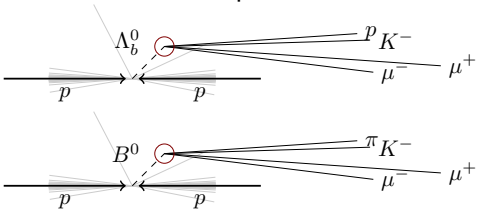
Hadronic molecules $\Longleftrightarrow^{???}$



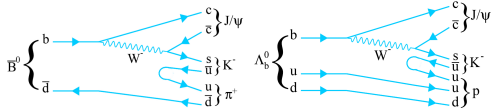
Almost-stable hadrons

Lifetime measurements of Λ_b^0 and B^0

- identification of displaced vertex



- similar decay chains



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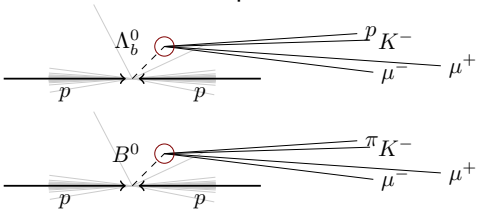

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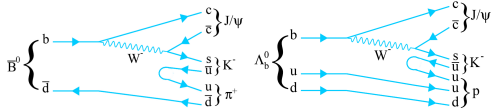
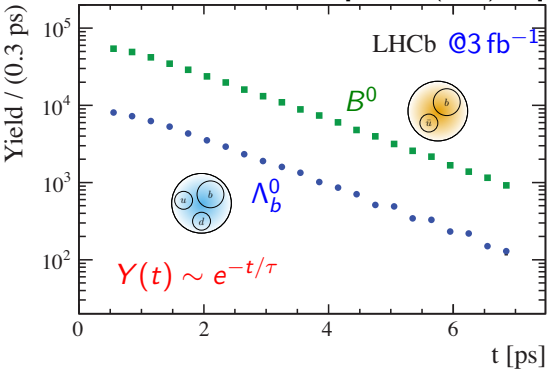


[PLB734 (2014) 122]

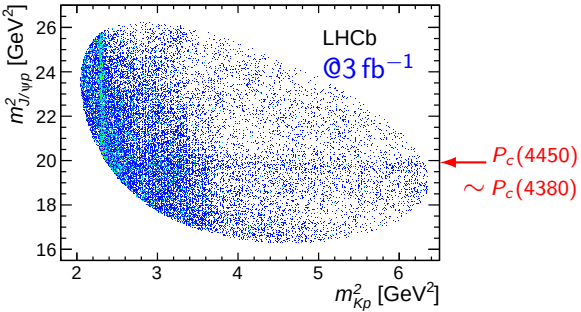


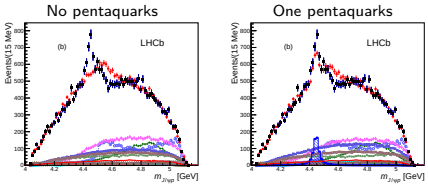
$$\tau_{\Lambda_b^0}/\tau_{B^0} = 0.974 \pm 0.006 \pm 0.004,$$

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

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

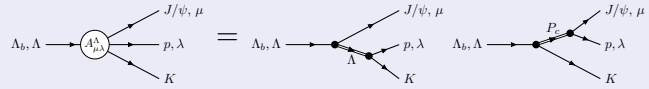
[PRL 115, 072001 (2015)]



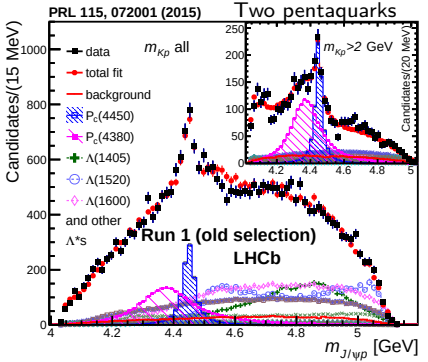


Amplitude analysis of 2015

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

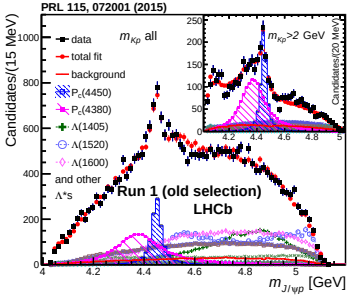


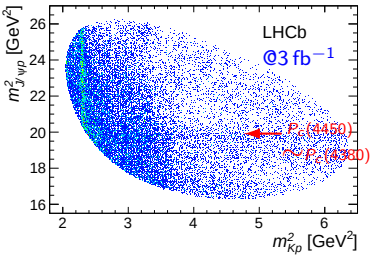
$\Rightarrow$ first ever observation of 5-quark states $[uudc\bar{c}]$.



