$Sin(2\beta_s)$ at CDF:

Updated measurement of the CP violating phase in the B_s-$\overline{B}_s$ system

Louise Oakes, for the CDF collaboration
University of Oxford

FPCP2010

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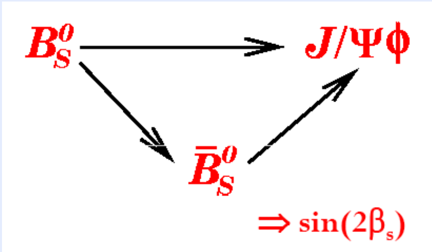
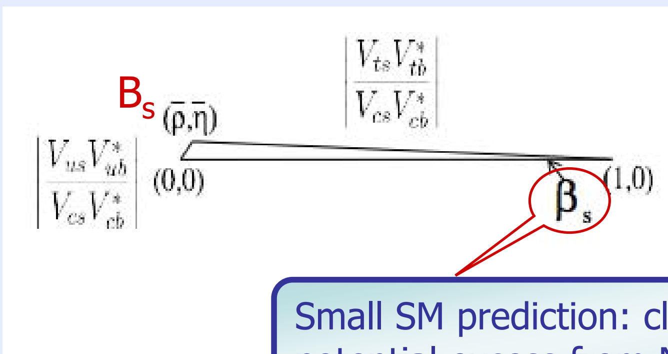
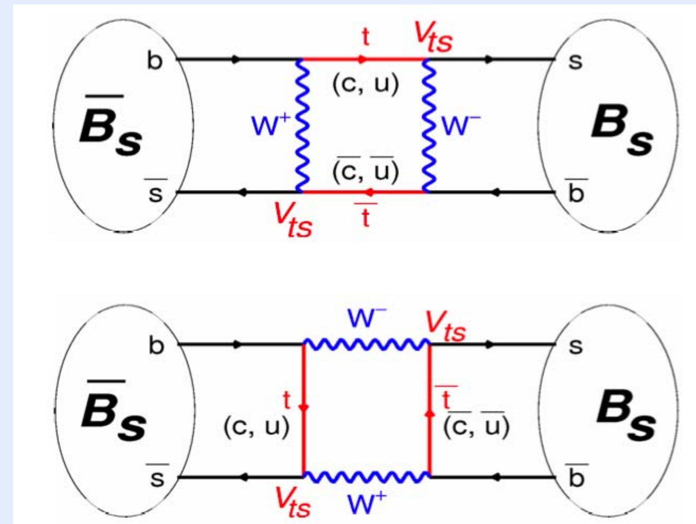
Search for New Physics in B_s mixing



CP violation in $B_s \rightarrow J/\psi\varphi$ occurs through interference of decays with and without mixing.



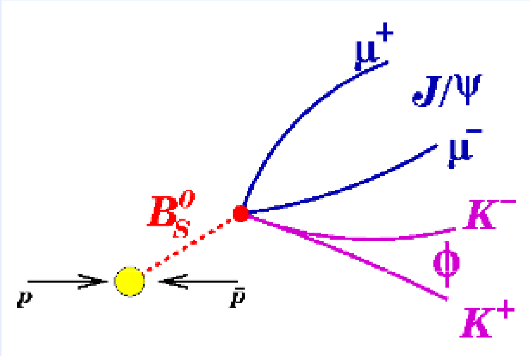
Small SM prediction: clear to see potential excess from NP



- New particles could enter weak mixing box diagrams and enhance CP violation
- Time evolution of flavour tagged $B_s \rightarrow J/\psi\varphi$ decays is very sensitive to New Physics
    - Decay width difference, $\Delta\Gamma$ and mixing phase would be effected by additional NP phase

Analysis overview

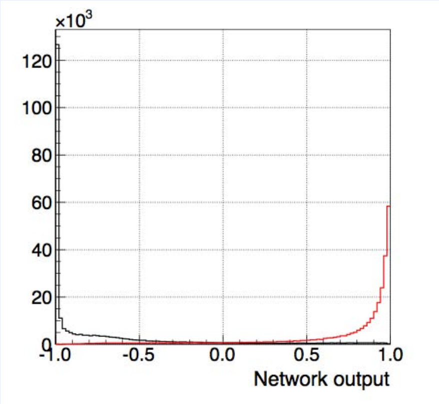
Reconstruct $B_s \to J/\psi(\to\mu^+\mu^-)\ \phi(\to K^+K^-)$



Di-muon trigger

↓

NN selection



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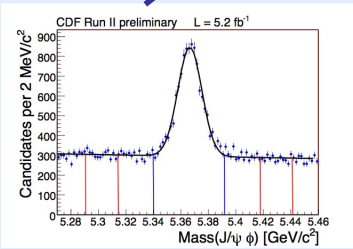
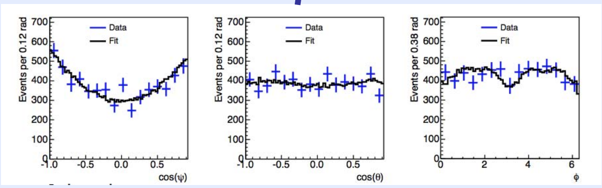
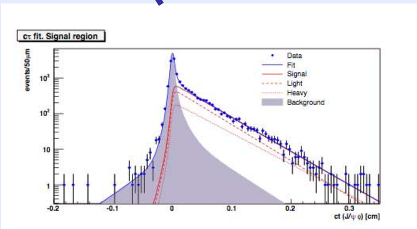
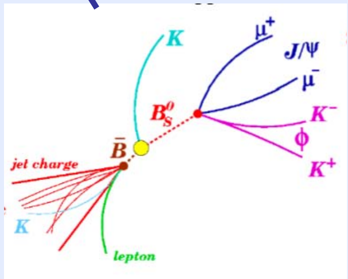
Simultaneous mass, angular, time dependent, flavour tagged fit

- B_s mass fit to separate signal from bkg
- Angular separation of CP eigenstates
- Time dependence of decay
- Flavour tagging to separate B_s and $\overline{B}_s$ decays

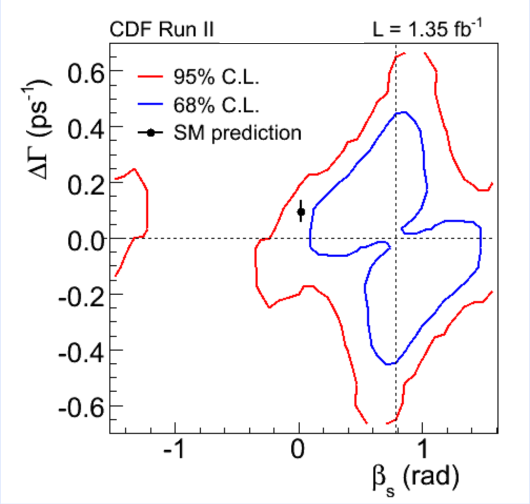




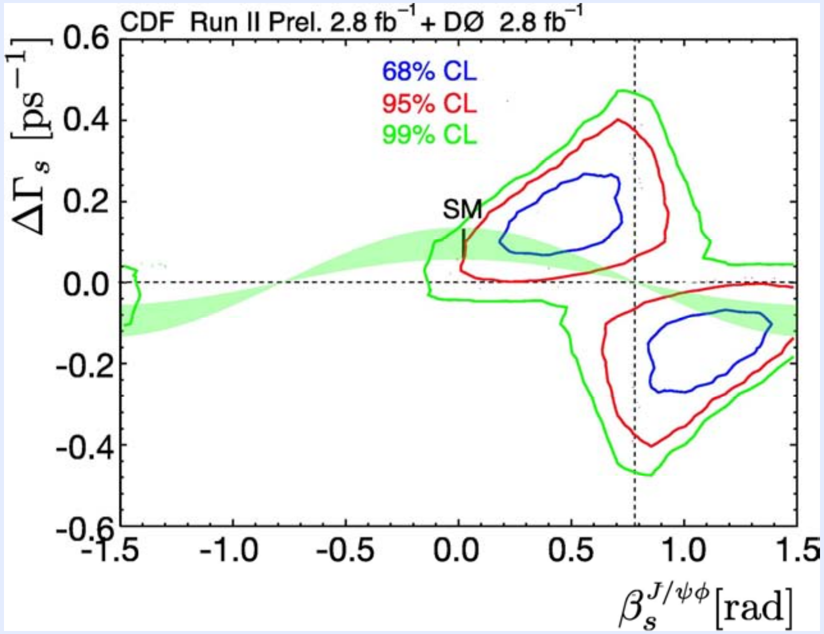




Recap of previous results

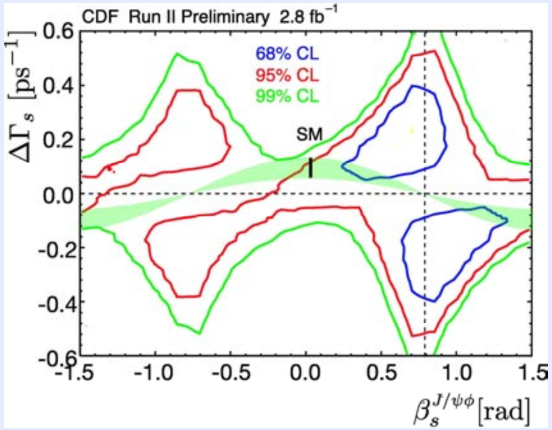


PRL 100, 161802 (2008)



