Searching for tetraquark through weak decays of b-baryons

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Phys. Rev. D 106, 114041 (2022); Eur. Phys. J. C 82, 1075 (2022)

第三届强子与重味物理理论与实验联合研讨会

Outline

- Introduction
- $\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$
- Search for tetraquarks
- Summary

Introduction

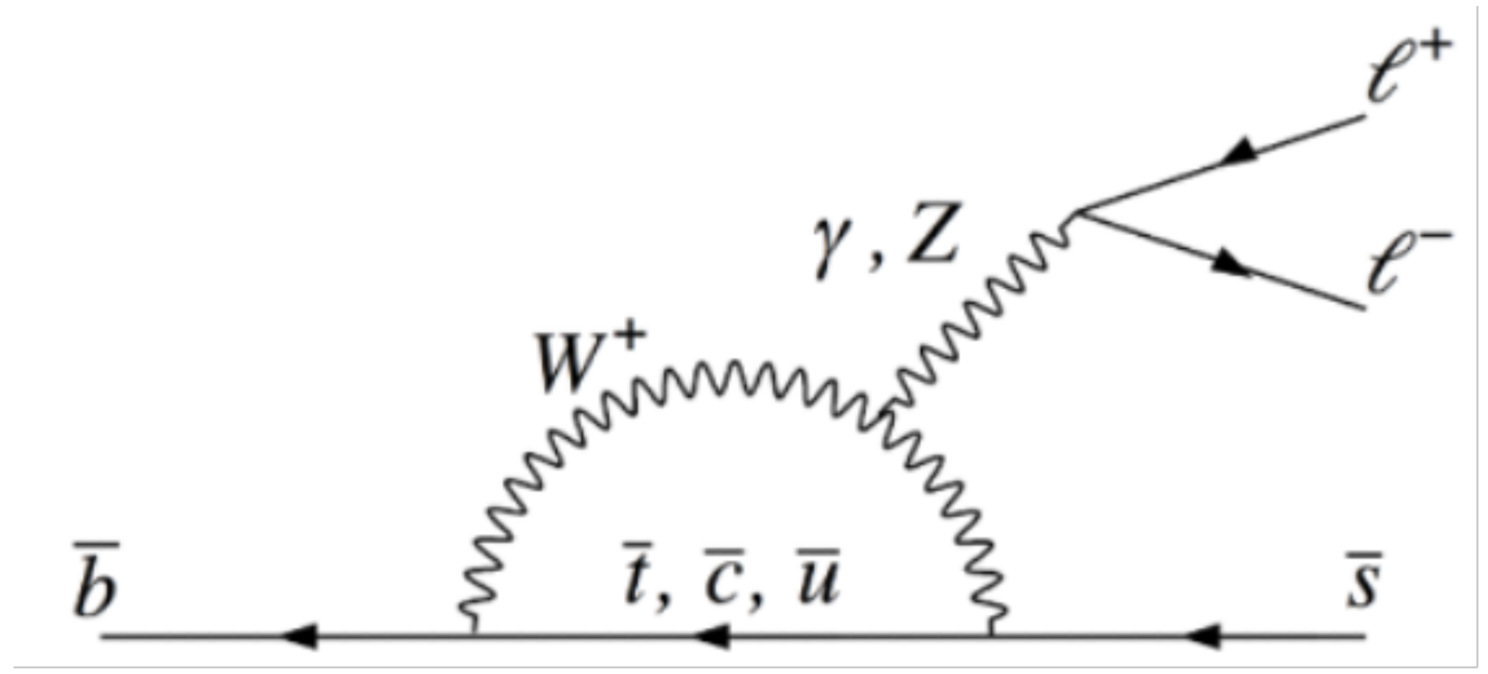
Lepton Universality

- Provide a platform for study of strong interactions

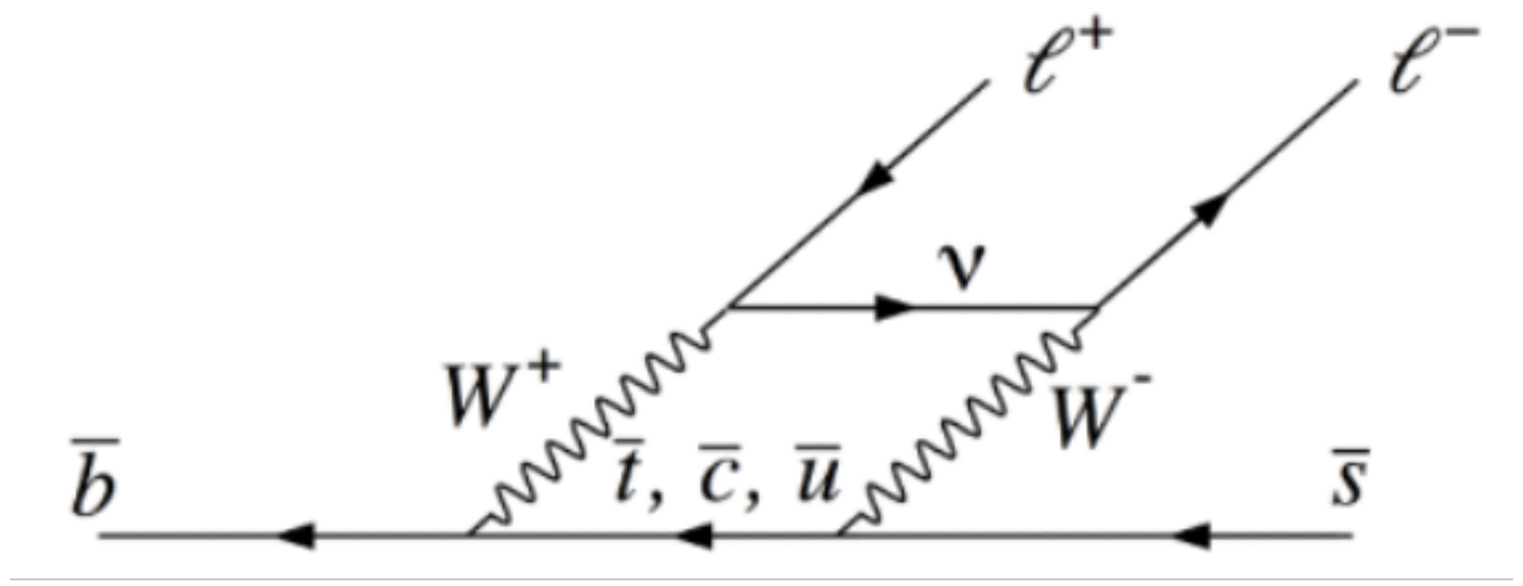
$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to K e^+ e^-)} \qquad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

$0.927^{+0.093,+0.036}_{-0.087,-0.035}$	Low-q^2	$0.994^{+0.090,+0.029}_{-0.082,-0.027}$	Low-q^2
$1.027^{+0.072,+0.027}_{-0.068,-0.026}$	Central-q^2	$0.949^{+0.072,+0.027}_{-0.041,-0.022}$	Central-q^2

LHCb, PRD108, 032002 (2023)



Penguin diagram



Box diagram

Introduction

Theoretical

- ✓Quark Model：
  - Light-Front Quark Model
  - Covariant Quark Model
  - Nonrelativistic Quark Model….
- ✓ QCD Sum rules (QCDSR)
- ✓ Light-Cone Sum rules (LCSR)
- ✓ Lattice QCD (LQCD)
- ✓Bethe-Salpeter approach…

Experimental

PHYSICAL REVIEW LETTERS **131,** 151801 (2023)

Measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ Differential Branching Fraction

R. Aaij *et al.*[*]
(LHCb Collaboration)

LHCb, PRL 131, 151801 (2023)

JHEP
Published for SISSA by Springer

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Differential branching fraction and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays

LHCb, JHEP 06, 115 (2015)

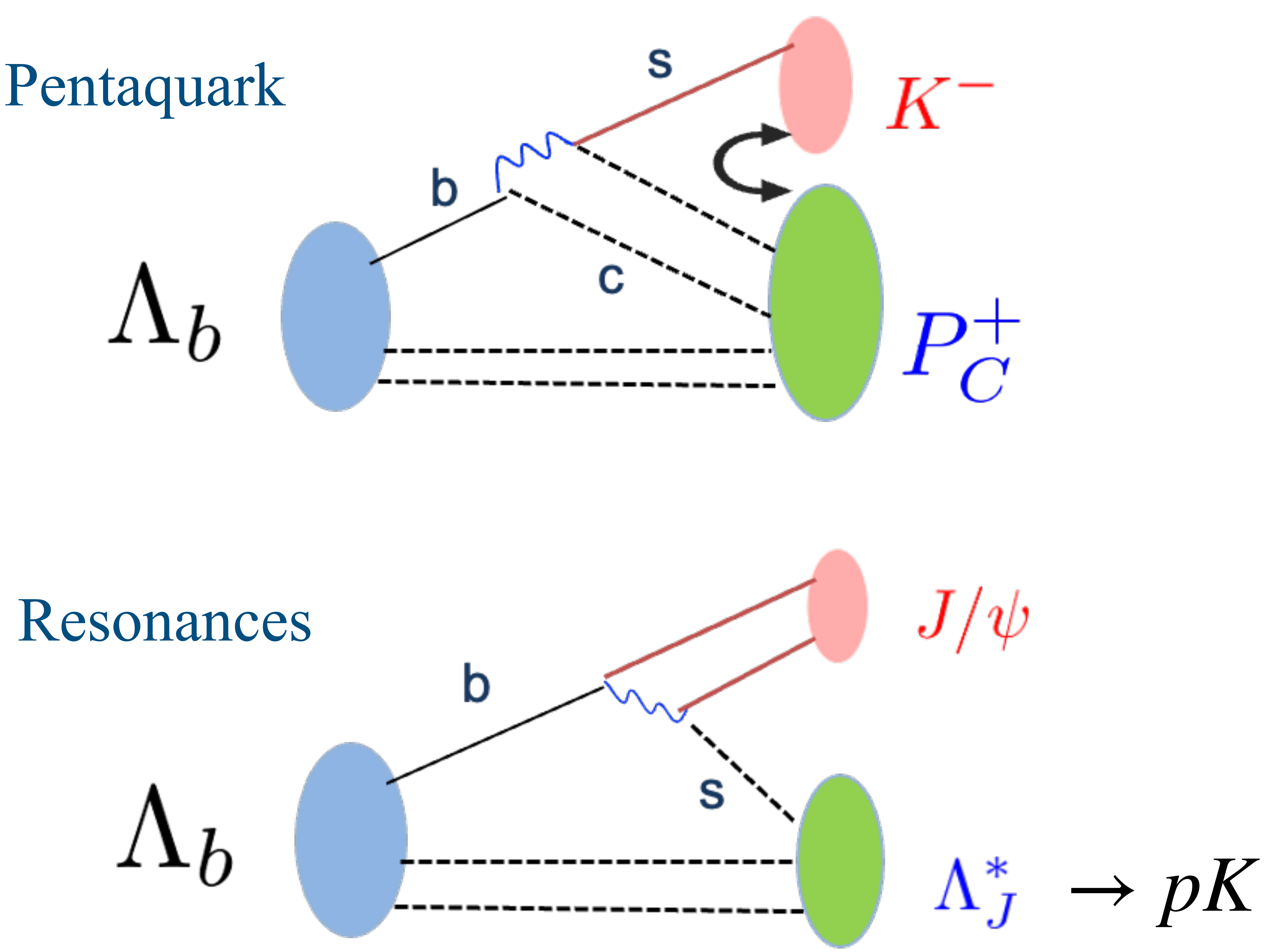
PRL **107,** 201802 (2011) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2011

