Overview of the non-perturbative aspects working group activities

Elisabeth Maria Niel - EPFL, Lausanne

GDR-InF annual workshop 2022

Domaine Lyon Saint-Joseph

Non-perturbative aspects WG

Conveners: Aoife Bharucha, Antoine Gérardin, Elisabeth Niel

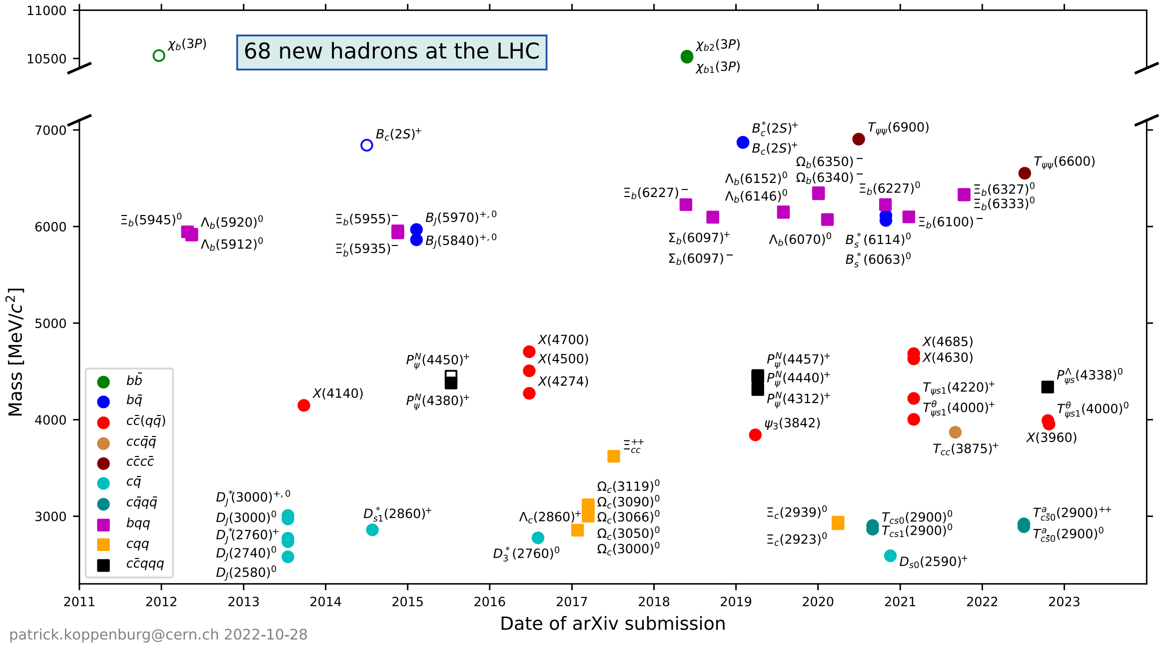
Subjects:

1. Heavy-flavour production
2. Spectroscopy
3. Understanding and measurement of form factors

Goals:

1. Test QCD predictions
2. Inputs needed for other measurements and interpretation of NP sensitive channels
3. Exotic bound states of quarks (tetra- and pentaquarks)

→ Overlap with GDR QCD



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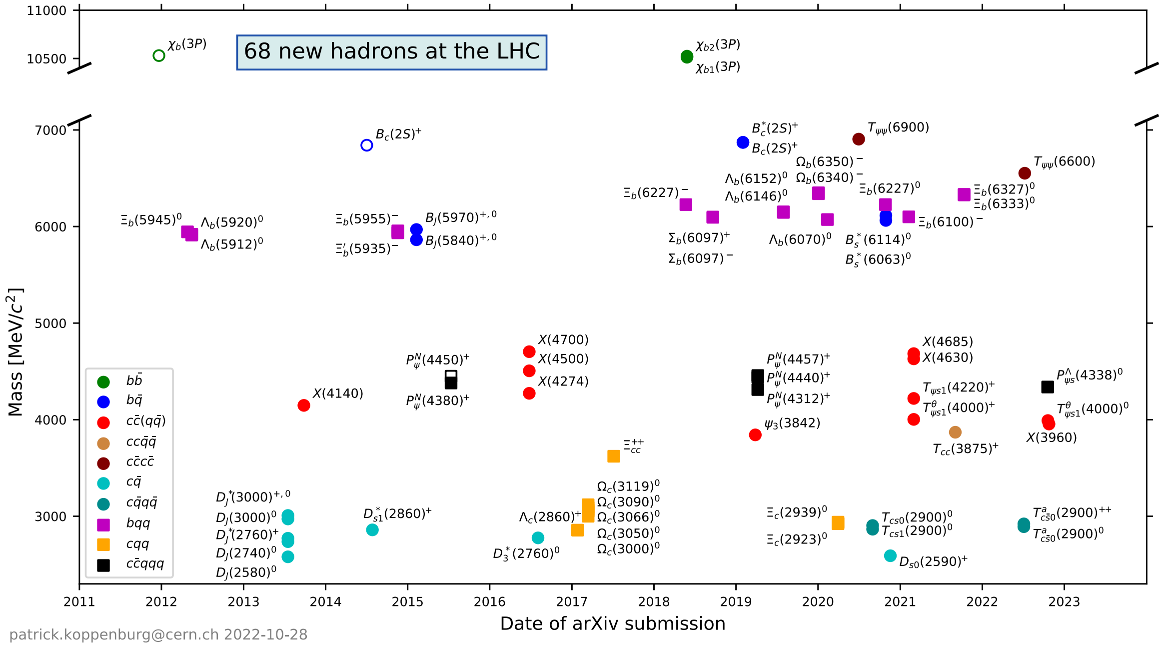


Summary of (some) of the on-going activities in France

1. Me : heavy-flavour production and spectroscopy
2. Aoife : Form factors

Heavy flavour production

A tool to test Quantum Chromodynamics QCD in high-energy hadronic collisions in different regimes:

1. Production in *pp*:

   - (Open) heavy flavour production in *pp* collisions: partonic hard scattering process in *p*QCD (down to low p_T)
   - Quarkonium bound state: both perturbative (heavy-quark pair production) and non-perturbative (production of the bound state $\bar{q}q$) process, comparison to experimental data crucial.

2. In nucleus-nucleus and *p*-nucleus collisions:

   Hard scattering at early stage of the collisions, before Quark Gluon Plasma (QGP) forms.

   Used to study the Cold Nuclear Matter effects :
   - nuclear-modified parton densities
   - multiple scattering of partons
   - absorption or break-up of charmonium states by the colour screening mechanism: sequential suppression or recombination of $c\bar{c}$ pairs for charmonium production

Open heavy-flavour production

Factorization of the process : $i + j \rightarrow X + H$

Factorisation scale μ_F → separates the long and short-distance physics.

$$d\sigma = \sum_{i,j,k} f_i^A(x_1) \otimes f_j^B(x_2) \otimes d\sigma(ij \rightarrow kX) \otimes D_k^H(z)$$

incident partons : parton distribution functions, non perturbative (long distance)

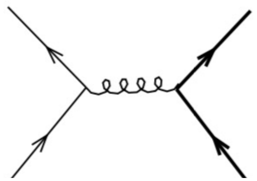
inelastic interaction producing heavy quarks: hard scattering cross section, computable perturbative

hadronization process of these quarks: fragmentation functions, non perturbative

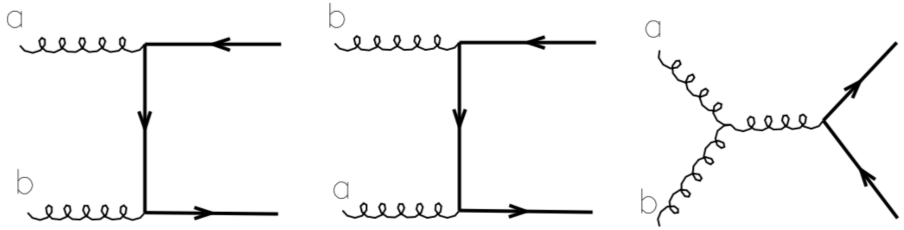
- $i\,, j$ active partons and anti-partons in the proton: $u, \bar{u}\,, d, \bar{d}, s, \bar{s}$ and eventually $c\,, \bar{c}$
- At the leading order (LO) two subprocesses:

dominant at the LHC ($\sim$ 85% at $\sqrt{S} = 14\,TeV$).

