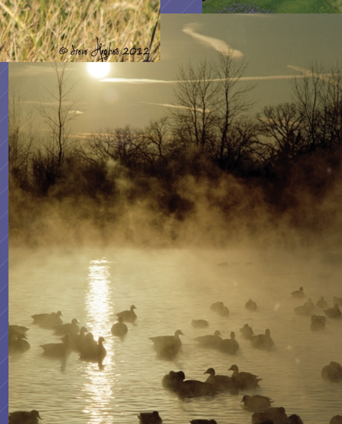
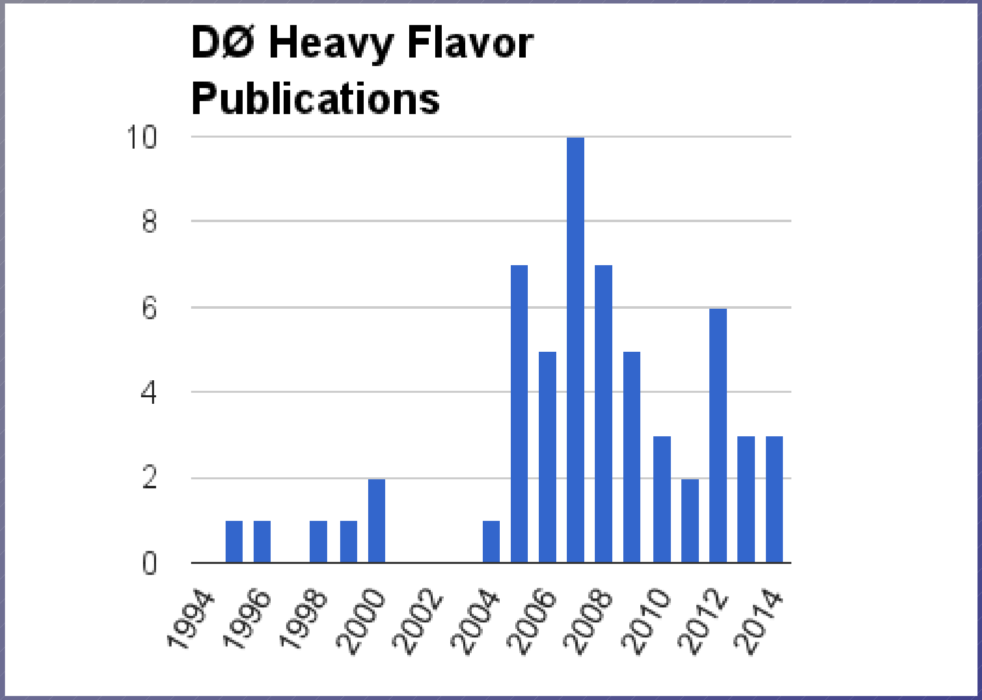
Heavy flavor physics at D0 in Run II



Snapshot of heavy flavor publications at D0



Thanks to Bob Hirosky for making this compilation

52 publications on several topics

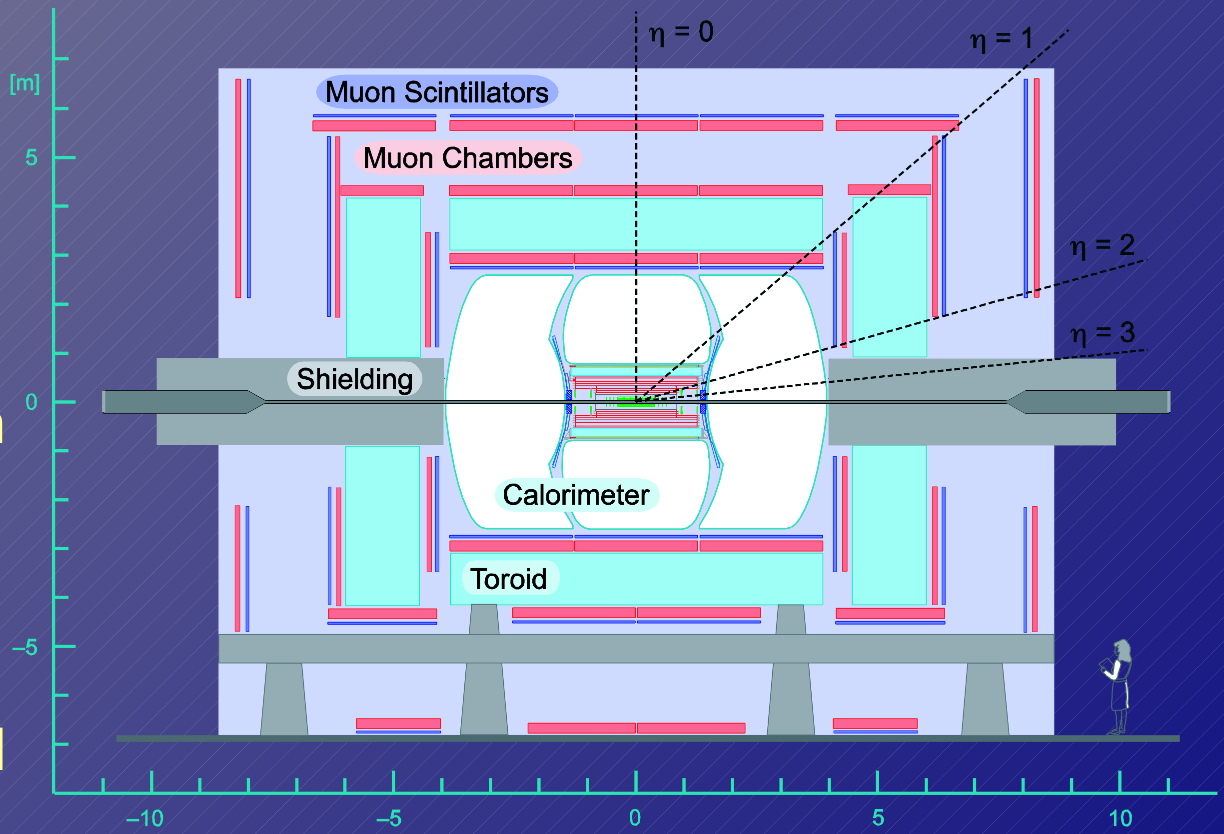
- B_s mixing
- CP-violating asymmetries
- rare decays
- spectroscopy and lifetimes

Can't cover it all!
Emphasize results where D0 has unique capabilities.

The muon system at D0

The muon system at D0 **enabled** the heavy flavor program. The large coverage in η provided good acceptance. The large number of interaction lengths provided a clean muon signature.

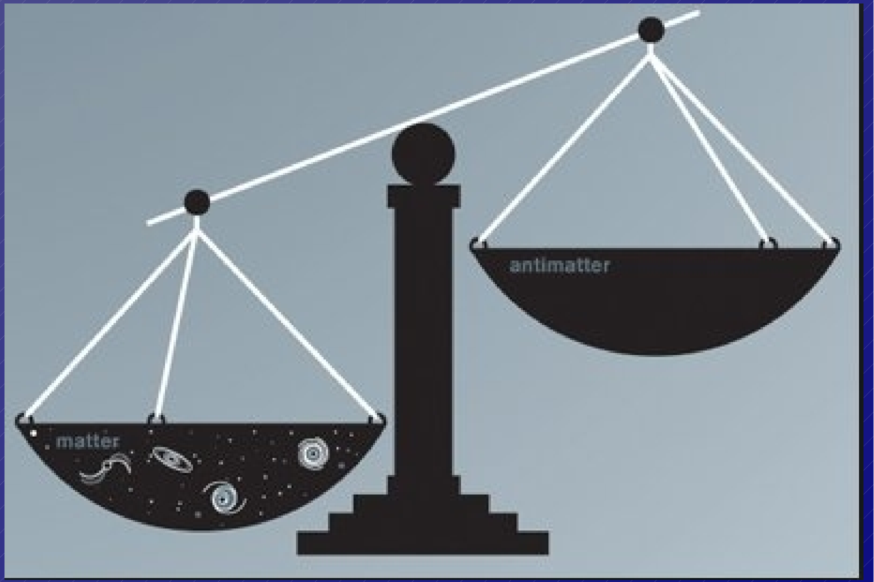
The regular reversal of the magnetic fields was crucial for cancelling detector asymmetries.



Physics Goals

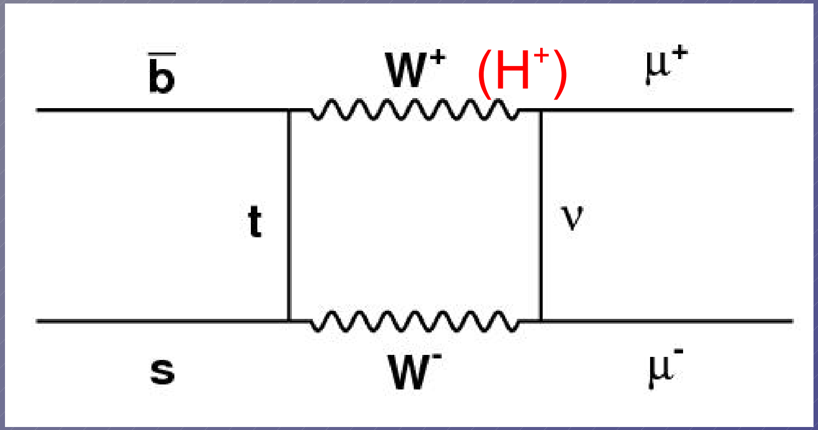
Search for new sources of CP violation and measurement of B_s mixing parameters.

The underlying reason for searching for CPV is the unexplained matter-antimatter asymmetry of the universe—a puzzle at least 50 years old. I would argue the puzzle is more like 80 years old.



Physics goals

Search for new physics through processes that are rare or forbidden in the standard model.



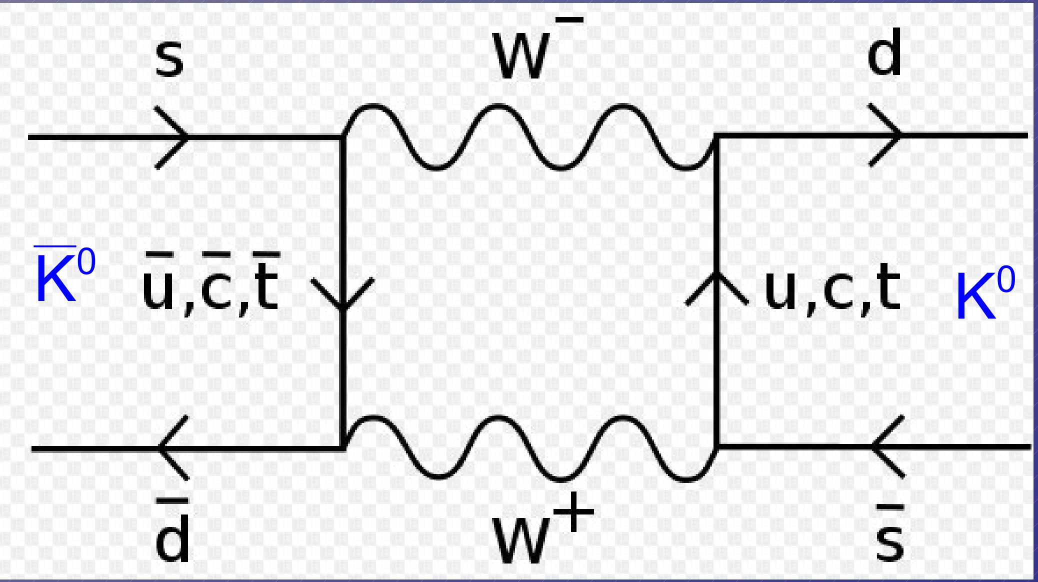
A highly suppressed process such as $B_s \to \mu\mu$ opens a window on new physics.

Precision test of QCD and models such as HQET through spectroscopy and lifetime measurements.

Searching for new QCD bound states.

B meson mixing and CP violation

Meson mixing and CP violation

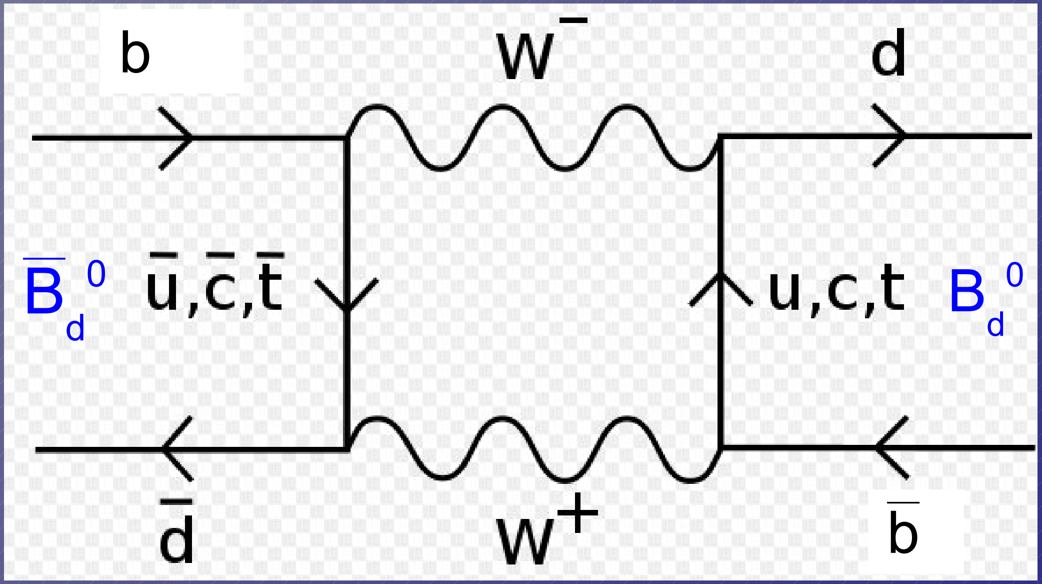


Neutral meson flavor mixing has played a huge role in B physics at D0.
When mesons mix, the flavor eigenstates are not the same as the mass eigenstates.
There may or may not be CPV in mixing.

