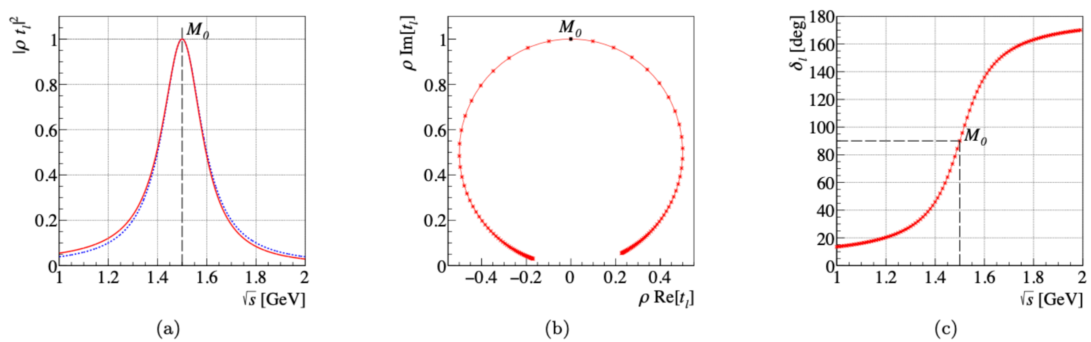
Challenges in amplitude analyses for heavy-meson spectroscopy at LHCb

Jonas Rademacker on behalf of LHCb

Eric (yesterday):

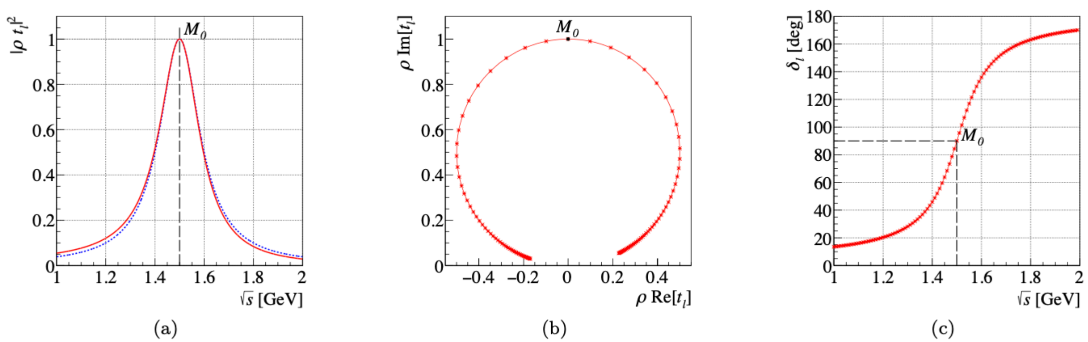
These days are over.



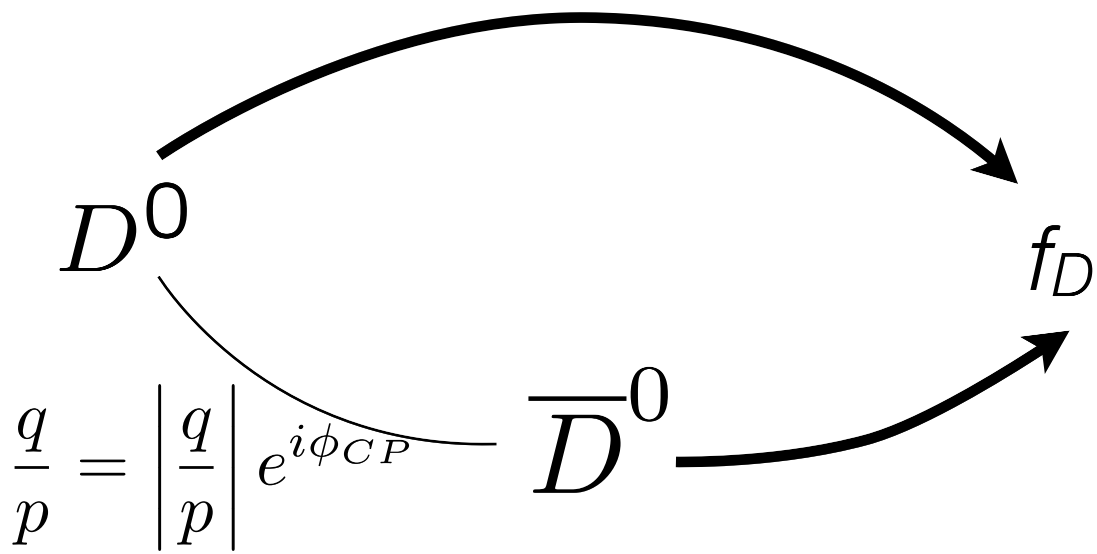
Eric (yesterday):

These days are over.

They are not.



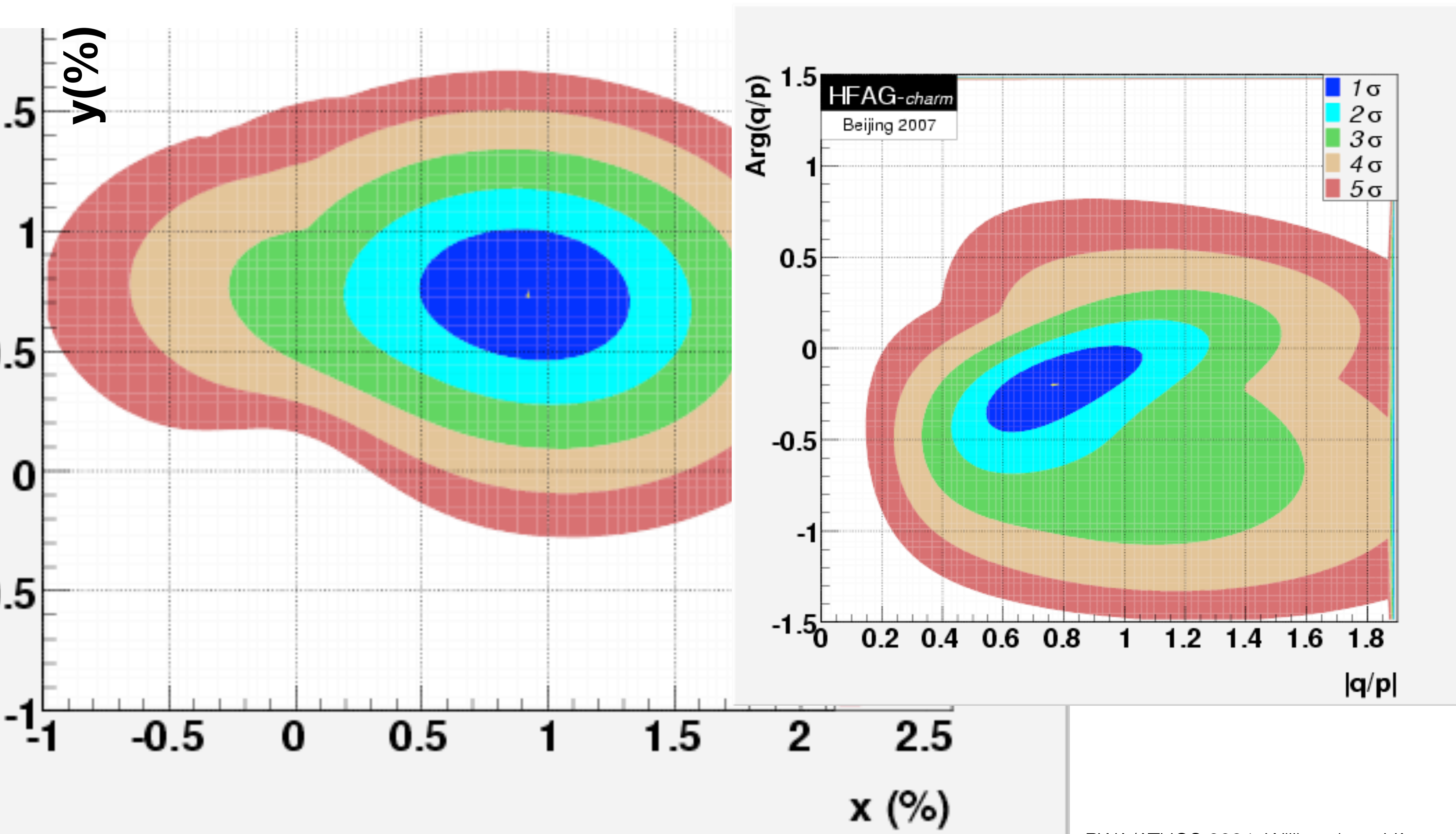
Time dependent CPV in charm



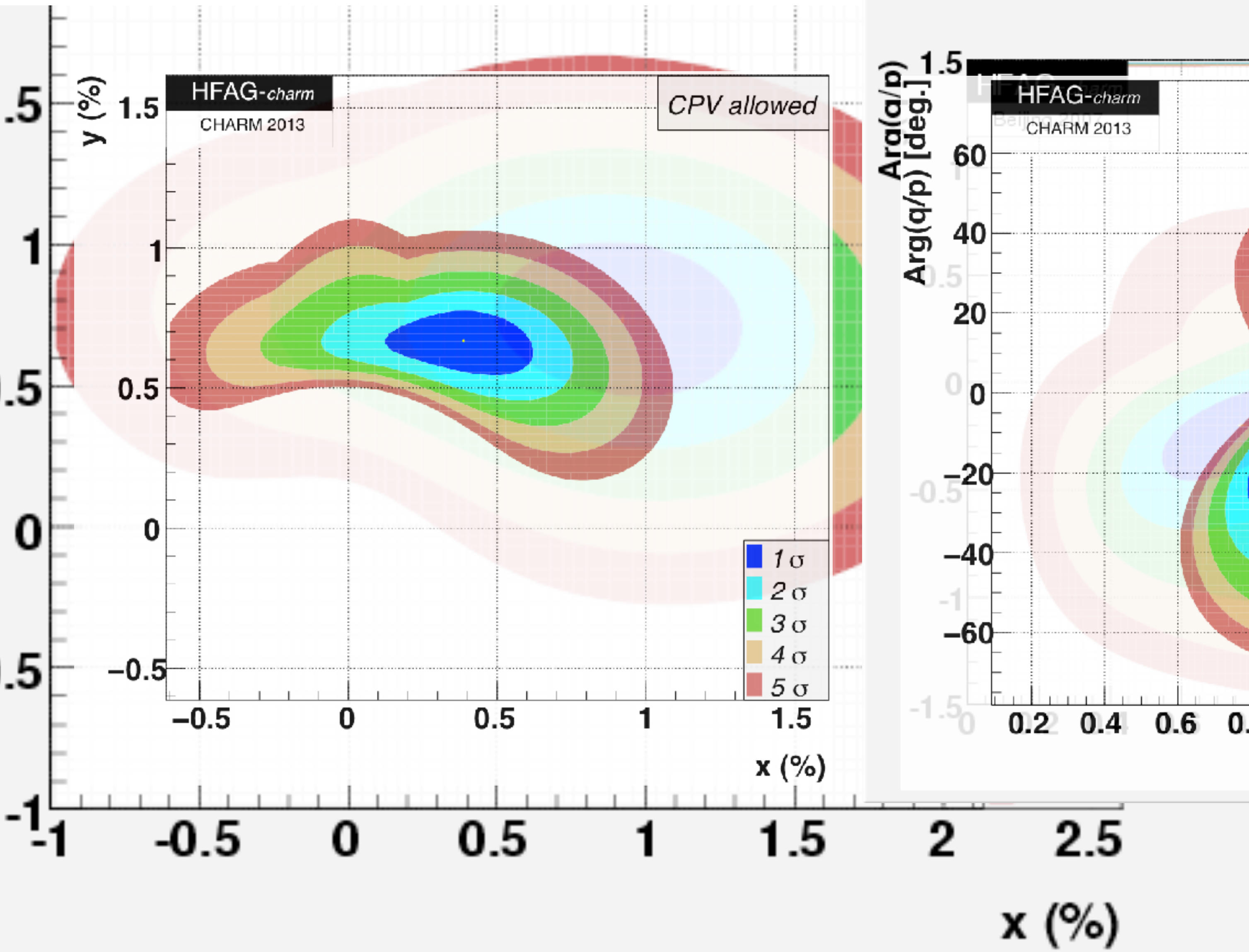
CP violation if $|q/p| \neq 1$ or $\phi_{CP} \neq 0$ (or π)

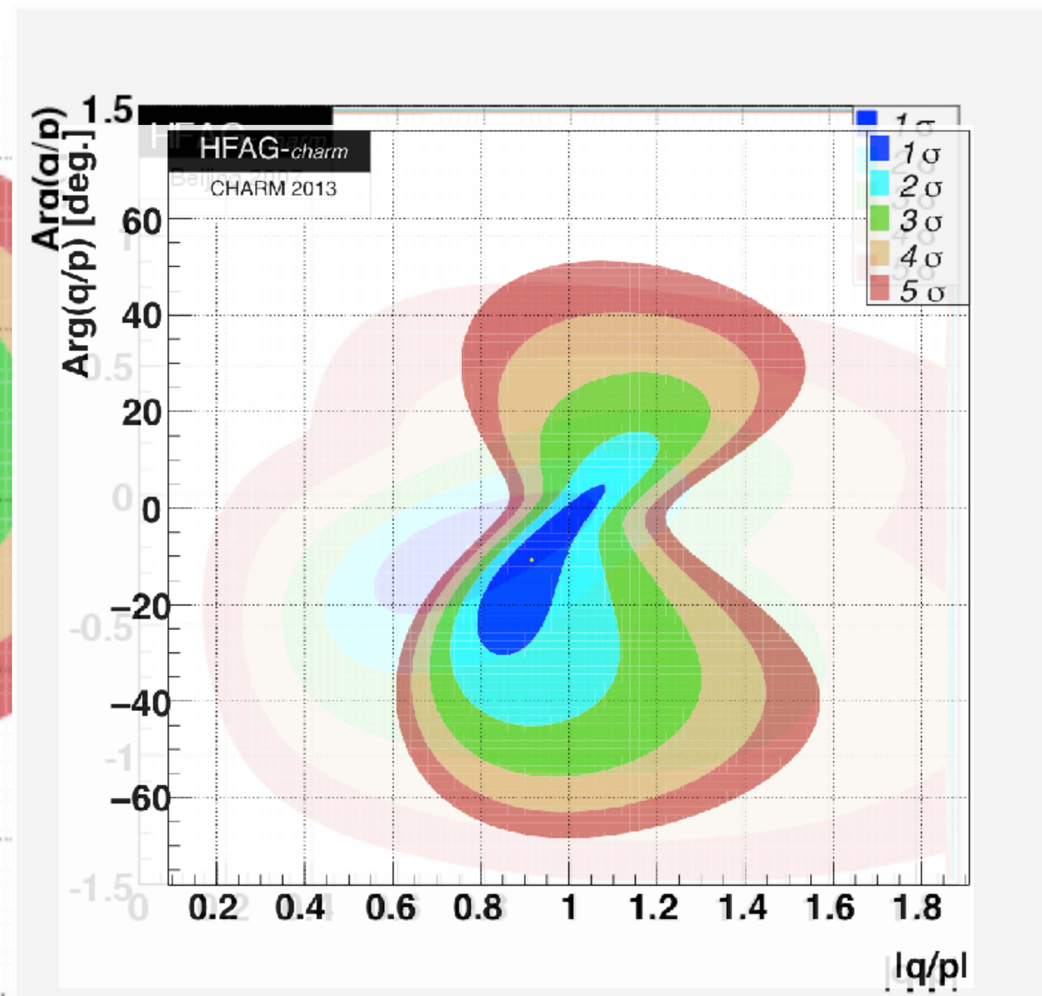
Superpositions of D^0 and $\overline{D}^0$ form particles with well-defined mass and width. Mass and width difference parametrised by $x = \frac{\Delta m}{\overline{\Gamma}}$ and $y = \frac{\Delta \Gamma}{2\overline{\Gamma}}$

Charm mixing in 2007

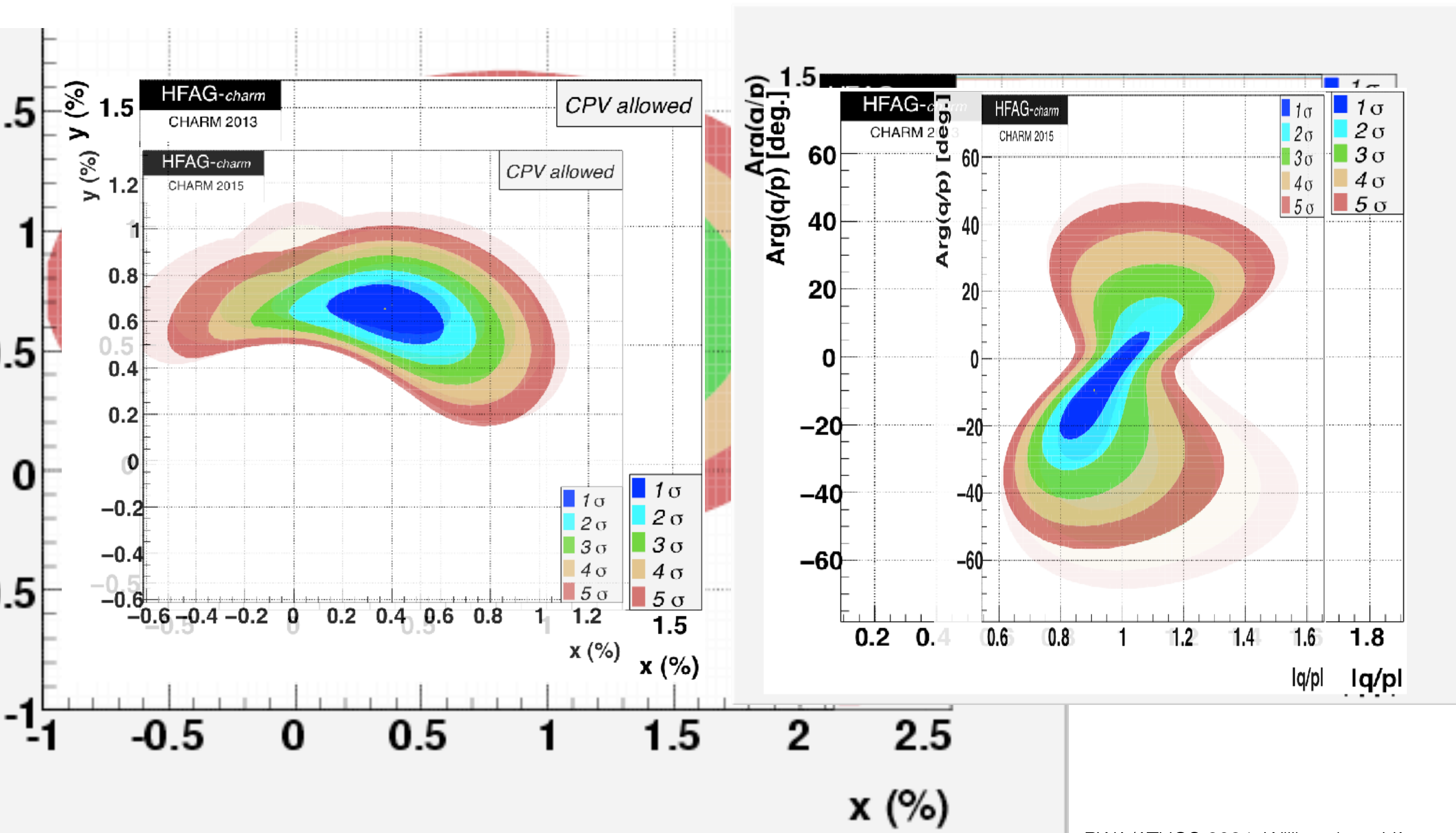


Charm mixing in 2013

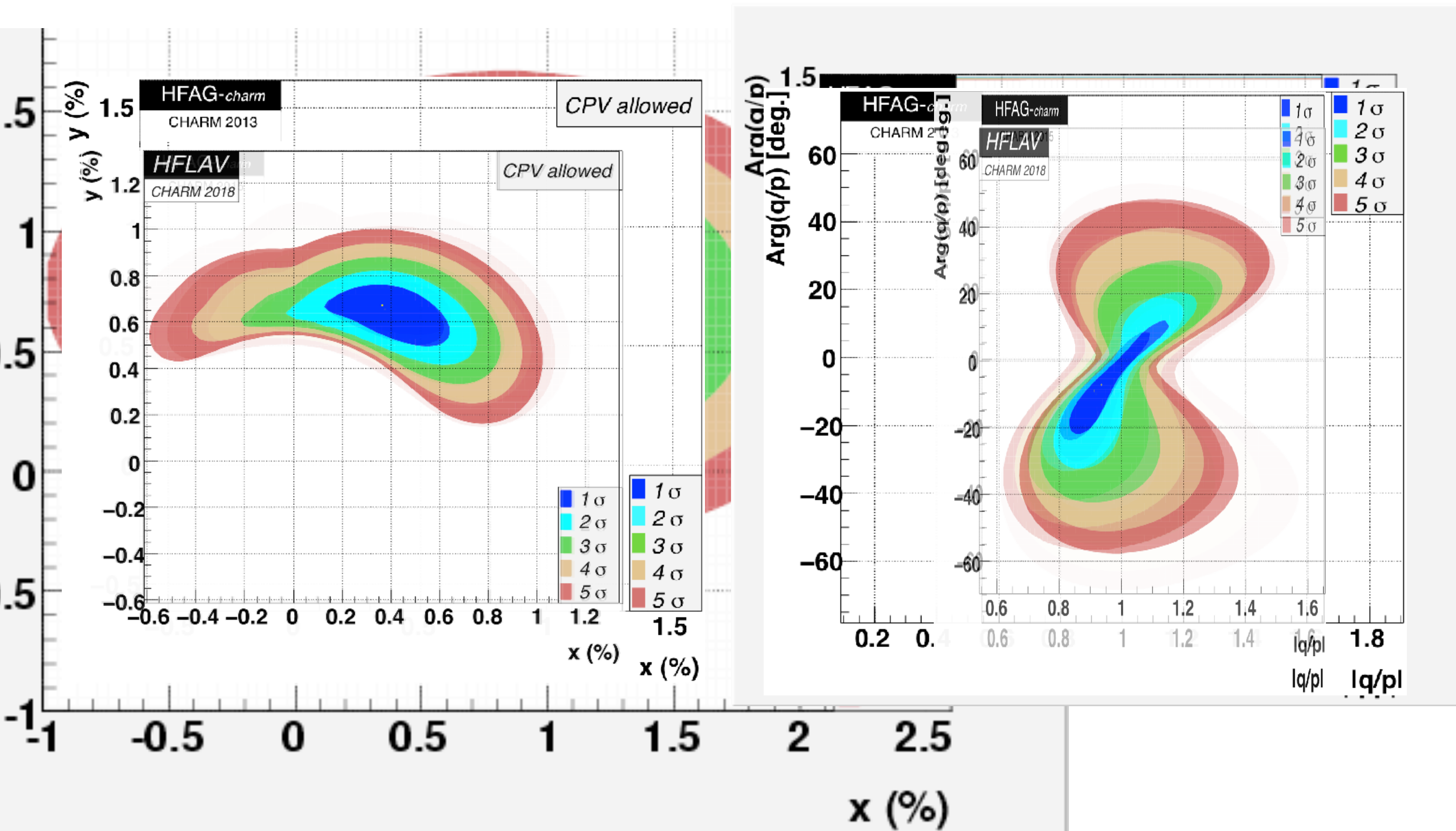




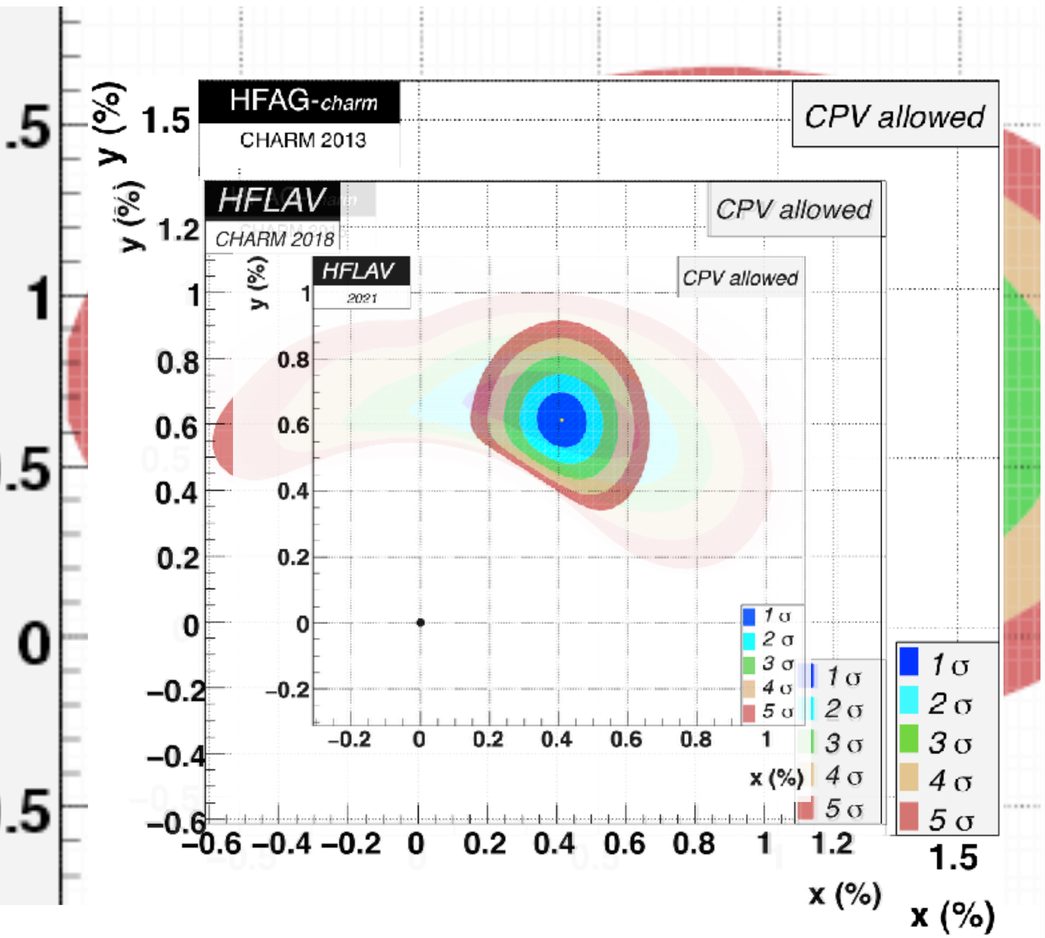
Charm mixing in 2015

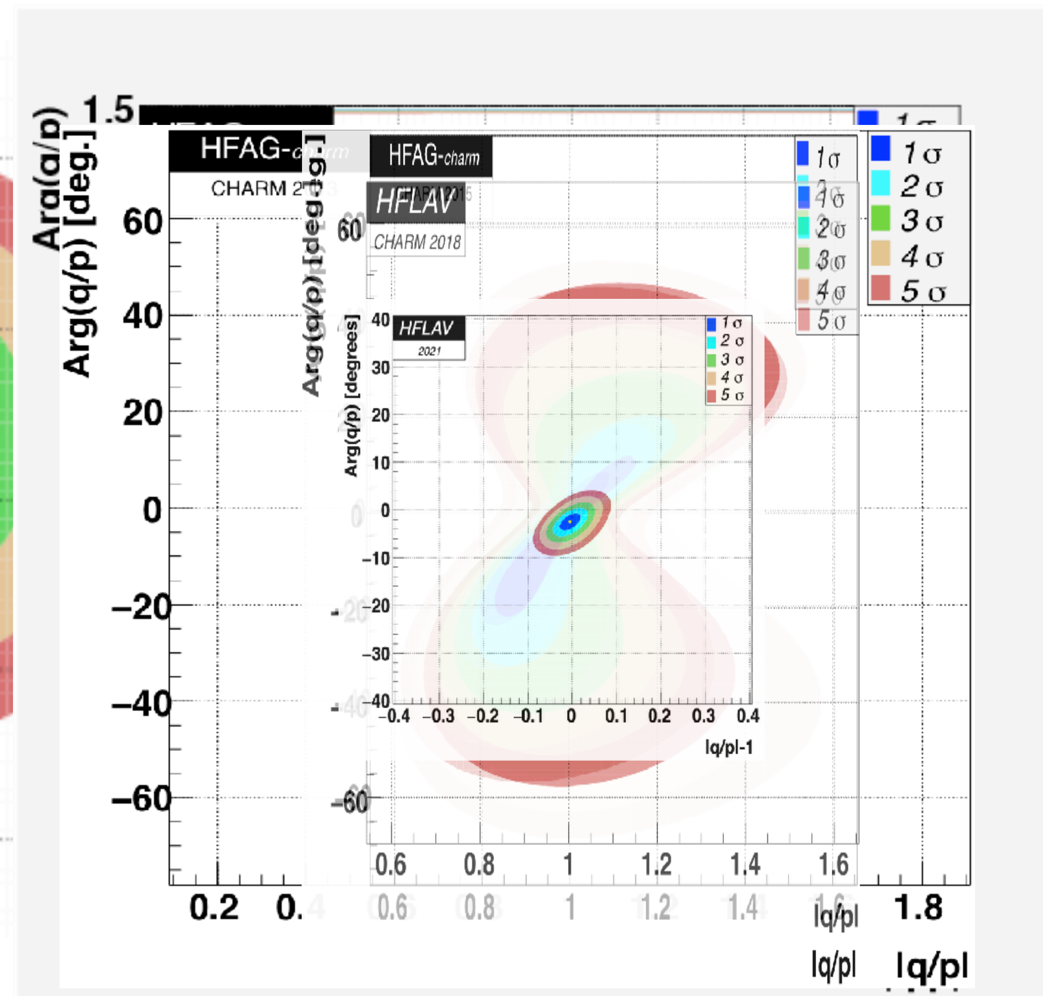


Charm mixing in 2018



Charm mixing in 2021



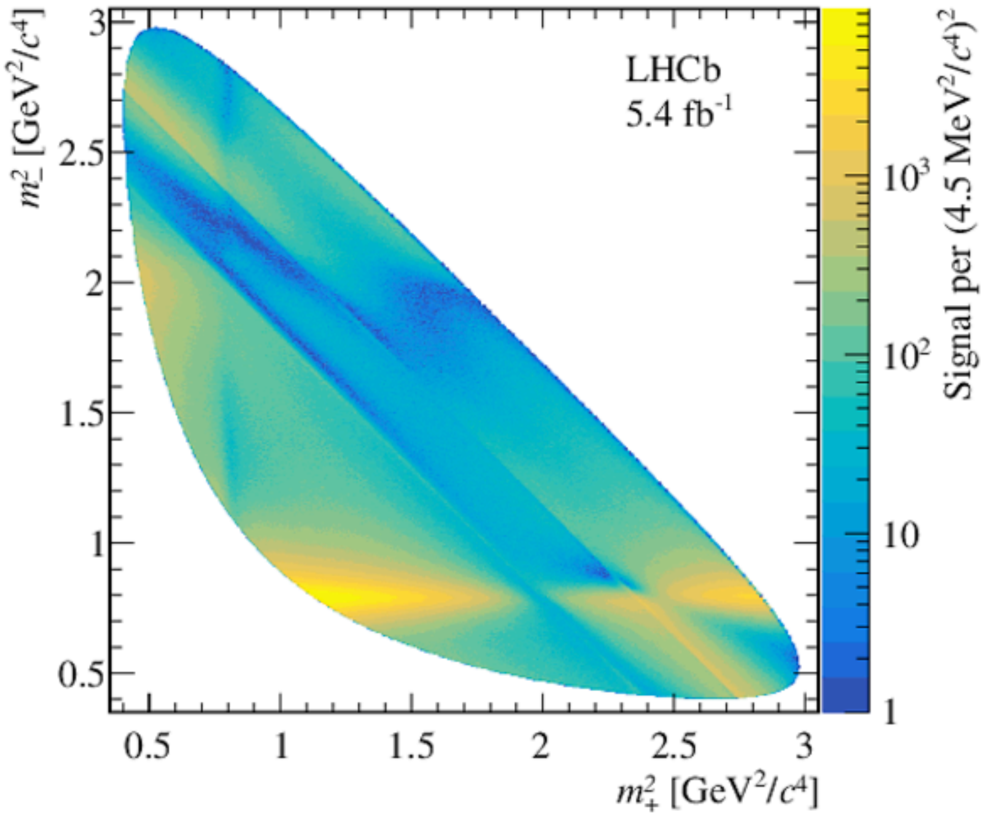


non-zero x at $> 5\sigma$

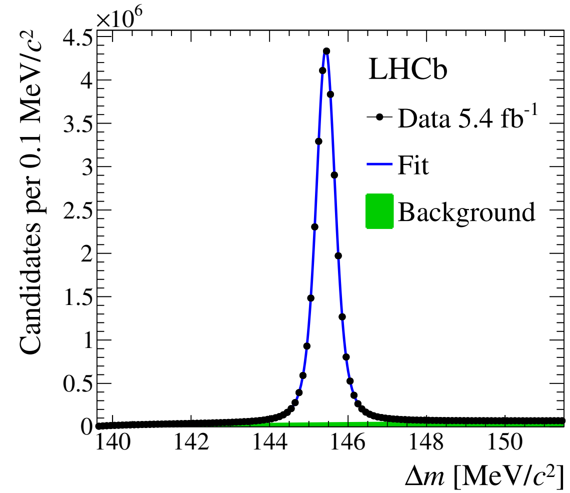
What was that???
LHCb model-independent mixing with $D^0 \to K_S\pi^+\pi^-$

LHCb: PRL 127 (2021) 11, 111801

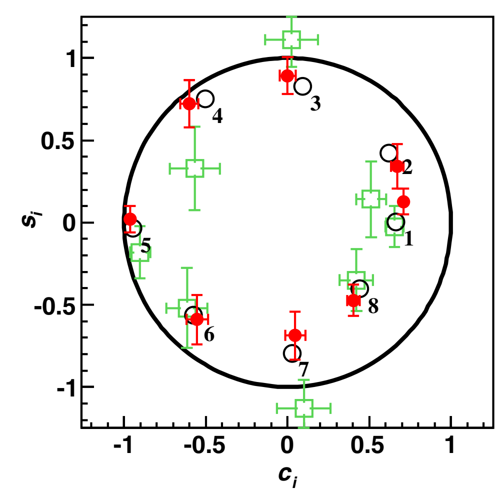
Method: Phys.Rev. D99 (2019) no.1, 012007



$$3.1 \times 10^7 \;\; D^0 \to K_S^0\pi^+\pi^-$$



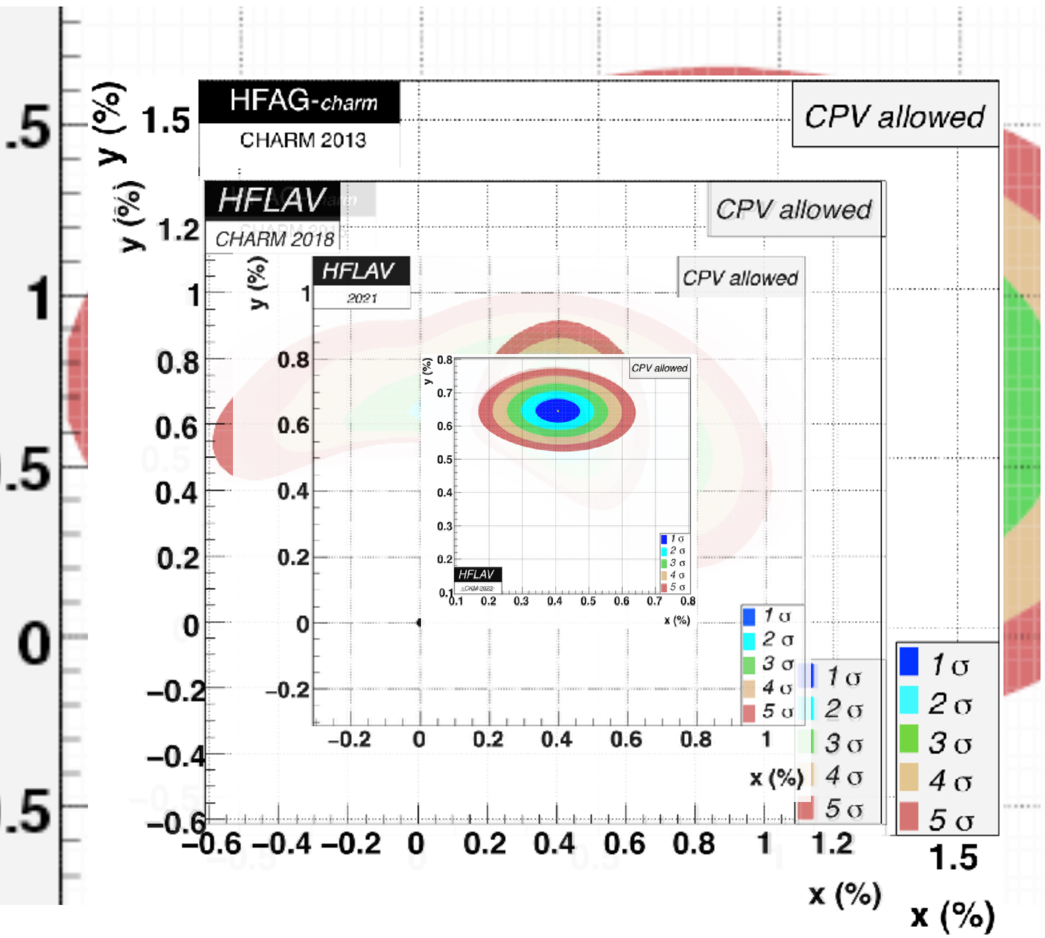
Critical: BES-III input

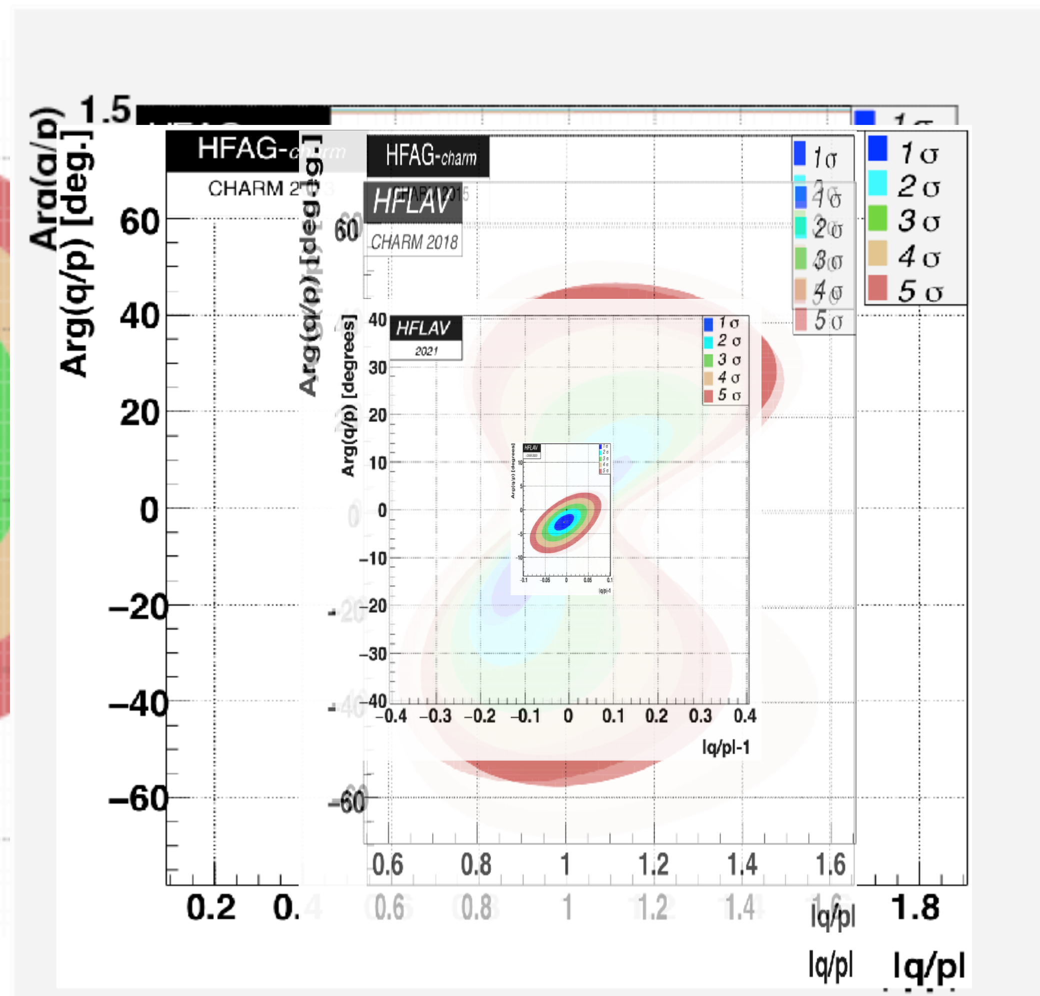


BESIII: PRL 124 (2020) 24, 241802

See also CLEO-c, Phys.Rev. D82 (2010) 112006

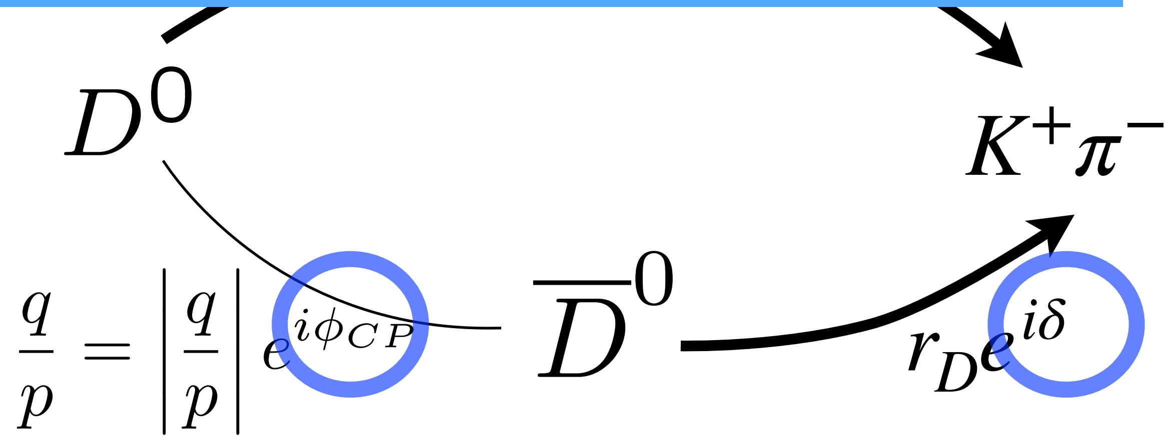
Charm mixing in 2023





Why has $D^0 \to K_S\pi^+\pi^-$ had such an impact?

Amplitude analyses are good at phases!



