Open Flavour Spectroscopy

Maurizio Martinelli
University of Milano Bicocca and INFN

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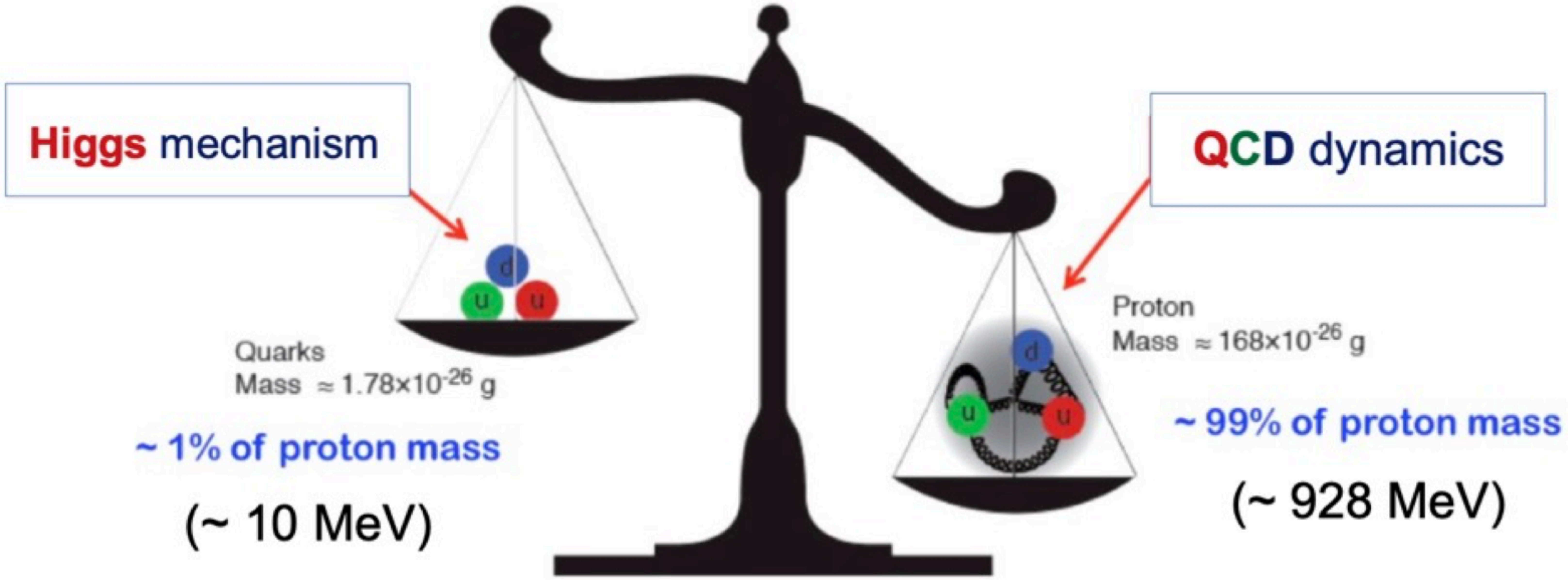
Motivation

Strong Interactions

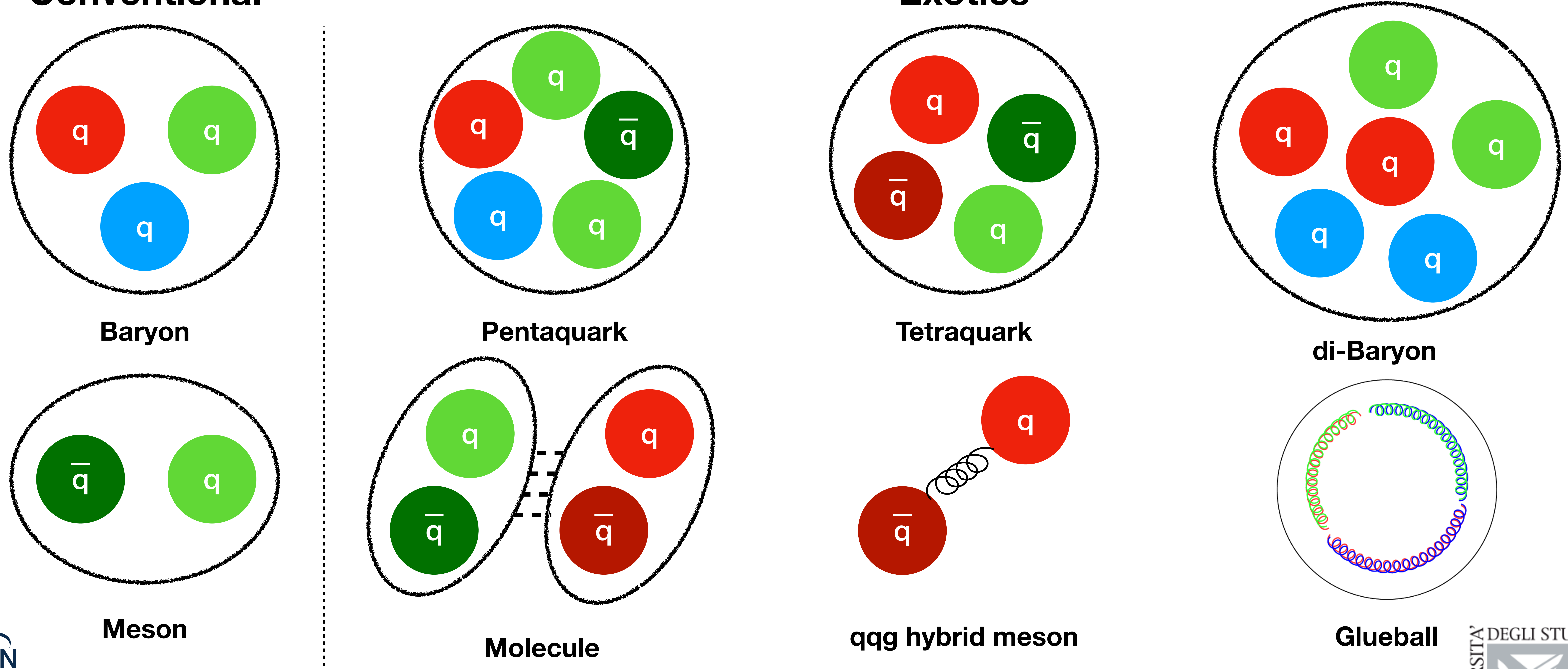
- **Quarks and gluons not isolated in nature**
  Confined in Hadrons
- **Spectroscopy gives insight into QCD in the non-perturbative region**
- **Complex exotic hadrons can reveal new or hidden aspects of QCD dynamics**



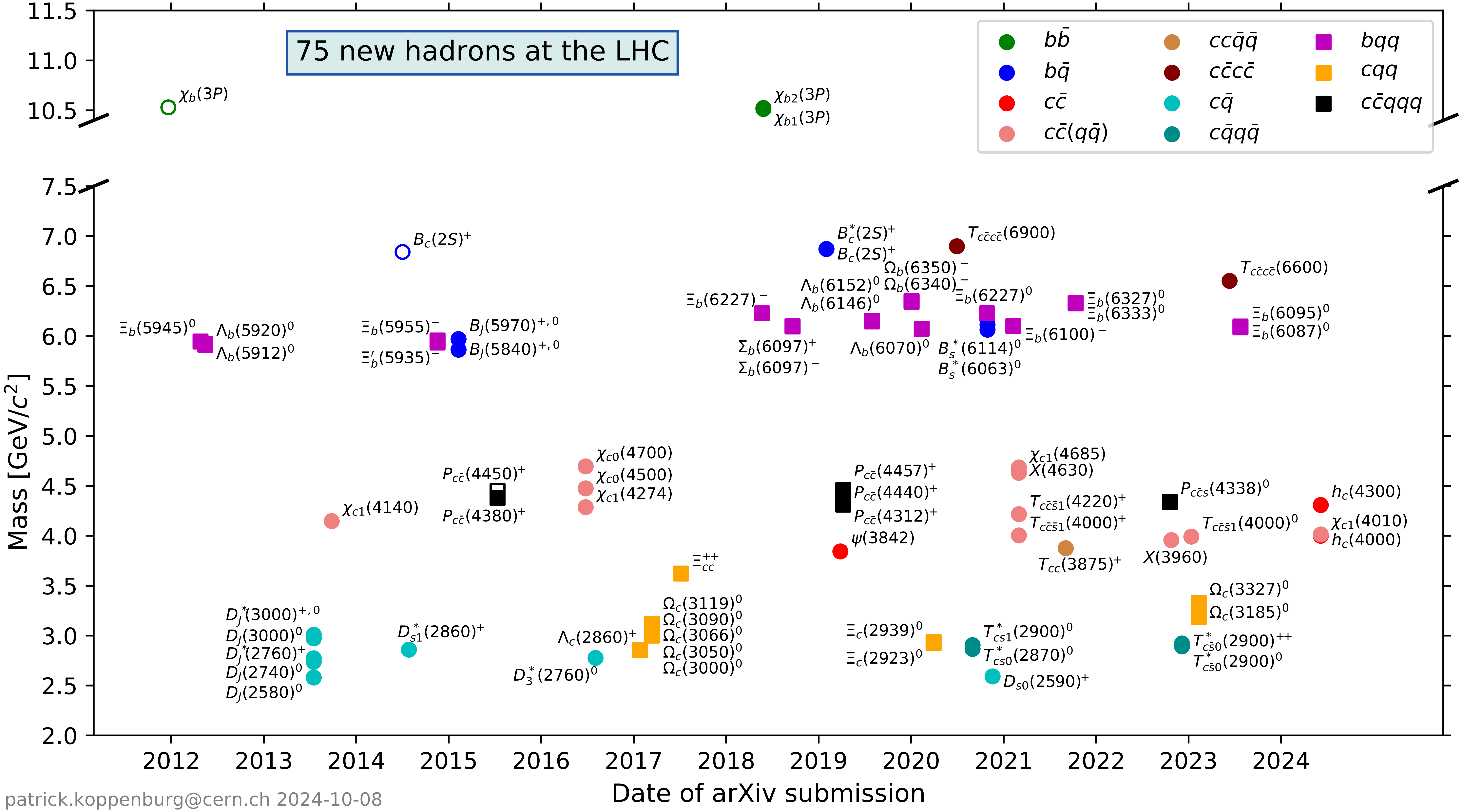
Hadron Types

Conventional

Exotics



An Ever-Rising Field



Analysis Techniques

Peak Hunting

Direct Production

- Identify particles via their prompt or secondary production by reconstructing two-body decays
- Angular properties determined by
  - production mechanism
  - decay chain

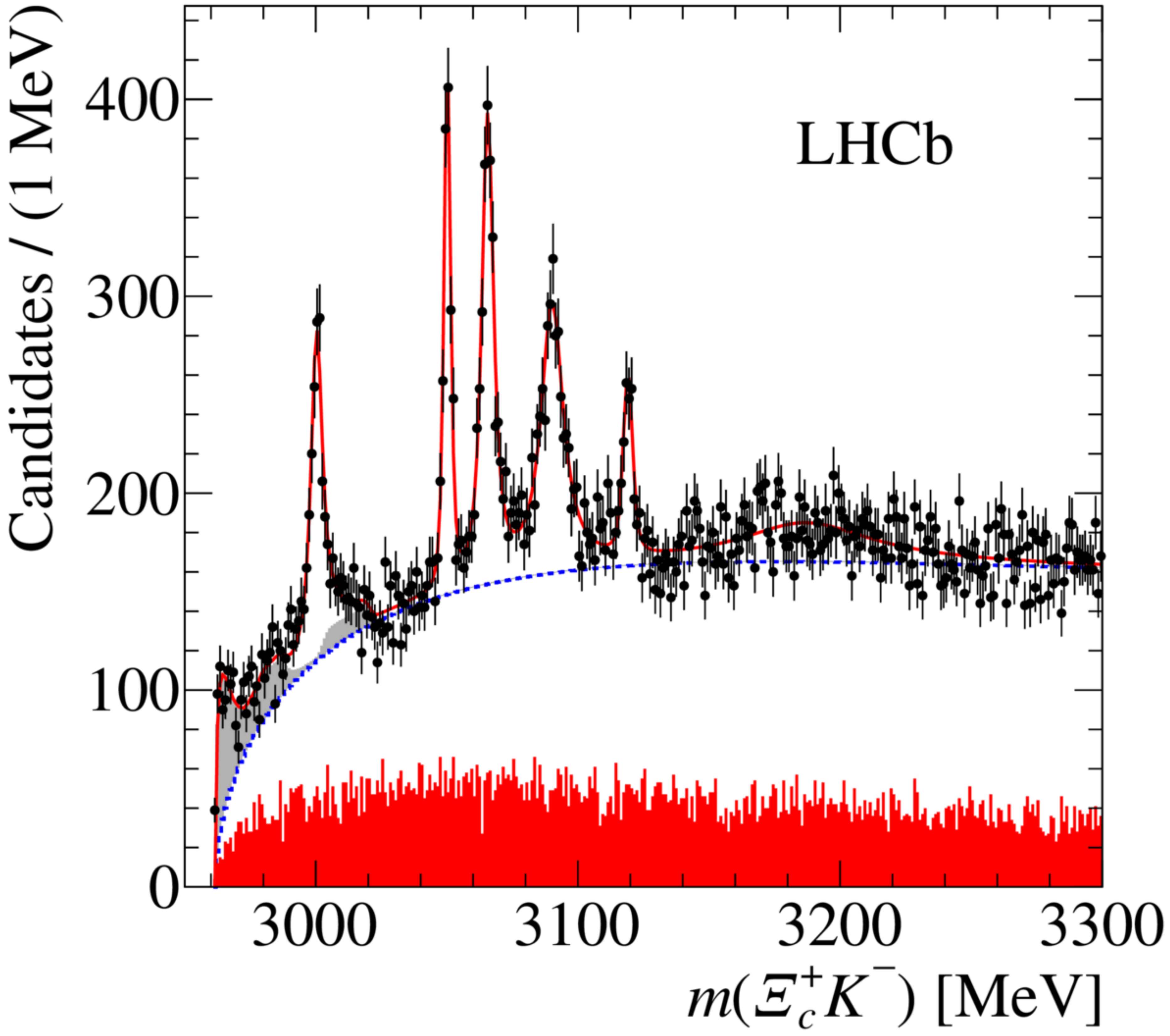
Advantages

- Relatively simple to model the signal
- Large datasets

Disadvantages

- Need optimal knowledge of the combinatorial and physical backgrounds

Phys. Rev. Lett. 118 (2017) 182001



Amplitude Analyses

Multibody Decays

- Model the decay and highlight the contribution of known and new resonances
- Often study resonances in the decays of heavy flavored particles (D, B, baryons)

