

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

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6/05/2008

# Introduction

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# 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  $B_s^0$  meson system is an excellent way to search for new physics
  - B-factories have established 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  $B_s^0$  system
  - CP violation in  $B_s^0$  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

$$\begin{array}{c} \text{Rate of} \\ \mathbf{B}_s^0 \end{array} \neq \begin{array}{c} \text{Rate of} \\ \mathbf{B}_s^0 \bar{\phantom{B}} \end{array}$$

- 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

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

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

Highly suppressed CPV (left side of matrix)  
Large CPV (top-right and bottom-left elements)  
Suppressed CPV (middle-right and bottom-middle elements)

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  $\beta$  and  $\beta_s$ .

- Can construct six unitary relations

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

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

↓ relates to the angle

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

$$\sin(2\beta) \sim 0.7 \text{ [well measured]}$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

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

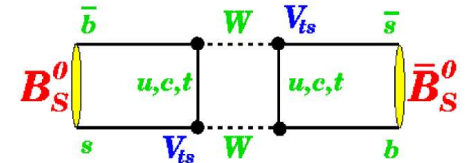
$$\sim 0.02 \text{ predicted tiny SM-CP phase!}$$

- non-unitarity would imply contributions from unknown physics

# Neutral $B_s$ system

- Time evolution of  $B_s$  flavor eigenstates from Schrödinger equation:

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



- Diagonalize mass and decay matrices  $\rightarrow$  obtain mass eigenstates

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

- The magnitude of the box diagram gives the oscillation frequency

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

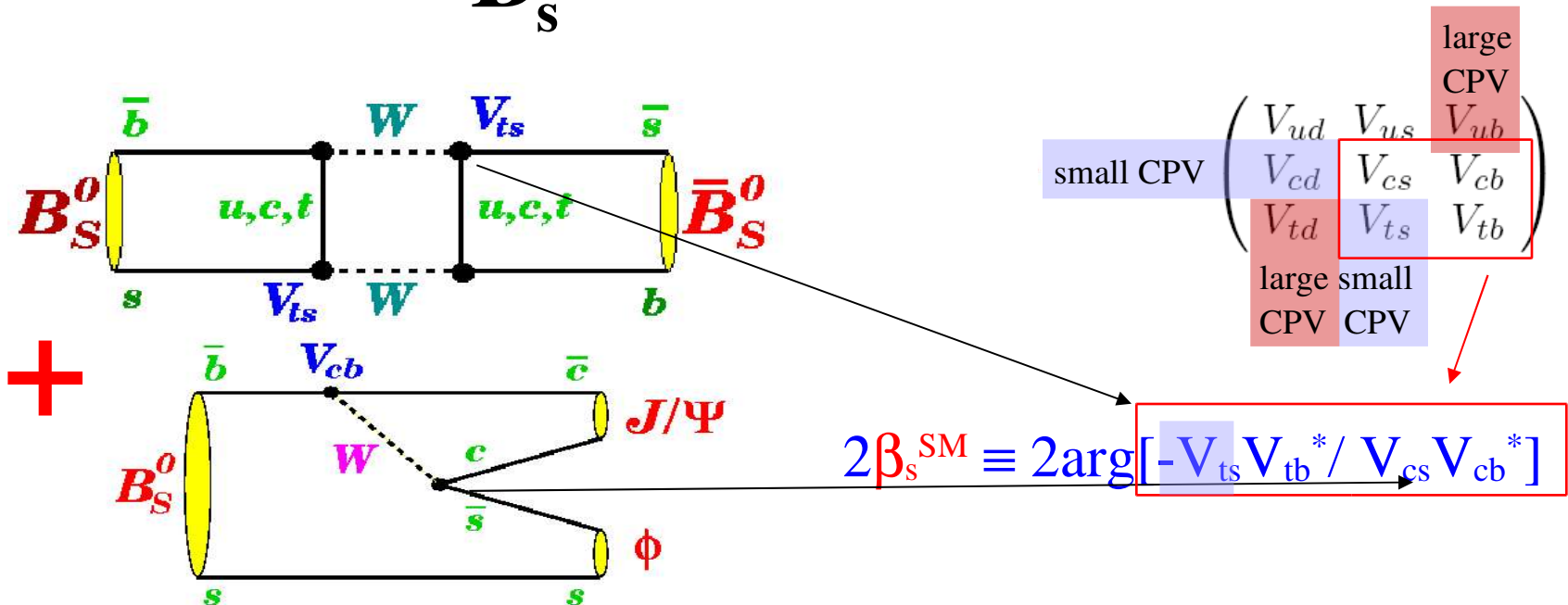
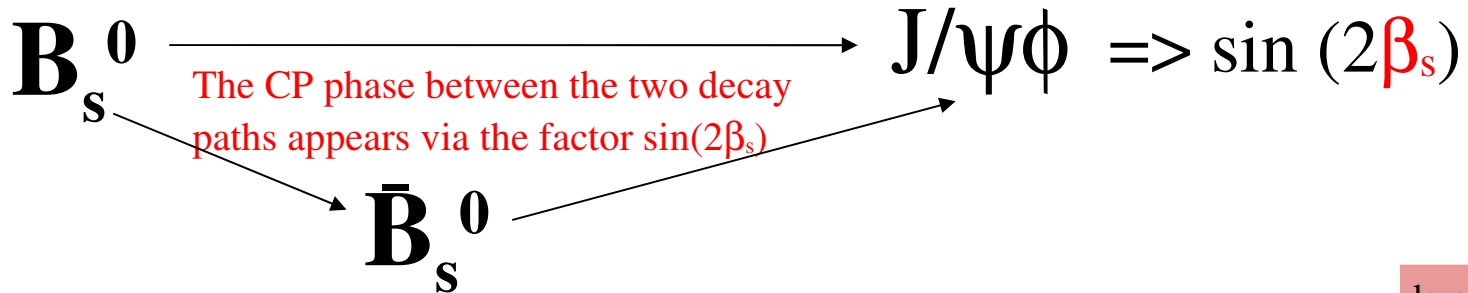
- The phase of the diagram gives the complex number  $q/p = e^{-i\phi_s}$  where  $\phi_s = \arg(-M_{12}/\Gamma_{12})$  [ CP-violating phase]

- Mass eigenstates have different decay widths (lifetimes)

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

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

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



CP violation phase  $\beta_s$  in SM is predicted to be very small



# CP violating phases : $\phi_s$ vs $\beta_s$

- $2\beta_s = 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] \sim 4.4^\circ$  (SM) phase of  $b \rightarrow ccs$  transition that accounts for interference of decay and mixing+decay
- $\phi_s = \arg[-M_{12}/\Gamma_{12}] \sim 0.24^\circ$  (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 inaccessible by current experiments (assumed zero). If NP occurs in mixing:

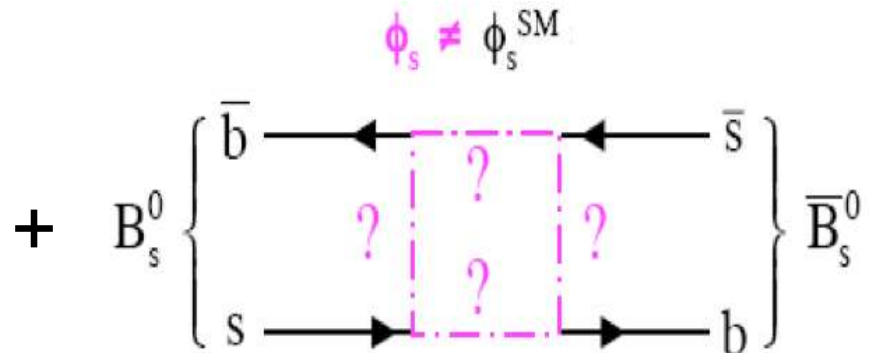
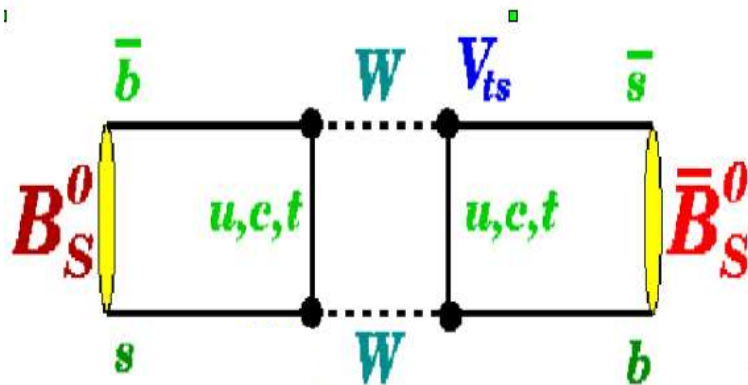
$$\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}} \sim \phi_s^{\text{NP}}$$

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

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  $2\beta_s = (2\beta_s^{\text{SM}} - \phi_s^{\text{NP}}) \sim -\phi_s^{\text{NP}}$
  - 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? )

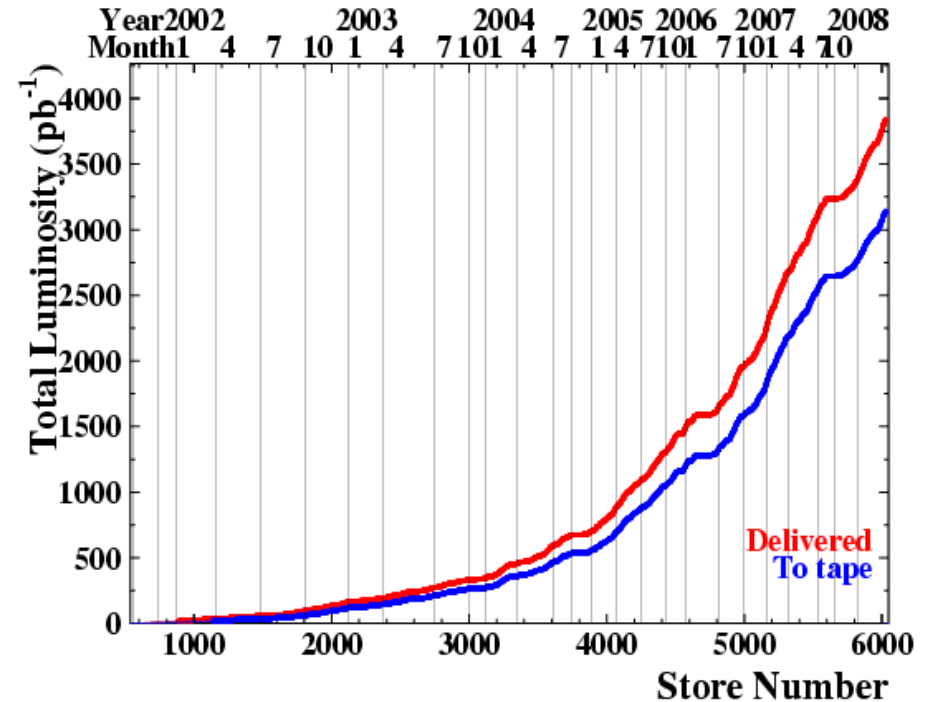
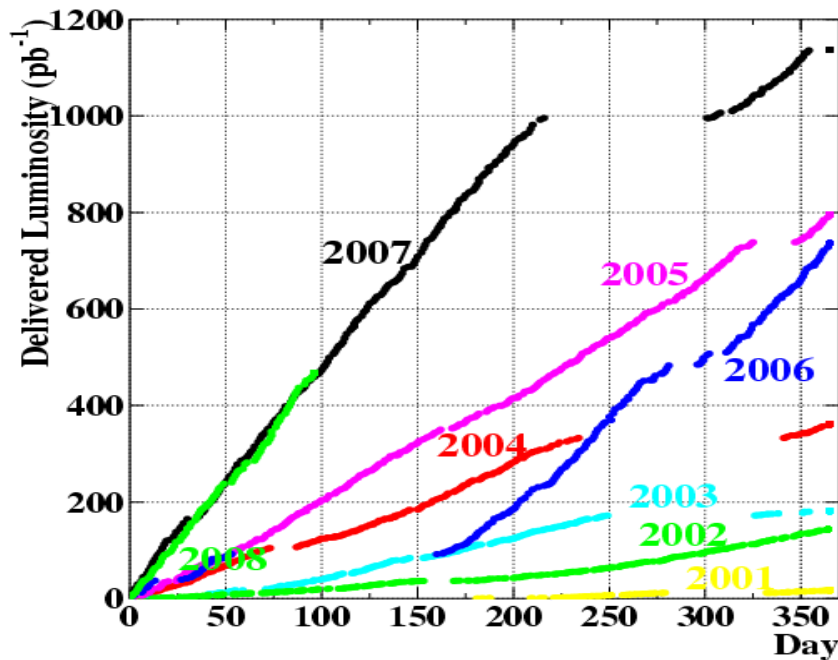


unknown flavor structure

# Experiment Overview

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# Introduction to the Tevatron

