Studies of CP-Conserving and CP-Violating Bs Mixing Parameters at DØ

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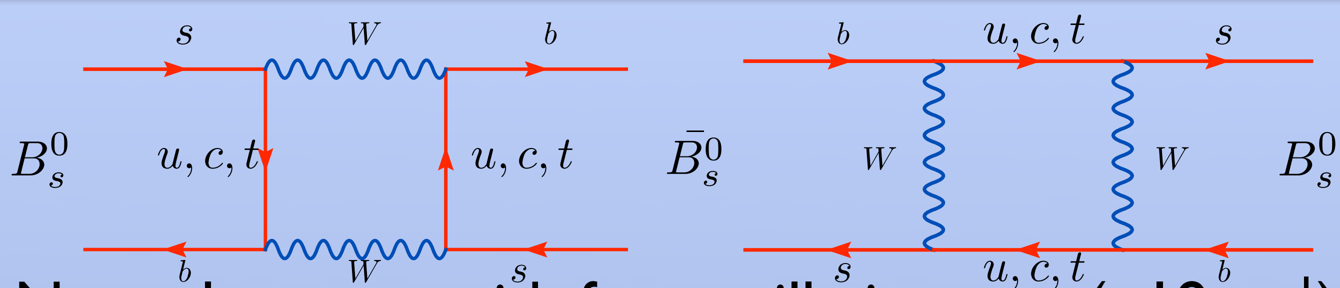
On behalf of the DØ Collaboration

Outline

- Bs meson sector;
- ΔM_s: Mass difference;
- $\Delta\Gamma_s$: Width difference;
- ϕ_s: CP-violating phase angle;
  - A^s_{SL}: Charge asymmetry;
- Combination results;
- Summary

Strange Properties of Beautiful Mesons



- Neutral mesons with fast oscillation rate (~18 ps^{-1})

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

- Flavour $B_s^0, \bar{B}_s^0$ and mass B_L, B_H eigenstates different

5 observables

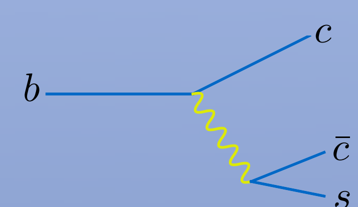
M$_{12}$ dominated by $b \longrightarrow t\bar{t}s$

$$M_s = \frac{M_H + M_L}{2}$$

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

$$\Gamma_s \equiv \frac{1}{\bar{\tau}_s} = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$



Γ$_{12}$ dominated by $b \longrightarrow c\bar{c}s$

$$\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

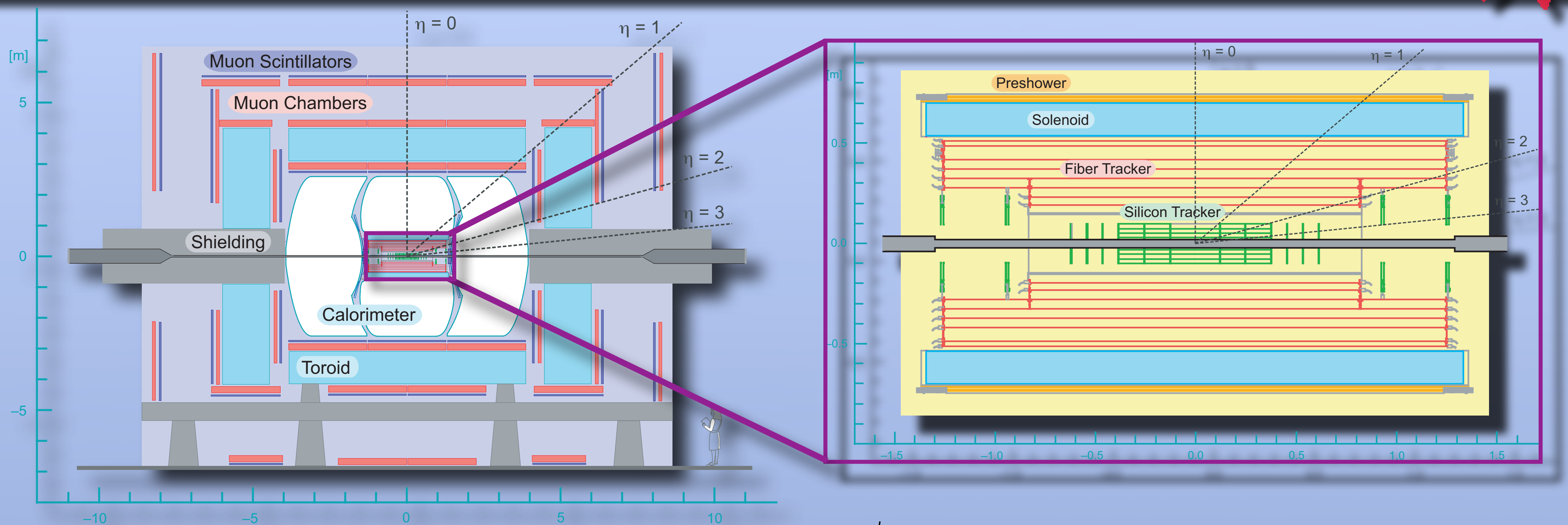
Measuring Beyond SM effects

- M_{12} sensitive to effects of new physics, both through $|M_{12}|$ and $\arg(M_{12})$.
- $|M_{12}|$ measured from $\Delta m_s \sim 2|M_{12}|$
- $\arg(M_{12})$ can be obtained through $\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$
- Γ_{12} from tree level processes; new physics unlikely, however NP can enter width difference through ϕ_s

  $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s \approx \Delta\Gamma_{SM}\cos\phi_s$

  $b \to s\gamma$ could change Γ_{12}
- leads to decrease in $\Delta\Gamma_s$.
- Gluinos and squarks in MSSM box diagrams can compete with SM contributions,

Measuring B_s mesons at DØ



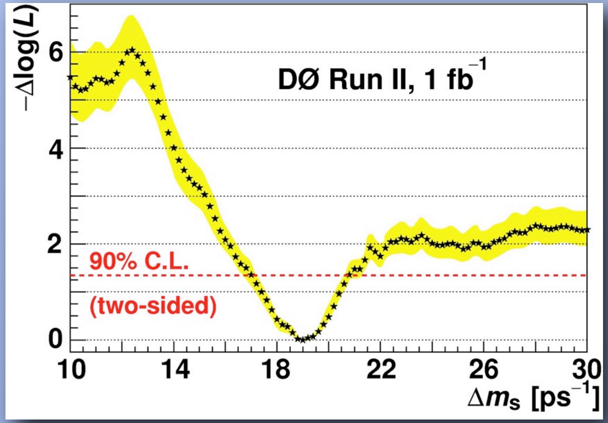
- Tevatron: proton–antiproton collisions at $\sqrt{s}$=1.96 TeV,
- Most B physics analyses utilise excellent 3-layer muon system with large $|\eta|<2$ coverage.
- Vertexing and decay-length measurements using silicon and fiber-tracking systems, enclosed within 2T field.
- Over 3fb^{-1} delivered by accelerator division to DØ since 2002.
- These analyses from ~1fb^{-1} integrated luminosity.

