B mixing and CP violation

Outline

- CPV in the Standard Model
- CPV and New Physics
- Mixing formalism
- Mixing measurements.
- CPV in B_d and B_s, with special focus New Physics in mixing. With current and future sensitivities.
- In terms of CKM/CP-violating angles: I'll mention β, ignore (the very important) γ, and discuss ϕ_s in some details. Details on β, γ (and α) in Adrian's talk.

CPV in the SM and the CKM matrix

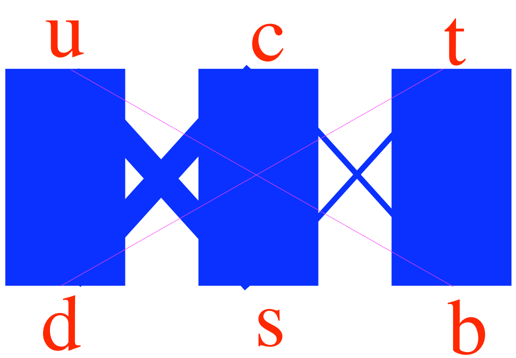
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Need complex elements in CKM matrix for CPV

- Amplitudes for $d \rightarrow u \propto V_{ud}$
- Reverse process = complex-conjugate:
  - $A(u \rightarrow d) \propto V_{ud}^*$
- CP-conjugate = complex conjugate
  - $A(\overline{d} \rightarrow \overline{u}) \propto V_{ud}^*$
  - $A(\overline{u} \rightarrow \overline{d}) \propto V_{ud}$

Structure of the CKM matrix

Quarks in SM:



CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

order in $\lambda = 0.22$

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

phases up to $\mathcal{O}(\lambda^3)$

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

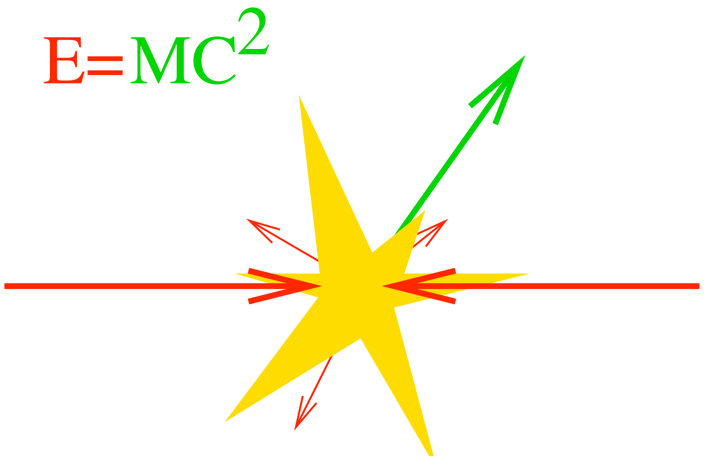
- Unitary matrix with 3 real parameters, one complex phase. This single complex phase parameterises CP Violation in SM.
- Striking hierarchical structure. Not predicted in SM, but allowed.
- Leads to Wolfenstein's idea to expand it in terms of λ.
- Up to λ^3, there are two complex elements with phases β and γ. Both β and γ are related to the aforementioned single complex phase and would vanish if it were zero.

Entry points for New Physics

2 Roads to New Physics

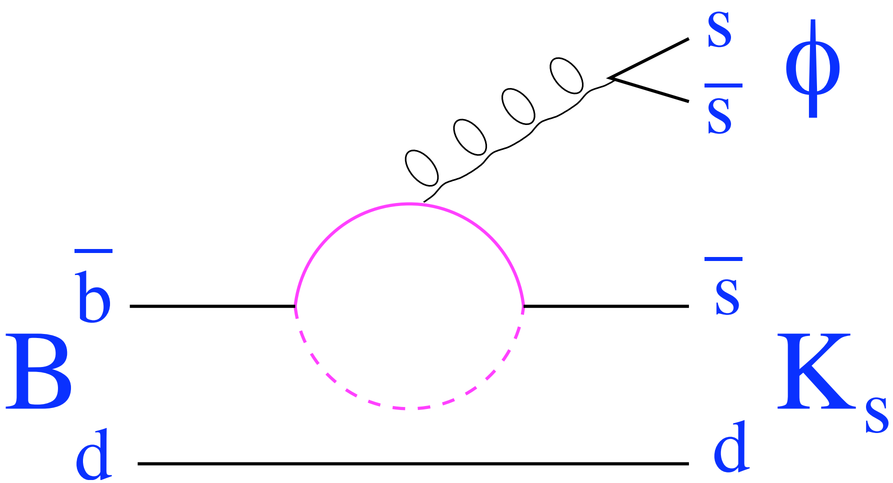
Direct Observations

Particles with $MC^2 > E$ cannot be produced directly...



Indirect effects

... but they can have an effect as virtual particles, especially in loops.



Mixing Formalism

K Anikeev et al: arXiv:hep-ph/0201071v2
Isard Dunietz, Robert Fleischer, Ulrich Nierste: arXiv:hep-ph/0012219v2
Alexander Lenz, Ulrich Nierste: arXiv:hep-ph/0612167v2

- Time evolution of B-Bbar described by Schrödinger Eq
- M = mass matrix
- Γ = decay matrix

$$|B(t)\rangle = a(t)|B\rangle + b(t)|\bar{B}\rangle$$

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}$$

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^{*} & M_{22} \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma_{22} \end{pmatrix}$$

Mixing Formalism

- In B- Bbar space:

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^{*} & M_{22} \end{pmatrix} \qquad \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma_{22} \end{pmatrix}$$

- Diagonalise (= find mass and width eigenstates):

$$M' = \begin{pmatrix} M_{H} & 0 \\ 0 & M_{L} \end{pmatrix} \qquad \Gamma' = \begin{pmatrix} \Gamma_{H} & 0 \\ 0 & \Gamma_{L} \end{pmatrix}$$

- Eigenvectors

$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle \qquad |B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$

CPV in mixing

- CPV if CP eigenstates ≠ mass eigenstates

$$\begin{aligned} CP|B_{H,L}\rangle &= \left(p|B\rangle \mp q|\bar{B}\rangle\right) \\ &= e^{i\kappa}p|\bar{B}\rangle - e^{-i\kappa}q|B\rangle \\ &= q|\bar{B}\rangle \mp p|B\rangle = \mp|B_{H,L}\rangle \ \text{ if } \frac{q}{p} = e^{i\kappa} \end{aligned}$$

- κ depends on convention. Convention-independent statement:

$$\text{No CPV in mixing} \Leftrightarrow \left|\frac{q}{p}\right| = 1 \Leftrightarrow a_{fs} = 0$$

Mixing Parameters

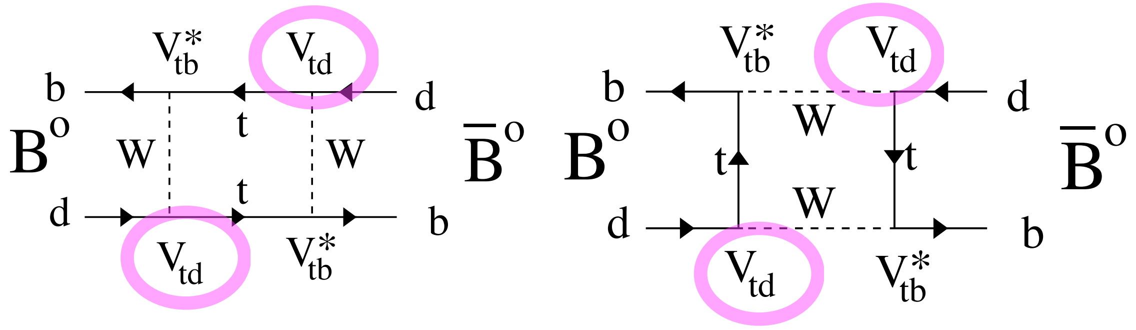
- M_{12} and ψ are sensitive to loop contributions and hence new physics
- Γ_{12} is dominated by tree contributions and therefore unlikely to be NP sensitive.

Parameter			SM (ca)
Δm_d	$\approx$	$2\left\|M_{12}^d\right\|$	$0.5ps^{-1}$
Δm_s	$\approx$	$2\left\|M_{12}^s\right\|$	$20ps^{-1}$
		$\psi_d \equiv \arg\left(-\frac{M_{12}^d}{\Gamma_{12}^d}\right)$	-0.9
		$\psi_s \equiv \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$	0.004
$\Delta\Gamma_d$	$\approx$	$\left\|\Gamma_{12}^d\right\| \cos\psi_d$	$0.003ps^{-1}$
$\Delta\Gamma_s$	$\approx$	$\left\|\Gamma_{12}^s\right\| \cos\psi_s$	$0.1ps^{-1}$
a_{fs}^d	$=$	$\frac{\Delta\Gamma_s}{\Delta m_d} \tan\psi_d$	$-5 \cdot 10^{-4}$
a_{fs}^s	$=$	$\frac{\Delta\Gamma_s}{\Delta m_s} \tan\psi_s$	$2 \cdot 10^{-5}$

Circled = New Physics Sensitive

Bd Mixing in the SM

- Mediated by mixing diagrams (here for Bd):



- both box diagrams $\propto (V_{tb}^* V_{td})^2 \propto e^{-i2\beta}$
- So in the SM, in this phase convention, $\frac{q}{p} \propto e^{-i2\beta}$
- This is a CPV phase, and it occurs in B mixing, however, it is not CP violation in the mixing.

Mixing Phases

- There's $\psi_{d,s}$ as in $a_{fs} = \frac{\Delta\Gamma_{d,s}}{\Delta m_{d,s}} \tan\psi_{d,s}$. This is a convention-independent variable that parameterises CPV in mixing. In the SM, it is very small in both the B_d and the B_s system.
- The mixing phase 2β is the phase of the Bd mixing diagram relative to the tree-level amplitude $B_d \to J/\psi Ks$ and similar decays, in the SM. β is large (21°). The equivalent in the Bs system, $-\beta_s$ or $-\chi$ is very small ($\beta_s \sim 1^o$) .
- $\phi_{d,s}$ is the actual mixing phase, including possible NP-induced phases $\phi_{d,s} = \mp 2\beta_{d,s} + \phi_{d,s}^{NP}$.

Phases in the Bs system

- In the Bs system all of the SM phases mentioned above are essentially zero.
- With the following assumption: NP phases affect M_{12} and not Γ_{12}, and using $M_{12} \gg \Gamma_{12}$, we get for the Bs system:

$$\psi_s \approx \phi_s \approx \phi_s^{NP}$$

- Note that these three phases are conceptually still different and that this does not work for the Bd system. It works only because the SM phases related to Bs mixing are all ~0.
- It is this absence of SM phases in mixing that makes the Bs system a particularly sensitive probe for NP.

The basic CPV and Mixing Measurement

- Want to measure

$$A(t) = \frac{N(B \to f) - N(\bar{B} \to f)}{N(B \to f) + N(\bar{B} \to f)} = C_f \cos(\Delta m\, t) + S_f \sin(\Delta m\, t)$$

Disclaimer: For simplicity, we neglected a few terms that should be taken into account for CPV in Bs.
This also does not take into account detector effects etc.

- For B-mixing measurements, f is a flavour-specific final state, which only B can decay to it, but not B-bar (C=1, S=0)

  For f-bar, we'd measure A(t)=1-cos(Δmt)

- For CPV measurements, f is often (but not necessarily) a CP eigenstate (no CPV → A(t)=0)

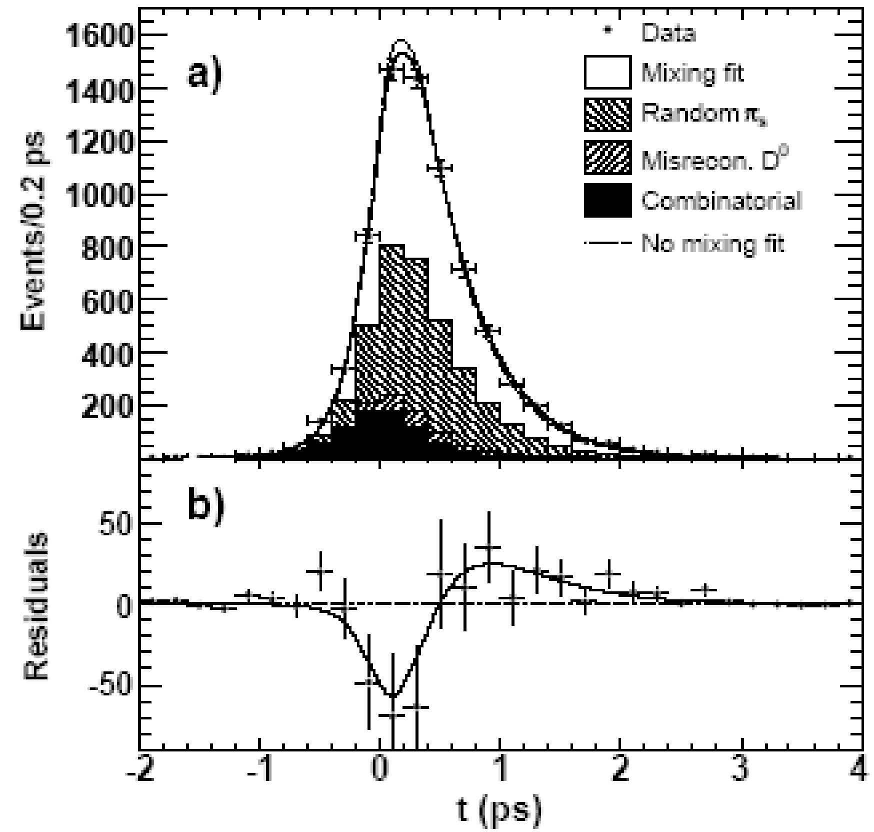
- Need to know flavour (B or B-bar) at t=0.

- Get decay time from decay distance and momentum.

Mixing... everybody does it

March 2007: D0 mix, too.

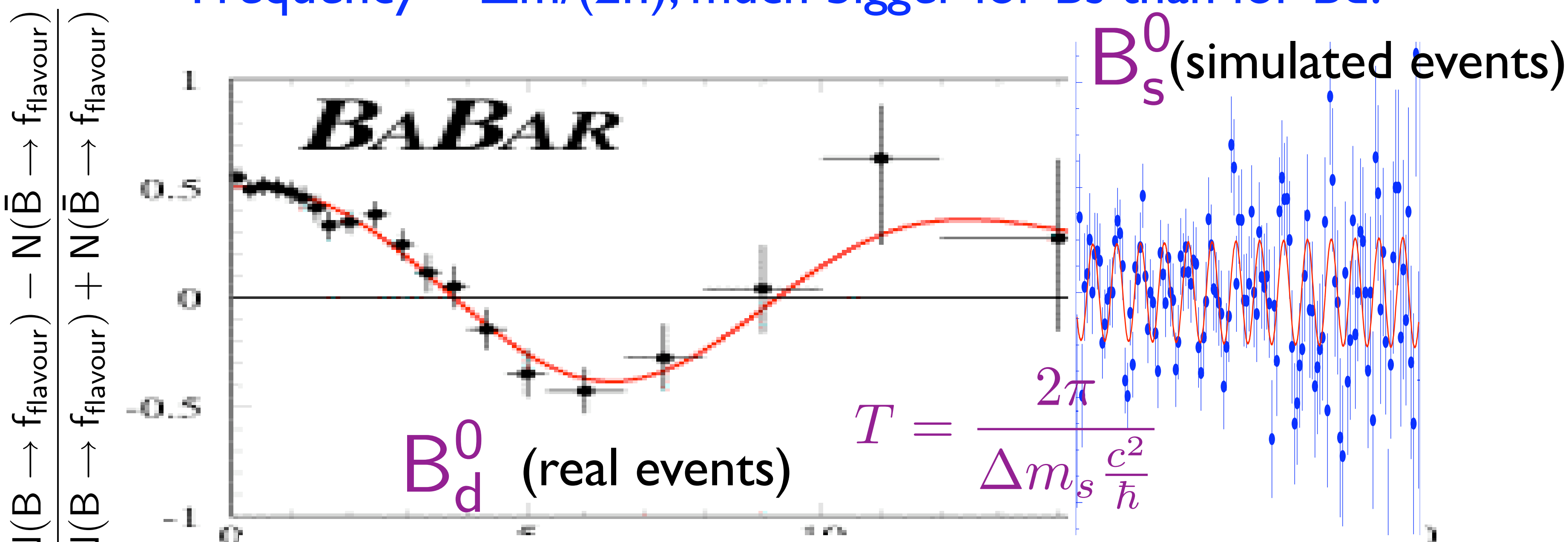
- Neutral Kaons $(\bar{s},d)$ do it
- Neutral Bd mesons $(\bar{b},d)$ do it
- Neutral Bs mesons $(\bar{b},s)$ do it.
- And since March we know that neutral D0 mesons $(c,\bar{d})$ do it, too.



