Heavy Flavor Physics at CDF & DØ

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(for the CDF & DØ collaborations)

40th Fermilab Users' Meeting: 6-7 June, 2007

What You're In For

1) >100 Heavy Flavor results from the Tevatron since start of Run II !
   - 48 Heavy Flavor publications
   - tragically, the organizers denied my request for an extra 2,980 minutes
   - cannot possibly cover it all in detail (apologies to those I slight)

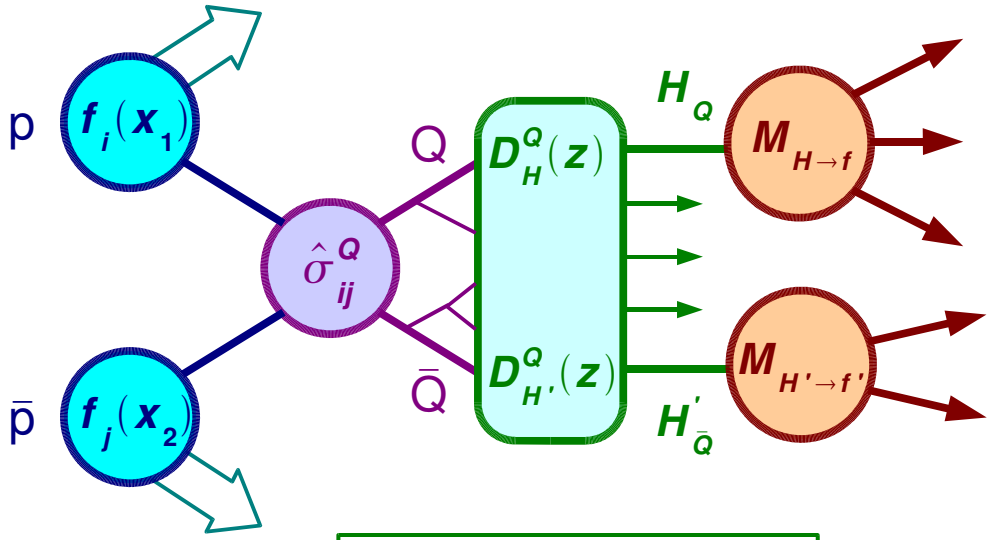
2) Concentrate on the Breadth of Heavy Flavor Physics
   - QCD Model Building
   - Direct Searches for Beyond SM effects
   - CKM Matrix / EW Symmetry ⇒ Indirect Searches
   - Use selected new results

3) Outline
   - Why Heavy Flavors at the Tevatron ?
   - Experimental Ingredients
   - Results and Future Prospects

www-d0.fnal.gov/Run2Physics/WWW/results/b.htm www-cdf.fnal.gov/physics/new/bottom/bottom.html

b's in the Wild

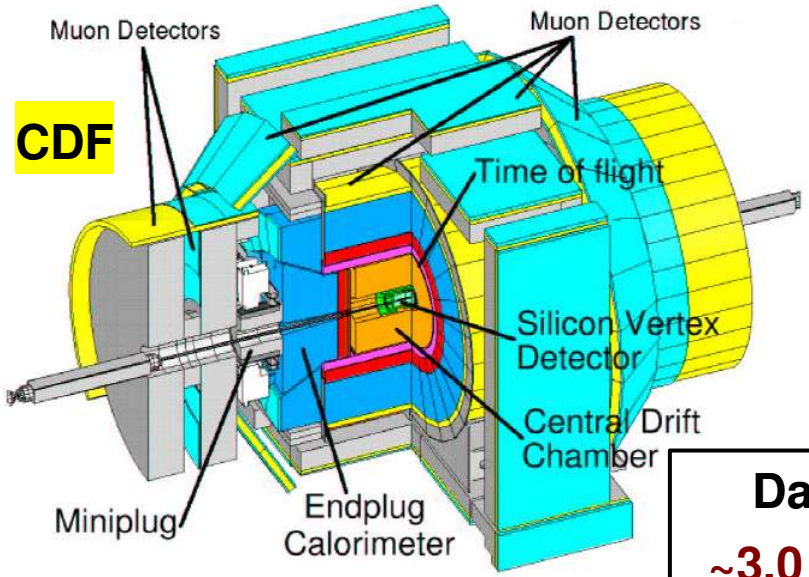
Hard Scatter
- perturb vs. non-pert QCD

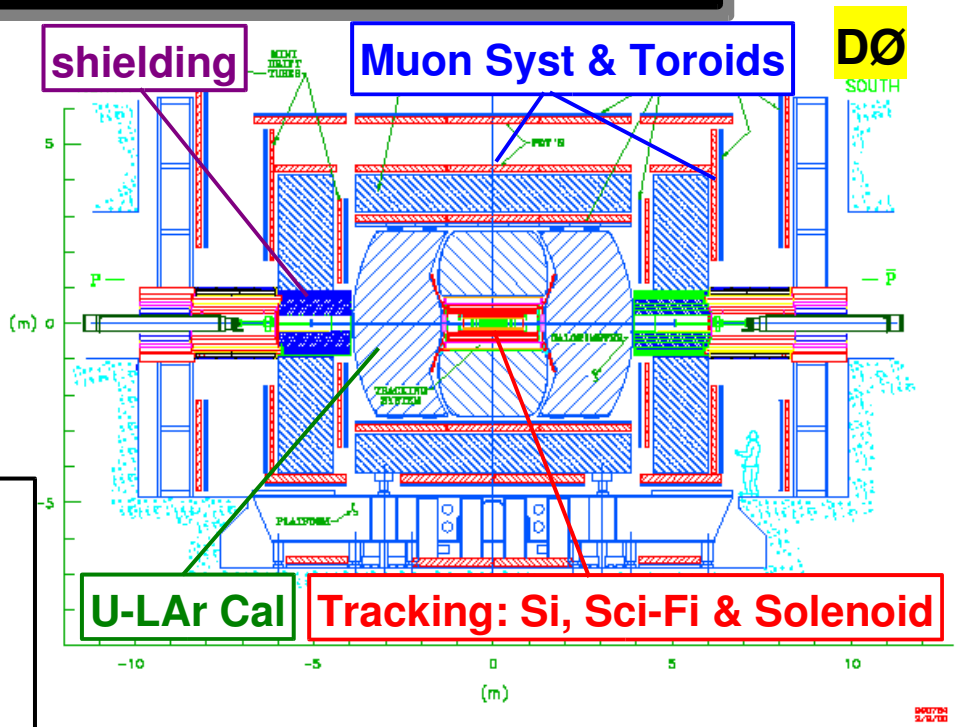


Hadronization
- fragmentation
- hadron properties
- QCD models

Decay
- QCD models
- EW symmetry breaking & CP-violation
- New Physics

CDF and DØ





Data Samples

~3.0 fb^{-1} delivered

~2.5 fb^{-1} recorded

1.3 fb^{-1} results

(one result w/ 2 fb^{-1} !)

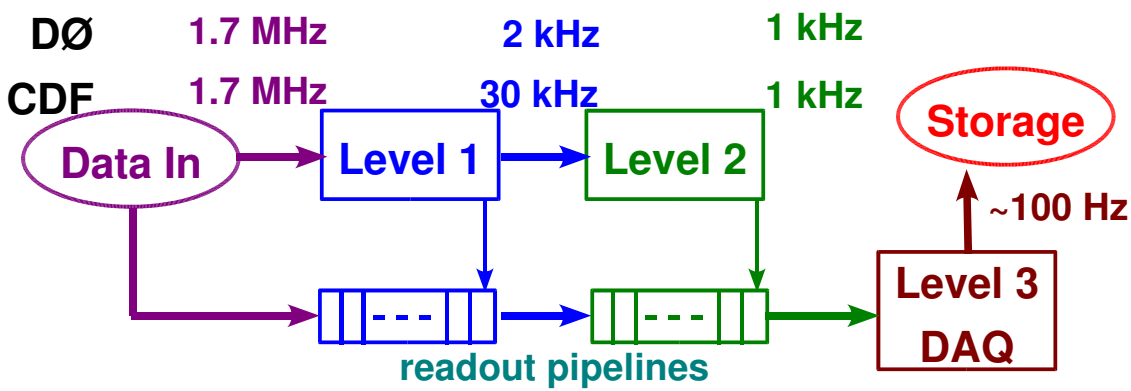
Production	LEP E_{CM}=91 GeV	B-Factories Υ(4S)	Tevatron (in accept)	LHCb (in accept)
Approx $b\bar{b}$ rate	0.35 Hz	20 Hz	6 kHz	50 kHz

Important at the Tevatron

- **Triggering**
- **Tracking/Vertexing: $L \sim O$(1 mm)**
- **Leptons: $BR(B \to l\, X) \sim 11\%$**
- **π / K Separation: CDF**

