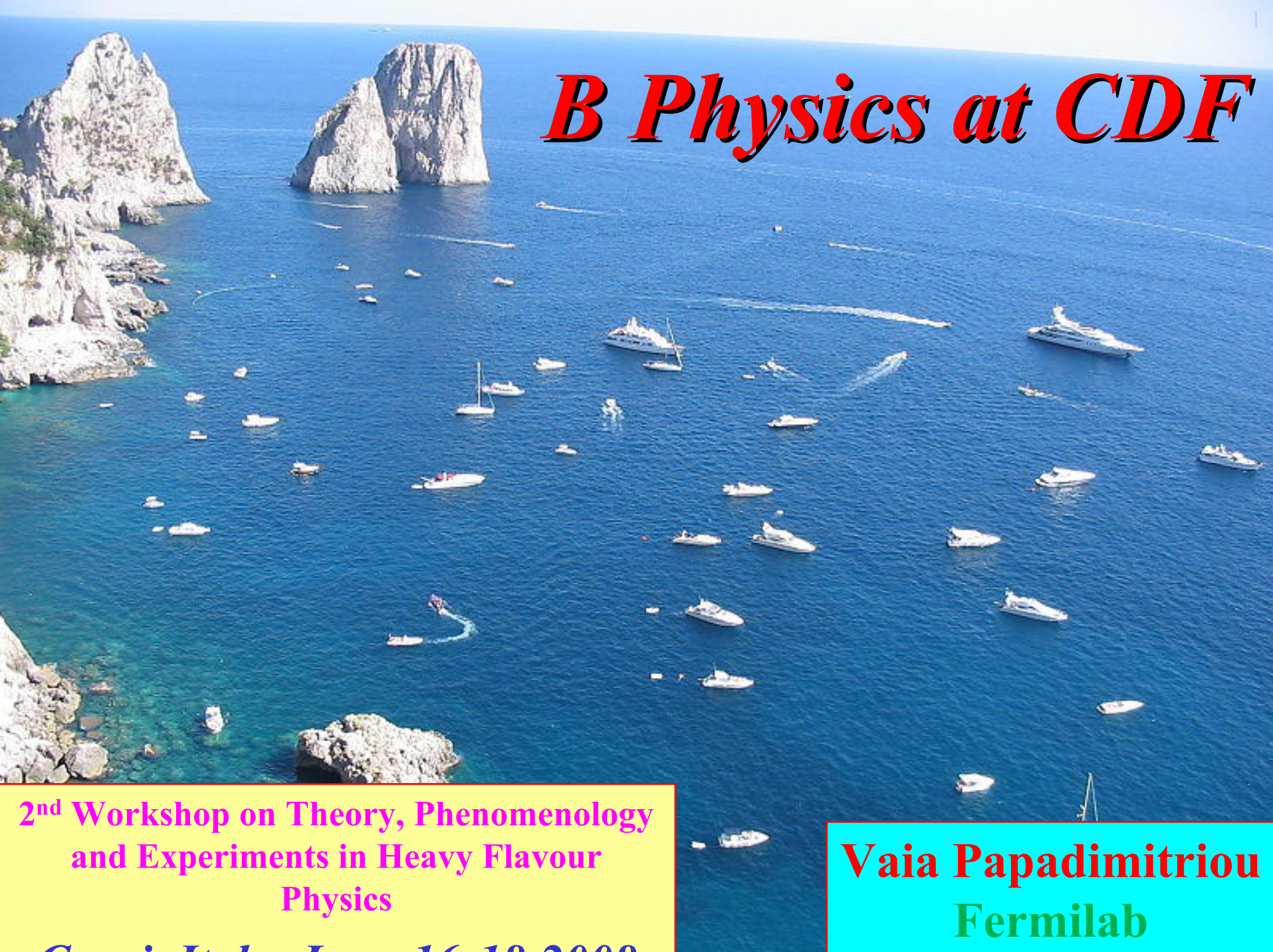


B Physics at CDF

2nd Workshop on Theory, Phenomenology and Experiments in Heavy Flavour Physics

Capri, Italy, June 16-18 2008

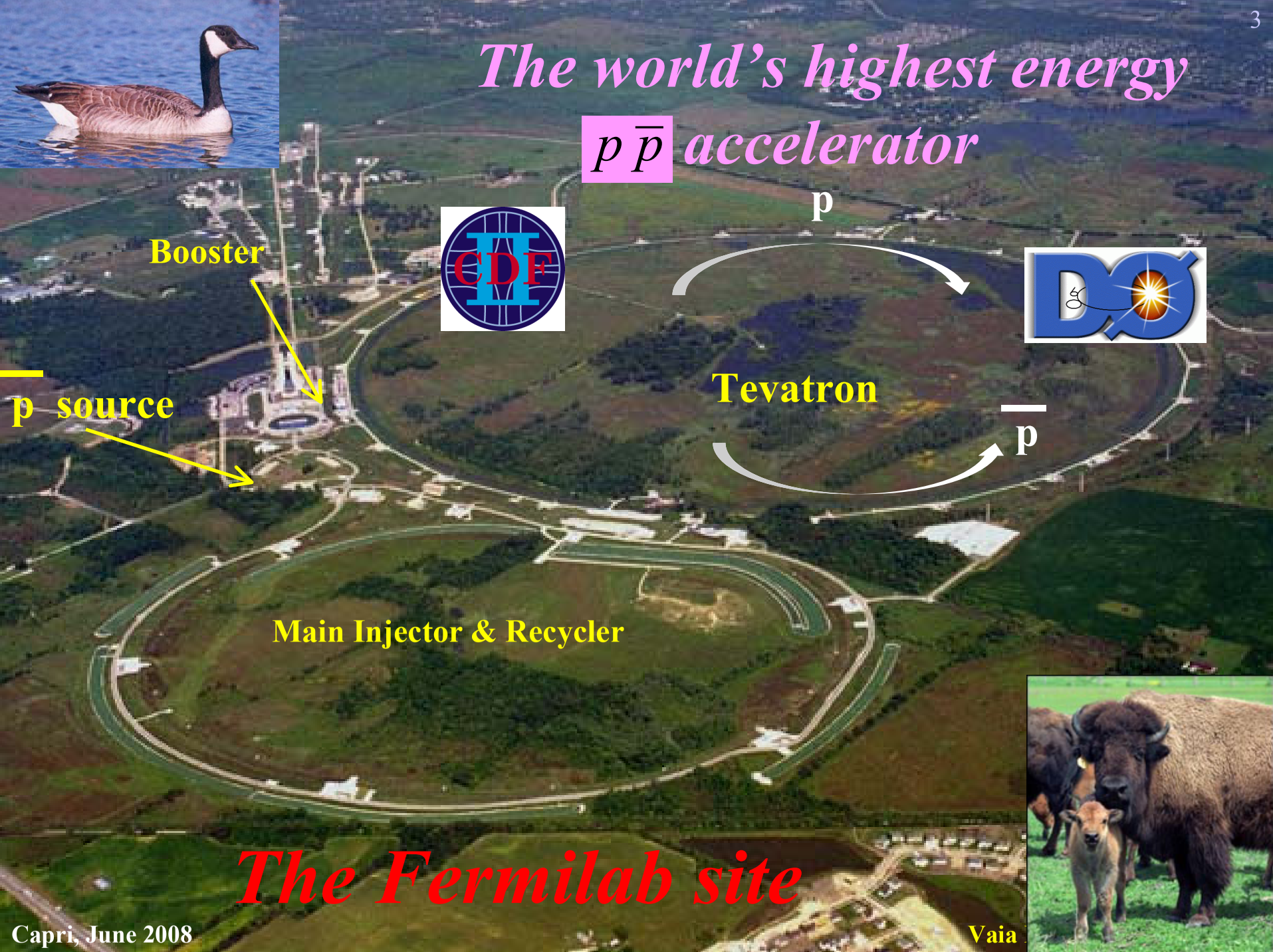
Vaia Papadimitriou

Fermilab

OUTLINE

- **Tevatron and the CDF detector**
- **B^{+-}, B^0 (B^{**})**
  - Production
  - Spectroscopy
- **B_s (B_s^{**})**
  - Spectroscopy
  - Lifetime
  - B_s mixing (Δm_s, $\Delta\Gamma_s$, ϕ_s)
  - CP violation
  - Branching fractions - Rare decays
- **B_c**
  - Mass
  - Lifetime
- **b-baryons**
  - Spectroscopy
  - Lifetime
  - Branching fractions
  - CP violation
- **Quarkonia**
  - Production
- **Conclusion**

The world's highest energy $p\,\bar{p}$ accelerator



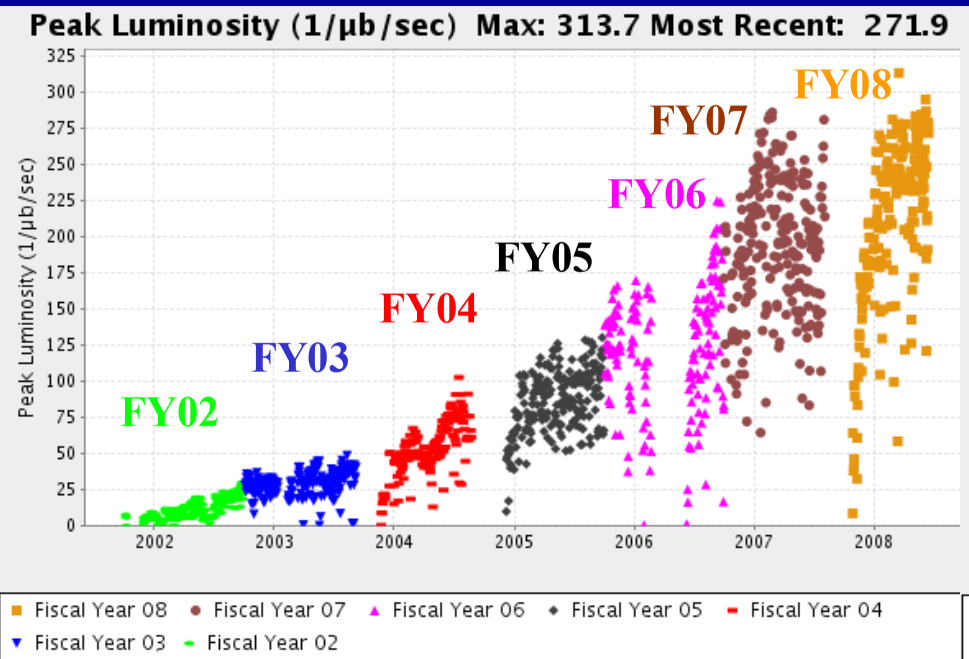
The Fermilab site

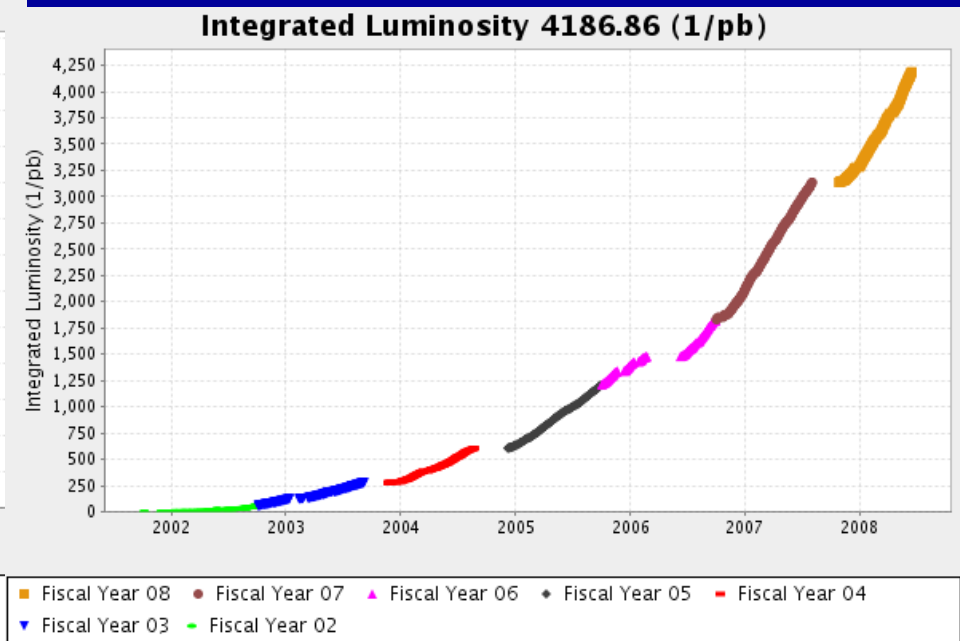
Tevatron Performance

- **Tevatron (Run I 1992-96, $\int L\,dt = 110\ pb^{-1}$):**
  - **p → ← pbar at $\sqrt{s}$ = 1.8 TeV, 3.5 μs between collisions**
- **Tevatron (Run II 2002-Present, $\int L\,dt = \sim 4.3\ fb^{-1}$):**
  - **p → ← pbar at $\sqrt{s}$ = 1.96 TeV, 396 ns between collisions**

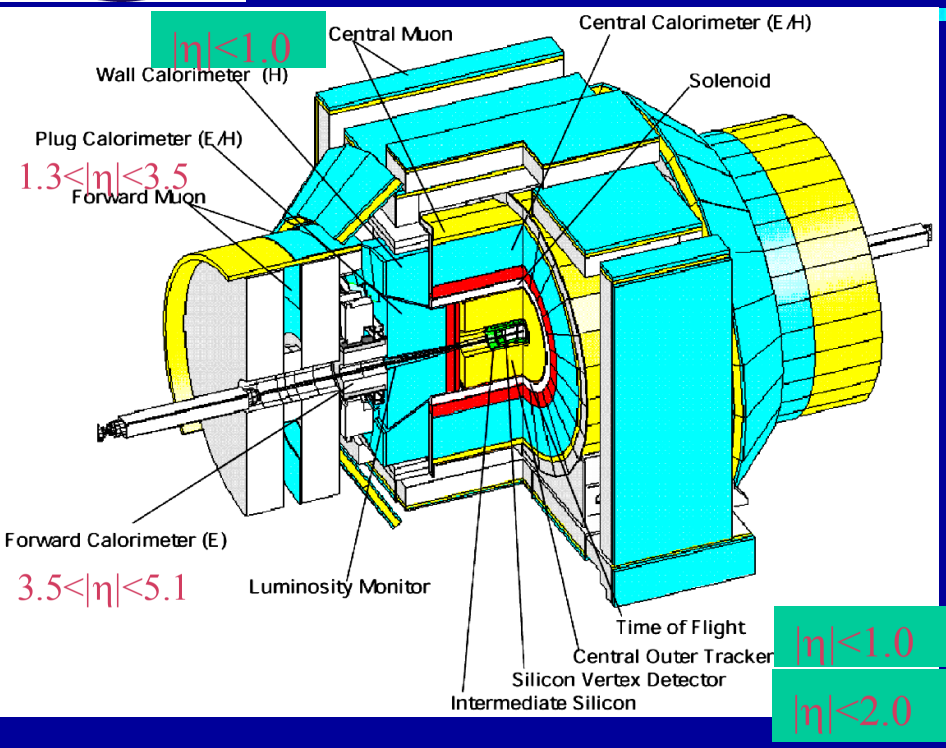
Best $3.15 \times 10^{32}\ cm^{-1}s^{-1}$ March 17, 2008

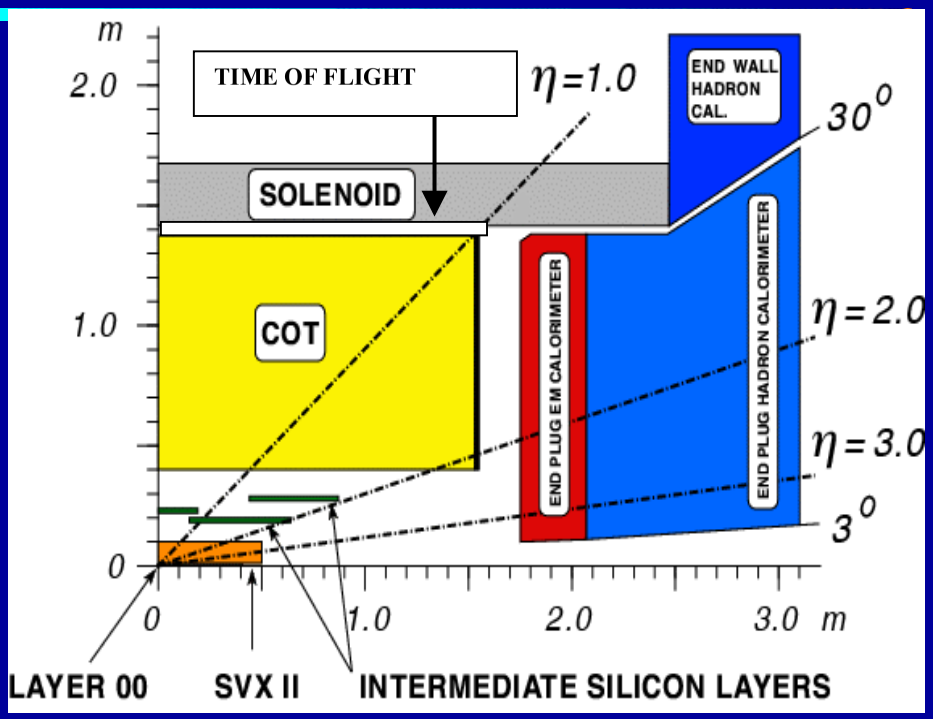
221.45 pb^{-1} delivered per experiment in May 2008
Weekly record of delivered luminosity: 56.1 pb^{-1}





The CDF Detector





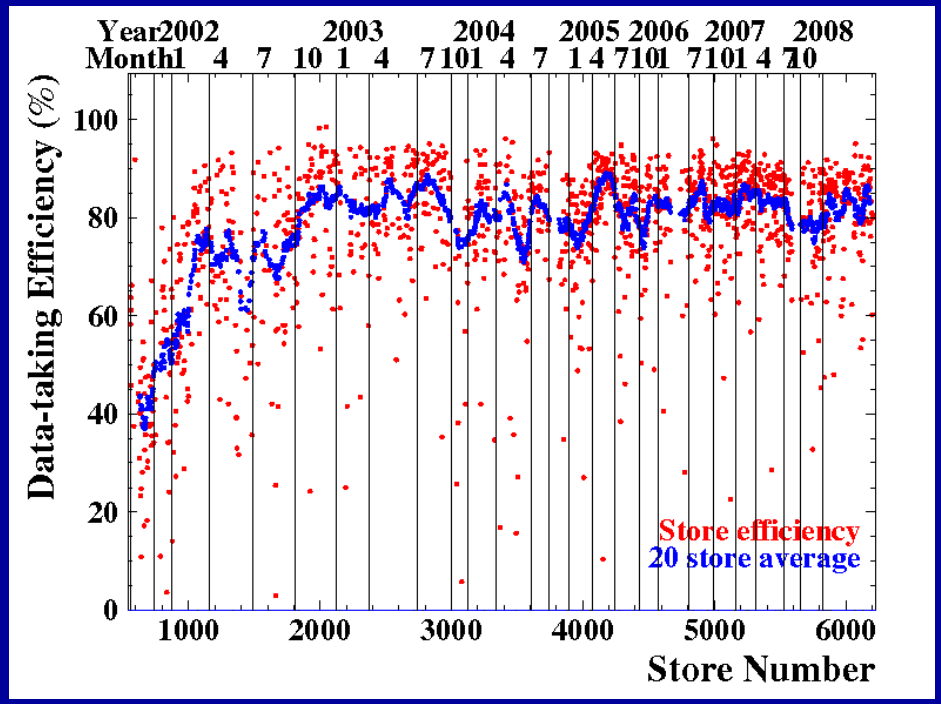
- Central drift chamber and silicon vertex detector in a magnetic field of 1.4 T
- Excellent vertex and mass resolution ($\sigma(p_T)/p_T^2 \sim 0.1\%$ GeV/c^{-1})
- I.P. resolution: 48 μm at 2 GeV/c

- Particle ID: dE/dx, ToF
- Muon triggers
- Tracking triggers (Hadronic B's)
  - L1: Tracks
  - L2: Secondary vertex

Data sets

- CDF uses data collected in the period 2002-2008 :
  - Out of the 4.3 fb-1 delivered to CDF, ~ 3.5 fb^{-1} have been recorded
  - up to ~ 2.8 fb^{-1} used for B physics analyses

Data taking efficiency: ~ 82%



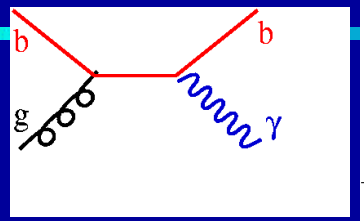
Trigger crucial point for B-Physics:

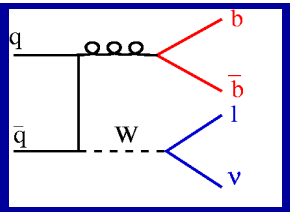
- 2 μ from J/ψ
- soft lepton, (soft lepton+non prompt track)
- 2 non-prompt tracks

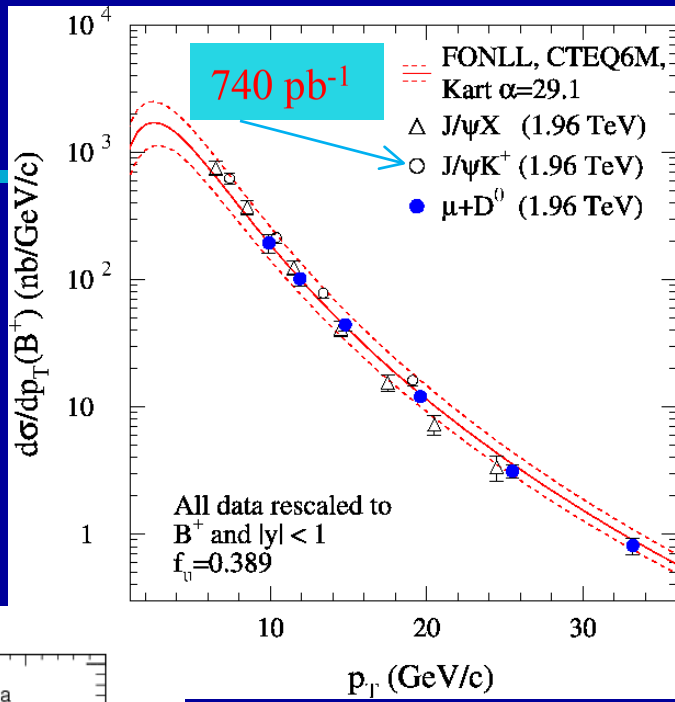
b-quark Production

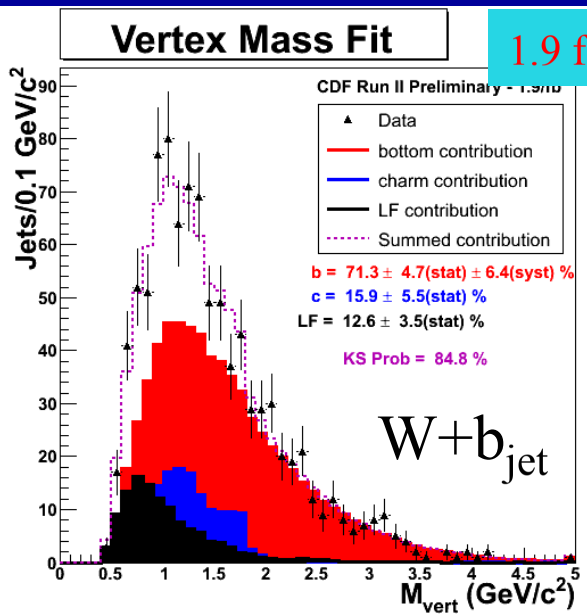
New Run-II measurements:

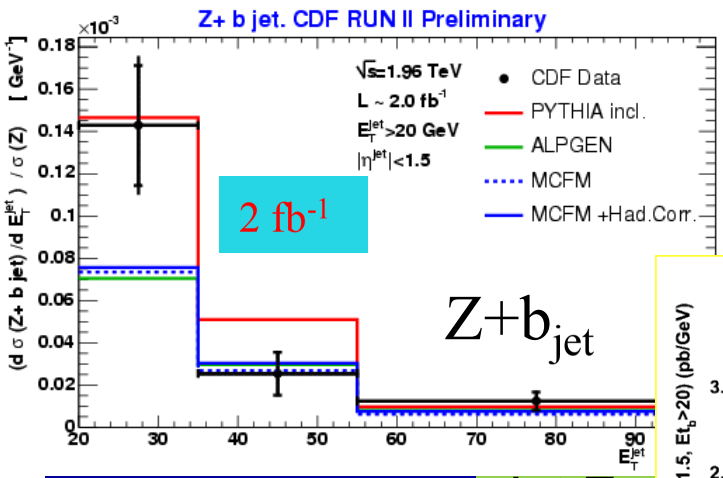
- B^+ cross section
- $W+b_{jet}$, $Z+b_{jet}$, $\gamma+b_{jet}$
  - Fit secondary vertex mass





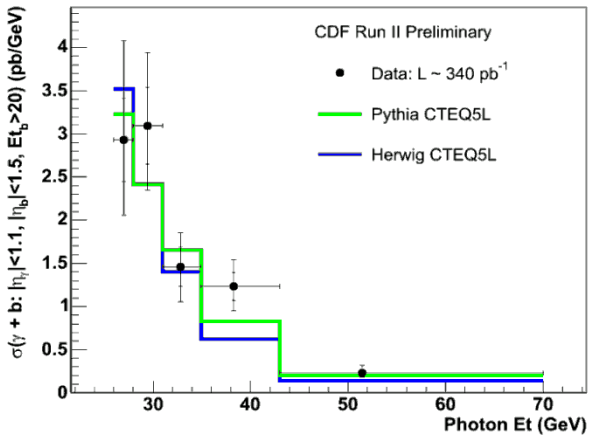






Jet E_T

$\gamma+b_{jet}$



- First measurement of $\gamma+b_{jets}$ and $W,Z+b_{jets}$
- Data agree well with theoretical predictions

b-Physics cross sections ($\sqrt{s} = 1.96\,\text{TeV}$)

b Production cross section:

$$\sigma(p\bar{p} \to H_b X) = \left(17.6 \pm 0.4(\text{stat})\,^{+2.5}_{-2.3}\,(\text{syst})\right)\mu b$$

$|y_{Hb}| < 0.6$,

PRD 71, 032001, (2005)

B^+ Production cross section:

$$\sigma_{B^+}\left(p_T \geq 6.0\,GeV/c, |y| < 1\right) = \left(2.78 \pm 0.24\right)\mu b$$

PRD 75, 012010, (2007)

Compare with: *1 nb at Υ(4S), 6 nb at the Z^0*

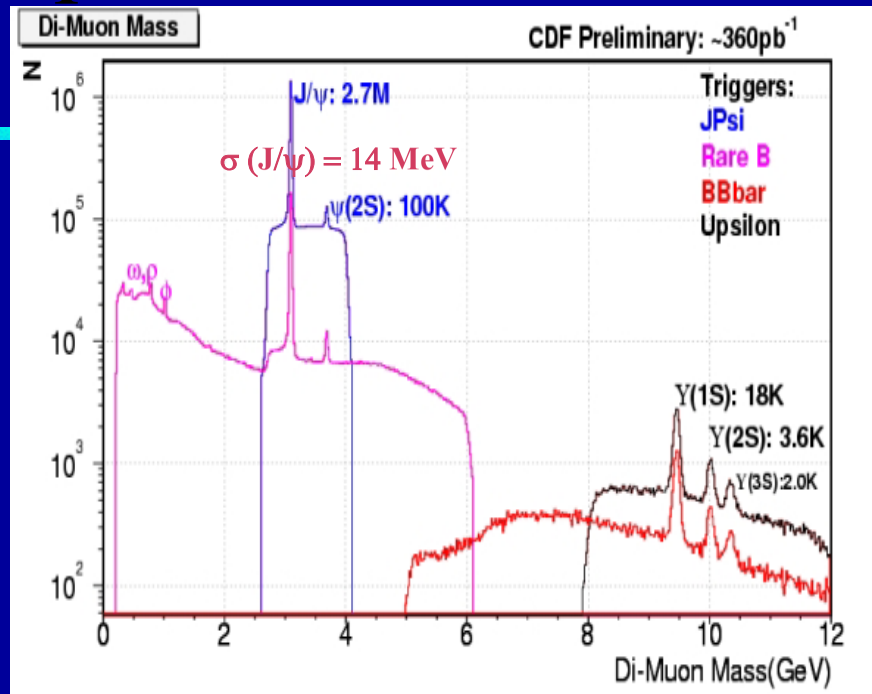
Inelastic cross section at Tevatron: ≈ 60 mb

→ factor 1/1000 trigger.

B-Physics Data samples

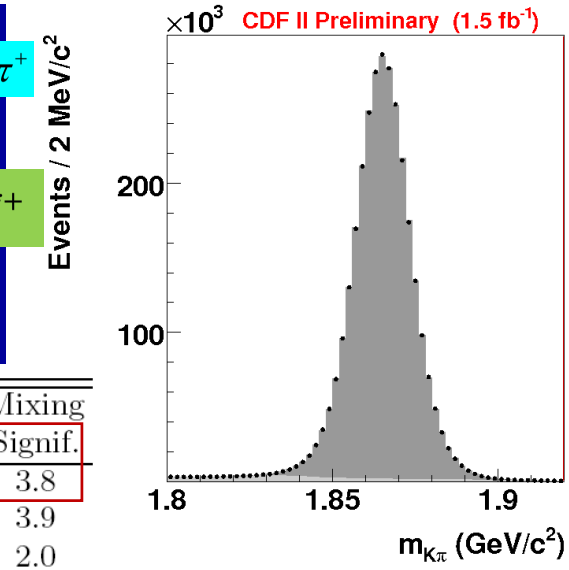
In 3 fb^{-1} of recorded data:

- J/ψ samples:
  - ~ 22 Million! ~ 20% are from B's
  - Reconstruct exclusive B mesons and b-baryons
- Semi-leptonic B → D lν X samples:
  - ~2 M events with fully reconstructed D
    - CDF lowers lepton trigger pt by requiring additional displaced track
- Fully hadronic decays
  - ~ 200 K events fully reconstructed B's
  - Requires trigger on secondary vertex (SVT)



$\pi^+ D^0 ; D^0 \to K^- \pi^+$

~ 3 M D^{*+}



				Mixing Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BABAR [8]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle [9]	3.64 ± 0.17	$0.6\ ^{+4.0}_{-3.9}$	$0.18\ ^{+0.21}_{-0.23}$	2.0

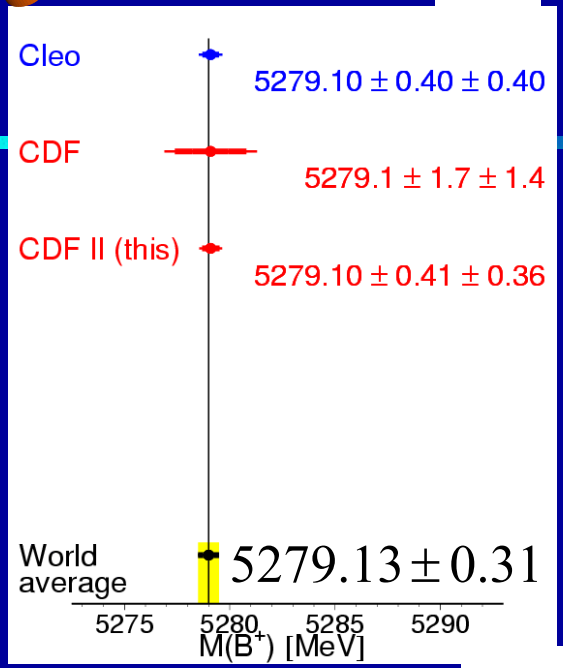
$B^{\pm}$, B^{0} (B^{**}) mesons

$B^{\pm}$, B^{0} (B^{**}) mesons

B hadron masses

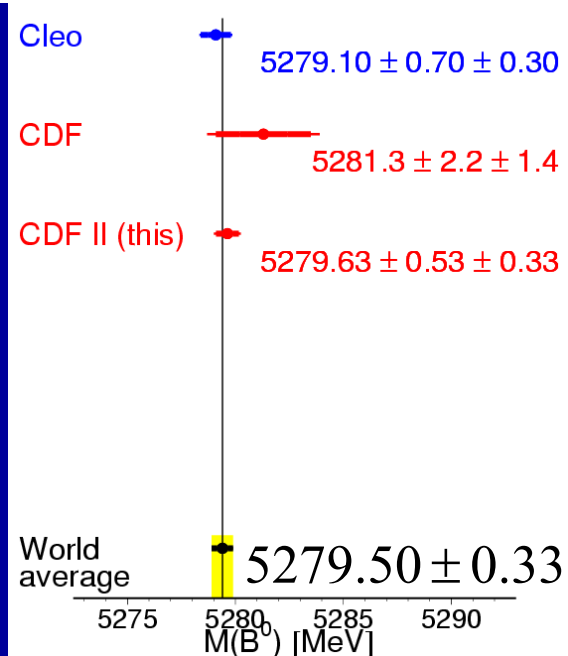
- B mass determination
  - Use clean J/ψK(φ) modes
  - Accurate tuning of momentum scale with large J/ψ sample

B^+



PRL 96, 202001 2006

B^0



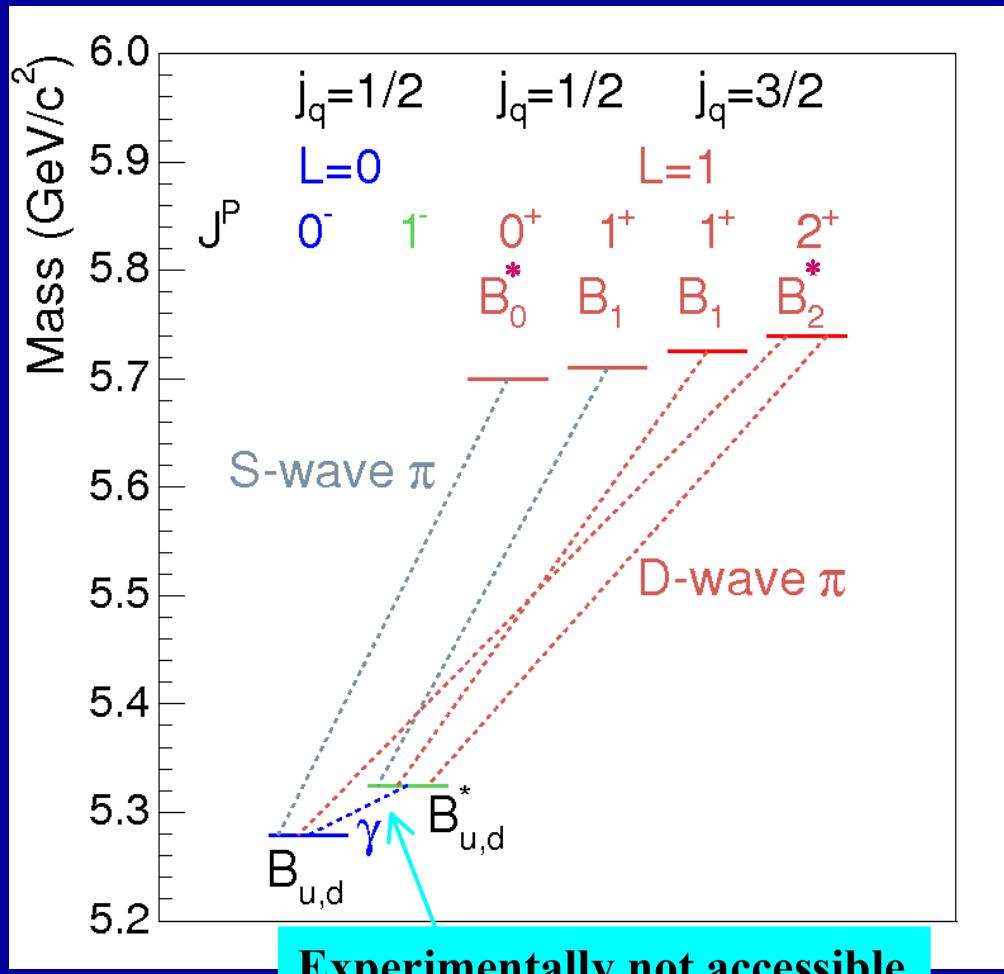
B hadron species	Mass (MeV/c^2) CDF Run II	Mass (MeV/c^2) PDG 2008 fit
B^+	**5279.10 ± 0.41 ± 0.36**	5279.13 ± 0.31
B^0	**5279.63 ± 0.53 ± 0.33**	5279.50 ± 0.33
B_s	**5366.01 ± 0.73 ± 0.33**	5366.1 ± 0.6

Systematics below 1 MeV for high statistics channels

Best single measurements of *b*-hadron masses

B** Spectroscopy

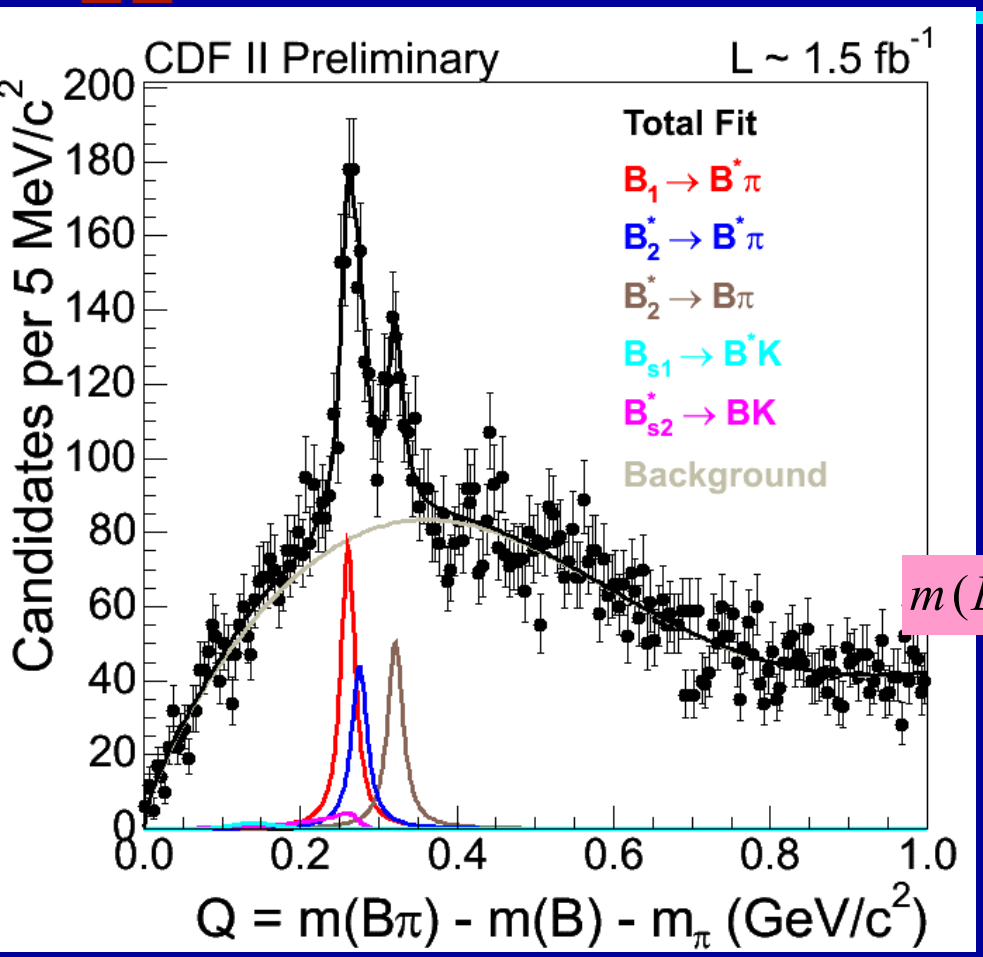
- B_1 and B_2* decay through D-wave → narrow resonances
- B_0* and B_1* decay through S-wave → wide resonances, difficult to distinguish from phase space



Experimentally not accessible

Observation of B^{**0} mesons

$$B^{**0} \to B^+\pi^- \text{ or } B^{**0} \to B^{+*}\pi^- ; B^{+*} \to B^+\gamma$$



$$B^+ \to J/\psi K^+ ; J/\psi \to \mu^+\mu^-$$

$$B^+ \to D^0 \pi^+ ; D^0 \to K^+\pi^-$$

$$B^+ \to D^0 3\pi^+ ; D^0 \to K^+\pi^-$$

$$Q(B_2^{*0}) = 321.2\,^{+1.7}_{-1.8}\,(\text{stat})\,^{+0.3}_{-0.4}\,(\text{syst})\,MeV/c^2$$

$$m(B_2^{*0}) - m(B_1^0) = 14.6\,^{+2.2}_{-2.5}\,(\text{stat})\,^{+0.7}_{-0.9}\,(\text{syst})\,MeV/c^2$$

$$\Gamma(B_2^{*0}) = 22.1\,^{+3.6}_{-3.1}\,(\text{stat})\,^{+3.5}_{-2.6}\,(\text{syst})\,MeV/c^2$$

$$357\,^{+46}_{-44}\,(stat)\,^{+34}_{-33}\;B_2^{*0} \to B\pi \text{ events}$$

$$m(B_2^{*0}) = 5739.9\,^{+1.7}_{-1.8}\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{syst})\,MeV/c^2$$

$$328\,^{+46}_{-44}\,(stat)\,^{+34}_{-33}\,(\text{syst})\;B_2^{*0} \to B^*\pi \text{ events}$$

$$m(B_1^0) = 5725.3\,^{+1.6}_{-2.1}\,(\text{stat})\,^{+0.8}_{-1.1}\,(\text{syst})\,MeV/c^2$$

$$496\,^{+72}_{-66}\,(stat)\,^{+113}_{-97}\;B_1^0 \to B^*\pi \text{ events}$$

$B_s^{(**)}$meson

$B_s^{(**)}$ meson

Orbitally Excited B_s-mesons

$$B_s^{**} \to B^+(B^{*+})K^-;$$
$$B^+ \to J/\psi K^- \text{ or } \overline{D}^0\pi^-$$

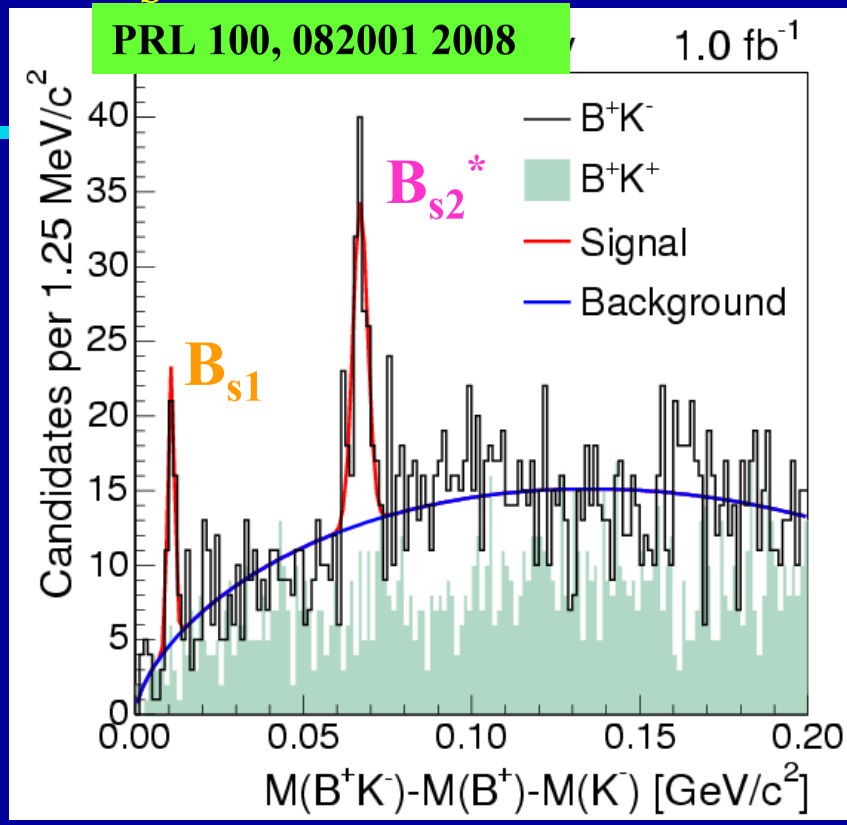
B_{s2}^*: 95±23 events

$$\Delta M = 66.96 \pm 0.39(\text{stat}) \pm 0.14(\text{syst})\, MeV/c^2$$
$$\sigma = 1.79 \pm 0.42; 2.88 \pm 0.75(\text{stat})\, MeV/c^2$$

B_{s1}: 36±9 events

$$\Delta M = 10.73 \pm 0.21(\text{stat}) \pm 0.14(\text{syst})\, MeV/c^2$$
$$\sigma = 0.64 \pm 0.25; 1.18 \pm 0.56(\text{stat})\, MeV/c^2$$

PRL 100, 082001 2008



- Two signals seen
  - **$B^*_{s2} \to BK$: >5.0σ, $m(B_{s2}^*)$=5839.6±0.7 MeV/c²**
    - already seen by OPAL, DELPHI and DØ
  - **$B_{s1} \to B^*K$: >5.0σ, $m(B_{s1})$=5829.4±0.7 MeV/c²**
    - First observation of the B_{s1} state
- Mass difference: 10.5 ± 0.6 MeV/c²

