The 6th China LHC Physics Workshop

Observation of new excited Ξ_c^0 states

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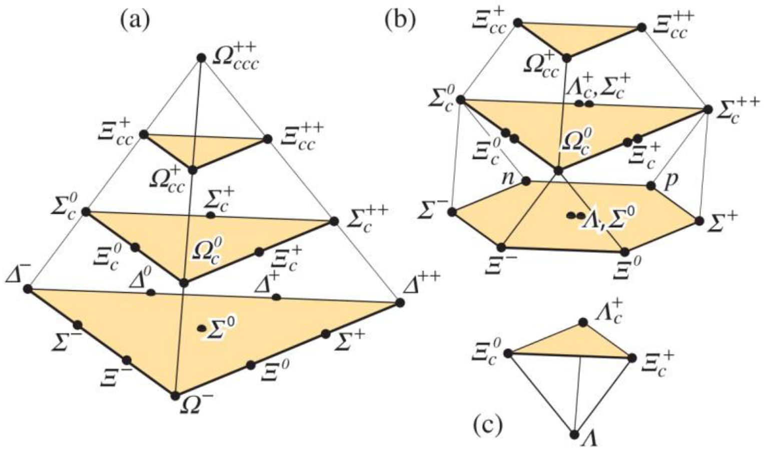
Motivation

- **Hadron spectroscopy** studies the masses and decays of hadrons.
- The properties of these hadrons are a result of quantum chromodynamics (QCD).
- QCD describes the theory of strong interactions between quarks and gluons, binding quarks and antiquarks into hadrons.

- SU(3) multiplets of ground states contain the (*u*, *d*, *s*) quarks.
- Can be extended to SU(4) by adding *c* quark.

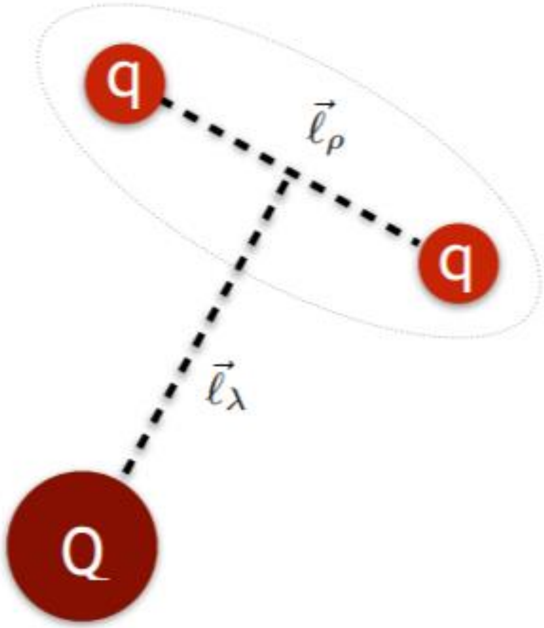


Motivation

Study structure of hardon
- Quark model
- Quarks and diquark
- Tightly bound or molecular

HQET : Heavy Quark Effective Theories
- Can be used to predict masses of heavy meson/baryon

Validate HQET by measuring excited states.



Heavy baryon model:
Diquark system (q,q)
Static heavy quark (Q)

Status

Beauty baryons

- Excited $\Sigma_b^{*\pm}$ states
  - $\Sigma_b^{*\pm} \to \Lambda_b^0 \pi^\pm$
  - PRL 122 (2019) 012001
- Excited Ω_b^- states
  - $\Omega_b^{*-} \to \Xi_b^0 K^-$
  - PRL 124 (2020) 082002
- Excited Λ_b^0 states
  - $\Lambda_b^{*0} \to \Lambda_b^0 \pi^+ \pi^-$ $\Lambda_b^{**0} \to \Lambda_b^0 \pi^+ \pi^-$
  - PRL 123 (2019) 152001 arXiv:2002.05112

Charmed baryons

- Excited Ω_c^0 states
  - $\Omega_c^{**0} \to \Xi_c^+ K^-$
  - PRL 118 (2017) 182001
- Excited Ξ_c^0 states
  - $\Xi_c^{**0} \to \Lambda_c^+ K^-$
  - PRL 124 (2020) 222001

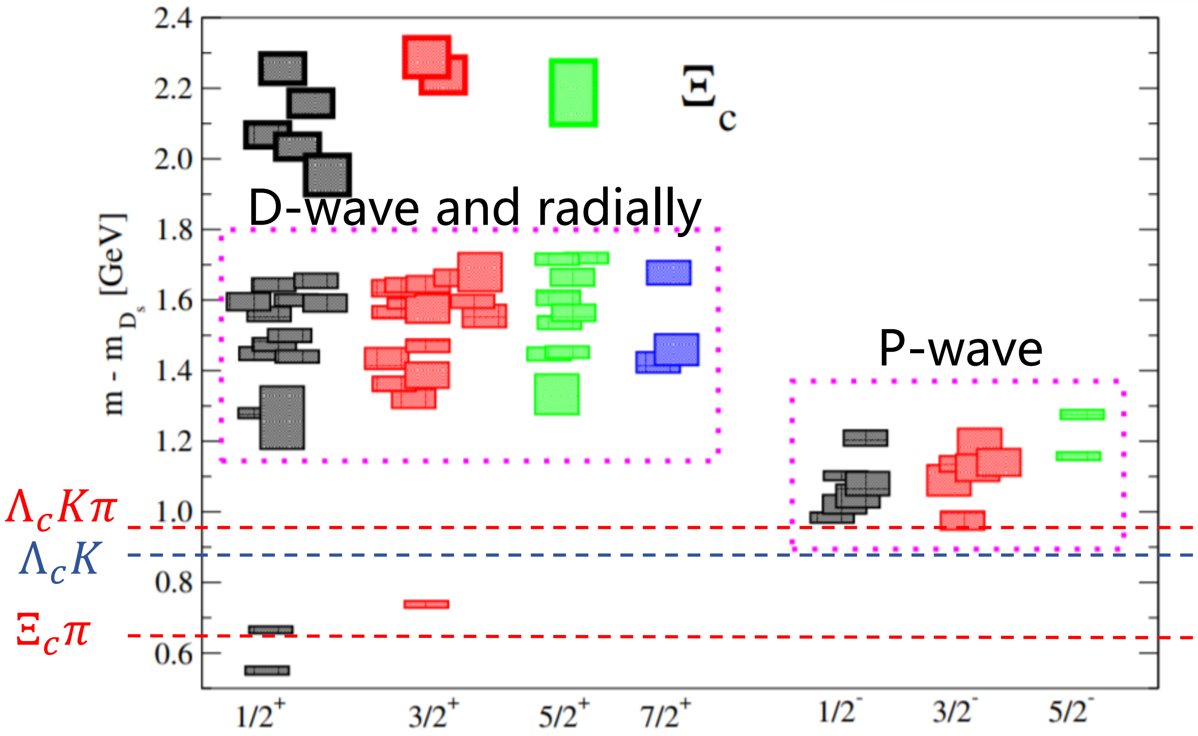
Decay chain:

$$\Xi_c^0 \to \Lambda_c^+ K^-$$
$$\hookrightarrow pK^-\pi^+$$

Masses prediction

Decay chain:

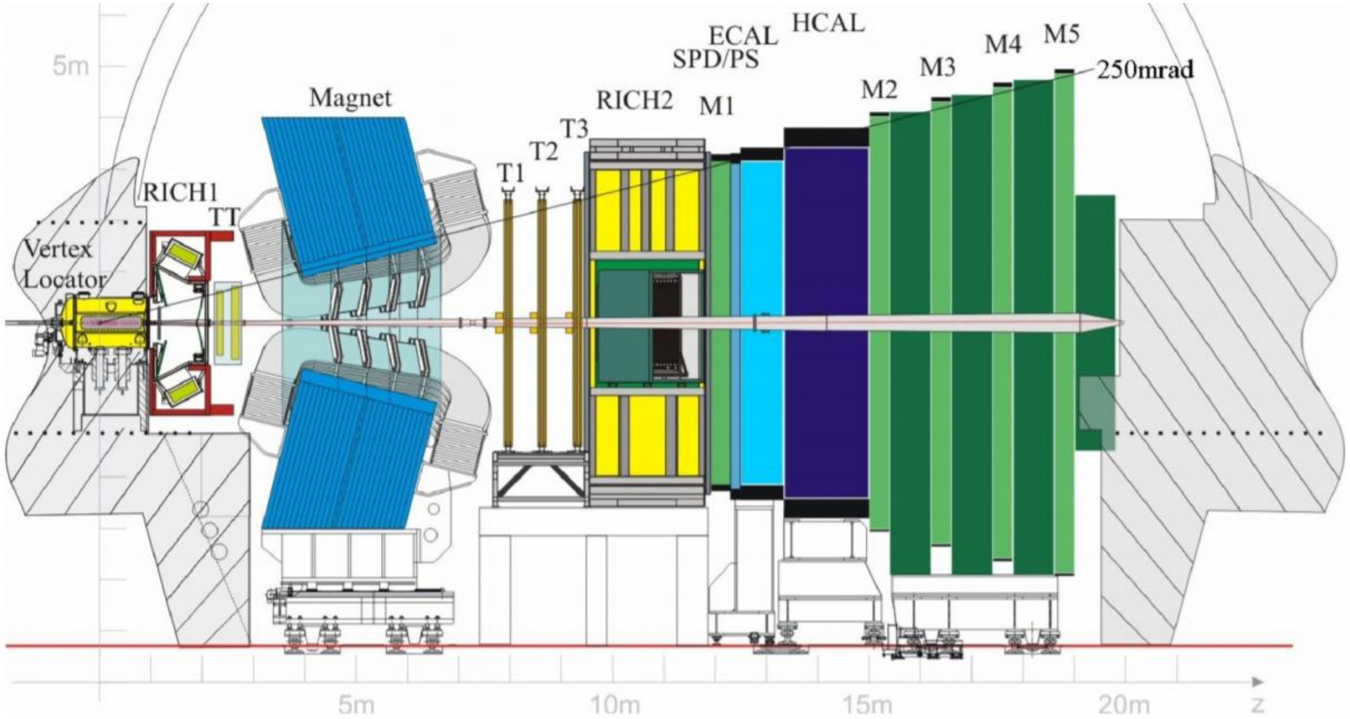
$\Xi_c^0 \to \Lambda_c^+ K^-$
$\hookrightarrow pK^-\pi^+$

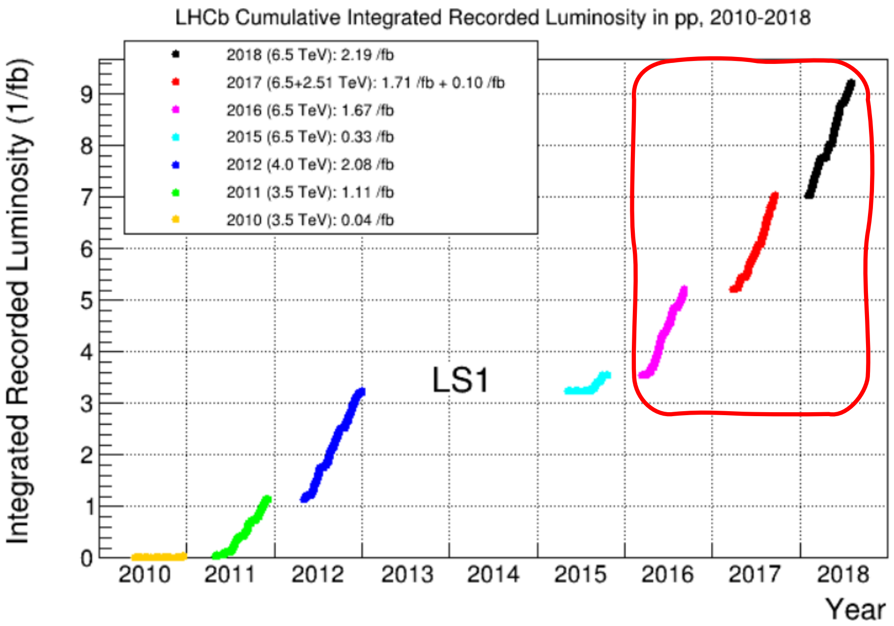


arXiv:1311.4806

Detector & data

- LHCb designed for charmed and bottom hardon.
- Excellent vertex, tracking and PID performance.





- 2016-2018 data at LHCb.
- Integrated luminosity: 5.57 fb^{-1}

Selection of Λ_c

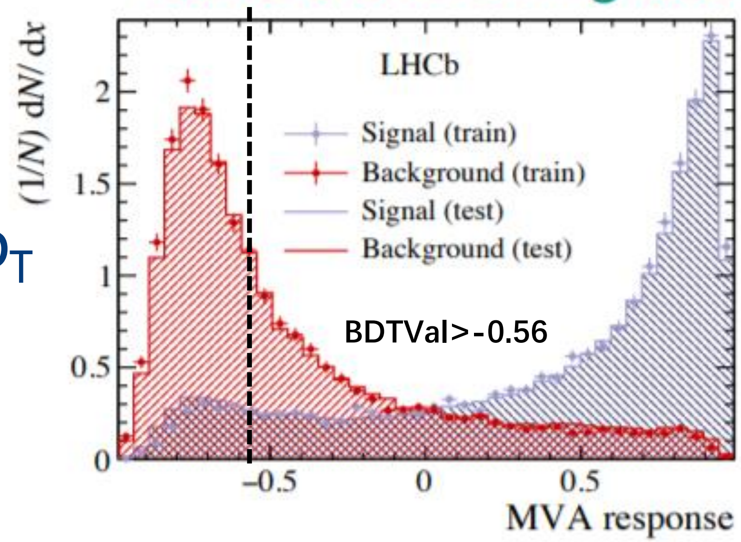
Decay chain:

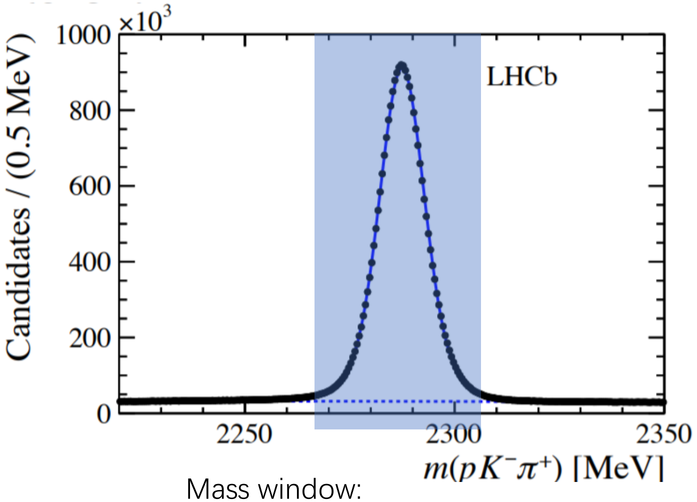
$\Xi_c^0 \to \Lambda_c^+ K^-$

$\hookrightarrow pK^-\pi^+$

- Select decays using multivariate boosted decision tree(BDT).
- Input variables based on decay topology and p_T and particle identification information of the children particles.

BDTG overtraining test





Mass window:
$M_{\mathrm{PDG}}(\Lambda_c^+) \pm 20\mathrm{MeV}$

About 125M Λ_c signal with purity of 93%.