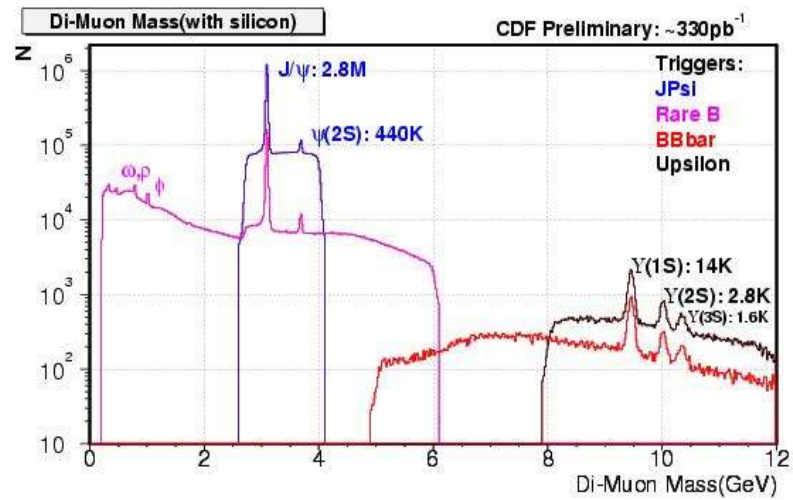
Triggering & Muons

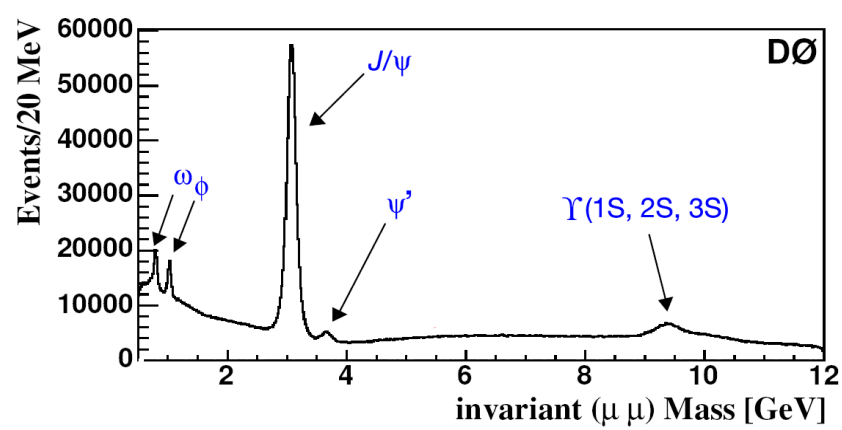
3 Level Trigger Systems



Muons	Coverage	Shielding
DØ	$\|\eta\| < 2.0$	12-18 λ_I
CDF	$\|\eta\| < 1.0$	>5 λ_I

Trigger	CDF	DØ
2-Track	P_T(trk)>2.0 GeV $0.12<d_0<1$ mm ΣP_T>5.5 GeV	—
l + Displ Trk	P_t^l>4, P_t^{trk}>2 GeV $0.12<d_0<1$ mm	—
1-Muon	—	P_T>3,4,5 GeV or P_T>5 GeV & $d_0/\sigma(d_0)$>3 (luminosity dependent)
2-Muon	$P_T(\mu's)$>1.5 GeV	$P_T(\mu's)$>2.0 GeV



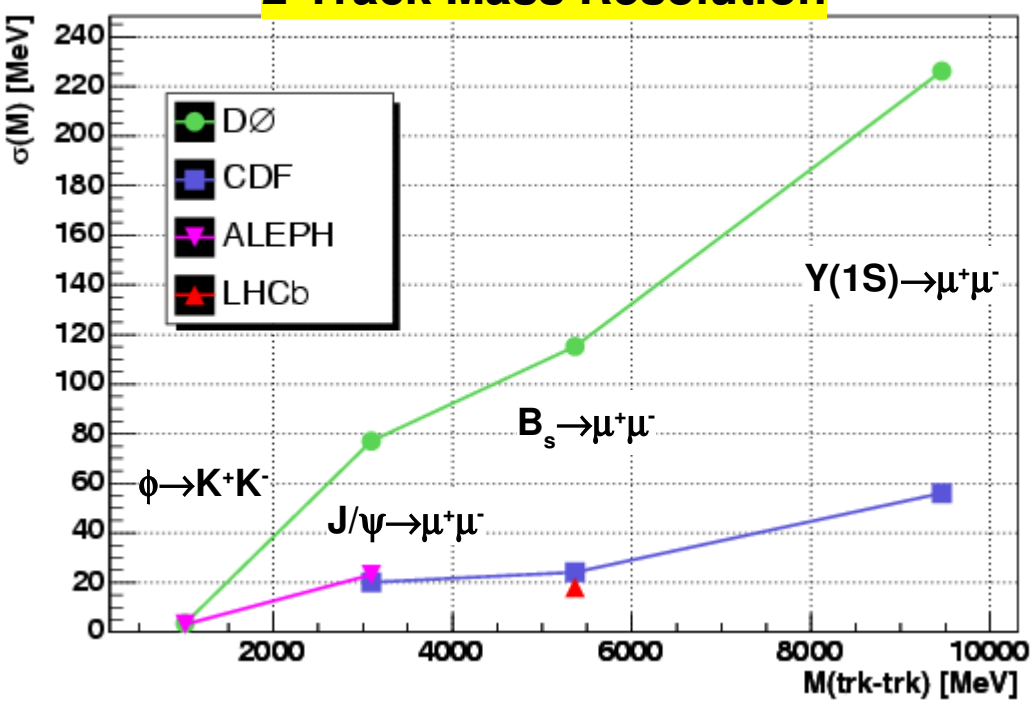


Tracking & Vertexing

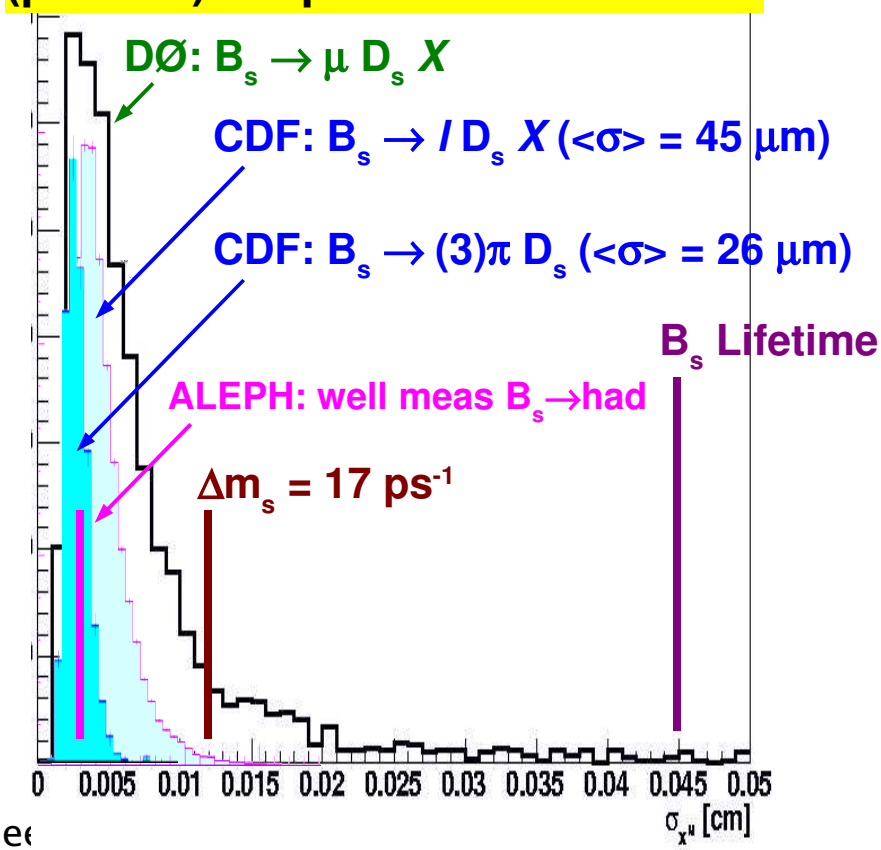
Exp	B	Radii [cm]	|η| Range	<Space Pts>
CDF	1.4 T	1.5 – 137	< 2.0	>100
D0	2.0 T	2.8 – 52	< 3.0	20

