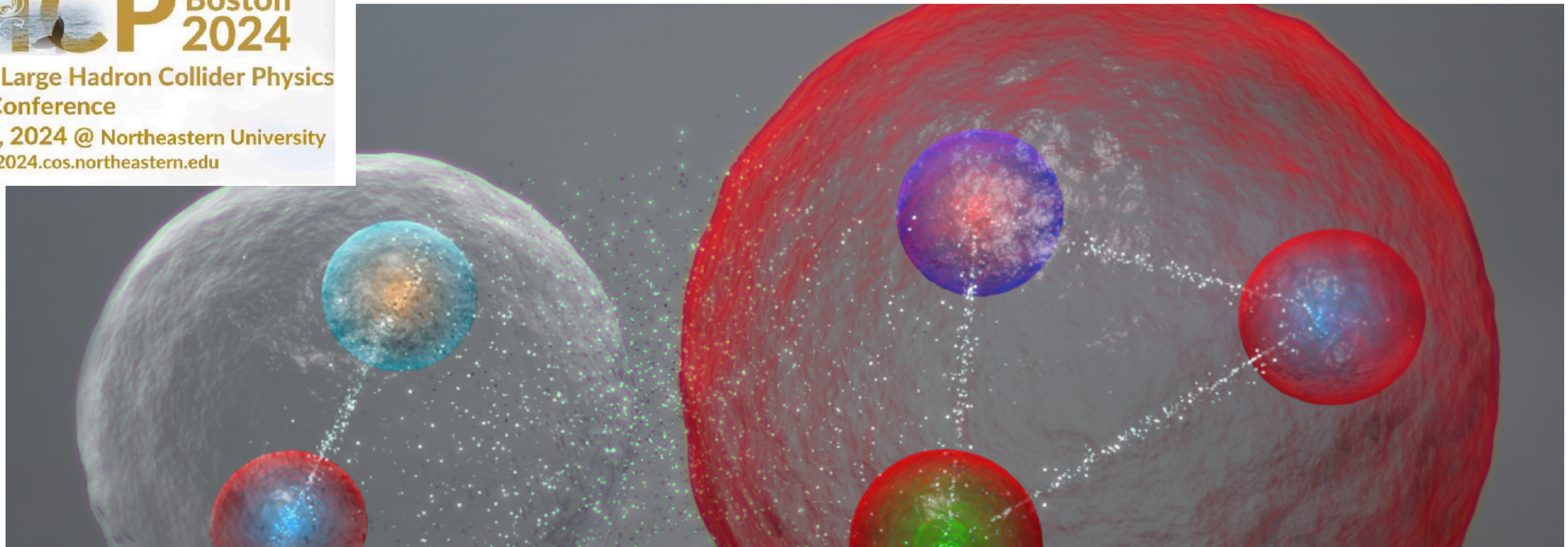
LHCP Boston 2024
The 12th Large Hadron Collider Physics Annual Conference
June 3-7, 2024 @ Northeastern University
http://lhcp2024.cos.northeastern.edu

Image courtesy of CERN



Hadron spectroscopy and hadron-hadron interactions

Paolo Gandini
INFN - Sezione di Milano

On behalf of the LHCb collaboration + results from CMS, ATLAS and ALICE

INFN MILANO
Istituto Nazionale di Fisica Nucleare
Sezione di Milano

LHCb

Outline

- This talk was originally assigned to Liupan An (LHCb), but unfortunately she was not able to attend
- This is the outline of the talk → as usual the shopping list is too long → I will cover only a small subset
- Hope to make justice to the good work by all the experiments in this rich field!

LHCb

- **Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays** NEW
  PRELIMINARY: PAPER-2023-047 about to be submitted to arXiv
- **Observation of exotic $J/\psi\phi$ resonances in CEP collisions** NEW
  PRELIMINARY: PAPER-2023-043 in preparation
- **Search for P_c in open charm modes**
  arXiv: 2404.07131 submitted to PRD

CMS

- **$\Xi_b \to \Psi(2S)\Xi$ & $\Xi_b^* \to \Xi_b \pi$** *Accepted for publication in Phys. Rev. D*
  https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH-23-002/index.html
- **f0(980) hadron in proton-lead collisions and evidence for its quark-antiquark composition**
  https://cms-results.web.cern.ch/cms-results/public-results/publications/HIN-20-002/index.html
  Submitted to Nature Physics

ALICE

- **Observation of abnormal suppression of $f_0(980)$ production in p-Pb collisions at $\sqrt{s}$ = 5.02 TeV**
  https://alice-publications.web.cern.ch/node/10258 *Phys. Lett. B 853 (2024) 138665*
- **Exploring the strong interaction of three-body systems at the LHC**
  https://alice-publications.web.cern.ch/node/9595 *arXiv:2308.16120*

Parallel sessions

More results and detailed presentations can be found in today's parallel session
Dedicated talks for each experiment + interesting theoretical insights

lun 03/06 | mar 04/06 | mer 05/06 | Tutti i giorni

Stampa | PDF | Schermo intero | Vista dettagliata | Applica

14:00	**Heavy flavor spectroscopy studies at LHCb**	*ISEC Room 142*	*Paolo Gandini*	14:00 - 14:18
	Heavy flavor spectroscopy studies at CMS	*ISEC Room 142*	*Kai Yi*	14:18 - 14:36
	Heavy flavor spectroscopy studies at Atlas	*ISEC Room 142*	*Vincenzo Canale*	14:36 - 14:54
15:00	**Theory perspectives on doubly-heavy flavor tetraquarks**	*ISEC Room 142*	*Randy Lewis*	14:54 - 15:12
	The Pentaquark Spectrum from Fermi Statistics	*ISEC Room 142*	*Antonio Polosa*	15:12 - 15:30

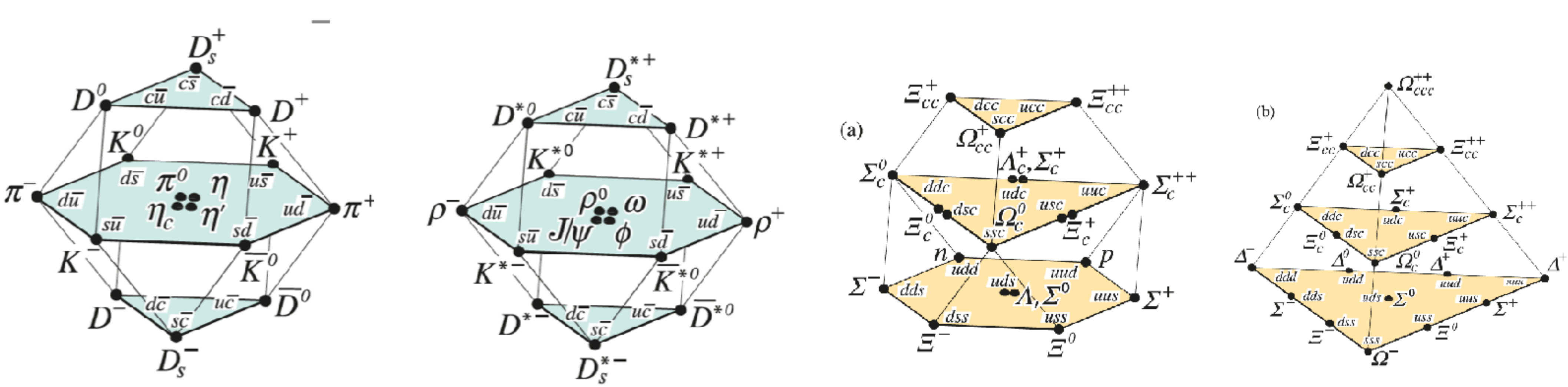
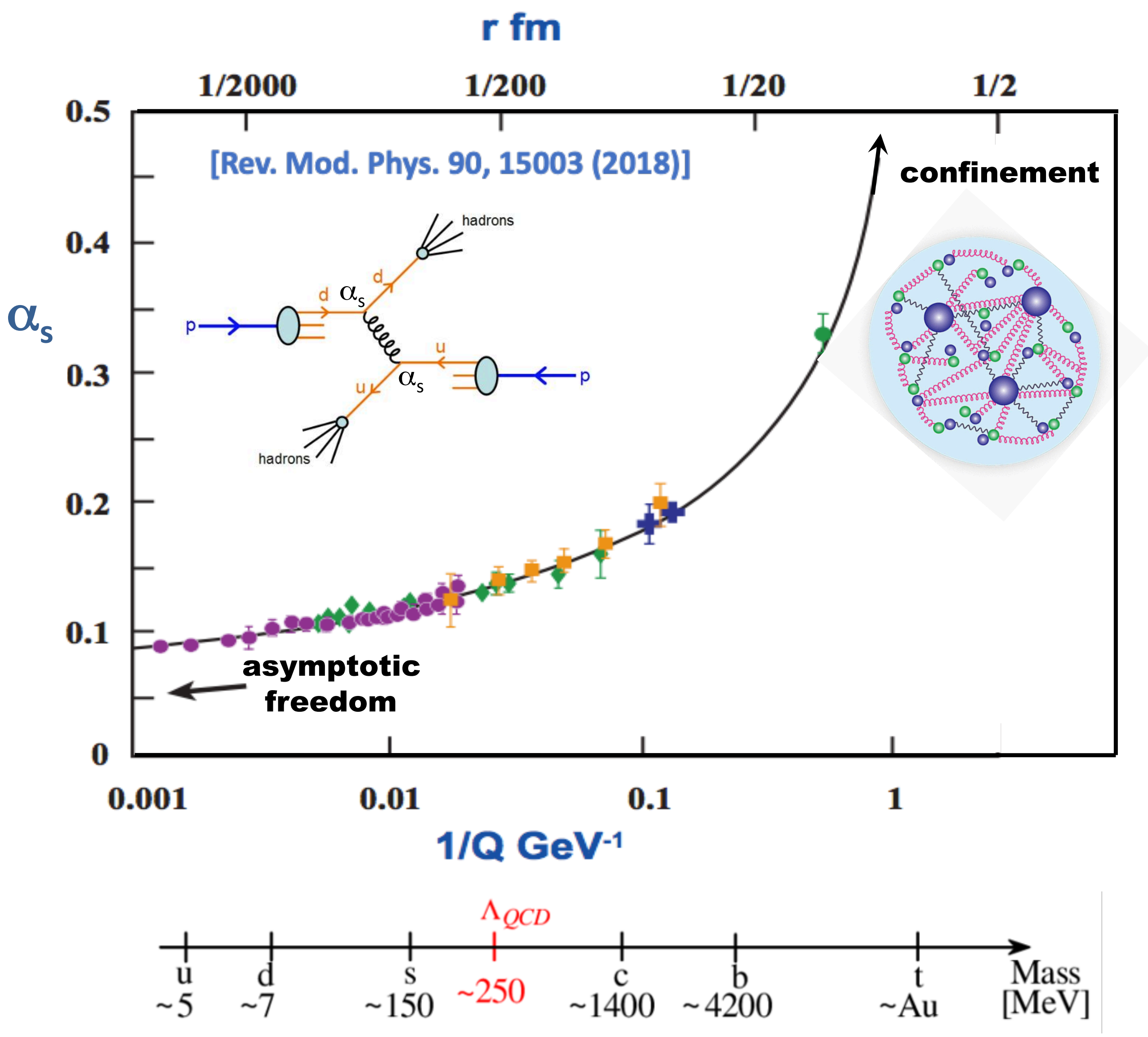
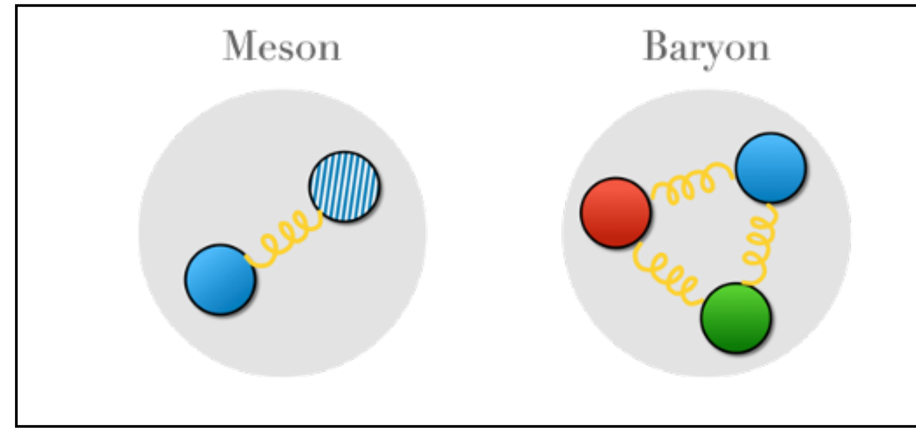


Image taken from PDG
[Review of Particle Physics]