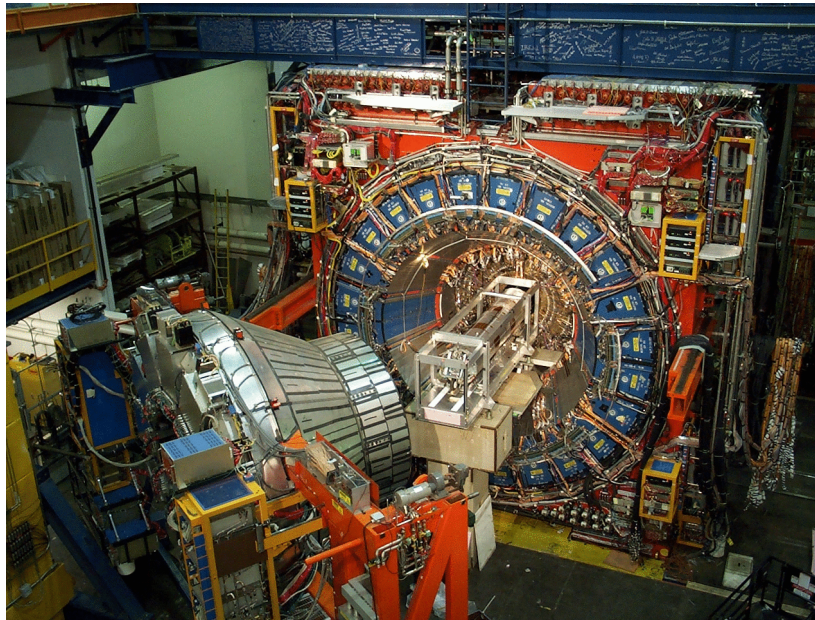


- Tevatron is the world highest energy accelerator:  $p\bar{p}$  at  $\sqrt{s}=1.96\text{TeV}$
- Will take data until Sept 2009 (may be extended 1 year)
- Expected integrated luminosity :  $\sim 5 - 6 \text{fb}^{-1}$  until 2009
- CDF has already  $3.2 \text{fb}^{-1}$  on tape [only  $1.3 \text{fb}^{-1}$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

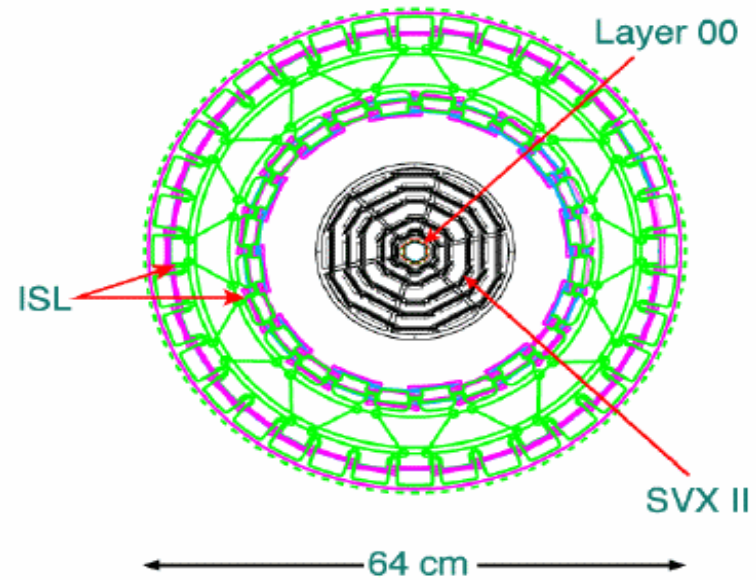
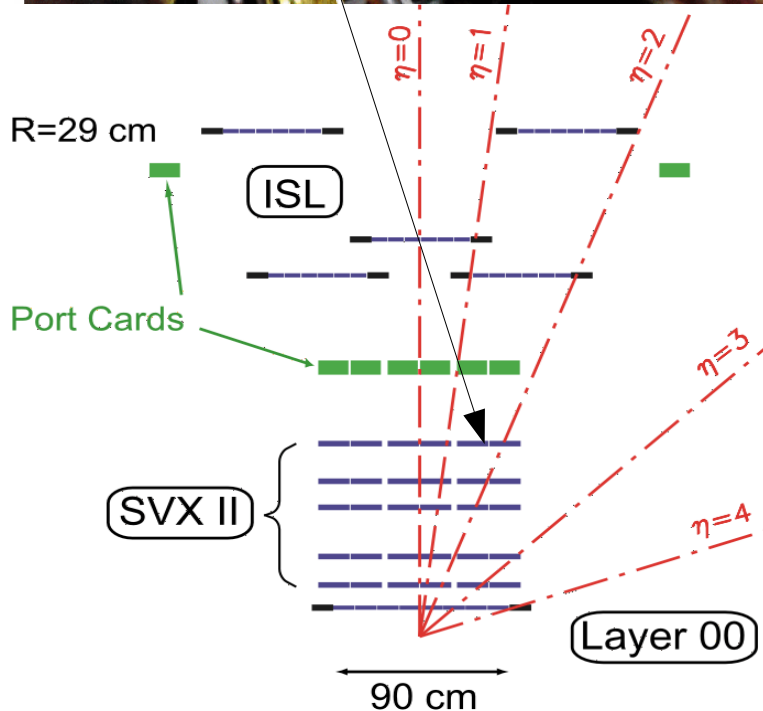
# Introduction to the CDF II detector

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  $\sim 25 \mu\text{m}$
- **Particle identification (PID):**  $dE/dx \sim 1.5 \sigma$  separation for K/pi with  $p > 2 \text{ GeV}$  and **TOF**  $\sim 2 \sigma$  K/pi with  $p < 1.5\text{-}1.8 \text{ GeV}$ .
- Good **e and  $\mu$  identification** by calorimeters and muon chambers



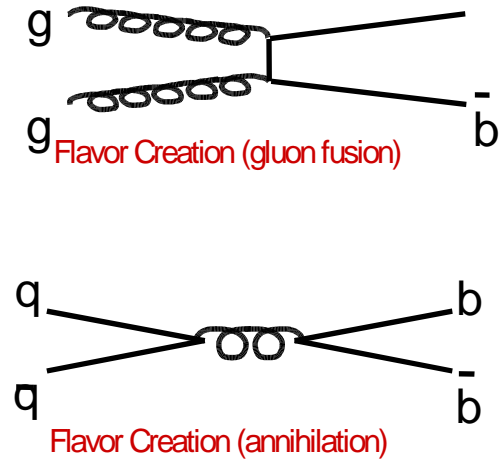
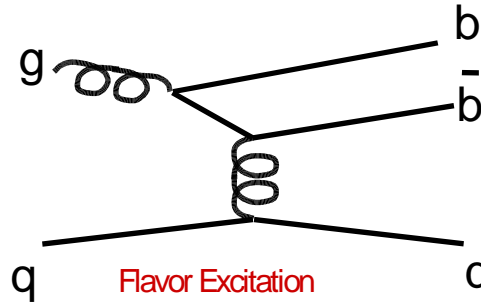
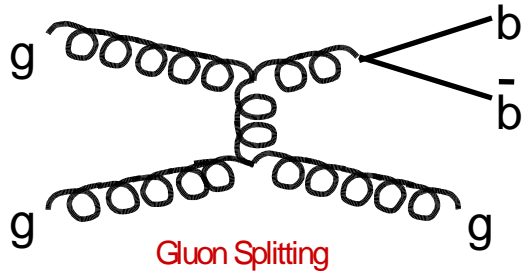
# The silicon detector



- Largest silicon detector operational
- 3 subsystems : L00, SVXII, ISL.
- Designed to operate initially during 1<sup>st</sup> 2-3 fb<sup>-1</sup> of runII, now it should operate until 6-8 fb<sup>-1</sup>
  - ➔ its maintenance is a challenge.
- CIEMAT plays a crucial role here.
- Essential for High  $p_T$  physics
- Essential for  $b$  physics

# Basics of B Physics at the Tevatron

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



- High cross section  $\sigma (p\bar{p} \rightarrow b\bar{b}) \sim 40 \mu\text{b}$  at  $\sqrt{s} = 2 \text{ TeV}$
- Quarks fragment into hadrons:  $\underline{B}_c^- (b\bar{c})$ ,  $\underline{\Lambda}_b (bdu)$ ,  $\underline{\Sigma}_b^+ (buu)$ ,  $\underline{\Sigma}_b^- (bdd)$  [Tevatron exclusive],  $B_s^0 (b\bar{s})$ ,  $\bar{B}_0 (bd)$ ,  $B^-(b\bar{u})$ , also  $B^*$ ,  $B^{**}$ , etc
- $\rightarrow$  Tevatron can be considered as a B factory

# Online B selection process

- Huge background to the process  $\sigma(p\bar{p} \rightarrow b\bar{b})$  in Tevatron:  $O(0.05 \text{ b})!$
  - B hadrons are filtered online using selective triggers based on clear signatures that overcome the QCD background
  - Our sample is selected by a  $J/\psi \rightarrow \mu\mu$  oriented **dimuon trigger**
- $BR(B \rightarrow J/\psi X) = 0.5 \%$ ;  $BR(J/\psi \rightarrow \mu\mu) = 6\%$

## Measurements :

Central tracking chamber:

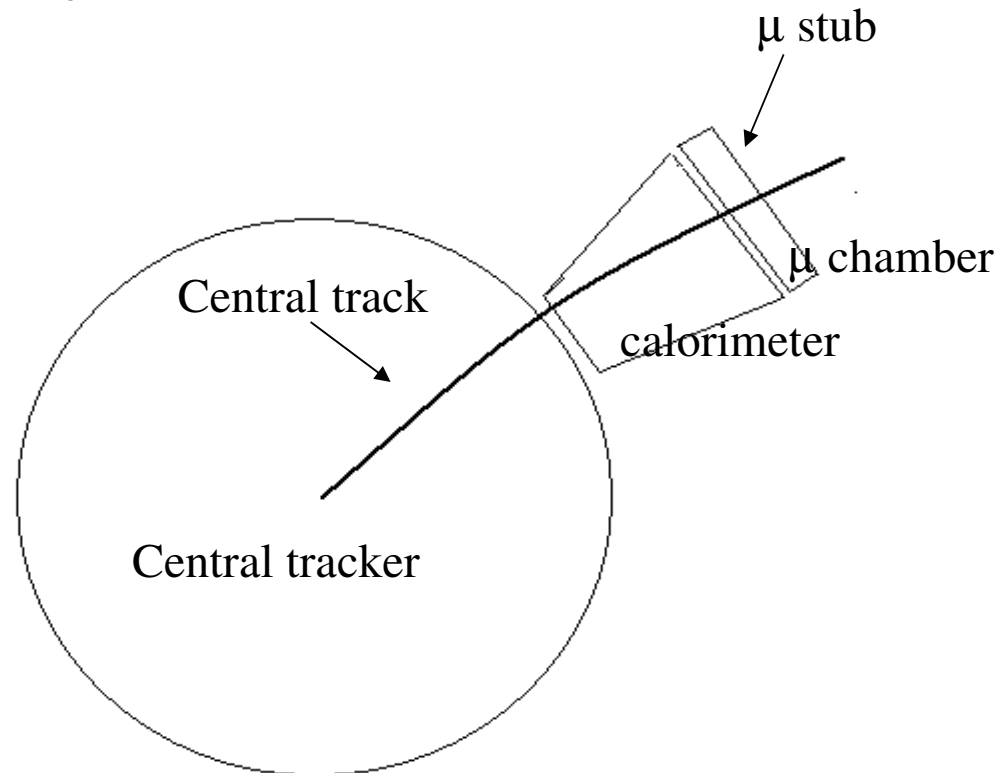
- Track momentum
- Trajectory

Muon chambers:

- Trajectory (stub)

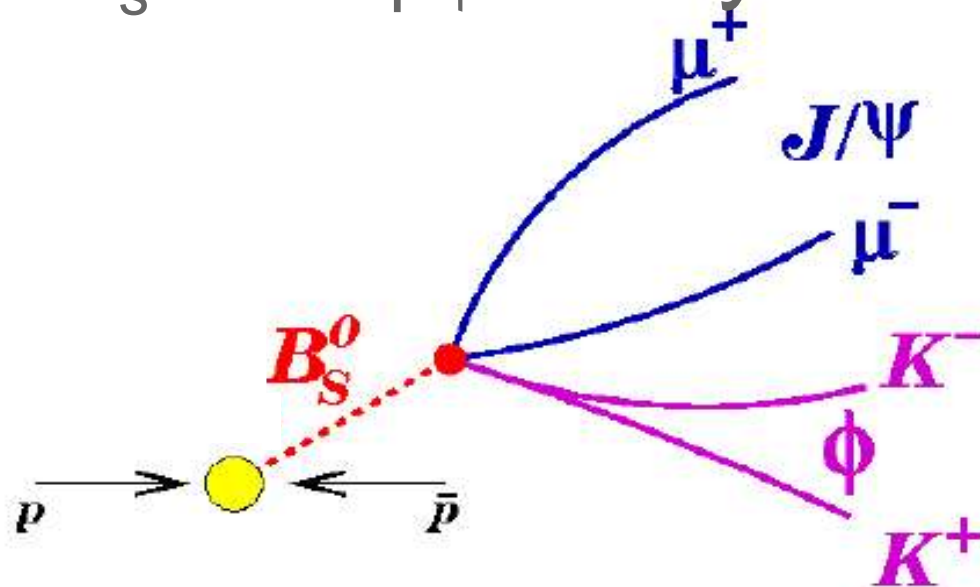
## Require :

