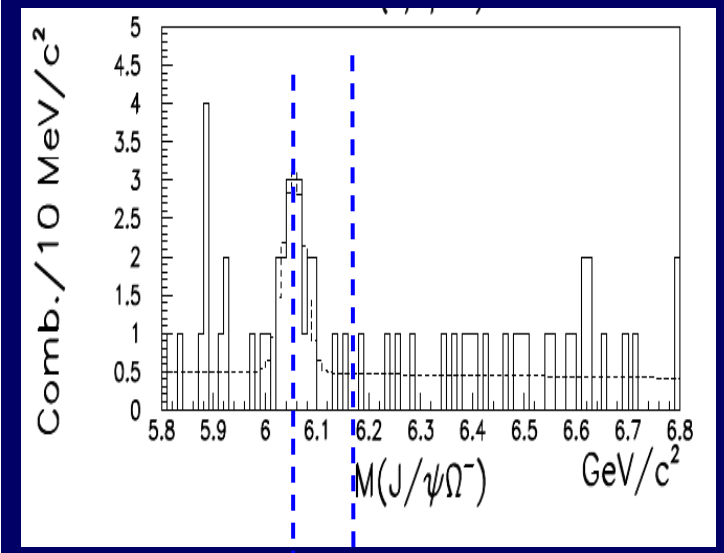
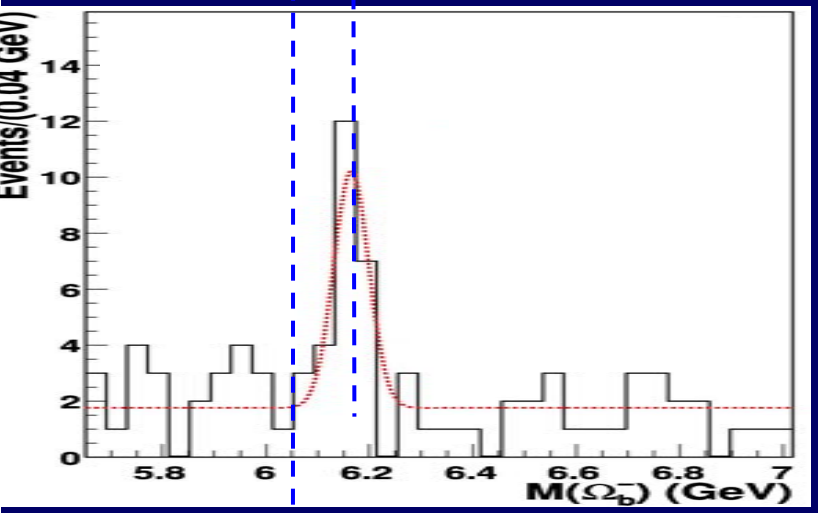
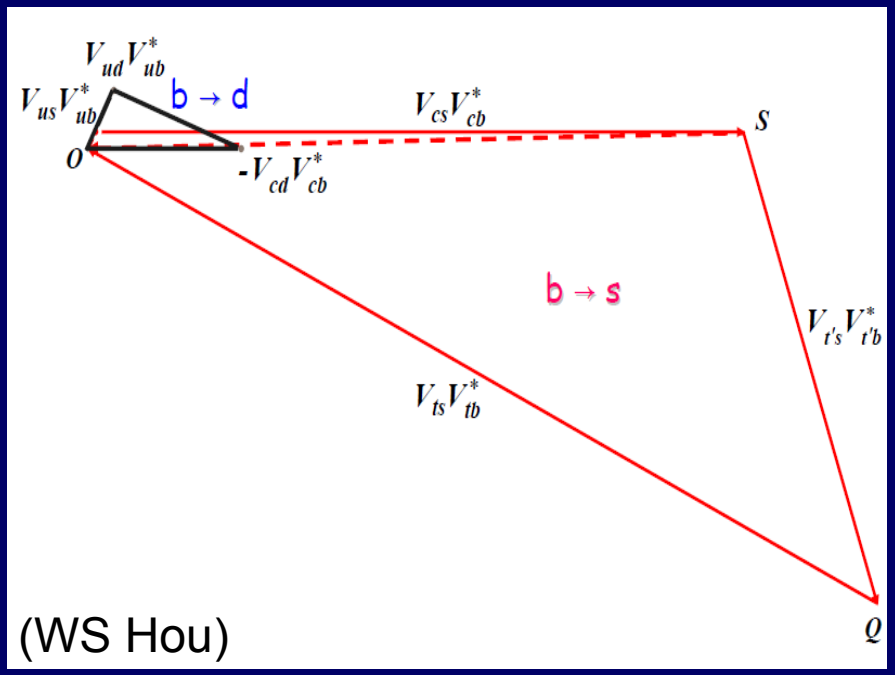
Results from the Tevatron -- Flavor

Brendan Casey, Fermilab





Spectroscopy



(WS Hou)

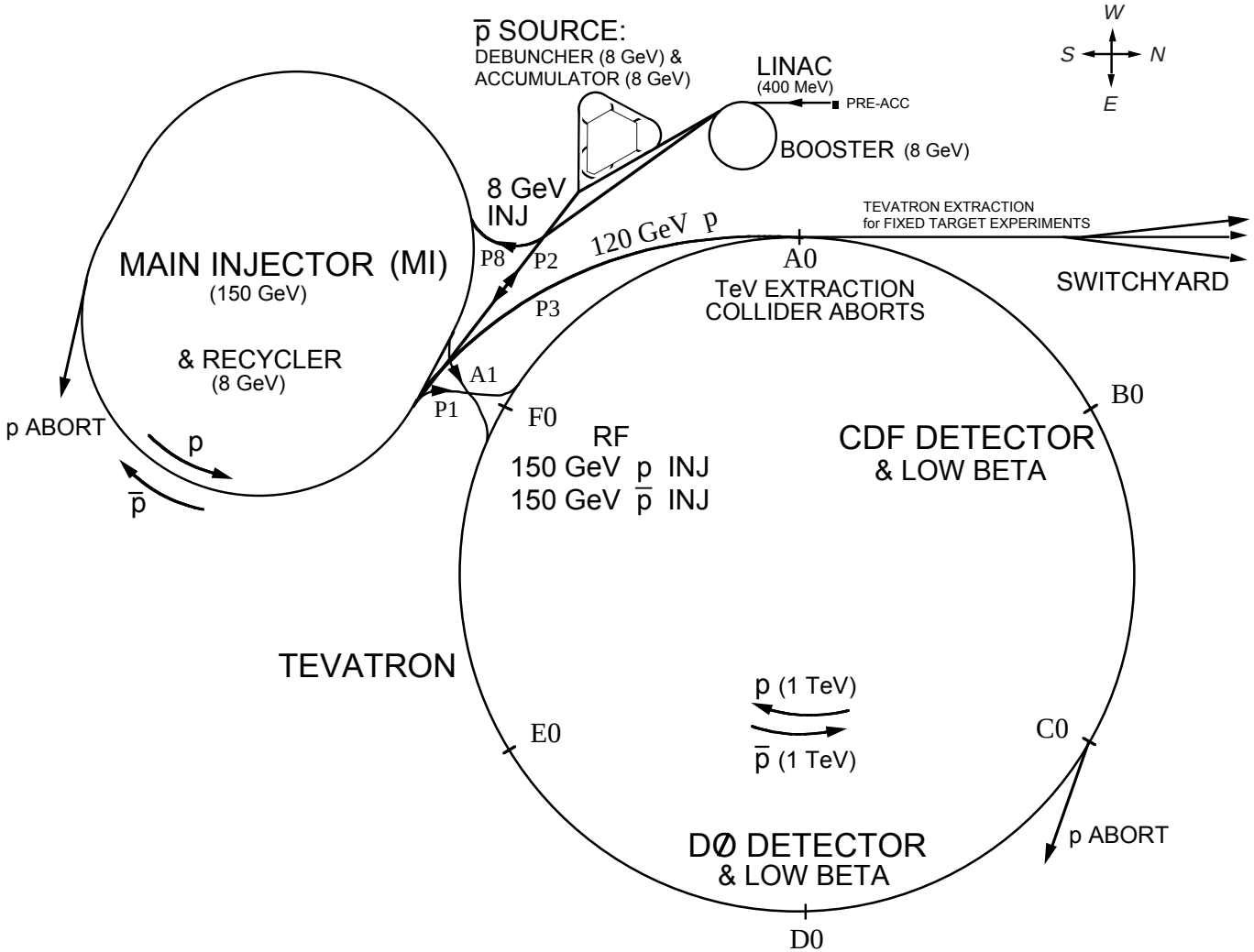
Anomalous CP Violation

Tevatron flavor program

- Goal:
  - Interesting and competitive results in the B factory era.
- Requirements:
  - Very large sample of b hadrons
  - Good detectors
    - **Particularly vertexing**
  - Niche
    - **Something you can do better than the B factories**

Tevatron

- Highest lum hadron machine + very large production cross sections = large b hadron sample



Peak lum:

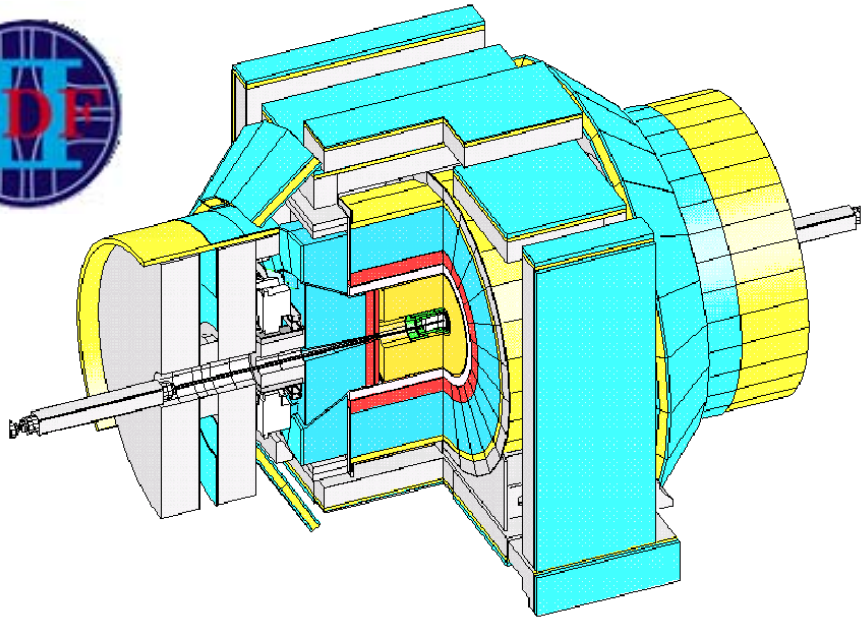
3.5×10^{32} cm^{-2}s^{-1}

Delivered: ~6 fb^{-1}

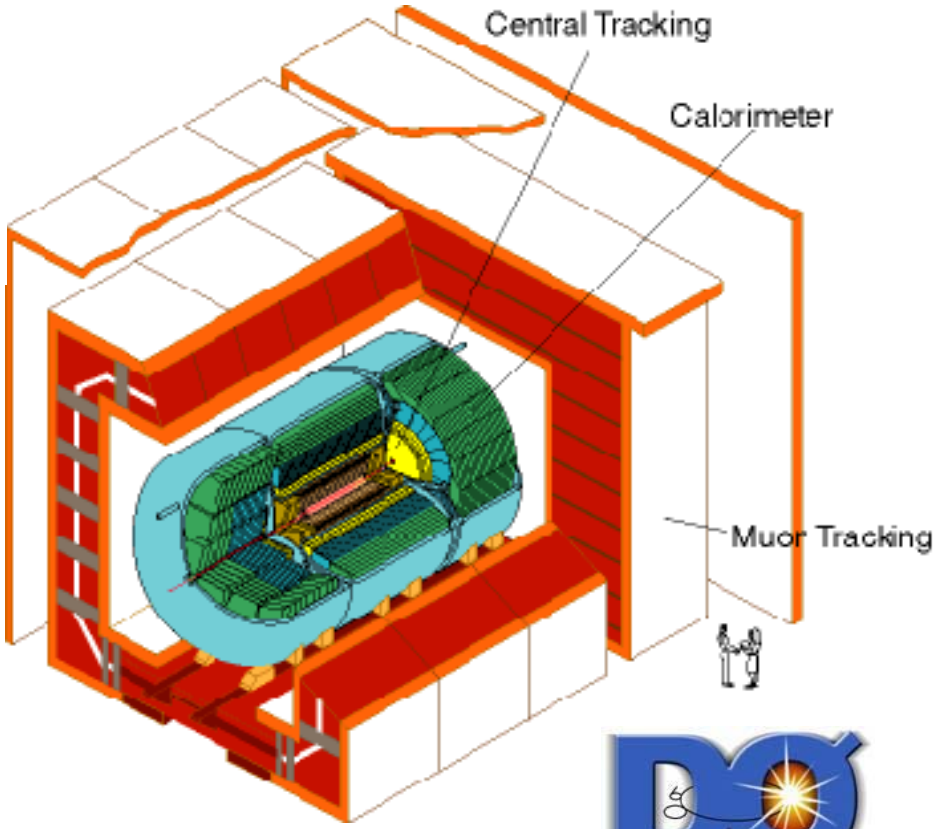
Expect : ~12 fb^{-1}

Micro-barn level cross sections for heavy hadrons after acceptance cuts.

