Internal structure of exotic hadron candidate $f_0(980)$ by using fragmentation functions

Shunzo Kumano

Institute of Modern Physics,
Chinese Academy of Sciences

Institute of Particle and Nuclear Studies, KEK

International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2026)
May 4-8, 2026, Bologna, Italy
https://dis2026.infn.it/

Ref. S. Kumano, arXiv:2511.20217206.

May 6, 2026

Contents

1. Introduction to fragmentation functions

2. Exotic hadron candidate $f_0(980)$

3. Criteria for judging “exotic” from fragmentation functions

4. Analysis results for $f_0(980)$

5. Summary

Purposes of investigating fragmentation functions

Semi-inclusive reactions have been used for investigating

- **origin of proton spin**

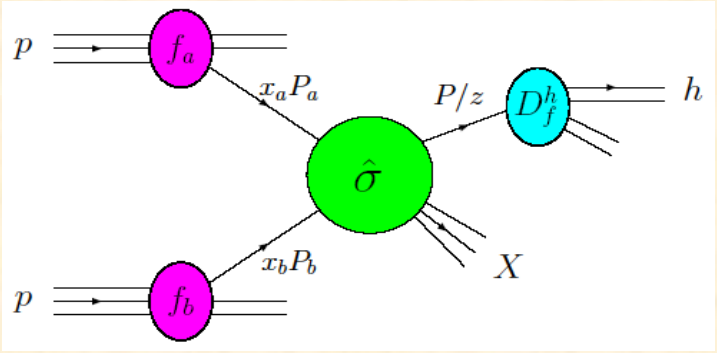
$$\vec{e}+\vec{p}\rightarrow e'+h+X,\quad \vec{p}+\vec{p}\rightarrow h+X \text{ (RHIC-Spin)}$$

Quark, antiquark, and gluon contributions to proton spin

(flavor separation, gluon polarization)

- **properties of quark-hadron matters** $A+A'\rightarrow h+X$ **(RHIC, LHC)**

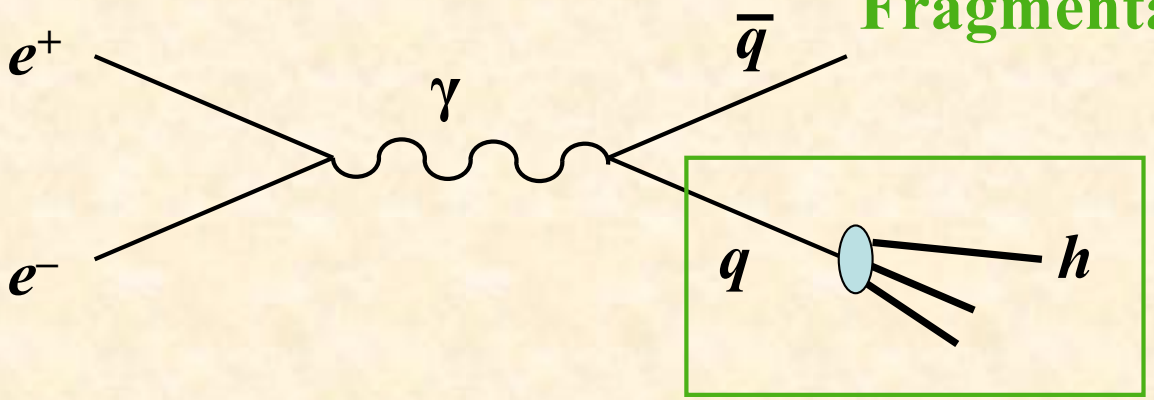
Nuclear modification (recombination, energy loss, …)



$$\sigma=\sum_{a,b,c} f_a(x_a,Q^2)\otimes f_b(x_b,Q^2)\otimes\hat{\sigma}(ab\rightarrow cX)\otimes D_c^{\pi}(z,Q^2)$$

