sin (2β_s) status from CDF

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Introduction

Beyond the Standard Model

- CP violation in B^0_s meson system is an excellent way to search for new physics
  - B-factories have established that, at tree level, 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 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

Neutral B_s system

Experimentally accessible

- Time evolution of B_s flavor eigenstates from Schrödinger equation:

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

- The magnitude of the box diagram gives the oscillation frequency

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

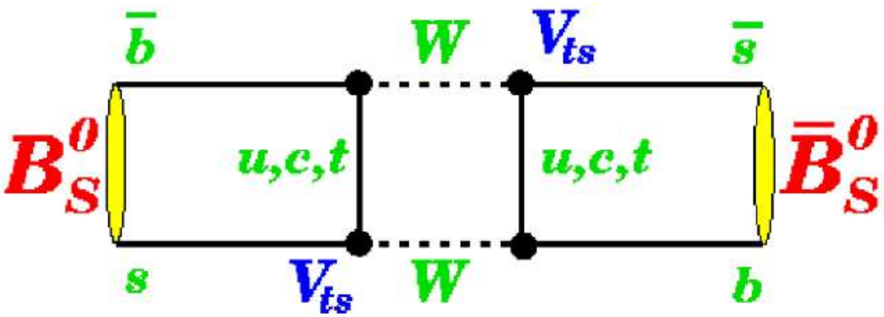
- The phase of the diagram gives the complex number $q/p = e^{-i\,\phi s}$

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

- Mass eigenstates have different decay widths (lifetimes)

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

- Mixing phase – sensitive to NP



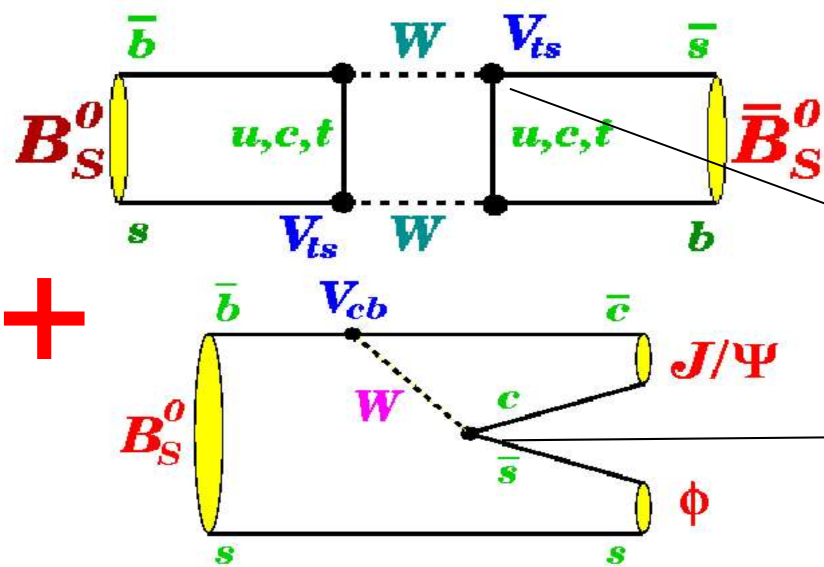
CP Violation in the S.M. ($B_s^0 \to J/\psi\phi$)

- The chance to observe CP violation comes from interference between decay-only and decay-through-mixing 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($2\beta_s$)



large CPV

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

large CPV small CPV

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

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

Experiment Overview

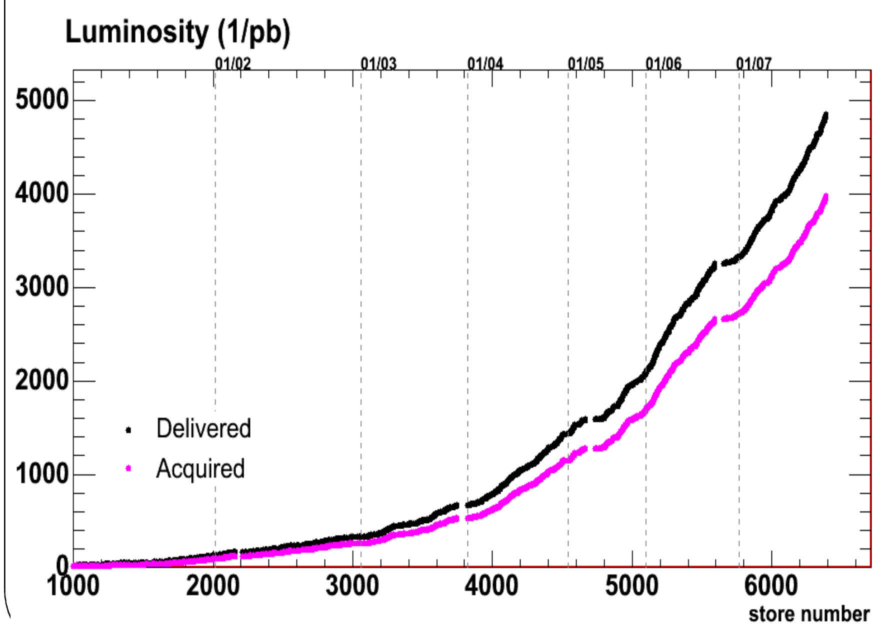
Introduction to the CDF II detector

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

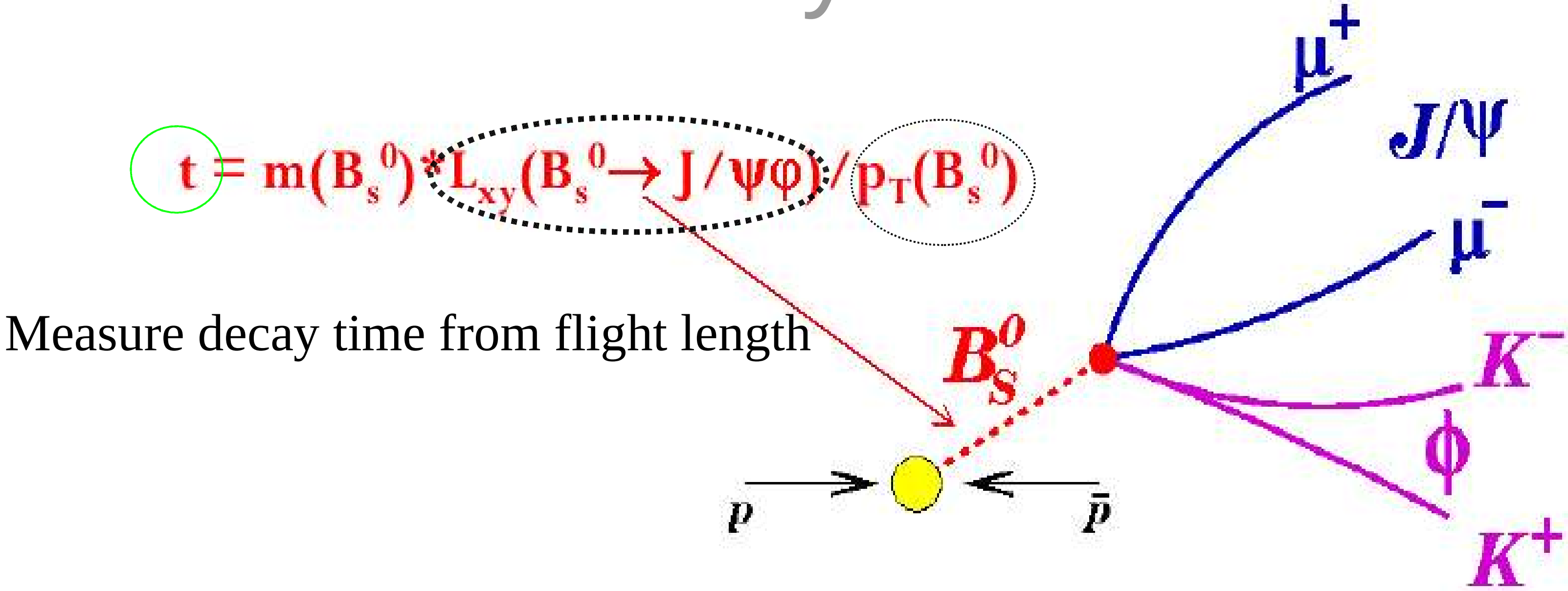
→ excellent mass and vertex rec.