Detectors



Both large multi purpose detectors with excellent impact parameter resolution and muon identification



CDF advantage:

momentum resolution plus trigger bandwidth.

DØ advantage:

Muon acceptance and purity.

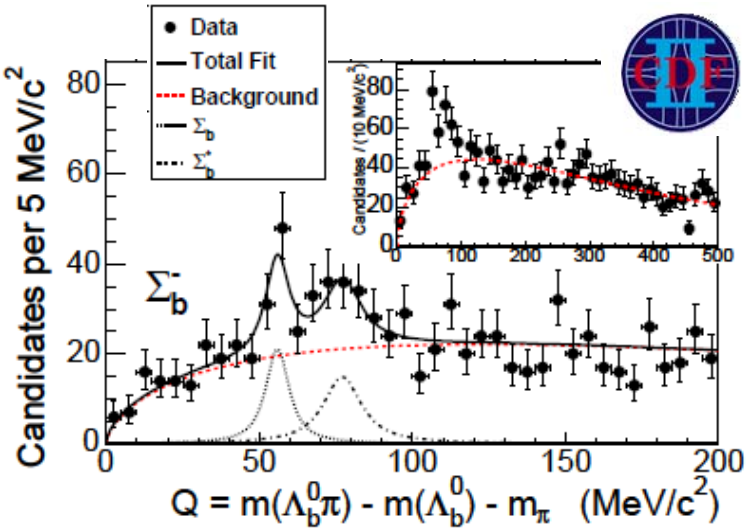
Common disadvantage:

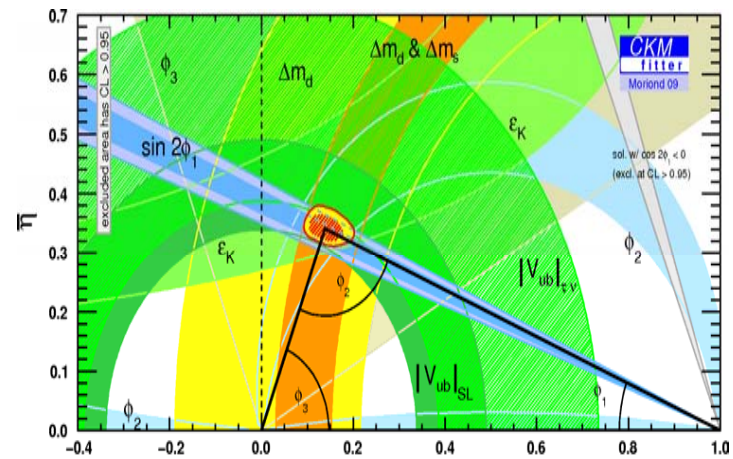
Low momentum photon ID

Niche

- High center of mass energy gives access to all b hadrons

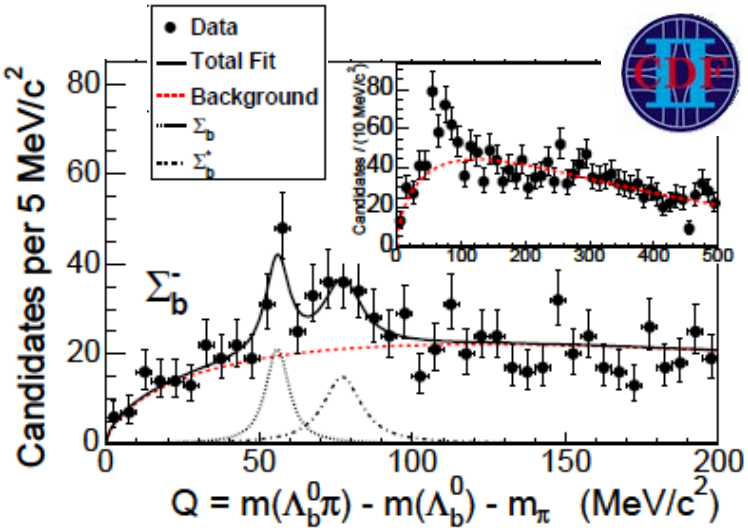
- Niche:
  - b hadron spectroscopy
  - B_s physics

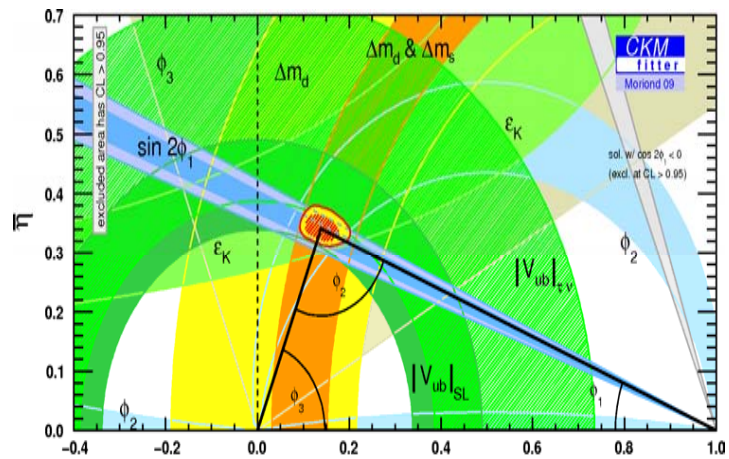


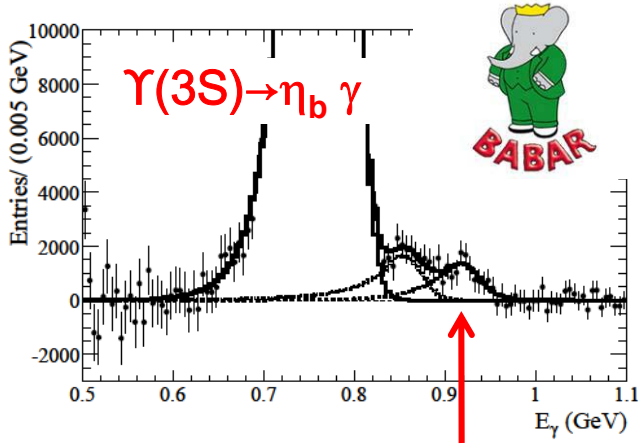


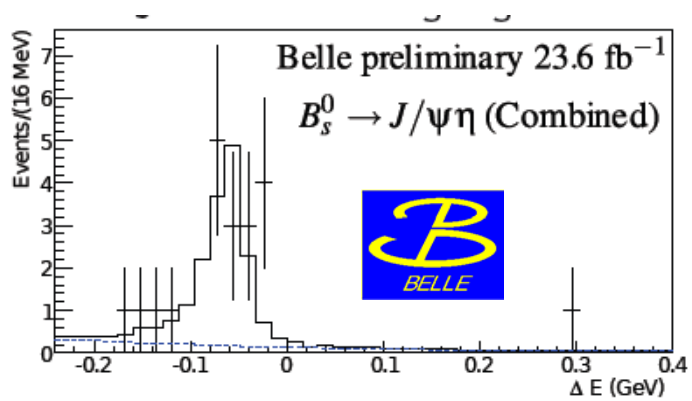
Niche

- High center of mass energy gives access to all b hadrons
- Niche:
  - b hadron spectroscopy
  - B_s physics
- Most can also be done at B factories running off the 4S but for now, this is our competitive niche.



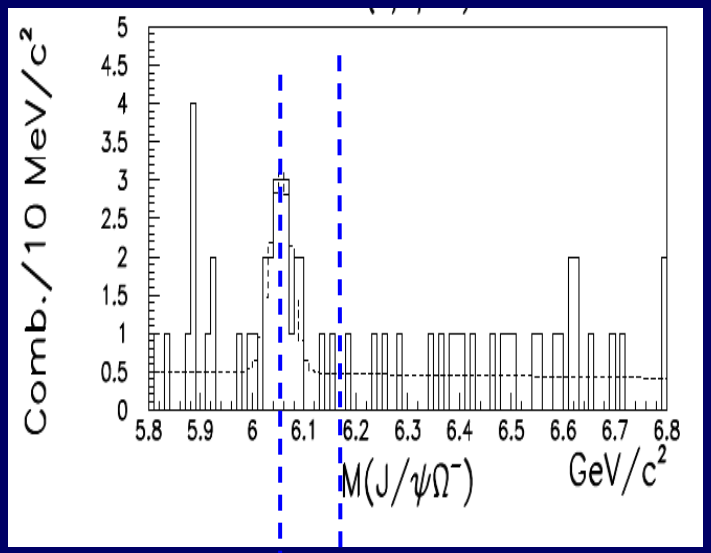


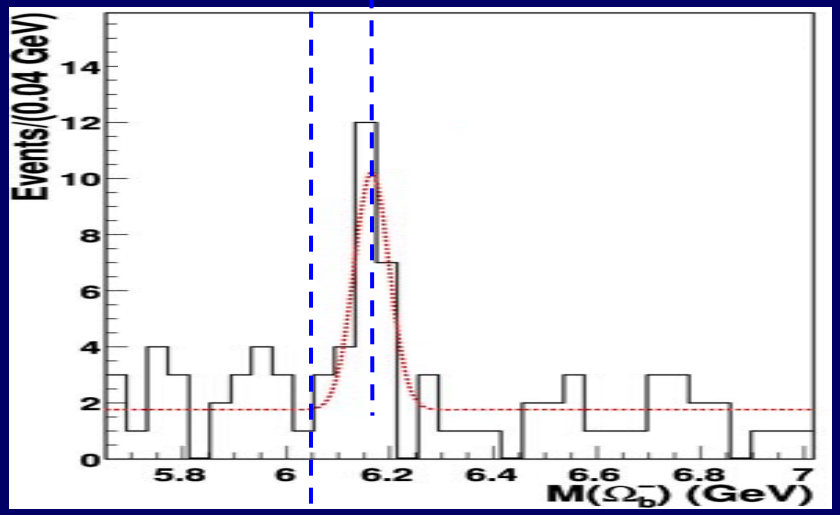




Spectroscopy

The Ω_b





Importance of Spectroscopy

- Spectroscopy is the study of how colored particles combine to form the colorless objects we observe.

$Q\bar{Q}$ $Q\bar{q}$ Qqq QQq qqq $q\bar{q}q\bar{q}$ $q\bar{q}g$

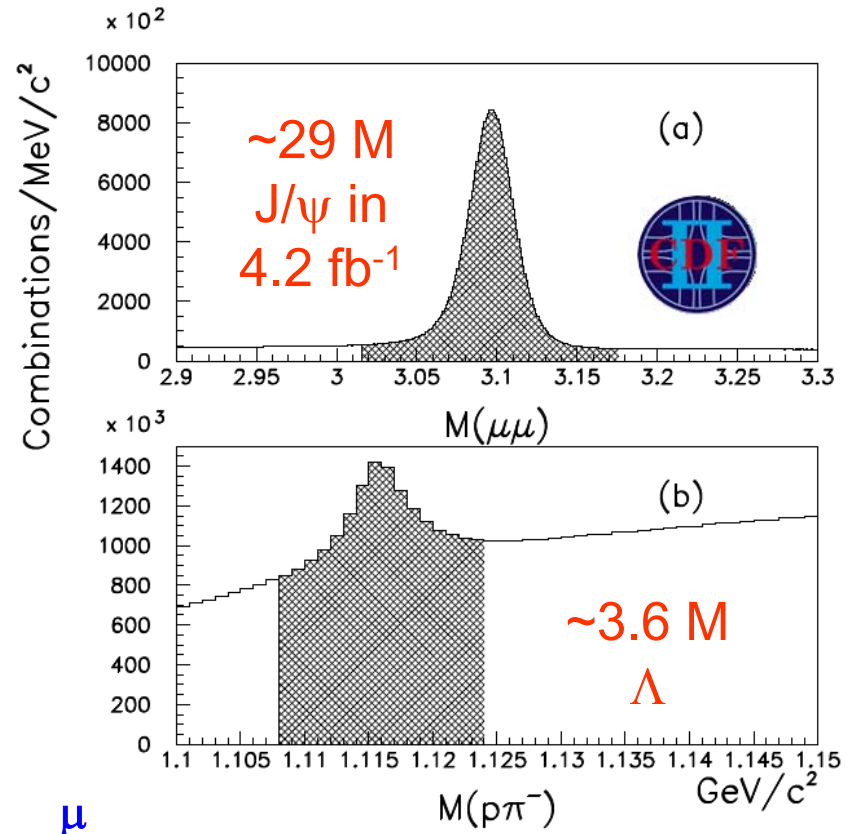
- Has played a vital role in our understanding of the Standard Model
  - Symmetries
  - The quark model
  - confinement
  - Lattice QCD
  - Exotic bound states

