Y(5S) Running: Goals, & What has been learned

Title II: Case for Y(5S) Running

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What We Hope to Learn

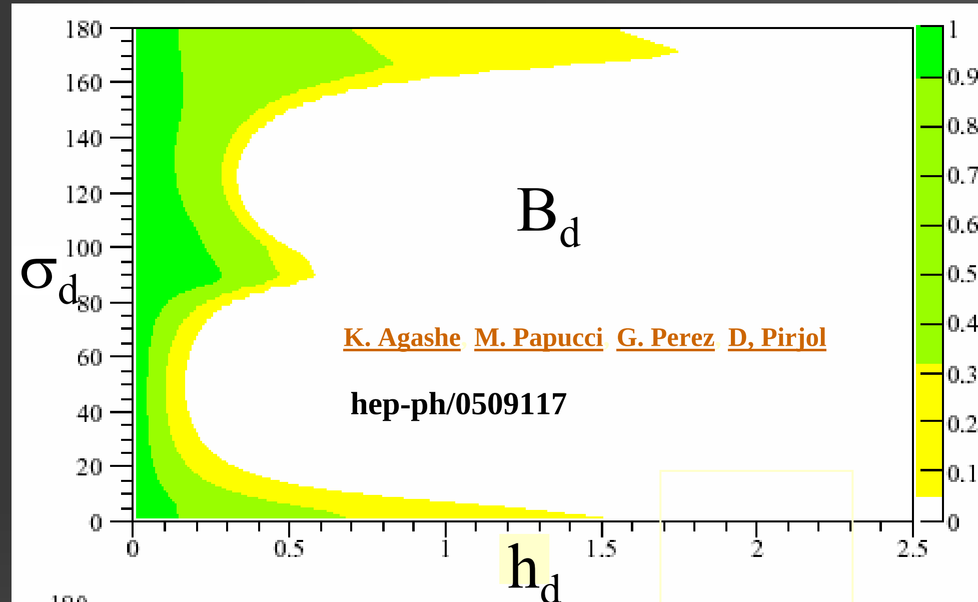
- Nature of Υ(5S)
  - One mystery: M(5S)-M(4S) > M(4S)-M(3S)
  - Suggestions of exotic states – Υ(5S) mixed with $b\bar{b}g$ state. (Ono, Sanda & Tornqvist, PRD 34, 186 1986)
  - Also for charm: $\psi(4030) = \frac{1}{\sqrt{2}}\left[(c\bar{c})_{3S} + c\bar{c}g\right], \quad \psi(4160) = \frac{1}{\sqrt{2}}\left[(c\bar{c})_{3S} - c\bar{c}g\right]$
  - What is produced- some answers already
- B_S Physics
  - Use B_S decays to interpret New Physics found directly at the LHC

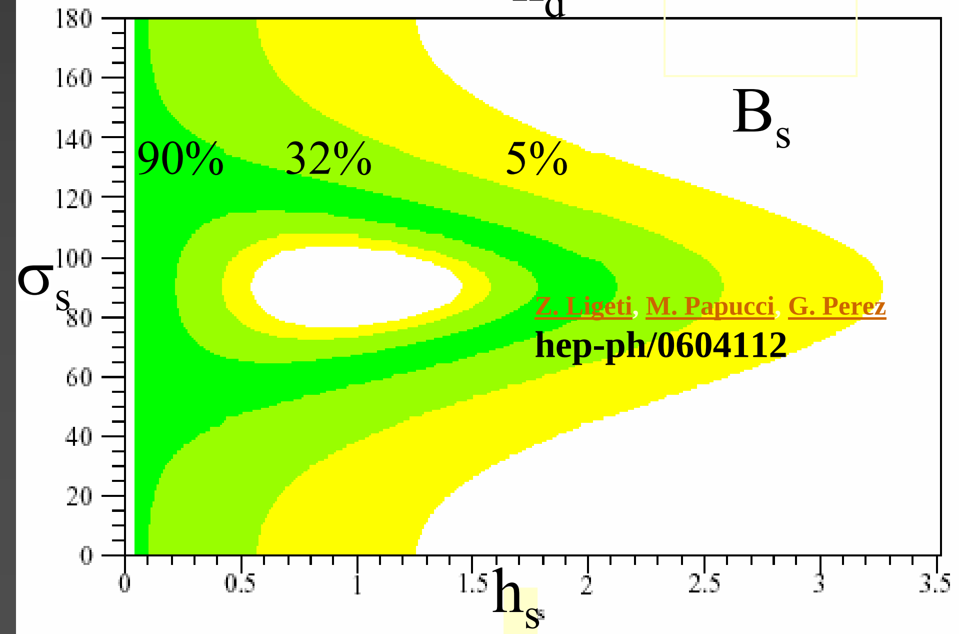
Limits on New Physics (NMFV)

- Assume NP in tree decays is negligible
- Use V_{ub}, A_{DK}, $S_{\psi K}$, $S_{\rho\rho}$, Δm_d, A_{SL}, fit to η, ρ, h_d, σ_d
- Parameterize as

$$1+he^{i\sigma}=\frac{\langle B^0_{d,s}|H^{full}|\bar{B}^0_{d,s}\rangle}{\langle B^0_{d,s}|H^{SM}|\bar{B}^0_{d,s}\rangle}$$

- Limit regions of NP via neutral B mixing
- For B_s use $\Delta m_d/\Delta m_s$ measurement





Some Definitions for B_S decays

- CP eigenstates

$$\left|B_s^{Even}(t)\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_S(t)\right\rangle - \left|\bar{B}_S(t)\right\rangle\right), \quad \left|B_s^{Odd}(t)\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_S(t)\right\rangle + \left|\bar{B}_S(t)\right\rangle\right)$$

- With a time evolution

$$\frac{d}{dt}\begin{pmatrix} \left|B_S(t)\right\rangle \\ \left|\bar{B}_S(t)\right\rangle \end{pmatrix} = \left(\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}\right)\begin{pmatrix} \left|B_S(t)\right\rangle \\ \left|\bar{B}_S(t)\right\rangle \end{pmatrix}$$

- Expect Γ_{12} to driven by SM tree level decays, mostly $B_S \rightarrow c\bar{c}s$, $D_S^{+(*)} D_S^{-(*)}$, $J/\psi\ \eta$….
- CP phase ~arg(M_{12}) is very small in SM, arg$(V_{tb}V_{ts}^*)^2$, so can easily show NP effects
- As usual, mass eigenstates are given by

$$\left|B_L(t)\right\rangle = p\left|B_S(t)\right\rangle + q\left|\bar{B}_S(t)\right\rangle, \quad \left|B_H(t)\right\rangle = p\left|B_S(t)\right\rangle - q\left|\bar{B}_S(t)\right\rangle$$

More Definitions

- $\Gamma = 1/\tau = (1/2)(\Gamma_H + \Gamma_L)$, $\Delta m = M_H - M_L$, $\Delta\Gamma = \Gamma_L - \Gamma_H$
- $\Delta m = 2|M_{12}|$, $\Delta\Gamma = 2|\Gamma_{12}|\cos\phi$, where

$$\frac{M_{12}}{\Gamma_{12}} = -\left|\frac{M_{12}}{\Gamma_{12}}\right| e^{i\phi}$$

- ϕ is very small in SM, $\sim\lambda^2\eta = 0.017$
- See Dunietz, Fleischer & Nierste [hep-ph/0012219]

CP Violation in B_S Mixing

- Lets consider the decay rate for a B_S to a CP eigenstate state f_{CP}

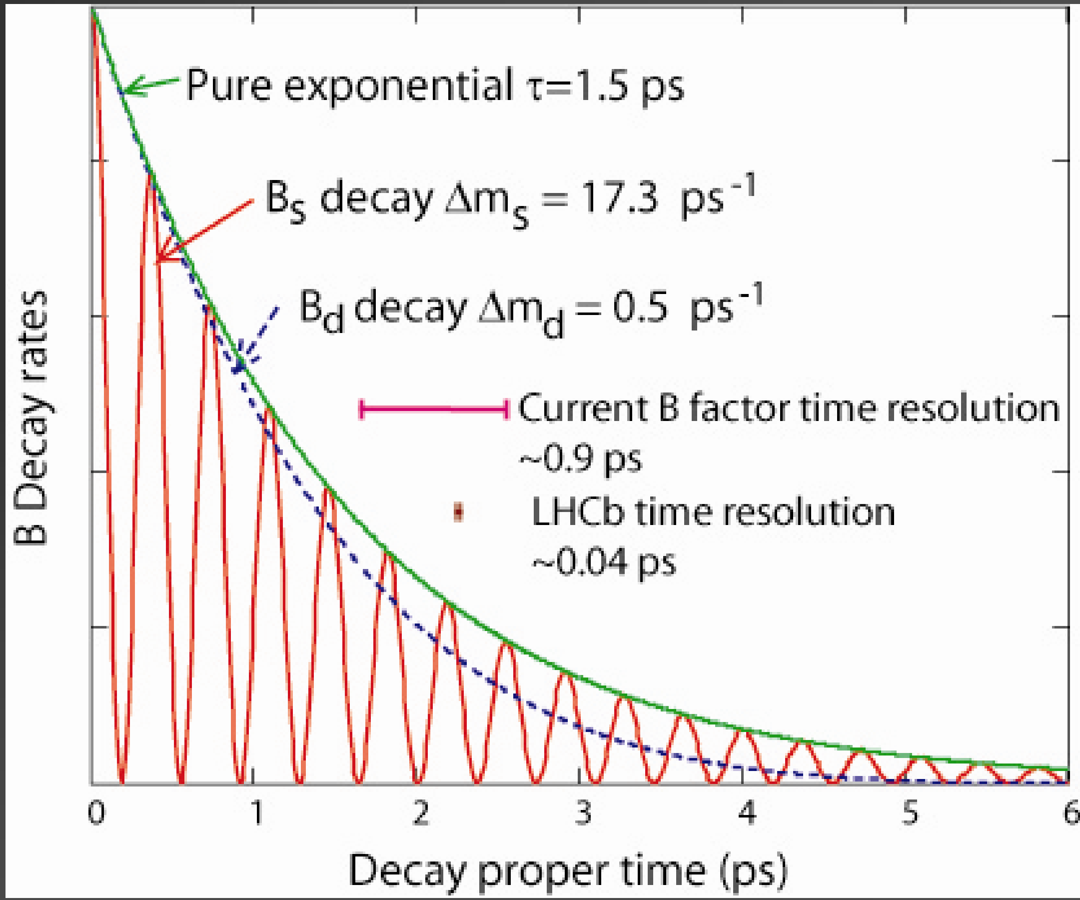
$$\Gamma(B_s(t) \to f_{CP}) \propto e^{-\Gamma_{CP}t}\left[\cosh\frac{\Delta\Gamma}{2}t - \eta_f \cos\phi \sinh\frac{\Delta\Gamma}{2}t + \eta_f \sin\phi \sin(\Delta m t)\right]$$

- η_f is + for CP+, - for CP -
- Measuring these rates requires good time resolution and flavor tagging to distinguish B_S from $\bar{B}_S$
- Alternatively, even with poor time resolution determining $\Delta\Gamma$ gives us a handle on CPV via the $\cos\phi$ term, after summing B_S & $\bar{B}_S$

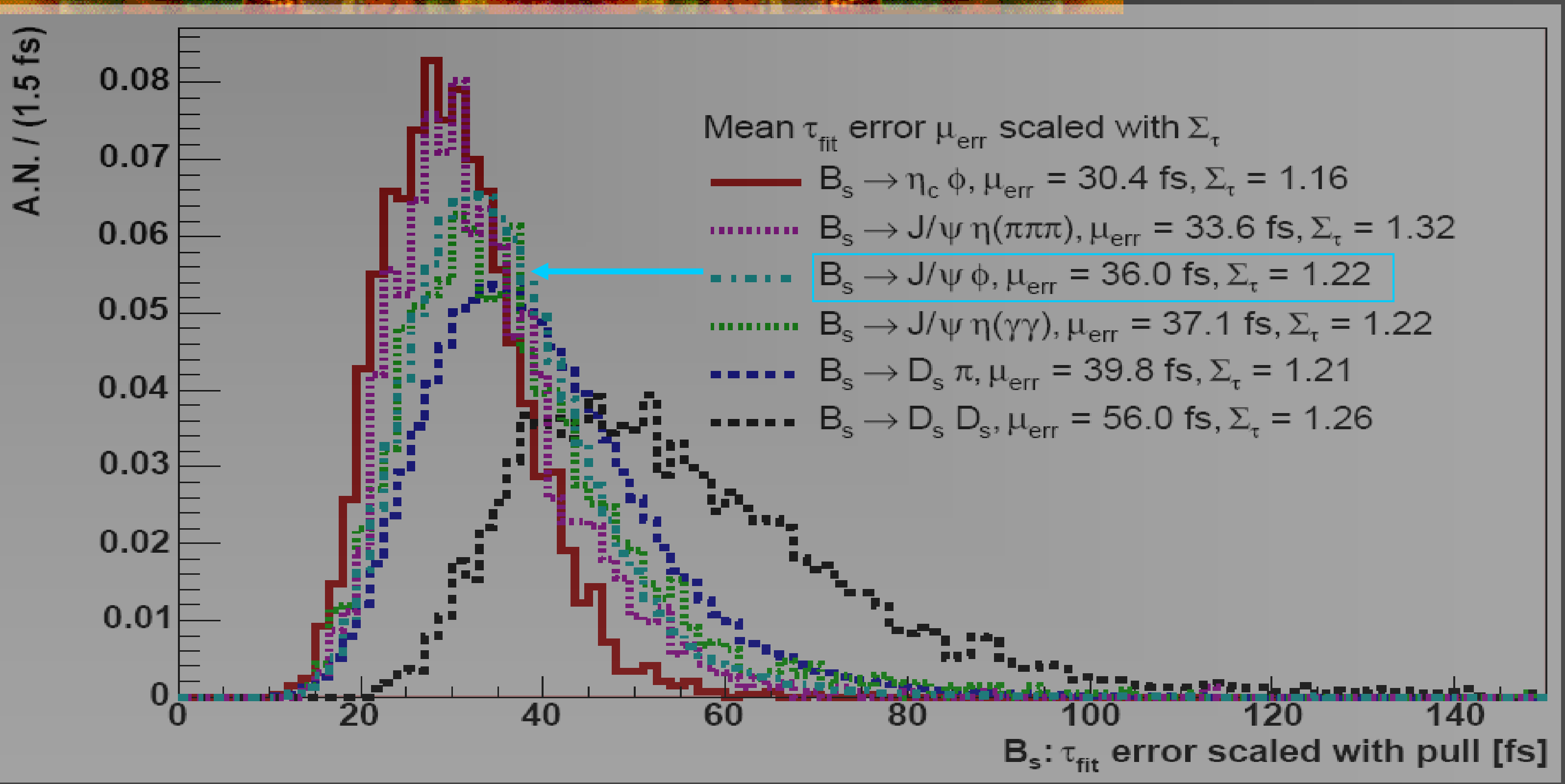
B_S Oscillation times

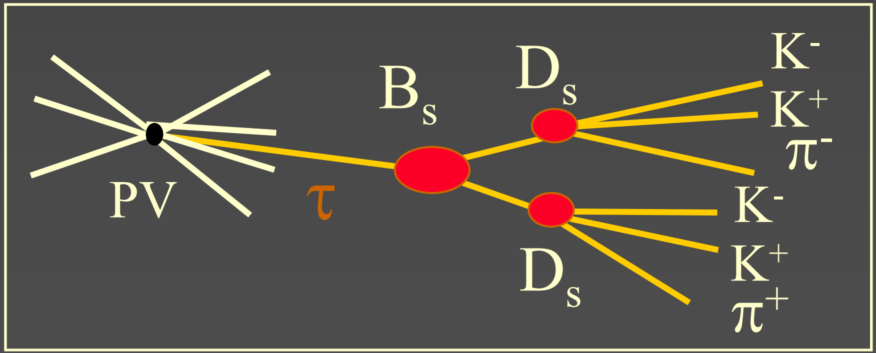
- Time dependent asymmetries in B_S decays are modulated

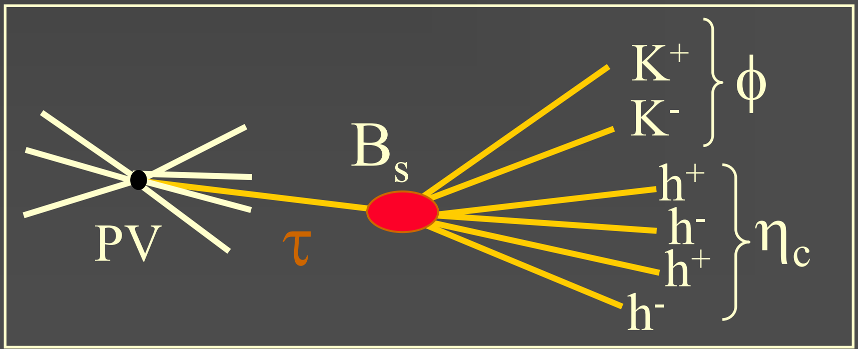
  $\Delta m_S = 17.3^{+0.33}_{-0.18} \pm 0.07$ ps^{-1} (CDF [hep-ex/0606027])
- Means B_S oscillations are really fast
- B factories cannot measure time dependent CP violation at the Y(5S)– this is the territory of LHCb



LHCb Proper Time Resolution







Untagged B_S Decays

- If we sum over B_S & $\bar{B}_S$ for a mixed CP state, such as $D_S^+\pi^-$, we have

$$\frac{1}{2}\left[\Gamma(f,t)+\Gamma(\bar{f},t)\right]=\Gamma_f \propto \exp\left(-\Gamma_L t\right)+\exp\left(-\Gamma_H t\right)$$

$$\propto 2\exp\left(-\Gamma t\right)\cosh\frac{\Delta\Gamma t}{2}$$

$$\Gamma_f \approx \Gamma - \frac{\left(\Delta\Gamma\right)^2}{2\Gamma}$$

- Where $\Gamma_f = (1/2)(\Gamma_H + \Gamma_L)$, $\Delta\Gamma = \Gamma_L - \Gamma_H$
- We can measure Γ_f, & Γ_H and possibly Γ_L (fewer states) & therefore $\Delta\Gamma$

New Physics in $\Delta\Gamma$

- $\Delta\Gamma_{SM}$ due to SM physics can be measured by summing up the common channels for B_S & $\overline{B}_S$ for the difference between CP+ and CP- states.
- $2B(B_S \rightarrow CP+ - B_S \rightarrow CP-) = \Delta\Gamma_{SM}/\Gamma$
- Thus it is necessary to measure the *B* for $D_S^{(*)+}D_S^{(*)-}$, $J/\psi\ \eta$, $J/\psi\ \phi$, and their angular distributions
- Estimates or Measurements of $\Delta\Gamma$
  - ~10% $\Delta\Gamma$, based on $B(B \rightarrow DD_S)$
  - D0: 0.15±0.10±0.04 & CDF: $0.47^{+0.19}_{-0.24} \pm 0.01$, not yet meaningful
- These exclusive modes could be measured by a B-factory. See A. Drutskoy [hep-ph/0604061]
- If there is a new physics phase then $\Delta\Gamma = \Delta\Gamma_{SM} \cos\phi$; many
- of these modes are difficult to measure in LHCb, because of the γ from the D_S^* decay

Rare Exclusive Branching Ratios

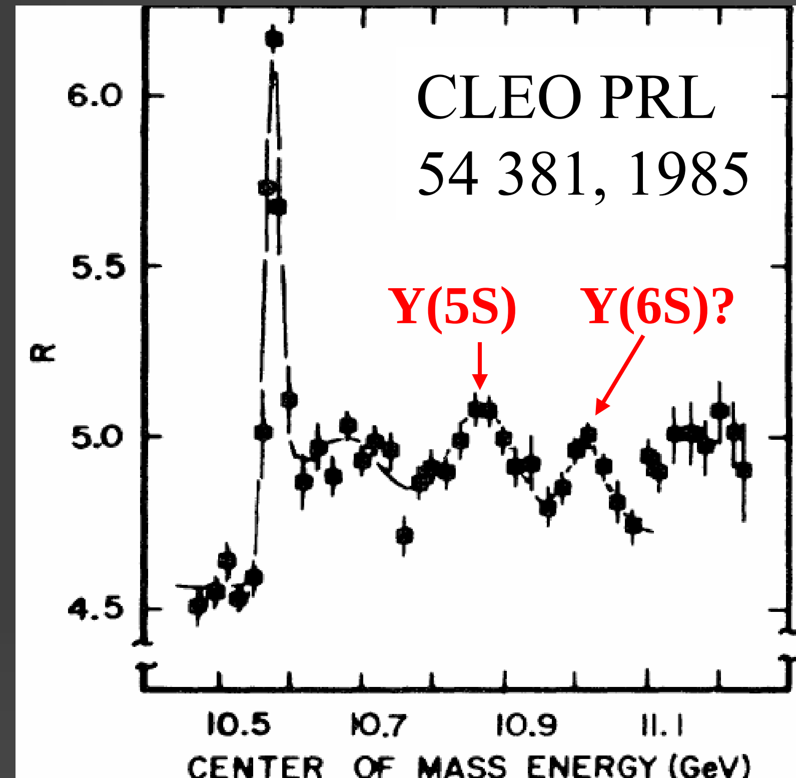
- LHCb will have trouble with modes with more than one γ or π^o, e.g. $B_S \rightarrow \phi\gamma$ is doable, as is $\phi\phi$, and also $\phi\eta$, but not $\eta\eta$
- Key modes include
  - $\phi\gamma$, and $K^* \gamma$
  - $\phi\mu^+\mu^-$
  - $\phi\phi$, and also $\phi\eta$

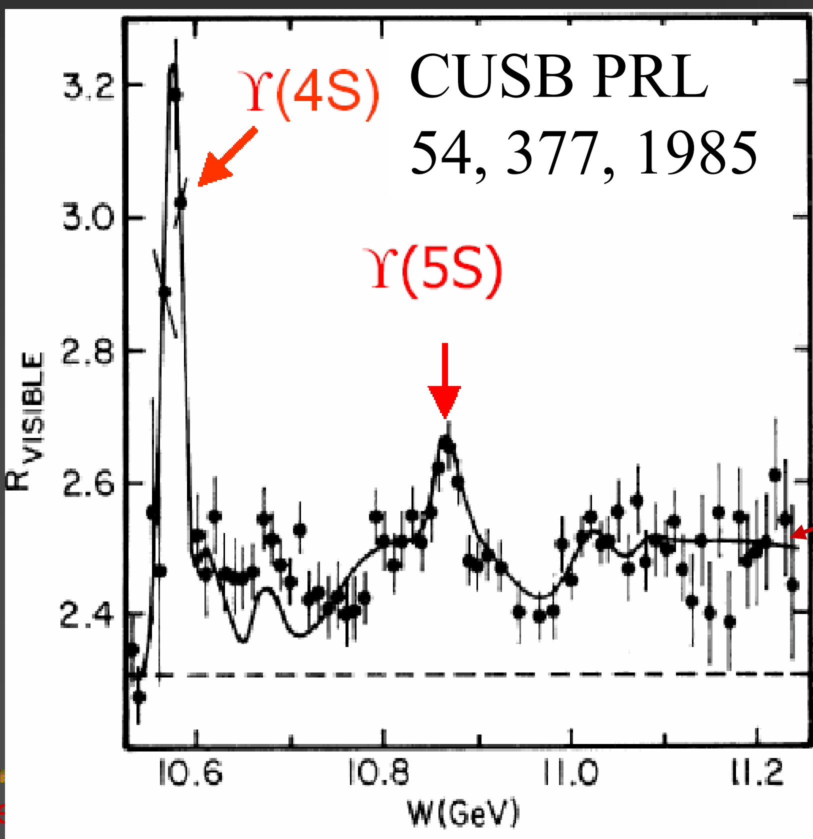
B & B_s Production at the $\Upsilon(5S)$

- Brief History
- Cross Section Measurements
- Model dependent B_s fractions f_s
- Methods for model independent f_s

Y(5S) Brief History

- CLEO & CUSB scan in 1985 0.07 fb^{-1} & 0.12 fb^{-1} taken on peak





•CUSB fit to modified potential model

•Almost nothing else learned

Cross-Section Measurements

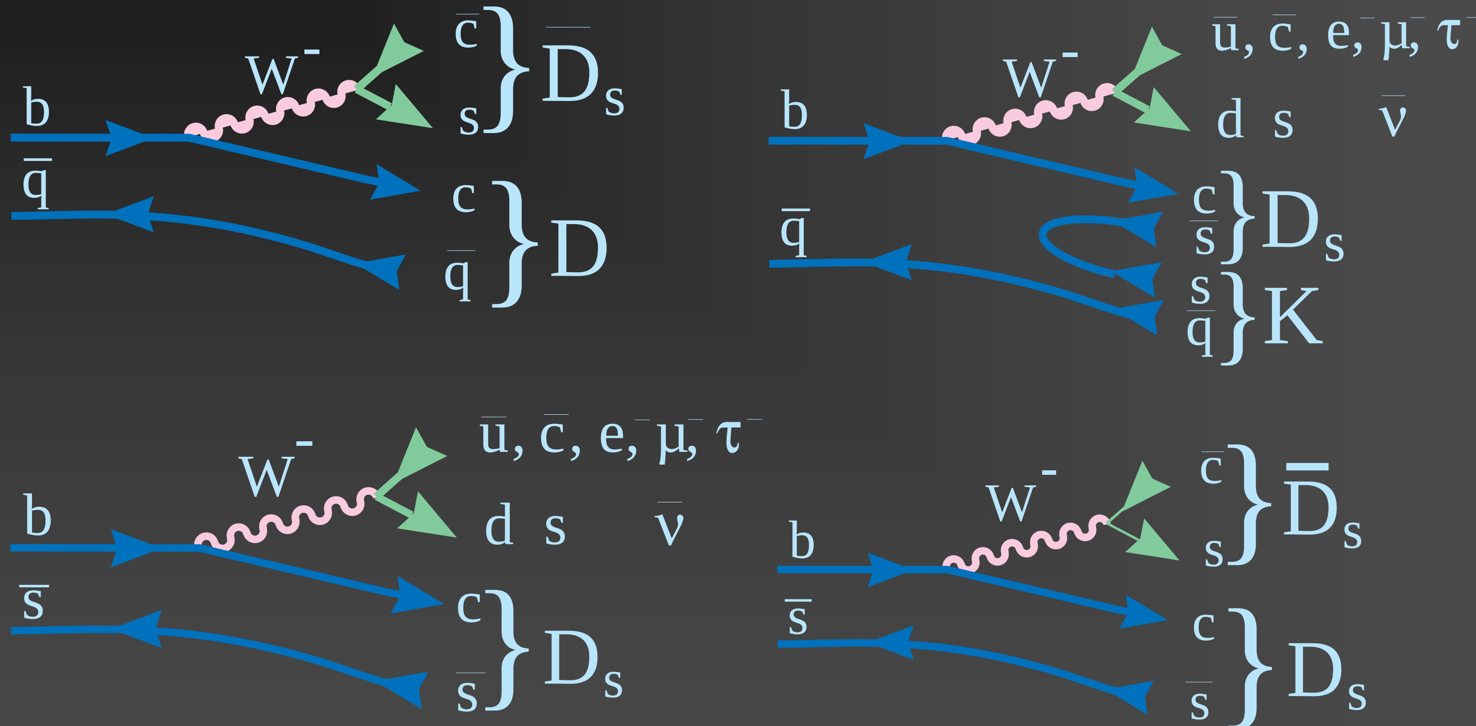
- New Data
  - CLEO III 2003 0.42 fb^{-1} at 10881 MeV
  - BELLE 2005 1.86 fb^{-1} at 10869 MeV
- This is a bit nasty since continuum data is taken almost 300 MeV in CME below & is usually taken at different times. So the continuum subtraction becomes a significant systematic error
  - CLEO: 0.301±0.002±0.039 nb (checked using # of tracks 0.8>x>0.6)
  - BELLE: 0.305±0.002±0.0016 nb (checked using J/ψ rate, assuming it's the same for B & B_S)
  - Remarkable agreement, ΔR~0.4

Model Dependent B_S Fractions, f_S

- Possible Y(5S) decay modes
  - $Y(5S) \rightarrow B_S^{(*)}\bar{B}_S^{(*)}$
  - $Y(5S) \rightarrow B^{(*)}\bar{B}^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$, $B\bar{B}\pi\pi$
  - Something else? Non-$b\bar{b}$ decays….
- Method: Choose a particle that has very different decay rates from B & B_S
  - Ex: D_S
  - $\mathcal{B}(Y(5S) \rightarrow D_S\ X)/2 = f_S \mathcal{B}(B_S \rightarrow D_S\ X) +$
    $(1-f_S)\ \mathcal{B}(Y(4S) \rightarrow D_S\ X)/2$
  - Need to get $\mathcal{B}(B_S \rightarrow D_S\ X)$ from theory

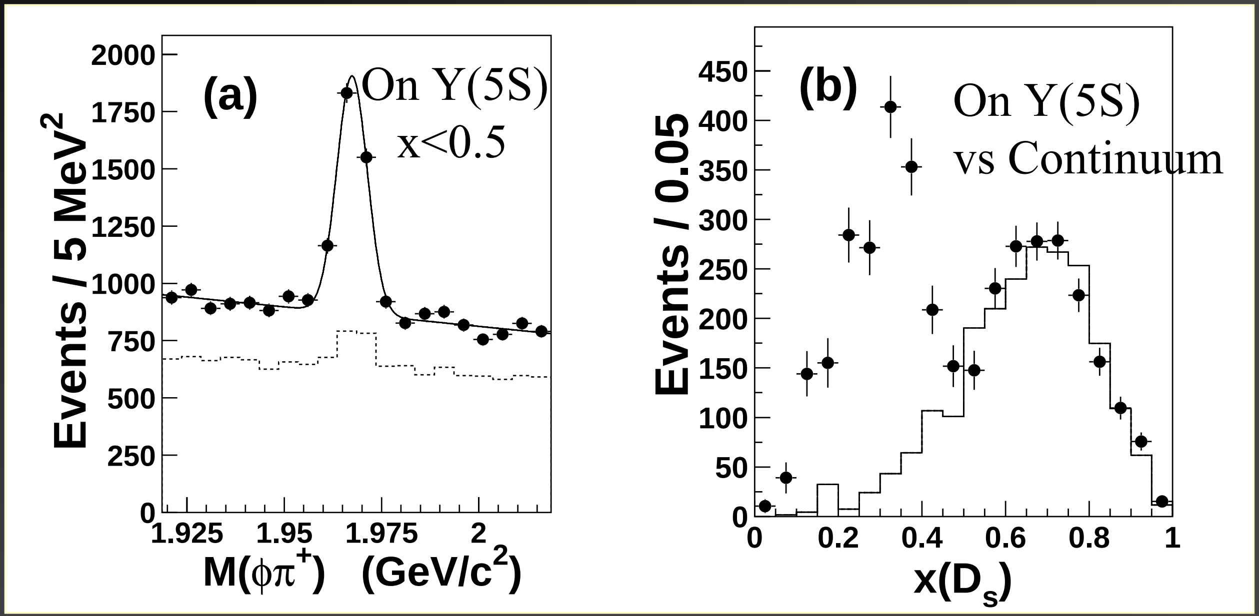
Model of D_S Production

- Must assume knowledge of $B(B_S \to D_S X)$



- Account for fragmentation that reduces D_S rate from B_S, CLEO & BELLE use same model $B(B_S \to D_S X) = (92 \pm 11)\%$

Measurements of f_s Using D_s Yields



Belle Y(5S) vs Continuum

- Now use $\mathcal{B}(D_S \rightarrow \phi\pi) = (3.5\pm0.4)\%$ See [hep-ph/0605134]
- CLEO D_S: $f_S = (21.8\pm3.5^{+8.5}_{-4.2})\%$ PRL **96**, 022002 (2006)
- BELLE D_S : $f_S = (21.2\pm1.8\pm5.5)\%$ hep-ex/0605110

Measurement of f_s Using ϕ Yields

- Here we need $\mathcal{B}(B_s \rightarrow \phi X)$
- Use CLEO-c inclusive yields for

  $\mathcal{B}(D^o \rightarrow \phi X)=(1.0\pm0.10\pm0.10)\%$

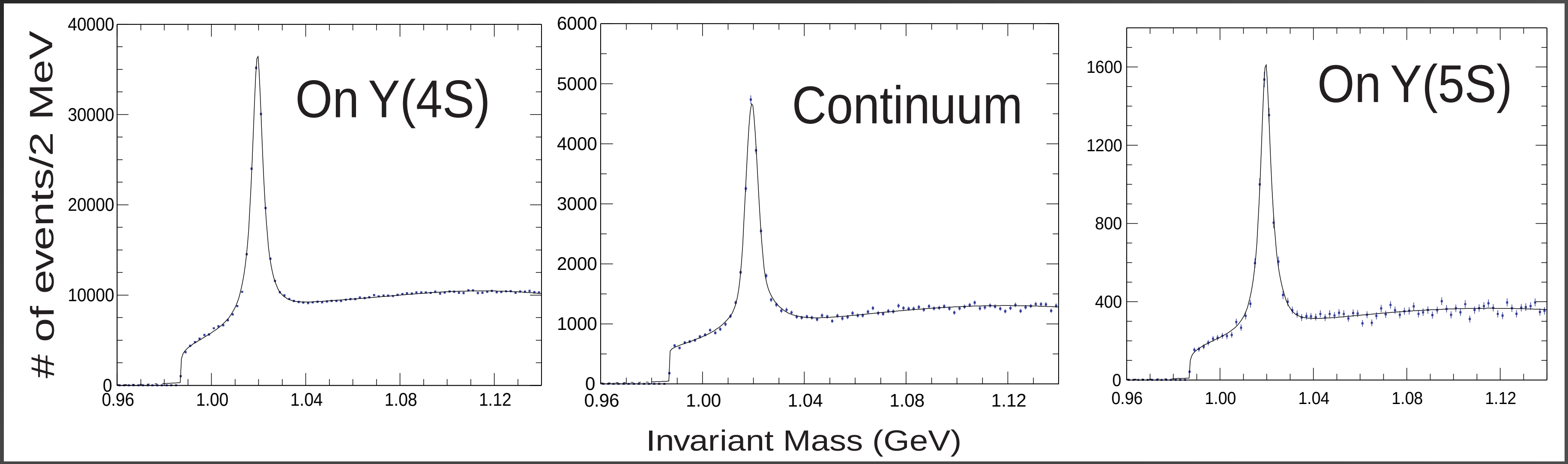
  $\mathcal{B}(D^+ \rightarrow \phi X)=(1.0\pm0.10\pm0.20)\%$

  $\mathcal{B}(D_s \rightarrow \phi X)=(15.1\pm2.1\pm1.5)\%$

  Preliminary [hep-ph/0605134]
- From $\mathcal{B}(B \rightarrow \phi X)=(3.5\pm0.3)\%$, ascertain that most of ϕ's arise from $B \rightarrow D$ & $D_s \rightarrow \phi$
- Predict that $\mathcal{B}(B_s \rightarrow \phi X)=(14.9\pm2.9)\%$

Measurement of f_s Using ϕ Yields -data

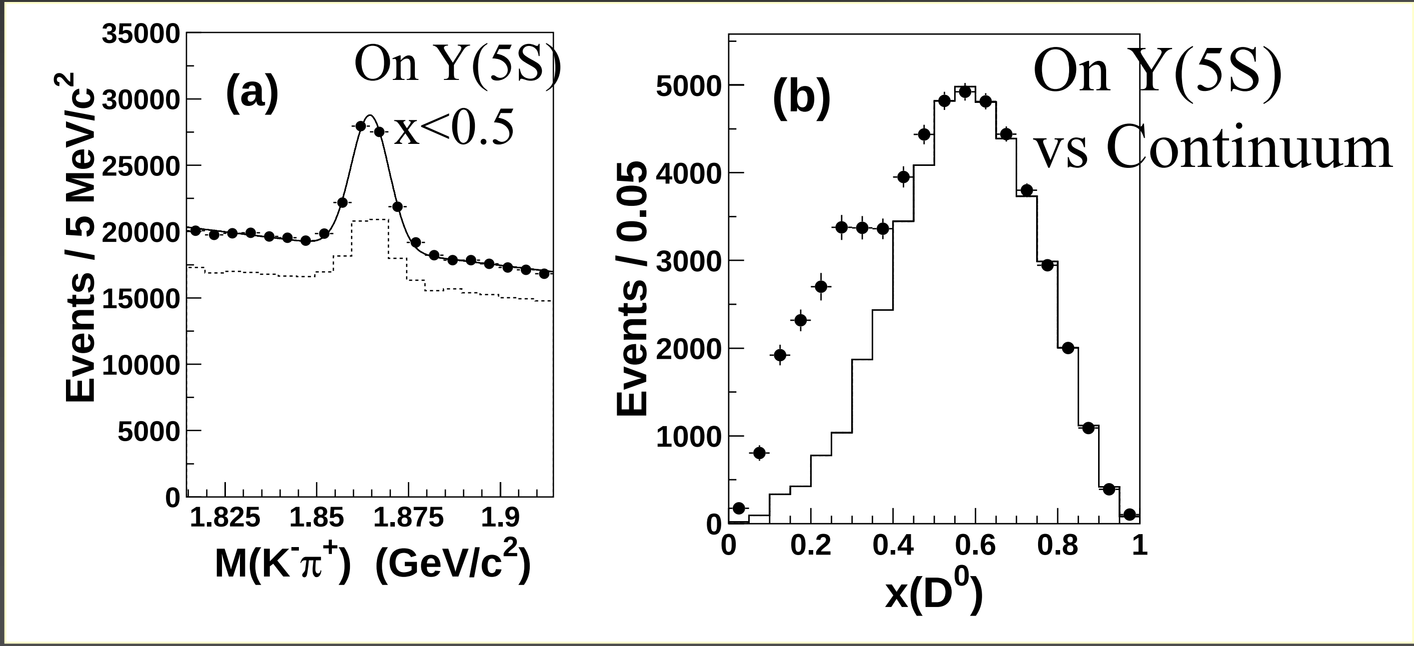
- CLEO inclusive ϕ yields, for $x<0.5$, $R_2<0.25$



- $f_S = (27.5 \pm 3.2^{+14.6}_{-6.1})\%$

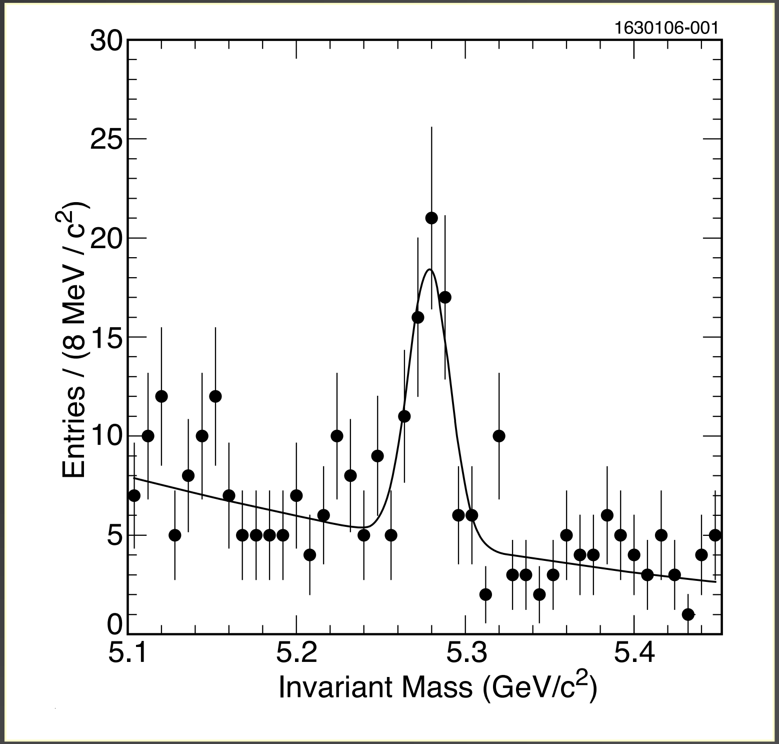
Measurement of f_s Using D° Yields

- Same model of B & B_s decay, predicts $\mathcal{B}(B_s \to D^o X) = (8\pm7)\%$
- BELLE D° : $f_s = (18.7\pm3.6\pm6.7)\%$ hep-ex/0605110



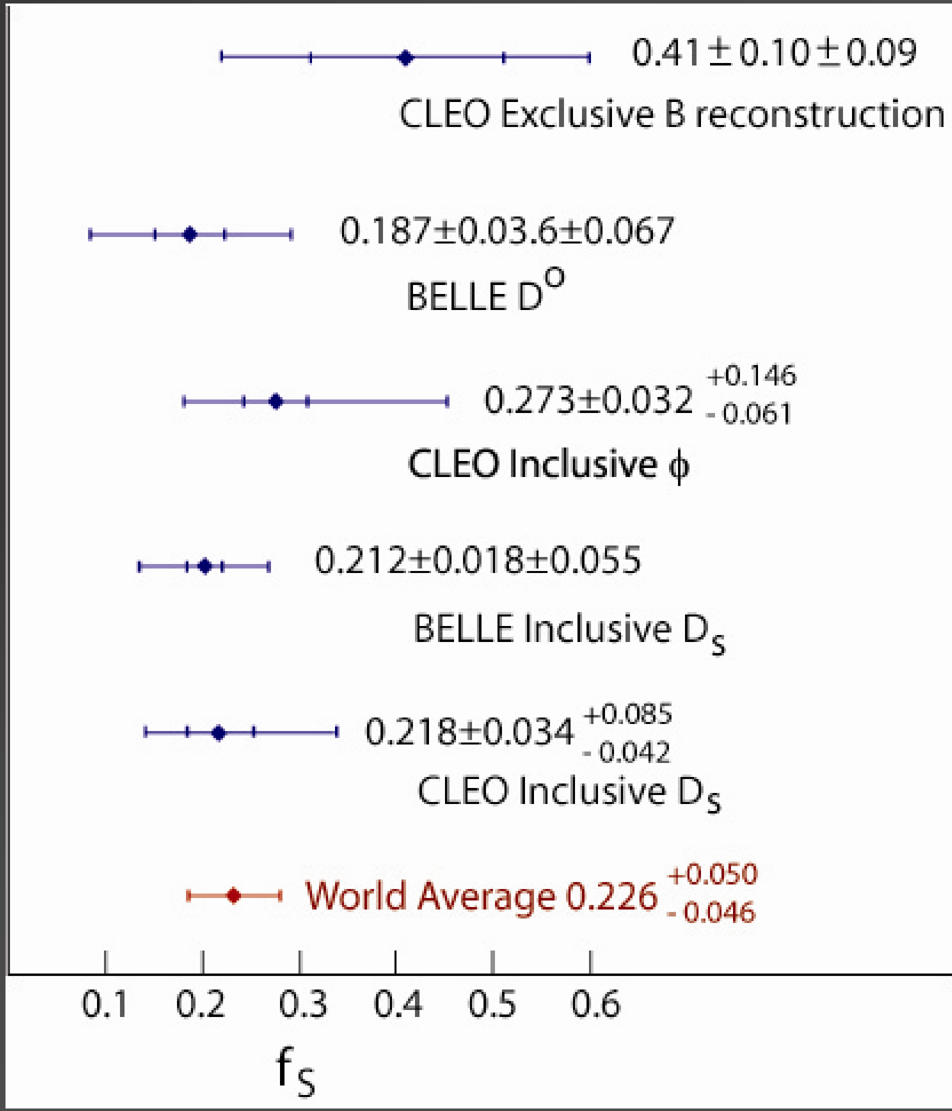
Other Methods

- CLEO: Measure B meson yield
- Use $B \rightarrow D^{(*)}(\pi \text{ or } \rho)$,
  $B \rightarrow J/\psi\ K(*)$
- Total of 53±9 events
- σ=0.177±0.030±0.016 nb,
- Translates to f_S=0.41±0.10±0.10



Summary of f_s Measurements

- Plot shows statistical & systematic errors added linearly
- Average takes into account the correlated systematic errors on Y(5S) cross-section
- Recall, model dependences

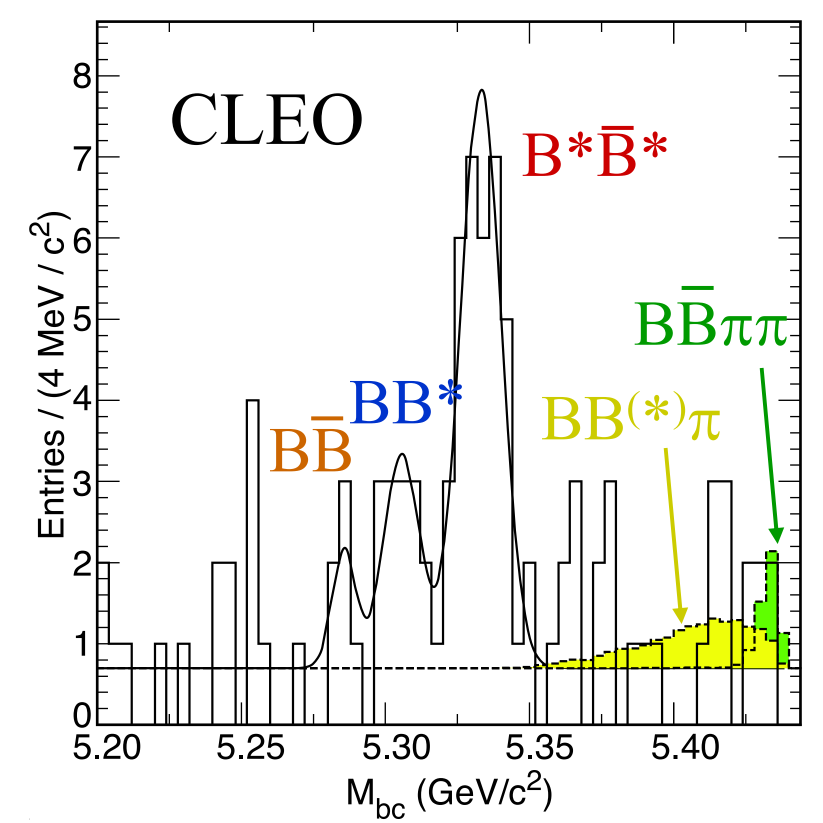


Model Independent Methods for f_s

- Use complete B_S mixing by measuring the ratio of like-sign dilepton events to opposite sign events. (A similar idea is used for finding the B_S production rate at hadron colliders, but with larger errors.)
- Count the number of events with single, double, triple and possibly quadruple D_S mesons
- (See R. Sia & S. Stone [hep-ph/0604201])

Other Υ(5S) Measurements

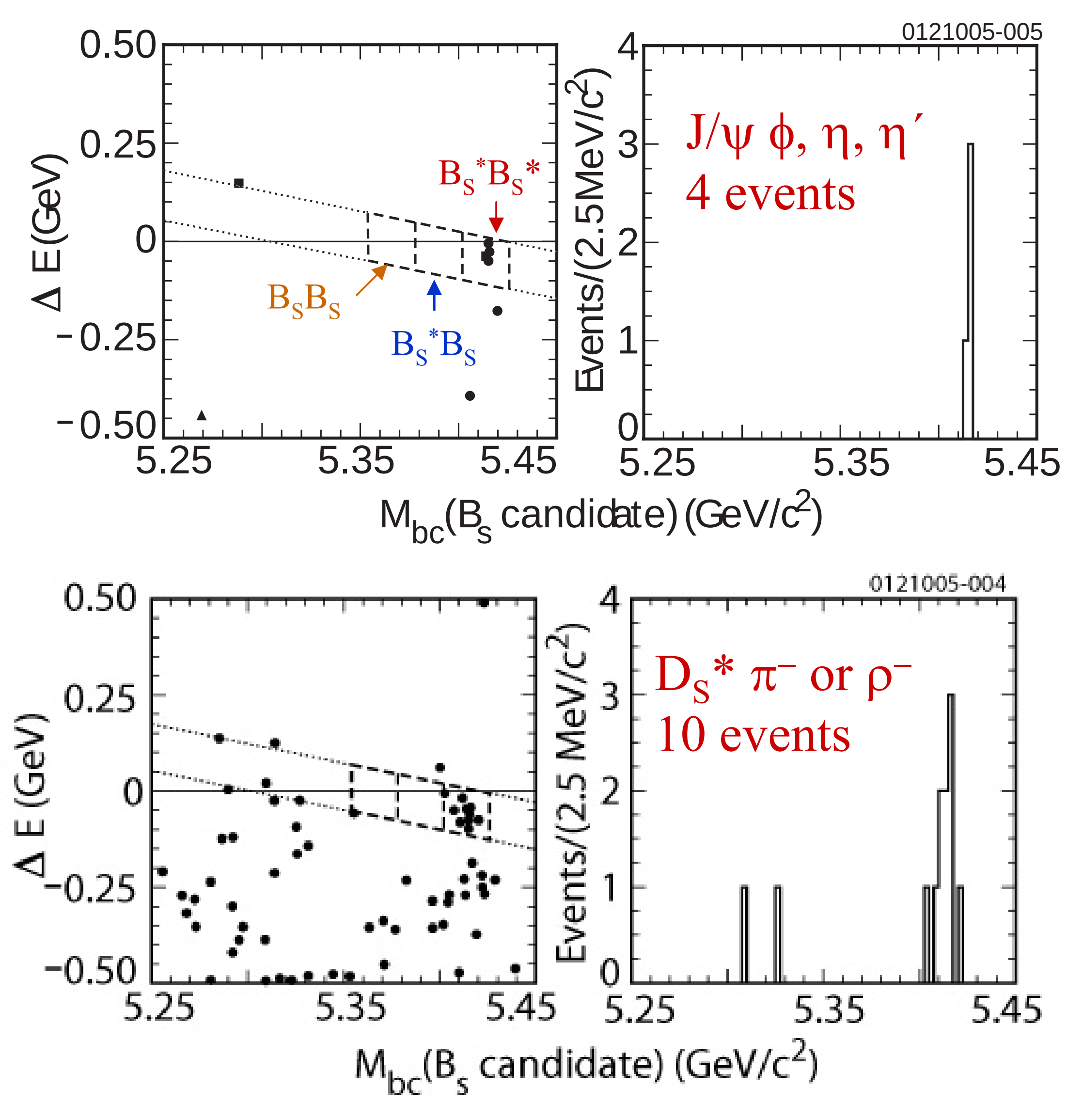
- Compared to Υ(4S) there is very little to report
- Production largest for $B^*\bar{B}^*$, consistent with models
  - $B\bar{B}/B^*\bar{B}^*$ < 22% @ 90% cl
  - $BB^*/B^*\bar{B}^*$ = (24±9±3)%
- B_S* mass
  - $M(B_S^*)-M(B^*)$=(87.6±1.6±0.2) MeV
  - $M(B_S^*)-M(B_S)$=(45.7±1.7±0.7) MeV consistent as expected from Heavy Quark Symm. with $M(B^*)-M(B)$ =45.78±0.35 MeV



Beam constrained mass with Suitable cuts on ΔE

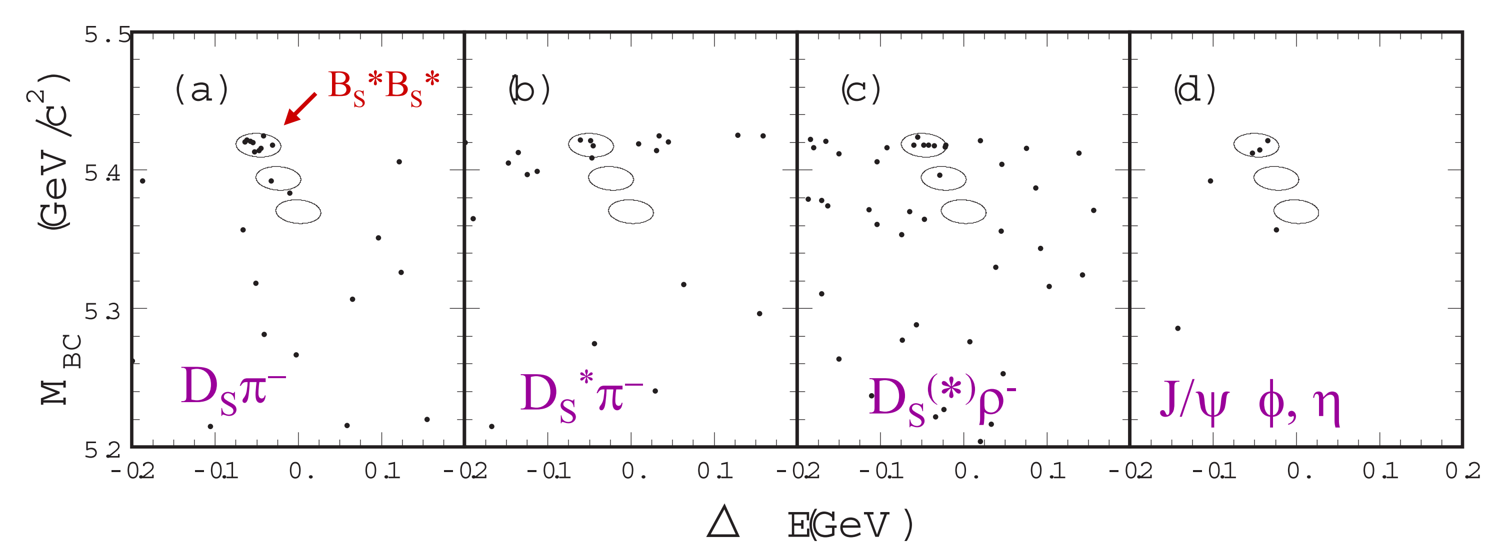
Exclusive B_S decays from CLEO

- All candidates are in the $B_S^* \bar{B}_S^*$ final state
  - $B_S B_S^* / B_S^* \bar{B}_S^*$ <0.16 @ 90% cl
  - $B_S \bar{B}_S / B_S^* \bar{B}_S^*$ <0.16 @ 90% cl
- For D_S decay modes use $\phi\pi$, $K^{*o}K^+$ & $K^o K^+$



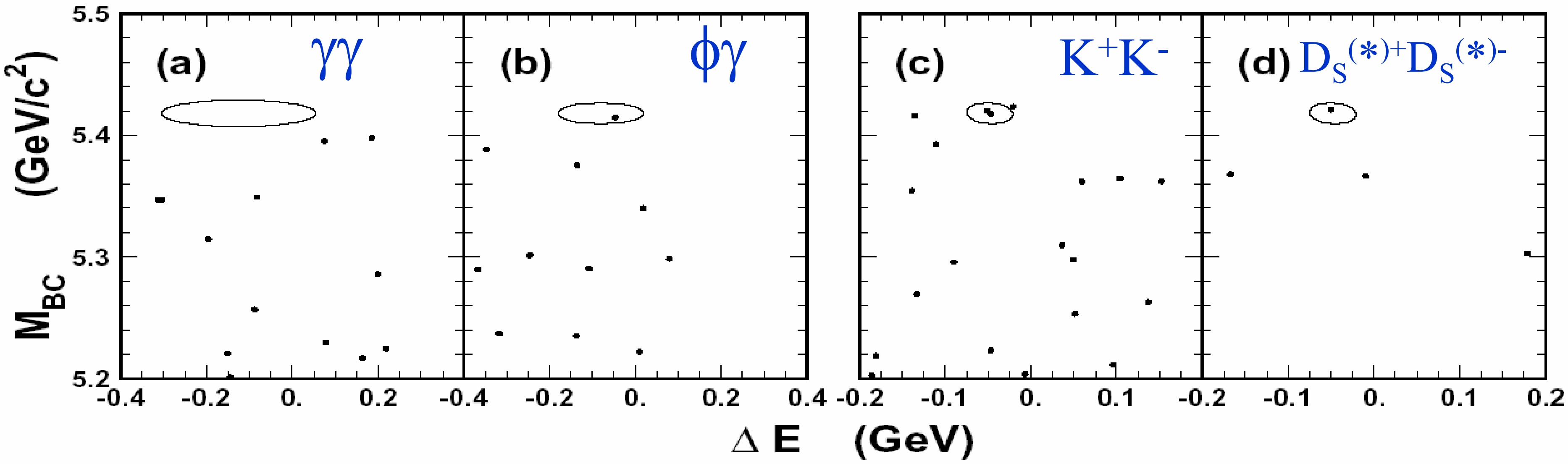
Exclusive B_S decays from Belle

- Most events also $B_S^*\bar{B}_S^*$



- $B_S^*\bar{B}_S^*$/all B_S= $(94^{+6}_{-9})\%$
- Total of 20±5 events
- Note that CLEO has 33±9 events/fb^{-1}, while Belle has 11±3 events/fb^{-1}, is CLEO more efficient, or is this just low statistics?

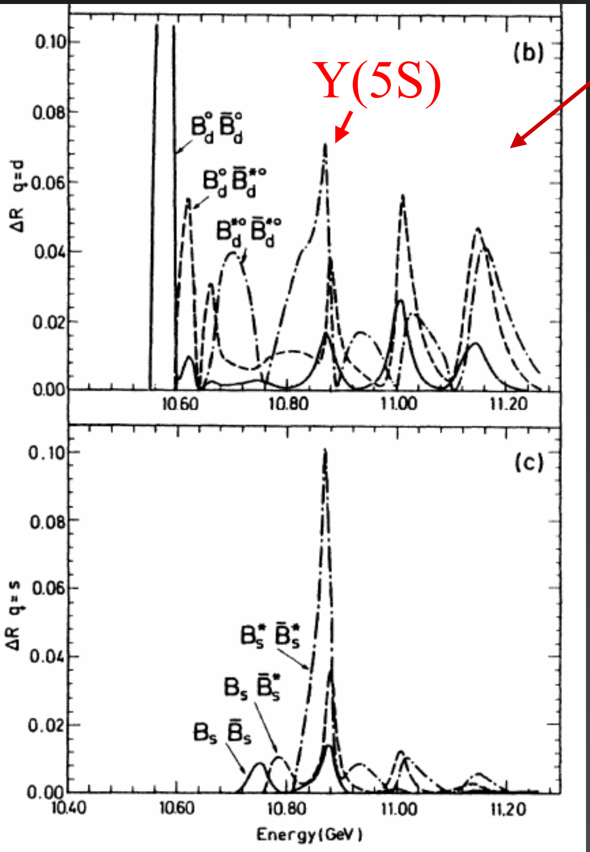
Rare Exclusive B_S Decays (Belle)



Decay mode	Yield, ev.	Backg., ev.	Eff. (%)	UL (10^{-4})	PDG UL (10^{-4})
$B_s \to \gamma\gamma$	0	0.5	20.0	0.56	1.48
$B_s \to \phi\gamma$	1	0.15	5.9	4.1	1.2
$B_s \to K^+K^-$	2	0.14	9.5	3.4	0.59
$B_s \to D_s^+ D_s^-$	0	0.02	0.020	710.	-
$B_s \to D_s^{*+} D_s^-$	1	0.01	0.0099	1270.	-
$B_s \to D_s^{*+} D_s^{*-}$	0	$<$0.01	0.0052	2730.	-

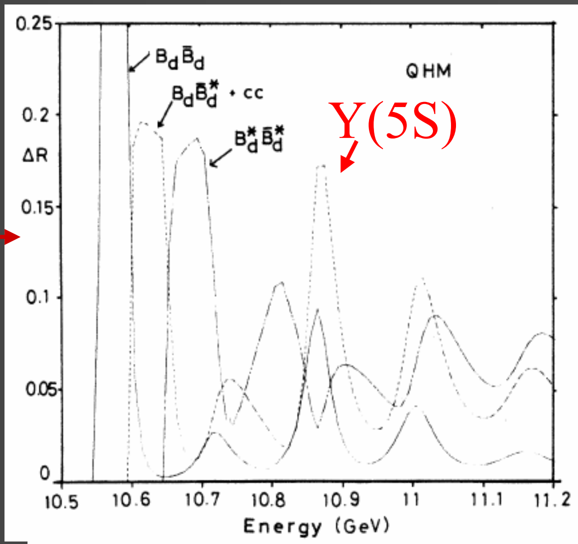
Comparisons with Models

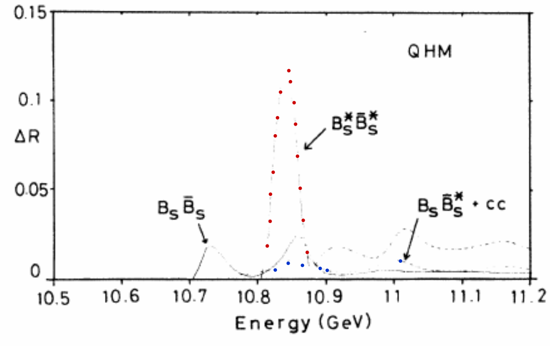
Unitarized Quark Model



- UQM predicts $\Delta R \sim 0.4$, $f_S = 38\%$, $B_S^* \bar{B}_S^*$ large
- QHM predicts $\Delta R \sim 0.7$, $f_S = 21\%$, $B_S^* \bar{B}_S^*$ large
- Other models:
  - Martin & Ng, Z Phys. C 40, 133 (1988)
  - Byers [hep-ph/9412292

Quark Hybrid Model





Yields: B factory

- In 500 fb^{-1} there will be ~6.6×10^7 total $B_S+\bar{B}_S$ produced
- Estimate from Drutskoy that in the current Belle detector they will find ~75 $D_S^{(*)+}D_S^{(*)-}$ events (using $D_S\to\phi\pi$, K^*K & K^oK^+) in 50 fb^{-1}, so ~500 fb^{-1} may be necessary. Here backgrounds may not be a problem…
- There will be $J/\psi\ \phi$, $J/\psi\ \eta^{(')}$ ~3.5/fb^{-1}
- Assume trigger will be ~100% efficient, so not mode dependent, unlike LHCb

Expected Yields for LHCb

Mode	Yield (2 fb^{-1})	S/B
$B_s \to J/\psi(\mu^-\mu^+)\phi(K^+K^-)$	131,000	8.3
$B_s \to \eta_c(h^-h^+h^-h^+)\phi(K^+K^-)$	3,000	1.7
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\gamma\gamma)$	8,500	0.5
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	3,000	0.3
$B_s \to J/\psi\ (\mu^-\mu^+)\ \eta'(\pi^+\pi^-\eta\ (\gamma\gamma))$	2,200	0.5
$B_s \to D_s(K^+K^-\pi^-)\ D_s(K^+K^-\pi^+)$	4,000	3.3

- My guess: this will accumulated sometime in 2009
- LHCb sensitivities: $\sigma(\phi)=0.02$ rad, $\sigma(\Delta\Gamma/\Gamma)=0.01$

Conclusions

- About 23% of the Υ(5S) decays to $B_S^{(*)}\overline{B}_S^{(*)}$ this cross-section is ~0.07 nb. The estimate is model dependent & not good enough for precision branching ratio measures
- Model independent means exist to measure the B_S yield when enough data is accumulated [hep-ph/0604201]
- Most of the B_S rate is produced via $B_S^*\overline{B}_S^*$
- A useful measurement of $\Delta\Gamma_{SM}$ can be carried out with a large data sample that will be complimentary to the LHCb measurement of $\Delta\Gamma$ via time dependent measurements using lifetimes giving a handle on cosϕ, the non-SM phase.
- Measurement of some absolute B_S branching ratios would be very useful for other experiments
- Some rare decay modes can be usefully measured in the LHCb era, especially if they have more than one neutral particle
- LHCb will measure time-dependent CPV in the B_S system

The End

CP Violation in B_S Mixing

- Lets consider the decay rate for a B_S to a final state f, A_f=<f|B_S>

$$\Gamma(B_s(t)\to f) = \mathcal{N}_f\,|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\,e^{-\Gamma t}$$
$$\times\left[\cosh\frac{\Delta\Gamma\,t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\,\cos(\Delta m\,t) + \mathcal{A}_{\Delta\Gamma}\,\sinh\frac{\Delta\Gamma\,t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\,\sin(\Delta m\,t)\right]$$

- $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$ For CP eigenstates $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \eta_f e^{-i\phi}$

$$\mathcal{A}_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad \mathcal{A}_{\rm CP}^{\rm mix} = -\frac{2\,{\rm Im}\,\lambda_f}{1+|\lambda_f|^2} \qquad \text{and} \qquad \mathcal{A}_{\Delta\Gamma} = -\frac{2\,{\rm Re}\,\lambda_f}{1+|\lambda_f|^2}$$

- Measuring these rates requires good time resolution