Strange hadrons spectroscopy at LHCb

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University of Milano Bicocca and INFN

Physics at Amber international Workshop
Château de Bossey, 19.03.2024

Outline

The LHCb Experiment

Strange Hadrons at LHCb

Recent Results

- Amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays (JHEP 02 (2019) 126)
- Studies of the resonance structure in $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ decays (Eur. Phys. J. C78 (2018) 443)
- Study of charmonium decays to $K^0_S K\pi$ in the $B \to (K^0_S K\pi)K$ channels (Phys. Rev. D 108, 032010 (2023))

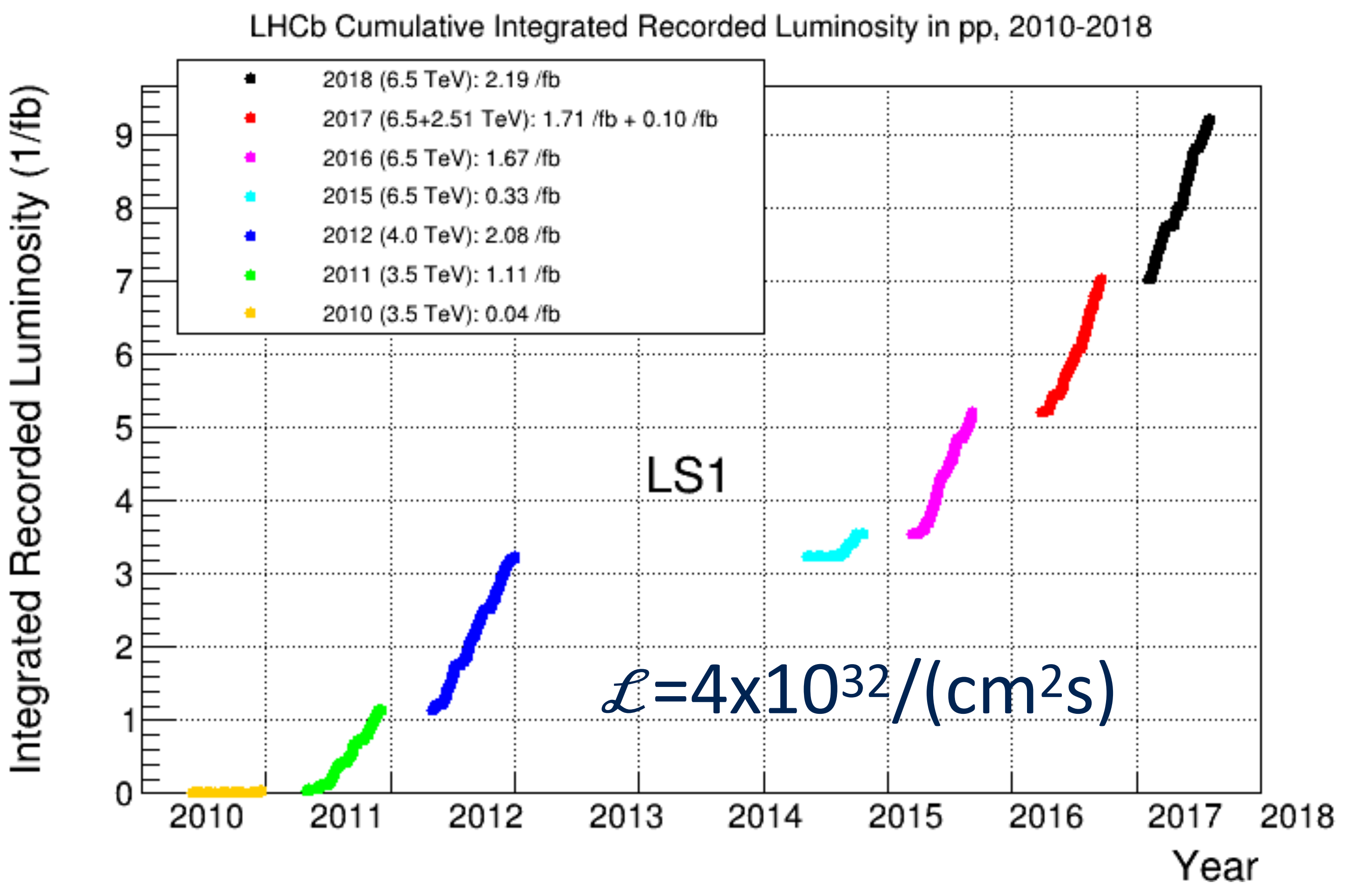
Summary

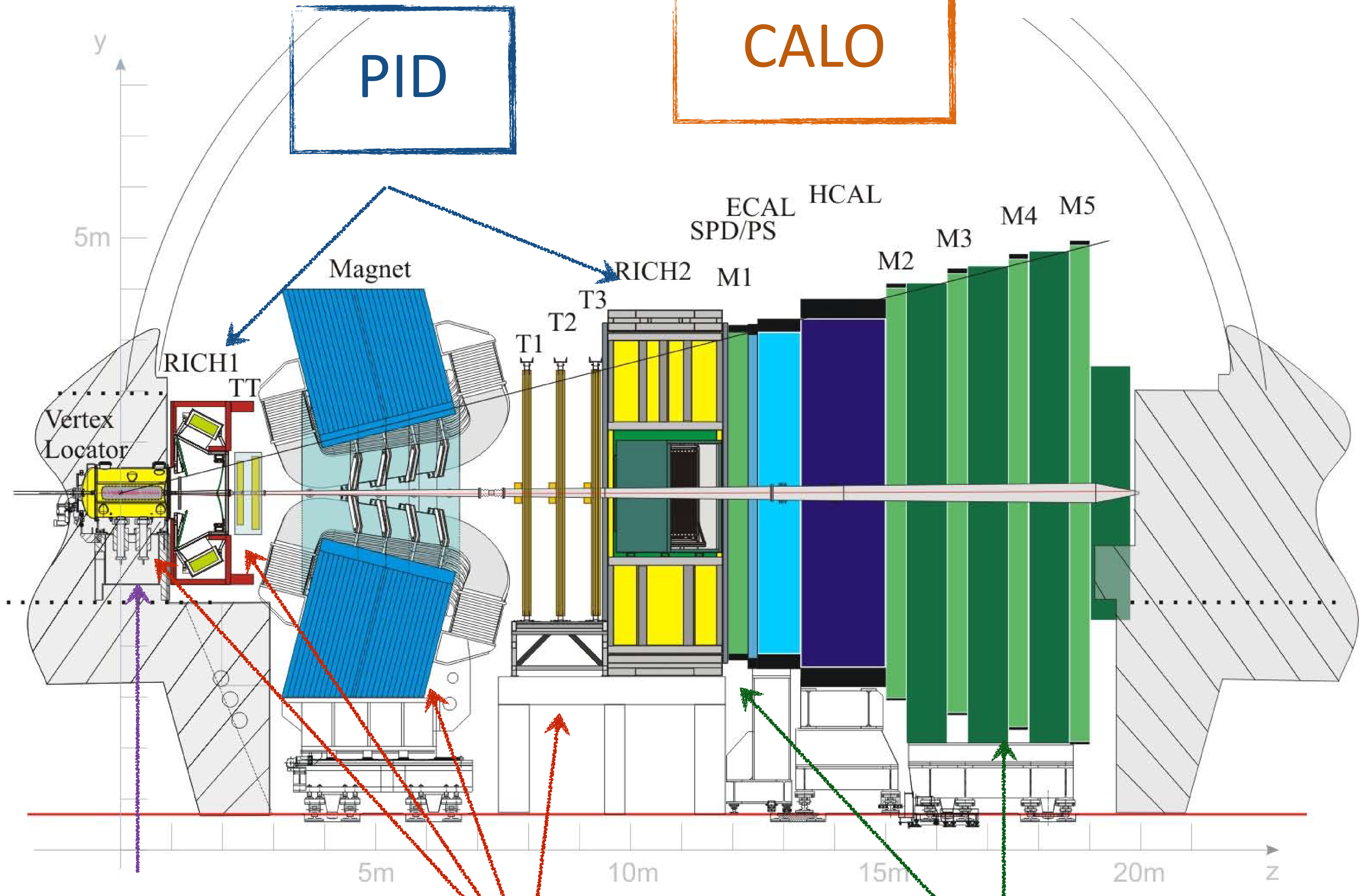
The LHCb Experiment

The LHCb Experiment

JINST 3 (2008) S08005

Charm quarks produced in high η at LHC
$\sigma(pp\to c\bar{c}) \sim 20\sigma(pp\to b\bar{b})$





$\varepsilon_{VELO}\approx 98\%$

$\delta t/t = 45 fs$

$\sigma(IP)\approx 20\mu m$

$\delta p/p \approx 0.5\%$

$\varepsilon_{Track}\approx 95\%$

$\varepsilon_{PID}(K)\approx 95\%$

$\varepsilon_{PID}(\mu)\approx 97\%$

$\varepsilon_{PID}(e)\approx 90\%$

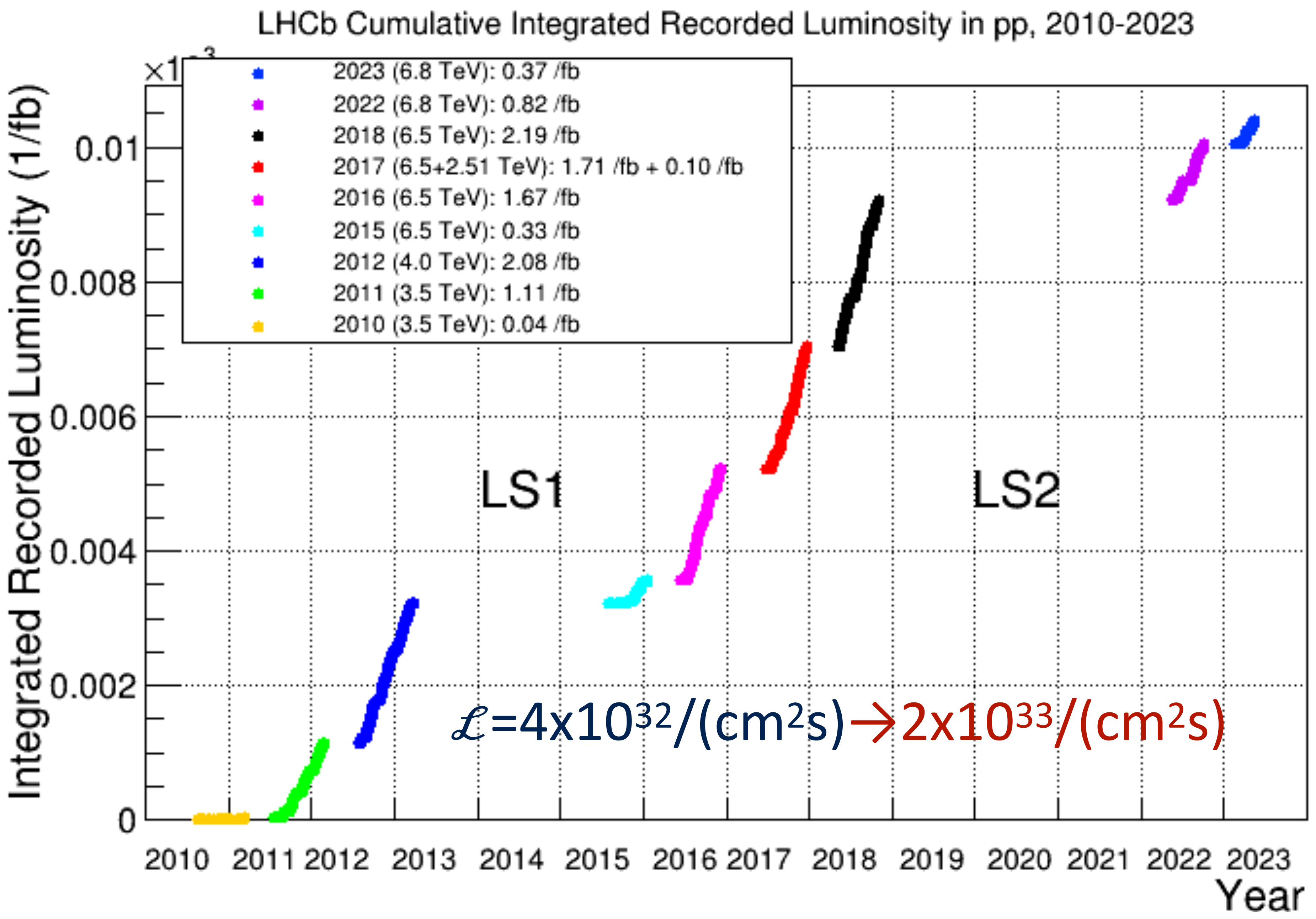
Int.J.Mod.Phys. A30 (2015) no.07, 1530022

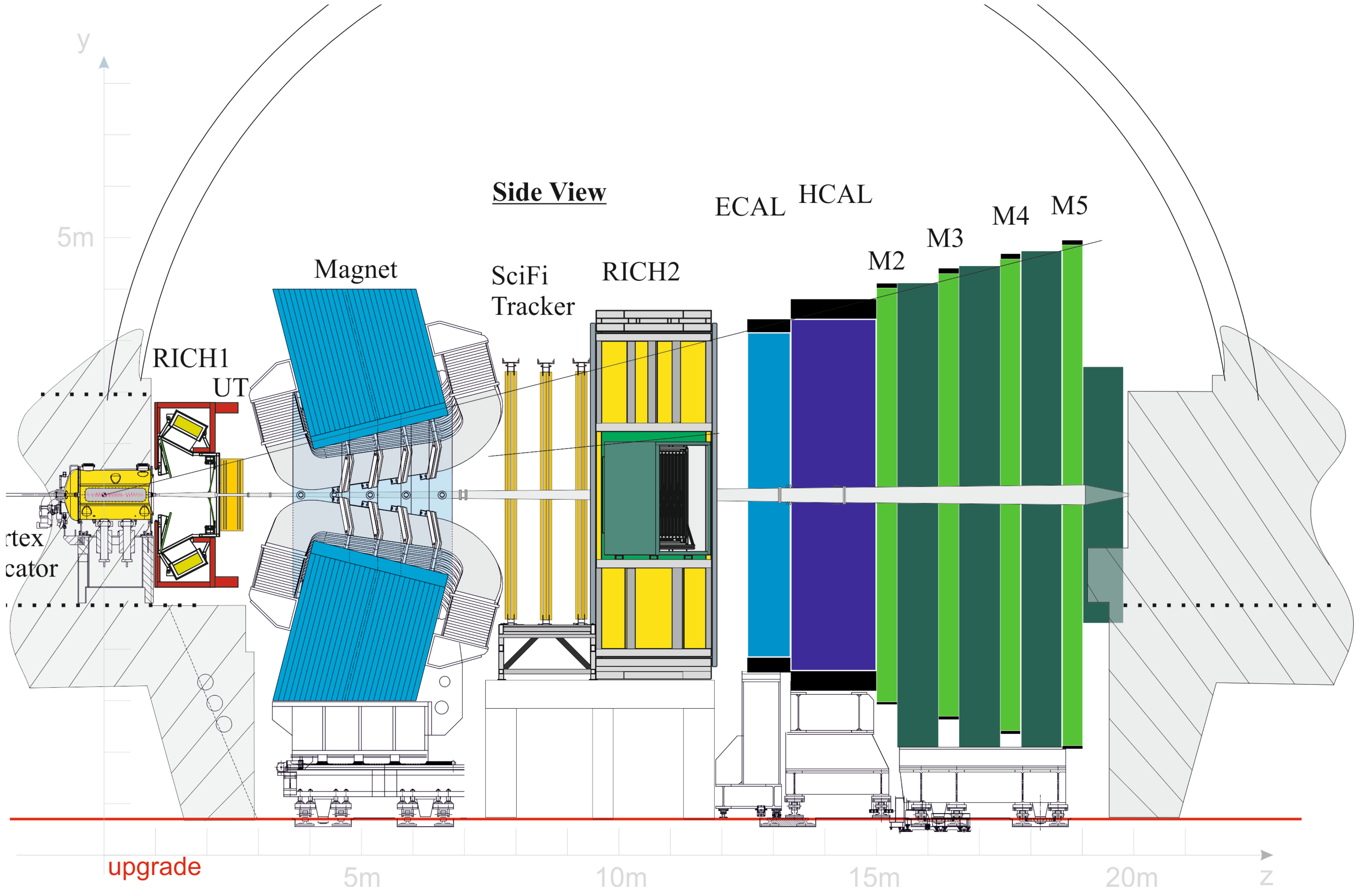
A New Detector for Run3 (2022-ongoing)

LHCb-DP-2022-002

LHCb Upgrade

- New Vertex Locator
- New Tracking Stations
- New RICH Electronics
- Fully Software Trigger



