LHCb: Tetraquarks

Zehua Xu
On behalf of the LHCb collaboration

LPC-Clermont, IN2P3/CNRS

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@ CERN

Outline

- Recap of tetraquark history at LHCb

- Doubly charged tetraquark and its neutral partner ($T^{a}_{c\bar{s}0}(2900)^{0/++}$)

  New **[LHCb-PAPER-2022-026 in preparation]**

- Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

  New **[LHCb-PAPER-2022-018,LHCb-PAPER-2022-019 in preparation]**

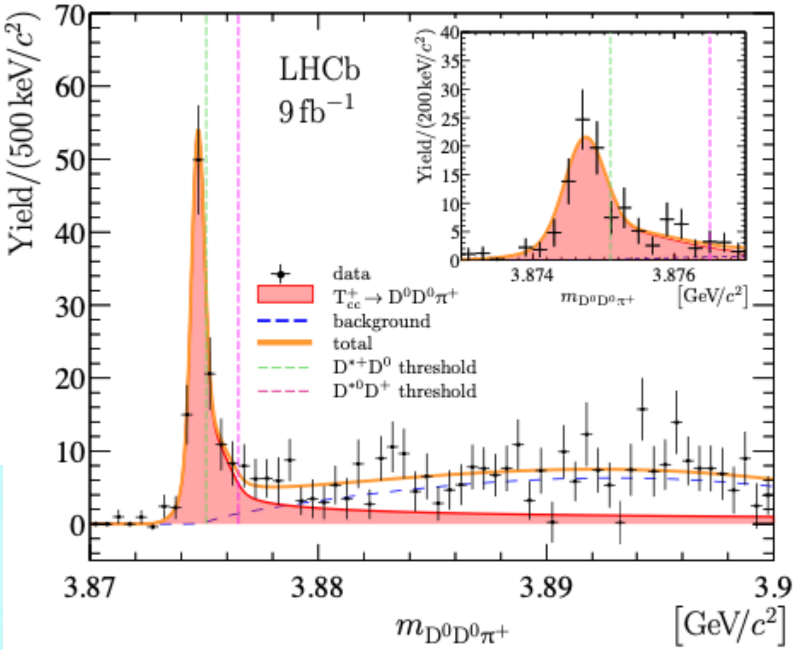
Recap of history

T_{cc}^{+} observation in $D^0D^0\pi^+$

[Nature Physics 18, 751–754 (2022)]

- First observation of same-sign doubly charmed tetraquark T_{cc}^{+}
- Very narrow state in $D^0D^0\pi^+$ mass spectrum
- Manifestly exotic with quark content $cc\bar{u}\bar{d}$
- Mass ~ 3875 MeV, very close to the $D^{*+}D^0$ threshold

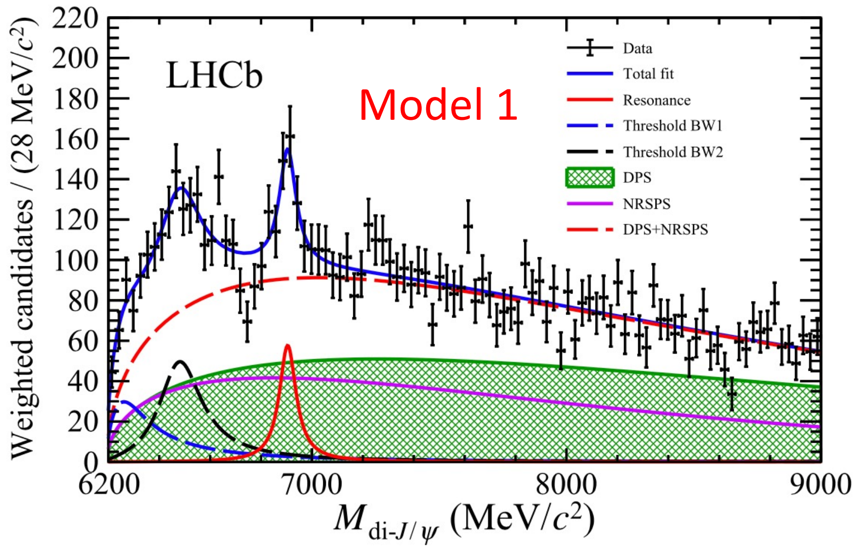
$$\delta m_{\rm BW} = -273 \pm 61({\rm stat}) \pm 5({\rm syst})^{+11}_{-14}({\rm model})\ {\rm keV}$$
$$\Gamma = 410 \pm 65({\rm stat}) \pm 43({\rm syst})^{+18}_{-38}({\rm model})\ {\rm keV}$$

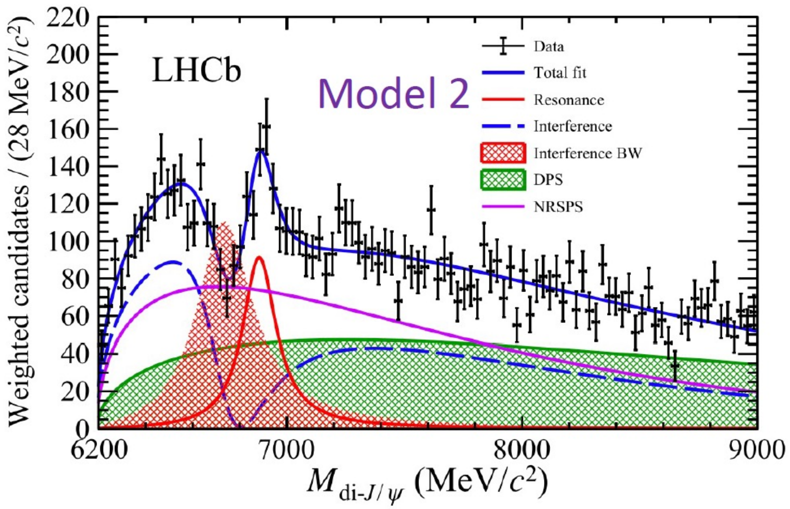


- Consistent with isoscalar $J^P = 1^+$
- No hint of possible T^0, T^{++} isospin partners

$T_{\psi\psi}(6900)$ observation

[Science Bulletin 65 (2020) 032]





- Model 1, no-interference fit:

$$M[T_{\psi\psi}(6900)] = 6905 \pm 11(\text{stat}) \pm 7(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma[T_{\psi\psi}(6900)] = 80 \pm 19(\text{stat}) \pm 33(\text{syst})\ \text{MeV}/c^2$$

- Model 2, simple model with interference:

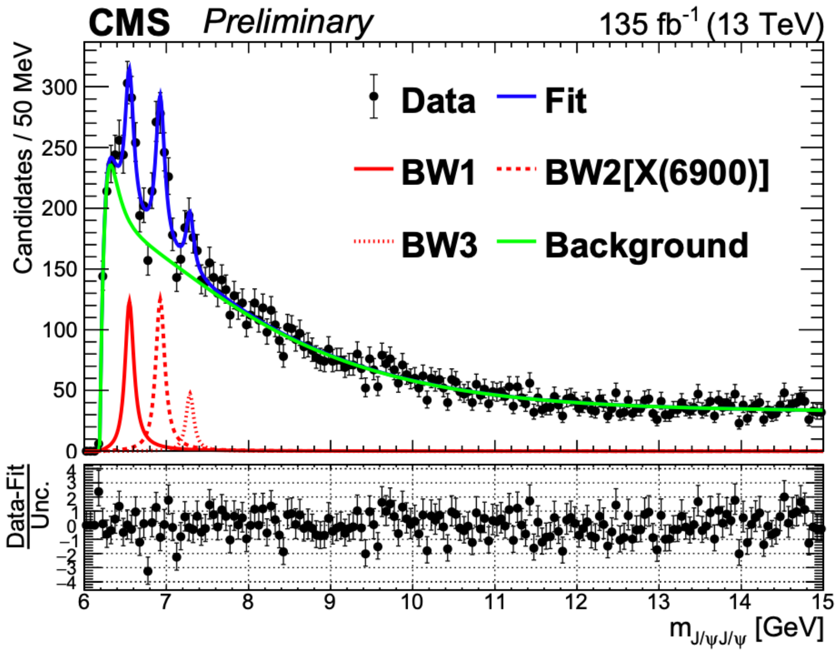
$$M[T_{\psi\psi}(6900)] = 6886 \pm 11(\text{stat}) \pm 11(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma[T_{\psi\psi}(6900)] = 168 \pm 33(\text{stat}) \pm 69(\text{syst})\ \text{MeV}/c^2$$

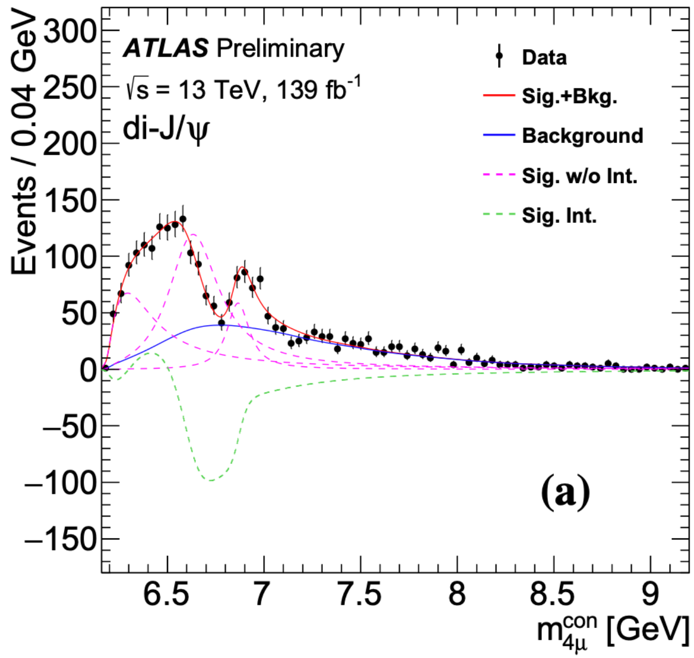
- The significance in two model both $> 5\sigma$, $T_{\psi\psi}(6900)$ is observed.

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

[CMS PAS BPH-21-003]

[ATLAS-CONF-2022-040]

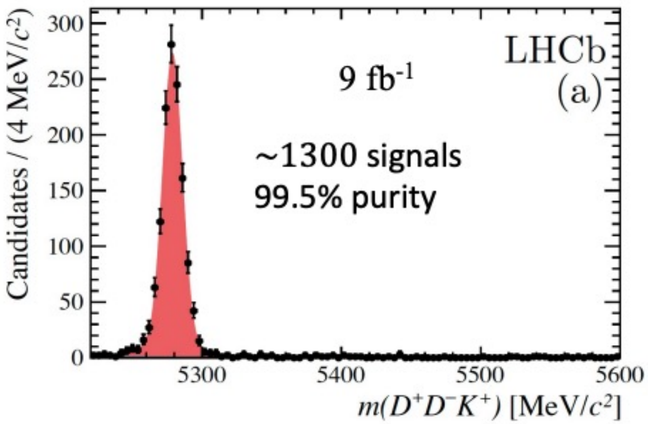


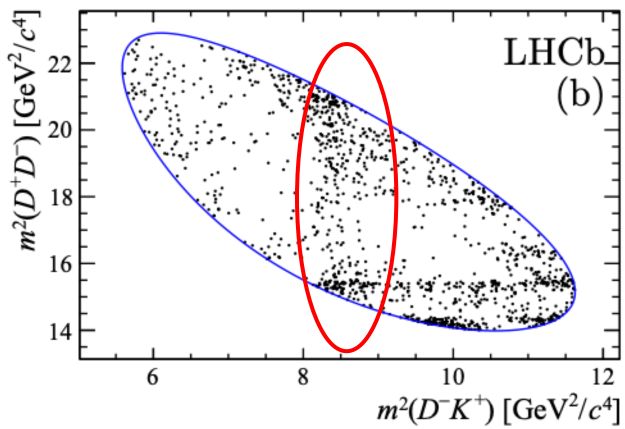


- $T_{\psi\psi}(6900)$ is confirmed by CMS and ATLAS
- $T_{\psi\psi}(6600)$ and $T_{\psi\psi}(7300)$ reported by CMS investigated by LHCb in future

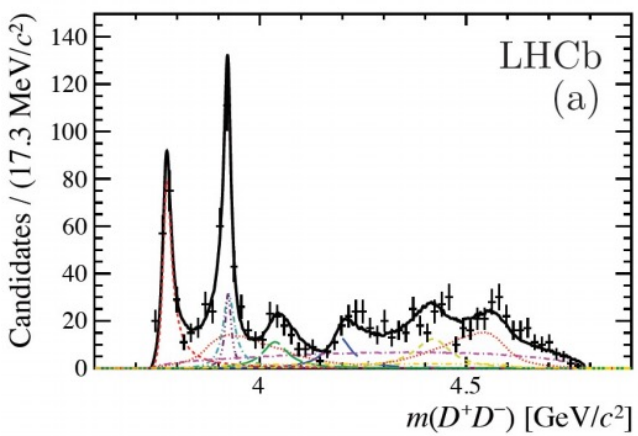
$T_{cs0(1)}(2900)^0$ observation [PRL 125 (2020) 242001, PRD 102 (2020) 112003]