- 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



- Excellent performance of Tevatron accelerator
- CDF has already **4 fb^{-1}** on tape
- Expect 6-8 fb^{-1} by end of the run 2
- This analysis uses 2.8 **fb^{-1}** (but equivalent to 2.0 fb^{-1}, no PID 2^{nd} half)

Overview of the 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)

- Maximum sensitivity to phase (sin 2β_s) depends on decay time resolution and separation of CP at decay and initial flavour of $B_s^0/\bar{B}_s^0$
- Purpose: disentangle all these features and measure the phase

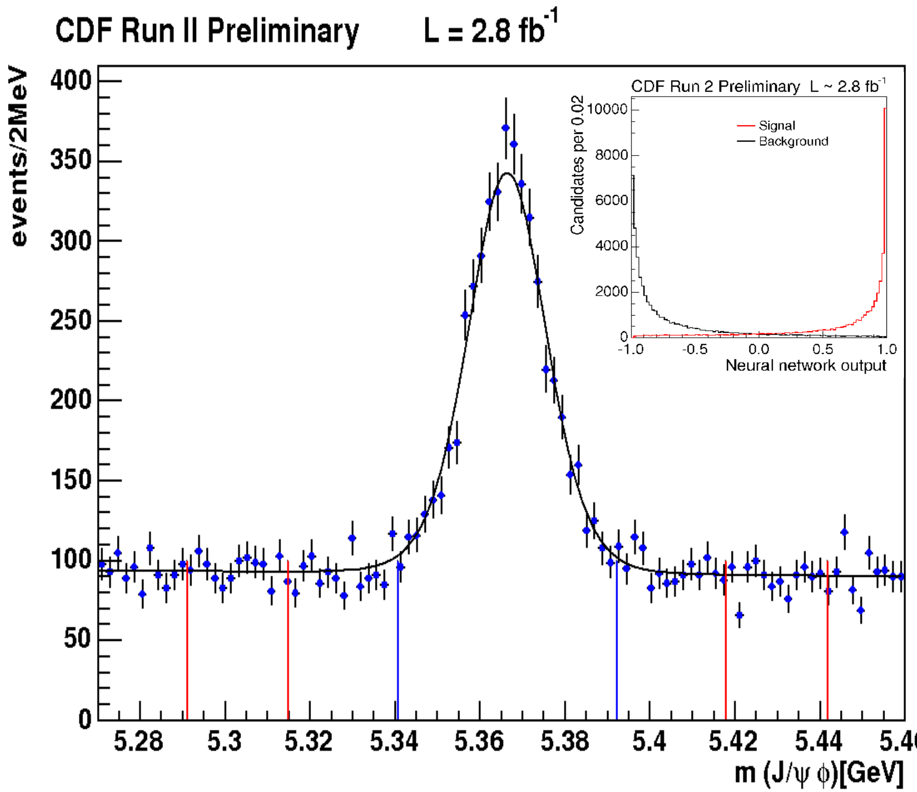
Measurement Strategy

- 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 (flavour 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, $\Delta\Gamma = \Gamma_L - \Gamma_H$)

$B_s^0 \to J/\psi\phi$ 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 (NO PID)

$N(B_s^0) \sim 3200$ (with PID expect ~3800)



Angular Analysis of Final States

Maximum sensitivity to phase if *CP*-even *and CP*-odd states are separated

We start with a sample of

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

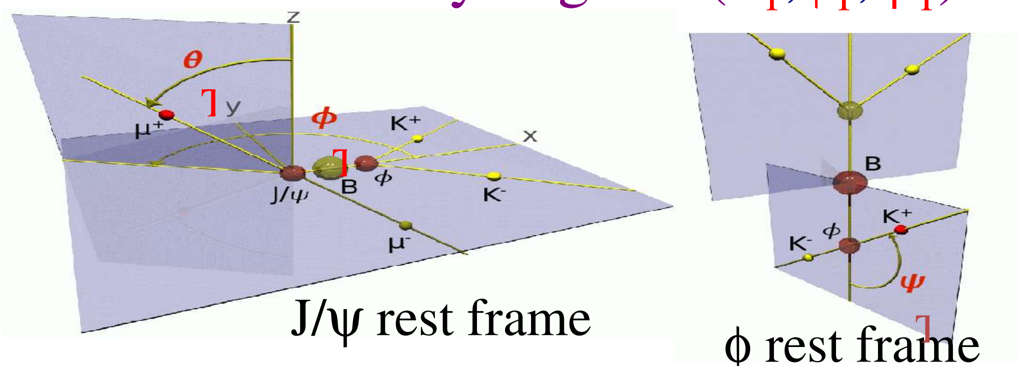
and we measure the time when each decay occurred.