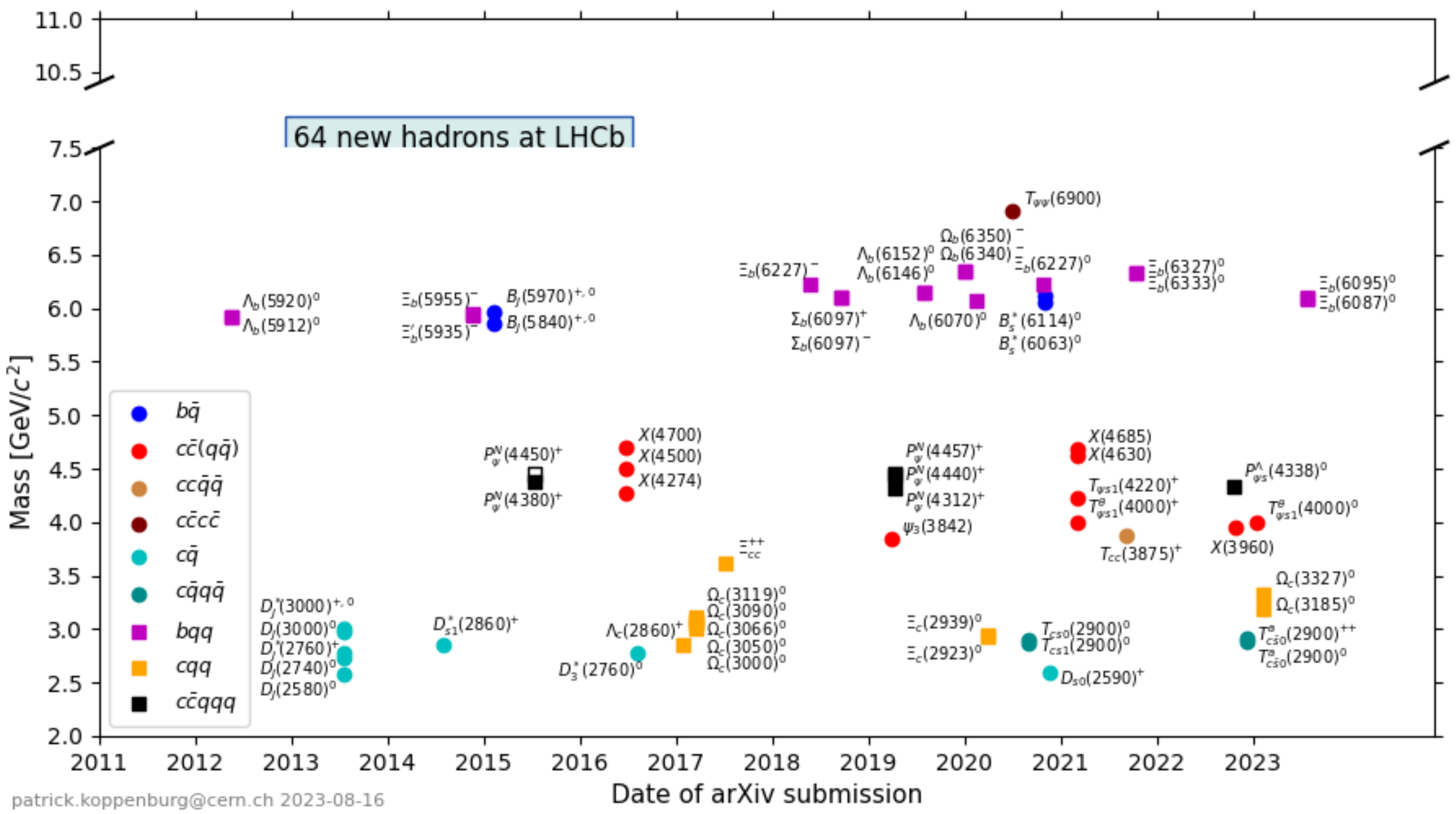


Strange Hadrons at LHCb

Spettroscopy at LHCb

Hadrons of Any Kind

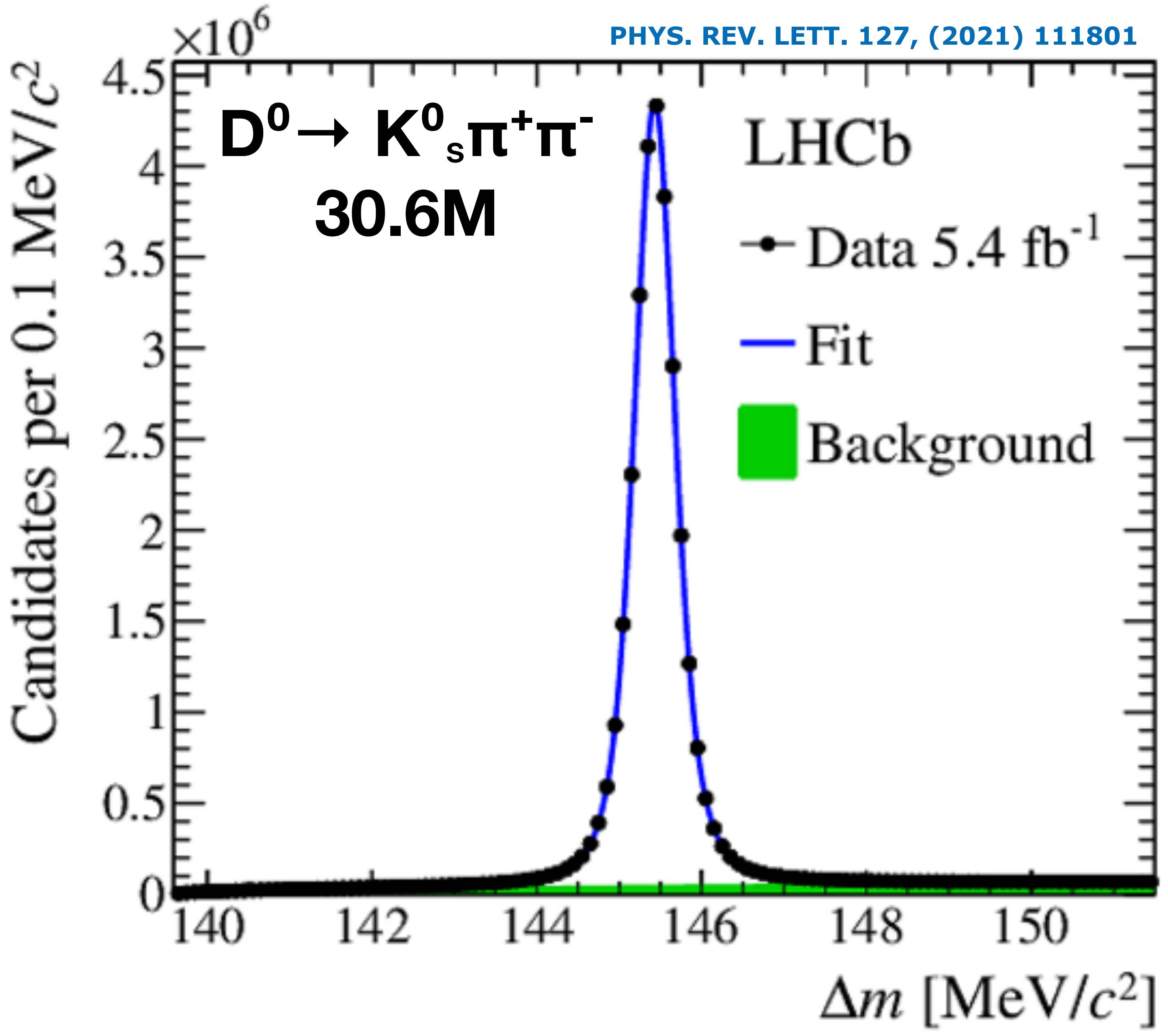
- **Mesons, Baryons, Tetraquarks, Pentaquarks**
- **Excellent PID performance**
- **Flexibility of the Trigger system**



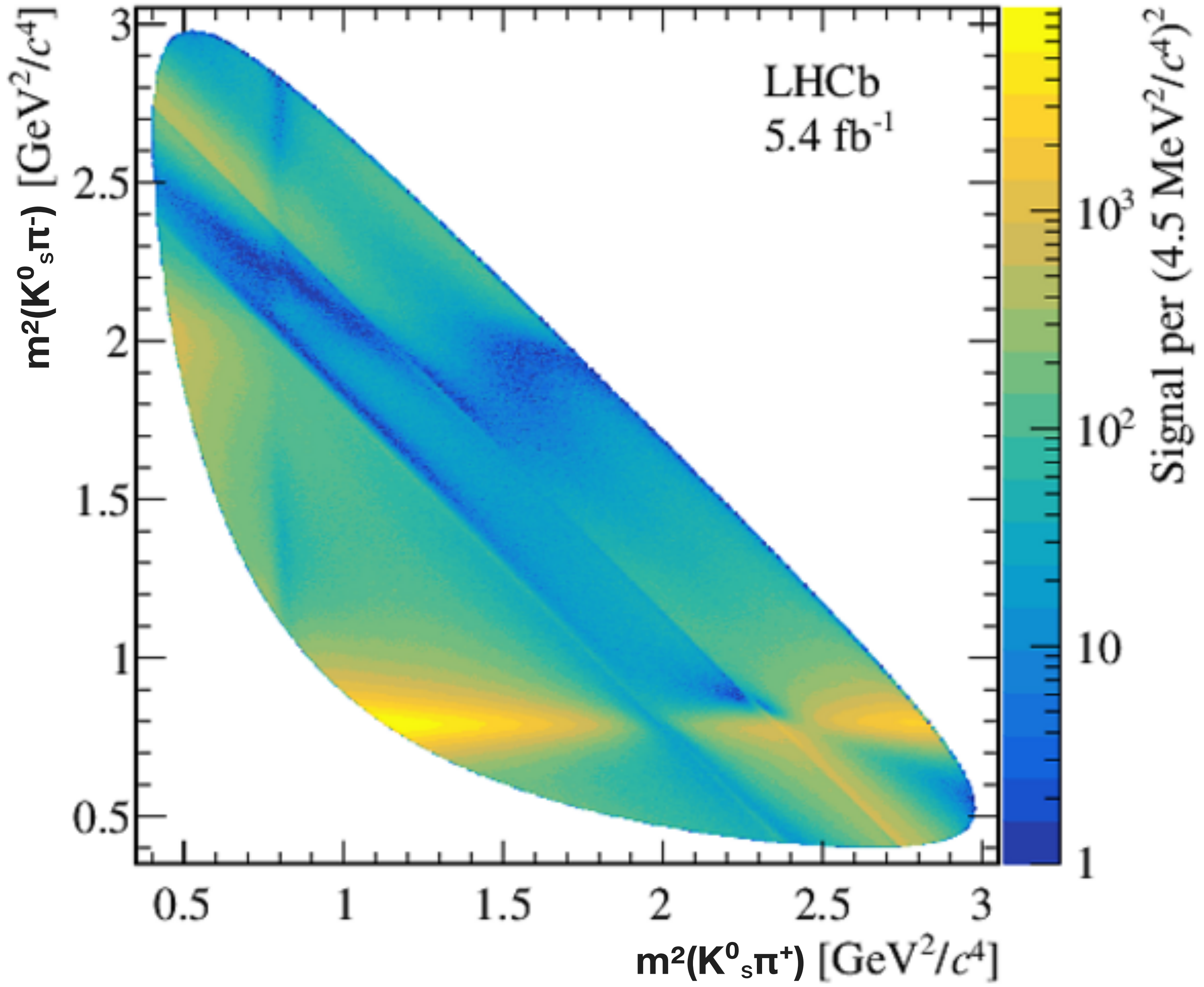
Light-Hadrons Spectroscopy at LHCb

Amplitude Analyses

- Direct production of light hadrons obviously happens but the multiplicity of tracks is so large that they are covered by large background
- Rather study resonances in heavy flavored particle decays (D, B, baryons)
- Allowed by clean signals and good understanding of detector efficiency



Dalitz Plot →



Recent Results

Strange Spectroscopy in D^0 Decays

Amplitude Analysis of 4-Body Charm Decays

- 4-Body Charm decays have a rich resonant structure, especially at low masses ($<1.7 GeV/c^2$)
- Good knowledge of the resonant substructure of the decay is important for other studies (i.e. CP Violation)
- With pseudoscalars only, 5D phase space

Amplitude Analysis of 4-Body D^0 Decays

B-tagged Decays

- **D^0 mesons reconstructed from $B \to D^{*+}\mu^- X$ with $D^{*+} \to D^0\pi^+$, or $B \to D^0\mu^- X$**
  Trigger selection on μ to improve efficiency determination
  Requirements on decay chain improve signal purity

Efficiency

- **Determined from simulation reconstructed as data**
- **Included in the fit by performing all the normalisation integrals over the simulated data - *integration sample***
- **Normalisation integrals independent from integration sample, but their uncertainty is → use approximation of model to generate the integration sample - *importance sampling***

Amplitude Analysis of 4-Body D^0 Decays

Isobar Model

- **Cascade decays**

$$D^0 \to X\,P_4$$
$$\hookrightarrow Y\,P_3$$
$$\hookrightarrow P_1 P_2$$

- **Quasi two-body decays**

$$D^0 \to X\,Y$$
$$\hookrightarrow P_3\,P_4$$
$$\hookrightarrow P_1\,P_2$$

- **Amplitudes are product of dynamical functions for each isobar and a spin factor**
  Dynamical functions: Breit-Wigner; K-matrix
  Spin factor from Covariant tensors

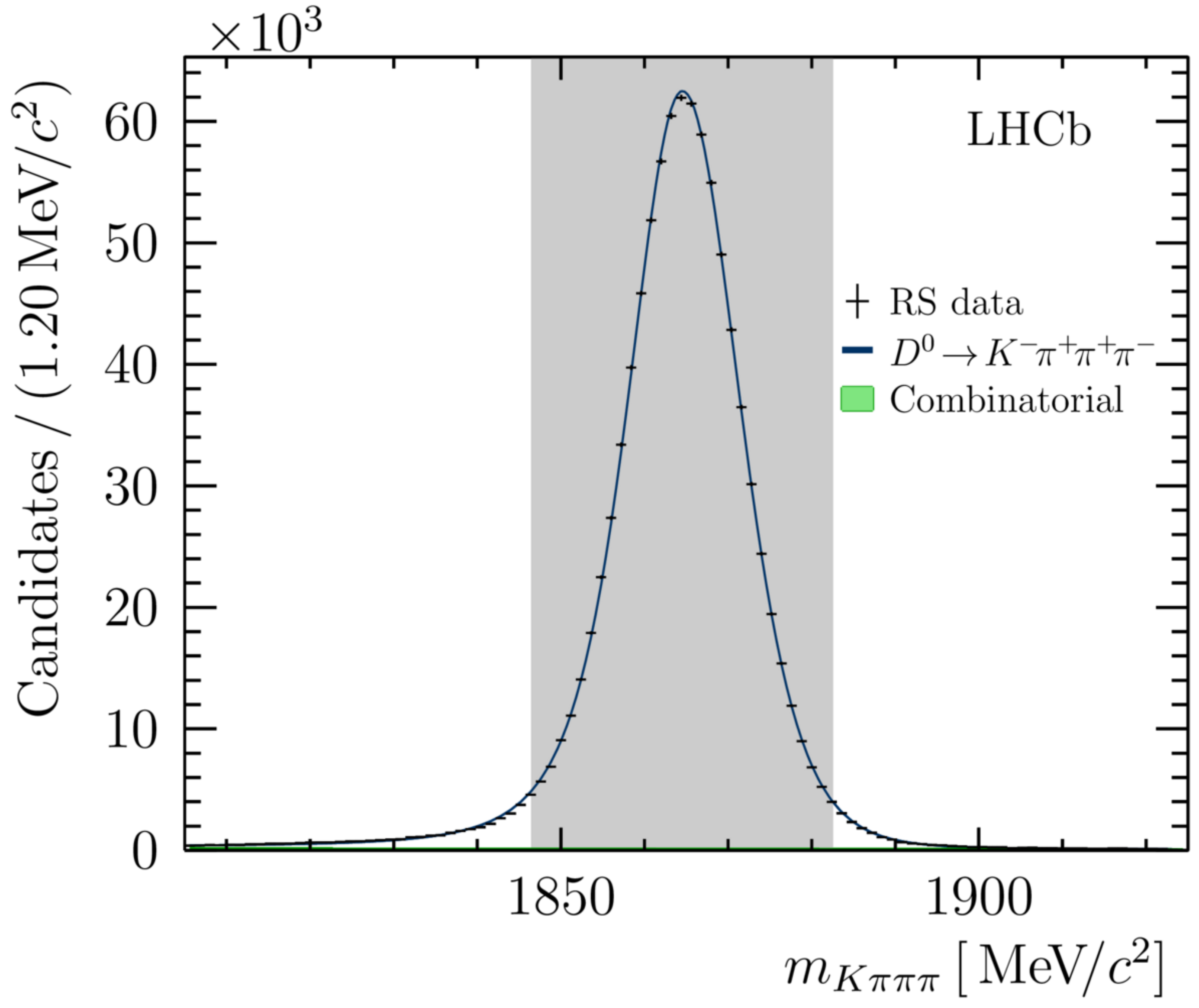
BW: $$\mathcal{T}(s) = \frac{\sqrt{k}B_L(q,0)}{m_0^2 - s - im_0\Gamma(s)}$$

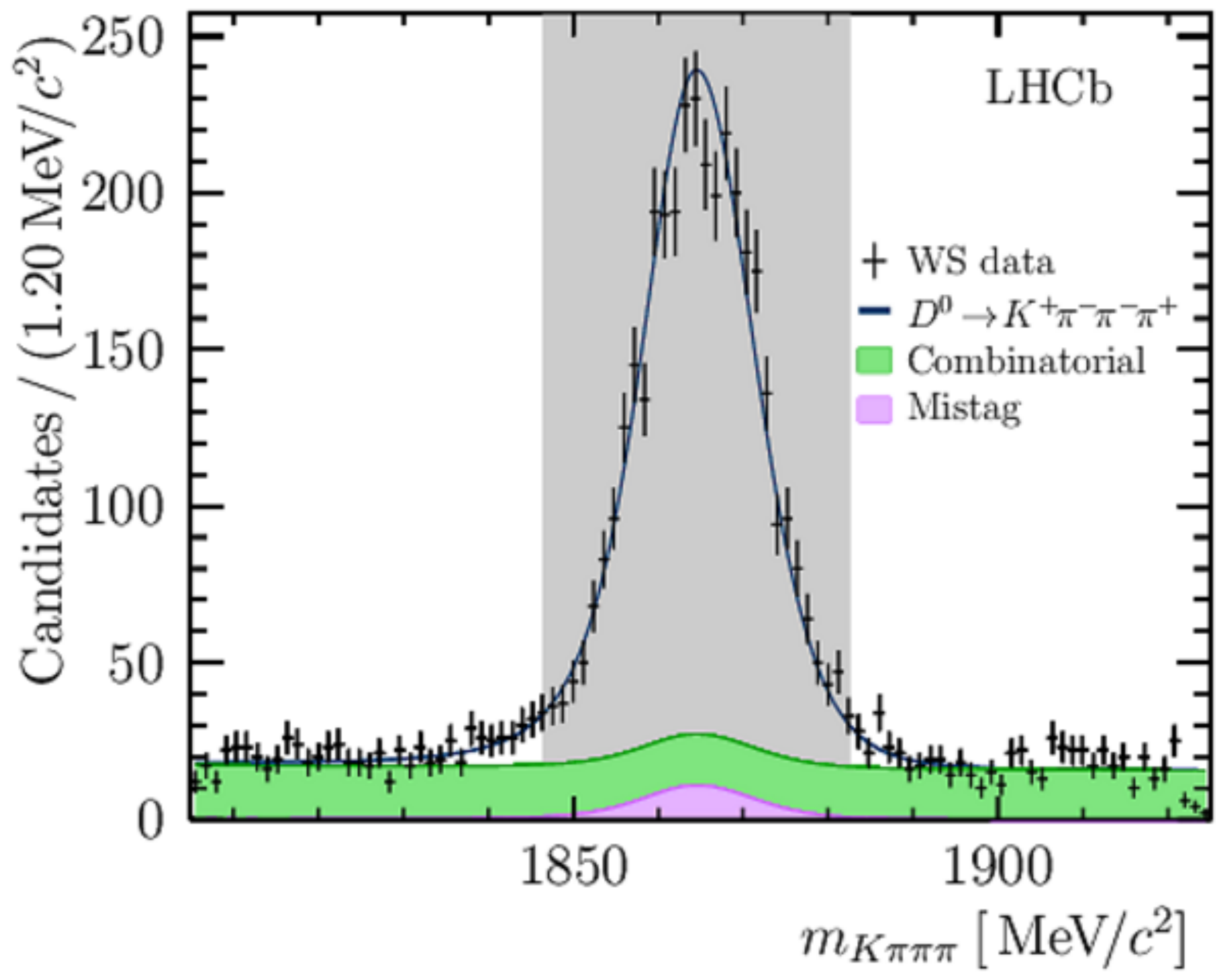
Signal Yields of $D^0 \to K^{\mp}\pi^{\pm}\pi^{\mp}\pi^{\pm}$