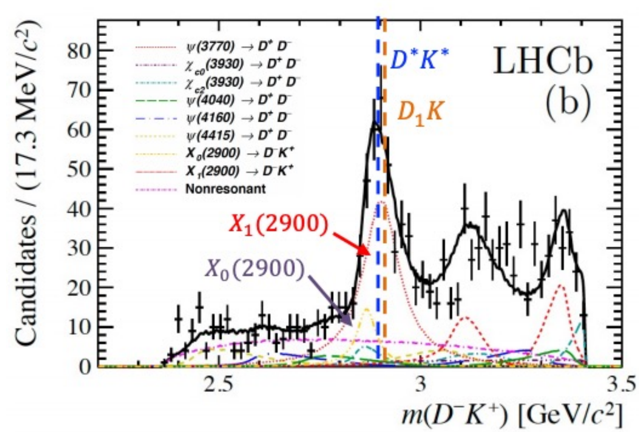
- $B^+ \to D^+ D^- K^+$, an ideal channel to search for open-charm tetraquark





- Amplitude analysis performed:



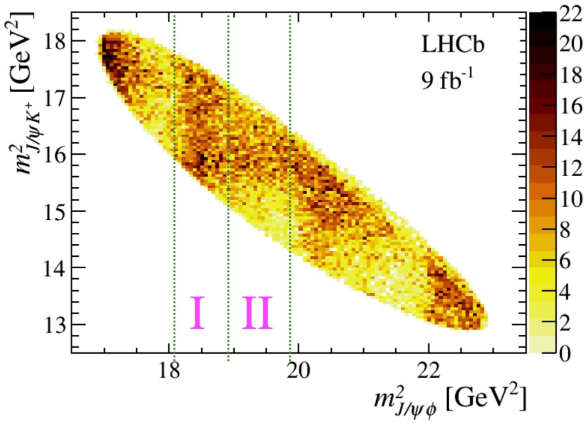


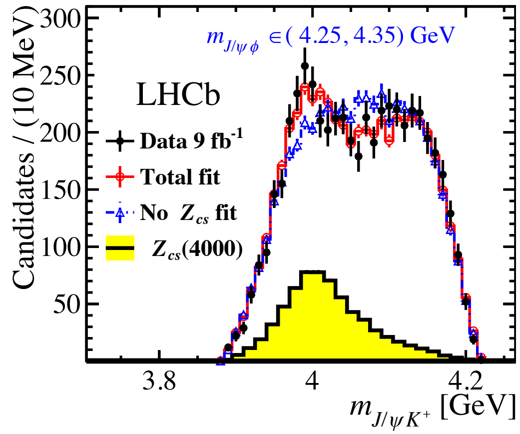
- First open charmed tetraquark observed

$T_{\psi s1}^{\phi}(4000)^{+}$ and $T_{\psi s1}(4220)^{+}$

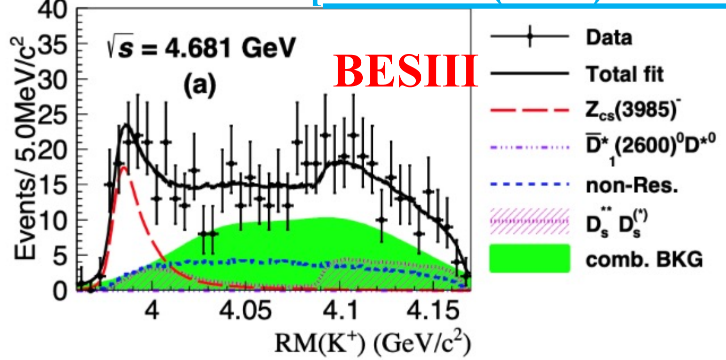
[PRL. 127 (2021) 082001]

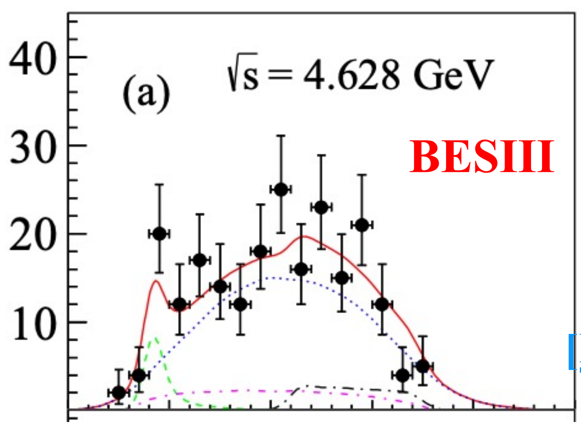
- $T_{\psi s1}^{\phi}(4000)^{+}$ and $T_{\psi s1}(4220)^{+}$ observed in $B^{+} \to J/\psi\phi K^{+}$





[PRL 126 (2021) 102001]





- Evidence of $T_{\psi s1}^{\phi}(3985)^{0}$ reported by BESIII in the $D_s^{+}D^{*-} + D^{-}D_s^{*+}$

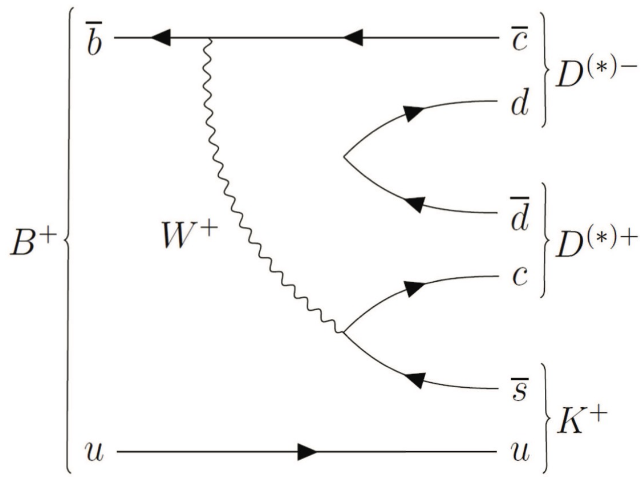
[PRL. 129 (2022) 112003]

- $T_{\psi s1}^{\phi}(4000)^{+}$ isospin partner searched in $B^{0} \to J/\psi\phi K_s^{0}$; expect some results at LHCb implication workshop tomorrow