Then, we need to know the CP of the final state …

but we can only do it on a statistical basis

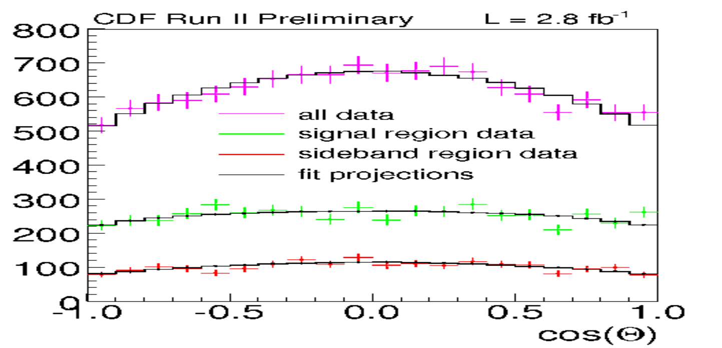
- $B \to VV$ (our $B_s^0 \to J/\psi\,\phi$ but also $B^0 \to J/\psi\,K^{*0}$, …) decay to two CP even states (S-wave or D-wave) and one CP odd (P-wave)
- Alternatively to the S,P,D-wave states one can use the "transversity basis": three independent components that use the vector mesons polarizations w.r.t. their direction of motion (pol.states $P_0, P_{\|}, P_{\perp}$)
- the "transversity angles" (θ_T, ϕ_T, ψ_T) are sensitive to the polarizations

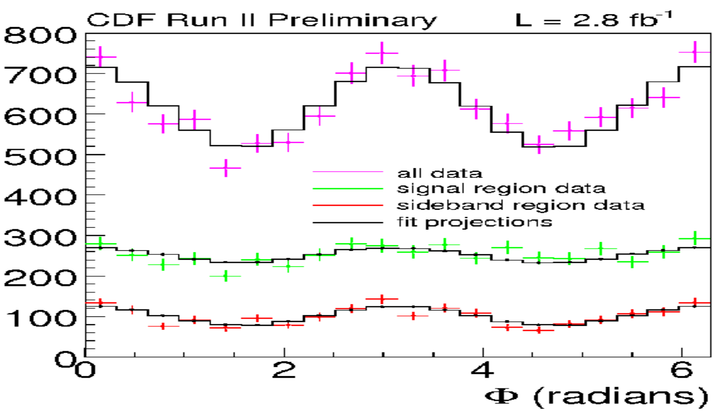
A.S.Dighe, I.Dunietz, H.J.Lipkin, J.L.Rosner; PLB369 (1996) 144

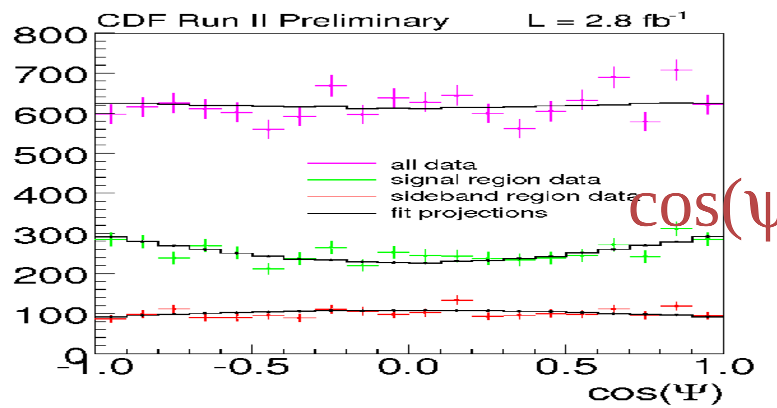


J/ψ rest frame

φ rest frame







$\cos(\psi_T)$

Analytical relationships from A.S.Dighe, et al, EPJ C6 (1999) 647

Angular correlations in decay products ⇨ separation of CP-components.

Flavor Tagging

Maximum sensitivity to phase if B^0_s and $\bar{B}^0_s$ separated

We have a sample of

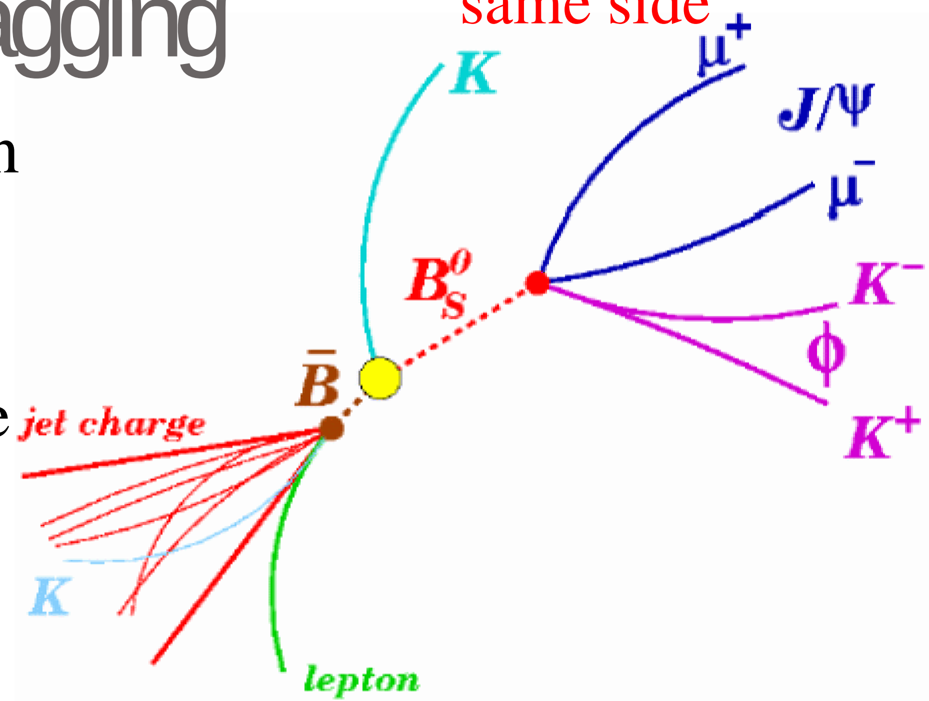
B^0_s *and* $\bar{B}^0_s \rightarrow J/\psi\,\phi \qquad (J/\psi \rightarrow \mu^+\mu^-, \phi \rightarrow K^+K^-)$

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 Flavour 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)



SST: exploits the charge/species correlations with associated particles produced in fragmentation that results in the reconstructed meson

OST: exploits the decay products of the other *b*-hadron in the event

- 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

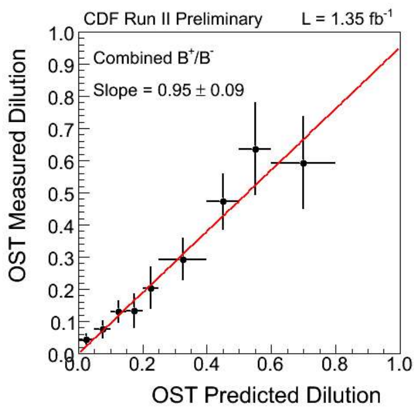
Quantifying Tagging Power

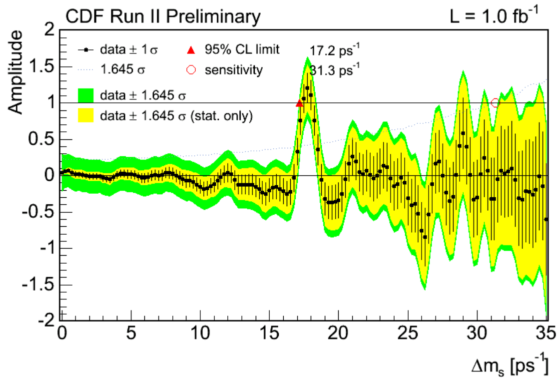
- To quantify tagging we use:
  - Efficiency $\varepsilon = N_{tagged} / N_{total} = (N_{RS}+N_{WS})/(N_{RS}+N_{WS}+N_{NT})$
  - "Dilution" $D = P_{tag} - P_{mistag} = (N_{RS}-N_{WS})/(N_{RS}+N_{WS})$

1. Using $B^{\pm}$ (OST)

2. In the B^0_s mixing (SST)

Each tag decision comes with an dilution estimate (event-per-event dilution), validated:





- The statistical power of the tagging is quantified by $\varepsilon \langle D^2 \rangle$ typically 4.8 % as detailed next.