Advantages

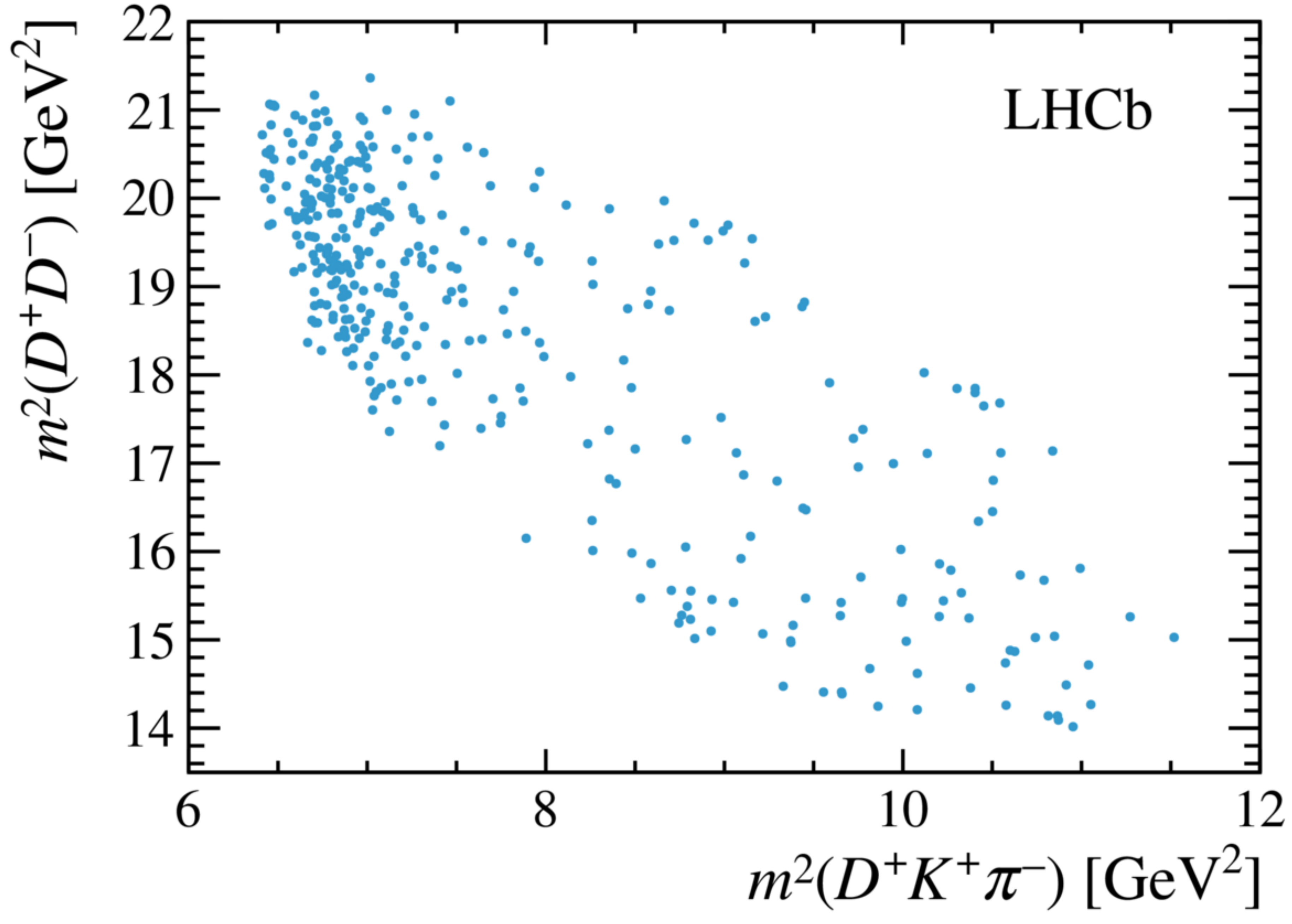
- Complete description of the decay with interference among the amplitudes

Disadvantages

- Require pure signals and good understanding of detector efficiency
- Model-dependent description
- Computationally intensive for complex decays

Efforts to standardise and document partial wave analyses frameworks

Phys. Rev. Lett. 126, (2021) 122002



Amplitude Analysis Frameworks

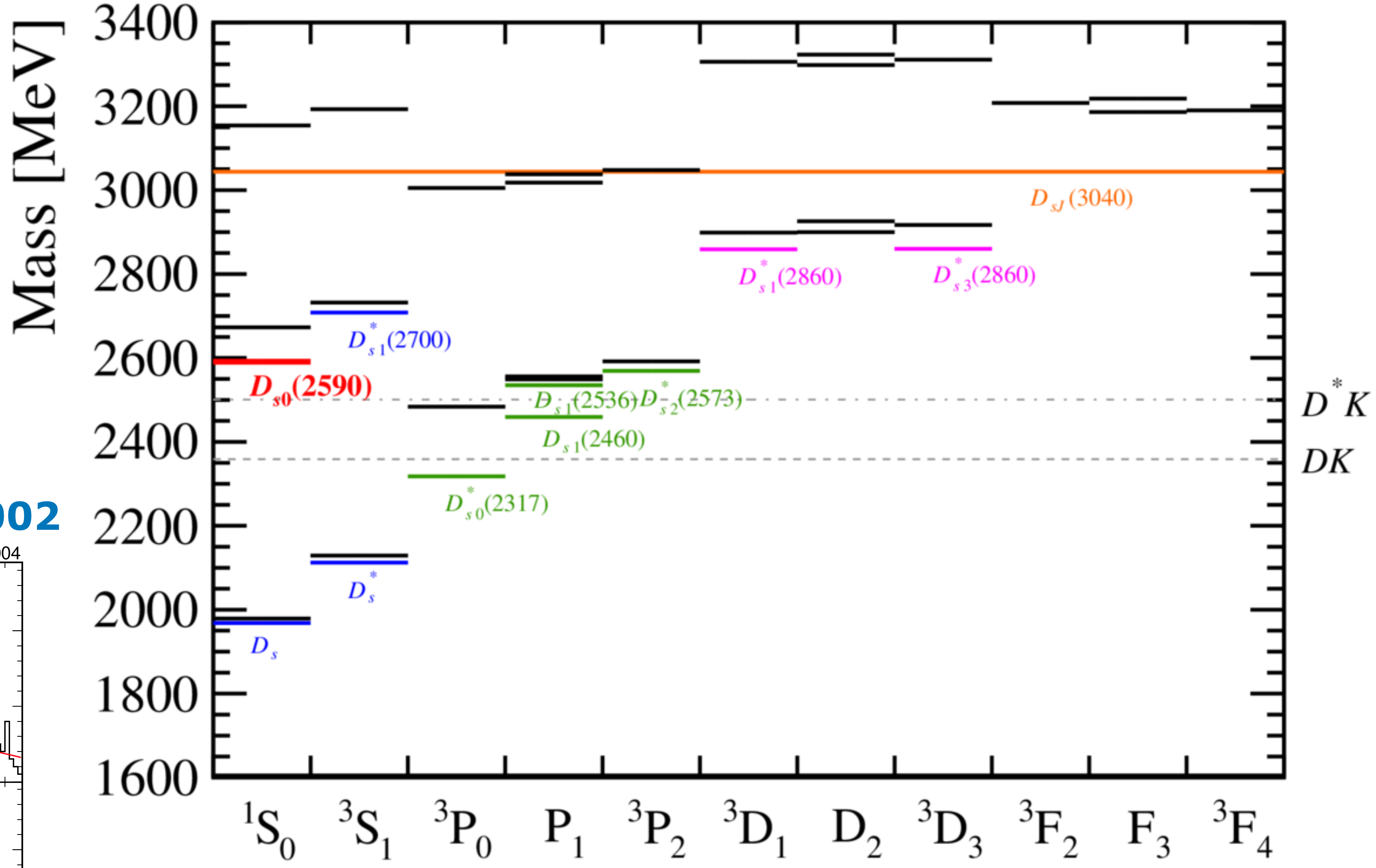
Project	Collaboration	Since	Latest commit	C++	Python	Julia	Cuda
AmpGen	CLEO / LHCb	2018	04/2024	✓			
AmpTools	BESIII / GlueX	2011	05/2024	✓			✓
BruFit	CLAS12	2020	07/2024	✓			
ComPWA (C++)		2012	01/2024	✓			
ComPWA project QRules		2020	10/2024		✓		
cFit		2012	05/2018	✓			
FDC-PWA	BESIII	2000		✓			
GPUPWA	BESIII	2011		✓			
HAMMER		2016	05/2024	✓	✓		
Ipanema		2017	03/2019	✓	✓		
Laura++	LHCb	2013		✓			
Mint2		2016	01/2020	✓			
Pawian	BESIII / PANDA	2010	10/2024	✓			
PyPWA	JLab	2014	05/2023		✓		
Rio++	LHCb	2016		✓			
ROOTPWA	COMPASS	2009	06/2020	✓	✓		✓
TARA	Crystal Barrel	1999		✓			
TensorFlowAnalysis AmpliTF	LHCb	2016	10/2023		✓		
TF-PWA	BESIII / LHCb	2019	10/2024		✓		
ThreeBodyDecays.jl	LHCb	2019	10/2024			✓	

Conventional Spectroscopy

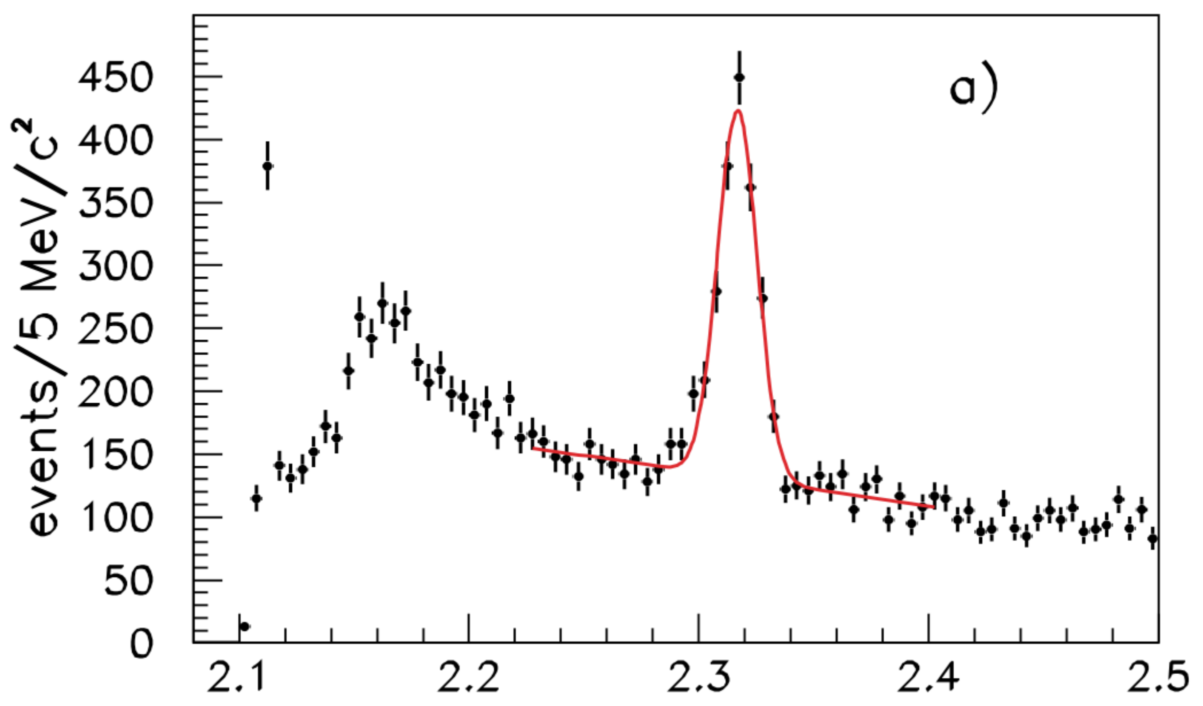
D meson Excitations

Continuously Developing Field

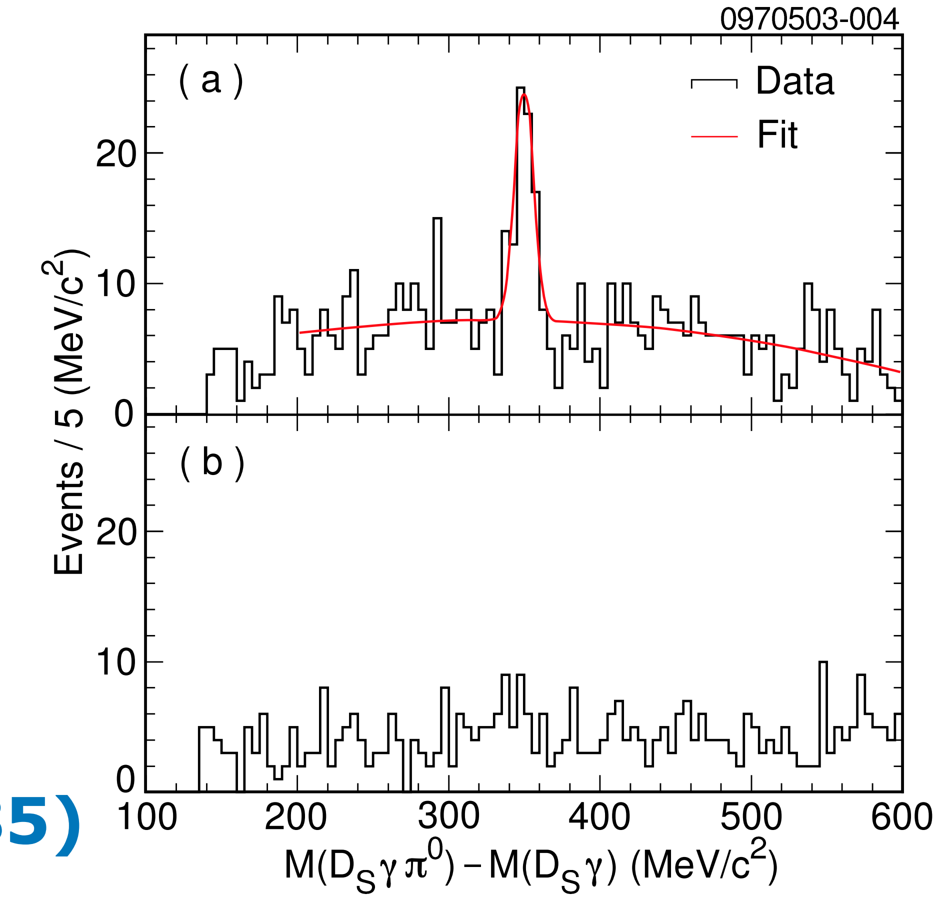
- Predictions of D and D_s mass eigenstates performed in 1985 from QCD potential models[1]
- BaBar and Belle experiments pioneered the search for previously undiscovered D mesons
- Excitement since the discovery of the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ resonances
- Fresh results from the study of B decays



