CP Violation Measurements at the Tevatron

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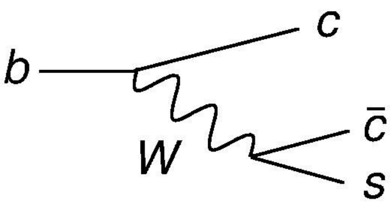
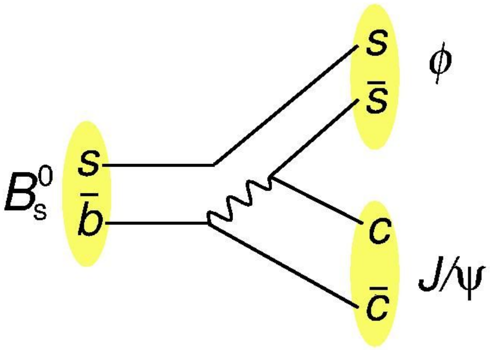
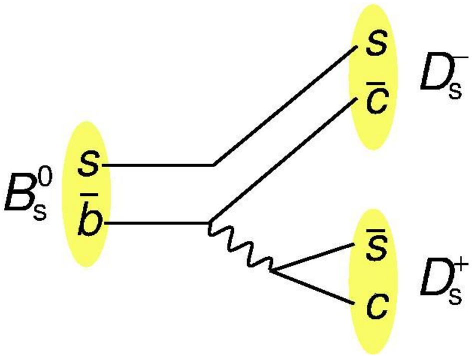






On Behalf of the CDF and D0 Collaborations

Introduction: Why and How?

The violation of CP symmetry is one of the three Sakharov conditions required to explain the observed matter/antimatter asymmetry in our universe;

The standard model contains CP violation, but it is insufficient by many orders of magnitude to fulfill observed asymmetry;

Measuring CPV at the particle level is therefore a promising topic for new physics.

At the Tevatron, we measure CPV in three complementary ways:

- **Direct CP Violation (A_{CP}):** $\Gamma(B\to f) \neq \Gamma(\bar{B}\to\bar{f})$

  e.g. Asymmetry in $B^+ \to J/\psi\ K^+\ (\pi^+)$ decays

PRL 100, 211802 (2008) – D0
PRL 97, 211802 (2006) - CDF

- **CPV in B Mixing ($A^{(s)}_{SL}$):** $\Gamma(\bar{B}\to f) \neq \Gamma(B\to\bar{f})$

  e.g. $B_s \to \mu^+ D_s^- X$

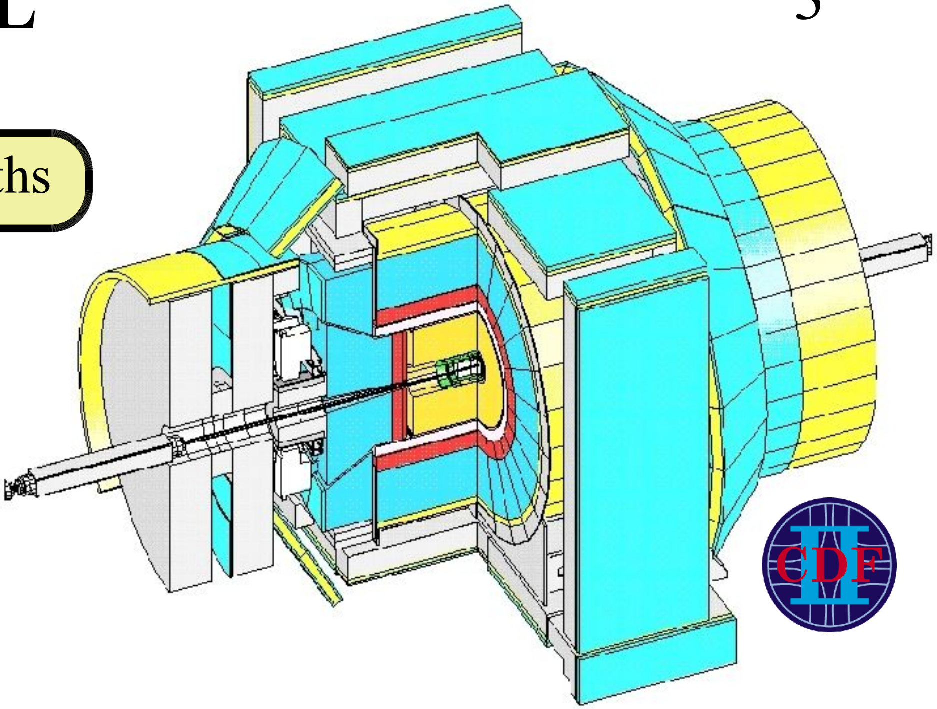
arXiv.org:0904.3907 – D0
CDF Public Note 9015

- **CPV in interference between mixing and decay diagrams**

  e.g. $B_s \to J/\psi\ \varphi$

PRL 100, 161802 (2008) - CDF
PRL 101, 241801 (2008) – D0

The Tevatron Detectors @ FNAL

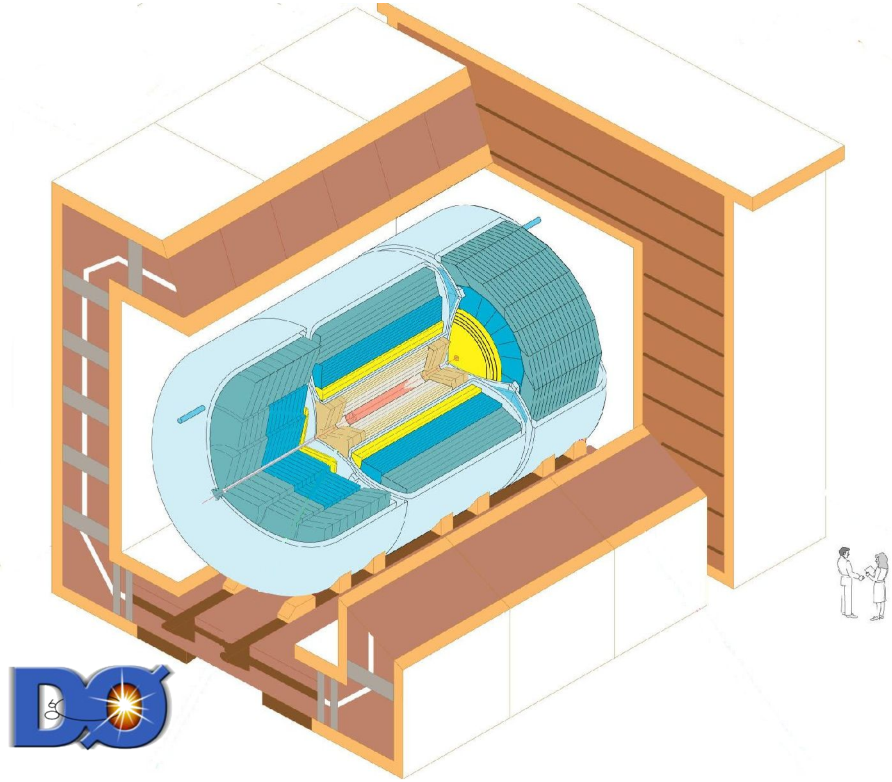


Complementary detectors, with different strengths

CDF:

- Large tracking volume – *excellent momentum resolution*;
- Displaced SV trigger collects valuable samples of *hadronic B meson decays*.

e.g. $B^0_s \to \varphi\varphi$; $B^0_{(s)} \to \pi^+\pi^-(K^+K^-)$



D0:

- Excellent *muon system*: wide acceptance and thick shielding;
- Periodic reversal of magnets allows *detector asymmetries to be measured and minimised*

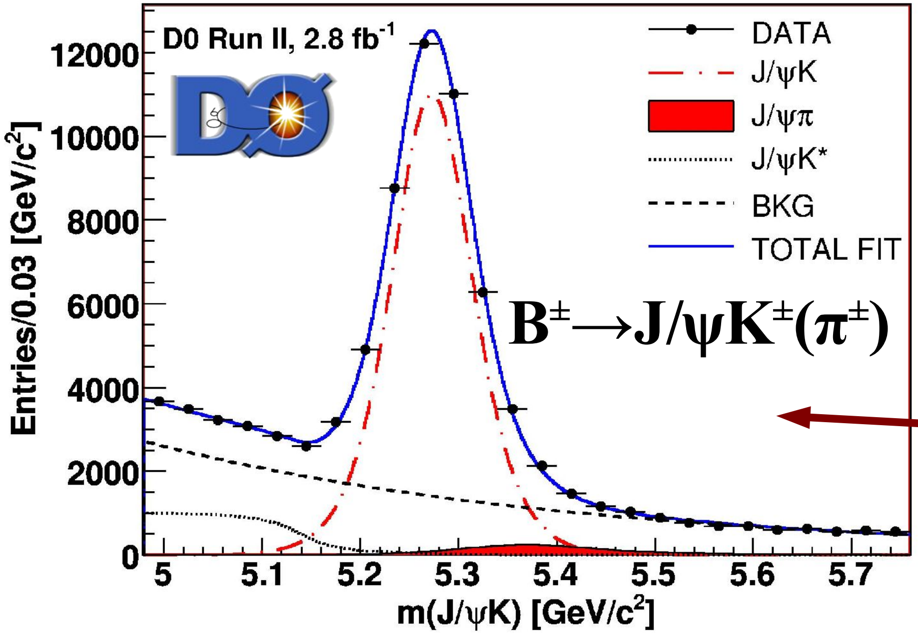
e.g. $B^+ \to J/\psi K^+$; $B^0_s \to \mu D_s^- X$

Tevatron performing better than ever, well-understood detectors, and experienced analysers.

Direct CP Violation

$$A_{CP}(B^{\pm}\to F^{\pm}) = \frac{N(B^{-}\to F^{-}) - N(B^{+}\to F^{+})}{N(B^{-}\to F^{-}) + N(B^{+}\to F^{+})}$$

PRL 100, 211802 (2008) – D0



$B^{\pm}\to J/\psi K^{\pm}(\pi^{\pm})$

Divide data into 8 samples by:

Solenoid polarity β **$\eta(J/\psi K^{\pm})$** **$q(K^{\pm})$**

Fit to extract $N_{\beta\eta q}(J/\psi K^{\pm})$ and $N_{\beta\eta q}(J/\psi\pi^{\pm})$

Solve **8 simultaneous eq^{ns}** to disentangle physics asymmetry and detector effects

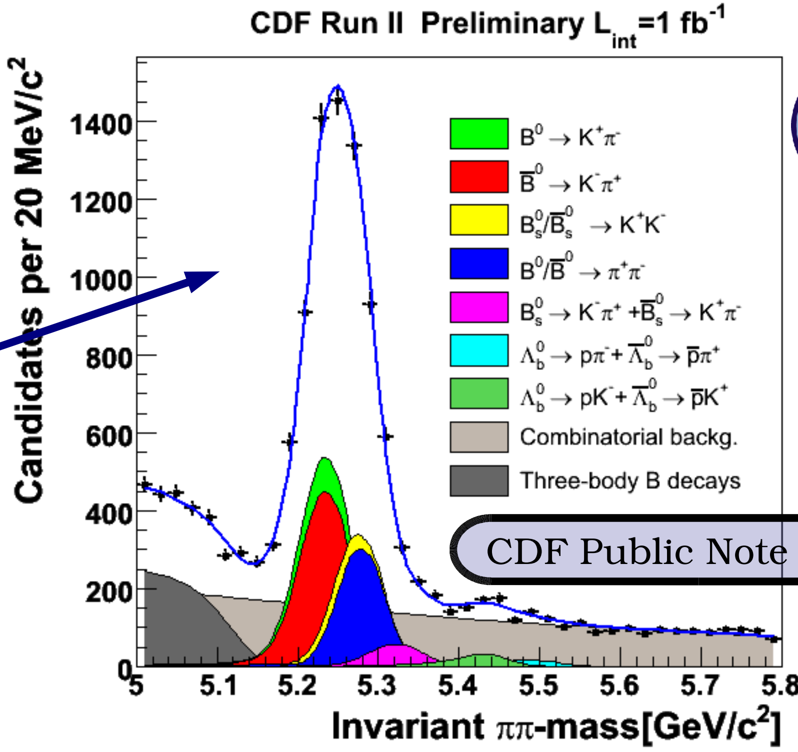
$$\mathbf{A_{CP}(J/\psi K^{\pm}) = 0.0075 \pm 0.0061 \pm 0.0027}$$
$$\mathbf{A_{CP}(J/\psi \pi^{\pm}) = -0.09 \pm 0.08 \pm 0.03}$$

Another direct CPV analysis: $\mathbf{B^0_{(s)} \to h^+h'^-}$ with h = K or π:

$$\mathbf{A_{CP}(B_s^0\to K^-\pi^+) = 0.39 \pm 0.15 \pm 0.08;}$$
$$\mathbf{A_{CP}(B^0\to K^+\pi^-) = -0.086 \pm 0.023 \pm 0.009;}$$

V_{ub} determined via $\mathbf{B^0\to\pi^+\pi^-}$ and $\mathbf{B_s^0\to K^-K^+}$ observables;

CDF now working on a new, improved analysis...