OST

$\varepsilon = 96 \pm 1\%$

$\sqrt{\langle D^2 \rangle} = 11 \pm 2\ \%$

$\varepsilon \langle D^2 \rangle = 1.2\ \%$

SST

$\varepsilon = 50 \pm 1\%$

$\sqrt{\langle D^2 \rangle} = 27 \pm 4\%$

$\varepsilon \langle D^2 \rangle = 3.6\ \%$

[used in 1st half only]

Un-binned Likelihood Fit

We have a sample of

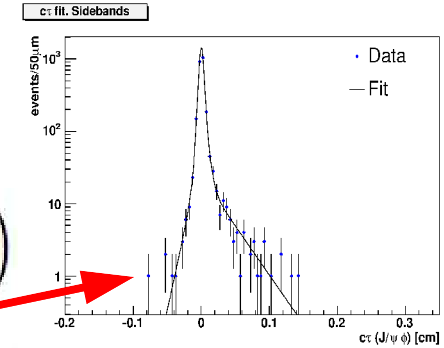
B^0_s *and* $\bar{B}^0_s \rightarrow J/\psi\,\phi\ (J/\psi \rightarrow \mu^+\mu^-,\ \phi \rightarrow K^+K^-)$

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 PDFs
  - reconstructed mass of $B_s^0, \bar{B}_s^0$ and its error, decay time and its error, transversity angles, flavour tag decision, dilution D
- Parameters in the 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

Both CDF and D0 have published their 1st determination of bounds on mixing-induced CP violation in $B_s^0 \rightarrow J/\psi\ \phi$ (references bellow). Today I will show :

→ new $(2\beta_s\ , \Delta\Gamma)$ confidence region (CDF, 2.8 **fb**$^{-1}$, ~2 **fb**$^{-1}$ equiv.)

→ new $2\beta_s$ confidence interval (CDF, 2.8 **fb**$^{-1}$, ~2 **fb**$^{-1}$ equiv.)

[the results are not intended to be published, just an update for ICHEP, next publication: PRD in winter with full PID and ~4 **fb**$^{-1}$]

→ combined CDF and D0 (from previous measurements, Phys. Rev. Lett. 100, 161802 [2008, CDF 1.35 **fb**$^{-1}$] and arXiv:0802.2255 [hep-ph, 2008, D0 2.8 **fb**$^{-1}$])

Likelihood

- Symmetry in likelihood expression :
  $2\beta_s \rightarrow \pi - 2\beta_s$, $\Delta\Gamma \rightarrow -\Delta\Gamma$, $\delta \rightarrow 2\pi - \delta$, $\delta_\perp \rightarrow \pi - \delta_\perp$

➔ These yield multiple solutions with non-Gaussian uncertanties, biased estimates, etc

➔ Point estimate irrealistic $\rightarrow$ quote confidence region

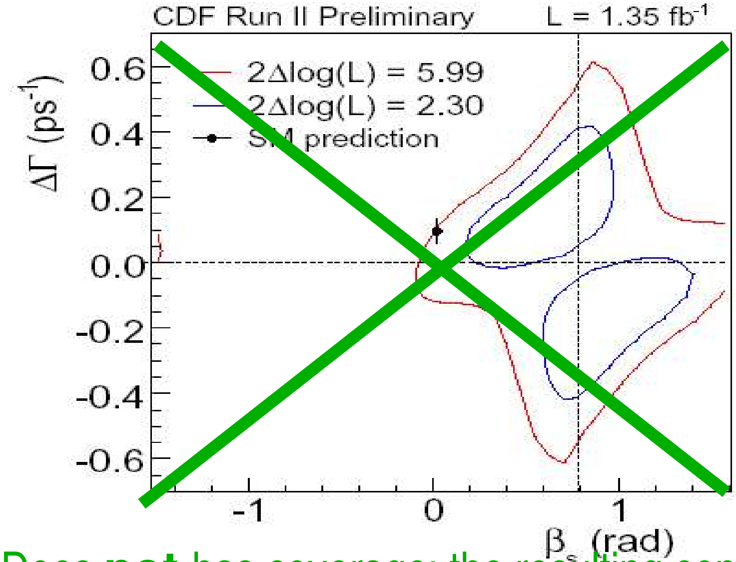
- using profile likelihood ratio ordering with rigorous frequentist inclusion of systematic uncertainties

Probabilistic method has to provide proper coverage

F-C guarantees coverage at quoted C.L. Accounts for non-asymptotic behavior of likelihood, i.e. log(L) non-parabolic, and possible large fluctuations of L shape from experiment-to-experiment

