B_s and CP Violation at the Tevatron

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Overview

Introduction:

- B_s Meson System
- CP Violation

Measurements:

- Semileptonic CP Asymmetry
- $B_s \to D_s^{(*)} D_s^{(*)}$
- $B_s \to J/\psi\ \varphi$
  + Introduction
  + Angular Analysis
  + Signal Selection
  + Flavour Tagging
  + Likelihood Fit
  + Results and Combinations

Summary and Outlook

B_s System

Flavour Eigenstates:

$$|B_s^0> = |\bar{b}s> \qquad |\bar{B}_s^0> = |b\bar{s}>$$

Mass Eigenstates:

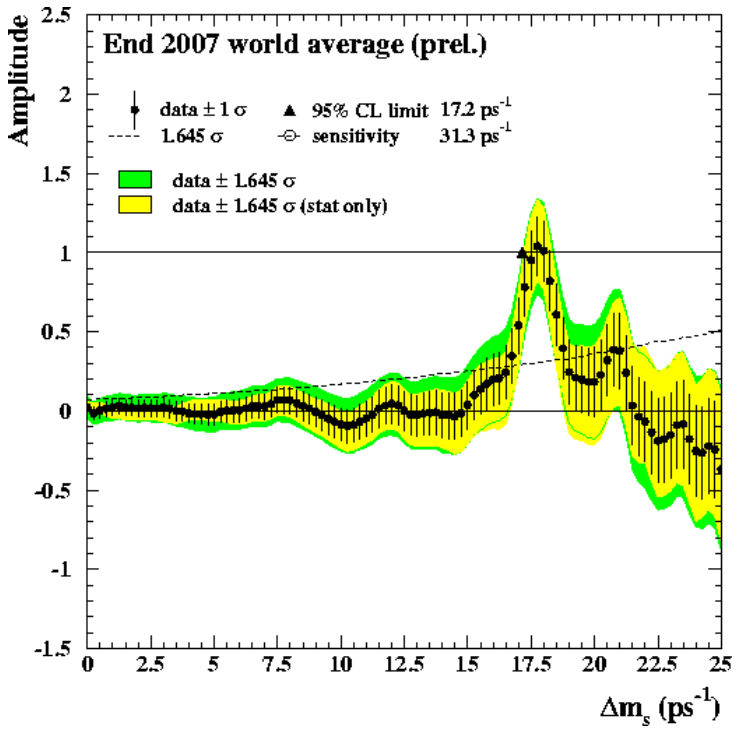
Time evolution given by Schroedinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} |B_s^0(t)> \\ |\bar{B}_s^0(t)> \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |B_s^0(t)> \\ |\bar{B}_s^0(t)> \end{pmatrix}$$

Eigenstates of the Hamiltonian:

$$|B_s^H(t)> \;=\; p|B_s^0(t)> - q|\bar{B}_s^0(t)> \qquad \text{“heavy”}$$

$$|B_s^L(t)> \;=\; p|B_s^0(t)> + q|\bar{B}_s^0(t)> \qquad \text{“light”}$$



mass difference: $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

width difference: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|cos(\phi_s)$

CP Violation

CP eigenstates:

$$|B_s^{even}> = \frac{1}{\sqrt{2}}(|B_s^0> - |\bar{B}_s^0>)$$
$$|B_s^{odd}> = \frac{1}{\sqrt{2}}(|B_s^0> + |\bar{B}_s^0>)$$

width difference: $\Delta\Gamma_s^{CP} = \Gamma_s^{even} - \Gamma_s^{odd}$

$$\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cdot cos\ \phi_s$$

In case of CP conservation:

$$|B_s^L >= |B_s^{even} >$$
$$|B_s^H >= |B_s^{odd} >$$

Expectations:

- Standard Model predicts very small value: Φ_s =0.004
- New Physics can considerably expand this

CP Violation in semileptonic B_s decays

Outline:

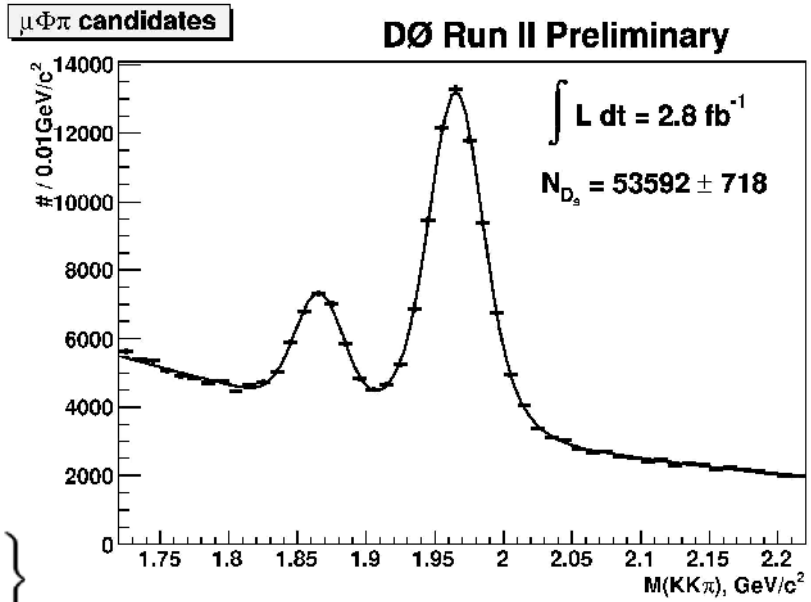
- $B_s^0 \to D_s^- \mu^+ \nu X,\ D_s^- \to \phi\pi^-,\ \phi \to K^+K^-$
- using initial state flavour tagging
- measure time-dependent CP asymmetry
- closely related to B_s mixing measurement

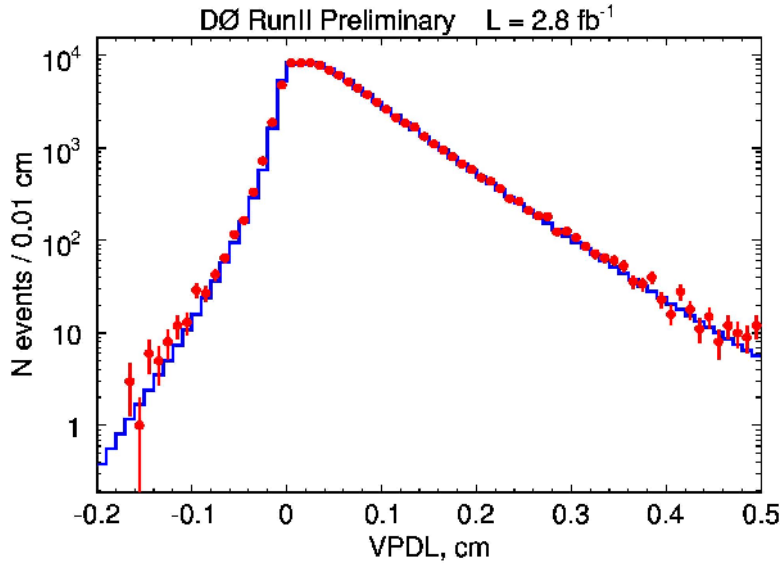
$$\Gamma(B^0(t) \to f) = N_f |A_f|^2 \frac{\exp(-\Gamma t)}{2} \left\{ \cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta M t) \right\}$$

$$\Gamma(\overline{B}^0(t) \to f) = N_f |A_f|^2 (1+a) \frac{\exp(-\Gamma t)}{2} \left\{ \cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta M t) \right\}$$

$$\Gamma(B^0(t) \to \overline{f}) = N_f |\overline{A}_{\overline{f}}|^2 (1-a) \frac{\exp(-\Gamma t)}{2} \left\{ \cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta M t) \right\}$$

$$\Gamma(\overline{B}^0(t) \to \overline{f}) = N_f |\overline{A}_{\overline{f}}|^2 \frac{\exp(-\Gamma t)}{2} \left\{ \cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta M t) \right\}$$





Result:

$$a_{sl}^s = -0.0024 \pm 0.0117(stat)^{+0.0015}_{-0.0024}(syst)$$

$B_s \to D_s^{(*)} D_s^{(*)}$, $\Delta\Gamma^{CP}$

Outline:

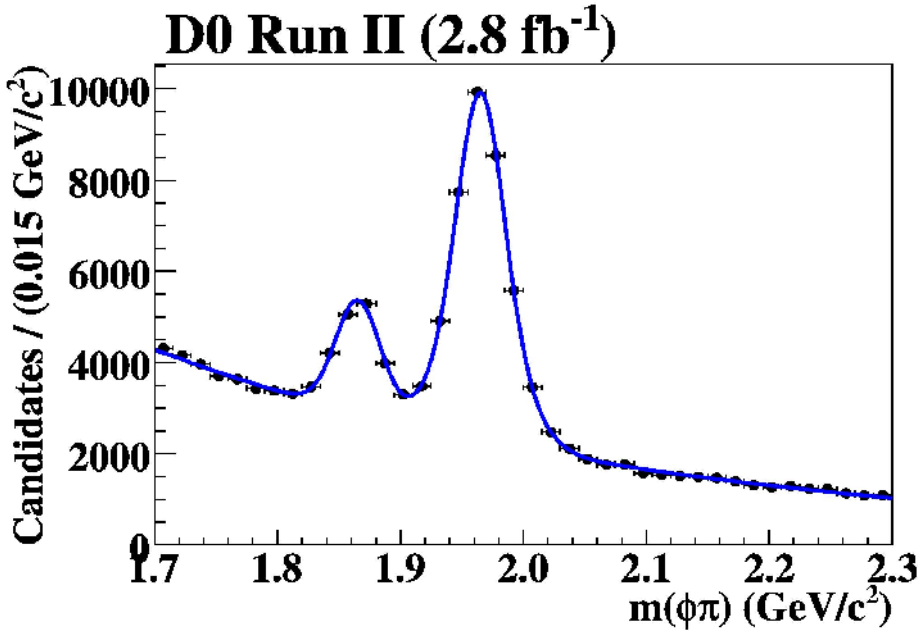
- D_s D_s final state is CP even
- measure branching ratio $2Br[f_{CP+}] \approx \frac{\Delta\Gamma_{CP}}{\Gamma}$
- no flavour tagging required
- assuming Standard Model: measure $\Delta\Gamma/\Gamma$
- with non-zero phase: constrain relation
  $\Delta\Gamma/\Gamma = \Delta\Gamma_{CP}/\Gamma \cdot cos\ \phi$

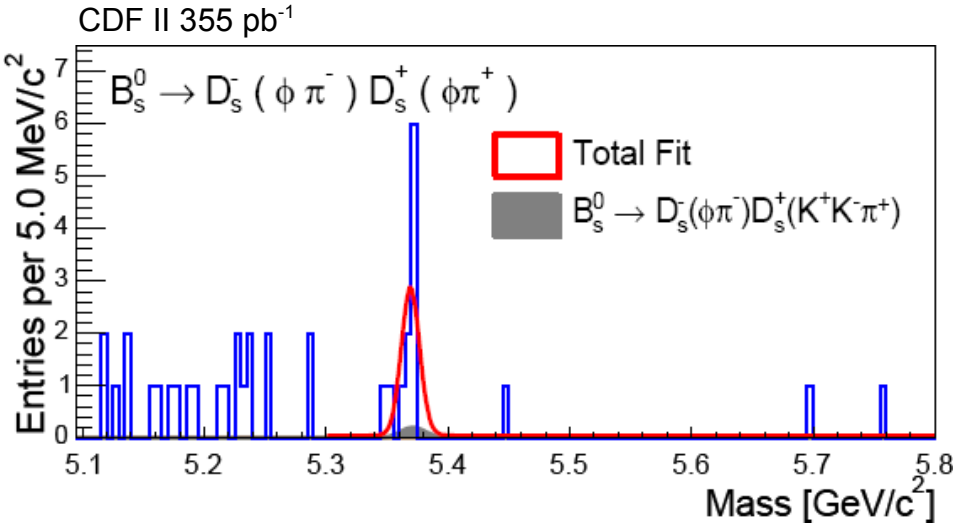
D0 Analysis on 2.8/fb: $B_s \to D_s^{(*)} D_s^{(*)}$

- observed the decay at 3.2 σ
- first evidence for a width difference in B_s
  $\Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(stat) \pm 0.022(syst)$

CDF Analysis on 355/pb: $B_s \to D_s$ D_s

- observed the decay at 7.5 σ
- limit: $\Delta\Gamma_s^{CP}/\Gamma_s \geq 0.012$ at 95% C.L.



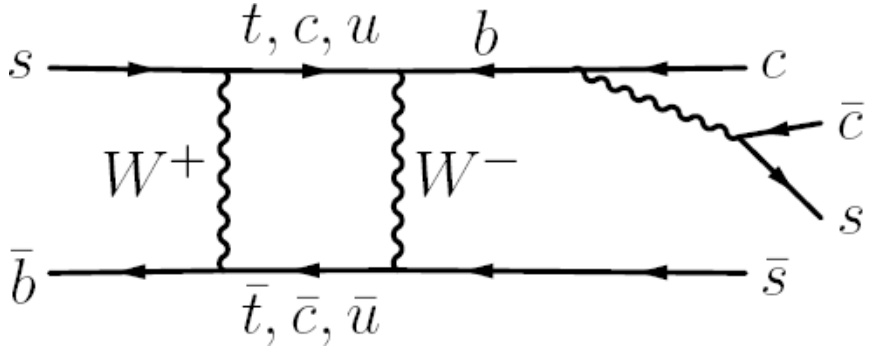


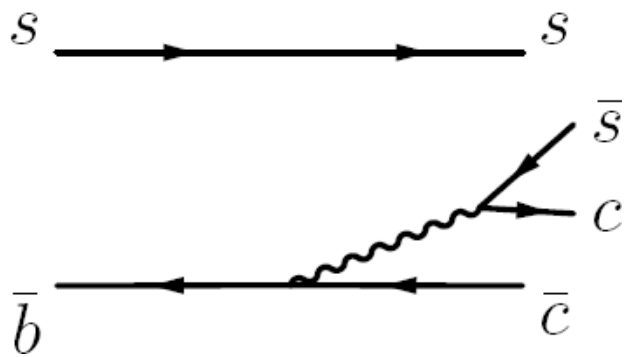
B_s -> J/ψ φ Introduction

Decay:

$$B_s \to J/\psi\,\phi,\, J/\psi \to \mu^+\mu^-,\, \phi \to K^+K^-$$

- decay on quark level similar to D_s D_s final state
- colour suppressed, but easier to trigger
- final state can be reached with and without mixing





- interference of both: CP violating phase β_s
- New Physics can contribute to that phase
- final state is a mixture of even and odd CP eigenstates
- disentangle CP states by angular distributions of the decay products

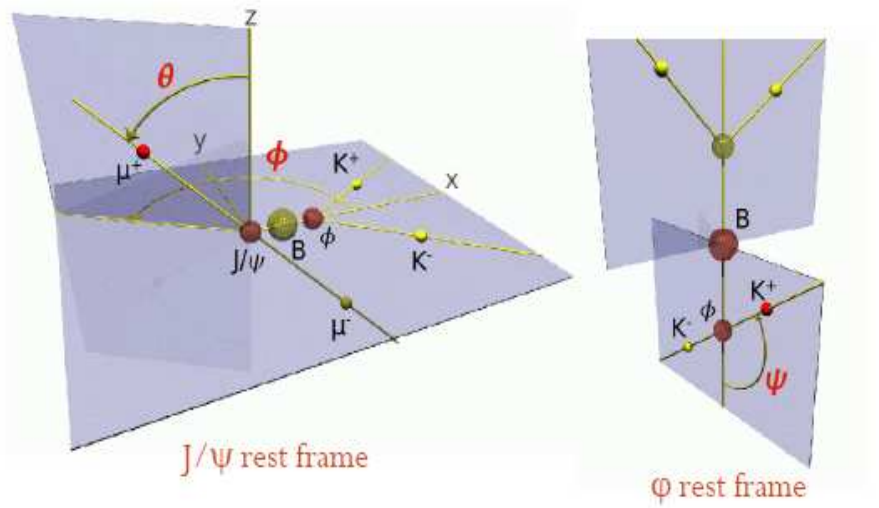
B_s -> J/ψ φ Angular Analysis

B_s	$\longrightarrow$	$J/\Psi\ (\rightarrow \mu^+\mu^-)$	$\phi\ (\rightarrow K^+K^-)$
(spin=0)		(spin=1)	(spin=1)