$q\bar{q} \rightarrow Q\bar{Q}$



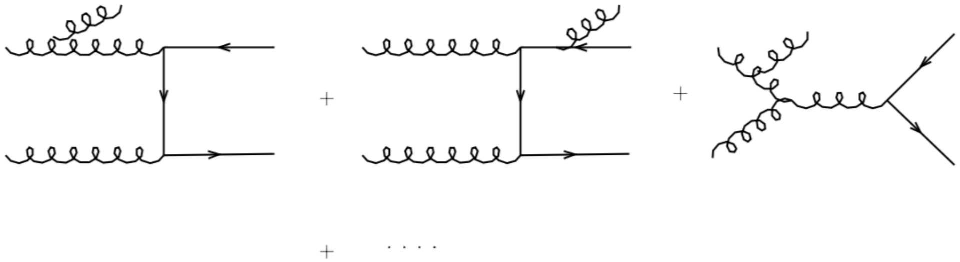
$gg \rightarrow Q\bar{Q}$



- At the next-to-leading order NLO O(α_S^3) : up to $0 \leq p_T \leq 5 * m_Q$, then need the fragmentation functions to account for the shift of momentum between b quark and B meson

Real Emission Diagrams

$q\bar{q} \rightarrow Q\bar{Q}g$

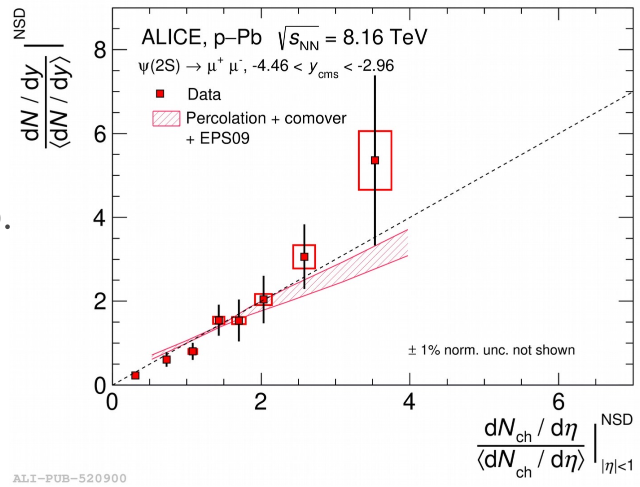


Heavy-flavour production

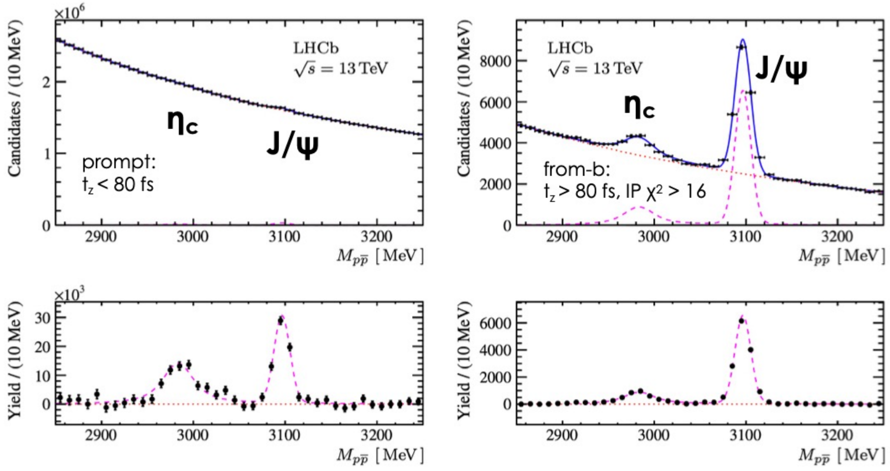
https://arxiv.org/abs/2204.10253

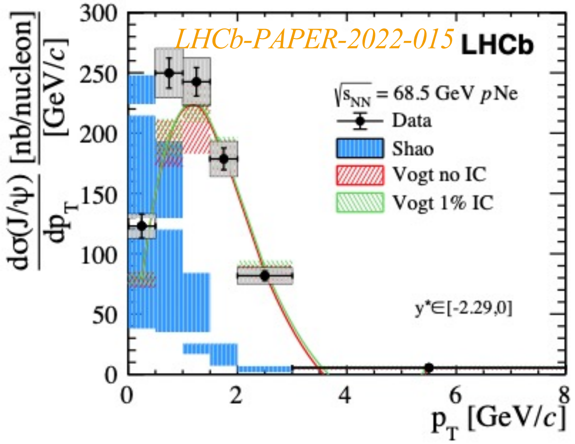
Activities in France:

- **ALICE** : charmonium production as a function of charged-particle multiplicity. Study multiparton interactions in a single hadron-hadron collisions
- **CMS** : study of the fragmentation of jets (with J/ψ) in PbPb and pp collisions (see Batoul's talk).
- **LHCb** : charmonium production in *pp* collisions, open and hidden charm production in fixed-target collisions and baryon-to-meson ratio in PbPb collisions.
- **Belle II:** bottomium spectroscopy (see Pavel's talk)

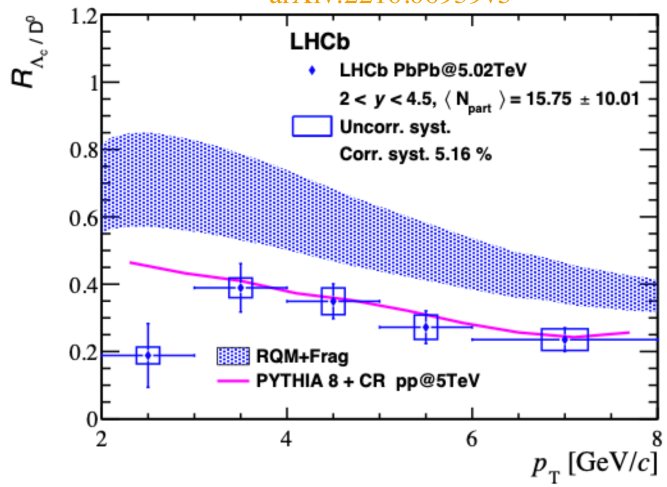


Eur.Phys.J.C 80(2020) 191





arXiv:2210.06939v5

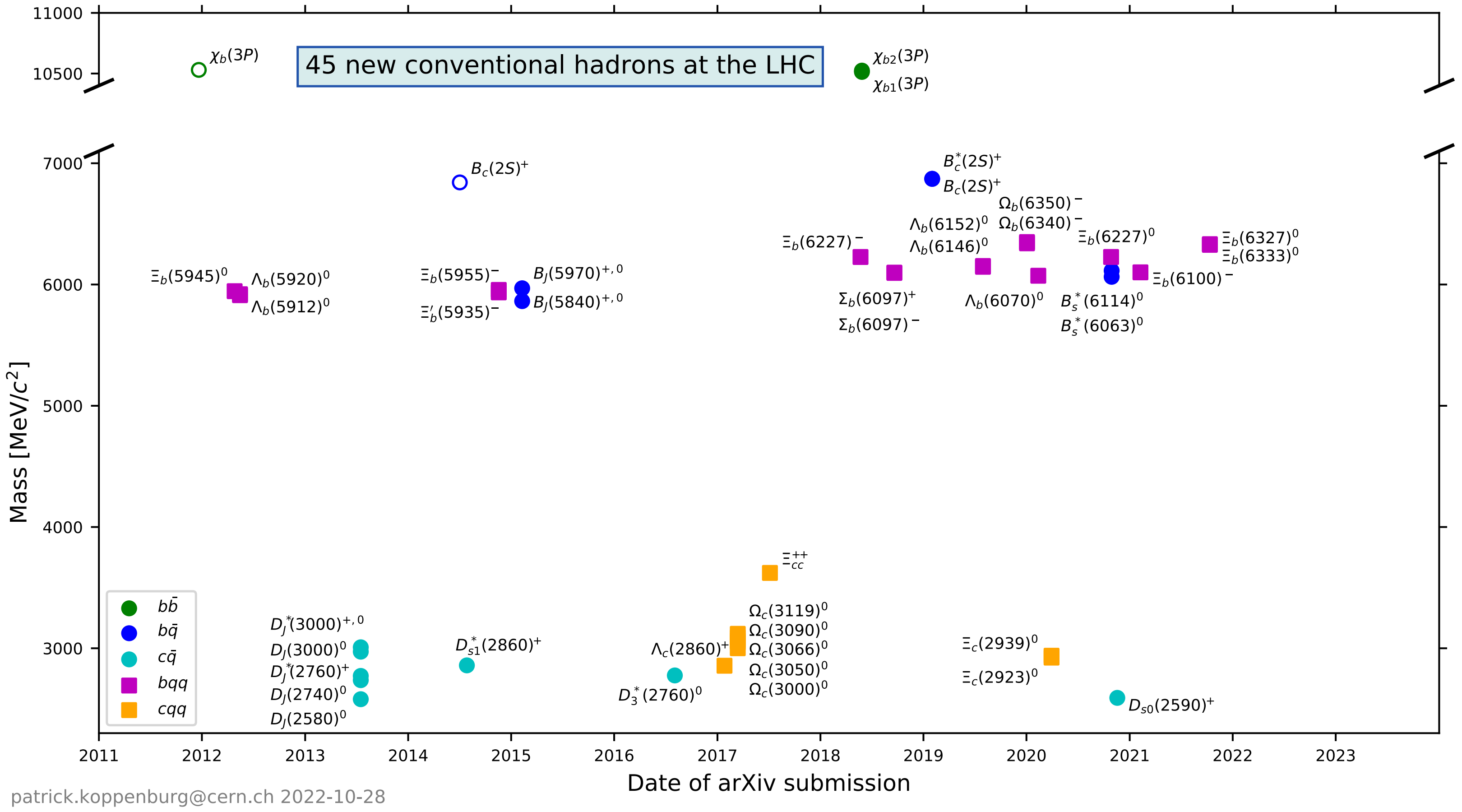


Theory (large contribution from France):