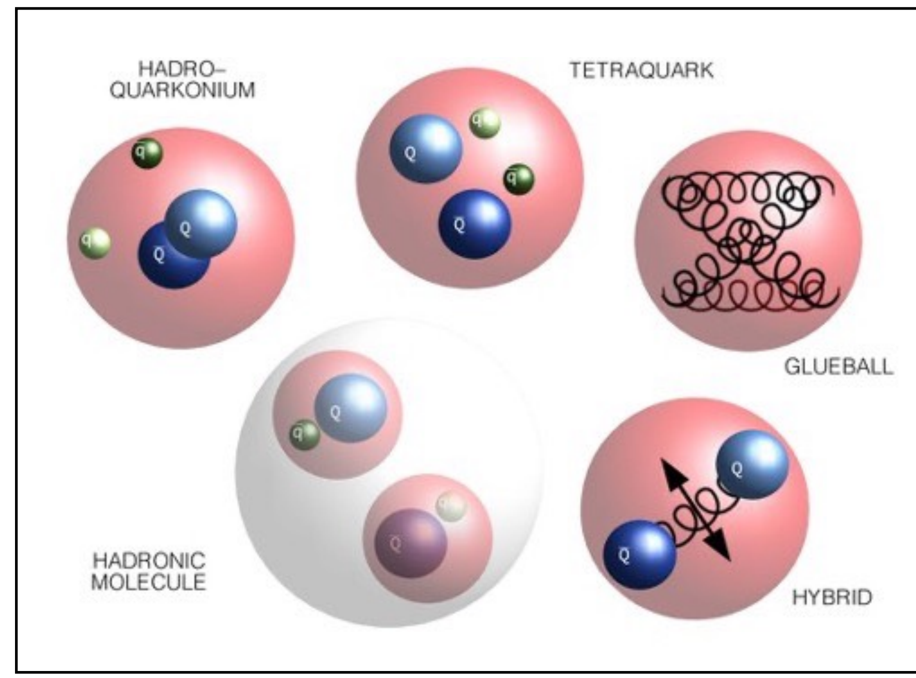
Introduction: QCD



Conventional hadrons



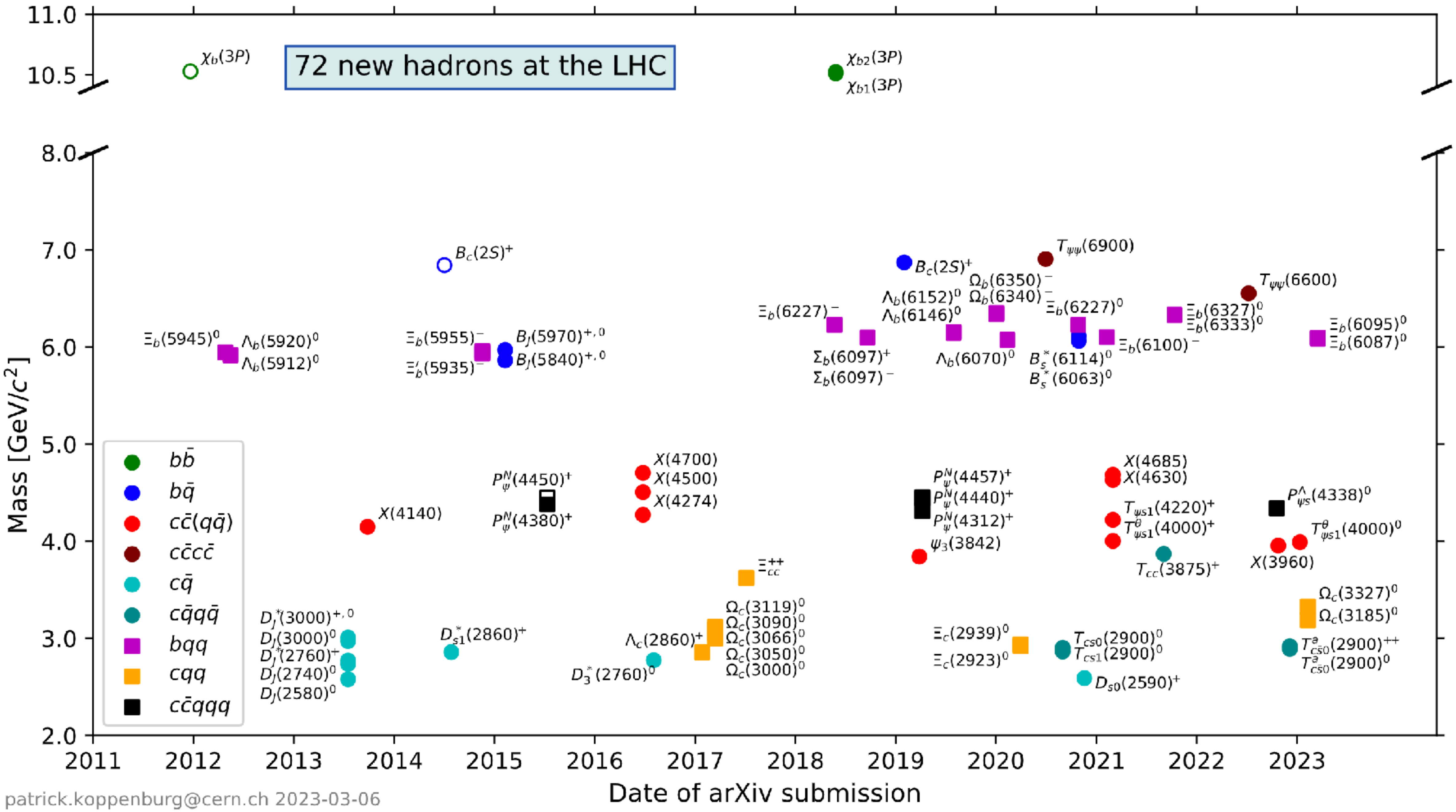
Exotic hadrons



- **QCD dilemma:** understanding the non-perturbative property of QCD at low-energy scale
- **Hadron spectroscopy:** a main tool to probe QCD at low-energy regime
- **Heavy quarks bring advances both experimentally and theoretically**

New hadrons at LHC

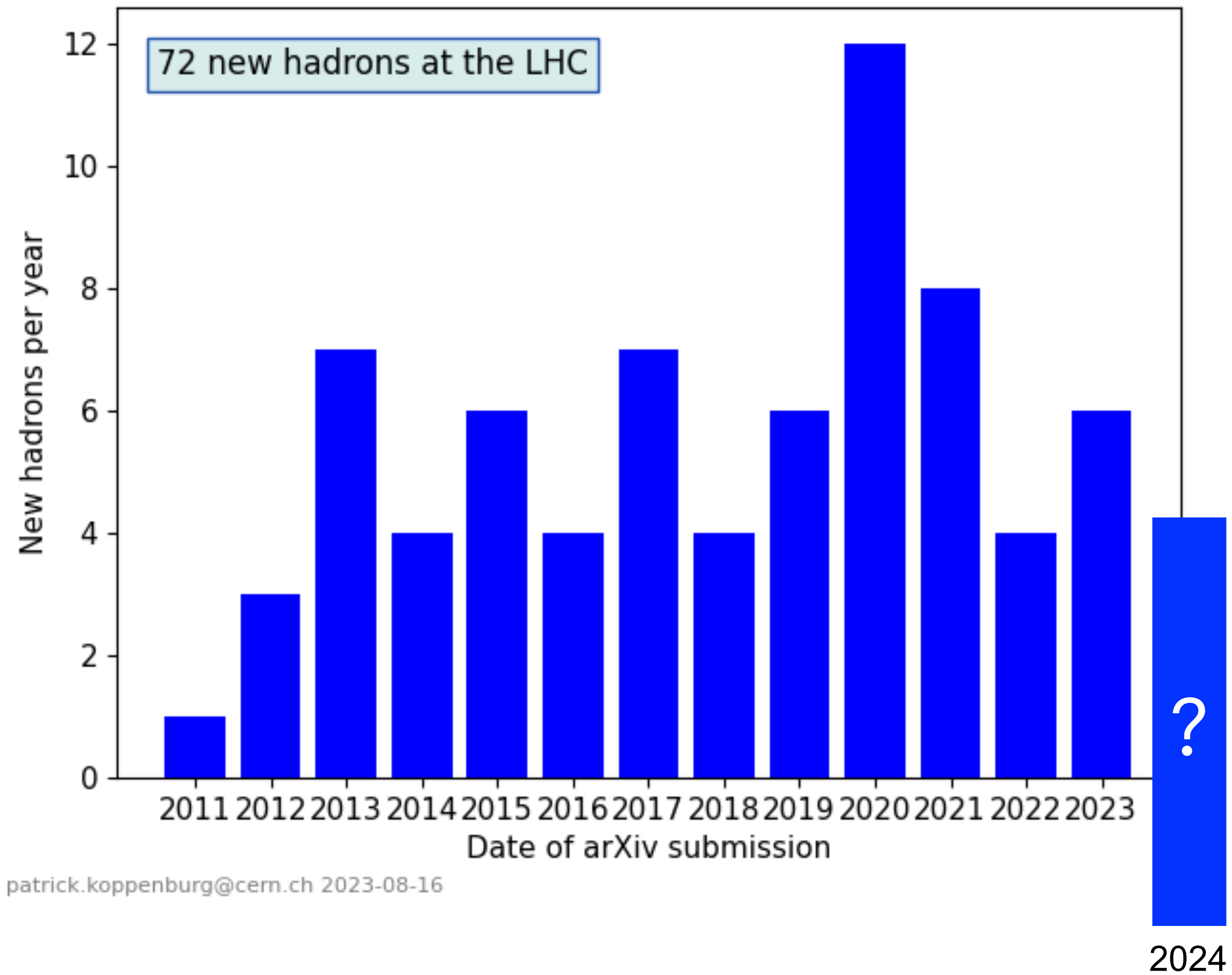
- Spectroscopy is a super-active field at LHC and all the experiments are contributing!
- So far 72 hadrons have been discovered at the LHC, of which 64 by LHCb
- The list is growing… All sectors represented

