Mixing and CP Violation at the Tevatron

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IN THE CITY OF NEW YORK

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Outline

- B_s mixing
- D mixing: mixing interference in decay
- CP Violation:
  - $B^+ \rightarrow J/\psi\ K^+$: CPV in decays
  - Semileptonic A_{CP}: CPV in mixing
  - $B_s \rightarrow J/\psi\ \phi$: CPV in interference of mixing and decay
- Conclusions

(Throughout this talk, charge conjugated modes are implicitly assumed.)

Mixing

$$|B_1\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle + |\bar{B}^0\rangle\right) = |B_H\rangle$$

$$|B_2\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle - |\bar{B}^0\rangle\right) = |B_L\rangle$$

Mass Eigenstates
(and CP eigenstates
if ignore CP violation)

Weak Eigenstates

$$\hat{H}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

- Then B_1 and B_2 are eigenstates with

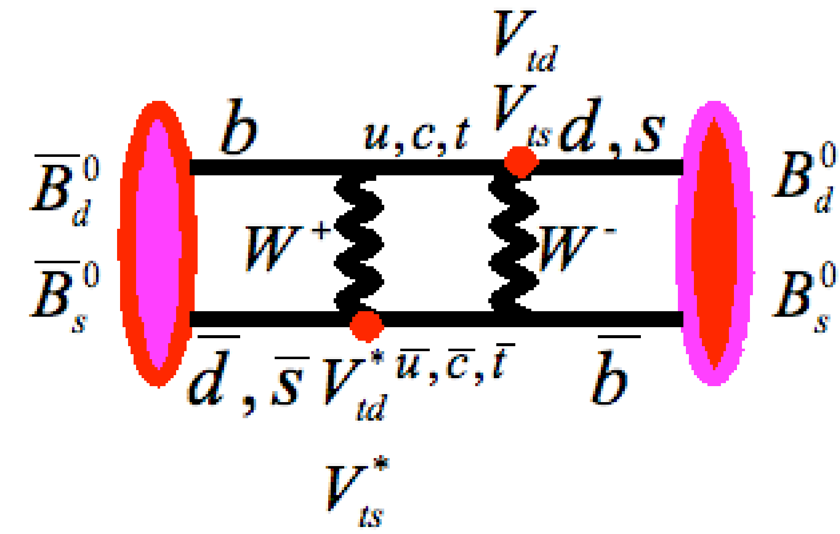
masses: $m_{1,2} = M \pm \frac{\Delta m}{2}$ and lifetimes: $\Gamma_{1,2} = \Gamma \pm \frac{\Delta\Gamma}{2}$

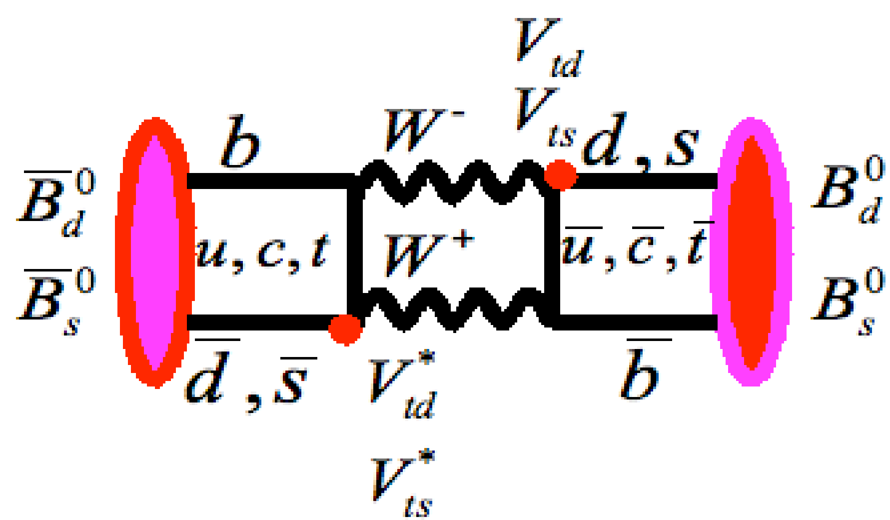
Define $x = \Delta M/\Gamma$, $y = \Delta\Gamma/2\Gamma$, and

$x' = x\cos\delta + y\sin\delta$, $y' = -x\sin\delta + y\cos\delta$
(δ is a strong phase)

Feynman Diagrams (B)

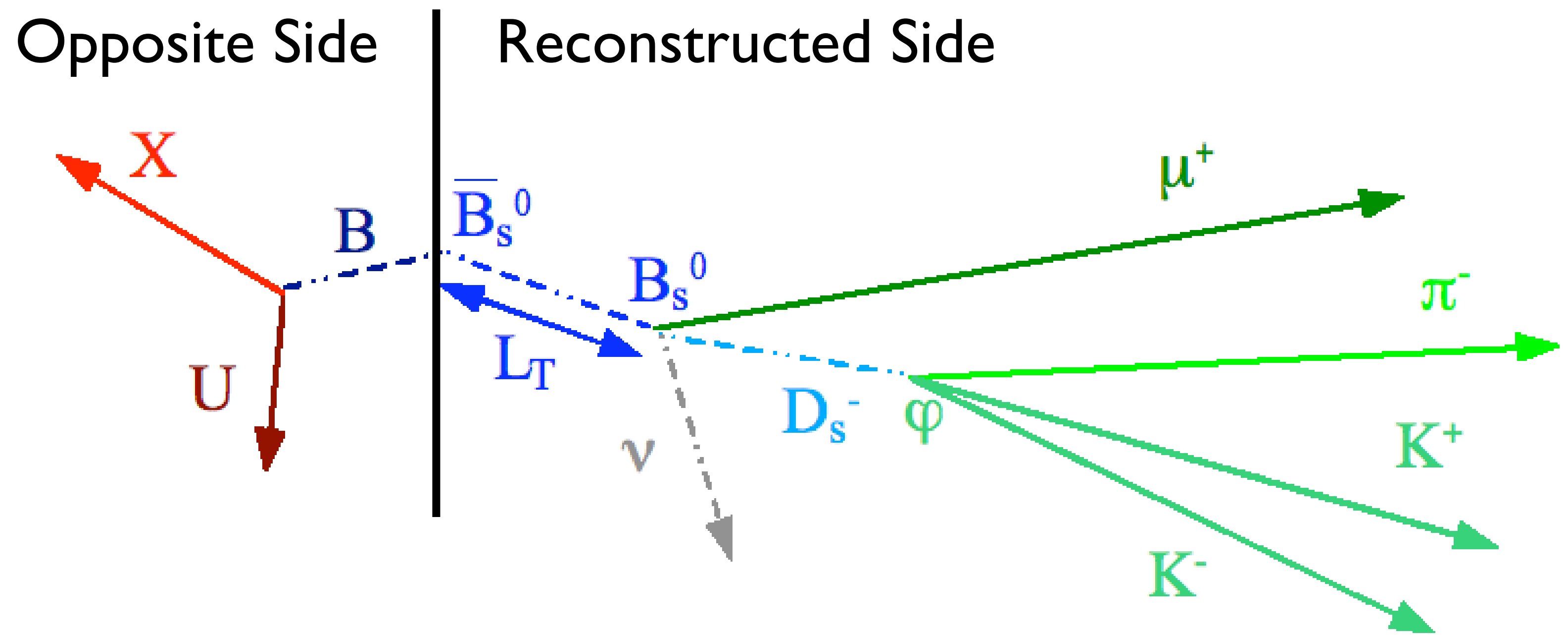
- Processes (dominantly) mediated by box diagrams
  - Since V_{tb} is large, diagrams with top quarks dominant
  - In M_{12}, mass comes in as m_{top}^2/m_W^2
  - High oscillation frequency was the first experimental indication of large top quark mass (1987)
- Sensitive to new heavy particles in loops





- $\Delta m_d \propto |V_{tb}^* V_{td}|^2$
- $\Delta m_s \propto |V_{tb}^* V_{ts}|^2$