Two body modes measure final-state-dependent x', y', which are x, y rotated by the strong phase difference between $D^0 \to f_D$ and $\overline{D}^0 \to f_D$

The magic of Amplitude Analyses measures this phase at the same time as $x, y, |q/p|, \phi_{CP}$

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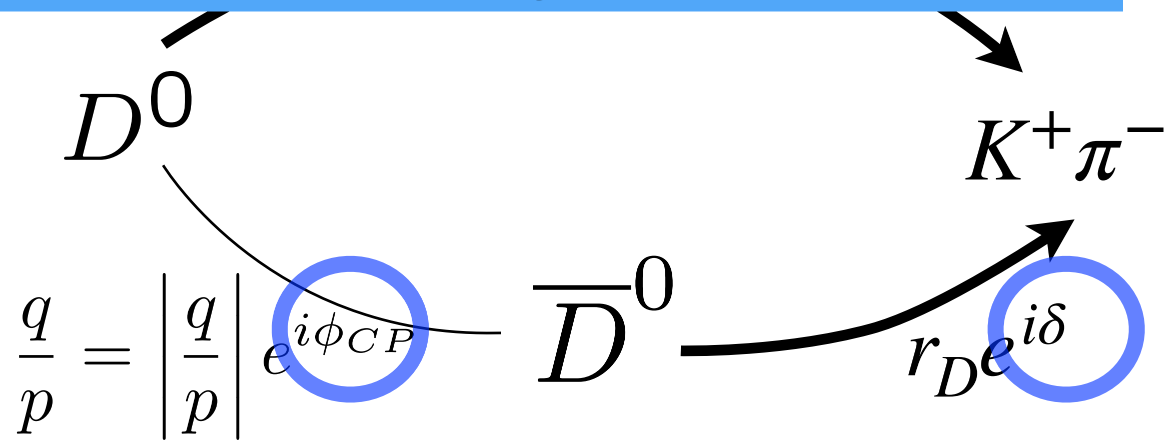
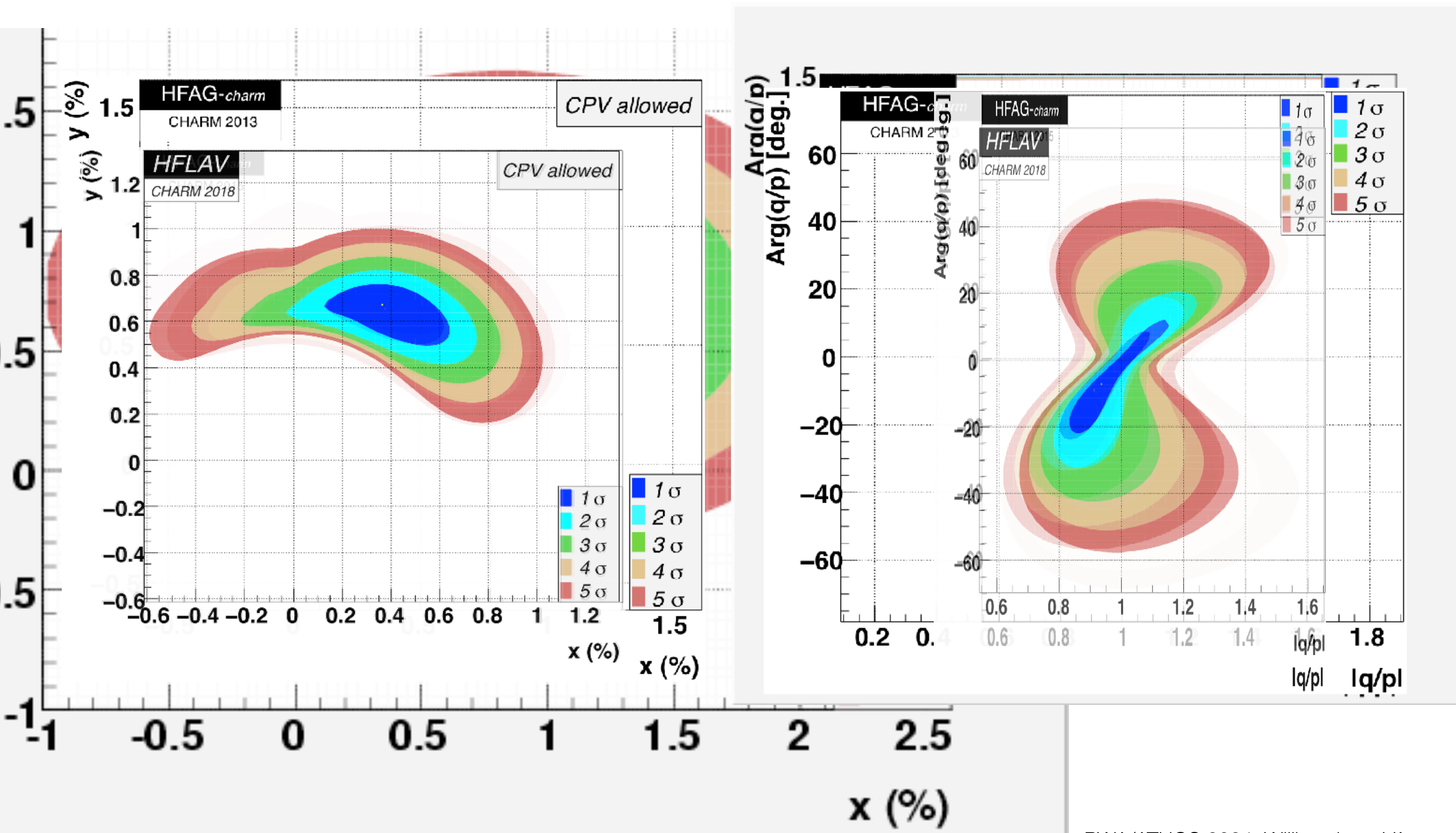


Two body modes measure final-state-dependent x', y', which are x, y rotated by the strong phase difference between $D^0 \to f_D$ and $\overline{D}^0 \to f_D$

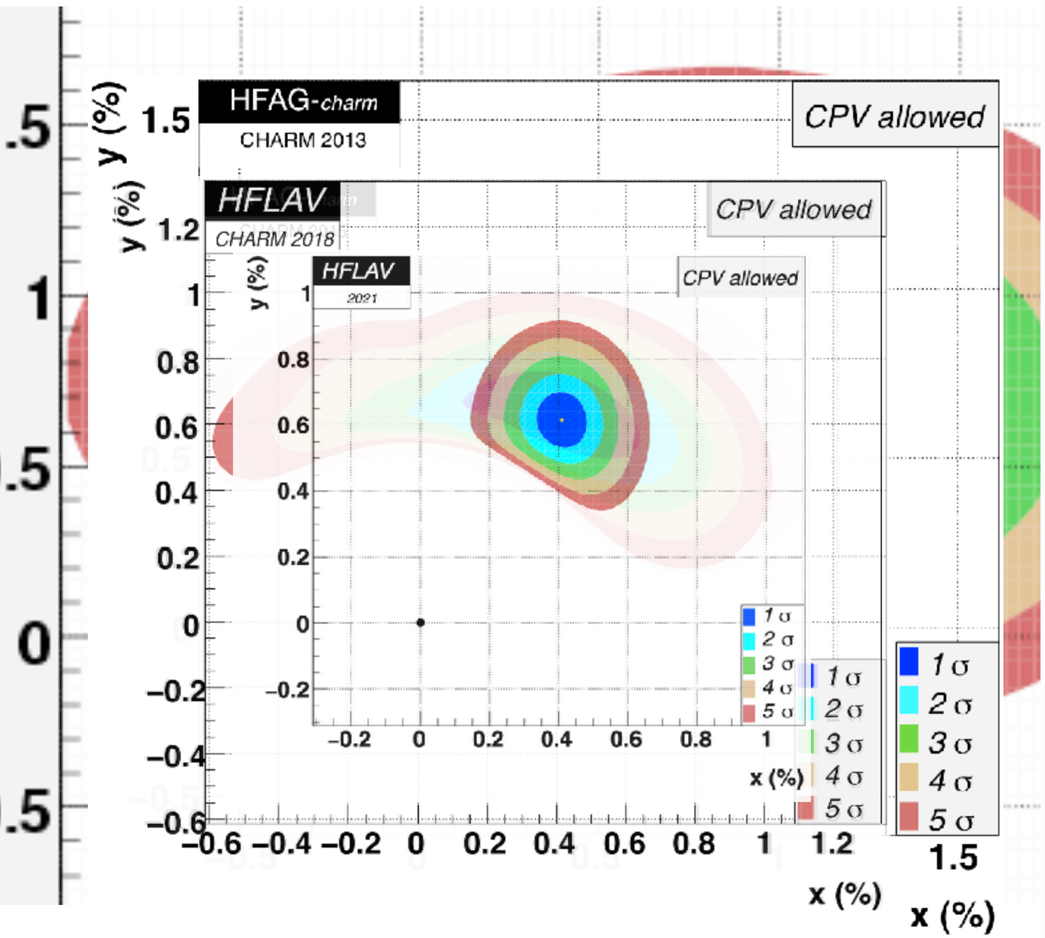
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

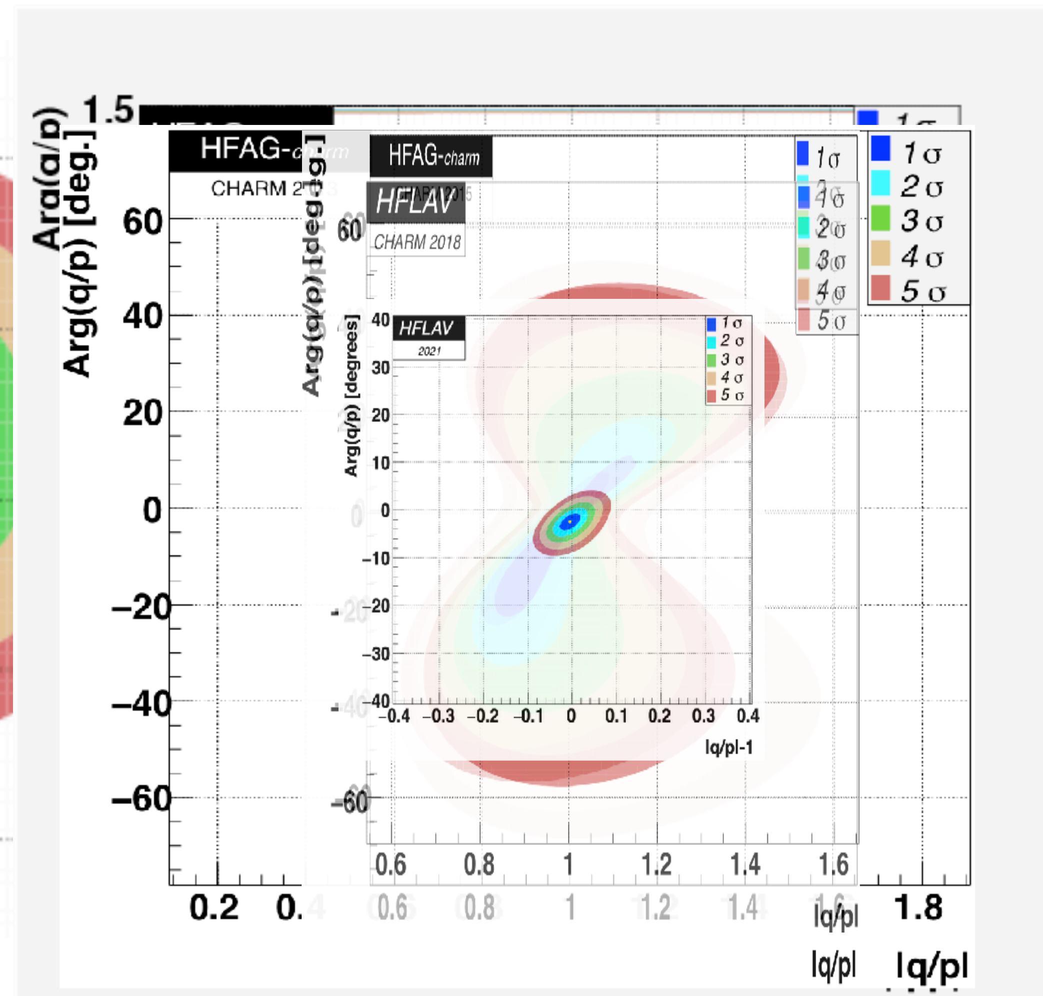
The magic of Amplitude Analyses measures this phase at the same time as $x, y, |q/p|, \phi_{CP}$

Charm mixing in 2018



Charm mixing in 2021

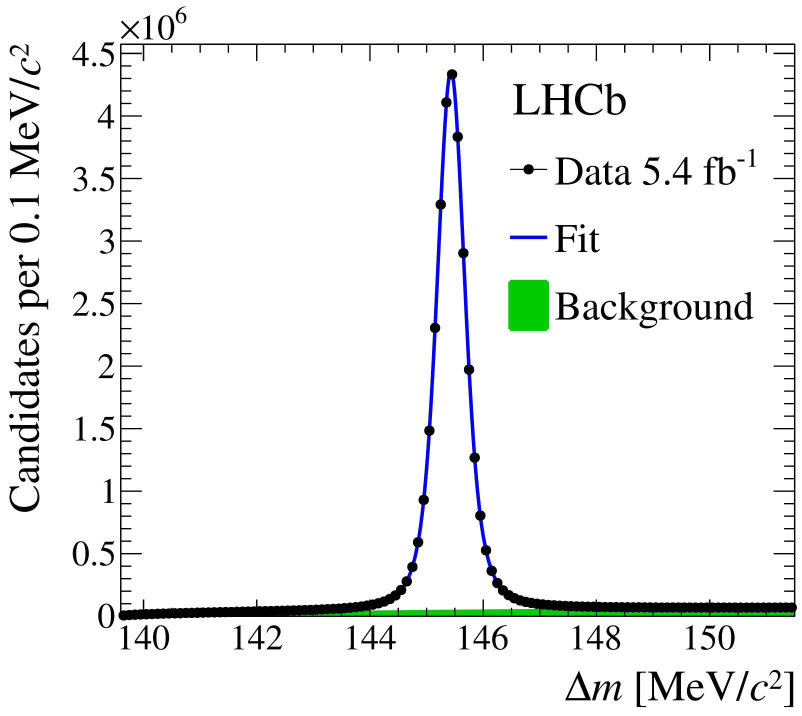




non-zero x at $> 5\sigma$

Why has $D^0 \to K_S\pi^+\pi^-$ had such an impact?

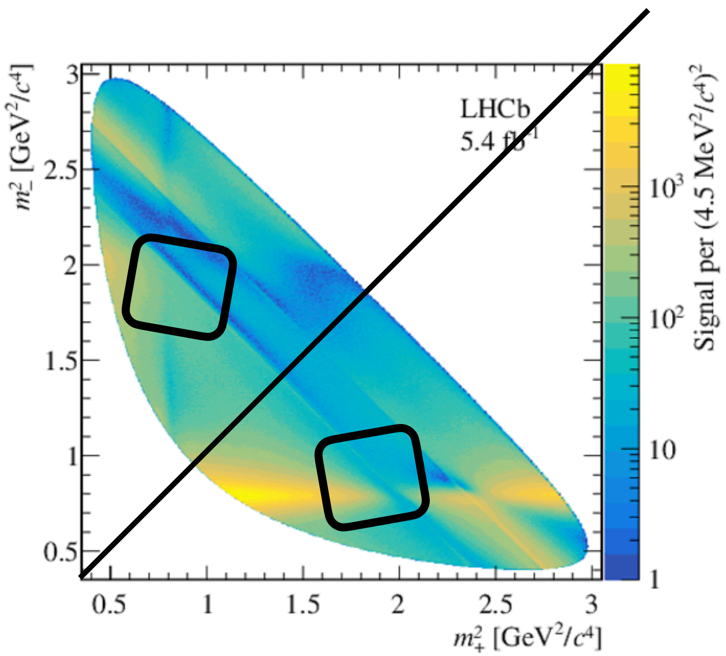
LHCb charm data are clean and plentiful



$$3.1 \times 10^7 \quad D^0 \to K_S^0\pi^+\pi^-$$

Why has $D^0 \to K_S\pi^+\pi^-$ had such an impact?

The "bin-flip" method ensures that many systematic uncertainties largely cancel.



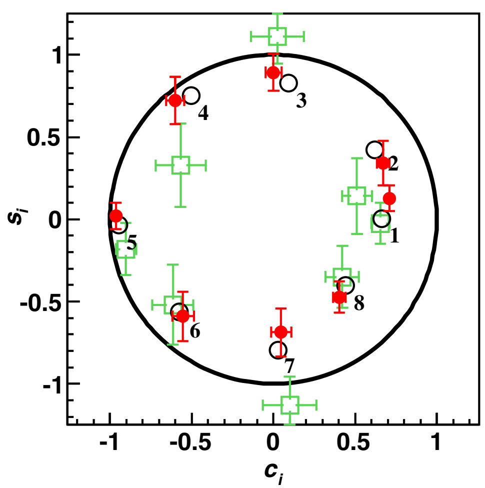
Methods is based on (time-dependent) ratios of yields in CP-conjugate bins with identical kinematics.

LHCb: PRL 127 (2021) 11, 111801

Method: Phys.Rev. D99 (2019) no.1, 012007

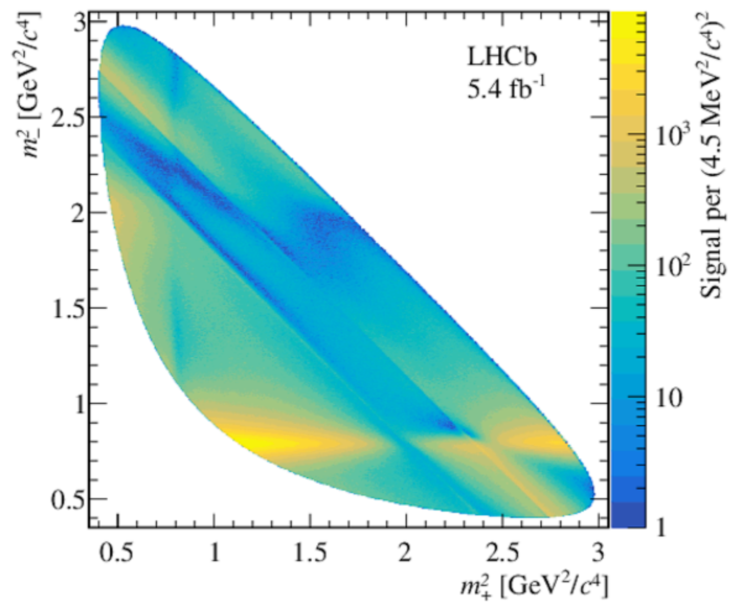
Why has $D^0 \to K_S\pi^+\pi^-$ had such an impact?

Binned analysis with BES III input removes amplitude model dependence



BESIII: PRL 124 (2020) 24, 241802

See also CLEO-c, Phys.Rev. D82 (2010) 112006



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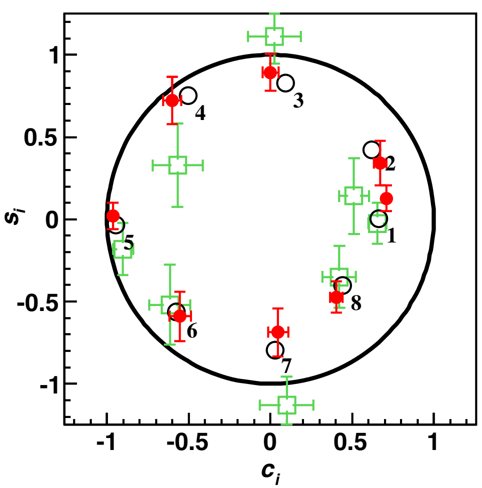

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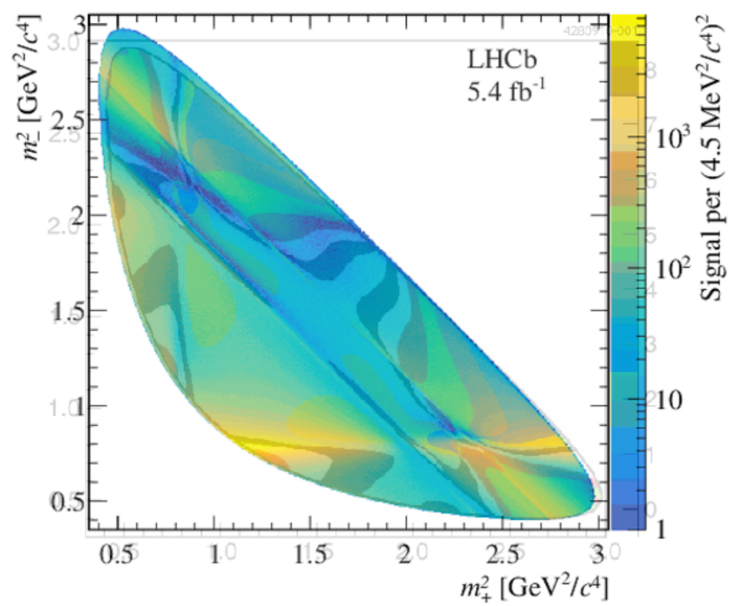

LHCb: PRL 127 (2021) 11, 111801

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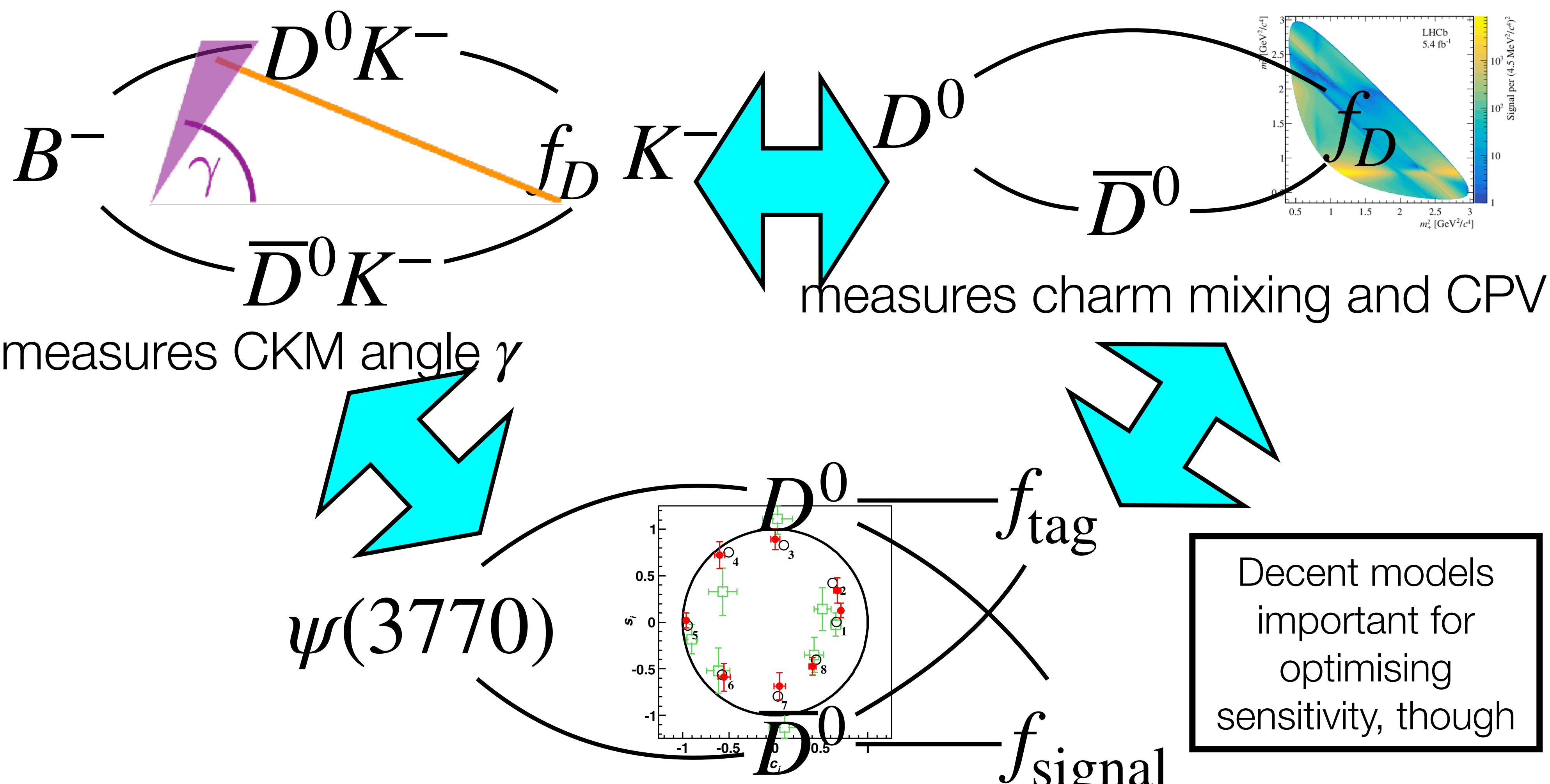
Details in my talk, yesterday

Same BESIII input also crucial for model-independent γ



measures CKM angle γ

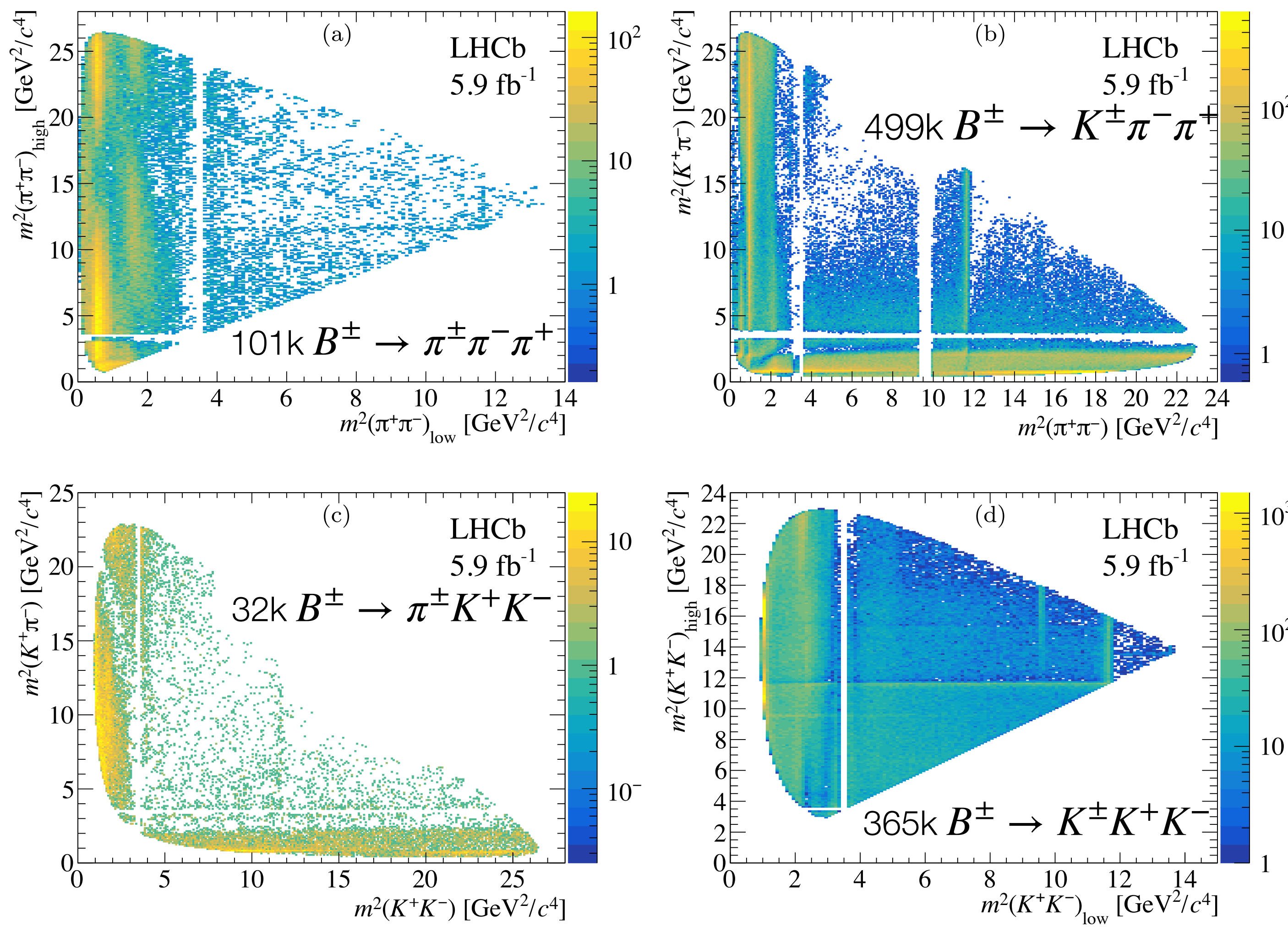
measures charm mixing and CPV

measures charm interference, especially strong phases

Decent models important for optimising sensitivity, though

Large CP violation in $B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008



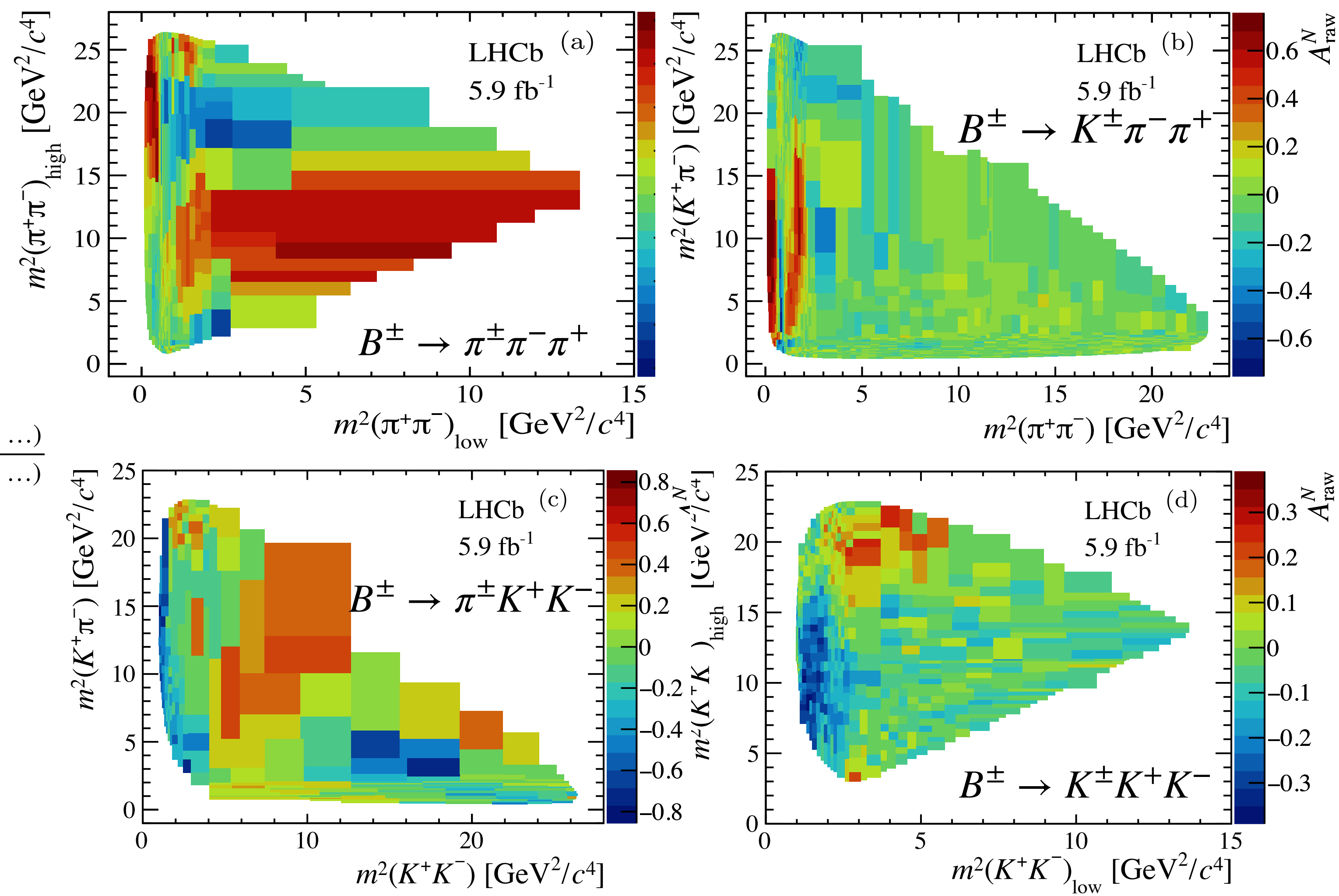
See also: LHCb: PRL 112 (2014) 1, 011801, PRD 90 (2014) 11, 112004, PRL 123 (2019) 23, 231802, PRL 124 (2020) no.3, 031801, PRD101 (2020) no.1, 012006,
BELLE: PRD 96 (2017) 3, 031101

Large CP violation in $B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008

Color scale:

$$\frac{\Gamma(B^+ \to \ldots) - \Gamma(B^- \to \ldots)}{\Gamma(B^+ \to \ldots) + \Gamma(B^- \to \ldots)}$$



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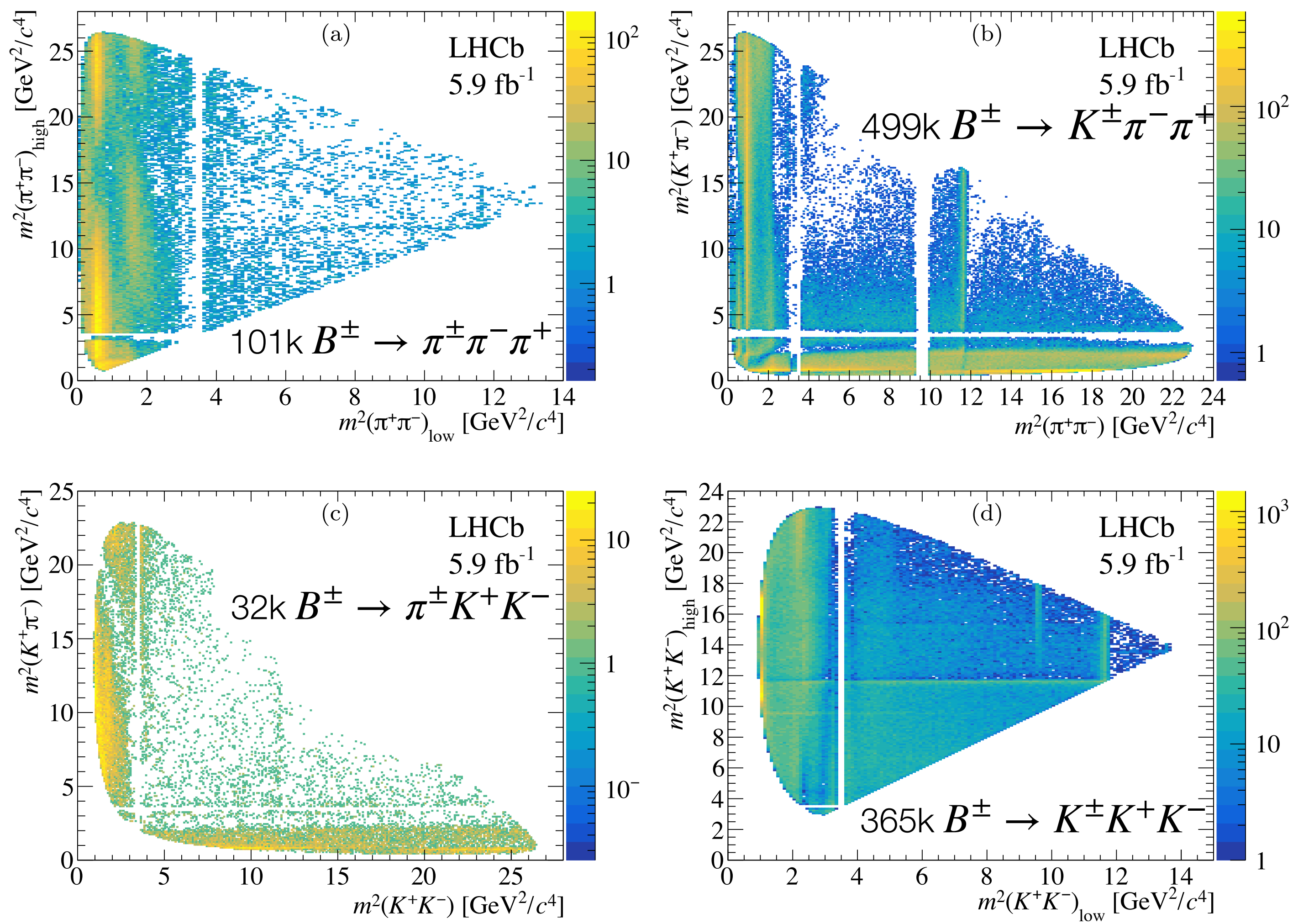

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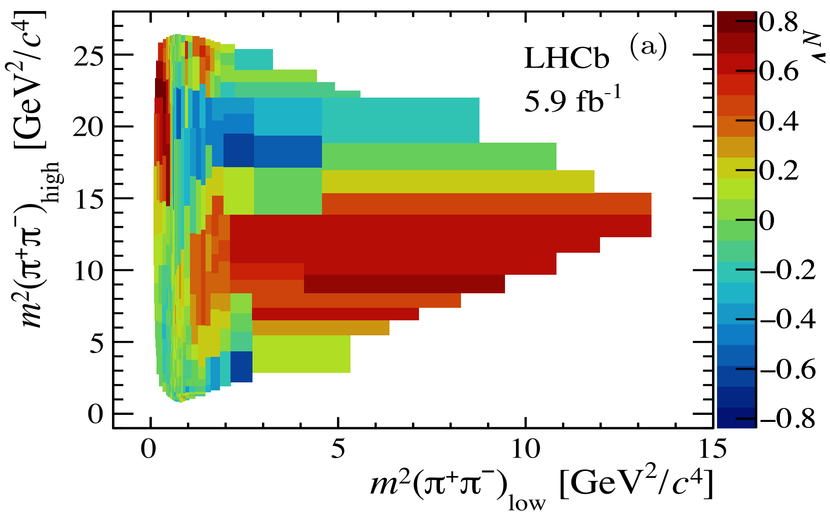
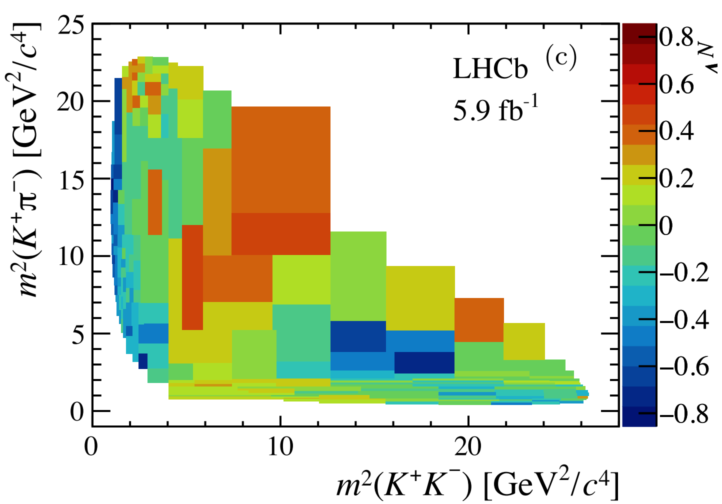
$B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008



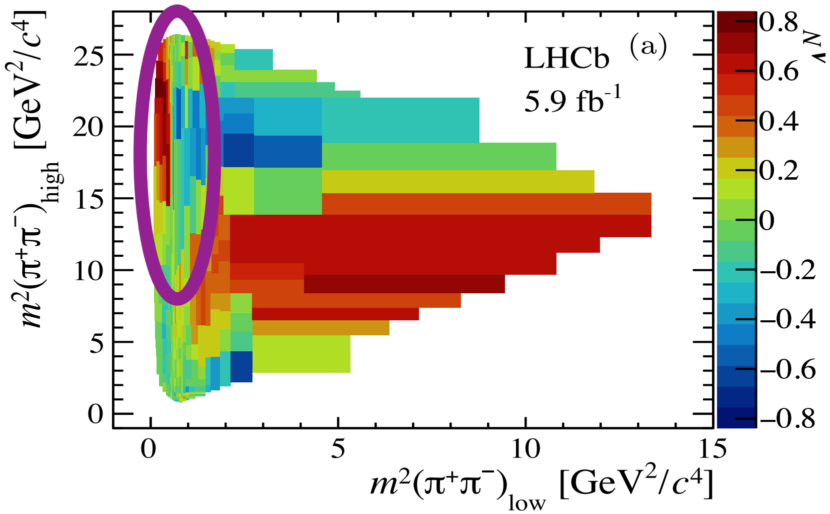


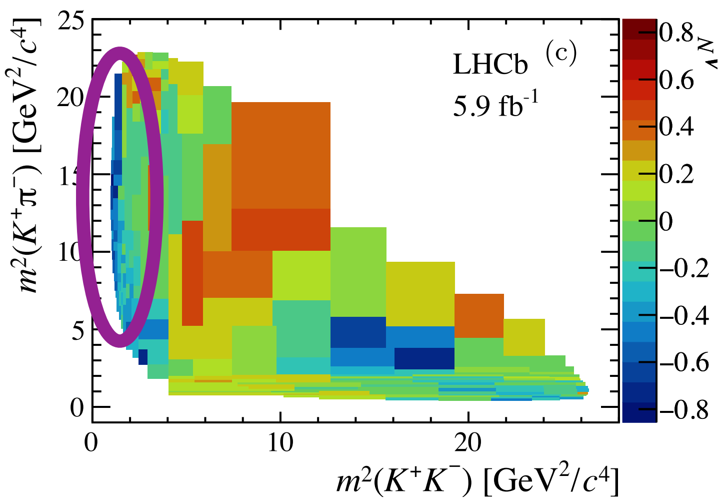
What provides the strong phase in $A_{CP} \propto \sin(\Delta\phi_{weak})\ \sin(\Delta\delta_{strong})$?

where the Δ indicates the phase differences between two interfering amplitudes contributing to the process; $\Delta\phi_{weak}$ changes sign under CP, $\Delta\delta_{strong}$ does not.

$B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008





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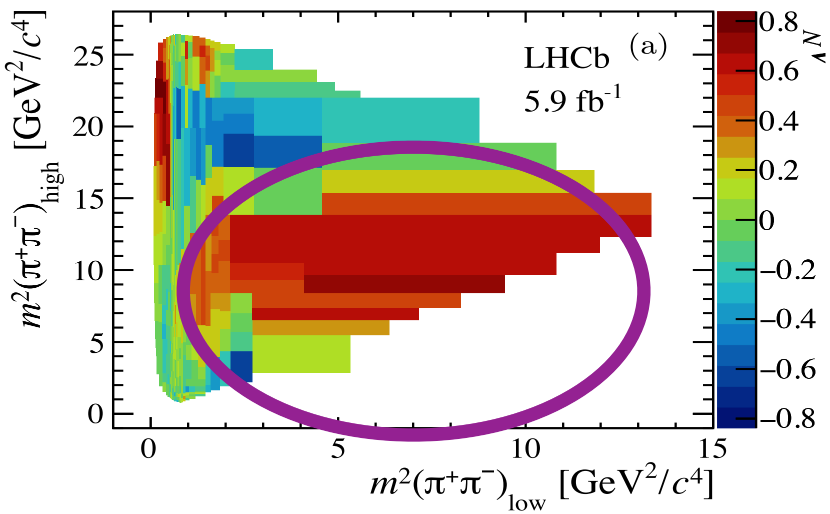
where the Δ indicates the phase differences between two interfering amplitudes contributing to the process; $\Delta\phi_{weak}$ changes sign under CP, $\Delta\delta_{strong}$ does not.

For low mass region, where large CPV is observed, $KK \leftrightarrow \pi\pi$ re-scattering could play a key role

See Phys.Rev.D 89 (2014) 9, 094013 for theoretical motivation. The amplitude analysis of $B^\pm \to \pi^\pm K^+ K^-$ in PRL 123 (2019) 23, 231802 includes a re-scattering component. The $B^\pm \to \pi^\pm\pi^+\pi^-$ in PRL 124 (2020) 3, 031801, Phys.Rev.D 101 (2020) 1, 012006 describes the observed CPV as interference of S and P wave, without a re-scattering component.

$B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008



What provides the strong phase in

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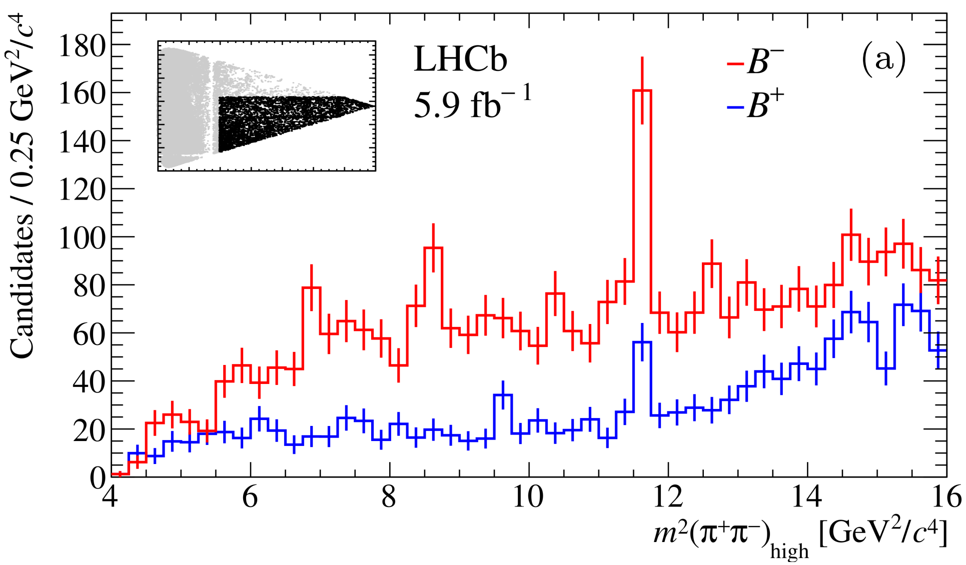
where the Δ indicates the phase differences between two interfering amplitudes contributing to the process; $\Delta\phi_{weak}$ changes sign under CP, $\Delta\delta_{strong}$ does not.

But what about this region with huge CPV?