EUR. PHYS. J. C78 (2018) 443

RS and WS samples

- **Right-Sign: Cabibbo favoured $D^0 \to K^-\pi^+\pi^-\pi^+$ (N_S=891k, P=99.6% in 2011/12)**
- **Wrong-Sign: Doubly Cabibbo suppressed $D^0 \to K^+\pi^-\pi^+\pi^-$ (N_S=3k, P=82.4% in 2011/12)**
- **Contamination of RS in WS (Mistag)**





Resonant Structure of $D^0 \to K^\mp\pi^\pm\pi^\mp\pi^\pm$

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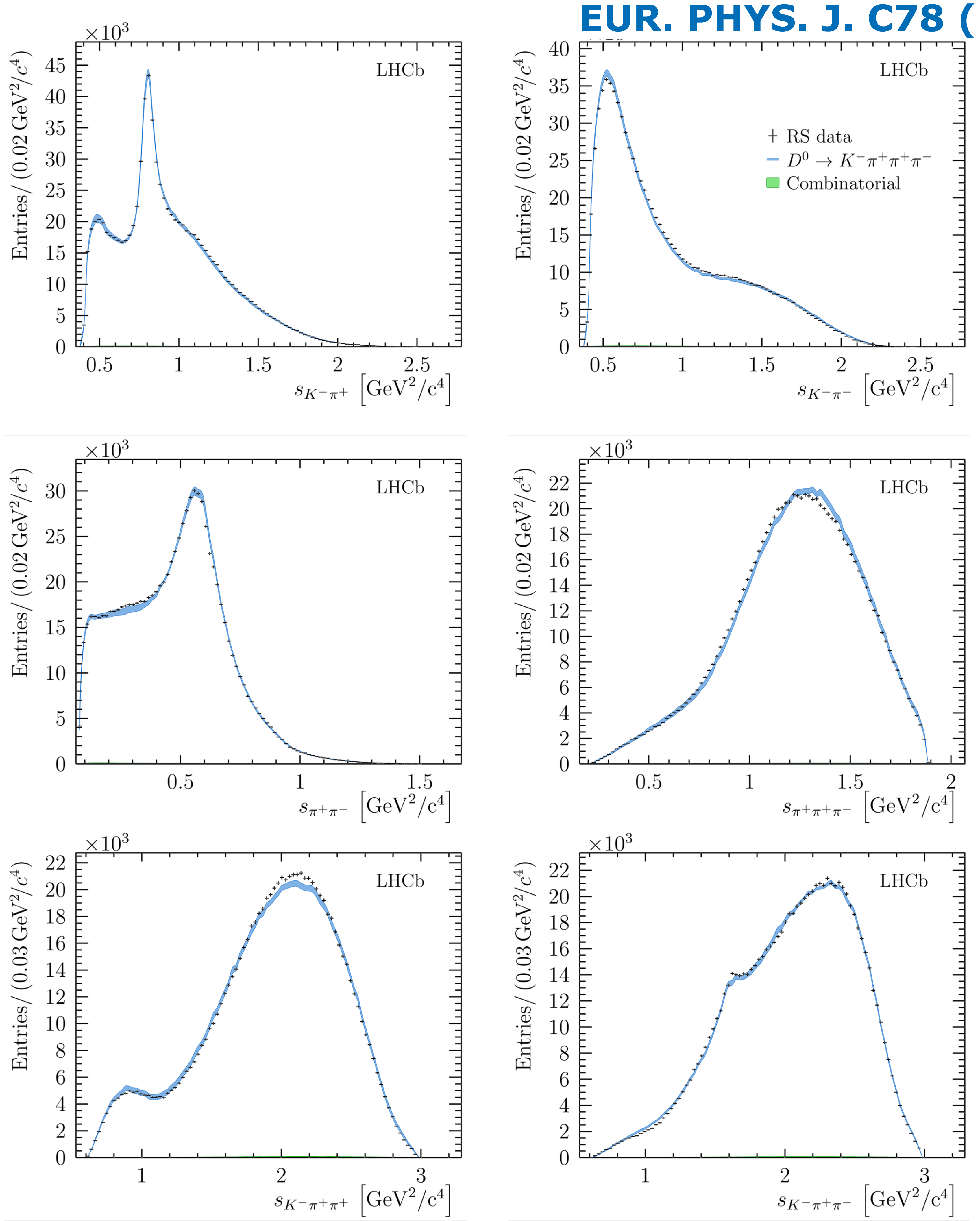
Fit Results $D^0 \to K^-\pi^+\pi^-\pi^+$

	Fit Fraction [%]	$\lvert g\rvert$	$\arg(g)[^o]$
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=0}$	$7.34 \pm 0.08 \pm 0.47$	$0.196 \pm 0.001 \pm 0.015$	$-22.4 \pm 0.4 \pm 1.6$
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=1}$	$6.03 \pm 0.05 \pm 0.25$	$0.362 \pm 0.002 \pm 0.010$	$-102.9 \pm 0.4 \pm 1.7$
$\left[\overline{K}^*(892)^0\rho(770)^0\right]^{L=2}$	$8.47 \pm 0.09 \pm 0.67$		
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=0}$	$0.61 \pm 0.04 \pm 0.17$	$0.162 \pm 0.005 \pm 0.025$	$-86.1 \pm 1.9 \pm 4.3$
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=1}$	$1.98 \pm 0.03 \pm 0.33$	$0.643 \pm 0.006 \pm 0.058$	$97.3 \pm 0.5 \pm 2.8$
$\left[\rho(1450)^0\overline{K}^*(892)^0\right]^{L=2}$	$0.46 \pm 0.03 \pm 0.15$	$0.649 \pm 0.021 \pm 0.105$	$-15.6 \pm 2.0 \pm 4.1$
$\rho(770)^0\left[K^-\pi^+\right]^{L=0}$	$0.93 \pm 0.03 \pm 0.05$	$0.338 \pm 0.006 \pm 0.011$	$73.0 \pm 0.8 \pm 4.0$
$\alpha_{3/2}$		$1.073 \pm 0.008 \pm 0.021$	$-130.9 \pm 0.5 \pm 1.8$
$\overline{K}^*(892)^0\left[\pi^+\pi^-\right]^{L=0}$	$2.35 \pm 0.09 \pm 0.33$		
$f_{\pi\pi}$		$0.261 \pm 0.005 \pm 0.024$	$-149.0 \pm 0.9 \pm 2.7$
β_1		$0.305 \pm 0.011 \pm 0.046$	$65.6 \pm 1.5 \pm 4.0$
$a_1(1260)^+K^-$	$38.07 \pm 0.24 \pm 1.38$	$0.813 \pm 0.006 \pm 0.025$	$-149.2 \pm 0.5 \pm 3.1$
$K_1(1270)^-\pi^+$	$4.66 \pm 0.05 \pm 0.39$	$0.362 \pm 0.004 \pm 0.015$	$114.2 \pm 0.8 \pm 3.6$
$K_1(1400)^-\left[\overline{K}^*(892)^0\pi^-\right]\pi^+$	$1.15 \pm 0.04 \pm 0.20$	$0.127 \pm 0.002 \pm 0.011$	$-169.8 \pm 1.1 \pm 5.9$
$K_2^*(1430)^-\left[\overline{K}^*(892)^0\pi^-\right]\pi^+$	$0.46 \pm 0.01 \pm 0.03$	$0.302 \pm 0.004 \pm 0.011$	$-77.7 \pm 0.7 \pm 2.1$
$K(1460)^-\pi^+$	$3.75 \pm 0.10 \pm 0.37$	$0.122 \pm 0.002 \pm 0.012$	$172.7 \pm 2.2 \pm 8.2$
$\left[K^-\pi^+\right]^{L=0}\left[\pi^+\pi^-\right]^{L=0}$	$22.04 \pm 0.28 \pm 2.09$		
$\alpha_{3/2}$		$0.870 \pm 0.010 \pm 0.030$	$-149.2 \pm 0.7 \pm 3.5$
$\alpha_{K\eta'}$		$2.614 \pm 0.141 \pm 0.281$	$-19.1 \pm 2.4 \pm 12.0$
β_1		$0.554 \pm 0.009 \pm 0.053$	$35.3 \pm 0.7 \pm 1.6$
$f_{\pi\pi}$		$0.082 \pm 0.001 \pm 0.008$	$-147.0 \pm 0.7 \pm 2.2$
Sum of Fit Fractions	$98.29 \pm 0.37 \pm 0.84$		
χ^2/ν	$40483/32701 = 1.238$		



Resonant Structure of $D^0 \to K^\mp\pi^\pm\pi^\mp\pi^\pm$

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

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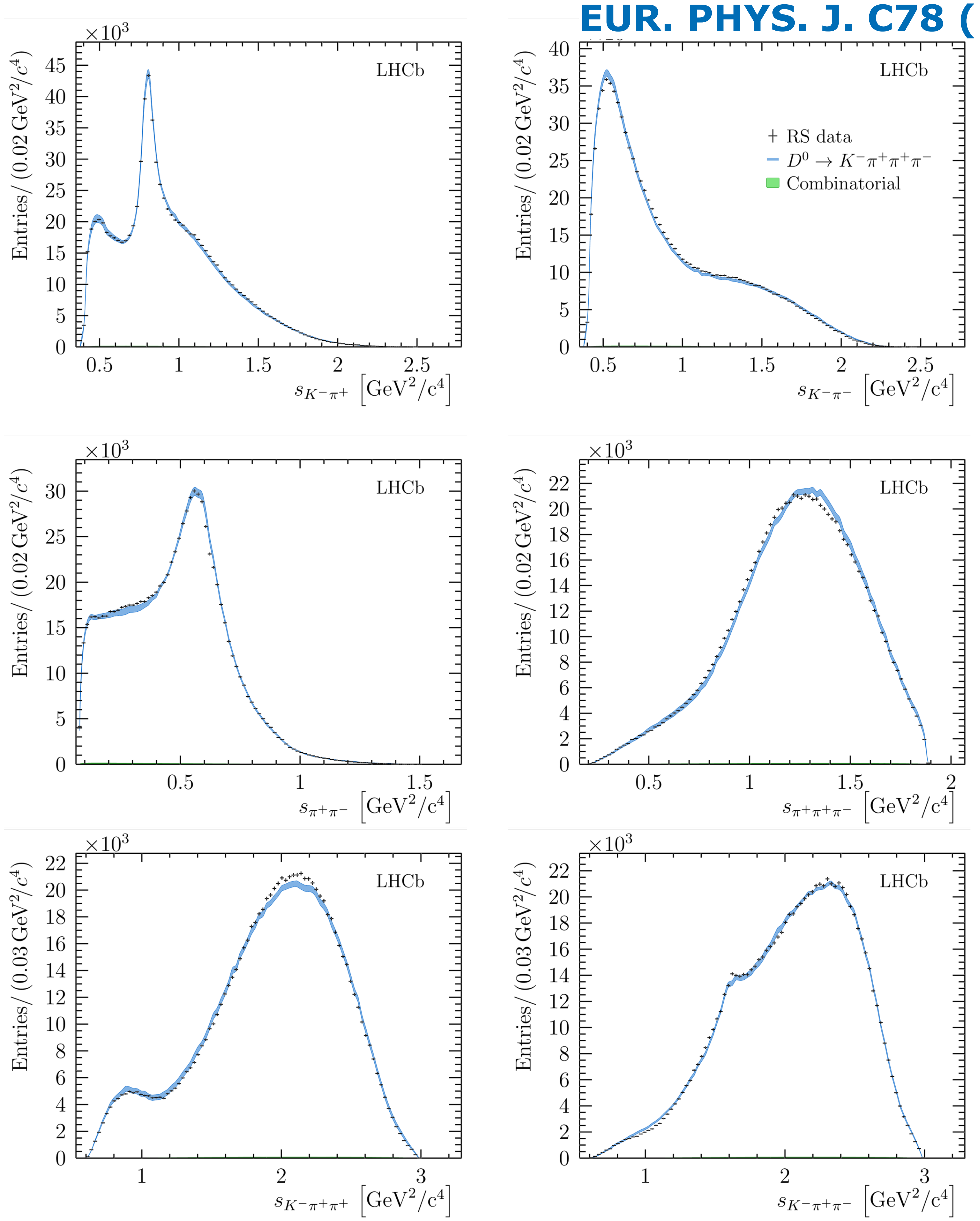

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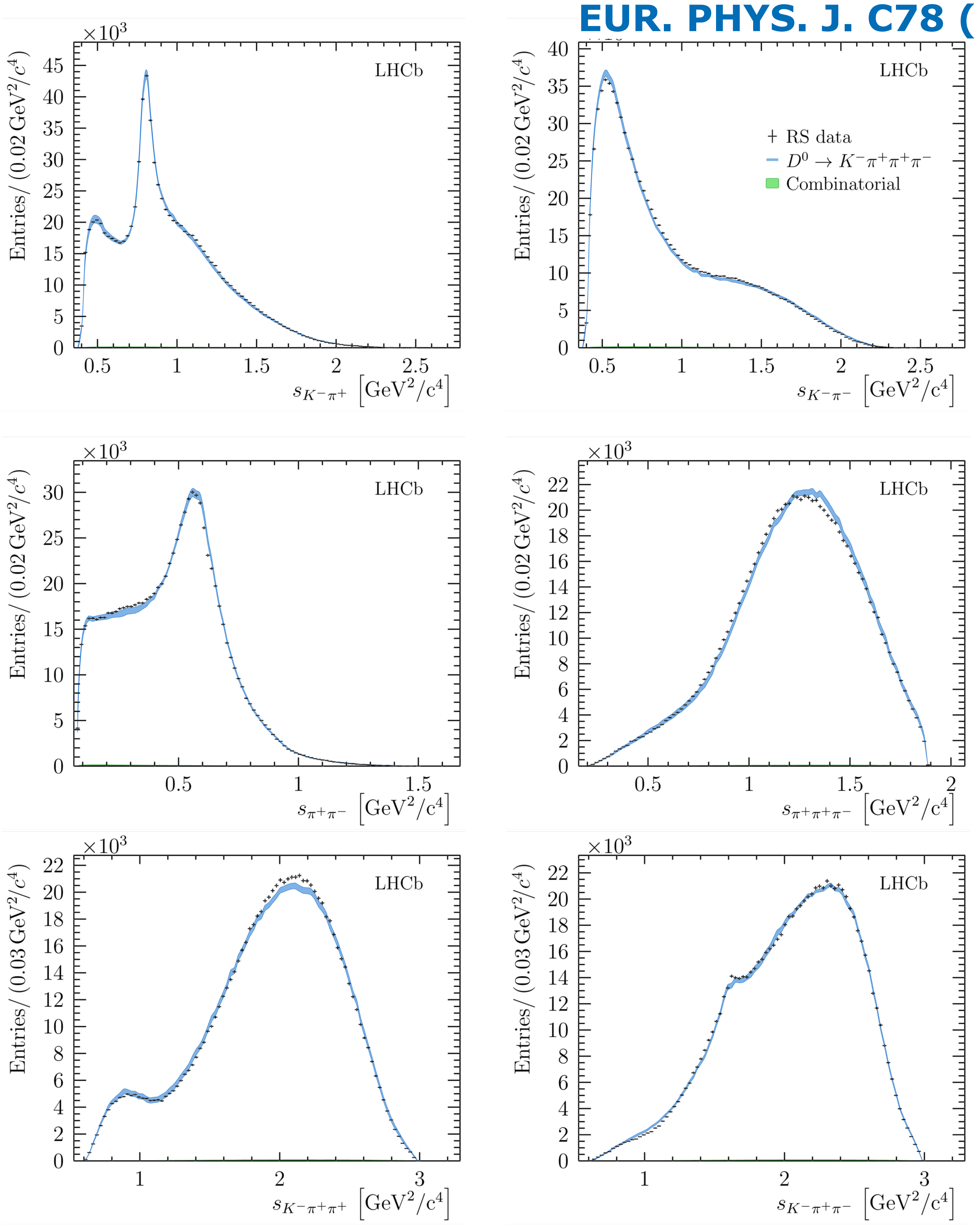

Strange Resonances in $D^0 \to K^\mp\pi^\pm\pi^\mp\pi^\pm$

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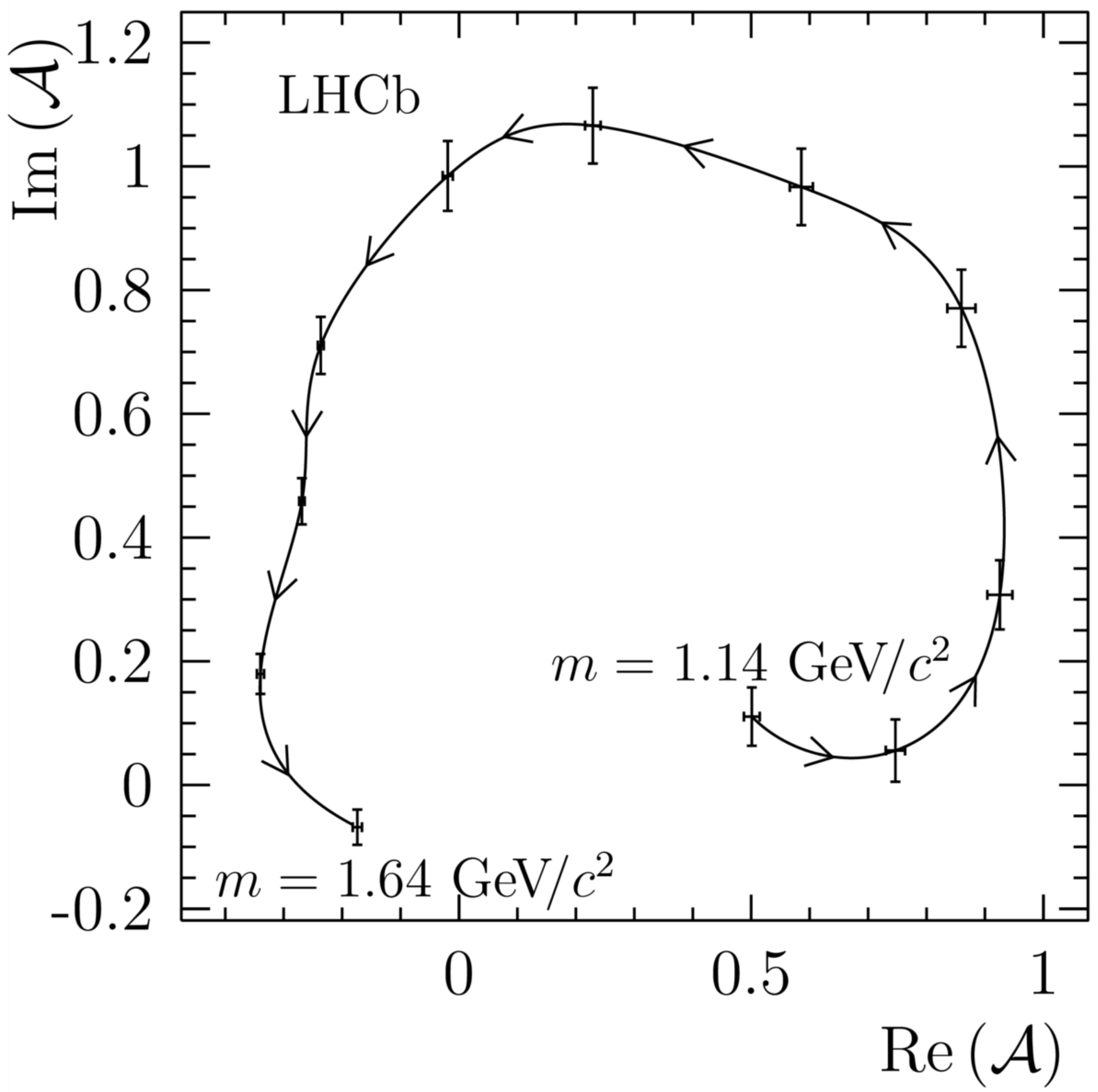
$K_1(1270)^-$

