Recent results from LHCb

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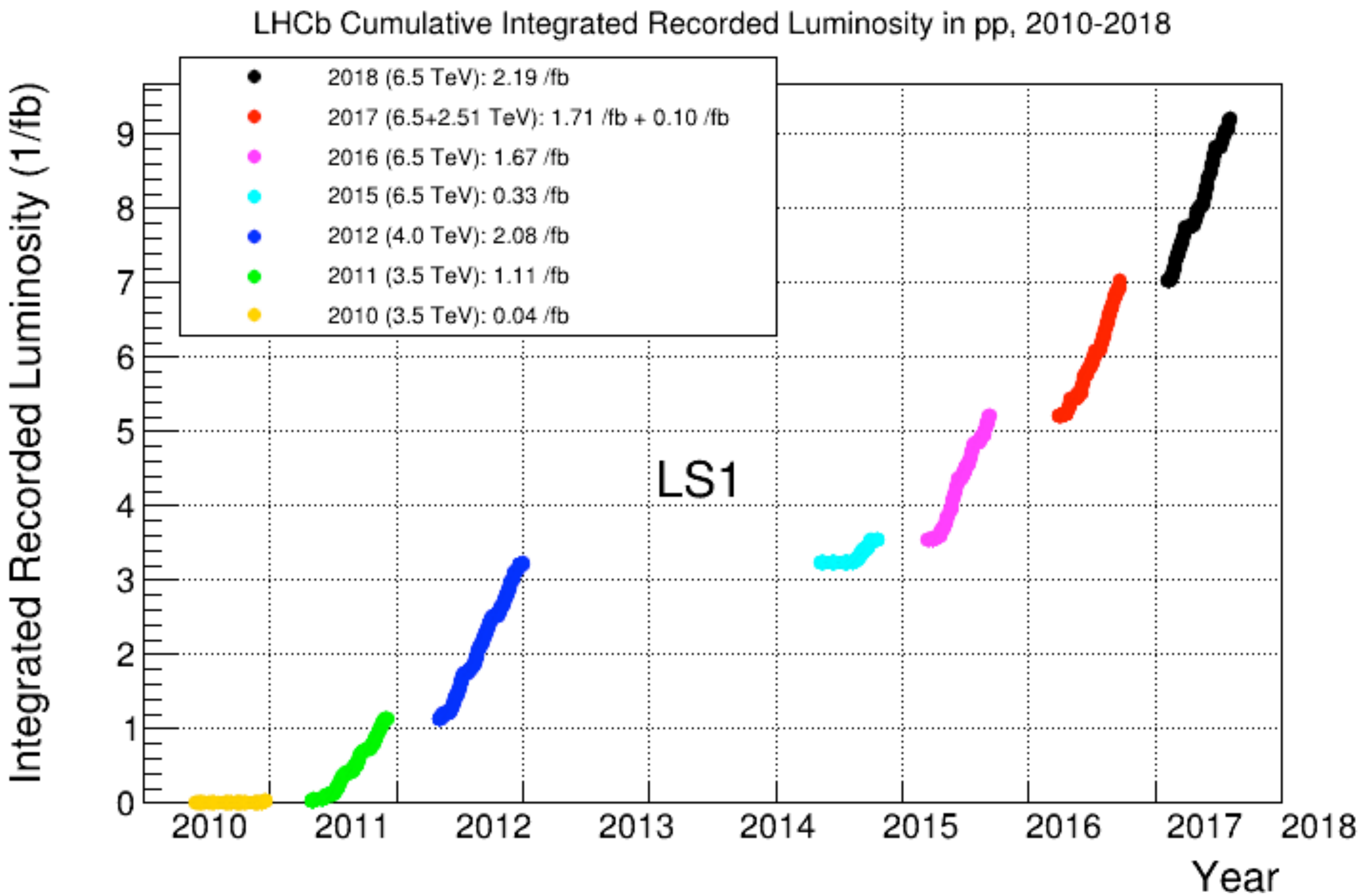
News from the pit:

Run 2 is over: 9.2 fb^{-1} of *pp* data on disk!

Large samples of *p-Pb* and *Pb-Pb* data



Outline

beauty

- Measurement of the CKM angle γ
- Amplitude analysis of $B^0 \to K^0_S \pi^+ \pi^-$

charm - mesons

- Branching fractions of doubly Cabibbo-suppressed decays of $D^+_{(s)}$ mesons
- Dalitz plot analysis of $D^+ \to K^- K^+ K^+$
- Measurement if the charm-mixing parameter y_{CP}

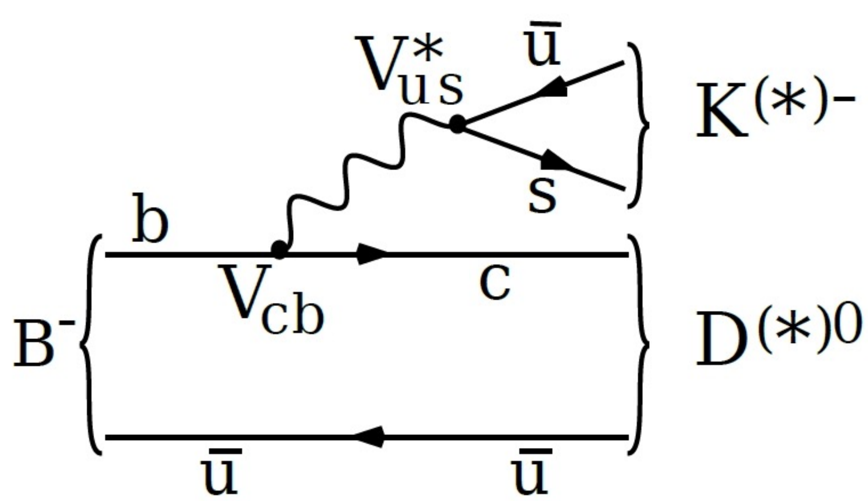
charm - baryons

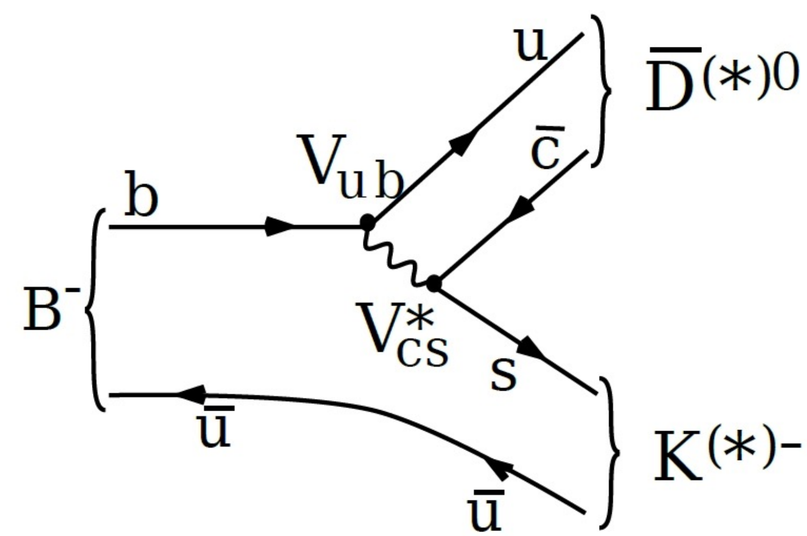
- Charm-baryon spectroscopy with Dp final states
- Measurement of the Ω^0_c lifetime
- Measurement of the Ξ^{++}_{cc} lifetime

beauty

The UT angle γ is the only CP-violating parameter that can be measured using only tree-level decays: an essential benchmark!

$B \to DK$





γ determined from interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ with negligible theoretical uncertainty

several different methods, depending on the D-meson decay

$$D^0 \to \underbrace{K^-K^+,\ \pi^-\pi^+}_{\text{GLW: CP eigenstates}},\ \underbrace{K^+\pi^-,\ K^+\pi^-\pi^+\pi^-}_{\text{ADS: DCS}},\ \underbrace{K_S^0\pi^+\pi^-, K_s^0K^+K^-}_{\text{GGSZ: Dalitz plot}}$$

Best sensitivity obtained combining different methods and decays:

$$B^\pm \to DK^\pm,\quad B^\pm \to D^*K^\pm,\quad B^\pm \to DK^{*\pm}, B^0 \to DK^{*0},\ \cdots$$

Measurement of the CKM angle γ using $B^{\pm} \to DK^{\pm}$ with $D \to K^0_S\pi^+\pi^-,\ K^0_S K^+ K^-$ JHEP **08** (2018) 176

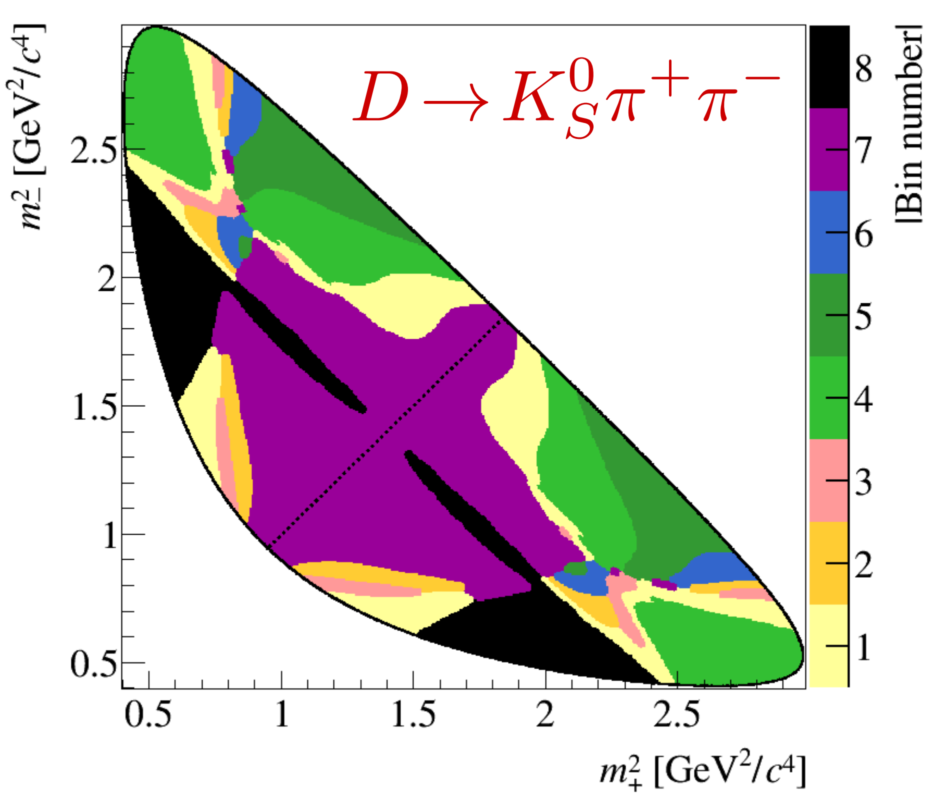
- The amplitude for $B^- \to [K^0_S h^+ h^-]_D K^-$:

$$A_{B^-} \propto A_D(m^2_-, m^2_+) + r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}(m^2_-, m^2_+)$$

- The Dalitz plot density :

$$\frac{d\Gamma}{dm^2_-\, dm^2_+} = A^2_D(m^2_-, m^2_+) + r^2_B A^2_D(m^2_+, m^2_-) + \boxed{2r_B\ \mathrm{Re}[A_D(m^2_-, m^2_+) A^*_D(m^2_+, m^2_-)\ e^{-i(\delta_B - \gamma)}]}$$

symmetric w.r.t $m_+ = m_-$, $m_{\pm} \equiv m(K^0_S h^{\pm})$



- model-independent analysis: strong phase in bins of the Dalitz plot from CLEO-c
  PRD **82** (2010) 112006
- Bins designed for optimal sensitivity to γ
- $B \to D^{*\pm}\mu^{\mp}\nu_{\mu}X,\ B^{\pm} \to D\pi^{\pm}$: control channels

- The Dalitz plot is divided into 2n bins, from $i=-n$ to $i=+n$. The populations of bins $\pm i$ are

$$N^+_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

$$N^-_{\pm i} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

normalization factors ($h_{B^\pm}$)

fraction of decays in bins $\pm i$ (F)

strong phases from CLEO-c ($c_{\pm i}$, $s_{\pm i}$)

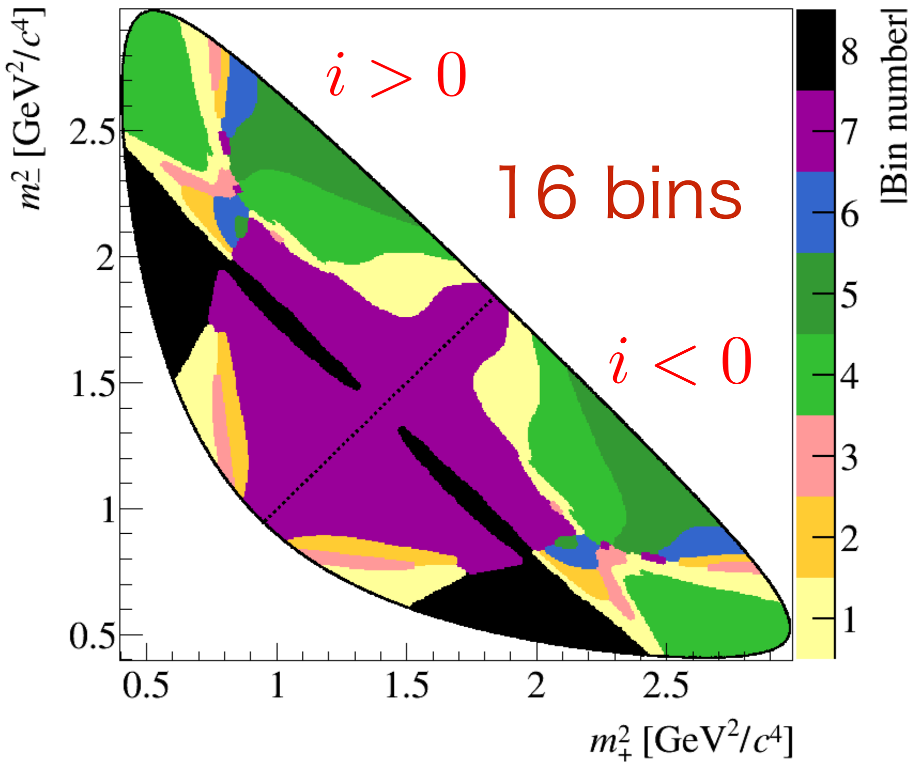
$$F_i = \frac{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)}{\sum_j \int_j dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)}$$

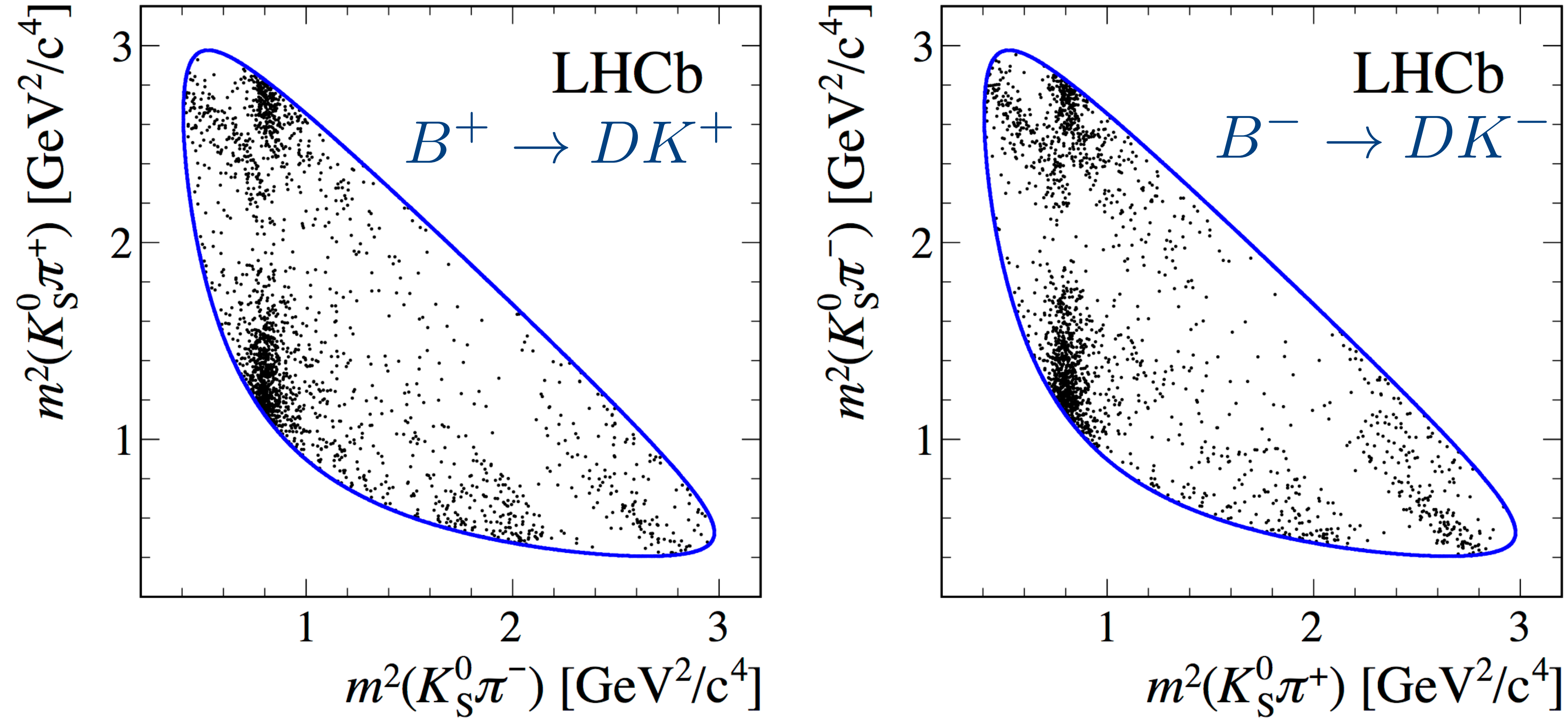
from $B \to D^{*\pm}\mu^{\mp}\nu_\mu X$ with $D^{*+}\to D^0\pi^+,\ D^0 \to K_S^0\pi^+\pi^+$

$$c_i \equiv \frac{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)||A_D(m_+^2, m_-^2)| \cos[\delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)]}{\sqrt{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2 \int_i dm_-^2\, dm_+^2\, |A_D(m_+^2, m_-^2)|^2}}$$

$\gamma,\ r_B,\ \delta_B$ translated into $x_\pm \equiv r_B \cos(\delta_B \pm \gamma),\quad y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$

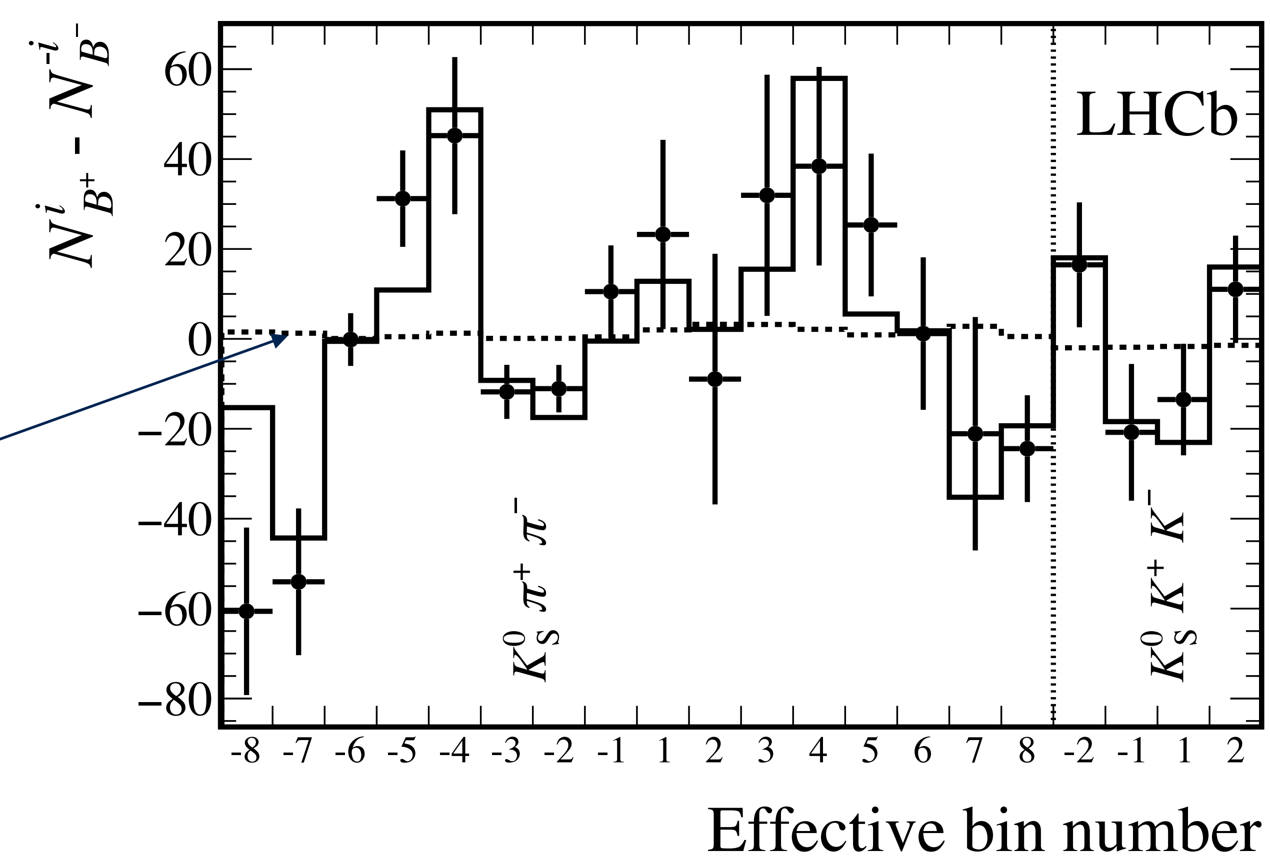
$D \to K^0_S\pi^+\pi^-$ ($\sim 3.8K$ $B^\pm$ candidates)





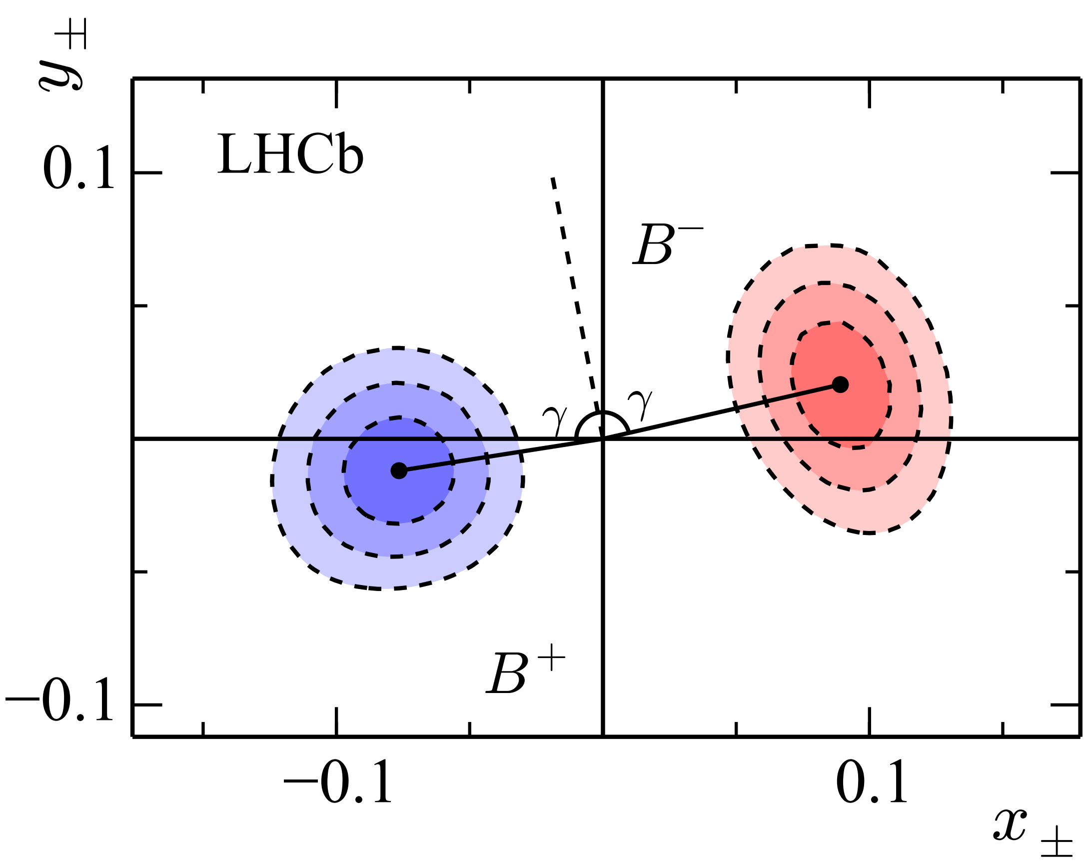
JHEP **08**, 176

- $B^\pm \to DK^\pm$ yields determined independently as a cross-check, and compared to the nominal fit
- data fitted assuming no CPV
  $x_+ = x_- \equiv x_0, \quad y_+ = y_- \equiv y_0$
- p-value of 2x10^{-6} disfavours CP-conserving hypothesis



