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Use of $B \to J/\psi f_0$ decays to discern the $q\bar{q}$ or tetraquark nature of scalar mesons

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Scalar meson quandry

- While 0^- and 1^- mesons follow a simple rule that adding an s-quark increases their mass, the 0^+ mesons are difficult to understand in this context

Isospin	1^- state	mass	$q\bar{q}$	0^+ state	mass
1	ρ	776 MeV	$(u\bar{u}+d\bar{d})\sqrt{2}$	$a_0(980)$	980 MeV
0	ω	783 MeV	$(uu-d\bar{d})\sqrt{2}$	$f_0(500)$ or σ	500 MeV
1/2	K*(892)	892 MeV	(u or d) $\bar{s}$	$\kappa(800)$	800 MeV
0	ϕ	1020 MeV	$s\bar{s}$	$f_0(980)$	980 MeV

- Suggestions that scalars are tetraquarks

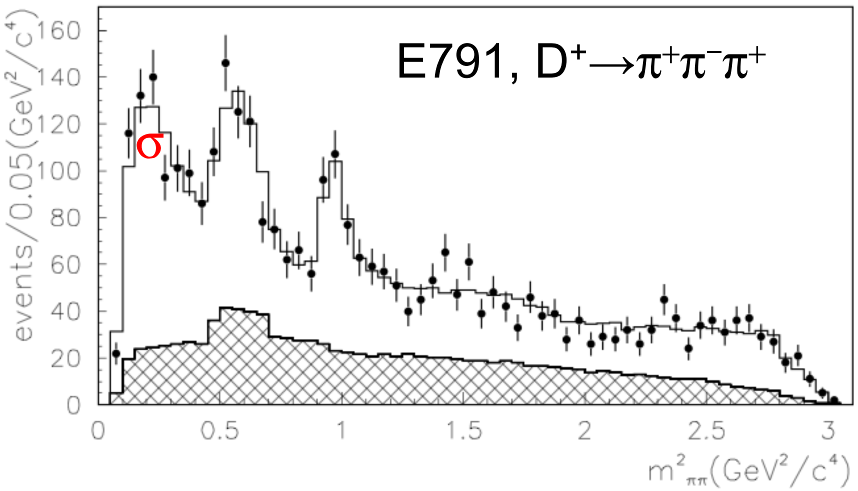
Issues

- What is basic structure of matter?
  - Are the $f_0(500)$ & $f_0(980)$ 2 quark or 4 quark states?
  - We need to know this if we are to understand mesons made only of gluons (glueballs)
- What complications arise in other measurements due to quark substructure?
  - Ex: CP violation studies in $B \rightarrow J/\psi$ + scalar, or any other meson with non-qq structure. See Fleischer, Knegjens & Ricciardi [arXiv:1109.1112]
  - Maybe a concern for other meson states

