Recent Developments in Tetraquark Studies at LHCb

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Bundesministerium für Bildung und Forschung

QNP 2024

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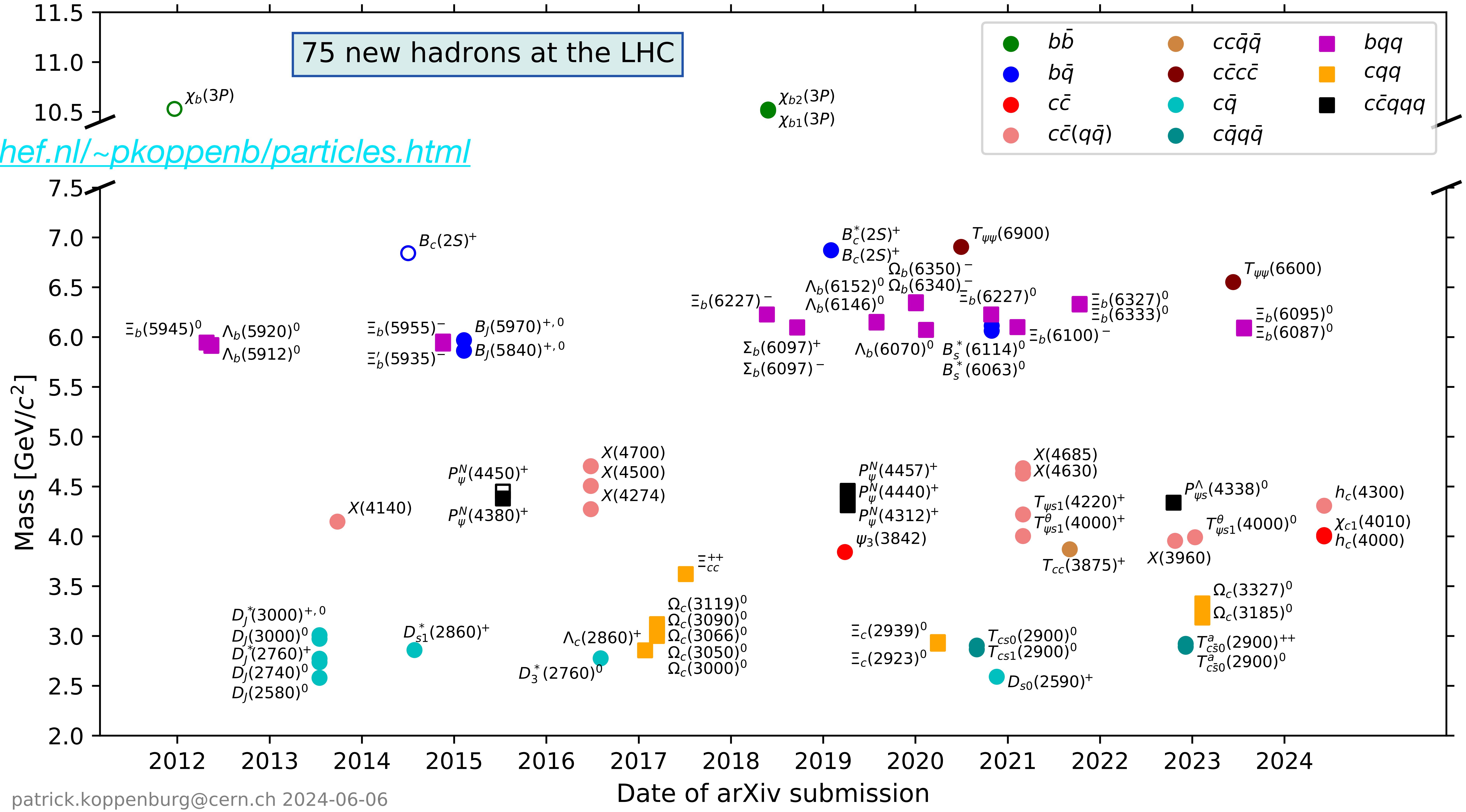
Hadron Spectroscopy at the LHC

https://www.nikhef.nl/~pkoppenb/particles.html



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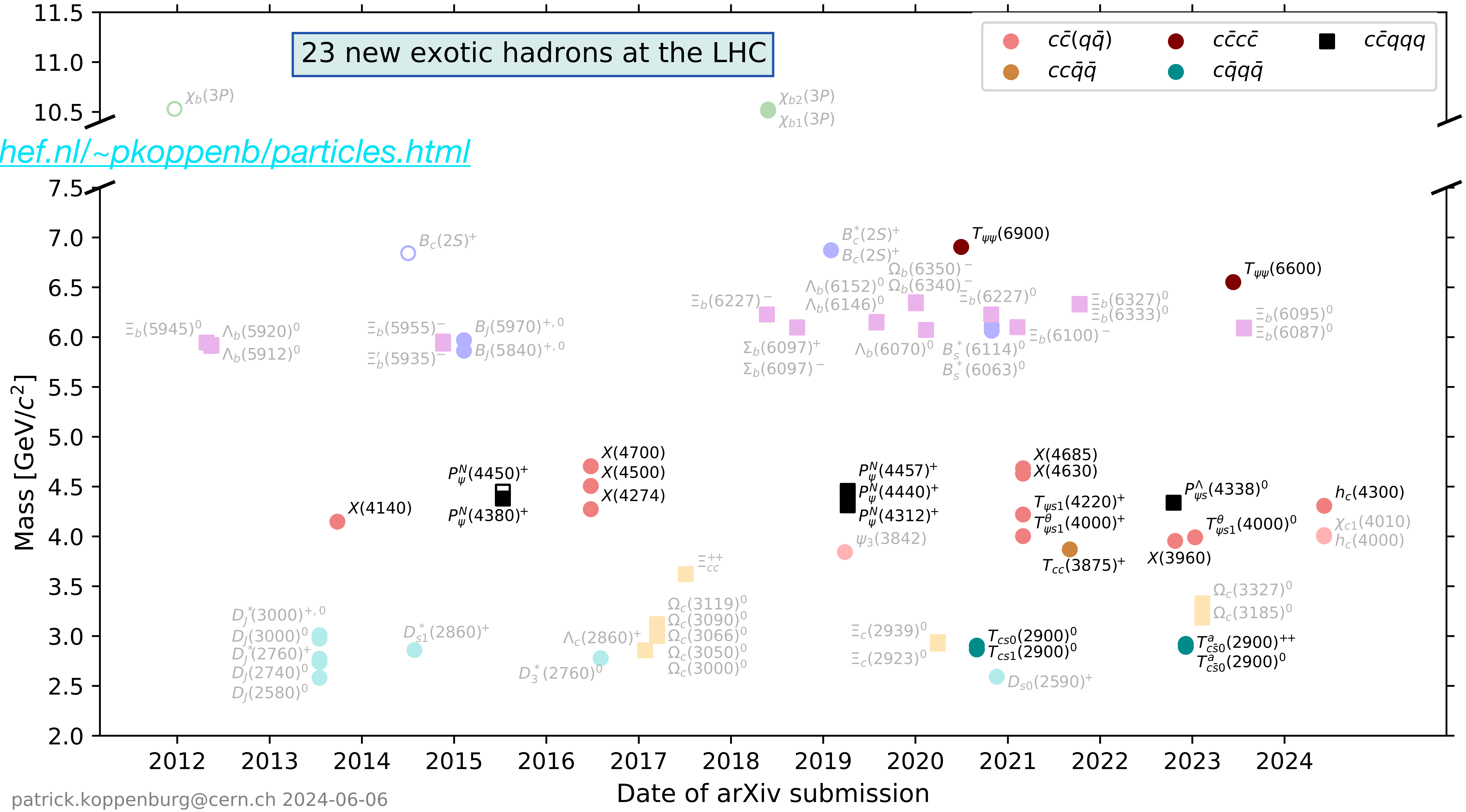

Hadron Spectroscopy at the LHC

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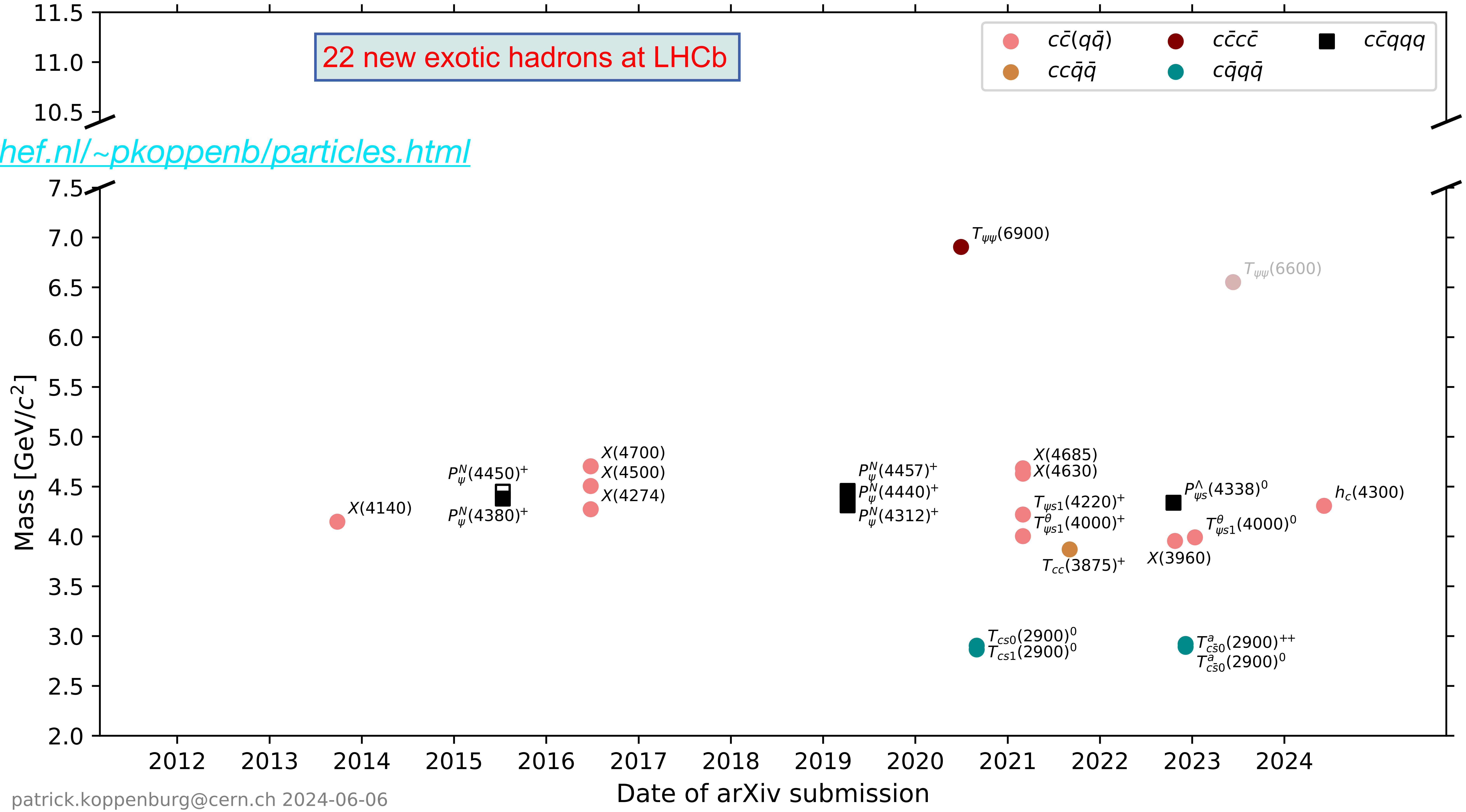
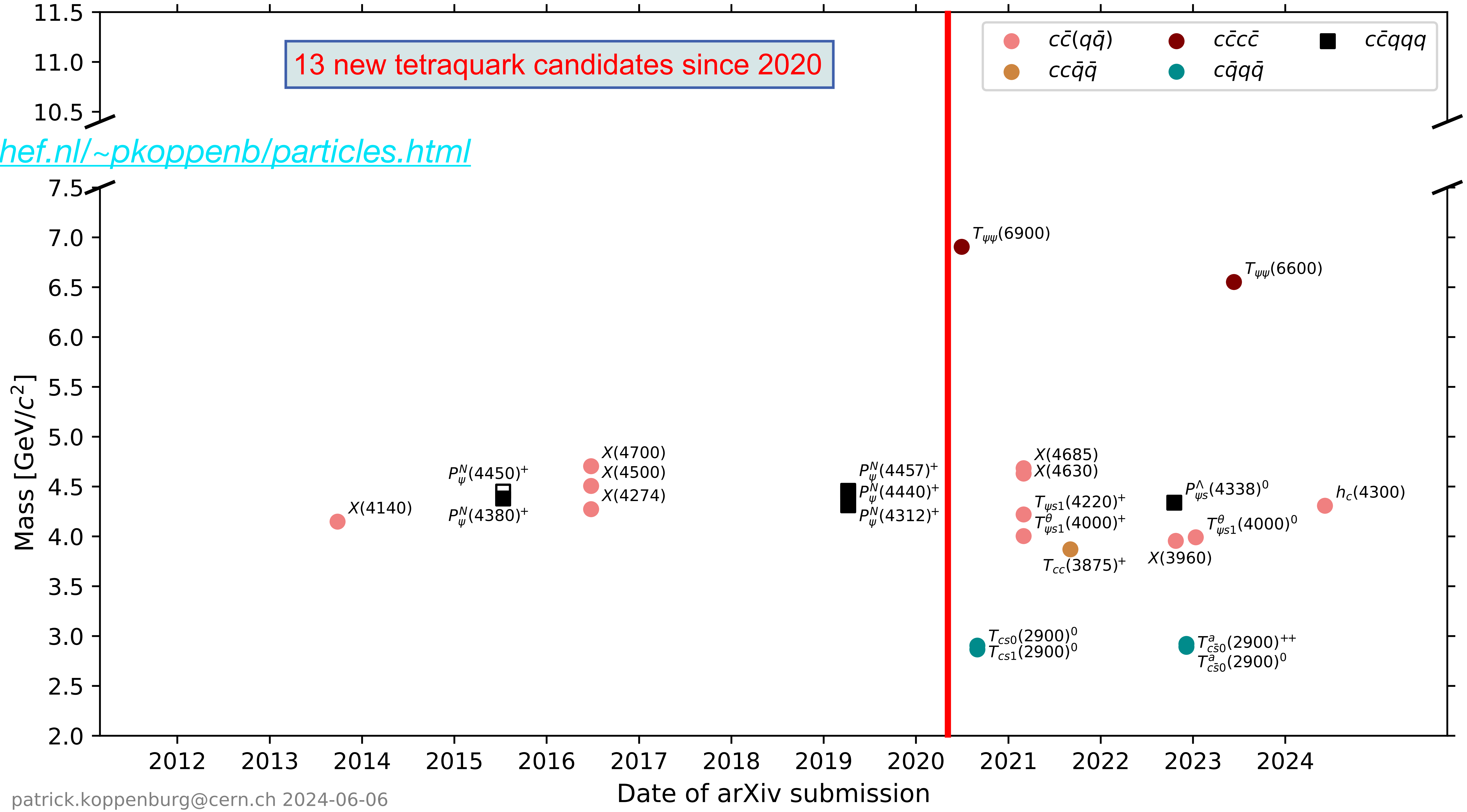


