Searches for New Physics in Charm and Bottom Decays at the Tevatron

Rencontres de Blois, 20th May 2014

Mark Williams, Indiana University

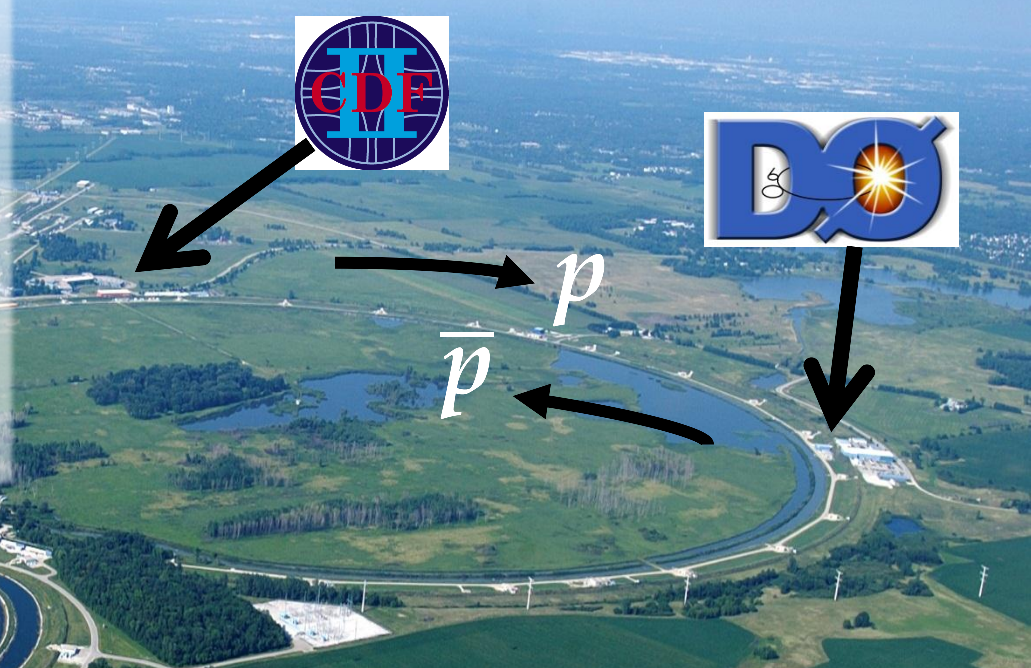
Tevatron Accelerator

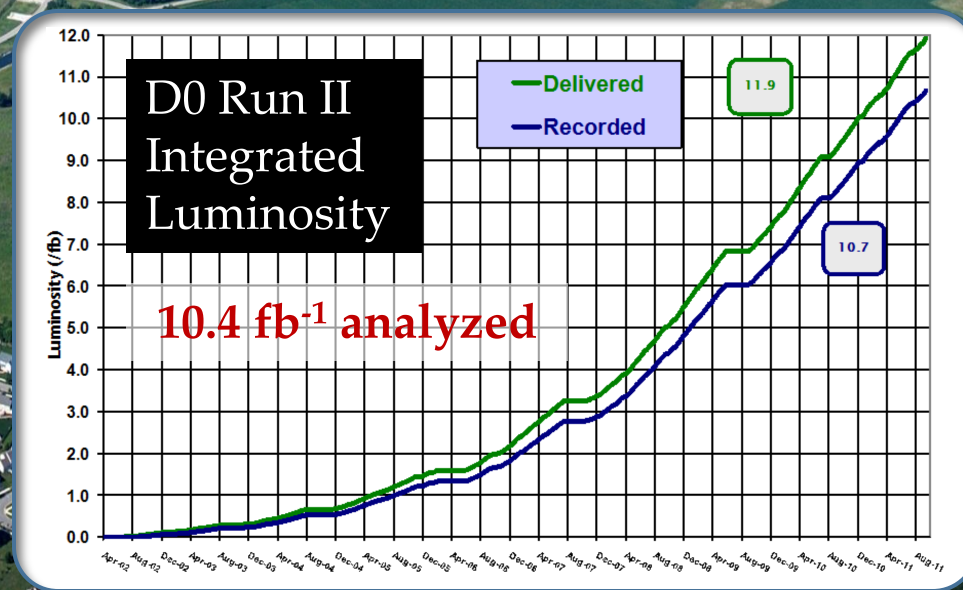
Tevatron accelerator located at the Fermilab site, 30 miles west of Chicago;

Collided protons and antiprotons at $\sqrt{s} = 1.96$ TeV

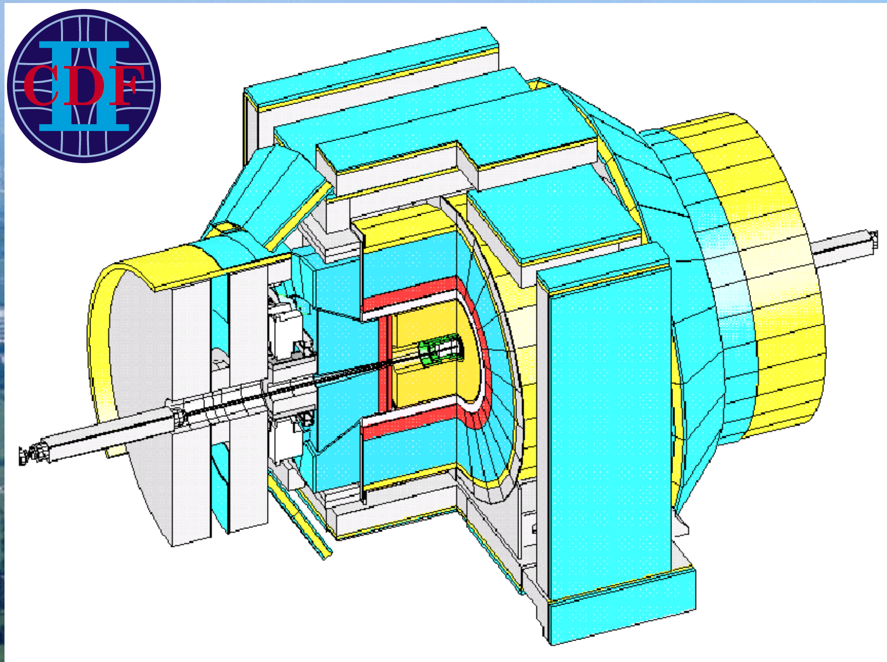
No production asymmetries: symmetric initial state

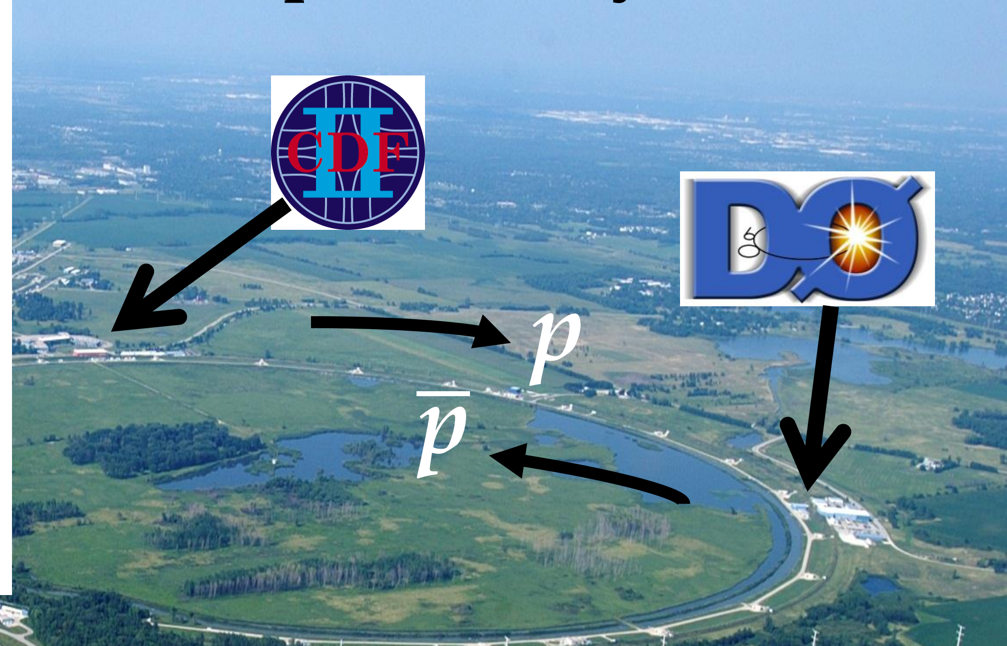
Collisions ended in September 2011





Complementary Detectors



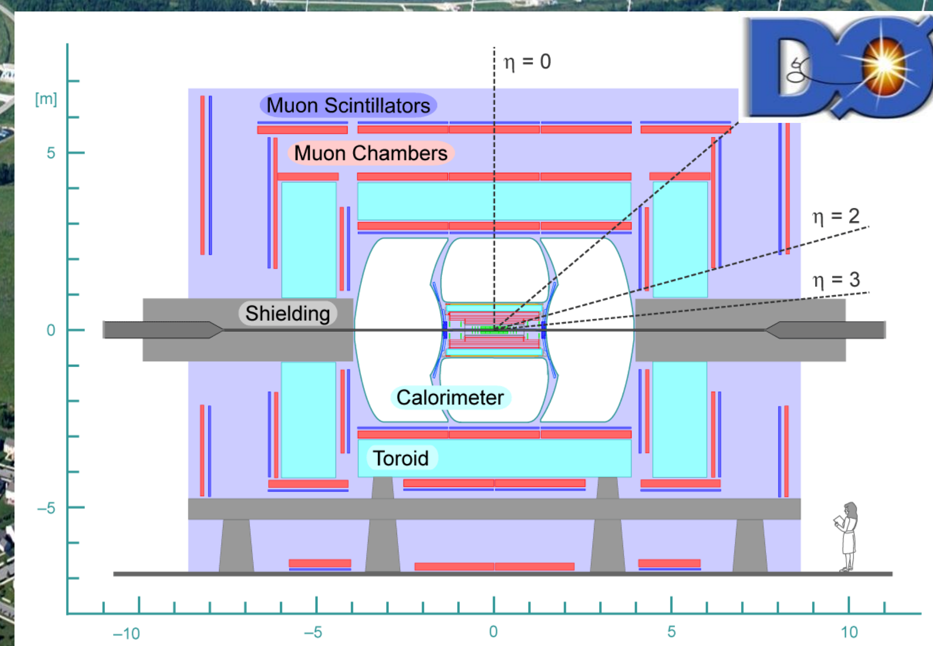


CDF: large tracking volume, dedicated secondary vertex trigger

⇒ Excellent mass resolution and hadronic decay program

D0: Wide muon acceptance, charge-symmetric tracker, regular magnet polarity reversal

⇒ Unique data set for CPV analyses, especially with muons



Overview

"Study of **CP-violating** charge asymmetries of single muons and like-sign dimuons in ppbar collisions" Phys. Rev. D **89**, 012002 (2014), arXiv:1310.0447

"Measurement of the **direct CP-violating** charge asymmetry in $D_s^{\pm} \to \varphi\pi^{\pm}$" Phys. Rev. Lett. **112**, 111804 (2014), arXiv:1312.0741

"Search for the **X(4140) state** in $B^{+} \to J/\psi\varphi K^{+}$ decays with the D0 detector" Phys. Rev. D **89**, 012004 (2014), arXiv:1309.6580

"Study of orbitally **excited B mesons** and evidence for a new $B\pi$ resonance" Submitted to Phys. Rev. D, arXiv:1309.5961

"Measurement of **b baryon** properties at CDF" Phys. Rev. **D 89**, 072014 (2014), arXiv:1403.8126

"Measurement of the $B_c^{+} \to J/\psi\mu^{+}\nu$ relative cross section using the complete CDF dataset" CDF Public Note 11083

