Measurement of CP Violation and Search for New Physics in $B_s \to J/\psi\phi$ Decays with CDF

Juan Pablo Fernández Ramos
C.I.E.M.A.T.
24/04/2008

Introduction

Beyond the Standard Model

The search for physics beyond the standard model is pursued through a broad program of physics at the Tevatron

- Direct searches for evidence of new physics (SUSY ?)
- Indirect searches : check internal consistency of Standard Model

CP violation in B^0_s meson system is an excellent way to search for new physics

- B-factories have stablished that, at leading order, NP effects, if existing in B^0, B^+decays, have a magnitude < O(10%). However, there exists an important corner not explored by them: the B^0_s system
- CP violation in B^0_s predicted to be extremely small in the SM.
- Contribution from new physics could come through the enhancement of loop processes

What is CP violation?

CP violation is the non-conservation of charge and parity quantum numbers

Rate of B_s^0 $\neq$ Rate of $\overline{B}_s^0$

It is an ingredient that may help to explain matter-antimatter asymmetry in the universe

What Is what we measure?

look at any **difference** in properties like decay rate, angular decomposition of the amplitude, etc **between** a decay and its “mirror image” resulting from C and P transformations

CP Violation in the Standard Model (S.M.)

Described within framework of the CKM mechanism

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Large CPV

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

Highly suppressed CPV

Large CPV

Suppressed CPV

where $\lambda = \sin\theta_c = 0.23 = |V_{us}|$

Imaginary terms give rise to CP violation

Unitarity of CKM Matrix

The S.M. does not fix the values of the CKM matrix elements, but it does imply certain fundamental restrictions that can be conveniently written as angles of unitary triangles (from requiring the CKM transformation matrix to be orthonormal). Two of these angles are the CP violation related β and β_s.

Can construct six unitary relations

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

relates to the angle

$\beta \equiv \arg[-V_{td}V_{tb}^*/V_{cd}V_{cb}^*] = O(1)$

sin(2β)~0.7 [well measured]

$\beta_s \equiv \arg[-V_{ts}V_{tb}^*/ V_{cs}V_{cb}^*] = O(\lambda^2)$

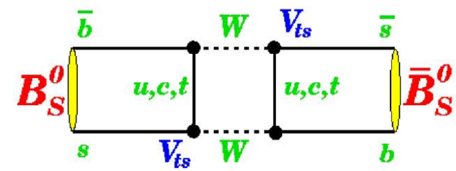
~0.02 predicted tiny SM-CP phase!

non-unitarity would imply contributions from unknown physics

Neutral B_s system

- Time evolution of B_s flavor eigenstates from Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix} \equiv \left[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}}\right]\begin{pmatrix} B_s^0(t) \\ \overline{B}_s^0(t) \end{pmatrix}$$



- Diagonalize mass and decay matrices→ obtain mass eigenstates

$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$ $\quad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$ (mixture of flavor eigenstates)

Experimentally accessible

- The magnitude of the box diagram gives the oscillation frequency

$\Delta m_s = m^H - m^L \approx 2|M_{12}|$; $\quad \Delta m_s = 17.77 \pm 0.12\ \mathrm{ps}^{-1}$ (CDF)

- The phase of the diagram gives the complex number $q/p = e^{-i\,\phi s}$

where $\phi_s = \arg(-M_{12}/\Gamma_{12})$ [CP-violating phase]

- Mass eigenstates have different decay widths (lifetimes)

$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos\phi_s$; $\quad \Delta\Gamma = 0.07 \pm 0.04\ \mathrm{ps}^{-1}$ [A.Lenz et al, JHEP06(2007) 072]

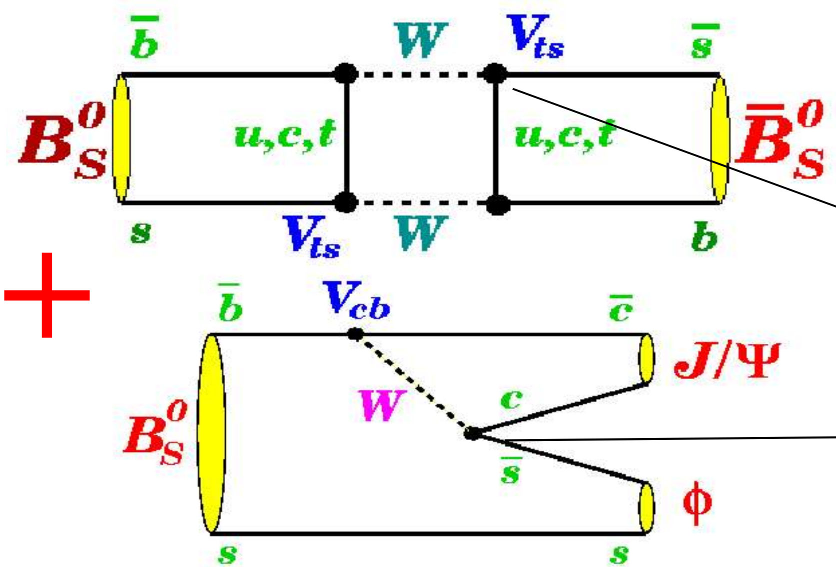
CP Violation in the S.M. ($B_s^0 \to J/\psi\phi$)

The chance to observe CP violation comes from interference between mixing and decay amplitudes

$$B_s^0 \longrightarrow J/\psi\phi \quad \Rightarrow \sin(2\beta_s)$$

$$B_s^0 \longrightarrow \bar{B}_s^0 \longrightarrow J/\psi\phi$$

The CP phase between the two decay paths appears via the factor sin($2\beta_s$)



$$\begin{array}{cccc} & & & \text{large CPV} \\ \text{small CPV} & V_{ud} & V_{us} & V_{ub} \\ & V_{cd} & V_{cs} & V_{cb} \\ & V_{td} & V_{ts} & V_{tb} \\ & \text{large CPV} & \text{small CPV} & \end{array}$$

$$2\beta_s^{SM} \equiv 2\arg[-V_{ts}V_{tb}^*/ V_{cs}V_{cb}^*]$$

CP violation phase β_s in SM is predicted to be very small

CP violating phases : ϕ_s vs β_s

- $2\beta_s = 2\arg[-V_{ts}V_{tb}^{*}/ V_{cs}V_{cb}^{*}] \sim 4.4^{o}$ (SM) phase of $b \rightarrow ccs$ transition that accounts for interference of decay and mixing+decay

- $\phi_s = \arg[-M_{12}/\Gamma_{12}] \sim 0.24^{o}$ (SM)

  $\arg[M_{12}] = \arg(V_{tb}V_{ts}^{*})^2$ matrix element that connects matter to antimatter through oscillation.

  $\arg[\Gamma_{12}] = \arg[(V_{cb}V^{*}_{cs})^2 + V_{cb}V^{*}_{cs}V_{ub}V^{*}_{us} + (V_{ub}V^{*}_{us})^2]$ width of matter and antimatter into common final states.

- Both SM values experimentally unaccessible by current experiments (assumed zero). If NP occurs in mixing:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP} \sim \phi_s^{NP}$$

$$2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} \sim -\phi_s^{NP}$$

standard approximation: $\phi_s = -2\beta_s$

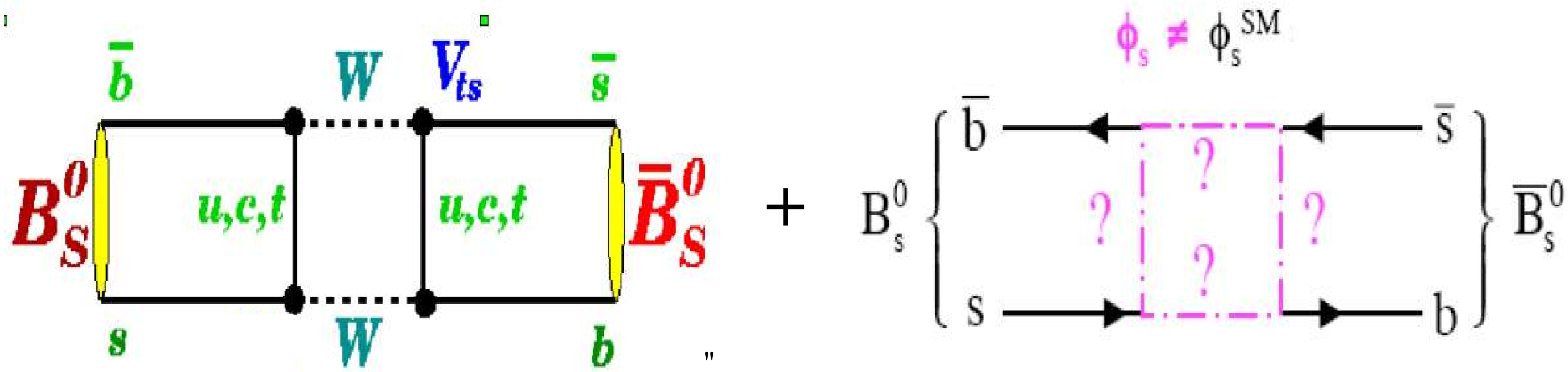
New Physics CPV in B_s^0 Decays

Under the existence of new physics ...

In $B_s^0 \rightarrow J/\psi\phi$, we would measure $2\beta_s = (2\beta_s^{SM} - \phi_s^{NP}) \sim -\phi_s^{NP}$

Observation of large CP phase in $B_s^0 \rightarrow J/\psi\phi$

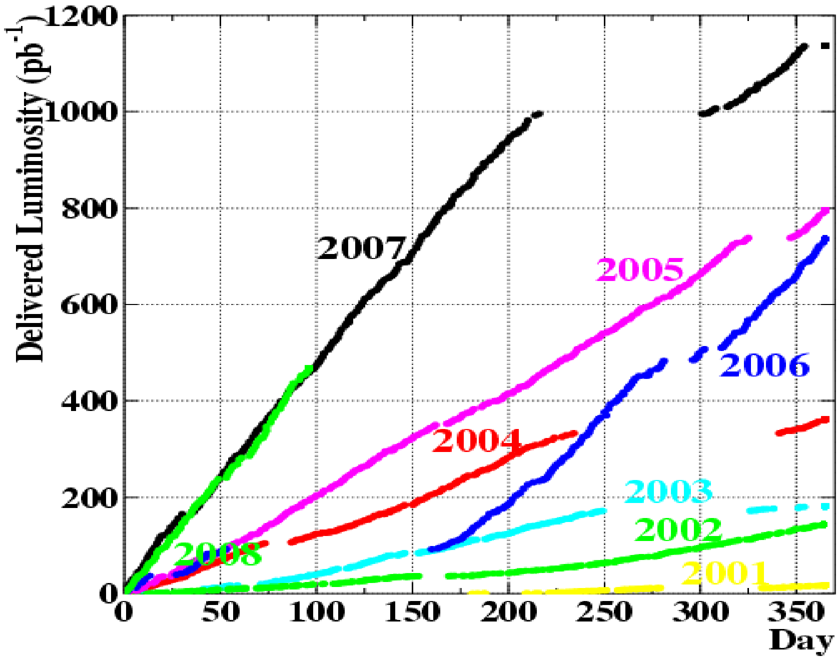
$\Rightarrow$ unequivocal sign of new physics (new unknown contribution in the loop process?)

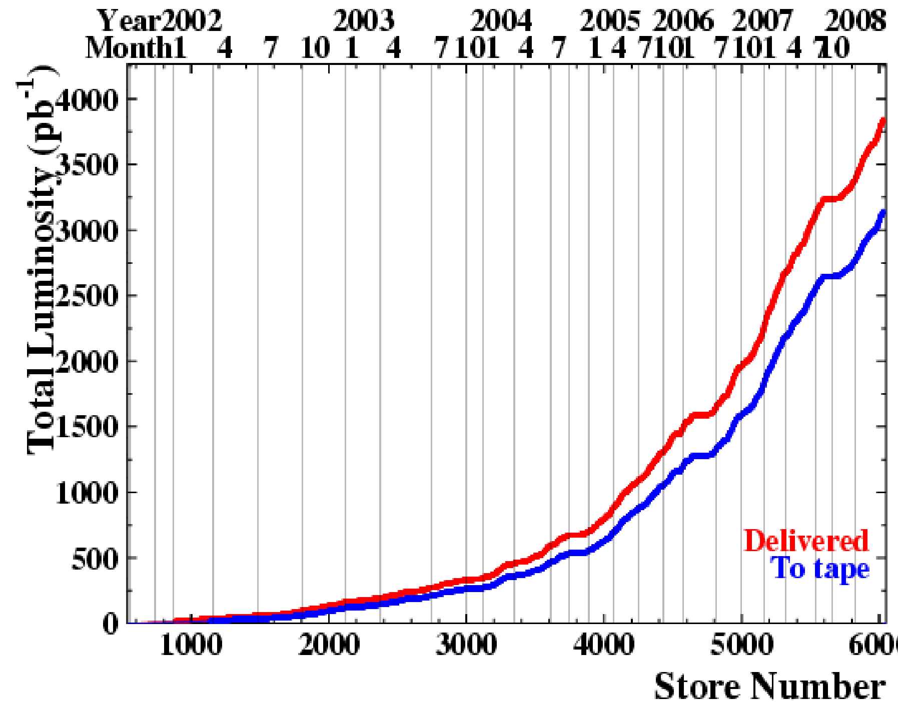


unknown flavor structure

Experiment Overview

Introduction to the Tevatron





- Tevatron is the world highest energy accelerator: $p\bar{p}$ at $\sqrt{s}$=1.96TeV
- Will take data until Sept 2009 (may be extended 1 year)
- Expected integrated luminosity : ~ **5 - 6 fb^{-1}** until 2009
- CDF has already **3.2 fb^{-1}** on tape [only 1.3 **fb^{-1}** (tagged analysis) / 1.7 **fb^{-1}** (untagged) fully analized]