Results from Run II

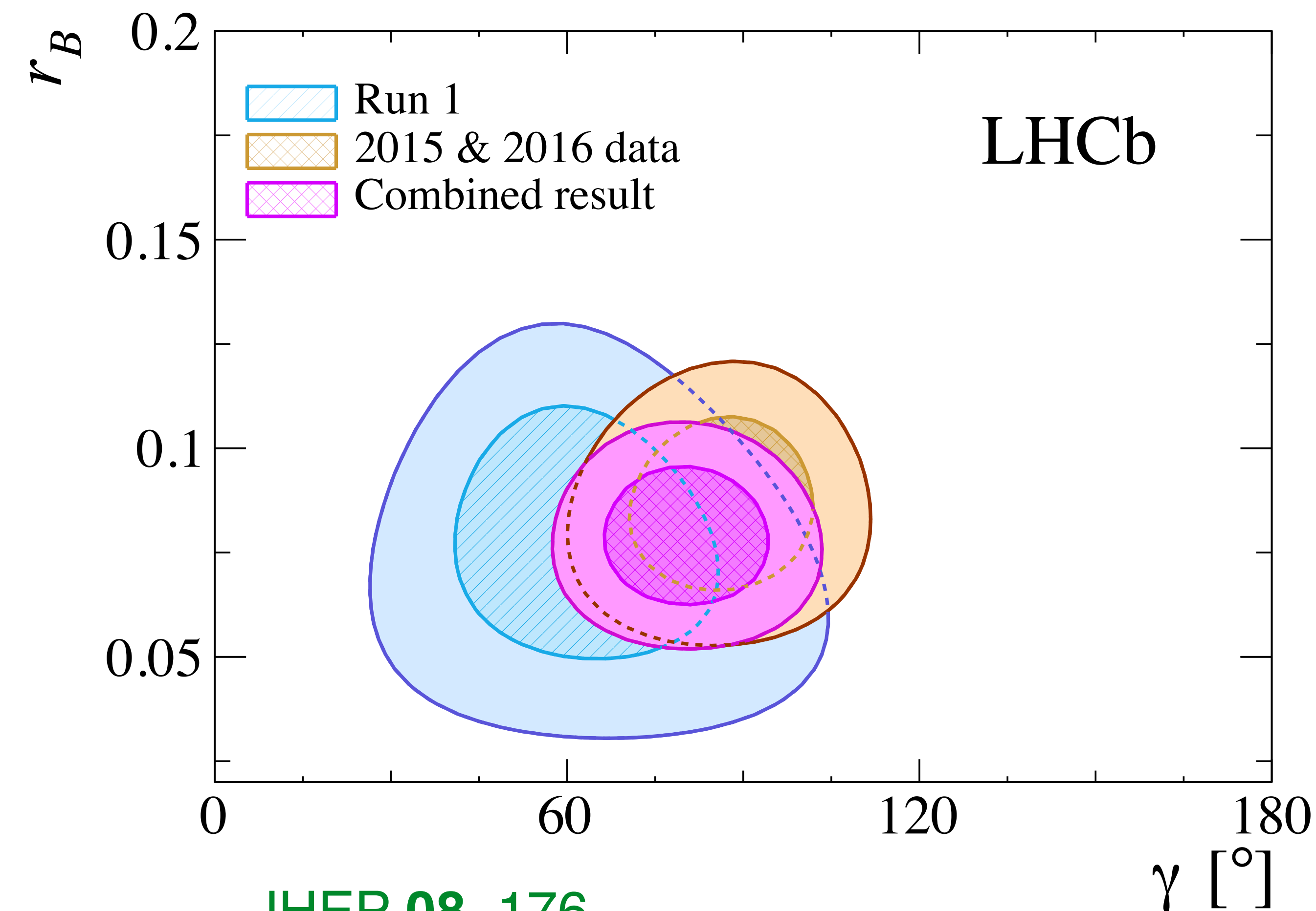
$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$



$$|(x_+, y_+) - (x_- y_-)| = (17.0 \pm 2.7) \times 10^{-2}$$

6.4σ : first observation of CPV in $B^\pm \to DK^\pm$ with $D^0 \to K^0_S h^+ h^-$

Combining Run I + II



JHEP **08**, 176

$$\gamma = 80^\circ\ {}^{+10^\circ}_{-9^\circ}\ \left({}^{+19^\circ}_{-18^\circ}\right)$$

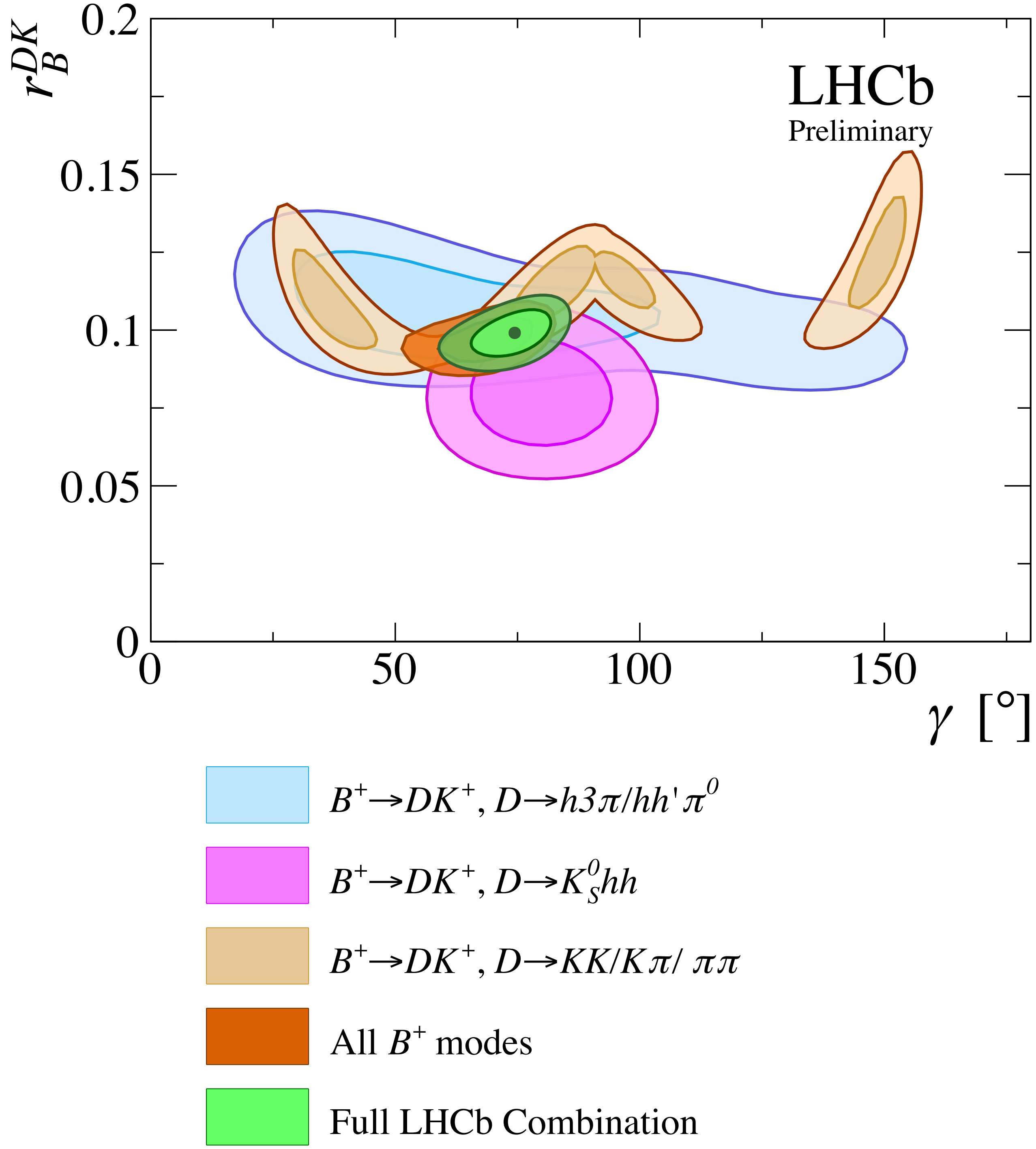
$$r_B = 0.080\ {}^{+0.011}_{-0.011}\ \left({}^{+0.022}_{-0.023}\right)$$

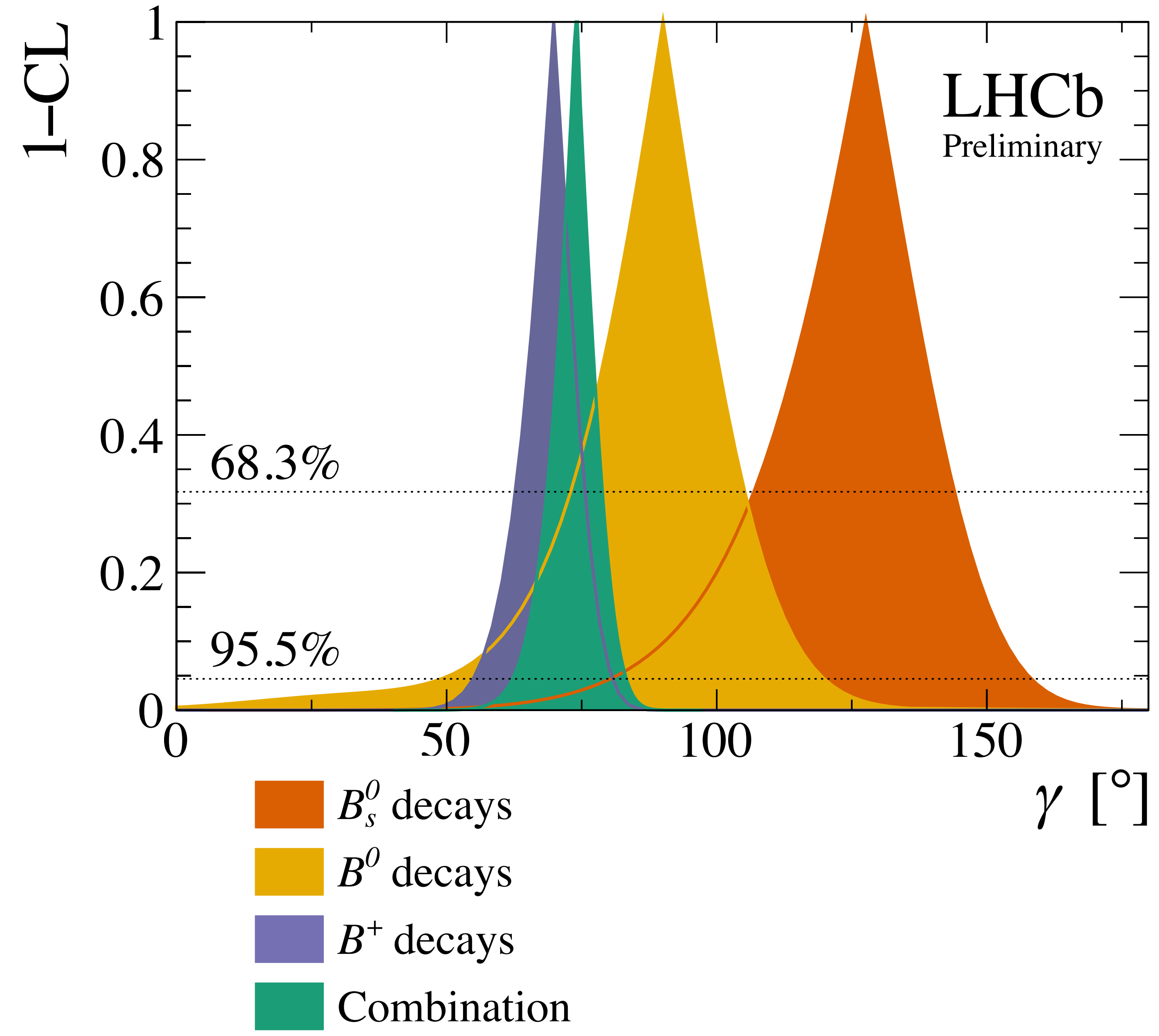
$$\delta_B = 110^\circ\ {}^{+10^\circ}_{-10^\circ}\ \left({}^{+19^\circ}_{-20^\circ}\right)$$

breaking down results by methods illustrates the power of combination

LHCb-CONF-2018-002

γ combination driven by $B^{\pm} \to D^{(*)} K^{(*)\pm}$





$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$$

Amplitude Analysis of the Decay $\bar{B}^0 \to K_S^0\pi^+\pi^-$ and First Observation of the CP Asymmetry in $\bar{B}^0 \to K^*(892)^-\pi^+$

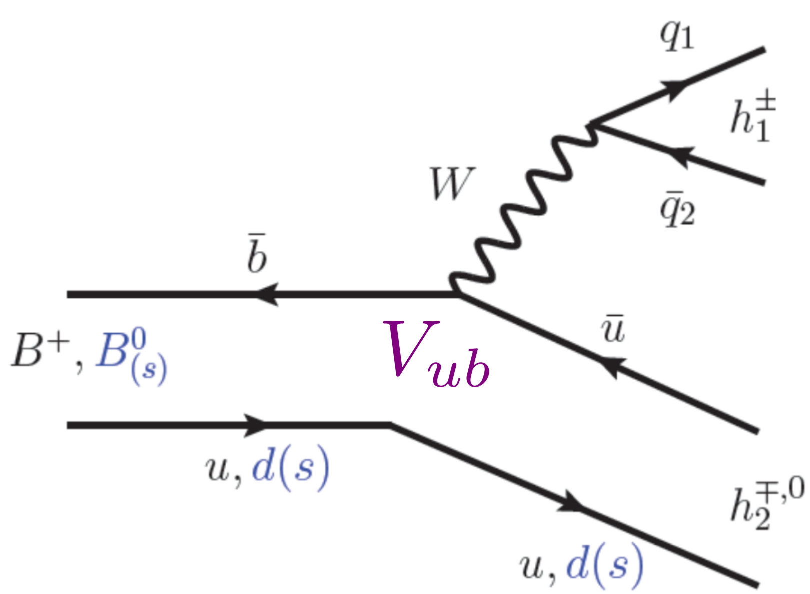
PRL 120 (2018), 261801

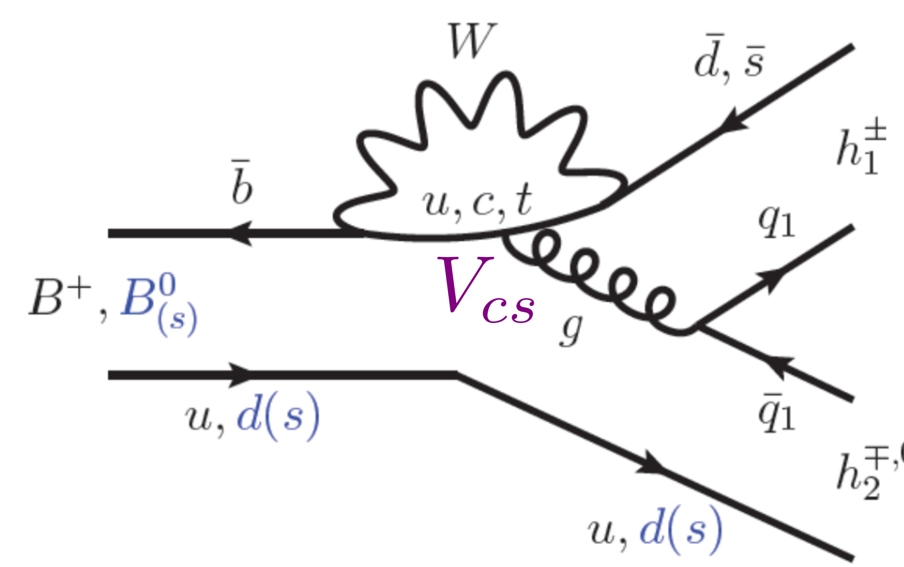
Same diagrams for

$B^0 \to K_S^0\pi^+\pi^-$,

$B^+ \to K^+\pi^0$,

$B^0 \to K^+\pi^-$





amplitudes with similar magnitudes: sizable *CP* violation expected

The $K\pi$ "puzzle":

$$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.006$$

$$A_{CP}(B^+ \to K^+\pi^0) = +0.040 \pm 0.021$$

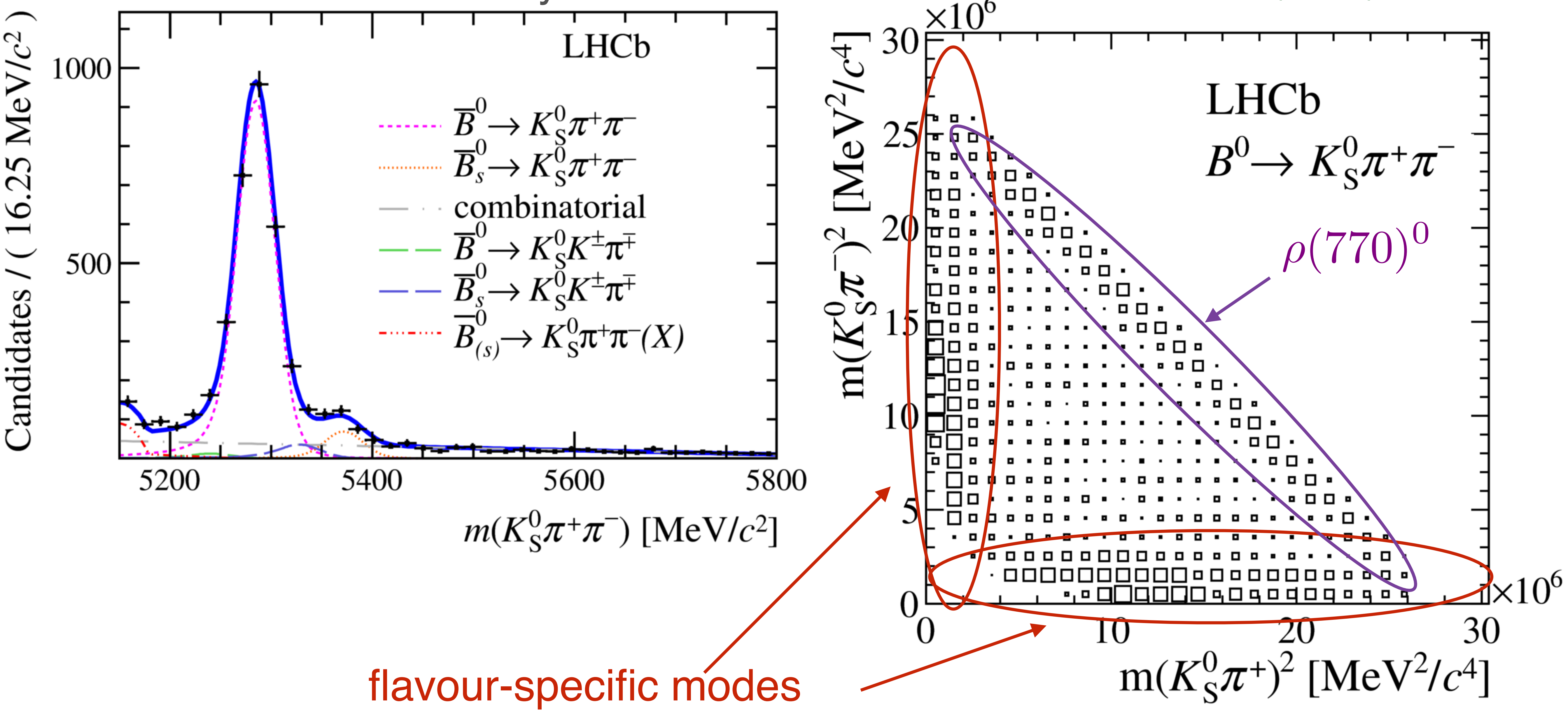
From QCD factorisation: *CP* asymmetries expected to be similar

At present, statistics is not large enough for tagged, time-dependent Dalitz plot fit

Time-integrated, untagged $(B^0 + \overline{B}^0)$ analysis (tagging eff. only ~5%)

~3 200 decays

PRL 120 (2018), 261801



Decay amplitude parameterised by the isobar model:

$$A = \sum c_k F_k(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-})$$

$$\overline{A} = \sum \bar{c}_k F_k(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-})$$

$F_k \rightarrow$ *CP*-conserving

$c_k \neq \bar{c}_k \rightarrow$ *CP* violation

neglecting the yet unobserved *CP* violation in mixing:

$$\mathcal{S}_{\rm pdf} \propto |A(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-})|^2 + |\overline{A}(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-})|^2$$

for flavour-specific quasi two-body modes:

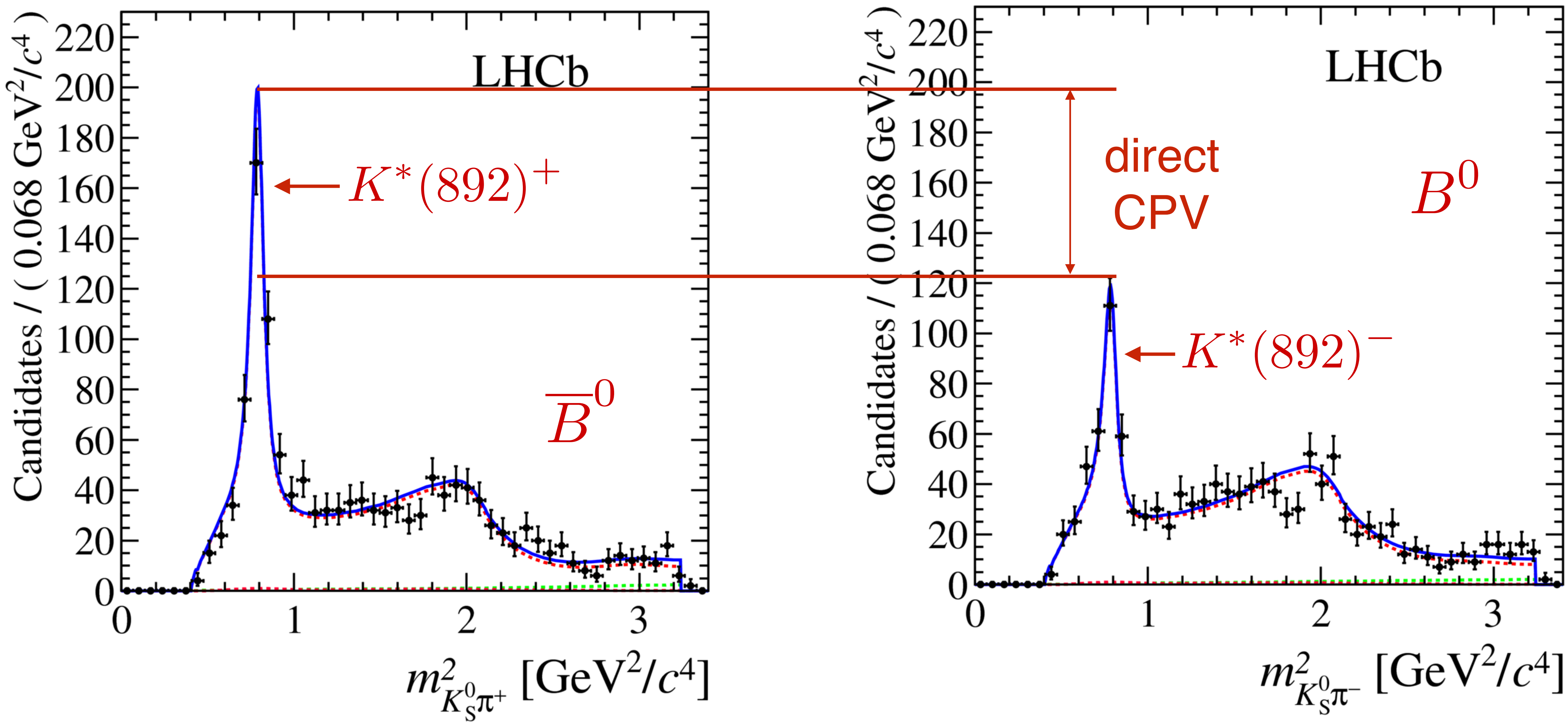
$$\mathcal{A}_{\rm raw} = \frac{|\bar{c}_k|^2 - |c_k|^2}{|\bar{c}_k|^2 + |c_k|^2}$$

$$\mathcal{A}_{CP} = \mathcal{A}_{\rm raw} - \mathcal{A}_{\rm det}(\pi^\pm) - \mathcal{A}_{\rm prod}(B^0/\overline{B}^0)$$