Final dimuon asymmetry update

Measure charge asymmetry in production of inclusive muons, and like-charge dimuons from initially symmetric $p\bar{p}$ collisions

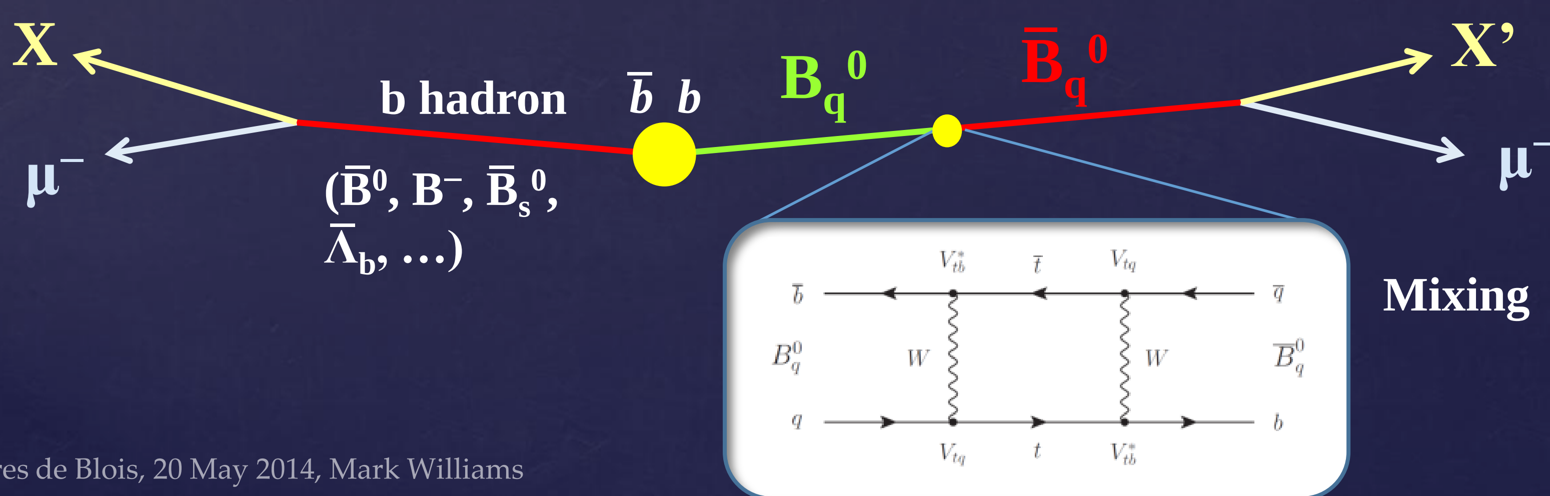
Correct for detector asymmetries (dominated by asymmetry in $K \rightarrow \mu$ and in muon reconstruction)
$\Rightarrow$ Resulting quantity is a ***model-independent*** measure of CP violation

Final dimuon asymmetry update

Measure charge asymmetry in production of inclusive muons, and like-charge dimuons from initially symmetric $p\bar{p}$ collisions

Correct for detector asymmetries (dominated by asymmetry in $K \to \mu$ and in muon reconstruction)
$\Rightarrow$ Resulting quantity is a ***model-independent*** measure of CP violation

Interpreted in terms of CPV in **$B_{(s)}^0$ meson mixing** (parameters: **a^d_{sl}, a^s_{sl}**)…

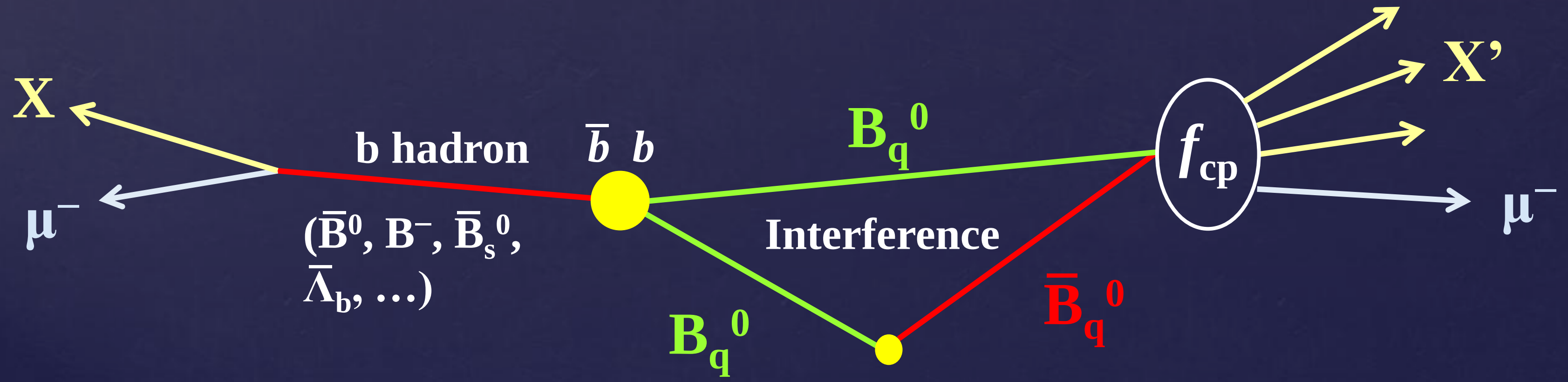


Final dimuon asymmetry update

Measure charge asymmetry in production of inclusive muons, and like-charge dimuons from initially symmetric $p\bar{p}$ collisions

Correct for detector asymmetries (dominated by asymmetry in K→μ and in muon reconstruction)
⇒ Resulting quantity is a ***model-independent*** measure of CP violation

Interpreted in terms of CPV in $B_{(s)}^0$ meson mixing (parameters: $\mathbf{a^d_{sl}}$, $\mathbf{a^s_{sl}}$), **and** in **interference between mixed and direct B^0 decays** ($\Delta\Gamma_d$)



Final dimuon asymmetry update

1) Measure raw asymmetries by counting muons:

Raw single muon charge asymmetry, $a = \dfrac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$

Raw same-sign dimuon charge asymmetry, $A = \dfrac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$

2) Correct for background asymmetries from detector effects:

Model-independent asymmetries – i.e. the degree of CP violation in muon production

$$\boldsymbol{a_{CP} = a - a_{bkg}}$$

$$\boldsymbol{A_{CP} = A - A_{bkg}}$$

Background asymmetries: dominated by different interactions of particles/antiparticles in the detector

Final dimuon asymmetry update

History:

Three previous measurements from D0, all find asymmetry significantly larger than SM prediction

$\int L dt$	asymmetry A_{CP}
1.0 fb^{-1}	$(-0.28 \pm 0.13 \pm 0.09)\%$
6.1 fb^{-1}	$(-0.252 \pm 0.088 \pm 0.092)\%$
9.0 fb^{-1}	$(-0.276 \pm 0.067 \pm 0.063)\%$

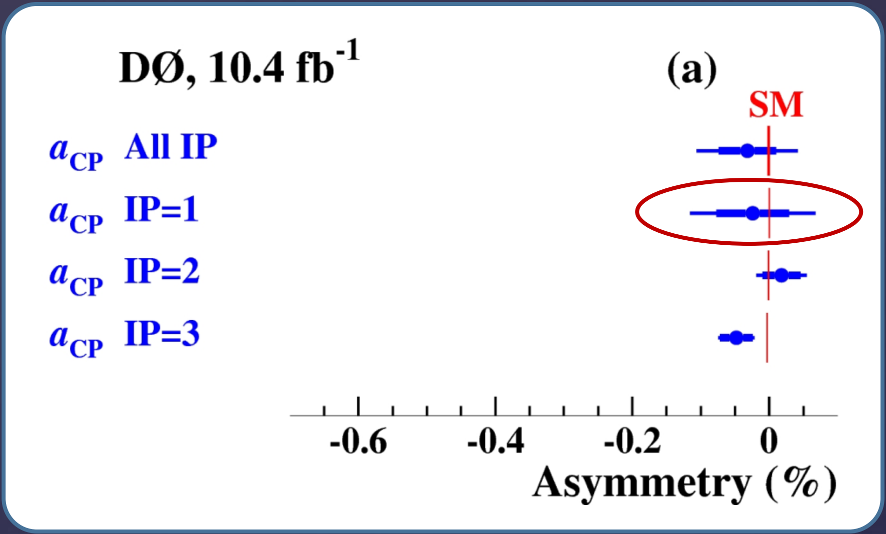
What's new?

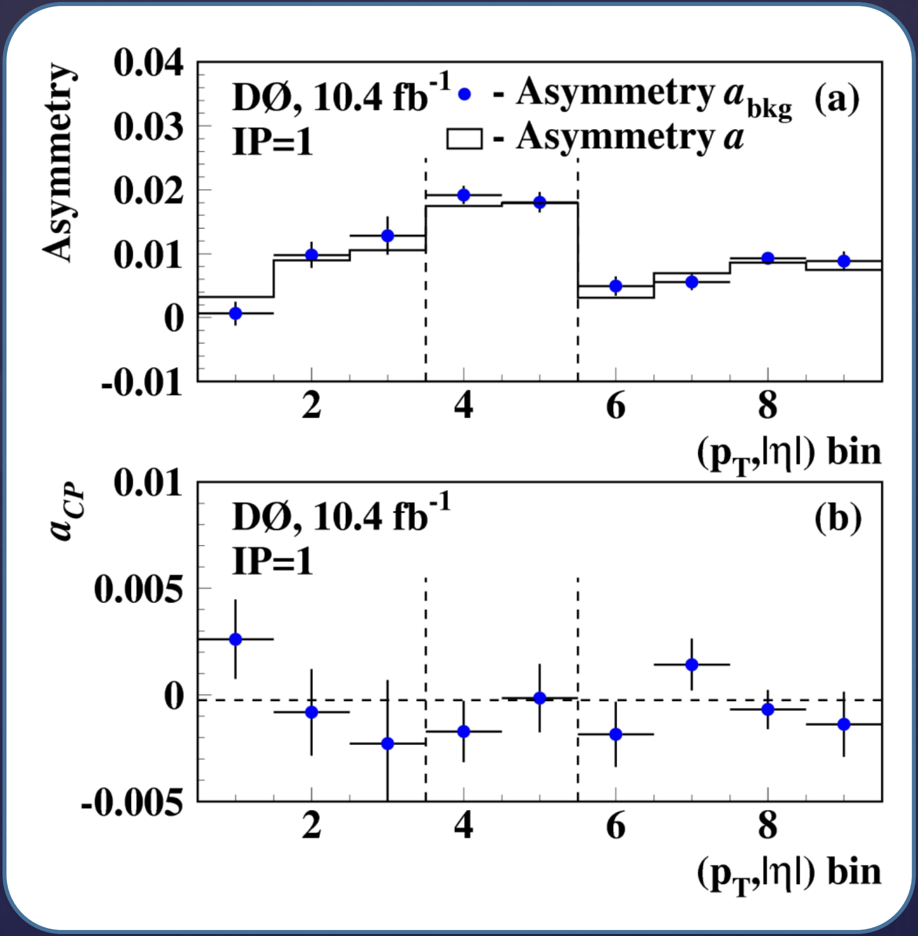
- Full Tevatron Run II sample analyzed (10.4 fb^{-1})
- Measurement performed in 9 kinematic bins of (p_T,$|\eta|$) $\Rightarrow$ improved granularity of background asymmetries
- Separate analysis in 3 impact parameter regions for single muons, 3$\otimes$3=6 regions for dimuons $\Rightarrow$ more sensitivity to differentiate possible sources of CPV, also validates treatment of BG asymmetries.
- Now consider additional SM source from CPV in interference