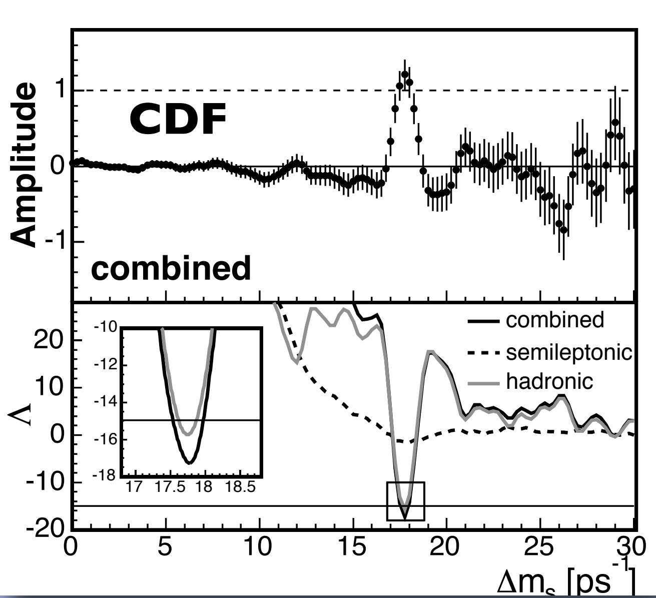
Mass Difference Δm_s

- In 2006

DØ Collab. PRL 97 021802 (2006)

  - DØ first direct double-sided bound on Δm_s, rules out potential large effects from new physics
  - CDF precision measurement.





$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat}) \pm 0.07\,(\text{syst})$$

CDF Collab. PRL 97 242003 (2006)

DØ to update shortly with improved analysis, increased luminosity and additional decay modes.

Width Difference $\Delta\Gamma_s$

- Width difference in B_s system predicted in SM as

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.127 \pm 0.024$$

(A. Lenz, U. Nierste, hep-ph/0612167).

- Effects from New Physics processes may reduce width difference

CP - even final states $\Delta\Gamma_s\uparrow$

CP - odd final states $\Delta\Gamma_s\downarrow$

- DØ results from:
  - $B_s \to D_s^{(*)} D_s^{(*)}$,
  - $B_s \to J/\psi\ \phi$.

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

- Width difference $\Delta\Gamma_s = \Delta\Gamma_s^{\mathrm{CP}} \cos\phi_s$, where $\Delta\Gamma_s^{\mathrm{CP}} \equiv 2|\Gamma_{12}| = \Gamma(\mathrm{even}) - \Gamma(\mathrm{odd})$ is the difference between the CP-even and CP-odd final-states.

- Decay of $B_s \rightarrow D_s^+ D_s^-$ is pure CP-even

- Under certain theoretical assumptions $D_s^{(*)} D_s^{(*)}$ is mainly CP-even.
  Some uncertainties in theoretical assumptions.

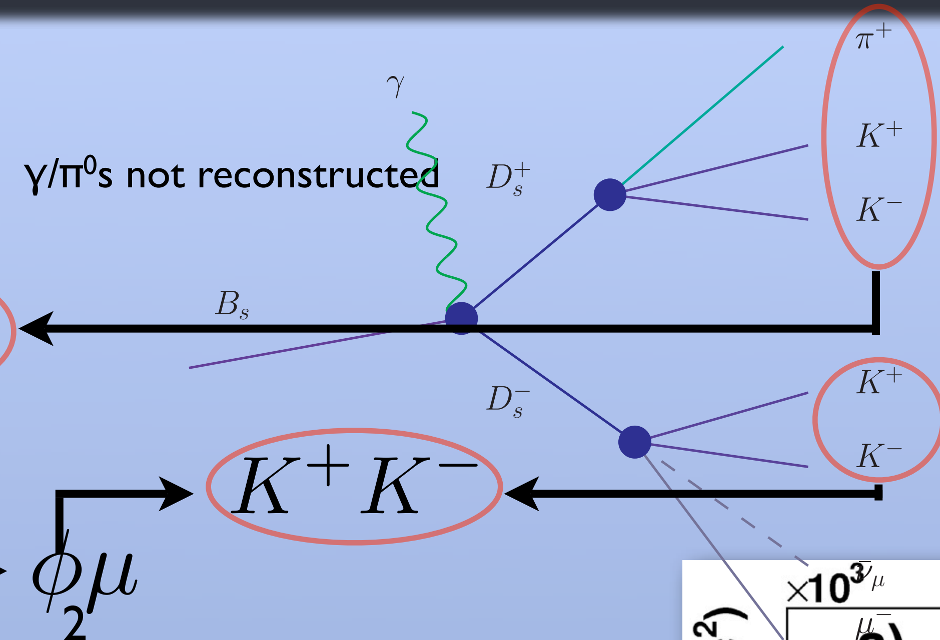
Requires validation by experiment

- Under these assumptions, measurement of branching fraction allows determination of the width difference $\Delta\Gamma_s^{\mathrm{CP}}$

$$2\mathrm{Br}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = \frac{\Delta\Gamma_s^{\mathrm{CP}}}{\Gamma_s}\left\{1 + \mathcal{O}\left(\frac{\Delta\Gamma_s}{\Gamma_s}\right)\right\}$$

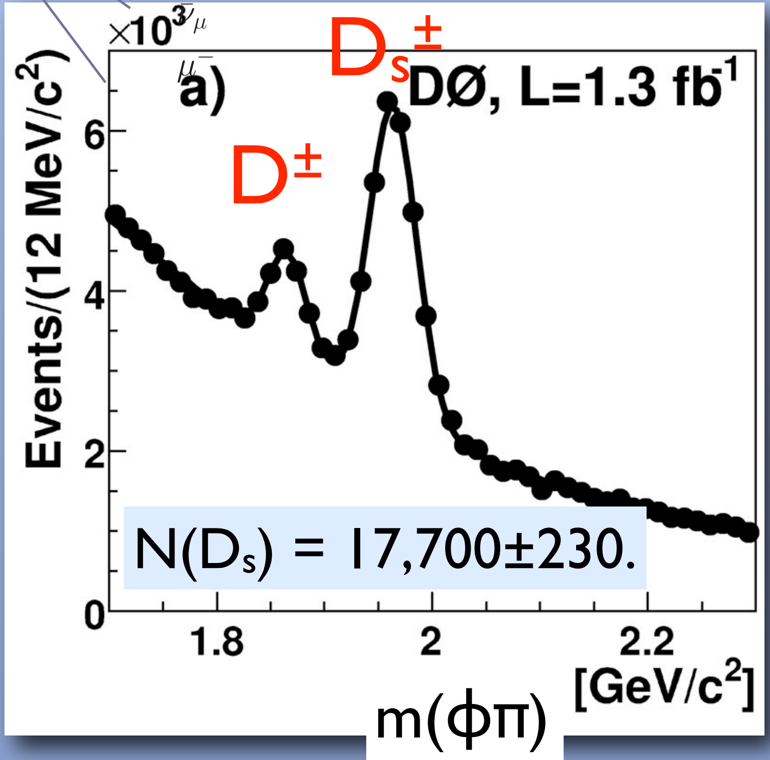
- $\Delta\Gamma_s^{\mathrm{CP}}$ is independent to CP-violation, provides a further check on NP.