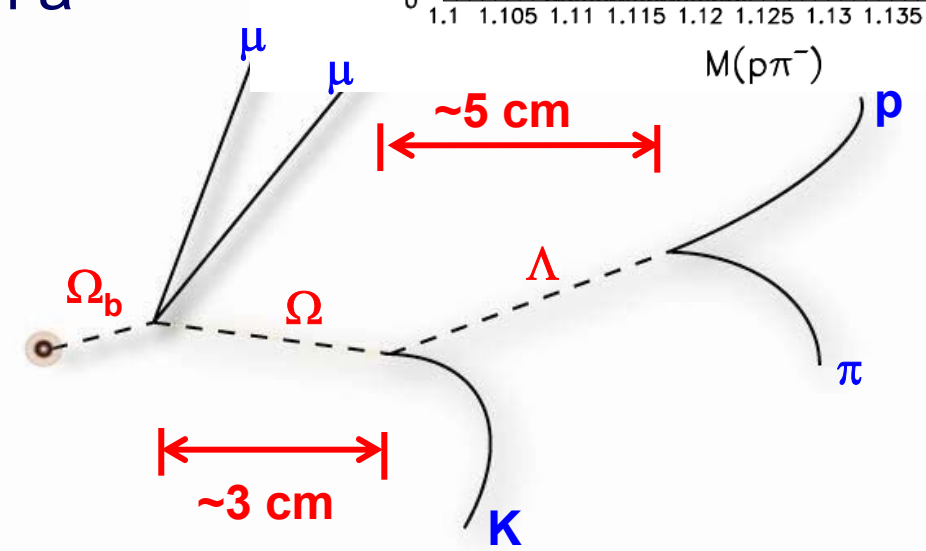
- Observables:
  - Allowed or forbidden
  - Mass, width, spin
  - Production and decay properties

- If physics beyond the Standard Model is strongly coupled, many of the tools used to understand low energy spectroscopy will be needed for high energy spectroscopy
  - Little higgs, 4th generation, dynamical symmetry breaking mechanisms…

B Baryon spectroscopy at the Tevatron

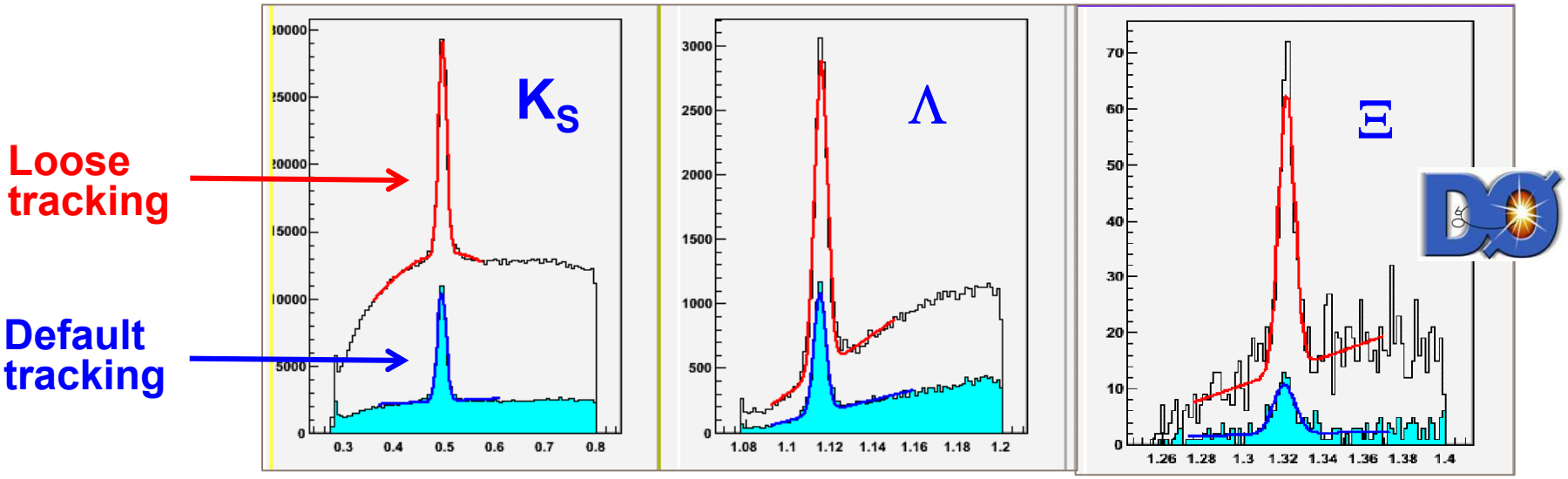
- Very large data set so can afford to look in clean modes containing $J/\psi \rightarrow \mu\mu$ in the final state
- Many also contain long lived particles like Λ which also help reduce backgrounds
- Strategy: start with $B_d \rightarrow J/\psi\ K_S$ and replace the K_S with a baryon
  - $\Lambda_b \rightarrow J/\psi\ \Lambda$
  - $\Xi_b \rightarrow J/\psi\ \Xi$
  - $\Omega_b \rightarrow J/\psi\ \Omega$





Tracking for very long lived particles

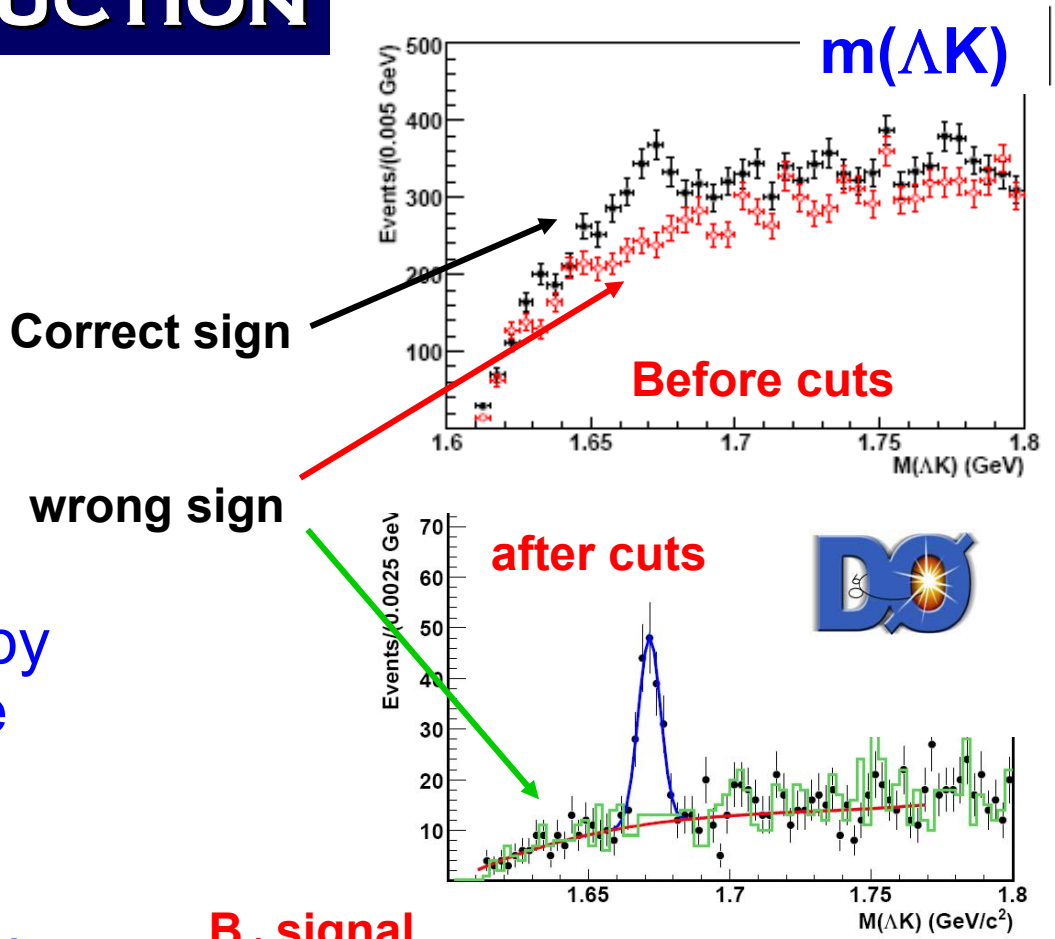
- Complication at DØ:
  - Standard tracking is inefficient for very long lived particles (impact parameters > 2 cm)
    - **Too slow to run algorithms with looser cuts on all the data**
  - Can run looser tracking (imp ~ 10 cm) on events containing $J/\psi \rightarrow \mu\mu$

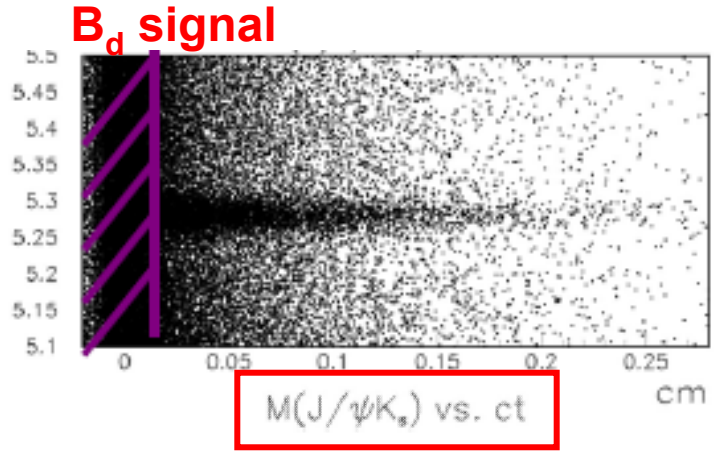


  - Still complicated and only first 1.3 fb^{-1} available for analysis
- CDF tracker radius is ~2x DØ's so not really a problem.
  - CDF has results up to 4.2 fb^{-1}

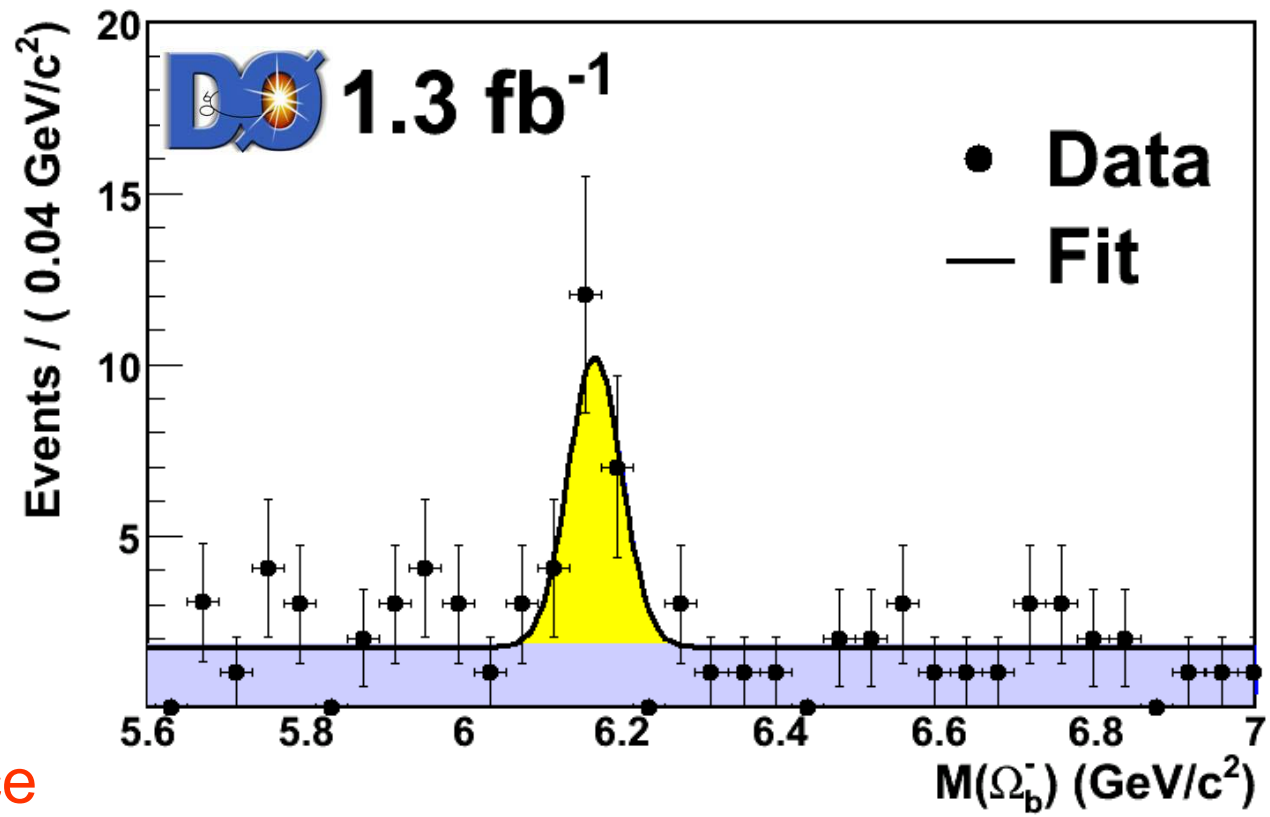
Background reduction

- Difficult to use MC
  - Momentum,
  - mass,
  - lifetime unknown
- DØ:
  - Remove background by tuning on intermediate resonances
- CDF:
  - simple cuts motivated by other b hadrons + more data.





