Measurement of CP violation in B-meson decays at DØ

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http://www-d0.fnal.gov/~rakitin/SLAC.pdf

Why study CP-violation?

- To explain baryon asymmetry of the Universe we need sources of CP-violation from beyond the Standard Model
- SM predicts CPV effects to be relatively small
- Many New Physics models may significantly increase these effects [hep-ph/9803370]:
  - Multi-Higgs Doublet models with no "Natural Flavor Conservation"
  - Supersymmetric models with "Effective SUSY"
  - Supersymmetric models with "R-Parity Violation"
  - Left-Right Symmetric models
  - 4th generation models
  - Z-mediated Flavor Changing Neutral Currents

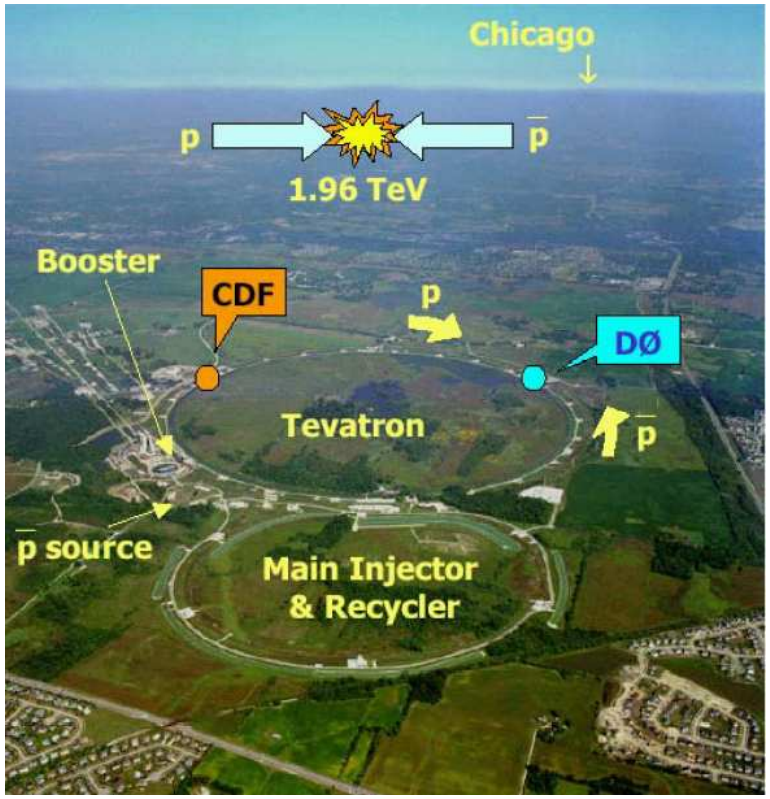
Measurement of the large CPV where it is predicted to be small may reveal NP

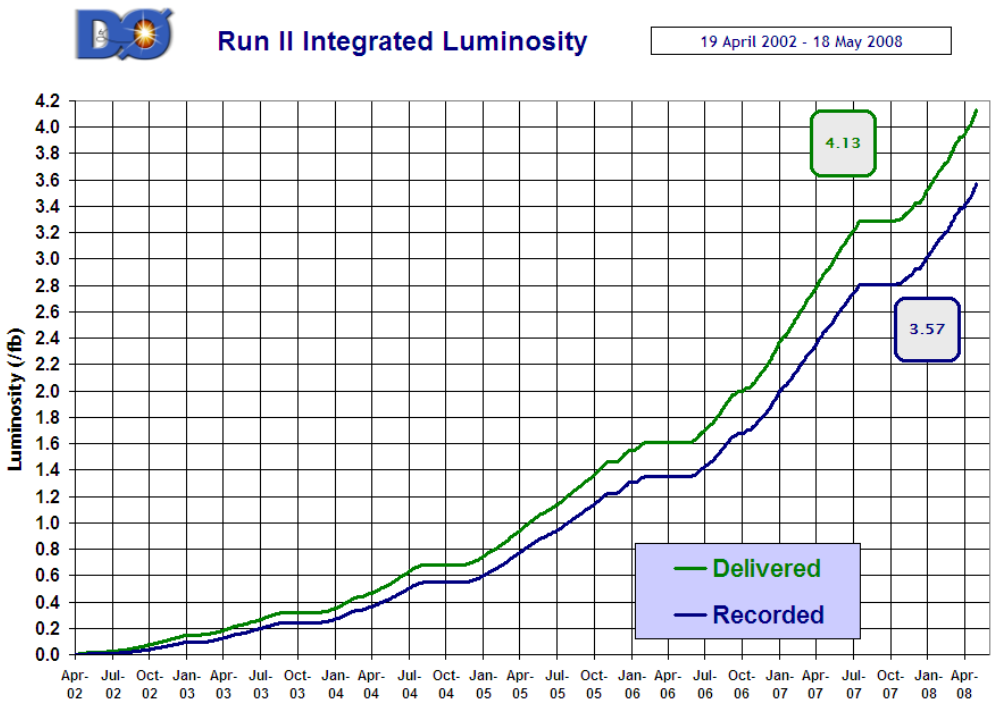
Why CP-violation in B mesons?

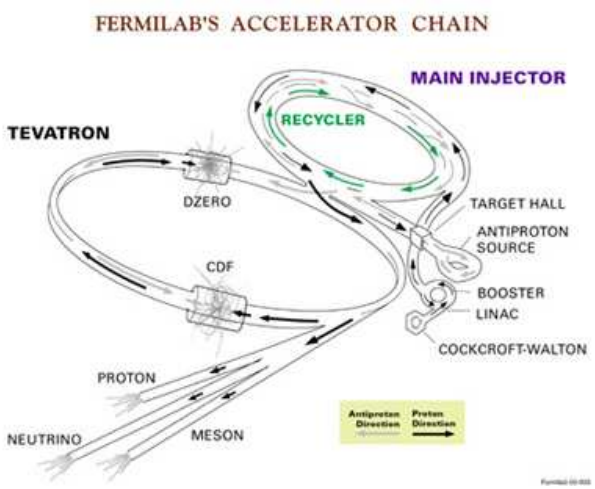
- B-factories excluded large NP contributions from tree-level B-decays
- SM predicts small CP phases at loop-level B-decays but large phases from NP are still possible [hep-ph/9803370, hep-ph/0210167]
- SM also predicts small direct CP asymmetries in B mesons, which NP may increase
- The decays $B_s \to J/\psi\phi$ (CP-violating phase) and $B^+ \to J/\psi K$ (CP asymmetry) are ideal for investigating these effects

I am going to talk about these two analyses performed at DØ experiment at Tevatron

Tevatron Collider at Fermilab



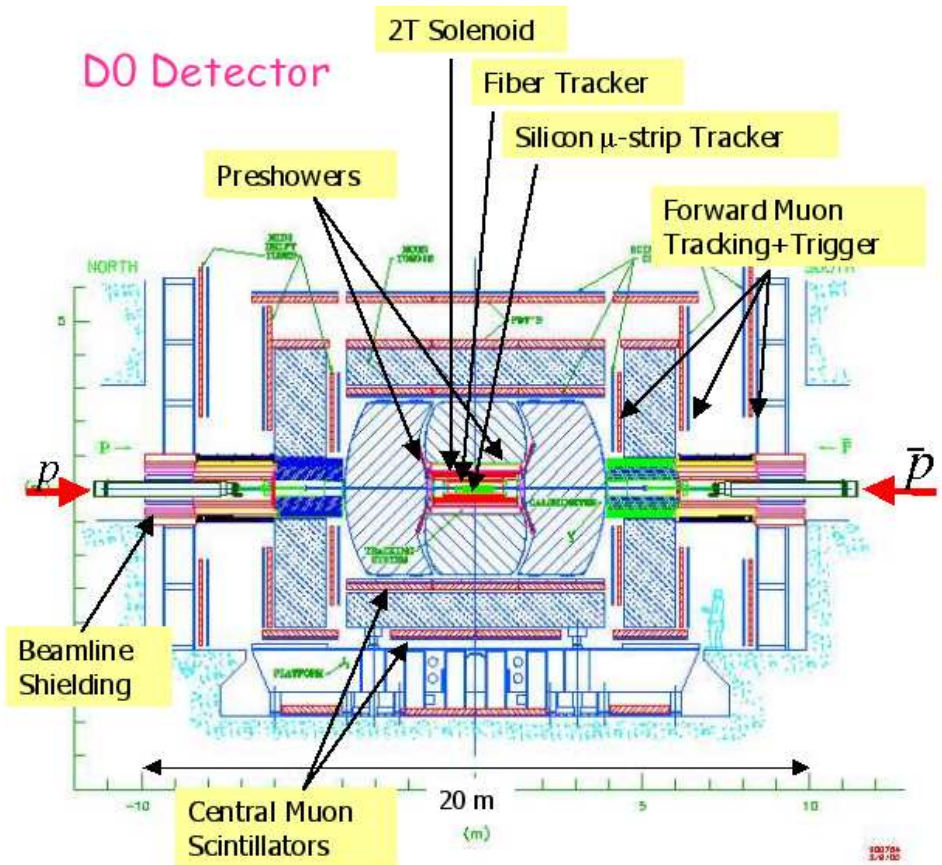




- 36×36 $p\bar{p}$ bunches, 10^{12} (10^{10}) p $(\bar{p})$ per bunch
- Bunches collide every 396 ns at CM energy 1.96 TeV
- Record $\mathcal{L}_{inst} = 315 \times 10^{30}$ cm^{-2} sec^{-1}
- $\int \mathcal{L} dt$ up to 50 pb^{-1}/week!
- Integrated $\mathcal{L} \sim 3.4$ fb^{-1} on tape, up to ~ 2.8 fb^{-1} used

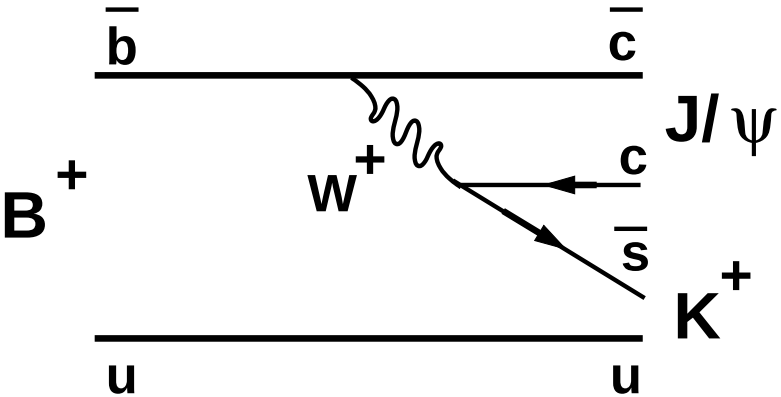
DØ Detector

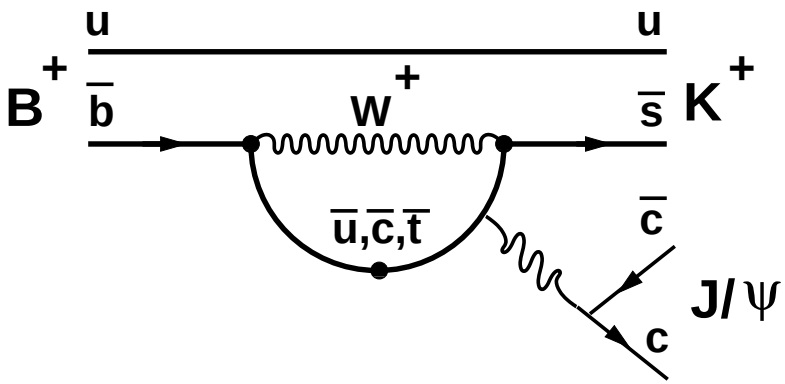
- Silicon and fiber trackers immersed into 2 T solenoid, coverage $|\eta| < 3$
  - Precise vertexing and tracking
  - New Layer 0 silicon on beam pipe in 2006 improves impact parameter resolution
- Muon system (central + forward), coverage $|\eta| < 2$
  - Includes its own magnet – toroid
- Two magnets – solenoid and toroid – flip polarities every two weeks
  - Unique feature of DØ
  - Diminishes detector asymmetries



Measurement of direct CP-violation in $B^+ \to J/\psi K^+$ decay

The decay $B^{\pm} \to J/\psi K^{\pm}$ goes via two diagrams:





- Their interference produces small asymmetry $A_{CP} = 0.003$ [hep-ph/0605080]
- New Physics can significantly enhance this asymmetry

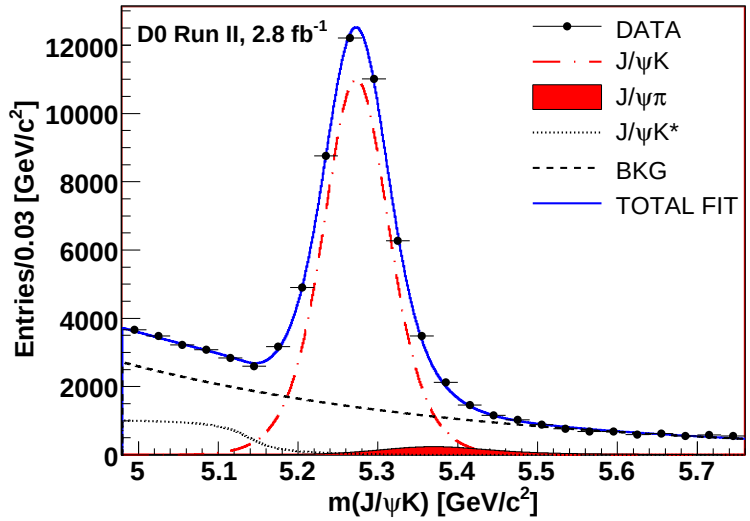
Analysis outline

- We divide $J/\psi K$ sample into 8 categories according to:
  - ☞ Solenoid polarity, β
  - ☞ Sign of kaon pseudorapidity, γ
  - ☞ Kaon charge, q
- Number of events in each category:

  $$n_q^{\beta\gamma} = \frac{1}{4} N \epsilon^{\beta} (1 + q A^{raw})(1 + \gamma A_{det})(1 + q\gamma A_{fb})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma})(1 + q\beta\gamma A_{ro})$$

  where
  - N - number of signal events in the sample
  - ϵ^{β} - fraction of integrated luminosity with magnet polarity β ($\epsilon^{+} + \epsilon^{-} = 1$)
  - A^{raw} - integrated raw charge asymmetry we want to measure
  - A_{fb} - forward-backward asymmetry (more kaons go in proton direction)
  - A_{det} - north-south asymmetry of the detector
  - $A_{q\beta\gamma}$ - decrease of acceptance of kaons bent by the magnet
  - $A_{\beta\gamma}$ - detector forward-backward asymmetry remaining after magnet polarity flip
  - $A_{q\beta}$ - change in kaon reconstruction efficiency after magnet polarity flip
- Fit for 8 $n_q^{\beta\gamma} \Longrightarrow$ obtain 8 equations with 8 unknowns
- Solve for $A^{raw} \Longrightarrow$ obtain $A_{CP}(B^{+} \to J/\psi K^{+})$