Event Selection

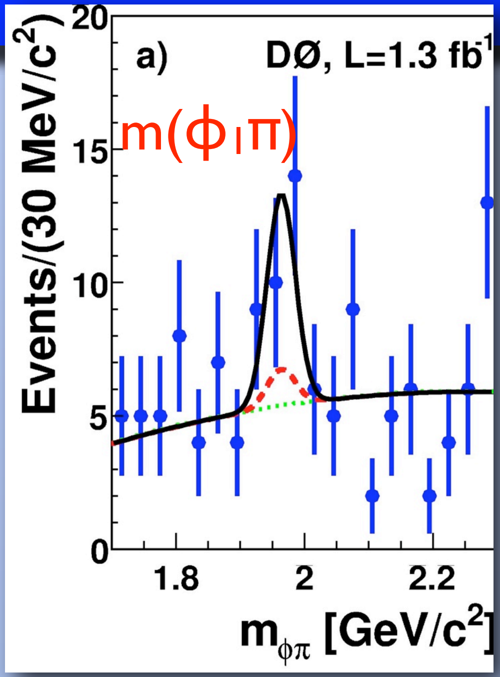


$$B_s^0 \to D_s^{(*)} D_s^{(*)}$$

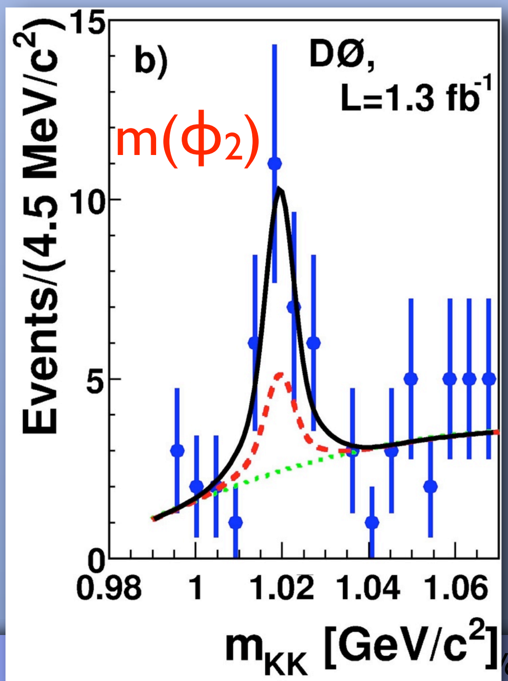
- Use 2-dimensional unbinned maximum log-likelihood technique to simultaneously fit:
  - $m(KK)$ from $D_s \to \phi\mu$,
  - $m(\phi\pi)$.
- Normalised to decay $B_s \to D_s^{(*)} \mu \nu X$, reduce detector related systematic effects.



Results: $B_s \rightarrow D_s^{(*)} D_s^{(*)}$



$$N(D_s^{(*)} D_s^{(*)}) = 13.4^{+6.6}_{-6.0}$$



- Signal $D_s^{(*)} D_s^{(*)}$: Joint production of $D_s(\Phi_1\pi)$ and Φ_2 mesons,
- Background: uncorrelated production and peaking contributions,
- Increased precision from previous measurement (ALEPH).
- DØ measures

$$\mathrm{Br}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.039^{+0.019}_{-0.017}\,(\mathrm{stat})^{+0.016}_{-0.015}\,(\mathrm{syst})$$

- Allows indirect estimate of $\Delta\Gamma_s$ through:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx 2\mathrm{Br}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$$

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079^{+0.038}_{-0.035}(\mathrm{stat})^{+0.031}_{-0.030}(\mathrm{syst})$$

- Consistent with SM. $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.127 \pm 0.024$

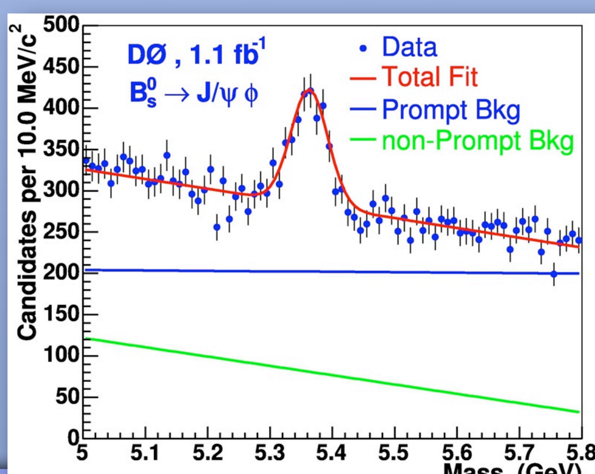
$B_s \to J/\psi\ \phi$

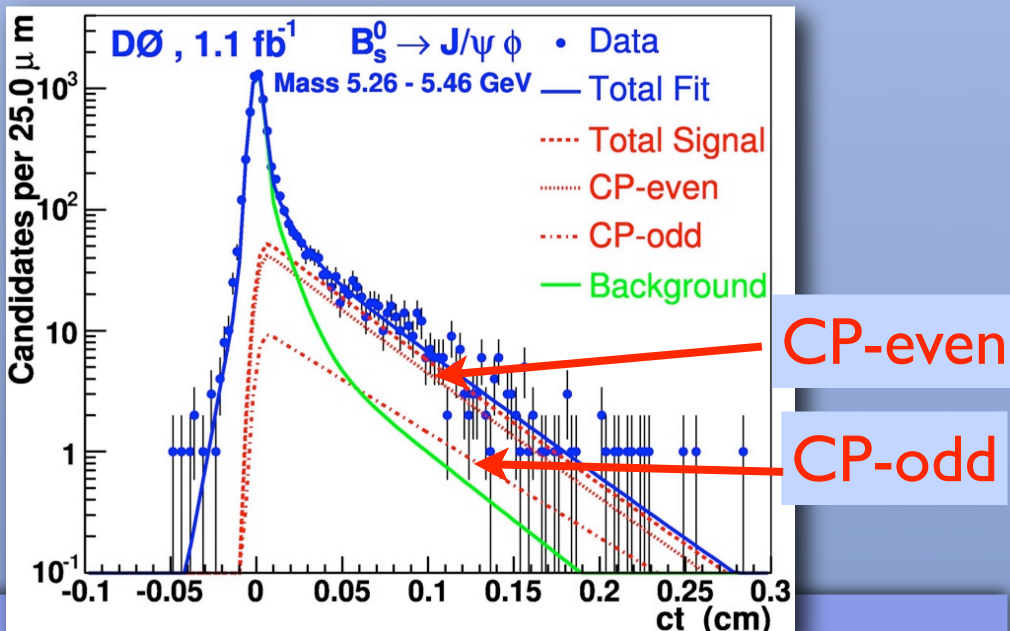
$$\left.\begin{array}{l} B_s^0 \\ \bar{B}_s^0 \end{array}\right\rangle J/\psi(\mu^+\mu^-)\phi(K^+K^-)$$