Doubly charged tetraquark and its neutral partner

Motivation of searching for $T^{a}_{c\bar{s}0}(2900)^{0/++}$

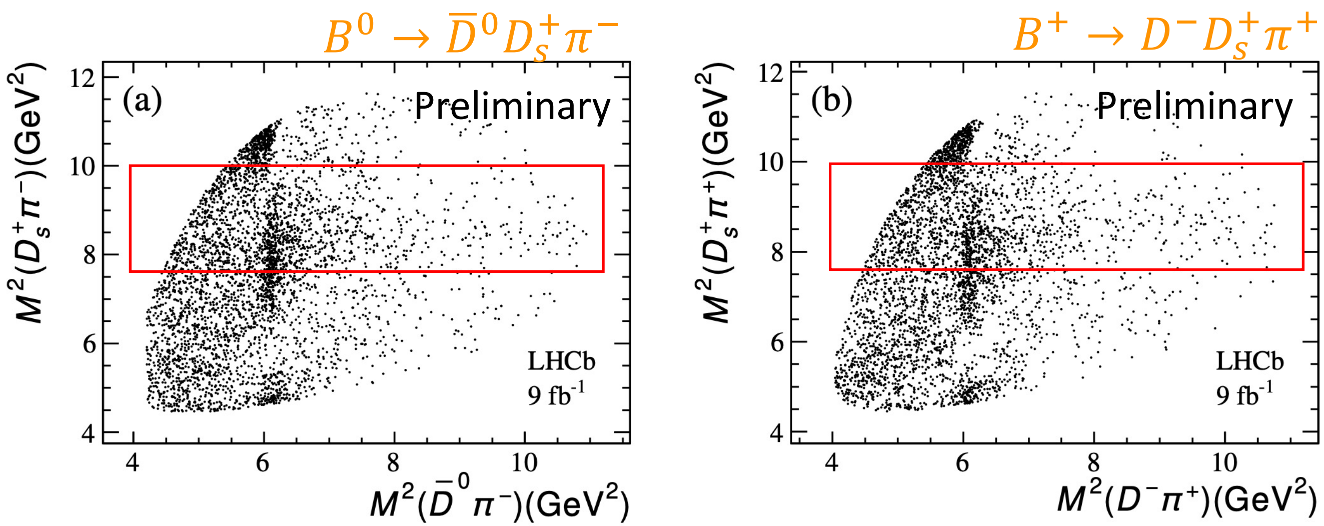
- $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$ observed, are there their isospin partners?
- Possible to search for isospin partner in $D_s^+\pi^+$ or $D_s^+\pi^-$ final states in $B^+ \to D^- D_s^+ \pi^+$ and $B^0 \to \overline{D}^0 D_s^+ \pi^-$
- Help to determine whether or not D_{sJ} $(D_s^+\pi^0)$ states have some tetraquark states theorized [PRL 90 (2003) 242001]



Dataset

[LHCb-PAPER-2022-026]

- Full LHCb Run 1+2 dataset;
- After loose PID cuts and multivariate analysis, $B^+ \to D^- D_s^+ \pi^+$ yields ~3940 and $B^0 \to \bar{D}^0 D_s^+ \pi^-$ yields ~4420, purity > 90%

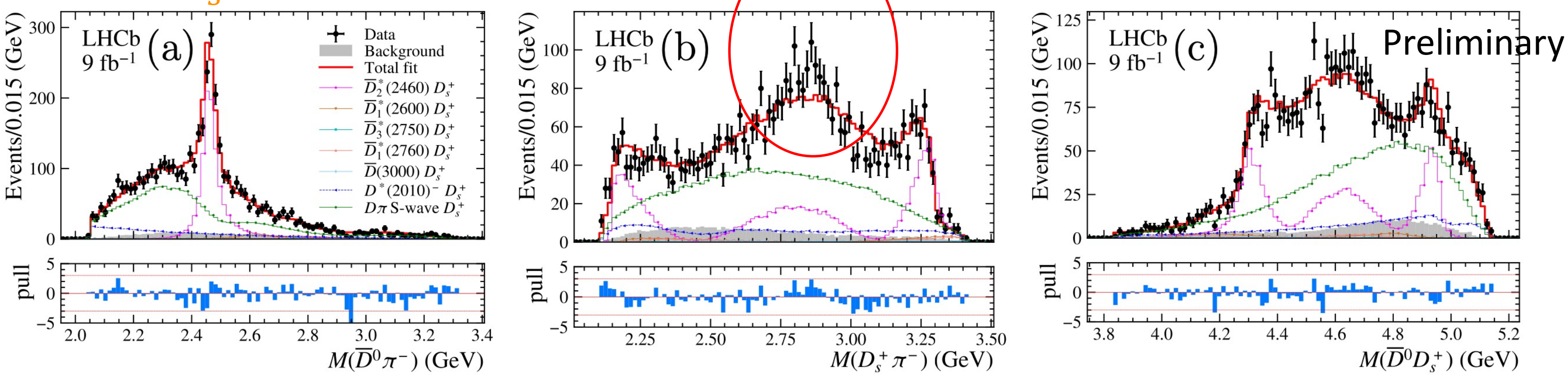


- There are hints of $T^a_{c\bar{s}0}(2900)^0$ and $T_{c\bar{s}0}(2900)^{++}$ from Dalitz plots
- Joint Dalitz plot fit performed

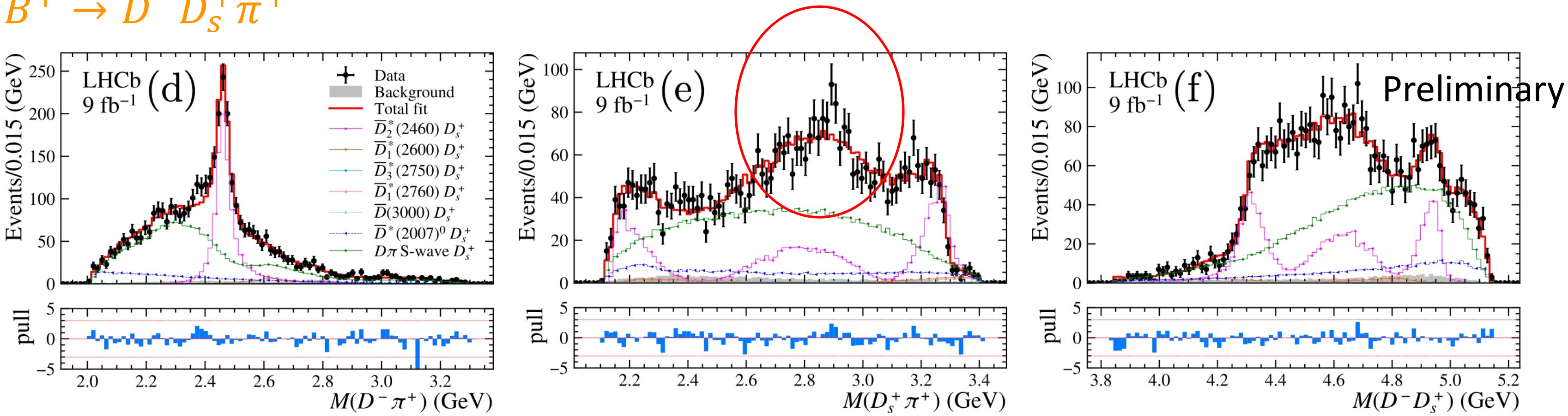
Dalitz fit with only D^*

[LHCb-PAPER-2022-026]