- **Exotic-hadron search**

Fragmentation Function



Fragmentation: hadron production from a quark, antiquark, or gluon

Fragmentation function is defined by

$$F^h(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}$$

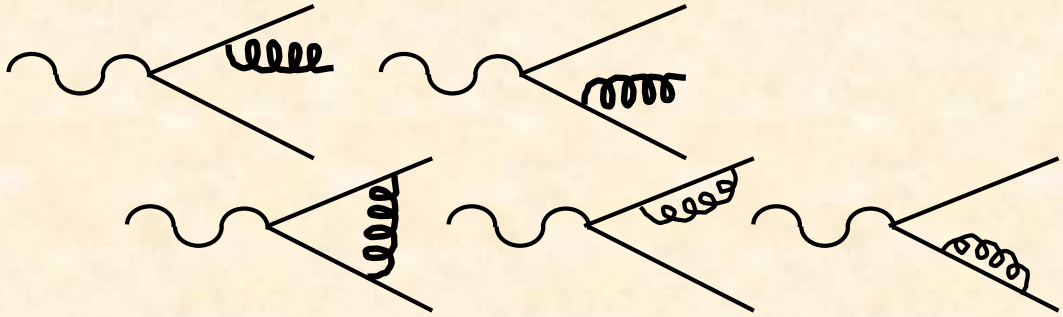
$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q}$$

(Energy fraction = hadron energy scaled to the beam energy)

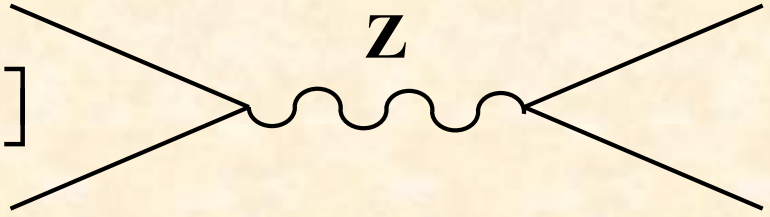
σ_{tot} = total hadronic cross section

$$\sigma_{tot} = \sum_q \sigma_0^q(s)\left[1 + \frac{\alpha_s(s)}{\pi}\right]$$

Higher-order correction



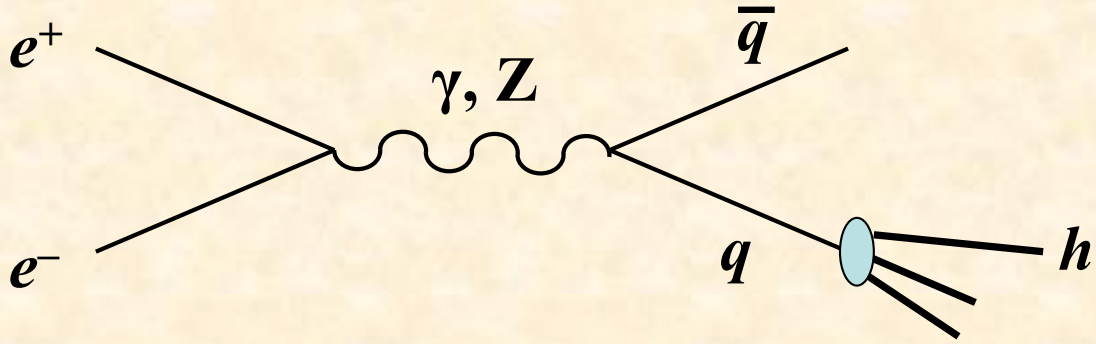
$$\sigma_0^q(s) = \frac{4\pi\alpha^2}{s}\left[e_q^2 + (\gamma\text{-}Z \text{ interference}) + (Z \text{ term})\right]$$



Variable z

$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q} = \frac{E_h}{E_q}$$

note $s = Q^2$



- Hadron energy / Beam energy
- Hadron energy / Primary quark or antiquark energy

Fragmentation functions

A fragmentation process occurs from quarks, antiquarks, and gluons, so that F^h is expressed by their contributions:

$$F^h(z,Q^2) = \sum_i \int_z^1 \frac{dy}{y} C_i\left(\frac{z}{y},Q^2\right) D_i^h(y,Q^2)$$

Calculated in perturbative QCD

Non-perturbative (determined from experiments)

$C_i(z,Q^2)$ = coefficient function

$D_i^h(z,Q^2)$ = fragmentation function of hadron h from a parton i

Energy sum rule

$D_i^h\left(z,Q^2\right)=$ probability to find the hadron h from a parton i with the energy fraction z

Energy conservation: $\sum_h \int_0^1 dz\, z\, D_i^h\left(z,Q^2\right)=1$

$h=\pi^+,\ \pi^0,\ \pi^-,\ K^+,\ K^0,\ \bar{K}^0,\ K^-,\ p,\ \bar{p},\ n,\ \bar{n},\ \cdots$