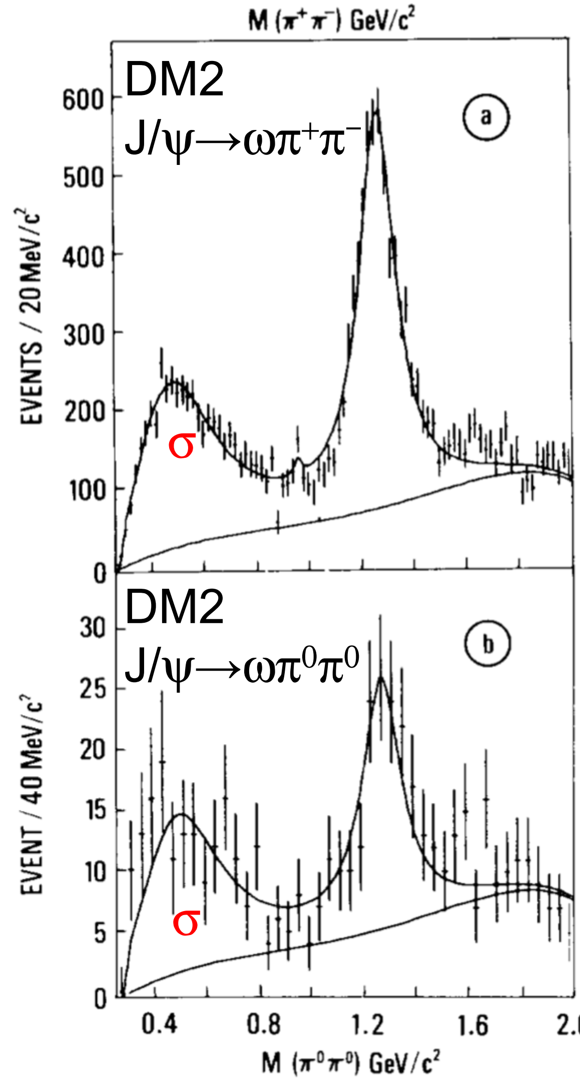
Much Interest

- S. Weinberg, "Tetraquark Mesons in Large N Quantum Chromodynamics," arXiv:hep-ph/1303.0342
- G. t'Hooft et al., "A Theory of Scalar Mesons," arXiv:hep-ph/0801.2288
- A. H. Fariborz et al. "Global aspects of the scalar meson puzzle," arXiv:hep-ph/0902.2825
- R. L. Jaffe, Multi-Quark Hadrons I. The Phenomenology of $Q^2\bar{Q}^2$ Mesons, Phys. Rev. D15 (1977) 267

Knowledge about σ

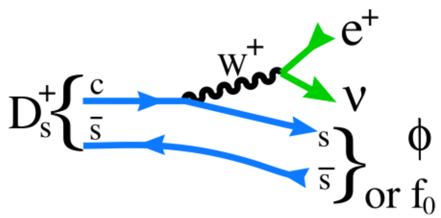


- Also ππ scattering experiments, vector meson radiative decays, etc…
- Mass & Width are uncertain PDG “estimate” M=400-550 MeV, Γ=400-700 MeV



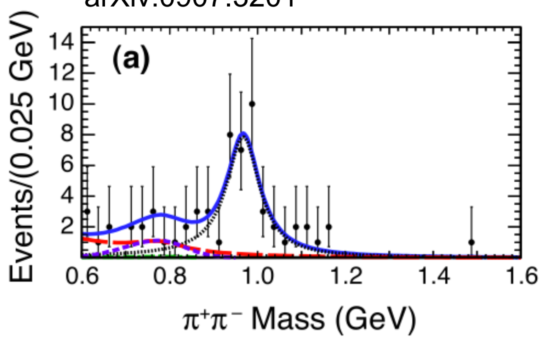
Knowledge about $f_0(980)$

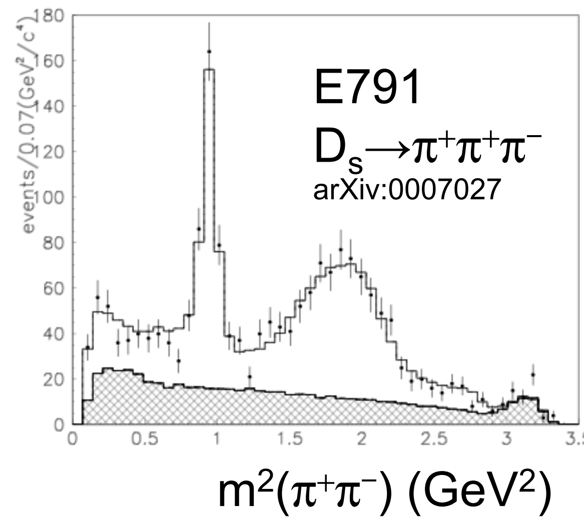
- $f_0(980)$ seen in many experiments
- In weak decays



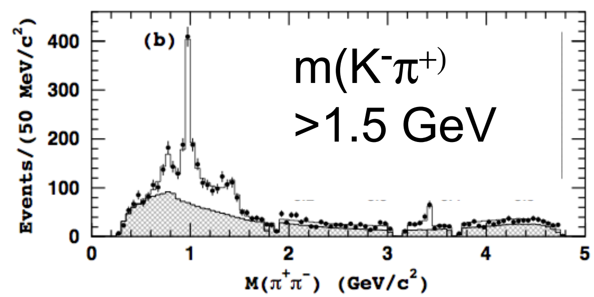
Note $s\bar{s}$ is I=0, e.g. ρ not allowed

