Interpretation of $\Omega(2012)$ as a $\Xi(1530)K$ molecular state

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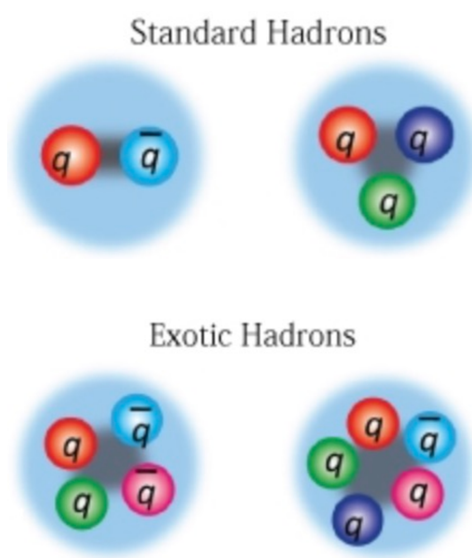
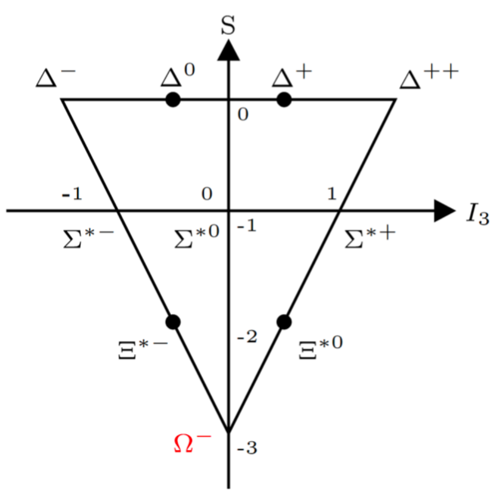
Quark model and Exotic hadrons



- **Quark Model:** $q\bar{q}$ mesons and qqq baryons
- **Exotic Hadrons:** most of which containing heavy quarks, especially the charm.
- **Light hadrons are also exciting:** excited nucleon N^*, hybrid meson (π_1, η_1), glueball, multiquark ($\Lambda(1405)$, $\boldsymbol{\Omega(2012)}$)…

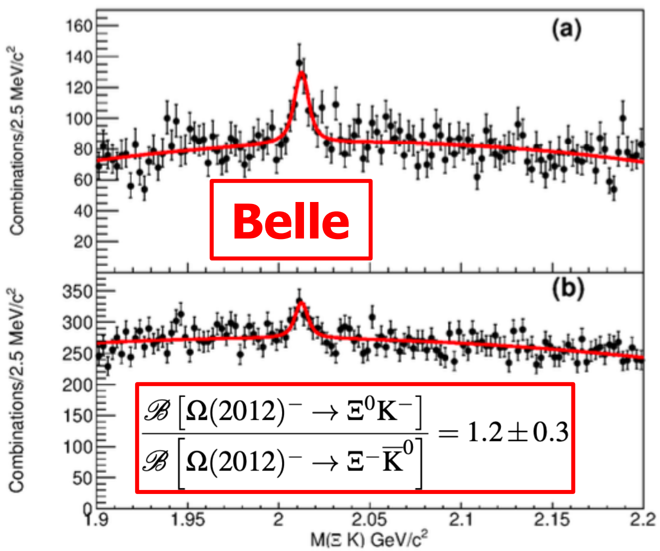
Ω family: **Poorly understood!**

$\Omega(1673)$:****	1964
$\Omega(2012)$:***	2018
$\Omega(2250)$:***	1986
$\Omega(2380)$:**	1987
$\Omega(2470)$:**	1988

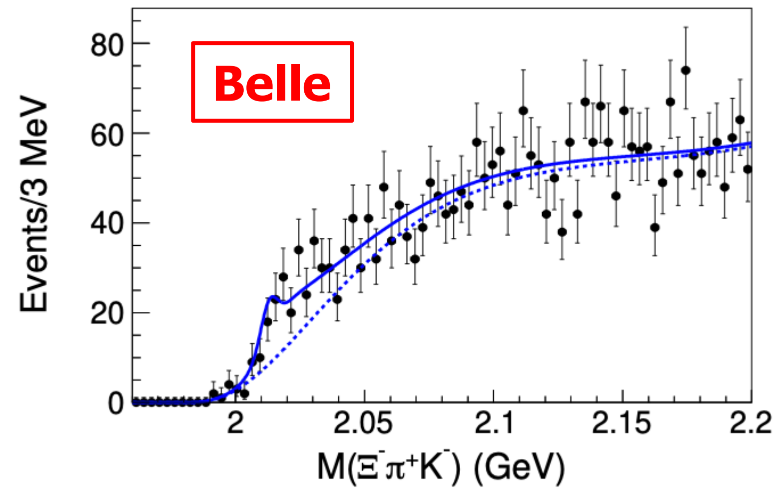


Observation and confirmations of $\Omega(2012)$:

The $\Omega(2012)$ state was first observed by Belle in 2018 in the decay modes $\Omega^* \to \Xi^0 K^-, \Xi^- K_S^0$! It is confirmed recently in the three-body decay $\Omega^* \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$.