1.7 w/ Layer 0 ⟶ 25% gain in proper time resolution

2-Track Mass Resolution



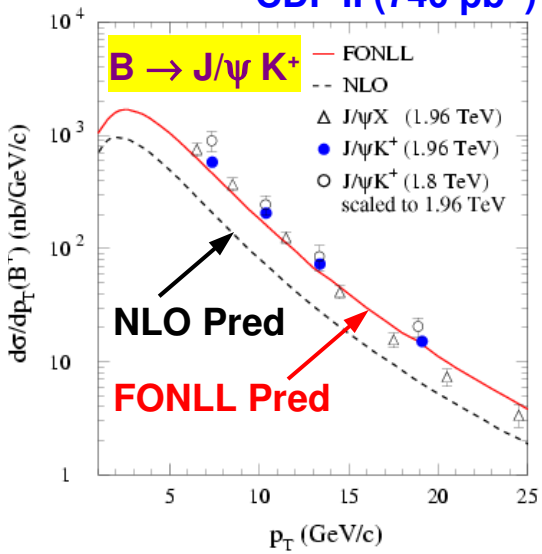
(pseudo) Proper Time Resolution



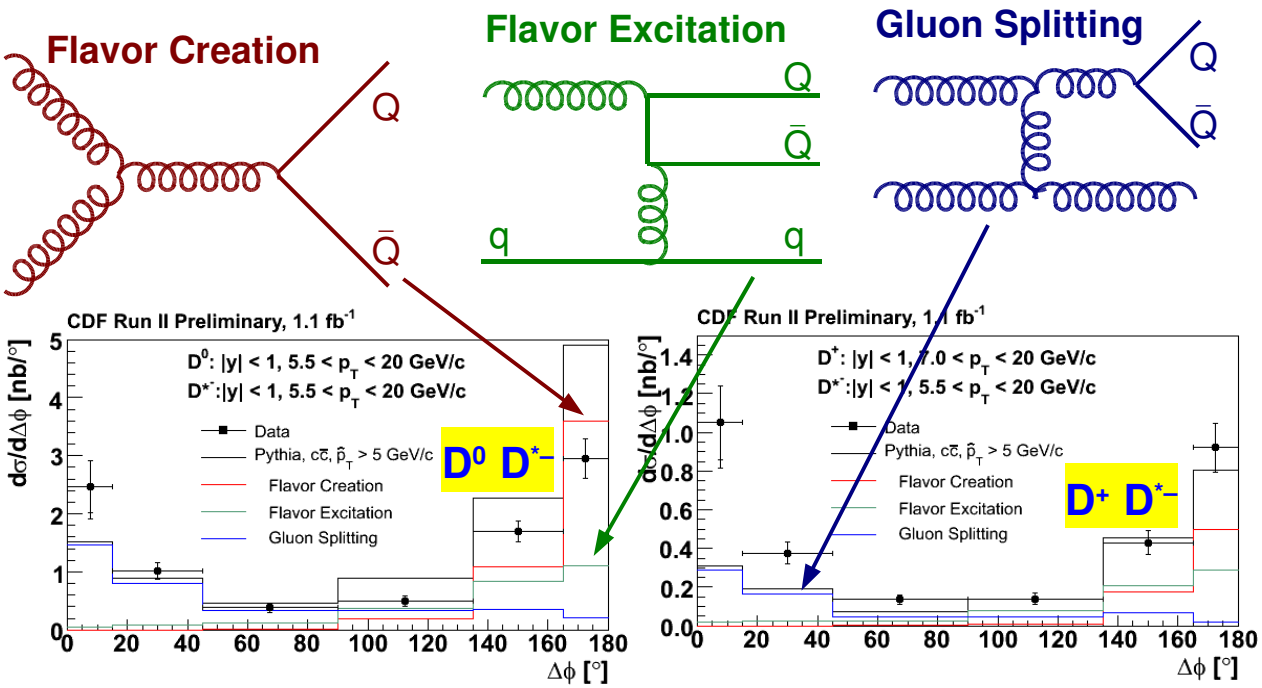
Heavy Quark Production

Theory-Data now agree in *b*-Prod

CDF II (740 pb^{-1})

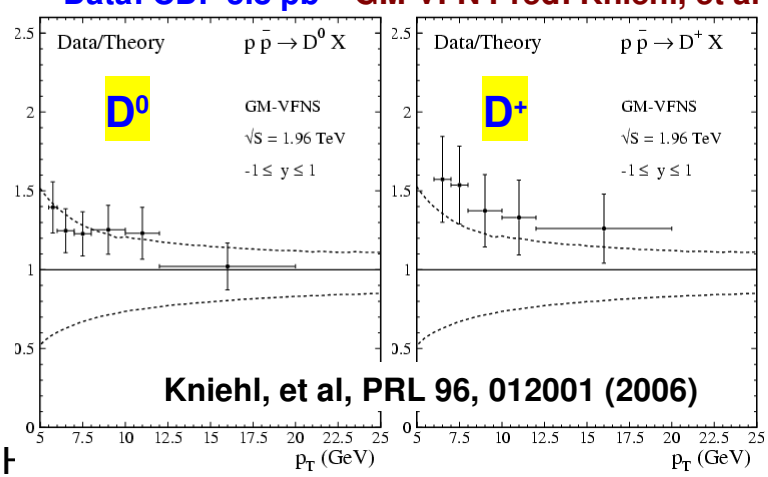


Q-Q Angular Correlations: sensitive to prod.



But discrepencies linger in *c*'s

Data: CDF 5.8 pb^{-1} GM-VFN Pred: Kniehl, et al

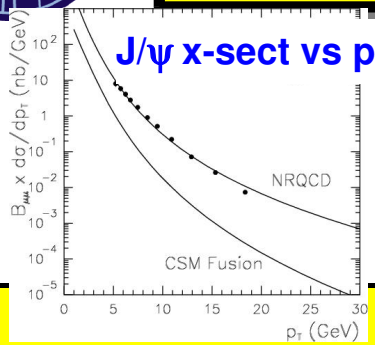


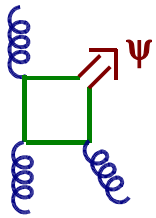
CDF Meas of Charm Meson Pairs

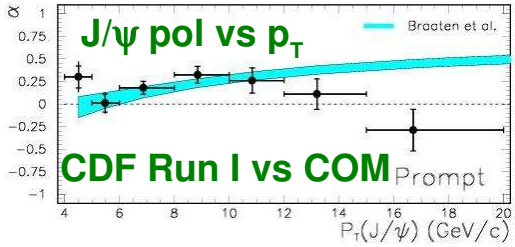
- $D^0/D^+ + D^*$ Selection in 1.1 fb^{-1}
- comp to LO+parton shower: PYTHIA (tune A)
- data favors more *collinear* heavy-Q prod

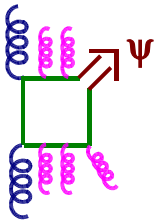
Onium Production

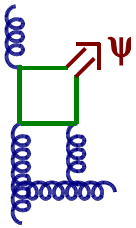
CDF Run I vs CSM







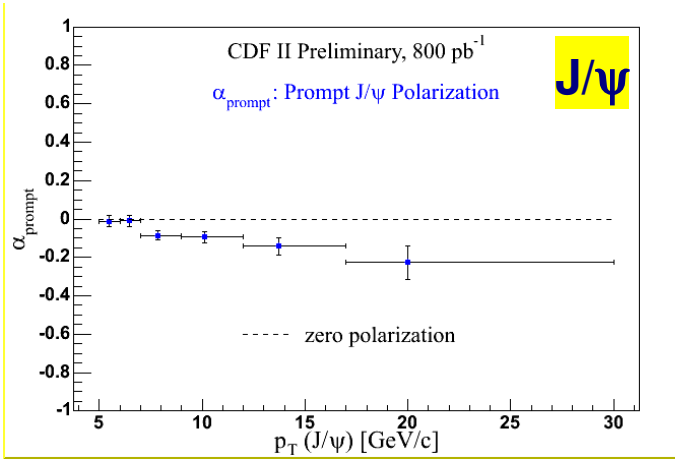


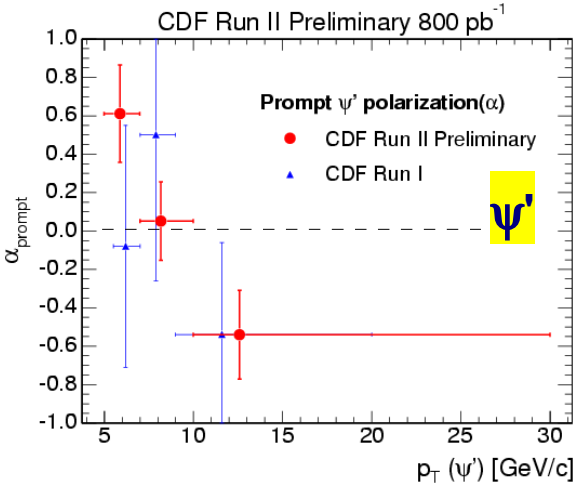


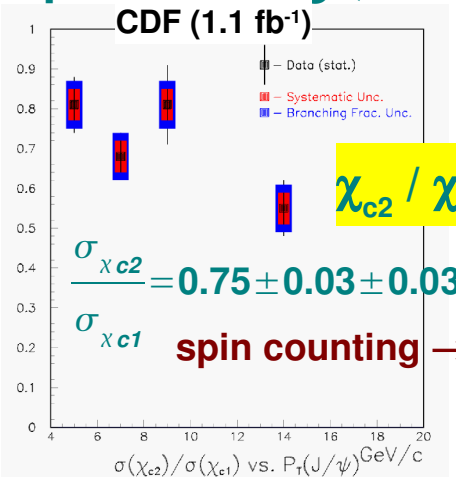
	Color Singlet	Color Octet (NRQCD) [Braaten & Flemming]	Pomeron-Inspired (new) [Khoze, et al, EPJ C39 (2005)]
total x-sect	x10–50 too low	agrees at hi-p_T	adjustable
pol. (hi-p_T)	~none	transverse (α>0)	longitudinal (α<0)
J/ψ source	$\chi_c \rightarrow J/\psi$	prompt	prompt

New CDF Results (most precise available) favor Khoze, et al

- **Prompt J/ψ and ψ' Polarization** — **longitudinal at high p_T**
- **χ_{c2} / χ_{c1} production** — **differs from spin counting (COM)**







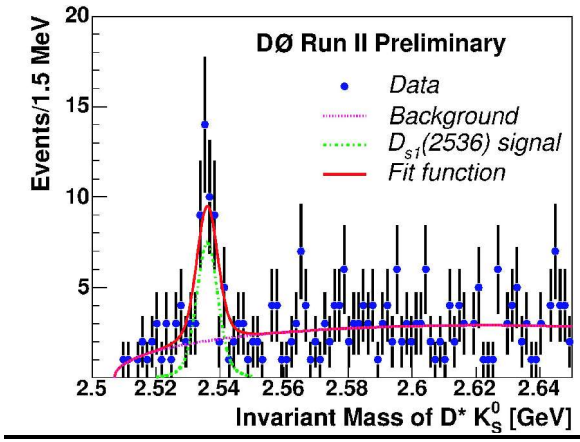
$$\frac{\sigma_{\chi c2}}{\sigma_{\chi c1}} = 0.75 \pm 0.03 \pm 0.03 \pm 0.04 (BR)$$

spin counting → 5/3

Heavy Hadrons: D_s^{**} & Σ_b

Tevatron: good hunting ground for Heavy-Quark Hadrons

- B_c, excited states, heavy baryons, X(3872), penta-quarks,...