DØ Results



August 08

1.3 fb^{-1}

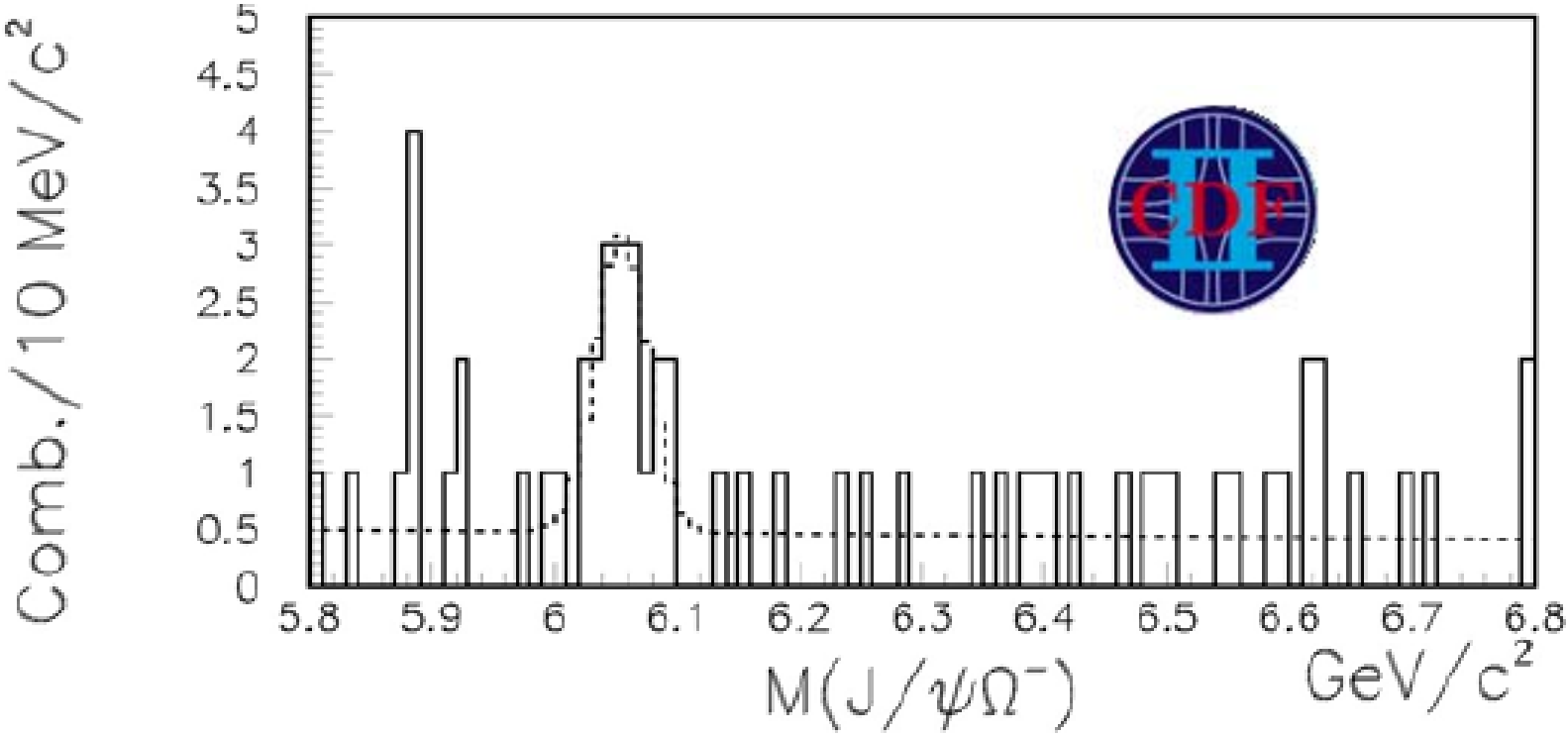
18 ± 5 events

5.4 σ significance

m = 6165 ± 10 ± 13 MeV

PRL 101, 232002 (2008)

CDF Results



May 09

4.2 fb^{-1}

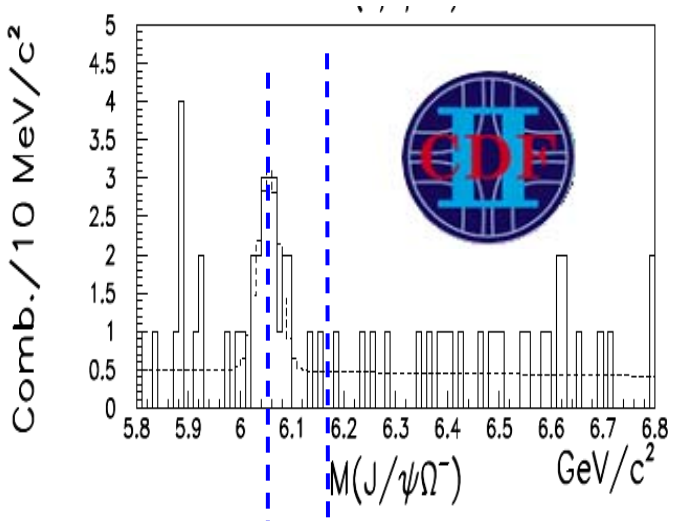
12 ± 4 events

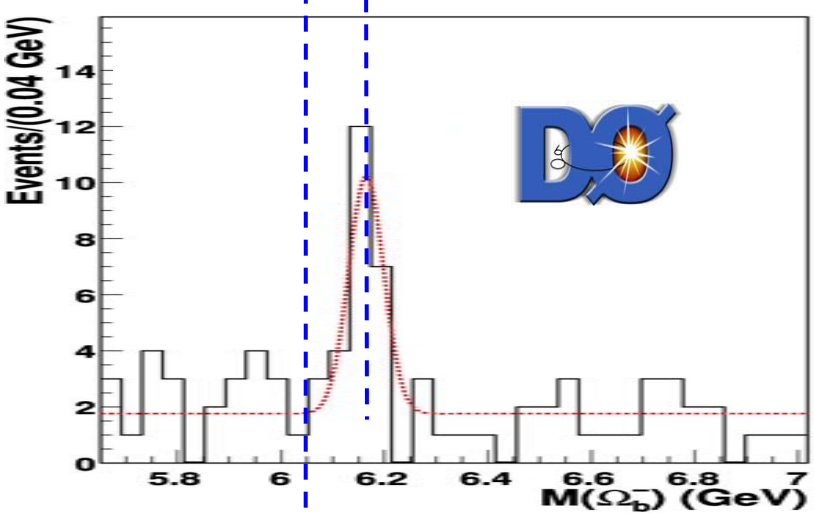
5.5 σ significance

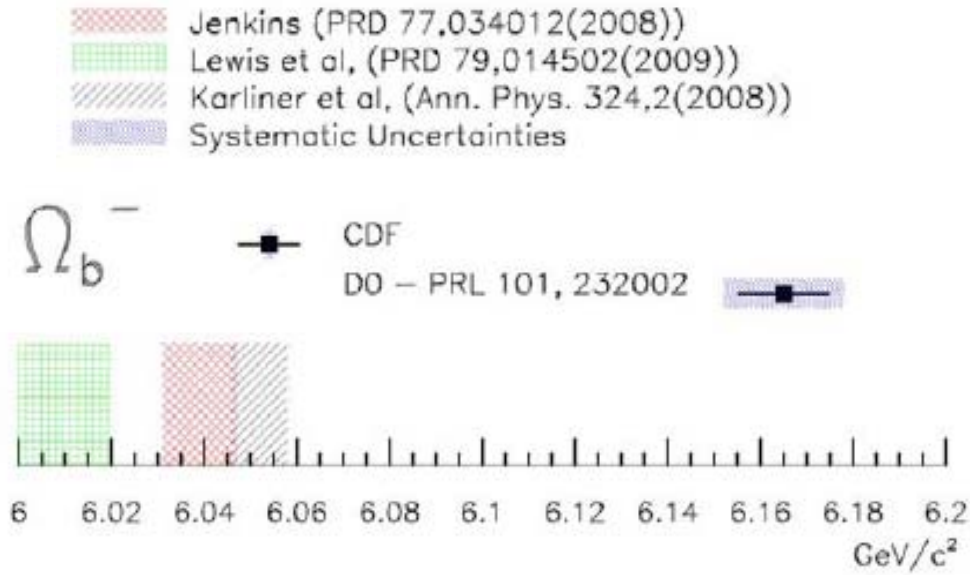
m = 6054.4 ± 6.8 ± 0.9 MeV

arXiv:0905.3123v1 submitted to PRD

Comparison







Mass measurements differ by

111 ± 12 ± 14 MeV

CDF does not confirm DØ observation

Same production rate?

$$\frac{f(b \to \Omega_b^-) Br(\Omega_b^- \to J/\psi\, \Omega^-)}{f(b \to \Xi_b^-) Br(\Xi_b^- \to J/\psi\, \Xi^-)} = 0.80 \pm 0.32(stat)^{+0.14}_{-0.22}(syst)$$

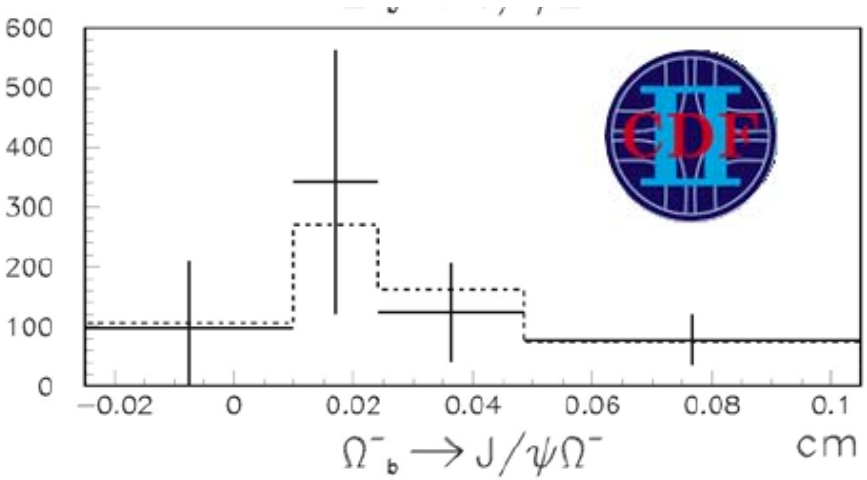
$$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Xi_b^- \to J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01$$

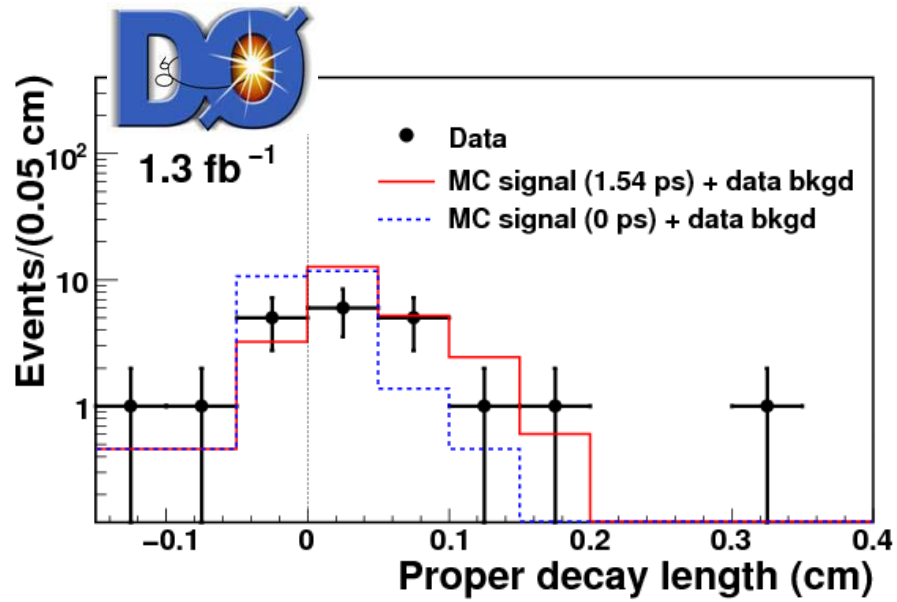
1.3 σ difference in production rate

1.6 σ stat only

$$\frac{\sigma B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.045^{+0.017}_{-0.012}(stat.) \pm 0.004(syst.)$$

Same lifetime?





CDF

$$c\tau(\Omega_b) = 340^{+160}_{-120}\,\mu m$$

DØ

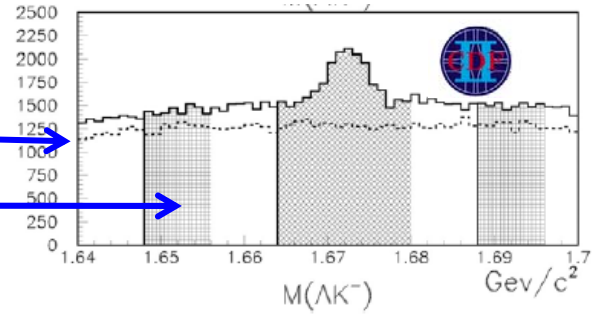
no measurement, just comparison with 0 μm and 460 μm proper decay lengths

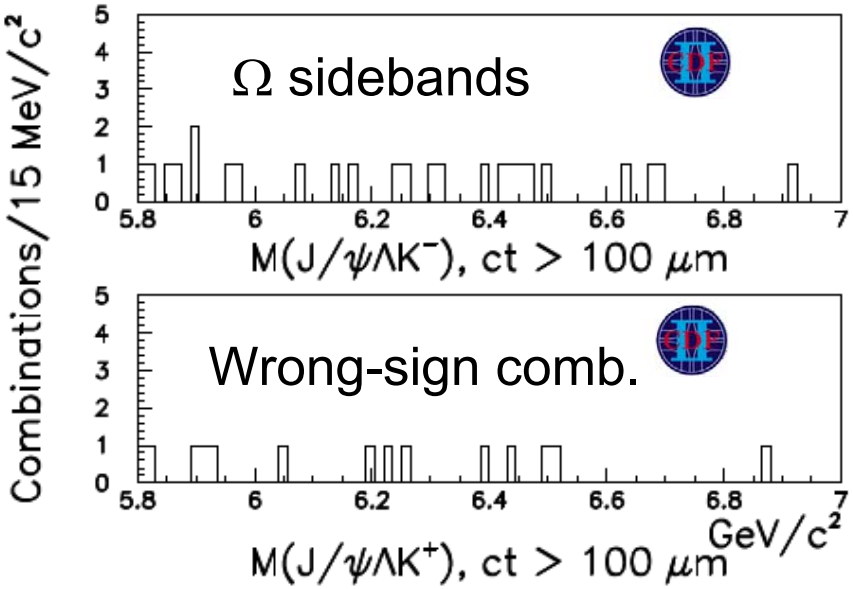
Both consistent with a weakly decaying particle

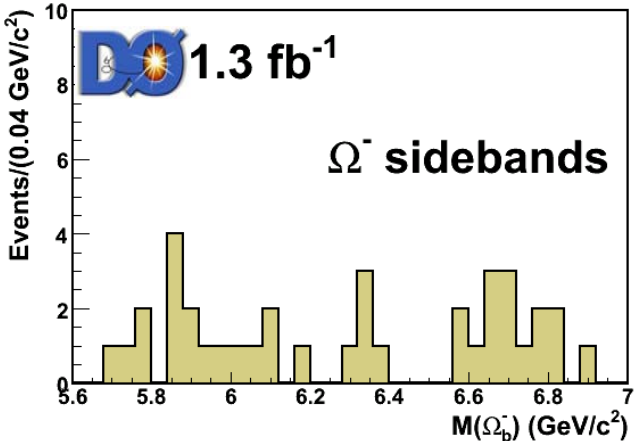
Peaking backgrounds?