CDF Public Note 8579

CPV in B_s Mixing

Oscillations arise from box diagrams, which introduce off-diagonal elements into the time evolution equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B_s^0}(t)\rangle\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B_s^0}(t)\rangle\end{pmatrix}$$

- Mass eigenstates: $|\mathbf{B}_{sH}\rangle = \mathbf{p}|\mathbf{B}_s\rangle - \mathbf{q}|\overline{\mathbf{B}}_s\rangle$

  $|\mathbf{B}_{sL}\rangle = \mathbf{p}|\mathbf{B}_s\rangle + \mathbf{q}|\overline{\mathbf{B}}_s\rangle$

If CP symmetry is violated:

$p \neq q$; $\varphi_{12} \neq 0$

Mass states are not pure CP states

- Experimental quantities:

$\Delta M_s = M_H - M_L \approx 2|M_{12}|$; *($17.77 \pm 0.12\ ps^{-1}$)*

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\varphi_{12}$;

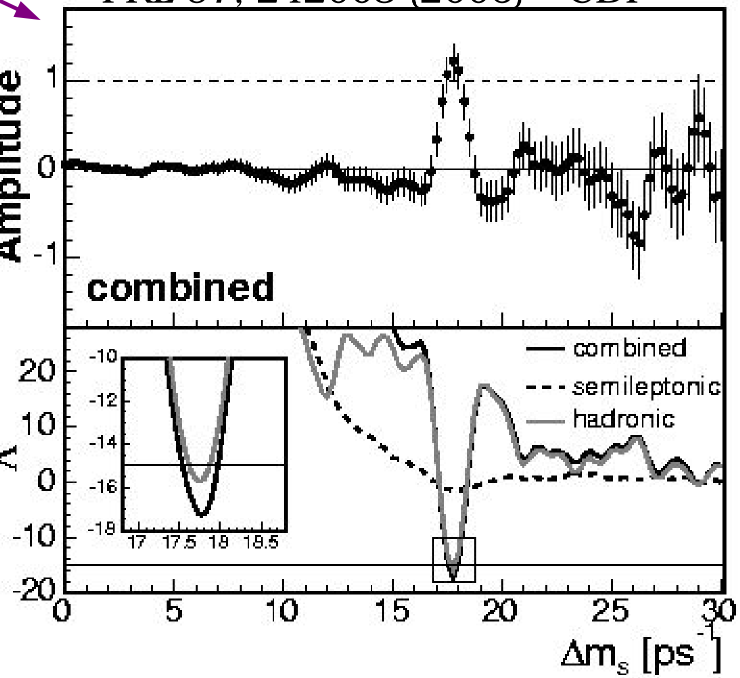
$a^S_{SL} = \Delta\Gamma_s/\Delta m_s\ \tan\varphi_{12}$ *($2x10^{-5}$ in SM)*

where $\varphi_{12} = \arg[-M_{12}/\Gamma_{12}]$ *(0.004 in SM)*

$a^{(s)}_{SL}$ measured from time-dependent or time-integrated asymmetry studies.

First step: Observe mixing!

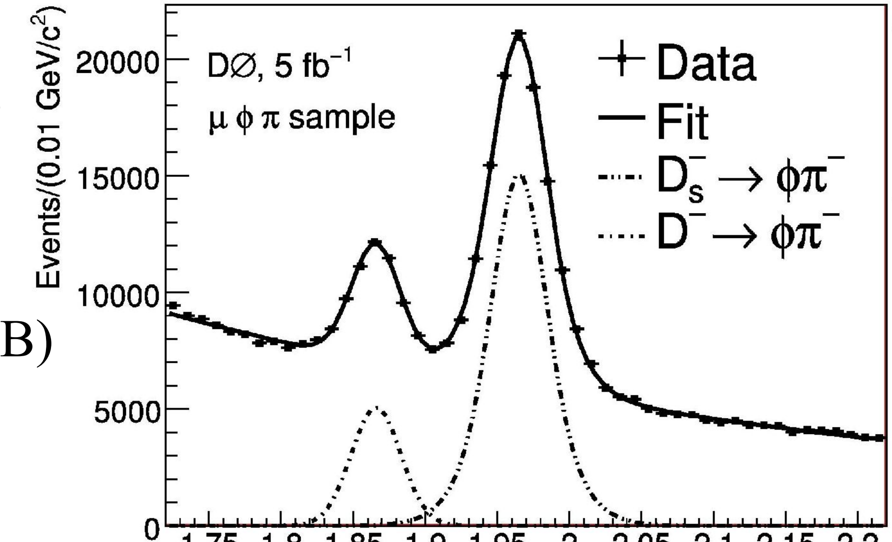
PRL 97, 242003 (2006) – CDF



a^s_{sl} from Time-Dependent Analysis $B^0_s \to \mu^+ \nu D^-_s X$

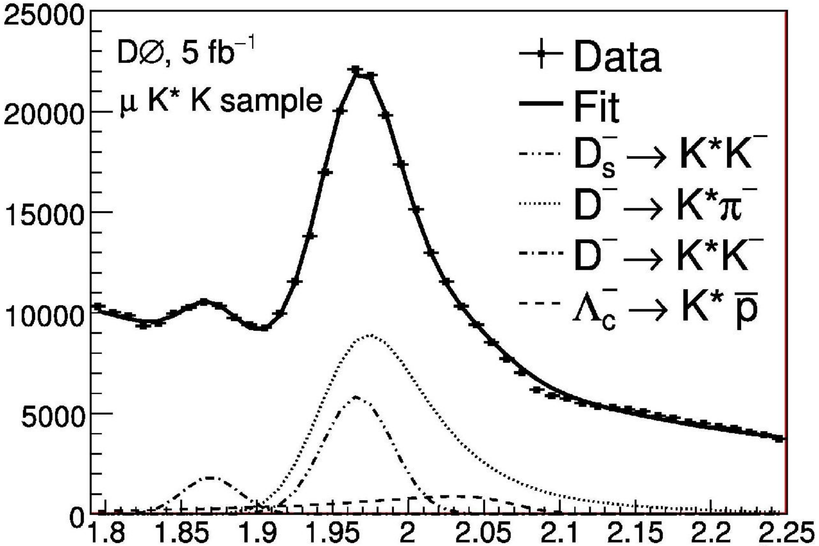
Reconstruct two final states;
Use likelihood ratio method to optimise $S/\sqrt{(S+B)}$

$\mu^+\varphi(K^+K^-)\pi^-$



$N(D^-_s) = 81{,}394 \pm 865$

$\mu^+K^{*0}(K^+\pi^-)K^-$



$N(D^-_s) = 33{,}557 \pm 1200$

Assuming no direct CPV (i.e. decay amplitudes $|A_f| = |\bar{A}_{\bar{f}}|$):

$$\Gamma(B^0_s \to \mu^- X) = N_f \cdot |A_f|^2 \cdot (1 - a^s_{sl}) \cdot e^{-\Gamma_s t} \cdot \tfrac{1}{2}[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)] \quad \textit{Mixed decay}$$

$$\Gamma(B^0_s \to \mu^+ X) = N_f \cdot |A_f|^2 \cdot (\ \ 1\ \ ) \cdot e^{-\Gamma_s t} \cdot \tfrac{1}{2}[\cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)] \quad \textit{Direct decay}$$

⇒ a^s_{sl} can be determined by **fitting time-dependent (lifetime) asymmetry.**

[Mixing factor is $(1 + a^s_{sl})$ for Conjugate decay.]

a^s_{sl} from Time-Dependent Analysis

- B^0_s and $\bar{B}^0_s$ cases need to be distinguished to improve precision – **use opposite-side 'flavor tagging'**;
- Proper decay length is mis-measured due to missing neutrino momentum – **apply 'K-factors'** derived from MC;
- Backgrounds need to be well-modeled – use mass fits and MC to **extract composition**;
- Detector asymmetries need to be accounted for – fold into the fit, using **regularly reversed toroid polarity** as a handle.
- Efficiencies, resolutions...