Excludes 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

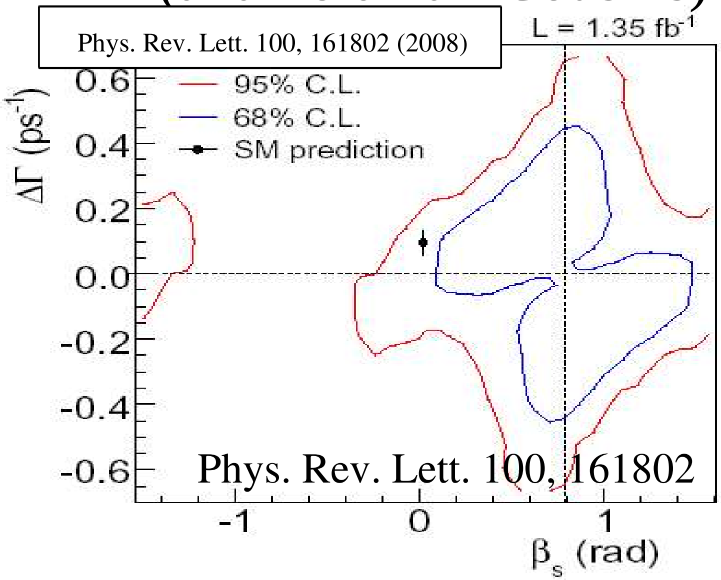
2D-Likelihood contour



Does **<u>not</u>** 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

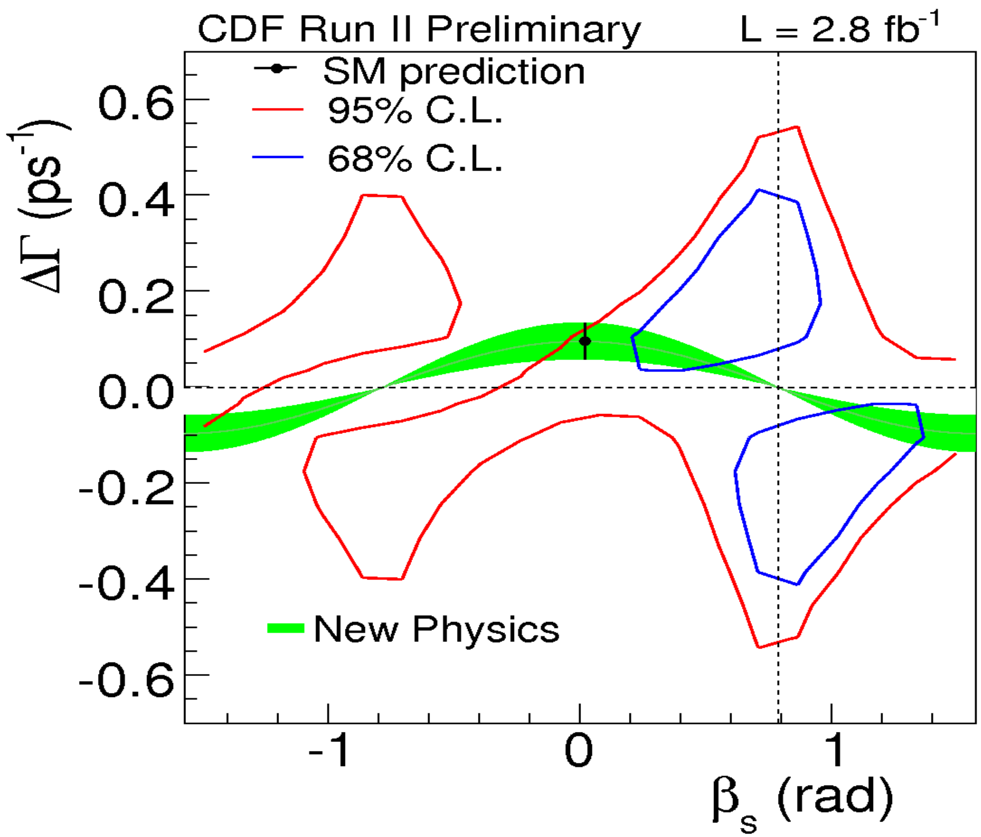
Example of 2D-L contour vs Profile-L Ratio ordering for the 1.35 fb^{-1} CDF result

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

Confidence region with profile-Likelihood Ratio ordering and rigorous frequentist inclusion of systematic uncertainties. 2D region is projection of a multidimensional region in the space of all (27) fit parameters

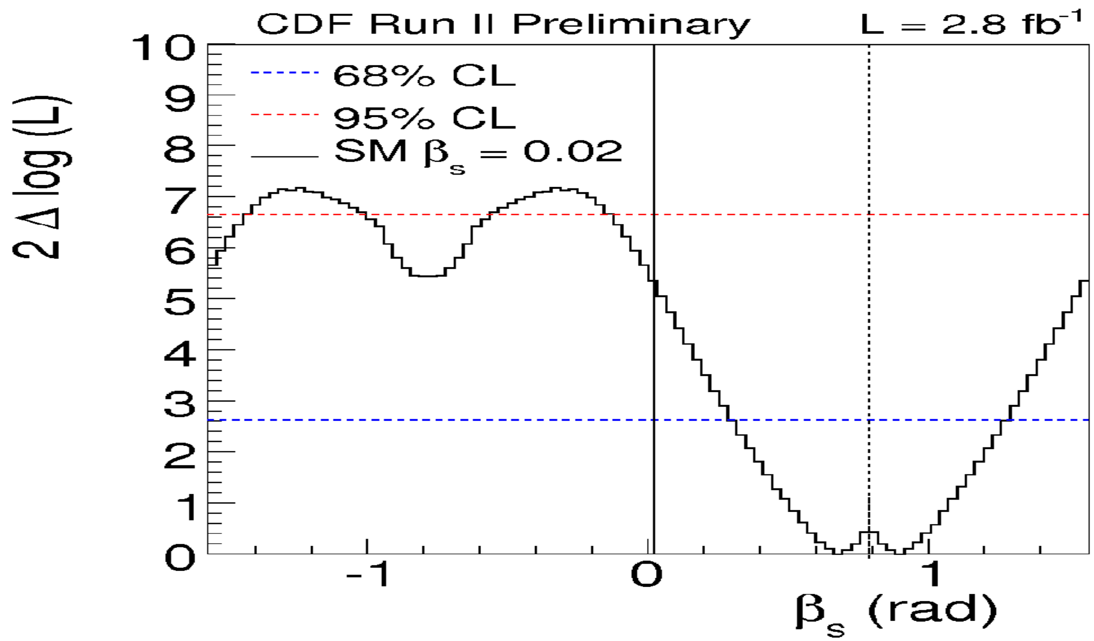
Assuming the SM, the probability of observing a fluctuation as large or larger than what observed in data is 7%, corresponding to 1.8σ

Expect to shrink further once PID will be available for full dataset



β_s 1D Intervals

- $\Delta\Gamma$ treated as a nuisance parameter
  - ➔ $\beta_s \in [0.28, 1.29]$ at 68% CL



- Assuming no CP violation (β_s = 0), we also measure

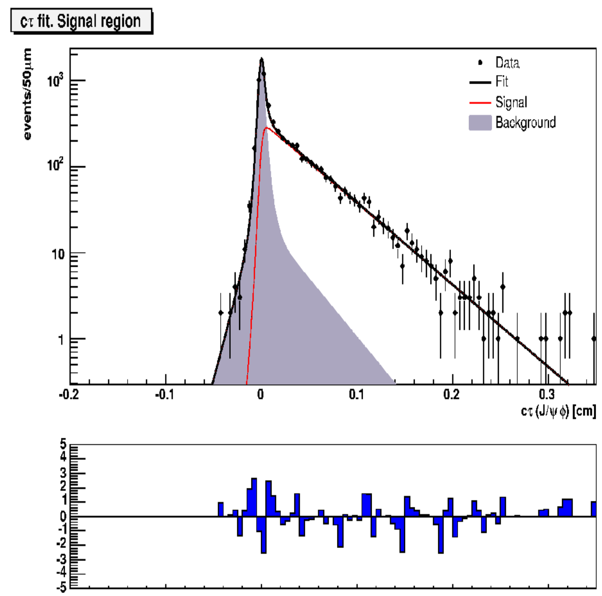
$c\tau_s = 459 \pm 12\ (\text{stat}) \pm 3\ (\text{syst})\ \mu\text{m}$