Quark model: $\pi^+(u\bar{d}),\ \pi^0((u\bar{u}-d\bar{d})/2),\ \pi^-(\bar{u}d),$

$K^+(u\bar{s}),\ K^0(d\bar{s}),\ \bar{K}^0(\bar{d}s),\ K^-(\bar{u}s),$

$p(uud),\ \bar{p}(\bar{u}\bar{u}\bar{d}),\ n(udd),\ \bar{n}(\bar{u}\bar{d}\bar{d}),\ \cdots$

Favored fragmentaion

(from a quark which exists in a naive quark mode)

for example $D_u^{\pi^+},\ D_{\bar{d}}^{\pi^+}$

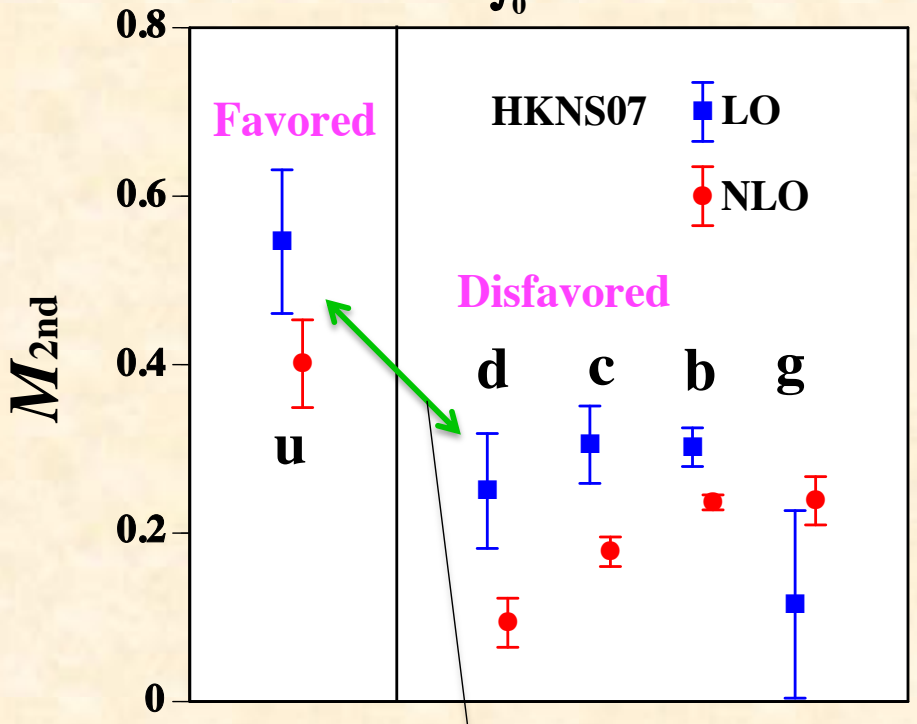
Unfavored fragmentaion

(from a quark which doe not exist in a naive quark mode)

for example $D_d^{\pi^+},\ D_{\bar{u}}^{\pi^+},\ D_s^{\pi^+}$

2nd moments of pion fragmentation functions

$$M_{2\mathrm{nd}} = \int_0^1 dz\, z\, D_i^{\pi^+}(z)$$



2nd moments of
M. Hirai, SK, T.-H. Nagai, K. Sudoh,
PRD 75 (2007) 094009.

There are distinct differences between
the favored and disfavored 2nd moments.

→ It could be used for exotic-hadron studies.

Criteria for determining f_0 structure by its fragmentation functions

M. Hirai, S. Kumano, M. Oka, K. Sudoh, PRD 77 (2008) 017504.

Possible configurations of $f_0(980)$

(1) ordinary u,d - meson $\quad \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$

(2) strange meson, $\quad s\bar{s}$

(3) tetraquark $(K\bar{K})$, $\quad \frac{1}{\sqrt{2}}(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})$

(4) glueball $\quad gg$

Contradicts with experimental widths

$\Gamma_{\text{theo}}(f_0 \to \pi\pi) = 500-1000$ MeV $\gg \Gamma_{\text{exp}} = 40-100$ MeV

$\Gamma_{\text{theo}}(f_0 \to \gamma\gamma) = 1.3-1.8$ keV $\gg \Gamma_{\text{exp}} = 0.205$ keV

Contradicts with lattice-QCD estimate

$m_{\text{lattice}}(f_0) = 1600$ MeV $\gg m_{\text{exp}} = 980$ MeV

There could difference in fragmentation functions for f_0 depending on its internal structure.

