# CP violation measurements with $B_s \to J/\psi\phi$ decays at the Tevatron

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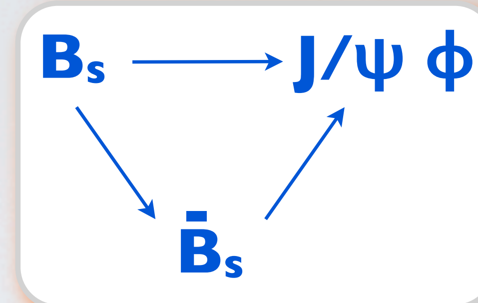
on behalf of the CDF & the DØ collaborations

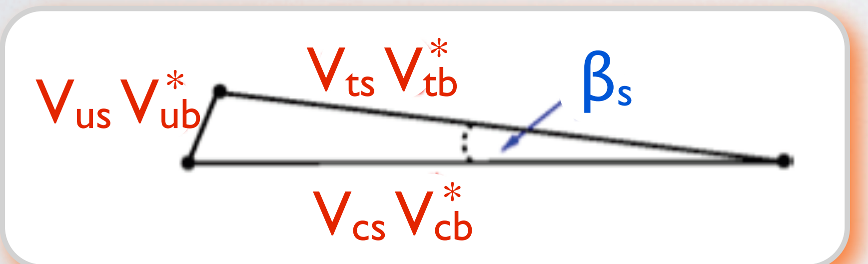


BEAUTY 2011, Amsterdam, April 2011

# motivation

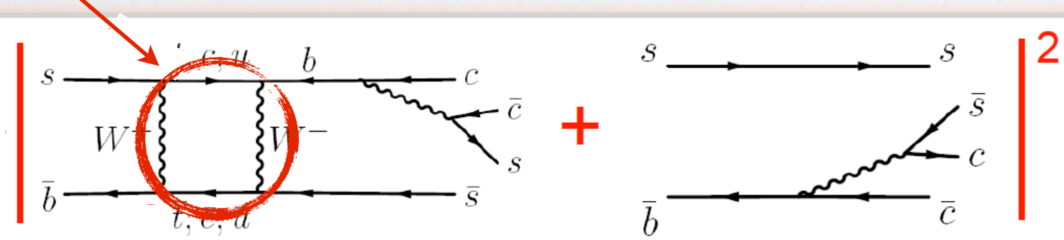
- CPV in $B_s \to J/\psi\phi$ decays occurs through interference between decays with and w/o mixing.
Analogous to the measurement of sin2$\beta$ with $B^0 \to J/\psi K_s^0$ events.
But with $B_s \to J/\psi\phi$ events we measure sin2$\beta_s$.




- **SM predicts very small observable phase $\beta_s$:** $2\beta_s^{SM} = 2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = \lambda^2\eta = 0.038 \pm 0.002$

- The CPV phase $\phi_s = \arg\left(\frac{-M_{12}^s}{\Gamma_{12}^s}\right)$ could be enhanced by contribution of new physics NP in the box:

decay rate ~ 

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

with $\phi_s^{SM} = 0.0042 \pm 0.0014$

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

If B.SM physics with $\phi_s^{NP} >> \phi_s^{SM}, \beta_s^{SM}$ :

$\phi_s \sim \phi_s^{NP} \sim -2\beta_s$

# measurement method

- $\phi_s$ and $\Delta\Gamma_s$ will be measured by studying the time evolution of flavour tagged $B_s \longrightarrow J/\psi\phi$ decays.

- Decay of a pseudo-scalar $B_s$ into 2 vector-mesons $J/\psi$ and $\phi$ with 3 possible orbital angular momentum L final states. Linear polarization states of the $J/\psi$ and $\phi$ provide a convenient basis for the analysis of the $B_s \longrightarrow J/\psi\phi$ decay.

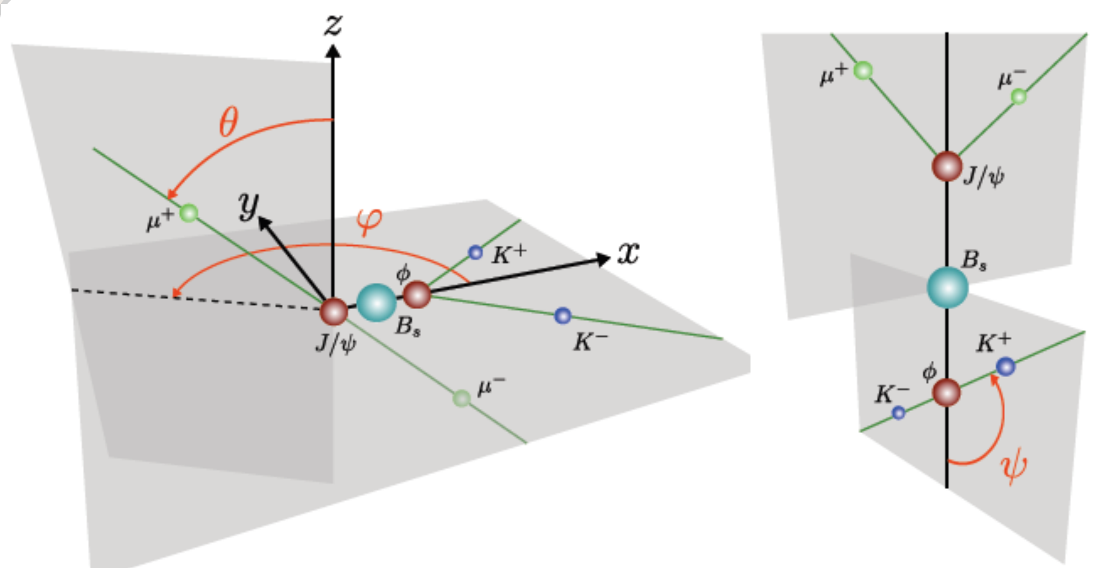
➛ characterization by 3 independent complex amplitudes:

$A_0$ L=0 - CP-even final state
$A_{||}$ L=2 - CP-even final state
$A_\perp$ L=1 - CP-odd final state

and 2 relative strong phases $\delta_{//}$ and $\delta_\perp$ w.r.t. $A_0$.

- The $J/\psi\phi$ final state is a mixture of CP-even (~75 %) and CP-odd (~25%) states

➛ Measure **angular distributions $\theta_T$, $\phi_T$** and $\psi_T$ to disentangle the 3 final states and so separate CP eigenstates.