Topology:

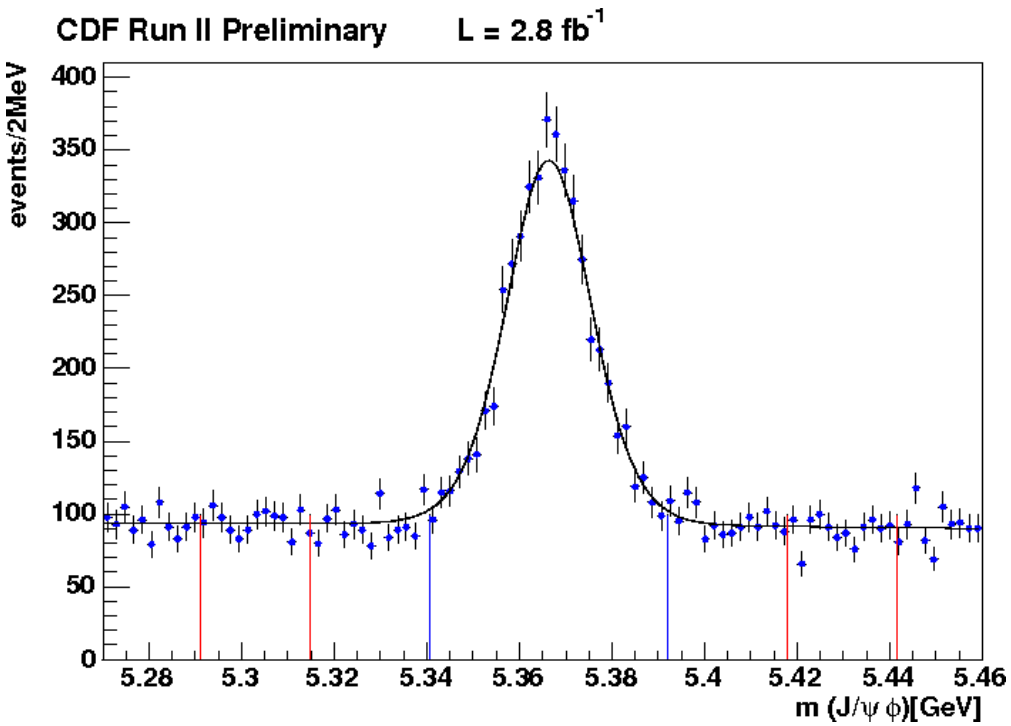
- conservation of angular momentum
- three different final states for L=0,1,2
- angular distributions used to distinguish CP even and odd contributions
- commonly used *transversity basis* leads to three decay Amplitudes

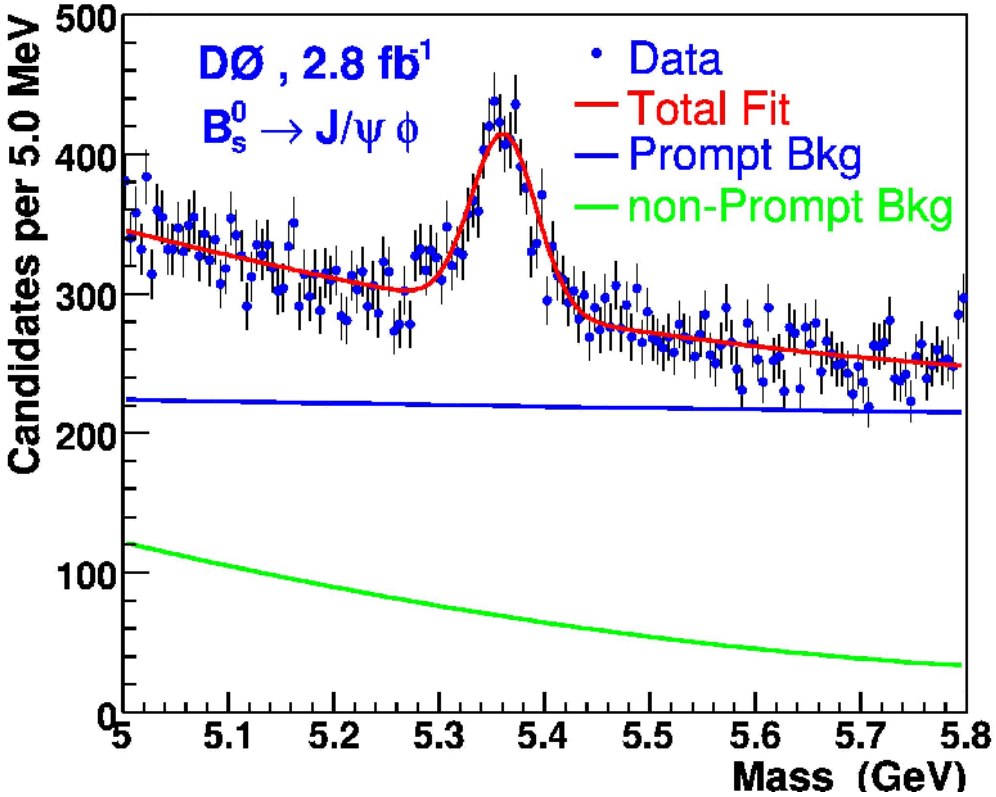
L		CP
0	s-wave	even
1	p-wave	odd
2	d-wave	even



$A_\perp$	CP odd
A_0	CP even
$A_\parallel$	CP even

B_s -> J/ψ φ Signal Selection

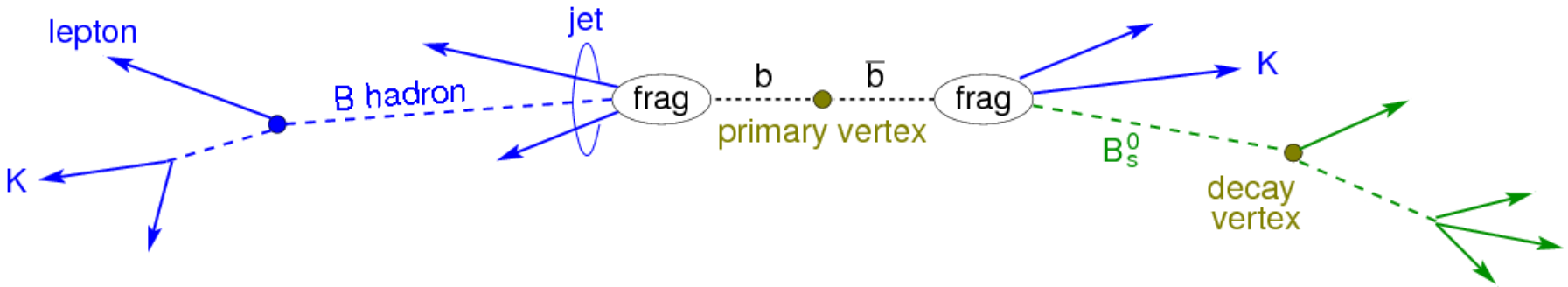




- about 3200 events
- di-muon trigger
- neural network selection
- no particle ID information

- about 2000 events
- di-muon trigger
- cut based candidate selection

B_s -> J/ψ φ Flavour Tagging



B flavour tagging:

- determine initial state B_s meson flavour
- used to resolve time dependence in

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f_{CP}) - \Gamma(B_s^0 \to f_{CP})}{\Gamma(\bar{B}_s^0 \to f_{CP}) + \Gamma(B_s^0 \to f_{CP})} \approx \pm sin(2\beta_s) sin(\Delta m_s t)$$