CLEO $D_s \to \pi^+\pi^- e^- \nu$
arXiv:0907.3201





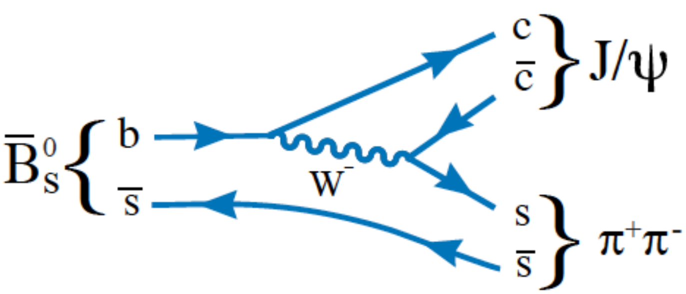
Belle $B^- \to K^-\pi^+\pi^-$
arXiv:0512066

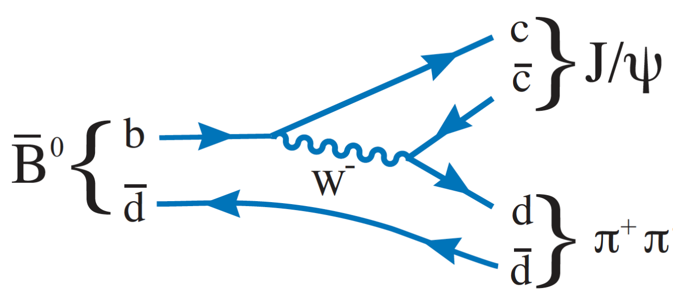


- Also LHCb $B_s \to J/\psi\, \pi^+\pi^-$ (predicted in arXiv:0812.2832)

$B^0_{(s)} \rightarrow J/\psi\pi^+\pi^-$

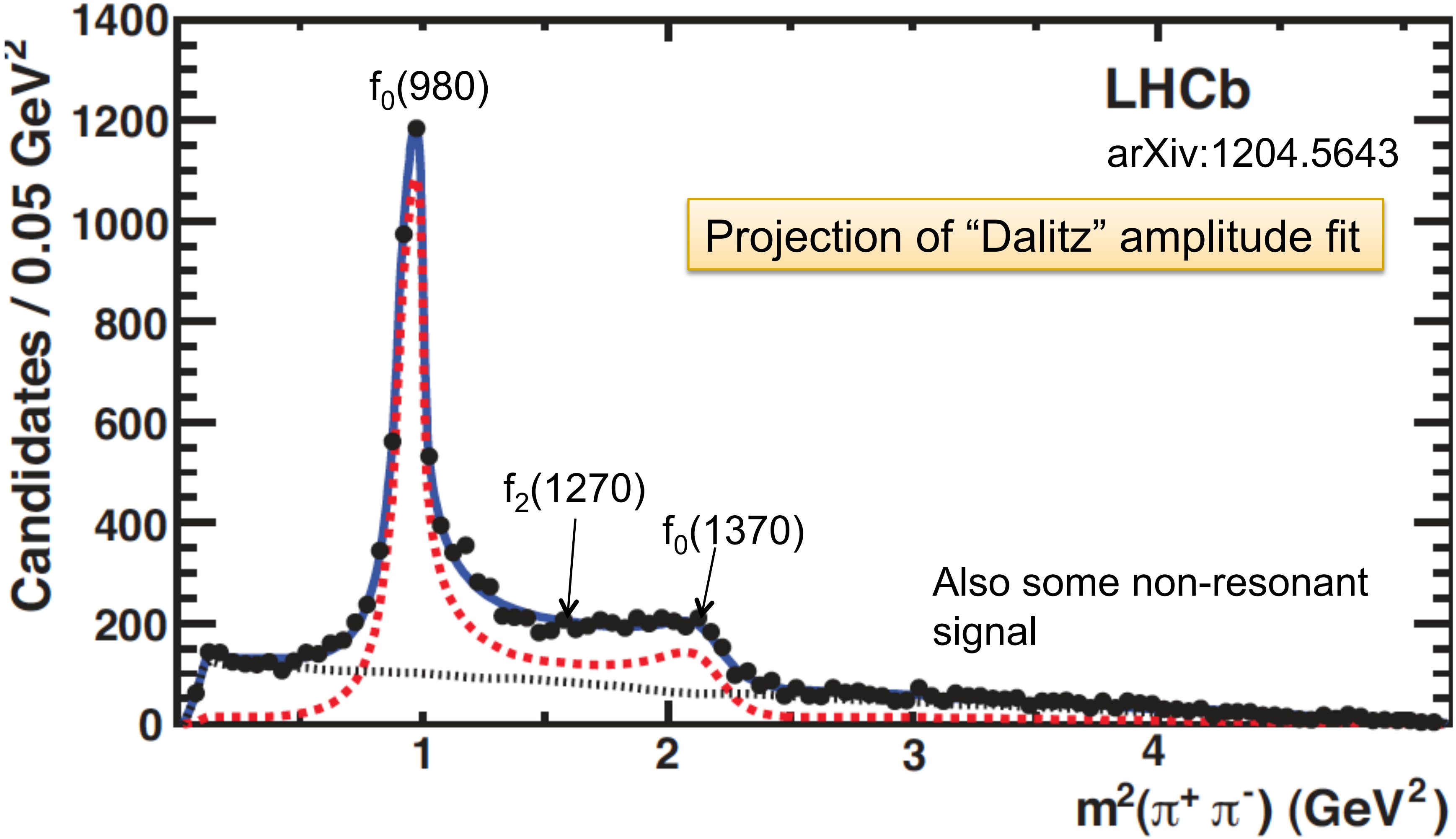
- What can these decays tell us about σ & $f_0(980)$?
- These resonances plus others can be made via the following decay diagrams:



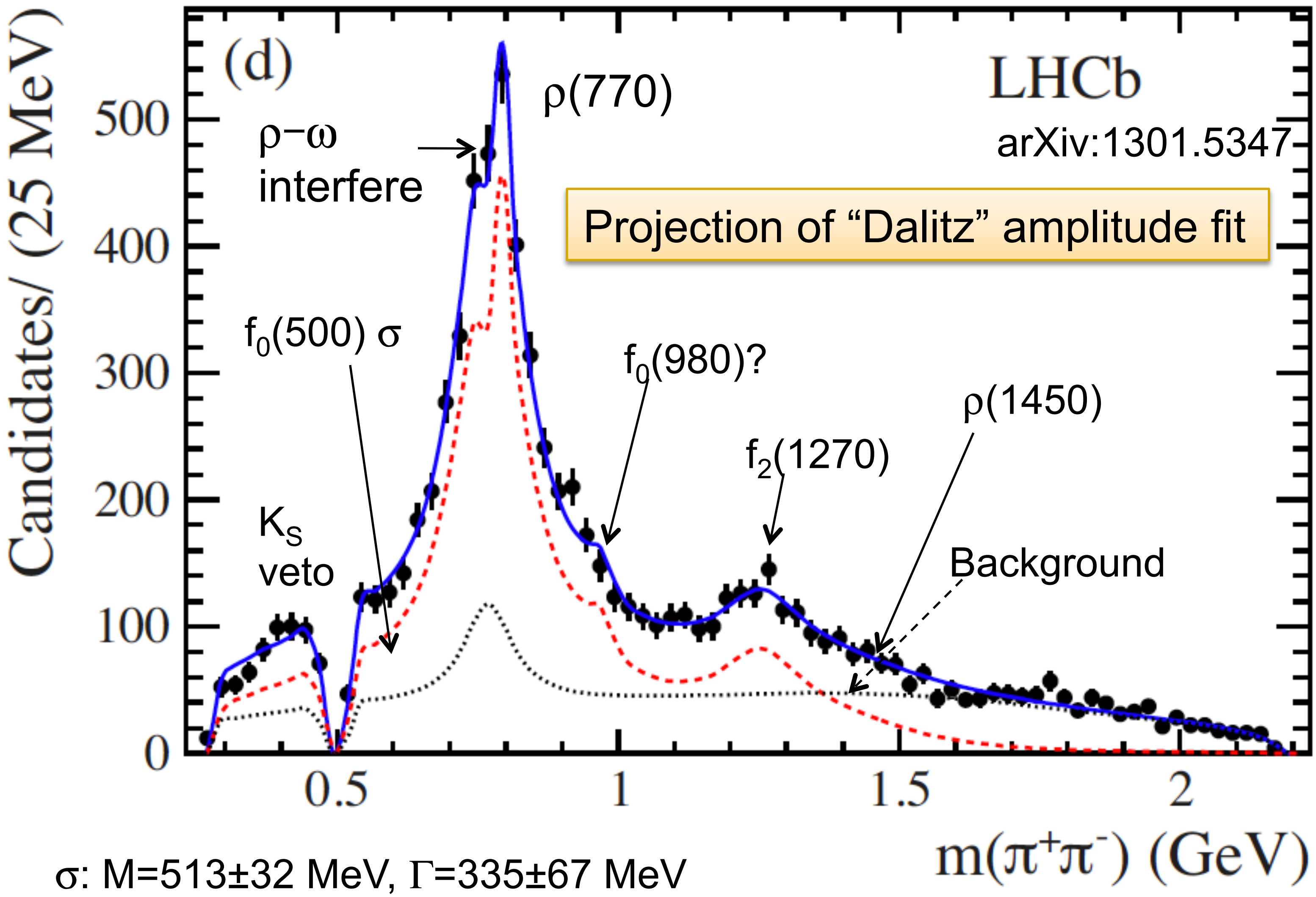


Again, I=0

LHCb: $B_s \to J/\psi\pi^+\pi^-$



LHCb: $B^o \rightarrow J/\psi\pi^+\pi^-$



σ: M=513±32 MeV, Γ=335±67 MeV

$\mathcal{B}(B \to J/\psi f)$

LHCb Measurements

Final state	$\overline{B}^0_s$	$\overline{B}^0$
σ	-	$9.60^{+3.79}_{-1.70} \times 10^{-6}$
f_0	$3.40^{+0.63}_{-0.16} \times 10^{-4}$	$< 1.7 \times 10^{-6}$

Quark substructure

- $q\bar{q}$ model

$$