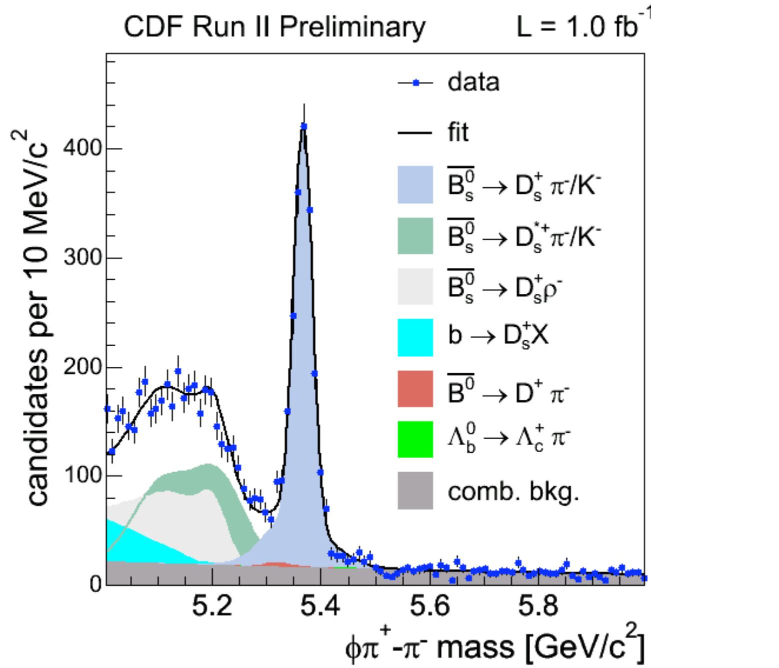
Analysis Strategy

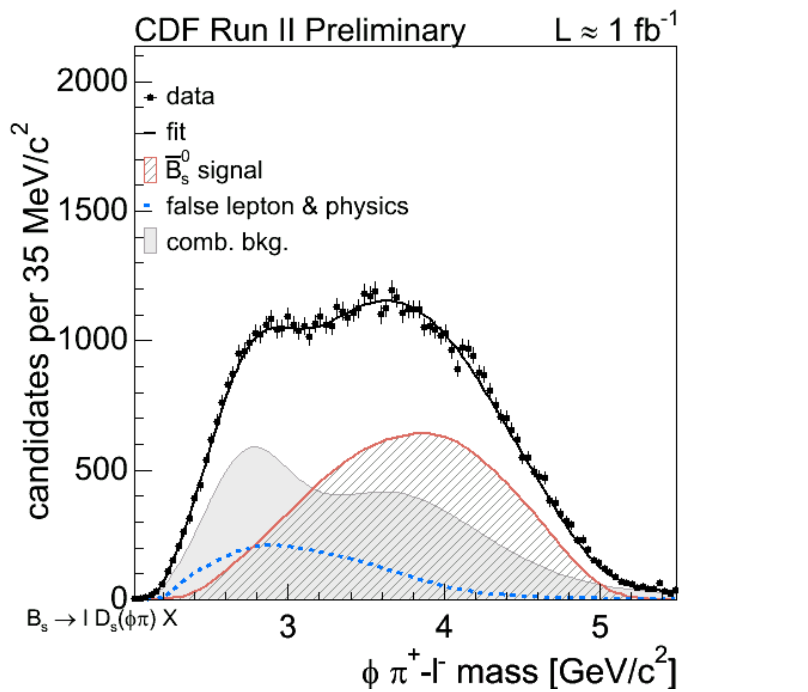


- Reconstruct B_s decay on one side, flavor at decay time is given by charges of decay products, measure momentum and (transverse) decay length L_T (to determine proper lifetime)
- Tag flavor at production using either "opposite side" b-hadron (most b's are pair-produced), or "same side" hadron from fragmentation (for B_s, in principle a K)

Reconstruction

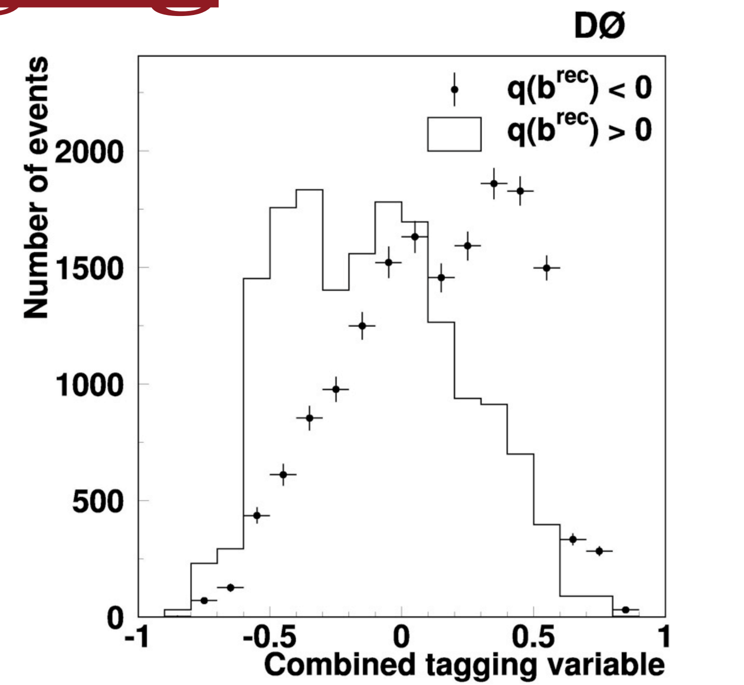
- Look for $B_s \rightarrow D_s X$
  - X can be leptons, 1 or 3 pions
  - Consider multiple D_s decay channels
- Use NN (CDF) / likelihood (DØ) to increase S/B
  - CDF includes particle ID based on TOF, dE/dx in drift chamber
- In semileptonic B_s decays do not reconstruct B_s momentum fully
  - ➡ Apply a "K-factor" to rescale momentum

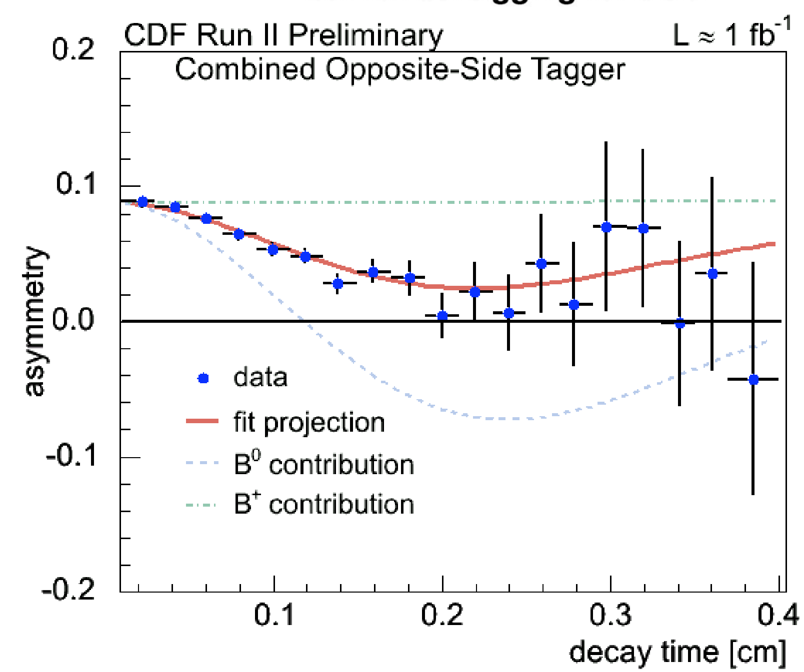




Flavor Tagging

- At the Tevatron, most b quarks are produced in $b\bar{b}$ pairs
  - Can use opposite-side b quark for tagging
  - Same-side hadrons also useful (but usually less pure, because sensitive to fragmentation fluctuations)
- Both experiments combine tags in NN (CDF) or likelihood (DØ)
- Verify performance using B_d mixing

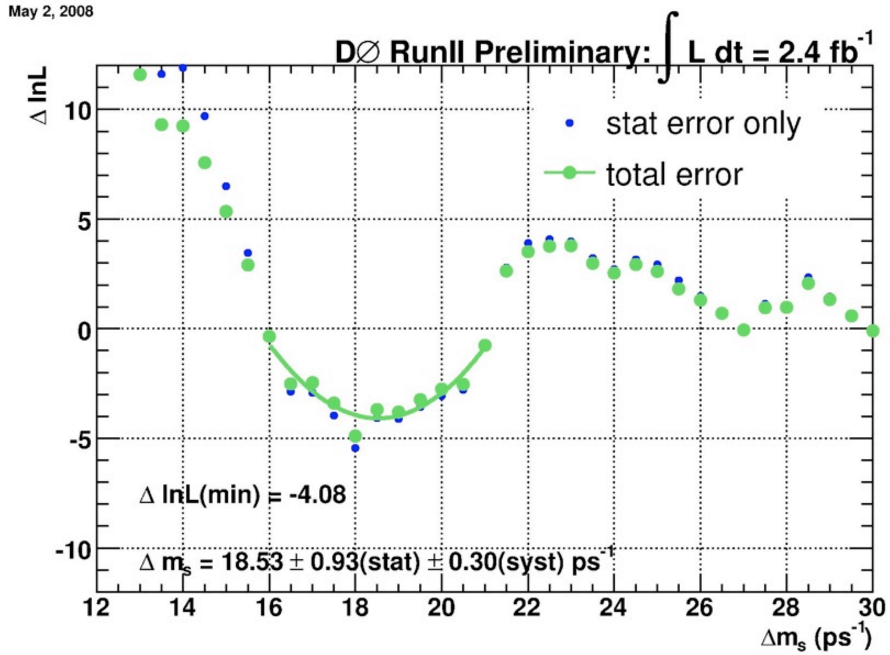




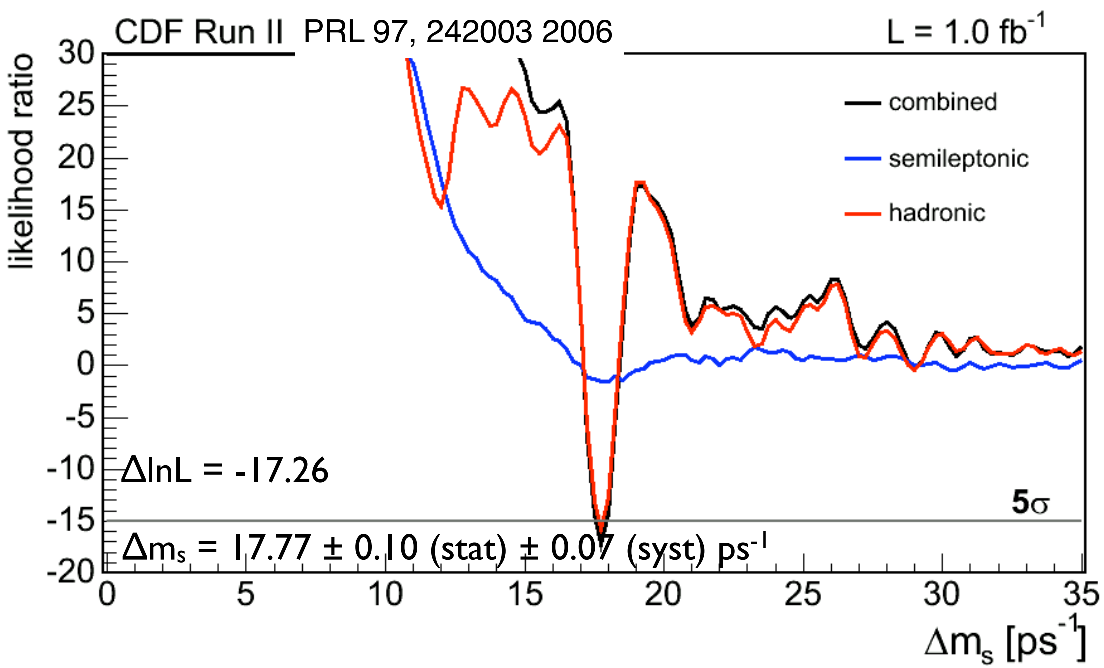
Result

- Maximizing sensitivity requires using all information (uncertainties) on an event-by-event basis
  - ➡ Unbinned maximum likelihood fits