Theory predictions

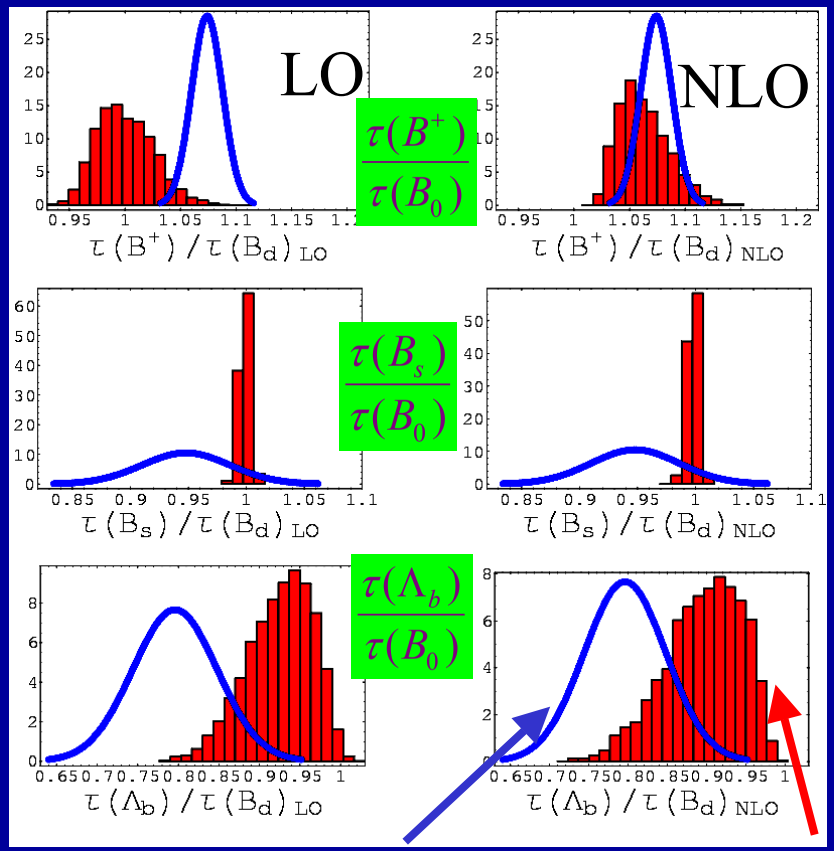
$M[MeV/c^2]$	$\Gamma[MeV]$
5844 - 5899	1; 2.6; 7±3
5831 - 5886	< 1; 2.8±1.2

Vaia Papadimitriou

B hadron lifetimes

- B hadron lifetimes provide understanding of detector, trigger, analysis biases
- B hadron decays dominated by b-quark decay
  - Effect of spectator quarks can be included with perturbative expansions in terms of $1/m_b$ (HQET)
    - Expect small differences between lifetimes of different species
    - Non-perturbative ME from lattice, Wilson coeff. from perturbative QCD
      - NLO improves agreement
    - Ratios reduce theory uncertainties

C. Tarantino, hep-ph/0310241 and Eur.Phys. J C33, S895 (2004)



Experiment

Theory

Lifetimes

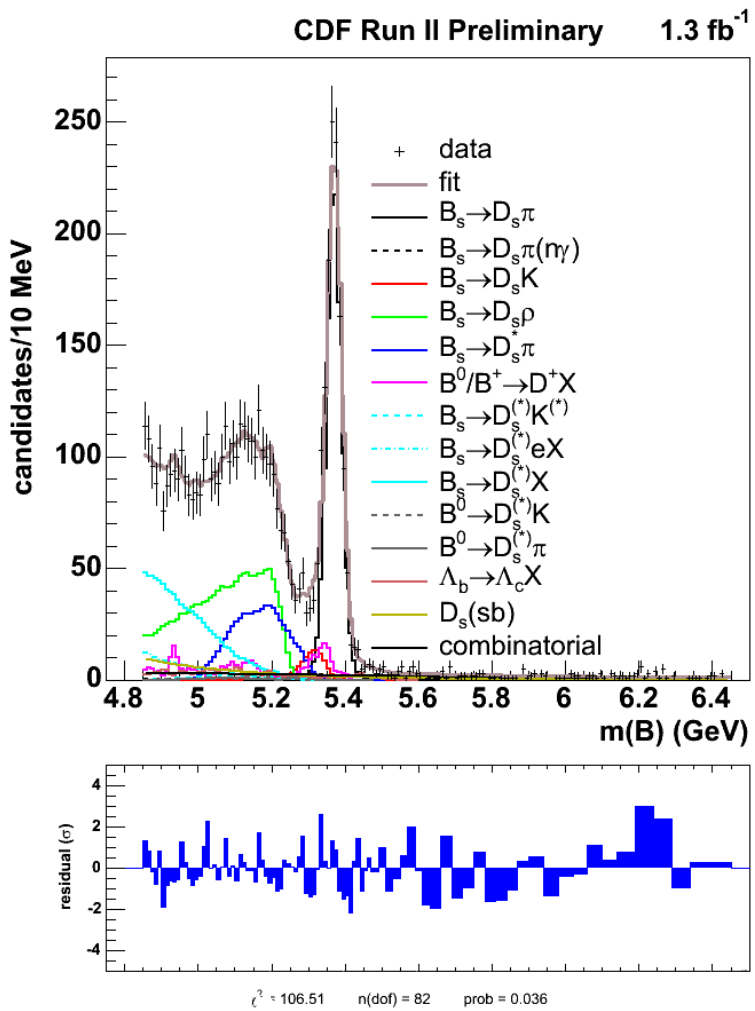
- Several new results included in HFAG 2008 averages
  - B^0, B^+ dominated by BaBar/Belle
  - B_s: dominated by CDF/D0, LEP

Lum. pb^{-1}	CDF J/ψ modes 1000/1700	CDF hadronic 360/1300	CDF semi-leptonic (Hi pt) 260	HFAG 2008
B0	1.551±0.019±0.011	1.511±0.023±0.013	1.473±0.036±0.054	1.530 ± 0.009
B+	1.630±0.016±0.011	1.661±0.027±0.013	1.653±0.029±0.032	1.638 ± 0.011
B+/B0	1.051±0.023±0.004	1.10±0.02±0.01	1.123±0.040±0.040	1.071 ± 0.009
Bs	1.494±0.054±0.009 1.52 ± 0.04 ± 0.02	1.598±0.097±0.017 1.518±0.041±0.025		1.470 ± 0.026
Bs/B0	0.963±0.047±0.005	1.06±0.07±0.01		0.961 ± 0.018

From τ_s, $\Delta\Gamma_s$ fit

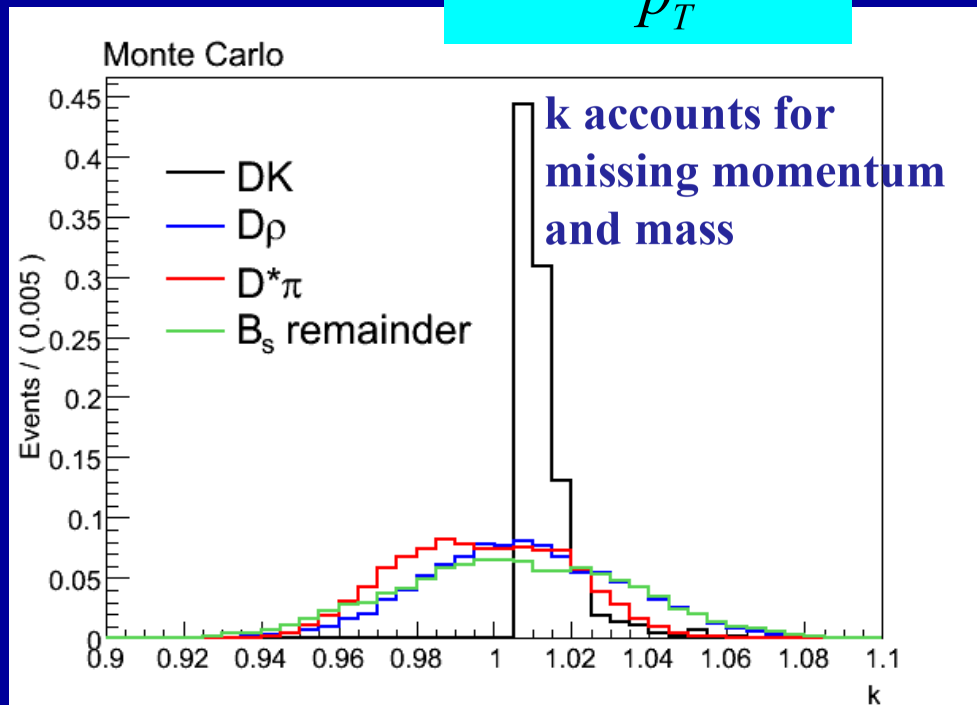
B_s lifetime using hadronic decays

Use fully reconstructed ($B_s^0 \to D_s^- \pi^+ X; D_s^- \to \varphi \pi^-$) and partially reconstructed ($B_s^0 \to D_s K, D_s \rho, D_s^* \pi, \ldots$) decay channels in flavor-specific modes.



~1100 fully reconstructed and ~2000 partially reconstructed decays

$$ct = \frac{L_{xy} \cdot m_B^{rec}}{p_T} \cdot k$$



B_s lifetime using hadronic decays

The lifetime for the control samples:

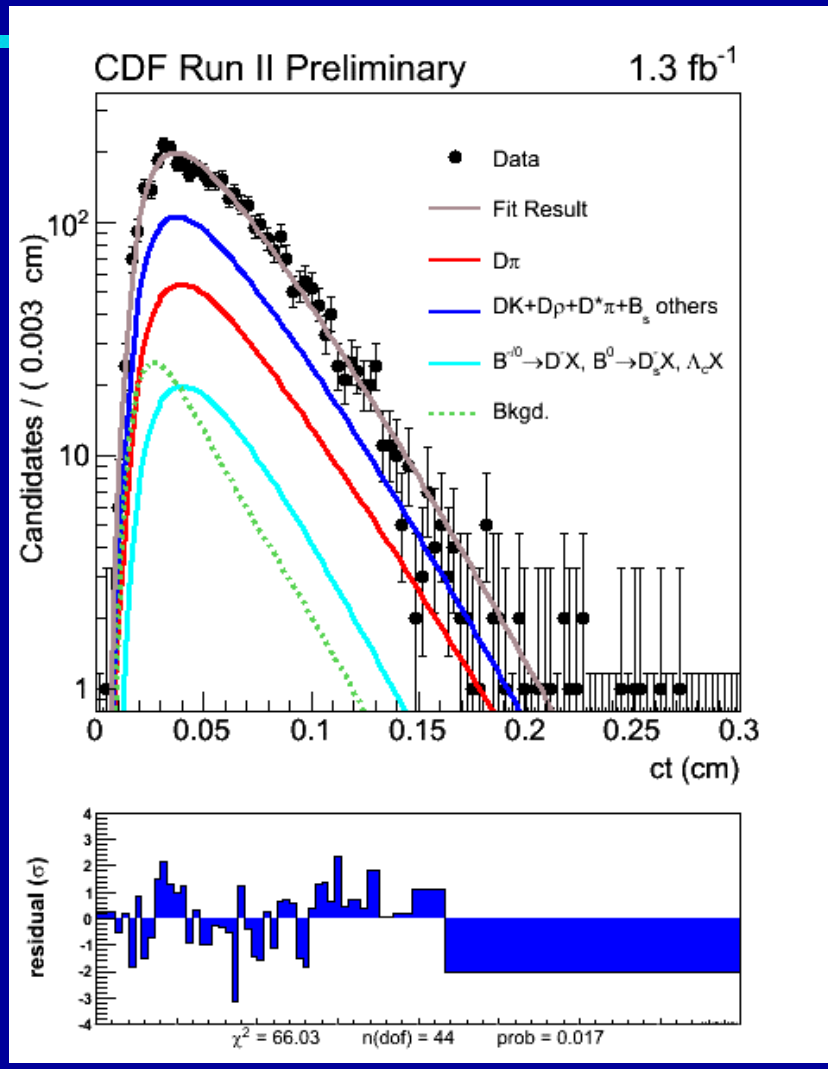
$$B^0 \to D^- \pi^+ X; D^- \to K\pi^+\pi^-$$

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

$$B^+ \to \overline{D}^0\pi^+; \overline{D}^0 \to K^+\pi^-$$

agrees well with PDG

$$\tau(B_s) = 1.518 \pm 0.041(\text{stat}) \pm 0.025(\text{syst})\,\text{ps}$$



Largest systematics:

- background modeling
- MC p_T and trigger reweighting

World's best flavour-specific

- same precision as from the $B_s^0 \to J/\psi\,\varphi$ decay.

B mixing

- Flavor eigenstate ≠ Hamiltonian eigenstate
  - There is transition between meson and anti-meson

$q = b, s$

- Simplified Schroedinger equation describing mixing and decay

$$i\frac{d}{dt}\begin{pmatrix} B_q^0(t) \\ \overline{B_q^0}(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} B_q^0 \\ \overline{B_q^0} \end{pmatrix} \qquad \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix}; \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

- **The mass and lifetime eigenstates (with $\Gamma_{12}/M_{12} << 1$)**

$$|B_L> = p|B_q^0> + q|\overline{B}_q^0>$$

$$|B_H> = p|B_q^0> - q|\overline{B}_q^0>$$

$$\Delta m_q = m_H - m_L = 2|M_{12}^q|$$

$$\Delta\Gamma_q = \Gamma_L - \Gamma_H \cong -2|\Gamma_{12}^q|\mathrm{Re}(\frac{\Gamma_{12}^q}{M_{12}^q}) = 2|\Gamma_{12}^q|\cos(\varphi_s)$$

$$\tau_q = \frac{2}{\Gamma_H + \Gamma_L}$$

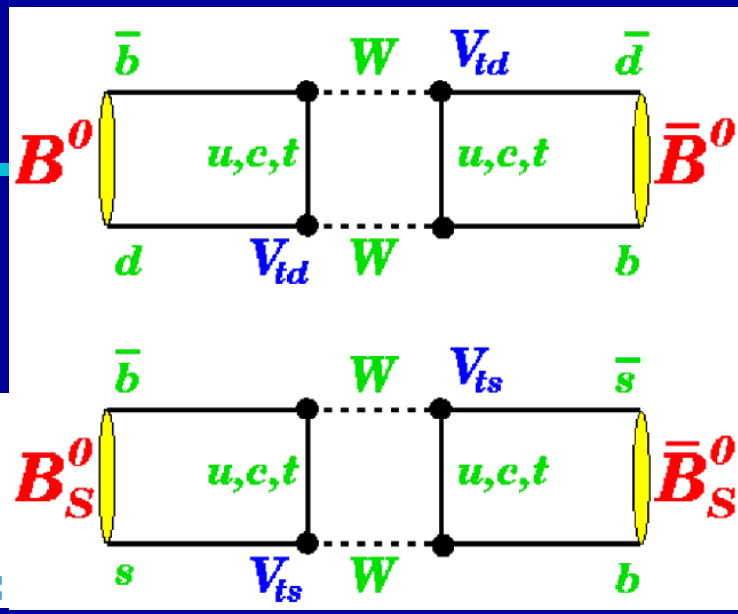
For the B_s meson: Δm_s, $\Delta\Gamma_s$ and φ_s are sensitive to New Physics ($|\Gamma_{12}|$ is not)
The phase ($\varphi_s = -2\beta_s$) is small in SM, but could be large in a New Physics scenario.

The Tevatron experiments can currently measure several of these quantities

B mixing

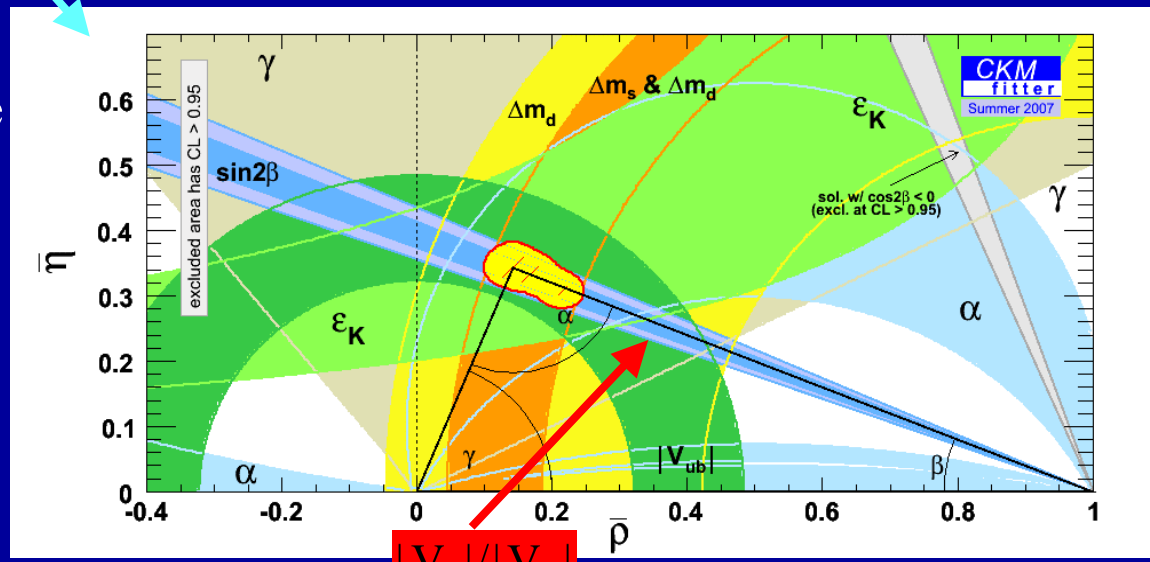
- Neutral B's mix:
  - SM interpretation with box diagrams
    - Frequency $\Delta m_{d,s} \propto |V_{td,s}|^2$
    - Constraints to CKM weak due to theory uncertainties

      Theory accuracy ~5% in ratio $\Delta m_d/\Delta m_s$
  - B_d mixing measured and established clearly for some time now.
    - LEP, CDF-I, CDF-II, D0-II, **BaBar, Belle**
  - Bs mixing not observed till spring 2006
    - Limits set by LEP, SLD, CDF-I, CDF-II, D0-II



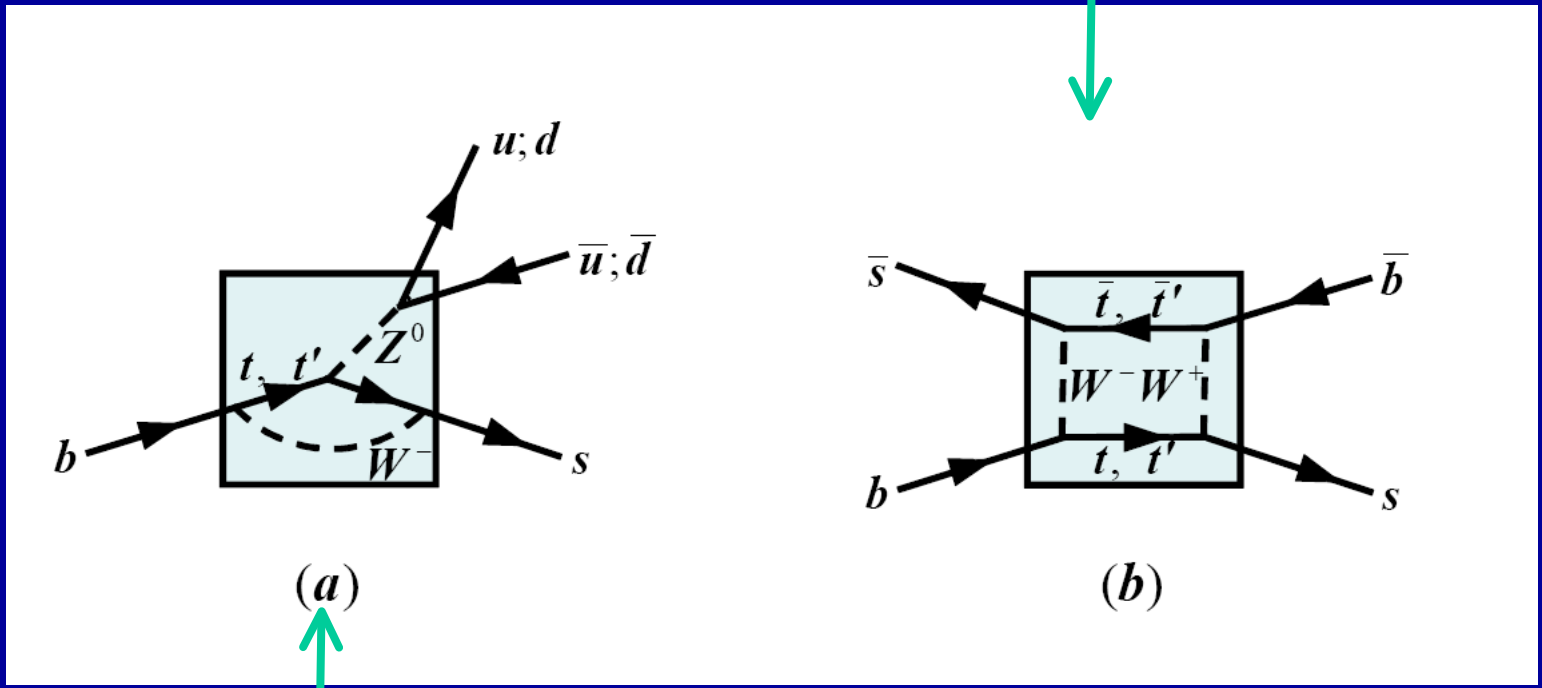
$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\xi \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

from LATTICE



New physics may affect $\Delta m_s/\Delta m_d$

Example of New Physics: a 4th generation quark that contributes to the mixing phase

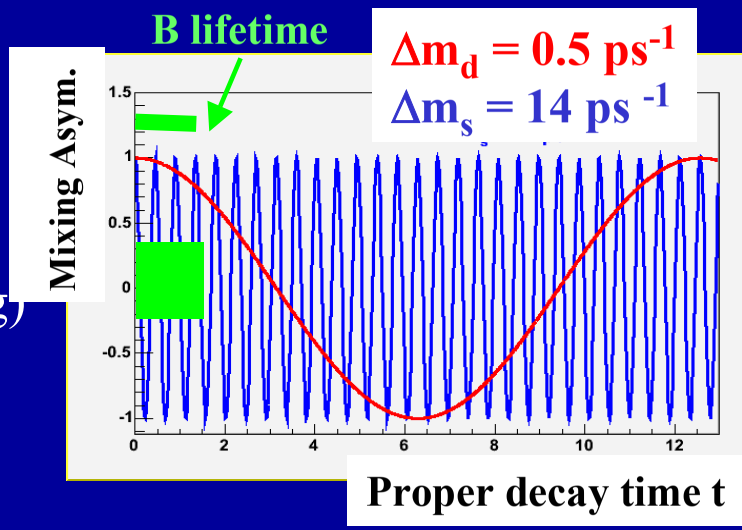


Would have other measureable consequences: e.g. an impact on direct CP violation in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$