Hadron Spectroscopy at the LHC



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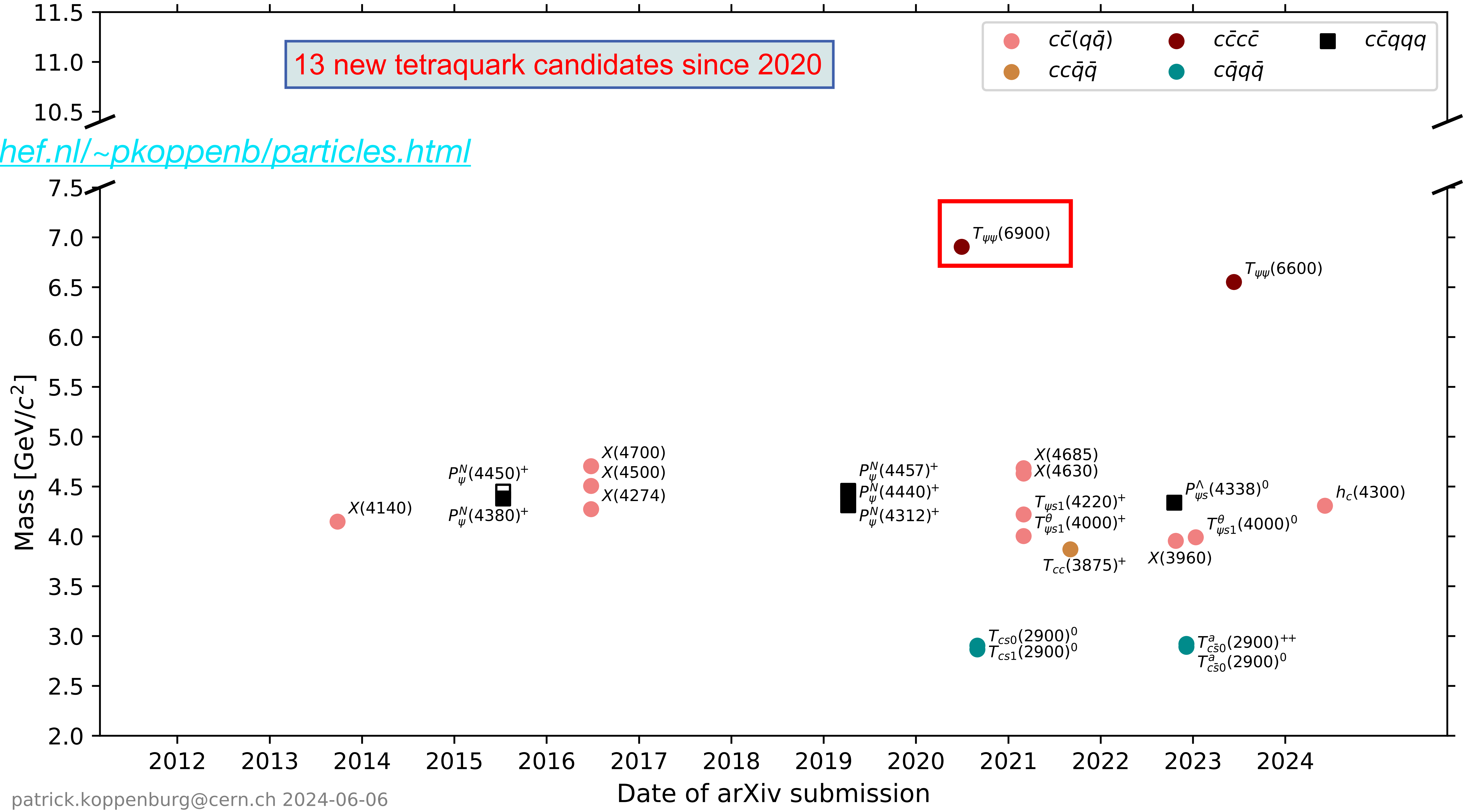
$T_{\psi\psi}(6900)$ observation in prompt di-J/ψ production



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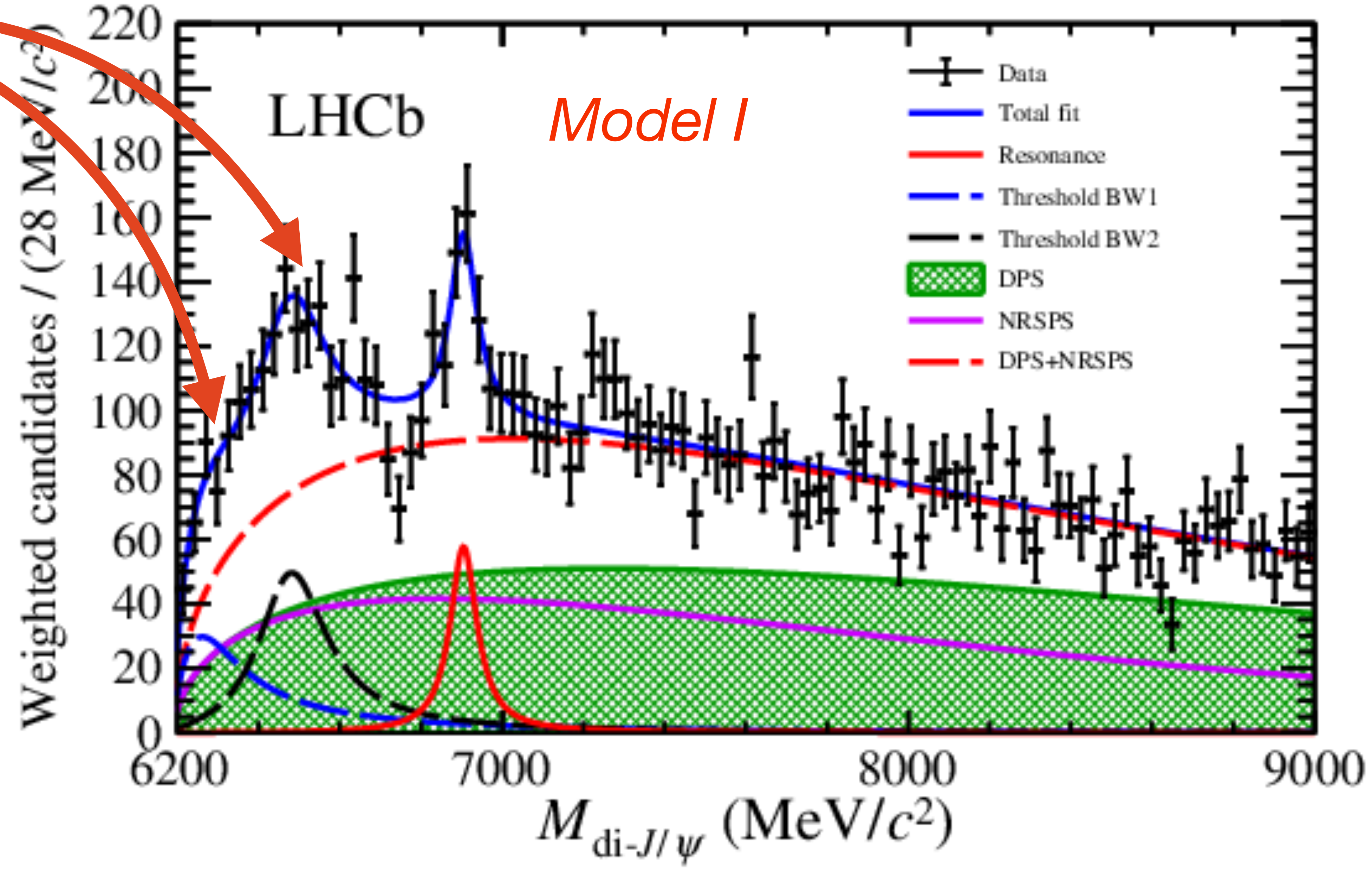
$T_{\psi\psi}(6900)$ observation in prompt di-J/ψ production