CP-Even
CP-Odd
final states

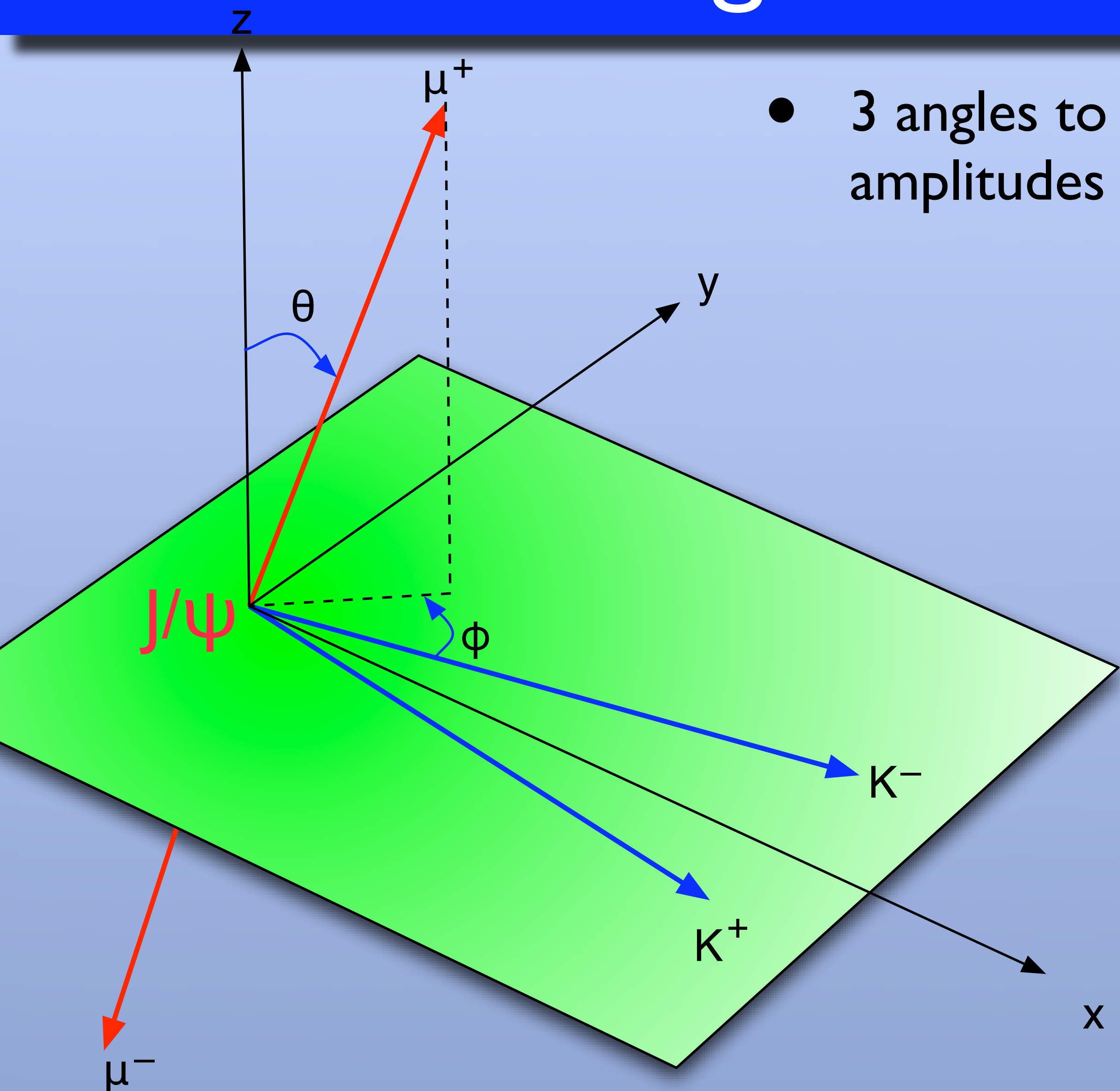
Phys. Rev. Lett. 98 , 121801 (2007)

- Untagged B_s decays to $J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$,
- Different angular distributions for the CP eigenstates,
- Separation of even and odd modes with time-dependent angular analysis of final-state particles,
- Clean experimental signal.