PRL121(2018)052003;



PLB860(2025)139224

No three-body decay was found:

$$\mathcal{R}_{\Xi K}^{\Xi\pi K} = \frac{\mathcal{B}(\Omega(2012) \to \Xi(1530)(\to \Xi\pi)K)}{\mathcal{B}(\Omega(2012) \to \Xi K)} < 11.9\%$$

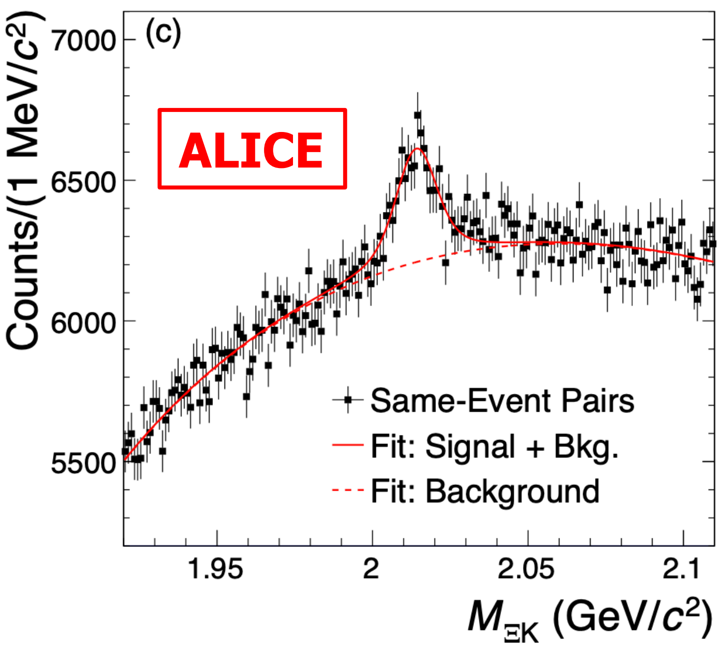
PRD100(2019) 032006

$$\mathcal{R}_{\Xi\bar{K}}^{\Xi\pi\bar{K}} = 0.99 \pm 0.26 \pm 0.06.$$

Based on a more accurate model!

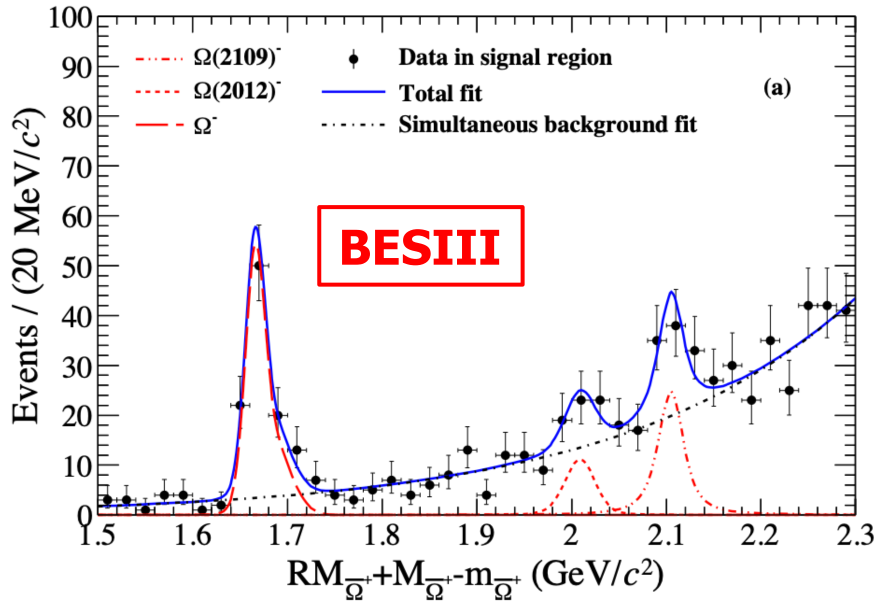
Observation and confirmations of $\Omega(2012)$:

ALICE and BESIII Collaborations confirmed the existence of the $\Omega(2012)$ state in 2025!



PRD112(2025) 092002

$$\mathscr{B}\left[\Omega(2012)^- \to \Xi\overline{K}\right] = 0.62^{+0.27}_{-0.17}.$$



$$e^+e^- \to \Omega^{*-}\bar{\Omega}^+ + c.c.$$

PRL134(2025)131903

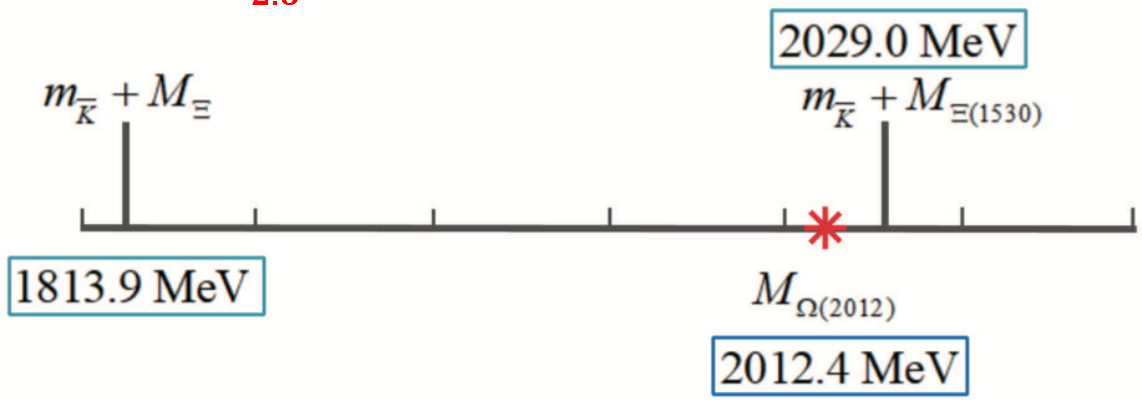
$\Omega(2012)$

PDG:

$M = 2012.5 \pm 0.6$ MeV

$\Gamma = 6.4^{+3.0}_{-2.6}$ MeV

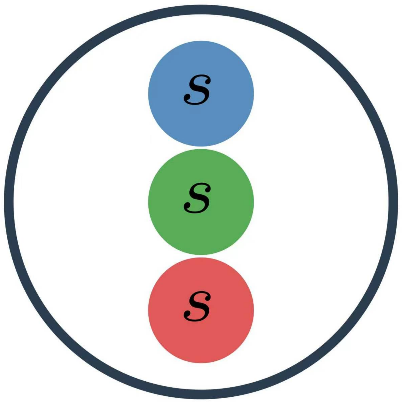
J. J. Xie, L. S. Geng, CPL41(2024)081402



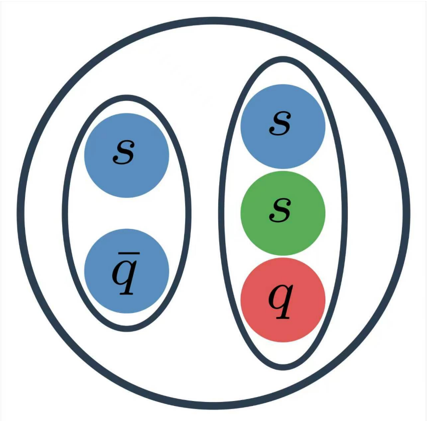
16 MeV below the $\Xi(1530)\bar{K}$ mass threshold

Theoretical interpretations of $\Omega(2012)$:

Excited sss baryon



$\Xi(1530)\bar{K}$ molecule



$J^P = 3/2^-$

PRD98(2018)014031;101(2020)016002;105(2022)094006;107(2023)034015;110(2024)034007;CPC46(2022)103102;47(2023)063104…

$\Xi\bar{K}$ decay mode is dominant.
Three-body $\Xi\pi\bar{K}$ decay mode is strongly suppressed!

PRD98(2018)056013;98(2018)076012;101(2020)094016;102(2020)074025;106(2022)034022;113(2026)036014;CPL41(2024)081402…

The $\Xi\pi\bar{K}$ mode is important in the molecular picture!

Mass sum rule for the $\Xi(1530)K$ molecule

We construct the $\Xi(1530)K$ molecular pentaquark current with $J^P = 3/2^-$:

$$\eta_\mu = \sqrt{\frac{1}{3}}\epsilon^{abc}[\bar{q}^d(x)\mathrm{i}\gamma_5 s^d(x)][2(s^{aT}(x)\mathcal{C}\gamma_\mu q^b(x))s^c(x) + (s^{aT}(x)\mathcal{C}\gamma_\mu s^b(x))q^c(x)] \, .$$

Isoscalar I = 0: $$J_\mu(x) = \frac{1}{\sqrt{2}}(J_{\Xi^{*0}} \cdot J_{K^-} - J_{\Xi^{*-}} \cdot J_{\bar{K}^0})$$

It can couple to both negative and positive-parity states:

$$\langle 0|J_\mu|\Omega^*; 3/2^-\rangle = f_- u_\mu(p) \, ,$$

$$\langle 0|J_\mu|\Omega^{*\prime}; 3/2^+\rangle = f_+ \gamma_5 u_\mu(p) \, ,$$

Parity projected sum rules:

The two-point correlation function:

$$\Pi_{\mu\nu}(p^2) \equiv \mathrm{i}\int \mathrm{d}^d x\ \mathrm{e}^{ip\cdot x}\,\langle 0|T[J_\mu(x)\bar{J}_\nu(0)]|0\rangle$$
$$= -g_{\mu\nu}\Pi_{3/2}(p^2) + \dots\,,$$
$$= -g_{\mu\nu}\left[(f_-)^2\frac{\not{p}+m_-}{m_-^2-p^2} + (f_+)^2\frac{\not{p}-m_+}{m_+^2-p^2}\right] + \dots$$
$$= -g_{\mu\nu}\left[\Pi^{\mathrm{phe}}_{\not{p}}(p^2)\not{p} + \Pi^{\mathrm{phe}}_{I}(p^2)\right] + \dots\,.$$

Positive-parity

Negative-parity

So the spectral functions with definite parities are:

$$\rho^{\mathrm{phe}}_{\mp} = \sqrt{s}\rho^{\mathrm{phe}}_{\not{p}}(s) \pm \rho^{\mathrm{phe}}_{I}(s)$$

$$\rho^{\mathrm{phen}}_{\not{p}}(s) = f_-^2\delta(s-m_-^2) + f_+^2\delta(s-m_+^2)\,,$$
$$\rho^{\mathrm{phen}}_{I}(s) = f_-^2 m_-\delta(s-m_-^2) - f_+^2 m_+\delta(s-m_+^2)$$

Parity projected sum rules:

The parity projected sum rules were obtained as:

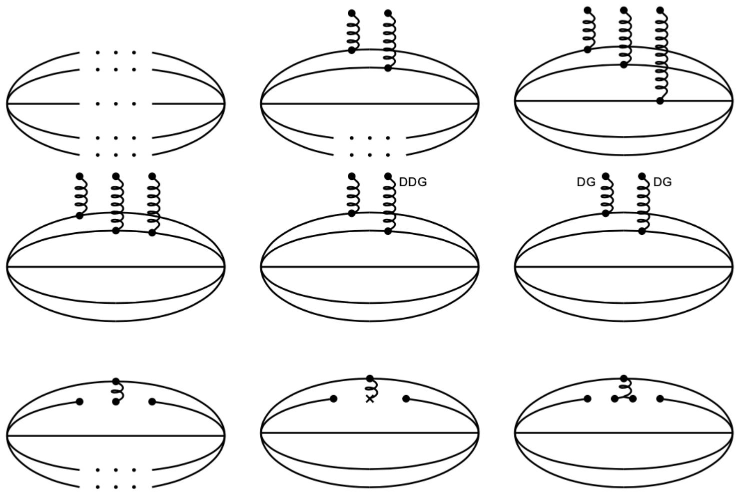
Hadron mass:

$$m_{\mp}^2(s_0, M_B^2) = \frac{\int_{s_<}^{s_0} [\sqrt{s}\rho_{\not p}^{\mathrm{OPE}}(s) \pm \rho_I^{\mathrm{OPE}}(s)] s \, \mathrm{e}^{-s/M_B^2} \mathrm{d}s}{\int_{s_<}^{s_0} [\sqrt{s}\rho_{\not p}^{\mathrm{OPE}}(s) \pm \rho_I^{\mathrm{OPE}}(s)] \, \mathrm{e}^{-s/M_B^2} \mathrm{d}s}$$

Coupling constant:

$$f_{\mp}^2(s_0, M_B) = \frac{\int_{s_<}^{s_0} [\sqrt{s}\rho_{\not p}^{\mathrm{OPE}}(s) \pm \rho_I^{\mathrm{OPE}}(s)] \mathrm{e}^{-s/M_B^2} \mathrm{d}s}{2m_{\mp}} \times \mathrm{e}^{m_{\mp}^2/M_B^2}$$

The OPE series are calculated up to dim-13:



The IR safety can be guaranteed by using the following propagator:

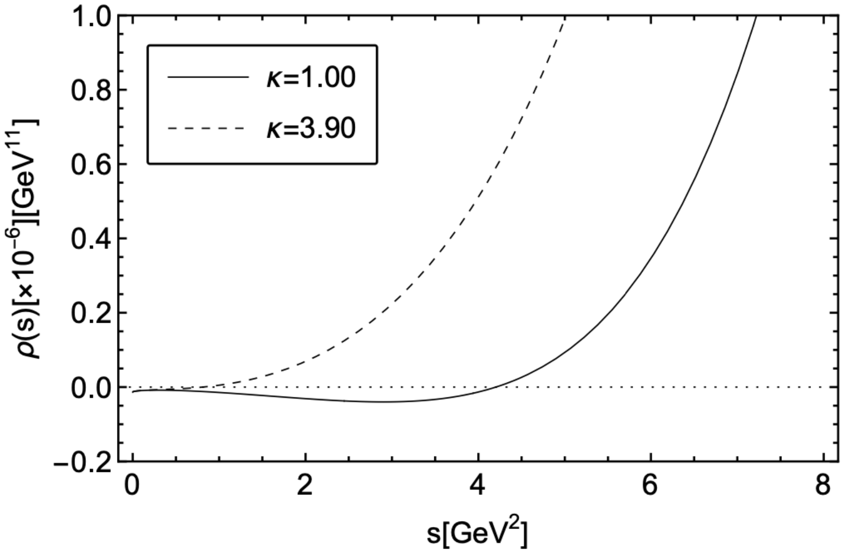
$$\gamma^{\mu\nu\rho} := \gamma^{\mu}\gamma^{\nu}\gamma^{\rho}\,, \quad g^{\{\mu\rho}x^{\sigma\}} := g^{\mu\rho}x^{\sigma} + g^{\mu\sigma}x^{\rho} + g^{\rho\sigma}x^{\mu}\,,$$
$$g^{\{\mu\rho}\gamma^{\sigma\}} := g^{\mu\rho}\gamma^{\sigma} + g^{\mu\sigma}\gamma^{\rho} + g^{\rho\sigma}\gamma^{\mu}\,,$$
$$x^{\{\mu}x^{\rho}\gamma^{\sigma\}} := x^{\mu}x^{\rho}\gamma^{\sigma} + x^{\mu}x^{\sigma}\gamma^{\rho} + x^{\rho}x^{\sigma}\gamma^{\mu}\,,$$
$$G^{a}_{\mu\nu;\rho} := \tilde{D}^{ab}_{\rho}G^{b}_{\mu\nu}, G^{a}_{\mu\nu;\rho\sigma} := \tilde{D}^{ab}_{\sigma}\tilde{D}^{bc}_{\rho}G^{c}_{\mu\nu}\,,$$