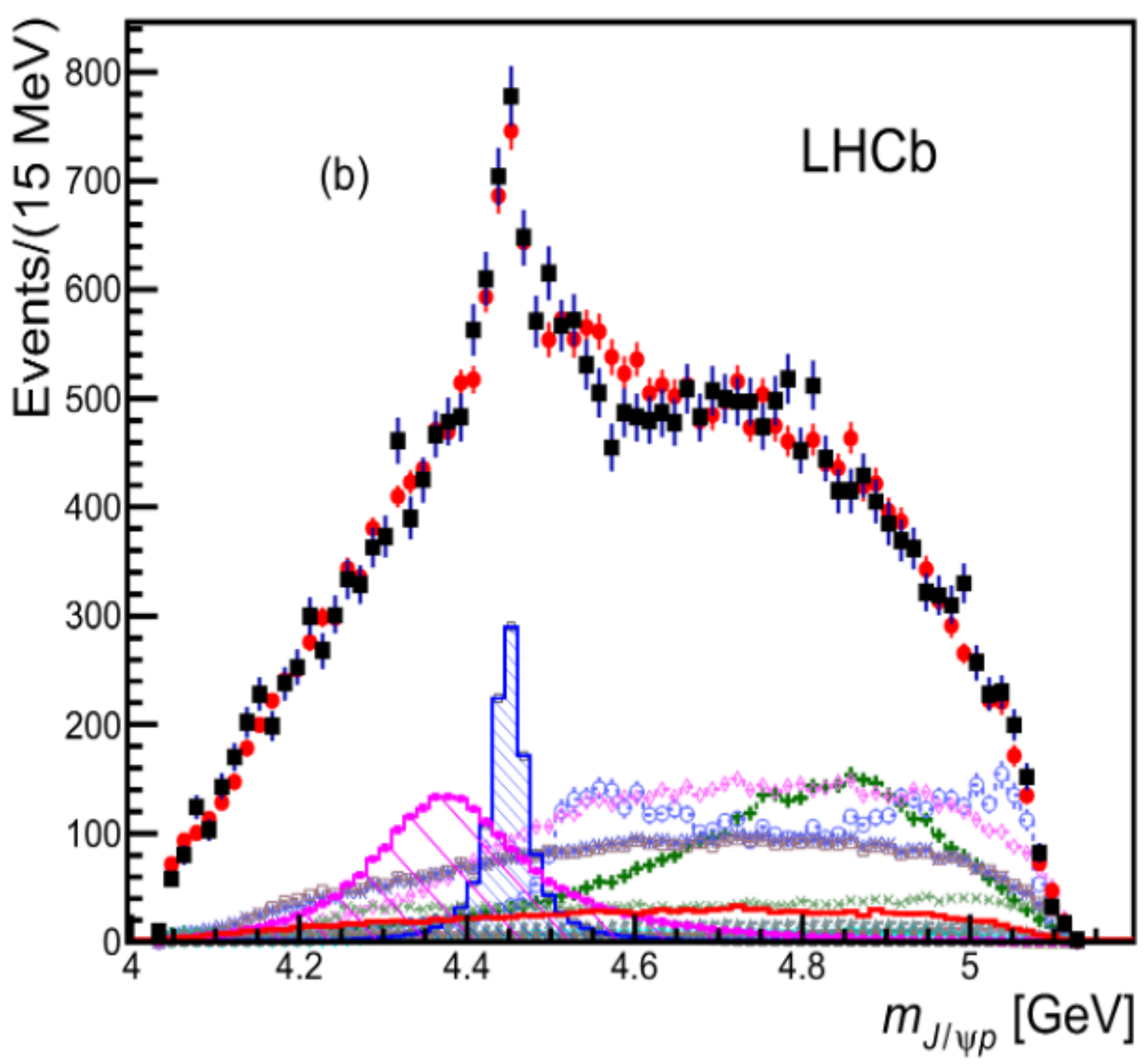
Observation of the Baryonic Flavor-Changing Neutral Current Decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

CDF, PRL 107, 201802 (2011)

$\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

☑ Pentaquark production





LHCb, Phys. Rev. Lett. 115, 072001 (2015)
LHCb, Phys. Rev. Lett. 122, 222001 (2019)

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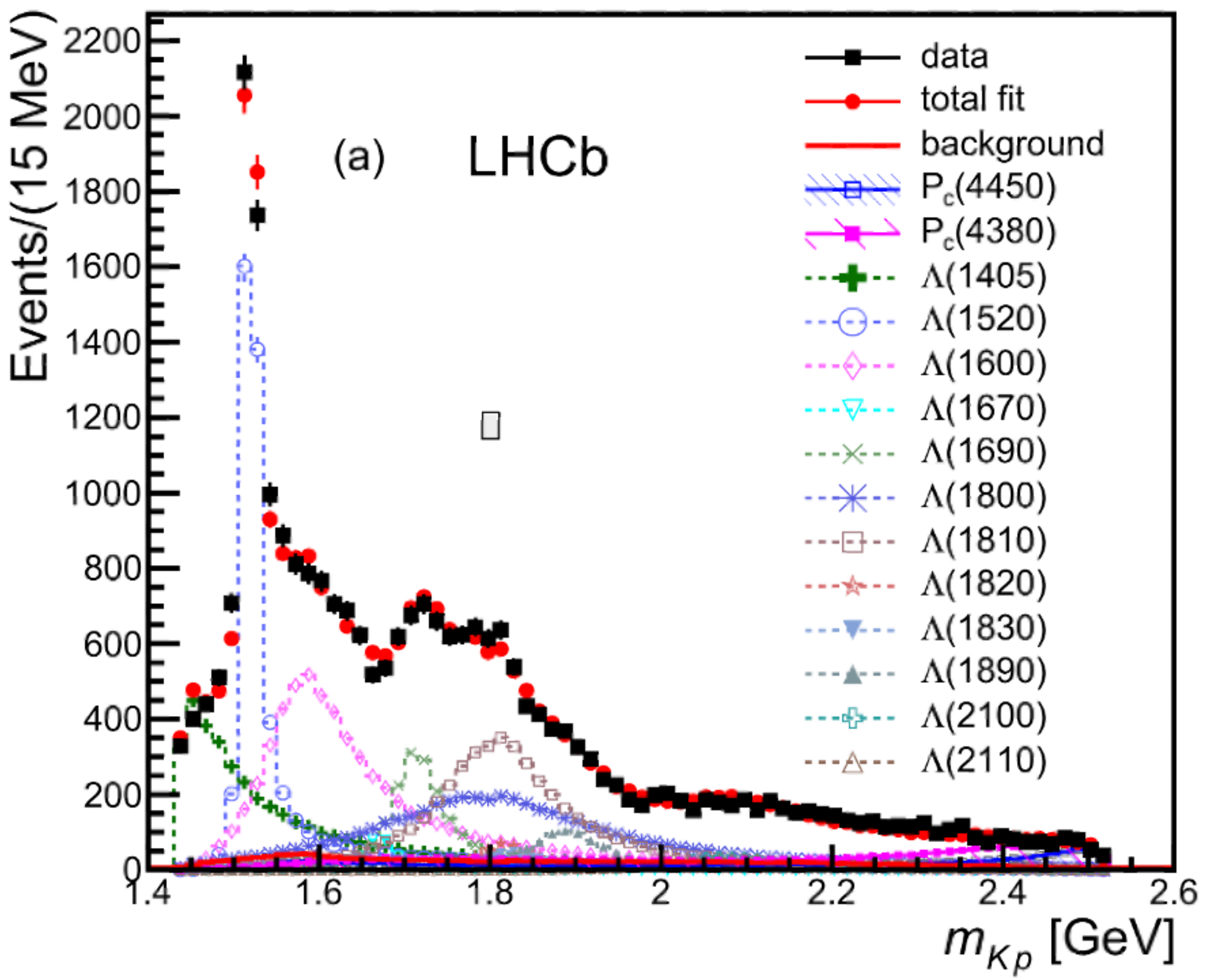
$\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

$\Lambda^*_{1405}, \Lambda^*_{1520}, \Lambda^*_{1600}, \Lambda^*_{1690}, \Lambda^*_{1800}, \Lambda^*_{1810}$