- Favored and disfavored fragmentation functions
- 2nd moments and functional forms

$s\bar{s}$ picture for $f_0(980)$

$$M \equiv \int_0^1 zD(z)\,dz \quad \text{(2nd moment)}$$

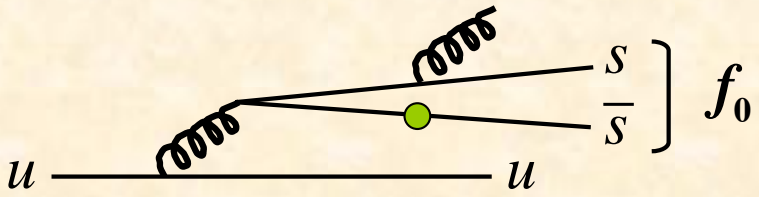
2nd moment: $M(u) < M(s) \lesssim M(g)$

Peak of function: $z_{max}(u) < z_{max}(s)$

More energy is transferred to f_0 from the parent s.

Naive estimates!

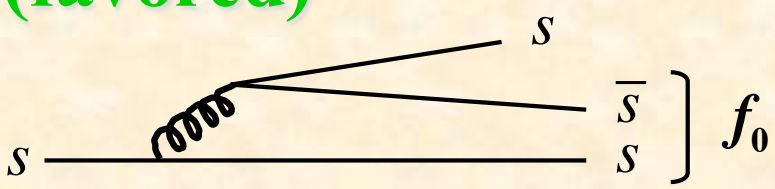
u (disfavored)



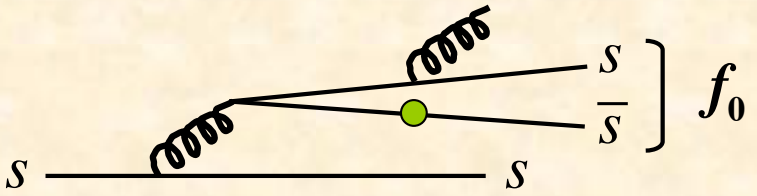
O (g^3)

+ one O (g^3) term of gluon radiation from the antiquark

s (favored)



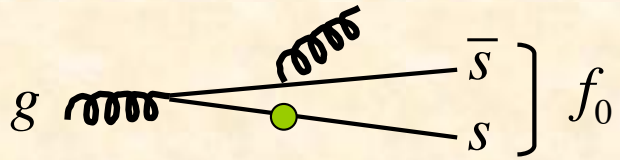
O (g^2)



O (g^3)

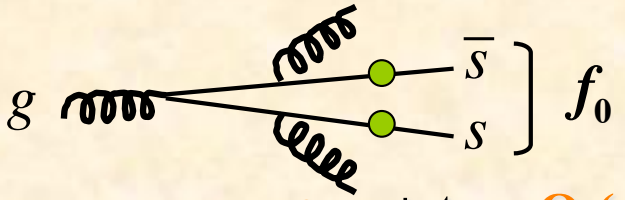
+ one O (g^3) term of gluon radiation from the antiquark

g



O (g^2)

+ one O (g^2) term of gluon radiation from the quark



O (g^3)

+ two O (g^3) terms of gluon radiation from the quark or antiquark

Naive judgment

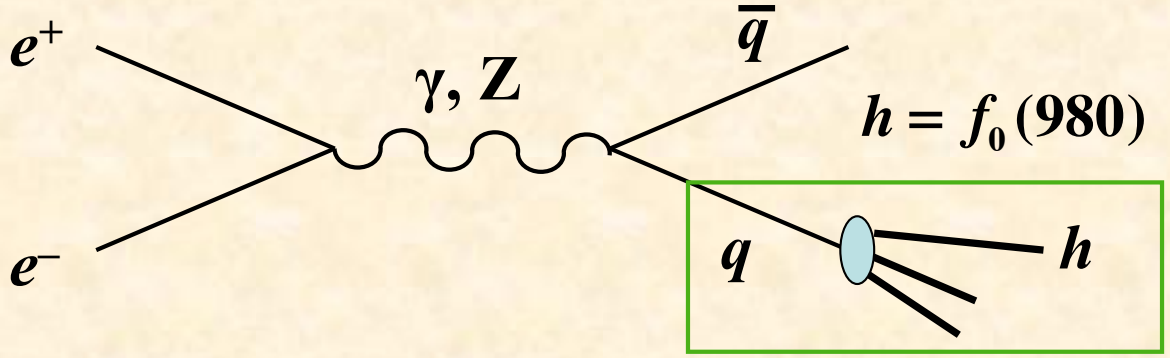
Type	Configuration	2nd Moment	Peak z
Nonstrange $q\bar{q}$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$M(s)<M(u)<M(g)$	$z_{\max}(s)<z_{\max}(u)$
Strange $q\bar{q}$	$s\bar{s}$	$M(u)<M(s)\lesssim M(g)$	$z_{\max}(u)<z_{\max}(s)$
Tetraquark	$(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{\max}(u)=z_{\max}(s)$
$K\bar{K}$ Molecule	$(K^+K^-+K^0\bar{K}^0)/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{\max}(u)=z_{\max}(s)$
Glueball	gg	$M(u)=M(s)<M(g)$	$z_{\max}(u)=z_{\max}(s)<z_{\max}(g)$