The model for the decay amplitude

flavour-specific modes

Resonance	Parameters	Lineshape	Value references
$K^*(892)^-$	$m_0 = 891.66 \pm 0.26$ $\Gamma_0 = 50.8 \pm 0.9$	RBW	[27]
$(K\pi)_0^-$	$\mathcal{R}e(\lambda_0) = 0.204 \pm 0.103$ $\mathcal{I}m(\lambda_0) = 0$ $\mathcal{R}e(\lambda_1) = 1$ $\mathcal{I}m(\lambda_1) = 0$	EFKLLM [28]	[28]
$K_2^*(1430)^-$	$m_0 = 1425.6 \pm 1.5$ $\Gamma_0 = 98.5 \pm 2.7$	RBW	[27]
$K^*(1680)^-$	$m_0 = 1717 \pm 27$ $\Gamma_0 = 332 \pm 110$	Flatté [29]	[27]
$f_0(500)$	$\mathrm{m}_0 = 513 \pm 32$ $\Gamma_0 = 335 \pm 67$	RBW	[30]
$\rho(770)^0$	$m_0 = 775.26 \pm 0.25$ $\Gamma_0 = 149.8 \pm 0.8$	GS [31]	[27]
$f_0(980)$	$m_0 = 965 \pm 10$ $g_\pi = 0.165 \pm 0.025$ GeV $g_K = 0.695 \pm 0.119$ GeV	Flatté	[32]
$f_0(1500)$	$m_0 = 1505 \pm 6$ $\Gamma_0 = 109 \pm 7$	RBW	[27]
χ_{c0}	$m_0 = 3414.75 \pm 0.31$ $\Gamma_0 = 10.5 \pm 0.6$	RBW	[27]
Nonresonant (NR)		Phase space	



First observation (6σ) of CP violation in $B^0 \to K^*(892)^-\pi^+$

$$\mathcal{A}_{CP}(K^*(892)^-\pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012$$
$$\mathcal{A}_{CP}((K\pi)_0^-\pi^+) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027$$
$$\mathcal{A}_{CP}(K_2^*(1430)^-\pi^+) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03$$
$$\mathcal{A}_{CP}(K^*(1680)^-\pi^+) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03$$
$$\mathcal{A}_{CP}(f_0(980)K^0_S) = 0.28 \pm 0.27 \pm 0.05 \pm 0.14$$

charm: mesons

Measurement of the branching fractions of the decays $D^+ \to K^-K^+K^+$, $D^+ \to \pi^-\pi^+K^+$ and $D_s^+ \to \pi^-K^+K^+$

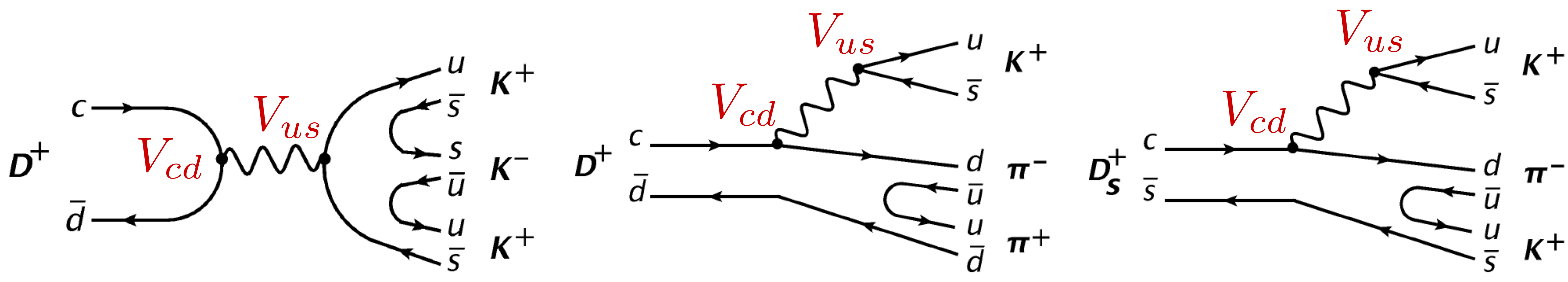
arXiv:1810.03138

- charm: not light enough for χPT, not heavy enough for HQE

- theoretical description of decay dynamics relies on phenomenological models

- branching fractions and resonant structure are crucial inputs

Doubly Cabibbo-suppressed decays



Method:

measure ratio of branching fractions of signal and normalization modes

$$\frac{\mathcal{B}(D^+_{(s)} \to f_{\text{signal}})}{\mathcal{B}(D^+_{(s)} \to f_{\text{norm}})} = \frac{N^{\text{prod}}_{\text{signal}}}{N^{\text{prod}}_{\text{norm}}}, \quad N^{\text{prod}} = \sum_i^{N_{\text{bins}}} \frac{N_i^{\text{obs}}}{\varepsilon_i}$$

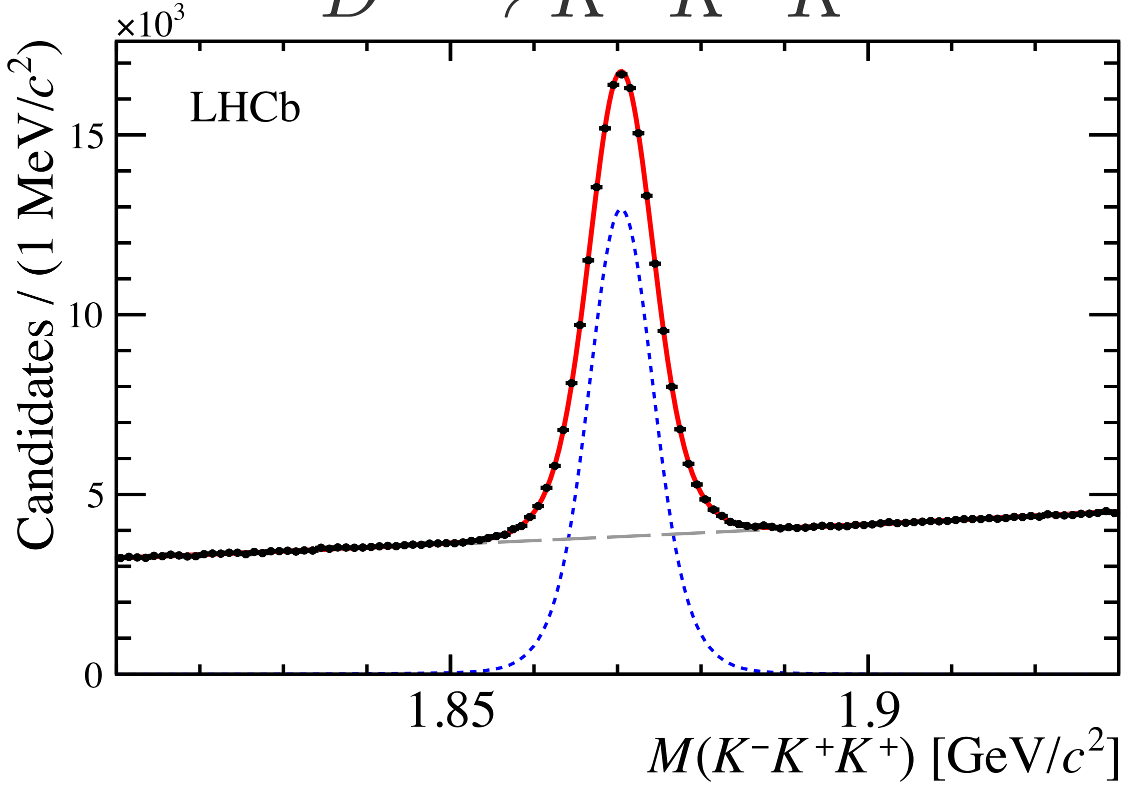
$\varepsilon_i \to$ efficiency as a function of the Dalitz plot coordinates

$N_i^{\text{obs}} \to$ yields in bins of the Dalitz plot

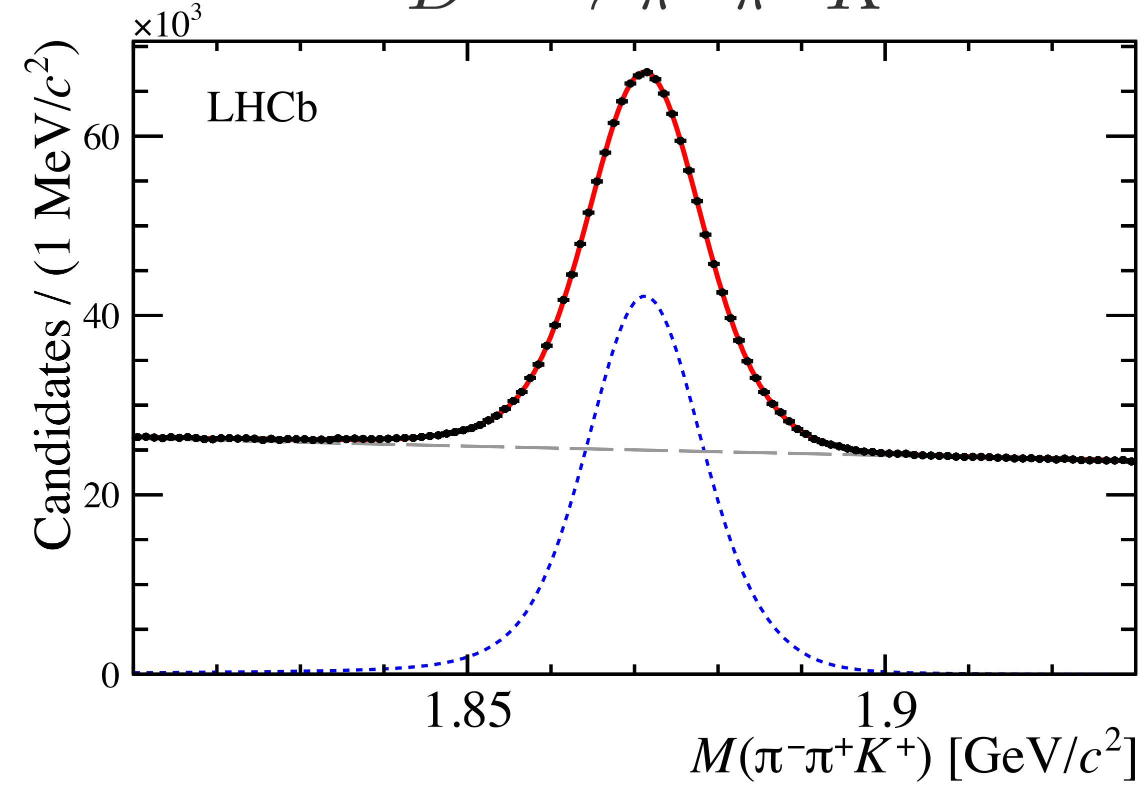
$$\frac{\mathcal{B}(D^+ \to K^- K^+ K^+)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}, \quad \frac{\mathcal{B}(D^+ \to \pi^- \pi^+ K^+)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}, \quad \frac{\mathcal{B}(D_s^+ \to \pi^- K^+ K^+)}{\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)}$$

arXiv:1810.03138

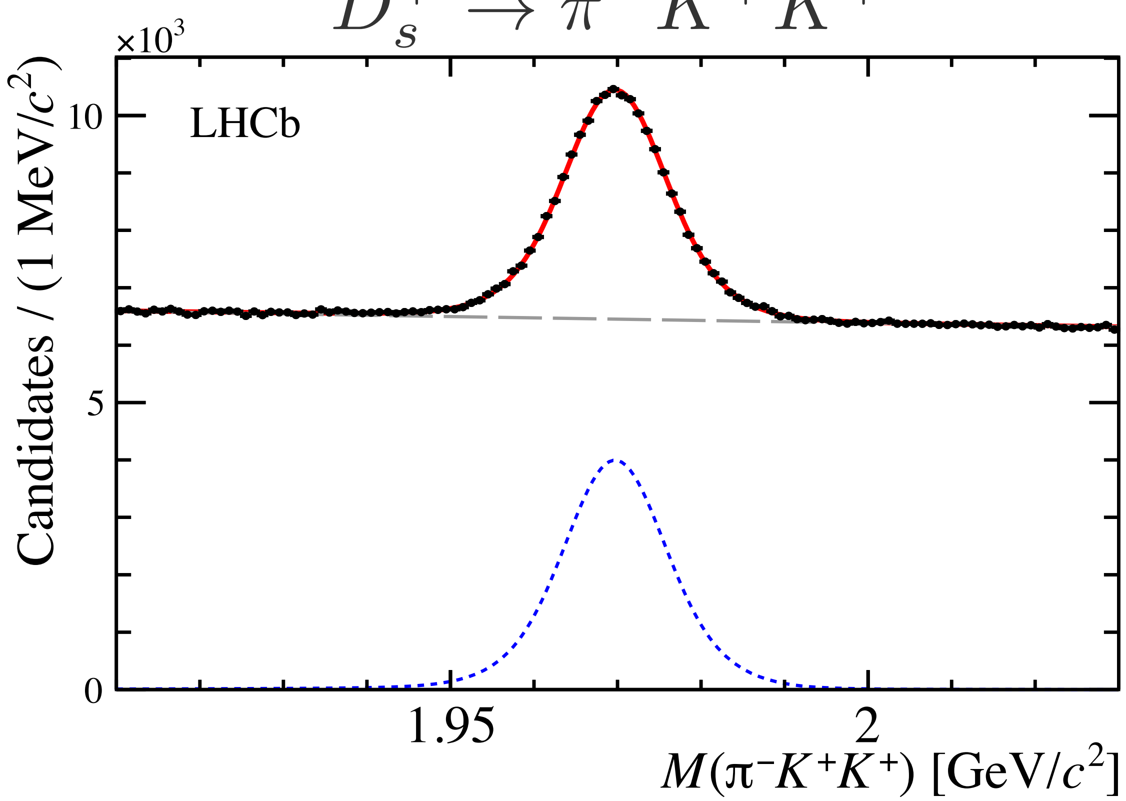
$D^+ \to K^- K^+ K^+$



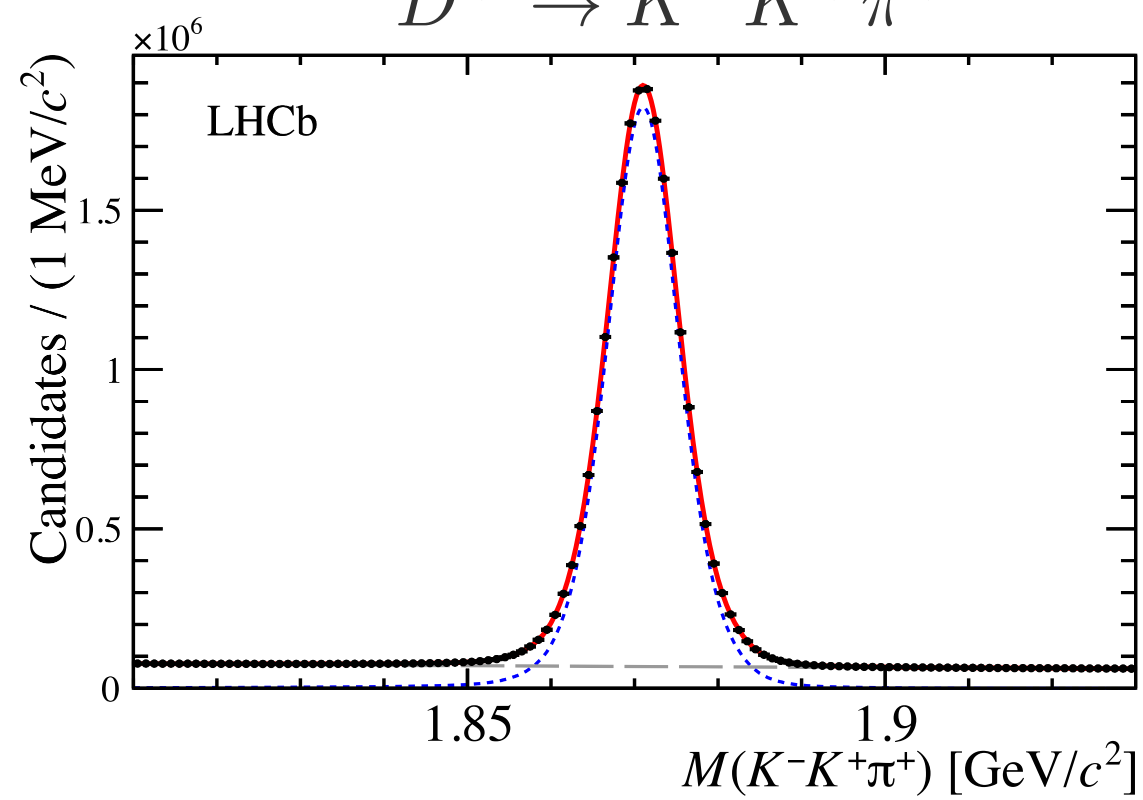
$D^+ \to \pi^- \pi^+ K^+$



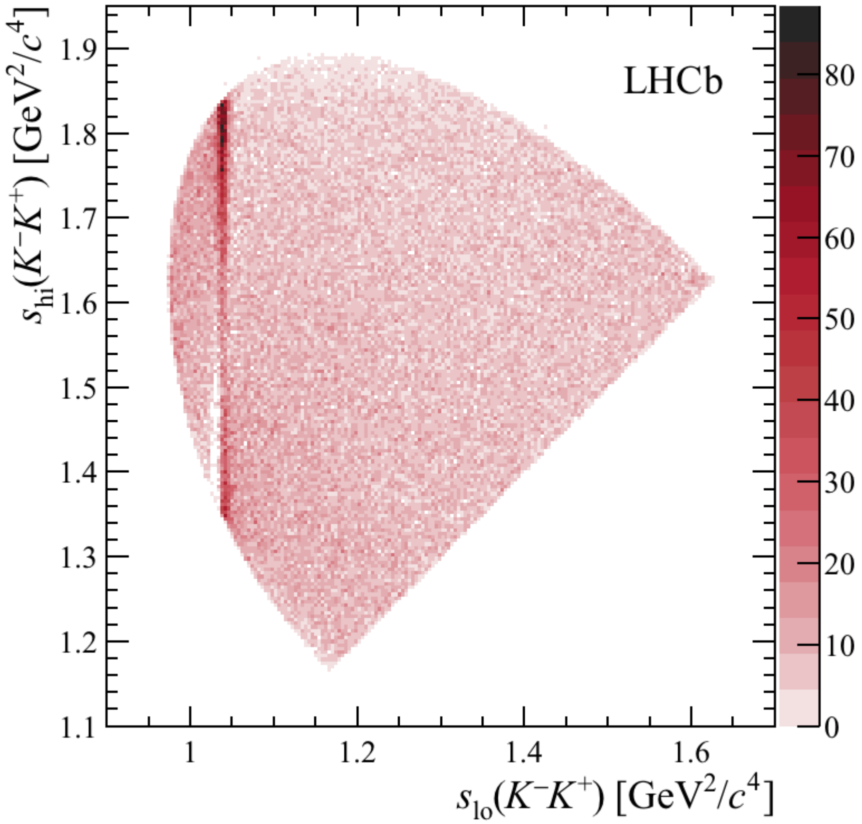
$D_s^+ \to \pi^- K^+ K^+$



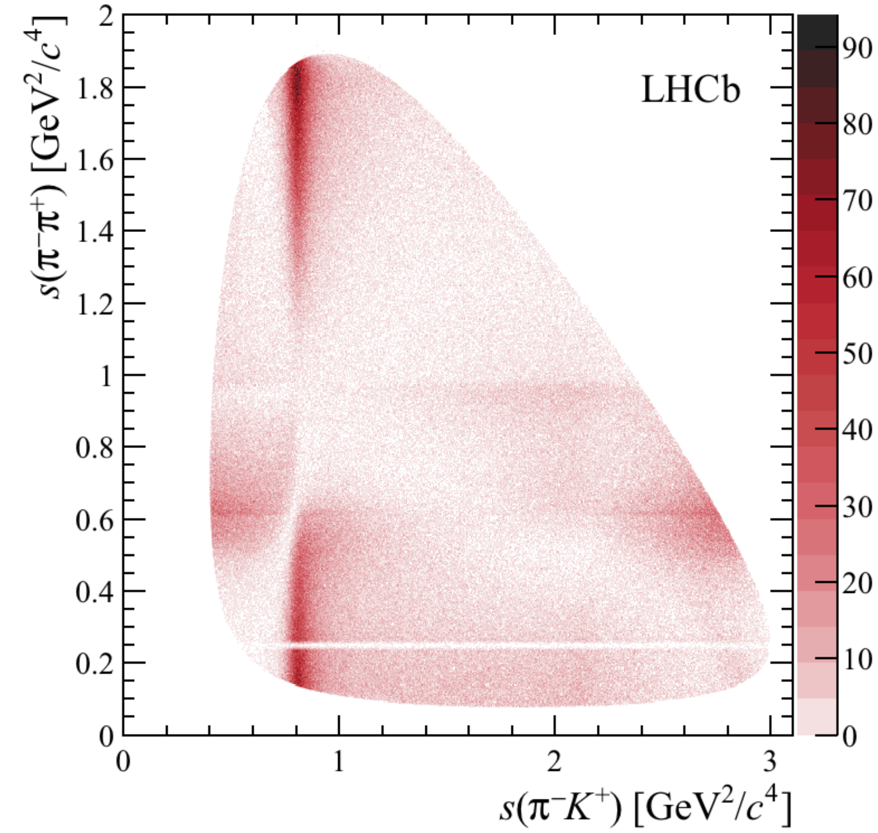
$D^+ \to K^- K^+ \pi^+$



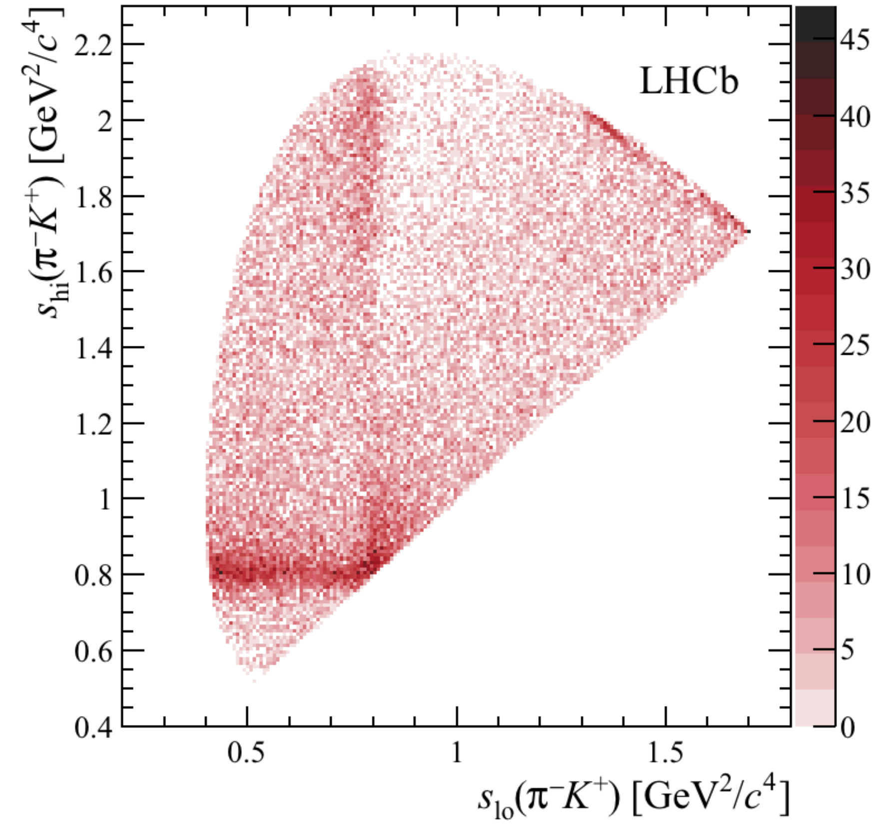
$D^+ \to K^- K^+ K^+$



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



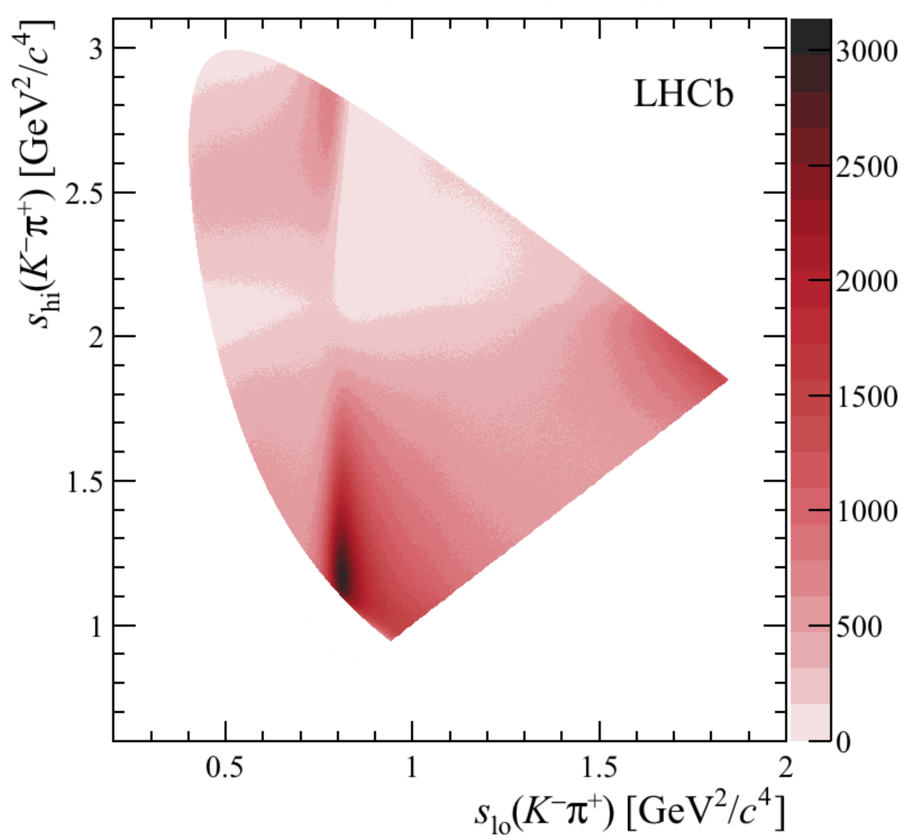
$D_s^+ \to \pi^- K^+ K^+$



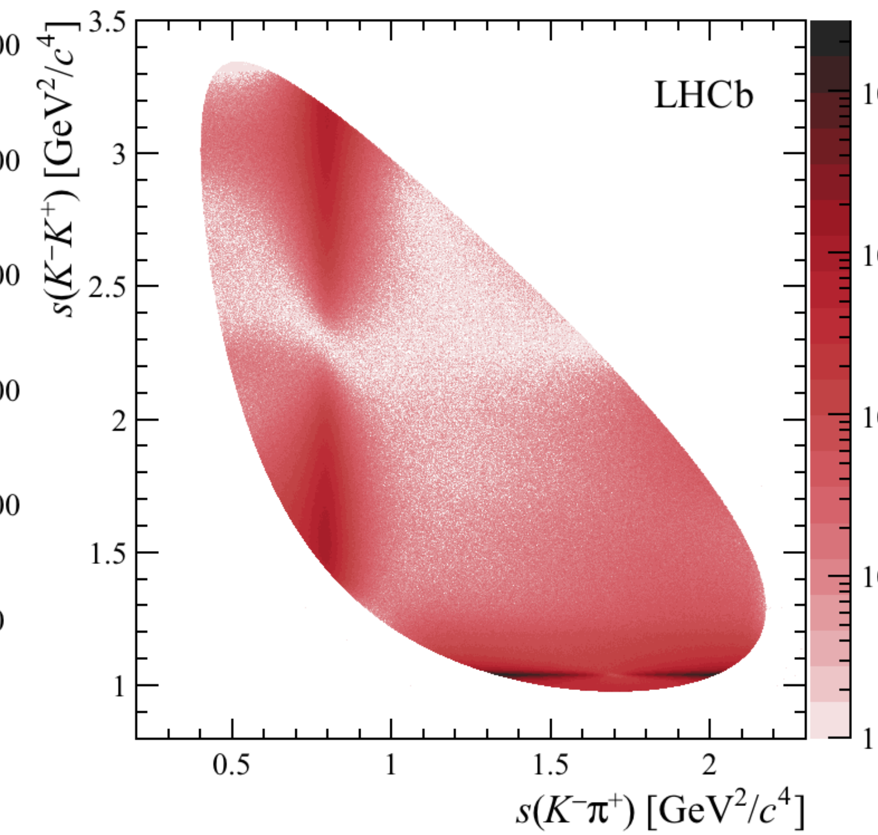
Dalitz plots of signals and normalization modes