Wei-Shu Hou, arXiv:hep-ph/0803.1234

B mixing

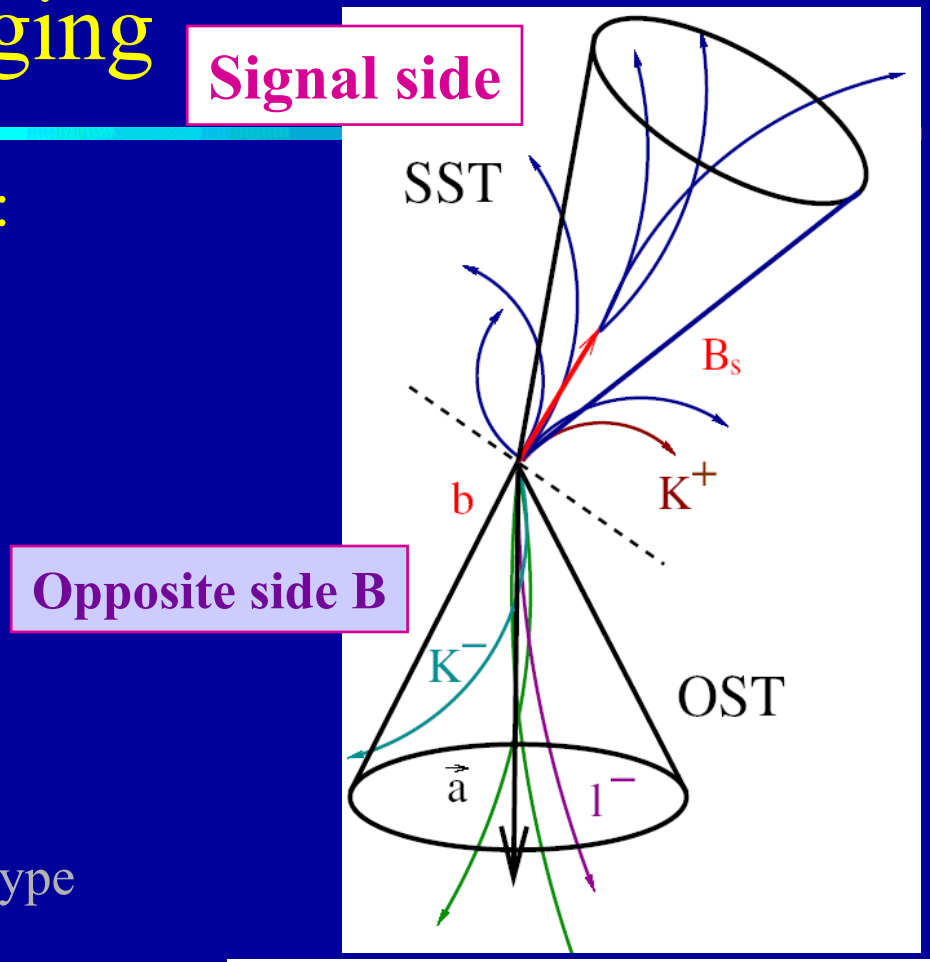
- Basic ingredients for the measurement:
  - High statistics samples of neutral B's in flavor specific decays
    - $J/\psi K$, $D\pi$, $D3\pi$, $l\nu DX$
  - Proper decay length reconstruction
    - Fully reconstructed modes provide better accuracy
  - Tagging of flavor at production (flavor tagging)
    - Key problem at the Tevatron!
    - Equivalent statistical power: $N\,\varepsilon D^2$
      - **ε = tagger efficiency**
      - **D = tagger dilution = $2*\eta-1$ (η = probability of correct tag)**

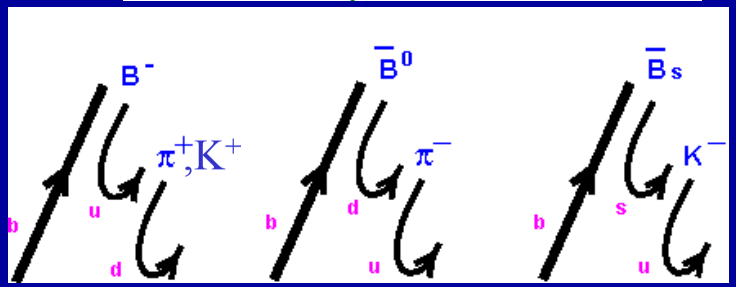


- Measure: $A(t) = (N_{nm}-N_m)/N = D\cos(\Delta m\, t)$
  - N_{nm} (N_m): number of B's with same (different) flavor at production and decay
  - Mixing measurement calibrates dilution

Flavor tagging

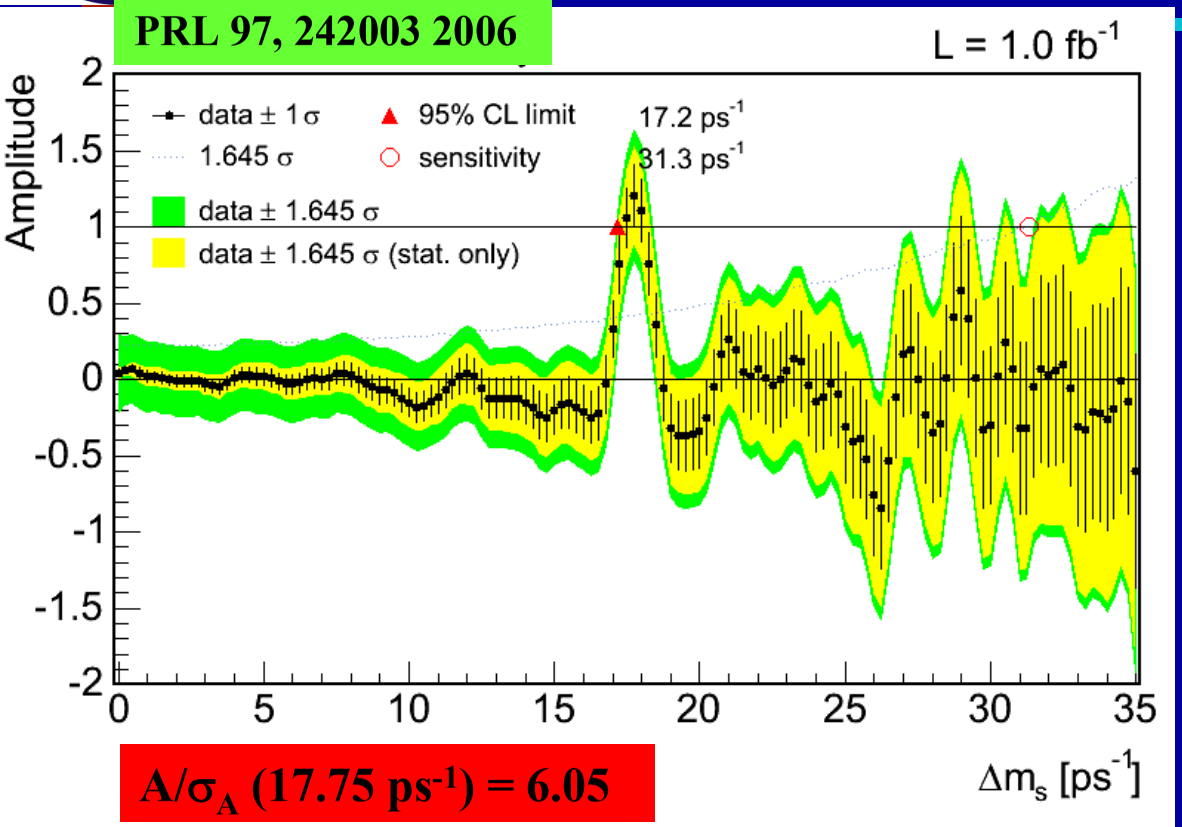
- Opposite side techniques (OST):
  - total $\varepsilon D^2 \sim 1.2\ \%$
    - Soft Muon Tag
    - Soft Electron Tag
    - Jet Charge Tag
- Same side techniques (SST):
  - Sign of nearby track is correlated to b type (SST)
    - Tagging power depends on B type
    - PID helps for B_s
    - **$\varepsilon D^2 \sim 3.6\%$** in B_s





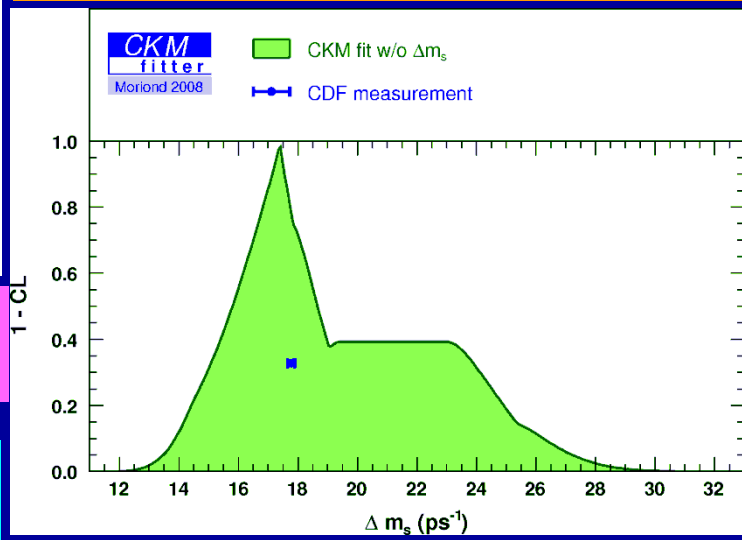
B_s Mixing: $|M_{12}|$ and Δm_s

PRL 97, 242003 2006



A/σ_A (17.75 ps^{-1}) = 6.05

- 5600 fully, and 3100 partially reconstructed hadronic B_s decays
- 61500 partially reconstructed semileptonic B_s decays

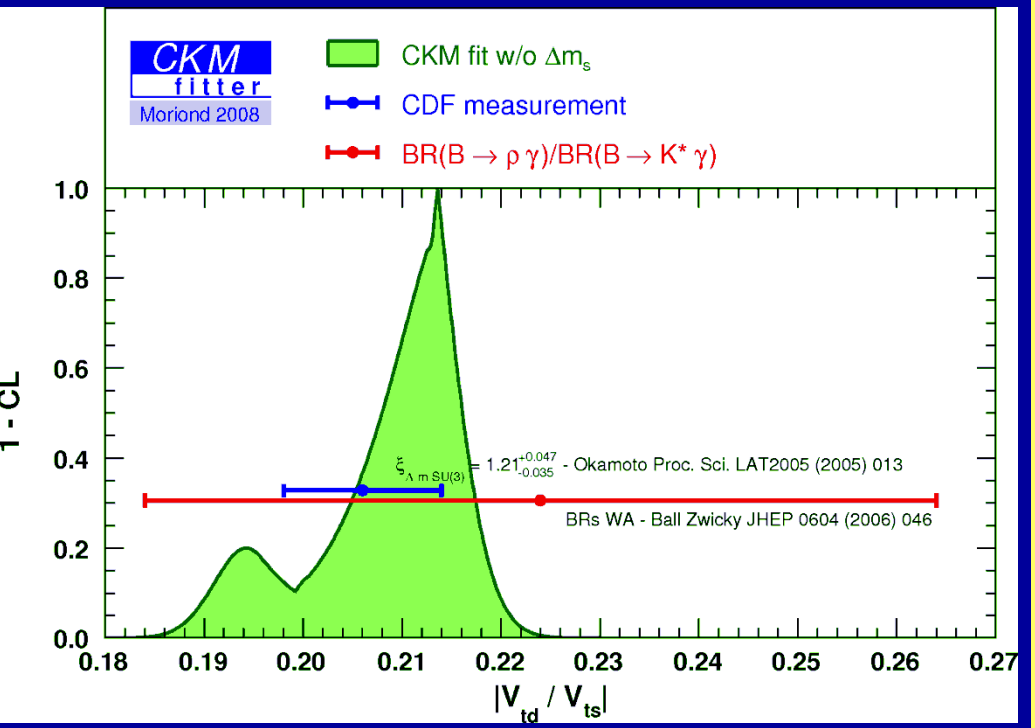


$$\Delta m_s = 17.77 \pm 0.10\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{ps}^{-1}$$

- 8×10^{-8} probability that random fluctuations could produce a comparable signal (>5σ)

B_s Mixing: Constraints

PRL 97, 242003 2006



- use measured Δm_s to constrain CKM

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B_s}}{m_{B_d}}}$$

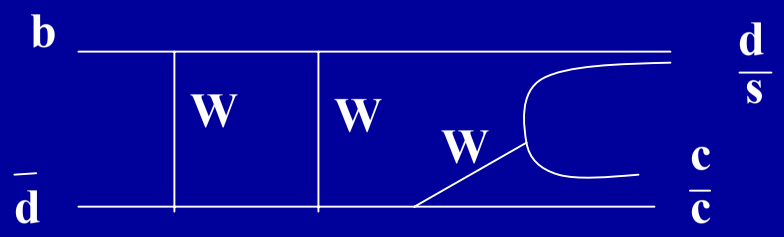
$$= 0.2060 \pm 0.0007\,(\text{exp})\,{}^{+0.0081}_{-0.0060}(\text{theor})$$

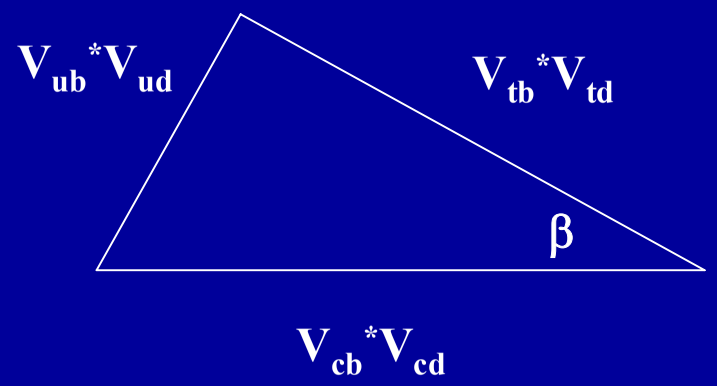
- agrees with SM prediction
- x5 more precise than previous determination
- limited by Lattice uncertainty

Similarities between the decays $B^0_s \to J/\psi\,\phi$ and $B^0 \to J/\psi\,K^{0*}$

Measuring the bd unitarity triangle :

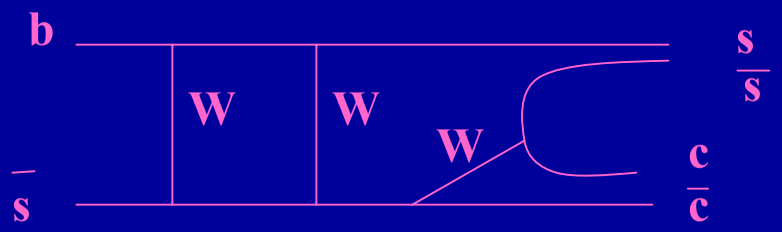
$B^0 \to J/\psi\, K^{0*}$

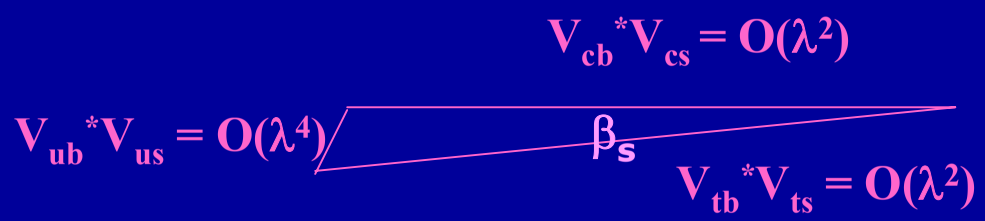




Measuring the bs unitarity triangle:

$B_s^0 \to J/\psi\, \phi$





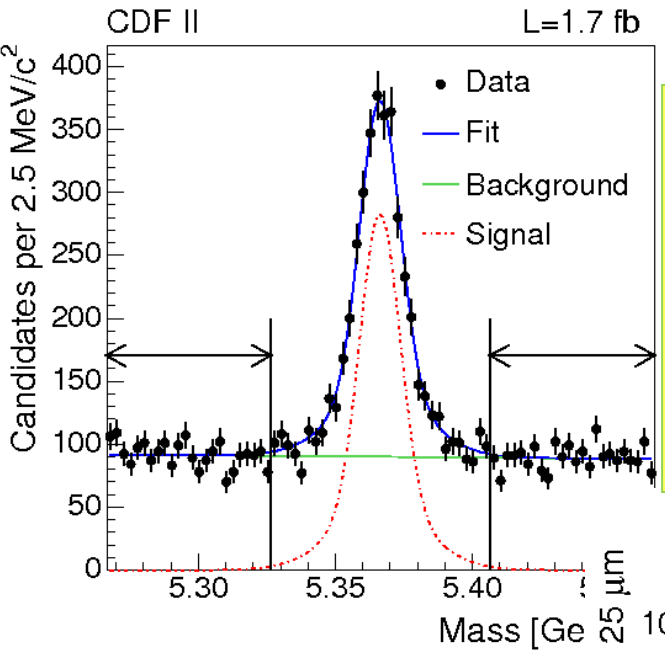
$2\beta_s = -\varphi_s$

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

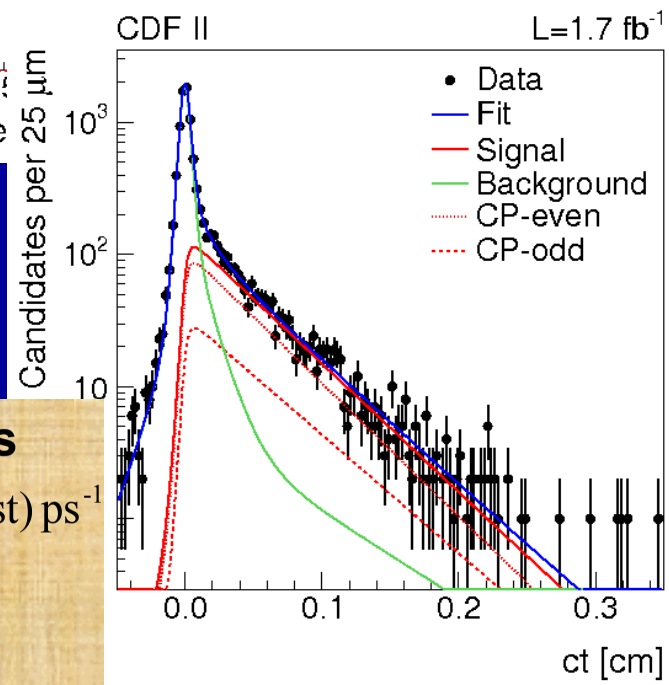
$B_s^0 \to J/\psi\,\varphi$: τ_s and $\Delta\Gamma_s$ (assume $\beta_s = 0$)

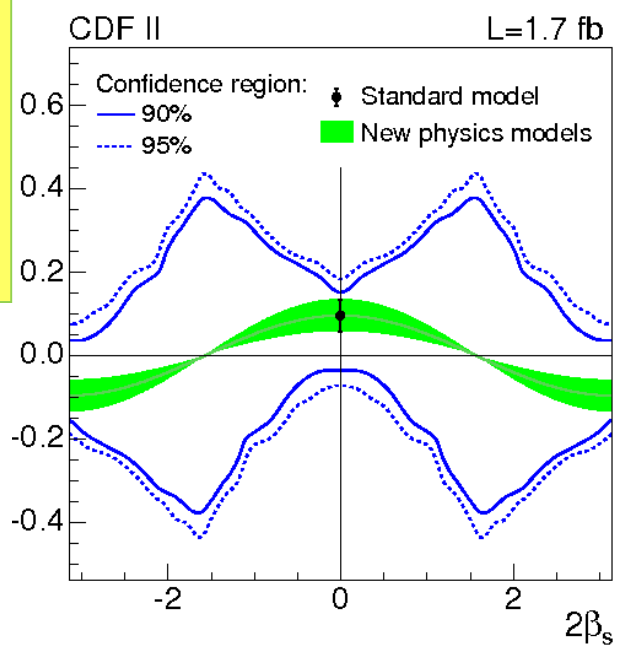
PRL 100, 121803 2008

~2,500 signal events (untagged)



The final state is a mixture of CP-even and CP-odd states that are distinguished by using the angular distributions of the decay products.