$\Delta\Gamma_s = 0.02 \pm 0.05\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{ps}^{-1}$

and the transversity amplitudes

$|A_{\parallel}(0)|^2 = 0.241 \pm 0.019\ (\text{stat}) \pm 0.007$

$|A_0(0)|^2 = 0.508 \pm 0.024\ (\text{stat}) \pm 0.008$



Reminder : DØ published Results

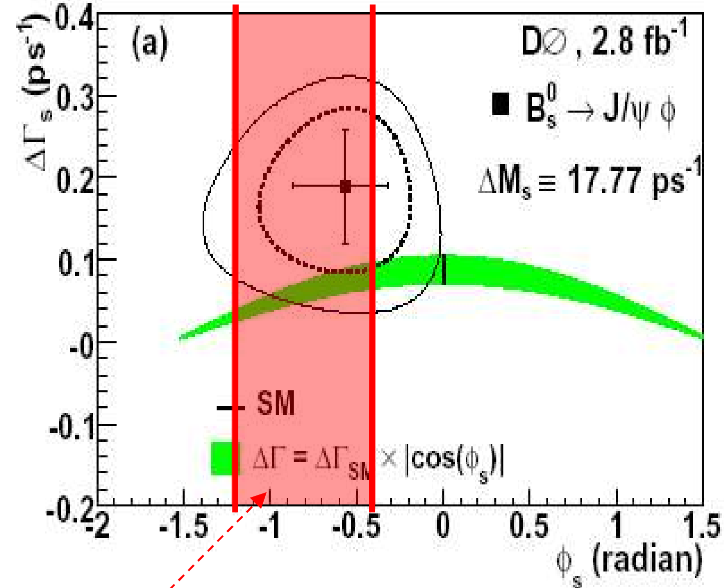
- DØ observes a fluctuation consistent with CDF
- Chooses to quote the results in terms of $\phi_s = -2\beta_s$ (arXiv:0802.2255)
- DØ quotes a point-estimate with strong phases constrained from