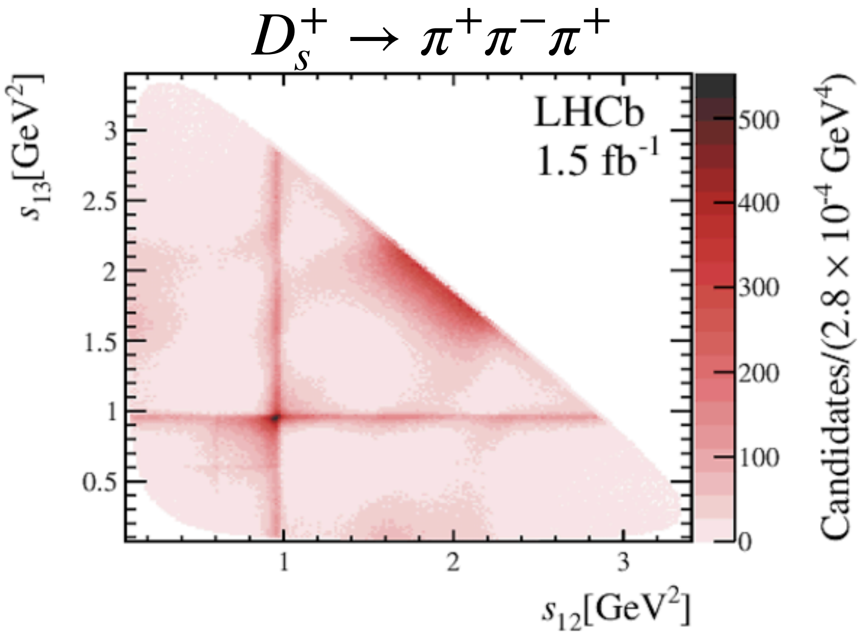
$\chi_{c0}(1P)$ plays important role

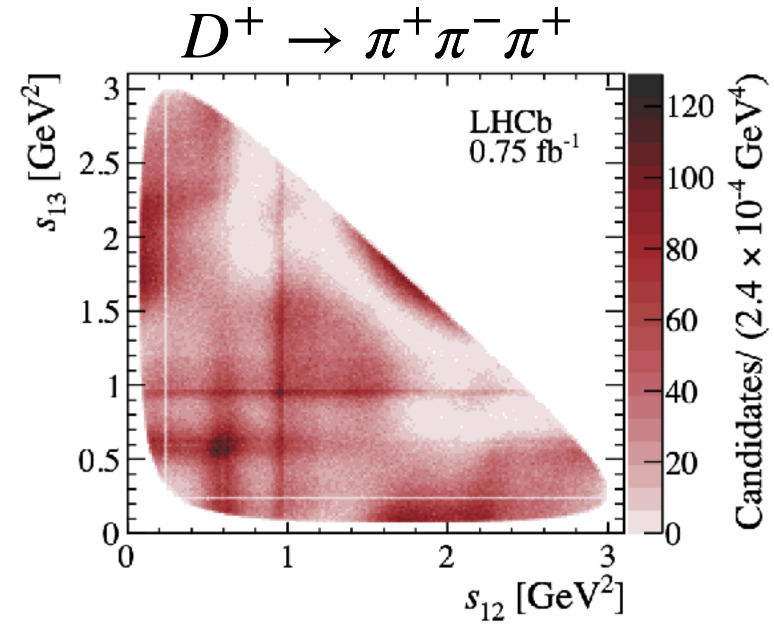
Models with model-independent components

$D^+_{(s)} \to \pi^+\pi^-\pi^+$

LHCb: JHEP 06 (2023) 044

LHCb: JHEP 07 (2023) 204





	Fit Fraction (FF) [%]			
S-wave	84.97 ±	0.14 ±	0.30 ±	0.63
$\rho(770)^0$	1.038 ±	0.054 ±	0.097 ±	0.11
$\omega(782)$	0.360 ±	0.016 ±	0.034 ±	0.016
$\rho(1450)^0$	3.86 ±	0.15 ±	0.14 ±	2.0
$\rho(1700)^0$	0.365 ±	0.050 ±	0.045 ±	0.34
combined	6.14 ±	0.27 ±	0.34 ±	1.9
$f_2(1270)$	13.69 ±	0.14 ±	0.22 ±	0.49
$f_2'(1525)$	0.0528 ±	0.0070 ±	0.015 ±	0.0087

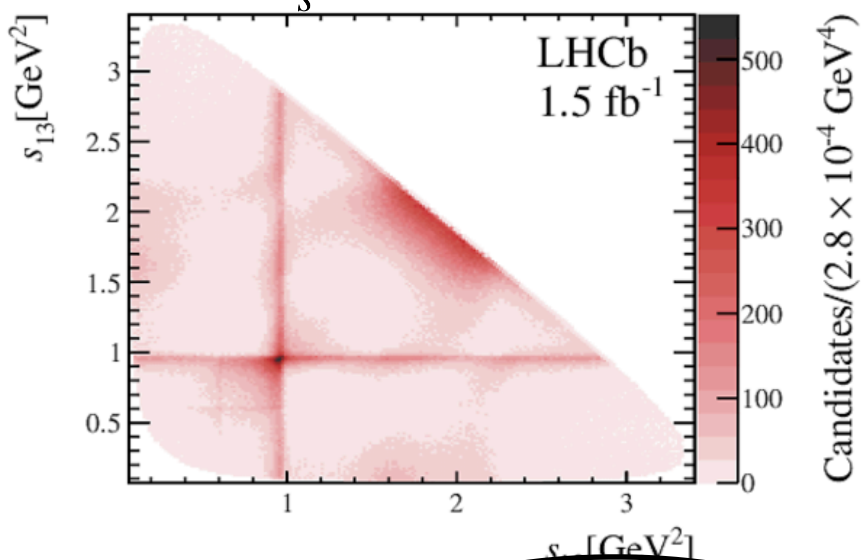
Component	Fit fraction [%]			
$\rho(770)^0\pi^+$	26.0	± 0.3	± 1.6	± 0.3
$\omega(782)\pi^+$	0.103	± 0.008	± 0.014	± 0.002
$\rho(1450)^0\pi^+$	5.4	± 0.4	± 1.3	± 0.8
$\rho(1700)^0\pi^+$	5.7	± 0.5	± 1.0	± 1.0
$f_2(1270)\pi^+$	13.8	± 0.2	± 0.4	± 0.2
S-wave	61.8	± 0.5	± 0.6	± 0.5

$D^+_{(s)} \to \pi^+\pi^-\pi^+$

LHCb: JHEP 06 (2023) 044

LHCb: JHEP 07 (2023) 204

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



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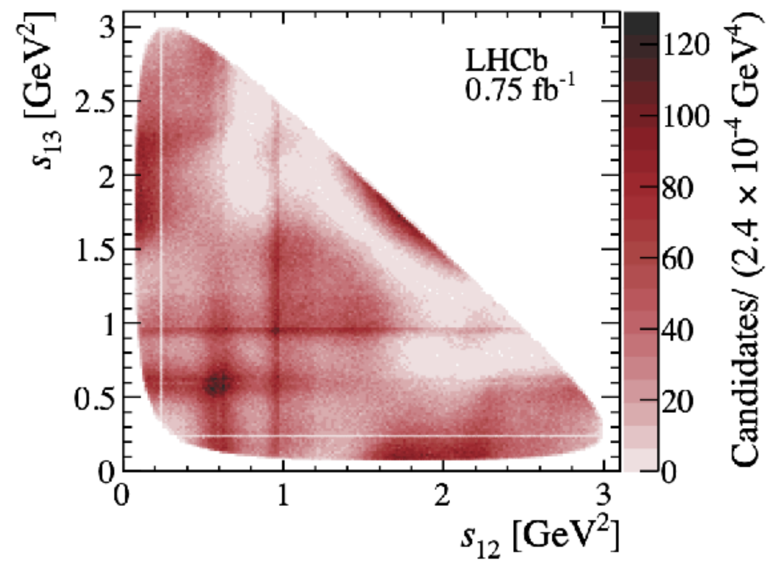

S-wave 85%

S-wave	[illegible]	[illegible]	[illegible]	[illegible]
$\rho(770)^0$	1.0[illegible]	[illegible]	[illegible]	[illegible]
$\omega(782)$	0.360 ±	[illegible]	[illegible]	0.016
$\rho(1450)^0$	3.86 ±	0.15 ±	0.14 ±	2.0
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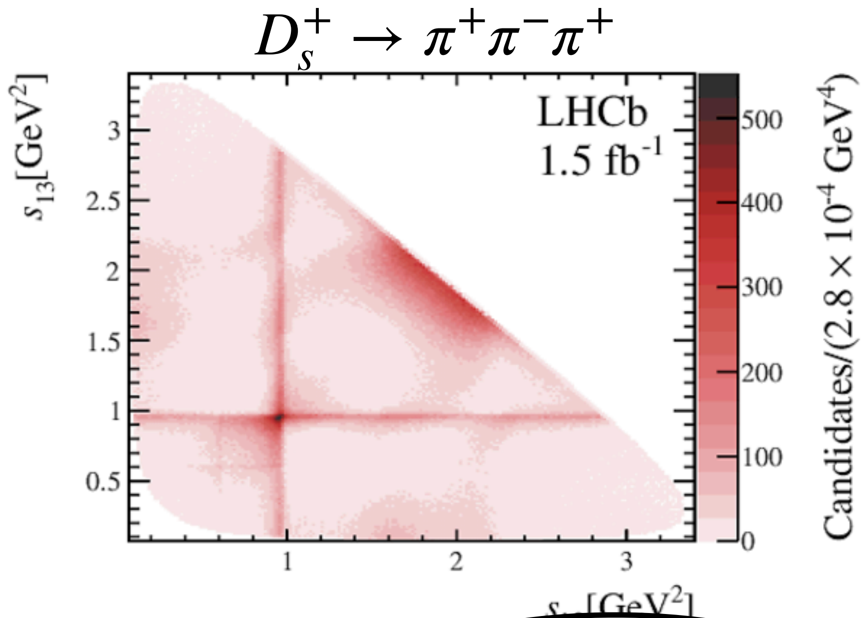
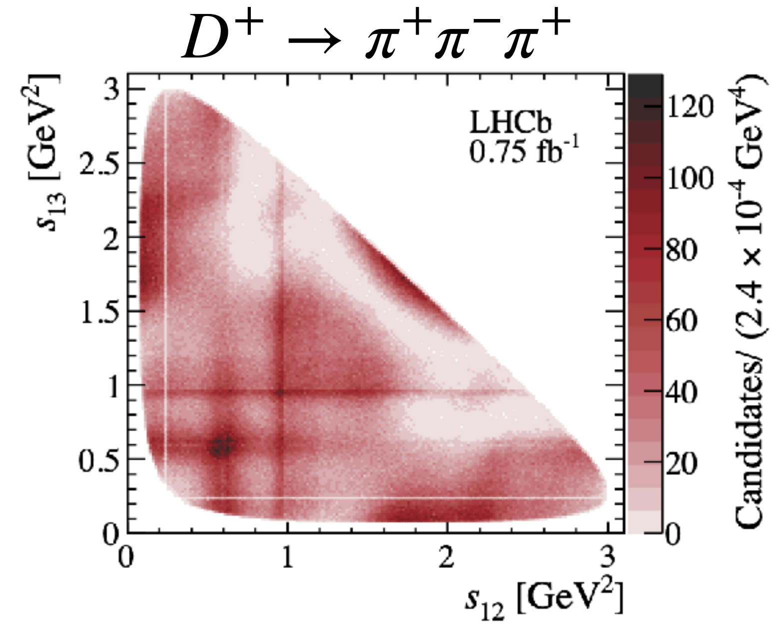
$D^+_{(s)} \to \pi^+\pi^-\pi^+$

LHCb: JHEP 06 (2023) 044

LHCb: JHEP 07 (2023) 204





S-wave 85%

S-wave	[illegible]	[illegible]	[illegible]
$\rho(770)^0$	1.0[illegible]	[illegible]	[illegible]
$\omega(782)$	$0.360 \pm$	[illegible]	[illegible] ± 0.016
$\rho(1450)^0$	$3.86 \pm$	$0.15 \pm$	0.14 ± 2.0
$\rho(1700)^0$	$0.365 \pm$	$0.050 \pm$	0.045 ± 0.34
combined	$6.14 \pm$	$0.27 \pm$	0.34 ± 1.9
$f_2(1270)$	$13.69 \pm$	$0.14 \pm$	0.22 ± 0.49
$f_2'(1525)$	$0.0528 \pm$	$0.0070 \pm$	0.015 ± 0.0087

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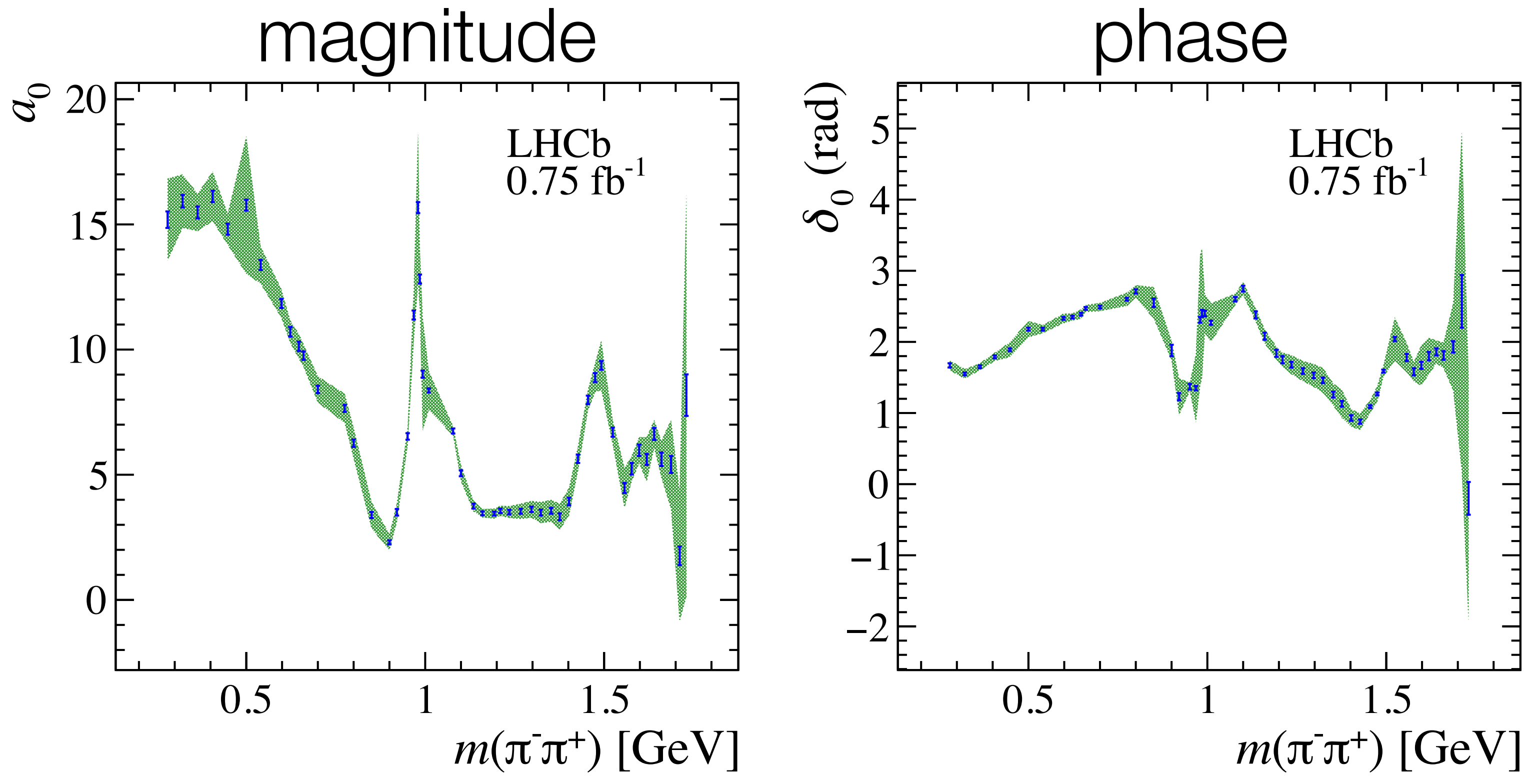
$\rho(1700)^0\pi^+$	5.7	± 0.5	± 1.0	± 1.0
$f_2(1270)\pi^+$	13.8	[illegible]	[illegible]	± 0.2
S-wave	[illegible]	[illegible]	[illegible]	[illegible]0.5

S-wave 62%

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

LHCb: JHEP 06 (2023) 044

Quasi model-independent (QMI) $\pi^+\pi^-$ S-wave in $D^+ \to \pi^+\pi^-\pi^+$



Blue point with error bars: fit result at given mass point, with stat error

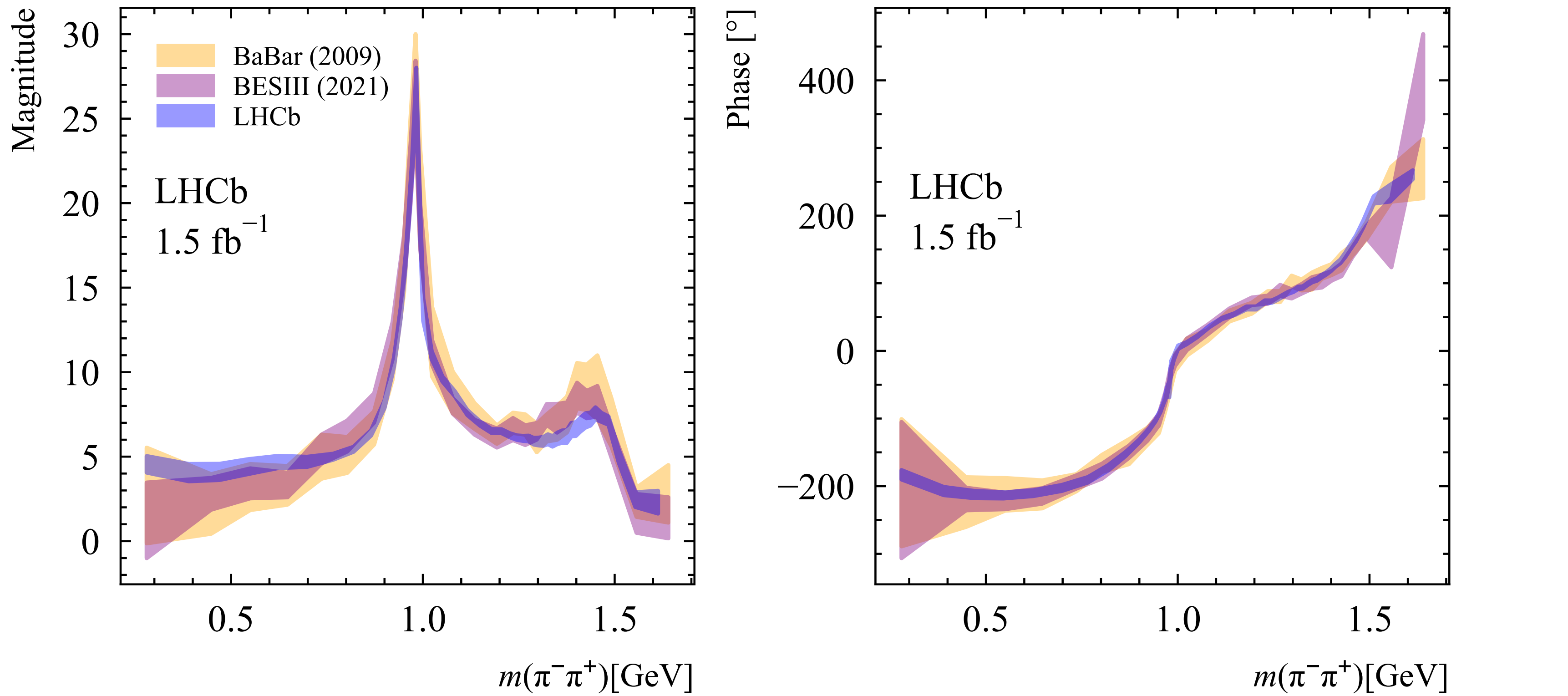
Green band: 2-D cubic spline with sys and stat errors

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

LHCb: JHEP 07 (2023) 204
BESIII: PRD 106 (2022) 11, 112006.
BaBar: PRD 79 (2009) 032003.

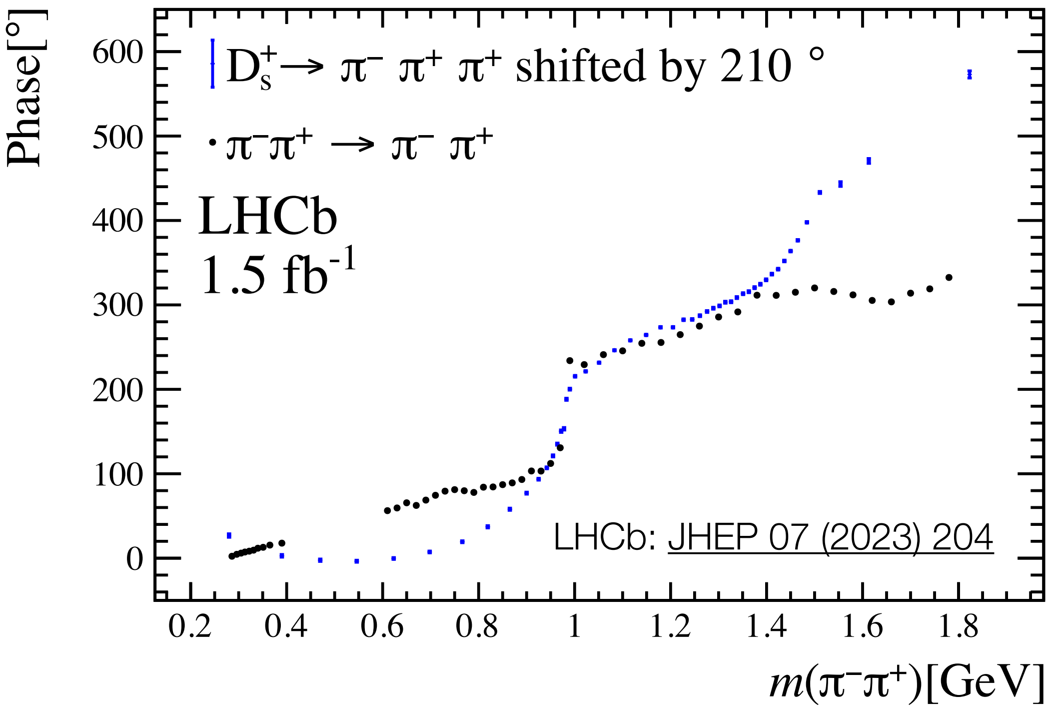
Quasi model-independent (QMI) $\pi^+\pi^-$ S-wave in $D_s^+ \to \pi^+\pi^-\pi^+$

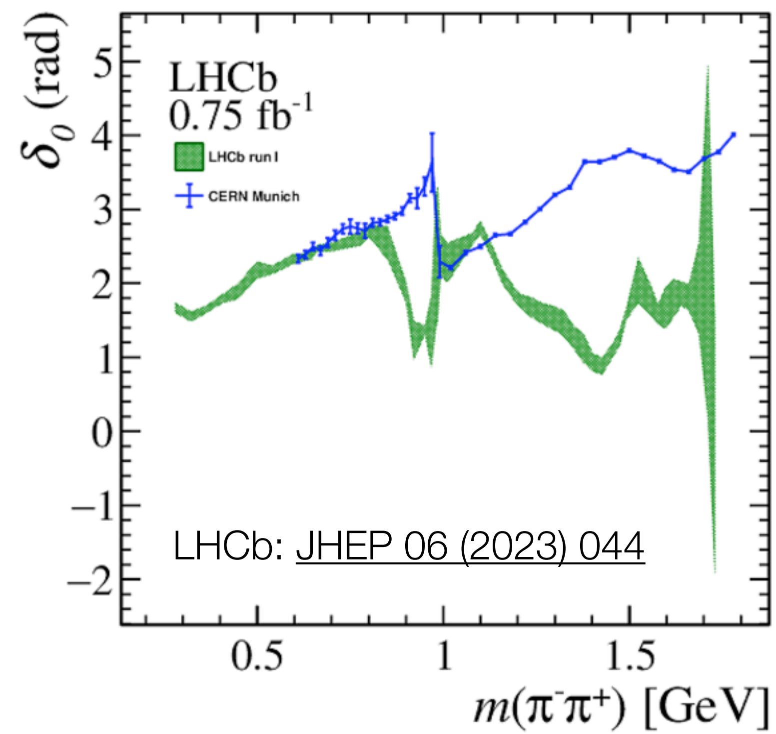
magnitude　　　phase



$D_s^+, D^+ \to \pi^+\pi^-\pi^+$ and scattering data

Comparing $\pi^+\pi^-$ S-wave in $D_s, D^+ \to \pi^+\pi^-\pi^+$ with that obtained from scattering data.



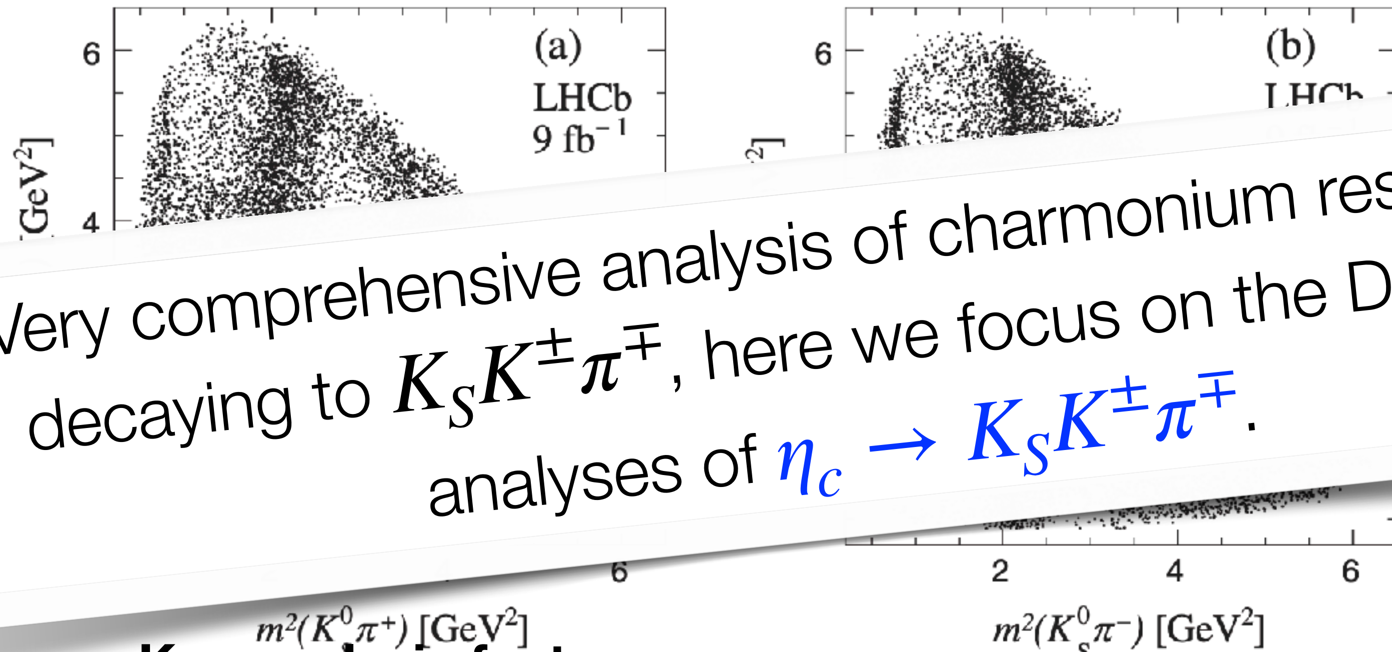


Scattering data: CERN-Munich experiment, Nucl. Phys. B64 (1973) 134, and re-analysis of those data by J Ochs, J. Phys. G: Nucl. Part. Phys. 40 043001. Below 0.4GeV from NA48/2: Eur. Phys. J. C70 (2010) 635.

$B^+ \to K_S K^{\mp} \pi^{\pm} K^+$

LHCb: PRD 108 (2023) 3, 032010

$\eta_c \to K_S K^- \pi^+$ $\eta_c \to K_S K^+ \pi^-$



Very comprehensive analysis of charmonium resonances decaying to $K_S K^{\pm} \pi^{\mp}$, here we focus on the Dalitz plot analyses of $\eta_c \to K_S K^{\pm} \pi^{\mp}$.

Key analysis features:

- $K\pi$ S-wave described with model independent method (bins with one complex number per bin)
- $a_0(980)$ described by coupled channel formula following PRD 57, 3860 (1998) (Christal Barrel).
- Other resonances: Breit-Wigner

$B^+ \to K_S K^{\mp}\pi^{\pm} K^+$

LHCb: PRD 108 (2023) 3, 032010

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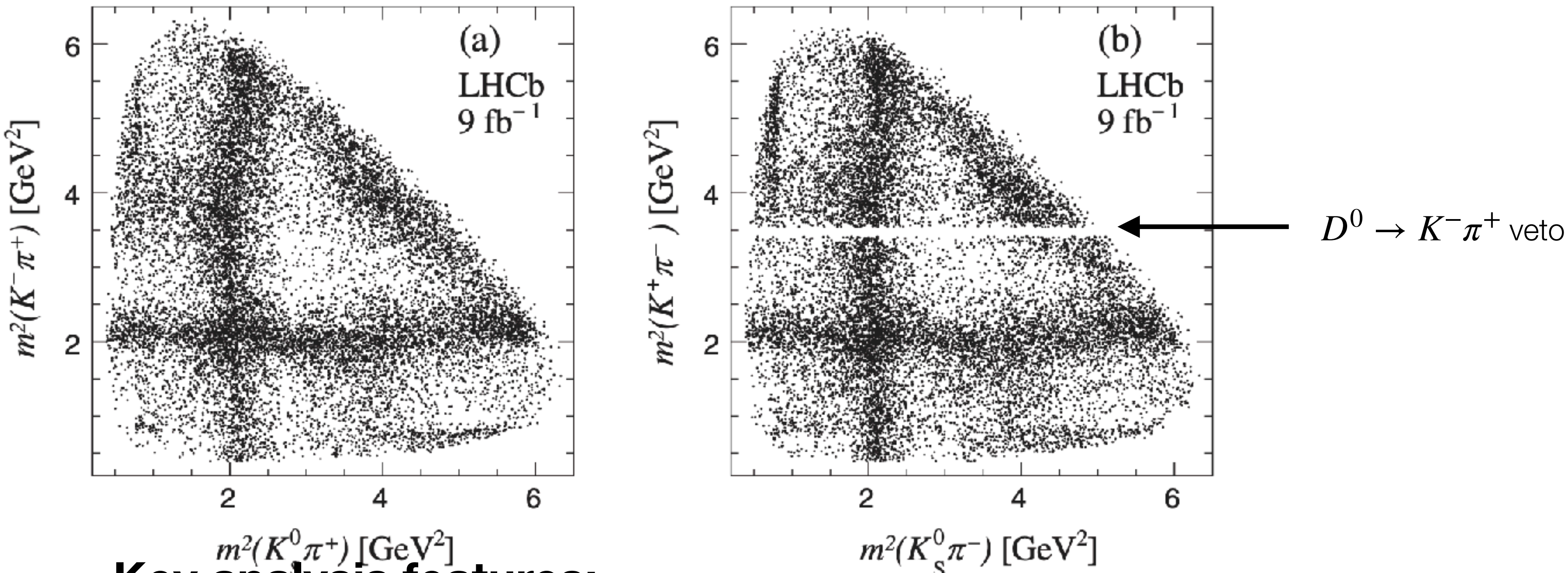

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LHCb: PRD 108 (2023) 3, 032010

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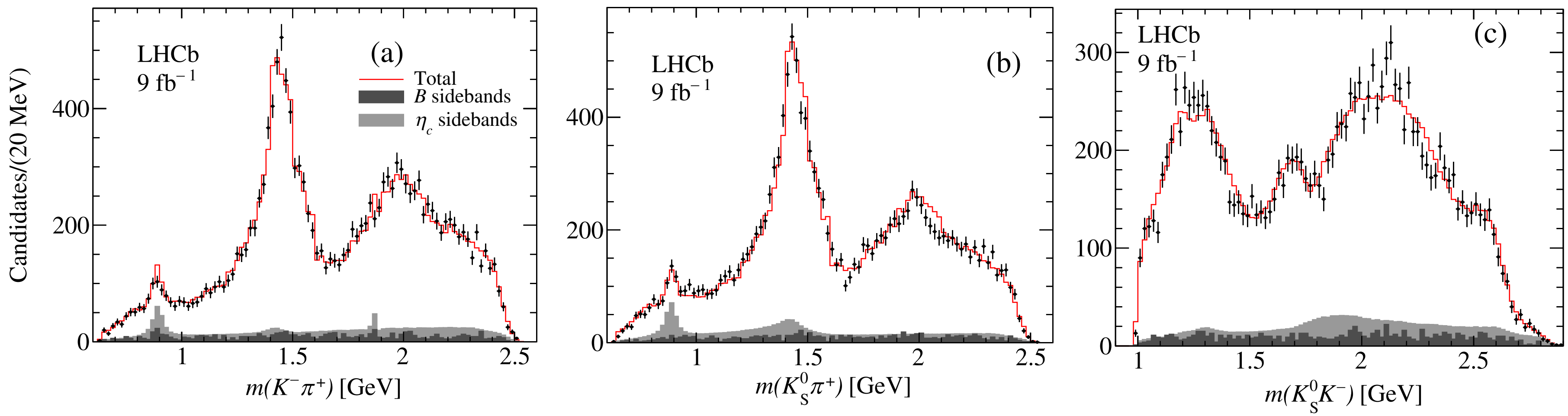
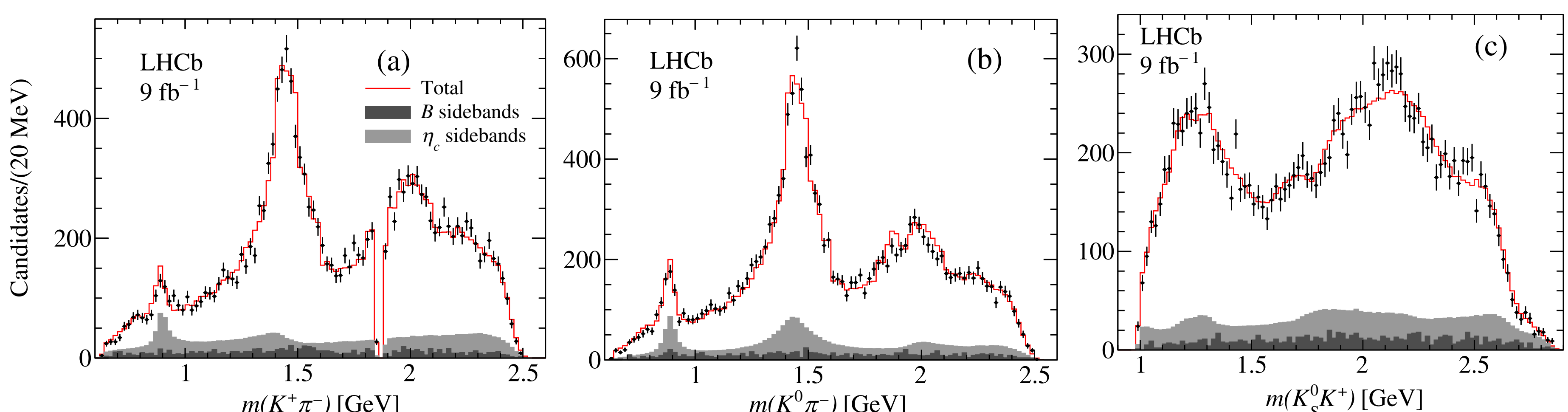


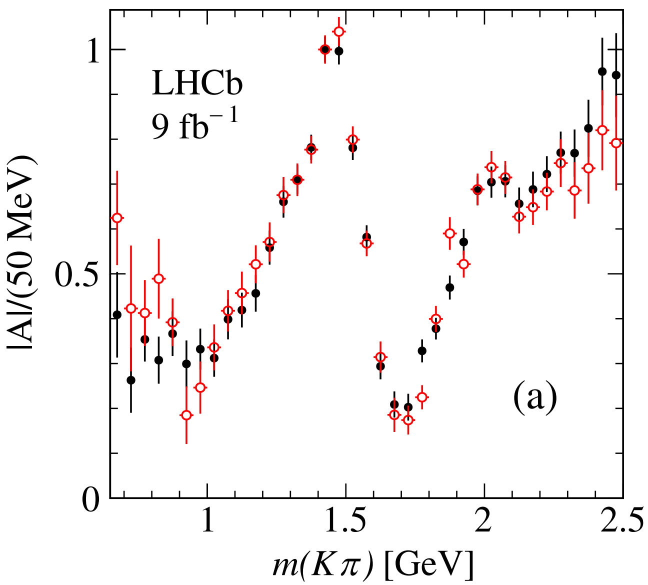
$\eta_c \to K_S K^+ \pi^-$



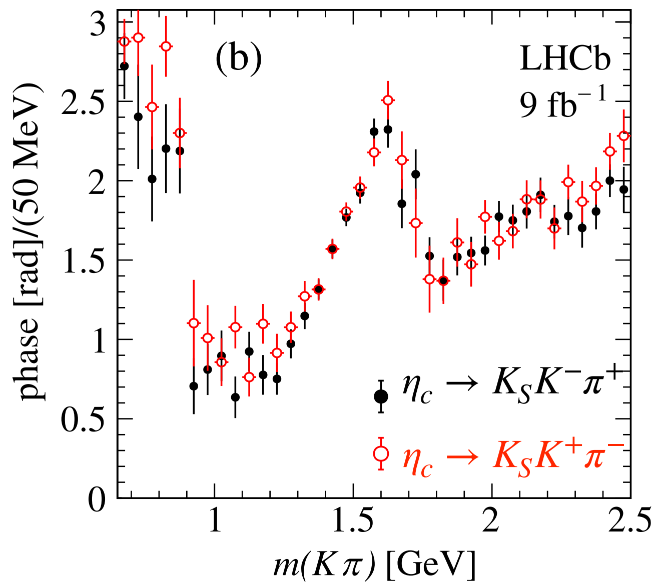
$B^+ \to K_S K^{\mp} \pi^{\pm} K^+$, the $K\pi$ S-wave

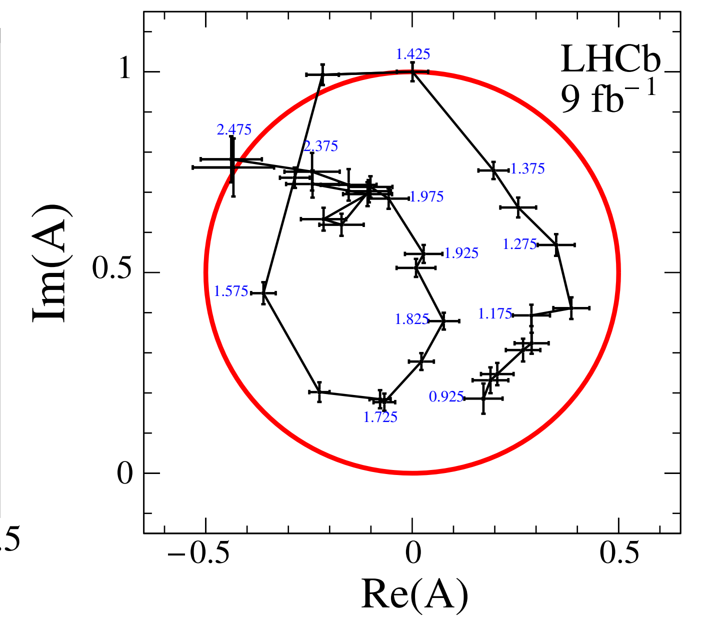
LHCb: PRD 108 (2023) 3, 032010

Magnitude



Phase





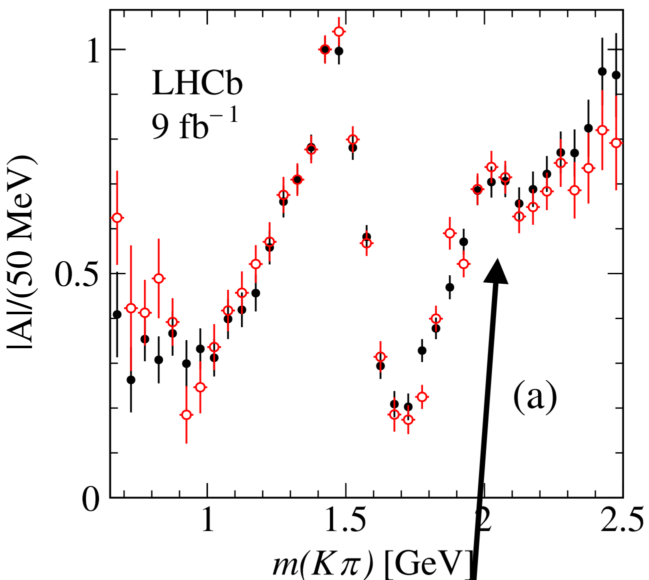
Separately for $\eta_c \to K_S K^- \pi^+$ and $\eta_c \to K_S K^+ \pi^-$

Averaged over both modes

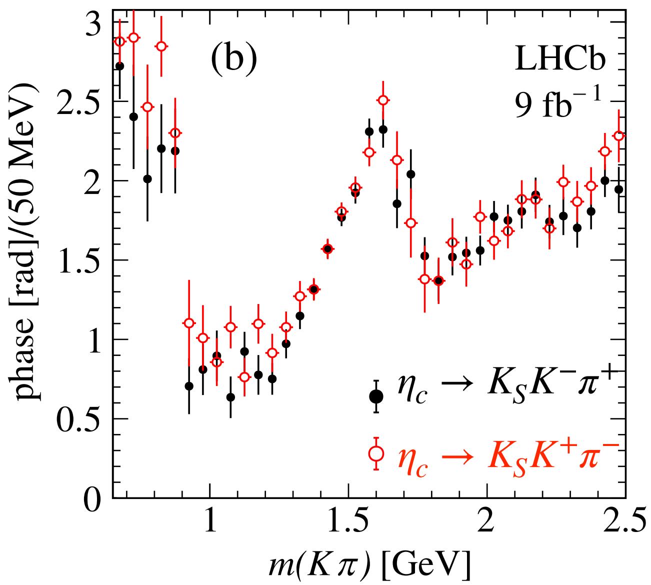
$B^+ \to K_S K^{\mp}\pi^{\pm} K^+$, the $K\pi$ S-wave

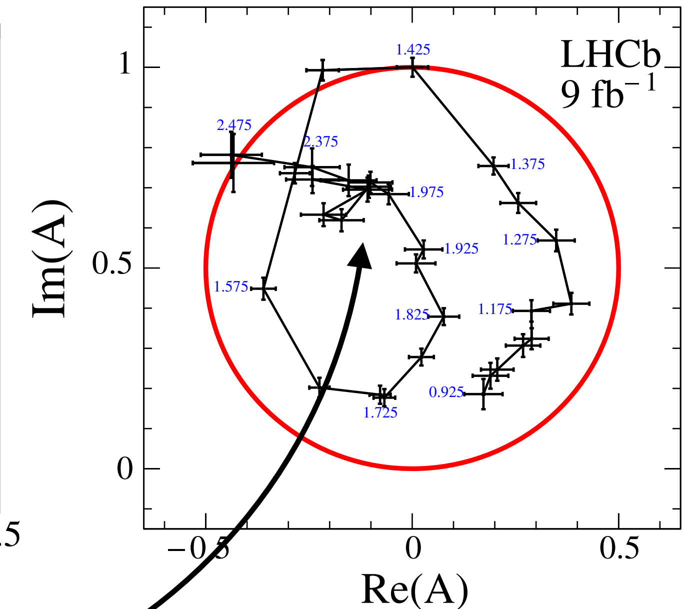
LHCb: PRD 108 (2023) 3, 032010

Magnitude



Phase





Separately for $\eta_c \to K_S K^-\pi^+$ and $\eta_c \to K_S K^+\pi^-$

Averaged over both modes

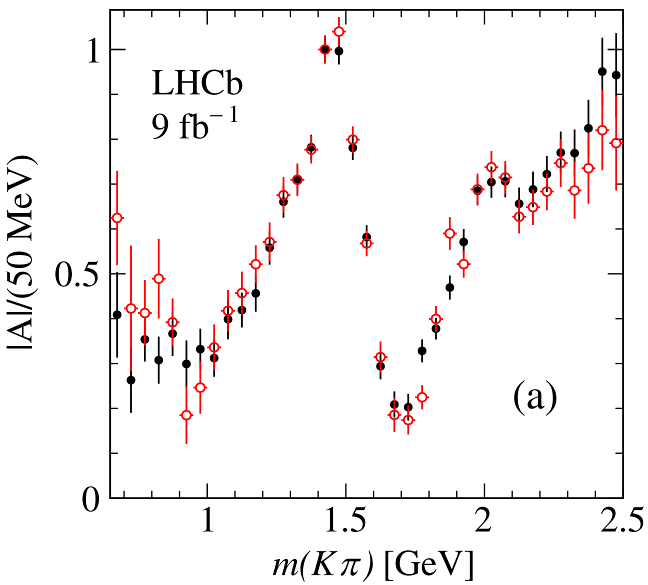
$K_0^*(1950)$ seen by LASS Nucl. Phys. B296, 493 (1988)

and BaBar PRD 104, 072002 (2021) (3.3σ).