\begin{aligned}
|f_0\rangle &= \cos\phi|s\bar{s}\rangle + \sin\phi|n\bar{n}\rangle \\
|\sigma\rangle &= -\sin\phi|s\bar{s}\rangle + \cos\phi|n\bar{n}\rangle, \\
\text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right).
\end{aligned}
$$

- tetraquark model

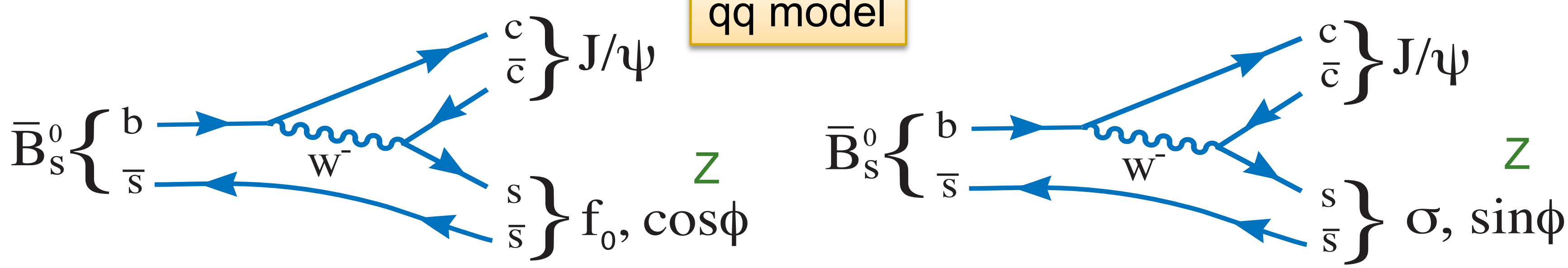
$$
|f_0\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right), \quad |\sigma\rangle = [ud][\bar{u}\bar{d}]
$$