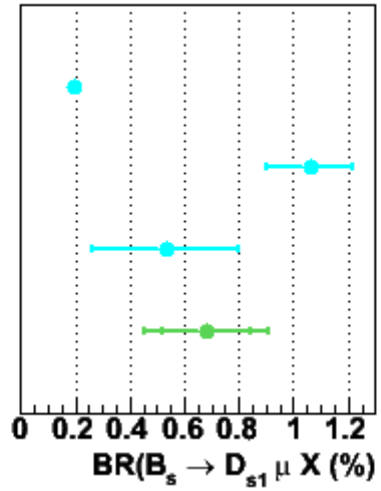


DØ: $B_s \to \mu D_s^{**} X$ (1st observation)

$N(D_{s1}) = 43.8 \pm 8.3$

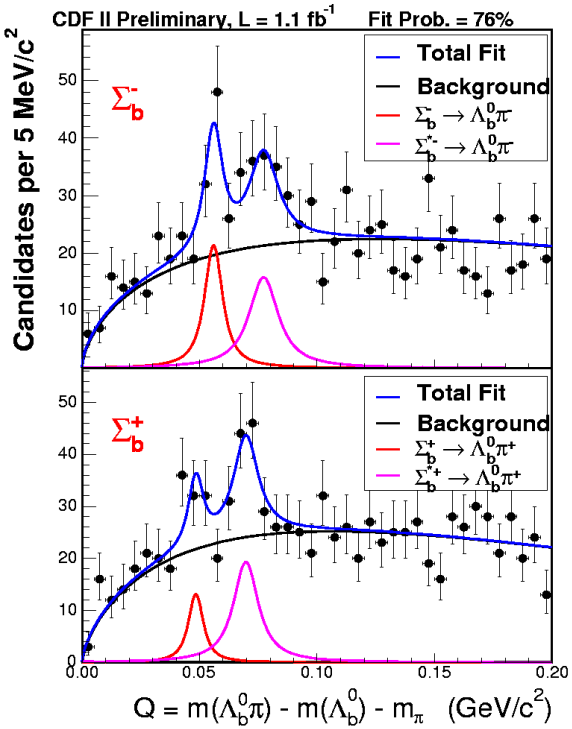
$M(D_{s1}) = 2535.7 \pm 0.6 \pm 0.5$ MeV

(PDG06: 2535.34±0.31 MeV)



DØ prelim

$BR(B_s \to \mu D_{s1} X)$
0.20
1.06±0.16
0.53±0.27
0.68±0.16±0.16



CDF: Σ_b (1st observation)

$N(\Sigma_b^-) = 60^{+15+8}_{-14-4}$

$N(\Sigma_b^{*-}) = 74^{+18+16}_{-17-5}$

$N(\Sigma_b^+) = 29^{+12+5}_{-12-3}$

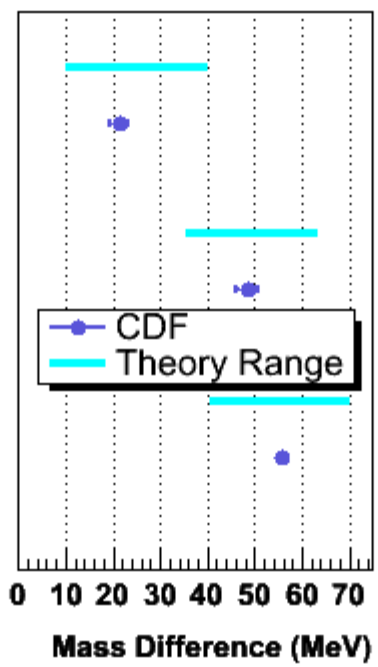
$N(\Sigma_b^{*+}) = 74^{+17+10}_{-16-6}$

see talk by J. Pursley

$M(\Sigma_b^{*\pm}) - M(\Sigma_b^{\pm})$ $\quad 21.3^{+2.0+0.4}_{-1.9-0.2}$

$M(\Sigma_b^{+}) - M(\Lambda_b)$ $\quad 48.4^{+2.0}_{-2.3} \pm 0.1$

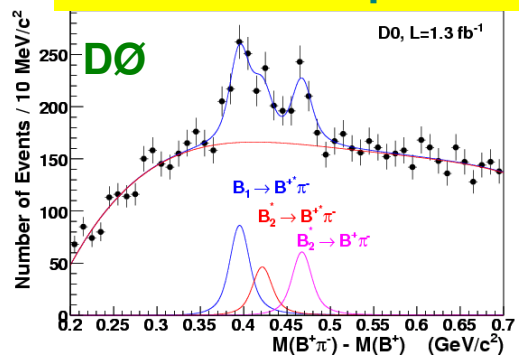
$M(\Sigma_b^{-}) - M(\Lambda_b)$ $\quad 55.9 \pm 1.0 \pm 0.1$