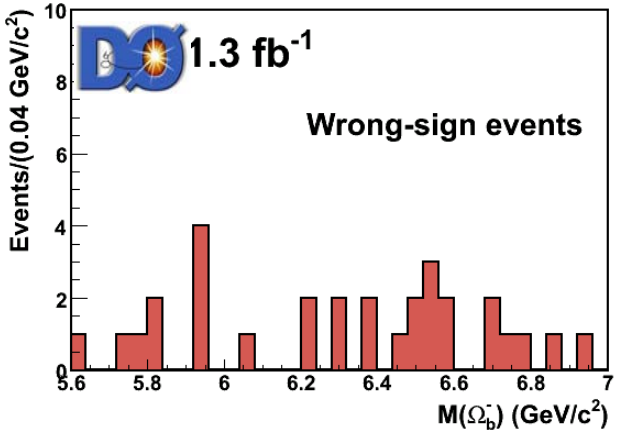
Wrong-sign comb.

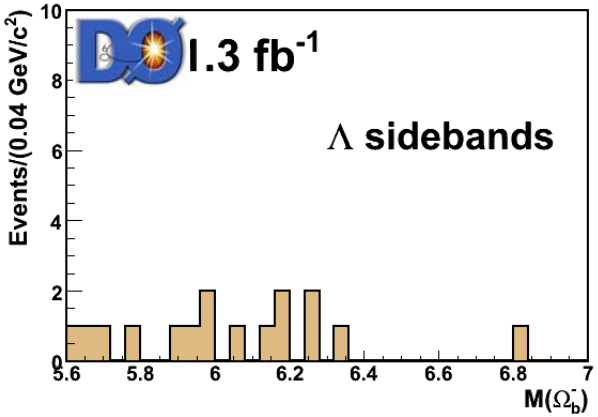
Ω sidebands





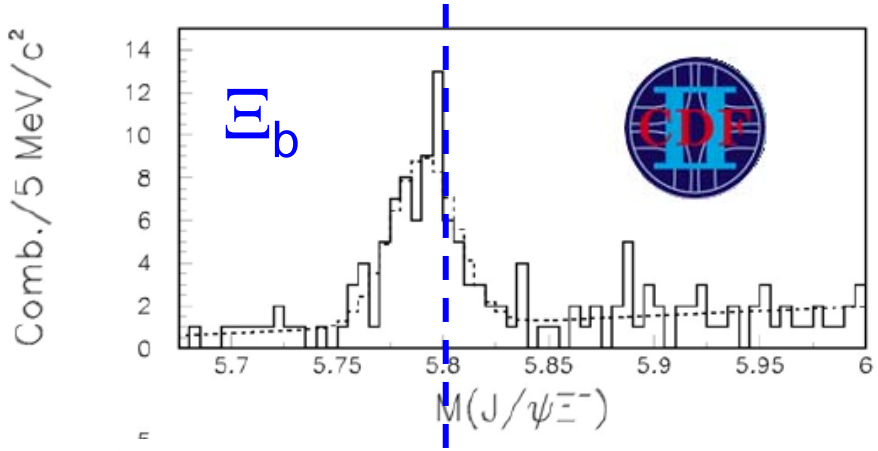


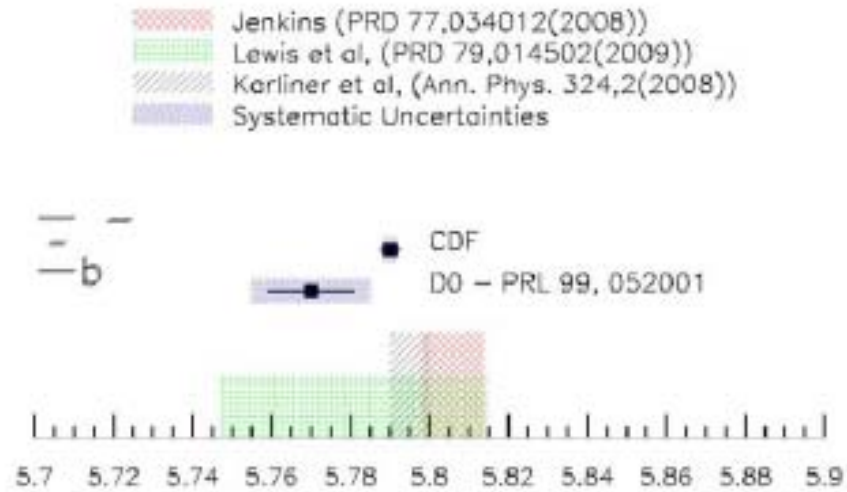


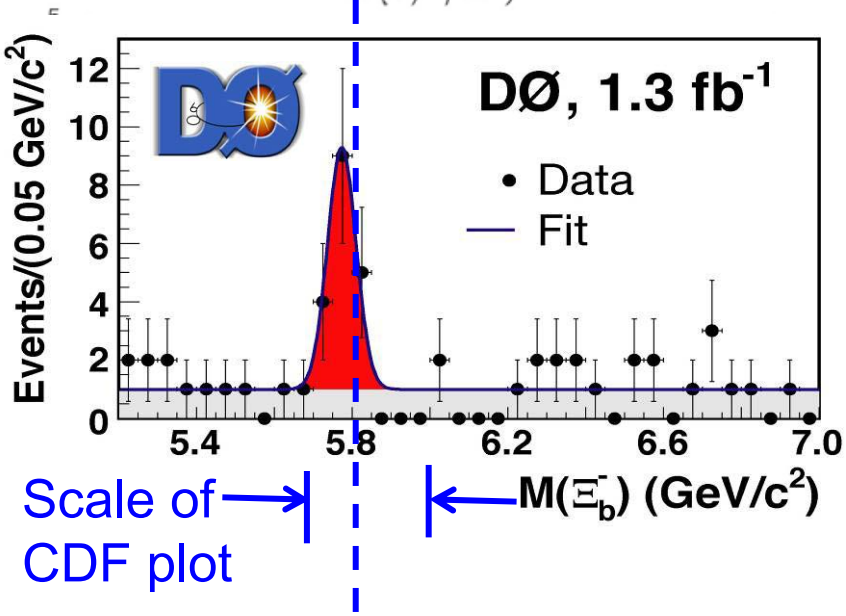


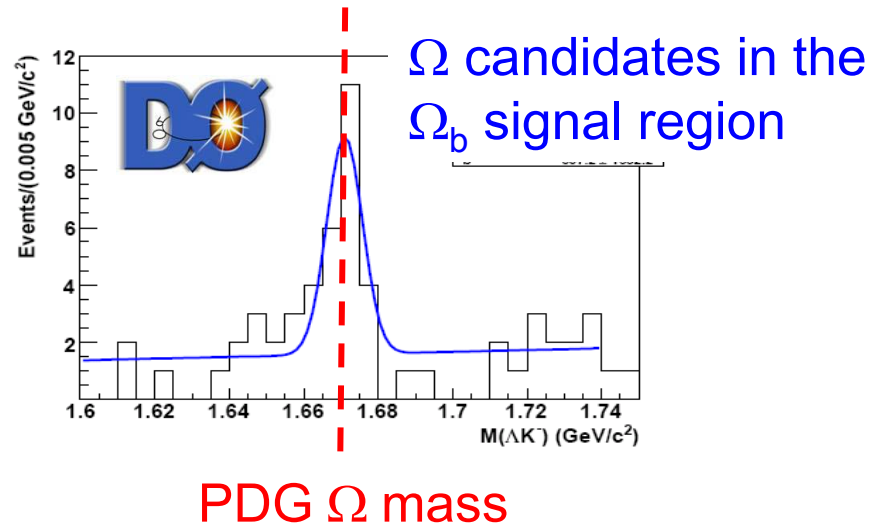
Both experiments demonstrate lack of peaking background with sidebands and wrong-sign combination events

Momentum Scale?





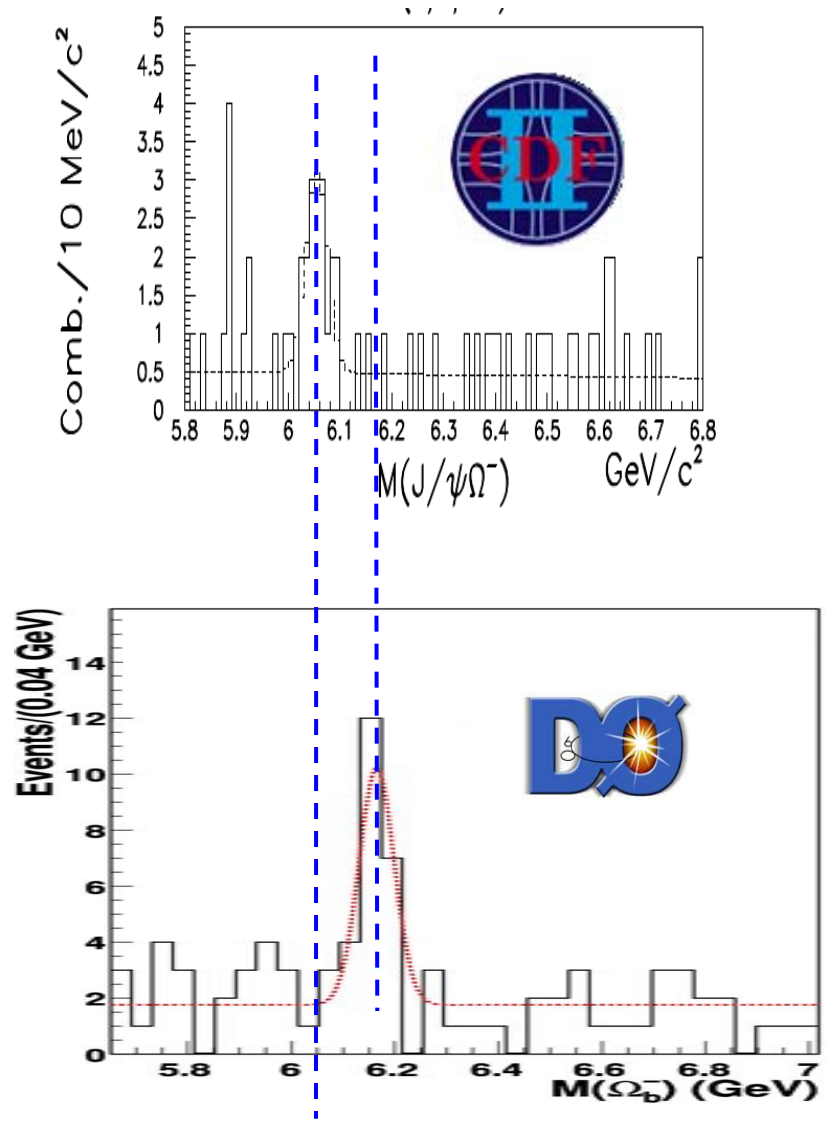




Both experiments agree on all other hadrons.
Intermediate resonances also in the correct place