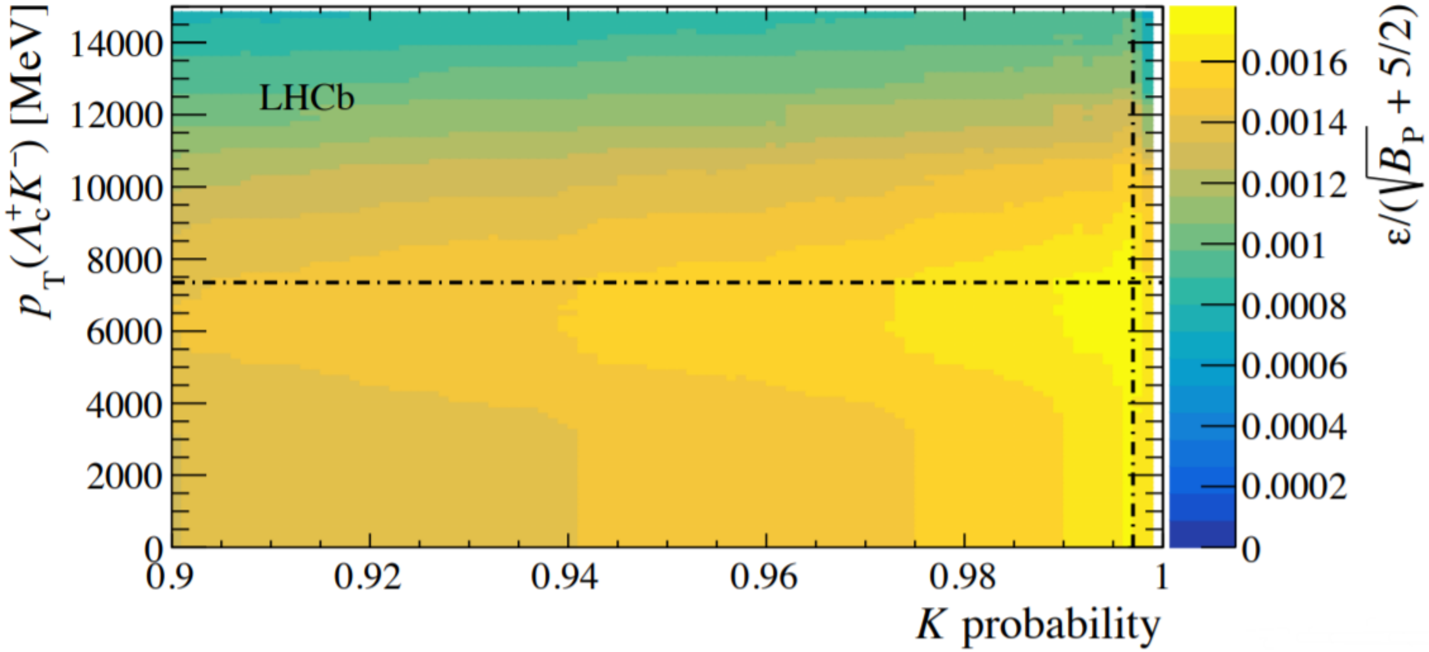
Selection of K

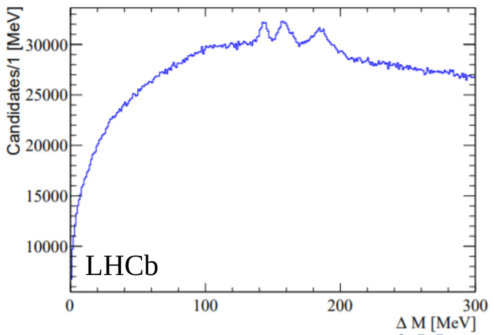
Decay chain:

$$\Xi_c^0 \to \Lambda_c^+ K^-$$
$$\hookrightarrow pK^-\pi^+$$

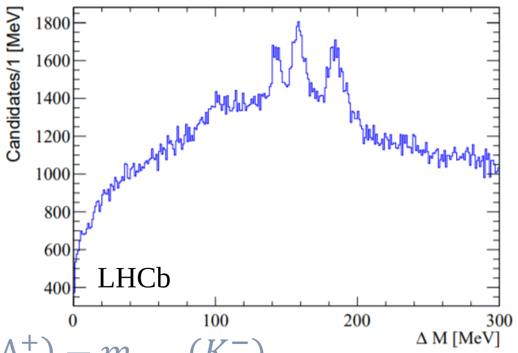
- Select decays using a 2-Dimensional cut

- Optimizing selection simultaneously in **particle identification response** of the bachelor kaon and the $\mathbf{p_T}$ of the mother particle.





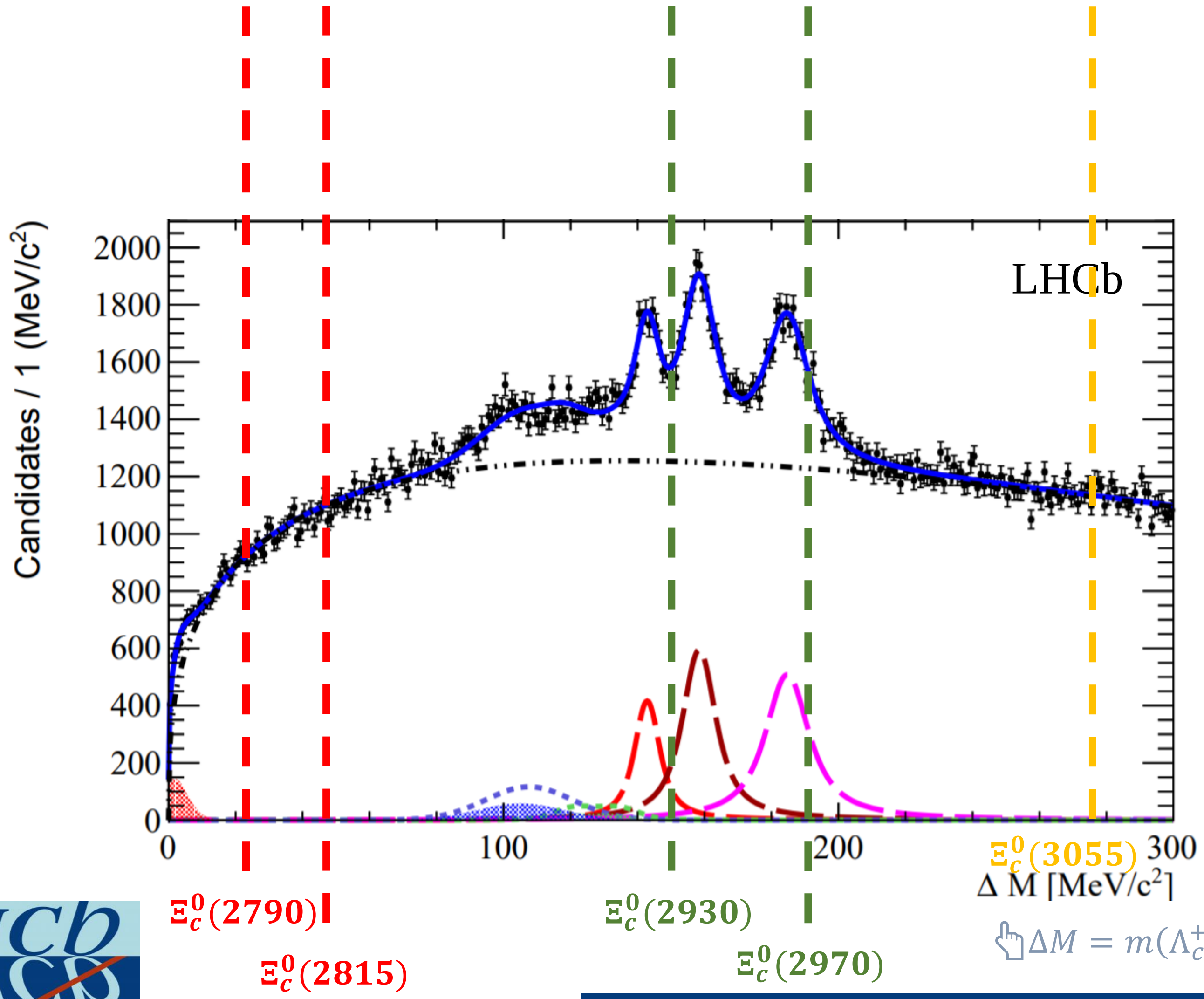
After cut



$$\Delta M = m(\Lambda_c^+K^-) - m(\Lambda_c^+) - m_{pdg}(K^-)$$

Reject 95.25% background while keeping 35.15% signal.