Phys. Rev. Lett. 90 (2003) 242001



Phys. Rev. D68 (2003) 032002



[1]Godfrey and Isgur, PRD32 189-231 (1985)

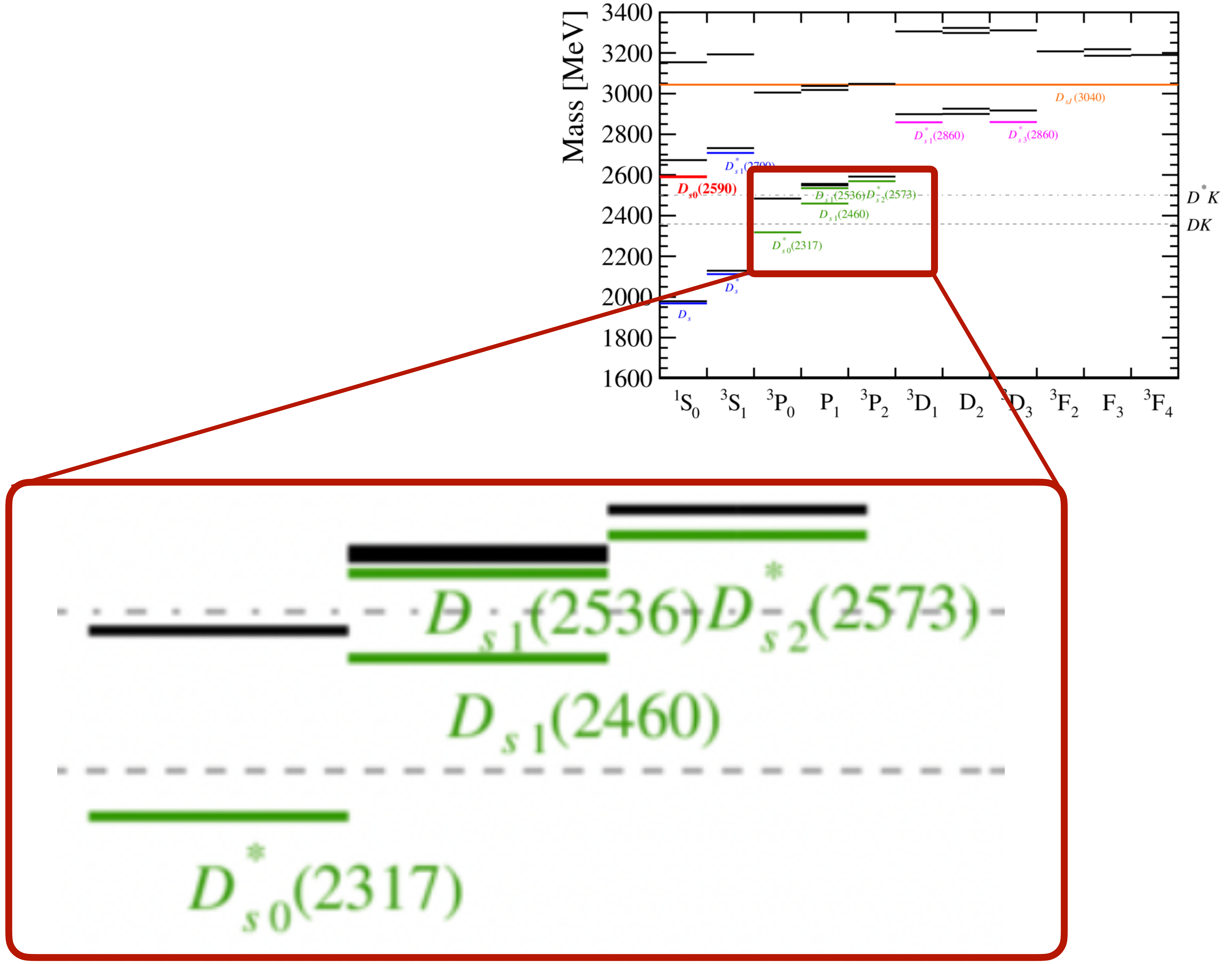
Why so Interesting?

Masses much smaller than expected

- $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ resonances below DK and D^*K mass thresholds, respectively[1] ($c\bar{s}$)
- Interpretation as tetraquarks[2,3] ($[cq][\bar{s}\bar{q}]$) or $D^{(*)}K$ molecules[4,5]

Not only $c\bar{s}$

- Further states compatible with [cs] observed recently in $B \to DDK$ decays raised additional interest



[1]Godfrey and Moats, PRD93 034035 (2016)
[2]Maiani et al, PRD71 014028 (2005)
[3]Browder et al, PLB578 365 (2004)
[4]Barnes et al., PRD68 054006 (2003)
[5]van Beveren and Rupp, PRL91 012003 (2003)

D-meson Excitation Results from B Decays

$B \longrightarrow D^* \pi\pi$

- **$D^*\pi$ states allow natural and unnatural spin-parity**
  Except 0+, forbidden by angular momentum and parity conservation
- **Pioneered by Belle (560 signal candidates)**
- **Studied in details by LHCb with 79k signal candidates**

$B \longrightarrow DDK\pi$

- **Selection of $K\pi$ S-wave gives access to unnatural spin parity in $DK\pi$ system**

$B \longrightarrow DDK$

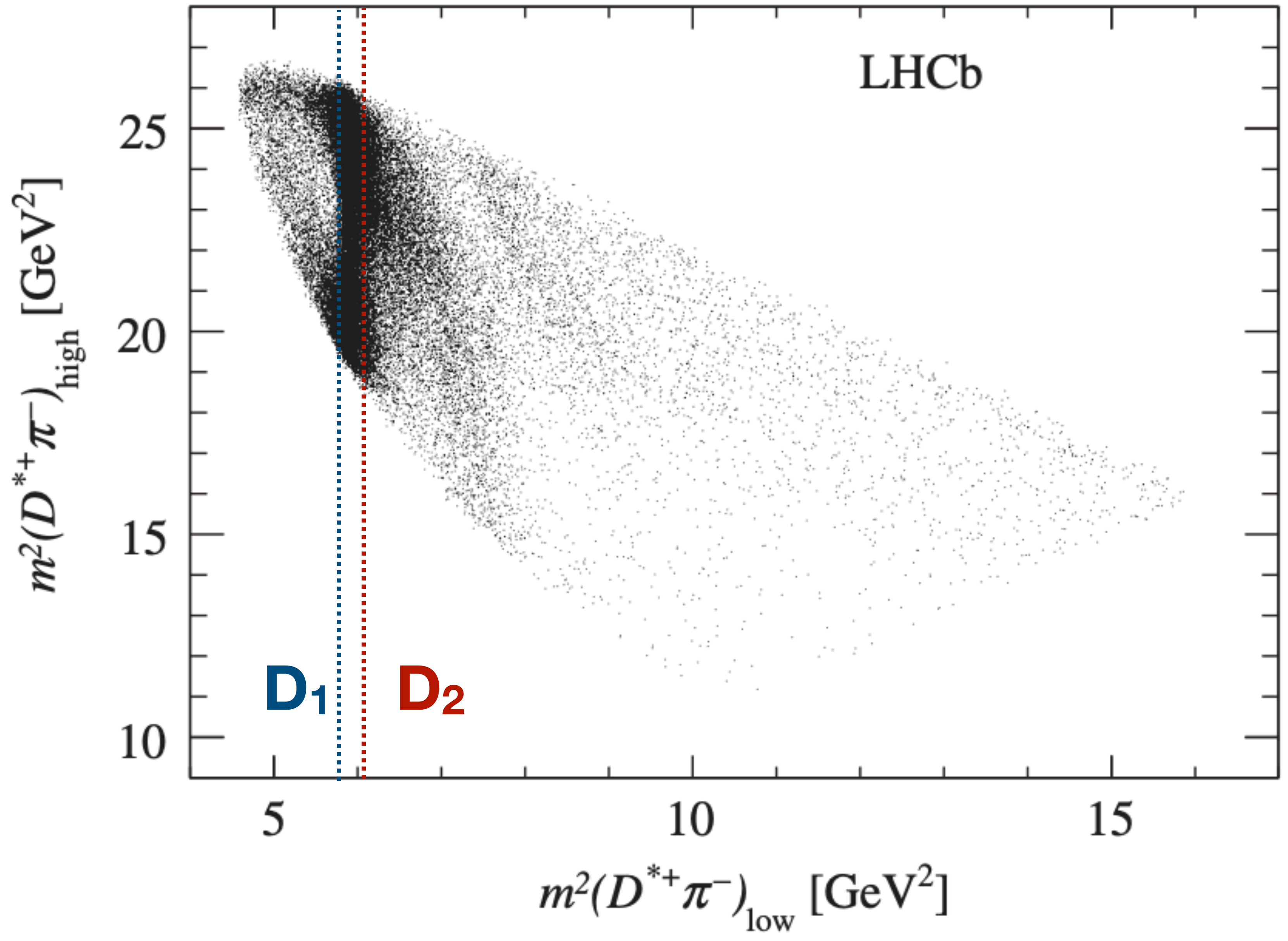
- **Limit to D_{sJ} mesons to DK: natural spin parity**

$B \to D^*\pi\pi$

Phys. Rev. D 101 (2020) 032005

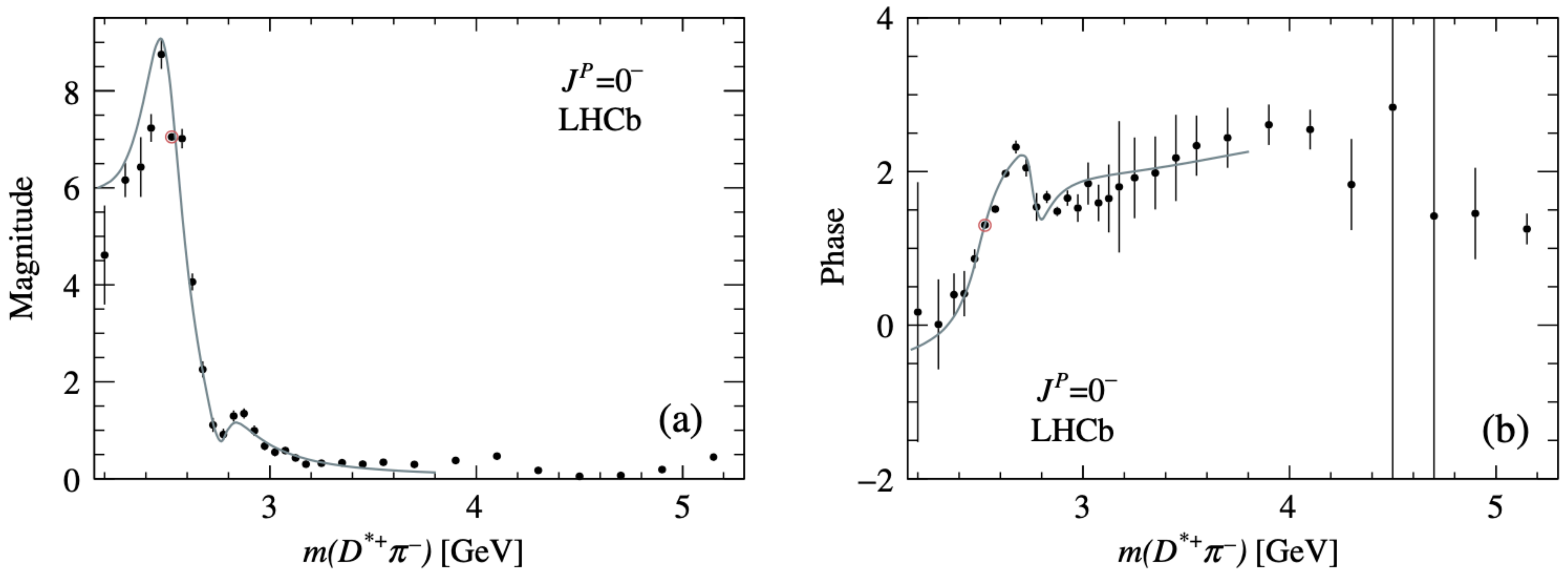
Dalitz Plot

- Clear presence of $D_1(2420)$ and $D_2(2460)$
- Further weak bands at higher masses
- Background model from subtraction of high-purity sample from low-purity one
- Efficiency from simulations



Amplitude Analysis

- Study of the four-body decay
  $B^+ \to (D^0\pi_s^+)_{D^{*+}}\pi^+\pi^-$
- Amplitudes: Breit-Wigner + Zemach Tensors
- Alternative amplitudes parametrisation: Quasi Model Independent
  $D^*\pi$ mass range divided in 31 bins with different complex coefficients (magnitude and phase in each bin) free to float (1 bin fixed → 60 floating parameters) - Iterative process on one J^P amplitude with the others fixed