B_s decay diagrams

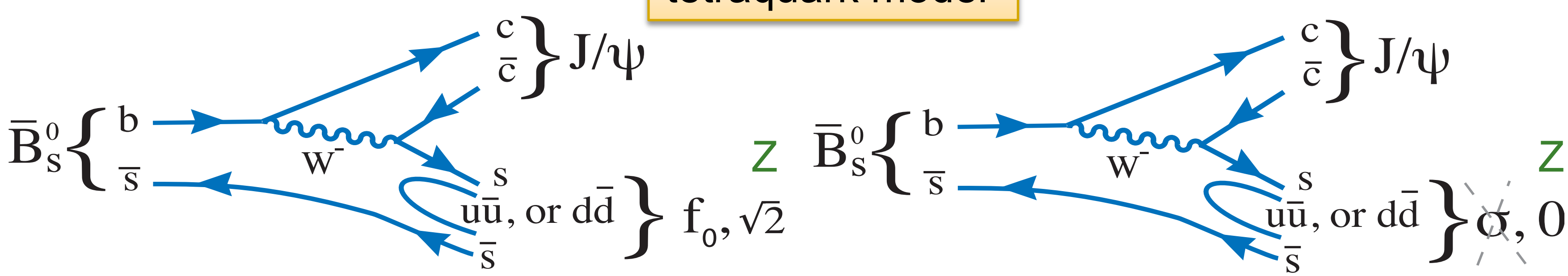
$$\Gamma(\bar{B}^0_s \to J/\psi f) = C \left| F^f_{B_s}\left(m^2_{J/\psi}\right) \right|^2 \left| V_{cs} \right|^2 \Phi Z^2$$

form factor　　phase space　　coupling

qq̄ model



tetraquark model

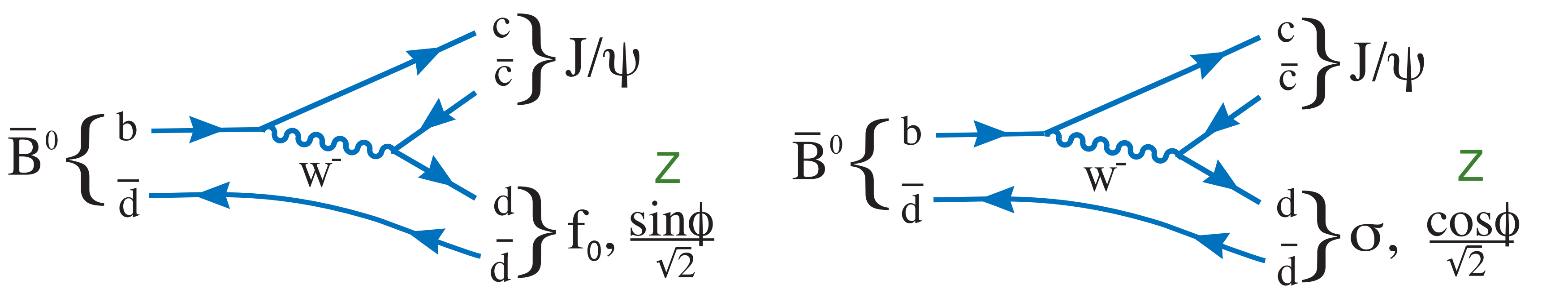


First prediction: If σ is a tetraquark it will not be seen in $B_s \to J/\psi\sigma$

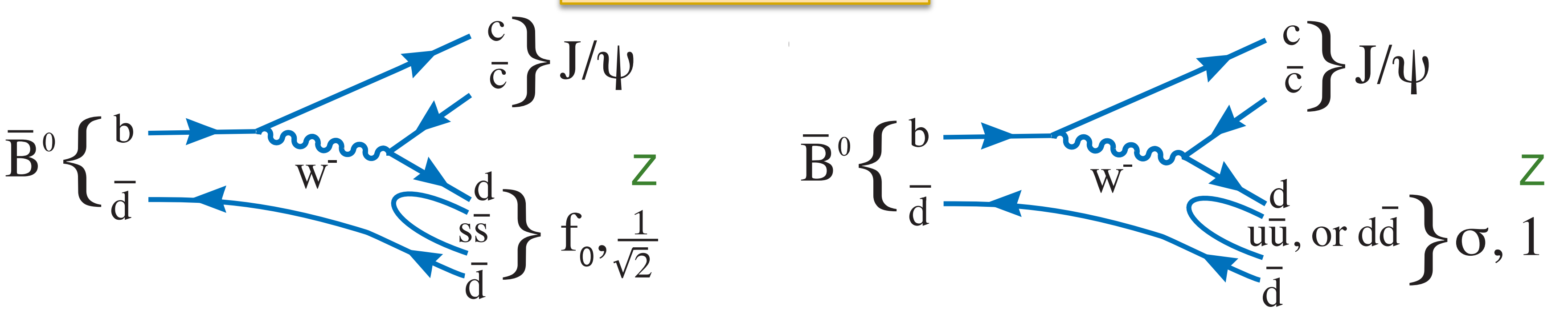
B^0 decay diagrams

$$\Gamma(\bar{B}^0 \to J/\psi f) = C\left|F^f_{B^0}\left(m^2_{J/\psi}\right)\right|^2 \left|V_{cd}\right|^2 \Phi Z^2$$