Mixing has been known since the 1950's in the neutral Kaon system.

In the Kaon system, the lifetime difference between the two mass eigenstates is a factor of 500. This lifetime difference made possible the discovery of CP violation in 1964.

B_d^0 and B_s^0 mixing

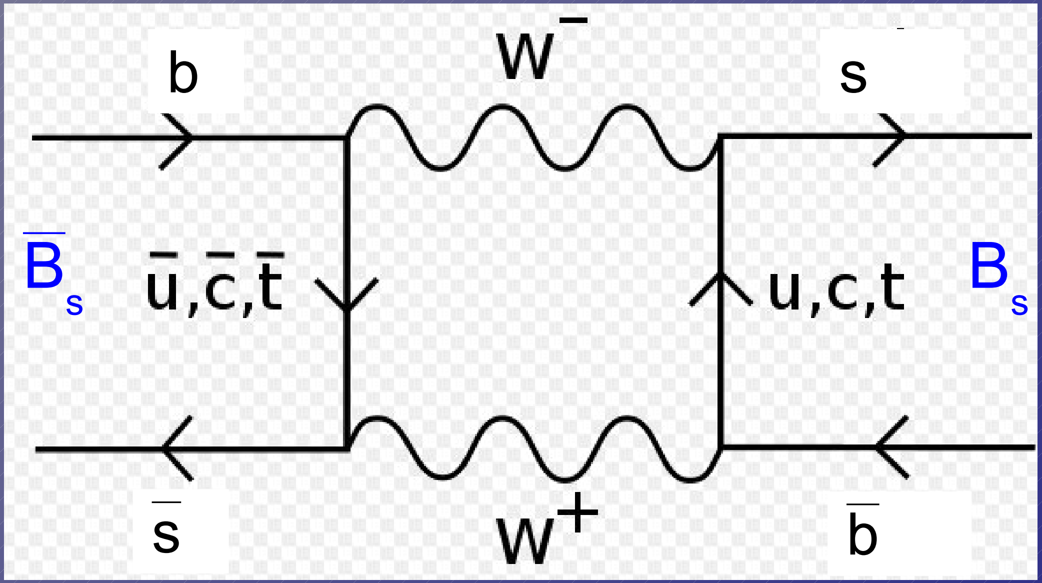


Replace the *s*-quark with a *b*-quark and you have B_d^0 mixing.

If the other quark is *s*, you have B_s^0 mixing.

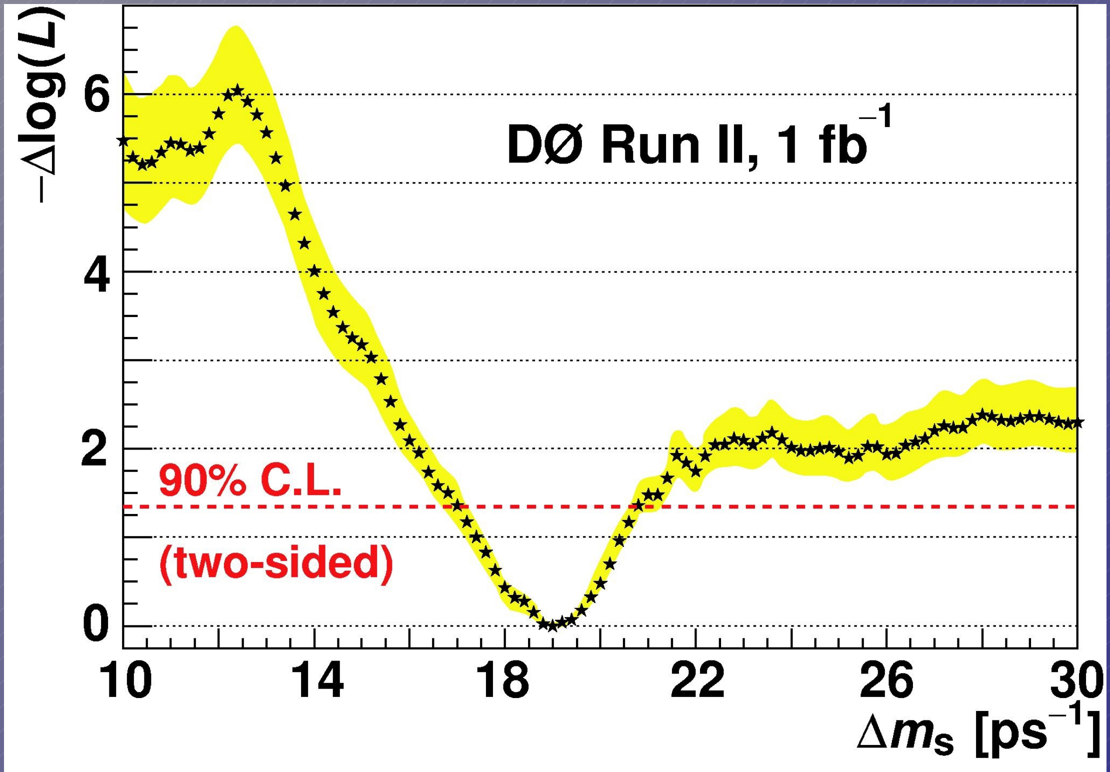
B_d^0 mixing was discovered at ARGUS (DESY) in 1987, and was evidence that the top quark was heavy.

B_d^0 and B_s^0 mixing



To characterize mixing:
Δm, the mass difference between the two mass eigenstates
ΔΓ, the width difference between the two mass eigenstates.
Φ, possible CP-violating phase (different definitions depending on decay).

B_s^0 mixing



In the early days of RunII, observing B_s mixing was a major goal. D0 obtained the first two-sided bound on the mass difference Δm_s.

The decay used was

$B_s \rightarrow \mu D_s X$ with $D_s \rightarrow \Phi\pi$

The 90% CL range was

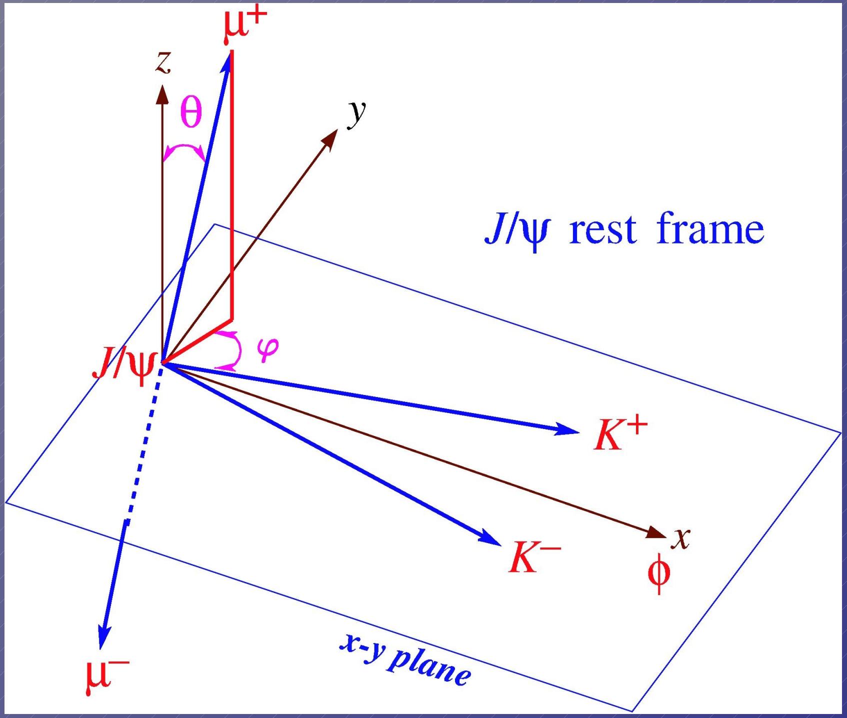
17 to 22 ps^{-1}

The current PDG value is 17.7 ps^{-1}

Phys. Rev. Lett. 97, 021082 (2006).

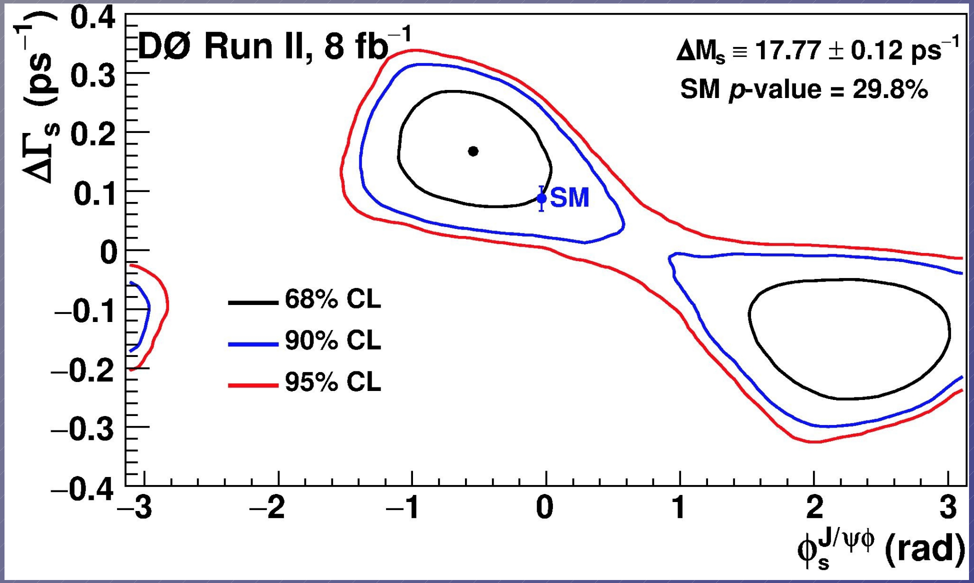
$B_s^0 \rightarrow J/\psi\varphi$

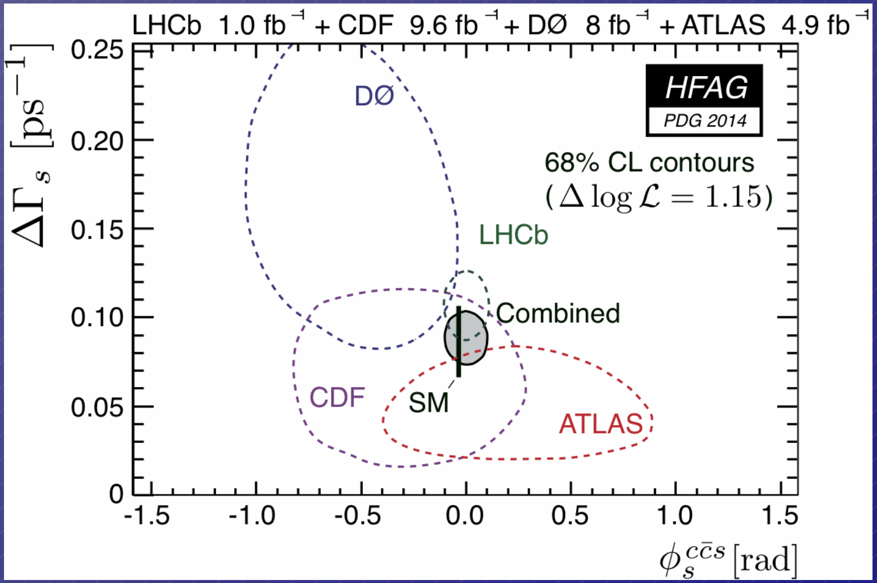
D0 has made three measurements of mixing parameters in the B_s system using the decay $B_s \rightarrow J/\psi\varphi$, using 1.1 fb^{-1}, 2.8 fb^{-1}, and 8 fb^{-1} . This is a complicated decay, a pseudoscalar decaying to two vectors.



$$\frac{d^4\Gamma}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \propto$$
$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)|A_0(t)|^2$$
$$+\sin^2\psi(1-\sin^2\theta\sin^2\varphi)|A_{\|}(t)|^2$$
$$+\sin^2\psi\sin^2\theta|A_{\perp}(t)|^2$$
$$+(1/\sqrt{2})\sin 2\psi\sin^2\theta\sin 2\varphi \mathrm{Re}(A_0^*(t)A_{\|}(t))$$
$$+\ (1/\sqrt{2})\sin 2\psi\sin 2\theta\cos\varphi \mathrm{Im}(A_0^*(t)A_{\perp}(t))$$
$$-\ \sin^2\psi\sin 2\theta\sin\varphi \mathrm{Im}(A_{\|}^*(t)A_{\perp}(t)).$$