- These resonances give main contributions

- Λ_b decays depend on different resonances and their interference terms



LHCb, Phys. Rev. Lett. 115, 072001 (2015)

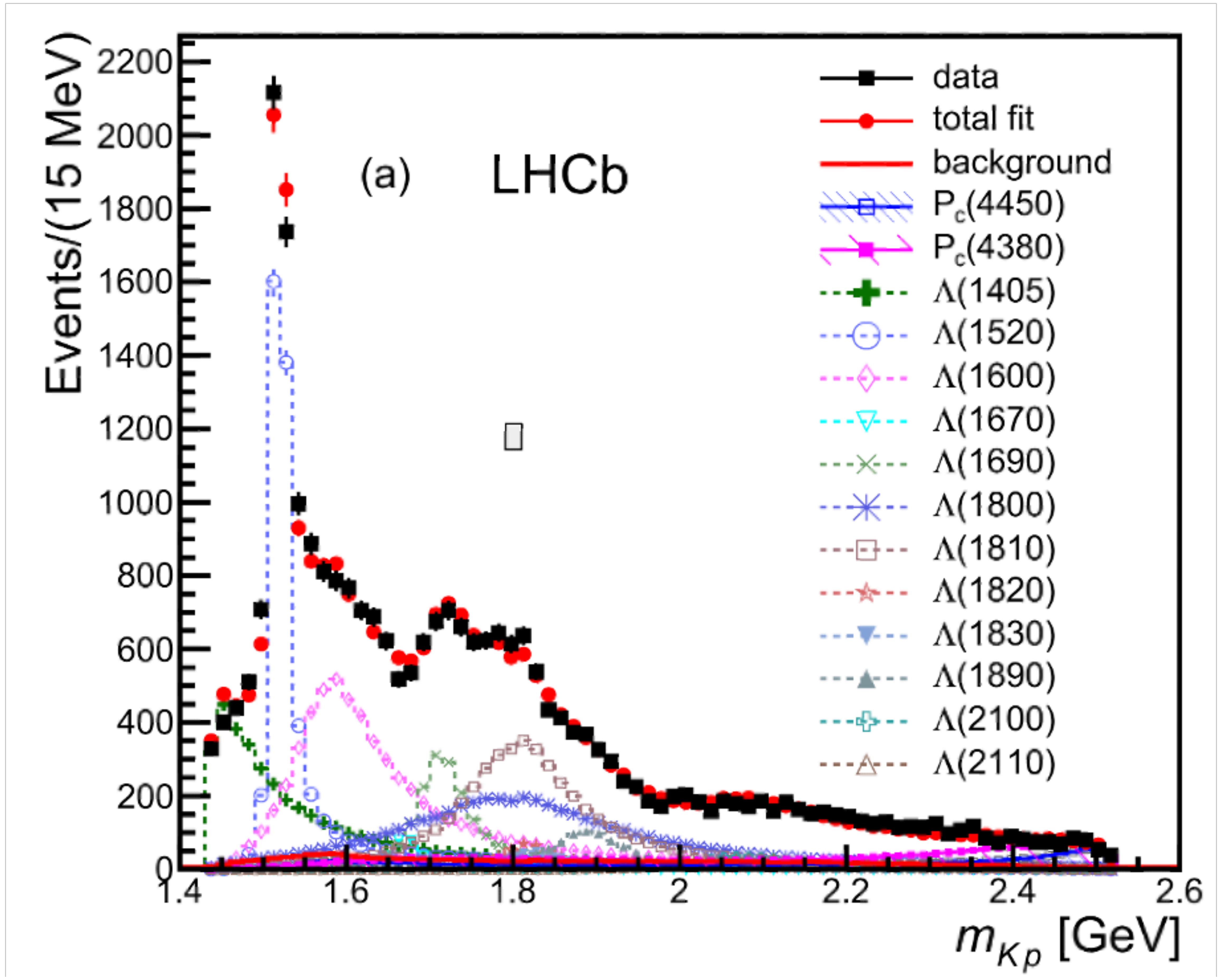
$\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

~~Λ^*_{1405}~~, Λ^*_{1520}, Λ^*_{1600}, ~~Λ^*_{1690}~~, Λ^*_{1800}, Λ^*_{1810}

✓ Λ^*_{1405} does not reach the threshold
$m_{\Lambda^*_{1405}} < m_p + m_K$

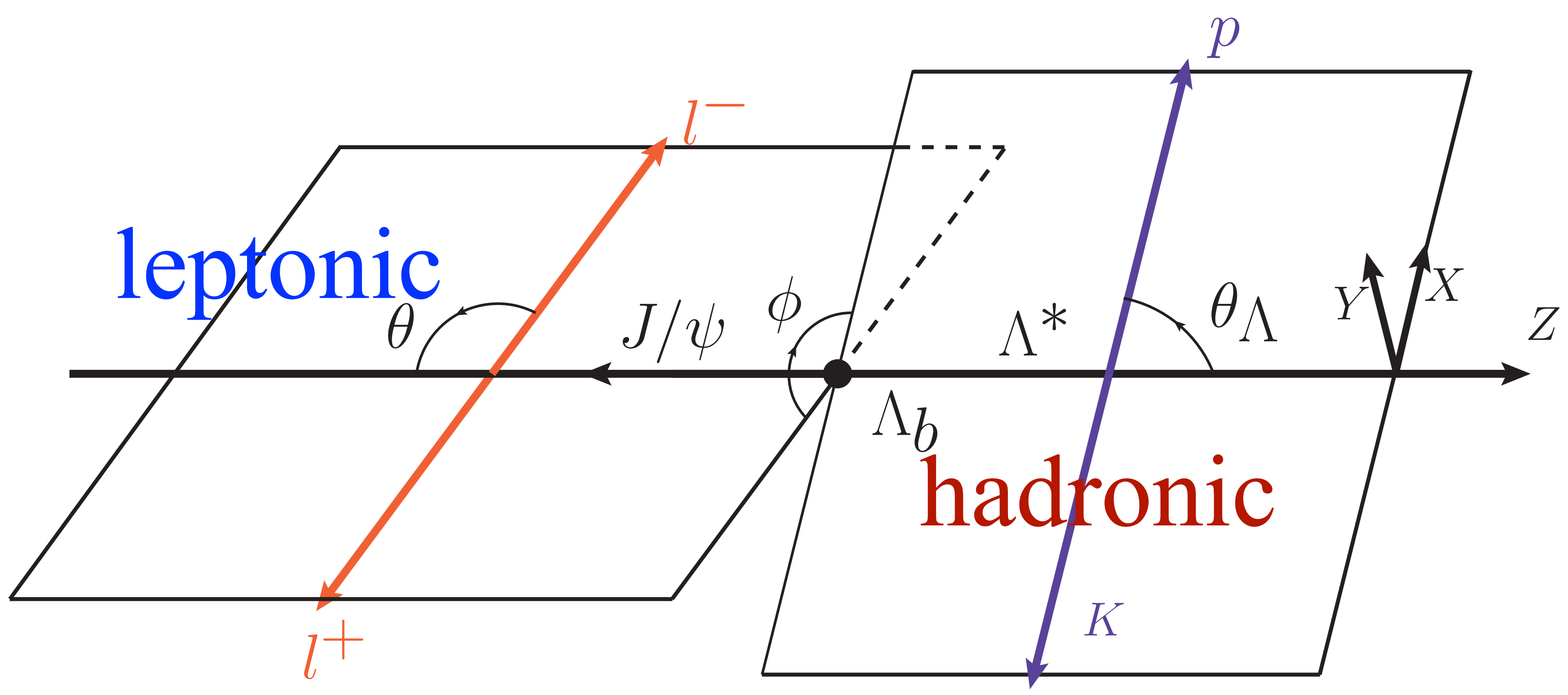
✓ Λ^*_{1800} and Λ^*_{1810} are very close
They will be treated together

✓ Λ^*_{1690} has a tiny contribution
Small integrated width



LHCb, Phys. Rev. Lett. 115, 072001 (2015)

$\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$



$$\mathcal{M}(\Lambda_b \to \Lambda_J^* J/\psi) \propto \langle \Lambda_J^* | (\bar{s}b)^\mu_{V-A} | \Lambda_b \rangle \epsilon^*_\mu(s_{J/\psi})$$

$$i\mathcal{M}(\Lambda_J^* \to pK) = \mathcal{A}_J \times D^{*J_{\Lambda^*}}_{s_{\Lambda^*},s_p}(\phi_\Lambda, \theta_\Lambda)$$

$$i\mathcal{M}(J/\psi \to \ell^+\ell^-) = 2ieg \times L^{\lambda_{J/\psi}}_{\lambda_-,\lambda_+}(\theta, \phi)$$

Extract coupling constant

$$g^2 = \frac{3\Gamma(J/\psi \to l^+l^-) m^2_{J/\psi}}{4\alpha_{em}(m^2_{J/\psi} + 2m^2_\ell)\sqrt{m^2_{J/\psi} - 4m^2_\ell}}$$

$$i\mathcal{M} = \sum_{\Lambda_J^*} \sum_{s_{\Lambda^*} s_{J/\psi}} i\mathcal{M}(\Lambda_b \to \Lambda_J^* J/\psi)$$

$$\times\, i\mathcal{M}(\Lambda_J^* \to pK) \frac{i}{p^2_{\Lambda^*} - m^2_{\Lambda_J^*} + i m_{\Lambda_J^*}\Gamma_{\Lambda_J^*}}$$

$$\times\, i\mathcal{M}(J/\psi \to \ell^+\ell^-) \frac{i}{q^2 - m^2_{J/\psi} + i m_{J/\psi}\Gamma_{J/\psi}}$$