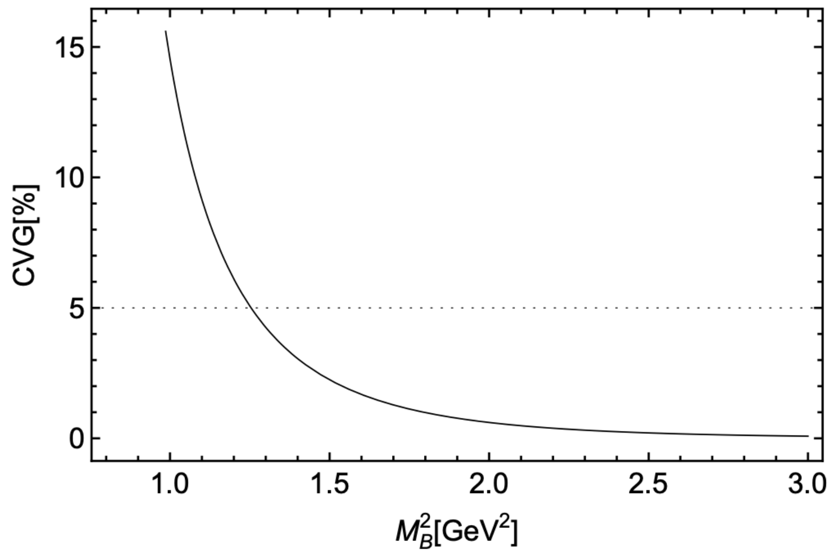
$$\begin{aligned}
S^{ij}(x) = {} & \frac{\mathrm{i}\Gamma\left(\frac{d}{2}\right)\not{x}}{2\pi^{d/2}(-x^2)^{d/2}}\delta^{ij} + \frac{m\Gamma\left(\frac{d}{2}-1\right)}{4\pi^{d/2}(-x^2)^{d/2-1}}\delta^{ij} - \frac{\delta^{ij}}{12}\langle\bar{\psi}\psi\rangle + \frac{\mathrm{i}m\delta^{ij}}{12d}\langle\bar{\psi}\psi\rangle\not{x} - \frac{\delta^{ij}}{48d}\langle g\bar{\psi}\sigma G\psi\rangle x^2 \\
& - \frac{\mathrm{i}\delta^{ij}x^2\not{x}}{2^4 3^4(d+2)}g^2\langle\bar{\psi}\psi\rangle^2 + \frac{\mathrm{i}\delta^{ij}mx^2\not{x}}{2^4 3d(d+2)}\langle g\bar{\psi}\sigma G\psi\rangle - \frac{\delta^{ij}x^4\langle\bar{\psi}\psi\rangle\langle g^2G^2\rangle}{2^6 3^2 d(d+2)} - \frac{\delta^{ij}x^4}{2^4 3^4 d(d+2)}g^2 m\langle\bar{\psi}\psi\rangle^2 \\
& - \frac{\mathrm{i}\delta^{ij}\Gamma\left(\frac{d}{2}-1\right)\not{x}\langle g^3 fG^3\rangle}{2^8 3^3 d(d+2)\pi^{d/2}(-x^2)^{d/2-3}} + \frac{\Gamma\left(\frac{d}{2}-1\right)\gamma^{\mu}\not{x}\gamma^{\nu}}{16\pi^{d/2}(-x^2)^{d/2-1}}gG^{a}_{\mu\nu}T^{a}_{ij} \\
& + \left[\frac{\Gamma\left(\frac{d}{2}-2\right)\left(\gamma^{\mu\rho\nu}+\gamma^{\rho\mu\nu}-4g^{\mu\rho}\gamma^{\nu}\right)}{96\pi^{d/2}(-x^2)^{d/2-2}} + \frac{\Gamma\left(\frac{d}{2}-1\right)\left(x^{\mu}\gamma^{\rho}\not{x}\gamma^{\nu}+x^{\rho}\gamma^{\mu}\not{x}\gamma^{\nu}\right)}{48\pi^{d/2}(-x^2)^{d/2-1}}\right] gG^{a}_{\mu\nu;\rho}T^{a}_{ij} \\
& + \left(\frac{-\Gamma\left(\frac{d}{2}-2\right)\left(2g^{\{\mu\rho}x^{\sigma\}}+g^{\{\mu\rho}\gamma^{\sigma\}}\not{x}\right)}{2^8\times 3\pi^{d/2}(-x^2)^{d/2-2}} + \frac{\Gamma\left(\frac{d}{2}-1\right)x^{\{\mu}x^{\rho}\gamma^{\sigma\}}\not{x}}{192\pi^{d/2}(-x^2)^{d/2-1}}\right)\gamma_{\nu}gG^{a}_{\mu\nu;\rho\sigma}T^{a}_{ij} \\
& + g^2G^{a}_{\mu\nu}G^{b}_{\rho\sigma}(T^aT^b)_{ij}\left[\frac{-\mathrm{i}\Gamma\left(\frac{d}{2}-1\right)x^{\nu}x^{\sigma}\gamma^{\mu}\not{x}\gamma^{\rho}}{96\pi^{d/2}(-x^2)^{d/2-1}} + \frac{-\mathrm{i}\Gamma\left(\frac{d}{2}-2\right)g^{\nu\sigma}\gamma^{\mu}\not{x}\gamma^{\rho}}{192\pi^{d/2}(-x^2)^{d/2-2}}\right. \\
& \left. + \frac{\mathrm{i}\Gamma\left(\frac{d}{2}-2\right)}{2^8\times 3\pi^{d/2}(-x^2)^{d/2-2}}\left(-6g^{\nu\sigma}\not{x}\gamma^{\mu\rho} - 4x^{\sigma}\gamma^{\mu\nu\rho} + 6x^{\mu}\gamma^{\nu\rho\sigma} - 4x^{\nu}\gamma^{\mu\sigma\rho} + 3\gamma^{\mu}\not{x}\gamma^{\nu\rho\sigma}\right)\right],
\end{aligned}$$

Mass sum rule for $\Xi(1530)K$

Factorization violation: $\langle\bar{q}\bar{q}qq\rangle = \kappa\langle q\bar{q}\rangle^2$