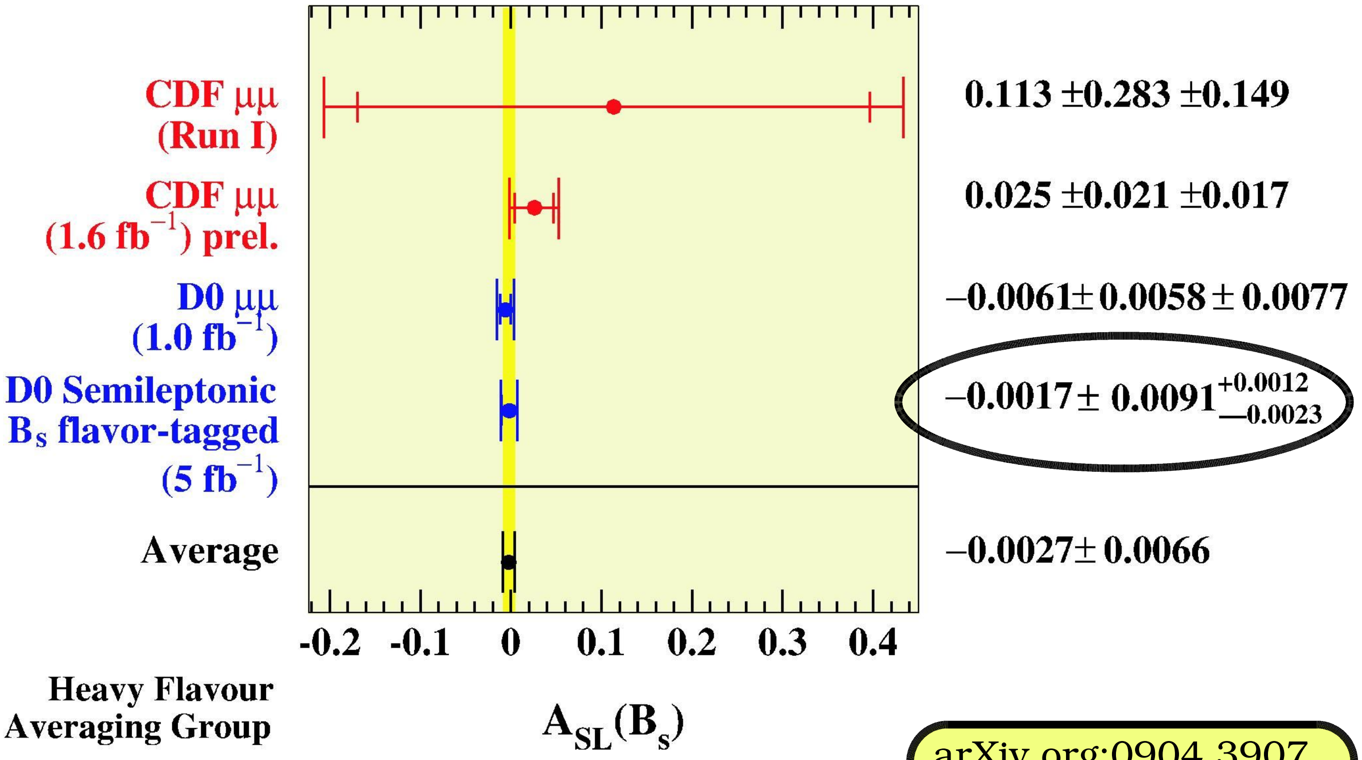
$a^S_{SL} = \Delta\Gamma_s/\Delta m_s \ \tan\varphi_{12}$

SM Expectation:

$= (0.0206 \pm 0.0057) \text{ x } 10^{-3}$

from **W.A.** $\Delta\Gamma_s$, Δm_s, φ_{12}:

$= (-8.4^{+5.2}_{-6.7}) \text{ x } 10^{-3}$



arXiv.org:0904.3907
Submitted to PRL

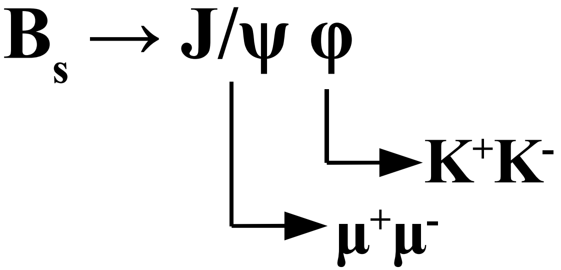
CPV in Interference Between Mixing and Decays

In $\overset{(-)}{B}_s$ decays to a common final state (e.g. J/ψ φ), there is a relative phase between the B_s mixing amplitude, and subsequent decay amplitudes:

$$\boldsymbol{\varphi_s = -2\beta_s = 2\cdot\arg[-V_{tb}V^*_{ts}/V_{cb}V^*_{cs}]}$$ *(-0.04 in the SM)*

New physics can significantly change this phase: $\boldsymbol{\varphi_s = \varphi_s^{SM} + \varphi_s^{NP}}$

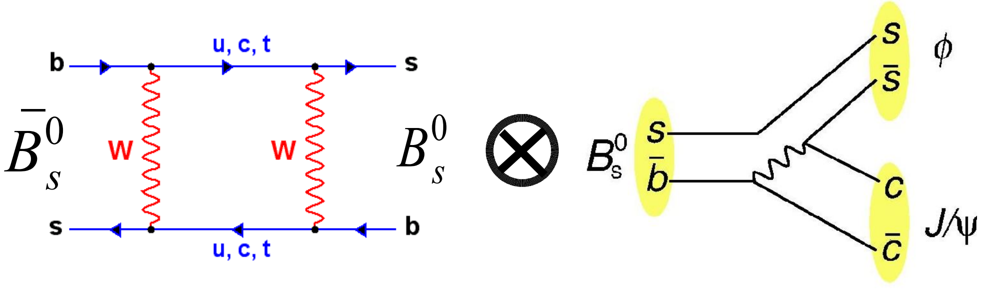
"The Golden Channel" P → VV decay



J/ψ φ is a superposition of CP-even and CP-odd states. Angular analysis required to separate CP components;

Three distinct polarisations: *longitudinal*, mutually *parallel*, and mutually *perpendicular*: complex amplitudes $\mathbf{A_0(t), A_\parallel(t), A_\perp(t)}$;

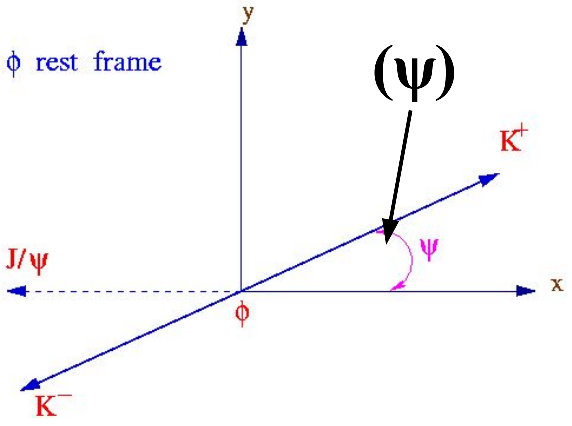
Perform likelihood fit over *time-dependent angular distribution*, to extract the CPV parameter φ_s, mean lifetime $\bar{\tau}_s$, width difference $\Delta\Gamma_s$, and $A_0(0)$, $A_\parallel(0)$, $A_\perp(0)$.