$B_s \to J/\psi\phi$





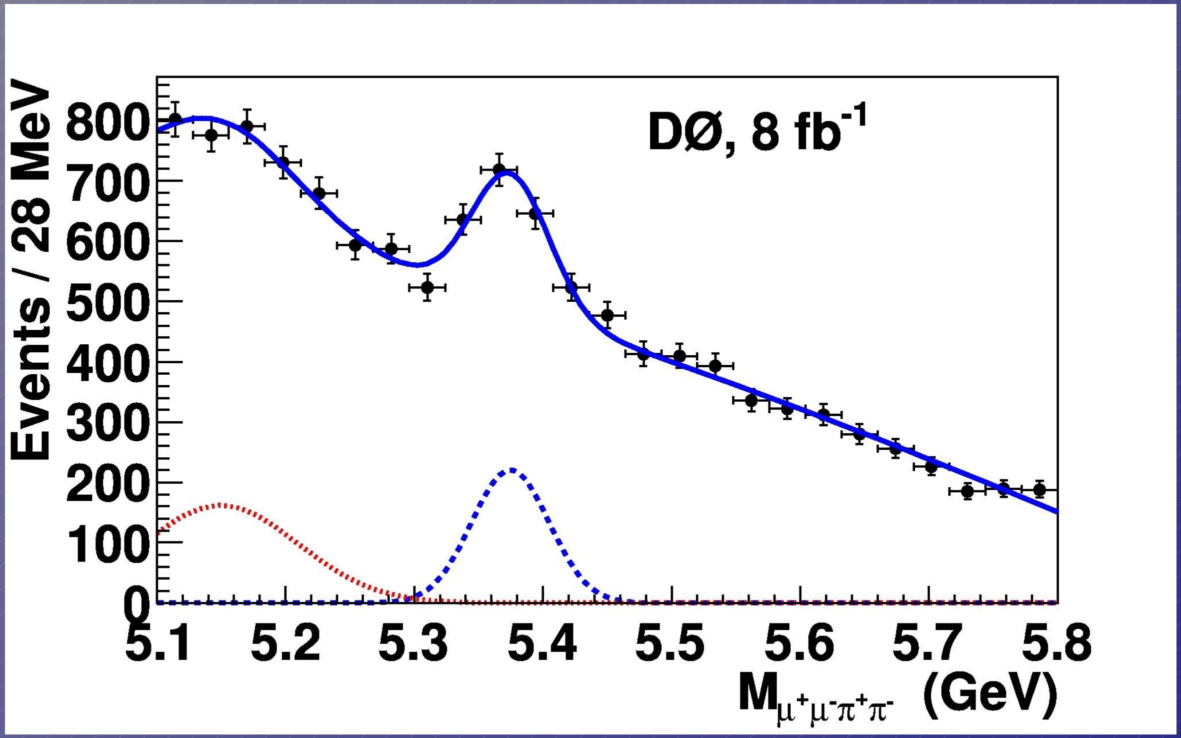
Phys. Rev. D85, 032006 (2012)

For a while we (and CDF) thought there might be some BSM physics in the mixing angle, but that turned out not to be the case.

More on mixing later!

$B_s^0 \rightarrow J/\psi f_0(980)$

An offshoot of the $B_s \rightarrow J/\psi\varphi$ analysis is the B_s or $B^0 \rightarrow J/\psi X$ where X in this case is the $f_0(980) \rightarrow \pi\pi$. We observed this decay and measured the branching fraction with respect to $B_s \rightarrow J/\psi\varphi$.



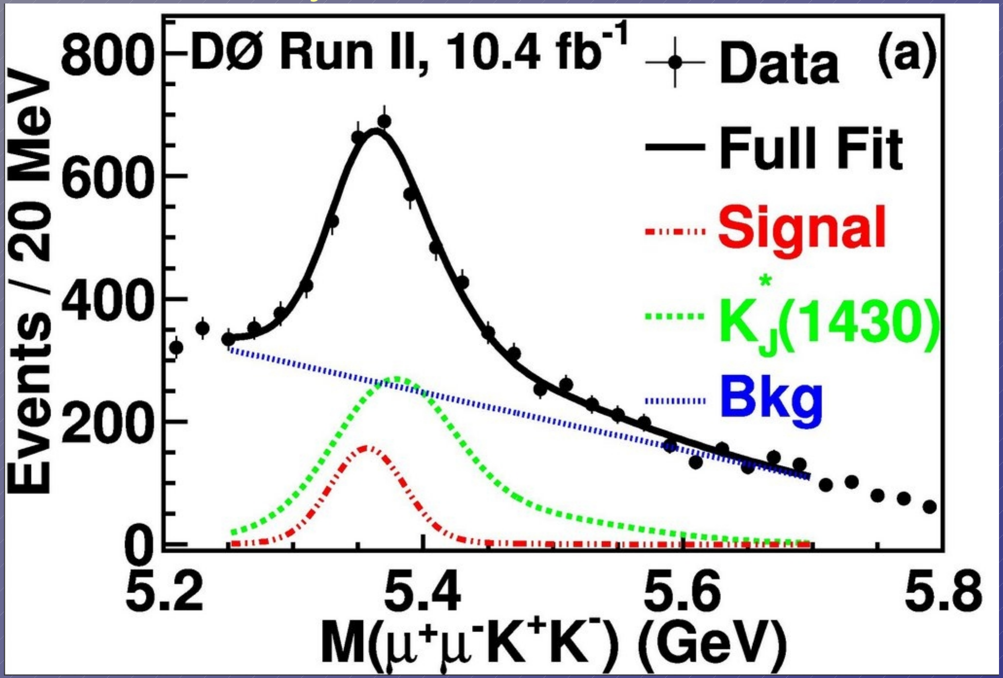
We were about to publish this when LHCb just beat us.

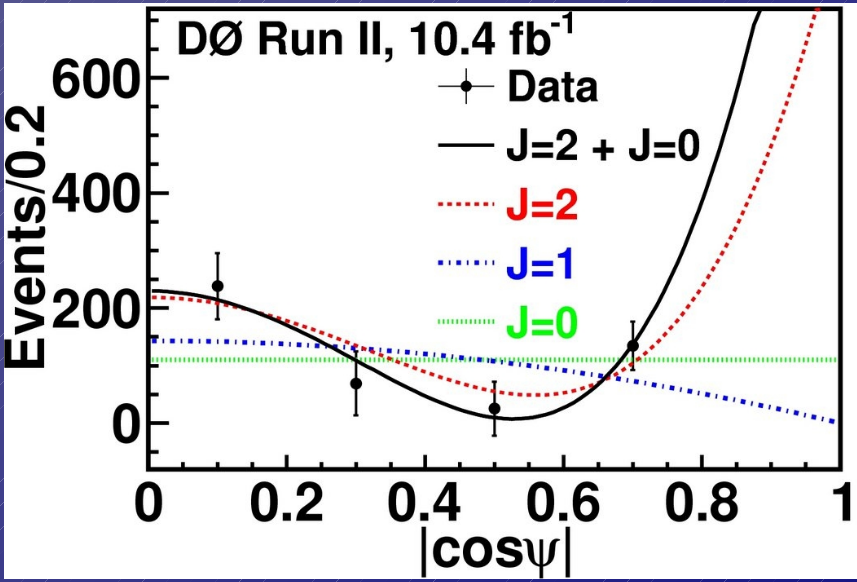
This mode in very interesting b/c it is pure CP-odd.
Still working on extracting a lifetime.

R=0.275 ± 0.041 (stat) ± 0.061(sys)
Phys. Rev. D 85, 011103 (2012).

$B^0_s \rightarrow J/\psi f_2'(1525)$

The $f'_2(1525)$ is seen in the KK final state. It is a J=2 meson, this decay was also observed by LHCb.

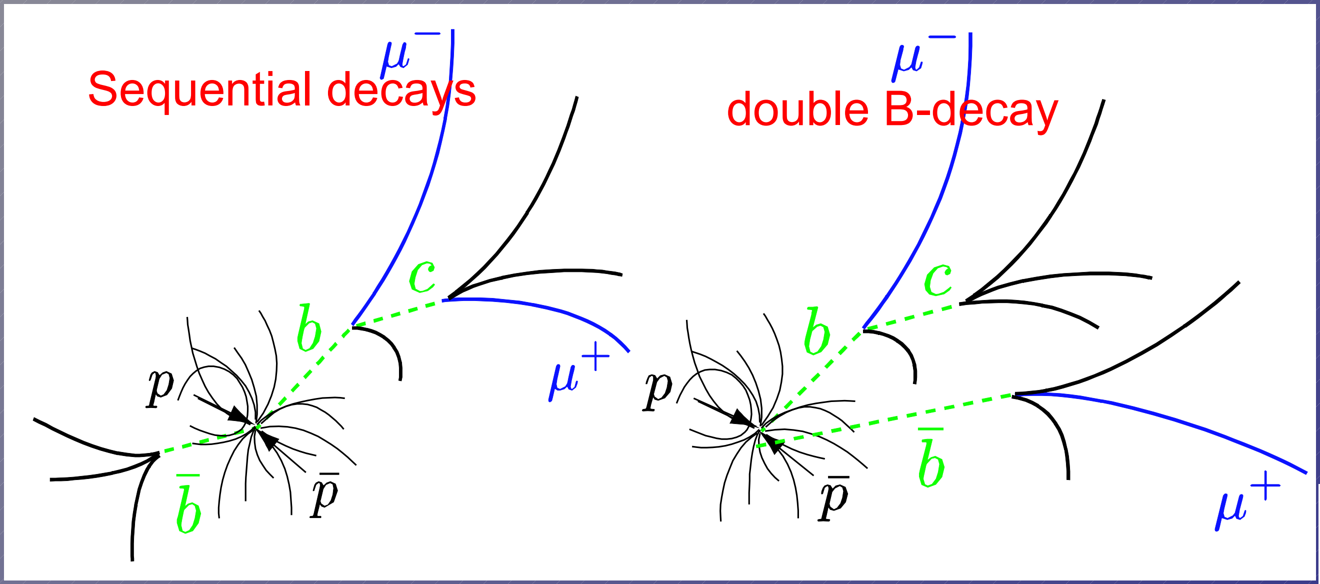




An angular analysis indicates that the final state is a mixture of J=0 and J=2.
Phys. Rev. D86, 092011 (2012).