- Signal described with a Breit-Wigner lineshape
- Near di-J/ψ threshold enhancements could be due to feed down from heavier quarkonia decays or mixture of other four-quark states
- Model I: no-interference fit

$$M\left(T_{\psi\psi}(6900)\right) = 6905 \pm 11\ (\text{stat})\ \pm 7\ (\text{syst})\ \text{MeV}$$

$$\Gamma\left(T_{\psi\psi}(6900)\right) = 80 \pm 19\ (\text{stat})\ \pm 33\ (\text{syst})\ \text{MeV}$$



LHCb-PAPER-2020-011; arXiv:2006.16957

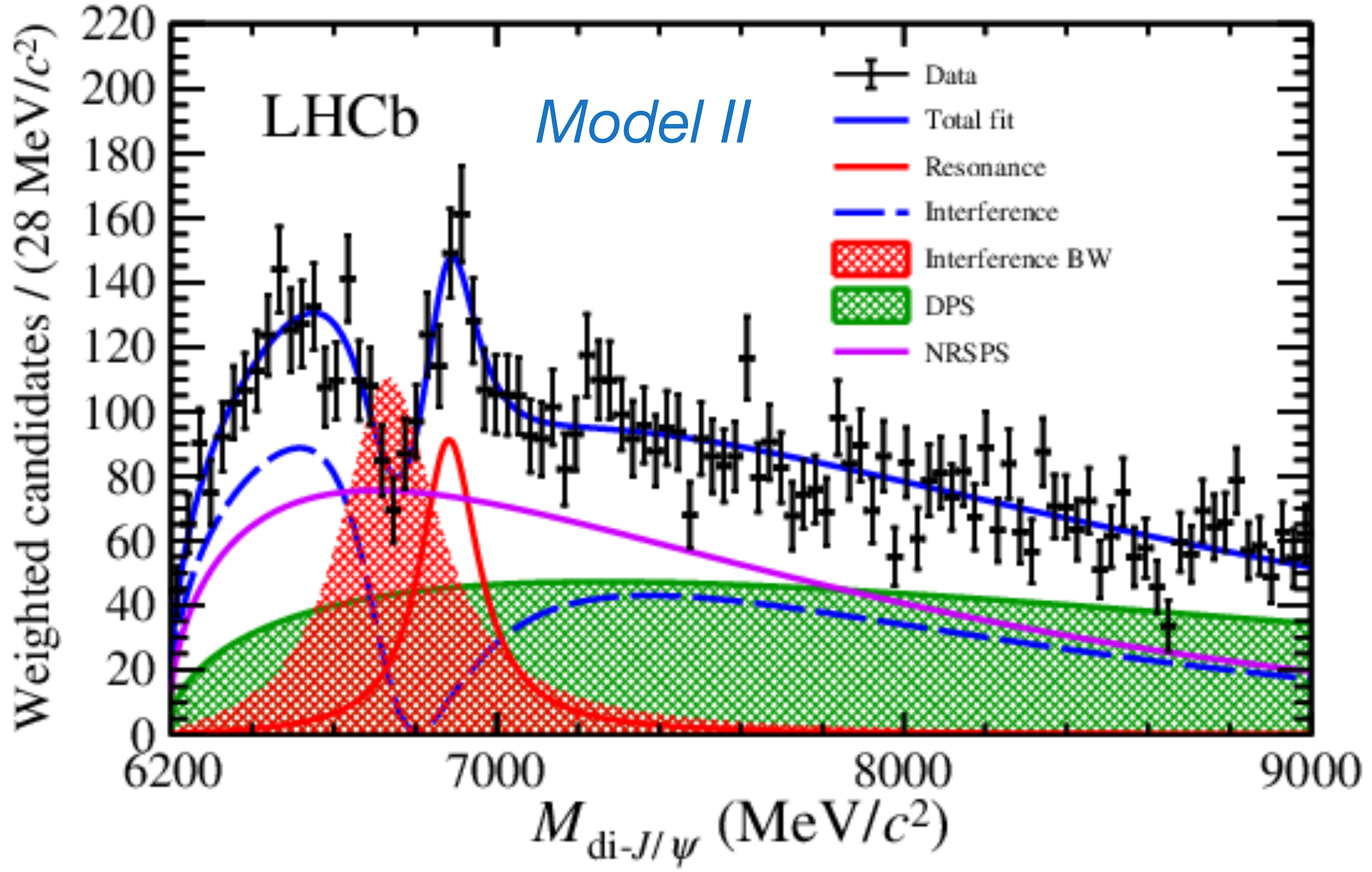
$T_{\psi\psi}(6900)$ observation in prompt di-J/ψ production

- Model II: including interference with non-resonant di-J/ψ production

$$M\left(T_{\psi\psi}(6900)\right) = 6886 \pm 11\,(\text{stat}) \pm 11\,(\text{syst})\,\text{MeV}$$

$$\Gamma\left(T_{\psi\psi}(6900)\right) = 168 \pm 33(\,\text{stat}\,) \pm 69\,(\text{syst})\,\text{MeV}$$

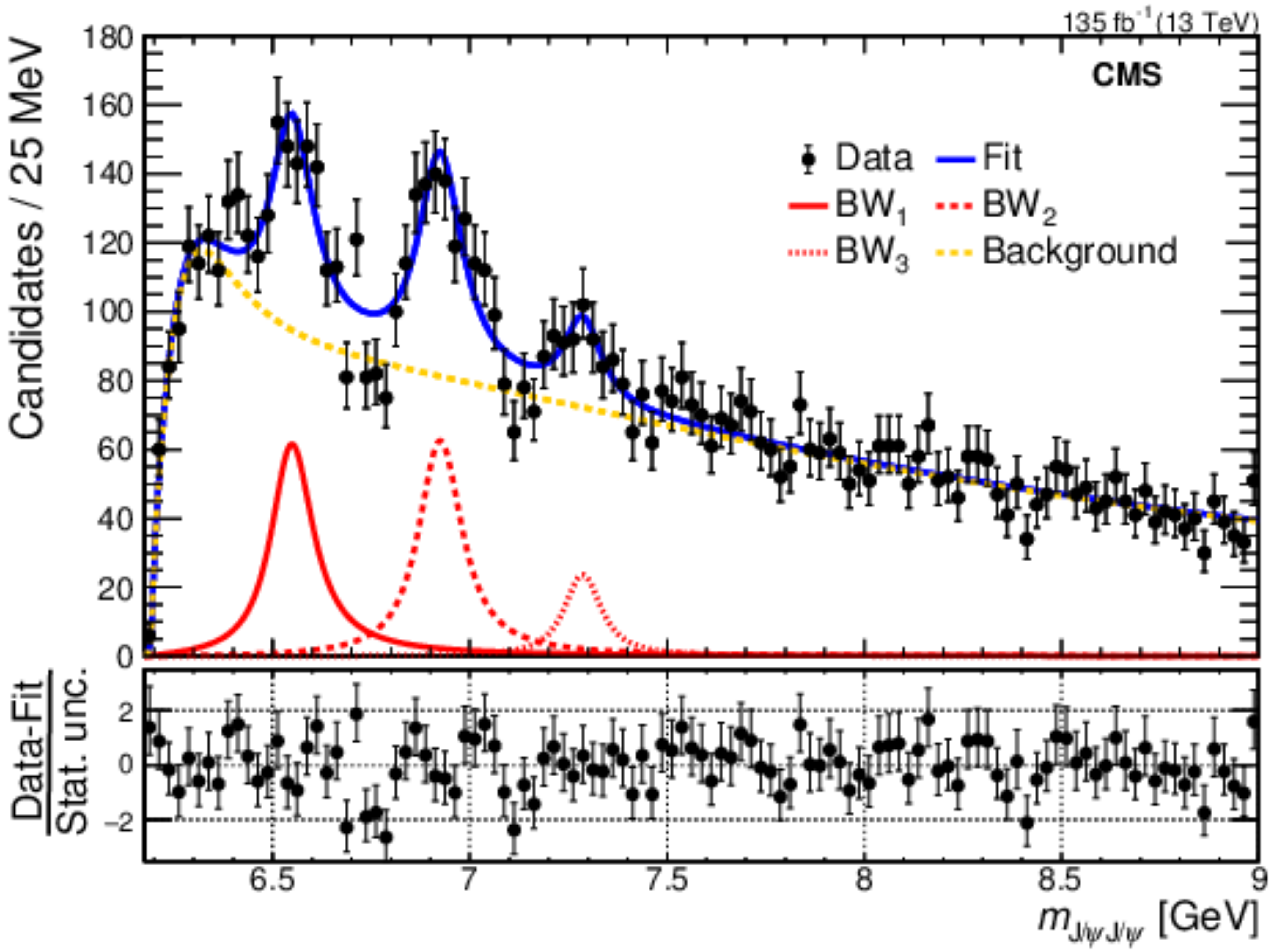
- Interpreted as $cc\bar{c}\bar{c}$ state, further investigation determining spin-parity quantum numbers necessary
- Significance in both models $> 5\sigma$
- $T_{\psi\psi}(6900)$ also confirmed by CMS and ATLAS