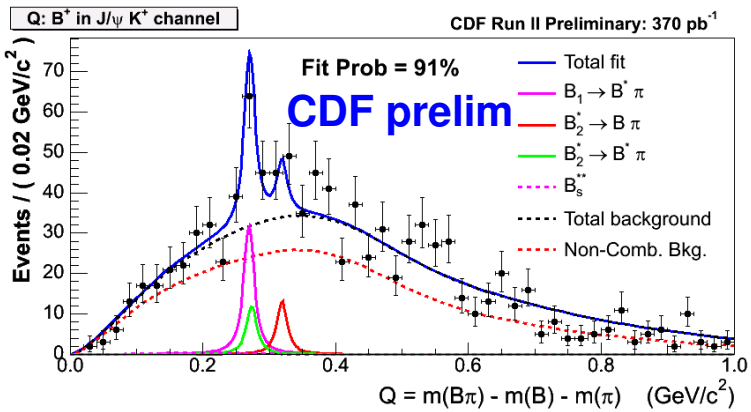


CDF prelim $\Sigma^{(*)\pm}$ Masses

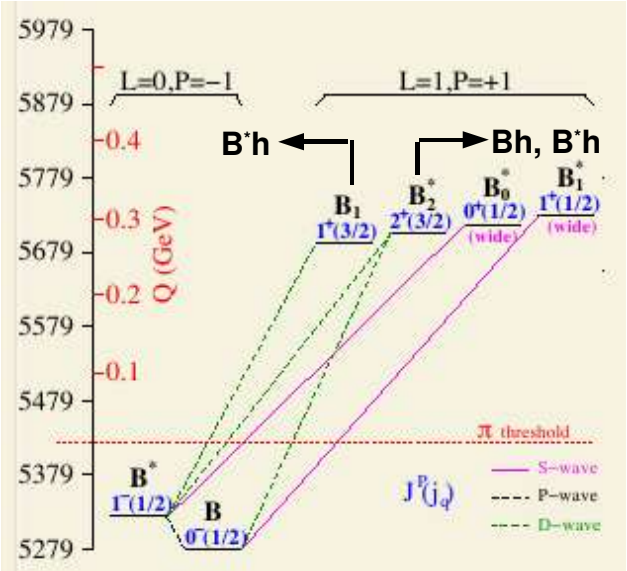
More Heavy Hadrons: B** States

B** : 1st State Separation

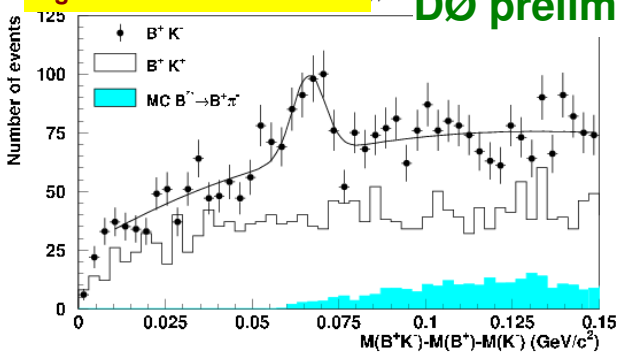


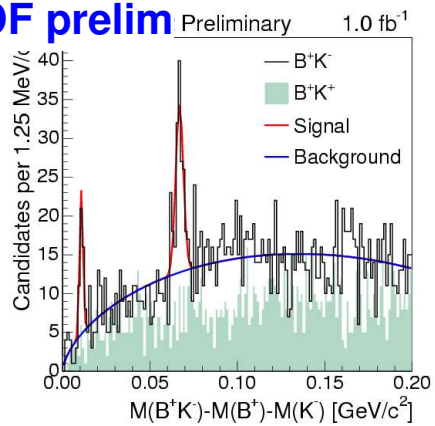


Orbitally Excited B Mesons

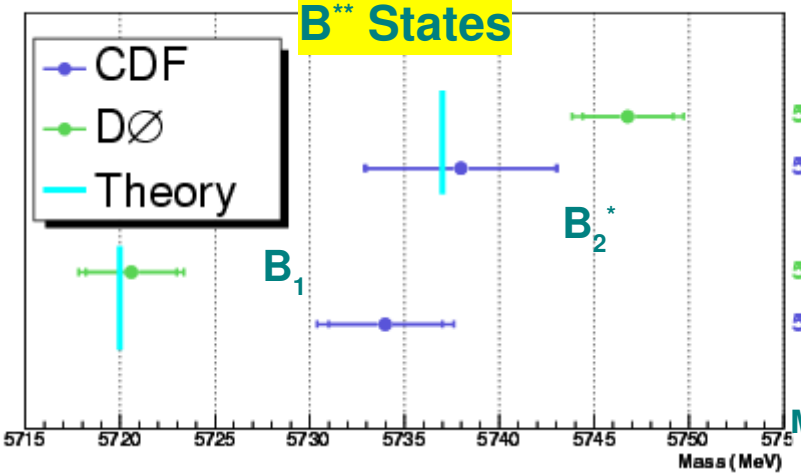


Bs** : 1st Evidence





B** States



not observed by DØ

pred. to be below B* K threshold

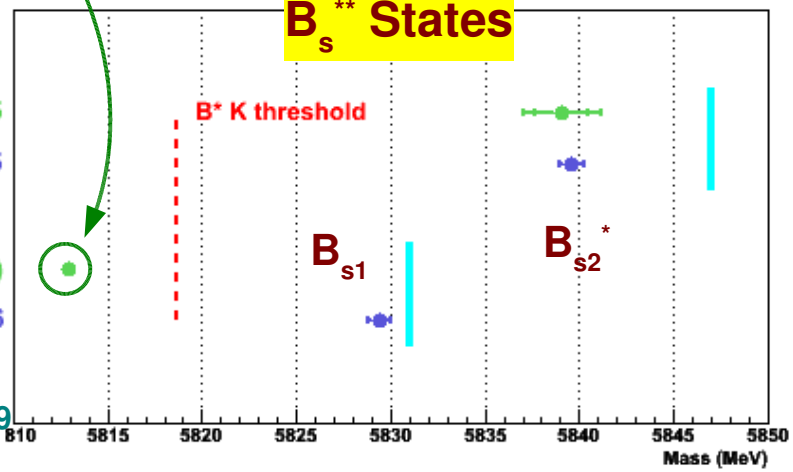
if DØ ΔM(B**) is correct

5746.8±2.4±1.7	5839.1±1.4±1.5
5738.0±5.0±1.0	5839.6±0.4±0.5
5720.6±2.4±1.4	pred from ΔM(B**)
5734.0±3.0±2.0	5829.4±0.2±0.6

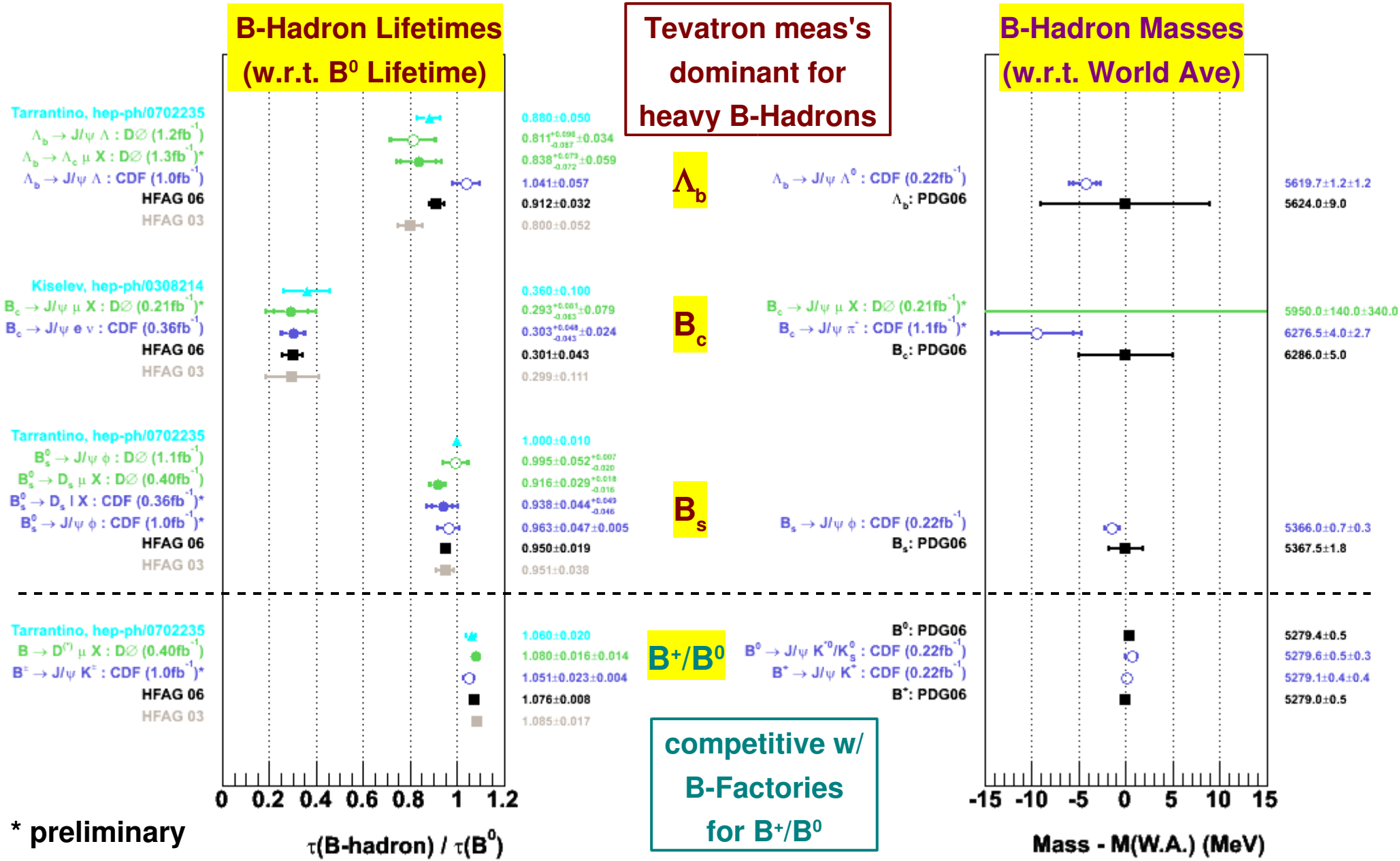
Theory

Matsuki, et al, hep-ph/0605019

Bs** States



Lifetimes and Masses



* preliminary

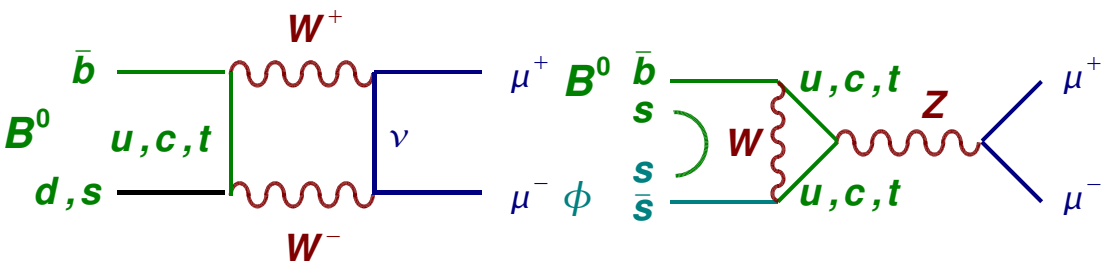
Rare Decays and FCNCs

Large B-samples ⇒ sens. to rare decays

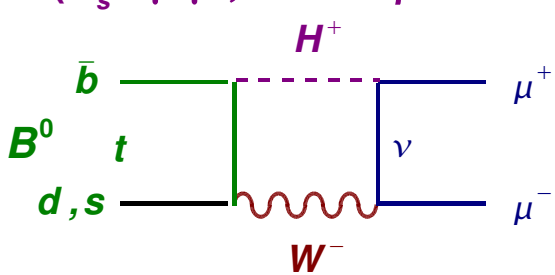
- Hadronic BRs below 10^{-5}
  - many modes obs. for 1st time
  - $B_s \to h^+h'^-$, $\psi(2S)\phi$, $\phi\phi$, $D_s 3\pi^\pm$, ...
- Leptonic BRs below 10^{-7}