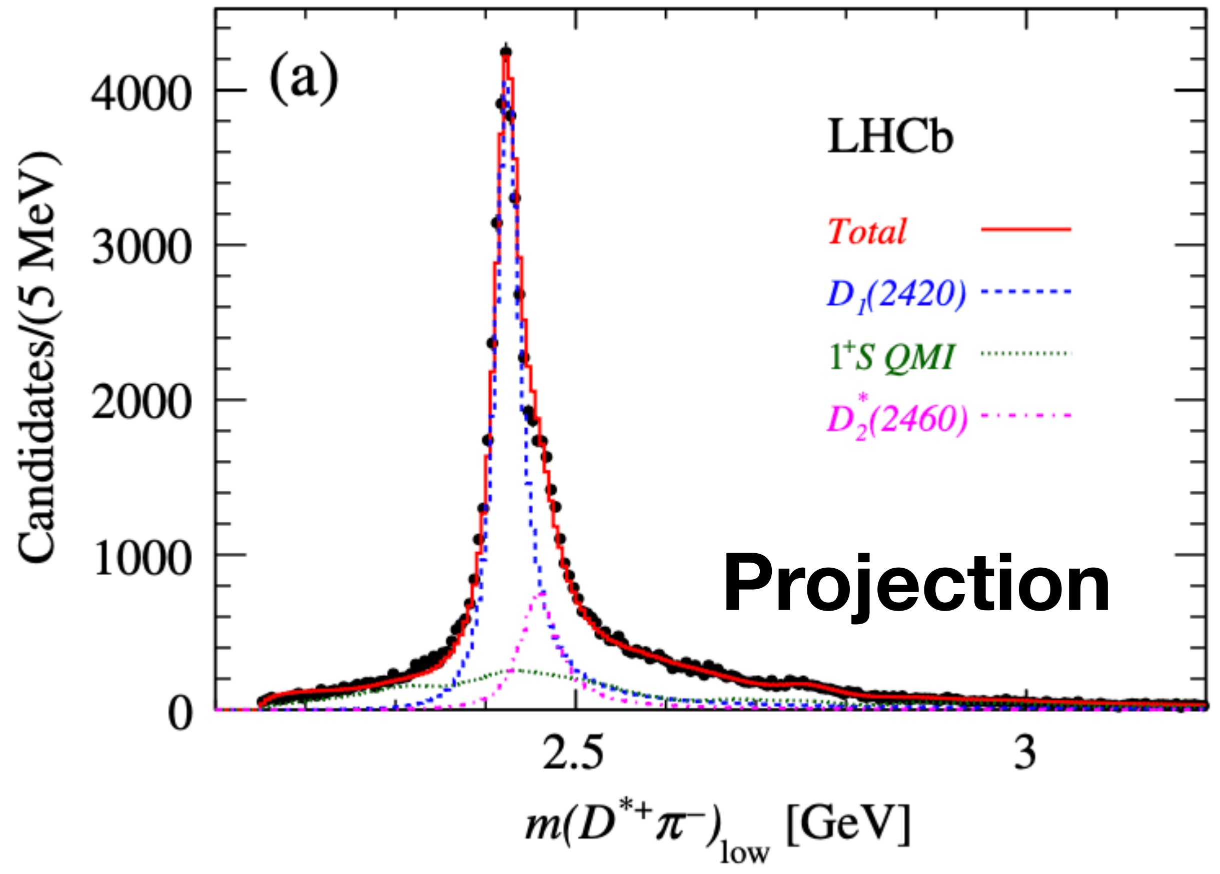
B⟶D*ππ Fit Results

Phys. Rev. D 101 (2020) 032005

Mixture of QMI and BW

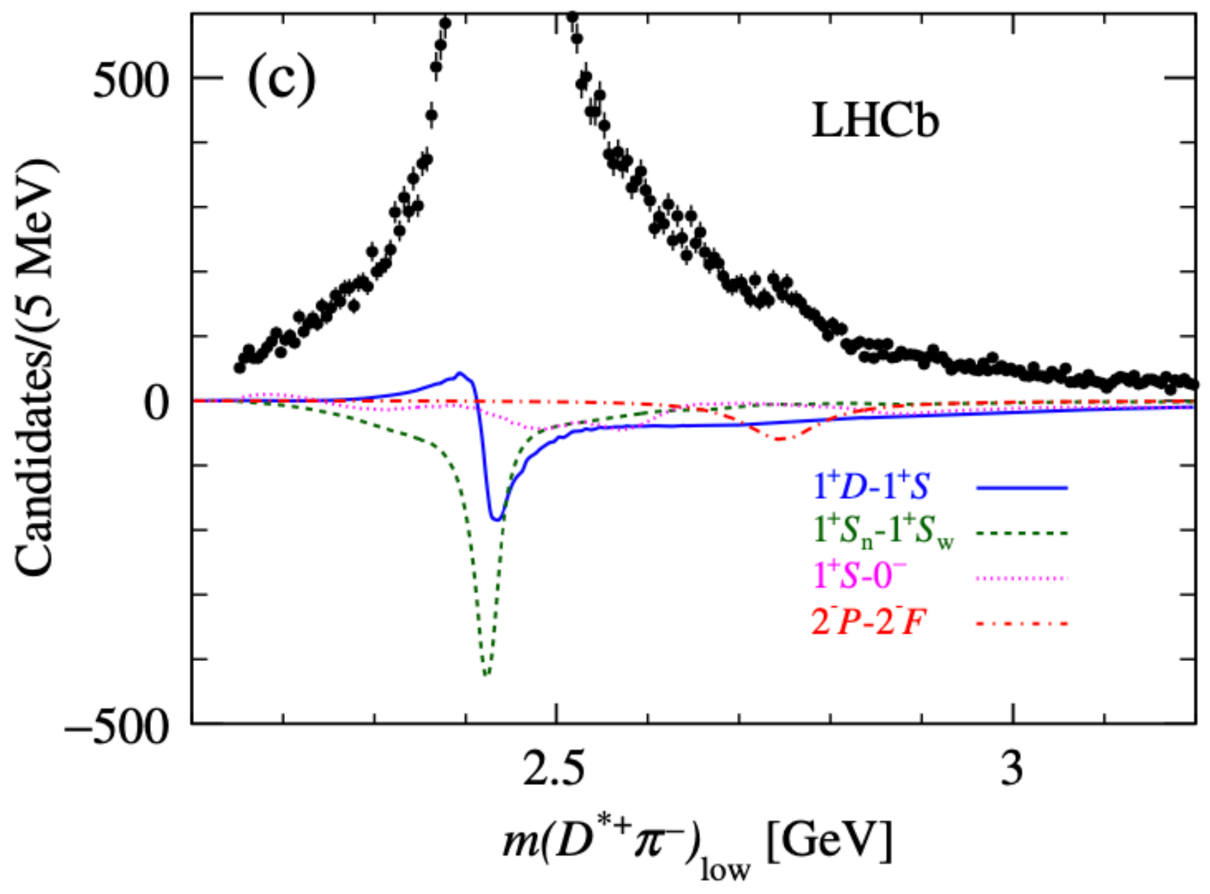
- Nominal model made of a combination of QMI ($1^{+}S$ and 0^{-}) states and BW amplitudes

Resonance	J^P	Fraction (%)	Phase (rad)
$D_1(2420)$	1^+D	$59.8 \pm 0.3 \pm 2.9$	0
1^+S QMI	1^+S	$28.3 \pm 0.3 \pm 1.9$	$-1.19 \pm 0.01 \pm 0.15$
$D_2^*(2460)$	2^+	$15.3 \pm 0.2 \pm 0.3$	$-0.71 \pm 0.01 \pm 0.48$
$D_1(2420)$	1^+S	$2.8 \pm 0.2 \pm 0.5$	$1.43 \pm 0.02 \pm 0.31$
0^- QMI	0^-	$10.6 \pm 0.2 \pm 0.7$	$1.94 \pm 0.01 \pm 0.19$
$D_1^*(2600)$	1^-	$6.0 \pm 0.1 \pm 0.6$	$1.20 \pm 0.02 \pm 0.05$
$D_2(2740)$	2^-P	$1.9 \pm 0.1 \pm 0.4$	$-1.57 \pm 0.04 \pm 0.15$
$D_2(2740)$	2^-F	$3.2 \pm 0.2 \pm 1.1$	$1.11 \pm 0.04 \pm 0.29$
$D_3^*(2750)$	3^-	$0.35 \pm 0.04 \pm 0.05$	$-1.17 \pm 0.07 \pm 0.31$
Sum		$128.2 \pm 0.6 \pm 3.8$	

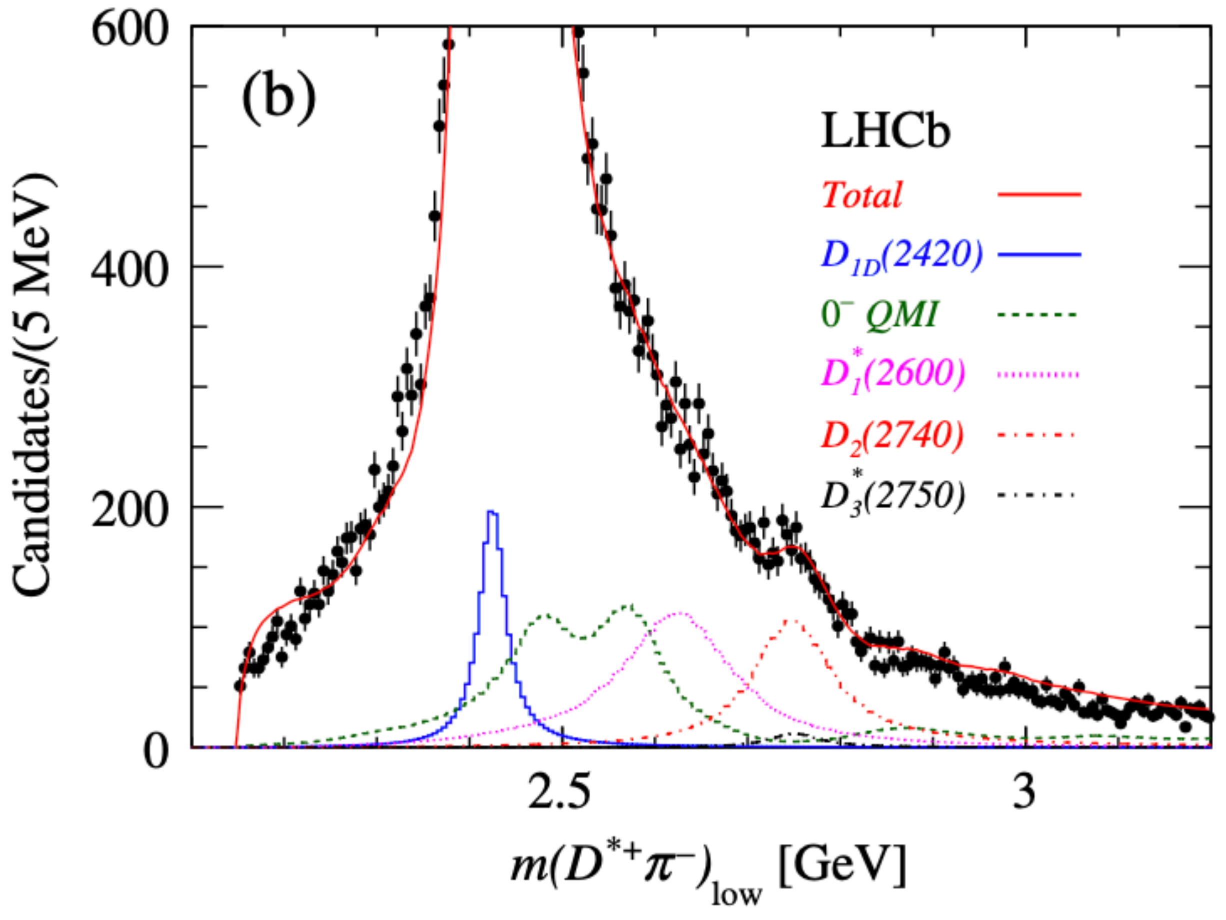


Projection

Interference



Detail



$B \to D^* \pi\pi$ Summary

Phys. Rev. D 101 (2020) 032005

Results

- Quantum numbers established for $D_1(2420)$, $D_1(2430)$, $D_0(2550)$, $D_1^*(2600)$, $D_2(2740)$, $D_3^*(2750)$
- Indications of presence of higher mass D_1 and D_0' resonances above 2800 MeV
- Mixing between D_1 and D_1' resonances found marginally compatible with 0 (2.3σ)

		$\mathcal{B}(B^- \to R^0\pi^-) \times \mathcal{B}(R^0 \to D^{*+}\pi^-) \times 10^{-4}$	
Resonance	J^P	This analysis	Belle collaboration
$D_1(2420)$	1^+	$8.42 \pm 0.08 \pm 0.40 \pm 1.40$	
$D_1(2430)$	1^+S	$3.51 \pm 0.06 \pm 0.23 \pm 0.57$	
$D_2^*(2460)$	2^+	$2.08 \pm 0.03 \pm 0.14 \pm 0.34$	$1.8 \pm 0.3 \pm 0.3 \pm 0.2$
$D_0(2550)$	0^-	$0.72 \pm 0.01 \pm 0.07 \pm 0.12$	
$D_1^*(2600)$	1^-	$0.68 \pm 0.01 \pm 0.07 \pm 0.11$	
$D_2(2740)$	2^-	$0.33 \pm 0.02 \pm 0.14 \pm 0.05$	
$D_3^*(2750)$	3^-	$0.11 \pm 0.01 \pm 0.02 \pm 0.02$	
D_1	1^+	$7.95 \pm 0.09 \pm 0.34 \pm 1.30$	$6.8 \pm 0.7 \pm 1.3 \pm 0.3$
D_1'	1^+	$2.96 \pm 0.30 \pm 0.41 \pm 0.48$	$5.0 \pm 0.4 \pm 1.0 \pm 0.4$