- Phys.Rev.Lett. 114(2015), 092005
- Phys.Rev.Lett. 114(2015), 092006
- Eur.Phys.J.C 75(2015) 7, 313
- Nucl.Phys.B 945(2019) 114662
- Phys.Lett.B 786(2018) 342-346
- JHEP 05(2015) 103
- Phys.Rev.Lett. 110(2013) 042002
- Phys.Rev.D 93 (2016) 034041

Spectroscopy I: conventional

→**Conventional spectroscopy**:



Over the past 10 years more than 60 new hadrons discovered at LHC

Spectroscopy I: conventional

→**Conventional spectroscopy**:

- production of doubly heavy baryons:
  - Observation $\Xi_{cc}^{++} \rightarrow \Xi_c'^{+}\pi^{+}$ JHEP05(2022)038
  - Search for $\Xi_{bc}^{+} \rightarrow J/\psi\Xi_c^{+}$ arXiv: 2204.09541

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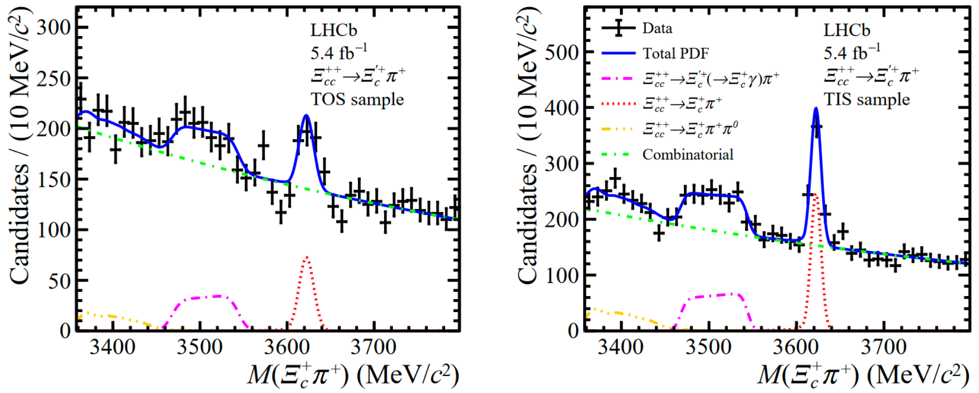

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10.$$

- Measure pcle properties and compare with theory predictions.
- In this case, inconsistent with any previous theoretical predictions

Spectroscopy I: conventional

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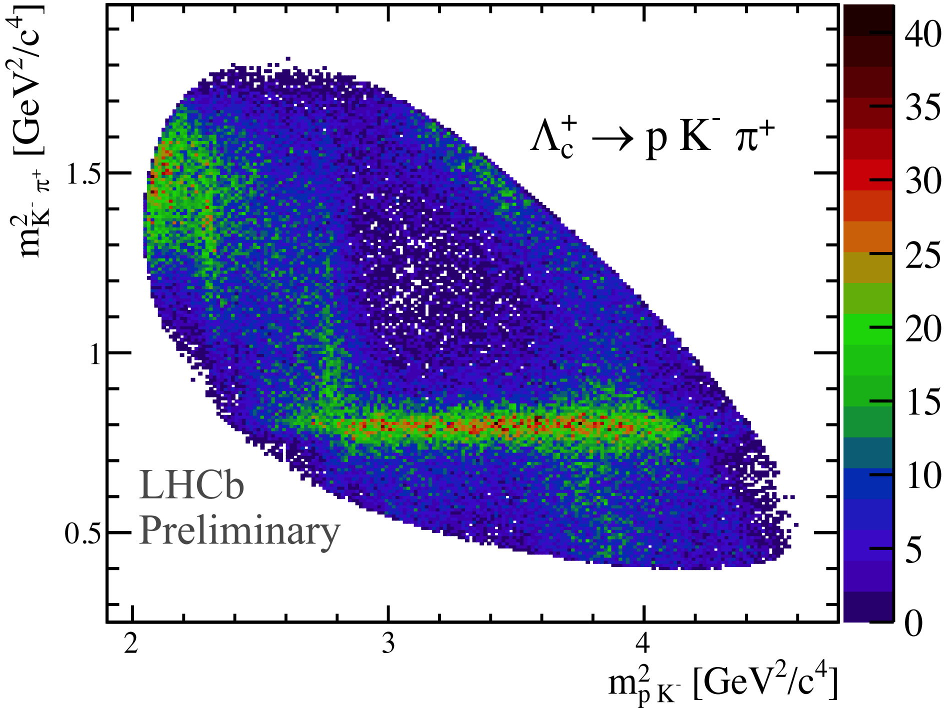
- amplitude analysis of mesons and baryons multi-body decays:
  - $D_s^+ \to \pi^+ \pi^- \pi^+$ arXiv: 2208.03300
  - $D^+ \to \pi^+ \pi^- \pi^+$ arXiv: 2209.09840
  - $\boldsymbol{\Lambda_c^+ \to p\, K^- \pi^+}$
  - $\boldsymbol{\Lambda_b \to p\, K^- \gamma}$ **(on-going)**

Amplitudes analysis: France

- AmAn $\Lambda_c^+ \to p\, K^- \pi^+$: measure polarization for promptly produced (*i.e.* not from B decays).
  LHCb Run 2 (only 2016), *pp* collisions at $\sqrt{s} = 13$ TeV

https://tel.archives-ouvertes.fr/tel-03414369

- Challenge: model building



Particle	J^P	Overall status
$\Lambda(1116)$	$1/2^+$	****
$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*