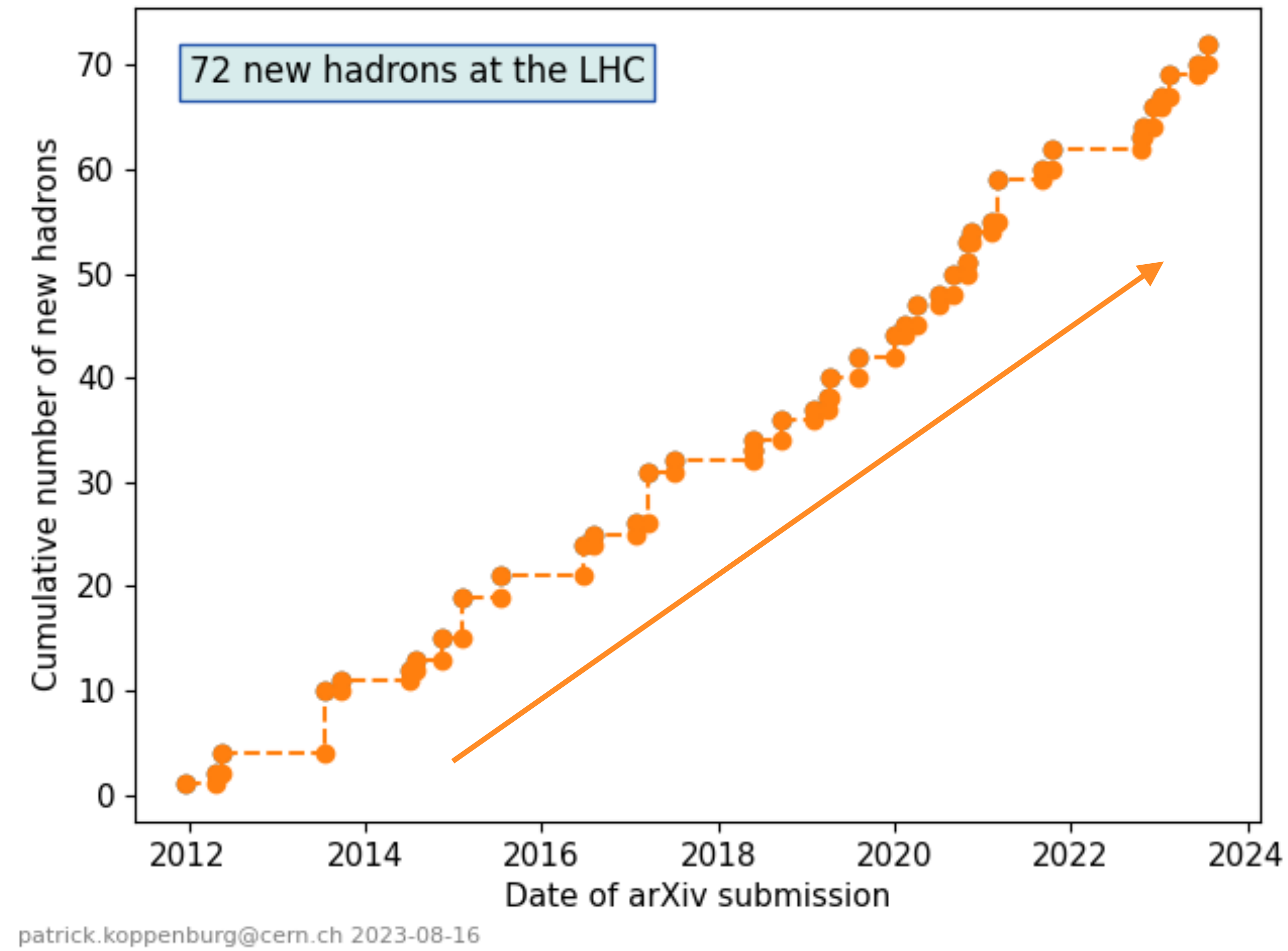


LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

New hadrons at LHC

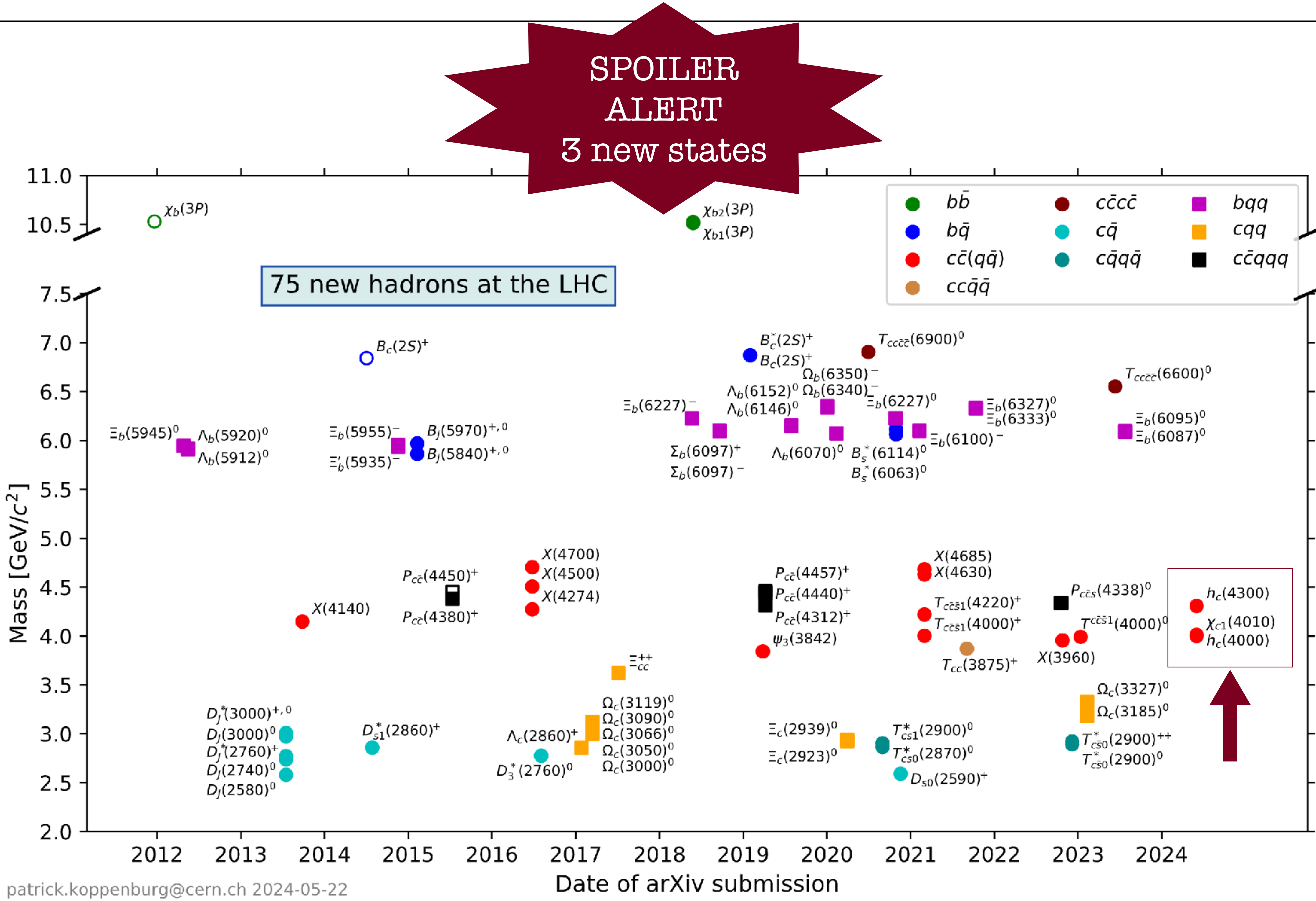
- In 2024, no new hadrons yet!
- But summer conferences have just started…
- And Run3 data taking is in full steam…





LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

New hadrons at LHC



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

Selected results by

LHCb

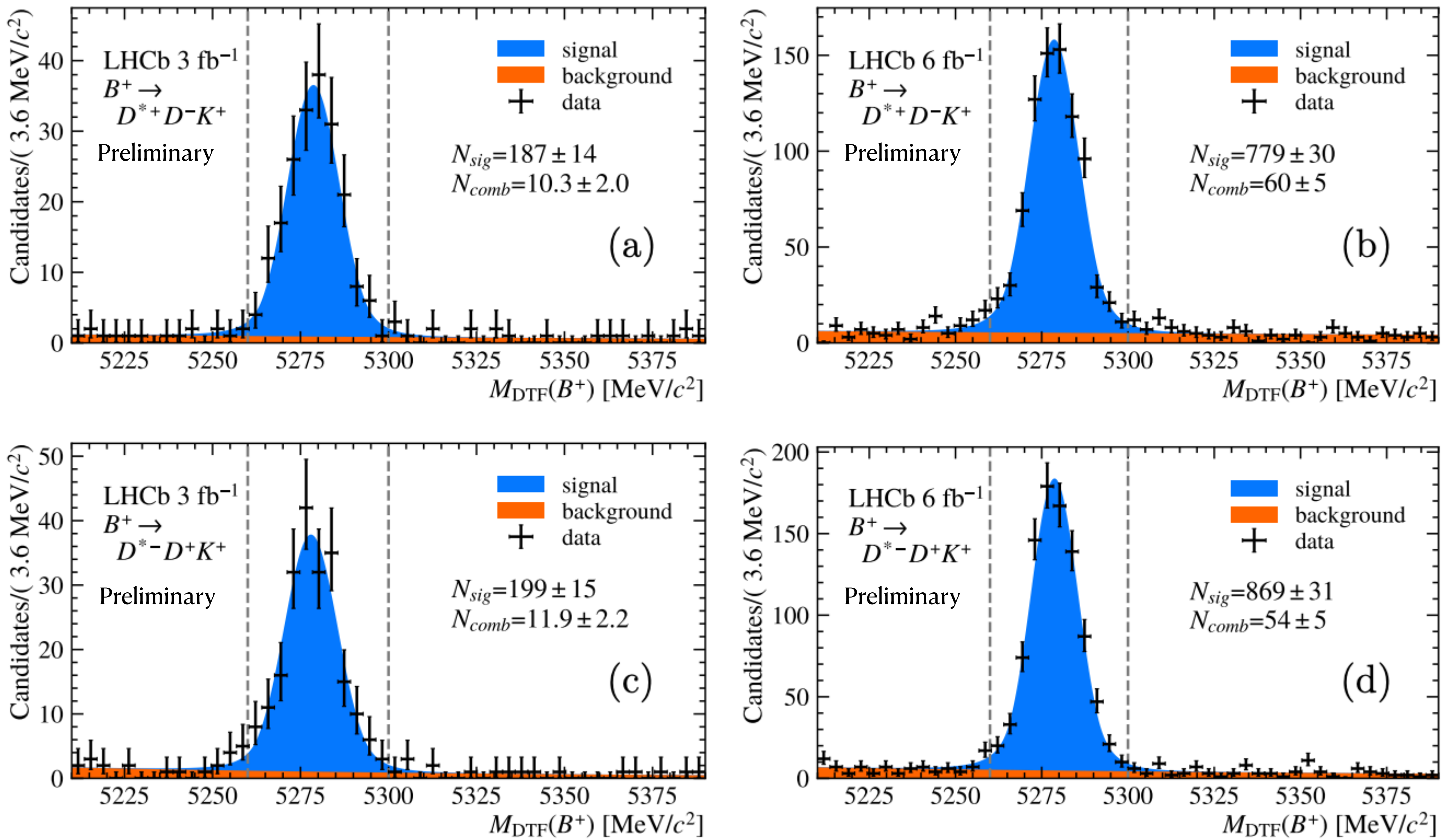
Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$

NEW

Preliminary
PAPER-2023-047to be submitted to arXiv

$$B^+ \to D^{*+} D^- K^+ \qquad B^+ \to D^{*-} D^+ K^+$$

- A simultaneous amplitude fit performed to two channels
- Include contributions from resonances decaying to $D^{*-}D^+$ and $D^{*+}D^-$ (states linked by C parity)
- Determine the C parity of any new states



Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$

NEW

Preliminary
PAPER-2023-047to be submitted to arXiv

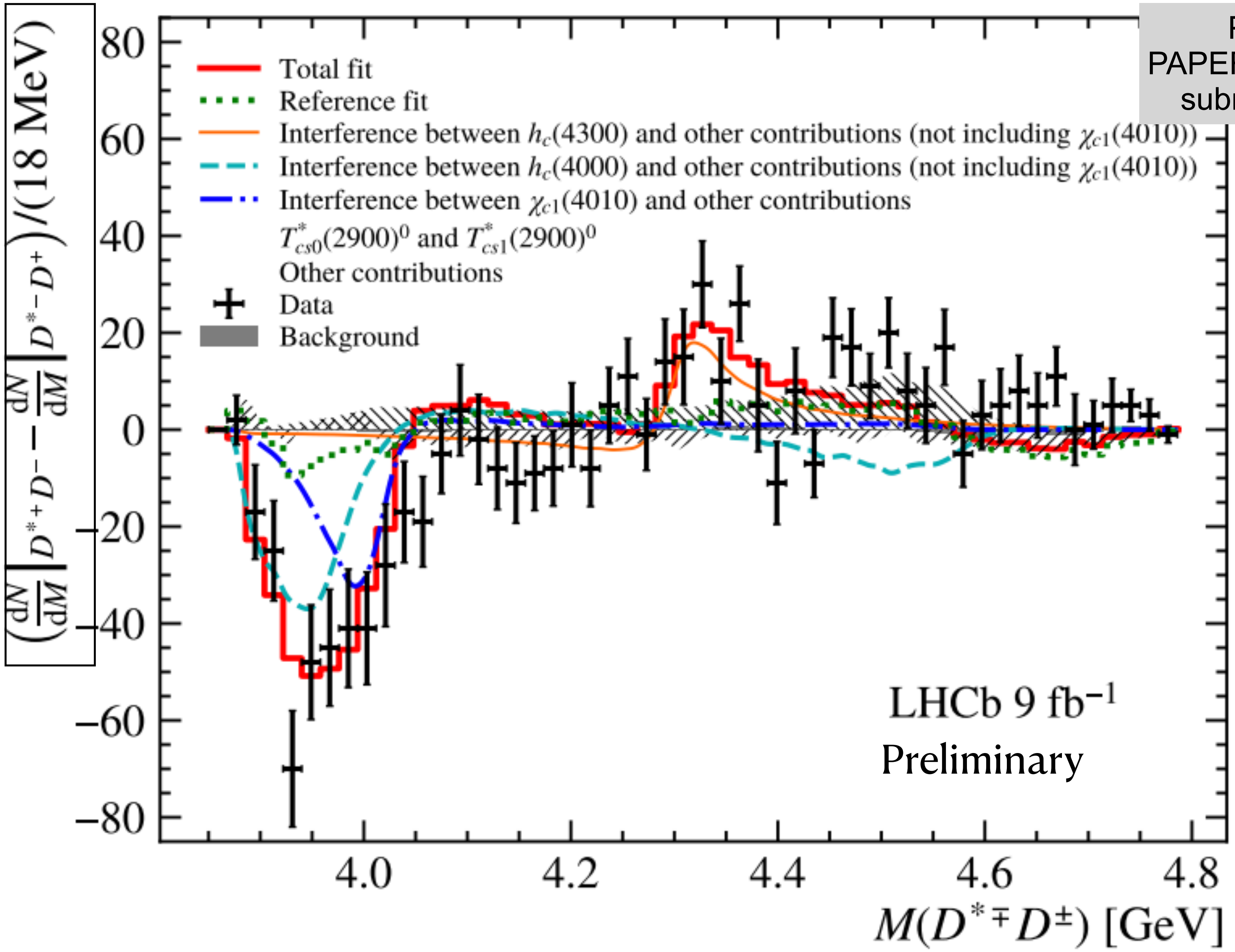
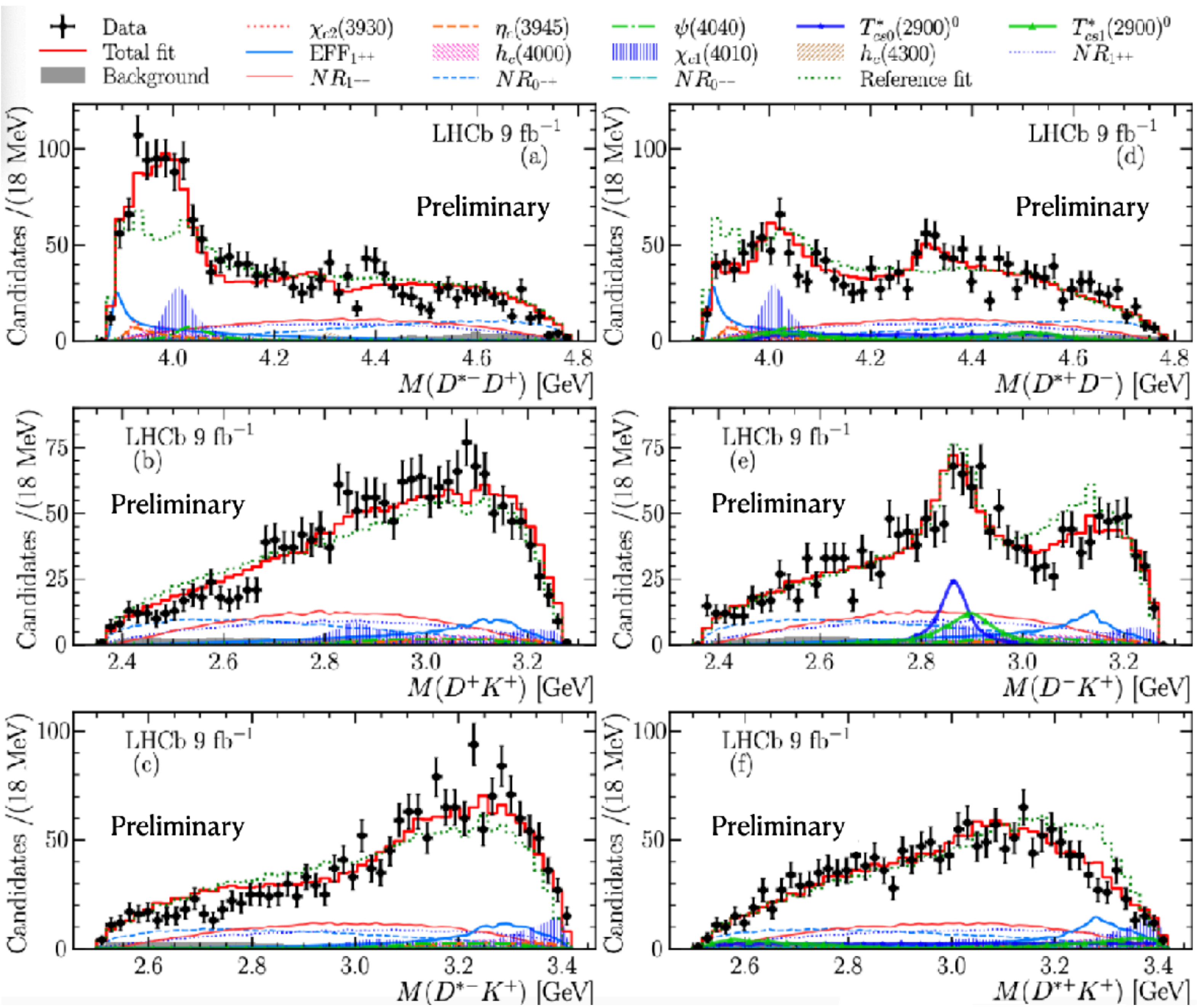