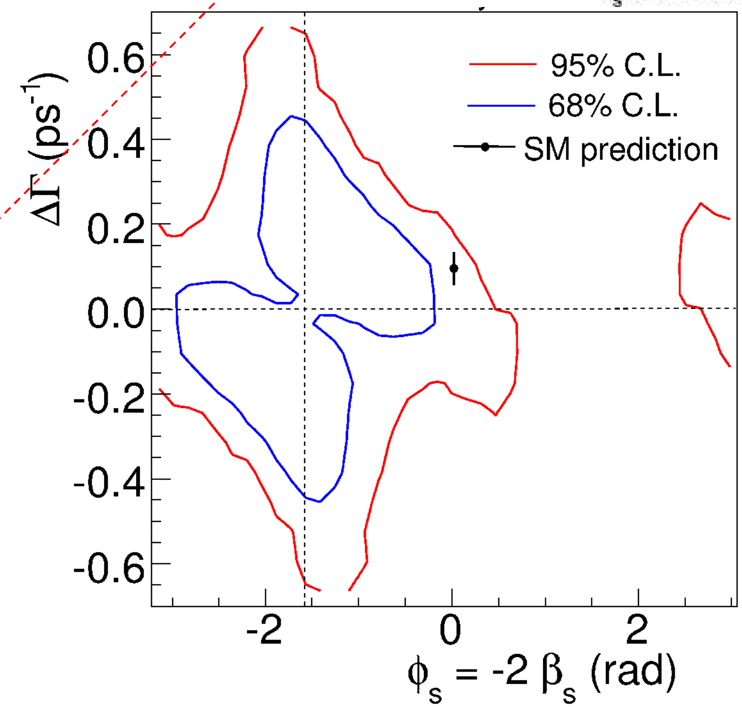
  $B^0 \rightarrow J/ K^{*0}$

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

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

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

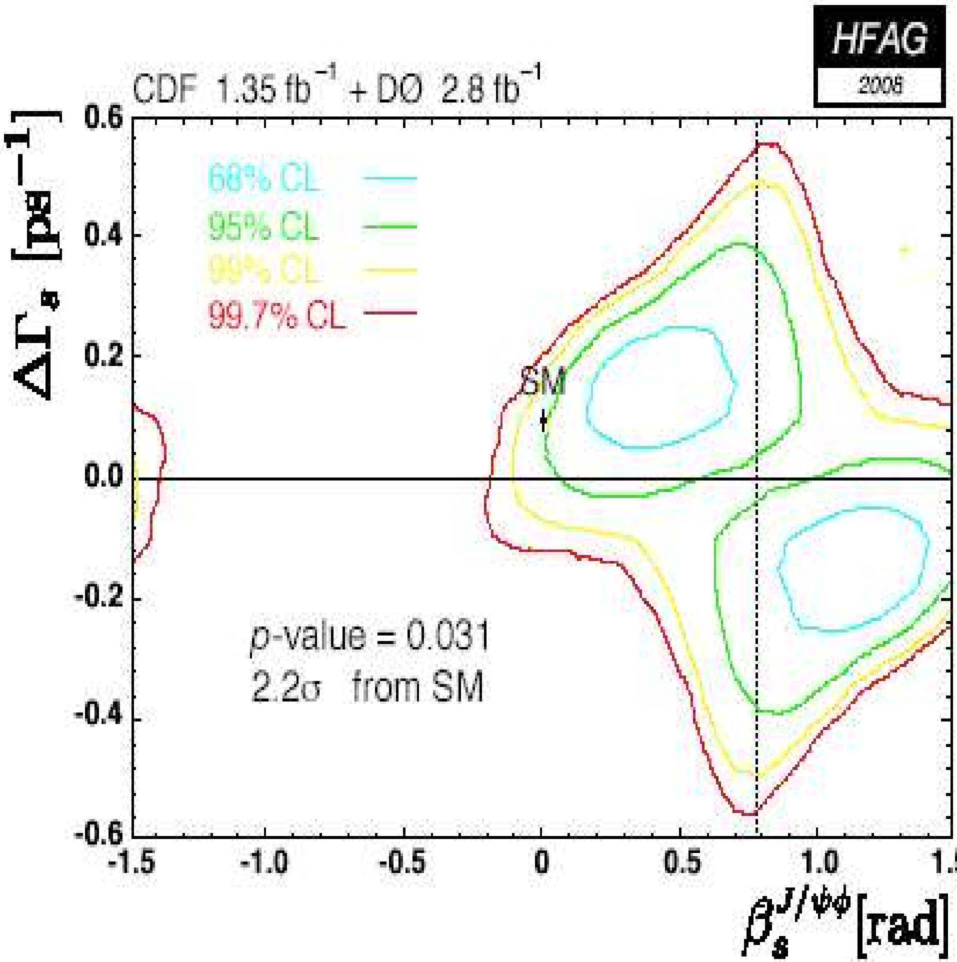




Tevatron combination

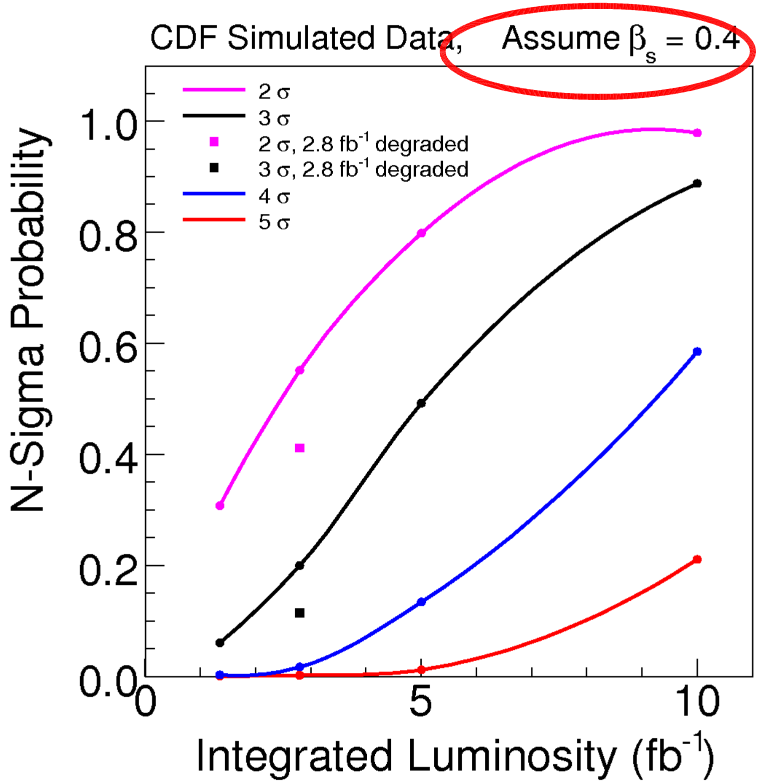
Combine CDF and D0 iso-CL regions with no constrains and previously checked for coverage (a' la HFAG):

2.2σ consistency with SM.



Future

- Tevatron can search for anomalously large values of β_s
- Shown results 2.8 fb^{-1}, but 4 fb^{-1} already on tape to be analysed soon
- Expect 6-8 fb^{-1} by the end of the run 2
- Analysis to be improved and optimized:
  - better flavour tagging
  - calibrated PID
  - more statistics from other triggers



- 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 mixing phase with great precision

Conclusions

Conclusions

- First update on larger dataset confirms old result and provides tighter constraints (15% to 7% agreement with SM), although several ingredients are still in the works

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

- Both CDF and DØ observe 1-2 sigma β_s deviations from SM predictions. SM agreement reduces to 2.2σ when combined.

- Interesting to see how these effects evolve with more data

Back up

Un-binned Likelihood Fit

- Fit with separate PDFs for signal and background

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

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

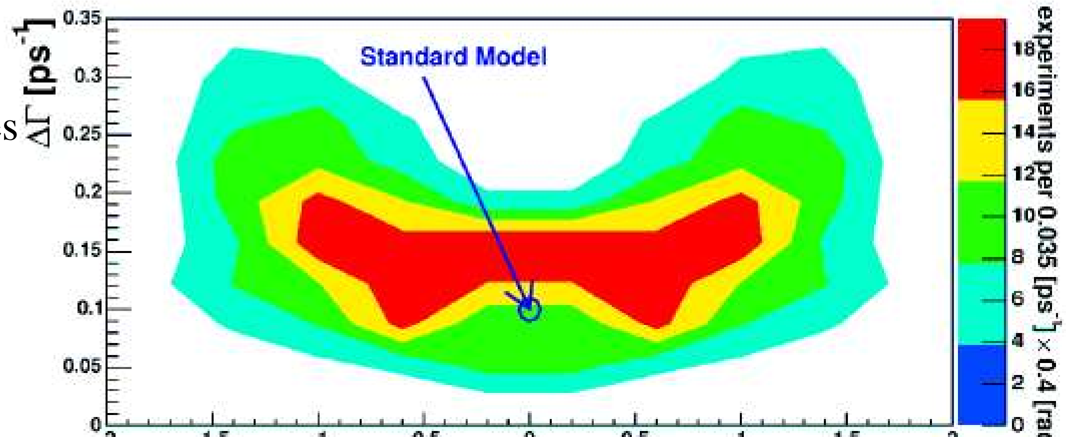
  - $P_s(m|\sigma_m)$ – Single Gaussian fit to signal mass
  - $P_s(ct, \boldsymbol{\rho}, \xi|\mathbf{D}, \sigma_{ct})$ – Probability for $\bar{B}_s^0/B_s^0$
  - $P_b(m)$ – Linear fit to background mass distribution
  - $P_b(ct|\sigma_{ct})$ – Prompt background, one negative exponential, and two positing exponentials
  - $P_b(\boldsymbol{\rho})$ – 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 =0, is undetermined

$$\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

b) L invariant under two transformations:

$$2\beta_s \to -2\beta_s,\ \delta_\perp \to \delta_\perp + \pi$$
$$\Delta\Gamma \to -\Delta\Gamma,\ 2\beta_s \to 2\beta_s + \pi$$

→ 4 equivalent minima

Angular Probability Distribution: time evolution

- General relation for B-> VV

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

B^0_s term

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

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

anti-B^0_s

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

f( ): angular distribution for a given polarization state

- ρ = {$\cos\theta_T$, φ_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 dependen-ce; they are different for different initial state flavor

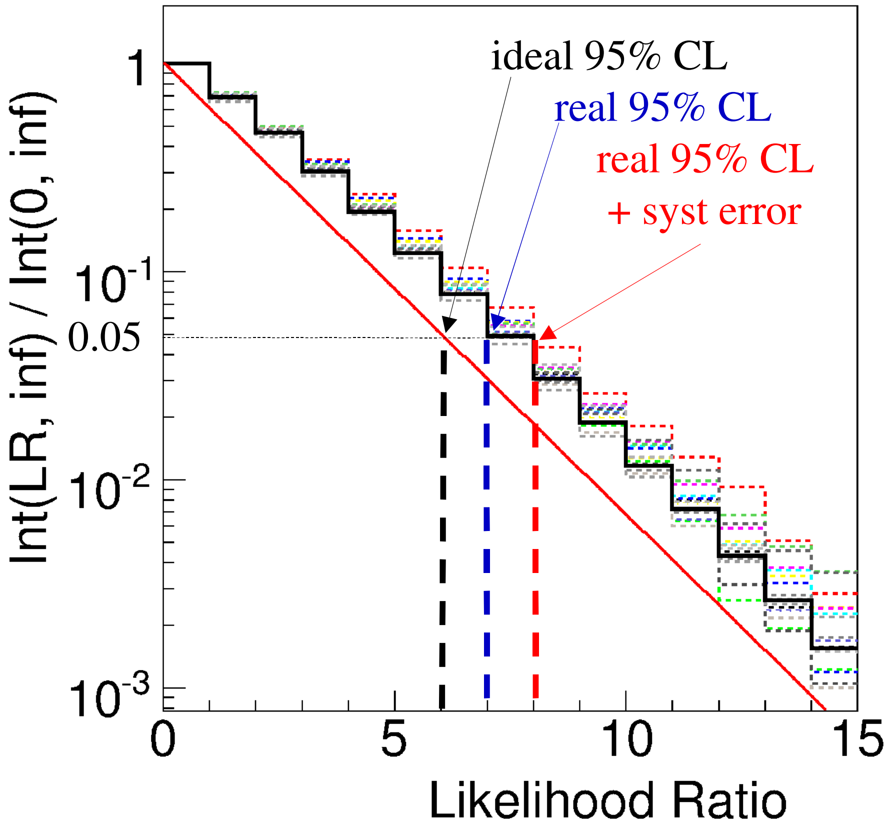
$\delta_\parallel = \arg(A_\parallel A_0^*)$, $\delta_\perp = \arg(A_\perp A_0^*)$ are the phases of $A_\parallel$ and $A_\perp$ relative to A_0