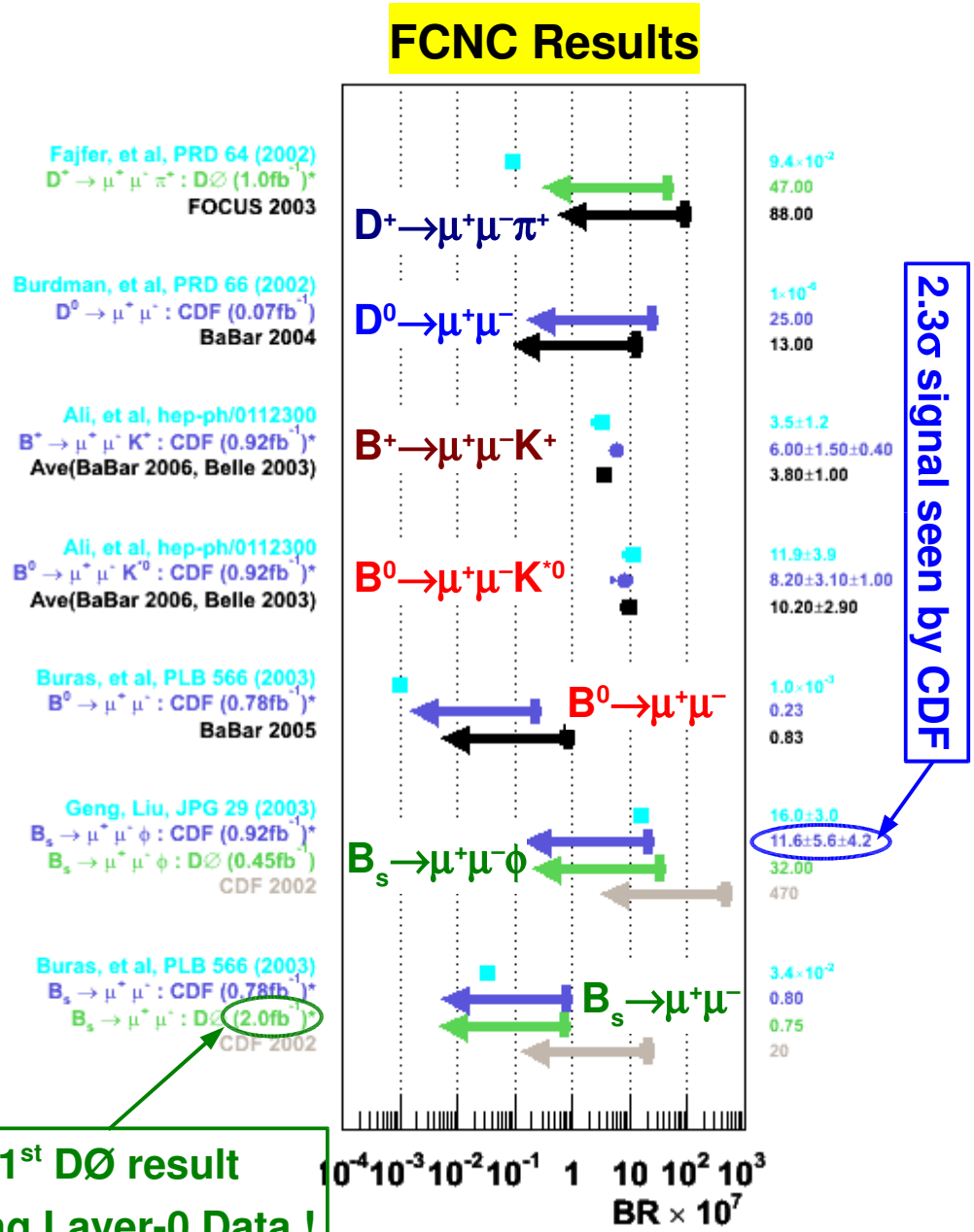
Flavor Changing Neutral Currents

- small BRs in SM



- large enhancements in other models
  - $B(B_s \to \mu^+\mu^-) \propto \tan^{6(4)}\beta$ in MSSM (2HDM)





Mixing and CP Violation

EW Symmetry Breaking ⇒ Weak ≠ Mass ≠ CP Eigenstates

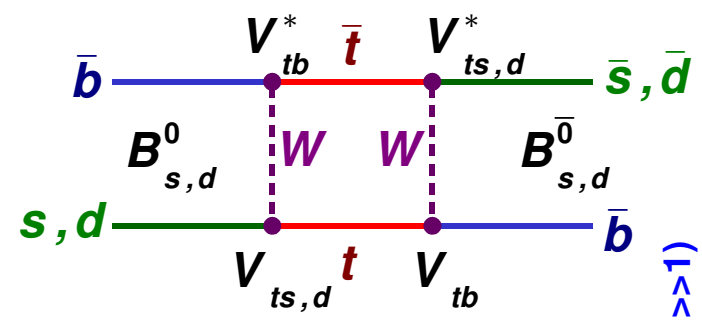
$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}=\left(M-i\frac{\Gamma}{2}\right)\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

$$|B_{H,L}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

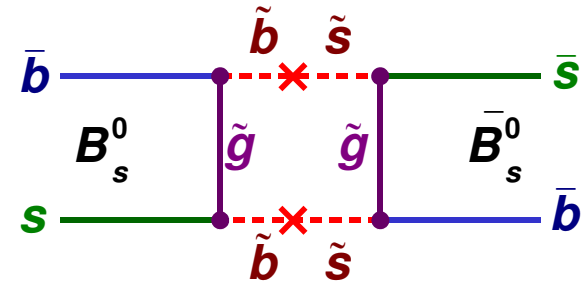
$$|B_{odd,even}\rangle = |B^0\rangle \pm |\bar{B}^0\rangle$$

- SM 1 source of CP-violation
- MSSM 43 sources of CP-violation

SM Diagram



SUSY



(+ charginos, neutralinos, etc @ tanβ >>1)

Observables

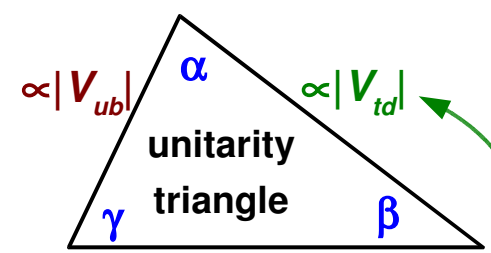
$\Delta m = M_H - M_L \sim 2|M_{12}|$ sens. to NP

$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$ not sens. to NP

$\Delta\Gamma_s = \Gamma_L - \Gamma_H = \Delta\Gamma_{CP}\cos\phi_s$ very sens. to NP

(ϕ_s = -0.5 – -0.8 in 4-gen models)

Hou,Nagashima,Soddu; hep-ph/0610385



In the SM

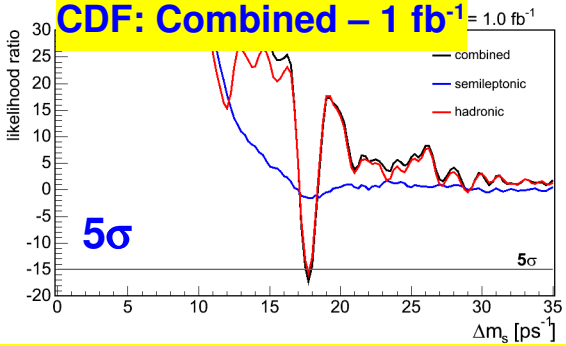
$$\frac{\Delta\Gamma_s}{\Delta m_s} = O\left(\frac{m_b^2}{m_t^2}\right) \text{ (QCD)}$$

$$\phi_s \sim 0.25^o$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{M_{Bd}}{M_{Bs}}\frac{f_{Bd}^2 B_{Bd}}{f_{Bs}^2 B_{Bs}}\left|\frac{V_{td}}{V_{ts}}\right|^2$$

B_s Mixing

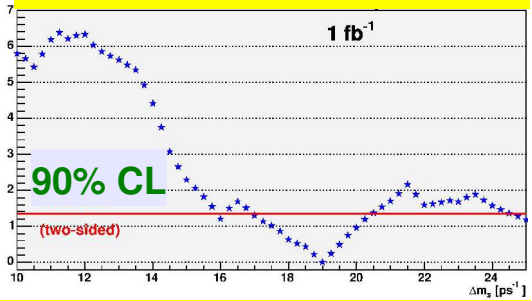
CDF: Combined – 1 fb^{-1}



Δm_s = 17.77 ± 0.10 ± 0.07 ps^{-1}

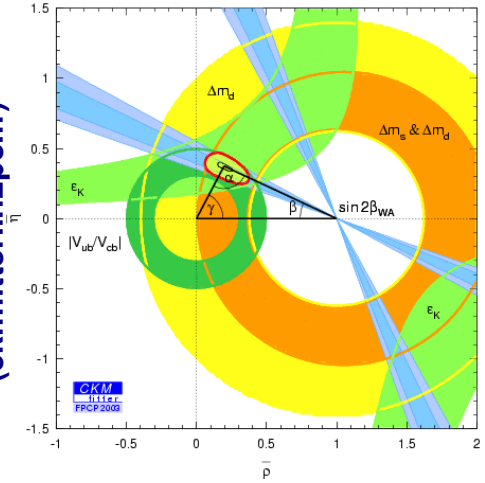
Exp	Mode	Sample	$\langle \varepsilon D^2 \rangle$ OST	SST	Sens [ps^{-1}]
ALEPH	Hadronic	28.5	27%		13.6
DØ	$l\, D_s(\phi\pi, K^*K, K^0_s K)$	43,000	2.5%		16.5
CDF	$l\, D_s$ (all)	61,500	1.8%	4.8%	19.3
	$D_s(\phi\pi, K^*K, 3\pi)$ (3)π	8,700	1.8%	3.7%	30.7