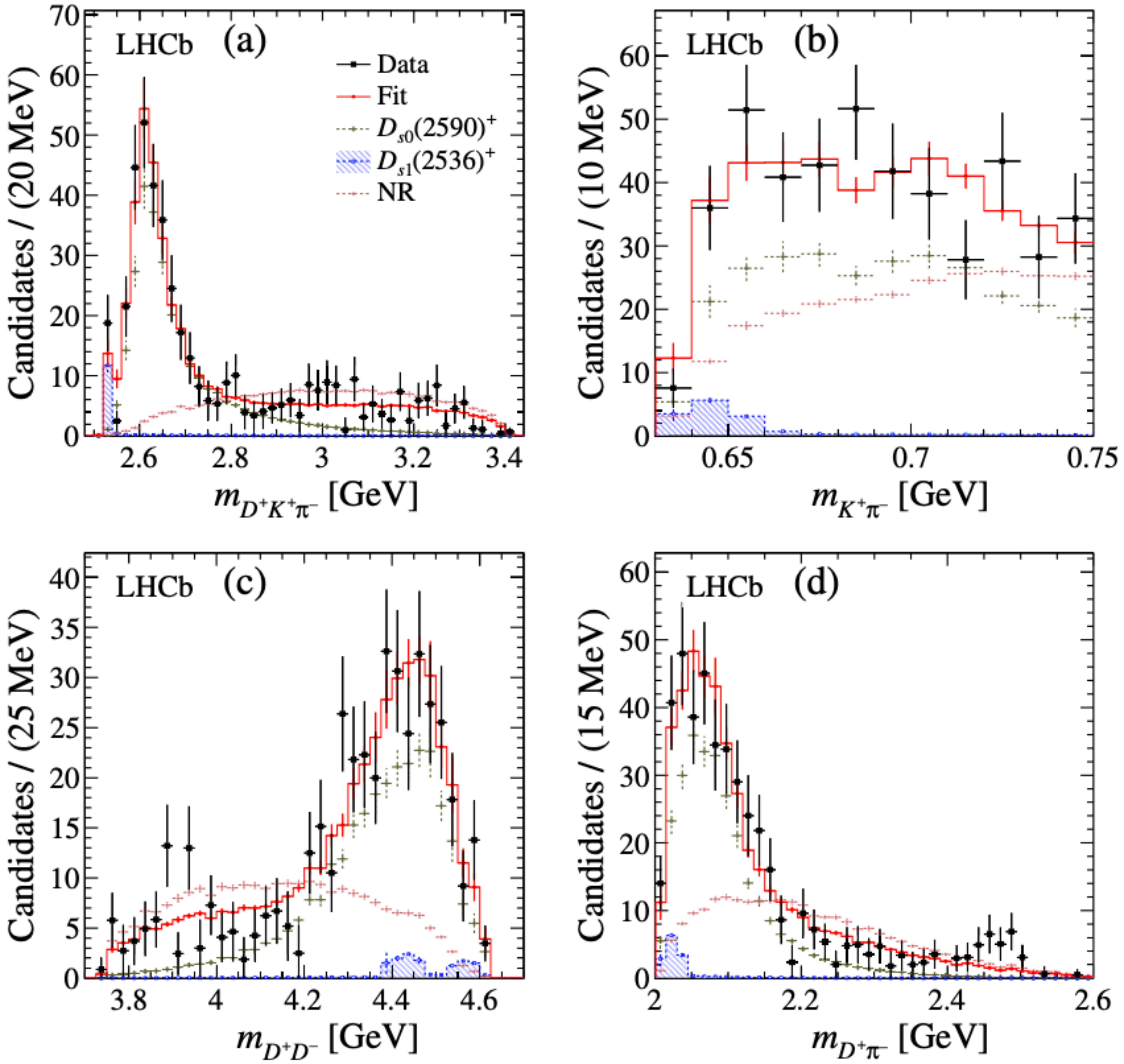
B⟶DDKπ

Phys. Rev. Lett. 126, 122002 (2021)

DKπ System

- **Access states with unnatural spin-parity ($0^-,1^+,2^-$,..)**
  Assumes Kπ system in S-wave ($J^P=0^+$) below $K^*(892)^0$ resonance
- **Amplitude analysis for data with $m_{K\pi}$<0.75GeV**
  Three D_s^+ components:
  - $D_{s1}(2536)^+$ (1^+)
  - D_{sJ} at ~2.6GeV
  - Non-resonant (0^-)
  Kπ as $J^P=0^+$ $K_0^*(700)^0$

	Fit fraction ($\times 10^{-2}$)
$D_{s0}(2590)^+$	$63 \pm 9(\text{stat}) \pm 9(\text{syst})$
$D_{s1}(2536)^+$	$3.9 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})$
NR	$51 \pm 11(\text{stat}) \pm 19(\text{syst})$
D_{s0}^+–NR	$-18 \pm 18(\text{stat}) \pm 24(\text{syst})$
D_{s1}^+/D_{s0}^+	$6.1 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})$

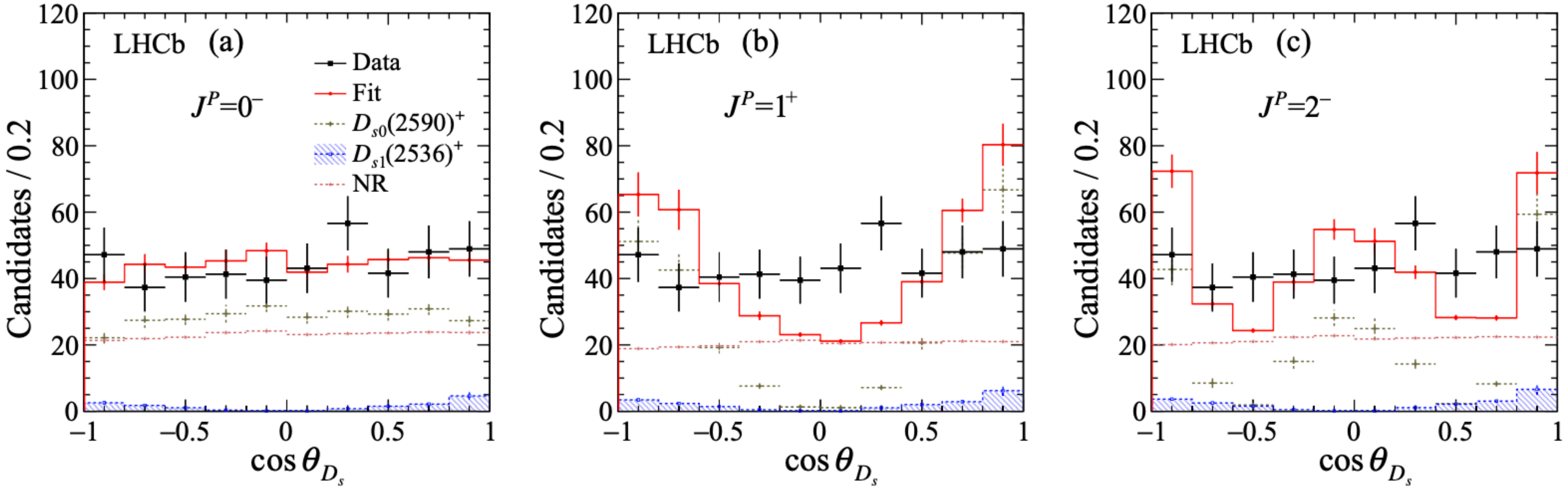


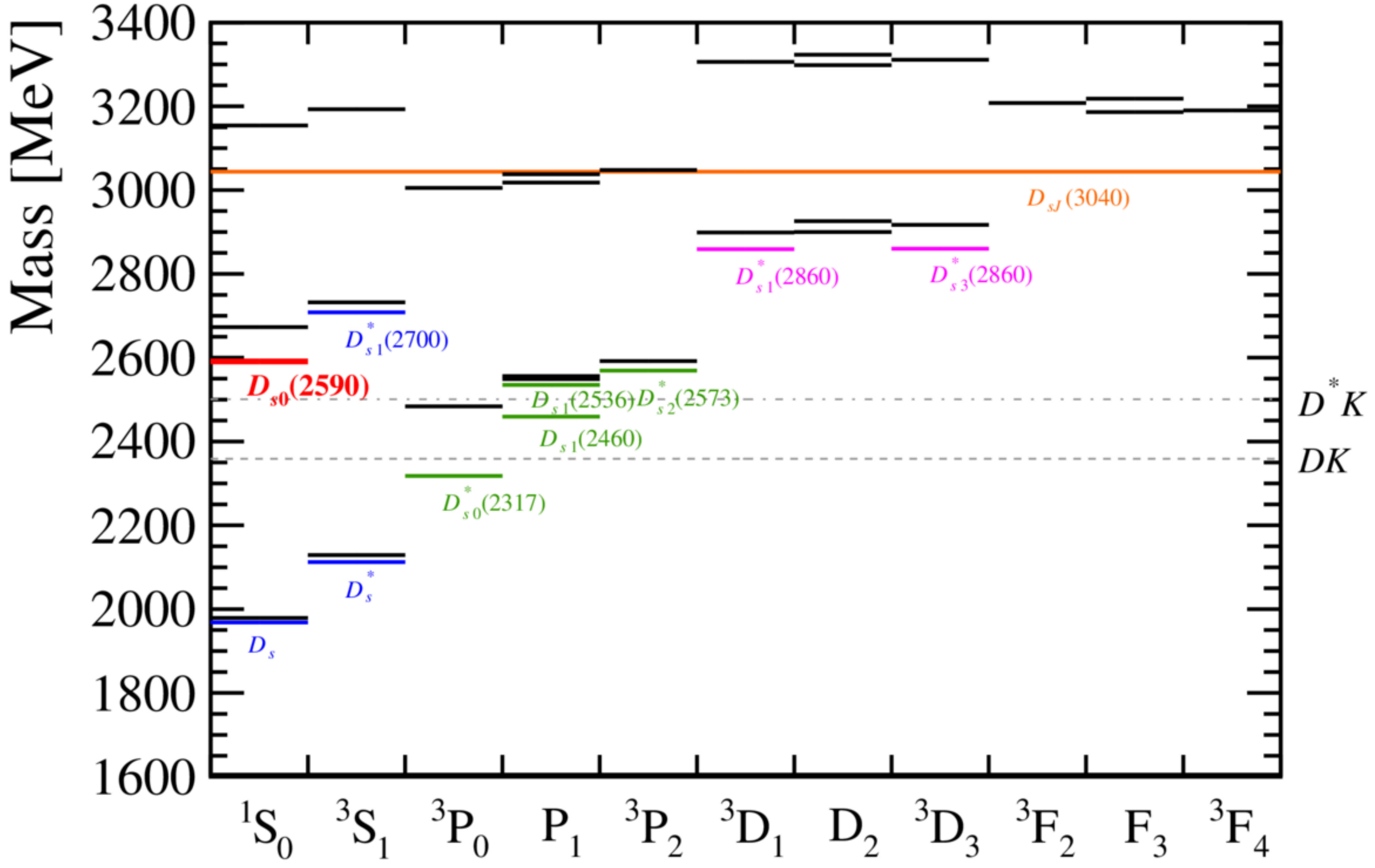
$D_{s0}(2590)^+$ in $B \to DDK\pi$

Phys. Rev. Lett. 126, 122002 (2021)

$D_{s0}(2590)^+$ Properties

- Mass = 2591±6±7 MeV
- Width = 89±16±12 MeV
- Tested Spin-Parity → $J^P = 0^+$ favoured



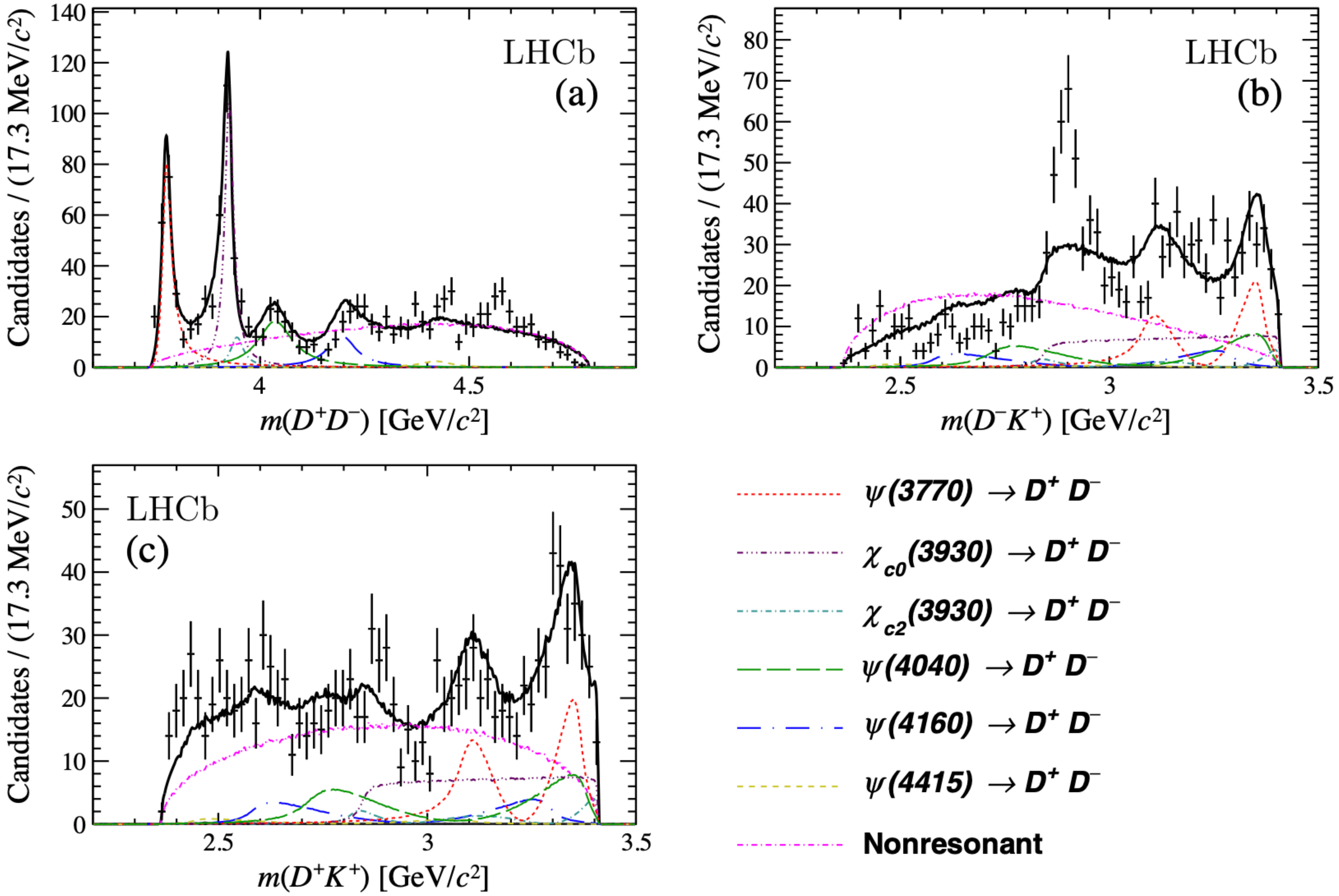


B→DDK

Phys. Rev. Lett. 125, 242001 (2020)