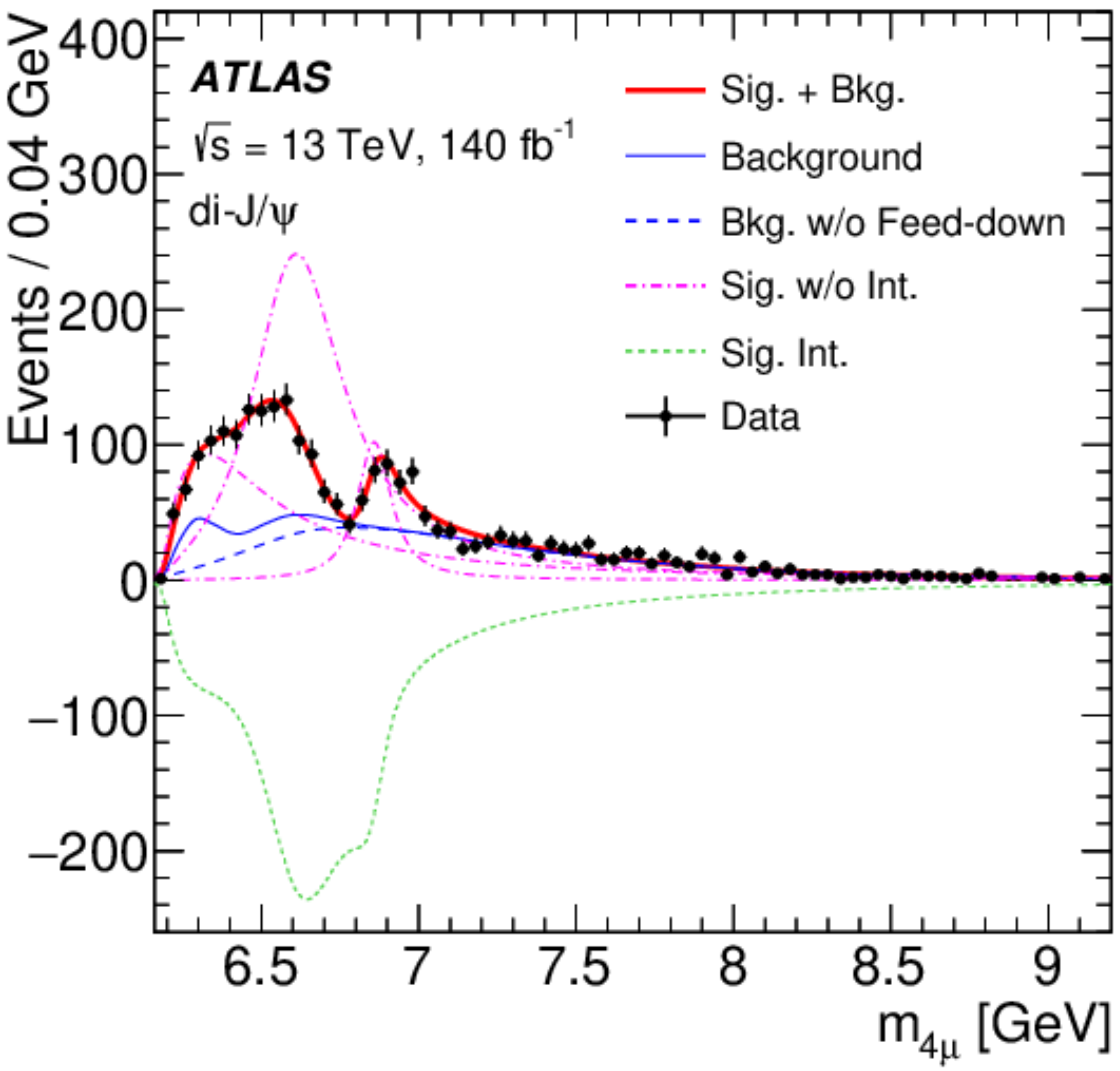
LHCb-PAPER-2020-011; arXiv:2006.16957

$T_{\psi\psi}$(6900): Confirmed by CMS and ATLAS

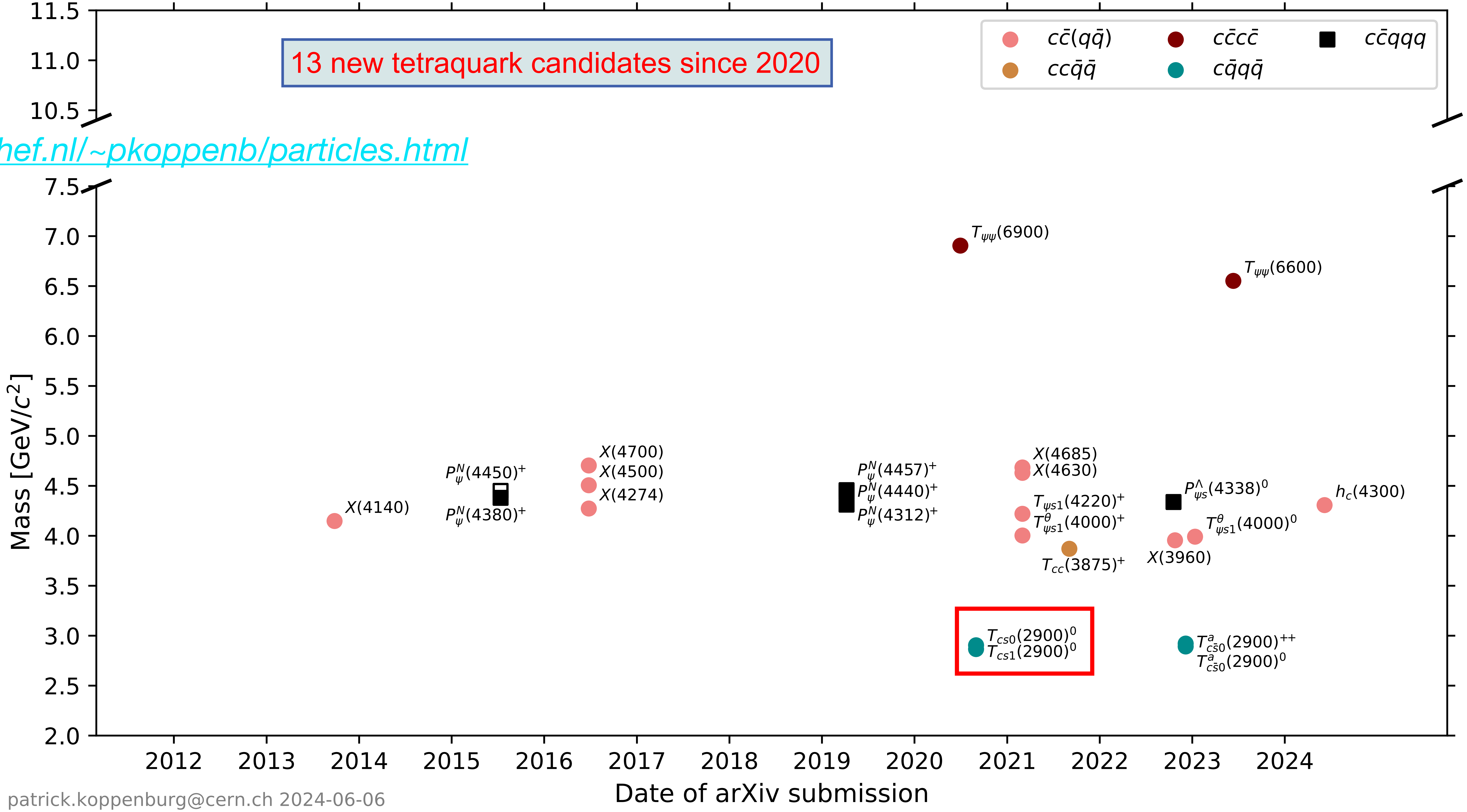
CMS-BPH-21-003; arXiv:2306.07164



arXiv:2304.08962; CERN-EP-2023-03



$T_{cs0(1)}(2900)^0$ observation in $B^+ \to D^+D^-K^+$ Decays



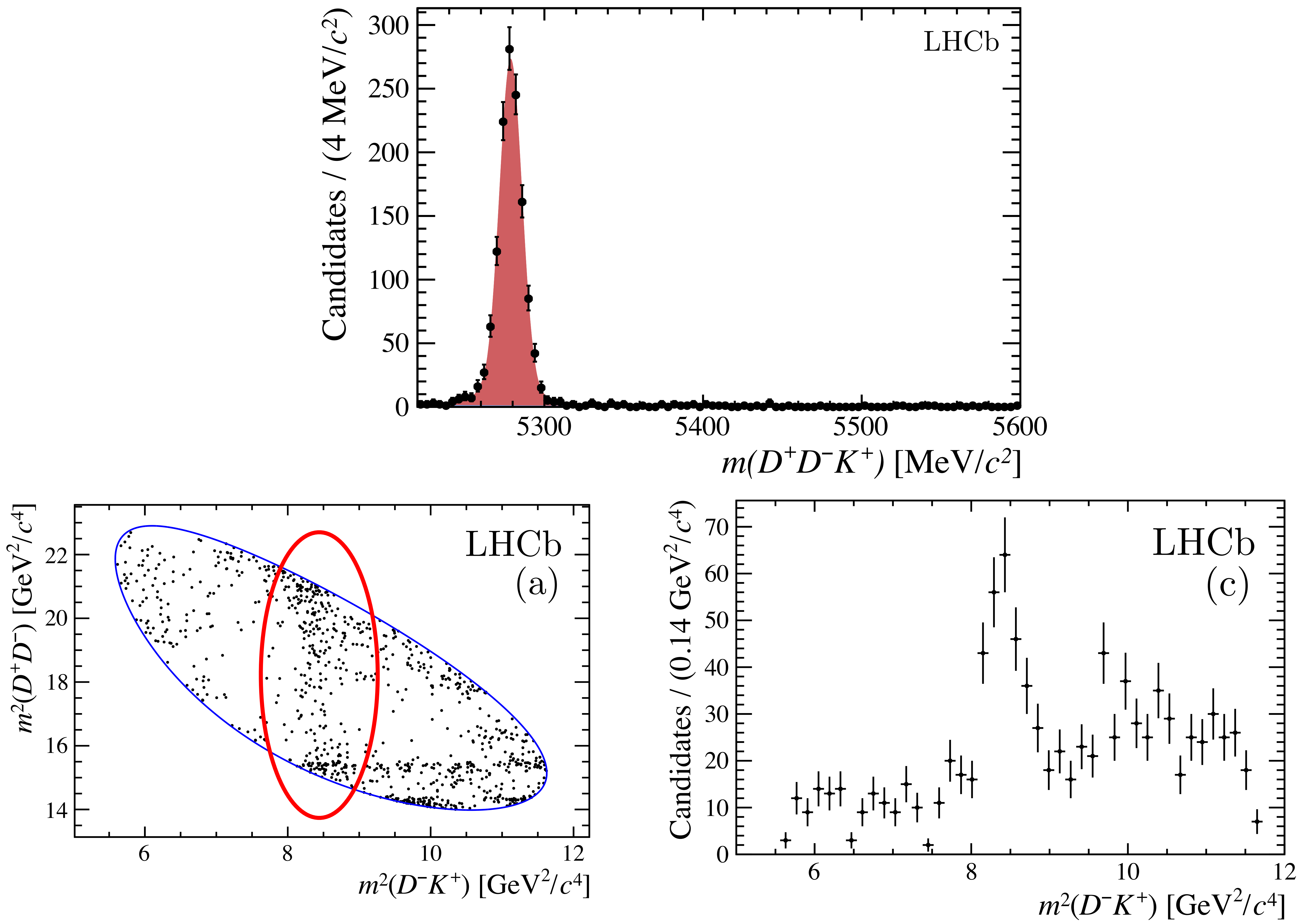
https://www.nikhef.nl/~pkoppenb/particles.html

$T_{cs0(1)}(2900)^0$ observation in $B^+ \to D^+D^-K^+$ Decays

- Clean environment to study open-charm tetraquarks
- Any resonance in the D^-K^+ channel has minimal quark content $\bar{c}d\bar{s}u$
- Also possible to search for doubly charged tetraquarks in D^+K^+

  → No such tetraquarks were observed in this analysis

- Decay also allows to study $c\bar{c}$ resonant structure in the D^+D^- channel



arXiv:2009.00026; LHCb-PAPER-2020-025

$T_{cs0(1)}(2900)^0$ observation in $B^+ \to D^+D^-K^+$ Decays

arXiv:2009.00026; LHCb-PAPER-2020-025

- Amplitude analysis reveals that data cannot be reasonably described without D^-K^+ resonances

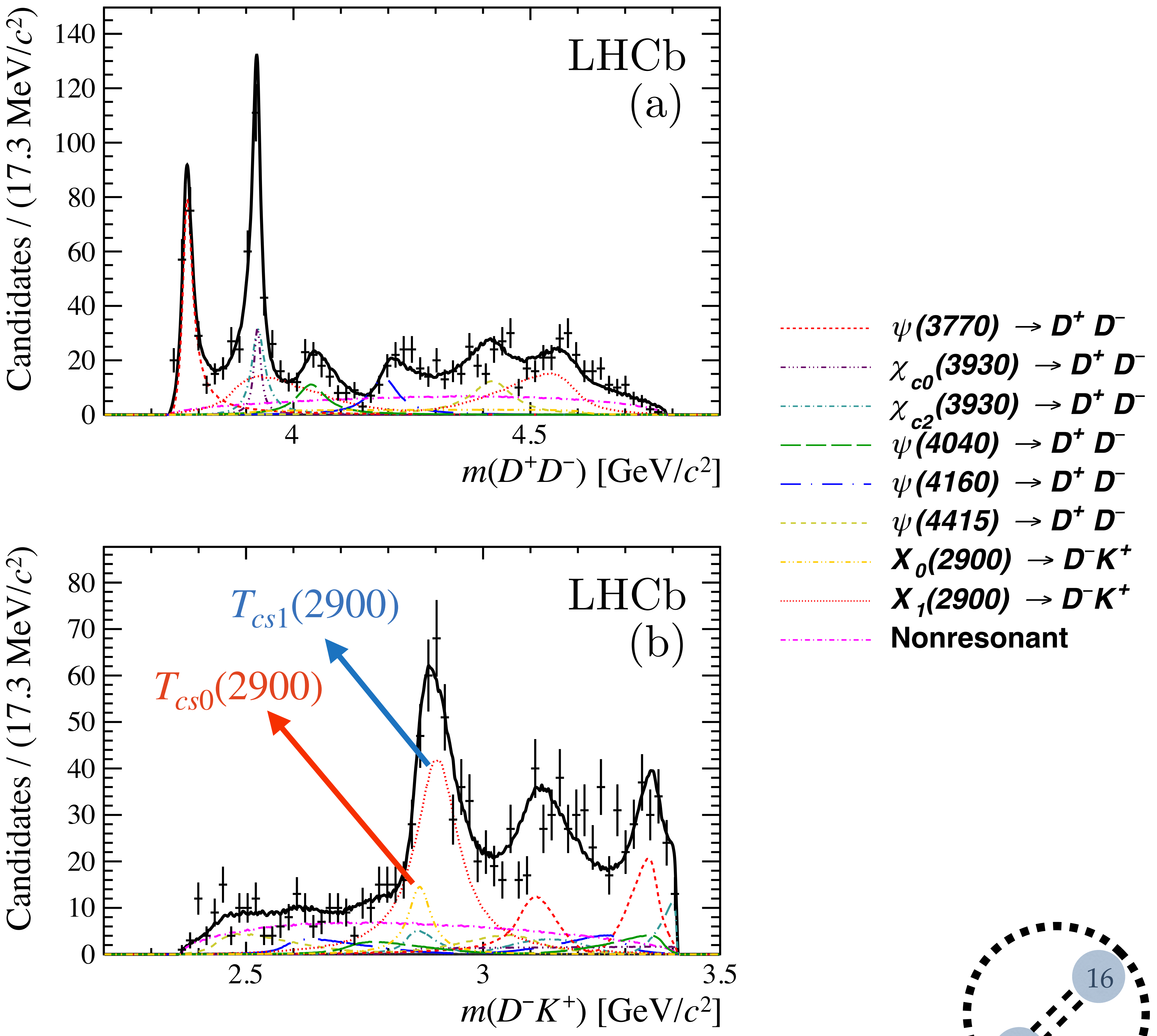
$$M(T_{cs0}(2900)) = 2.866 \pm 0.007 \pm 0.002 \text{ GeV}$$