Figure 3: Difference between the $M(D^*D)$ distributions of the two channels ($B^+ \to D^{*+}D^-K^+$ and $B^+ \to D^{*-}D^+K^+$). Only interference between states with the same J^P but different C-parities, and reflections from $T^*_{\bar{c}\bar{s}0,1}(2900)^0$ resonances, have significant contributions. The reference fit where $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$ are not included is shown as green dashed line.

Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$

NEW

Preliminary
PAPER-2023-047to be submitted to arXiv



$\eta_c(3945)$, $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$
J^{PC} equal to 0^{-+}, 1^{+-}, 1^{++} and 1^{+-}

Property	This work	Previous work
$T^*_{\bar{c}s0}(2900)^0$ mass (MeV)	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}s0}(2900)^0$ width (MeV)	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}s1}(2900)^0$ mass (MeV)	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}s1}(2900)^0$ width (MeV)	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}s0}(2900)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}s1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}s0}(2900)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}s1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

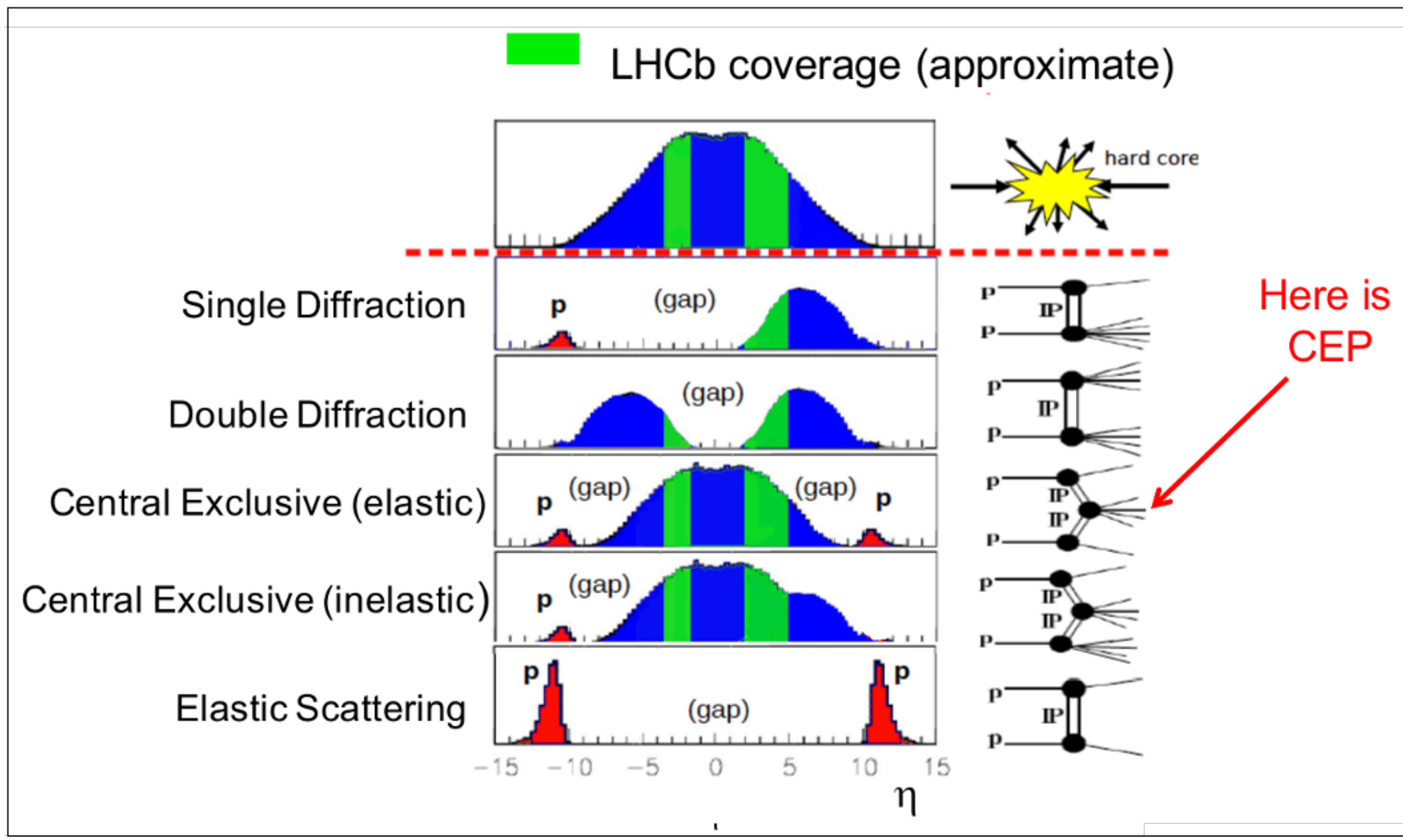
- Four charmonium(-like) states are observed: at least 3 are new
- Existence of 2 tetraquark resonances in D^-K^+ confirmed (different channel, already observed $B^+ \to D^+D^-K^+$)

Observation of exotic J/ψΦ resonances in CEP

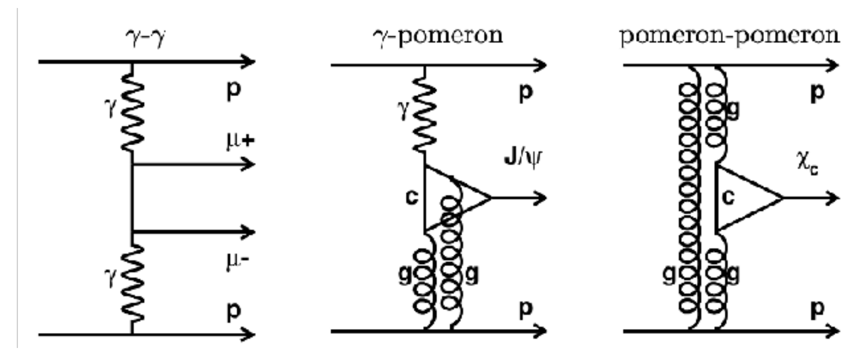
NEW

Preliminary
PAPER-2023-043
in preparation

- Central Exclusive Production can be done at LHCb → What do we look for?
- pp → p + X + p (rapidity gaps and protons intact)
- Colourless objects in QCD, Very low PT objects, Clean experimental environment
- Rich Physics: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica



After D. d'Enterria arxiv 0806.0883



✓Experimentally clean even @LHC

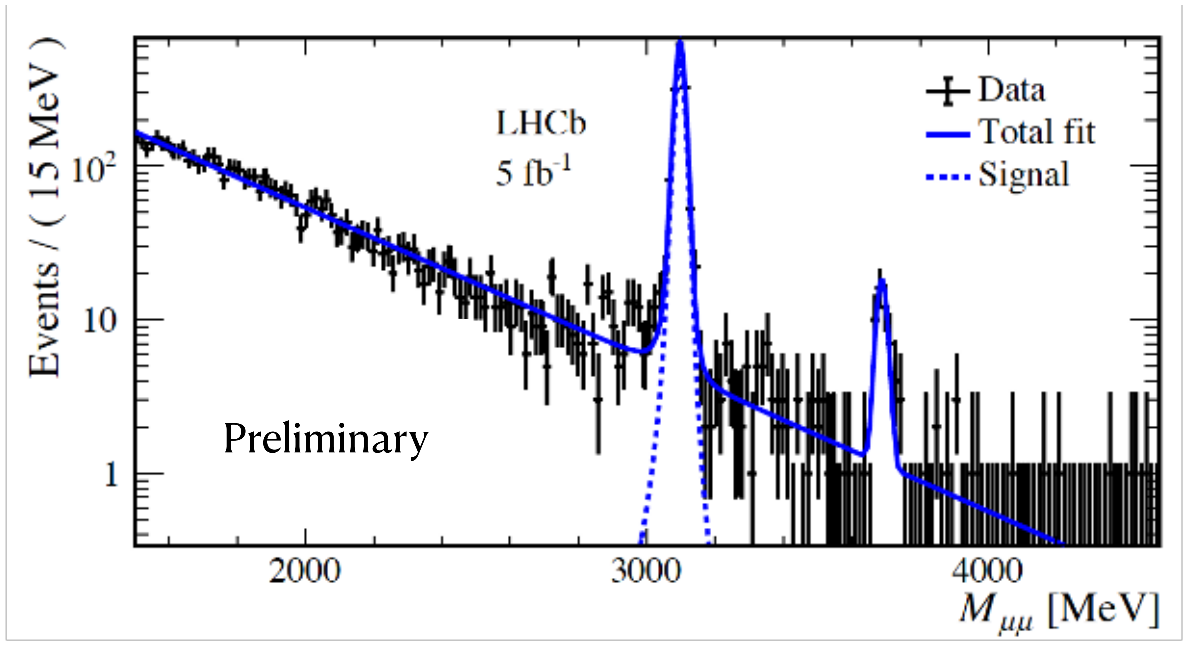
✓Spin-parity option narrowed down

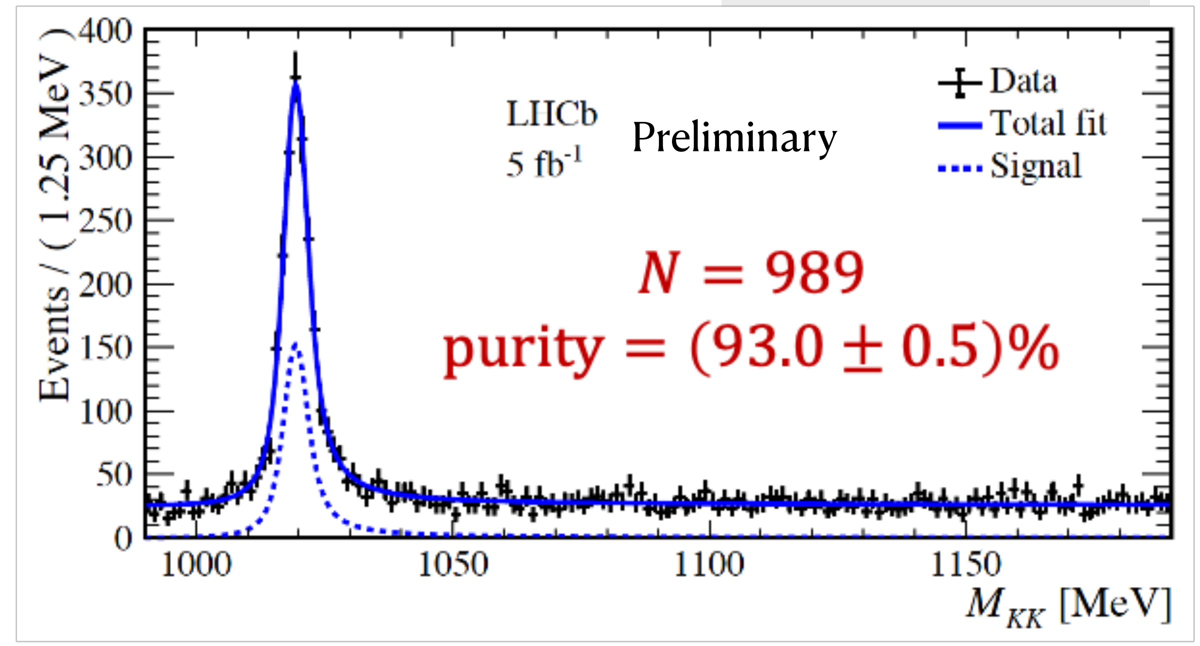
✘Much smaller rate

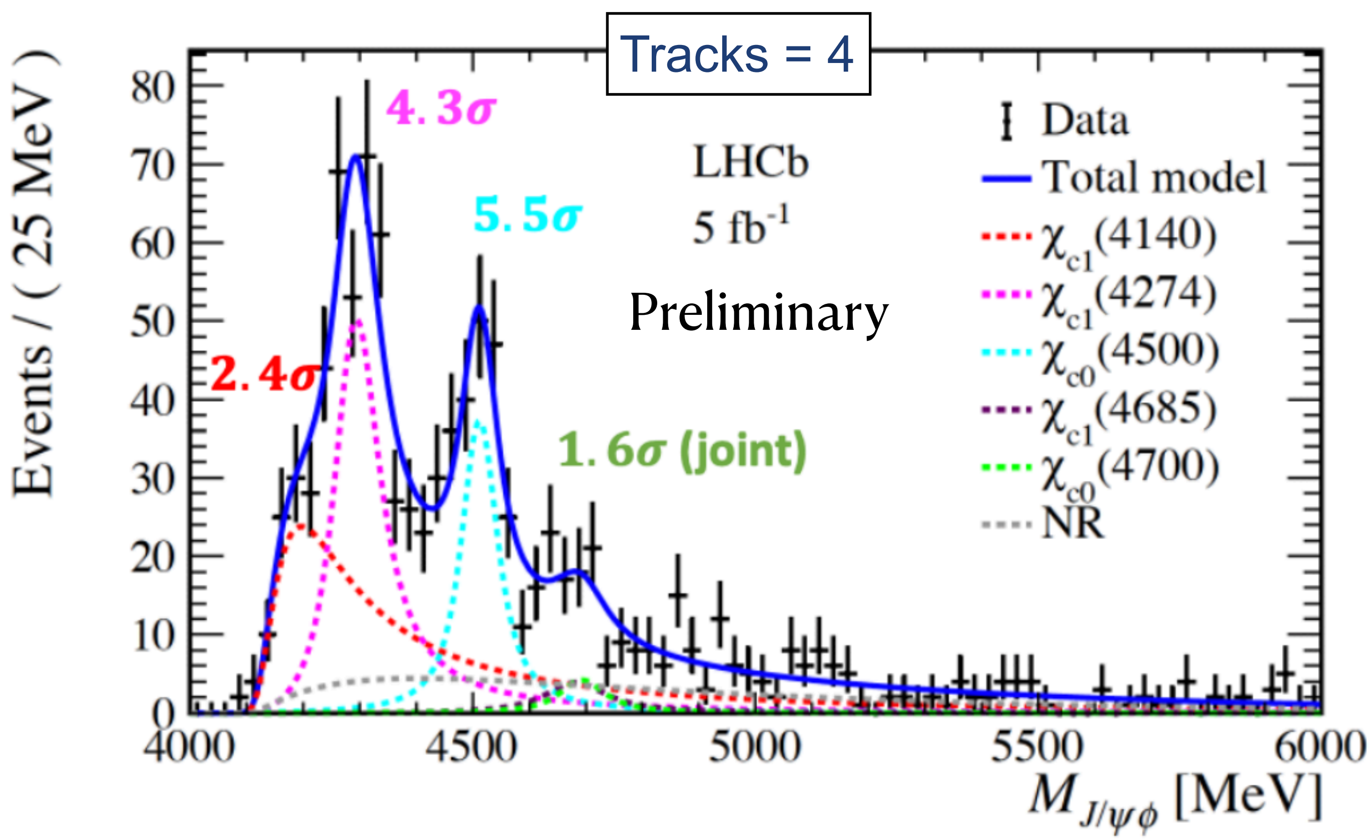
Observation of exotic $J/\psi\Phi$ resonances in CEP

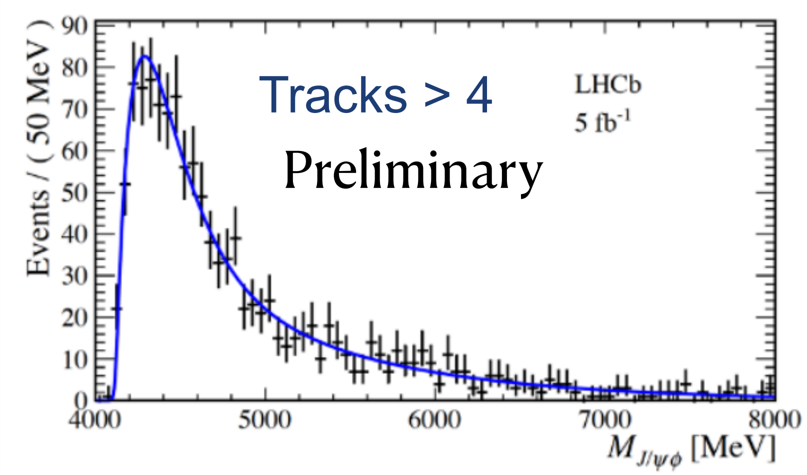
NEW

Preliminary
PAPER-2023-043
in preparation





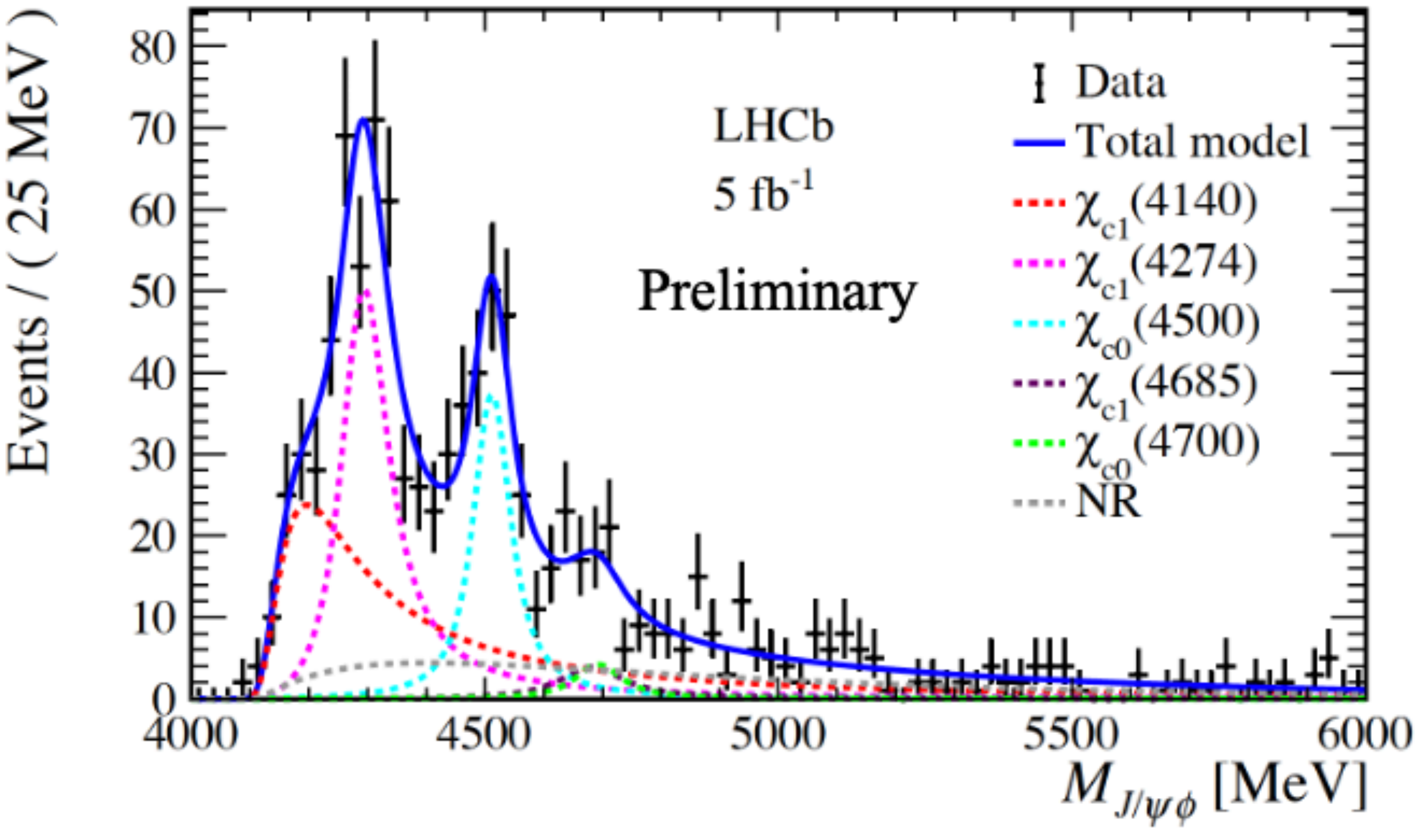




Observation of exotic J/ψΦ resonances in CEP

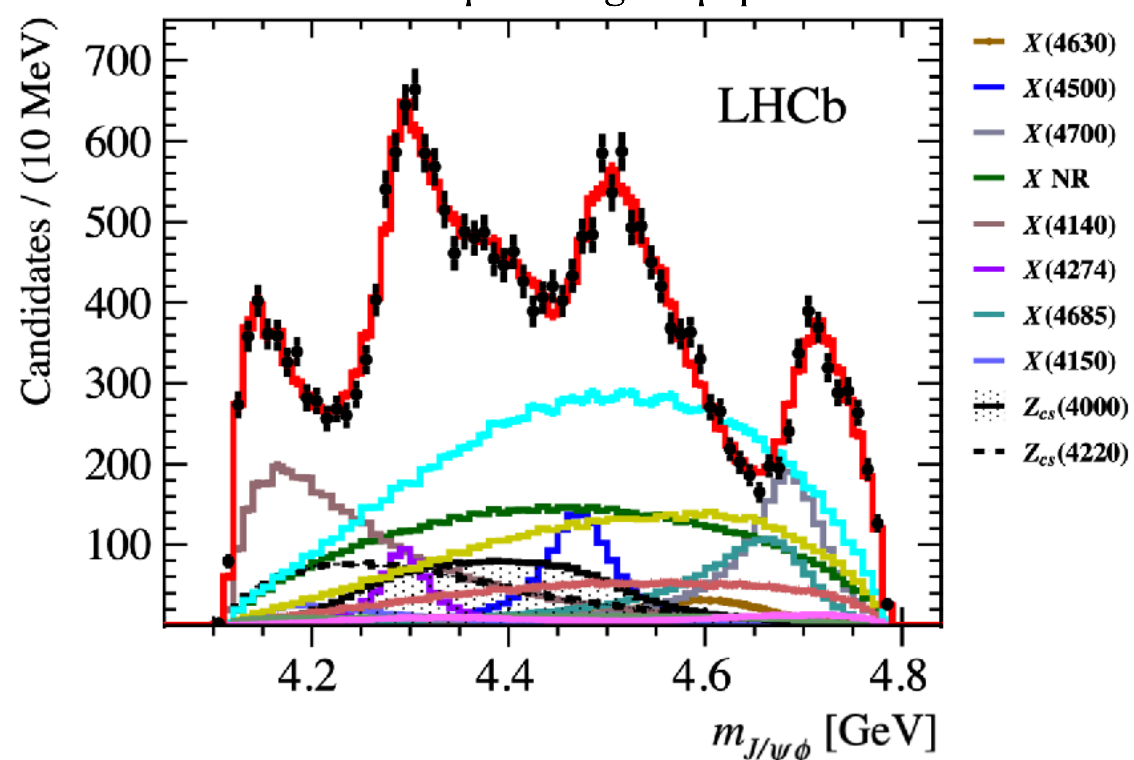
NEW

Preliminary
PAPER-2023-043
in preparation



[PRL 127 (2021) 082001]

Zoomed version of the spectrum from tetraquark original paper



Mass & width measurement
slightly higher mass of X(4500)

Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

Cross-section measurement

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\ \text{pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\ \text{pb},$$

$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\ \text{pb},$$

$$\sigma_{NR} \times \mathcal{B}_{\text{eff}}^{NR} = (0.46^{+0.25}_{-0.19}{}^{+0.21}_{-0.22})\ \text{pb},$$