CDF: 1.3fb^{-1} result
P-value for SM point =15% -> significance 1.5σ

CDF: 2.8fb^{-1} result
P-value for SM point =7% -> significance 1.8σ



Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

CDF Public Note 9787

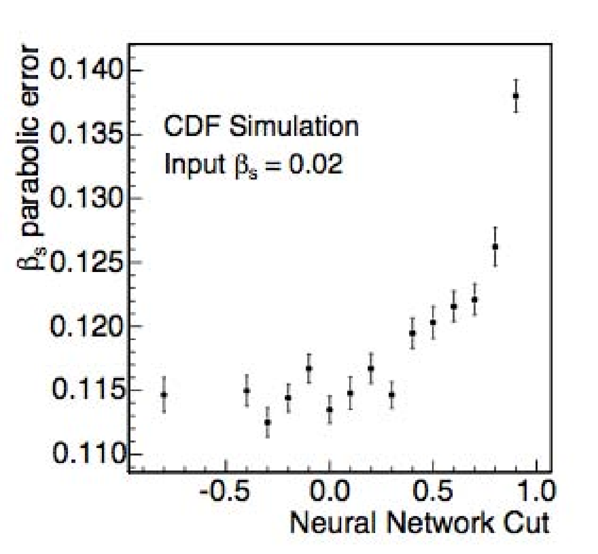
CDF Public Note 9458

New CDF $\sin(2\beta_s)$ results for FPCP 2010

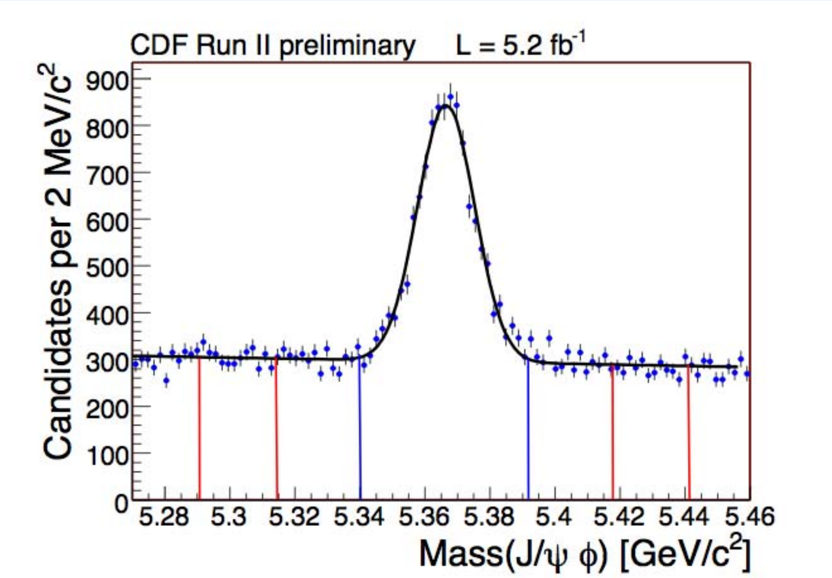
Data sample and selection for update

Statistically limited analysis - high quality selection is essential:

- Key role of particle ID
  - recalibrated for this result
- Neural network selection
  - optimised on pseudo experiments to minimise statistical errors on β_s
- Fully data-driven recalibration of B-tagging
  - SSKT updated for this measurement



- Integrated luminosity: $5.2 fb^{-1}$
- Signal events: ~6500
  (c.f. $2.8 fb^{-1}$ with ~3150 signal events)



Flavour tagging

- Flavour tagging - Opposite side tag (OST) and same side kaon tag (SSKT) - important component of the measurement

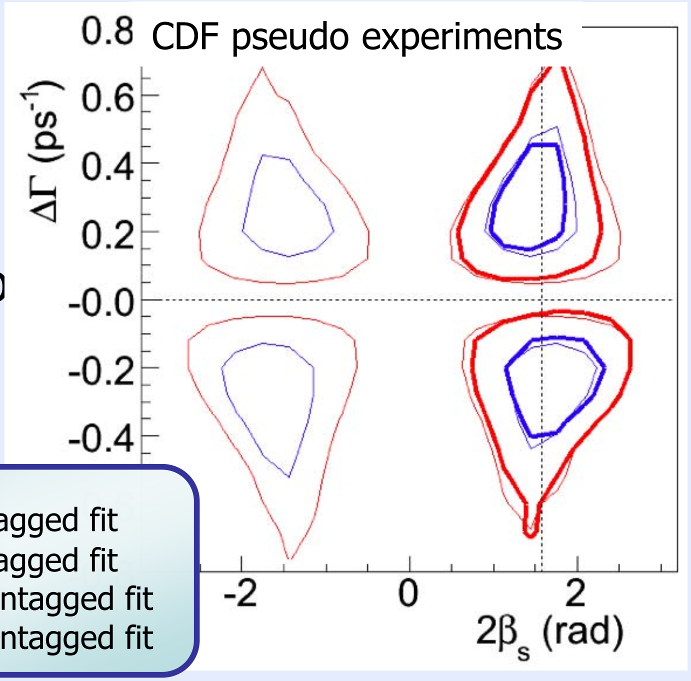
- Fit without flavour tagging, has four fold ambiguity:
  - β_s and $\Delta\Gamma$ symmetric
  - strong phases symmetric about pi

$$\begin{aligned} \beta_s &\rightarrow \frac{\pi}{2} - \beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \\ \phi_{\parallel} &\rightarrow 2\pi - \phi_{\parallel} \\ \phi_{\perp} &\rightarrow \pi - \phi_{\perp} \end{aligned}$$

and

$$\begin{aligned} \beta_s &\rightarrow -\beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \end{aligned}$$

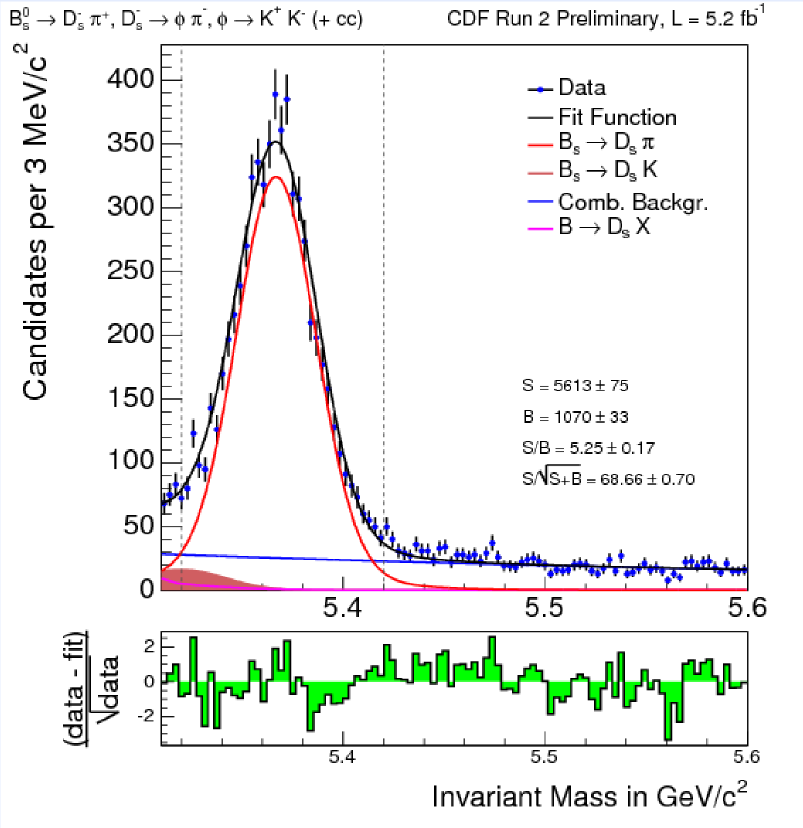
- Addition of flavour tagging allows us to follow time dependence of B_s and $\overline{B}_s$ separately
  -> Removes half of the ambiguity



B flavour tagging: SSKT calibration

- SSKT updated for this analysis
- calibrated on B_s mixing measurement
- B_s mixing measured with $5.2fb^{-1}$
- First CDF calibration of a SSKT on data
- Uses several decay modes:

$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to K^* K^-,\ K^* \to K^+ \pi^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to (3\pi)^-$$
$$B_s^0 \to D_s^- (3\pi)^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$

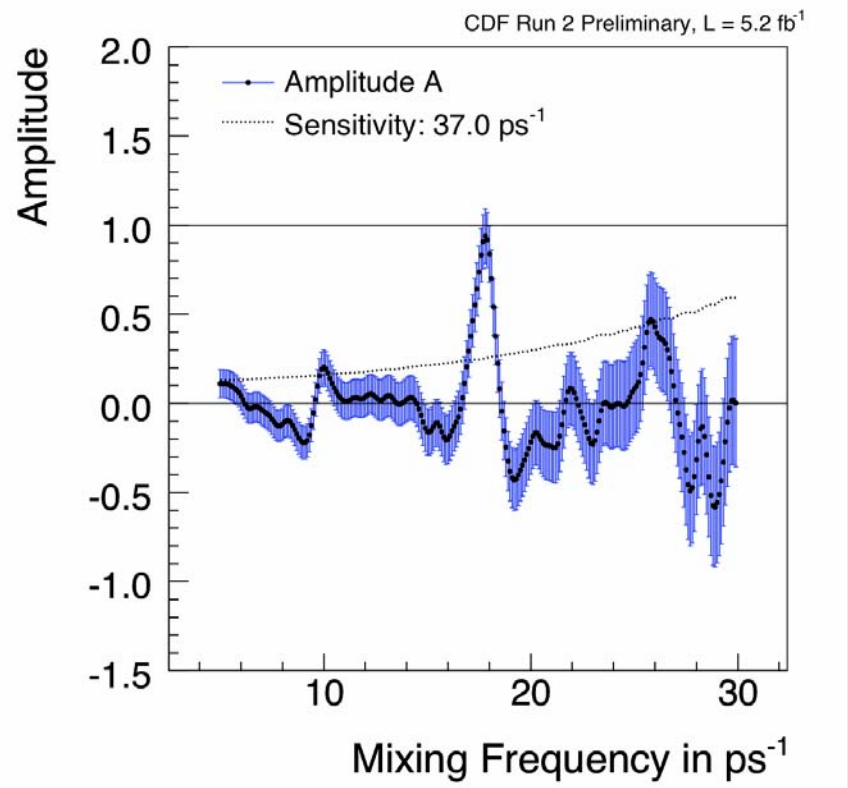


golden mode

http://www-cdf.fnal.gov/physics/new/bottom/100204.blessed-sskt-calibration/index.html