BaBar

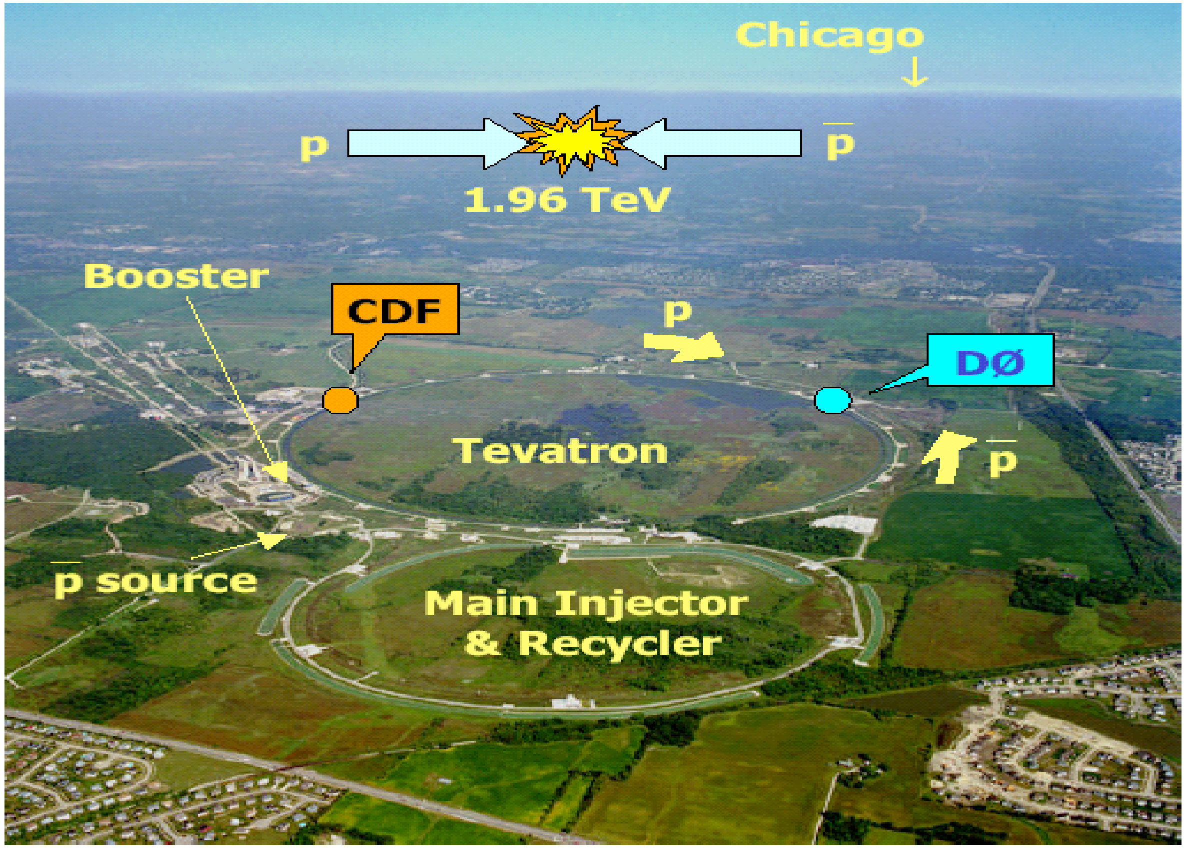
B mixing

- B mixing is best observed in decays to flavour eigenstates
- It is measured in time-dependent decay rate asymmetries.
- Frequency = $\Delta m/(2\pi)$, much bigger for Bs than for Bd.



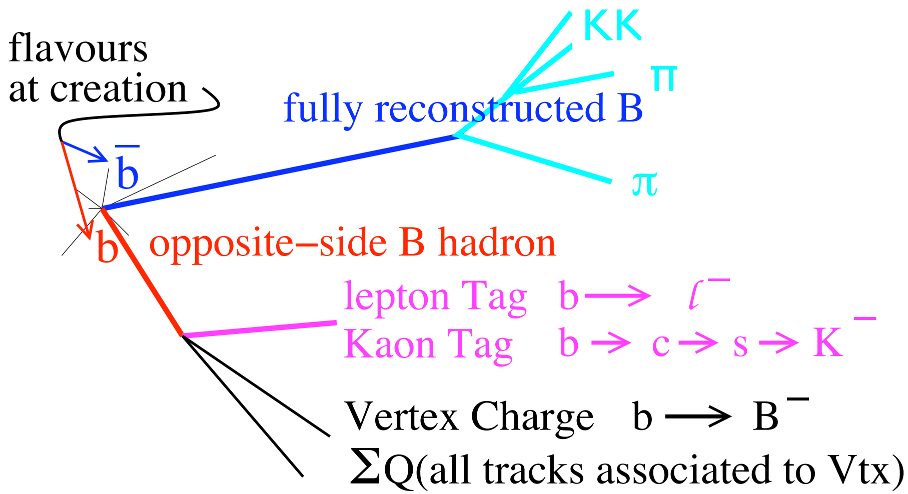
Bd:T ~ 12.6ps   Bs:T << 1ps

Tevatron

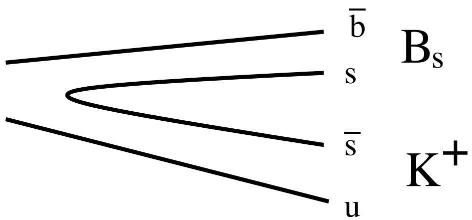


- Run II started mid 2001
- p – p̄ collisions at $E_{cm} = 1.96$ TeV
- 2.5M collisions per second. $\sim 2,500$ $b\bar{b}$ pairs per second. $\times 2$.
- Make all kinds of B's. Only source of significant number of B_s mesons.

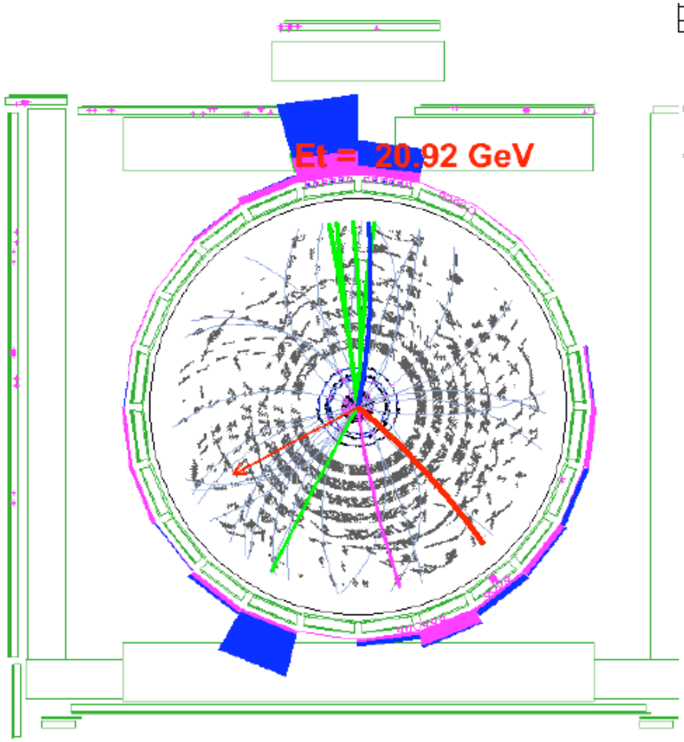
Measurement Principle



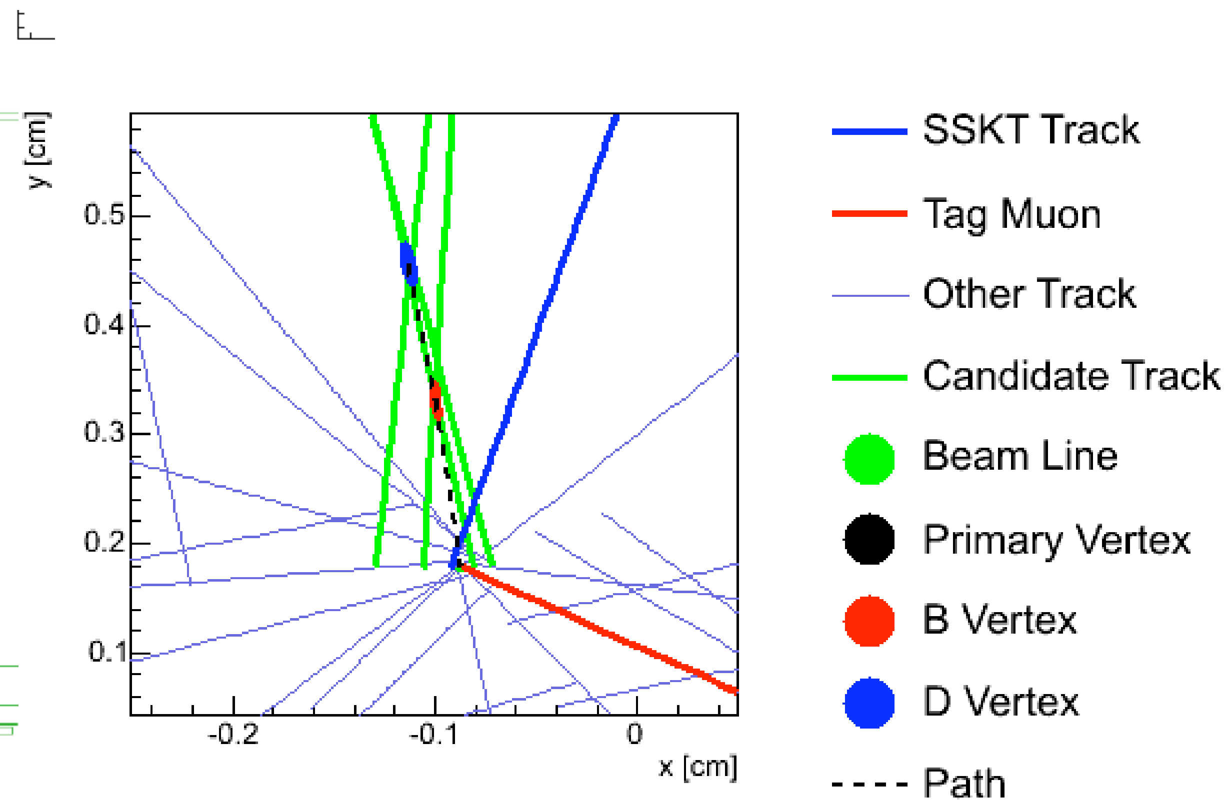
Same Side Kaon Tag (B_s)



A Bs→Ds(Φ(KK)π) π event at CDF



CDF Tracker



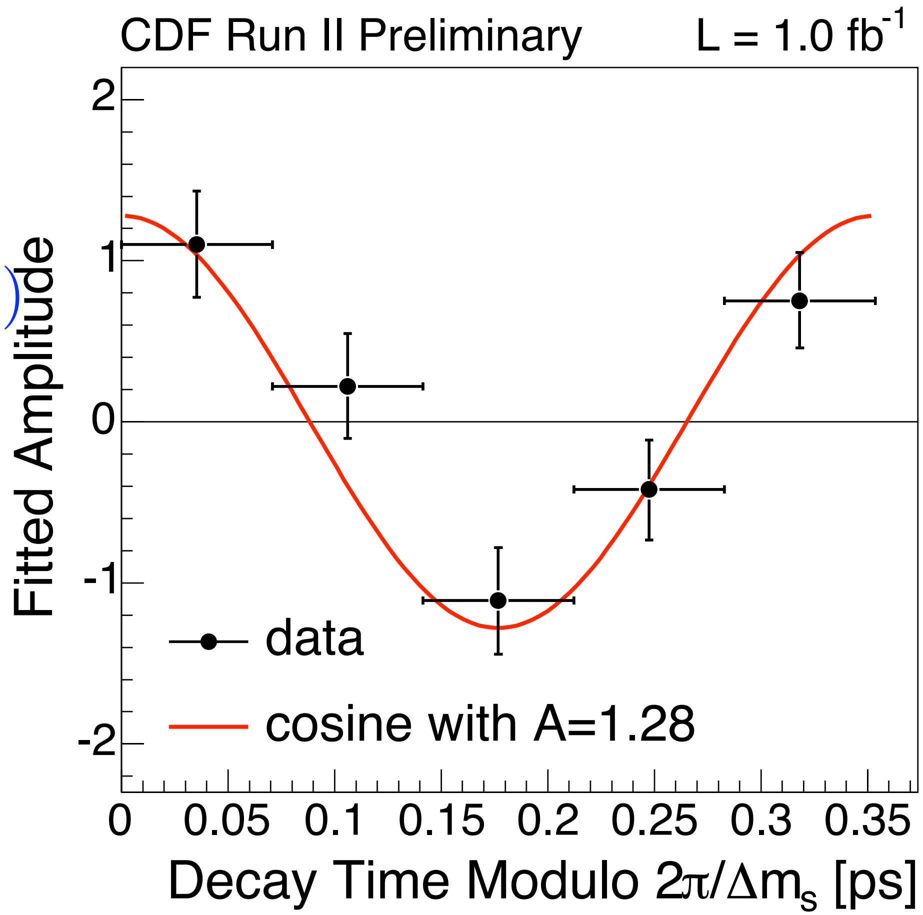
Inside the beampipe

Result

- $\Delta m_s^{(CDF)} = 17.77 ps^{-1}$
  $\pm 0.10 ps^{-1} (stat) \pm 0.07 ps^{-1} (sys)$

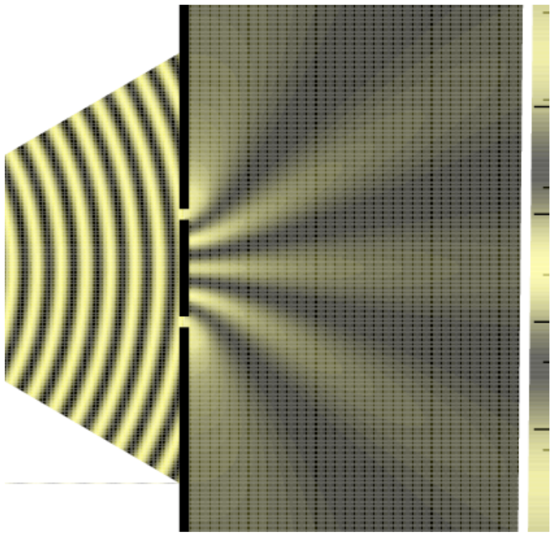
- Compare to SM prediction from other measurements (CKM fitter):

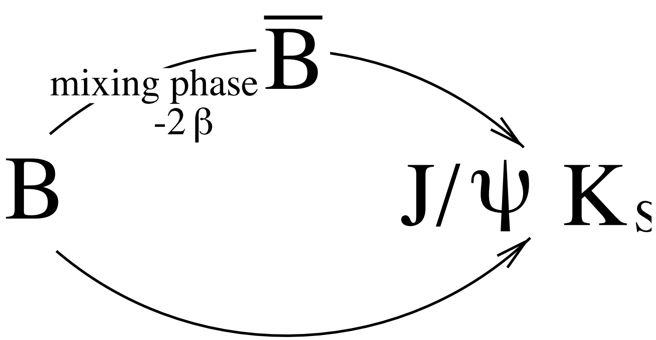
  $\Delta m_s^{(SM)} = 23.4^{+4.1}_{-4.9}\ ps^{-1}$



period T ~ 0.35ps
(compare Bd: T ~13ps)

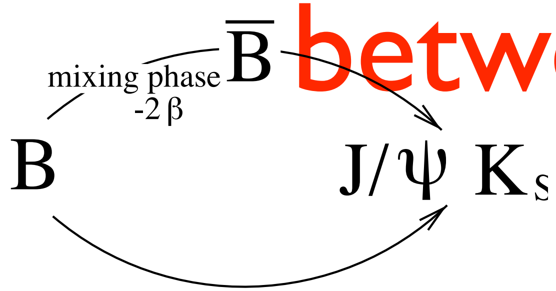
CPV in the interference between mixing and decay

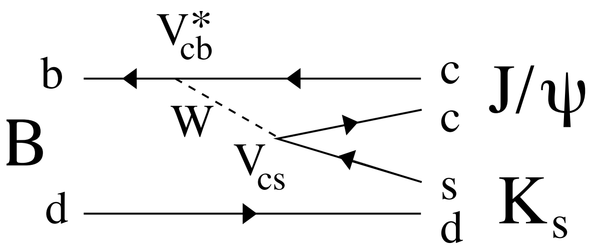




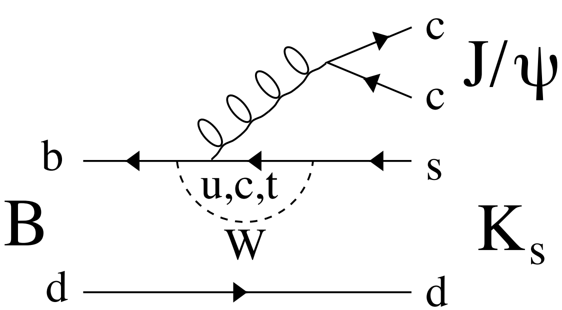
- The basic principle of all CPV measurements is the same: Two or more decay paths to the same final state interfere.
- The measurable CPV quantity is the phase difference between those paths.