$B^0 \to \overline{D}^0 D_s^+ \pi^-$



$B^+ \to D^- D_s^+ \pi^+$

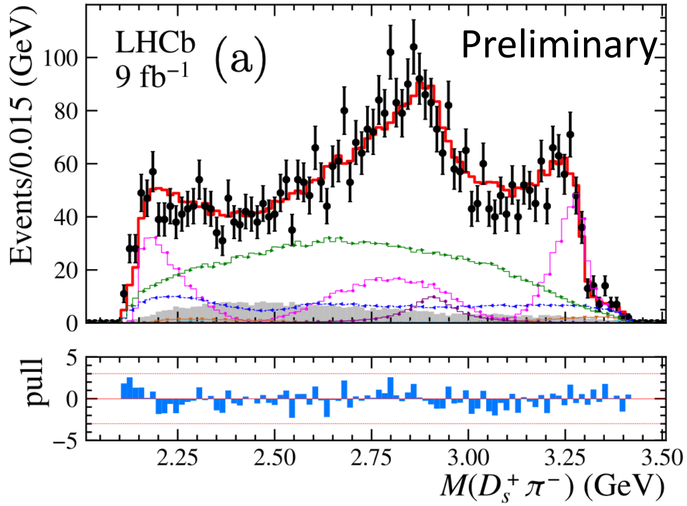


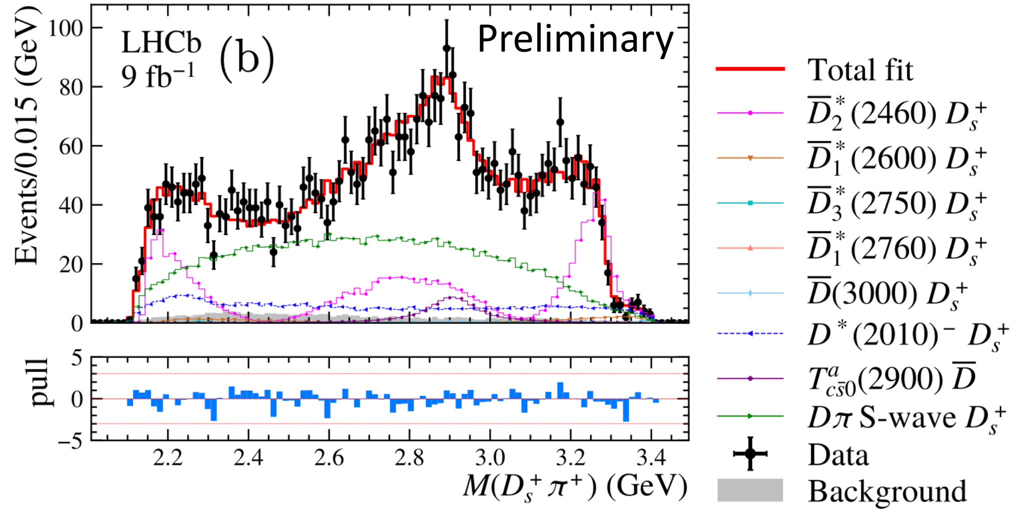
- Fit poorly describes data around 2.9 GeV in $D_s^+\pi^-(\pi^+)$

Dalitz fit with $T^{a}_{c\bar{s}0}(2900)^{0/++}$

[LHCb-PAPER-2022-026]

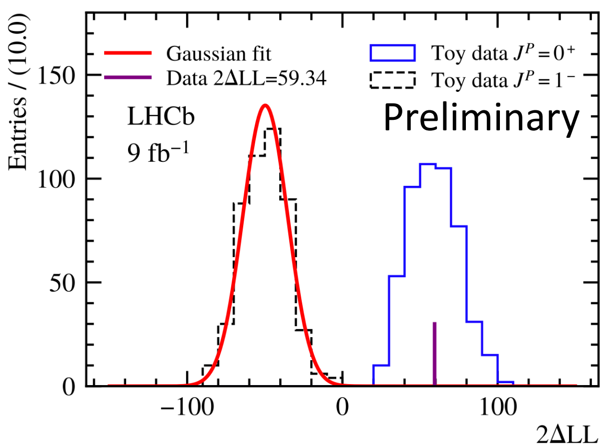
$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $\quad$ $B^+ \to D^- D_s^+ \pi^+$



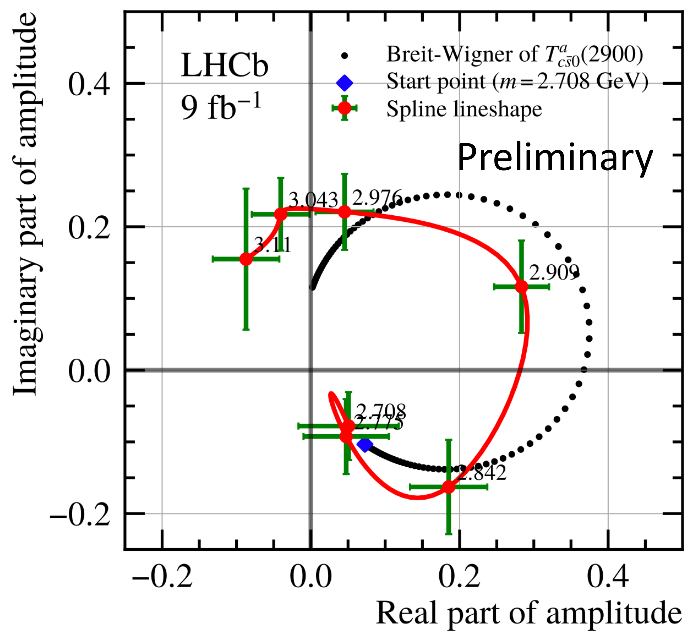


- The fit greatly improved;
- Significance of $T^{a}_{c\bar{s}0}(2900)^{0/++}$ >9σ
- Strong preference for J^P as 0^+ (>7σ)
- Mass and width are measured