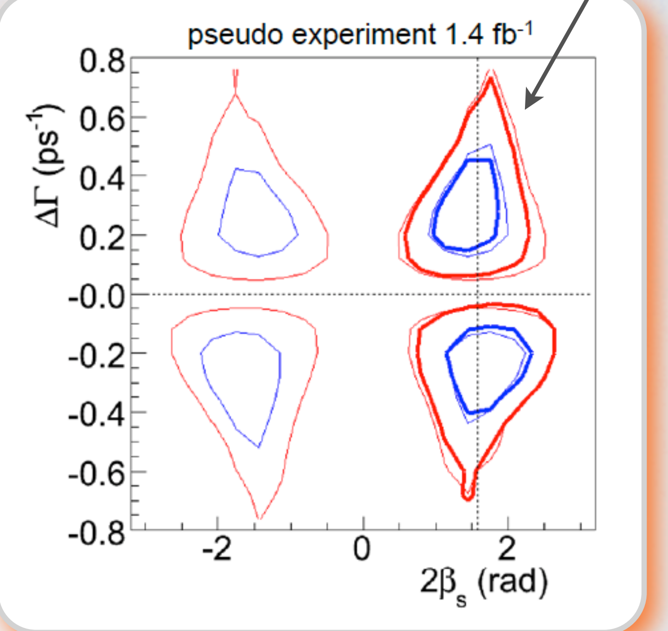

J/ψ rest frame φ rest frame

# measurement method (2)

- Fit differential decay rates for $B_s$ and $\bar{B}_s$:

$$\frac{d^4\Gamma(B_s \longrightarrow J/\psi\phi)}{dt\, d\cos\theta_T\, d\phi_T\, d\cos\psi_T} = f(\phi_s, \Delta m_s, \Delta\Gamma_s, \tau_s, A_0, A_{||}, A_{\perp}, \delta_{||}, \delta_{\perp})$$

with flavour tagging




- **Flavour tagging** used to disentangle the 2 initial states $B_s$ and $\bar{B}_s$.

  **Untagged analyses** allow higher efficiencies

  ➛ still sensitive to $\cos\phi_s$ and $(\exp^{-\Gamma_H} - \exp^{-\Gamma_L})\sin\phi_s$ thanks to sizeable width difference $\Delta\Gamma_s$ between the $B_s$ eigenstates

  ➛ **sign ambiguity on the weak phase for a given $\Delta\Gamma_s$.**

- **Multidimensional unbinned likelihood fit** to background+signal distributions of:
  - reconstructed invariant mass $M(J/\psi\phi)$,
  - reconstructed proper decay time $1/\Gamma$,
  - 3 angles $\theta_T$, $\phi_T$ and $\psi_T$, convoluted to **detector acceptance,**

for each $B_s \longrightarrow J/\psi\phi$ reconstructed decay weighted by its **flavour tagging probability**,

  - mass and lifetime uncertainties, tagging dilution.

# previous measurements

- With low statistics (**1.1** to **1.35 fb$^{-1}$**), CDF and DØ performed **untagged analyses**.

DØ - PRL 98, 121801 (2007)
CDF - PRL 100, 121803 (2008)

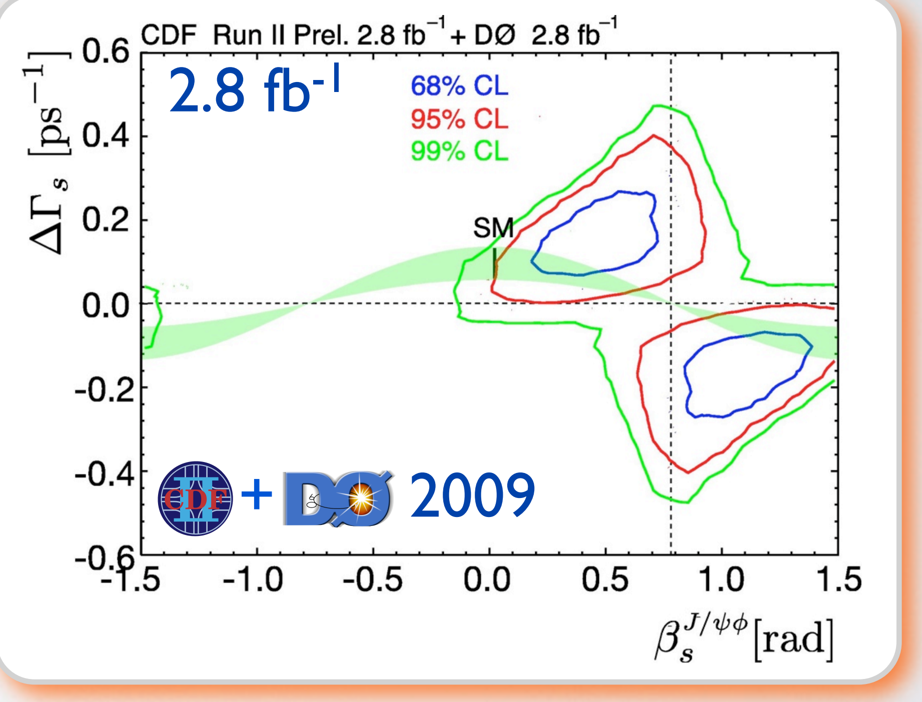
- First **flavour tagged** result from CDF with **1.35 fb$^{-1}$** suggests a **1.5σ** deviation from the S.M. expectation.

CDF - PRL 100, 161802 (2008)

- Updates with **2.8 fb$^{-1}$**:
  - CDF and DØ results were consistent and observed each a deviation in the same direction of ~1.8σ w.r.t. the SM central point (p-value ~ 7 % ).
  - combination CDF + DØ : **2.1σ** deviation w.r.t. the SM central point (p-value = 3.4 %).

DØ - PRL 101, 241801 (2008)
CDF - Public Note 9458 (2008)

➛ combination
DØ Public Note 5928




- **Present measurements**: with increased statistics.
  - CDF: based on **5.2 fb$^{-1}$** with improved particle Id, NN, flavour tagging (SST) and contribution of S-wave included.
  - DØ: based on **6.1 fb$^{-1}$** with improved selection and no same side tagger anymore.