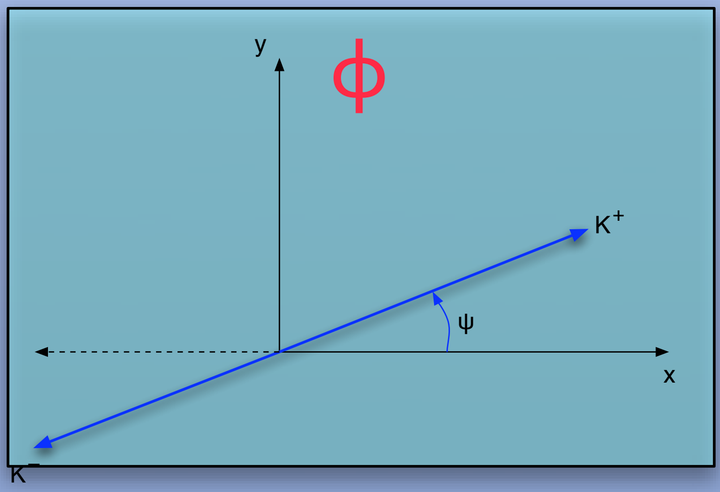




Angular variables



- 3 angles to separate polarisation amplitudes



Angular variables

- 3
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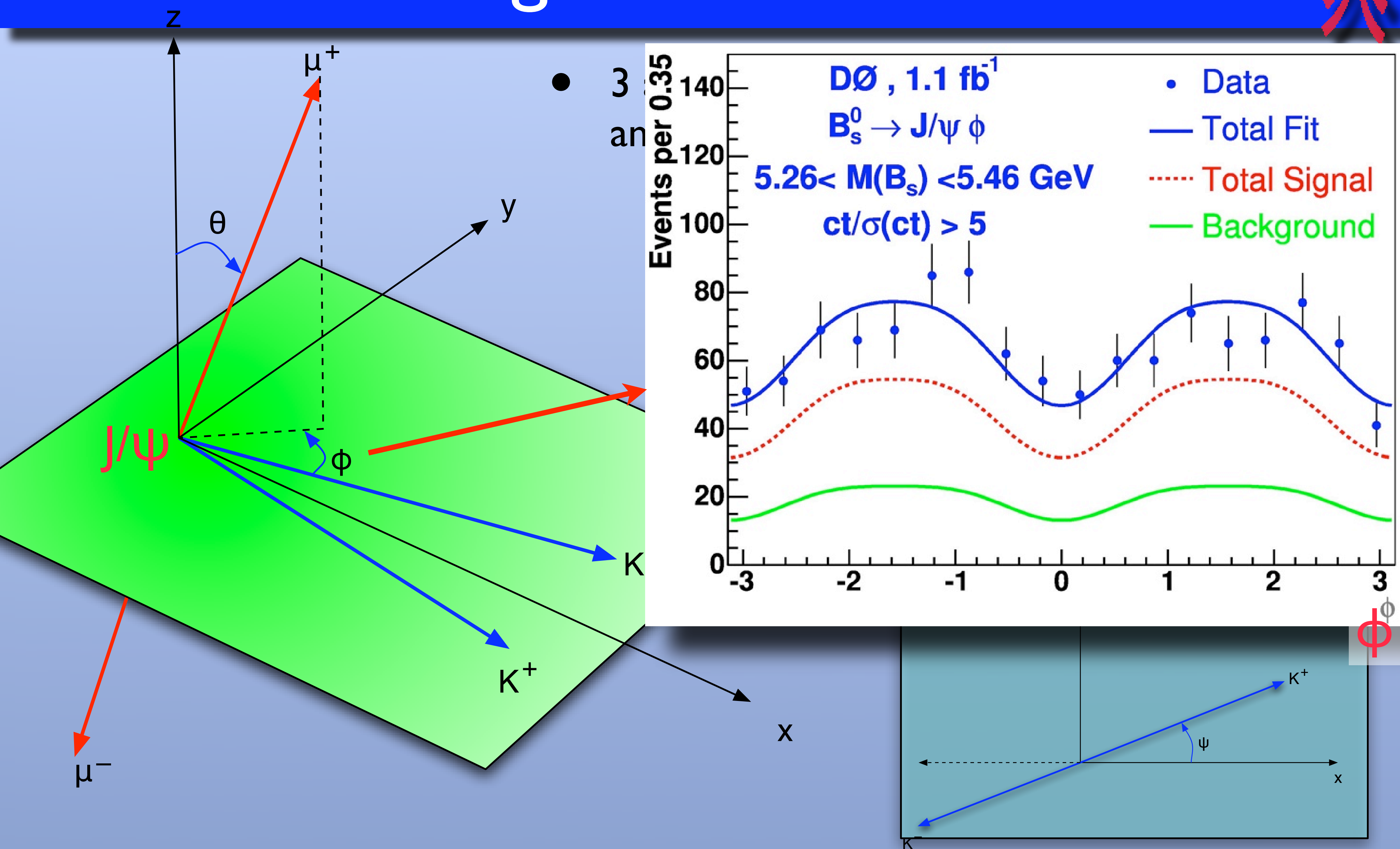
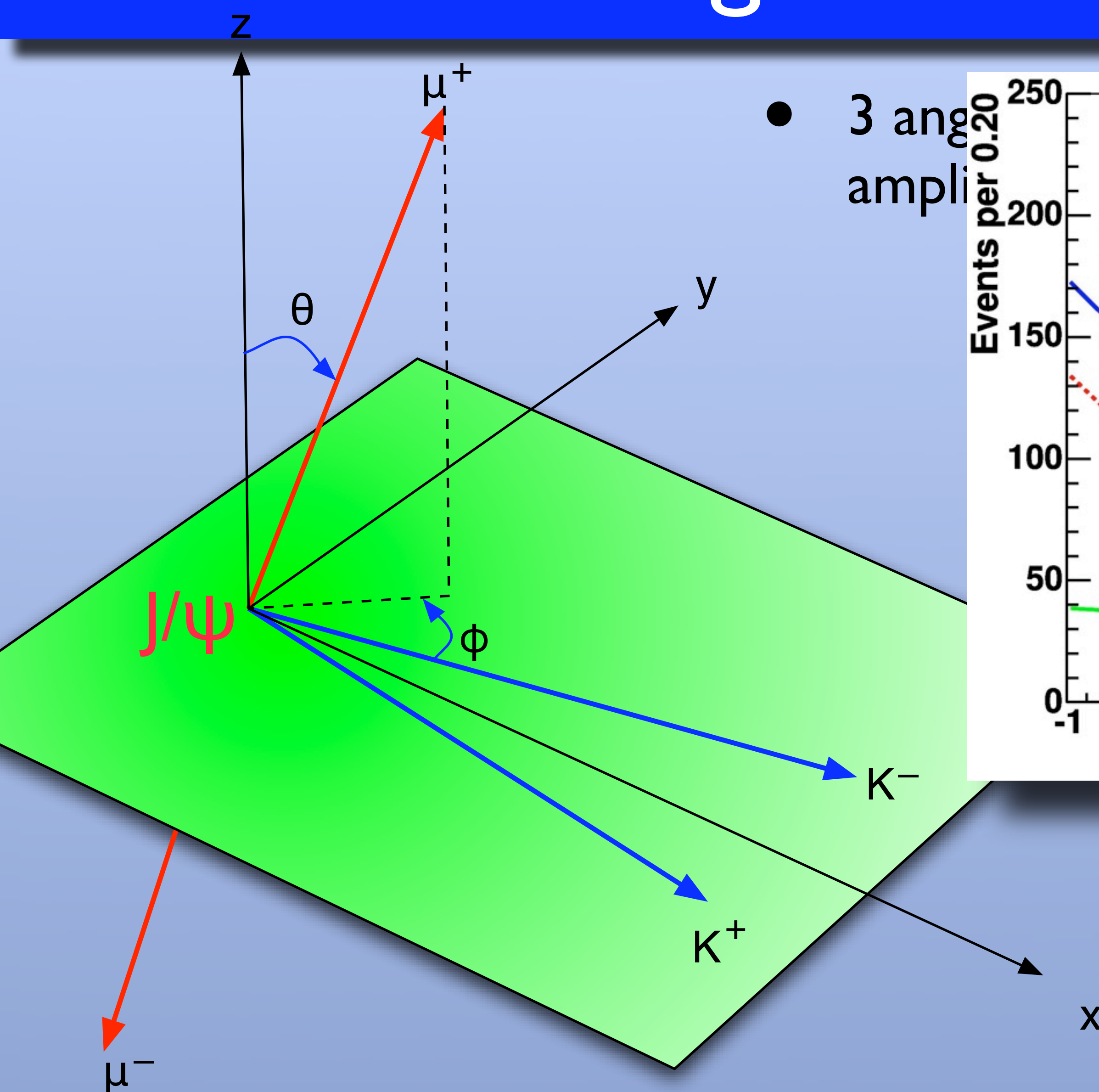