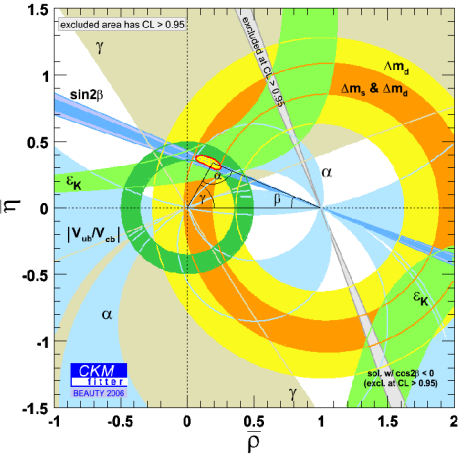
DØ Prelim: Combined – 1 fb^{-1}



17 < Δm_s < 21 ps^{-1} (90% CL)

CKM Fitter: FPCP 2003
(ckmfitter.in2p3.fr)





CKM Fitter: Beauty 2006

see also Utfit:
http://utfit.roma1.infn.it/

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007\,(\text{exp})^{+0.0081}_{-0.0060}\,(\text{theor}) = \sqrt{\frac{M_{Bs}}{M_{Bd}}\,\frac{f^2_{Bs}B_{Bs}}{f^2_{Bd}B_{Bd}}\,\frac{\Delta m_d}{\Delta m_s}}$$

CDF Measurement

±0.5% (Δm_d)

±0.3% (Δm_s)

±3.4% ($f^2_{Bs}B_{Bs}/f^2_{Bd}B_{Bd}$)

BaBar and Belle Ave: $0.200 \pm 0.016\,(\text{exp})^{+0.016}_{-0.015}\,(\text{theo})$ $\left(\frac{B\to\rho\gamma}{B\to K^*\gamma}\right)$

M.Okamoto hep-lat/0510113

$\Delta\Gamma$ and CPV Phase in B_s Mesons

1) Ang. dist's in $B_s \to J/\psi\,\phi$ DØ,CDF
   - fit for $\Delta\Gamma_s$, τ_{ave}, helicity comp's, strong phases, ϕ_s (new DØ)

2) Charge Asym's in Decay DØ
   - $p\bar{p} \to \mu^{\pm}\mu^{\pm} X$

$$A_{SL}^{\mu\mu} = \frac{N(b\bar{b}\to\mu^+\mu^+) - N(b\bar{b}\to\mu^-\mu^-)}{N(b\bar{b}\to\mu^+\mu^+) + N(b\bar{b}\to\mu^-\mu^-)} = A_{SL}^{d} + \frac{f_s Z_s}{f_d Z_d} A_{SL}^{s}$$

$$\left(Z_q = \frac{1}{1-(\Delta\Gamma_q/2\Gamma_q)^2} - \frac{1}{1+(\Delta m_q/\Gamma_q)^2} \right)$$

   - $B_s \to D_s\,\mu\,X$

$$A_{SL}^{s} = \frac{N(B_s\to\mu^+D_s^-) - N(B_s\to\mu^-D_s^+)}{N(B_s\to\mu^+D_s^-) + N(B_s\to\mu^-D_s^+)} \sim \frac{1}{2}\frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

3) CP-specific Final States
   - $B_s \to K^+K^-$ Lifetime CDF

$$\tau_{CP-even} \sim \frac{1}{\Gamma_s}\left[\frac{1}{1+(\Delta\Gamma_{CP}/2\Gamma_s)}\right]$$

   - $B_s \to D_s^{(*)}D_s^{(*)}$ BR DØ,CDF

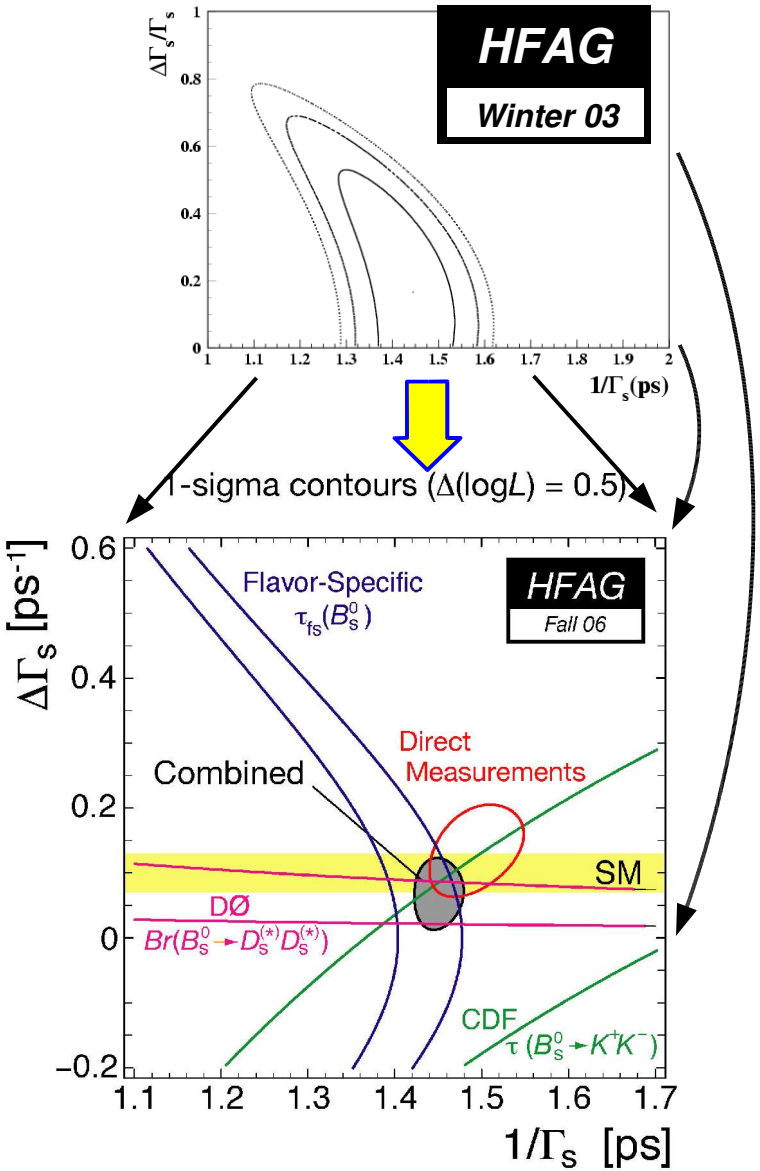
$$2BR_{even} = \frac{\Delta\Gamma_{CP}}{\Gamma}\left[\frac{1}{1+\Delta\Gamma_{CP}/2\Gamma}\right]$$

4) Flavor Specific Lifetime DØ,CDF
   - $B_s \to l\,D_s\,X$

$$\tau_{fs} = \frac{1}{\Gamma_s}\left[\frac{1+(\Delta\Gamma_s/2\Gamma_s)^2}{1-(\Delta\Gamma_s/2\Gamma_s)^2}\right]$$

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

Combined Results



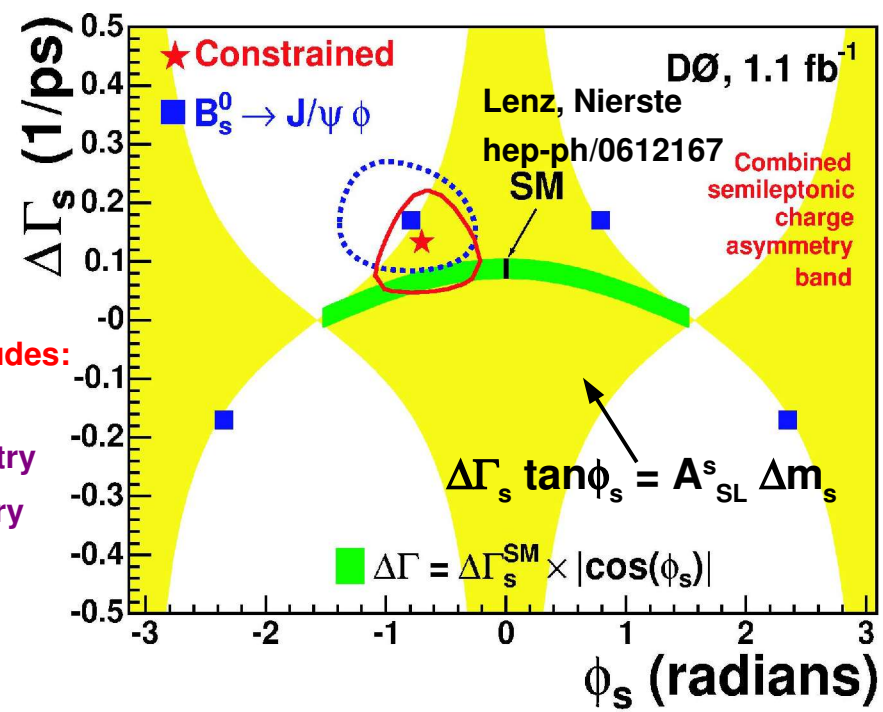
$$\Delta\Gamma_s = 0.071^{+0.053}_{-0.057}\ \text{ps}^{-1}$$

$$(-0.04 < \Delta\Gamma_s < +0.17)\ \text{ps}^{-1}\ (95\%\ \text{CL})$$

Combining DØ Results

	DØ Combination	SM Pred
$\Delta\Gamma_s$	0.13 ± 0.09 ps^{-1}	0.088 ± 0.017 ps^{-1}
ϕ_s	$-0.70^{+0.47}_{-0.39}$	$(4.2 \pm 1.4) \times 10^{-3}$