Mass spectrum of $\Lambda_c^+ K^-$

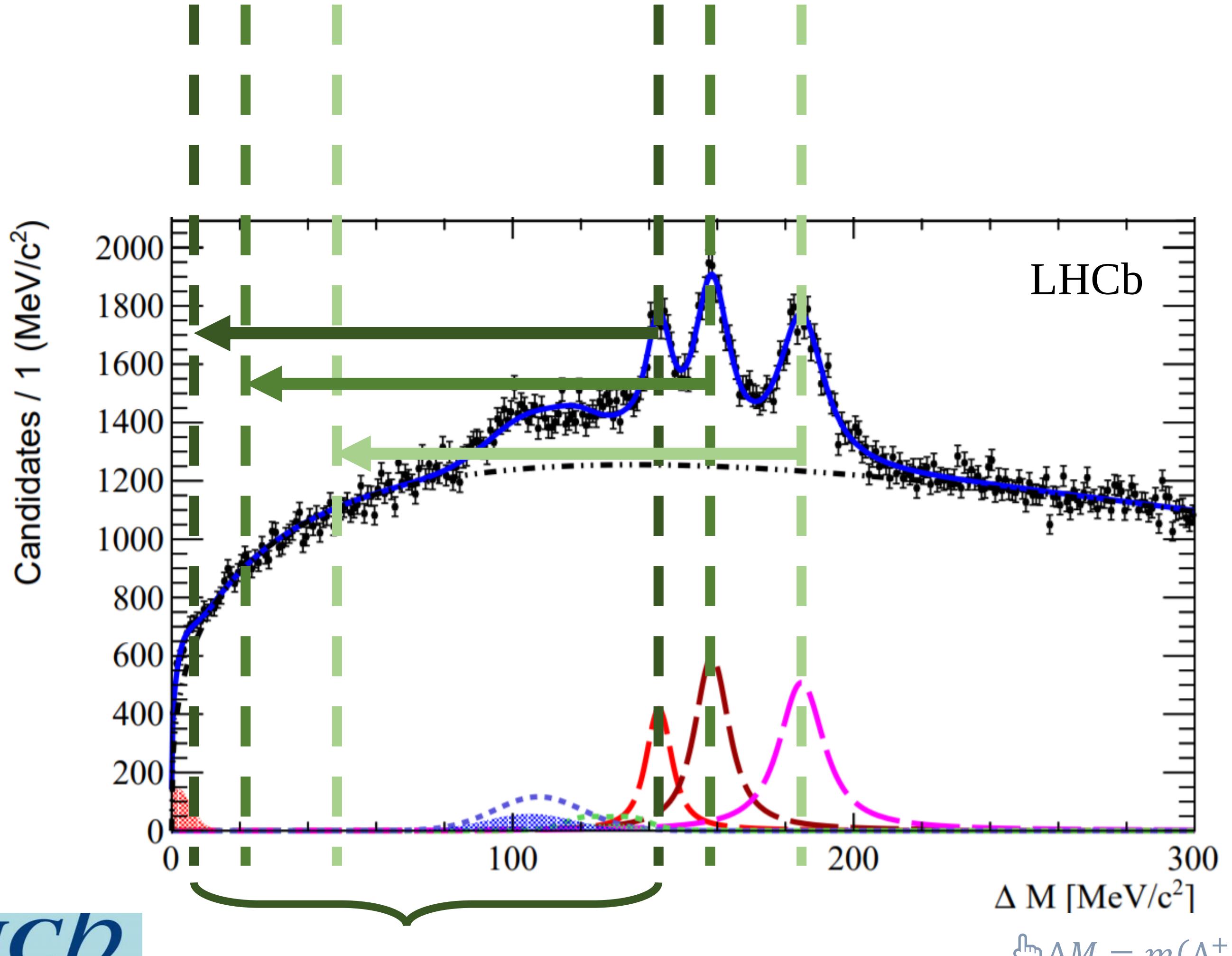


$\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m_{pdg}(K^-)$

- All currently known Ξ_c^0 states (PDG) are marked if the mass bigger than threshold.

- Yellow – Not been seen
  - $\Xi_c^+(3055)$ has been observed PhysRevD.89.052003
- Red – Not been seen in this decay
- Green – Observed in this decay
  - $\Xi_c^0(2930)$ is actually two states
  - Some strange things in $\Xi_c^0(2970)$

Mass spectrum of $\Lambda_c^+ K^-$



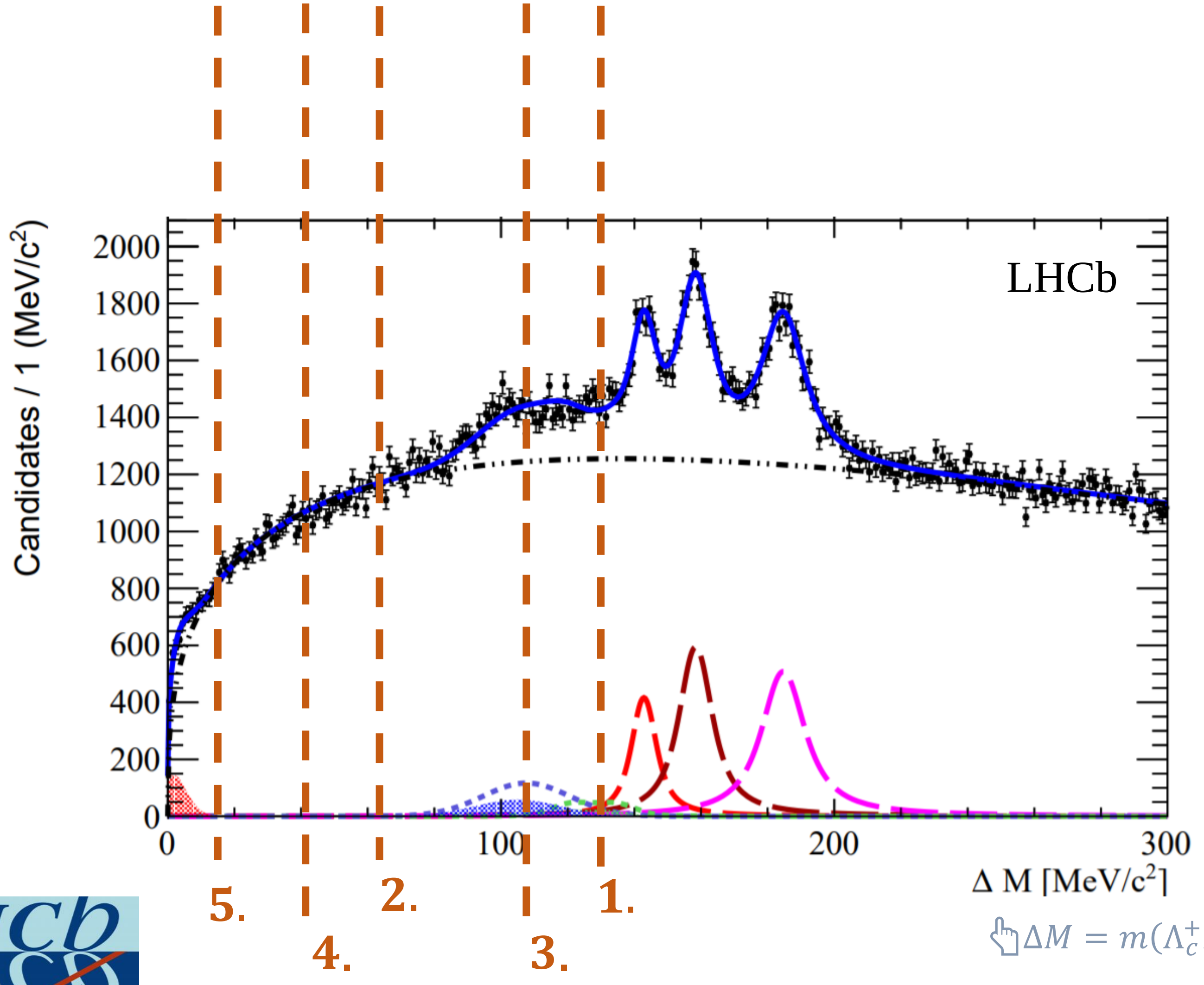
$\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m_{pdg}(K^-)$

Partially reconstructed mode are considered:

- $\Xi_c^{**0} \to \Lambda_c^+ K^- \pi^0$,
- $\Xi_c^{**+} \to \Lambda_c^+ K^- \pi^+$,

then the pion is missing.