Angular distributions of $\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

Spin-1/2 baryon

$$\langle \Lambda_J^*(p',s')|\bar{s}\gamma^\mu b|\Lambda_b(p,s)\rangle$$

$$= \bar{u}(p',s')\left(\gamma_\mu f_1^p + \frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}} f_2^p + \frac{p^\mu_{\Lambda_J^*}}{m_{\Lambda_J^*}} f_3^p\right) u(p,s)$$

$$\langle \Lambda_J^*(p',s')|\bar{s}\gamma^\mu\gamma_5 b|\Lambda_b(p,s)\rangle$$

$$= \bar{u}(p',s')\left(\gamma_\mu g_1^p + \frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}} g_2^p + \frac{p^\mu_{\Lambda_J^*}}{m_{\Lambda_J^*}} g_3^p\right) \gamma_5 u(p,s)$$

MCN model

$$f(M^2_{pK}) = (a_0 + a_2 p_\Lambda^2 + a_4 p_\Lambda^4)\exp\left(-\frac{6m_q^2 p_\Lambda^2}{2\tilde{m}_\Lambda{}^2(\alpha^2_{\Lambda_b} + \alpha^2_{\Lambda^*})}\right)$$

Λ^*_{1600}

Form factor	a_0	a_2	a_4
f_1^+	0.467	0.615	0.0568
f_2^+	−0.381	−0.2815	−0.0399
f_3^+	0.0501	−0.0295	−0.00163
g_1^+	0.114	0.300	0.0206
g_2^+	−0.394	−0.307	−0.0445
g_3^+	−0.0433	0.0478	0.00566

$\alpha_{\Lambda*(1600)} = 0.387$

Int. J. Mod. Phys. A 27, 1250016 (2012)

Angular distributions of $\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

Spin-3/2 baryon:helicity-base

$$\langle \Lambda^*_{1520}(p',s')|\bar{s}\gamma^\mu b|\Lambda_b(p,s)\rangle =$$

$$\bar{u}_\lambda(p',s')\Bigg(f_0^{3/2}\frac{m_{\Lambda^*_{1520}}}{s_{p+}}\frac{(m_{\Lambda_b}-m_{\Lambda^*_{1520}})p^\lambda q^\mu}{q^2}$$

$$+f_+^{3/2}\frac{m_{\Lambda^*_{1520}}}{s_{p-}}\frac{(m_{\Lambda_b}+m_{\Lambda^*_{1520}})p^\lambda(q^2(p^\mu+p'^\mu)-q^\mu(m^2_{\Lambda_b}-m^2_{\Lambda^*_{1520}}))}{q^2 s_{p+}}$$

$$+f_\perp^{3/2}\frac{m_{\Lambda^*_{1520}}}{s_{p-}}\left(p^\lambda\gamma^\mu-\frac{2p^\lambda(m_{\Lambda_b}p'^\mu+m_{\Lambda^*_{1520}}p^\mu)}{s_{p+}}\right)$$

$$+f_{\perp'}^{3/2}\frac{m_{\Lambda^*_{1520}}}{s_{p-}}\left(p^\lambda\gamma^\mu-\frac{2p^\lambda p'^\mu}{m_{\Lambda^*_{1520}}}+\frac{2p^\lambda(m_{\Lambda_b}p'^\mu+m_{\Lambda^*_{1520}}p^\mu)}{s_{p+}}+\frac{s_{p-}g^{\lambda\mu}}{m_{\Lambda^*_{1520}}}\right)\Bigg)u(p,s)$$

vector

LQCD

$$f(M^2_{pK}) = F + A(\omega - 1)$$

Lattice QCD

Form factor	F	A
$f_0^{3/2}$	3.54(29)	−14.7(3.3)
$f_+^{3/2}$	0.0432(64)	1.63(19)
$f_\perp^{3/2}$	−0.068(18)	2.49(35)
$f_{\perp'}^{3/2}$	0.0461(18)	−0.161(27)
$g_0^{3/2}$	0.0024(38)	1.58(17)
$g_+^{3/2}$	2.95(25)	−12.2(2.9)
$g_\perp^{3/2}$	2.92(24)	−11.8(2.8)
$g_{\perp'}^{3/2}$	−0.037(14)	0.09(25)

Phys. Rev. D 105, 054511 (2022)

$\Lambda_b \to \Lambda_J^*(pK^-)J/\psi(\ell^+\ell^-)$

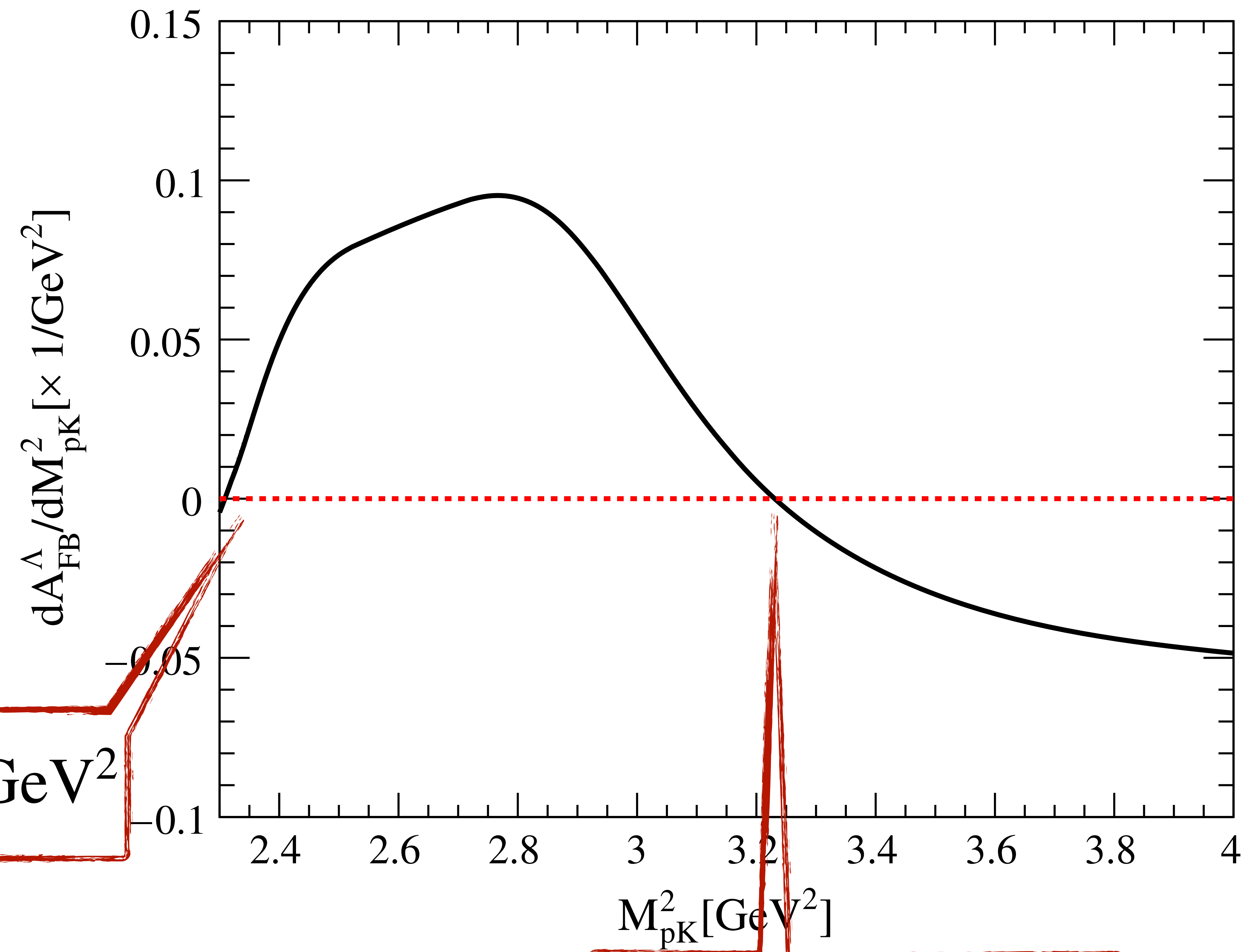
$$A_{\rm FB}^{\Lambda} = \frac{[\int_0^1 - \int_{-1}^0] d\cos\theta_\Lambda \frac{d^2\Gamma}{dM_{pK}^2 d\cos\theta_\Lambda}}{[\int_0^1 + \int_{-1}^0] d\cos\theta_\Lambda \frac{d^2\Gamma}{dM_{pK}^2 d\cos\theta_\Lambda}}$$

$$\frac{dA_{\rm FB}^{\Lambda}}{dM_{pK}^2} \propto \sum_{s_{\Lambda_b}, s_{\Lambda_J^*} = \pm\frac{1}{2}} (2\hat{m}_\ell^2 + 1) \mathcal{R}_e\left(H^{\frac{3}{2}}_{s_{\Lambda_b}, s_{\Lambda_J^*}} H^{\frac{1}{2}*}_{s_{\Lambda_b}, s_{\Lambda_J^*}}\right)$$

neglect Λ^*_{1600} contribution

$$\frac{dA_{\rm FB}^{\Lambda}}{dM_{pK}^2} \propto \mathcal{R}_e(L_{\Lambda^*_{1520}} L_{\Lambda^*_{1800}})$$

$$\mathcal{R}_e(L_{\Lambda*_{1520}} L^*_{\Lambda*_{1800}}) \sim (M_{pK}^2 - m^2_{\Lambda^*_{1520}})(M_{pK}^2 - m^2_{\Lambda^*_{1800}}) = 0$$