qq̄ model



tetraquark model



Rate ratios

Label	Mode ratio	Rate ratio	$\mathcal{Z}^2$ $q\bar{q}$	$\mathcal{Z}^2$ tetraquark
$r^{0f_0}_{sf_0}$	$\frac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \frac{\lvert V_{cd}\rvert^2 \Phi^{f_0}_{B^0}}{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}$	$\frac{1}{2}\tan^2\phi$	$\frac{1}{4}$
$r^{0f_0}_{0\sigma}$	$\frac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \frac{\Phi^{f_0}_{B^0}}{\Phi^{\sigma}_{B^0}}$	$\tan^2\phi$	$\frac{1}{2}$
$r^{s\sigma}_{sf_0}$	$\frac{\Gamma(\bar{B}^0_s \to J/\psi\, \sigma)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \frac{\lvert F^{\sigma}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \frac{\Phi^{\sigma}_{B^0_s}}{\Phi^{f_0}_{B^0_s}}$	$\tan^2\phi$	0
$r^{sf_0}_{0\sigma}$	$\frac{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \frac{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \frac{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}{\lvert V_{cd}\rvert^2 \Phi^{\sigma}_{B^0}}$	2	2

Last ratio is independent of model, allows measurement of form factor ratio

Form-factors

- $r_{0\sigma}^{sf_0}$ is independent of whether the states are $q\bar{q}$ or tetraquark, so we determine

$$\frac{|F_{B_s^0}^{f_0}(m_{J/\psi}^2)|}{|F_{B^0}^{\sigma}(m_{J/\psi}^2)|} = 0.99_{-0.04}^{+0.13}$$

- Li et al suggest using $r_{sf_0}^{s\sigma}$ to measure ϕ in the $q\bar{q}$ model, & compute $|F_{B_s^0}^{\sigma}(m_{J/\psi}^2)|^2/|F_{B_s^0}^{f_0}(m_{J/\psi}^2)|^2 = 1$
- Fleischer et al. predict in the tetraquark model that $\mathcal{B}(\overline{B}^0 \to J/\psi\, f_0,\ f_0 \to \pi^+\pi^-) \sim (1-3)\times 10^{-6}$

Form-factors II

- They use $|F^{f_0}_{B^0}(m^2_{J/\psi})|/|F^{f_0}_{B^0_s}(m^2_{J/\psi})|$ =0.69 from El-Bennich et al. If a unit form-factor is used then their prediction doubles & the tetraquark nature of the $f_0(980)$ becomes inconsistent with the LHCb upper limit of 1.1×10^{-6}.
- Using the limit on the measured ratio $r^{0f_0}_{sf_0}$, we find $\phi<29^o$ @ 90% cl
- LHCb assumes the similar ratio $|F^{f_0}_{B^0}(m^2_{J/\psi})/|F^{\sigma}_{B^0}(m^2_{J/\psi})|$ =1, & find $\phi<31^o$ @ 90% cl (using $r^{0f_0}_{0\sigma}$)

Predictions

- Our null prediction for $B_s \to J/\psi\sigma$ is ameliorated somewhat by the possibility of mixing between the tetraquark states and higher order diagrams. However this leads to rate of no more than 1% of the $B_s \to J/\psi f_0$ rate
- Mixing of other isoscalar mesons can be measured by just using decays of B^0 & $B_s \to J/\psi F$, i.e. the mixing angle can be measured from one state alone!
- Thus future data using $B_{(s)} \to J/\psi F$ decays can tell us about the substructure of isoscalar mesons

The End

For more details see S. Stone & L. Zhang, PRL 111, 062001 (2013) arXiv: 1305.6554