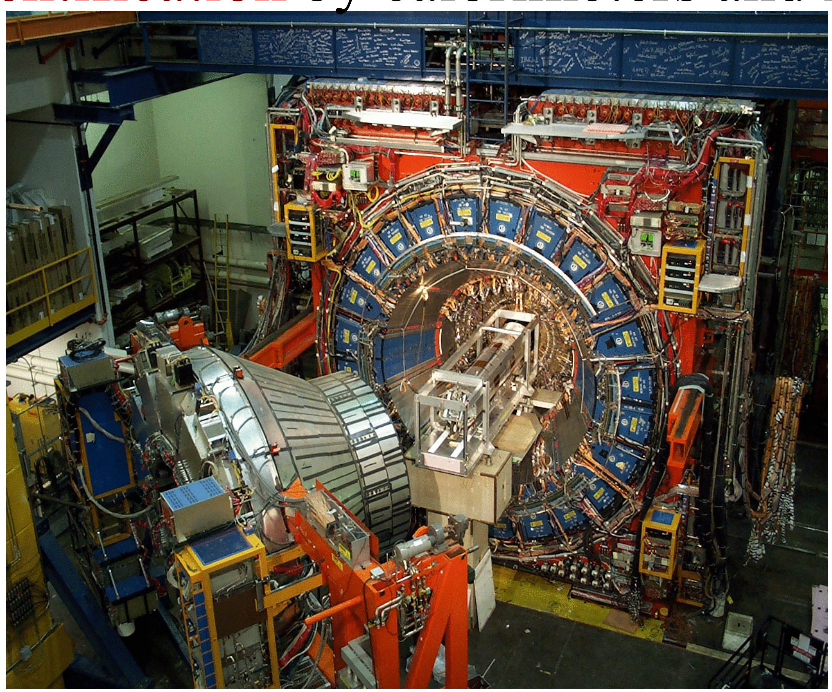
Introduction to the CDF II detector

CDF II detector includes (**relevant to this analysis**)

- Central tracking: silicon vertex detector surrounded by a drift chamber
  - p_T resolution $\Delta p_T/p_T = 0.0015\, p_T$
  - vertex resolution ~ 25 μm

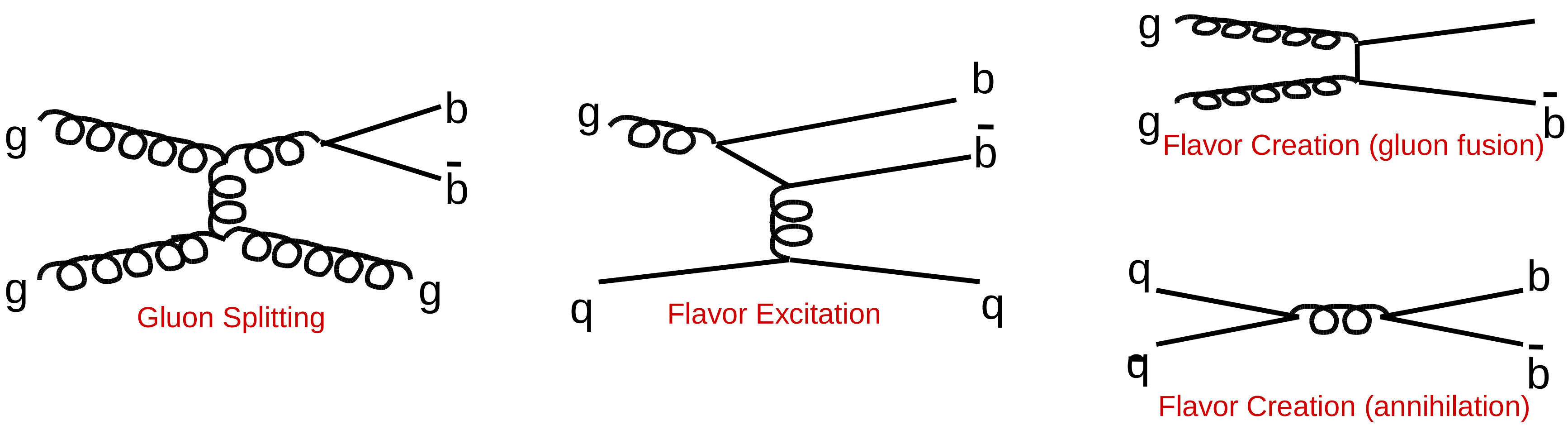
excellent mass and vertex rec.

- Particle identification (PID): dE/dx ~1.5 σ separation for K/pi with p>2 GeV and TOF ~2 σ K/pi with p<1.5-1.8 GeV.
- Good e and μ identification by calorimeters and muon chambers



Basics of B Physics at the Tevatron

- b-quarks produced in $b\bar{b}$ pairs. Lowest order α_s^2 production:



- High cross section $\boldsymbol{\sigma}$ ($\mathbf{p\bar{p}} \to \mathbf{b\bar{b}}$) ~ 40 μb at $\sqrt{s}$ = 2 TeV
- Quarks fragment into hadrons: B_c^- ($b\bar{c}$), Λ_b(bdu), Σ_b^+ (buu), Σ_b^- (bdd) [Tevatron exclusive], $\bar{B}_s^0$ ($b\bar{s}$), $\bar{B}_0$($b\bar{d}$), B^-($b\bar{u}$), also B*, B**, etc
- $\rightarrow$ Tevatron can be considered as a B factory

Online B selection process

- Huge background to the process $\sigma\,(p\bar{p} \to b\bar{b})$ in Tevatron: O(0.05 b)!
- B hadrons are filtered online using selective triggers based on clear signatures that overcome the QCD background
- Our sample is selected by a $J/\psi \to \mu\mu$ oriented dimuon trigger

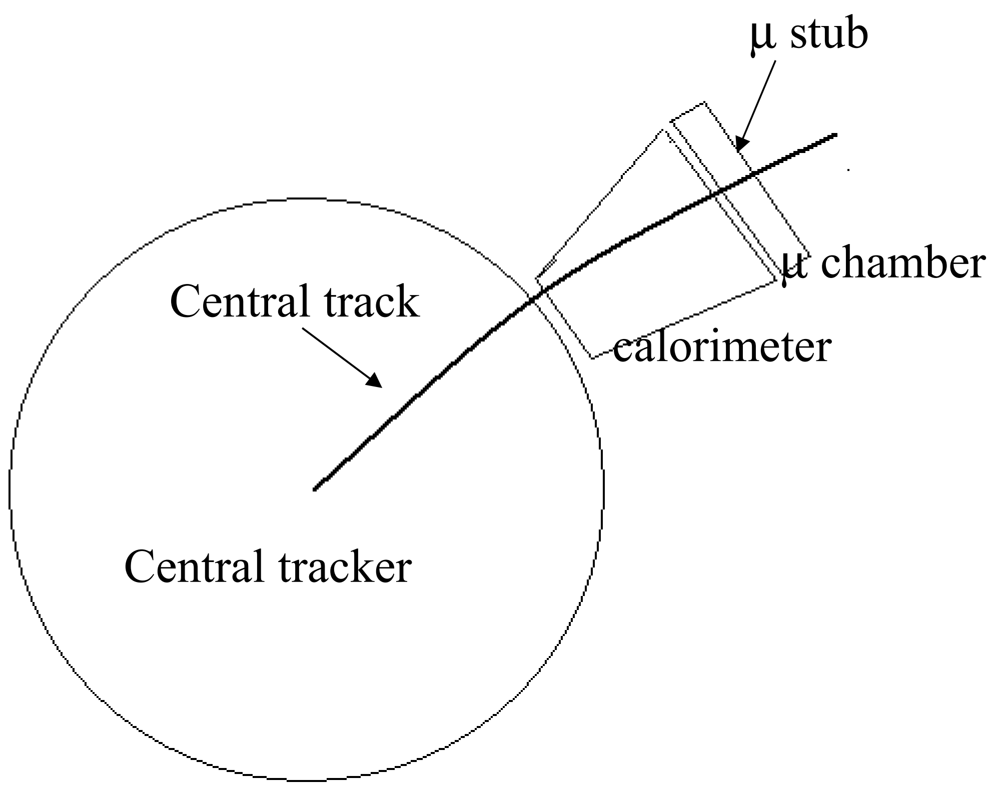
$BR(B \to J/\psi\ X) = 0.5\ \%$; $BR(J/\psi \to \mu\mu) = 6\%$

Measurements :

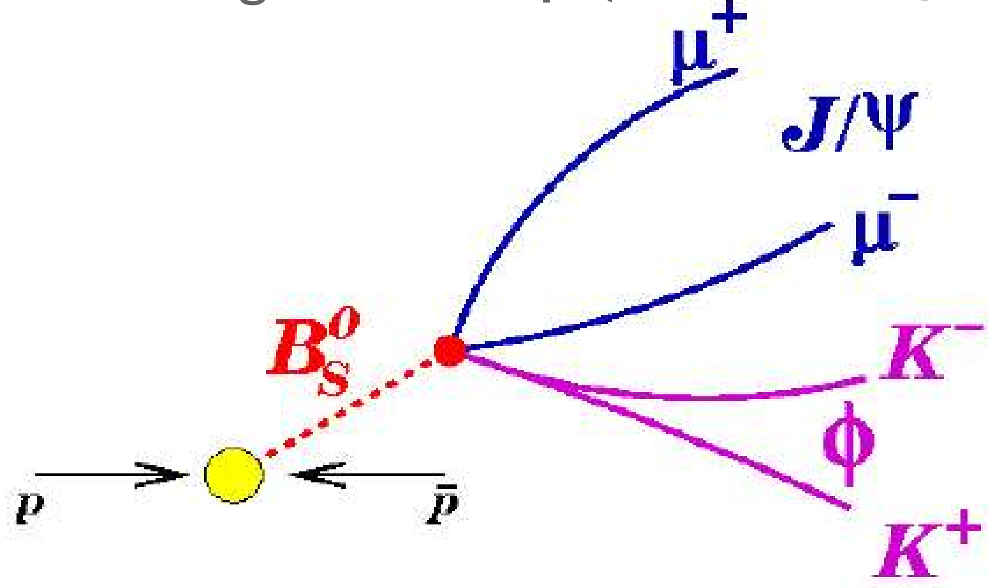
Central tracking chamber:
- Track momentum
- Trajectory

Muon chambers:
- Trajectory (stub)

Require :
- Central track
- Muon stub
- Position and angle match between central track and muon stub



Overview of $B_s^0 \to J/\psi\phi$ Decay



B_s^0 travels ~ 450 μm before decaying into J/ψ and φ

Spin-0 B_s^0 decays to spin-1 J/ψ and spin-1 φ

⇒ final states with l = 0, 2 (CP-even) and l =1 (CP-odd)

The sensitivity of the analysis to the CP-violating parameters _ depends on decay time, CP at decay, and initial flavor of B_s^0/B_s^0

Purpose: disentangle all these features

Measurement Strategy

Reconstruct $B_s^0 \to J/\psi(\to \mu^+\mu^-)\ \phi(\to K^+K^-)$

Use angular properties of the $J/\psi\ \phi$ decay to separate angular momentum states which correspond to CP eigenstates

Identify initial state of B_s meson (flavor tagging) and thus separate time evolution of B_s^0 and $\bar{B}_s^0$ to maximize sensitivity to CP asymmetry ($\sin 2\beta_s$)

Perform un-binned maximum likelihood fit to extract signal parameters of interest (e.g. β_s, $\Delta\Gamma = \Gamma_L - \Gamma_H$)

Signal reconstruction and Lifetime determination

$B_s^0 \to J/\psi\phi$ Signal Selection

Use an artificial neural network (ANN) to efficiently separate signal from background

ANN training

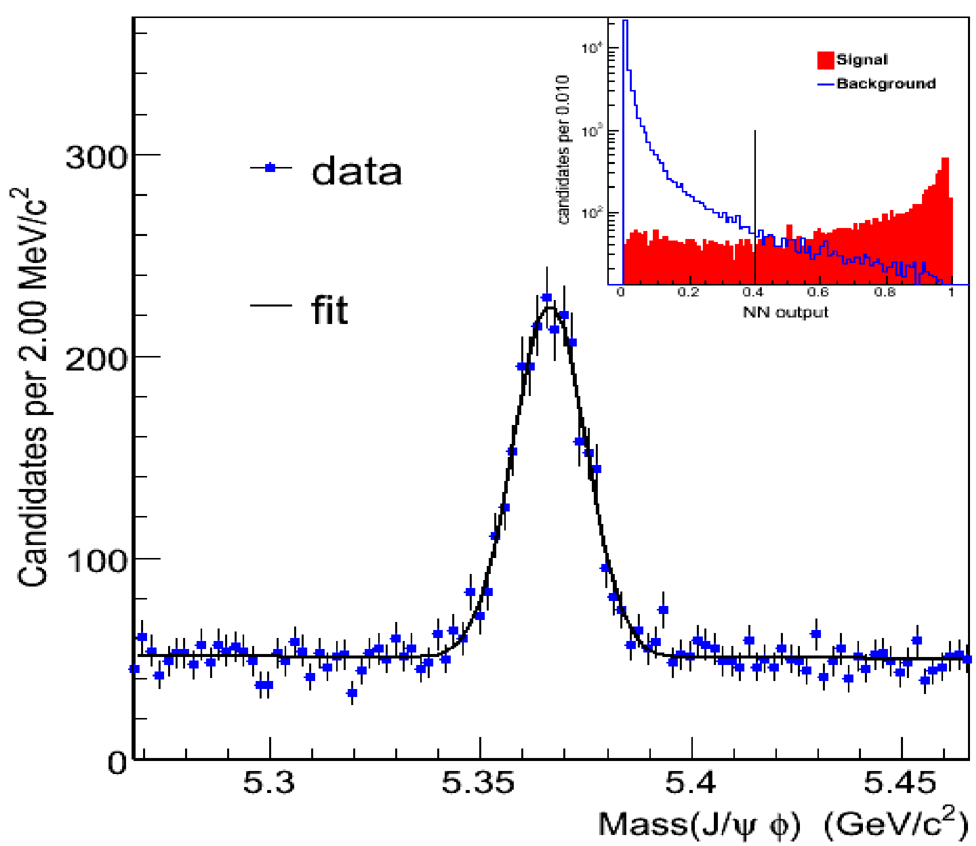
- Signal from Monte Carlo reconstructed as it is in data
- Bkg. from $J/\psi\phi$ sidebands