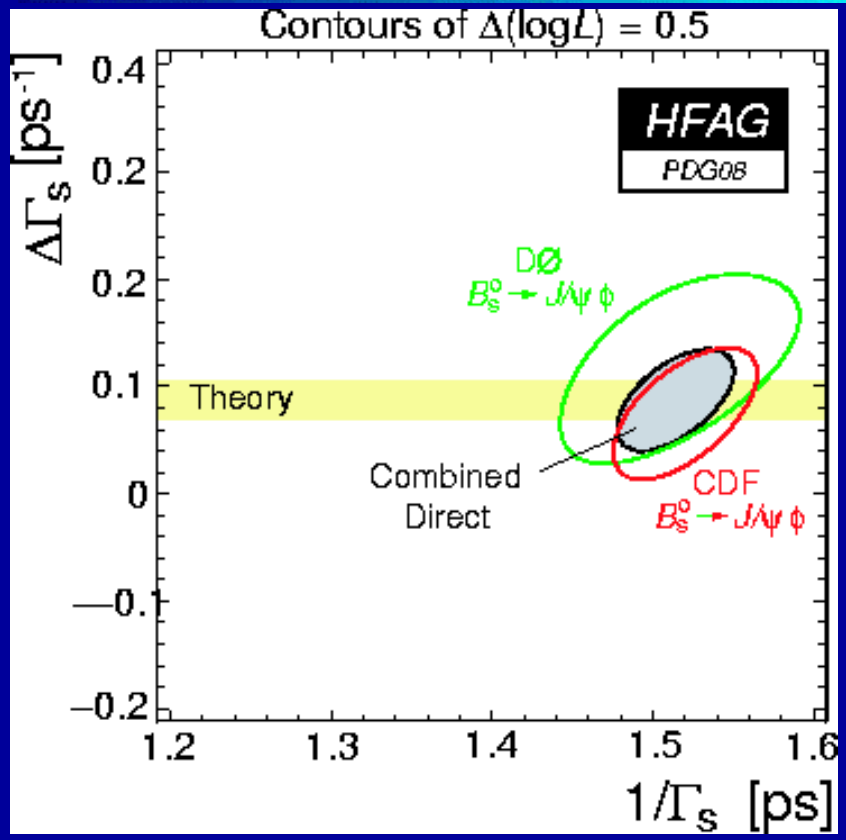
$\tau_s = 1.52 \pm 0.04 \pm 0.02$ ps

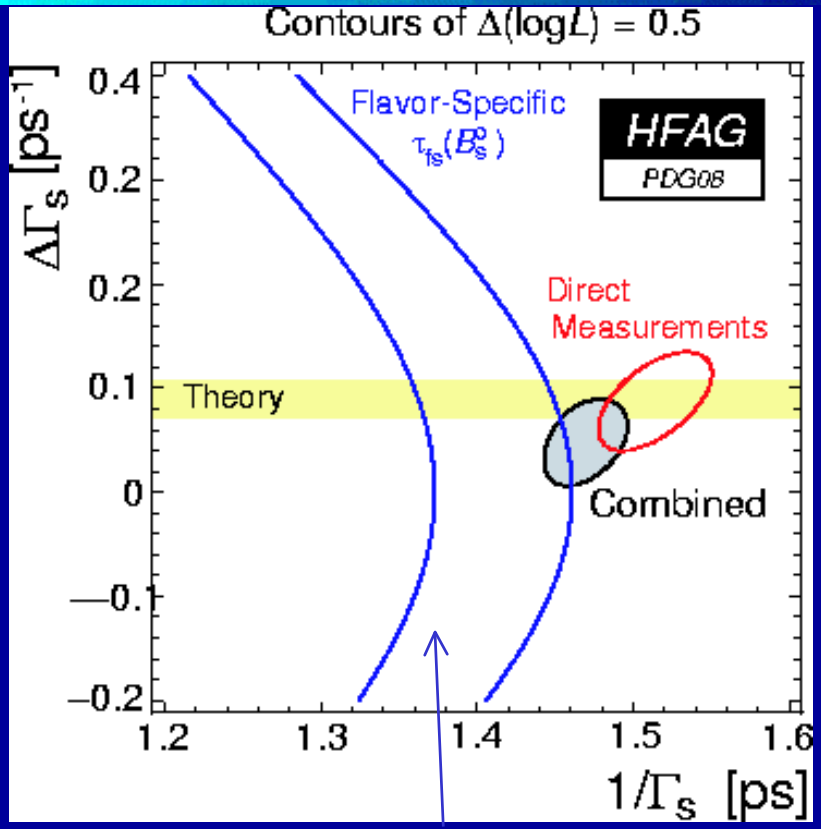
$\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$

PRL 100, 121803 (2008)

World's best measurement

Status of $\Delta\Gamma_s$





In the SM it is predicted that:

$$\Delta\Gamma_s = 2|\Gamma_{12}| \cdot \cos(2\beta_s) = 0.096 \pm 0.039\,\text{ps}^{-1}$$

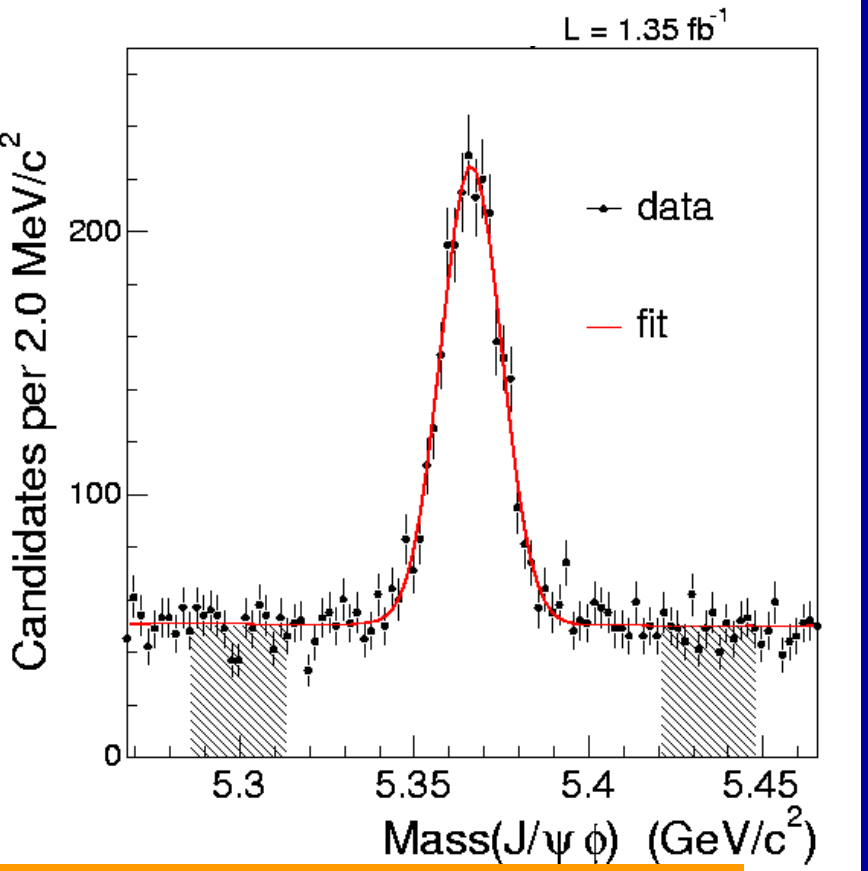
Lenz, Nierste: J. High Energy Phys. 0706, 072 (2007)

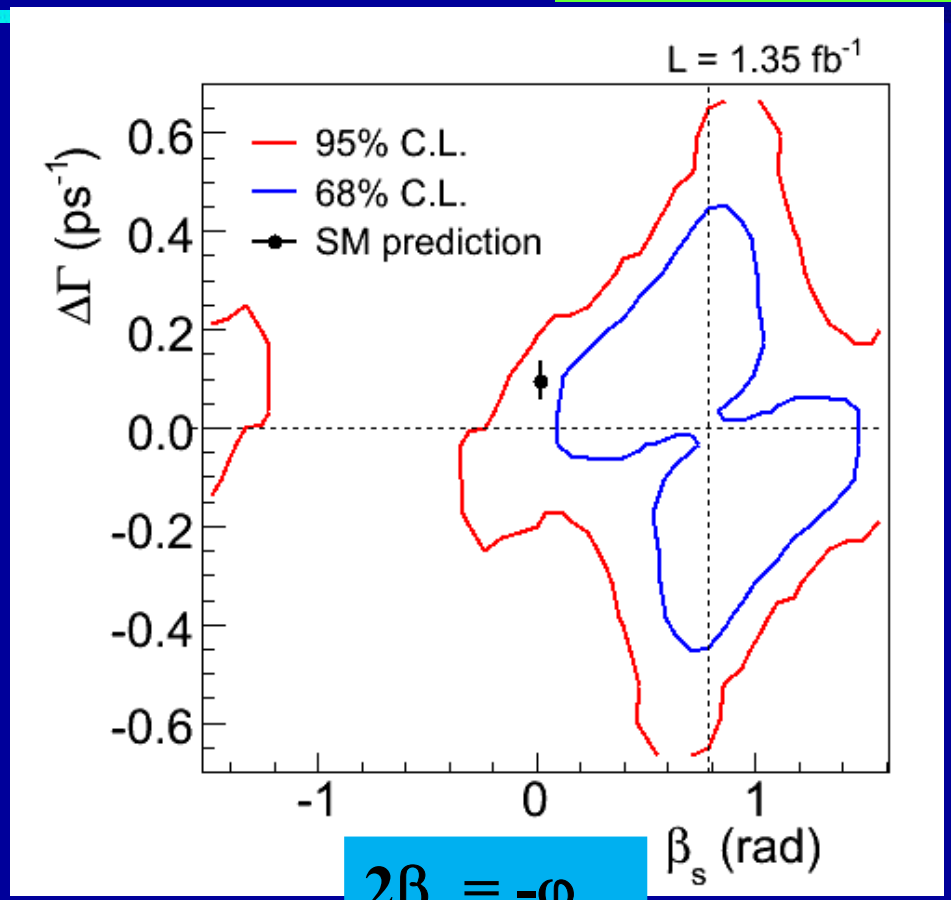
Mostly Tevatron results.
The latest CDF τ_s measurement as well as input from the D0 $B_s \to D_s^{(*)} D_s^{(*)}$ analysis not included yet.

Fit for β_s

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

PRL 100, 161802 2008





$2\beta_s = -\varphi_s$

2019±73 signal events (tagged)

Assuming the SM values of:

$$2\beta_s = 0.04, \Delta\Gamma_s = 0.096\,\text{ps}^{-1}$$

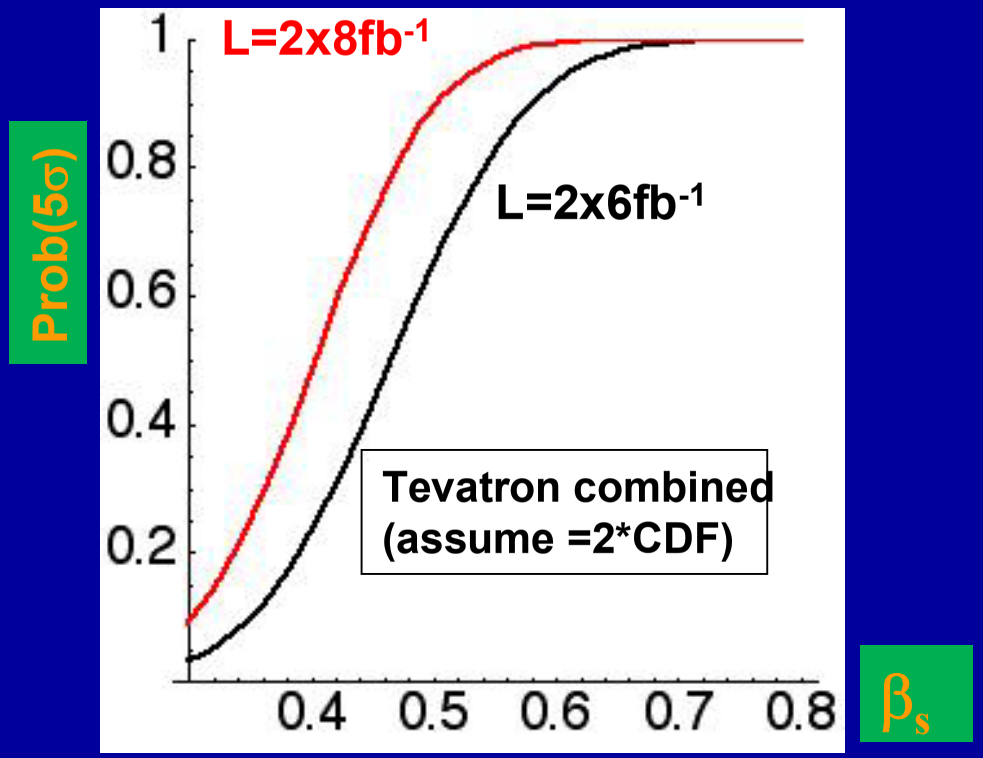
P-value: 0.15 (1.5 σ)

Fitting only for $2\beta_s$: $2\beta_s \in [0.32, 2.82]$ at 68% CL

Vaia Papadimitriou

Tevatron outlook for β_s

- This assumes no analysis improvements, and no external constraints, but same signal yield and experimental resolution.
- Further improvements can be realized by adding more signals (triggers) or by tagging improvements.



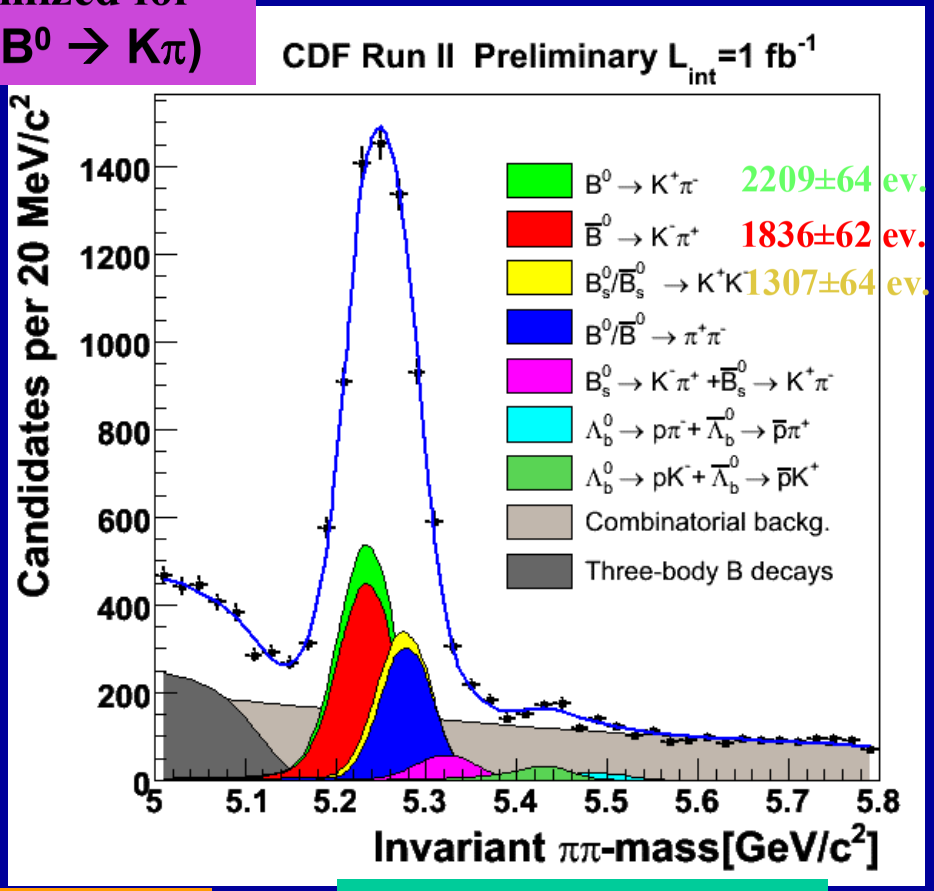
If $\beta_s \geq 0.4$, the Tevatron can discover New Physics

$B^0 \to h^+ h'^- \quad (h, h' = \pi \text{ or } K)$

Optimized for $A_{CP}(B^0 \to K\pi)$

- Exploit the two-track trigger sample.
- Combine mass, kinematics and PID in an unbinned maximum likelihood fit to extract the fraction of each of the expected components.
- P_T(track) > 2 GeV/c; K/π separation of 1.4σ.

  1.4σ ⟶ 1.6σ by including TOF information.



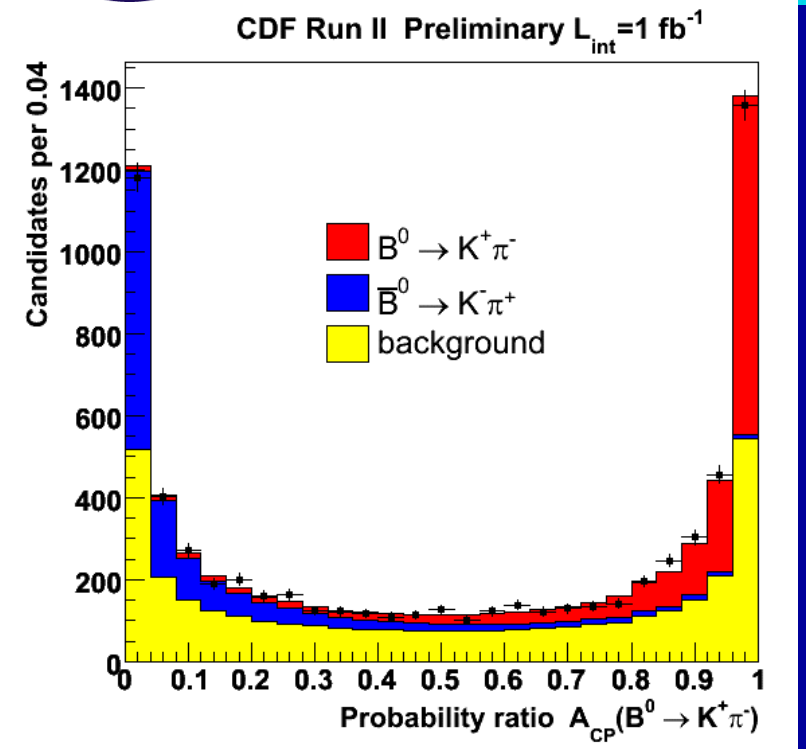
6509 ± 159 events
σ = 39 ± 0.8 MeV/c²

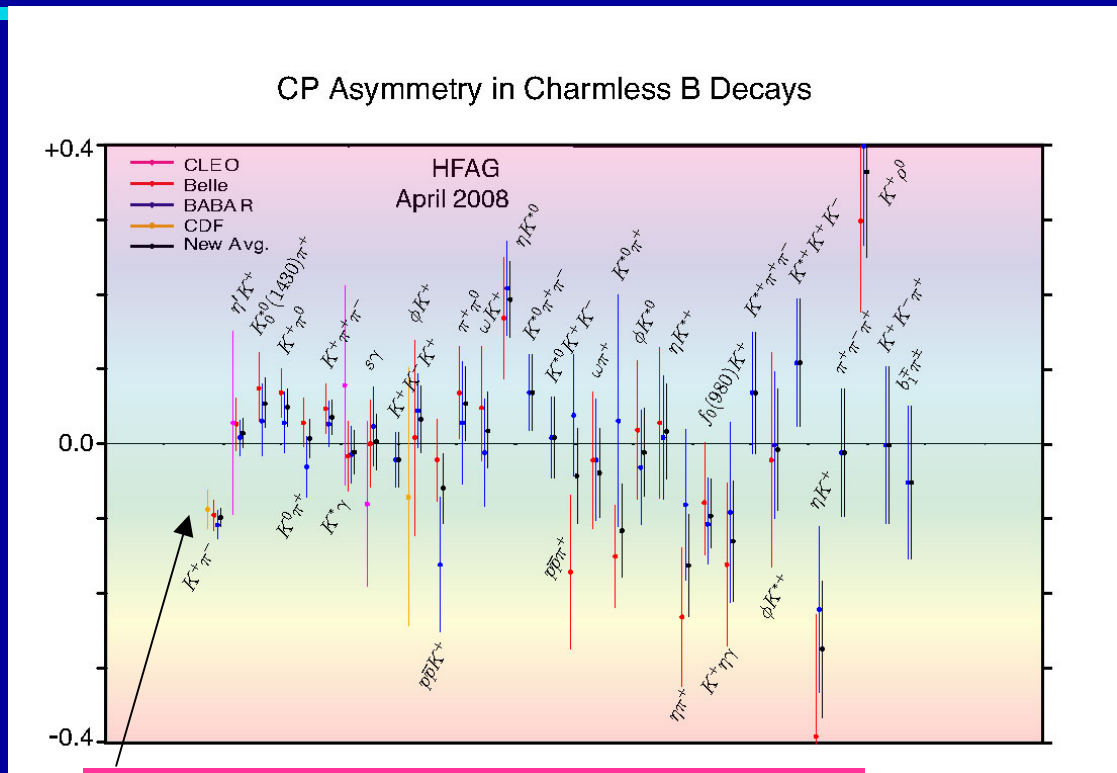
$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.259 \pm 0.017(stat.) \pm 0.016(syst.)$$

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} = 0.020 \pm 0.008(stat.) \pm 0.006(syst.)$$

$$Br(B^0 \to K^+K^-) < 0.7 \times 10^{-6}$$

Direct CP Violation at the Tevatron



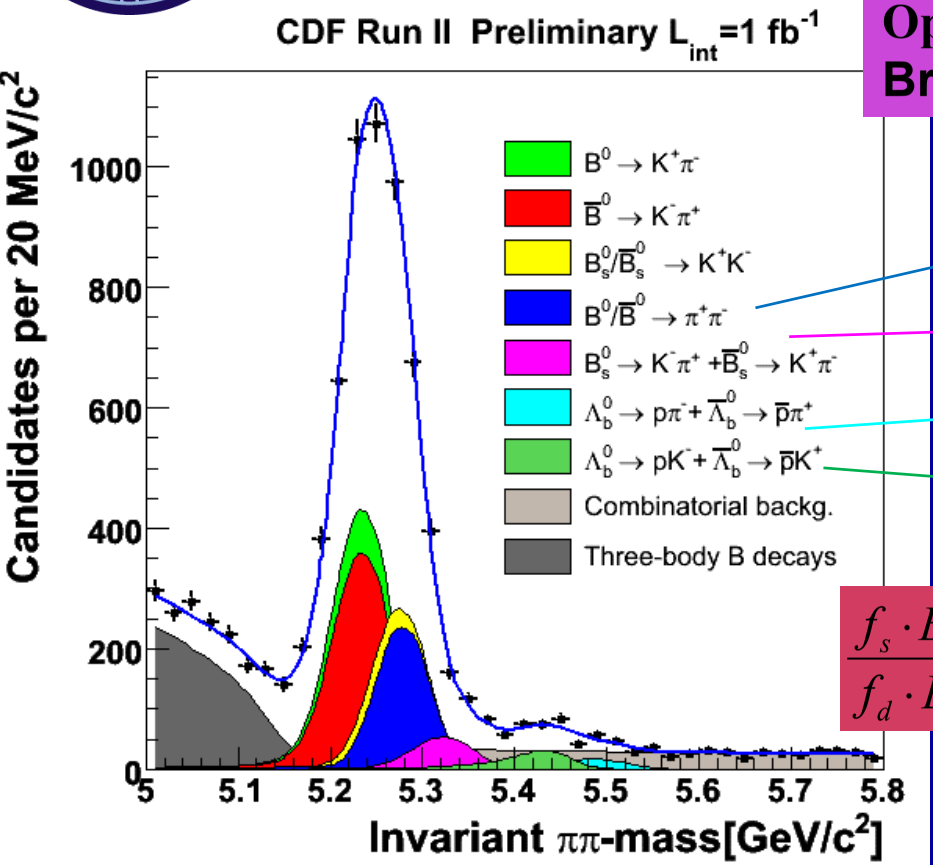


Already significant contribution to $A_{CP}(B^0 \to K\pi)$ from CDF (1fb^{-1})

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

Expect improved measurement from the Tevatron with increasing statistics.

$B_s^0 \to h^+ h'^- \quad (h, h' = \pi \text{ or } K)$



Optimized for $Br(B_s^0 \to K\pi^+)$

mode	events	significance
$B_s^0 \to \pi^+\pi^-$	$26 \pm 16 \pm 14$	1.5σ
$B_s^0 \to K^-\pi^+$	$230 \pm 34 \pm 16$	8.2σ
$\Lambda_b^0 \to p\pi^-$	$110 \pm 18 \pm 16$	6.0σ
$\Lambda_b^0 \to pK^-$	$156 \pm 20 \pm 11$	11.5σ

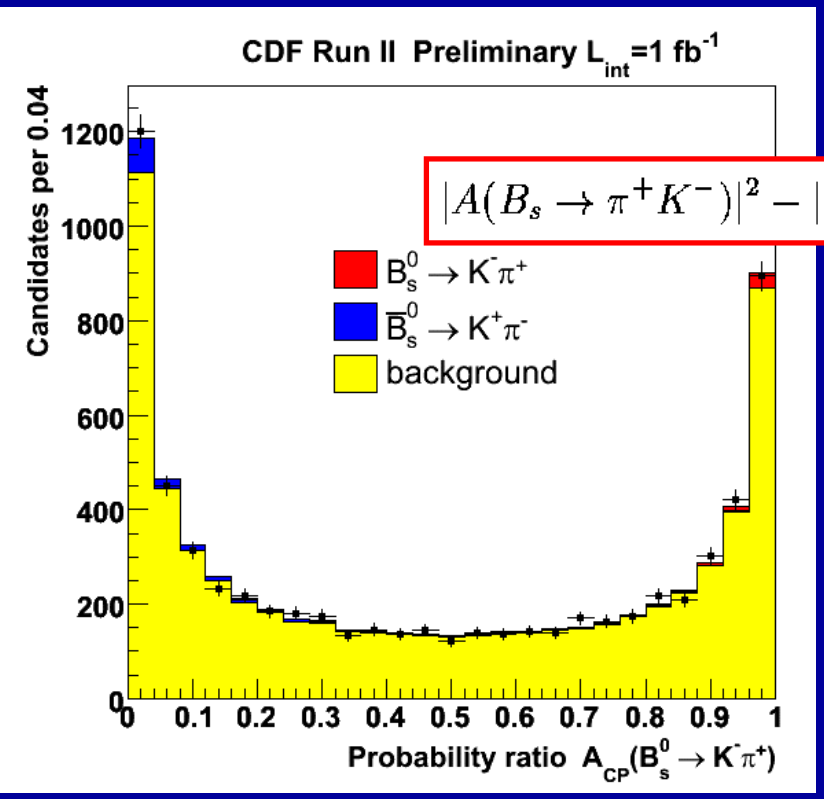
$$\frac{f_s \cdot BR(B_s^0 \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.071 \pm 0.010(\text{stat.}) \pm 0.007(\text{stat.})$$

$$\frac{f_s \cdot BR(B_s^0 \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.347 \pm 0.020(stat.) \pm 0.021(syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to \pi^+\pi^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.007 \pm 0.004(stat.) \pm 0.005(syst.)$$

$$Br(B_s^0 \to \pi^+\pi^-) < 1.3 \times 10^{-6}$$

Direct CP Violation in the B_s



According to:
Gronau ,Rosner PRD 71, 074019, (2005)
Lipkin, PLB 621:126 (2005)

$$|A(B_s \to \pi^+K^-)|^2 - |A(\bar{B}_s \to \pi^-K^+)|^2 = |A(\bar{B}_d \to \pi^+K^-)|^2 - |A(B_d \to \pi^-K^+)|^2$$

- SM prediction for $A_{CP}(B_s \to K^-\pi^+) = 0.37$

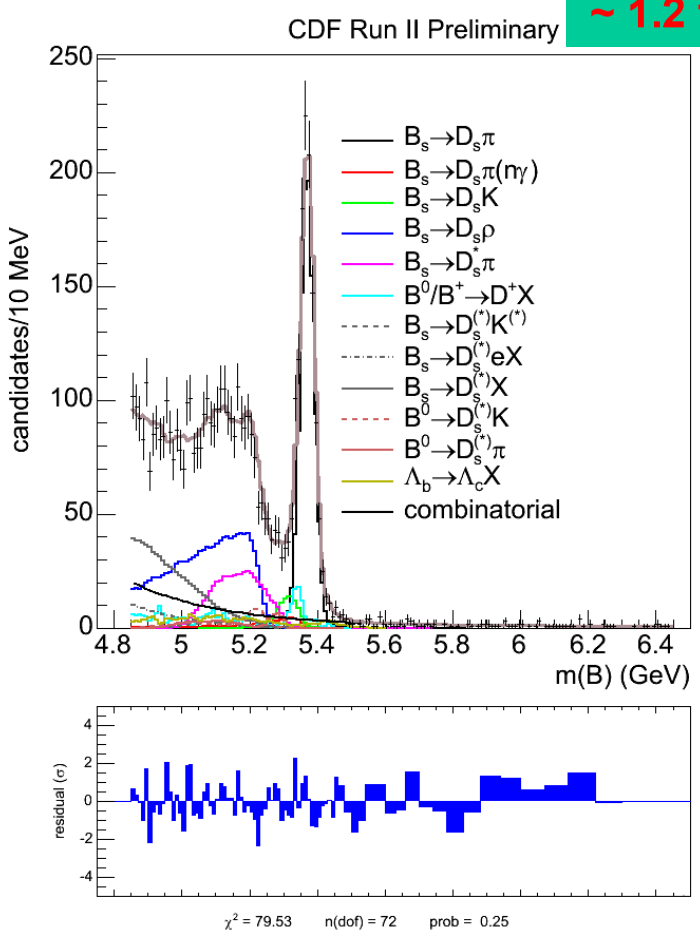
$$A_{CP}(B_s^0 \to K^-\pi^+) = \frac{N(\bar{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\bar{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)} = 0.39 \pm 0.15\,(\text{stat}) \pm 0.08\,(\text{syst})$$

The first measurement of direct CP violation in the B_s meson system. Significance of 2.5 σ and consistent with SM expectations.

First observation of the decay $\overline{B}_s^0 \to D_s^{\pm} K^{\mp}$

$D_s^{\pm} \to \varphi\pi^{\pm}; \varphi \to KK$

~ 1.2 fb^{-1}



This decay is interesting in the context of studying the interference between:

$$\overline{B}_s^0 \to D_s^+ K^- \text{ and } \overline{B}_s^0 \to D_s^- K^+$$

as well as for the study of angle γ through a time dependent , flavor-tagged analysis.

Measure branching fraction with respect to the Cabibbo-favoured mode.

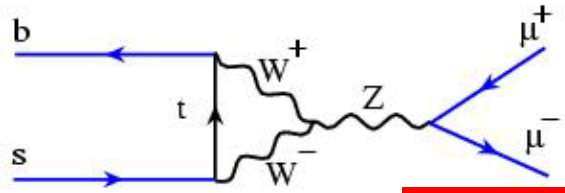
$$\frac{Br(\overline{B}_s^0 \to D_s^{\pm} K^{\mp})}{Br(\overline{B}_s^0 \to D_s^{+} \pi^{-})} = 0.107 \pm 0.019(\text{stat}) \pm 0.008(\text{syst})$$

Signal: 109 ± 19 (stat.) (7.9σ)

Result consistent with the analogous B^0 mode.

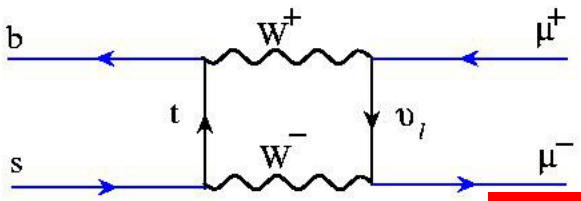
$B_{s(d)} \rightarrow \mu\mu$

Sensitive probe of New Physics

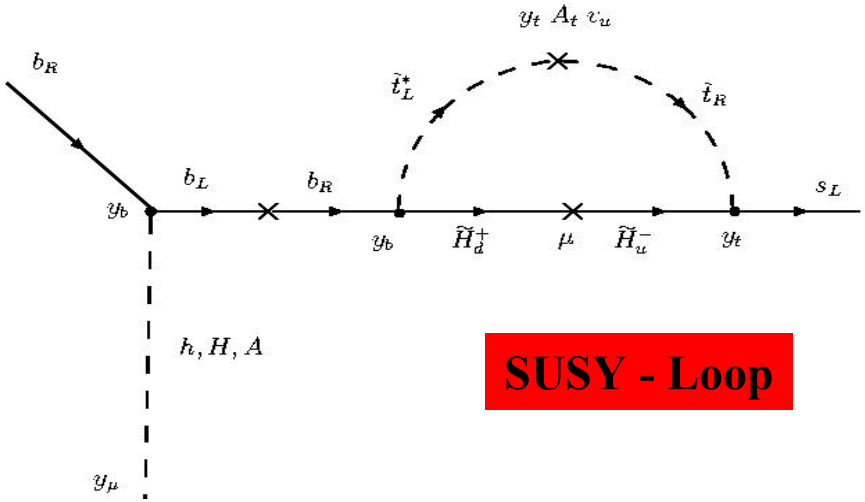


SM penguin

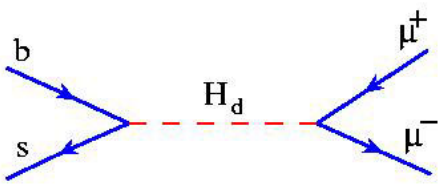
BR prediction: (3.5±0.9) x 10^{-9}



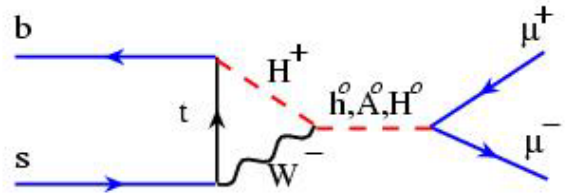
SM box



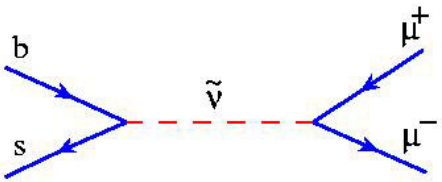
SUSY - Loop



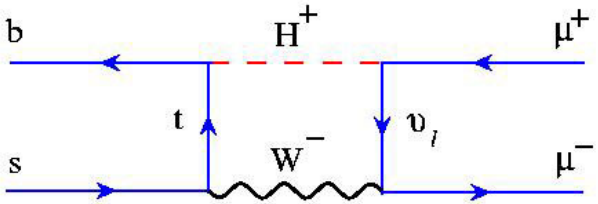
Higgs mediated - tree



2HDM - penguin



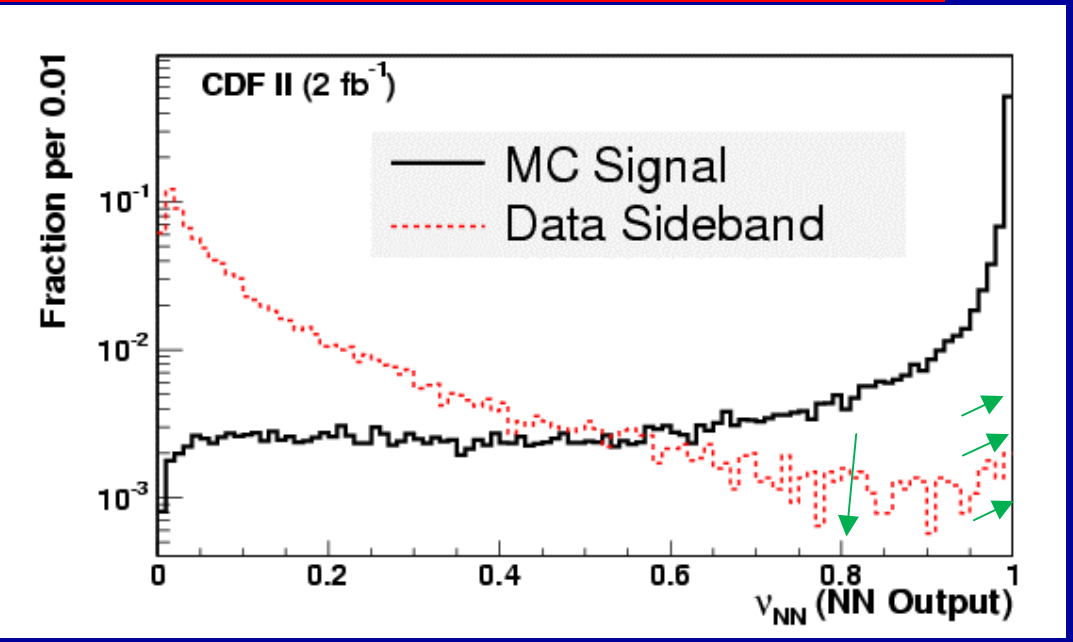
R parity violating



2HDM - box

$B_{s(d)} \rightarrow \mu^+\mu^-$

Multi-variate Neural Network Discriminant



$$p_T^{\mu\mu} > 4\,\mathrm{GeV/c}$$

Normalize with the decay

$$B^{\pm} \rightarrow J/\psi\, K^{\pm}$$

N_{bkg} expected: 2.08±0.22
ses: (9.5±0.7) x 10^{-9}

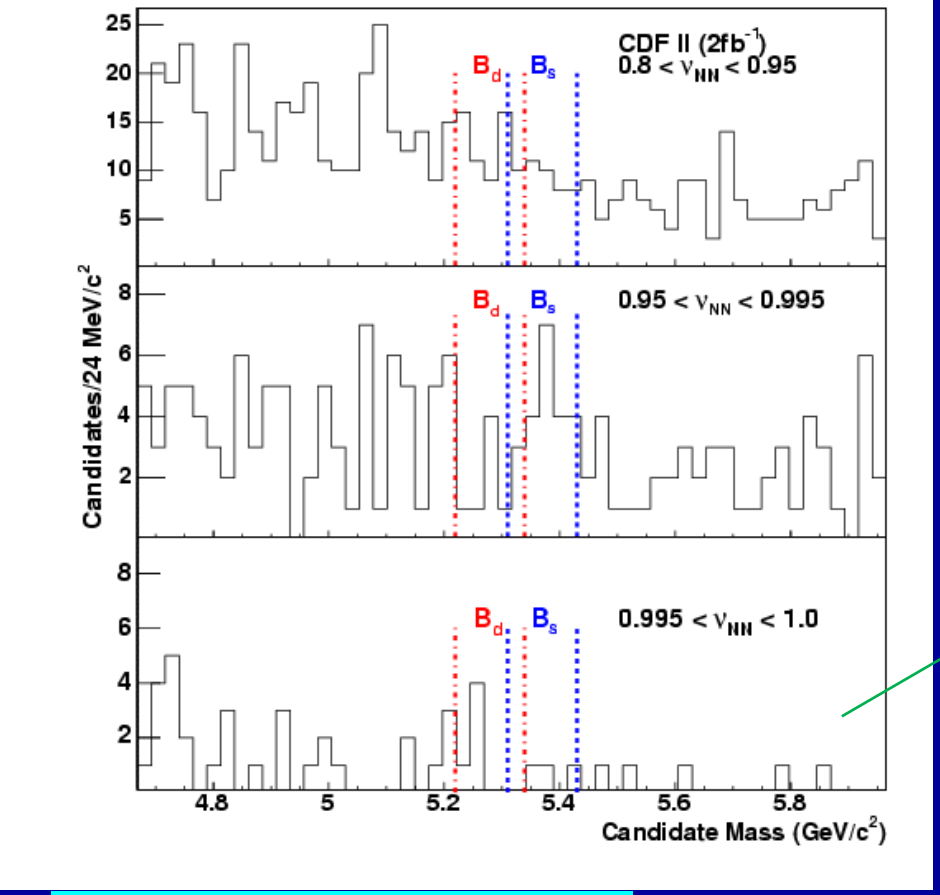
CMU-CMU

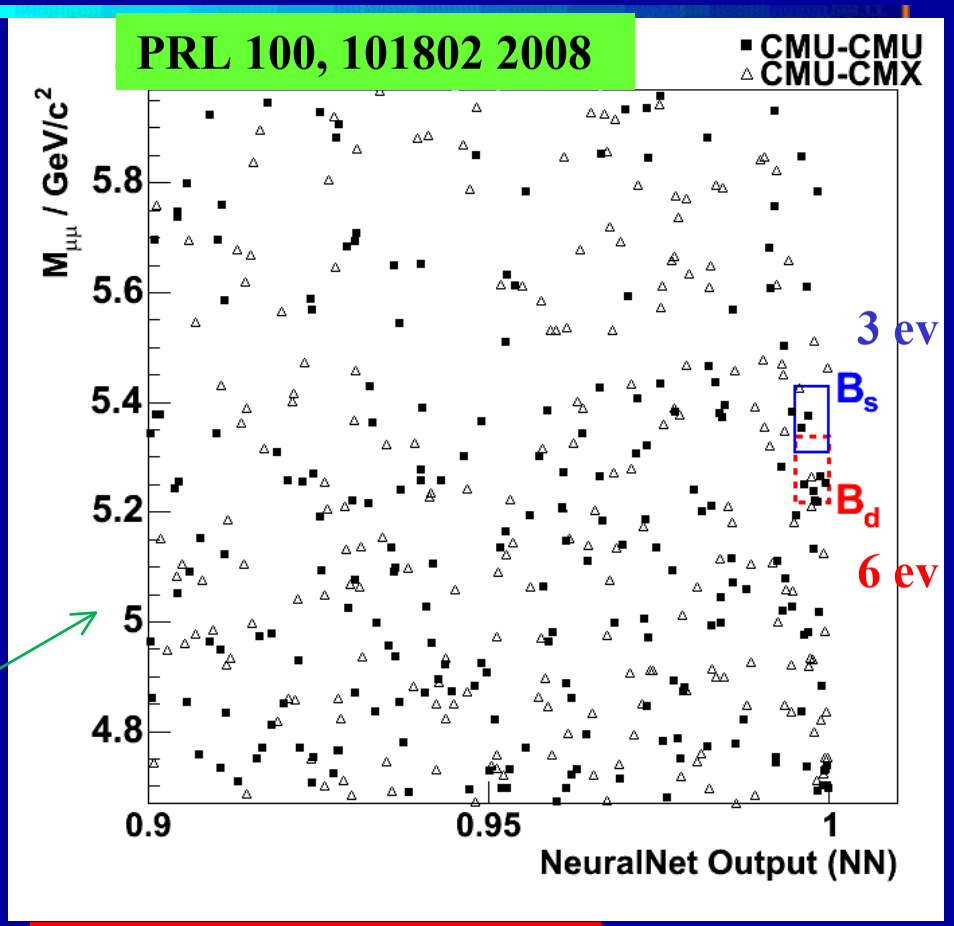
N_{bkg} expected: 1.56±0.22
ses: (1.5±1.0) x 10^{-8}

CMU-CMX

$$B_s^0 \rightarrow \mu\mu$$

$B_{s(d)} \rightarrow \mu\mu$





$BR(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8}$ **95% CL**

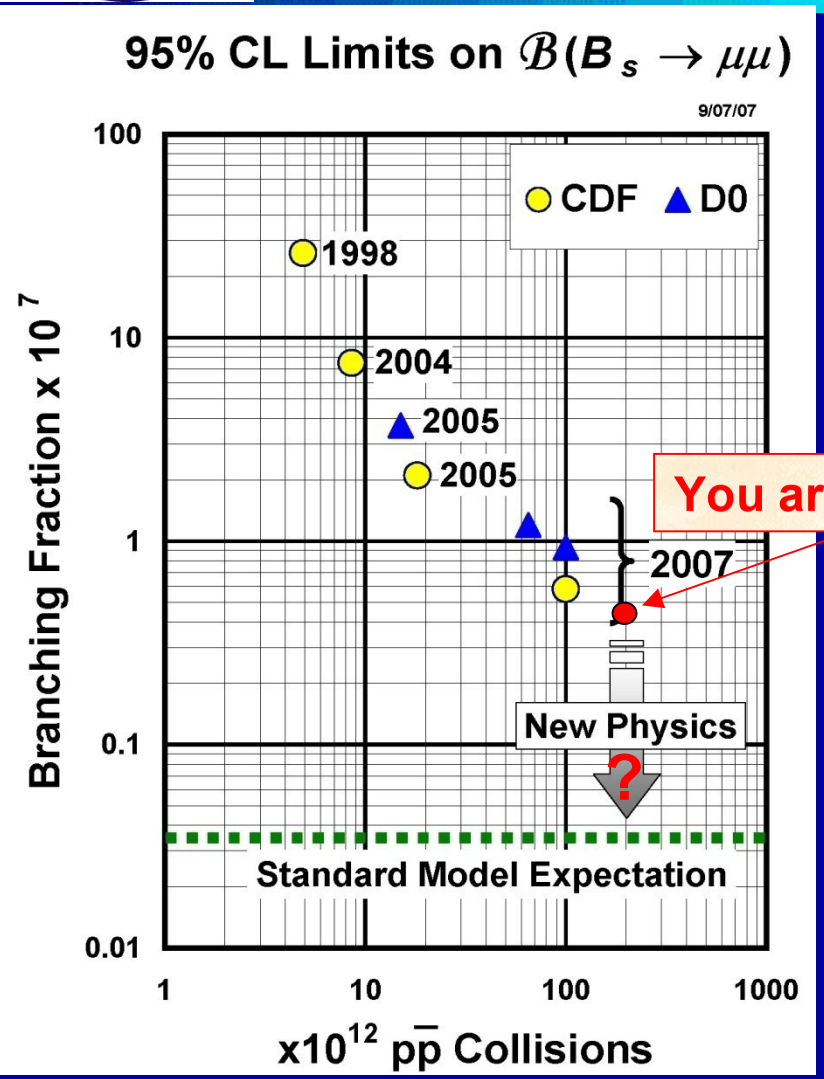
$BR(B_s \rightarrow \mu\mu) < 4.7 \times 10^{-8}$ **90% CL**

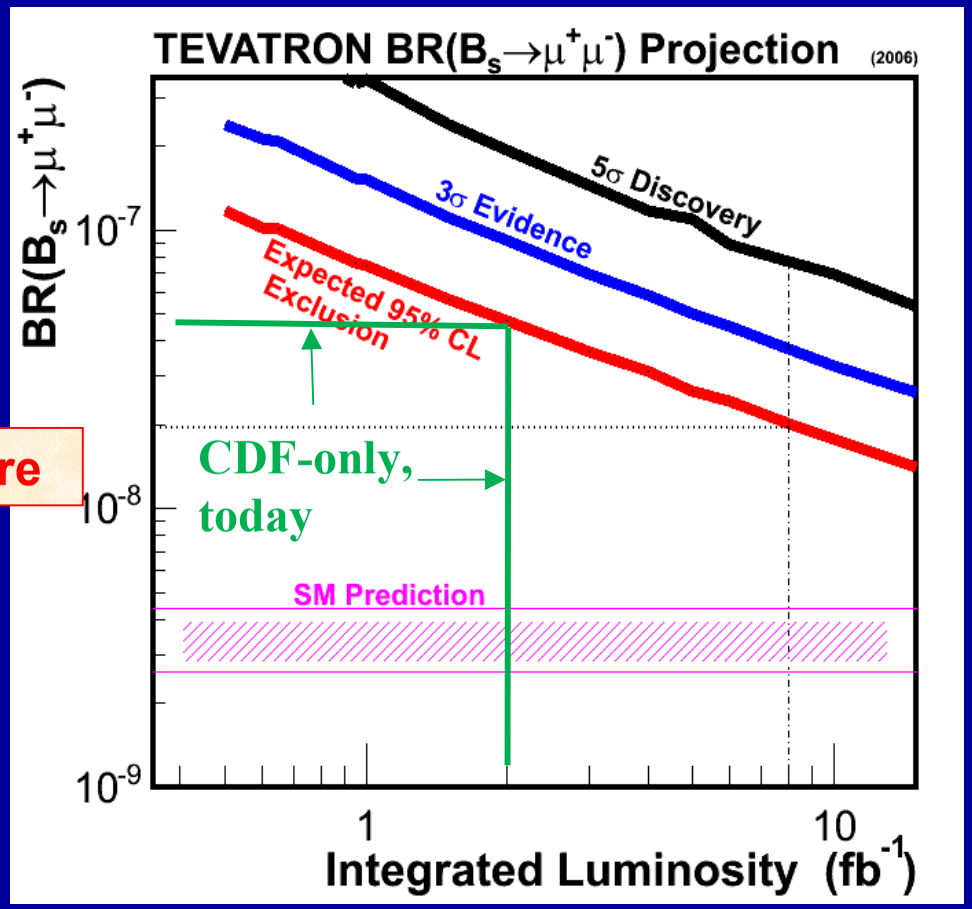
World's most stringent limit

$BR(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-8}$ **95% CL**

$BR(B_d \rightarrow \mu\mu) < 1.5 \times 10^{-8}$ **90% CL**

$B_{s(d)} \rightarrow \mu\mu$



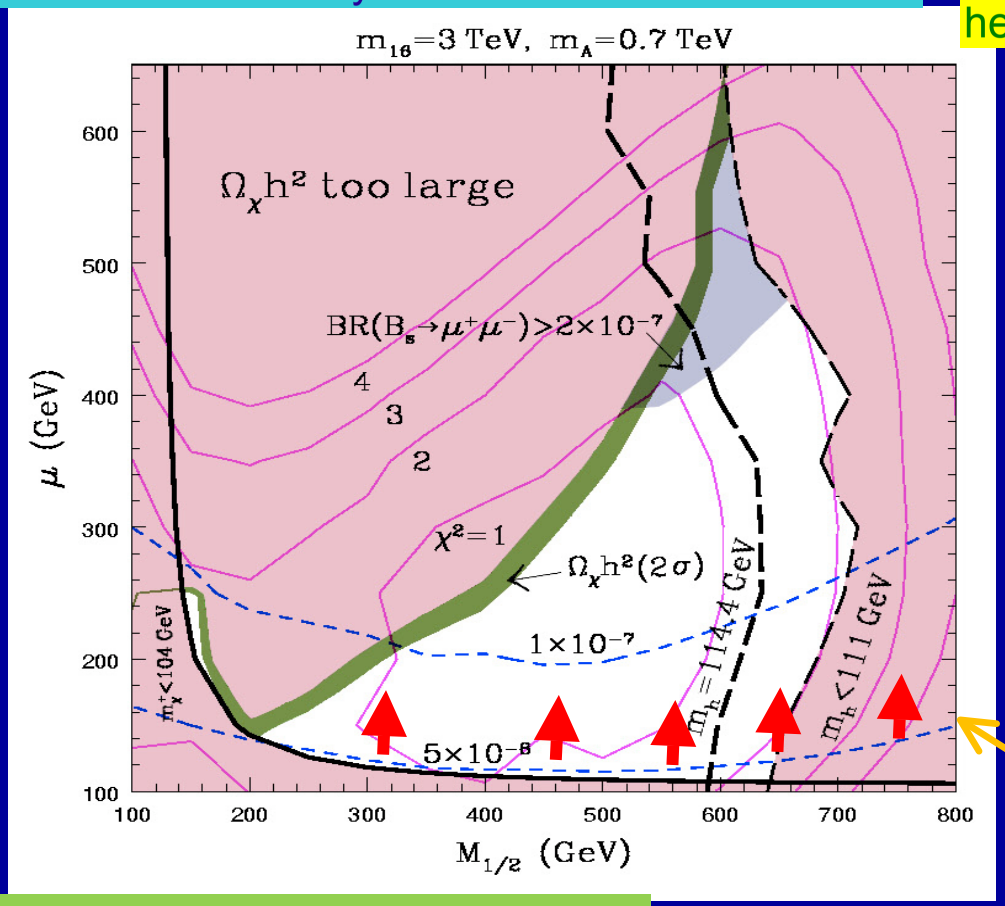


2×10^{-8} is reachable with 8 fb^{-1} which corresponds to 6xSM (→ 4 x SM with two Experiments)

$B_{s(d)} \rightarrow \mu\mu$: Physics Reach

- SUSY SO(10) Unification
  - Allows for massive neutrino
  - Relic density of cold dark matter

R. Dermisek et al.
hep-ph/0507233



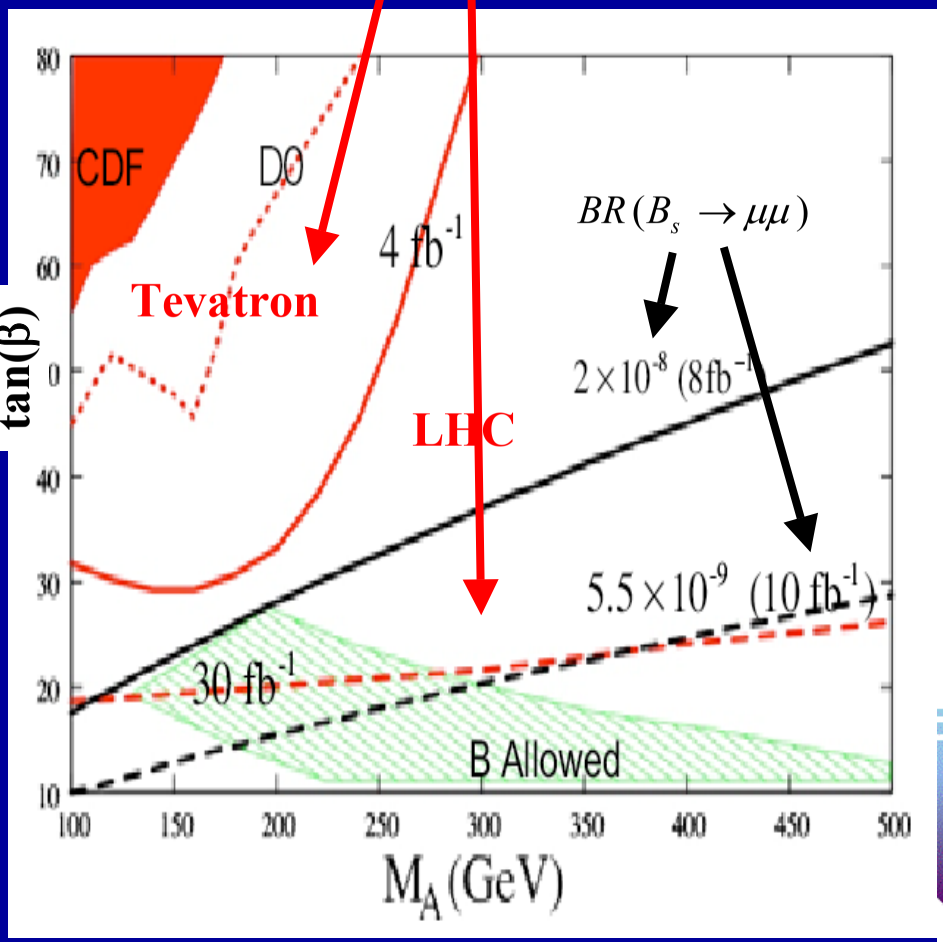
Pink regions are excluded by either theory or other experiments.
Green region is the WMAP preferred region.
Gray region is excluded by previous $B_s \rightarrow \mu\mu$ limit.

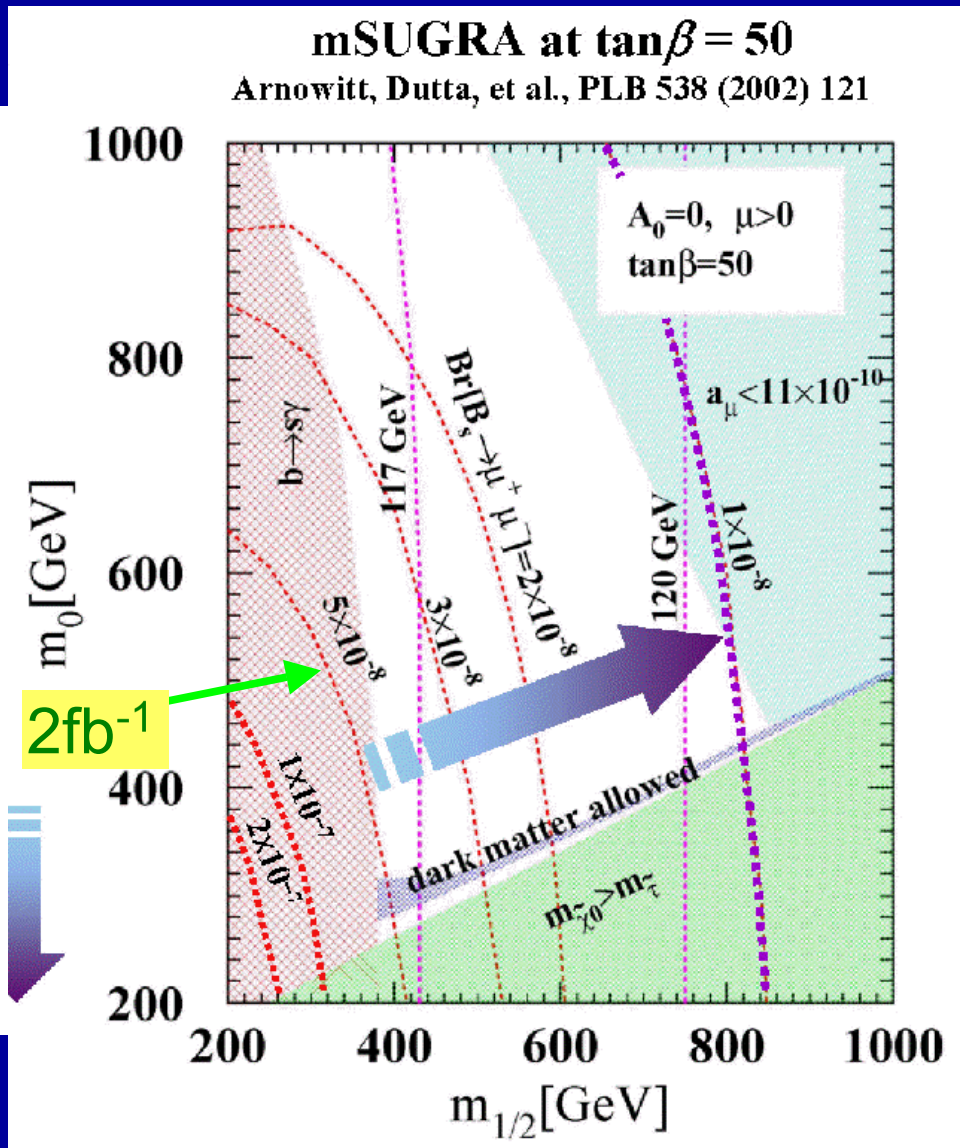
The current $B_s \rightarrow \mu\mu$ limit Is limiting drastically the available space

tan(β)~50 constrained by unification of Yukawa couplings

$B_{s(d)} \to \mu\mu$: Physics Reach

Direct searches of A/H → $\tau^+\tau^-$

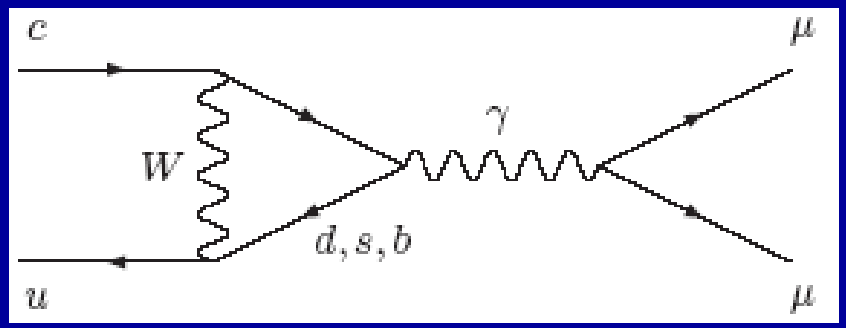


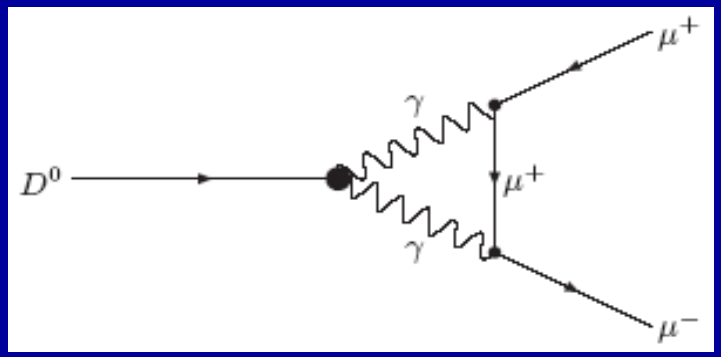


M. Carena et al., PRD 76, 035004 (2007)

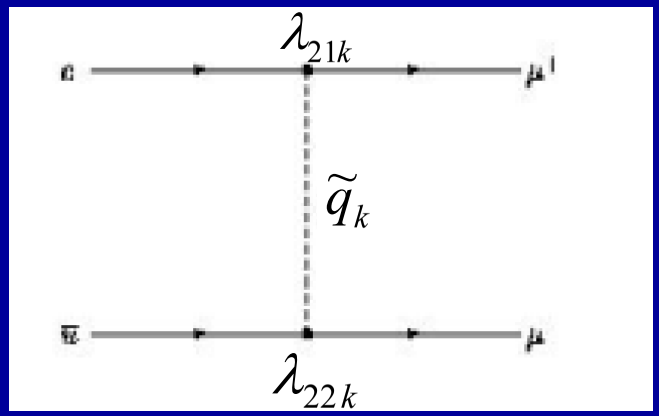
The FCNC decay $D^0 \rightarrow \mu\mu$

In SM, $Br(D^0 \rightarrow \mu^+\mu^-) \geq 4\times10^{-13}$





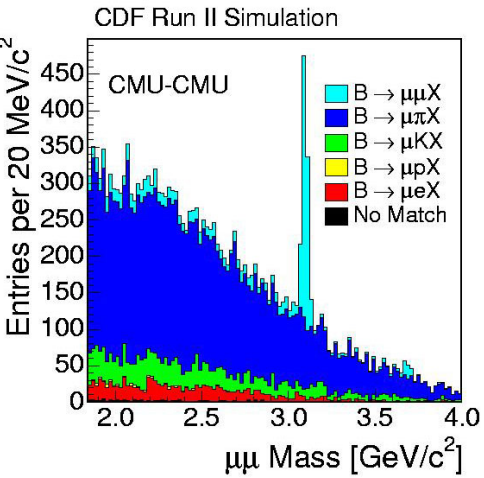
Enhancements possible at R-parity violating SUSY models



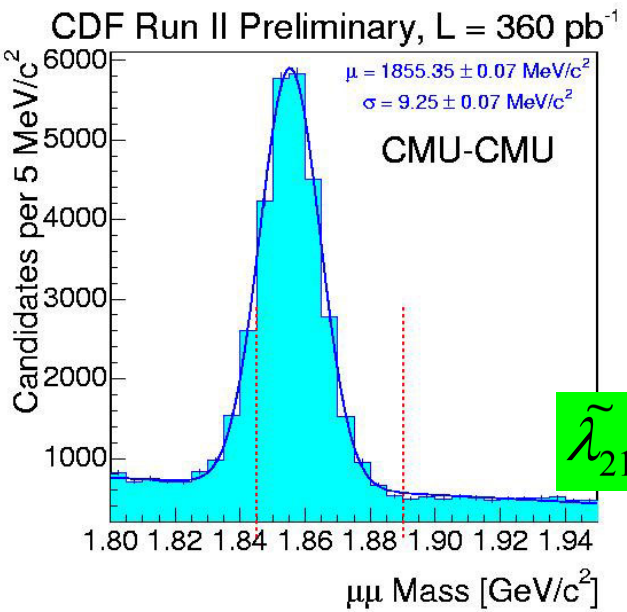
Best current limit from BaBar

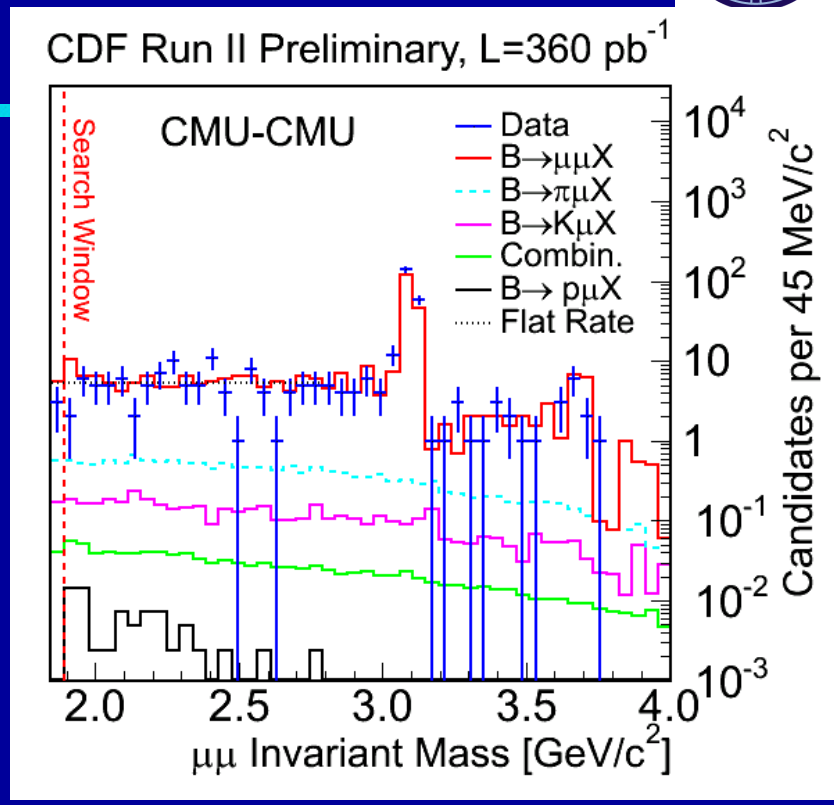
$Br(D^0 \rightarrow \mu^+\mu^-) < 1.3\times10^{-6}$ **90% CL**

$D^0 \rightarrow \mu\mu$



$D_0 \rightarrow K^+\pi^-$ used as a control sample





$$\tilde{\lambda}_{21k} \cdot \tilde{\lambda}_{22k} < 9.8 \times 10^{-4}$$

CMU - CMU : 3 ev. observed (4.9 ± 1.3 bkg)
CMU - CMX : 0 ev. observed (2.7 ± 1.0 bkg)
CMX - CMX : 1 ev. observed (1.0 ± 0.5 bkg)

$D_0 \rightarrow \pi^+\pi^-$ used for normalization

$Br(D^0 \rightarrow \mu^+\mu^-) < 0.43 \times 10^{-6}$ **90% CL** **ses: 6.5 x 10⁻⁷**

$Br(D^0 \rightarrow \mu^+\mu^-) < 0.53 \times 10^{-6}$ **95% CL** **ses: 7.8 x 10⁻⁷**

B_c meson

B_c meson

$B_c^{\pm}$

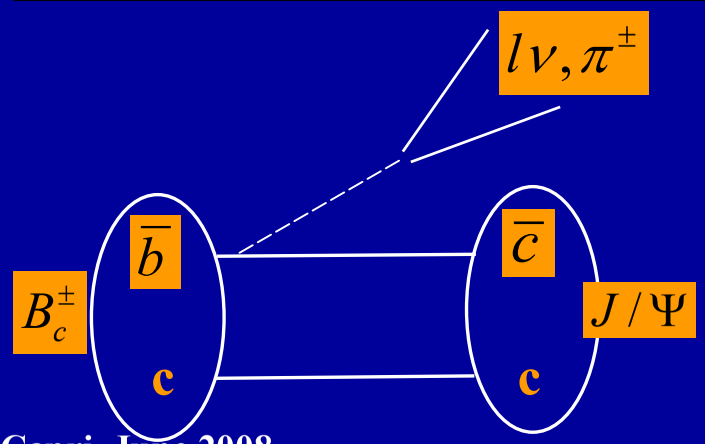
Heaviest ground state of two different quarks

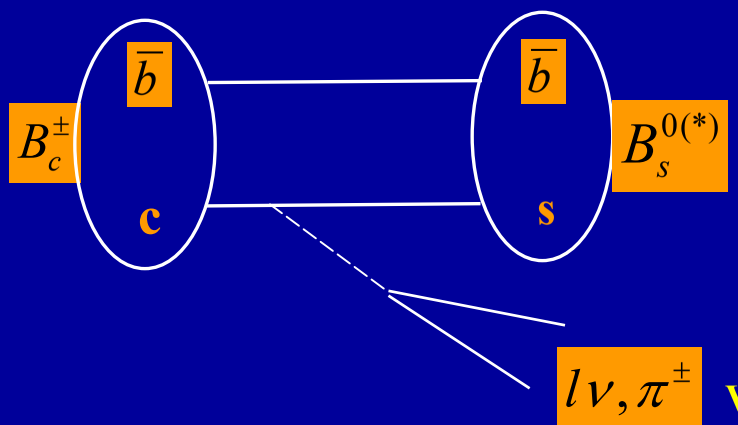
species	~ prod. fraction
$B^{\pm}$	40%
B_0	40%
B_s	10%
b-baryons	10%
B_c	~0.05%

Latest cross section calculation: 7.4 nb
Phys. Lett. B605, 311 (2005)