First exotic measurement in CEP

Search for Pc in open charm modes

arXiv: 2404.07131
submitted to PRD

- Inclusive search performed using 5.7 fb^{-1} data from 2016-2018
- Reconstruction of several different modes & combinations:
  - $\Lambda_c^+ \to pK^-\pi^+, D^- \to K^+\pi^-\pi^-, D^0 \to K\pi$
  - $\Sigma_c^{++(0)} \to \Lambda_c^+\pi^{+(-)}, D^{(*-)} \to D^{(-0)}\pi^-$

hidden-charm pentaquarks

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	$\overline{D}^0$	+1	$1/2$	1	0	✓
Λ_c^+	D^-	0	$-1/2$	1	0	✓
Λ_c^+	D^{*-}	0	$-1/2$	1	0	✓
Σ_c^{++}	$\overline{D}^0$	+2	$3/2$	1	0	✓
Σ_c^{++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{++}	D^{*-}	+1	$1/2$	1	0	×
Σ_c^0	$\overline{D}^0$	0	$-1/2$	1	0	✓
Σ_c^0	D^-	−1	$-3/2$	1	0	✓
Σ_c^0	D^{*-}	−1	$-3/2$	1	0	×
Σ_c^{*++}	$\overline{D}^0$	+2	$3/2$	1	0	✓
Σ_c^{*++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{*++}	D^{*-}	+1	$1/2$	1	0	✓
Σ_c^{*0}	$\overline{D}^0$	0	$-1/2$	1	0	✓
Σ_c^{*0}	D^-	−1	$-3/2$	1	0	✓
Σ_c^{*0}	D^{*-}	−1	$-3/2$	1	0	✓

doubly-charmed pentaquarks & excited Ξ_{cc}

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	D^0	+1	$-1/2$	3	2	✓
Λ_c^+	D^+	+2	$1/2$	3	2	✓
Λ_c^+	D^{*+}	+2	$1/2$	3	2	✓
Σ_c^{++}	D^0	+2	$1/2$	3	2	×
Σ_c^{++}	D^+	+3	$3/2$	3	2	×
Σ_c^{++}	D^{*+}	+3	$3/2$	3	2	×
Σ_c^0	D^0	0	$-3/2$	3	2	×
Σ_c^0	D^+	+1	$-1/2$	3	2	×
Σ_c^0	D^{*+}	+1	$-1/2$	3	2	×
Σ_c^{*++}	D^0	+2	$1/2$	3	2	✓
Σ_c^{*++}	D^+	+3	$3/2$	3	2	✓
Σ_c^{*++}	D^{*+}	+3	$3/2$	3	2	×
Σ_c^{*0}	D^0	0	$-3/2$	3	2	✓
Σ_c^{*0}	D^+	+1	$-1/2$	3	2	✓
Σ_c^{*0}	D^{*+}	+1	$-1/2$	3	2	×

10 modes too statistically limited to set up upper limits

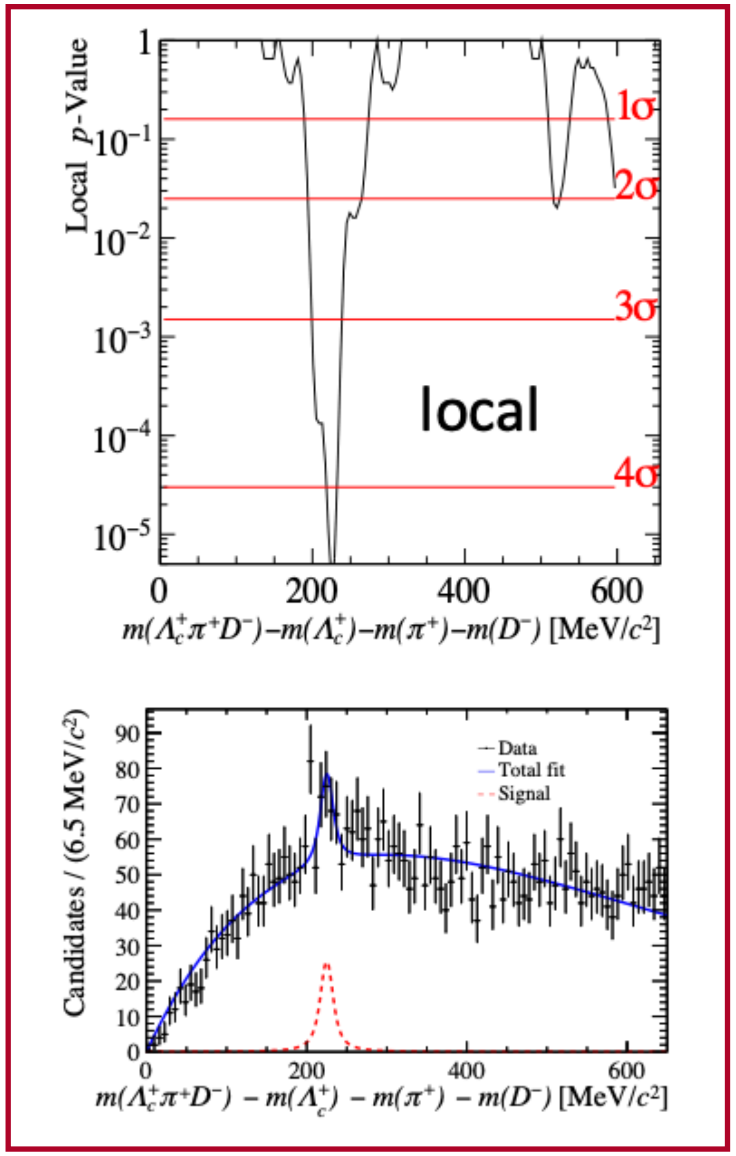
Search for Pc in open charm modes

arXiv: 2404.07131
submitted to PRD

- Every combination investigated (complete list in the paper)
- No significant signal found
- Upper Limits set for all combinations

$$R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\rightarrow\Lambda_c^+ D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$$

Decay Mode	Width (MeV/c^2)	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times10^{-3}$) 90% CL	UL ($\times10^{-3}$) 95% CL
$\Lambda_c^+\pi^+D^-$	0	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	15	4.50	3.62	225	108.2 ± 25.3	4.72	4.90
$\Lambda_c^+\pi^-D^-$	0	3.36	1.90	257	38.1 ± 12.4	4.28	4.56
	5	3.86	2.71	253	62.1 ± 17.1	4.62	4.83
	10	4.18	3.20	249	83.7 ± 21.2	4.72	4.88
	15	4.44	3.56	249	103.5 ± 24.6	4.77	4.92
$\Lambda_c^+\pi^+\overline{D}^0$	0	3.18	1.58	245	41.9 ± 13.7	2.87	3.06
	5	3.73	2.53	245	67.6 ± 19.2	3.22	3.35
	10	4.06	3.06	245	91.6 ± 24.1	3.29	3.39
	15	4.30	3.42	245	115.0 ± 28.5	3.30	3.40



$c\bar{c}uud$
$M \sim 4520.69$ MeV

- Pseudo-experiments indicate average number of channels fluctuate above 3σ is 7±5, so we conclude the results are consistent with background-only
- Known Pc states tested and yields all agree with zero

$P_c(4312)^+$	$M = 4311.9$ MeV, $\Gamma = 10$ MeV
$P_c(4440)^+$	$M = 4440$ MeV, $\Gamma = 21$ MeV
$P_c(4457)^+$	$M = 4457.3$ MeV, $\Gamma = 6.4$ MeV

Selected results by

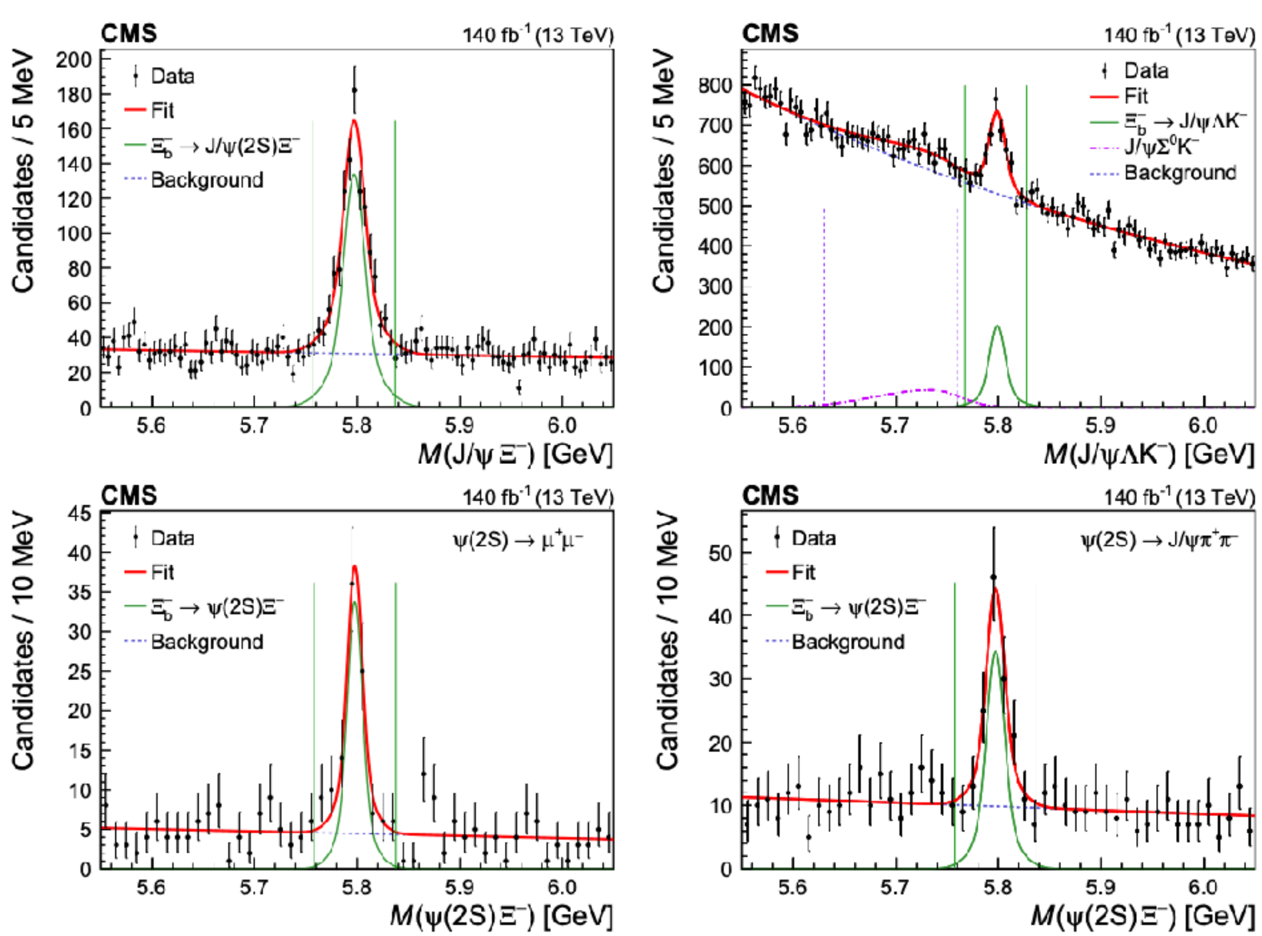
CMS

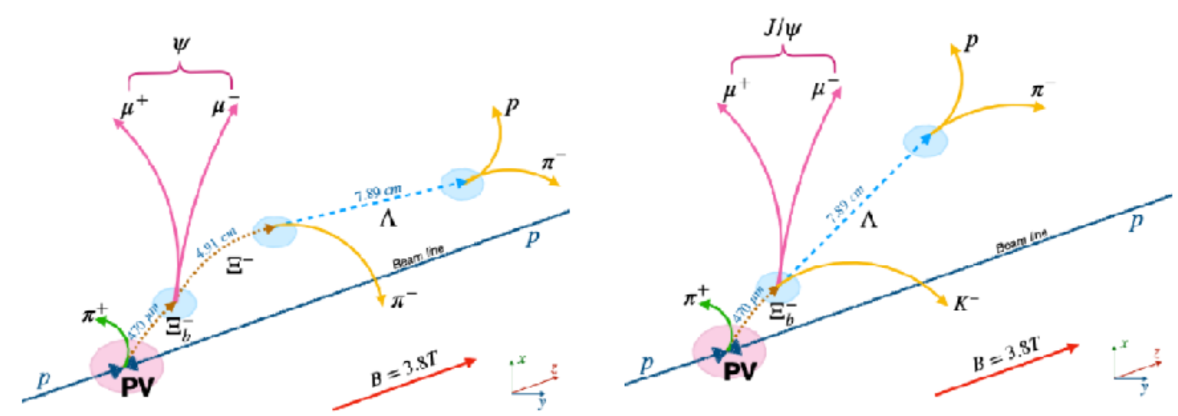
$\Xi_b \to \Psi(2S)\Xi$ and $\Xi_b^* \to \Xi_b\pi$

- Integrated luminosity of 140 fb^{-1}
- Muon final states and different final states (different topologies)
- Several measurements in one paper (BFs, Production and competitive mass measure)

Accepted
in Phys. Rev. D
CMS-BPH-23-002
CERN-EP-2024-038

Decay channel	N	$m^{\text{fit}}_{\Xi_b^-}$ (MeV)	σ_{eff} (MeV)
$\Xi_b^- \to J/\psi\Xi^-$	846 ± 40	5797.1 ± 0.6	16.3 ± 1.0
$\Xi_b^- \to J/\psi\Lambda K^-$	920 ± 98	5798.8 ± 0.9	11.9 ± 1.5
$\Xi_b^- \to J/\psi\Sigma^0 K^-$	880 ± 170	—	—
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to \mu^+\mu^-$)	74 ± 11	5797.7 ± 1.4	11.1 ± 2.0
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to J/\psi\pi^+\pi^-$)	90 ± 14	5797.2 ± 1.7	13.1 ± 2.8





$$R_{\Xi_b^{*0}} = \frac{\sigma(pp \to \Xi_b^{*0}X)\,\mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.23 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{syst})$$

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B})$$

$$M(\Xi_b^{*0}) = 5952.4 \pm 0.1\,(\text{stat+syst}) \pm 0.6\,(m_{\Xi_b^-})\,\text{MeV}$$