CP Violation in the interference between mixing and decay





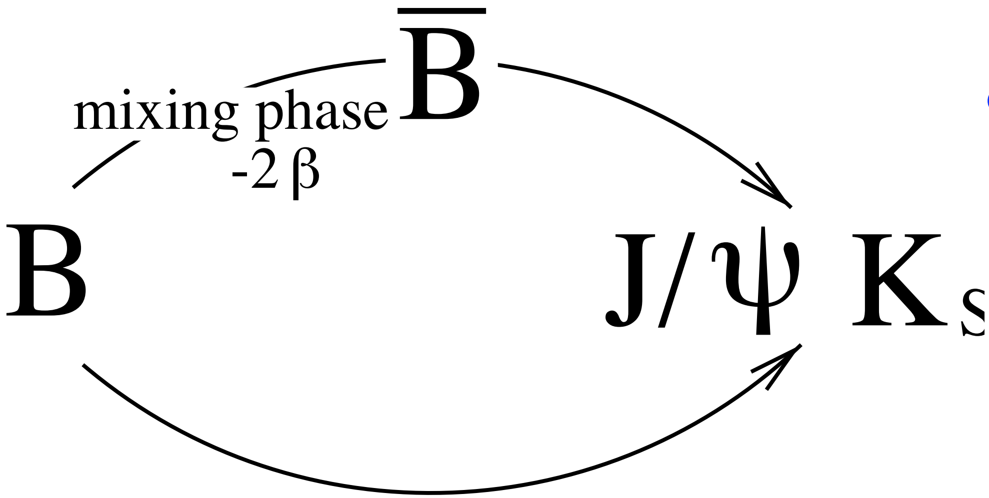
tree diagram: all CKM elements real, so phase = 0



Penguin diagram more tricky. Can ignore contribution from lightest quark, u, in loop (heavy is good in loop). Then CKM elements involved: $V_{ts}, V^*_{tb}, V_{cs}, V^*_{cb}$, all real, so phase = 0.

Both amplitudes involved in decay have same phase 0, so their sum has phase 0

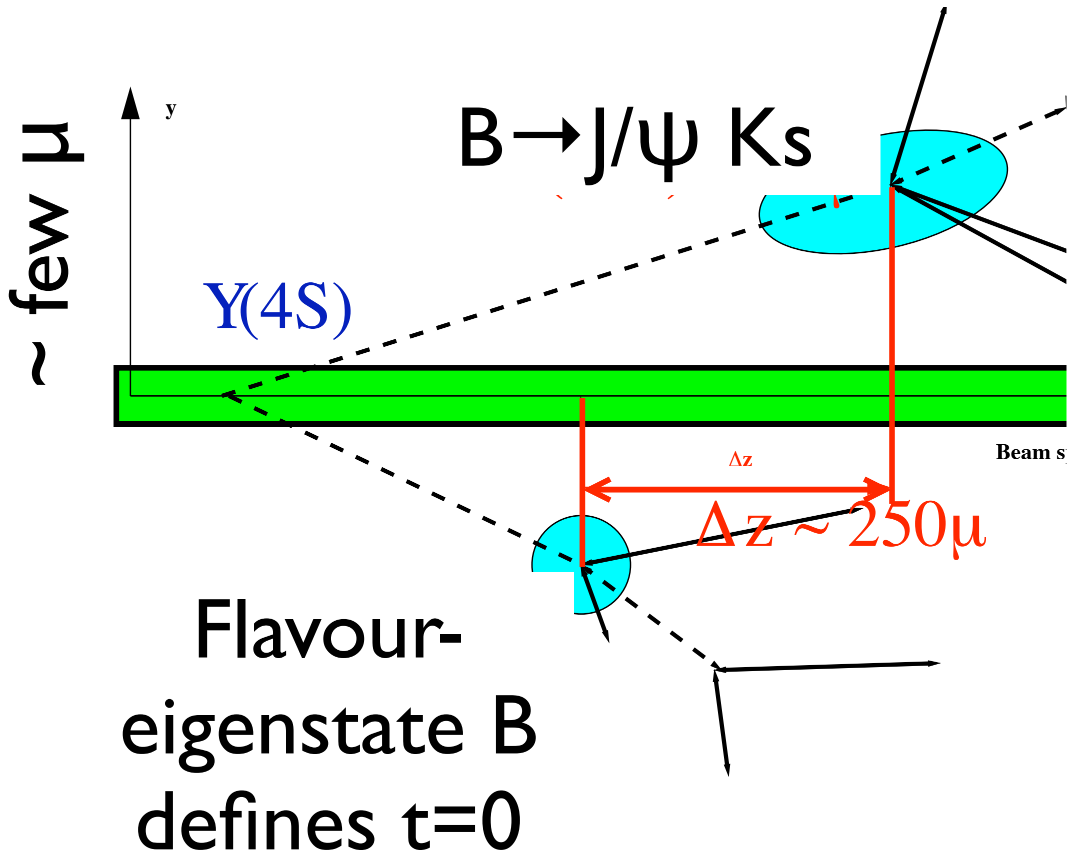
sin2β



- The amplitude of the CP violating asymmetry is the sine of the phase difference between the decay paths.

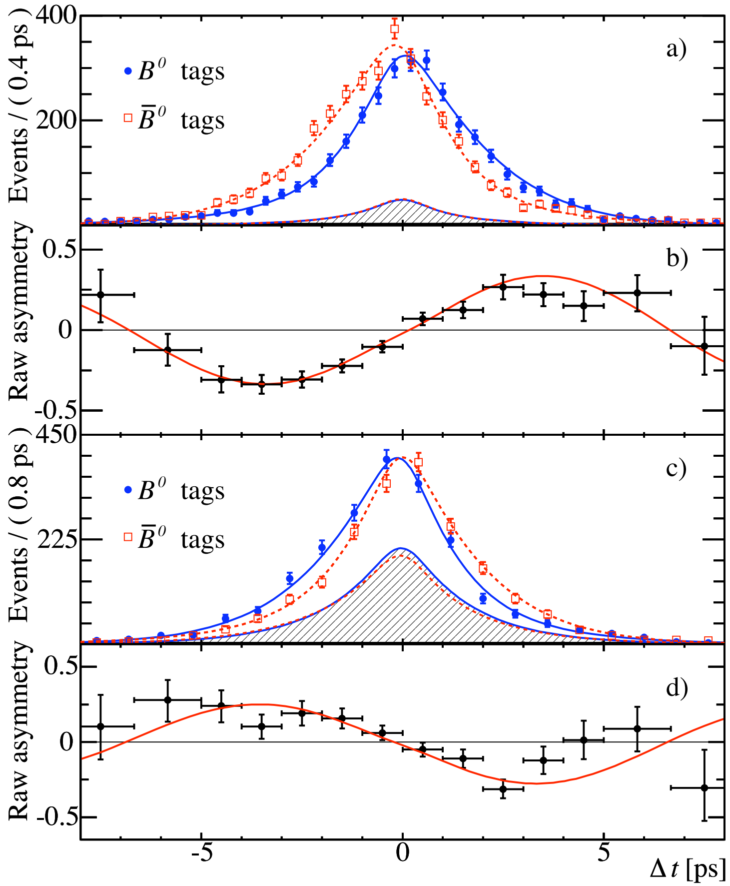
$$A(t) = \frac{N(B \to J/\psi K_s)(t) - N(\bar{B} \to J/\psi K_s)(t)}{N(B \to J/\psi K_s)(t) + N(\bar{B} \to J/\psi K_s)(t)}$$
$$= \sin(2\beta)\ \sin(\Delta m_d\, t)$$

At the B-factories



- Decay of B to flavour state defines t=0.
- Due to quantum entanglement, the other B is opposite flavour at t=0.
- Get time difference from difference in z.

Latest Result from BaBar and BELLE (updates from March 07)



- A combination of CP-odd J/ψX modes, J/ψ Ks being the main contribution. To plot.
- Also J/ψ K-long with opposite CP - bottom plot
- <BaBar, BELLE> 0.678 ± 0.025 (Average by HFAG)
- SM prediction from other measurements: $0.799^{+0.044}_{-0.094}$ (CKMFitter)
- More on sin2β in Adrian's talk.

The Bs system and φ_s

$$
\begin{array}{rcl}
\hline\hline
S_{J/\psi\phi} & = & \sin\left(-2\beta_s + \phi_s^{NP}\right) \\
\hline
\Delta\Gamma_s & = & \left|\Gamma_{12}^s\right| \cos\left(\psi_s + \phi_s^{NP}\right) \\
\hline
a_{fs}^s & = & \frac{\Delta\Gamma_s}{\Delta m_s} \tan\left(\psi_s + \phi_s^{NP}\right) \\
\hline\hline
\end{array}
$$

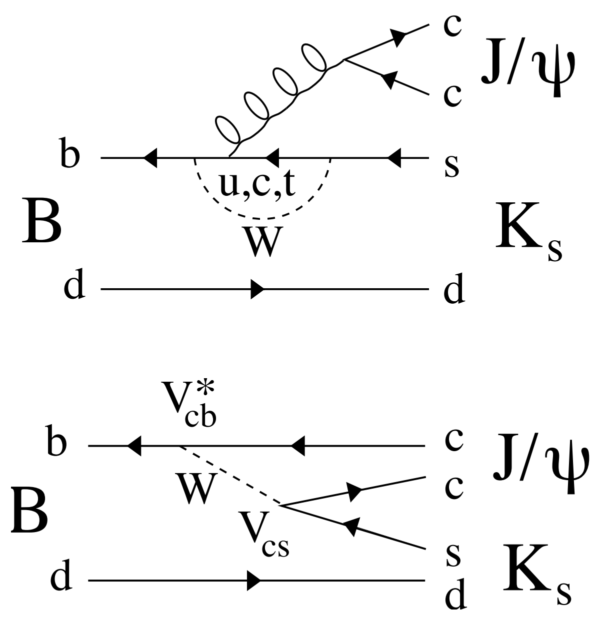
$\beta_s \approx 0.02$

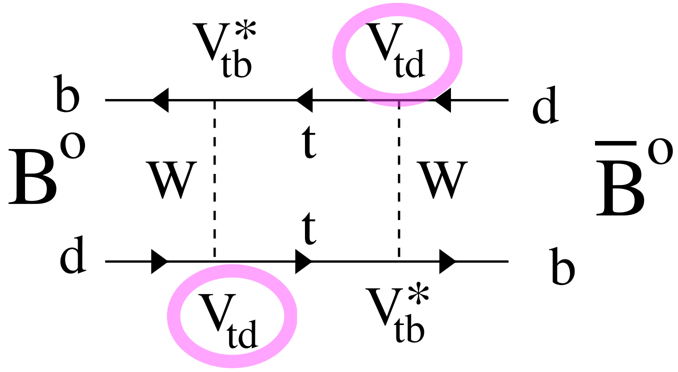
$\psi_s \approx 0.004$

- The phases involved in Bs mixing in the SM are essentially zero. So if we measure something, it'll be NP (for now at least - LHCb should soon be sensitive to β_s)
- Measure effectively the same NP phase in many different ways - CPV in J/ψΦ, angular correlations in J/ψΦ, ΔΓ, CP in mixinig (a_{fs} or A^s_{sl}). Usually its simply called ϕ_s .

CPV in J/ψ Φ

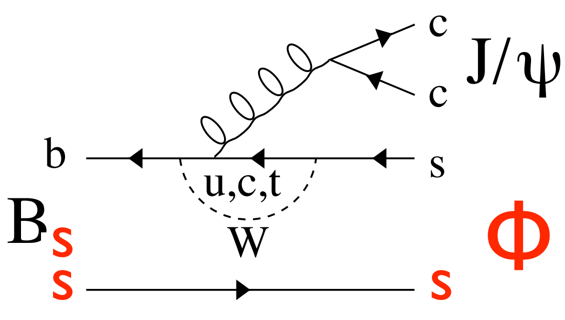
- Same thing works for Bs, just replace d with s quark.

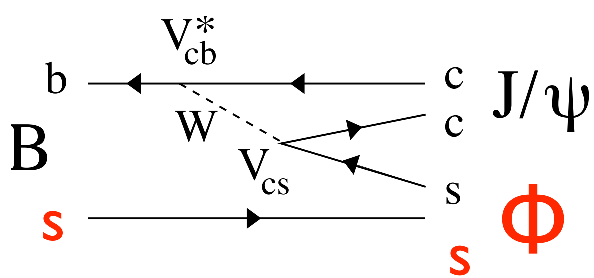


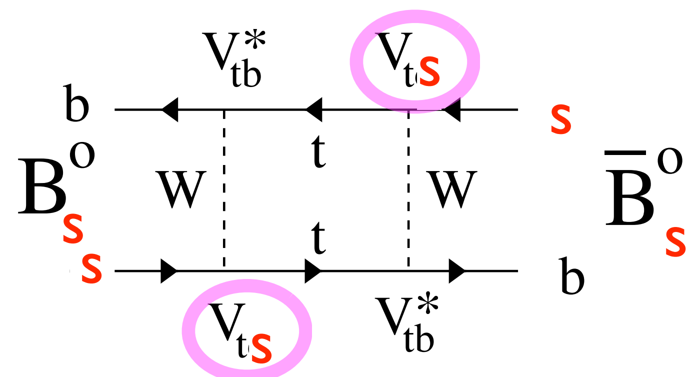


CPV in J/ψ Φ

- Same thing works for Bs, just replace d with s quark.
- (there are some additional complications - see later)







ΔΓ

- ΔΓ = width (inverse lifetime) difference between Bh and Bl
- No CPV in mixing, so it's also the width difference between B-even and B-odd.
- ΔΓd is too small to be measured in the near future, expect no enhancement from NP (rather the opposite). Let's focus on ΔΓs.

