On a possible Interpretation of the 5q signal
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Evidence of new hadrons

Role of reaction theory

The Pc and the Z’s
Long time ago hadrons were made from valence quarks.
before we can address the following question...

dibaryon

diquark + di-antiquark

diquark + di-antiquark

pentaquark

dimeson molecule

q̅q̅g hybrid

 glueball
…we need to know how to interpret “peaks”

is it always a direct channel resonance?
S-matrix principles: Crossing, Analyticity, Unitarity

Crossing

\[ A(s, t) = \sum_l A_l(s) P_l(z_s) \]

Analyticity

\[ A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon) \]

bumps/peaks on the real axis (experiment) come from singularities in the complex domain.

Unitarity

\[ A_l(s + i\epsilon) \neq A_l(s - i\epsilon) \]
Can the s-channel band originate from a non-s-channel pole

\[ \Lambda_b \rightarrow K^- p J/\psi \]
\[ I(s) = \int_{P.S.(s)} dt |A(t)|^2 \]

\[ A(s, t) = A(t) \]
anatomy of the full, $A(s,t)$ amplitude and its partial waves

$->$ an s-channel singularity out-of a t-channel pole

$$A(s, t) = A(t) \quad \text{pole (peak) in } t$$

$$= b(s) + \sum_{l>0} (2l + 1)b_l(s)P_l(z_s)$$

$$t = t(s, z_s) \text{ kinematical relation}$$

$$\int dz_s$$

partial wave projection induces singularities in $s$

(aka. left cuts)
\[ b(s) = \frac{1}{2} \int_{-1}^{1} dz_{s} A(t) \quad I(s) = \sum_{l>0} |b_{l}(s)|^2 + |b(s)|^2 \]

singularity in each partial wave manifests in more or less abrupt “edge”
\[ |A(t)|^2 = |b(s) + \sum_{l>0} \cdots|^2 \]

\[ I(s) = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2 \]
\[ e^+e^- \rightarrow Y(4260) \rightarrow \pi^0 D^0 D^{**} \]

**D_1(2420) (t-channel)**

or

**Z_c(3900) (s-channel)**

from S. Olsen
suppose coherence between partial waves is broken

\[ |A(t)|^2 \to |\sum_{l>0} \cdots|^2 + |b(s)|^2 = |A(s, t)|^2 \]

signal in the Dalitz plot
but no change in the projection \( I(s) \)!

\[ I(s) = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2 \]
coherence between t-channel partial waves will be distorted if there are s-channel interactions. e.g. in the l=0 wave

\[
b(s) \rightarrow t(s) \left[ \frac{1}{\pi} \int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s' - s} \right]
\]
\[ t = b(s) + \sum_{l>0} (2l + 1)b_l(s)P_l(z_s) \]

\[ \int dz_s t(s) \rho(s') + t(s) \left[ \frac{1}{\pi} \int_{str} ds' \rho(s') \frac{b(s')}{s' - s} \right] \]

**remove** \( b(s) \) and replace it with \( b'(s) \)

\[ b(s) \rightarrow b'(s) = b(s) + t(s) \left[ \frac{1}{\pi} \int_{str} ds' \rho(s') \frac{b(s')}{s' - s} \right] \]
can the s-channel interaction, (though de-coherence) generate narrow s-bands?

\[ b'(s) - b(s) = t(s) \left[ \frac{1}{\pi} \int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s' - s} \right] \]

- t(s) has a peak in s (e.g. J/psi + p -> J/psi + p resonate)
- [...] has a peak as a function of s

\[ b(s) = \frac{1}{2} \int_{-1}^{1} dz_s \frac{\beta}{m_t^2 - t(s, z_s)} \]

b(s) has singularities for complex s
$$\frac{1}{\pi} \int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s' - s}$$

$s$-singularity of $b(s)$ becomes a second sheet singularity of the integral (i.e. physical amplitude) $\rightarrow$ very much like a resonance

Coleman-Norton theorem

t-channel resonance can produce s-channel “band” if:

- all particles on-shell
- $m_2$ and $m_1$ collinear
- $v(m_2) > v(m_1)$
\[ A(t) \rightarrow A(s, t) = [A(t) - b(s)] + b'(s) \]

\[ = \sum_{l>0} (2l + 1)b_l(s)P_l(z_s) + b'(s) \]

- **Dalitz plot distribution changes**

\[ |A(t)|^2 \neq |A(s, t)|^2 \]

- **Projection changes if** \[ |b'(s)|^2 \neq |b(s)|^2 \]

\[ I(s) = \int_{P.S.(s)} dt |A(t)|^2 = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2 \]

\[ \rightarrow \sum_{l>0} |b_l(s)|^2 + |b'(s)|^2 \]