Positivity of spectral function





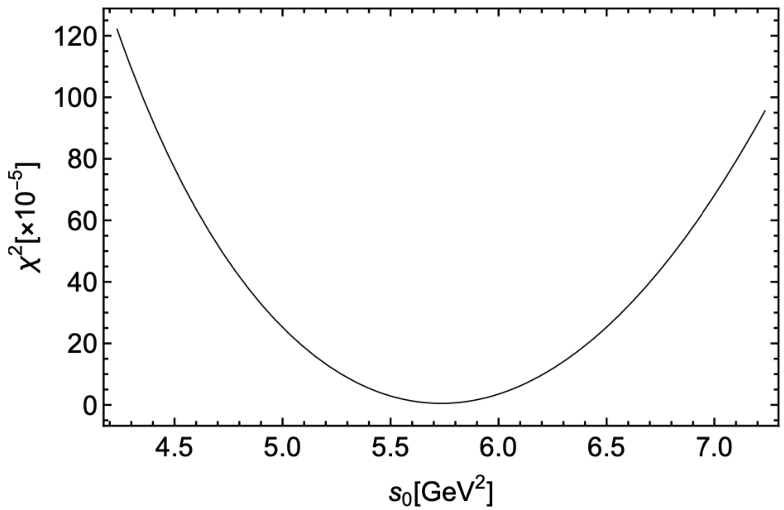
$$\mathrm{CVG} \equiv \left|\frac{\Pi_-^{12+13}(\infty, M_B^2)}{\Pi_-(\infty, M_B^2)}\right| \leq 5\%\,,$$

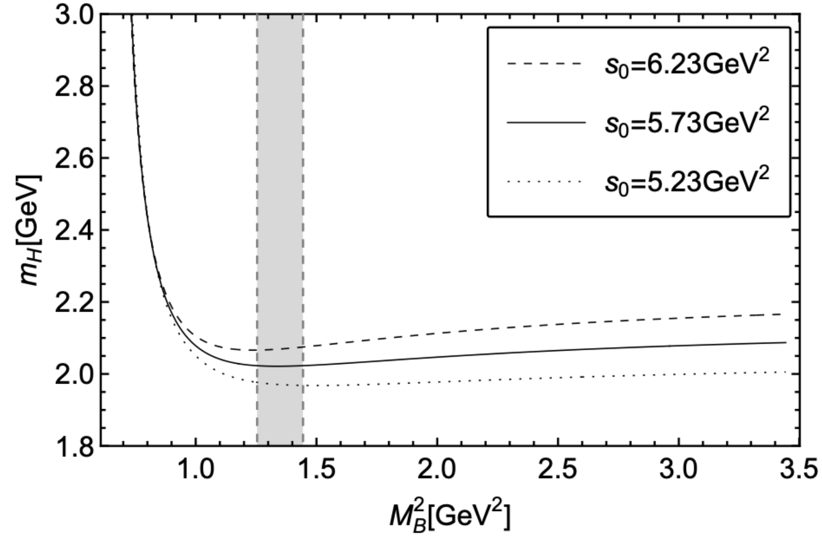
$$\mathrm{PC} \equiv \left|\frac{\Pi_-(s_0, M_B^2)}{\Pi_-(\infty, M_B^2)}\right| \geq 50\%\,.$$

Borel Widow

$$1.25\ \mathrm{GeV}^2 \leq M_B^2 \leq 1.44\ \mathrm{GeV}^2$$

Mass sum rule for $\Xi(1530)K$





$$\chi^2(s_0) = \sum_{i=1}^{N} \left[\frac{m_H(s_0, M_{B,i}^2)}{\bar{m}_H(s_0)} - 1 \right]^2$$

$$m_{\Xi(1530)K} = 2.02 \pm 0.12 \text{ GeV},$$
$$f_- = (4.60 \pm 1.17) \times 10^{-4} \text{ GeV}^6$$

$\downarrow$

$$\boldsymbol{s_0 = 5.73} \text{ GeV}^2$$

Agree with the mass of $\Omega(2012)$.

QCD sum rules for hadron decay

Two-body strong decays: $\Omega^* \to \Xi^0 K^-, \Xi^- \bar{K}^0$

- Three-point correlation function

$$\Pi_\mu(p_1^2, p_2^2, p^2) \equiv \int d^d x d^d y \; e^{ip_1 \cdot x} e^{ip_2 \cdot y} \Gamma(x, y) ,$$

$$\Gamma(x, y) \equiv \langle 0 | T[J_\Xi(x) J_{\bar{K}}(y) \bar{J}_\mu(0)] | 0 \rangle ,$$

Inserting complete set of intermediate hadronic states:

transition matrix element

$$\Pi_\mu(p_1^2, p_2^2, p^2) = \frac{\lambda_{\bar{K}} f_\Xi u(p_1) \langle \bar{K}(p_2) \Xi(p_1) | \Omega^*(p) \rangle f_- \bar{u}_\mu(p)}{(p^2 - m_{\Omega^*}^2 + i\varepsilon)(p_1^2 - m_\Xi^2 + i\varepsilon)(p_2^2 - m_{\bar{K}}^2 + i\varepsilon)} + \dots$$

Effective Lagrangian

$$\mathcal{L}_{K\Xi\Omega^*} = \mathrm{i}g_{\Omega^*\Xi\bar{K}}\overline{\Xi}\gamma'^{\mu\nu\lambda}\gamma^5\left(\partial_\mu\Omega^*_\nu\right)\partial_\lambda\bar{K} + h.c.\,,$$

where $\gamma'^{\mu\nu\lambda} = i\varepsilon^{\mu\nu\lambda\alpha}\gamma_\alpha\gamma_5$.