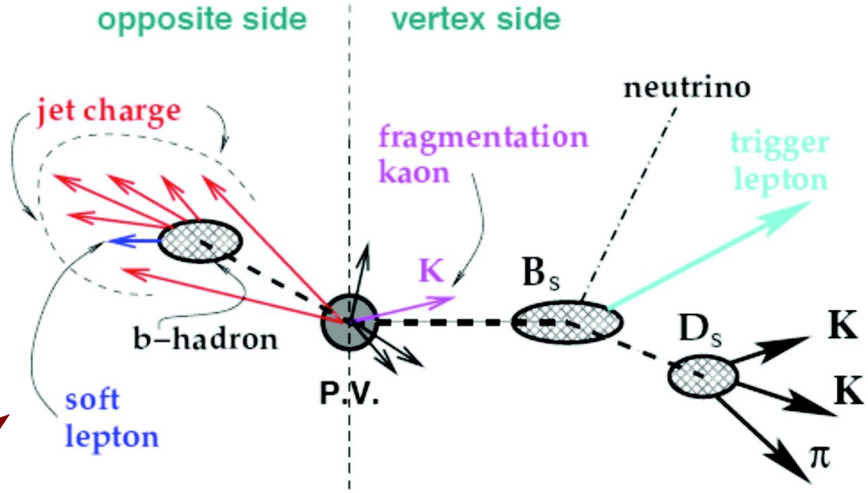


The Golden Channel: $B_s \to J/\psi\ \varphi$ (1)

$$\begin{aligned}\frac{d^4\Gamma[Bs\to J/\psi(\mu\mu)\varphi(K^+K^-)]}{d\cos\theta\ d\varphi\ d\cos\psi\ dt} = {} & f_1(\theta,\varphi,\psi)|\mathbf{A_0(t)}| + f_2(\theta,\varphi,\psi)|\mathbf{A_\parallel(t)}| + f_3(\theta,\varphi,\psi)|\mathbf{A_\perp(t)}| \\ & + f_4(\theta,\varphi,\psi)\mathcal{R}[\mathbf{A_0^*(t)A_\parallel(t)}] + f_5(\theta,\varphi,\psi)\mathcal{I}[\mathbf{A_0^*(t)A_\perp(t)}] \\ & + f_6(\theta,\varphi,\psi)\mathcal{I}[\mathbf{A_\parallel^*(t)A_\perp(t)}]\end{aligned}$$

where (θ,φ,ψ) are characteristic decay angles, e.g.:





Complex amplitudes $\mathbf{A_{0,\parallel,\perp}(t)}$ depend on:

- Parameters: ΔM_s, $\Delta\Gamma$, $\bar{\tau}_s$, φ_s;
- Initial flavor of the $\overset{(-)}{B}_s$ meson;
- Boundary values at $t = 0$;
- Phases of complex amplitudes δ_1 and δ_2.

Flavor tagging

Tagging power:

CDF: $\varepsilon D^2 = 1.8\%$ (OST)

D0: $= 2.5\%$ (OST); 4.7% (total)

where efficiency $\varepsilon = N_{tag} / N_{tot}$

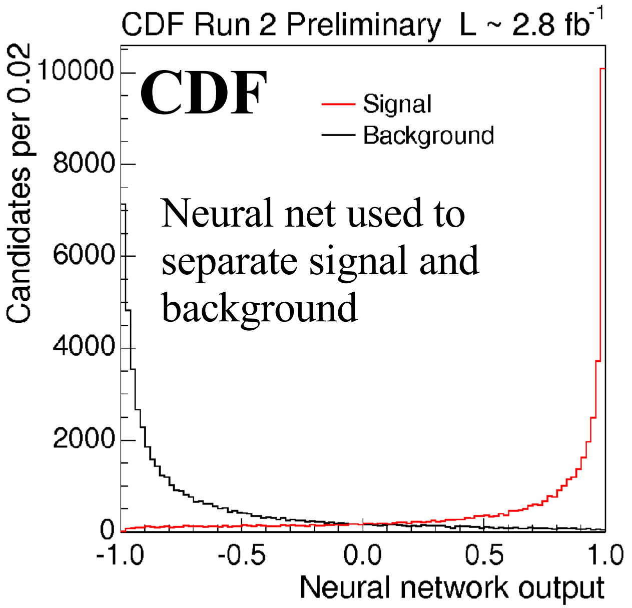
Dilution $D = (N_{right} - N_{wrong}) / N_{tag}$

The Golden Channel: $B_s \rightarrow J/\psi\ \varphi$ (2)

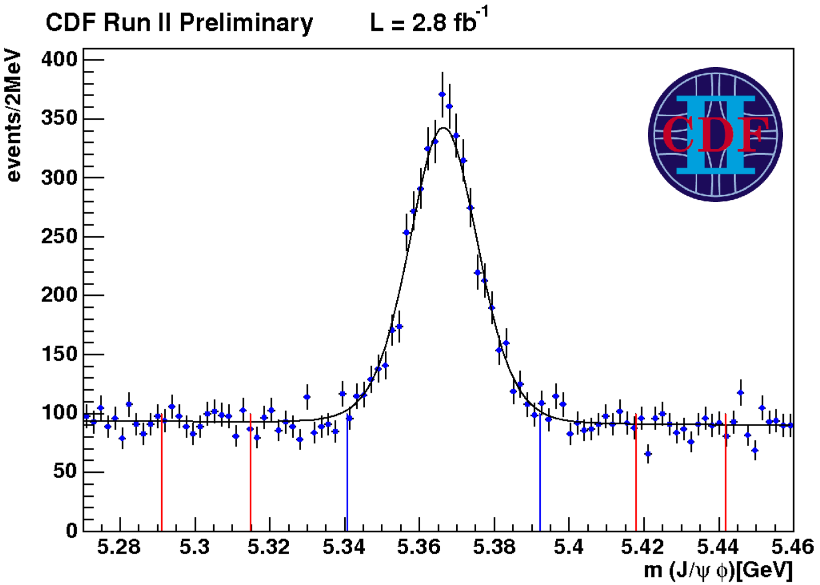
Stage 1: Select signal candidates:

D0: cut-based selection (~2K B_s events);

CDF: neural net (~3K B_s events).