Lenz,Nierste hep-ph/0612167

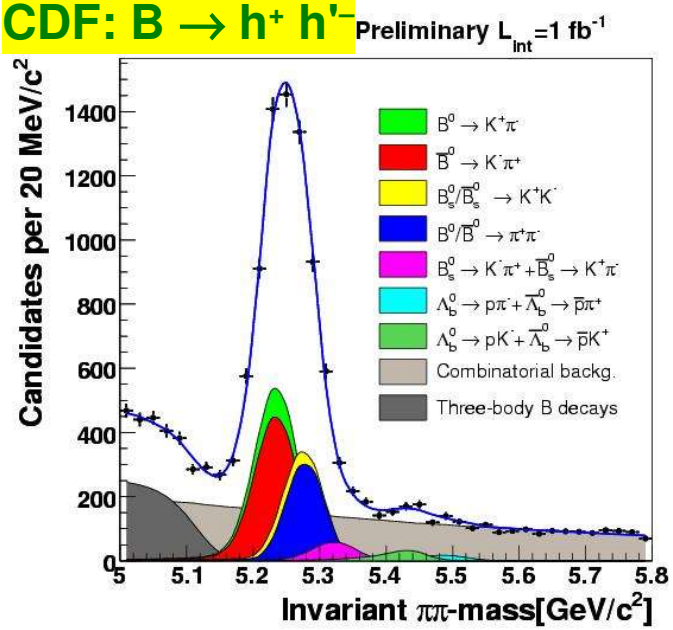


"Constrained" Includes:

- $B_s \to J/\psi\ \phi$
- $B_s \to \mu\ X$ Asymmetry
- Dimuon Asymmetry
- World Average: τ_{fs}

Direct CP-Violation in B_d and B_s

CDF: $B \to h^+ h'^-$



$N(B_s \to K^-\pi^+) = 230 \pm 38$

$N(B_s \to K^+K^-) = 1307 \pm 64$

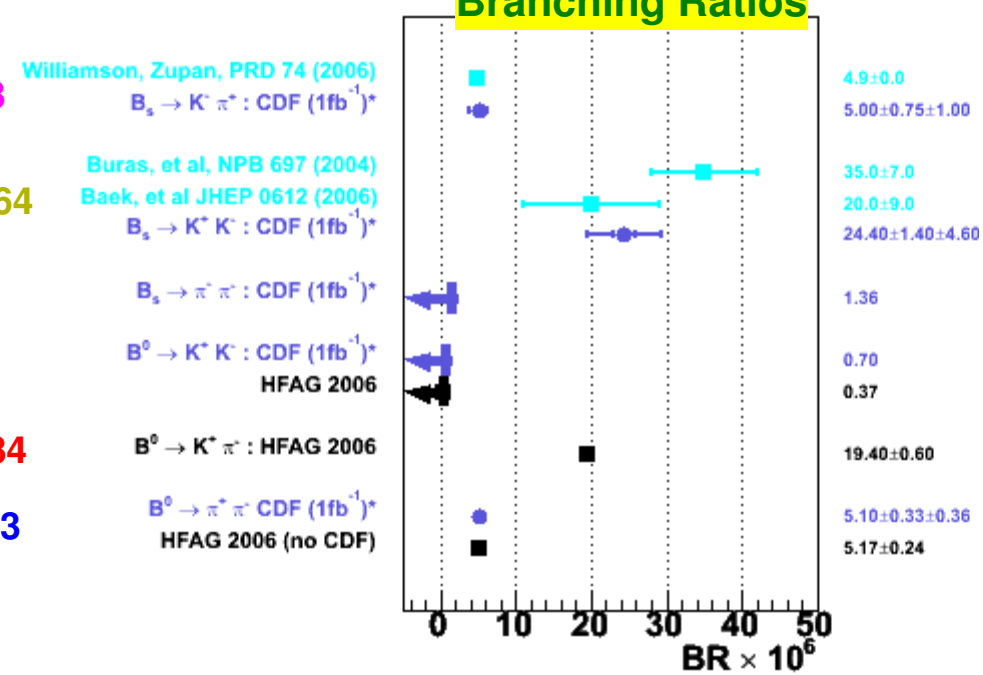
$N(B_s \to \pi^+\pi^-) = 26 \pm 21$

$N(B^0 \to K^+K^-) = 61 \pm 43$

$N(B^0 \to K^+\pi^-) = 4045 \pm 84$

$N(B^0 \to \pi^+\pi^-) = 1121 \pm 63$

Branching Ratios



$$A_{CP} = \frac{N(\bar{B} \to \bar{f}) - N(B \to f)}{N(\bar{B} \to \bar{f}) + N(B \to f)}$$

$A_{CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.023 \pm 0.009$

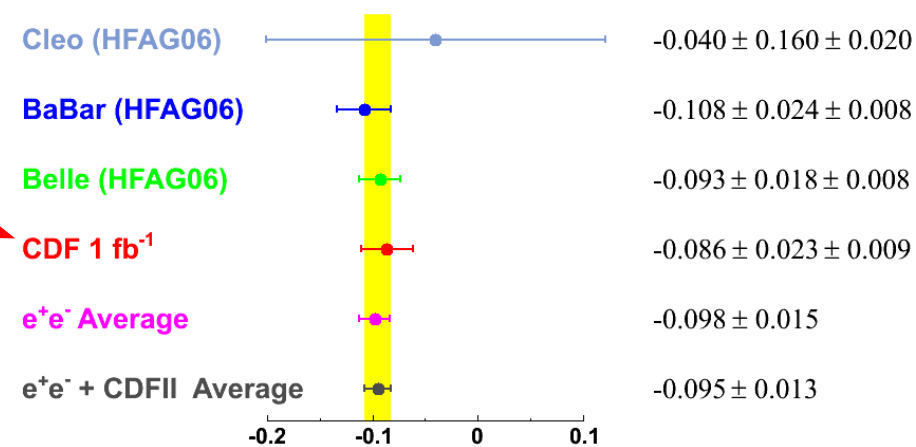
$A_{CP}(B_s \to K^-\pi^+) = 0.039 \pm 0.15 \pm 0.08$

competitive w/ B-Factories

$$\frac{A(\bar{B}^0 \to K^-\pi^+) - A(B^0 \to K^+\pi^-)}{A(B_s \to K^-\pi^+) - A(\bar{B}_s \to K^+\pi^-)} = 0.84 \pm 0.42 \pm 0.15$$

= 1 in the SM

$A_{CP}(B^0 \to K^+\pi^-)$



The Future

Detectors and Data Collection

- up to 8 fb^{-1} (per exp) with expected data (note: increasingly restrictive triggers)
- DØ Layer-0 Silicon: 25% improvement in proper time res.

B-Hadron Properties: Production, Lifetimes, BRs, Spectroscopy...

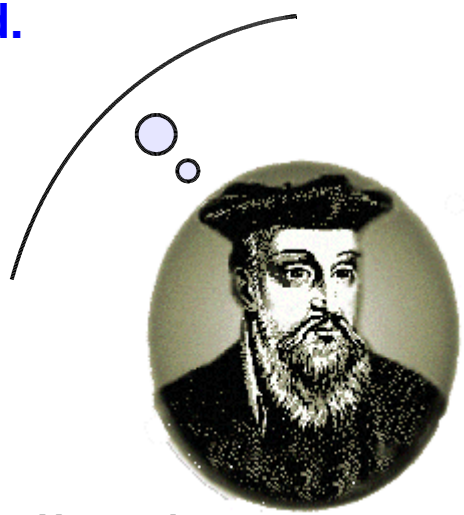
- continue production studies using angular distrib's, onia polarization
- heavy states and their properties: B_c, Σ_b, Ξ_b, ...
- increasing sensitivity to rare decay modes

FCNC Decays

- should observe $\mu^+ \mu^- \phi$ (get w/in x10 of $\mu^+ \mu^-$) if close to SM pred.
- asymmetries in $B_s \to \mu^+ \mu^- X$

EW Symmetry Breaking, Unitarity Triangle, CP-Violation

- $|V_{td} / V_{ts}|$ now dominated by theory error
- fits to flavor tagged $B_s \to J/\psi\, \phi \Rightarrow$ simul. sens. to $\Delta\Gamma_s$, ϕ_s, Δm_s
- sensitivity to γ from $B_s \to K^+ \pi^-$



Nostradamus says...
I knew it all along !

Summary

Remarkable Progress in B Physics since Start of Run II !

B Properties: Production, Masses, Lifetimes, BRs, Spectroscopy...

- many heavy states and decays modes observed for the first time
- lifetime & mass accuracy improved by > factor of 2
- valuable tests of QCD Modeling: SU(3), etc.

FCNC Decays

- limits have improved by several orders of magnitude since Run II
- $B_s \to \mu^+ \mu^- \phi$ approaching a measurement
- $B_s \to \mu^+ \mu^-$ limits only a factor of 30 from SM

EW Symmetry Breaking / Unitarity Triangle

- Δm_s now measured: $|V_{td} / V_{ts}|$ error dominated by theory
- now achieving sensitivity to CPV phase ϕ_s
- Direct CP asymmetry measurements competitive with B-Factories