Particle	J^P	overall
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***

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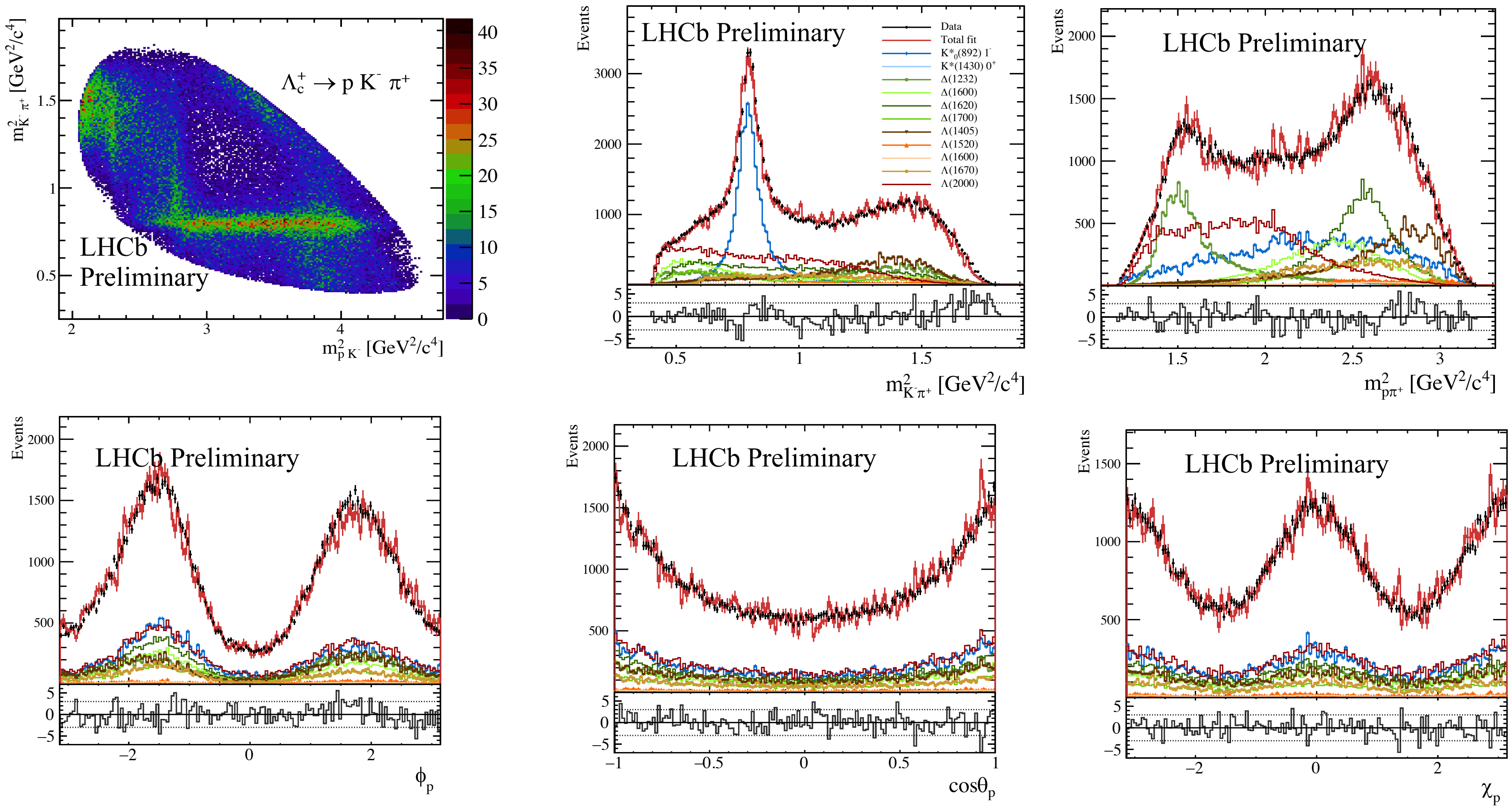
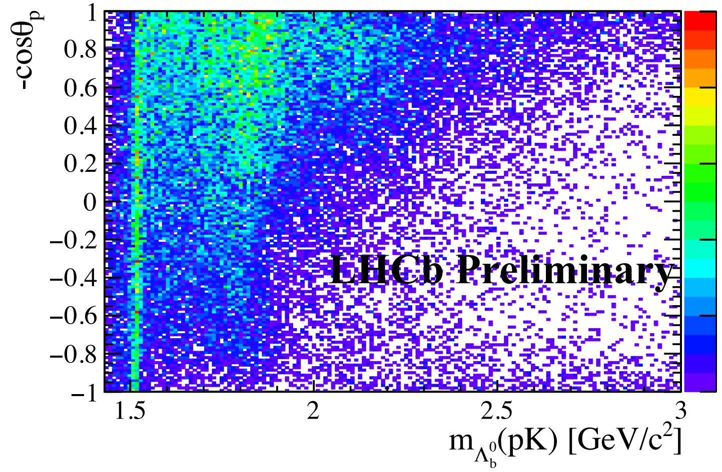


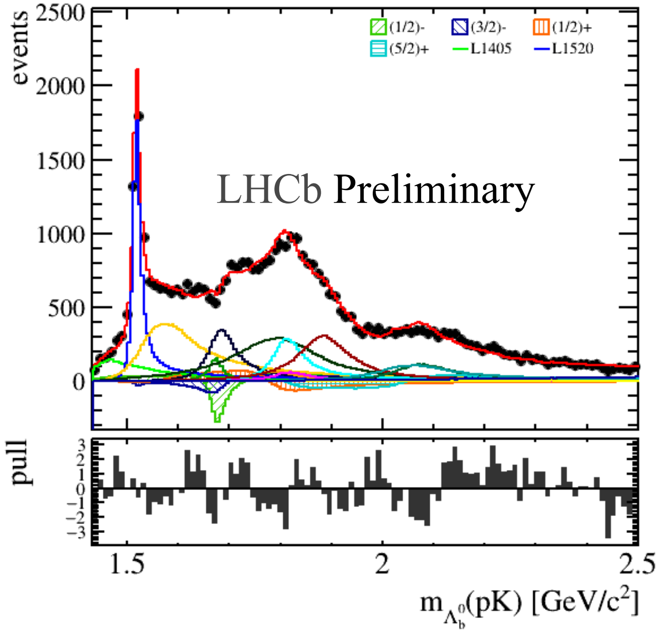
Res	M0	M1	M2	M3	M4	M5	M6
pK channel							
$\Lambda^*(1405)$	✗	✔	✔	✔	✔	✔	✔
$\Lambda^*(1520)$	✔	✔	✔	✔	✔	✔	✔
$\Lambda^*(1600)$	✗	✗	✔	✔	✔	✔	✔
$\Lambda^*(1670)$	✔	✔	✔	✔	✔	✔	✔
$\Lambda^*(1690)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(1800)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(1810)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(1820)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(1830)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(1890)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(2000)$	✗	✔	✔	✔	✔	✔	✔
$\Lambda^*(2100)$	✗	✗	✗	✗	✗	✗	✗
$\Lambda^*(2110)$	✗	✗	✗	✗	✗	✗	✗
$p\pi$ channel							
$\Delta^{++}(1232)$	✔	✔	✔	✔	✔	✔	✔
$\Delta^{++}(1600)$	✗	✗	✗	✗	✔	✔	✔
$\Delta^{++}(1620)$	✗	✗	✗	✗	✗	✗	✔
$\Delta^{++}(1700)$	✗	✗	✗	✗	✗	✔	✔
$K\pi$ channel							
$K^*(700)$	✗	✗	✗	✔	✔	✔	✔
$K^*(892)$	✔	✔	✔	✔	✔	✔	✔
$K^*(1410)$	✗	✗	✗	✗	✗	✗	✗
$K_0^*(1430)$	✗	✗	✗	✔	✔	✔	✔
Fit χ^2/ndf							
N_{par}	18	26	30	34	38	42	46
m^2_{pK}	217.17	40.66	9.18	10.80	12.18	12.30	11.85
$m^2_{K\pi}$	27.27	25.15	12.32	12.43	14.72	13.31	11.60
$m^2_{p\pi}$	55.82	22.64	10.60	12.24	12.50	11.82	11.12
$\cos(\theta_p)$	7.50	6.48	6.28	6.62	7.20	7.73	8.19
χ	6.59	5.44	5.50	5.57	6.35	6.68	7.05
ϕ_p	6.27	5.52	6.08	6.04	6.56	7.19	8.09
$m^2_{pK}, m^2_{p\pi}$	389.18	29.97	7.32	10.38	11.86	11.80	5.04
FF	1.030	0.932	1.100	1.030	1.119	1.102	1.129

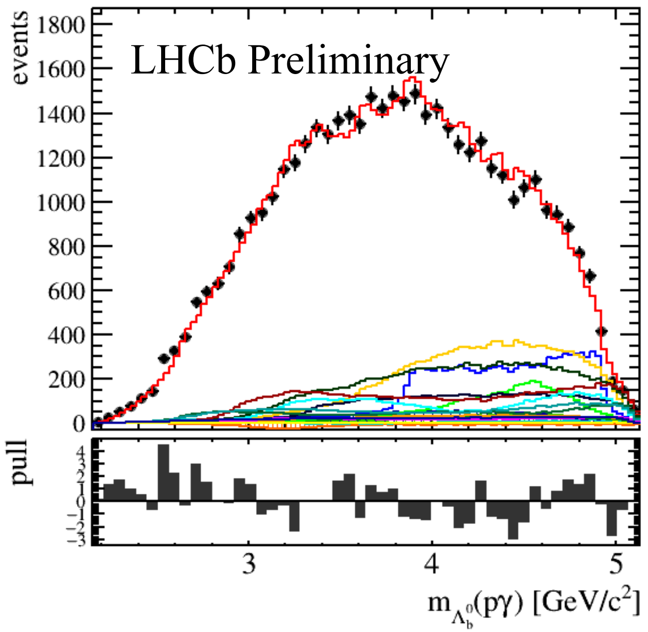
Amplitudes analysis: France

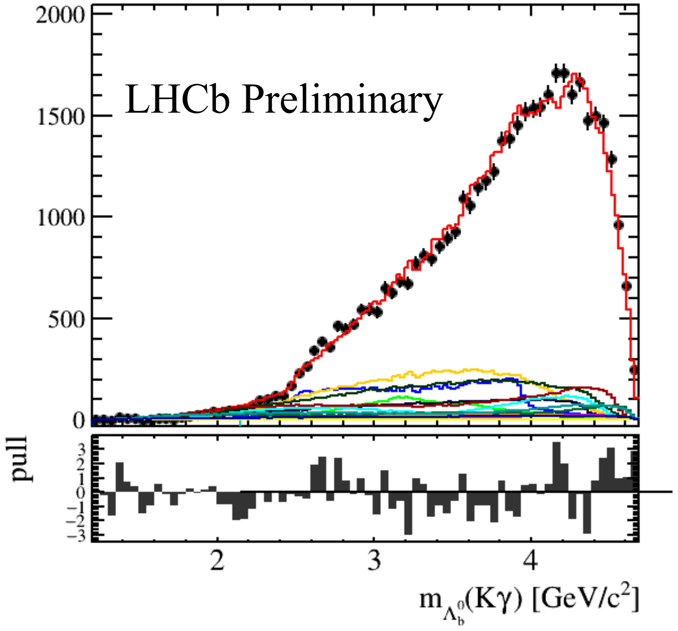
AmAn $\Lambda_b \to p\, K^- \gamma$

- Helicity formalism studied in this paper : arXiv:2002.02692
- Similar to the pentaquark analysis $\Lambda_b \to p\, K^- J/\psi$ but at $q^2 = 0$
- input for interpretation of LFU measurement (R_{pK}) and and ongoing angular analyses