B flavour tagging: SSKT calibration

- Mixing amplitude ≈1 :
  - tagger assesses its performance accurately
- Amplitude > 1
  - tagger underestimates its power
- Amplitude < 1
  - tagger overestimates performance
- Measured amplitude used to scale event by event tagging dilution



$$\mathcal{A} = 0.94 \pm 0.15\ (\text{stat.}) \pm 0.13\ (\text{syst.})$$

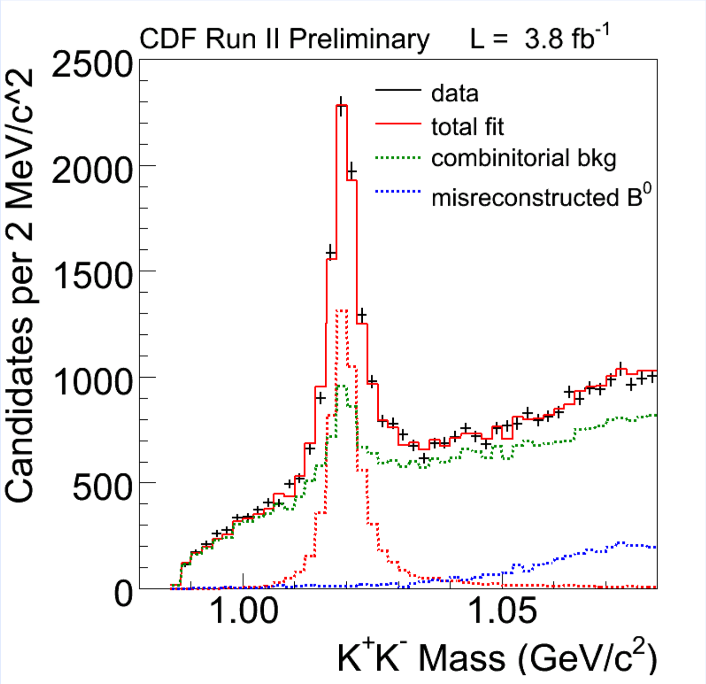
$$\Delta m_s = 17.79 \pm 0.07\ ps^{-1}\quad (\text{stat. only})$$

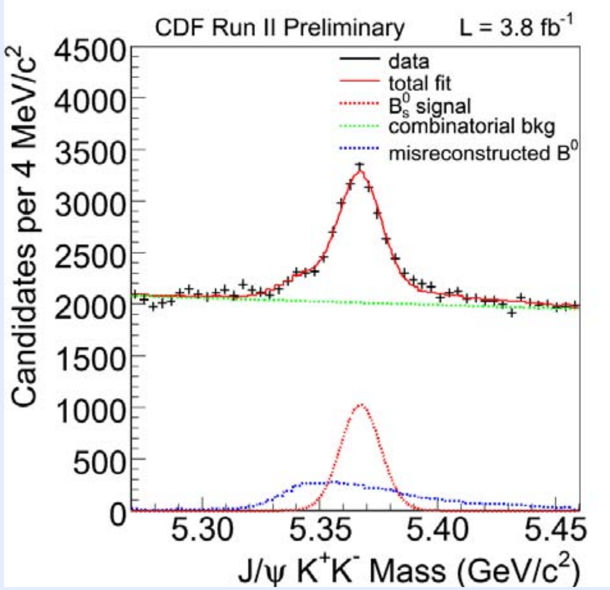
$$\epsilon \mathcal{A}^2 D^2 \approx 3.2 \pm\ 1.4\ \%$$

Agreement between this and the published CDF measurement is very good

S-wave contamination

- Potential contamination of $B_s \to J/\psi\varphi$ signal by: $B_s \to J/\psi$ KK (KK non-resonant) and $B_s \to J/\psi$ f^0 where KK and f^0 are S-wave states
- Predicted up to 15%
  contamination of total sample
  (~6% of signal)
  could bias towards SM value of β_s





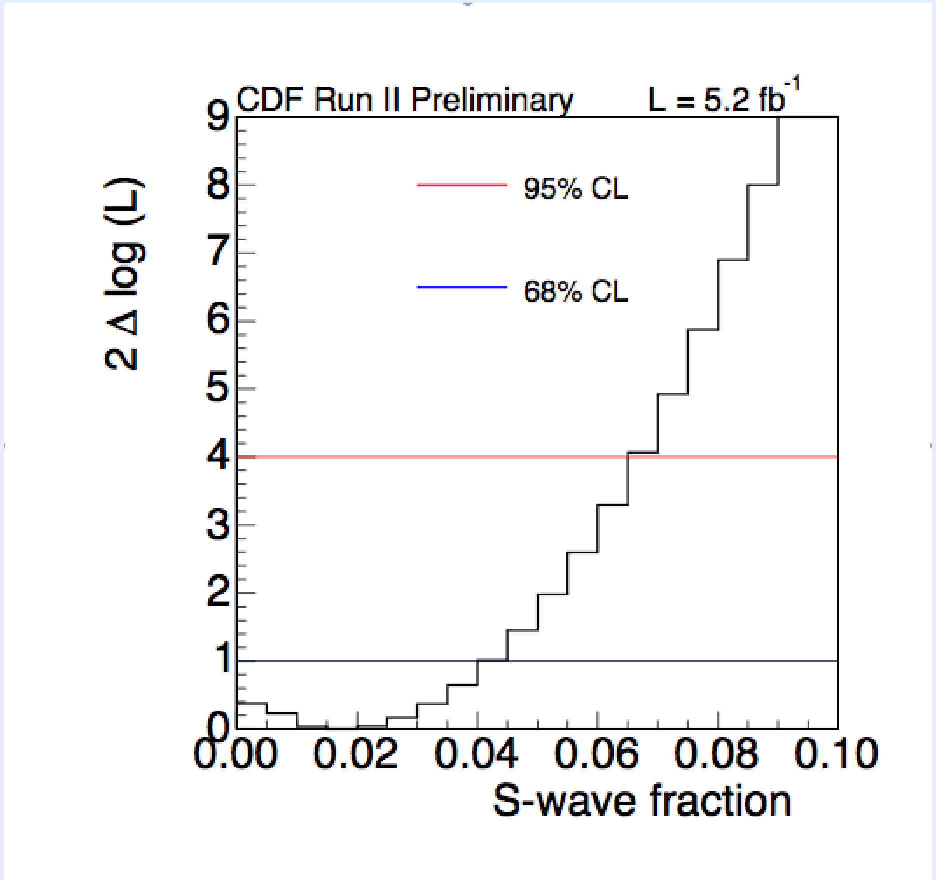
Invariant KK mass (above)

- combinatorial background from B_s sidebands
- B^0 reflections modelled from MC
- Fractions fixed from B_s mass fit (left)

Inclusion of S-wave KK component

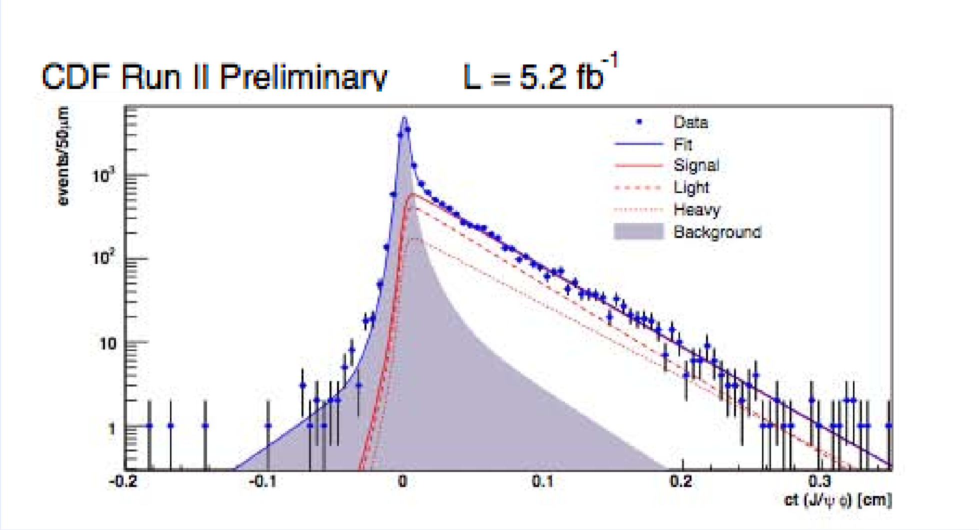
- S-wave KK component has been added to full angular, time-dependent likelihood fit.
- Both f^0 and non-resonant KK are considered flat in mass within the small selection window, φ meson mass is modelled by asymmetric, relativistic Breit Wigner.
- J/ψ KK (f^0) is pure CP odd state
- KK mass is NOT a fit parameter

The fitted fraction of KK S-wave contamination in the signal is
< 6.7% at the 95% CL



Checking the fitter: projections

Fit projections on physical parameters such as B_s lifetime used to check performance of the likelihood fit



B_s lifetime distribution consisting of:

- B_s^H (short lived) ....
- B_s^L (long lived) – – – – – –

Flavour tagged fit with β_s =0.0

- Tagged $B_s \rightarrow J/\psi\varphi$ likelihood fit
- CP violating phase, β_s = 0 , set to SM prediction

CDF II Preliminary 5.2fb $^{-1}$

$$\tau_s = 1.53 \pm 0.025 \text{ (stat.) } \pm 0.012 \text{ (syst.) ps}$$

$$\Delta\Gamma = 0.075 \pm 0.035 \text{ (stat.)} \pm 0.01 \text{ (syst.) } ps^{-1}$$