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

[arXiv:1904.03947]





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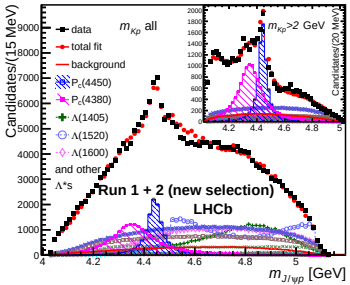

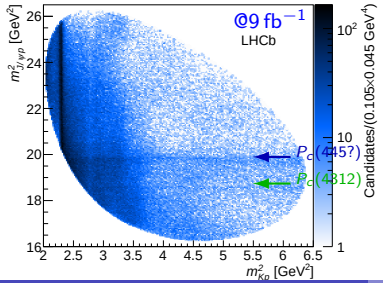

Gain in statistics $\times 9$

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

- Luminosity: $3\,\text{fb}^{-1} \oplus 6\,\text{fb}^{-1}$,
- 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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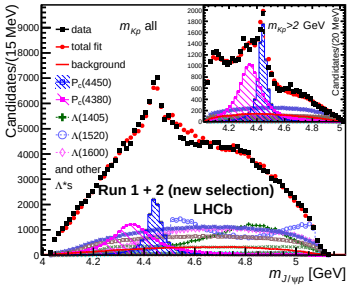

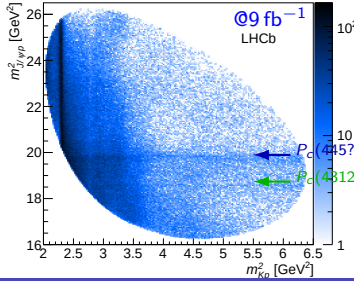

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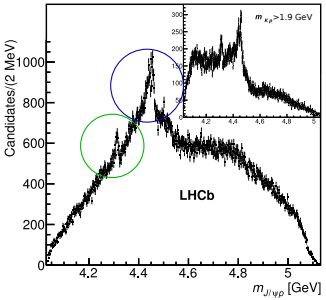


New features

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

Extracting resonance properties

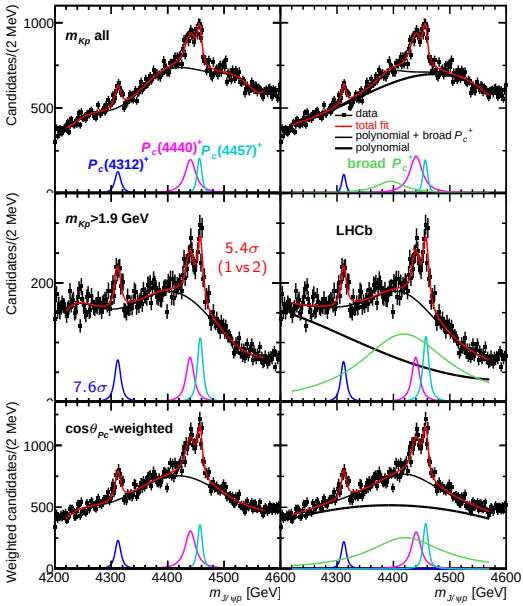
[arXiv:1904.03947]

1-dim. fit and extensive systematic studies:

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

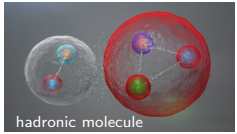
Mass and width of the peaks

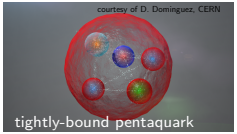
State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)
$P_c(4380)^+$	inconclusive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



Plausible interpretation of P_c states

[arXiv:1904.03947]





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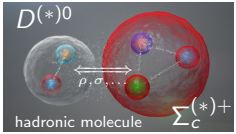


