Heavy Flavors at the Tevatron
(a whirlwind tour of recent results)

Hal Evans

Indiana University

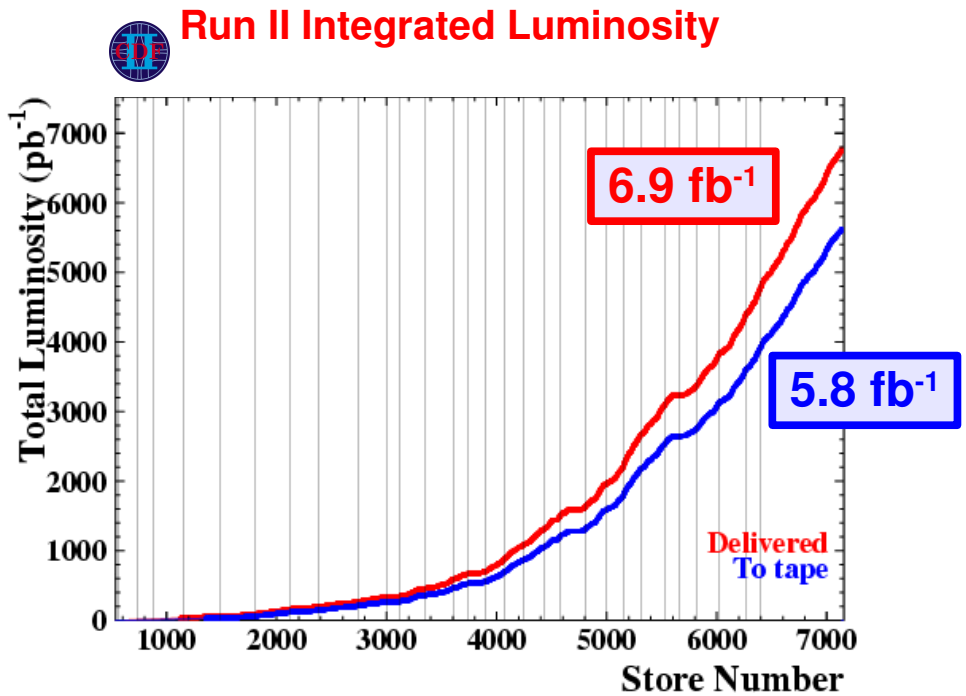
for the CDF & DØ collaborations

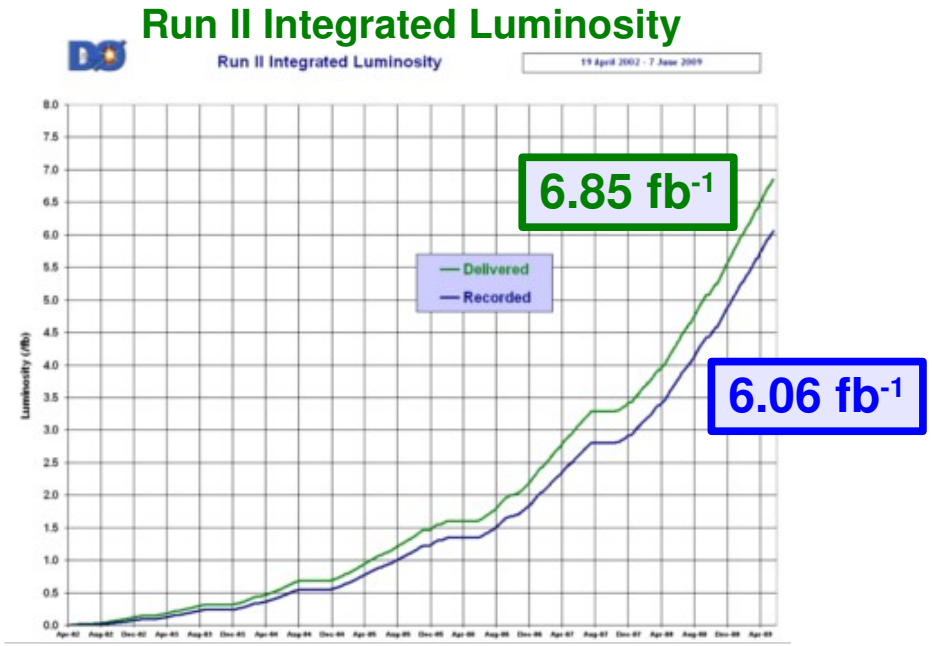
XXIèmes Rencontres de Blois

21-26 June, 2009

Château Royal de Blois

Large Datasets





A Wealth of Heavy Flavor Results: 85 Run II Publications (50 CDF, 35 DØ)

- **Some Highlights**
  - **Measurement of Δm_s , $\Delta\Gamma_s$, CP-violating phase**
  - **1st Observation of: Ξ_b , Σ_b/Σ_b^* , Ω_b – Precise Measurements of: Λ_b , B_c , B_s**
  - **$B_{d/s}^{**}$ and D_s^{**} states and exotics (X/Y)**
  - **Rare (leptonic) B and D decays**
  - **and many more .....**

Results since 2008

CDF Results

1)	Ω_b^- and Ξ_b^- Properties	arXiv:0905.3123
2)	Λ_b Lifetime in $\Lambda_b \to \Lambda_c \pi$	cdf/pub/bottom/public/9408
3)	$\sigma(B_c)$ x BR($B_c \to J/\Psi\ \mu\ \nu$)	CDF Note 9740
4)	*b*-Hadron $\to \mu\ D^0\ X$ X-section	arXiv:0903.2403
5)	Res. Struct in $B^+ \to J/\psi\ \phi\ K^+$	PRL 102, 242002 (2009)
6)	BR($\Lambda_b \to \Lambda_c \mu \nu$) / BR($\Lambda_b \to \Lambda_c \pi$)	PRD 79, 032001 (2009)
7)	B_s Lifetime in $B_s \to D_s\ \pi$	CDF Note 9203v2
8)	Multi-muon Event Production	arXiv:0810.5357
9)	CPV Phase in $B_s \to J/\psi \phi$	cdf/anal/bottom/public/9458
10)	X(3872) Mass	CDF Note 9454
11)	Search for Narrow Resonances below Ψ	CDF Note 9410
12)	Search for $B_{s/d} \to e\ \mu$	CDF Note 9413
13)	B^+ Lifetime in $B^+ \to D^0\ \pi$	CDF Note 9370
14)	B_c Lifetime in $B_c \to J/\psi\ /\ X$	CDF Note 9294
15)	Search for $D^0 \to \mu^+\ \mu^-$	CDF Note 9226

DØ Results

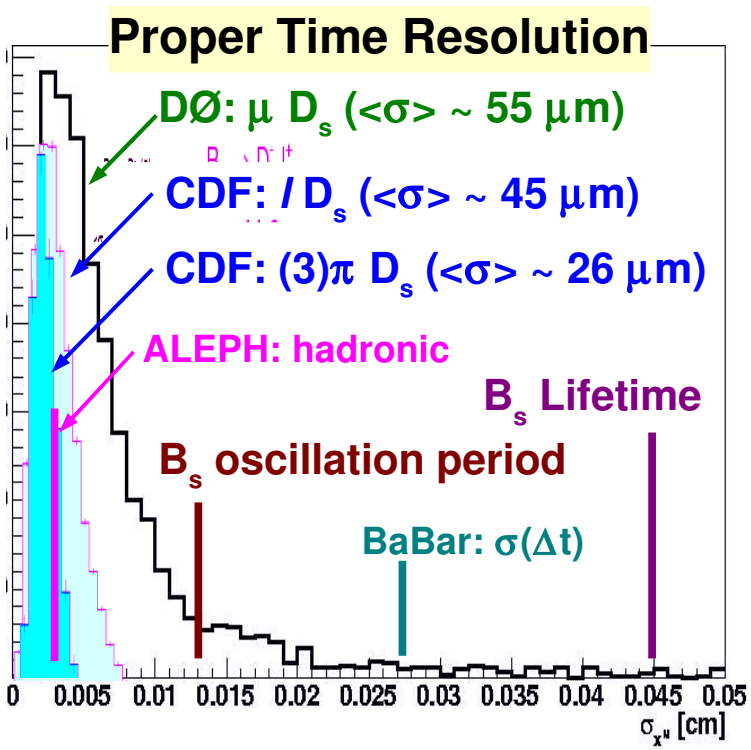
1)	DØ Combined $\Delta\Gamma_s$ vs CPV-phase	DØ Note 5933
2)	CPV Asymmetry in $B_s \to D_s\ \mu\ X$	arXiv:0904.3907
3)	Search for Dimuon Excess in 1.6 <*r*<10 cm	DØ Note 5905
4)	Expected $B_s \to \mu^+\ \mu^-$ Limit w/ 5fb^{-1}	DØ Note 5906
5)	Study of $B_s \to D_s^{(*)}\ D_s^{(*)}$	PRL 102, 091801 (2009)
6)	Angular and Lifetime Param's in $B_d \to J/\psi\ K^*$ / $B_s \to J/\psi\ \phi$	PRL 102, 032001 (2009)
7)	Observation of the Ω_b^- Baryon	PRL 101, 232002 (2008)
8)	B_c Lifetime in Semilept Mode	PRL 102, 092001 (2009)
9)	Ψ(1S,2S) Polarization	PRL 101, 182004 (2008)
10)	$B \to \psi(2S)$ / $B \to J/\psi$	arXiv:0805.2576
11)	Observation of $B_c \to J/\psi\ \pi$	PRL 101, 012001 (2008)
12)	CPV in $B^+ \to J/\psi\ K^+$	PRL 100, 211802 (2008)
13)	$\Delta\Gamma_s$ and CPV Phase in $B_s \to J/\psi \phi$	PRL 101, 241801 (2008)

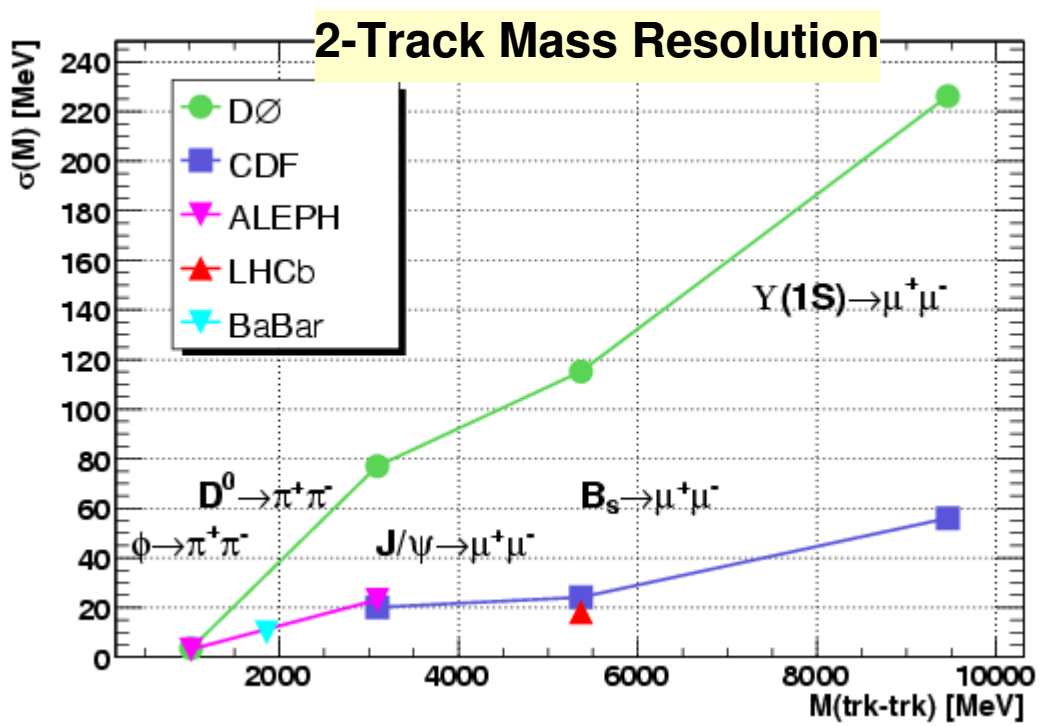
Concentrate on: B-Hadron Properties | CP-Violation | Production (backup)

Tragically Ignore: everything else (sorry!)

Detector Performance

	CDF	DØ
Unique Trigger	2-Track Hadronic	Muons w/out Impact Parameter
Muons	$\lvert\eta\rvert < 1.0$; $>5\ \lambda_I$	$\lvert\eta\rvert < 2.0$; $12\text{-}18\ \lambda_I$; toroid
Tracking	1.5-137 cm ; B=1.4 T ; $\lvert\eta\rvert < 2.0$	1.7-52 cm ; B=2.0 T ; $\lvert\eta\rvert < 3.0$
π/K Sep.	dE/dx & TOF	---

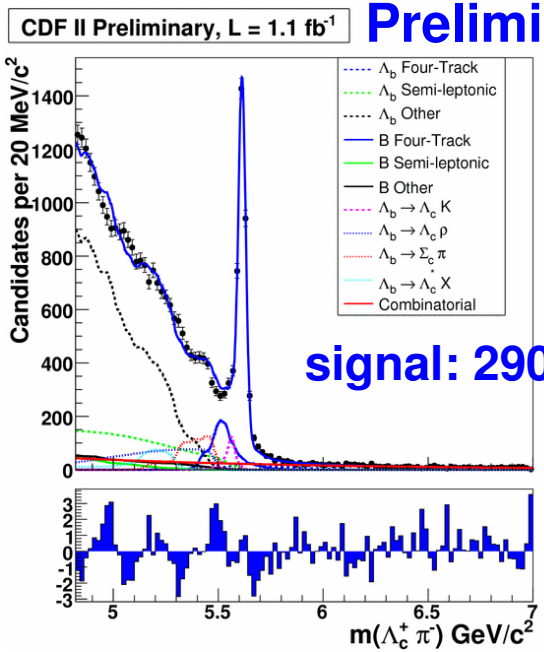




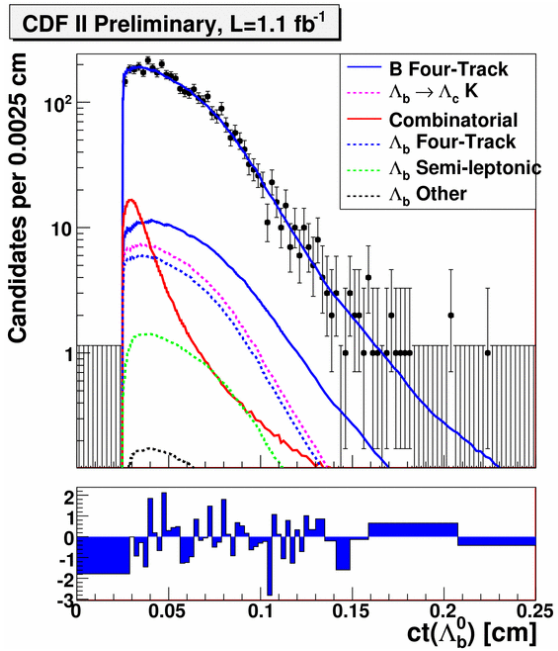
Progress on the Λ_b

Preliminary: $\Lambda_b \rightarrow \Lambda_c(pK\pi)\,\pi$

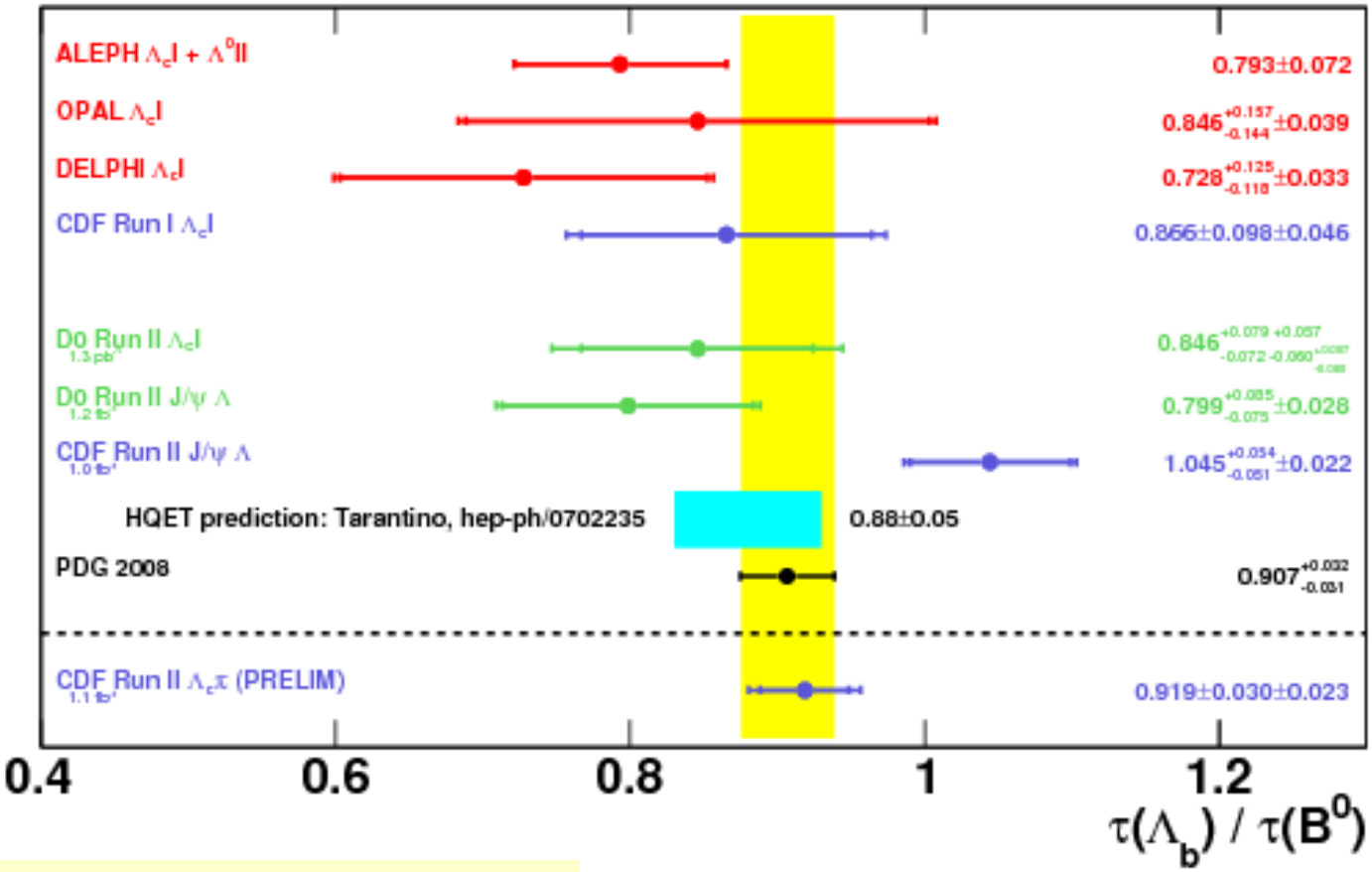
Using Two Displaced Track Triggers



signal: 2905±58



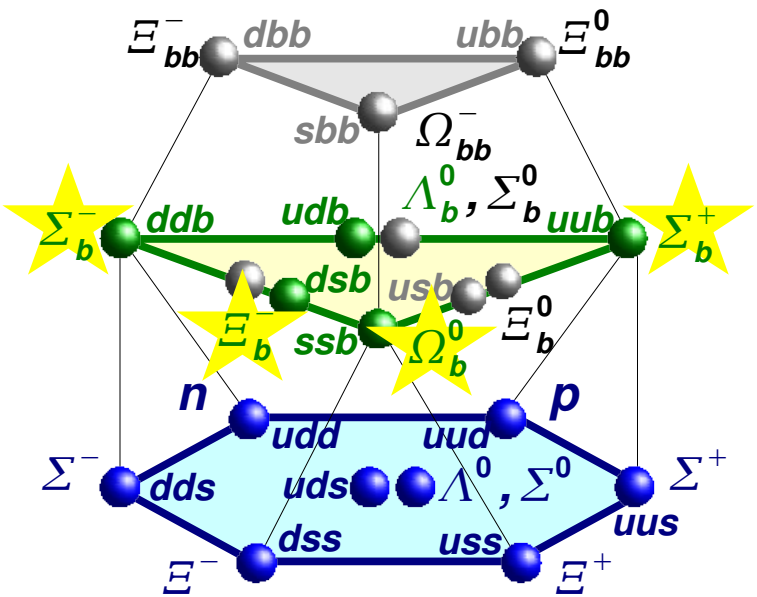
Comparison to World Ave and HQET



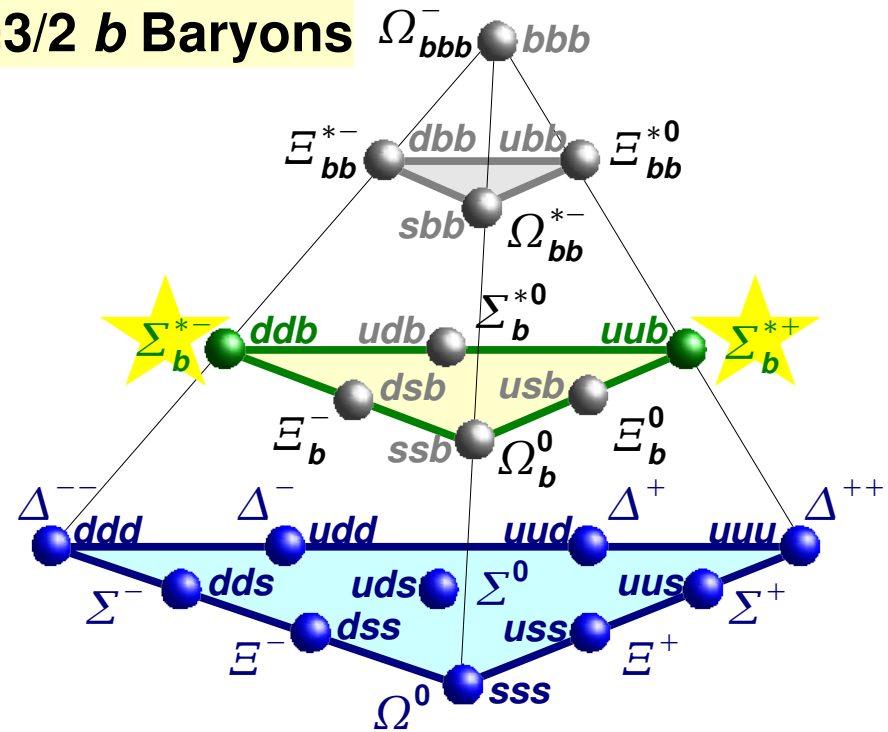
$c\tau(\Lambda_b) = 420.1 \pm 13.7 \pm 10.6\ \mu m$

More *b* Baryons

J **=1/2** ***b*** **Baryons**



J **=3/2** ***b*** **Baryons**



b **= 3**

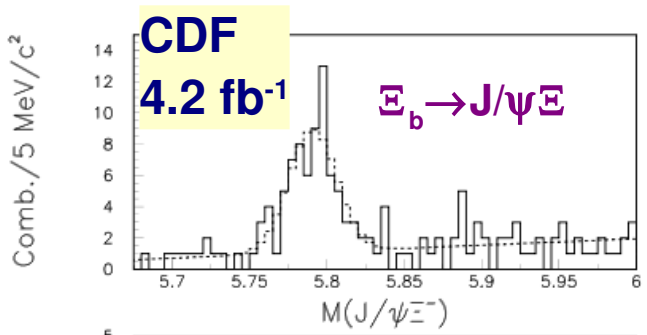
b **= 2**

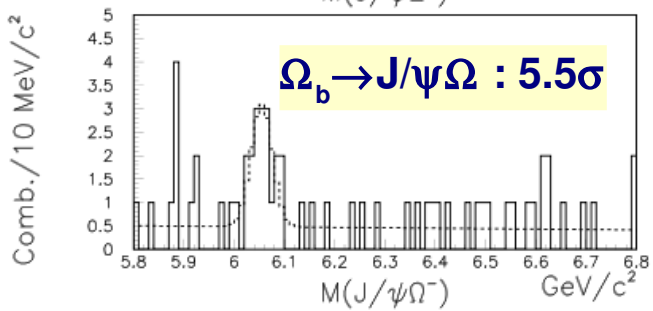
b **= 1**

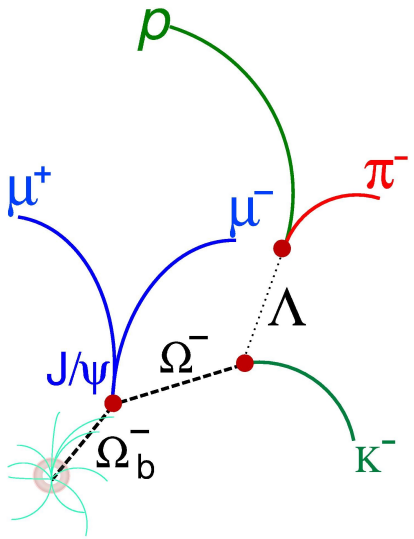
b **= 0**

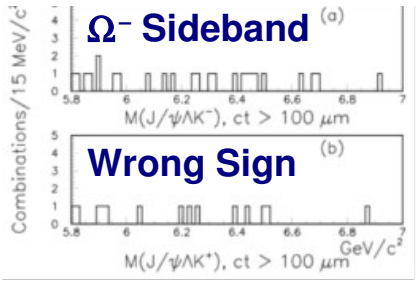
Baryon	CDF	DØ
$\Sigma_b^{(*)}$	June 2007	---
Ξ_b^-	June 2007	June 2007
Ω_b^-	May 2009	August 2008

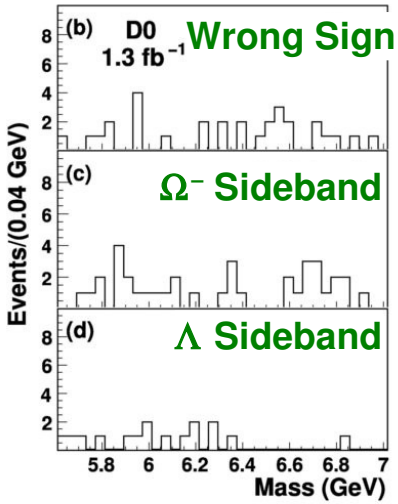
$\Omega_b \to J/\psi\ \Omega$ and $\Xi_b \to J/\psi\ \Xi$

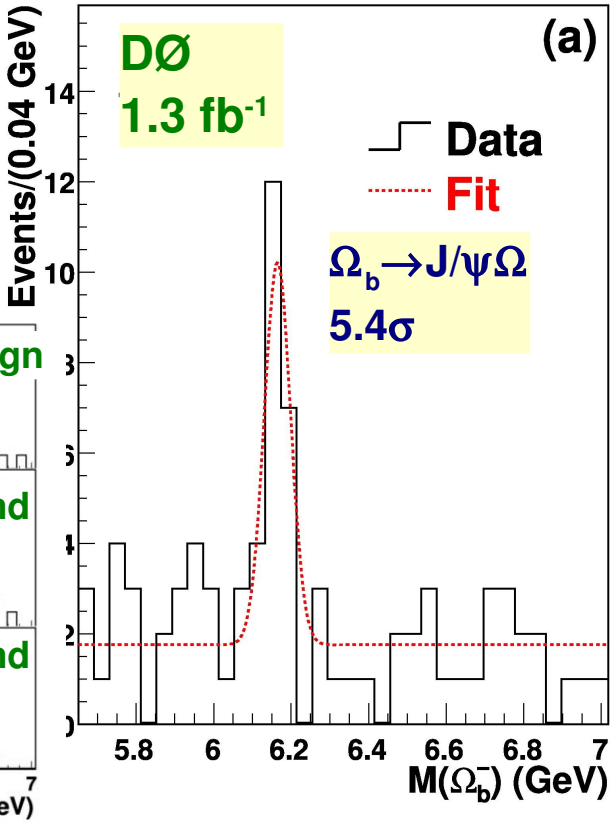




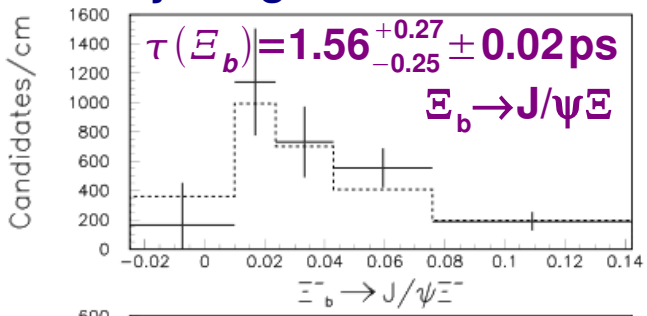


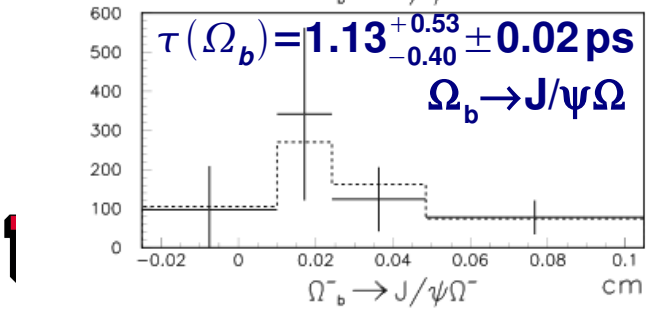


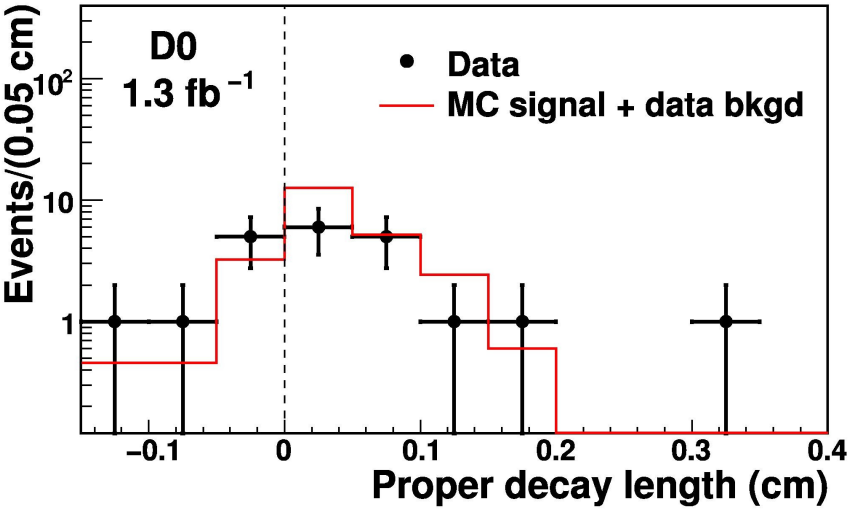




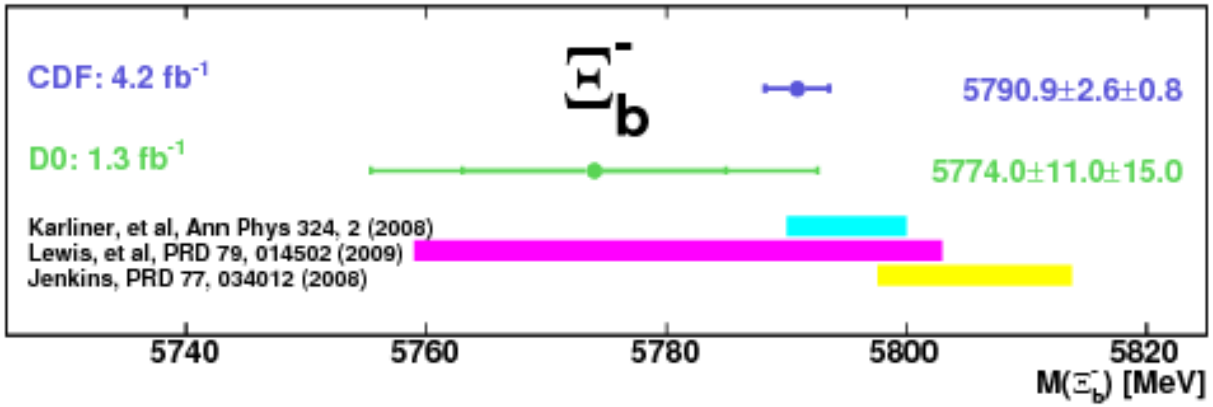
Decay Length Distrib's





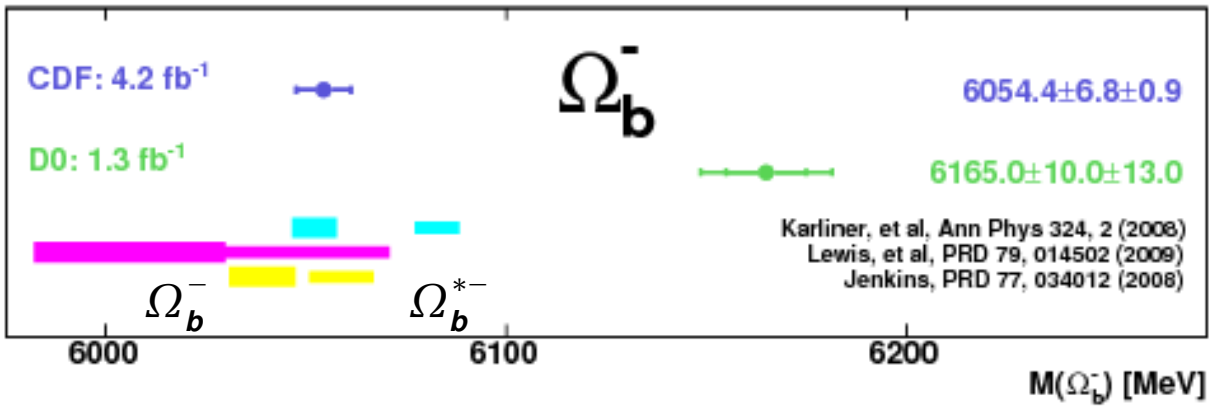


The Same Ω_b ???



Ξ_b: good agreement:

- CDF vs DØ
- Exp vs Theory



$$M(\Omega_b^-)^{D0} - M(\Omega_b^-)^{CDF} = 111 \pm 12 \pm 14 \text{ MeV}$$

~6σ difference
(10x largest syst)

CDF: $\dfrac{\sigma(\Omega_b^-)}{\sigma(\Xi_b^-)} \dfrac{BR(\Omega_b^- \to J/\psi\,\Omega^-)}{BR(\Xi_b^- \to J/\psi\,\Xi^-)} = 0.27 \pm 0.12 \pm 0.01$

D0: $\dfrac{f(b \to \Omega_b^-)}{f(b \to \Xi_b^-)} \dfrac{BR(\Omega_b^- \to J/\psi\,\Omega^-)}{BR(\Xi_b^- \to J/\psi\,\Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$

~1.3σ difference (Gaussian Errors)

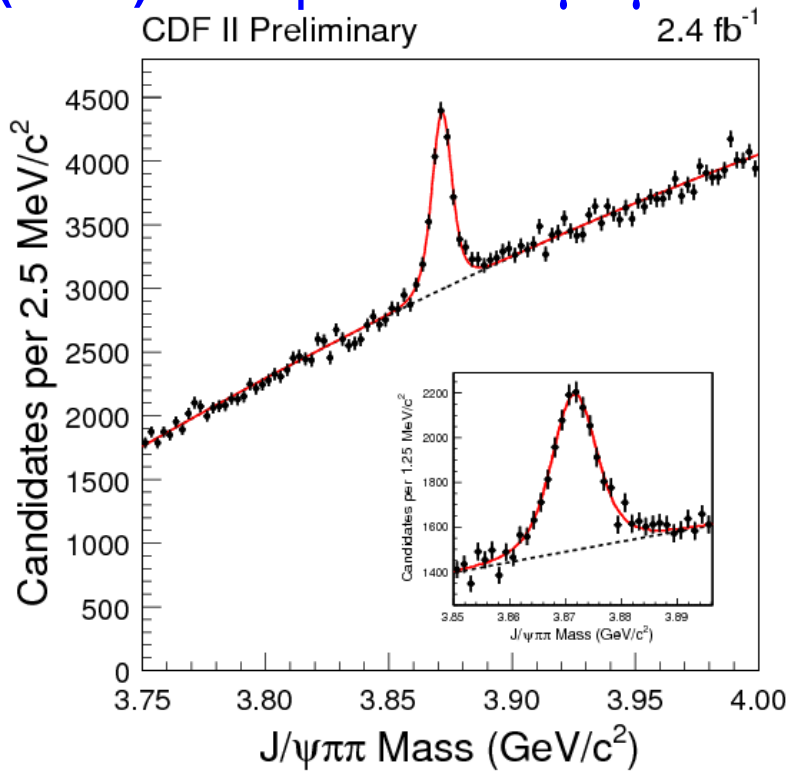
Charmonium-like Exotica

J^{PC}	States	Main Decay	Discovered	*Possible* Interpretation
1^{++}	X(3872) X(3875)	$J/\psi\ \pi^+\pi^-$ $D^0\bar{D}^0\pi^0, D^0\bar{D}^{*0}$	Belle 03 Belle 05	D-D* molecule, tetraquark
1^{--}	Y(4008) * Y(4260) Y(4325) Y(4660) * X(4630) *	$J/\psi\ \pi^+\pi^-$ $J/\psi\ \pi^+\pi^-$ $\psi(2S)\ \pi^+\pi^-$ $\psi(2S)\ \pi^+\pi^-$ $\Lambda_c^+\Lambda_c^-$	Belle 07 BaBar 05 BaBar 06 Belle 07 Belle 08	 $c\bar{c}g$ $\psi(3D)$
2^{++}	Z(3930) * $Z^{\pm}(4430)$ * $Z_{1,2}^{\pm}$	$D\bar{D}$ $\psi(2S)\ \pi^{\pm}$ $\chi_{c1}\ \pi^{\pm}$	Belle 05 Belle 07 Belle 08	$\chi_{c2}(2P)$
$?^{??}$	X(3940) * Y(3940) Y(4140) * X(4160)	$D\bar{D}^*$ $J/\psi\ \omega$ $J/\psi\ \phi$ $D^*\bar{D}^*$	Belle 07 Belle 05 CDF 09 Belle 07	$\eta_c(3S)$ $\chi_{c1}(2P), c\bar{c}g$

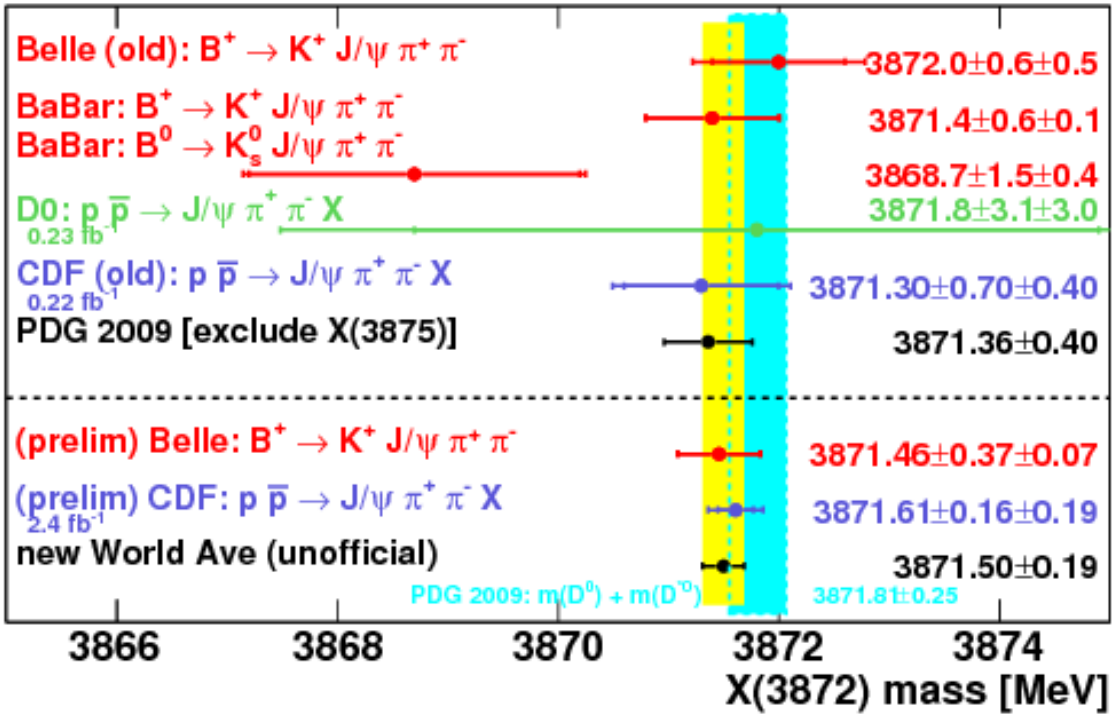
* only one observation – needs confirmation

CDF X(3872) Mass Measurement

$X(3872) \to J/\psi\ \pi^+\ \pi^- \to \mu^+\ \mu^-\ \pi^+\ \pi^-$



World-Best Mass Measurement



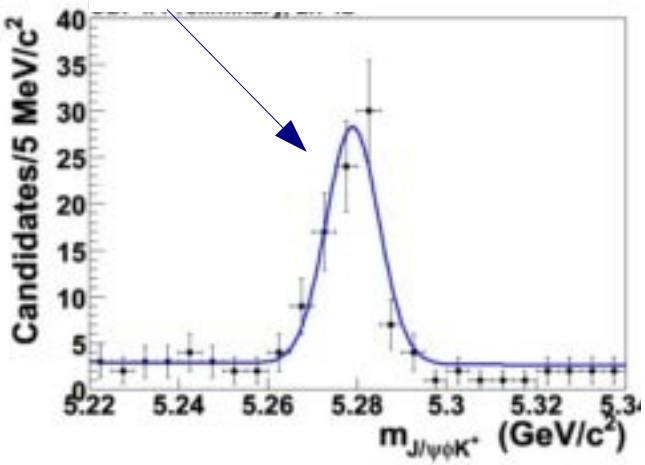
What is it ??? (CDF's input)

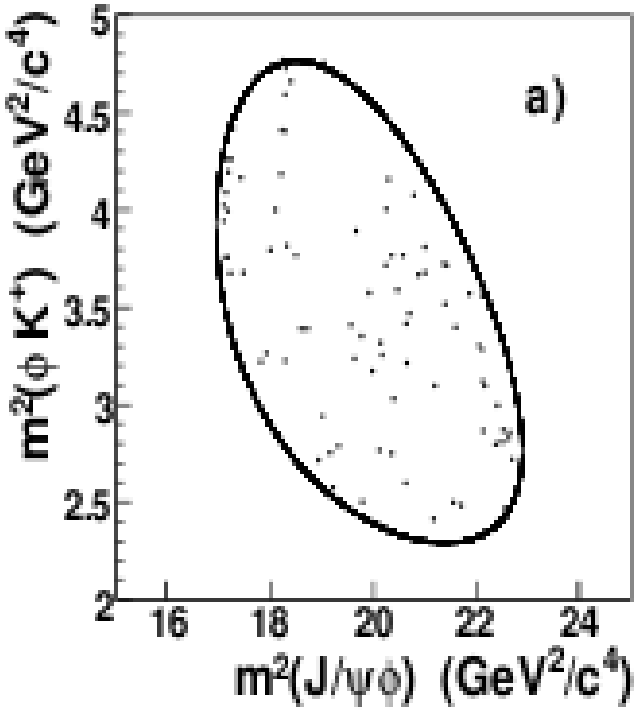
- 1^{++} or 2^{-+} — decay products angular distrib's — PRL 98, 132002 (2007)
- not two states — $\Delta m < 3.2$ MeV (90% CL) [for equal mixture] — prelim
- possibly D-D* — new $M_X < m(D^0) + m(D^{*0})$ — prelim
- or...not D-D* — prod. x-section too low — Bignamini, Grinstein, Piccini, Polosa, Sabelli arXiv:0906.0882

Structure in $B^+ \to J/\psi\ \phi\ K^+$

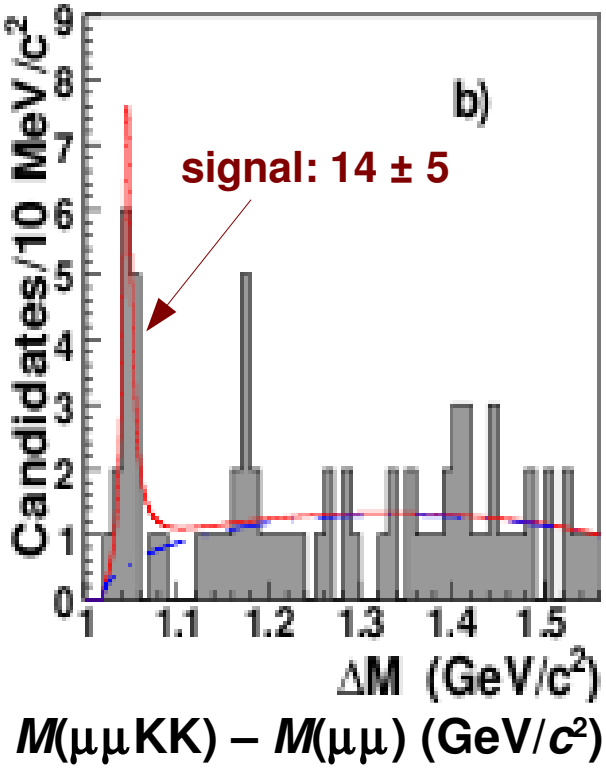
$B^+ \to Y(4140)\ K^+$
$\quad \hookrightarrow J/\psi\ \phi$
$\qquad \hookrightarrow K^+ K^-$
$\qquad \hookrightarrow \mu^+ \mu^-$

75 ± 10 cand's





CDF: 2.7 fb^{-1}



arXiv:0903.2229

- Significance > 3.8 σ

- Assuming S-wave Breit-Wigner
  - $M = 4143.0 \pm 2.9 \pm 1.2$ MeV $\qquad \Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV

- Above open-charm threshold, but similar decay to $Y(3930) \to J/\psi\ \omega$

EW Symmetry Breaking ⇔ Flavor

EW Sym. Breaking ⇒ CKM Matrix ⇒ Different Quark Eigenstates

Weak

$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}=\begin{pmatrix}M-i\frac{\Gamma}{2} & M_{12}-i\frac{\Gamma_{12}}{2}\\ M_{12}-i\frac{\Gamma_{12}}{2} & M-i\frac{\Gamma}{2}\end{pmatrix}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

CP

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

Mass

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

B_s Observables

17.77 ± 0.12 ps^{-1}	Δm_s	=	$M_H-M_L\sim2\lvert M_{12}\rvert$	sensitive to new physics
	$\Delta\Gamma_s^{CP}$	=	$\Gamma_{even}-\Gamma_{odd}\sim2\lvert\Gamma_{12}\rvert$	not sensitive to new physics
$+0.062^{+0.034}_{-0.037}$ ps^{-1}	$\Delta\Gamma_s$	=	$\Gamma_L-\Gamma_H\sim2\lvert\Gamma_{12}\rvert\cos\phi_s$	VERY sensitive to new physics
see	ϕ_s	=	$arg\left[-M_{12}/\Gamma_{12}\right]$	$\phi_s^{meas} = \phi_s^{SM}(\sim0.004) + \phi_s^{NP}$
following	β_s	=	$arg\left[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right]$	$\beta_s^{meas} = \beta_s^{SM}(\sim0.02) - \phi_s^{NP}/2$
$1.472^{+0.024}_{-0.026}$ ps	$\bar{\tau}_s$	=	$\frac{2}{\Gamma_L+\Gamma_H}$	$\left(\phi_s^{meas}\sim-2\beta_s^{meas}\sim\phi_s^{NP}\right)$

PDG 2009 world averages

Width Difference & CPV in the B_s

1) Ang. Distrib's in $B_s \to J/\psi\ \phi$

– fit for ϕ_s/β_s ; $\Delta\Gamma_s$; .....

2) Charge Asym's in Decay

– $p\bar{p} \to \mu^\pm \mu^\pm X$

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

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

– $B_s \to \mu\ D_s\ X$

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

3) Flavor-specific Lifetime

– $B_s \to l\ D_s\ X$

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

4) CP-specific Final States

– $B_s \to K^+ K^-$

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

– $B_s \to D_s^{(*)} D_s^{(*)}$

$$2\,\mathrm{BR}(B_s \to D_s^{(*)+} D_s^{(*)-}) = \frac{\Delta\Gamma_s}{\Gamma_s\cos\phi_s}\left[\frac{1}{1-2x_f} - \frac{\Delta\Gamma_s\cos\phi_s}{2\Gamma_s}\right]$$

(x_f = CP-odd fraction)

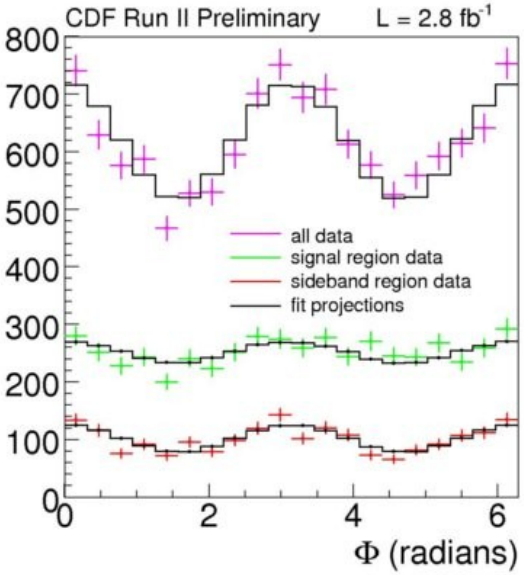
Assumes:

i. $B_s^{odd} \to D_s D_s^*$ forbidden [$m_c \to \infty$, some $1/N_{col}$ terms negl]

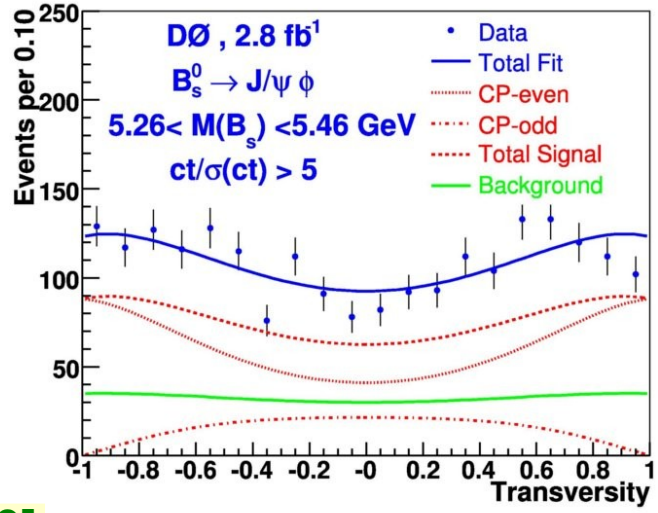
ii. $\Delta\Gamma_s^{CP}$ saturated by $B_s \to D_s^{(*)} D_s^{(*)}$ [SV-limit]

iii. small CP-odd fraction [x_f]

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

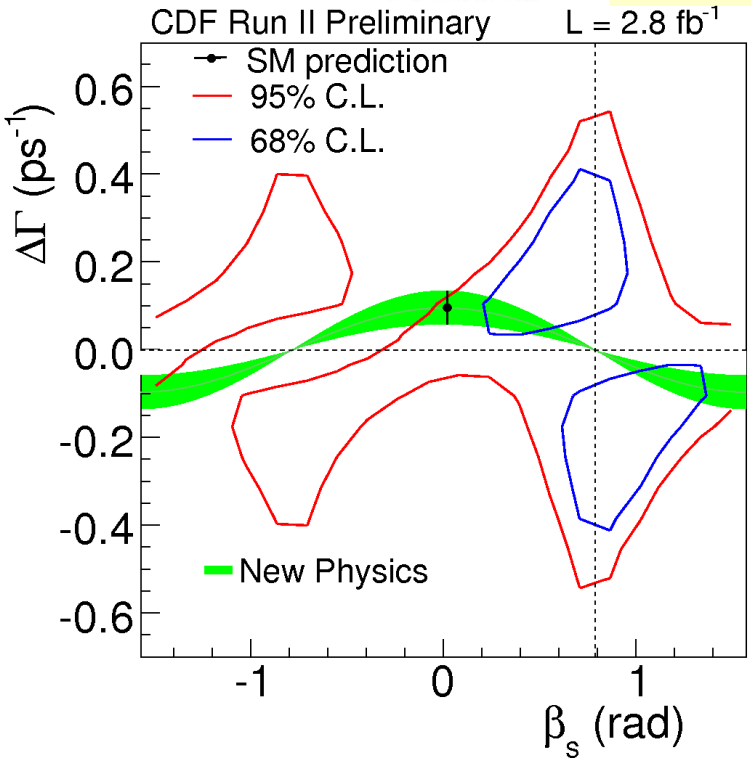


Fits Use:
3 decay angles
proper decay time
initial state flavor tag
***m*(B_s)**

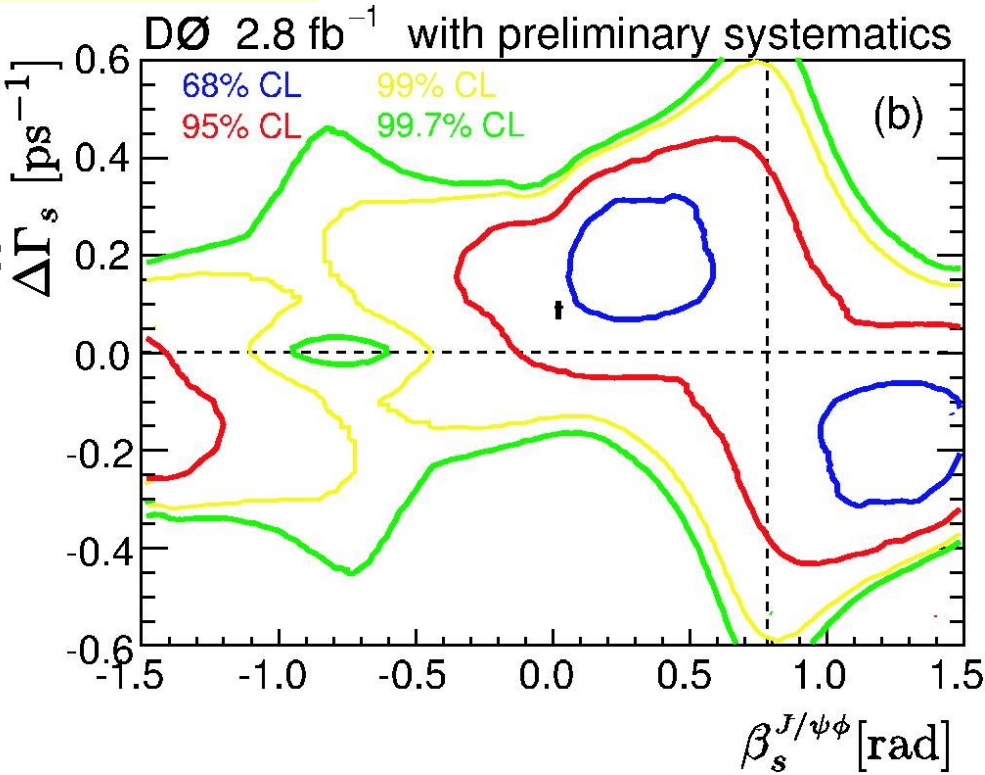


B_s Signal

3,166 ± 56 [CDF] **1,967 ± 65 [D0]**

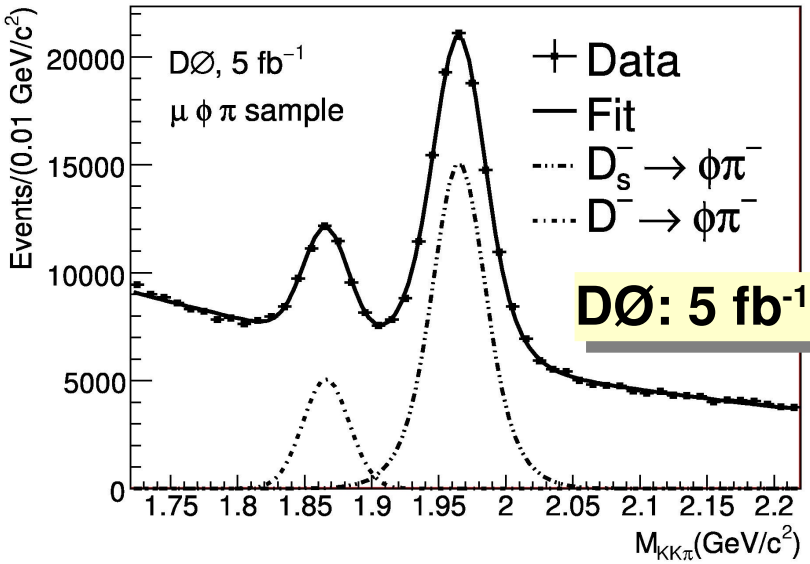


Results Include:
- **unconstrained strong phases**
- **contours w/ systematics & adjusted to proper cover.**

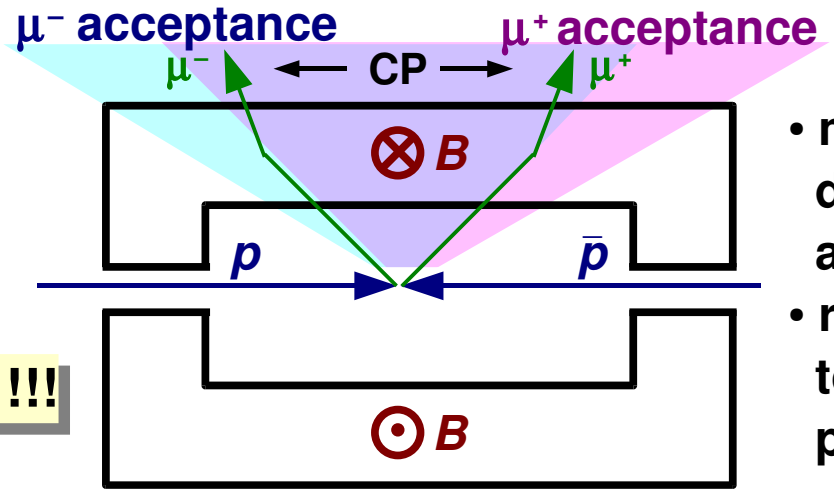


CPV in $B_s \to \mu D_s X$

$B_s \to \mu D_s(\phi\pi)X$: 81,394±865 cand's

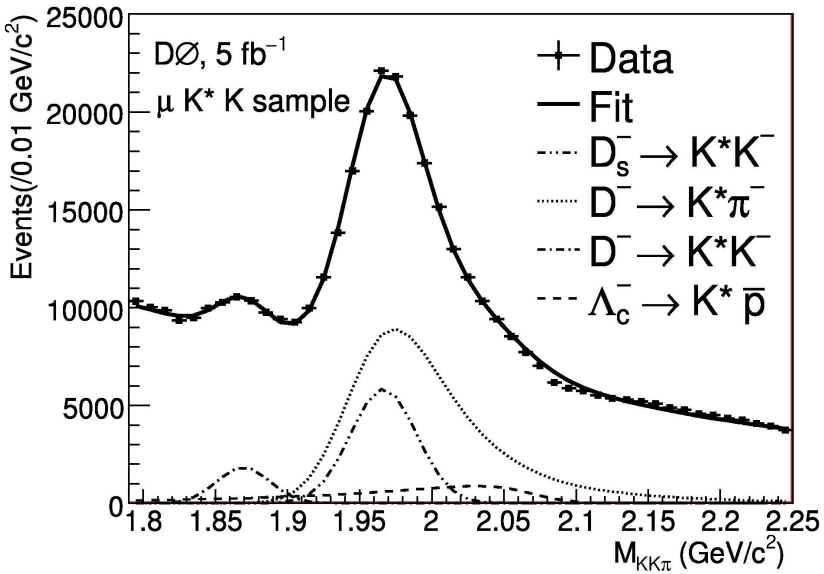


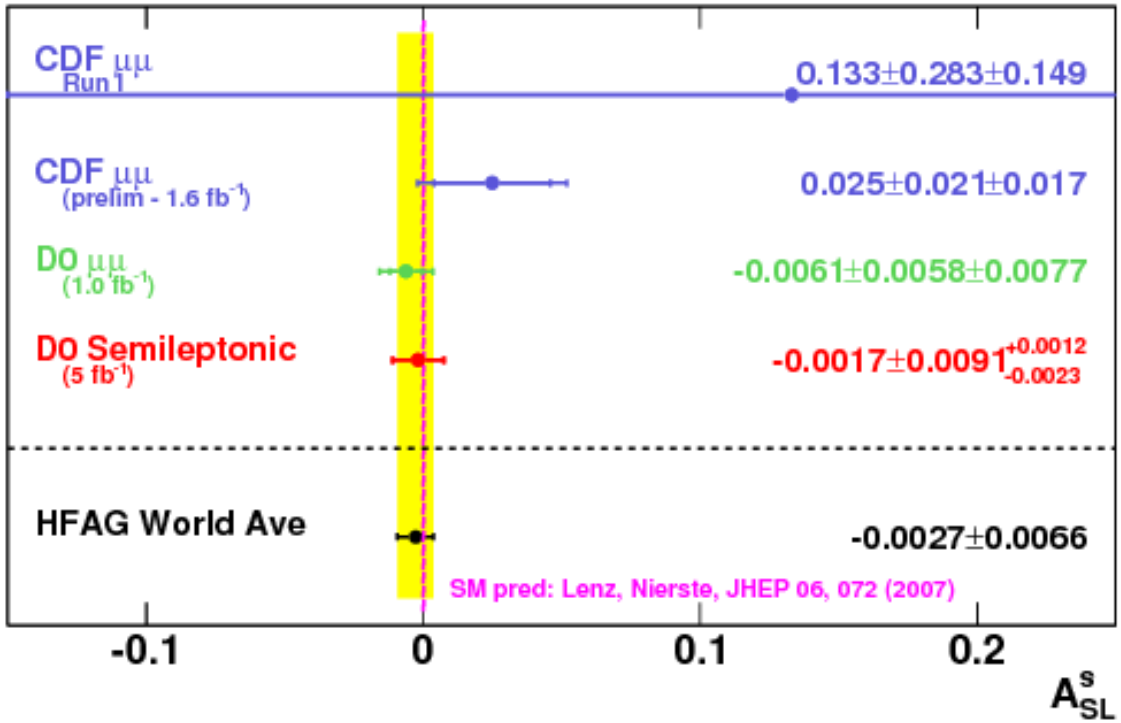
DØ: 5 fb^{-1} !!!



- **measure/correct detector-related asymmetries**
- **regularly flip toroid & solenoid polarities**

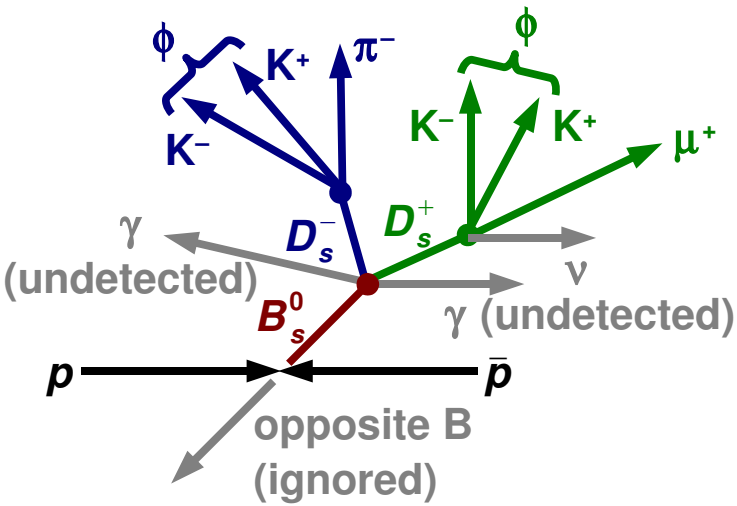
$B_s \to \mu D_s(K^*K)X$: 33,557±1,200 cand's

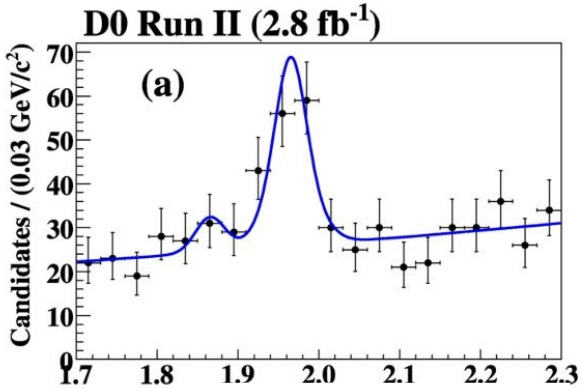




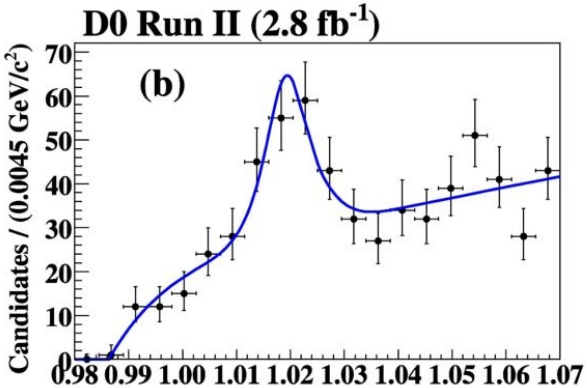
BR($B_s \to D_s^{(*)} D_s^{(*)}$)

$$D_s^{*-} \to \gamma/\pi^0 D_s^- \to \phi\pi^-$$
$$D_s^{*+} \to \gamma/\pi^0 D_s^+ \to \phi\mu^+\nu$$

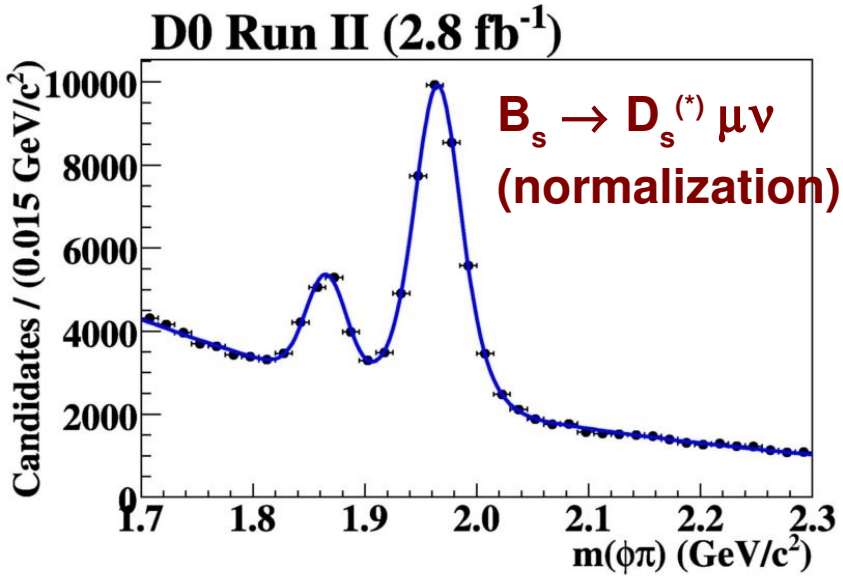




$m(\phi\pi)$: $D_s \to \phi\ \pi$



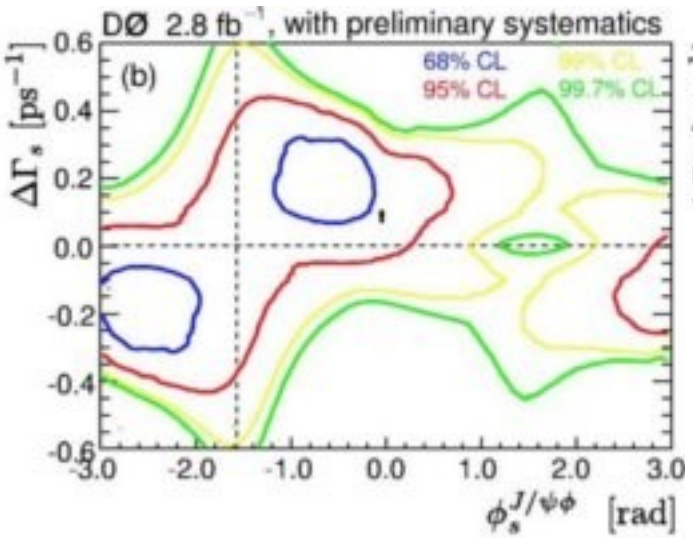
$m(KK)$: $D_s \to \phi\ \mu\ \nu$



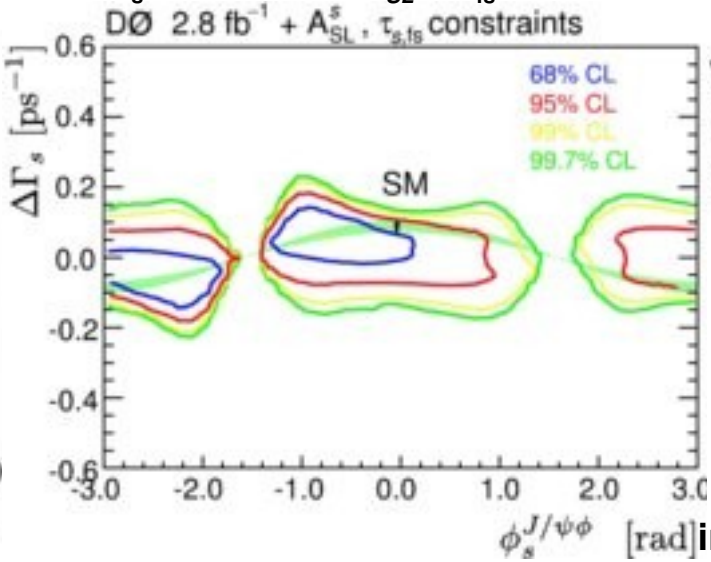
- **Signal: 26.6 ± 8.4 (3.2σ)**
- **BR($B_s \to D_s^{(*)} D_s^{(*)}$)**
  = 0.035 ± 0.010(stat) ± 0.008(syst) ± 0.007(BR's)
- $$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx \frac{2\,BR(B_s^0 \to D_s^{(*)} D_s^{(*)})}{1 - BR(B_s^0 \to D_s^{(*)} D_s^{(*)})}$$
  $$= 0.072 \pm 0.021 \pm 0.022$$

DØ Combination: 2.8 fb^{-1}

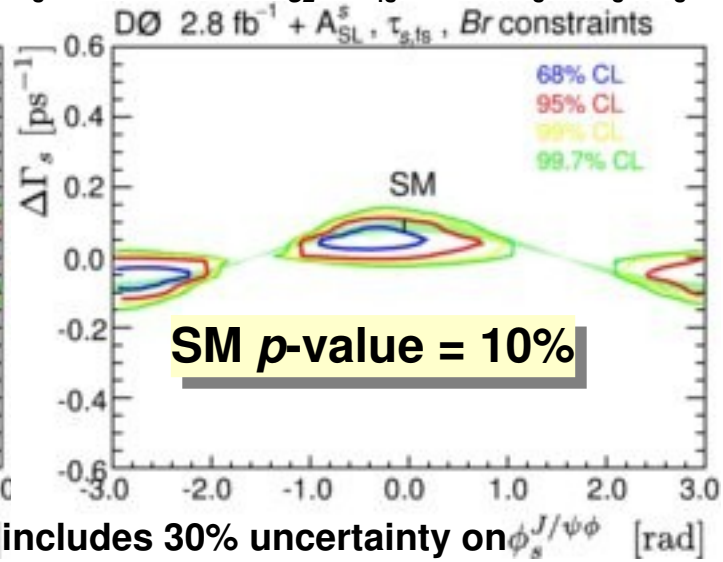
$B_s \to J/\psi\ \phi$ alone



$B_s \to J/\psi\ \phi + A^s_{SL} + \tau_{fs}$



$B_s \to J/\psi\ \phi + A^s_{SL} + \tau_{fs} + BR(B_s \to D_s^{(*)} D_s^{(*)})$



SM *p*-value = 10%

includes 30% uncertainty on $BR(B_s \to D_s^{(*)} D_s^{(*)})$ vs $\Delta\Gamma_s$ relationship

Example Gains (HFAG 2008 CDF-DØ combination of ϕ_s results – 90% CL regions)

$B_s \to J/\psi\ \phi$	$B_s \to J/\psi\ \phi\ A_{SL}^s + \tau_{fs}$
[–1.47;–0.29] ∪ [–2.85;–1.65]	[–1.26;–0.13] ∪ [–3.00;–1.88]

~5% Gain

Work in Progress

- DØ 1D confidence intervals for ϕ_s and $\Delta\Gamma_s$
- CDF + DØ combination

Conclusions & Plans

Broad Spectrum of Heavy Flavor Physics at the Tevatron

- quite complementary to the B-Factories

Many Important Results since the start of Run II

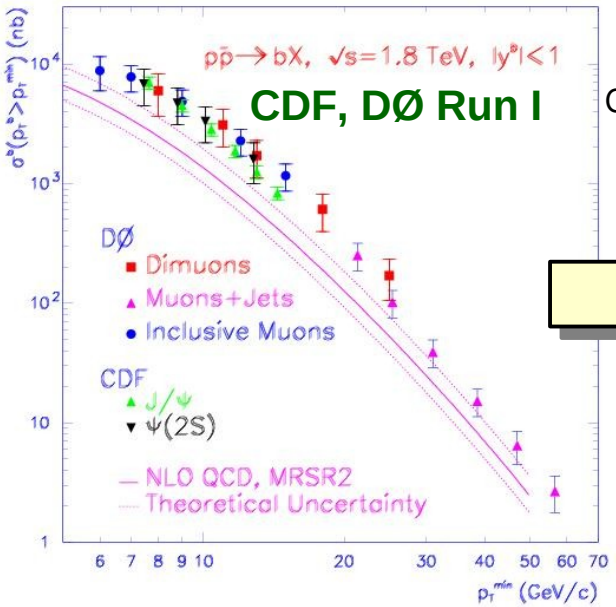
- Discovery of New *B*-states and Better Understanding of Old Ones
- Rare Decay Modes
- B_s Mixing
- CP-violation in B_s System ⇒ a hint of New Physics ???
- ...to name just a few

More to Come

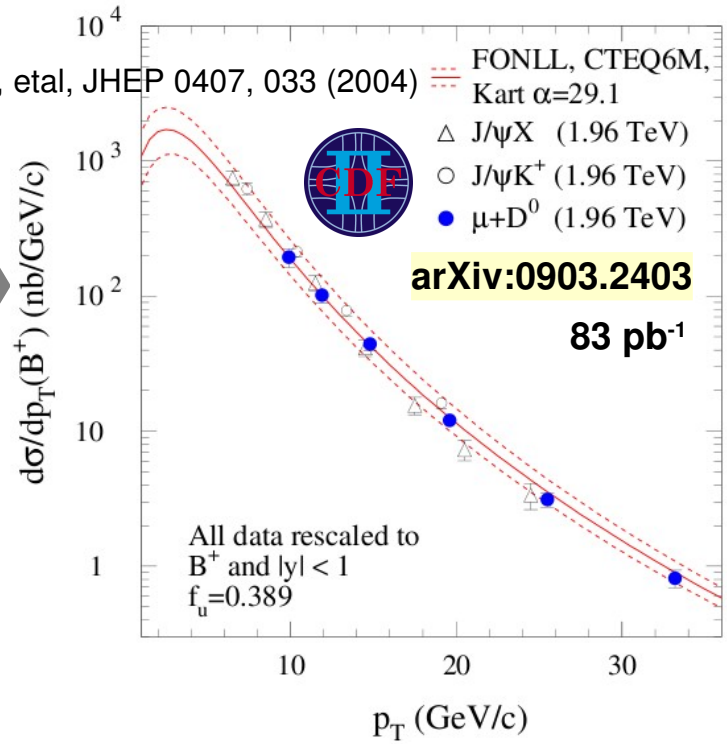
- expect ~factor of two increase in dataset by end of Run II
- many analyses are statistics limited: Baryons, Rare Decays, CP-violation,...

Stay Tuned for Surprises !

Understanding *b*-Production

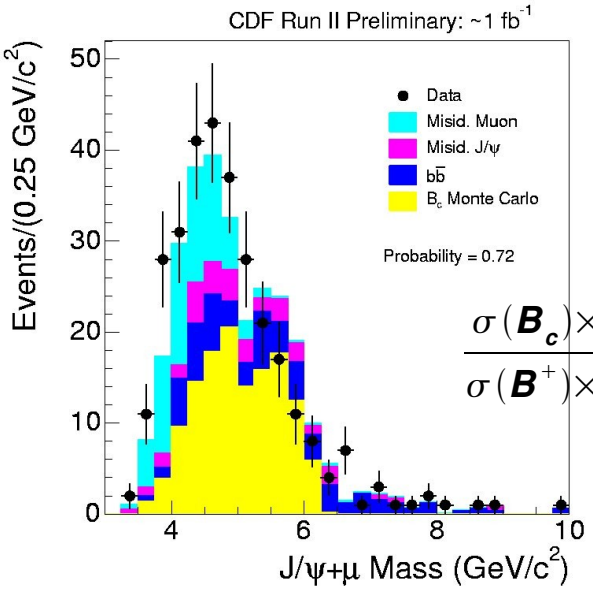


Caciari, etal, JHEP 0407, 033 (2004)



Enlightenment:

1) ***B*'s instead of *b*'s**
2) **FONLL calc's**
3) **Consistent fragment.**
4) **Production radius (more later...)**



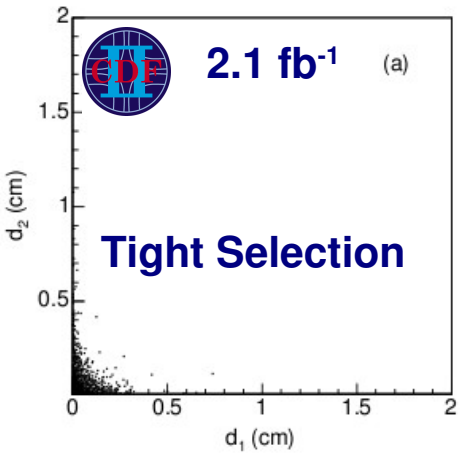
Now on to Details !

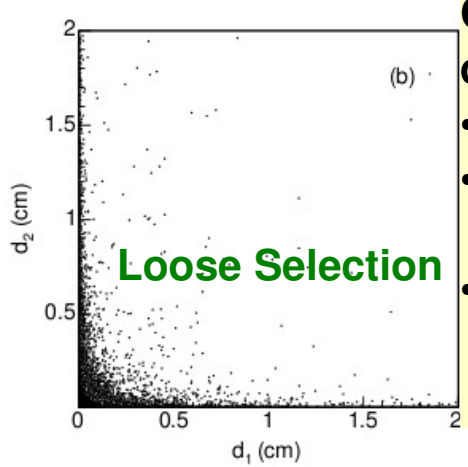
- **B_c Production**

Preliminary: 1 fb^{-1}

$$\frac{\sigma(B_c)\times BR(B_c\to J/\psi\,\mu\,\nu)}{\sigma(B^+)\times BR(B^+\to J/\psi\,K^+)} = \begin{cases} 0.295\pm0.040\,(\text{stat})^{+0.033}_{-0.026}\,(\text{syst})\pm0.036\,(p_T) & [\,p_T(B)>4\,\text{GeV}\,] \\ 0.227\pm0.033\,(\text{stat})^{+0.024}_{-0.017}\,(\text{syst})\pm0.014\,(p_T) & [\,p_T(B)>6\,\text{GeV}\,] \end{cases}$$

Still some surprises ?

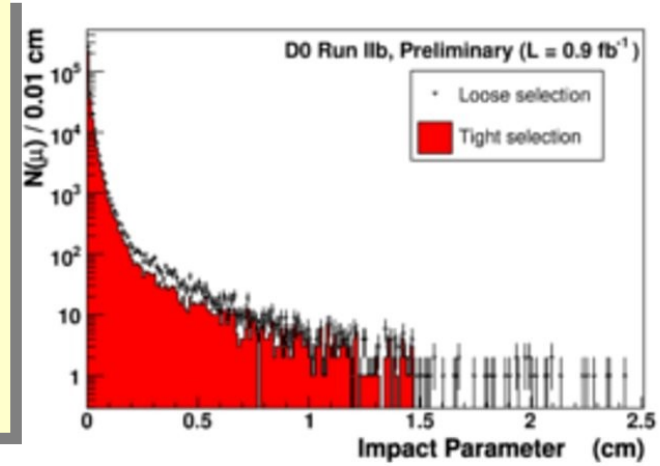




CDF observes excess diumon production

- **~1.6 < *r* < 10 cm**
- **explains prev. x-sect excess**
- **sign of pair-prod of 3 new, light states ?**

Giromini, et al, arXiv:0810.5730



Requirement	CDF (arXiv: 0810.5357 – 2.1 fb^{-1})	DØ (preliminary – 1.0 fb^{-1})
$p_T(\mu)$; $\lvert\eta\rvert$; Δz_0	≥ 3 GeV ; < 0.54 ; < 1.5 cm	≥ 3 GeV ; < 1.0 ; < 1.5 cm
Cosmic Veto	$\lvert\Delta\phi\rvert$ < 3.135 rad	$\lvert\Delta\phi\rvert$ < 3.135 rad
Timing	n/a	$\lvert\Delta t(A)\rvert$ < 10 ns ; $\lvert\Delta t(C)\rvert$ < 10 ns (wrt Beam X'ing)
M(μμ)	5 – 80 GeV	5 – 80 GeV
"Loose" Sel.	≥ 3 / 7 hits in Silicon	≥ 3 hits in Silicon
"Tight" Sel.	hits in 2 innermost layers + ≥ 2 other Si hits	hit in Si L0 + ≥ 2 other Si hits
"Excess"	72,553 ± 7,264	712 ± 462 ± 942
Excess/Loose	(12 ± 1) %	(0.40 ± 0.26 ± 0.53) %