An Unexpected Result

- **Primary target of the analysis is the study of charmonium resonances in the DD system**
- **Found that the DK system could not be described properly**

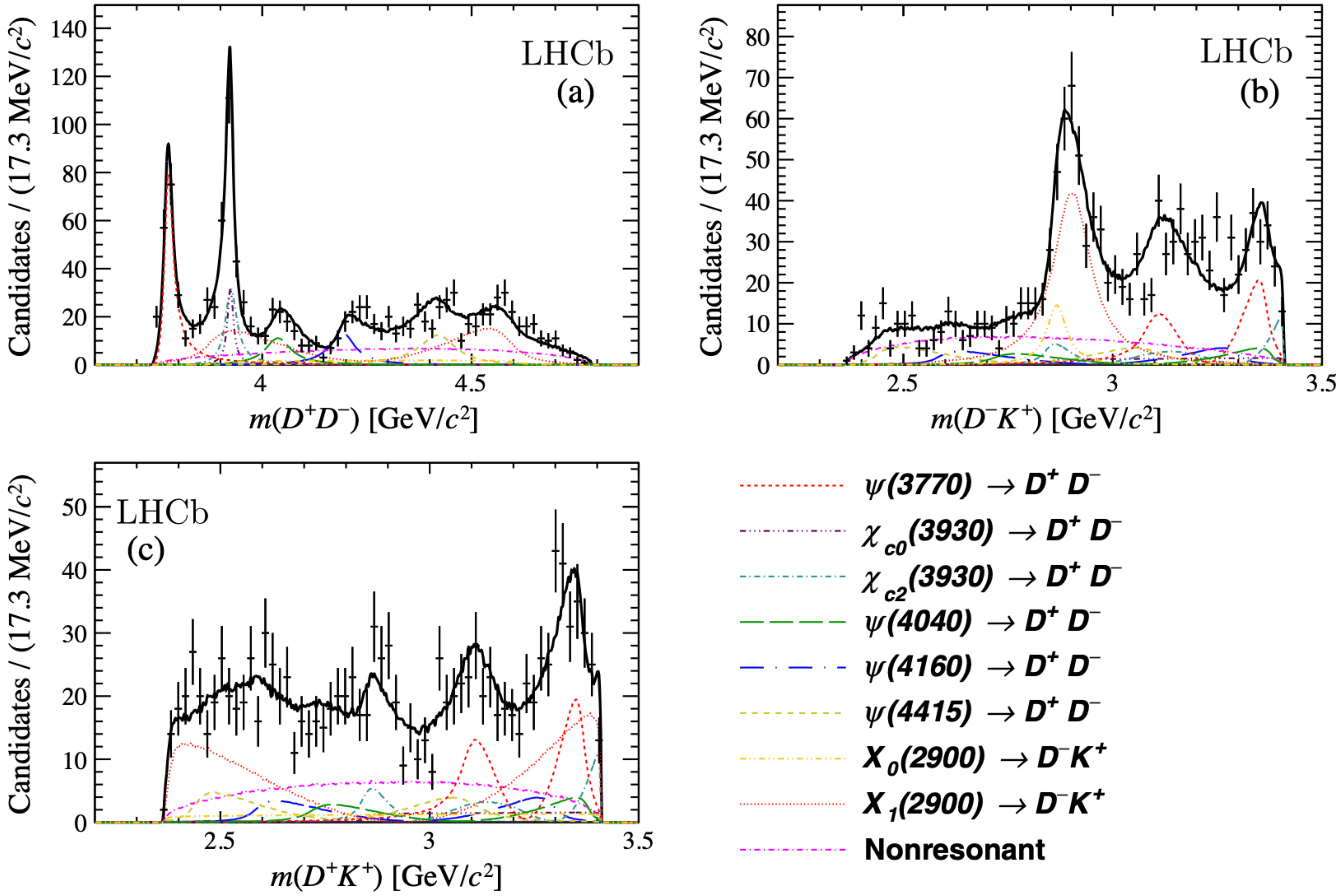


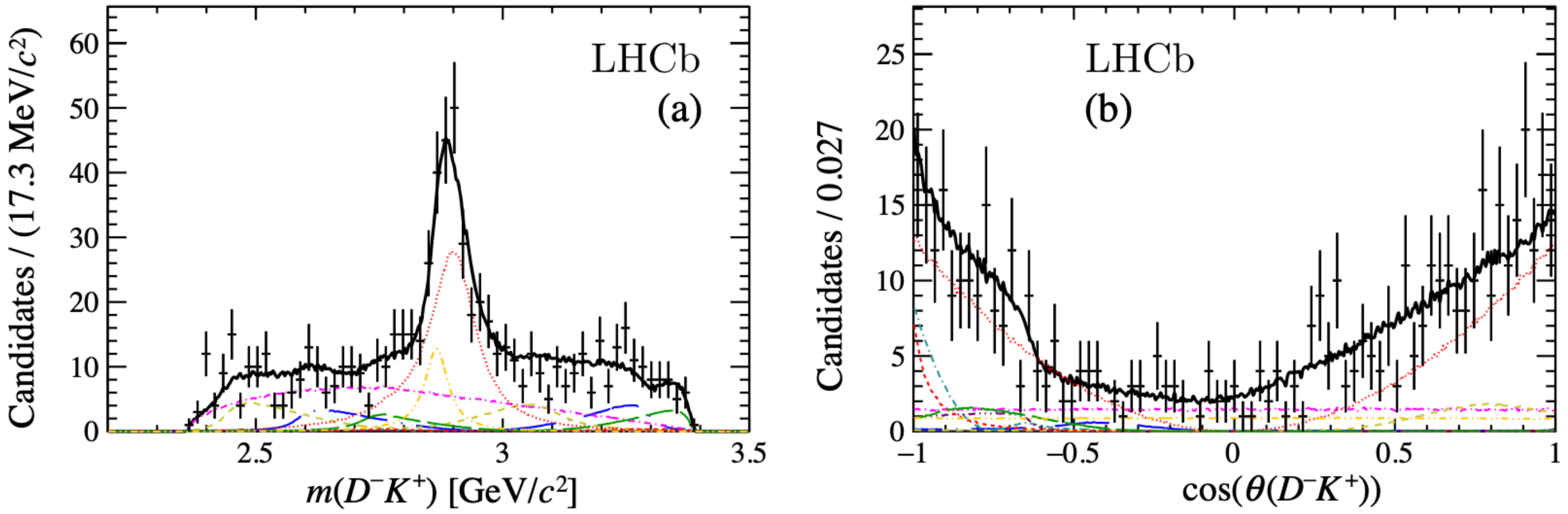
B⟶DDK

Phys. Rev. Lett. 125, 242001 (2020)

An Unexpected Result

- **Primary target of the analysis is the study of charmonium resonances in the DD system**
- **Found that the DK system could not be described properly**
- **Fit model significantly improves with the addition of two new D^-K^+ states around 2900 MeV with spin 0 and 1**
  Cannot exclude hadronic effects due to the vicinity of D*K* threshold
- **Suppressing reflections from charmonium resonances with m(DD)>4GeV gives further confidence**





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Tetraquarks!

Tetraquark in the Charm System

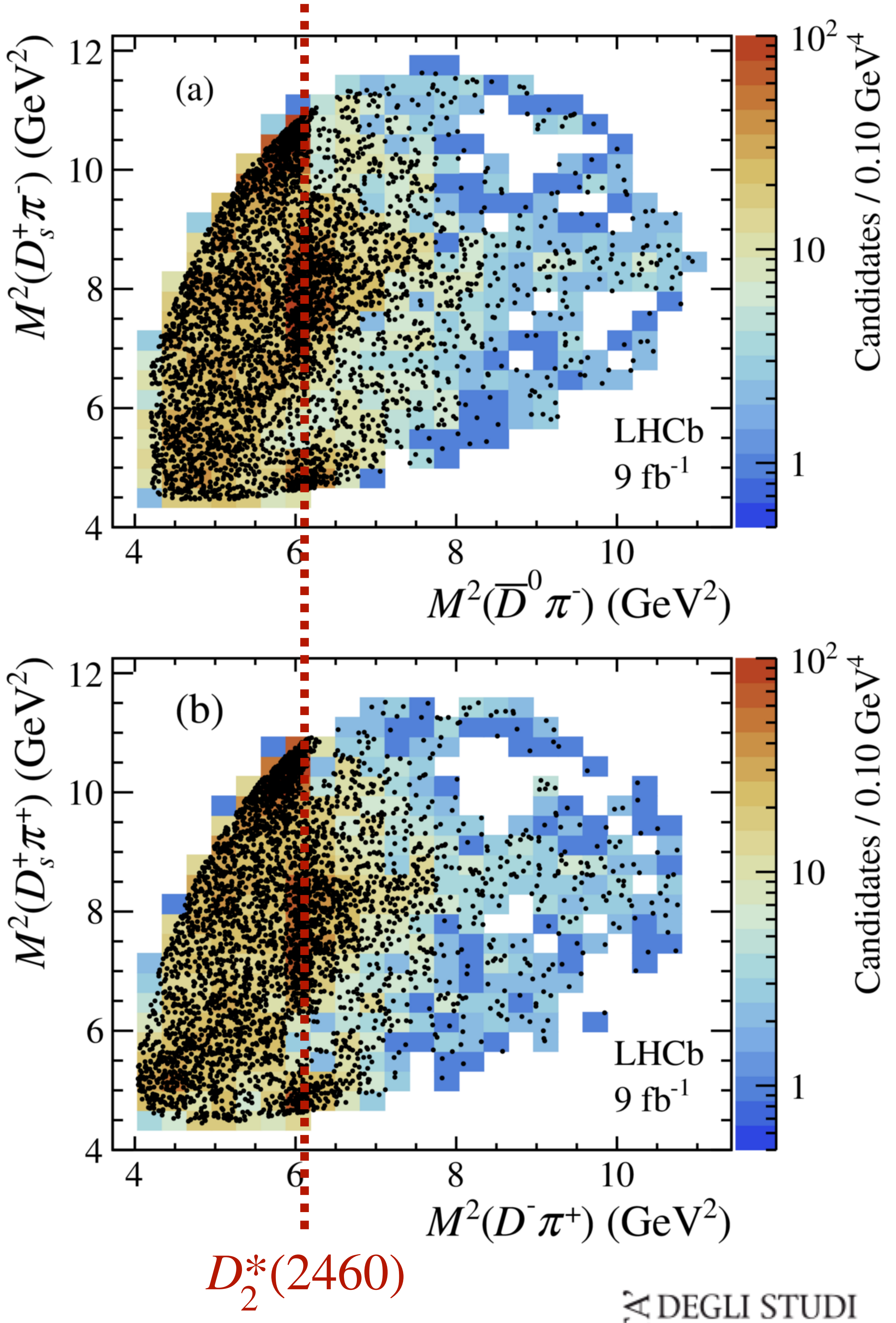
Phys. Rev. Lett. 131, 041902 (2023)
Phys. Rev. D108, 012017 (2023)

Chase started with X(5568)

- **Observed by D0[1] in $B_s\pi^\pm$ system $[b\bar{s}u\bar{d}]$ but not confirmed**

Search in the Charm sector

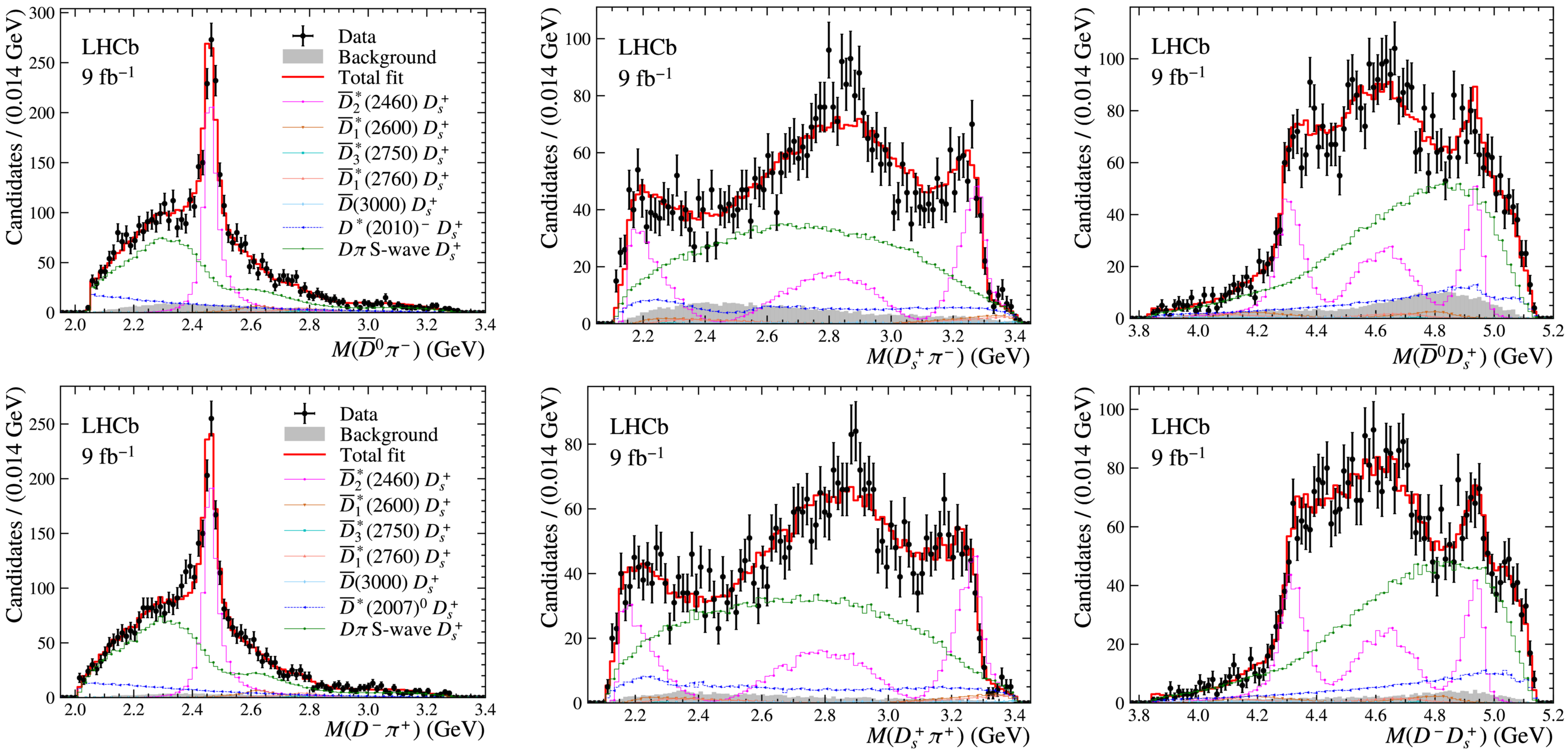
- **Similarly possible to search for $[c\bar{s}u\bar{d}]$ and $[c\bar{s}\bar{u}d]$ in the $D_s^+\pi^\pm$ system**
- **$X_0(2900)$ and $X_1(2900)$ generated theoretical speculations[2] and predictions**
- **$B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ are ideal candidates for this search**
  Conventional contributions from excited $\bar{D}^*$ resonances in $\bar{D}^0\pi^-$ and $D^-\pi^+$
- **Signal Yields at LHCb (9/fb)**
  $B^0 \to \bar{D}^0 D_s^+ \pi^-$: ~4000, P=90.7%
  $B^+ \to D^- D_s^+ \pi^+$: ~3750, P=95.2%
- **Dalitz plots show similar structure as expected from isospin symmetry**
  Study them with a simultaneous fit