Variables used in network

- B_s^0: p_T and vertex prob.
- J/ψ: p_T and vertex prob.
- φ : mass and vertex prob.
- K^+, K^-: p_T and PID

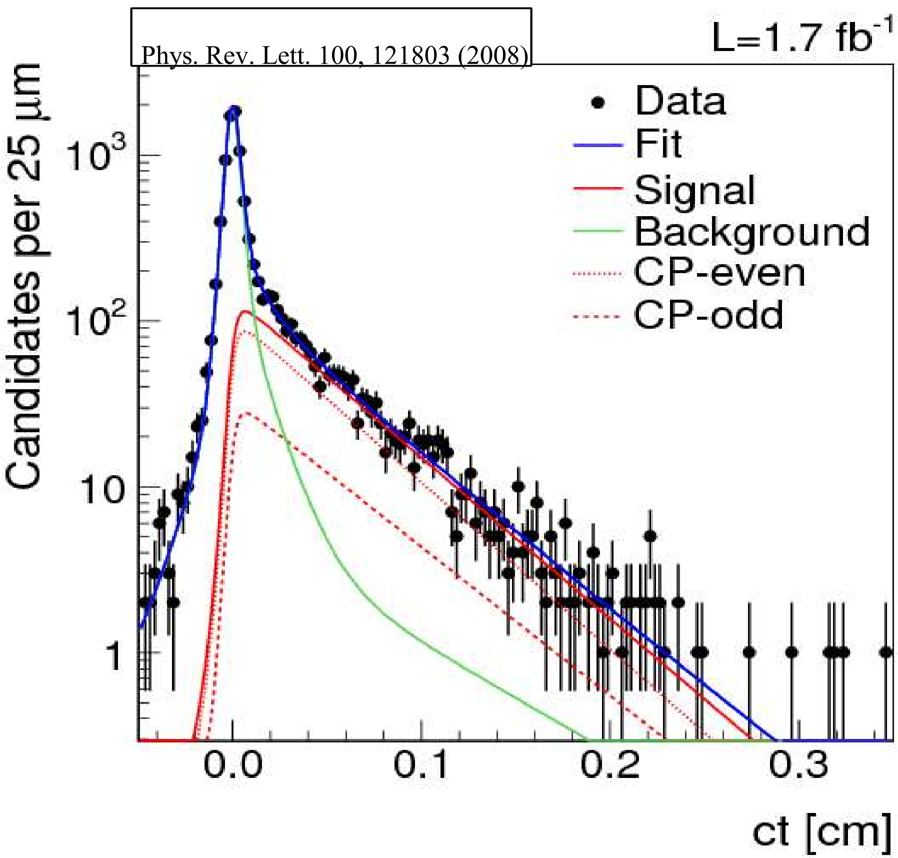
$N(B_s^0) \sim 2000$ in $1.35 fb^{-1}$

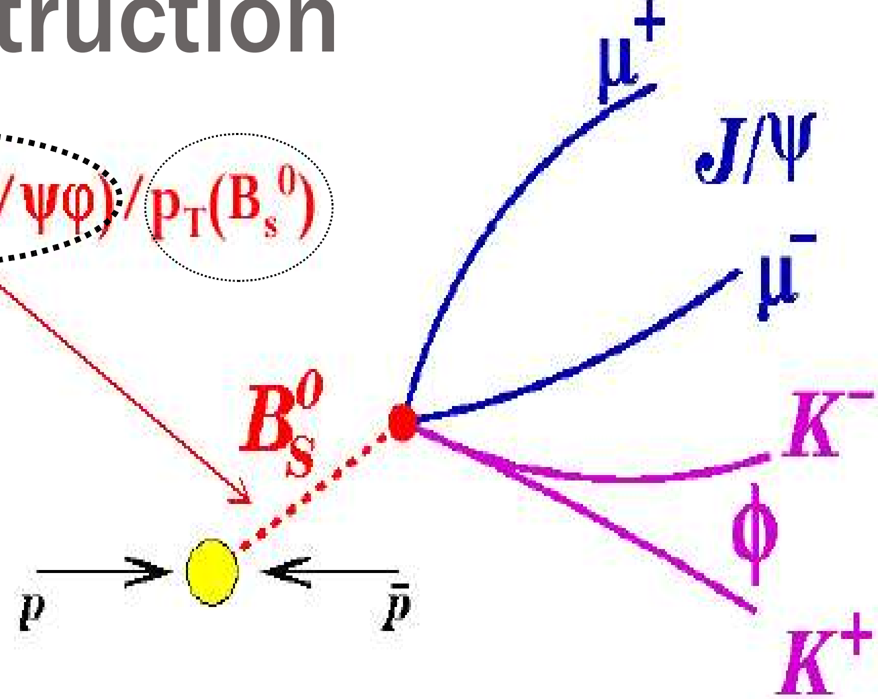
CDF Run II Preliminary, L = 1.35 fb^{-1}



B_s^0 Lifetime Reconstruction

$$t = m(B_s^0) * L_{xy}(B_s^0 \to J/\psi\varphi) / p_T(B_s^0)$$





- Peak at 0 comes from prompt J/ψ (main source: Drell Yan)
- Long lived tail is mostly our $B_s^0 \to J/\psi\phi$ Signal

[Fit: No flavor tagging, $2\beta_s$ fixed to SM value]

Angular Analysis of Final States

We have a sample of

B^0_s *and* $\bar{B}^0_s \rightarrow J/\psi\ \phi \quad (J/\psi \rightarrow \mu^+\mu^-,\ \phi \rightarrow K^+K^-)$

and we know the time when each decay occurred.

We need to know the CP of the final state …

but we can only do it on a statistical basis

- $B \to VV$ (our $B_s^0 \to J/\psi\, \phi$ but also $B^0 \to J/\psi\, K^{*0}$, …) decay to two CP even states (S-wave or D-wave) and one CP odd (P-wave)
- Alternatively to the S,P,D-wave states one can use the "transversity basis": the three independent components in which the vector mesons polarizations w.r.t. their direction of motion are:
  - longitudinal (0)
  - transverse but parallel to each other (||)
  - transverse but perpendicular to each other ($\perp$)

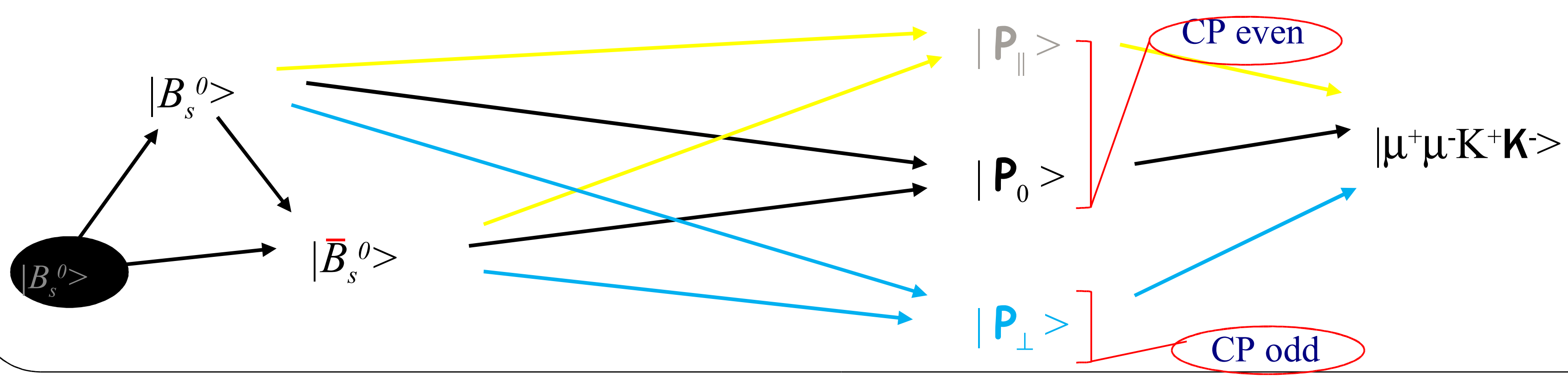
CP even

CP odd

Each final pol.state $P_0, P_{\parallel}, P_{\perp}$ has transition amplitude $A_0, A_{\parallel}, A_{\perp}$; $\langle B^0_s | P \rangle = A$

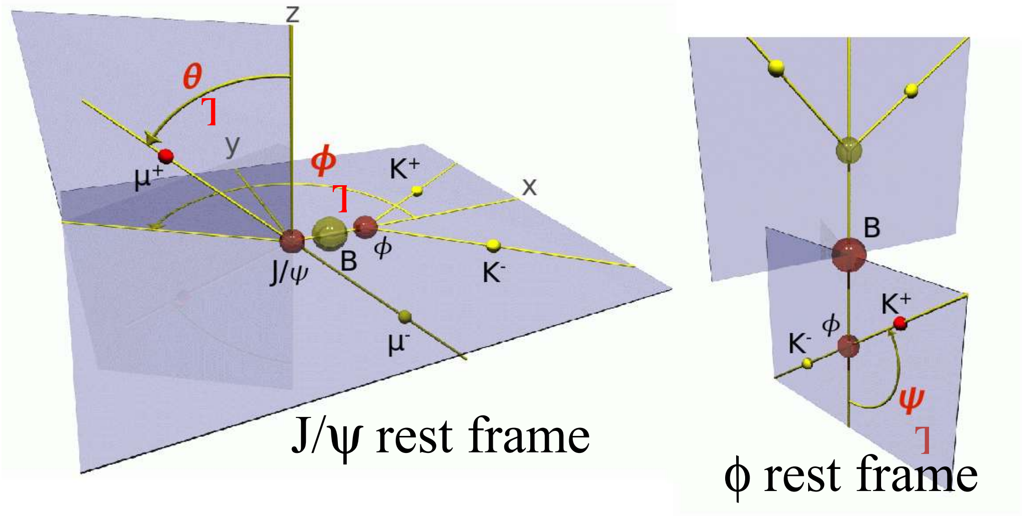
The $\langle B^0_{s,phys}(t) \,|\, P \rangle = A(t)$ are convolutions of decay and oscillation functions

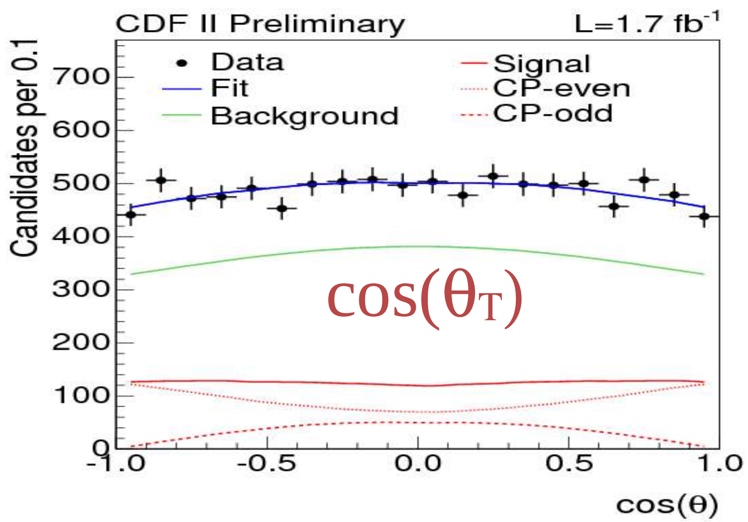
Oscillations Intermediate "final" state ($J/\psi\ \phi$) Final State

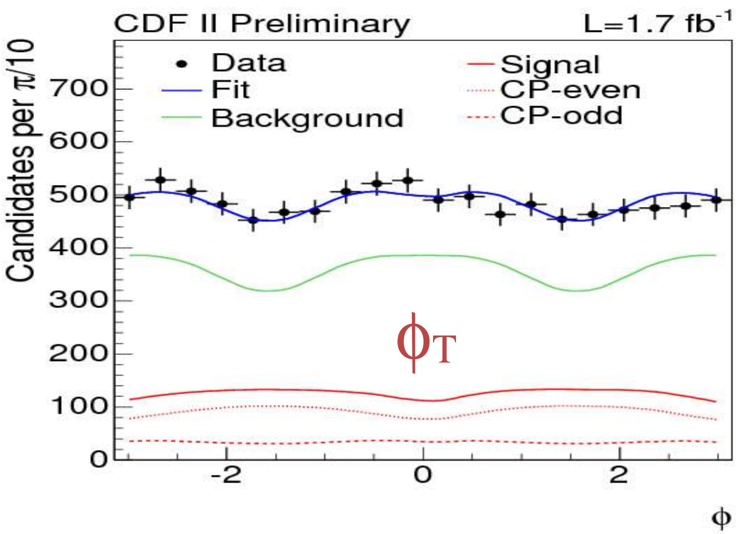


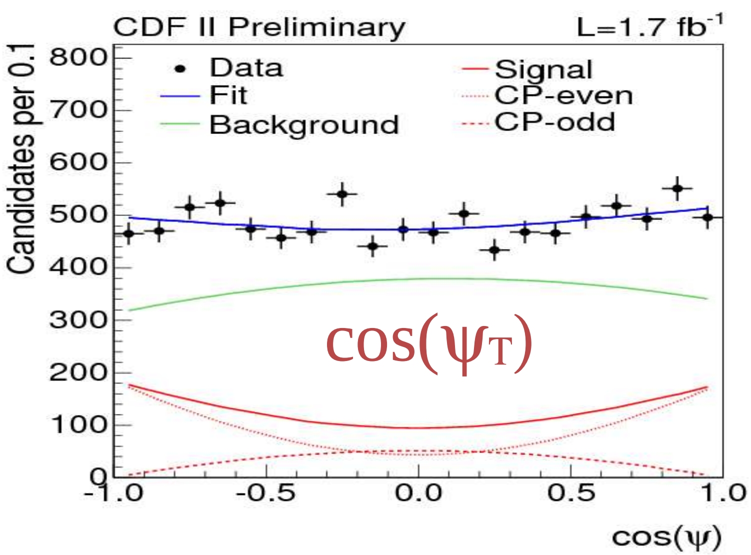
- the "transversity angles" (θ_T, ϕ_T, ψ_T) are sensitive to the polarizations

A.S.Dighe, I.Dunietz, H.J.Lipkin, J.L.Rosner; PLB369 (1996) 144









The analytical relationships are detailed next ...