$$|A_{\|}(0)|^2 = 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst.)}$$

$$|A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst.)}$$

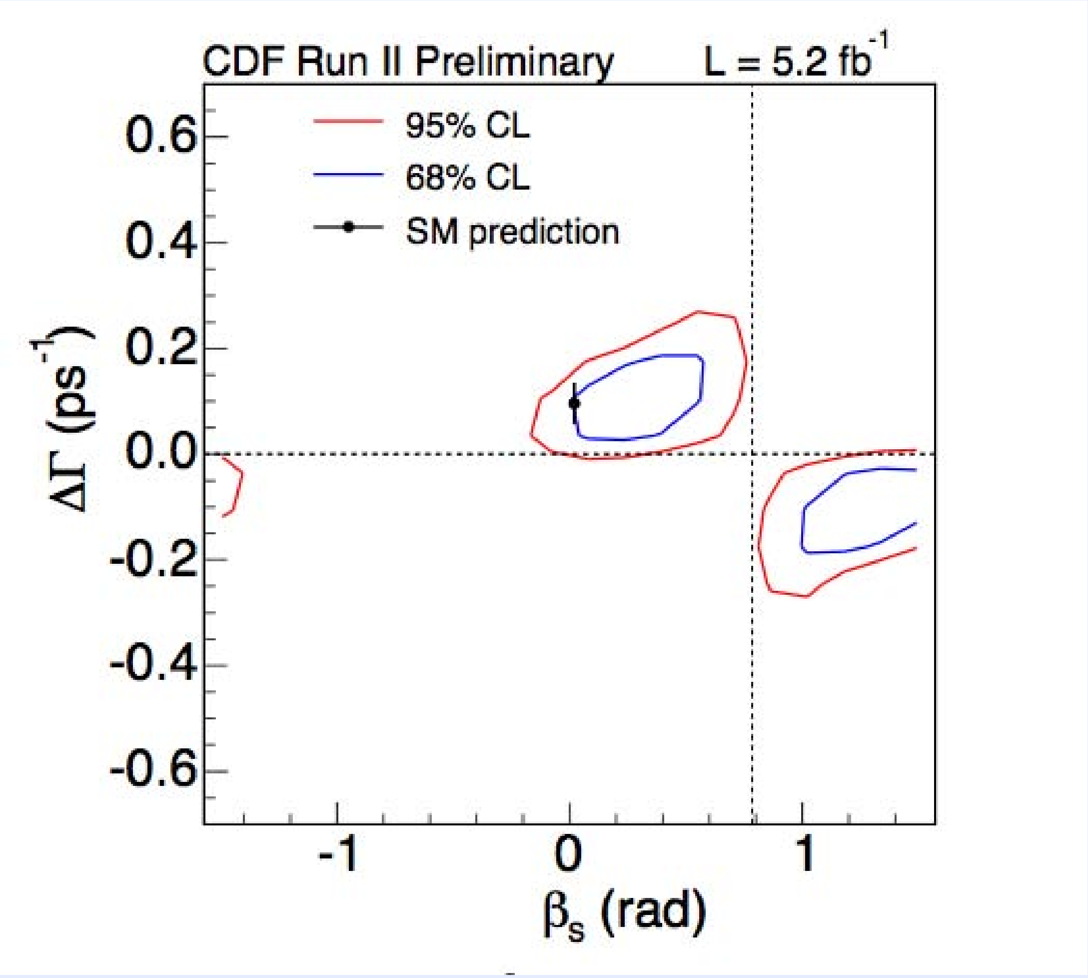
$$\phi_{\perp} = 2.95 \pm 0.64 \text{ (stat)} \pm 0.07 \text{ (syst.)}$$

PDG value:

$$\tau_s = 1.47^{+0.026}_{-0.027} \text{ ps}$$

World's most precise single measurement of B_s lifetime and decay width difference

New CDF measurement of β_s



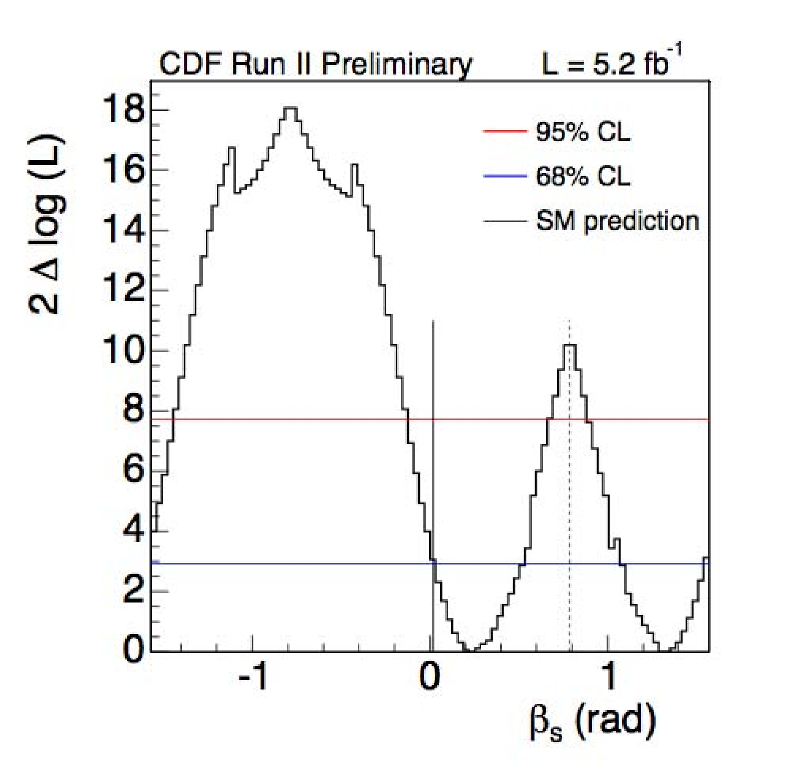
Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

P-value for SM point: 44%
(0.8σ deviation)

New CDF measurement of β_s

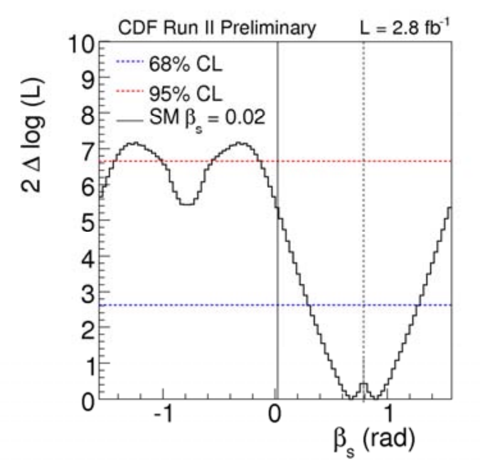
68% CL: [0.0, 0.5] U [1.1, 1.5]
95% CL: [-0.1, 0.7] U [0.9, pi/2]
U [-pi/2, -1.5]

1D likelihood profile for β_s

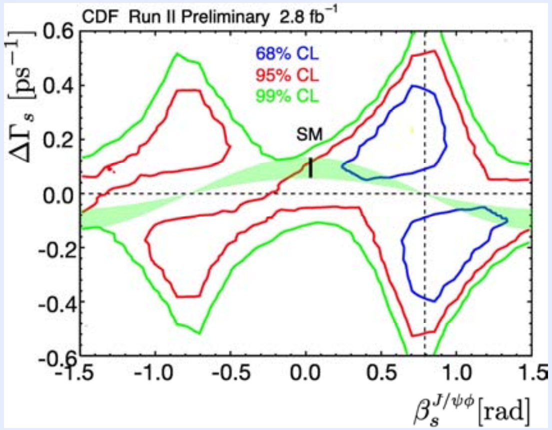


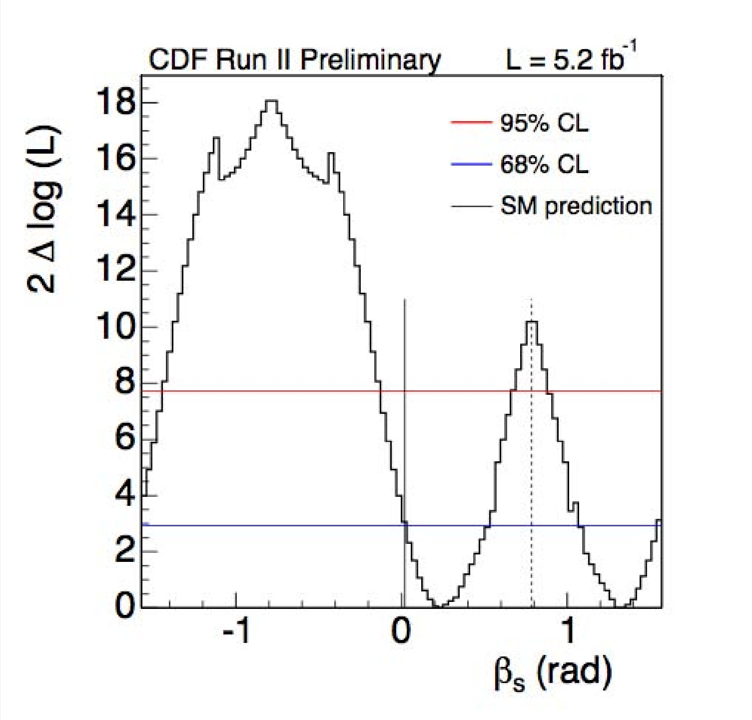
P-value for SM point: 31% (1.0σ deviation)