DØ - Public Note 6098
CDF - Public Note 10206

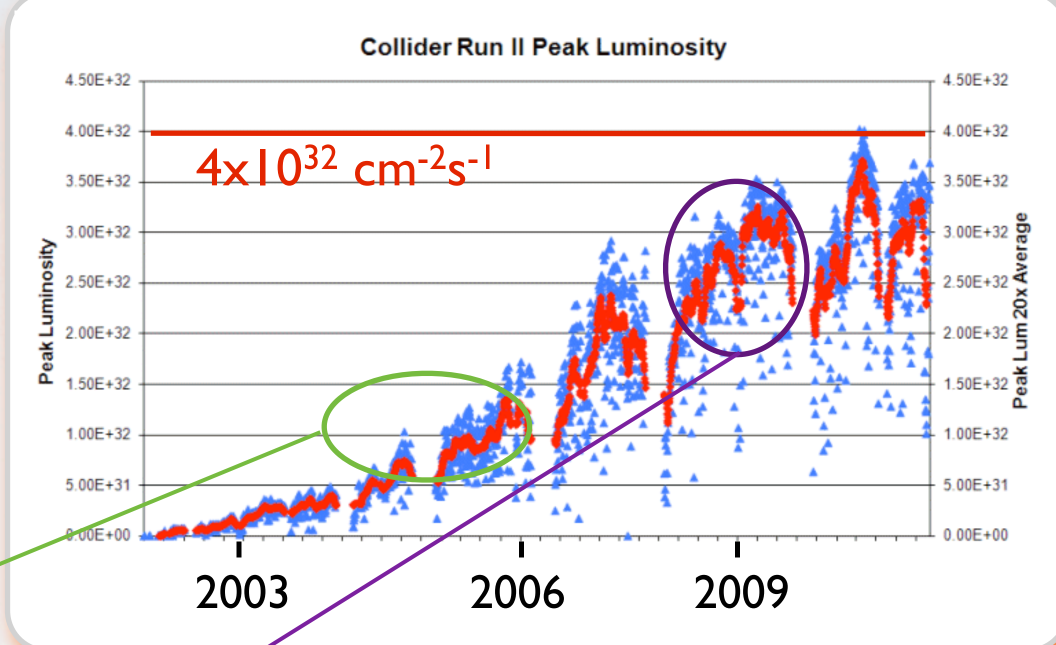
# experimental environment

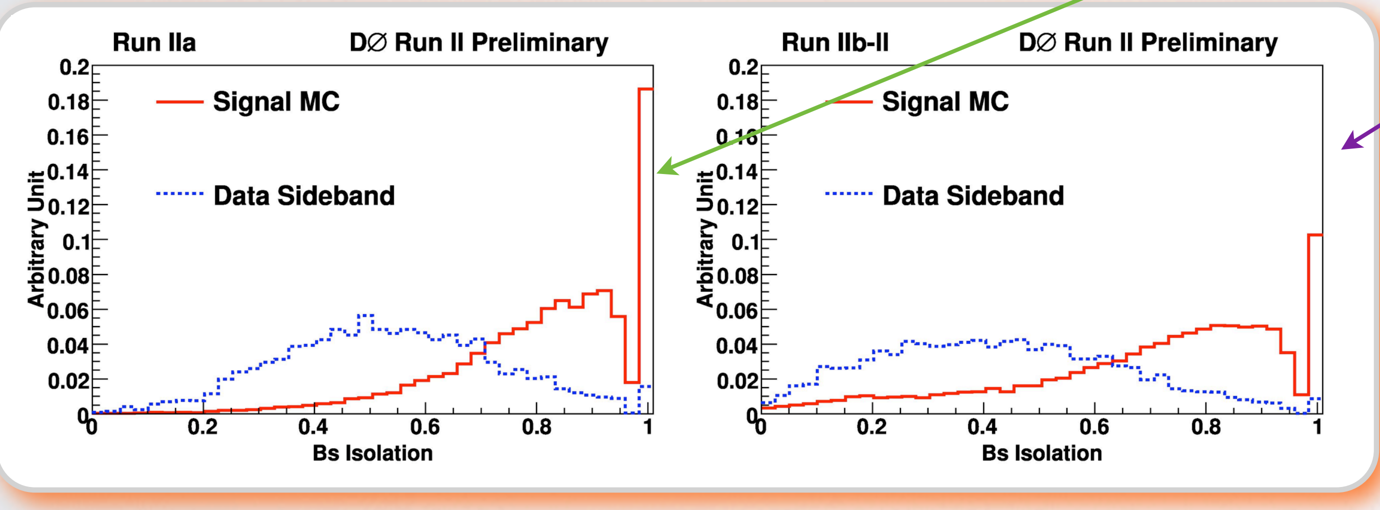
## Tevatron Run II (since 2001):

- $\sqrt{s}$ = 1.96 Tev,
- inst. lumi ~ $3.5 \times 10^{32}$ $cm^{-2}s^{-1}$,
- total lumi. ~ 10.5 $fb^{-1}$ delivered.
- end of run : 2011, ~ 11 $fb^{-1}$ analysable.

## Tevatron offers:

- large $b\bar{b}$ production rate,
  ~$40 \times 10^6$ $b\bar{b}$ pairs/hour produced,
- high integrated luminosity.




## But also:

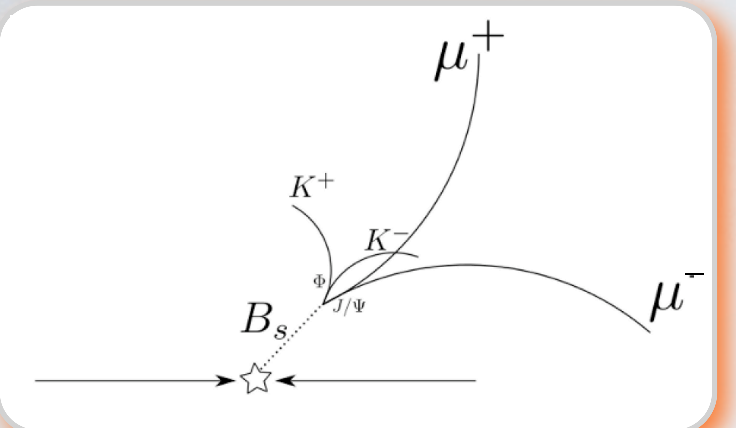
- huge background (> x1000),
- high track multiplicity environment.

→ underlying differences w.r.t. the instantaneous luminosity.

## CDF and DØ's major assets for this measurement :

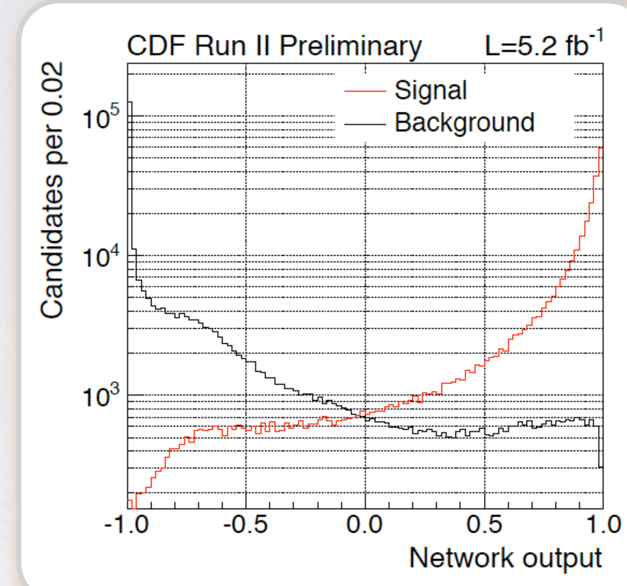
- highly selective triggers based on **single- and di-muon triggers**,
- **good vertex** and **mass** resolutions.