$K_1(1270)^-$ $m_0 = 1289.81 \pm 0.56 \pm 1.66\,\text{MeV}/c^2$; $\Gamma_0 = 116.11 \pm 1.65 \pm 2.96\,\text{MeV}/c^2$	Partial Fractions [%]	$\|g\|$	$\arg(g)[^o]$
$\rho(770)^0 K^-$	$96.30 \pm 1.64 \pm 6.61$		
$\rho(1450)^0 K^-$	$49.09 \pm 1.58 \pm 11.54$	$2.016 \pm 0.026 \pm 0.211$	$-119.5 \pm 0.9 \pm 2.3$
$\overline{K}^*(892)^0 \pi^-$	$27.08 \pm 0.64 \pm 2.82$	$0.388 \pm 0.007 \pm 0.033$	$-172.6 \pm 1.1 \pm 6.0$
$[K^-\pi^+]^{L=0}\,\pi^-$	$22.90 \pm 0.72 \pm 1.89$	$0.554 \pm 0.010 \pm 0.037$	$53.2 \pm 1.1 \pm 1.9$
$\left[\overline{K}^*(892)^0 \pi^-\right]^{L=2}$	$3.47 \pm 0.17 \pm 0.31$	$0.769 \pm 0.021 \pm 0.048$	$-19.3 \pm 1.6 \pm 6.7$
$\omega(782)\,[\pi^+\pi^-]\,K^-$	$1.65 \pm 0.11 \pm 0.16$	$0.146 \pm 0.005 \pm 0.009$	$9.0 \pm 2.1 \pm 5.7$

$K(1460)^-$

- The presence of this resonance is further justified by the Argand diagram from the Model Independent Partial Wave Analysis



$K(1460)^-$ $m_0 = 1482.40 \pm 3.58 \pm 15.22\,\text{MeV}/c^2$; $\Gamma_0 = 335.60 \pm 6.20 \pm 8.65\,\text{MeV}/c^2$	Partial Fractions [%]	$\|g\|$	$\arg(g)[^o]$
$\overline{K}^*(892)^0 \pi^-$	$51.39 \pm 1.00 \pm 1.71$		
$[\pi^+\pi^-]^{L=0}\,K^-$	$31.23 \pm 0.83 \pm 1.78$		
f_{KK}		$1.819 \pm 0.059 \pm 0.189$	$-80.8 \pm 2.2 \pm 6.6$
β_1		$0.813 \pm 0.032 \pm 0.136$	$112.9 \pm 2.6 \pm 9.5$
β_0		$0.315 \pm 0.010 \pm 0.022$	$46.7 \pm 1.9 \pm 3.0$

Resonant Structure of $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

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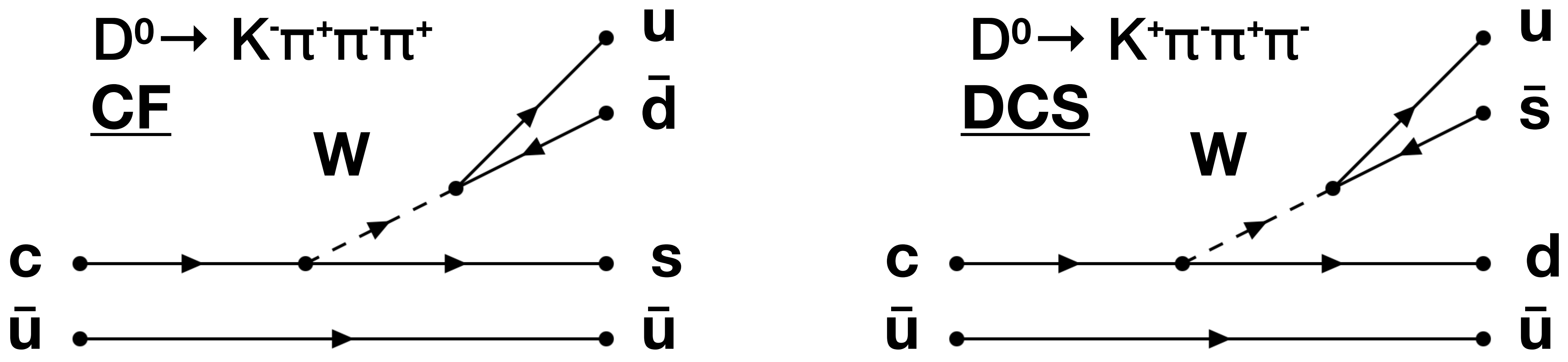
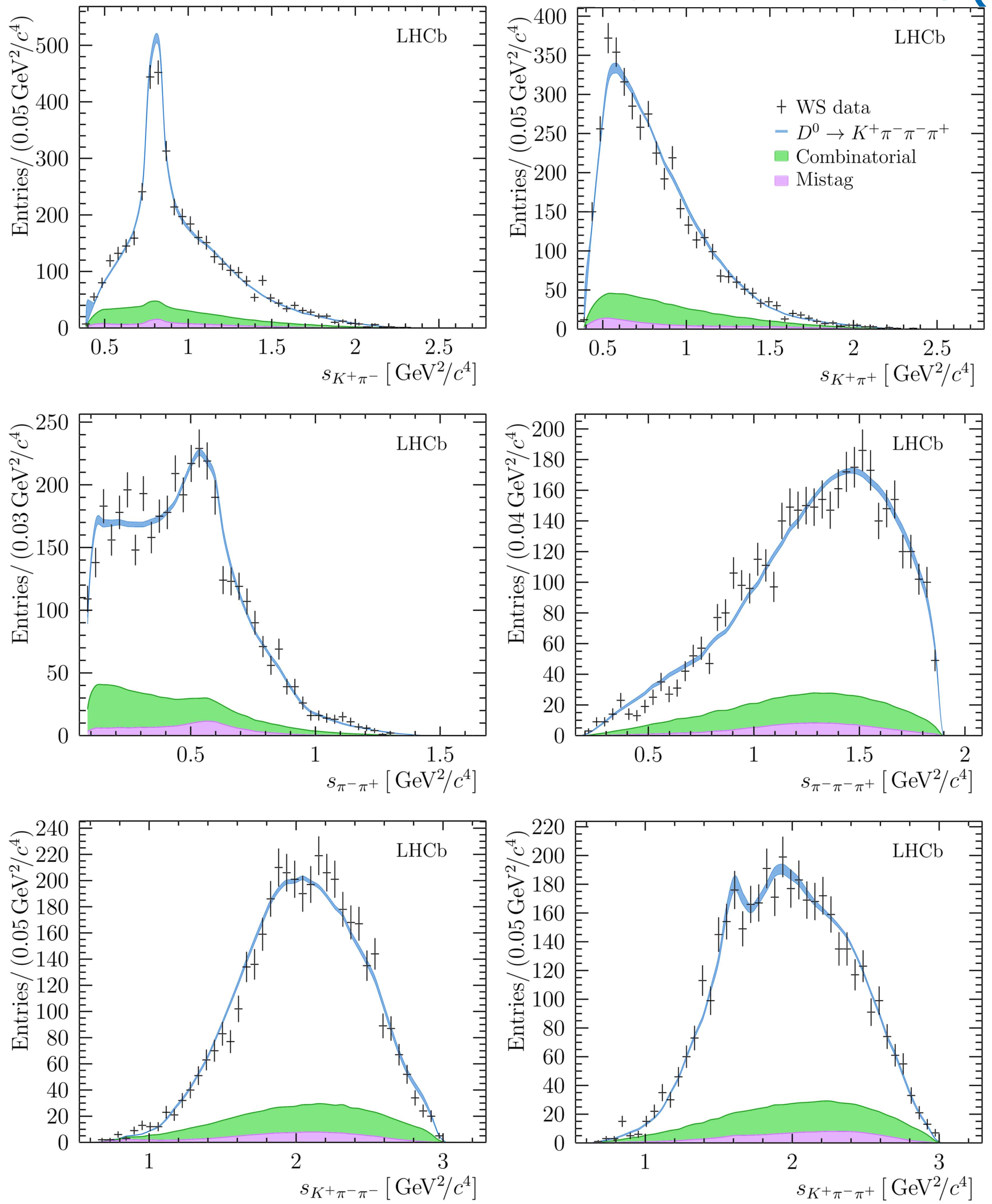
Fit Results $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

- 3-Body resonance parameters fixed to RS fit
- Largest fraction from $K_1\pi$ (colour-favoured W emission)

	Fit Fraction [%]	$\|g\|$	$\arg(g)[^o]$
$\left[K^*(892)^0\rho(770)^0\right]^{L=0}$	$9.62 \pm 1.58 \pm 1.03$	$0.205 \pm 0.019 \pm 0.010$	$-8.5 \pm 4.7 \pm 4.4$
$\left[K^*(892)^0\rho(770)^0\right]^{L=1}$	$8.42 \pm 0.83 \pm 0.57$	$0.390 \pm 0.029 \pm 0.006$	$-91.4 \pm 4.7 \pm 4.1$
$\left[K^*(892)^0\rho(770)^0\right]^{L=2}$	$10.19 \pm 1.03 \pm 0.79$		
$\left[\rho(1450)^0K^*(892)^0\right]^{L=0}$	$8.16 \pm 1.24 \pm 1.69$	$0.541 \pm 0.042 \pm 0.055$	$-21.8 \pm 6.5 \pm 5.5$
$K_1(1270)^+\pi^-$	$18.15 \pm 1.11 \pm 2.30$	$0.653 \pm 0.040 \pm 0.058$	$-110.7 \pm 5.1 \pm 4.9$
$K_1(1400)^+\left[K^*(892)^0\pi^+\right]\pi^-$	$26.55 \pm 1.97 \pm 2.13$	$0.560 \pm 0.037 \pm 0.031$	$29.8 \pm 4.2 \pm 4.6$
$\left[K^+\pi^-\right]^{L=0}\left[\pi^+\pi^-\right]^{L=0}$	$20.90 \pm 1.30 \pm 1.50$		
$\alpha_{3/2}$		$0.686 \pm 0.043 \pm 0.022$	$-149.4 \pm 4.3 \pm 2.9$
β_1		$0.438 \pm 0.044 \pm 0.030$	$-132.4 \pm 6.5 \pm 3.0$
$f_{\pi\pi}$		$0.050 \pm 0.006 \pm 0.005$	$74.8 \pm 7.5 \pm 5.3$
Sum of Fit Fractions	$101.99 \pm 2.90 \pm 2.85$		
χ^2/ν	$350/239 = 1.463$		





Signal Yield of $D^0 \rightarrow K^+K^-\pi^+\pi^-$

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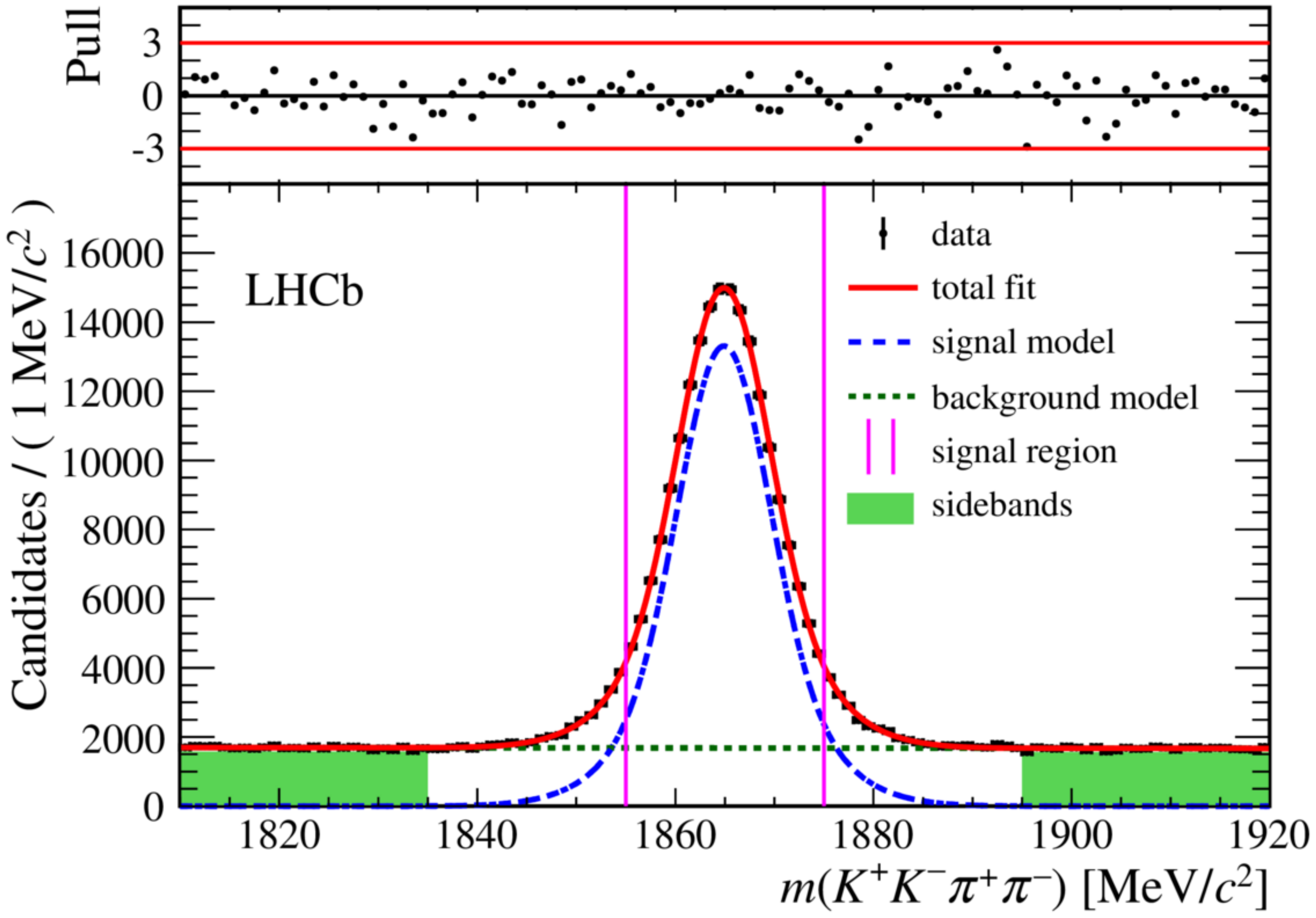
Run1 Sample (2011/12)

- Cabibbo suppressed $D^0 \rightarrow K^+K^-\pi^+\pi^-$ (N_S=160k, P=82.8%)
- Mass fit used to extract fraction of signal decays and background in ±2σ region



Resonant Structure of $D^0 \to K^+K^-\pi^+\pi^-$

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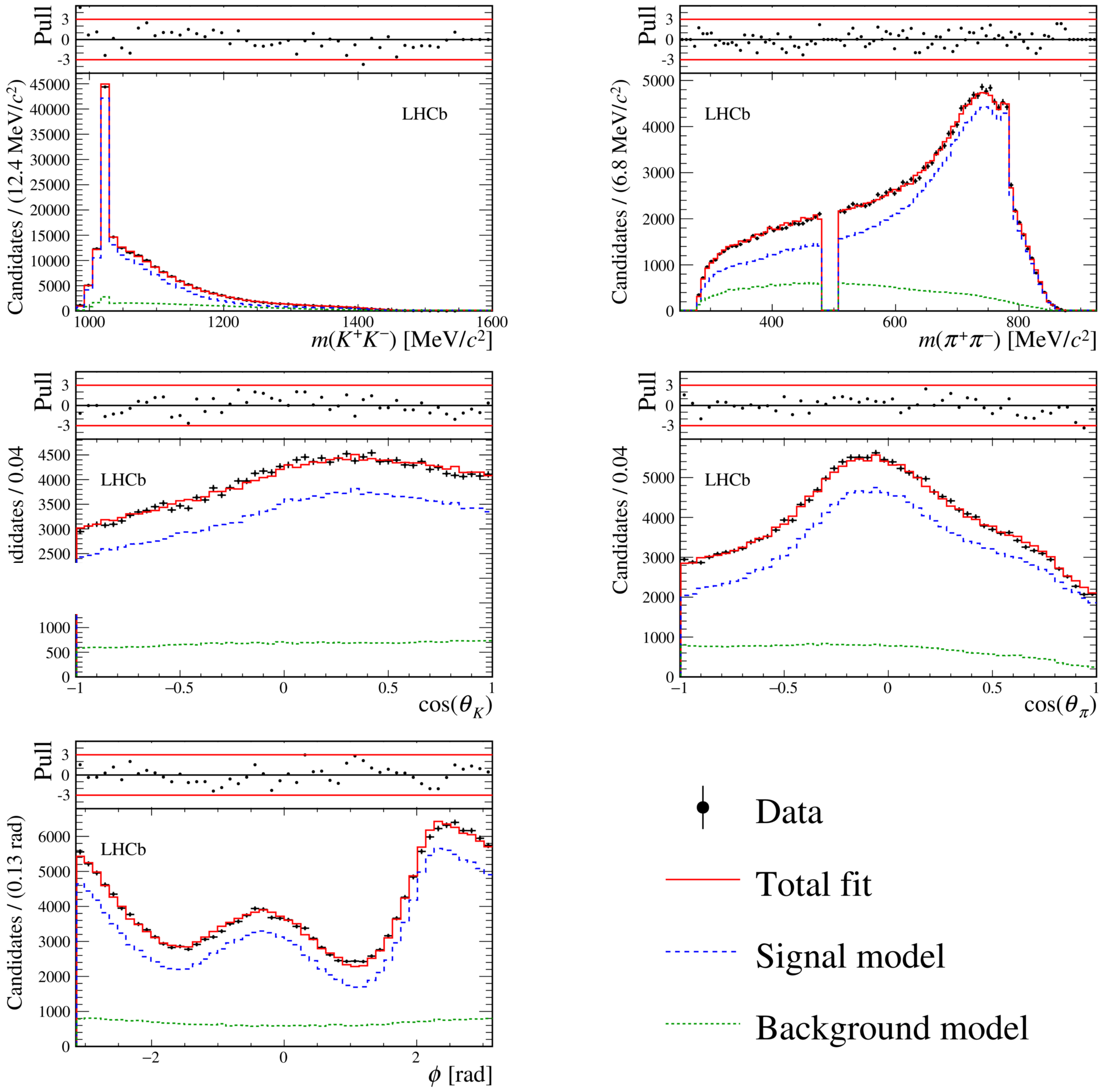
Fit Results $D^0 \to K^+K^-\pi^+\pi^-$

