S-Waves & the extraction of β_s

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Mystery of Scalar Mesons

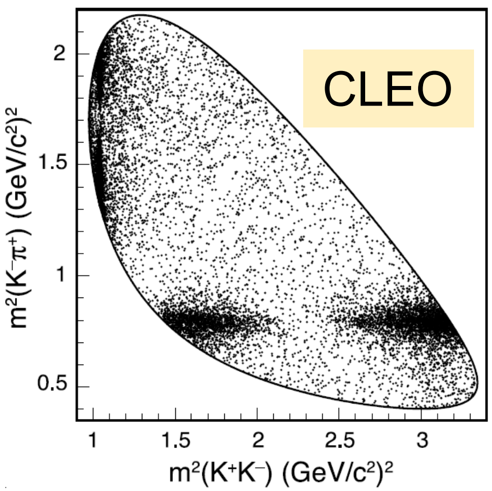
- 0^+ nonet is not ~~well~~ understood
- Compare 0^- versus 0^+

Quarks	Pseudoscalar		Scalar	
	Particle	Mass (MeV)	Particle	Mass (MeV)
$1/\sqrt{2}(u\bar{u}+d\bar{d})$	π^o	135	σ ?	~600
$u\bar{d}$	π^+	139	a_o^+	980
$u\bar{s}$	K^+	495	κ^+ ?	~900
$\sim s\bar{s}$	η'	960	f_o	980

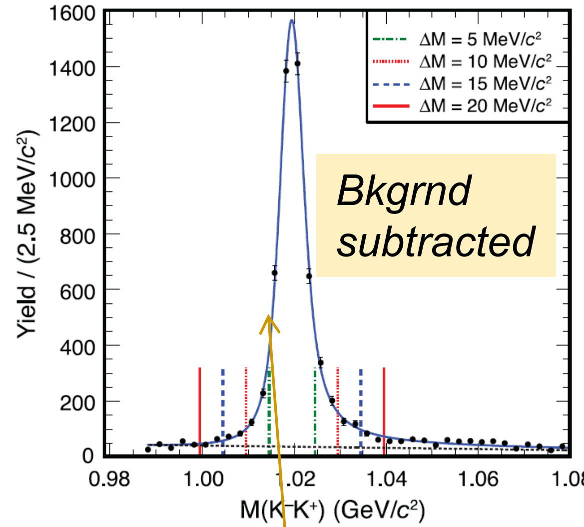
  - For 0- nonet, the mass increases by ~400 MeV for each s quark. Why isn't this true for the 0+ nonet?
  - Why aren't the a_o & the σ degenerate in mass?
- Suggestions that the 0^+ are 4-quark states

S-waves in $D_s \rightarrow K^+K^-\pi^+$ decays

- Dalitz analyses (also E687)



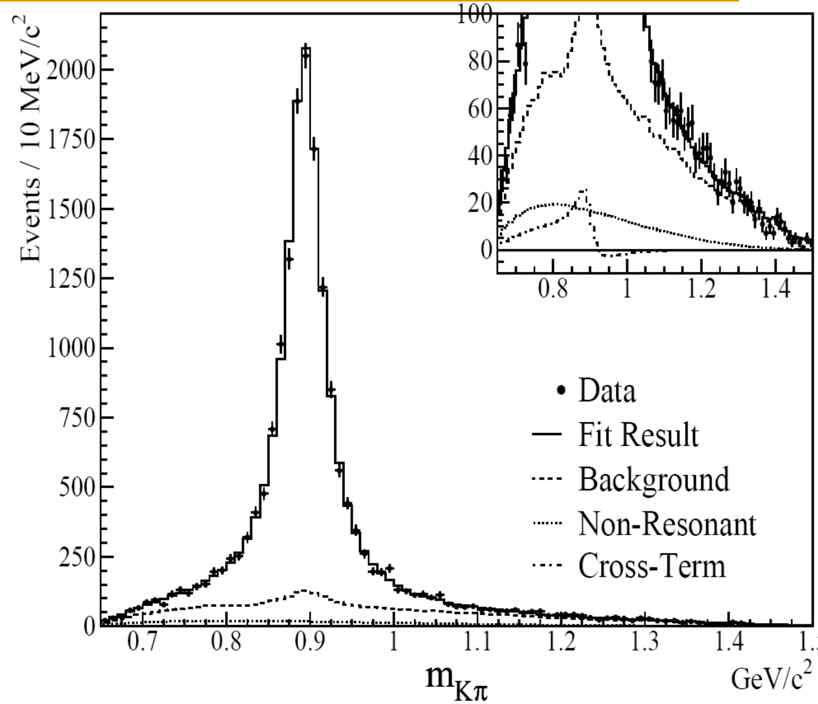
Particle	J^P	Fit Fraction (%) (sums to 130%)
K*(892)	1^-	47.4±1.5
ϕ(1020)	1^-	42.2±1.6
f_o(980)	0^+	28.2±1.9
f_o(1370)	0^+	4.3±0.6
K_o*(1430)	0^+	3.9±0.5
f_o(1710)	0^+	3.4±0.5

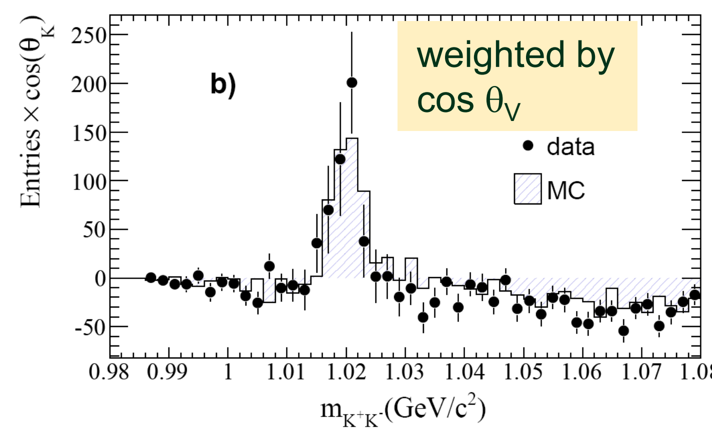


- Fit using a linear S-wave + Breit-Wigner convoluted with Gaussian for the ϕ. Find 6.3% (8.9%) S-wave for ±10 MeV (±15 MeV)

S-waves via Interference in semileptonic decays

- $D^+ \to K^- \pi^+ \mu^+ \nu$: Though $K\pi$ is dominantly K*, FOCUS observed an interfering S-wave amplitude with a rate fraction of (2.7±0.4)% for $0.8 < m(K\pi) < 1.0$ GeV
- $D_s \to K^+ K^- e^+ \nu$: S-wave fraction of $(0.22^{+0.12}_{-0.08})\%$ for $1.01 < m(K^+K^-) < 1.3$ GeV (BaBar)

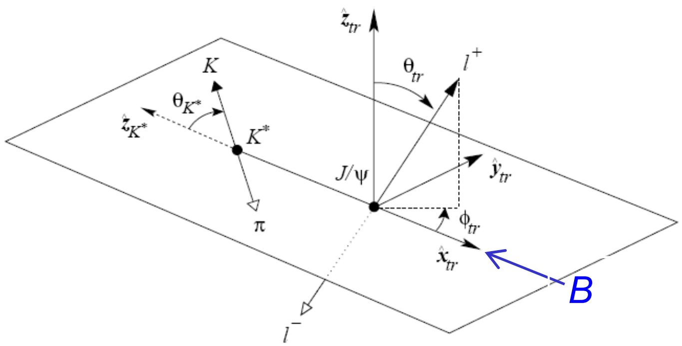


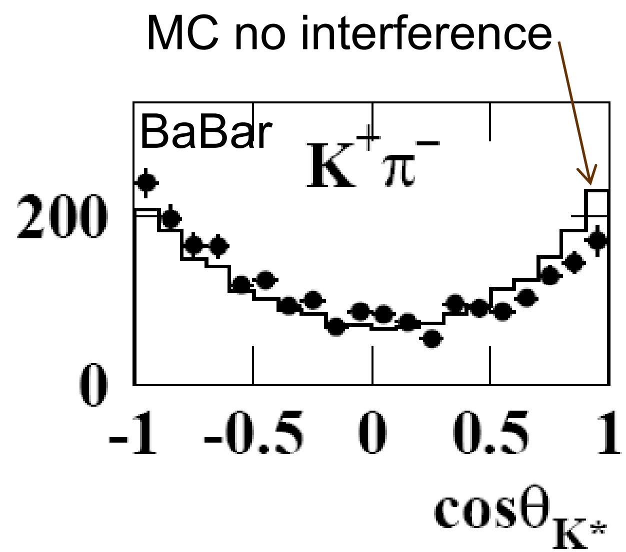


The S-Wave in $B \to J/\psi K^*$

- Two Vectors in final states so a transversity analysis is required
- BaBar & Belle measure interference between S & P waves in K* decay angle
- The fraction of S-wave intensity is (7.3±1.8)% for

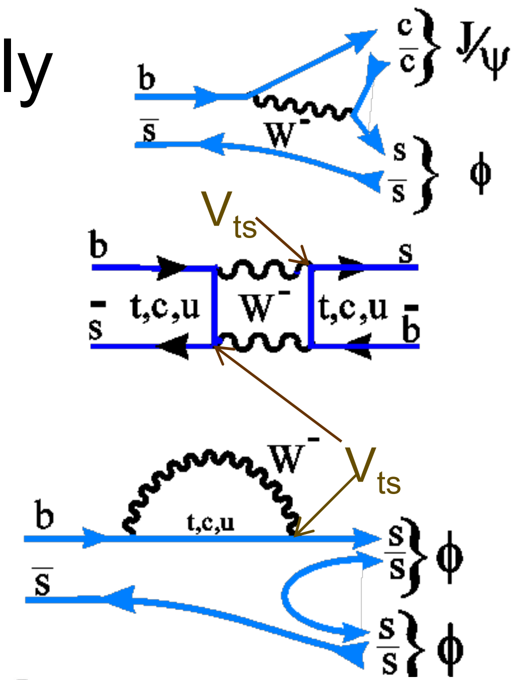
  $0.8 < m(K\pi) < 1.0$ GeV
- BaBar uses this interference to remove ambiguities in the measurement of $\cos(2\beta)$

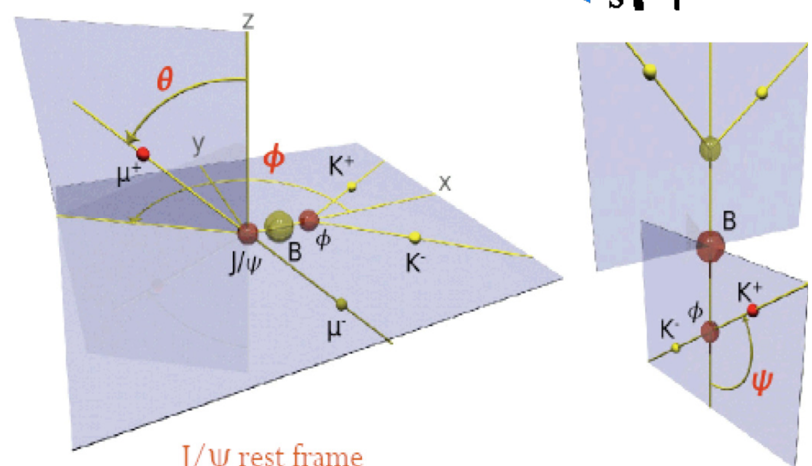




Measuring β_s in B_s Decays

- Thus far $B_s \rightarrow J/\psi\phi$ used exclusively
- $B_s \rightarrow \phi\phi$ suggested, for null measurement, as decay phase cancels mixing phase
- These modes are Vector-Vector final state, so must disentangle CP+ & CP- final states using a time-dependent angular analysis





J/ψ rest frame

φ rest frame

Technique

- Without S-waves & $\Delta\Gamma$=0

$$A(B_s \to J/\psi\phi) = A_0(m_\phi)/E_\phi \epsilon^{*L}_{J/\psi} - A_{\|}\epsilon^{*T}_{J/\psi}/\sqrt{2} - iA_\perp \epsilon^*_\phi \cdot \hat{\mathbf{p}}/\sqrt{2},$$

- A_0 P=+ longitudinal, $A_{||}$ P=+ trans, $A_\perp$ P= - trans

$$\frac{d^4\Gamma[B_s \to (\ell^+\ell^-)_{J/\psi}(K^+K^-)_\phi]}{d\cos\theta \ d\phi \ d\cos\psi \ dt} = \frac{9}{32\pi}[2|A_0|^2\cos^2\psi(1-\sin^2\theta\cos^2\phi)$$

$$+\sin^2\psi\{|A_{||}|^2(1-\sin^2\theta\sin^2\phi) + |A_\perp|^2\sin^2\theta - \text{Im}(A^*_{||}A_\perp)\sin 2\theta\sin\phi\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\{\text{Re}(A_0^*A_{||})\sin^2\theta\sin 2\phi + \text{Im}(A_0^*A_\perp)\sin 2\theta\cos\phi\}] \quad .$$

- For $\overline{B}_s$ replace $A_\perp$ by $-A_\perp$.
- Strait-forward to add finite $\Delta\Gamma$
- S-Wave term cannot be ignored (Stone & Zhang [arXiv:0812.2832])
- So must add in S-wave amplitude

All terms [Xie et al, arXiv:098.3627]

- Time dependence (for ex.)

$$|A_0(t)|^2 \quad = \quad |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \; + \; \sin\Phi \sin(\Delta m_s t)\right]$$

- Can write

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\cos\theta\, d\cos\psi\, d\varphi} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$

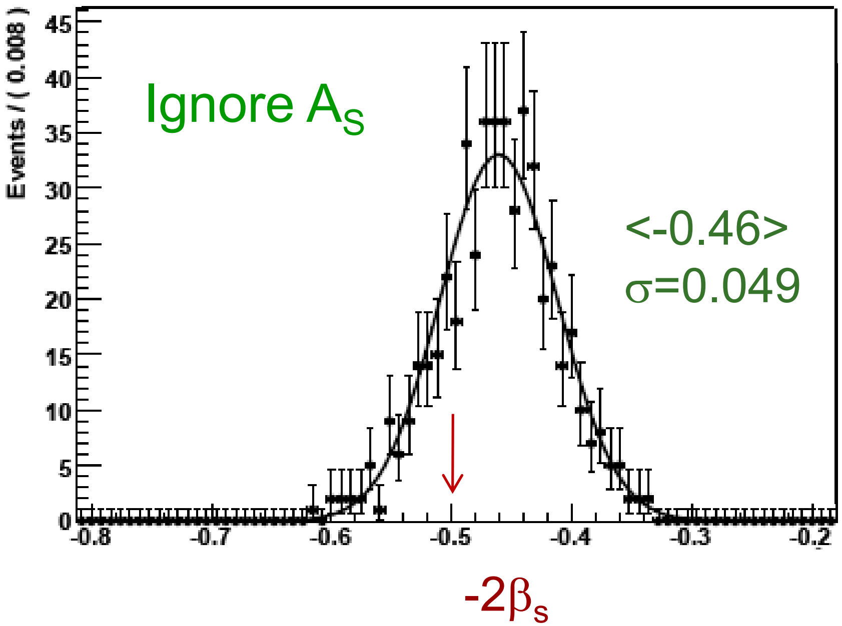
k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta_l, \theta_K, \varphi)$
1	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$	$4\sin^2\theta_l \cos^2\theta_K$
2	$\|A_{\|\|}(t)\|^2$	$\|\bar{A}_{\|\|}(t)\|^2$	$(1+\cos^2\theta_l)\sin^2\theta_K - \sin^2\theta_l \sin^2\theta_K \cos 2\varphi$
3	$\|A_\perp(t)\|^2$	$\|\bar{A}_\perp(t)\|^2$	$(1+\cos^2\theta_l)\sin^2\theta_K + \sin^2\theta_l \sin^2\theta_K \cos 2\varphi$
4	$\Im\{A_{\|\|}^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_{\|\|}^*(t)\bar{A}_\perp(t)\}$	$2\sin^2\theta_l \sin^2\theta_K \sin 2\varphi$
5	$\Re\{A_0^*(t)A_{\|\|}(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{\|\|}(t)\}$	$-\sqrt{2}\sin 2\theta_l \sin 2\theta_K \cos\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\sqrt{2}\sin 2\theta_l \sin 2\theta_K \sin\varphi$
7	$\|A_S(t)\|^2$	$\|\bar{A}_S(t)\|^2$	$\frac{4}{3}\sin^2\theta_l$
8	$\Re\{A_S^*(t)A_{\|\|}(t)\}$	$\Re\{\bar{A}_S^*(t)\bar{A}_{\|\|}(t)\}$	$-\frac{2}{3}\sqrt{6}\sin 2\theta_l \sin\theta_K \cos\varphi$
9	$\Im\{A_S^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_S^*(t)\bar{A}_\perp(t)\}$	$\frac{2}{3}\sqrt{6}\sin 2\theta_l \sin\theta_K \sin\varphi$
10	$\Re\{A_S^*(t)A_0(t)\}$	$\Re\{\bar{A}_S^*(t)\bar{A}_0(t)\}$	$\frac{8}{3}\sqrt{3}\sin^2\theta_l \cos\theta_K$

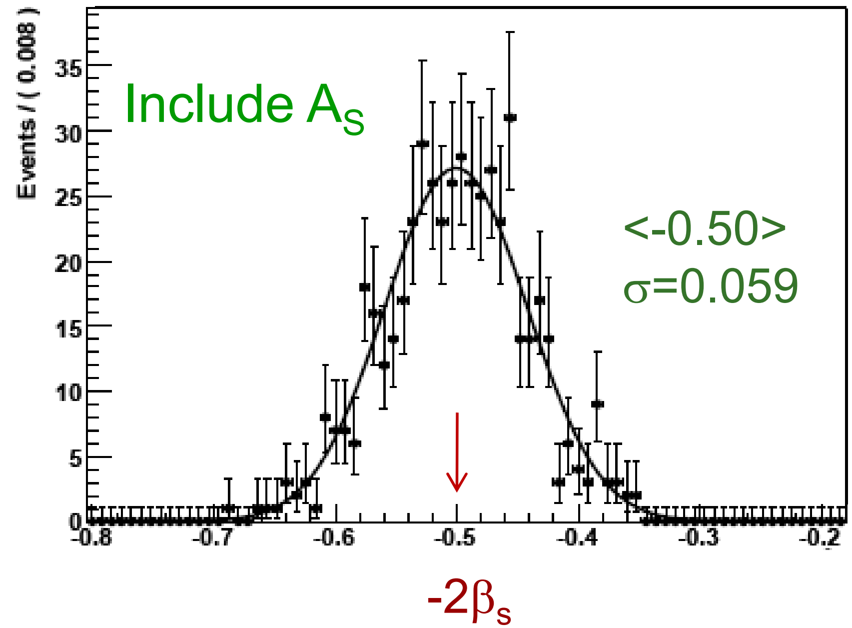
Estimate of S-wave Effect

- Adding A_S can only increase the experimental error. The size of the effect depends on many factors including the magnitude & phase of the S-wave amplitude, β_s, values of the strong phases, detector acceptances, biases…
- One simulation for LHCb by Xie et al
  - Assumes either 5% or 10% S-wave with phases either 0 or 90^o.
  - Simulates many Pseudo experiments

Results of ignoring S-wave

Generate $-2\beta_s = -0.5$





- Find bias of -10%
- Error increases by ~20%.
- Can also use to eliminate δ_s ambiguity

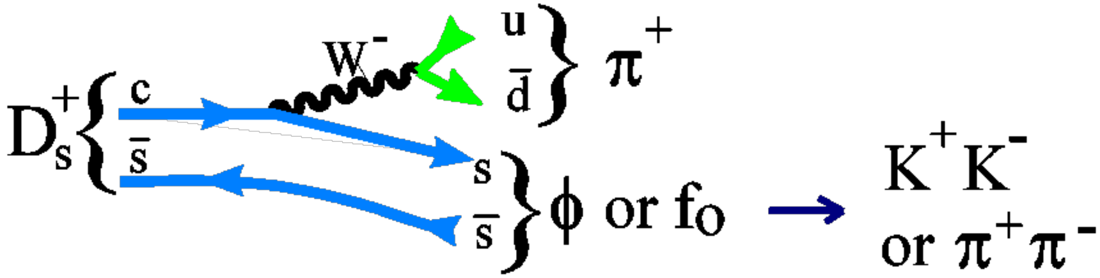
Estimates of $J/\psi\, f_o(980)$

- Can use S-wave materializing as $f_o(980)$ for CP measurements (Stone & Zhang [arXiv:0812.2832])
- The final state $J/\psi\ f_o$ is a CP+ eigenstate
- No angular analysis is necessary! This is just like measuring $J/\psi\ K_s$. The modes $J/\psi\eta$ & $J/\psi\ \eta'$ can also be used, but they involved γ's in the decay & thus have lower efficiency at hadron colliders
- Define:

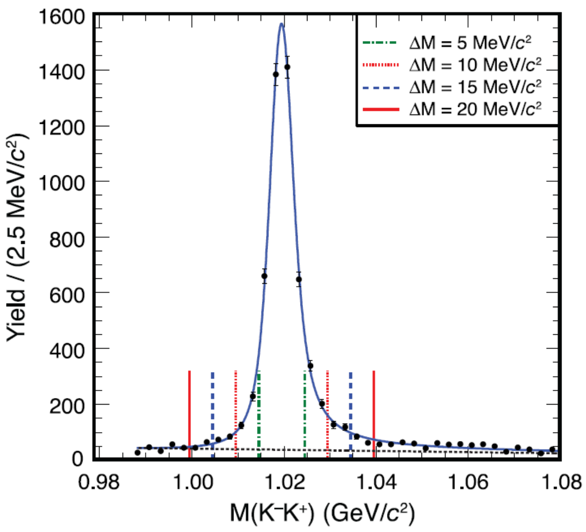
$$R_{f/\varphi} = \frac{\Gamma\left(B_s \to J/\psi f_0; f_0 \to \pi^+\pi^-\right)}{\Gamma\left(B_s \to J/\psi\phi; \phi \to K^+K^-\right)}$$

Estimate Using Hadronic D_s Decays

- $M(B_s)-M(J/\psi)=5366-3097 = 2270$ MeV
- $M(D_s)-M(\pi) = 1830$ MeV, not too different

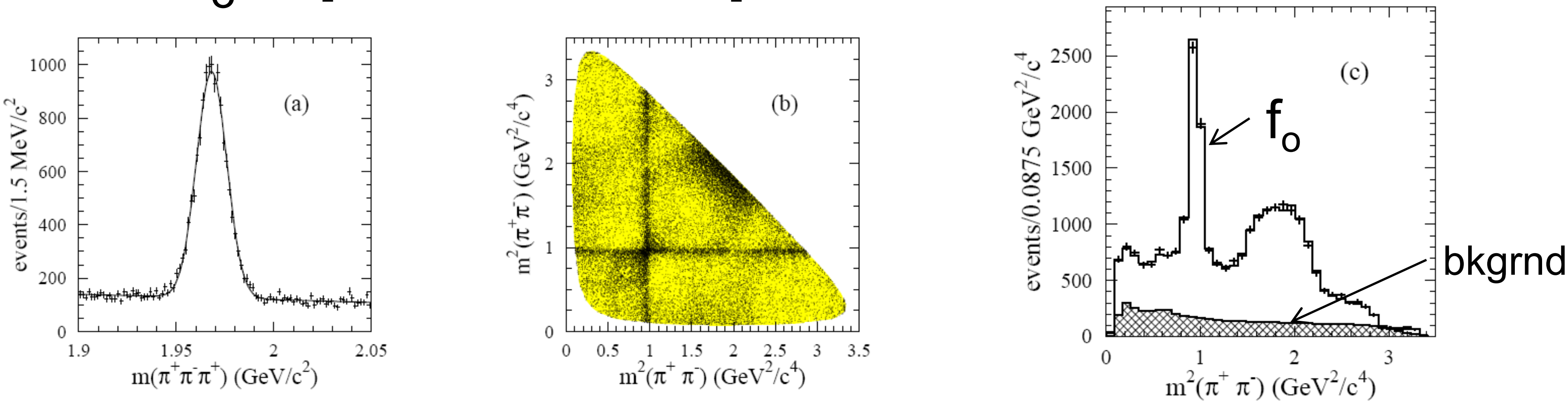


- Use CLEO result for $D_s \to K^+K^-\pi^+$ extrapolated to zero ϕ width to extract $\mathcal{B}(D_s \to \phi\pi^+, \phi \to K^+K^-)$ = (1.6±0.1)% (use only for this comparison)



Estimate from $D_s \to h^+h^-\pi^+$

- CLEO: $\mathcal{B}(D_s \to \pi^+\pi^+\pi^-) = (1.11 \pm 0.07 \pm 0.04)\%$
- Use BaBar Dalitz analysis to estimate fraction of $f_o\pi^+$ [arXiv:0808.0971]



- Estimate (27±2)% of final state is in narrow f_o peak

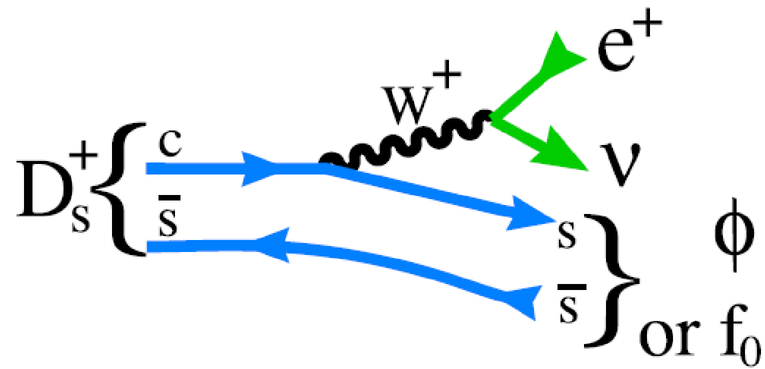
$$R'_{f/\varphi} = \frac{\Gamma\left(D_s \to f_0\pi^+; f_0 \to \pi^+\pi^-\right)}{\Gamma\left(D_s \to \phi\pi^+; \phi \to K^+K^-\right)} = (19 \pm 2)\%$$

There is more S-wave under f_o peak

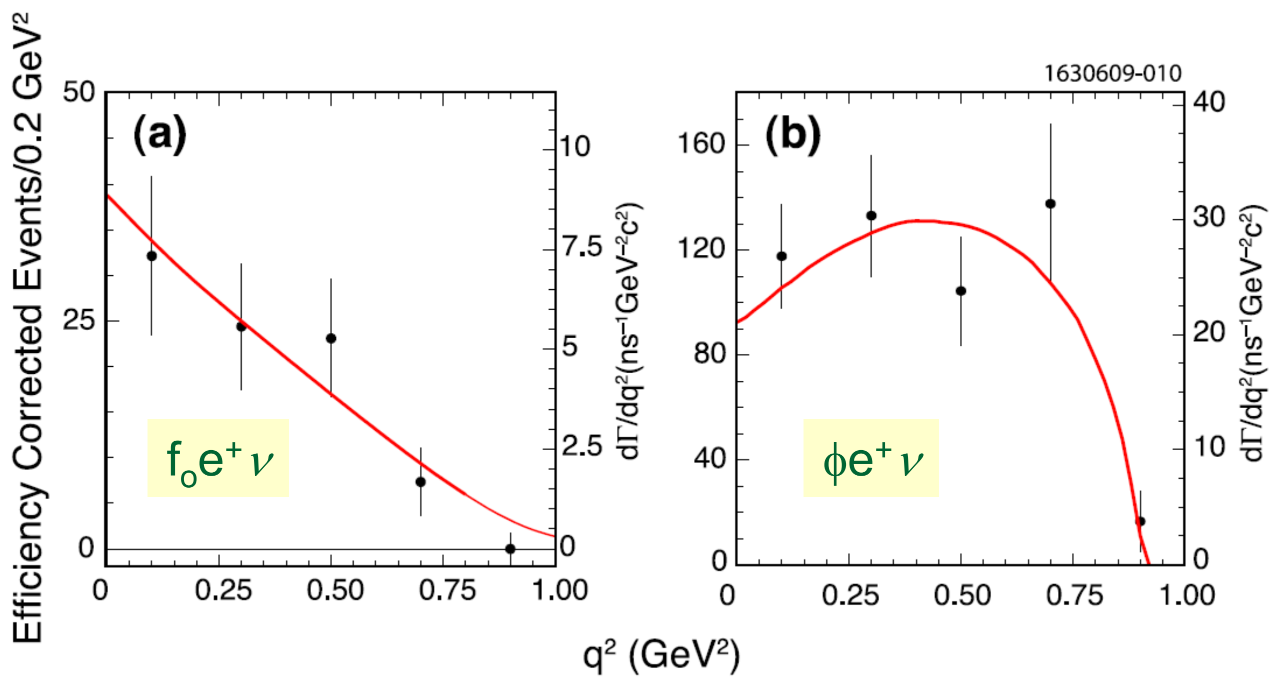
Estimate from $D_s \to (\phi/f_o)\ e^+\ \nu$

- Compare semileptonic rates near $q^2=0$ to get maximum phase space

  CLEO [arXiv:907.3201]



- $$\frac{d\Gamma}{dq^2}$$



Semileptonic estimate

- At q^2=0, where phase space is closest to $B_s \to J/\psi(\phi/f_o)$
- $$R_{f/\phi} \equiv \frac{\frac{d\Gamma}{dq^2}(D_s^+ \to f_0(980)e^+\nu,\ f_0 \to \pi^+\pi^-)\mid_{q^2=0}}{\frac{d\Gamma}{dq^2}(D_s^+ \to \phi e^+\nu,\ \phi \to K^+K^-)\mid_{q^2=0}} = (42 \pm 11)\%$$
- Note that at q^2=0 and in the case of $D_s \to \phi\pi$, the ϕ is forced into a longitudinal polarization state
- CDF measures only 53% ϕ_L, so these ratios may be too large by x2

Theory Estimates of $R_{f_0/\phi}$

- Colangelo, De Fazio & Wang [arXiv:1002.2880]
- Use Light Cone Sum Rules at leading order
- Prediction 1: Using measured $\mathcal{B}(J/\psi\ \phi)$= $(1.3\pm2.4)\times10^{-3}$
  - $\mathcal{B}(J/\psi f_o)=(3.1\pm2.4)\times10^{-4}$ (0th order), R=24%
  - $\mathcal{B}(J/\psi f_o)=(5.3\pm3.9)\times10^{-4}$ (leading order), R=41%
- Prediction 2: Using ff for ϕ from Ball & Zwicky [arXiv:hep-ph/0412079]