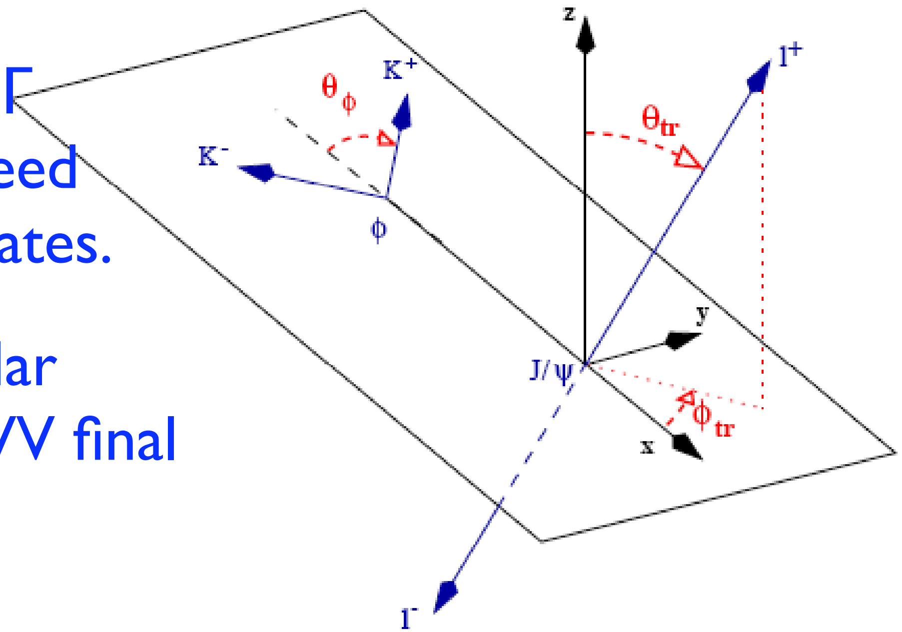
Parameter			SM (ca)
Δm_d	$\approx$	$2\left\|M_{12}^d\right\|$	$0.5ps^{-1}$
Δm_s	$\approx$	$2\left\|M_{12}^s\right\|$	$20ps^{-1}$
ψ_d	$\equiv$	$\arg\left(-\frac{M_{12}^d}{\Gamma_{12}^d}\right)$	$-0.9 = -5^o$
ψ_s	$\equiv$	$\arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$	$0.004 = 0.2^o$
$\Delta\Gamma_d$	$\approx$	$\left\|\Gamma_{12}^d\right\| \cos\psi_d$	$0.003ps^{-1}$
$\Delta\Gamma_s$	$\approx$	$\left\|\Gamma_{12}^s\right\| \cos\psi_s$	$0.1ps^{-1}$
a_{fs}^d	$=$	$\frac{\Delta\Gamma_s}{\Delta m_d}\tan\psi_d$	$-5\cdot10^{-4}$
a_{fs}^s	$=$	$\frac{\Delta\Gamma_s}{\Delta m_s}\tan\psi_s$	$2\cdot10^{-5}$

Measuring $\Delta\Gamma$

- Option 1: Fit two exponentials to CP-mixed state (flavour eigenstate). Drawback: Needs huge statistics.
- Option 2: Fit lifetimes using decays to CP eigenstates
  - A bit problematic because of CPV - not only CP-even Bs can decay to CP even final state.
  - But because the mixing phase in the Bs system is so tiny, this effect is small for decays that are not affected by other CKM phases - e.g. J/ψΦ. And it can be quantified: $\Delta\Gamma^{\mathrm{meas}} = \Delta\Gamma\cos(\phi_s)$
  - This is for $B_s \to J/\psi\phi$ and similar. If additional phases contribute (like in $B_s \to KK$) they further reduce $\Delta\Gamma_s^{\mathrm{meas}}$

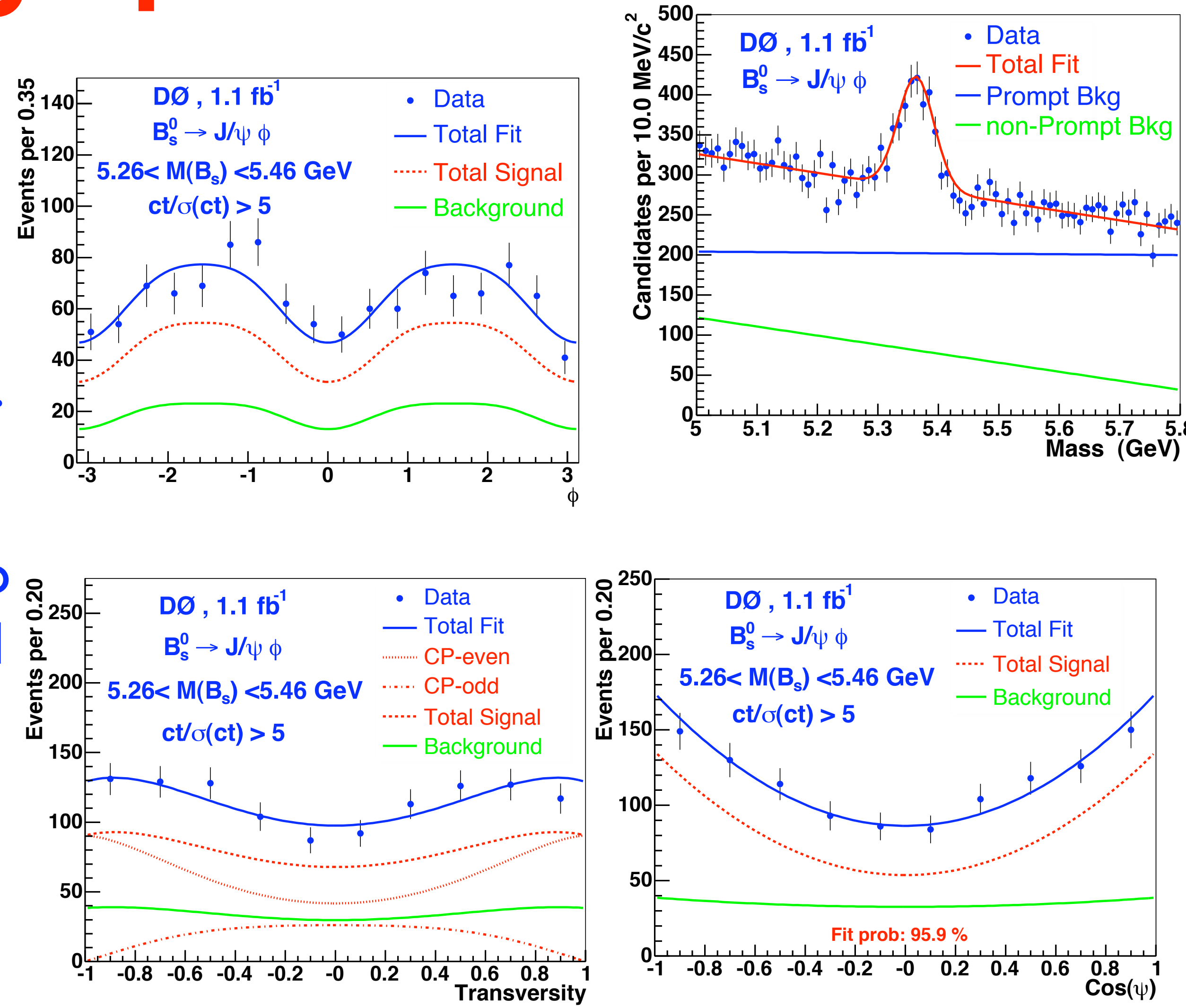
$B_s \rightarrow J/\psi\Phi$

- For both, CPV and $\Delta\Gamma$ measurements, we need decays to CP eigenstates.
- CP depends on angular momentum state of VV final state.
- Angular analyses can disentangle different angular momentum/CP states.



Bs→J/ψΦ at DØ

- DØ recently did such an analysis to measure ΔΓ and Φs.
- The plots on the right are their fits to mass (top-right) and the angular distributions.



PRL 98, 121801 (2007)

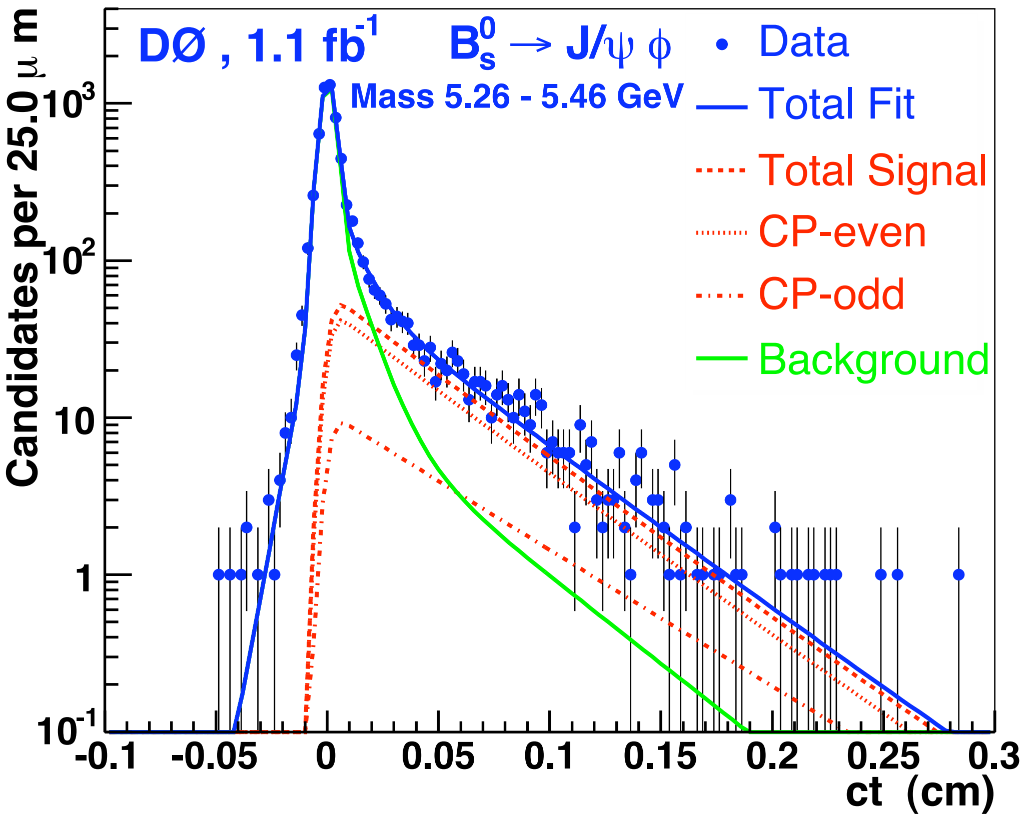
Bs→J/ψΦ at DØ

- Result of lifetime fit with φs=0:

  $\Delta\Gamma = 0.12^{+0.08}_{-0.10}$ ps^{-1}

- Fitting φs

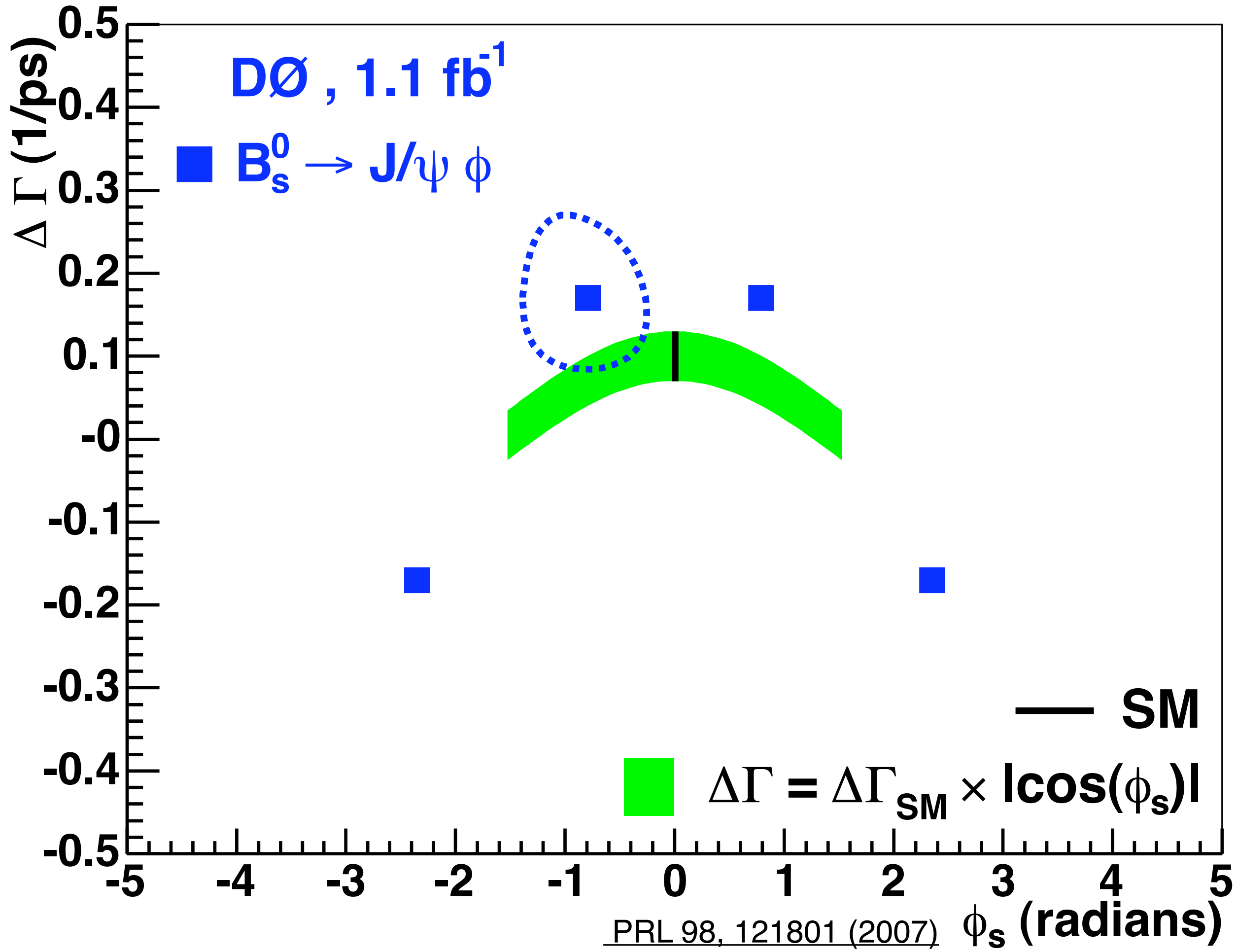
  $\phi_s = -0.8 \pm 0.6$



PRL 98, 121801 (2007)

Bs→J/ψΦ at DØ

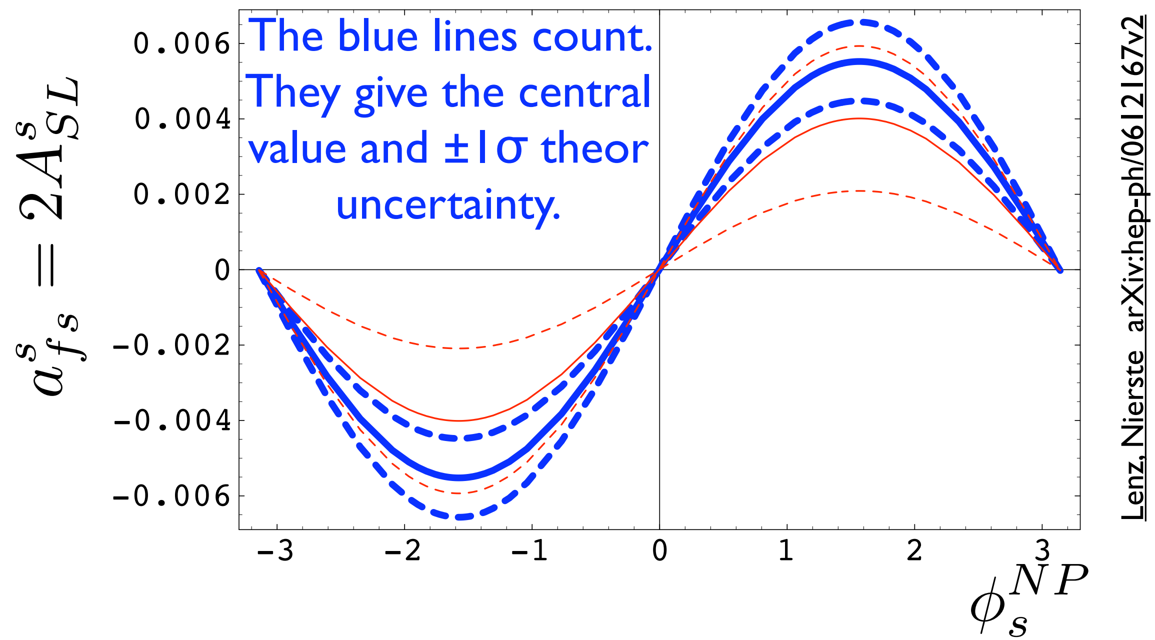
- DØ's result in φ-ΔΓ space.



PRL 98, 121801 (2007)

CPV in mixing

$$a_{fs} = 2\left(1 - \left|\frac{q}{p}\right|\right) = \frac{\Delta\Gamma}{\Delta m}\tan\left(\psi + \phi^{NP}\right)$$



Measurements (B-factories and DØ, some very recent results!)