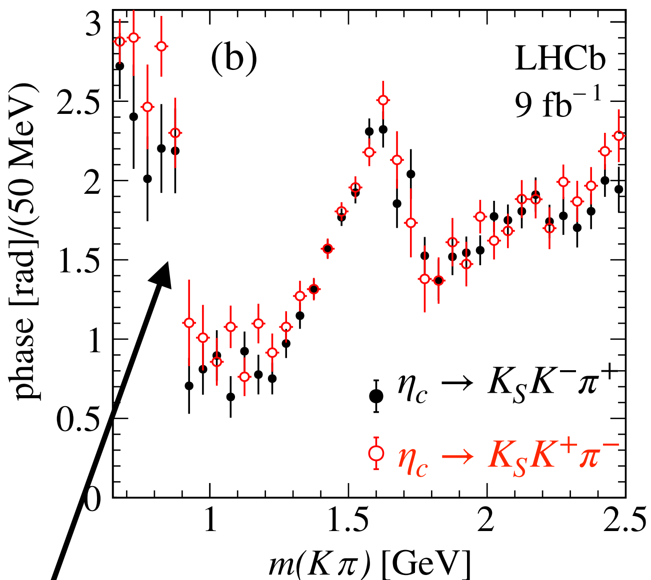
$B^+ \to K_S K^\mp \pi^\pm K^+$, the $K\pi$ S-wave

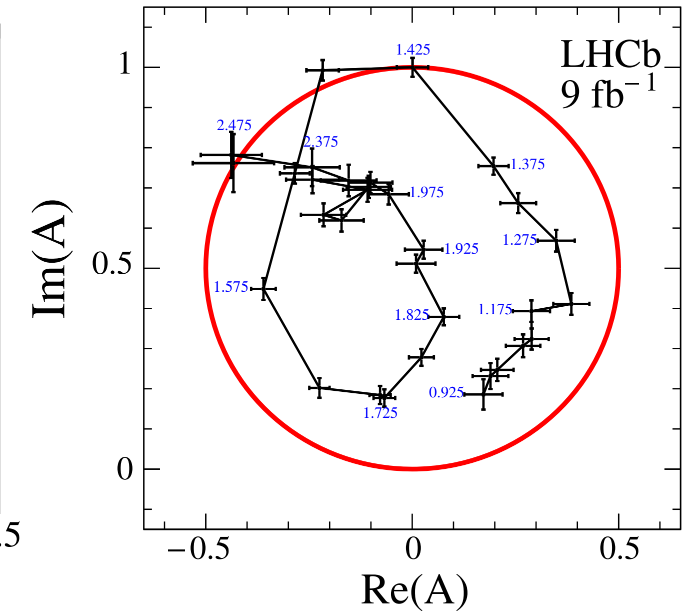
LHCb: PRD 108 (2023) 3, 032010

Magnitude



Phase





Separately for $\eta_c \to K_S K^- \pi^+$ and $\eta_c \to K_S K^+ \pi^-$

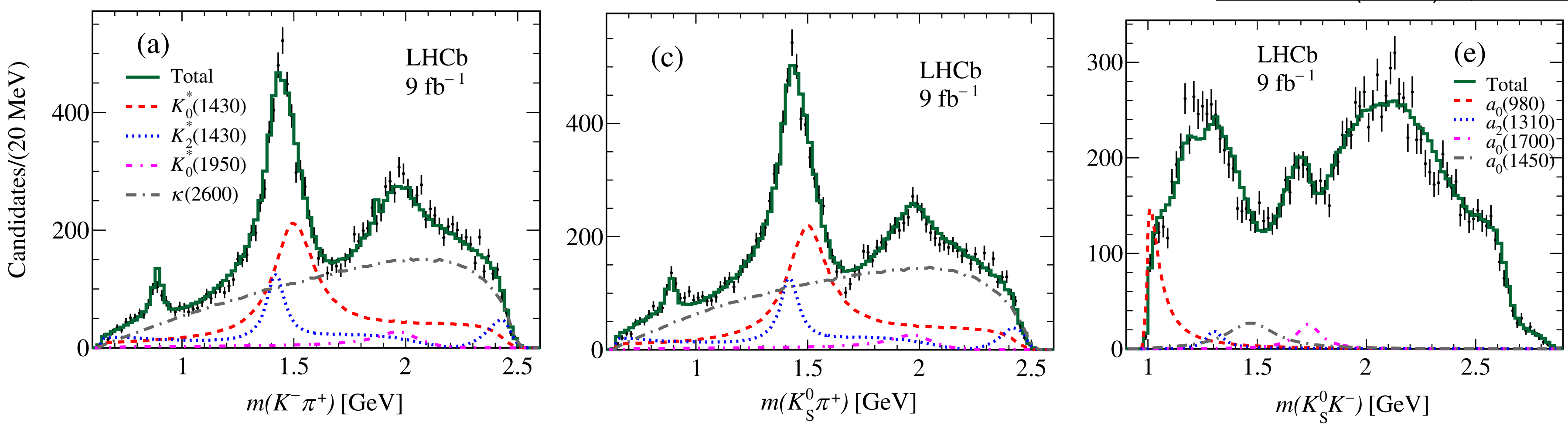
Averaged over both modes

Big jump in phase not understood. Too few known resonances to interfere with in this region might result in lack of constraints for model-independent method

$B^+ \to K_S K^{\mp} \pi^{\pm} K^+$ with model-*dependent* S-wave

$\eta_c \to K_S K^- \pi^+$

LHCb: PRD 108 (2023) 3, 032010



Resonance	Mass [MeV]	Γ [MeV]	Significance
$K_0^*(1430)$	$1493 \pm 4 \pm 7$	$215 \pm 7 \pm 4$	$\cdots$
$K_0^*(1950)$	$1980 \pm 14 \pm 19$	$229 \pm 26 \pm 16$	17.8σ
$a_0(1700)$	$1736 \pm 10 \pm 12$	$134 \pm 17 \pm 61$	12.7σ
$\kappa(2600)$	$2662 \pm 59 \pm 201$	$480 \pm 47 \pm 72$	36.6σ

Deviations in

- $B \to K^{*0}\mu^+\mu^-$

Deviations in

- $B \to K^{*0} \mu^+ \mu^-$
- $B^+ \to K^+ \mu^+ \mu^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$
- $B^+ \to K^+\mu^+\mu^-$
- $B_s \to \phi\mu^+\mu^-$

Deviations in

- $B \to K^{*0} \mu^+ \mu^-$
- $B^+ \to K^+ \mu^+ \mu^-$
- $B_s \to \phi \mu^+ \mu^-$
- $B^+ \to K^{*+} \mu^+ \mu^-$

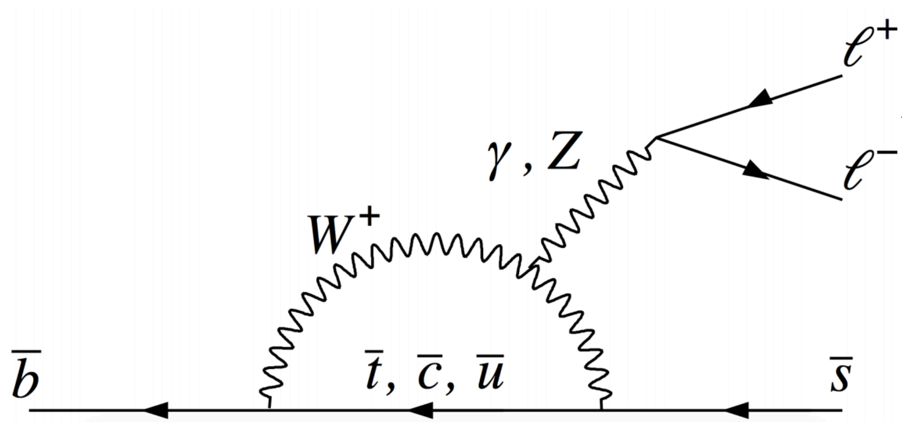
Deviations in

- $B \to K^{*0} \mu^+ \mu^-$
- $B^+ \to K^+ \mu^+ \mu^-$
- $B_s \to \phi \mu^+ \mu^-$
- $B^+ \to K^{*+} \mu^+ \mu^-$
- $\Lambda_b \to \Lambda \mu^+ \mu^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$
- $B^+ \to K^+\mu^+\mu^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$
- $\Lambda_b \to \Lambda\mu^+\mu^-$

all involve same process:



ℓ = e or μ

Deviations in

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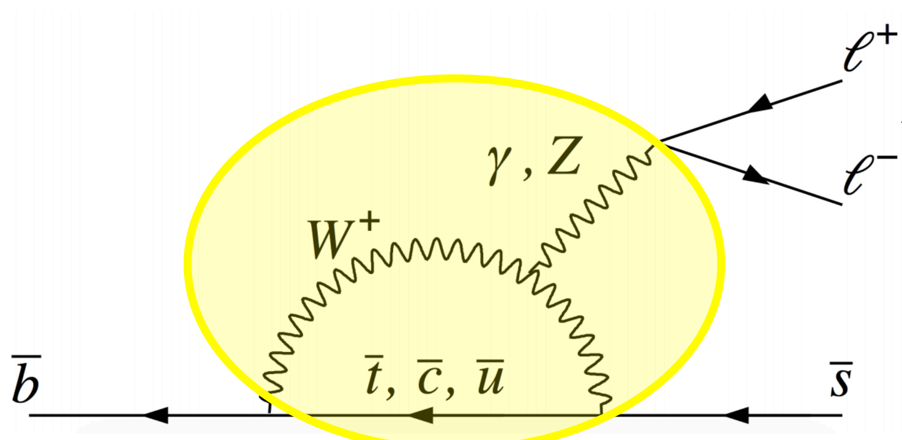

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Deviations in

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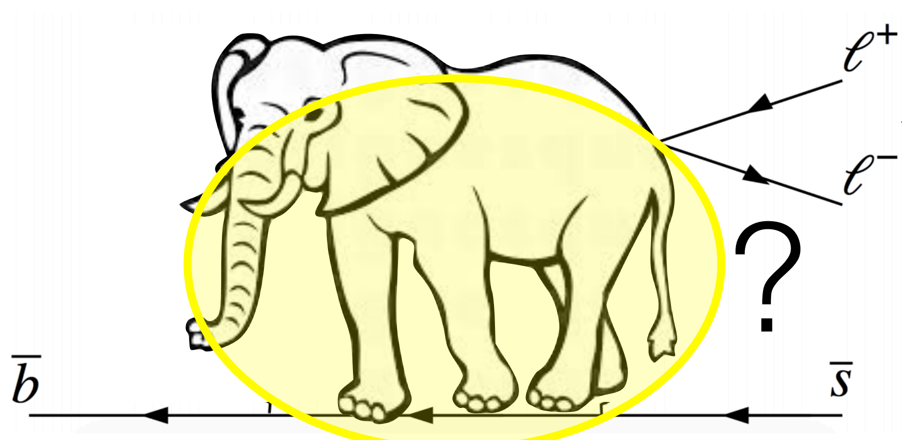
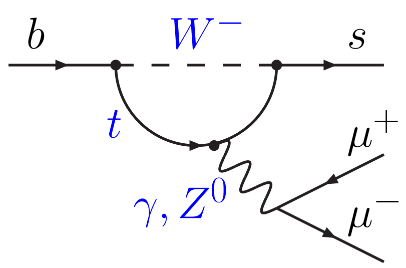


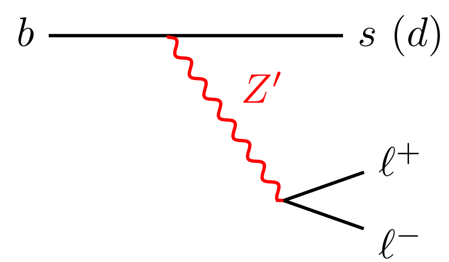
ℓ = e or μ

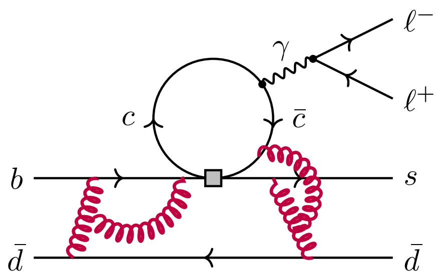
Amplitude Analysis of $B^0 \to K^* \mu^+ \mu^-$, long and short-distance effects.

LHCb:
arXiv:2405.17347 (27 May 2024)
PRL 132 (2024) 13, 131801
PRD 109 (2024) 5, 052009

Want to measure this

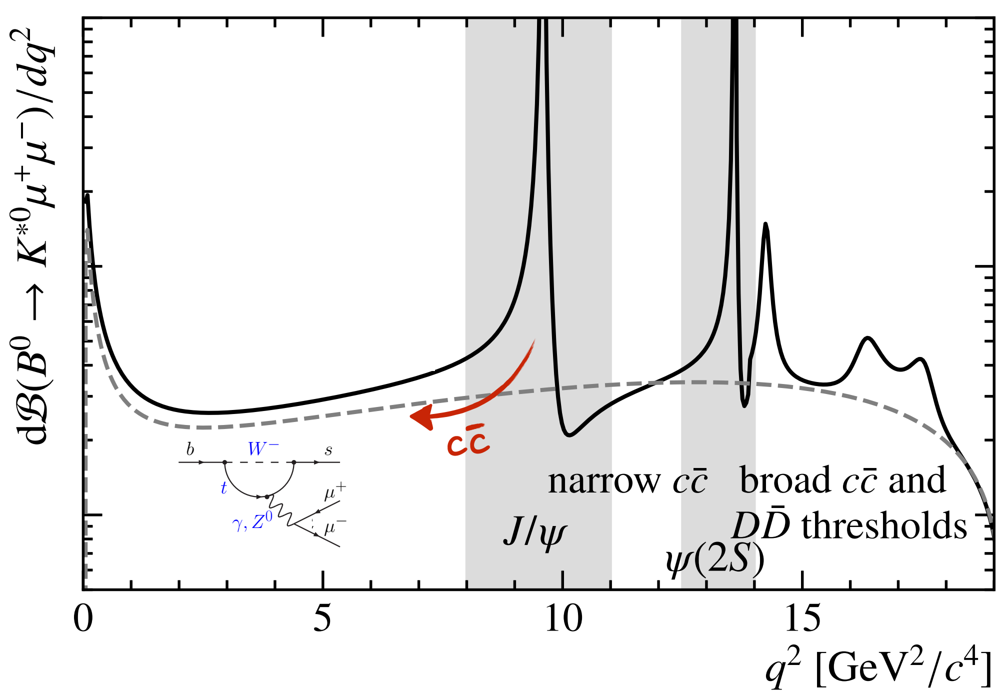






Analysis combines sophisticated amplitude analysis techniques, clever additional theory input, beautiful data

Resonance magnitudes and phases chosen arbitrarily for illustration purpose



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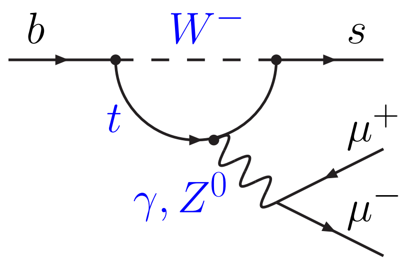
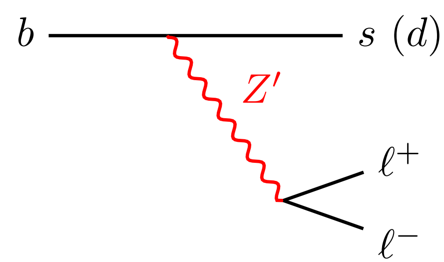
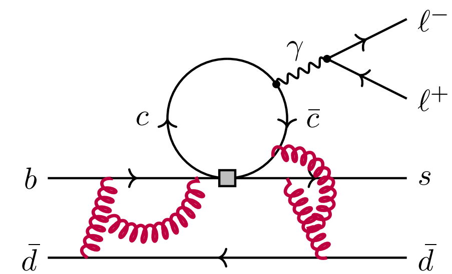


… hoping to find this (NP)





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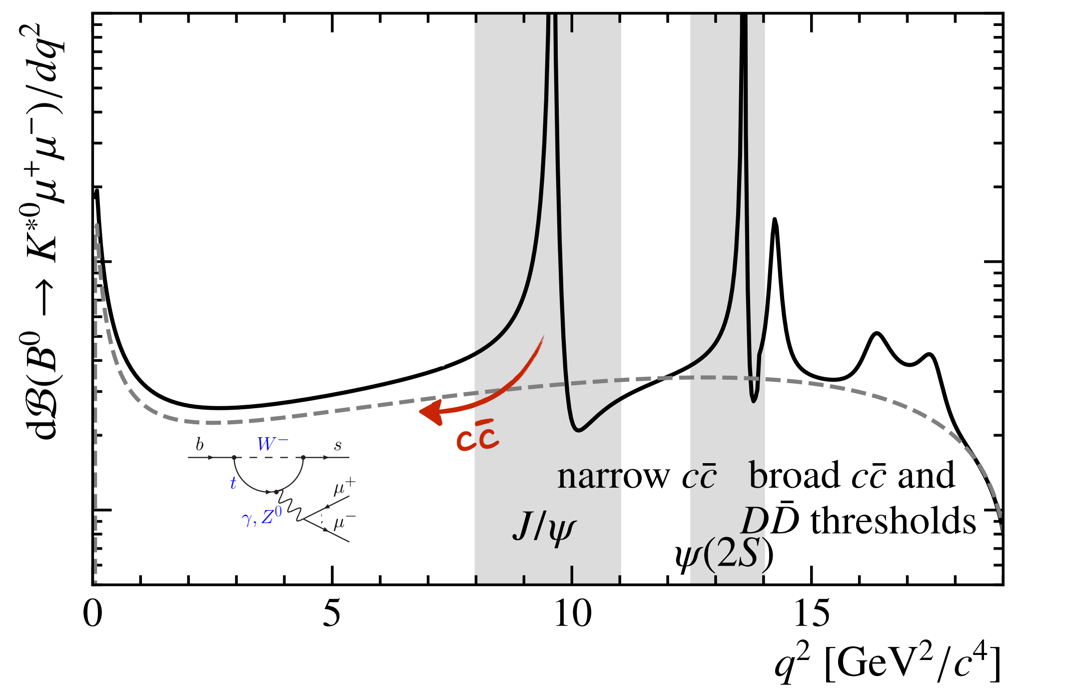

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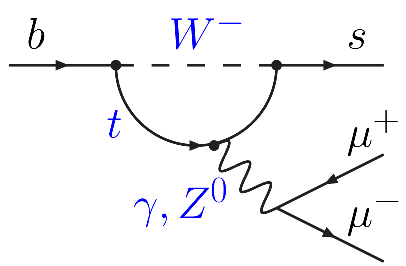

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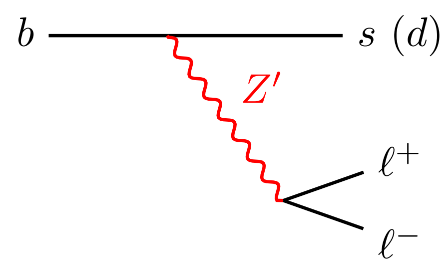
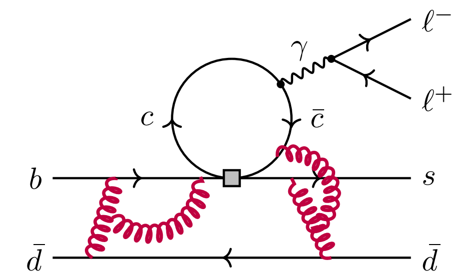


Need to understandSM $c\bar{c}$ loop



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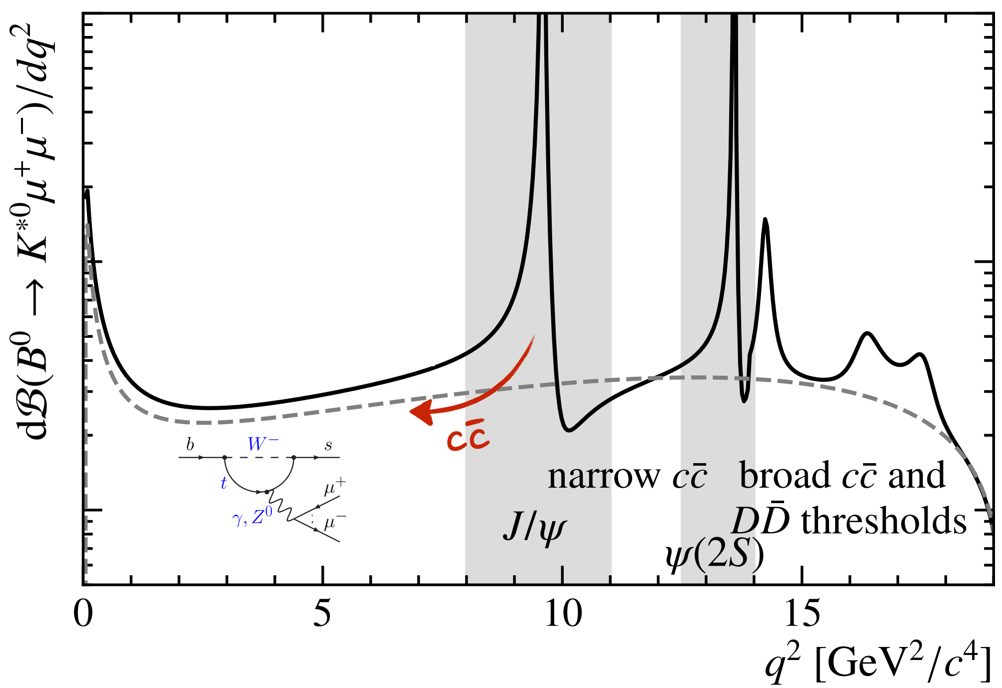

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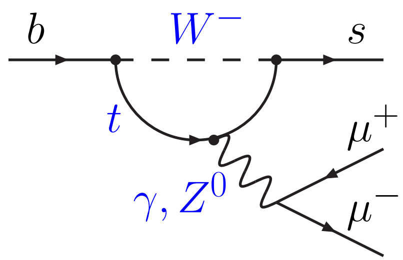

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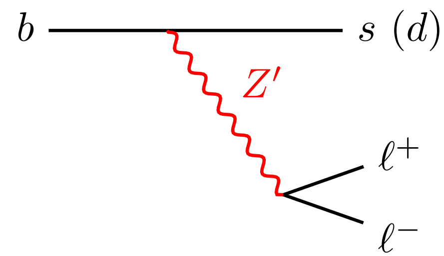

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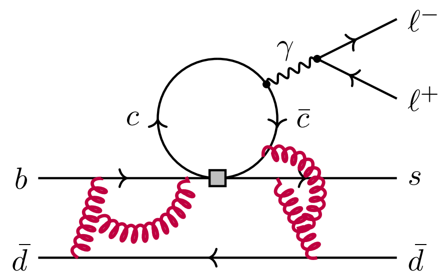
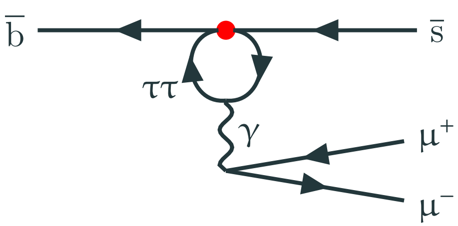


Analysis combines sophisticated amplitude analysis techniques, clever additional theory input, beautiful data

Bonus: sensitive to $B^0 \to K^*\tau^+\tau^-$



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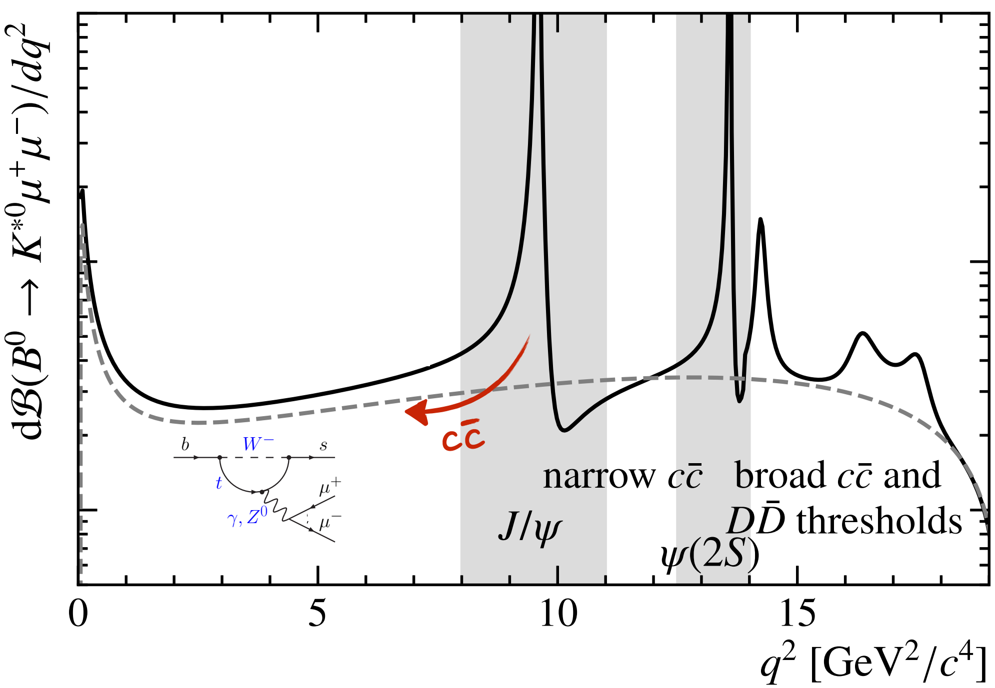

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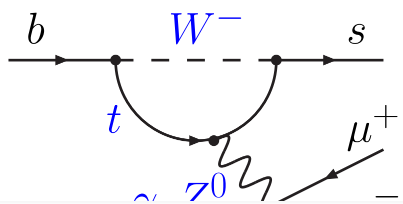

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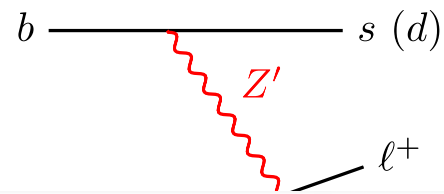

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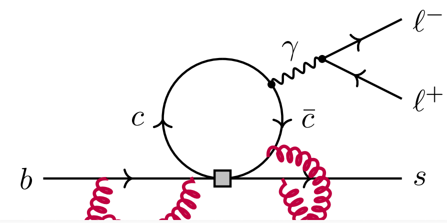


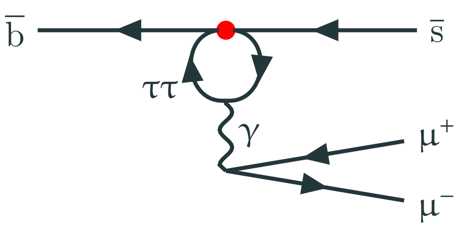
So, what have they found and how did they do it?
Eluned will tell you in the next talk.

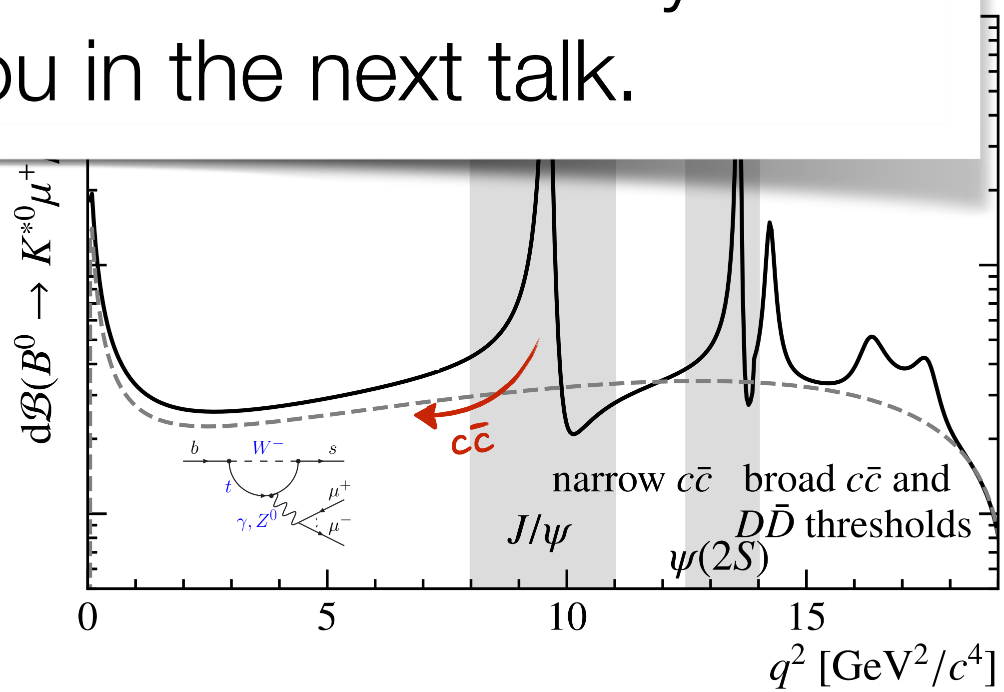
a

…rpose

additional theory input, beautiful data

Bonus: sensitive to $B^0 \to K^* \tau^+ \tau^-$

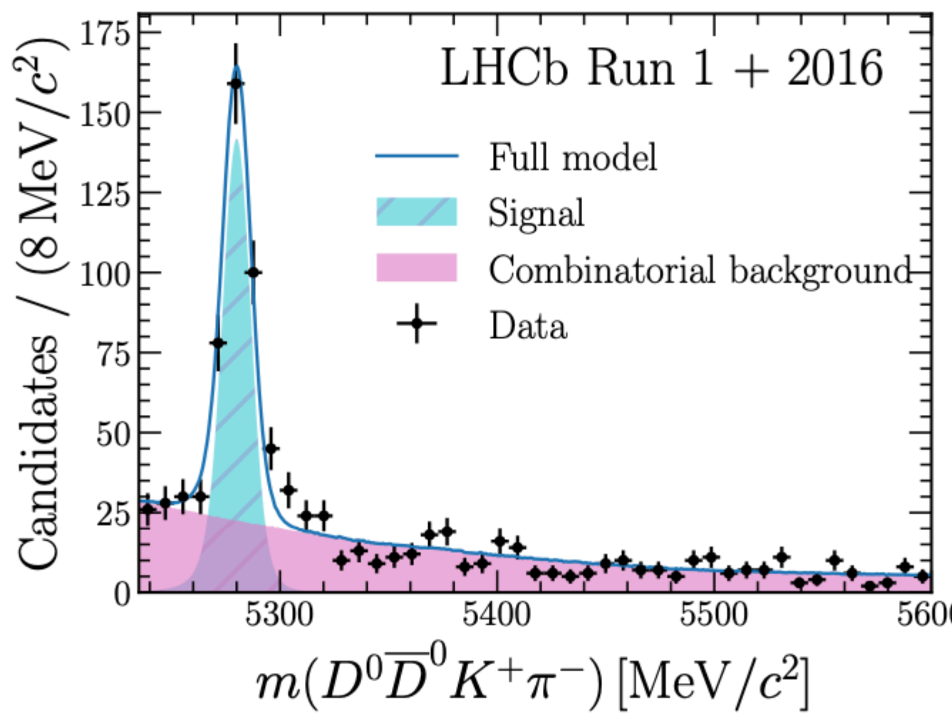




$B^0 \to D^0\overline{D}^0K^+\pi^-$ for $B^0 \to \mu^+\mu^-K^*$

Analysis of $B^0 \to D^0\overline{D}^0K^+\pi^-$ will provide further input on charm loops

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

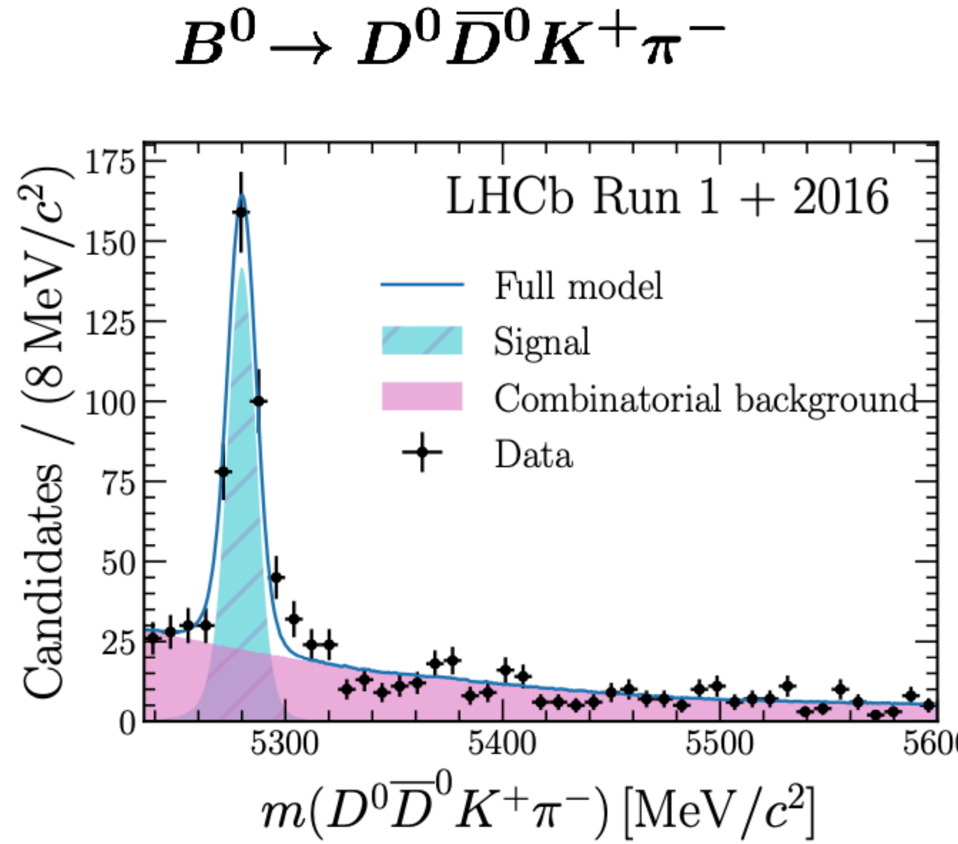


First step: first observation of this rare decay
PRD102,051102(2020)
4-body Amplitude Analysis ongoing.

$B^0 \to D^0\overline{D}^0K^+\pi^-$ for $B^0 \to \mu^+\mu^-K^*$

Analysis of $B^0 \to D^0\overline{D}^0K^+\pi^-$ will provide further input on charm loops

Only one of many reasons to study the amplitude structure of $B \to D\overline{D}X$ decays, which turn out to be remarkably rich.



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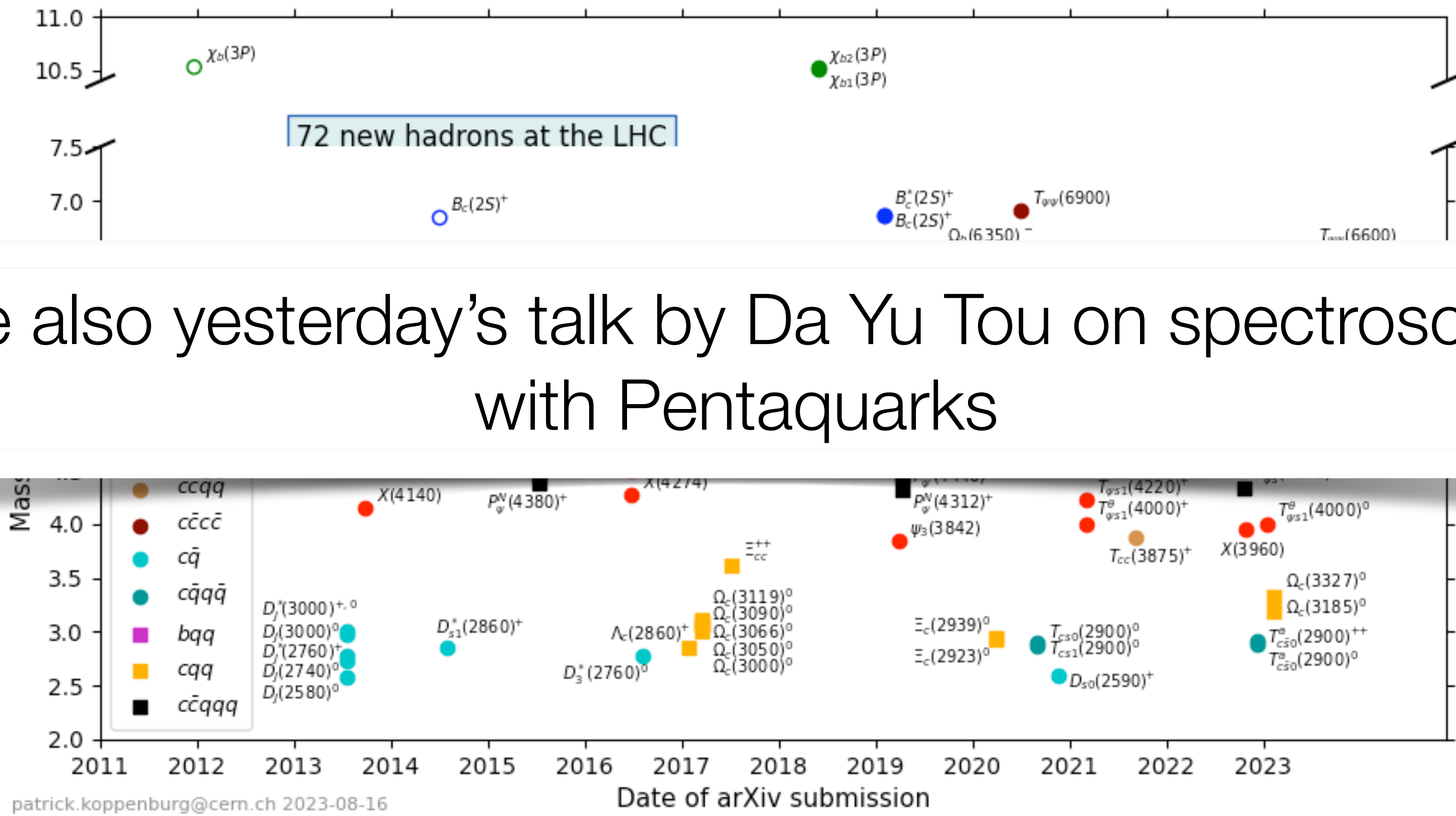
PRD102,051102(2020)
4-body Amplitude Analysis ongoing.