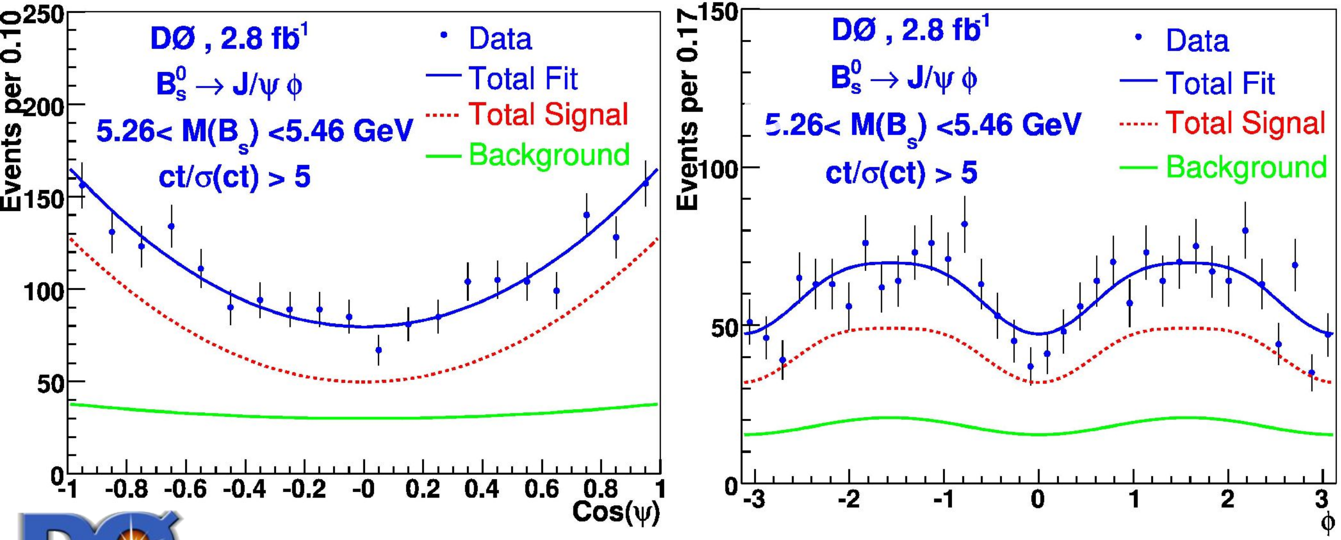
Neural net used to separate signal and background



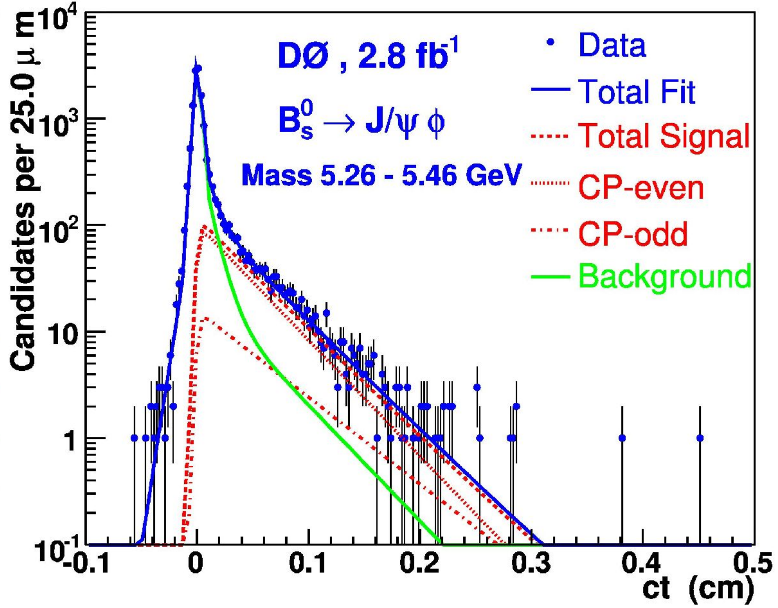
Stage 2: Tag initial Flavor:

Stage 3: Perform multi-dimensional fit: Use MC to simulate and model acceptances/efficiencies.