$\Sigma_c \overline{D}$ hadronic molecules

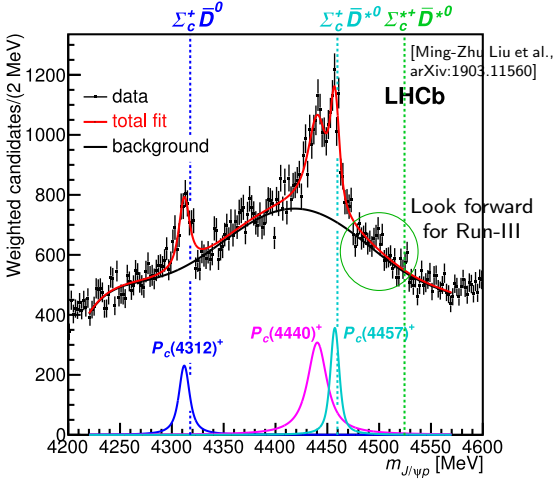
- Narrow width
  - Problematic in tightly-bound picture
  - Problematic in the rescattering picture
- Number of states (HQSS):

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

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

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

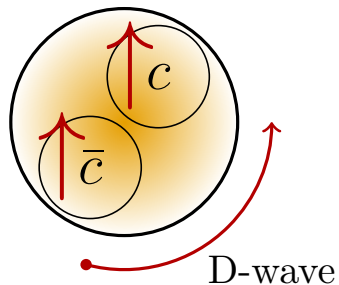
Many theoretical predictions of Σ_c D binding published before 2015 (see backup).



- Ampl.-Ana. is needed to check J^P.

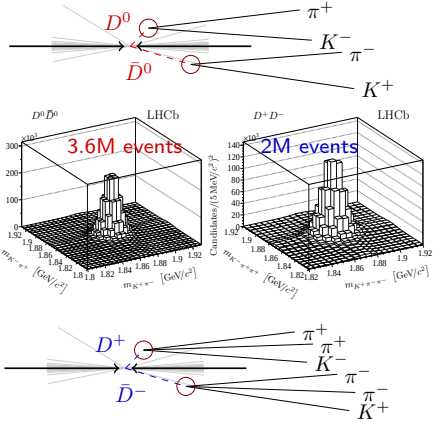
New narrow charmonium state $X(3842)$

$\psi_3(3842)$ $\Longleftrightarrow$



$D\bar{D}$ spectrum with $9\,\text{fb}^{-1}$ (Run-I+Run-II)

[arXiv:1903.12240]



- displaced vertices
- $80-90\,\%$ purity

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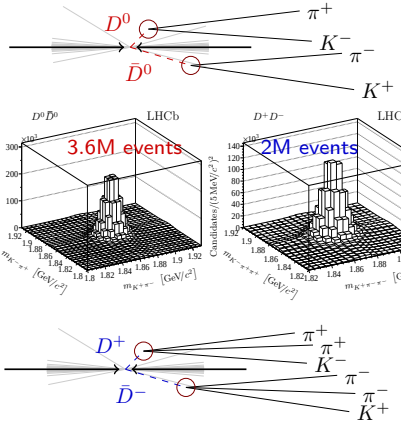

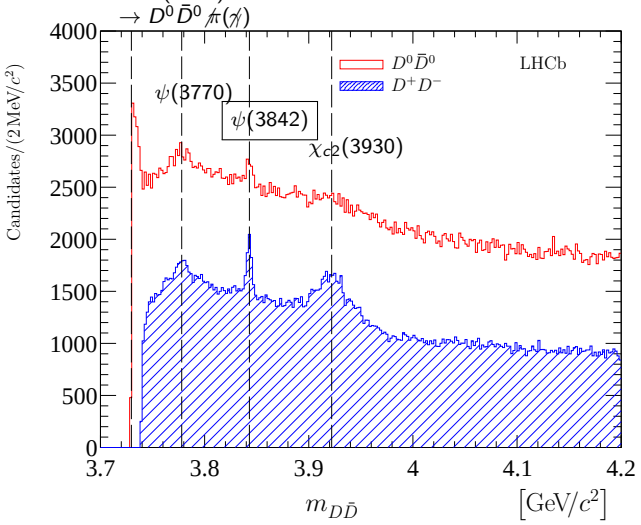

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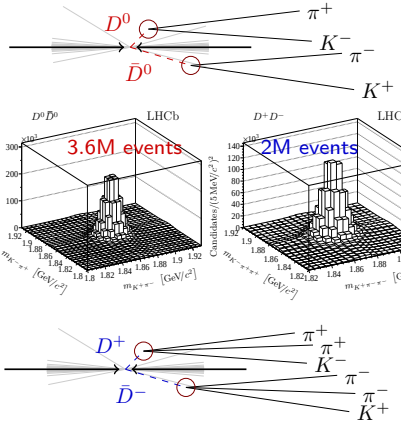