DØ: small contribution from hadronic channels

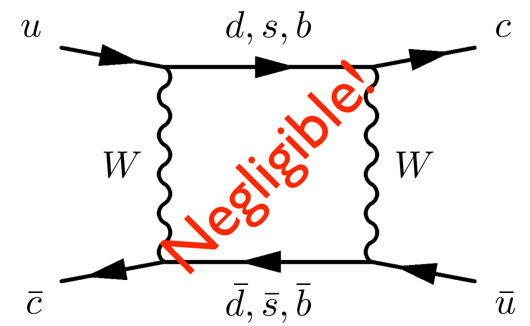


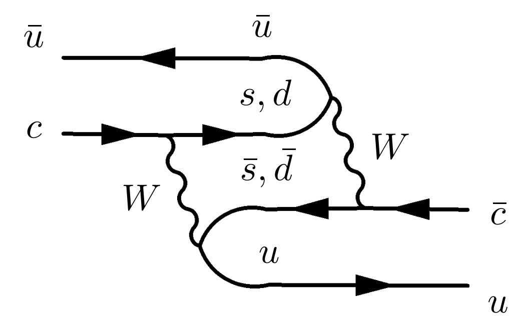
CDF: hadronic channels dominant large L1 bandwidth, SVT & PID



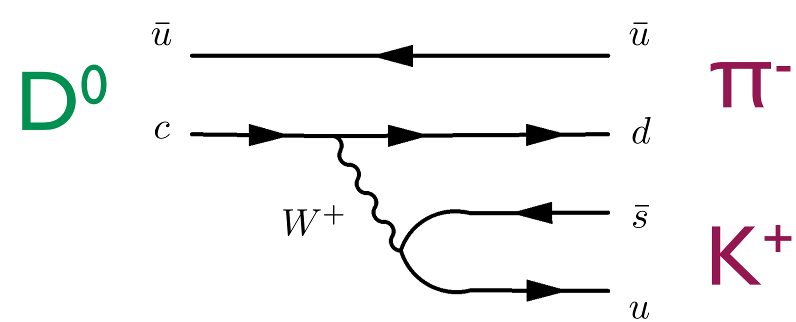
D Mixing

- D oscillations expected to be slow in the SM
  - Box diagram (ΔC=2) very small due to CKM & GIM suppressions
  - "Long range" (2 x ΔC=1) dominant, proportional to breaking of $SU(3)_f$
- Cannot observe oscillation
  - Mixing interference may be visible in doubly Cabibbo-suppressed decays





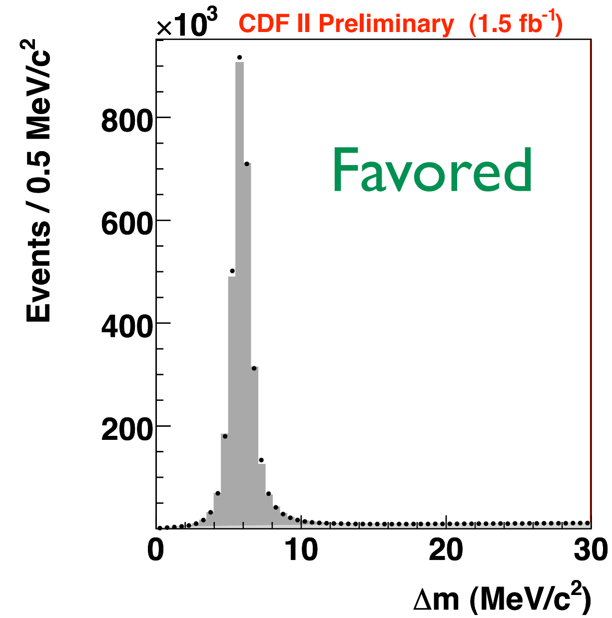
"Long Range"

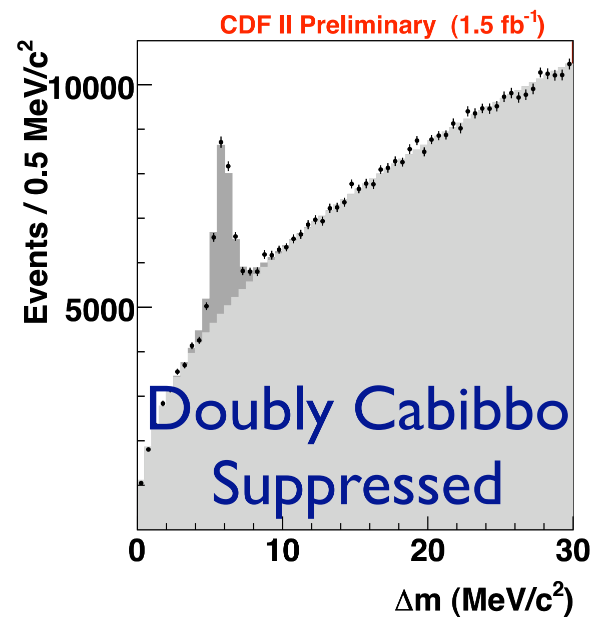


DCS Decay

Analysis Technique

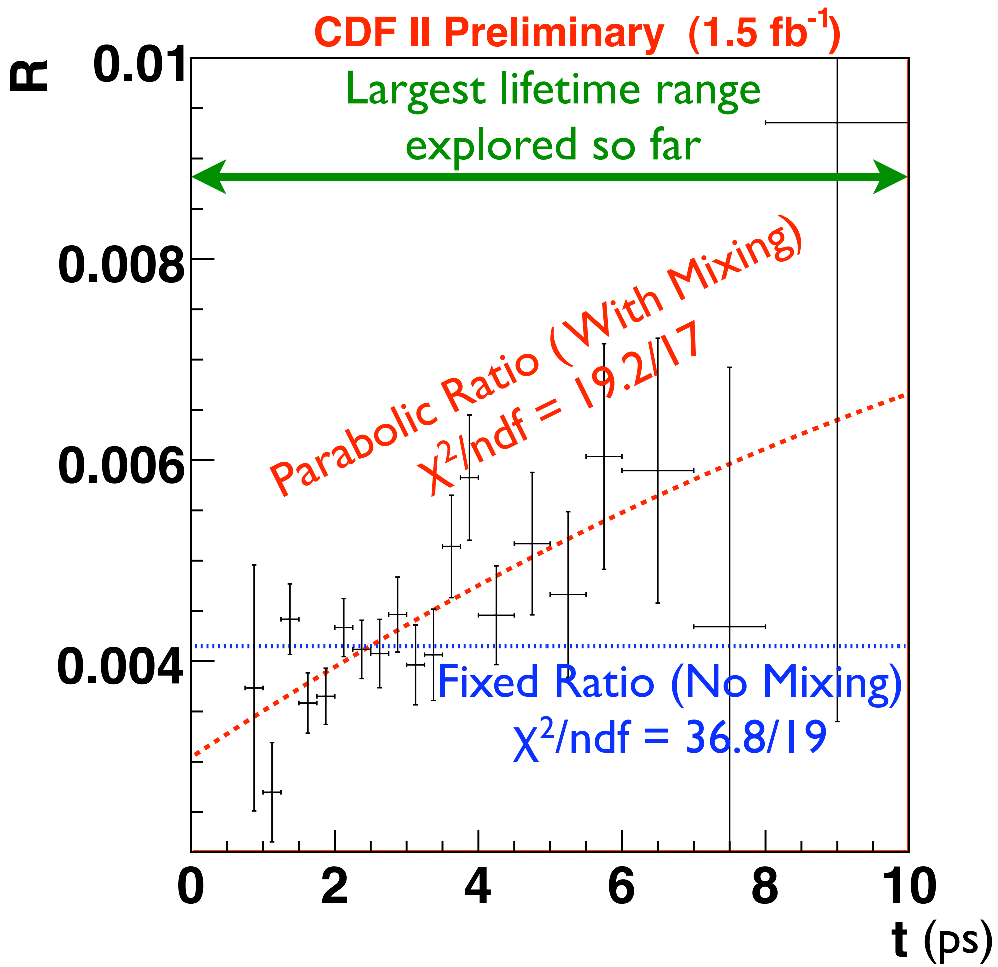
- Look for mixing-induced time dependence of $D^0 \to K^+\pi^-$ / $D^0 \to K^-\pi^+$ ratio
  - Sample collected with IP trigger
  - Use $D^{*+} \to \pi^+ D^0$, $D^0 \to K\pi$ chain to "tag" D^0 flavor at production
  - Include PID, reject $K\pi$ candidates that fall into D^0 mass window with both mass assignments
    - Look at $\Delta m = m(K\pi\pi) - m(K\pi) - m(\pi)$: should be ~5 MeV