Angular variables



- 3 ang
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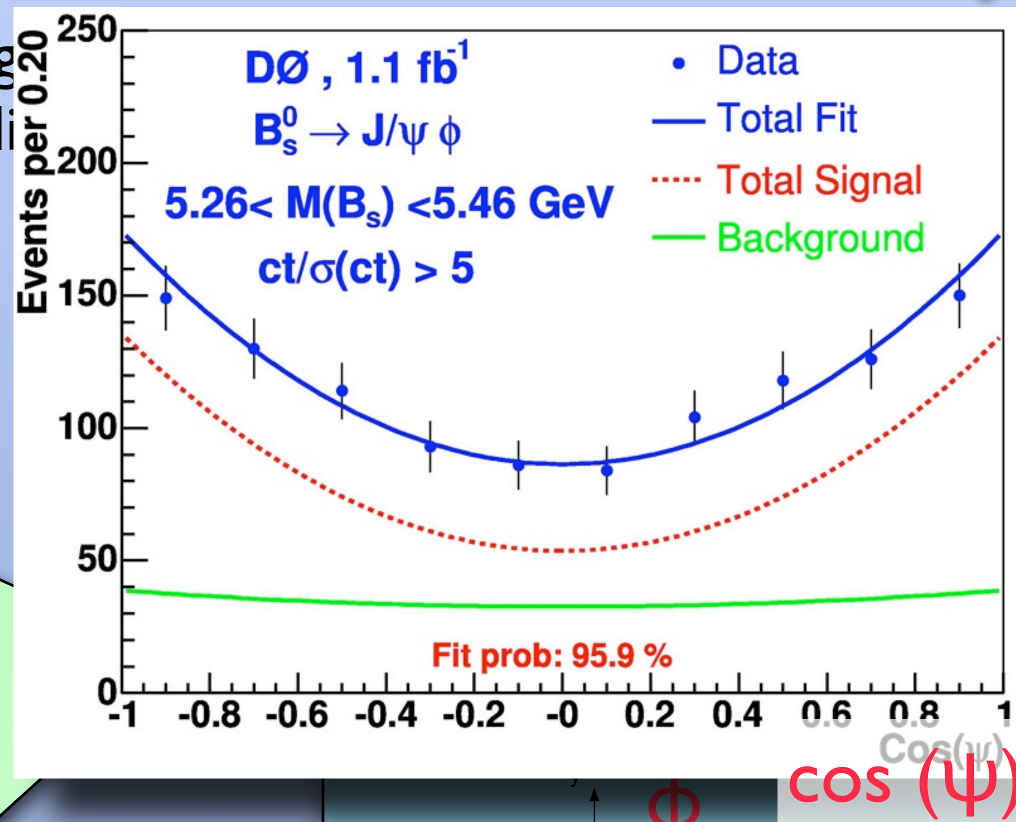
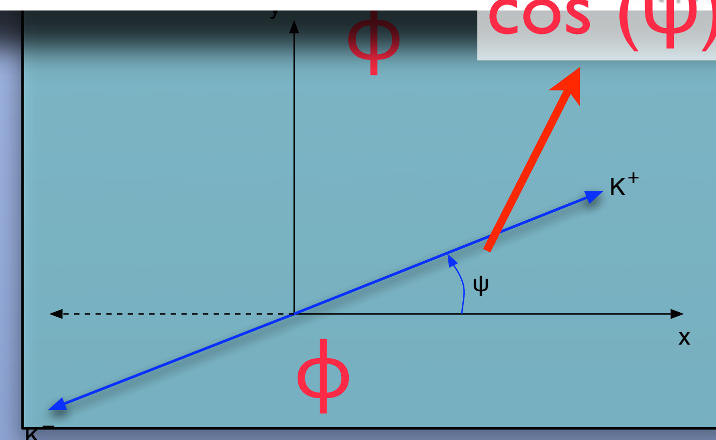
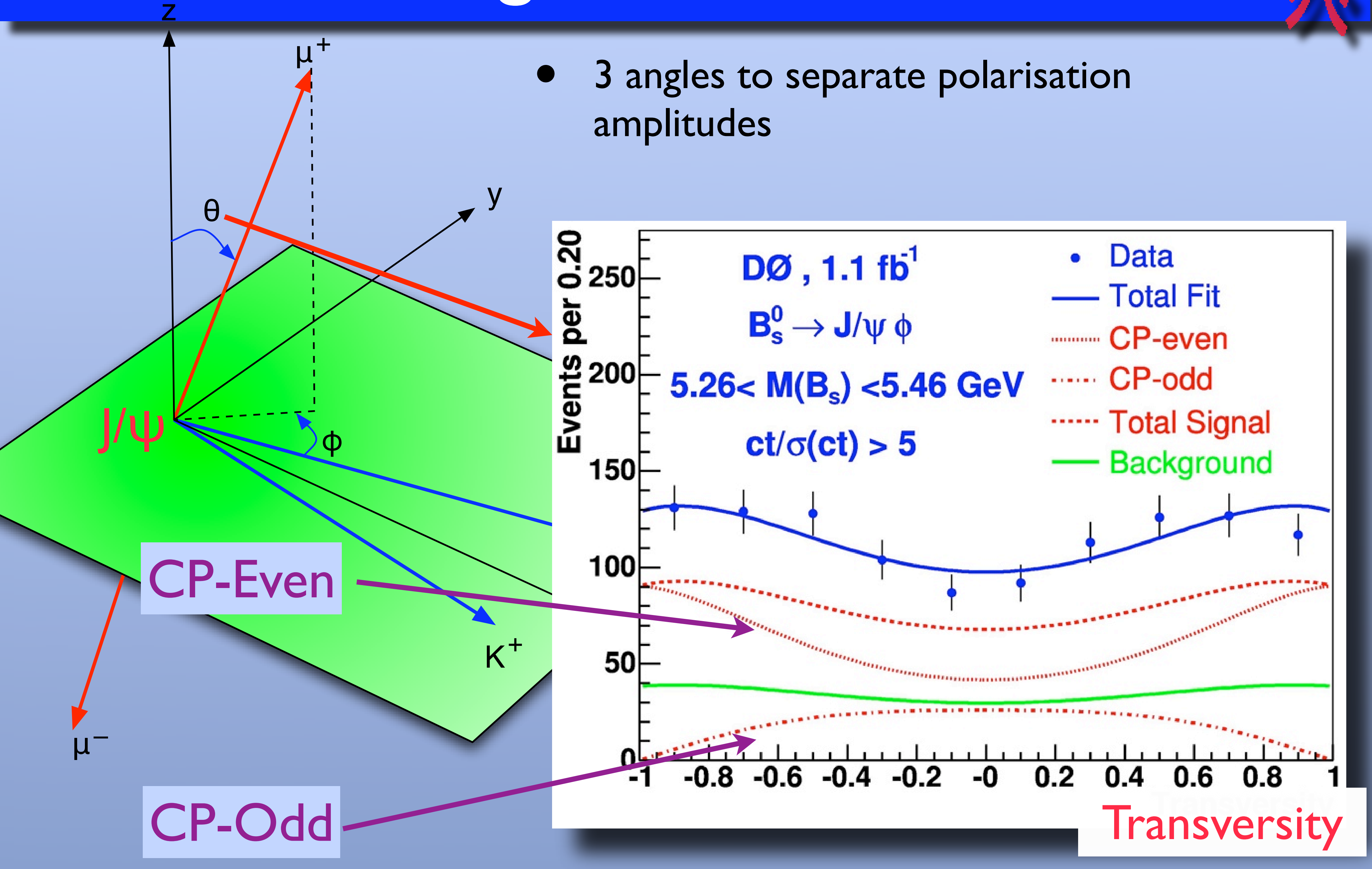




Angular variables

- 3 angles to separate polarisation amplitudes



$B_s \to J/\psi\ \phi$: Analysis

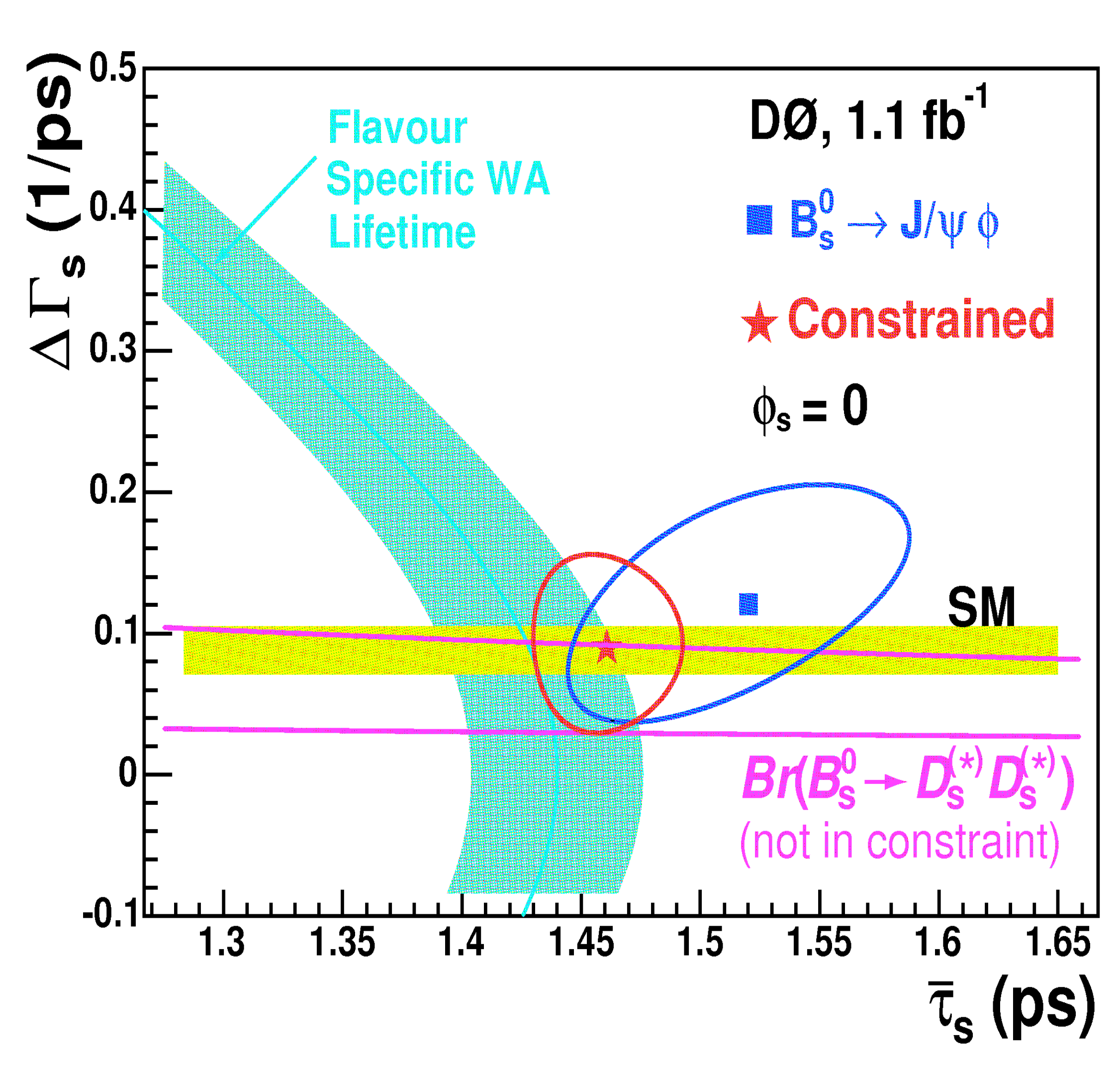
- Signal extracted from Likelihood fit using 23,343 events, yielding 1,039 ± 45 B_s candidates.
- Background parameterisations for: lifetime, invariant mass and angular distributions, with prompt and non-prompt components.
  - Prompt component from J/ψ and tracks from hadronisation
  - Non-prompt: J/ψ from B decay, tracks for ϕ meson from hadronisation or multi-body decays of same B meson.
- Extracted from fit:
  - Average lifetime,
  - Width difference,
  - (CP-violating phase),
  - Magnitude and relative phases of decay amplitudes.