Final dimuon asymmetry update

Results: a_{CP}

Consistency of a_{CP} with zero is an important closure test





All sources of CPV will be highly suppressed in this sample

Can also compare a and a_{bkg} in each of the 9 kinematic bins

Final dimuon asymmetry update

Results: A_{CP}

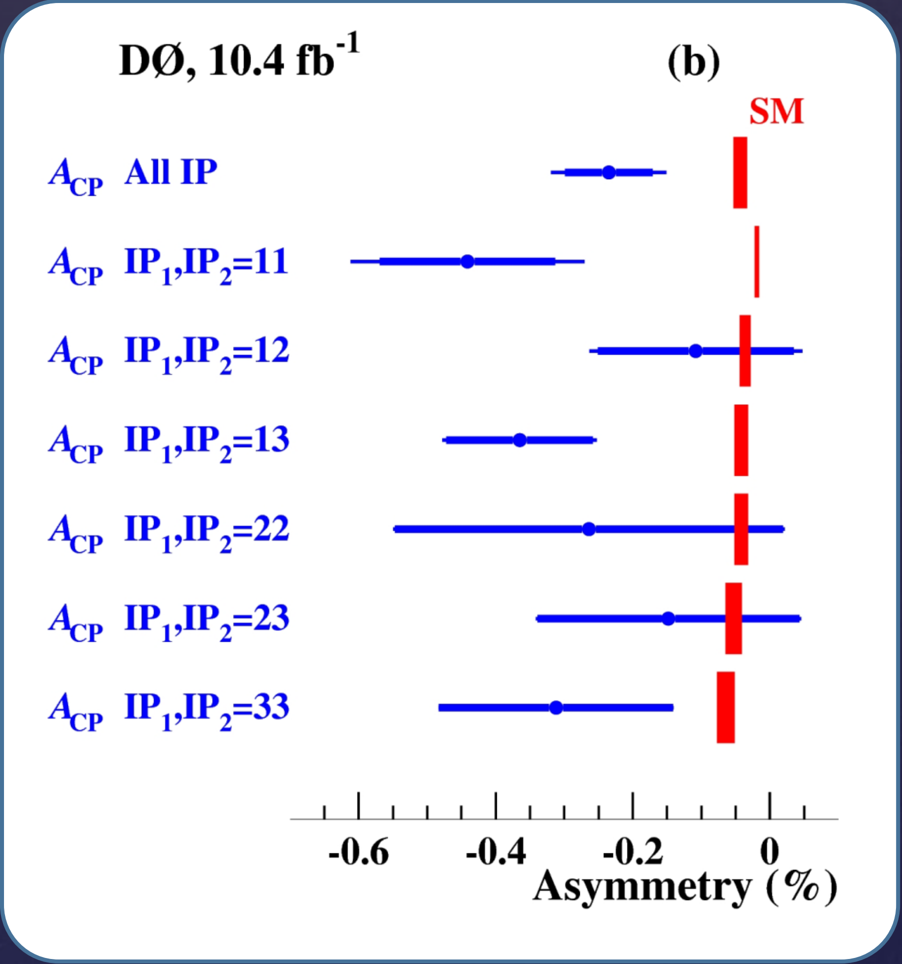
Major difference: global offset between observed raw asymmetry A and expected background A_{bkg}

$$A_{CP} = (-0.235 \pm 0.064 \pm 0.055)\%$$

Trend observed for all IP regions

Also consistently deviating from the SM prediction

A_{CP} consistent in all bins, despite raw asymmetry varying between +0.7%→ −0.5%



Final dimuon asymmetry update

Results: A_{CP}

Combining all 9 IP measurements (3 single muon + 6 same-sign dimuon)

Fit assuming *zero CP violation* gives:

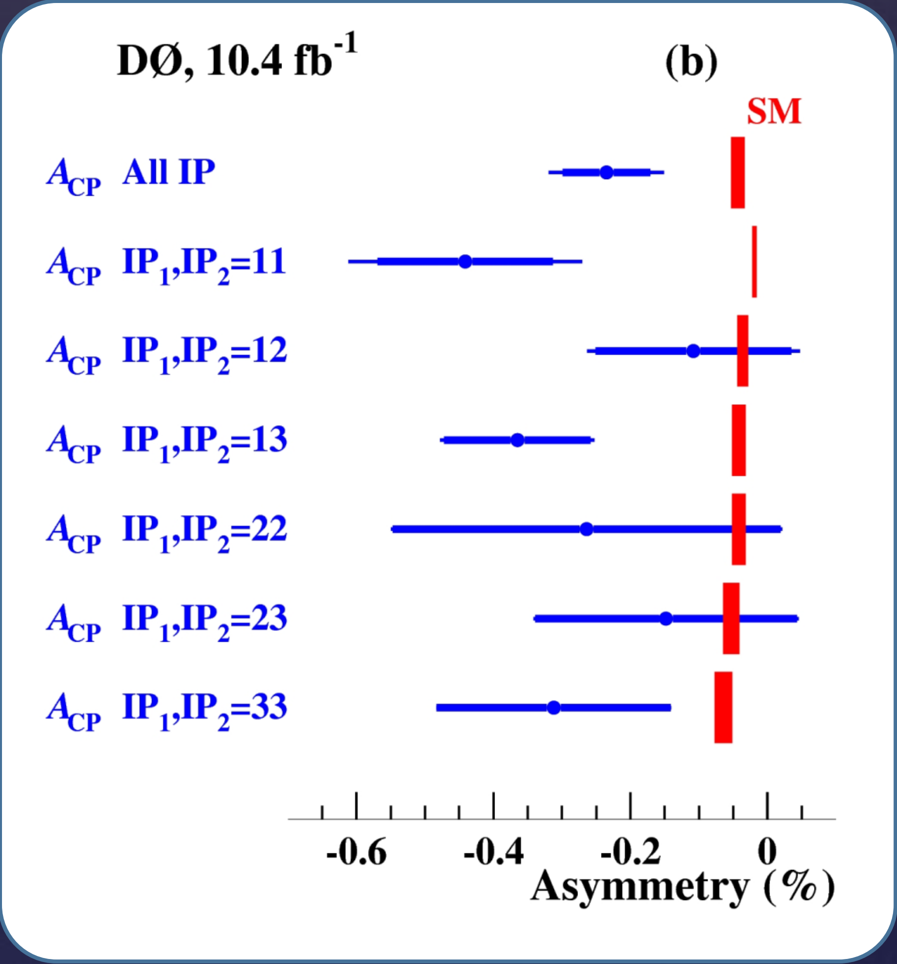
$$\chi^2 = 36.5 / 9 \text{ d.o.f}$$

4.1σ evidence for non-zero charge asymmetry

Fit to the SM predictions:

$$\chi^2 = 31.0 / 9 \text{ d.o.f}$$

3.6σ disagreement with SM predictions



Final dimuon asymmetry update

3 parameter fit:

χ^2/d.o.f. = 10.1/6

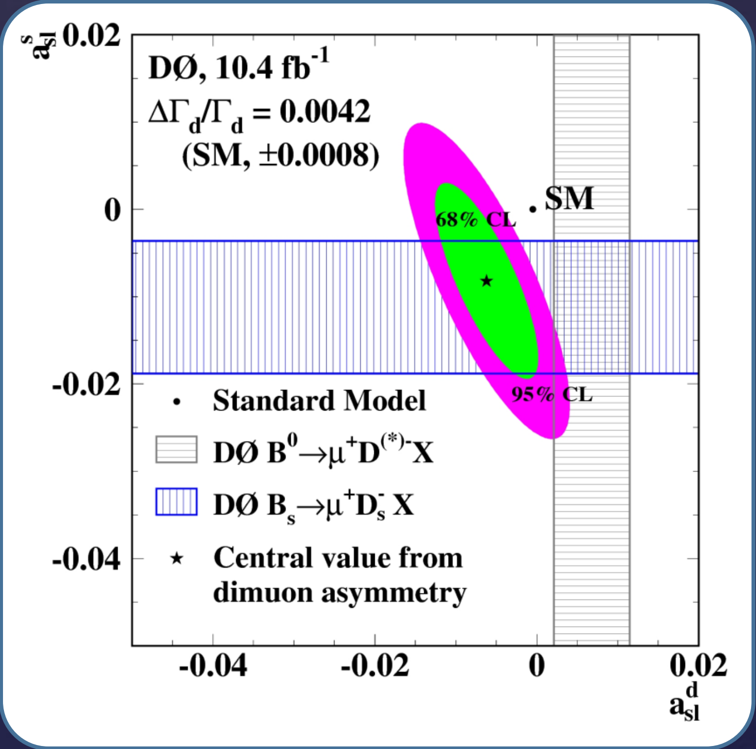
$$a^d_{sl} = (-0.62 \pm 0.43)\%$$
$$a^s_{sl} = (-0.82 \pm 0.99)\%$$
$$\Delta\Gamma_d/\Gamma_d = (+0.50 \pm 1.38)\%$$

$$\begin{pmatrix} \rho_{ds} = -0.61 \\ \rho_{d\Delta\Gamma} = -0.03 \\ \rho_{s\Delta\Gamma} = +0.66 \end{pmatrix}$$

Disagrees with the SM point at the 3.0σ level

Visualized by projecting onto (a^d_{sl},a^s_{sl}) plane at the SM prediction of $\Delta\Gamma_d/\Gamma_d$

(SM value of $\Delta\Gamma_d/\Gamma_d$ = +0.42% agrees with the central value of the fit)



Final dimuon asymmetry update

Both mixing asymmetries a^s_{sl} and a^d_{sl} have been recently measured with good precision (D0, LHCb, BaBar)

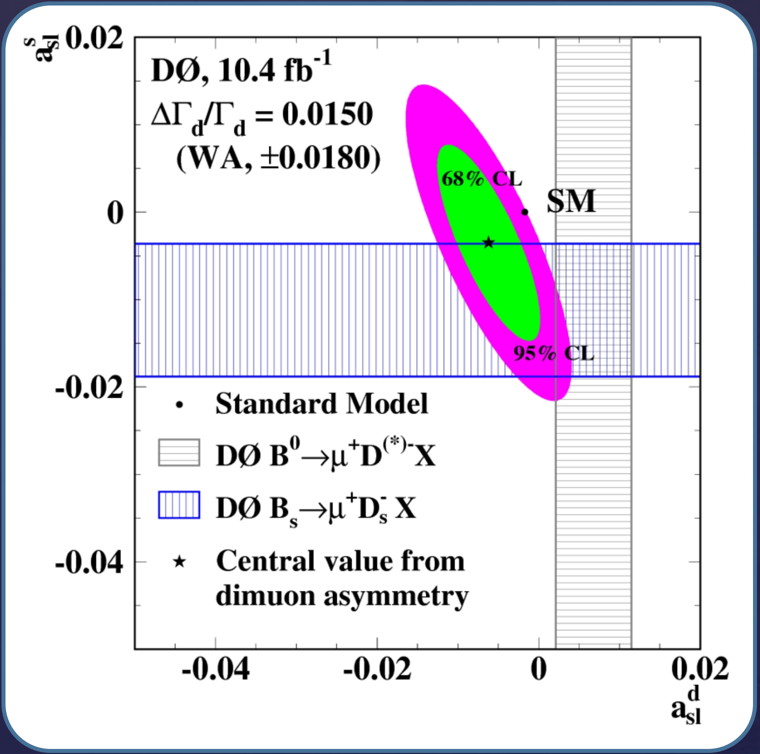
In contrast, $\Delta\Gamma_d/\Gamma_d$ is poorly constrained experimentally:

We can repeat the fit with $\Delta\Gamma_d/\Gamma_d$ fixed to this world average

$$\Delta\Gamma_d/\Gamma_d = (+1.5 \pm 1.8)\%$$

Mixing asymmetries are then in agreement with SM within **1.9σ**

Important to perform independent measurements of $\Delta\Gamma_d/\Gamma_d$



Direct CPV in $D_s^\pm \to \varphi\pi^\pm$ Decays

What?

$$A_{D_s} = \frac{\Gamma(D_s^+) - \Gamma(D_s^-)}{\Gamma(D_s^+) + \Gamma(D_s^-)}$$

Only single published measurement (CLEO, 2013):
$A_{D_s} = (-0.5 \pm 0.8 \pm 0.4)\%$

Why?