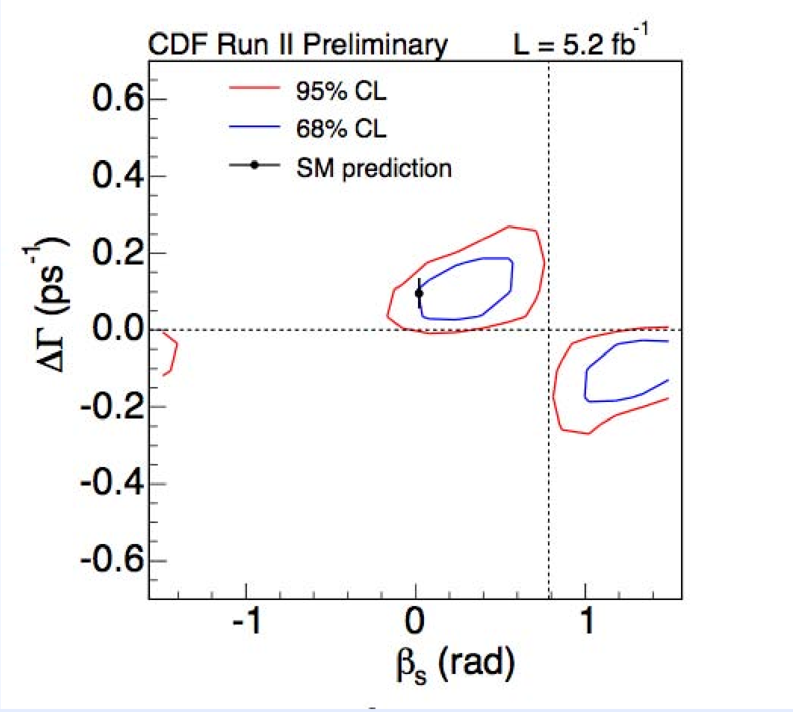
Comparisons



ICHEP 2008 results







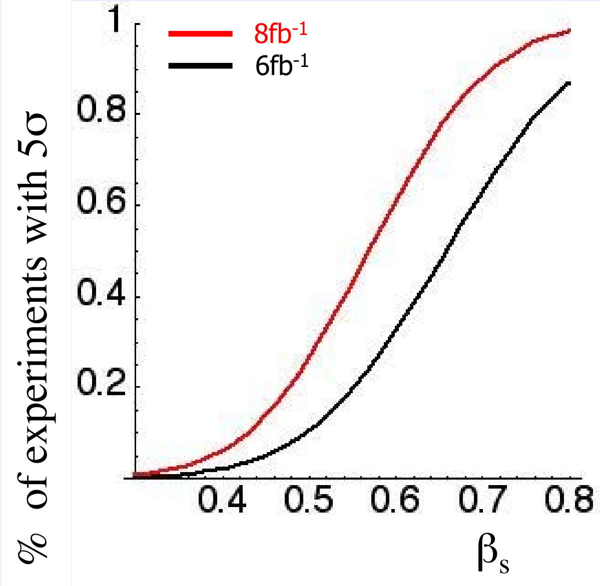
Summary

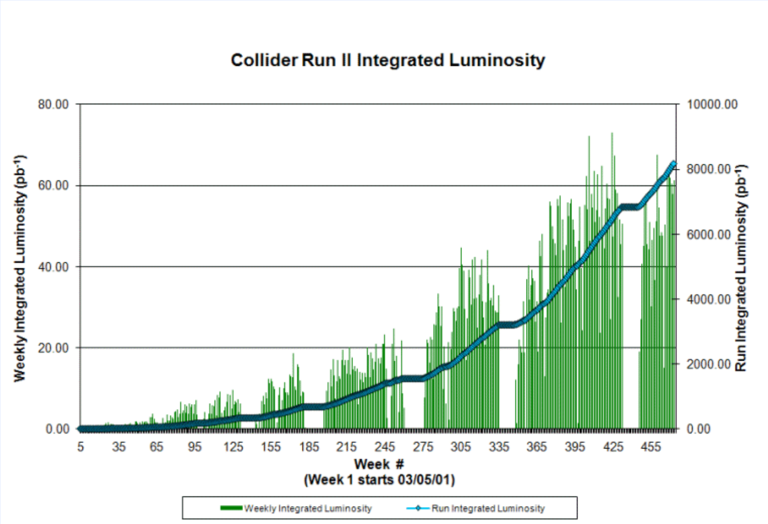
- First showing of updated CDF search for NP in $B_s \rightarrow J/\psi\varphi$
  - Tightened constraints on CP violating phase β_s

  [0.0, 0.5] U [1.1, 1.5] (68% CL)
  [-0.1, 0.7] U [0.9, pi/2] U [-pi/2, -1.5] (95% CL)
  - P-value for SM point: 44% (0.8σ)
  - World's best measurement of B_s lifetime and decay width difference in hypothesis of no CP violation
- Not only doubled the sample size - many improvements to analysis:
  - Included contribution from S-wave KK final state
    - measured contamination of <6.7% at 95% CL
  - More powerful NN selection
  - Fully calibrated B flavour tagging and PID

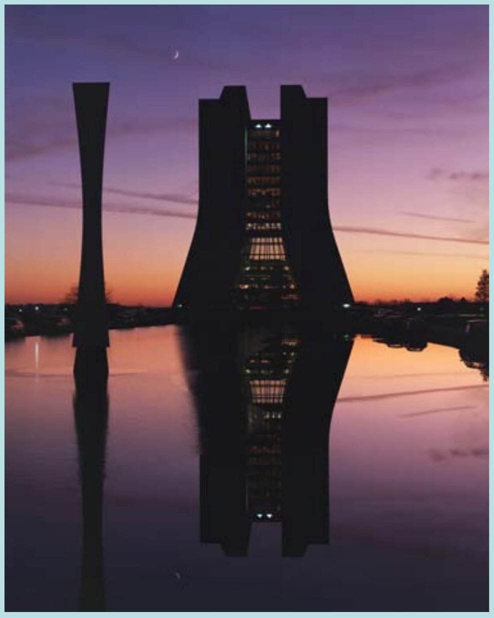
Future prospects

- Tevatron delivering record luminosity, CDF records ~60pb^{-1} per week
- By end of 2011 will have doubled again the dataset, and made further improvements to analysis
- Search for NP in B_s mixing at CDF has potential to observe/exclude wide range of non-SM mixing phase values





Back up



Inclusion of S-wave KK component

- S-wave KK component included in decay rate:

$$\rho_B(\theta,\phi,\psi,t,\mu) = \frac{9}{16\pi}\left|\left[\sqrt{1-F_s}\,h(\mu)\,\mathbf{A}(t) + e^{i\delta_s}\sqrt{F_s}\,\frac{g(\mu)}{\sqrt{3}}\,\mathbf{B}(t)\right]\times\hat{n}\right|^2$$

phi meson mass propagator, relativistic (asymmetric) Breit Wigner — $h(\mu)$

S-wave K^+K^- (f^0), flat mass distribution — $g(\mu)$

Admixture of CP odd and even time dependence of J/psi phi final state — $\mathbf{A}(t)$

Fraction of S-wave KK component in signal — F_s

CP odd time dependence of J/psi KK final state — $\mathbf{B}(t)$

- Integrate out KK mass dependence:

$$\begin{aligned}\rho_B(\theta,\psi,\phi,t) &= (1-F_s)\cdot P_B(\theta,\psi,\phi,t) + F_s Q_B(\theta,\psi,\phi,t)\\ &+ 2\frac{\sqrt{27}}{16\pi} Re\left[\mathcal{I}_\mu\left((\mathbf{A}_-\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot|f_-(t)|^2 + (\mathbf{A}_+\times\hat{n})\cdot(\mathbf{B}\times\hat{n})\cdot f_+(t)\cdot f_-^*(t)\right)\right]\end{aligned}$$

- where:
  - I(mu) is an integrated mass and relative phase interference term
  - P_B and Q_B are the decay rates for the P-wave phi and S-wave KK states

Fit function

Use a multivariate fit combining angular analysis and time dependence

- Fit without flavour tagging:

$$\mathcal{L}_i = f_s \cdot \underline{P_s(m)} \cdot \underline{T(t,\psi,\theta,\phi)} \cdot \underline{P_s(\sigma_t)} + (1-f_s) \cdot \underline{P_b(m)} \cdot \underline{P_b(t,\sigma_t)} \cdot \underline{P_b(\sigma_t)} \cdot \underline{P_b(\psi) \cdot P_b(\theta) \cdot P_b(\phi)}$$

signal

background

mass terms **time dependence and angular terms** **lifetime error terms**

- Flavour tagging added:

signal

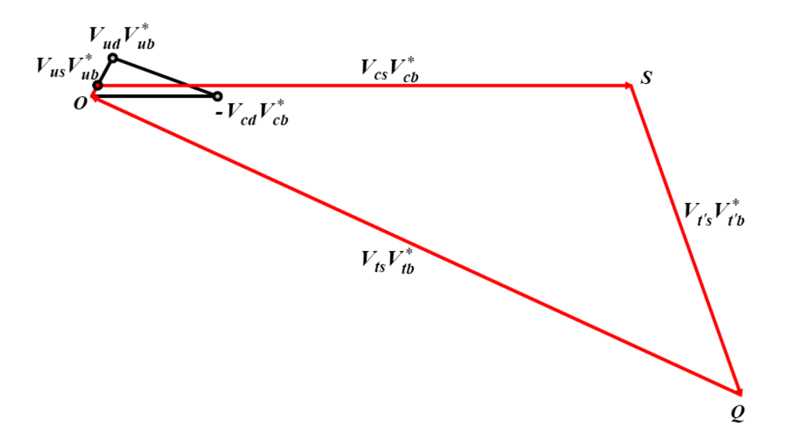
background

$$\mathcal{L}_i = f_s \cdot P_s(m) \cdot \underline{P_s(\xi)} \cdot \underline{T(t,\psi,\theta,\phi,\mathcal{D},\xi)} \cdot P_s(\sigma_t) \cdot \underline{P_s(\mathcal{D})} + (1-f_s) \cdot P_b(m) \cdot P_b(\xi) \cdot P_b(t,\sigma_t) \cdot P_b(\psi) \cdot P_b(\theta) \cdot P_b(\phi) \cdot P_b(\sigma_t) \cdot \underline{P_b(\mathcal{D})}$$

terms altered or added by **tag decision** or **tagging dilution**

Potential NP contributions

- 4th generation could enhance the weak mixing diagram in the neutral B_s system
- George W.S. Hou suggests the *t′* as a possible contribution to the mixing box diagrams
- SM contains the ingredients to generate the 100% Baryon Asymmetry of the Universe (BAU)
- Predicted CP violation from 3 generations is negligible compared to what is observed in BAU
- 4th generation of quarks would lead to “unitarity quadrangle” -> enhances SM CP violation by 10 orders of magnitude!



$$V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} + V_{t's}V^*_{t'b} = 0$$

arXiv:0803.1234v3 George W.S. Hou

Systematic errors

- Systematic study for point estimates uses pseudo experiments to estimate potential effects of any mis-parameterisations in the fitter.
- 2 techniques used:
  - Generating pseudo experiments using an altered parameterisation, fitting with default model
  - Generating pseudo experiments according to histograms of real data distribution

Systematic	$\Delta\Gamma$	$c\tau_s$	$\|A_\parallel(0)\|^2$	$\|A_0(0)\|^2$	$\phi_\perp$
Signal efficiency:					
Parameterisation	0.0024	0.96	0.0076	0.008	0.016
MC reweighting	0.0008	0.94	0.0129	0.0129	0.022
Signal mass model	0.0013	0.26	0.0009	0.0011	0.009
Background mass model	0.0009	1.4	0.0004	0.0005	0.004
Resolution model	0.0004	0.69	0.0002	0.0003	0.022
Background lifetime model	0.0036	2.0	0.0007	0.0011	0.058
Background angular distribution:					
Parameterisation	0.0002	0.02	0.0001	0.0001	0.001
$\sigma(c\tau)$ correlation	0.0002	0.14	0.0007	0.0007	0.006
Non-factorisation	0.0001	0.06	0.0004	0.0004	0.003
$B^0 \to J\psi K^*$ crossfeed	0.0014	0.24	0.0007	0.0010	0.006
SVX alignment	0.0006	2.0	0.0001	0.0002	0.002
Mass error	0.0001	0.58	0.0004	0.0004	0.002
$c\tau$ error	0.0012	0.17	0.0005	0.0007	0.013
Pull bias	0.0028		0.0013	0.0021	
Totals	0.01	3.6	0.015	0.015	0.07