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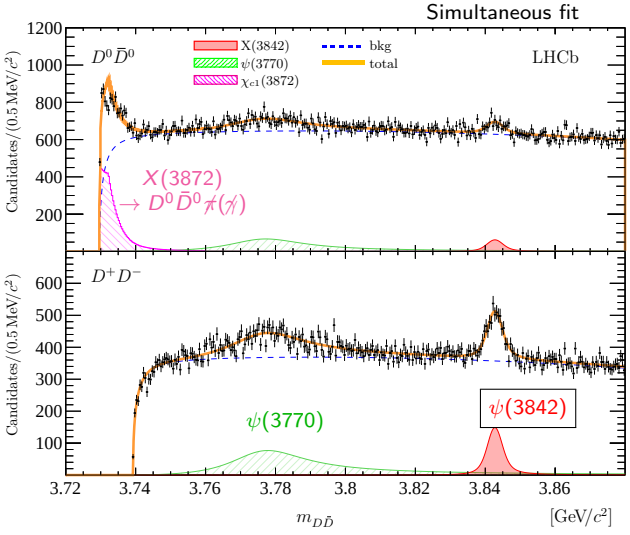

New state is consistent with 1^3D_3 ($\psi_3(1D)$), $J^{PC}=3^{--}$.

Conclusion

Exciting news on the color physics from LHCb:

- Confirmation of the $B_c(2S)$ and $B_c^*(2S)$ states,
- Groundbreaking update on pentaquarks,
- Amazing $D\bar{D}$ spectrum with new charmonium state, $\psi_3(3842)$.

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Not shown:

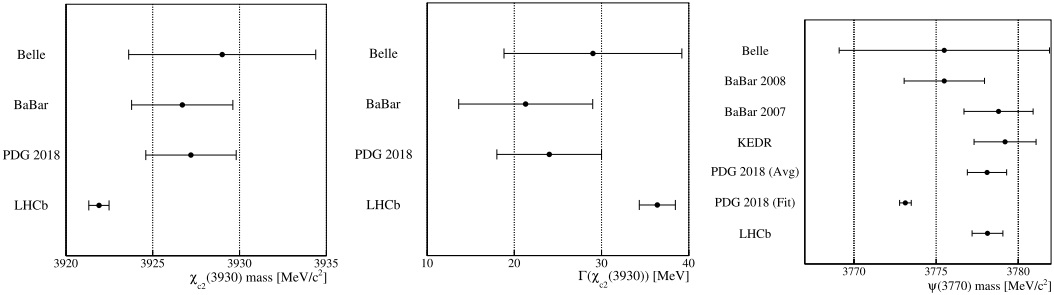
- new decay channel of Ξ_{cc}, $\Xi_{cc} \to \pi^+ \Xi_c$
- first observation of the $\Lambda_b \to \Lambda\gamma$
- Observation of $B^0_{(s)} \to J/\psi p\bar{p}$
- Observation of $\Xi_c \to \phi p$
- Many more, see complete list [here].

Thank you for the attention

backup slides follow...