$$\Gamma(T_{cs0}(2900)) = 57 \pm 12 \pm 4 \text{ MeV}$$

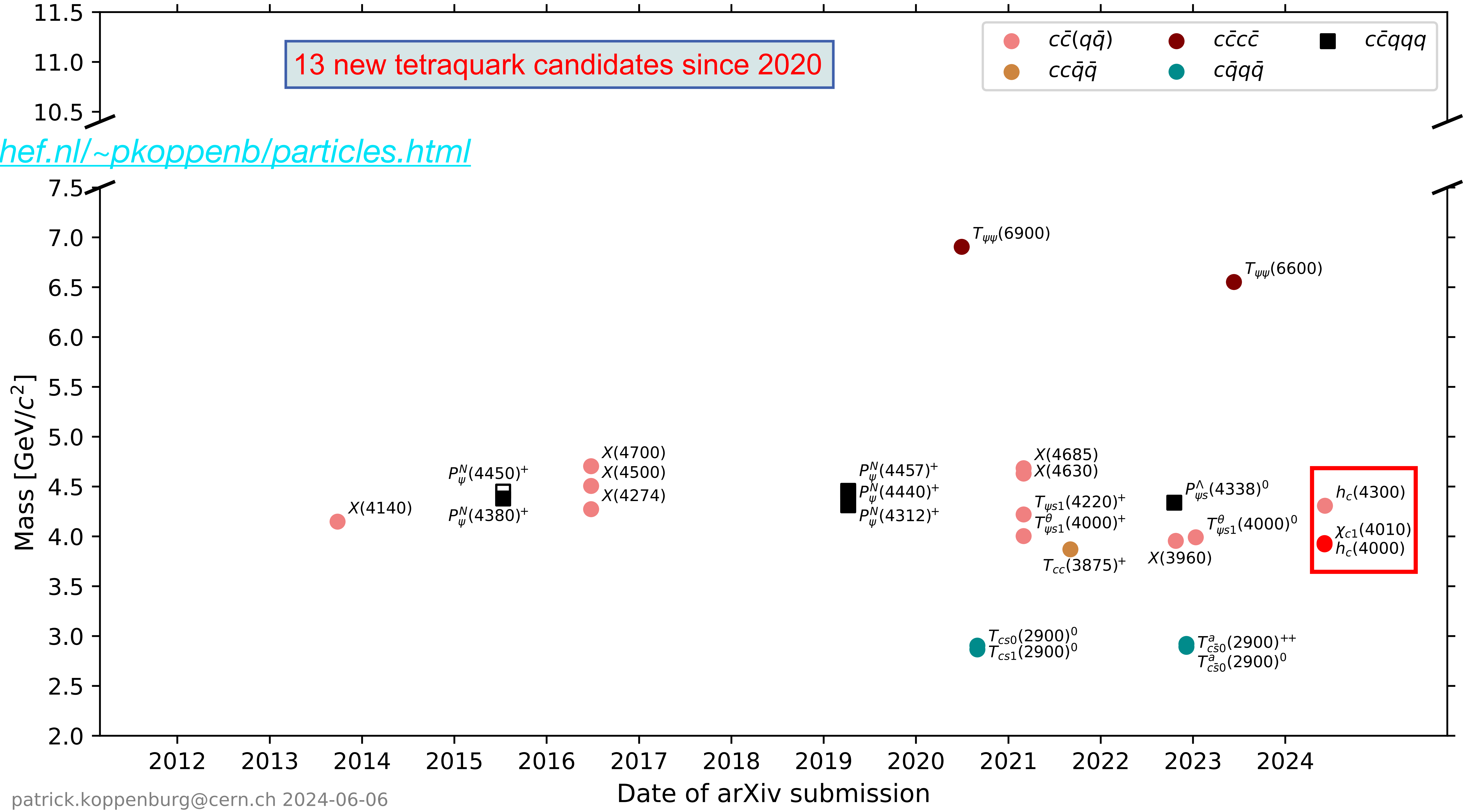
$$M(T_{cs1}(2900)) = 2.904 \pm 0.005 \pm 0.001 \text{ GeV}$$

$$\Gamma(T_{cs1}(2900)) = 110 \pm 11 \pm 4 \text{ MeV}$$

- First open-charm tetraquark observed!



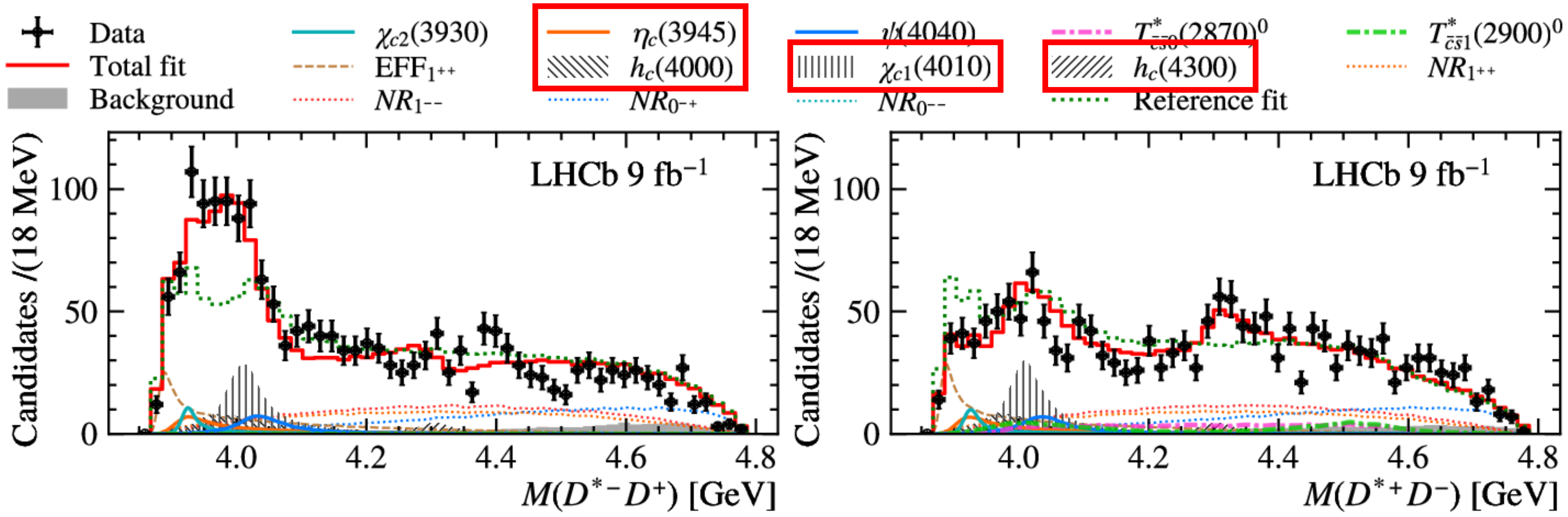
Charmonium(-like) States in $B^+ \to D^{*\pm} D^{\mp} K^+$ Decays

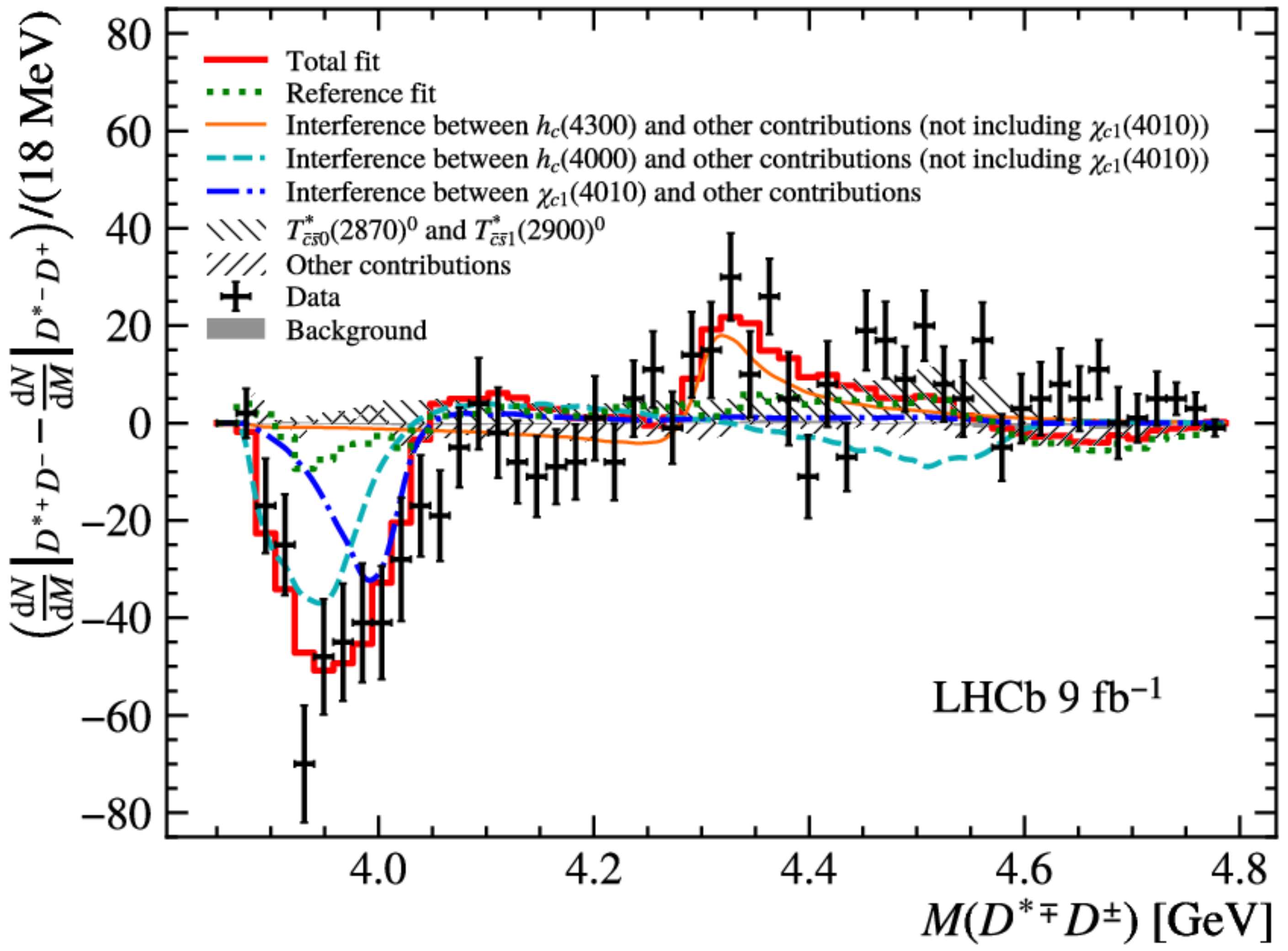


https://www.nikhef.nl/~pkoppenb/particles.html

Charmonium(-like) States in $B^+ \to D^{*\pm}D^{\mp}K^+$ Decays

[arXiv:2406.03156; LHCb-PAPER-2023-047]

