B Physics at the Tevatron

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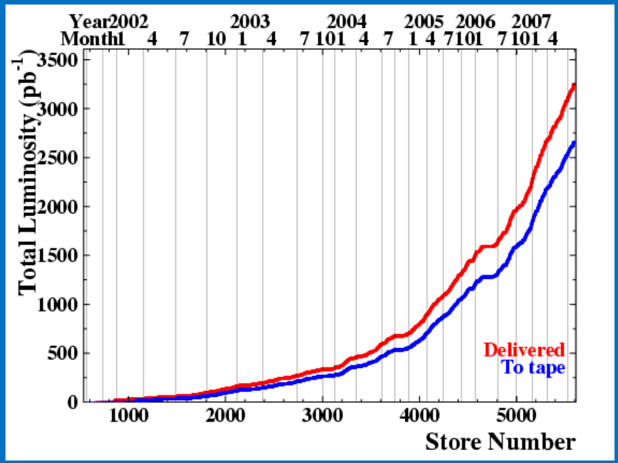
Experimental results in B Physics from CDF and DO

What is so compelling about the physics of the b quark?

The large mass of the b quark allows a theoretical approach to b-hadron properties (masses, decay rates, ..) known as the Heavy Quark Effective Theory (HQET)

Quarks of the third generation are important for probing the origin of CP violation. New physics will generally give new CP, and couple to the heavier quarks.

Why the Tevatron?



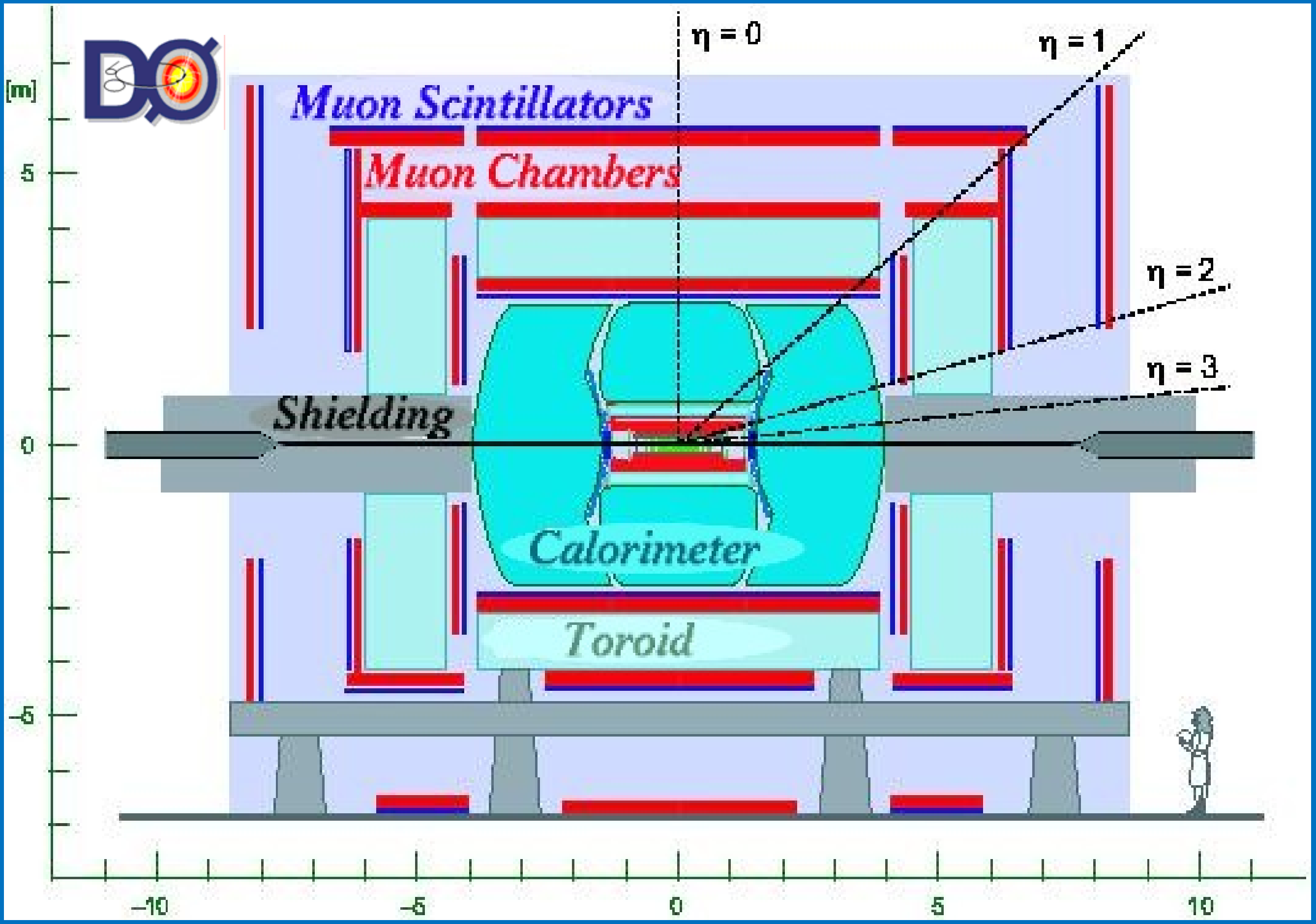
B-factories: B^+/B^0 mesons from the $\Upsilon(4S)$

Tevatron : B^+, B^0, B^0_s, B^+_c, excited b-mesons, b baryons, excited b-baryons, rare decays…

In general the most important components of a general purpose detector system, for B physics, is:

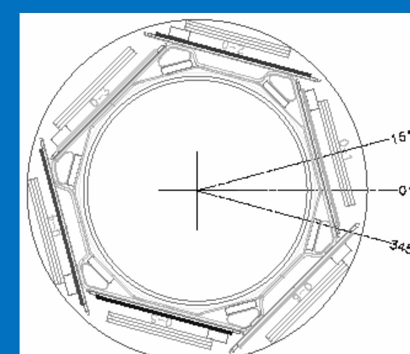
- tracking.
- muon [+electron] id
- triggering: B hadrons comprise is $\mathcal{O}(10^{-3})$ of all events.

  Charmless decay modes have branching fractions $\mathcal{O}(10^{-6})$

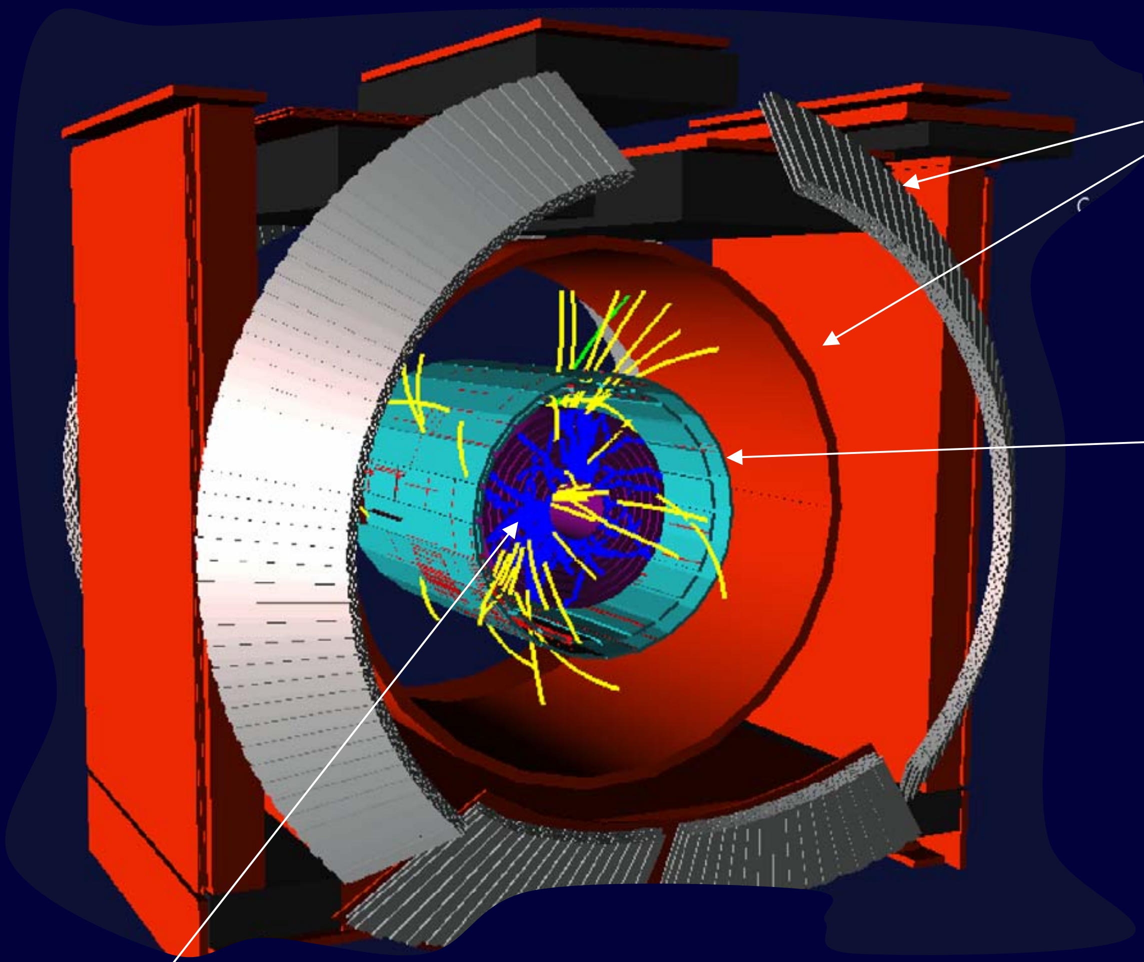


The D0 Silicon tracker…..

- surrounded by a fibre tracker at a distance 19.5 cm < r <51.5 cm
- now augmented by a high-precision inner layer (“Layer 0”)
    - 71 (81) μm strip pitch →
    - factor two improvement in impact parameter resolution



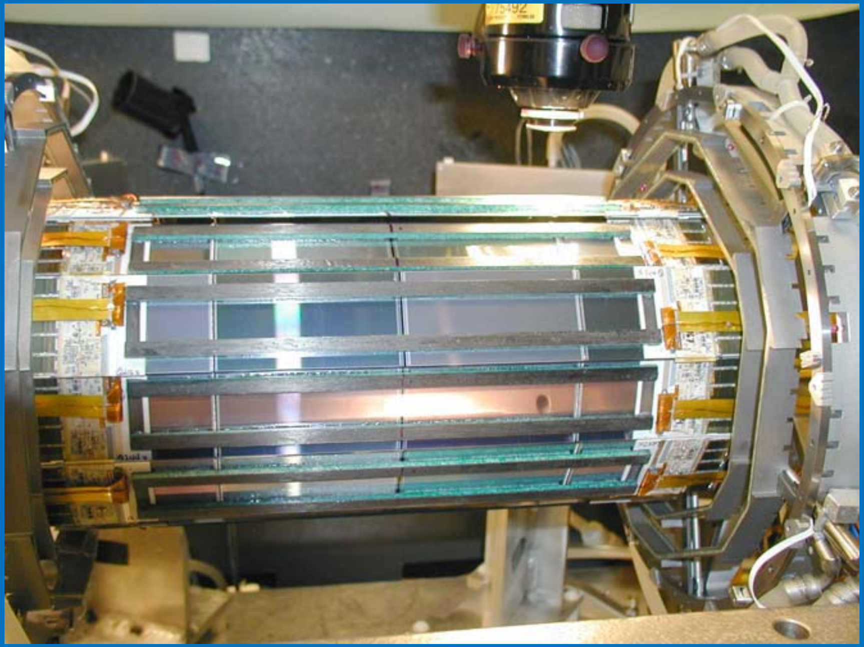
CDF Detector showing as seen by the B physics group.

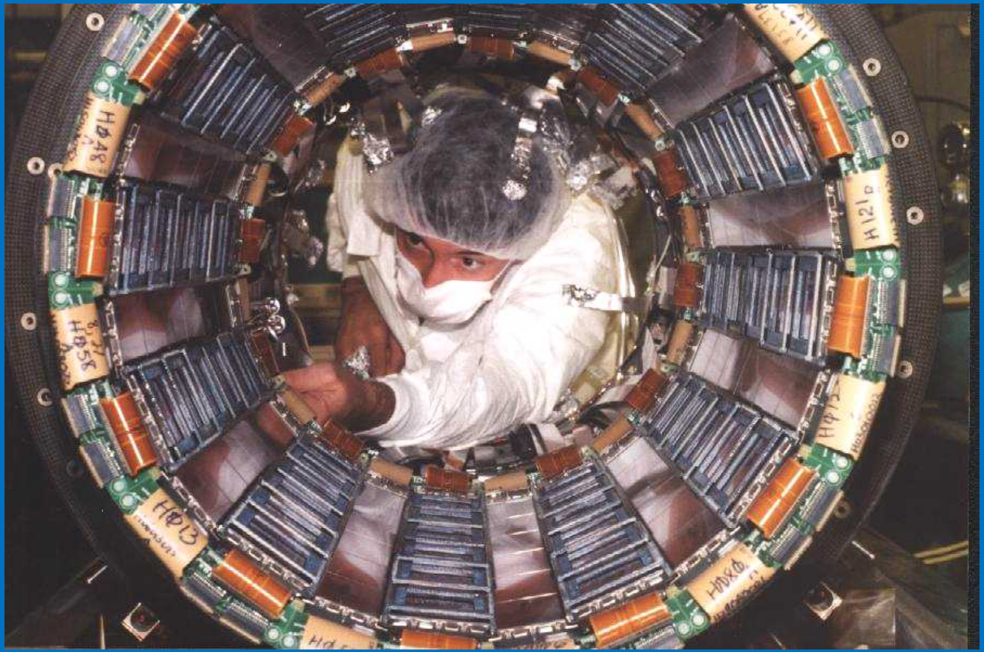


Muon chambers for triggering on the $J/\psi \rightarrow \mu^{+}\mu^{-}$ and μ Identification.

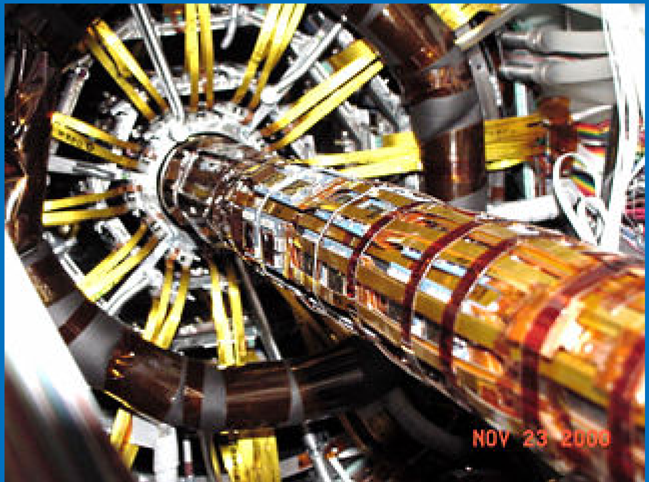
Strip chambers, calorimeter for electron ID

Central outer tracker
dE/dX and TOF system for particle ID
$r < 132$ cm $\quad B = 1.4$ T $\quad$ for momentum resolution.





L00: 1.6 cm from the beam.
50 μm strip pitch
Low mass, low M-S.



And another thing which is really special about this system is the trigger!

The Silicon Vertex Trigger (SVT)

* Provides precision impact parameter information at L2

* Beam crossing: SVX samples & holds on a dual-ported analog pipeline.

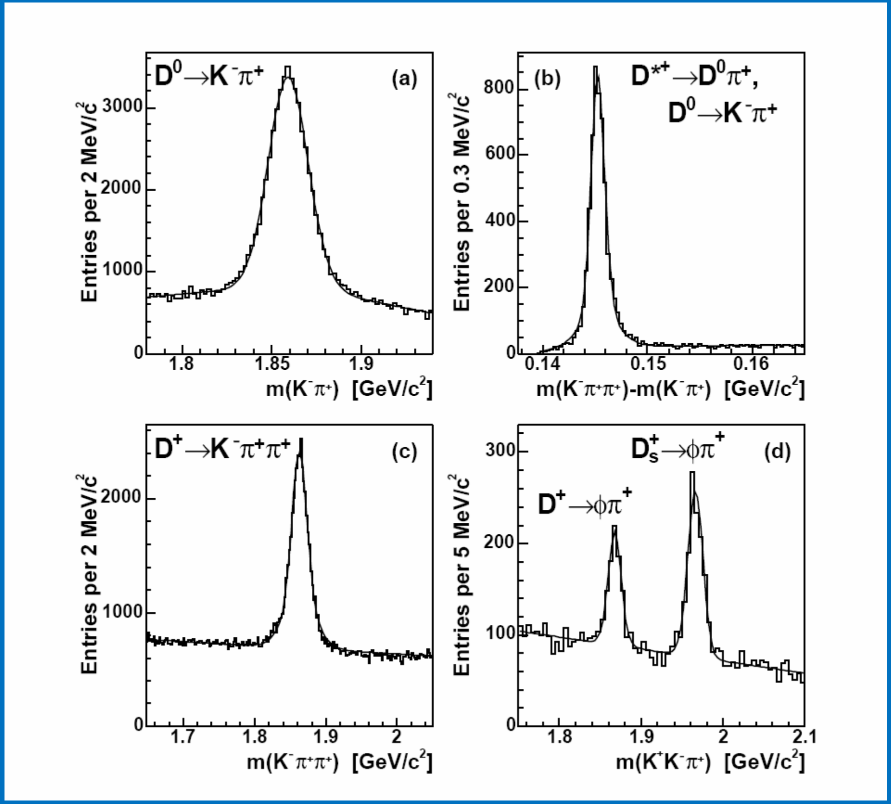
… when a Level 1 Accept occurs, the readout cell is read *without incurring deadtime* ➔ allows high rate at L1

massive cleanup of B-triggers using impact parameter information at L2.

Run I: most (almost all) B-physics relies on the J/ψ trigger, yielding now millions of events.

other hadronic decays go straight down the beam pipe.

Run II: These decays and many more are suddenly visible ⟶



➔ Major impact on B physics!

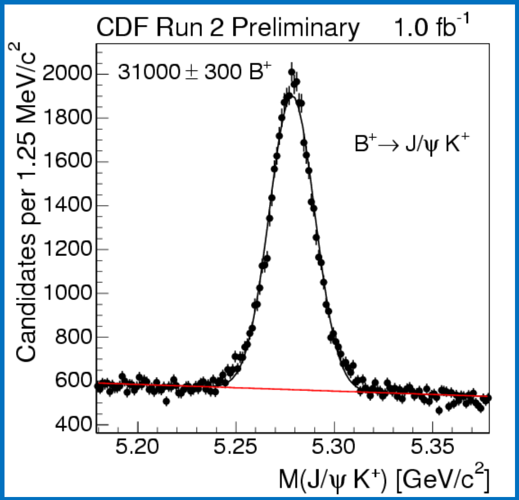
Hadron collider: large cross sections, large data sample, new B triggers:

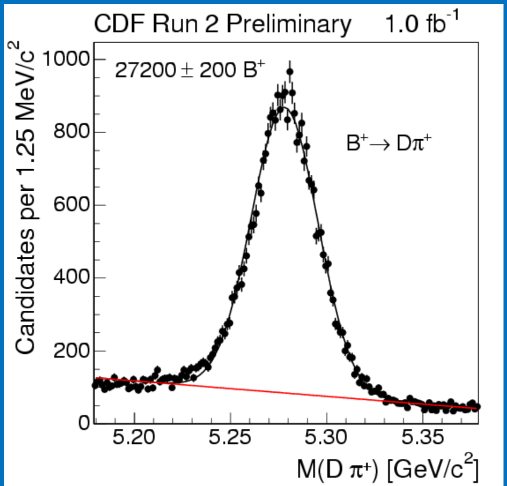
SVT (CDF) collects practically as many reconstructed B decays as the J/ψ trigger.

J/ψ trigger

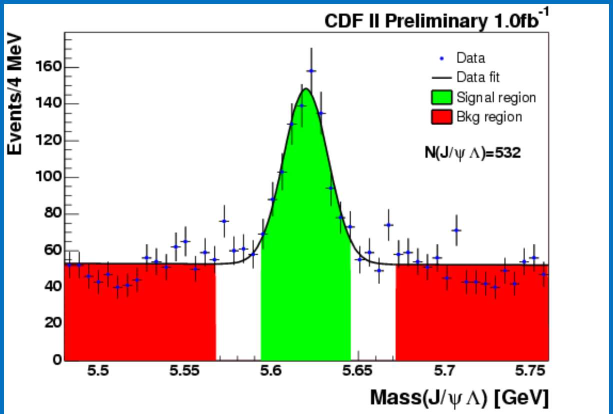
Hadronic B trigger

B^+ decays:

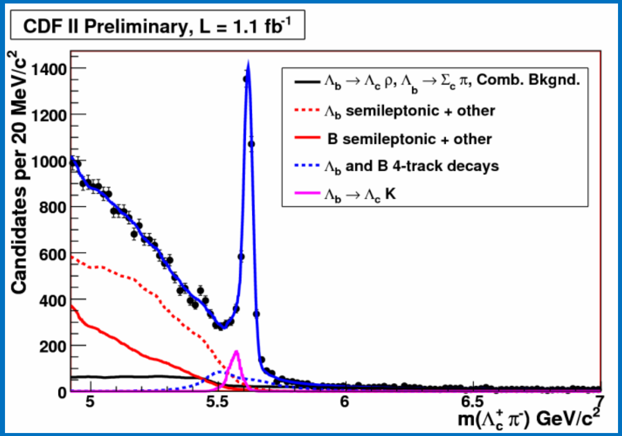




Λ_b decays



532 events $\Lambda_b \to J/\psi\ \Lambda$

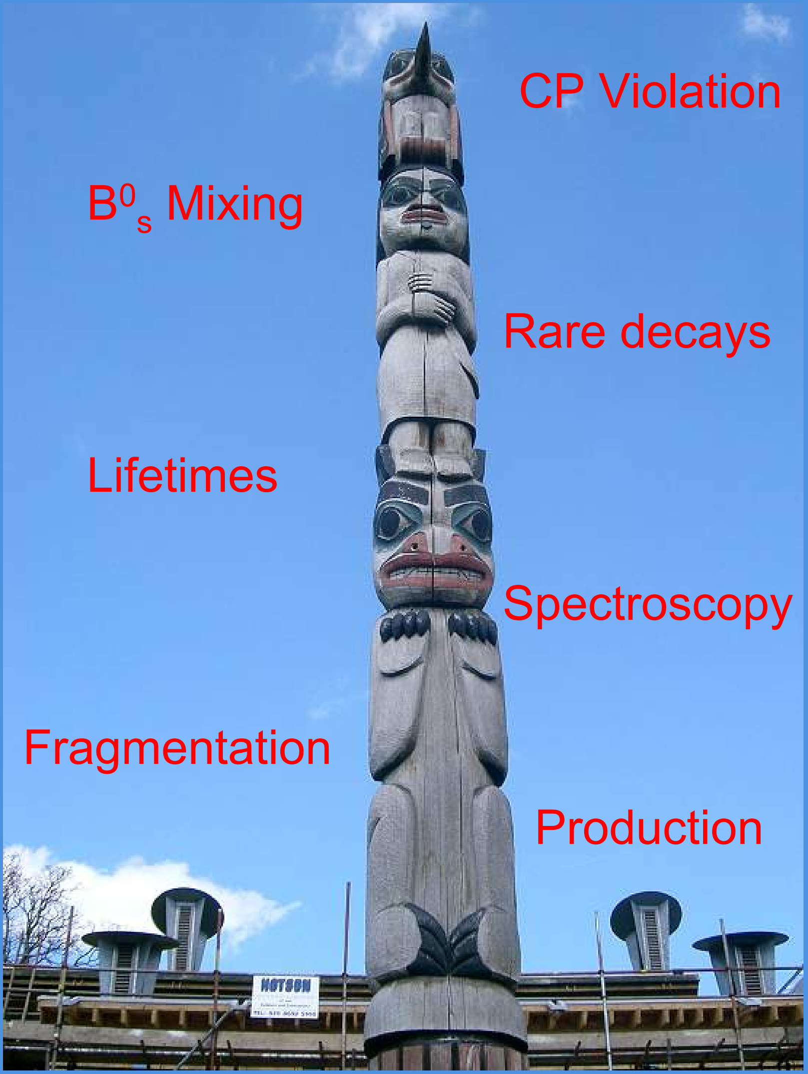


2.8 K events $\Lambda_b \to \Lambda_c\ \pi$

Any big differences for B physics?

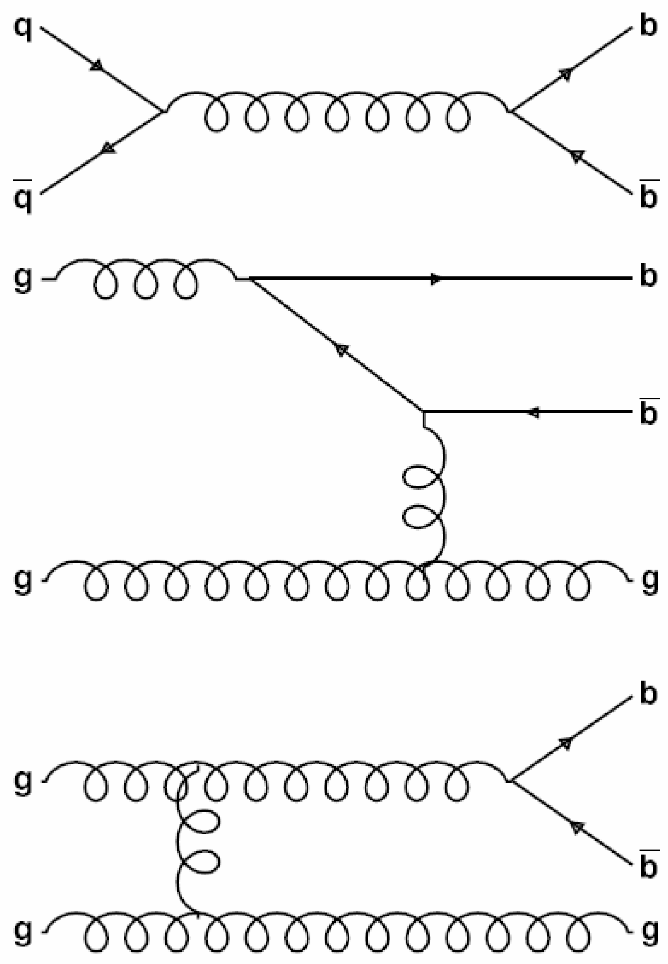
• Muon coverage	Is superior in D0
• Trigger	The "displaced vertex" trigger in CDF is a major factor in B-physics.
• Momentum Resolution	Is superior in CDF, leading generally to higher signal better S:N goes like Bl^2
• Forward tracking	Is superior in D0
• Tracking of V0's	Is superior in CDF, probably due to the difficulty of finding these in the D0 fibre tracker.

~~CP~~ in B^0_s



"Before you can reach to the top of a tree and understand the buds and flowers, you will have to go deep to the roots, because the secret lies there. And the deeper the roots go, the higher the tree goes." - NIETZSCHE

Production. Fragmentation.



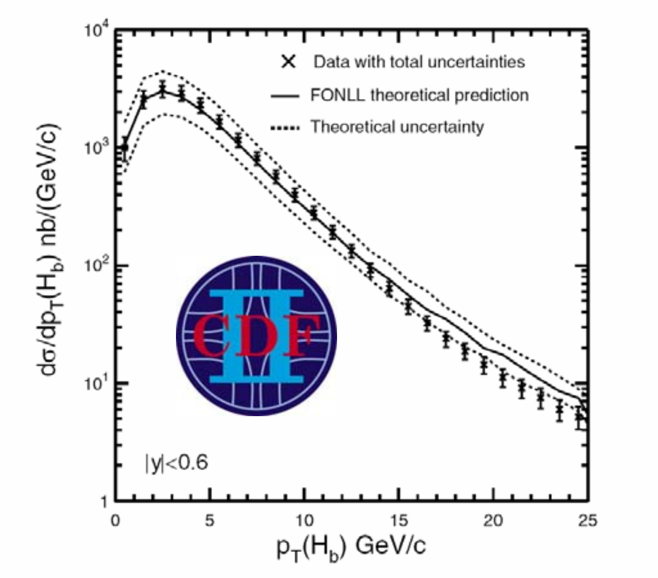
Production cross section is large!

At sqrt(s)=1960 GeV/c^2 :

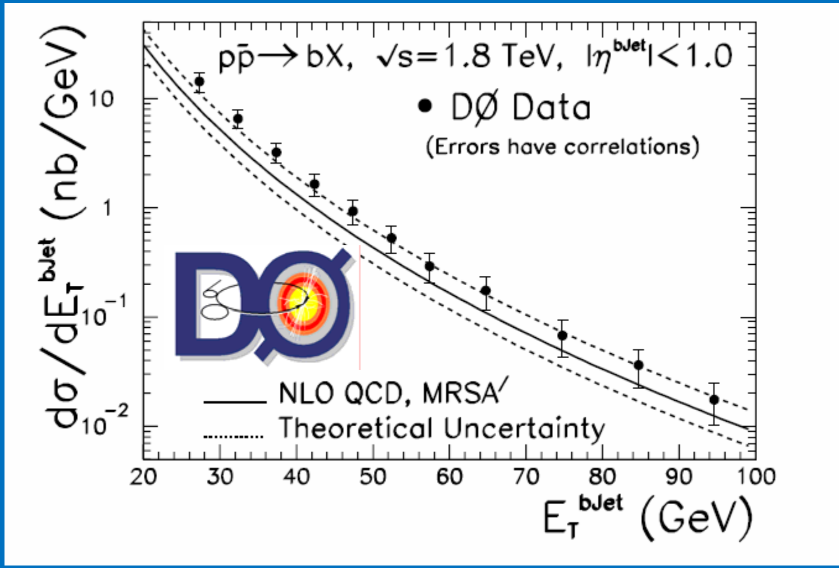
$\sigma = 17.6 \pm 0.4(\text{stat})\ ^{+.2.5}_{-2.3}\ (\text{syst})\ \mu\text{b}$ |y|<0.6 (CDF)

[compare 1 nb at $\Upsilon(4S)$, 6 nb at the Z^0]

Total $p\bar{p}$ inelastic cross section is greater by about three orders of magnitude



Phys. Rev. D **71**, 032001 (2005)
Mesured in inclusive J/ψ events.



Phys. Rev. Lett. 85, 5068 - 5073 (2000)
Measured using tagged jets.

The fragmentation fractions into various b hadron species has been measured in semileptonic decays:

$$\frac{f_u}{f_d} = 1.054 \pm 0.018\,(\text{stat})\ ^{+0.025}_{-0.045}\,(\text{sys})\ \pm 0.058\,(\mathcal{B}),$$

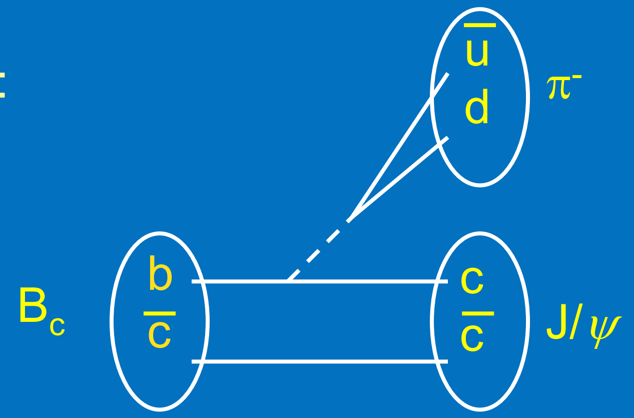
$$\frac{f_s}{f_u + f_d} = 0.160 \pm 0.005\,(\text{stat})\ ^{+0.011}_{-0.010}\,(\text{sys})\ ^{+0.057}_{-0.034}\,(\mathcal{B}),$$

$$\frac{f_{\Lambda_b}}{f_u + f_d} = \underline{0.281} \pm 0.012\,(\text{stat})\ ^{+0.058}_{-0.056}\,(\text{sys})\ ^{+0.128}_{-0.087}\,(\mathcal{B}).$$

arXiv:0801.4375v1

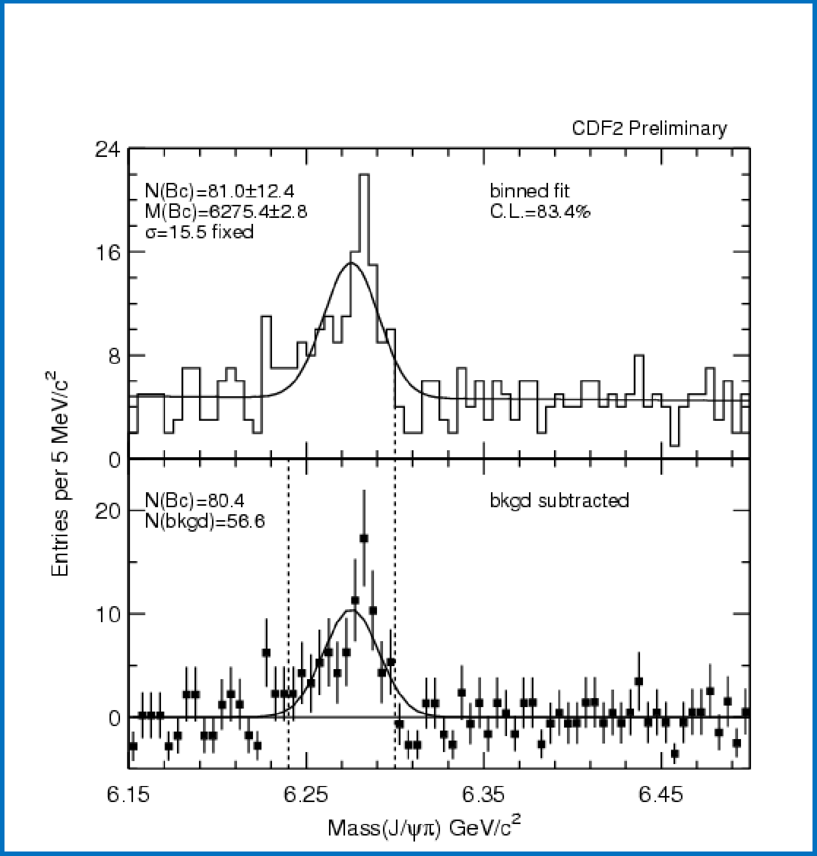
A small sample of B_c^+ events has been seen:

Semileptonic decays, too!

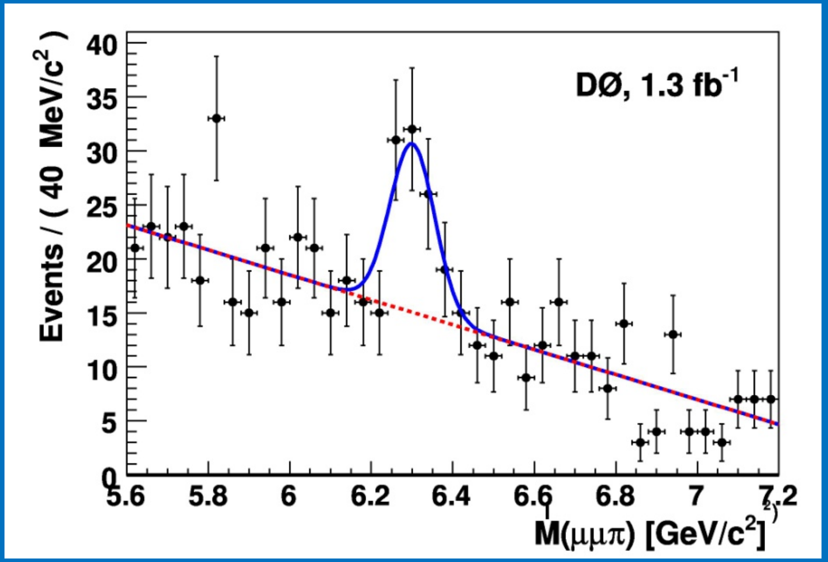


D0: 54 ± 12 signal events (1.3 fb^{-1})

CDF: 81 ± 12 signal events (2.2 fb^{-1})



arXiv:0712.1506v1



arXiv:0802.4258v1

$M(B_c)_{CDF} = 6274.1 \pm 3.2 \pm 2.6$ MeV/c^2

$M(B_c)_{D0} = 6300 \pm 14$ (stat) ± 5 (sys) MeV/c^2

$M(B_c)_{LAT} = 6304 \pm 12$ MeV/c^2

Spectroscopy

* Orbitally excited B^0 mesons (L=1, B^{0**})

* Orbitally excited B^0_s mesons (L=1, B_s^{**})

* New bottom baryons (buu and bdd), part of a new I-triplet Σ_b

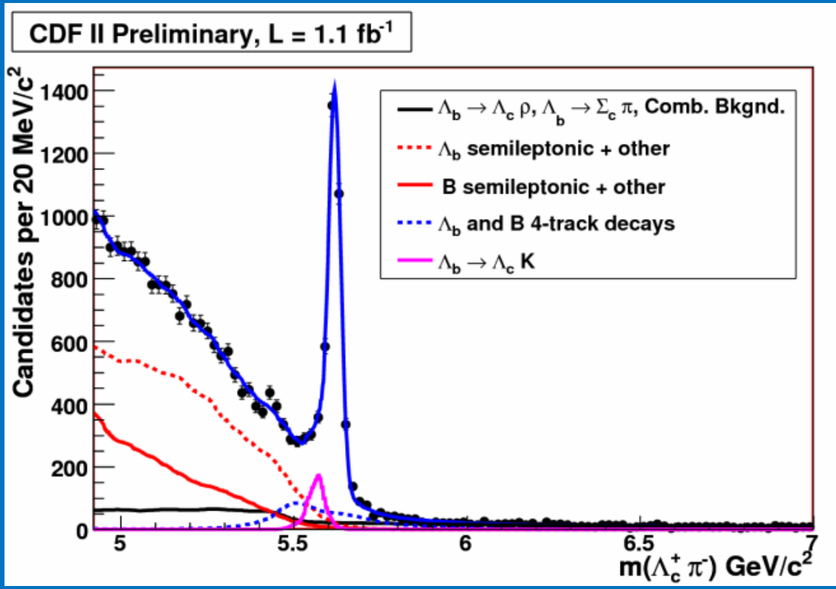
* The Ξ_b^- baryon (bsd)

$\Sigma_b^{(*)\pm}$ (four particles)

Start with 2.8K events

$\Lambda_b \rightarrow \Lambda^+_c \pi^-$
$\Lambda^+_c \rightarrow pK^-\pi^+$ in the hadronic trigger.

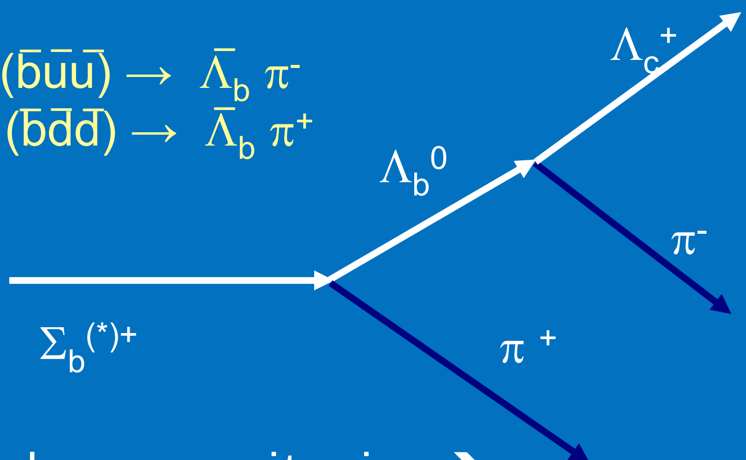
add a “soft” pion.

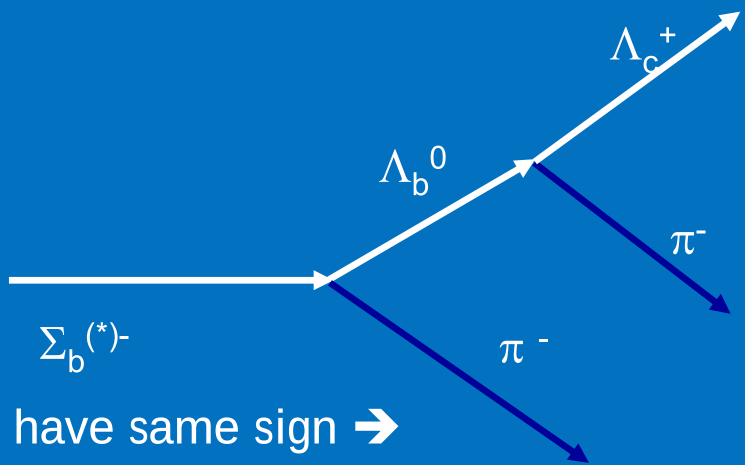


Σ_b+ (buu) $\rightarrow \Lambda_b \pi$+
Σ_b- (bdd) $\rightarrow \Lambda_b \pi$-

I-spin partners, not antiparticles!

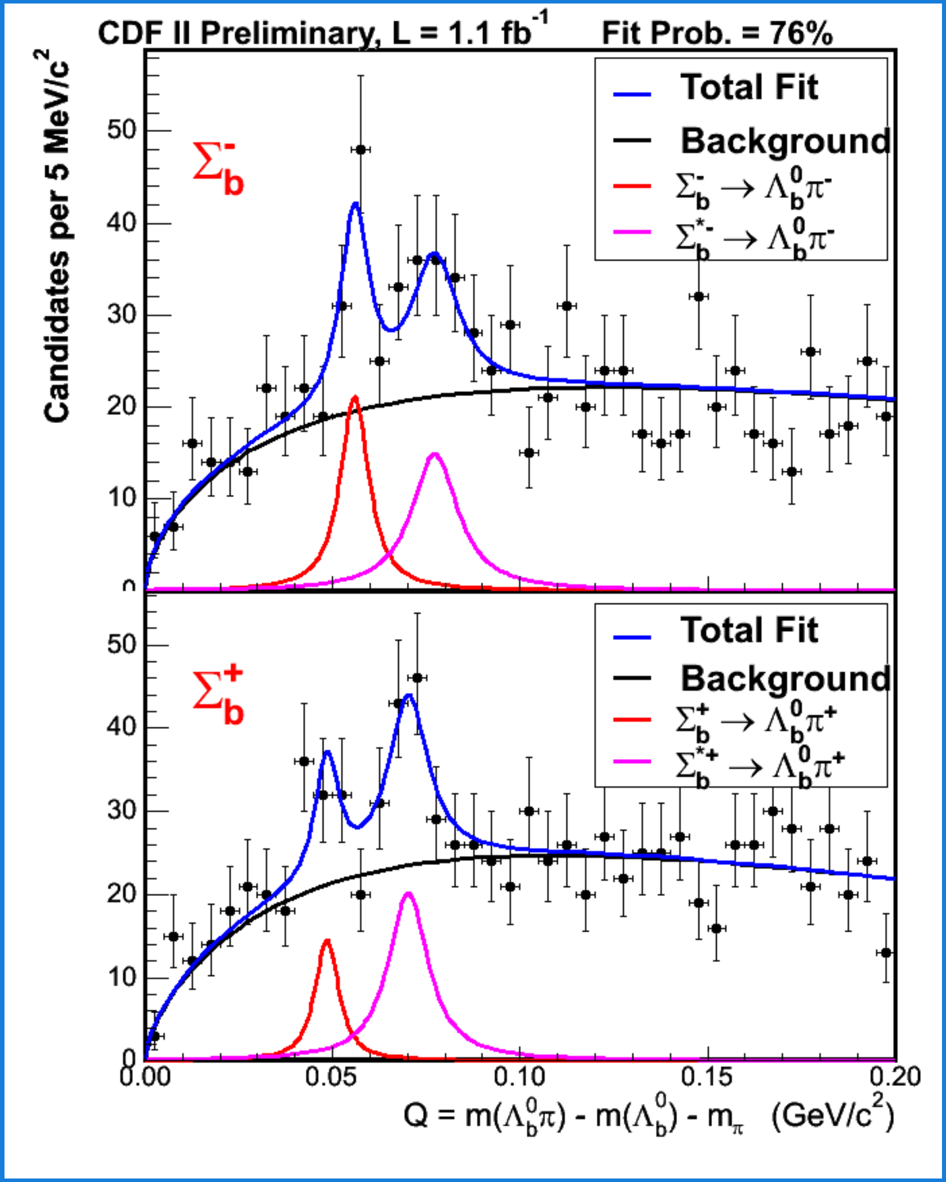
$\bar{\Sigma}_b^+ (\bar{b}\bar{u}\bar{u}) \rightarrow \bar{\Lambda}_b \pi^-$
$\bar{\Sigma}_b^- (\bar{b}\bar{d}\bar{d}) \rightarrow \bar{\Lambda}_b \pi^+$





Pions have opposite sign ➔ $\Sigma_b^{(*)+}$

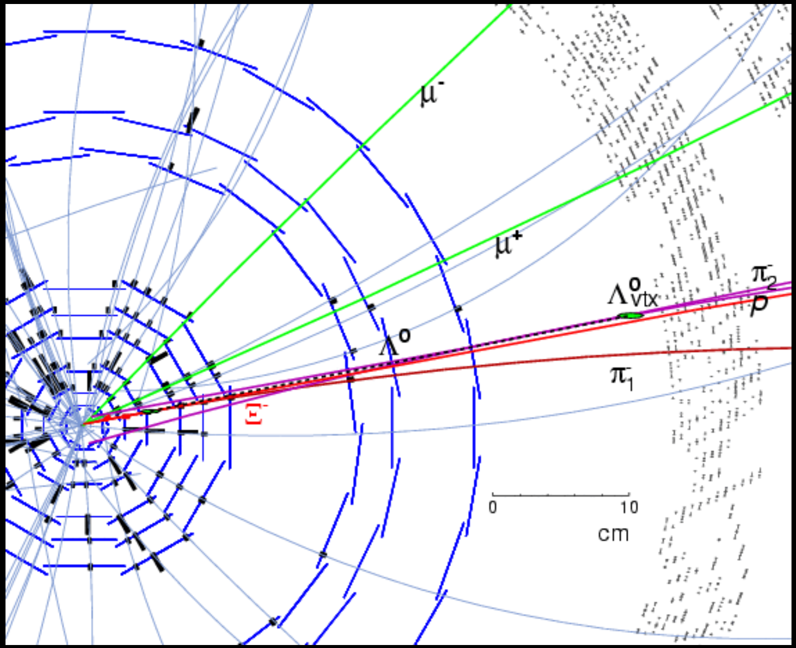
Pions have same sign ➔ $\Sigma_b^{(*)-}$

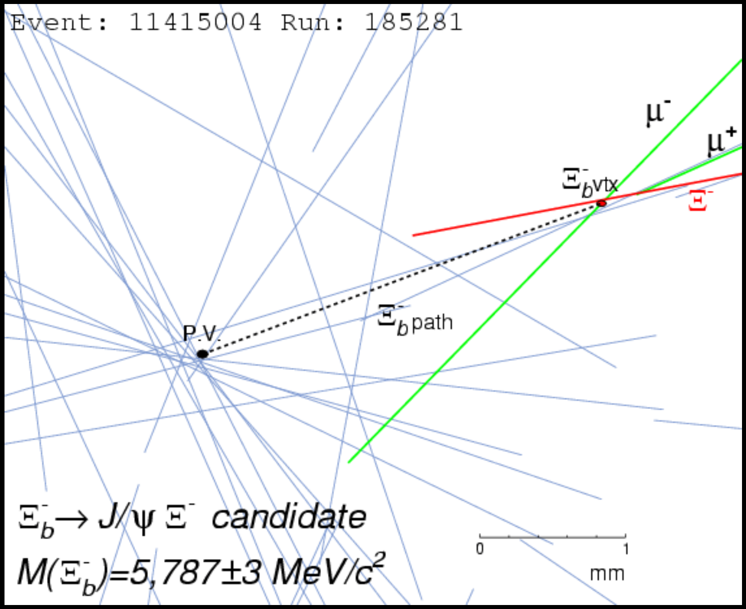


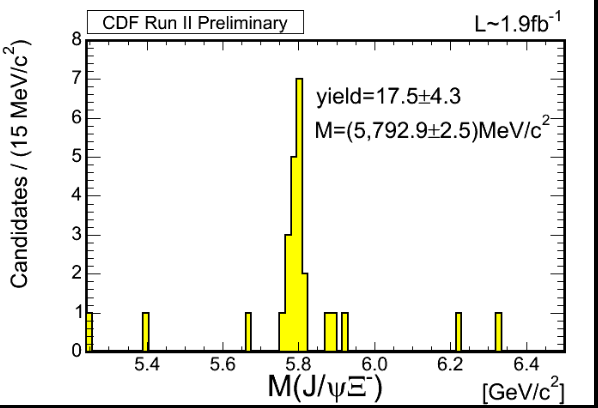
CDF measures mass, hyperfine splitting and isospin splitting:

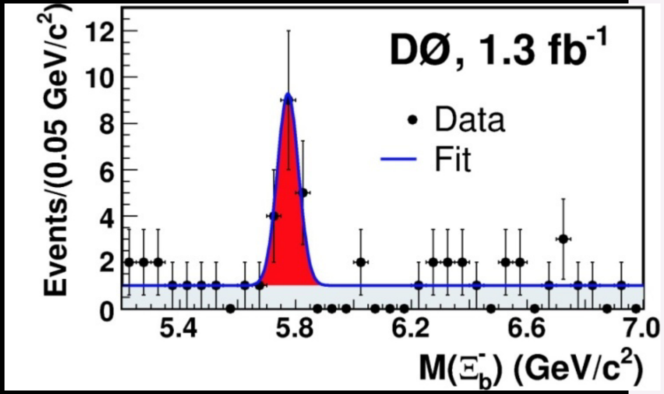
$$m_{\Sigma_b^+} = 5807.8^{+2.0}_{-2.2}\ (\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$
$$m_{\Sigma_b^-} = 5815.2 \pm 1.0\ (\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV}/c^2$$
$$m(\Sigma_b^*) - m(\Sigma_b) = 21.2^{+2.0}_{-1.9}\ (\text{stat.})^{+0.4}_{-0.3}\ (\text{syst.})\ \text{MeV}/c^2$$

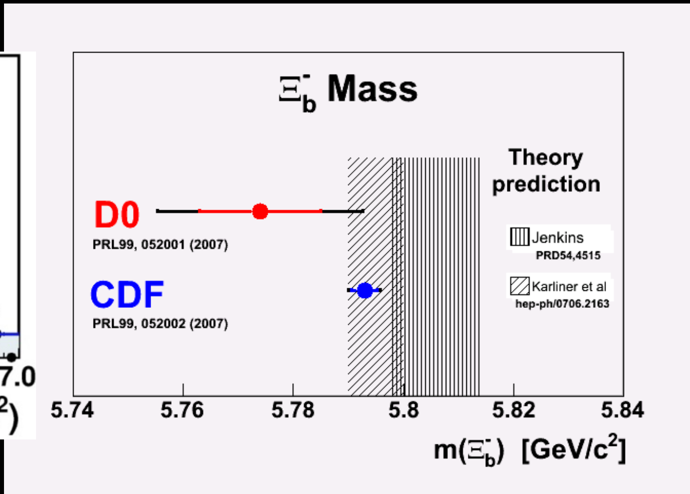
Discovery of the Ξ_b^- Baryon (D0) and confirmation (CDF)



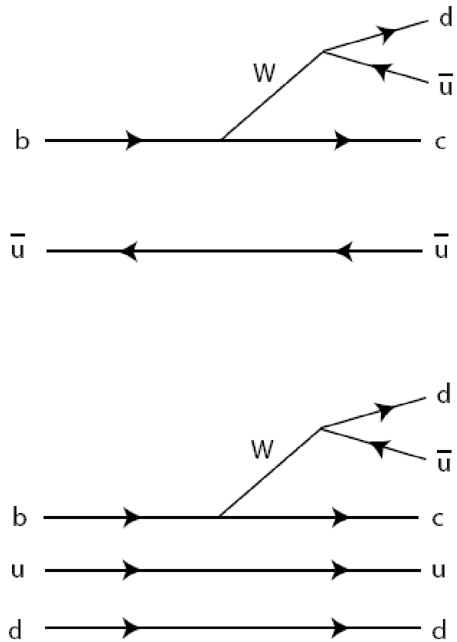




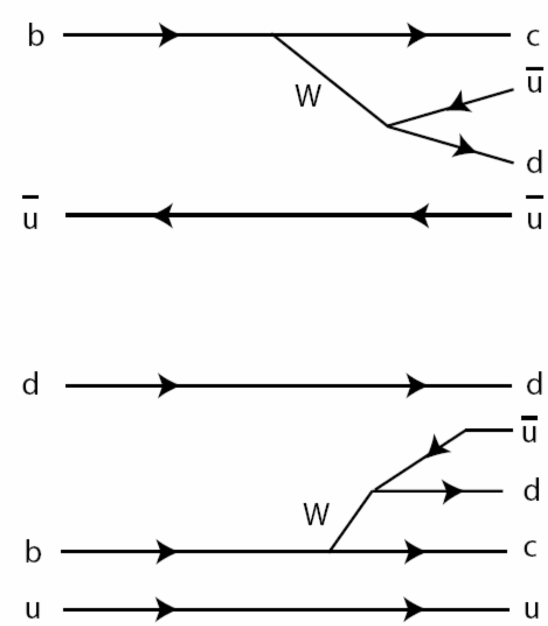




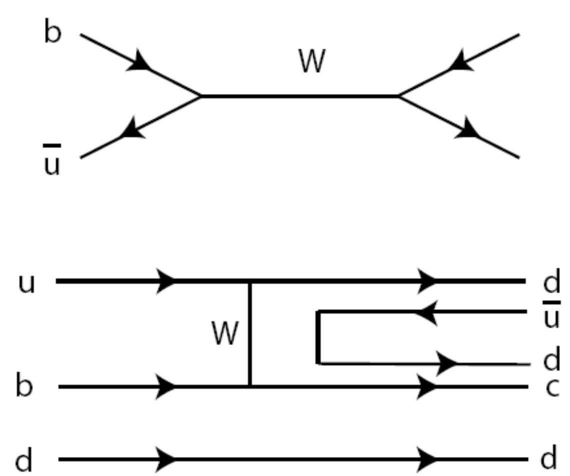
B Hadron Lifetimes.



Spectator model: all b hadron lifetimes are equal.



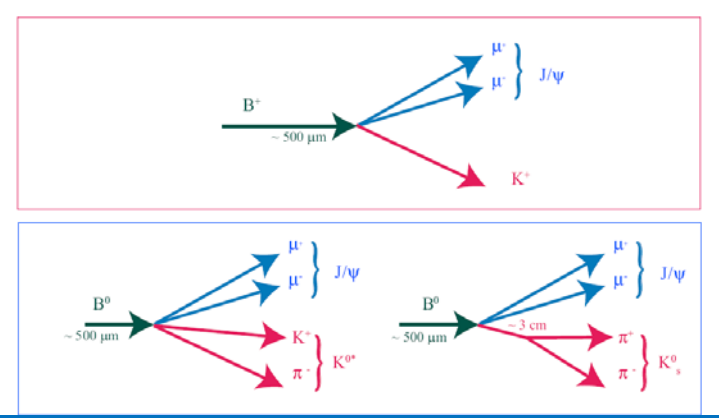
Pauli interference prolongs lifetimes: +5% for B^+, +3% for Λ_b



Weak annihilation or scattering reduces lifetimes -7% Λ_b

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \cdot \left[A_0 + A_2\left(\frac{\Lambda_{QCD}}{m_b}\right)^2 + A_3\left(\frac{\Lambda_{QCD}}{m_b}\right)^3\right]$$

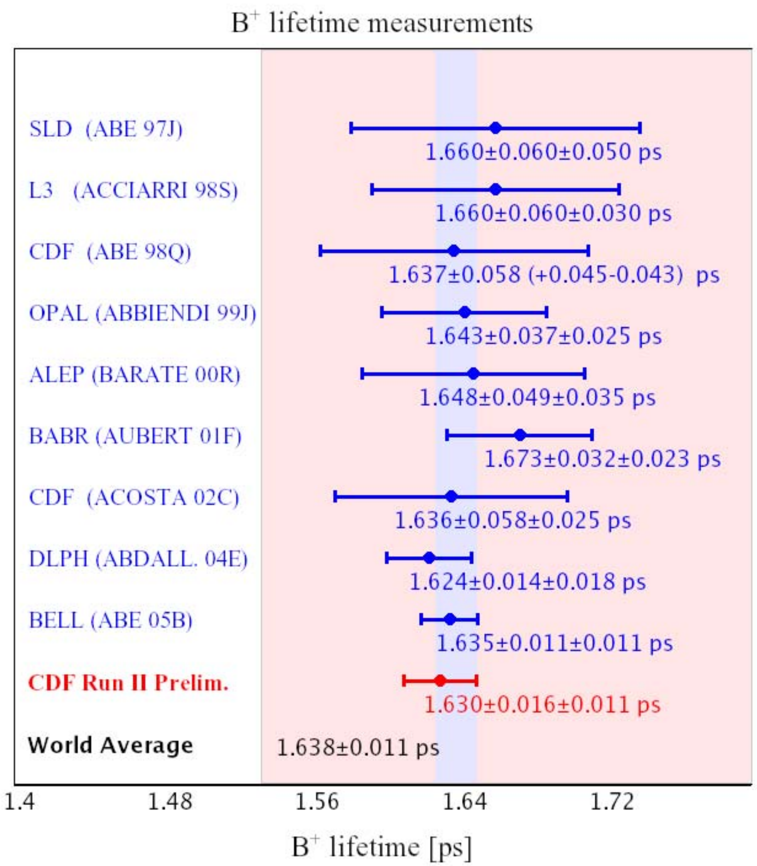
Lifetime (μm)		Measured Value (PDG2006)
τ_{B+}	=	1.643 ±0.010 ps,
τ_{B^0}	=	1.527 ±0.008 ps,
$\tau_{B_s^0}$	=	1.454 ±0.040 ps,
τ_{Λ_b}	=	1.288 ±0.065 ps,
Lifetime ratio	Predicted range	Measured Value (PDG2006)
$\tau(B^+)/\tau(B^0)$	1.04 – 1.08	1.076 ± 0.008
$\bar{\tau}(B_s^0)/\tau(B^0)$	0.99 – 1.01	0.914 ± 0.030
$\tau(\Lambda_b)/\tau(B^0)$	0.86 – 0.95	0.844 ± 0.043

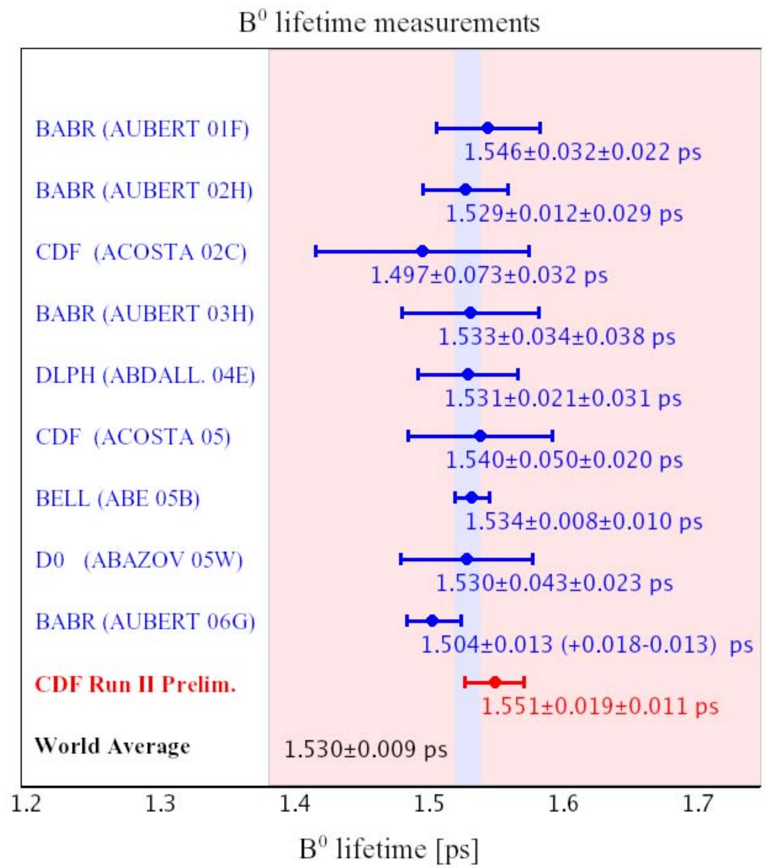


Easiest way to measure lifetime: fully reconstructed events from the J/ψ trigger, no bias on lifetime.

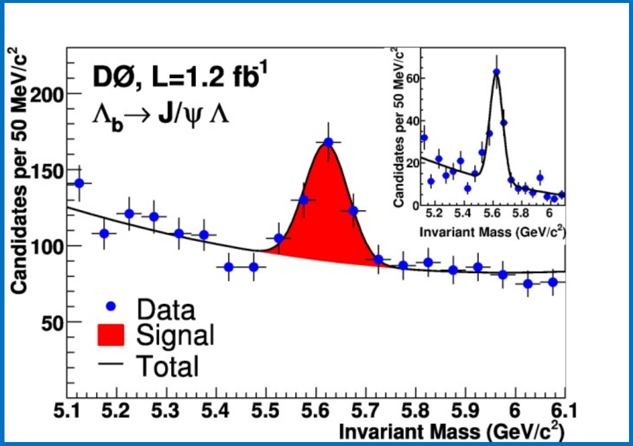
Measures τ_+/τ_0 = 1.051±0.024±0.004

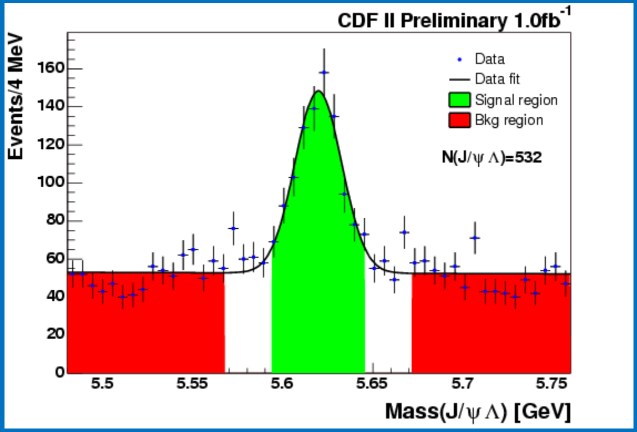
Systematics controlled at less than the percent level.

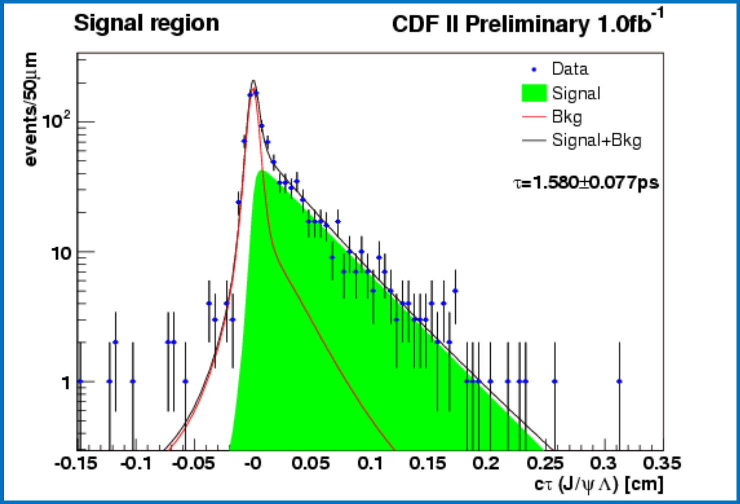


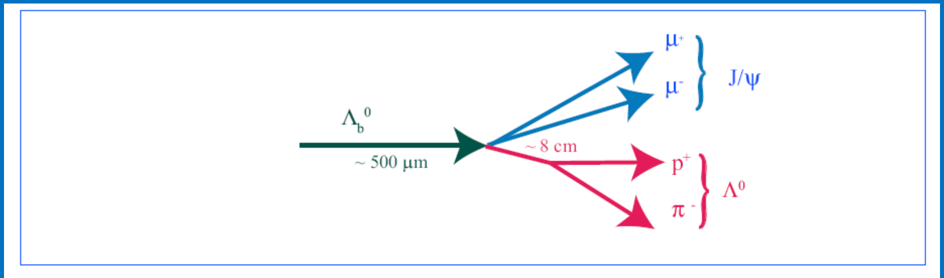


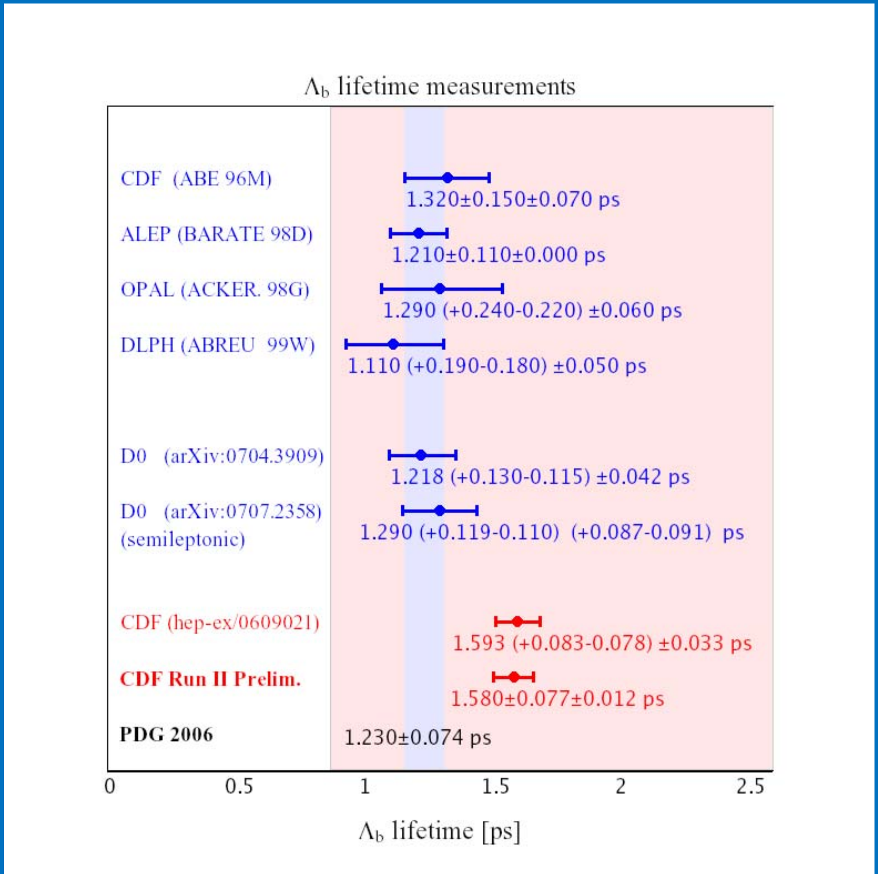
Same technique for the Λ_b









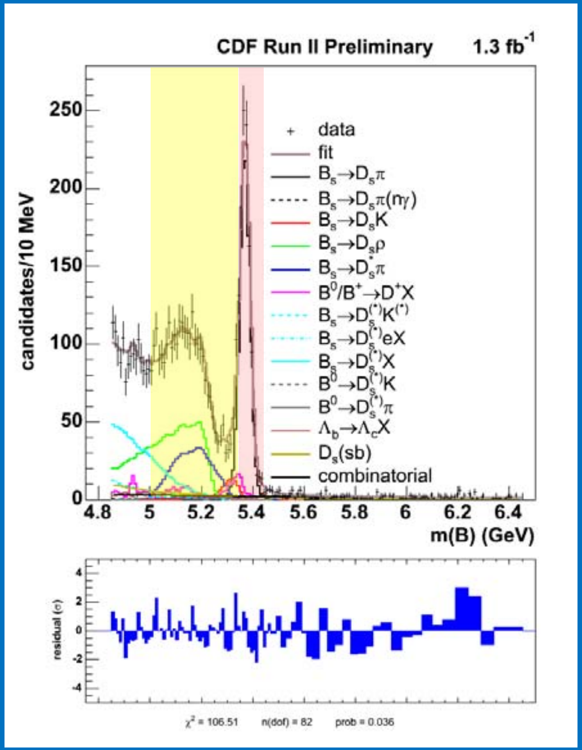


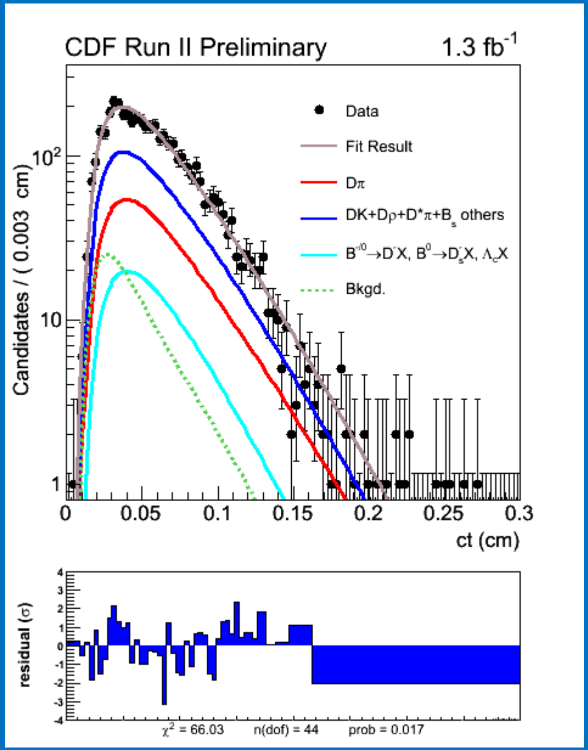
For the B^0_s, the situation is more difficult, since the $J/\psi\ \phi$ is a combination of two states (τ_H and τ_L) in unequal proportions. Further analysis of this state described later.

Alternative: measure the lifetime in a flavor-specific decay mode $B_s \to D_s \pi X$

➔Measure the lifetime from the SVT Trigger, which makes a very jagged cut on the lifetime. $c\tau(B_s) = 455.0 \pm 12.2$ (stat.) ± 7.4 (syst.) μm

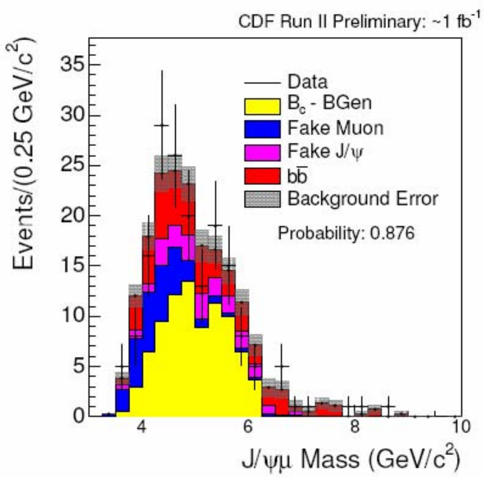
Analysis uses fully reconstructed and partially reconstructed decays.

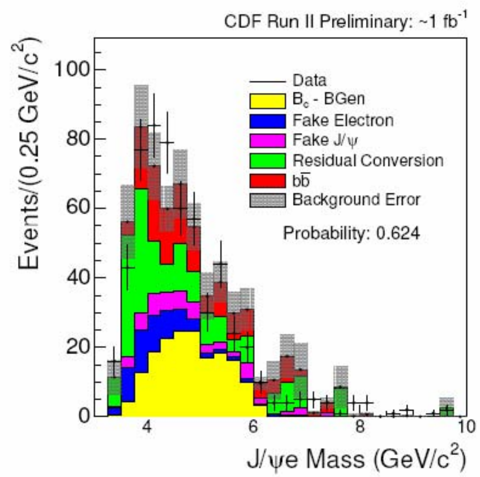


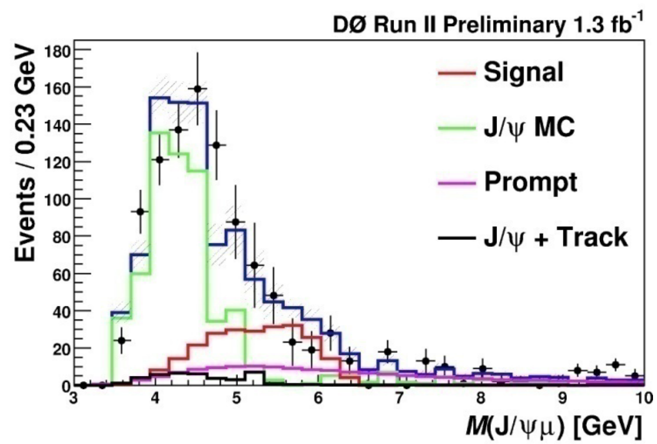


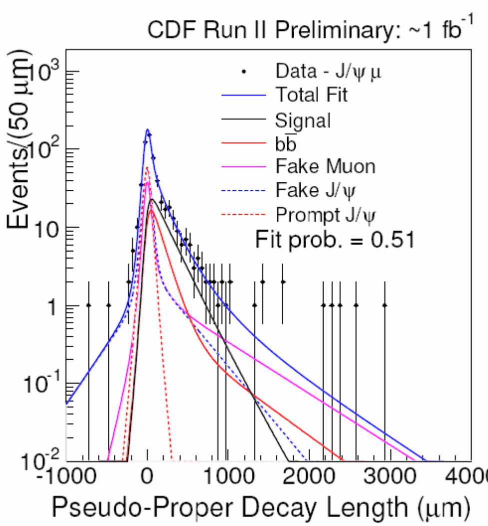
HQET: $c\tau(B^0_s) = (1.00 \pm 0.01)\ c\tau(B^0)$ PDG: $c\tau(B^0) = 459 \pm 0.027\ \mu m$

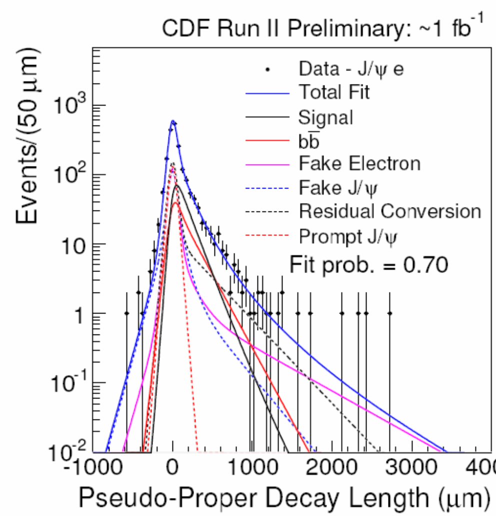
B^+_c lifetime: shortest of all b hadrons, since both b- or c-quark can decay.
Use semileptonic decay modes $B^+_c \rightarrow J/\psi\ (e^+,\mu^+)$
No mass peak, no sidebands, so backgrounds need to be carefully estimated using data and Monte Carlo. D0 Note 5524-Conf

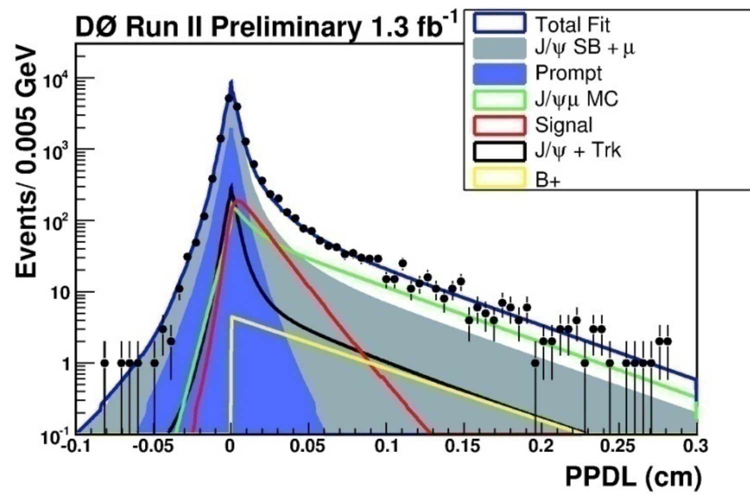




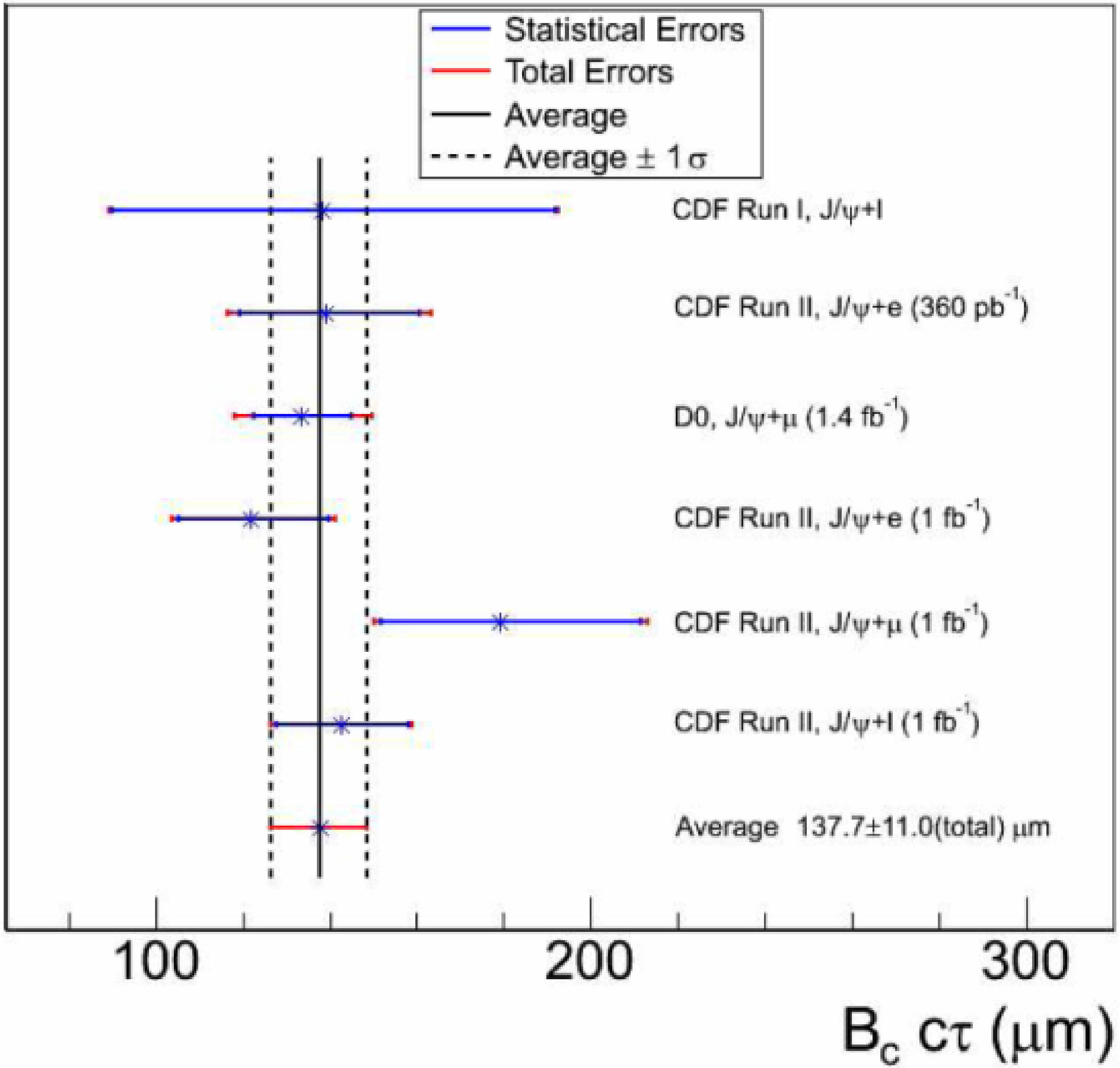








B_c Lifetime Measurements



Search for rare decays

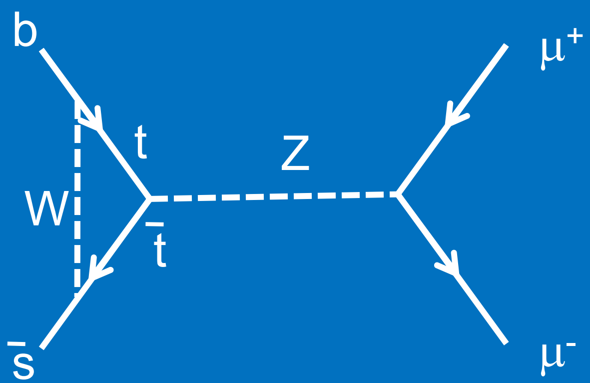
$B^0_{d,s} \rightarrow \mu^+\mu^-$

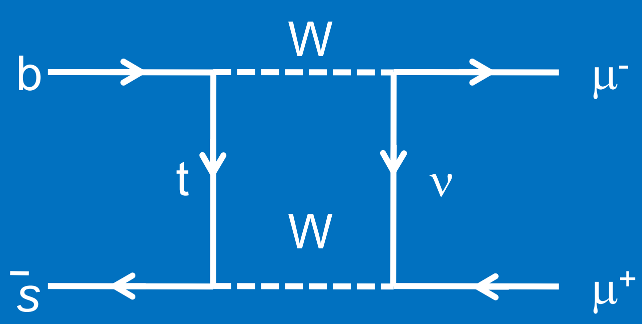
A Highly suppressed FCNC process

SM Expectation: $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$

$BR(B^0_d \rightarrow \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$

G. Buchalla and A. J. Buras, Nucl. Phys. B400, 225 (1993)
A.J. Buras, Phys. Lett. B 566 115 (2003)



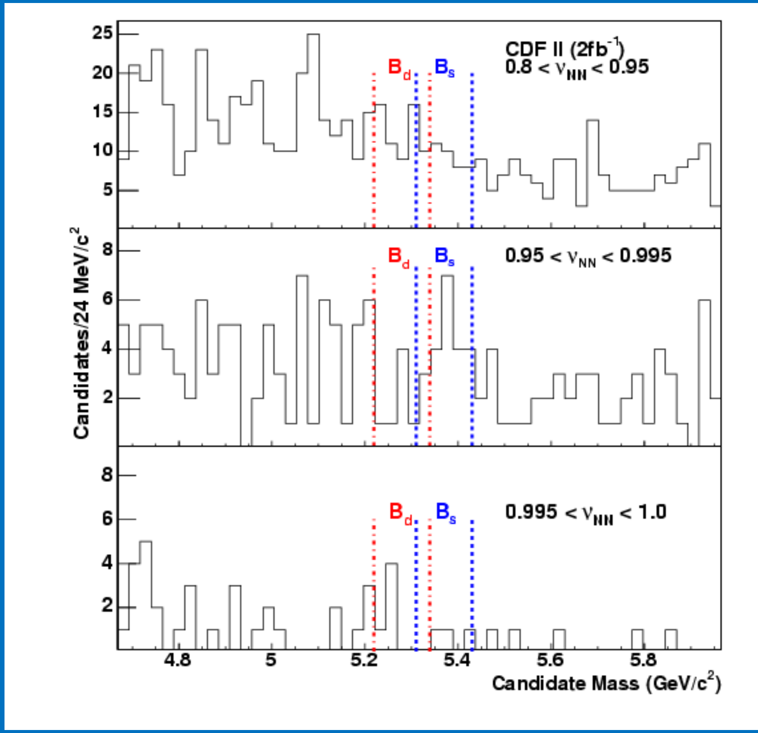


$B^0_d \rightarrow \mu^+\mu^-$

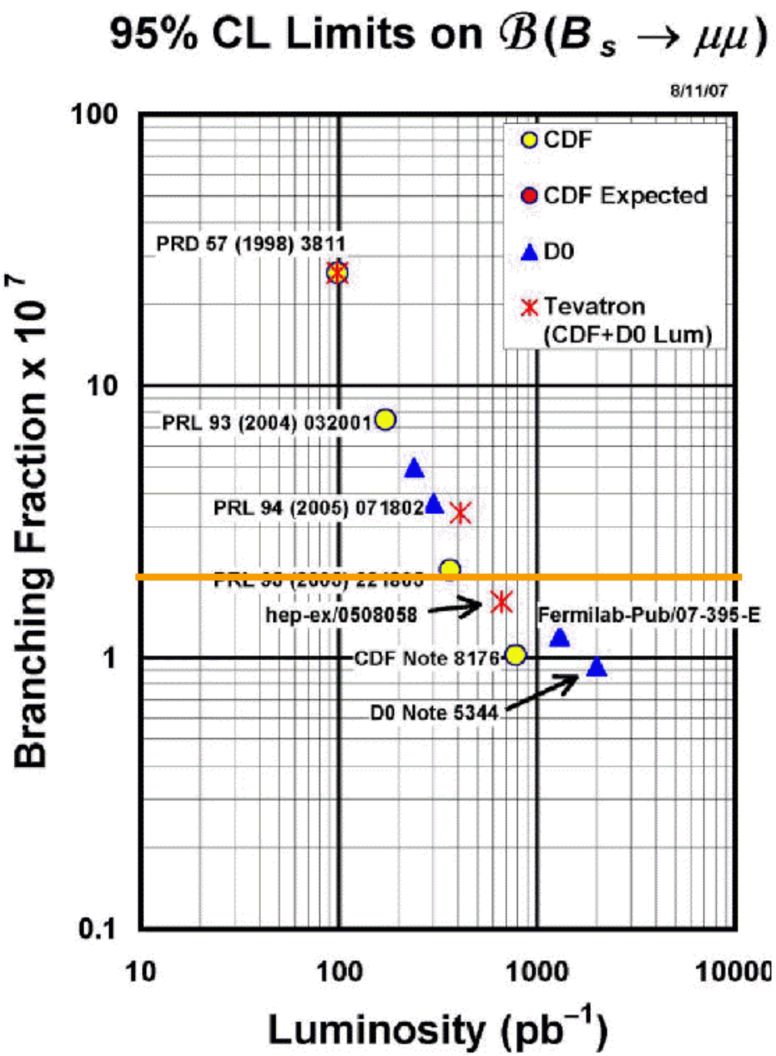
CDF Limit: 1.8×10^{-8} (95% C) 2fb-1

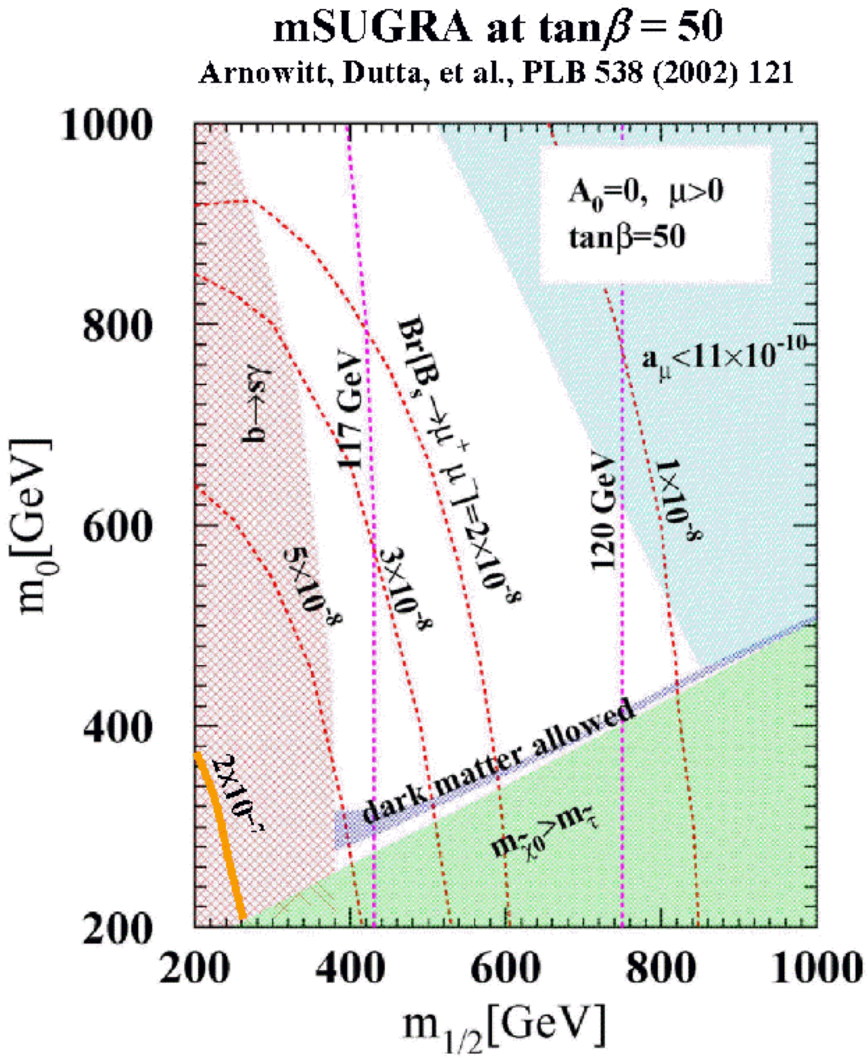
$B^0_s \rightarrow \mu^+\mu^-$

CDF Limit: 5.8×10^{-8} (95% CL) $2fb^{-1}$
D0 Limit: 9.8×10^{-8} (95% CL) $2fb^{-1}$



$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

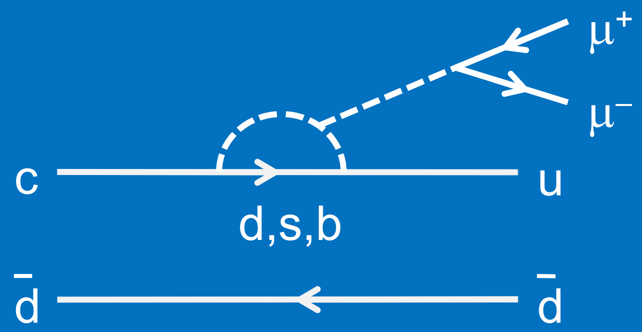




New physics in loops with down-type quarks?

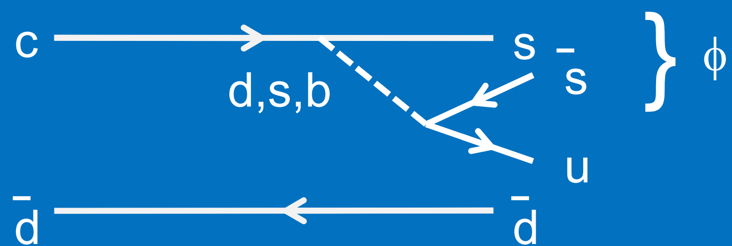
$D^+ \to \pi^+ \mu^+ \mu^-$

Phys. Rev. Lett. 100 , 101801 (2008)

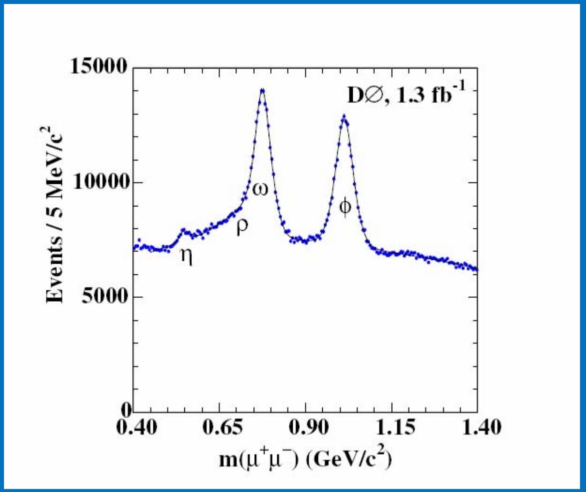


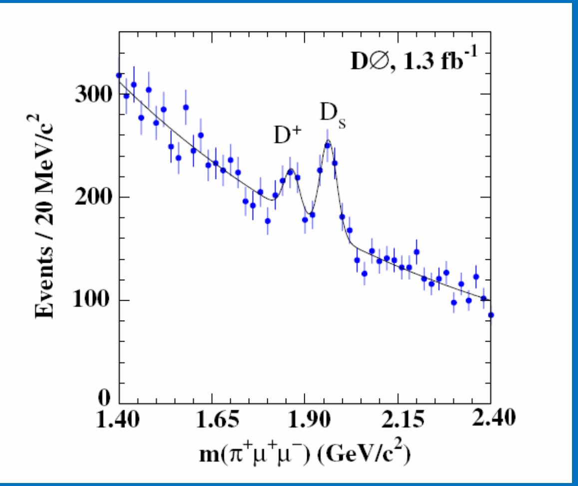
FCNC

SM O(10^{-9})



Background





$$\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}, \quad 90\% \text{ C.L.}$$

Mixing

There are two states in the B^0_s system, the so-called "Flavor eigenstates"

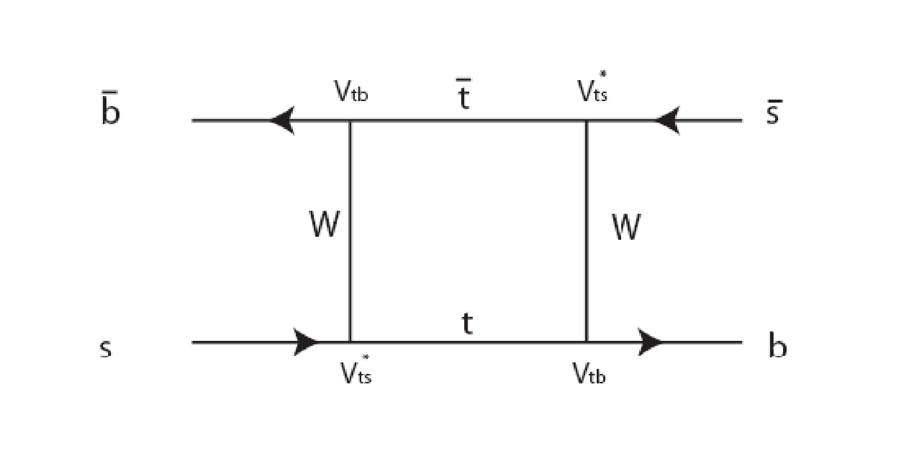
$$\left|B_s^{\,0}\right\rangle = \left|\bar{b}s\right\rangle$$
$$\left|\bar{B}_s^{\,0}\right\rangle = \left|b\bar{s}\right\rangle$$

They evolve according to the Schrödinger eqn

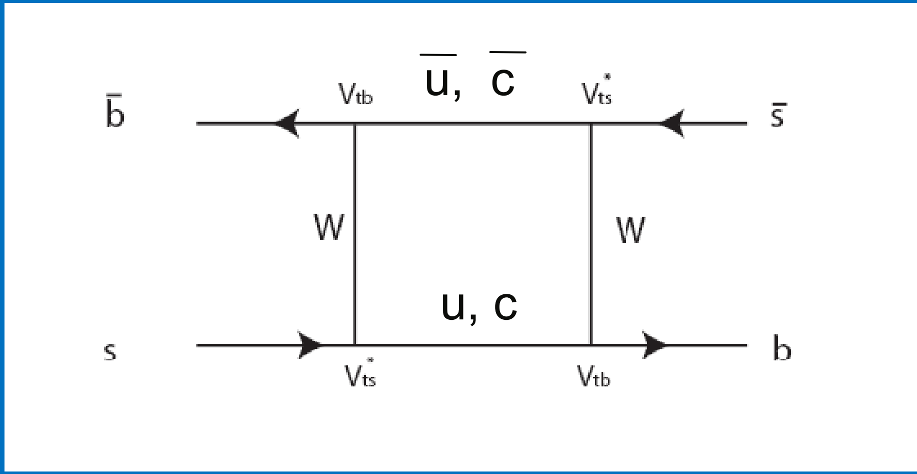
$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H \begin{pmatrix} a \\ b \end{pmatrix}$$

$$H = M - \frac{i}{2}\Gamma$$

and M, Γ Hermitian Matrices



M: Dispersive diagrams



Γ: Absorptive diagrams

$$\left|B^0{}_{S,L}\right\rangle = p\left|B_S{}^0\right\rangle + q\left|\bar{B}_S{}^0\right\rangle$$
$$\left|B^0{}_{S,H}\right\rangle = p\left|B_S{}^0\right\rangle - q\left|\bar{B}_S{}^0\right\rangle$$

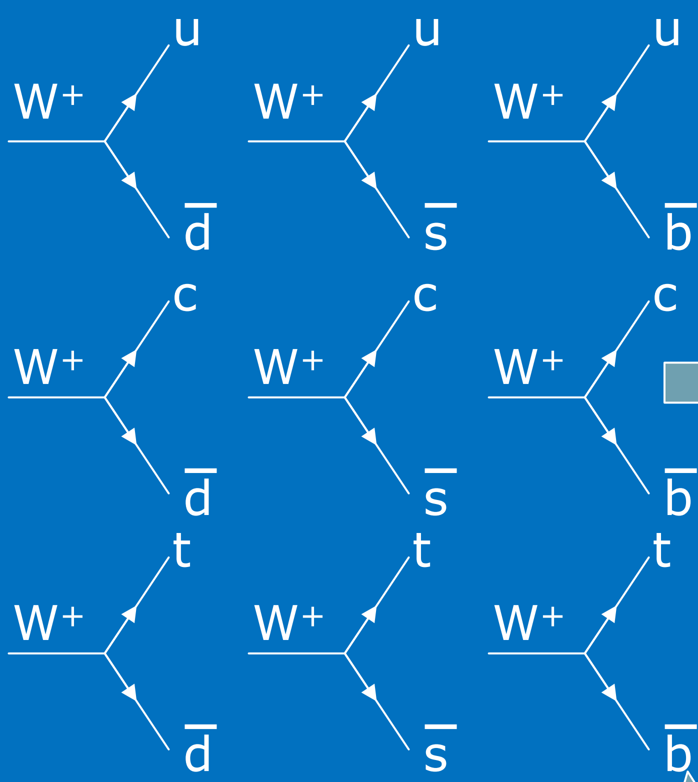
The magnitude of the box diagram gives the oscillation frequency Δm.

The phase of the diagram gives the complex number q/p, with magnitude of very nearly 1 (in the standard model).

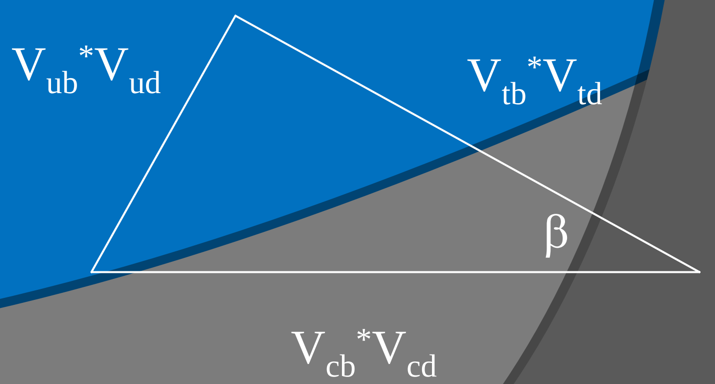
$$M_{12} = -\frac{G_F^2 M_W^2 \eta_B M_{B_0^s} B_{B_0^s} f_{B_0^s}^2}{12\pi^2} S_0\left(\frac{M_t^2}{M_W^2}\right)\left(V_{ts}^* V_{tb}\right)^2$$

$$\left(\frac{\Delta m}{2}\right)^2 = \left|M_{12}\right|^2 \qquad \frac{q}{p} = e^{-i\varphi_M} = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}$$

The chief prediction of the CKM model is that the CKM matrix is unitary, and that implies a number of constraints, including the "Unitarity Triangle"



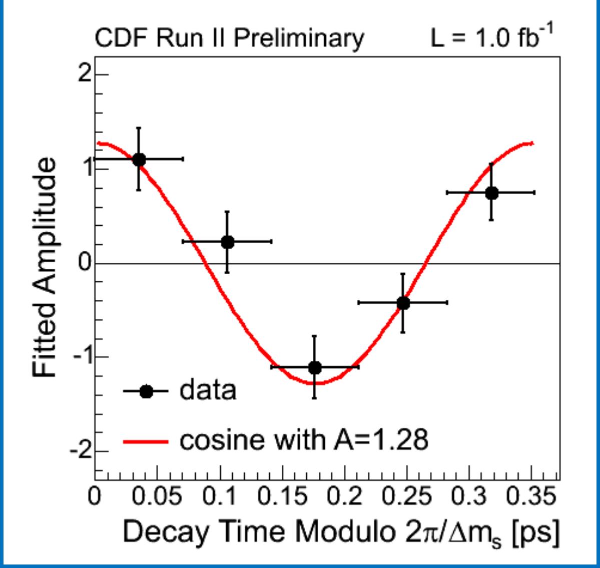
$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



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

Mixing is important to validate the CKM mechanism:

$$\frac{\Delta m_d}{\Delta m_S} = \frac{m_{B^0}}{m_{B^0_S}} \frac{\eta_{B^0}}{\eta_{B^0_S}} \frac{f^2_{B^0} B_{B^0}}{f^2_{B^0_S} B_{B^0_S}} \frac{|V_{td}|^2}{|V_{ts}|^2}.$$



Mixing probability

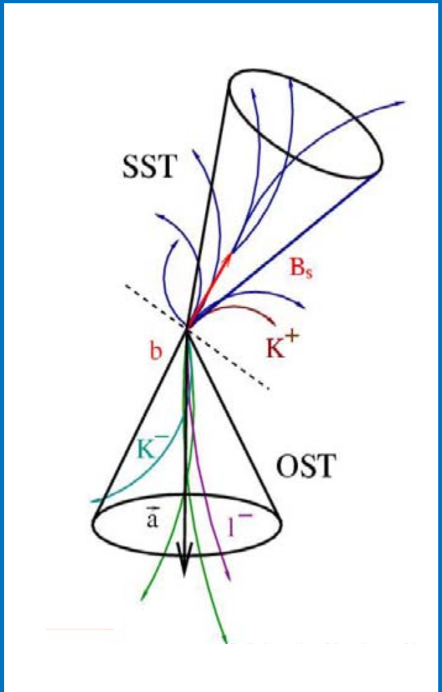
$$P(t) = \frac{1}{2\tau} e^{-t/\tau} (1 - \cos(\Delta m t))$$

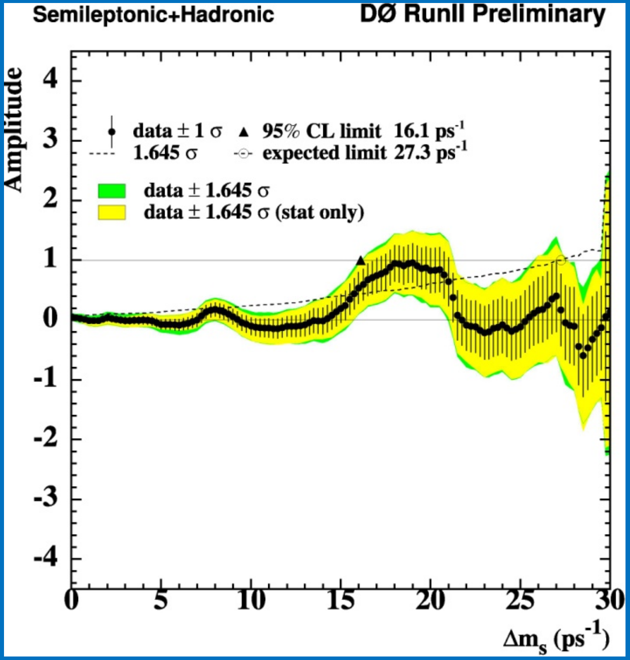
Mixing occurs when a B^0_s decays as a B^0_s.

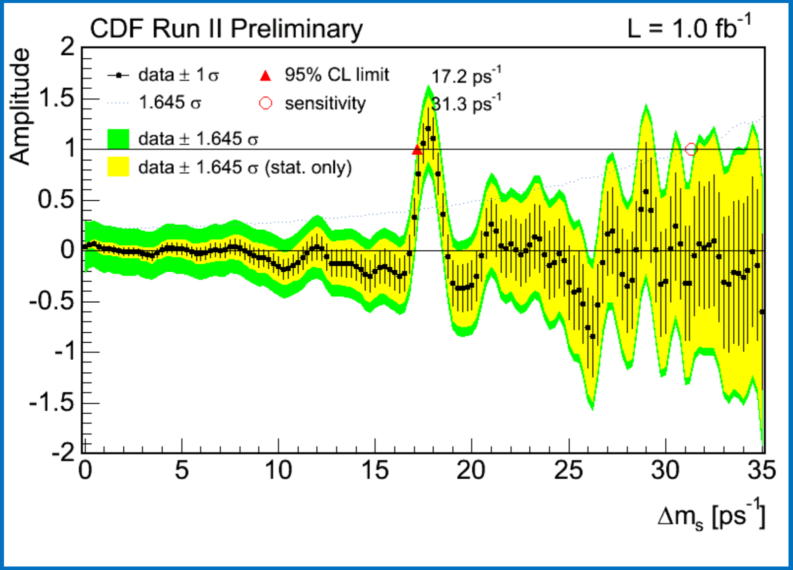
Decay to a flavor specific eigenstate tags the flavor at decay.

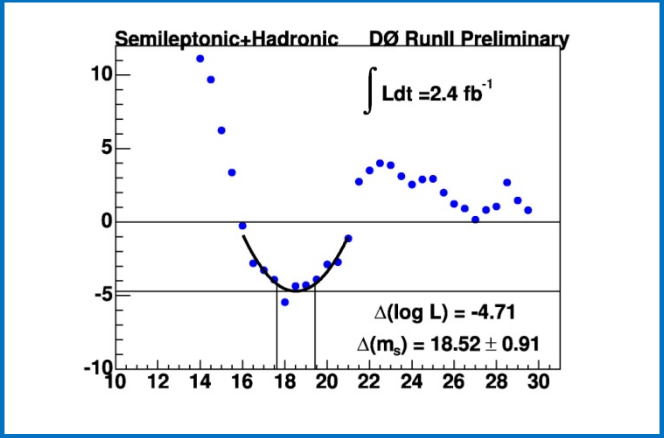
One of three tagging algorithms tags the flavor at production.

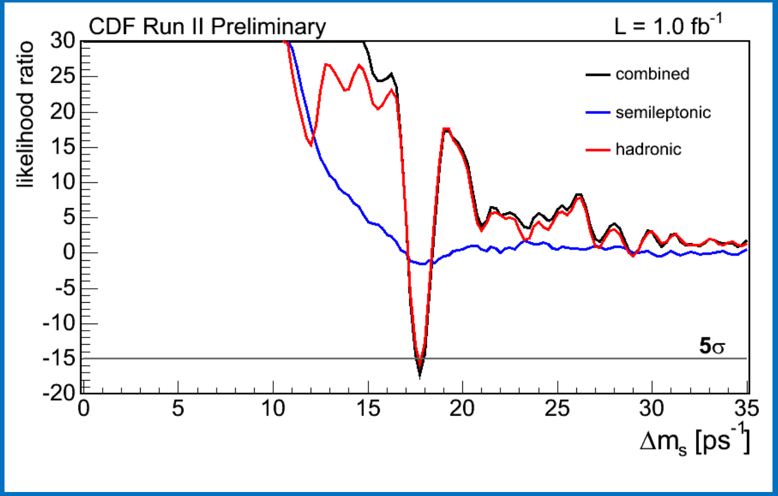
Good triggering, *full reconstruction of hadronic decays*, *excellent vertex resolution*, and *high dilution tagging* are all essential for this measurement, which made news in 2006.











$\Delta m_s = 18.56 \pm 0.87(\text{stat})\ \text{ps}^{-1}$

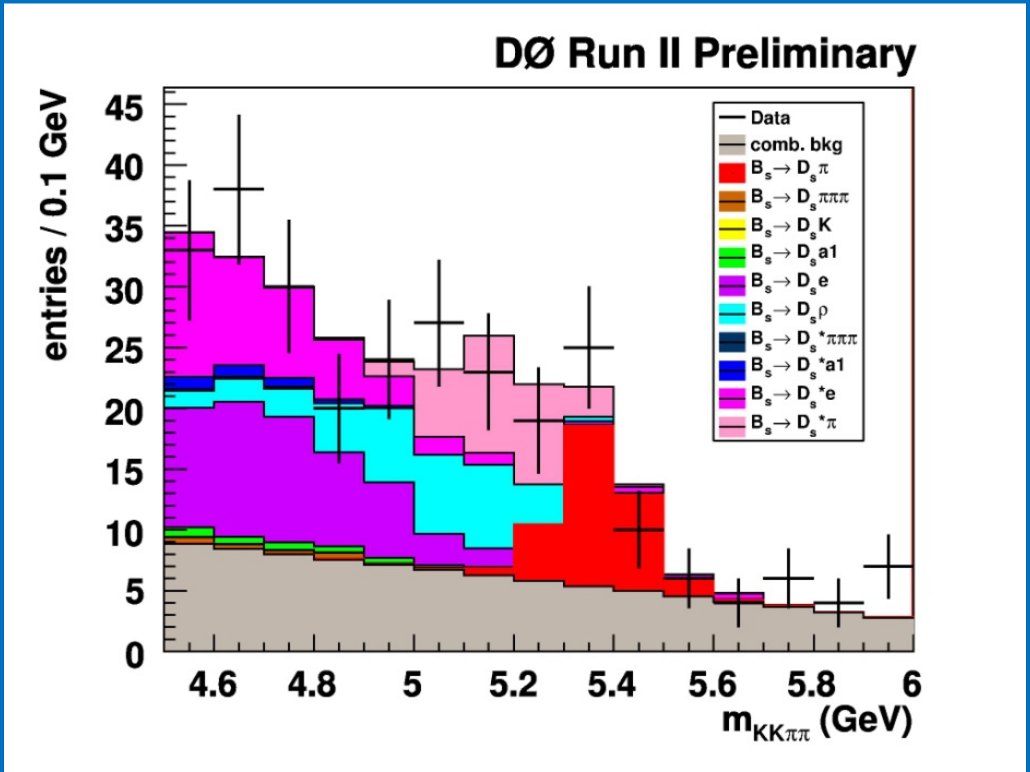
(D0 CONF Note 5474)

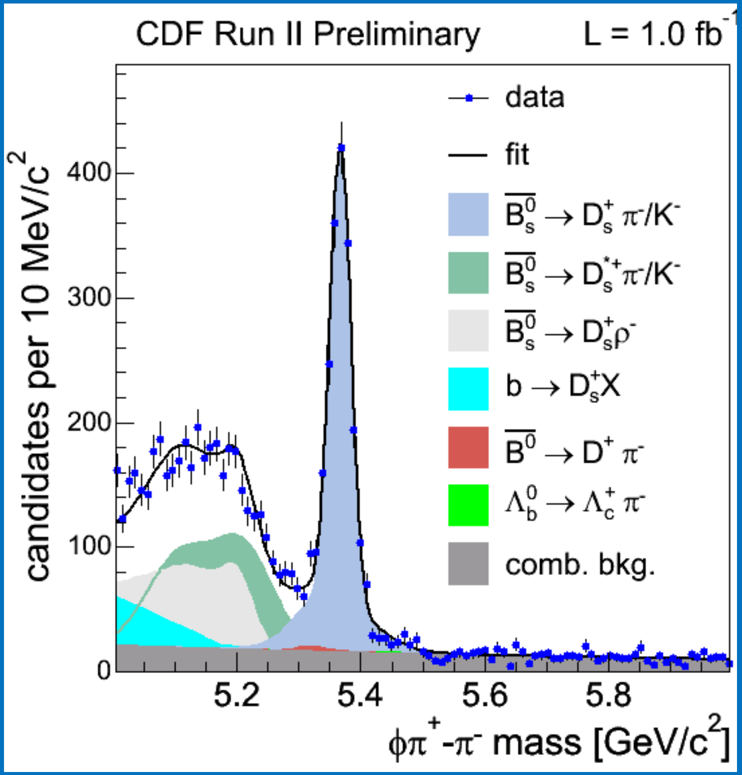
$\Delta m_s = 17.77 \pm 0.10(\text{sta}) \pm 0.07(\text{sys})\ \text{ps}^{-1}$

$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007\ (\text{exp}) + 0.0081 - 0.0060\ (\text{theor})$

(PRL 97, 242003 2006)

Role of the SVT Trigger /Momentum resolution can be easily seen from the mass plot of fully hadronic B decays from CDF and from D0:

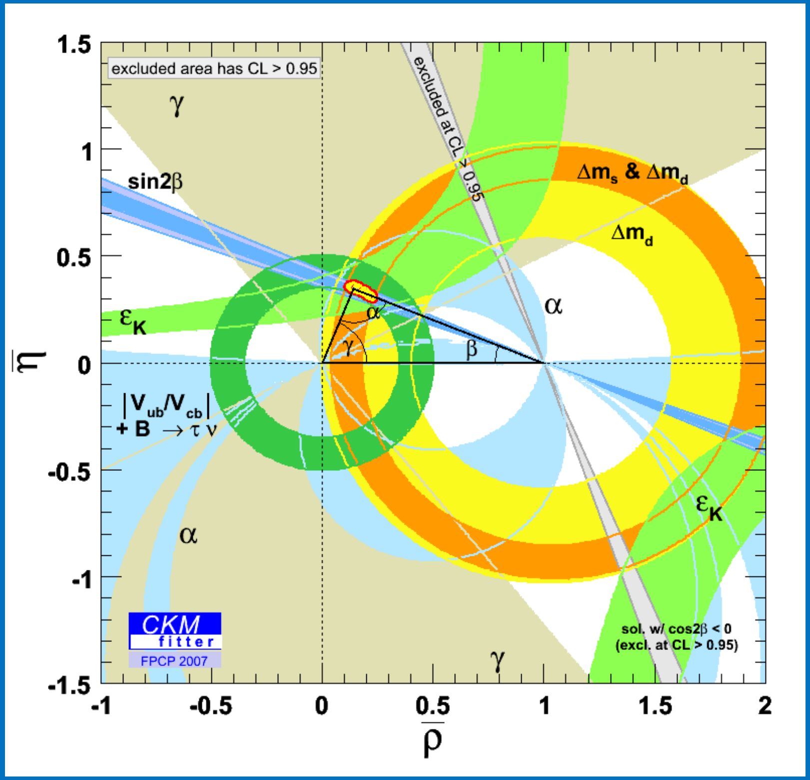




↑

These events are all opposite a trigger lepton, so they each have higher weight in a mixing analysis than this would suggest.

There are now various formulations summarizing the conclusions of a decade of running the B factories and the Tevatron, but



..the CKM mechanism seems to have survived a very stringent round of tests

➔The CKM Mechanism emerges as the dominant source in all processes covered in this summary plot.

CP Violation

There are 12 observed instances of CP violation:

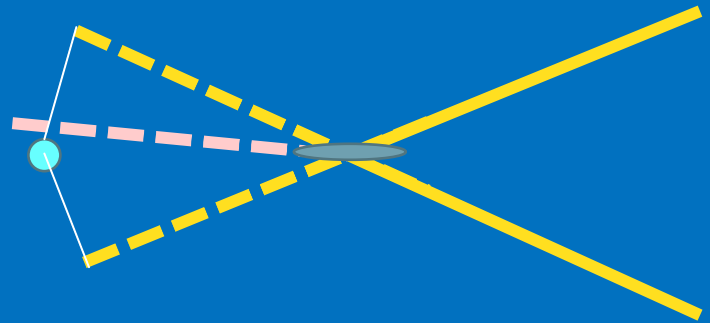
1. Indirect CP violation in the kaon system (ε_K)
2. Direct CP violation in the kaon system ε'/ε
3. CP Violation in the interference of mixing and decay in $B^0 \to J/\psi\ K^0$.
4. CP Violation in the interference of mixing and decay in $B^0 \to \eta' K^0$
5. CP Violation in the interference of mixing and decay in $B^0 \to K^+K^-K_s$
6. CP Violation in the interference of mixing and decay in $B^0 \to \pi^+\pi^-$
7. CP Violation in the interference of mixing and decay in $B^0 \to D^{*+}D^-$
8. CP Violation in the interference of mixing and decay in $B^0 \to f^0 K^0_s$
9. CP Violation in the interference of mixing and decay in $B^0 \to \psi\pi^0$
10. Direct CP Violation in the decay $B^0 \to K^-\pi^+$
11. Direct CP Violation in the decay $B \to \rho\pi$
12. Direct CP Violation in the decay $B \to \pi^+\pi^-$

Also:

Direct CP Violation in the decay $B^- \to K^-\pi^0$

Charmless Two-body decays

B→h^+h^-



Level 1 : Two tracks, opposite charge.

p_t > 2.0 for both tracks.

$p_t^1 + p_t^2$ > 5.5 GeV

$\delta\phi < 135^o$

Level 2 : Two body ($B^0 \to \pi^+\pi^-$)

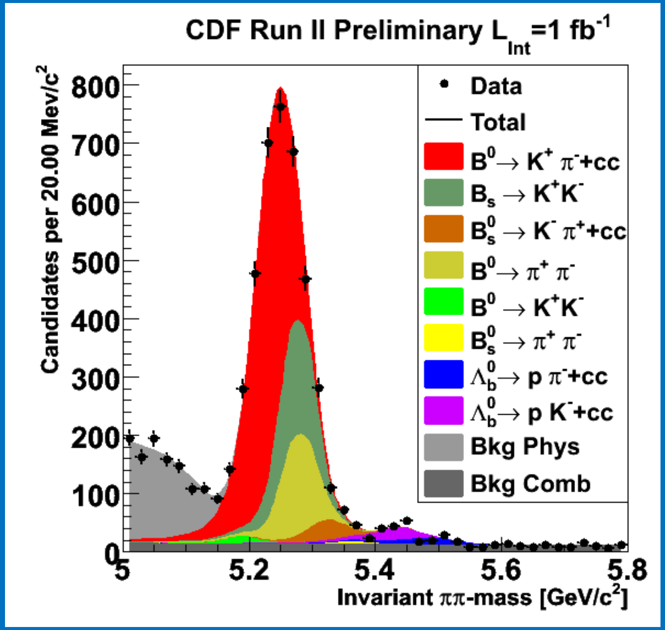
100 μm < $|d_0|$ < 1 mm

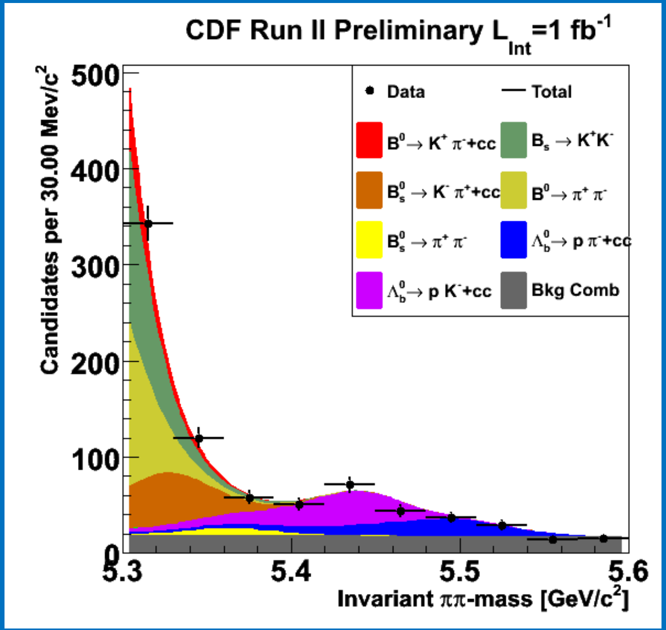
$\delta\phi > 20^o$

Positive L_{xy}

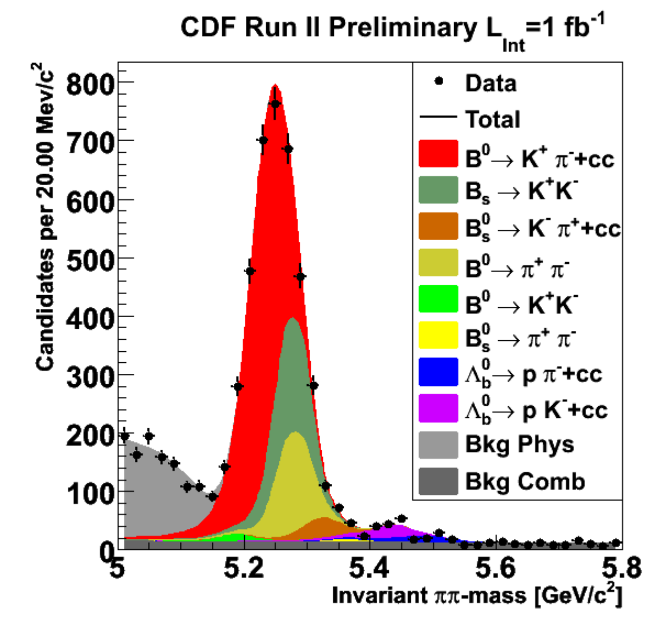
d_b < 140 μm.

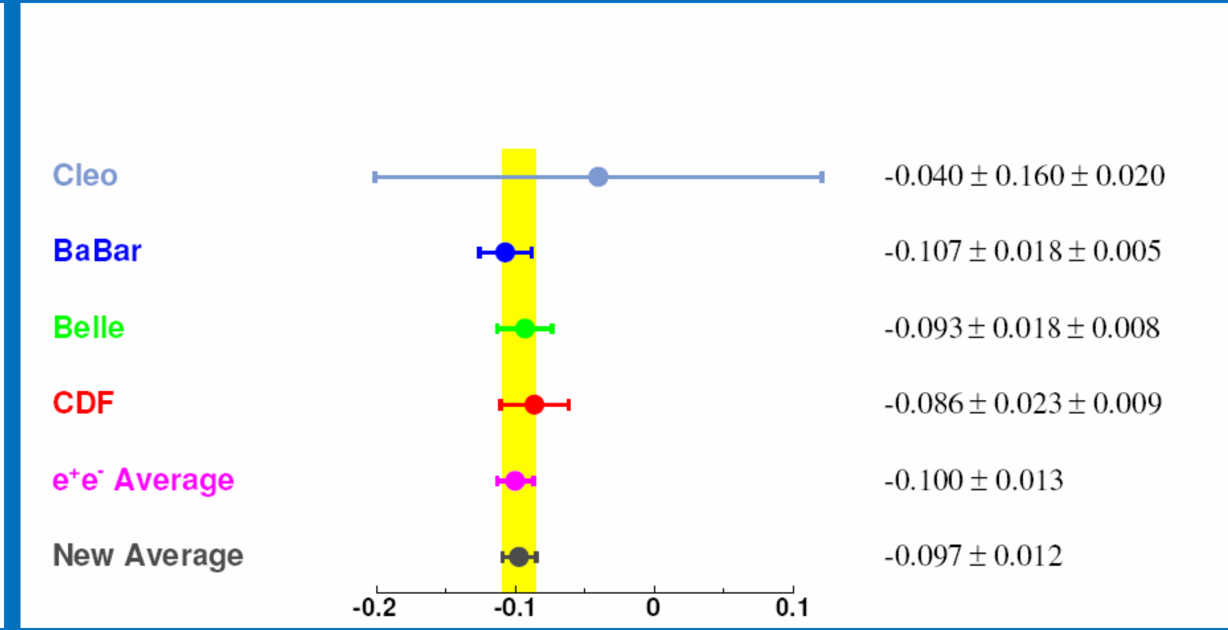
Many B^0, B^0_s, Λ_b decays pile up at practically the same mass. Use dE/dx and decay kinematics to separate them. Fit results:





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





$$A_{CP} = \frac{N(\bar{B}_s{}^0 \to K^+\pi^-) - N(B_s{}^0 \to K^-\pi^+)}{N(\bar{B}_s{}^0 \to K^+\pi^-) + N(B_s{}^0 \to K^-\pi^+)} = -0.39 \pm 0.015(stat) \pm 0.08(syst)$$

CP asymmetry measurement in B^0_s

$$A_{CP} = \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}\pi^+)}{\mathcal{B}(\Lambda_b^0 \to p\pi^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}\pi^+)} = 0.03 \pm 0.17(stat) \pm 0.05(syst)$$

$$A_{CP} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}K^+)} = 0.37 \pm 0.17(stat) \pm 0.03(syst)$$

First CP asymmetry measurements from baryons

CP Violation in B^0_s

Similar to the very famous measurement of sin(2β) in $B^0 \to J/\psi\, K^0$

- Full-fledged analysis requires flavor tagging.
- Δm_s is a required input.
- Analysis requires decays $B^0_s \to J/\psi\ \phi$ $J/\psi \to \mu^+\mu^-$ $\phi \to K^+K^-$
- Easy to collect with the dimuon trigger…

$B^0_s \rightarrow J/\psi\ \phi$.

B->V V decay to actually three distinct final states (S-wave, P-wave, and D-wave).

S,D Wave: CP even, short-lived, light.
P Wave: CP odd, long-lived, heavy.

These "final" states are actually intermediate states (final state is $\mu^+\mu^-K^+K^-$) so there is interference.

* Pure S, P,or D wave states would have distinct angular distributions.

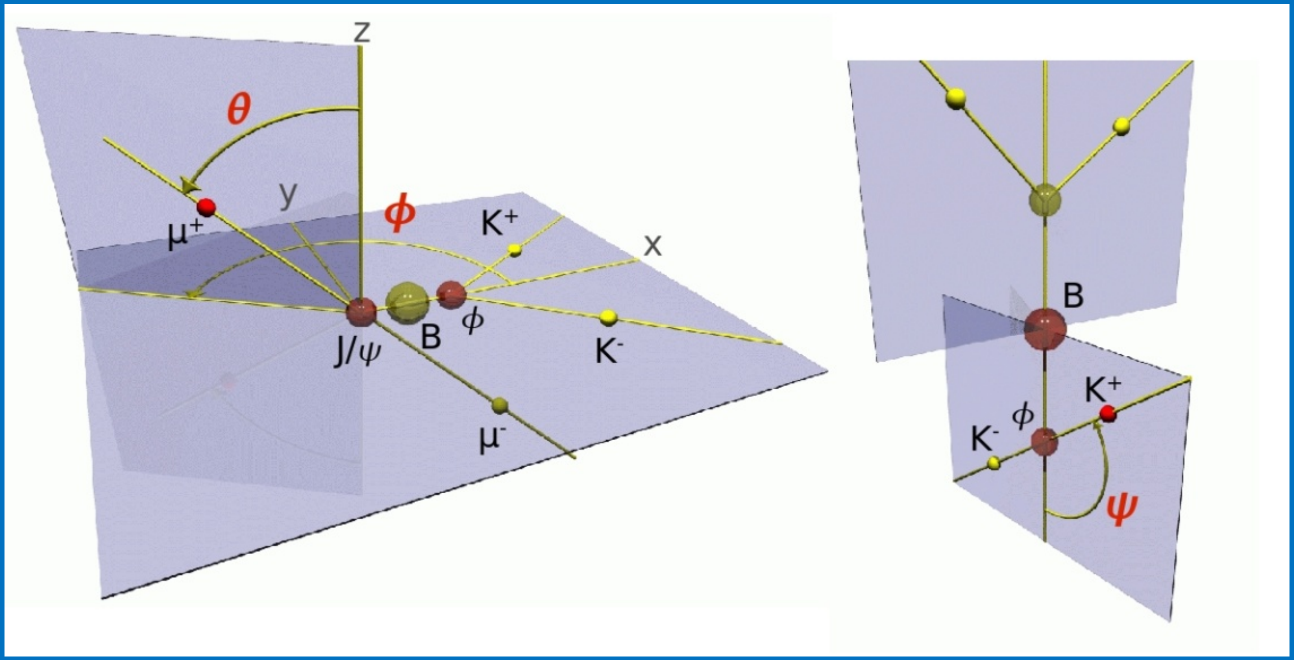
* With a mix of orbital angular momentum final states one can separate the decays on a statistical basis (angular analysis)

•Spin correlation of the vector mesons resembles that of the two photons two photons in positronium decay.

•Polarization of vector mesons can be perpendicular (CP odd), or parallel (CP even)

•And also longitudinal (CP even)

•Distributions in the angles θ, ϕ, and ψ sensitive to polarization.



A. S. Dighe, I. Dunietz, H. J. Lipkin, and J. L. Rosner, Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363.

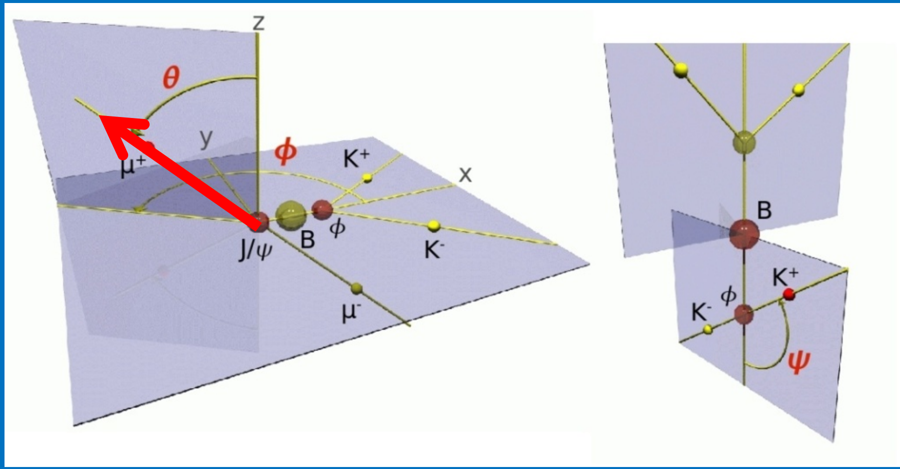
Time dependence of the angular distributions:

{ $A_\perp$, $A_{||}$, A_0 }: transition amplitude <B_s^0|P>to each final states { $P_\perp$, $P_{||}$, P_0 }

{ $\bar{A}_\perp$, $\bar{A}_{||}$, $\bar{A}_0$ }: transition amplitude <$\overline{B}_s^0$|P> " " " " " " " " " "

In the physical $B^0_{s,phys}$ meson the flavor content changes (B^0_s-$\overline{B^0}_s$ oscillations) with fast frequency of 17.77 ± 0.12 ps^{-1}

The amplitude <$B_{s,phys}^0(t)$|P> = A(t) (amplitude for a particle born as a B^0_s to decay into the state |P> after a time t) decays and oscillates.



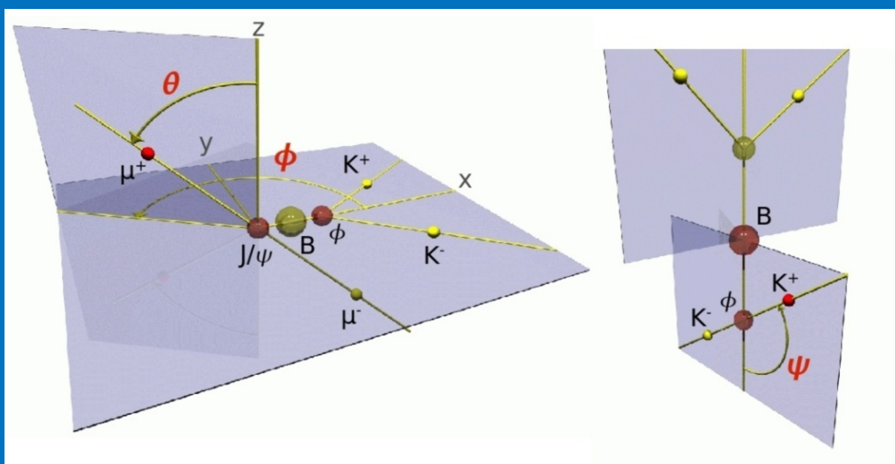
$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\phi, \cos\theta)$$

$$\vec{A} = (A_0(t)\cos\psi, \frac{-A_{||}(t)\sin\psi}{\sqrt{2}}, i\frac{A_\perp(t)}{\sqrt{2}})$$

$$P(\theta,\phi,\psi,t) = \frac{9}{16\pi}|\vec{A}(t)\times\hat{n}|^2$$

This innocent expression hides a lot of richness:

* CP Asymmetries through flavor tagging.
* sensitivity to ~~CP~~ without flavor tagging.
* sensitivity to *both* $\sin(2\beta_s)$ and $\cos(2\beta_s)$ simultaneously.
* Width difference
* Mixing Asymmetries



$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\phi, \cos\theta)$$

$$\vec{A} = (A_0(t)\cos\psi, \frac{-A_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{A_\perp(t)}{\sqrt{2}})$$

$$P(\theta,\phi,\psi,t) = \frac{9}{16\pi}|\vec{A}(t)\times\hat{n}|^2$$

… formula suggests an analysis of an oscillating polarization.

CP Violation in the interference of mixing and decay for the B^0_s system

Take: q/p from the mixing of $\overline{B^0}_s$ - B^0_s

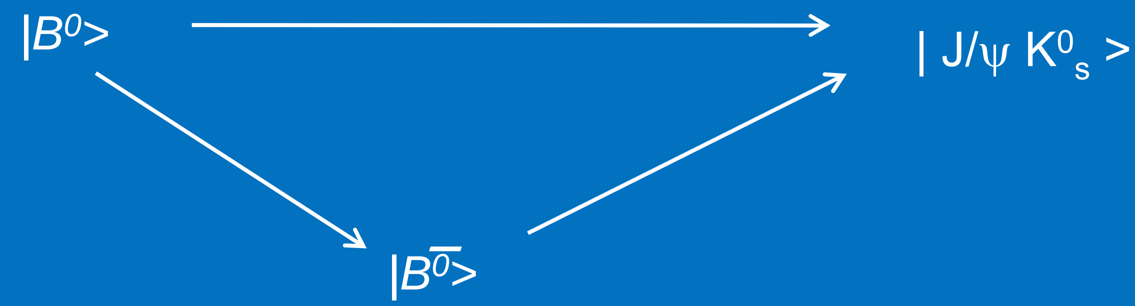
Take: $\bar{A}/A$ from the decay into $\{ P_\perp, P_{||}, P_0 \}$

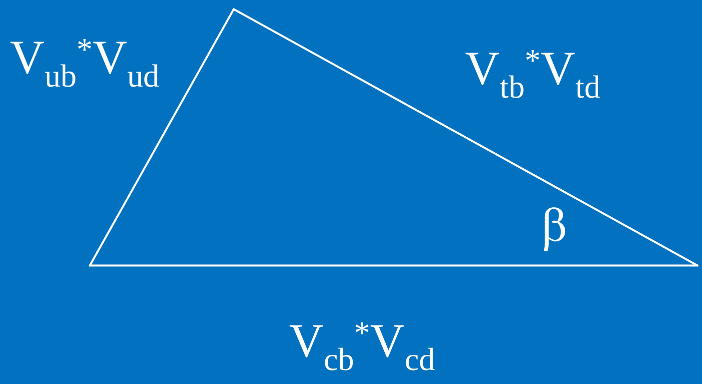
Form: the (phase) convention-independent and observable quantity:

$$\lambda = \frac{q}{p}\frac{\bar{A}}{A}$$

This number is real and unimodular if [H,CP]=0

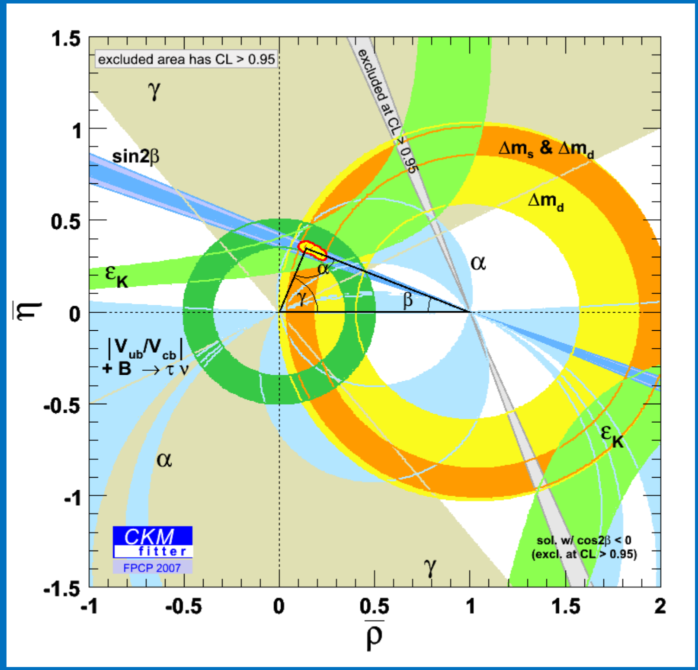
Many of the “new” CP observables are “CP violation in the interference of mixing and decay”:





BABAR, BELLE have used this decay to measure precisely the value of sin(2β) an angle of the **bd** unitarity triangle

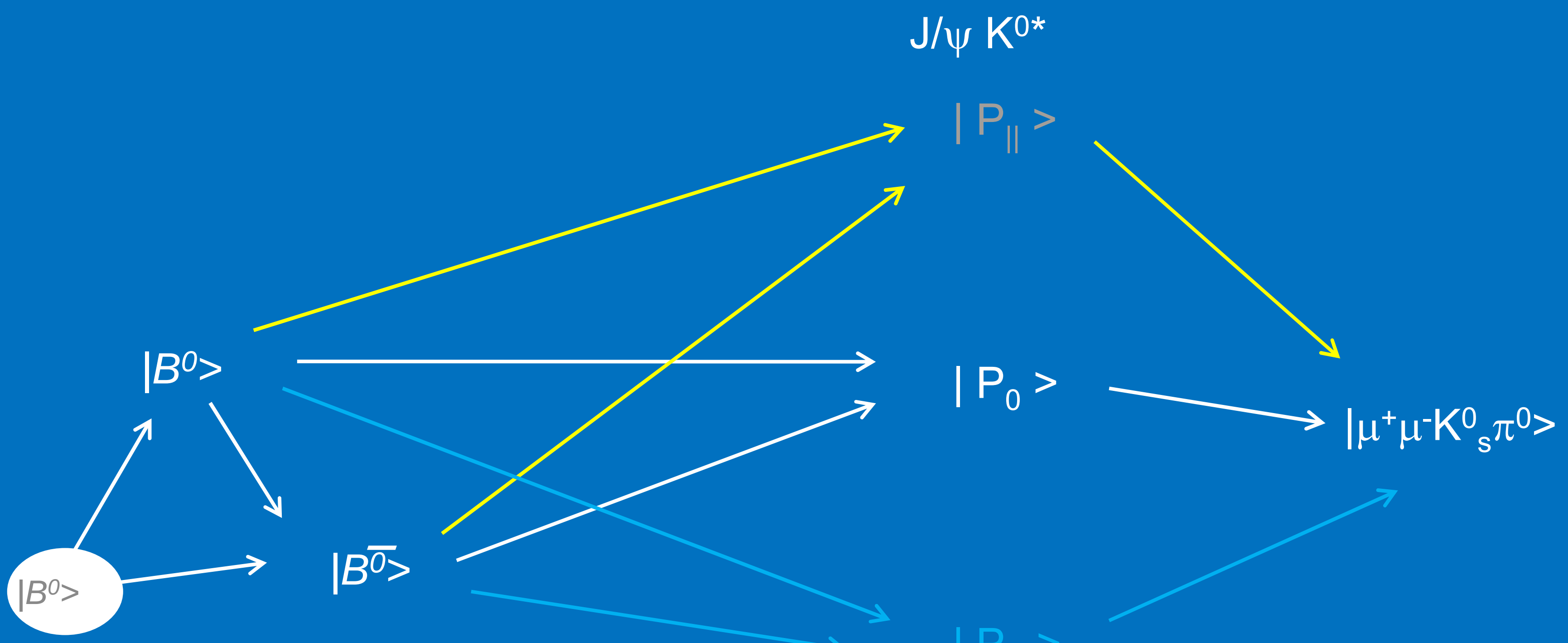
There was a 4-fold ambiguity in that measurement.➔



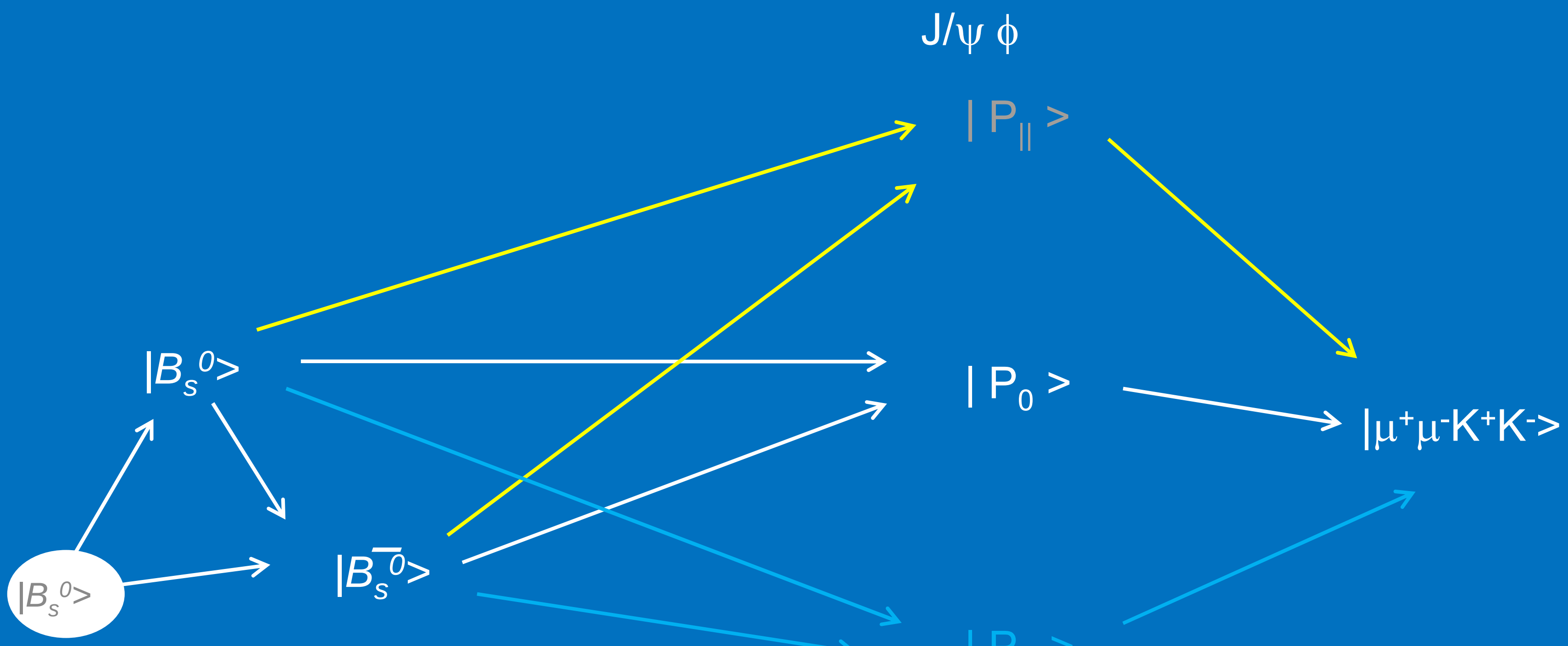
Babar, Belle removed this ambiguity by analyzing the decay

$B^0 \to J/\psi\, K^{0*}$ which is $B \to V\, V$ and measures $\sin(2\beta)$ and $\cos(2\beta)$

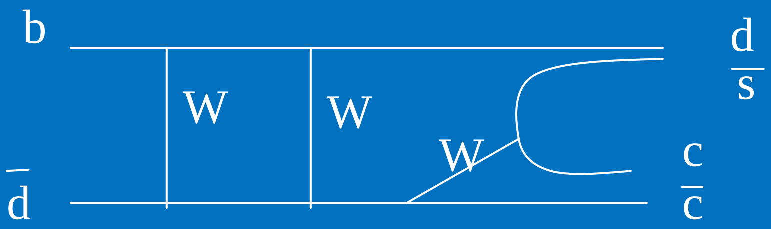
This involves angular analysis as described previously



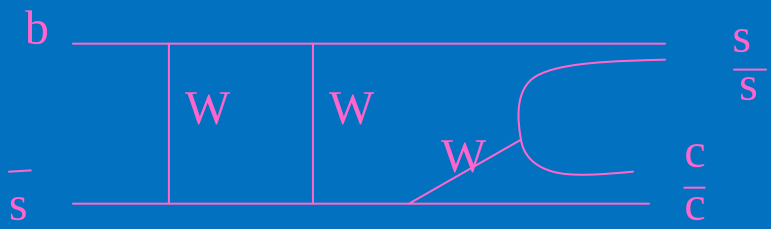
Today I will tell you about an analysis of an almost exact analogy, $|B_s^0\rangle \rightarrow J/\psi\ \phi$ (but I think that in the B^0_s system the phenomenology is even richer! Because of the width difference!)



The decay $B^0{}_s \to J/\psi\ \phi$ obtains from the decay $B^0 \to J/\psi\ K^{0*}$ by the replacement of a d antiquark by an s antiquark

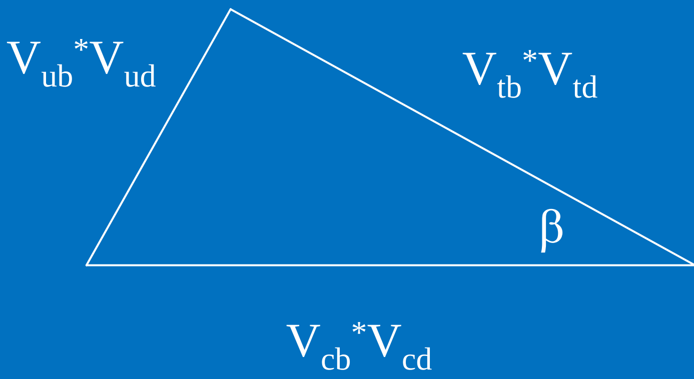


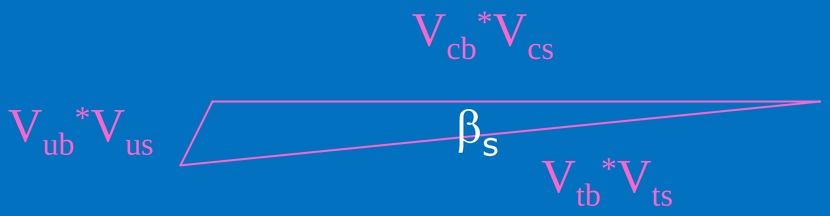
$B^0 \to J/\psi\ K^{0*}$



$B^0 \to J/\psi\ \phi$

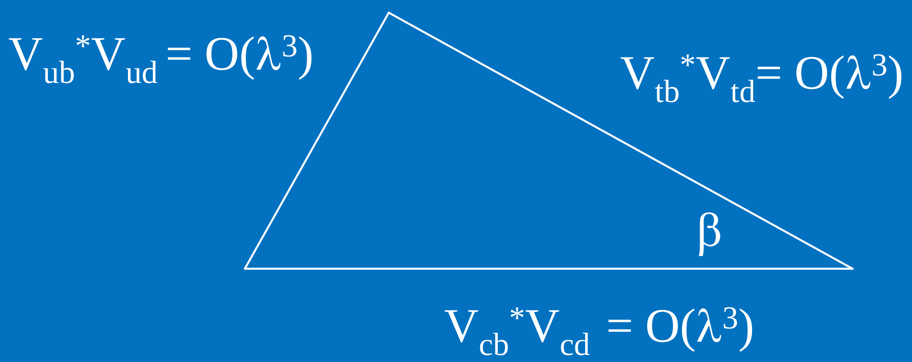
We are measuring then not the bd unitarity triangle but the bs unitarity triangle:

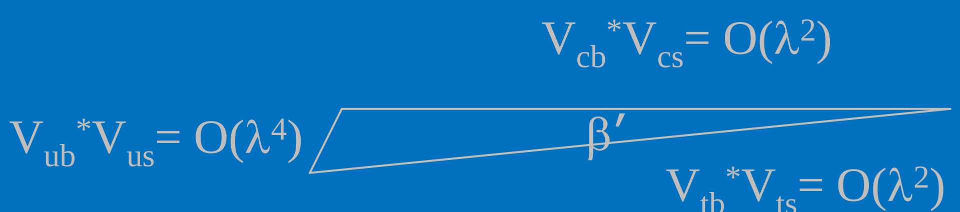




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}.$$





With $\lambda = 0.2272 \pm 0.0010$

$A = 0.818\ (+0.007\ -0.017)$

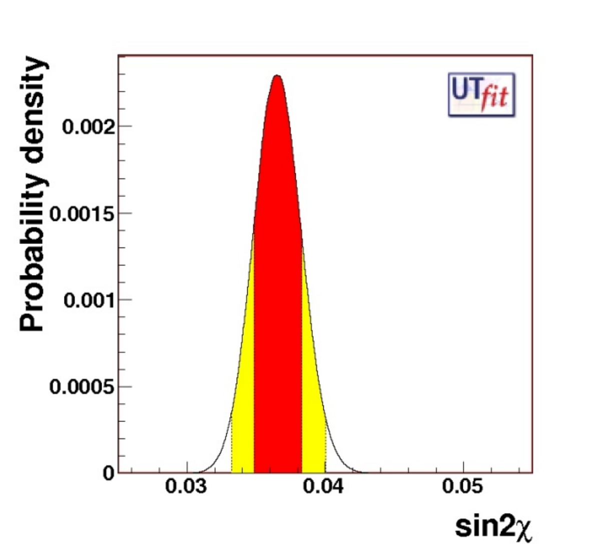
$\rho = 0.221\ (+0.064 -0.028)$

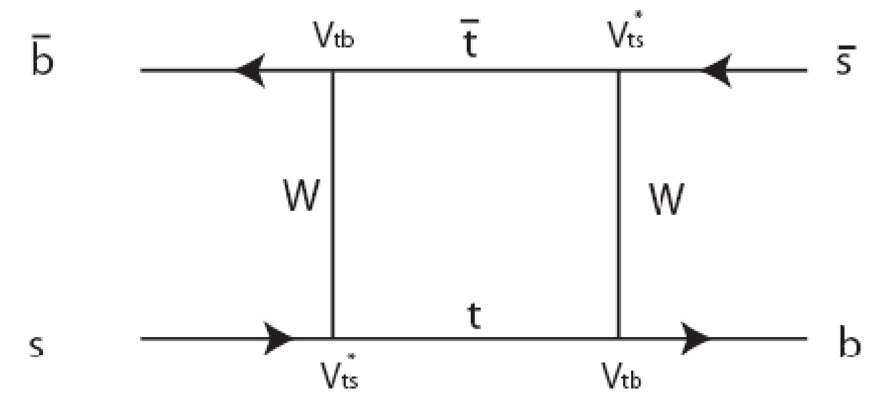
$\eta = 0.340\ (+0.017 -0.045)$

One easily obtains a prediction for β_s :

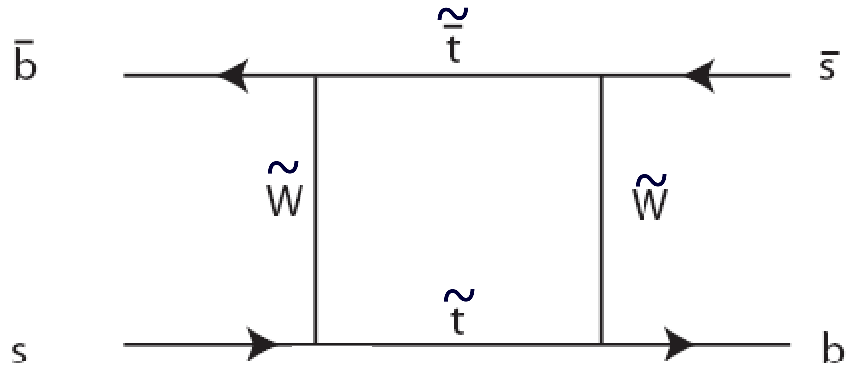
$$2\beta_s = 0.037 \pm 0.002$$

β_s, the phase of V_{ts} is expected to be close to zero in the standard model. and should not lead to detectable CP violation.





Small phase, small CP violation



Flavor structure of BSM physics unknown

However there may be other contributions to CP violation from other sources;

This is what makes this an important measurement.

“Hidden richness”

reference material

$$\hat{n} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$

$$\vec{A}(t) = (A_0(t)\cos\psi, -\frac{A_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{A_\perp(t)}{\sqrt{2}})$$

$$P(\theta,\varphi,\psi,t) = \frac{9}{16\pi}|\vec{A}(t)\times\hat{n}|^2$$

$$A_i(t) = \frac{a_i e^{-imt}e^{-\Gamma t/2}}{\sqrt{\tau_H+\tau_L\pm\cos 2\beta_s\cdot(\tau_L-\tau_H)}}\left[E_+(t)\pm e^{2i\beta'}E_-(t)\right]$$ B

$$\bar{A}_i(t) = \frac{a_i e^{-imt}e^{-\Gamma t/2}}{\sqrt{\tau_H+\tau_L\pm\cos 2\beta_s\cdot(\tau_L-\tau_H)}}\left[\pm E_+(t)+e^{-2i\beta_s}E_-(t)\right]\cdot$$ $\bar{B}$

where i = 0, para, perp and

$$E_\pm(t) = \frac{1}{2}\left[e^{+(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2})t} \pm e^{-(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m}{2})t}\right]$$

An analysis of the decay can be done with either a mix of B and $\bar{B}$ mesons (untagged) or with a partially separated sample (flavor tagged). Latter is more difficult and more powerful.

These expressions are:

* used directly to generate simulated events.

* expanded, smeared, and used in a Likelihood function.

* summed over B and $\bar{B}$ (untagged analysis only)

reference material

$$\mathbf{A}(t) = \mathbf{A}_+(t) + \mathbf{A}_-(t), \quad \bar{\mathbf{A}}(t) = \bar{\mathbf{A}}_+(t) + \bar{\mathbf{A}}_-(t)$$

$$\mathbf{A}_+(t) = \mathbf{A}_+ f_+(t) = (a_0 \cos\psi, -\frac{a_\parallel \sin\psi}{\sqrt{2}}, 0) \cdot f_+(t)$$

$$\bar{\mathbf{A}}_+(t) = \bar{\mathbf{A}}_+ \bar{f}_+(t) = (a_0 \cos\psi, -\frac{a_\parallel \sin\psi}{\sqrt{2}}, 0) \cdot \bar{f}_+(t),$$

$$\mathbf{A}_-(t) = \mathbf{A}_- f_-(t) = (0, 0, i\frac{a_\perp \sin\psi}{\sqrt{2}}) \cdot f_-(t)$$

$$\bar{\mathbf{A}}_-(t) = \bar{\mathbf{A}}_- \bar{f}_-(t) = (0, 0, i\frac{a_\perp \sin\psi}{\sqrt{2}}) \cdot \bar{f}_-(t).$$

obtain the overall time and angular dependence

$$\begin{aligned} P(\theta,\psi,\phi,t) &= \frac{9}{16\pi}\left\{|\mathbf{A}_+(\mathbf{t}) \times \hat{n}|^2 + |\mathbf{A}_-(\mathbf{t}) \times \hat{n}|^2 + 2Re((\mathbf{A}_+(\mathbf{t}) \times \hat{n}) \cdot (\mathbf{A}_-^*(\mathbf{t}) \times \hat{n}))\right\} \\ &= \frac{9}{16\pi}\left\{|\mathbf{A}_+ \times \hat{n}|^2 |f_+(t)|^2 + |\mathbf{A}_- \times \hat{n}|^2 |f_-(t)|^2 + 2Re((\mathbf{A}_+ \times \hat{n}) \cdot (\mathbf{A}_-^* \times \hat{n}) \cdot f_+(t) \cdot f_-^*(t))\right\}. \end{aligned}$$

and

$$\begin{aligned} P(\theta,\psi,\phi,t) &= \frac{9}{16\pi}\left\{|\bar{\mathbf{A}}_+(t) \times \hat{n}|^2 + |\bar{\mathbf{A}}_-(t) \times \hat{n}|^2 + 2Re(\bar{\mathbf{A}}_+(t) \times \hat{n}) \cdot (\bar{\mathbf{A}}_-^*(t) \times \hat{n}))\right\} \\ &= \frac{9}{16\pi}\left\{|\mathbf{A}_+ \times \hat{n}|^2 |\bar{f}_+(t)|^2 + |\mathbf{A}_- \times \hat{n}|^2 |\bar{f}_-(t)|^2 + 2Re((\mathbf{A}_+ \times \hat{n}) \cdot (\mathbf{A}_-^* \times \hat{n}) \cdot \bar{f}_+(t) \cdot \bar{f}_-^*(t)\right\}. \end{aligned}$$

reference material

Explicit time dependence is here:

where the diagonal terms are:

$$|\bar{f}_{\pm}(t)|^2 = \frac{1}{2}\frac{(1 \pm \cos 2\beta_s)e^{-\Gamma_L t} + (1 \mp \cos 2\beta_s)e^{-\Gamma_H t} \pm 2\sin 2\beta_s e^{-\Gamma t}\sin \Delta m t}{\tau_L(1 \pm \cos 2\beta_s) + \tau_H(1 \mp \cos 2\beta_s)},$$

$$|f_{\pm}(t)|^2 = \frac{1}{2}\frac{(1 \pm \cos 2\beta_s)e^{-\Gamma_L t} + (1 \mp \cos 2\beta_s)e^{-\Gamma_H t} \mp 2\sin 2\beta_s e^{-\Gamma t}\sin \Delta m t}{\tau_L(1 \pm \cos 2\beta_s) + \tau_H(1 \mp \cos 2\beta_s)}.$$

and the cross-terms, or interference terms, are: $f_+(t)f_-^*(t)$. For $\bar{B}$ and B, those terms are

$$\bar{f}_+(t)\bar{f}_-{}^*(t) = \frac{-e^{-\Gamma t}\cos \Delta m t - i\cos 2\beta_s e^{-\Gamma t}\sin \Delta m t + i\sin 2\beta_s(e^{-\Gamma_L t} - e^{-\Gamma_H t})/2}{\sqrt{[(\tau_L - \tau_H)\sin 2\beta_s]^2 + 4\tau_L\tau_H}},$$

$$f_+(t)f_-^*(t) = \frac{e^{-\Gamma t}\cos \Delta m t + i\cos 2\beta_s e^{-\Gamma t}\sin \Delta m t + i\sin 2\beta_s(e^{-\Gamma_L t} - e^{-\Gamma_H t})/2}{\sqrt{[(\tau_L - \tau_H)\sin 2\beta_s]^2 + 4\tau_L\tau_H}}.$$

… then, replace exp, sin*exp, cos*exp with smeared functions

The analysis of $B^0_s \to J/\psi\ \phi$ can extract these physics parameters:

β_s	CP phase
$\Delta\Gamma=\Gamma_H-\Gamma_L$	Width difference
$\tau=2/(\Gamma_H+\Gamma_L)$	Average lifetime
$A_\perp$ (phase $\delta_\perp$)	Decay Amplitude t=0
$A_\parallel$ (phase $\delta_\parallel$)	Decay Amplitude t=0
A_0 (phase 0)	Decay Amplitude t=0

The exact symmetry..

$$\begin{aligned} \beta_s &\to \frac{\pi}{2} - \beta_s, \\ \Delta\Gamma &\to -\Delta\Gamma, \\ \delta_{||} &\to 2\pi - \delta_{||}, \\ \delta_\perp &\to \pi - \delta_\perp. \end{aligned}$$

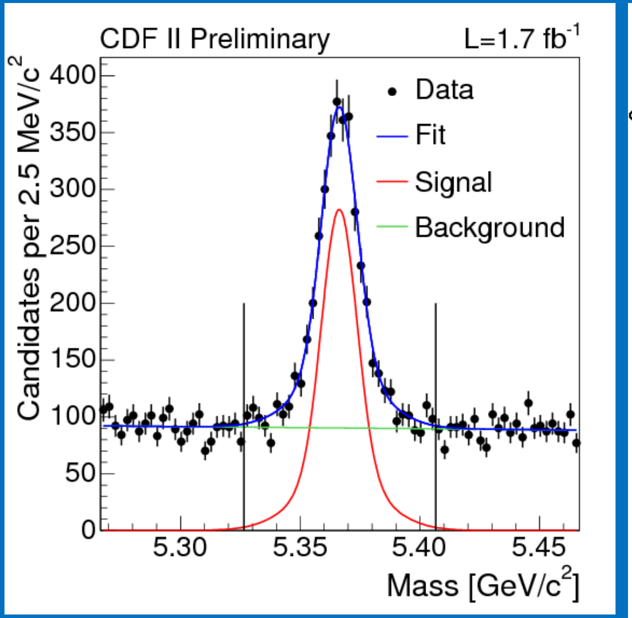
… is an experimental headache.

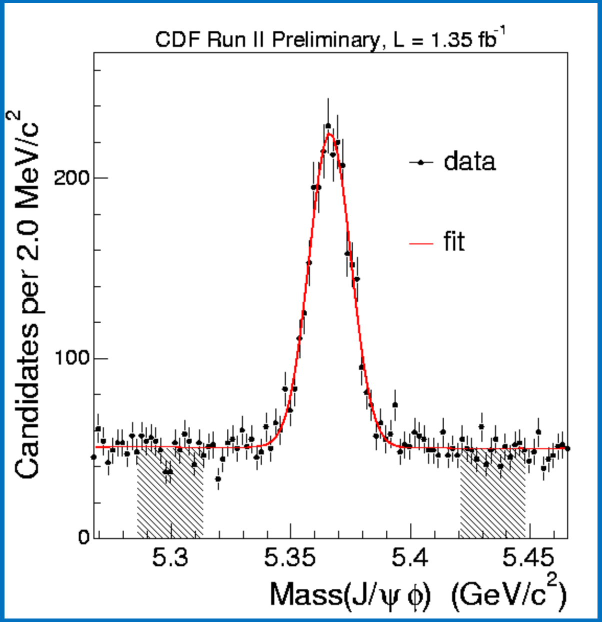
Curiosity #1: $\cos(2\beta_s)$ is easier to measure than $\sin(2\beta_s)$. It can be done in the untagged analysis for which the PDF contains time dependent terms:

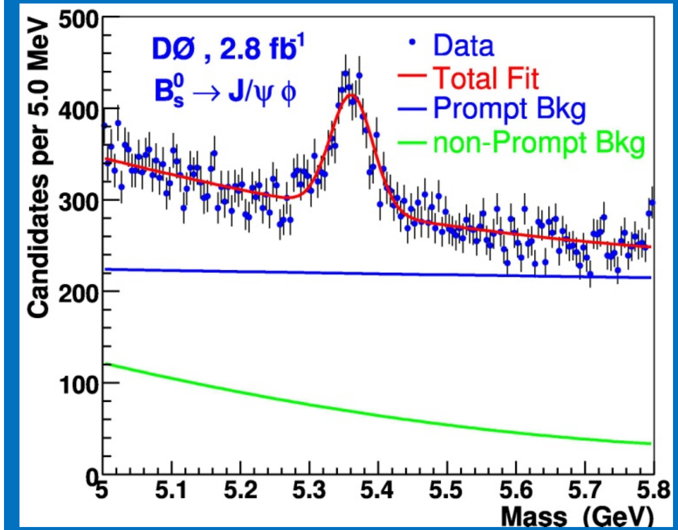
$$|\bar{f}_\pm(t)|^2 = \frac{1}{2}\frac{(1 \pm \cos 2\beta_s)e^{-\Gamma_L t} + (1 \mp \cos 2\beta_s)e^{-\Gamma_H t} \pm 2\sin 2\beta_s e^{-\Gamma t}\sin \Delta m t}{\tau_L(1 \pm \cos 2\beta_s) + \tau_H(1 \mp \cos 2\beta_s)},$$

$$|f_\pm(t)|^2 = \frac{1}{2}\frac{(1 \pm \cos 2\beta_s)e^{-\Gamma_L t} + (1 \mp \cos 2\beta_s)e^{-\Gamma_H t} \mp 2\sin 2\beta_s e^{-\Gamma t}\sin \Delta m t}{\tau_L(1 \pm \cos 2\beta_s) + \tau_H(1 \mp \cos 2\beta_s)}.$$

Physically this is accessible because one particular lifetime state (long or short) decays to the "wrong" angular distributions. Needs $\Delta\Gamma \neq 0$; no equivalent in $B^0 \to J/\psi\, K^{0*}$.







CDF, 2506 ± 51 events total..

… but 2019 ± 73 tagged

.. And in D0, 1967 ± 65 events, all tagged.

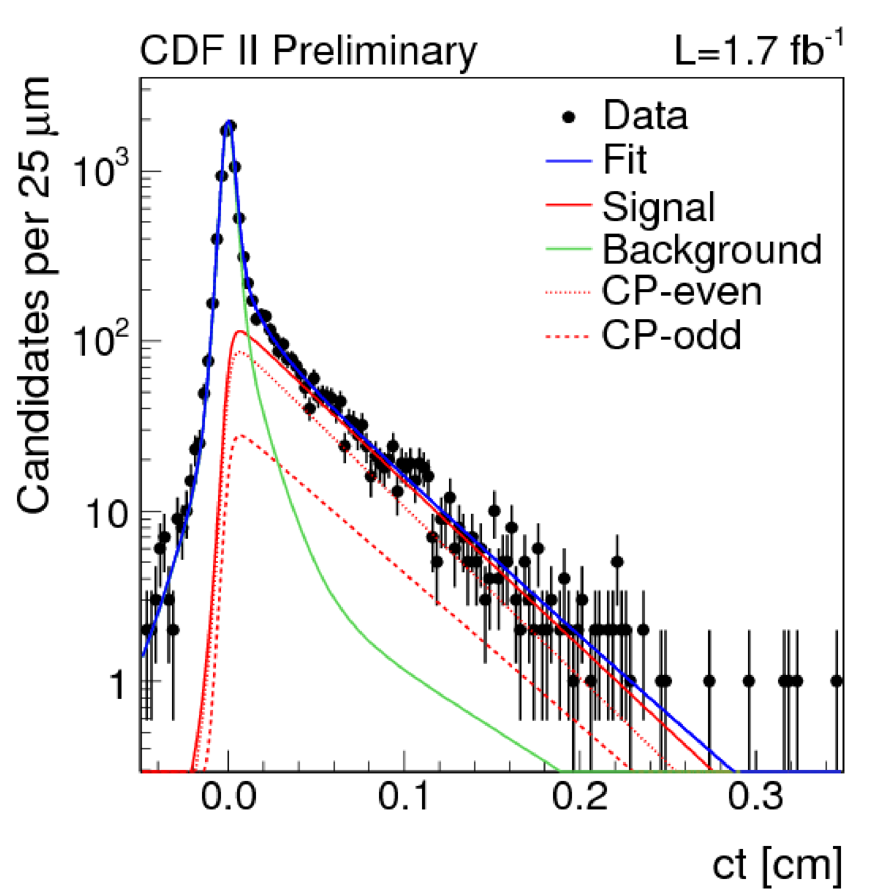
Next, we'll run through the CDF analysis, show what you get from flavor tagging, then show the D0 results.

Results untagged analysis

Phys. Rev. Lett. 100, 121803 (2008).

Standard Model Fit (no CP violation)

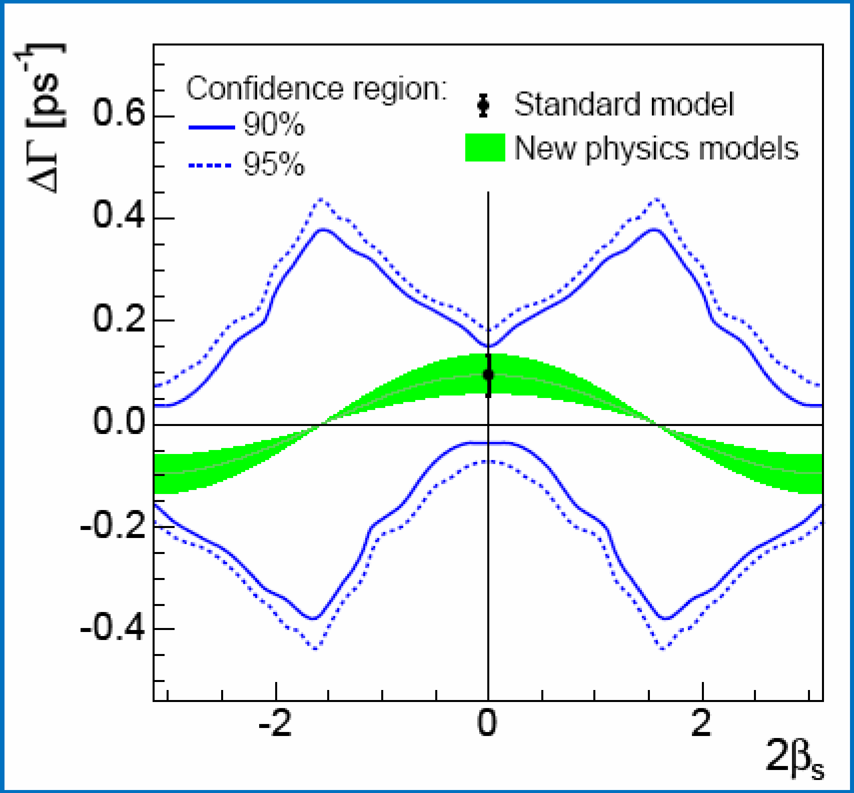
$$c\tau_s = 456 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.})\ \mu m$$
$$\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}\ (\text{stat.}) \pm 0.006\ (\text{syst.})\ ps^{-1}$$



HQET: $c\tau(B^0_s) = (1.00 \pm 0.01)\ c\tau(B^0)$

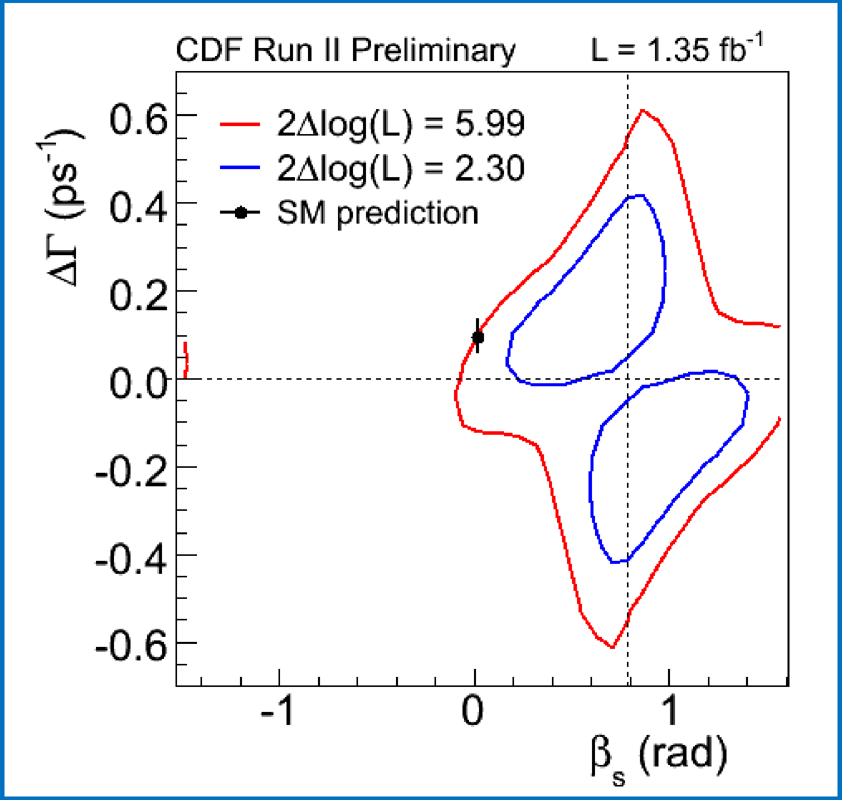
PDG: $c\tau(B^0) = 459 \pm 0.027\ \mu m$

This plot is Feldman-Cousins confidence region in the space of the parameters $2\beta_s$ and $\Delta\Gamma$



The symmetry you see occurs because the untagged analysis depends almost only on $\cos(2\beta_s)$ and almost not at all on $\sin(2\beta_s)$. Clearly the tagged analysis will remove this ambiguity. As you are about to see.