A.S.Dighe, I.Dunietz, H.J.Lipkin, J.L.Rosner; EPJ C6 (1999) 647

Angular Probability Distribution: time evolution

General relation for B-> VV

$$\frac{d^4 P(t,\vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2 \mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2 \mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2 \mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp| \mathcal{U}_+ f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel| \cos(\delta_\parallel) \mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp| \mathcal{V}_+ f_6(\vec{\rho}),$$

B^0_s term

A_0, $A_\parallel$, $A_\perp$: transition amplitudes to a given polarization state at t=0

Time dependence appears in *T*, *U*, *V*. Different for B_s^0 and $\bar{B}_s^0$

$$\frac{d^4 \overline{P}(t,\vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2 \mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2 \mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2 \mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp| \mathcal{U}_- f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel| \cos(\delta_\parallel) \mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp| \mathcal{V}_- f_6(\vec{\rho}),$$

anti-B^0_s

f(ρ): angular distribution for a given polarization state

$\rho = \{\cos\theta_T, \varphi_T, \cos\psi_T\}$

Angular Probability Distribution: time evolution

Separate terms for B^0_s, $\bar{B}^0_s$

CP asymmetry

$$\mathcal{T}_\pm = e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) \mp \cos(2\beta_s)\sinh\left(\frac{\Delta\Gamma}{2}t\right) \mp \eta\sin(2\beta_s)\sin(\Delta m_s t)\right]$$

where $\eta = +1$ for P and -1 for $\bar{P}$

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times \left[\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh\left(\frac{\Delta\Gamma t}{2}\right)\right].$$

Terms with Δm_s dependence; they are different for different initial state flavor

$\delta_\parallel = \arg(A_\parallel A_0^*)$, $\delta_\perp = \arg(A_\perp A_0^*)$ are the phases of $A_\parallel$ and $A_\perp$ relative to A_0

Knowledge of B^0_s mixing frequency needed (well measured by CDF-D0)

Cross check sample: $B^0 \to J/\psi(\to \mu^+\mu^-)\ K^{*0}(\to K^-\pi^+)$

High-statistics test of angular efficiencies and fitter

CDF results for $B^0 \to J/\psi\ K^{*0}$ (CDF-8950)

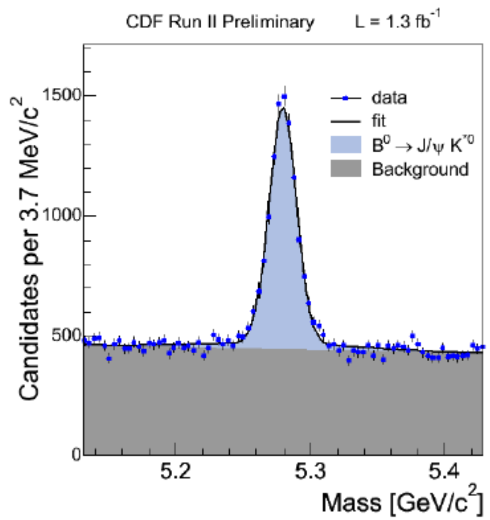
$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$

$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$

$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$

$\delta_\perp = \quad 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$



Results are in good agreement with Belle and BaBar results and uncertainties are competitive !

$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$

$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$

$\delta_\parallel = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$

$\delta_\perp = \quad 2.91 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$

Phys. Rev. D 76, 031102 (2007)

No width difference ($\Delta\Gamma = 0$)

Flavor Tagging

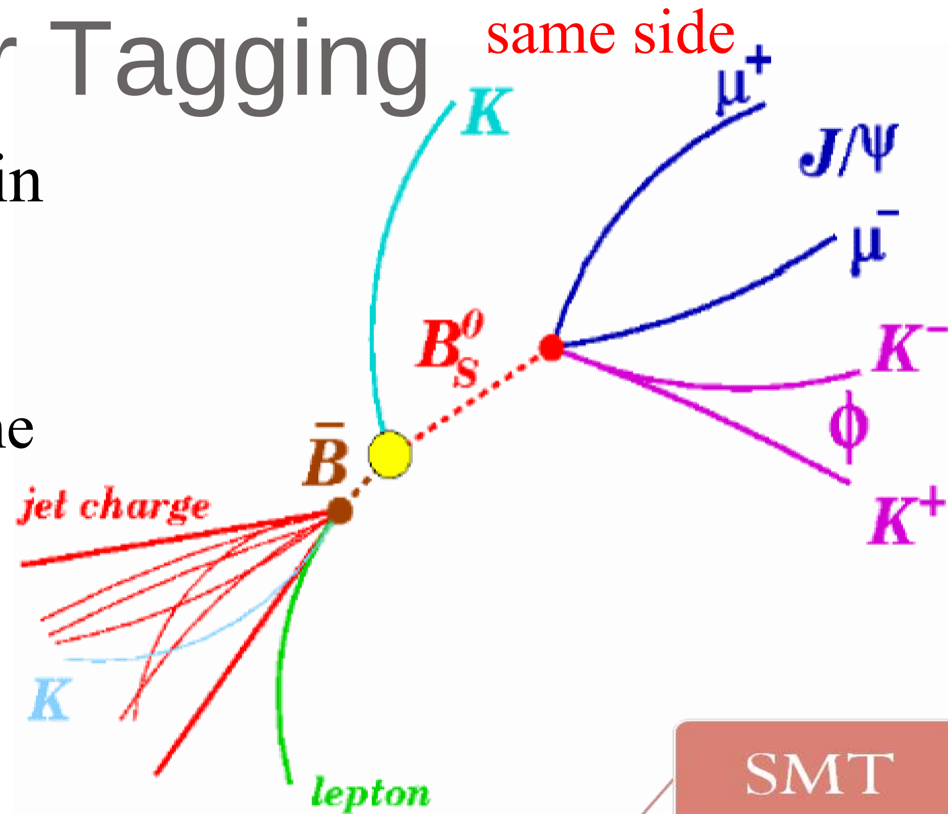
We have a sample of

B^0_s *and* $\bar{B}^0_s \rightarrow J/\psi\ \phi$ $\quad (J/\psi \rightarrow \mu^+\mu^-, \phi \rightarrow K^+K^-)$

of known decay-time and CP.

It will help to know whether a meson or an anti-meson was produced in the *pp* interaction….

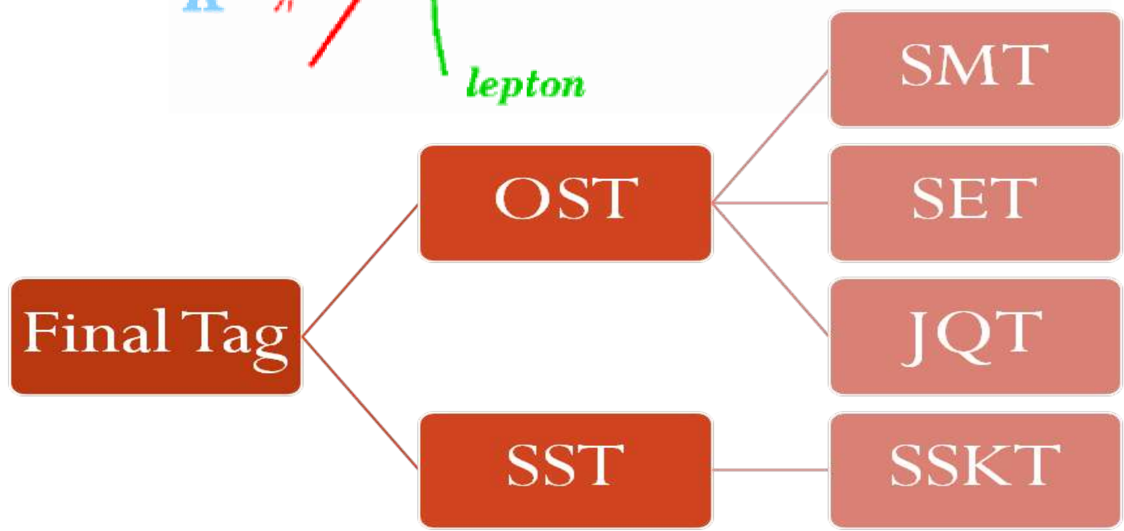
Overview of Flavor Tagging



- b quarks generally produced in pairs at Tevatron
  - Tag either the b quark which produces the J/ψφ (SST), or the other b quark (OST)

opposite side

- The final tag is the combination (properly weighted) of all the different tagging methods



Output: decision (b-quark or $\bar{b}$-quark) and the quality of that decision

Quantifying Tagging Power

The tagging of an event can be

of Right Sign (RS) if assigned "sign" = true "sign" (B^0_s or $\bar{B}^0_s$)

of Wrong Sign (WS)

Inconclusive (NT)

To quantify tagging we use:

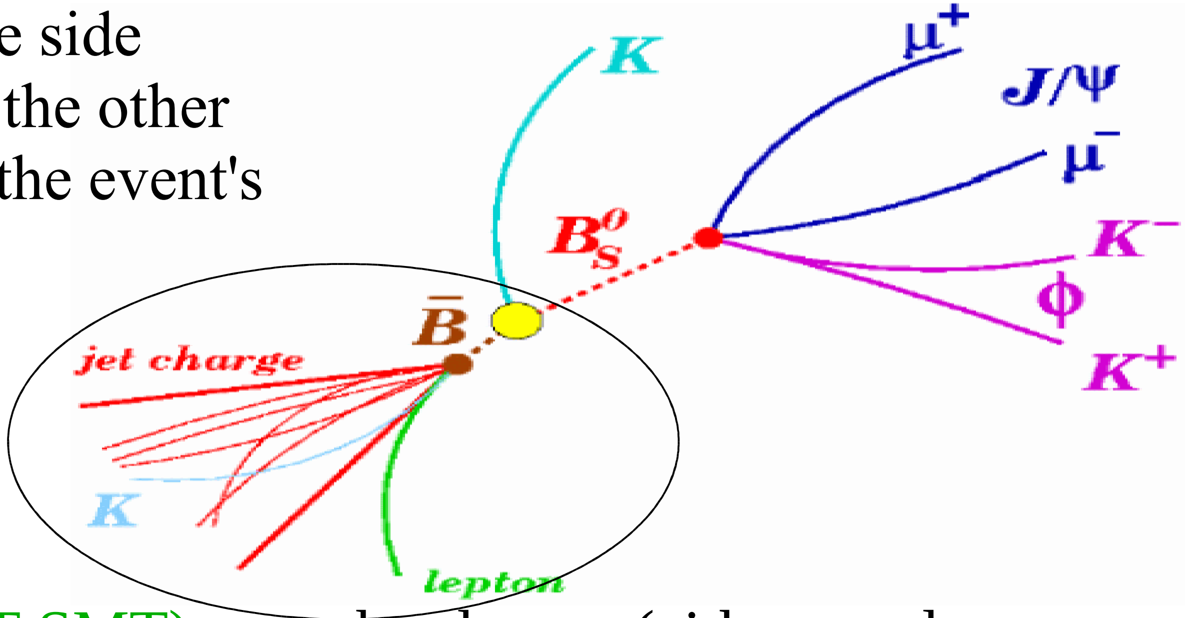
Efficiency $\varepsilon = N_{tagged} / N_{total} = (N_{RS}+N_{WS})/(N_{RS}+N_{WS}+N_{NT})$

"Dilution" $D = P_{tag} - P_{mistag} = (N_{RS}-N_{WS})/(N_{RS}+N_{WS})$

The statistical power of the tagging is quantified by
$\varepsilon \langle D^2 \rangle$ typically 4.5 % as detailed next.

Opposite Side Flavor Tagging (OST)

Tagging in the opposite side identifies the flavor of the other B-hadron produced in the event's final state.