Amplitude	$\lvert c_k \rvert$	$\arg(c_k)$ [rad]	Fit fraction [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	1 (fixed)	0 (fixed)	$23.82 \pm 0.38 \pm 0.50$
$D^0 \to K_1(1400)^+K^-$	$0.614 \pm 0.011 \pm 0.031$	$1.05 \pm 0.02 \pm 0.05$	$19.08 \pm 0.60 \pm 1.46$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$0.282 \pm 0.004 \pm 0.008$	$-0.60 \pm 0.02 \pm 0.10$	$18.46 \pm 0.35 \pm 0.94$
$D^0 \to K_1(1270)^+K^-$	$0.452 \pm 0.011 \pm 0.017$	$2.02 \pm 0.03 \pm 0.05$	$18.05 \pm 0.52 \pm 0.98$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$0.259 \pm 0.004 \pm 0.018$	$-0.27 \pm 0.02 \pm 0.03$	$9.18 \pm 0.21 \pm 0.28$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.359 \pm 0.036 \pm 0.624$	$0.44 \pm 0.02 \pm 0.03$	$6.61 \pm 0.15 \pm 0.37$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$0.249 \pm 0.005 \pm 0.017$	$1.22 \pm 0.02 \pm 0.03$	$4.90 \pm 0.16 \pm 0.18$
$D^0 \to K_1(1270)^-K^+$	$0.220 \pm 0.006 \pm 0.011$	$2.09 \pm 0.03 \pm 0.07$	$4.29 \pm 0.18 \pm 0.41$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$0.120 \pm 0.003 \pm 0.018$	$-2.49 \pm 0.03 \pm 0.16$	$3.14 \pm 0.17 \pm 0.72$
$D^0 \to K_1(1400)^-K^+$	$0.236 \pm 0.008 \pm 0.018$	$0.04 \pm 0.04 \pm 0.09$	$2.82 \pm 0.19 \pm 0.39$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$0.823 \pm 0.023 \pm 0.218$	$2.99 \pm 0.03 \pm 0.05$	$2.75 \pm 0.15 \pm 0.19$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$1.009 \pm 0.022 \pm 0.276$	$-2.76 \pm 0.02 \pm 0.03$	$2.70 \pm 0.11 \pm 0.09$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$1.379 \pm 0.029 \pm 0.373$	$1.06 \pm 0.02 \pm 0.03$	$2.41 \pm 0.09 \pm 0.27$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$1.311 \pm 0.031 \pm 0.018$	$0.54 \pm 0.02 \pm 0.02$	$2.29 \pm 0.08 \pm 0.08$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$0.049 \pm 0.001 \pm 0.004$	$-1.71 \pm 0.04 \pm 0.37$	$1.49 \pm 0.09 \pm 0.33$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$0.747 \pm 0.021 \pm 0.203$	$0.14 \pm 0.03 \pm 0.04$	$1.48 \pm 0.08 \pm 0.10$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$0.762 \pm 0.035 \pm 0.068$	$1.17 \pm 0.04 \pm 0.04$	$0.98 \pm 0.09 \pm 0.05$
$D^0 \to a_0(980)^0 f_2(1270)^0$	$1.524 \pm 0.058 \pm 0.189$	$0.21 \pm 0.04 \pm 0.19$	$0.70 \pm 0.05 \pm 0.08$
$D^0 \to a_1(1260)^+\pi^-$	$0.189 \pm 0.011 \pm 0.042$	$-2.84 \pm 0.07 \pm 0.38$	$0.46 \pm 0.05 \pm 0.22$
$D^0 \to a_1(1260)^-\pi^+$	$0.188 \pm 0.014 \pm 0.031$	$0.18 \pm 0.06 \pm 0.43$	$0.45 \pm 0.06 \pm 0.16$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$0.160 \pm 0.011 \pm 0.005$	$0.28 \pm 0.07 \pm 0.03$	$0.43 \pm 0.05 \pm 0.03$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$1.218 \pm 0.089 \pm 0.354$	$-2.44 \pm 0.08 \pm 0.15$	$0.33 \pm 0.05 \pm 0.06$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$0.195 \pm 0.015 \pm 0.035$	$2.95 \pm 0.08 \pm 0.29$	$0.27 \pm 0.04 \pm 0.05$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$1.388 \pm 0.095 \pm 0.257$	$1.71 \pm 0.06 \pm 0.37$	$0.18 \pm 0.02 \pm 0.07$
$D^0 \to [K^*(892)^0\overline{K}_2^*(1430)^0]_{L=1}$	$1.530 \pm 0.086 \pm 0.131$	$2.01 \pm 0.07 \pm 0.09$	$0.18 \pm 0.02 \pm 0.02$
		Sum of fit fractions	$129.32 \pm 1.09 \pm 2.38$
		χ^2/ndf	$9242/8121 = 1.14$



Resonant Structure of $D^0 \to K^+K^-\pi^+\pi^-$

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

Amplitude	$\lvert c_k \rvert$	$\arg(c_k)$ [rad]	Fit fraction [%]
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$D^0 \to [K^*(892)^0 \bar{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$
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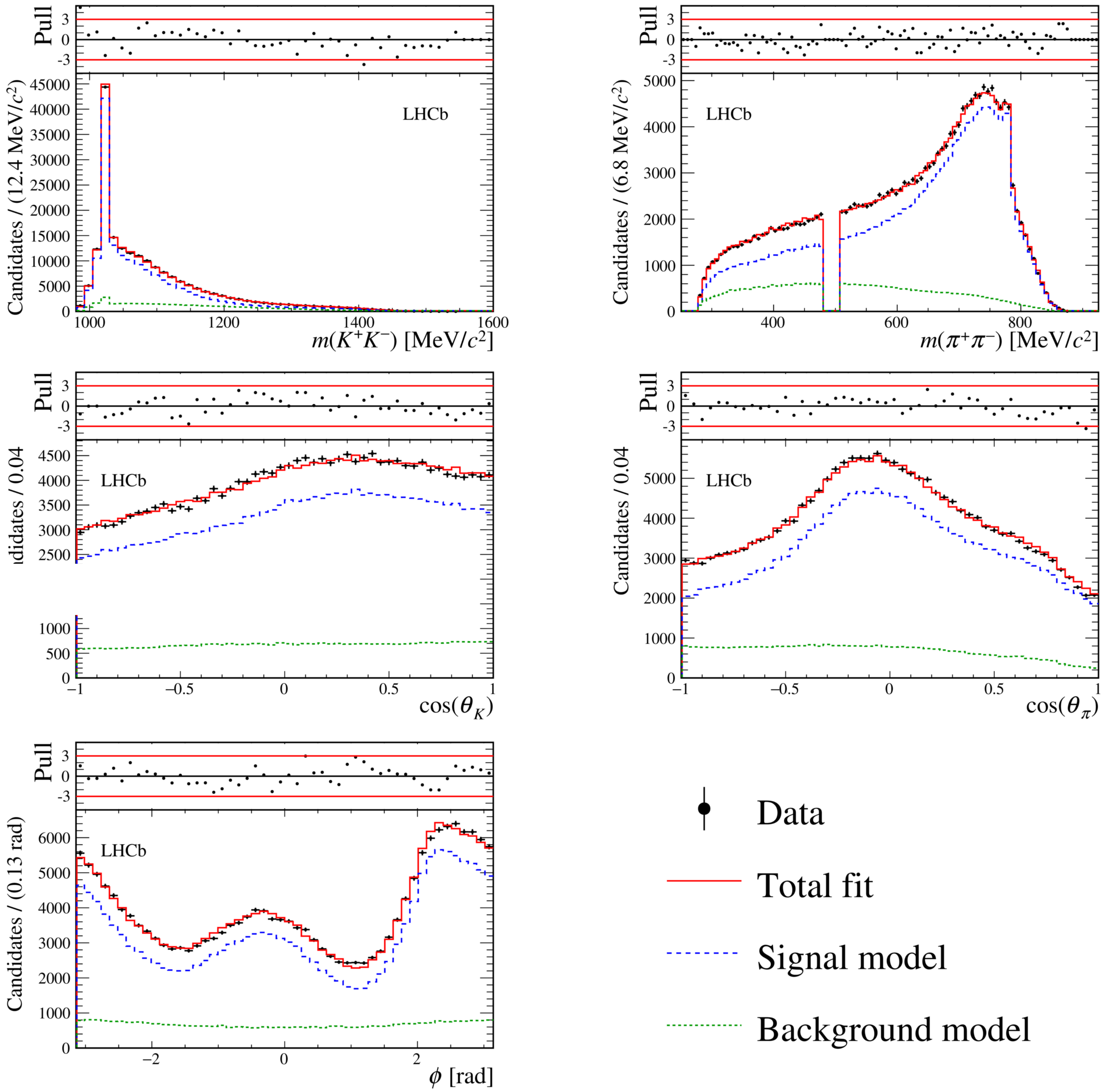

Resonant Structure of $D^0 \to K^+K^-\pi^+\pi^-$

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

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$D^0 \to [\bar{K}^*(1680)^0K^*(892)^0]_{L=1}$	$1.009 \pm 0.022 \pm 0.276$	$-2.76 \pm 0.02 \pm 0.03$	$2.70 \pm 0.11 \pm 0.09$
$D^0 \to \bar{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$1.379 \pm 0.029 \pm 0.373$	$1.06 \pm 0.02 \pm 0.03$	$2.41 \pm 0.09 \pm 0.27$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$1.311 \pm 0.031 \pm 0.018$	$0.54 \pm 0.02 \pm 0.02$	$2.29 \pm 0.08 \pm 0.08$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$0.049 \pm 0.001 \pm 0.004$	$-1.71 \pm 0.04 \pm 0.37$	$1.49 \pm 0.09 \pm 0.33$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=1}$	$0.747 \pm 0.021 \pm 0.203$	$0.14 \pm 0.03 \pm 0.04$	$1.48 \pm 0.08 \pm 0.10$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$0.762 \pm 0.035 \pm 0.068$	$1.17 \pm 0.04 \pm 0.04$	$0.98 \pm 0.09 \pm 0.05$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.524 \pm 0.058 \pm 0.189$	$0.21 \pm 0.04 \pm 0.19$	$0.70 \pm 0.05 \pm 0.08$
$D^0 \to a_1(1260)^+\pi^-$	$0.189 \pm 0.011 \pm 0.042$	$-2.84 \pm 0.07 \pm 0.38$	$0.46 \pm 0.05 \pm 0.22$
$D^0 \to a_1(1260)^-\pi^+$	$0.188 \pm 0.014 \pm 0.031$	$0.18 \pm 0.06 \pm 0.43$	$0.45 \pm 0.06 \pm 0.16$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$0.160 \pm 0.011 \pm 0.005$	$0.28 \pm 0.07 \pm 0.03$	$0.43 \pm 0.05 \pm 0.03$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=2}$	$1.218 \pm 0.089 \pm 0.354$	$-2.44 \pm 0.08 \pm 0.15$	$0.33 \pm 0.05 \pm 0.06$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$0.195 \pm 0.015 \pm 0.035$	$2.95 \pm 0.08 \pm 0.29$	$0.27 \pm 0.04 \pm 0.05$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$1.388 \pm 0.095 \pm 0.257$	$1.71 \pm 0.06 \pm 0.37$	$0.18 \pm 0.02 \pm 0.07$
$D^0 \to [K^*(892)^0\bar{K}_2^*(1430)^0]_{L=1}$	$1.530 \pm 0.086 \pm 0.131$	$2.01 \pm 0.07 \pm 0.09$	$0.18 \pm 0.02 \pm 0.02$
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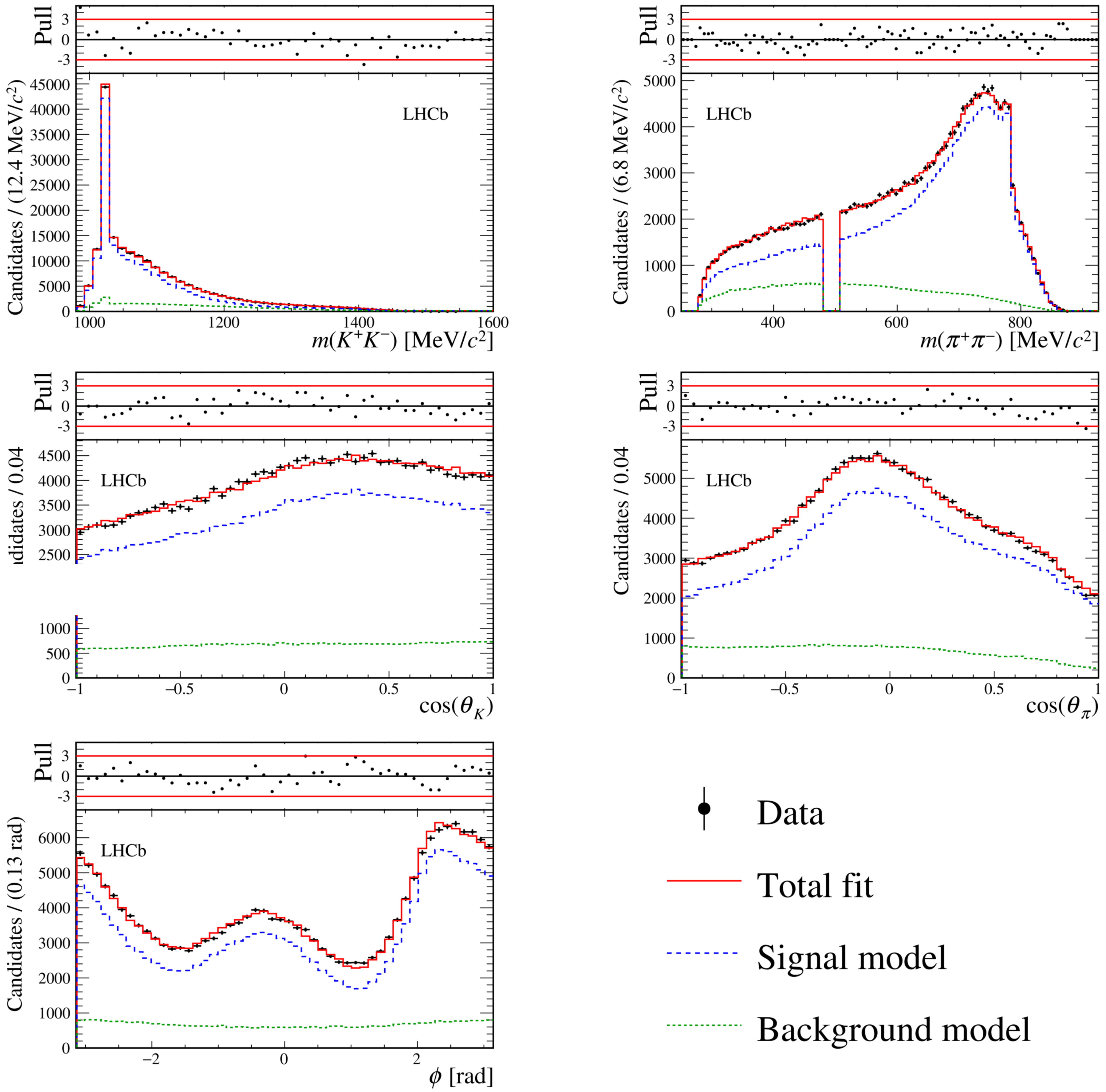

Strange Resonances in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

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$K_1(1270)^+$ and $K_1(1400)$

- It is interesting to notice that in this analysis the contributions of $K^*\pi$ and $(\rho\text{-}\omega)K$ are more balanced wrt to $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
- Interference is also much lower in this analysis
- No evidence of K(1460) is found

Amplitude	$\lvert c_k \rvert$	$\arg(c_k)$ [rad]	Fit fraction [%]
$a_1(1260)^+ \rightarrow [\phi(1020)\pi^+]_{L=0}$	1 (fixed)	0 (fixed)	100
$K_1(1270)^+ \rightarrow [K^*(892)^0\pi^+]_{L=0}$	$0.584 \pm 0.016 \pm 0.040$	$0.63 \pm 0.03 \pm 0.05$	$51.22 \pm 1.06 \pm 3.21$
$K_1(1270)^+ \rightarrow [(\rho - \omega)^0 K^+]_{L=0}$	1 (fixed)	0 (fixed)	$49.58 \pm 1.99 \pm 4.35$
$K_1(1270)^+ \rightarrow [K^+\pi^-]_{L=0}\pi^+$	$0.612 \pm 0.027 \pm 0.094$	$-1.94 \pm 0.04 \pm 0.08$	$6.27 \pm 0.48 \pm 1.66$
$K_1(1270)^+ \rightarrow [K^*(892)^0\pi^+]_{L=2}$	$0.859 \pm 0.044 \pm 0.060$	$-2.53 \pm 0.04 \pm 0.05$	$2.03 \pm 0.17 \pm 0.20$
$K_1(1270)^+ \rightarrow [\rho(1450)^0 K^+]_{L=0}$	$0.482 \pm 0.068 \pm 0.187$	$-2.37 \pm 0.10 \pm 0.45$	$1.50 \pm 0.47 \pm 1.04$
		Sum of fit fractions	$110.60 \pm 2.20 \pm 5.76$
$K_1(1400)^+ \rightarrow [K^*(892)^0\pi^+]_{L=0}$	1 (fixed)	0 (fixed)	100

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

$K_1(1270)^-$ $m_0 = 1289.81 \pm 0.56 \pm 1.66$ MeV/c^2; $\Gamma_0 = 116.11 \pm 1.65 \pm 2.96$ MeV/c^2

	Partial Fractions [%]	$\lvert g \rvert$	$\arg(g)[^o]$
$\rho(770)^0 K^-$	$96.30 \pm 1.64 \pm 6.61$		
$\rho(1450)^0 K^-$	$49.09 \pm 1.58 \pm 11.54$	$2.016 \pm 0.026 \pm 0.211$	$-119.5 \pm 0.9 \pm 2.3$
$\overline{K}^*(892)^0\pi^-$	$27.08 \pm 0.64 \pm 2.82$	$0.388 \pm 0.007 \pm 0.033$	$-172.6 \pm 1.1 \pm 6.0$
$[K^-\pi^+]^{L=0}\pi^-$	$22.90 \pm 0.72 \pm 1.89$	$0.554 \pm 0.010 \pm 0.037$	$53.2 \pm 1.1 \pm 1.9$
$[\overline{K}^*(892)^0\pi^-]^{L=2}$	$3.47 \pm 0.17 \pm 0.31$	$0.769 \pm 0.021 \pm 0.048$	$-19.3 \pm 1.6 \pm 6.7$
$\omega(782)[\pi^+\pi^-]K^-$	$1.65 \pm 0.11 \pm 0.16$	$0.146 \pm 0.005 \pm 0.009$	$9.0 \pm 2.1 \pm 5.7$