[1]Abazov et al., Phys. Rev. Lett. 117, 022003 (2016)
[2]Chen et al., Rep. Prog. Phys. 86, 026201 (2023)

Amplitude Fit Projections (Conventional)

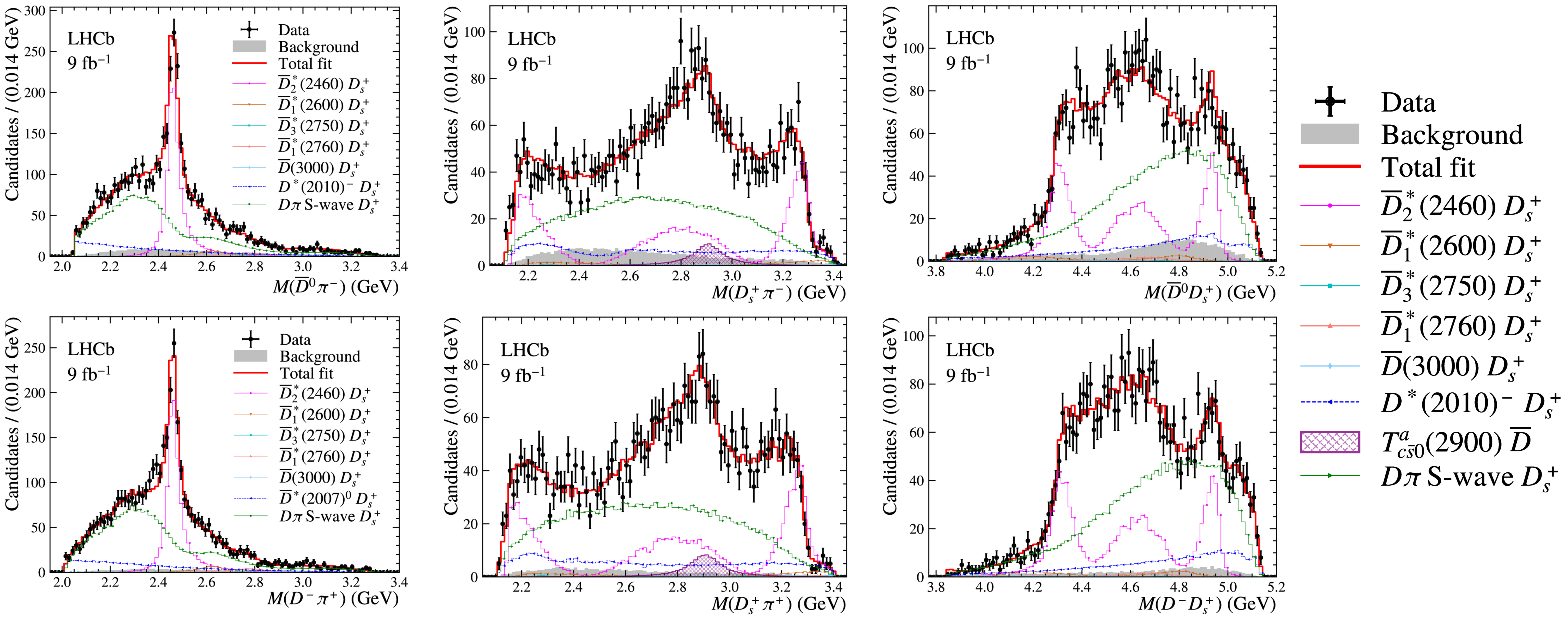
Phys. Rev. Lett. 131, 041902 (2023)
Phys. Rev. D108, 012017 (2023)



Conventional model cannot describe enhancement at m(Dsπ)~2.8GeV

Amplitude Fit Projections (+New State)

Phys. Rev. Lett. 131, 041902 (2023)
Phys. Rev. D108, 012017 (2023)



Addition of a new state $T^a_{c\bar{s}0}(2900)$ improves significantly the fit

Characterisation of the New State

Phys. Rev. Lett. 131, 041902 (2023)
Phys. Rev. D108, 012017 (2023)

Spin

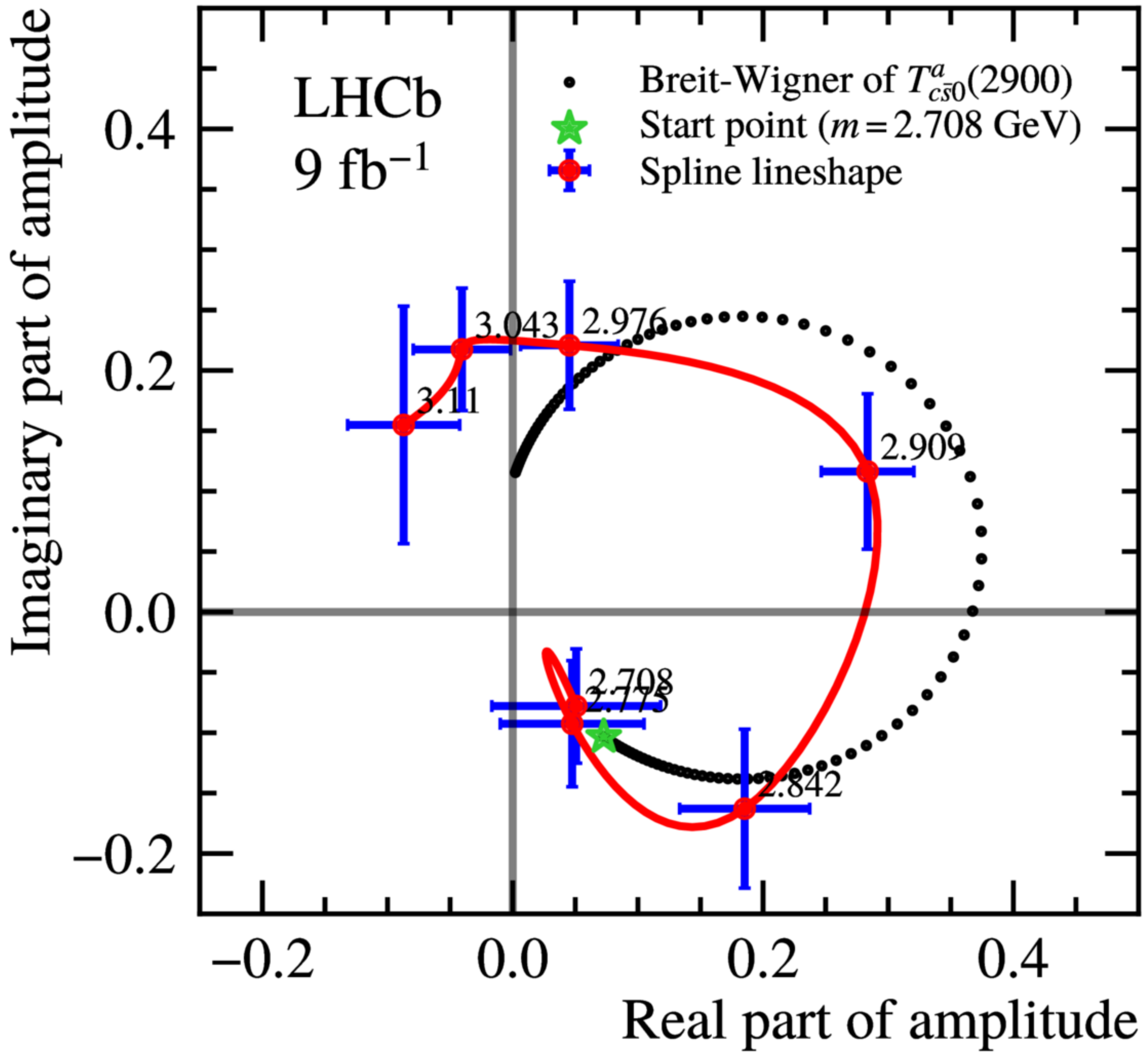
- Favoured solution 0^+, also tested with toys

Resonance

- Argand diagrams behaves circularly as expected

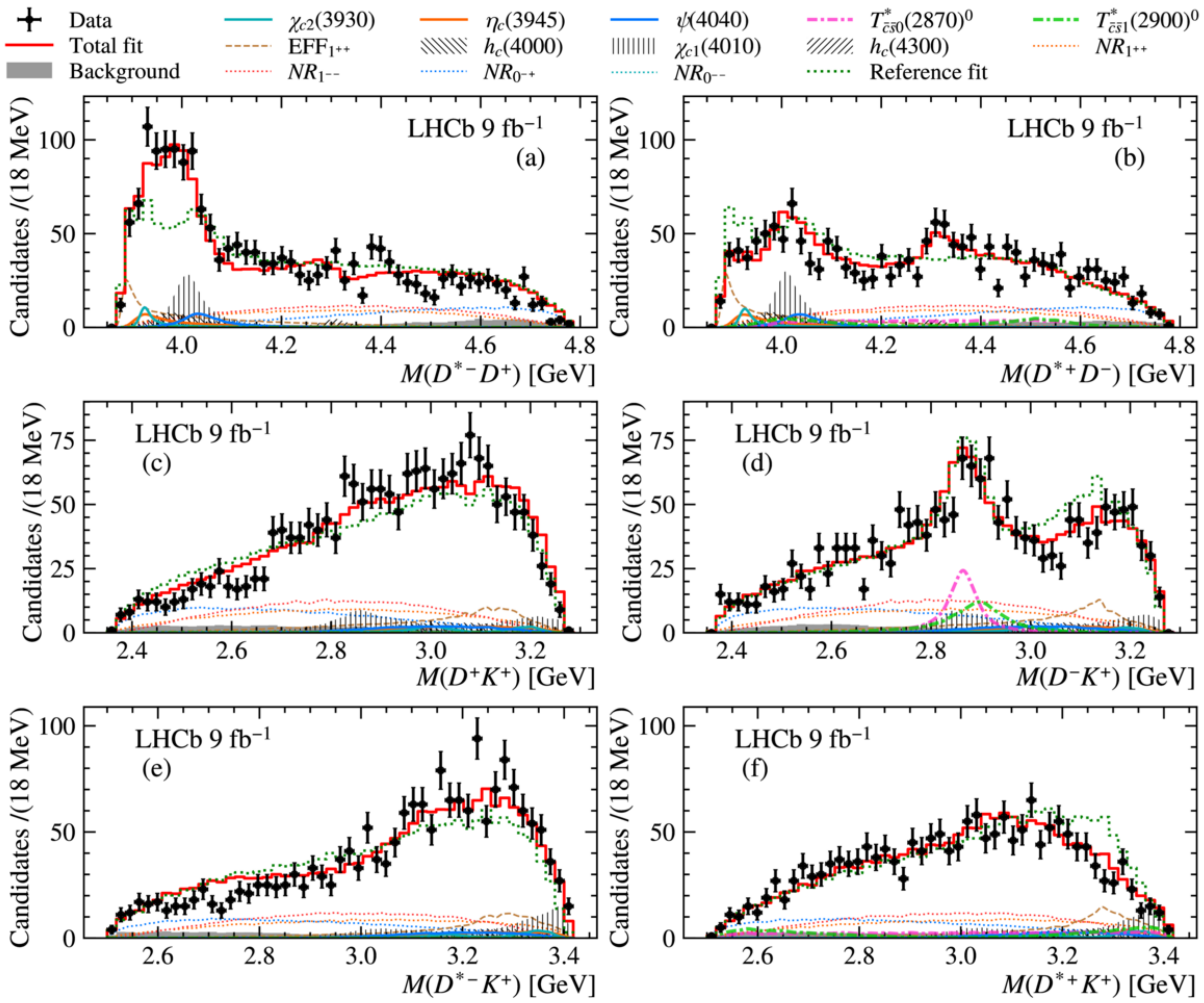
Mass and Width

- Isospin Triplet
  $M = 2.908 \pm 0.011 \pm 0.020$ GeV
  $\Gamma = 0.136 \pm 0.023 \pm 0.013$ GeV
- Separate fits
  $M_0 = 2.892 \pm 0.014 \pm 0.015$ GeV
  $\Gamma_0 = 0.119 \pm 0.026 \pm 0.013$ GeV
  $M_{++} = 2.921 \pm 0.017 \pm 0.020$ GeV
  $\Gamma_{++} = 0.137 \pm 0.032 \pm 0.017$ GeV



Confirmation from $B^+ \to D^*DK^+$

Phys. Rev. Lett. 133, 131902 (2024)