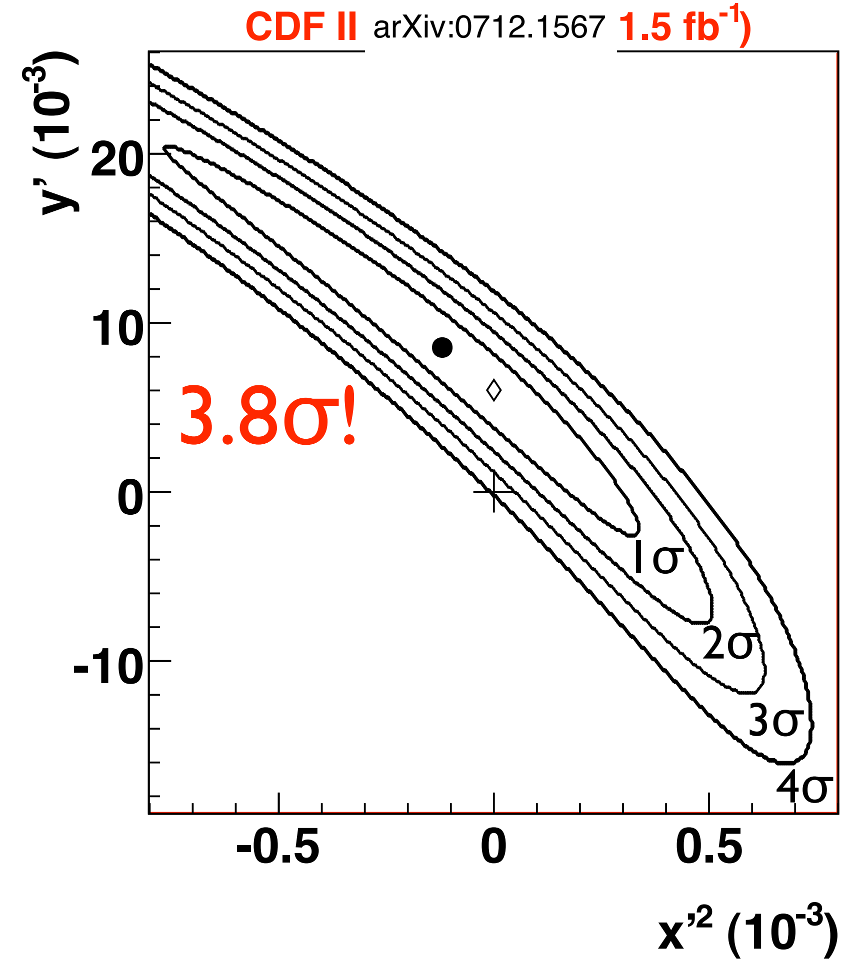




D Mixing!

$$R(t) = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$





- Dominant systematics: signal and background shapes, fraction of D^*'s from B decays

CP Violation

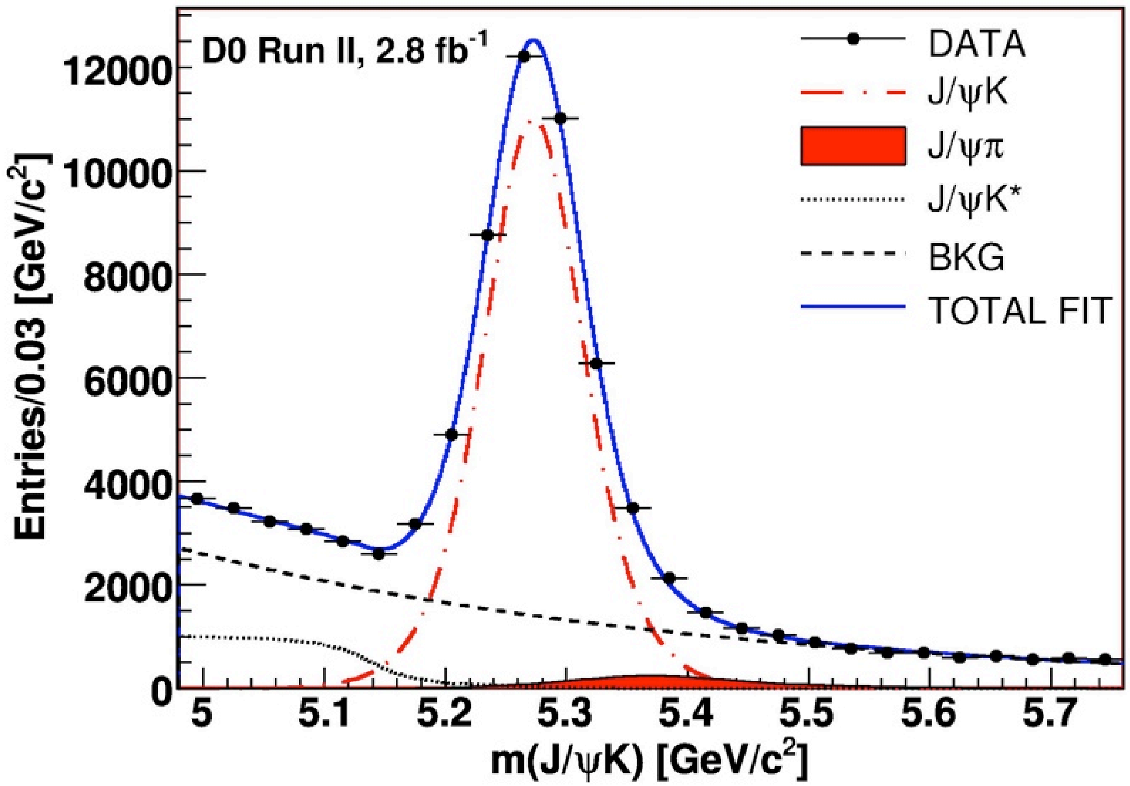
- In the decay amplitudes: $B^+ \rightarrow J/\psi\ K^+$
  - $\Gamma(B \rightarrow f) \neq \Gamma(CP(B) \rightarrow CP(f))$
  - Only possibility in charged meson decays
- In mixing: Same-Sign Dimuons
  - Observe through asymmetry in charged-current neutral meson decays: A_{SL}
- Interference between the two: $B_s \rightarrow J/\psi\ \phi$
  - Interference between decays without/with mixing: need common final state

$B^+ \to J/\psi\ K^+\ (\pi^+)$

- Select sample with J/ψ decaying to a pair of muons
  - Very clean sample, 40k candidate events
- Fit for asymmetries:
  - Divide sample in 8 based on solenoid polarity, sign of J/ψ K+ pseudo-rapidity η, and K charge

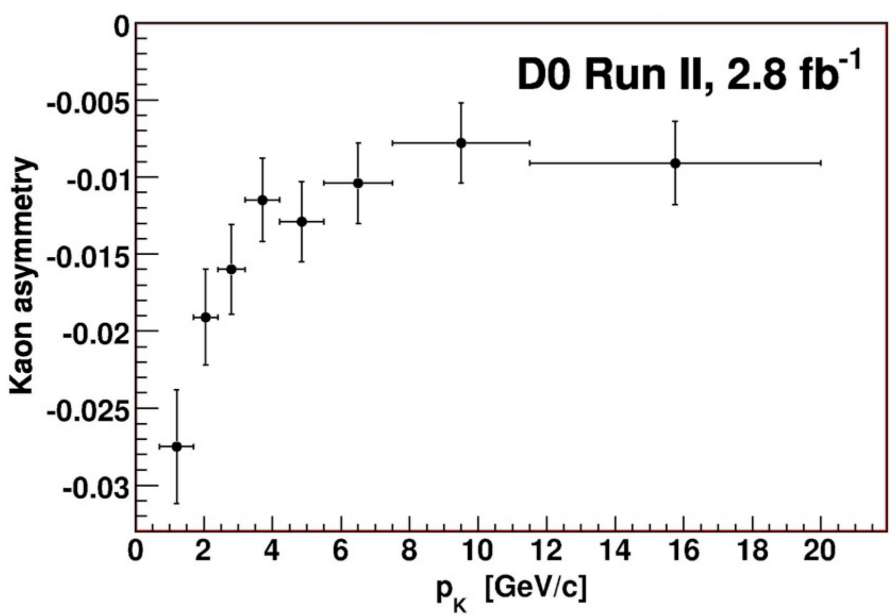
$$n_q^{\beta\gamma} = \frac{1}{4}N\epsilon^\beta(1+qA)(1+q\gamma A_{\mathrm{fb}})(1+\gamma A_{\mathrm{det}}) \times (1+q\beta\gamma A_{\mathrm{ro}})(1+q\beta A_{q\beta})(1+\beta\gamma A_{\beta\gamma})$$

  - All detector & forward-backward asymmetries found compatible with 0



$B^+ \to J/\psi\ K^+\ (\pi^+)$: Result

- Need to correct observed asymmetry for $K^\pm$ reconstruction asymmetry
  - Due to asymmetry in interactions (detector is made of matter)
  - Measure in $D^{*+} \to D^0\pi^+$, $D^0 \to \mu\nu_\mu K^-$