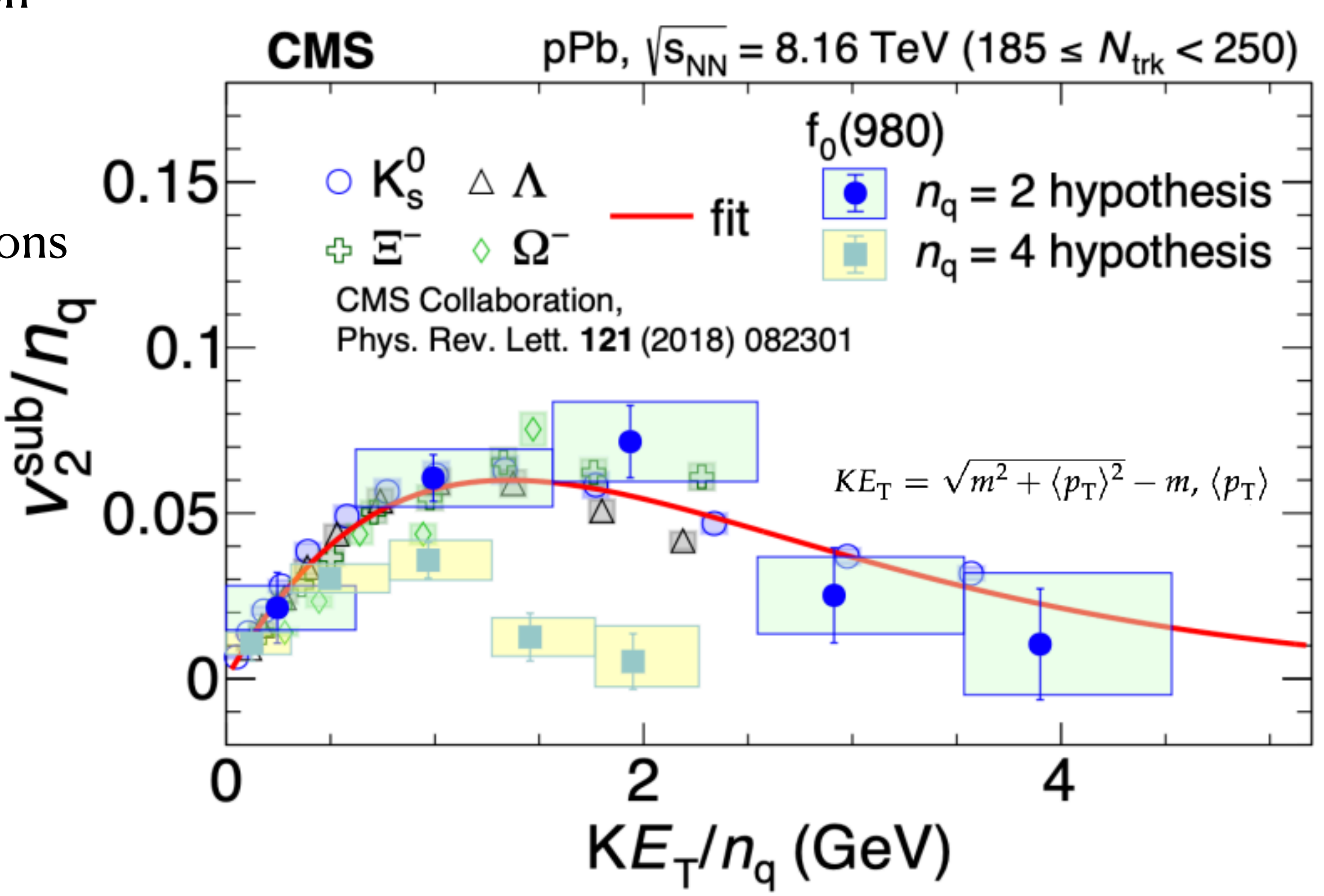
Thus, we can conclude that about a third of the Ξ_b^- baryons are produced from Ξ_b^* decays

f_0(980) hadron in p-Pb collisions

Submitted to Nature Physics
CMS-HIN-20-002
CERN-EP-2023-294

- f_0(980) hadron discovered half a century ago, but…
- Its quark content has not been settled:
  - Ordinary meson $q\bar{q}$?
  - Tetraquark $q\bar{q}q\bar{q}$?
  - Exotic state ?
  - Kaon-Antikaon $K\bar{K}$ molecule ?
  - Glue $q\bar{q}g$ hybrid ?

- Strong evidence that f_0(980) is an ordinary meson
- Inferred from scaling of elliptic anisotropies (v_2) with the number of constituent quarks (n_q)
- Empirically established using conventional hadrons in relativistic heavy ion collisions
- Other hypothesis on exotic nature ruled out



The argument of the function, KE_T/n_q, is related to the kinetic energy per constituent quark

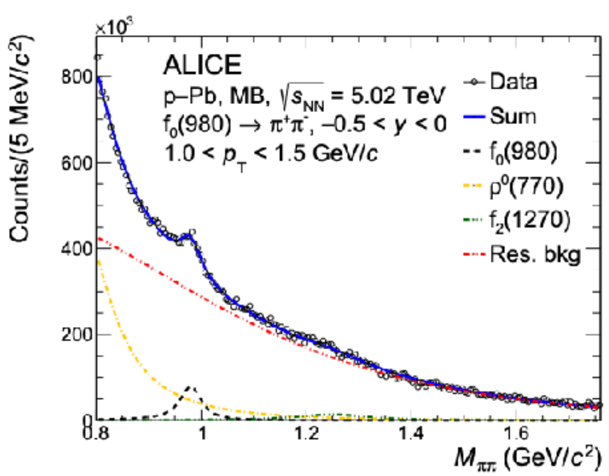
Selected results by

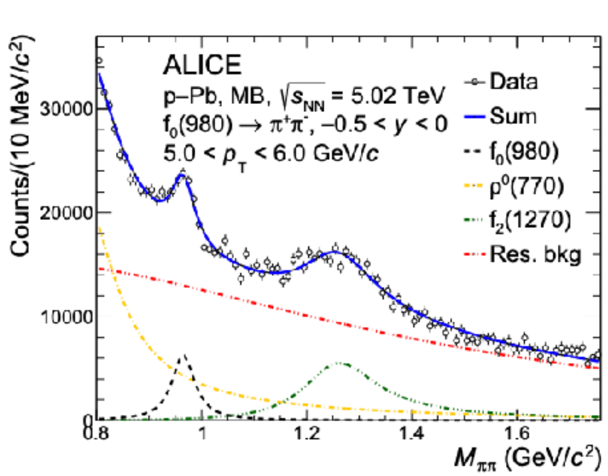
ALICE

Suppression of f0(980) production in p-Pb collisions

Phys. Lett. B 853 (2024) 138665

- Similar study to CMS
- Nuclear modification factor Q_{pPb} of $f_0(980)$ measured in various multiplicity ranges
- A lot of interesting results:
    - $f_0(980)$ nuclear modification factor is lower than unity: suppression
    - For p_T<4GeV
        - Lower than charged hadrons
        - Difference increases with multiplicity
        - Suppression of the $f_0(980)/\pi$ and $f_0(980)/K^*(892)^0$ depends on p_T
- The results on the particle yield ratios may help to understand the nature of the internal structure of $f_0(980)$ particle
- No enhancement at intermediate pt hints at 2-quark vs 4-quark structure

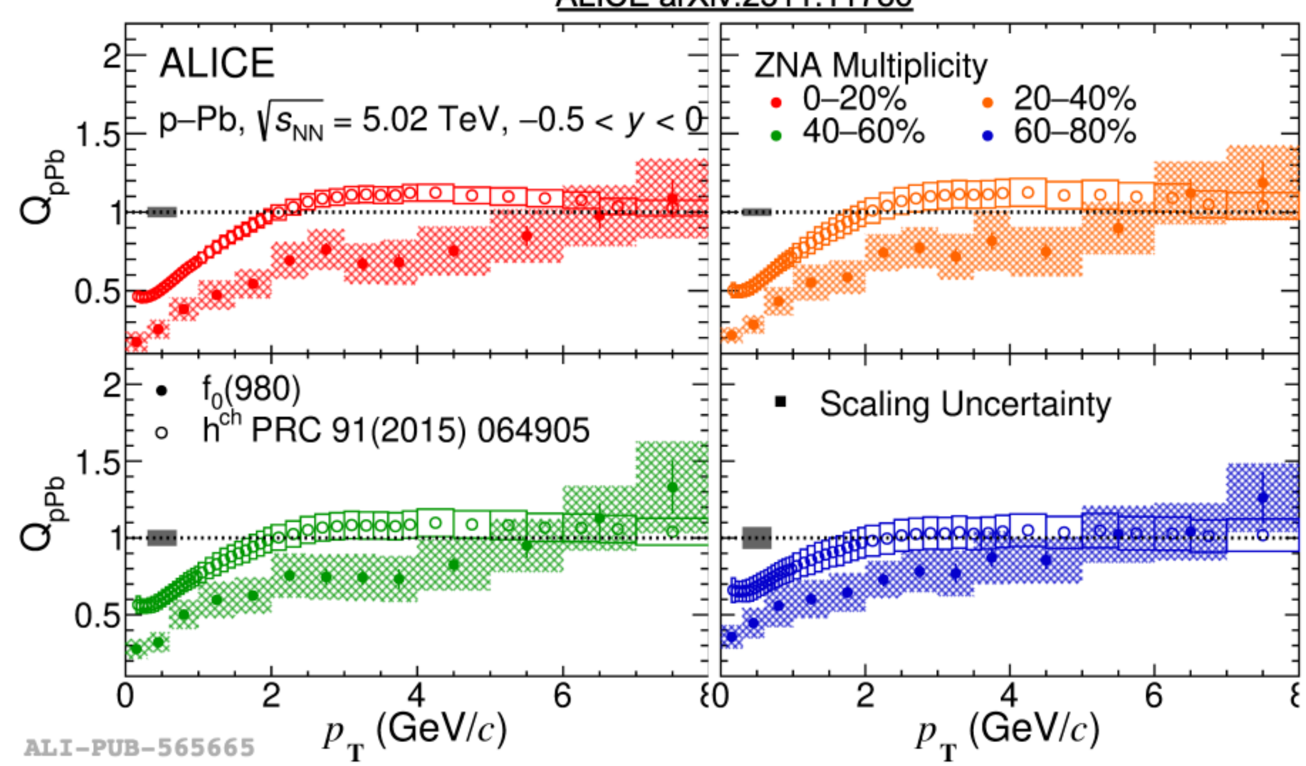




$$Q_{pPb} = \frac{d^2N^{pPb}_{f_0(980)}/dp_Tdy}{\langle T_{pPb}\rangle d^2\sigma^{pp}_{f_0(980)}/dp_Tdy},$$

Nuclear modification factor adapted to p-Pb collisions

ALICE arXiv:2311.11786



Clear suppression of f_0 nuclear modification factor production suggests impact of final state scattering and meson like structure

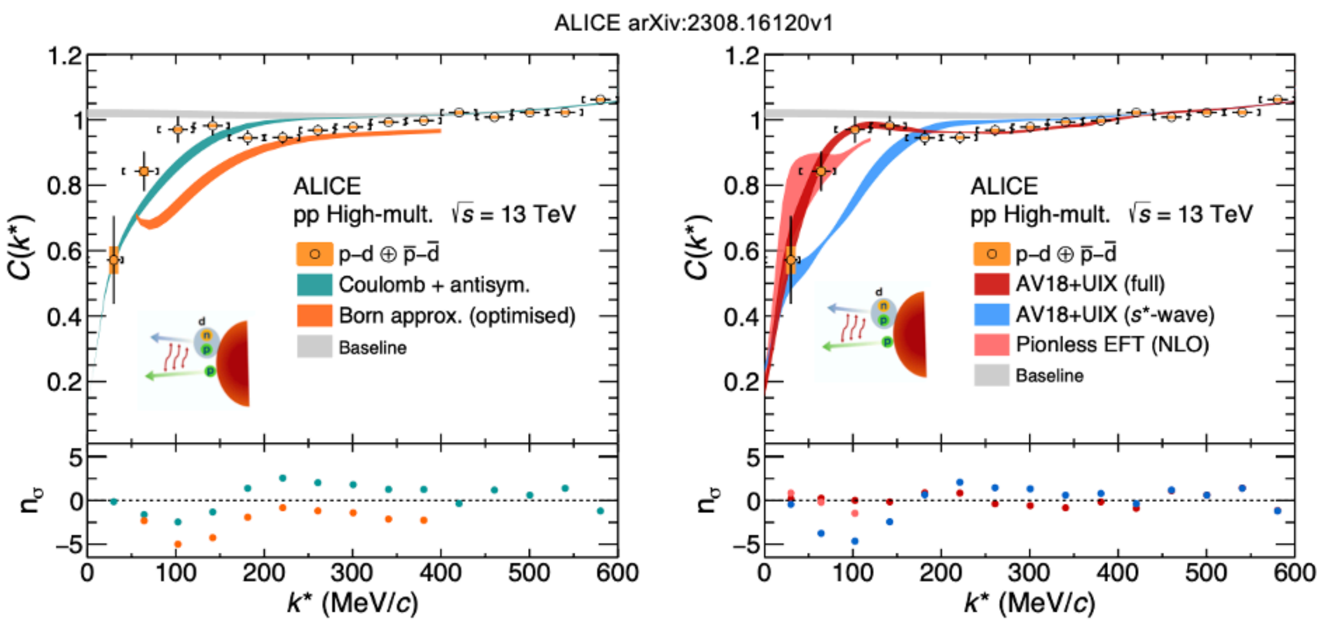
Strong interaction of 3-body systems at the LHC