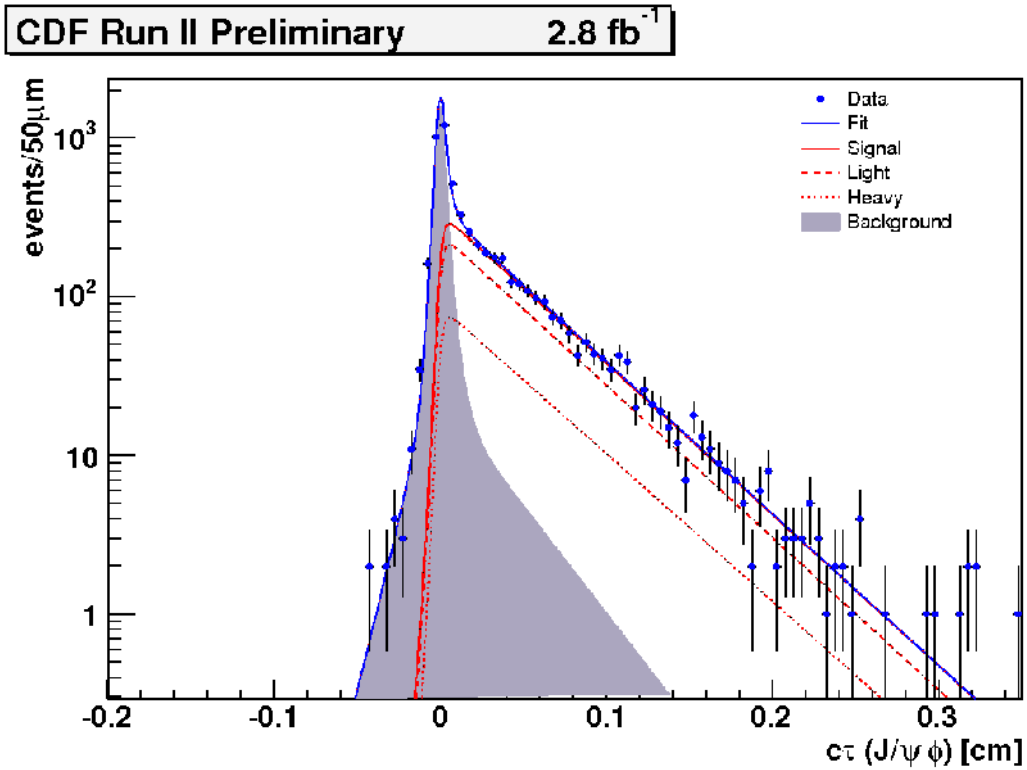
- sources of tagging information:
  * same side tagging: fragmentation of B_s meson
  * opposite side tagging: decay products of the other B hadron

- difficult in hadronic environment
- tagging power O(few %)

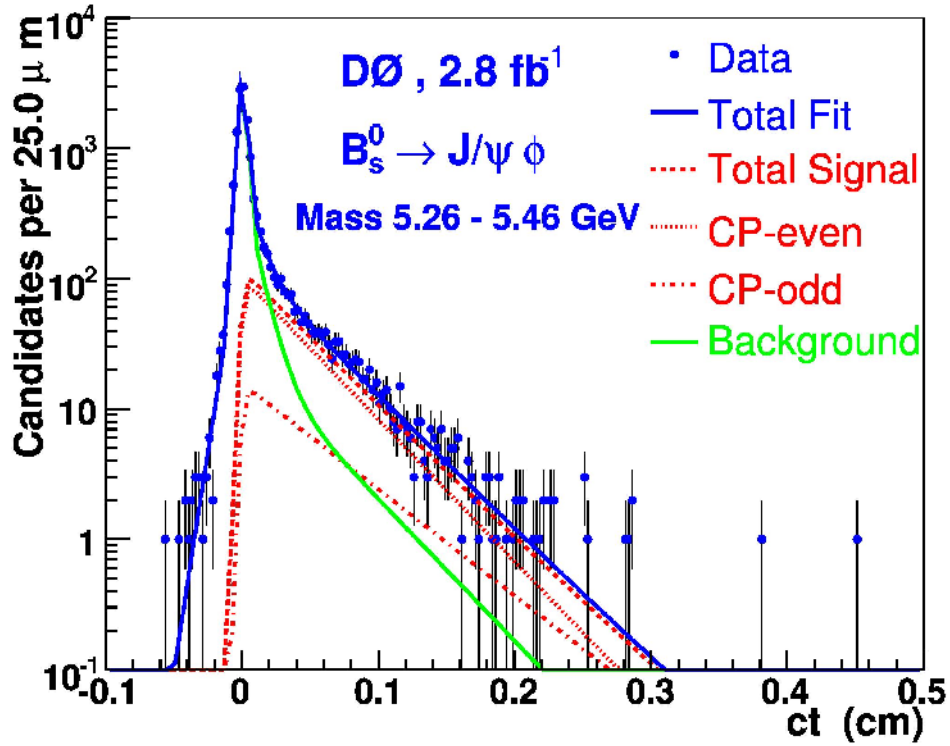
B_s -> J/ψ φ Likelihood Fit

Unbinned maximum likelihood fit:

- using mass, tagging information, proper decay time and angular distributions
- extract $\Delta\Gamma$ and β_s



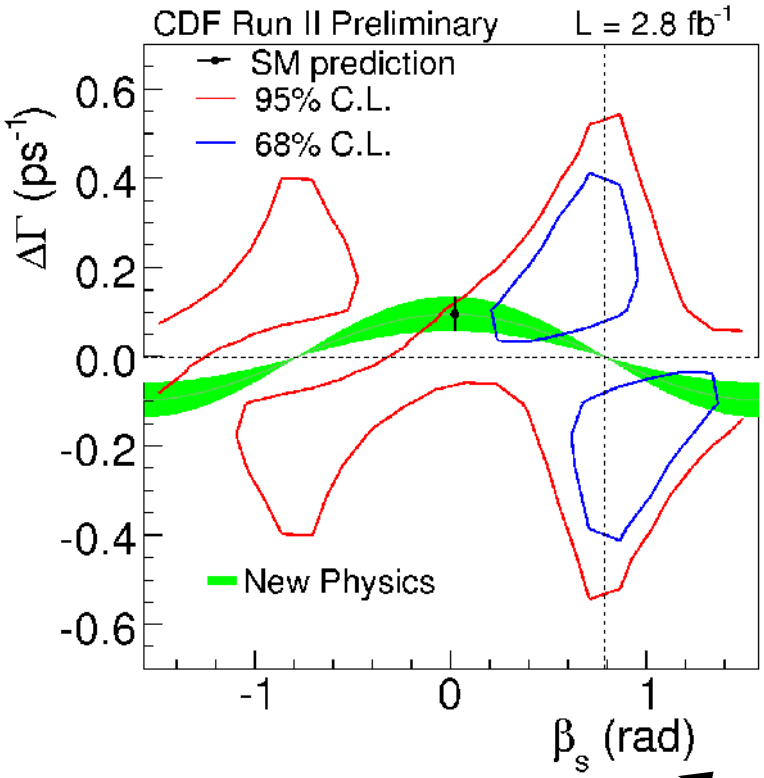
$$\tau(B_s^0) = (1.53 \pm 0.04(stat) \pm 0.01(syst))ps$$