$s_0^1 = 2.307$ GeV^2

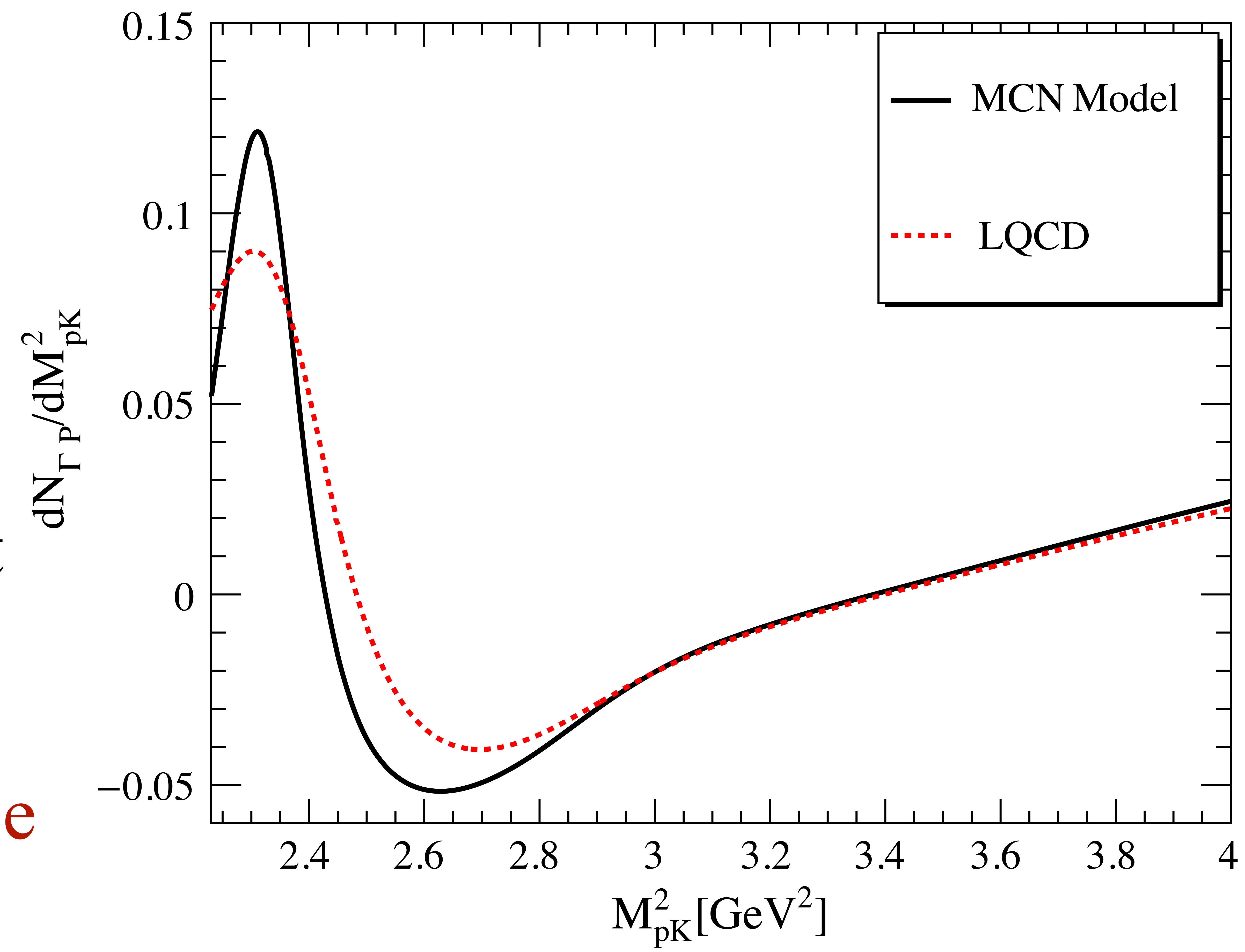
$s_0^2 = 3.231$ GeV^2

- Normalized polarized decay width

$$\frac{dN_{\Gamma_P}}{dM_{pK}^2} = \frac{\frac{d\Gamma(\frac{1}{2})}{dM_{pK}^2} - \frac{d\Gamma(-\frac{1}{2})}{dM_{pK}^2}}{\frac{d\Gamma(\frac{1}{2})}{dM_{pK}^2} + \frac{d\Gamma(-\frac{1}{2})}{dM_{pK}^2}}$$

- $s = +1/2$ is larger than $s = -1/2$ at small invariant mass

- mainly contributed by the interference of vector and axial-vector



polarized decay width is an important observable for studying hadron matrix element

Outline

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- Search for tetraquarks
- Summary

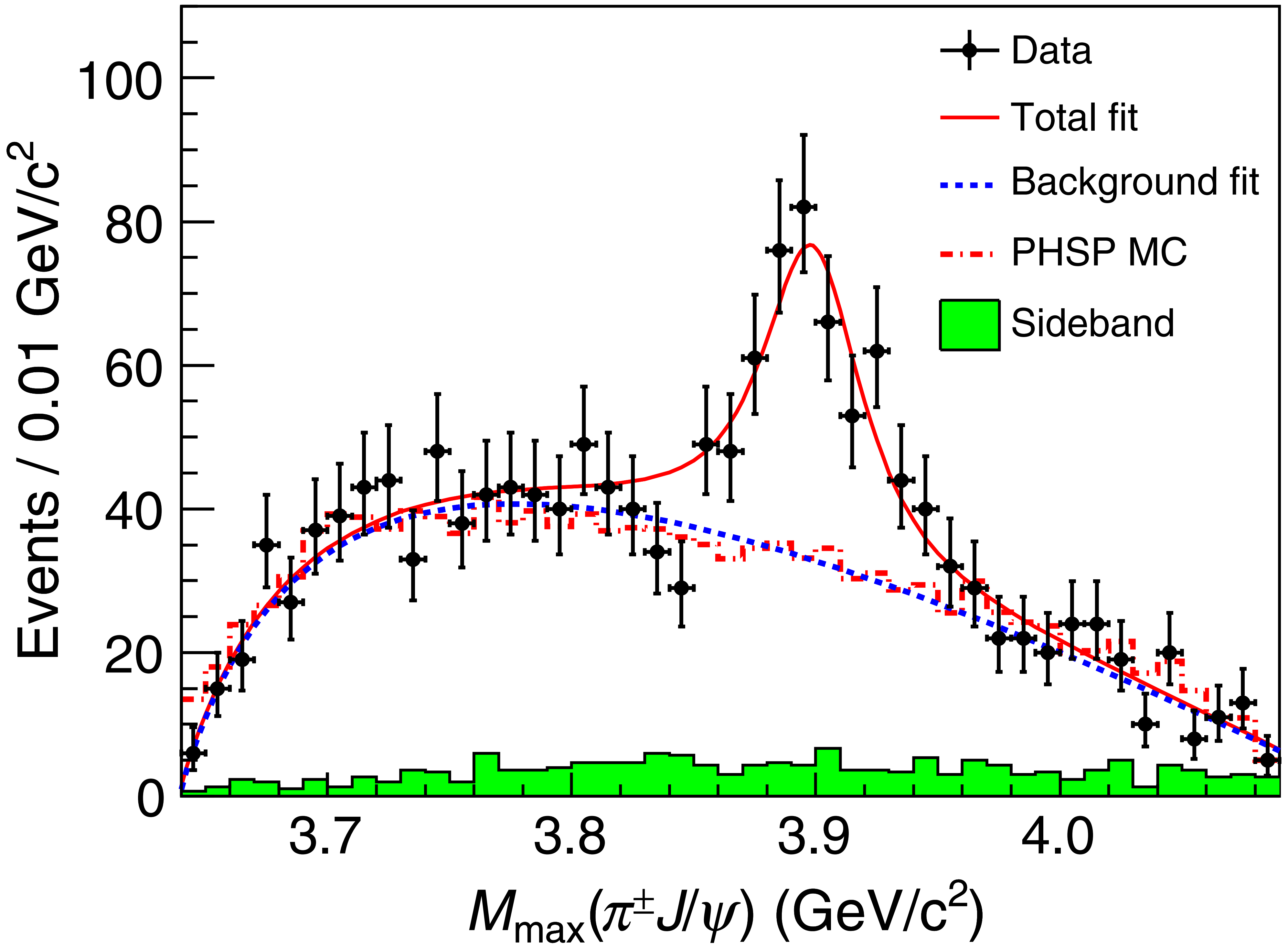
Search for tetraquarks

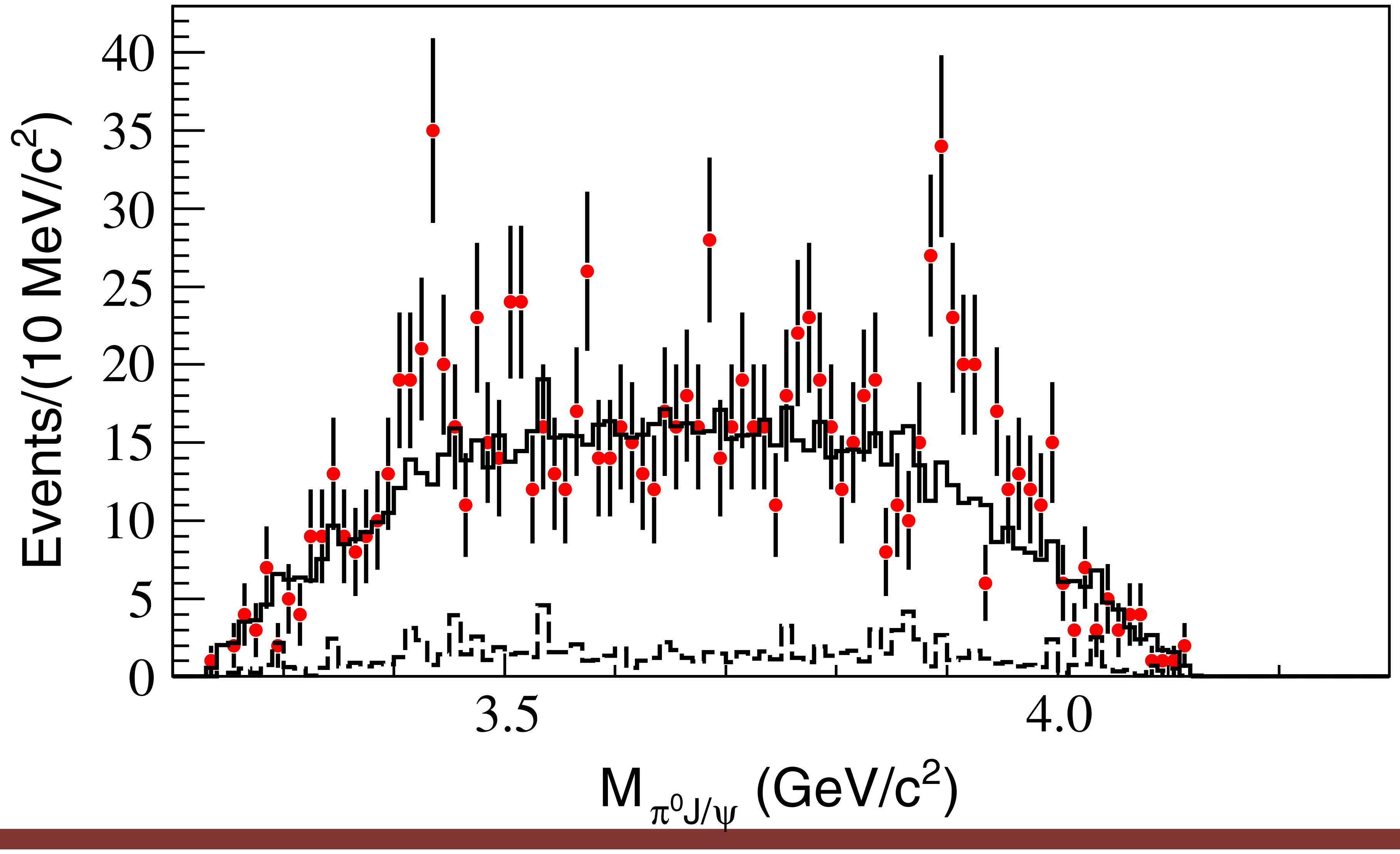
BESIII Collaboration
PRL 110. 252001 (2013)