(C.Schmidt)
in the single channel case $|b'(s)|^2 = |b(s)|^2$

for $s \sim s$.

$$
\left[ \frac{1}{\pi} \int_{s_{tr}} ds' \rho(s') \frac{b(s')}{s' - s} \right] \sim 2i\rho(s)b(s)
$$

$$
b'(s) = b(s) + t(s)[\cdots] \rightarrow [1 + 2i\rho(s)t(s)]b(s) = S(s)b(s)
$$

S(s) = unitary S-matrix element

and projection does NOT change

$$
I(s) = \int_{P.S.(s)} dt |A(t)|^2 = \sum_{l>0} |b_l(s)|^2 + |b(s)|^2
$$

$$
\rightarrow \sum_{l>0} |b_l(s)|^2 + |b'(s)|^2
$$
$e^+e^-(\text{at } 4260 \text{ MeV}) \rightarrow \pi^+\pi^- J/\psi \text{ at BESIII}$

$M^2(\pi^+J/\psi) \text{ (GeV/c}^2)^2$

$M = \frac{3.890 \pm 3.6 \pm 0.9 \text{ MeV}}{\text{LHCb}}$

$J/\psi(\mu^+\mu^-)(\text{GeV/c})$

$M^{\text{min}}(\mu^+\mu^-)$

$3.7 \pm 0.5 \text{ MeV}$

$\sigma^{\text{data}}$

$\sigma^{\text{MC}}$

$\sigma^{\text{Background}}$

$\sigma^{\text{Total}}$

$\text{PRL 110, 252001 (2013)}$

$\text{LHCb}$
Projection changes if interactions are inelastic

\[ A_\alpha(s) = b'_\alpha(s) + \sum_{l>0} \cdots \]

\[ \alpha = 1, 2, \cdots = (J/\psi p), (\chi_{c1}p) \cdots \]

\[ = (J/\psi \pi), (\bar{D}D^* + c.c) \cdots \]

\( P_c \)

\( Z_c(3900) \) in \( Y \rightarrow \pi \pi J/\psi \)

suppose there is peak from projection of a t-channel resonance in channel 2 and inelastic interaction between 1 and 2

\[ b'_1(s) \sim S_{1,2}b_2(s) \]

\[ |S_{1,2}| < 1 \]
The key to the XYZ phenomena are the many nearby channels

\[ \Lambda_b^0 \rightarrow \Lambda^* p \rightarrow K^- p \]

\[ M_{\Lambda_b^0} = 5.6195, \mu_{K^-} = 0.4937, \quad m_1 = m_{\chi_c} = 3.510, \quad m_2 = m_p = 0.93827 \]
\[ \lambda = m_{\Lambda^*} = 1.89 \text{ (they take)} \]

**Coleman-Norton requires**

\[ 1.89 < \lambda < 2.11 \text{ GeV} \]
\[ 4.45 < \sqrt{s_{\text{peak}}} < 4.65 \text{ GeV} \]

**Axes:** \( \text{Abs}[T(s)], \sqrt{s} \)

**Lines:** blue (\( \lambda = 1.89 \text{ GeV} \)), red (\( \lambda = 1.99 \text{ GeV} \)), yellow (\( \lambda = 2.0 \))
$Z_c(3900)$ Charged charmonium?

$e^+ e^- \rightarrow Y(4260) \rightarrow \pi^+ Z_c^- (3900) \rightarrow \pi^+ \pi^- J/\psi$

Breit-Wigner model fit close to $D^*D$ threshold

coupling to $DD^*$
$Y(4260) \rightarrow J/\psi \pi \pi$.

$Z_c(3900)$ via $D_0^*(2420)$ exchange

$Z_b(10610)$ via $B_{J}^{**}(5698)$ exchange
XYZ phenomena are seem to occur near inelastic thresholds

For the non-resonant [ (t-channel) induced singularities] interpretation there needs to be significant coupling between channels

Specific predictions for “the other” Dalitz plot distribution e.g.

\[ \Lambda_b \rightarrow K^- p \chi_{c1} \]

\[ Y(4260) \rightarrow \bar{D} D^* \pi \]
Origin of singularities (exchanges constrained by unitarity)

\[ A(s, t) \]

\[ \Lambda_b \rightarrow K^- \rho J/\psi \]

\[ s = s_p \] (pole)

\[ s = s_b \] (branch point)

\[ \beta \]

\[ s_{p-t} \]

physical region

(after s-channel projection + fsi)