72 new hadrons at the LHC, 64 of which at LHCb



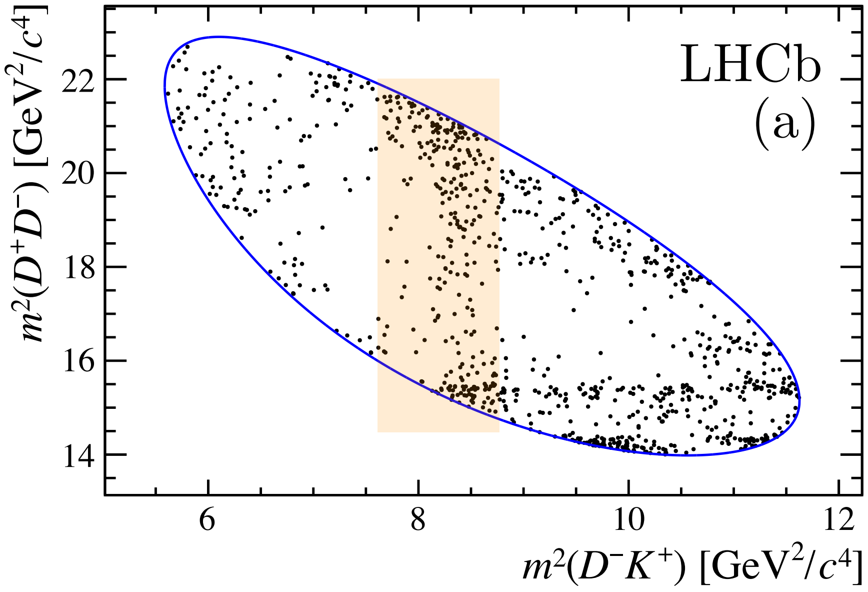
See also yesterday's talk by Da Yu Tou on spectroscopy with Pentaquarks

Plot by Patrick Koppenburg: https://www.nikhef.nl/~pkoppenb/particles.html

Really strange: First tetra flavour

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

$B^+ \to D^+ D^- K^+$ Dalitz Plot



Two new tretraquark states

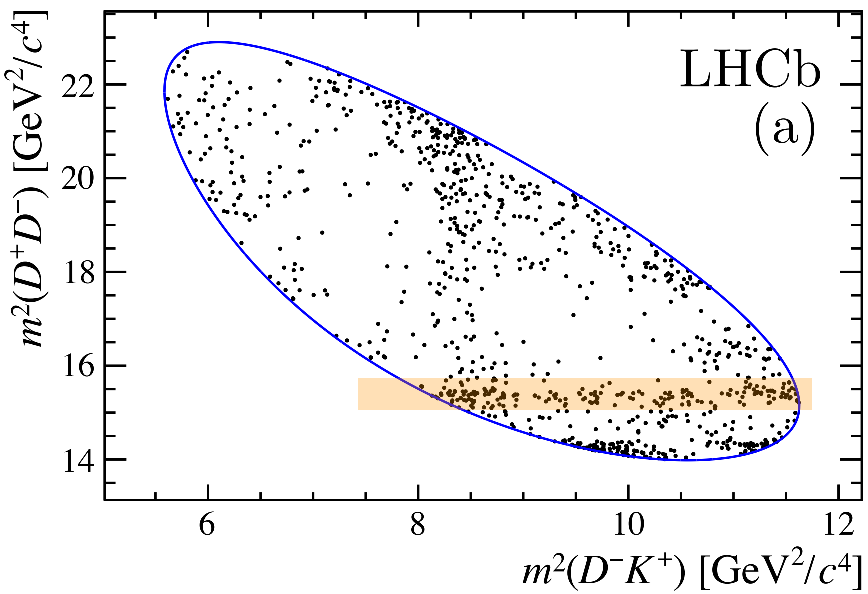
$T^*_{\bar{c}\bar{s}0}(2900)$

$T^*_{\bar{c}\bar{s}1}(2900)$

Two $\chi_c(3930)$

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

$B^+ \to D^+ D^- K^+$ Dalitz Plot



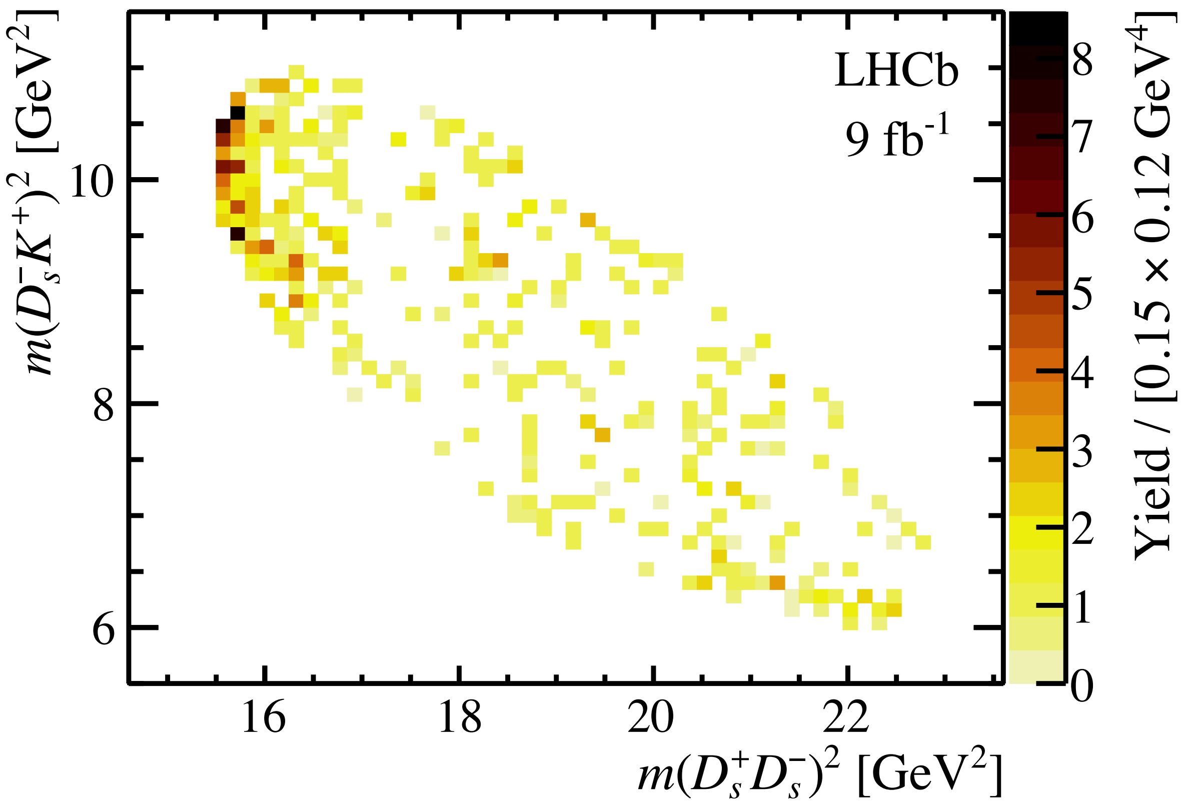
Previously observed $\chi_c(3930)$ seen as two states

$\chi_{c0}(3930)$

$\chi_{c2}(3930)$

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

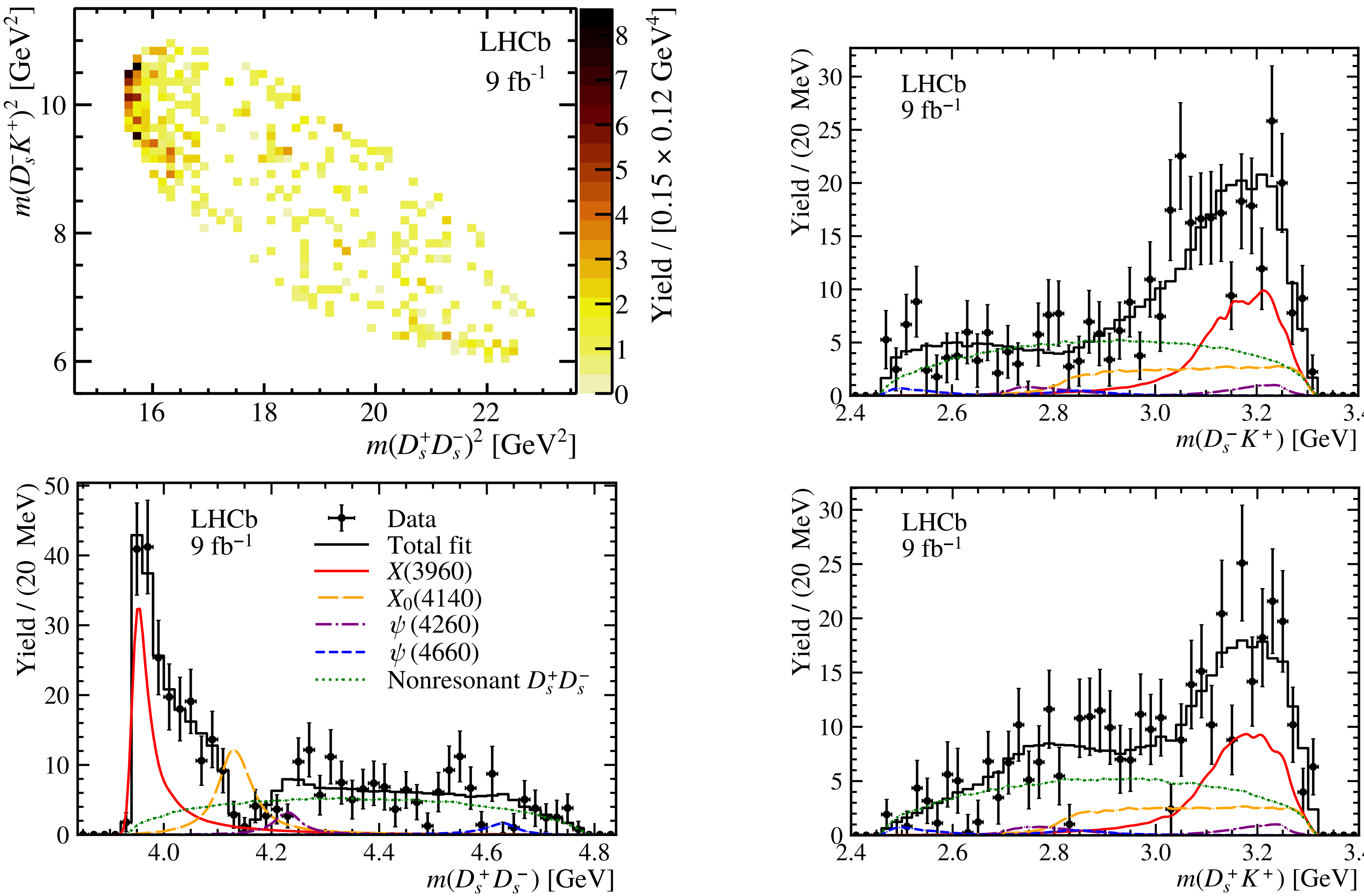
LHCb: PRL 131 (2023) 7, 071901



360 signal events

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

LHCb: PRL 131 (2023) 7, 071901



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

LHCb: PRL 131 (2023) 7, 071901

$$R(m \mid M_0, g_j) = \frac{1}{M_0^2 - m^2 - iM_0 \sum_j g_j \rho_j(m)}$$

BW

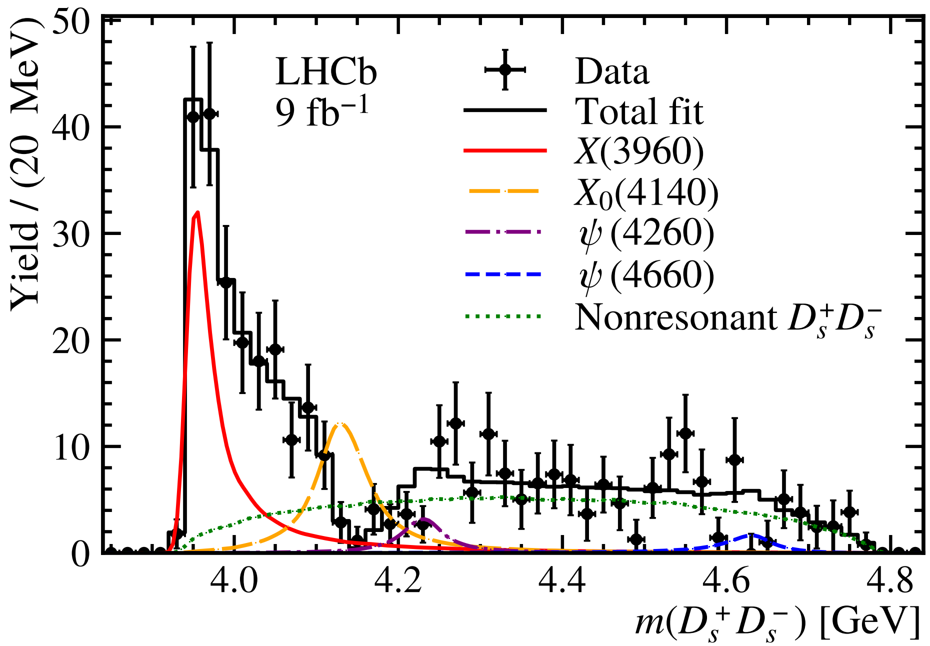
Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [60]	55 [60]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

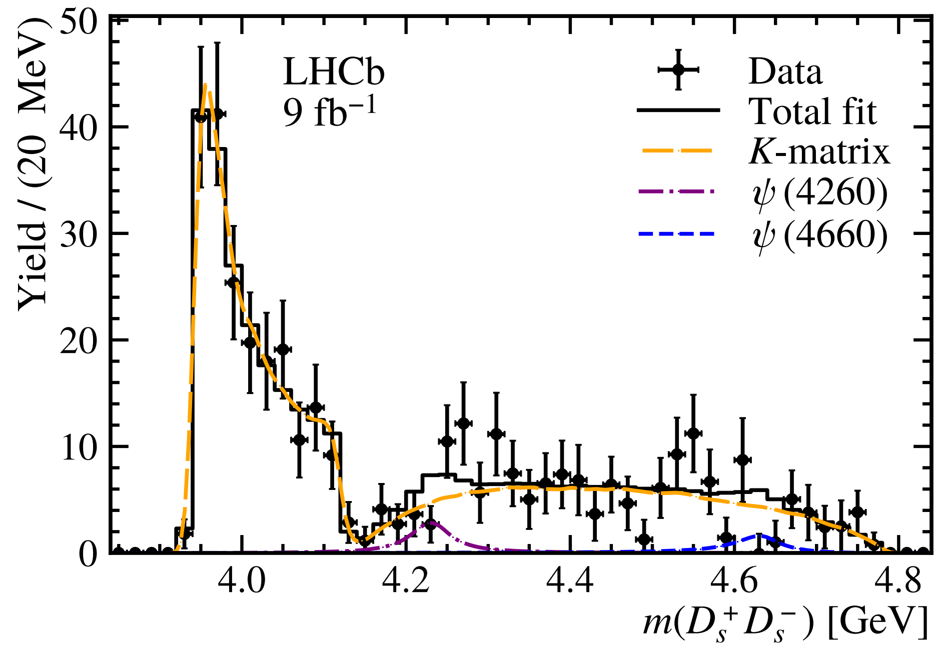
If this X(3960) is $\chi_{c0}(3930)$, then:

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

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

LHCb: PRL 131 (2023) 7, 071901





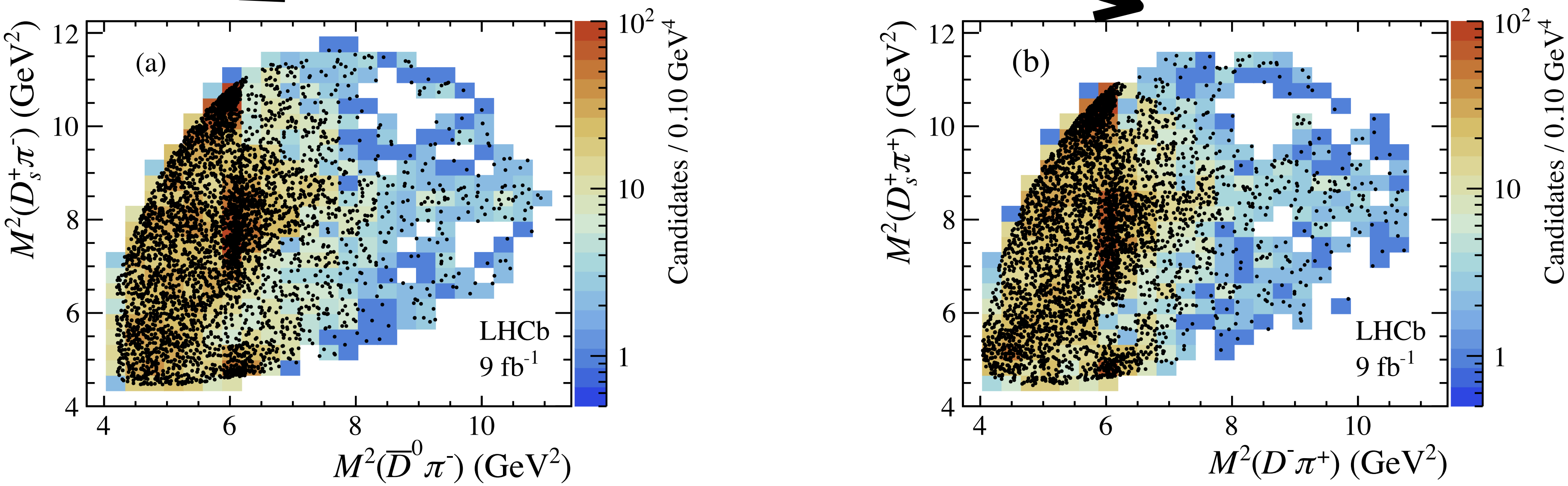
Dip could be caused by a new $X_0(4140)$. Alternative description is with a K-matrix for the $X(3950)$ where the opening of a $J/\psi\phi$ threshold causes the dip.

Fit prefers $X_0(4140)$ by 6 units in $\Delta \ln(\mathscr{L})$ (for one additional dof), but situation remains inconclusive

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

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017

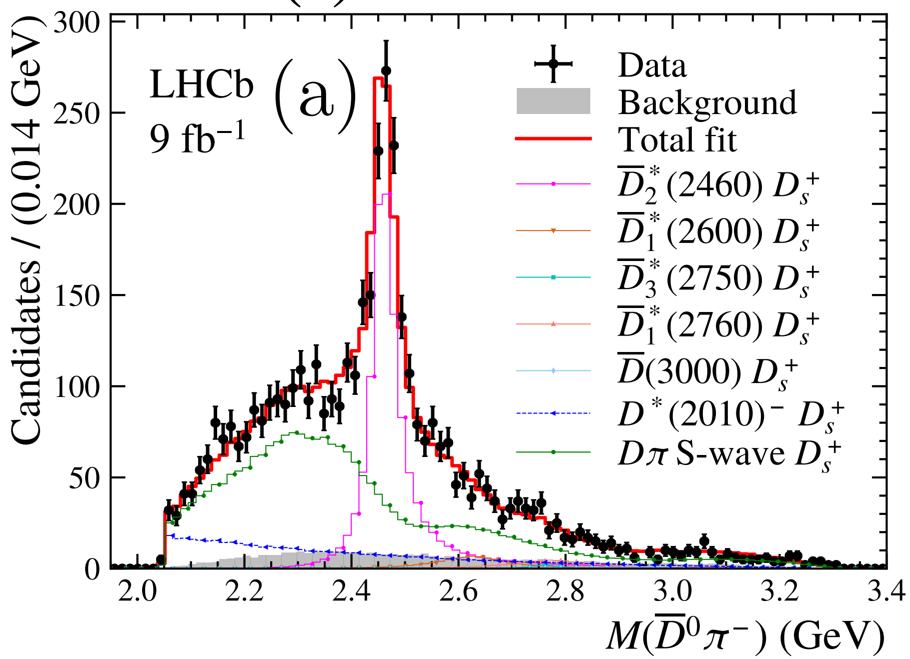
$$\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}$$

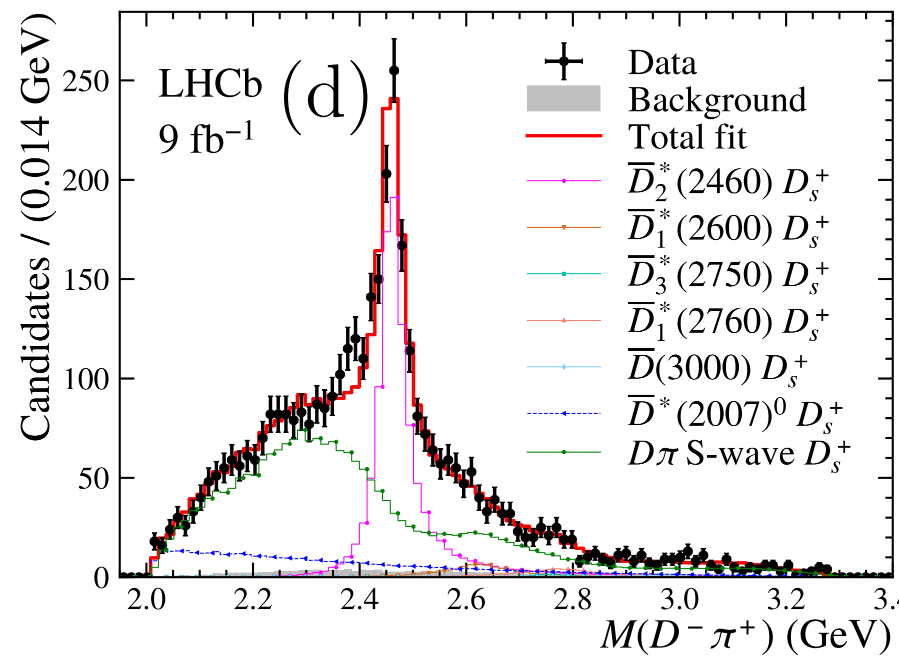


$B^0 \to \overline{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017

Fit with $D^*_{(s)}$ resonance only





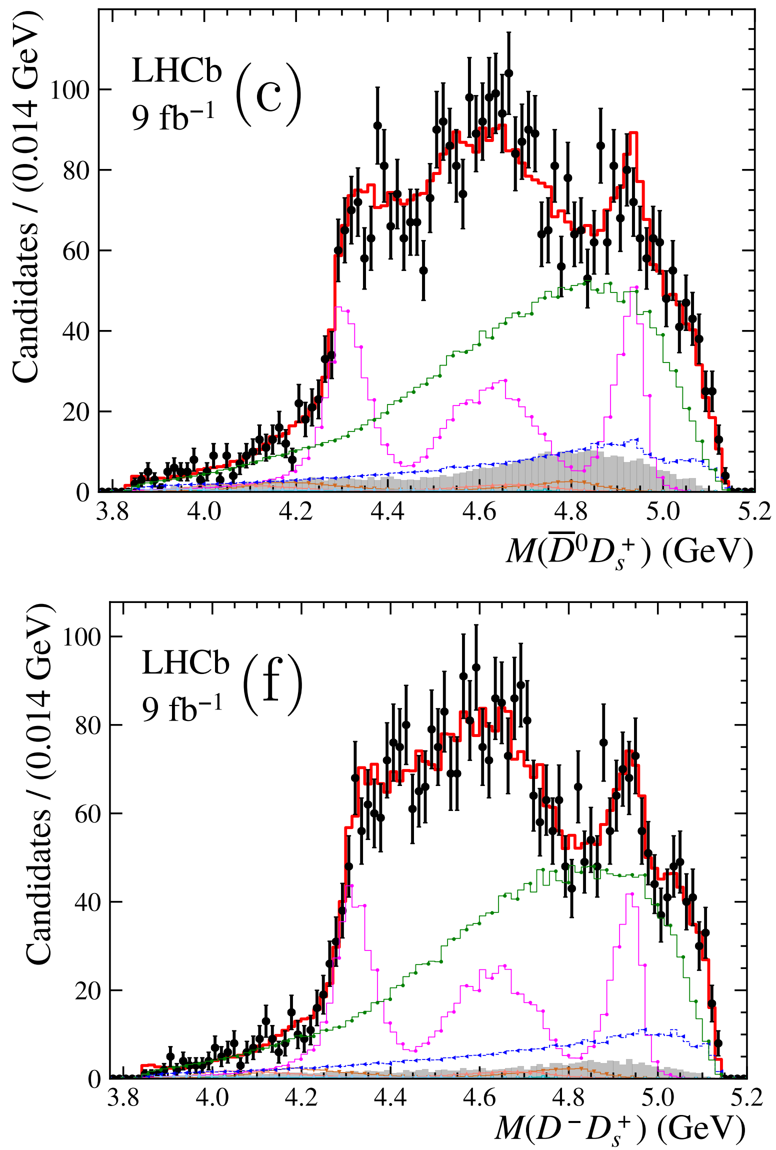
No evidence for additional $D^*_{(s)}$ resonances. Tried many, seen and unseen, with variable masses, widths and various spins.

No sign of $D_{s0}(2317)^0$ and $D_{s0}(2317)^{++}$, hypothesised* isotriplet partners of $D_{s0}(2317)^+$

*) PLB566 (2003) 193, PLB578 (2004) 365, PRD70 (2004) 096011, PRD86 (20012) 016006, PRL94 (2005) 016006, PRD71 (2005) 014028

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

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017

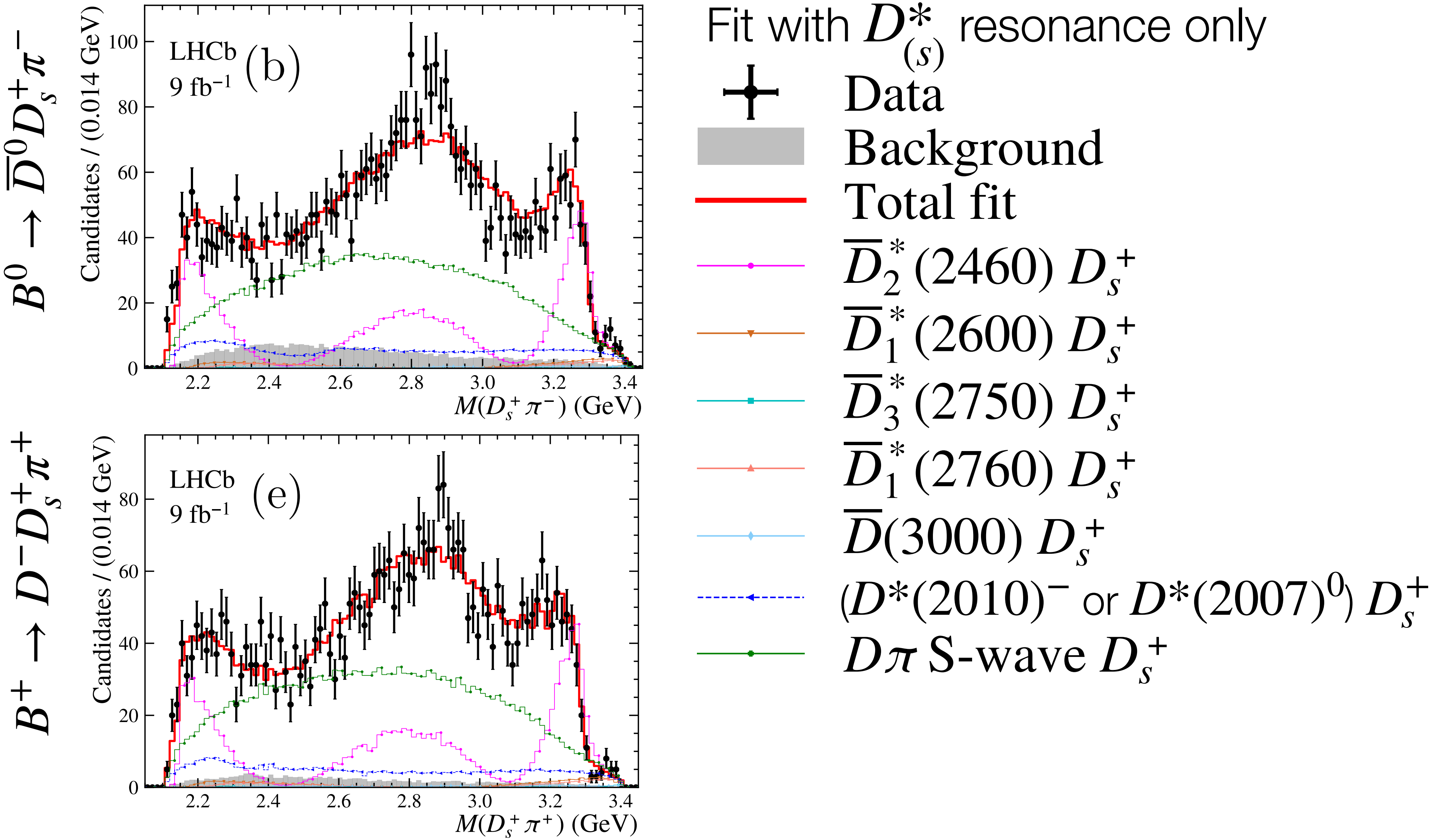


Fit with $D^*_{(s)}$ resonance only

- Data
- Background
- Total fit
- $\overline{D}_2^*(2460)\, D_s^+$
- $\overline{D}_1^*(2600)\, D_s^+$
- $\overline{D}_3^*(2750)\, D_s^+$
- $\overline{D}_1^*(2760)\, D_s^+$
- $\overline{D}(3000)\, D_s^+$
- $(D^*(2010)^-$ or $D^*(2007)^0)\, D_s^+$
- $D\pi$ S-wave D_s^+

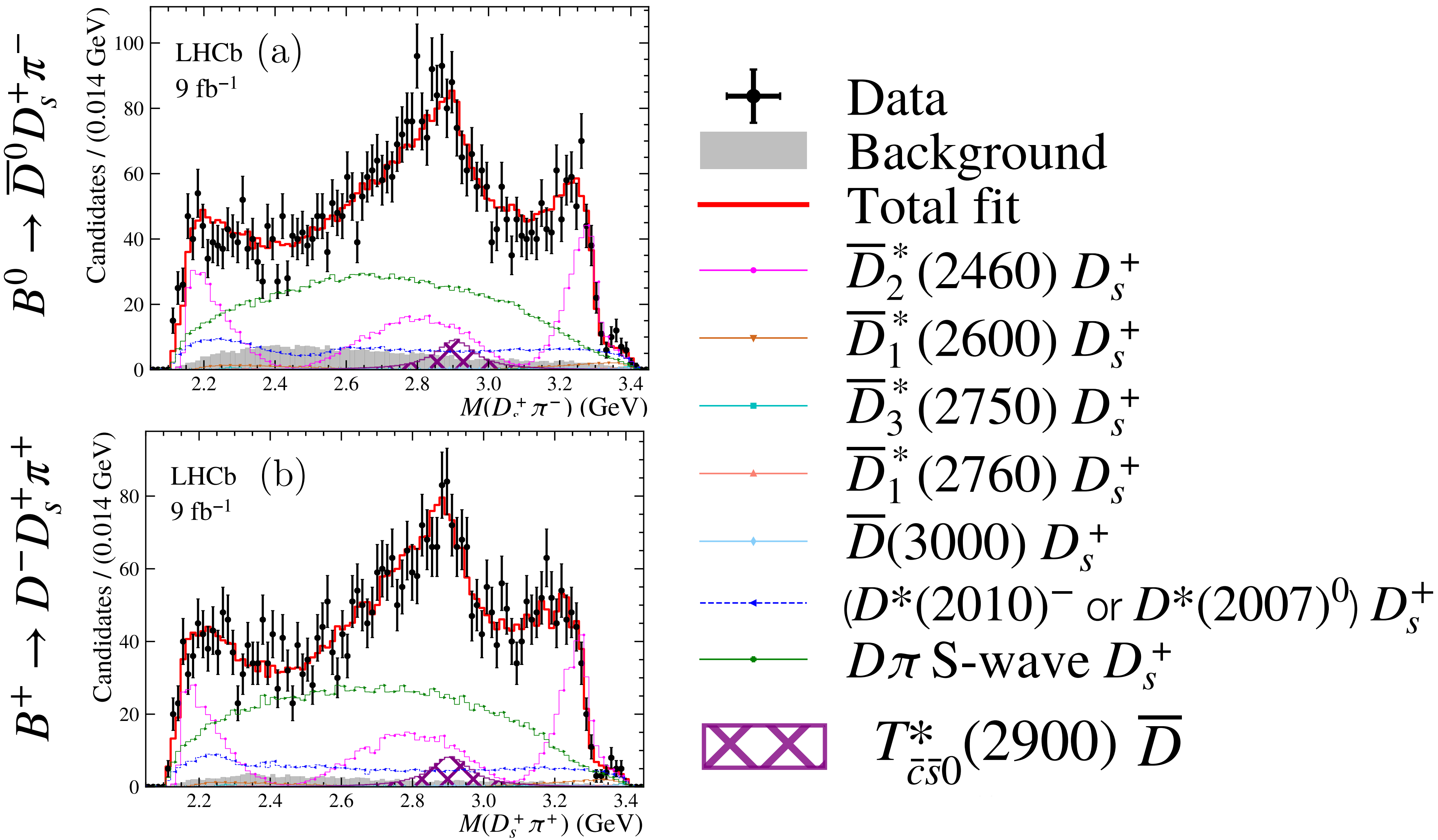
$B^0 \to \overline{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017



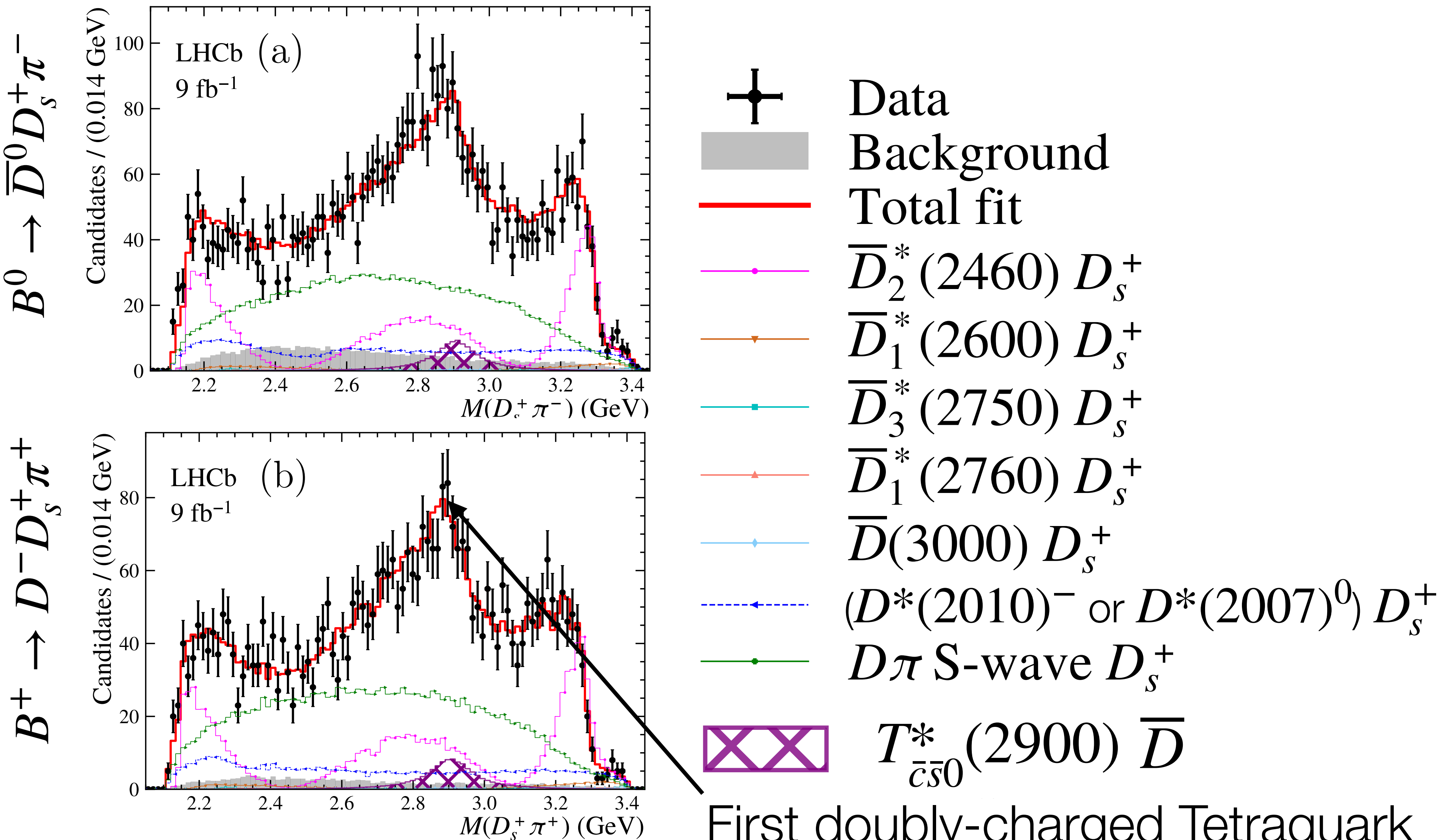
$B^0 \to \overline{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017



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

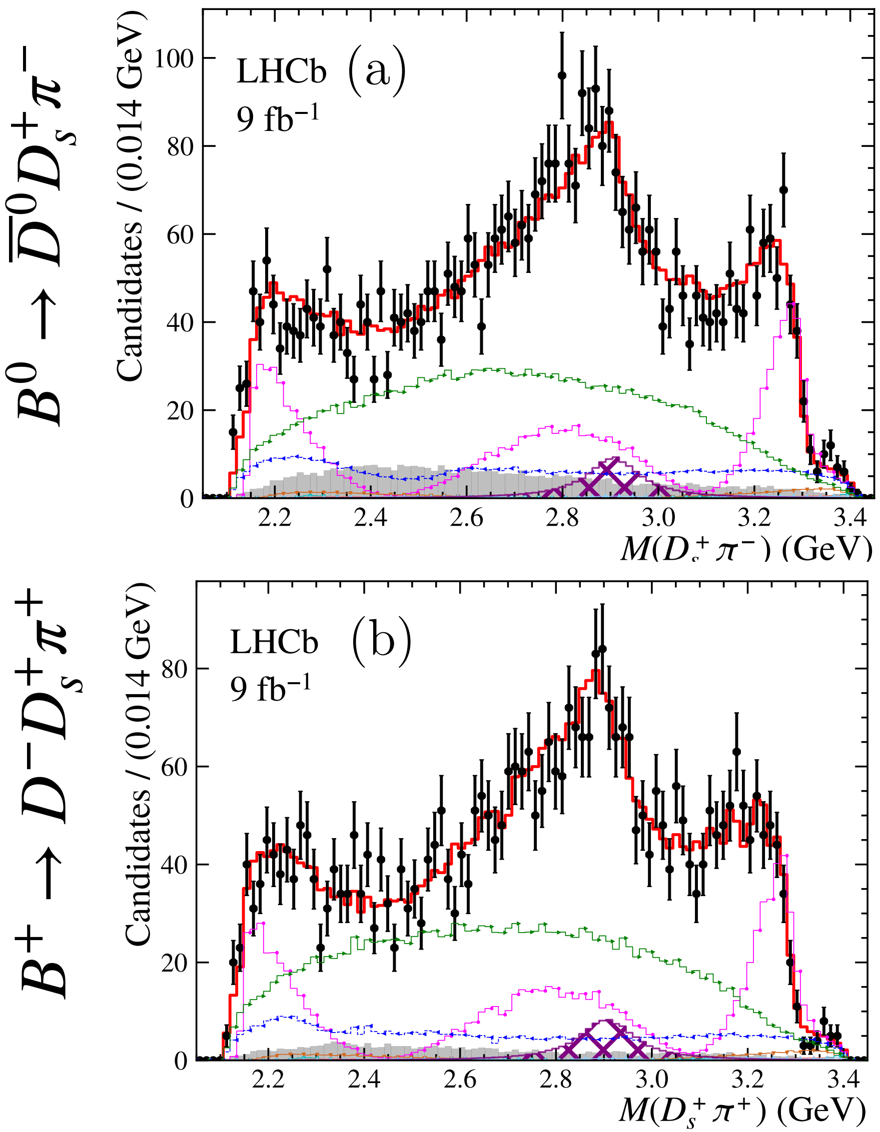
PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017



First doubly-charged Tetraquark

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

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017



$J^P = 0^+$

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.013\,\text{GeV}$$

$$T^*_{c\bar{s}0}(2900)^0 : M = 2.892 \pm 0.014 \pm 0.015\,\text{GeV}$$
$$\Gamma = 0.119 \pm 0.026 \pm 0.013\,\text{GeV}$$
$$T^*_{c\bar{s}0}(2900)^{++} : M = 2.921 \pm 0.017 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.137 \pm 0.032 \pm 0.017\,\text{GeV}$$

$T^*_{\bar{c}\bar{s}0}(2900)\ \overline{D}$

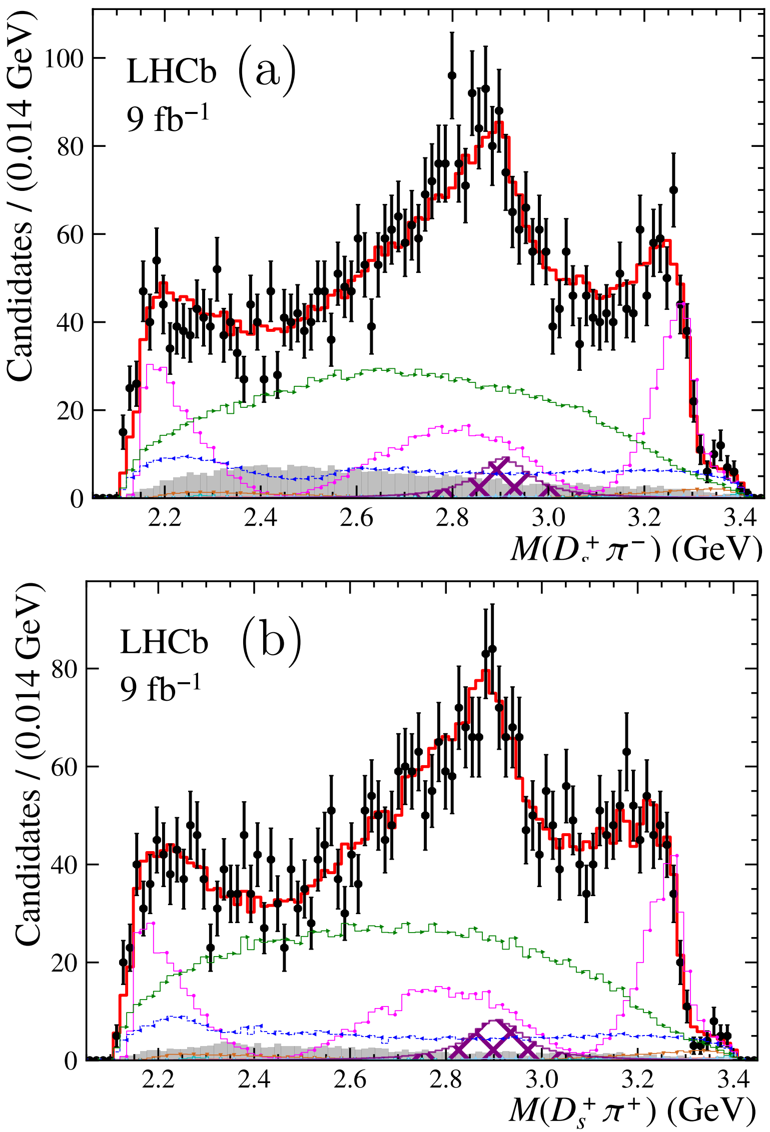
First doubly-charged Tetraquark

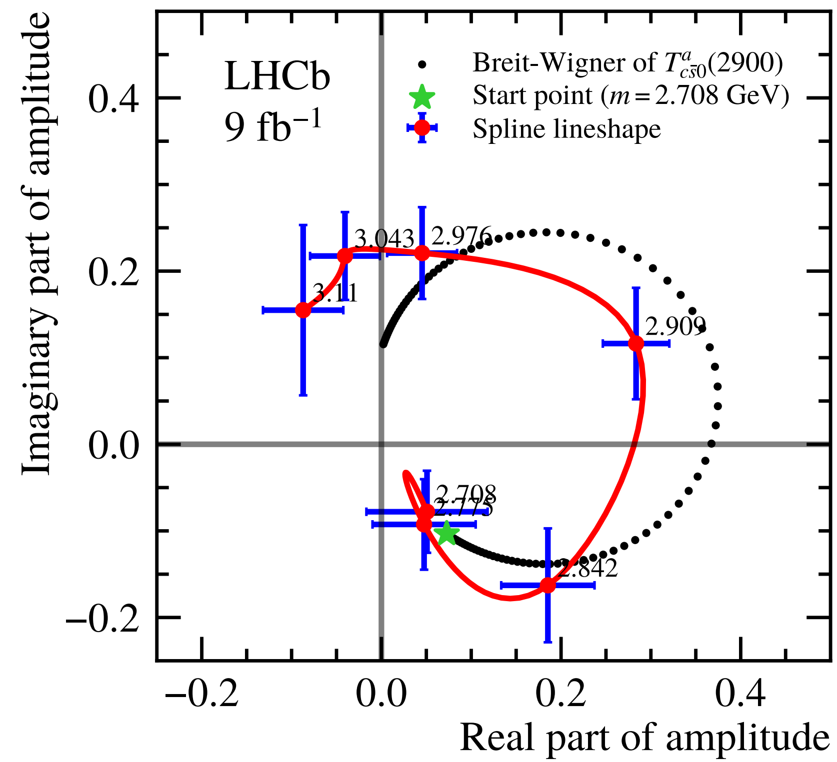
$B^0 \to \overline{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$

PRL 131 (2023) 4, 041902
PRD 108 (2023) 1, 012017

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

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

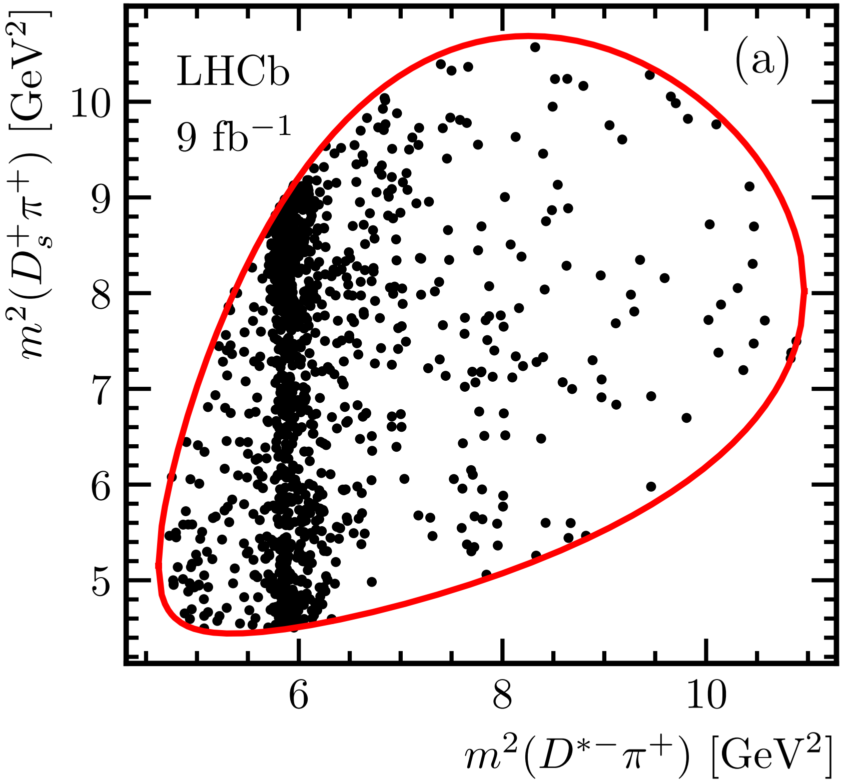


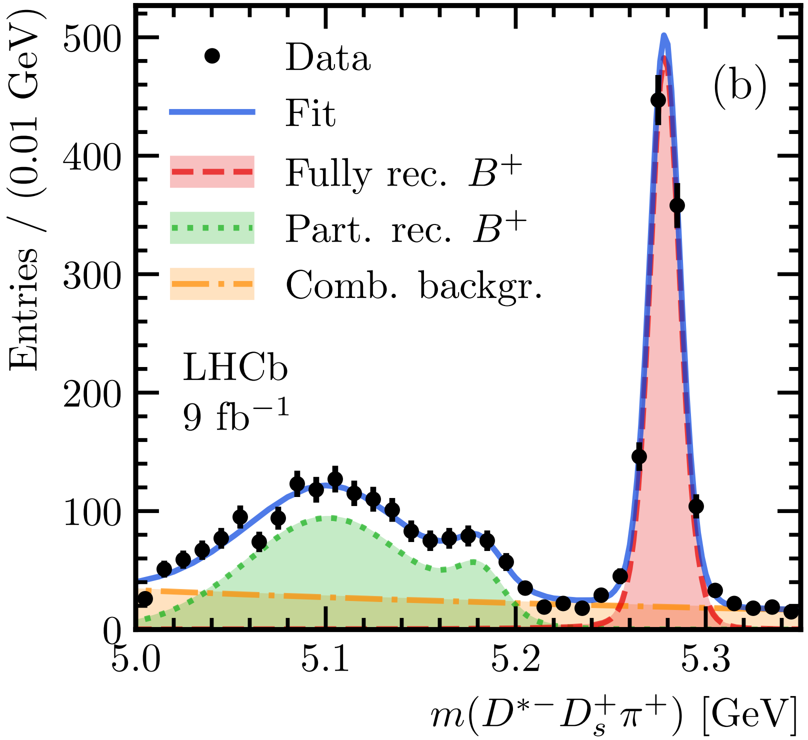


$T^*_{\bar{c}\bar{s}0}(2900)\ \overline{D}$

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

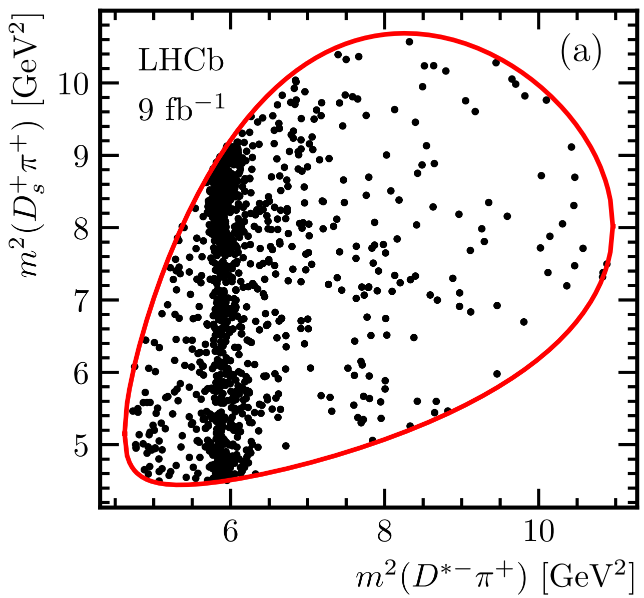
LHCb: arXiv:2405.00098 (2024)



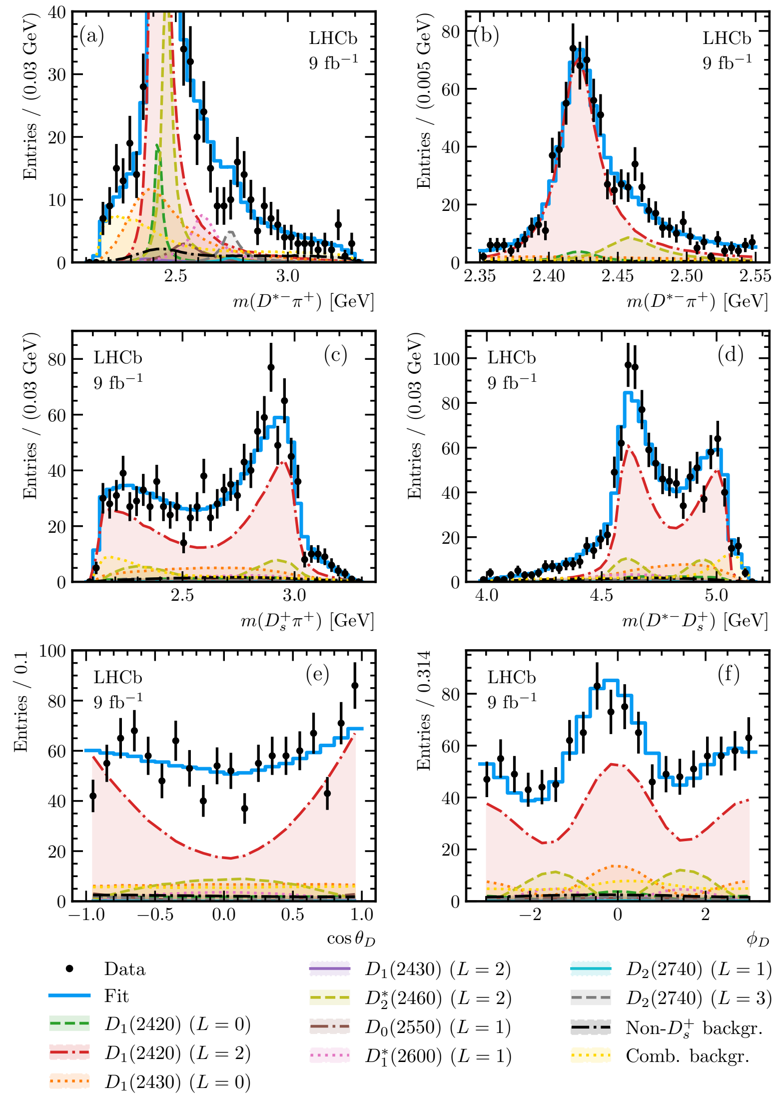


$B^+ \to D^{*-} D_s^+ \pi^+$

LHCb: arXiv:2405.00098 (2024)



No evidence of $T^*_{\bar{c}\bar{s}0}(2900)^{++}$ or other exotic contributions, here.