Submethods

Lepton tagging (SET,SMT): searches lepton (either an electron or a muon) in the other side coming from the semileptonic decay of the other B. The charge of this lepton is correlated with the flavor of the B hadron. E.g.: a l^- comes from a transition b-> q l^- $\bar{\nu}$ (i.e., a $\bar{B}^0$,$\bar{B}^0_s$ meson or a B^-)

Jet charge tagging (JQT): exploits the fact the sign of the sum of the charges (weighted by their momentum) of the jet is the same as the b quark that produces that jet.

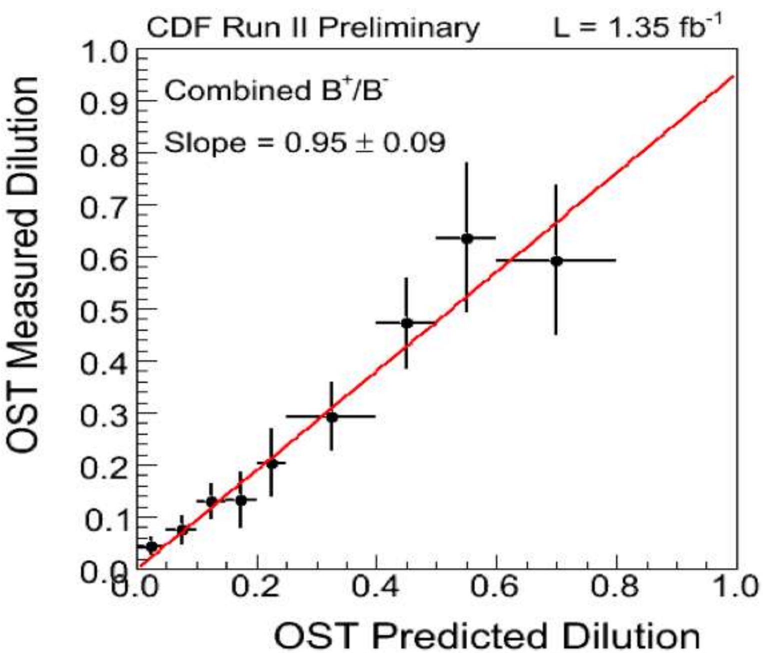
OST

Input to the Dilution function:

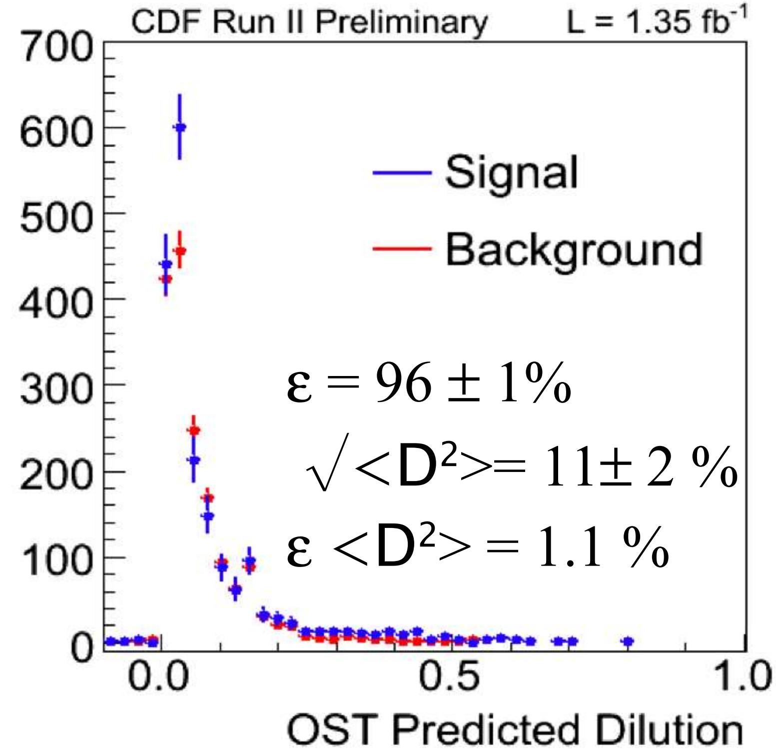
JQT: total jet charge (track-p_T weighted)

SET, SMT: PID likelihood $\otimes$ p_T^{rel}

It is calibrated and checked mainly with samples of events with B^+ or B^-



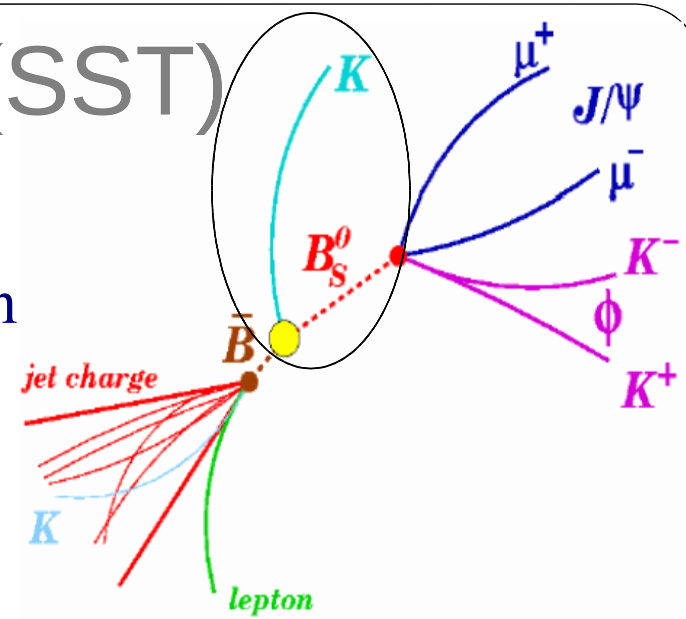
B^0_s , $\bar{B}^0_s$ sample



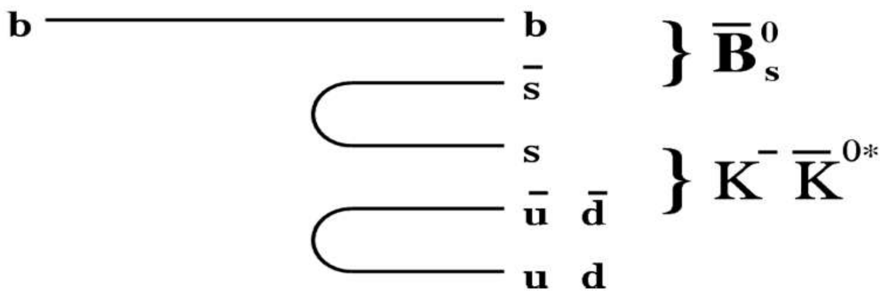
Where the "low" Dilution comes from? :

- some OS b outside acceptance region
- detector reconstruction effects
- fragmentation effects in the JQT
- b $\rightarrow$ c transitions in SET and SMT
- B oscillations
- others

Same Side Kaon Tagging (SST)



Tag on the leading fragmentation particle (LPF); in a B^0_s event is almost always a Kaon



Among candidate tracks:

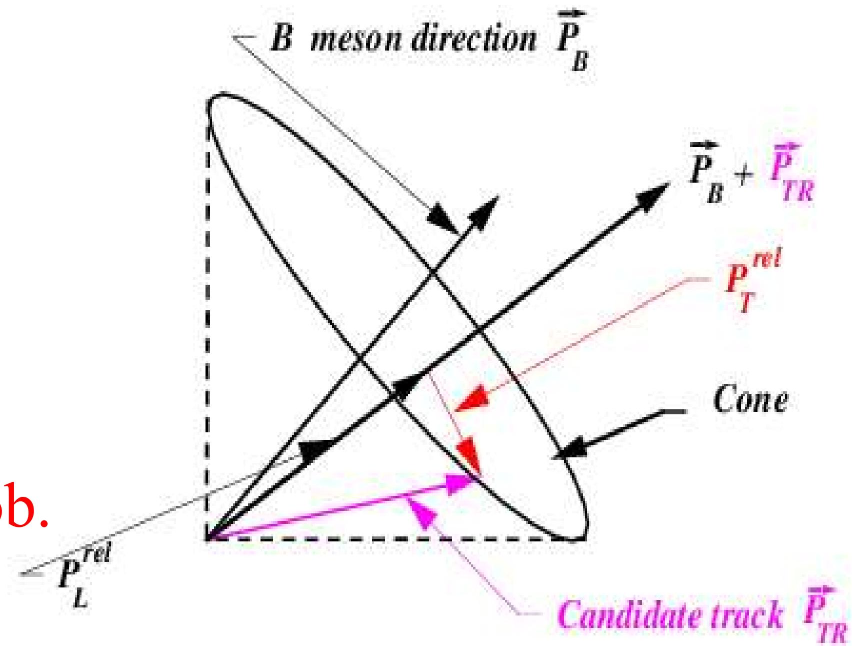
1. close to B meson

   $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.7$

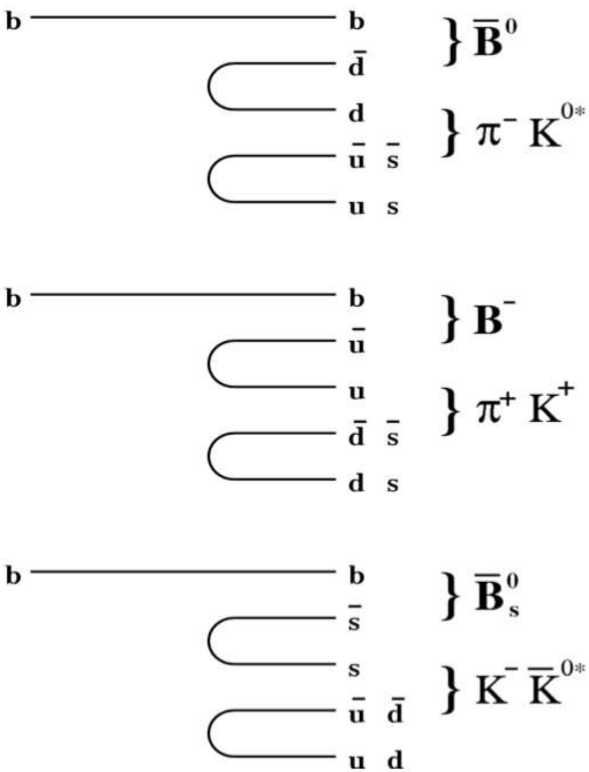
2. $p_T > 350$ MeV/c

3. coming from PV: $|d_0 / \sigma| < 3$

choose the one with highest NN prob. output (based on p_L^{rel}, p_T^{rel} rel. to $\mathbf{p_B} + \mathbf{p_{track}}$ direction & particle ID)

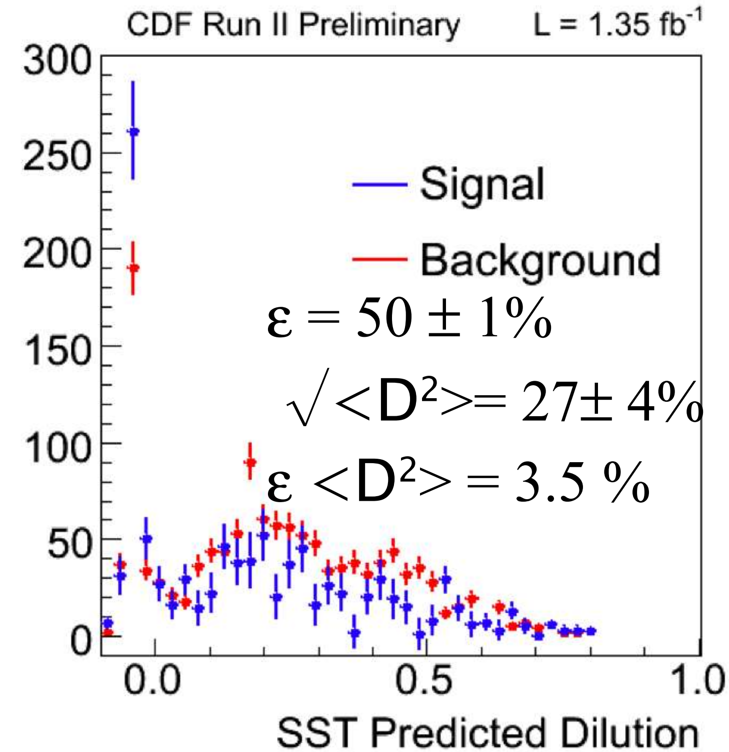


SST



B^+ or B^0 can not be used to calibrate since there the LFP is with large probability a π

B^0_s , $\bar{B}^0_s$ sample



- need to rely on MC
- cross checked in mixing ($B^0_s \rightarrow D_s^+\pi^-$)
- particle ID by ToF and dE/dx helps

Where the Dilution comes from ? :
- detector reconstruction effects
- fragmentation fluctuations
- PID limitations
- others

Un-binned Likelihood Fit

We have a sample of

B^0_s *and* $B^0_s \rightarrow J/\psi\ \phi\ (J/\psi \rightarrow \mu\mu^+\mu\mu^-,\ \phi \rightarrow K^+K^-)$

of "known" decay-time, CP and production flavor.

But this information is not know on a per-candidate basis. Wrap it up in a fit.