Strange Spectroscopy in B decays

Charmonium Decays

- Multibody B decays offer a large spectrum of resonant states, but their Dalitz plots are typically more populated at the borders
- A circumscription of the phase space is possible by studying charmonium resonances, which are abundantly produced in the process $B^+ \to (c\bar{c})K^+$
- Charmonium in turn decays to light hadrons (π,K) and provides a favourable ground for studying strange mesons resonances
- These studies are also conducted by other experiments

$B^+ \to K^0_S K^+ K^\pm \pi^\mp$ Decays

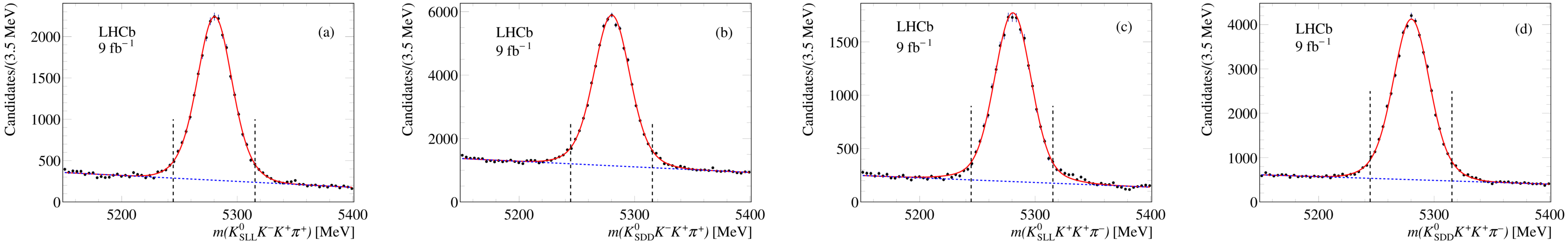
PHYS. REV. D108 032010 (2023)

Lots of Physics

- Branching fractions of $B^+ \to (c\bar{c})K^+$ decays (not covered in this talk)
- Amplitude analysis of charmonium resonances

Sample

- Full LHCb dataset (2011-2018): 9/fb
- KS candidates reconstructed when decaying inside (LL) and outside (DD) the VELO



N_S=21k	N_S=53k	N_S=18k	N_S=40k
P=80.0%	P=69.5%	P=82.3%	P=79.9%

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

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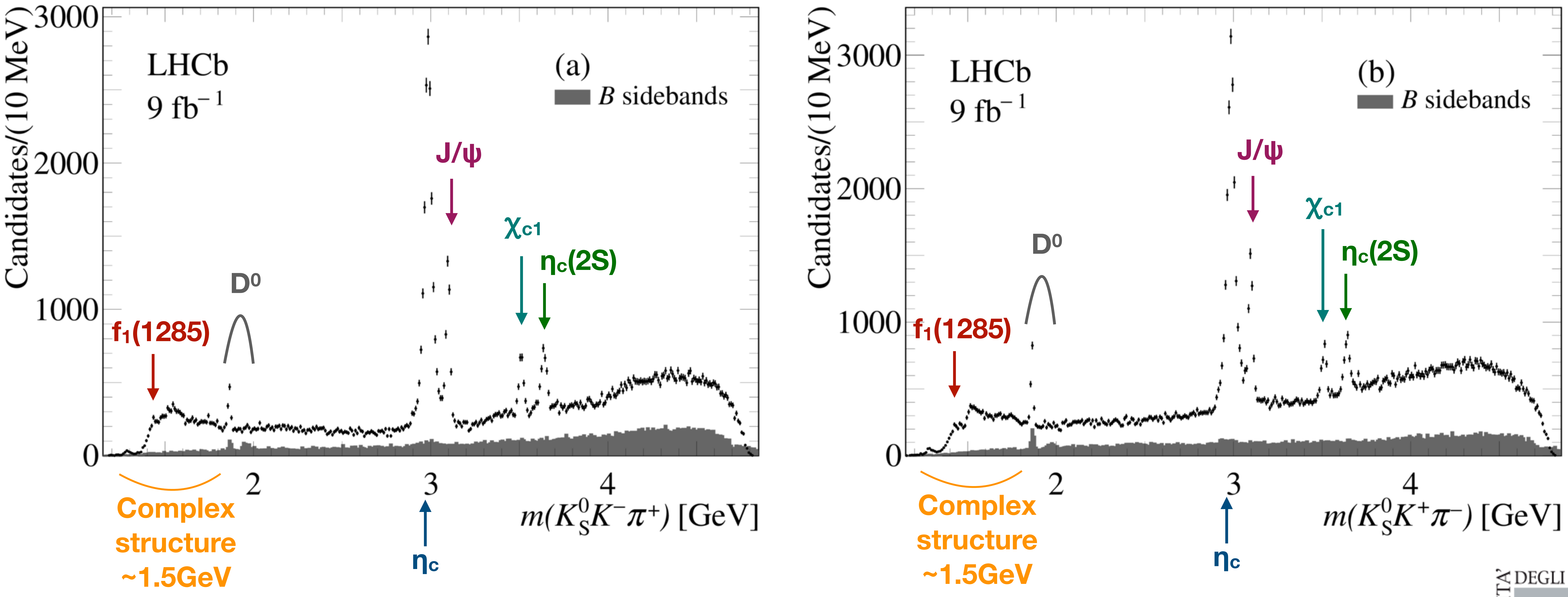
Charmonium with Good Purity



Selection of Charmonium Resonances

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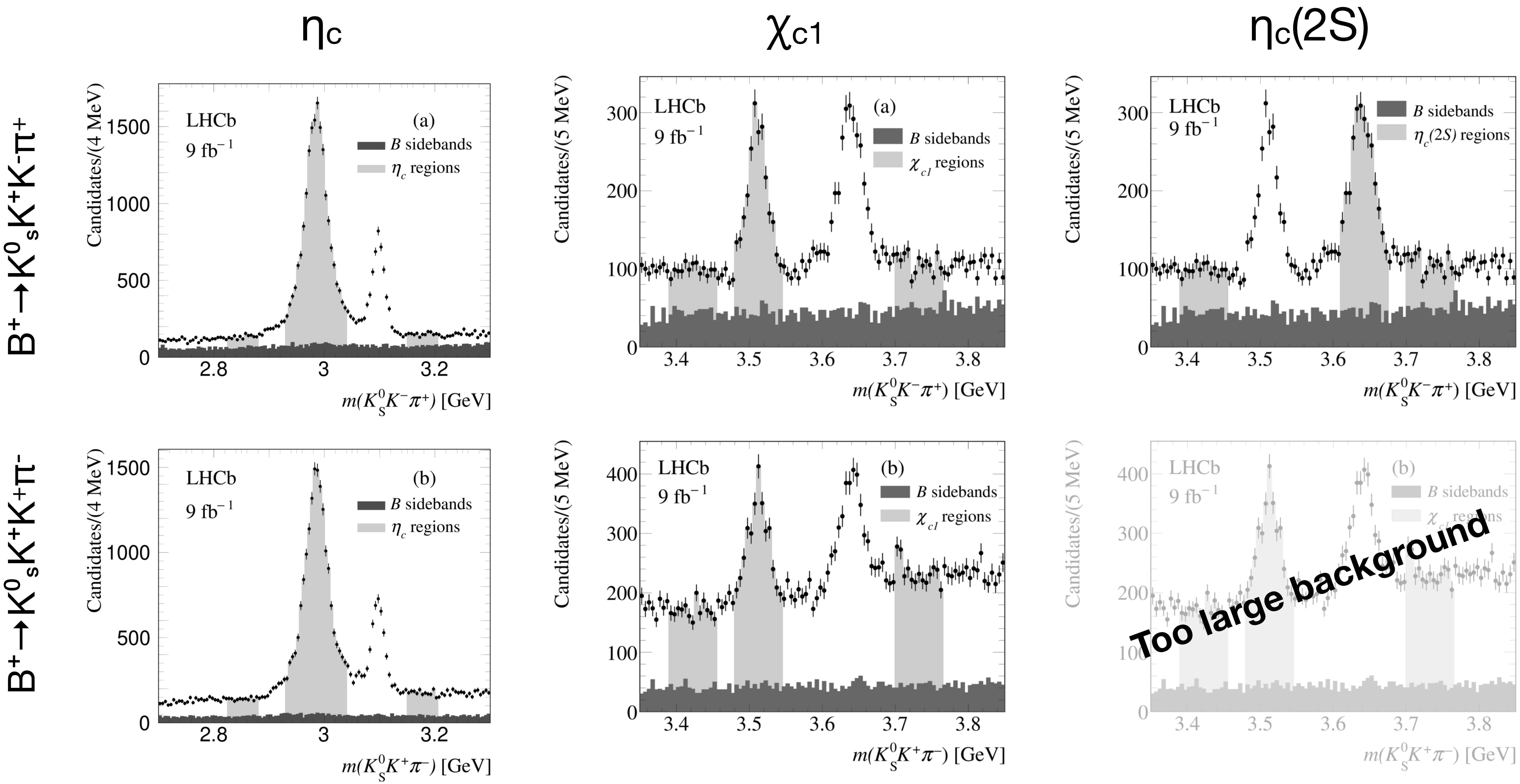
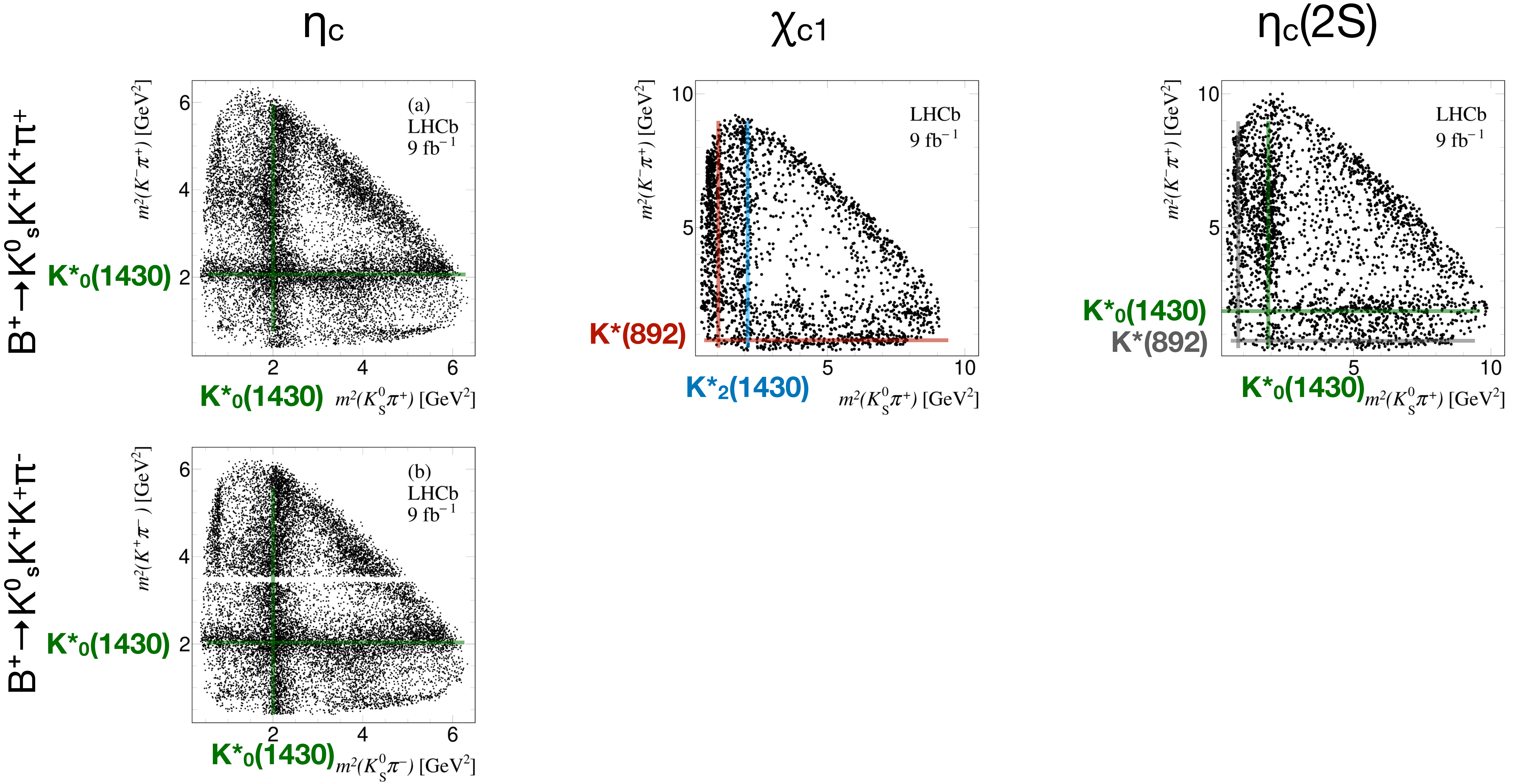


Dalitz Plot of Charmonium Resonances

PHYS. REV. D108 032010 (2023)



Dalitz Plot Analysis of $\eta_c \to K^0_S K\pi$ Decays

PHYS. REV. D108 032010 (2023)

2D Dalitz

- Approximately 15k signal candidates per channel
- $m^2(K^0\pi)$ vs. $m^2(K\pi)$
- Efficiency parametrised as function of $m^2(K^0\pi)$ and $\cos\theta_\pi$
- Two analyses: Quasi Model Independent and Isobar to gain insights of the $K\pi$ S-wave

QMI: amplitude and phase of S-wave fitted at equally spaced intervals of 50 MeV

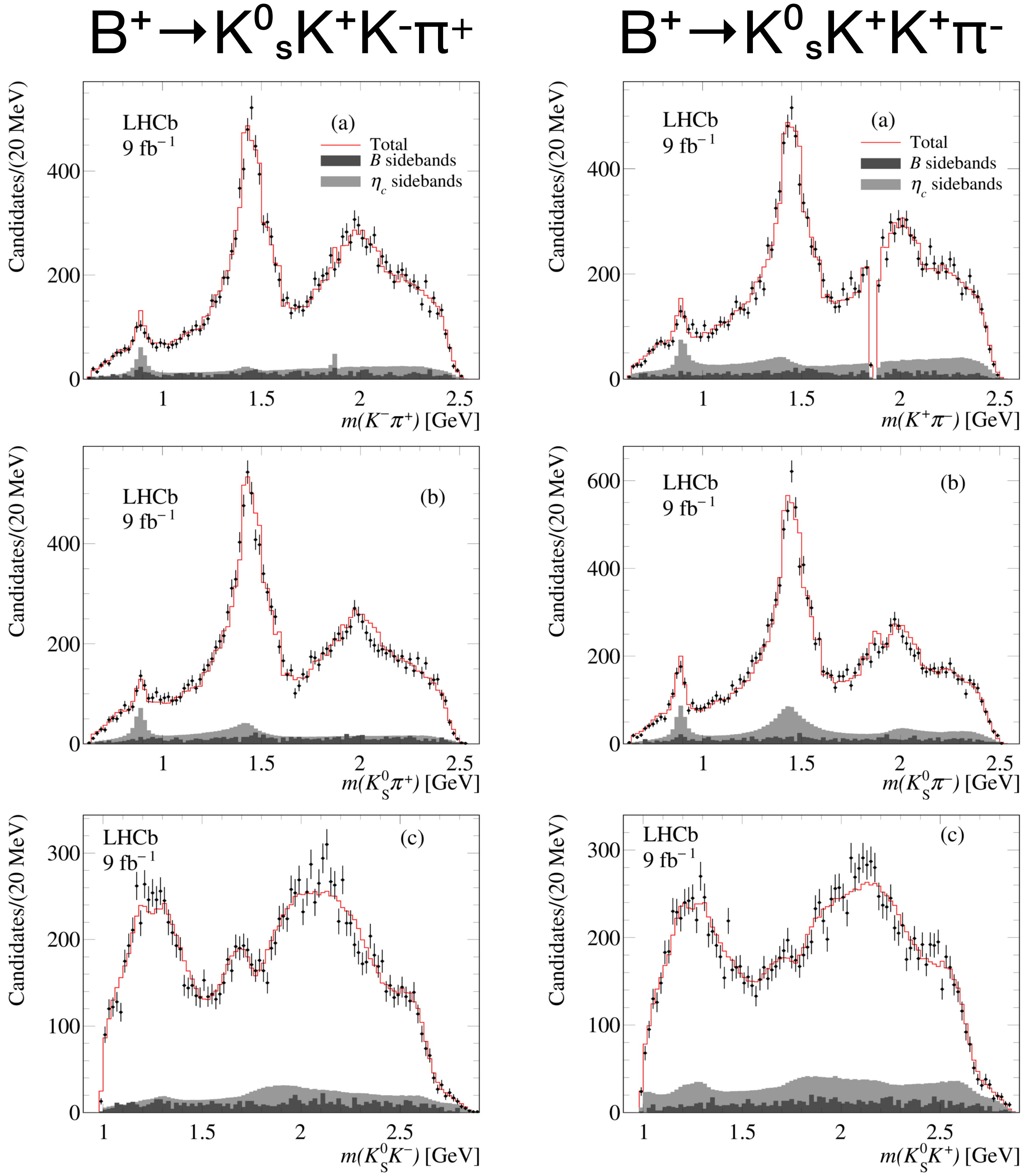
$$A_j = \frac{1}{\sqrt{2}}\left(a_j^{K\pi} e^{i\varphi_j^{K\pi}} + a_j^{K^0\pi} e^{i\varphi_j^{K^0\pi}}\right),\ a_j^{K\pi} = a_j^{K^0\pi} \text{ and } \varphi_j^{K\pi} = \varphi_j^{K^0\pi}$$

Isobar: Fit data with superposition of known and poorly known resonances

Quasi Model Independent Kπ S-wave Fit

PHYS. REV. D108 032010 (2023)