Since there is no difference between $D_u^{f_0}$ and $D_d^{f_0}$ in the models, they are assumed to be equal. On the other hand, $D_s^{f_0}$ and $D_g^{f_0}$ are generally different from them, so that they should be used for finding the internal structure. Therefore, simple and "model-independent" initial functions are

$$D_u^{f_0}(z,Q_0^2)=D_{\bar{u}}^{f_0}(z,Q_0^2)=D_d^{f_0}(z,Q_0^2)=D_{\bar{d}}^{f_0}(z,Q_0^2),\quad D_s^{f_0}(z,Q_0^2)=D_{\bar{s}}^{f_0}(z,Q_0^2),$$

$$D_g^{f_0}(z,Q_0^2),\qquad D_c^{f_0}(z,m_c^2)=D_{\bar{c}}^{f_0}(z,m_c^2),\qquad D_b^{f_0}(z,m_b^2)=D_{\bar{b}}^{f_0}(z,m_b^2).$$

Fragmentation functions for $f_0(980)$



$$z \equiv \frac{E_h}{\sqrt{s}/2} = \frac{2E_h}{Q} = \frac{E_h}{E_q}, \quad s = Q^2$$

$$F^h(z,Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}$$

σ_{tot} = total hadronic cross section

$$F^h(z,Q^2) = \sum_i \int_z^1 \frac{dy}{y} C_i\left(\frac{z}{y}, Q^2\right) D_i^h(y,Q^2)$$

Initial functions

$$D_u^{f_0}(z,Q_0^2) = D_d^{f_0}(z,Q_0^2) = N_u^{f_0} z^{\alpha_u^{f_0}} (1-z)^{\beta_u^{f_0}}$$

$$D_s^{f_0}(z,Q_0^2) = N_s^{f_0} z^{\alpha_s^{f_0}} (1-z)^{\beta_s^{f_0}}$$

$$D_g^{f_0}(z,Q_0^2) = N_g^{f_0} z^{\alpha_g^{f_0}} (1-z)^{\beta_g^{f_0}}$$

$$D_c^{f_0}(z,m_c^2) = N_c^{f_0} z^{\alpha_c^{f_0}} (1-z)^{\beta_c^{f_0}}$$

$$D_b^{f_0}(z,m_b^2) = N_b^{f_0} z^{\alpha_b^{f_0}} (1-z)^{\beta_b^{f_0}}$$

- $D_q^{f_0}(z,Q_0^2) = D_{\bar{q}}^{f_0}(z,Q_0^2)$
- $Q_0 = 1$ GeV
  $m_c = 1.43$ GeV
  $m_b = 4.3$ GeV

$$N = M \frac{\Gamma(\alpha+\beta+3)}{\Gamma(\alpha+2)\Gamma(\beta+1)}, \quad M \equiv \int_0^1 zD(z)dz$$