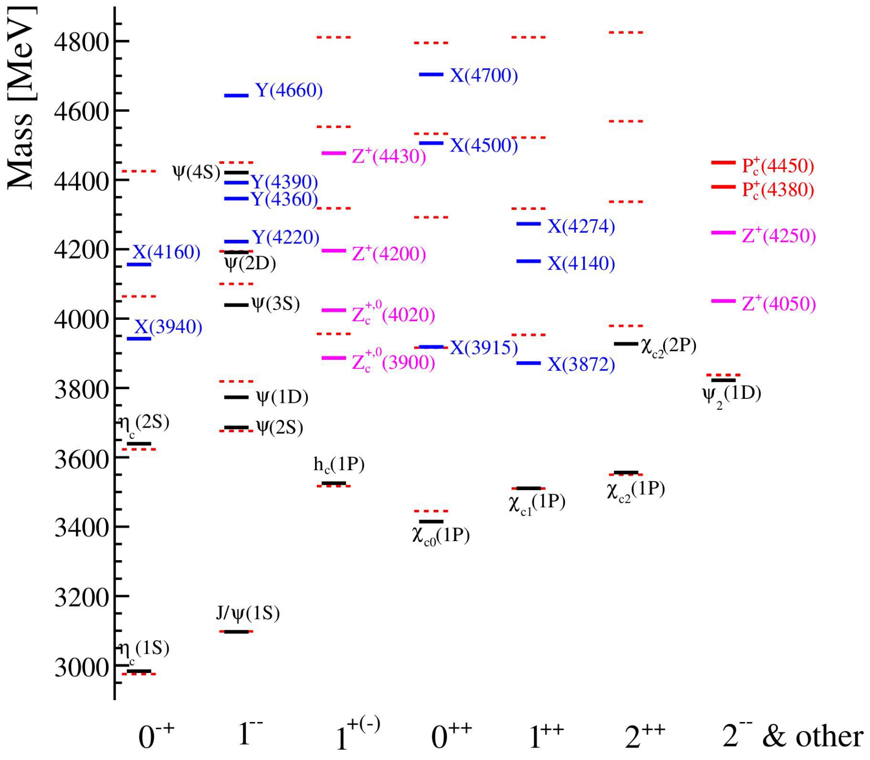




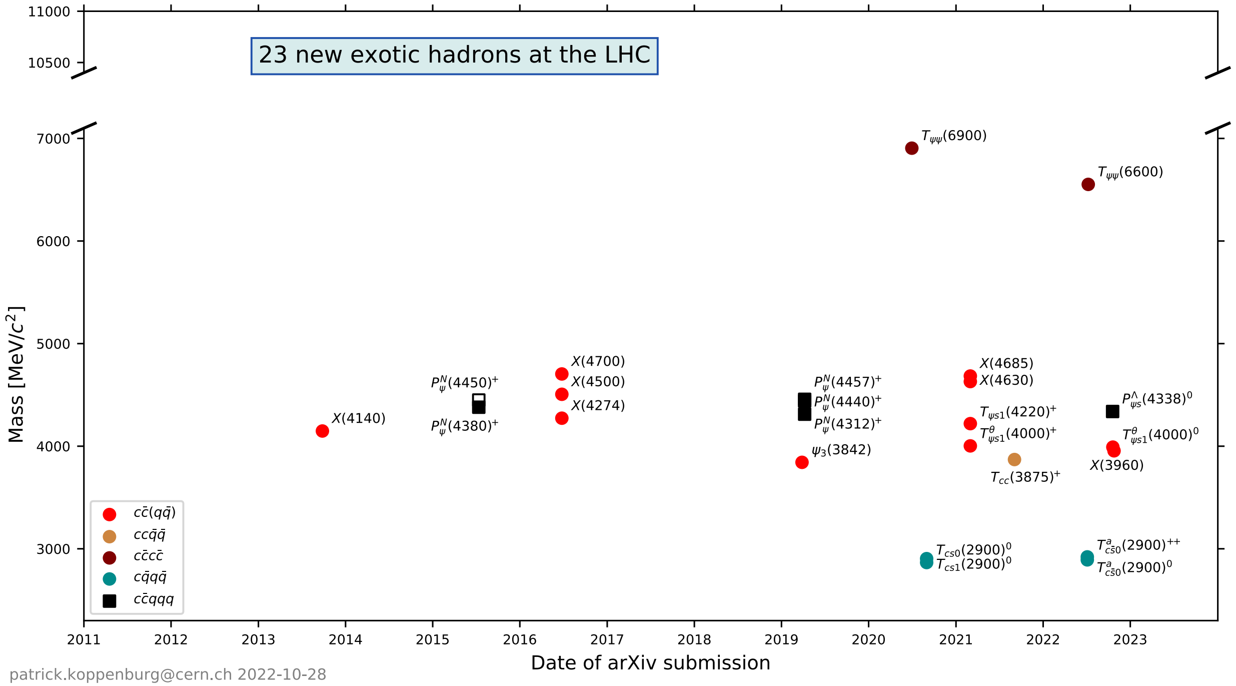


Spectroscopy II: exotics

- The particle zoo is growing!
- Multiquark hadrons exotic:
    - Tetraquarks: minimal quark content $qq\bar{q}\bar{q}$
    - Pentaquark: minimal quark content $qqqq\bar{q}$
- Not in the charmonium or bottonium spectrum



S. L. Olsen, T. Skwarnicki, et al., Rev. Mod. Phys. 90 (2018) 015003



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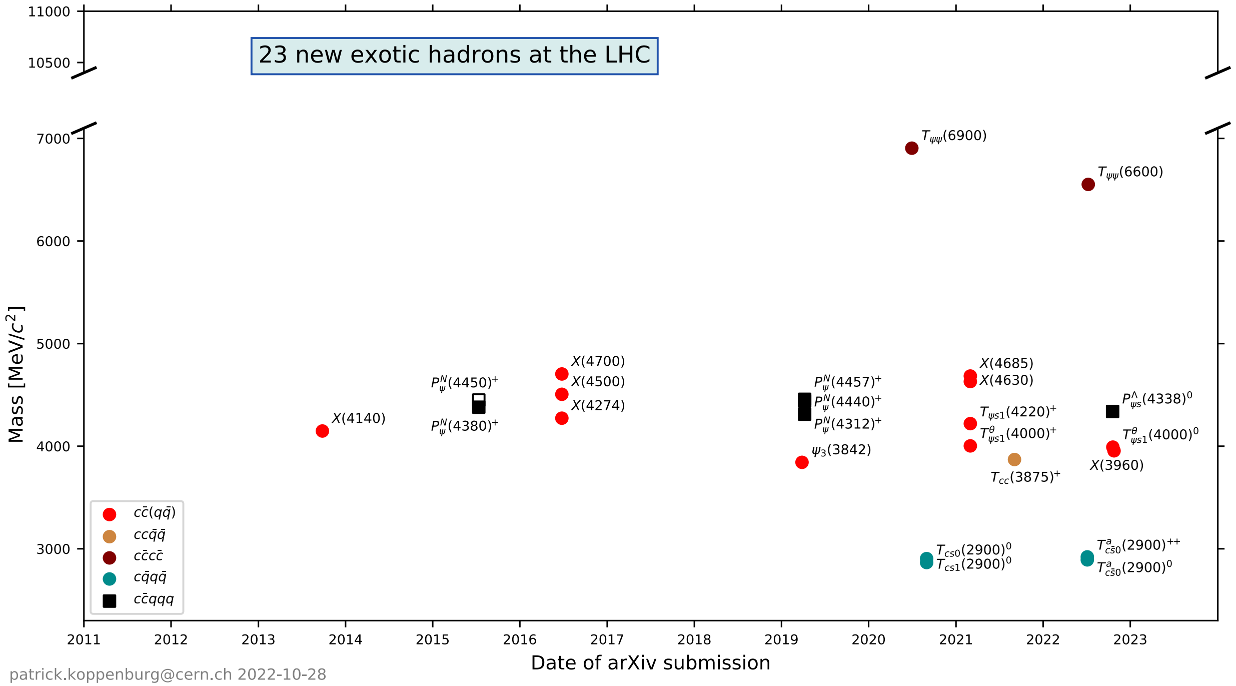
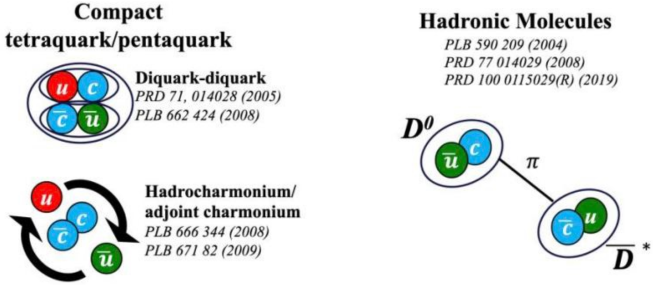
- Not in the charmonium or bottonium spectrum
- New naming scheme proposed by LHCb: arxiv2206.15233
  - ➢ T for **tetra** and P for **penta**
  - ➢ Superscript: indicate isospin, parity and G-parity
  - ➢ Subscript: heavy quark content