First observation of charged $Z_c(3900)^{\pm}$

Confirmed by Belle and CLEO-c

PRL 110. 252002 (2013); PLB 727. 366 (2013)





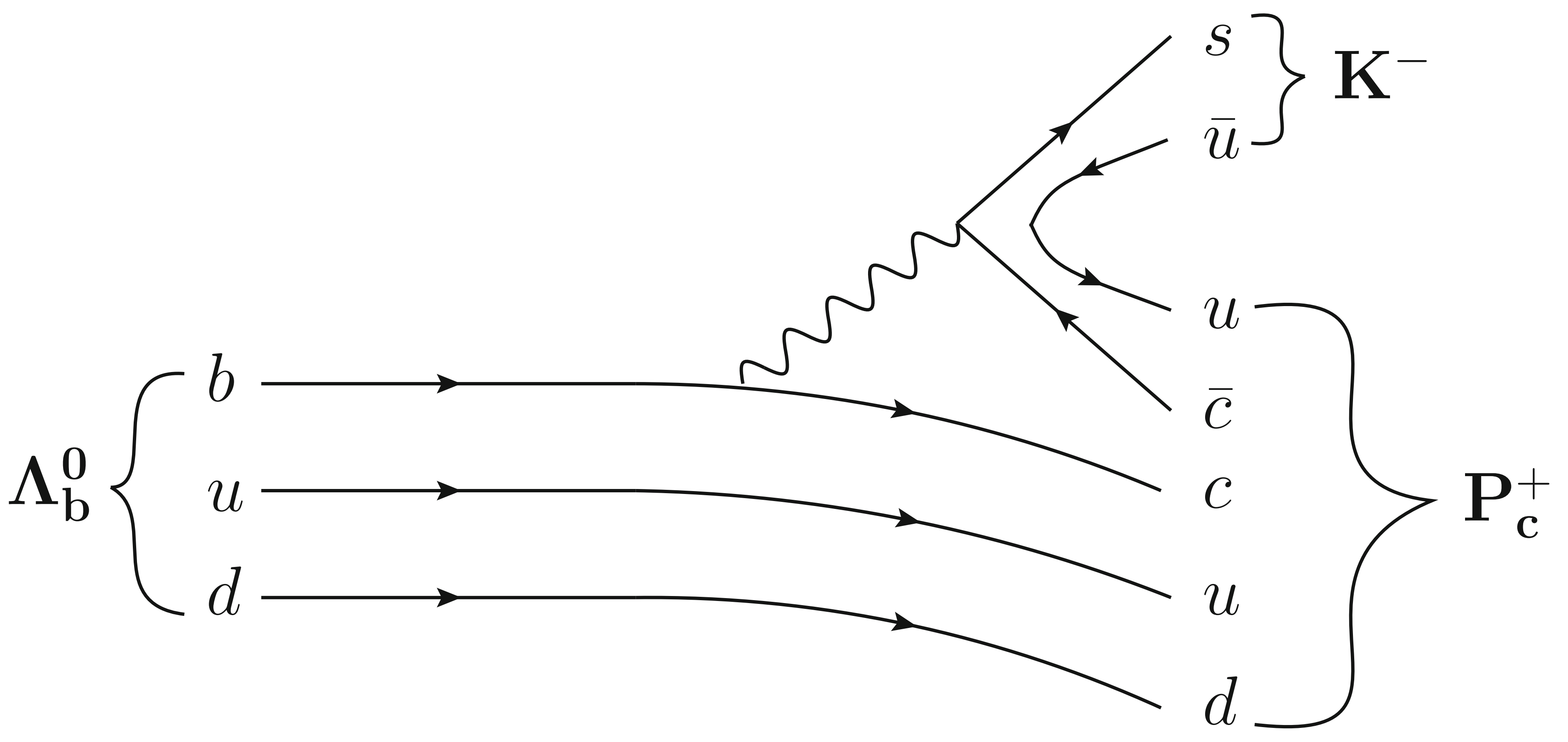
BESIII Collaboration
PRL 115. 112003 (2015)

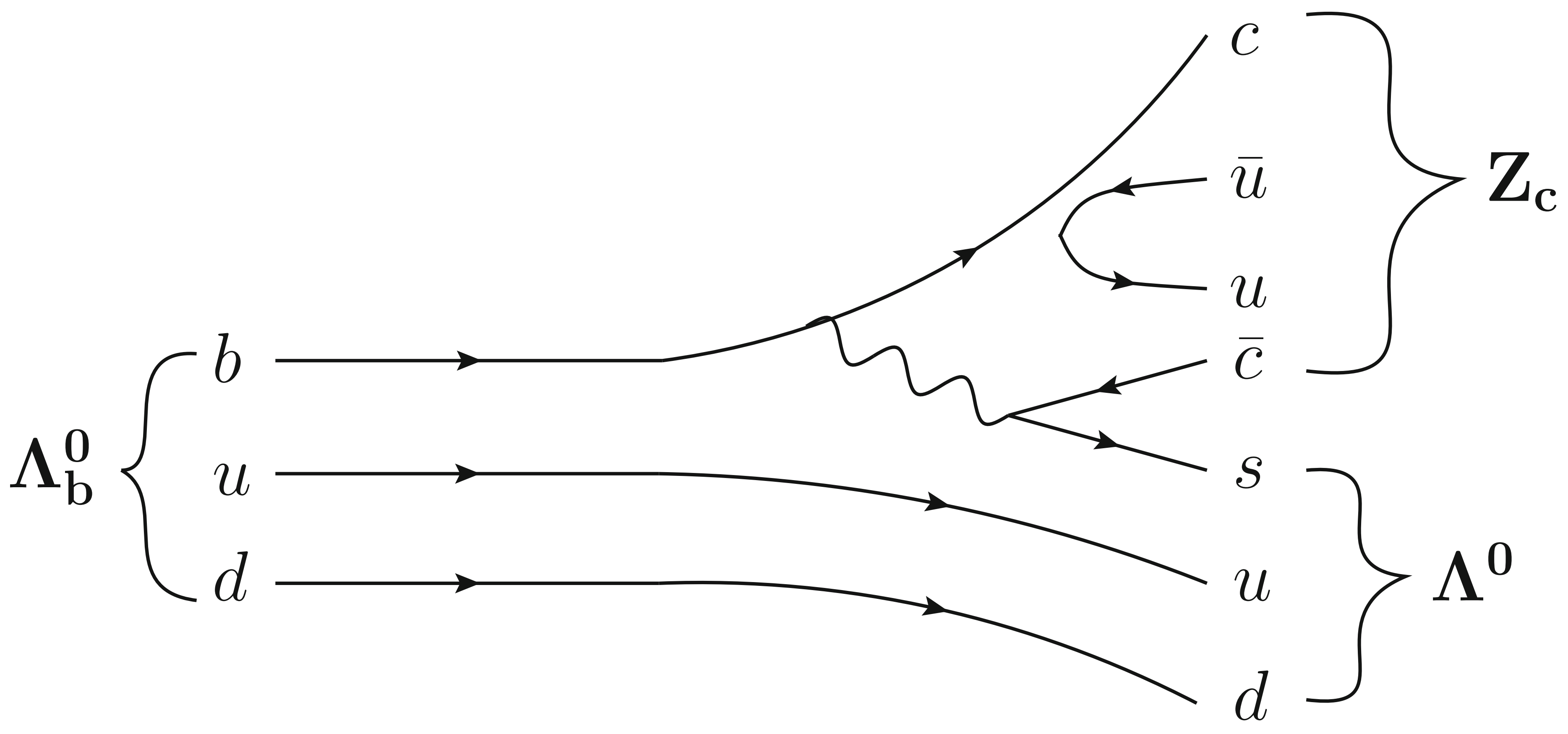
First observation of neutral $Z_c(3900)^0$