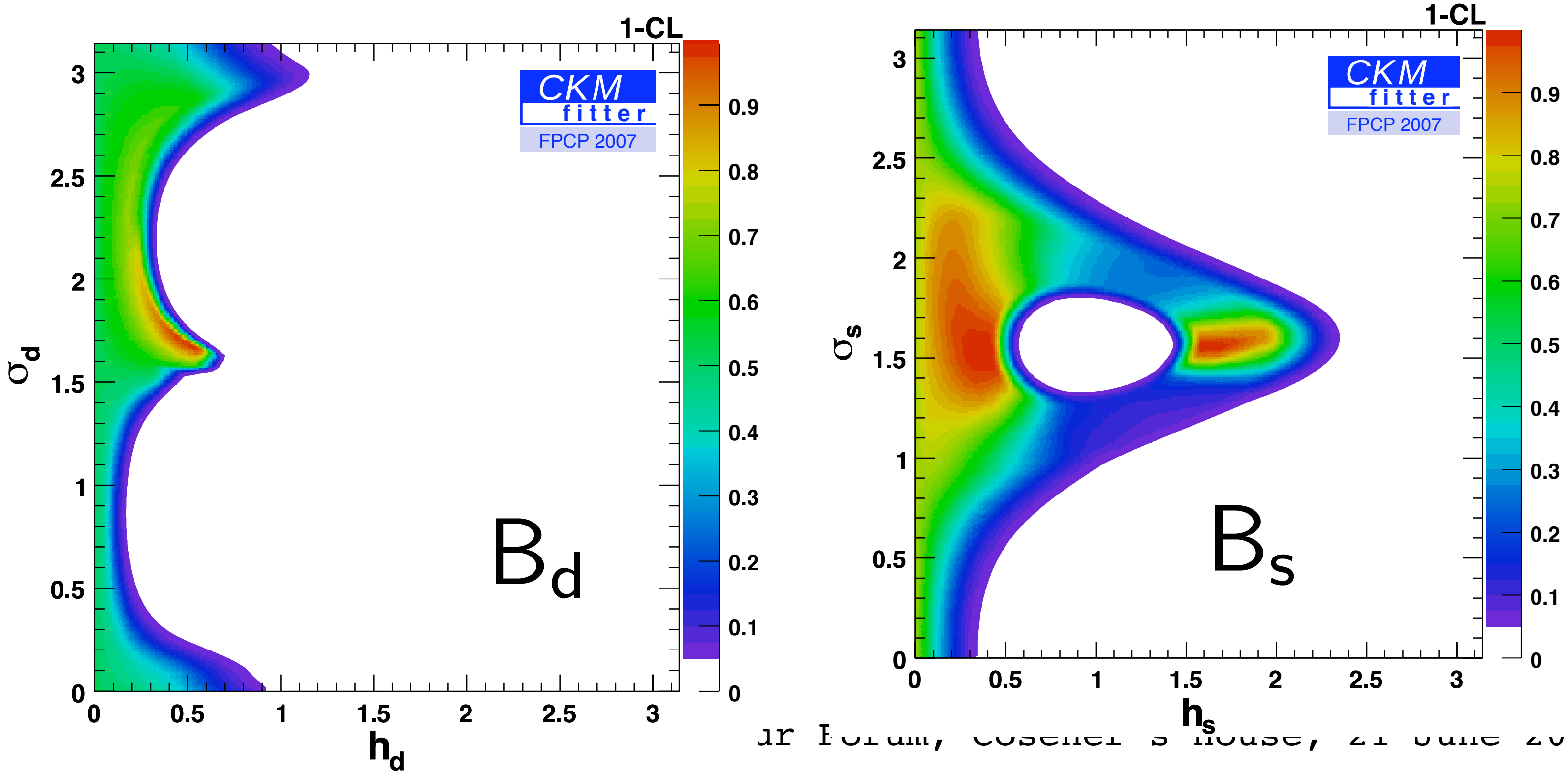
$$\mathcal{A}^d_{\mathrm{SL}} = -0.0047 \pm 0.0046 \qquad \mathcal{A}^s_{\mathrm{SL}} = +0.0003 \pm 0.0093$$

What Next?

- Now and very near future:
  - B factories keep improving results in Bd sector - but for the really interesting issues in Bd see Adrian's talk.
  - New results in Bs system ($\Delta\Gamma$, φs in $Bs \rightarrow J/\psi\ \Phi$) are in the pipeline at Tevatron. Will have 8× as much data at the end of Run II, so ~16× the stats relative to DØ result shown.
- Near future (start next year): LHCb. Huge numbers of Bs (and Bd), precision measurements of $\Delta\Gamma$, Φs, a_{fs} and much more.
- A bit more speculative:
  - Medium/long term: Upgraded LHCb: Very precise Φs, a^{s}_{fs}
  - Long term: Super B factory, e.g. for a^{d}_{fs} , phps a^{s}_{fs}

New Physics Constraints

- Parameterise NP as: $M_{12}^{q} = (1 + h_q e^{2i\sigma_q}) M_{12}^{q,\mathrm{SM}}$
- This implies: $\phi_s^{NP} = \arg\left(1 + h_s e^{2i\sigma_s}\right)$

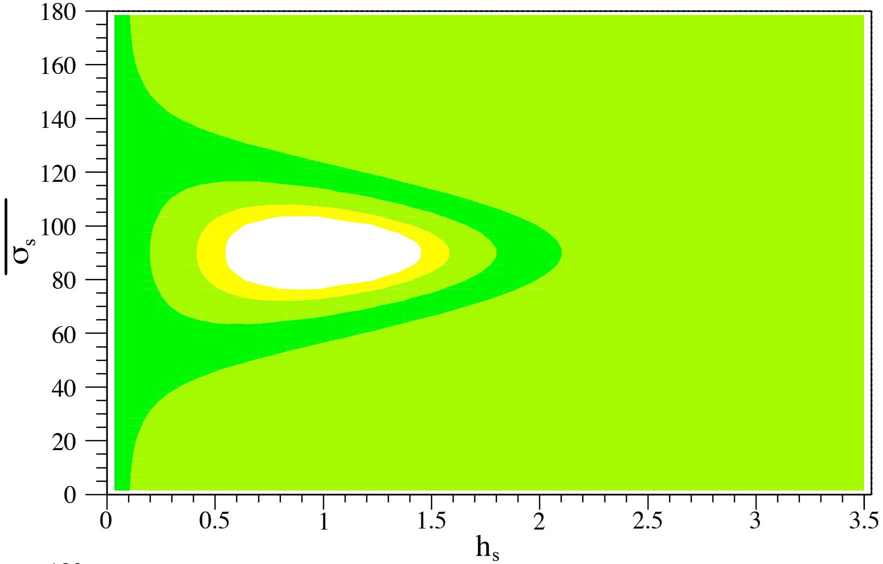


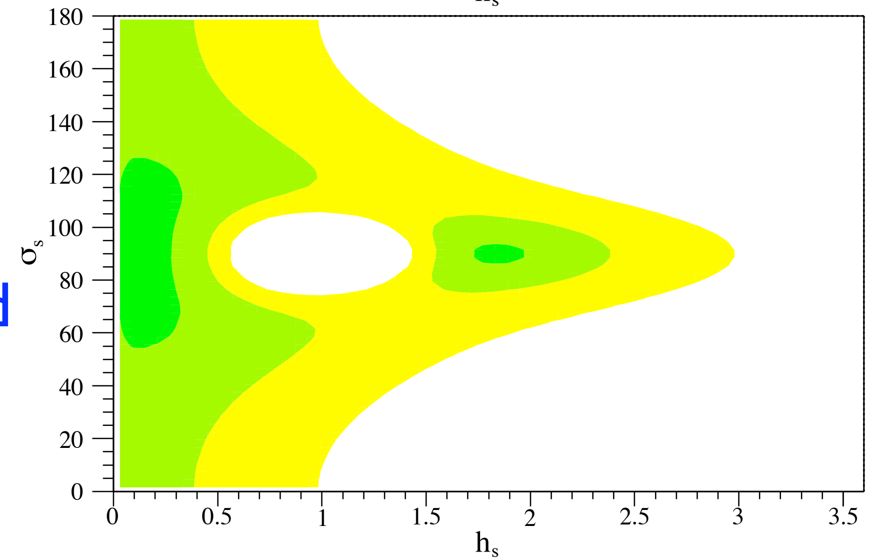
Impact of Δm_s

- Parameterise NP as:

$$\Delta m_q = \Delta m_q^{\rm SM}\left|1 + h_q e^{2i\sigma_q}\right|$$

- Constrains in the h-σ plane before and after the CDF's (first) Bs mixing measurement.
- Δms measurement pretty much as expected by SM, but reduces NP parameter space

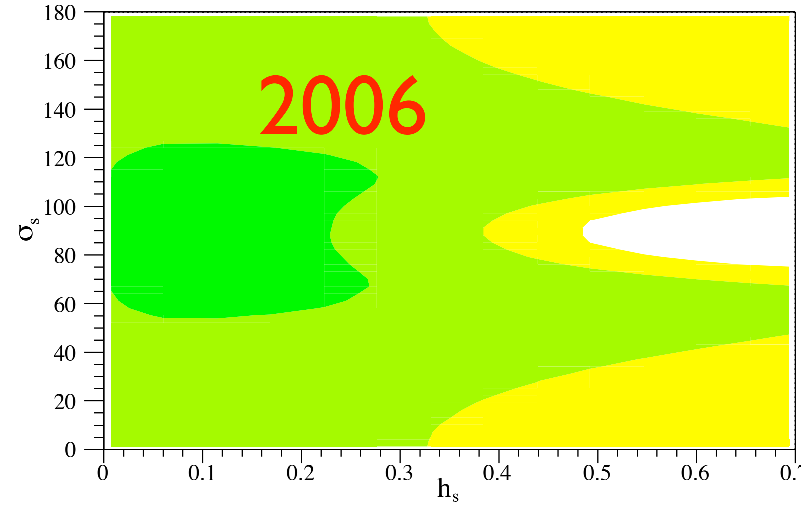




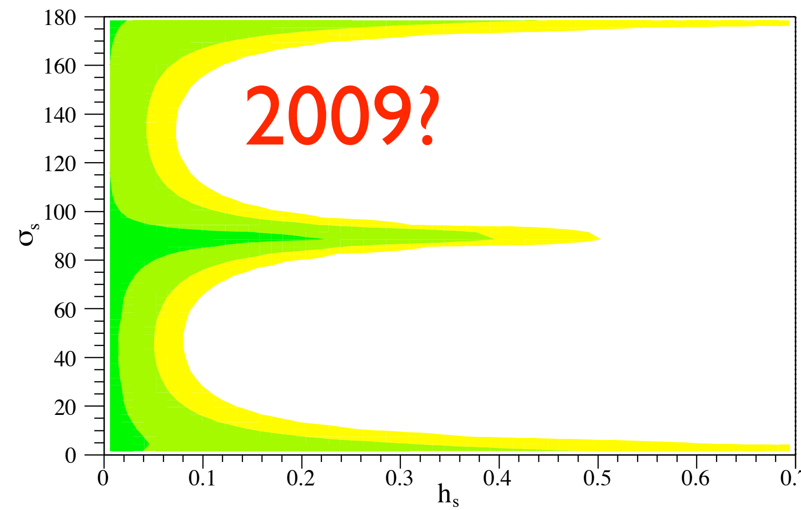
arXiv:hep-ph/0604112v3
Zoltan Ligeti, Michele Papucci, Gilad Perez

Impact of LHCb's Φ sensitivity
(for 2/fb = nominal year)

- Top plot shows NP constraints in 2006 (incl CDF's Δm)
- Bottom plot for a hypothetical LHCb measurement of $\phi_s = 0.04 \pm 0.03$
- Projected LHCb sensitivity for 2/fb: $\sigma(\phi_s) = 0.02$



arXiv:hep-ph/0604112v3
(copied, scaled and otherwise altered and manipulated by JR)



arXiv:hep-ph/0604112v3

Summary

$\sin(2\beta), \Delta m_d, \Delta\Gamma_d, a^d_{fs}$ $\sin(\phi_s), \Delta m_s, \Delta\Gamma_s, a^s_{fs}$

✓ = measured precisely and >3σ above zero

☟ = unknown and highly sensitive to New Physics

Outlook for NP

$\sin(2\beta), \Delta m_d, \Delta\Gamma_d, a^d_{fs}$ $\sin(\phi_s), \Delta m_s, \Delta\Gamma_s, a^s_{fs}$

- Because SM phases involved in B_s mixing* are so tiny, it's esp. sensitive to NP. $\sin(\phi_s), \Delta\Gamma, a^s_{fs}$ all depend on same ϕ_s^{NP}
- Expect significant improvements on $(\Delta\Gamma_s, \phi_s)$ from Tevatron. But non-zero ϕ_s measurement possible only for very large NP phase. Would be a welcome surprise!
- LHCb (~2009) Precise $\Delta\Gamma_s$ and especially ϕ_s down to SM value with high NP-sensitivity. Expect also NP-sensitivity in a^s_{fs}
- NP hints in B_d not so likely to come from $\Delta\Gamma_d, a^d_{fs}$ in near future - but watch out for sin2β in Adrian's talk.

*Not all SM CPV phases in the Bs sector are small. The CKM phase γ is large in the SM and is an important parameter to be measured in both Bd and Bs decays - see next talk.

Backup

Status Summary

$\sin(2\beta), \Delta m_d, \Delta\Gamma_d, a^d_{fs}$ $\sin(\phi_s), \Delta m_s, \Delta\Gamma_s, a^s_{fs}$

✓ = measured precisely and >3σ above zero

☟ = unknown and highly sensitive to New Physics

- Bd: Δm_d and especially $\sin 2\beta$ measured precisely at B-factories. Measurements/limits on $\Delta\Gamma_d, a^d_{fs}$ exists, none significantly above zero.
- Bs: Δm_s measured recently. Paramter-space for others limited, but no precise measurements, yet.

Event Sample

- 5600 full reconstructed hadronic $B_s \to D_s \pi$ decays,
- 3100 partially reconstructed hadronic Bs decays, and
- 61500 partially reconstructed semileptonic $B_s \to D_s\, l\, \nu\, X$ decays
- Best time resolution from hadronic decays. Need momentum to reconstruct decay time from decay distance. Missing momentum in semileptonic decays deteriorates time resolution.

CPV in mixing

$$a_{fs} = 2\left(1 - \left|\frac{q}{p}\right|\right) = \frac{\Delta\Gamma}{\Delta m}\tan\left(\psi + \phi^{NP}\right)$$

- Measure in untagged time-integrated decay rate asymmetries to flavour-specific decays, usually semileptonic:

$$A_{SL}^{s,unt} = \frac{N(\mu^+ D_s^-) - N(\mu^- D_s^+)}{N(\mu^+ D_s^-) + N(\mu^- D_s^+)} = \frac{a_{fs}^s}{2}$$

- Get higher stats (but more difficult systematics) w/o reconstructing Ds, but measuring the di-muon asymmetry:

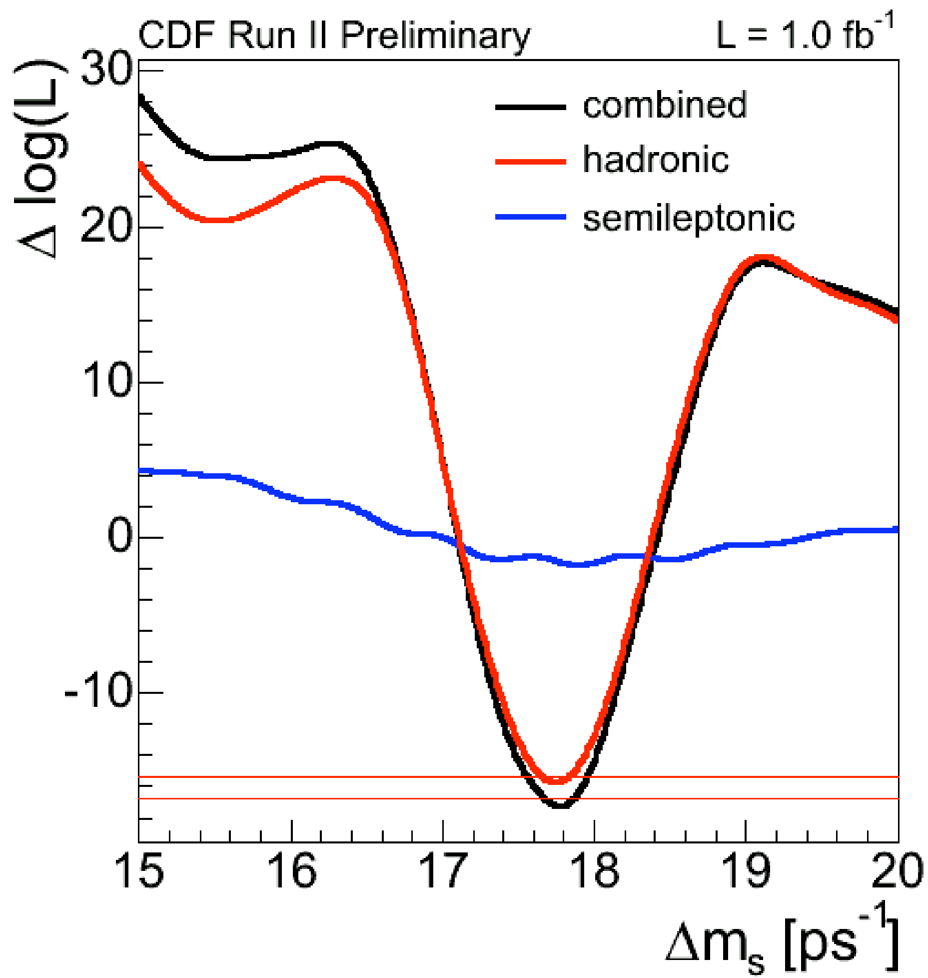
$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- Current state of affairs (mainly B-factories and Tevatron)

$$\mathcal{A}_{\rm SL}^{d} = -0.0047 \pm 0.0046 \qquad \mathcal{A}_{\rm SL}^{s} = +0.0003 \pm 0.0093$$

Likelihood for hadronic/ semileptonic

- Fully reconstructed hadronic decays < 10% of data sample.
- But nearly 100% of mixing measurement.
- Reason: No missing momentum→Better time resolution.
- Crucial detector element: Hadronic B trigger.