Tagged analysis: likelihood contour in the space of the parameters β_s and $\Delta\Gamma$

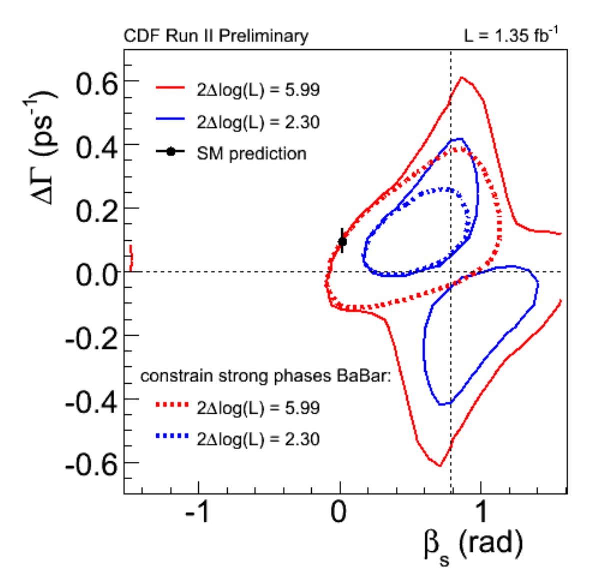


One ambiguity is gone, now this one

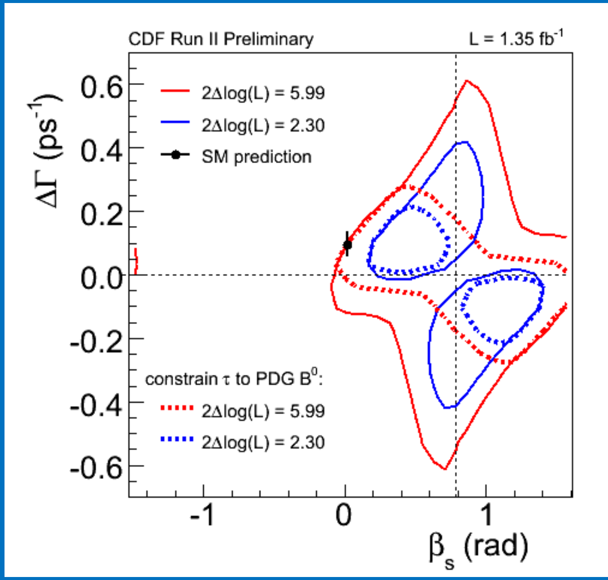
$$\beta_s \rightarrow \frac{\pi}{2} - \beta_s,$$
$$\Delta\Gamma \rightarrow -\Delta\Gamma,$$
$$\delta_{\|} \rightarrow 2\pi - \delta_{\|},$$
$$\delta_{\perp} \rightarrow \pi - \delta_{\perp}.$$

remains

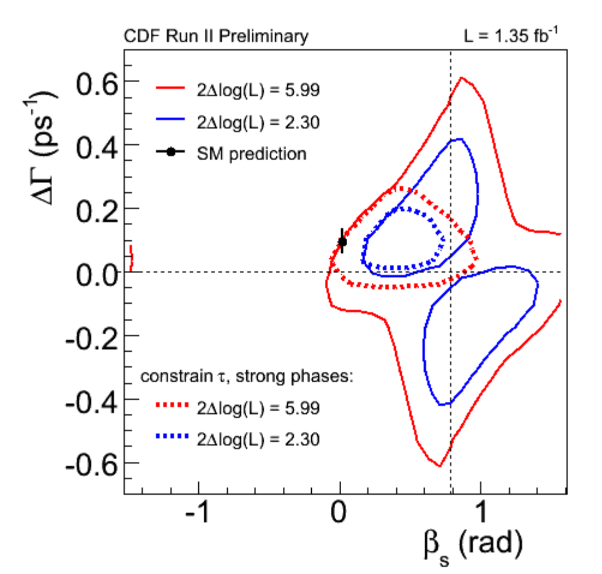
Constrain strong phases $\delta_{\|}$ and $\delta_{\perp}$ to BaBar Value



Constrain τ_s to PDG Value for B^0



Apply both constraints.

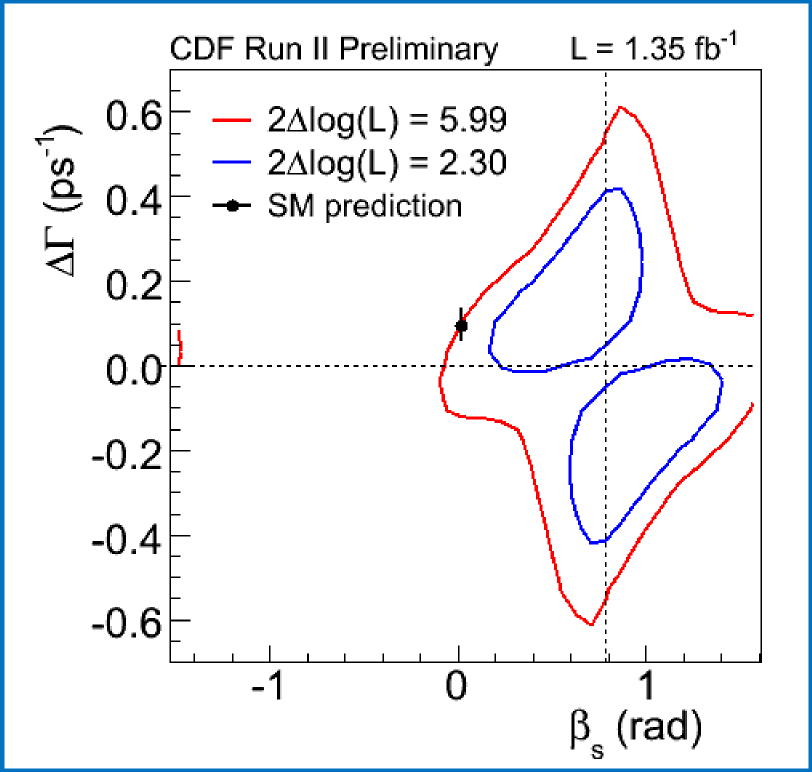


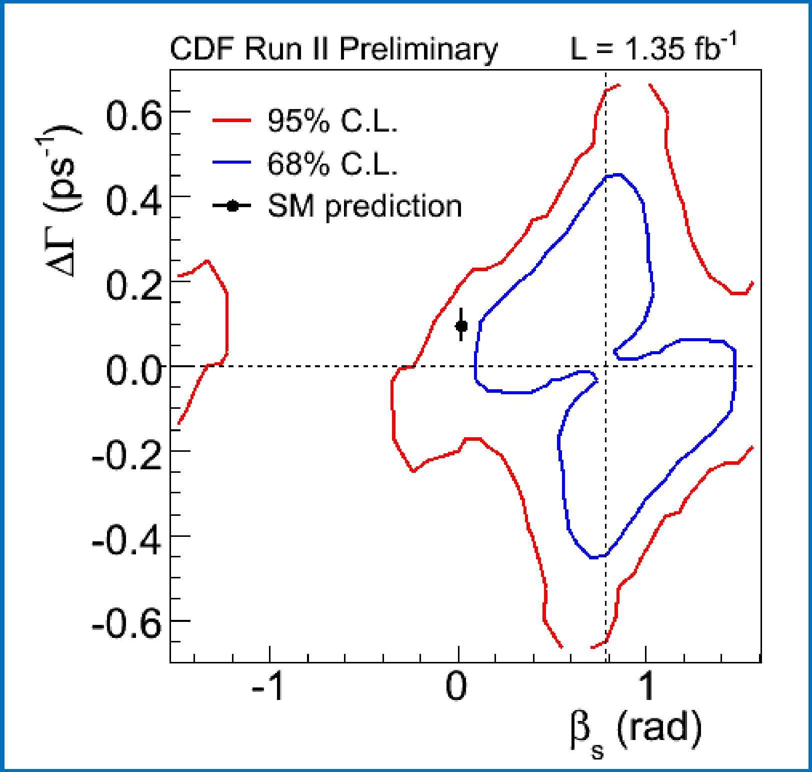
using values reported in:

B. Aubert et al. (BABAR Collaboration),
Phys. Rev. D 71, 032005 (2005).

A Feldman-Cousins confidence region in the β_s-$\Delta\Gamma$ plane is the main result. This interval is based on p-values obtained from Toy Monte Carlo and represents regions that contain the true value of the parameters 68% (95%) of the time.

arXiv:0712.2397v1

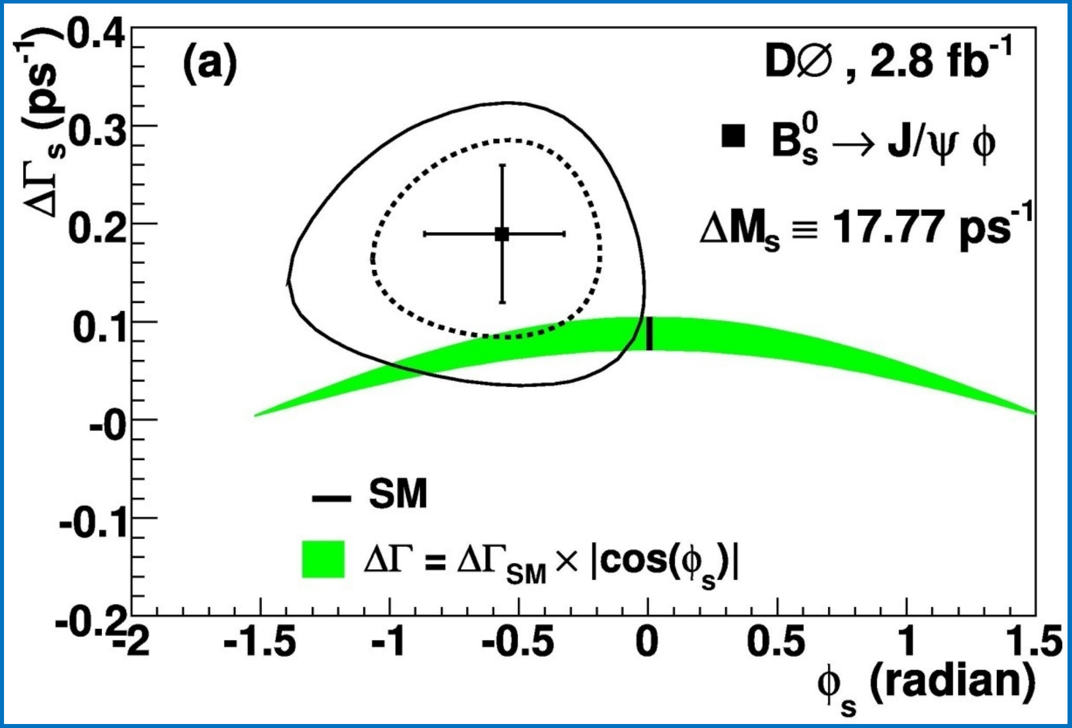




The standard model agrees with the data at the 15% CL

D0 Result:

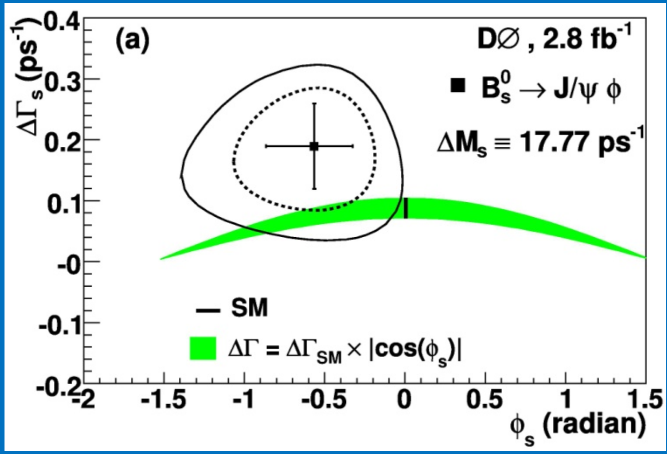
arXiv:0802.2255v1



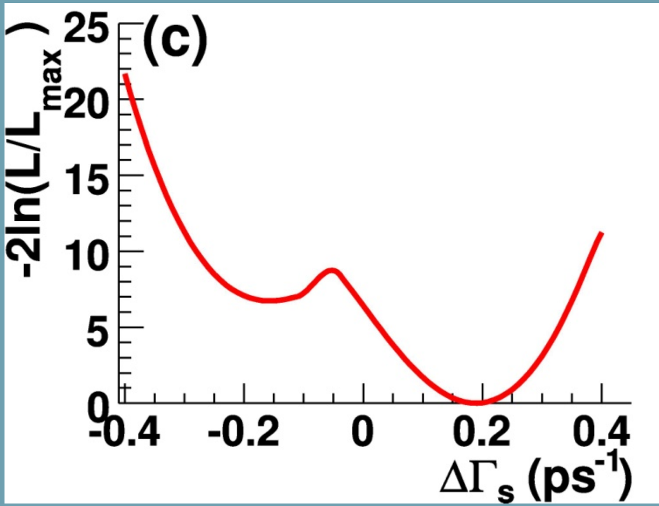
Strong phases varying around the world average values (for $B^0 \rightarrow J/\psi\ K^*$!!)

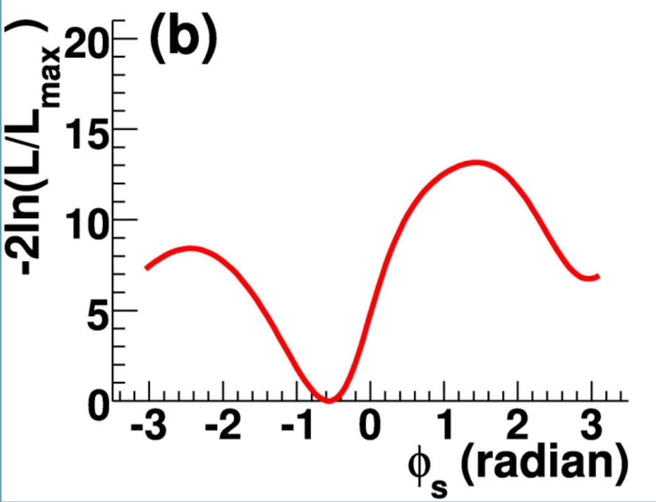
Uncertainty taken to be ± $\pi/5$

and $0.06 < \Delta\Gamma_s < 0.30$ ps^{-1}. To quantify the level of agreement with the SM, we use pseudo-experiments with the "true" value of the parameter ϕ_s set to -0.04. We find the probability of 6.6% to obtain a fitted value of ϕ_s lower than -0.57.

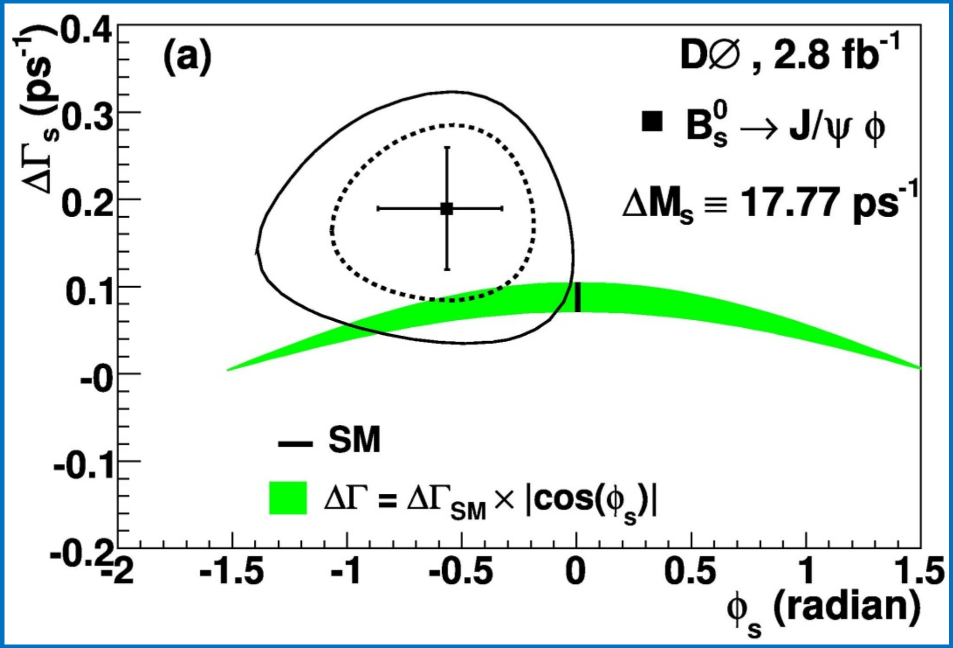


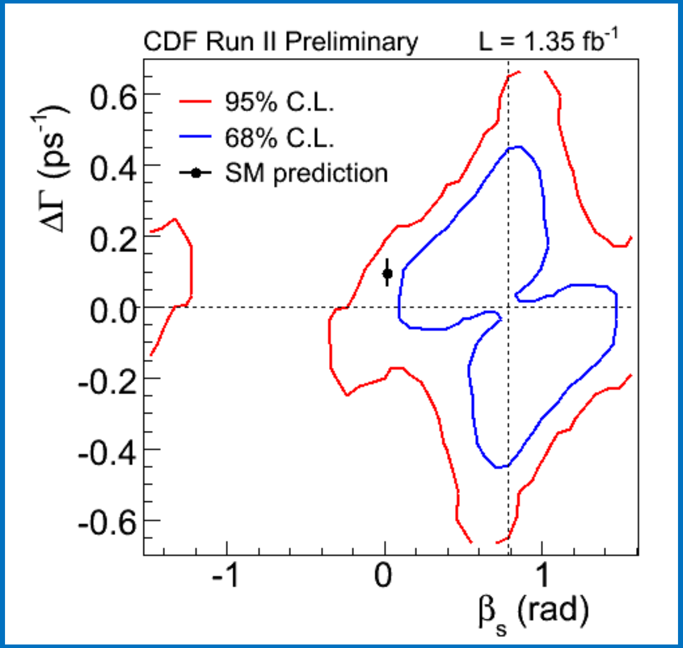
Likelihood contours for just DG and for just ϕ_s=-2β_s





Outlook





Note $\phi_s = -2\beta_s$

- Fluctuation or something more, it does go in the same direction.
- CDF estimates confidence level at 15% using p-values to obtain $Ln(L/L_0)$
- D0 estimates confidence level a 6.6% using the probability to extract a lower value than seen in the data, from toy.

Other analysis sensitive to β_s: Semileptonic asymmetry

$$\mathcal{A}_{\rm SL}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to \ell^+ X\right] - d\Gamma/dt\left[M^0_{\rm phys}(t) \to \ell^- X\right]}{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to \ell^+ X\right] + d\Gamma/dt\left[M^0_{\rm phys}(t) \to \ell^- X\right]} = \frac{1-|q/p|^4}{1+|q/p|^4}.$$

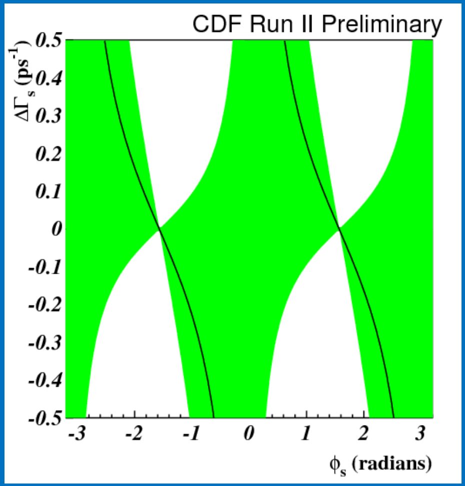
Very weak dependence on ϕ_s=-2β_s

$$A^s_{SL} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$$

Where:

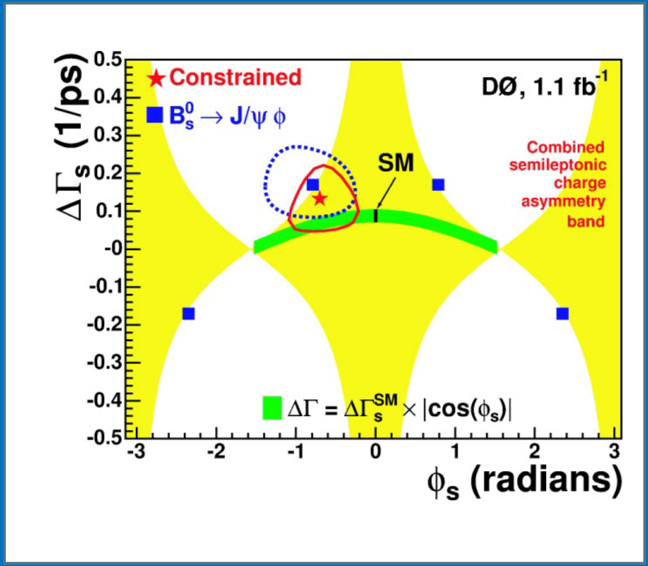
$\Delta\Gamma/\Delta M_s$ =(49.7 ±9.4) ±10^{-4}

(hep-ph/0612167)



Black: central value

Green: 68% allowed.



D0: Contours 39%CL

- A^s_{SL}= 0.020 ± 0.028 (CDF)

http://www-cdf.fnal.gov/physics/new/bottom/070816.blessed-acp-bsemil/

- A^s_{SL}= 0.0001 ± 0.0090 (stat) (D0)

Phys. Rev. D 76, 057101 (2007)

UTFit group has made an “external” combination.

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than $\boxed{3\sigma}$ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

- “re-introduces” the ambiguity into the D0 result.
- does so by symmetrizing.
- cannot fully undo the strong phase constraint.

- I am showing you this conclusion, but not endorsing it very enthusiastically.

CDF and D0 plan to make an “internal combination” for the near future.

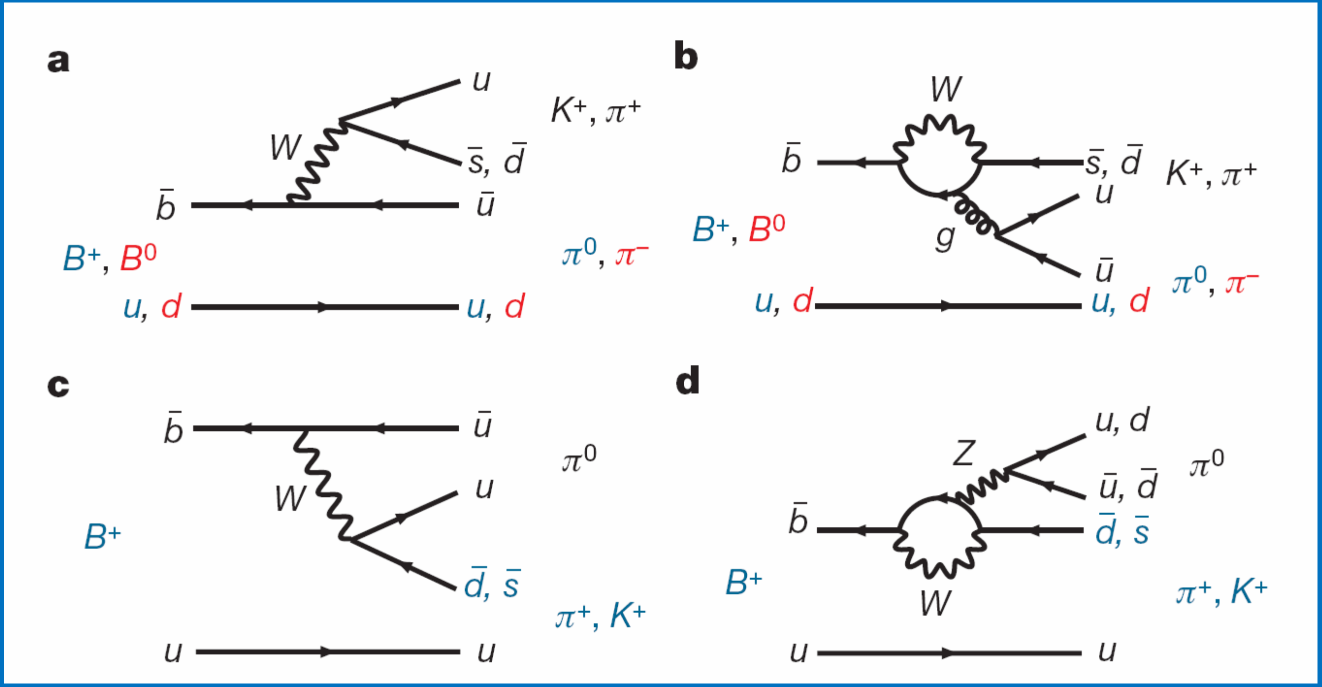
Elsewhere there is another anomaly that *may* also have to do with b→s

* Direct CP in $B^+ \to K^+ \pi^0$ and $B^0 \to K^+\pi^-$ are generated by the b →s transition. These should have the same magnitude.

* But Belle measures $\Delta\mathcal{A} \equiv \mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = +0.164 \pm 0.037,$ (4.4 σ)

* Including BaBar measurements: > 5σ

Lin, S.-W. *et al. (The Belle collaboration) Nature* 452, 332–335 (2008).



•The electroweak penguin can break the isospin symmetry

•*But then extra sources of CP violating phase would be required in the penguin*

Conclusion

- Towards the end of a 20-year program in proton-antiproton physics: some terribly interesting times for the physics of the b-quark.

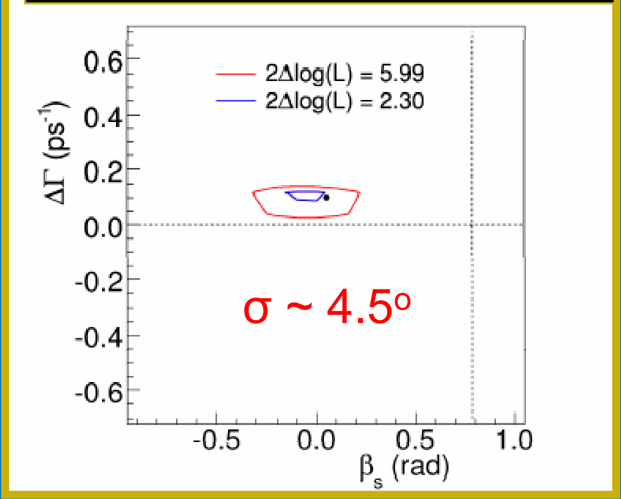
- An anomaly from the B factories
- Are quantum loop corrections to the $b \to s$ transitions to blame?

- If so, precision measurements of the CP asymmetries in the B^0_s system are a clean way to sort it out.

- D0 and CDF have just demonstrated the feasibility of doing those measurements.

- Higher precision, higher statistics measurements could give us a even stronger hint before the LHC turns on.

Baseline expectation w/ 6/fb



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