$A_{CP}(B^+ \to J/\psi K^+) =$
$0.0075 \pm 0.0061\,(stat) \pm 0.0027\,(syst)$

$A_{CP}(B^+ \to J/\psi \pi^+) =$
$-0.09 \pm 0.08\,(stat) \pm 0.03\,(syst)$

arXiv:0802.3299

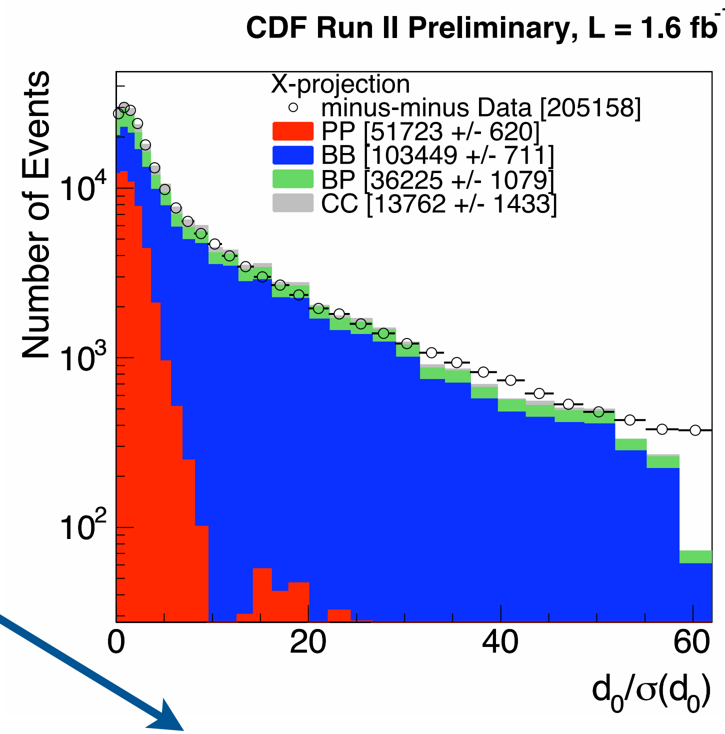
(Dominant systematic is mass distribution model)

Same-Sign Dimuons

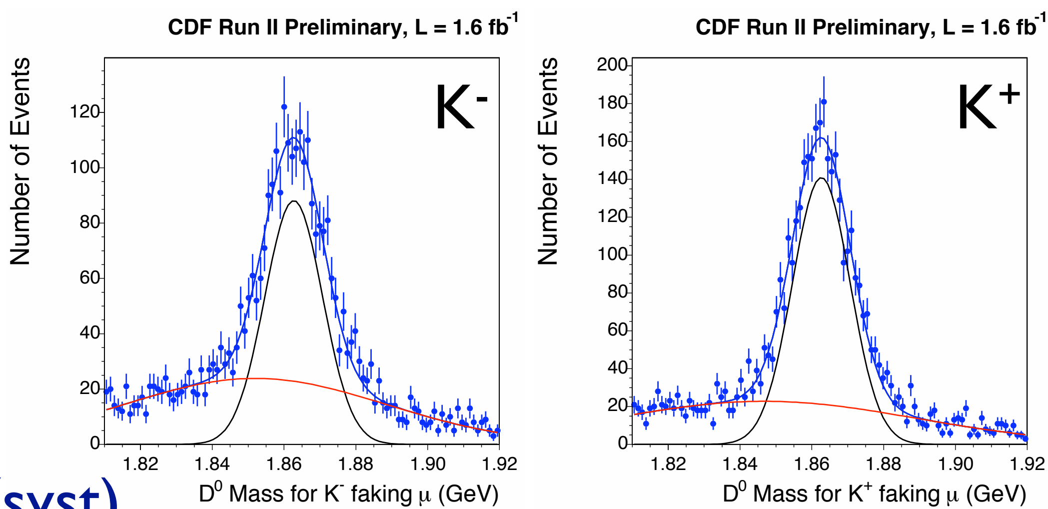
- Measure $A_{SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}$
- Multiple techniques:
  - Use all dimuon events, and estimate contributions from all processes (incl. sequential decays, Drell-Yan, instrumentals, etc): DØ (2006) Phys. Rev. D 74 , 092001 (2006)
  - Use all dimuon events but use impact parameter distributions to unfold contributions from various sources: CDF
- Then derive A^q_{SL} from sample composition, or
  - Use flavor-specific decays, e.g. $B_s \to \mu^+\nu D_s^- X$: DØ

Inclusive Measurements

- New CDF measurement uses 2-D (μμ) impact parameter significance distribution
  - Asymmetry from K/π faking muon measured in D^{*+} decays, + unfold direct and sequential decay contributions



$A^{\mu\mu}_{SL}$= 0.0080 ± 0.0090 (stat) ± 0.0068 (syst)



DØ 2006 fully inclusive measurement using "8 subsamples technique":

$A^{\mu\mu}_{SL}$= -0.0053 ± 0.0025 (stat) ± 0.0018 (syst)

A^d_{SL} & A^s_{SL}

- $A^{\mu\mu}_{SL}$ has contributions from both B_d and B_s:
  - Use A^d_{SL} from the B-factories, B_d and B_s production ratios, and mixing parameters to extract A^s_{SL}
- From CDF impact parameter analysis:
  - $A^s_{SL} = 0.020 \pm 0.021$ (stat) ± 0.016 (syst) ± 0.009 (inputs)
- From DØ inclusive analysis:
  - $A^s_{SL} = -0.0064 \pm 0.0101$ (uncertainties combined)

Phys. Rev. D 76 , 057101 (2007)

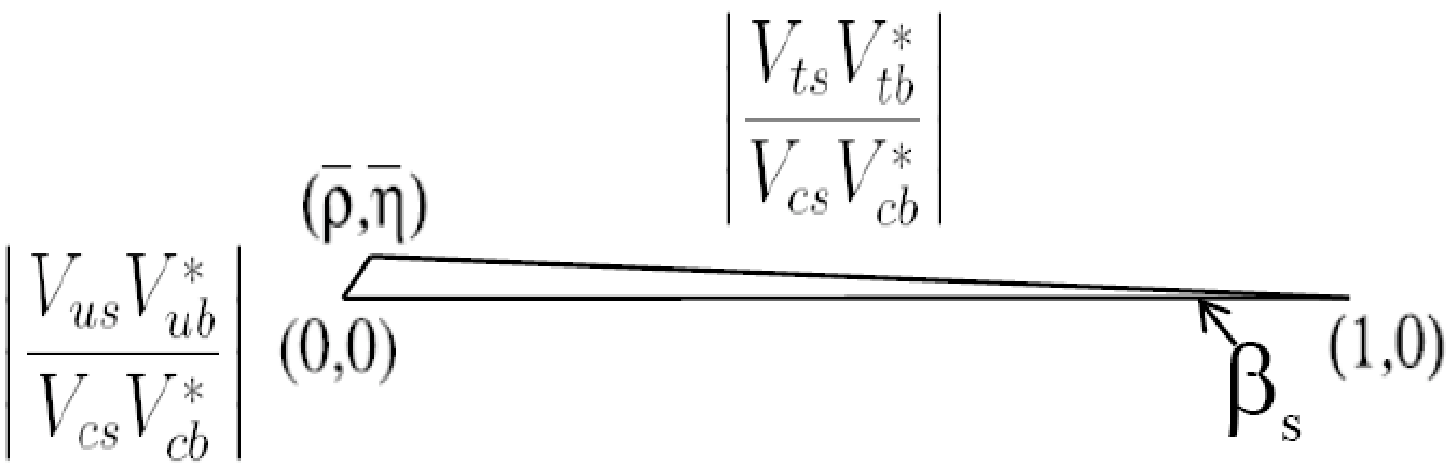
- From DØ exclusive measurement ($B_s \rightarrow \mu^+\nu D_s^- X$):
  - $A^s_{SL} = 0.0245 \pm 0.0193$ (stat) ± 0.0035 (syst)

Phys. Rev. Lett. 98 , 151801 (2007)

$B_s \to J/\psi\ \phi$: CPV in Interference

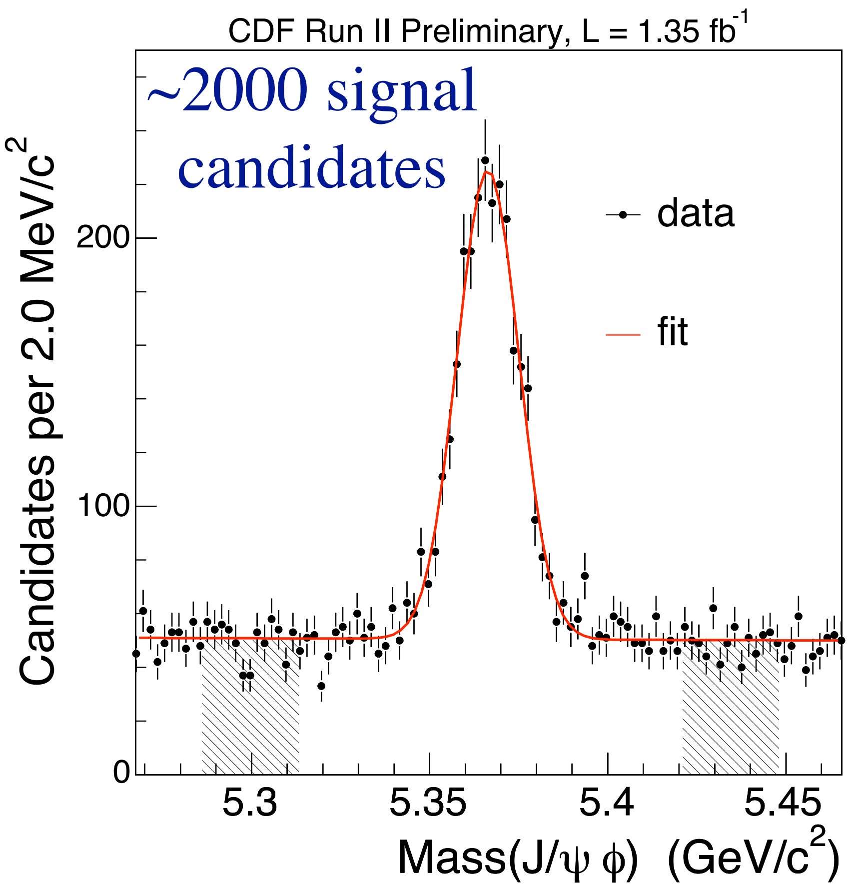
- Equivalent of $B_d \to J/\psi\ K_S$ in B_d system
  - Access to the equivalent of $\sin(2\beta)$: $\sin(-\phi_s)$ or $\sin(2\beta_s)$