arXiv:1810.03138

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



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



	Yields [$\times 10^3$]		
Channel	*MagDown*	*MagUp*	Total
$D^+ \to K^-K^+K^+$	67.61 ± 0.33	66.69 ± 0.33	134.30 ± 0.47
$D^+ \to \pi^-\pi^+K^+$	401.2 ± 1.0	393.7 ± 1.0	794.9 ± 1.4
$D_s^+ \to \pi^-K^+K^+$	33.7 ± 0.4	33.6 ± 0.4	67.2 ± 0.5
$D^+ \to K^-K^+\pi^+$	$11\,657 \pm 4$	$11\,482 \pm 4$	$23\,139 \pm 5$
$D^+ \to K^-\pi^+\pi^+$ (†)	$103\,282 \pm 10$	$101\,008 \pm 10$	$204\,290 \pm 14$
$D^+ \to K^-\pi^+\pi^+$ (††)	$80\,197 \pm 10$	$78\,530 \pm 10$	$158\,727 \pm 13$
$D_s^+ \to K^-K^+\pi^+$	$11\,629 \pm 4$	$11\,414 \pm 4$	$23\,044 \pm 5$

$$\frac{\mathcal{B}(D^+ \to K^-K^+\pi^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (10.282 \pm 0.002 \pm 0.068) \times 10^{-2}$$

(calibration mode)

$$\frac{\mathcal{B}(D^+ \to K^-K^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (6.541 \pm 0.025 \pm 0.042) \times 10^{-4},$$

$$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (5.231 \pm 0.009 \pm 0.023) \times 10^{-3},$$

$$\frac{\mathcal{B}(D_s^+ \to \pi^-K^+K^+)}{\mathcal{B}(D_s^+ \to K^-K^+\pi^+)} = (2.372 \pm 0.024 \pm 0.025) \times 10^{-3},$$

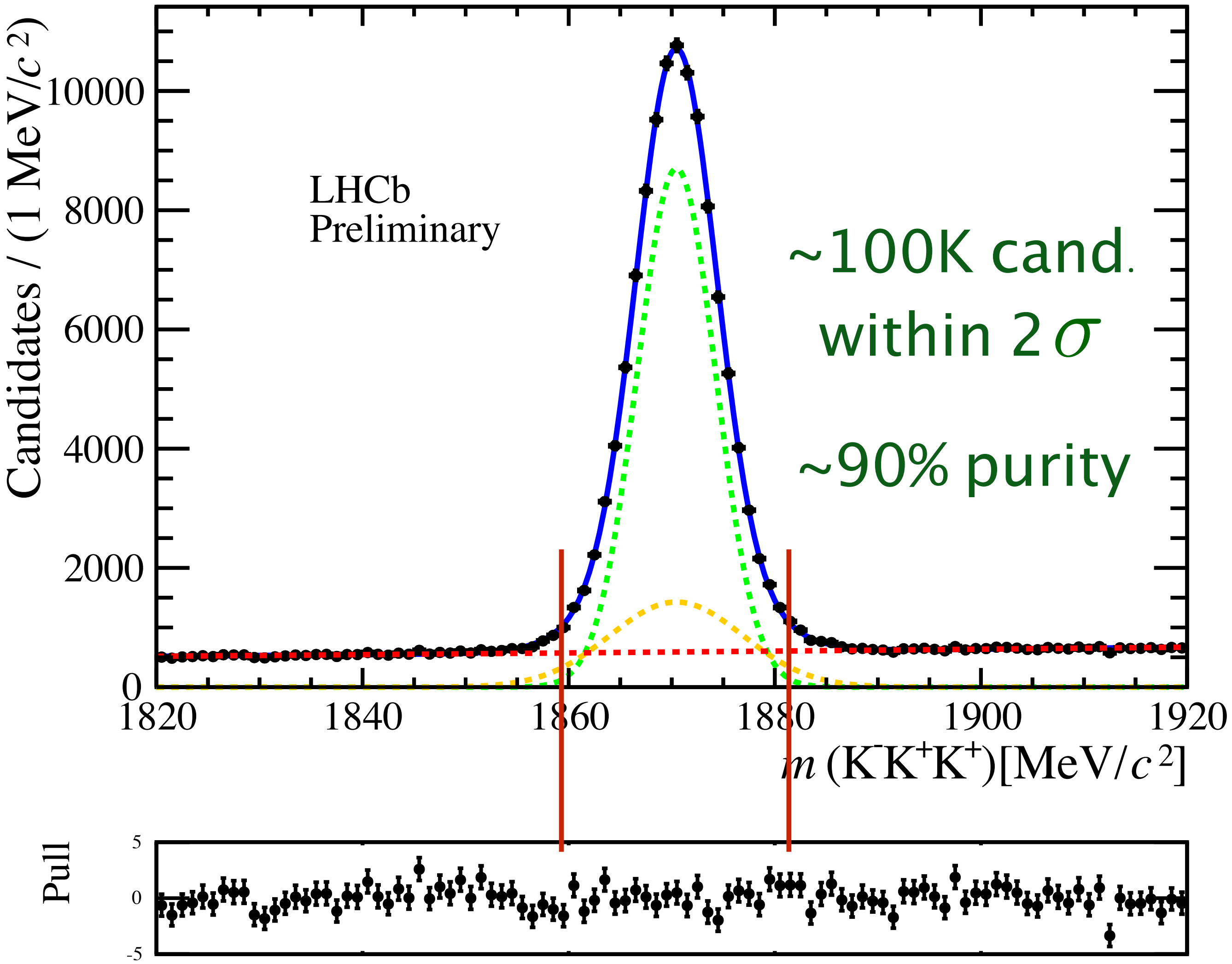
These results: an improvement of ~40X compared to previous measurements

Dalitz plot analysis of $D^+ \to K^- K^+ K^+$

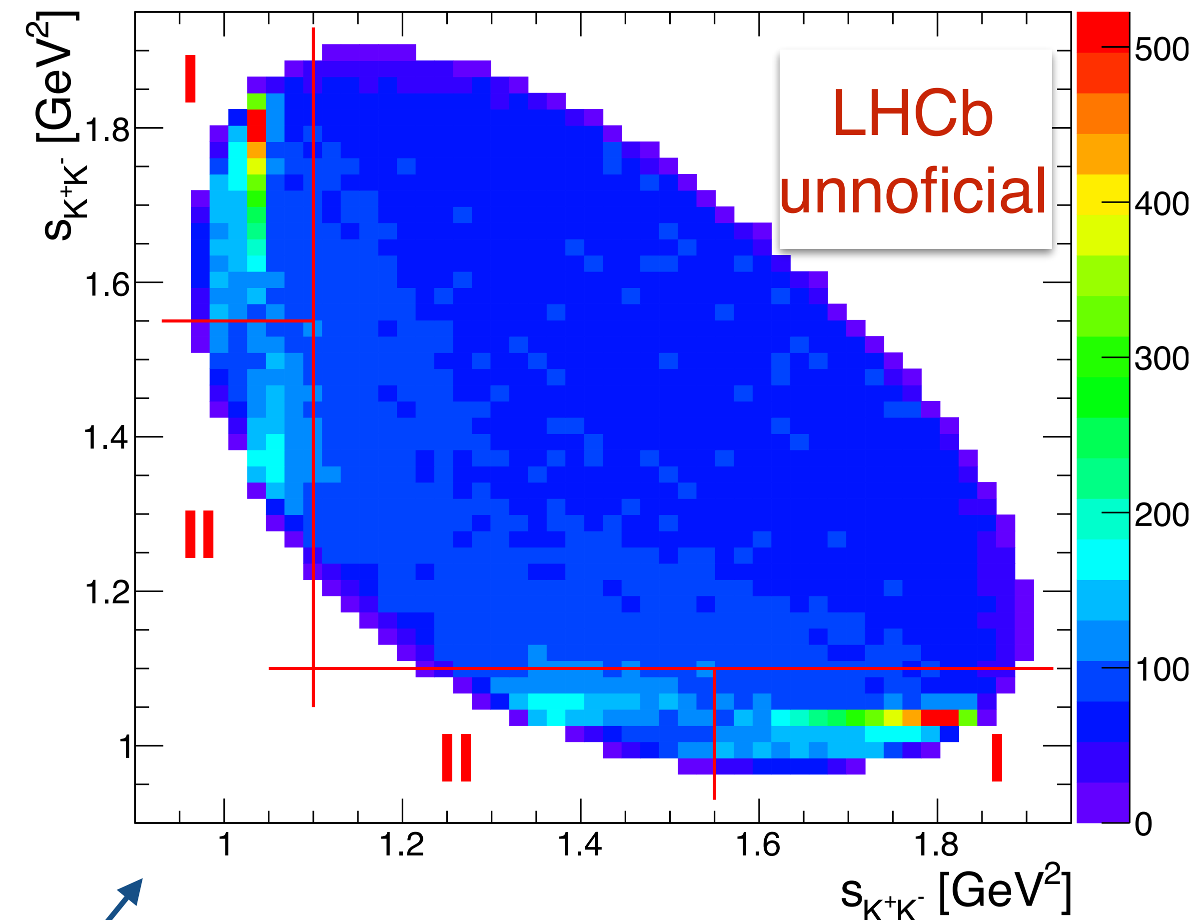
- first determination of resonant structure of this DCS decay
- data fitted using a decay amplitude derived from an effective chiral Lagrangian with resonances
- obtention of $K^- K^+ \to K^- K^+$ scattering amplitudes

LHCb-PAPER-2018-039, in preparation

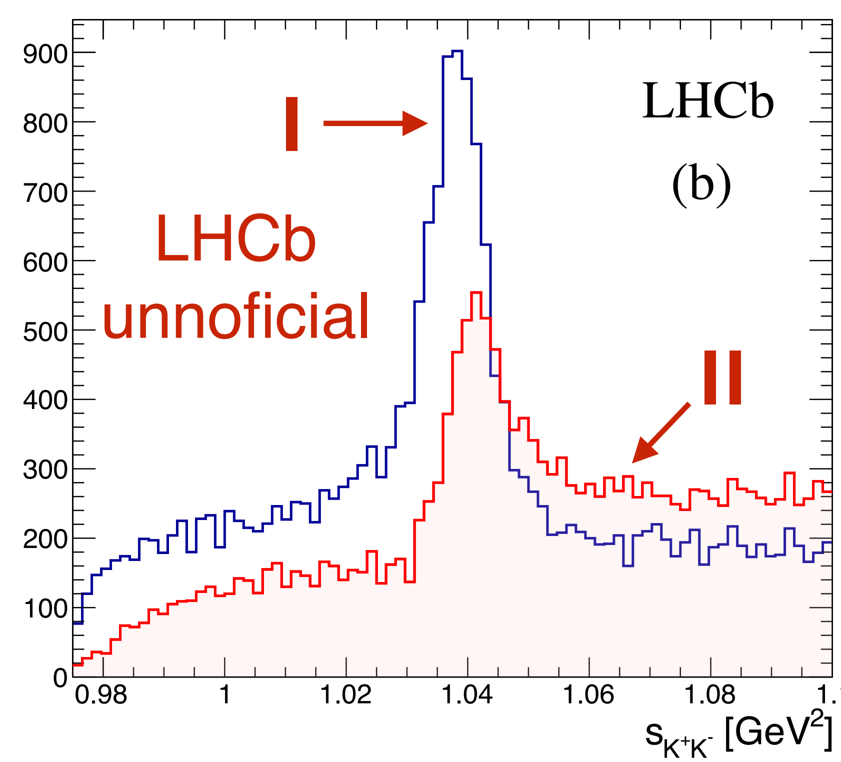
$D^+ \to K^- K^+ K^+$ signal:



Dalitz plot of candidates in the signal region



invariants computed with D^+ mass constraint



interference between S- and P-waves

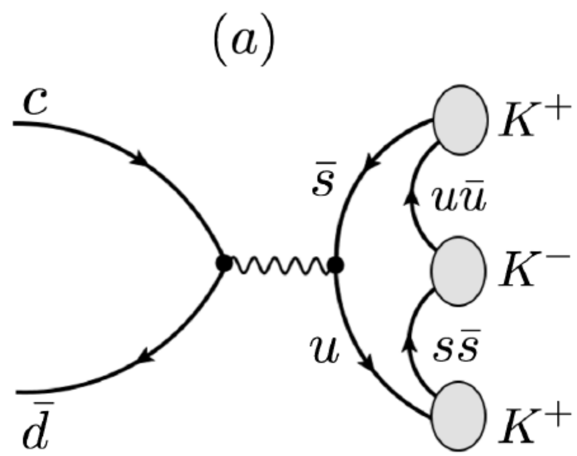
LHCb-PAPER-2018-039

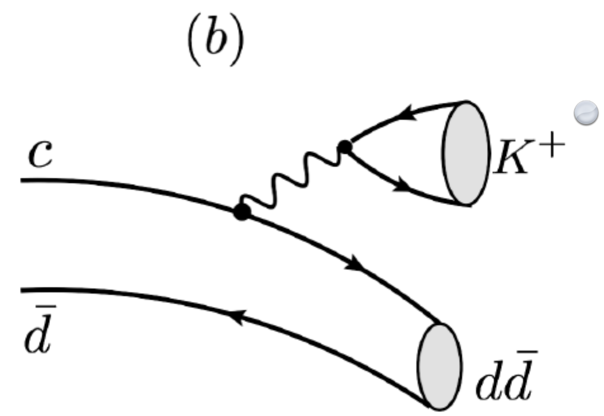
$D^+ \to K^- K^+ K^+$ Dalitz plot fit with the Triple-M amplitude

Triple–M: a model based on a chiral Lagrangian PRD **98** (2018) 056021

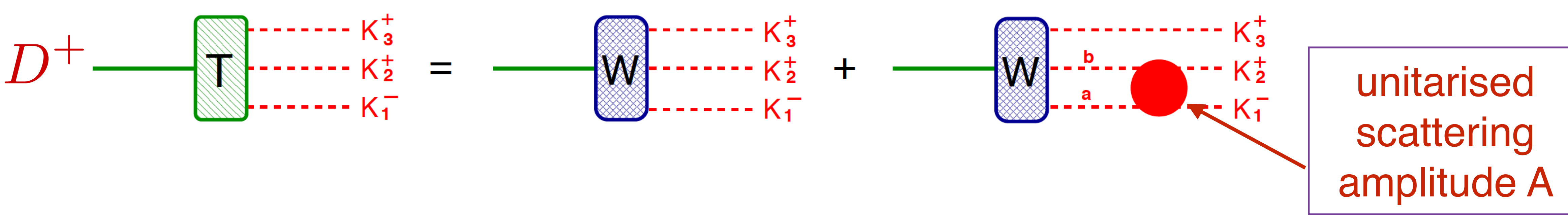
the key hypothesis:

annihilation topology dominates





- cannot form a ϕ or a K^+K^- pair without rescattering



annihilation: $\mathcal{T} = \mathcal{T}_{\text{weak}} \times [1 + \text{loop} \times \text{A} + (\text{loop} \times \text{A})^2 + (\text{loop} \times \text{A})^3 + ...]$

spectator: $\mathcal{T} = \mathcal{T}_{\text{weak}} \times \boxed{(\text{loop} \times \text{A})} \times [1 + \text{loop} \times \text{A} + (\text{loop} \times \text{A})^2 + (\text{loop} \times \text{A})^3 + ...]$

strong amplitude calculated on solid theoretical grounds: ChPT

Dalitz plot fit with the Triple-M amplitude

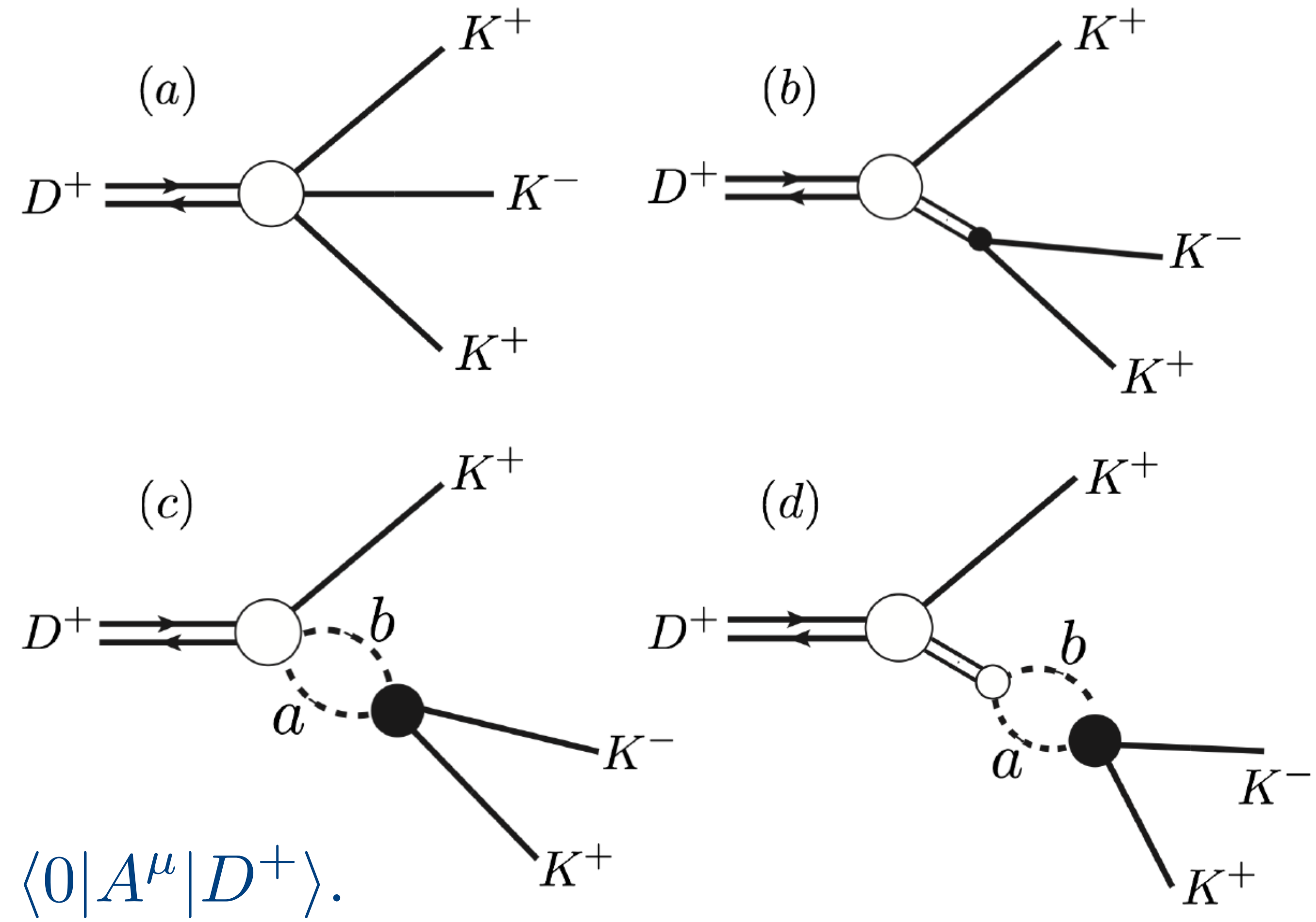
the Triple–M amplitude:

- coupled channels (I=0 and I=1):

$$ab = K\overline{K},\ \pi\pi,\ \pi\eta,\ \eta\eta,\ \rho\pi$$

- 4 resonances (minimal *SU*(3) content):

$$f_0(980),\ a_0(980),\ f_0(1370),\ \phi(1020)$$



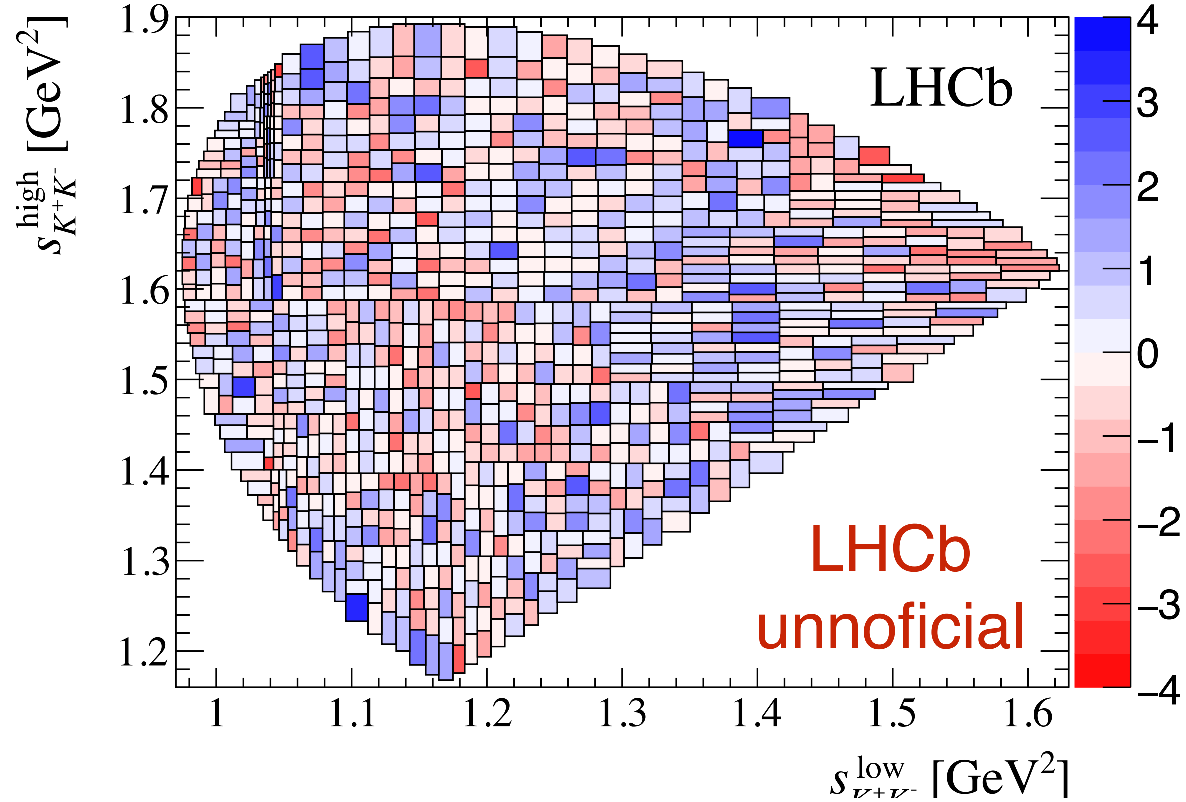
$$\mathcal{T} = \langle (KKK)^+|T|D^+\rangle = \underbrace{\langle (KKK)^+|A_\mu|0\rangle}\ \langle 0|A^\mu|D^+\rangle.$$