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV and}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV},$$



Argand diagram of $T^{a}_{c\bar{s}0}(2900)^{0/++}$ [LHCb-PAPER-2022-026]



- The fit using seven spline points to describe $T^{a}_{c\bar{s}0}(2900)^{0/++}$ lineshape;
- Consistent with Breit-Wigner lineshape, further supports the resonance character

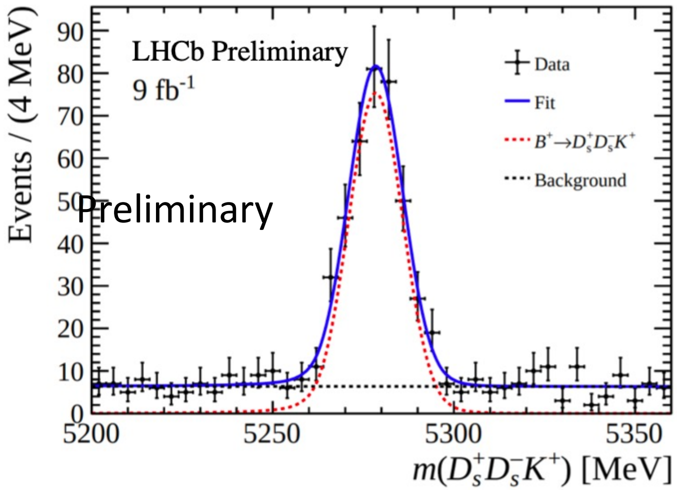
Observation of $D_s^+ D_s^-$ Threshold Resonances in $B^+ \to D_s^+ D_s^- K^+$

$B^+ \to D_s^+ D_s^- K^+$ at LHCb

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

- Motivation:
  - $B^+ \to D_s^+ D_s^- K^+$ has not been observed previously
  - $\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)$ allows to estimate partial width of X near threshold [arXiv: 1602.08421]
  - Also search for other exotics

- Signal reconstruction using LHCb Run 1+2 dataset;
  - B^+ yield ~360 candidates with 84.4% purity

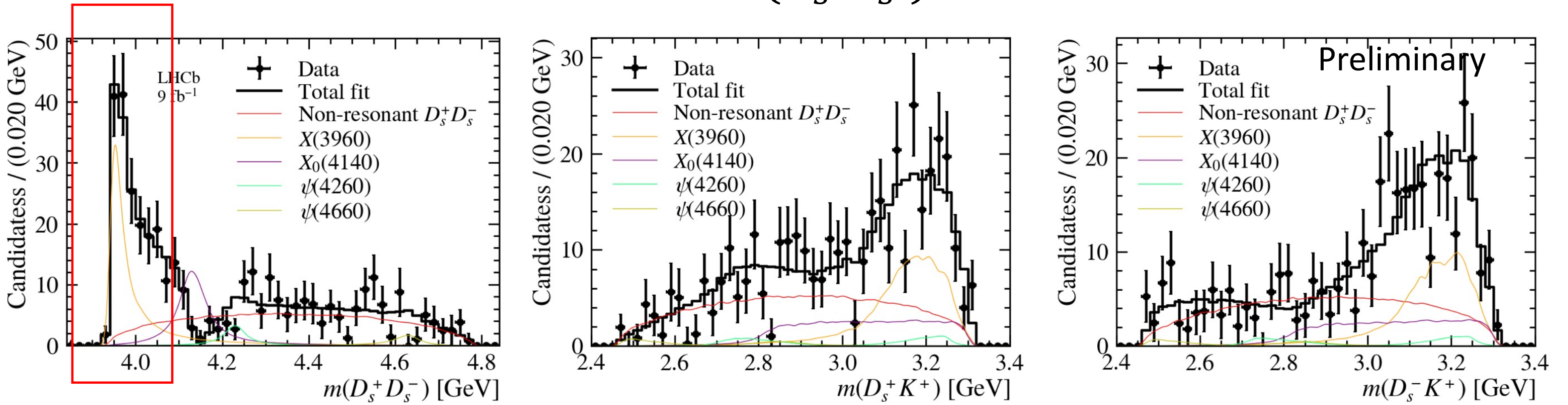


- Dalitz plot analysis to understand the resonance structure

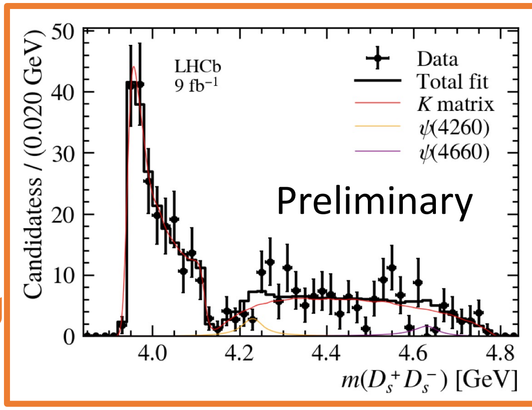
Dalitz analysis

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

- Near-threshold enhancement in $m(D_s^+ D_s^-)$



- Baseline model well describes data
  - 0^{++}: $X(3960)$, $X(4140)$ and NR; 1^{--}: $\psi(4260)$ and $\psi(4660)$
- $X(3960)$:
  - Significance $> 12\sigma$
  - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} ($> 9\sigma$)
- $X(4140)$:
  - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} ($> 3\sigma$)
  - The dip can also described by $J/\psi \to D_s^+ D_s^-$ scattering



$X(3960)$ and $\chi_{c0}(3930)$

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

	M [MeV]	Γ [MeV]	J^{PC}
$X(3960)$	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}
$\chi_{c0}(3930)$	3924 ± 2	17 ± 5	