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





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



- $B_s^0$  travels  $\sim 450 \mu\text{m}$  before decaying into  $J/\psi$  and  $\phi$
- Spin-0  $B_s^0$  decays to spin-1  $J/\psi$  and spin-1  $\phi$   
 $\Rightarrow$  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  $B_s^0/\bar{B}_s^0$
- Purpose: disentangle all these features

# Measurement Strategy

- Reconstruct  $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-) \phi(\rightarrow K^+K^-)$
- 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.  $\beta_s$ ,  $\Delta\Gamma = \Gamma_L - \Gamma_H$ )

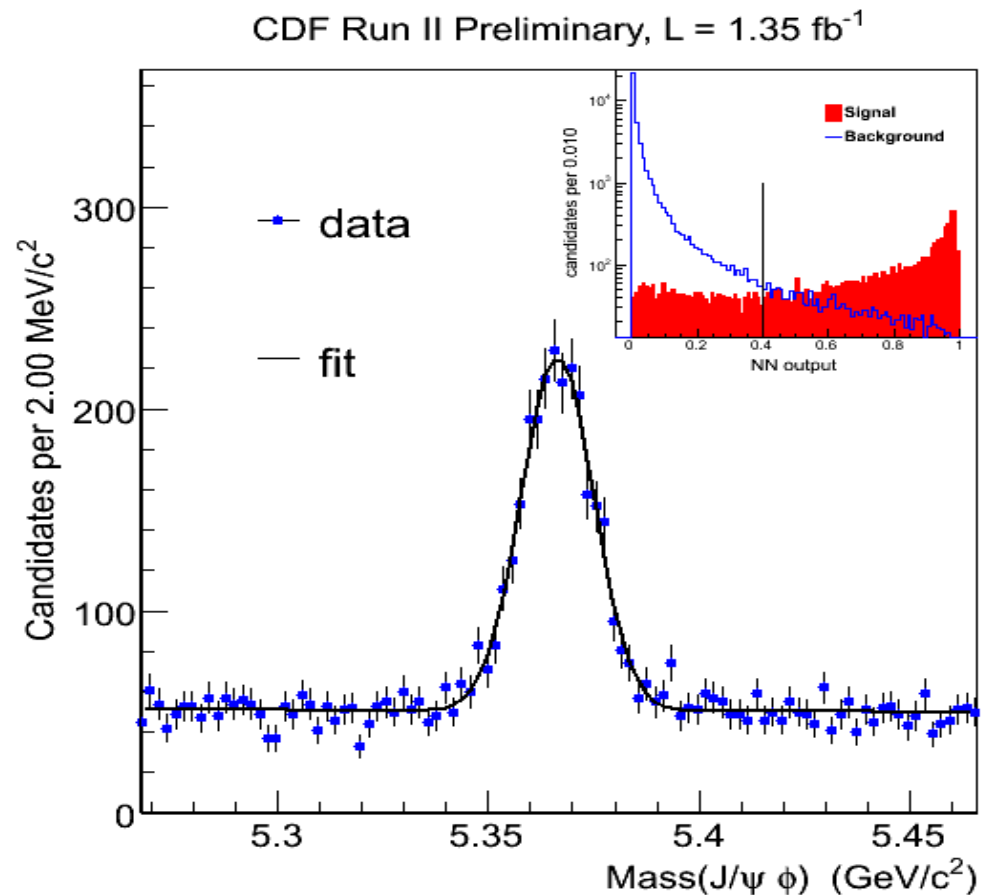
# Signal reconstruction and Lifetime determination

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# $B_s^0 \rightarrow J/\psi \phi$ Signal Selection

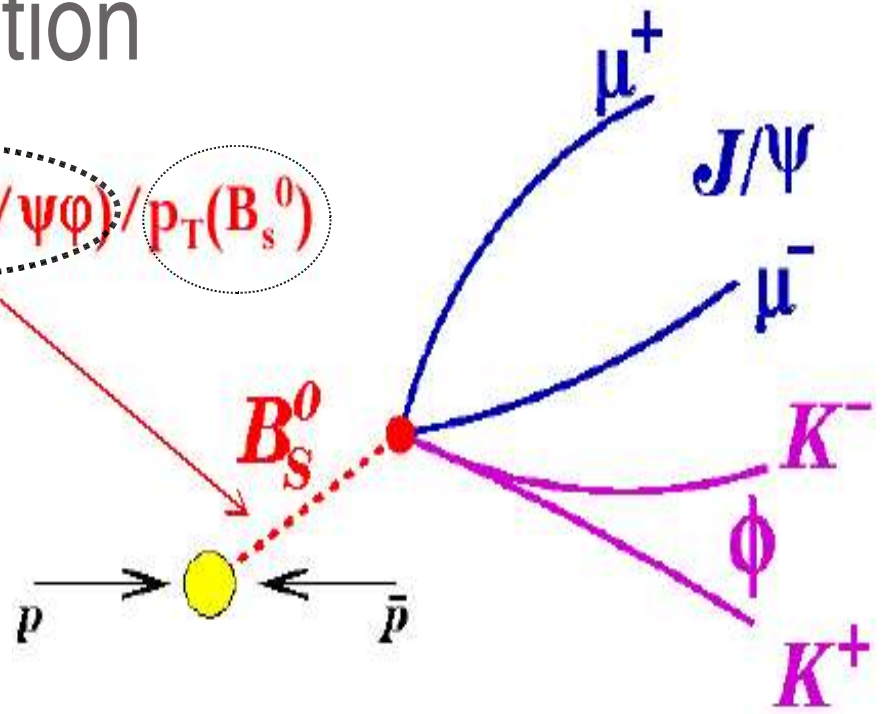
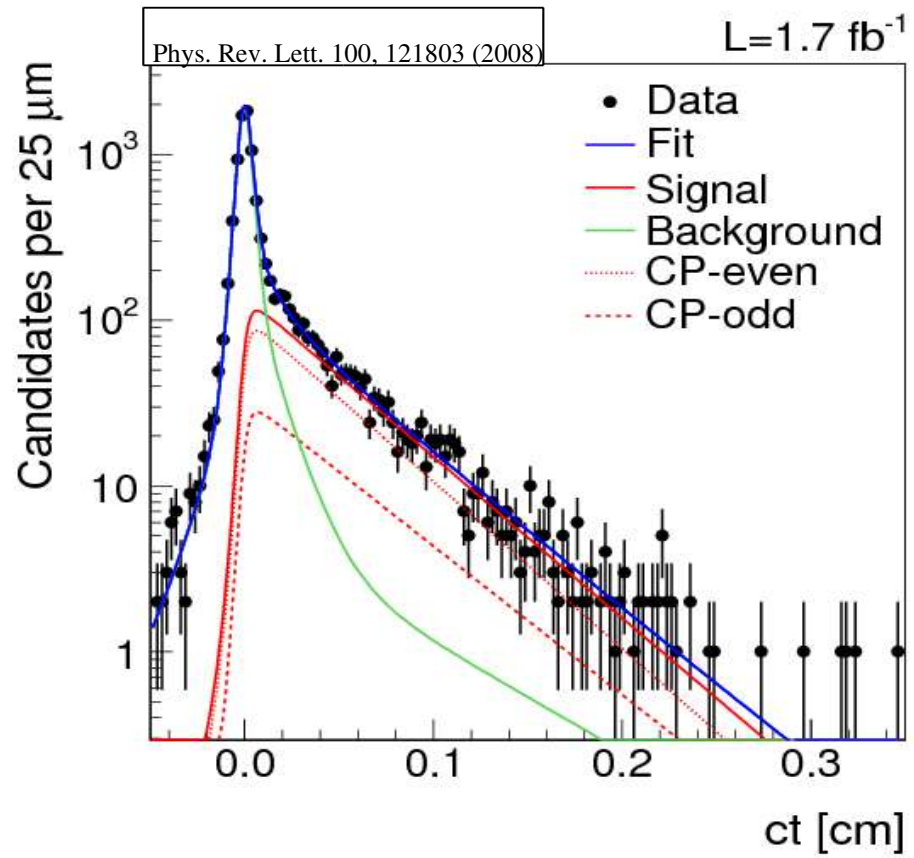
- Use an artificial neural network (ANN) to efficiently separate signal from background
- ANN training
  - Signal from Monte Carlo reconstructed as it is in data
  - Bkg. from  $J/\psi \phi$  sidebands
- Variables used in network
  - $B_s^0$ :  $p_T$  and vertex prob.
  - $J/\psi$ :  $p_T$  and vertex prob.
  - $\phi$ : mass and vertex prob.
  - $K^+, K^-$ :  $p_T$  and PID

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



# $B_s^0$ Lifetime Reconstruction

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



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

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

# Angular Analysis of Final States

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We have a sample of

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

and we know the time when each decay occurred.

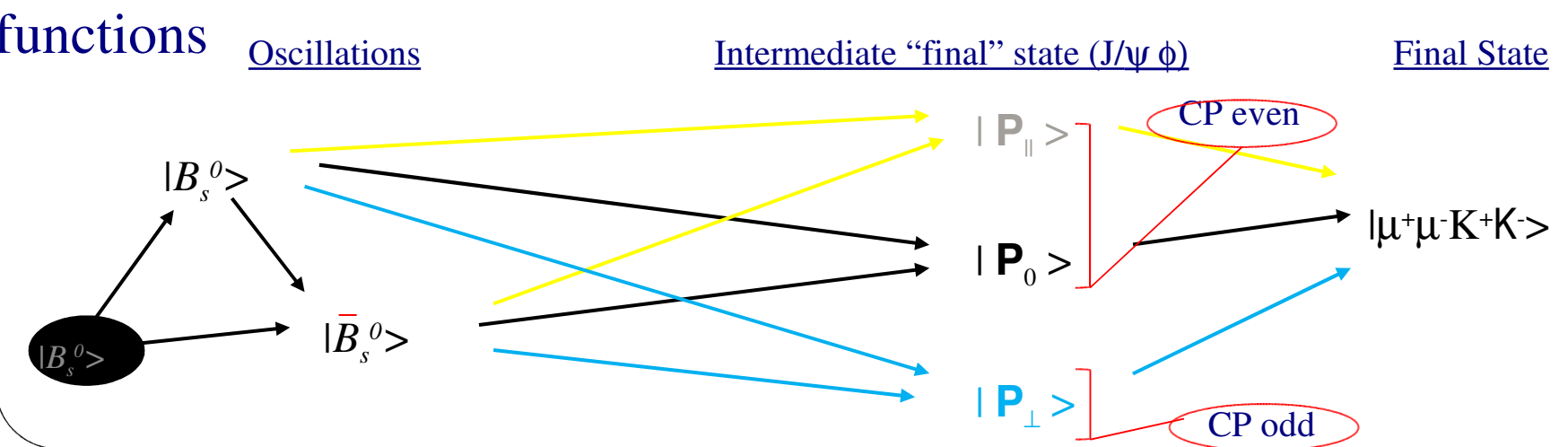
We need to know the CP of the final state ...

but we can only do it on a statistical basis

- $B \rightarrow VV$  (our  $B_s^0 \rightarrow J/\psi \phi$  but also  $B^0 \rightarrow J/\psi K^{*0}$ , ...) 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 (**||**) ] CP even
  - transverse but perpendicular to each other (**⊥**) ] CP odd