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

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

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: $\phi_s = -2\ _{s}$

- $B \to VV$ (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 (||)

  CP even

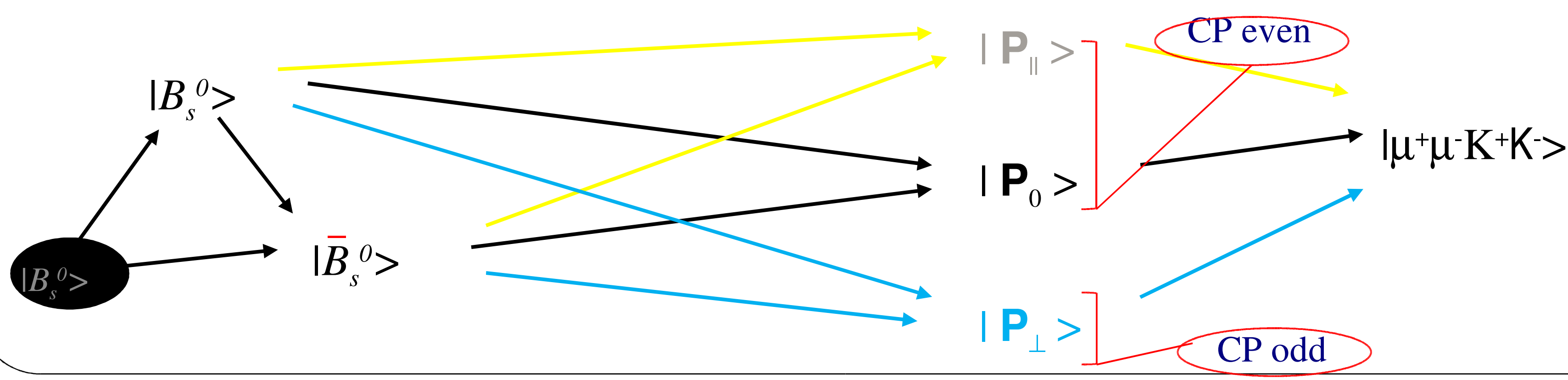
  - transverse but perpendicular to each other (⊥)

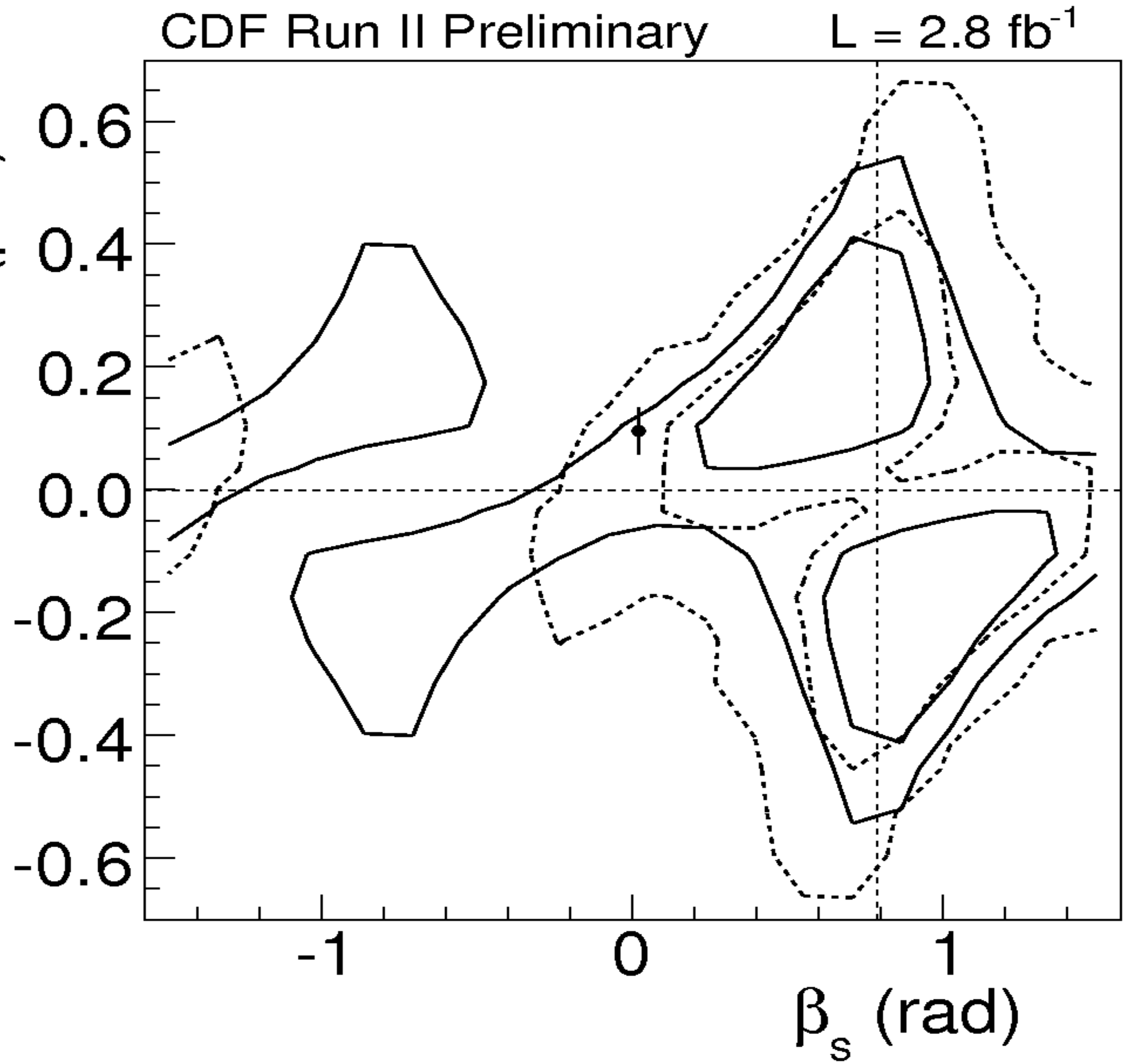
  CP odd

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

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

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




CDF Run II Preliminary
L = 2.8 fb^{-1}
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
$\Delta\Gamma$ (ps^{-1})
-1
0
1
β_s (rad)