Minimal quark content	Current name	$I^{(G)}, J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+, J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_{\psi}(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+, J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}, J^P = 1^+$	$T^{\theta}_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}, J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+, J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+, J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_{\psi}(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^{\Lambda}_{\psi s}(4459)^0$



Challenges: the nature of these states is not established

QCD state, size 1 fm

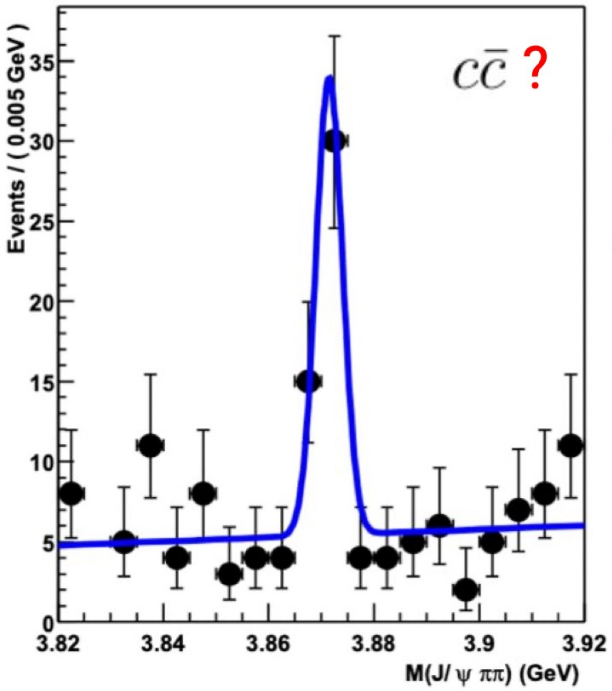


Two hadrons bound by QCD analog of Van der Waals force, Size 1-10 fm

Spectroscopy II: exotics

- First hints: Belle 2003 in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decays
  PRL 91 (2003) 262001

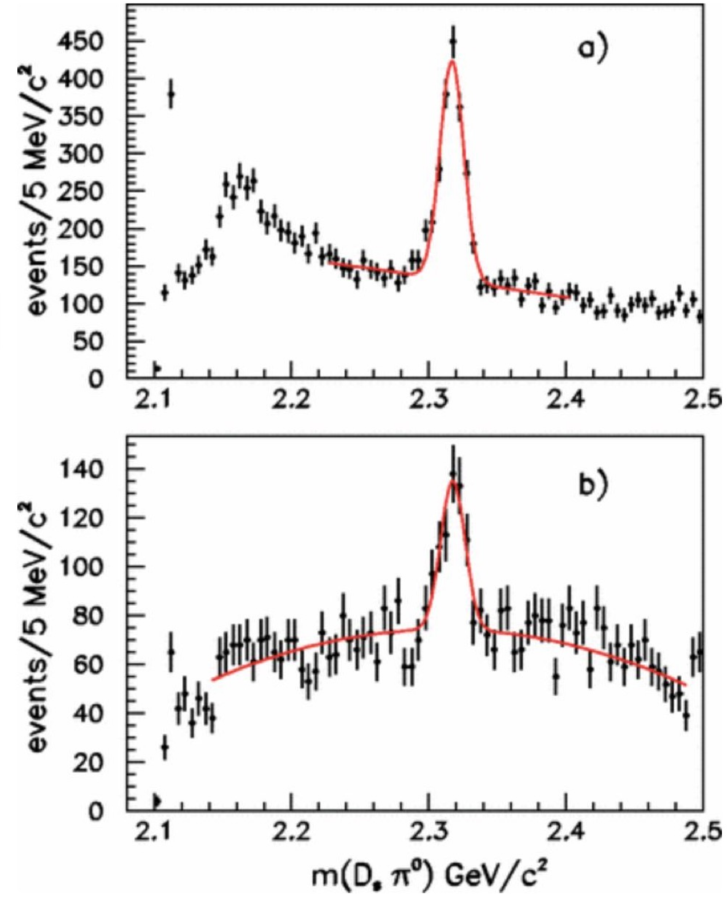
  Confirmed by LHCb in $J^{PC} = 1^{++}$
  PRL. 110 (2013) 222001



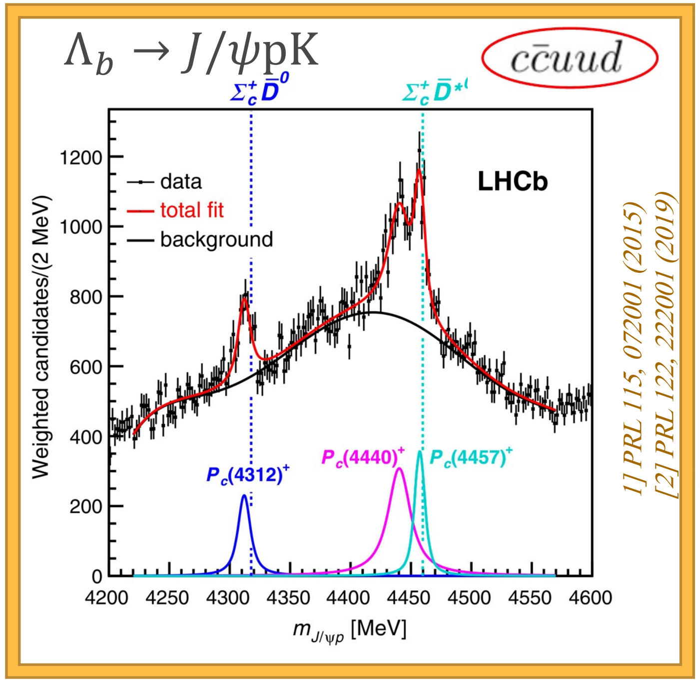
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-} J/\psi$

- Candidate: $D_{s0}^{*}(2317)$ BABAR 2003 in the $D_s^{+}\pi^{0}$

  PRL 90, 242001 (2003)