Overview of fit

Single event likelihood decomposed and factorized in:

$$f_s P_s(m|\sigma_m) P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) P_s(\sigma_t) P_s(\mathcal{D})$$

$$+(1 - f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D})$$

P_s : probability distribution functions (PDFs) for signal

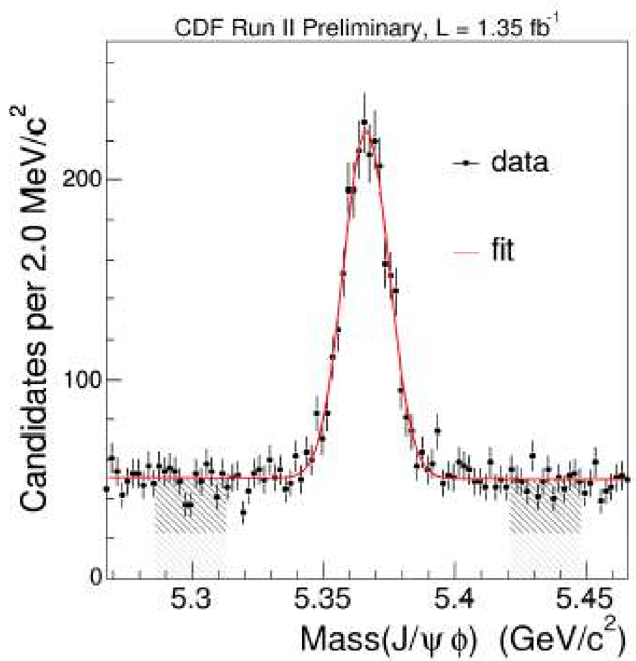
P_b : PDFs for background

f_s : signal fraction (fit parameter)

Measured quantities that enter in the fit and their probability function (I)

reconstructed mass of B_s^0, $\bar{B}_s^0$ and its error, decay time and its error, transversity angles, flavor tag decision, dilution D

$$f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D}) + (1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D})$$



Mass: discriminate signal against background

$P_s(m|\sigma_m)$: Gaussian N (m,σ_m)

$P_b(m)$: 1st order polynomial

Measured quantities that enter in the fit and their probability function (II)

reconstructed mass of B_s^0, $\bar{B}_s^0$ and its error, decay time and its error, transversity angles, flavor tag decision, dilution D

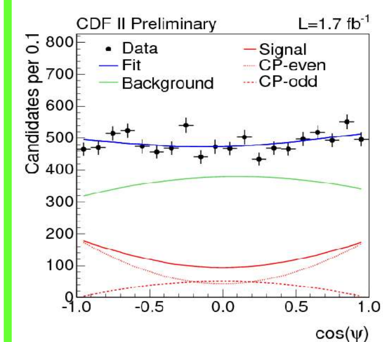
$$f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D}) + (1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D})$$

$$\underbrace{\frac{1+\xi\mathcal{D}}{2} P(t,\vec{\rho}|\sigma_t)\epsilon(\vec{\rho})}_{B_s^0} + \underbrace{\frac{1-\xi\mathcal{D}}{2} \bar{P}(t,\vec{\rho}|\sigma_t)\epsilon(\vec{\rho})}_{\bar{B}_s^0}$$

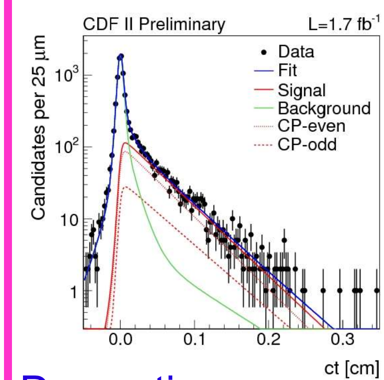
$\xi=\{-1,0,+1\}$: tag decision

D: event-per-event dilution

$\varepsilon(\rho)$: detector effects obtained from MC



Angles: Separate CP-even from CP-odd final states



Decay-time: Lifetime of each CP state

$P_b(t\,|\,\sigma_t)$: delta function at t = 0 + one (two) exponentials for t < 0 (t > 0) ⊗ Gaussian resolution function

$P_b(\rho) = P_b(\cos\theta_T)\, P_b(\varphi_T)\, P_b(\cos\psi_T)$; P_b's from sidebands events

Measured quantities that enter in the fit and their probability function (III)

reconstructed mass of B_s^0, $\bar{B}_s^0$ and its error, decay time and its error, transversity angles, flavor tag decision, dilution D

$$f_s P_s(m|\sigma_m) P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) P_s(\sigma_t) P_s(\mathcal{D}) + (1-f_s) P_b(m) P_b(t|\sigma_t) P_b(\vec{\rho}) P_b(\sigma_t) P_b(\mathcal{D})$$

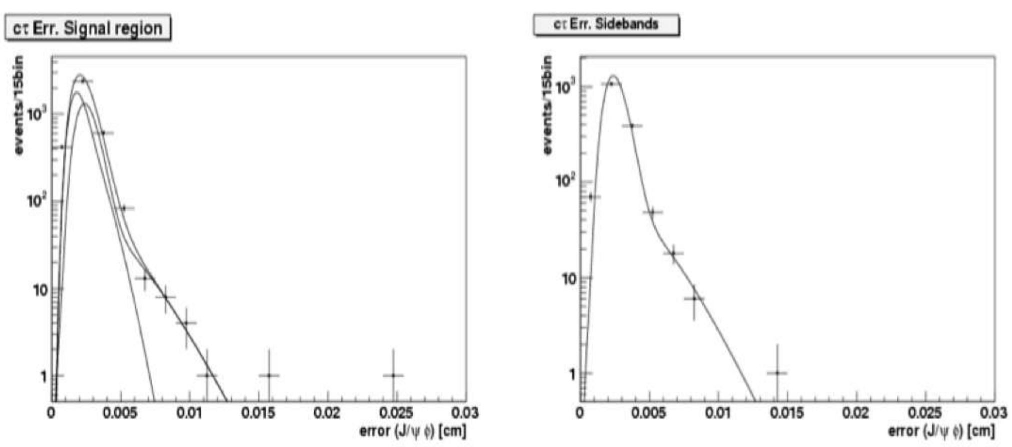
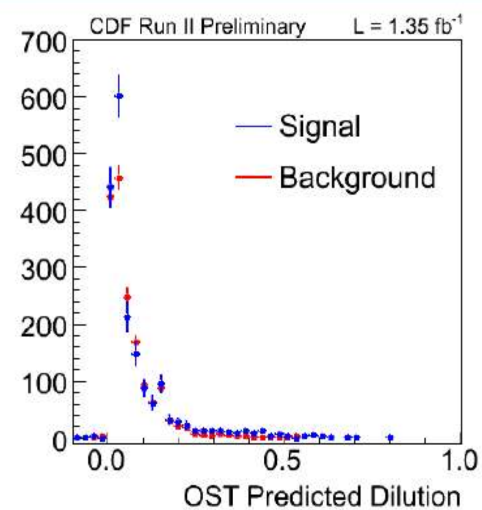


FIG. 37: Lifetime error projection in signal region(left) and sideband region(right).



TTagging : flavor of initial state

Parameters in Fit

The relevant ones : β_s , $\Delta\Gamma$

plus many nuisance parameters: mean width $\Gamma = (\Gamma_L+\Gamma_H)/2$,

$|A_\perp(0)|^2$, $|A_\parallel(0)|^2$, $|A_0(0)|^2$, $\delta_\parallel = \arg(A_\parallel A_0^*)$, $\delta_\perp = \arg(A_\perp A_0^*)$ ...

Results

1. Untagged analysis (do not use information on production flavor) arXiv:0712.2348; PRL 100, 121803 (2008)

   → τ and $\Delta\Gamma$

2. Tagged analysis arXiv:0712.2397, accepted by PRL

   → ($2\beta_s$, $\Delta\Gamma$) confidence region

   → $2\beta_s$ confidence interval

   (quote results with and without external theory constraints)

Untagged analysis

- Dependence on production flavor cancels out

$$
\begin{aligned}
\mathcal{T}_{\pm} = e^{-\Gamma t} \quad &\times \quad [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \\
& \qquad \cancel{\mp \eta \sin(2\beta_s)\sin(\Delta m_s t)}] \, , \\
\mathcal{U}_{\pm} = \pm e^{-\Gamma t} \quad &\times \quad [\cancel{\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)} \\
& - \quad \cancel{\cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)}\sin(\Delta m_s t) \\
& \pm \quad \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)] \, , \\
\mathcal{V}_{\pm} = \pm e^{-\Gamma t} \quad &\times \quad [\cancel{\sin(\delta_\perp)\cos(\Delta m_s t)} \\
& - \quad \cancel{\cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)} \\
& \pm \quad \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)] \, .
\end{aligned}
$$

- Suited for precise measurement of width-difference and average lifetime (maximum sensitivity obtained when assuming a given value for β_s)
- Marginally sensitive to CP-violation

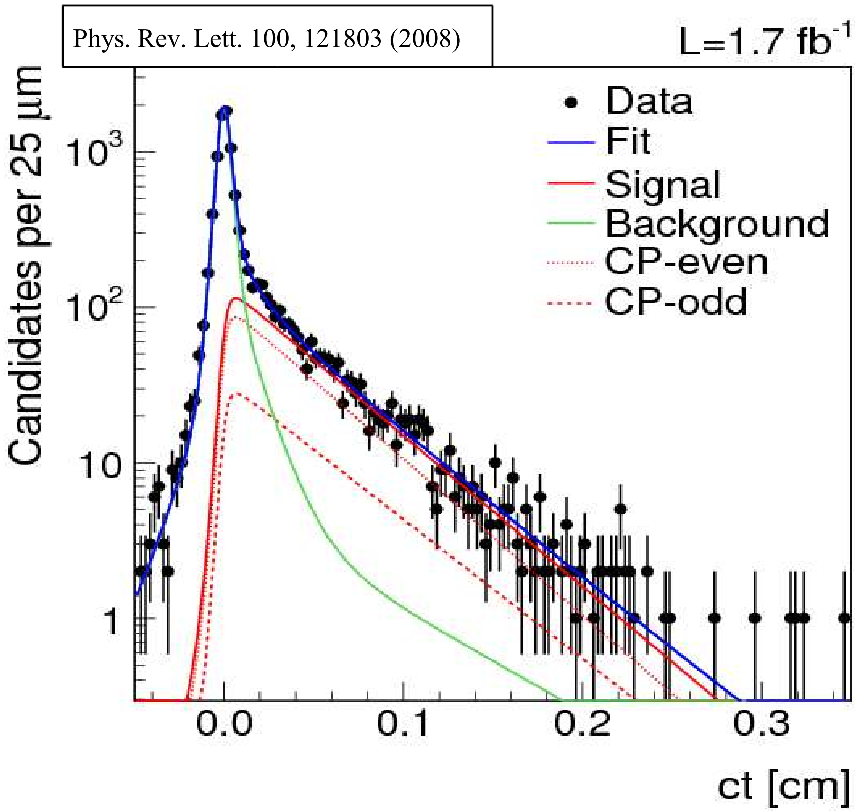
Untagged analysis: results

B_s^0 mean lifetime and width difference

(CP conservation assumption: $2\beta_s = 0$)

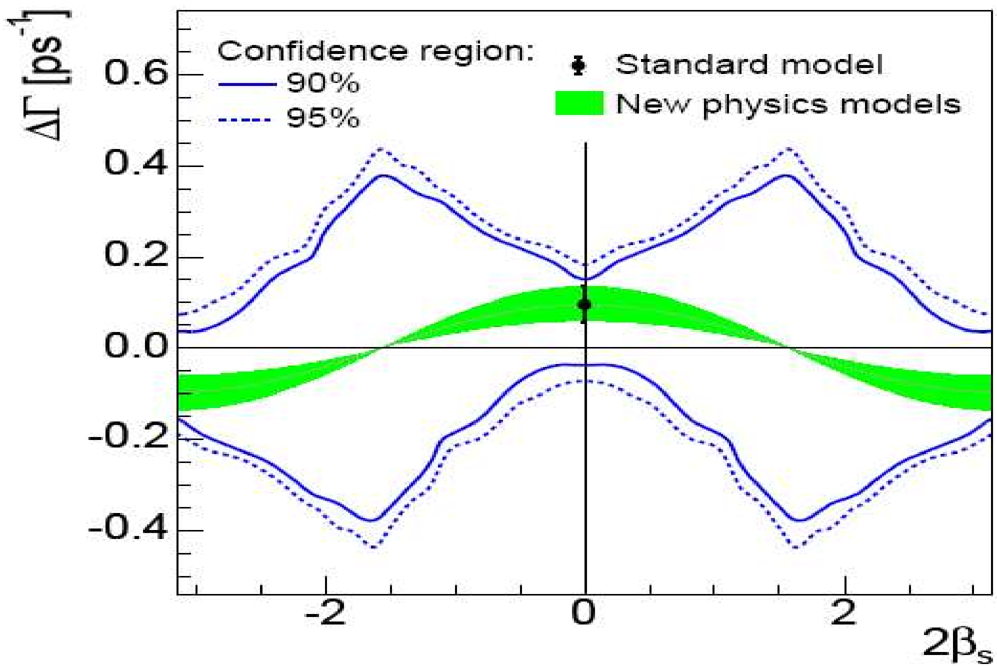
$\tau = 1/\Gamma = 2 / (\Gamma_L + \Gamma_H) = 1.52 \pm 0.04 \pm 0.02$ ps

$\Delta\Gamma = \Gamma_L - \Gamma_H = 0.08 \pm 0.06 \pm 0.01$ ps^{-1} (best measurement to date)



Untagged analysis: results

$(2\beta_s, \Delta\Gamma)$ confidence region



Due to symmetries in the likelihood 4 solutions are possible in $(2\beta_s\text{-}\Delta\Gamma)$ plane; in particular can not determine simultaneously the sign of $2\beta_s$ and $\Delta\Gamma$