Angles

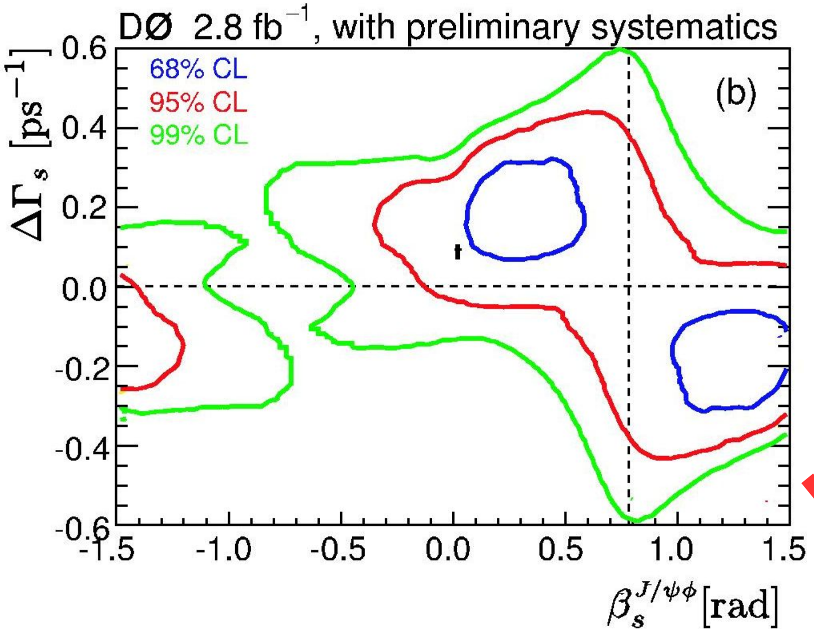


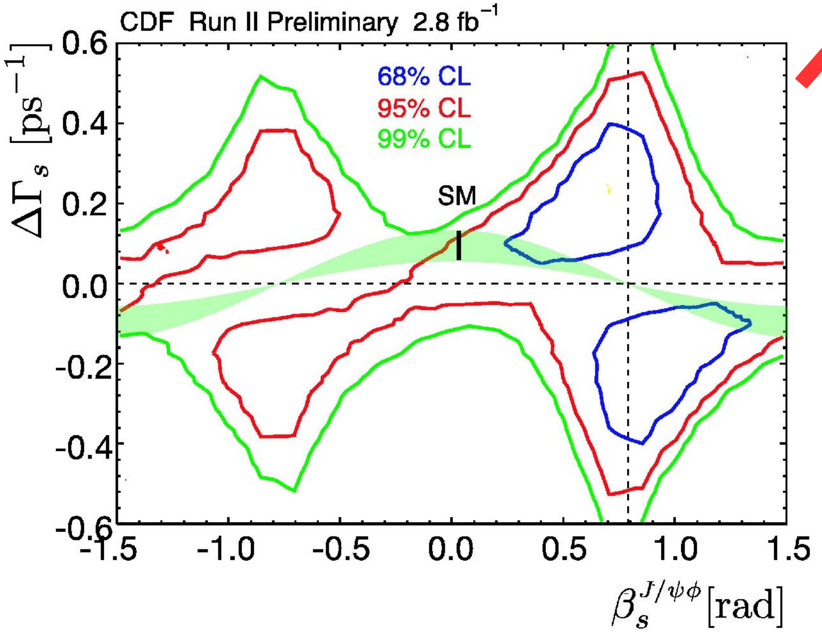
Lifetime



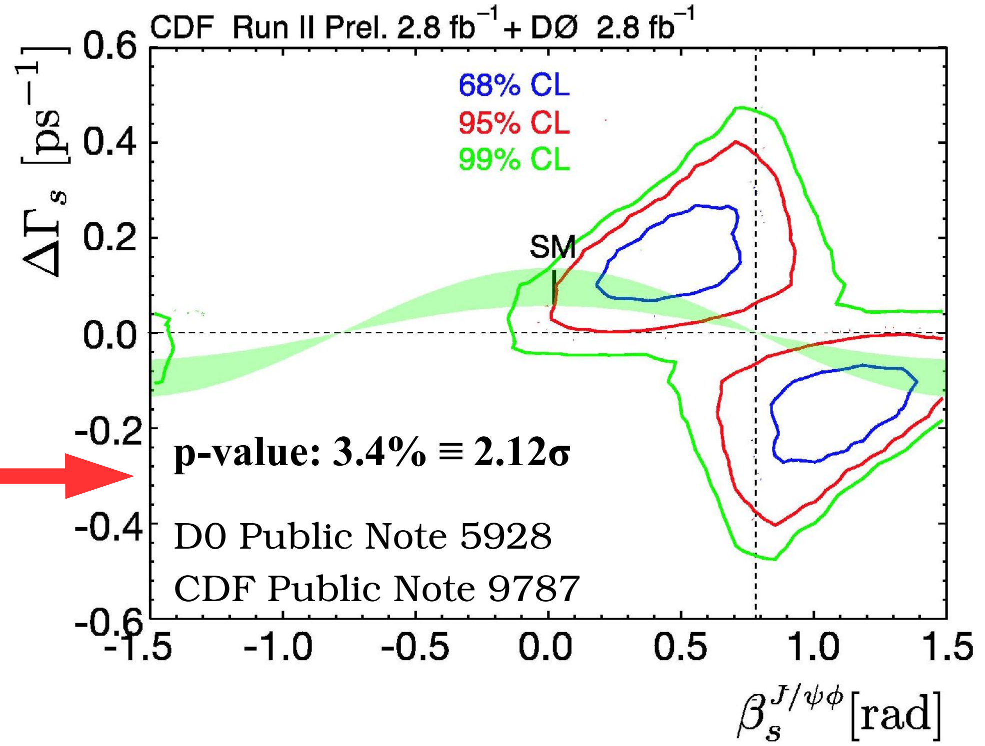
The Golden Channel: $B_s \to J/\psi\ \varphi$ (3)

Stage 4: Account for systematics, and non-Gaussian uncertainties (use pseudo-experiments).





Stage 5: Combine Results:



p-value: 3.4% ≡ 2.12σ

D0 Public Note 5928

CDF Public Note 9787

	D0	CDF	
$\Delta\Gamma_s$:	0.19 ± 0.07	0.02 ± 0.05	ps^{-1}
$\tau(B_s)$:	1.52 ± 0.06	1.53 ± 0.04	ps
φ_s:	$-0.57\,^{+0.25}_{-0.30}$	[-0.56, -2.58] (68%)	
ΔM_s:	Constrained to 17.77 ± 0.12 ps^{-1}		

A Bright Future

Both CDF and D0 are working (very) actively on updates to this legacy analysis.

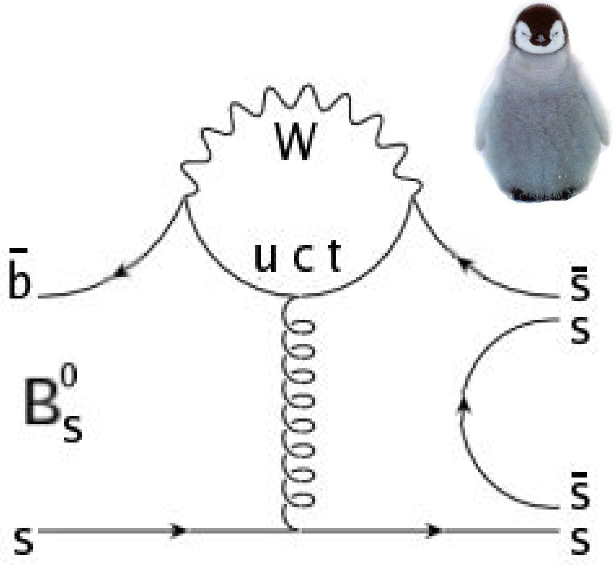
Future prospects are very exciting:

- Uncertainties are statistically dominated, and we already now have ~7fb^{-1} collected by each detector;
- Improvements in selection (NN, BDT) will improve S/√(S+B);
- New tagging algorithms are under investigation;

Tevatron Combination Group are working on a combined fit to CDF/D0 data sets in all dimensions (not just φ_s and $\Delta\Gamma_s$).

We can also study the charmless analogue: $B_s \rightarrow \varphi\varphi$

- An independent P→VV decay: can extract $\Delta\Gamma_s$, φ_s etc;
- Dominant SM process is the b→s penguin;
- Polarisation study is underway at CDF;
- Current result is the first stage – measure branching ratio relative to J/ψφ decay.



CDF Public Note 10064
February 2010

No Charm, but still Golden: $B_s \to \phi\phi$

$$\frac{\mathcal{B}(B_s \to \phi\phi)}{\mathcal{B}(B_s \to J/\psi\ \phi)} = \frac{N_{\phi\phi}}{N_{J/\psi\phi}} \bullet \frac{\mathcal{B}(J/\psi \to \mu\mu)}{\mathcal{B}(\phi \to K^+K^-)} \bullet \frac{\varepsilon_{J/\psi\phi}}{\varepsilon_{\phi\phi}} \bullet \varepsilon_\mu$$

This measurement

Taken from PDG World Average

At least one muon must be identified in muon detector: applies only to $J/\psi\phi$ channel, and derived from **data** as a function of p_T:

Mean $\varepsilon_\mu = 0.8695 \pm 0.0044$ *(stat.)*

Combined trigger/selection efficiencies, derived from **simulation**, after re-weighting MC to match data:

Ratio $= 0.939 \pm 0.030$ *(stat.)* ± 0.009 *(syst.)*

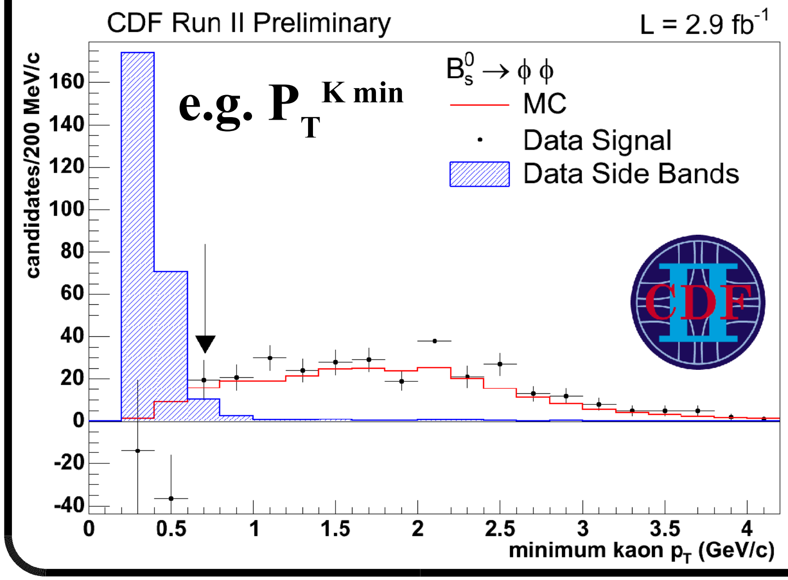
Square cuts optimized for S/√(S+B)

$B_s \longrightarrow \phi\phi$

Variable	cut
L_{xy}	$> 330\mu m$
$P_T^{K\ min}$	> 0.7 GeV/c
χ^2_{xy}	< 17
d0(B)	$< 65\mu m$
$d0^{\phi}_{max}$	$> 85\mu m$

$B_s \longrightarrow J/\psi\phi$

Variable	cut
L_{xy}	$> 290\mu m$
P_T^{ϕ}	> 1.36 GeV/c
χ^2_{xy}	< 18
d0(B)	$< 65\mu m$
$P_T^{J/\psi}$	> 2.0 GeV/c



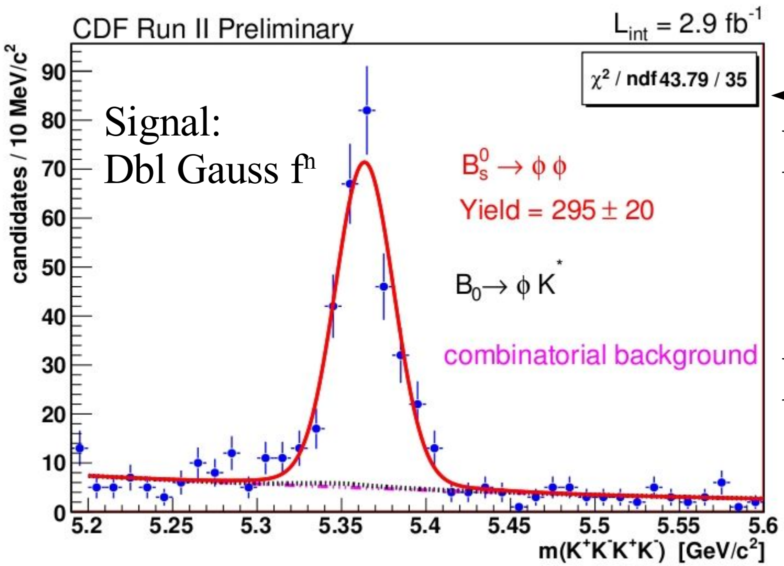
Displaced SV trigger used to select events, with only one muon requiring ID confirmation: *largely independent of J/ψ-triggered sample used in precision measurements.*

No Charm, but still Golden: $B_s \to \varphi\varphi$

Contribution of backgrounds from reflections are estimated from simulation:

$F[B^0 \to J/\psi\ K^{0*}(K^+\pi^-)]$ = (4.2 ± 0.9) %

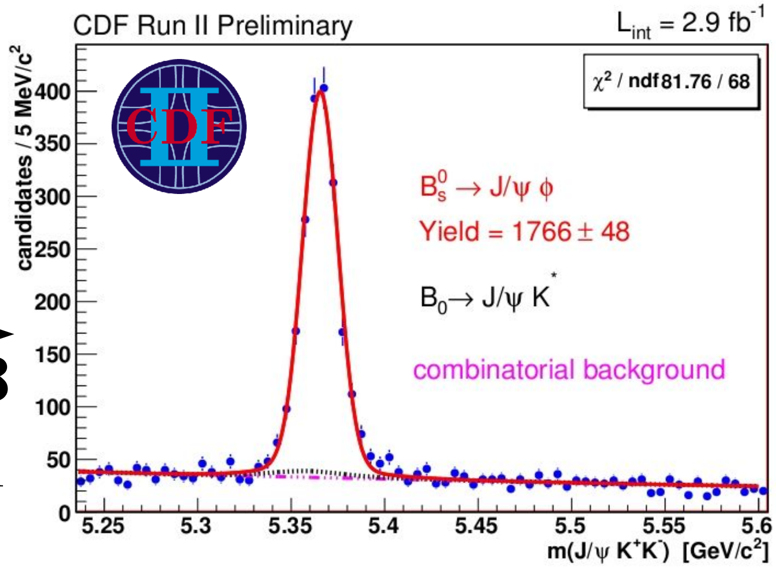
$F[B^0 \to \varphi\ K^{0*}(K^+\pi^-)]$ = (0.0134 ± 0.0002) %



Signal:
Dbl Gauss fn

$N_{\varphi\varphi} = 295 \pm 20$
± 12

$N_{J/\psi\varphi} = 1766 \pm 48$
± 41



$$\frac{\mathcal{B}(B_s \to \varphi\varphi)}{\mathcal{B}(B_s \to J/\psi\ \varphi)} = [1.78 \pm 0.14\ (stat.) \pm 0.20\ (syst.)]\cdot 10^{-2}$$

$$\mathcal{B}(B_s \to \varphi\varphi) = [2.40 \pm 0.21\ (stat.) \pm 0.27\ (syst.) \pm 0.82\ (BR)]\cdot 10^{-5}$$

Theory:
arXiv:hep-ph/0612290:

QCDF(1): $2.18^{+3.04}_{-1.70}$ 10^{-5}

QCDF(2): $1.95^{+1.31}_{-0.80}$ 10^{-5}

Summary and Outlook

- **CPV is generating excitement at the Tevatron:**
  - Early suggestions of disagreement with SM;
  - Multiple independent measurements, two independent detectors;
  - Data sample is increasing rapidly;
  - Data-driven techniques are also lowering systematics (e.g. kaon asymmetry measurement).
- **Many other studies have been/are being produced, e.g.**
  - $B_s \rightarrow D^{(*)}_s D^{(*)}_s$ – can measure $\Gamma_s^{CP\text{-even}} - \Gamma_s^{CP\text{-odd}}$
  - Same-sign dimuon asymmetry – another handle on $a^{(s)}_{sl}$.
- **Pointing the way for the LHC, and setting (tough) standards to beat!**

Thanks for Listening