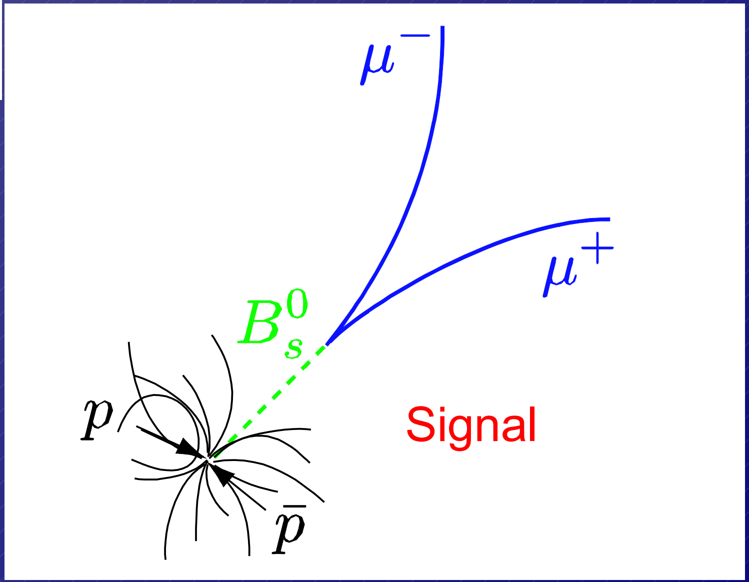
Rare Decays

Search for the decay $B_s \to \mu\mu$

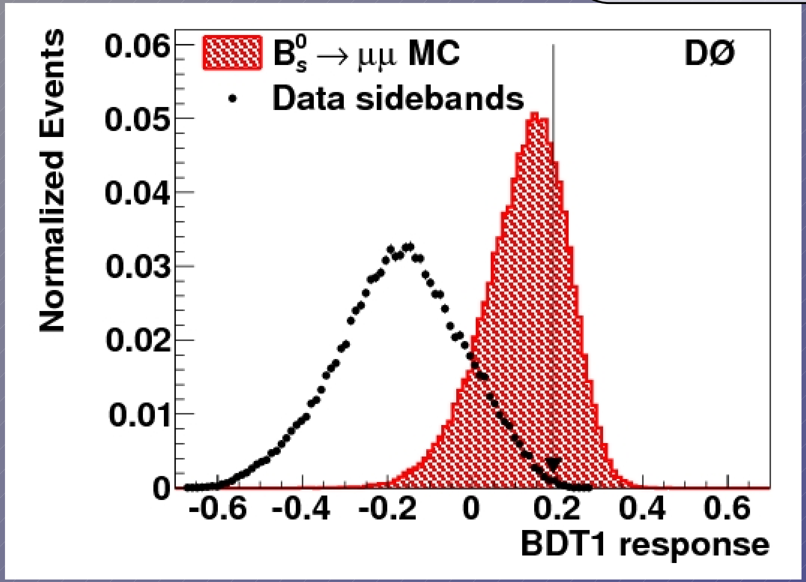


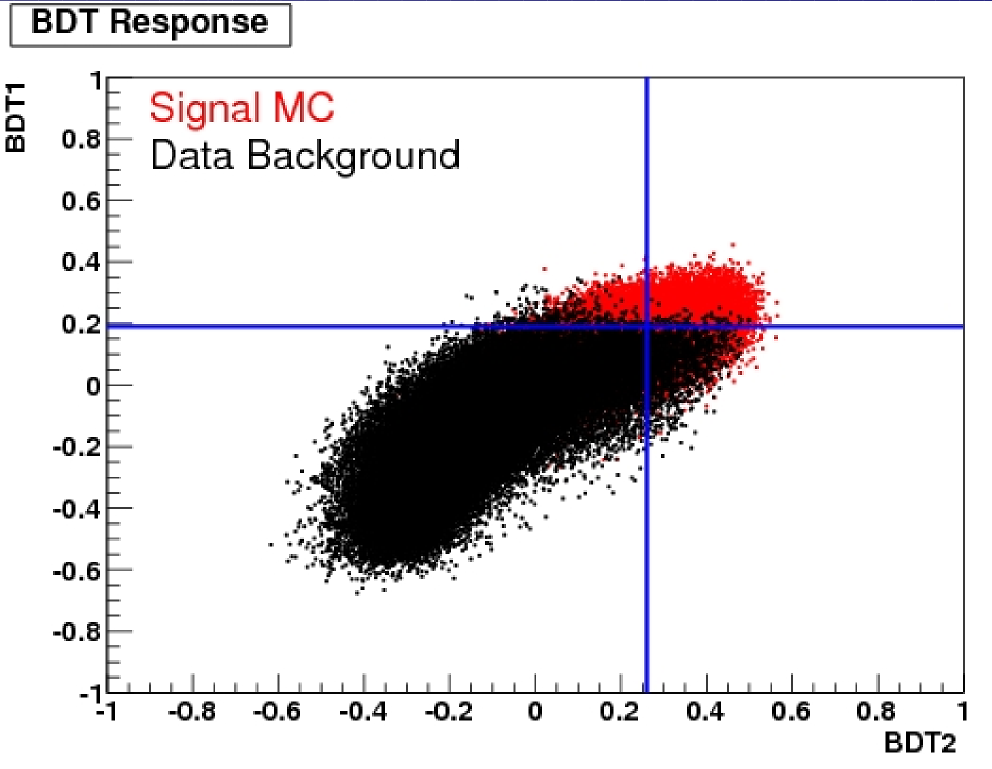
This decay is heavily suppressed in the SM, so a possible window on new physics.

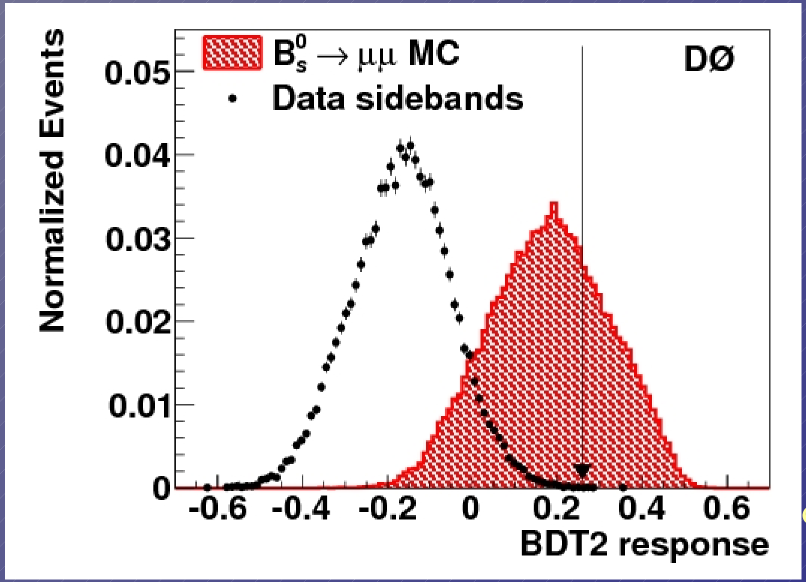
D0 published four searches for $B_s \to \mu\mu$. with 0.24 fb^{-1}, 1.3 fb^{-1}, 6.1 fb^{-1}, and 10.4 fb^{-1}. Many BSM models predicted enhancements over the SM expectation.



Search for $B_s \to \mu\mu$

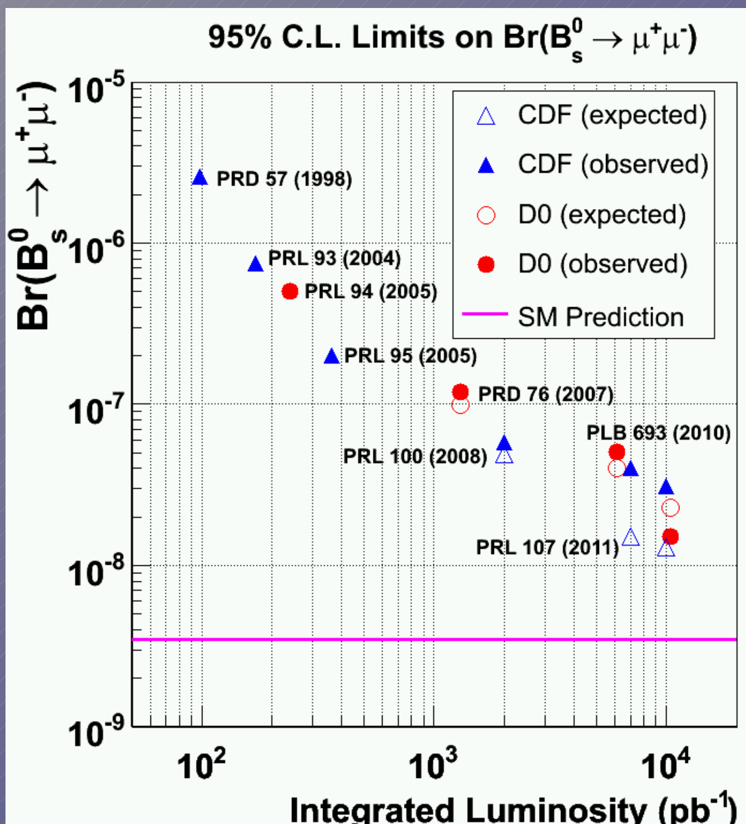


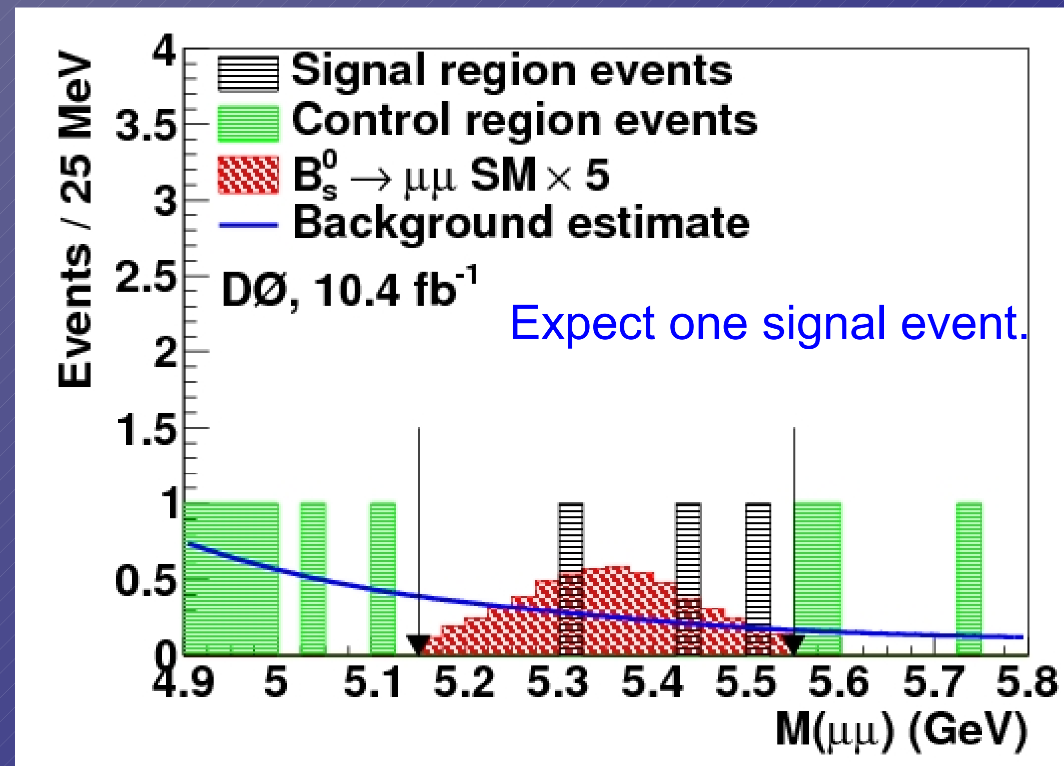




We trained two BDTs, one for sequential decays, one for double B decays

Search for $B_s \to \mu\mu$



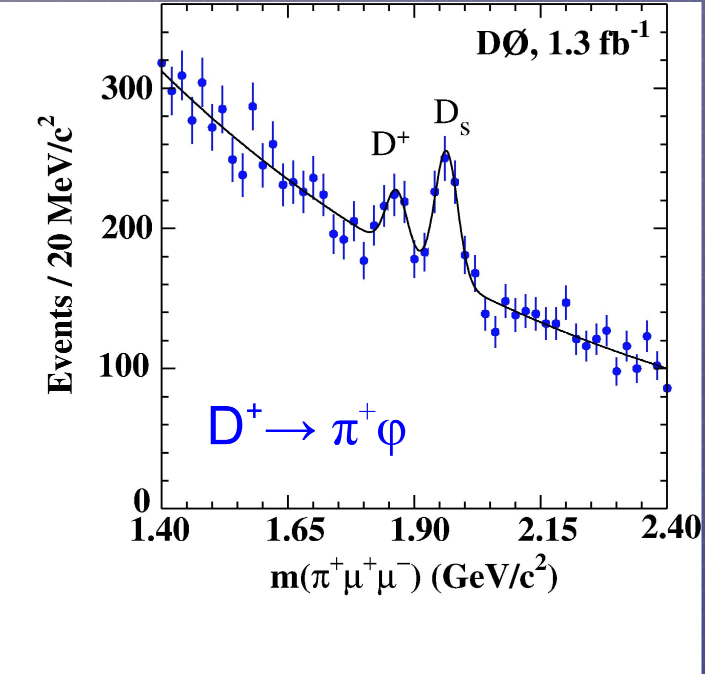


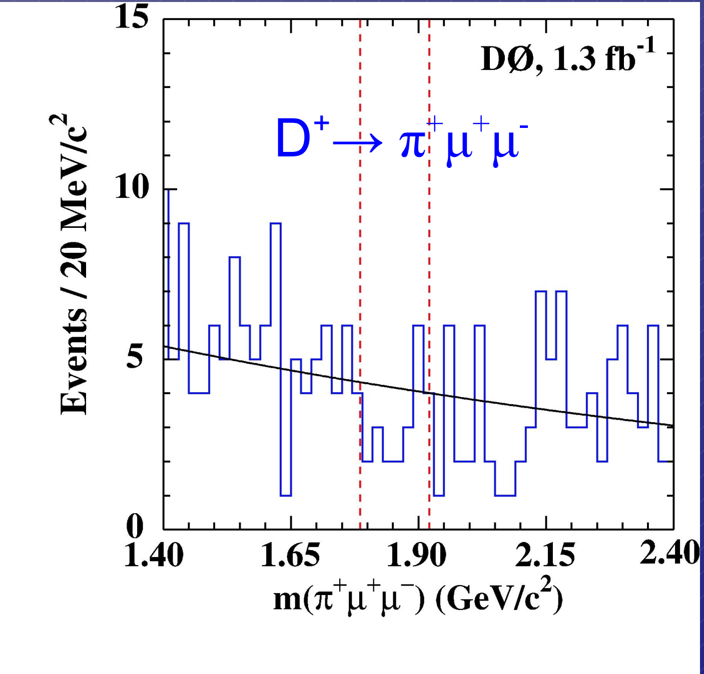
Phys. Rev. D87, 072006 (2013)

$BR(B_s \to \mu\mu) < 15 \times 10^{-9}$ at 95% CL, best Tevatron limit.

In 2013, both CMS and LHCb observed this decay at >4σ, at the SM rate.

Search for $D^+ \rightarrow \pi^+\mu^+\mu^-$



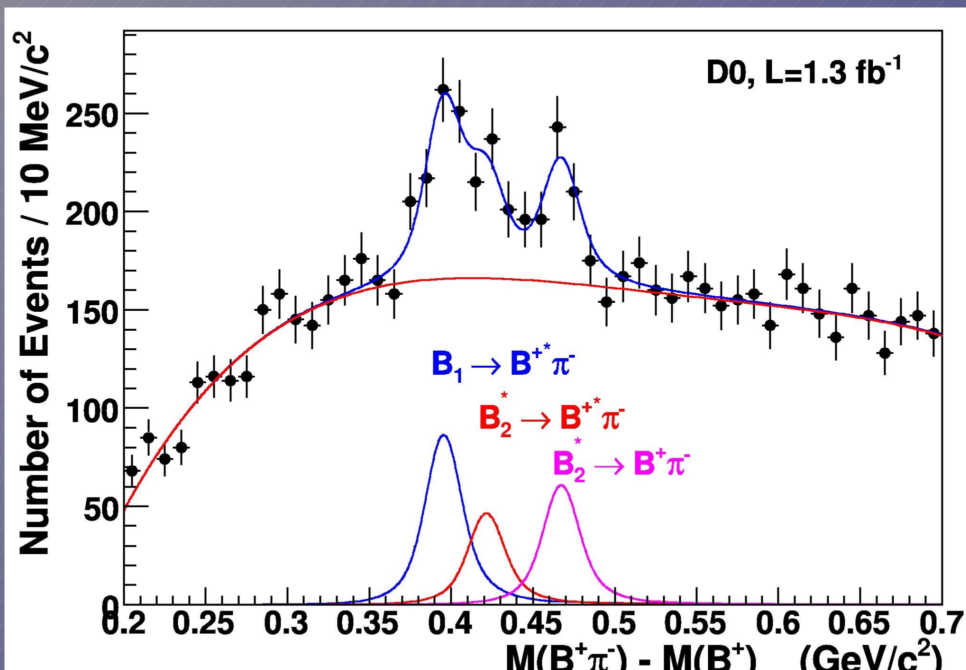


Phys. Re. Lett. 100, 101801 (2007)

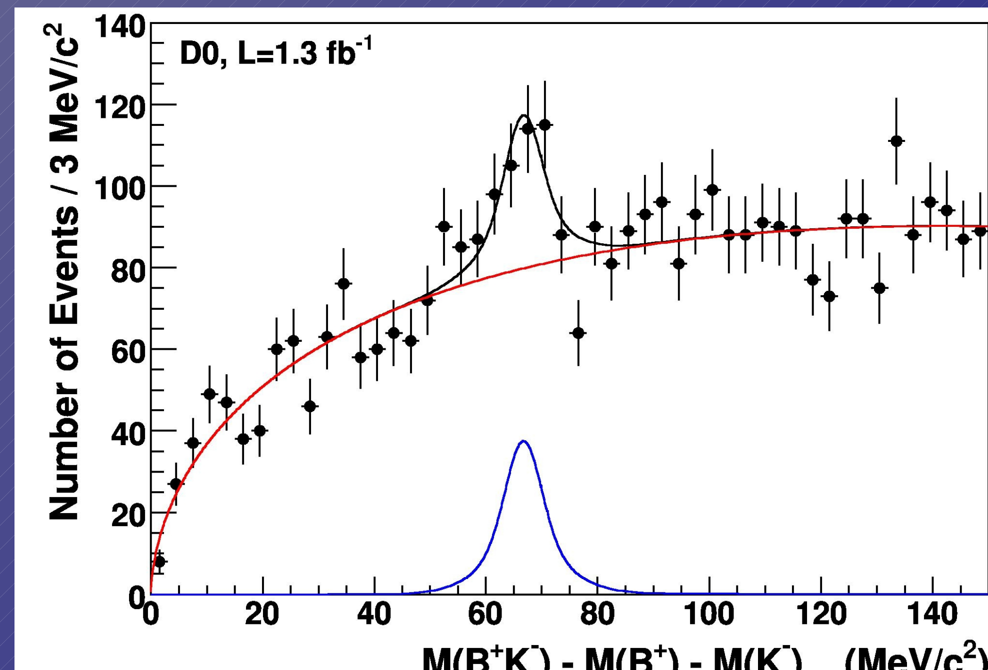
Some BSM models predict FCNC enhancements for up-type quarks only.
This 1.3 fb^{-1} analysis produced what is still the best limit on $D^+ \rightarrow \pi^+\mu^+\mu^-$
$BR(D^+ \rightarrow \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$.

Spectroscopy and lifetimes

Excited B and B_s mesons



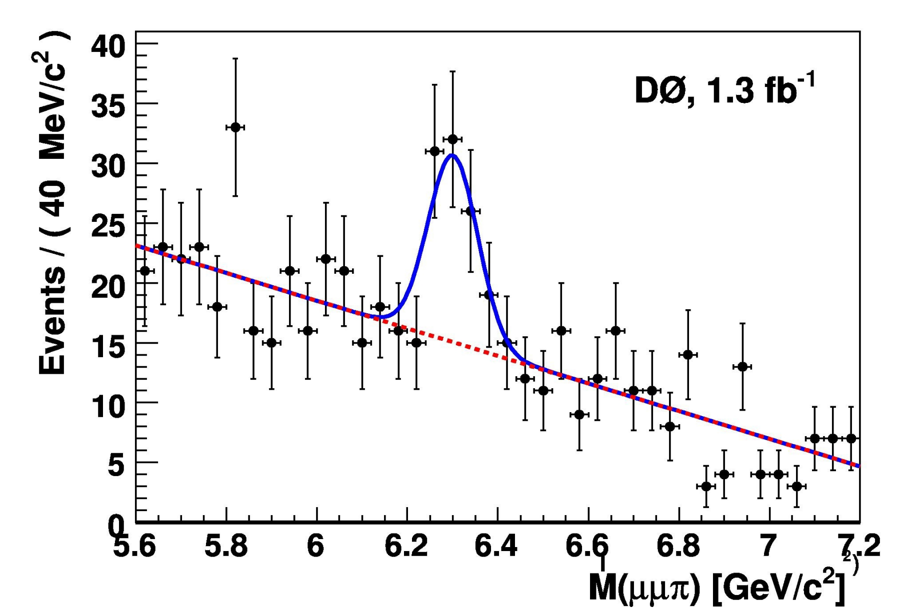
Phys. Rev. Lett. 99, 172001 (2007).

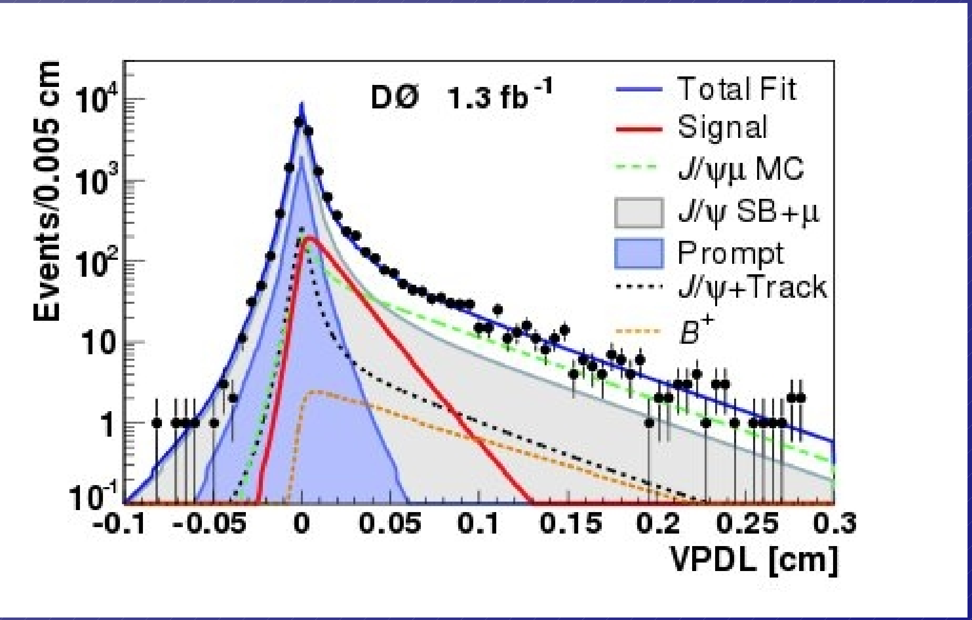


Phys. Rev. Lett. 100,082002 (2008).

We have two results on excited B mesons: the first direct observation of B_1 and B_2^* decaying to $B^{(*)}$ π , and observation of $B_{s2} \to BK$. Due to angular momentum and parity conservation, these states decay through L=2 and are narrow.

B_c mesons



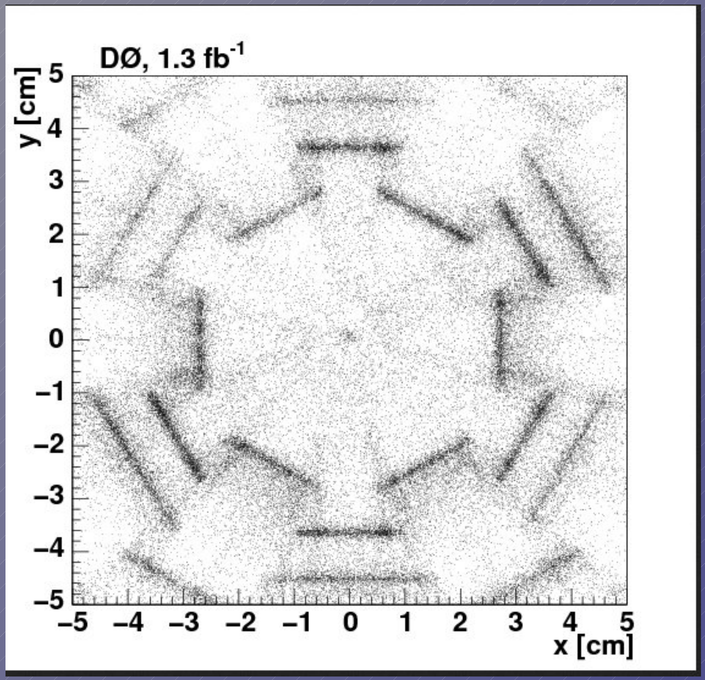


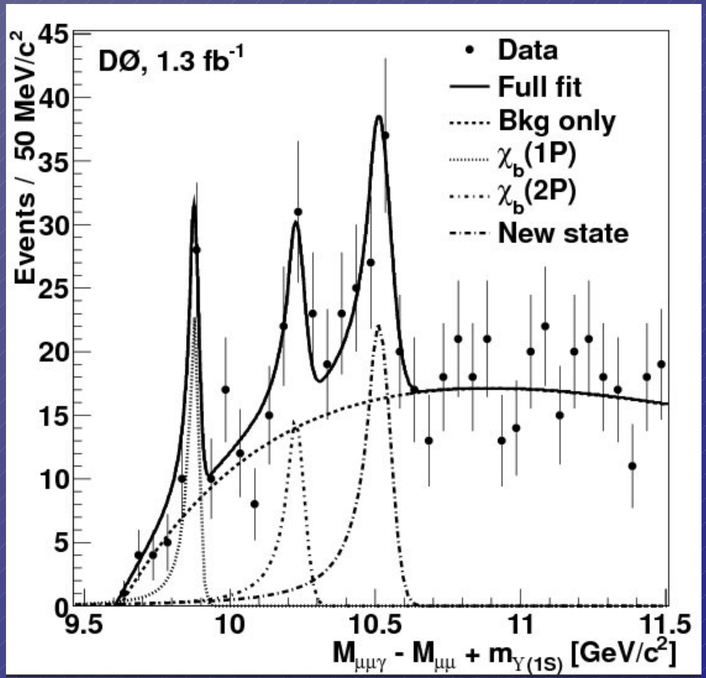
Phys. Rev. Lett. 101,012001 (2008)

Phys. Rev. Lett. 012, 092001 (2009).

We have two results on the B_c meson—5.2 σ observation in the exclusive decay $B_c \rightarrow J/\psi\pi$, and a lifetime measurement in semileptonic decays with $\tau = [0.448 \pm 0.37\ (\text{stat}) \pm 0{,}032\ (\text{syst})]$ ps.

X →Υ(1s) γ with γ→e^+e^-

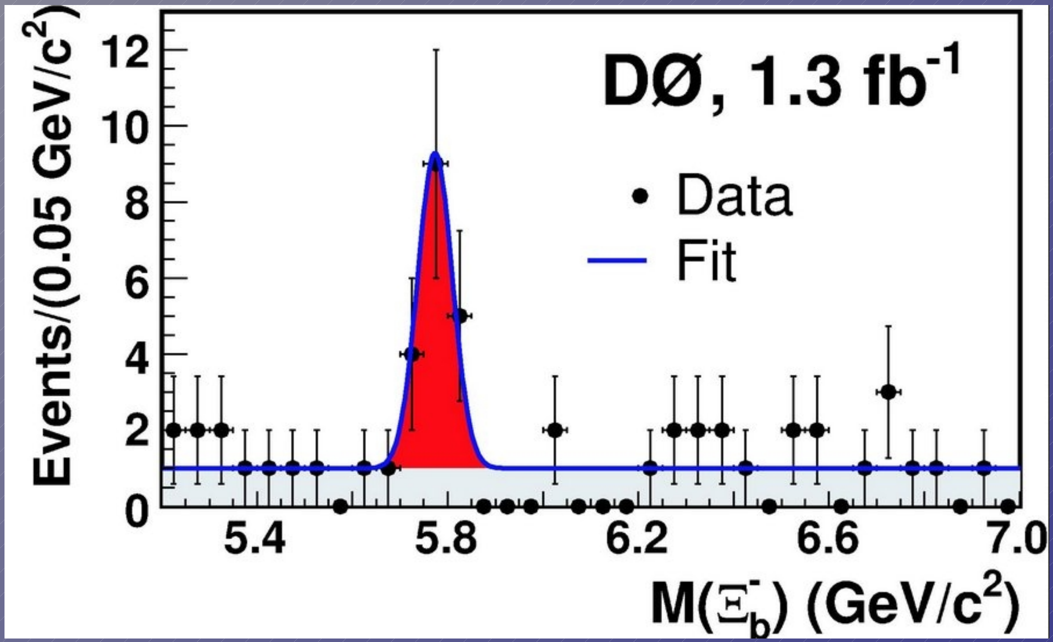




x-ray of the SMT, using γ→ee

Possibly a χ_b(3P) state, but until you measure the spin you don't know for sure. There are 65 ± 11 signal events 5.6 σ significance. First observed by ATLAS. Phys. Rev. D86, 031103R (2012).

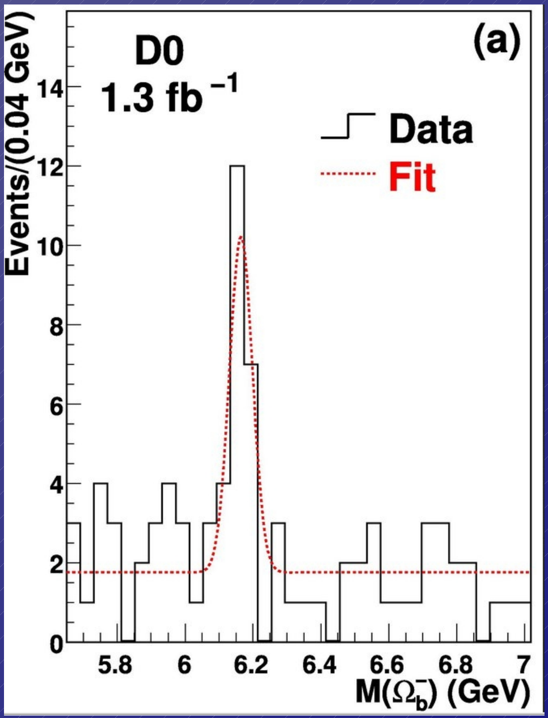
B-baryons: Ξ_b and Ω_b



First observation of Ξ_b

Confirmed in RunIIb

Phys. Rev. Lett. 99, 052001 (2007)

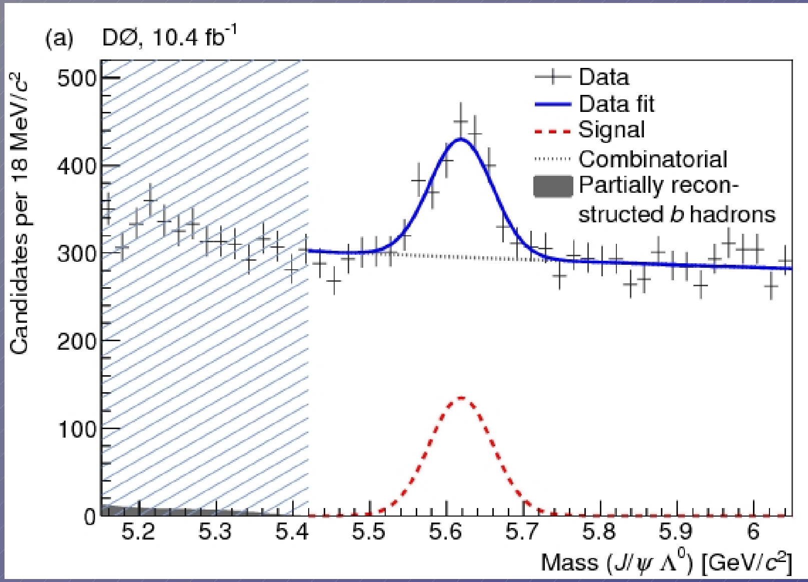


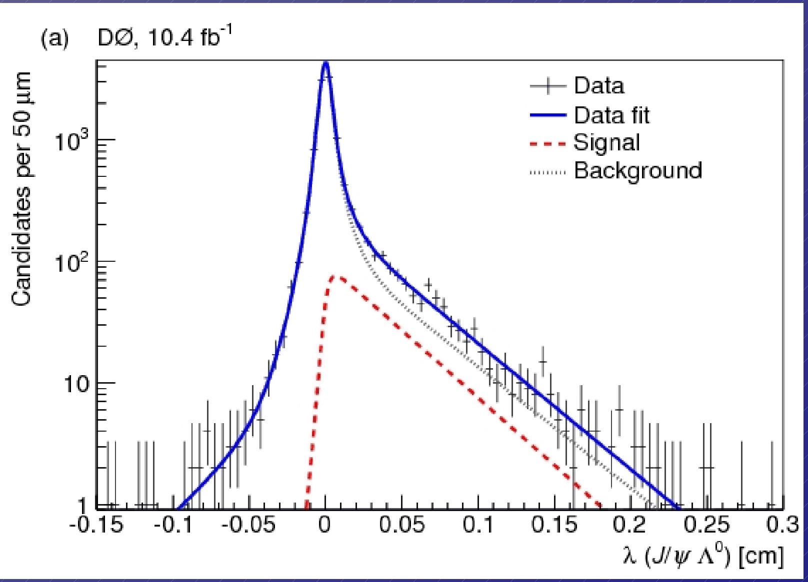
Observation of Ω_b

NOT confirmed in RunIIb

Phys. Rev. Lett. 99, 052001 (2007)

Λ_b Lifetime measurements

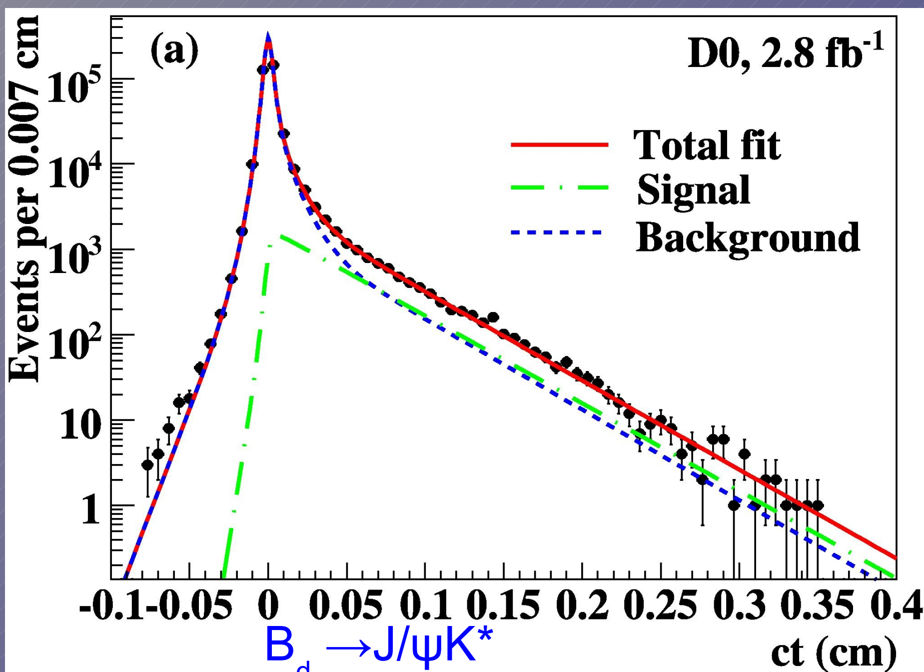


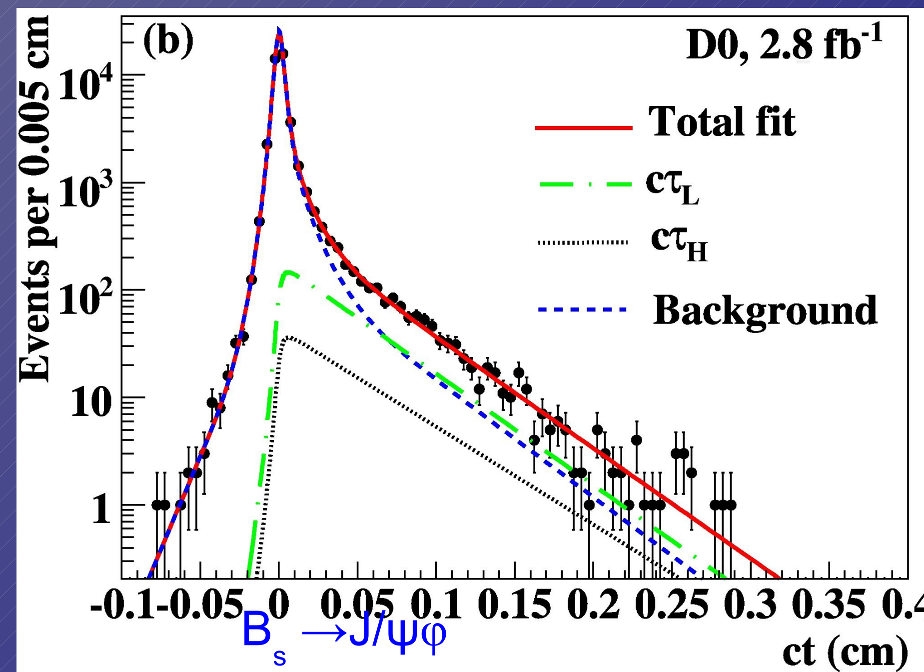


Phys. Rev. D85, 112003 (2003)

We had four measurements of the Λ_b lifetime, the first with 0.25 fb^{-1} and 61 signal candidates, the last with 10.4fb^{-1} and 755 signal candidates. $\tau(\Lambda b)$=[1.303 ± 0.075 (stat) ± 0.035(sys)] ps.

B_d and B_s lifetime measurements





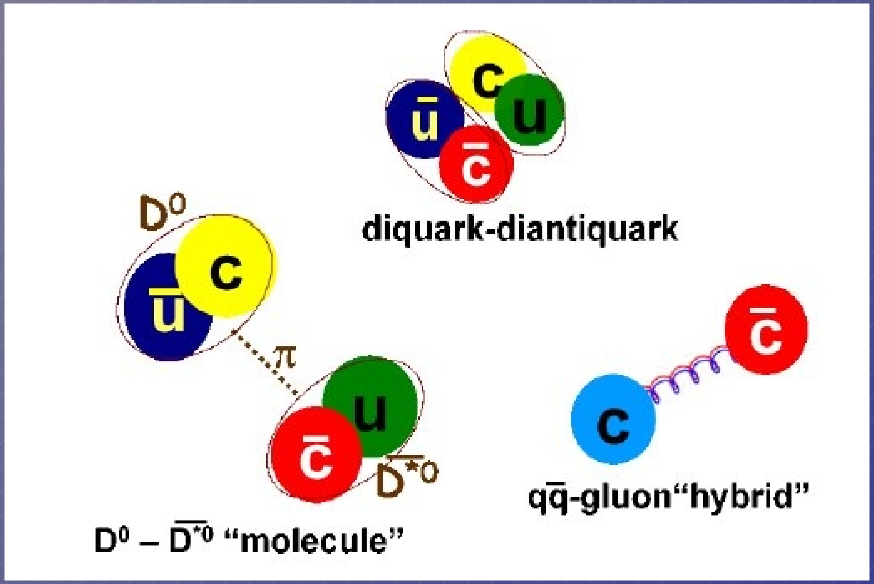
Phys. Rev. Lett. 102, 032001 (2009)

We have measurements of the B_d and B_s lifetimes in exclusive decays. The ratio of these lifetimes should be 1, by HQEF, these data agree. We also have a measurement of the B_s lifetime in semileptonic decays, which will be superseded soon.

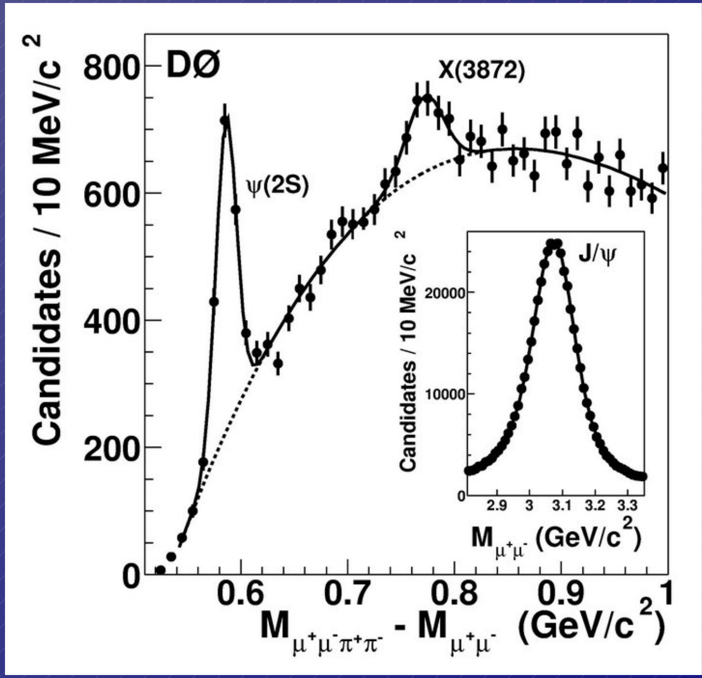
Exotic mesons

Exotic mesons are a new class of particles, not standard q-qbar states. The situation with these states is very confused.

X(3872) seen by several experiments, including D0

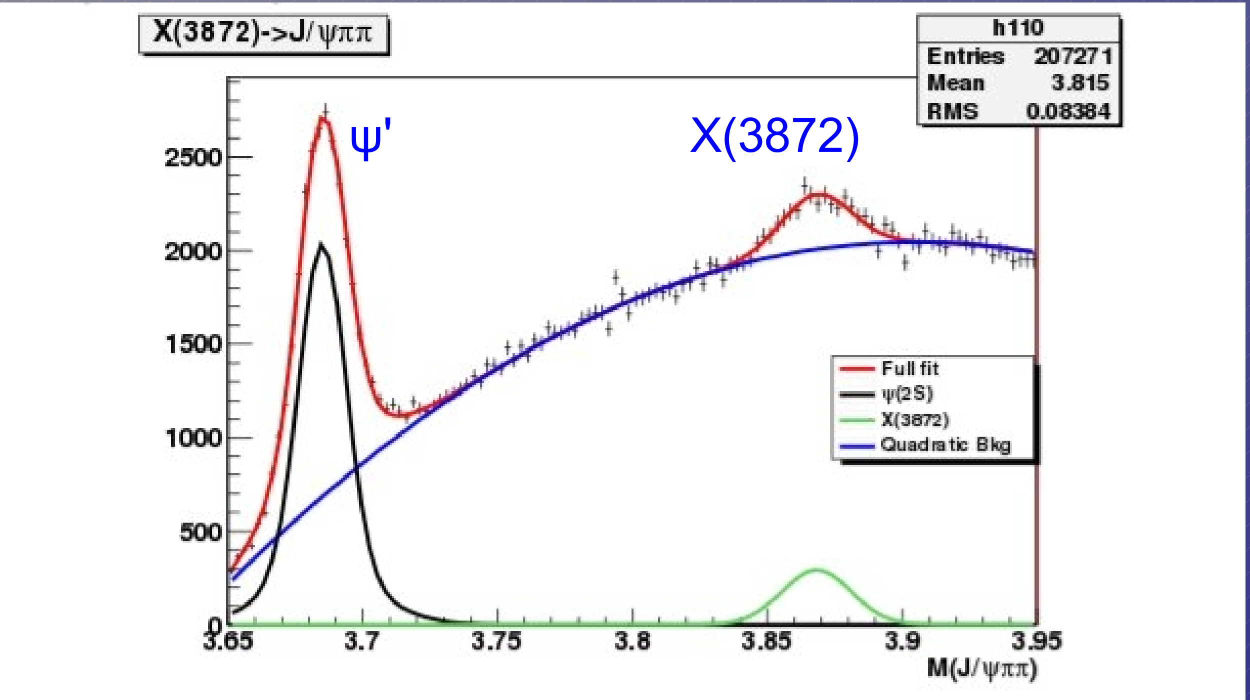


arXiv:0801.3867 (2012).



Phys. Rev. Lett. 93, 162002 (2004). RunIIa

Exotic mesons



$X(3872)$: Mass = 3.868 GeV/c^2 $\pm$ 0.001 $N(X) = 3783 \pm 292$

ψ': Mass = 3.685 GeV/c^2 $\pm$ 0.000 $N(\psi') = 20462 \pm 564$

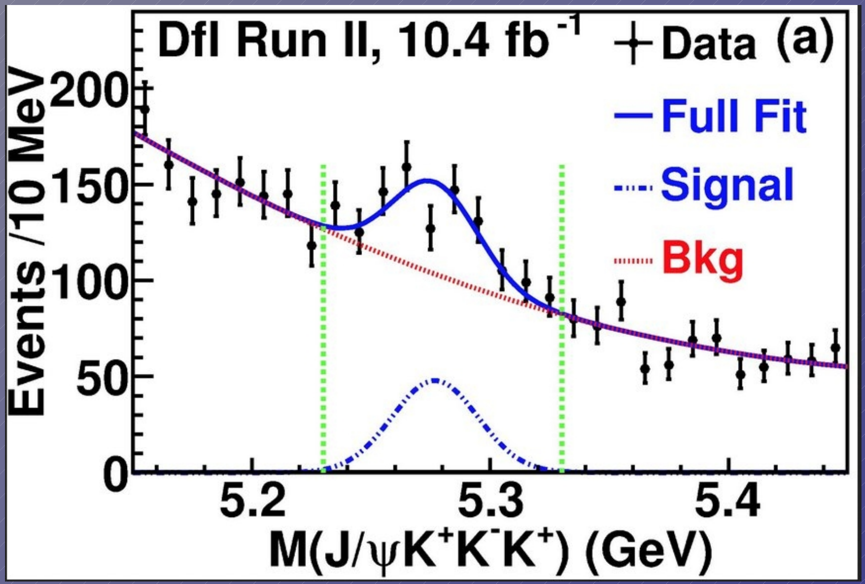
χ^2/ndf = 114/110 $\approx$ 1.04

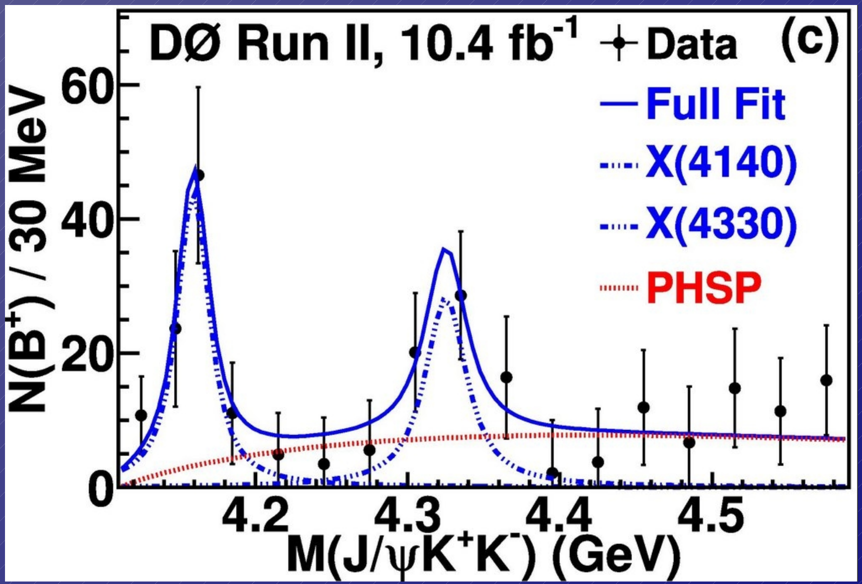
We have a beautiful X(3872) signal in RunIIb data.

This plot was made by my undergrad Nick McCleerey last summer.

X(4140)

Another J/ψ X analysis: $B^{\pm} \rightarrow J/\psi\ \Phi\ K^{\pm}$. We see evidence for $X(4140) \rightarrow J/\psi\ \Phi$ and a possible enhancement at higher mass.



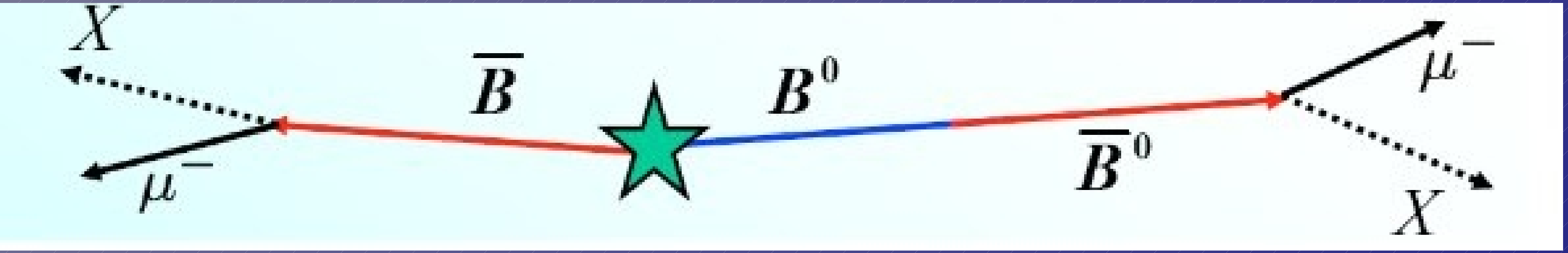


CDF and CMS see this state, LHCb and Belle do not. We have 3.1 σ evidence.

Phys. Rev. D84, 12004 (2014).

Back to mixing and CPV

Like-sign dimuon charge asymmetry



Like-sign dimuons occur when one B meson mixes and the other does not.

$$A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

If, after correcting for backgrounds, the asymmetry is non-zero, it is inherently CPV.

Dimuon charge asymmetry

$\int Ldt$	asymmetry A_{CP}		DØ , Phys.Rev. D
1.0 fb^{-1}	$(-0.28 \pm 0.13 \pm 0.09)\%$	1.7σ *	**74**, 092001 (2006)
6.1 fb^{-1}	$(-0.252 \pm 0.088 \pm 0.092)\%$	3.2σ *	**82**, 032001 (2010)
9.0 fb^{-1}	$(-0.276 \pm 0.067 \pm 0.063)\%$	3.9σ *	**84**, 052007 (2011)
10.4 fb^{-1}	$(-0.235 \pm 0.064 \pm 0.055)\%$	3.6σ **	**89**, 012002 (2014)

* Discrepancy with A_{CP}^{mix}(SM) only.

** Discrepancy with A_{CP}^{mix}(SM) and A_{CP}^{int}(SM).

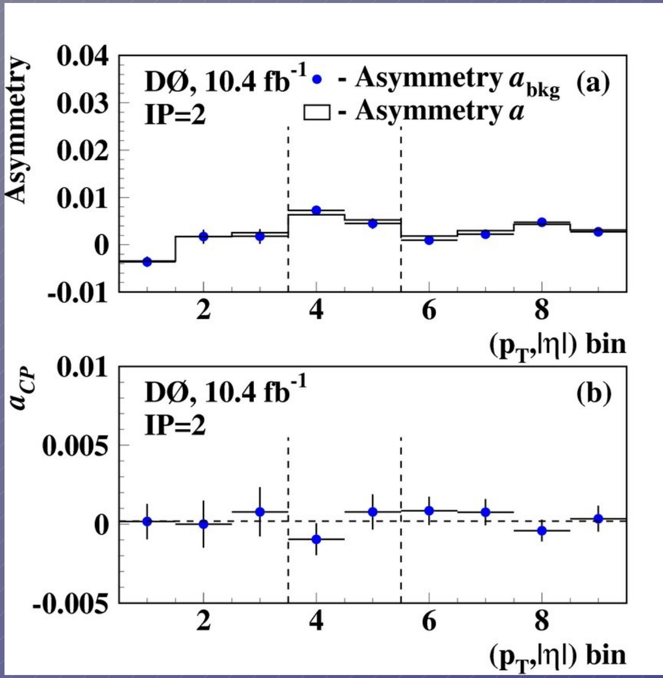
For CPV in interference see Phys. Rev. D **87**, 074020 (2013).

From Bruce's talk at FPCP

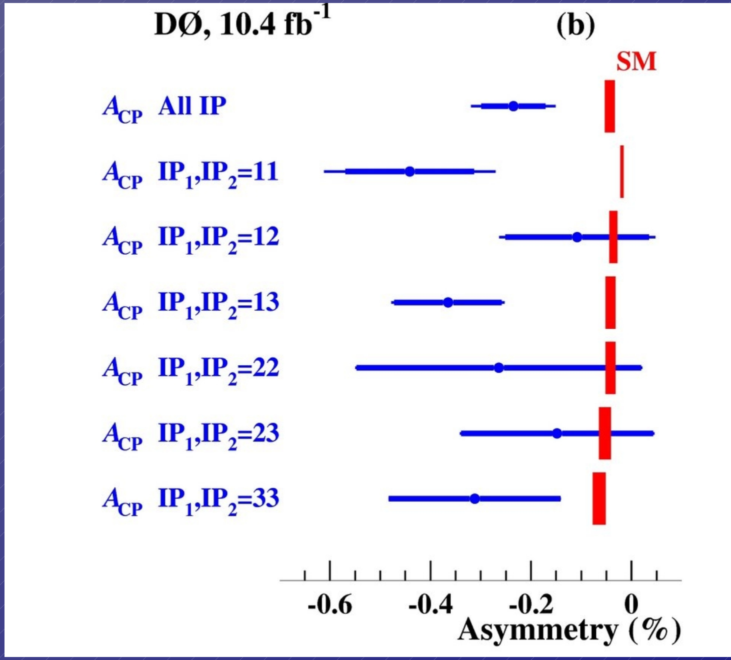
This measurement has been pursued for years and has been stable for years.