$B^+ \to D^{*-}D^+\pi^+$, $B^+ \to D^{*+}D^-\pi^+$ LHCb-PAPER-2023-047

C

$$A^{D^{*-}D^+\pi^+}(x) = \sum_{j\in R(D^{*\pm}D^{\mp})} c_j A_j(x) + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)$$

$$A^{D^{*+}D^-\pi^+}(x) = \sum_{j\in R(D^{*\pm}D^{\mp})} C_j \times c_j A_j(x) + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)$$

Resonances in $D^{*-}D^+$ related to those in $D^{*+}D^-$ by C-parity,

$$R_J(D^{*-}D^+) = C_J \cdot R_J(D^{*+}D^-)$$

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

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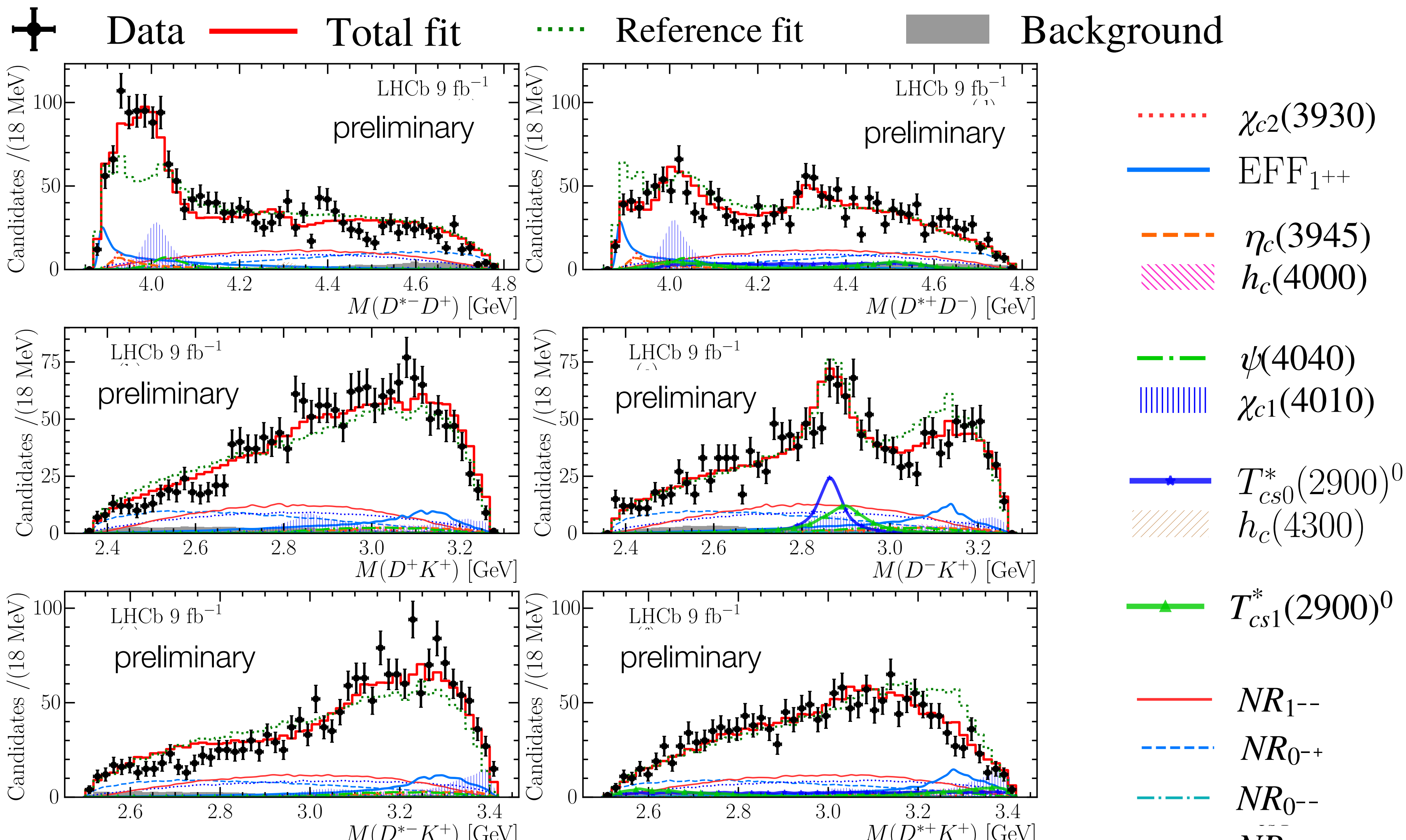

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

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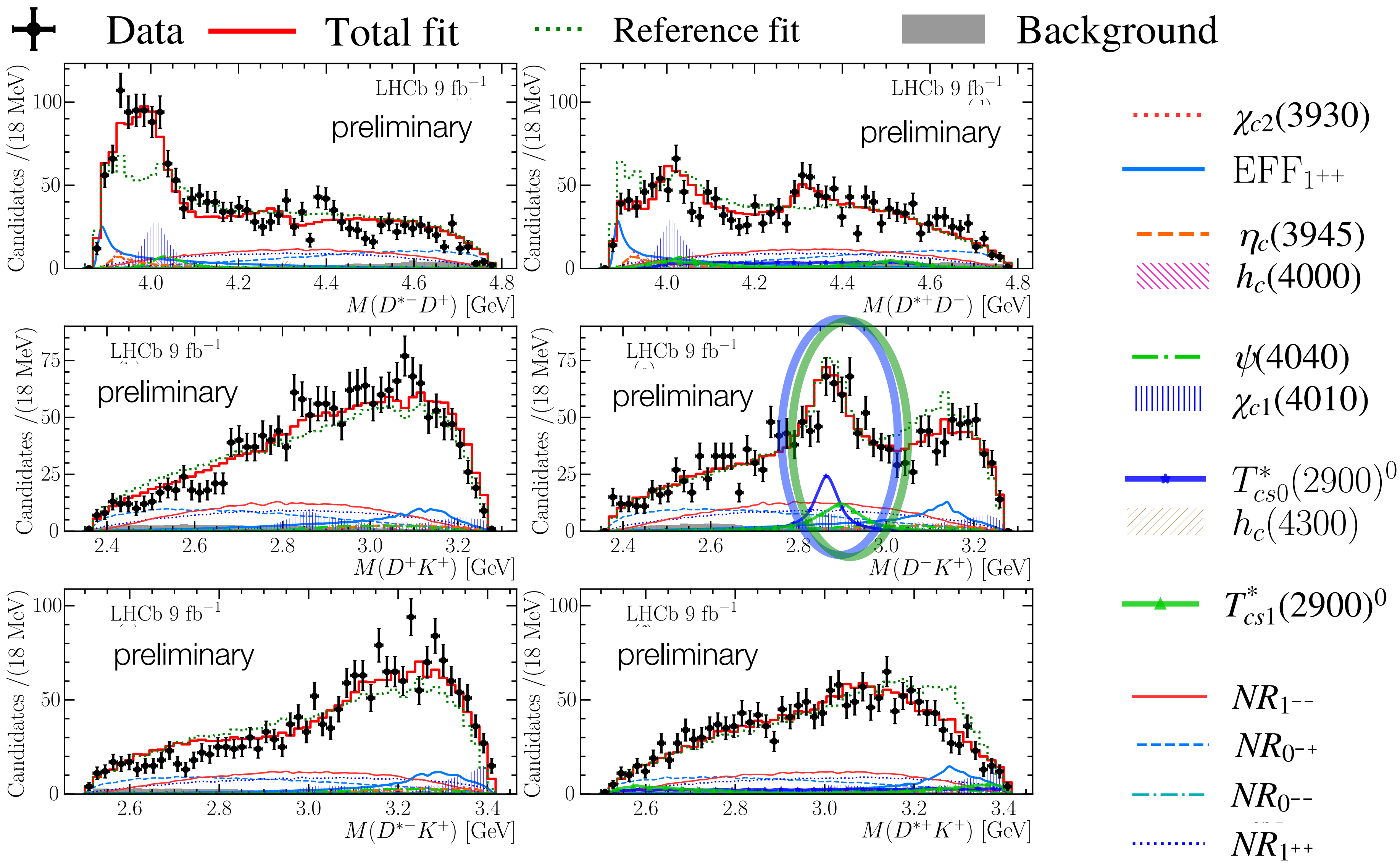

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

LHCb-PAPER-2023-047

LHCb-preliminary

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

Total NR FF ~ 50%

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

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LHCb-preliminary

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

Total NR FF ~ 50%

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

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LHCb-preliminary

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

Total NR FF ~ 50%

3 new (or disguised?) charmonium-like resonances

$\eta_c(3945)$ $h_c(4000)$ $h_c(4010)$ $h_c(4300)$

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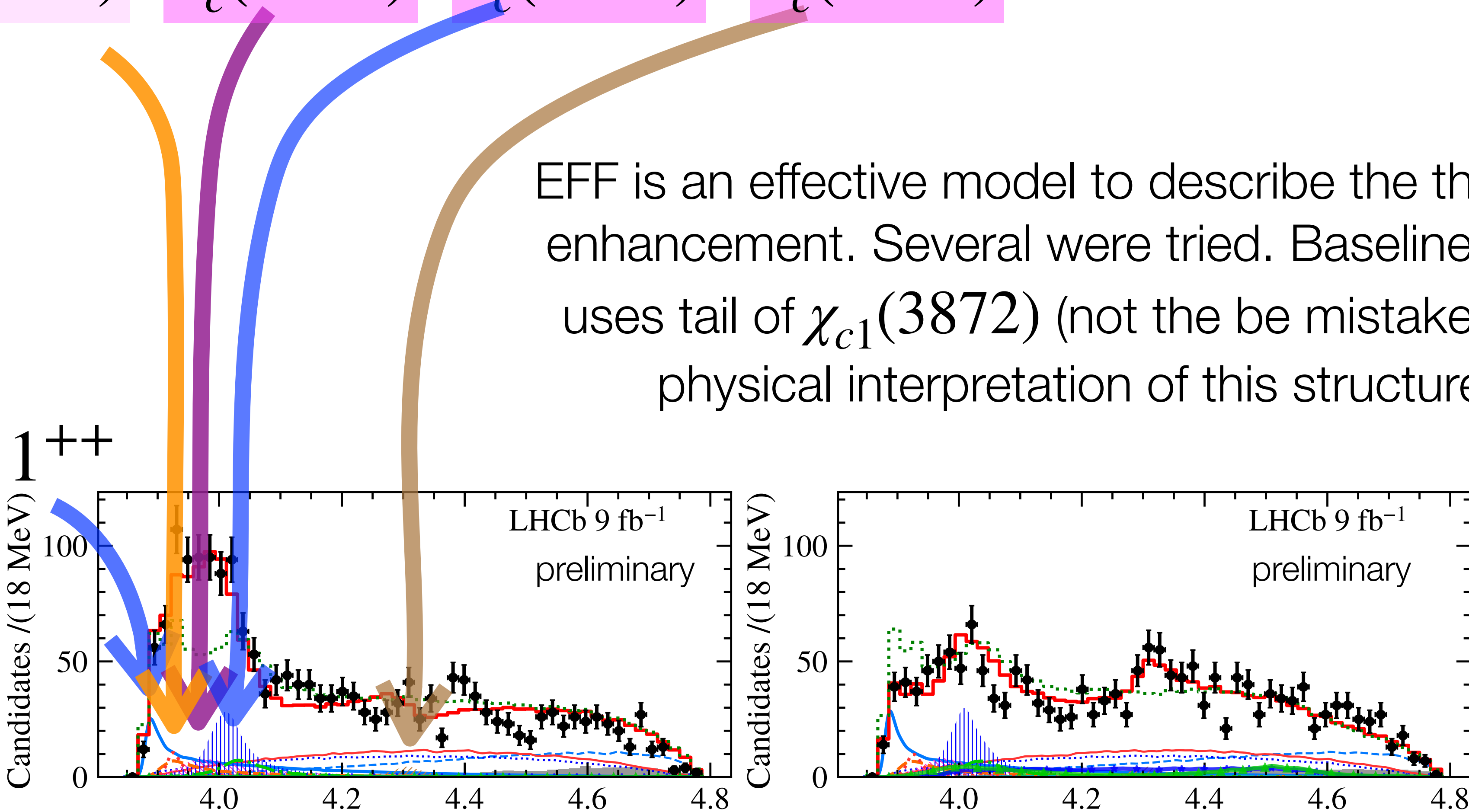
EFF is an effective model to describe the threshold enhancement. Several were tried. Baseline model uses tail of $\chi_{c1}(3872)$ (not the be mistaken as a physical interpretation of this structure).

EFF 1^{++}



3 new (or disguised?) charmonium-like resonances

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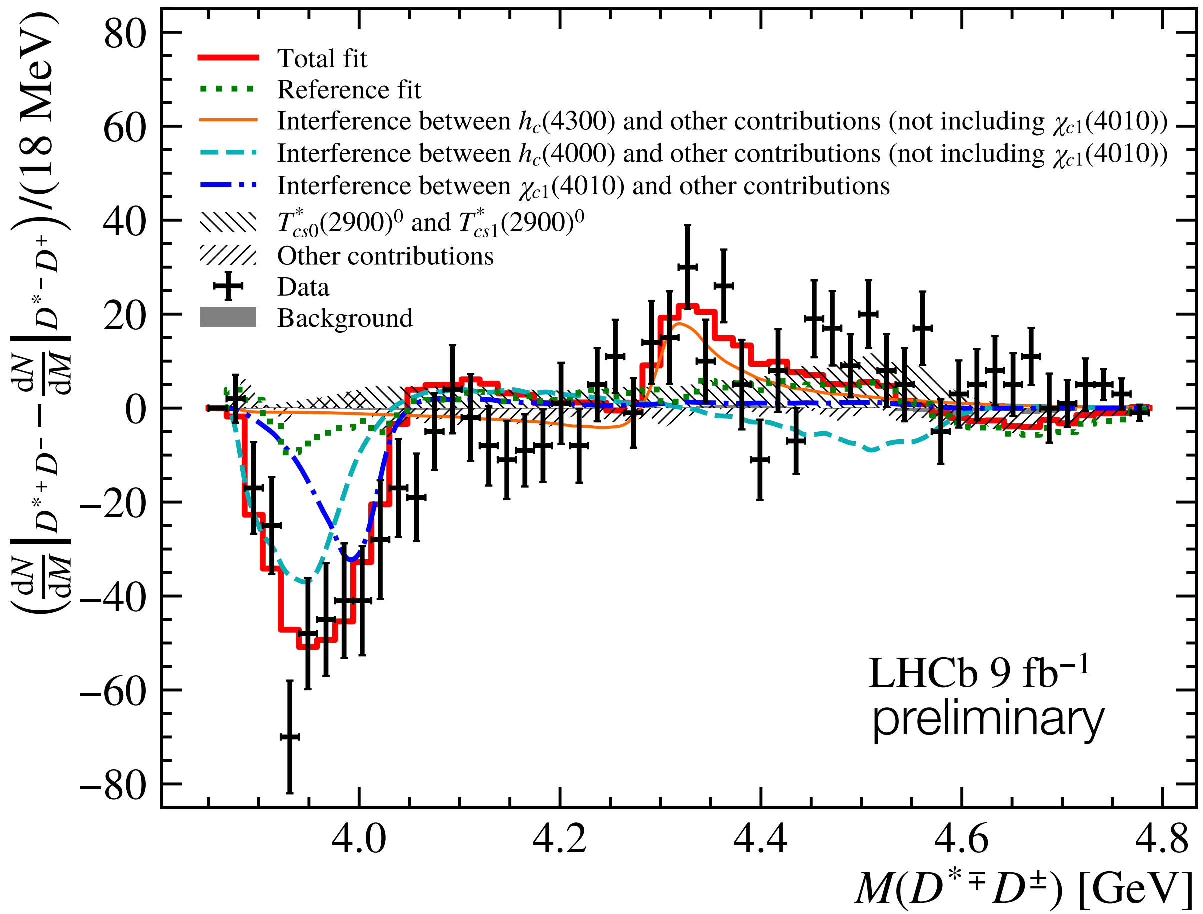
Difference between $M(D^{*-}, D^{+})$ and $M(D^{*+}, D^{-})$ distributions



$\mathrm{EFF}_{1^{++}}$	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)^{\dagger}$	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)^{\dagger}$	1^{--}
$h_c(4300)$	1^{+-}

Only interference between states with the same J^P but different C, and reflections from $T^*_{cs0,1}(2900)^0$, have significant contributions

Meike Küßner, earlier today

One Prominent Example: The Lightest Hybrid Candidate

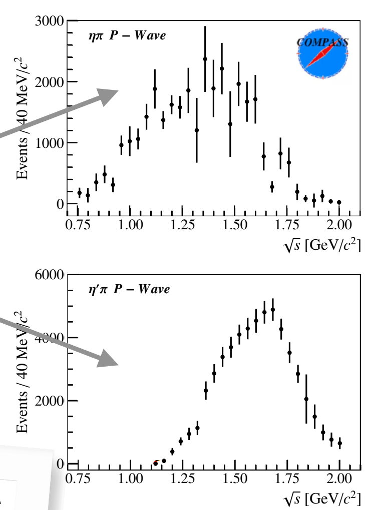
Two π_1 hybrid candidates below 2 GeV are listed in PDG

- one at around 1.4 GeV only seen in $\pi\eta$
- the other at around 1.6 GeV seen in $\pi\eta'$ but not in $\pi\eta$

➡ Parameters obtained by Breit-Wigner fits!

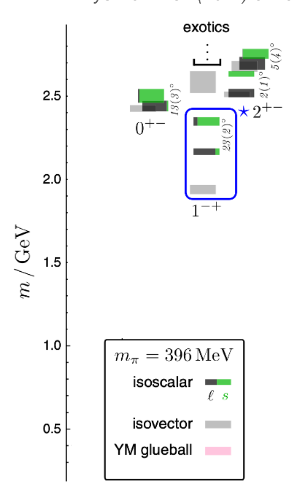
➡ Theory: Only one π_1 state predicted slightly below 2 GeV

200 MeV apart!



Eur.Phys.J.C 81 (2021) 12, 1056

Phys.Rev. D84 (2011) 074023



Did we fall into the same trap with our $h_c(4000)$, $\chi_{c1}(4010)$,$h_c(4300)$? If so, what did we really observe?

3 new (or disguised?) charmonium-like resonances

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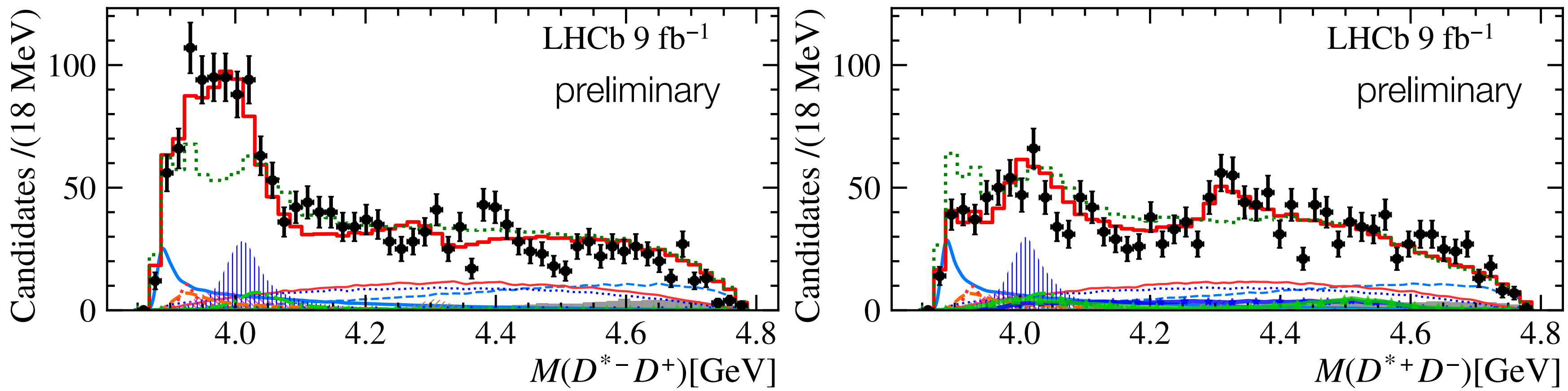

This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC}=0^{-+}$	$X(3940)$ [9]	$J^{PC}=?^{??}$	$\eta_c(3S)$	$J^{PC}=0^{-+}$
$m_0=3945\,^{+28\,+37}_{-17\,-28}$	$\Gamma_0=130\,^{+92\,+101}_{-49\,-70}$	$m_0=3942\pm 9$	$\Gamma_0=37\,^{+27}_{-17}$	$m_0=4064$	$\Gamma_0=80$
$h_c(4000)$	$J^{PC}=1^{+-}$	$X(4020)$ [35]	$J^{PC}=?^{?-}$	$h_c(2P)$	$J^{PC}=1^{+-}$
$m_0=4000\,^{+17\,+29}_{-14\,-22}$	$\Gamma_0=184\,^{+71\,+97}_{-45\,-61}$	$m_0=4025.5\,^{+2.0}_{-4.7}\pm 3.1$	$\Gamma_0=23.0\pm 6.0\pm 1.0$	$m_0=3956$	$\Gamma_0=87$
$\chi_{c1}(4010)$	$J^{PC}=1^{++}$			$\chi_{c1}(2P)$	$J^{PC}=1^{++}$
$m_0=4012.5\,^{+3.6\,+4.1}_{-3.9\,-3.7}$	$\Gamma_0=62.7\,^{+7.0\,+6.4}_{-6.4\,-6.6}$			$m_0=3953$	$\Gamma_0=165$
$h_c(4300)$	$J^{PC}=1^{+-}$			$h_c(3P)$	$J^{PC}=1^{+-}$
$m_0=4307.3\,^{+6.4\,+3.3}_{-6.6\,-4.1}$	$\Gamma_0=58\,^{+28\,+28}_{-16\,-25}$			$m_0=4318$	$\Gamma_0=75$
		$\chi_c(4274)$ [36]	$J^{PC}=1^{++}$	$\chi_{c1}(3P)$	$J^{PC}=1^{++}$
		$m_0=4294\pm 4\,^{+6}_{-3}$	$\Gamma_0=53\pm 5\pm 5$	$m_0=4317$	$\Gamma_0=39$

LHCb-preliminary

References in backup slides

3 new (or disguised?) charmonium-like resonances

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$h_c(4000)$	$J^{PC}=1^{+-}$	$X(4020)$ [35]	$J^{PC}=?^{?-}$	$h_c(2P)$	$J^{PC}=1^{+-}$
$m_0=4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0=184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0=4025.5\,^{+2.0}_{-4.7}\pm 3.1$	$\Gamma_0=23.0\pm 6.0\pm 1.0$	$m_0=3956$	$\Gamma_0=87$
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$m_0=4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0=62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0=3953$	$\Gamma_0=165$
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		$m_0=4294\pm 4\,^{+6}_{-3}$	$\Gamma_0=53\pm 5\pm 5$	$m_0=4317$	$\Gamma_0=39$

LHCb-preliminary

[6] Particle Data Group, R. L. Workman *et al.*, *Review of particle physics*, Prog. Theor. Exp. Phys. **2022** (2022) 083C01, and 2023 update.

[34] T. Barnes, S. Godfrey, and E. S. Swanson, *Higher charmonia*, Phys. Rev. **D72** (2005) 054026, arXiv:hep-ph/0505002.

[36] LHCb collaboration, R. Aaij *et al.*, *Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$*, Phys. Rev. Lett. **127** (2021) 082001, arXiv:2103.01803.

[9] Belle collaboration, P. Pakhlov *et al.*, *Production of new charmoniumlike states in $e^+e^- \to J/\psi D^{(*)}\bar{D}^{(*)}$ at $\sqrt{s} \approx 10$ GeV*, Phys. Rev. Lett. **100** (2008) 202001,

[35] BESIII collaboration, M. Ablikim *et al.*, *Observation of a neutral charmonium-like state $Z_c(4025)^0$ in $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$*, Phys. Rev. Lett. **115** (2015) 182002.

3 new (or disguised?) charmonium-like resonances

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Changing the EFF (modelled as tail of $\chi_{c1}(3872)$) with $J^{PC} = 1^{++}$ to tail of $Z_c(3900)$ with $J^{PC} = 1^{+-}$ flips the J^{PC} of the $h_c(4300)$ to 1^{++}, making it compatible with $\chi_c(4275)$. However, fit quality deteriorates substantially, making this an unlikely scenario.

m_0 … $_{-3.9\,-3.7}$	Γ_0 … $_{-6.4\,-6.6}$			m_0 …	Γ_0 …
$h_c(4300)$	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

LHCb-preliminary

[6] Particle Data Group, R. L. Workman *et al.*, *Review of particle physics*, Prog. Theor. Exp. Phys. **2022** (2022) 083C01, and 2023 update.

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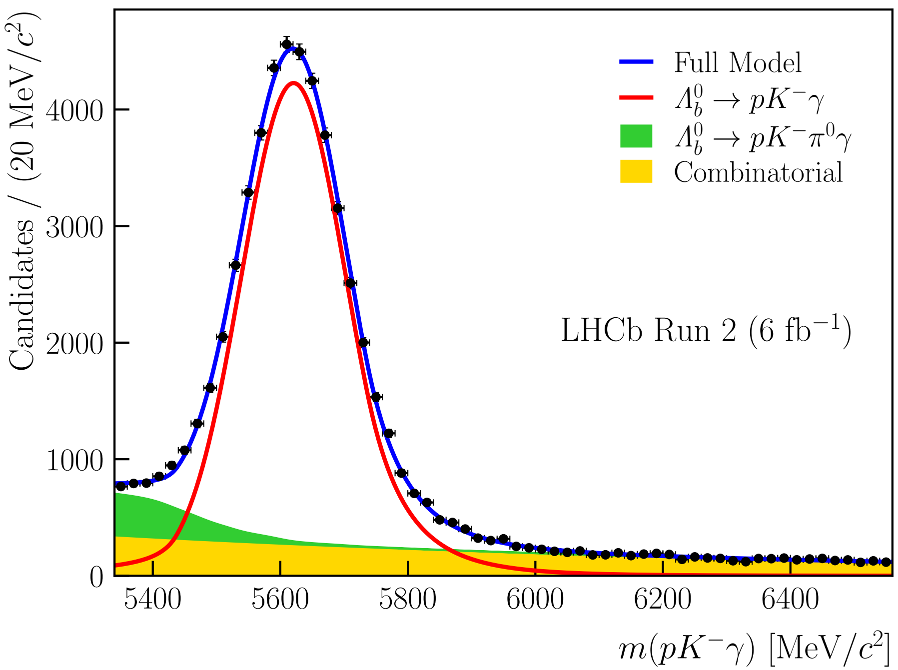
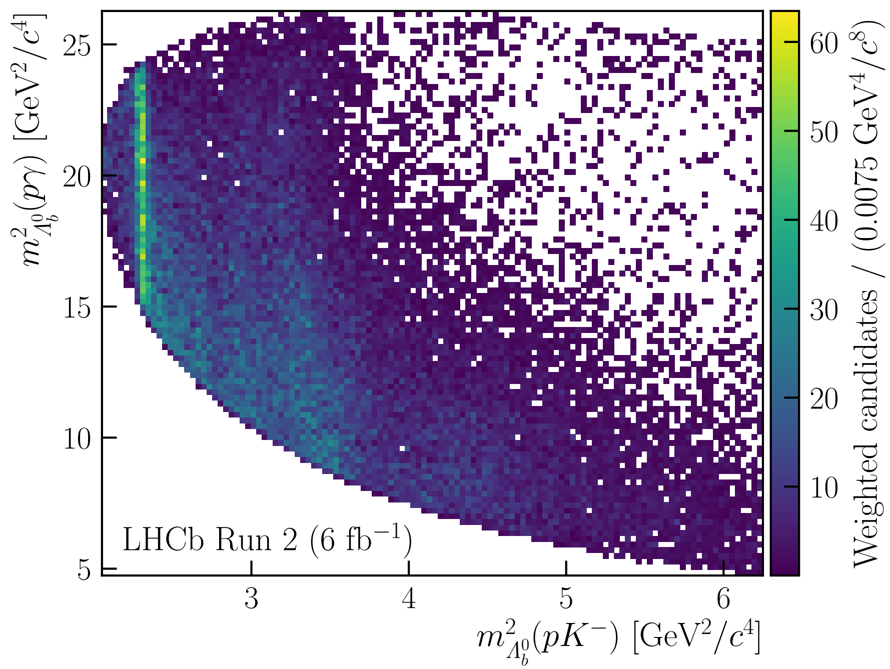
$\Lambda_b^0 \to pK^-\gamma$

LHCb arxiv:2403.03710 (2024)





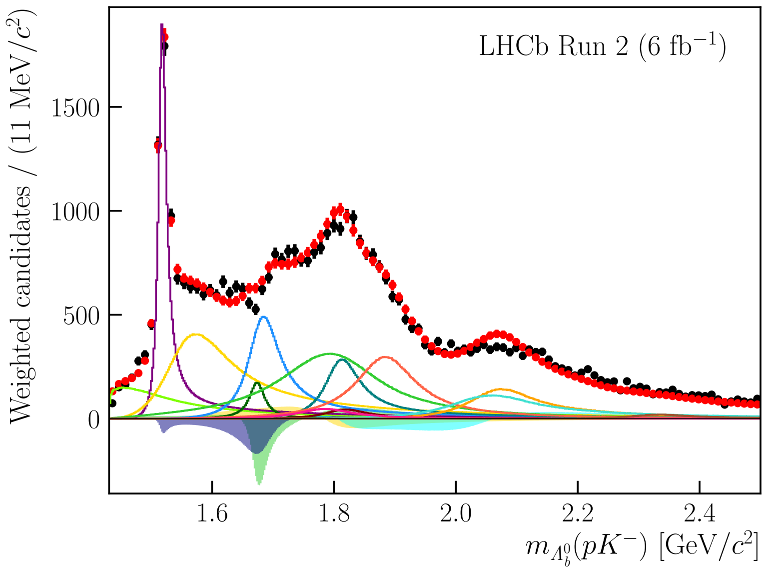
52k $\Lambda_b^0 \to pK^-\gamma$ events (6.9k run I and 45.6k run II - plots run 2 only)

$\Lambda_b^0 \to pK^-\gamma$

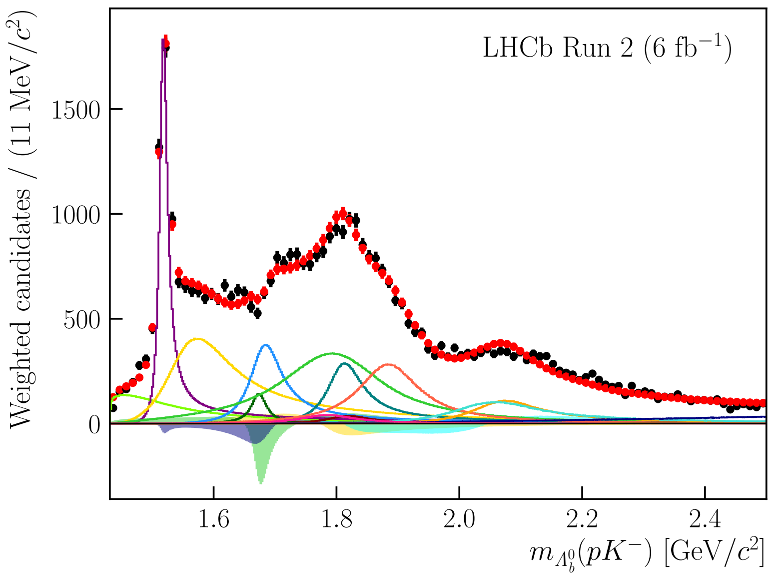
LHCb arxiv:2403.03710 (2024)

$\Lambda(1405)$	$1/2^-$
$\Lambda(1520)$	$3/2^-$
$\Lambda(1600)$	$1/2^+$
$\Lambda(1670)$	$1/2^-$
$\Lambda(1690)$	$3/2^-$
$\Lambda(1800)$	$1/2^-$
$\Lambda(1810)$	$1/2^+$
$\Lambda(1820)$	$5/2^+$
$\Lambda(1830)$	$5/2^-$
$\Lambda(1890)$	$3/2^+$
$\Lambda(2100)$	$7/2^-$
$\Lambda(2110)$	$5/2^+$
$\Lambda(2350)$	$9/2^+$

Model with known Λ, only (Fixed M, Γ)



Model with known Λ, plus NR$\left(\frac{3}{2}^-\right)$

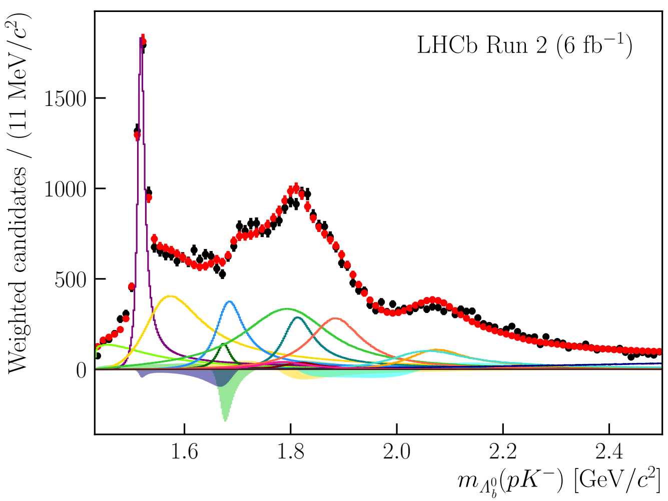


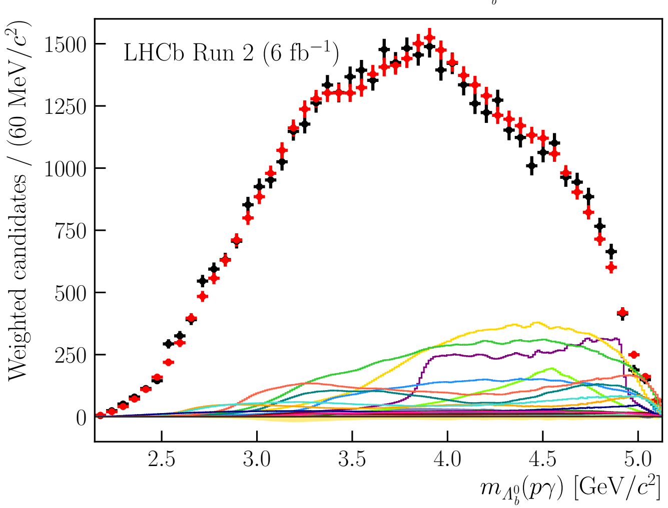
Lots of helicity couplings, multiple minima.
However: Fit fractions stable across minima, so, here, fit fractions, not couplings, are the measured result.
Uncertainties from bootstrapping.

Plots show run II only, result is for run I + run II

$\Lambda_b^0 \to pK^-\gamma$

LHCb arxiv:2403.03710 (2024)





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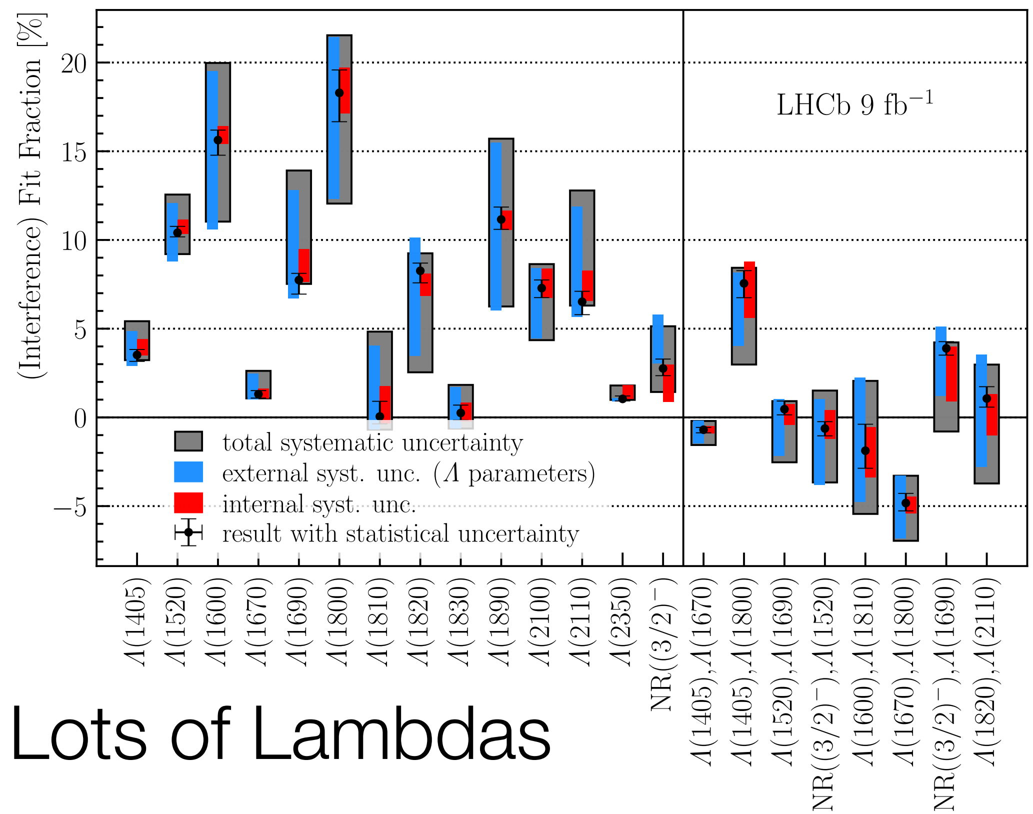
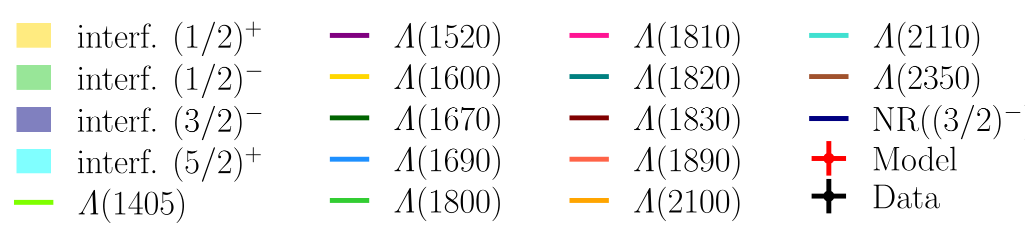
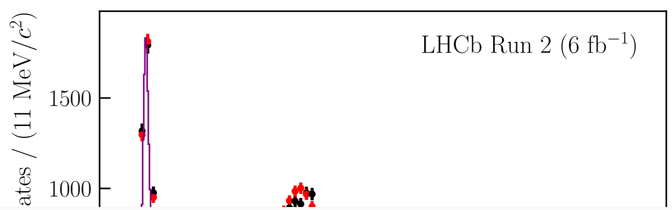


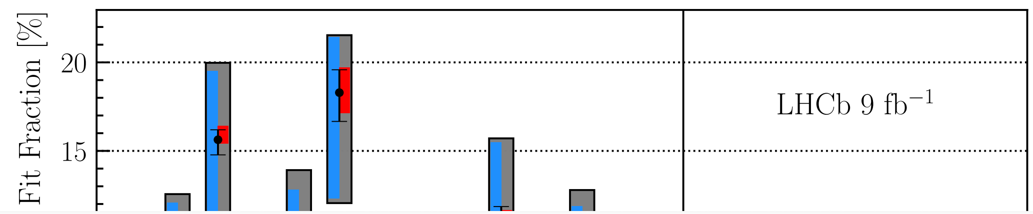
Lots of Lambdas



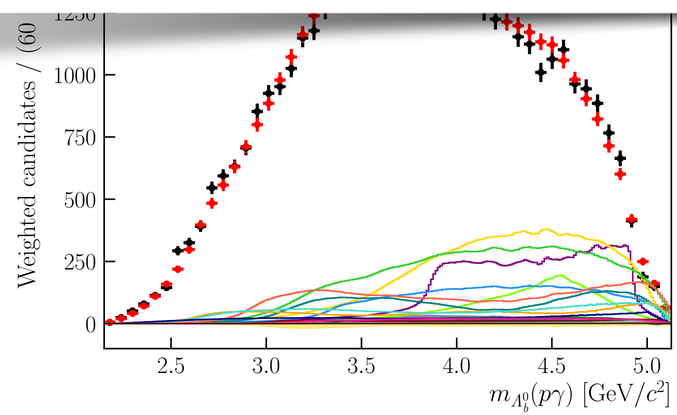
$\Lambda_b^0 \to pK^-\gamma$

LHCb arxiv:2403.03710 (2024)





You can find this model on Misha + Ilya’s amplitude serialisation site: https://rub-ep1.github.io/amplitude-serialization/julia/lb2pkg.html



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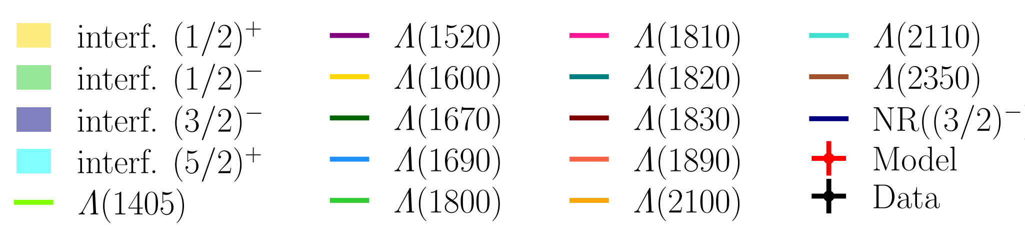


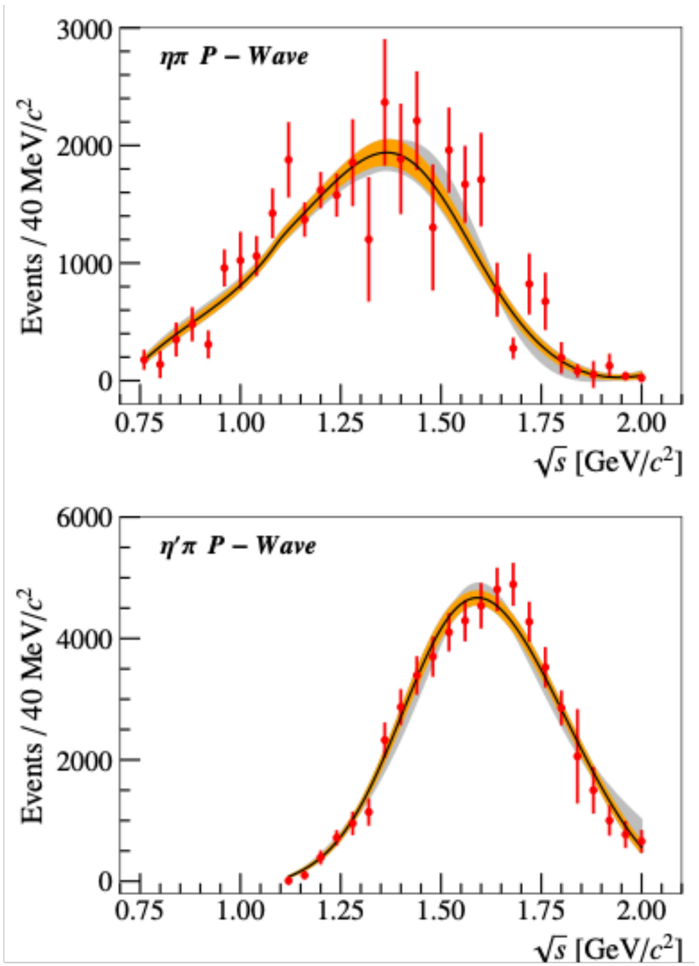
Plots show run II only, result is for run I + run II

Challenges (in lieu of conclusions)

- Too much high quality data: Huge, clean datasets allow high precision measurements
  - Needs high-quality models
  - Or model-independent methods. (However, “model-independent" methods usually still need models as input, e.g. for optimisation - better models mean better (statistical) precision, here, too. In some cases, models are needed to give meaning to model-independent results)
  - Numerically challenging
- Perennial challenge: how to build (sufficiently) good models - and when to stop
  - Parametrisation of threshold enhancements, rescattering, triangle diagrams, …
  - If we see new resonances in a $\sum$ BW analysis - how confident can we be they are real and new? How can we do better? How much better is good enough?
  - How to complete an amplitude analysis within duration of PhD?
  - Analysis reproducibility
- Interpretation of what we’ve seen - what are all those new structures?