Mass distribution of $J/\psi K$



Unbinned likelihood fit of the inv. mass distribution of $\mu\mu K$ system

$\beta\gamma q$	$J/\psi K$	$J/\psi\pi$	$J/\psi K^{*0}$	Background
$+++$	5104±87	337 ± 44	692 ± 77	4079 ± 151
$+-+$	5131±87	222 ± 42	689 ± 78	4170 ± 151
$++-$	4999±85	212 ± 40	767 ± 76	3978 ± 149
$+--$	5098±86	144 ± 38	523 ± 77	4395 ± 150
$-++$	4973±86	158 ± 41	578 ± 78	4397 ± 151
$--+$	5039±86	127 ± 39	663 ± 78	4281 ± 150
$-+-$	4965±85	242 ± 41	794 ± 76	3880 ± 148
$---$	4906±84	138 ± 39	724 ± 75	4006 ± 147
Total	40222 ± 242	1578 ± 119	5429 ± 217	33192 ± 425

Asymmetries

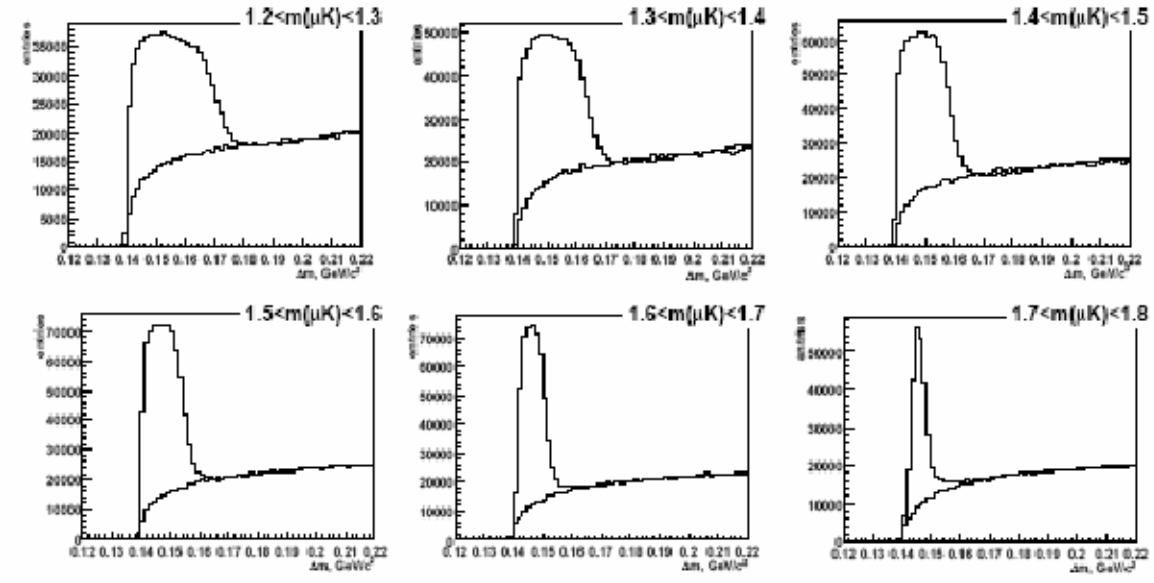
	$J/\psi K$	$J/\psi\pi$	Background
N	40217±243	1577±118	33189±424
ϵ^+	0.5060±0.0030	0.5060±0.0030	0.5010±0.0064
A^{raw}	-0.0070±0.0060	-0.0887±0.0807	-0.0205±0.0128
A_{fb}	0.0013±0.0060	0.0453±0.0890	-0.0170±0.0128
A_{det}	-0.0033±0.0060	0.2061±0.0826	-0.0158±0.0128
A_{ro}	-0.0050±0.0060	-0.0207±0.0873	-0.0024±0.0128
$A_{\beta\gamma}$	0.0001±0.0060	-0.1896±0.0823	0.0274±0.0128
$A_{q\beta}$	-0.0030±0.0060	0.0499±0.0801	-0.0145±0.0128

Kaonic A^{raw} has to be corrected for kaon asymmetry:

- Reaction $K^- + N \rightarrow$ hyperon $+ \pi$ has no analog $K^+ + N$, therefore $N(K^+) > N(K^-)$

Correction for kaon asymmetry

- This asymmetry measured in the channel
  $c \to D^{*+} \to D^0\pi^+, D^0 \to \mu^+\nu K^-$ (2.8 fb^{-1})
- No CPV is expected in this decay [hep-ph/0311371]



- Plot $\Delta m = m(\mu K\pi) - m(\mu K)$ distributions: wrong-sign (q_μ, q_π, q_K are the same) and right-sign (q_K is different)
- Width of the right-sign peak depends on $m(\mu K) \Longrightarrow$ bin in $m(\mu K)$
- Background under the peak is sideband-subtracted using events at high Δm (far from the peak)
- For every $\beta\gamma q$ combination perform sideband-subtraction in all $m(\mu K)$ bins, sum the results $\Longrightarrow$ obtain 8 numbers $N_q^{\beta\gamma}$
- Solve for corresponding raw kaon asymmetry

Correction for kaon asymmetry

This raw kaon asymmetry must be

- corrected for sample composition
- averaged over kaon momentum
  - Cross-section $\sigma(K+N)$ and, therefore, the kaon asymmetry itself depend on kaon momentum
- subtracted from A^{raw}

to obtain:

$$A_{CP}(B^+ \to J/\psi K^+) = 0.0075 \pm 0.0061(\text{stat.}) \pm 0.0027(\text{syst.})$$

For pions such correction is covered by systematic error:

$$A_{CP}(B^+ \to J/\psi \pi^+) = -0.0887 \pm 0.0807(\text{stat.}) \pm 0.0283(\text{syst.})$$

Results

- Asymmetry $A_{CP}(B^+ \to J/\psi K^+)$ is consistent with zero
- Precision is of the order of SM prediction
- Consistent with current PDG value $A_{CP} = 0.015 \pm 0.017$, but factor of three better precision

- Asymmetry $A_{CP}(B^+ \to J/\psi \pi^+)$ is also consistent with zero
- Also consistent with PDG value $A_{CP} = 0.09 \pm 0.08$
- Has a competitive precision

Measurement of CP-violation in $B_s \to J/\psi\phi$ decay

CKM matrix

CKM matrix relates quark weak flavor and mass eigenstates:

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

$$= \begin{vmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{vmatrix} + \mathcal{O}(\lambda^4)$$

- In SM CP-violation is governed by only one parameter η (complex phase)
- NP may provide plenty of new complex phases

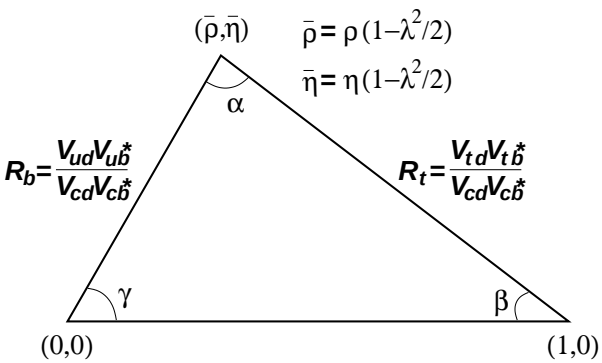
CKM Matrix Unitarity Condition

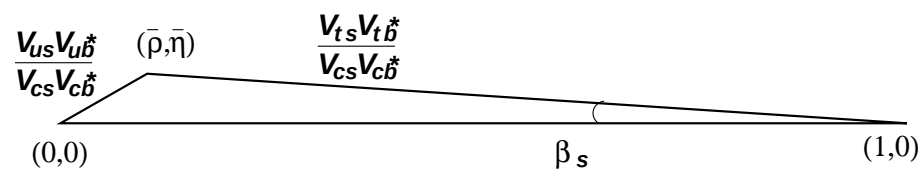
$$V^{\dagger}_{CKM} V_{CKM} = 1$$

This translates into:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

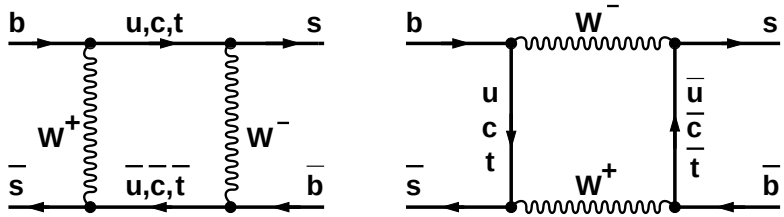
$$V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0$$





- Both triangles have the same area, proportional to CPV level
- The triangles involve different elements of CKM matrix
  - First triangle provides for measurement of $\sin 2\beta$ from $B_d \to J/\psi K_S$ decay
  - Similarly, 2nd triangle provides for $\sin 2\beta_s$ from $B_s \to J/\psi\phi$ (harder to do)

B_s-mixing



Weak eigenstates: $i\frac{d}{dt}\begin{pmatrix}|\overline{B_s}(t)\rangle\\|B_s(t)\rangle\end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix}|\overline{B_s}(t)\rangle\\|B_s(t)\rangle\end{pmatrix}$

CP eigenstates: $|B_s^{odd}\rangle = |B_s(t)\rangle - |\overline{B_s}(t)\rangle$
$|B_s^{even}\rangle = |B_s(t)\rangle + |\overline{B_s}(t)\rangle$

Mass eigenstates: $|B_s^{Heavy}\rangle = p|B_s(t)\rangle - q|\overline{B_s}(t)\rangle$
$|B_s^{Light}\rangle = p|B_s(t)\rangle + q|\overline{B_s}(t)\rangle$

Observables:

- $\Delta M_s = M_H - M_L \approx 2|M_{12}^s|$
- $\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \approx 2|\Gamma_{12}^s|$
- $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}^s|\cos\phi_s$,
  where CP-violating phase $\phi_s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right) \approx 0.004$ in SM
- Average lifetime $\overline{\tau} \equiv 1/\overline{\Gamma}$, where $\overline{\Gamma} = \frac{1}{2}(\Gamma_L + \Gamma_H)$

New Physics Phase ϕ_s^{NP}

- In Standard Model both $\beta_s^{SM} = 0.02$ and $\phi_s^{SM} = -0.004$ are small, beyond current experimental reach
- New Physics may introduce a new phase ϕ_s^{NP} such that:
  - ☞ $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$
  - ☞ $\phi_s = \phi_s^{SM} + \phi_s^{NP}$
- If ϕ_s^{NP} is large then $\phi_s \approx -2\beta_s \approx \phi_s^{NP}$

We use $B_s \to J/\psi\phi$ decay to measure this phase

Vector amplitudes

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

Spin $0 \to 1 + 1 \quad (\ell = 0, 1, 2)$

$J/\psi\phi$ system is a mixture of three different states with following time-dependent amplitudes:

- $A_0(t)$ – longitudinal polarization, $\ell = 0, 2$, CP $= +$
- $A_{||}(t)$ – transverse polarization with parallel spin orientation, $\ell = 0, 2$, CP $= +$
- $A_\perp(t)$ – transverse polarization with perpendicular spin orientation, $\ell = 1$, CP $= -$

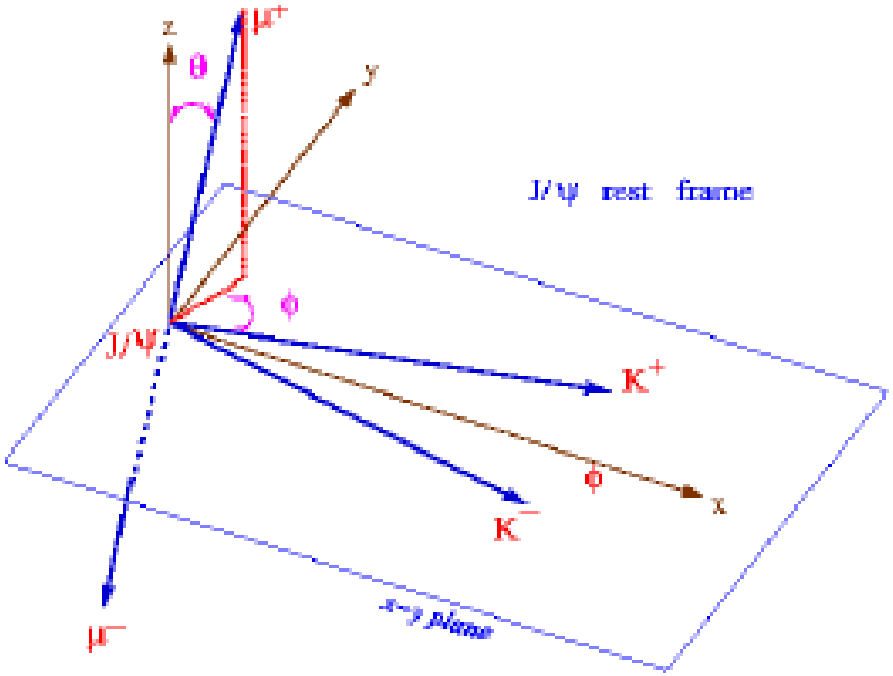
$$|A_0(0)|^2 + |A_{||}(0)|^2 + |A_\perp(0)|^2 = 1$$

Observables:

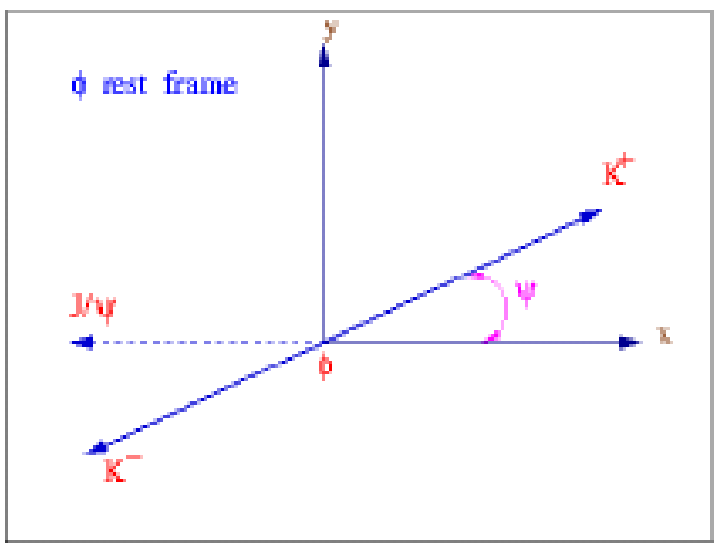
- $|A_\perp(0)|$
- $|A_0(0)|^2 - |A_{||}(0)|^2$
- $\delta_1 \equiv \arg(A_{||}^*(0) A_\perp(0)) = -\delta_{||} + \delta_\perp$
- $\delta_2 \equiv \arg(A_0^*(0) A_\perp(0)) = -\delta_0 + \delta_\perp$

δ_1 and δ_2 are CP-conserving strong phases

Angles



- x-axis – direction of ϕ momentum in J/ψ rest frame
- x-y plane – defined by K^+ and K^- momenta in J/ψ rest frame
- Angle θ (transversity) – between z-axis and μ^+ (in J/ψ rest frame)
- Angle ϕ – between K^+ and μ^+ projection (in J/ψ rest frame)



- Angle ψ – between x-axis and K^+ (in ϕ rest frame)

Differential rate

Time-dependent differential rate:

$$\frac{d^4\Gamma}{d\cos\theta\ d\phi\ d\cos\psi\ dt} =$$

$$2\cos^2\psi(1-\sin^2\theta\cos^2\phi)\cdot|A_0(t)|^2$$

$$+\sin^2\psi(1-\sin^2\theta\sin^2\phi)\cdot|A_{||}(t)|^2$$

$$+\sin^2\psi\sin^2\theta\cdot|A_\perp(t)|^2$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi\cdot\mathsf{Re}(A_0^*(t)A_{||}(t))$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\theta\cos\phi\cdot\mathsf{Im}(A_0^*(t)A_\perp(t))$$

$$-\sin^2\psi\sin 2\theta\sin\phi\cdot\mathsf{Im}(A_{||}^*(t)A_\perp(t))$$

Amplitudes (no B_s initial flavor tagging)

$|A_0(t)|^2 = |A_0(0)|^2 \cdot \mathcal{T}_+$
$|A_{||}(t)|^2 = |A_{||}(0)|^2 \cdot \mathcal{T}_+$
$|A_\perp(t)|^2 = |A_\perp(0)|^2 \cdot \mathcal{T}_-$
$\mathrm{Re}(A_0^*(t)A_{||}(t)) = |A_0(0)| \cdot |A_{||}(0)| \cdot \cos(\delta_2 - \delta_1) \cdot \mathcal{T}_+$
$\mathrm{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)| \cdot |A_\perp(0)| \cdot [-\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \sin\phi_s \cos\delta_2]$
$\mathrm{Im}(A_{||}^*(t)A_\perp(t)) = |A_{||}(0)| \cdot |A_\perp(0)| \cdot [-\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \sin\phi_s \cos\delta_1]$

where

$\mathcal{T}_\pm = \frac{1}{2}[(1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t}]$

- Sensitive to $\Gamma_L, \Gamma_H, \phi_s, \delta_1, \delta_2$
- Not sensitive to ΔM_s
- Equations are invariant under simultaneous transformation $\phi_s \to \pi - \phi_s$, $\Delta\Gamma \to -\Delta\Gamma$, $\delta_1 \to \pi - \delta_1$ and $\delta_2 \to \pi - \delta_2 \Longrightarrow$ four-fold ambiguity

Amplitudes (with B_s initial flavor tagging)

Upper signs: $B_s(0) = |B_s^0\rangle$, lower signs: $B_s(0) = |\overline{B_s^0}\rangle$

$$|A_0(t)|^2 = |A_0(0)|^2 \cdot [\mathcal{T}_+ \pm e^{-\overline{\Gamma}t} \sin\phi_s \sin(\Delta M_s t)]$$
$$|A_{||}(t)|^2 = |A_{||}(0)|^2 \cdot [\mathcal{T}_+ \pm e^{-\overline{\Gamma}t} \sin\phi_s \sin(\Delta M_s t)]$$
$$|A_\perp(t)|^2 = |A_\perp(0)|^2 \cdot [\mathcal{T}_- \mp e^{-\overline{\Gamma}t} \sin\phi_s \sin(\Delta M_s t)]$$

$$\mathrm{Re}(A_0^*(t)A_{||}(t)) = |A_0(0)| \cdot |A_{||}(0)| \cdot \cos(\delta_2 - \delta_1)[\mathcal{T}_+ \pm e^{-\overline{\Gamma}t} \sin\phi_s \sin(\Delta M_s t)]$$

$$\mathrm{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)| \cdot |A_\perp(0)| \cdot [e^{-\overline{\Gamma}t}(\pm \sin\delta_2 \cos(\Delta M_s t) \mp \cos\delta_2 \sin(\Delta M_s t)\cos\phi_s) - \tfrac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t})\sin\phi_s \cos\delta_2]$$

$$\mathrm{Im}(A_{||}^*(t)A_\perp(t)) = |A_{||}(0)| \cdot |A_\perp(0)| \cdot [e^{-\overline{\Gamma}t}(\pm \sin\delta_1 \cos(\Delta M_s t) \mp \cos\delta_1 \sin(\Delta M_s t)\cos\phi_s) - \tfrac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t})\sin\phi_s \cos\delta_1]$$

where

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

Amplitudes (with B_s initial flavor tagging)

- Sensitive to $\Gamma_L, \Gamma_H, \phi_s, \delta_1, \delta_2, \Delta M_s$
- But we do not determine ΔM_s, but fix it to CDF's measurement [PRL **97**, 242003 (2006)]
- Sign ambiguity for ϕ_s for given $\Delta\Gamma$ is resolved $\Longrightarrow$ two-fold ambiguity

☞ For given tagged event:

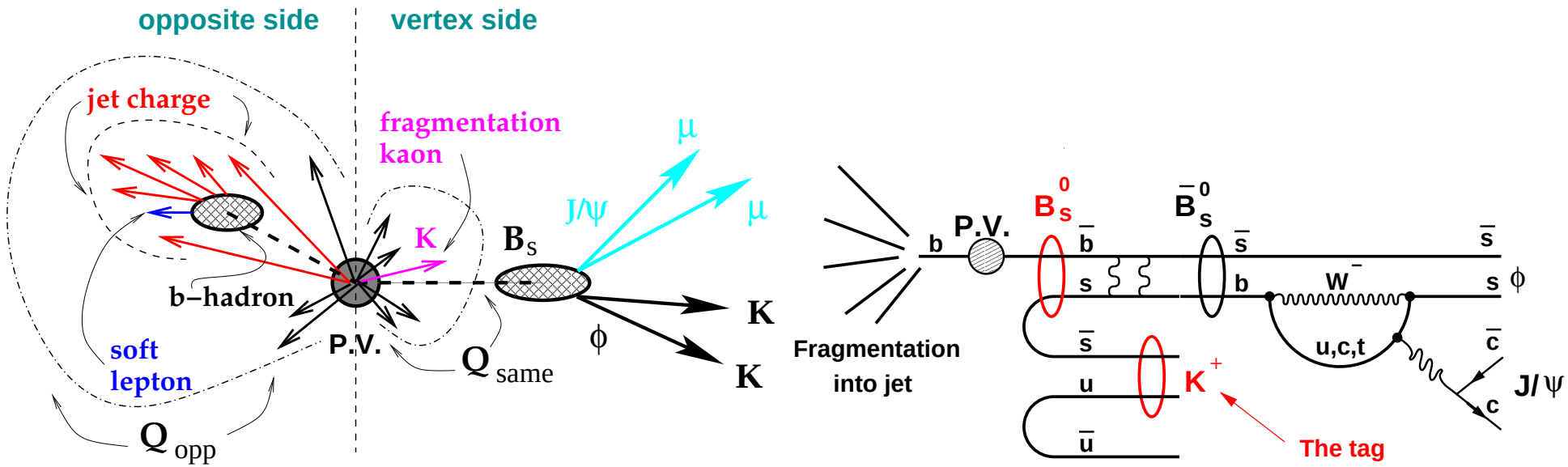
$$\text{rate} = p(B_s)\cdot \text{ rate } (B_s) + (1 - p(B_s))\cdot \text{ rate } (\overline{B_s})$$

☞ If event is not tagged $p(B_s) = 0.5 \Longrightarrow$ all B_s flavor terms cancel

A few words about B_s flavor tagging

B_s flavor tagging

We need to determine (tag) B_s meson production flavor which may be different from decay flavor

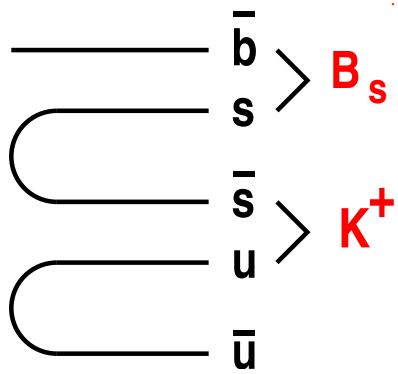


Two main classes of tagging methods:

- ☞ **Same-Side Tagging:** "One-track", Q_{same}...
- ☞ **Opposite-Side Tagging:** jet-charge, soft-lepton, Q_{opp}...

We develop "Comb. SST", "Comb. OST" and merge them into single "All" tagger

Tagging characteristics:



- Number of Right-Sign (B_s-K^+ and $\overline{B_s}$-K^-) correlations, N_{RS}
- Number of mistagged Wrong-Sign (e.g., B_s-K^- and $\overline{B_s}$-K^+) correlations, N_{WS}
- Number of events with no tag found, N_{NT}
- Tagging efficiency $\epsilon = \frac{N_{tagged}}{N_{total}} = \frac{N_{RS}+N_{WS}}{N_{RS}+N_{WS}+N_{NT}}$ and dilution $D = \frac{N_{RS}-N_{WS}}{N_{RS}+N_{WS}}$
- Tagging power $\epsilon D^2 \Longleftarrow$ to be maximized

Tagging in MC and data

- Same-side tagging:
  - ☞ B_s production flavor is obtained from MC truth information
  - ☞ SST analysis can only be done on MC
  - ☞ SST can be verified on self-tagging $B_u \to J/\psi K$ sample
    - – B_u flavor is determined from kaon charge $\Longrightarrow$ in both data and MC
    - – The agreement between dilutions in data and MC is reasonably good which justifies using SST in B_s decays

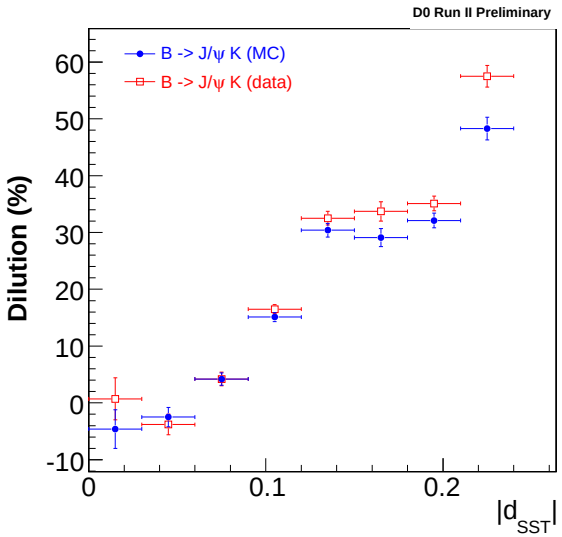
- Opposite-side tagging:
  - ☞ Opposite-side flavor tagging does not depend on the B-meson flavor
  - ☞ Can use $B_d \to \nu_\mu \mu D^{*-}$ data sample to develop OST for B_s [**PRD74**, 112002 (2006)]

Taggers' combination

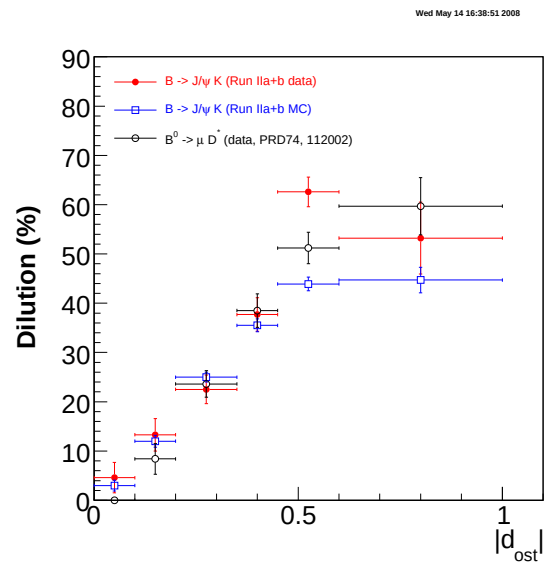
- To obtain "Combined SST" we merge different SST algorithms by using likelihood ratio method
- Similar thing is done for "Combined OST"
  - Unfortunately, OST has low efficiency
  - So, when OST is not present, we use the Q_{opp} obtained as p_t-weighted $\sum q_i$ of **all** tracks on opposite side
  - The Q_{opp} has 100% tagging efficiency, but lower dilution
- Finally, both "combined SST" and "combined OST"$/Q_{opp}$ are amalgamated into single "All" tagger
- This single tagger has pretty high power $\epsilon D^2 \approx 4\text{-}5\%$