The most recent measurement divided the data into several bins of impact parameter, p_T, and η.

Dimuon charge asymmetry

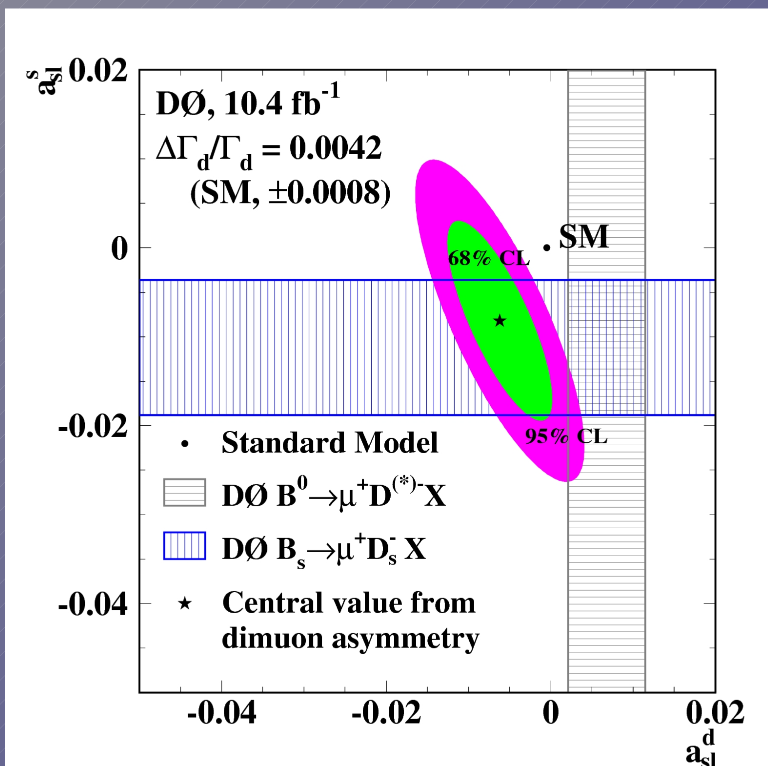


Closure test—one of four tests indicating that background asymmetries are well understood.



The final measured asymmetries.

Semileptonic charge asymmeties



$\Delta\Gamma_d/\Gamma_d$ fixed to SM value

In addition to the dimuon charge asymmetry, D0 has measured the semileptonic charge asymmetries in B_d^0 and B_s^0 decays.

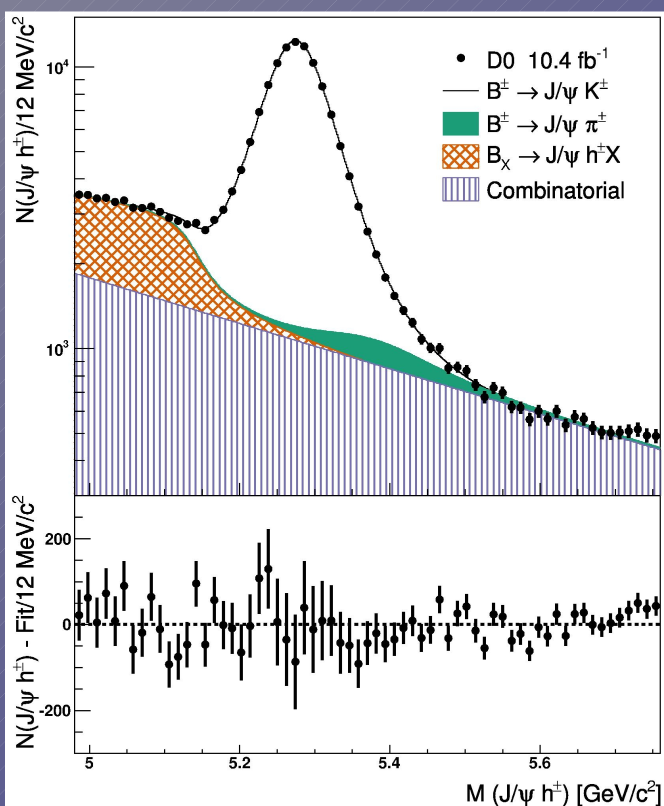
$$a^q_{sl} = \frac{\Gamma(\bar{B}^0_q \rightarrow B^0_q \rightarrow \ell^+ X) - \Gamma(B^0_q \rightarrow \bar{B}^0_q \rightarrow \ell^- X)}{\Gamma(\bar{B}^0_q \rightarrow B^0_q \rightarrow \ell^+ X) + \Gamma(B^0_q \rightarrow \bar{B}^0_q \rightarrow \ell^- X)}$$

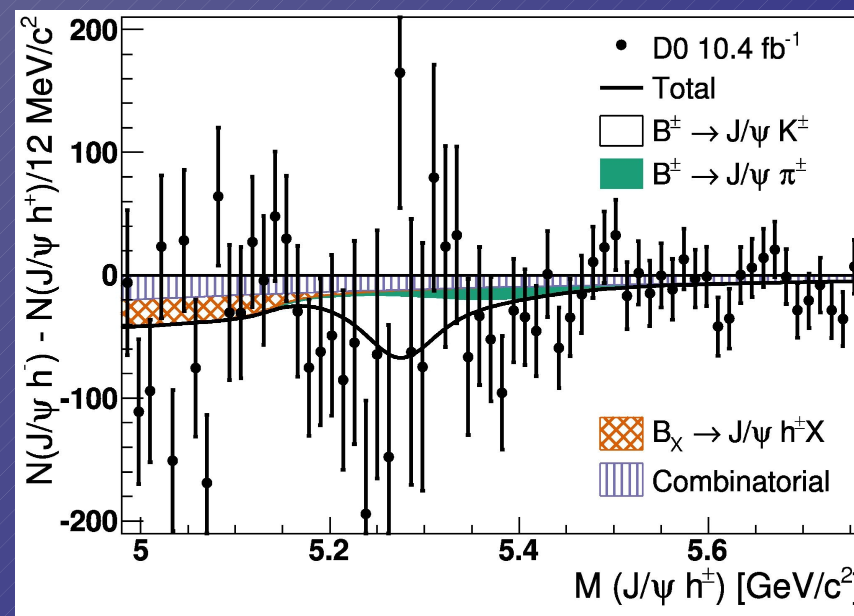
a^d_{sl} = [0.68 ± 0.45 (stat) ± 0.14(sys)]%
Phys. Rev. D86,072009 (2012)

a^s_{sl} = [-1.12 ± 0.74 (stat) ± 0.17 (syst)]%
Phys. Rev. Lett. 110, 011801 (2013)

Search for direct CPV in B^+ decays

Techniques developed in the dimuon and semileptonic charge asymmetry measurements are immediately applicable to other measurements, such as a search for direct CPV in $B^+ \to J/\Psi K^+$ and $B^+ \to J/\Psi \pi^+$

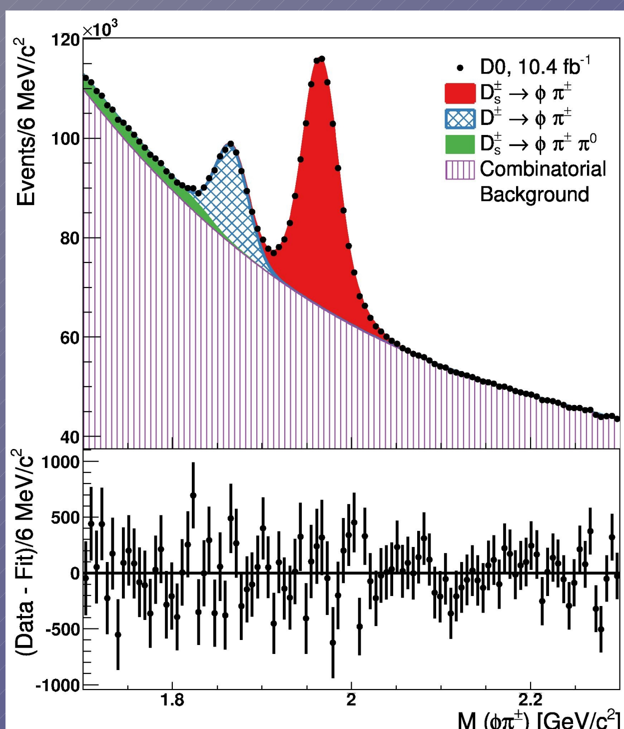


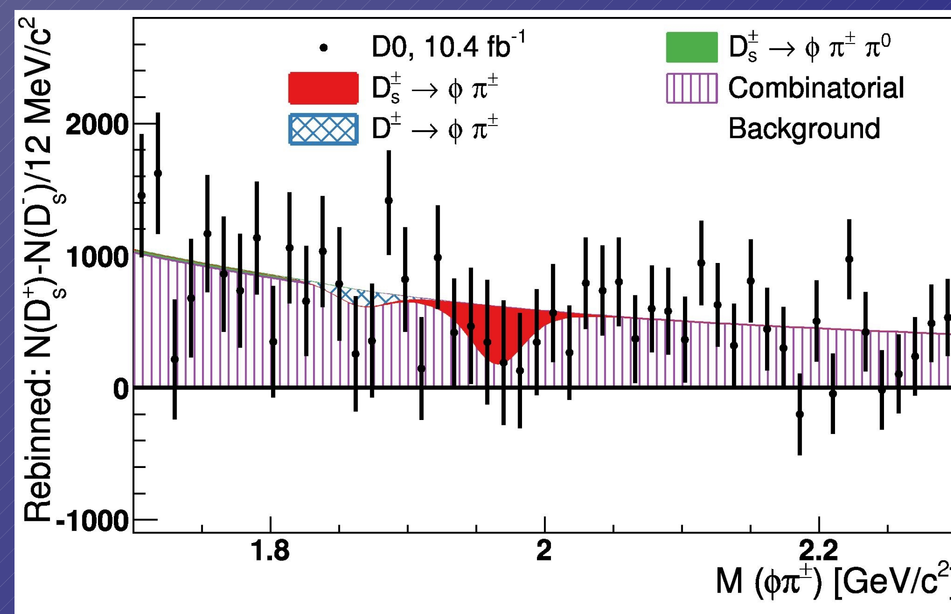


$A^{J/\Psi K} = [0.59 \pm 0.39]\%$
$A^{J/\Psi \pi} = [-4.2 \pm 4.5]\%$
Phys. Rev. Lett. 110, 241801 (2013).

Search for Direct CPV in $D_s \rightarrow \phi\pi$

This analysis has the distinction of being the first HF analysis in D0 to NOT have a muon in the final state.





A_{CP} = [-0.38 ± 0.27]%

Phys. Rev. Lett 112, 111804 (2014).

Summary and thoughts

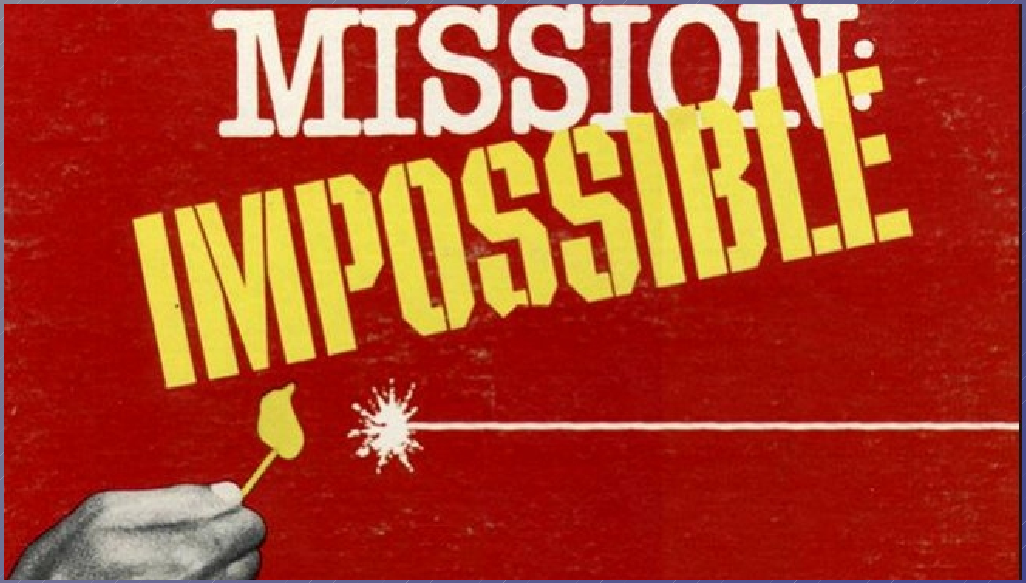
The range of heavy flavor physics results is truly impressive.
There's more to come! (See Rick van Kooten's talk).

Much credit goes to those who designed and built the detector.

With the exception of the like-sign dimuon charge asymmetry, our results are all consistent with the standard model.

The questions we started out to answer still remain, and we must not give up.

Farewell to Mark



Mark Williams is off to a CERN fellowship at the end of June.

Your mission, Mark, should you choose to accept it, is to confirm or refute the D0 like-sign dimuon charge asymmetry with LCHb data.

Backup

arXiv:1308.1048
LHCb talk at PASCOS, 2013