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

Component	$J^{P(C)}$	Fit fraction [%] $B^+ \to D^{*+}D^-K^+$	Fit fraction [%] $B^+ \to D^{*-}D^+K^+$	Branching fraction $[10^{-4}]$
$\mathrm{EFF}_{1^{++}}$	1^{++}	$10.9^{+2.3\ +1.6}_{-1.2\ -2.1}$	$9.9^{+2.1\ +1.4}_{-1.0\ -1.9}$	$0.74^{+0.16\ +0.11}_{-0.08\ -0.14} \pm 0.07$
$\eta_c(3945)$	0^{-+}	$3.4^{+0.5\ +1.9}_{-1.0\ -0.7}$	$3.1^{+0.5\ +1.7}_{-0.9\ -0.6}$	$0.23^{+0.04\ +0.13}_{-0.07\ -0.05} \pm 0.02$
$\chi_{c2}(3930)^\dagger$	2^{++}	$1.8^{+0.5\ +0.6}_{-0.4\ -1.2}$	$1.7^{+0.5\ +0.6}_{-0.4\ -1.1}$	$0.12^{+0.03\ +0.04}_{-0.03\ -0.08} \pm 0.01$
$h_c(4000)$	1^{+-}	$5.1^{+1.0\ +1.5}_{-0.8\ -0.8}$	$4.6^{+0.9\ +1.4}_{-0.7\ -0.7}$	$0.35^{+0.07\ +0.10}_{-0.05\ -0.05} \pm 0.03$
$\chi_{c1}(4010)$	1^{++}	$10.1^{+1.6\ +1.3}_{-0.9\ -1.6}$	$9.1^{+1.4\ +1.2}_{-0.8\ -1.4}$	$0.69^{+0.11\ +0.09}_{-0.06\ -0.11} \pm 0.06$
$\psi(4040)^\dagger$	1^{--}	$2.8^{+0.5\ +0.5}_{-0.4\ -0.5}$	$2.6^{+0.5\ +0.4}_{-0.4\ -0.5}$	$0.19^{+0.04\ +0.03}_{-0.03\ -0.03} \pm 0.02$
$h_c(4300)$	1^{+-}	$1.2^{+0.2\ +0.2}_{-0.5\ -0.2}$	$1.1^{+0.2\ +0.2}_{-0.5\ -0.2}$	$0.08^{+0.01\ +0.02}_{-0.03\ -0.01} \pm 0.01$
$T^*_{\bar{c}\bar{s}0}(2870)^{0,\dagger}$	0^+	$6.5^{+0.9\ +1.3}_{-1.2\ -1.6}$	...	$0.45^{+0.06\ +0.09}_{-0.08\ -0.10} \pm 0.04$
$T^*_{\bar{c}\bar{s}1}(2900)^{0\dagger}$	1^-	$5.5^{+1.1\ +2.4}_{-1.5\ -1.6}$	...	$0.38^{+0.07\ +0.16}_{-0.10\ -0.11} \pm 0.03$
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^\pm)$	1^{--}	$20.4^{+2.3\ +2.1}_{-0.6\ -2.6}$	$18.5^{+2.1\ +1.9}_{-0.5\ -2.3}$	$1.39^{+0.16\ +0.14}_{-0.04\ -0.17} \pm 0.12$
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^\pm)$	0^{--}	$1.2^{+0.6\ +0.7}_{-0.1\ -0.6}$	$1.1^{+0.6\ +0.6}_{-0.1\ -0.5}$	$0.08^{+0.04\ +0.05}_{-0.01\ -0.04} \pm 0.01$
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^\pm)$	1^{++}	$17.8^{+1.9\ +3.6}_{-1.4\ -2.6}$	$16.1^{+1.7\ +3.3}_{-1.3\ -2.3}$	$1.21^{+0.13\ +0.24}_{-0.10\ -0.17} \pm 0.11$
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^\pm)$	0^{-+}	$15.9^{+3.3\ +3.3}_{-1.2\ -3.3}$	$14.5^{+3.0\ +3.0}_{-1.1\ -3.0}$	$1.09^{+0.23\ +0.22}_{-0.08\ -0.23} \pm 0.09$

$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-}K^+$ **forbidden by spin-parity**

Confirmation from $B^+ \to D^* D K^+$

Phys. Rev. Lett. 133, 131902 (2024)

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
$\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0, D^{(*)+}]$	$(4.5^{+0.6}_{-0.8}{}^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+}]$	$(3.8^{+0.7}_{-1.0}{}^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\{\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0, D^{(*)+}]/\mathcal{B}[B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+}]\}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

Tension in the ratio of Branching fractions

Summary

Summary

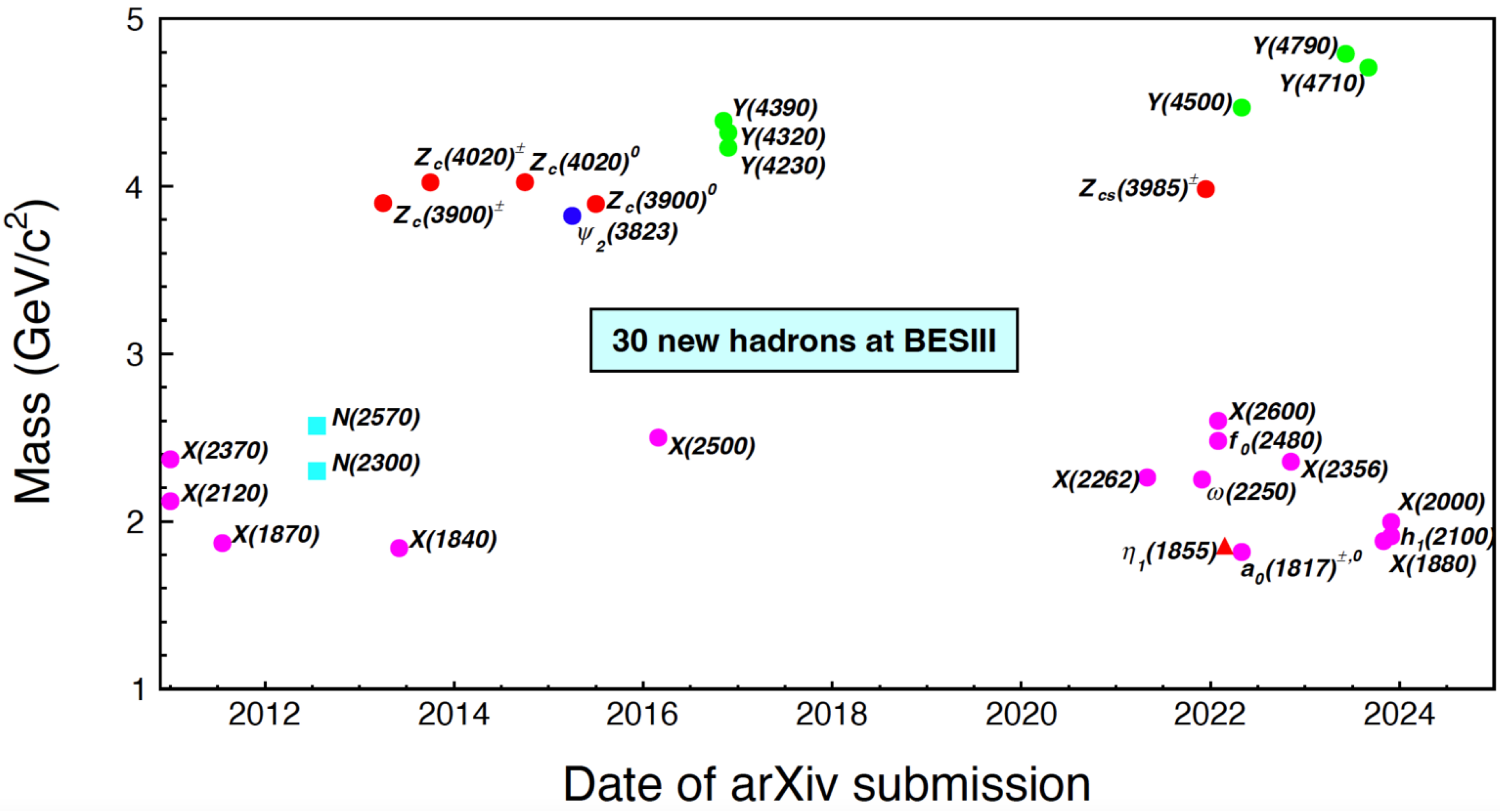
Exciting Times for Spectroscopy

- Thanks to the large datasets and ingenuity of colleagues from various experiments, many new results being published in the last 10 years
- Spectrum of conventional excitations of D mesons being filled
- Resonances compatible with Tetraquarks have been found

Questions

- Still unclear why some conventional D resonances do not agree with theory predictions
- Exotic states have been found and require precise accommodation in our theoretical framework

Spares



30 new hadrons at BESIII
Mass (GeV/c2)
Date of arXiv submission
5
4
3
2
1
2012
2014
2016
2018
2020
2022
2024
Y(4790)
Y(4710)
Y(4500)
Y(4390)
Y(4320)
Y(4230)
Zc(4020)±
Zc(4020)0
Zc(3900)±
Zc(3900)0
ψ2(3823)
Zcs(3985)±
N(2570)
N(2300)
X(2370)
X(2120)
X(1870)
X(1840)
X(2500)
X(2600)
f0(2480)
X(2356)
X(2262)
ω(2250)
X(2000)
h1(2100)
X(1880)
η1(1855)
a0(1817)±,0

Results from Continuum

At LHC

- **Combine promptly produced D mesons with π and K mesons from the same primary vertex**
- **Very large combinatorial background**
- **Production of any J^P state is permitted**
- **LHCb developed a strong program with Run1**

  Difficult to improve further in this direction even with new data

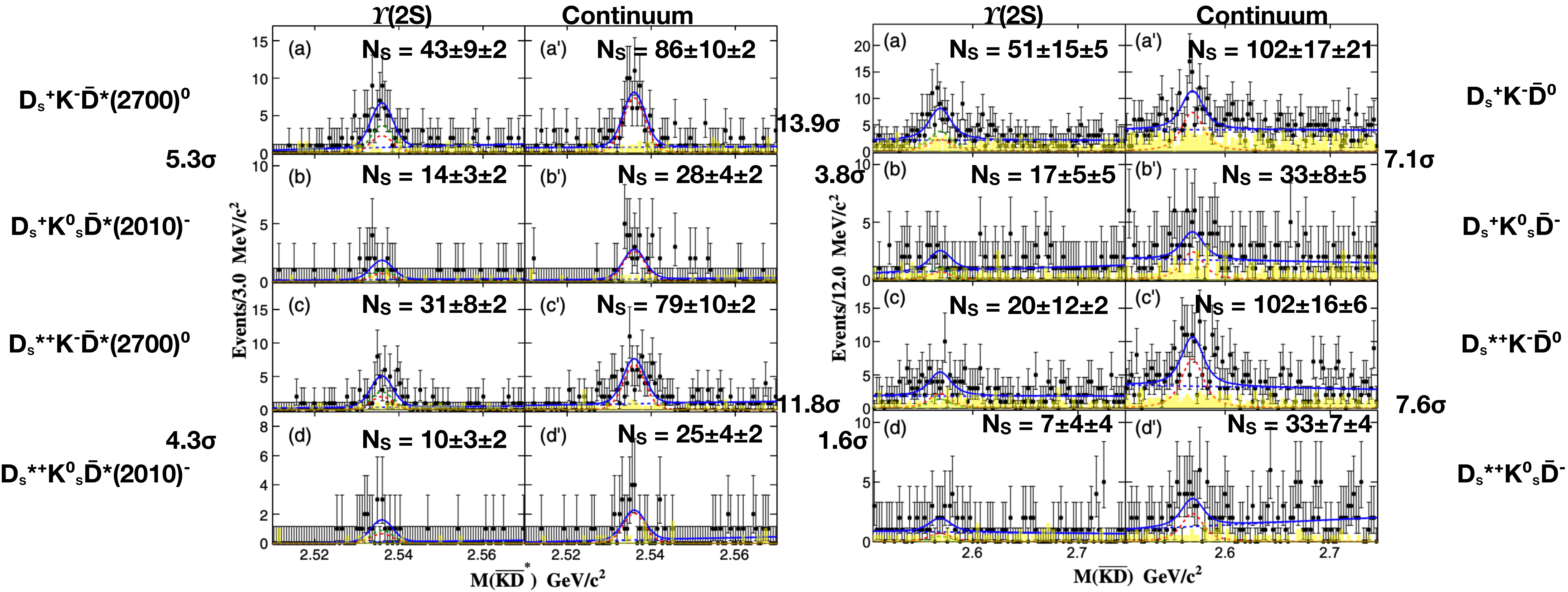
e^+e^-

- **Needs large enough energy above $c\bar{c}$ threshold**
- **Better to avoid B mesons production (below $\Upsilon(4S)$)**
- **Belle studied $\Upsilon(2S)\rightarrow D_s^{(*)+}D_{sJ}^-$ decays**

  Knowing the initial energy, needs only to reconstruct a $D_s^{(*)}$ and a K to infer the $D^{(*)}$ momentum from recoil

Recent DsJ Spectroscopy at Belle

Phys. Rev. D108 (2023) 112015



Isospin ratio $\mathcal{B}(D_{sJ}^- \to K_S^0 D^{(*)-})/\mathcal{B}(D_{sJ}^- \to K^- \bar{D}^{(*)0})$	
$D_{s1}(2536)^-$ decays	$0.48 \pm 0.07 \pm 0.02$
$D_{s2}^*(2573)^-$ decays	$0.49 \pm 0.10 \pm 0.02$

B->DDKπ Systematics

TABLE II. Systematic uncertainties on the pole mass and width of the $D_{s0}(2590)^+$ state, and fit fractions of the three D_s^+ components. The individual sources are added in quadrature to obtain the total uncertainty. The notations are the same as these in Table I.

			Fit fraction ($\times 10^{-2}$)				
Source	m_R [MeV]	Γ_R [MeV]	D_{s0}^+	D_{s1}^+	NR	D_{s0}^+–NR	D_{s1}^+/D_{s0}^+
$D_{s0}(2590)^+$ width model	6.1	8.0	4.7	0.0	15.0	19.6	0.5
$D_{s1}(2536)^+$ mass shape	0.3	4.3	2.3	0.6	3.5	5.3	1.1
$K^+\pi^-$ mass shape	2.7	2.6	3.0	0.2	1.2	4.4	0.1
Blatt-Weisskopf factor	0.7	3.4	2.8	0.3	1.3	3.0	0.2
Including $c\bar{c}$ resonances	1.1	5.4	2.7	0.1	6.3	10.0	0.4
$D^+\pi^-$ resonance veto	2.4	2.1	4.6	0.3	9.4	4.6	0.2
Simulation correction	0.2	1.1	0.3	0.1	0.7	0.8	0.2
Momentum calibration	0.5	0.4	1.3	0.0	1.4	2.5	0.2
Total	7.2	11.7	8.6	0.8	19.3	23.9	1.4