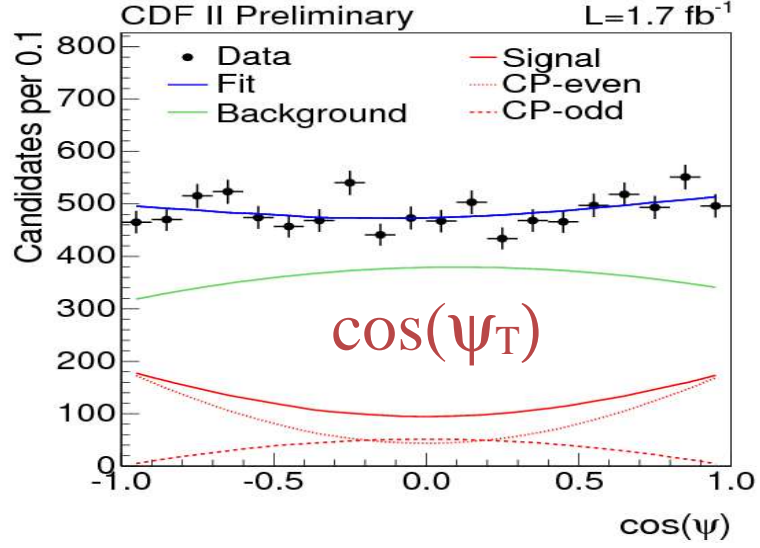
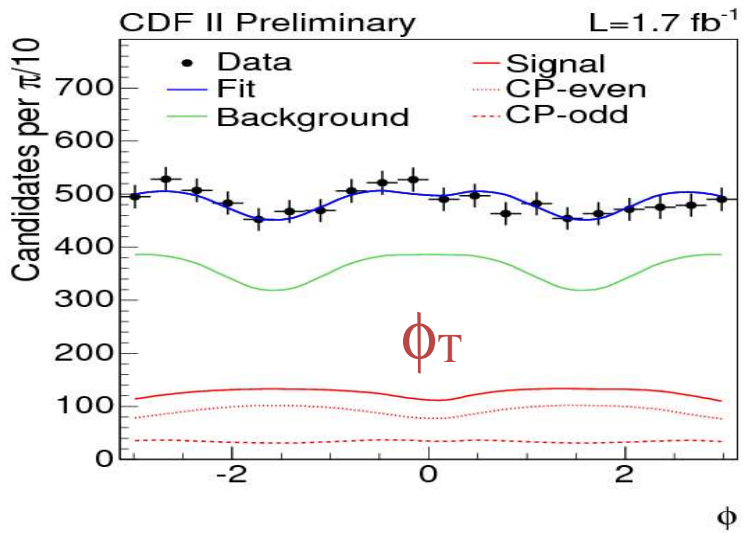
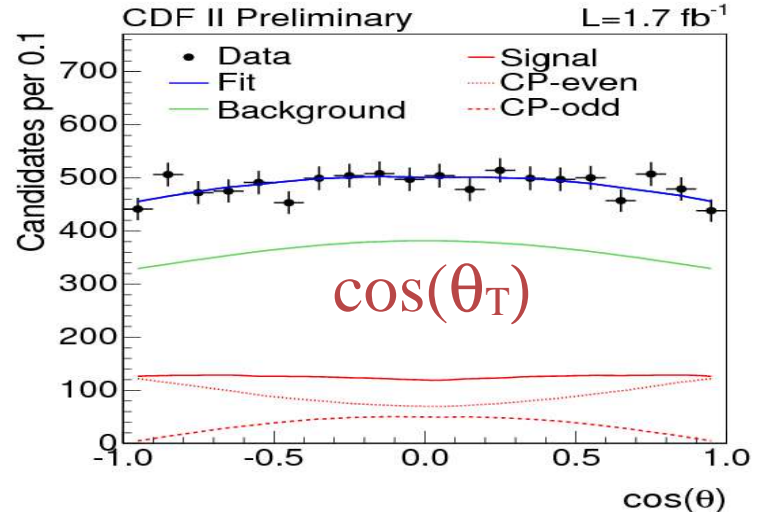
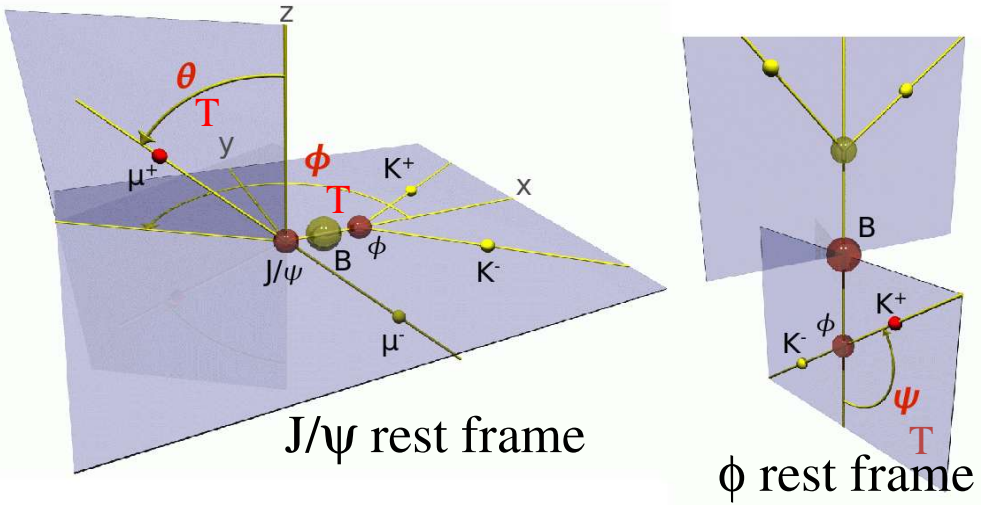
Each final pol.state  $P_0, P_{||}, P_{\perp}$  has transition amplitude  $A_0, A_{||}, A_{\perp}; \langle B_s^0 | P \rangle = A$

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



the “transversity angles” ( $\theta_T, \phi_T, \psi_T$ ) 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

$$\begin{aligned}
 \frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} &\propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_{\parallel}|^2 T_+ f_2(\vec{\rho}) \\
 &+ |A_{\perp}|^2 T_- f_3(\vec{\rho}) + |A_{\parallel}| |A_{\perp}| U_+ f_4(\vec{\rho}) \\
 &+ |A_0| |A_{\parallel}| \cos(\delta_{\parallel}) T_+ f_5(\vec{\rho}) \\
 &+ |A_0| |A_{\perp}| V_+ f_6(\vec{\rho}),
 \end{aligned}$$

$B_s^0$  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  $\bar{B}_s^0$

$$\begin{aligned}
 \frac{d^4 \bar{P}(t, \vec{\rho})}{dt d\vec{\rho}} &\propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_{\parallel}|^2 T_+ f_2(\vec{\rho}) \\
 &+ |A_{\perp}|^2 T_- f_3(\vec{\rho}) + |A_{\parallel}| |A_{\perp}| U_- f_4(\vec{\rho}) \\
 &+ |A_0| |A_{\parallel}| \cos(\delta_{\parallel}) T_+ f_5(\vec{\rho}) \\
 &+ |A_0| |A_{\perp}| V_- f_6(\vec{\rho}),
 \end{aligned}$$

anti- $B_s^0$

$f(\cdot)$ : angular distribution for a given polarization state

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

# Angular Probability Distribution: time evolution

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

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

CP asymmetry

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

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

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

Terms with  $\Delta m_s$  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  $B_s^0$  mixing frequency needed (well measured by CDF-D0)

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

- High-statistics test of angular efficiencies and fitter
- CDF results for  $B^0 \rightarrow J/\psi K^{*0}$  (CDF-8950)

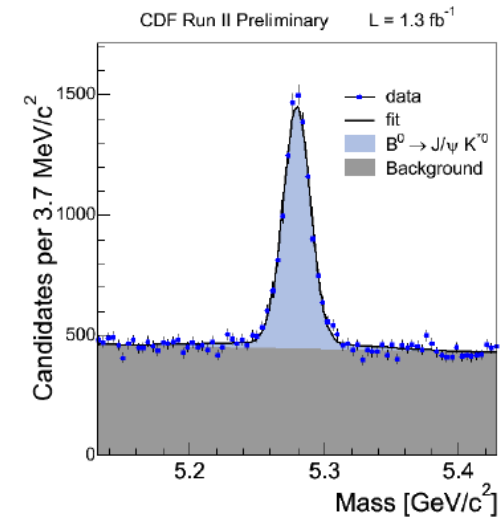
$$c\tau = 456 \pm 6 \text{ (stat)} \pm 6 \text{ (syst)} \mu\text{m}$$

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

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

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

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



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

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

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

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

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

Phys. Rev. D 76, 031102 (2007)

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

# Flavor Tagging

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We have a sample of

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

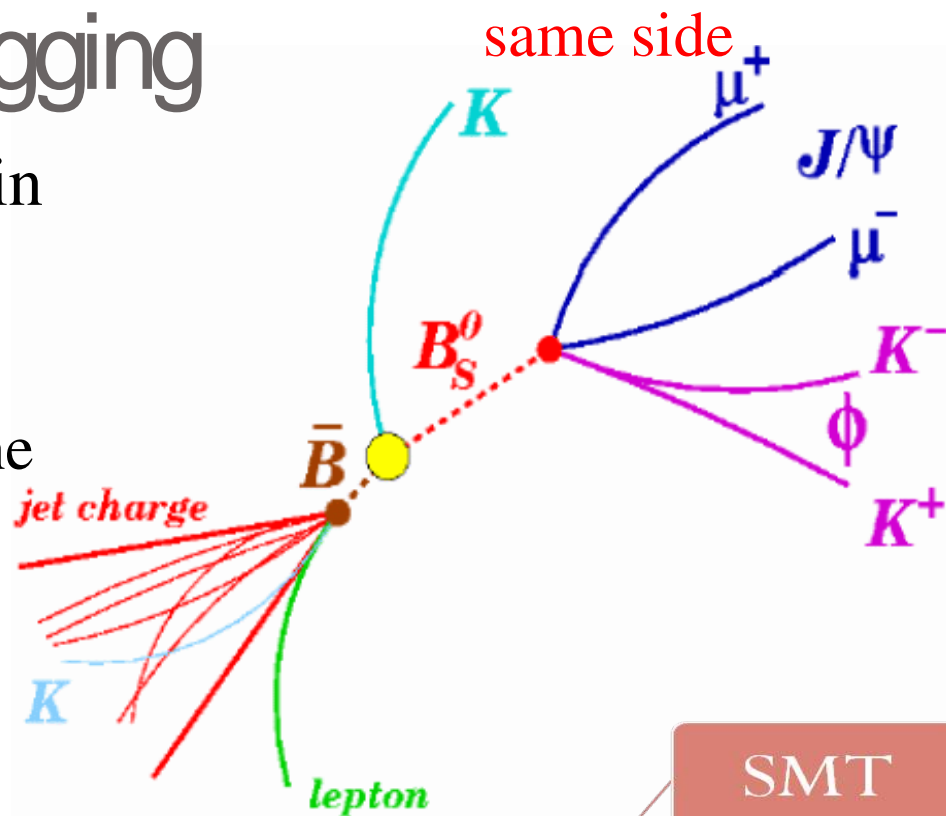
of known decay-time and CP.

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

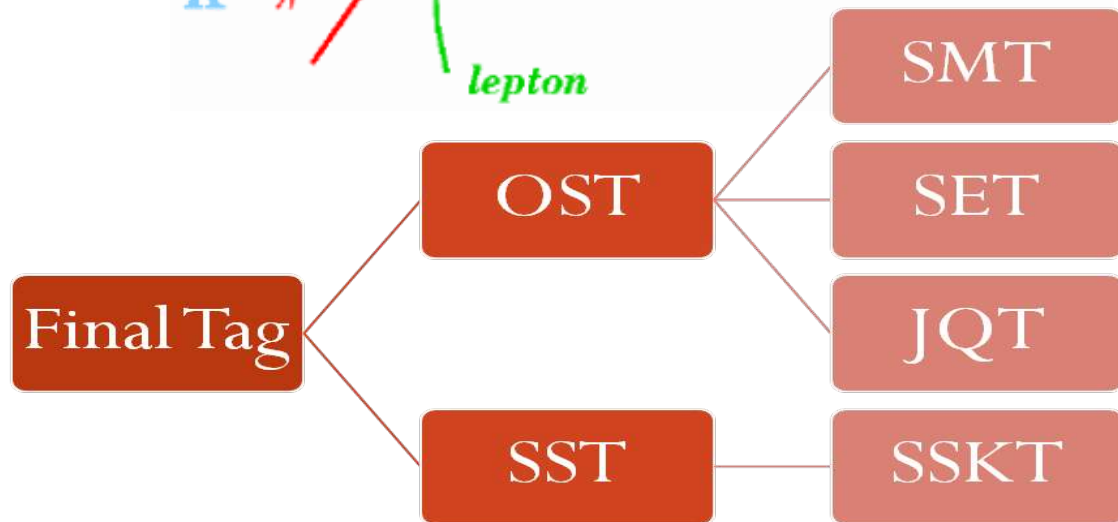
# Overview of Flavor Tagging

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

opposite side



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



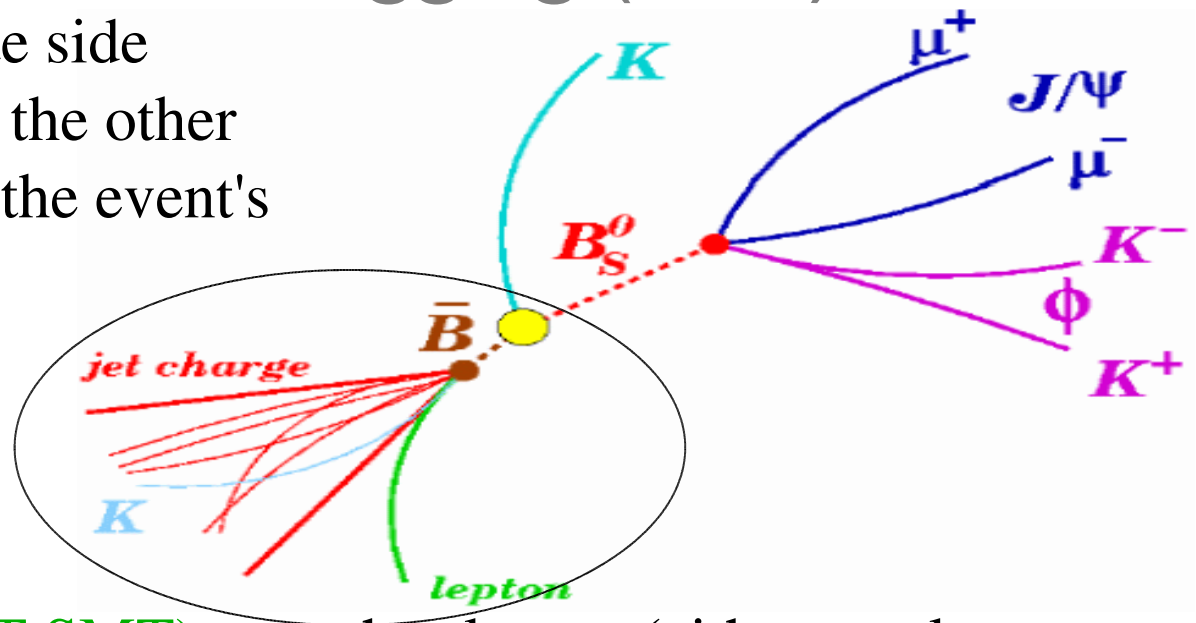
Output: decision ( $b$ -quark or  $\bar{b}$ -quark) and the quality of that decision