Results: $\Delta\Gamma_s$

- Under no CP-violation (ϕ_s=0),
- $B_s \rightarrow J/\psi\ \phi$ yields most precise direct $\Delta\Gamma_s$ measurement:

$$\Delta\Gamma_s = 0.12^{+0.08}_{-0.10} \pm 0.02\,\mathrm{ps}^{-1}$$

$$\bar{\tau}_s = 1.52 \pm 0.08^{+0.01}_{-0.03}\,\mathrm{ps}$$



- Increased luminosity and enhanced analysis on-way.
- $B_s \rightarrow D_s^{(*)} D_s^{(*)}$ consistent with SM and other measurements.

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079^{+0.038}_{-0.035}(\mathrm{stat})^{+0.031}_{-0.030}(\mathrm{syst})$$

CP-Violating phase: ϕ_s

- Small value predicted in SM: ~-0.03 rad.
- For untagged initial state, decays of $B_s \rightarrow J/\psi\ \phi$ gives interference terms between CP-odd and CP-even states
- Relates to the time-dependent width through

  $$\Gamma_s(t) \sim (e^{-\Gamma_L t} - e^{-\Gamma_H t}) \sin\phi_s$$

- Sensitivity to ϕ_s with sizeable $\Delta\Gamma_s$,
- DØ measurement performed with $B_s \rightarrow J/\psi\ \phi$;
  - Same data as for $\Delta\Gamma_s$ analysis, where
  - ϕ_s is now a free parameter in the fitting procedure.

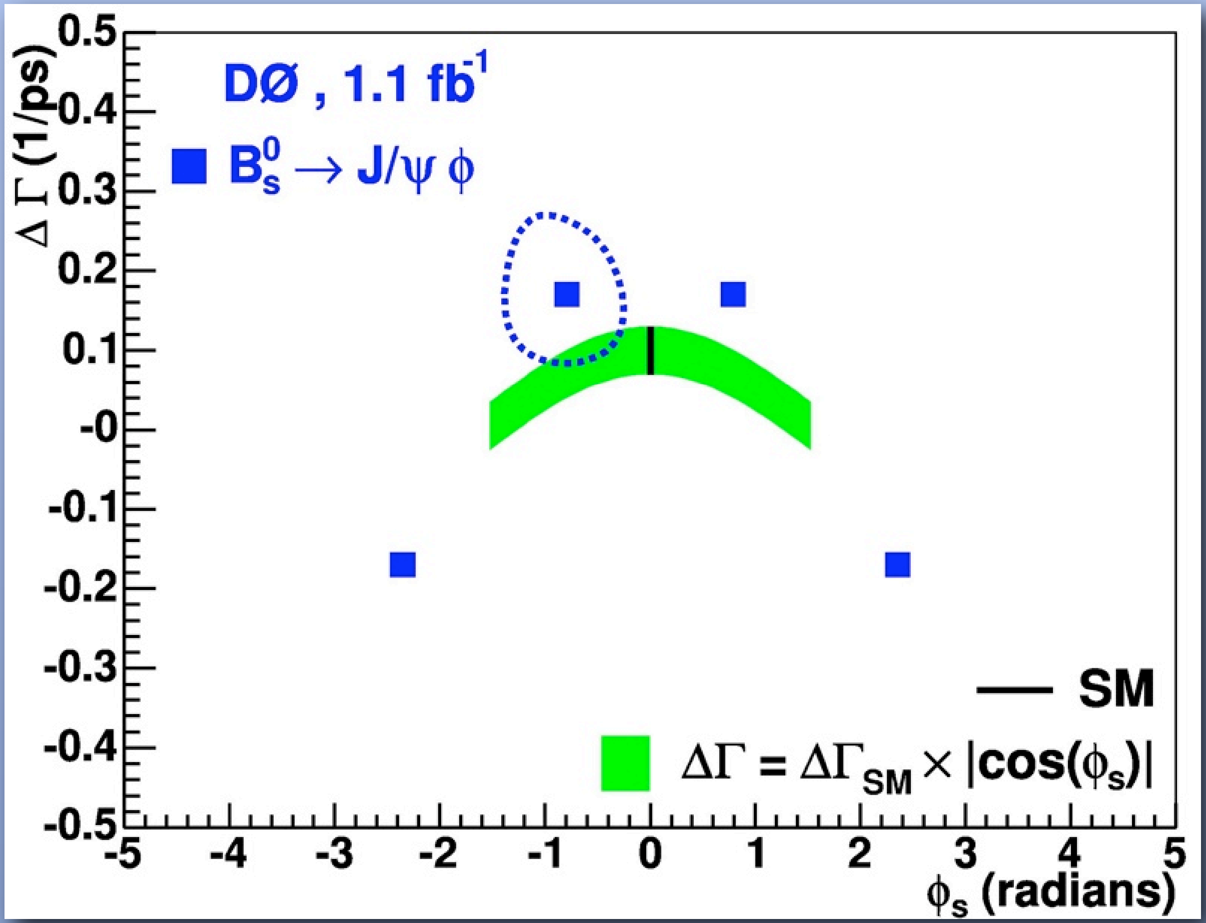
Results: ϕ_s

- First direct constraint on ϕ_s

$$\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01} \qquad \Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.02\,\mathrm{ps}^{-1}$$