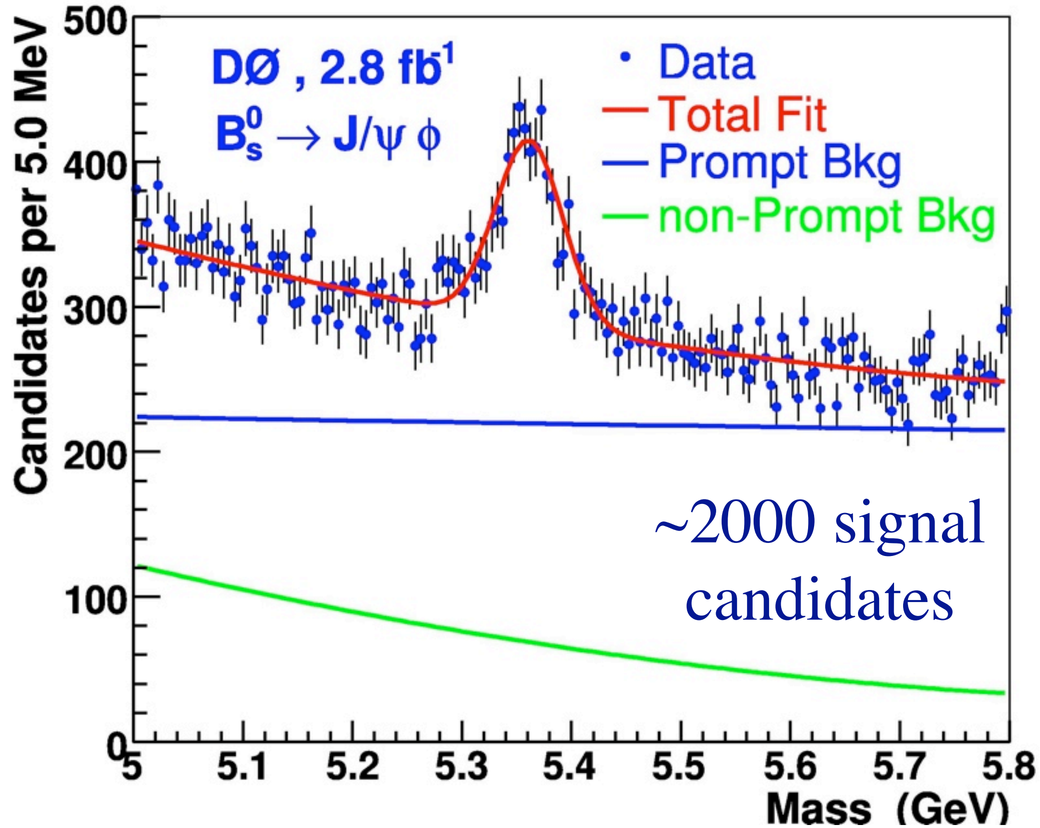
  - But β_s is much smaller in the SM than β:



$B_s \to J/\psi\ \phi$ Signal

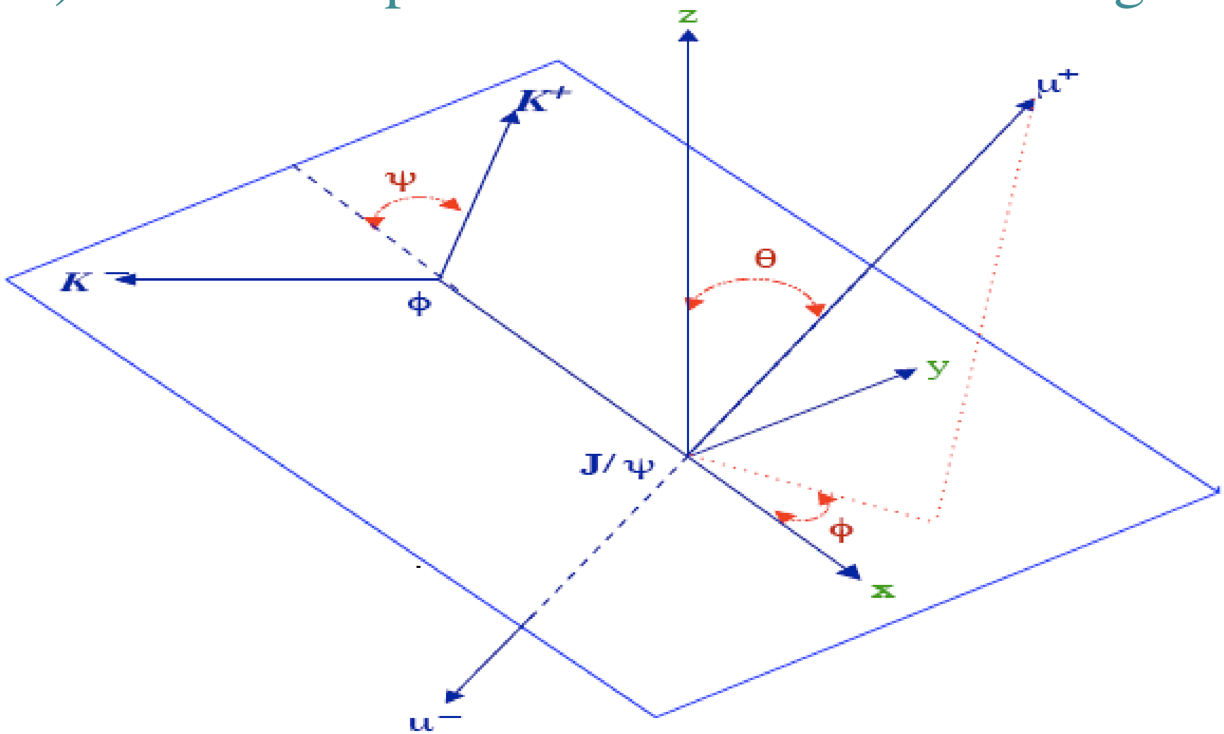
- CDF uses neural network, with variables including PID from TOF & dE/dx in drift chamber
- DØ uses "square cuts" event selection (no PID)





J/ψ φ CP? → Decay Angles

- VV final state ⇒ both CP eigenvalues possible.
  - Disentangle by determining relative polarization of J/ψ and φ
    - Express angular dependence in J/ψ rest frame (“transversity basis”) in terms of polarization ⇒ extract CP eigenvalue



Flavor Tagging

- Needed to constrain flavor of decaying B_s
  - Removes a twofold ambiguity in result
- Both experiments use both opposite-side and same-side tags
  - DØ: combined tagging power $\varepsilon\mathcal{D}^2 = 4.68$ %
  - CDF:
    - OST tagging power $\varepsilon\mathcal{D}^2 = 1.28$ %
    - SST tagging power $\varepsilon\mathcal{D}^2 = 3.65$ %