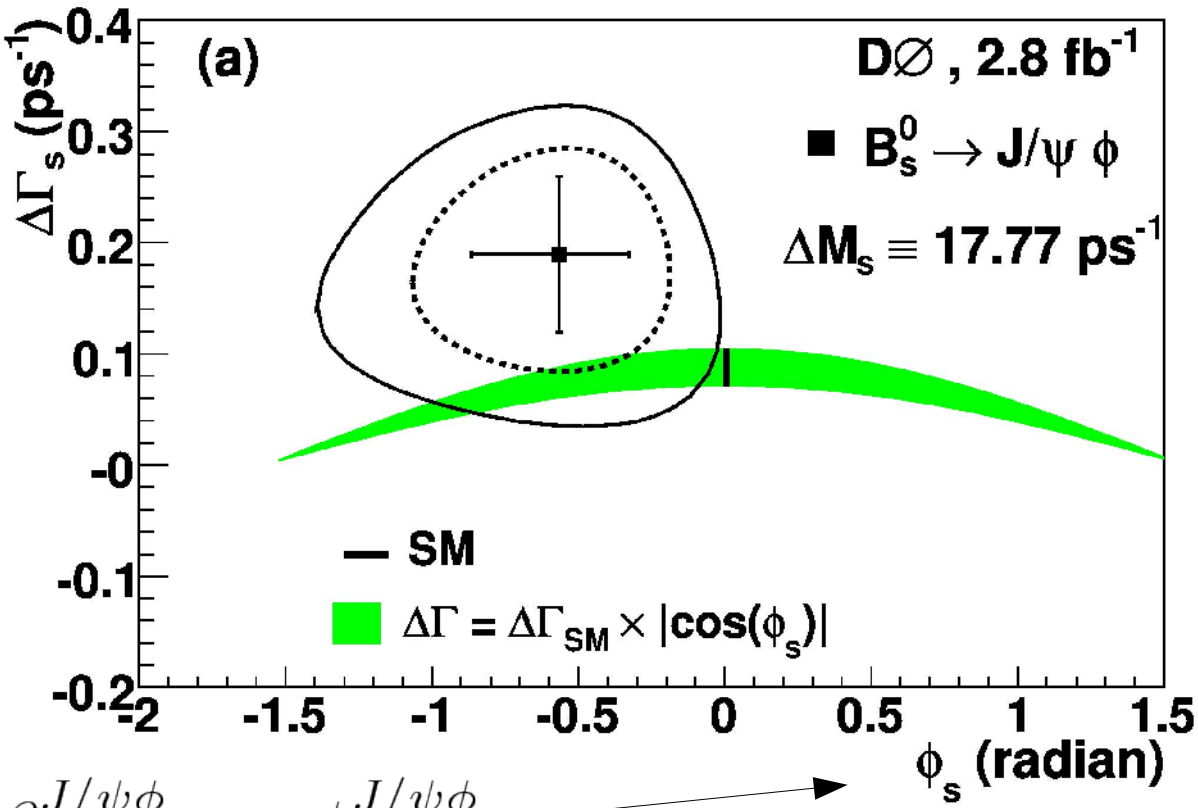


$$\tau(B_s^0) = (1.52 \pm 0.05(stat) \pm 0.01(syst))ps$$

B_s -> J/ψ φ Result

Non gaussian errors require evaluation of confidence regions:





$$2\beta_s^{J/\psi\phi} = -\phi_s^{J/\psi\phi}$$

1.8 σ from SM (p = 7%)

constraint on strong phase
1.7 σ from SM (p = 8.5 %)

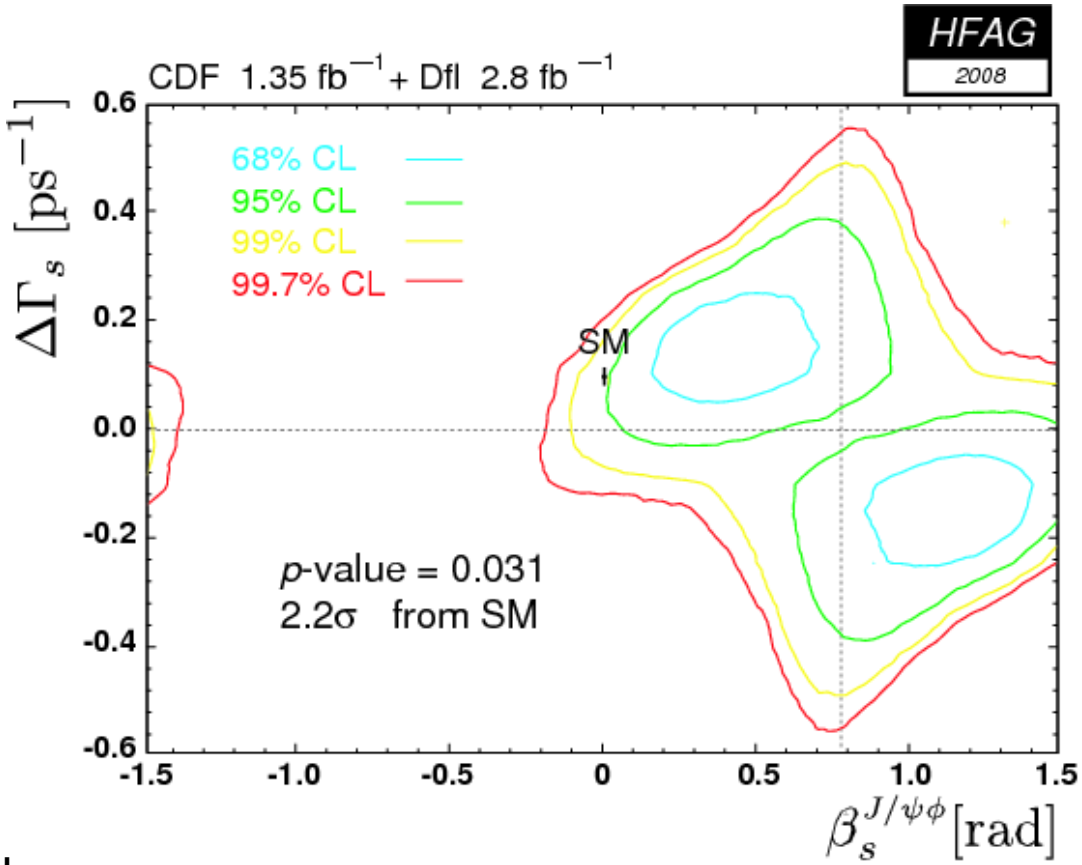
B_s -> J/ψ φ Combined Result

Status:

- both results are compatible with the Standard Model at 1.7 to 1.8 σ
- both results show same tendency

Combination:

- HFAG combined current 2.8/fb D0 with previous 1.35/fb CDF result
- combined confidence region is 2.2 σ away from SM expectation



Plans:

- collect as much data as the Tevatron allows
- D0: improve candidate selection
- CDF: use particle ID information, improved flavour tagging
- new combination by simultaneous minimization of CDF and D0 likelihood functions

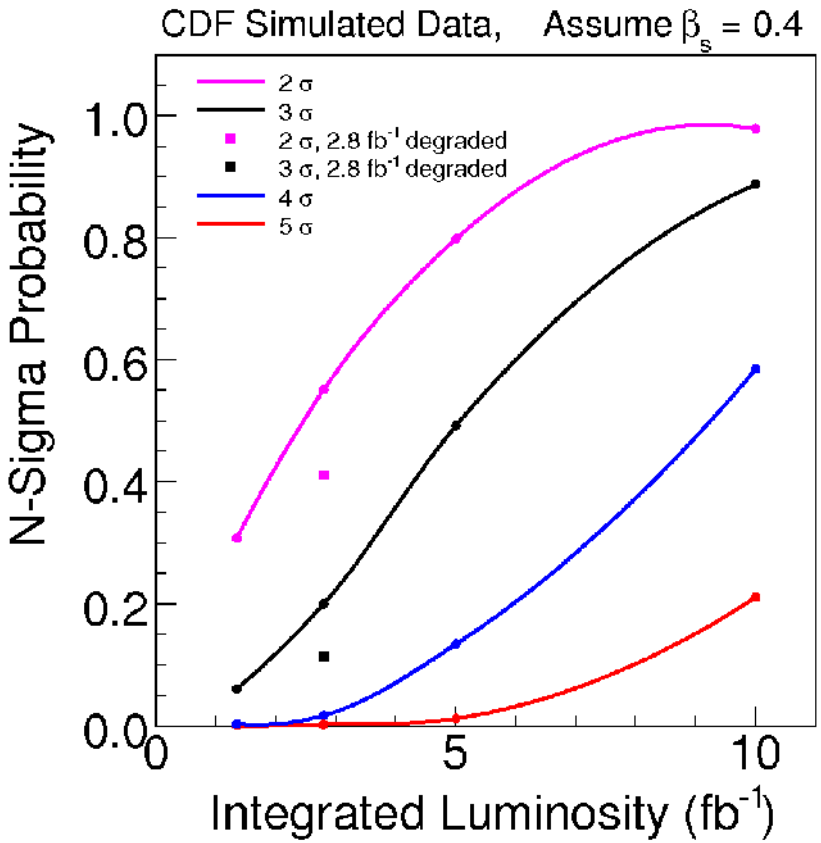
Summary and Outlook

Status:

- D0 measured CP asymmetry in semileptonic decays
- CDF and D0 have seen $B_s \to D_s D_s$
- $B_s \to J/\psi\ \varphi$ analyses:
  - CDF has 1.8 σ deviation from SM
  - D0 has 1.7 σ deviation from SM
  - deviations are to the same directions
  - HFAG combination has 2.2 σ significance

Outlook:

- more data will help all measurements
- other analysis improvements in preparation
- more powerful combination
  for $B_s \to J/\psi\ \varphi$ planned



References

Semileptonic CP Asymmetry:

- D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B55/

$B_s \to D_s^{(*)} D_s^{(*)}$

- CDF: Phys.Rev.Lett.100:021803,2008
- D0: arXiv.org:0811.2173

$B_s \to J/\psi\ \varphi$

- CDF: http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/
- D0: arXiv.org:0802.2255
- HFAG: http://hep.physics.indiana.edu/~rickv/hfag/combine_dGs.html

Backup

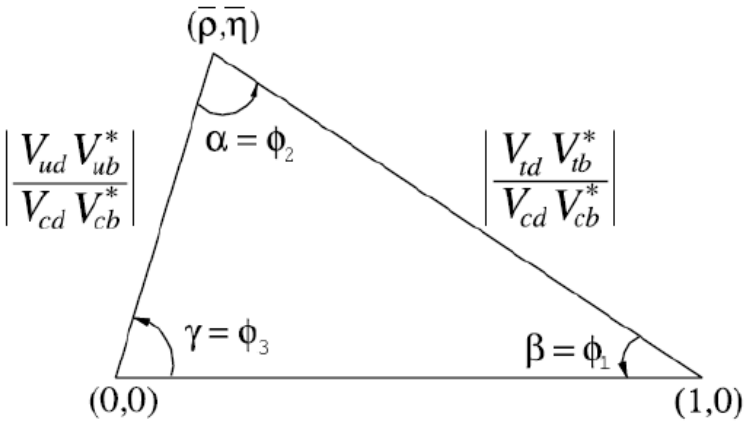
The CKM Matrix

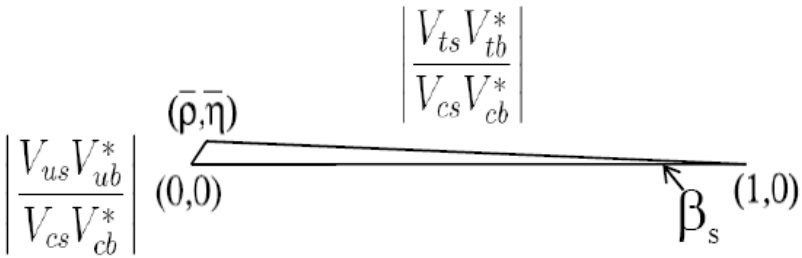
Cabibbo-Kobayashi-Maskawa matrix connects mass and weak eigenstates:

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

- probability conservation requires unitarity
- unitarity relations can be visualized as *unitarity triangles*:

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



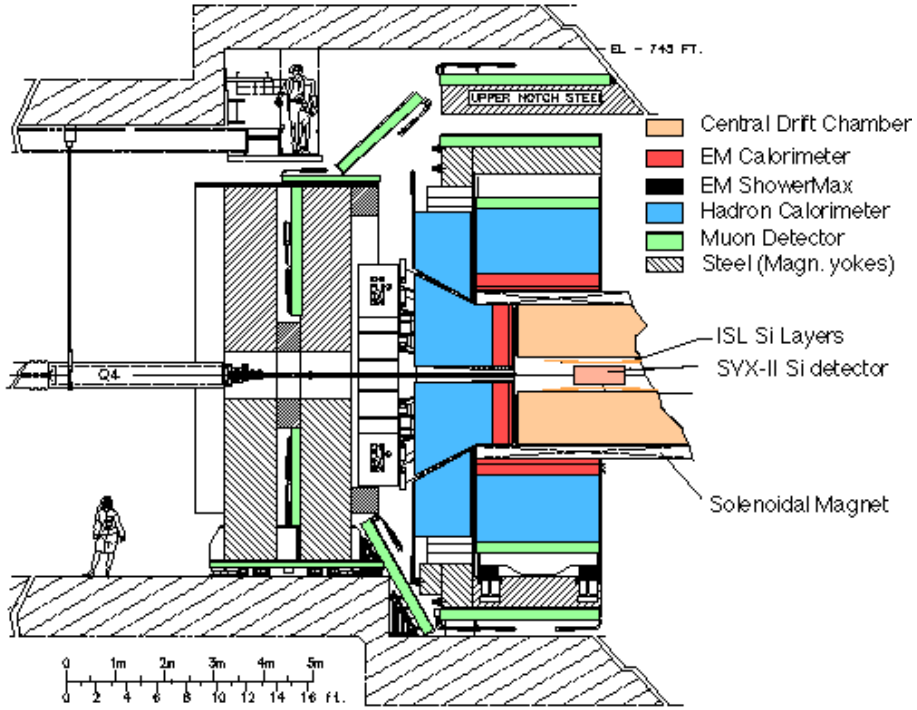


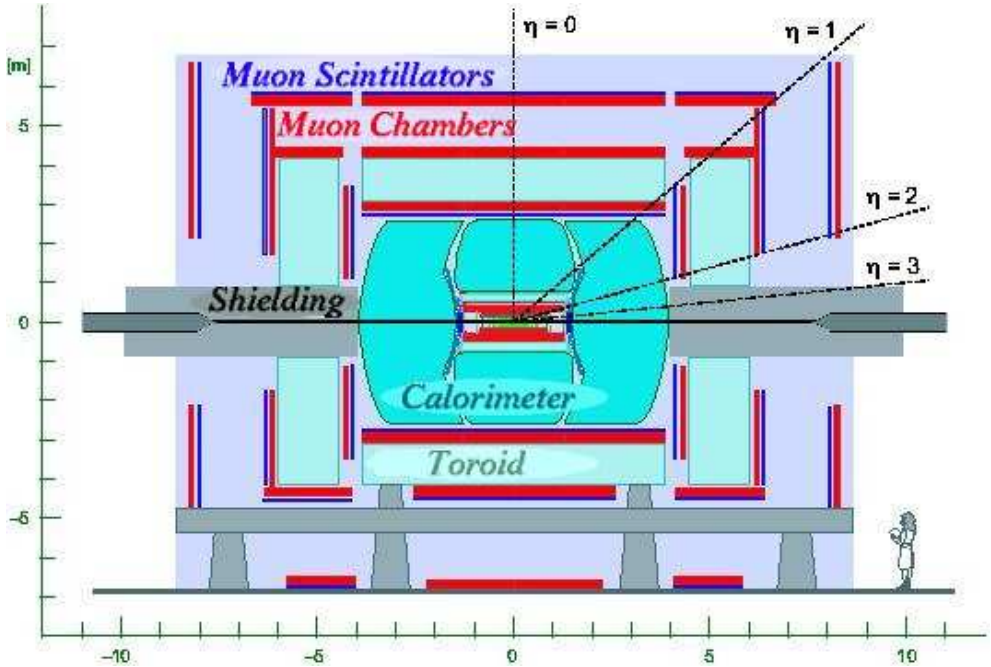
Tevatron and Fermilab

Tevatron:

- still the world's most powerful accelerator
- proton-antiproton collisions at 1.96 GeV/c^2
- still the only place to study B_s mesons
- located at Fermilab near Chicago

CDF and D0





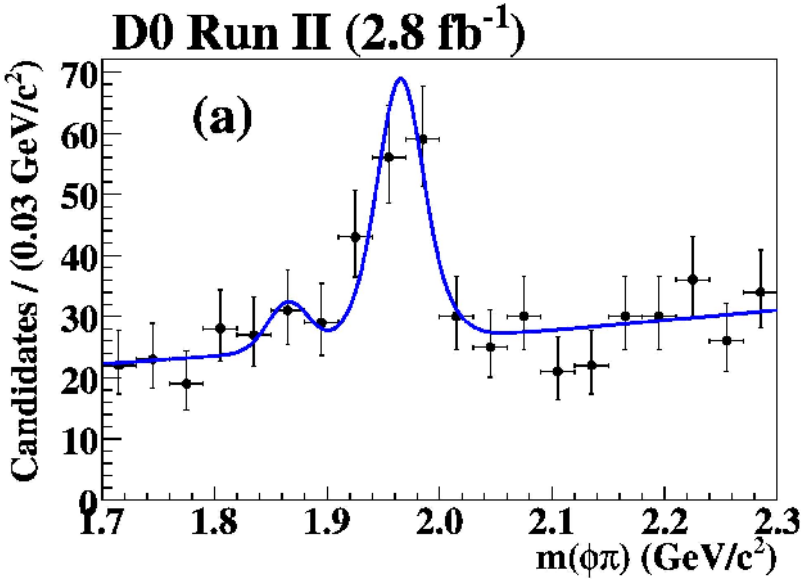
CDF:

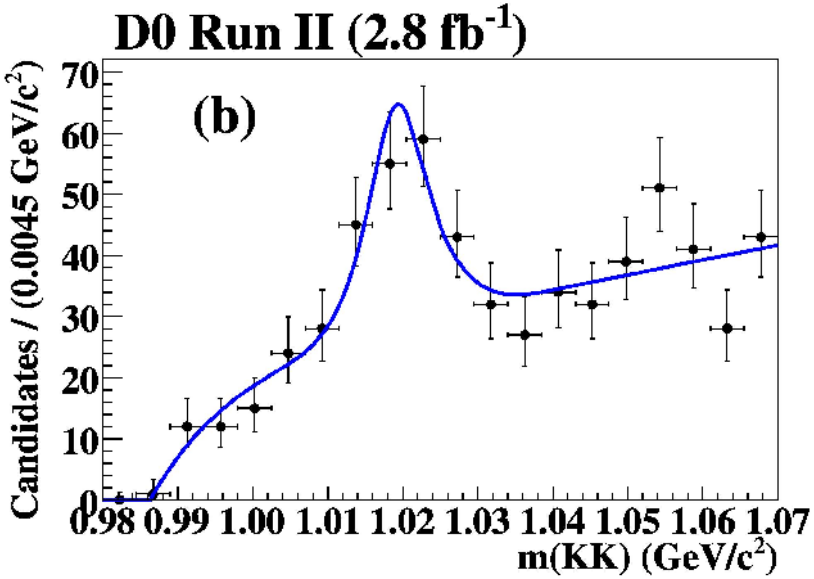
- good vertex resolution, large tracker
- pion/kaon separation by dE/dx and TOF

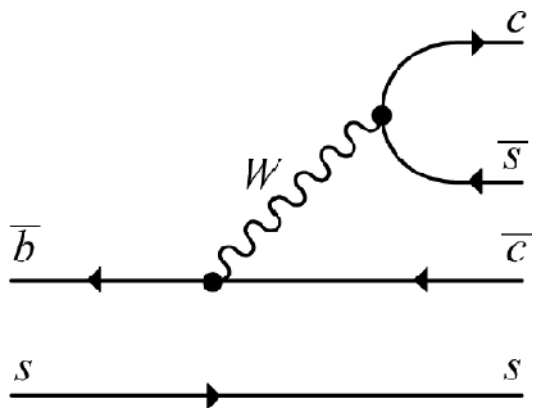
D0:

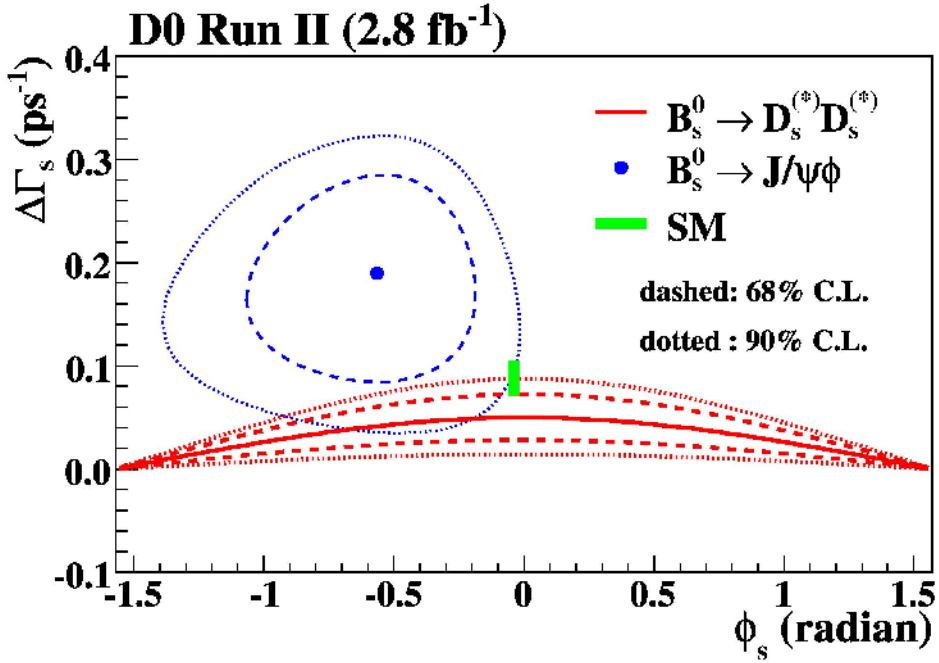
- large tracking and muon coverage
- magnetic field can be reversed

$B_s \to D_s^{(*)} D_s^{(*)}$, $\Delta\Gamma^{CP}$









B_s -> J/ψ φ Likelihood Function

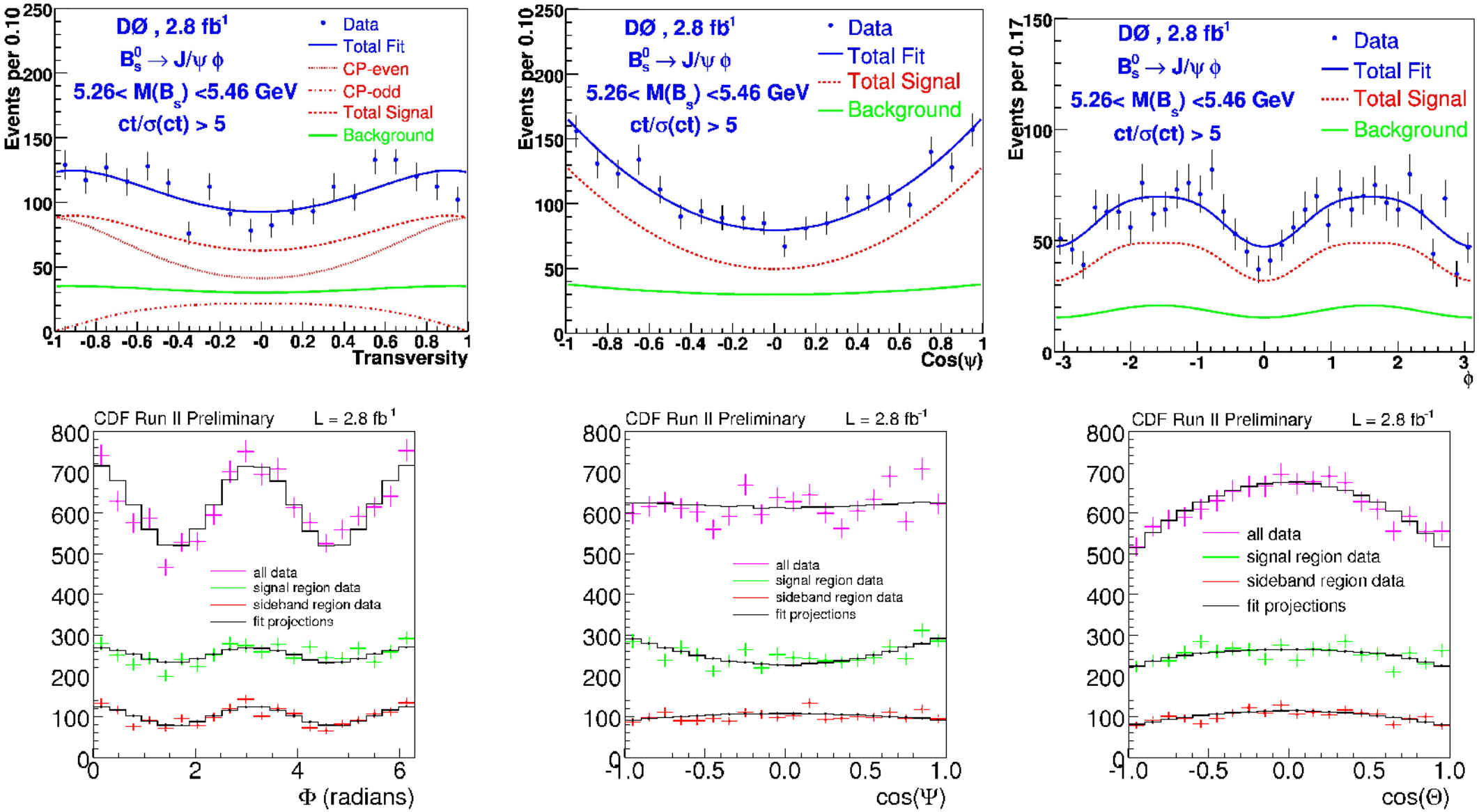
$$
\begin{aligned}
\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto\ & |A_0|^2 f_1(\vec{\rho})\mathcal{T}_+(t) + |A_{||}|^2 f_2(\vec{\rho})\mathcal{T}_+(t) \\
+\ & |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_-(t) + |A_0||A_{||}| f_5(\vec{\rho})\cos(\delta_{||})\mathcal{T}_+(t) \\
+\ & |A_{||}||A_\perp|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