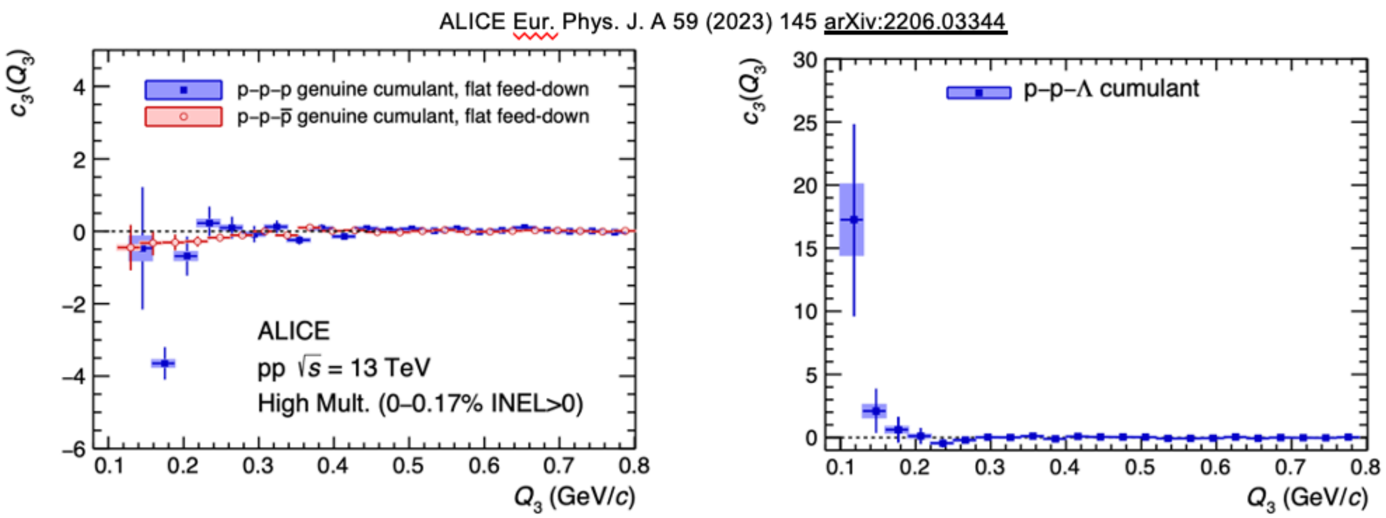
- Measure the correlation functions of 3-body systems with femtoscopic techniques

arXiv:2308.16120

Proton-deuteron correlations
Distance comparable to the proton radius

$p-p-p/\bar{p}$ and $p-p-\Lambda$





Non zero 3-particle cumulant hints for 3-body forces

Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data (Av18+UIX full)

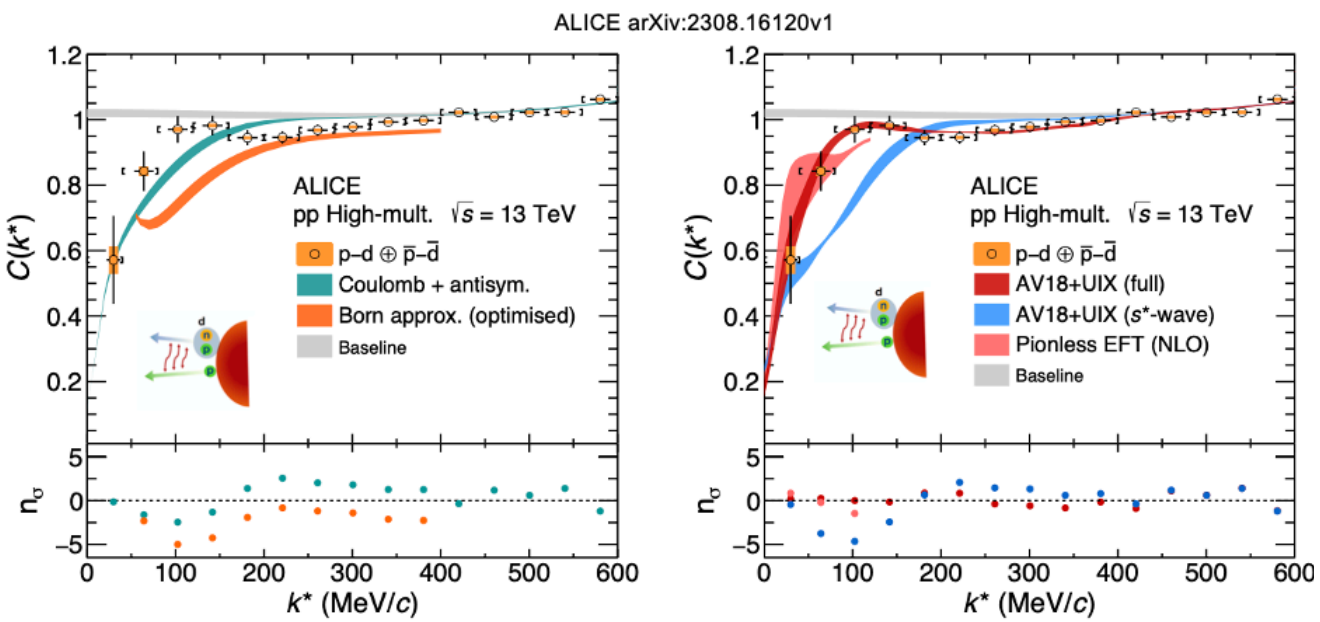
published results from Run 2

Strong interaction of 3-body systems at the LHC

- Measure the correlation functions of 3-body systems with femtoscopic techniques

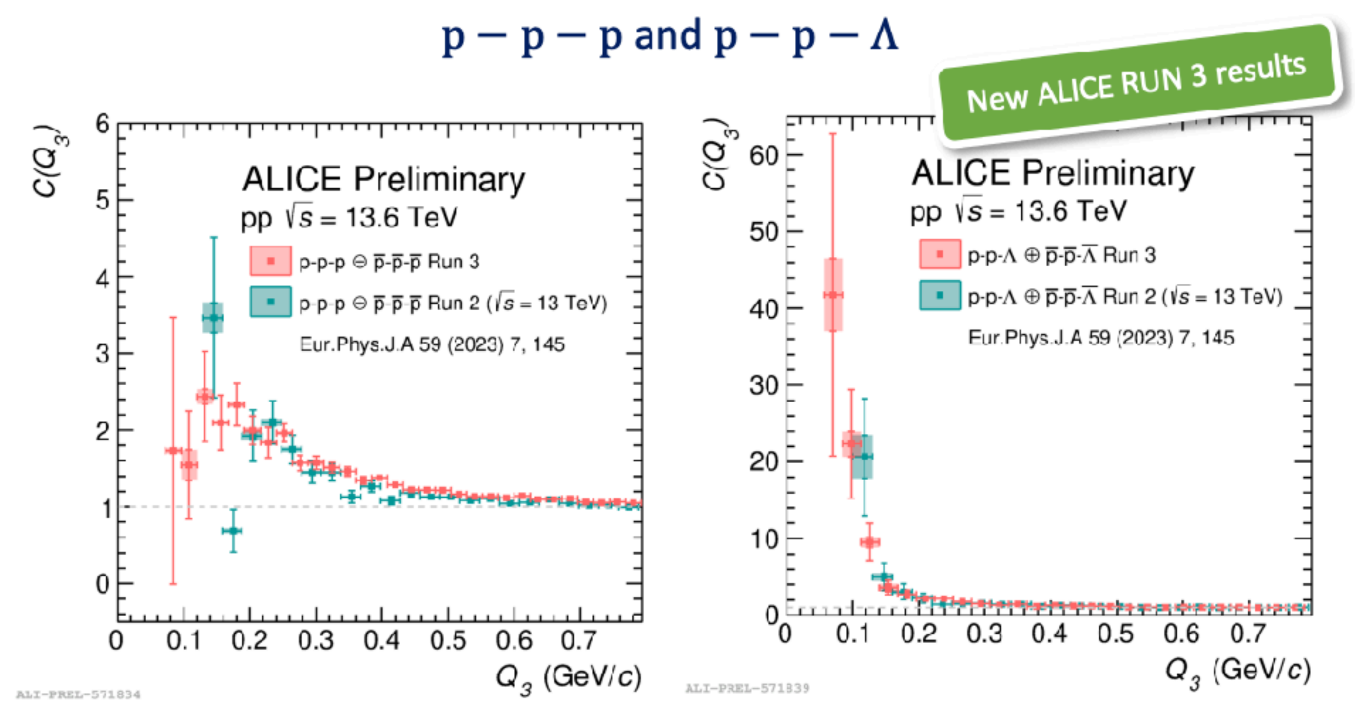
arXiv:2308.16120

Proton-deuteron correlations
Distance comparable to the proton radius



Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data
(Av18+UIX full)

$p - p - p$

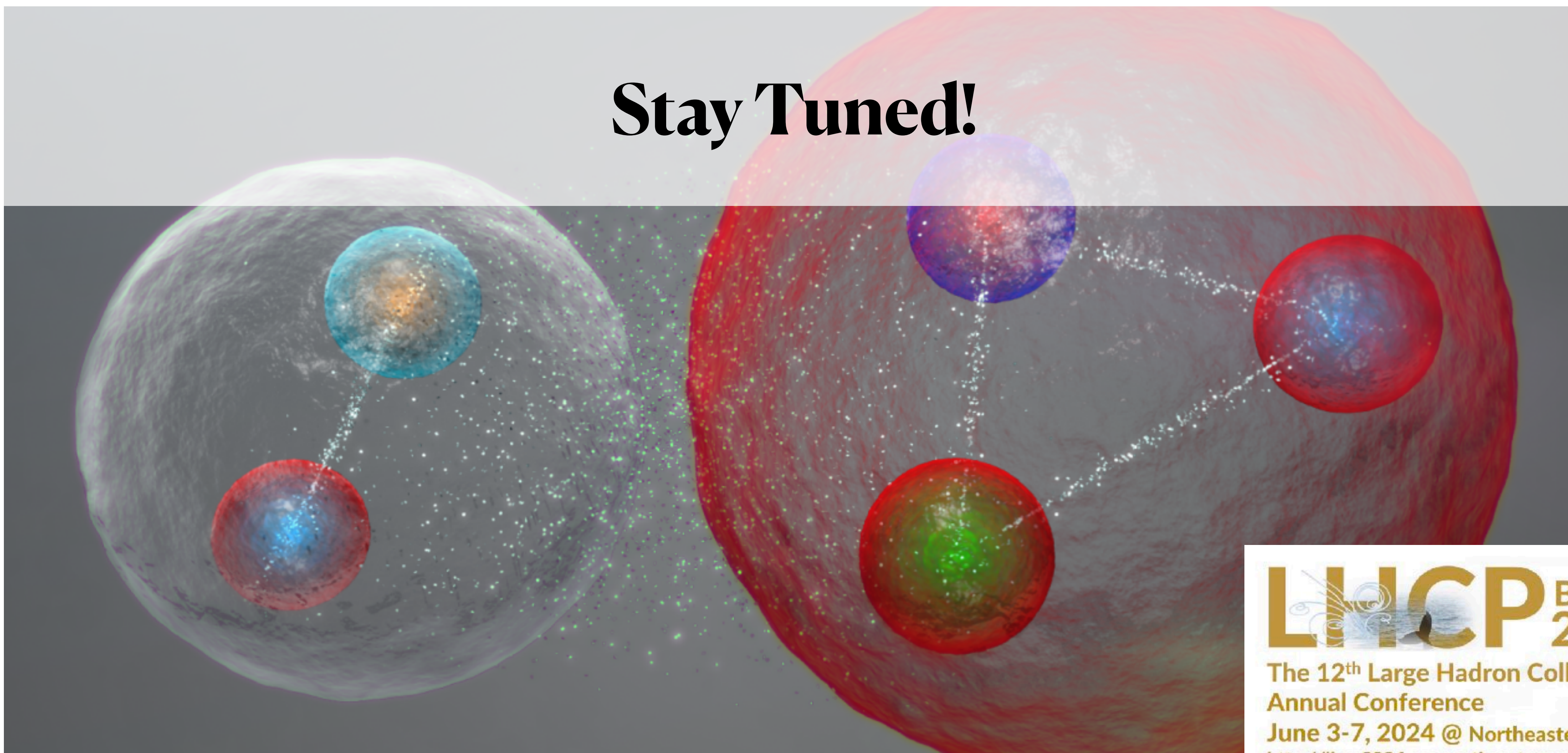


- First result for Run3
- Preliminaries results from RUN3
- Improvement in term of uncertainties
- Message is confirmed

Conclusions

- LHC is a wonderful playground for hadrons physics!
- Unprecedented & probably unique opportunity for these type of studies
- Upgrade era started: higher statistics + access to states with lower production rates
- Summer conferences are just starting → plenty of new results expected!

Image courtesy of CERN



LHCP Boston 2024
The 12th Large Hadron Collider Physics Annual Conference
June 3-7, 2024 @ Northeastern University
http://lhcp2024.cos.northeastern.edu

Backup Slides