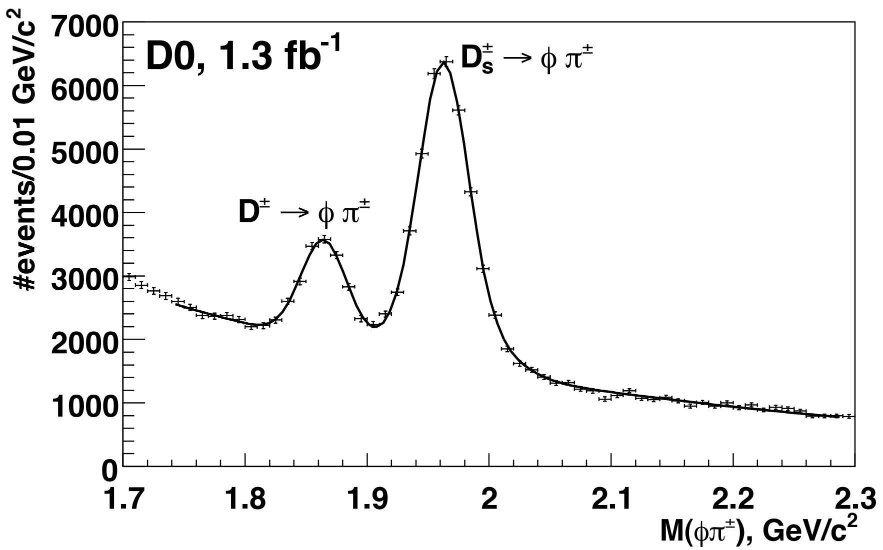
DØ's direct Asl measurement

- DØ measured afs from 27k B→(Ds→Φπ)μ events.

$$a_{fs} = 2\left(1 - \left|\frac{q}{p}\right|\right) = \frac{\Delta\Gamma}{\Delta m}\tan\psi$$

$$A_{SL}^{s,unt} = \frac{N(\mu^+ D_s^-) - N(\mu^- D_s^+)}{N(\mu^+ D_s^-) + N(\mu^- D_s^+)} = \frac{a_{fs}^s}{2}$$

- Systematic error from detection asymmetry controlled by frequently switching the magnetic field.



PRL 98, 151801 (2007)

$$A_{SL}^{s,unt} = [1.23 \pm 0.97\,(\text{stat}) \pm 0.17\,(\text{syst})] \times 10^{-2}.$$

Indirect measurements

- Di-muon asymmetry (measures a combination of A_{sl}^{s}, A_{sl}^{d}

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- DØ

$$\frac{1}{4}\left(\mathcal{A}_{\mathrm{SL}}^{d} + \mathcal{A}_{\mathrm{SL}}^{s}\frac{f_s'\chi_s}{f_d'\chi_d}\right) = -0.0023 \pm 0.0011(\mathrm{stat}) \pm 0.0008(\mathrm{syst})$$

- CDF

$$f_d'\,\chi_d(1 - |q/p|_d^2) + f_s'\,\chi_s(1 - |q/p|_s^2) = +0.006 \pm 0.017$$

- Combine this and result for and PDG for other parameters HFAG get $\mathcal{A}_{\mathrm{SL}}^{s} = +0.0003 \pm 0.0093$

BaBar & BELLE

- BaBar at the PEPII collider and BELLE at KEKB, two experiments built to measure CP violation in the B system.
- They collide e+ e- at an energy just high enough to produce an $\Upsilon(4S)$ (at rest in the e+ e- cm frame), a bound b-bbar state just heavy enough to decay to a $\mathrm{B_d^0}\ \overline{\mathrm{B_d^0}}$ or $\mathrm{B^+}\ \mathrm{B^-}$ pair. (It is not heavy enough to decay to $\mathrm{B_s^0}\ \overline{\mathrm{B_s^0}}$ or any other species of B hadron.)
- To summarise: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow \mathrm{B}\ \overline{\mathrm{B}}$
- Both started data taking in 1999

Asymmetric B factories

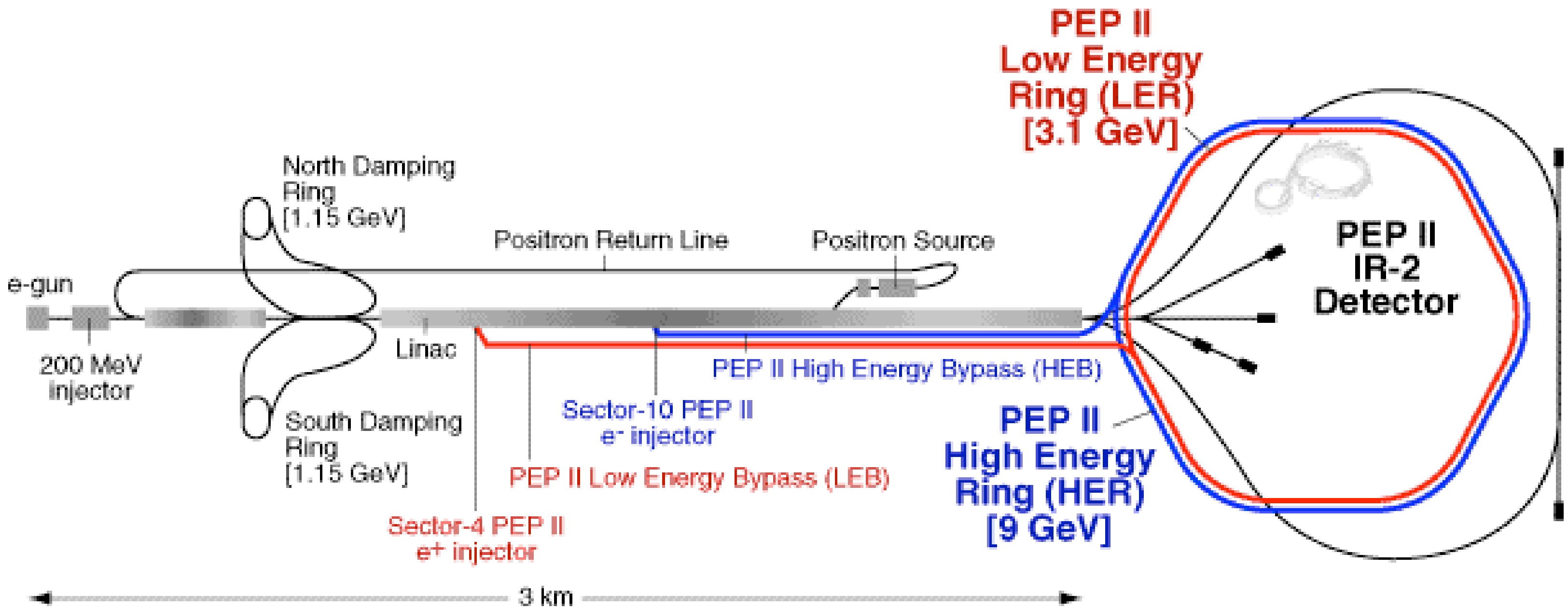
- Need to measure decay times much better than mixing period (T~13ps for Bd) and preferably better than B lifetime (~1.5ps).
- Don't actually measure times, but decay distances. However, in the e+e- c.m. frame, the two B-mesons are essentially at rest. No decay distance → no time measurement.
- Trick: Collide e+ and e- with different energies to boost c.m. frame. B factories get βγ~0.5. So in 1.5ps in the B frame, the particle moves in the lab frame:

$$c\beta\gamma t = 300\frac{\mu m}{ps} \cdot 0.5 \cdot 1.5ps \sim \frac{1}{4}mm$$

- That can be done. Resolution at BaBar: 0.07mm for fully reconstructed B, 0.16mm for partially reconstructed B

$$e^+e^- \to \Upsilon(4S) \to \mathrm{B}\,\overline{\mathrm{B}}$$

The PEP-II LINAC+Ring



here is an animated version of this

Asl in Bd system

$$\mathcal{A}_{\mathrm{SL}}^{d} = -0.0047 \pm 0.0046$$

- B factories:

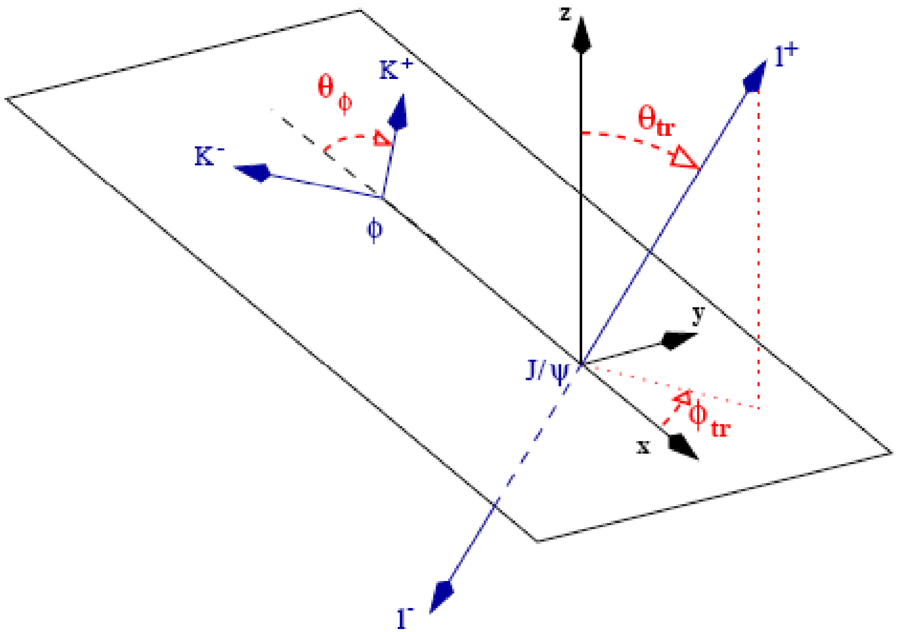
CPV in $B_s \to J/\psi\ \Phi$ vs $B_d \to J/\psi K_s$

$B_d \to J/\psi\ K$

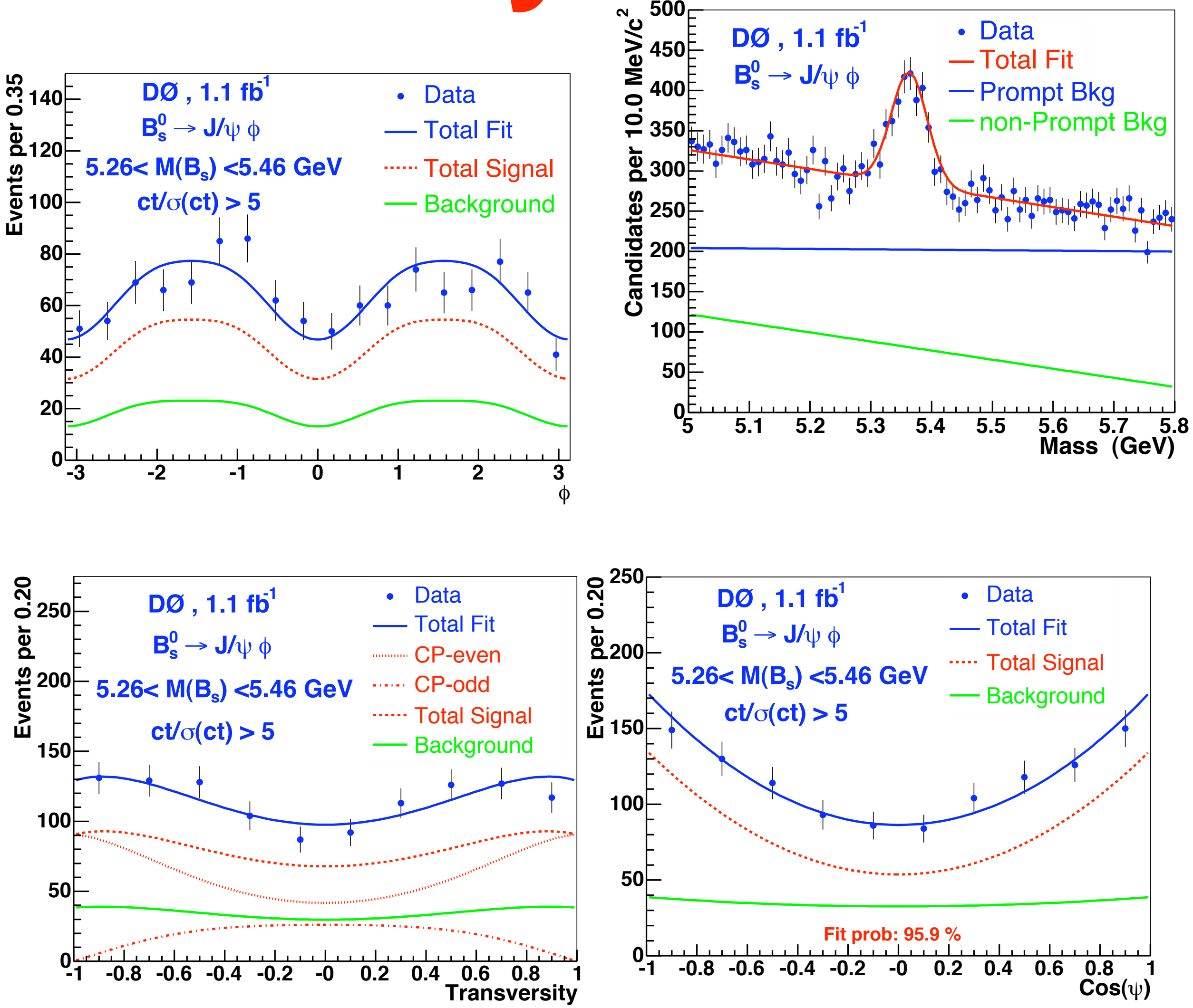
- Large CPV phase $2\beta = 42°$.
- Good for seeing CPV in the SM.
- Precisely measured at B factories.