Recent experimental progress for f_0

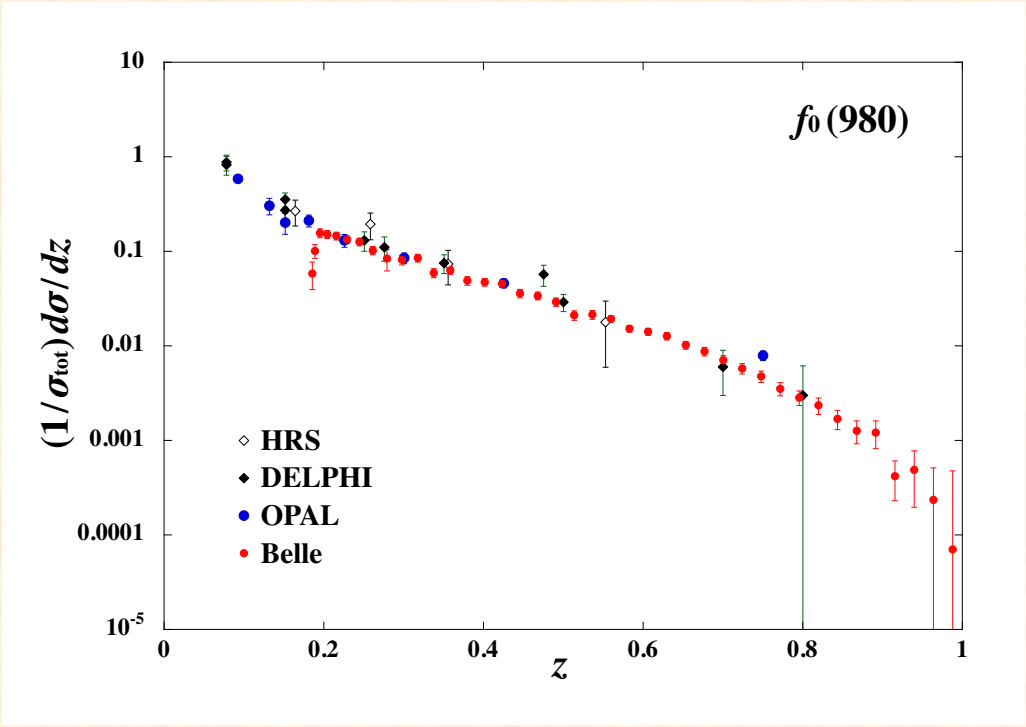
Total number of data: 23 (before Belle) → 63

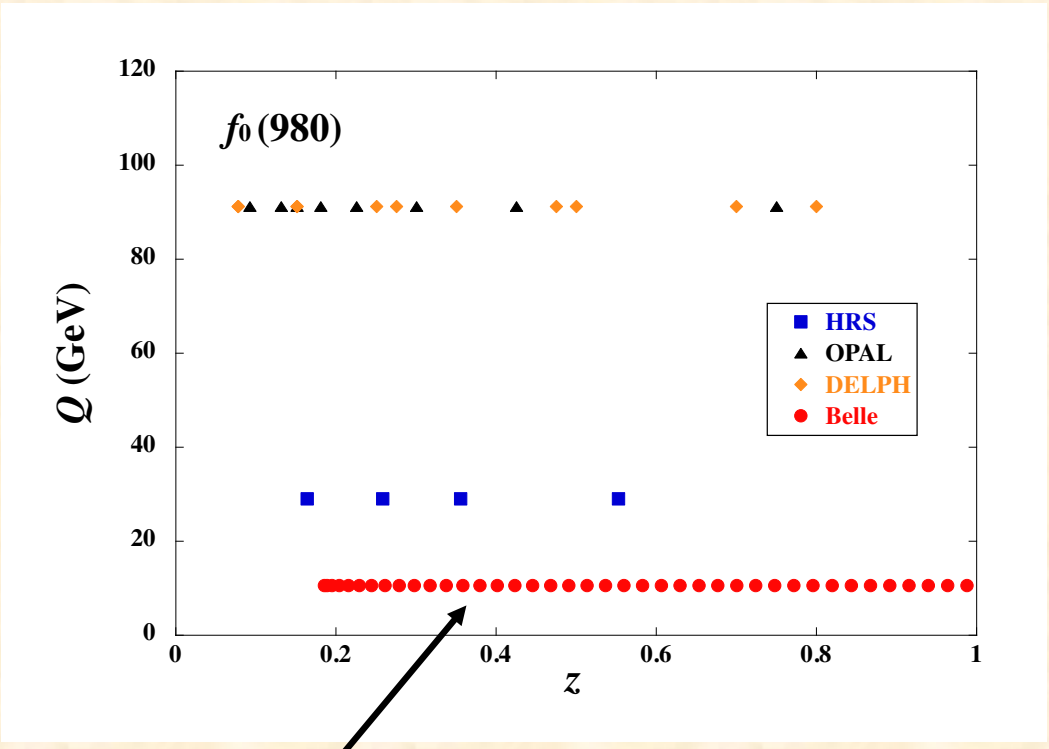
Exp. collaboration	$\sqrt{s}$ (GeV)	# of data
HRS	29	4
OPAL	91.2	8
DELPHI	91.2	11
Belle	10.58	40

R. Seidl *et al.*, (Belle Collaboration), Phys. Rev. D 111 (2025) 052003.

Advantages:

- accurate
- wide range of z
- Q^2 evolution can be probed.