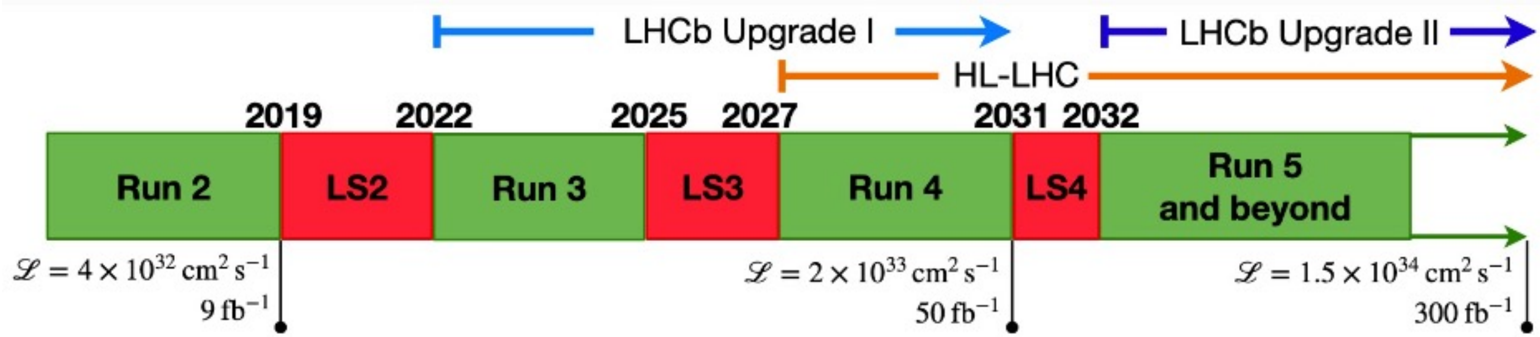
- Same particles?
  - Latest Lattice QCD shows the enhancement near the threshold of $D_s^+ D_s^-$ due to the presence of $\chi_{c0}(3930)$ [arXiv: 2207.08490]

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\times\mathcal{FF}^X_{B^+\to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\times\mathcal{FF}^X_{B^+\to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

  - X has an exotic nature: creation of $s\bar{s}$ from vacuum is suppressed wrt. $u\bar{u}$ and $d\bar{d}$; $X \to D_s^+D_s^-$ has smaller phase-space than $X \to D^+D^-$

- Different particles?
  - No obvious candidate within conventional multiplets for them; likely to be exotic

Summary and Prospects



- **Very fruitful tetraquarks results at LHCb, e.g. charmonium-like, double charmed, fully charmed states and etc.; recent interesting results:**
  - Two new tetraquark candidates $T^{a}_{c\bar{s}0}(2900)^{0/++}$ observed
  - $X(3960)$ near $D_s^+ D_s^-$ threshold observed

- **Larger statistics in Run 3 boosts multiquark states searching:**
  - Search for more tetraquarks and their isospin partners
  - Study J^P and other properties of tetraquark states
  - Theoretical predictions very helpful
  - ……