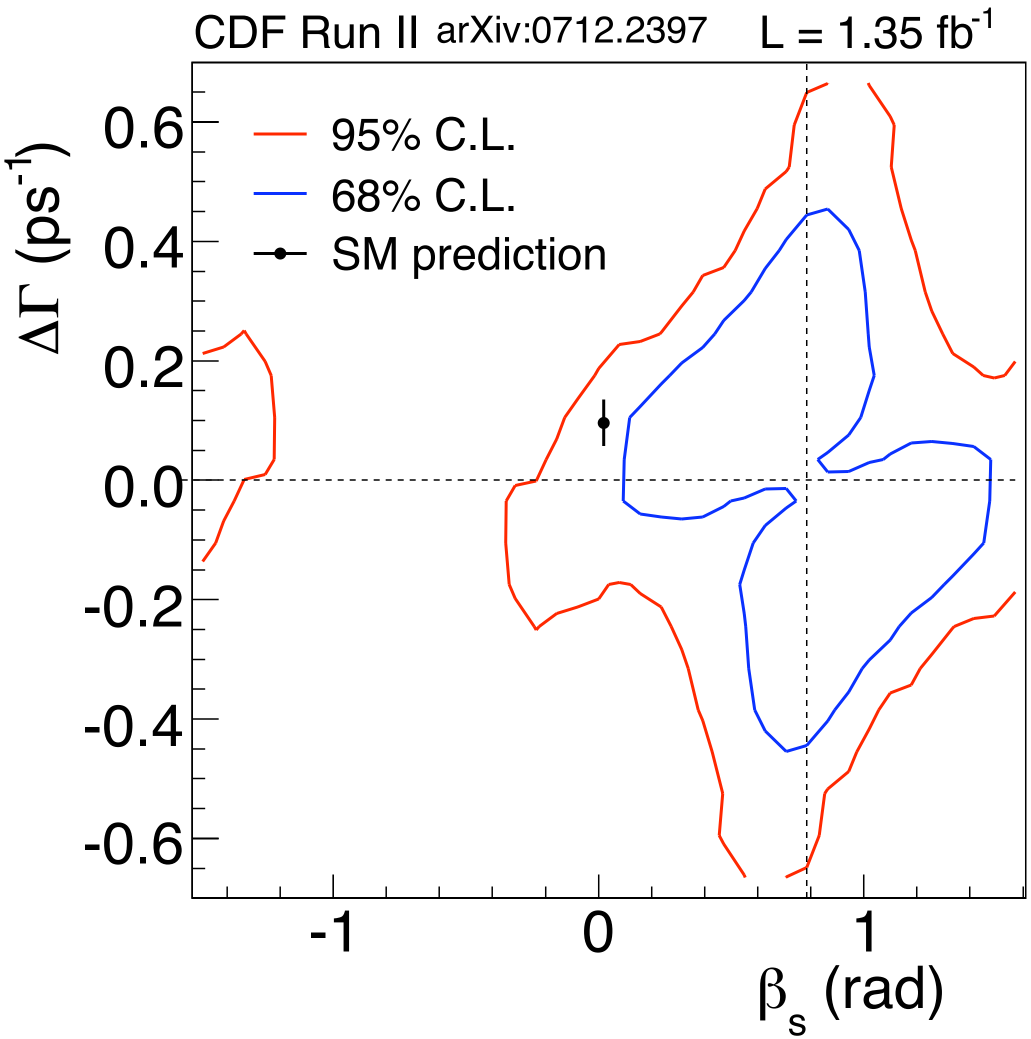
Fit

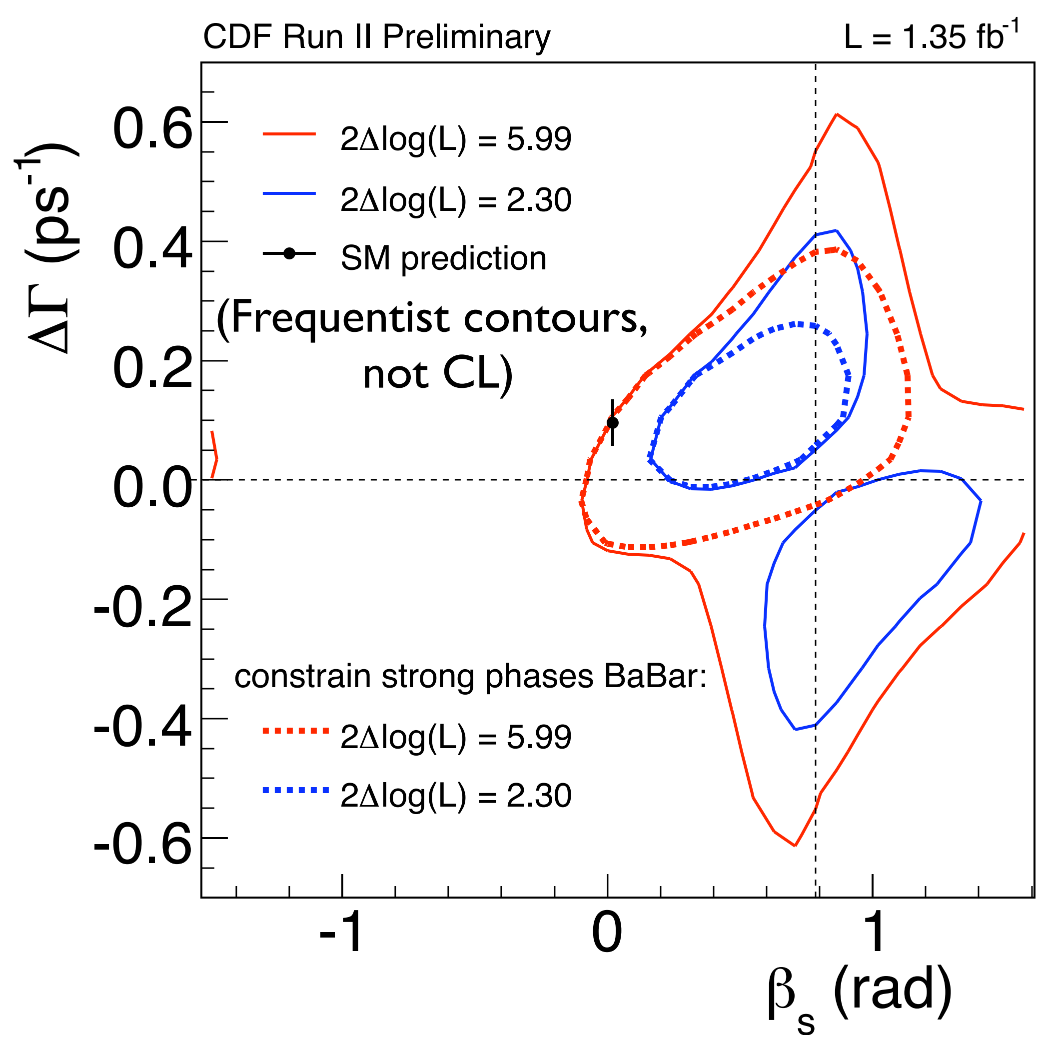
- Use unbinned maximum likelihood fit to maximize sensitivity
  - Constrain $\Delta m_s = 17.77 \pm 0.12\ ps^{-1}$
  - (Constrain or float strong phases)
  - Extract average lifetime, $\Delta\Gamma_s$, ϕ_s ($=-2\beta_s$), magnitudes of polarization amplitudes, and strong phases
- NB: detector efficiencies are not flat vs transversity angles, correct
- CDF likelihood profiles not parabolic close to minima
  - Use Feldman-Cousins-like likelihood ratio ordering to build 2-D confidence region

Result: CDF

SM probability: 15% ✓

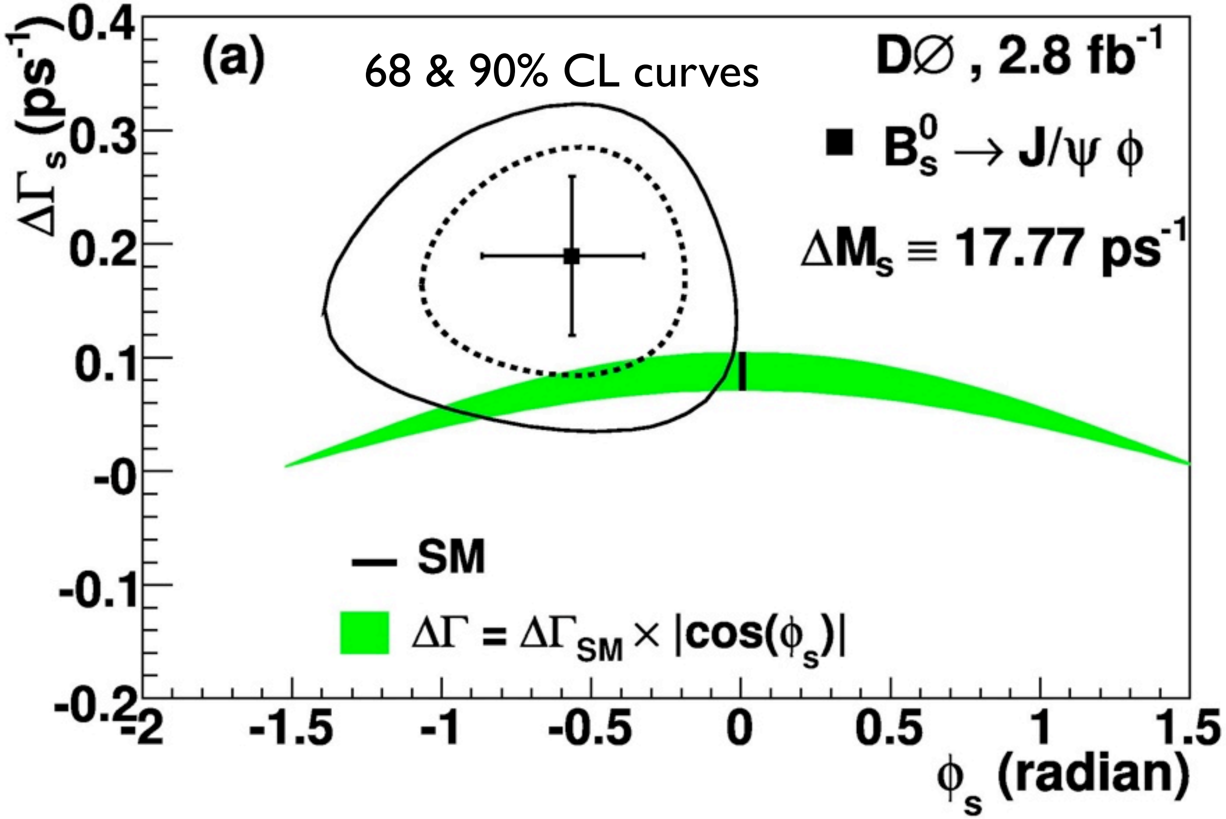
With BABAR constraints on strong phases from $B^0 \to J/\psi\ K^{*0}$





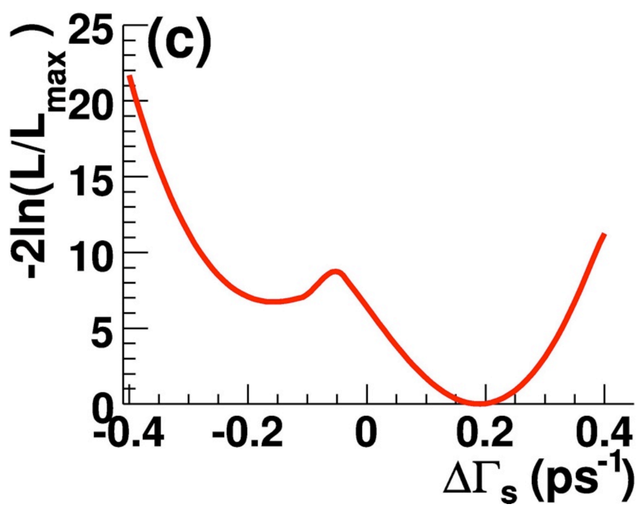
Result: DØ

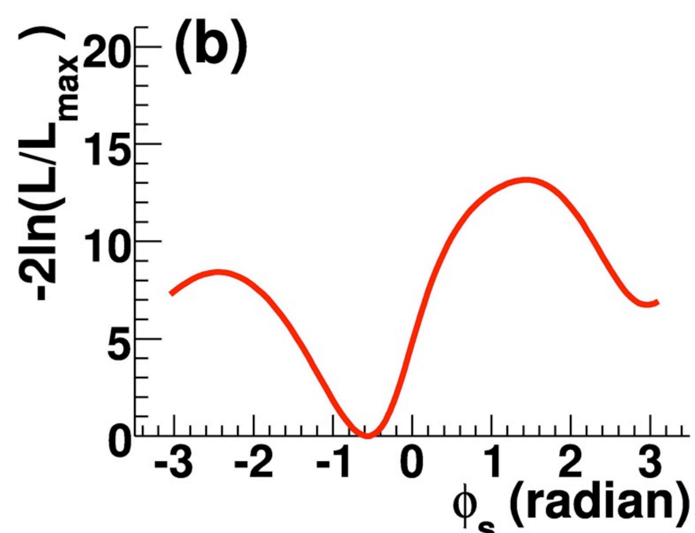
arXiv:0802.2255



(With BABAR constraints on strong phases from $B^0 \rightarrow J/\psi\ K^{*0}$)