$B_s \to J/\psi\ \Phi$

- Tiny CPV phase - SM prediction $2\chi \approx 2°$
- Good for seeing new phases due to New Physics with little SM "background". If you see CPV it's New Physics (and it's not MFV).
- No precise measurement, yet.


z
l^+
K^+
θ_ϕ
θ_{tr}
K^-
ϕ
y
J/ψ
ϕ_{tr}
x
l^-

ΔΓ from Bs→J/ψΦ



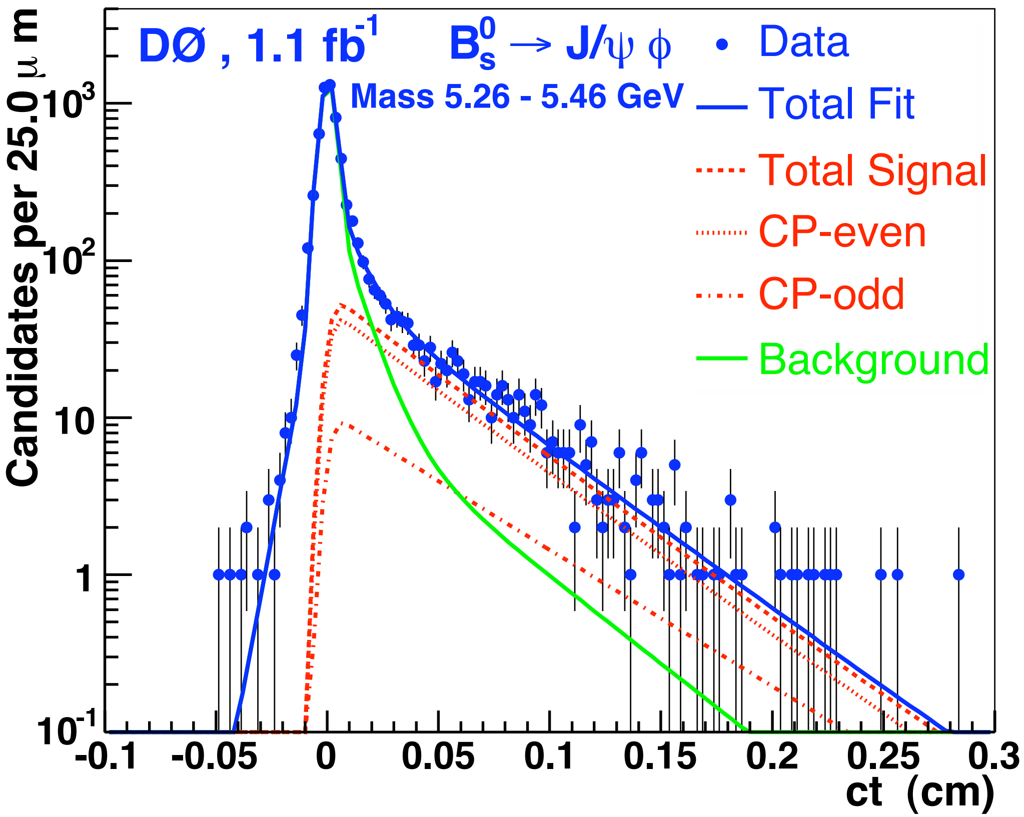
PRL 98, 121801 (2007)

- Result of lifetime fit with φs=0:

  $\Delta\Gamma = 0.12^{+0.08}_{-0.10}$ ps^{-1}

- Fitting φs

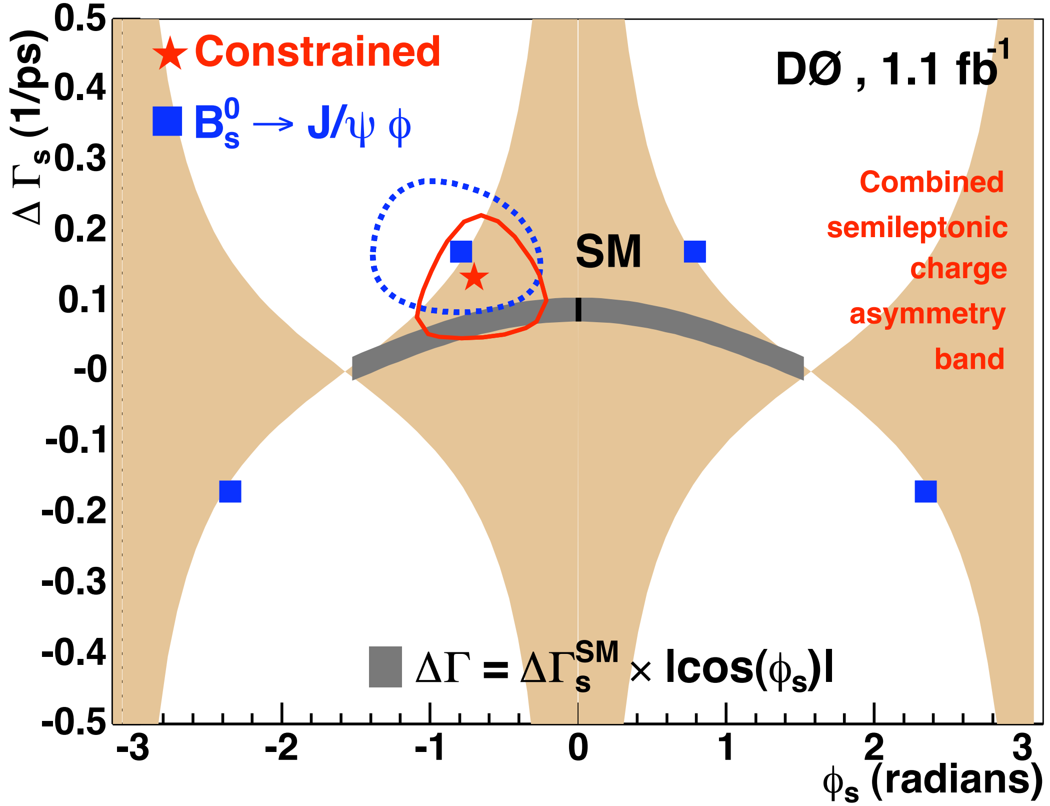
  $\phi_s = -0.8 \pm 0.6$



PRL 98, 121801 (2007)

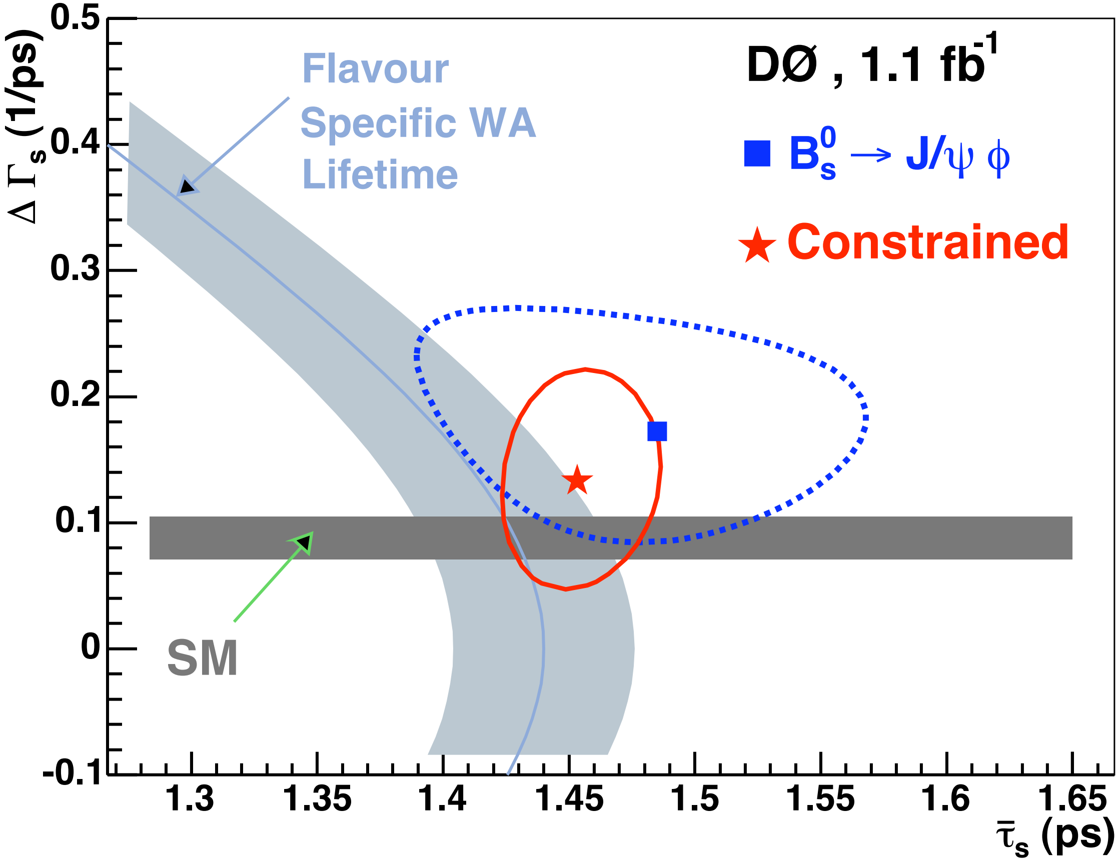
DØ result on Asl

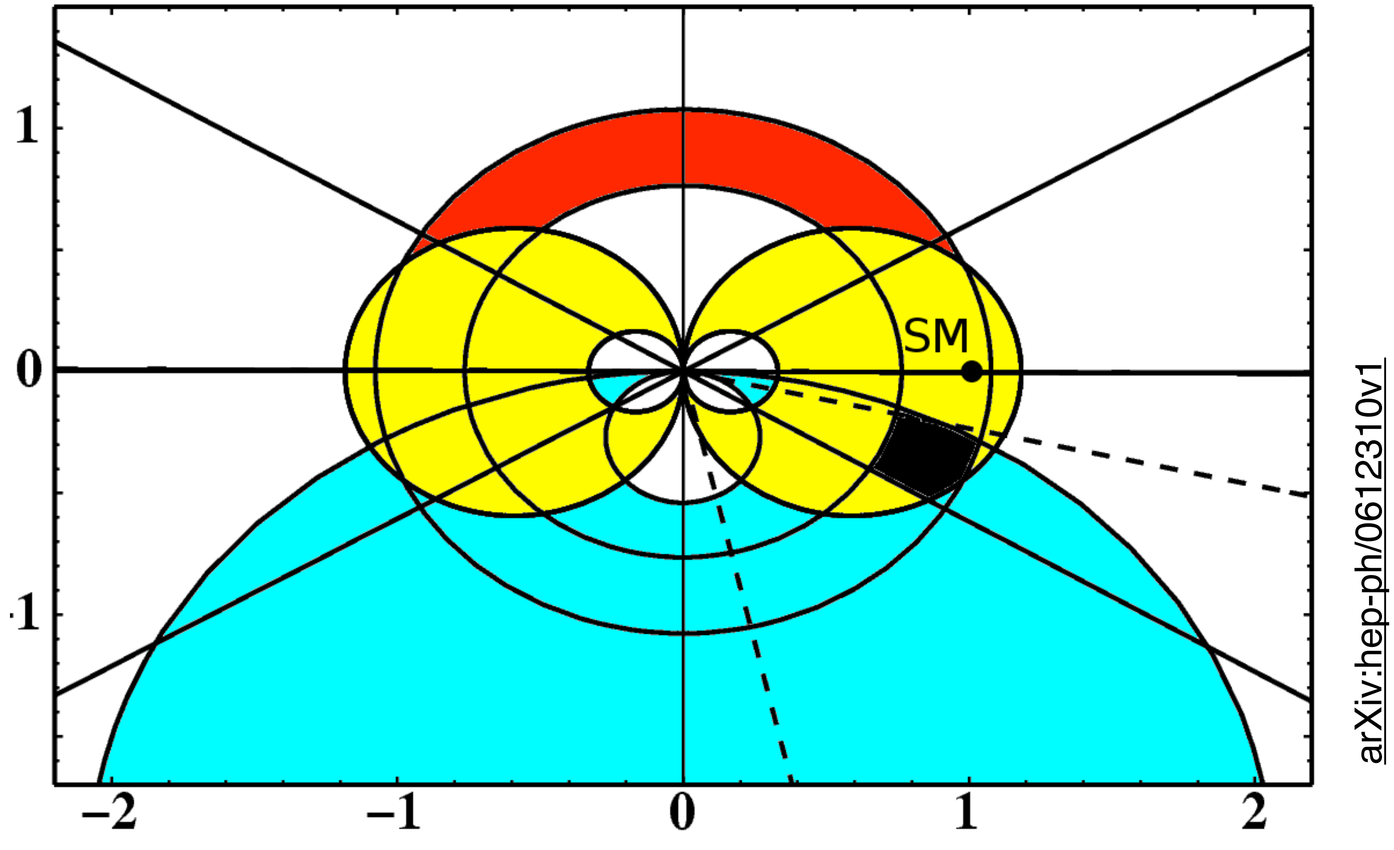
- The plot on the shows how the constraint from D0's Asl measurements shrinks the error elipse in the Φ–ΔΓ plane.



DØ result on Asl

- The plot on the shows how the constraint from Asl shrinks the error elipse in the lifetime-ΔΓ plane.




1
0
-1
-2
-1
0
1
2
SM
arXiv:hep-ph/0612310v1

Note: To measure a mixing-induced CP asymmetry (S_f term) in a $b \to s\bar{q}q$ decay of a B_d meson one needs a neutral Kaon in the final state, so that the

$$b(\bar{d}) \to \bar{q}qs(\bar{d}) \quad \text{and} \quad \bar{b}(d) \to \bar{q}q\bar{s}(d)$$

decays of B_d and $\overline{B}_d$ can interfere.

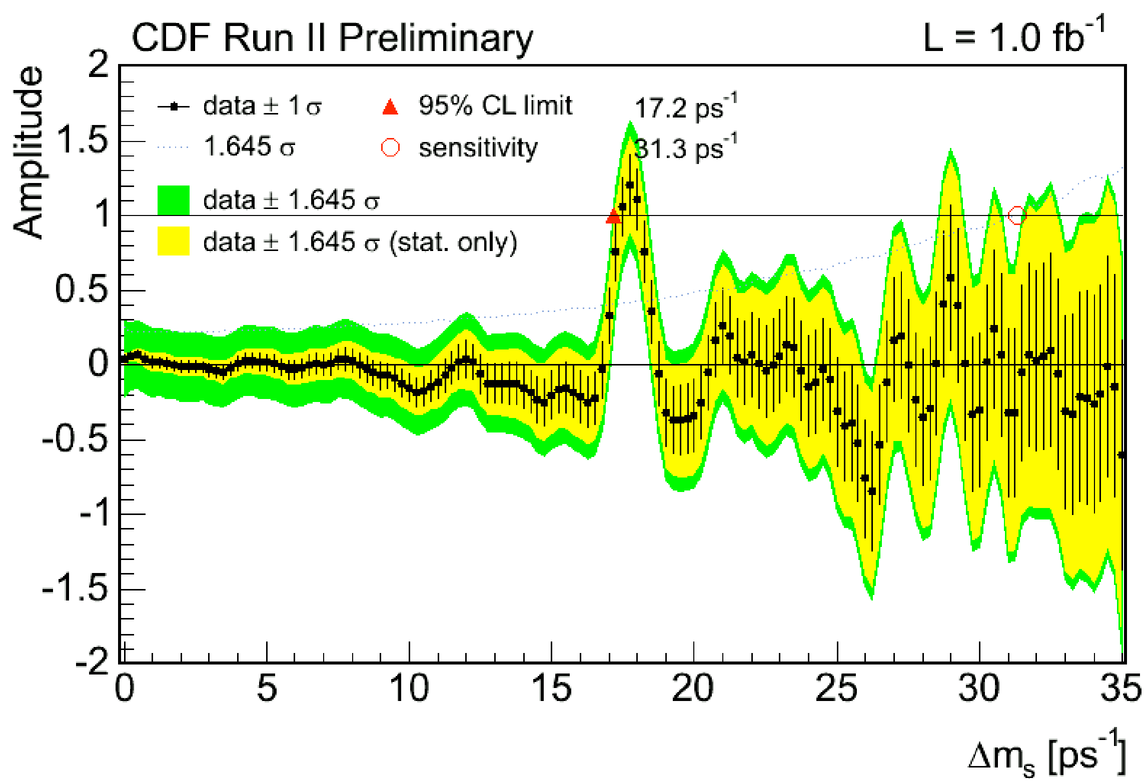
In a $\overset{(-)}{B}_s$ decay, however, one has a flavourless final state:

$$b(\bar{s}) \to \bar{q}qs(\bar{s}), \qquad \bar{b}(s) \to \bar{q}q\bar{s}(s)$$

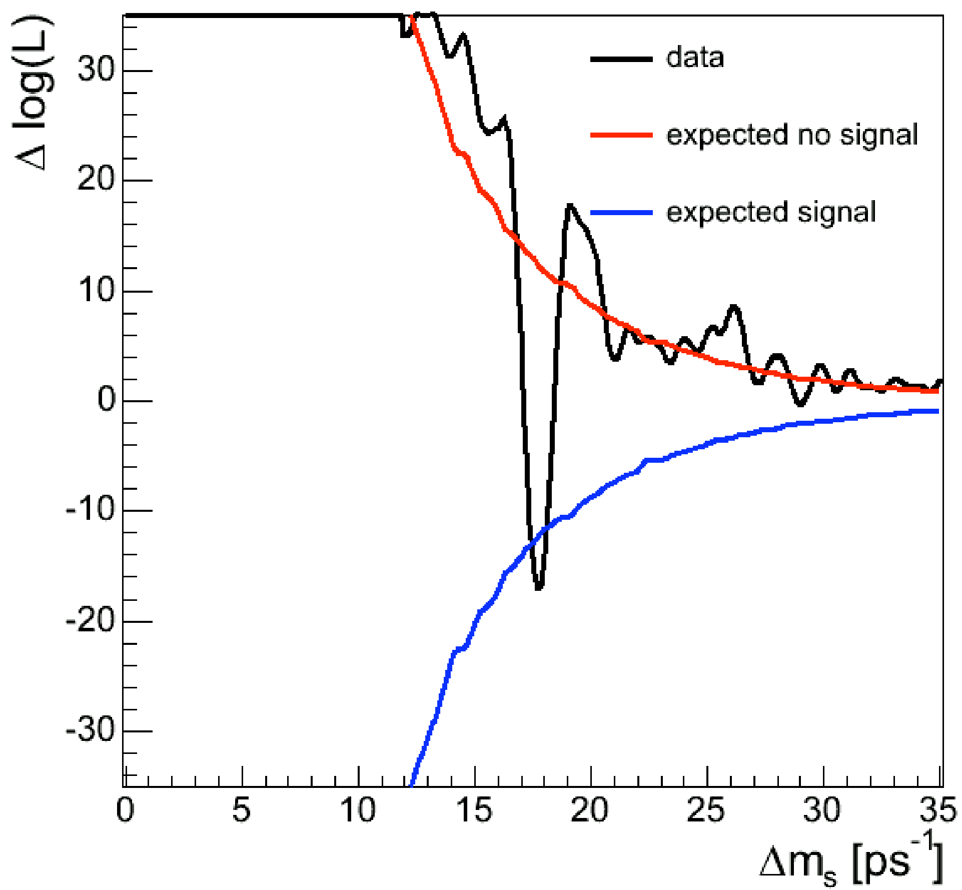
and the needed interference occurs in any final state.