$$R_L = \frac{B(B_s \to J/\psi f_0)}{B(B_s \to J/\psi \phi_L)}$$

R_L =0.13±0.06 (0th order),

=0.22±0.10 1st order

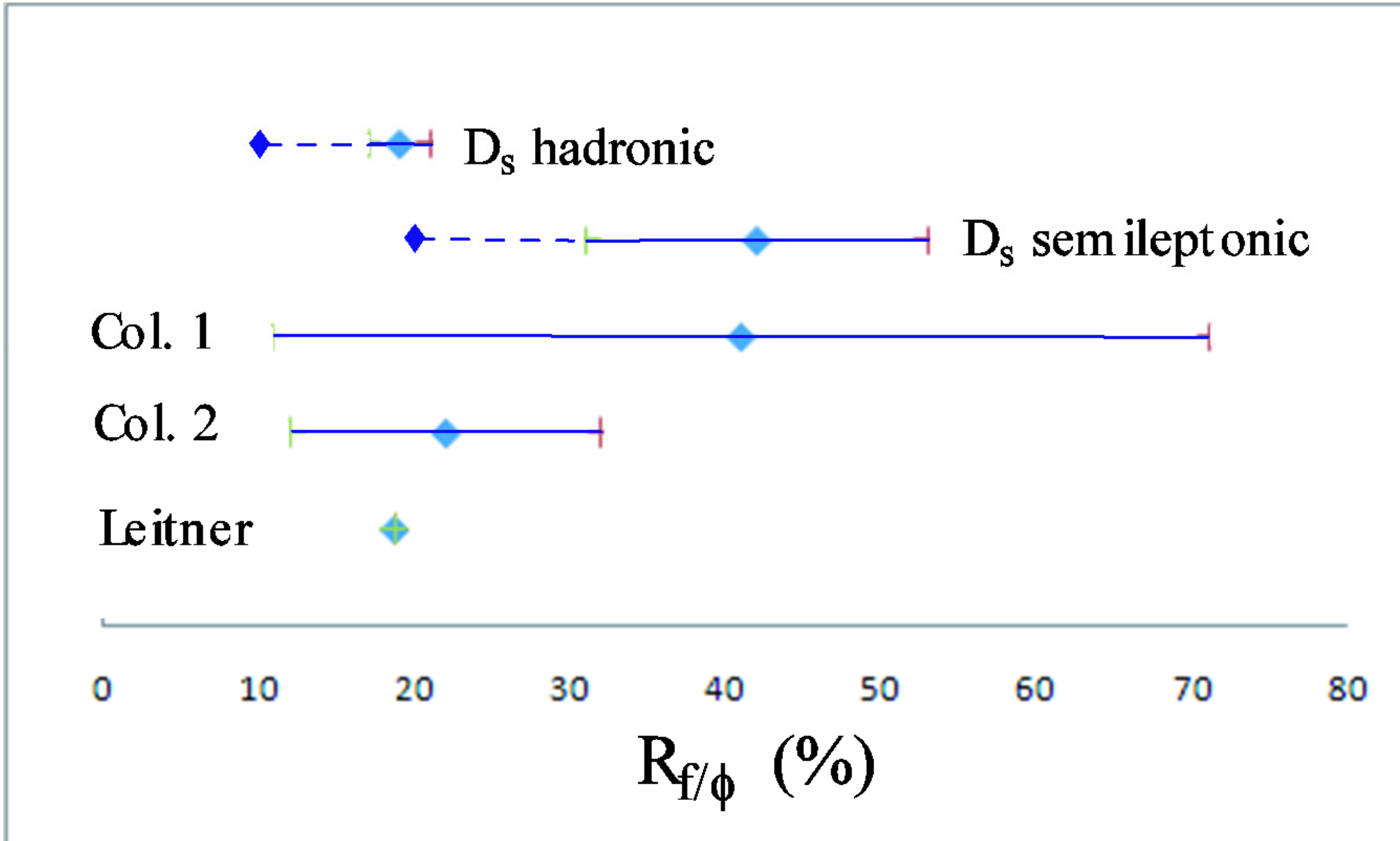
Check on Prediction

- Note that Colangelo et al predict
- $\mathcal{B}(D_s \to f_o e^+ \nu)$ = $\left(2.0^{+0.5}_{-0.4}\right) \text{x} 10^{-3}$,
- While CLEO measures
- $\mathcal{B}(D_s \to f_o e^+ \nu) = (4.0 \pm 0.6 \pm 0.6) \times 10^{-3}$,
- Which implies that the calculated form-factor is low by a factor of 2, thus compensating for $\Gamma\phi_L/\Gamma_{total} = 0.53$

QCD Factorization

- O. Leitner etal [arXiv:1003.5980]
  - Assume f_{Bs} = 260 MeV, f_{fo} = 380 MeV
- Predict $\mathcal{B}(B_s \rightarrow J/\psi\ f_o) = 1.70 \times 10^{-4}$.
- $\mathcal{B}(B_s \rightarrow J/\psi\ \phi) = 9.30 \times 10^{-4}$.
- $R_{fo/\phi}$ = 0.187. They show small variation with $B_s \rightarrow f_o$ form factor; "annihilation" effects important and decrease f_o rate.
- "S-wave kaons or pions under the ϕ peak in $J/\psi\phi$ are very likely to originate from the similar decay $J/\psi f_o$. Therefore, the extraction of the mixing phase from $J/\psi\phi$ may well be biased by this S-wave effect which should be taken into account in experimental analysis"