# Quantifying Tagging Power

- The tagging of an event can be
  - of Right Sign (RS) if assigned “sign” = true “sign” ( $B_s^0$  or  $\bar{B}_s^0$ )
  - of Wrong Sign (WS)
  - Inconclusive (NT)
- To quantify tagging we use:
  - Efficiency  $\epsilon = N_{\text{tagged}} / N_{\text{total}} = (N_{\text{RS}} + N_{\text{WS}}) / (N_{\text{RS}} + N_{\text{WS}} + N_{\text{NT}})$
  - “Dilution”  $D = P_{\text{tag}} - P_{\text{mistag}} = (N_{\text{RS}} - N_{\text{WS}}) / (N_{\text{RS}} + N_{\text{WS}})$
- The statistical power of the tagging is quantified by  $\epsilon \langle D^2 \rangle$  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  $\bar{l}$  comes from a transition  $b \rightarrow q \bar{l} \bar{\nu}$  (i.e., a  $B^0$ ,  $B_s^0$  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.

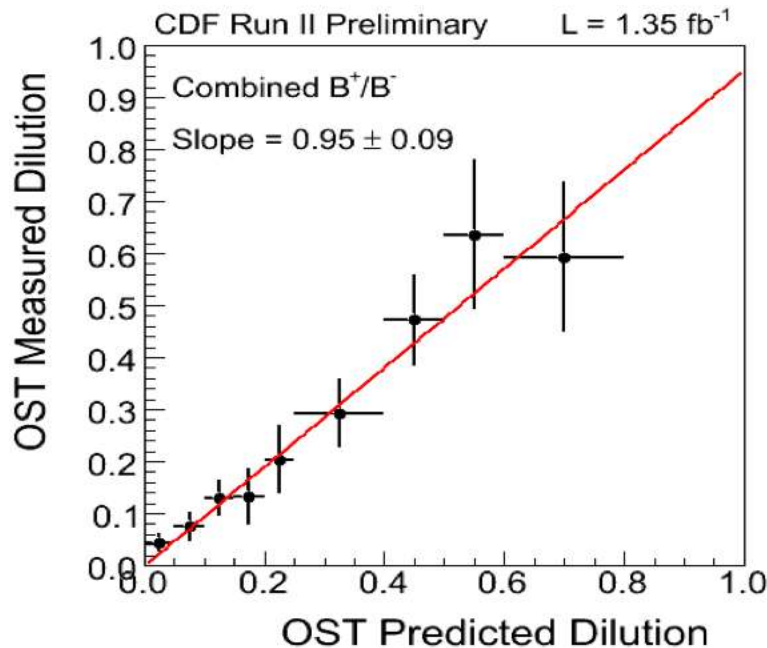
# OST

Input to the Dilution function:

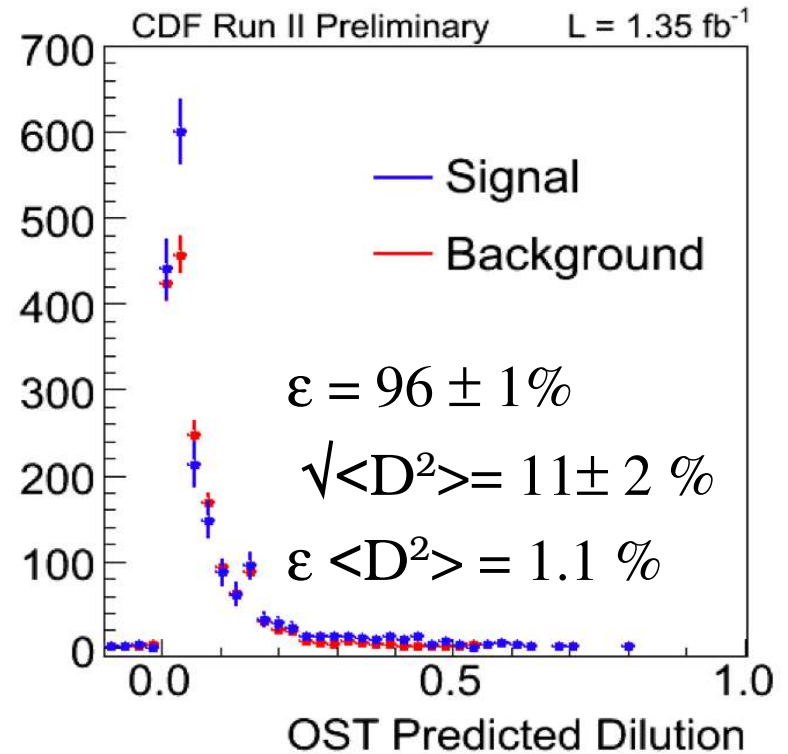
**JQT**: total jet charge (track- $p_T$  weighted)

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

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



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



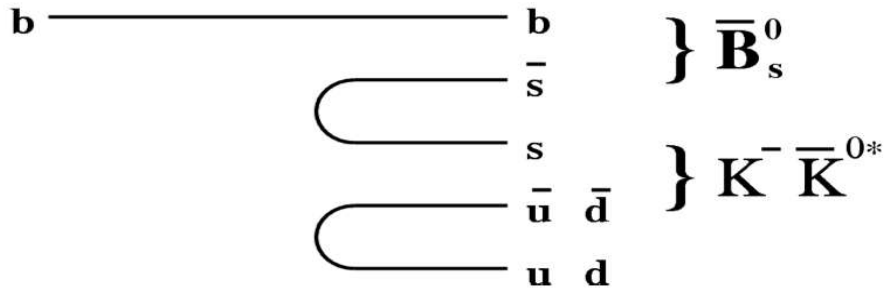
Where the “low” Dilution comes from? :

- 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  $B_s^0$  event is almost always a Kaon



- Among candidate tracks:

- close to B meson

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

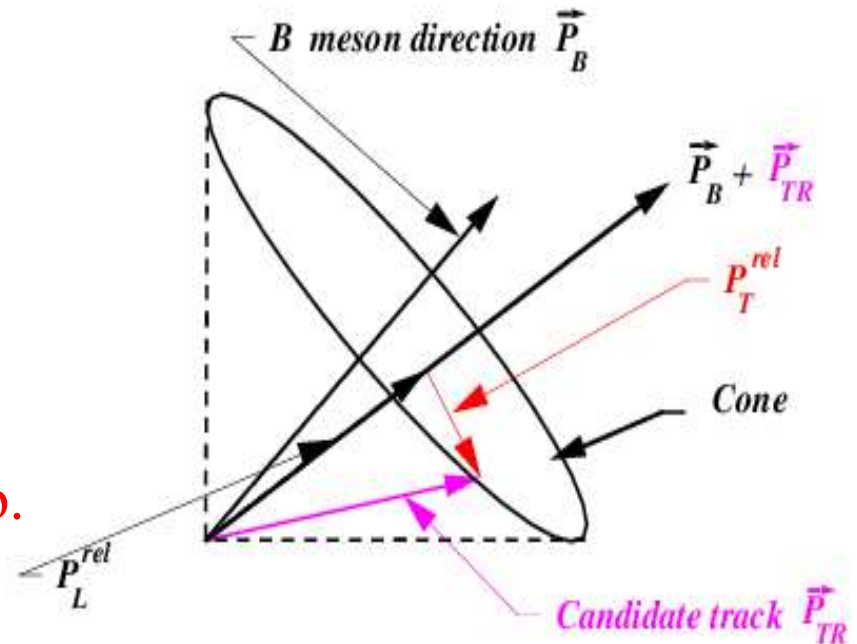
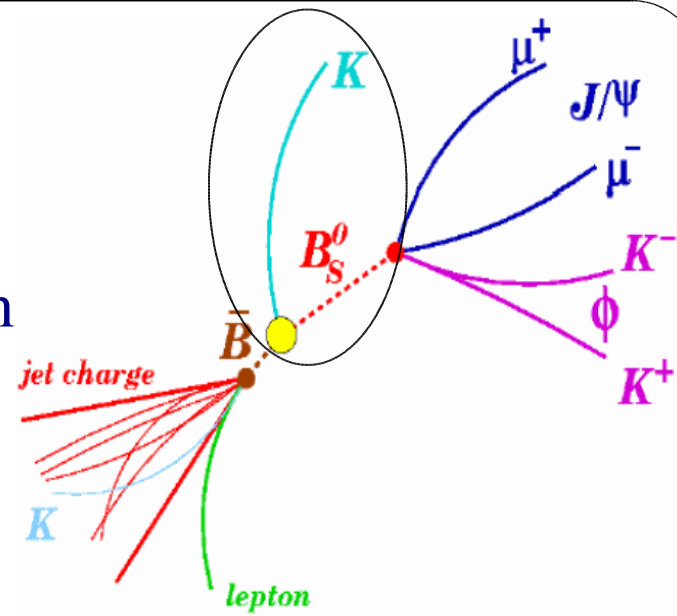
- $p_T > 350 \text{ MeV}/c$

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

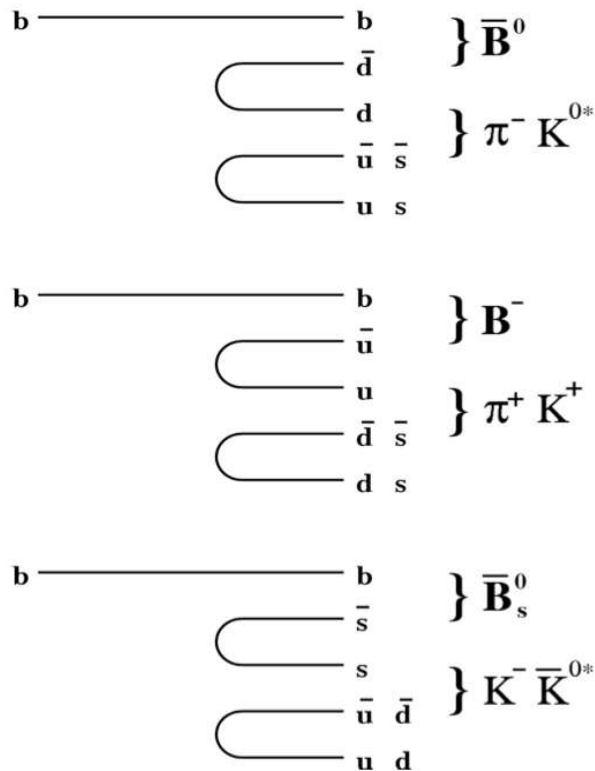
choose the one with **highest NN prob.**

**output** (based on  $p_L^{\text{rel}}, p_T^{\text{rel}}$  rel. to

$\mathbf{p}_B + \mathbf{p}_{\text{track}}$  direction & particle ID)



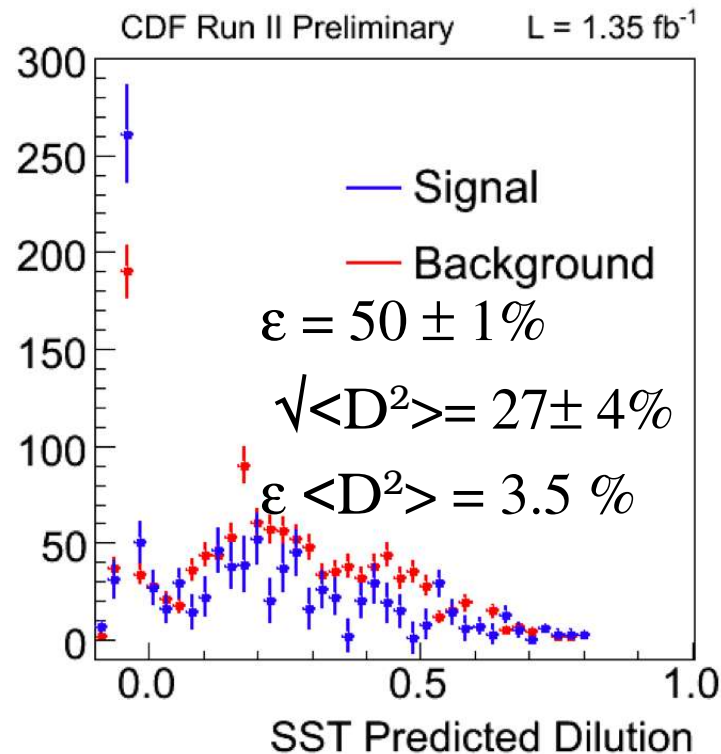
# SST



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

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

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



Where the Dilution comes from ? :

- detector reconstruction effects
- fragmentation fluctuations
- PID limitations
- others

# Un-binned Likelihood Fit

---

We have a sample of

$$B_s^0 \text{ and } B_s^0 \rightarrow J/\psi \phi \quad (J/\psi \rightarrow \mu^+ \mu^-, \phi \rightarrow K^+ K^-)$$

of “known” decay-time, CP and production flavor.