Backup

Illustration of what we are worried about regarding the $h_c(4000), \chi_{c1}(4010), h_c(4300)$:

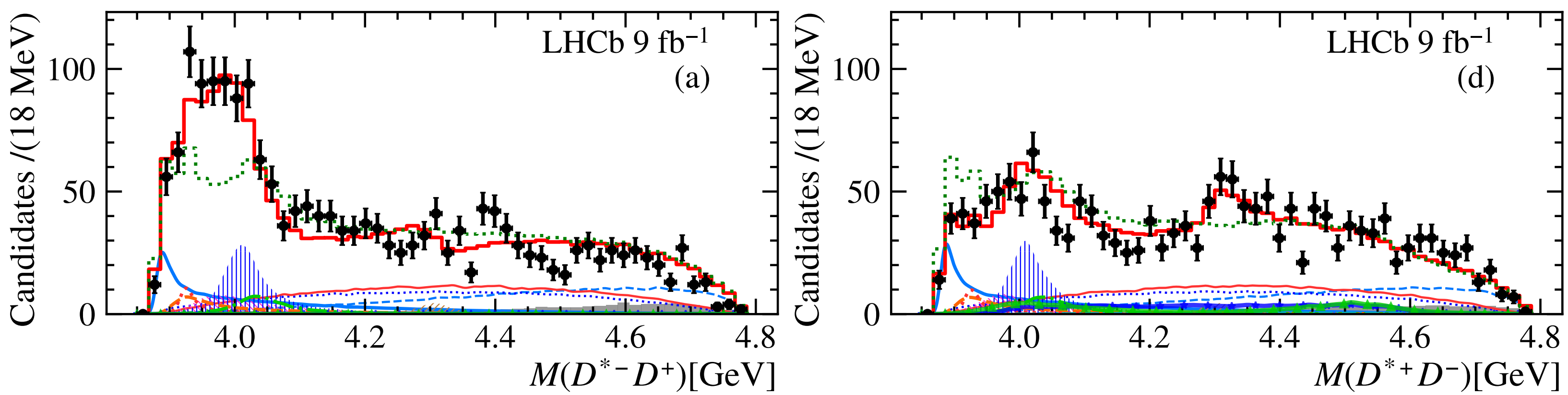


B. Kopf, M. Albrecht, H. Koch, **M. Küßner**, J. Pychy, X. Qin and U. Wiedner, Eur. Phys. J. C 81, no.12, 1056 (2021)

These two structures in $\eta\pi$ and $\eta'\pi$ are can be described by the same complex pole in a K-matrix analysis, but would yield different masses/width in a BW analysis. Did we fall into the same trap? How can we find out?

Also: what about the role of the description of the threshold enhancement in this context?

3 new (or disguised?) charmonium-like resonances



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$h_c(4300)$ $J^{PC} = 1^{+-}$ $m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$ $\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$	$\chi_c(4274)$ [36] $J^{PC} = 1^{++}$ $m_0 = 4294 \pm 4\,^{+6}_{-3}$ $\Gamma_0 = 53 \pm 5 \pm 5$	$h_c(3P)$ $J^{PC} = 1^{+-}$ $m_0 = 4318$ $\Gamma_0 = 75$ $\chi_{c1}(3P)$ $J^{PC} = 1^{++}$ $m_0 = 4317$ $\Gamma_0 = 39$

[6] Particle Data Group, R. L. Workman *et al.*, *Review of particle physics*, Prog. Theor. Exp. Phys. **2022** (2022) 083C01, and 2023 update.

[34] T. Barnes, S. Godfrey, and E. S. Swanson, *Higher charmonia*, Phys. Rev. **D72** (2005) 054026, `arXiv:hep-ph/0505002`.

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[35] BESIII collaboration, M. Ablikim *et al.*, *Observation of a neutral charmonium-like state $Z_c(4025)^0$ in $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$*, Phys. Rev. Lett. **115** (2015) 182002.

$D_s^+ \to \pi^+\pi^-\pi^+$ projections and 2-D pull

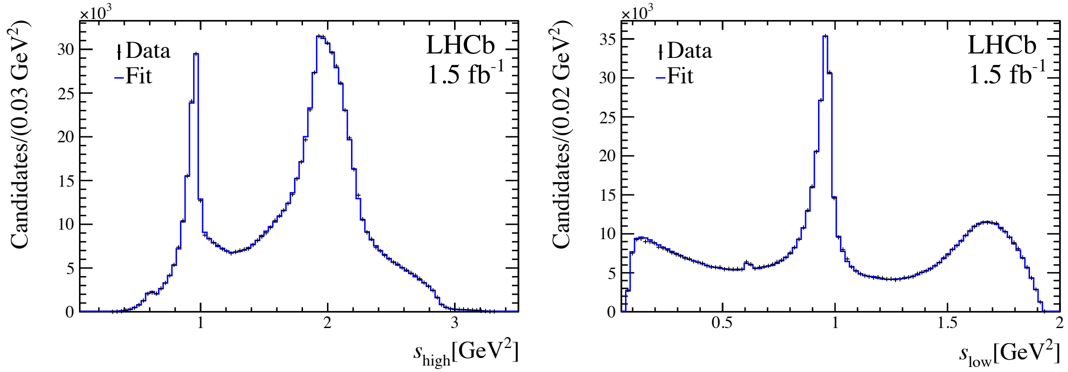


Figure 5: The folded Dalitz plot projections (left) s_{high} and (right) s_{low}.

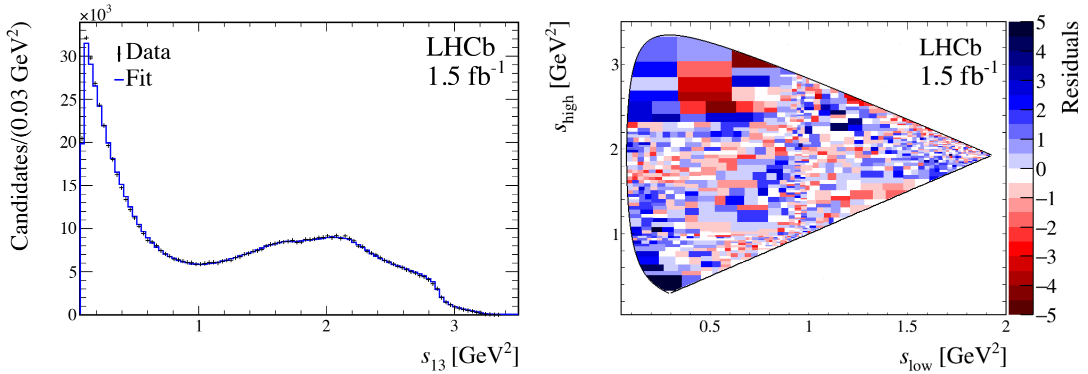
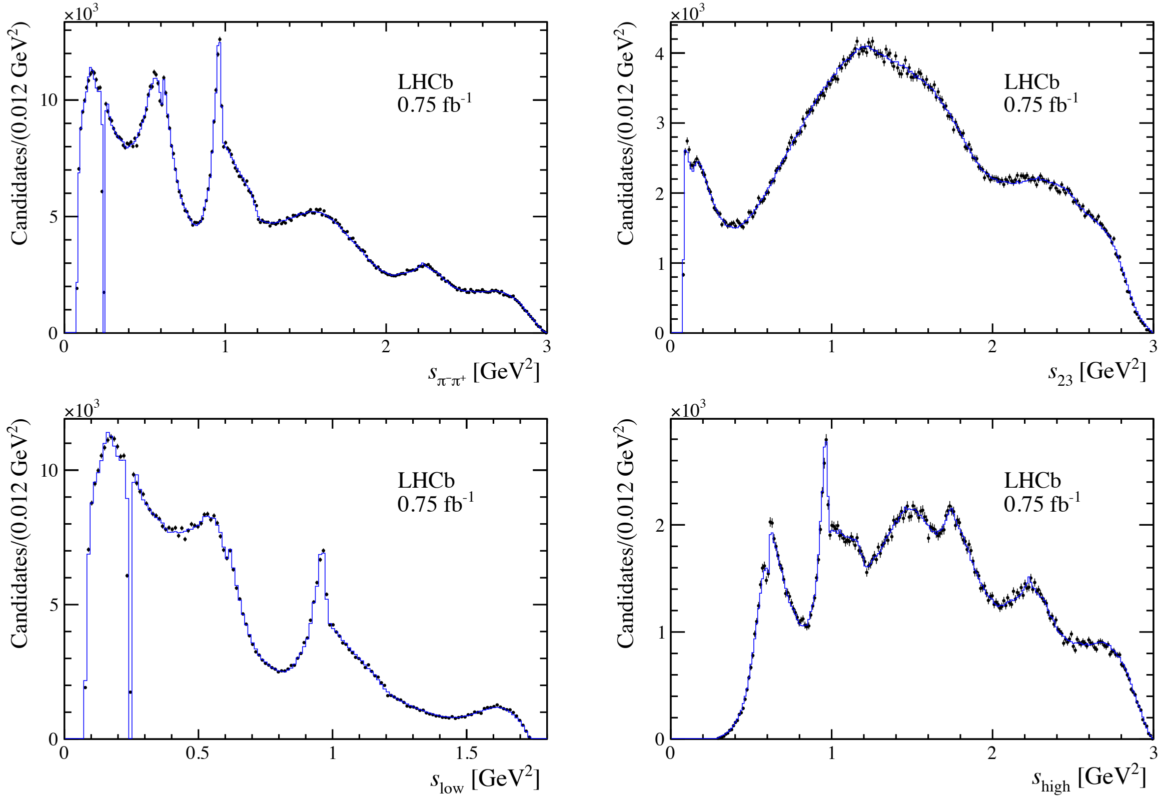
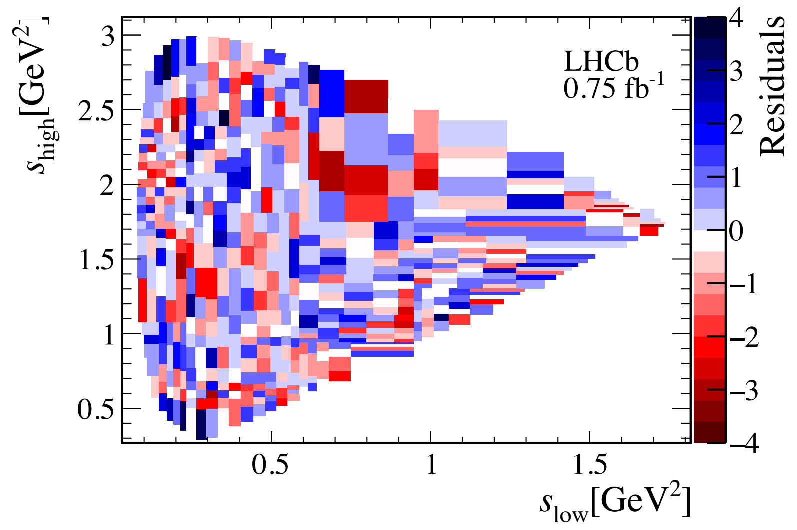


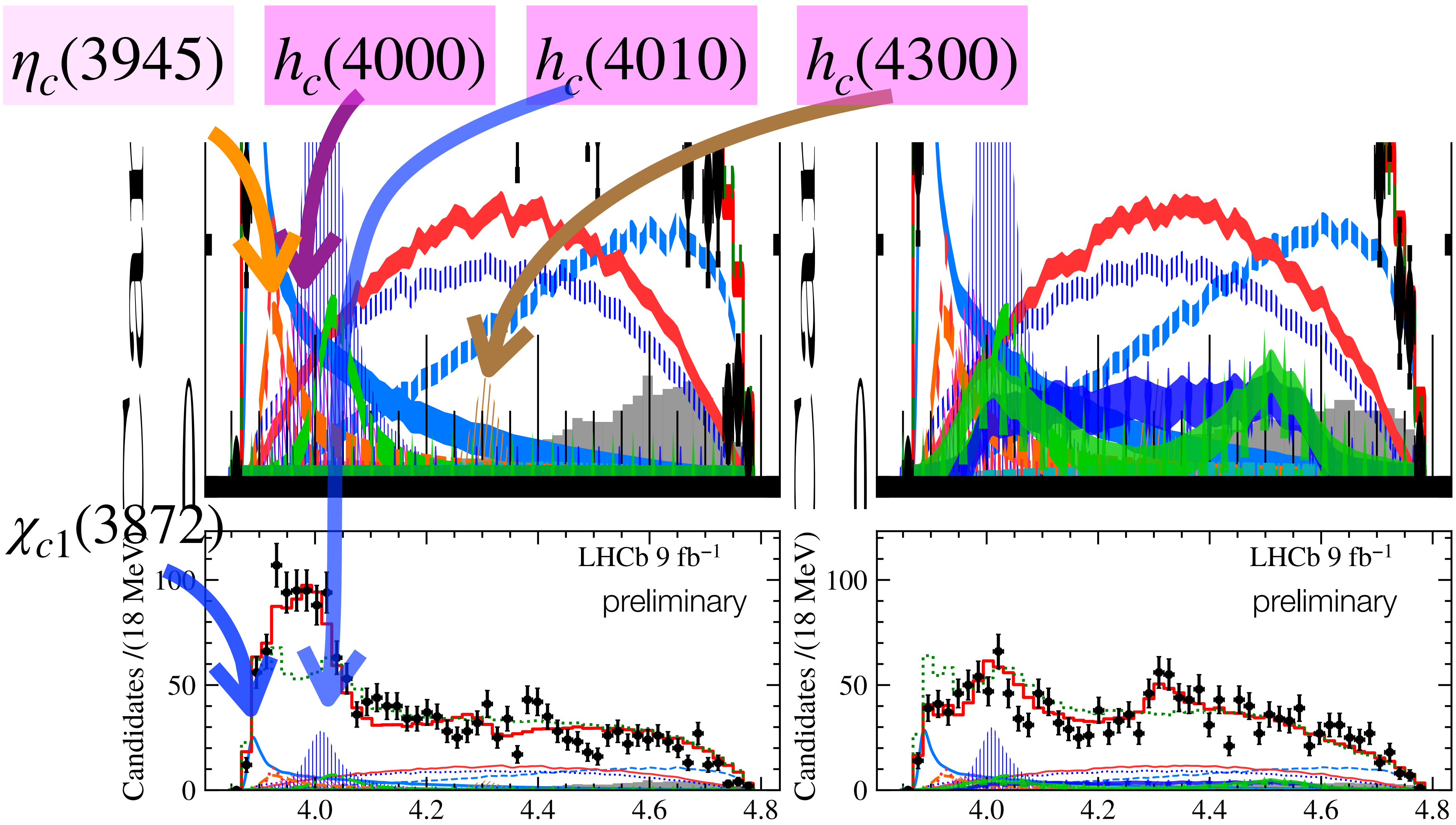
Figure 6: (Left) The unfolded Dalitz plot projection s_{13}; (right) the folded distribution of the normalised residuals across the Dalitz plot.

$D^+ \to \pi^+\pi^-\pi^+$ projections and 2-D pull



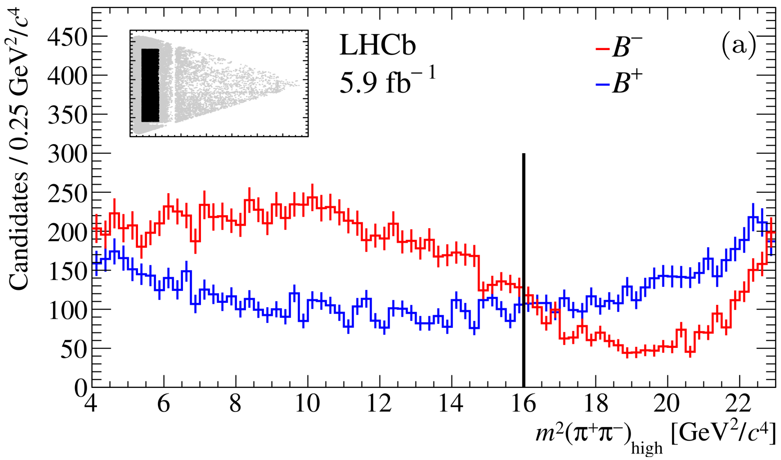


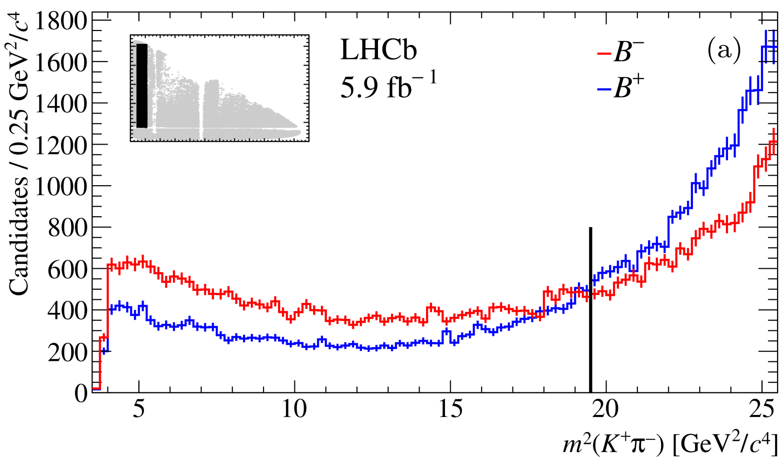
3 new (or disguised?) charmonium-like resonances



$B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008





What provides the strong phase in $A_{CP} \propto \sin(\Delta\phi_{weak})\ \sin(\Delta\delta_{strong})$?

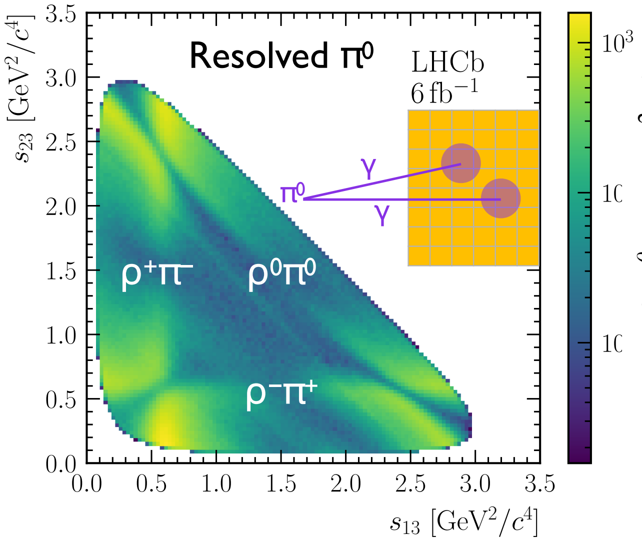
where the Δ indicates the phase differences between two interfering amplitudes contributing to the process; $\Delta\phi_{weak}$ changes sign under CP, $\Delta\delta_{strong}$ does not.

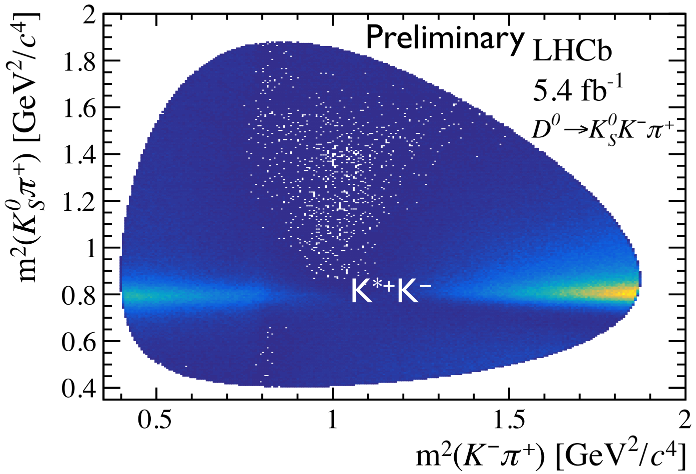
For low mass region, where large CPV is observed, $KK \leftrightarrow \pi\pi$ re-scattering could play a key role (see Phys.Rev.D 89 (2014) 9, 094013)

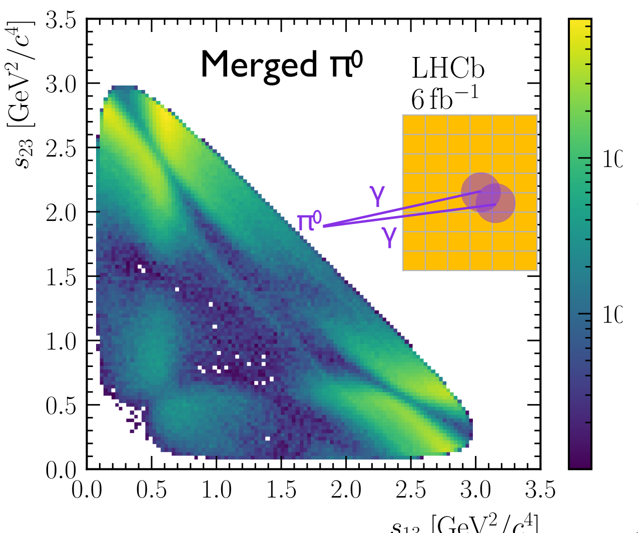
More model avoidance!

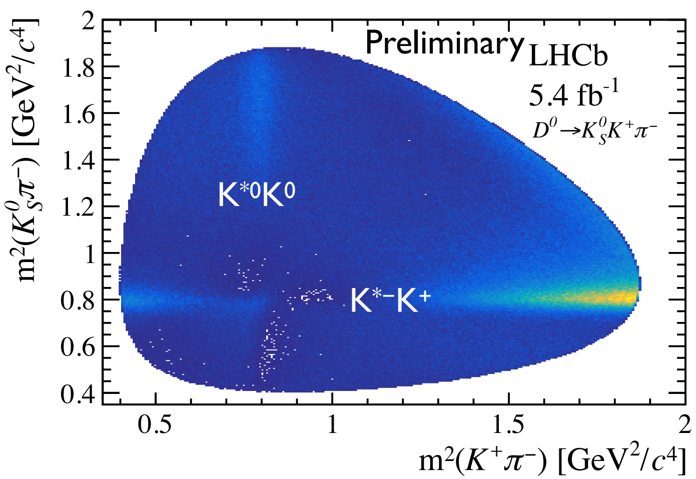
Search for CPV $D \to \pi^+\pi^-\pi^0$, $D \to K_S K^\pm \pi^\pm$

LHCb: JHEP 09 (2023) 129 (2023)









Energy test (~unbinned version of χ^2 test) reveals no significant difference between CP-conjugate Dalitz plots.

Note however, that current sensitivity insufficient to discover CPV at level seen in 2-body decays.

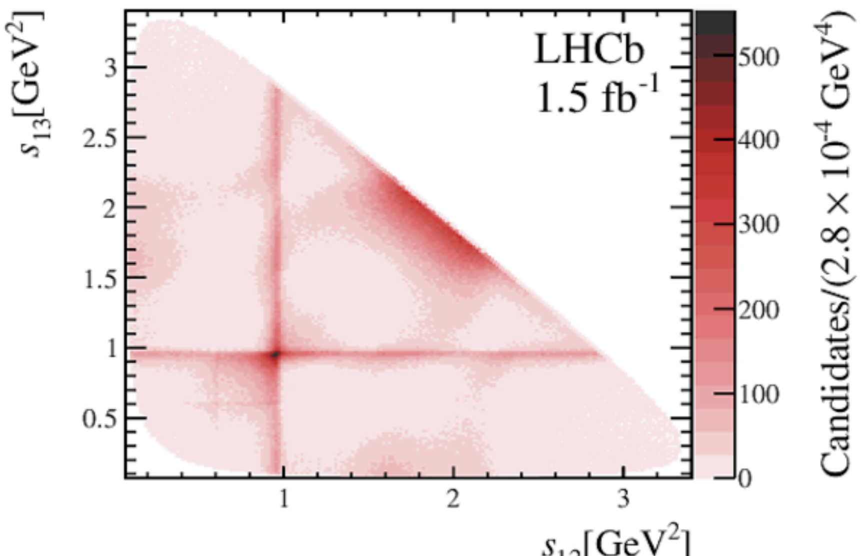
See also:

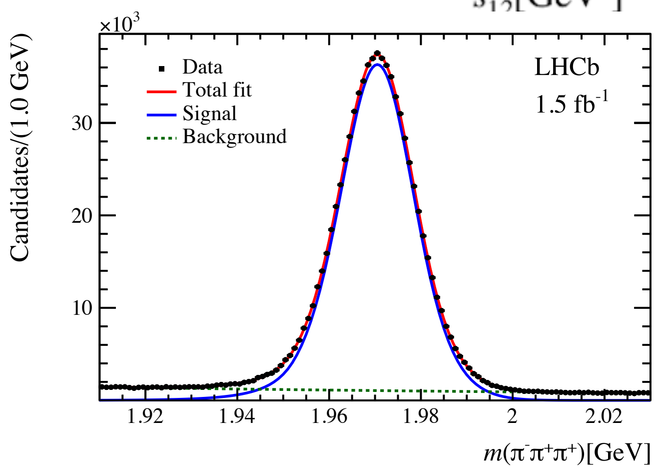
$D^+_{(s)} \to \pi^+\pi^-\pi^+$

LHCb: JHEP 06 (2023) 044

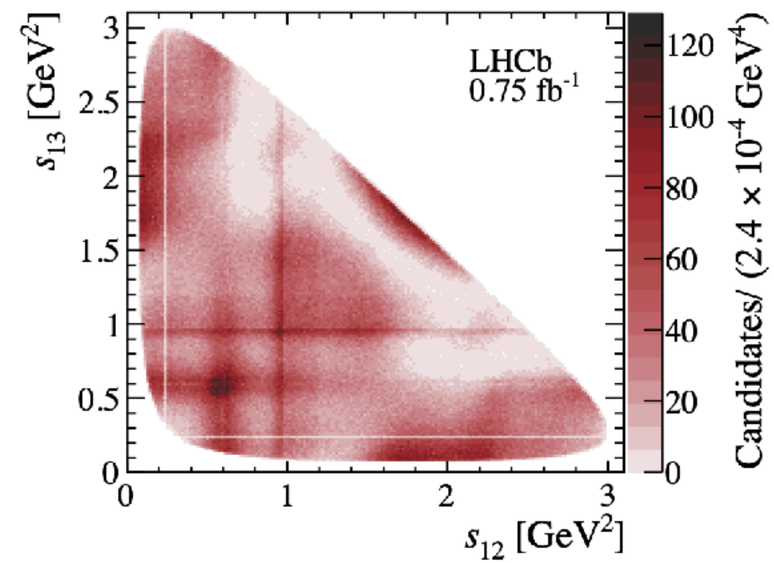
LHCb: JHEP 07 (2023) 204

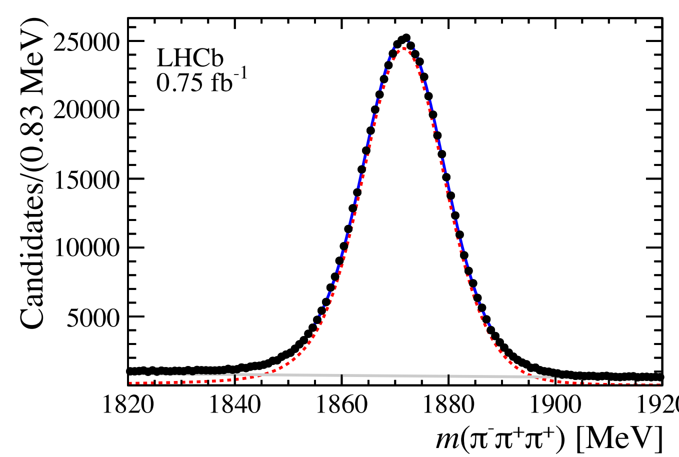
$D^+_s \to \pi^+\pi^-\pi^+$





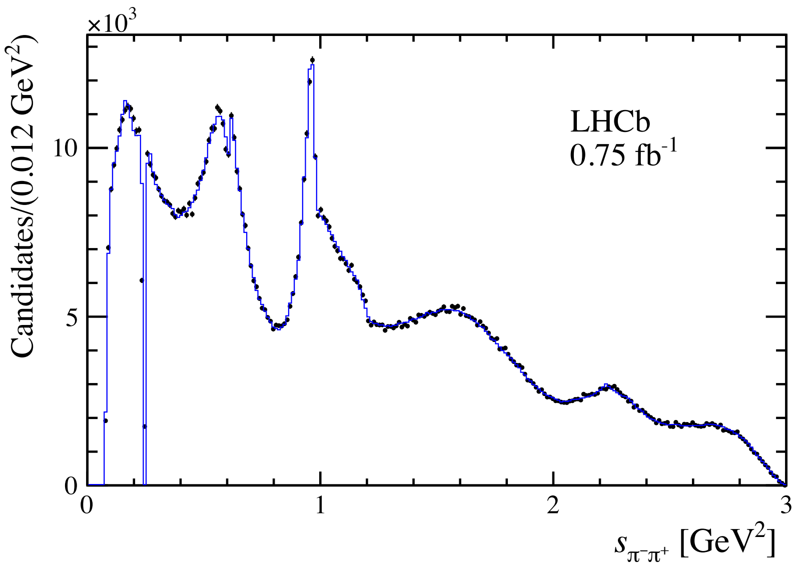
$D^+ \to \pi^+\pi^-\pi^+$

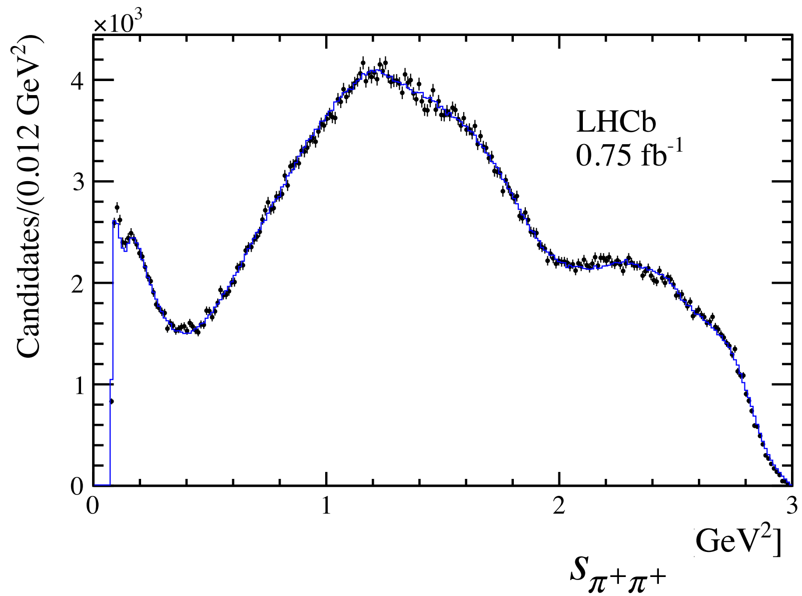




$D^+ \to \pi^+\pi^-\pi^+$ projections

LHCb: JHEP 06 (2023) 044



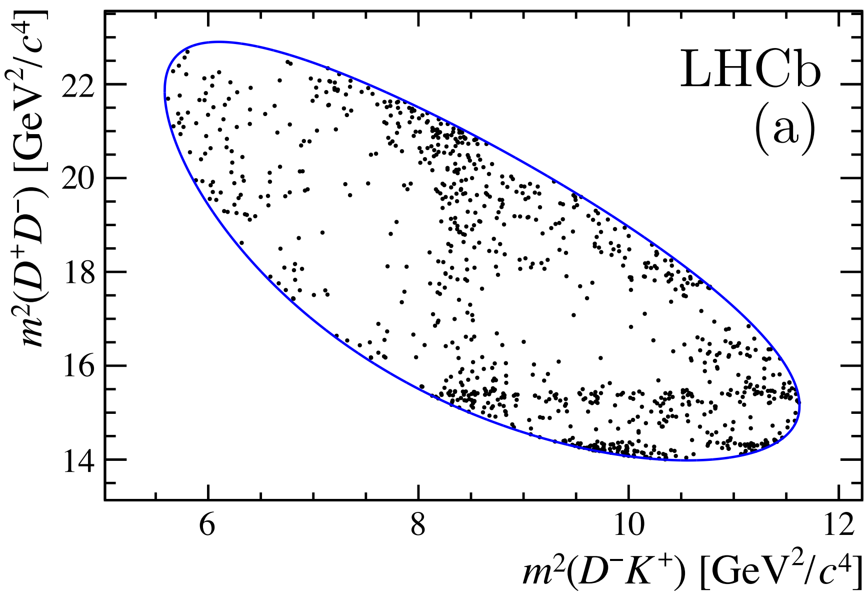


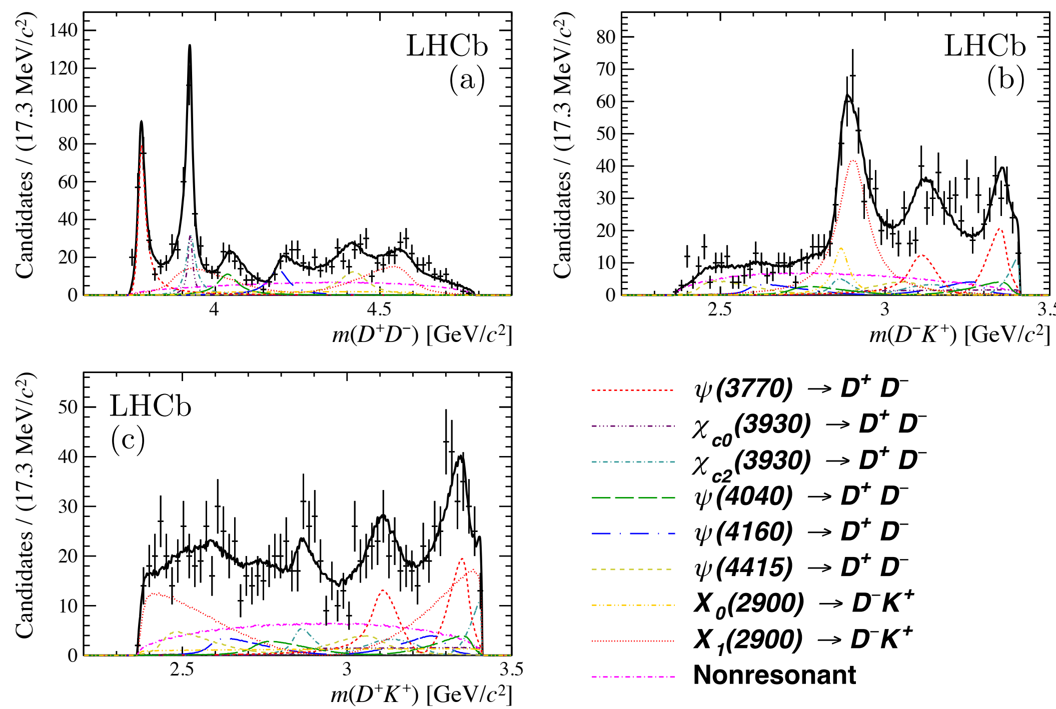
Component	Magnitude	Phase [°]	Fit fraction [%]
$\rho(770)^0\pi^+$	1 [fixed]	0 [fixed]	$26.0 \pm 0.3 \pm 1.6 \pm 0.3$
$\omega(782)\pi^+$	$(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$	$-103.3 \pm 2.1 \pm 2.6 \pm 0.4$	$0.103 \pm 0.008 \pm 0.014 \pm 0.002$
$\rho(1450)^0\pi^+$	$2.66 \pm 0.07 \pm 0.24 \pm 0.22$	$47.0 \pm 1.5 \pm 5.5 \pm 4.1$	$5.4 \pm 0.4 \pm 1.3 \pm 0.8$
$\rho(1700)^0\pi^+$	$7.41 \pm 0.18 \pm 0.47 \pm 0.71$	$-\ 65.7 \pm 1.5 \pm 3.8 \pm 4.6$	$5.7 \pm 0.5 \pm 1.0 \pm 1.0$
$f_2(1270)\pi^+$	$2.16 \pm 0.02 \pm 0.10 \pm 0.02$	$-100.9 \pm 0.7 \pm 2.0 \pm 0.4$	$13.8 \pm 0.2 \pm 0.4 \pm 0.2$
S-wave			$61.8 \pm 0.5 \pm 0.6 \pm 0.5$
$\sum_i \mathrm{FF}_i$			112.8

Really strange: First tetra flavour

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

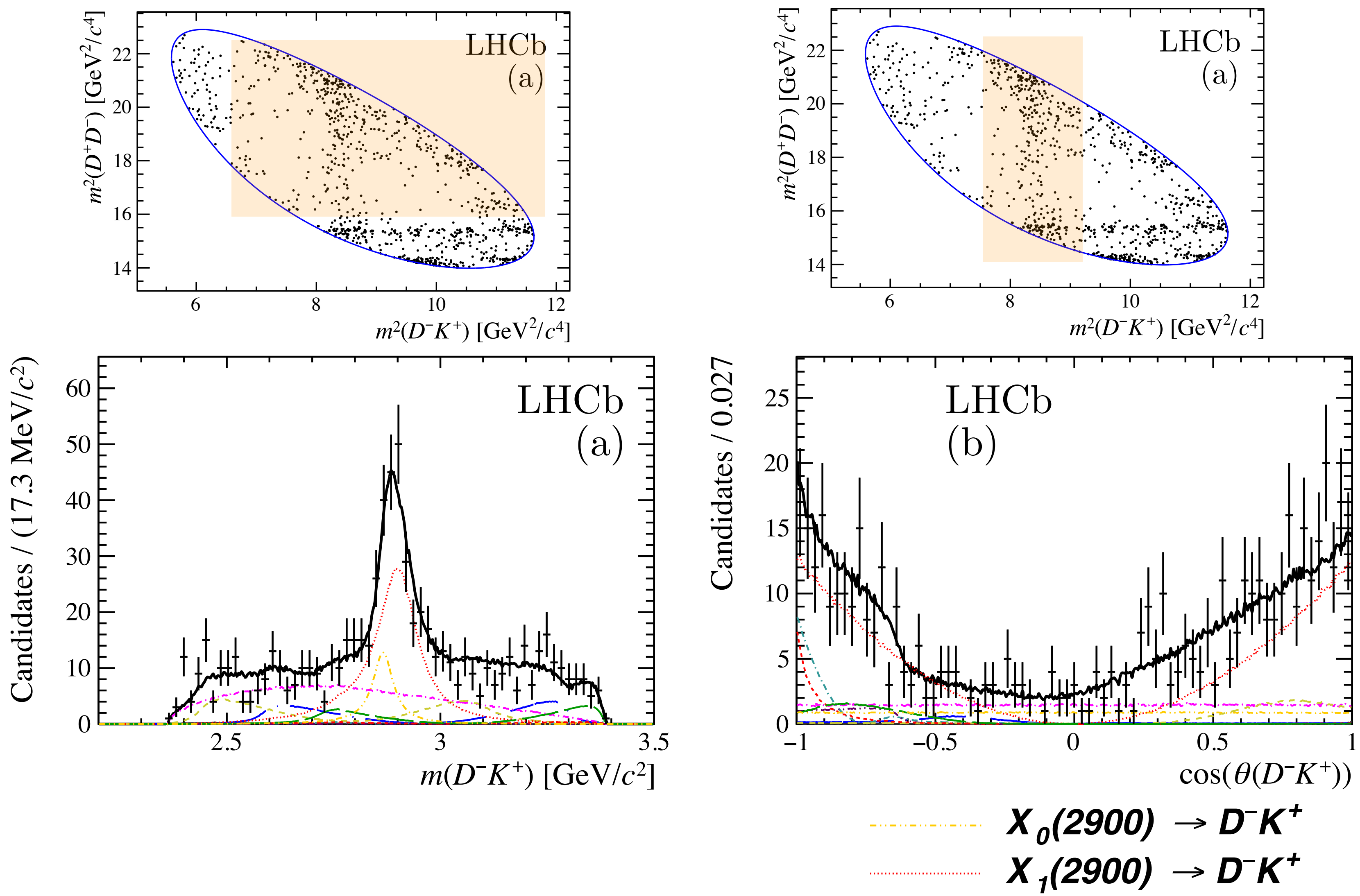
$B^+ \to D^+ D^- K^+$ Dalitz Plot





X(2900) region

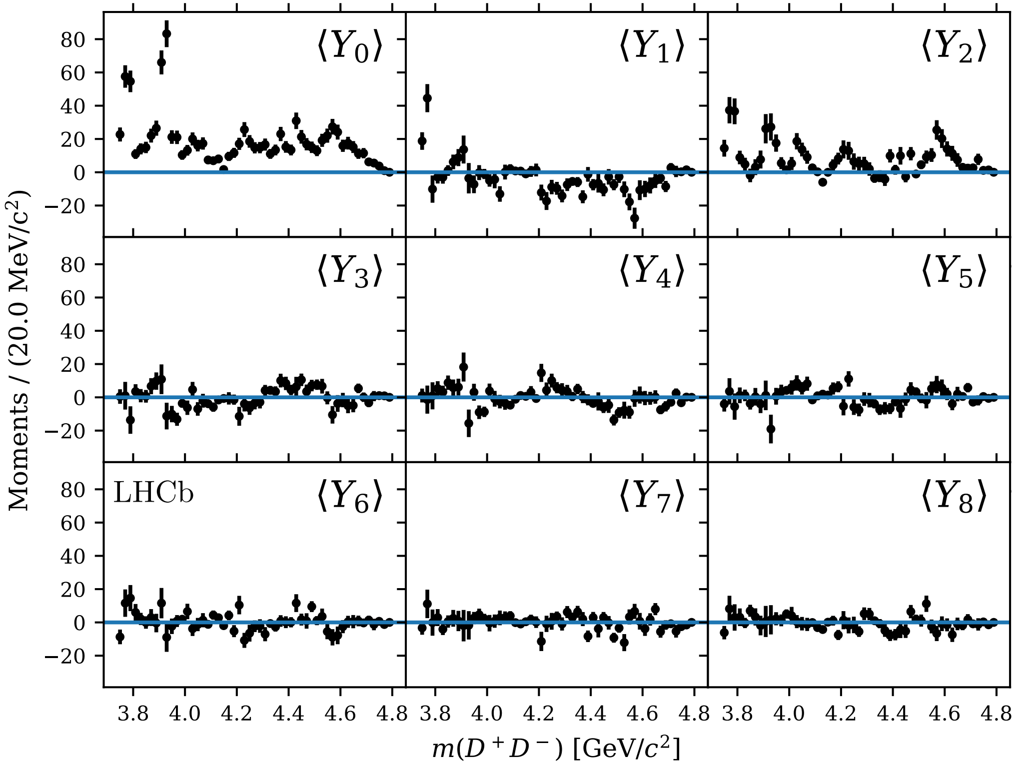
LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003



First tetra flavour confirmation with model-independent analysis.