Tagger verification on data/MC

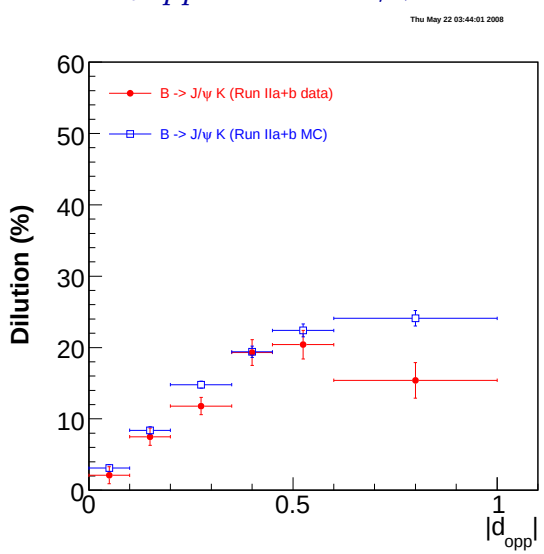
SST in $B_u \to J/\psi K$



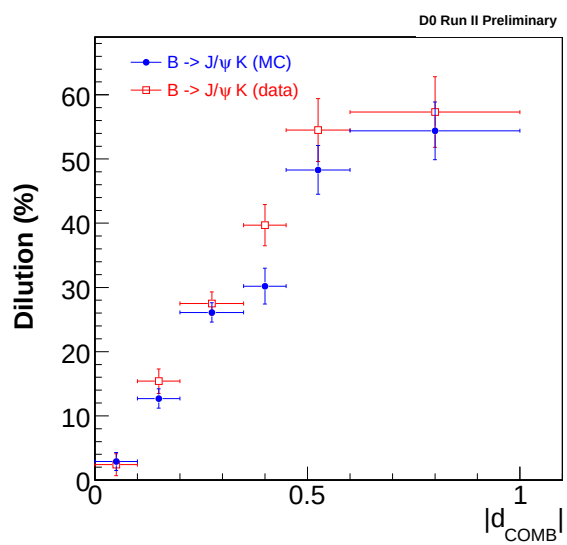
OST in $B_u \to J/\psi K$ and $B_d \to \nu_\mu \mu D^{*-}$ (**data**)



Q_{opp} in $B_u \to J/\psi K$



"All" tagger in $B_u \to J/\psi K$



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

Likelihood function

☞ We perform simultaneous unbinned likelihood fit to the B_s mass, lifetime and three angles

☞ Altogether, there are 33 free parameters in the fit

$$\mathcal{L} = \prod_{i=1}^{N} [f_{sig}\mathcal{F}^i_{sig} + (1 - f_{sig})\mathcal{F}^i_{bkg}],$$

where

- N – total number of events
- f_{sig} – signal fraction
- $\mathcal{F}^i_{sig/bkg}$ – signal/background distribution the fit variables

Background:

– "Prompt" J/ψ coming directly from primary vertex

– "Non-prompt" J/ψ coming from a b-hadron

Fit constraints

– Mixing parameter ΔM_s is constrained to CDF's measurement [PRL **97**, 242003 (2006)]

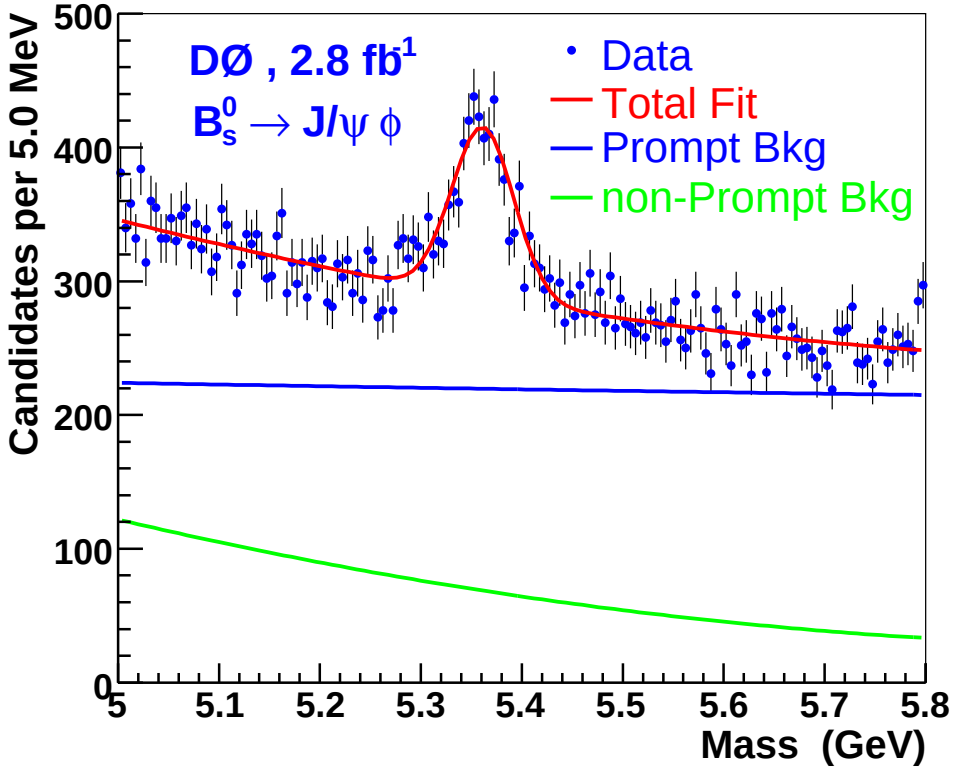
– Strong phases δ_1 and δ_2 are constrained from BaBar's measurements in $B \to J/\psi K^{*0}$ [hep-ex/0704.0522]

- We have two-fold ambiguity
  - ☞ $\Delta\Gamma > 0, \cos\phi_s > 0, \cos\delta_1 > 0, \cos\delta_2 < 0$
  - ☞ $\Delta\Gamma < 0, \cos\phi_s < 0, \cos\delta_1 < 0, \cos\delta_2 > 0$
- For $B \to J/\psi K^{*0}$ the values $\delta_1 = -0.46$ and $\delta_2 = 2.92$ are preferred over $\delta_1 = 3.60$ and $\delta_2 = 0.22$ on both theoretical and experimental grounds [hep-ex/0704.3575, page 153], [PRD**64**, 117503]
- We constrain $\delta_1 = -0.46$ and $\delta_2 = 2.92$ with narrow Gaussians to allow for SU(2) symmetry breaking

Fit results

Invariant mass of

$J/\psi\phi$ system

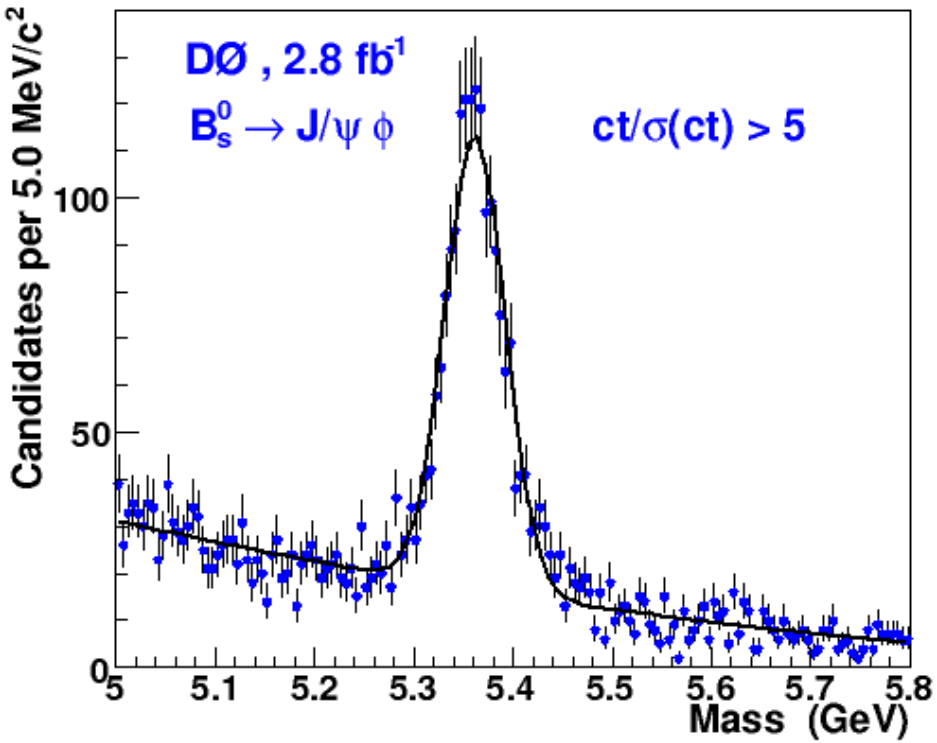


$N = 1967 \pm 65(\text{stat.})$ events

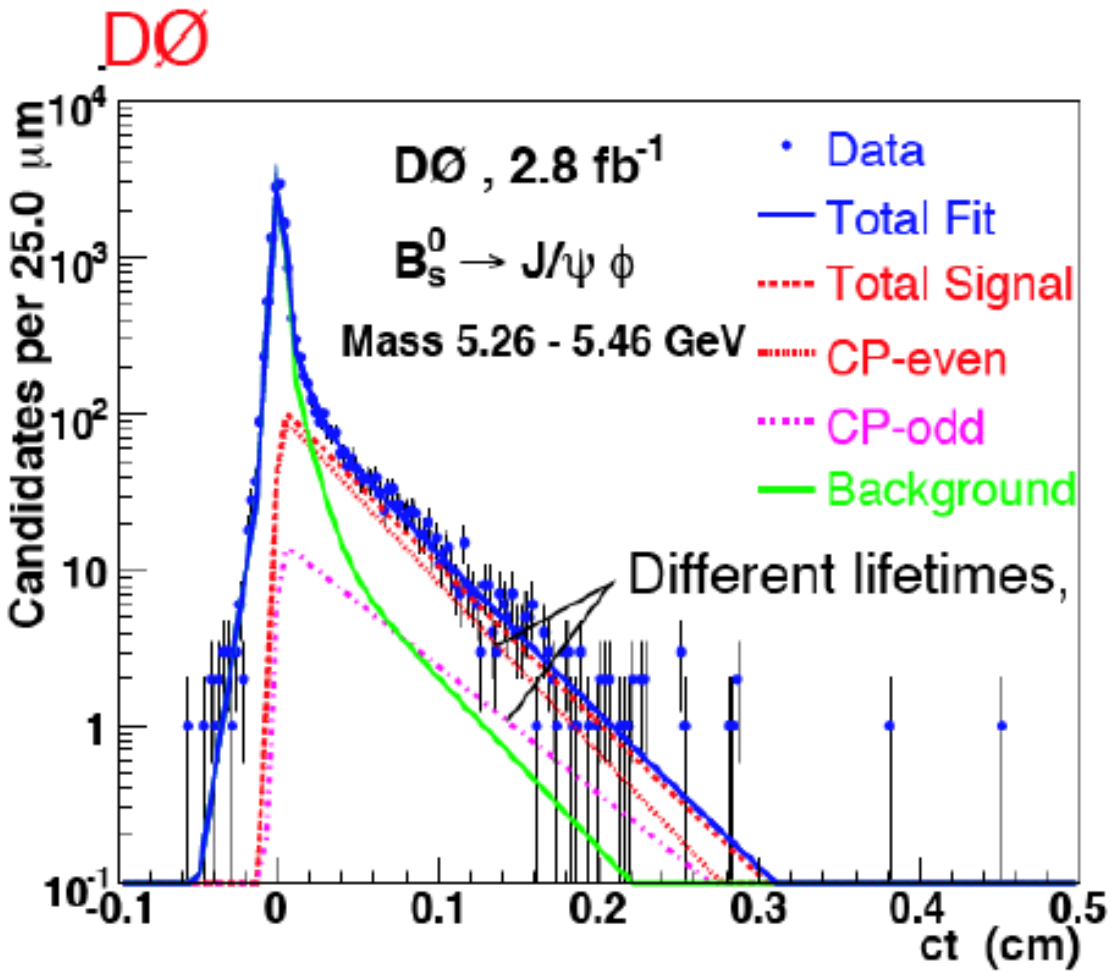
Invariant mass of

$J/\psi\phi$ system

with prompt background suppression



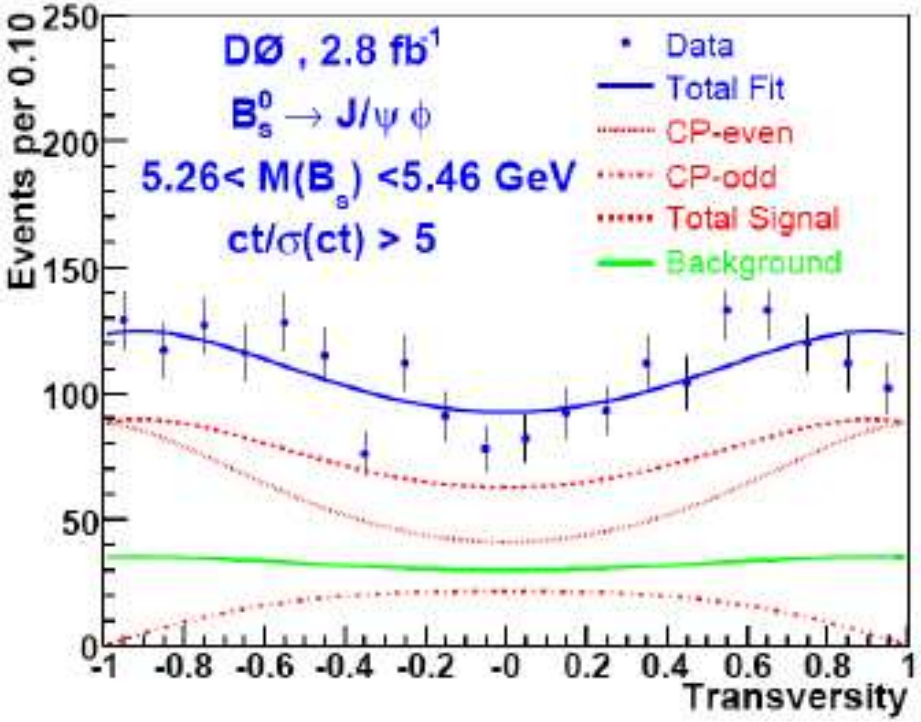
Fit results

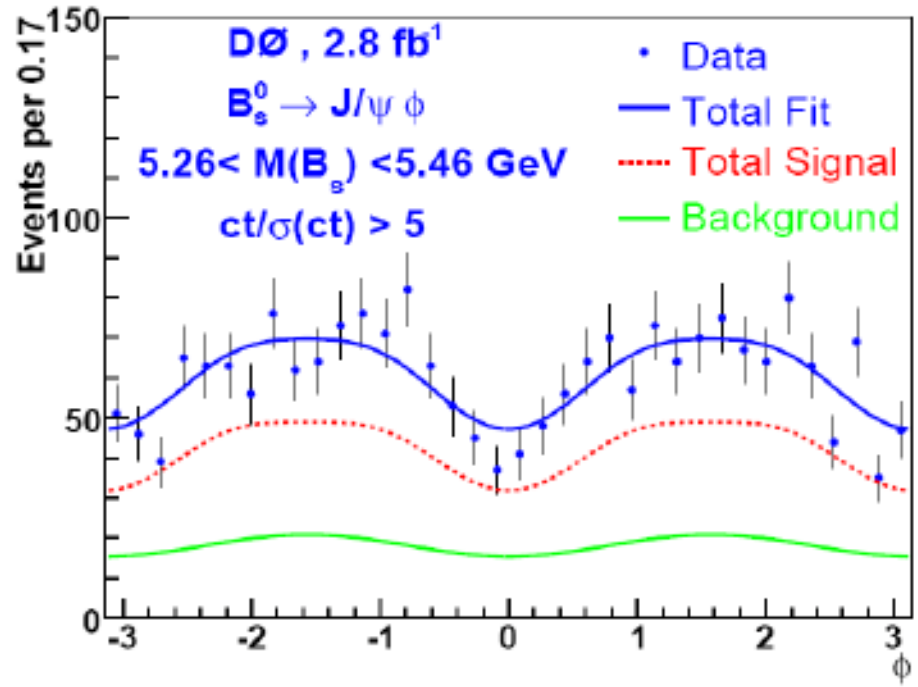


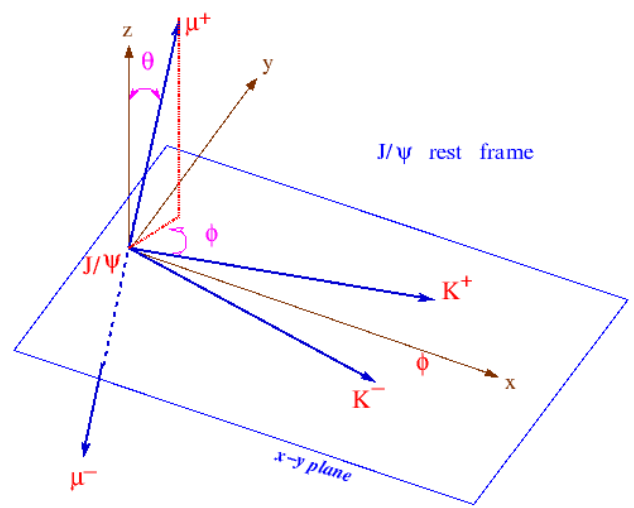
$$\Delta\Gamma = 0.14 \pm 0.07(\text{stat.} + \text{syst.})\ \text{ps}^{-1}\ (\text{when}\ \phi_s \equiv \phi_s^{SM})$$

$$\overline{\tau} = 1.53 \pm 0.05 \pm 0.01\ \text{ps}$$

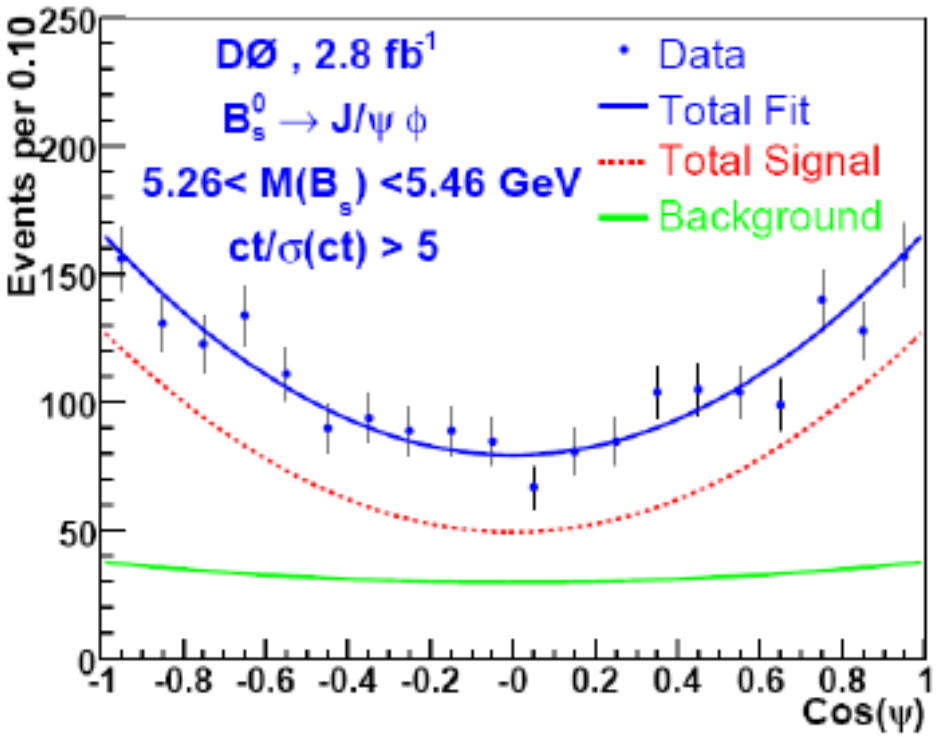
Fit results

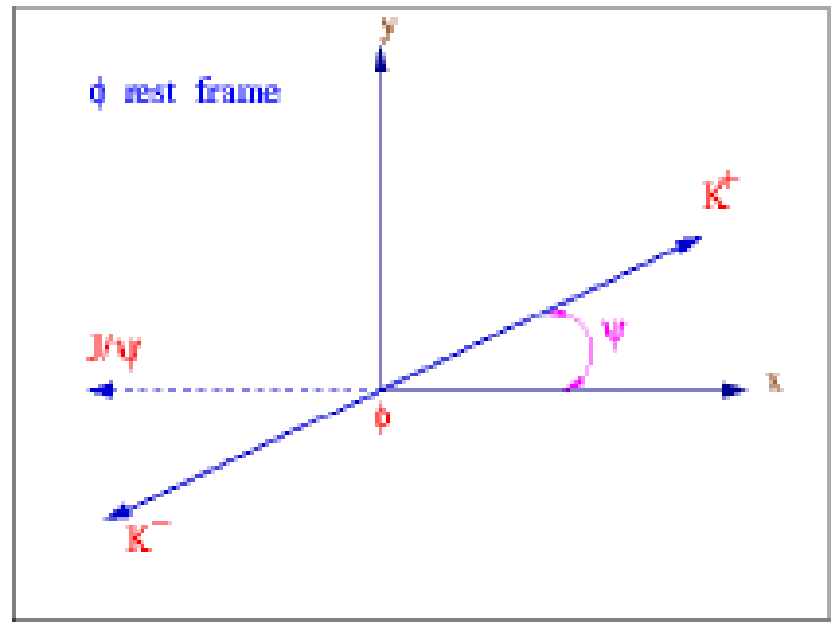

DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
CP-even
CP-odd
Total Signal
Background
Events per 0.10
Transversity


DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
Total Signal
Background
Events per 0.17
φ

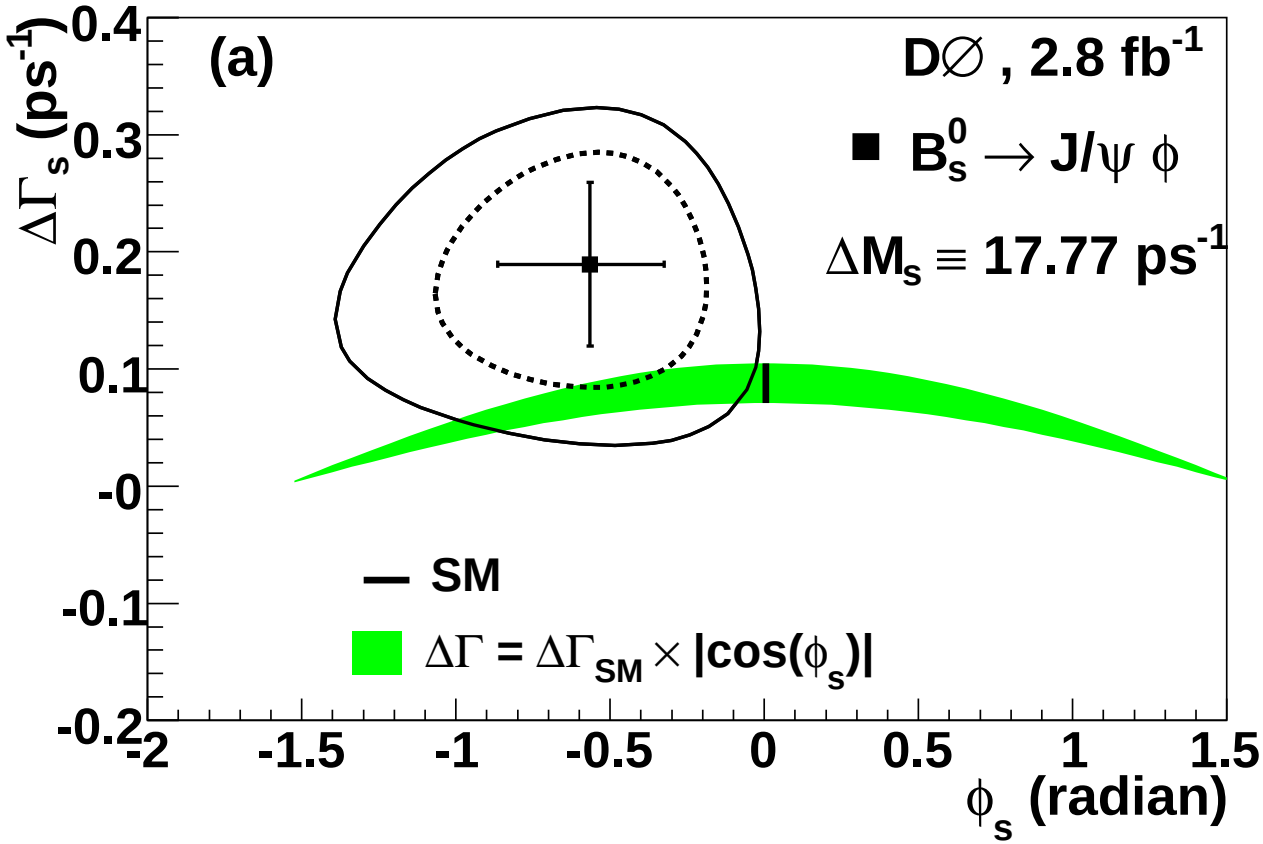

z
θ
μ+
y
J/ψ rest frame
φ
J/ψ
K+
φ
x
K−
μ−
x-y plane

Fit results


DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
Total Signal
Background
Events per 0.10
Cos(ψ)


φ rest frame
y
x
K^+
K^-
J/ψ
ψ
φ

Fit results



Dashed - 68.3% CL, solid - 90% CL

Main result:

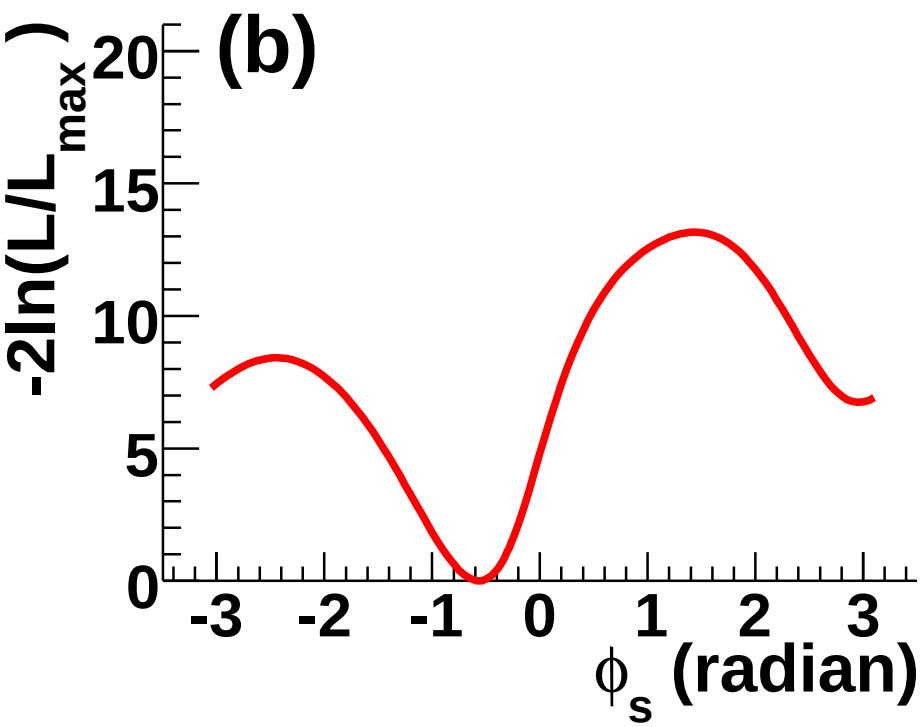
$$\Delta\Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01}\ \text{ps}^{-1},\ \phi_s = -0.57^{+0.24+0.07}_{-0.30-0.02}$$

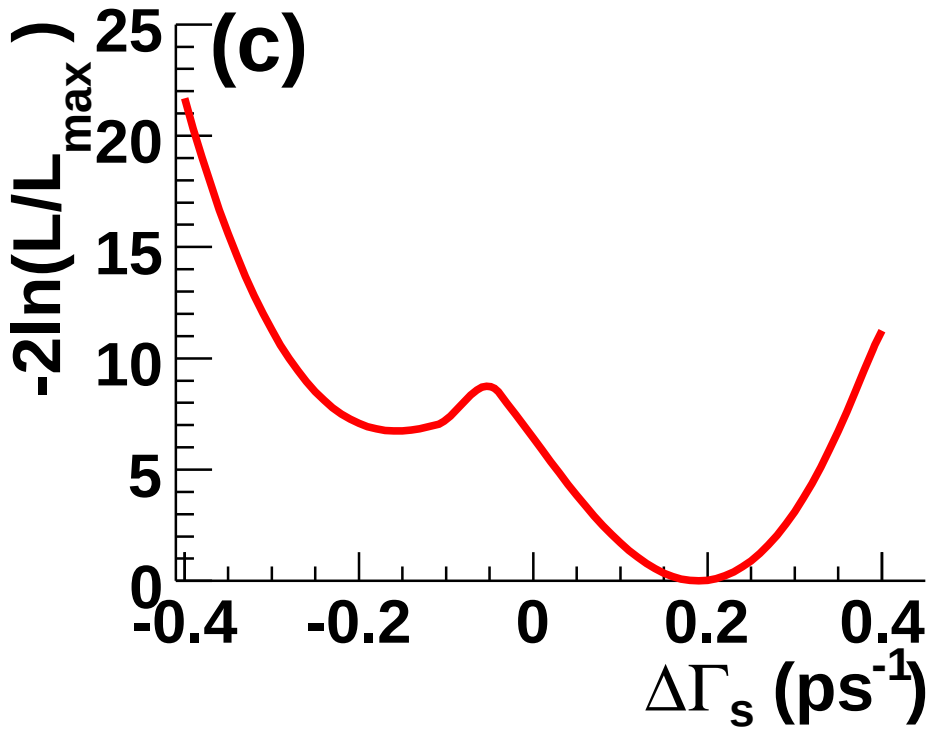
[hep-ex/0802.2255, Sub. to PRL]

Probability of SM value is $\sim 7\%$

Fit results

Likelihood profiles:

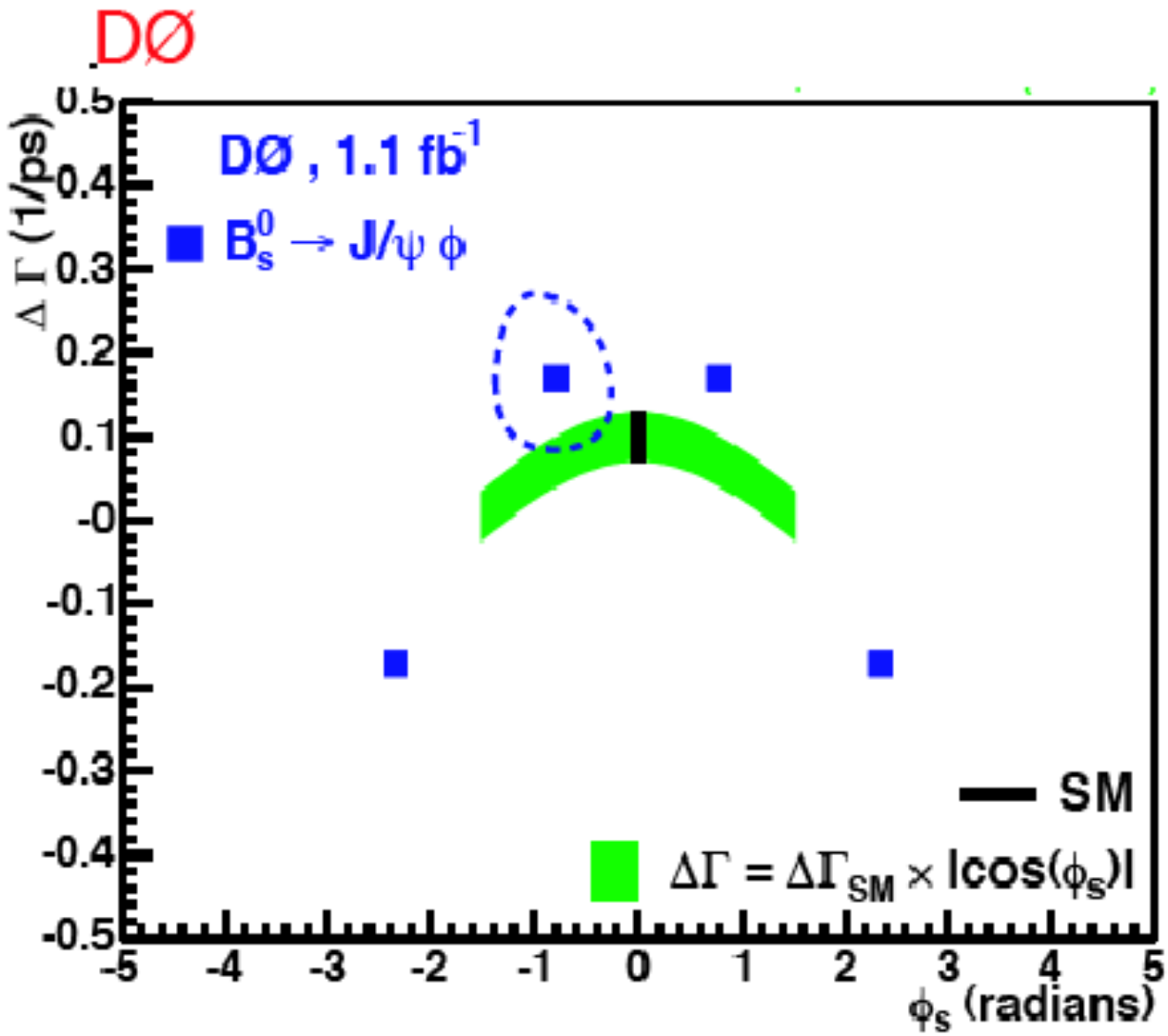




Numerical results

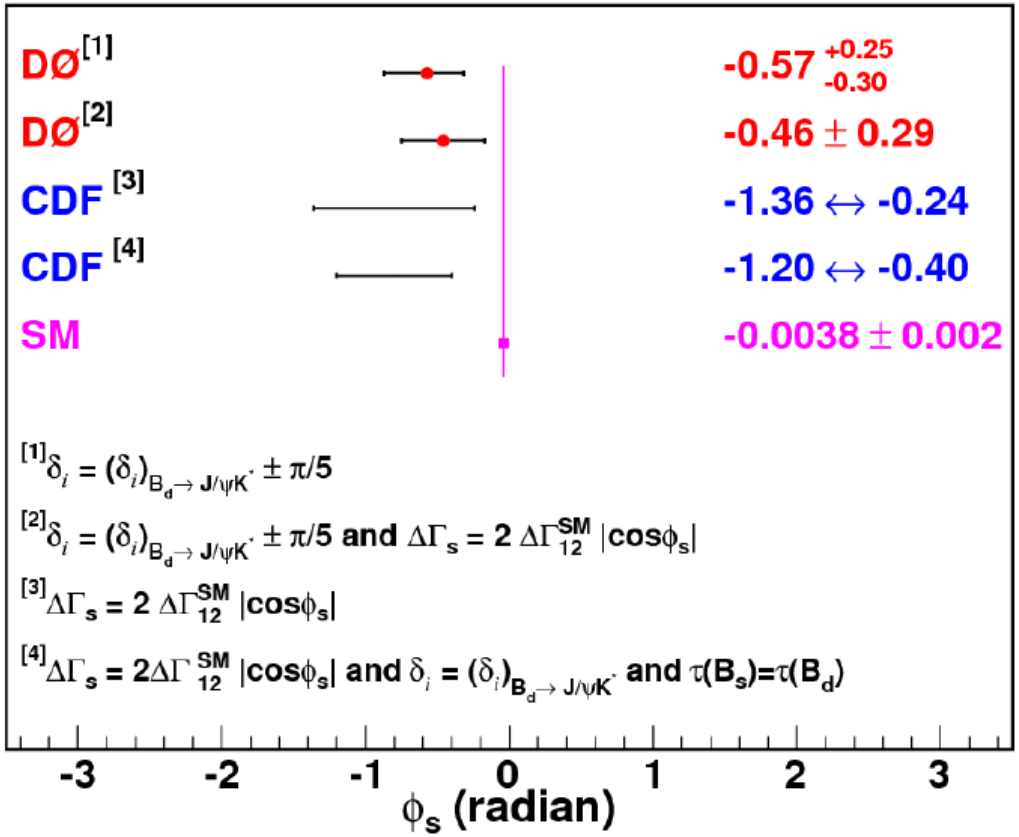
Variable	Free ϕ_s	$\phi_s \equiv \phi_s^{SM}$	$\Delta\Gamma_s \equiv \Delta\Gamma_s^{SM} \cdot \lvert\cos\phi_s\rvert$
$\overline{\tau}$, ps	1.52±0.06	1.53±0.06	1.49±0.05
$\Delta\Gamma_s$ (ps^{-1})	0.19±0.07	0.14±0.07	0.083±0.018
$A_\perp(0)$	0.41±0.04	0.4±0.04	0.45±0.03
$\lvert A_0(0)\rvert^2 - \lvert A_{\lvert\lvert}(0)\rvert^2$	0.34±0.05	0.35±0.04	0.33±0.04
δ_1	-0.52±0.42	-0.48±0.45	-0.47±0.42
δ_2	3.17±0.39	3.19±0.43	3.21±0.40
ϕ_s	$-0.57^{+0.24}_{-0.30}$	$\equiv -0.04$	-0.46±0.28
ΔM_s (ps^{-1})	$\equiv 17.77$	$\equiv 17.77$	$\equiv 17.77$

Results without tagging



For comparison: **untagged** 1.1 fb^{-1} analysis

Comparison to other experiments



Shown is the DØ sign convention for ϕ_s, which is opposite to the CDF's $2\beta_s$ [hep-ex/0712.2397]

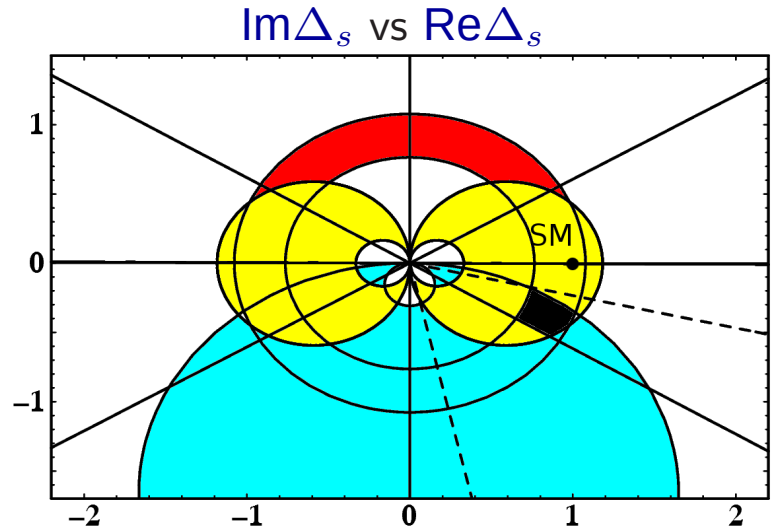
- CDF did not provide central value, but only variation limits for $2\beta_s$
- CDF is hoping to have an updated result with a larger dataset by ICHEP'08

New Physics?

NP may change B_s Hamiltonian parameters by introducing a complex number $\Delta_s \equiv |\Delta_s| \cdot e^{i\phi_s^{NP}}$ [hep-ph/0612167] as follows:

- $\Delta M_s = \Delta M_s^{SM} \cdot |\Delta_s|$
- $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

$\Delta_s = 1$ in SM



- Red: from CDF's ΔM_s measurement [PRL **97**, 242003 (2006)]
- Yellow: from $\Delta\Gamma_s/\Delta M_s$ with $\Delta\Gamma_s$ from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis
- Blue: from DØ 's a_{SL}^s measurement [PRD **76**, 057101 (2007)]
- Forward and backward regions: from sign of $\Delta\Gamma_s$ from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis
- Dashed wedge: from ϕ_s from DØ [PRL**98**, 121801 (2007)] - untagged 1.1 fb^{-1} analysis
- In SM all regions should intersect in point (1,0)

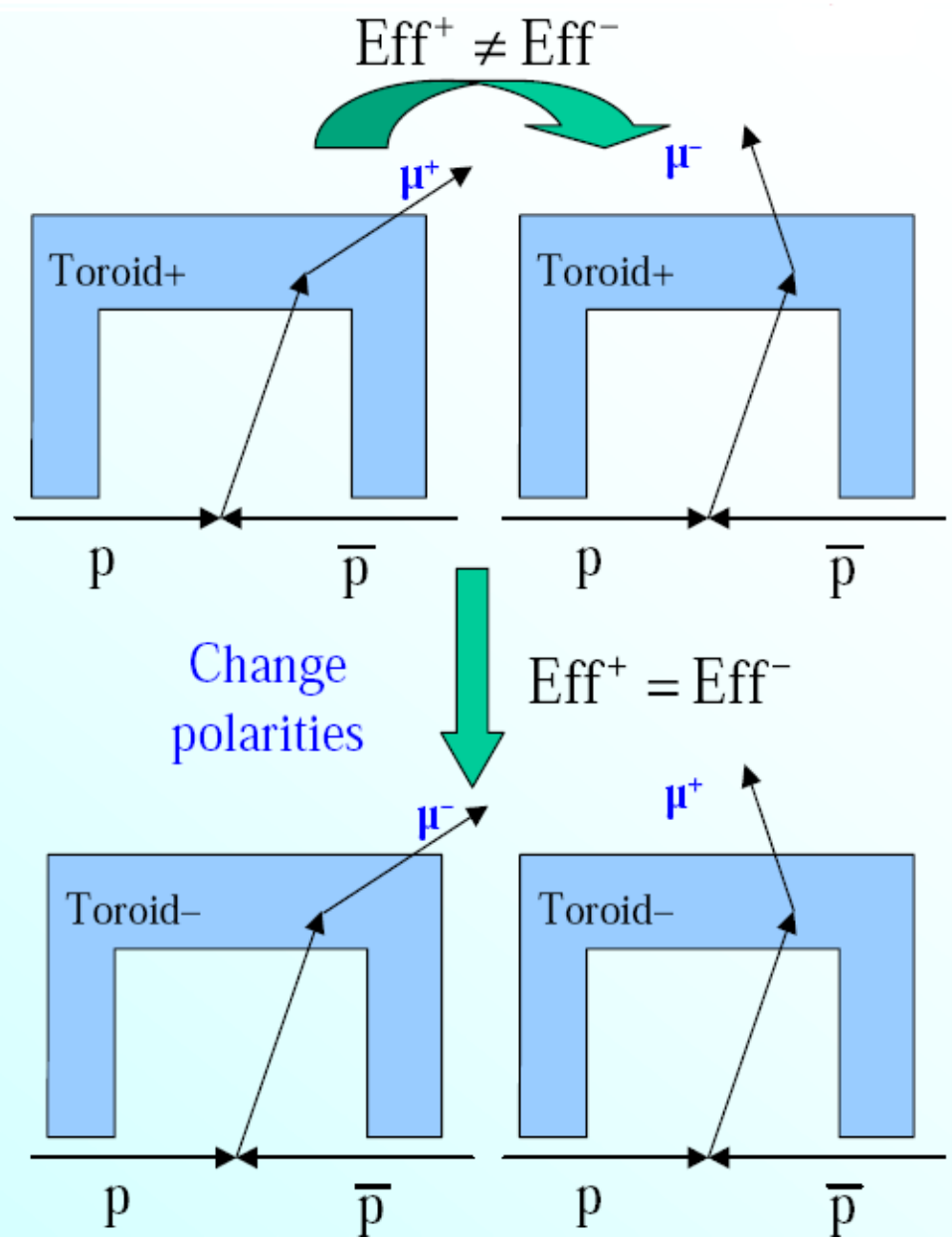
Experimental situation (black area) shows some deviation from SM which may grow as the uncertainties decrease

Conclusion

- Measured large CP-violation where it is predicted to be small may reveal New Physics
- Direct CP asymmetry in $B \to J/\psi K$ decay is consistent with zero
- The uncertainty on this asymmetry is of order of SM prediction
- The large phase ϕ_s in $B_s \to J/\psi\phi$ decay may indicate New Physics
- The uncertainty on ϕ_s is statistically dominated $\Longrightarrow$ more data needs to be analyzed to be sure that we actually see the New Physics
- This will happen in the nearest future

Backup

Toroid polarity



- Reversing magnet polarity helps reduce detector asymmetries in muon reconstruction
- Systematics is also diminished

Obtaining D^* asymmetry

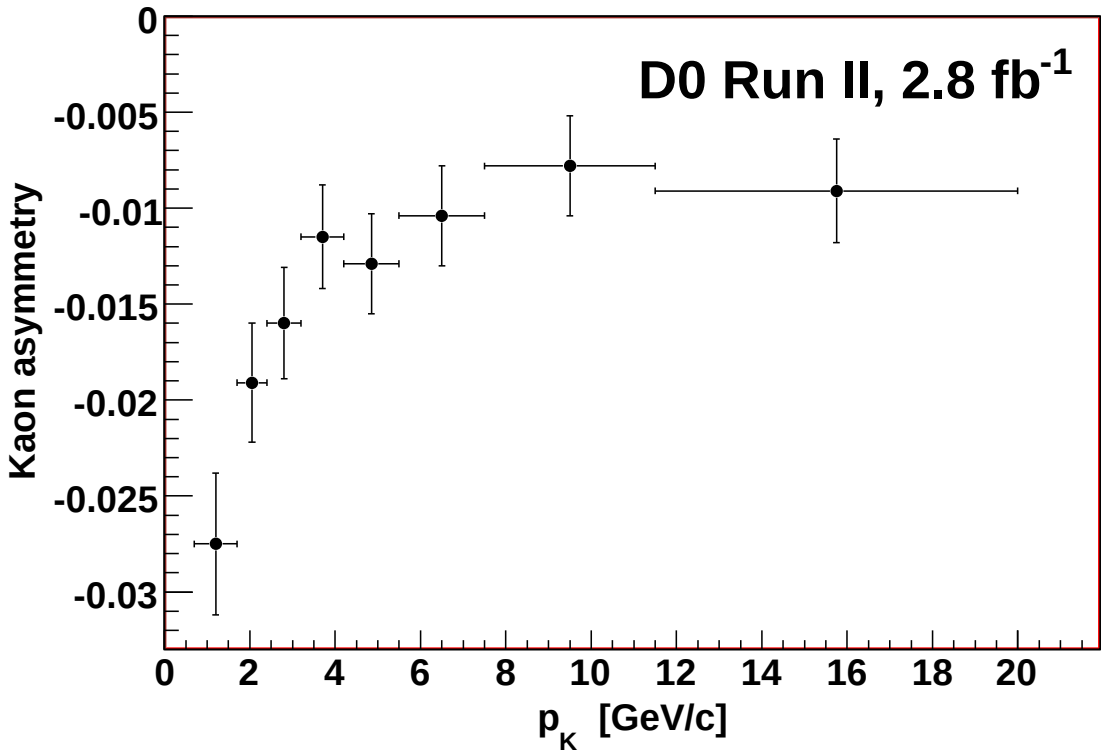
- For each $\beta\gamma q$ combination we bin the sample in $m(\mu K)$
- For each bin in $m(\mu K)$ we choose signal and sideband regions for right-sign and wrong-sign charge correlations
- Signal region is chosen to maximize $S/\sqrt{S+B}$ for each $m(\mu K)$ bin
- Sideband region is chosen to be 0.19 GeV$/c^2 < \Delta m < 0.22$ GeV$/c^2$
- $B = N_{wrong}^{sig.reg.} \frac{N_{right}^{sideband}}{N_{wrong}^{sideband}}$
- $S = N_{right}^{sig.reg.} - B$
- Then numbers of signal events in all $m(\mu K)$ bins are added up $\Longrightarrow$ obtain $n_q^{\beta\gamma}$
- Solve system of equations to find asymmetry

D^* sample composition

Mode	Branching, %
$\mu^+ K^- \nu$	3.51 ± 0.11
$\mu^+ K^{*-} \nu$	2.17 ± 0.16
$K^{*-} \to K^- \pi^0$	$1/3 \cdot$ Br(K^*)
$K^{*-} \to K^0 \pi^-$	$2/3 \cdot$ Br(K^*)
$\mu^+ \pi^- \nu$	0.28 ± 0.02
$\mu^+ \rho^- \nu$, $\rho^- \to \pi^- \pi^0$	0.19 ± 0.04

Corrected kaon asymmetry $A_K(D^*) = A(D^*)/f_K$

Kaon asymmetry $A_K(D^*)$ vs. p_K



The average kaon asymmetry is

$$A_K = \sum_{i=1}^{N_{bins}} A_{K,i}(D^*) \frac{N_i(J/\psi K)}{N(J/\psi K)} = -0.0145 \pm 0.0010(\text{stat.})$$

Direct CPV systematics

Source	$J/\psi K$	$J/\psi\pi$
Variation of fixed fit parameters by $\pm 1\sigma$	0.0002	0.0004
Variation of fiting range	0.0004	0.0129
Shape of $J/\psi\pi$ and $J/\psi K^*$ contribution	0.0025	0.0252
Bkg from $q_\mu \cdot q_\pi < 0$	0.0008	–
Varying rec. eff. for D^0 contribution to D^* sample	0.0005	–
Asymmetry in π reconstruction	–	0.0002
Total	0.0027	0.0283

SST Algorithms

All used SST algorithms can be divided into two groups:

1. **One-track algorithms** which select a particular track and infer b-quark flavor from its charge

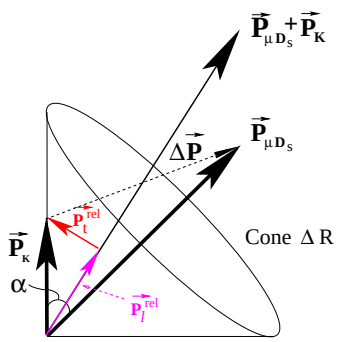
2. **Many-track algorithms** which use p_t-weighted average charge of all tracks around $\vec{p}(B_s)$: $Q_{SST}(p_t, \kappa) = \frac{\sum q \cdot p_t^\kappa}{\sum p_t^\kappa}$

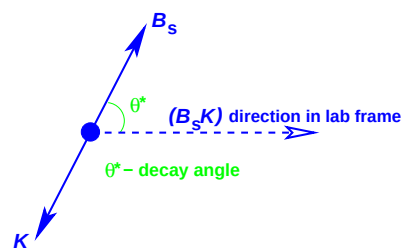
- Often different one-track taggers pick up the same track $\Longrightarrow$ highly correlated
- Let's pick the best tagger from each group
- Best one-track tagger: "Min. $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$"
- Best many-track tagger: $Q_{SST}(p_t, \kappa = 0.6)$"
- Let's combine both these taggers together to improve ϵD^2

List of used same-side taggers:

We are using the following SSTs (one-track and many-track taggers):

- ☞ Min. p_t^{rel}
- ☞ Max. p_L^{rel}
- ☞ Max. p_t
- ☞ Min. $|\Delta\vec{P}| \equiv |\vec{p}(B_s) - \vec{p}(K)|$
- ☞ Best: Min. ΔR
- ☞ Max. $\cos\alpha$
- ☞ Min. $\cos\theta^*$
- ☞ Max. $\cos\theta^*$
- ☞ Min. $m(B_sK)$
- ☞ Random track
- ☞ $Q_{jet}(p_t, \kappa) = \frac{\sum q \cdot p_t^{\kappa}}{\sum p_t^{\kappa}}$
- ☞ $Q_{jet}(p_t^{rel}, \kappa) = \frac{\sum q \cdot (p_t^{rel})^{\kappa}}{\sum (p_t^{rel})^{\kappa}}$
- ☞ $Q_{jet}(p_L^{rel}, \kappa) = \frac{\sum q \cdot (p_L^{rel})^{\kappa}}{\sum (p_L^{rel})^{\kappa}}$
- ☞ Best: $Q_{jet}(p_t, \kappa = 0.6)$



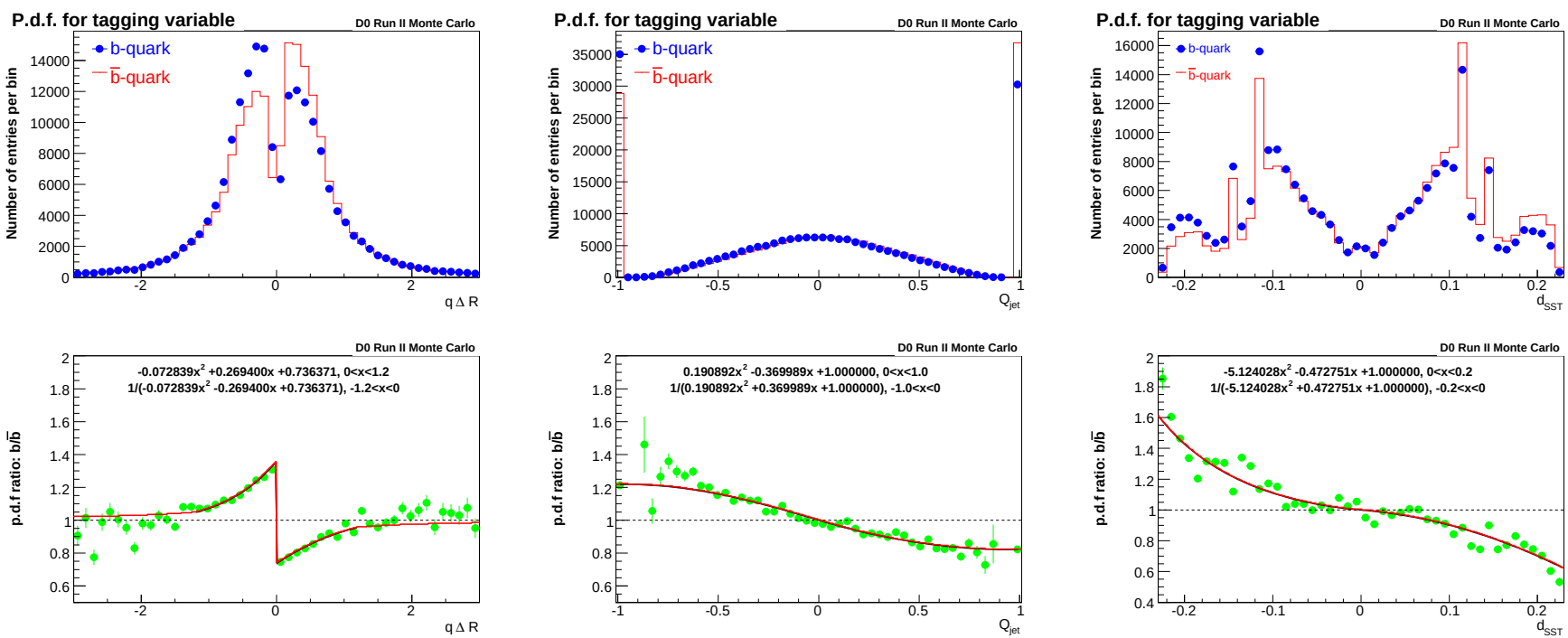


- One-track: p_t^{rel} and p_L^{rel} are $\perp$ and $||$ components of SST candidate's momentum $\vec{p}(K)$ w.r.t $\vec{p}(B_sK)$
- $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$ and angle α are taken between $\vec{p}(B_s)$ and $\vec{p}(K)$
- θ^* – decay angle of B_sK-system, *i.e.* angle between directions of $\vec{p}(B_sK)$ and $\vec{p}(B_s)$ in reference frame of B_sK system
- $\kappa = 0.0, 0.1, 0.2, ...1.0$
- Q_{jet}: p_t^{rel} and p_L^{rel} are $\perp$ and $||$ components of SST candidate's momentum $\vec{p}(K)$ w.r.t $\vec{p}(B_s)$

Combination of two SST methods

- We obtain P.D.F.s of "$q \cdot \Delta R$" for "Min. ΔR" tracks with charge q for b and $\bar{b}$ quarks
- If their ratio $y_{\Delta R} = \frac{f(b)}{f(\bar{b})} > 1$ then it was b-quark, otherwise $\bar{b}$-quark
- Calculate "joint P.D.F. ratio" for "Min. ΔR" and $Q_{SST}(p_t, \kappa = 0.6)$ taggers: $y_{sst} = y_{\Delta R} \cdot y_Q$
- Introduce a variable $d_{sst} = \frac{1-y_{sst}}{1+y_{sst}}$ and determine b-quark flavor for each event from its sign
- Calculate even-by-event dilution D as a function of d_{sst}

"Min. ΔR" P.D.F.s | $Q_{SST}(p_t, \kappa = 0.6)$ P.D.F.s | "Joint P.D.F.s"



ϵD^2 for combined SST

MC		Tagger	ϵ, %	D, %	"Unbinned" ϵD^2, %	"Binned" ϵD^2, %
$B_u \to J/\psi K$	data	"Min. ΔR"	82.1 $\pm$ 1.1	20.2 $\pm$ 0.7	3.34 $\pm$ 0.22	3.73 $\pm$ 0.24
		"$Q_{jet}(p_t, 0.6)$"	88.4 $\pm$ 1.2	19.3 $\pm$ 0.6	3.28 $\pm$ 0.22	4.06 $\pm$ 0.24
		"Comb. SST"	88.4 $\pm$ 1.2	19.0 $\pm$ 0.6	3.19 $\pm$ 0.22	4.81 $\pm$ 0.26
$B_u \to J/\psi K$	Monte Carlo	"Min. ΔR"	79.2 $\pm$ 0.5	18.6 $\pm$ 0.5	2.74 $\pm$ 0.15	2.82 $\pm$ 0.15
		"$Q_{jet}(p_t, 0.6)$"	89.0 $\pm$ 0.6	19.6 $\pm$ 0.5	3.43 $\pm$ 0.17	3.92 $\pm$ 0.17
		"Comb. SST"	89.1 $\pm$ 0.6	17.8 $\pm$ 0.5	2.82 $\pm$ 0.15	4.02 $\pm$ 0.17
$B_s \to \mu D_s(\phi\pi)$	Monte Carlo	"Min. ΔR"	84.9 $\pm$ 0.6	14.8 $\pm$ 0.5	1.86 $\pm$ 0.14	1.96 $\pm$ 0.14
		"$Q_{jet}(p_t, 0.6)$"	93.0 $\pm$ 0.7	13.9 $\pm$ 0.5	1.80 $\pm$ 0.14	2.25 $\pm$ 0.15
		"Comb. SST"	93.0 $\pm$ 0.7	14.2 $\pm$ 0.5	1.86 $\pm$ 0.14	2.49 $\pm$ 0.16
$B_s \to J/\psi\phi$	Monte Carlo	"Min. ΔR"	78.7 $\pm$ 0.7	13.4 $\pm$ 0.7	1.41 $\pm$ 0.14	1.57 $\pm$ 0.15
		"$Q_{jet}(p_t, 0.6)$"	81.5 $\pm$ 0.7	13.8 $\pm$ 0.6	1.55 $\pm$ 0.15	1.84 $\pm$ 0.16
		"Comb. SST"	81.5 $\pm$ 0.7	13.1 $\pm$ 0.6	1.40 $\pm$ 0.14	2.01 $\pm$ 0.16

- "Unbinned" ϵD^2 is a direct product of ϵ and D^2
- "Binned" ϵD^2 is a sum of ϵD^2's in $|d|$ bins
- We see some improvement in "binned" ϵD^2 due to SST combination for all decay signatures

OST

- OST was developed on $B_d \to \mu D^*$ data sample [**PRD74**, 112002 (2006)]
- Must be the same for B_d and B_s
- Also, a combination of a few taggers:
  - soft muon
  - soft electron
  - secondary-vertex

Combination SST + OST/Q_{opp}

- Same combination technique as for SST
- If OST present make "joint P.D.F." $y_{comb} = y_{sst} \cdot y_{ost}$
- If OST not present take $y_{comb} = y_{sst} \cdot y_{opp}$
- Introduce variable $d_{comb} = \frac{1-y_{comb}}{1+y_{comb}}$
- Infer b-quark production flavor from sign of d_{comb}
- Obtain event-by-event dilution with function $D(d_{comb})$

ϵD^2 for SST + OST/Q_{opp}

- SST + OST/Q_{opp} are also combined using P.D.F.s

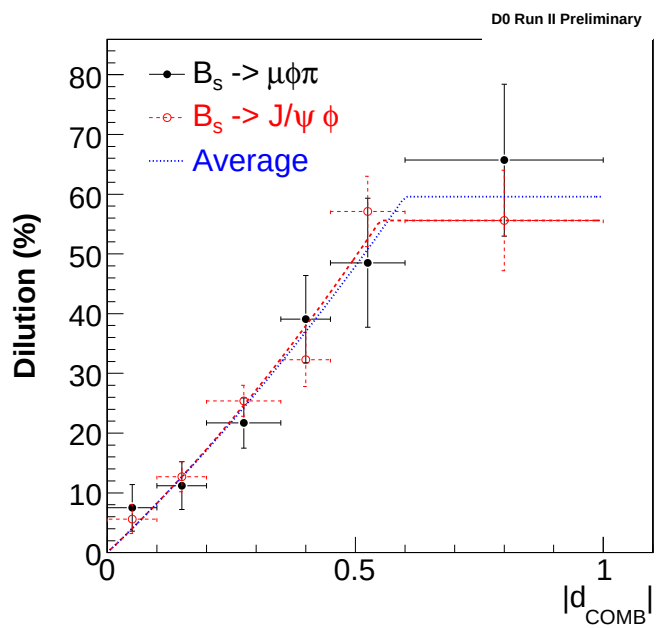
Sample		Tagger	ϵ, %	D, %	Unbinned ϵD^2, %	Binned ϵD^2, %
$B_u \to J/\psi K$	Monte Carlo	"Comb. SST"	89.1 ± 0.6	17.8 ± 0.5	2.82 ± 0.15	4.02 ± 0.17
		"Comb. OST"	18.3 ± 0.2	22.2 ± 1.1	0.90 ± 0.09	1.26 ± 0.09
		"Q_{opp}"	99.9 ± 0.6	10.3 ± 0.5	1.06 ± 0.09	1.31 ± 0.10
		"All"	100.0 ± 0.6	18.3 ± 0.5	3.33 ± 0.17	4.76 ± 0.18
$B_u \to J/\psi K$	data	"Comb. SST"	88.4 ± 1.2	19.0 ± 0.6	3.19 ± 0.22	4.81 ± 0.26
		"Comb. OST"	16.9 ± 0.3	26.8 ± 1.4	1.21 ± 0.13	1.91 ± 0.15
		"Q_{opp}"	100.0 ± 1.3	9.8 ± 0.6	0.97 ± 0.12	1.36 ± 0.14
		"All"	100.0 ± 1.3	18.9 ± 0.6	3.58 ± 0.23	5.79 ± 0.27
$B_s \to \mu D_s(\phi\pi)$	Monte Carlo	"Comb. SST"	93.0 ± 0.7	14.2 ± 0.5	1.86 ± 0.14	2.49 ± 0.16
		"Comb. OST"	25.4 ± 0.3	23.2 ± 1.0	1.37 ± 0.12	2.02 ± 0.13
		"Q_{opp}"	99.9 ± 0.7	6.9 ± 0.5	0.48 ± 0.07	0.78 ± 0.09
		"All"	100.0 ± 0.7	14.8 ± 0.5	2.20 ± 0.15	3.86 ± 0.19
$B_s \to J/\psi\phi$	Monte Carlo	"Comb. SST"	81.5 ± 0.7	13.1 ± 0.6	1.40 ± 0.14	2.01 ± 0.16
		"Comb. OST"	24.4 ± 0.3	27.6 ± 1.1	1.86 ± 0.16	2.70 ± 0.17
		"Q_{opp}"	98.3 ± 0.8	9.3 ± 0.6	0.84 ± 0.11	1.24 ± 0.13
		"All"	98.3 ± 0.8	15.7 ± 0.6	2.43 ± 0.18	4.43 ± 0.23

- Tagging power ϵD^2 grows as a result of combination
- Combined tagging power for both B_s decay modes is $(4.09 \pm 0.14)\%$

Calibration curves

To obtain event-by-event dilution for B_s we:

- plot $D(d_{comb})$ dependence for $B_s \to \mu D_s(\phi\pi)$ Monte Carlo (black)
- plot $D(d_{comb})$ dependence for $B_s \to J/\psi\phi$ Monte Carlo (red)
- obtain weighted-average points from both plots (SST fragmentation does not depend on the B_s decay mode)
- fit them with parabola + constant (blue)

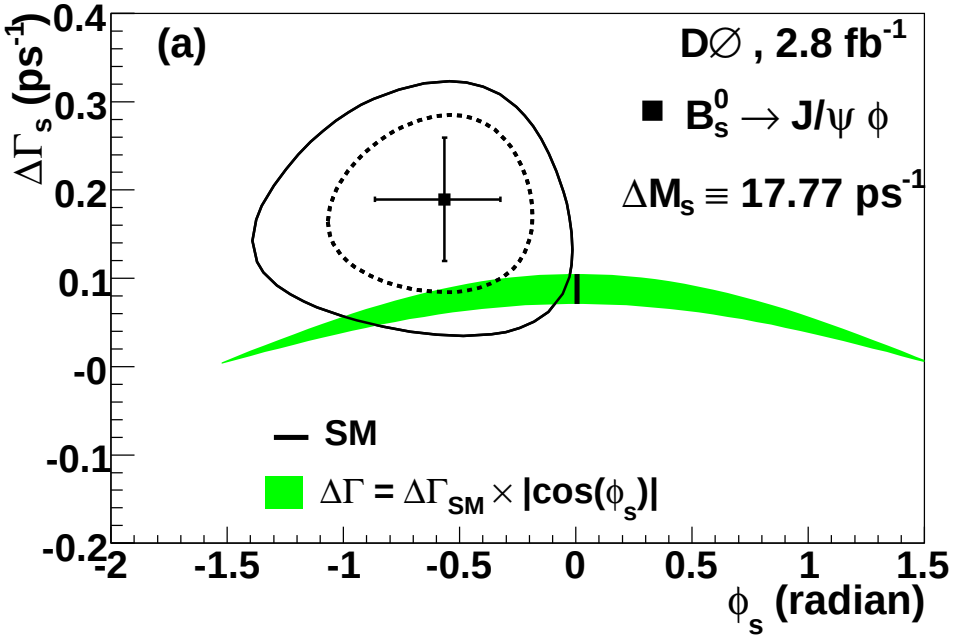


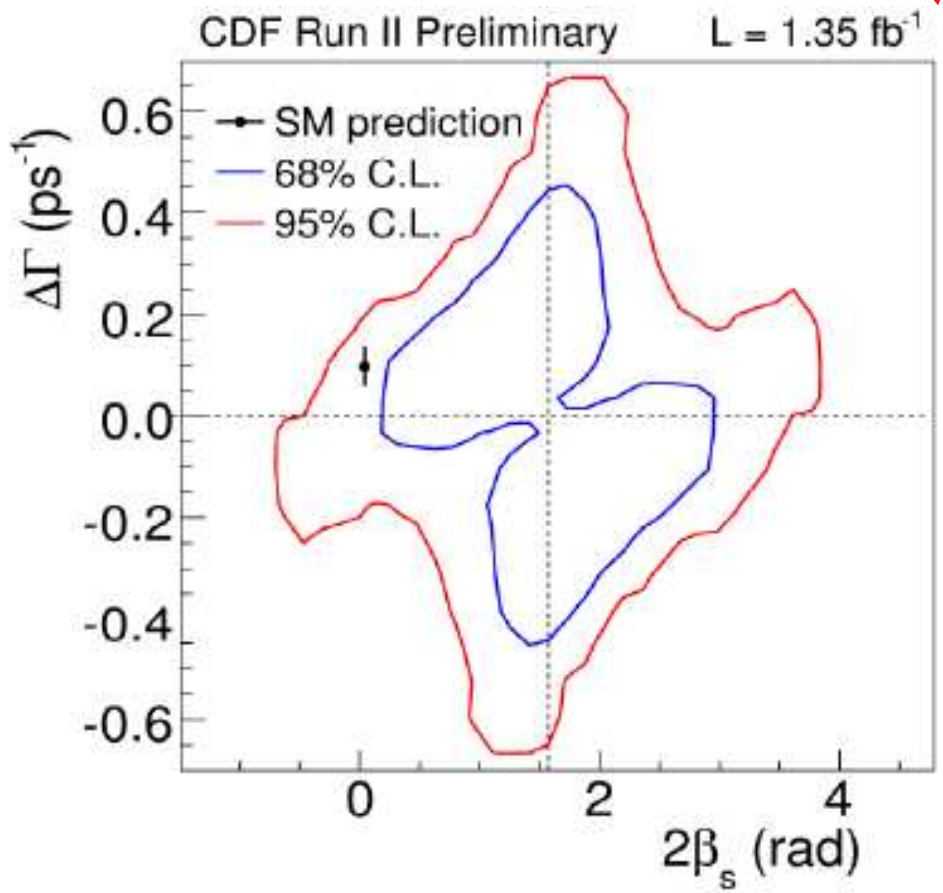
Dilution grows as $|d_{comb}|$ grows, quite close to ideal case $D = 100\% \cdot |d_{comb}|$

All likelihood parameters

Number	Variable	Value
1	f_{sig} (N_{sig})	0.0409±0.0013 (1967±65)
2,3	M, σ (MeV/c^2)	5361.4±1.0, 30.1±1.0
4	$\overline{\tau}$ (μm)	456±17
5	$\Delta\Gamma$(ps^{-1})	0.19±0.07
6	$\lvert A_\perp(0)\rvert$	0.41±0.04
7	$\lvert A_0(0)\rvert^2 - \lvert A_{\lvert\lvert}(0)\rvert^2$	0.34±0.05
8,9	δ_1, δ_2	-0.52±0.42, 3.17±0.39
10	ϕ_s	$-0.57^{+0.24}_{-0.30}$
11	ΔM_s(ps^{-1})	$\equiv 17.77$
12	S	1.24±0.01
13, 14, 15	Bkg mass polynom: a_{1p}, a_{1l}, a_{2l}	-0.06±0.03, -1.45±0.08, 0.68±0.11
16, 17, 18	Bkg time exp. norm.: f_-, f_+, f_{++}	0.049±0.004, 0.155±0.004, 0.035±0.003
19, 20, 21	Bkg time exp. slope: $b_-, b_+, b_{++}(\mu m)$	65±3, 88±3, 399±21
22, 23, 24, 25	Transversity polynom: $X_{2p}, X_{4p}, X_{2l}, X_{4l}$	0.85±0.09, -0.60±0.09, 0.39±0.17, -0.23±0.19
26, 27, 28, 29	ϕ polynom: $Y_{1p}, Y_{2p}, Y_{1l}, Y_{2l}$	-0.23±0.01, -0.10±0.02, -0.15±0.02, -0.00±0.04
30, 31	ψ polynom: Z_{2p}, Z_{2l}	0.05±0.02, 0.27±0.06
32, 33	Interference-like terms in bkg: Int_p, Int_l	-0.011±0.003, -0.018±0.001

Comparison DØ and CDF





$$\phi_s = -2\beta_s$$

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

Source	$\overline{\tau}$ (ps)	$\Delta\Gamma_s$ (ps^{-1})	$A_\perp(0)$	$\lvert A_0(0)\rvert^2 - \lvert A_{\parallel}(0)\rvert^2$	ϕ_s
Acceptance	$\pm$0.003	$\pm$0.003	$\pm$0.005	$\pm$0.03	$\pm$0.005
Signal mass model	-0.01	$+$0.006	-0.003	-0.001	-0.006
Flavor purity estimate	$\pm$0.001	$\pm$0.001	$\pm$0.001	$\pm$0.001	$\pm$0.01
Background model	$+$0.003	$+$0.02	-0.02	-0.01	$+$0.02
ΔM_s input	$\pm$0.01	$\pm$0.001	$\pm$0.001	$\pm$0.001	$^{+0.06}_{-0.01}$
Total	$\pm$0.01	$^{+0.02}_{-0.01}$	$^{+0.01}_{-0.02}$	$\pm$0.03	$^{+0.07}_{-0.02}$