Point estimates: results comparison

Tagged, with S-wave

$$
\begin{aligned}
c\tau &= 458.64 \pm 7.54 \text{ (stat.) } \mu m \\
\Delta\Gamma &= 0.075 \pm 0.035 \text{ (stat.) } ps^{-1} \\
|A_{\parallel}|^2 &= 0.231 \pm 0.014 \text{ (stat.)} \\
|A_0|^2 &= 0.524 \pm 0.013 \text{ (stat.)} \\
\phi_{\perp} &= 2.95 \pm 0.64 \text{ (stat.)}
\end{aligned}
$$

Tagged, no S-wave

$$
\begin{aligned}
c\tau &= 459.1 \pm 7.7 \text{ (stat.) } \mu m \\
\Delta\Gamma &= 0.073 \pm 0.03 \text{ (stat.) } ps^{-1} \\
|A_{\parallel}|^2 &= 0.232 \pm 0.014 \text{ (stat.)} \\
|A_0|^2 &= 0.523 \pm 0.012 \text{ (stat.)} \\
\phi_{\perp} &= 2.80 \pm 0.56
\end{aligned}
$$

Untagged, with S-wave

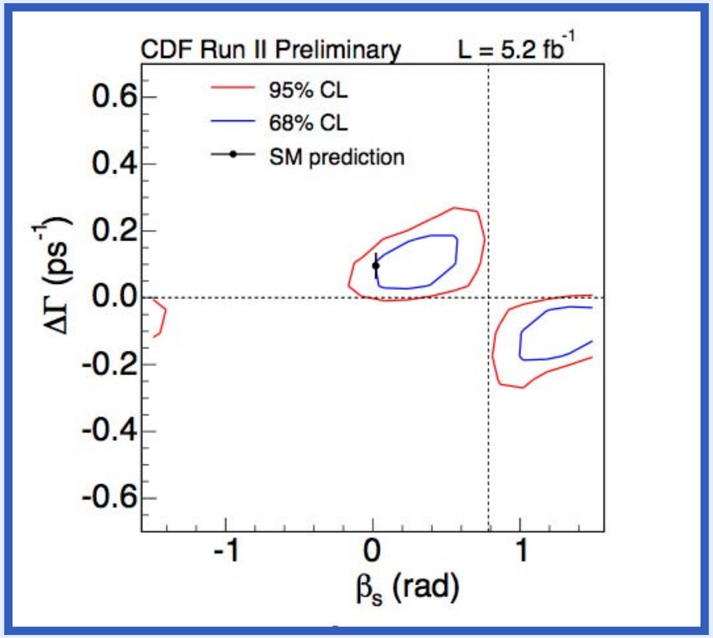
$$
\begin{aligned}
c\tau &= 456.93 \pm 7.69 \text{ (stat.) } \mu m \\
\Delta\Gamma &= 0.071 \pm 0.036 \text{ (stat.) } ps^{-1} \\
|A_{\parallel}|^2 &= 0.233 \pm 0.015 \text{ (stat.)} \\
|A_0|^2 &= 0.521 \pm 0.013 \text{ (stat.)}
\end{aligned}
$$

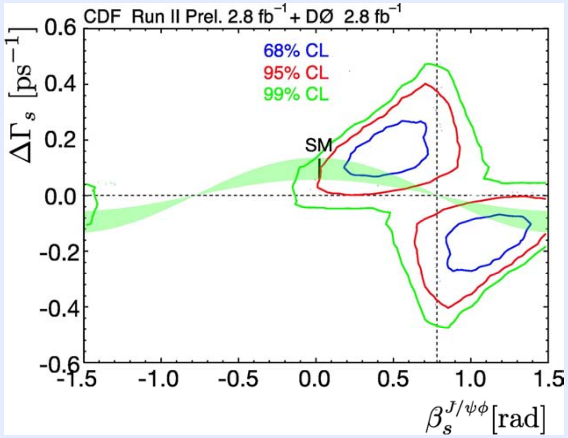
Untagged, no S-wave

$$
\begin{aligned}
c\tau &= 457.2 \pm 7.9 \text{ (stat.) } \mu m \\
\Delta\Gamma &= 0.070 \pm 0.04 \text{ (stat.) } ps^{-1} \\
|A_{\parallel}|^2 &= 0.233 \pm 0.016 \text{ (stat.)} \\
|A_0|^2 &= 0.520 \pm 0.013 \text{ (stat.)}
\end{aligned}
$$

Comparisons

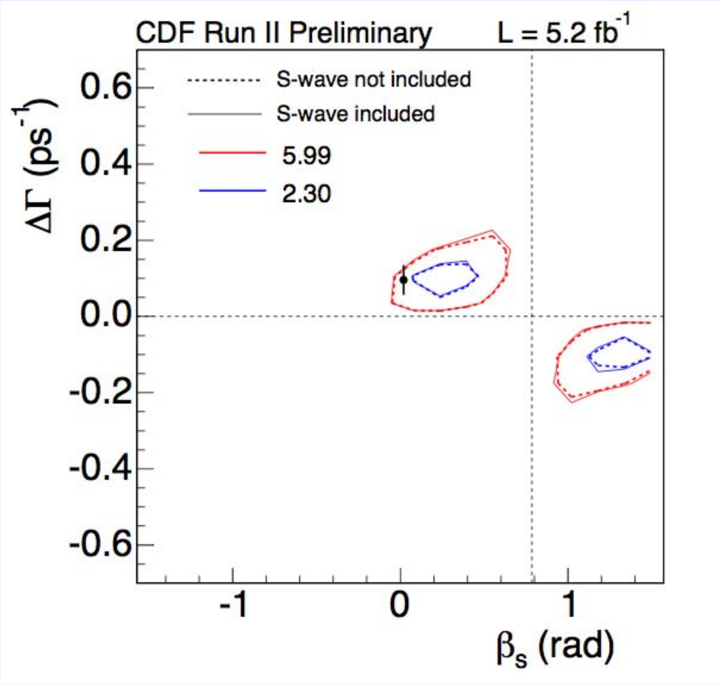
new CDF result





2009 Tevatron combined result

2D likelihood contours for β_s and $\Delta\Gamma$ without coverage adjustment



Inclusion in the fit of S-wave KK (f^0) contamination to phi meson signal has small effect on likelihood contours

Measurement of β_s: coverage adjustment

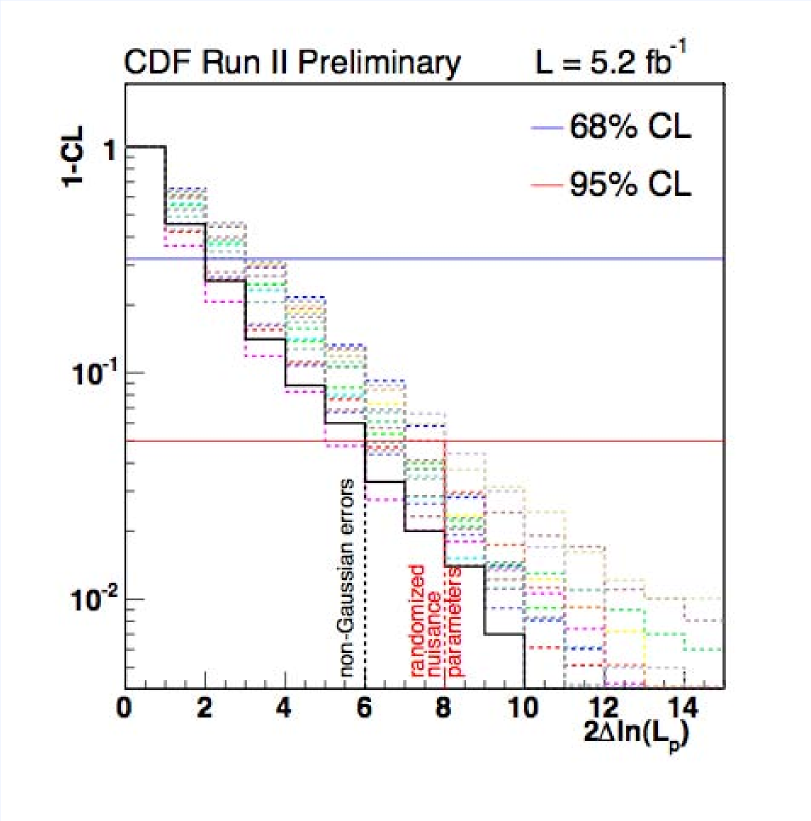
Use likelihood ratio ordering technique to account for non-Gaussian behaviour (ensure confidence regions not under-covered) and to include effect of systematics on the errors:

- Generate pseudo experiments at the SM point in the $\Delta\Gamma$-β_s plane.
- Fit with all parameters floating
- Fit again with $\Delta\Gamma$ and β_s fixed to the SM point
- Form a likelihood ratio:

$$\mathcal{LR} = 2\log\frac{\mathcal{L}(\beta_s^{J/\psi\phi}, \Delta\Gamma, \vec{\xi})}{\mathcal{L}(\vec{\xi})}$$