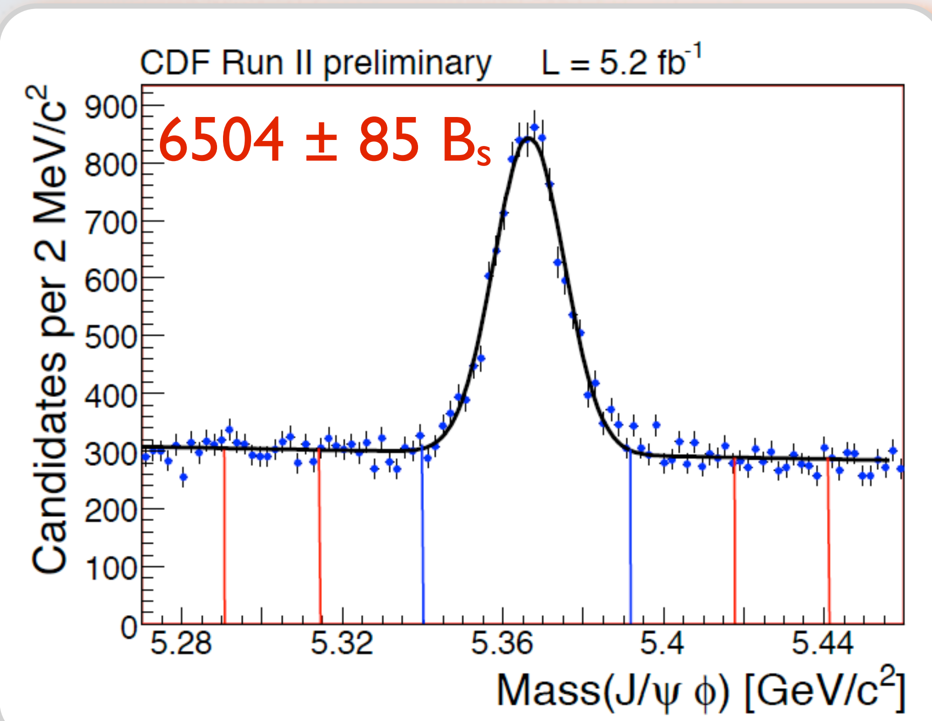
# $B_s \longrightarrow J/\Psi\phi$ reconstruction

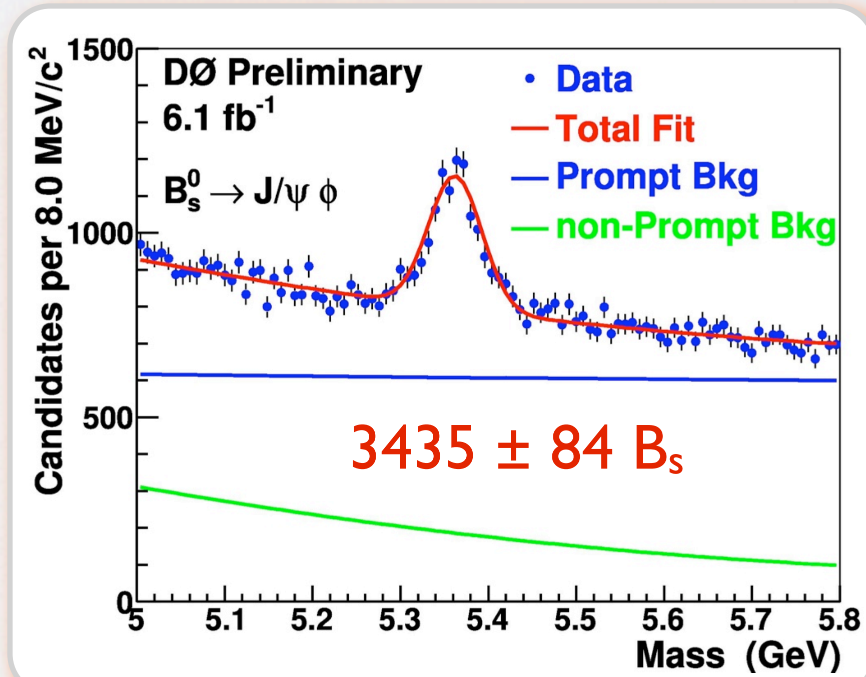



- This analysis is **statistically limited**: efficient selection is important.
- CDF and DØ apply ~ the same selection based on kinematical variables.
- **Further background suppression** by CDF by cutting on an (**new**) NN combining kinematical variables with particle identification.

Signal is simulated and background is modeled by data $B_s$ mass sideband regions for training.



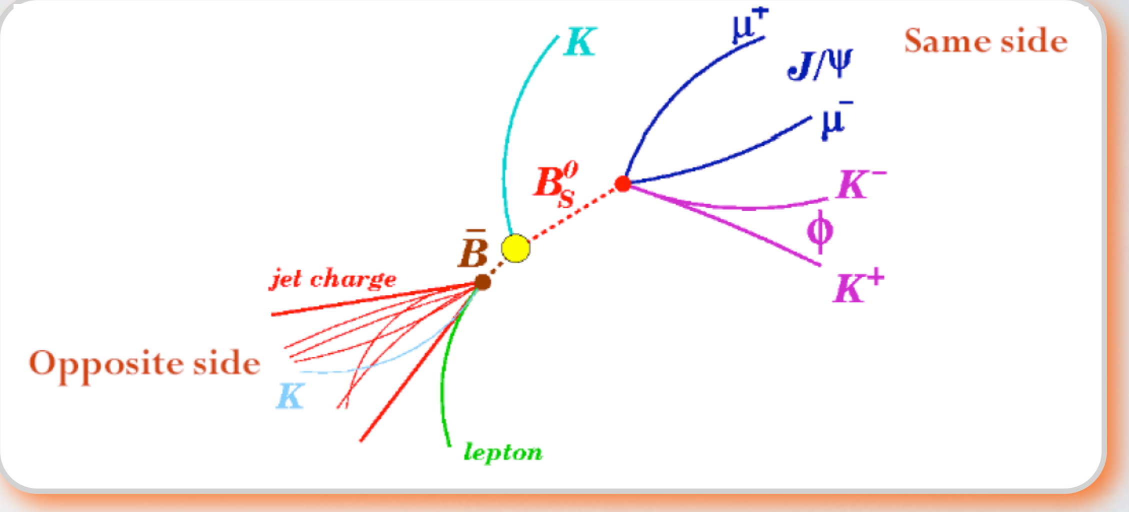



# flavour tagging

- Techniques developed and used in other B analyses. Calibration in data with inclusive and exclusive B decays of known flavours (for the OST) and with $B_s$ mixing measurement (SST).