LHCb: PRL 125 (2020) 242001

$$\langle Y_k^j \rangle = \sum_{l=1}^{N_j^{\mathrm{Data}}} w_l P_k \left(h_l(D^+D^-) \right)$$



Null hypothesis: Charmonium resonances up to spin 2 **can** explain the structure seen in m(DK)

First tetra flavour confirmation with model-independent analysis.

LHCb: PRL 125 (2020) 242001

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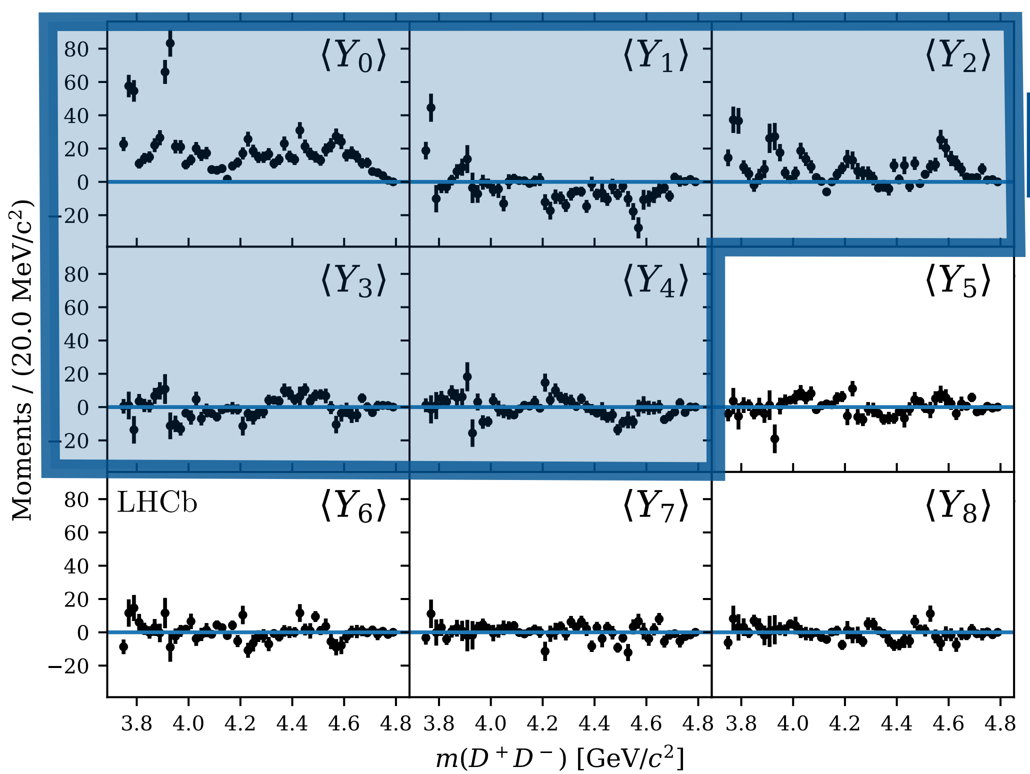

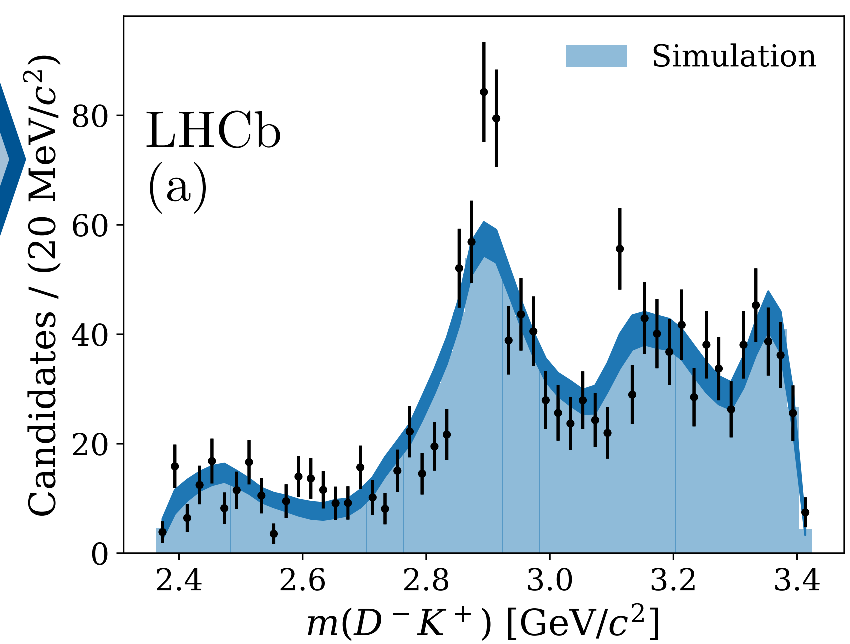

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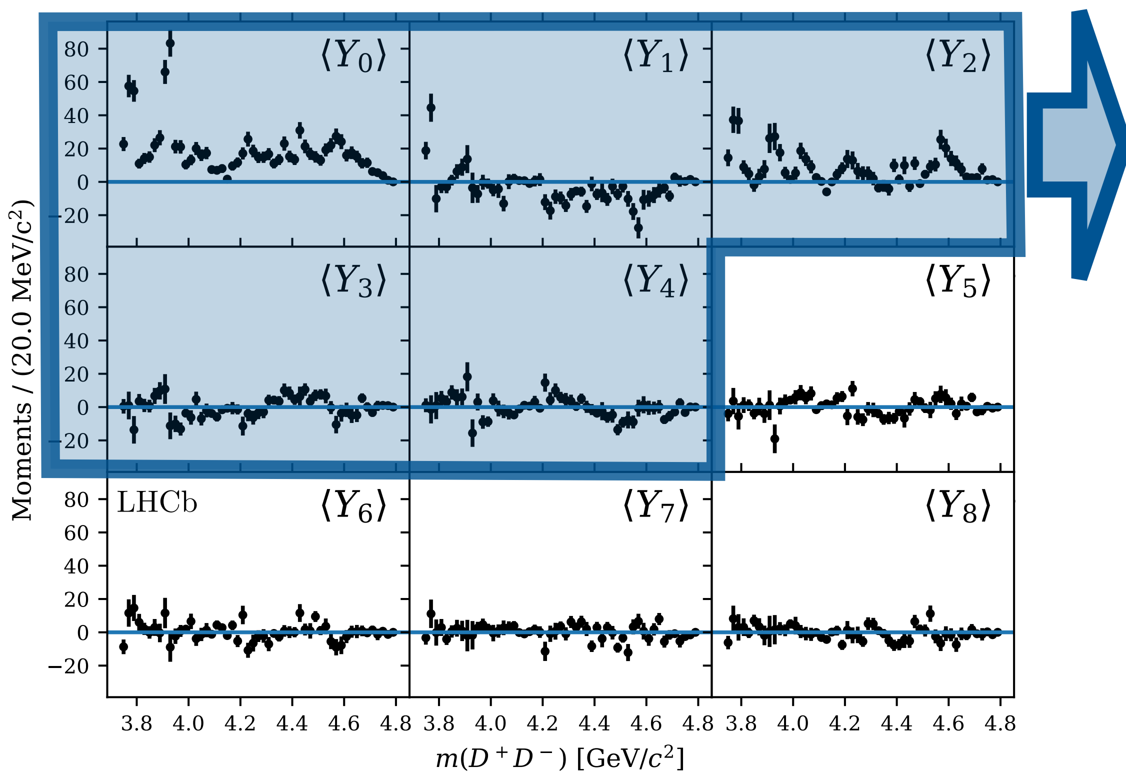

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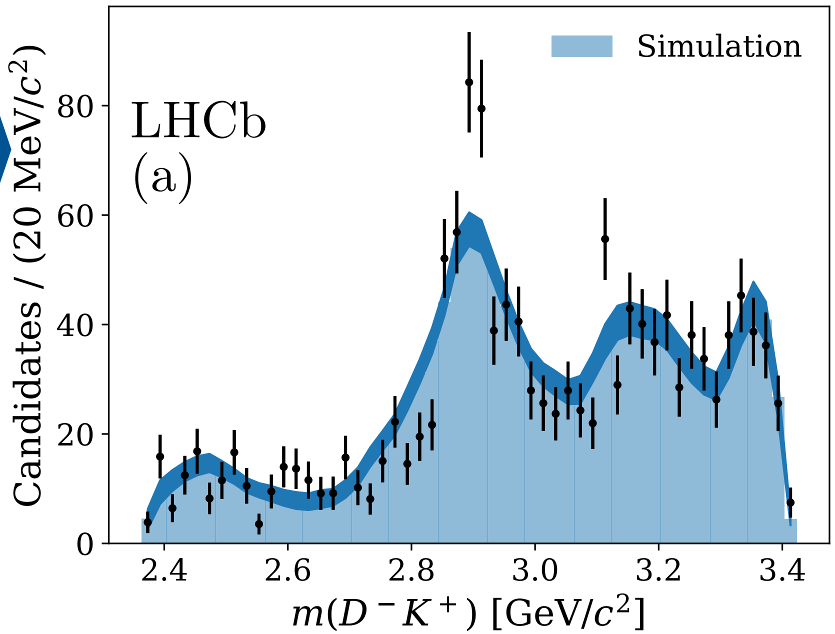
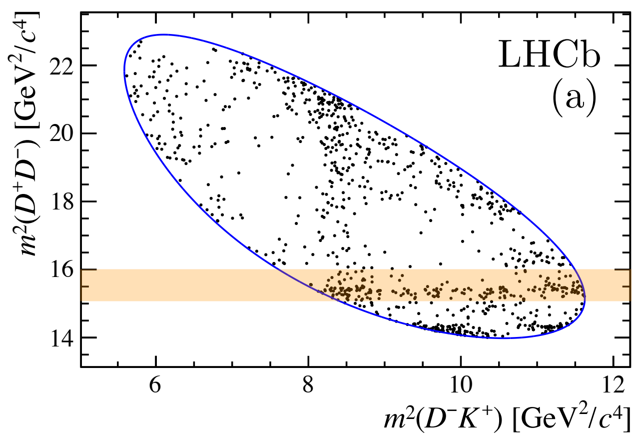
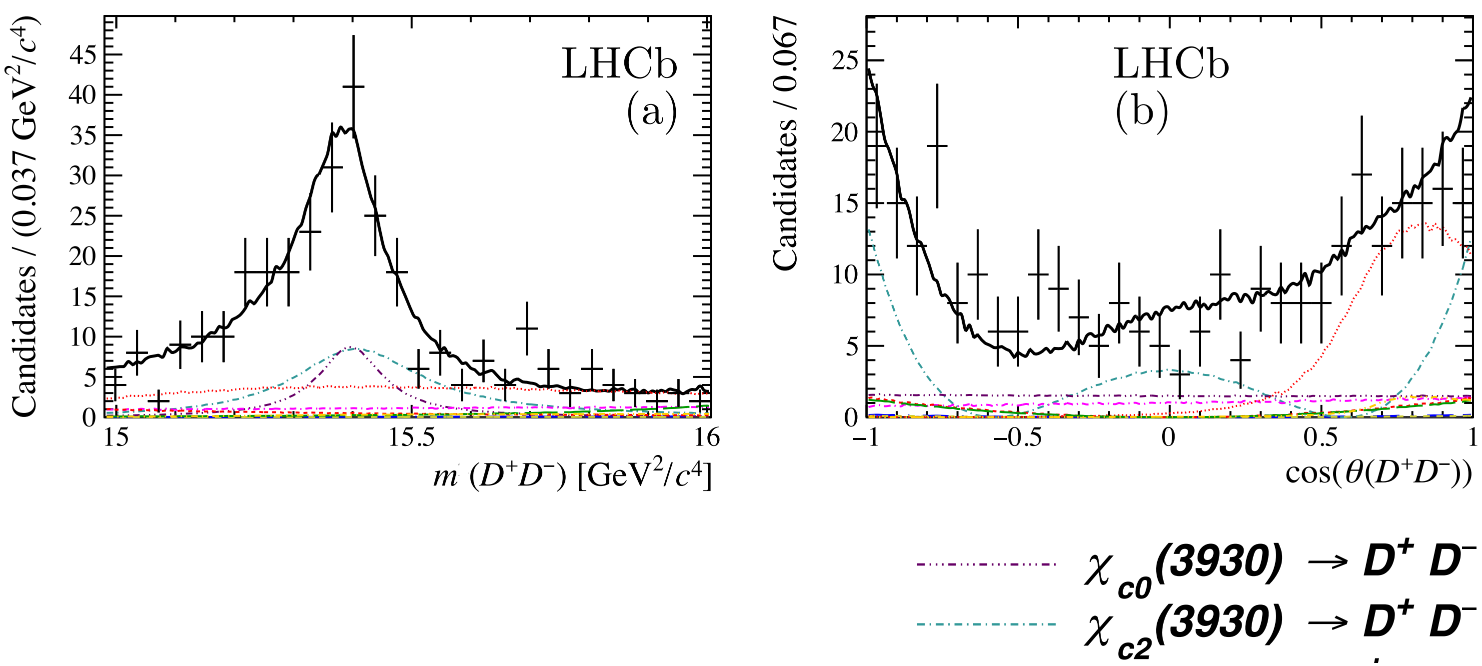


Rejected at 99.994% CL (3.9σ)

$\chi_{cJ}(3930)$ region

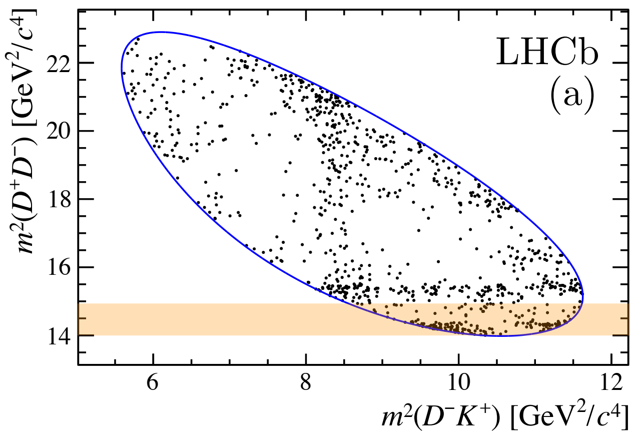
LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

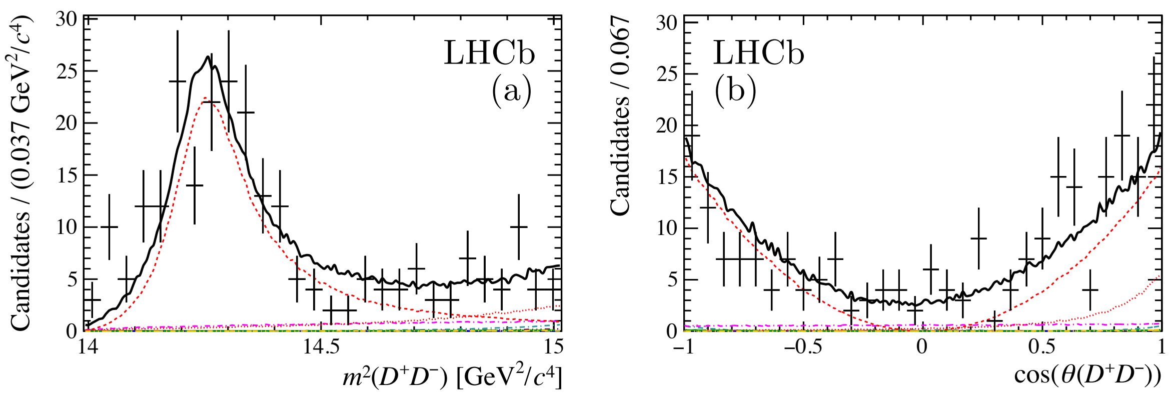




The missing bit

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003





ψ**(3770)** $\rightarrow$ ***D*$^+$ *D*$^-$**

$B^+ \to D^{*\mp} D^{\pm} \pi^+$

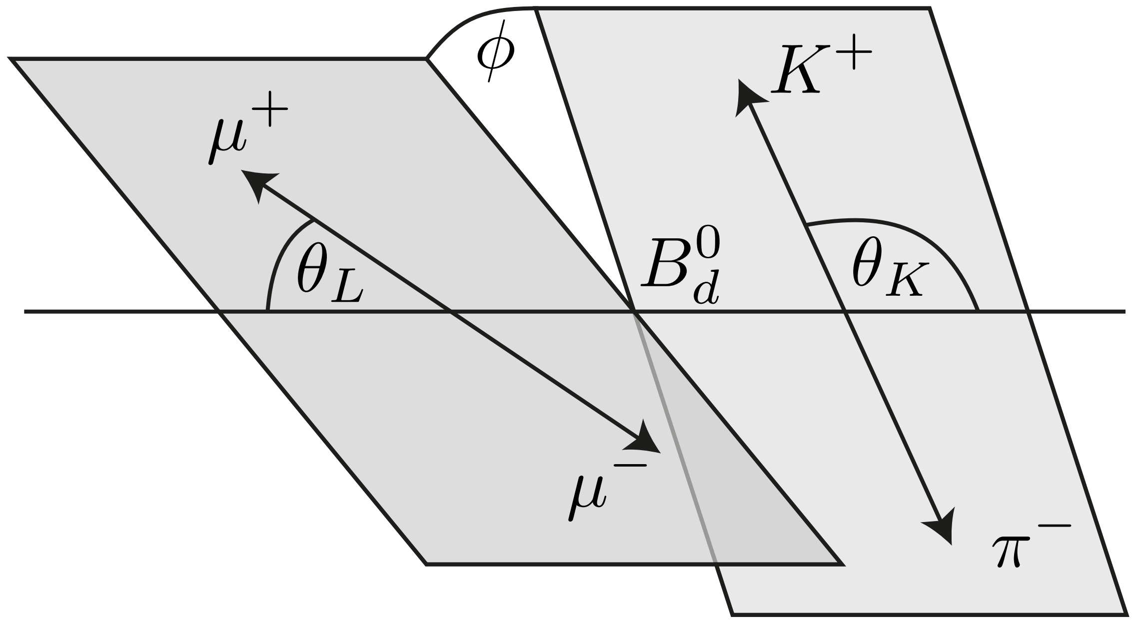
LHCb-PAPER-2023-047

Re-found the $T^*_{cs0,1}(2900)^0$

LHCb-preliminary

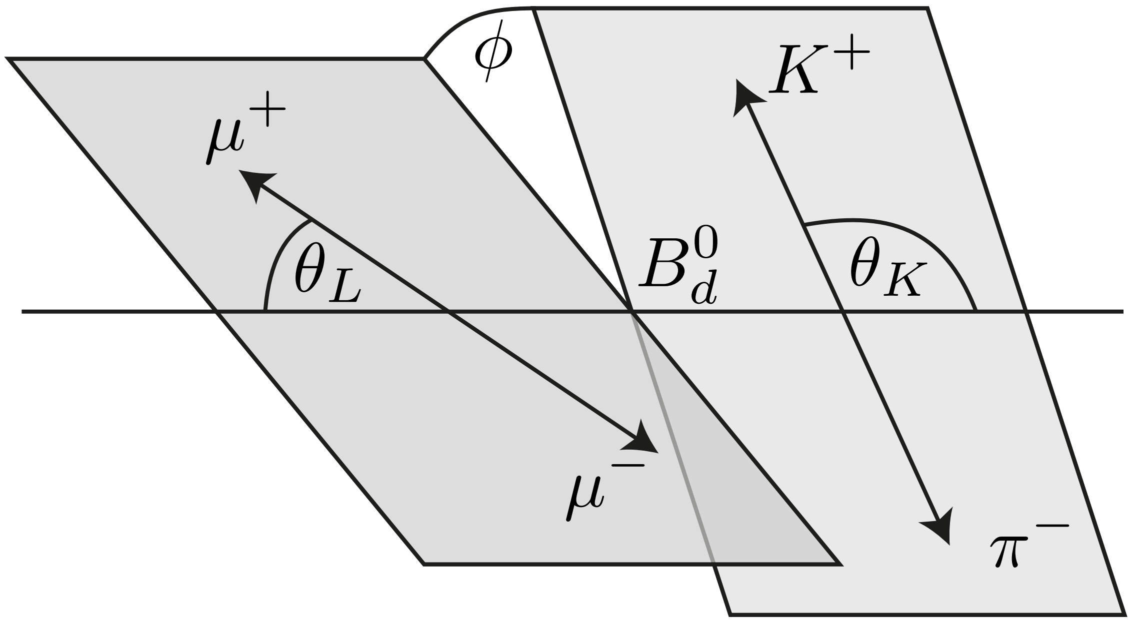
Property	This work	Previous work
$T^*_{cs0}(2900)^0$ mass (MeV)	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{cs0}(2900)^0$ width (MeV)	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{cs1}(2900)^0$ mass (MeV)	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{cs1}(2900)^0$ width (MeV)	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{cs0}(2900)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{cs1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{cs0}(2900)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{cs1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

B→K*μ+μ− and friends, P'5



$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_\mathrm{L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

B→K*μ⁺μ⁻ and friends, P'5



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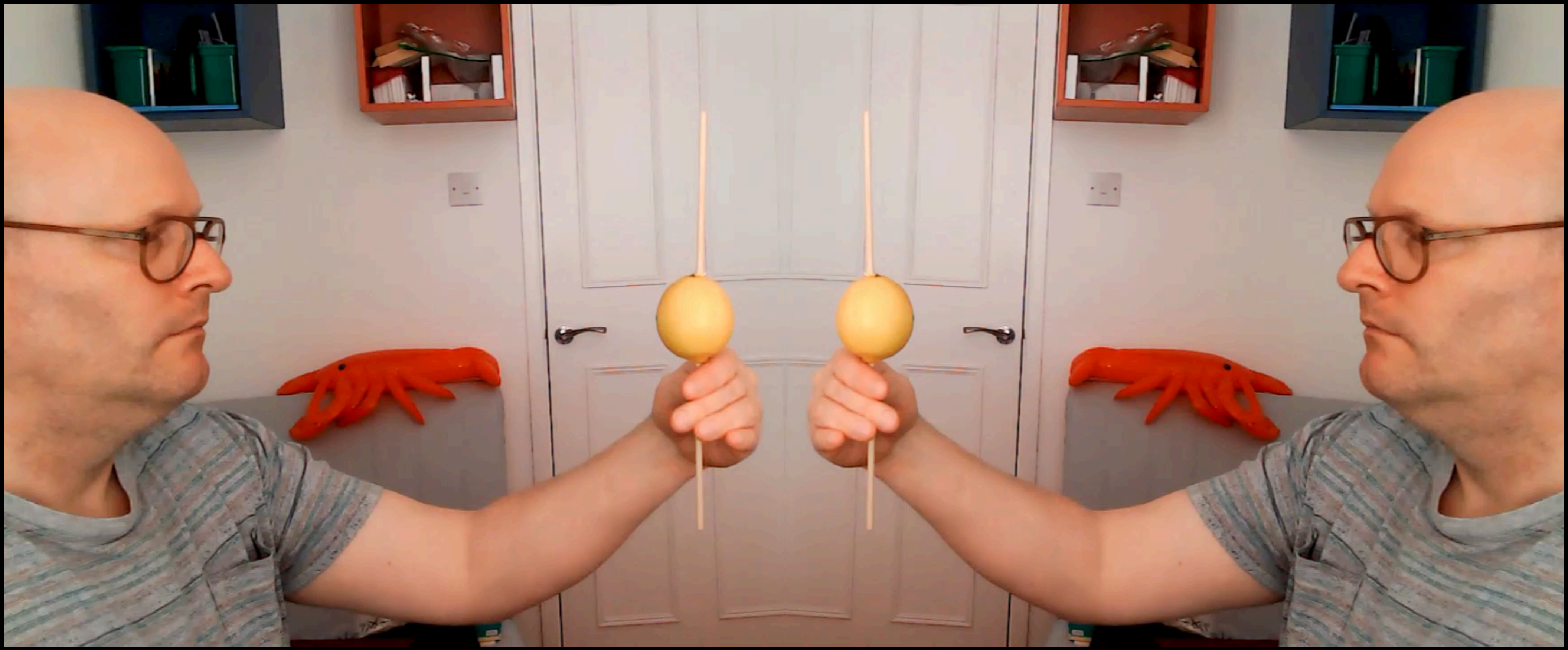
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_{\rm L})A_{\rm T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_{\rm L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_{\rm L}(1-F_{\rm L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_{\rm L})A_{Re}^{\rm T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_{\rm L}(1-F_{\rm L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_{\rm L}(1-F_{\rm L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

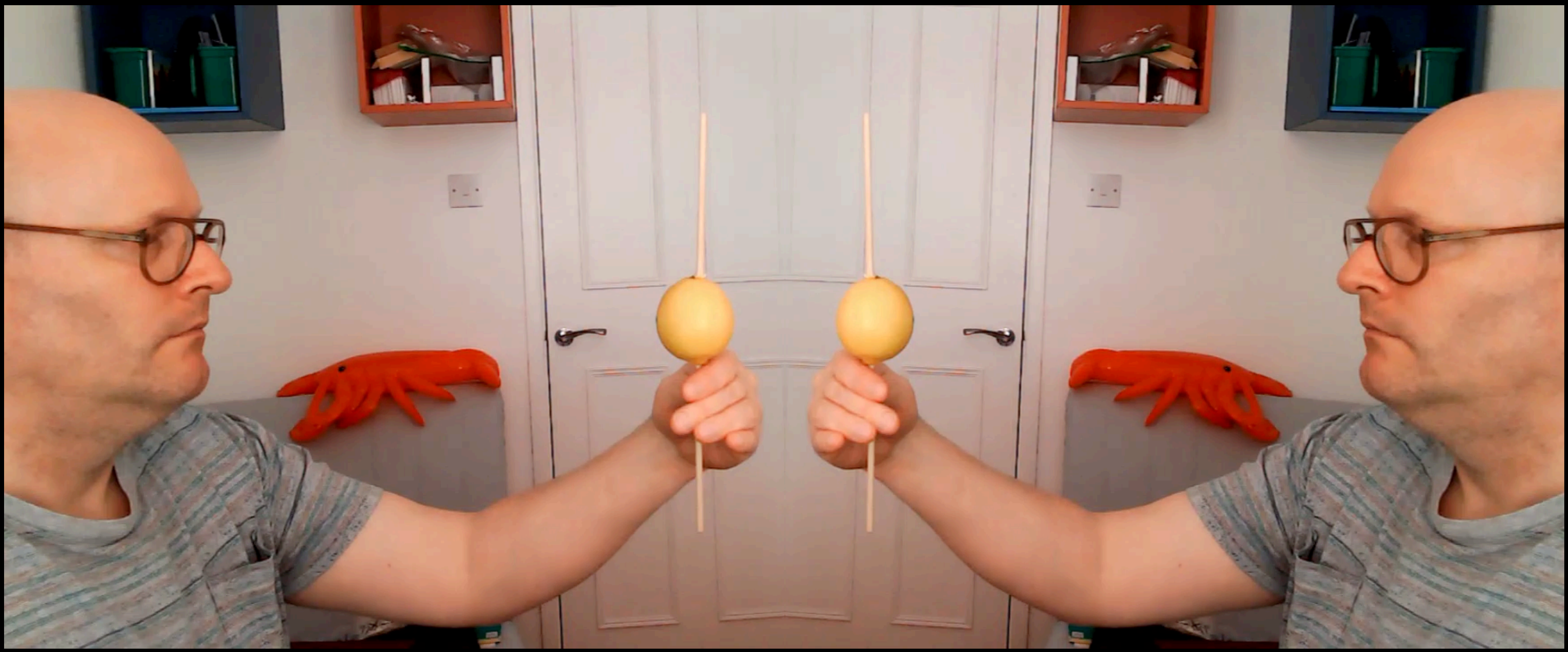
Normal (polar) Vector

Normal (polar) Vector

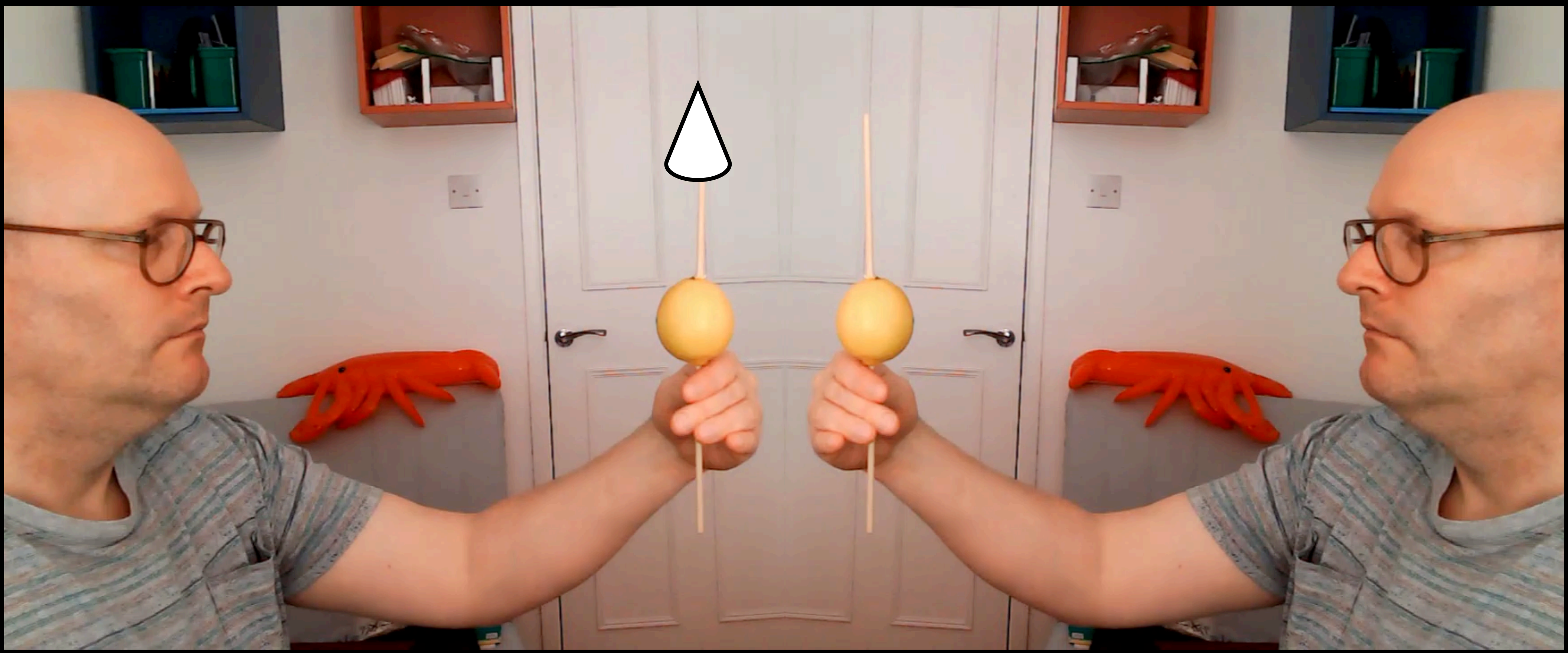
Axial Vector



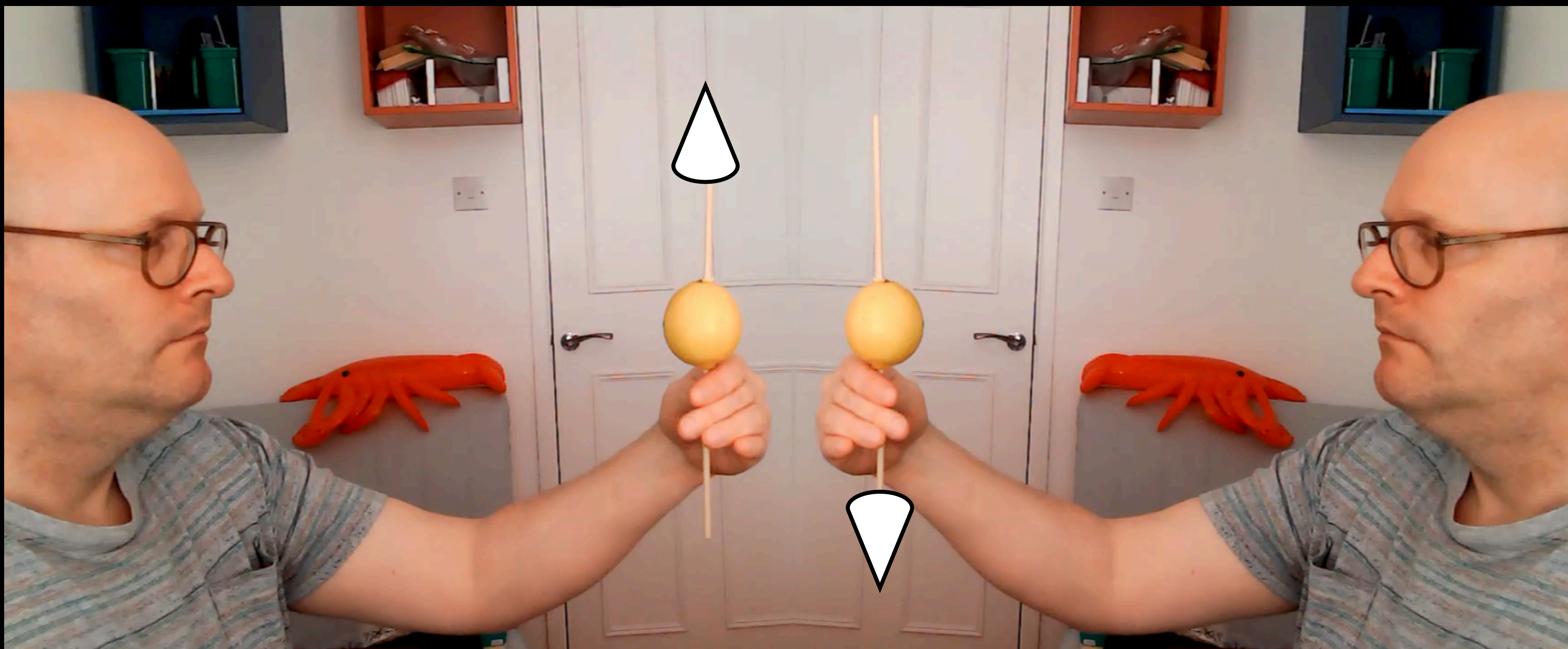
Axial Vector



Axial Vector



Axial Vector

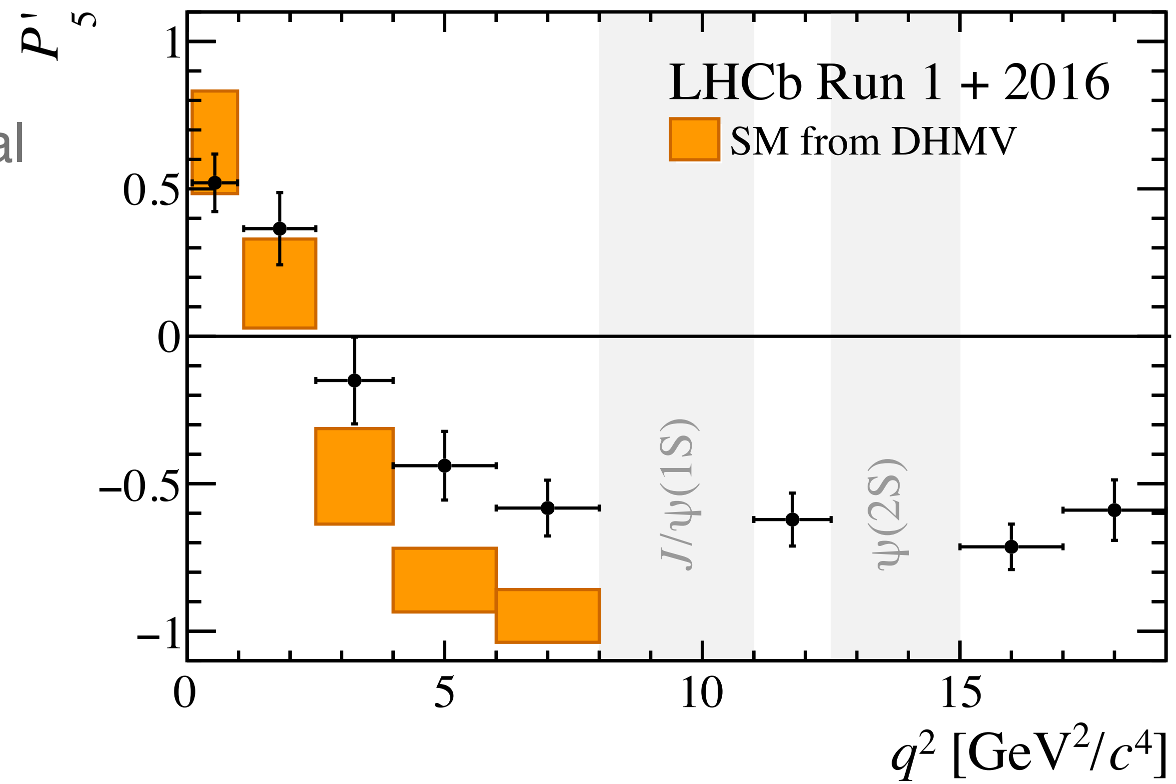


$B \to K^* \mu^+ \mu^-$: P'5

- Describes interference between polar and axial vector currents.
- Deviation from SM: 3.3 σ global significance.
- New Physics?
- Or might it be a miscalculation of non-perturbative QCD?

LHCb: Phys.Rev.Lett. 125 (2020)

Theory: JHEP 05 (2013) 137



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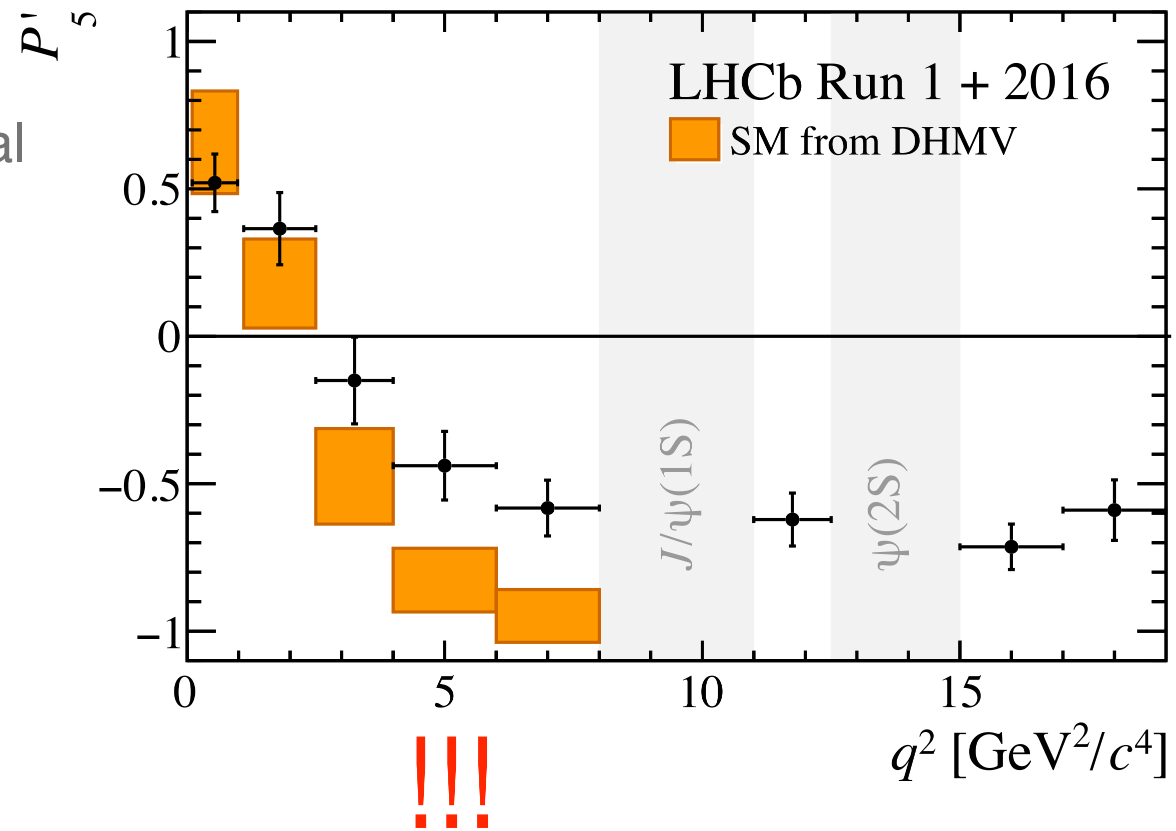
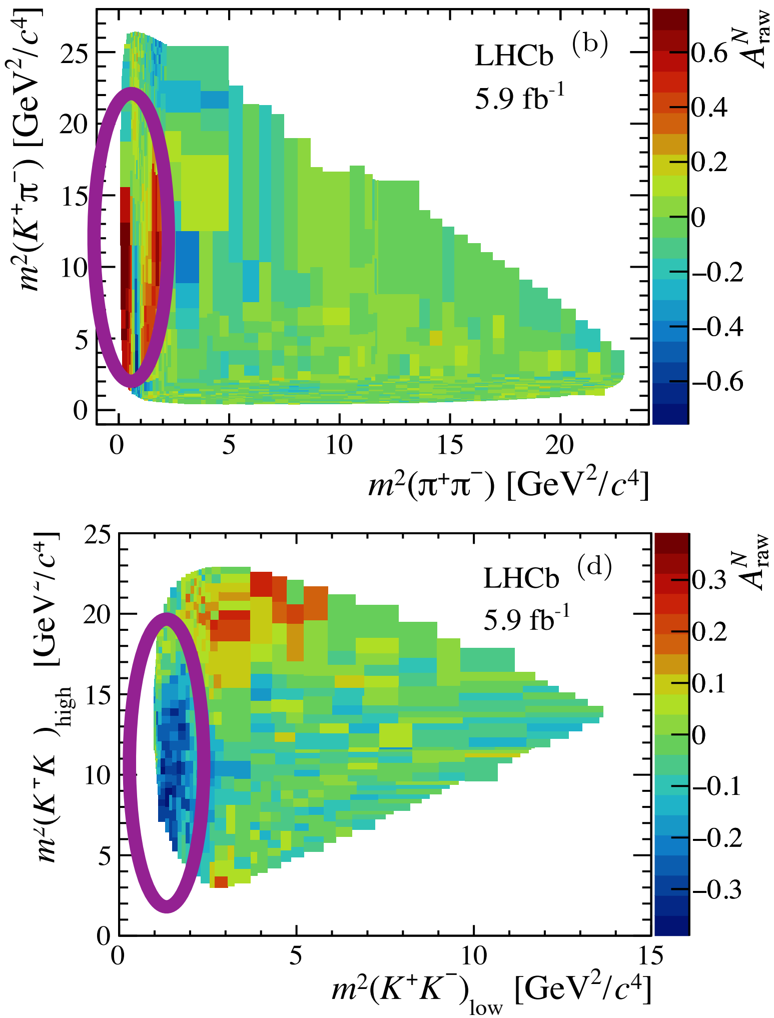


$B^+ \to$ 3 hadrons ($\pi^\pm$ or $K^\pm$)

LHCb: PRD 108 (2023) 1, 012008



What provides the strong phase in $A_{CP} \propto \sin(\Delta\phi_{weak})\ \sin(\Delta\delta_{strong})$?

where the Δ indicates the phase differences between two interfering amplitudes contributing to the process; $\Delta\phi_{weak}$ changes sign under CP, $\Delta\delta_{strong}$ does not.

For low mass region, where large CPV is observed, $KK \leftrightarrow \pi\pi$ re-scattering could play a key role (see Phys.Rev.D 89 (2014) 9, 094013)