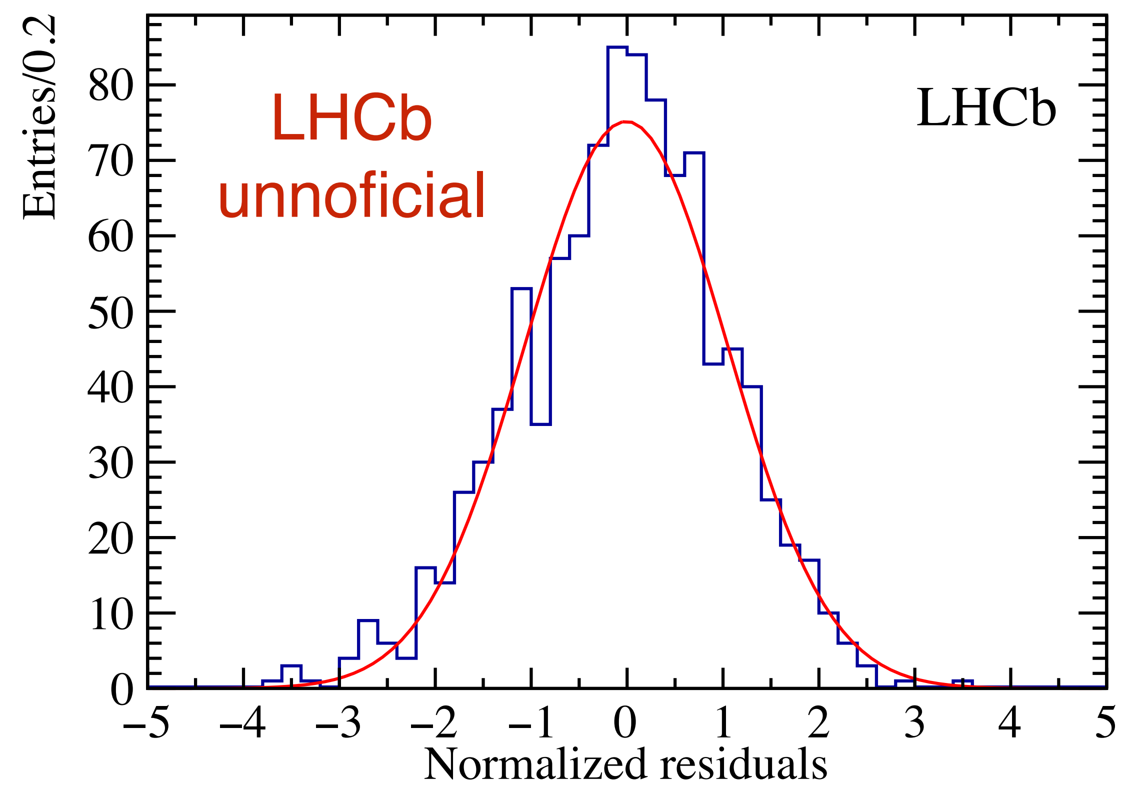
$$\langle\, 0\,|A^\mu|\, D^+(P)\rangle = -i\, G_F\ \sin^2\theta_C\, F_D\, P^\mu$$

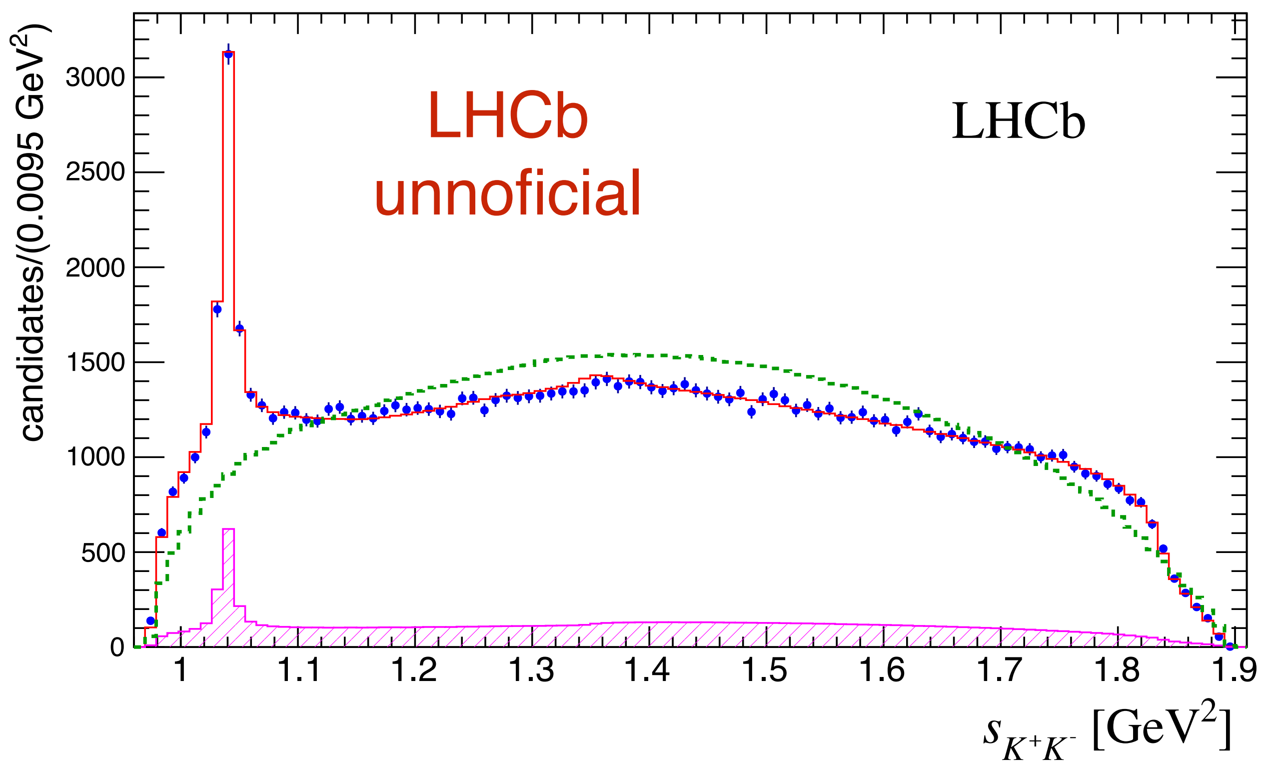
$$\langle K_1^- K_2^+ K_3^+ |\, T\,|\, D^+\rangle = \langle K_1^- K_2^+ K_3^+ |\, T_c\,|\, D^+\rangle\ +$$
$$\langle K_1^- K_2^+ (K_3^+)|\, T^{(0,1)}\,|\, D^+\rangle + \langle K_1^- K_2^+ (K_3^+)|\, T^{(0,0)}\,|\, D^+\rangle$$
$$\langle K_1^- K_2^+ (K_3^+)|\, T^{(1,1)}\,|\, D^+\rangle + \langle K_1^- K_2^+ (K_3^+)|\, T^{(1,0)}\,|\, D^+\rangle$$

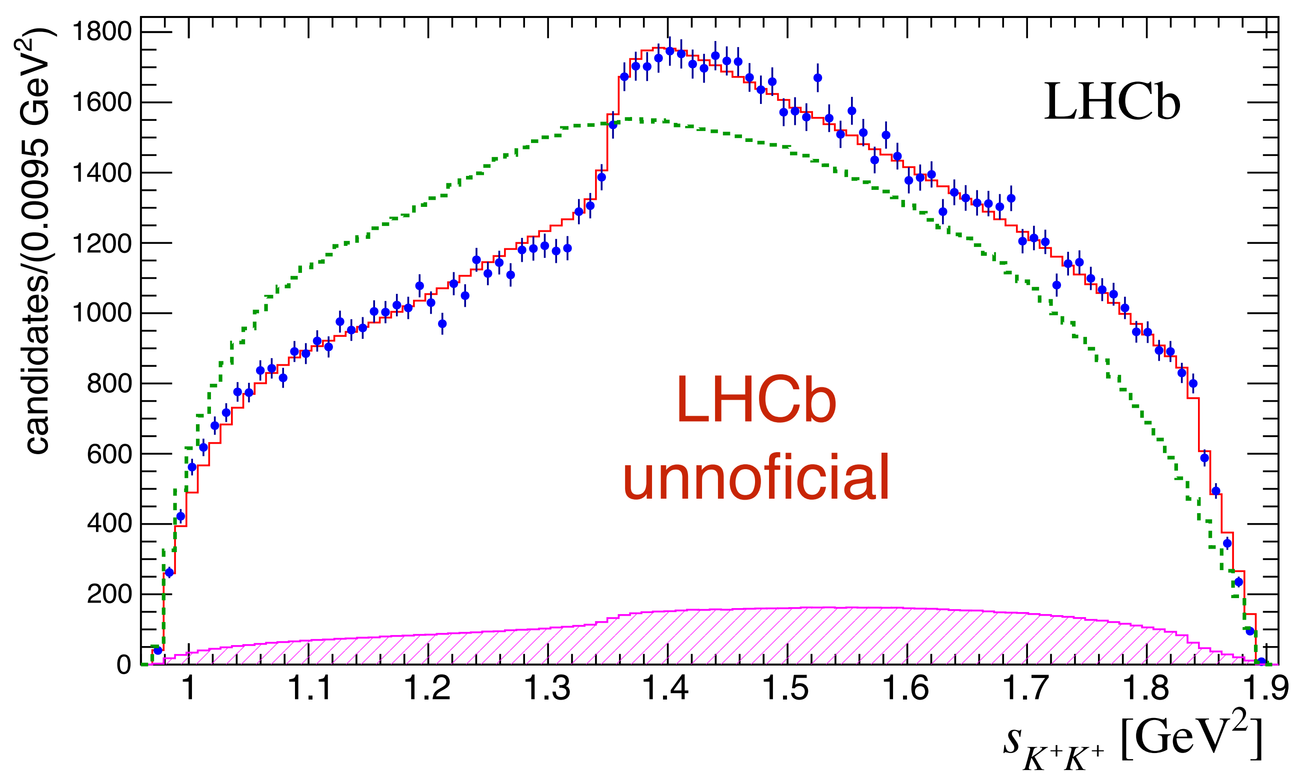
$T^{(\mathrm{J,I})}\ \rightarrow$ spin-isospin sub-amplitudes, including resonances (NLO)

Good fit is obtained with the Triple-M — $\chi^2/\mathrm{ndof} \sim 1.1$

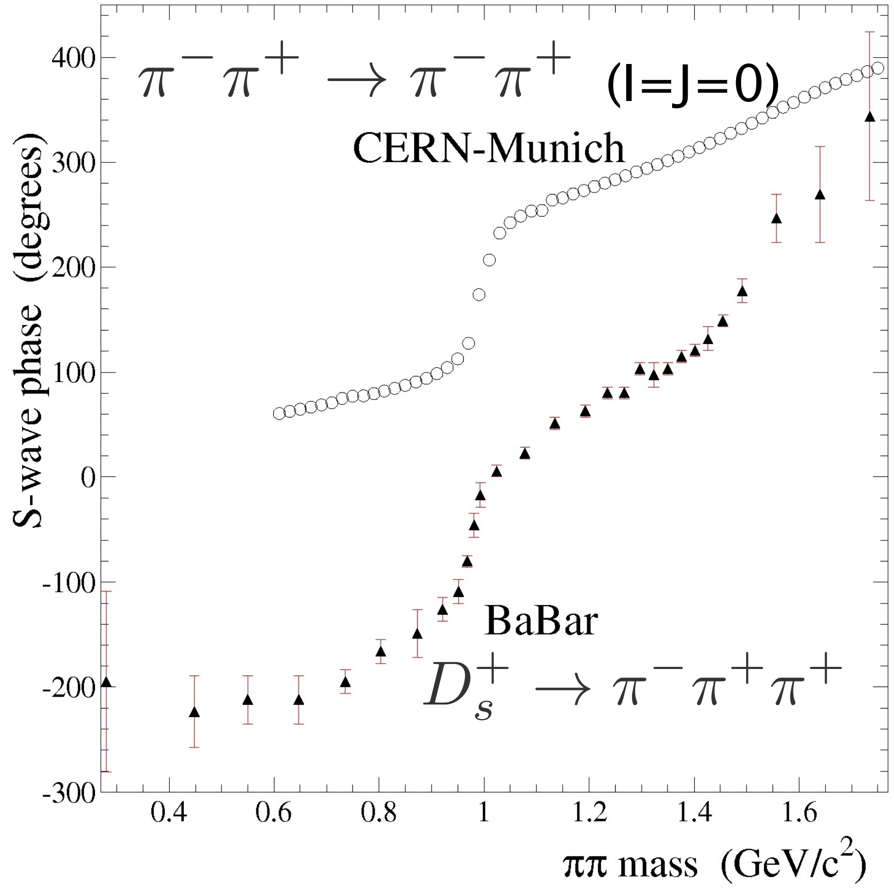


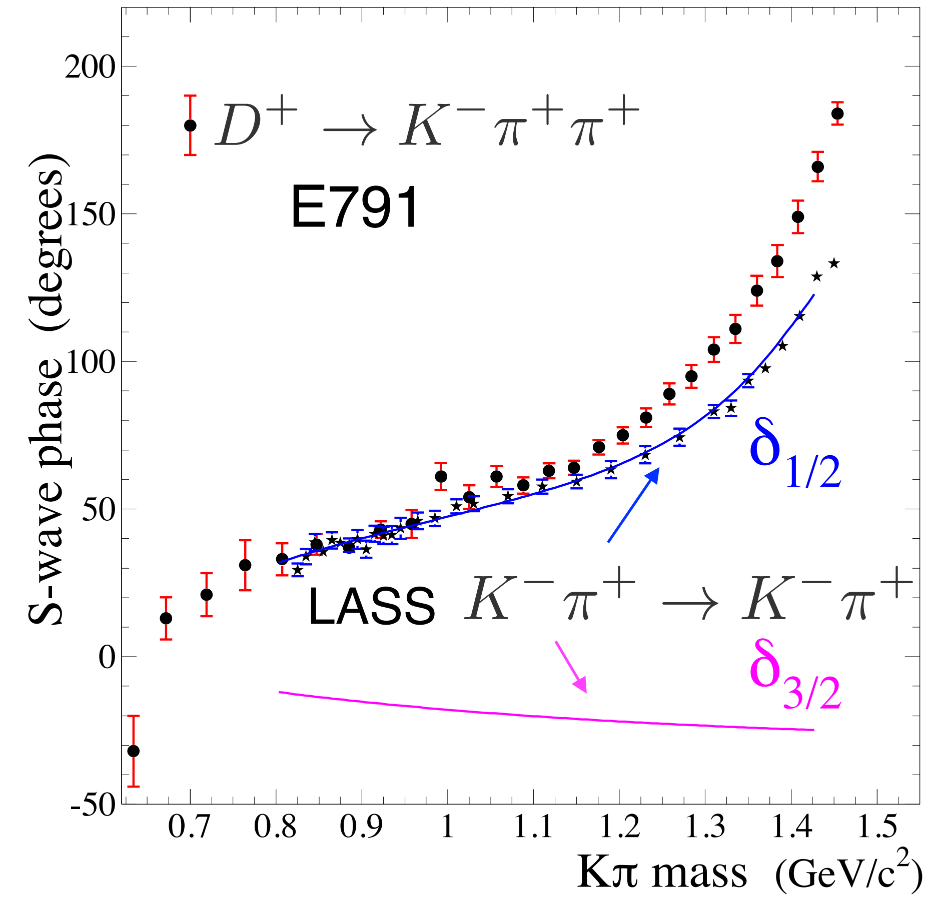






scattering amplitudes: well-defined spin and isospin

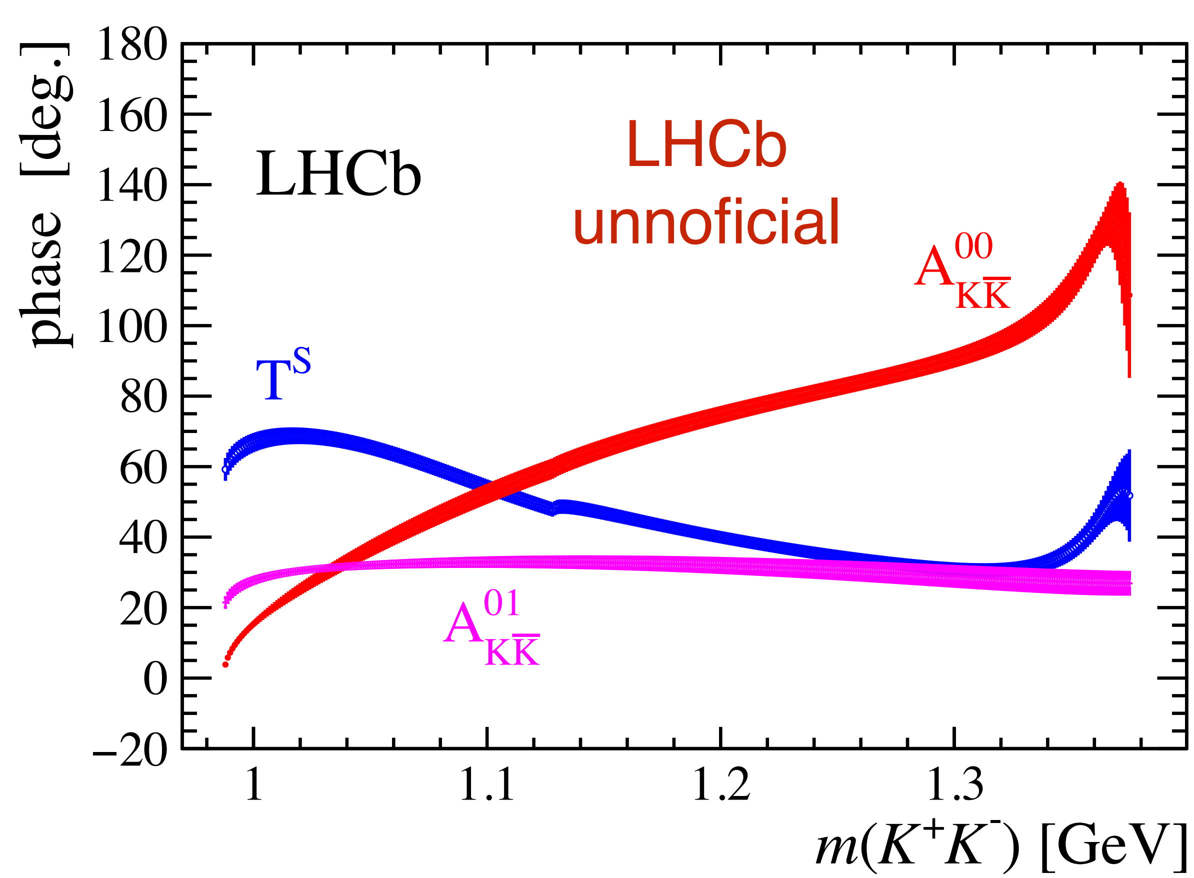




decay amplitudes: well-defined spin, 3-body FSI, weak vertex, isospin averaged

Phases from scattering and decay amplitudes, from the $D^+ \to K^-K^+K^+$ decay

$$T^S = T^S_{NR} + T^{00} + T^{01}$$



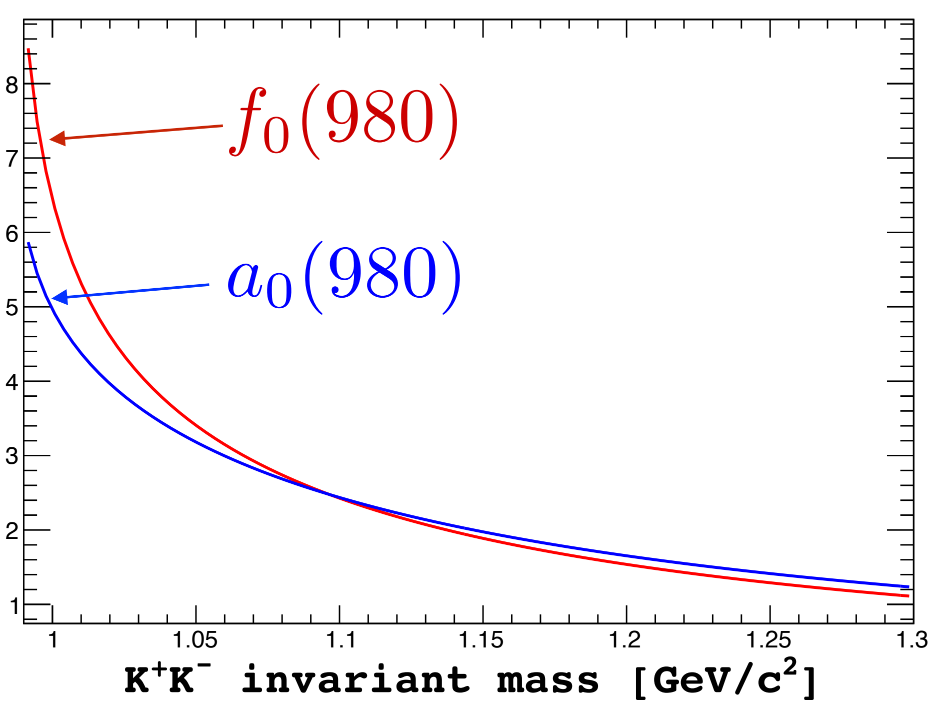
resonant structure:

- 94% S-wave
- 7% $\phi(1020)$

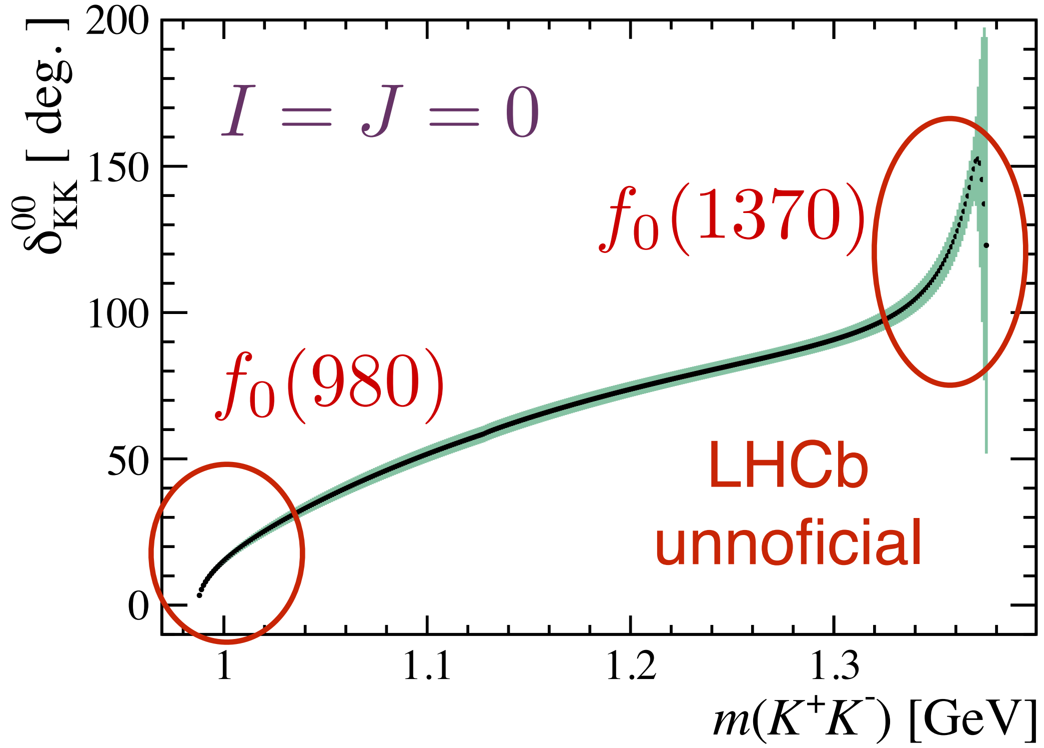
large interference between the various S-wave components:

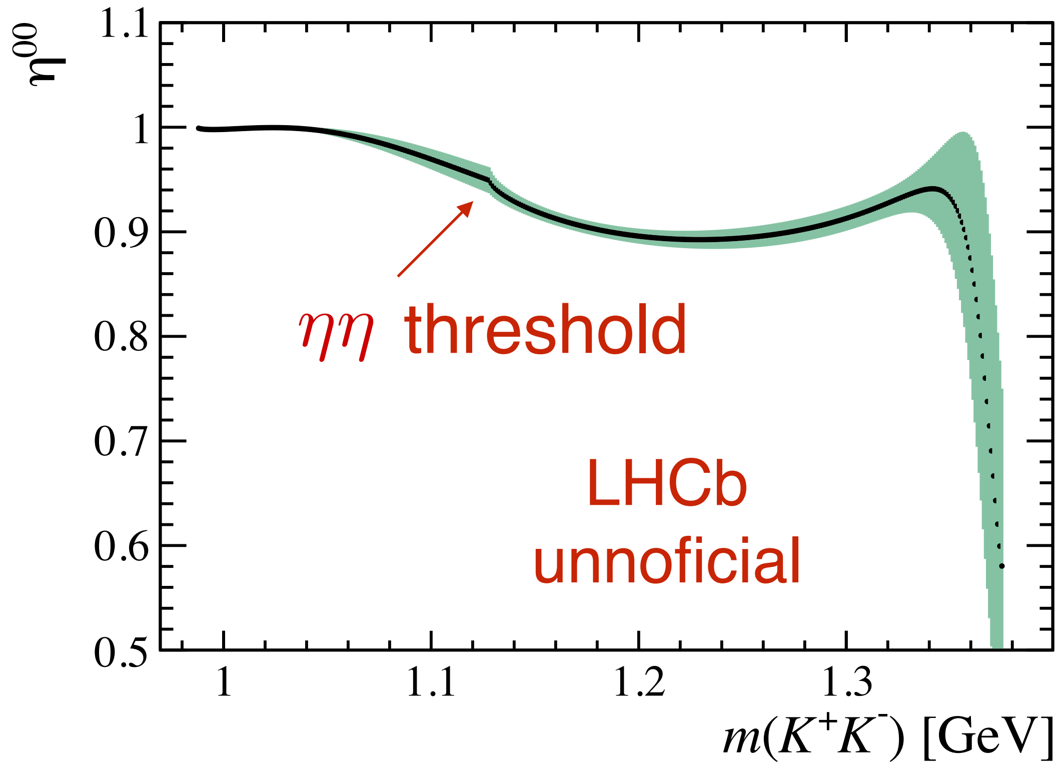
- improve Triple-M amplitude
- simultaneous analysis of

$D^+ \to \pi^-\pi^+\pi^+,\ D^+ \to \eta\pi^+\pi^0$



Triple-M prediction for phase shift and inelasticity of $K^+K^- \to K^+K^-$





Measurement of the charm-mixing parameter y_{CP}

- neutral *D*: mass eigenstates are linear combination of flavour eigenstates

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle, \qquad |D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

- average mass and width: $m \equiv \frac{m_1 + m_2}{2}, \quad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}$

- mixing is governed by two dimensionless parameters,

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}, \qquad x, y < 1\%$$

- if *CP* is conserved, mass and *CP* eigenstates coincide:

$$|D_1\rangle = |D_{CP-}\rangle = |D_-\rangle, \qquad |D_2\rangle = |D_{CP+}\rangle = |D_+\rangle$$

- all types of *CP* violation are contained in $\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\overline{A}_f}{A_f}\right| e^{i\phi}$

$\left|\frac{q}{p}\right| \neq 1:$ *CP*V in mixing;

$\phi \neq 0:$ *CP*V in interference between decays with and without mixing;

$\left|\frac{\overline{A}_f}{A_f}\right| \neq 1:$ *CP*V in the decay;

- for charged mesons, the decay time distribution follows a simple exponential. Not true for neutral mesons due to mixing.

- assuming no CPV in the decay:

$$\frac{d\Gamma}{dt}(D^0 \to h^+h^-) = e^{-\Gamma t}|A_{hh}|^2\left[1 - |p/q|(y\cos\phi - x\sin\phi)\Gamma t\right]$$

$$\frac{d\Gamma}{dt}(\overline{D}^0 \to h^+h^-) = e^{-\Gamma t}|A_{hh}|^2\left[1 - |q/p|(y\cos\phi + x\sin\phi)\Gamma t\right]$$

$$\frac{d\Gamma}{dt}(D^0 \to K^-\pi^+) = \frac{d\Gamma}{dt}(\overline{D}^0 \to K^-\pi^+) = e^{-\Gamma t}|A_{K\pi}|^2$$

- if CP is conserved $(|p/q| = 1,\ \phi = 0)$:

$$\frac{d\Gamma}{dt}(D^0 \to h^+h^-) = \frac{d\Gamma}{dt}(\overline{D}^0 \to h^+h^-) = e^{-\Gamma t}|A_{hh}|^2\,[1 - y\Gamma t]$$

- $D^0 \to K^+K^-/\pi^+\pi^-$: *CP*+ decays; $D^0 \to K^\pm\pi^\mp$: 50% *CP*+, 50% *CP*-

- $y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1 \approx \frac{1}{2}[(|q/p| + |p/q|y\cos\phi - (|q/p| - |p/q|x\sin\phi)]$ is equal to the mixing parameter y if *CP* is conserved.

- this measurement: y_{CP} from the difference between the widths of *CP*-even and *CP*-mixed D^0 decays,

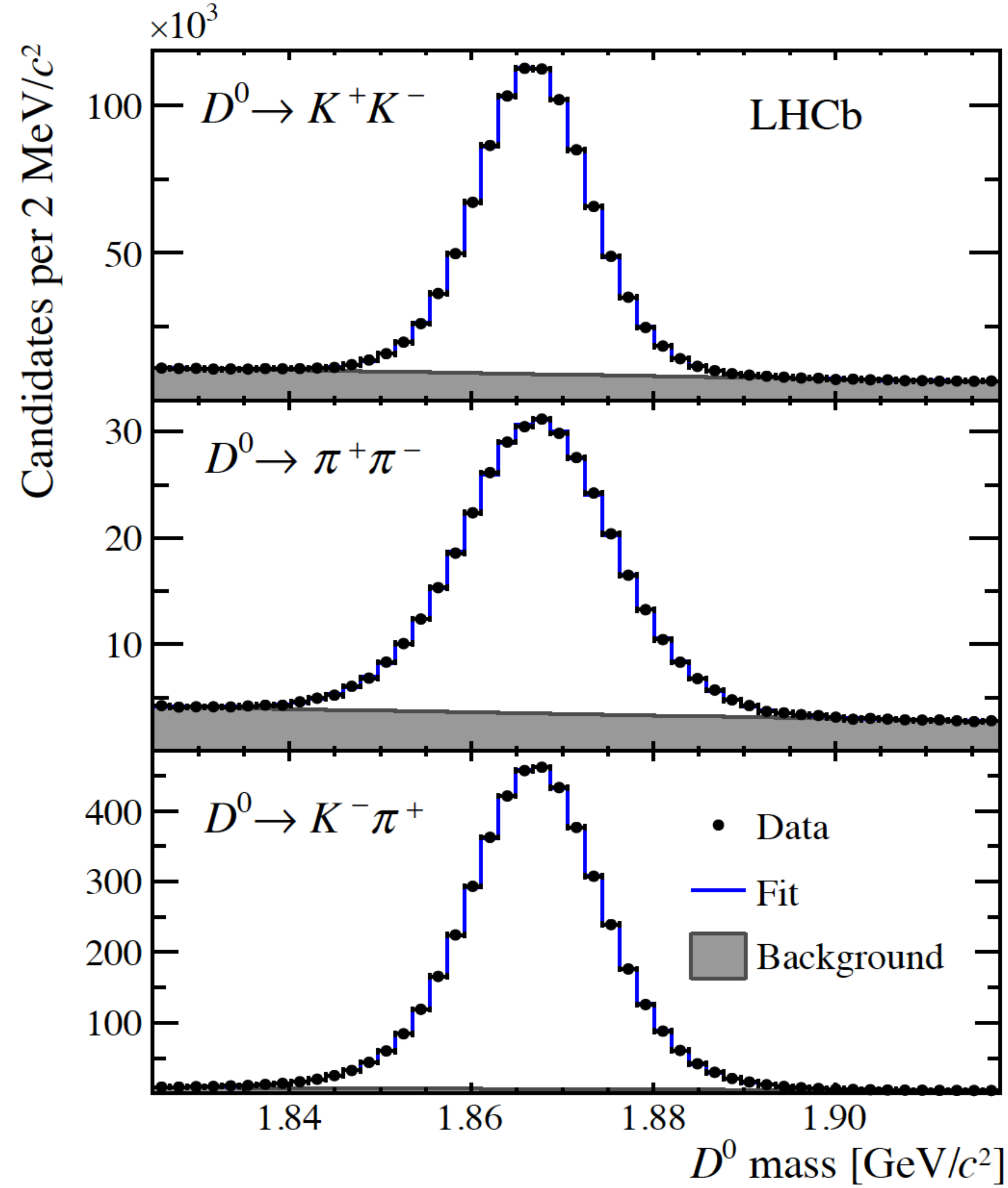
$$\Delta_\Gamma = \Gamma_{CP+} - \Gamma, \quad y_{CP} = \Delta_\Gamma/\Gamma$$

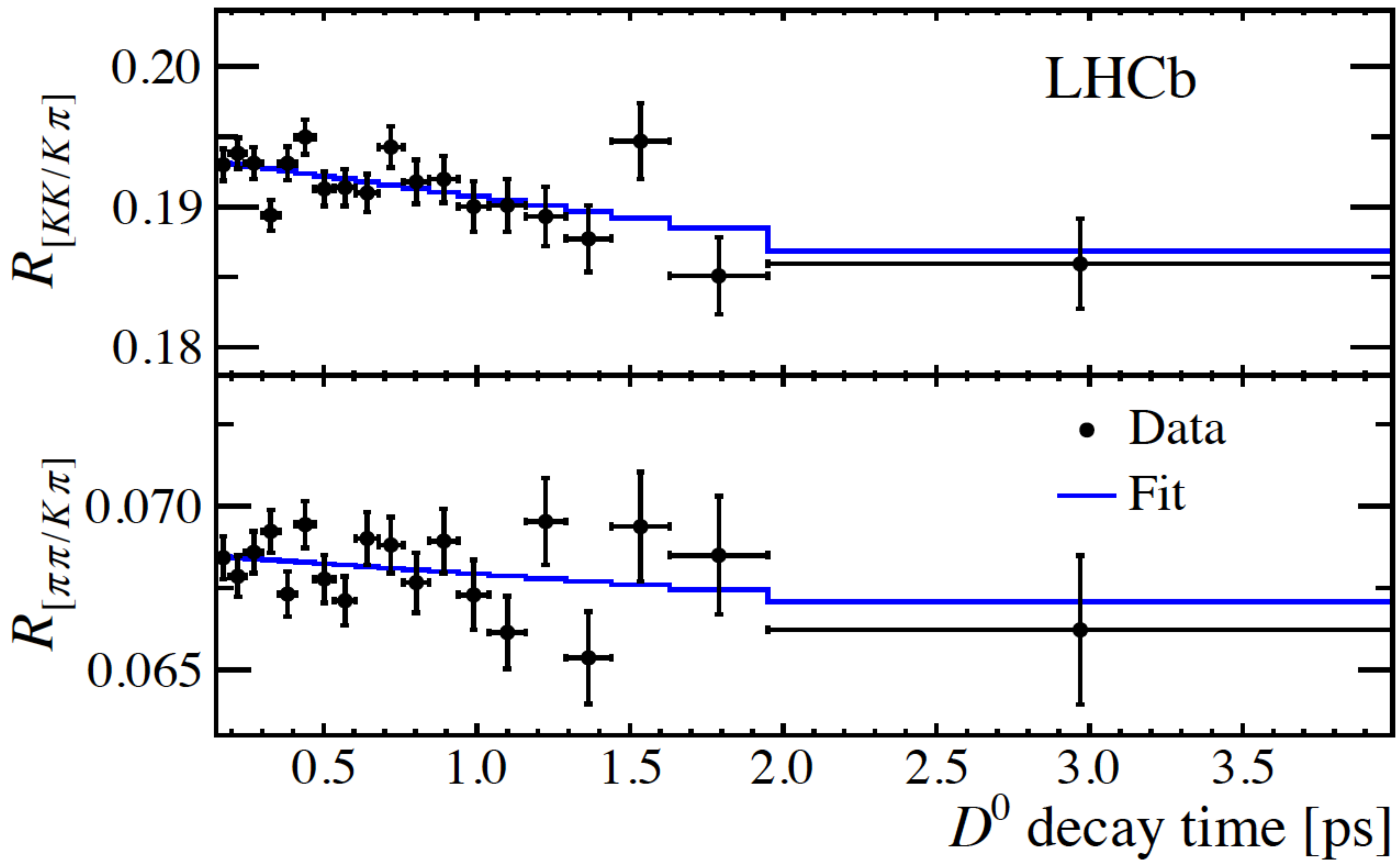
using

$$\Gamma = 2.4384 \pm 0.0089\ \mathrm{ps}^{-1}\ \mathrm{(PDG)}$$

- D^0 signals from $\overline{B} \to D^0 \mu^- \overline{\nu}_\mu X$
- bias in decay-time suppressed by imposing detachment requirements on the μ^- candidate
- data samples split into 19 bins of decay time
- ratios of efficiency corrected yields of $D^0 \to h^+ h^-,\ D^0 \to K^- \pi^+$ are computed for each bin
- distribution of signal-yield ratios fitted with

$$R_{[h^+h^-/K\pi]} = \frac{e^{-(\Delta_\Gamma - \Gamma)t}}{e^{-\Gamma t}}$$





this measurement: $y_{CP} = (0.57 \pm 0.13 \pm 0.09)\%$

world average (HFLAV): $y_{CP} = (0.84 \pm 0.16)\%$

consistent with mixing parameter y : $y = (0.62 \pm 0.07)\%$

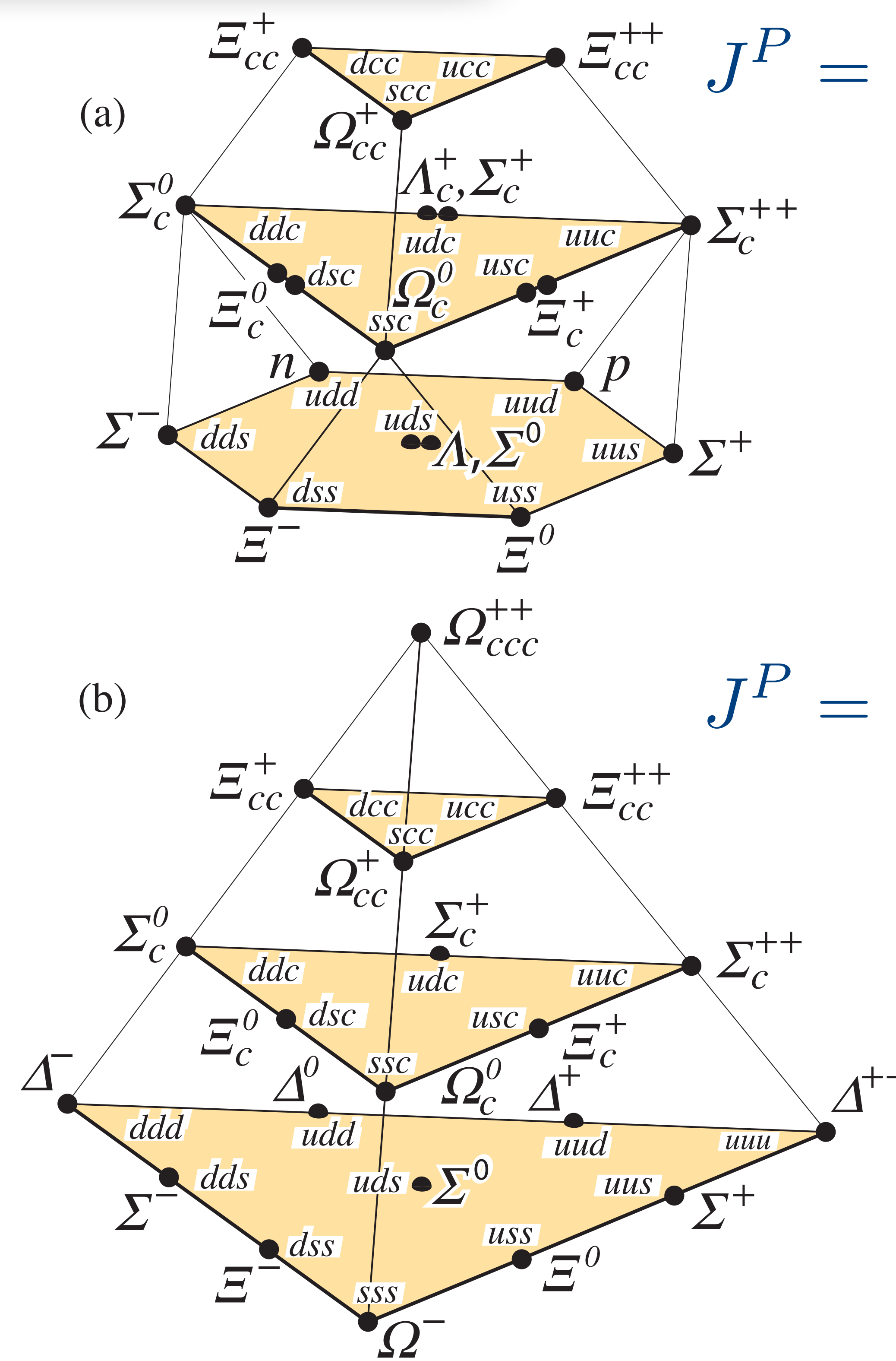
charm: baryons

Charm baryon spectroscopy with $D^0 p$ and $D^+ p$ final states

Baryons made from ***u, d, s*** and ***c*** quarks form SU(4) multiplets:

$J^P = \frac{1}{2}^+$: weakly decaying states

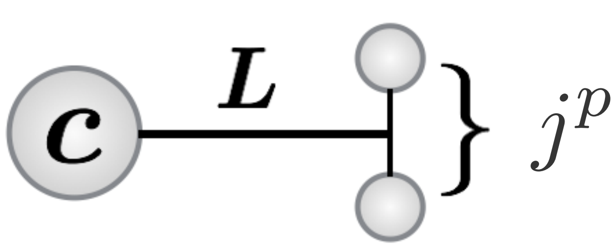
$J^P = \frac{3}{2}^+$: strong/electromagnetic decaying states into $J^P = \frac{1}{2}^+$



$J^P = \frac{1}{2}^+$

$J^P = \frac{3}{2}^+$

In HQET: charm baryon made of a ***c*** quark and a diquark

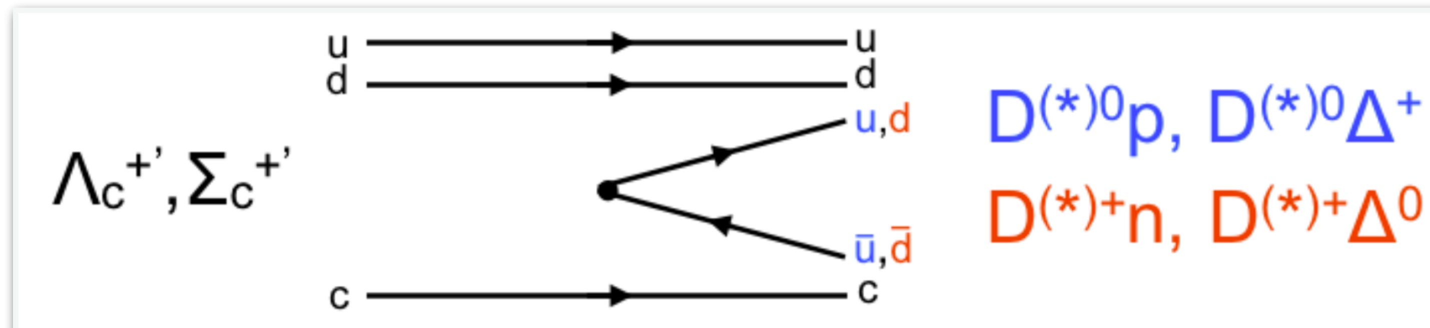


PDG 2018 : 24 known charmed baryons. Six added recently by LHCb.
Nine have no spin-parity assigned yet

Two methods to study the spectrum of charm baryons:
prompt production and $\Lambda_b \to H_c + X$ decays

Prompt production:

$pp \to H_c + X,\ H_c \to D^0 p / D^+ n$

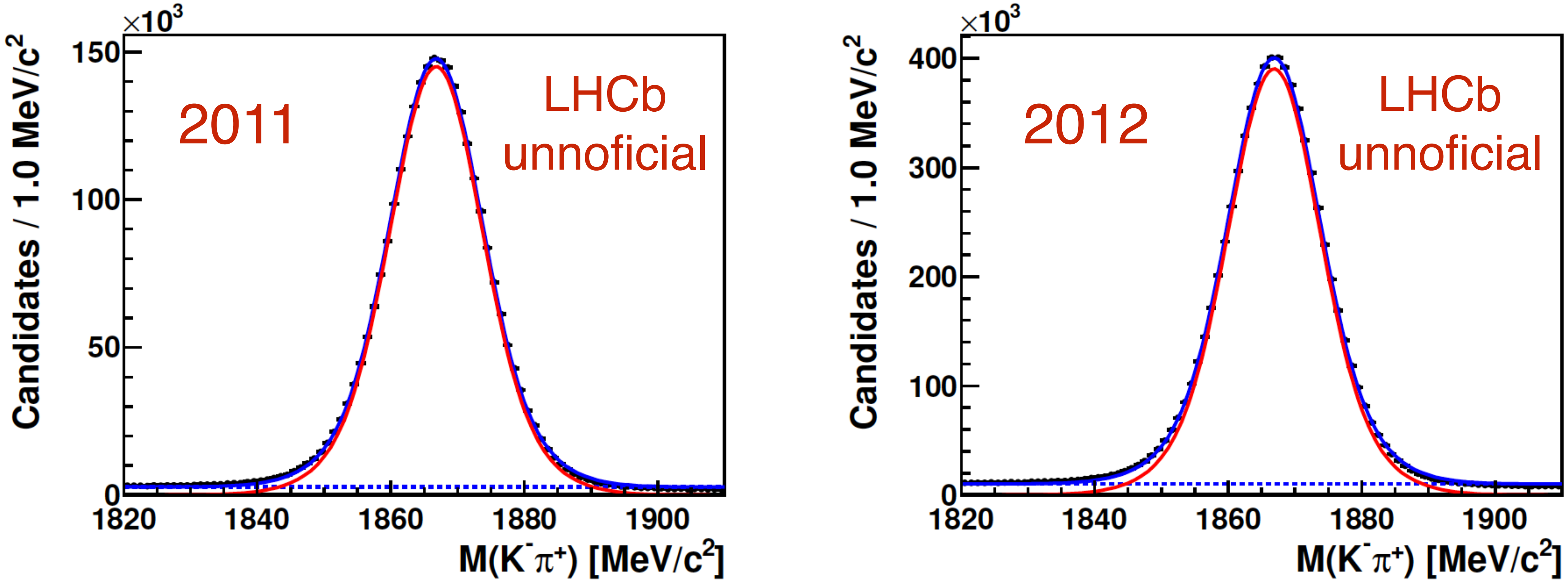


Reconstruct prompt $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays
and combine with a proton or antiproton coming from the primary vertex