- **Opposite Side Tagger** based on charged decay particles from the opposite side B meson. Discriminating variable built from an inclusive combination (likelihood ratio method or NN) of:
  - $e^+$ or $\mu^+$ from other B semi-leptonic decay,
  - charge of the opposite decay vertex,
  - opposite tracks charge (only DØ).




**OST tagging power = εfficiency x Dilution$^2$ ~ 1.2 % (CDF)**
**~ 2.5 % (DØ).**

$$\text{Dilution} = \frac{\text{correct - wrong}}{\text{correct + wrong}}$$

- **Same Side Tagger** ➛ charged $K^+$, sharing the same $s\bar{s}$ di-quark from fragmentation with same side $B_s$.
Impact from higher instantaneous luminosity (currently dropped by DØ).
CDF benefits from particle-Id (dE/dx and TOF).
**SST tagging power $\varepsilon D^2$ ~ 3.1 % (CDF).**

- Flavour is given as a **tagging probability** on an event-by-event basis.

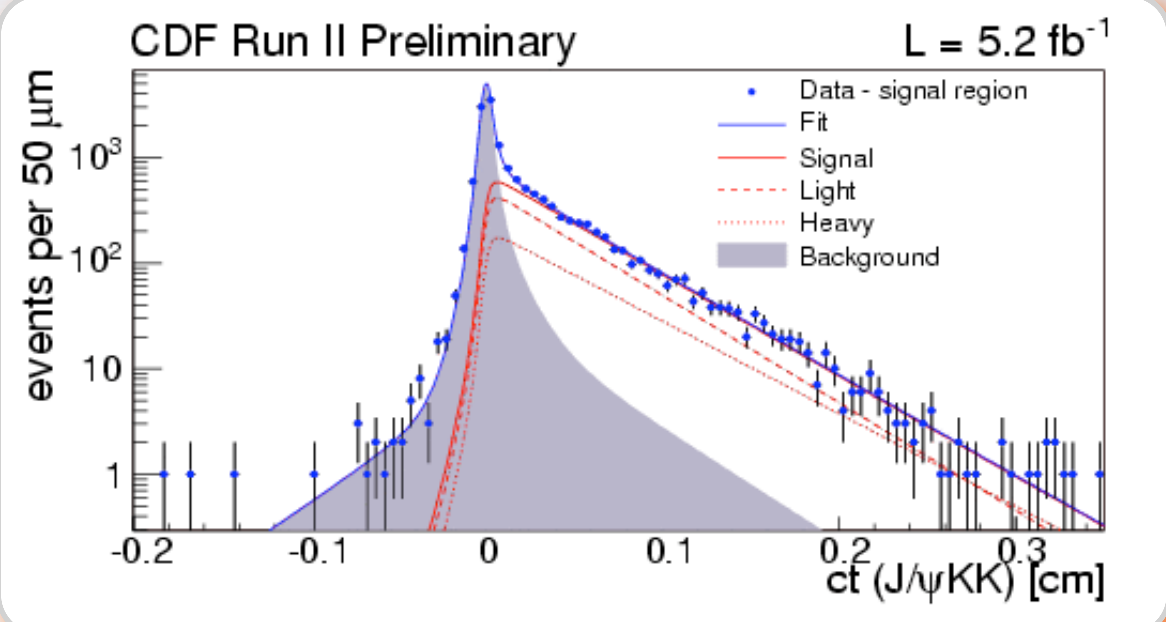
# CDF point estimates

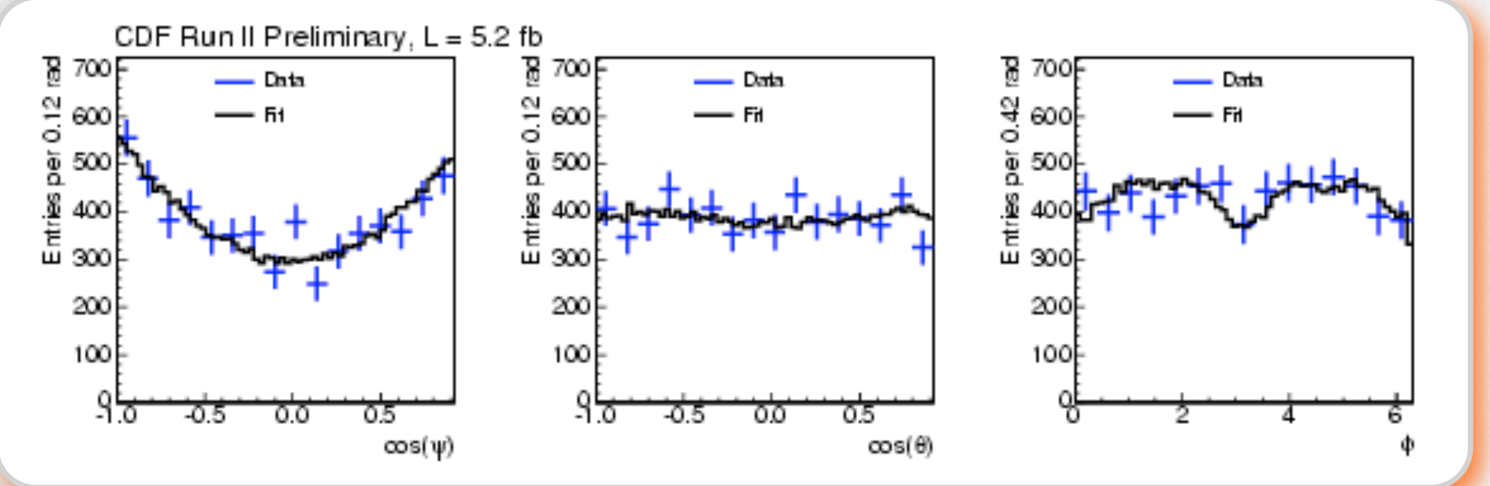
- Addition of an S-wave component due to $f_0$ or non-resonant $K^+K^-$contribution (both = flat KK invariant mass distributions under the $\phi$ mass peak).
  ➛ fitted fraction of **S-wave contamination is < 6.7 % @ 95 % C.L.** and can be neglected.