Search for tetraquarks

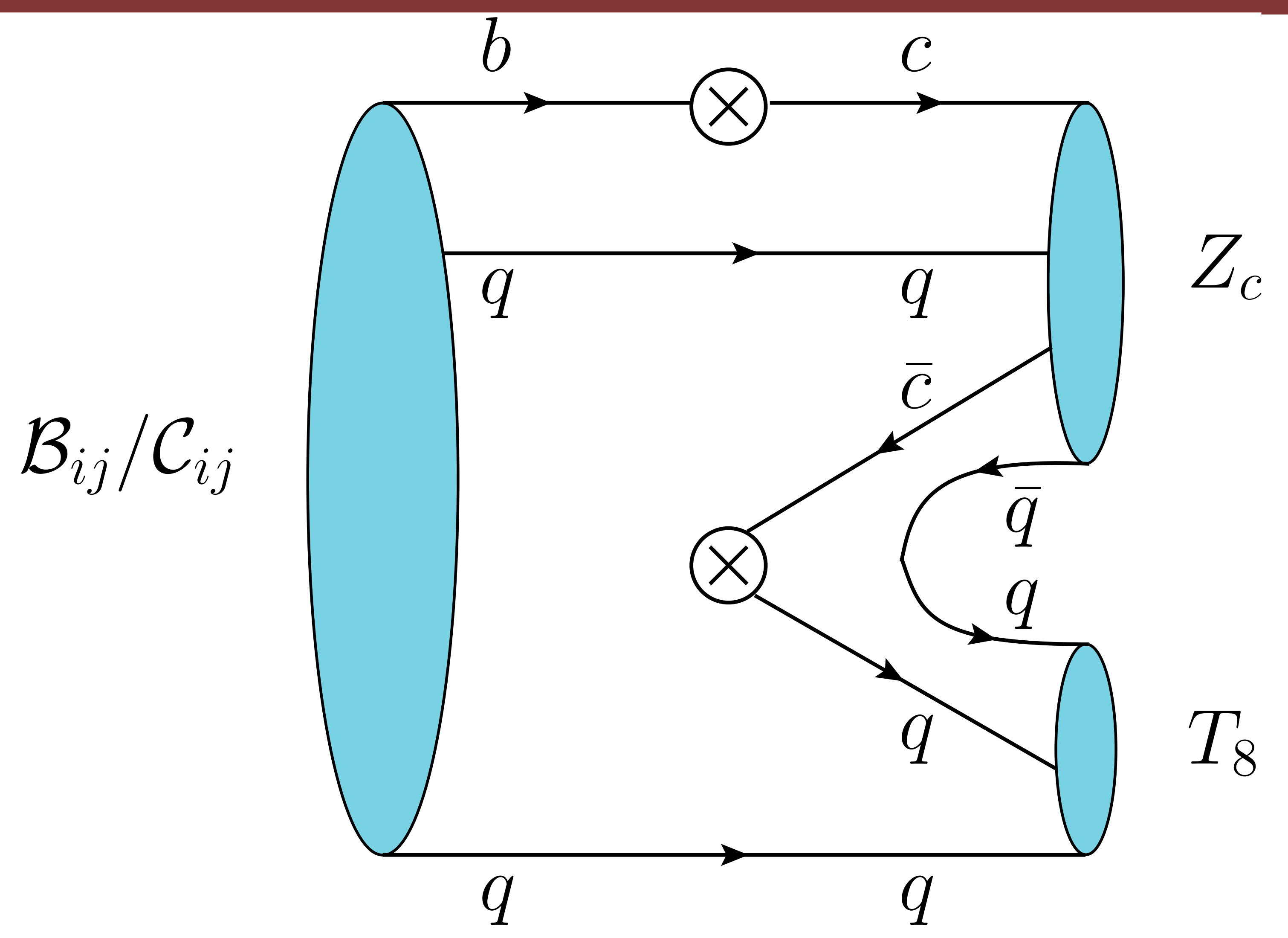
☑ Theoretical

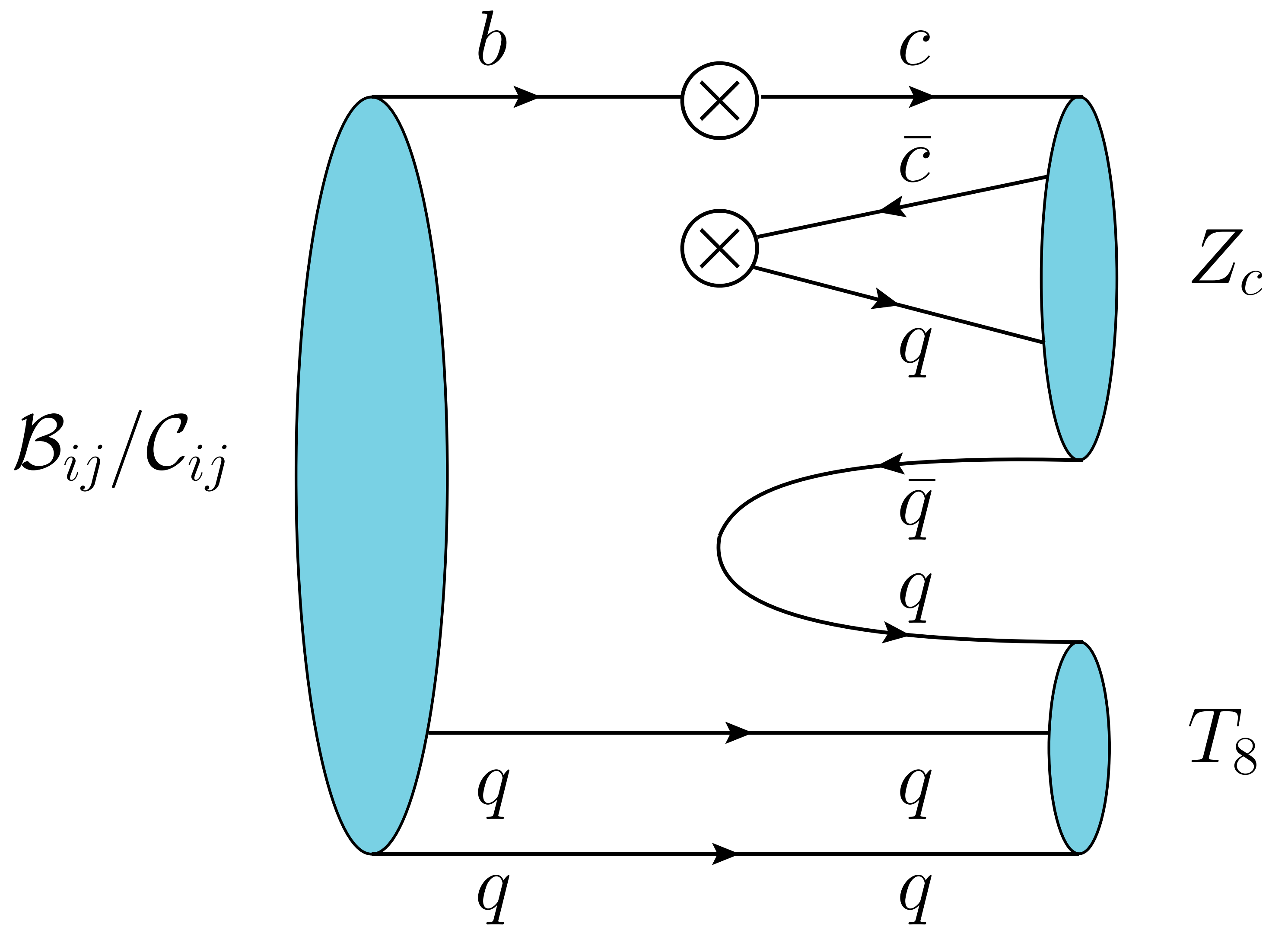
- Hadronic molecules
- Tetraquark
- Hadroquarkonia
- Kinematic





Search for tetraquarks





☑ flavor SU(3) analysis

$$(\mathcal{B})_{ij} = \begin{pmatrix} 0 & \Lambda_b^0 & \Xi_b^0 \\ -\Lambda_b^0 & 0 & \Xi_b^- \\ -\Xi_b^0 & -\Xi_b^- & 0 \end{pmatrix}$$

$$(\mathcal{C})_{ij} = \begin{pmatrix} \Sigma_b^+ & \frac{\Sigma_b^0}{\sqrt{2}} & \frac{\Xi_b'^0}{\sqrt{2}} \\ \frac{\Sigma_b^0}{\sqrt{2}} & \Sigma_b^- & \frac{\Xi_b'}{\sqrt{2}} \\ \frac{\Xi_b'^0}{\sqrt{2}} & \frac{\Xi_b'^-}{\sqrt{2}} & \Omega_b^- \end{pmatrix}$$

⇒

$$(\mathcal{Z}_c)_i^j = \begin{pmatrix} \frac{Z_{c\pi^0}}{\sqrt{2}} + \frac{Z_{c\eta_8}}{\sqrt{6}} & Z_{c\pi^+} & Z_{cK^+} \\ Z_{c\pi^-} & -\frac{Z_{c\pi^0}}{\sqrt{2}} + \frac{Z_{c\eta_8}}{\sqrt{6}} & Z_{cK^0} \\ Z_{cK^-} & Z_{c\overline{K}^0} & -\frac{2Z_{c\eta_8}}{\sqrt{6}} \end{pmatrix}$$

$$T_8 = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}$$

Search for tetraquarks

- The anti-triplet B-baryons decay into an octet tetraquark and a light baryon

$$
\begin{aligned}
\mathcal{H}_{eff} = & a_1(\mathcal{B})^{ij}(H_3)_{ij}(\mathcal{Z}_c)^l_k(T_8)^k_l + a_2(\mathcal{B})^{ij}(H_3)_{ik}(\mathcal{Z}_c)^k_l \\
& \times(T_8)^l_j + a_3(\mathcal{B})^{ij}(H_3)_{il}(\mathcal{Z}_c)^k_j(T_8)^l_k \\
& + a_4(\mathcal{B})^{ij}(H_3)_{kl}(\mathcal{Z}_c)^k_i(T_8)^l_j\ .
\end{aligned}
$$

- For the sextet B-baryons, the effective Hamiltonian reads

$$
\begin{aligned}
\mathcal{H}_{eff} = & b_1(\mathcal{C})^{ij}(H_3)_{ik}(\mathcal{Z}_c)^k_l(T_8)^l_j \\
& + b_2(\mathcal{C})^{ij}(H_3)_{il}(\mathcal{Z}_c)^k_j(T_8)^l_k \\
& + b_3(\mathcal{C})^{ij}(H_3)_{kl}(\mathcal{Z}_c)^k_i(T_8)^l_j\ .
\end{aligned}
$$

