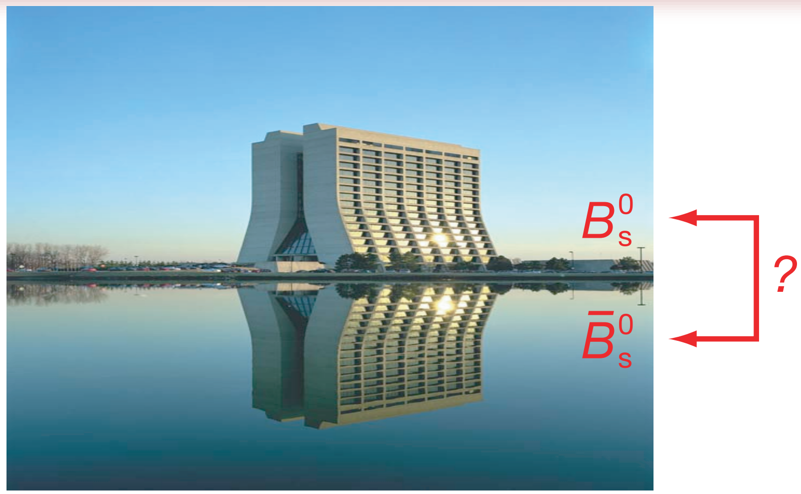
Tevatron Heavy Flavor Physics



Rick Van Kooten
Indiana University
(Representing the CDF & DØ Collaborations)

Fermilab Users' Meeting 2009
Fermilab, Batavia IL
3–4 June 2009

Outline

Just a flavor of Tevatron flavor physics...
(...and new since last Users' Meeting)

- Motivation
- Detector
- B_s^0 system
  - Exploration of mixing matrix
  - *CP* violation
- New *b* baryons
  - □$_b$
  - □$_b$ and □$_b$ properties
- Exotica
  - *Y*(4140)
- Rare Decays

Motivation

Why the huge matter-antimatter asymmetry in the universe?

Why Heavy Flavor Physics? *It's got it all!*

- Electroweak symmetry breaking → determines flavor structure
  CKM matrix, CP violation, FCNC's
- QCD Modeling: production, spectroscopy, masses, lifetimes, decays
  → Challenges lattice gauge, Heavy Quark Effective Theory, strong symmetries
- Searches for new physics → rare decays & departures in [CKM matrix, CP violation, FCNC's]

Why at the Tevatron?

- Produce heavier states not accessible anywhere else (at least until LHC):

$\bar{b}\,s$ $\bar{b}\,c$ $d\,\bar{b}$ $s\,\bar{b}$ $b\,u\,d$ $b\,u\,u$ $b\,s\,d$

B_s^0, B_c, B^{**}, B_s^{**}, ... Λ_b, Σ_b, Ξ_b, ...

→ Complementary to $\Upsilon(4S)$ *B* factories

$\bar{b}\,d$ B_d^0, B^+ $\bar{b}\,u$

Motivation

Why the huge matter-antimatter asymmetry in the universe?

Why Heavy Flavor Physics? *It's got it all!*

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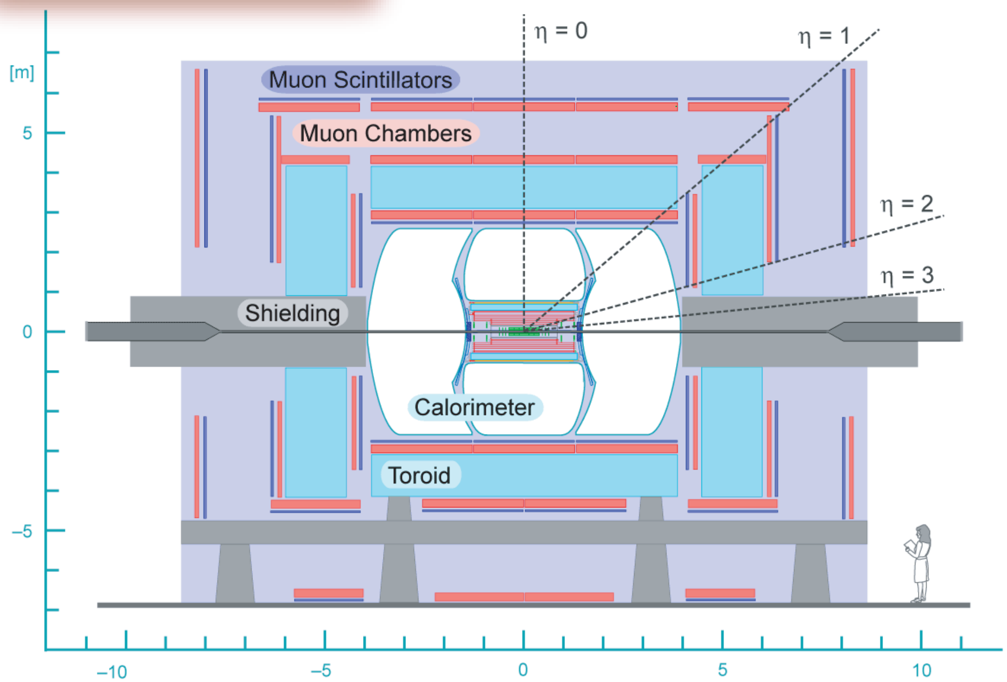
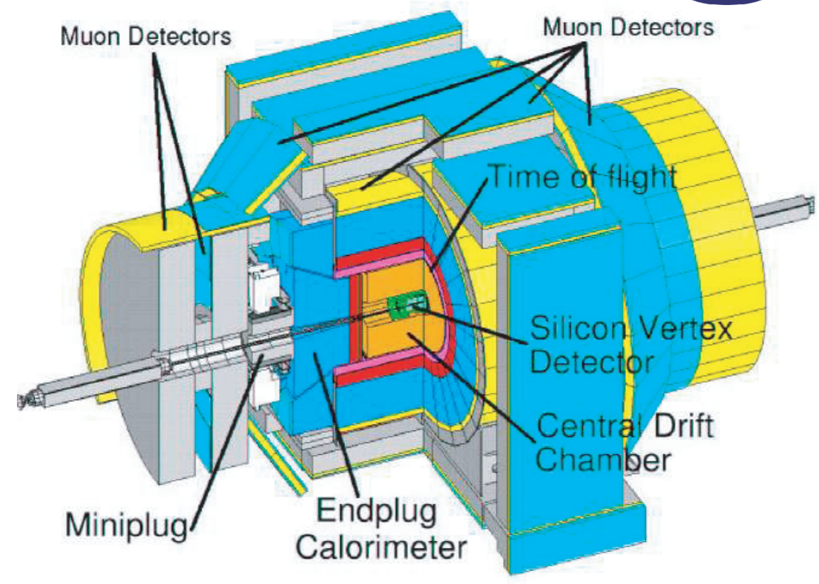
Why at the Tevatron?

- Produce heavier states not accessible anywhere else: B_s^0, B_c, B^{**}, B_s^{**}, Λ_b, Ξ_b, Σ_b ...
  → Complementary to $\Upsilon(4S)$ *B* factories
- Huge production rate (but also huge backgrounds: triggers for specific target decays)
  → Precision, rare decays, can also be competitive with *B* factories in some B^+ and B_d^0 decays

Detectors



CDF II Detector



Relevant for B physics:

DØ Tracker: excellent coverage & vertexing

- Silicon & scintillating fiber
- Small radii, but extending to |□| < 2
- New Layer 0 silicon on beam pipe in 2006, improving impact para. resol.

Triggered muon coverage: |□| < 2

E.g.triggers: dimuons, *single muons*, track displacement @ L2

CDF Tracker: excellent mass resolution & vertexing

- Silicon, Layer 00
- Large radii drift chamber, many hits, excellent momentum resolution
- dE/dx (and TOF): particle id

Triggered muon coverage: |□| < 1

E.g.triggers: dimuons, lepton + displ. track, *two displaced tracks*

Why the B_s^0 is so great

Weak Eigenstates propagate according to Schrodinger:

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

Diagonalize

CP Eigenstates: $|B_s^{odd}\rangle = |B_s^0\rangle + |\bar{B}_s^0\rangle \quad |B_s^{even}\rangle = |B_s^0\rangle - |\bar{B}_s^0\rangle$

Mass Eigenstates: $|B_s^H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \quad |B_s^L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$

Heavy *Light*

If CP conserved in mixing, $p=q$ $\quad |B_s^H\rangle = |B_s^{odd}\rangle \quad |B_s^L\rangle = |B_s^{even}\rangle$

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

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

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

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \quad \tau = \frac{1}{\Gamma_s}$$

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

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Mass Eigenstates: $|B_s^H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ (*Heavy*) $\quad |B_s^L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ (*Light*)

If CP conserved in mixing, $p=q$: $\quad |B_s^H\rangle = |B_s^{odd}\rangle \quad |B_s^L\rangle = |B_s^{even}\rangle$

$$\Delta m_s = M_H - M_L \sim 2|M_{12}| = 17.77 \pm 0.12\ \text{ps}^{-1}$$

← Precision! (better than theory)

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

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

Tiny for B_d^0 meson, but not for B_s^0 ! eigenstates propagate with different lifetimes!

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \quad ; \quad \tau = \frac{1}{\Gamma_s}$$

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$\Delta m_s = M_H - M_L \sim 2|M_{12}|$ Sensitive to new physics

$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$ Not sensitive to new physics

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$ *Very* sensitive to new physics

$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$; $\tau = \frac{1}{\Gamma_s}$

$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004$ in SM

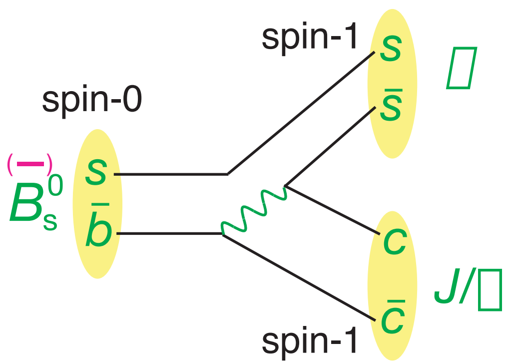
$\Delta\Gamma_s$ and ϕ_s

First assuming no *CP* violation in B_s mixing, $\phi_s \sim 0$

Mass and CP eigenstates the same

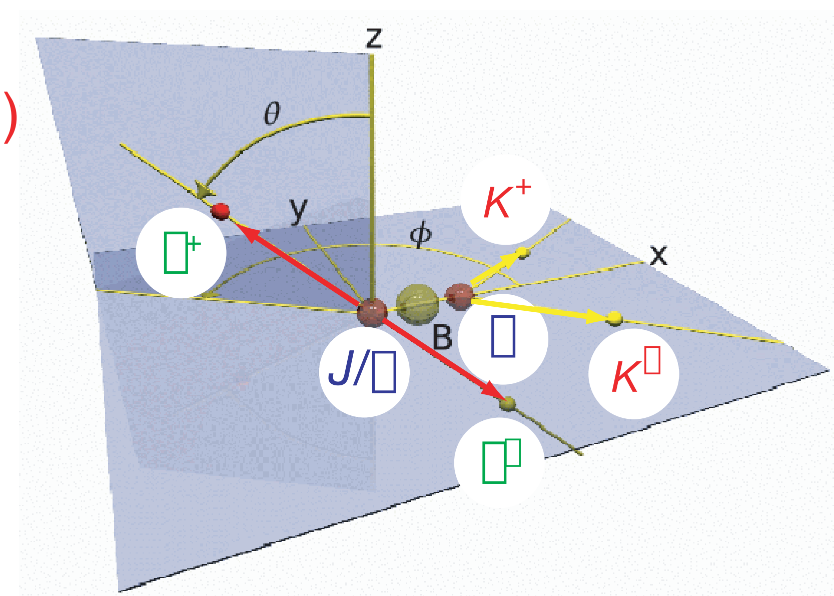
- Heavy (*H, CP-odd*) and Light (*L, CP-even*) B_s states

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \; ; \qquad \Gamma_s = (\Gamma_L + \Gamma_H)/2 \; ; \qquad \tau_s = \frac{1}{\Gamma_s}$$



Not "flavor-specific", predicted to be more *CP*-even than odd

- Decays into two vector mesons that are either *CP*-odd (*L*=1) or *CP*-even (*L*=0,2)
- Time-dependent angular distributions allow separation of components
- Simultaneous fit to lifetime and three angles "transversity basis"



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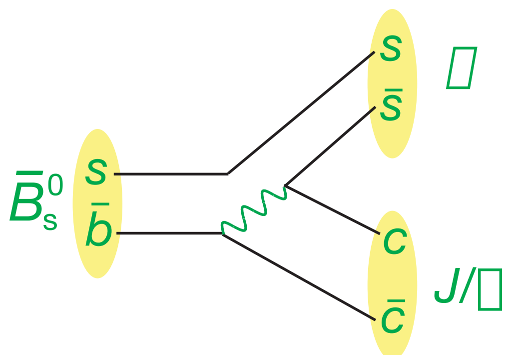
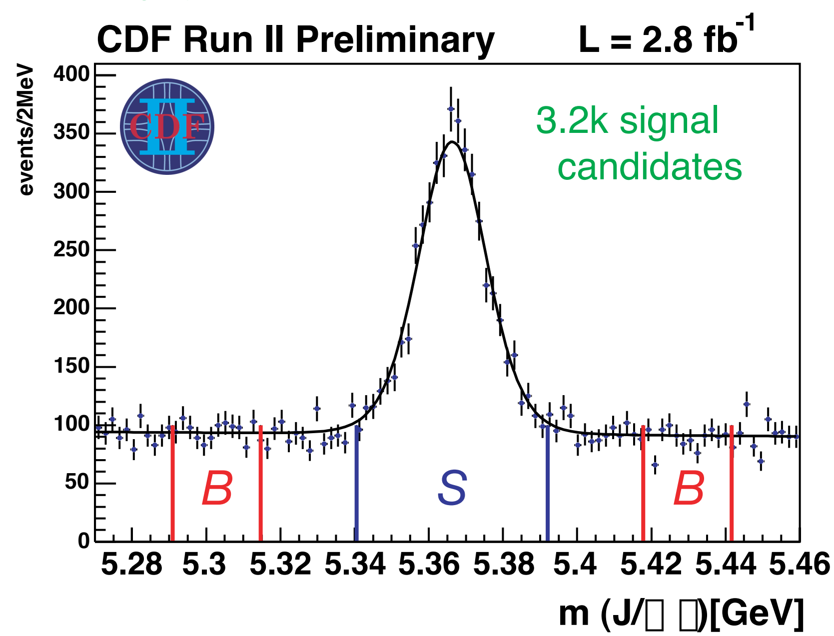


Not "flavor-specific", predicted to be more *CP*-even than odd

Update of 1.3 fb^{-1} published analysis to 2.8 fb^{-1}:



DØ: ~2k signal candidates

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$\Delta\Gamma_s$ and ϕ_s

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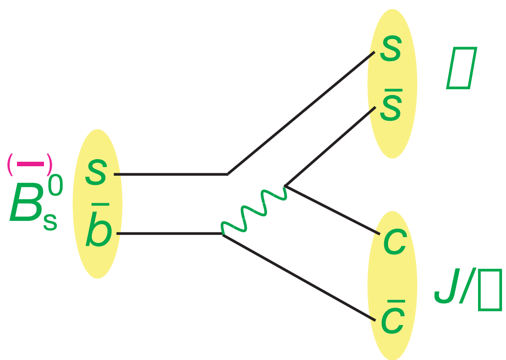

Not "flavor-specific", predicted to be more *CP*-even than odd

- Decays into two vector mesons that are either *CP*-odd (L=1) or *CP*-even (L=0,2)
- Time-dependent angular distributions allow separation of components
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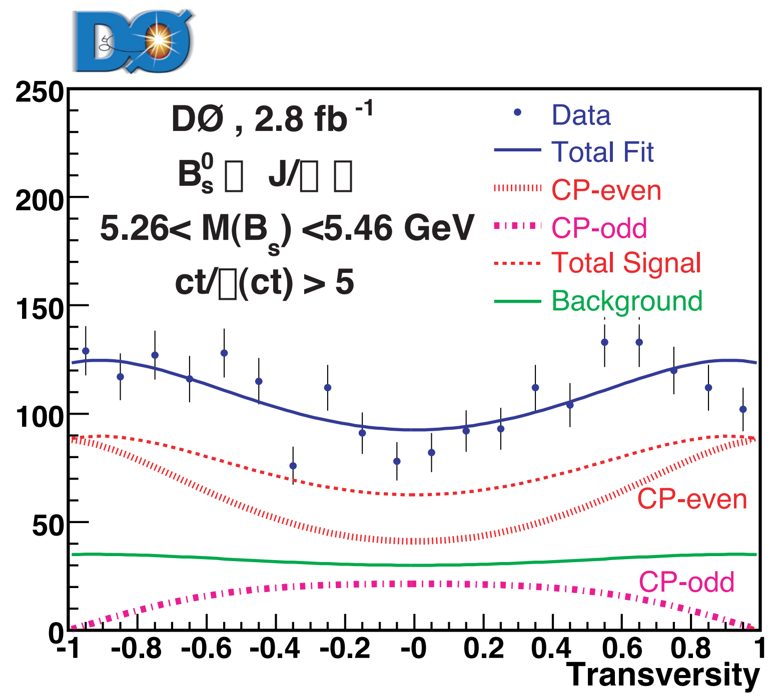

$\Delta\Gamma_s$ and τ_s

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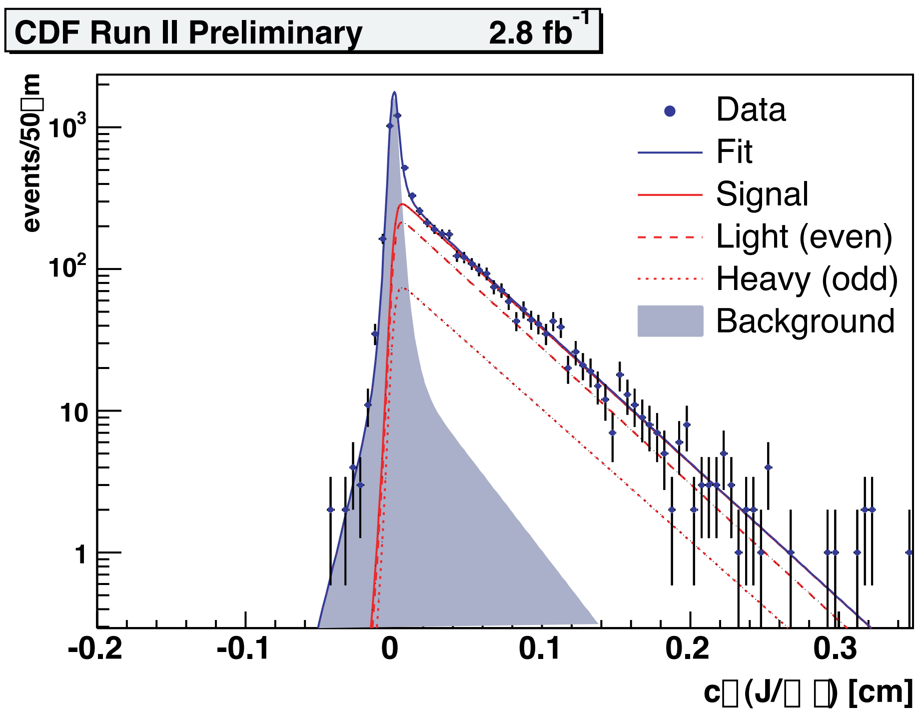
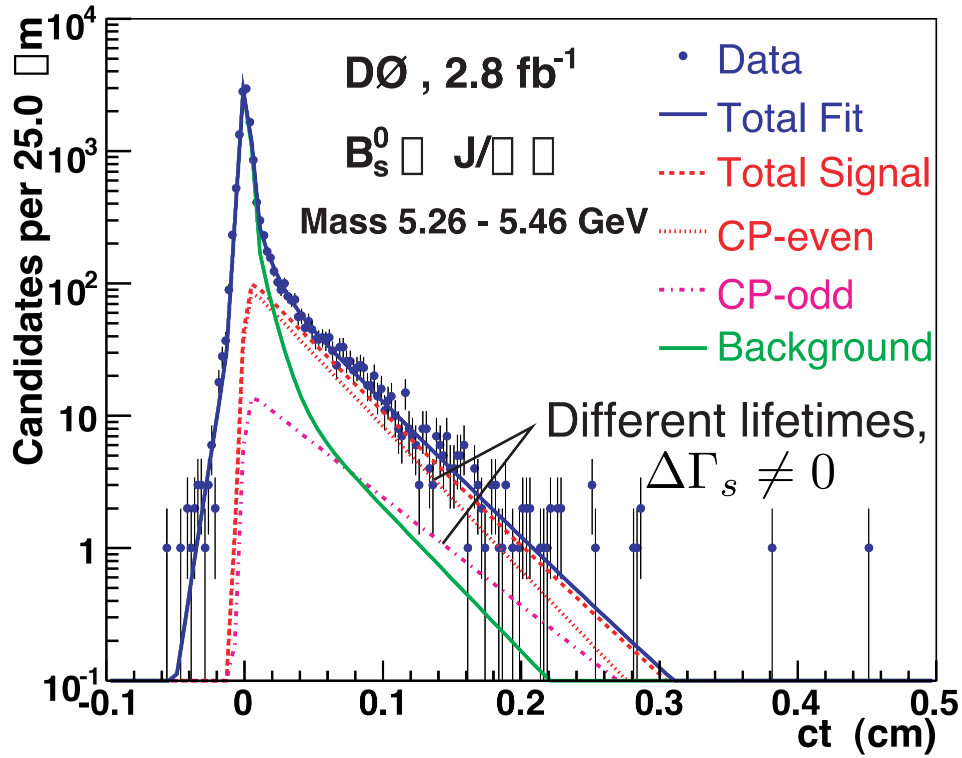
Mass and CP eigenstates the same





CDF/ANAL/BOTTOM/PUBLIC/9458

Phys. Rev. Lett. 101, 241801 (2008)

$$\Delta\Gamma_s = 0.02 \pm 0.05 \pm 0.01\,\mathrm{ps}^{-1}$$
$$\bar{\tau}_s = 1.53 \pm 0.04 \pm 0.01\,\mathrm{ps}$$

$$\Delta\Gamma_s = 0.14 \pm 0.07\,\mathrm{ps}^{-1}$$
$$\bar{\tau}_s = 1.53 \pm 0.05 \pm 0.01\,\mathrm{ps}$$

No flavor tag

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

c.f. $\Delta\Gamma_s^{SM,pred} = 0.088 \pm 0.017\,\mathrm{ps}^{-1}$ (hep-ph/0612167)

$(0.096 \pm 0.039\,\mathrm{ps}^{-1}$ if don't use $\Delta m_s^{\mathrm{meas.}}$)

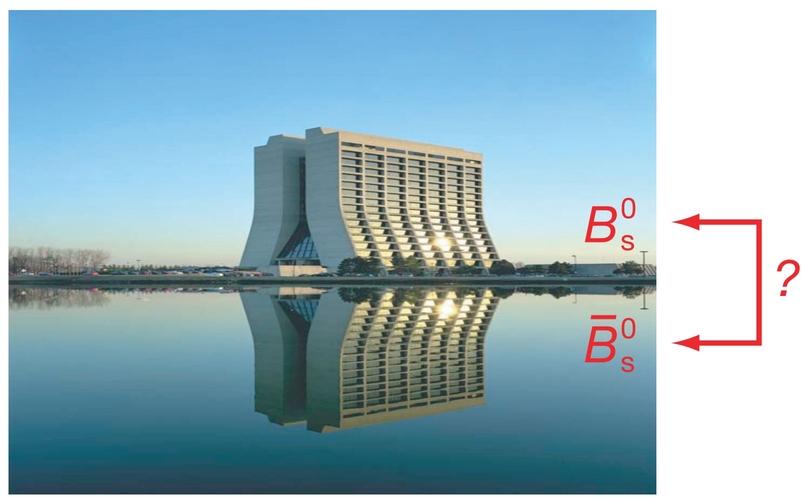
CP Violation

Three kinds:

B_s^0

- In decay: $|\mathcal{A}_f|^2 \neq |\bar{\mathcal{A}}_{\bar{f}}|^2$ (explored previously both CDF & DØ)
- In mixing: $|q/p|^2 \neq 1$ (update by DØ)
- In interference of decay and mixing amplitudes (CDF & DØ)

$$\phi_s \neq 0 \text{ or } \pi$$



CP Violation

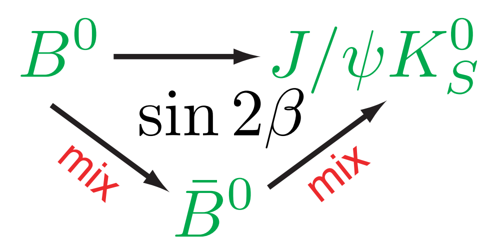
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!! (43 in MSSM)

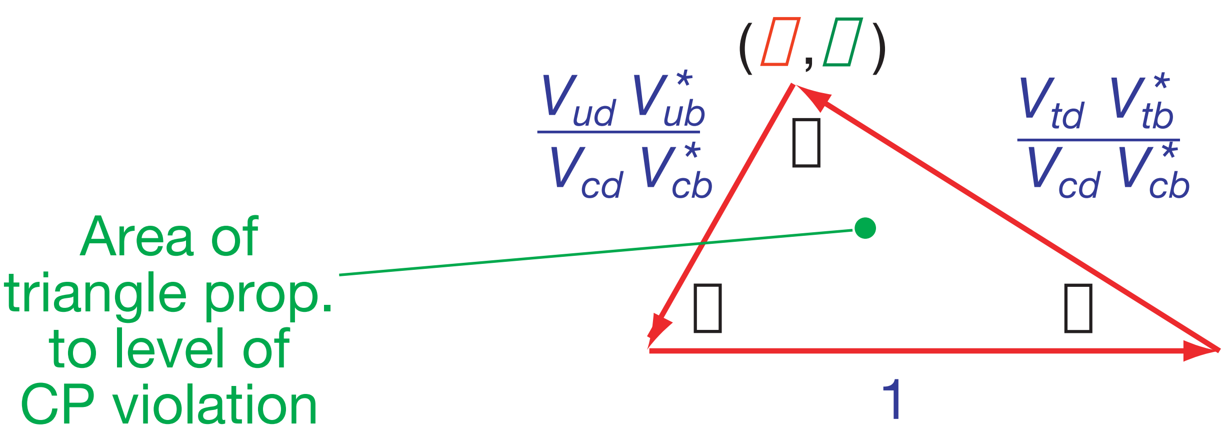
B_d unitarity condition

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

Golden mode, *B* factories



CP violation through interference of diagrams with and w/o mixing



CP Violation in B_s^0 System

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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B_s unitarity condition

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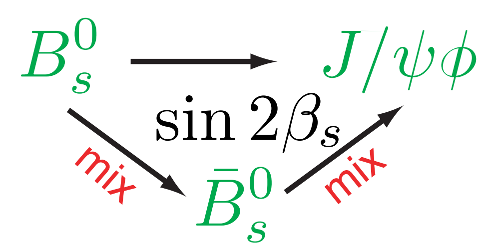
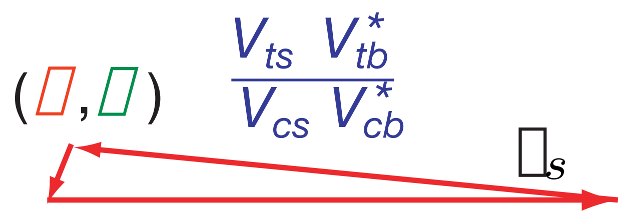
Golden mode, **Tevatron**



CP violation through interference of diagrams with and w/o mixing

"Squashed" Triangle



CP Violation in B_s^0 System

Explore new part of matrix!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

B_s unitarity condition

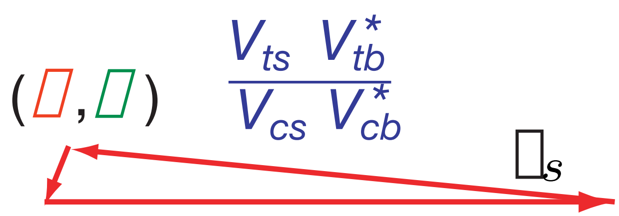
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$\beta_s^{SM} = \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$$

$$\approx 0.02$$

Tiny!

"Squashed" Triangle



CP Violation in B_s^0 System

- How could new physics affect these phases?

$$2\beta_s^{SM} = 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] \rightarrow \underset{\sim 0.04}{2\beta_s^{SM}} - \phi_s^{NP}$$

$$\phi_s^{SM} = \arg[-M_{12}/\Gamma_{12}] \rightarrow \underset{\sim 0.004}{\phi_s^{SM}} + \phi_s^{NP}$$

Subtracts from one, adds to other

- Both DØ and CDF also measure/observe the phase responsible for CP violation in $B_s^0 \rightarrow J/\psi\phi$ decays

In the absence of new physics, measures this

$$\phi_s = -2\beta_s \approx \phi_s^{NP}$$

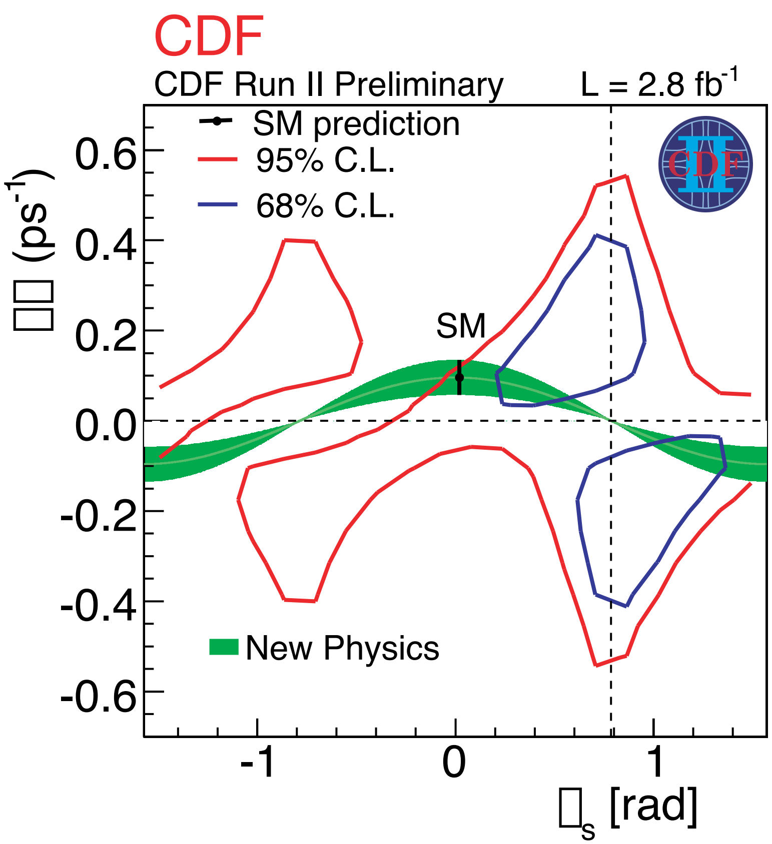
DØ CDF If large

- Use flavor tagging to identify initial flavor, B_s^0 or $\bar{B}_s^0 \rightarrow J/\psi\phi$ (and known value of Δm_s)

Flings the window open wide...

CP Violation in $B_s^0 \to J/\psi\phi$

- Now using initial state flavor tagging



Standard Model Probability = 7%, ~1.8σ

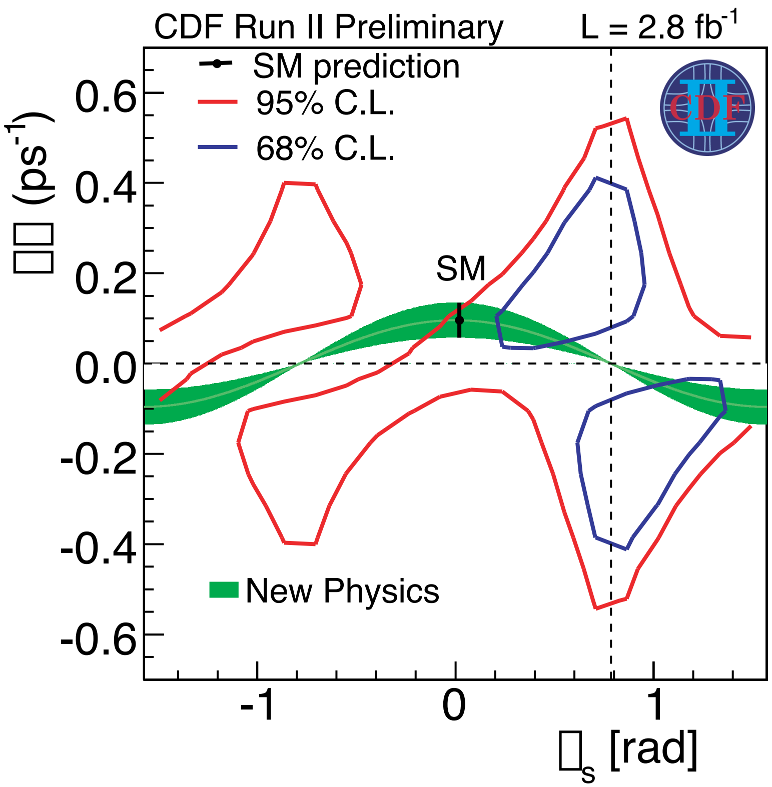
- Ambiguities:

$$2\beta_s^{J/\psi\phi} \to \pi - 2\beta_s^{J/\psi\phi} \quad \Delta\Gamma_s \to -\Delta\Gamma_s \quad \delta_\parallel \to 2\pi - \delta_\parallel \quad \delta_\perp \to \pi - \delta_\perp$$

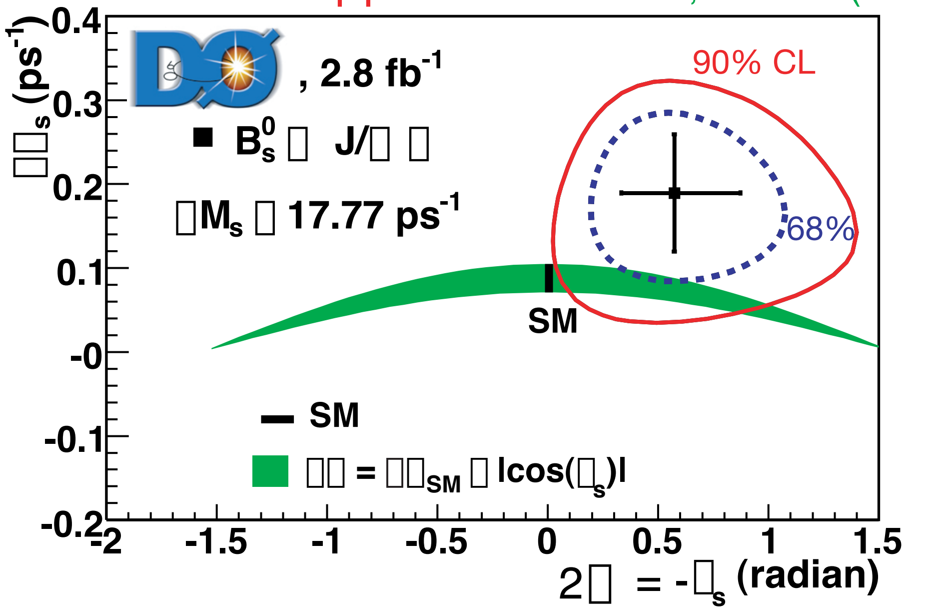
CP Violation in $B_s^0 \to J/\psi\phi$

- Now using initial state flavor tagging

CDF



DØ "Flipped" PRL 101, 241801 (2008)



...add weak constraints on strong phases, δ_i

(angles between polarization amplitudes in $B_s^0 \to J/\psi\phi$ decays)

Constrain based on B_d^0 observations

- Ambiguities:

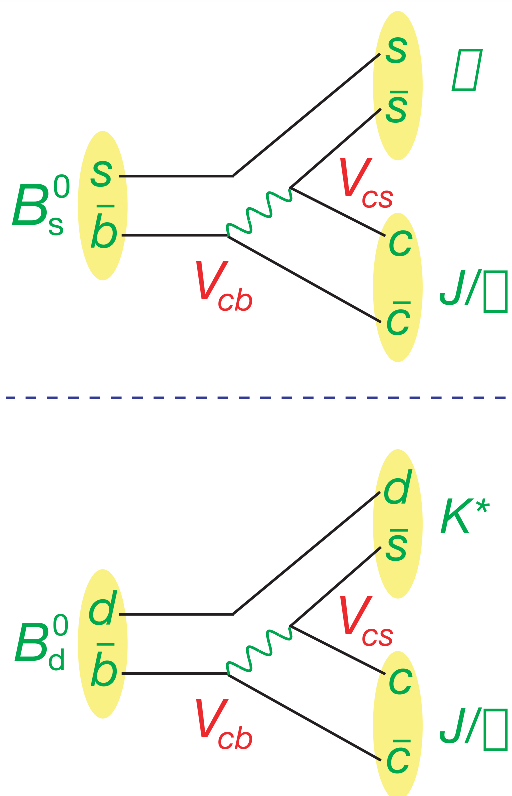
$$2\beta_s^{J/\psi\phi} \to \pi - 2\beta_s^{J/\psi\phi} \quad \Delta\Gamma_s \to -\Delta\Gamma_s \quad \delta_{\parallel} \to 2\pi - \delta_{\parallel} \quad \delta_{\perp} \to \pi - \delta_{\perp}$$

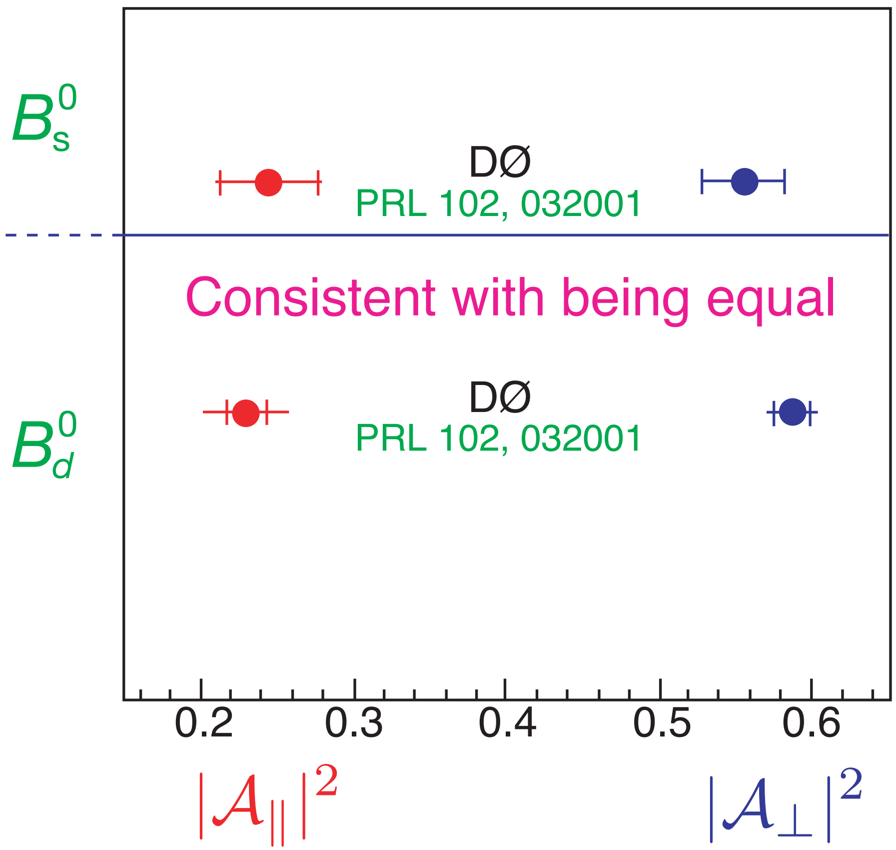
CP Violation in $B_s^0 \to J/\psi\phi$

Justification for DØ constraining δ_i?

Separate, *new* DØ analysis (w/o flavor tag)

- Same phases? (SU(3) symmetry?)

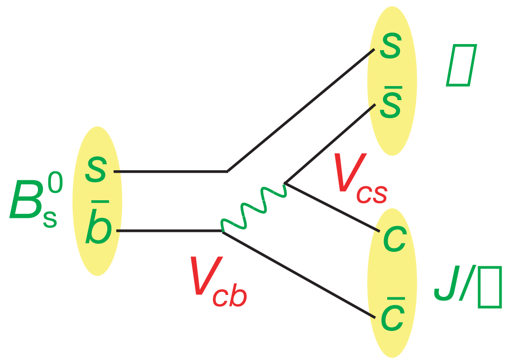


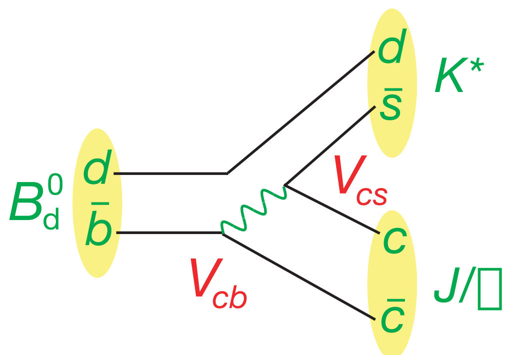


- M. Gronau, J.L. Rosner, Phys. Lett. B669, 321 (2008)

  strong phases $\delta_{\perp}$ and $\delta_{\parallel}$ should be equal within 10 degrees for B_s^0 and B_d^0

CP Violation in $B_s^0 \to J/\psi\phi$





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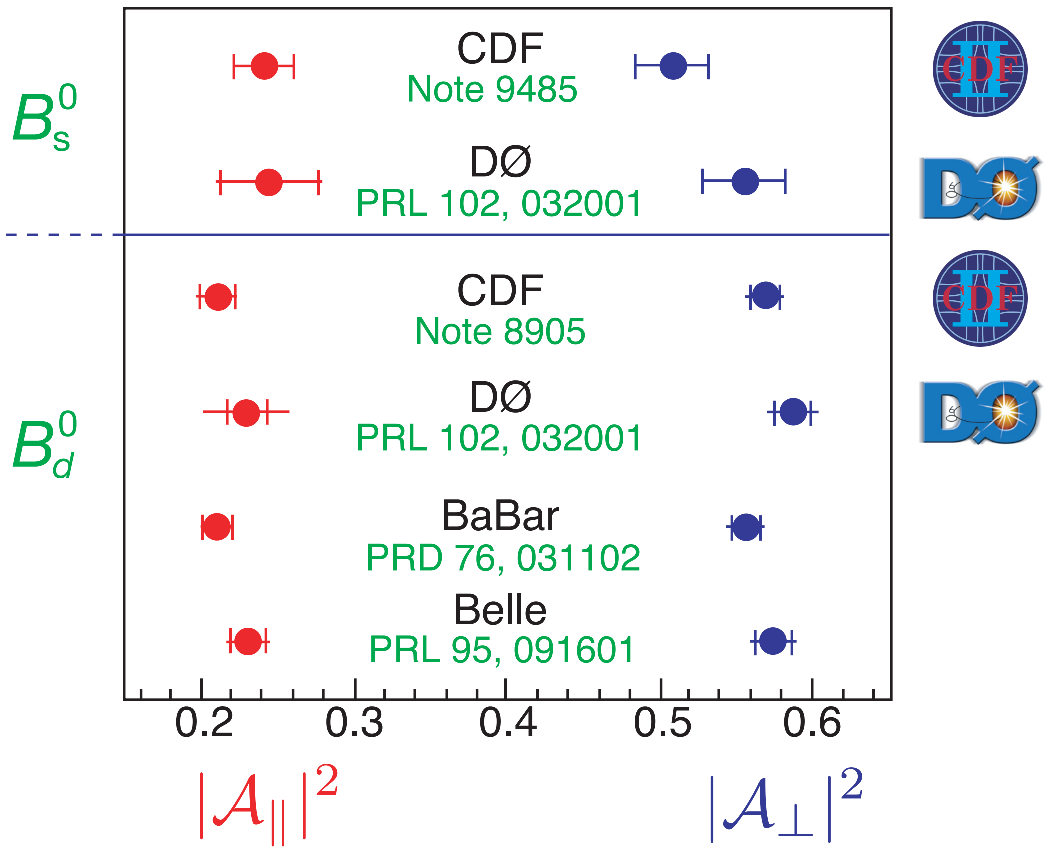
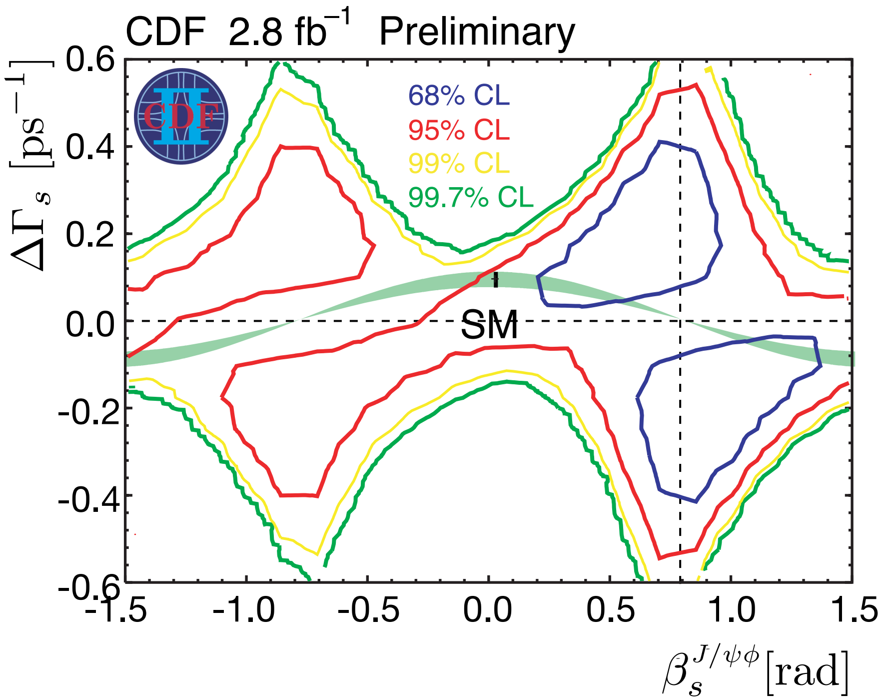
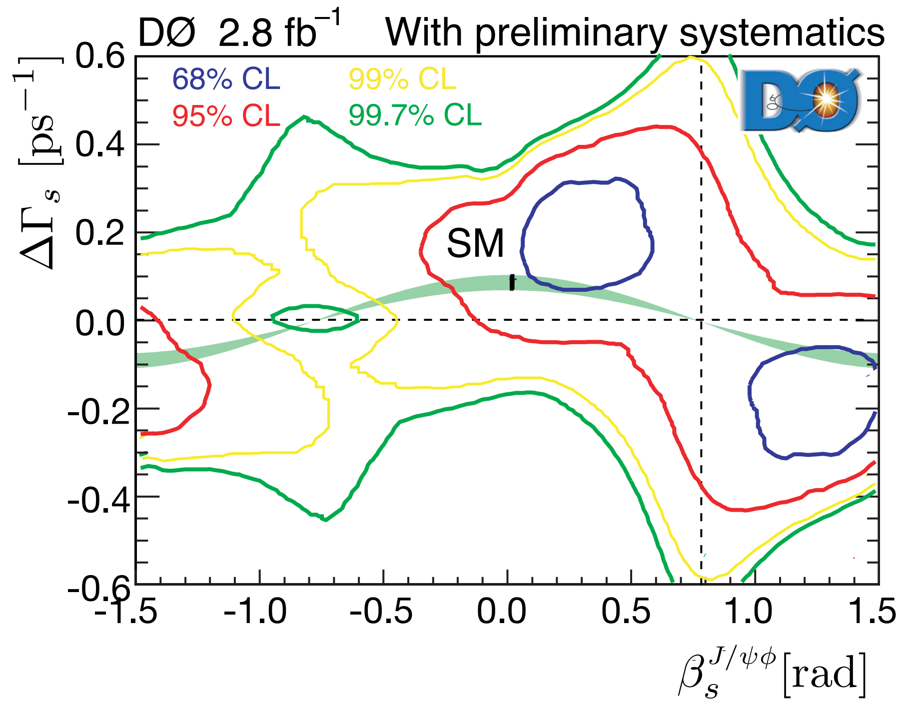


- M. Gronau, J.L. Rosner, Phys.Lett.B669, 321 (2008)

  strong phases $\delta_{\perp}$ and $\delta_{\parallel}$ should be equal within 10 degrees for the two states

- CDF & DØ sharing two-dim. likelihoods, adjust to same statistical coverage, DØ releasing constraints on □$_i$ for comparison/combin.





From publication: PRL 101, 241801 (2008);
DØ Note 5933-CONF

Stay tuned for

- Full combination
- Updates with more data

- DØ releasing weak constraints on strong phases
- Systematic uncertainties in 2-dim. likelihood (pub. had syst. unc. on 1-dim point estimates only)

Search for *CP* Violation in Semileptonic B_s^0 Decay

$$\mathcal{A}_{\rm SL}^s = \frac{N(\bar{B}_s^0(t) \to \ell^+\nu_\ell X) - N(B_s^0(t) \to \ell^-\bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+\nu_\ell X) + N(B_s^0(t) \to \ell^-\bar{\nu}_\ell X)} = \frac{|p/q|_s^2 - |q/p|_s^2}{|p/q|_s^2 + |q/p|_s^2}$$

$$|q/p|^2 \neq 1$$

CP violation in mixing

Experimentally, fit to:

Need flavor tagging

Unmixed

$$\left.\begin{array}{l}\Gamma(B_s^0 \to \mu^+ X) \\ \Gamma(\bar{B}_s^0 \to \mu^- X)\end{array}\right\} \propto \exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)]$$

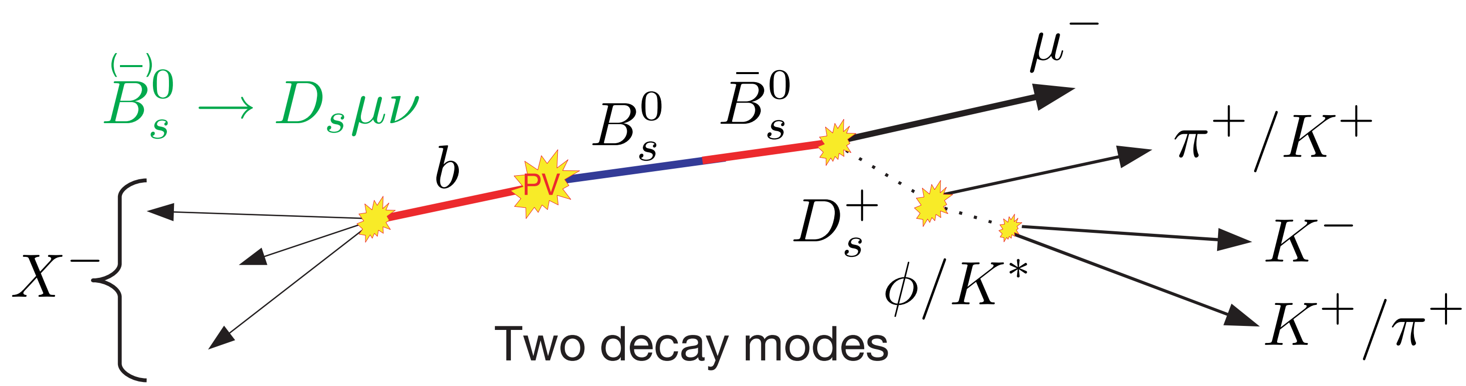
Mixed

$$\Gamma(\bar{B}_s^0 \to \mu^+ X) \propto (1 + \mathcal{A}_{\rm SL}^s)\exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

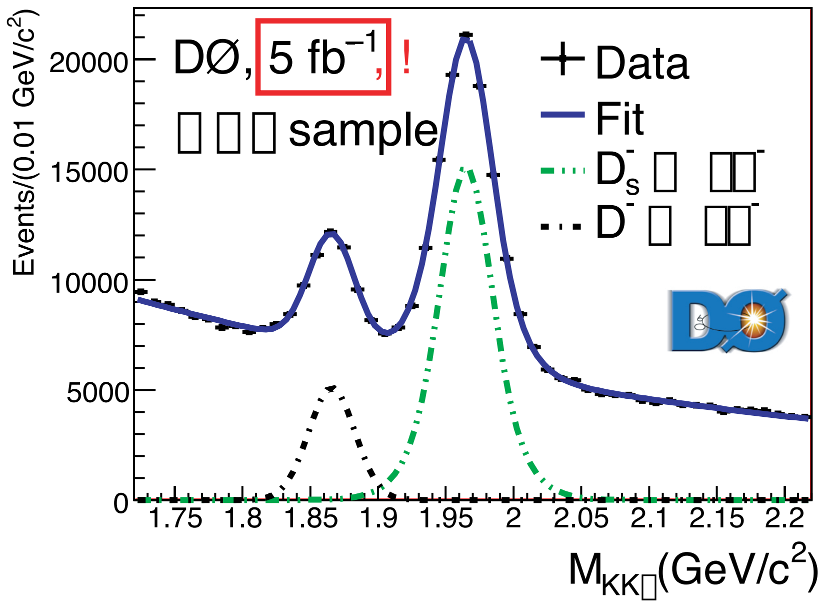
$$\Gamma(B_s^0 \to \mu^- X) \propto (1 - \mathcal{A}_{\rm SL}^s)\exp(-\Gamma_s t)[\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)]$$

$\overset{(-)}{B}{}_s^0 \to D_s \mu \nu$

Flavor tag

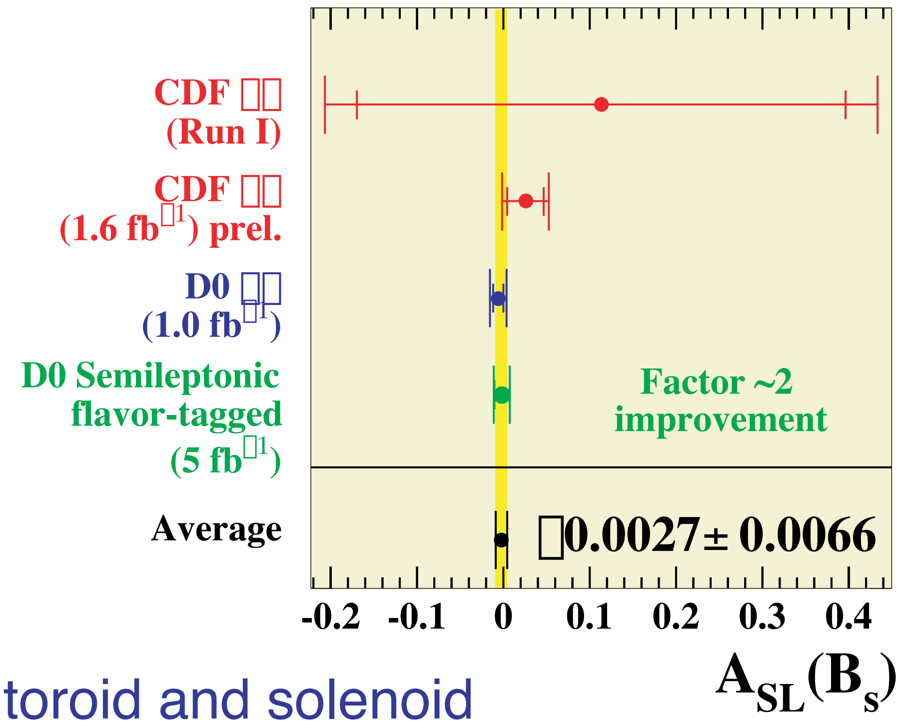


Search for *CP* Violation in Semileptonic B_s^0 Decay

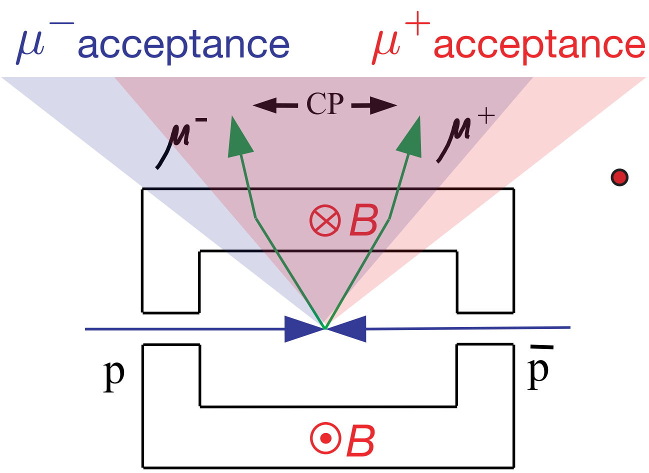


arXiv:0904.3907, sub. to PRL

$$\mathcal{A}_{\rm SL}^{s} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}$$



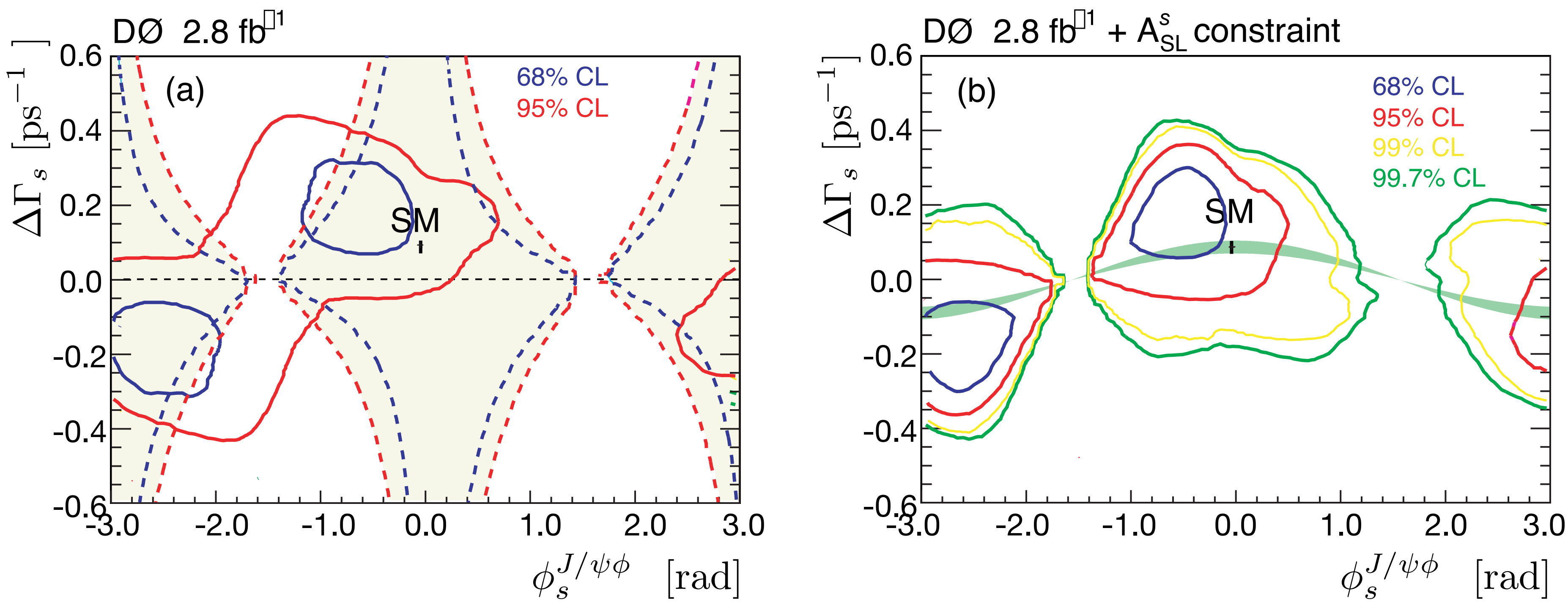
- ~115k total $\overset{(-)}{B}{}_s^0 \to D_s \mu\nu$ decays



- DØ toroid and solenoid polarities flipped regularly; control & measure detector asymmetries
(and then correct, some as large as 3%)

Search for *CP* Violation in Semileptonic B_s^0 Decay

$$\mathcal{A}_{\rm SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$



DØ Note 5933-CONF

- Green band is region allowed in new physics models given by

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

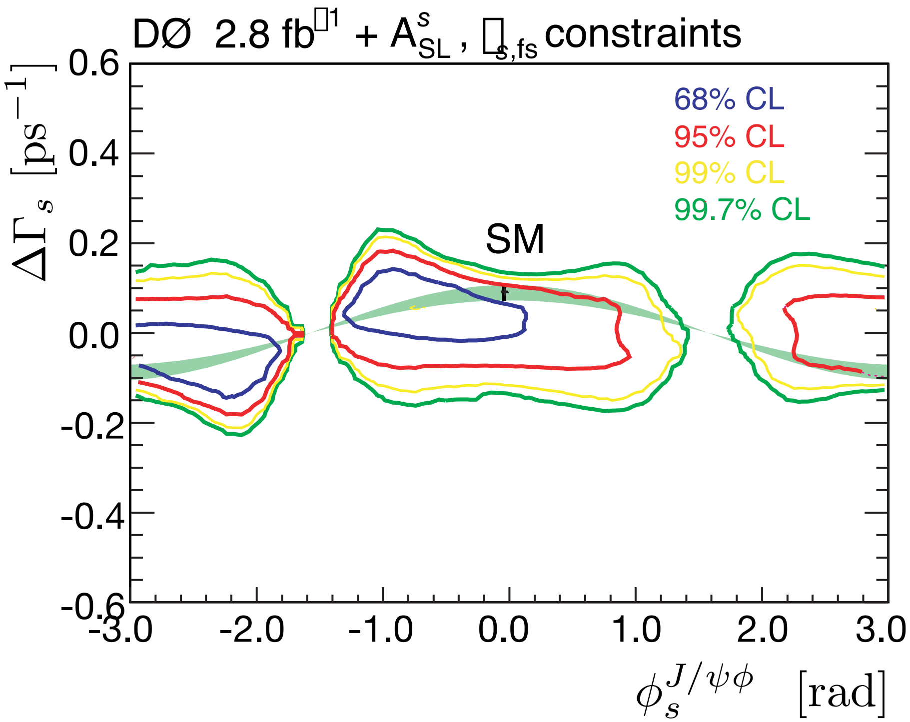
Search for *CP* Violation in B_s^0 System

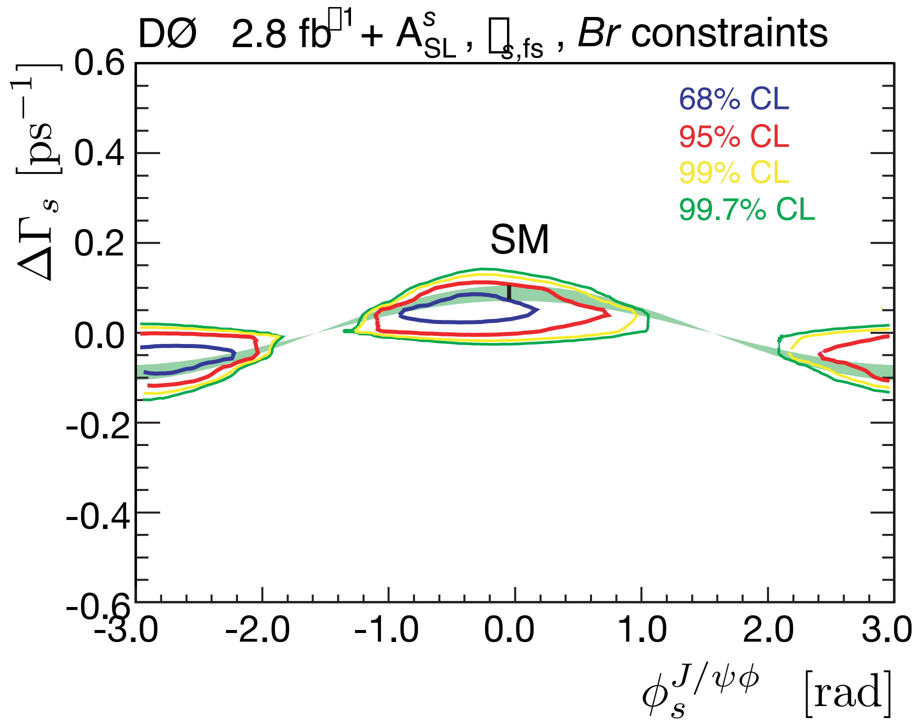
DØ Note 5933-CONF

$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s}\frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

DØ: Phys. Rev. Lett. 102, 091801 (2009)
(shown as special talk S.Youn last Users' Mtg.)

$$\mathcal{B}(B_s^0 \to D_s^{(*)+}D_s^{(*)-}) = 0.035 \pm 0.015$$

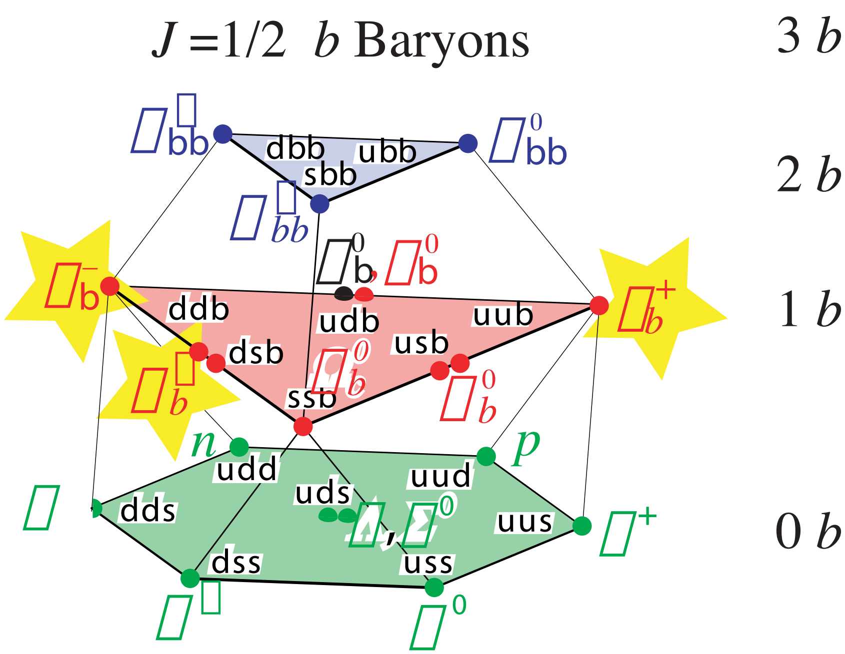


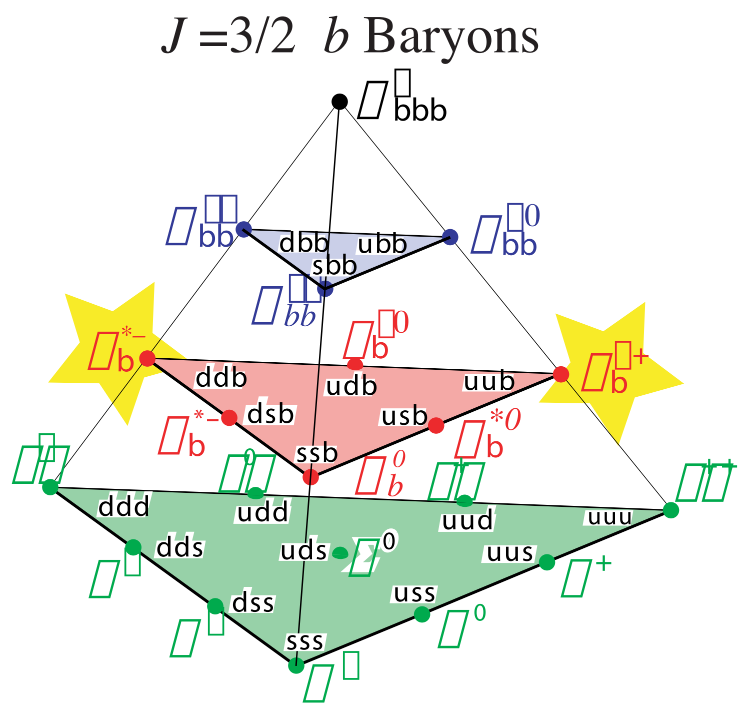


- World average value of B_s^0 flavor-specific lifetime of 1.456 ± 0.030 ps (HFAG) (50% CP-even, 50% CP-odd @ *t*=0)
- *p*-value of SM point = 10%
- Again, goal to combine w/ CDF

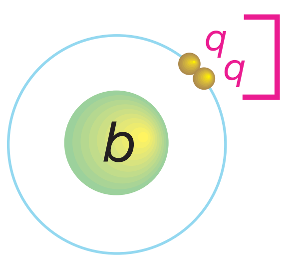
New *b*-Flavored Baryons

- Until 2006, ground state Λ_b was the only directly observed *b* baryon
- More statistics, can look for more states





L=0 "atomic" system,
heavy quark and light *diquark*



spin-0: Λ_b
spin-1: Σ_b

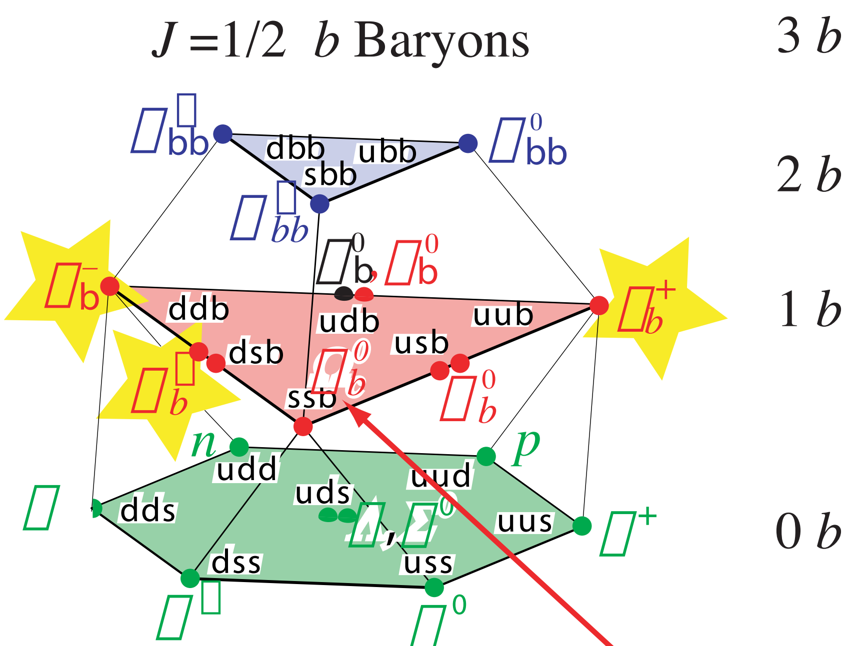
$\Lambda_b^0 = |bud\rangle$ DØ, CDF

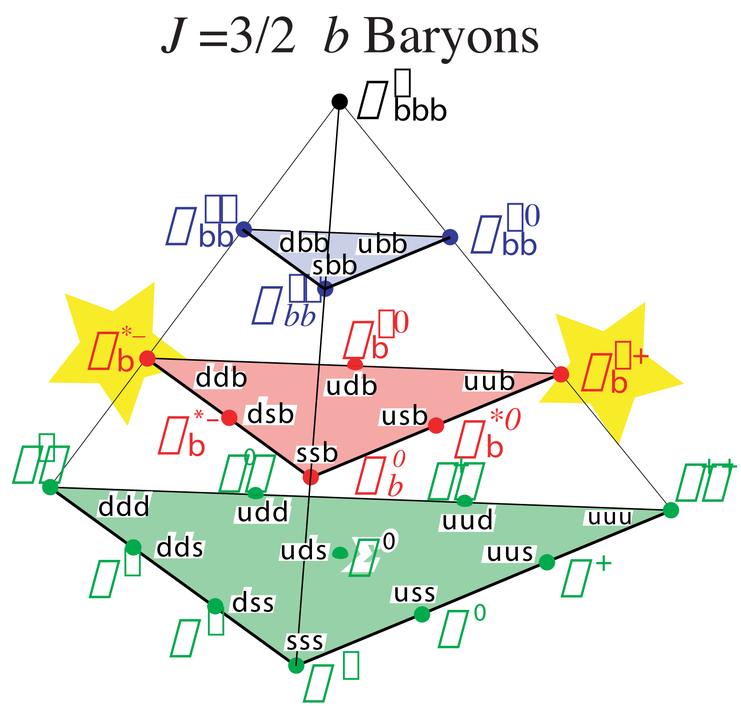
$\Sigma_b^- = |bqq\rangle, q = u, d$ CDF

$\Xi_b^- = |bds\rangle$ DØ, CDF

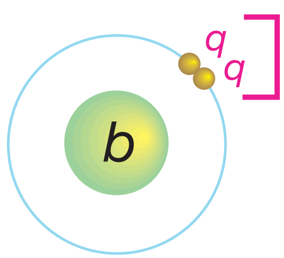
New *b*-Flavored Baryons

- Until 2006, ground state Λ_b was the only directly observed *b* baryon
- More statistics, can look for more states





L=0 "atomic" system,
heavy quark and light *diquark*



spin-0: Λ_b
spin-1: Σ_b

$$\Omega_b^- = |bss\rangle$$

$$\Lambda_b^0 = |bud\rangle$$

$$\Sigma_b^- = |bqq\rangle, q = u, d$$

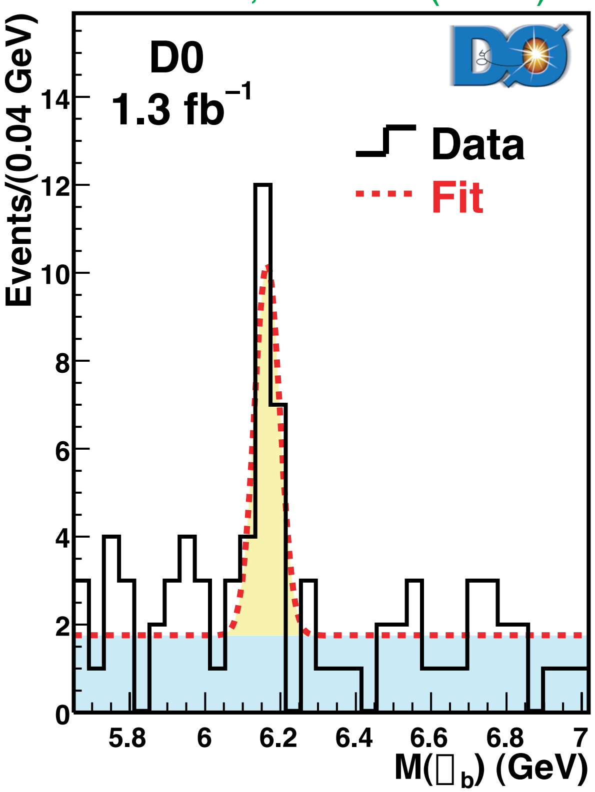
$$\Xi_b^- = |bds\rangle$$

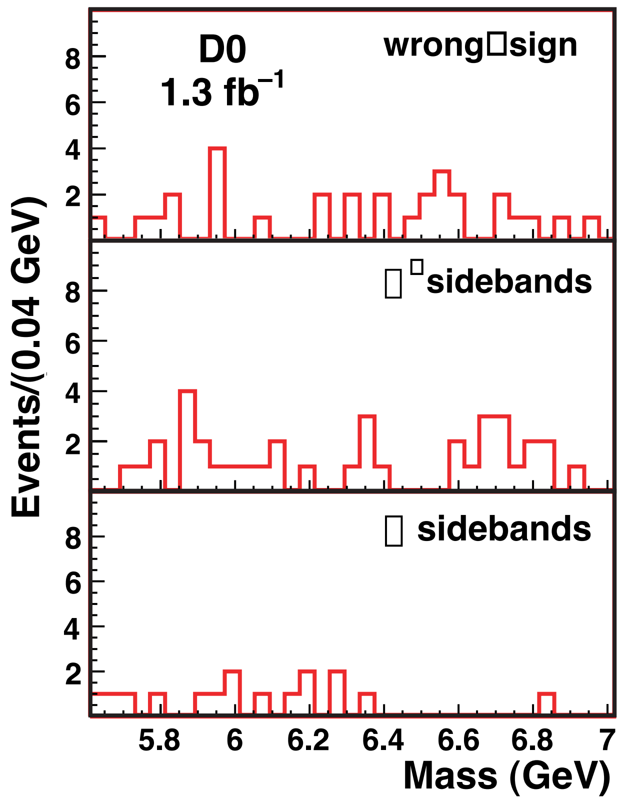
Ω_b Baryon

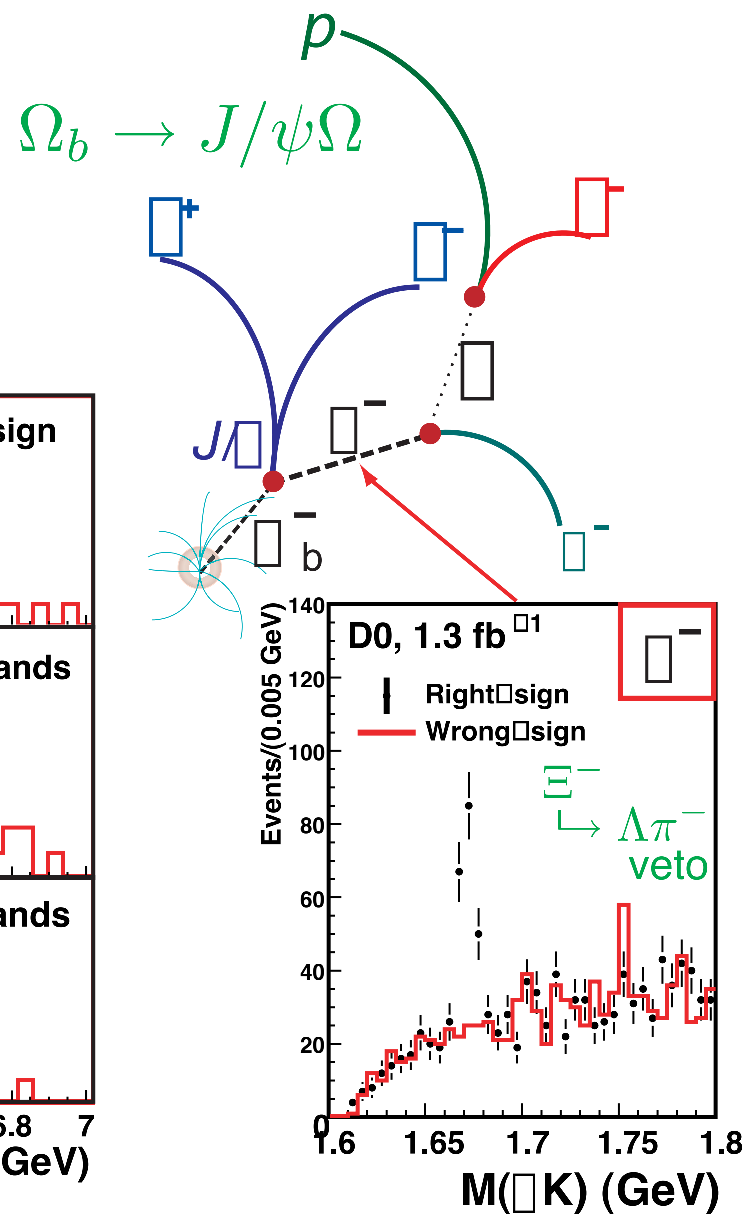
...doubly strange $|bss\rangle$

- Summer 2008, DØ analysis, 1.3 fb^{-1} building on previous Ξ_b^- observation

PRL **101**, 232002 (2008)

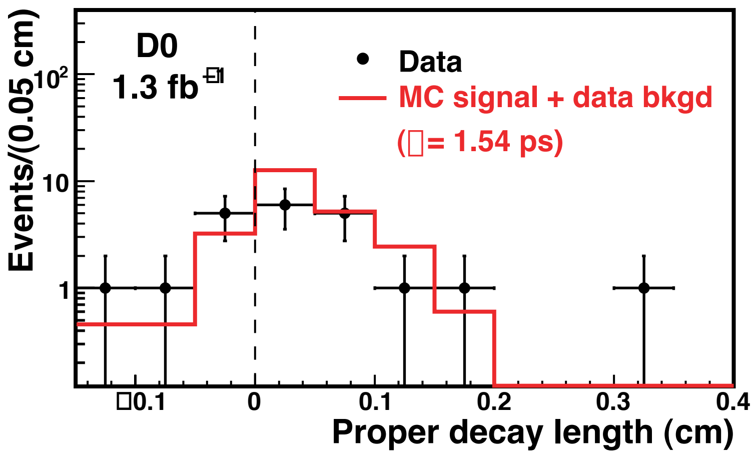






- Yield 17.8 ± 4.9 ± 0.8 candidates
- Likelihood ratio, stat. significance = 5.4σ
  Remains > 5σ with syst. checks
- After special track reprocessing, large impact parameter tracks

Ω_b Baryon



- Decay lengths consistent with weakly decaying *b* state
- Rate with respect to Ξ_b^- also measured (later comparison)

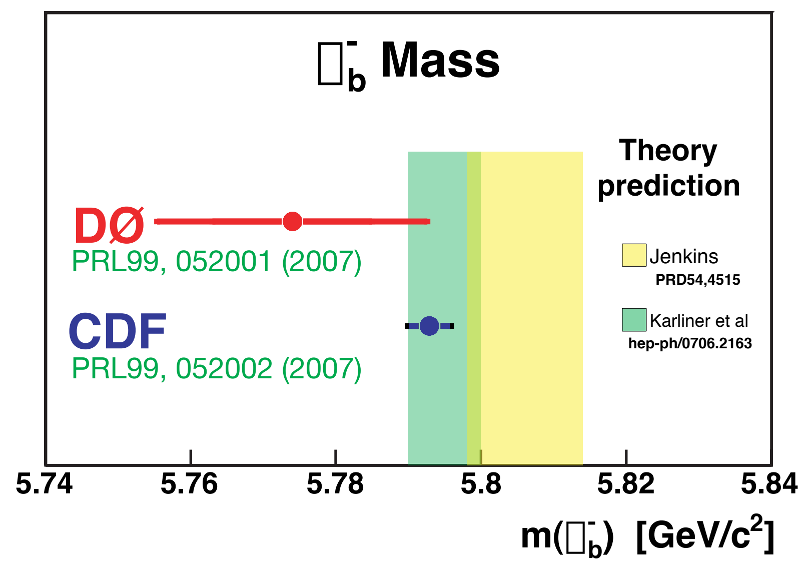
PRL **101**, 232002 (2008)

$$M(\Omega_b) = 6165 \pm 10 \pm 13\,\mathrm{MeV}$$

(expect 5.94 – 6.12 GeV back then)

Greater than expected values, careful checks:

- Mass measurements in MC samples
- Variation of selection criteria
- Comparison of data fitted masses of Λ_b^0 and Ξ_b^- consistent w/ PDG

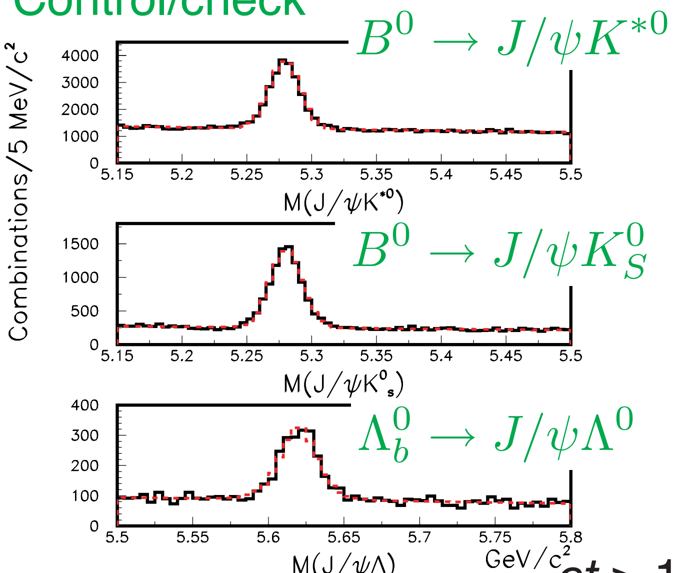


Ω_b Baryon (plus Ω_b and Ξ_b^- Properties)

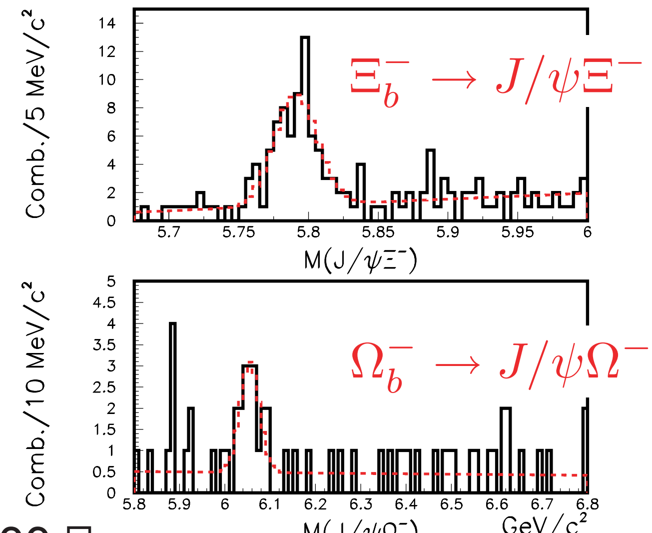
arXiv:0905.3123, submitted to PRD

- New result from CDF, 4.2 fb^{-1}, comprehensive reconstruction of *b* hadrons into J/ψ

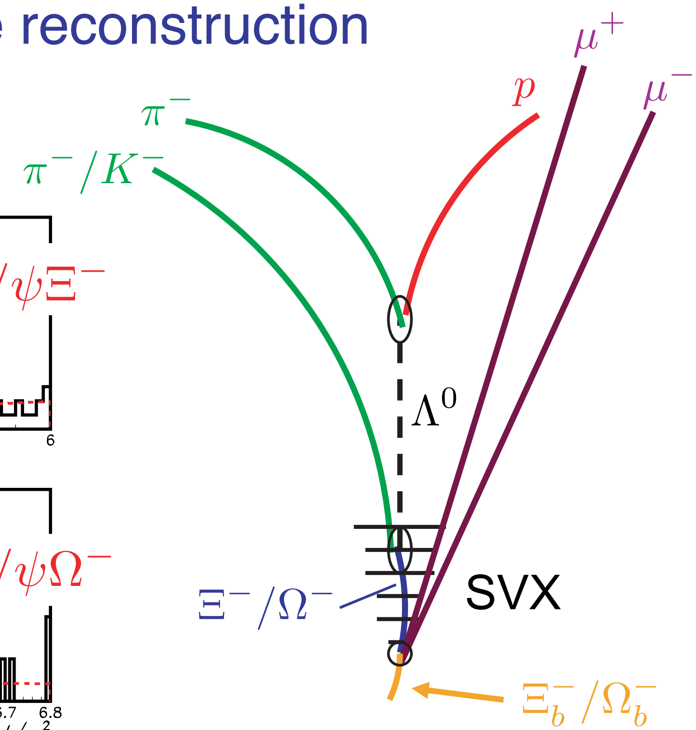
Control/check



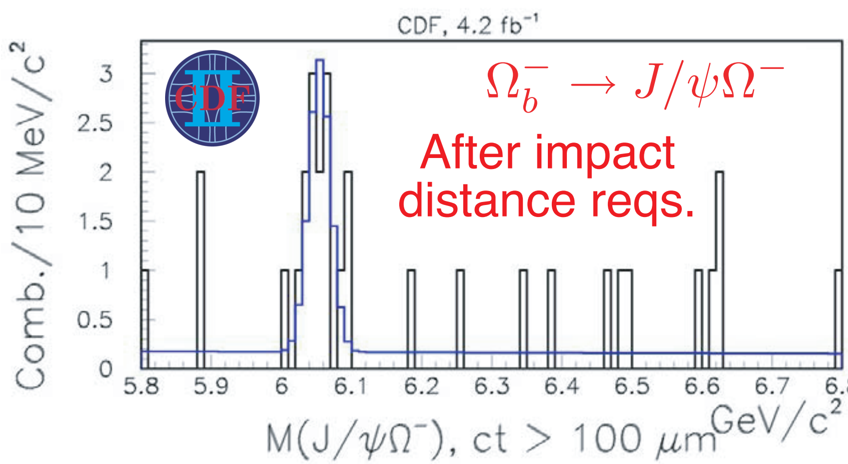
Measure



$ct > 100$ μm



- Yield: 16^{+6}_{-4} evts.
- Significance: 5.5σ (mass and lifetime info, likelihood ratio and toy MC's)

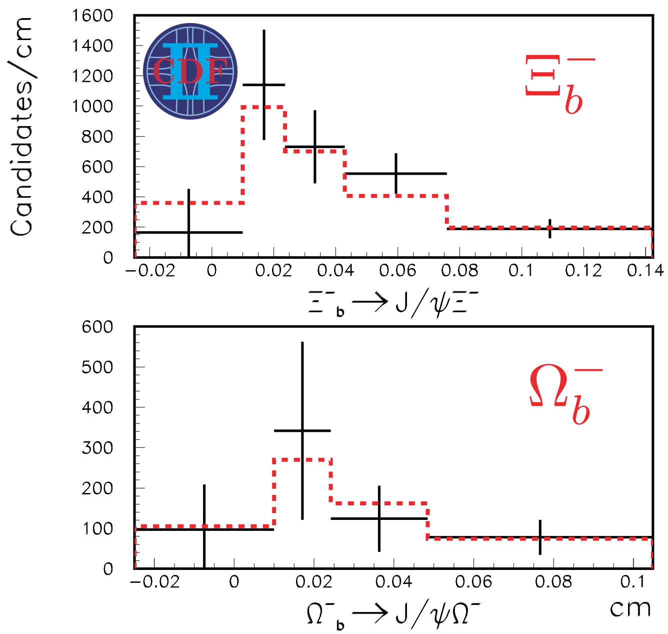


- Long decay lengths (cm) of charged Ξ^-/Ω^- ⟶ can use silicon tracking to improve impact parameter resolution (acceptance low for Ω^-)

Ω_b Baryon (plus Ω_b and Ξ_b^- Properties)

arXiv:0905.3123, submitted to PRD

- Masses from fit to sample with $c\tau > 100\ \mu m$
- Lifetime from yield in bins of $c\tau$ (no need to model background)



$$m(\Xi_b^-) = 5790.9 \pm 2.6 \pm 0.9\,\mathrm{MeV}$$
$$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \pm 0.02\,\mathrm{ps}$$

└ First exclusive Ξ_b^- lifetime!

$$m(\Omega_b^-) = 6054.4 \pm 6.8 \pm 0.9\,\mathrm{MeV}$$
$$\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.02\,\mathrm{ps}$$

└ First ever!

- Relative rates $6 < p_T(b\,\mathrm{bbaryon}) < 20\,\mathrm{GeV}$

$$\frac{\sigma(\Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^- \to J/\psi\Xi^-)} = 0.167^{+0.037}_{-0.025} \pm 0.012\ ;\ \frac{\sigma(\Omega_b^-)\mathcal{B}(\Omega-_b \to J/\psi\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^- \to J/\psi\Xi^-)} = 0.045^{+0.017}_{-0.012} \pm 0.004$$

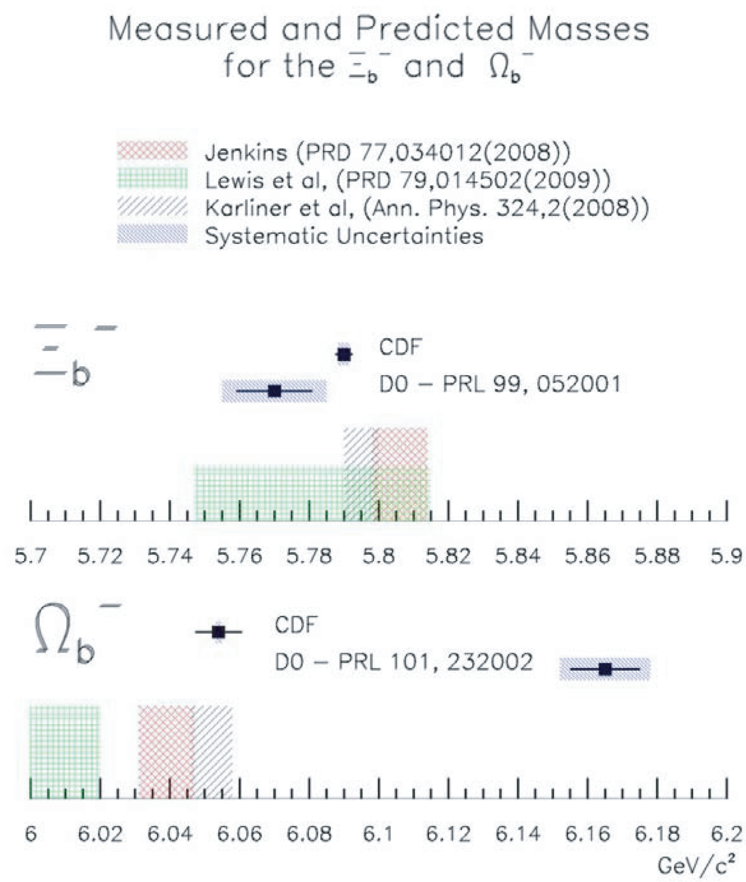
Ω_b Baryon : Comparison

Difference of measured masses:

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

Significant (~6σ) disagreement!

- DØ's largest mass systematic unc. is 10 times less than this difference
- DØ is working on an update of this measurement with an increased data set that may help address discrepancy.



Relative rates:

DØ:
$$\frac{f(b \to \Omega_b^-) \cdot \mathcal{B}(\Omega_b^- \to J/\psi\Omega^-)}{f(b \to \Xi_b^-) \cdot \mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}$$

CDF:
$$\frac{\sigma \cdot \mathcal{B}(\Omega_b^- \to J/\psi\Omega^-)}{\sigma \cdot \mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

1.3σ difference (assuming Gaussian unc.)

"Alphabet Soup" *...of charmonium-like states*

- $X(3872) \to J/\psi\pi^+\pi^-$ 2003, confirmed by CDF & DØ

  $J^{PC} = 1^{++} \text{ or } 2^{-+}$

(***New*** prelim. CDF measurement of X(3872) mass, best in world: 3871.61 ± 0.16 ± 0.19 MeV)

***B* Factories:**

- $Y(3940) \to J/\psi\omega$ 2005 $J^{PC} = 1^{--}$

  $Y(4260) \to J/\psi\pi^+\pi^-$

  $\vdots$

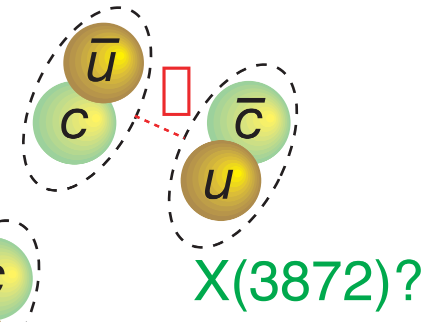
- $Z(4330)^{+} \to \psi(2S)\pi^+$! 2008 $J^{PC} = 2^{++}$

- Why weird? Above $D\bar{D}$ and $D\bar{D}^*$ thresholds: should decay to open charm and have tiny *Br's* to the above modes

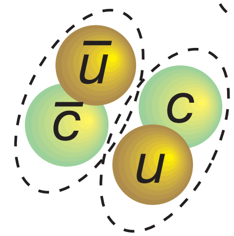
Exotic Mesons

...of charmonium-like states

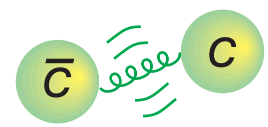
- Molecular states: loosely bound pair of charm states



- Tetraquarks: tightly bound diquark-antidiquark



- Charmonium hybrid states: excited gluonic degrees of freedom

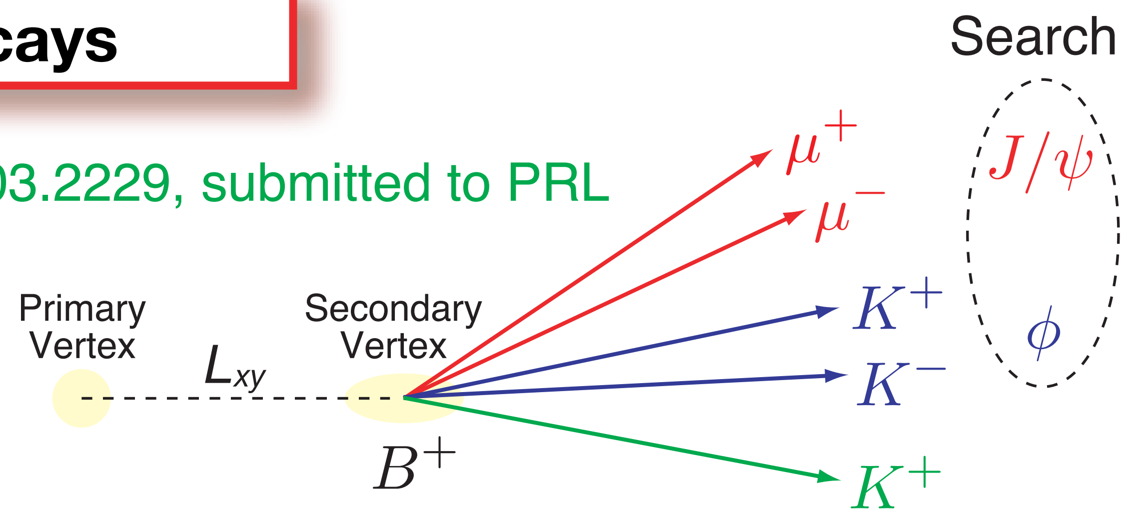


- $c\bar{c}$ tightly bound inside light hadronic matter
- Threshold effects?

Exotica in *B* Decays

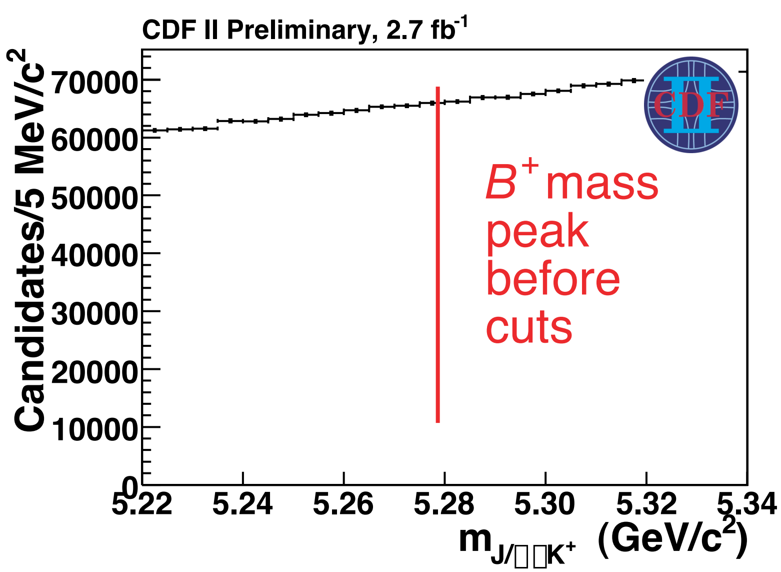
CDF in 2.7 fb^{-1}, arXiv:0903.2229, submitted to PRL

$$B^+ \rightarrow J/\psi \phi K^+$$
$$\phi \rightarrow K^+K^-, \quad J/\psi \rightarrow \mu^+\mu^-$$



Search for structure in $J/\psi\phi$ mass spectrum inside B^+ mass window

(...since $Y(3940) \rightarrow J/\psi\omega$ ...)

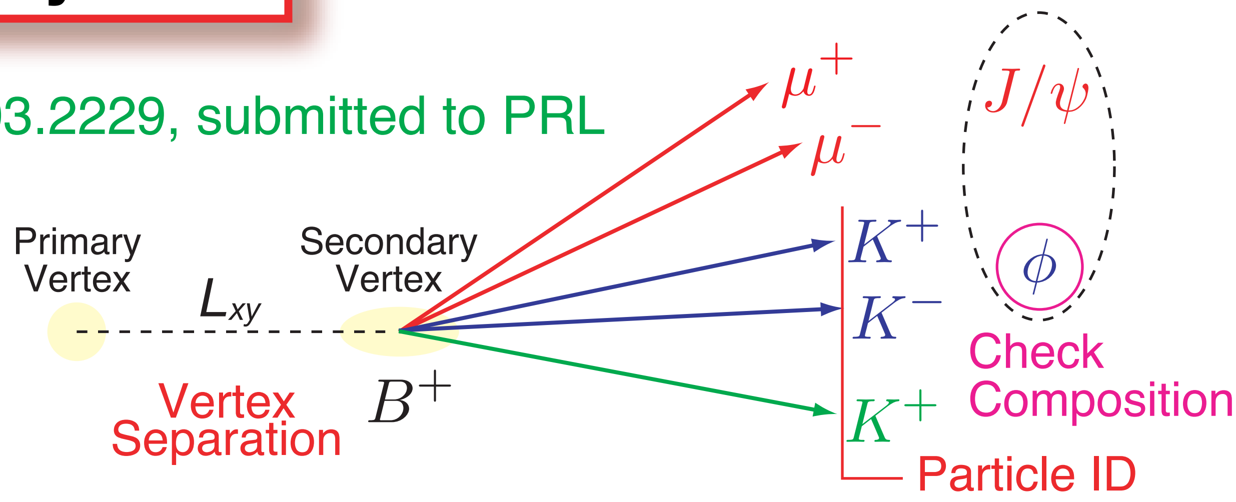


Exotica in *B* Decays

CDF in 2.7 fb^{-1}, arXiv:0903.2229, submitted to PRL

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

with $\phi \to K^+K^-$ and $J/\psi \to \mu^+\mu^-$



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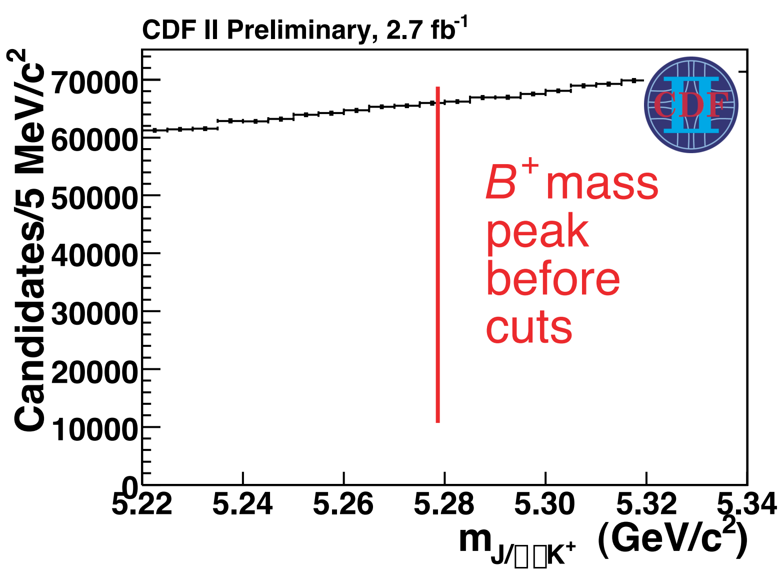
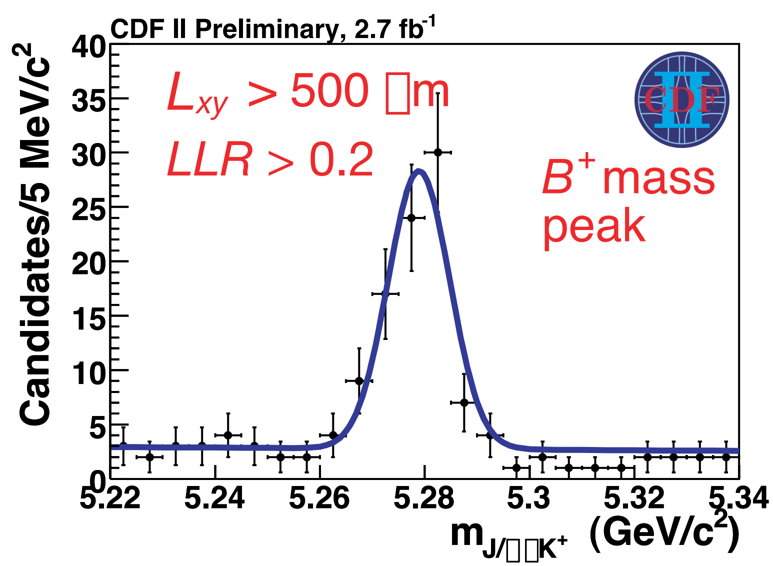
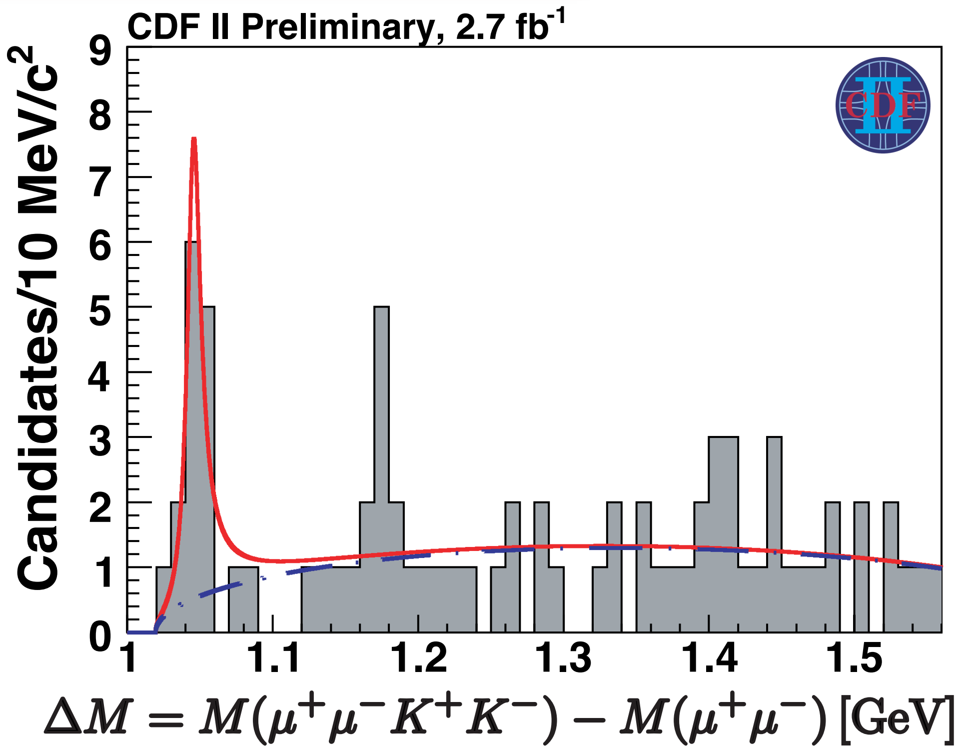




B decays provide a "clean laboratory"

Exotica in *B* Decays



$B_s^0 \to \psi(2S)\phi \to (J/\psi\pi^+\pi^-)\phi$

- Significance (toy MC):
  - 5.3σ, simple
  - 4.3σ, absence of prior mass and width prediction
  - 3.8σ, conservative background

arXiv:0903.2229, submitted to PRL

$Y(4140)$

$$\text{Yield} = 14 \pm 5$$

$$\Delta m = 1046.3 \pm 2.9 \pm 1.2\,\text{MeV}$$

$$m = 4143.0 \pm 2.9 \pm 1.2\,\text{MeV}$$

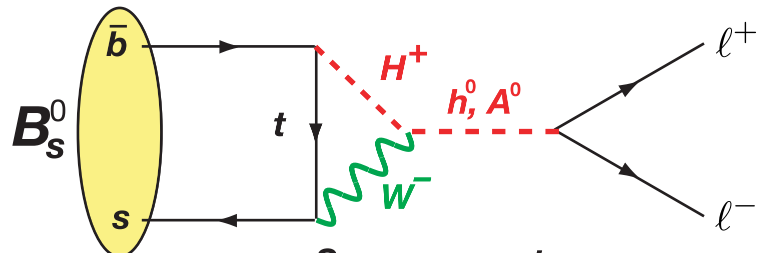
$$\text{Width} = 11.7^{+8.3}_{-5.0} \pm 3.7\,\text{MeV}$$

(strong decay)

- *Should* also decay to open charm
- Molecular state?

arXiv:0903.2529 [hep-ph]

Rare Decays



Supersymmetry

- The usual: $B_s^0, B_d^0 \to \mu^+\mu^-$

  Helicity suppressed in SM

  DØ, improved analysis, in 5 fb :

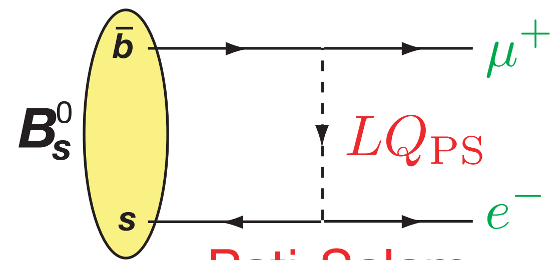
  DØ Note 5906-CONF

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\text{expect.}} < 4.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

  Further: adding single muon trigger

- Helicity suppression *and* lepton-flavor violating

$$B_s^0, B_d^0 \to \mu^+ e^-, e^+ e^-$$



Pati-Salam leptoquarks, spin-1

CDF in 2 fb^{-1}: (prel., CDF Note 9413)

$$\mathcal{B}(B_s^0 \to e\mu) < 2.0 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

$$M(LQ) > 47.4 \,\text{TeV}$$

$$\mathcal{B}(B_d^0 \to e\mu) < 6.4 \times 10^{-8}$$

$$M(LQ) > 58.6 \,\text{TeV}$$

Regrets...

- Λ_b lifetime in $\Lambda_b \to \Lambda_c \pi$ decays
- $\sigma(B_c) \cdot \mathcal{B}(B_c \to J/\psi \mu \nu)$
- Search for narrow resonances below Υ mesons
- B^+ lifetime in $B^+ \to D^0 \pi^+$
- Update B_s^0 lifetime in $B_s^0 \to D_s \pi$ decays
- $\mathcal{B}(B_s^0 \to D_s^{(*)} D_s^{(*)})$ and a measurement of $\Delta\Gamma^{CP}/\Gamma_s$
- Mass in $B_c \to J/\psi \pi$ (finalized)
- B_c lifetime (finalized)
- $\Upsilon(1S), \Upsilon(2S)$ polarization
- Search for FCNC D meson decays
- Relative rate of $B \to \psi(2S), J/\psi$
- Search for excess dimuons in $1.6 < r < 10$ cm

CDF: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html

DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm

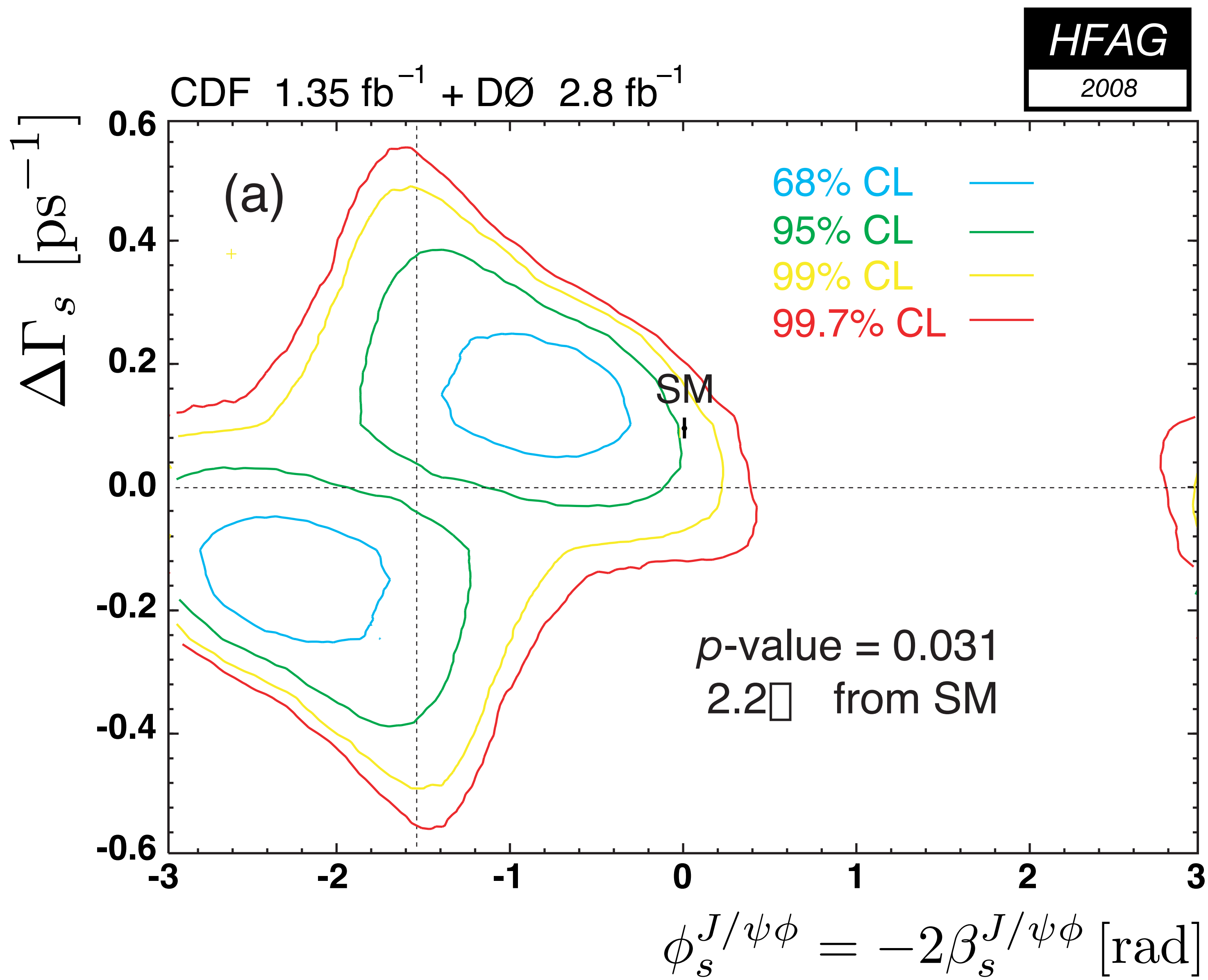
Conclusions & Prospects

- Diverse physics program at the Tevatron resulting in continued large gains in understanding of *B* physics
- Complementary to and competitive with the *B* factories
- B_s^0 system and CP studies opening a powerful new window: possibly already providing hints of new phenomena?

- Renaissance of spectroscopy (and properties) as new heavy states continue to flood in
- Continue to push on rare decays

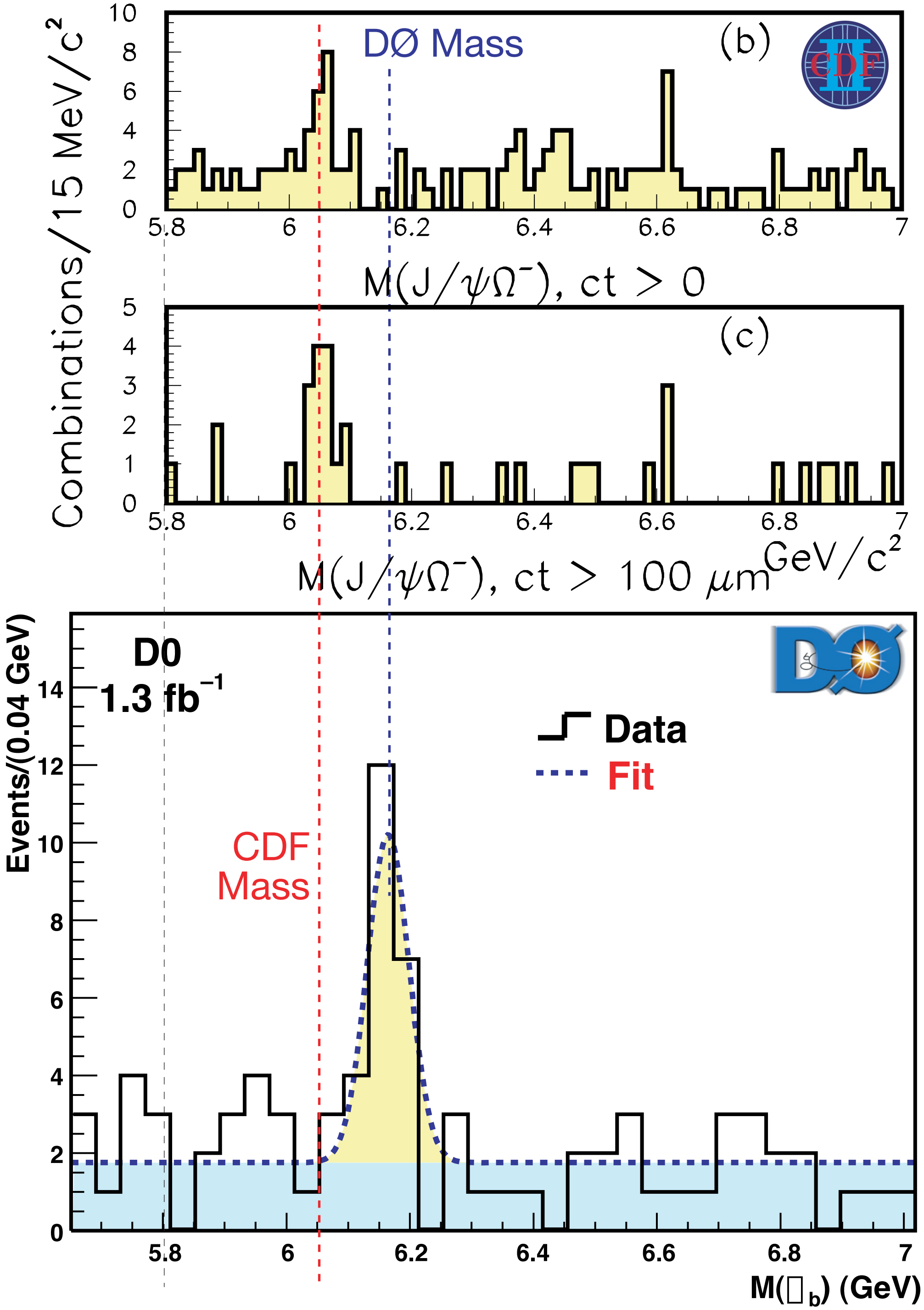
- Tevatron doing very well, expect to come close to *doubling* our analyzed data-set by the end of running; ***still statistics limited on most analyses!***

Backup Slides

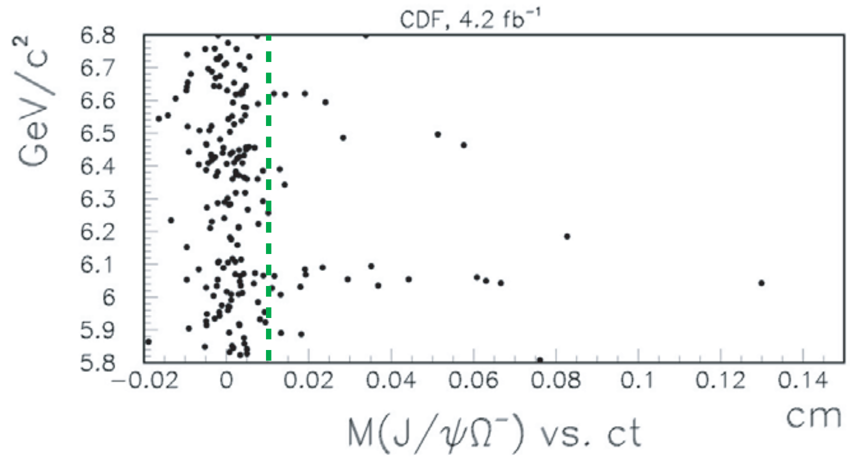


HFAG
2008
CDF 1.35 fb^{-1} + DØ 2.8 fb^{-1}
(a)
68% CL
95% CL
99% CL
99.7% CL
SM
p-value = 0.031
2.2σ from SM
$\Delta\Gamma_s$ [ps^{-1}]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-3
-2
-1
0
1
2
3
$\phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi}$ [rad]

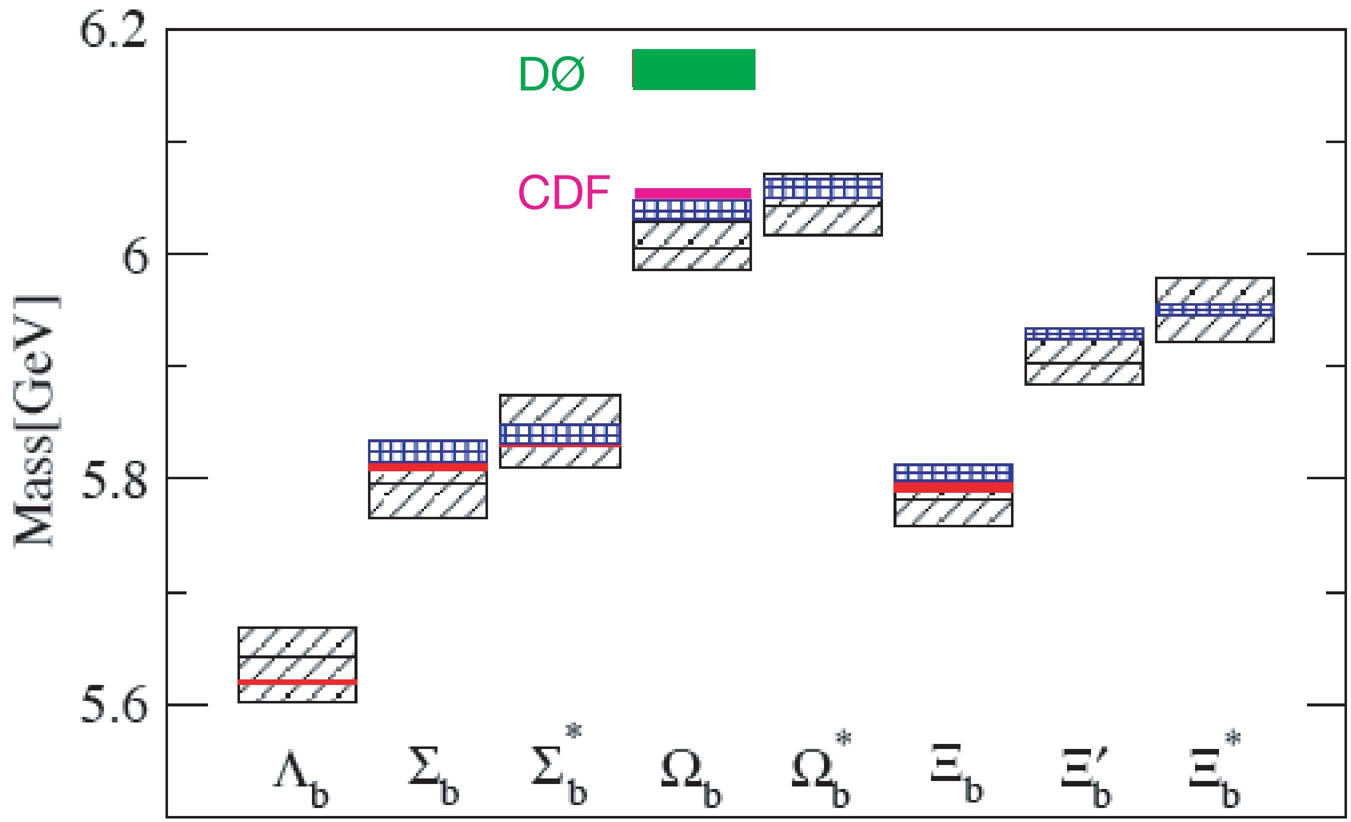
$$2\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \simeq \frac{\Delta\Gamma_s}{\Gamma_s \cos\phi_s} \left[\frac{1}{1-2x_f} - \frac{\Delta\Gamma_s \cos\phi_s}{2\Gamma_s} \right]$$



DØ Mass
(b)
CDF
M(J/ψΩ⁻), ct > 0
(c)
M(J/ψΩ⁻), ct > 100 μm
GeV/c²
Combinations/15 MeV/c²
D0
1.3 fb⁻¹
Data
Fit
CDF
Mass
Events/(0.04 GeV)
M(□b) (GeV)



CDF, 4.2 fb⁻¹
GeV/c²
cm
M(J/ψΩ⁻) vs. ct

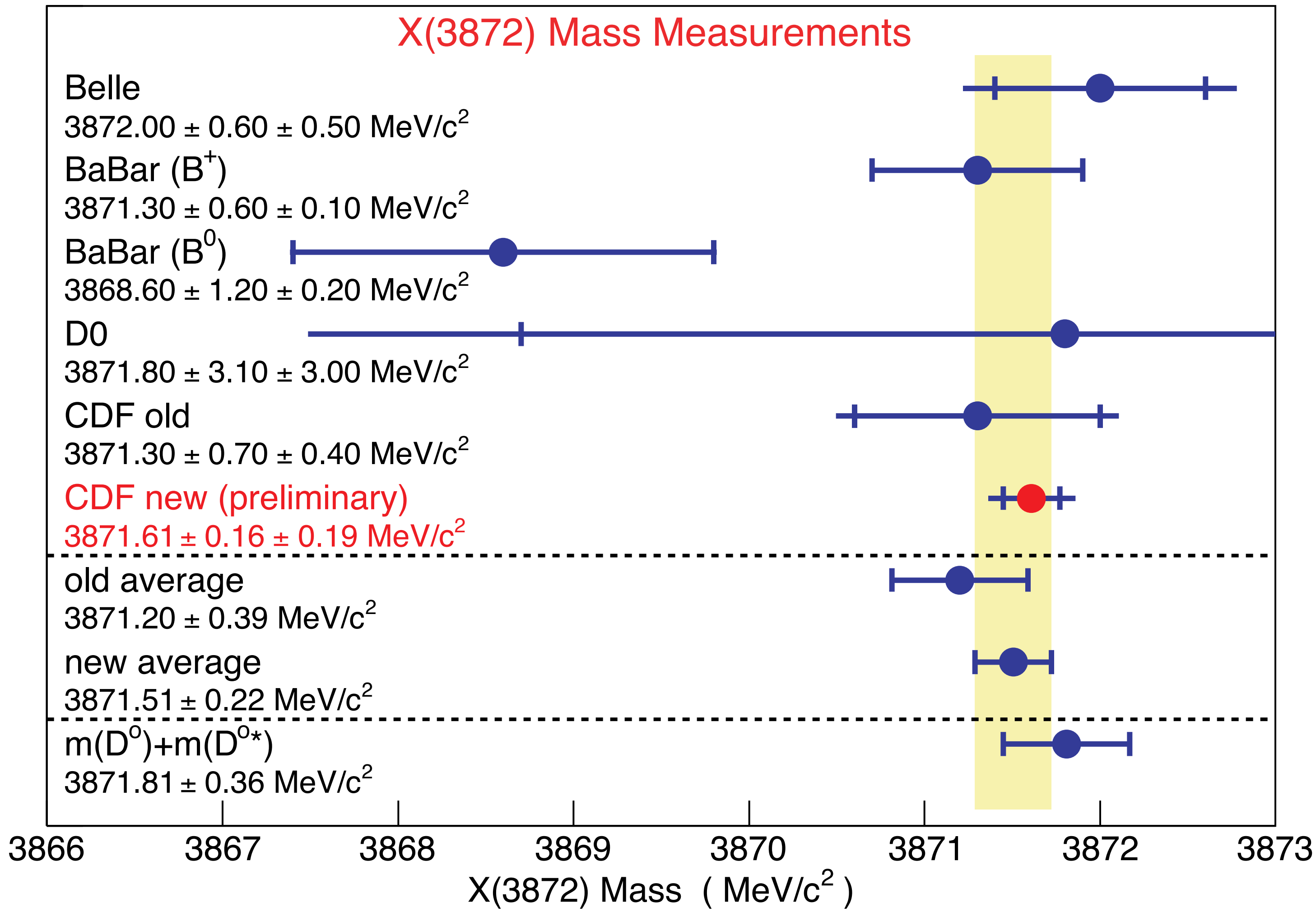


From Lewis et al., Phys.Rev.D79:014502,2009

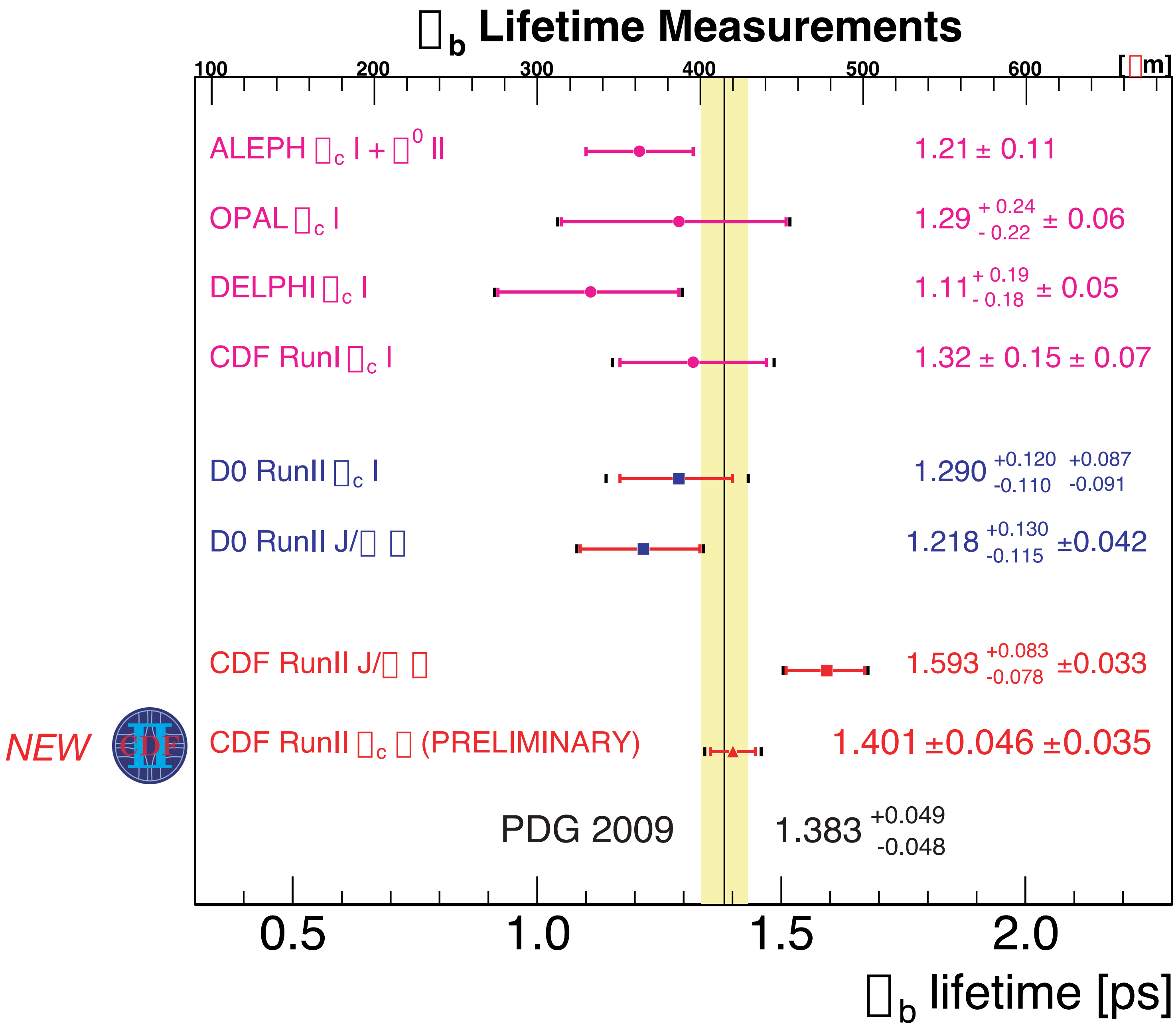
Black hatched: Lattice;

Blue boxed: SU(3) symmetry breaking, 1/mq, 1/Nc, expansion (Jenkins et al.)

X(3872) Mass



- (New) average is below, but within uncertainties of the *D*D* threshold.
  The explanation of the *X*(3872) as a bound *D*D* system is therefore still an option



□b Lifetime Measurements
100
200
300
400
500
600
[□m]
ALEPH □c l + □0 ll
1.21 ± 0.11
OPAL □c l
1.29 +0.24 -0.22 ± 0.06
DELPHI □c l
1.11 +0.19 -0.18 ± 0.05
CDF RunI □c l
1.32 ± 0.15 ± 0.07
D0 RunII □c l
1.290 +0.120 -0.110 +0.087 -0.091
D0 RunII J/□ □
1.218 +0.130 -0.115 ±0.042
CDF RunII J/□ □
1.593 +0.083 -0.078 ±0.033
NEW
CDF RunII □c □ (PRELIMINARY)
1.401 ±0.046 ±0.035
PDG 2009
1.383 +0.049 -0.048
0.5
1.0
1.5
2.0
□b lifetime [ps]

Search for Excess Dimuon Production 1.6 < r < 10 cm

DØ Note 5905-CONF

- Motivated as response to recent release of CDF multimuon ("ghost muon") result (arXiv:0810.5357 [hep-ex])
- Current DØ study limited to searching for dimuons in which one or both muons are produced at large radial distances ($1.6 < r \lesssim 10$ cm) from primary vertex

Overview

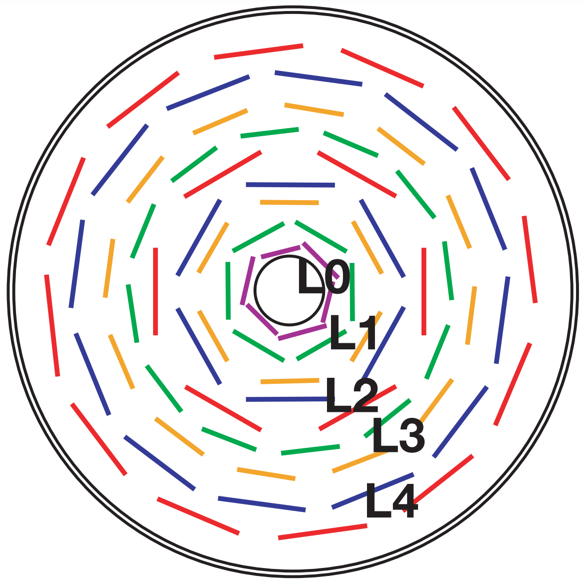
- Sample of dimuons selected to approximately match the sample used by CDF. Termed "loose" events
- Info from first layer (L0) of silicon detector used to find a subsample of these where we know both muons are produced within r < 1.6 cm - "tight" events
- Measure the efficiency and find the number of expected loose events, assuming no muons are produced beyond 1.6 cm (although know that there are regular sources of such muons such as decay-in-flight of π's and K's)
- Excess is measured as difference between observed and expected number of loose events

Search for Excess Dimuon Production $1.6 < r < 10$ cm

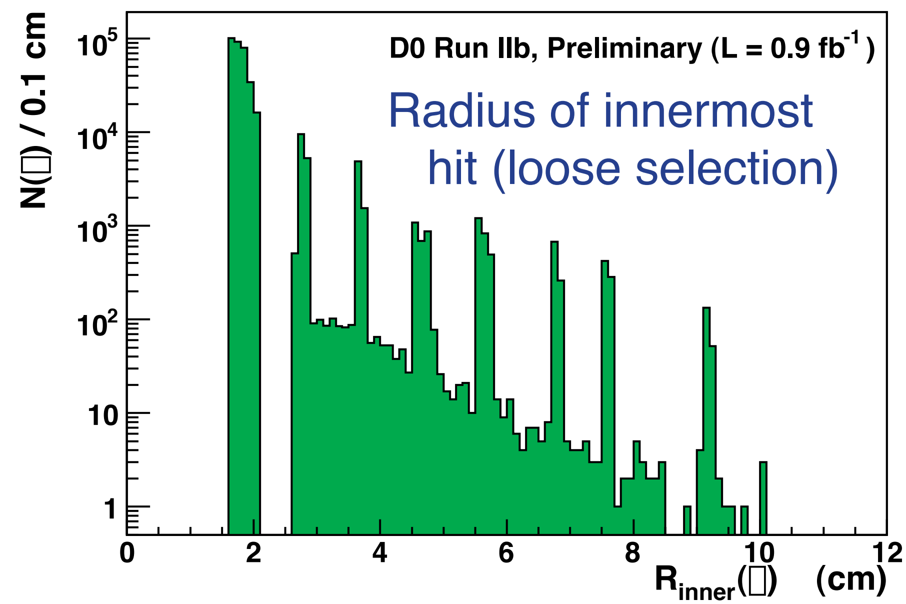
- Dataset corresponding to ~1 fb^{-1} , primarily on single or dimuon triggers
- Dimuon events selected according to:

Requirement	*CDF*	*DØ*	
$p_T(\mu)$	$\geq 3\,\mathrm{GeV}$	$\geq 3\,\mathrm{GeV}$	
$\lvert\eta\rvert$	< 0.54	< 1.0	
Δz_0	$< 1.5\,\mathrm{cm}$	$< 1.5\,\mathrm{cm}$	
Cosmic Veto	$\lvert\Delta\phi\rvert < 3.135\,\mathrm{rad}$	$\lvert\Delta\phi\rvert < 3.135\,\mathrm{rad}$	(Remove back- -to-back tracks)
Timing	N/A	$\lvert t(A)\rvert < 10\,\mathrm{ns}$ $\lvert t(C)\rvert < 10\,\mathrm{ns}$	(time diff. scintillator to beam crossing, inherent in trigger)
$M(\mu\mu)$	$5 < M(\mu\mu) < 80\,\mathrm{GeV}$	$5 < M(\mu\mu) < 80\,\mathrm{GeV}$	

Search for Excess Dimuon Production 1.6 < *r* < 10 cm



DØ Silicon Microvertex Detector



Requirement	*CDF*	*DØ*
"Loose" Selection	Hits in ≥3 silicon layers (of 7 avail.)	≥3 silicon hits
"Tight" Selection	Hits in two innermost silicon layers & ≥2 other silicon hits	Hits in L0 & ≥2 other silicon hits

Search for Excess Dimuon Production 1.6 < *r* < 10 cm

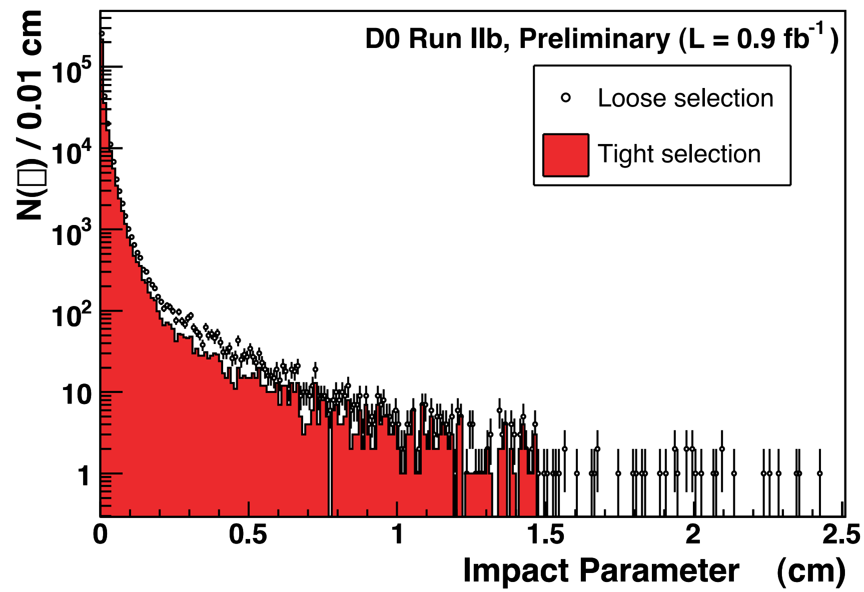
Results

$$N^{\text{obs}}(\text{loose}) = 177{,}535$$

$$N^{\text{obs}}(\text{tight}) = 149{,}161$$

- Using $N^{\text{obs}}(\text{tight})$ and known efficiency:

$$N^{\text{expect}}(\text{loose}) = 176,823 \pm 504$$



DØ Note 5905-CONF

$$N(\text{excess}) = 712 \pm 462 \pm 942$$

$$N(\text{excess})/N^{\text{obs}}(\text{loose}) = (0.40 \pm 0.26 \pm 0.53)\%$$

(c.f. ~12% CDF)

- Expect a small excess from known sources of radially displaced muons (punch-through, cosmic rays, decays-in-flight: $K \to \mu\nu \quad \pi \to \mu\nu$)