Measurement of β_s

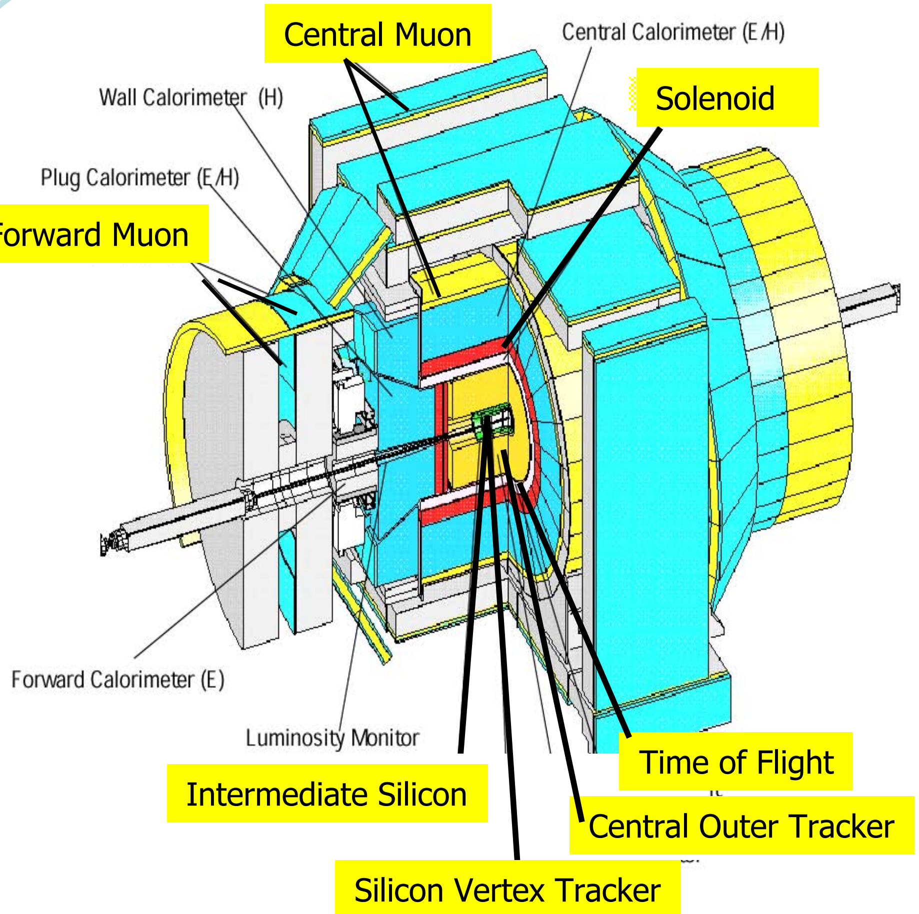
- Ideal case: produce fit value of β_s as we do for lifetime, etc.
- At current statistical level, fit shows some bias for β_s
- Instead, produce 2D likelihood contours in β_s - $\Delta\Gamma$ space
  - Perform fits on data with β_s and $\Delta\Gamma$ fixed at 400 points on 20x20 grid
  - Ratio of log likelihood value for fit at each point to the global minimum used to construct likelihood contour plots
- Use profile-likelihood ratio ordering technique to ensure coverage



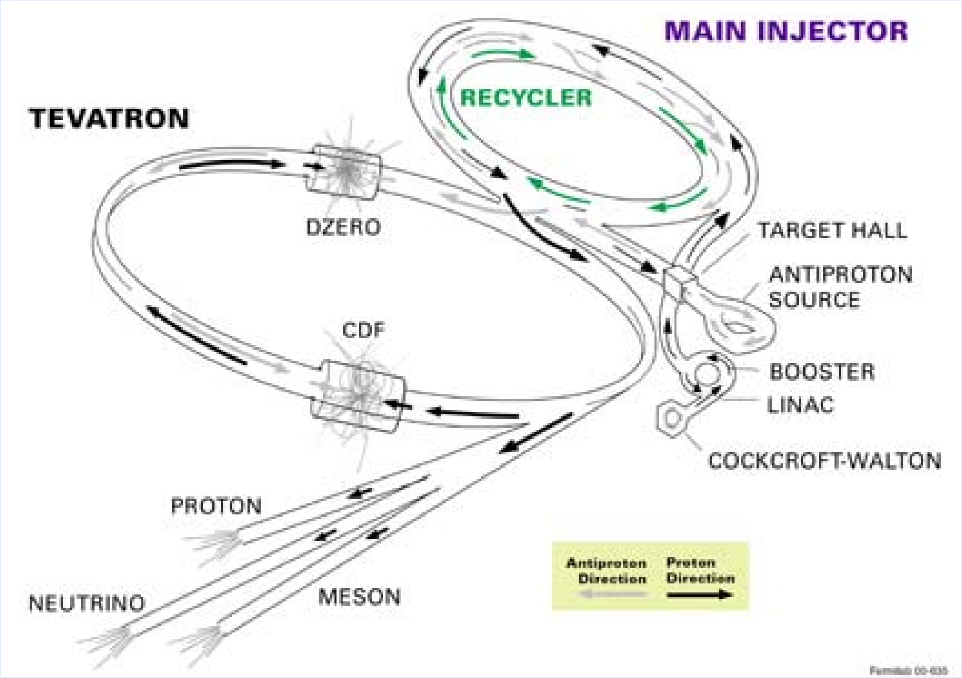
CDF detector

B physics at CDF:

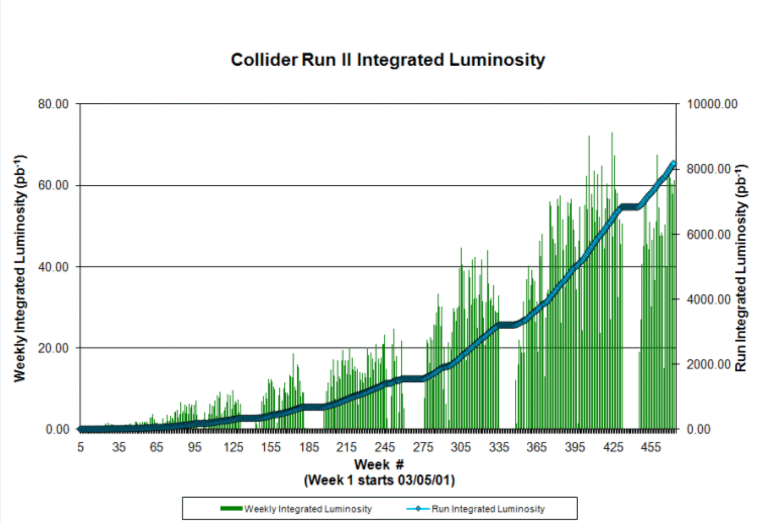
- Particle ID: dE/dx and TOF
- Excellent vertex resolution ~23μm and p_T resolution: $\sigma(p_T)/p_T^2 \sim 0.1$ (GeV/c)$^{-1}$
- Di-muon trigger (this analysis)
- Displaced vertex trigger: trigger level silicon tracking



Tevatron performance



- p-pbar collisions at 1.96TeV
- Constantly improving luminosity performance
  - peak instantaneous luminosity >3x10^{32} cm^{-2}s^{-1}
  - ~7fb^{-1} delivered to the experiments

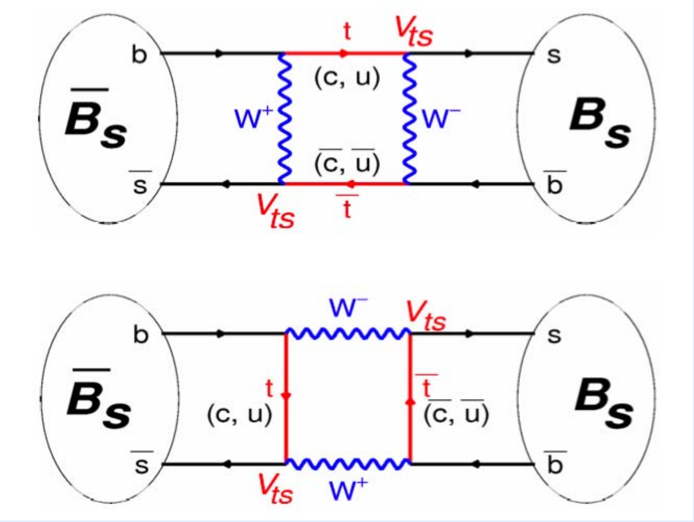


- High luminosity is a benefit but also a challenge for B physics
- Expect almost twice the current sample by end of run-II

CP violation in neutral B_s system

Flavour eigenstates:

$$|B_s^0\rangle = (\bar{b}s)$$
$$|\bar{B}_s^0\rangle = (b\bar{s})$$



Mixing of flavour eigenstates is governed by:

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

Flavour eigenstates are not mass eigenstates:

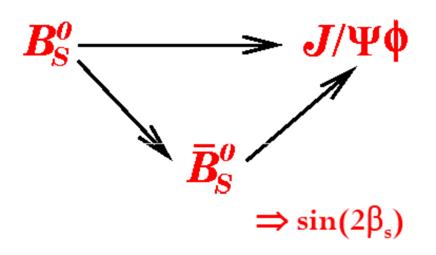
$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

Different masses -> mixing frequency: $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

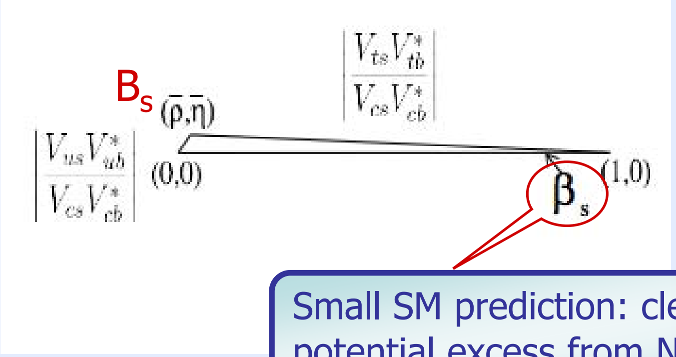
-> phase: $\varphi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \sim 0.004$

Different decay widths: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2\,|\Gamma_{12}|\cos(2\varphi_s^{SM})$

Search for New Physics in B_s mixing



CP violation in $B_s \to J/\psi\varphi$ occurs through interference of decays with and without mixing.