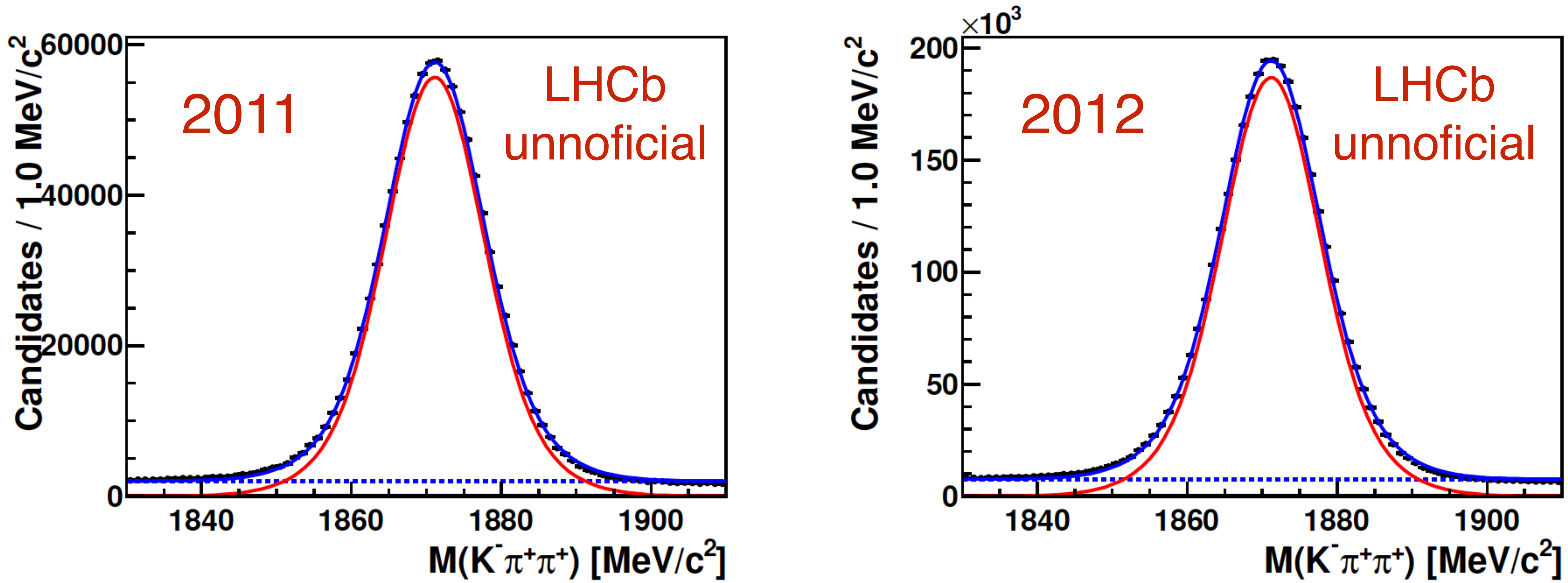
data from Run 1

the *D* signals…

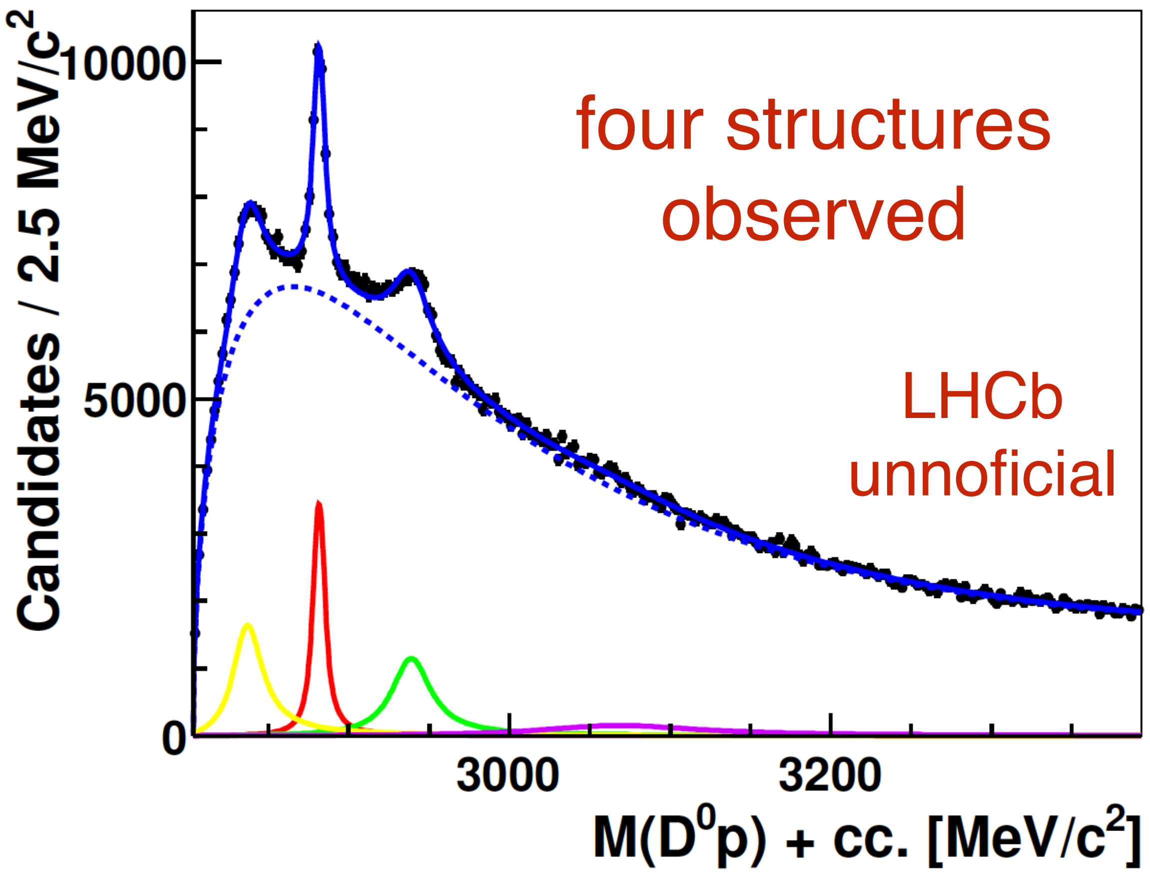
$D^0 \to K^- \pi^+$

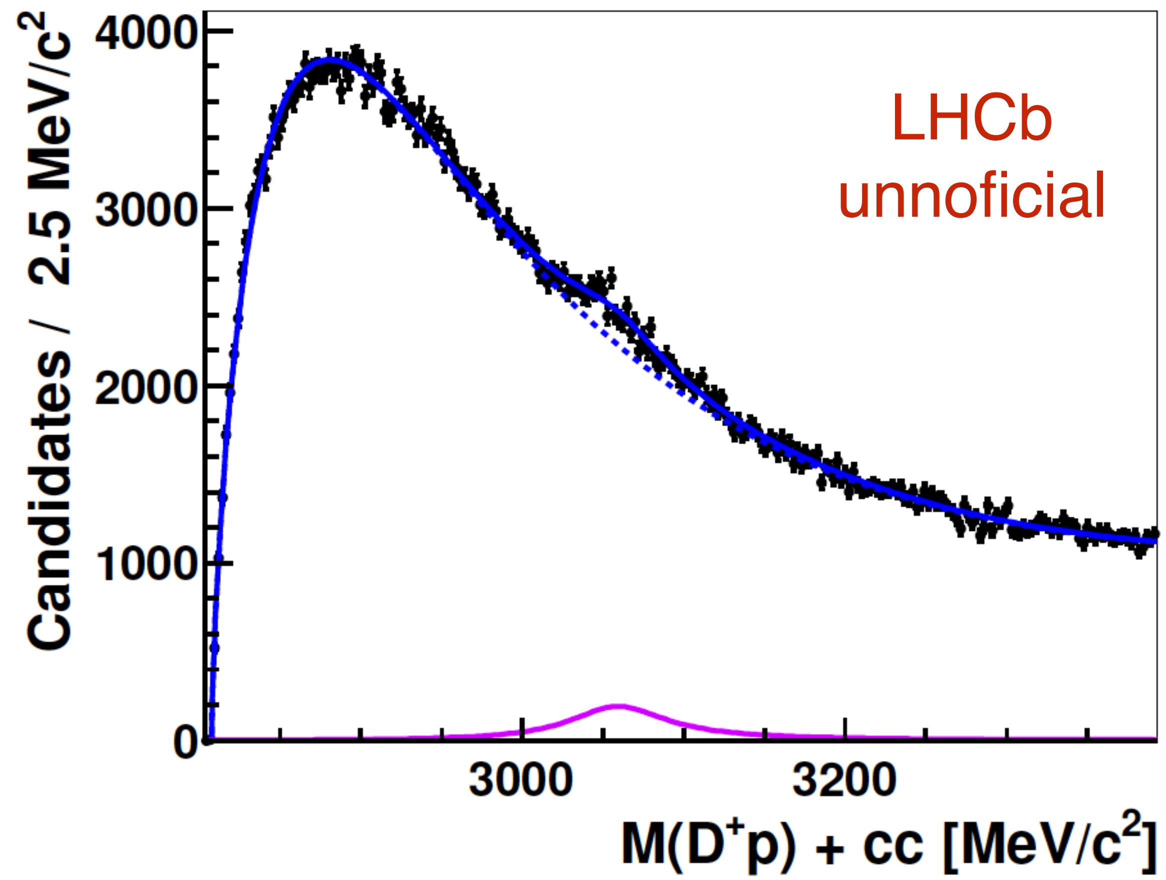


$D^+ \to K^- \pi^+ \pi^+$



…and the *Dp* spectra





signal: $$\mathrm{BW}(x; m, \Gamma) = 2xq(x, m_1, m_2) \times \frac{1}{(x^2 - m^2)^2 + m^2\Gamma^2(x)},$$

phase space factor: $$q(x; m_1, m_2) = \frac{1}{2x}\sqrt{(x^2 - (m_1 + m_2)^2)(x^2 - (m_1 - m_2)^2)},$$

$$x = M(Dp), \qquad m = M(\Lambda_c/\Sigma_c), \qquad m_1, m_2 = M(D), M(p)$$

Preliminary results

$$\Lambda_c(2840)^+ \rightarrow \quad m = 2839.0 \pm 0.1 \pm 1.2\mathrm{MeV}/c^2$$

$$\Gamma = 23 \pm 3 \pm 10\mathrm{MeV}/c^2$$

not consistent with the state listed in PDG and found in $\Lambda_b^0 \rightarrow D^0 p \pi^-$

$$\Lambda_c(2880)^+ \rightarrow \quad m = 2882.7 \pm 0.1 \pm 1.4\mathrm{MeV}/c^2$$

$$I(J^P) = 0(\tfrac{5}{2}^+) \qquad \Gamma = 7.4 \pm 0.4 \pm 3.6\mathrm{MeV}/c^2$$

$$\Lambda_c(2940)^+ \rightarrow \quad m = 2940.6 \pm 0.3 \pm 3.0\mathrm{MeV}/c^2$$

$$I(J^P) = 0(\tfrac{3}{2}^-) \qquad \Gamma = 28 \pm 2 \pm 14\mathrm{MeV}/c^2$$

well-established states, good agreement with PDG

$$\Sigma_c(3050)^+/\Sigma_c(3050)^{++} \rightarrow \quad m = 3060 \pm 2 \pm 9.0\mathrm{MeV}/c^2$$

$$\Gamma = 69 \pm 12 \pm 52\mathrm{MeV}/c^2$$

possible interpretation: isospin partners

Measurement of the Ω_c^0 baryon lifetime

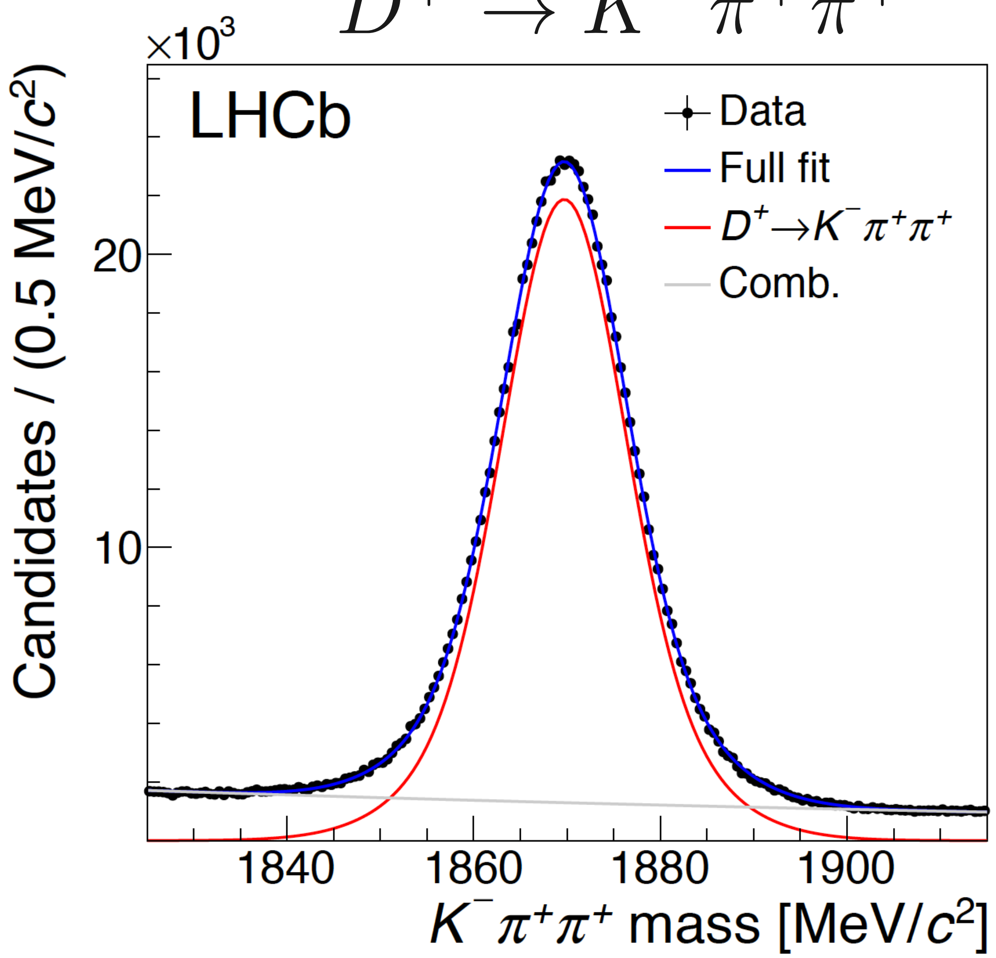
- HQE: inclusive decay rates through an expansion in powers of $\frac{1}{m_Q}$
- In the limit $m_Q \to \infty$, all H_Q hadrons have equal lifetimes
- Works well for *b* hadrons: $\tau(B^{\pm}) \sim \tau(B^0) \sim \tau(B_s^0) \sim \tau(\Lambda_b^0)$
- Fails for charm: $\tau(D^{\pm}) \sim 10 \times \tau(\Xi_c^0)$. Sizable higher-order corrections
- lifetimes are important for understanding non-perturbative effects
- expected lifetime hierarchy: $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$

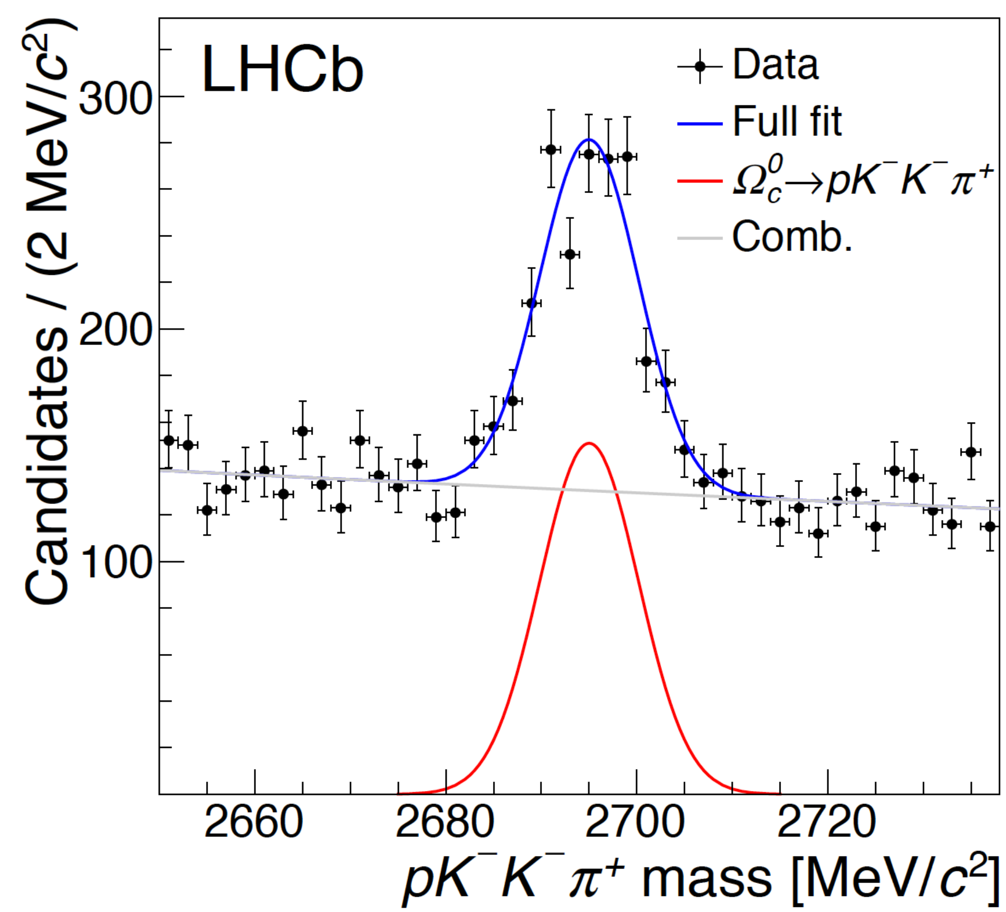
to reduce systematic uncertainties due to time-dependent efficiency:

$$r \equiv \frac{\tau(\Omega_c^0)}{\tau(D^+)} \quad \rightarrow \quad D^+ \text{ lifetime known to high accuracy}$$

$B \rightarrow D^+\mu^-\overline{\nu}_\mu X,$
$D^+ \rightarrow K^-\pi^+\pi^+$

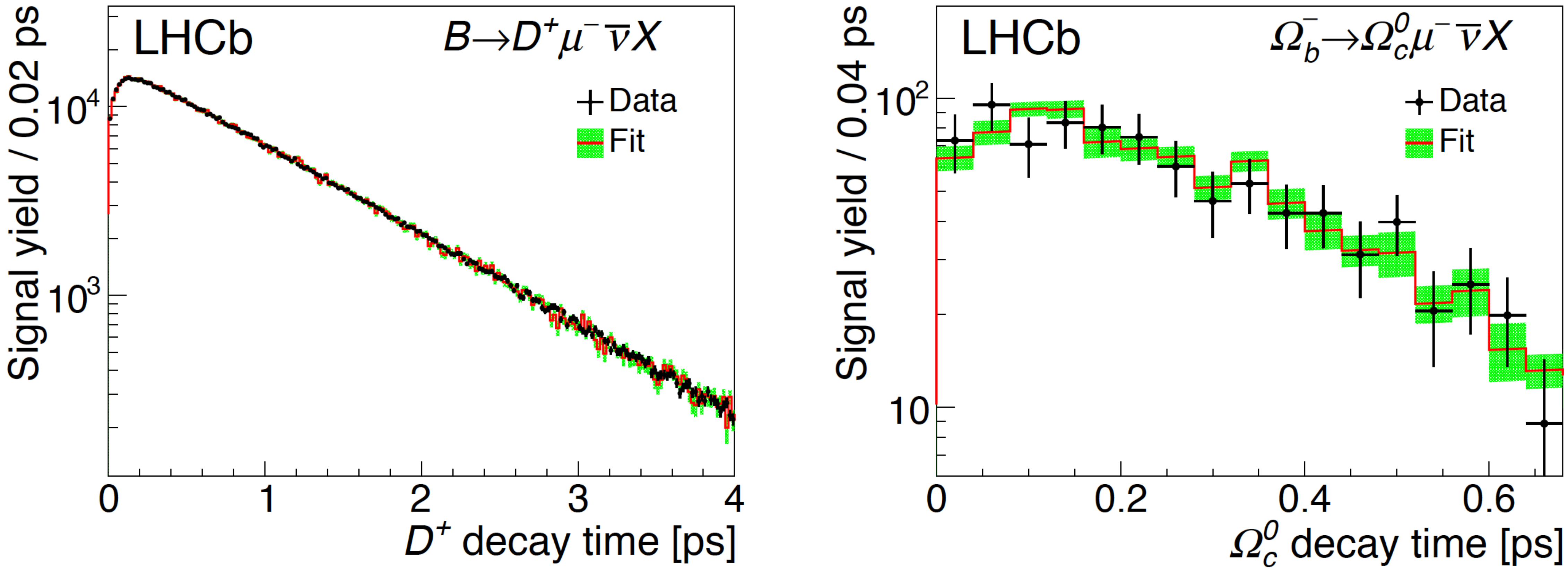
$\Omega_b^0 \rightarrow \Omega_c^0\mu^-\overline{\nu}_\mu X,$
$\Omega_c^0 \rightarrow pK^-K^-\pi^+$





Run 1 data: 978 ± 60 Ω_c^0 decays   PRL **121** (2018) 092003

decay-time distributions: computed from the positions of the H_c hadron and PV, and the H_c momentum ($\sigma_t \sim 85 - 100$ fs)



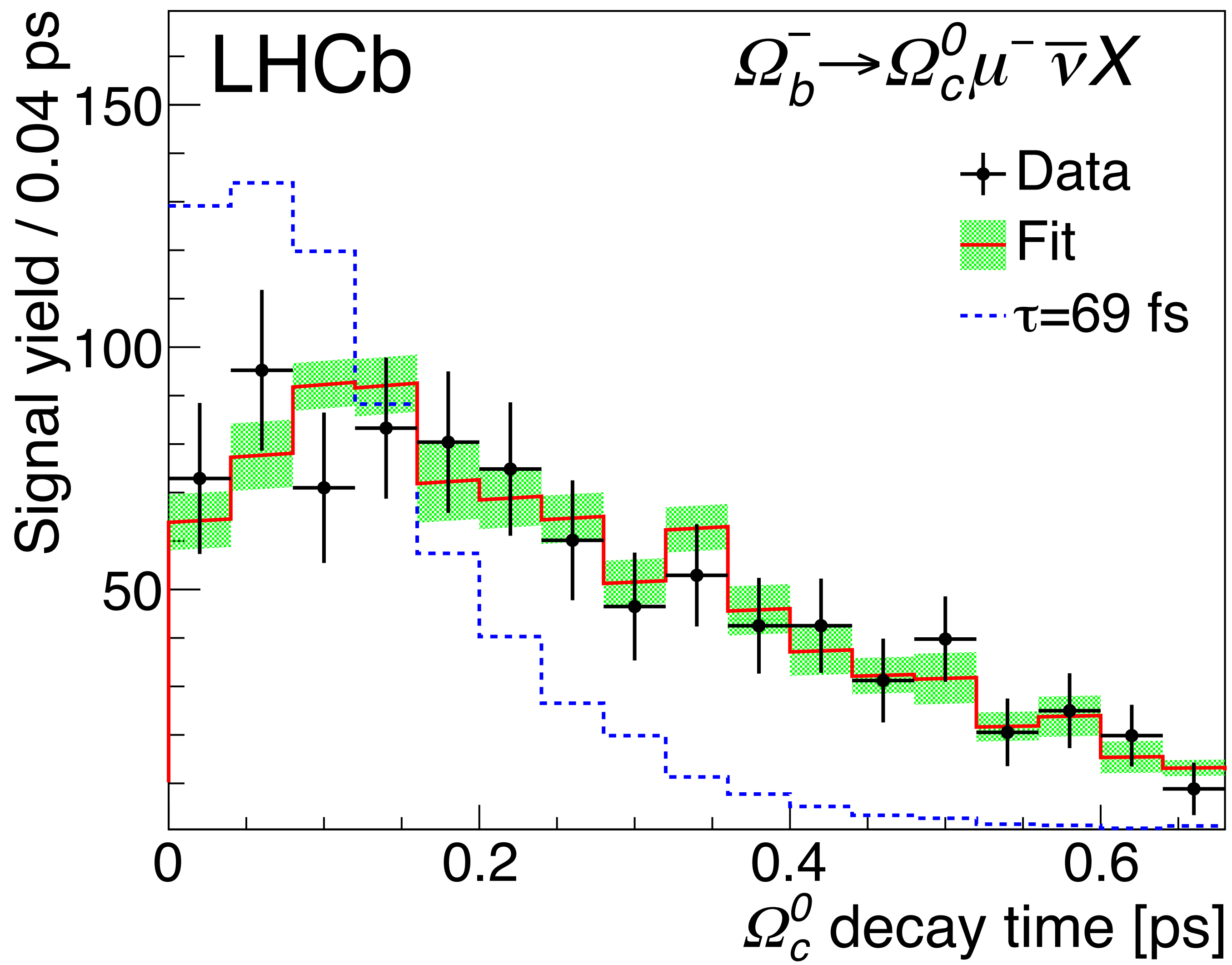
a simultaneous fit of the two H_c decay-time distributions:

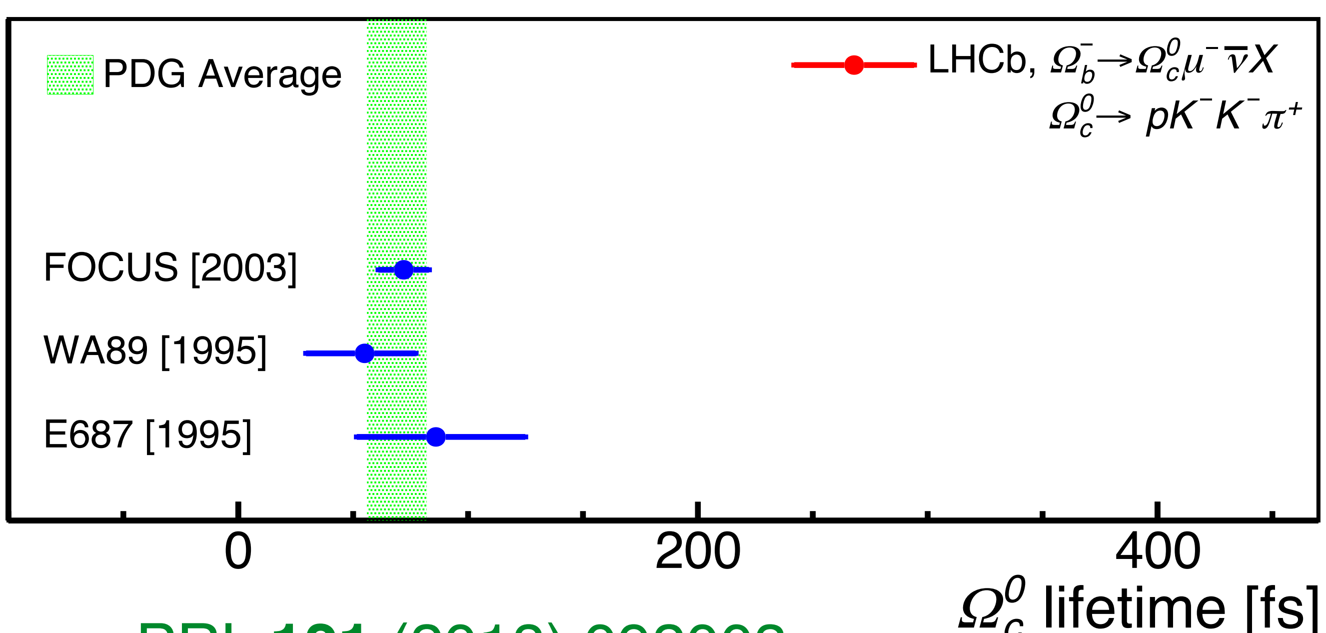
PRL **121** (2018) 092003

$$\frac{\tau(\Omega_c^0)}{\tau(D^+)} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$

previous world average: $\tau(\Omega_c^0) = 69 \pm 12 \text{ fs}$





PRL **121** (2018) 092003

the new lifetime hierarchy:

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

- Pauli interference between *s* quarks? $\Omega_c^0 = css$, $c \to W^+ s$
- spin of the ss system?
- Higher-order contributions in HQE from non-spectator diagrams?

Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}

- Quark model: Ξ_{cc} forms an isodoublet, $\Xi_{cc}^{++}(ccu)$ and $\Xi_{cc}^{+}(ccd)$
- Ξ_{cc}^{+} was not observed yet. $m(\Xi_{cc}^{++}) - m(\Xi_{cc}^{+})$ expected to be small

S. Fleck and J. Richard, Prog. Theo. Phys. **82** (1989) 760 :

More precisely, if one takes spin forces into account,[12)]

$$\mathcal{M}\left(ccu, \frac{2^+}{3}\right) \geq \frac{1}{2}\mathcal{M}(J/\Psi) + \mathcal{M}(D^*) \approx 3.56 \text{ GeV},$$

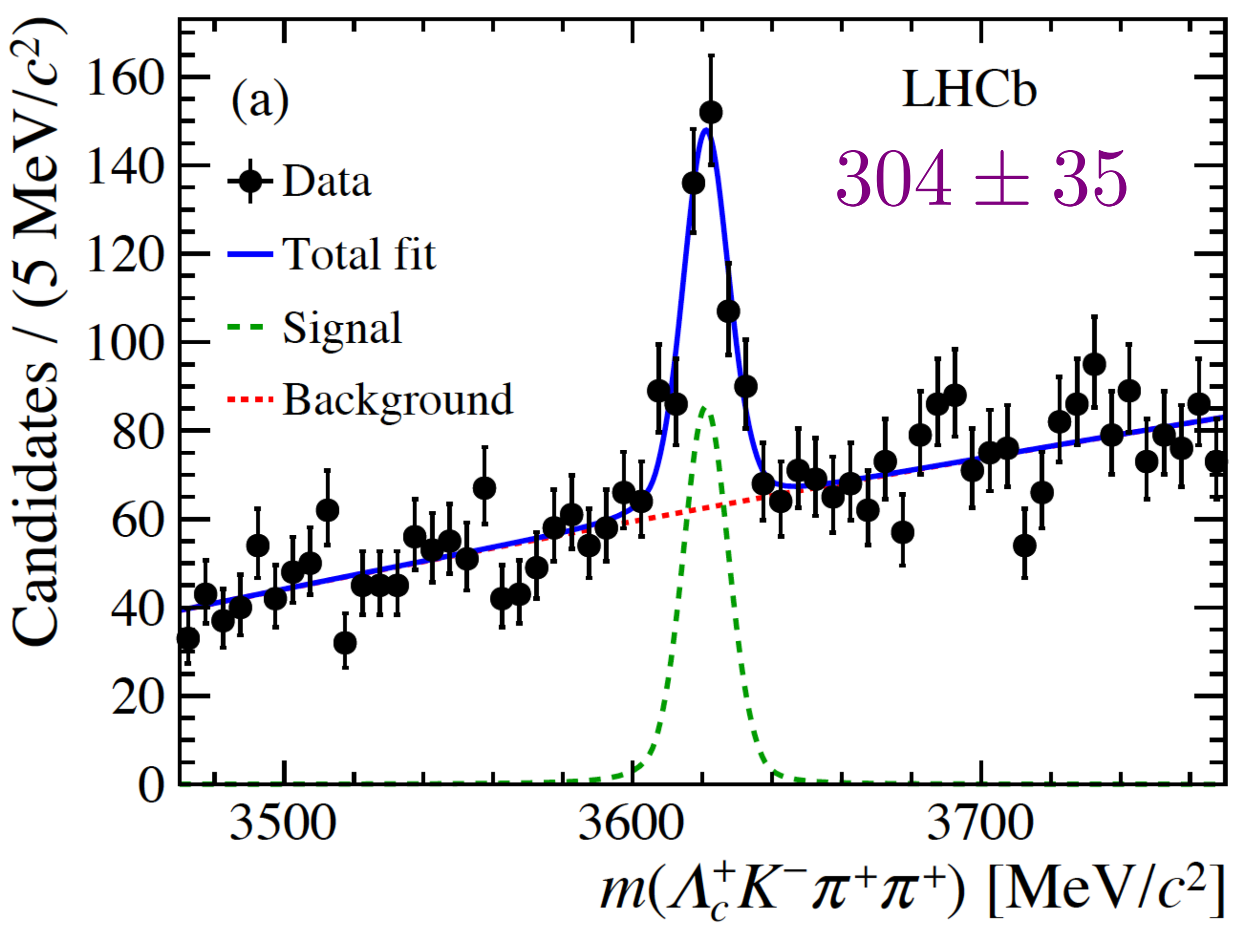
$$\mathcal{M}\left(ccu, \frac{1^+}{2}\right) \geq \frac{1}{2}\mathcal{M}(J/\Psi) + \frac{1}{4}\mathcal{M}(D^*) + \frac{3}{4}\mathcal{M}(D) \approx 3.45 \text{ GeV}. \quad (6)$$

It is very remarkable that, from the above inequalities, one predicts almost unambiguously the mass of the ground state (ccu) as:

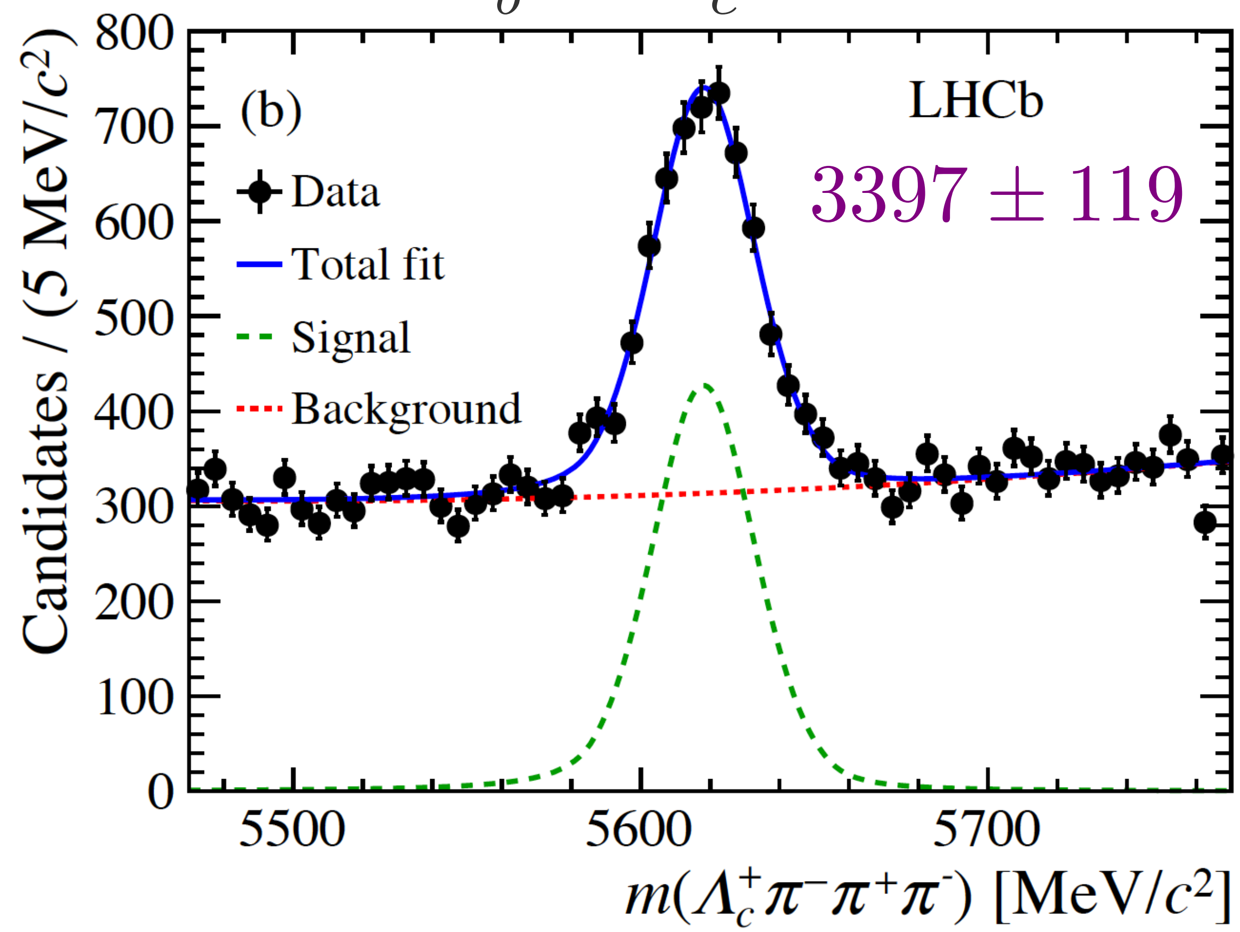
$$\mathcal{M} \approx 3.6 + 0.1 \text{ GeV}. \quad (7)$$

LHCb: $m(\Xi_{cc}^{++}) = 3.62140 \pm 0.00078 \text{ GeV}$ PRL 119 (2017) 112001

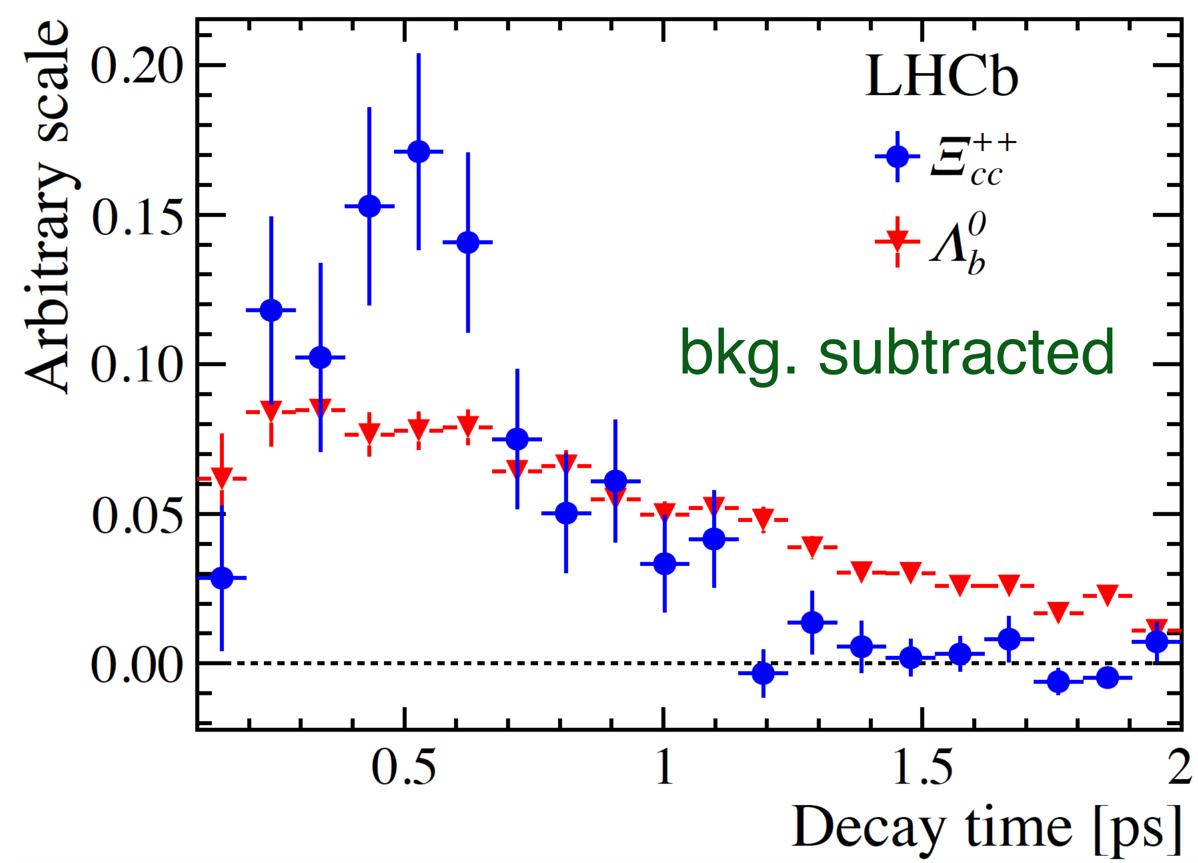
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+, \quad \Lambda_c^+ \to p K^- \pi^+$



$\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

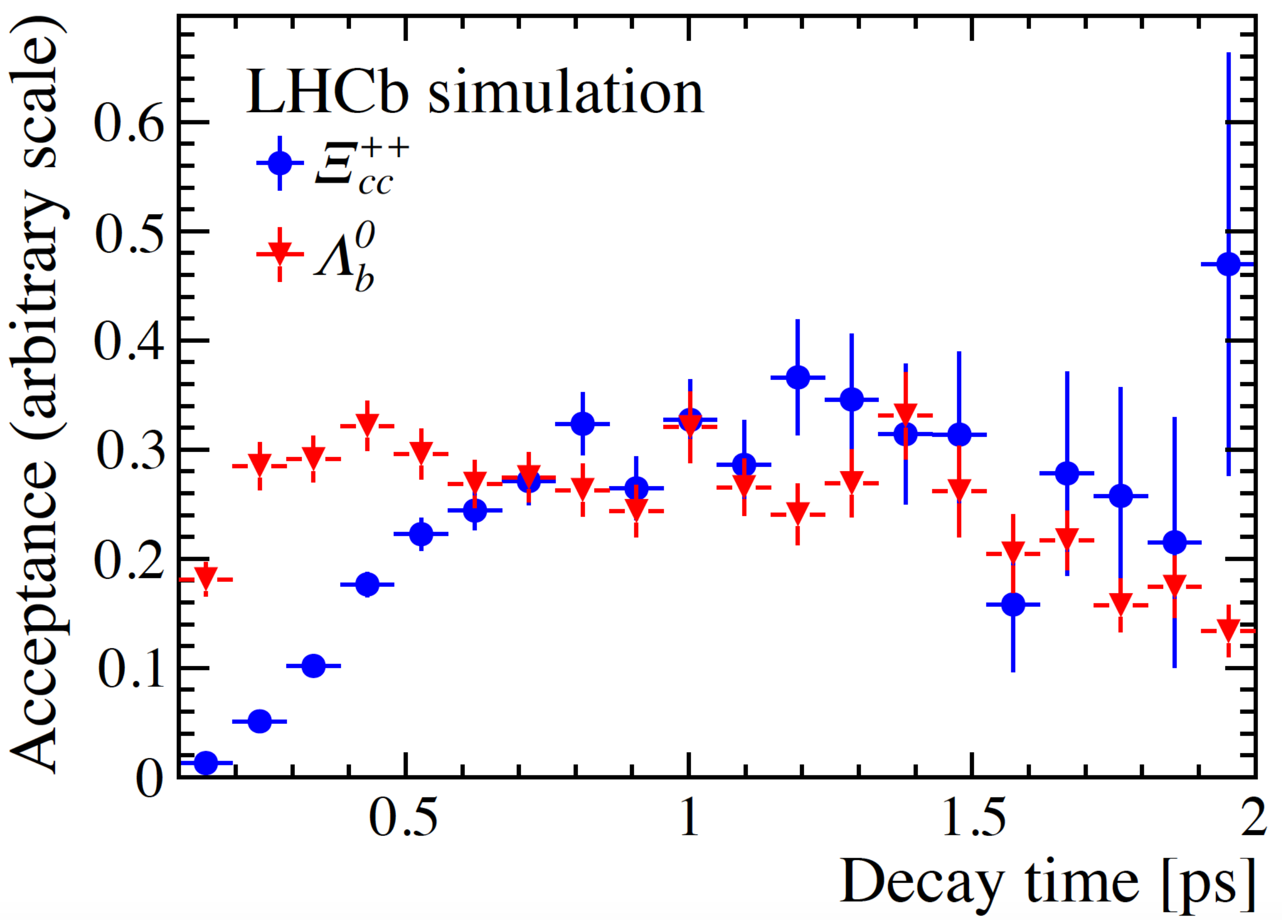


- first measurement of Ξ_{cc}^{++} lifetime
- control mode with similar topology: reduced systematic uncertainty
- $\sigma_t = 63$ fs for Ξ_{cc}^{++} and 32 fs for Λ_b^0
- 1.7 fb^{-1} @ 13 TeV (2015+2016)

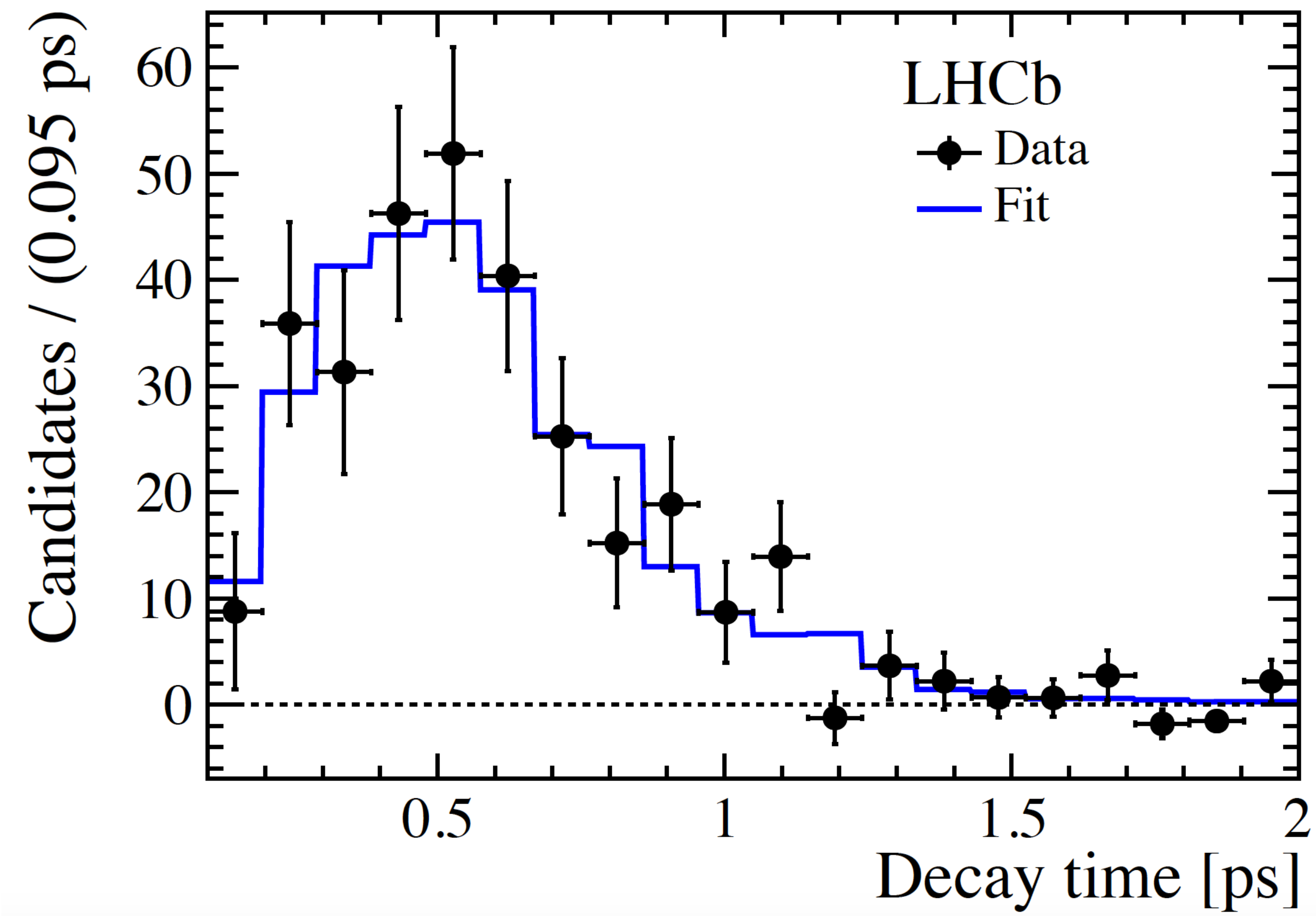


PRL **121** (2018) 052002

efficiency as a function of decay time



fitted decay-time distribution



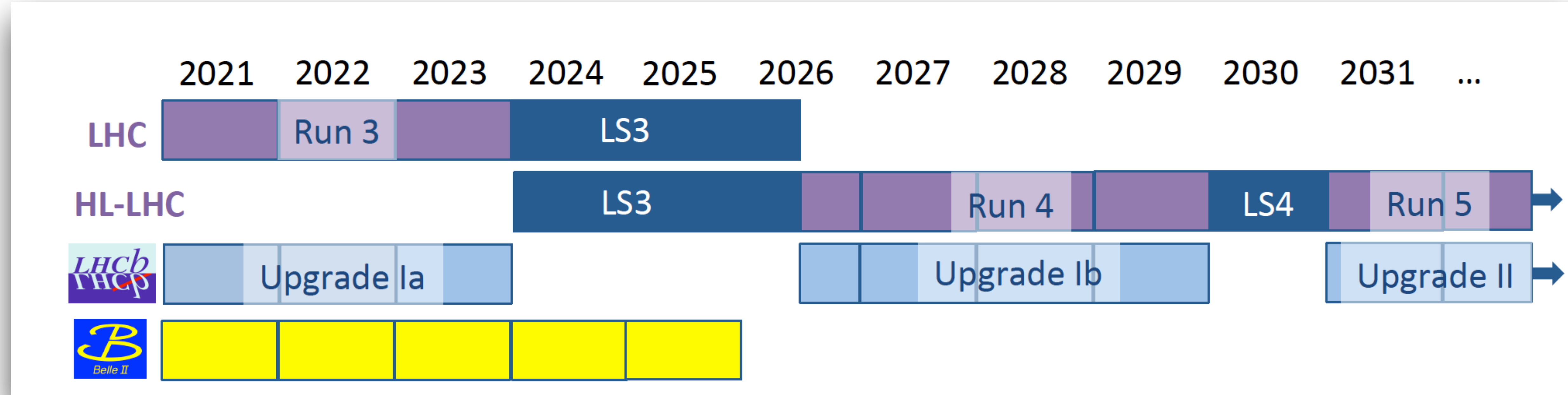
ratio of decay-time distributions

$$\frac{f_{\Xi_{cc}^{++}}(t)}{f_{\Lambda_b^0}(t)} = \frac{\varepsilon_{\Xi_{cc}^{++}}(t)}{\varepsilon_{\Lambda_b^0}} \times \exp\left(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})}\right)$$

$$\tau\left(\Xi_{cc}^{++}\right) = 0.256\,^{+0.024}_{-0.022}\,(\text{stat}) \pm 0.014\,(\text{syst})\ \text{ps}$$

weakly decaying nature of Ξ_{cc}^{++} is established

Looking ahead



- estimated uncertainty on γ : 1.5° with 23 fb^{-1}, and 0.35° with 300 fb^{-1}
- solution to the various anomalies: $R_{K^{(*)}}$, $R_{D^{(*)}}$, $R_{J/\psi}$, angular distributions
- precise measurements of $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$
- CPV in charm, precise measurement of charm-mixing parameters

New Physics may be discovered in the intensity limit!