4-fold ambiguity on *sign*(ϕ_s,$\Delta\Gamma_s$)
with flip of strong phase angles

$\Delta\Gamma$	$\cos\delta_1, \cos\delta_2$	ϕ_s
>0	>0,<0	-0.79
<0	>0, <0	+2.35
>0	<0,>0	+0.79
<0	<0,>0	-2.35



Combination of Results

- Additional measurements from DØ in charge asymmetry in:
  - di-muon decays, $$A_{SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}.$$
  - Semileptonic decays. $$A_{SL}^{\mathrm{unt}} = \frac{N(B_s \to D_s^-\mu^+\nu) - N(B_s \to D_s^+\mu^-\bar{\nu})}{N(B_s \to D_s^-\mu^+\nu) + N(B_s \to D_s^+\mu^-\bar{\nu})} \approx \frac{1}{2}A_{SL}^s$$
- CP-violation through mixing would produce non-zero charge asymmetry A_{SL}^s.
- Refer to talk by Pieter Van Den Berg, Monday 30 Jul for further details.
- Combined value from both measurements yields $A_{SL}^s = 0.0001 \pm 0.0090.$
- Provides important constraint in order to combine measurements.

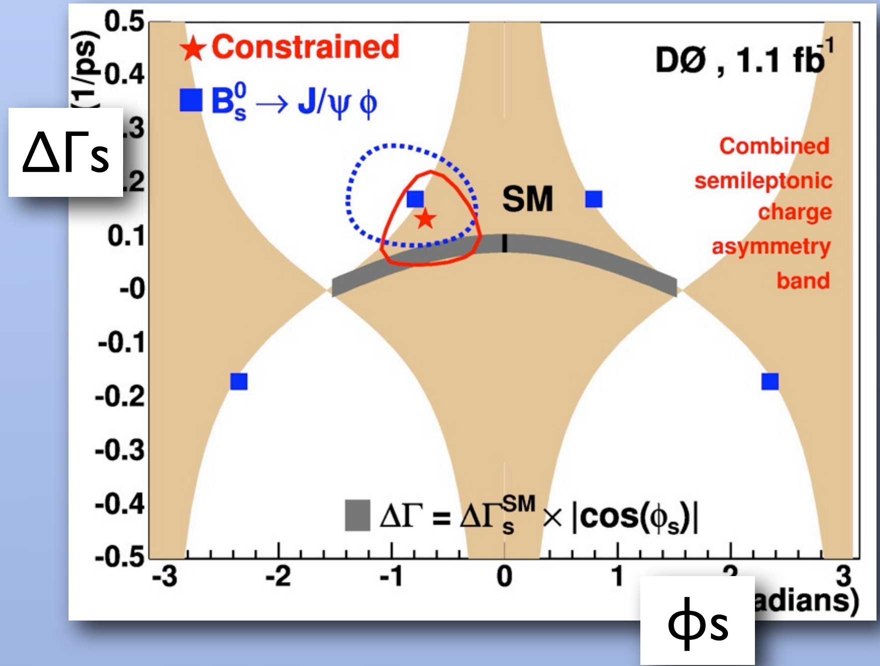
$$A_{SL} = \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

Combination Results

- Possible to extract additional constraint by combining measurements,

$$\Delta\Gamma_s \tan\phi_s = A^s_{SL}\Delta m_s = 0.02 \pm 0.16\,\mathrm{ps}^{-1}$$

- Includes external input:
  - Δm_s (CDF),
  - World-average flavour-specific Bs lifetime (includes DØ lifetime measurement).
    $\tau_{fs} = 1.440 \pm 0.036\,\mathrm{ps}^{-1}$ (HFAG)
- Refit $B_s \rightarrow J/\psi\ \phi$ data with new constraint.
- ϕ_s ~1.2σ from SM expectation,
- 4-fold ambiguity remains.



hep-ex/0702030, PRD

$\Delta\Gamma_s = 0.13 \pm 0.09\,\mathrm{ps}^{-1}$		Or		$\Delta\Gamma_s = -0.13 \pm 0.09\,\mathrm{ps}^{-1}$	
$\lvert\phi_s\rvert = 0.70^{+0.39}_{-0.47}$				$\lvert\phi_s\rvert = 2.44^{+0.47}_{-0.39}$	

Summary

- Exciting results in observable parameters of Bs sector
- Δm_s: Have precision measurement (CDF) CDF Collab. PRL 97 242003 (2006)
- $\Delta\Gamma_s$: Direct measurements Phys. Rev. Lett. 98 , 121801 (2007)
- ϕ_s: First direct constraint – sign ambiguity still to be resolved.
- Combined results of $\Delta\Gamma_s$, ϕ_s *hep-ex/0702030, PRD*
- All currently consistent with SM predictions, however
- Results statistically limited.
- With increased luminosity (4-8 fb^{-1}) expected from Tevatron, and improved analyses, will allow us to probe deeper into asymmetry within the Universe.

Backup

Γ

$$\frac{d^3\Gamma(t)}{d\cos\theta\ d\varphi\ d\cos\psi} \propto 2|A_0(0)|^2\,\mathcal{T}_+\ \cos^2\psi(1-\sin^2\theta\cos^2\varphi)+\sin^2\psi\{|A_\parallel(0)|^2\,\mathcal{T}_+\ (1-\sin^2\theta\sin^2\varphi)+|A_\perp(0)|^2\,\mathcal{T}_-\ \sin^2\theta\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\ \mathcal{T}_+\ \sin^2\theta\sin 2\varphi$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi\right.$$

$$\left.-|A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin\phi_s\ . \qquad (2)$$

$$\mathcal{T}_{+/-} = \tfrac{1}{2}\left((1\pm\cos\phi_s)e^{-\Gamma_L t}+(1\mp\cos\phi_s)e^{-\Gamma_H t}\right)$$

Likelihood fit parameters

Observable	CP conserved	free ϕ_s
$\Delta\Gamma$ (ps^{-1})	$0.12^{+0.08}_{-0.10}$	$0.17^{+0.09}_{-0.09}$
$\frac{1}{\overline{\Gamma}} = \overline{\tau}$ (ps)	$1.52^{+0.08}_{-0.08}$	1.49 ± 0.08
ϕ_s	$\equiv 0$	-0.79 ± 0.56
$\lvert A_0(0)\rvert^2 - \lvert A_{\parallel}(0)\rvert^2$	0.38 ± 0.05	0.37 ± 0.06
$A_{\perp}(0)$	0.45 ± 0.05	0.46 ± 0.06
$\delta_1 - \delta_2$	2.6 ± 0.4	2.6 ± 0.4
δ_1	–	3.3 ± 1.0
δ_2	–	0.7 ± 1.1

Systematics

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	ϕ_s
Procedure test	± 2.0	± 0.02	± 0.01	–
Acceptance	± 0.5	± 0.001	± 0.003	± 0.01
Reco. algorithm	$-8.0, +1.3$	$+0.001$	± 0.01	-0.01
Background model	$+1.0$	$+0.01$	-0.01	$+0.14$
Alignment	± 2.0	–	–	–
Total	$-8.8, +3.3$	± 0.02	± 0.02	$-0.01, +0.14$

Angles

In the coordinate system of the J/ψ rest frame (where the ϕ meson moves in the x direction, the z axis is perpendicular to the decay plane of $\phi \to K^+K^-$, and $p_y(K^+) \geq 0$), the transversity polar and azimuthal angles (θ, φ) describe the direction of the μ^+, and ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ in the ϕ rest frame.