Mass spectrum of $\Lambda_c^+ K^-$



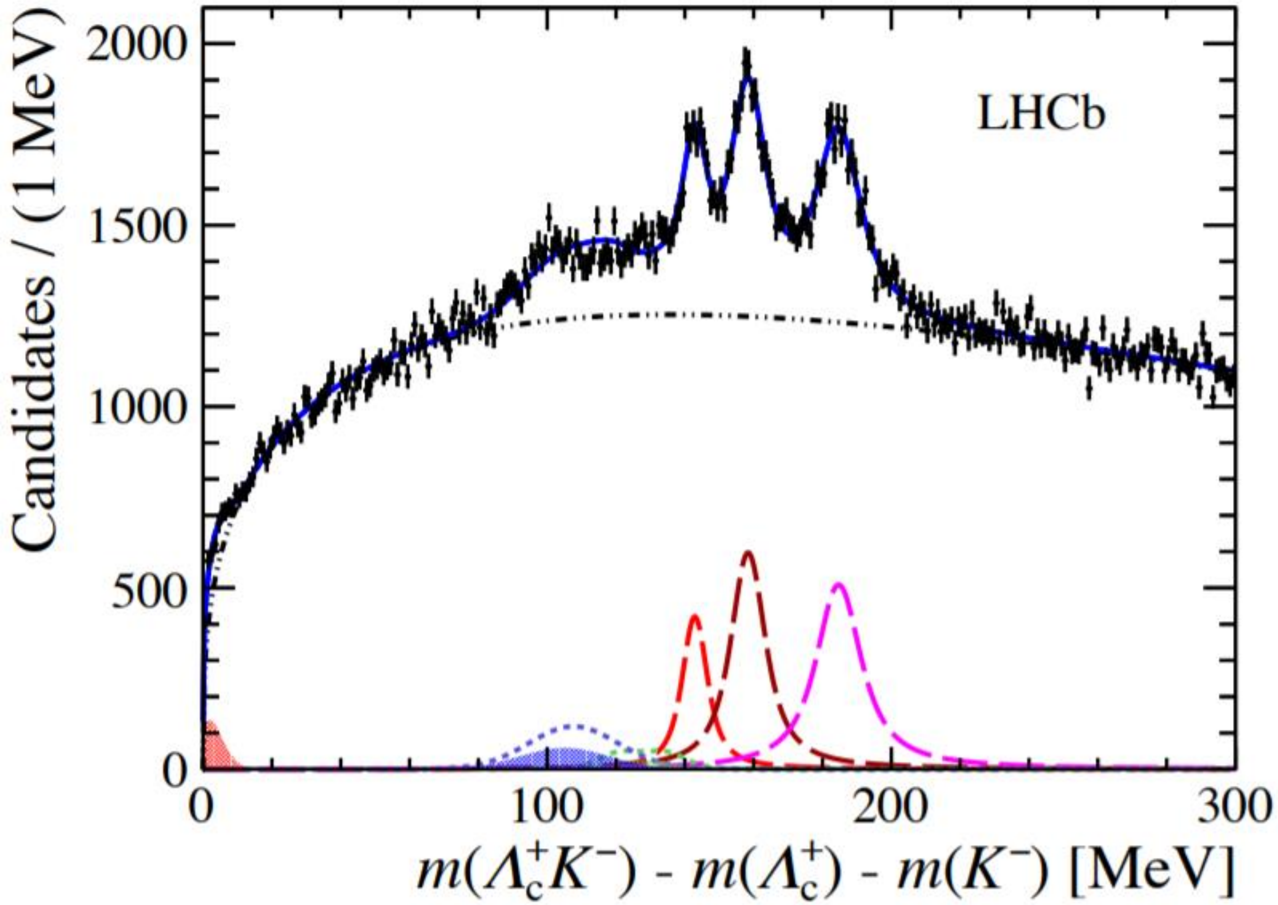
$\Delta M = m(\Lambda_c^+ K^-) - m(\Lambda_c^+) - m_{pdg}(K^-)$

Feeddown are considered:

1. $\Xi_c^{**+}(3080) \rightarrow (\Sigma_c^{++}(2455) \rightarrow \Lambda_c^+ \pi^+) K^-$
2. $\Xi_c^{**+}(3080) \rightarrow (\Sigma_c^{*++}(2520) \rightarrow \Lambda_c^+ \pi^+) K^-$
3. $\Xi_c^{**+}(3055) \rightarrow (\Sigma_c^{++}(2455) \rightarrow \Lambda_c^+ \pi^+) K^-$
4. $\Xi_c^{**+}(3055) \rightarrow (\Sigma_c^{*++}(2520) \rightarrow \Lambda_c^+ \pi^+) K^-$
5. $\Xi_c^{*+}(2970) \rightarrow (\Sigma_c^{++}(2455) \rightarrow \Lambda_c^+ \pi^+) K^-$

$\Lambda_c K$ from this channel.

Mass spectrum of $\Lambda_c^+ K^-$



$\Xi_c(2923)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2939)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2965)^0 \to \Lambda_c^+ K^-$

$PDF_{sig}(m) =$
$Gau(m) \otimes BW(m)$

$\Xi_c(2923)^+ \to \Lambda_c^+ K^- \pi^+$
$\Xi_c(3055)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3055)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$
$\Xi_c(3080)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3080)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$

MC shapes

Background

$PDF_{bkg}(m) = (\Delta m)^a e^{b(\Delta m)}$

PRL 124 (2020) 222001

Summary

- Three states are observed with large significance.
- Mass and width are measured:

Λ_c^+ mass error from PDG

Resonance	Peak of ΔM [MeV]	Mass [MeV]	Γ [MeV]
$\Xi_c(2923)^0$	$142.91 \pm 0.25 \pm 0.20$	$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$158.45 \pm 0.21 \pm 0.17$	$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$184.75 \pm 0.26 \pm 0.14$	$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$	$14.1 \pm 0.9 \pm 1.3$

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- Found two structures around previous $\Xi_c^0(2930)$
  - Statistics increasing
  - Different production mechanism (B-factories and LHCb)

Collaboration	Decay Mode	Mass [MeV]	Width [MeV]	Significance
Belle	$\Lambda_c^+\pi^-K_S^0$	$2977.1 \pm 8.8 \pm 3.5$	-	1.5σ
Babar	$\Lambda_c^+\pi^-K_S^0$	$2972.9 \pm 4.4 \pm 1.6$	$31 \pm 7 \pm 8$	1.7σ
Belle	$\Xi_c(2645)^+\pi^-$	$2965.7 \pm 2.4^{+1.1}_{-1.2}$	$15 \pm 6 \pm 3$	6.1σ
Belle	$\Xi_c(2645)^+\pi^-$ $\Xi_c'\pi^-$	$2970.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$	$30.3 \pm 2.3^{+1.0}_{-1.8}$	$> 5\sigma$
PDG			$28.1^{+3.4}_{-4.0}$	

- $\Xi_c^0(2965)$ is very close to $\Xi_c^0(2970)$
  - but mass and width are different
  - B-factories have not observed the $\Xi_c^0(2970)$ in $\Lambda_c^+K^-$ channel

Discussion

- Gell-Mann-Okubo formula for baryons:

$$m(\Omega_c^{**0}) - m(\Xi_c^{**0}) = m(\Xi_c^{**0}) - m(\Sigma_c^{**0})$$

- We have:

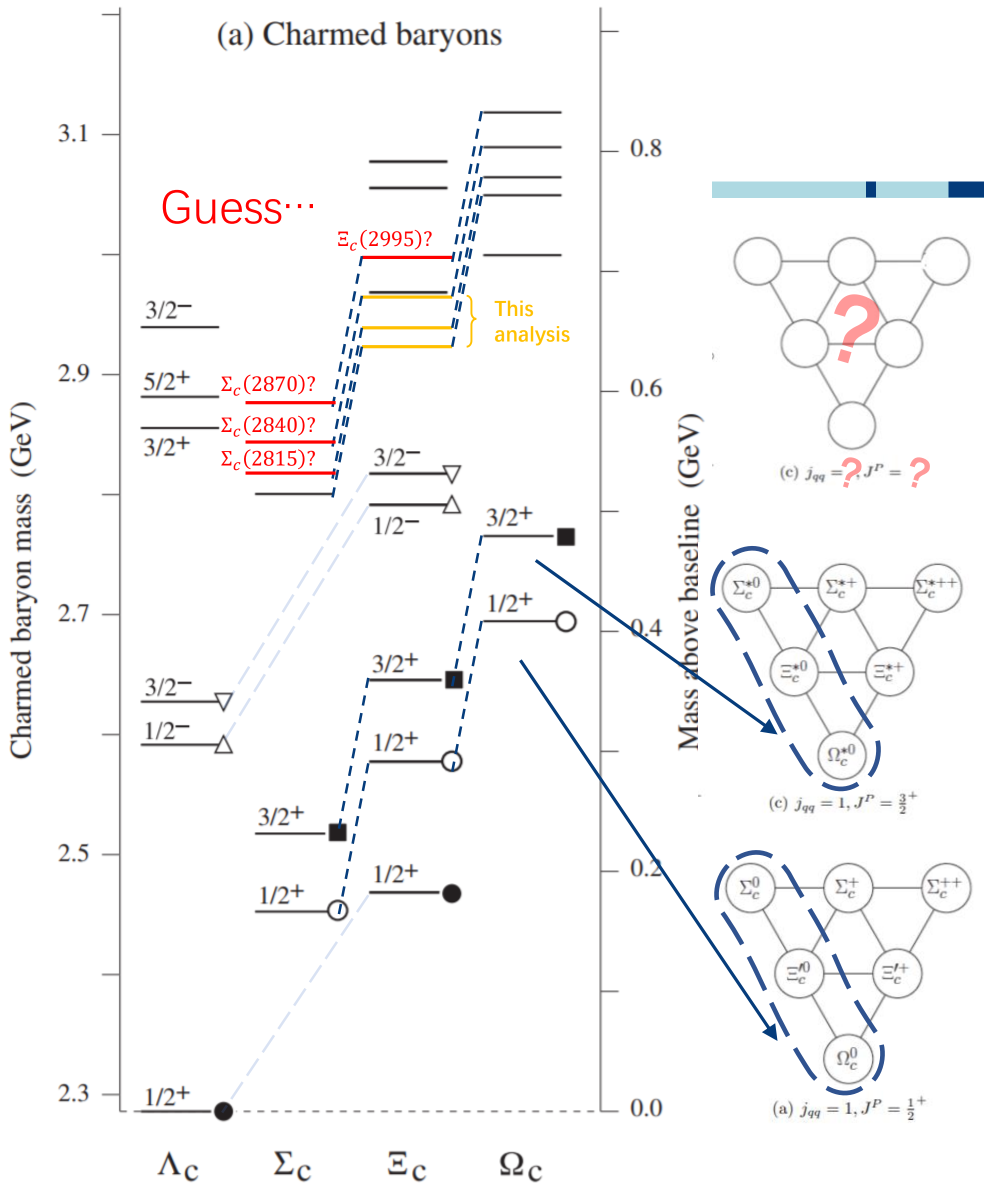
$$m(\Omega_c^0(3050)) - m\left(\Xi_c^0(2923)\right)$$
$$\approx m\left(\Xi_c^0(2923)\right) - m\left(\Sigma_c^0(2800)\right) \approx 125\ \mathrm{MeV}$$

They should have the same J^{PC}

- And:

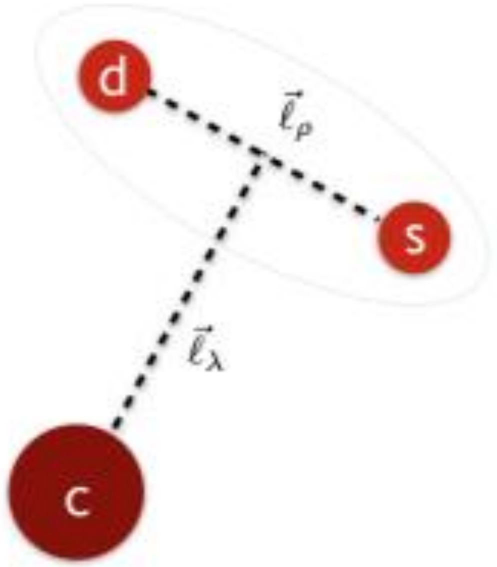
$$m\left(\Omega_c^0(3065)\right) - m\left(\Xi_c^0(2939)\right) \approx 125\ \mathrm{MeV}$$
$$m\left(\Omega_c^0(3090)\right) - m\left(\Xi_c^0(2965/2970)\right) \approx 125\ \mathrm{MeV}$$