- **Assuming no CPV in the $B_s$ system ($\beta_s = \beta_s^{SM} = 0$),** CDF obtains most precise single measurements of lifetime and decay width difference:

$\tau_s$ = 1.53 ± 0.025 (stat.) ± 0.012 (syst.) ps

$\Delta\Gamma_s$ = 0.075 ± 0.035 (stat.) ± 0.01 (syst.) $ps^{-1}$

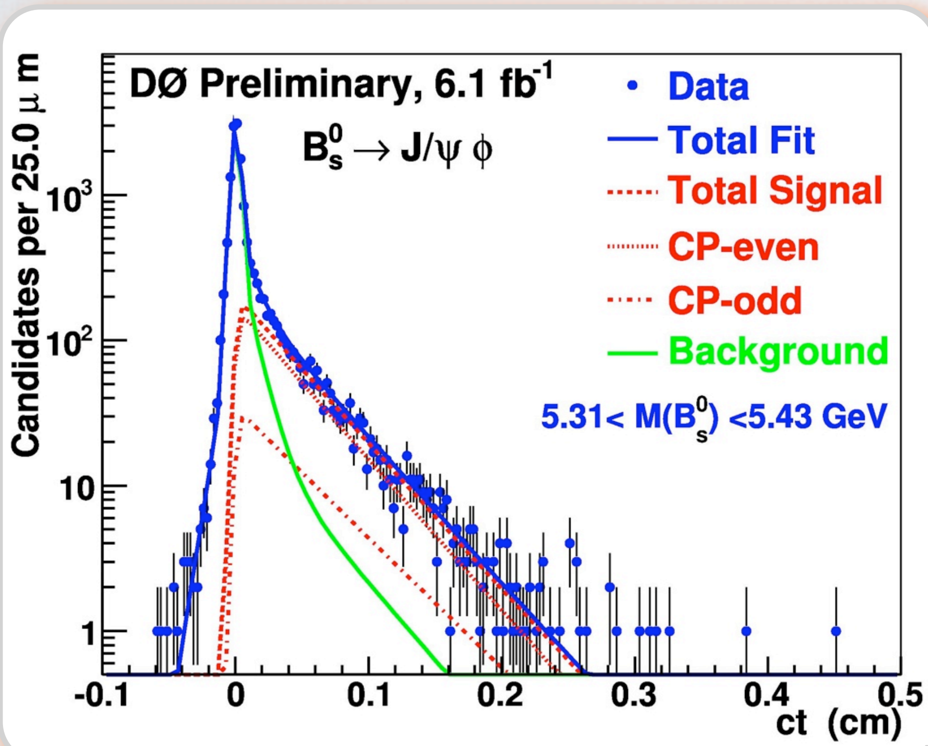


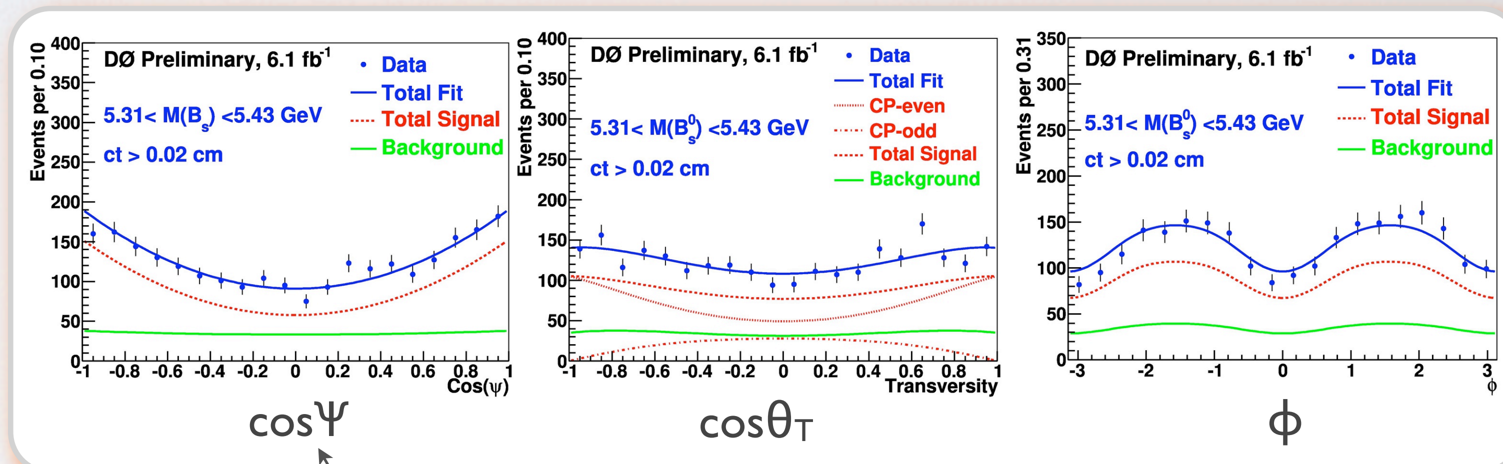




- Also most precise measurement of $|A_0(0)|^2$, $|A_{||}(0)|^2$ and $|A_\perp(0)|^2$. And the strong phase $\delta_\perp$ is also extracted, in agreement with previous determinations.

# DØ point estimates

- S-wave found to be non-significant ➛ not included.
- gaussian constraints on $\Delta m_s$ (PDG) and on strong phases $\delta_i$ (values from $B^0 \longrightarrow J/\Psi K^*$ under U(3) flavour symmetry assumption).
- two background components: prompt and non-prompt $J/\psi$ associated to a $\phi$ candidate.




an S-wave would show a FB asymmetry

Multidimensional fit projection:

$\tau_s$ = 1.47 ± 0.04 (stat.) ± 0.01 (syst.) ps

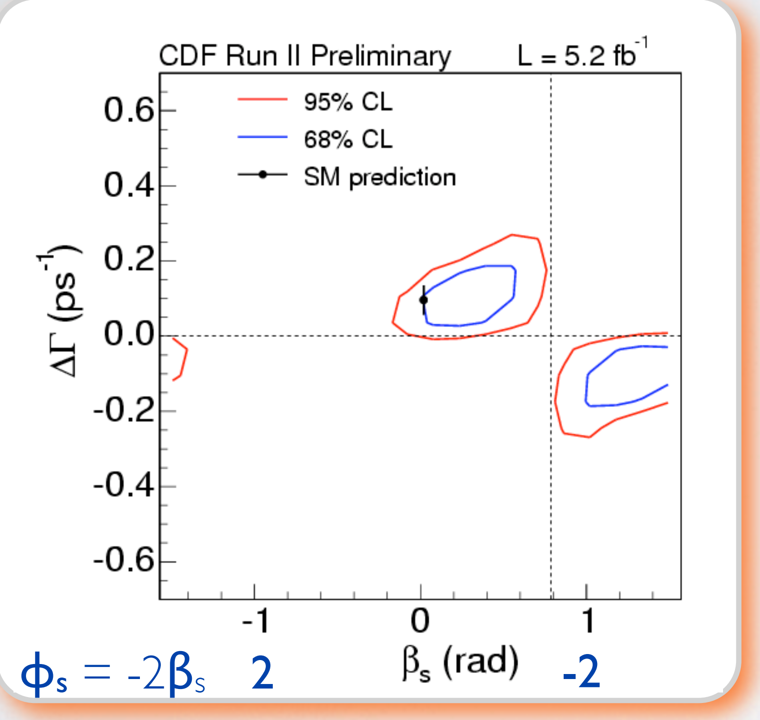
$\Delta\Gamma_s$ = 0.15 ± 0.06 (stat.) ± 0.01 (syst.) $ps^{-1}$