Impact of new measurements on charmonium

Impact of new $D\bar{D}$ spectrum

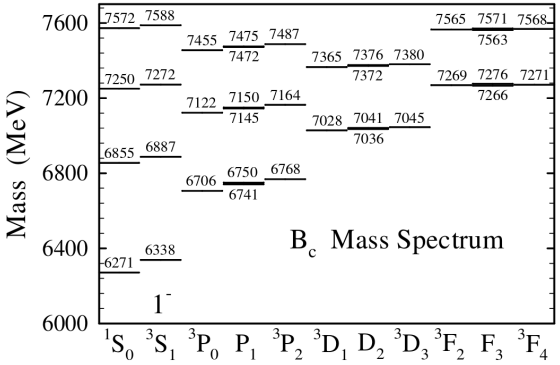


Great interest in community

- $\psi_3(3842)$ is just seen on lattice, [arXiv:1905.03506v1]

B_c spectrum in relativistic quark model

[St. Godfrey PRD 70 054017 (2004)]



P_c interpretations

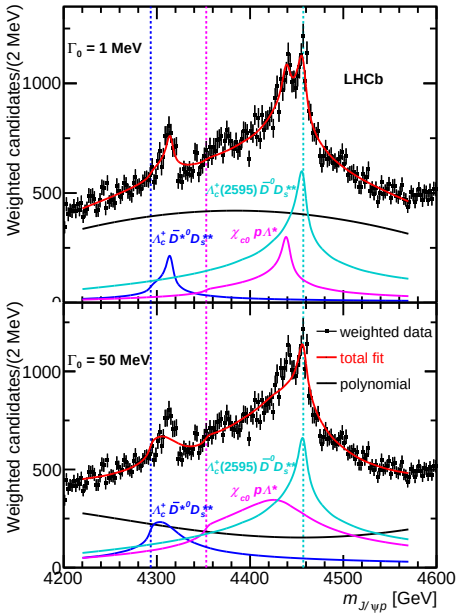
- $\Sigma_c D$ binding (published before 2015)
  - W. L. Wang et al., Phys. Rev. C84 (2011) 015203
  - Z.-C. Yang et al., Chin. Phys. C36 (2012) 6
  - J.-J. Wu et al., Phys. Rev. C85 (2012) 044002,
- Dynamically generated (see references in arXiv:1904.03947)
- Heavy-quark-spin-symmetry (HQSS) consequences
  - Ming-Zhu Liu et al., arXiv:1903.11560
  - C.W. Xiao et al., arXiv:1904.01296
- $P_c(4312)$ pole position and molecular binding,
  C. Fernandez, A. Pilloni, MM (JPAC Collaboration), arXiv:1904.10021.
- Tightly-bound pentaquark models (see references in arXiv:1904.03947)

Rescattering interpretation

Triangle singularity [see Appendix of arXiv:1904.03947]

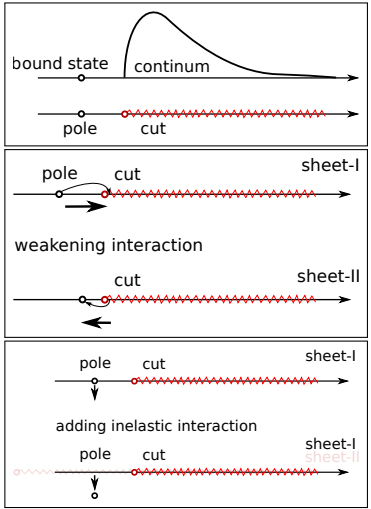
- There are many thresholds around P_c peaks
  - $\Lambda_c \bar{D}^0$, $\Sigma_c \bar{D}^0$, $\chi_c N^*$ with different exchanges as suggested in [Guo et al.(PRD92 (2015) 071502), U.-G. Meißner et al. (PLB751 (2015) 59), X.-H. Liu et al. (PLB757 (2016) 231), MM (arXiv:1507.06552)]
- An appropriate 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 have been found



Investigation on molecular picture

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



Scattering-length approximation

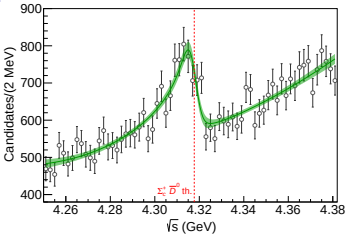
$$T_{ij}^{-1} = m_{ij} - ik_i\delta_{ij},$$
$$k_i = \sqrt{s - s_i}$$

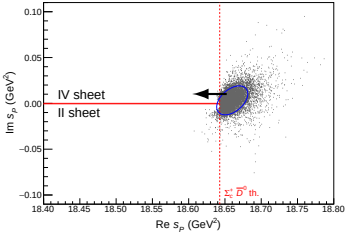
Two channels: $\Sigma_c^+\bar{D}^0$ and $J/\psi p$.

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.





Consistent with the **virtual state**