No CPV expected in SM – tree and loop diagrams have same weak phase

⇒ **Strong test of CPV mechanism in SM, sensitive to New Physics**

Also *assumed* to have zero CPV in several other measurements:

- $\mathbf{a^s_{sl}}$ in $B_s^0 \to \bar{B}_s^0 \to D_s\mu\nu X$
- D_s **production asymmetry** @ LHCb

⇒ **Important experimental input for future measurements – reduces dependence on theoretical assumptions**

Direct CPV in $D_s^{\pm} \to \varphi\pi^{\pm}$ Decays

How?

$$A_{D_s} = A - A_{det} - A_{phys}$$

Simultaneous fit of sum and difference distributions to extract raw charge asymmetry

Tiny contribution from possible CPV in B→D (from MC and PDG)

Account for (small) contributions from detector asymmetries (data-driven)

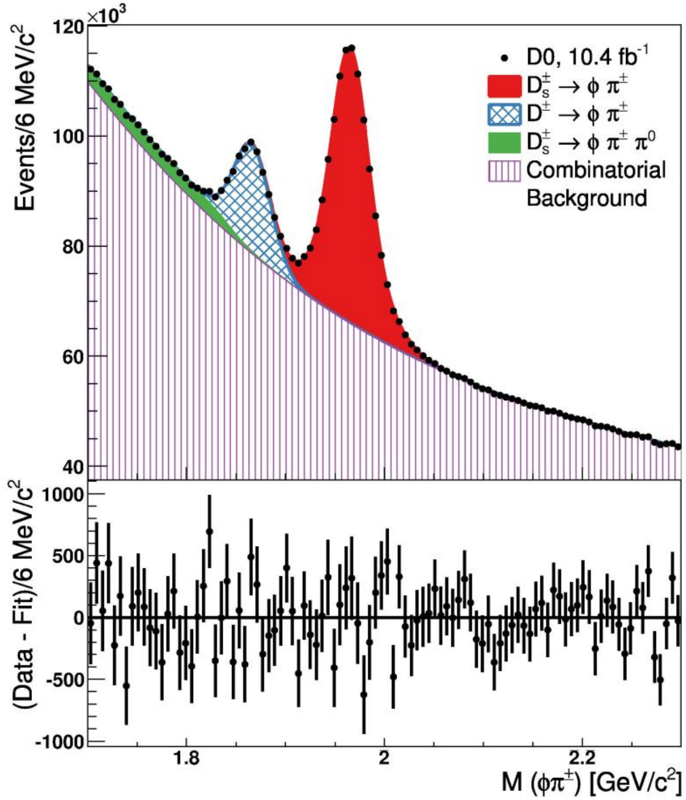
$K^+K^-\pi^{\pm}$ final state:

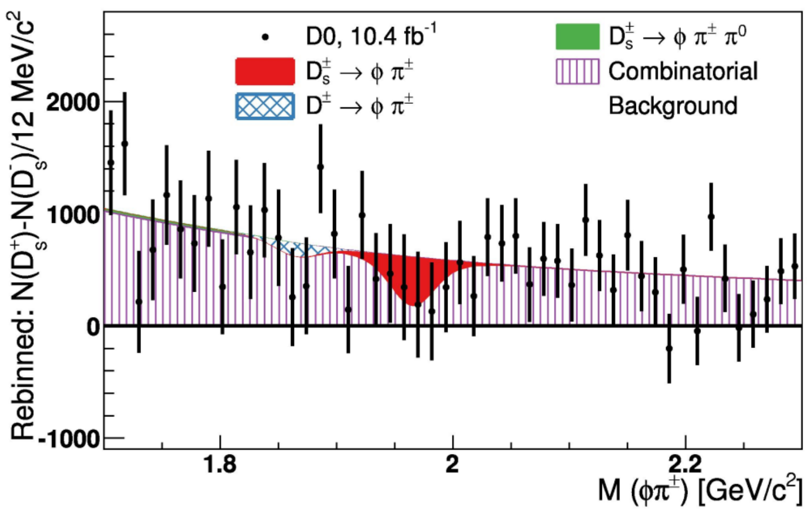
- Dominant kaon asymmetry almost cancels
- Negligible pion asymmmetry (symmetric tracker)

Direct CPV in $D_s^{\pm} \to \phi\pi^{\pm}$ Decays

How?

$$A_{D_s} = A - A_{det} - A_{phys}$$





$$A_{D_s} = (-0.38 \pm 0.26 \pm 0.08)\%$$

- Consistent with SM,
- Most precise measurement

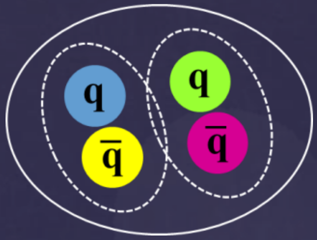
Search for X(4140) State

Increasing interest in, & evidence for, **exotic states**, inconsistent with meson/baryon scheme (mass, width, decays, charge)

X(4140) is one such exotic state, with a mixed experimental past:

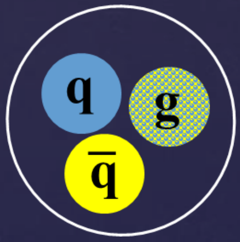
- CMS & CDF see 5σ (>3σ) evidence
- Nothing observed by LHCb or Belle

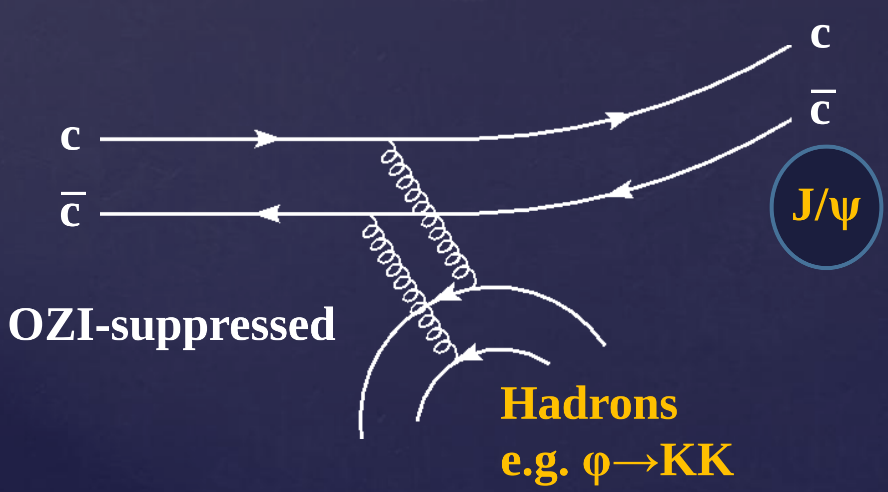
Meson molecule



Tetraquark

Quark-gluon hybrid





Evidence has been in decays
$B^+ \to X(4140)K^+$, $X(4140) \to J/\psi\phi$

Why exotic? For conventional charmonium, decay is OZI-suppressed, and no sign of favored open-charm decay X(4140)→DD

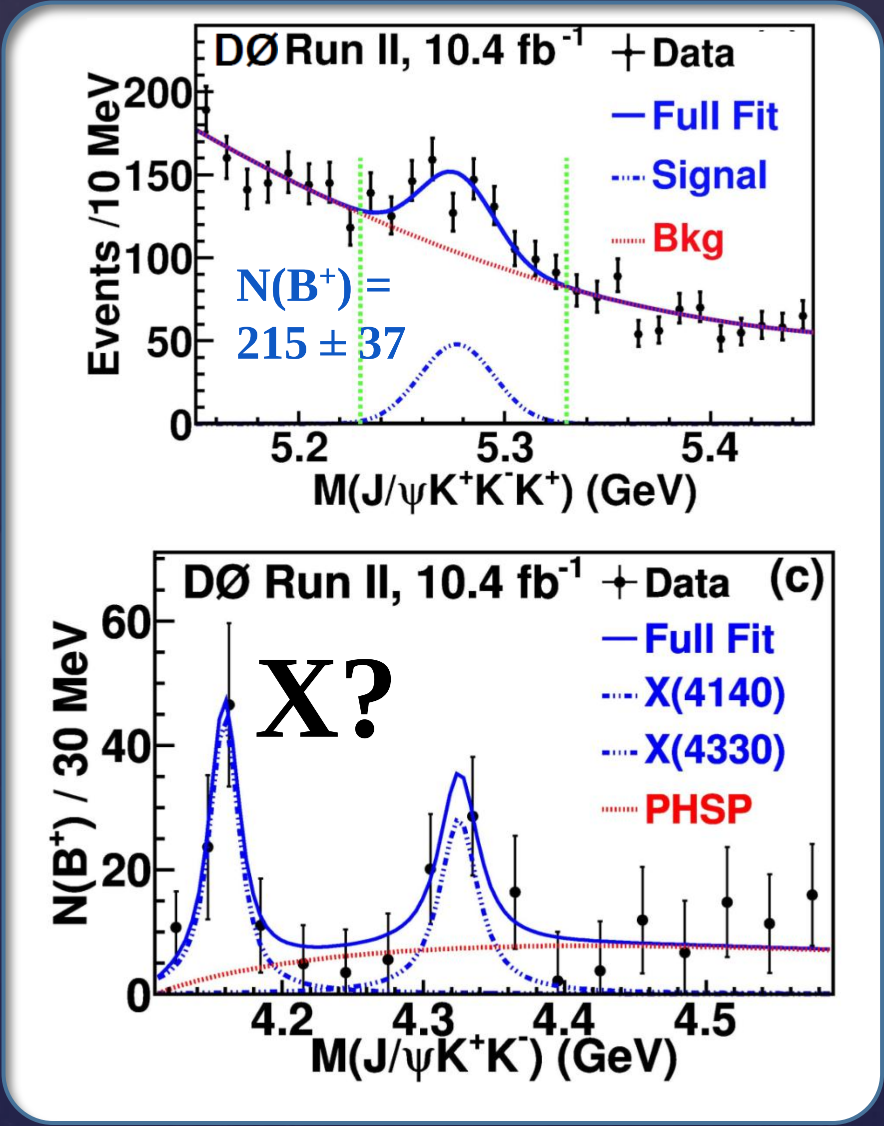
Search for X(4140) State

Event selection optimized to select
$B^\pm \to J/\psi(\mu^+\mu^-)\varphi(K^+K^-)K^\pm$

Search for peaking backgrounds, and apply vetos where needed [$\psi(2S)\to J/\psi\pi\pi$)]

After $B^\pm$ signal confirmed, fit $M(J/\psi\varphi K)$ in bins of $M(J/\psi\varphi)$ to search for resonances:

- **3.1σ** evidence for narrow resonance consistent with X(4140)
- Second excess at higher mass (**1.7σ**)