Summary of R estimates

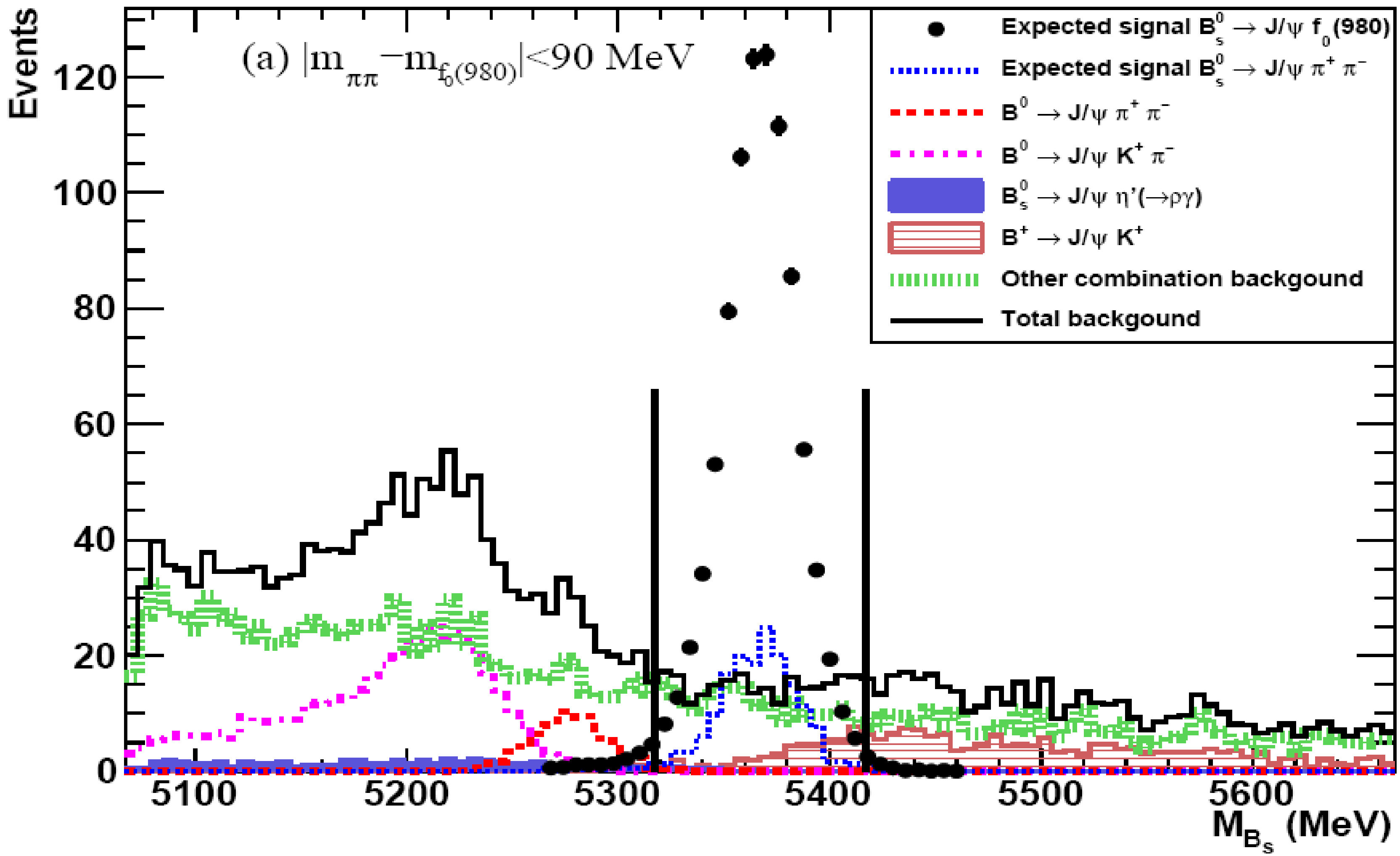


- Measurement will constrain theories

β_s Sensitivity Using $J/\psi\ f_o$

- From Stone & Zhang [arXiv:0909.5442] for LHCb
- Assume $R_{fo/\phi} = 25\%$
- Assume 2 fb^{-1} at 14 TeV (~4 fb^{-1} at 7 TeV)
- Error in $-2\beta_s$
  - $J/\psi\ \phi$: ± 0.03 rad (not including S-wave)
  - $J/\psi\ f_o$, $f_o \rightarrow \pi^+\pi^-$: ± 0.05 rad
  - $J/\psi\ f_o + J/\psi\ \eta'$, $\eta' \rightarrow \pi^+\pi^-\gamma$: ± 0.044 rad
- The f_o mode should be useful

$B_s \to J/\psi f_o$ Signal Selection



Conclusions

- S-waves are ubiquitous, they appear whenever looked for, & must be taken into account in $B_s \rightarrow J/\psi\ \phi$ measurements of amplitudes, phases, & CP violation
- In addition, it would be prudent to add S-wave amplitudes in the analysis of $B \rightarrow K^* \mu^+ \mu^-$ & surely in $B_s \rightarrow \phi\phi$
- $B_s \rightarrow J/\psi\ f_o$ will add to the statistical precision on the measurement of $-2\beta_s$, & hopefully will provide useful checks since angular measurements are not necessary