But this information is not known on a per-candidate basis.

**Wrap it up in a fit.**

# Overview of fit

Single event likelihood decomposed and factorized in:

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

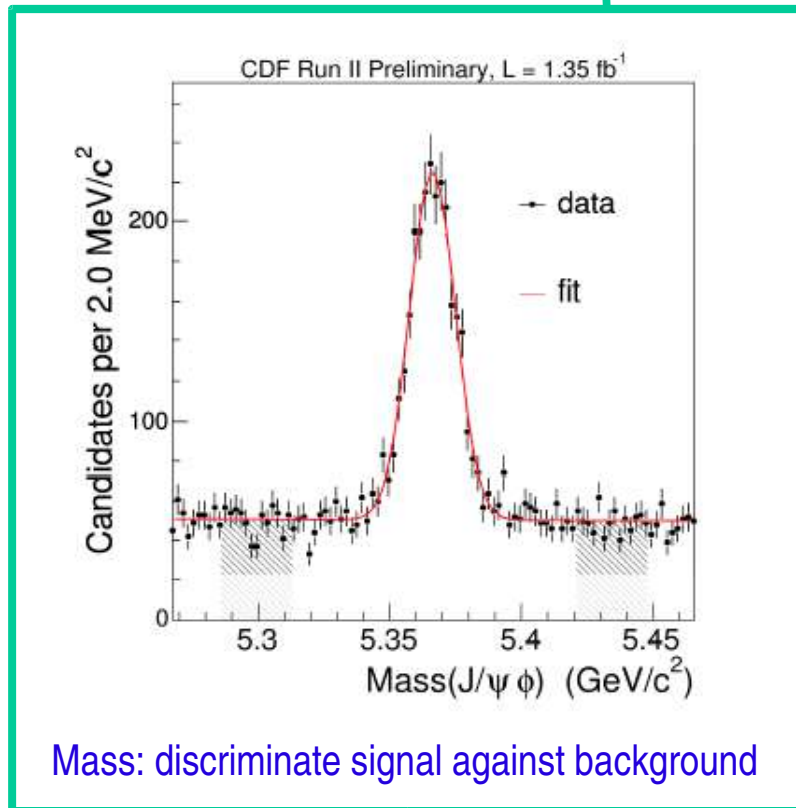
$P_s$ : probability distribution functions (PDFs) for signal

$P_b$ : PDFs for background

$f_s$ : signal fraction (fit parameter)

- Measured quantities that enter in the fit and their probability function (I)
  - reconstructed mass of  $B_s^0, B_s^0$  and its error, decay time and its error, transversity angles, flavor tag decision, dilution D

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



$P_s(m|\sigma_m)$  : Gaussian  $N(m, \sigma_m)$

$P_b(m)$  : 1<sup>st</sup> 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  $D$

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

$$\frac{1 + \xi D}{2} P(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho}) + \frac{1 - \xi D}{2} \bar{P}(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho})$$

$B_s^0$

$\bar{B}_s^0$

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

$D$ : event-per-event dilution

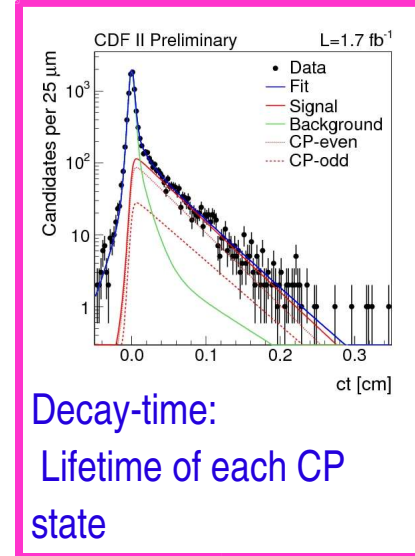
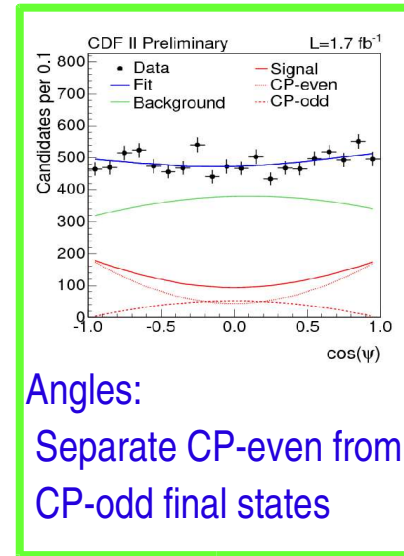
$\epsilon(\rho)$ : detector effects

obtained from MC

$P_b(t | \sigma_t)$ : delta function at  $t = 0$  + one (two) exponentials for

$t < 0$  ( $t > 0$ )  $\otimes$  Gaussian resolution function

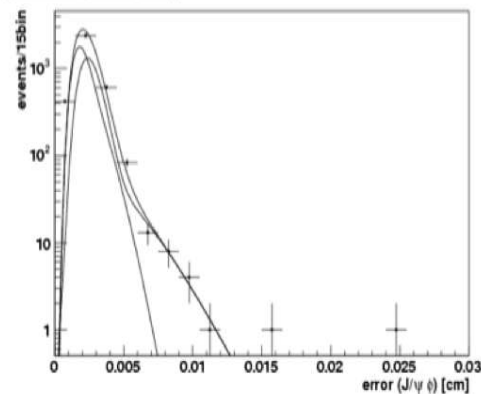
$P_b(\rho) = P_b(\cos \theta_T) P_b(\varphi_T) P_b(\cos \psi_T)$ ;  $P_b$ 's from sidebands events



- Measured quantities that enter in the fit and their probability function (III)
  - reconstructed mass of  $B_s^0, B_s^0$  and its error, decay time and its error, transversity angles, flavor tag decision, dilution D

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

ct Err. Signal region



ct Err. Sidebands

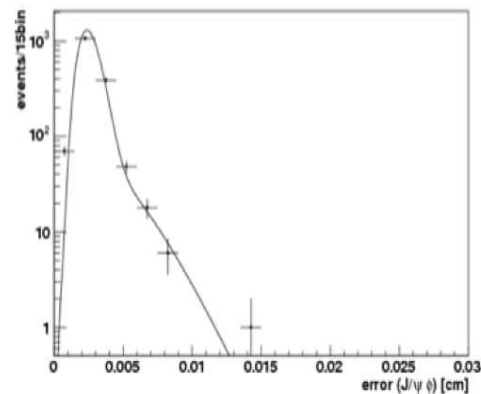
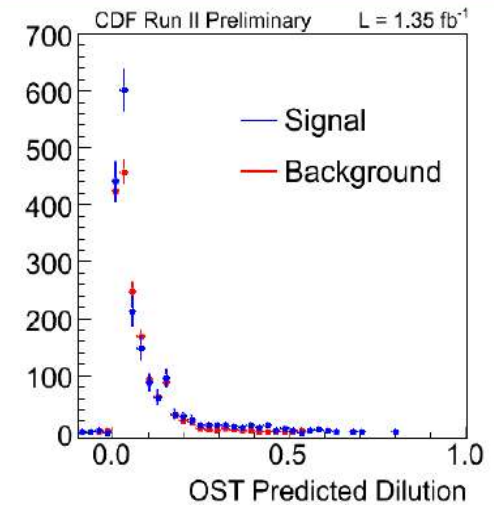


FIG. 37: Lifetime error projection in signal region(left) and sideband region(right).



Tagging : flavor of initial state

# Parameters in Fit

- The relevant ones:  $\beta_s, \Delta\Gamma$
- plus many nuisance parameters: mean width  $\Gamma = (\Gamma_L + \Gamma_H)/2$ ,  $|A_{\perp}(0)|^2, |A_{\parallel}(0)|^2, |A_0(0)|^2, \delta_{\parallel} = \arg(A_{\parallel} A_0^*), \delta_{\perp} = \arg(A_{\perp} A_0^*) \dots$



# Results

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## 1. Untagged analysis (do not use information on production flavor)

arXiv:0712.2348; PRL 100, 121803 (2008)

→  $\tau$  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

$$T_{\pm} = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta\Gamma t/2) \mp \eta \sin(2\beta_s) \sin(\Delta m_s t)],$$

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

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

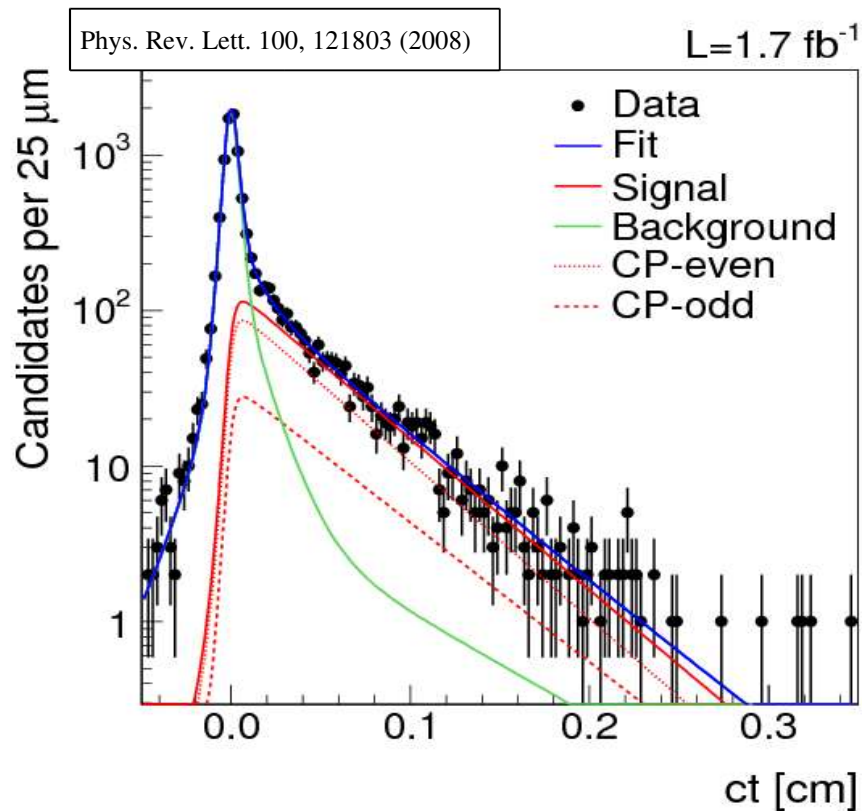
- Suited for precise measurement of width-difference and average lifetime (maximum sensitivity obtained when assuming a given value for  $\beta_s$ )
- Marginally sensitive to CP-violation