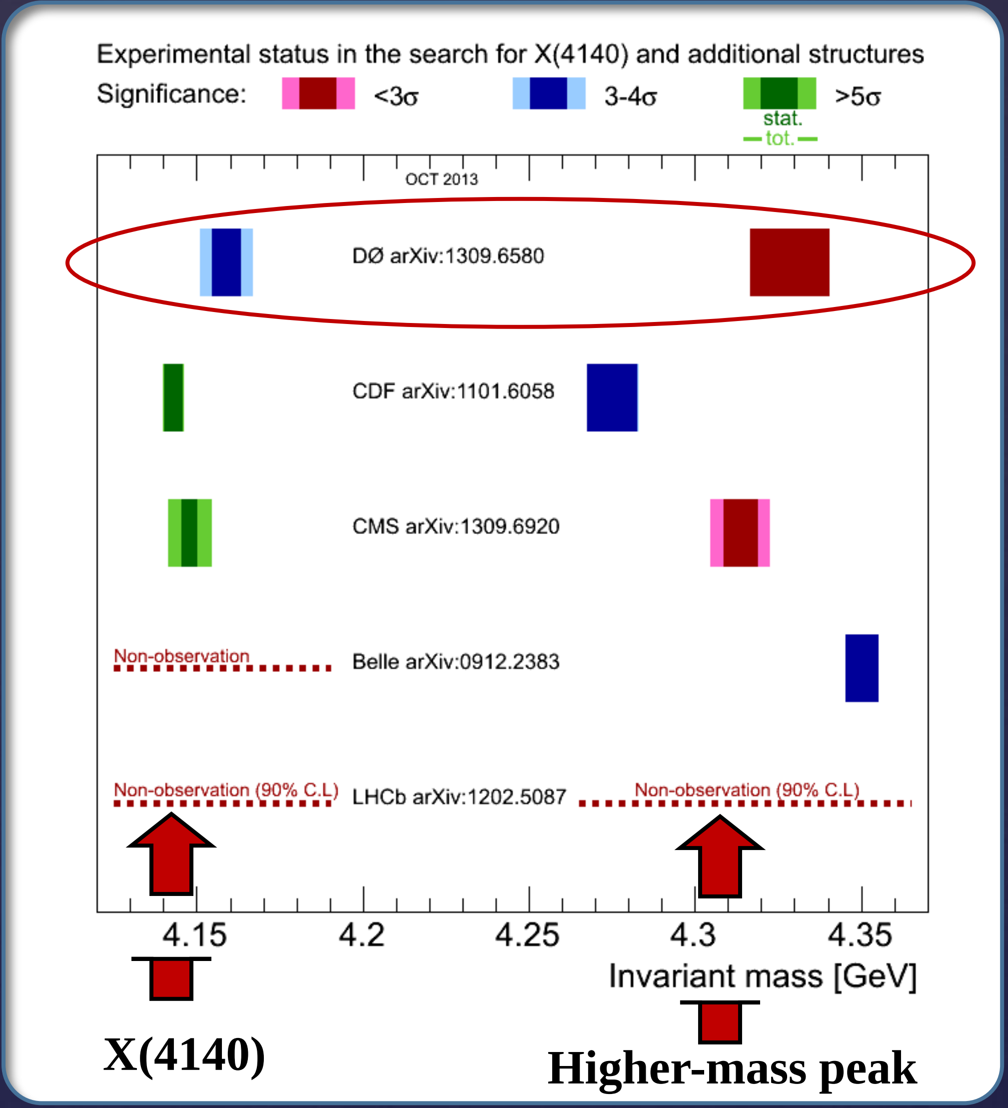


Search for X(4140) State

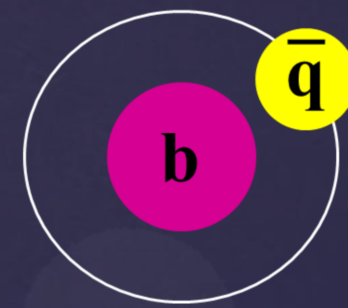
X(4140) properties:

- $M = 4159.0 \pm 4.3 \pm 6.6$ MeV
- $\Gamma = 19.9 \pm 12.6 \, {}^{+3.0}_{-8.0}$ MeV
- $\dfrac{B(B^{\pm} \rightarrow X(4140)K^{\pm})}{B(B^{\pm} \rightarrow J/\psi\varphi K^{\pm})} = (19 \pm 7 \pm 4)\%$

Still no experimental consensus – need more data



Excited B Mesons



= {u, d, s}

B mesons are ‘hydrogen atom’ of QCD

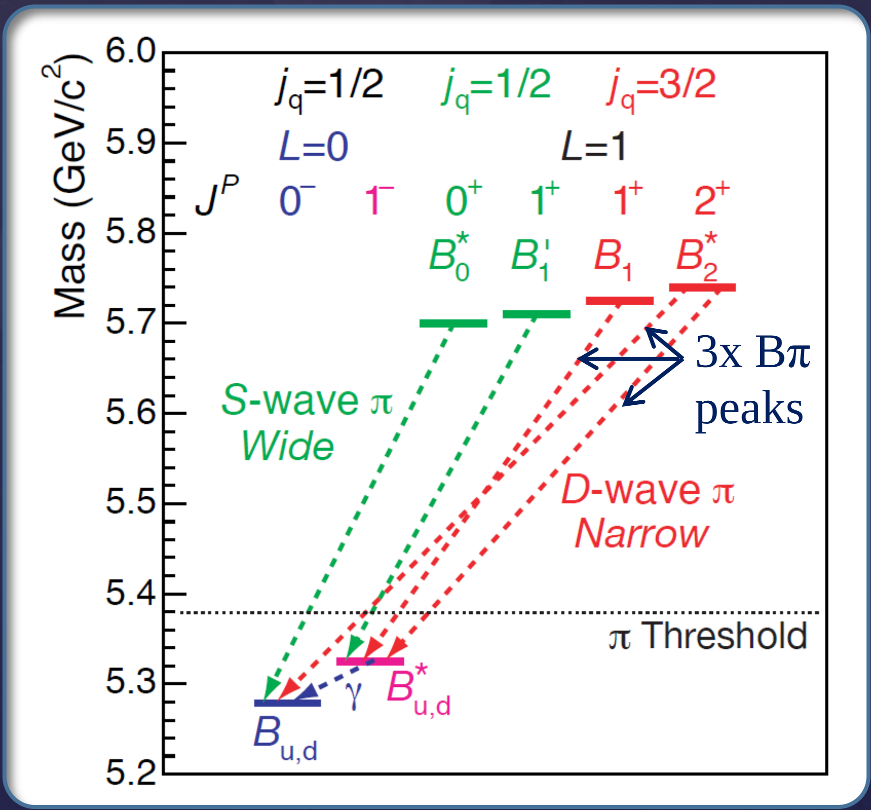
⇒ Energy levels given in terms of light-quark degrees-of-freedom (j, L, J, r)

Strong tests of heavy-quark effective theories, lattice QCD, …

Orbitally-excited states, **$B_{(s)}$**** de-excite to ground state or B* through single pion (kaon) channel

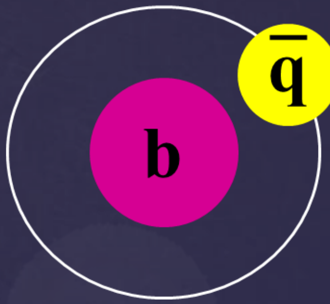
Can search for the narrow j_q=3/2 states; expect to see three peaks in
Q value **M(Bh) – M(B) – M(h)**

B*→Bγ ⇒ 46 MeV splitting of decays to B and B*



Excited B Mesons

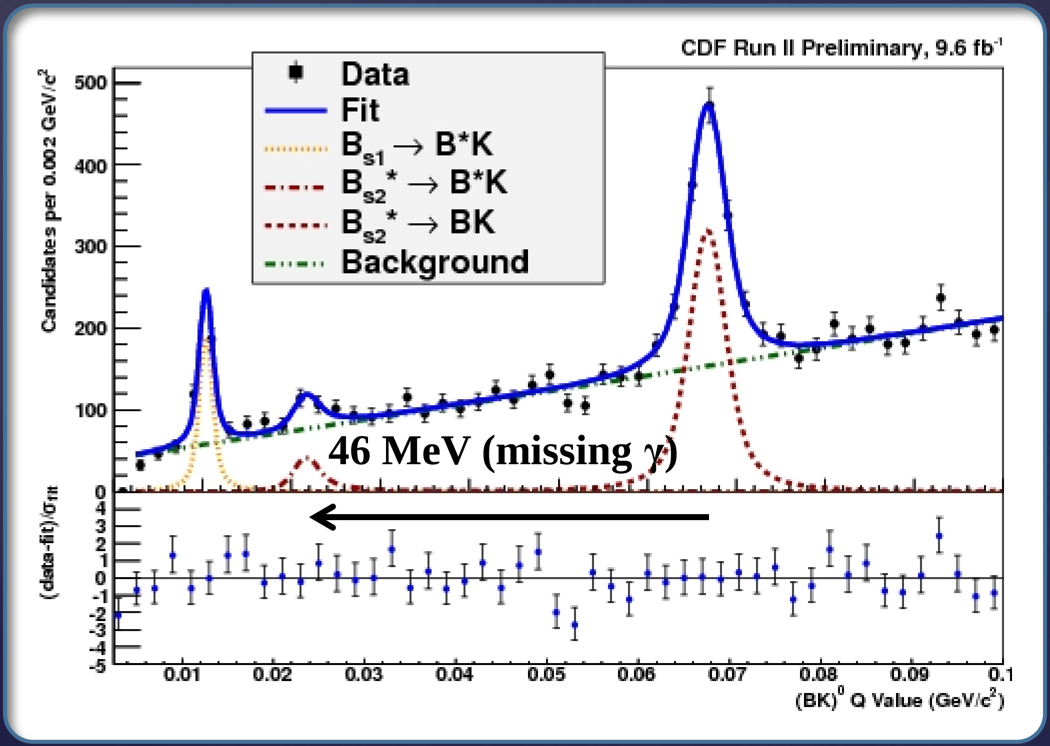
Investigate all three light-quark flavors:



$= \{u, d, s\}$

$B^{+**} \to B^0\pi^+$ **$B^{0**} \to B^+\pi^-$** **$B_s^{0**} \to B^+K^-$**

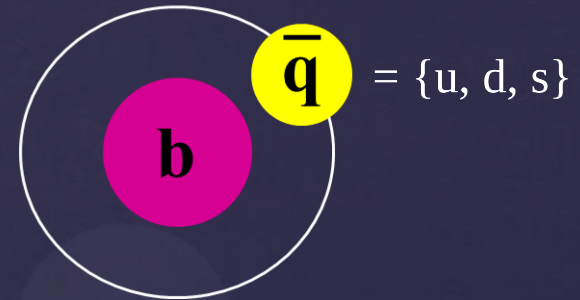
With three B decay topologies: **$B \to J/\psi K$, $D\pi$, $D\pi\pi\pi$**



Good K/π separation
$\Rightarrow$ very clean B_s^{0**} signals

All three resonances observed

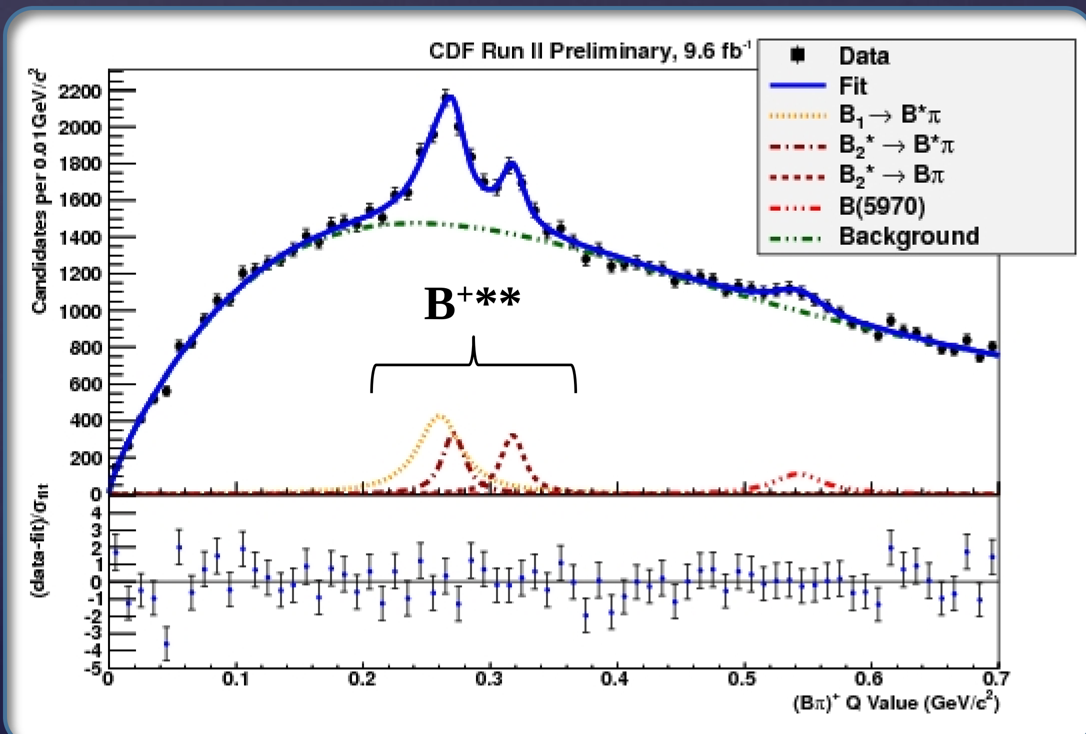
Excited B Mesons



Investigate all three light-quark flavors:

$B^{+**} \to B^0 \pi^+$ $B^{0**} \to B^+ \pi^-$ $B_s^{0**} \to B^+ K^-$

With three B decay topologies: $B \to J/\psi K$, $D\pi$, $D\pi\pi\pi$



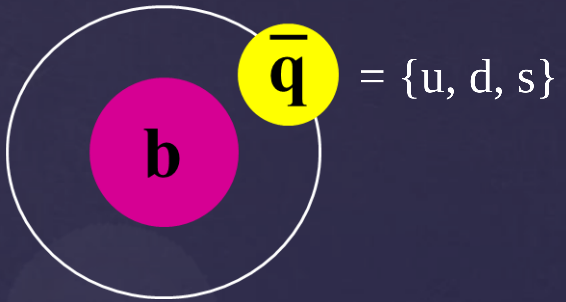
First observation of charged states

(similar results for B^{0**})

All masses, widths, and relative production rates measured for three flavors.

Consistent results in different B decay channels

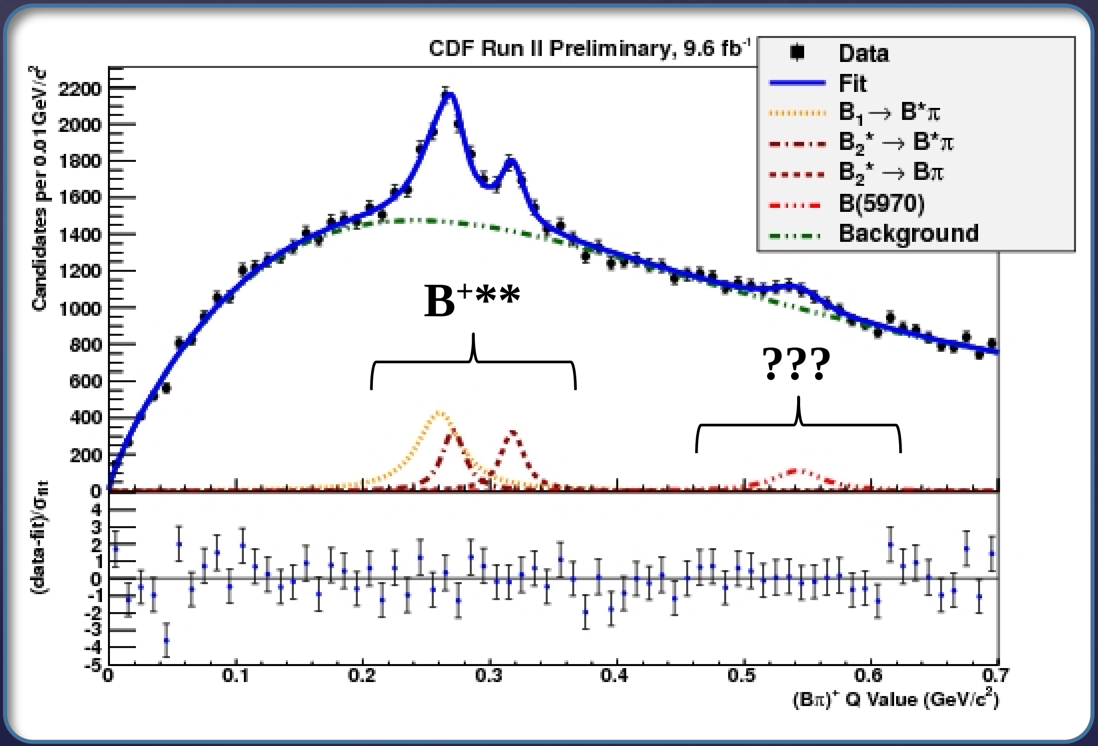
Excited B Mesons



Investigate all three light-quark flavors:

$B^{+**} \rightarrow B^0\pi^+$ **$B^{0**} \rightarrow B^+\pi^-$** **$B_s^{0**} \rightarrow B^+K^-$**

With three B decay topologies: **$B \rightarrow J/\psi K$, $D\pi$, $D\pi\pi\pi$**



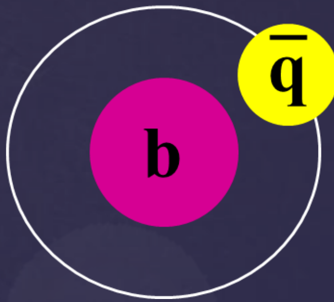
First observation of charged states

(similar results for B^{0**})

All masses, widths, and relative production rates measured for three flavors.

Consistent results in different B decay channels

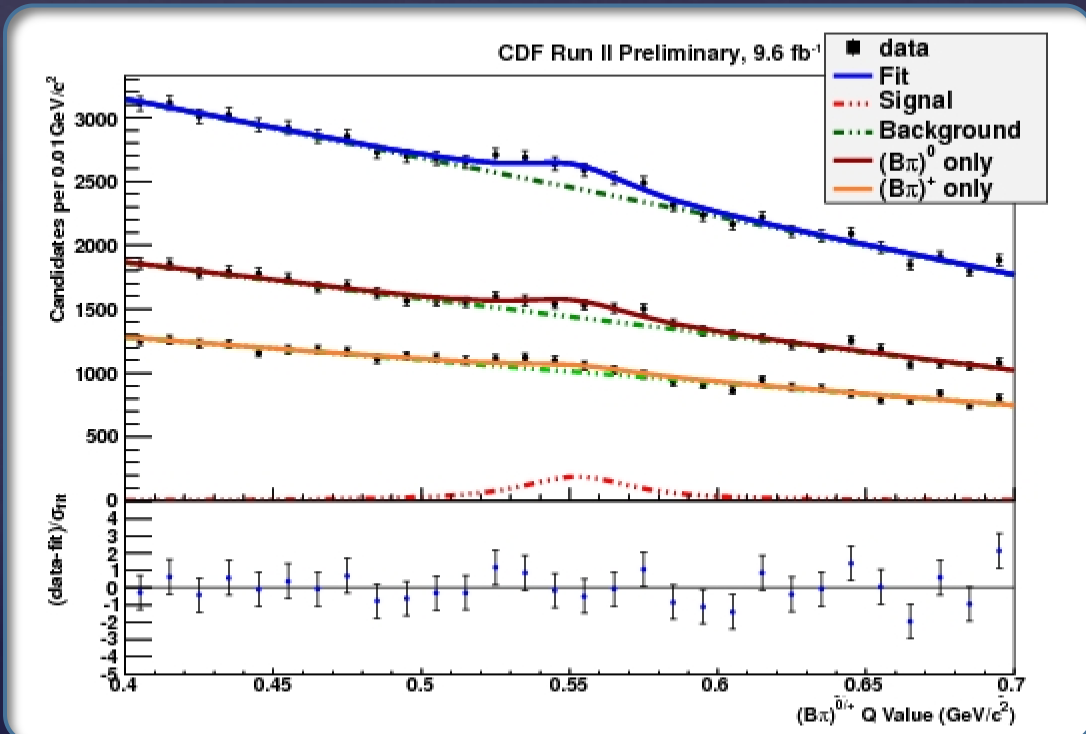
Excited B Mesons



Investigate all three light-quark flavors:

$B^{+**} \to B^0\pi^+$ **$B^{0**} \to B^+\pi^-$** **$B_s^{0**} \to B^+K^-$**

With three B decay topologies: **$B \to J/\psi K$, $D\pi$, $D\pi\pi\pi$**

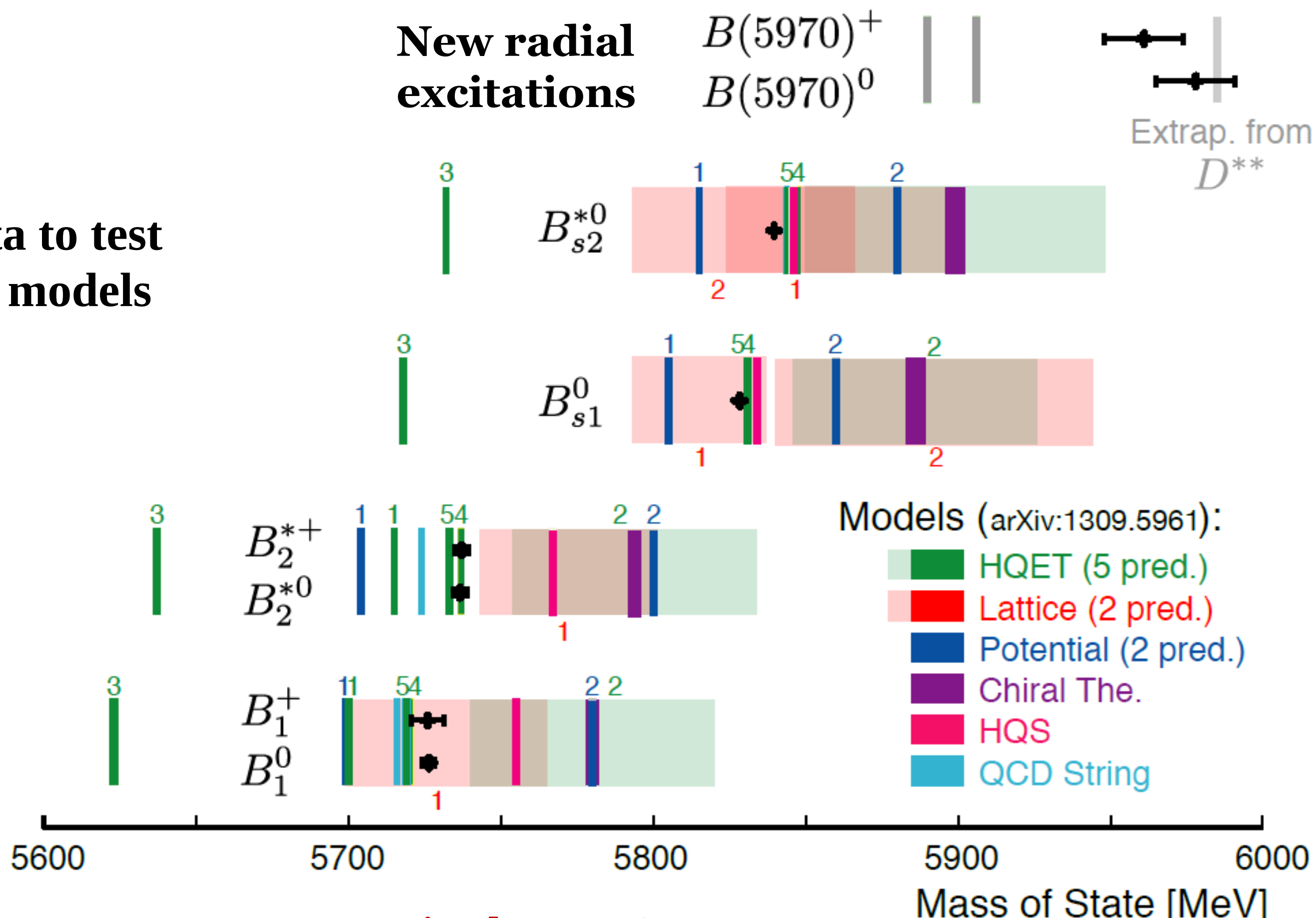


Unexpected resonance observed at higher mass (5970 MeV)