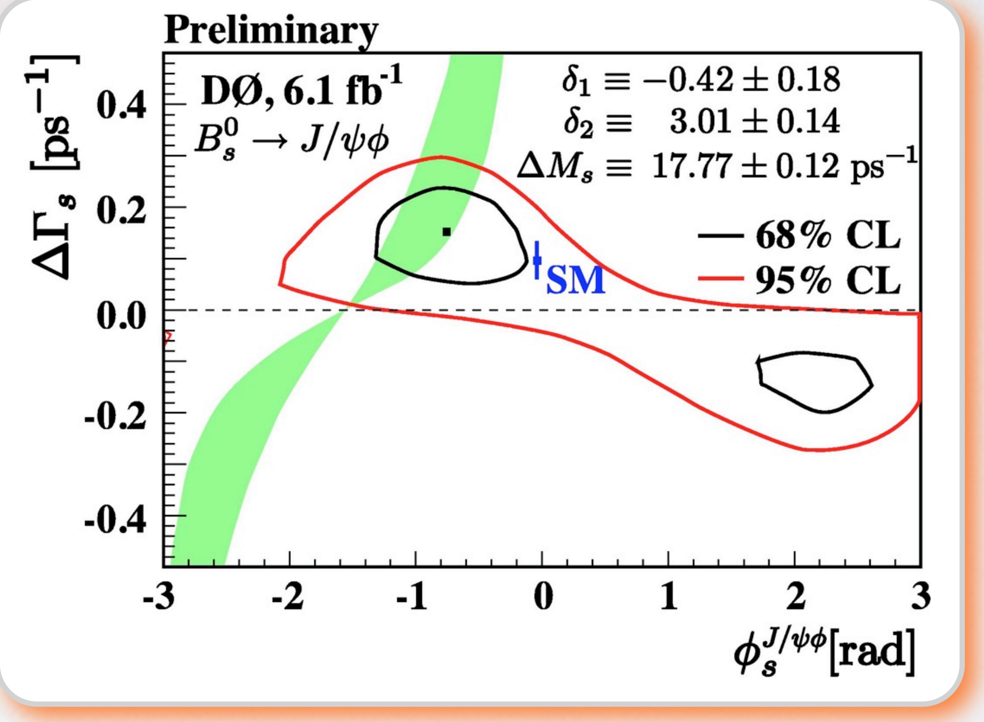
$\phi_s$ = -0.76 ± 0.37 (stat.) ± 0.02 (syst.)

# $\phi_s$-$\Delta\Gamma_s$ C.L. contours

- Analysis statistically limited: the likelihood is not gaussian.

➛ a likelihood-C.L. conversion curve, including effects of systematic uncertainties, is determined by an ensemble study.




Likelihood function theoretical symmetries:

$\phi_s \longrightarrow \pi-\phi_s$

$\Delta\Gamma_s \longrightarrow -\Delta\Gamma_s$

$\delta_{||} \longrightarrow 2\pi-\delta_{||}$

$\delta_{\perp} \longrightarrow \pi-\delta_{\perp}$

CDF: $\phi_s \in [-\pi, -1.78] \cup [-1.36, 0.26] \cup [2.88, \pi]$ @ 95 % C.L.
$0.8\sigma$ deviation from SM central point

DØ: $\phi_s \in [-1.65, 0.24]$, $\Delta\Gamma_s \in [0.014, 0.263]$ ps$^{-1}$
and $\phi_s \in [1.14, 2.93]$, $\Delta\Gamma_s \in [-0.235, -0.040]$ ps$^{-1}$ @ 95 % C.L.
$1.1\sigma$ deviation from SM central point

# $B_s \longrightarrow J/\Psi f_0(980)$ decay

- Current $\phi_s$ measurement is statistically limited ➛ add the $B_s \longrightarrow J/\Psi f_0(980)$ decay mode. This decay channel is a **CP eigenstate** ➛ no angular analysis needed and different systematics uncertainties.

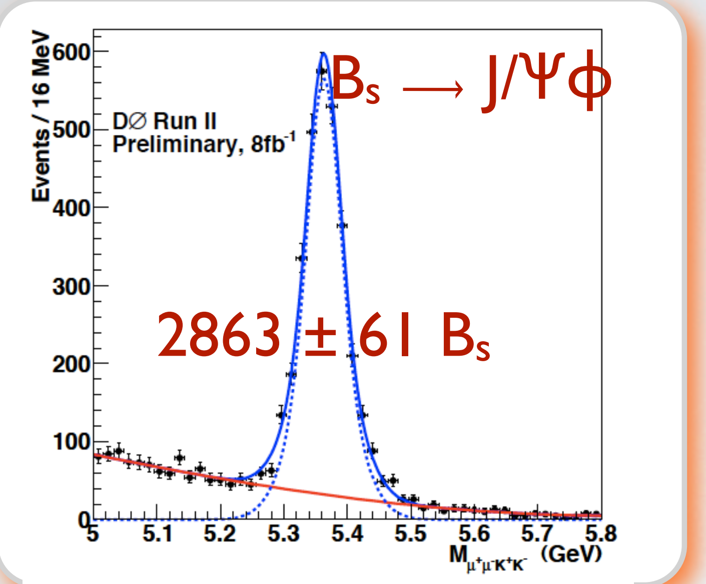
- DØ measures the ratio of the $B_s \longrightarrow J/\Psi f_0$ and $B_s \longrightarrow J/\Psi\phi$ branching fraction, with identical reconstruction criteria for the 2 decay modes ➛ systematics cancellation:

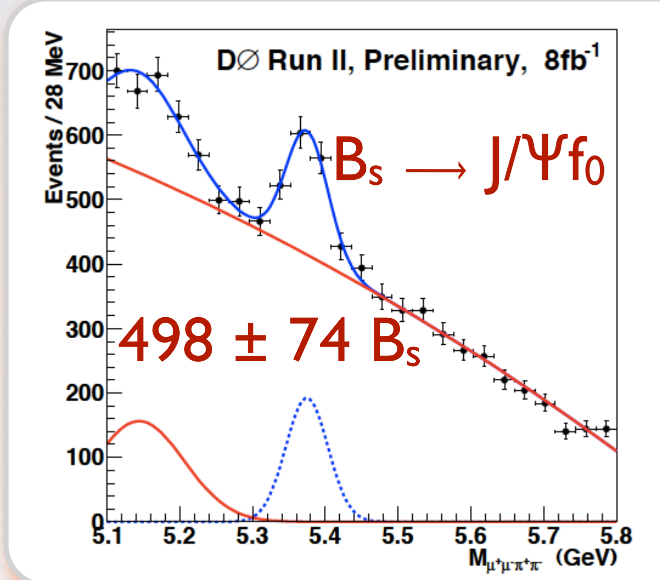
$$R = \frac{B.R.\ (B_s \longrightarrow J/\psi f_0(980),\ f_0(980) \longrightarrow \pi^+\pi^-)}{B.R.\ (B_s \longrightarrow J/\psi\phi,\ \phi \longrightarrow K^+K^-)} = \frac{\#\ B_s \longrightarrow J/\psi f_0(980) \times \varepsilon_{reco}^{J/\psi\phi}}{\#\ B_s \longrightarrow J/\psi\phi \times \varepsilon_{reco}^{J/\psi f0}}$$