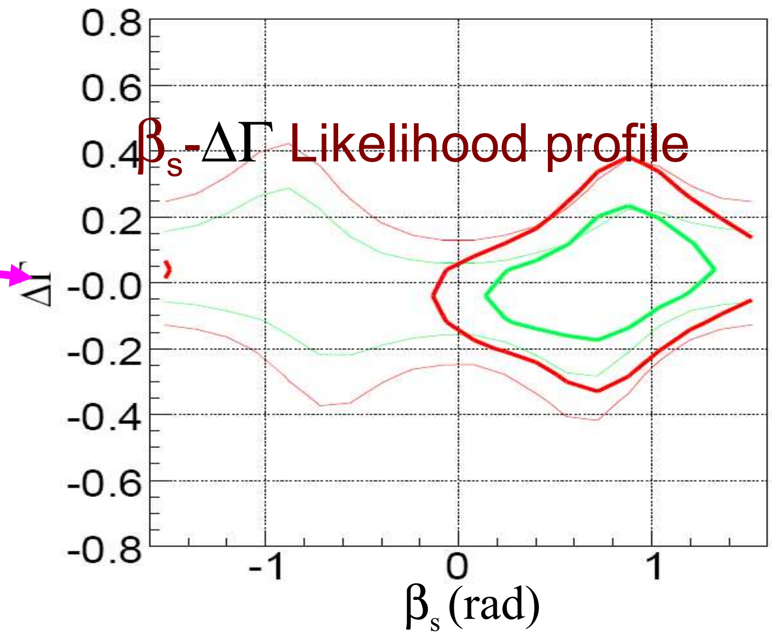
NP region by $\Delta\Gamma = |\Gamma_{12}| \cos \phi_s$ where $|\Gamma_{12}| = 0.048 \pm 0.018$

A.Lenz, U.Nierste JHEP 06, 072 (2007)

New physics is expected to have almost no impact on Γ_{12}

Tagged analysis

- Study effect of tagging using
- pseudo-experiments



- $\beta_s \rightarrow -\beta_s$ no longer a symmetry

- Likelihood expression has double minima due to symmetry

$$2\beta_s \rightarrow \pi - 2\beta_s,\ \Delta\Gamma \rightarrow -\Delta\Gamma,\ \delta_{\parallel} \rightarrow 2\pi - \delta_{\parallel},\ \delta_{\perp} \rightarrow \pi - \delta_{\perp}$$

Likelihood function non gaussian

➔There is no parabolic minima → can't quote point estimate!

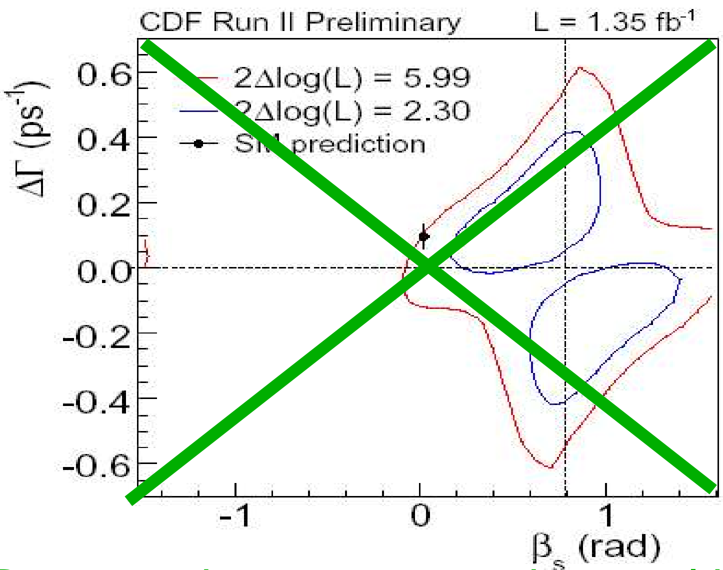
➔Quote confidence region

- using profile likelihood ratio ordering with rigorous frequentist inclusion of systematic uncertainties (a la Feldman-Cousins)

Probabilistic method has to provide proper coverage

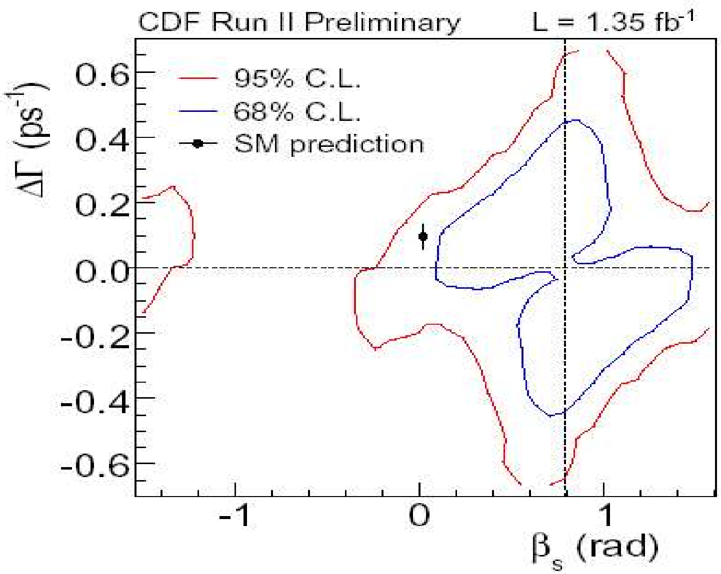
Exclude a given β_s-$\Delta\Gamma$ pair if it can be excluded for any choice of the 20+ nuisance parameters within 5σ of their estimated values. This corresponds to evaluating a 27-dimensional confidence region (in all physics and nuisance parameters) and then project it into the 2-dimensional space of interest.

2D-Likelihood contour



Does **not** has coverage: the resulting confi-dence region does not contain the true value with desired CL independently of true value.

Profile-Likelihood Ratio ordering
(a la Feldman-Cousins)

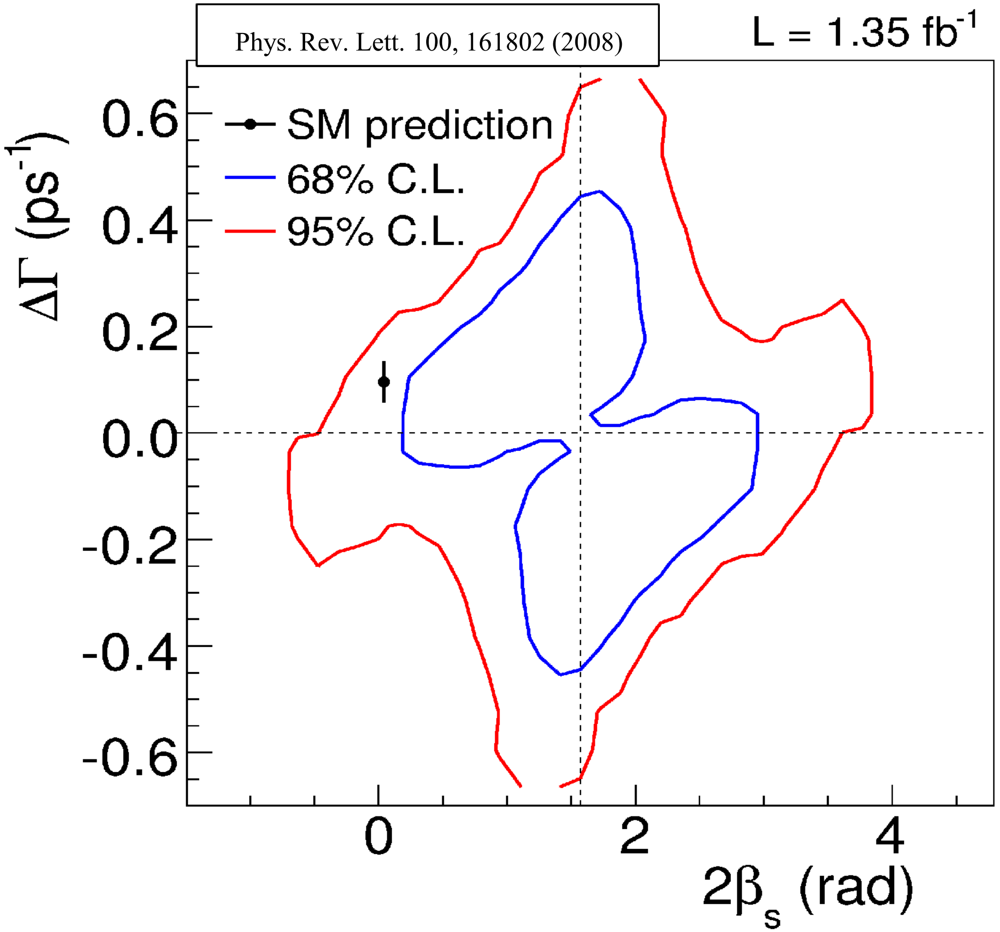


Above procedure has been corrected to have right coverage.

Flavor Tagged $2\beta_s$ - $\Delta\Gamma$ Confidence Region

Confidence region with profile-Lilkelihood Ratio ordering and rigorous frequentist inclusion of systematic uncertainties.

Assuming the SM, the probability of observing a fluctuation as large or larger than what observed in data is 15%, corresponding to 1.5σ



β_s 1D Intervals

$\Delta\Gamma$ treated as a nuisance parameter

➔ $2\beta_s \in [0.32, 2.82]$ at 68% CL

Constraining $|\Gamma_{12}| = 0.048 \pm 0.018$ in $\Delta\Gamma = |\Gamma_{12}|\cos\phi_s$,

A.Lenz, U.Nierste JHEP 06, 072 (2007)

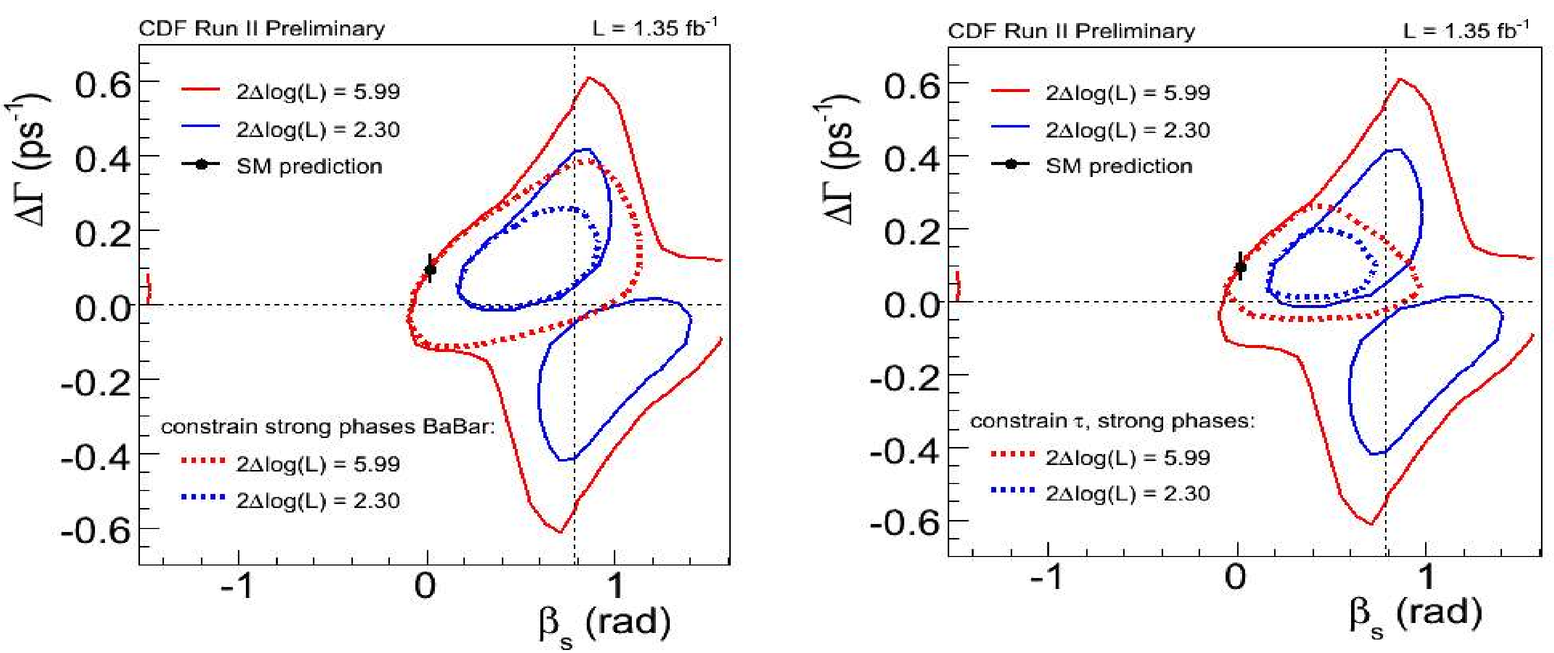
$\delta_{\parallel}$, $\delta_{\perp}$ from BaBar's $B^0 \rightarrow J/\psi\ K^{*0}$ and on equal B^0_s and B^0 lifetimes

PRD 76, 031102 (2007)