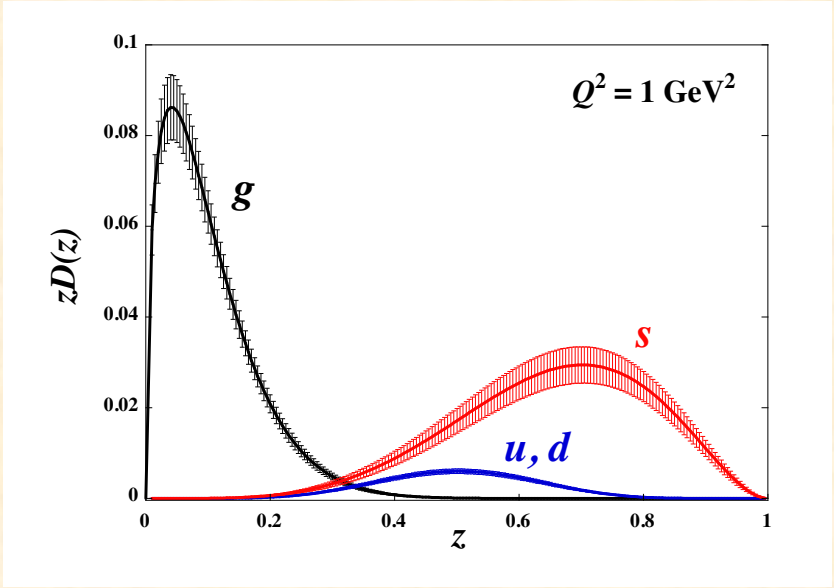




New Belle data

Global analysis result

Type	Configuration	2nd Moment	Peak z
$q\bar{q}$ Nonstrange	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$M(s)<M(u)<M(g)$	$z_{\max}(s)<z_{\max}(u)$
$q\bar{q}$ Strange	$s\bar{s}$	$M(u)<M(s)\lesssim M(g)$	$z_{\max}(u)<z_{\max}(s)$
Tetraquark	$(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{\max}(u)=z_{\max}(s)$
$K\bar{K}$ Molecule	$(K^+K^-+K^0\bar{K}^0)/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{\max}(u)=z_{\max}(s)$
Glueball	gg	$M(u)=M(s)<M(g)$	$z_{\max}(u)=z_{\max}(s)<z_{\max}(g)$



$M(u)=M(d)=0.0019,\quad M(s)=0.0121,\quad M(g)=0.0127$

- $M(u)<M(s)\lesssim M(g)$
- $z_{\max}(u)<z_{\max}(s)$

$\rightarrow f_0 \simeq s\bar{s}$

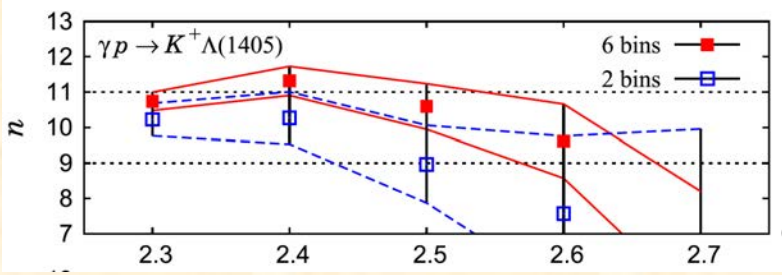
$f_0 = K\bar{K}$ (or tetra quark) at low energies ???

$\rightarrow f_0 = s\bar{s}$ at high energies

as implied for $\Lambda(1405)$ in 2016

by using constituent counting rule

in perturbative QCD.



$\leftarrow n_\Lambda = 5$

$\leftarrow n_\Lambda = 3$

Constituent counting rule in perturbative QCD

W.-C. Chang, SK, T. Sekihara, PRD 93 (2016) 034006.

Summary

Exotic hadrons could be found by studying fragmentation functions. As an example, the $f_0(980)$ meson was investigated.