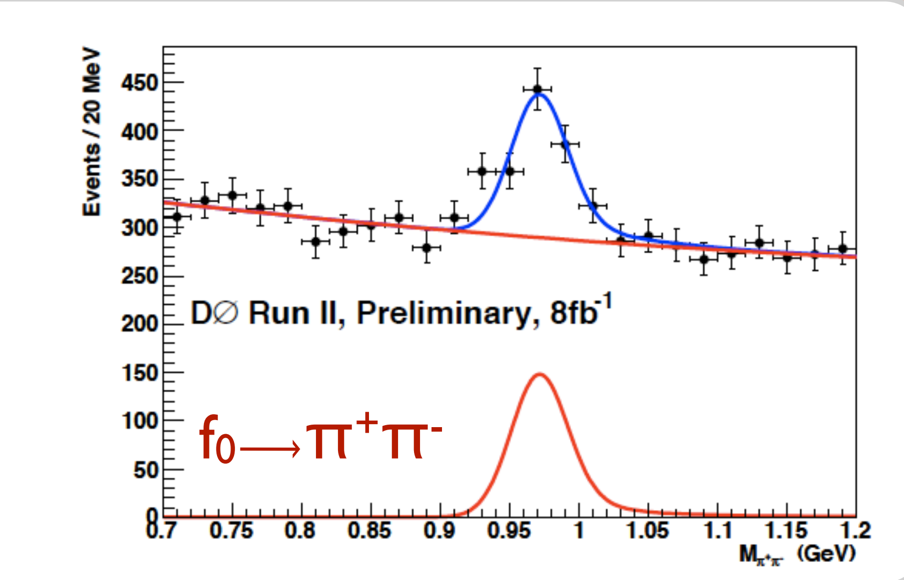
- This measurement is based on 8 $fb^{-1}$ of analysed data and after a complete **re-optimization of the reconstruction criteria** : 2 Boosted Decision Tree discriminants built to discriminate the prompt and the non-prompt $J/\psi$ background against the $B_s$ signal.

- CDF has presented also a new first measurement of this ratio in March 2011, see talk by M. Dorigo: "Suppressed $B_s$ Decays at the Tevatron" at same conference.

# $B_s \longrightarrow J/\Psi f_0(980)$ decay (2)




- Efficiencies estimated in MC and determined for each run range separately (triggers, tracking):

| data sample | $\varepsilon^{J/\psi f0}_{reco}$ | $\varepsilon^{J/\psi\phi}_{reco}$ | ratio R |
|---|---|---|---|
| 1 | 0.0231 ± 0.0004 | 0.0191 ± 0.0004 | 0.210 ± 0.0321 |
| 2 | 0.0191 ± 0.0004 | 0.0146 ± 0.0003 | 0.228 ± 0.0353 |
| 3 | 0.00636 ± 0.00018 | 0.00529 ± 0.00015 | 0.210 ± 0.032 |

➠ DØ's measurement: R = 0.210 ± 0.032 (stat.) ± 0.036 (syst.)

and CDF: = 0.292 ± 0.020 (stat.) ± 0.017 (syst.)

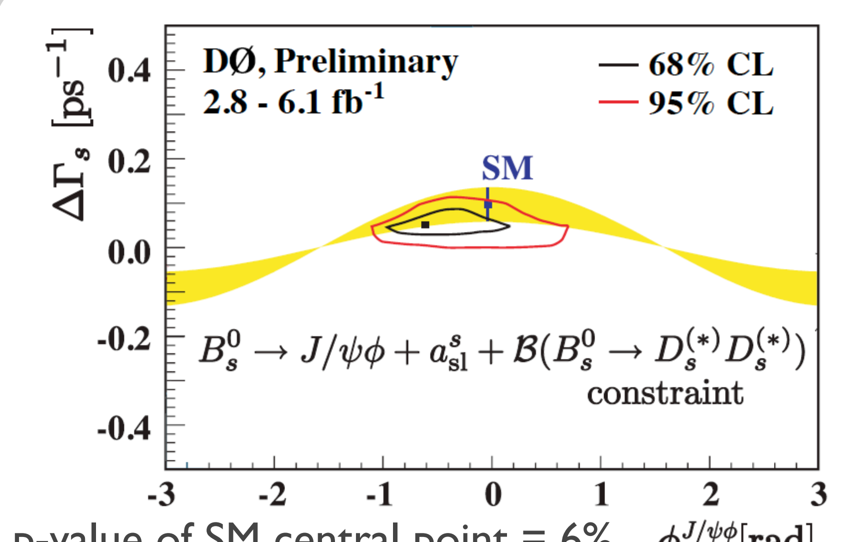
in good agreement with Belle and LHCb results.

# conclusion

- Most direct and precise experimental results on the CPV phase $\phi_s$ and the mass eigenstates width difference $\Delta\Gamma_s$ come from the Tevatron, using reconstructed $B_s \longrightarrow J/\psi\phi$ decays

CDF and DØ latest measurements have been presented, based on 5.2 and 6.1 $fb^{-1}$ of collected data respectively.

- **Error contour has significantly decreased** with higher dataset.
- New results are consistent and also **consistent with previous Tevatron measurements** using $B_s \longrightarrow J/\psi\phi$ decays.
- **Consistency with SM has improved**.
- New results demonstrate also **better consistency with NP models predictions** and are in good agreement with the anomalous like-sign dimuon charge asymmetry result, under the assumption of a single source of CPV in the $B_s$ system.




p-value of SM central point = 6%

## and outlook

- Not the final word yet:
  - twice as much data are still to be analysed,
  - analysis improvements are in progress: wider acceptance, better selection and inclusion of new decay modes. Namely **CDF and DØ have measured the relative branching ratio of $B_s \longrightarrow J/\psi f_0$** w.r.t. the $B_s \longrightarrow J/\psi\phi$ one. But other modes are possible, for instance: $B_s \longrightarrow \psi(2S)\phi$, $B_s \longrightarrow J/\psi K_s$, $B_s \longrightarrow J/\psi K^*$,
  - combination of CDF+DØ results with $B_s \longrightarrow J/\psi\phi$ decays,
  - Tevatron performs extensive study of CPV in $B_s$ system: combinations of all measurements.

# thank you

# comparison of data periods