Spectroscopy II: pentaquarks



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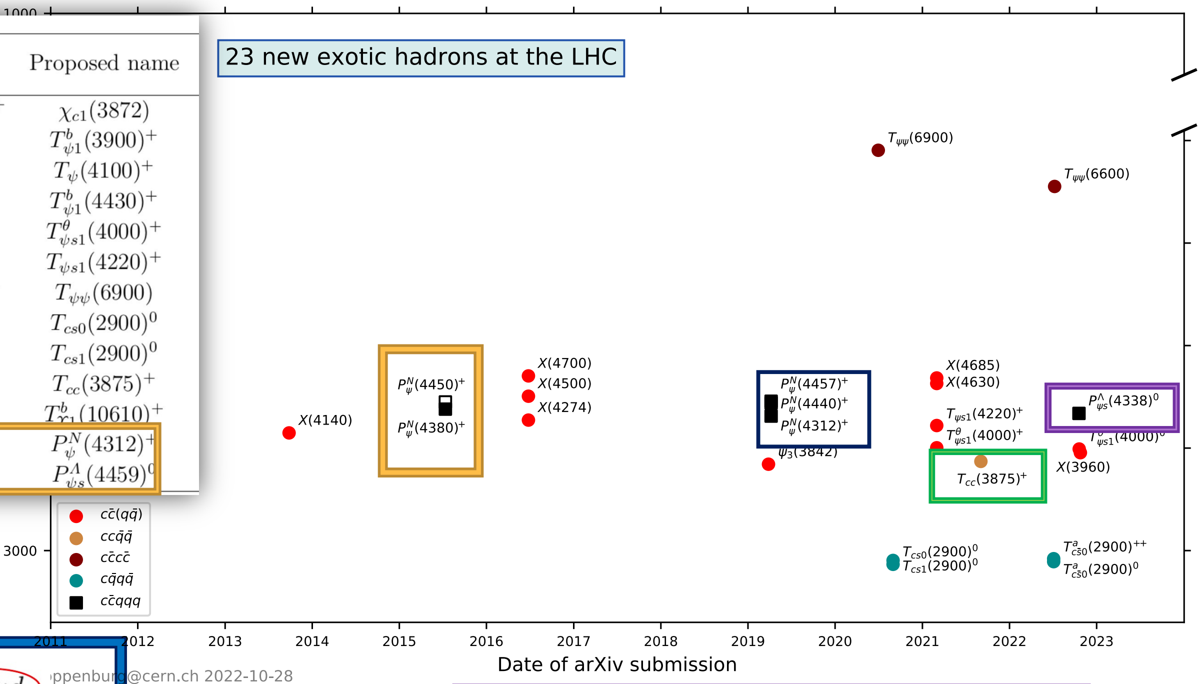
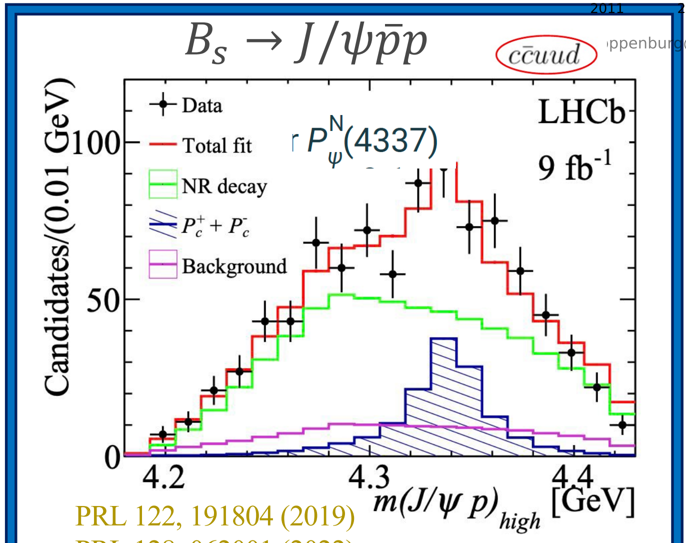
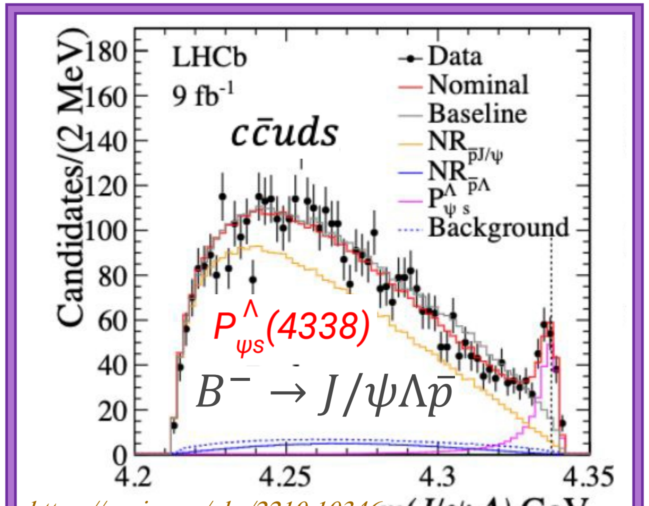


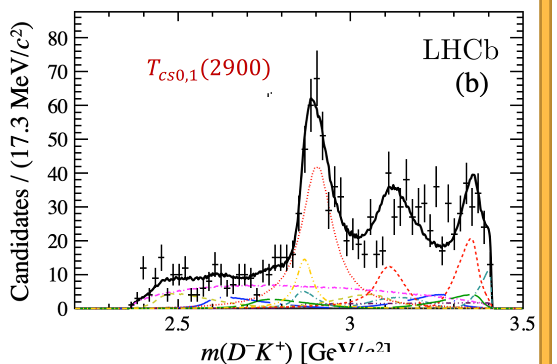


PRL 122, 191804 (2019)
PRL 128, 062001 (2022)



https://arxiv.org/abs/2210.10346

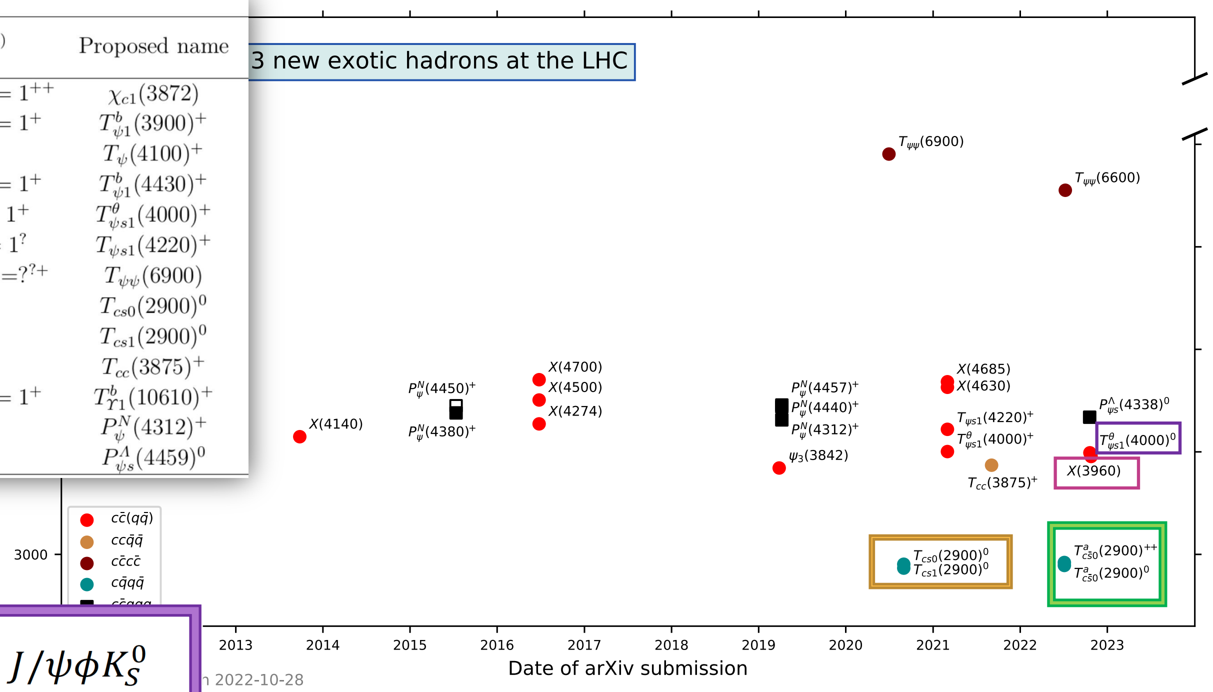
Spectroscopy II: tetraquarks



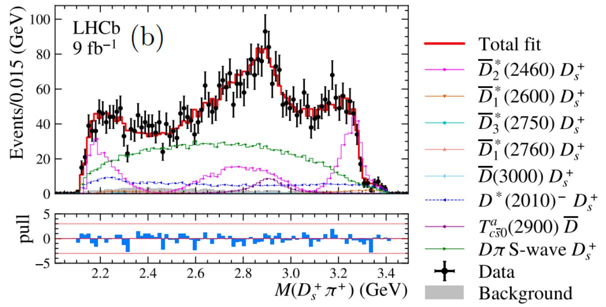
Phys.Rev.D102(2020) 112003
Phys. Rev. Lett. 125 (2020) 242001

$cs\bar{u}\bar{d}$

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ??^+$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$