Small SM prediction: clear to see potential excess from NP

Different masses -> mixing frequency:	$\Delta m_s = m_H - m_L \approx 2|M_{12}|$
-> phase:	$\varphi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \sim 0.004$
Different decay widths:	$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(2\varphi_s^{SM})$

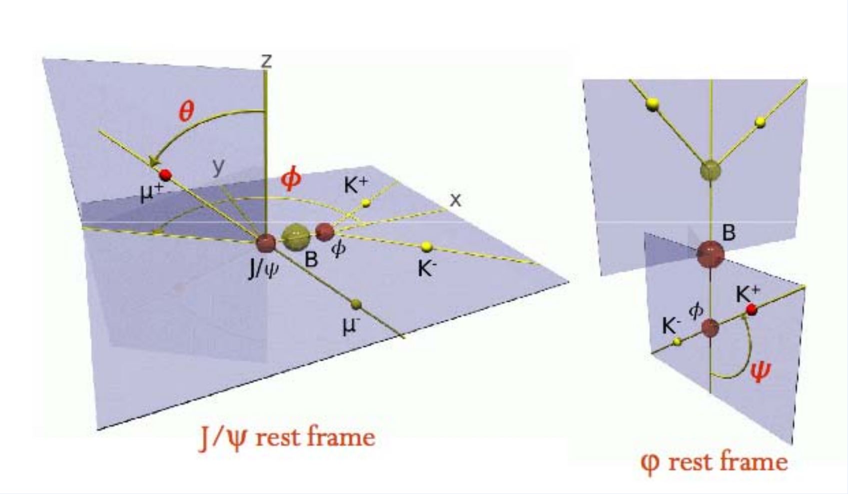
A New Physics effect would contribute to both the phases φ_s and β_s by introducing a new physics phase:

$$\varphi_s = \varphi_s^{SM} + \varphi_s^{NP} \text{ and } 2\beta_s = 2\beta_s^{SM} - \varphi_s^{NP}$$

So, if NP phase dominates we measure $2\beta_s \approx -\varphi_s \approx \varphi_s^{NP}$

Fit function: angular separation

Final state is a mixture of CP even (~75%) and odd (~25%) states.



$|A_0|^2$: polarisation longitudinal, parallel
$|A_{//}|^2$: polarisation transverse, parallel
$|A_{perp}|^2$: polarisation transverse, perpendicular

Three angular momentum states of J/ψ phi:

L=0	S-wave	**CP even**
L=1	P-wave	**CP odd**
L=2	D-wave	**CP even**

Can separate final CP states using angular variables

Transversity basis describes these contributions as: A_0, $A_{//}$ (CP even), A_{perp} (CP odd) according to their polarisation.

Can be separated using the angular distributions of the final state particles

Transversity basis

Polarisation of vector mesons w.r.t direction of motion:

$|A_0|^2$: polarisation longitudinal, parallel

$|A_{//}|^2$: polarisation transverse, parallel

$|A_{perp}|^2$: polarisation transverse, perpendicular

We let the $A's$ be normalized such that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$.

The predicted angular distributions can be found from the following prescription Let $\hat{n}$ be the unit vector in the direction of the l^+ (J/ψ rest frame),

$$\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta),$$

and let A be a complex vector defined as

$$\mathbf{A} = (A_0\cos\psi, -\frac{A_\parallel \sin\psi}{\sqrt{2}}, i\frac{A_\perp \sin\psi}{\sqrt{2}}).$$

The angular distributions are governed by the probability density

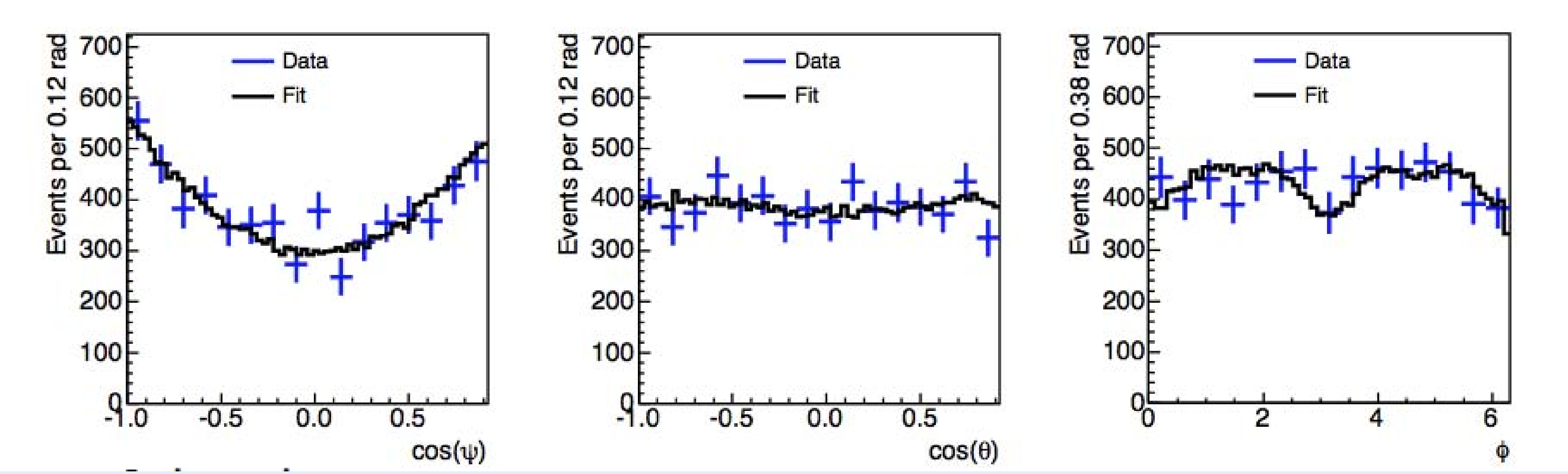
$$P(\theta,\phi,\psi) = \frac{9}{16\pi}|\mathbf{A}\times\hat{n}|^2.$$

This is normalized such that

$$\int\int\int \frac{9}{16\pi}|\mathbf{A}\times\hat{n}|^2 \sin\theta d\theta\, d\phi \sin\psi\, d\psi = 1.$$

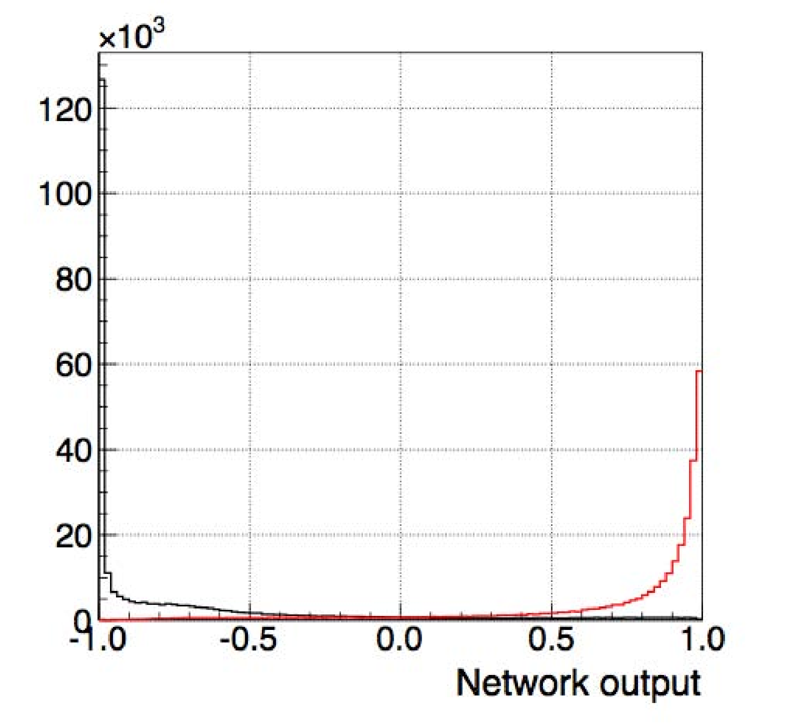
Checking the fitter: projections

- Angular distributions are used to separate CP odd and even final states in both the tagged and untagged fit
- The signal fit projections for these parameters are shown below
- Used to check our parameterisation of the angular distributions



NN selection

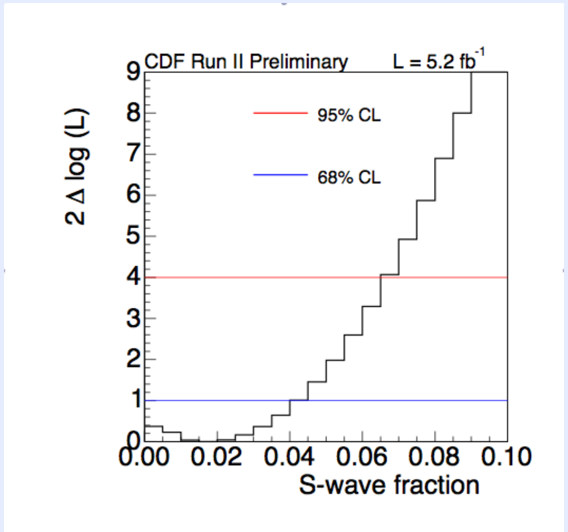
- For final selection use Artificial Neural Network (ANN)
- Trained on realistic MC
- Most significant inputs are
  - Kaon momenta
  - vertex probabilities for the B_s, J/ψ and ϕ
- 2.8fb^{-1} update optimised NN cut value by maximising $S/\sqrt{(S+B)}$
- New result optimises by selecting NN value which minimises β_s errors



Distribution of signal and background ANN output (MC)

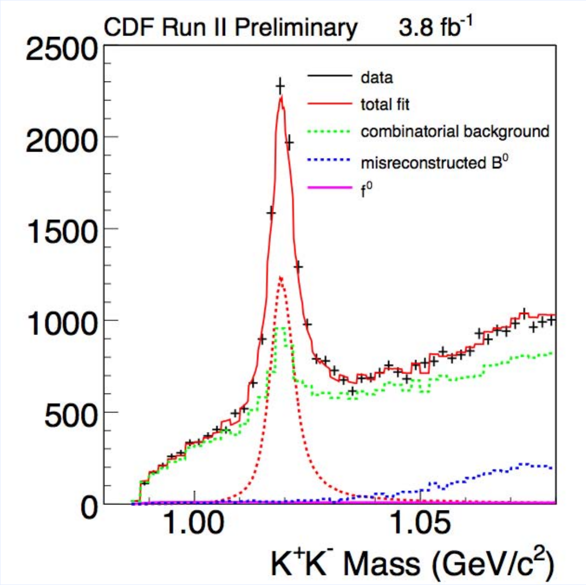
Inclusion of S-wave KK component

- S-wave KK component has been added to full angular, time-dependent likelihood fit.
- Both f^0 and non-resonant KK are considered flat in mass within the small selection window, φ meson mass is modelled by asymmetric, relativistic Breit Wigner.
- J/ψ KK (f^0) is pure CP odd state
- KK mass is NOT a fit parameter



The fitted fraction of KK S-wave contamination in the signal is **< 6.7% at the 95% CL**

Fixing the f^0 fraction to the central value found in the full likelihood fit gives



Comparison of data periods