Final state	Fraction [%]	Phase [rad]
	$B^+ \to K^0_S K^+ K^- \pi^+$	
$(K\pi)_S K$	$120.6 \pm 2.4 \pm 5.4$	0.
$a_0(1450)\pi$	$2.4 \pm 0.4 \pm 0.8$	$2.48 \pm 0.07 \pm 0.09$
$K_2^*(1430)K$	$16.6 \pm 0.8 \pm 0.9$	$4.31 \pm 0.03 \pm 0.11$
$a_2(1320)\pi$	$0.7 \pm 0.2 \pm 0.5$	$4.18 \pm 0.10 \pm 0.27$
$a_0(980)\pi$	$11.3 \pm 0.6 \pm 0.9$	$-2.93 \pm 0.03 \pm 0.03$
$a_0(1700)\pi$	$1.5 \pm 0.2 \pm 0.2$	$2.00 \pm 0.08 \pm 0.14$
$K_2^*(1980)K$	$2.8 \pm 0.3 \pm 1.0$	$-0.08 \pm 0.07 \pm 0.14$
$a_2(1750)\pi$	$0.2 \pm 0.1 \pm 0.1$	$-3.56 \pm 0.20 \pm 0.24$
Sum	$156.1 \pm 2.7 \pm 11.4$	
$\chi^2/\text{ndf} = 1706/(1597-17) = 1.08$		
	$B^+ \to K^0_S K^+ K^+ \pi^-$	
$(K\pi)_S K$	$106.0 \pm 2.8 \pm 8.5$	0.
$a_0(1450)\pi$	$0.8 \pm 0.3 \pm 0.4$	$1.64 \pm 0.14 \pm 0.47$
$K_2^*(1430)K$	$17.8 \pm 0.9 \pm 1.0$	$4.32 \pm 0.03 \pm 0.13$
$a_2(1320)\pi$	$0.7 \pm 0.2 \pm 0.5$	$4.22 \pm 0.11 \pm 0.93$
$a_0(980)\pi$	$9.7 \pm 0.6 \pm 0.3$	$-3.02 \pm 0.04 \pm 0.05$
$a_0(1700)\pi$	$0.8 \pm 0.2 \pm 0.2$	$2.10 \pm 0.11 \pm 0.24$
$K_2^*(1980)K$	$6.3 \pm 0.6 \pm 1.9$	$0.13 \pm 0.05 \pm 0.08$
$a_2(1750)\pi$	$0.2 \pm 0.2 \pm 0.3$	$-3.87 \pm 0.22 \pm 0.16$
Sum	$143.7 \pm 2.9 \pm 8.8$	
$\chi^2/\text{ndf} = 1686/(1589-17) = 1.07$		
	$B \to K^0_S K K \pi$	
$(K\pi)_S K$	$114.4 \pm 1.8 \pm 4.6$	0.
$a_0(1450)\pi$	$1.4 \pm 0.2 \pm 0.4$	$2.31 \pm 0.06 \pm 0.09$
$K_2^*(1430)K$	$17.1 \pm 0.6 \pm 0.7$	$4.32 \pm 0.02 \pm 0.08$
$a_2(1320)\pi$	$0.7 \pm 0.1 \pm 0.4$	$4.20 \pm 0.08 \pm 0.26$
$a_0(980)\pi$	$10.5 \pm 0.4 \pm 0.4$	$-2.97 \pm 0.02 \pm 0.03$
$a_0(1700)\pi$	$1.0 \pm 0.1 \pm 0.1$	$2.04 \pm 0.06 \pm 0.12$
$K_2^*(1980)K$	$3.5 \pm 0.3 \pm 0.9$	$0.06 \pm 0.04 \pm 0.07$
$a_2(1750)\pi$	$0.2 \pm 0.1 \pm 0.1$	$-3.69 \pm 0.15 \pm 0.16$
Sum	$148.8 \pm 2.0 \pm 4.8$	



Quasi Model Independent Kπ S-wave Fit

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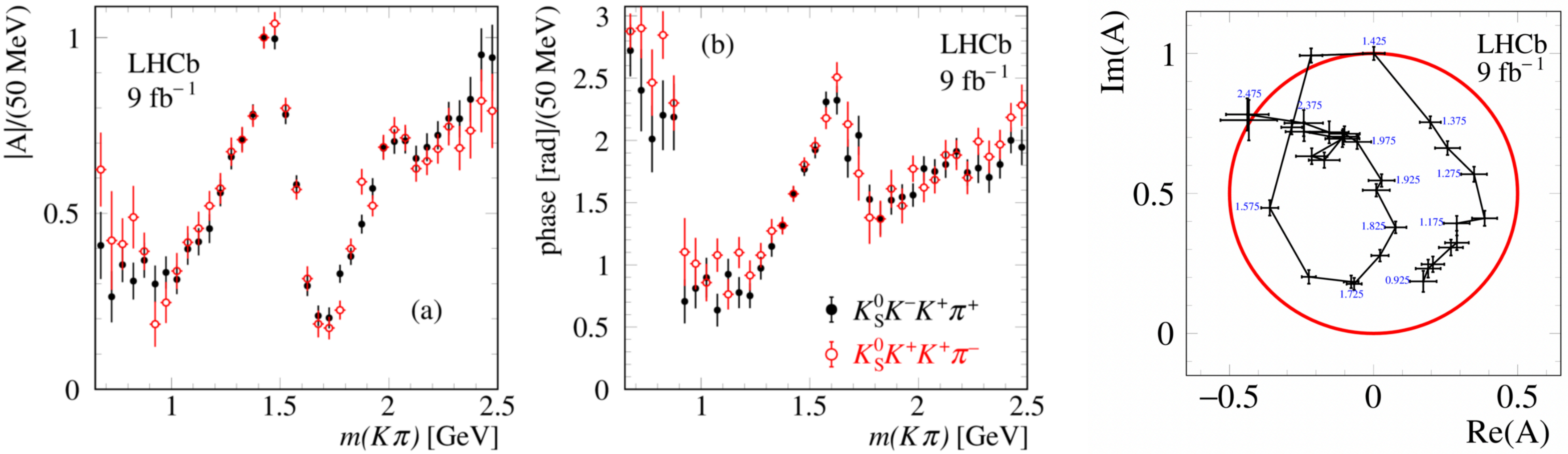


Isobar Model Fit

PHYS. REV. D108 032010 (2023)

κ(2600)

- A large S-wave amplitude is required for the model to fit

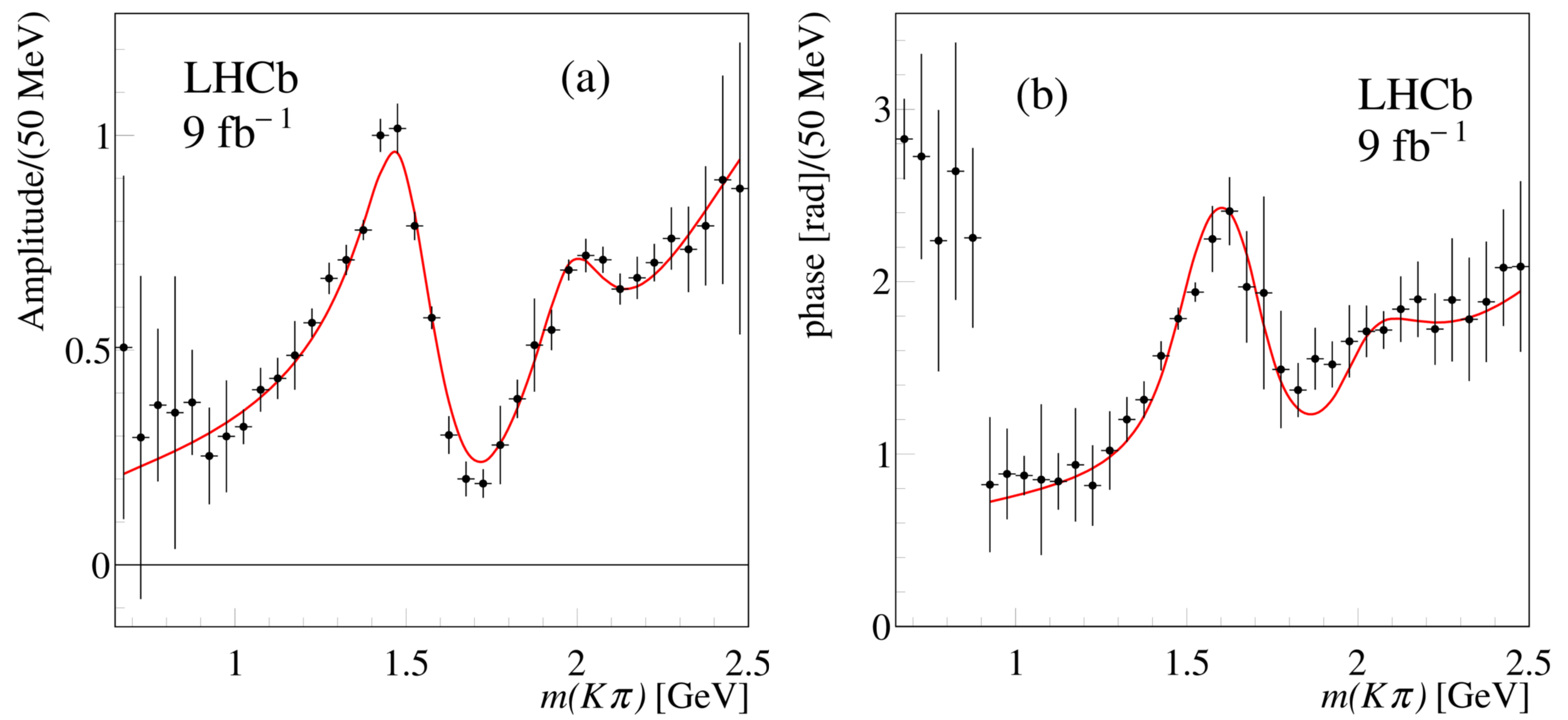
Low mass κ/K^*_0(700)

- Tested, non-significant improvement to the fit

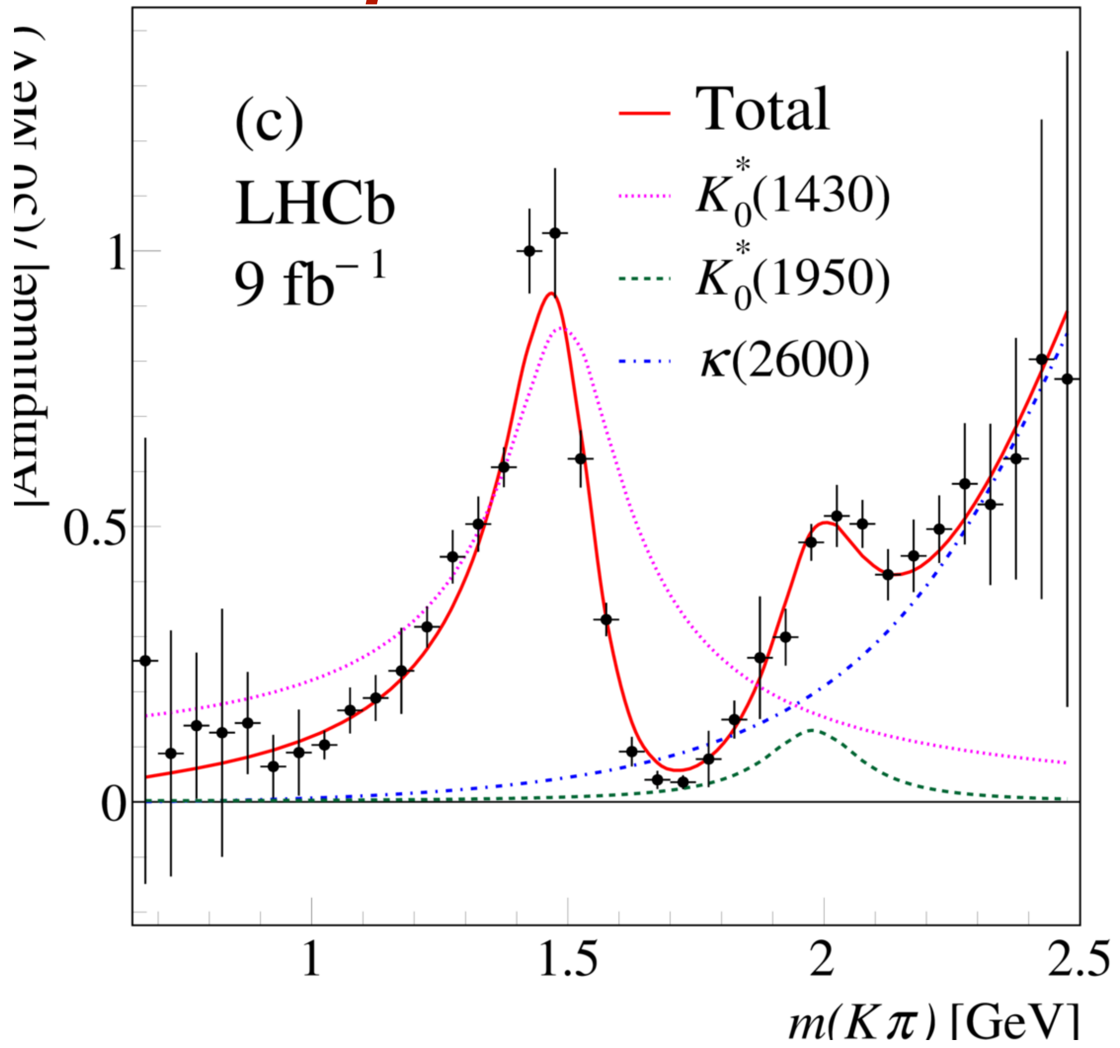
Poorly known resonances

- K^*_2(1980) consistent with zero
- K^*_0(1430), K^*_0(1950), a_0(1700)

Resonance	Mass [MeV]	Γ [MeV]	Δ(2 log $\mathcal{L}$)	Significance
$K_0^*(1430)$	$1493 \pm 4 \pm 7$	$215 \pm 7 \pm 4$	-	-
$K_0^*(1950)$	$1980 \pm 14 \pm 19$	$229 \pm 26 \pm 16$	316	17.8σ
$a_0(1700)$	$1736 \pm 10 \pm 12$	$134 \pm 17 \pm 61$	161	12.7σ
$\kappa(2600)$	$2662 \pm 59 \pm 201$	$480 \pm 47 \pm 72$	1338	36.6σ



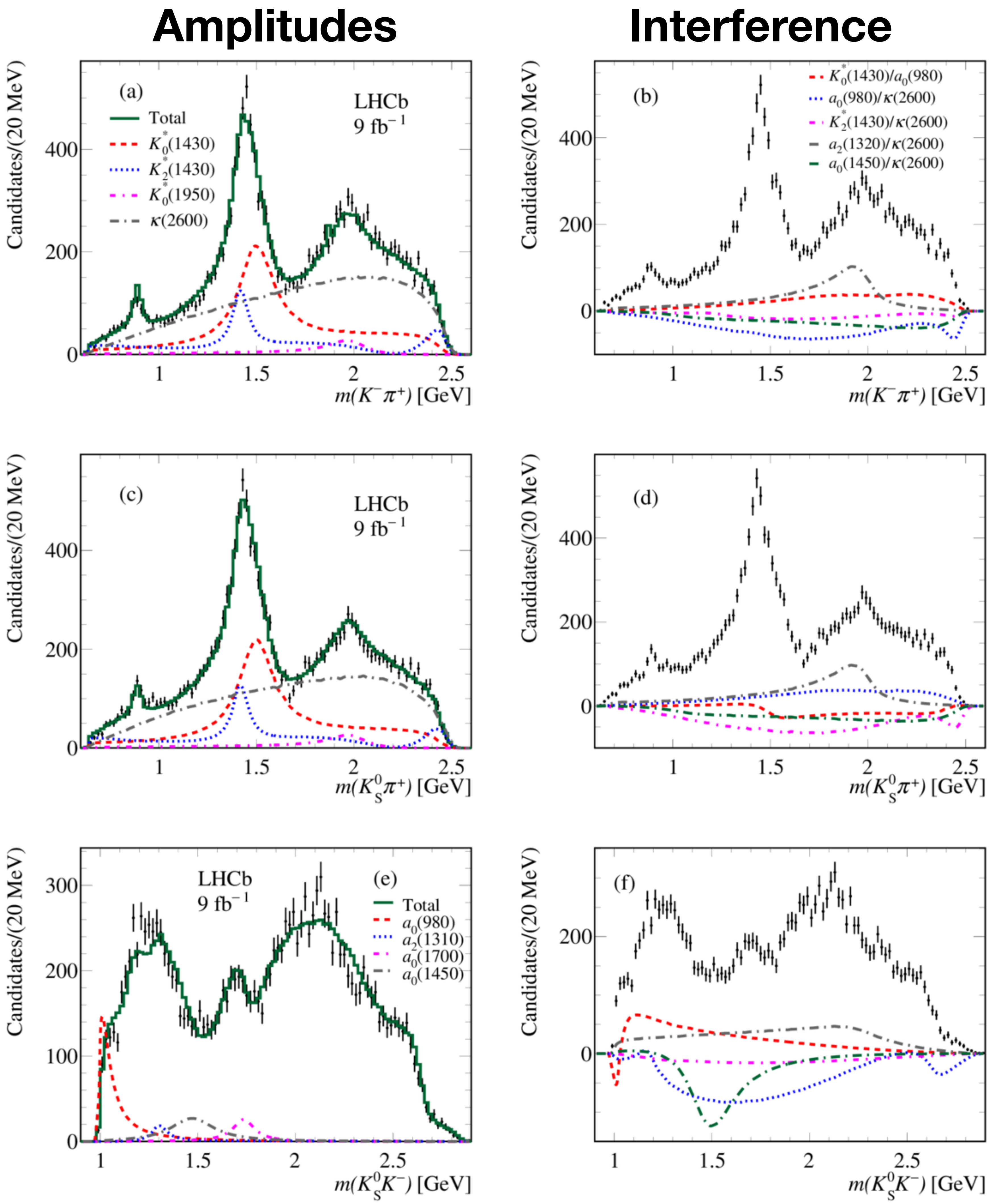
Comparison with QMI



Isobar Model Fit

PHYS. REV. D108 032010 (2023)