- **4.4σ** significance
- Seen in both **$B^0\pi^+$** and **$B^+\pi^-$** channels
- Consistent with *radial* excitation – first evidence reported for B hadron

Excited B Mesons

Wealth of new data to test and develop QCD models



R. Van Kooten, Moriond QCD 2014

B Baryons

Many heavy baryons observed for the first time in the Tevatron/LHC era

Masses and lifetimes provide testing bed for QCD models

New CDF analysis with full Tevatron dataset ⇒ comprehensive analysis of several charmed and bottom ground-state baryons:

1) Measure **masses** and **lifetimes** of Λ_b^0, Ξ_b^-, Ω_b^- in decays $X_b \to J/\psi X$, $X = \{\Lambda^0, \Xi^-, \Omega^-\}$

2) Measure masses of charm and beauty cascade baryons

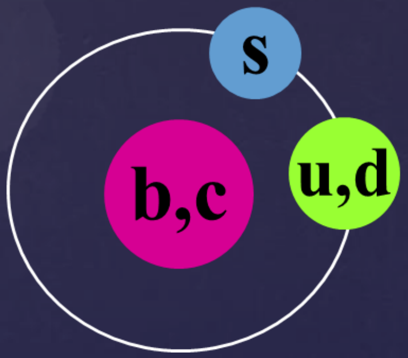
   - $\Xi_b^- \to \Xi_c^0 \pi^-$ $\quad$ $\Xi_c^0 \to \Xi^- \pi^+$
   - $\Xi_b^0 \to \Xi_c^+ \pi^-$ $\quad$ $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$

3) First evidence for corresponding doubly-strange *b* baryon

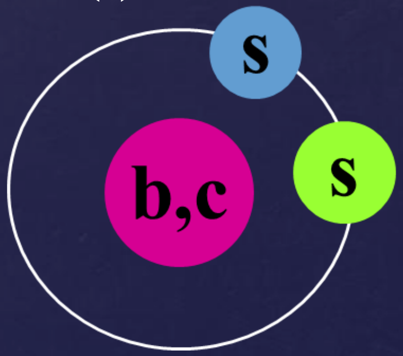
   - $\Omega_b^- \to \Omega_c^0 \pi^-$ $\quad$ $\Omega_c^0 \to \Omega^- \pi^+$

$\Xi_b^{-(0)} = d(u)sb$

$\Xi_c^{0(+)} = d(u)sc$



$\Omega_{b(c)}^{-(0)} = ssb(c)$



B Baryons

Summary of Results

Final state	Mass (MeV/c^2)	$c\tau$ (μm)	Yield
$\Xi_c^0(\Xi^- \pi^+)$	2470.85 ± 0.24	-	3582 ± 82
$\Xi_c^+(\Xi^- \pi^+ \pi^+)$	2468.00 ± 0.18	-	5714 ± 108
$\Lambda_b(J/\psi\,\Lambda)$	5620.15 ± 0.31	468.4 ± 10.5	2920 ± 120
$\Xi_b^-(J/\psi\,\Xi^-)$	5793.2 ± 1.9	396 ± 43	112 ± 19
$\Xi_b^-(\Xi_c^0\,\pi^-)$	5794.8 ± 5.0	-	33 ± 6
$\Xi_b^0(\Xi_c^+\,\pi^-)$	5788.7 ± 4.3	-	62 ± 9
$\Omega_b^-(J/\psi\,\Omega^-)$	6050.0 ± 4.1	497^{+159}_{-119}	22 ± 6
$\Omega_b^-(\Omega_c^0\,\pi^-)$	6029 ± 11	-	$5.5\pm^{+2.5}_{-2.4}$

Compare LHCb:

$c\tau(\Xi_b^-)$ =
464.7 ± 31.3μm

$c\tau(\Omega_b^-)$ =
461.7 ± 72.0μm

Also measure isospin splitting in $\Xi_{b(c)}$:

Only experiment to measure Ξ_b mass splitting

$M(\Xi_c^0) - M(\Xi_c^+)$	$2.85 \pm 0.30 \pm 0.04$	(MeV/c^2)
$M(\Xi_b^-) - M(\Xi_b^0)$	$4.7 \pm 4.7 \pm 0.7$	

Summary

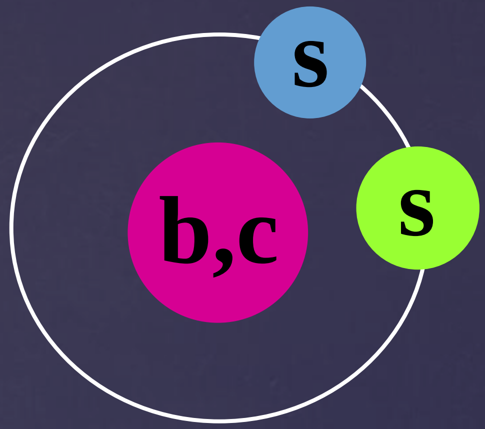
Tevatron experiments still active and producing papers

- Updating measurements with full dataset – reusing tools and expertise
- Taking advantage of unique attributes (e.g. CPV / asymmetries)
- Opportunistic use of data based on other experiments/theory (e.g. exotics)

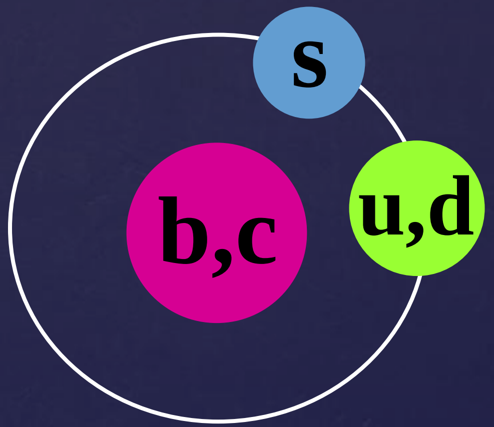
Continued puzzle in same-charge dimuon asymmetry

- Need dedicated measurements of $\Delta\Gamma_d/\Gamma_d$ to rule-out possible NP here