(1) 2nd moments and functional forms could be used as criteria for finding quark configuration.

(2) Accurate analysis became possible due to the Belle data in 2025.

(3) Global analysis of $e^+ + e^- \to f_0 + X$ data

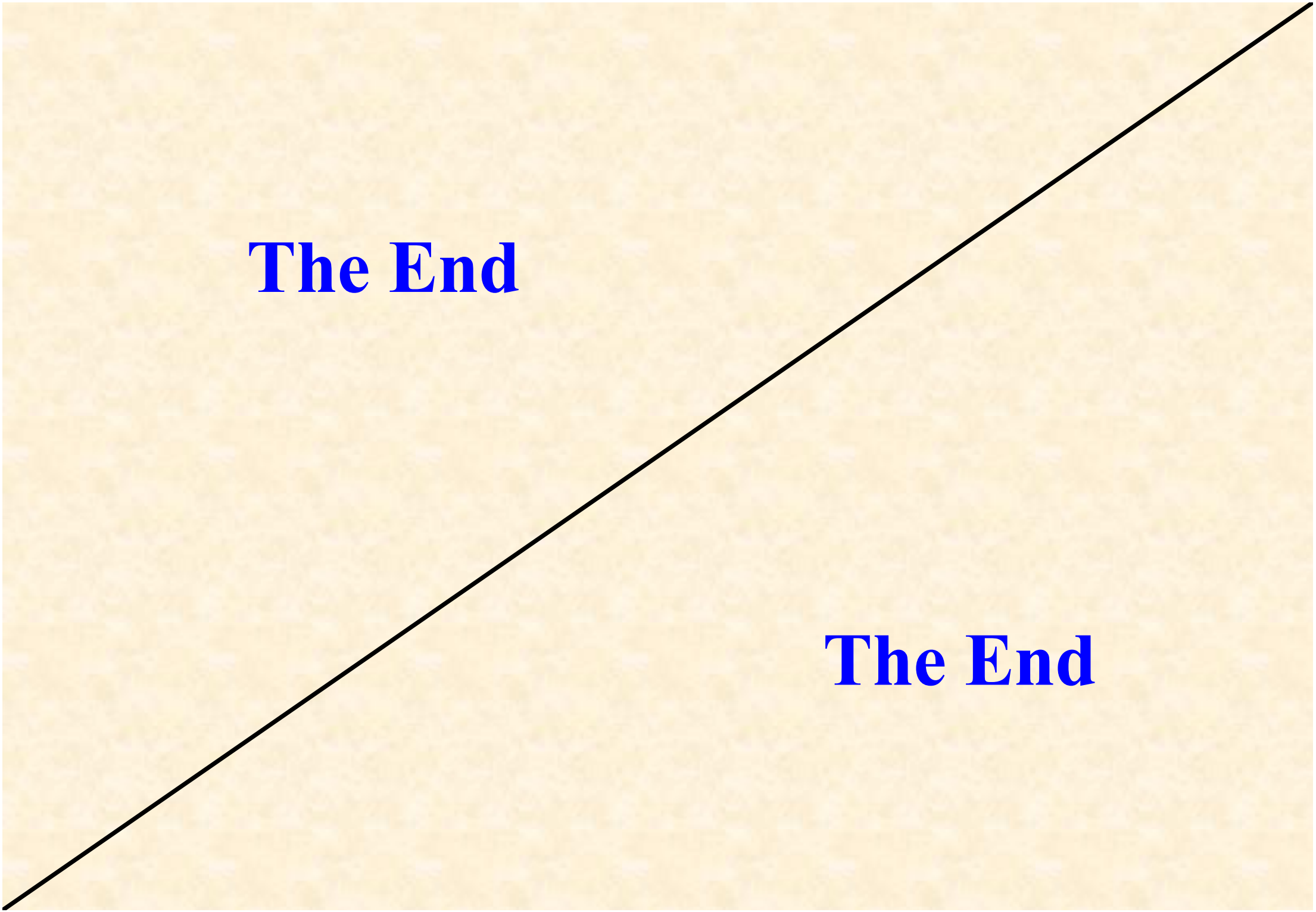
The results indicates $f_0 = s\bar{s}$ structure.

→ The $f_0(980)$ structure could look different depending on energies.

Low energies: $f_0 = K\bar{K}$ (or tetraquark)
High energies: $f_0 = s\bar{s}$

} just a possibility at this stage.

The End



The End