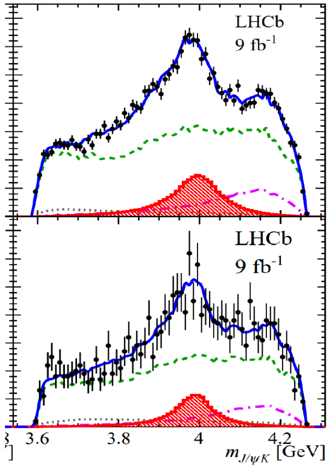
$T^a_{c\bar{s}0}(2900)^{0,++}$ in $B \to DD_s\pi$



LHCb−PAPER−2022−026

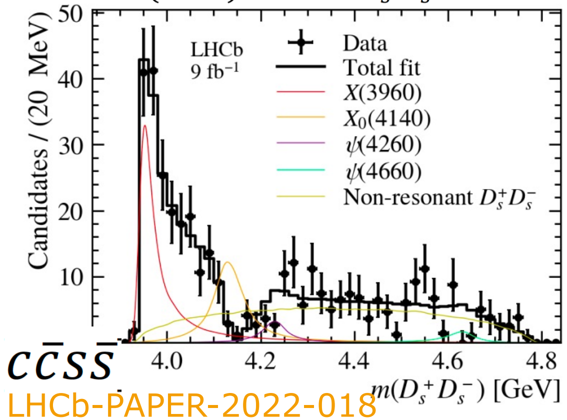
$c\bar{s}u\bar{d}$, $c\bar{s}d\bar{u}$

$T^\theta_{\psi s1}(4000)^0$ in $B^0 \to J/\psi\phi K^0_S$



LHCb−PAPER−2022−040

$X(3960)$ in $B^+ \to D_s^+D_s^-K^+$



$c\bar{c}s\bar{s}$

LHCb-PAPER-2022-018

BACKUP

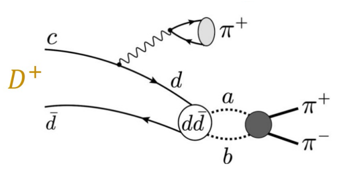
Spectroscopy I: conventional

→**Conventional spectroscopy**:

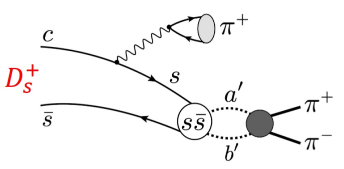
- production of doubly heavy baryons:

  Observation $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ JHEP05(2022)038
  Search for $\Xi_{bc}^{+} \to J/\psi\Xi_c^+$ arXiv: 2204.09541

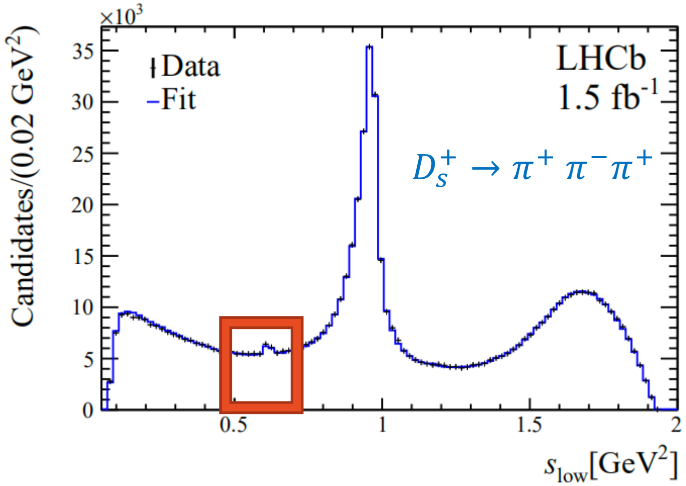
- amplitude analysis of mesons and baryons multi-body decays:
  - $D_s^+ \to \pi^+\pi^-\pi^+$ arXiv: 2208.03300
  - $D^+ \to \pi^+\pi^-\pi^+$ arXiv: 2209.09840
  - $\Lambda_c^+ \to p K^-\pi^+$(on-going)
  - $\Lambda_b \to p K^-\gamma$ (on-going)



$\sum_i d\bar{q}_i q_i \bar{d} = \pi^+\pi^- + \frac{1}{2}\pi^0\pi^0 - \frac{2}{\sqrt{6}}\pi^0\eta + K^0\bar{K}^0 + \frac{1}{3}\eta\eta$

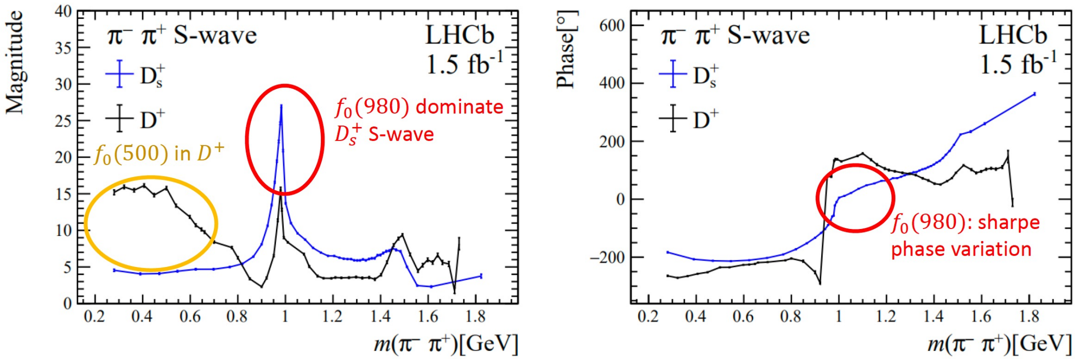


$\sum_i s\bar{q}_i q_i \bar{s} = K^+K^- + K^0\bar{K}^0 + \frac{1}{3}\eta\eta$



1. S-wave is dominant
2. First observation of $\omega(782) \to \pi^+\pi^-$

- Compare to $D^+ \to \pi^+\pi^-\pi^+$



- $f_0(500)$Dynamical pole of the $\pi\pi \leftrightarrow \pi\pi$ scattering
- $f_0(980)$ strongly couples to KK channel

Spectroscopy I: conventional

→**Conventional spectroscopy**:

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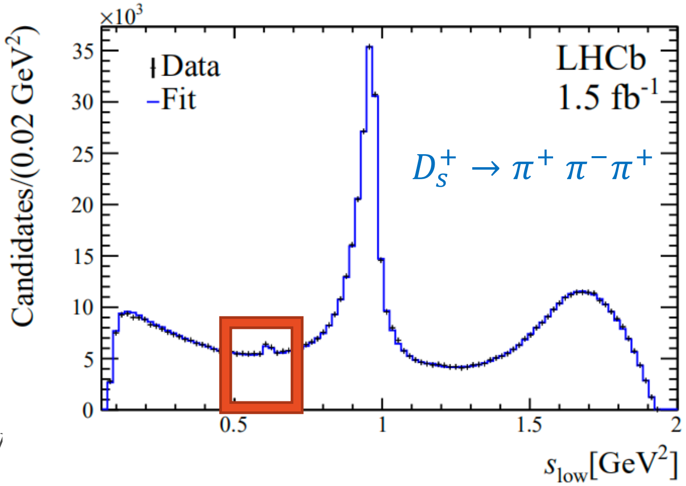
  Search for $\Xi_{bc}^{+} \to J/\psi\Xi_c^+$ arXiv: 2204.09541

- amplitude analysis of mesons and baryons multi-body

  - $D_s^+ \to \pi^+\pi^-\pi^+$ arXiv: 2208.03300
  - $D^+ \to \pi^+\pi^-\pi^+$ arXiv: 2209.09840
  - $\Lambda_c^+ \to p\,K^-\pi^+$ arXiv: 2208.03262
  - $\Lambda_b \to p\,K^-\gamma$ (on-going)



1. S-wave is dominant
2. First observation of $\omega(782) \to \pi^+\pi^-$

Resonance	Magnitude	Phase [°]	Fit fraction (FF) [%]
S-wave			84.97 ± 0.14
$\rho(770)^0$	0.1201 ± 0.0030	79.4 ± 1.8	1.038 ± 0.054
$\omega(782)$	0.04001 ± 0.00090	-109.9 ± 1.7	0.360 ± 0.016
$\rho(1450)^0$	1.277 ± 0.026	-115.2 ± 2.6	3.86 ± 0.15
$\rho(1700)^0$	0.873 ± 0.061	-60.9 ± 6.1	0.365 ± 0.050
combined	–	–	6.14 ± 0.27
$f_2(1270)$	1 (fixed)	0 (fixed)	13.69 ± 0.14
$f_2'(1525)$	0.1098 ± 0.0069	178.1 ± 4.2	0.0455 ± 0.0070
sum of fit fractions			104.3
χ^2/ndof (range)	[1.45 – 1.57]		