Final state	Fraction [%]	Phase [rad]
	$B^+ \to K^0_S K^+ K^- \pi^+$	
$K^*_0(1430)K$	$35.1 \pm 1.3 \pm 2.9$	0.
$a_0(980)\pi$	$5.6 \pm 0.8 \pm 1.6$	$-3.39 \pm 0.08 \pm 0.13$
$K^*_2(1430)K$	$15.4 \pm 1.0 \pm 1.1$	$3.53 \pm 0.03 \pm 0.10$
$a_2(1320)\pi$	$1.1 \pm 0.2 \pm 0.3$	$-2.90 \pm 0.11 \pm 0.26$
$K^*_0(1950)K$	$3.9 \pm 0.4 \pm 0.3$	$-0.46 \pm 0.06 \pm 0.63$
$a_0(1700)\pi$	$1.7 \pm 0.3 \pm 0.4$	$1.00 \pm 0.08 \pm 0.17$
$a_0(1450)\pi$	$3.4 \pm 0.5 \pm 0.8$	$-4.78 \pm 0.08 \pm 0.17$
$a_2(1750)\pi$	$0.3 \pm 0.1 \pm 0.1$	$2.43 \pm 0.17 \pm 0.17$
$\kappa(2600)K$	$63.9 \pm 3.4 \pm 8.1$	$-0.42 \pm 0.05 \pm 0.14$
Sum	$130.5 \pm 4.0 \pm 8.9$	
$\chi^2/\text{ndf} = 1798/(1589-19) = 1.15$		
	$B^+ \to K^0_S K^+ K^+ \pi^-$	
$K^*_0(1430)K$	$32.0 \pm 1.2 \pm 2.8$	0.
$a_0(980)\pi$	$4.9 \pm 0.6 \pm 1.0$	$-3.37 \pm 0.08 \pm 0.11$
$K^*_2(1430)K$	$13.8 \pm 1.0 \pm 1.2$	$3.56 \pm 0.03 \pm 0.11$
$a_2(1320)\pi$	$1.2 \pm 0.2 \pm 0.3$	$-2.82 \pm 0.11 \pm 0.24$
$K^*_0(1950)K$	$3.4 \pm 0.4 \pm 0.3$	$-0.42 \pm 0.06 \pm 0.64$
$a_0(1700)\pi$	$0.7 \pm 0.2 \pm 0.2$	$1.18 \pm 0.11 \pm 0.28$
$a_0(1450)\pi$	$2.0 \pm 0.4 \pm 0.7$	$-4.86 \pm 0.10 \pm 0.22$
$a_2(1750)\pi$	$0.3 \pm 0.1 \pm 0.1$	$2.24 \pm 0.18 \pm 0.17$
$\kappa(2600)K$	$59.8 \pm 3.4 \pm 7.3$	$-0.32 \pm 0.05 \pm 0.12$
Sum	$118.1 \pm 2.7 \pm 8.0$	
$\chi^2/\text{ndf} = 1738/(1584-21) = 1.11$		
	$B \to K^0_S K K \pi$	
$K^*_0(1430)K$	$33.4 \pm 0.9 \pm 2.0$	0.
$a_0(980)\pi$	$5.1 \pm 0.5 \pm 0.8$	$-3.38 \pm 0.06 \pm 0.08$
$K^*_2(1430)K$	$14.6 \pm 0.7 \pm 0.8$	$3.54 \pm 0.02 \pm 0.07$
$a_2(1320)\pi$	$1.1 \pm 0.1 \pm 0.2$	$-2.89 \pm 0.08 \pm 0.18$
$K^*_0(1950)K$	$3.7 \pm 0.3 \pm 0.2$	$-0.44 \pm 0.04 \pm 0.45$
$a_0(1700)\pi$	$1.1 \pm 0.2 \pm 0.2$	$1.05 \pm 0.06 \pm 0.15$
$a_0(1450)\pi$	$2.6 \pm 0.3 \pm 0.5$	$-4.82 \pm 0.06 \pm 0.13$
$a_2(1750)\pi$	$0.3 \pm 0.1 \pm 0.1$	$2.33 \pm 0.12 \pm 0.11$
$\kappa(2600)K$	$61.8 \pm 2.4 \pm 5.4$	$-0.37 \pm 0.03 \pm 0.09$
Sum	$123.7 \pm 2.7 \pm 4.7$	



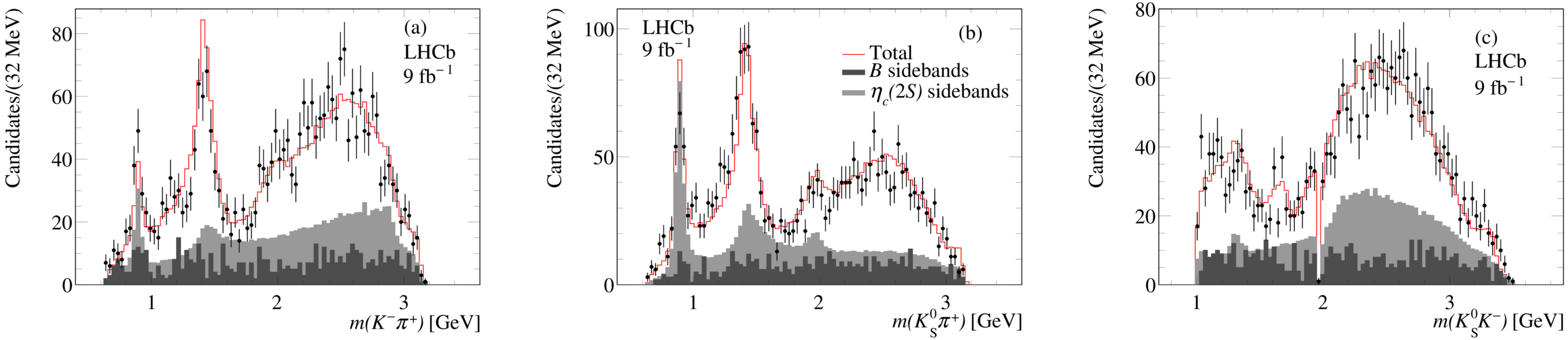
Dalitz Plot Analysis of $\eta_c(2S) \to K^0_S K \pi$ Decays

PHYS. REV. D108 032010 (2023)

Much Lower Data

- Approximately 2800 decays in $B^+ \to K^0_S K^+ K^- \pi^+$
- Using the same model of η_c (Isobar only)
- Very large interference

Final state	Fraction [%]	Phase [rad]
$K_0^*(1430)K$	$25.5 \pm 3.3 \pm 4.1$	0.
$K_2^*(1430)K$	$24.5 \pm 3.3 \pm 4.4$	$3.10 \pm 0.11 \pm 0.08$
$K_0^*(1950)K$	$3.7 \pm 1.3 \pm 1.1$	$-0.82 \pm 0.17 \pm 0.24$
$a_0(1700)^- \pi^+$	$1.7 \pm 1.1 \pm 0.5$	$1.22 \pm 0.32 \pm 0.90$
$a_0(1450)^- \pi^+$	$7.8 \pm 1.9 \pm 1.0$	$1.86 \pm 0.14 \pm 0.56$
$a_2(1750)^- \pi^+$	$4.9 \pm 1.4 \pm 1.1$	$-1.75 \pm 0.15 \pm 0.39$
$\kappa(2600)K$	$124.2 \pm 9.0 \pm 7.7$	$-0.91 \pm 0.10 \pm 0.08$
Sum	$192.3 \pm 10.9 \pm 10.0$	
$\chi^2/\text{ndf} = 578/(591\text{-}13) = 1.00$		



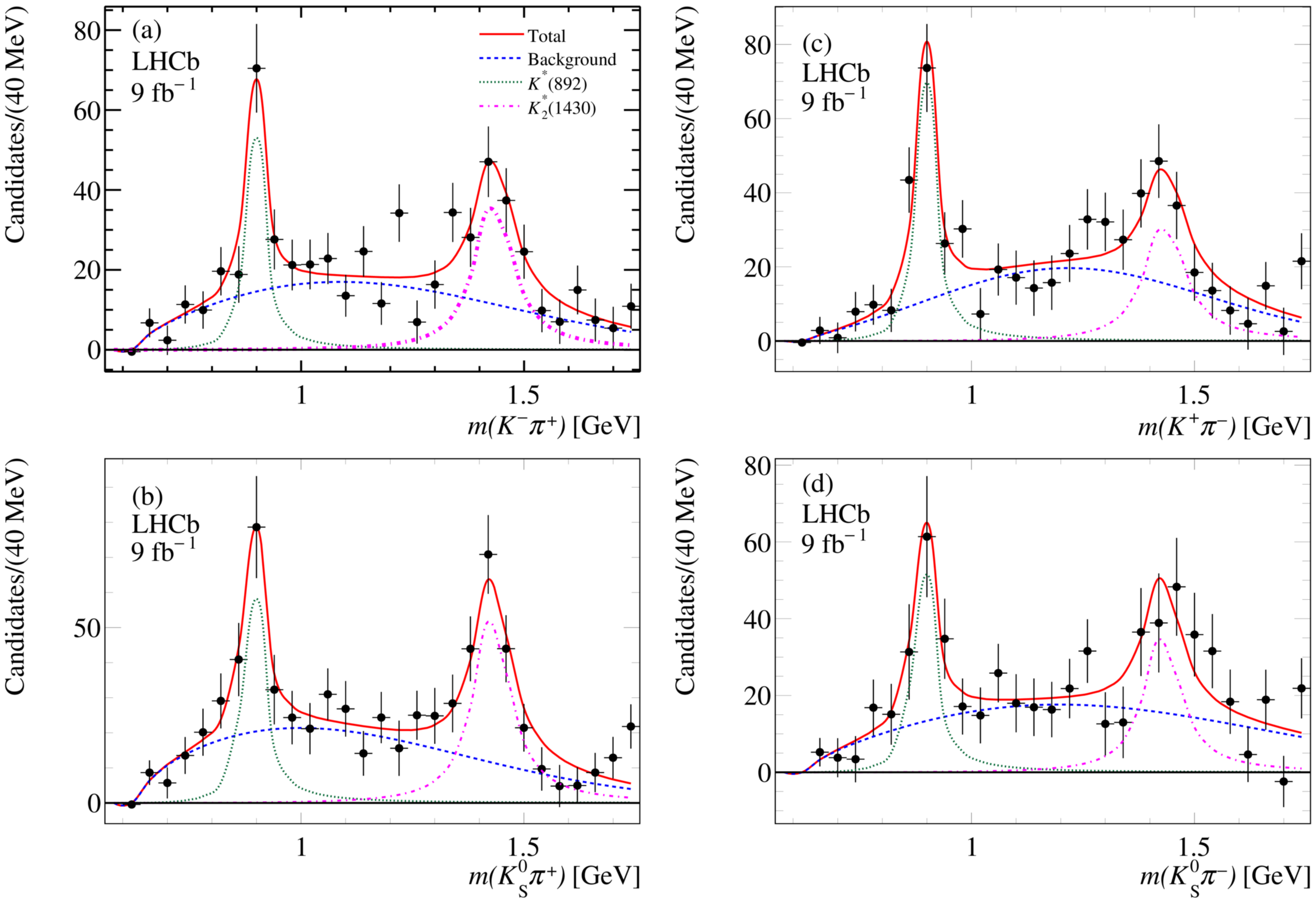
Dalitz Plot Analysis of $\chi_{c1} \to K^0_S K\pi$ Decays

PHYS. REV. D108 032010 (2023)

High Background

- Dalitz plot not feasible in this case
- Simplified approach: fit only the m(Kπ) and m(K⁰π) distributions
- Efficiency corrected

Decay mode	Fraction	Branching fraction ($\times 10^{-3}$)
$\mathcal{B}(\chi_{c1} \to K^*(892)^0 \bar{K}^0)$	$0.099 \pm 0.012 \pm 0.004$	$1.04 \pm 0.13 \pm 0.04 \pm 0.09$
$\mathcal{B}(\chi_{c1} \to K_2^*(1430)^0 \bar{K}^0)$	$0.111 \pm 0.015 \pm 0.005$	$1.17 \pm 0.16 \pm 0.05 \pm 0.10$
$\mathcal{B}(\chi_{c1} \to K^*(892)^+ K^-)$	$0.112 \pm 0.016 \pm 0.013$	$1.18 \pm 0.17 \pm 0.14 \pm 0.10$
$\mathcal{B}(\chi_{c1} \to K_2^*(1430)^+ K^-)$	$0.143 \pm 0.018 \pm 0.006$	$1.61 \pm 0.19 \pm 0.19 \pm 0.14$



Summary

Summary

Strange Hadrons Spectroscopy at LHCb

- **A byproduct of amplitude analyses of B and D decays**
- **(Relatively) Large yields with high purity**
- **Many interesting results can be extracted**
  $K^*_0(1950)$ established
  New parametrisation of the Kπ S-wave including $K^*_0(1430)$, $K^*_0(1950)$, and κ(2600)
- **KK and Kπ S-waves can be studied**

Spares

Systematic Uncertainties $D^0 \to K^\mp \pi^\pm \pi^\mp \pi^\pm$

Tested With PseudoExperiments

- Size of Integration Sample (Resampling)
- Background description in WS fit
- Flavour Misidentification
- Detection Asymmetry
- Alternative Models

Tested With Alternative Fits

- Background Description
- Selection Efficiency
- Resonance Shapes

Tested With Multiple Fits of Resampled Data

- Background Description
- Uncertainties of the Fixed Parameters

Systematic Uncertainties $D^0 \rightarrow K^+K^-\pi^+\pi^-$

Tested With PseudoExperiments

- Fit Bias
- Background description
- Flavour Misidentification
- Detection Asymmetry
- Alternative Models

Tested With Alternative Fits

- Background Description
- Selection Efficiency
- Resonance Shapes

Tested With Multiple Fits of Resampled Data

- Background Description
- Uncertainties of the Fixed Parameters

Systematic Uncertainties $\eta_c \to K^0_S K\pi$

Sources of Uncertainties

- **Efficiency Correction**
  $\epsilon(m(K^0_S K), cos\theta_\pi) \to \epsilon_1(m(K^0_S K))\epsilon_2(cos\theta_\pi)$
- **Trigger Selection**
  TOS vs. No-TOS
- **Uncertainty on Signal Purity**
  ±5% change in BDT selection
- **Radius of the Blatt-Weisskopf factor (1.5/GeV)**
  Varied in (0.5 ÷ 2.5)/GeV range
- **Background Model**
  Random variations of background model

Negligible

- **Fit Bias**
- **Sidebands**

	Amplitudes						Phases					
Final state	Eff	Trig	Pur	r	Back	Tot	Eff	Trig	Pur	r	Back	Tot
$(K\pi)_S K$	3.27	0.89	1.03	4.01	0.48	5.37	-	-	-	-	-	-
$a_0(1450)\pi$	0.65	0.29	0.24	0.16	0.06	0.77	0.04	0.07	0.03	0.00	0.03	0.09
$K_2^*(1430)K$	0.02	0.17	0.04	0.86	0.48	1.00	0.08	0.06	0.03	0.05	0.01	0.11
$a_2(1320)\pi$	0.38	0.10	0.34	0.04	0.08	0.53	0.21	0.08	0.14	0.05	0.01	0.27
$a_0(980)\pi$	0.70	0.05	0.47	0.12	0.34	0.92	0.01	0.02	0.02	0.00	0.02	0.04
$a_0(1700)\pi$	0.12	0.05	0.05	0.08	0.01	0.16	0.10	0.08	0.02	0.00	0.00	0.14
$K_2^*(1980)K$	0.04	0.08	0.19	0.96	0.16	1.00	0.10	0.06	0.04	0.08	0.01	0.14
$a_2(1750)\pi$	0.05	0.01	0.05	0.03	0.03	0.09	0.04	0.14	0.05	0.11	0.06	0.20

Final state	Eff	Trig	Pur	r	Back	Tot	Eff	Trig	Pur	r	Back	Tot
$(K\pi)_S K$	6.06	2.94	2.80	4.39	0.20	8.52	-	-	-	-	-	-
$a_0(1450)\pi$	0.30	0.12	0.24	0.14	0.06	0.43	0.31	0.35	0.08	0.01	0.01	0.47
$K_2^*(1430)K$	0.32	0.08	0.30	0.88	0.54	1.13	0.09	0.07	0.04	0.06	0.01	0.13
$a_2(1320)\pi$	0.32	0.09	0.30	0.08	0.11	0.47	0.27	0.13	0.19	0.05	0.86	0.93
$a_0(980)\pi$	0.01	0.17	0.02	0.22	0.26	0.46	0.02	0.02	0.03	0.02	0.02	0.06
$a_0(1700)\pi$	0.12	0.00	0.08	0.08	0.01	0.17	0.18	0.15	0.03	0.00	0.01	0.24
$K_2^*(1980)K$	0.46	0.11	0.43	1.77	0.22	1.89	0.04	0.01	0.06	0.05	0.01	0.08
$a_2(1750)\pi$	0.21	0.10	0.13	0.02	0.03	0.27	0.09	0.02	0.06	0.11	0.19	0.25

Systematic Uncertainties $\eta_c(2S) \to K^0_S K\pi$

Sources of Uncertainties

- **Efficiency Correction**
  Use 2D-binned map
- **Trigger Selection**
  TOS vs. No-TOS
- **Uncertainty on Signal Purity**
  ±5% change in BDT selection
- **Radius of the Blatt-Weisskopf factor (1.5/GeV)**
  Varied in (0.5 ÷ 2.5)/GeV range
- **Background Model**
  Random variations of background model

	Amplitudes						Phases					
Final state	Pur	Par	r	Back	Eff	Tot	Pur	Par	r	Back	Eff	Tot
$K_0^*(1430)K$	1.92	1.25	0.17	0.91	3.26	4.1	-	-	-	-	-	-
$K_2^*(1430)K$	2.47	0.43	1.24	0.86	3.30	4.4	0.06	0.02	0.04	0.02	0.01	0.08
$K_0^*(1950)K$	0.60	0.22	0.37	0.18	0.74	1.1	0.03	0.09	0.08	0.21	0.01	0.24
$a_0(1700)^-\pi^+$	0.32	0.05	0.29	0.13	0.02	0.45	0.18	0.05	0.11	0.87	0.12	0.90
$a_0(1450)^-\pi^+$	0.94	0.04	0.19	0.32	0.19	1.03	0.10	0.04	0.09	0.53	0.09	0.56
$a_2(1750)^-\pi^+$	0.53	0.15	0.42	0.11	0.79	1.05	0.03	0.04	0.08	0.38	0.03	0.39
$\kappa(2600)K$	4.33	3.28	4.97	0.01	2.40	7.74	0.04	0.05	0.04	0.02	0.01	0.08

Negligible

- **Fit Bias**
- **Sidebands**

Systematic Uncertainties $\chi_{c1} \rightarrow K^0_S K\pi$

Sources of Uncertainties

- **Decay Modes**
  Difference between separate results
- **Uncertainty on Signal Purity**
  ±5% change in BDT selection
- **Radius of the Blatt-Weisskopf factor (1.5/GeV)**
  Varied in (0.5 ÷ 2.5)/GeV range

Amplitude Analysis of 4-Body D^0 Decays

Software: AmpGen

- **C++ and ROOT based with multithreading (OpenMP)**
- **Isobar model**
  - coherent sum of amplitudes
  - polarised sum of amplitudes for particles carrying spin
  - incoherent sum of amplitudes for background description
- **Spin Formalism**
  Covariant Tensors (Rarita-Schwinger)
  Canonical helicity formalism
- **Quasiparticles**
  Fictional decaying particles to describe for example S-wave with K-matrix

Modelling 3-Body Resonances

3-Body Running Width

- The width of 2-body resonances is typically given by

$$\Gamma(s) = \frac{\Gamma_0 q m_0}{q_0\sqrt{s}}\left(\frac{q}{q_0}\right)^{2L} B_L(q, q_0)^2$$

- In 3-body resonances one must account for the dynamics of the intermediate decay process
- We decided to express it in terms of the spin-averaged matrix element of the decay integrated over the phase space of the three-particle final state

$$\Gamma(s) \propto \frac{1}{s}\int ds_{ab} ds_{bc} \left|\mathscr{M}_{R\to abc}\right|^2, \Gamma(m_0^2) = \Gamma_0$$

3-Body Amplitude

$$\mathscr{T}(s) = \frac{\sqrt{k}F(q)}{m_0^2 - s - i m_0 \Gamma(s)}, F(q) = e^{-r^2q^2/2}$$