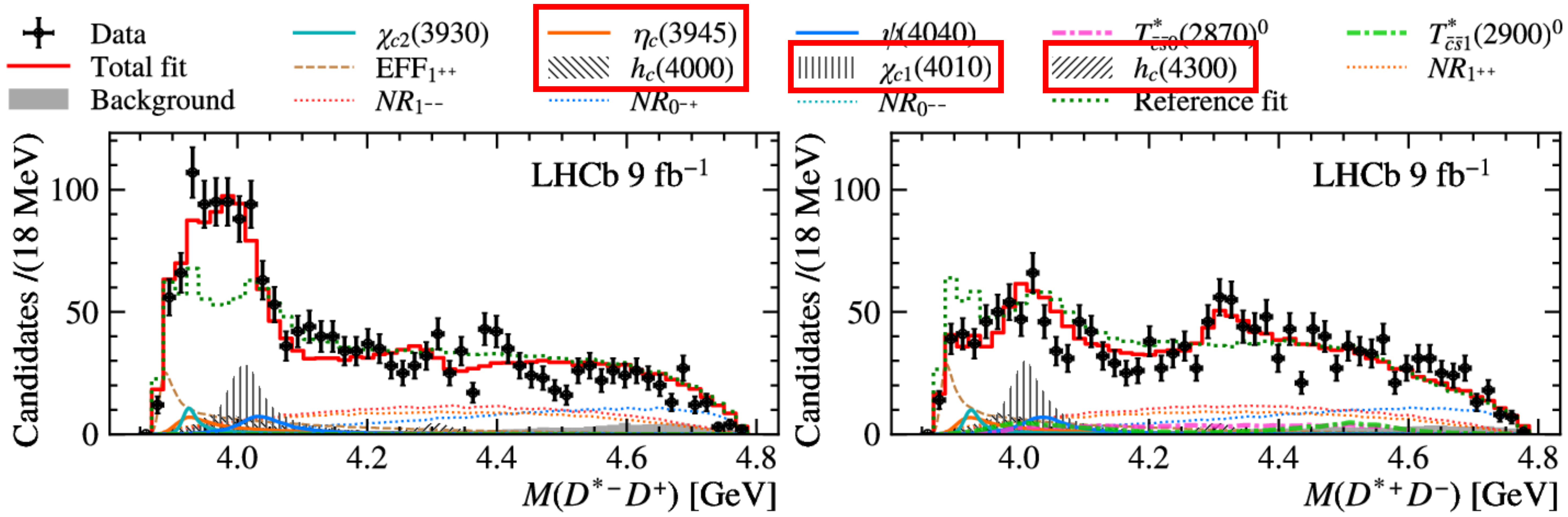




- Four **charmonium(-like)** states are observed decaying into $D^{*\pm}D^{\mp}$
- Any **charmonium(-like)** resonance must have equal contribution to $B^+ \to R\left(D^{*\pm}D^{\mp}\right)K^+$
- Interference effects between resonances can result in differences in the final states
- Simultaneous analysis of $B^+ \to D^{*+}D^-K^+$ and $B^+ \to D^{*-}D^+K^+$ allows fit sensitive to C-Parity of resonance R

Charmonium(-like) States in $B^+ \to D^{*\pm} D^{\mp} K^+$ Decays

This work	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$
$h_c(4000)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$
$h_c(4300)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$



- Units of MeV for masses and widths are implied

[arXiv:2406.03156; LHCb-PAPER-2023-047](arXiv:2406.03156)

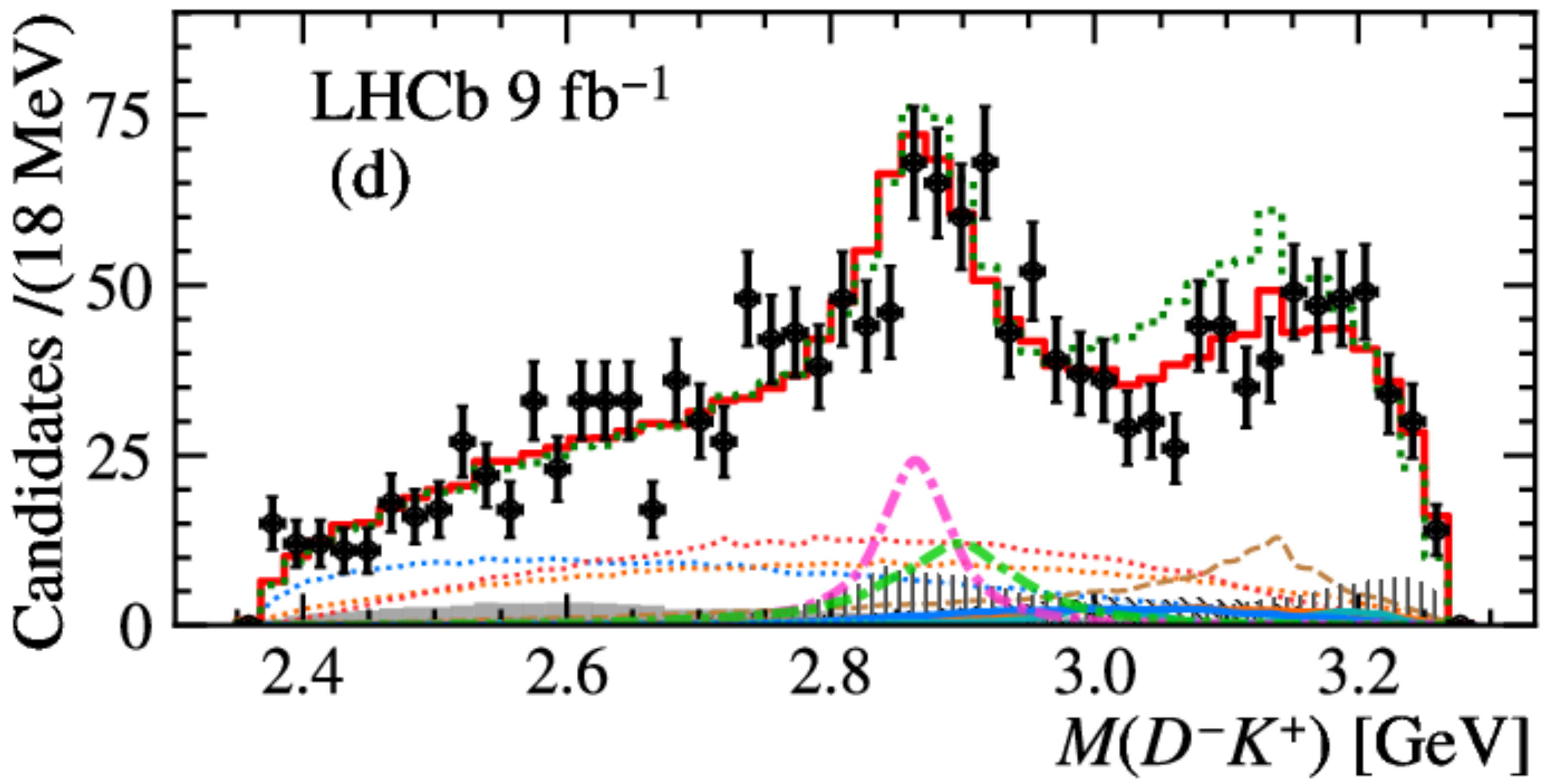
- Statistical significances of 10σ, 9.1σ, 16σ and 6.4σ, respectively
- Other J^{PC} quantum numbers are rejected with 5.7σ
- The $\eta_c(3945)$ agrees reasonably with the previously observed $X(3940)$ state, the other states have not been observed
- Isospin **not measured** and while there are predicted conventional states nearby, exotic contribution are possible

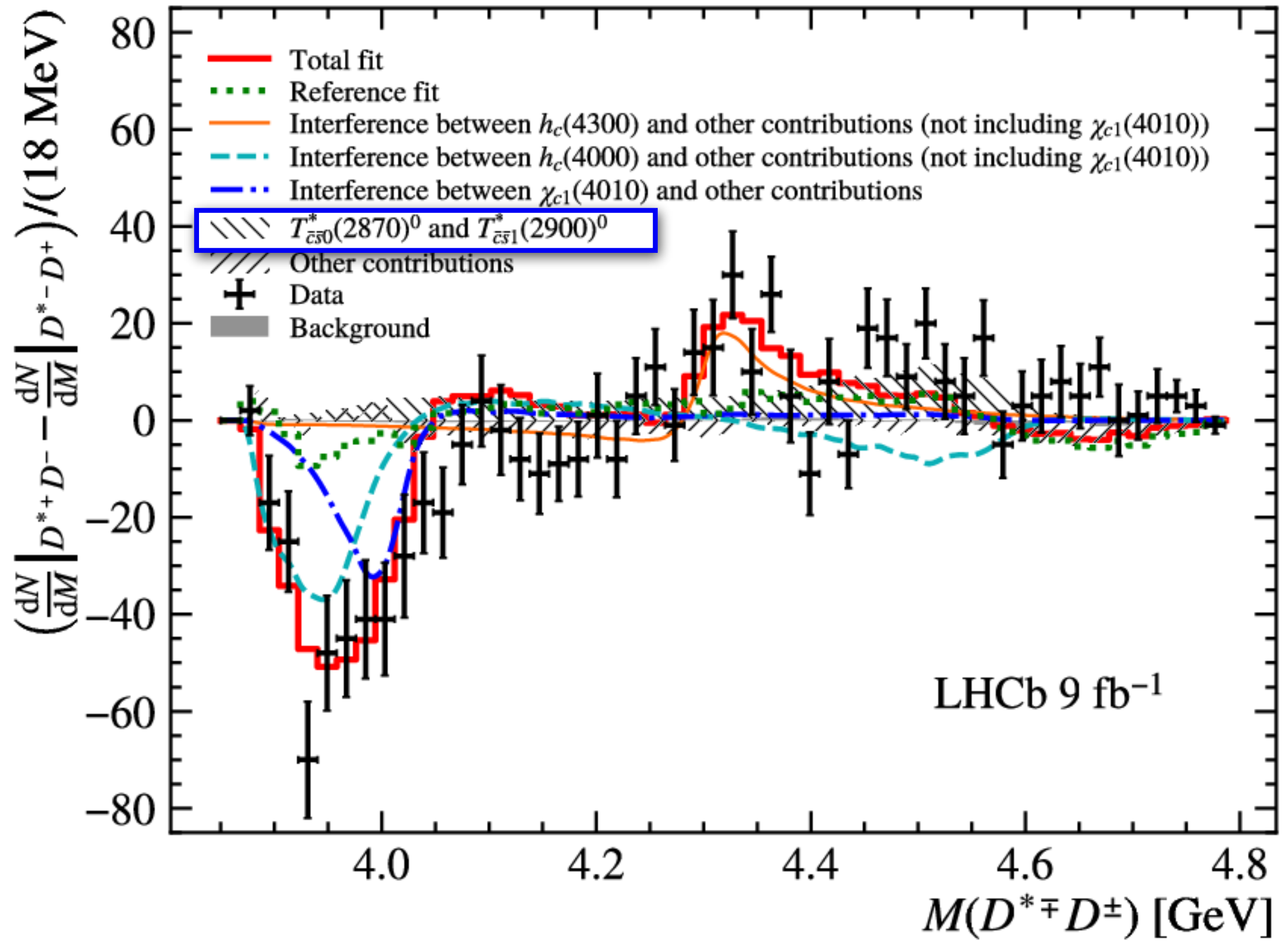
Confirming $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}1}(2900)^0$

arXiv:2406.03156; LHCb-PAPER-2023-047

- As seen before, states originally observed in $B^+ \to D^+D^-K^+$
- Now confirmed in a different production channel $B^+ \to D^{*+}D^-K^+$
- Statistical significance of 11σ and 9.2σ, respectively
- Discrepancies might be of value for future analyses