More measurements on their way for the summer…



Extra Material

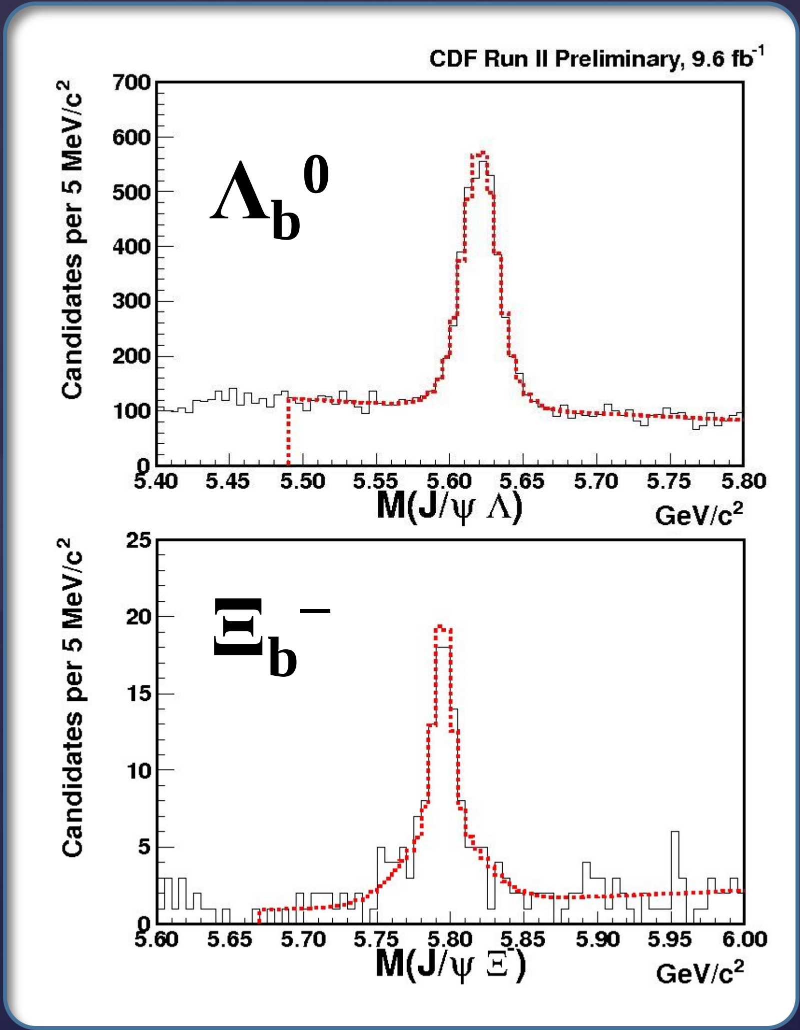


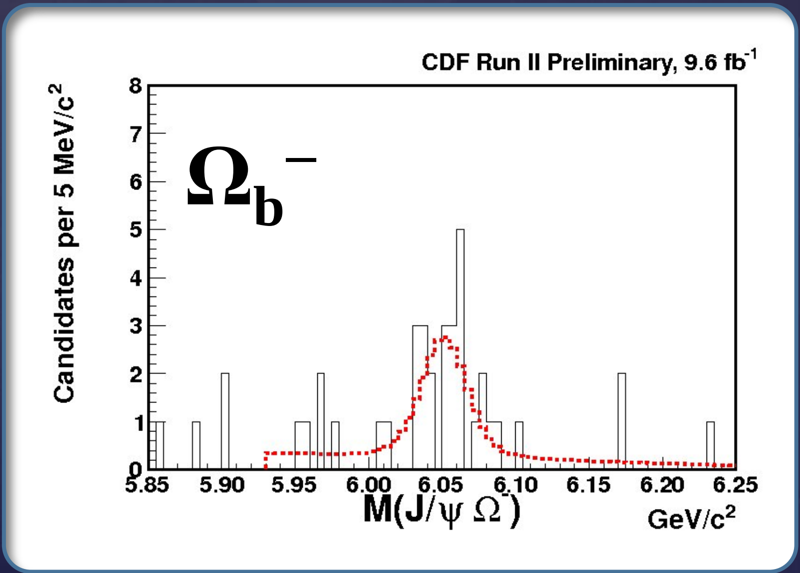
B Baryons

Lifetimes

$X_b \to J/\psi X$ channels provide unbiased trigger for lifetime measurements

1) Perform unbinned mass fit for $c\tau > 100\mu m$ range





B Baryons

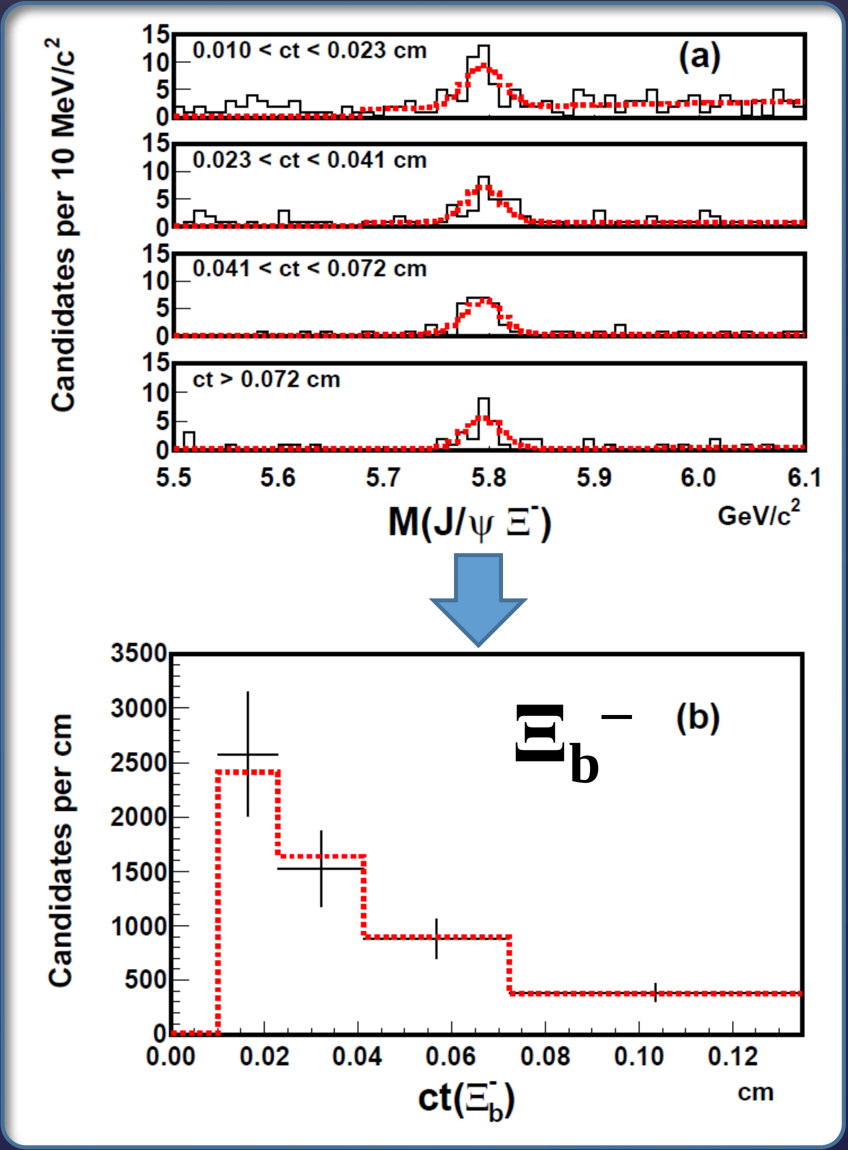
Lifetimes

$X_b \rightarrow J/\psi X$ channels provide unbiased trigger for lifetime measurements

1) Perform unbinned mass fit for $c\tau > 100\mu m$ range

2) Repeat fit in bins of proper decay length, with mass parameters fixed, to extract lifetime

e.g. **Ξ_b^- case**

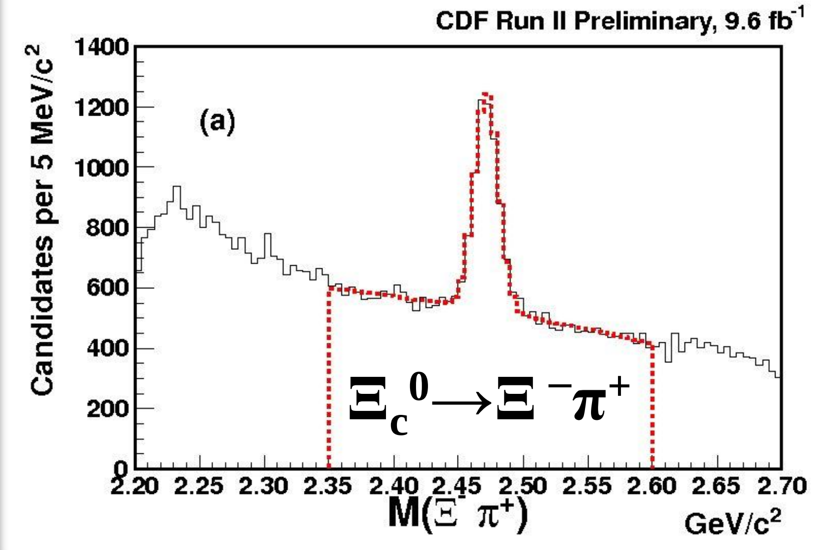


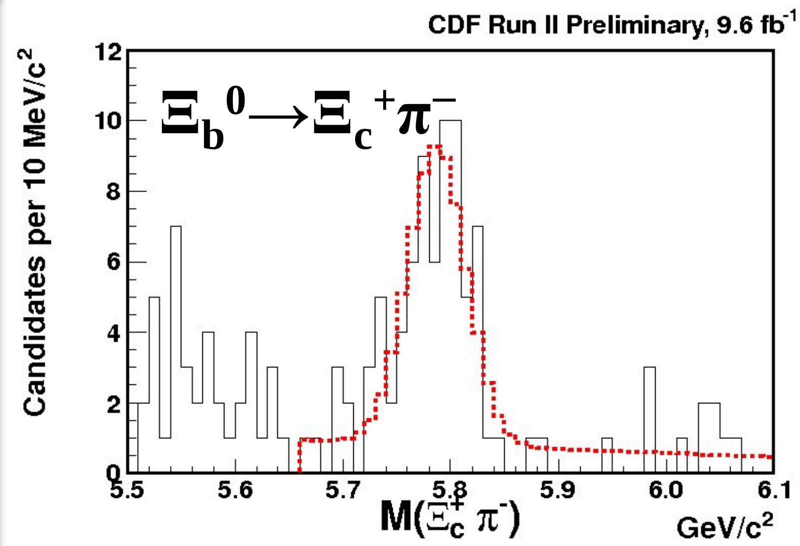
B Baryons

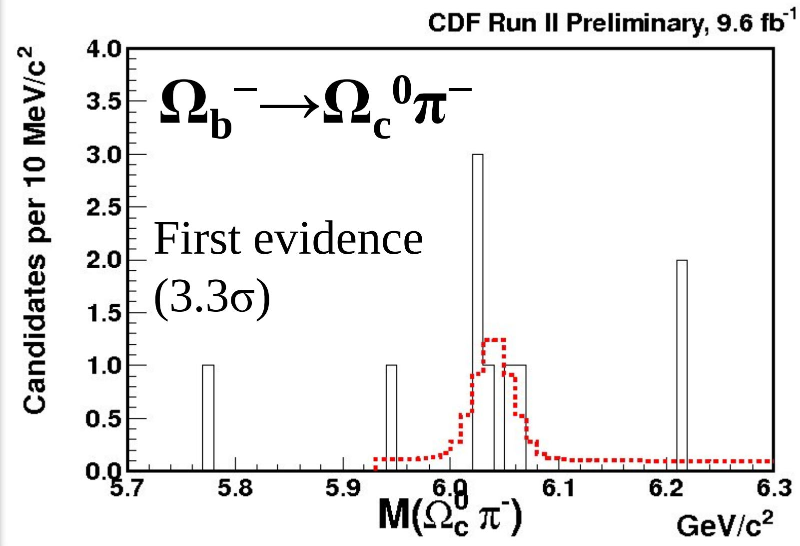
Hadronic decays of charm and beauty baryons

Use displaced SV trigger

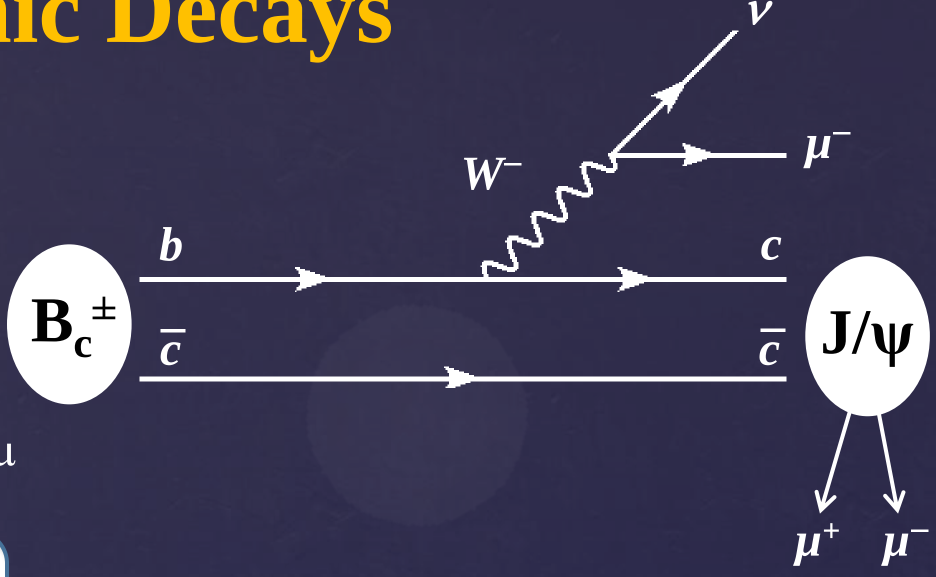
Unbinned fits to extract masses







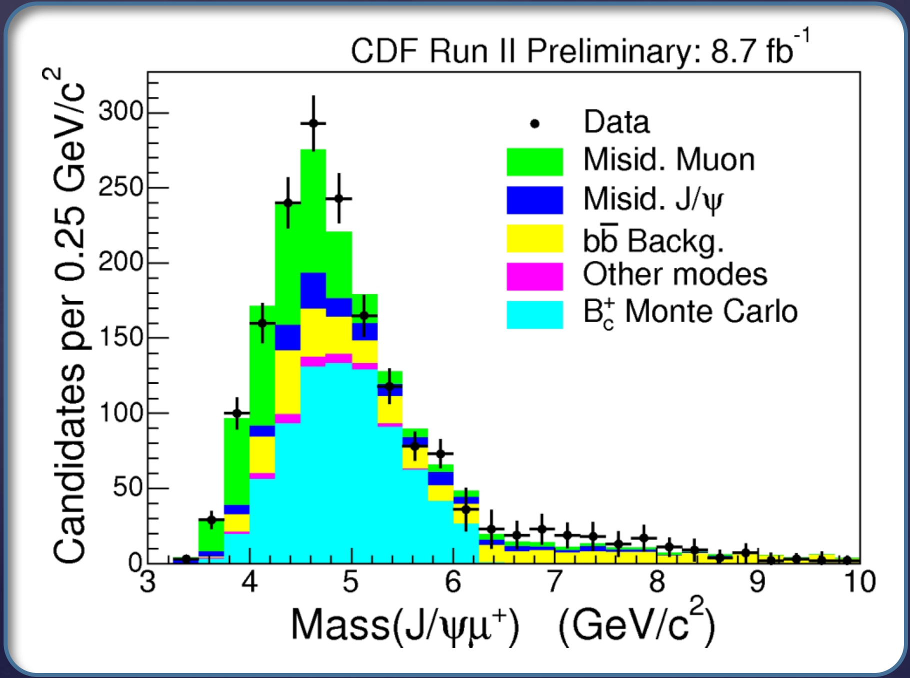
$B_c^{\pm}$ in Semileptonic Decays



Distinctive decay with 3 muons

Missing neutrino ⇒ wide reconstructed mass peak

Peaking background from mis-identified h→μ



$$N(B_c^{+}) = 739.5 \pm 39.6 \; ^{+19.8}_{-23.9}$$

$$\frac{\sigma(B_c^{+}) \cdot BR(B_c^{+} \rightarrow J/\psi \mu^{+} \nu)}{\sigma(B^{+}) \cdot BR(B^{+} \rightarrow J/\psi K^{+})} = 0.211 \pm 0.012 \; ^{+0.021}_{-0.020}$$