Search for tetraquarks

$$\begin{aligned}
\Gamma(\Xi_b^- \to Z_{c\pi^0}\Sigma^-) &= \Gamma(\Xi_b^- \to Z_{c\pi^-}\Sigma^0)\,,\\
\Gamma(\Lambda_b^0 \to Z_{c\overline{K}^0}n) &= \Gamma(\Lambda_b^0 \to Z_{cK^-}p)\,,\\
\Gamma(\Lambda_b^0 \to Z_{c\pi^0}n) &= \frac{1}{2}\Gamma(\Lambda_b^0 \to Z_{c\pi^-}p)\,,\\
\Gamma(\Xi_b^0 \to Z_{c\pi^+}\Sigma^-) &= \Gamma(\Xi_b^0 \to Z_{c\overline{K}^0}n)\,,\\
\Gamma(\Xi_b^0 \to Z_{c\overline{K}^0}\Lambda^0) &= \Gamma(\Xi_b^- \to Z_{cK^-}\Lambda^0)\,,\\
\Gamma(\Lambda_b^0 \to Z_{c\pi^+}\Sigma^-) &= \Gamma(\Lambda_b^0 \to Z_{c\pi^0}\Sigma^0)\\
&= \Gamma(\Lambda_b^0 \to Z_{c\pi^-}\Sigma^+)\,,\\
\Gamma(\Lambda_b^0 \to Z_{cK^+}\Sigma^-) &= 2\Gamma(\Lambda_b^0 \to Z_{cK^0}\Sigma^0)\\
&= \Gamma(\Xi_b^- \to Z_{cK^-}n)\,,
\end{aligned}$$

$$\begin{aligned}
\Gamma(\Xi_b^0 \to Z_{c\pi^0}\Lambda^0) &= \Gamma(\Xi_b^0 \to Z_{c\eta_8}\Sigma^0)\\
&= \frac{1}{2}\Gamma(\Xi_b^- \to Z_{c\pi^-}\Lambda^0)\\
&= \frac{1}{2}\Gamma(\Xi_b^- \to Z_{c\eta_8}\Sigma^-)\,,\\
\Gamma(\Xi_b^0 \to Z_{c\overline{K}^0}\Sigma^0) &= \frac{1}{2}\Gamma(\Xi_b^0 \to Z_{cK^-}\Sigma^+)\\
&= \frac{1}{2}\Gamma(\Xi_b^- \to Z_{c\overline{K}^0}\Sigma^-)\\
&= \Gamma(\Xi_b^- \to Z_{cK^-}\Sigma^0)\,.
\end{aligned}$$

- ☑ Based on different valence quark components, taking $Z_c^{\pm}$ as $Z_{c\pi^{\pm}}$ and Z_c^0 as $Z_{c\pi^0}$.
- ☑ Ignoring the mass difference between final state baryons.
- ☑ The SU(3) symmetry breaking in bottom quark decay is pretty small.

Search for tetraquarks

- Adopt the factorized ansatz to compute the decay width.

$$\mathcal{M}\left(\Lambda_b^0 \to \Lambda^0 Z_c^0(3900)\right) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2 R_{Z_c} f_{Z_c} M_{Z_c} \times \left\langle \Lambda^0 \left| (\bar{s}b)^{\mu}_{V-A} \right| \Lambda_b^0 \right\rangle \epsilon_{\mu}^*(s_{Z_c})$$

$$\left\langle 0 \left| J_{\mu}^Z \right| Z_c \right\rangle = f_{Z_c} M_{Z_c} \epsilon_{\mu}(s_{Z_c})$$

$$f_{Z_c} = 0.0051 \text{ GeV}^4$$

S.S. Agaev, K.Azizi, H. Sundu PRD 96, 034026 (2017)

Z.G. Wang, T. Huang, PRD 89, 054019 (2013)

$$a_2 = c_1 + c_2/N_c$$
$$C_1(m_b) = -0.248,$$
$$C_2(m_b) = 1.107$$

$$J_{\nu}^Z(x) = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}} \left\{ \left[u_a^T(x) C\gamma_5 c_b(x)\right] \left[\bar{u}_d(x)\gamma_{\nu} C \bar{c}_e^T(x)\right] - \left[u_a^T(x) C\gamma_{\nu} c_b(x)\right] \left[\bar{u}_d(x)\gamma_5 C \bar{c}_e^T(x)\right] \right\}$$

$$\Gamma(\Lambda_b^0 \to \Lambda^0 Z_c^0(3900)) = 8.61 \times 10^{-20} \text{ GeV},$$
$$\mathcal{B}(\Lambda_b^0 \to \Lambda^0 Z_c^0(3900)) = 1.93 \times 10^{-7}.$$

Search for tetraquarks

☑ Estimate of branching fractions of b-baryon decays where tetraquarks appear in the final states.

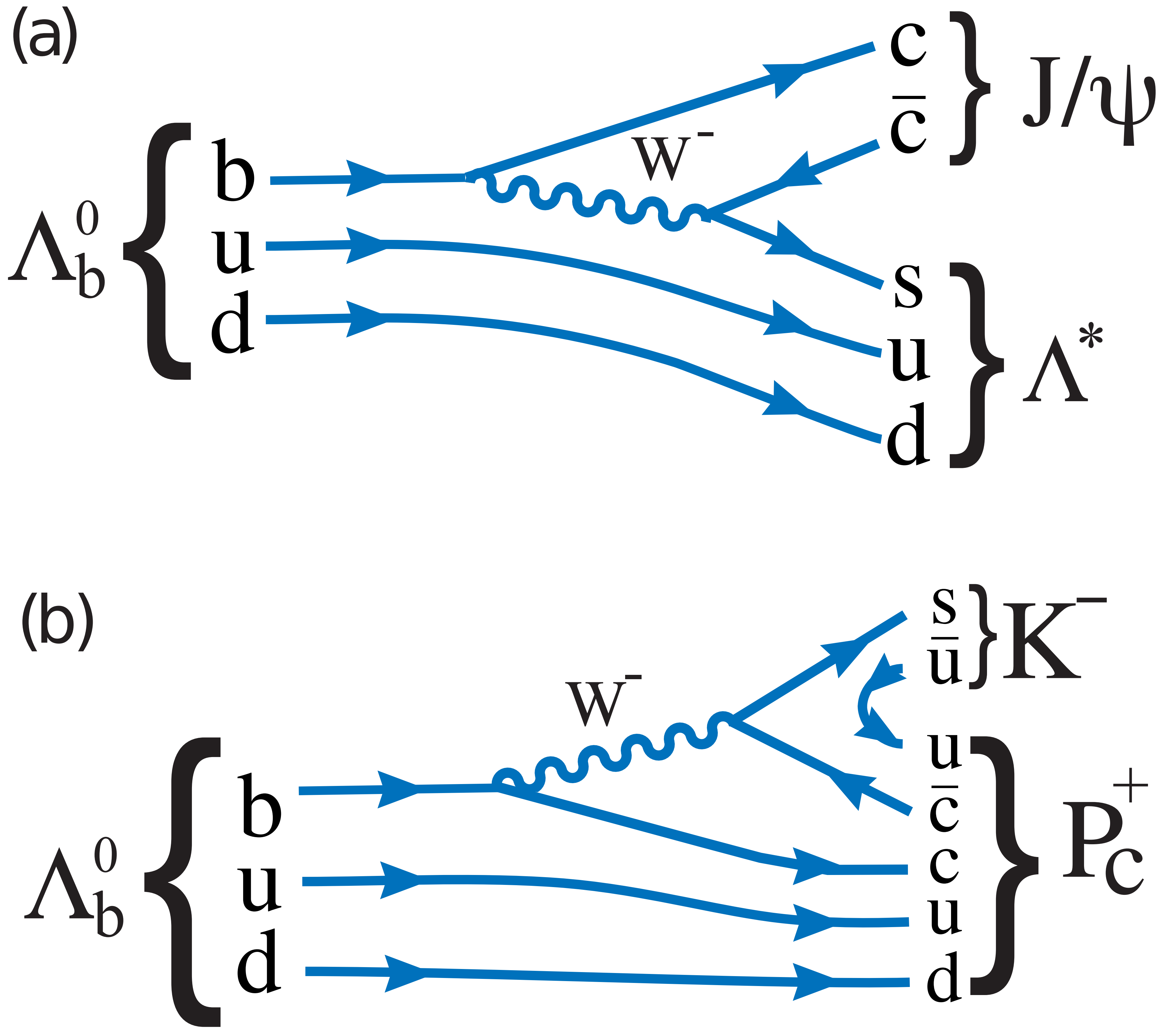
Channel	Branching fraction	Channel	Branching fraction
$\Xi_b^- \to \Sigma^- Z_c^0(3900)$	2.01×10^{-8}	$\Xi_b^- \to \Sigma^0 Z_c^-(3900)$	2.01×10^{-8}
$\Xi_b^- \to \Lambda^0 Z_c^-(3900)$	1.26×10^{-8}	$\Xi_b^- \to \Sigma^- Z_{c\eta_8}$	1.26×10^{-8}
$\Xi_b^0 \to \Lambda^0 Z_c^0(3900)$	5.94×10^{-9}	$\Xi_b^0 \to \Sigma^0 Z_{c\eta_8}$	5.94×10^{-9}
$\Lambda_b^0 \to \Lambda^0 Z_c^0(3900)$	1.93×10^{-7}		

Summary

- ☑ We have derived the angular distribution of Lambda_b decay with three resonances.
- ☑ Our analysis can improve our understanding on $Z_c(3900)$.
- ☑ We presented numerical predictions for the partial decay widths and branching fractions of various channels.

Thank you for your attention!

Backup



LHCb, Phys. Rev. Lett. 115, 072001 (2015)

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays