Evidence for $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{CP}/\Gamma_s$

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SungWoo YOUN
Fermilab / Northwestern

Wayne State University, Detroit

Outline

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Tevatron & DØ Detector

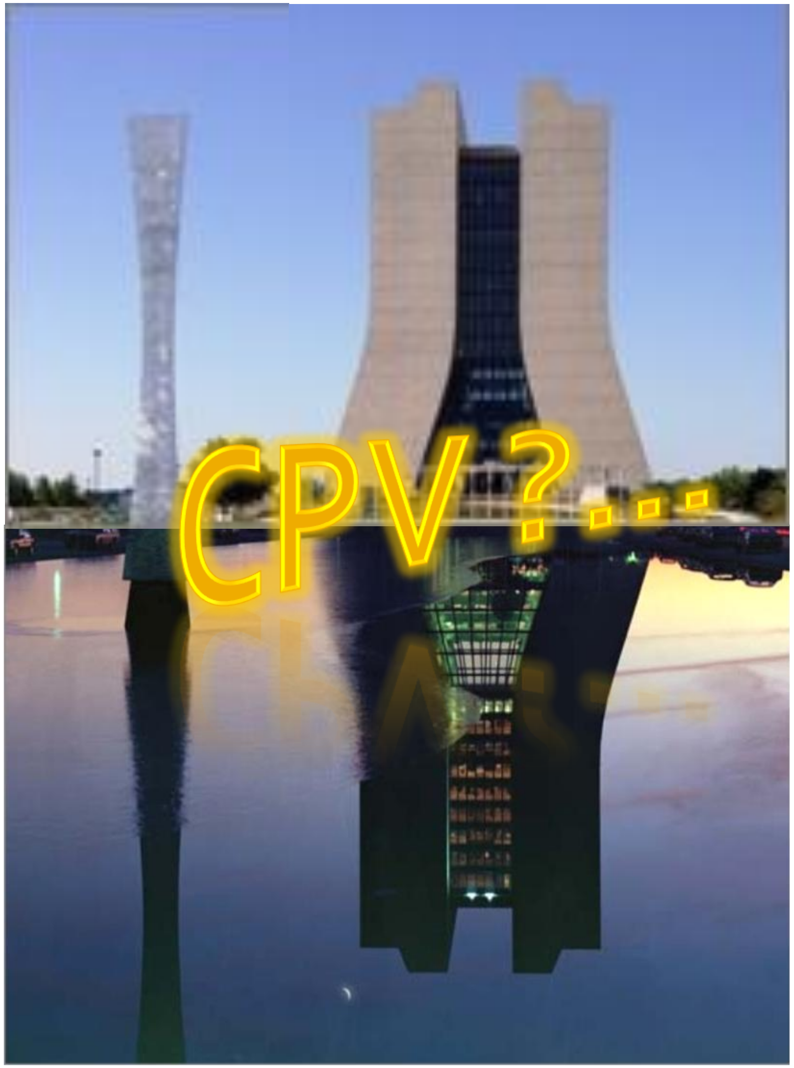
Analysis Procedure

- Sampling
- 2D Likelihood Fitting
- Sample Composition
- Normalization

Systematic Uncertainties

Result & Conclusion

Phys. Rev. Lett. 102, 091801 (2009)
[arXiv.org:0811.2173]



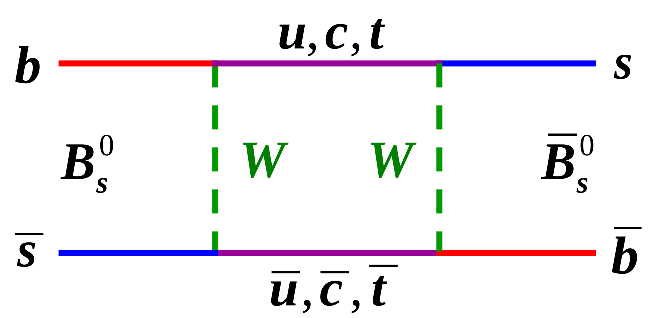
Introduction

B_s^0 Meson

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

M: mass matrix, Γ: decay matrix

$M_{12}=M_{21}^*$, $\Gamma_{12}=\Gamma_{21}^*$ → *Mixing*



Mass / CP eigenstates

$$Mass: \begin{cases} |B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \\ |B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \end{cases}, \quad p^2 + q^2 = 1$$

$$CP: \begin{cases} |B^{even}\rangle = \frac{1}{\sqrt{2}}|B_s^0\rangle - \frac{1}{\sqrt{2}}|\bar{B}_s^0\rangle \\ |B^{odd}\rangle = \frac{1}{\sqrt{2}}|B_s^0\rangle + \frac{1}{\sqrt{2}}|\bar{B}_s^0\rangle \end{cases}$$

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

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\Delta\Gamma_s^{CP} \left(\equiv 2|\Gamma_{12}|\right) = \Gamma_s^{even} - \Gamma_s^{odd}$$

$$\Rightarrow \Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$$

(*New Physics*)

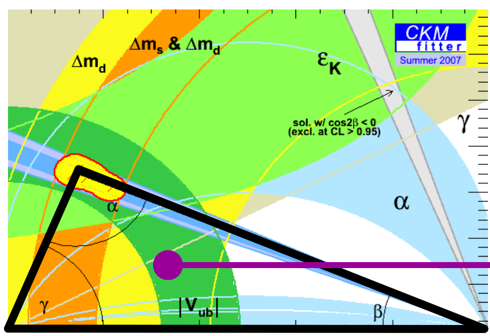
$$\phi_s = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)$$: *CPV mixing phase*

CPV & $\Delta\Gamma_s^{CP}$

CKM Matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Unitary Triangle:



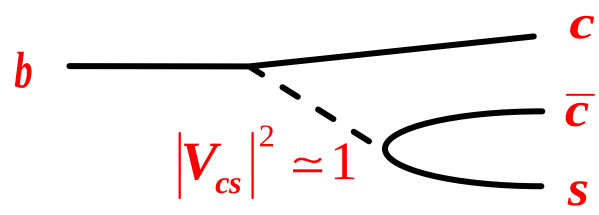
proportional to level of CPV

In SM, CP asymmetry vanishes

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- CPV in B_s^0 mixing ~ 0

$|\Gamma_{12}|$ ($\approx\Delta\Gamma_s^{CP}$) is dominated by $b\rightarrow c\hat{c}s$ quark transition



- Ex) $B_s^0 \rightarrow D_s^+ D_s^-$, $B_s^0 \rightarrow J/\psi\varphi$

- coupling is non-negligible → $\Delta\Gamma_s^{CP}$ could be sizable

- CKM-favored tree-level decays → $\Delta\Gamma_s^{CP}$ is insensitive to NP $\Delta\Gamma_s^{CP} \approx \Delta\Gamma_s^{SM}$

$\Delta\Gamma_s = \Delta\Gamma_s^{CP}\cos\varphi_s$: Any deviation of φ_s from zero → new sources

$\Delta\Gamma_s^{CP}$

For a single final state f:

$$Br(B_s^0 \to f) + Br(B_s^0 \to \bar{f})$$

$$= \Gamma(B_s^{even})\left(\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H}\right) + \Gamma(B_s^{odd})\left(\frac{1-\cos\phi_s}{2\Gamma_L} + \frac{1+\cos\phi_s}{2\Gamma_H}\right)$$

$$\Rightarrow\ 2Br(B_s^0 \to f) = \Delta\Gamma_f^{CP}\left(\frac{\frac{1}{1-2x_f}+\cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f}-\cos\phi_s}{2\Gamma_H}\right)$$

$$x_f = CP\text{-}odd\ \ fraction : \frac{\Gamma(B_s^{odd})}{\Gamma(B_s^{even})} \equiv \frac{x_f}{1-x_f}$$

For B_s^0 system:

- sum over all final states through b→cc̄s transition

$$\Delta\Gamma_s^{CP} = \sum_{\substack{f\in \\ b\to c\bar{c}s}} \left[2Br(B_s^0 \to f)\cdot\left(\frac{\frac{1}{1-2x_f}+\cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f}-\cos\phi_s}{2\Gamma_H}\right)^{-1}\right]$$

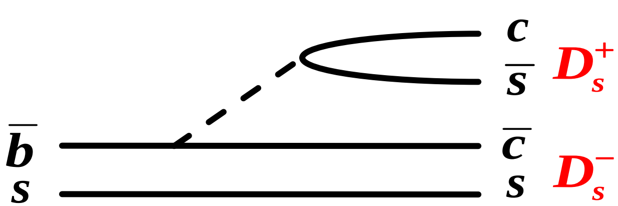
- theoretical uncertainty : b→uūs (~3-5%) (Phys. Rev. D 63, 114015 (2001))

Theoretical Assumptions

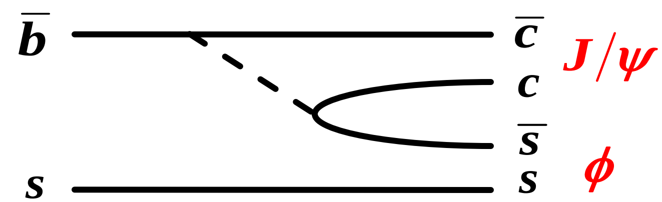
i) In the Shifman-Voloshin (SV) limit (m_b-2m_c → 0) with $N_c \to \infty$

- multi-particle final states vanish (Sov. J. Nucl. Phys. 47, 511 (1988))

- effective color factor suppresses class II spectator decays (~1/N_c)
(Phys. Lett. B 316, 567 (1993))



class I (color-allowed)



class II (color-suppressed)

- $\Delta\Gamma_s^{CP}$ is saturated by $\Gamma(B_s^0 \to D_s^{(*)} D_s^{(*)})$: $D_s^{(*)} = D_s$ or D_s^*

$$2Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP} \left(\frac{\frac{1}{1-2x_f} + \cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f} - \cos\phi_s}{2\Gamma_H} \right)$$

- theoretical uncertainty : <~ 0.01/0.15 (Nucl. Phys. B 374, 263(1992))

Theoretical Assumptions

ii) In the heavy quark (HQ) limit ($m_c \to \infty$) (Phys. Lett. B 316, 567 (1993))

- D_s and D_s^* become degenerate
- amplitude of CP–odd component vanishes
- $D_s^{(*)} D_s^{(*)}$ final state becomes CP-even: $x_f = 0$

$$2Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP} \left(\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H} \right)$$

- polarization study to disentangle CP structure

iii) In the SM ($\varphi_s = 0$)

$$\frac{\Delta\Gamma_s^{SM}}{\Gamma_s} \simeq \frac{2Br(B_s^0 \to D_s^{(*)} D_s^{(*)})}{1 - Br(B_s^0 \to D_s^{(*)} D_s^{(*)})}$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H, \quad \Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$$

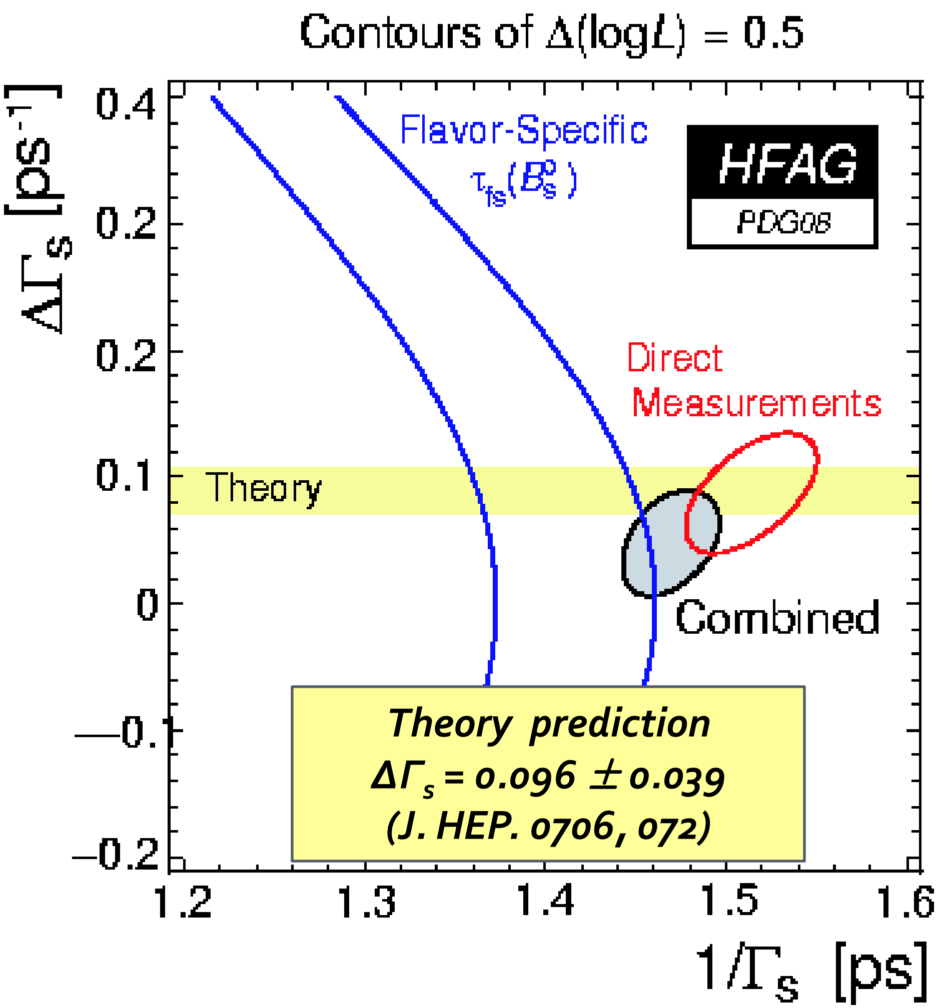
Lifetime information from BRs without lifetime fits !

Flavor-Specific:

- $B_s^o \rightarrow D_s^{(*)}\mu\nu$
- lifetime measurement
- 50% CP-even / 50% CP-odd

Direct Measurements:

- $B_s^o \rightarrow J/\Psi\varphi$ (DØ & CDF)
- angular analysis: $\Delta\Gamma_s$ & φ_s



Flavor-Specific:

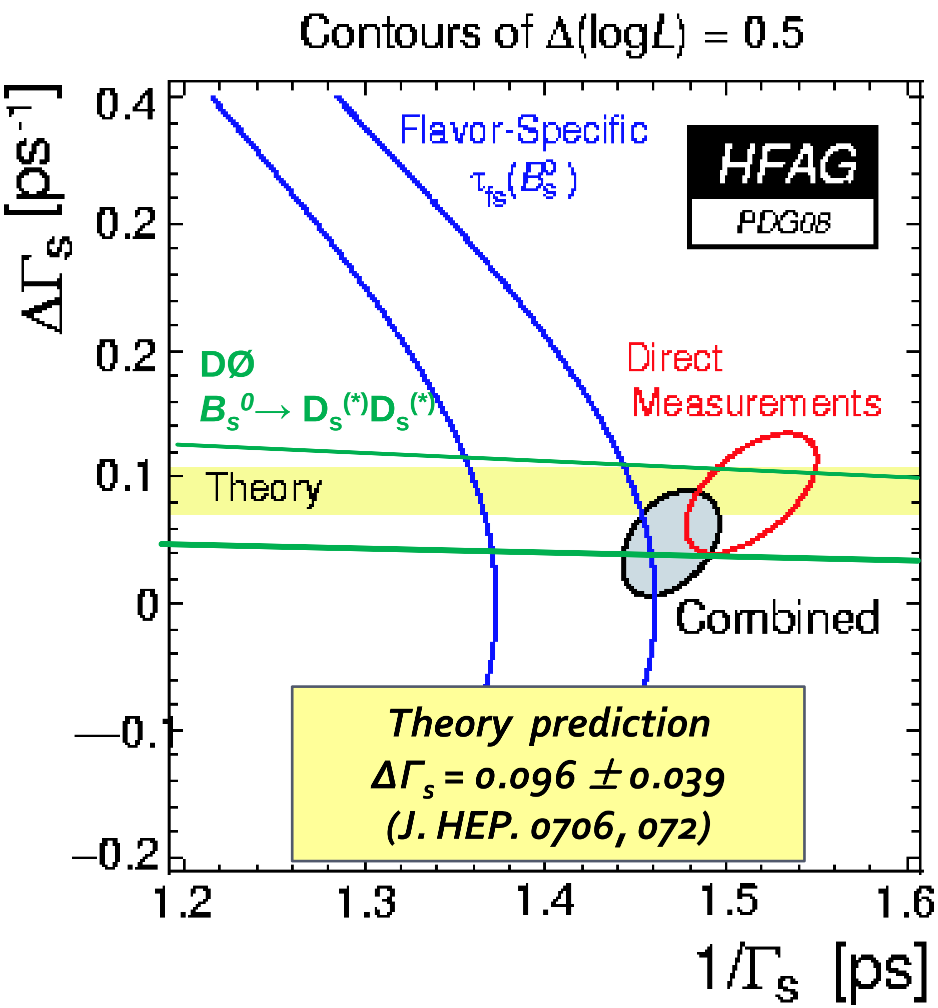
- $B_s^o \to D_s^{(*)} \mu\nu$
- lifetime measurement
- 50% CP-even / 50% CP-odd

$B_s^o \to D_s^{(*)} D_s^{(*)}$:

- theory based analysis: CP-even
- consistent with theory
- compatible error band
- untagged: efficiency, purity, acceptance
- simple measurement

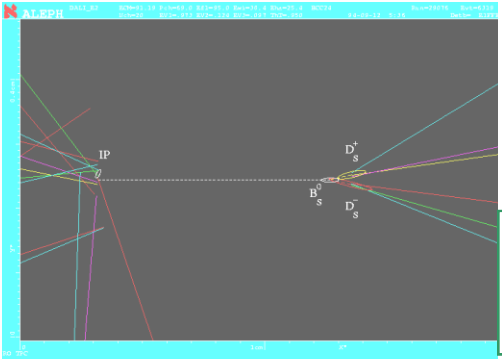
Direct Measurements:

- $B_s^o \to J/\Psi\varphi$ (DØ & CDF)
- angular analysis: $\Delta\Gamma_s$ & φ_s



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

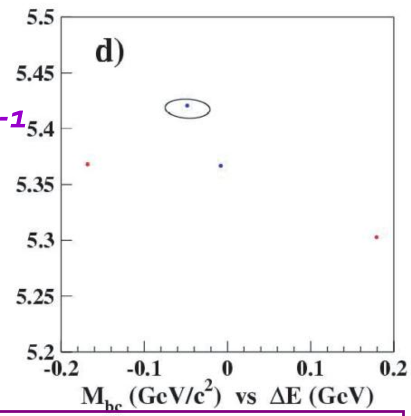
ALEPH (2000) - φφ correlation in Z decays



$$N = 18.5 \pm 6.7$$

$$Br = 0.077 \pm 0.034^{+0.038}_{-0.026}$$

Belle (2006) – 1.86 fb⁻¹ at Υ(5S) resonance

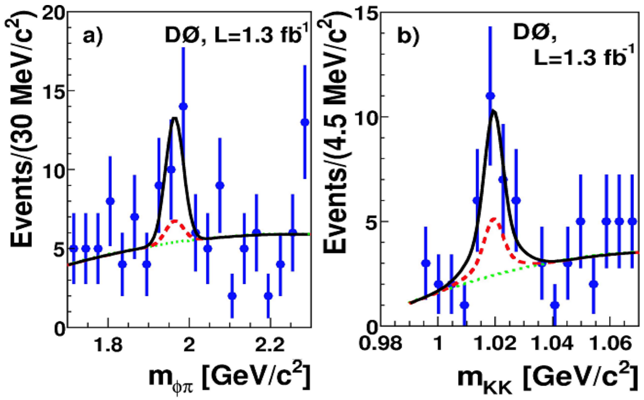


$$Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) < 27.3\%$$

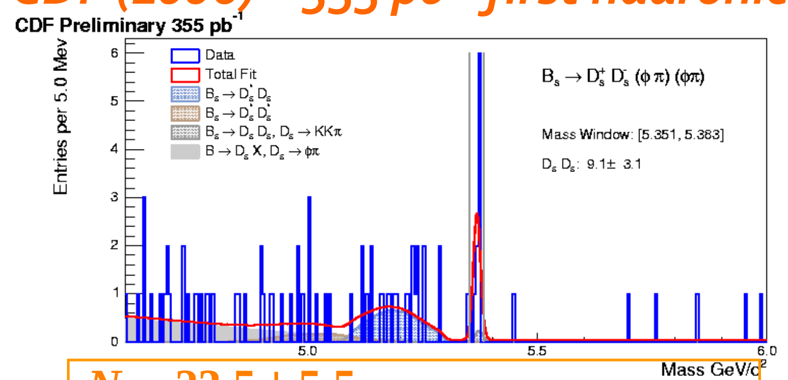
DØ (2007) – 1.3 fb⁻¹ $D_s D_s$ correlation

$$N = 13.4^{+6.6}_{-6.0}$$

$$Br = 0.039^{+0.019+0.016}_{-0.017-0.015}$$



CDF (2006) – 355 pb⁻¹ first hadronic

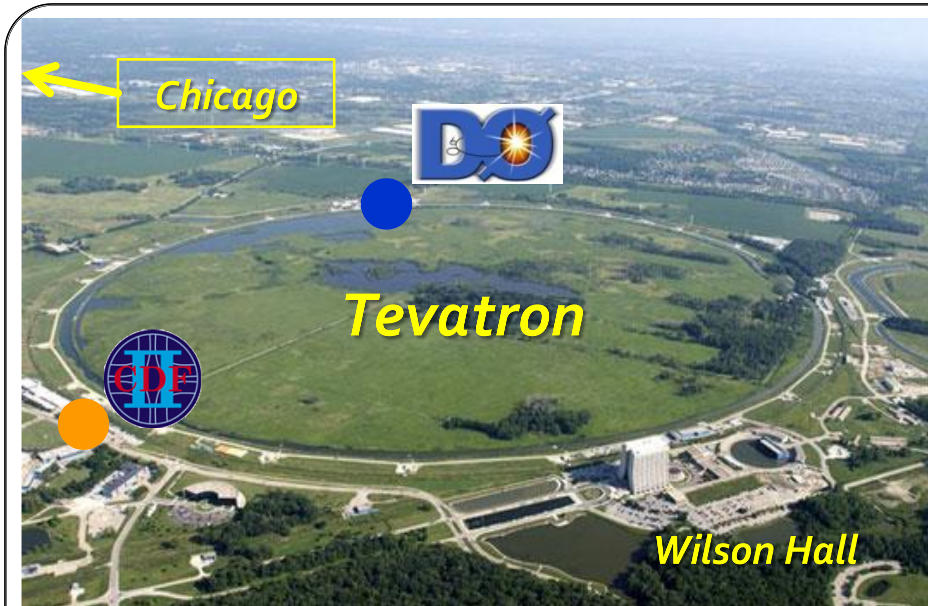


$$N = 23.5 \pm 5.5$$

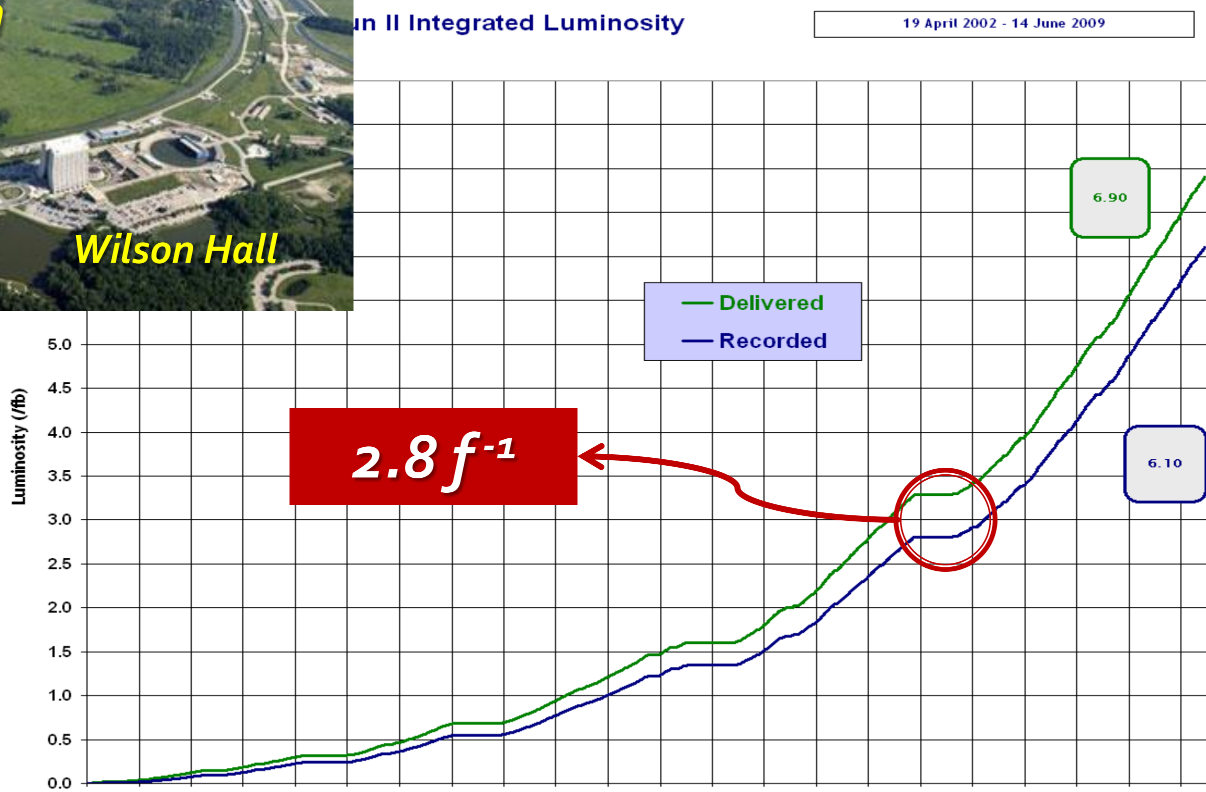
$$Br(B_s^0 \to D_s^+ D_s^-) / Br(B^0 \to D_s^+ D^-)$$

Tevatron & DØ Detector

Tevatron

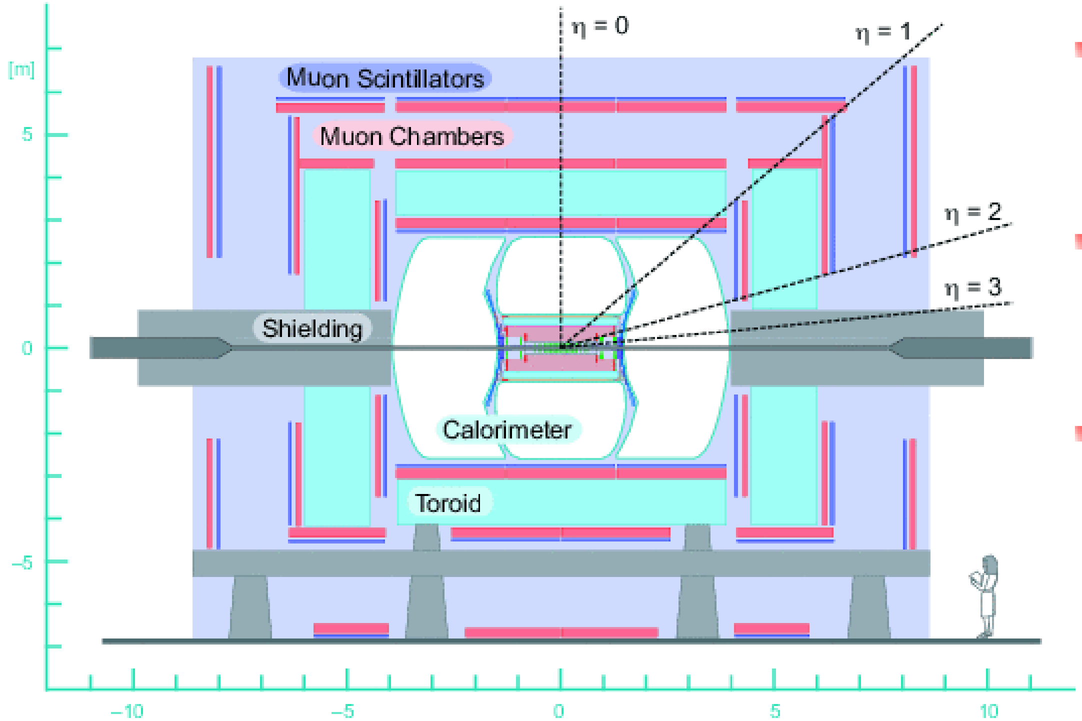


- *Excellent performance*
  - 6.9 (6.1) fb^{-1} deliver (record)
  - > 90% efficiency
  - > $3x10^{32}$ $cm^{-2}s^{-1}$



- *p-pbar collider*
- *4 miles*
- $\sqrt{s}$ = 1.96 TeV
- *DØ & CDF*

DØ Detector

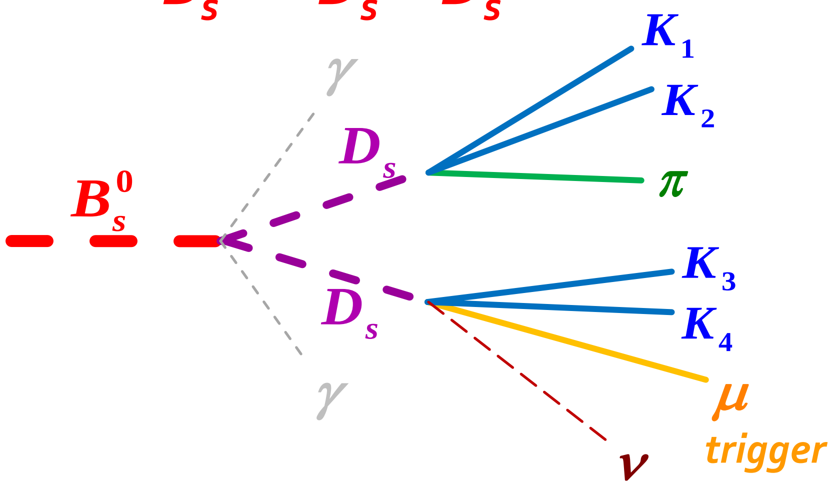


- **Solenoid magnet**
  - 2 T
- **Calorimeter**
  - uranium / liquid Ar
- **Muon system**
  - drift tubes & scintillators
  - 1.8 T toroid
  - excellent muon triggers
  - $|\eta| < 2.0$
- **Tracking system**
  - Silicon Microstrip Track & Central Fiber Track
  - essential for displaced vertices
  - Layer Ø in 2006

Analysis Procedure

Overall Procedure

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

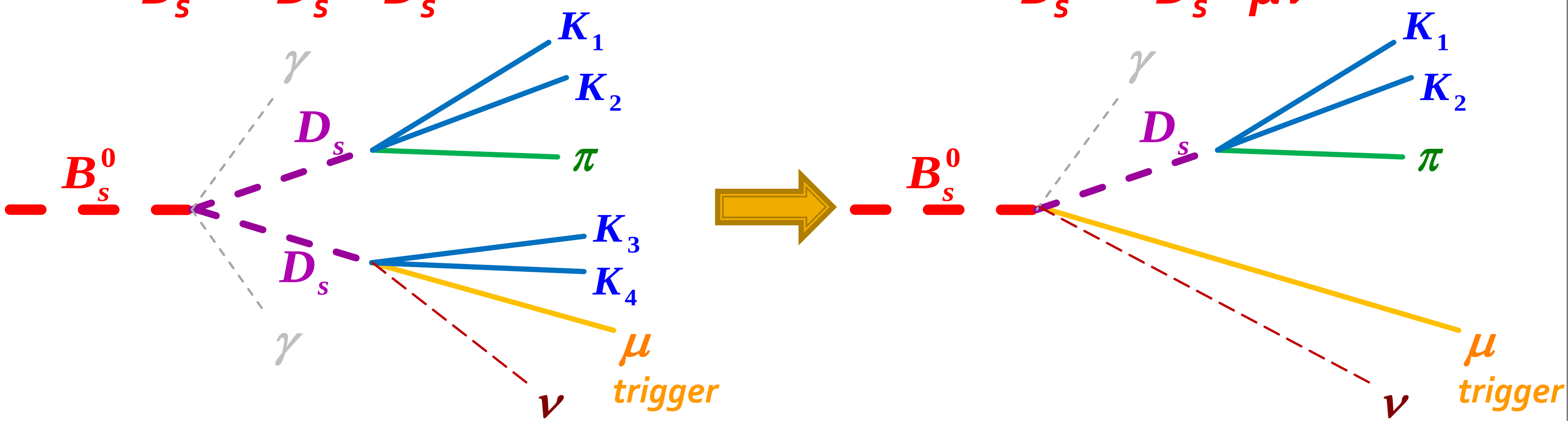


Correlation between two D_s mesons

Overall Procedure

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

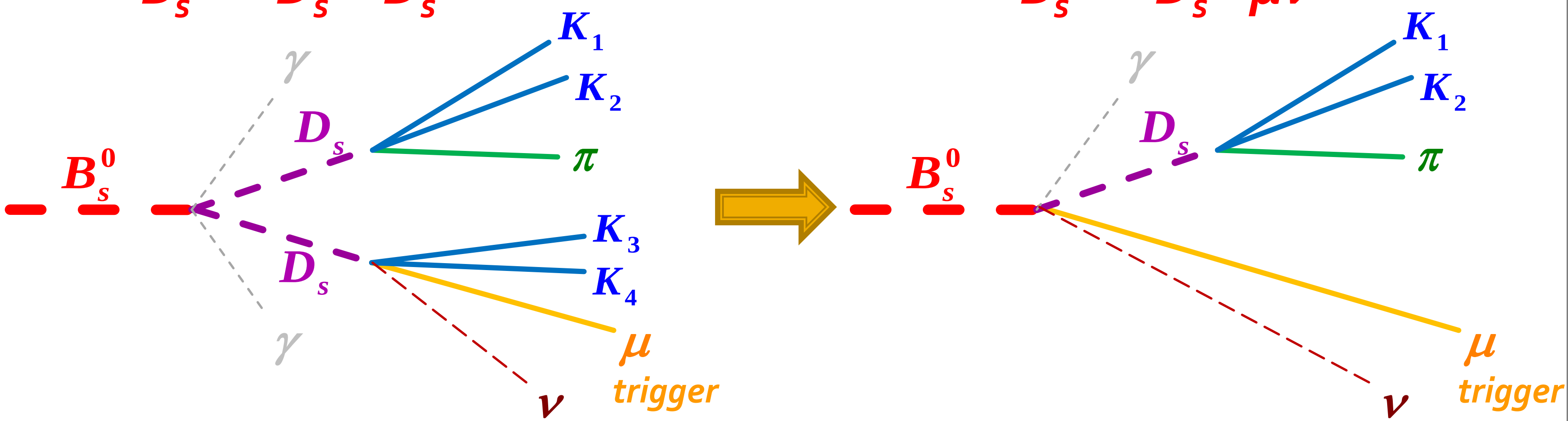
$B_s^0 \rightarrow D_s^{(*)} \mu\nu$



Correlation between two D_s mesons

Overall Procedure

$B_s^o \rightarrow D_s^{(*)} D_s^{(*)}$ $\qquad$ $B_s^o \rightarrow D_s^{(*)} \mu\nu$



Correlation between two D_s mesons

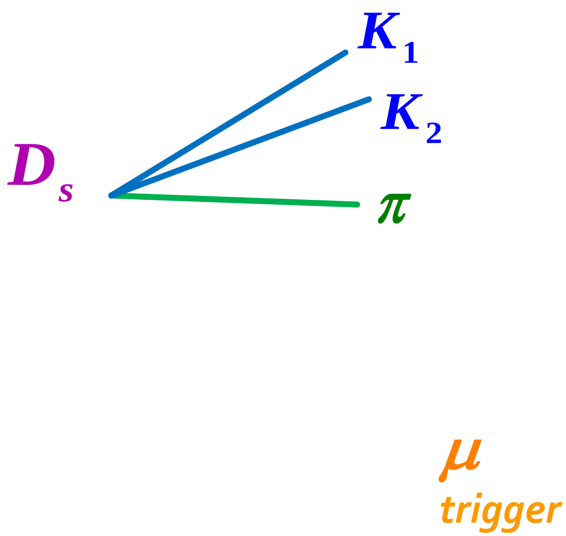
$$\frac{N(B_s \rightarrow D_s^{(*)} D_s^{(*)})}{N(B_s \rightarrow D_s^{(*)} \mu\nu)} = 2R \cdot \frac{\varepsilon(B_s \rightarrow D_s^{(*)} D_s^{(*)})}{\varepsilon(B_s \rightarrow D_s^{(*)} \mu\nu)}$$

$$R \equiv \frac{Br(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \cdot Br(D_s \rightarrow \varphi\mu\nu) \cdot Br(\varphi \rightarrow K^+ K^-)}{Br(B_s \rightarrow D_s^{(*)} \mu\nu)}$$

(many detector-related systematic effects cancel)

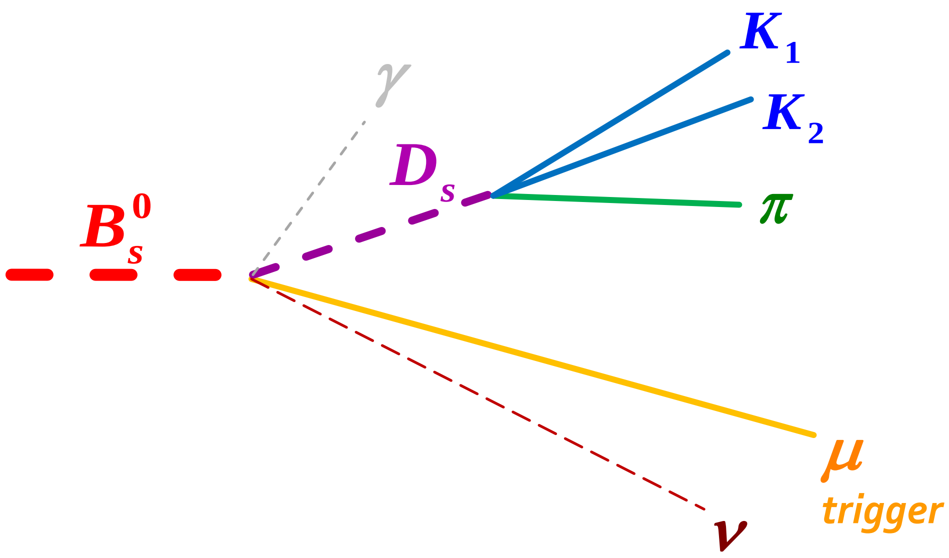
Sampling - Common

Common Sample ($D_s + \mu$)



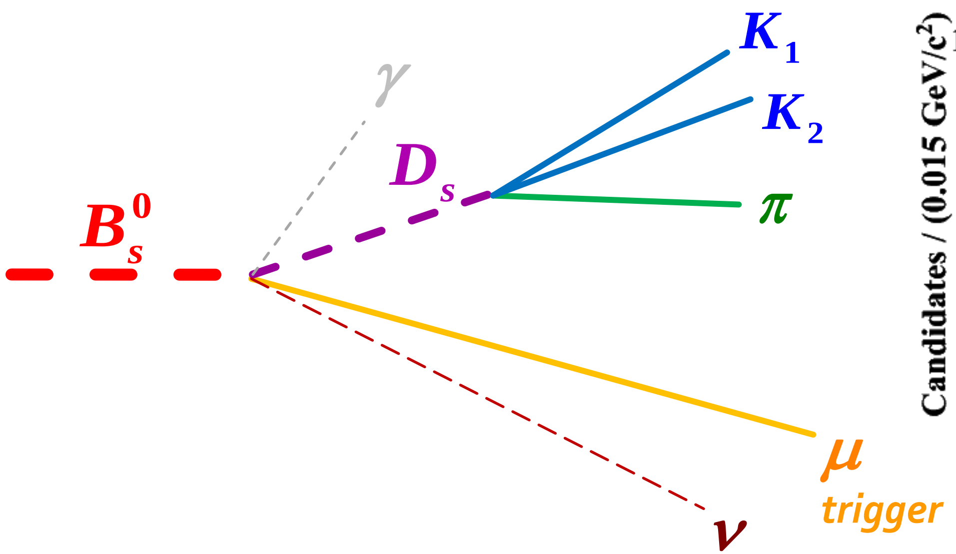
Sampling - $D_s\mu$

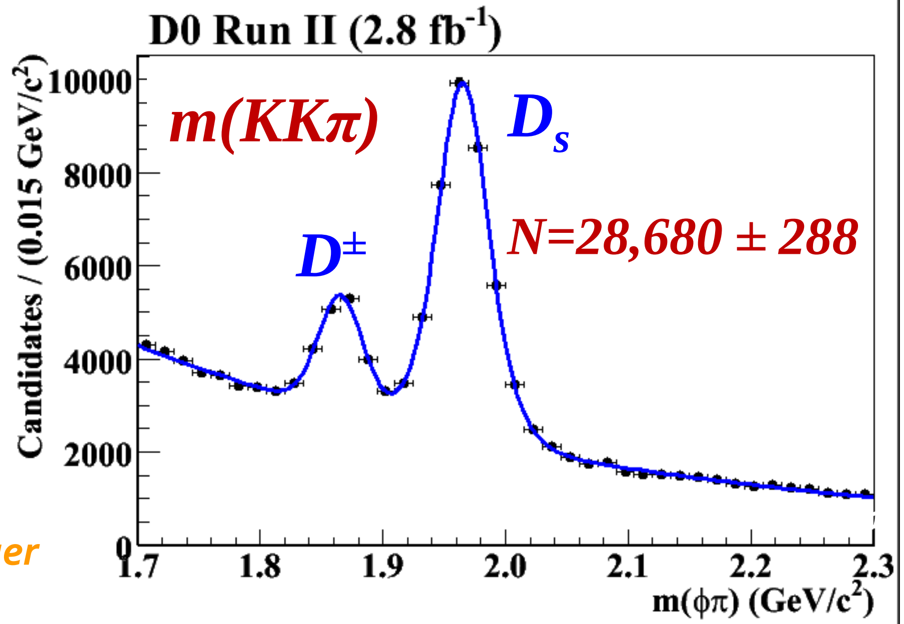
$D_s\mu$ Sample ($B_s^0 \rightarrow D_s^{(*)}\mu\nu$, …) - normalization



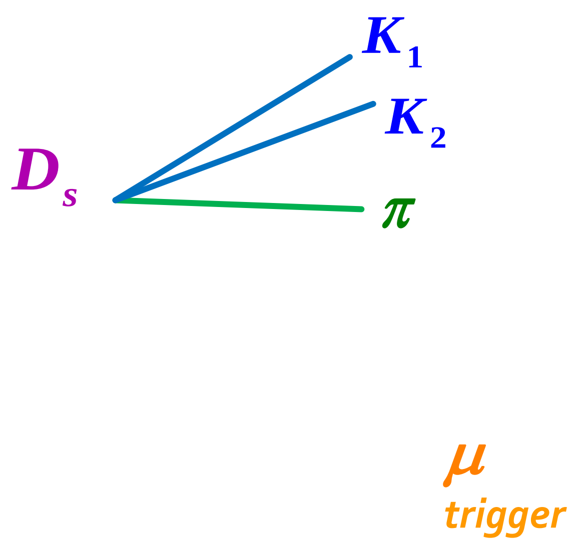
Sampling - $D_s\mu$

$D_s\mu$ Sample ($B_s^0 \rightarrow D_s^{(*)}\mu\nu$, ...) - normalization





Common Sample ($D_s + \mu$)



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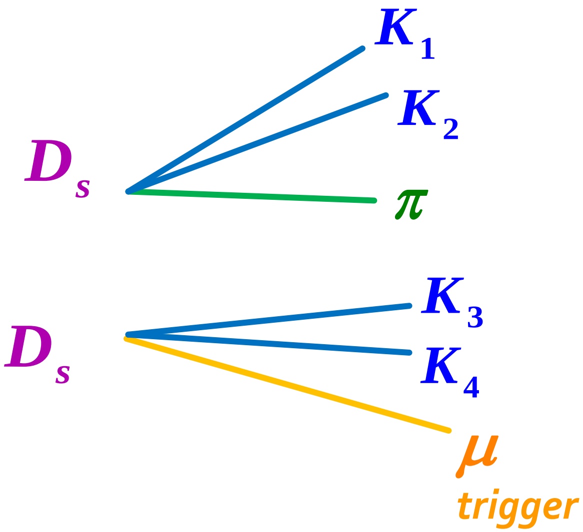
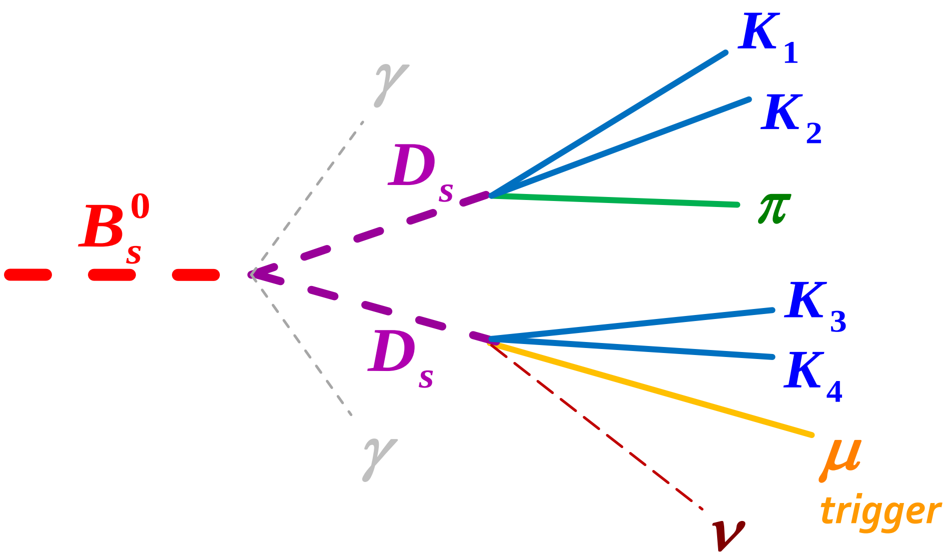
$D_s \varphi \mu$ Sample ($B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$, …) - signal



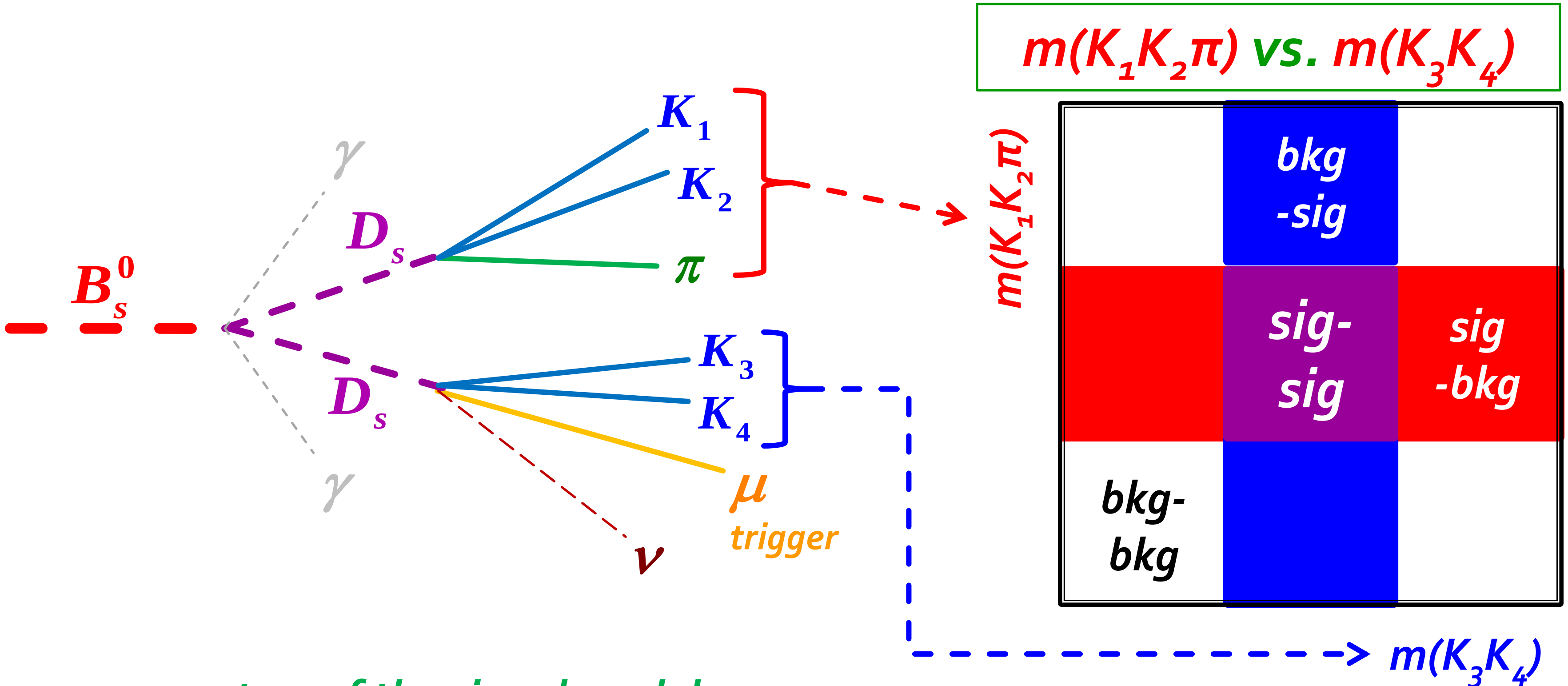
Sampling - $D_s\varphi\mu$

$D_s\varphi\mu$ Sample ($B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$, ...) - signal



Correlated Production

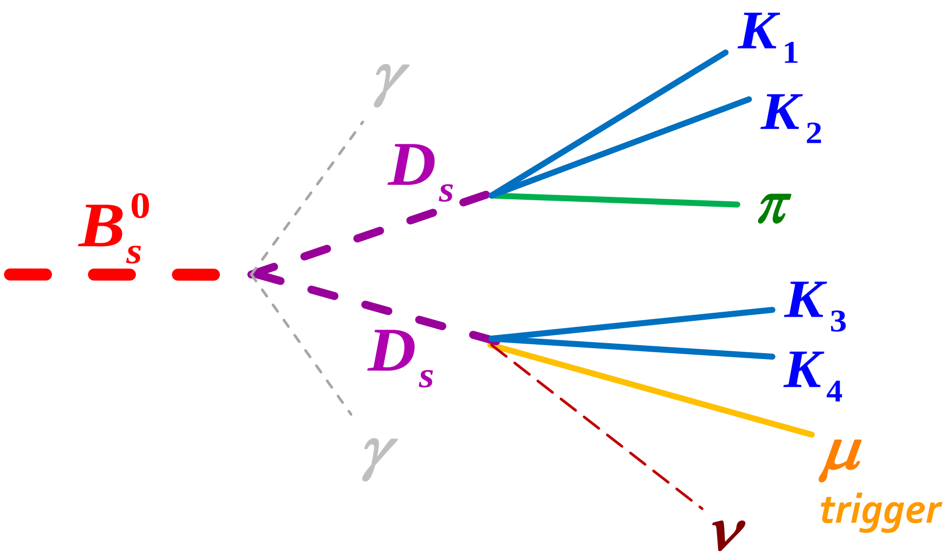
$D_s\varphi\mu$ Sample ($B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$, …) - signal

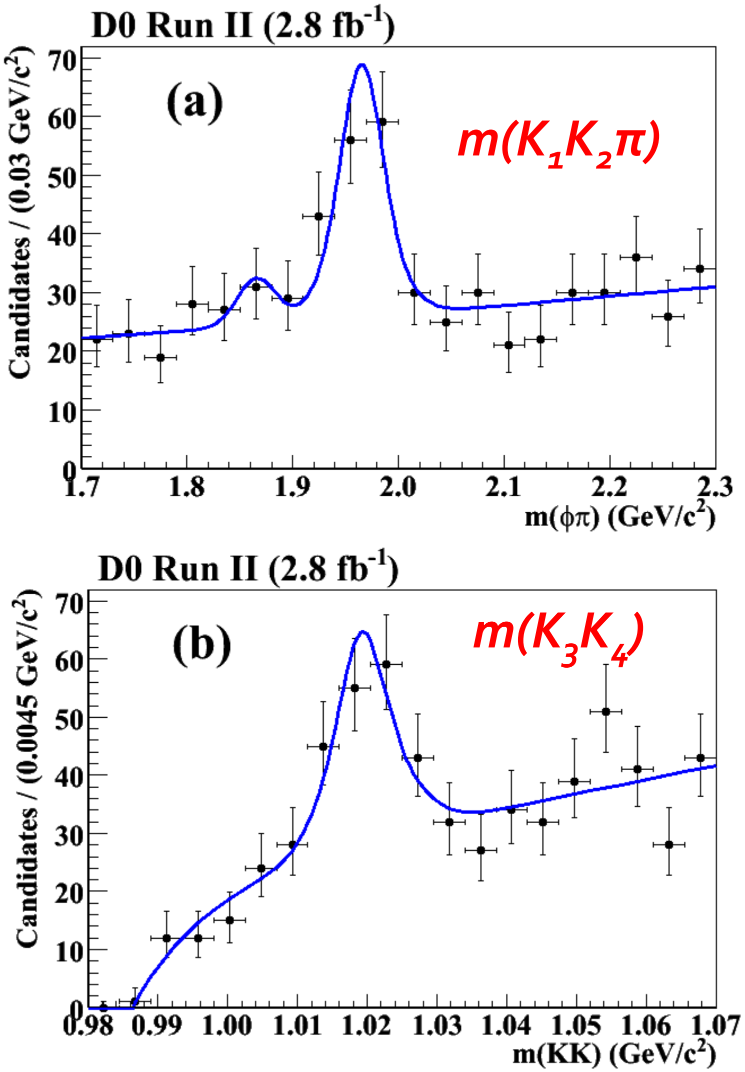


- parameters of the signal models: determined from $D_s\mu$ sample

2-D Max. Likelihood Fit

$m(K_1K_2\pi)$ vs. $m(K_3K_4)$





N(correlated) = 31.0 ± 9.4

Background

Physics-suppressed

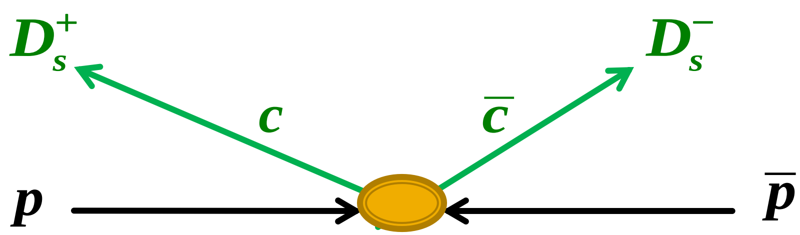
Process	Remark	Recipe	Contrib.
$B_s^0 \to D_s^{(*)} D_s^{(*)} X$	two gluons required	negligible	~ 0 %

Kinematics-suppressed → Sample composition

Process	Remark	Recipe	Contrib.
$B^{\pm,0} \to D_s^{(*)} D_s^{(*)} K X$	low mass ($D_s \varphi\mu$)	$m(D_s\varphi\mu) > 4.3$ GeV	5 ± 2 %
$B_s^0 \to D_s^{(*)} \mu\nu\varphi$	high mass ($\varphi\mu$)	$m(\varphi\mu) > 1.85$ GeV	0 ± 3 %

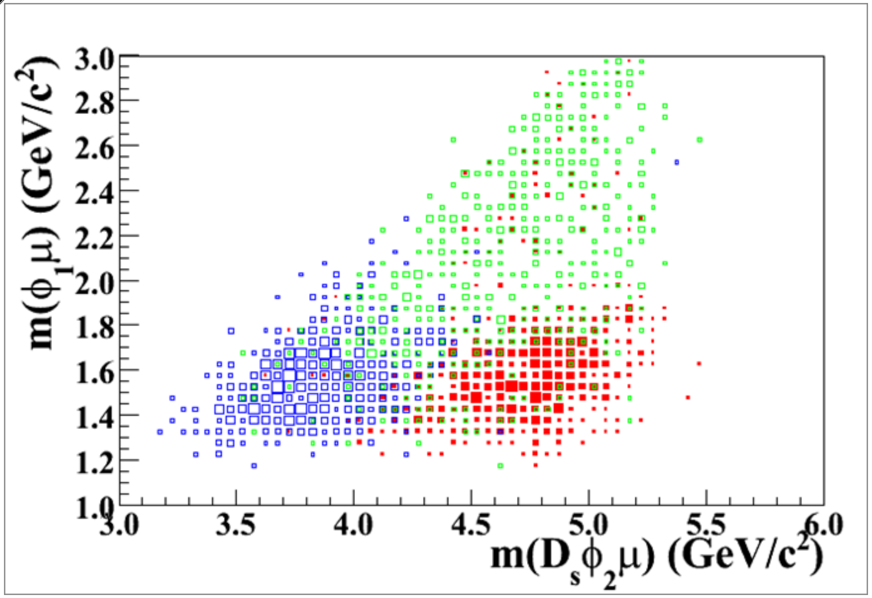
$c\bar{c}$ contamination

f_{cc} ($D_s\mu$ sample) = 10.3 ± 2.5 %
from lifetime distribution for Δm_s analysis



Process	Comment	Recipe	Contrib.
$c\bar{c} \to D_s^{(*)} \varphi\mu X$	short decay length	lifetime cut	2 ± 1 %

Sample Composition

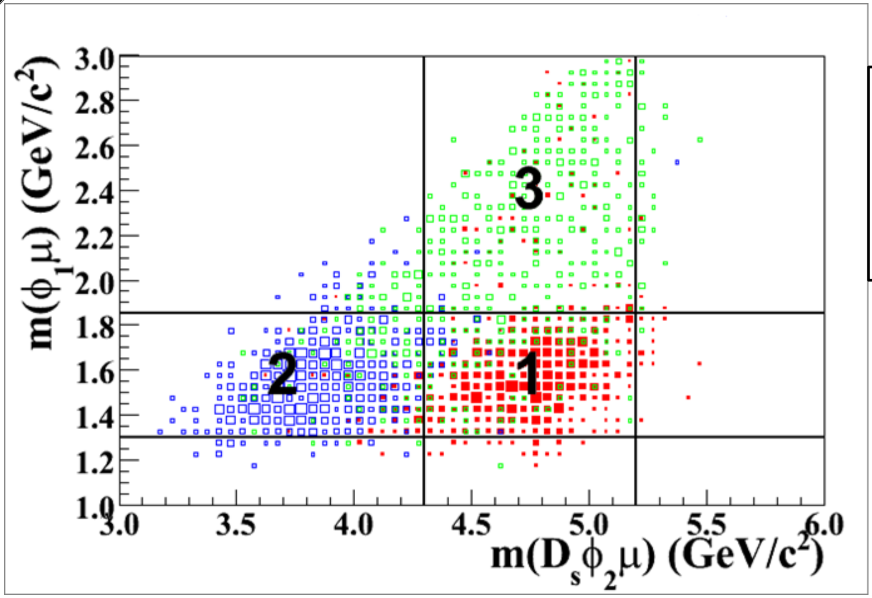


a: $B_s^o \rightarrow D_s^{(*)} D_s^{(*)}$

b: $B^{\pm,o} \rightarrow D_s^{(*)} D_s^{(*)} KX$

c: $B_s^o \rightarrow D_s^{(*)} \mu\nu\varphi$

Sample Composition

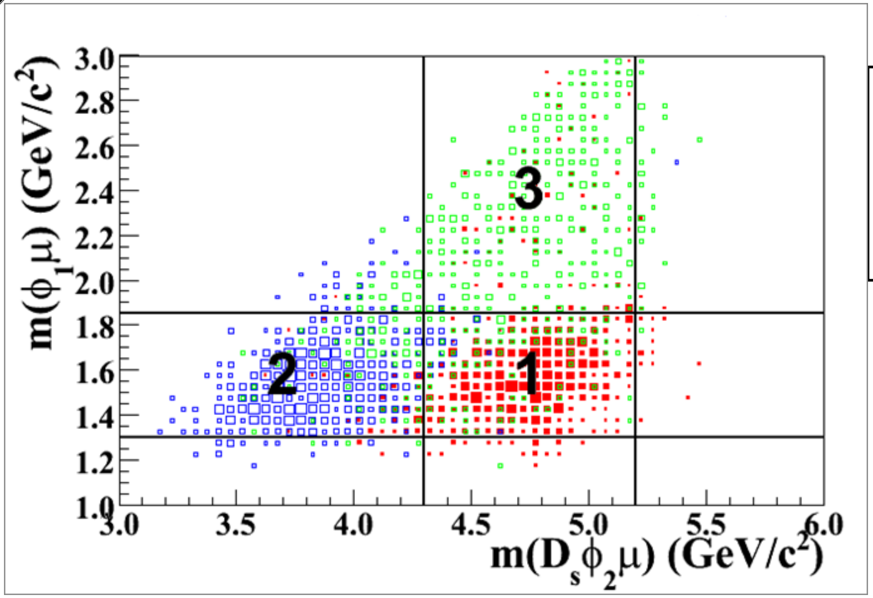


M_i : *total # of events for channel* i *(data)*
n_j : *total # of events in region* j *(fitting)*
$f_{i,j}$: *frac. for channel* i *in region* j *(MC)*

$$\Rightarrow \begin{pmatrix} f_{a,1} & f_{b,1} & f_{c,1} \\ f_{a,2} & f_{b,2} & f_{c,2} \\ f_{a,3} & f_{b,3} & f_{c,3} \end{pmatrix} \begin{pmatrix} M_a \\ M_b \\ M_c \end{pmatrix} = \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

a: $B_s^o \rightarrow D_s^{(*)} D_s^{(*)}$
b: $B^{\pm,o} \rightarrow D_s^{(*)} D_s^{(*)} KX$
c: $B_s^o \rightarrow D_s^{(*)} \mu\nu\varphi$

Sample Composition



M_i : total # of events for channel i (data)
n_j : total # of events in region j (fitting)
$f_{i,j}$: frac. for channel i in region j (MC)

$$\Rightarrow \begin{pmatrix} f_{a,1} & f_{b,1} & f_{c,1} \\ f_{a,2} & f_{b,2} & f_{c,2} \\ f_{a,3} & f_{b,3} & f_{c,3} \end{pmatrix} \begin{pmatrix} M_a \\ M_b \\ M_c \end{pmatrix} = \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

a: $B_s^o \rightarrow D_s^{(*)} D_s^{(*)}$
b: $B^{\pm,o} \rightarrow D_s^{(*)} D_s^{(*)} KX$
c: $B_s^o \rightarrow D_s^{(*)} \mu\nu\varphi$

$$N(D_s^{(*)} D_s^{(*)}) = N(correlated) \cdot F_{a,1}$$

$$where, \ F_{a,1} = \frac{f_{a,1} \cdot M_a}{\sum_i f_{i,1} \cdot M_i}$$

Signal yield: $N(B_s^o \rightarrow D_s^{(*)} D_s^{(*)}) = 26.6 \pm 8.4$
significance = 3.2 σ (Evidence !)

Systematic Uncertainties

Systematic Uncertainties

Source	Uncertainty
$Br(B_s^0 \to D_s^{(*)} \mu\nu)$	0.0061
$Br(D_s \to \varphi\pi) \cdot Br(\varphi \to KK)$	0.0032
$Br(D_s \to \varphi\mu\nu)/Br(D_s \to \varphi\pi)$	0.0026
$\varepsilon(D_s^{(*)} D_s^{(*)}) / \varepsilon(D_s^{(*)} \mu\nu)$	0.0065
$N(D_s^{(*)} D_s^{(*)})$: Matrix	0.0036
fitting procedure	0.0021
ccbar	0.0013
$f(B_s^0 \to D_s^{(*)} \mu\nu)$	0.0004
$N(D_s\mu)$	0.0004
Total	0.0108
Statistical Uncertainty	0.0104

- Poor Input branching ratios
  - largest source (> 45%)
  - room for further improvement
- Reconstruction efficiency (~35%)
  - trigger effect
  - tracking efficiency
- BKG Estimation (Matrix method)
- ccbar contamination ~ 1%

Result & Conclusion

Result

Branching ratio

- $Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010\ (stat) \pm 0.011\ (syst)$
- significance: 3.2 σ

$$\frac{N(B_s \to D_s^{(*)} D_s^{(*)})}{N(B_s \to D_s^{(*)} \mu\nu)} = 2R \cdot \frac{\varepsilon(B_s \to D_s^{(*)} D_s^{(*)})}{\varepsilon(B_s \to D_s^{(*)} \mu\nu)}$$

$$R \equiv \frac{Br(B_s \to D_s^{(*)} D_s^{(*)}) \cdot Br(D_s \to \varphi\mu\nu) \cdot Br(\varphi \to K^+K^-)}{Br(B_s \to D_s^{(*)} \mu\nu)}$$

Result

Branching ratio

- $Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010\ (stat) \pm 0.011\ (syst)$
- significance: 3.2 σ

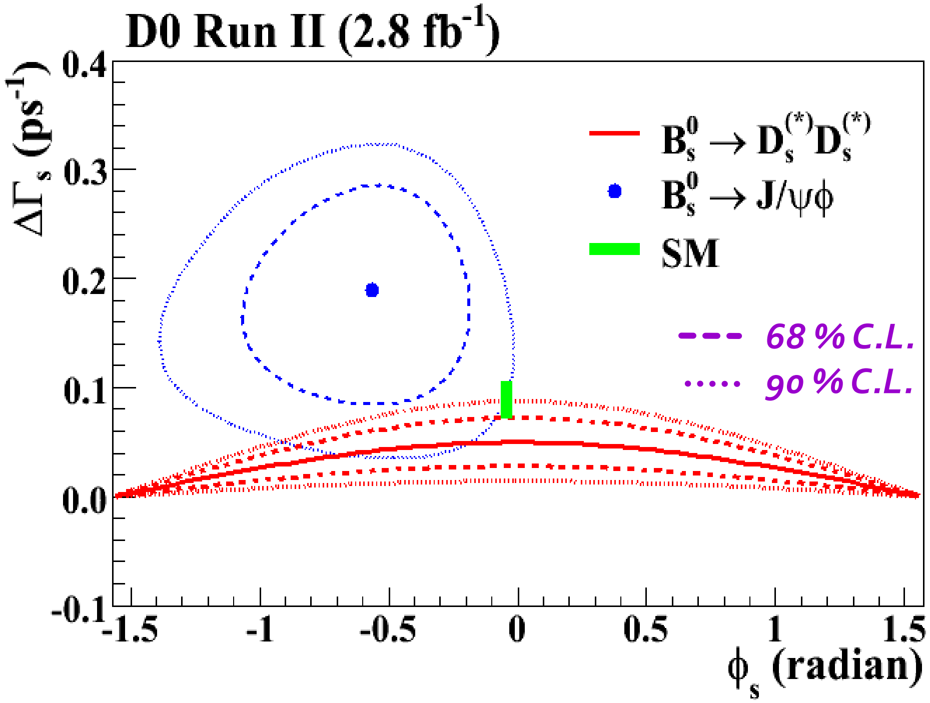
Lifetime difference and CPV information

- under theoretical assumptions

$$2Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP} \left(\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H} \right)$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H, \quad \Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$$



Result

Branching ratio

- $Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010\ (stat) \pm 0.011\ (syst)$
- significance: 3.2 σ

Lifetime difference and CPV information

- under theoretical assumptions
- in the SM framework

$$\frac{\Delta\Gamma_s^{SM}}{\Gamma_s} \simeq \frac{2Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})}{1 - Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})} = 0.072 \pm 0.021(stat) \pm 0.022(syst)$$

	$Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$	$\Delta\Gamma_s / \Gamma_s$
ALEPH (2000)	$0.077 \pm 0.034_{-0.026}^{+0.038}$	$0.167 \pm 0.070_{-0.053}^{+0.079}$
D0 (2007, 1.3 fb^{-1})	$0.039_{-0.017}^{+0.019}{}_{-0.015}^{+0.016}$	$0.081_{-0.035}^{+0.039}{}_{-0.030}^{+0.033}$
WA (end of 2007)	0.046 ± 0.022	0.096 ± 0.048
Theory	0.048 ± 0.009	0.127 ± 0.024