# Untagged analysis: results

$B_s^0$  mean lifetime and width difference

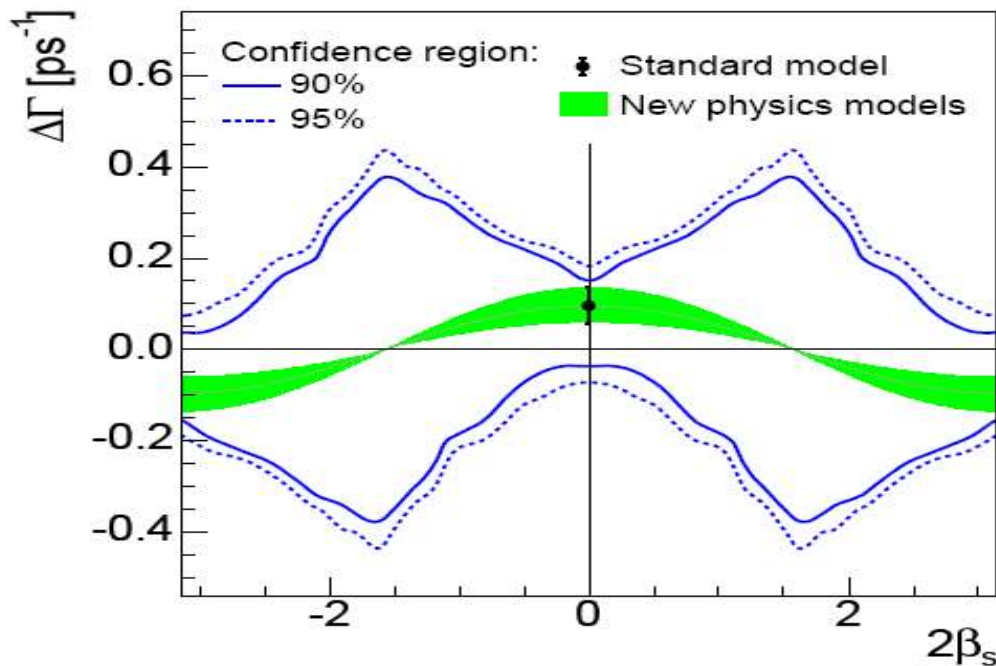
(*CP conservation assumption:  $2\beta_s = 0$* )

- $\tau = 1/\Gamma = 2 / (\Gamma_L + \Gamma_H) = 1.52 \pm 0.04 \pm 0.02$  ps
- $\Delta\Gamma = \Gamma_L - \Gamma_H = 0.08 \pm 0.06 \pm 0.01$  ps<sup>-1</sup> (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  $(2\beta_s, \Delta\Gamma)$  plane; in particular can not determine simultaneously the sign of  $2\beta_s$  and  $\Delta\Gamma$

NP region by  $\Delta\Gamma = |\Gamma_{12}| \cos \phi_s$

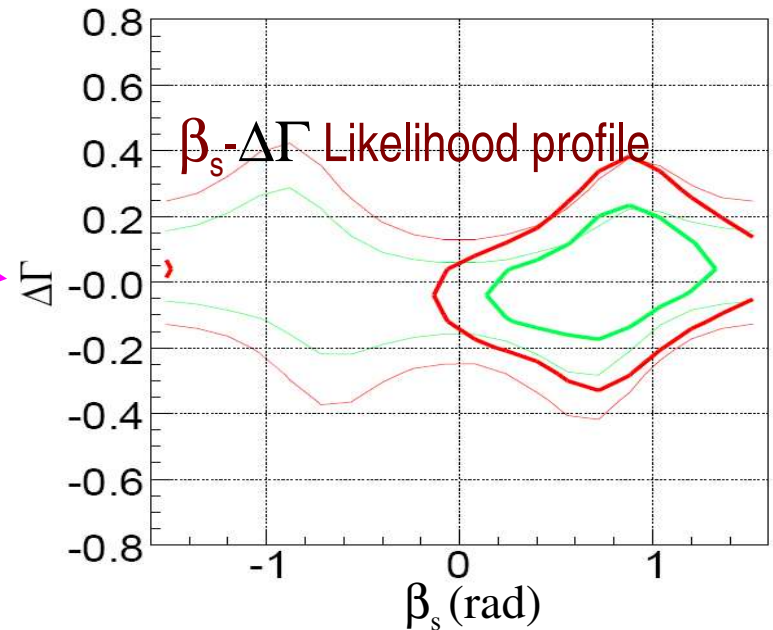
where  $|\Gamma_{12}| = 0.048 \pm 0.018$

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

New physics is expected to have almost no impact on  $\Gamma_{12}$

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

Likelihood function non gaussian

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

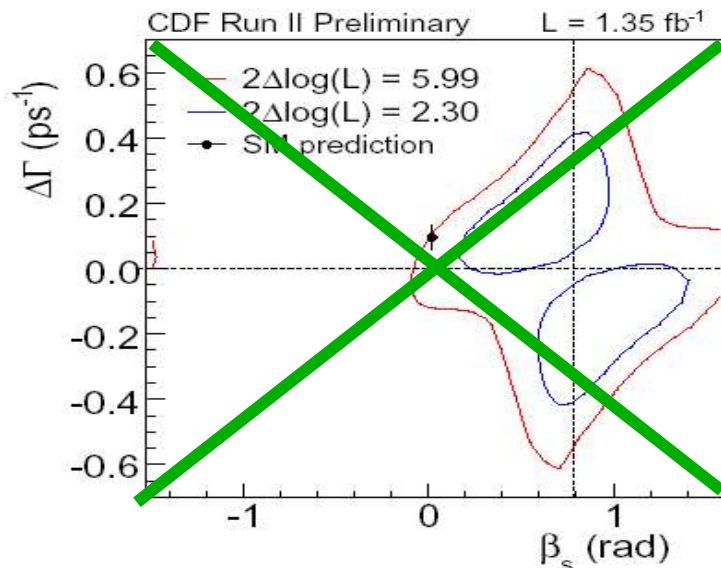
➔ Quote confidence region

- 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  $\beta_s$ - $\Delta\Gamma$  pair if it can be excluded for any choice of the 20+ nuisance parameters within  $5\sigma$  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.

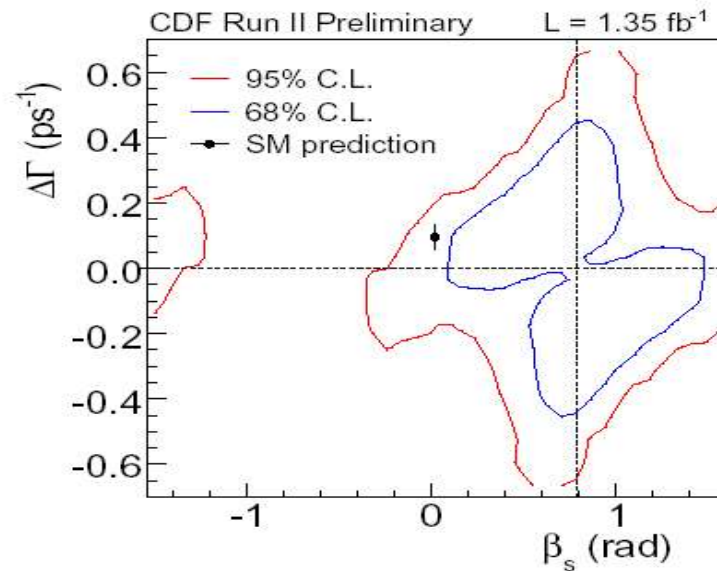
## 2D-Likelihood contour



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

## Profile-Likelihood Ratio ordering

(a la Feldman-Cousins)

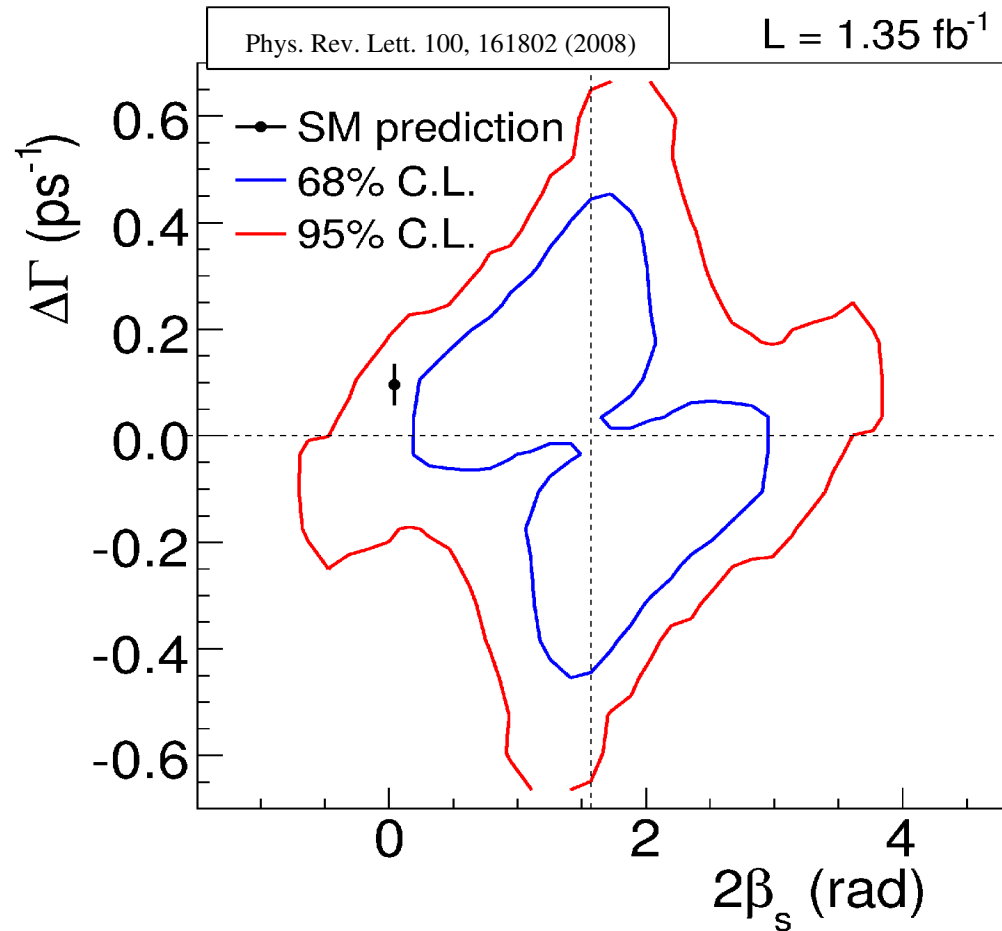


Above procedure has been corrected to have right coverage.

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

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

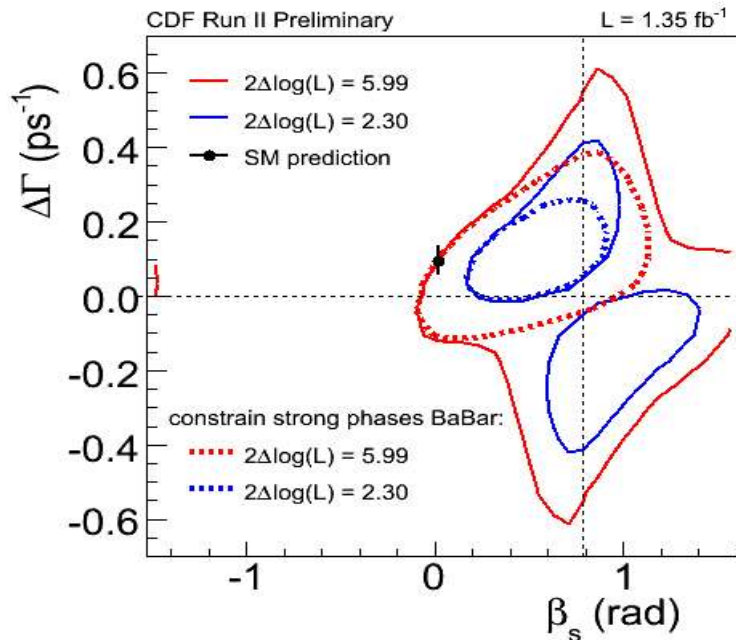
Assuming the SM, the probability of observing a fluctuation as large or larger than what observed in data is 15%, corresponding to  $1.5\sigma$