➔ $2\beta_s \in [0.40, 1.20]$ at 68% CL

Constrain strong phases

Constrain lifetime and strong phases



DØ Results

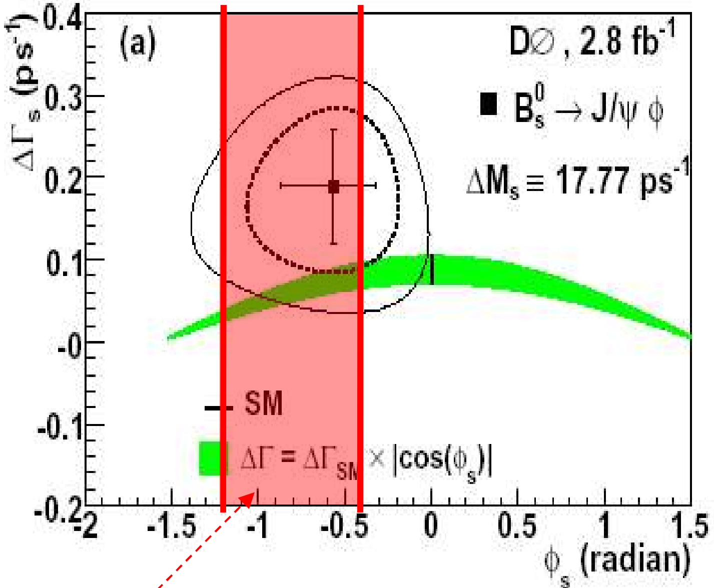
- DØ chooses to quote the results in terms of $\phi_s = -2\beta_s$ **(arXiv:0802.2255)**
- DØ quotes a point-estimate with strong phases constrained from

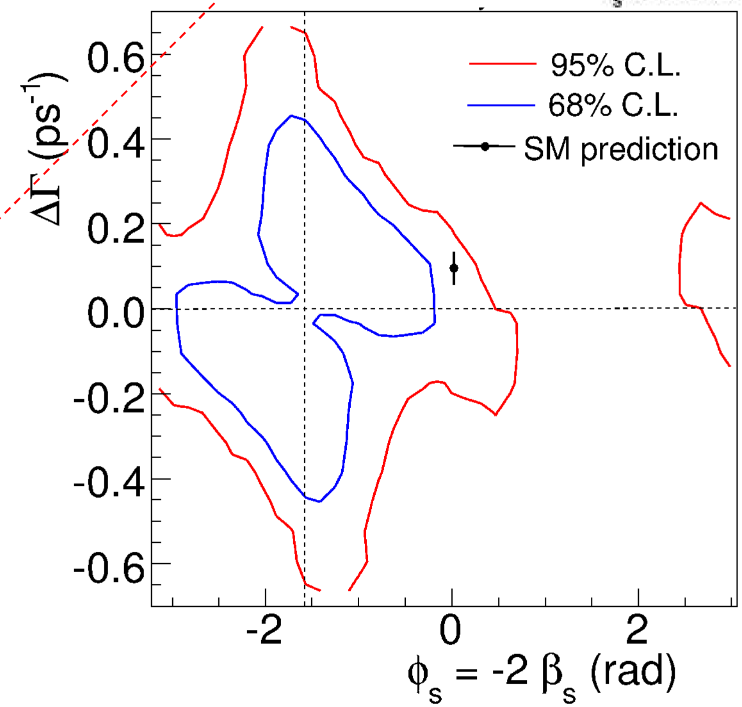
  $B^0 \to J/\psi K^{*0}$

  $$\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})^{+0.07}_{-0.02}(\text{syst})$$

- This makes the result dependent on theoretical assumptions
- Can be compared to CDF constrained result

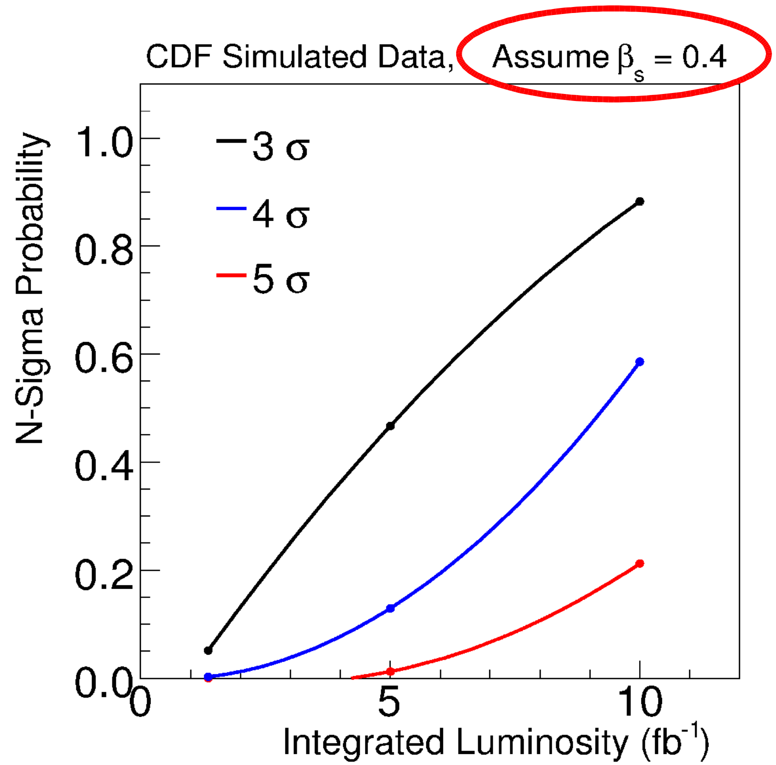
$2\beta_s \in [0.40,1.20]$ @ 68% CL





Future

- Tevatron can search for anomalously large values of β_s
- Shown results 1.3 fb^{-1}, but 3 fb^{-1} already on tape to be analyzed soon
- Expect 6-8 fb^{-1} by the end of the run 2
- Analysis to be improved and optimized:
  - ~30% statistics from other triggers
  - better flavor tagging
  - signal optimization based on expected statistical errors



- If β_s is indeed large CDF results have good chance to prove it

- CPV in B_s system is one of the main topics in LHC_b B Physics program

→ will measure $\phi_s = -2\beta_s$ with great precision

Conclusions

Conclusions

- First measurements of CPV in B_s system done by CDF

- Significant regions in β_s space are ruled out

- Soon after, confirmed by D0

- Best measurements of B_s decay width difference and of the best lifetime measurements

- Both CDF and DØ observe 1-2 sigma β_s deviations from SM predictions

- Interesting to see how these effects evolve with more data

Back up

-UTFit collaboration has done first attempt to combine results and claim a 3σ deviation from SM expectation:

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than $\boxed{3\sigma}$ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

- "re-introduces" the ambiguity into the D0 result.
- does so by symmetrizing.
- uses "CDF likelihood profile" results instead of "CDF FC" results
- not endorsing it very enthusiastically the conclusion of this combination.

CDF and D0 plan to make a more appropriate "internal combination" for the near future

http://arxiv.org/pdf/0803.0659

Difference in direct CP violation between charged and neutral B meson decays

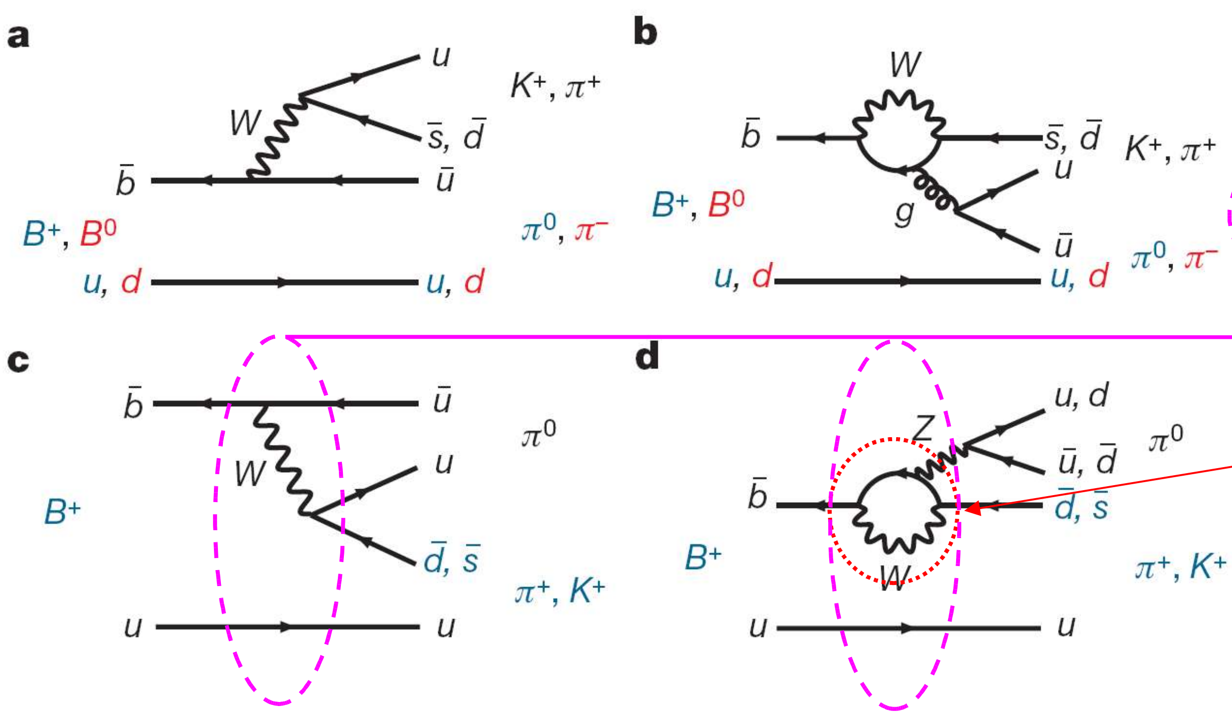
BELLE; Nature 452(2008)332

Elsewhere there is another anomaly that *may* also have to do with b→s

* Direct CP in B+→K+ p0 and B0-> K+pi- are generated by the b →s transition. These should have the same magnitude.

* But Belle measures $\Delta\mathcal{A} \equiv \mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = +0.164 \pm 0.037$, .4 σ)

* Including BaBar measurements: > 5σ



negligible CPV phase within the SM: can not affect **ΔA** by much

… unless the **penguin** loop picks up CPV phase from **NP**

The electroweak penguin can break the isospin symmetry

But then extra sources of CP violating phase would be required in the penguin

Un-binned Likelihood Fit

Fit with separate PDFs for signal and background

$$f_s P_s(m|\sigma_m) P_s(ct, \vec{\rho}, \xi|\mathcal{D}, \sigma_{ct}) P_s(\sigma_{ct}) P_s(\mathcal{D})$$

$$+(1 - f_s) P_b(m) P_b(ct|\sigma_{ct}) P_b(\vec{\rho}) P_b(\sigma_{ct}) P_b(\mathcal{D})$$

$P_s(m|\sigma_m)$ – Single Gaussian fit to signal mass

$P_s(ct, \rho, \xi|\mathcal{D}, \sigma_{ct})$ – Probability for $\overline{B}_s^0/B_s^0$

$P_b(m)$ – Linear fit to background mass distribution

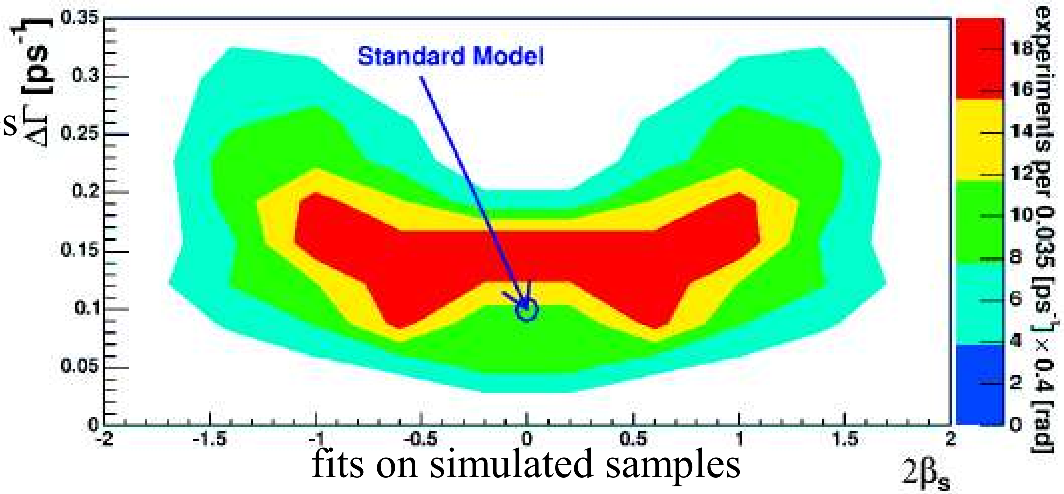
$P_b(ct|\sigma_{ct})$ – Prompt background, one negative exponential, and two positing exponentials

$P_b(\rho)$ – Empirical background angle probability distributions

Use scaled event-per-event errors for mass and lifetime fits and event-per-event dilution

β_s in Untagged Analysis

- Fit for the CPV phase
- Biases and non-Gaussian estimates in pseudo-experiments
- Strong dependence on true values for biases on some fit parameters.



fits on simulated samples

a) Dependence on one parameter in the likelihood vanishes for some values of other parameters:

e.g., if $\Delta\Gamma=0$, $\delta_\perp$ is undetermined $\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$

b) L invariant under two transformations:

$$2\beta_s \rightarrow -2\beta_s,\ \delta_\perp \rightarrow \delta_\perp + \pi$$

$$\Delta\Gamma \rightarrow -\Delta\Gamma,\ 2\beta_s \rightarrow 2\beta_s + \pi$$

$\rightarrow$ 4 equivalent minima

Systematics

- Systematic uncertainties studied by varying all nuisance parameters +/- 5 σ from observed values and repeating LR curves (dotted histograms)

- Nuisance parameters:
    - lifetime, lifetime scale factor uncertainty,
    - strong phases,
    - transversity amplitudes,
    - background angular and decay time parameters,
    - dilution scale factors and tagging efficiency
    - mass signal and background parameters
    - …

- Take the most conservative curve (dotted red histogram) as final result