SM probability: ~7% ✓





Combination & Prospects

- UT*fit*: arXiv:0803.0659
  - Strong phases derived from BABAR $B_d \rightarrow J/\psi\ K^*$ may not be completely valid, so try to unfold this from DØ result
    - (UT*fit* combination also uses asymmetries)
  - Some uncertainty with this, but any of the tried procedures lead to values of ϕ_s 3σ or more from the Standard Model
- For both CDF and DØ, the measurement uncertainty is completely dominated by statistics
  - ➡ Result will still improve quite a bit
- If confirmed, this would be the first evidence for CP violation outside the CKM mechanism.

Conclusions

- Evidence for D mixing seen by CDF
- $A_{CP}(B^+ \rightarrow J/\psi K^+)$ and A^s_{SL} compatible with 0
- B_s mixing parameters:
  - Δm_s: evidence by DØ, observation by CDF
  - $\Delta\Gamma_s$: good agreement with Standard Model
  - ϕ_s: suggestion of CP violation beyond the CKM mechanism?

To be continued....

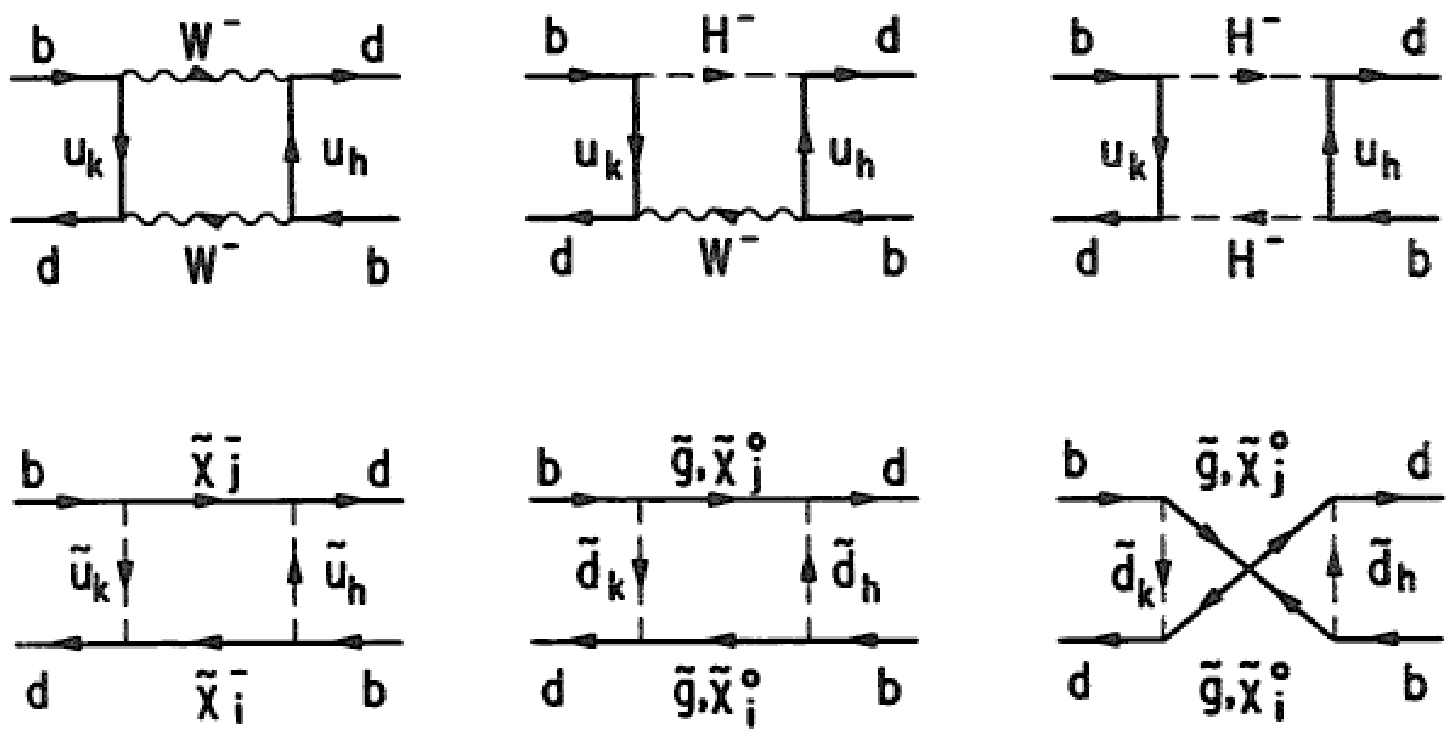
$B_{d,u}$ and B_s

- Many aspects of CP violation in $B_{d,u}$ well measured
  - Lots from B-factories, and important Tevatron contributions
    - e.g. $B^+ \rightarrow J/\psi\, K^+$
  - Tevatron also has access to large B_s sample!
- CP violation expected to be small in b-c transitions from B_s in the Standard Model

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

New Physics in B Mixing

- Supersymmetric contributions for example (See Bertolini et al., Nucl. Phys. B353, 591 (1991)), but note that you still need flavor violation
- See for example Foster et al., Phys.Lett.B641:452-460,2006



B Mesons Decay!

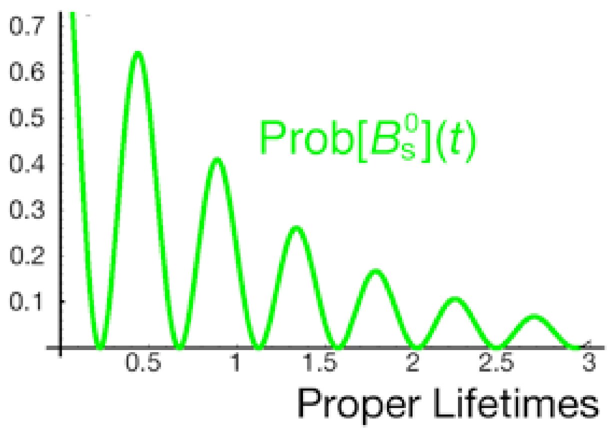
Extract frequency

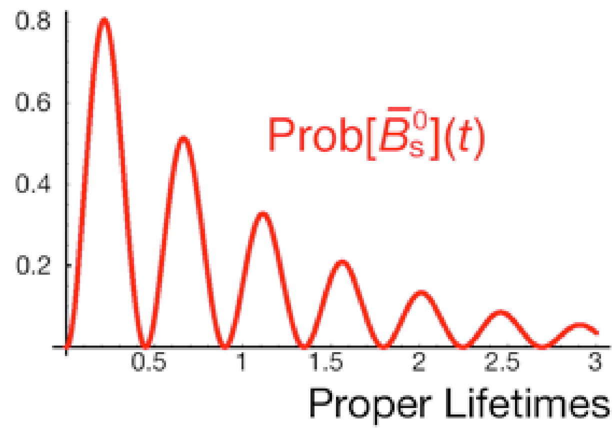
- If initially start with a B_s^0

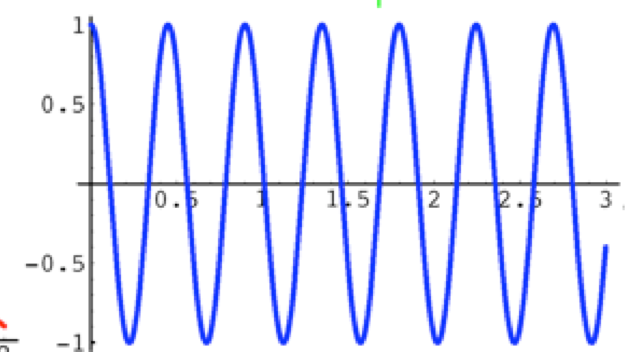
$$\mathrm{Prob}[B_s^0](t) = \frac{1}{4}\left[\exp(-\Gamma_1 t) + \exp(-\Gamma_2 t) + 2\exp(-\Gamma t)\cos(\Delta m_s t)\right]$$

$$\mathrm{Prob}[\bar{B}_s^0](t) = \frac{1}{4}\left[\exp(-\Gamma_1 t) + \exp(-\Gamma_2 t) - 2\exp(-\Gamma t)\cos(\Delta m_s t)\right]$$

- For B_s^0







Take asymmetry of two:

$$A = \frac{N[B^0](t) - N[\bar{B}^0](t)}{N[B^0](t) + N[\bar{B}^0](t)}$$

- What we get from it: $\Delta m_s \propto |V_{tb}^* V_{ts}|^2$

- $\Delta m_d \propto |V_{tb}^* V_{td}|^2$ — V_{tb}^*: ~1, V_{td}: tiny
- $\Delta m_s \propto |V_{tb}^* V_{ts}|^2$ — V_{tb}^*: ~1, V_{ts}: still small, but larger than V_{td}