transition matrix element

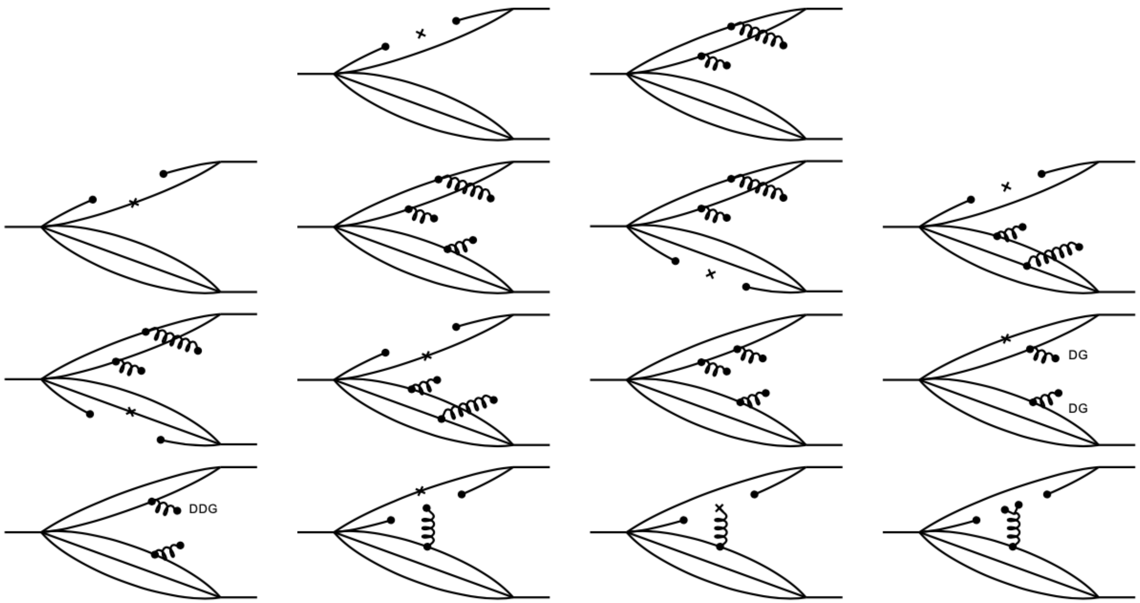
$$\langle\bar{K}(p_2)\Xi(p_1)|\Omega^*(p)\rangle = \bar{u}(p_1)\mathrm{i}g_{\Omega^*\Xi\bar{K}}\gamma'^{\mu\nu\lambda}\gamma^5 p_2^\lambda p^\mu u_\nu(p)$$

Keep the $\hat{p}_1\gamma^\mu\gamma^5$ structure:

Coupling constant

$$\Pi_\mu(p_1^2,p_2^2,p^2) = \left(1+\frac{m_{\bar{K}}^2}{p_2^2-m_{\bar{K}}^2+\mathrm{i}\varepsilon}\right)\frac{\frac{1}{3}m_\Xi \mathrm{i}g_{\Omega^*\Xi\bar{K}}\lambda_{\bar{K}}f_\Xi f_-}{(p^2-m_{\Omega^*}^2+\mathrm{i}\varepsilon)(p_1^2-m_\Xi^2+\mathrm{i}\varepsilon)} + \dots.$$

The OPE series are calculated up to dim-10:

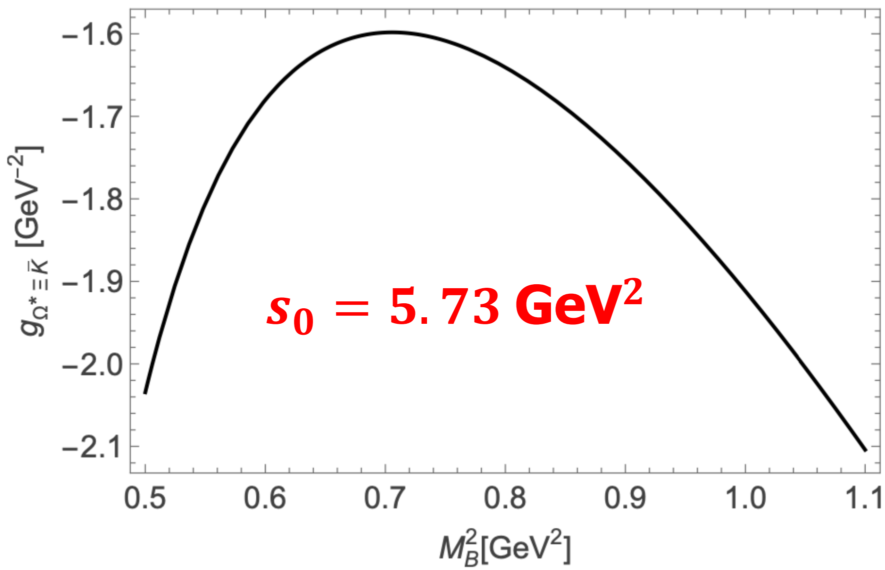


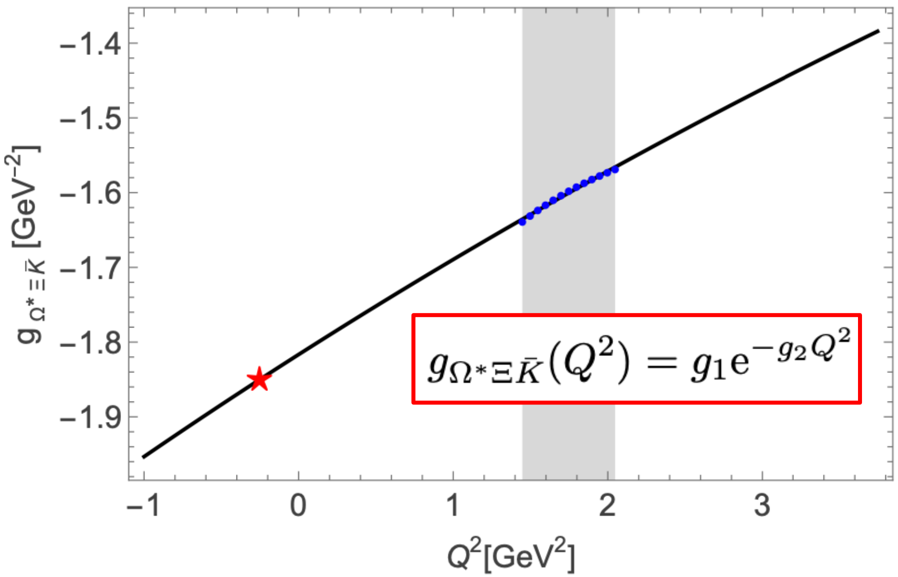
$$\frac{1}{3} m_\Xi m_{\bar{K}}^2 i g_{\Omega^*\Xi\bar{K}} \lambda_{\bar{K}} f_\Xi f_- \frac{Q^2 + m_{\bar{K}}^2}{Q^2} \frac{e^{-m_{\Omega^*}^2/M_B^2} - e^{-m_\Xi^2/M_B^2}}{m_{\Omega^*}^2 - m_\Xi^2} = \int_0^{s_0} ds \rho(s) e^{-s/M_B^2}$$

Decay width:

$$\Gamma(\Omega^* \to \Xi\bar{K}) = \frac{\sqrt{\lambda(m_{\Omega^*}^2, m_\Xi^2, m_{\bar{K}}^2)}}{192\pi m_{\Omega^*}^3} g_{\Omega^*\Xi\bar{K}}^2 \times (m_{\Omega^*}^2 - 2m_{\Omega^*} m_\Xi - m_{\bar{K}}^2 + m_\Xi^2)^2 \times (m_{\Omega^*}^2 + 2m_{\Omega^*} m_{\bar{K}} - m_{\bar{K}}^2 + m_\Xi^2) .$$

Sum rules for the coupling constant: $\Xi^- \overline{K}^0$channel





Coupling constant and decay width are:

$$g_{\Omega^*\Xi^-\overline{K}^0} = -1.85^{+0.87}_{-0.69}\ \text{GeV}^{-2}$$

$$\Gamma\left(\Omega^* \to \Xi^-\overline{K}^0\right) = 0.44^{+0.51}_{-0.21}\ \text{MeV}$$

For the $\Xi^0 K^-$ channel: isospin breaking only from the mass splitting

$$g_{\Omega^* \Xi^0 K^-} = 1.88^{+0.88}_{-0.70}\ \text{GeV}^{-2}$$

$$\Gamma(\Omega^* \to \Xi^0 K^-) = 0.52^{+0.60}_{-0.31}\ \text{MeV}$$

Total decay width of the $\Xi(1530)K$ molecule :

$$\Gamma(\Omega^* \to \Xi \bar{K}) = 0.96^{+0.79}_{-0.41}\ \text{MeV}$$

$$\mathcal{R}^{\Xi^- \bar{K}^0}_{\Xi^0 K^-} \equiv \frac{\mathcal{B}[\Omega(2012) \to \Xi^- \bar{K}^0]}{\mathcal{B}[\Omega(2012) \to \Xi^0 K^-]} = \frac{\Gamma(\Omega^* \to \Xi^- \bar{K}^0)}{\Gamma(\Omega^* \to \Xi^0 K^-)} \approx 0.85$$

Belle's result:

$$\frac{\mathscr{B}\left[\Omega(2012)^- \to \Xi^0 \mathrm{K}^-\right]}{\mathscr{B}\left[\Omega(2012)^- \to \Xi^- \overline{\mathrm{K}}^0\right]} = 1.2 \pm 0.3$$

PRL121(2018)052003

Summary

- The observation of $\boldsymbol{\Omega(2012)}$ has inspired lots of theoretical investigations on its inner structure and quantum numbers.
- We calculate its mass and two-body decays $\boldsymbol{\Omega^* \to \Xi^0 K^-, \Xi^- \bar{K}^0}$ by considering $\Omega(2012)$ as a **$\boldsymbol{\Xi(1530)\mathrm{K}}$ molecular state,** based on the two-point and three-point QCD sum rules. Our results of the hadron mass, decay width and relative branching ration are consistent with the experimental results.
- Theoretical calculations of the three-body decay $\boldsymbol{\Omega^* \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}}$ is useful for further investigation.

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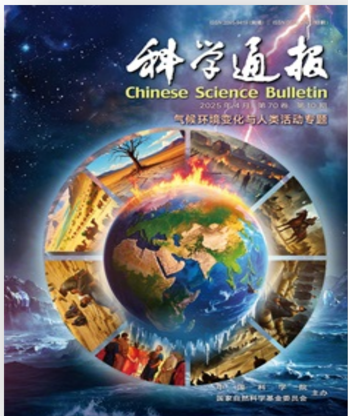

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