- More analysis on going……
  - Other channels
  - Angular distribution
  - ……

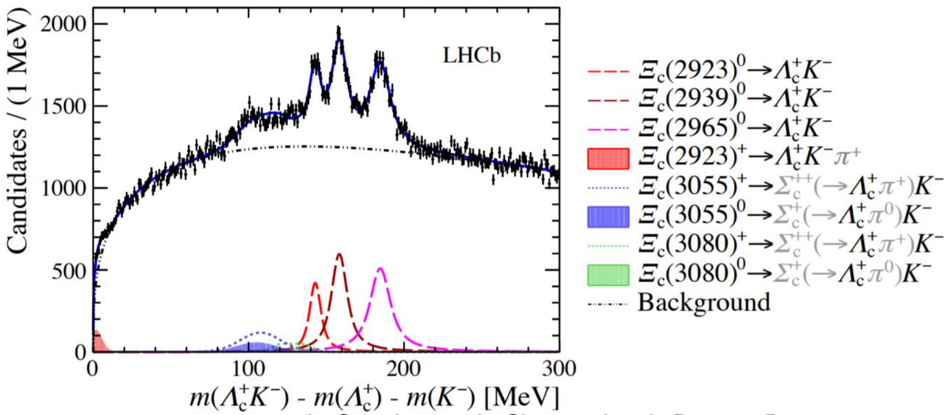


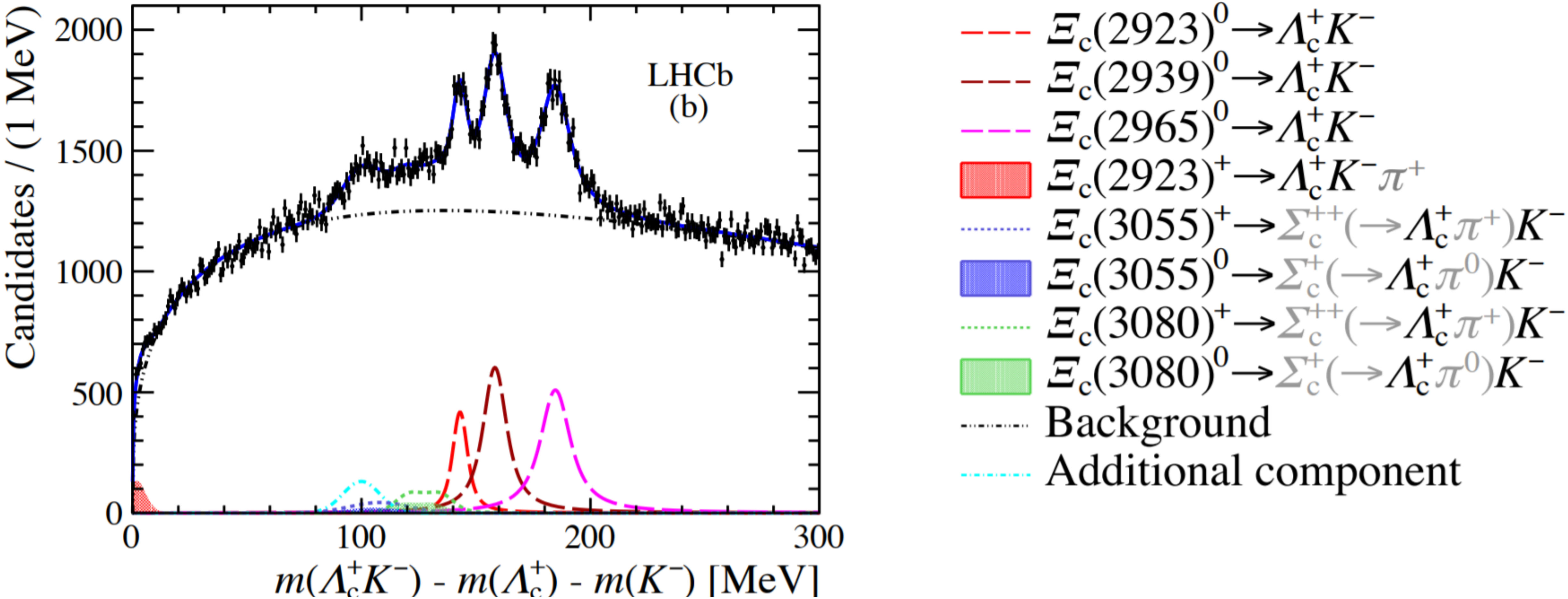
Mass plot from PDG

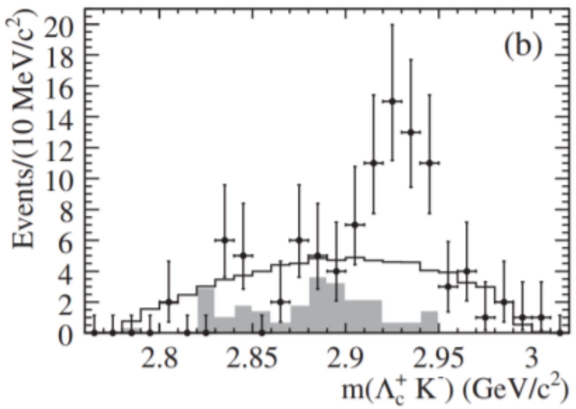
Backup



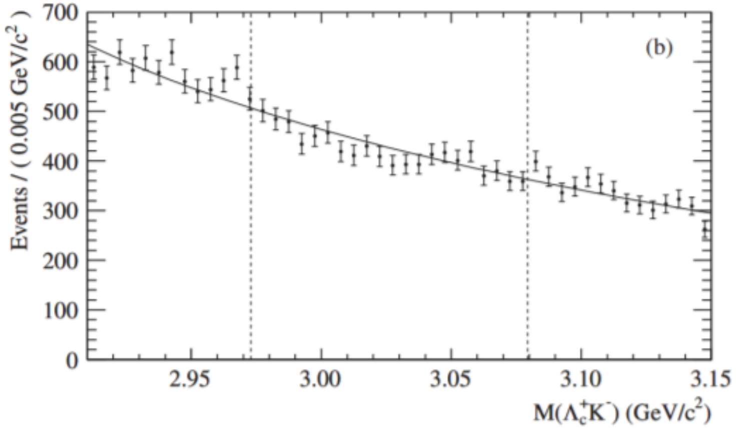
$\vec{\ell}_\rho$	Orbital angular momentum between the two light quarks
$\vec{\ell}_\lambda$	Orbital angular momentum between the heavy quark and the diquark system
$\vec{L} = \vec{\ell}_\rho + \vec{\ell}_\lambda$	Total orbital angular momentum
$\vec{s}_{qq} = \vec{s}_{q_1} + \vec{s}_{q_2}$	Sum of light quarks spins
$\vec{s}_{Q=b,c}$	Spin of the heavy quark
$\vec{j}_{qq} = \vec{L} + \vec{s}_{qq}$	Angular momentum of the diquark system
$\vec{J} = \vec{j}_{qq} + \vec{s}_Q$	Total angular momentum of the heavy meson


Candidates / (1 MeV)
LHCb
$\Xi_c(2923)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2939)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2965)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2923)^+ \to \Lambda_c^+ K^- \pi^+$
$\Xi_c(3055)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3055)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$
$\Xi_c(3080)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3080)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$
Background
$m(\Lambda_c^+ K^-)$ - $m(\Lambda_c^+)$ - $m(K^-)$ [MeV]

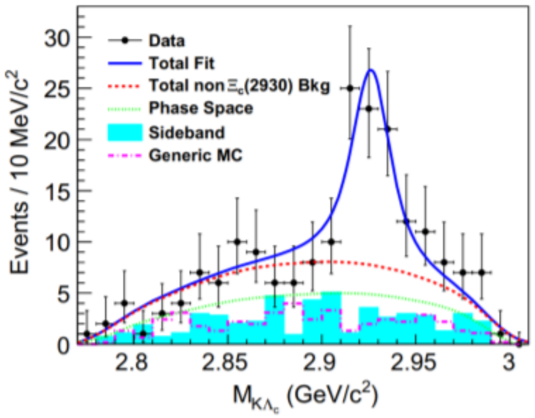

Candidates / (1 MeV)
LHCb
(b)
$\Xi_c(2923)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2939)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2965)^0 \to \Lambda_c^+ K^-$
$\Xi_c(2923)^+ \to \Lambda_c^+ K^- \pi^+$
$\Xi_c(3055)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3055)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$
$\Xi_c(3080)^+ \to \Sigma_c^{++}(\to \Lambda_c^+ \pi^+) K^-$
$\Xi_c(3080)^0 \to \Sigma_c^{+}(\to \Lambda_c^+ \pi^0) K^-$
Background
Additional component
$m(\Lambda_c^+ K^-)$ - $m(\Lambda_c^+)$ - $m(K^-)$ [MeV]



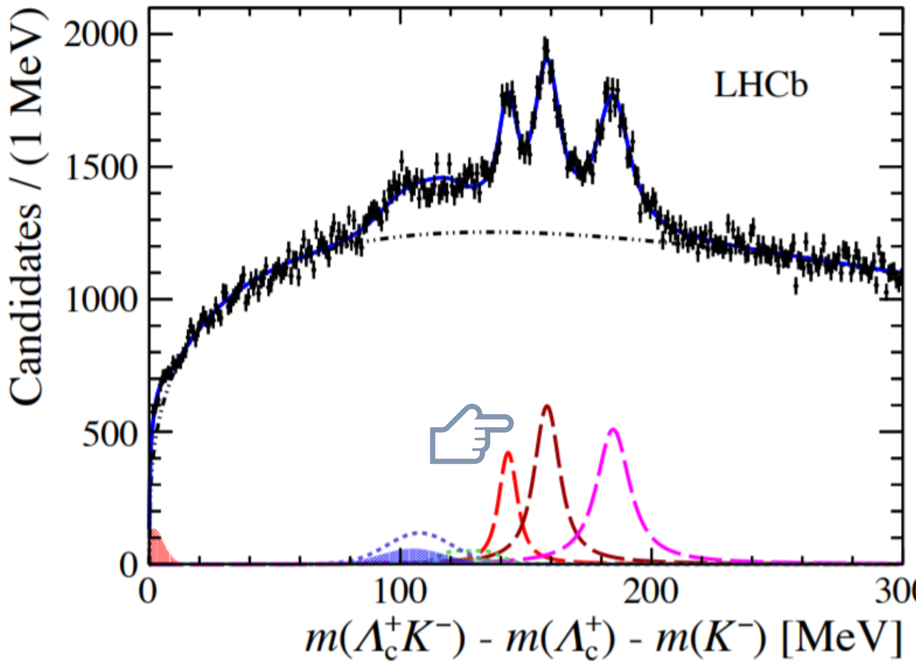
(a) BaBar collaboration [4]



(b) BaBar collaboration [5]



(c) Belle collaboration [7]