Conclusion

- *Evidence for $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ using 2.8 fb^{-1}*
  - 26.6 ± 8.4 signal events (3.2 σ)
  - $Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010$ (stat) ± 0.011 (syst)
- *CPV information and lifetime difference*
  - under various theoretical assumptions
  - $\Delta\Gamma_s^{SM} / \Gamma_s = 0.072 \pm 0.021$ (stat) ± 0.022 (syst)
  - consistent with experiment and theory
- *Powerful constraint on mixing and CPV in B_s^0 system*
  - significant improvement of scientific understanding of CPV
  - theoretical errors controlled and CP structure disentangled
- *First single experimental measurement for $\Delta\Gamma_s \neq 0$ at > 3 σ*

Backup Slides

DPF 2009 (July 26 ~31)

SungWoo YOUN
Fermilab / Northwestern

Wayne State University, Detroit

B_s^0 Meson

B mesons have offered direct ways to determine the phase structure of the CKM matrix for verification of the SM, and could be the key to understanding one of the fundamental mysteries of physics:

Dominance of matter in our present universe

Scientists conducting studies of CP (charge-parity) violation in neutral particle systems (K, B, ν, …) have shed light on such imbalance

CPV in the B_s system is a prime candidate for the discovery of non-standard physics:

CPV in the SM ~ zero (CKM) → observation = NP

Decays of B_s mesons to CP eigenstates could provide further information on the matter-antimatter asymmetry

Significance

Significance for maximum likelihood fit

- $S = \text{sqrt}\{ -2 \ln(L_0 / L_{max}) \}$

  L_0 : likelihood value returned by the fit with the bkg. only hypothesis

  L_{max} : likelihood value returned by the nominal (bkg.+sig. hypothesis) fit

- correlated background is considered and systematic uncertainties are included in calculation

  smear N(correl. bkg) using Gamma distribution

  smear fitting parameters by ±1σ using Gaussian distributions

  repeat the fit 10,000 times to calculate significance

  average the individual significances

$$S = \frac{\sum_i S_i}{N} \quad (N = 10{,}000)$$

Significance = 3.2 σ

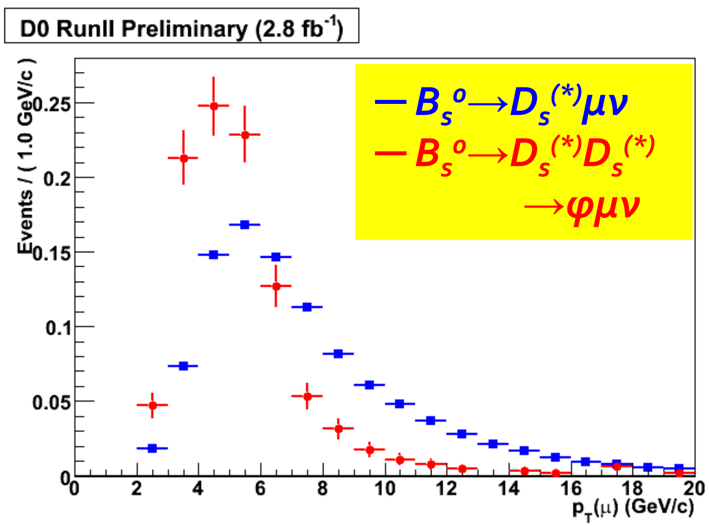
Single Muon Trigger Efficiency

Single Muon Trig. Model

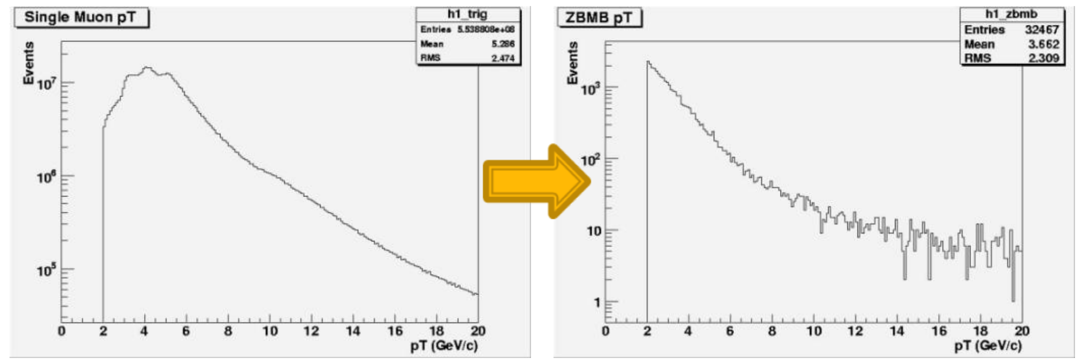
Complicated to correct for the difference in p_T distributions from different decay processes

- *ex) $b \to \mu$ vs $b \to c \to \mu$*

Understanding trigger effect is essential for low p_T physics

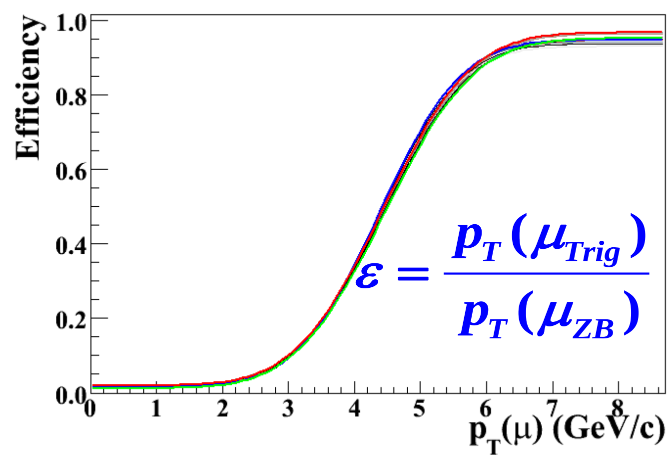


Inclusive single muon sample



triggered muon p_T — unbiased muon p_T

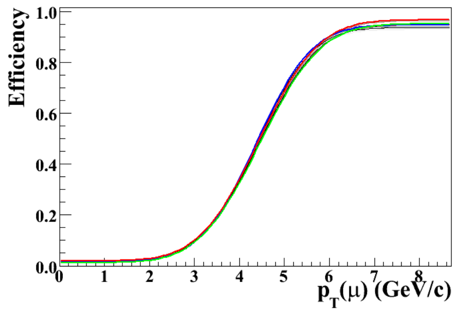
Universal Trigger Turn-on Curve



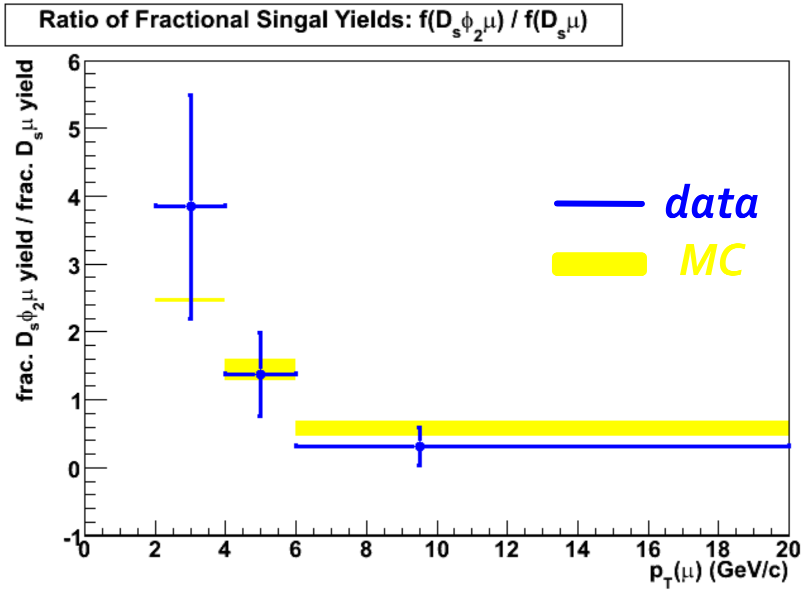
Single Muon Trig. Model

Two trigger models

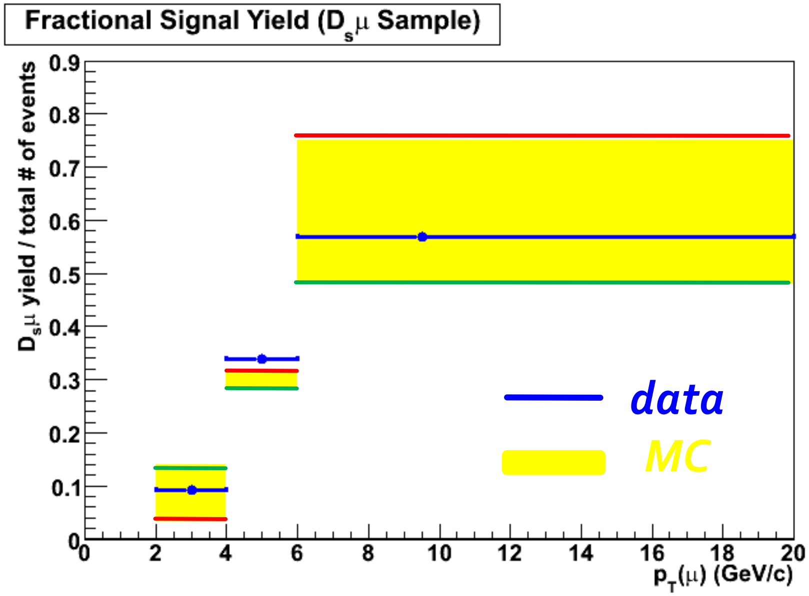
- one w/ turn-on (weighted)
- one w/o turn-on (un-weighted)



Yes vs. No



Ratio of signal yields: $f(D_s\varphi\mu) / f(D_s\mu)$



signal yields of $D_s\mu$ sample

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