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05





And many others…

2021 2022 2023 2024

← Run2 Run3 →

CERN-EP-2021-025
LHCb-PAPER-2020-044
September 16, 2021

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

arXiv:2103.01803 ; LHCb-PAPER-2020-044

CERN-EP-2022-198
LHCb-PAPER-2022-031
June 12, 2024

Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^-\to J/\psi\Lambda\bar{p}$ decays

arXiv:2210.10346; LHCb-PAPER-2022-031

CERN-EP-2022-258
LHCb-PAPER-2022-040
7 October 2023

Evidence of a $J/\psi K^0_S$ structure in $B^0\to J/\psi\phi K^0_S$ decays

arXiv:2301.04899 ; LHCb-PAPER-2022-040

CERN-EP-2024-157
07 June 2024

Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays

arXiv:2406.17006 ; LHCb-PAPER-2024-015

CERN-EP-2021-165
LHCb-PAPER-2021-031
September 2, 2021

Observation of an exotic narrow doubly charmed tetraquark

arXiv:2109.01038; LHCb-PAPER-2021-031

CERN-EP-2022-239
LHCb-PAPER-2022-026
July 27, 2023

First observation of a doubly charged tetraquark and its neutral partner

arXiv:2212.02716 ; LHCb-PAPER-2022-026

A Prospect for Exotic Spectroscopy: Semileptonic Decays

- Semileptonic decays comprise more than 10 % of all B decays

- So far used for $\left|V_{cb}\right|$ measurements, lepton flavor universality tests, CP asymmetry tests, rare processes etc ..

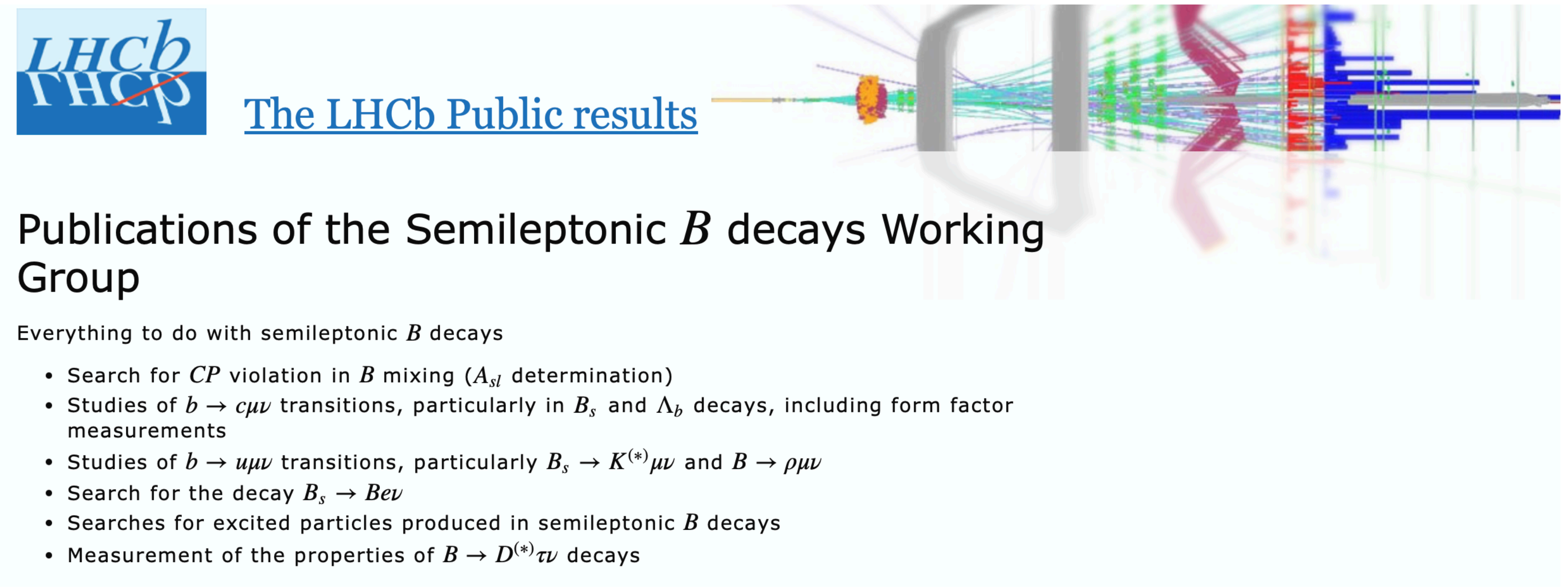
- There are no complicated **cross channel** effects compared to typical LHCb Dalitz Analyses

PHYSICAL REVIEW LETTERS **126**, 192001 (2021)

Where Is the Lightest Charmed Scalar Meson?

Meng-Lin Du,[1,*] Feng-Kun Guo,[2,3,†] Christoph Hanhart,[4,‡] Bastian Kubis,[1,§] and Ulf-G. Meißner[1,4,5,∥]
[1]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[2]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
[3]*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
[4]*Institute for Advanced Simulation, Institut für Kernphysik and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[5]*Tbilisi State University, 0186 Tbilisi, Georgia*

PRL 126 192001 (2021)

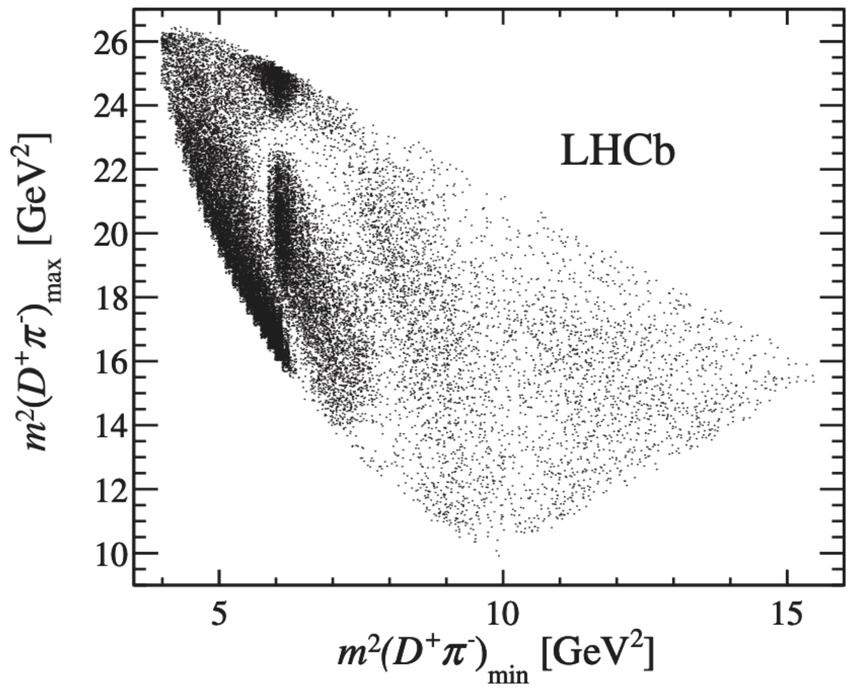

The LHCb Public results

Publications of the Semileptonic B decays Working Group

Everything to do with semileptonic B decays

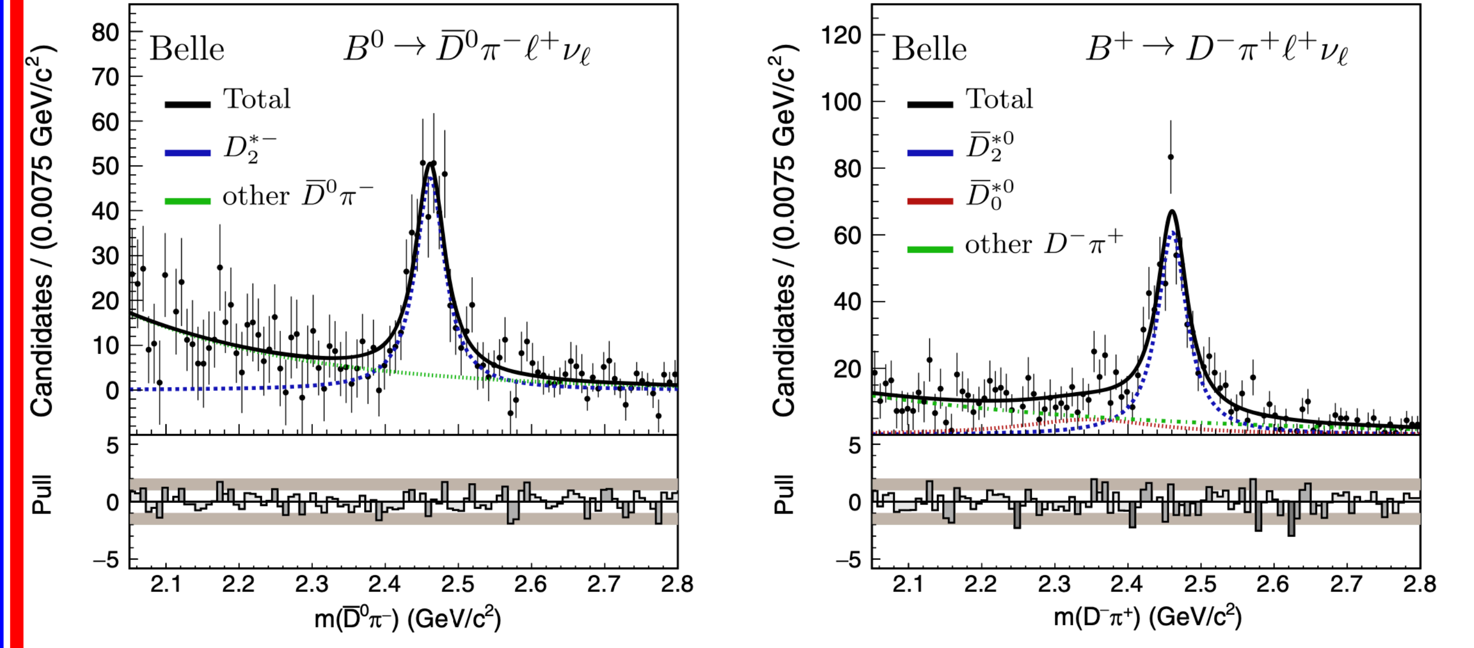
- Search for CP violation in B mixing (A_{sl} determination)
- Studies of $b \to c\mu\nu$ transitions, particularly in B_s and Λ_b decays, including form factor measurements
- Studies of $b \to u\mu\nu$ transitions, particularly $B_s \to K^{(*)}\mu\nu$ and $B \to \rho\mu\nu$
- Search for the decay $B_s \to Be\nu$
- Searches for excited particles produced in semileptonic B decays
- Measurement of the properties of $B \to D^{(*)}\tau\nu$ decays