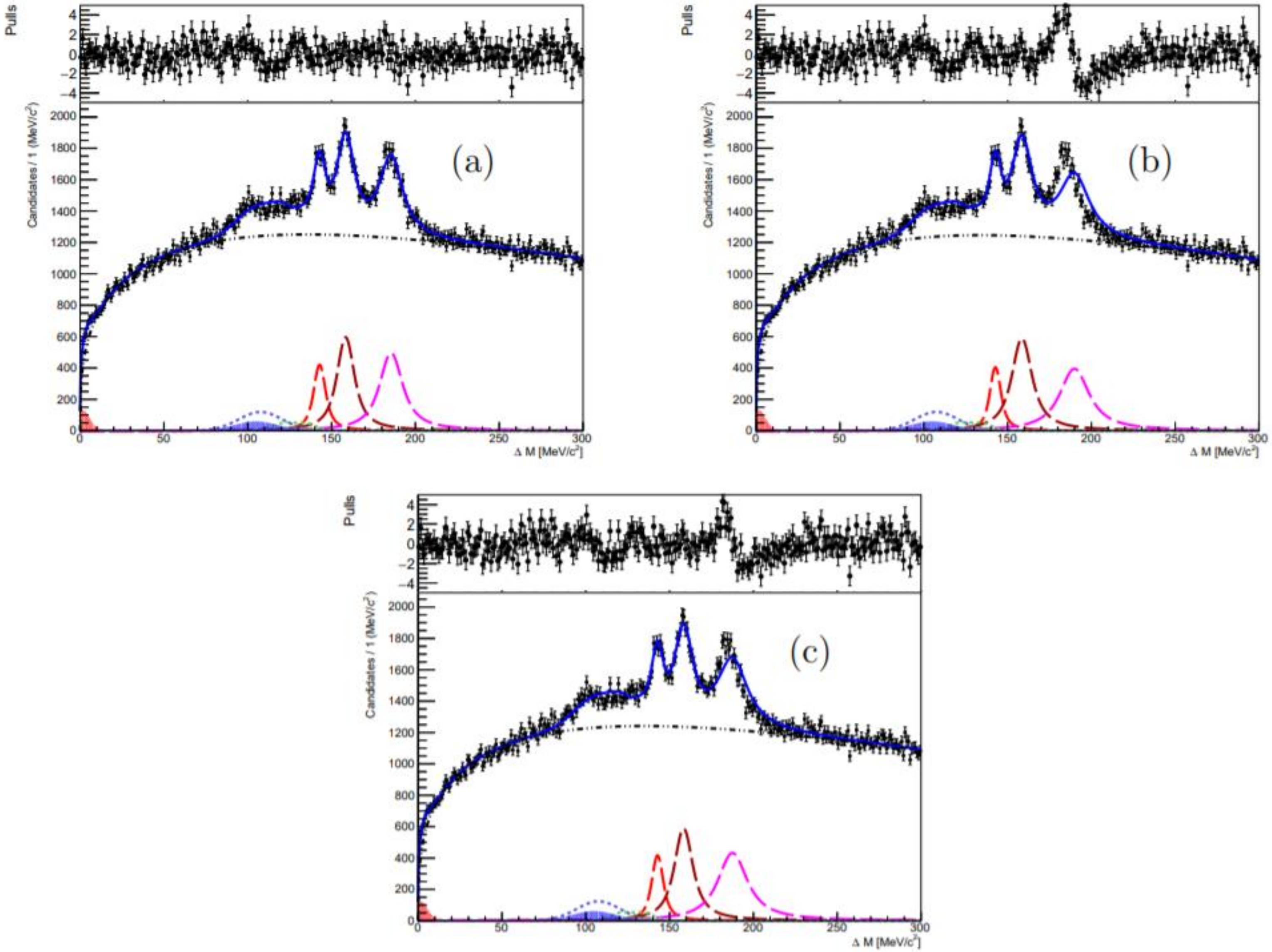
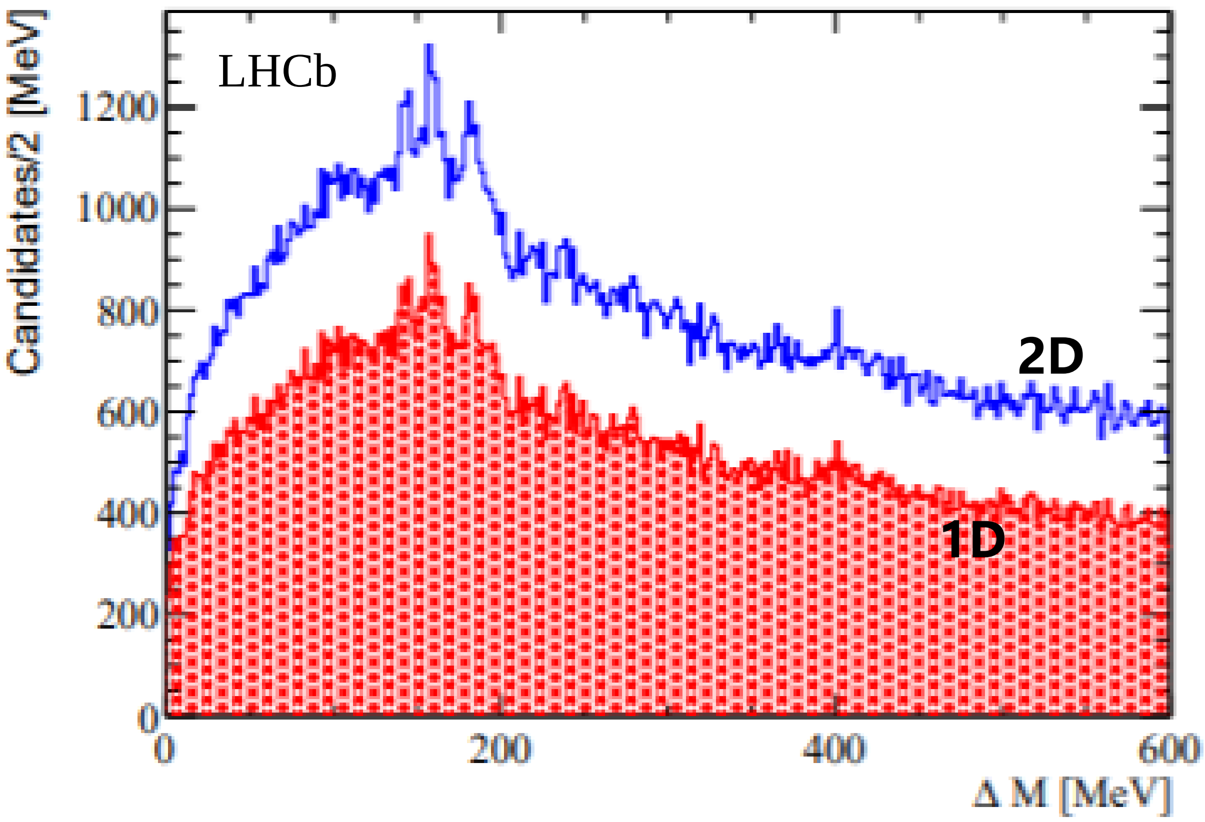


Figure 55: The fit where the peak at highest mass has been fixed to previously measured values ((a) [13], (b) [14] and (c) [9])

Source	$\Xi_c(2920)^0$ $(m[\,\text{MeV}], \Gamma[\,\text{MeV}])$	$\Xi_c(2940)^0$ $(m[\,\text{MeV}], \Gamma[\,\text{MeV}])$	$\Xi_c(2970)^0$ $(m[\,\text{MeV}], \Gamma[\,\text{MeV}])$
Alternative fit model	(0.17, 1.59)	(0.14, 0.44)	(0.04, 1.09)
Resonance interferences	(0.08, 0.72)	(0.06, 0.95)	(0.11, 0.74)
Momentum scaling uncertainty	(0.04, 0.00)	(0.05, 0.00)	(0.06, 0.00)
Energy losses	(0.04, 0.00)	(0.04, 0.00)	(0.04, 0.00)
Data-MC discrepancy	(0.00, 0.57)	(0.00, 0.25)	(0.00, 0.26)
Total	(0.20, 1.84)	(0.17, 1.07)	(0.14, 1.34)
PDG mass uncertainty	(0.14, 0.00)	(0.14, 0.00)	(0.14, 0.00)

Table 24: Summary of the contributions to the systematic errors on the resonance parameters, where in every case the absolute deviation from the nominal fit is quoted.

1D vs. 2D cut of kaon



1D
ProbNNk>0.997
$P_T(\Lambda_c^+ K^-)$>7400 MeV

signal efficiency is 29.2% at a 98.6% background rejection.

2D
ProbNNk>0.996
$P_T(\Lambda_c^+ K^-)$>7350 MeV

signal efficiency is 35.19% at a 95.25% background rejection.