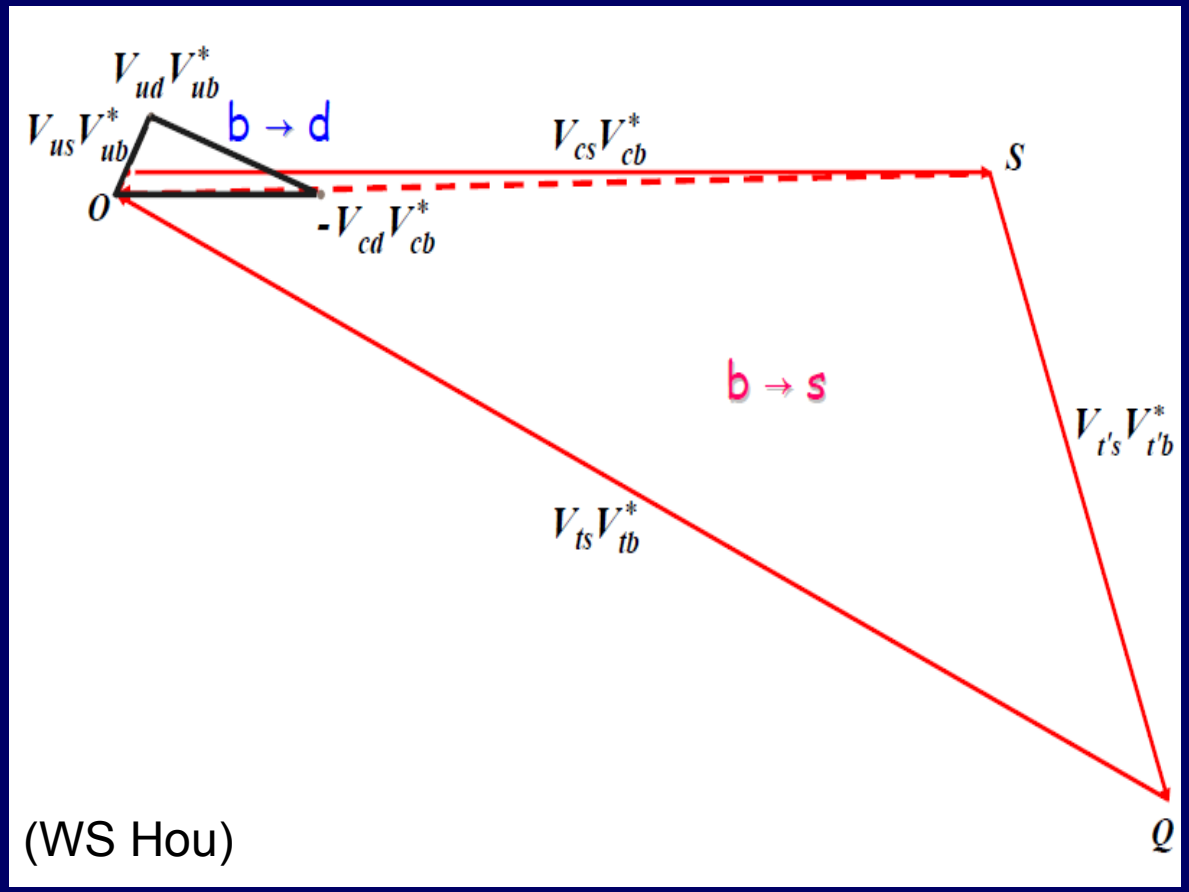
Ω_b Conclusions

- Both experiments claim observation of the Ω_b but the masses differ by > 100 MeV
  - CDF's mass measurement agrees with expectations, DØ's does not
- Both results robust and seem to agree on other properties within large uncertainties
- More data coming (and on tape at DØ) so hopefully this will be resolved soon



Anomalous CP Violation

In B_s mixing

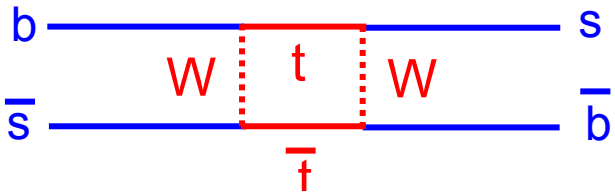


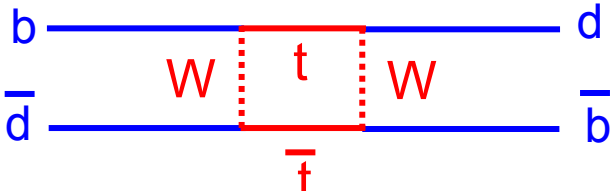
(WS Hou)

CP Violation

- CP Violation allows us to differentiate matter interactions from anti-matter interactions
- CP Violation is needed to explain our existence
- CP violation already seen in B and K systems is not enough
- Motivates current searches:
  - Neutrinos
  - Atomic and lepton EDMs
  - Rare decays with loops
  - Neutral meson mixing
- Today: B_s system

B_s versus B_D



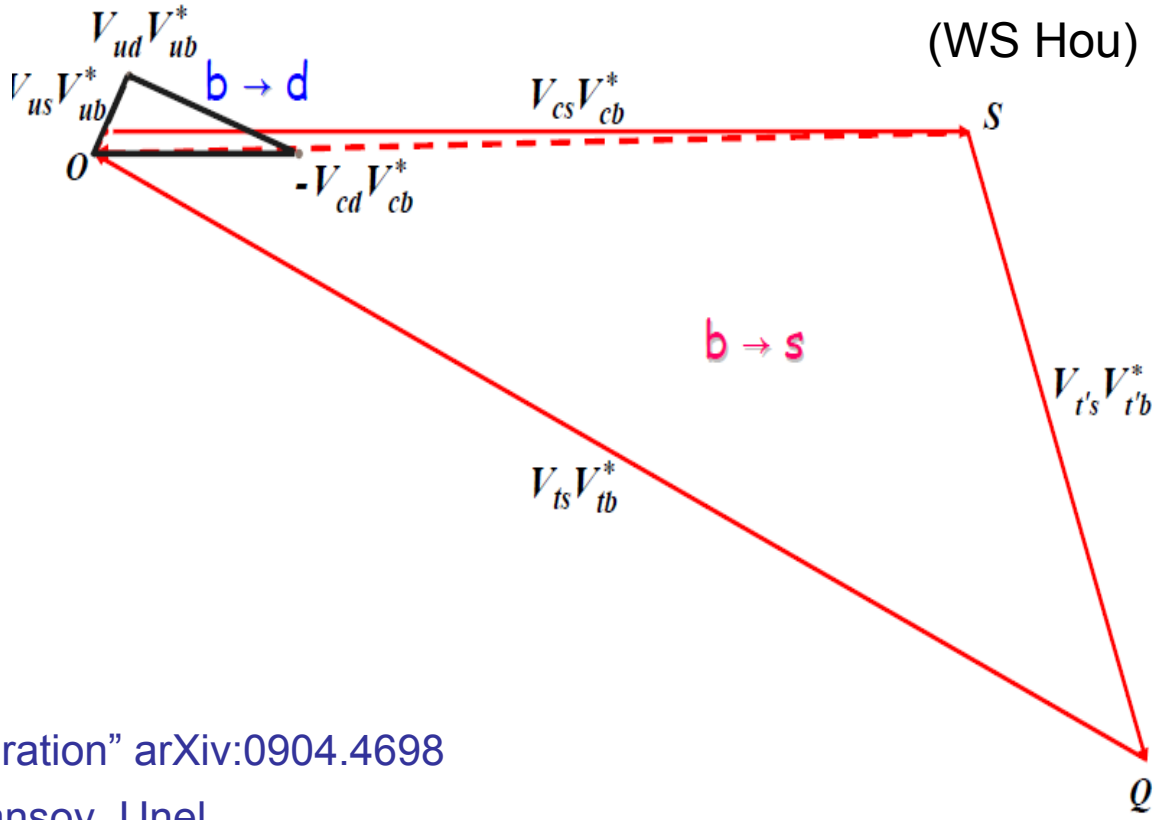


Probing for new CP violating phases that effect B_s mixing but have little or no effect on B_d mixing

Good example is 4th generation models

Penalty in weak interactions for skipping a generation

$$V_{t's} >> V_{t'd}$$



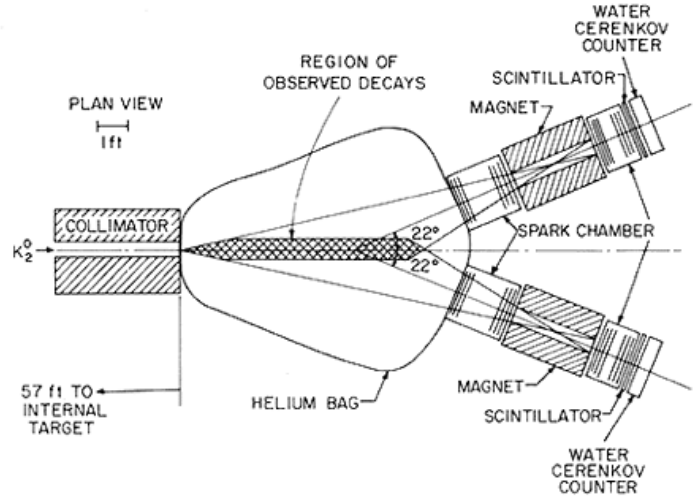
Recent summary:

"Four Statements about the 4th Generation" arXiv:0904.4698

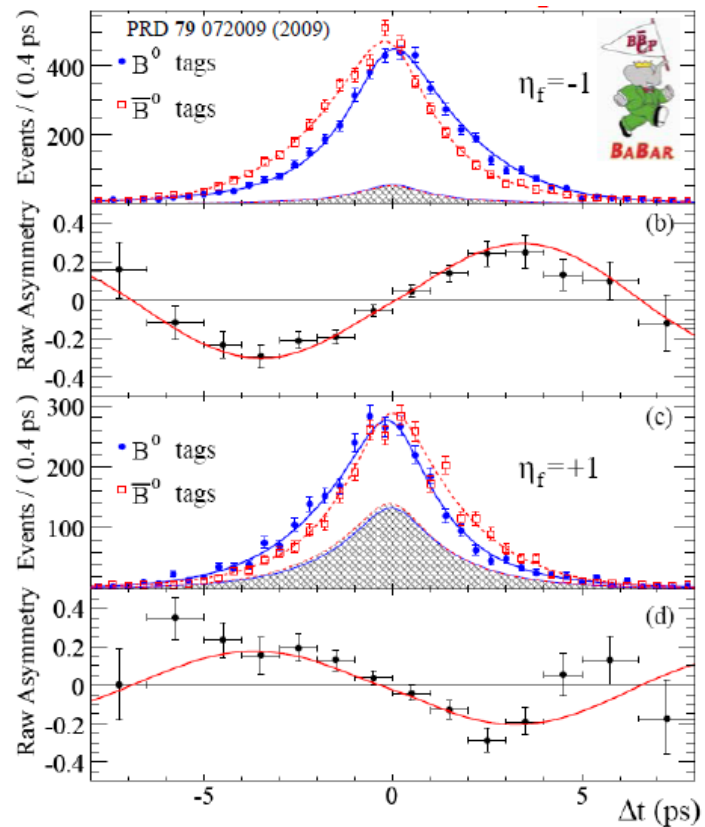
Holdom, Hou, Hurth, Mangano, Sultansoy, Unel

Phenomenology

- 'Kaon' type CPV:
  - $K_{Short} \neq K_{even}$, $K_{Long} \neq K_{odd}$
    - **Experiment: study of decays of K_{Short} and K_{Long}**
    - **$\Delta\Gamma$: lifetime difference between states**

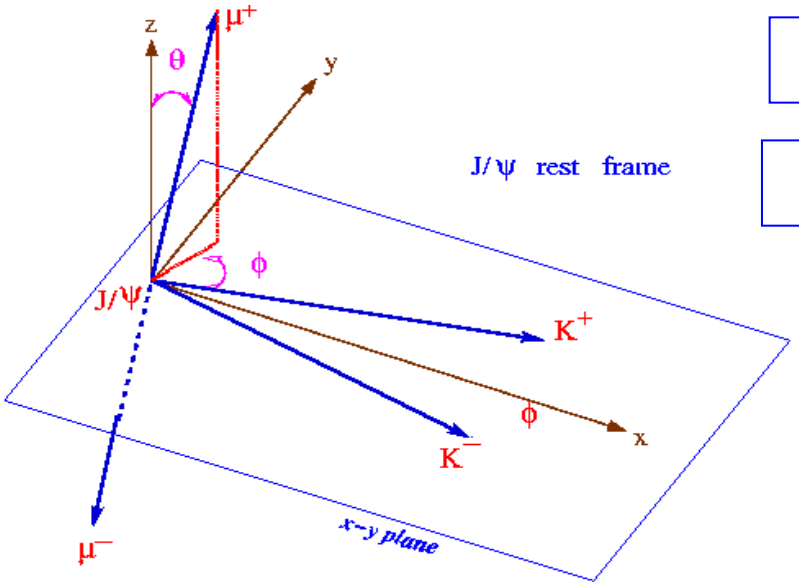


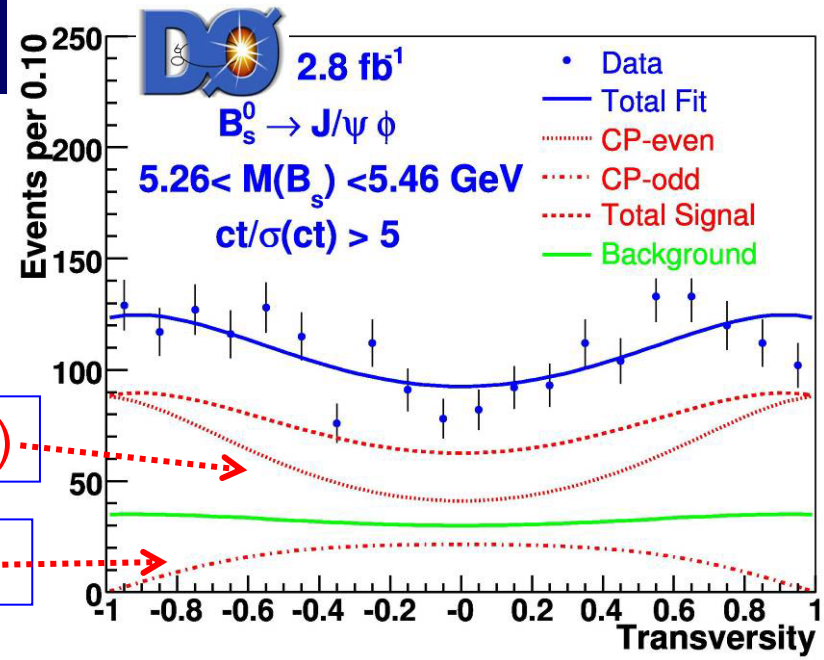
- 'B_d' type CPV:
  - interference in decays before or after mixing
    - **Experiment: separate the time dependence of B_d and anti-B_d decaying to CP eigenstates**
    - **Δm: time it takes to mix**
- B_s:
  - Interference between mixing and decay (B_d type)
  - $\Delta\Gamma_s$ > experimental resolution: separate study of heavy and light decay channels (Kaon type)
    - **Experiment: both**

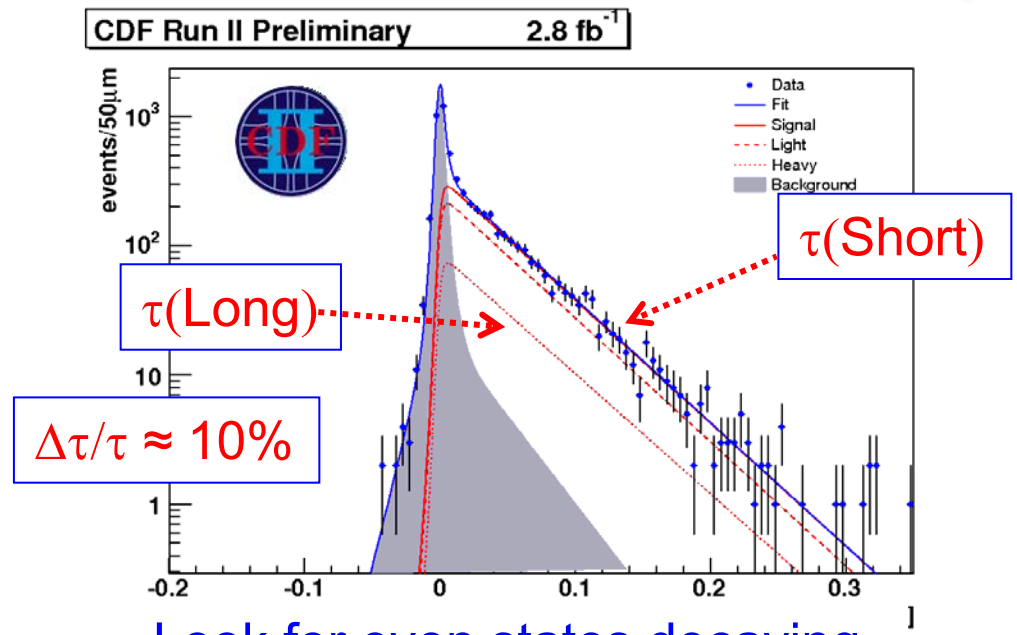


$B_s \to J/\psi\ \phi$: Kaon type CPV

Pseudo scalar →Vector + Vector.
Both even and odd states contribute.







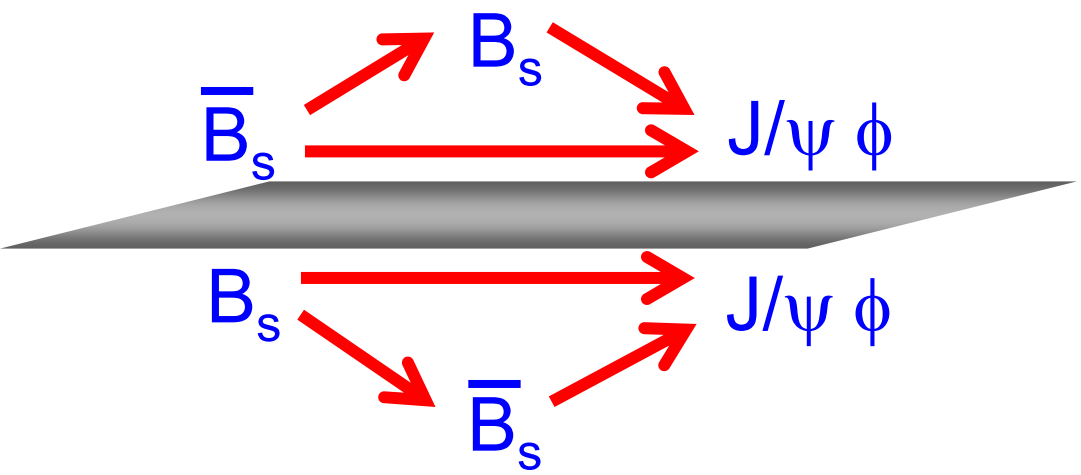
Angular analysis tells if its even or odd.

Lifetime measurement tells if its long or short

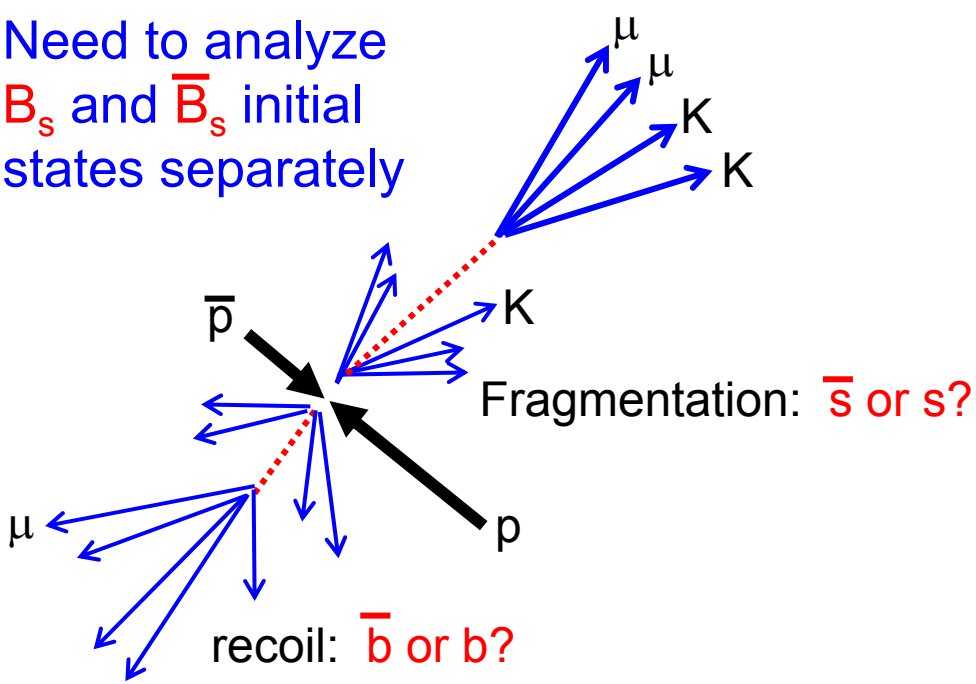
Look for even states decaying with a longer lifetime⇒ CPV

$B_s \to J/\psi\ \phi$: B_D TYPE CPV

Mirror image of a double slit experiment

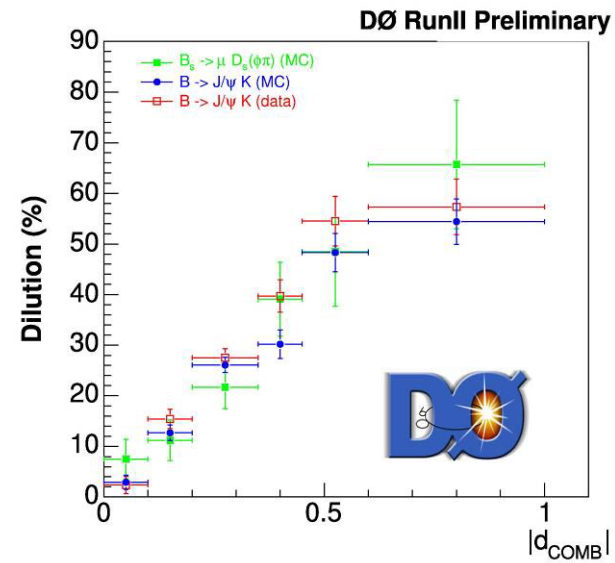


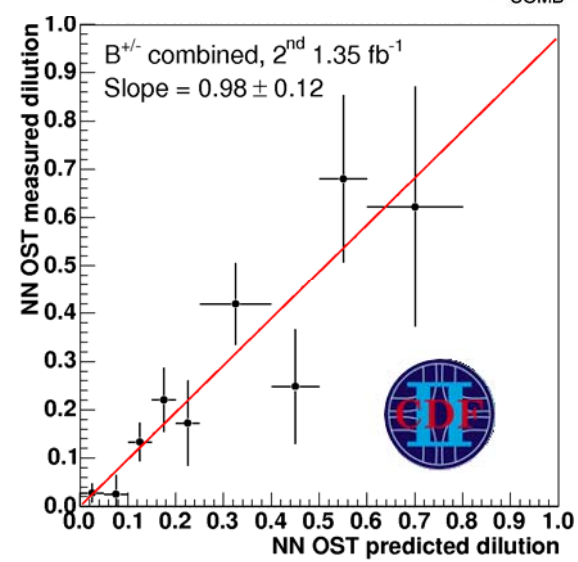
Need to analyze B_s and $\bar{B}_s$ initial states separately



Validate tagging performance using $B^{\pm}$ samples

Actual performance





expected performance

J/ψ φ RESULTS

Results taken from a multi-parameter fit including flavor, lifetime, polarization, backgrounds, CP conserving, and CP violating interference

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

on amplitudes for B_s^0 (upper sign) and $\bar{B}_s^0$ (lower sign) are given by the following equations:

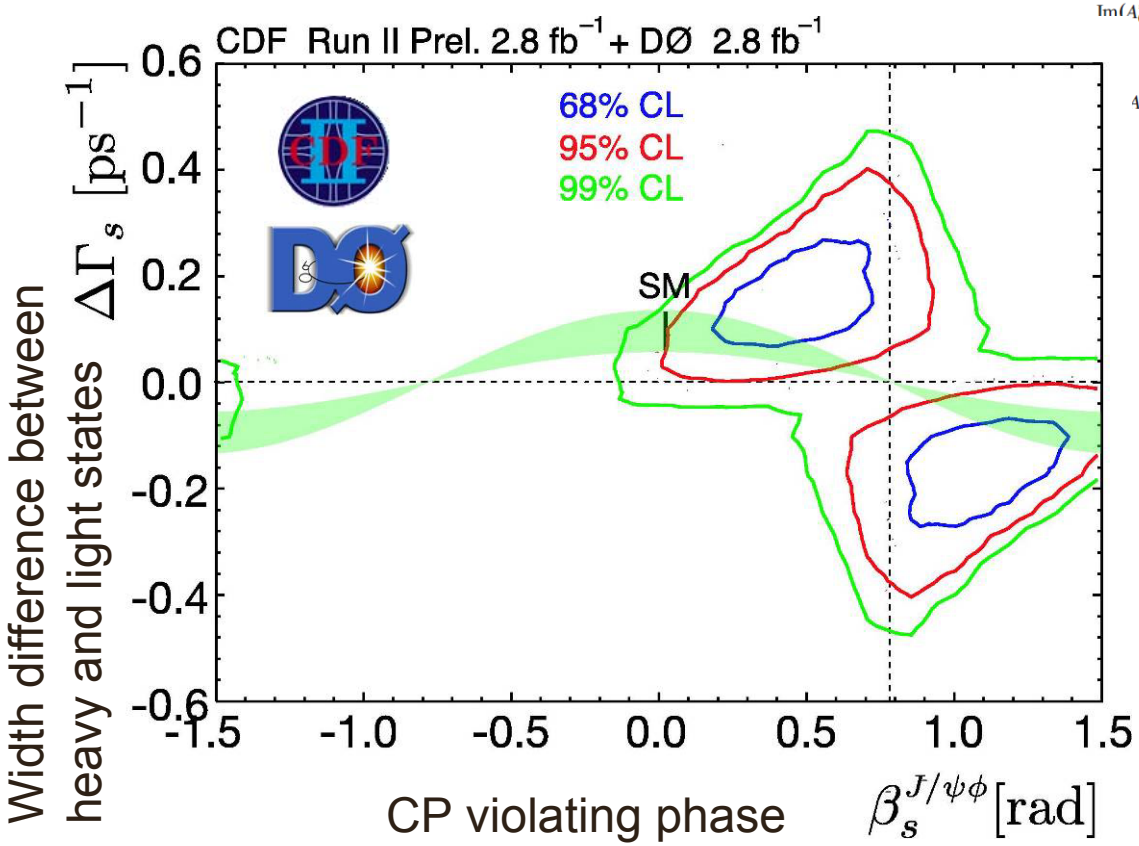
$$|A_0(t)|^2 = |A_{0,\parallel}(0)|^2[\mathcal{T}_+ \pm e^{-\bar{\Gamma}_s t}\sin\phi_s\sin(\Delta M_s t)], \qquad |A_\perp(t)|^2 = |A_\perp(0)|^2[\mathcal{T}_- \mp e^{-\bar{\Gamma}_s t}\sin\phi_s\sin(\Delta M_s t)],$$

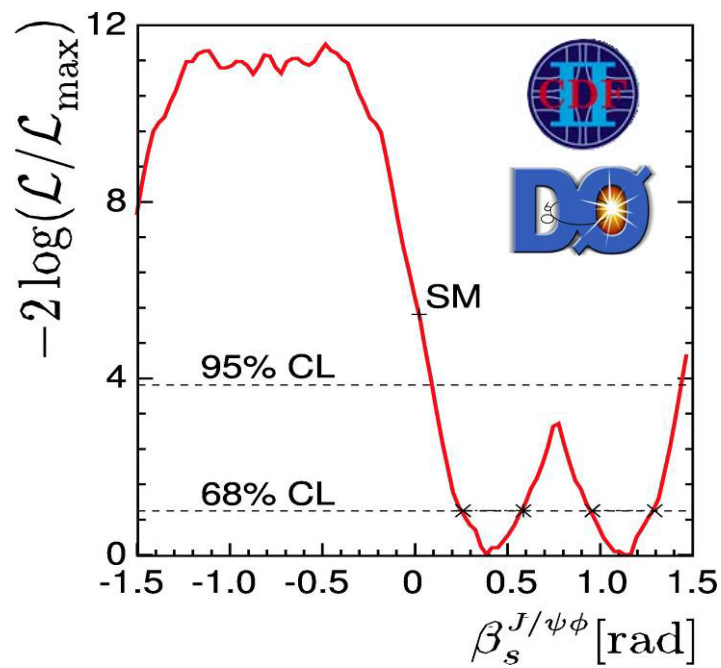
$$\mathrm{Re}(A_0^*(t)A_\parallel(t)) = |A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\times[\mathcal{T}_+ \pm e^{-\bar{\Gamma}_s t}\sin\phi_s\sin(\Delta M_s t)],$$

$$\mathrm{Im}(A_0^*(t)A_\perp(t)) = |A_0(0)||A_\perp(0)|\times[e^{-\bar{\Gamma}_s t}(\pm\sin\delta_2\cos(\Delta M_s t)\mp\cos\delta_2\sin(\Delta M_s t)\cos\phi_s)$$
$$-(1/2)(e^{-\Gamma_H t}-e^{-\Gamma_L t})\sin\phi_s\cos\delta_2],$$

$$A_\parallel^*(t)A_\perp(t)) = |A_\parallel(0)||A_\perp(0)|\times[e^{-\bar{\Gamma}_s t}(\pm\sin\delta_1\cos(\Delta M_s t)\mp\cos\delta_1\sin(\Delta M_s t)\cos\phi_s)$$
$$-(1/2)(e^{-\Gamma_H t}-e^{-\Gamma_L t})\sin\phi_s\cos\delta_1],$$

$$\mathcal{T}_\pm = (1/2)[(1\pm\cos\phi_s)e^{-\Gamma_L t}+(1\mp\cos\phi_s)e^{-\Gamma_H t}]$$





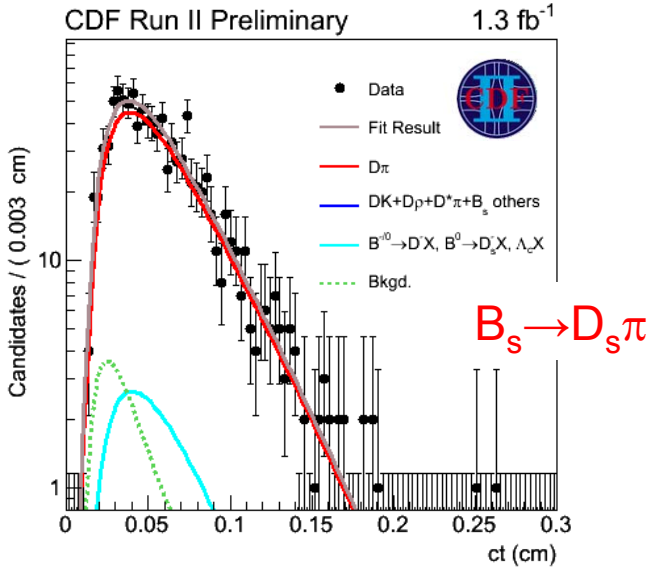
$0.1 < \beta_s < 1.42$ @ 95% CL

(2% chance SM is still OK) ($\beta_s \approx 0.04$)

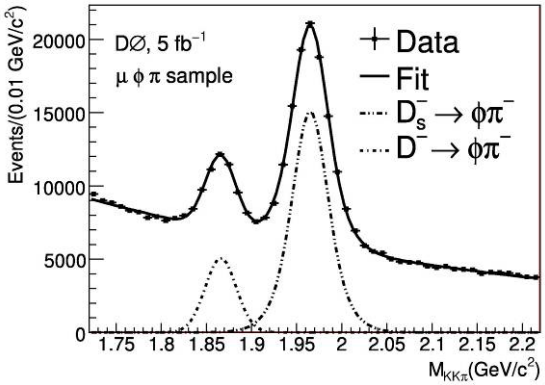
Info from other channels

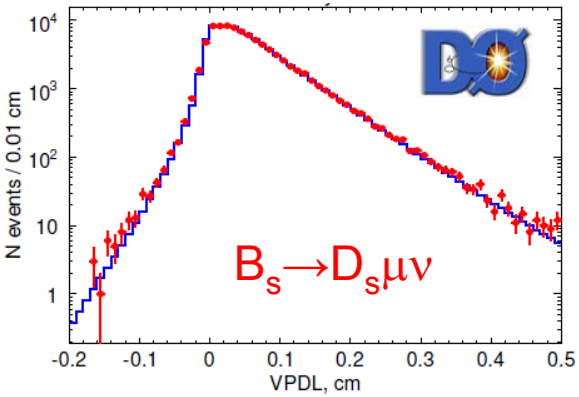
$$A_{SL} = \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

Flavor specific lifetimes

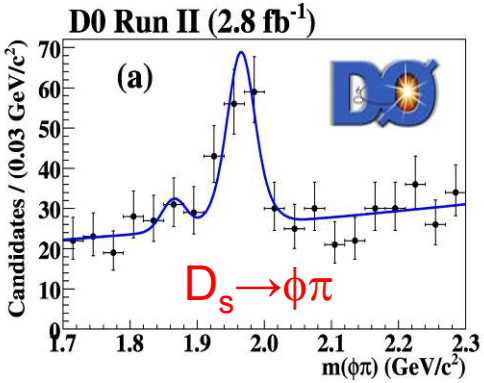


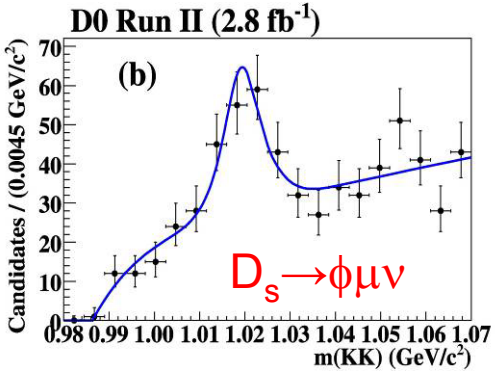
n(μ^+) versus n(μ^-) versus time in semileptonic B_s decay





Direct measurements of width difference





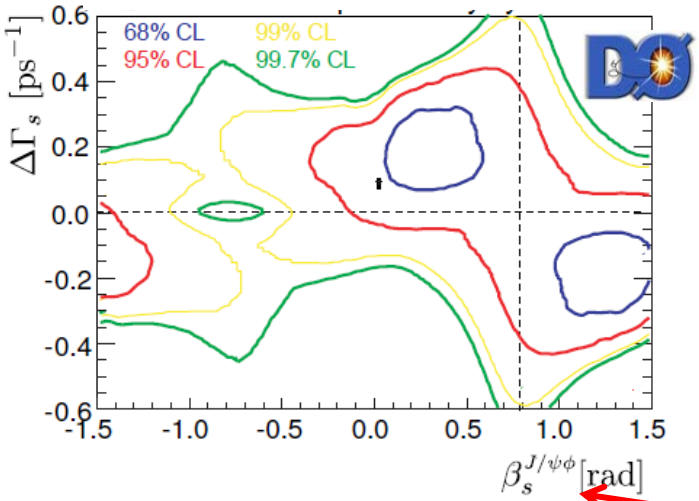
$$\tau_{FS} = \frac{1}{\overline{\Gamma}_s}\left(\frac{1+y^2}{1-y^2}\right)$$

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

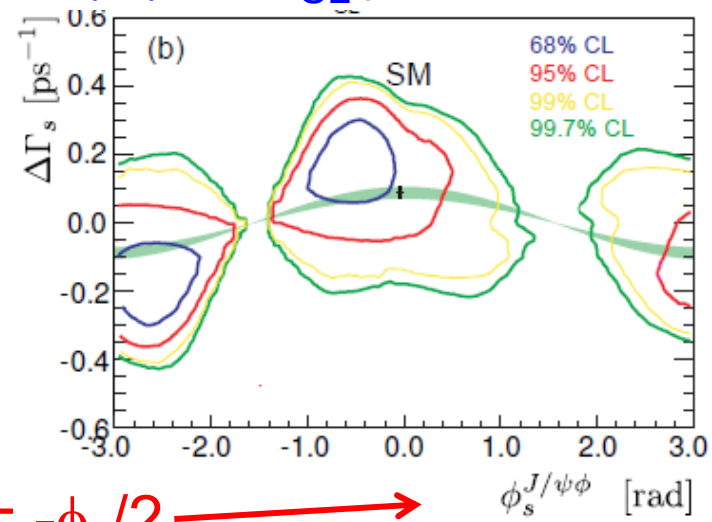
$$2\mathrm{B}\left(B_s \to D_s^{(*)} D_s^{(*)}\right) \approx \frac{\Delta\Gamma}{\cos\phi_s}\left(\frac{1+\cos\phi_s}{2\Gamma+\Delta\Gamma} + \frac{1-\cos\phi_s}{2\Gamma-\Delta\Gamma}\right)$$

Info from other channels

DØ J/ψ φ only

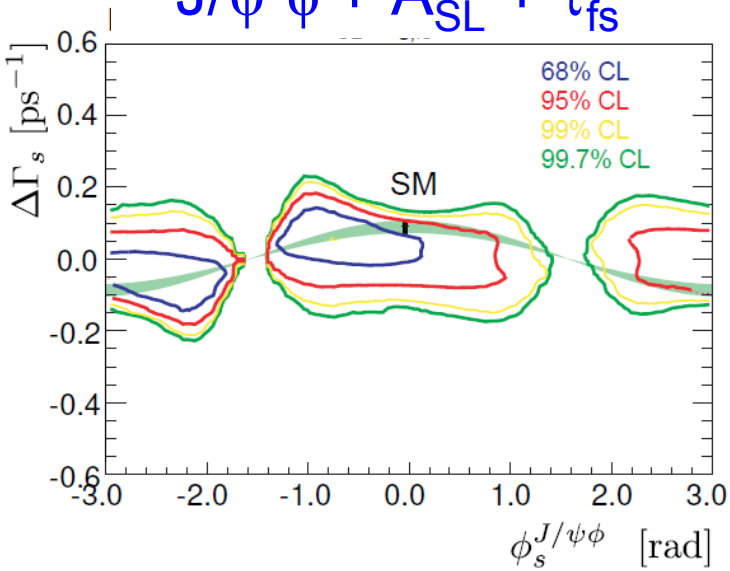


J/ψ φ + A_{SL}(world average)

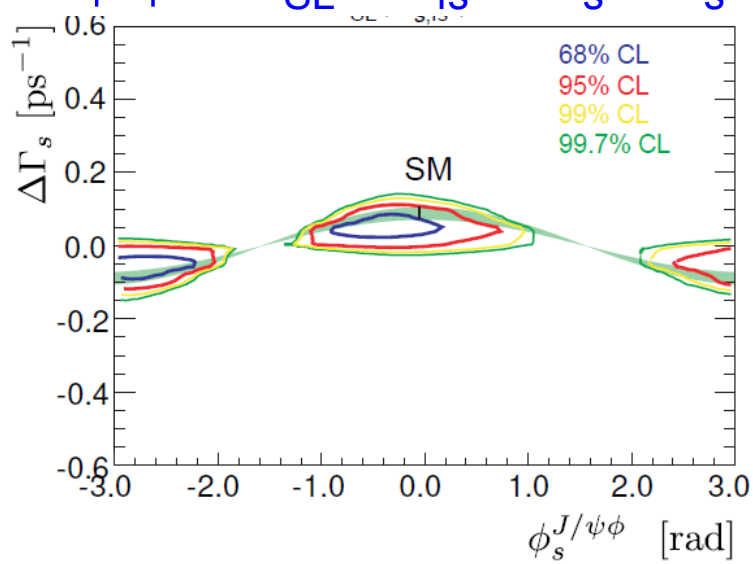


$\beta_s = -\phi_s/2$

J/ψ φ + A_{SL} + τ_{fs}



J/ψ φ + A_{SL} + τ_{fs} + $D_s^{(*)}D_s^{(*)}$



Anomalous CP Violation conclusions

- 45 years after the discovery of $K_L \rightarrow \pi\pi$ we still haven't found enough CP violation to explain the matter in our universe.
- There are hints in the B_s system but not yet significant enough to draw conclusions
- Good news: Much more data is around the corner
  - **Tevatron, 4S and 5S running, LHC**