$B \to D\pi\pi$



LHCB-PAPER-2016-026

Belle II $B \to D\pi\ell^+\nu_\ell$



PRD 107, 092003 (2023)

Exploit: Searches for exotic states in semileptonic B decays

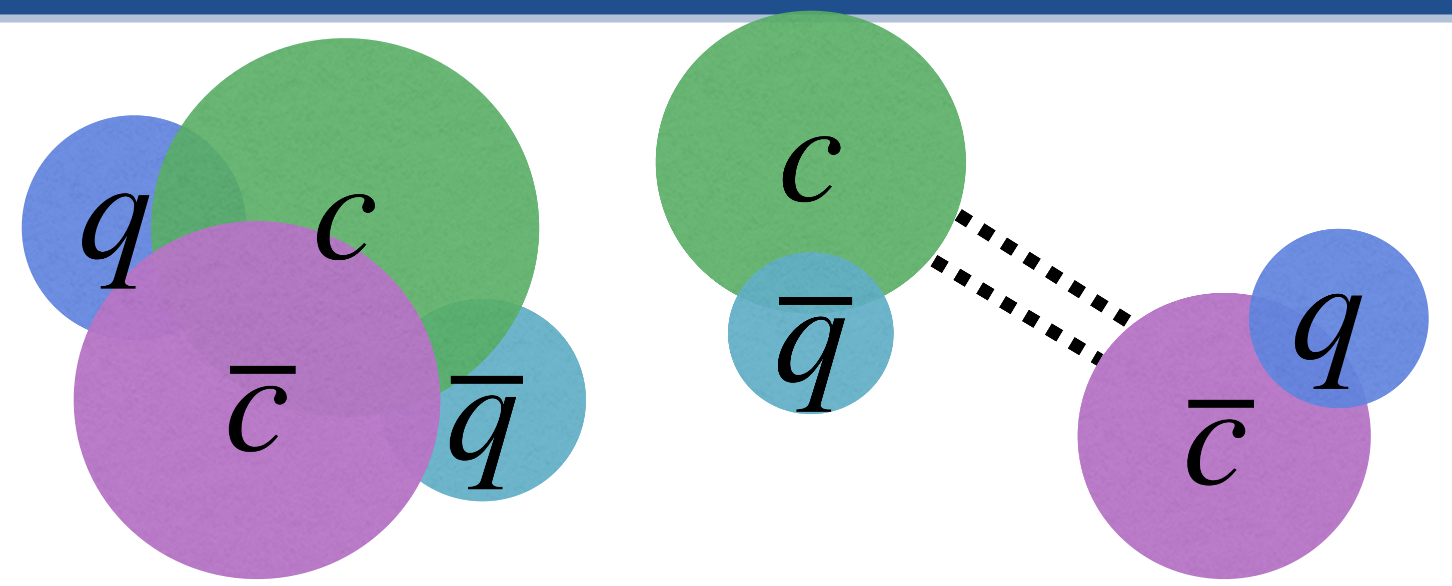
Summary & Further Prospects

- Many new tetraquark candidates have been observed in LHC Run 2
- Exploit semileptonic decays in tetraquark searches
- LHC Run1&2 → Run3&4: 10x statistics

  → Search for more tetraquarks and isospin partners

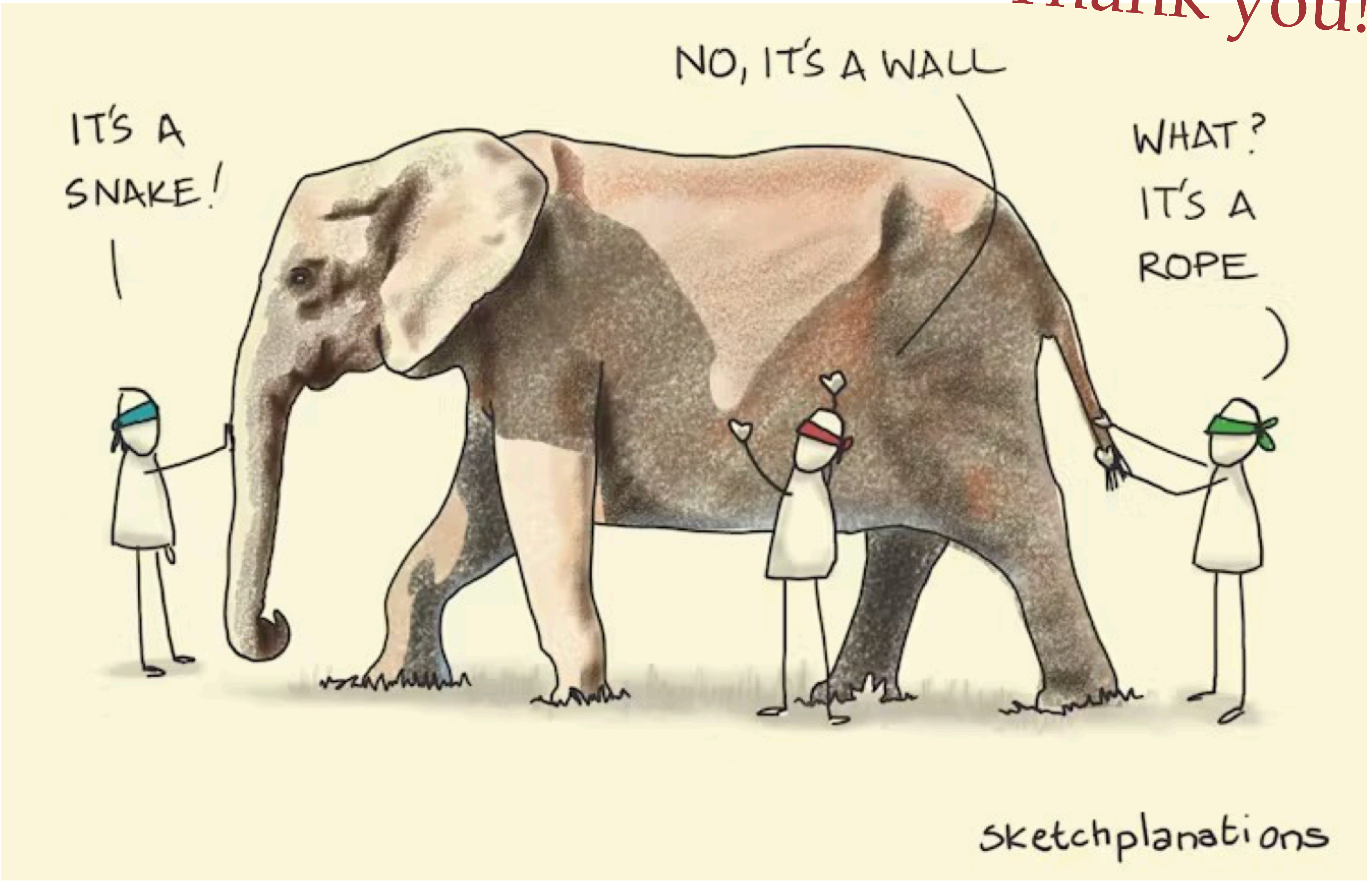
  → Study spin-parity quantum numbers and various other properties of tetraquarks
- Nature of multiquark states still highly debated

  → compact states, hadronic molecules?
- Collaboration with theory colleagues important



and others ...

Thank you!



Backup

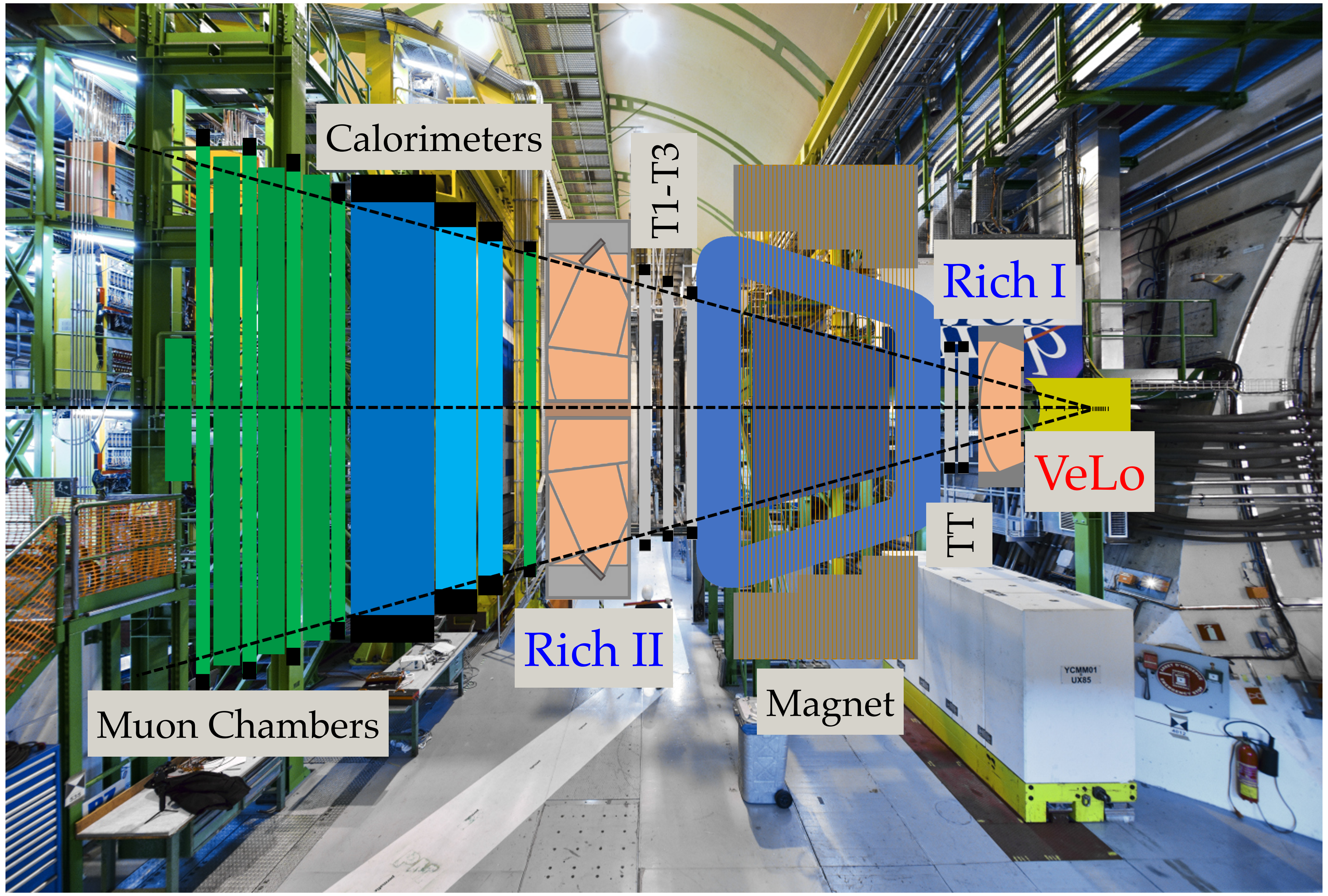
Backup - LHCb Detector

- **Heavy hadrons** are predominantly produced in beam direction

→ LHCb is built as a forward spectrometer

- Multiple subdetectors for precise reconstruction of decay products

  1. VeLo for vertex tracking near the *pp* interaction point
  2. RICH Cherenkov detectors for particle identification
  3. Multiple tracking systems
  4. Calorimeters for energy depositions



An excellent setup for spectroscopy of heavy hadrons