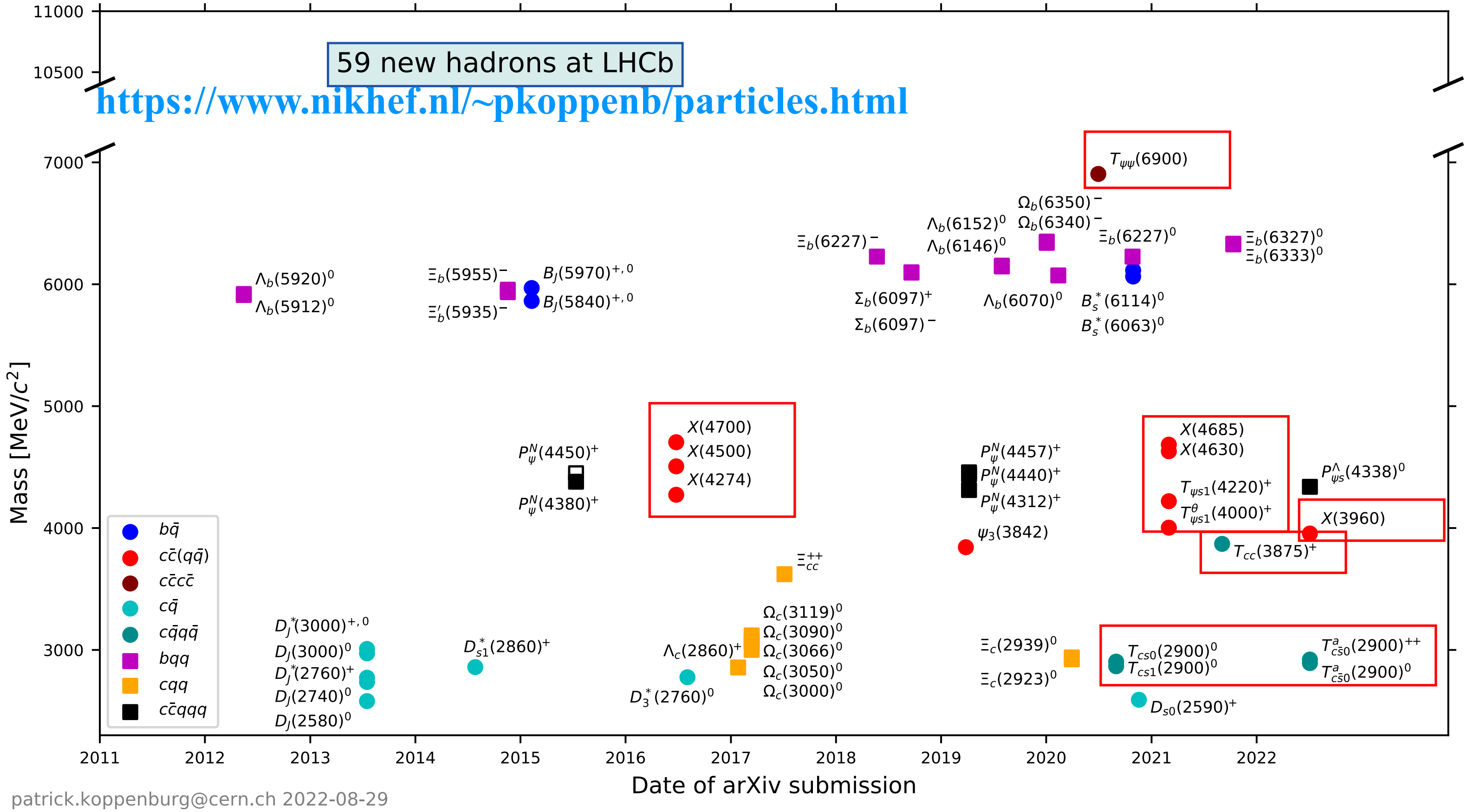
Backup

Thanks for your attention

Introduction

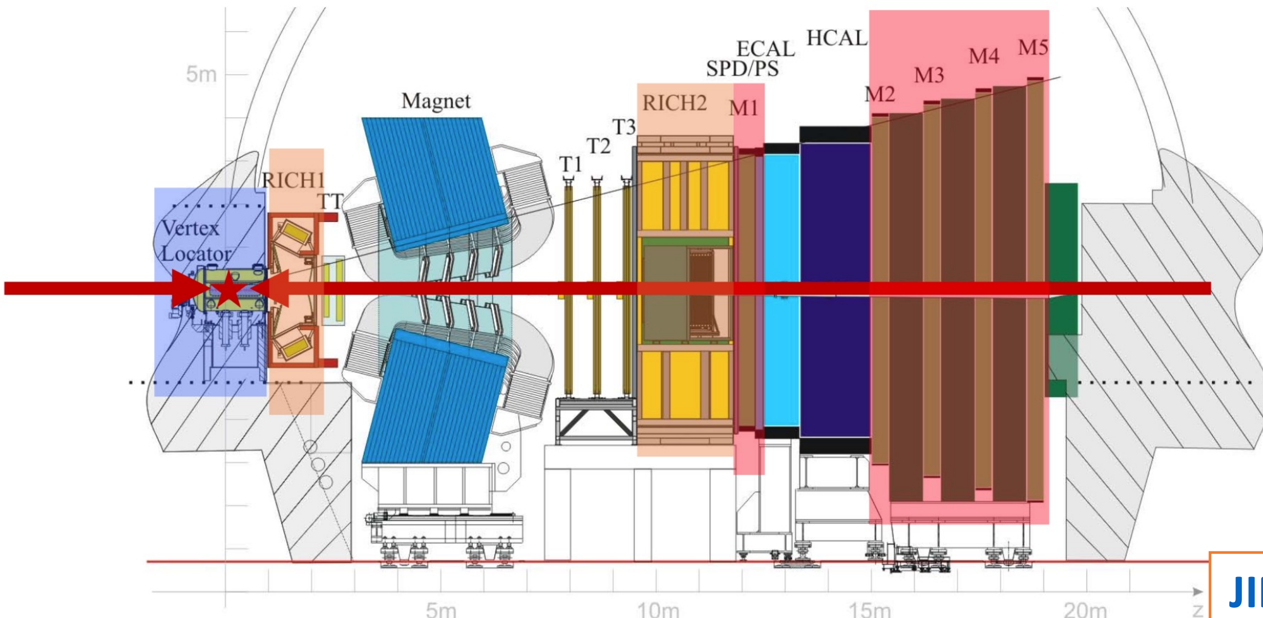
- First tetraquark candidate observed at BELLE in 2003 **[PRL 91 (2003) 262001]**
- 59 new hadrons observed at LHCb, 10+ are tetraquark states
- Following "Exotic hadron naming convention" proposed by LHCb

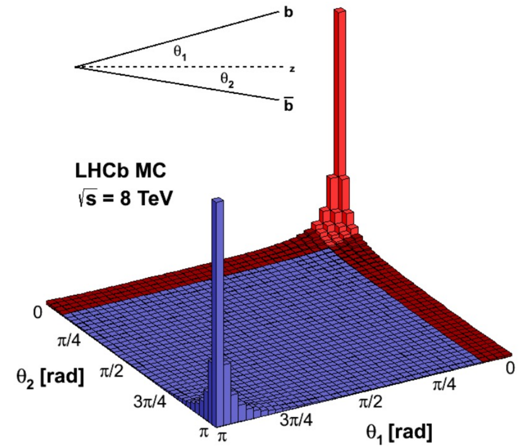
[arXiv: 2206.15233]



The LHCb detector

- LHCb is a dedicated heavy flavor physics experiment at LHC
  - ~20,000/s $b\bar{b}$ generated at LHCb point in Run2
  - A single-arm forward region spectrometer covering $2 < \eta < 5$





JINST 3 (2008) S08005

Vertex:	$\sigma_{IP} = 20\ \mu m$
Time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ ($5 - 100$ GeV/c)
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

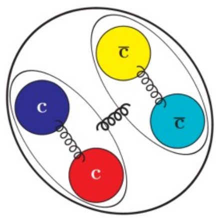
Exotic Hadron Naming Convention [arXiv: 2206.15233]

- Many new exotic hadrons do not fit into the current PDG naming convention;
- Rule of new naming convention:
  - Any states with less than 4 quarks will remain unchanged
  - Use T for tetraquarks and P for pentaquarks
  - Superscripts will indicate isospin, parity and G-parity
  - Subscripts Υ, ψ and ϕ indicate hidden beauty, charm and strangeness

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

Search for full charmed $cc\bar{c}\bar{c}$ tetraquark

- Motivation:
  - $T_{QQ\bar{Q}\bar{Q}}$ ($Q = c$ or b) states is isolated from both quarkonia and quarkonium-like exotic states
  - A $T_{cc\bar{c}\bar{c}}$ can decay into a pair of charmonia



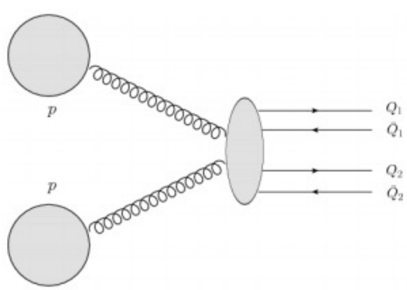
[arXiv: 1803.02522]

J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	–
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

Decays in $2J/\psi$ directly or with feed-down

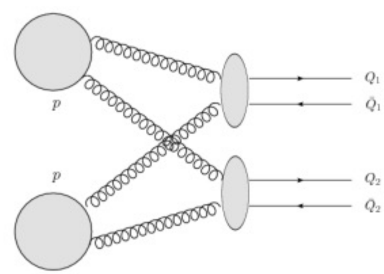
- Prompt J/ψ pair production:

Single parton scattering (SPS)



- $T_{cc\bar{c}\bar{c}}$ state is a special case of SPS

Double parton scatterings (DPS)



- Dominates high J/ψ pair mass region

Outline

- Open charmed tetraquarks:
  - Observation of D^-K^+ structure in $B^+ \to D^+D^-K^+$ $(T_{cs0(1)}(2900)^0)$
    [PRL 125 (2020) 242001, PRD 102 (2020) 112003]
  - Doubly charged tetraquark and its neutral partner $(T^a_{c\bar{s}0}(2900)^{0/++})$
    New [LHCb-PAPER-2022-026 in preparation]
- Doubly charmed tetraquark $T_{cc}(3875)^+$ [Nature Physics 18, 751–754 (2022)]
- Open charmed tetraquark $T_{\psi\psi}(6900)$ [Science Bulletin 65 (2020) 032]
- Charmonium-like tetraquark
  - Observation of a resonant structure near the $D_s^+D_s^-$ threshold
    New [LHCb-PAPER-2022-018,LHCb-PAPER-2022-019 in preparation]
  - Tetraquarks in in $B^+ \to J/\psi\phi K^+$
- Sizeable ω contribution to $\chi_{c1}(3872) \to \pi^+\pi^-J/\psi$
  [LHCb-PAPER-2021-045]