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

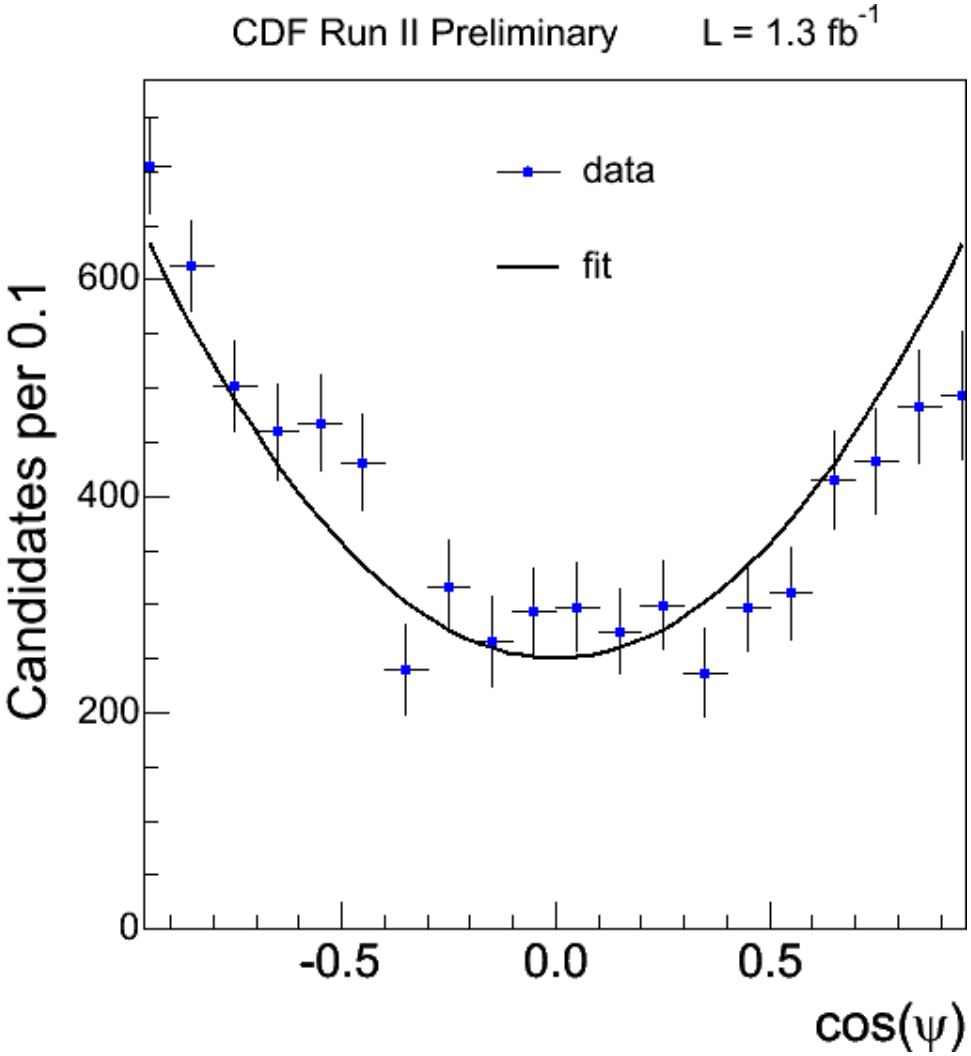
Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
  $\delta_{||} = arg(A_{||} A_0^*)$
- Decay width difference
- CPV Phase

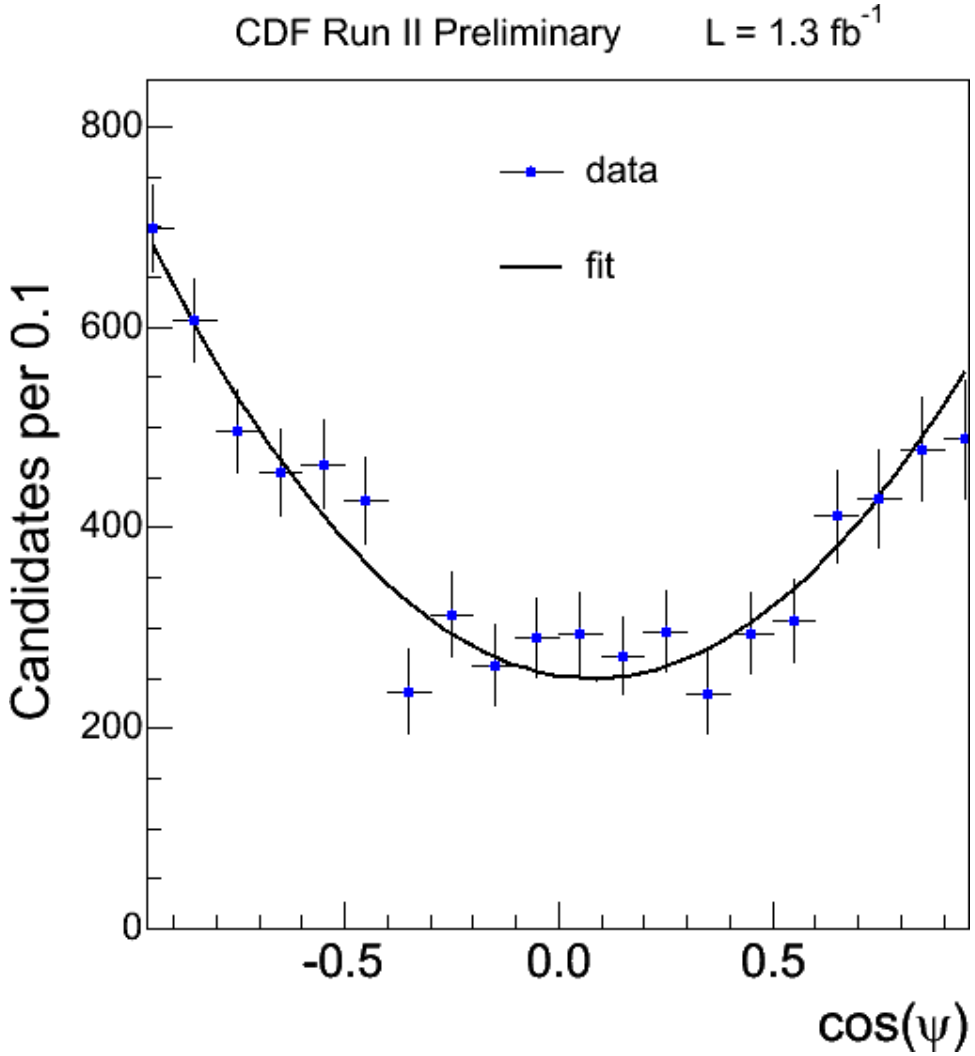
B_s -> J/ψ φ Angular Distributions



B^0 -> J/ψ K* S-wave Contributions



fit without s-wave



fit with s-wave