$\Rightarrow$ B_s physics is the El Dorado of $b \to s\bar{q}q$ penguin physics!

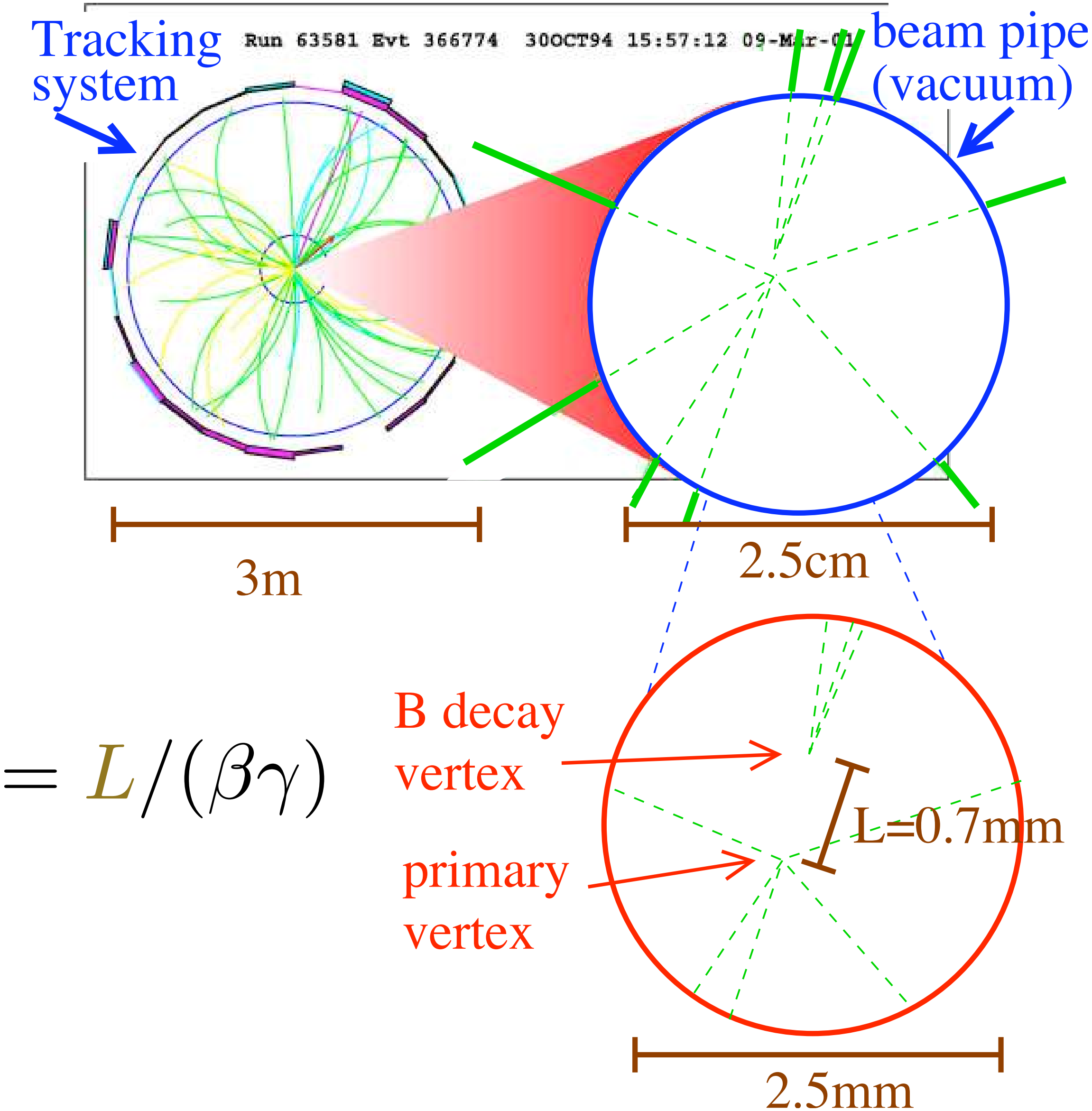
Ulrich Nierste at Beauty 2006



CDF Run II Preliminary
L = 1.0 fb^{-1}
Amplitude
data ± 1 σ
1.645 σ
data ± 1.645 σ
data ± 1.645 σ (stat. only)
95% CL limit
sensitivity
17.2 ps^{-1}
31.3 ps^{-1}
Δm_s [ps^{-1}]

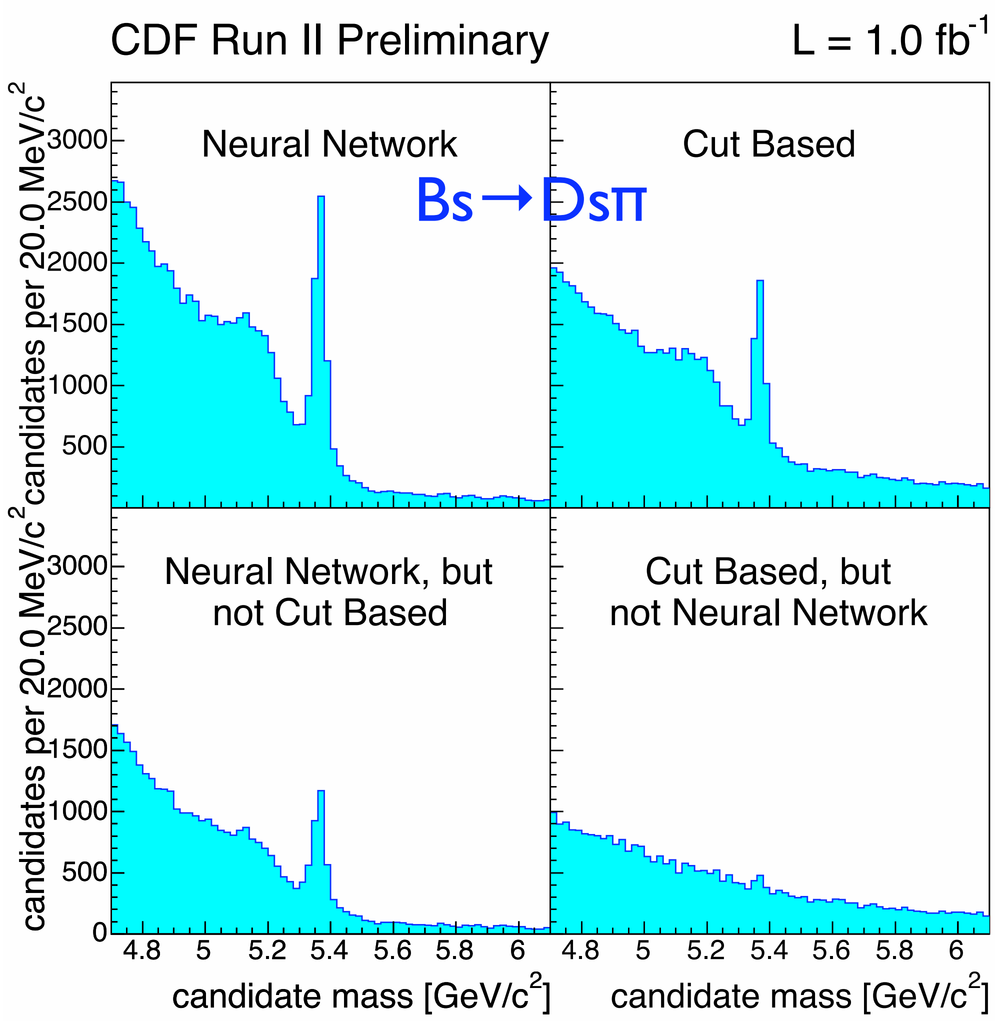

Δ log(L)
30
20
10
0
-10
-20
-30
0
5
10
15
20
25
30
35
Δm_s [ps^{-1}]
data
expected no signal
expected signal

Lifetime Measurements



$$t = L/(\beta\gamma)$$

- 5600 full reconstructed hadronic Bs→Dsπ decays, 3100 partially reconstructed hadronic Bs decays, and 61500 partially reconstructed semileptonic Bs→Ds l ν X decays



LHCb Sensitivities with 2 fb^{-1}

Subset of studied modes

	Channel	Yield	B/S	Precision
γ	$B_s \to D_s^{-+} K^{+-}$	5.4k	< 1.0	$\sigma(\gamma) \sim 14°$
	$B_d \to \pi^+ \pi^-$	36k	0.46	$\sigma(\gamma) \sim 4°$
	$B_s \to K^+ K^-$	36k	< 0.06	
	$B_d \to D^0 (K\pi, KK) K^{*0}$	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	$\sigma(\gamma) \sim 7° - 10°$
	$B^- \to D^0 (K^-\pi^+, K^+\pi^-) K^-$	28k, 0.5k	0.6, 4.3	$\sigma(\gamma) \sim 5° - 15°$
	$B^- \to D^0 (K^+K^-, \pi^+\pi^-) K^-$	4.3 k	2.0	
	$B^- \to D^0 (K_S\pi^+\pi^-) K^-$	1.5 - 5k	< 0.7	$\sigma(\gamma) \sim 8° - 16°$
α	$B_d \to \pi^+ \pi^- \pi^0$	14k	< 0.8	$\sigma(\alpha) \sim 10°$
	$B \to \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	
β	$B_d \to J/\psi(\mu\mu)K_S$	216k	0.8	$\sigma(\sin 2\beta) \sim 0.022$
Δm_s	$B_s \to D_s^- \pi^+$	80k	0.3	$\sigma(\Delta m_s) \sim 0.01\ ps^{-1}$
ϕ_s	$B_s \to J/\psi(\mu\mu)\phi$	131k	0.12	$\sigma(\phi_s) \sim 1.3°$
Rare decays	$B_s \to \mu^+\mu^-$	17	< 5.7	
	$B_d \to K^{*0} \mu^+\mu^-$	7.7 k	0.4	$\sigma(C_7^{eff}/C_9^{eff}) \sim 0.13$
	$B_d \to K^{*0} \gamma$	35k	< 0.7	$\sigma(A_{CP}) \sim 0.01$
	$B_s \to \phi \gamma$	9.3 k	< 2.4	
charm	$D^{*+} \to D^0 (K^-\pi^+) \pi^+$	100 M		

Results: sensitivity to ϕ_s

Channels (sensitivity for ϕ_s with 2 fb^{-1})	$\sigma(\phi_s)\,[rad]$	$Weight\left(\sigma/\sigma_i\right)^2$ [%]
$B_s \to D_s(K^+K^-\pi)D_s(K^+K^-\pi^+)$	0.133	2.6
$B_s \to J/\psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	0.142	2.8
$B_s \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$	0.109	3.9
$B_s \to \eta_c(h^-h^+h^-h^+)\phi(K^+K^-)$	0.108	3.9
Combined sensitivity for pure CP eigenstates	**0.059**	**13.2**
$B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	**0.023**	**86.8**
Combined sensitivity for all CP eigenstates	***0.021***	***100.0***

Combined sensitivity with *10 fb^{-1}* at LHC*b*: $\sigma(\phi_s) = \pm 0.0$[illegible] rad (statistical)

Parameter	***Sensitivity with 2 fb^{-1}***	***Channels***
$\Delta\Gamma_s/\Gamma_s$	0.0092	$B_s \to J/\psi\phi$
R_T	0.00040	$B_s \to J/\psi\phi$
Δm_s	0.007 ps^{-1}	$B_s \to D_s\pi^+$
W_{tag}	0.0036	$B_s \to D_s\pi^+$

- Results for Δm_s and w_{tag} are from $B_s \to D_s\pi^+$
- Very precise value of Δm_s: ~ 0.04 % uncertainty

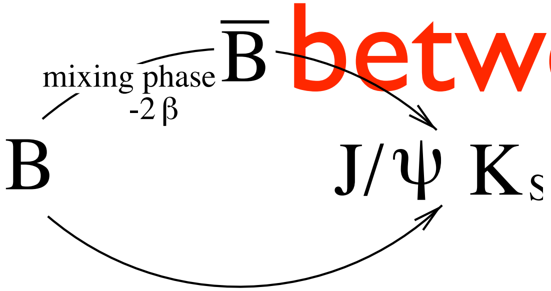
Time Evolution of B system

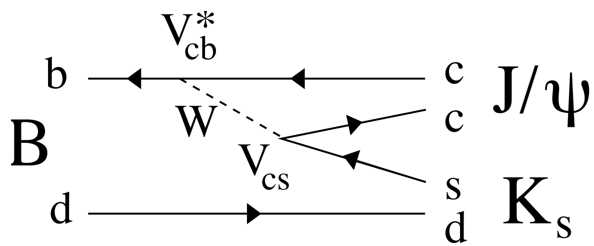
$$|B_H(t)\rangle = e^{-iM_H t} e^{-\frac{1}{2}\Gamma_H t} |B_H\rangle$$

$$|B_L(t)\rangle = e^{-iM_L t} e^{-\frac{1}{2}\Gamma_L t} |B_L\rangle$$

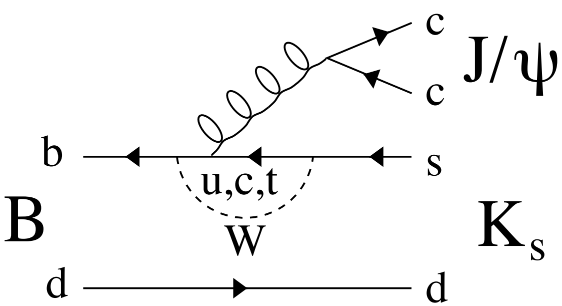
$$\begin{aligned} |\mathrm{B}^0(t)\rangle &= \frac{1}{2p}\left(e^{-(iM_L t + \frac{1}{2}\Gamma_L)t}|B_L\rangle + e^{-(iM_H t + \frac{1}{2}\Gamma_H)t}|B_H\rangle\right) \\ |\overline{\mathrm{B}}^0(t)\rangle &= \frac{1}{2q}\left(e^{-(iM_L t + \frac{1}{2}\Gamma_L)t}|B_L\rangle - e^{-(iM_H t + \frac{1}{2}\Gamma_H)t}|B_H\rangle\right) \end{aligned}$$

CP Violation in the interference between mixing and decay



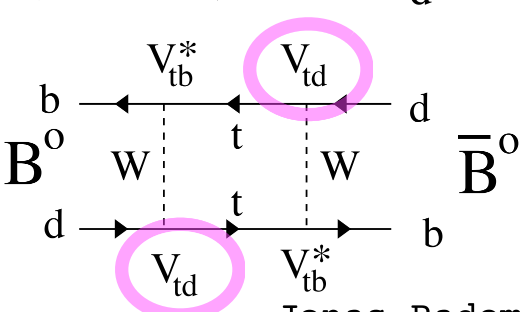


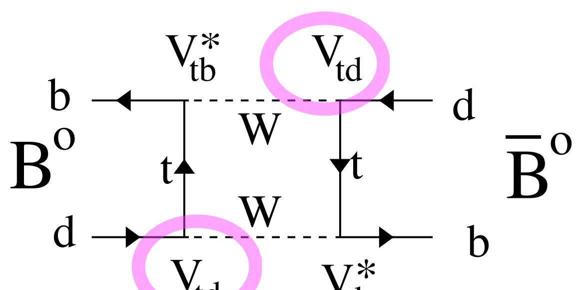
tree diagram: all CKM elements real, so phase = 0



Penguin diagram more tricky. Can ignore contribution from lightest quark, u, in loop (heavy is good in loop). Then CKM elements involved: $V_{ts}, V_{tb}^*, V_{cs}, V_{cb}^*$, all real, so phase = 0.

Both amplitudes involved in decay have same phase 0, so their sum has phase 0





both box diagrams $\propto (V_{tb}^* V_{td})^2$, V_{tb} real, but $V_{td} \propto e^{-i\beta}$, so phase = -2β