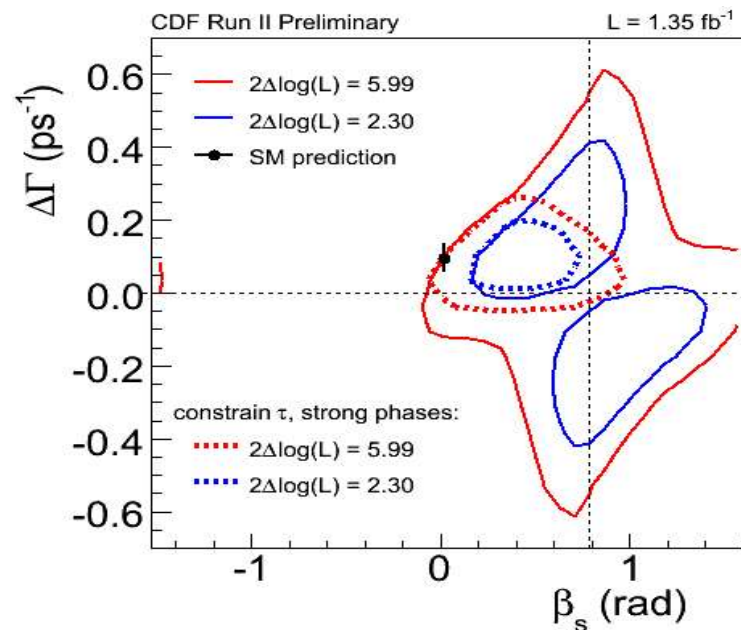
# $\beta_s$ 1D Intervals

- $\Delta\Gamma$  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

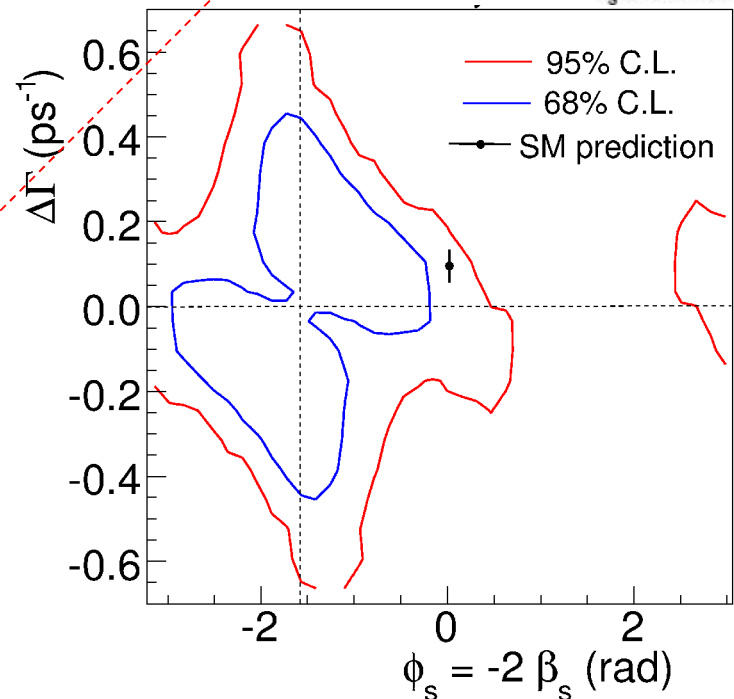
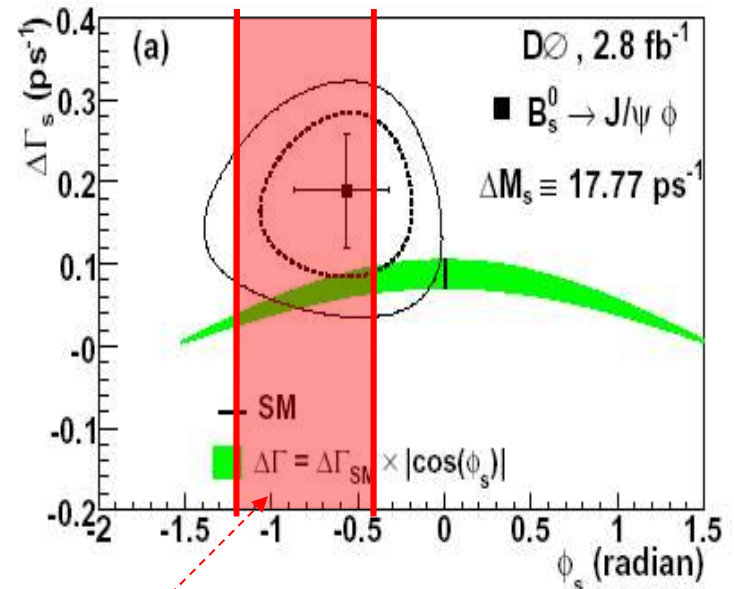




# DØ Results

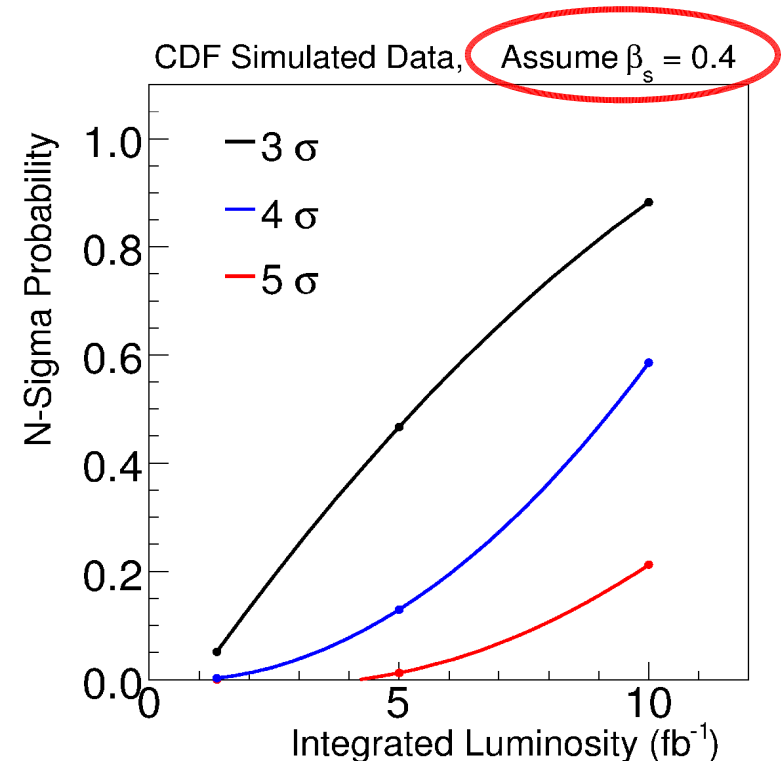
- DØ chooses to quote the results in terms of  $\phi_s = -2\beta_s$  ([arXiv:0802.2255](https://arxiv.org/abs/0802.2255))
- DØ quotes a point-estimate with strong phases constrained from  $B^0 \rightarrow J/\psi K^{*0}$
- This makes the result dependent on theoretical assumptions
- Can be compared to CDF constrained result

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



# Future

- Tevatron can search for anomalously large values of  $\beta_s$
- Shown results  $1.3 \text{ fb}^{-1}$ , but  $3 \text{ fb}^{-1}$  already on tape to be analyzed soon
- Expect  $6\text{-}8 \text{ fb}^{-1}$  by the end of the run 2
- Analysis to be improved and optimized:
  - $\sim 30\%$  statistics from other triggers
  - better flavor tagging
  - signal optimization based on expected statistical errors
- If  $\beta_s$  is indeed large CDF results have good chance to prove it
- CPV in  $B_s$  system is one of the main topics in LHC<sub>b</sub> B Physics program



# Conclusions

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# Conclusions

- First measurements of CPV in  $B_s$  system done by CDF
- Significant regions in  $\beta_s$  space are ruled out
- Soon after, confirmed by D0
- Best measurement of  $B_s$  decay-width-difference and one of the best lifetime-measurements
- Both CDF and DØ observe 1-2 sigma  $\beta_s$  deviations from SM predictions
- Interesting to see how these effects evolve with more data

# Contributors

- These results are the product of many people's hard efforts!
  - Joe Boudreau ,Gian Piero Di Giovanni, Michael Feindt, **Juan-Pablo Fernández**, Ivan Furic, Karen Gibson, Gavril Giurgiu, Guillermo Gómez-Ceballos, Michal Kreps, Thomas Kuhr, **Luis Labarga**, Chunlei Liu, Khaldoun Makhoul, Petar Maksimovic, Michael Milnik , Manfred Paulini, Christoph Paus, Aurore Savoy-Navarro
- See this web-page for more details
  - [http://www.fnal.gov/pub/today/archive\\_2008/today08-01-17.html](http://www.fnal.gov/pub/today/archive_2008/today08-01-17.html)

Back up

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

We combine all the available experimental information on  $B_s$  mixing, including the very recent tagged analyses of  $B_s \rightarrow J/\Psi\phi$  by the CDF and DØ collaborations. We find that the phase of the  $B_s$  mixing amplitude deviates more than  $3\sigma$  from the Standard Model prediction. While no single measurement has a  $3\sigma$  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 disfavors 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.

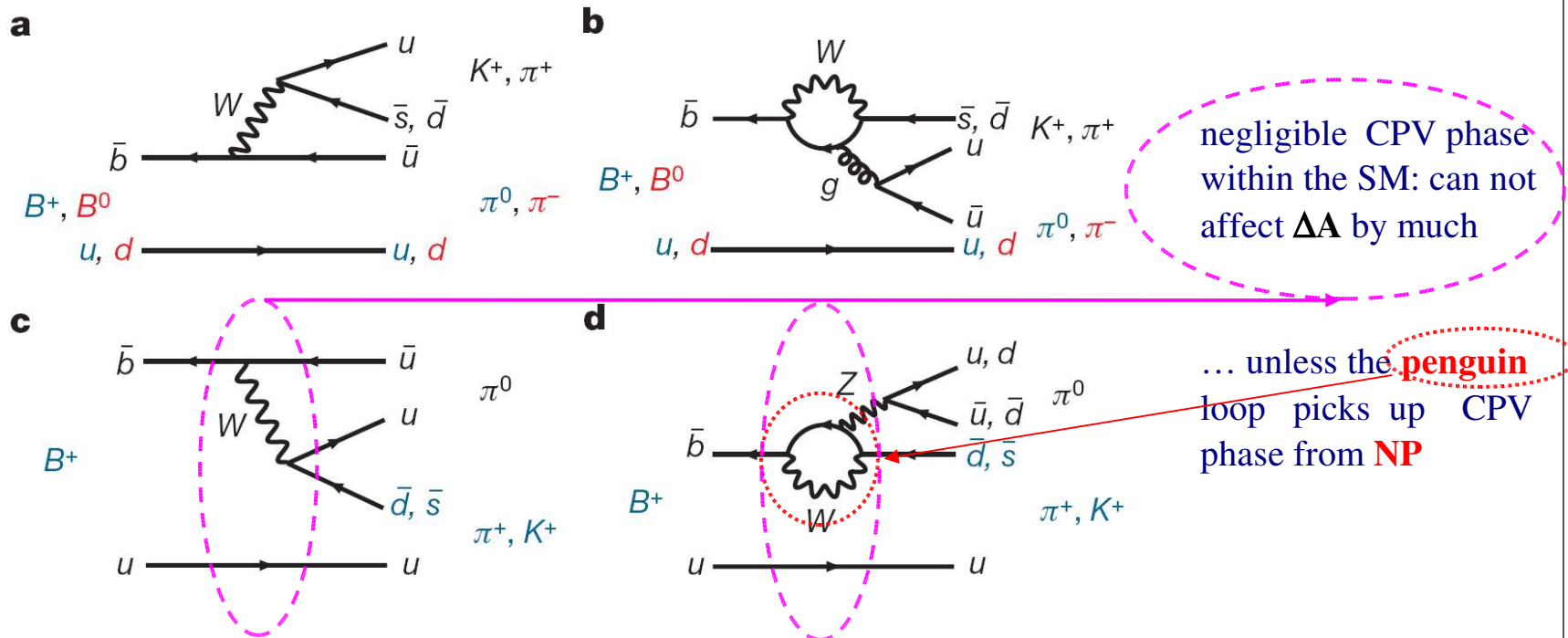
CDF and D0 plan to make a more appropriate “internal combination” for the near future

Elsewhere there is another anomaly that *may* also have to do with  $b \rightarrow s$

\* Direct CP in  $B^+ \rightarrow K^+ \pi^0$  and  $B^0 \rightarrow K^+ \pi^-$  are generated by the  $b \rightarrow s$  transition. These should have the same magnitude.

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

\* Including BaBar measurements:  $> 5\sigma$



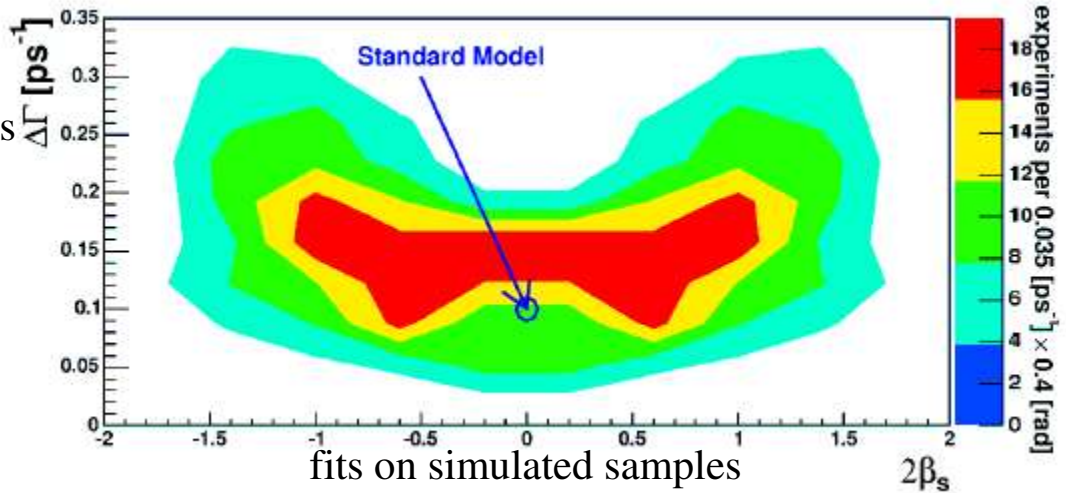
The electroweak penguin can break the isospin symmetry

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



# $\beta_s$ 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.



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

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

b) L invariant under two transformations:

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

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

→ 4 equivalent minima

# Systematics

- Systematic uncertainties studied by varying all nuisance parameters  $\pm 5\sigma$  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