Rich spectroscopy

It decays weakly





Observation of the decay $B_c^{\pm} \rightarrow J/\Psi\pi^{\pm}$

Evidence and mass measurement

Run II, 360 pb^{-1}

PRL 96, 082002 2006

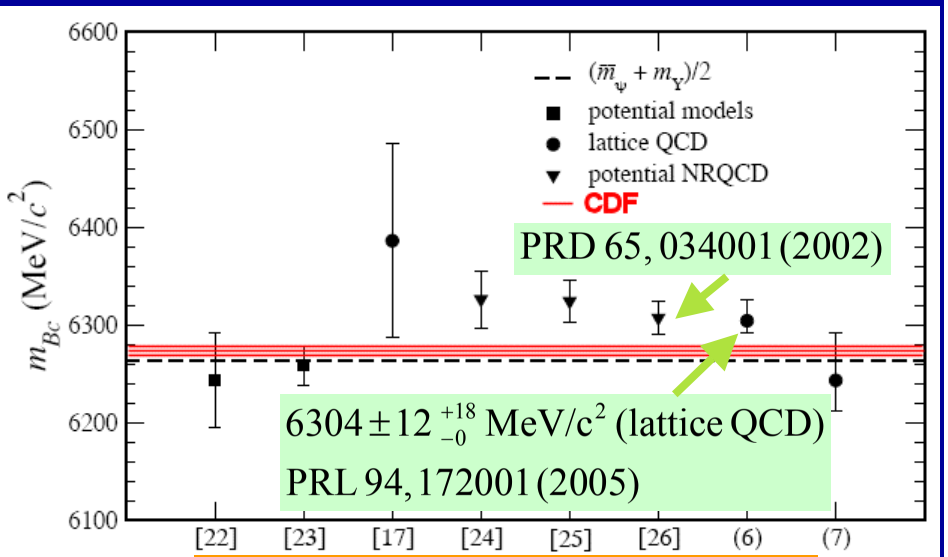
Run II, 2.4 fb^{-1}

PRL 100, 182002 2008

❖ New CDF analysis

➢ control sample 21.1 K

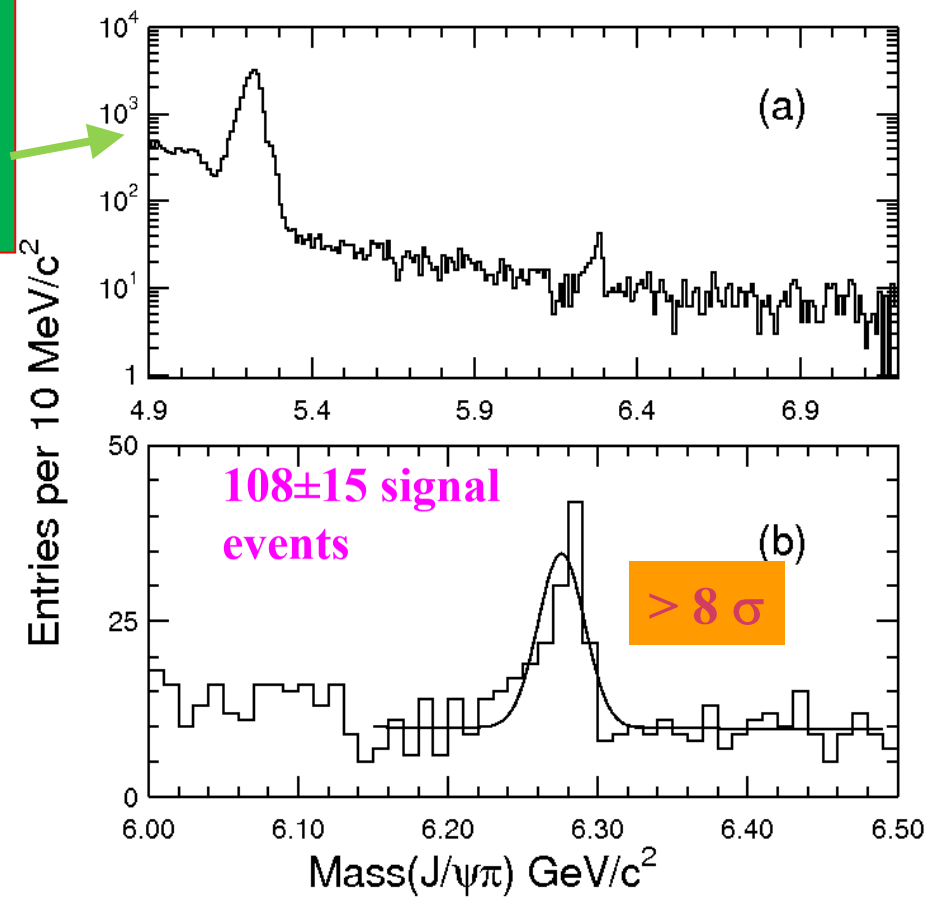
$B_u^{\pm} \longrightarrow J/\psi K^{\pm}$



References for theory models

Theory in relatively good agreement

Potential models, NRQCD, LQCD

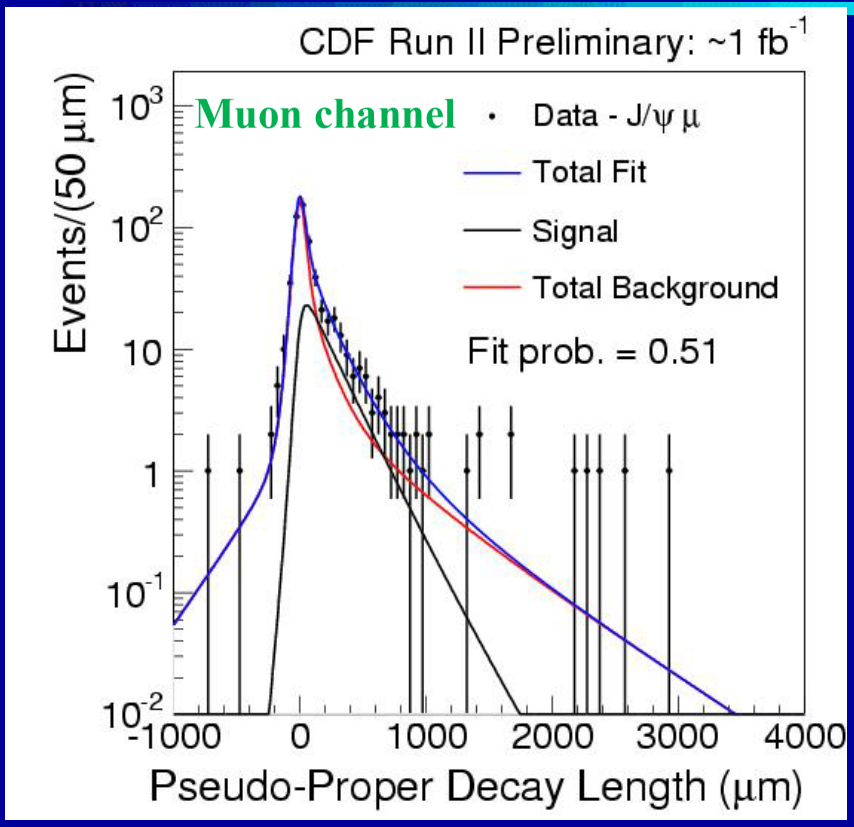


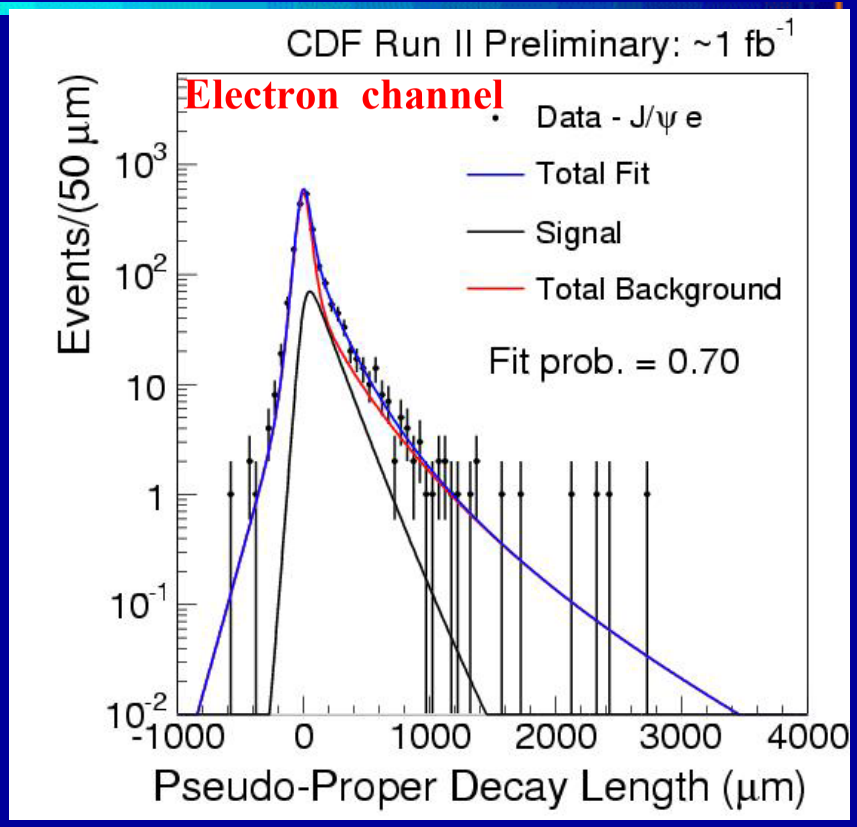
$M(B_c) = 6275.6 \pm 2.9\,(stat) \pm 2.5(syst)$ MeV/c^2

B_c Lifetime

Run II, ~1 fb^{-1}

$$B_c^{\pm} \to J/\psi\, l^{\pm}\nu;\, J/\psi \to \mu\mu$$





$$c\tau = 179.1\,^{+32.6}_{-27.2}\,(\text{stat})\,\mu\text{m}$$

$$c\tau = 121.7\,^{+18.0}_{-16.3}\,(\text{stat})\,\mu\text{m}$$

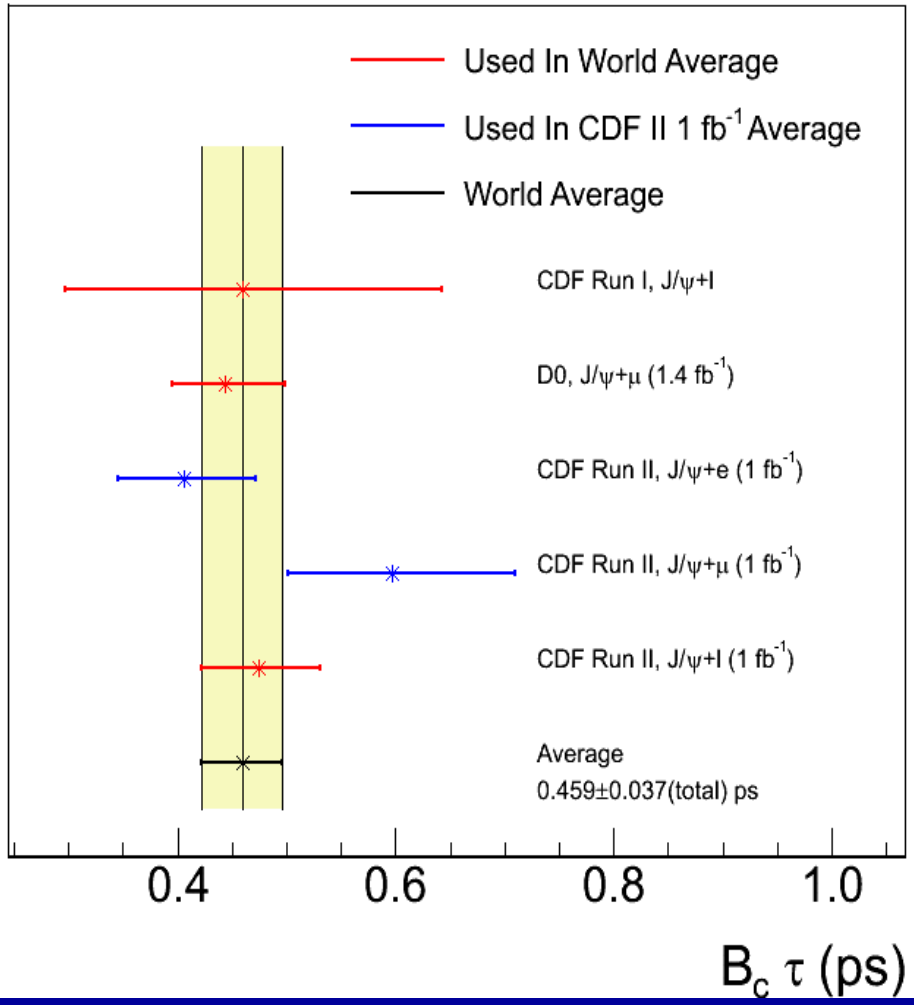
Extended log likelihood fit, combined for two channels:

$$c\tau(B_c) = 142.5\,^{+15.8}_{-14.8}\,(\text{stat}) \pm 5.5\,(\text{syst})\,\mu\text{m}$$

$$\tau(B_c) = 0.475\,^{+0.052}_{-0.049}\,(\text{stat}) \pm 0.018\,(\text{syst})\,\text{ps}$$

B_c Lifetime

$$B_c^{\pm} \to J/\psi\, l^{\pm}\nu\,;\, J/\psi \to \mu\mu$$



Unofficial world average B_c lifetime:

$$\tau(B_c) = 0.459 \pm 0.037\,\text{ps}$$

Predicted B_c lifetime:

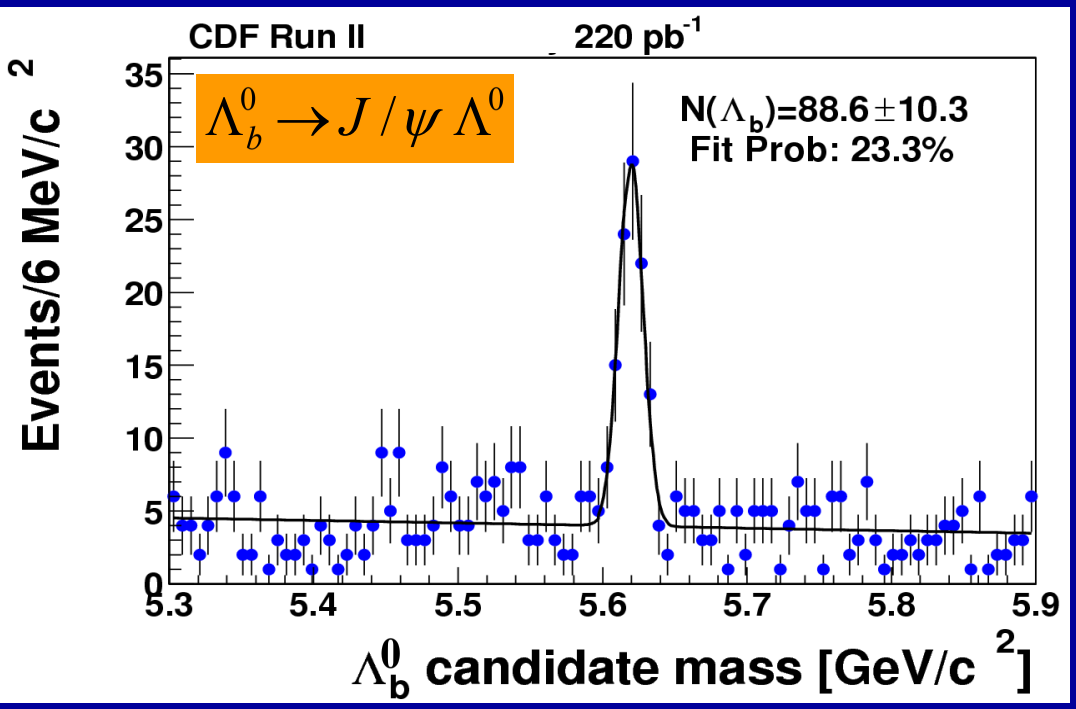
$$\tau(B_c) = 0.47 - 0.59\ \text{ps}$$

b-Baryons

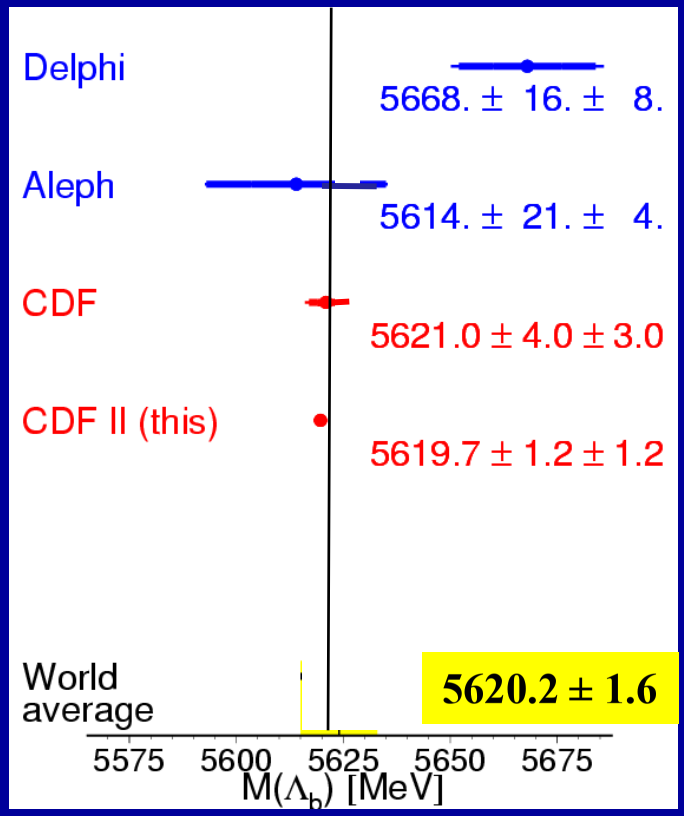
b - Baryons

Λ_b mass

CDF has the largest available sample of Λ_b's, including both J/ψ and hadronic decays.



Λ_b mass



PRL 96, 202001 2006

Source	$B^0 \to J/\psi K^0_s$	$\Lambda_b \to J/\psi \Lambda$
Tracking & Corrections		
momentum scale	0.2	0.2
Tracking	1.0	from $B^0 \to J/\psi K^0_s$
Fitting	0.7	from $B^0 \to J/\psi K^0_s$
Total Systematic Uncertainty	1.2	1.2

MeV

Λ_b^0 Lifetime predictions

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

(NLO) Gabbiani et al., hep-ph/0407004 and PRD70 094031 (2004)

- $\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$ theory

(NLO) C. Tarantino, hep-ph/0310241 and Eur. Phys. J. C33 S895 (2004)

- $\tau(\Lambda_b)/\tau(B^0) = 0.88 \pm 0.05$ theory

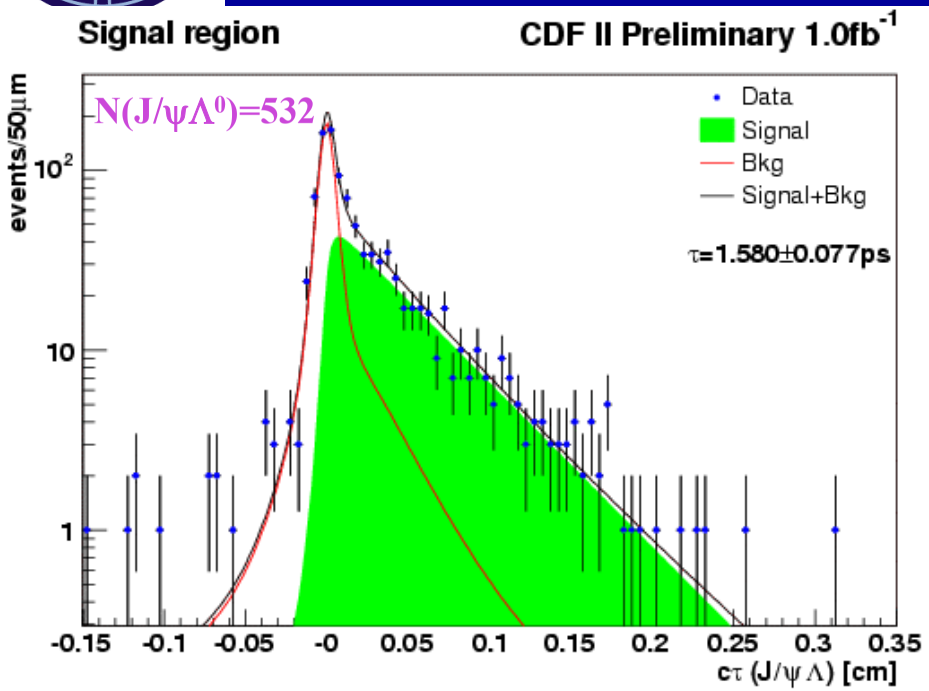
Λ_b^0 Lifetime

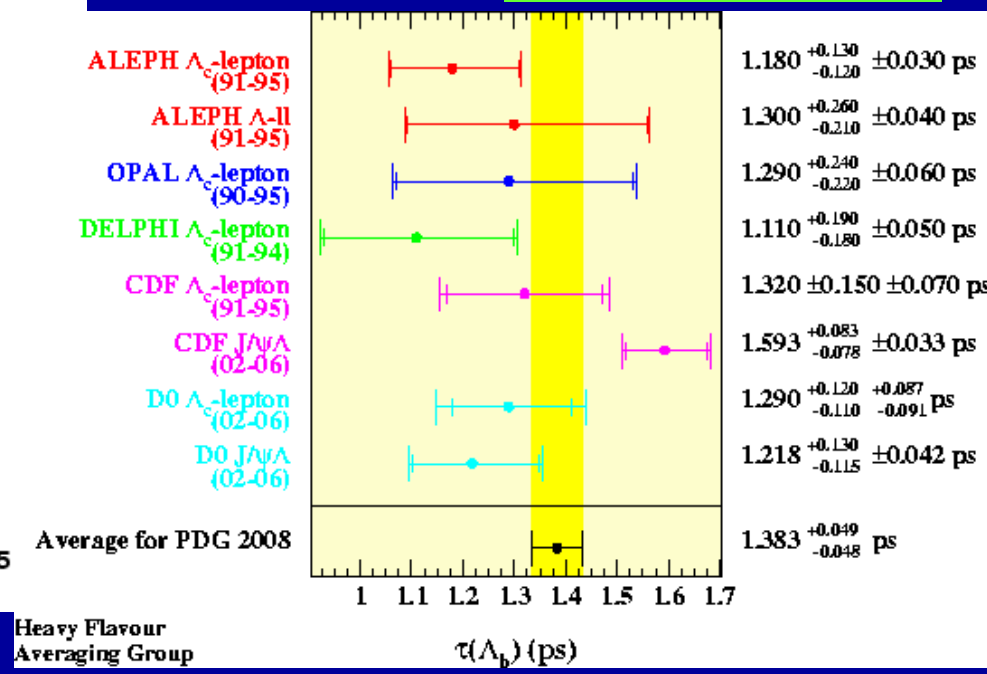
$$\Lambda_b \to J/\psi \Lambda^0 ; J/\psi \to \mu\mu ; \Lambda^0 \to p\pi^-$$

Run II, 1 fb^{-1}

Update on:

PRL 98, 122001 2007





$$\tau(\Lambda_b) = 1.580 \pm 0.077(\text{stat}) \pm 0.012(\text{syst})\,\text{ps}$$

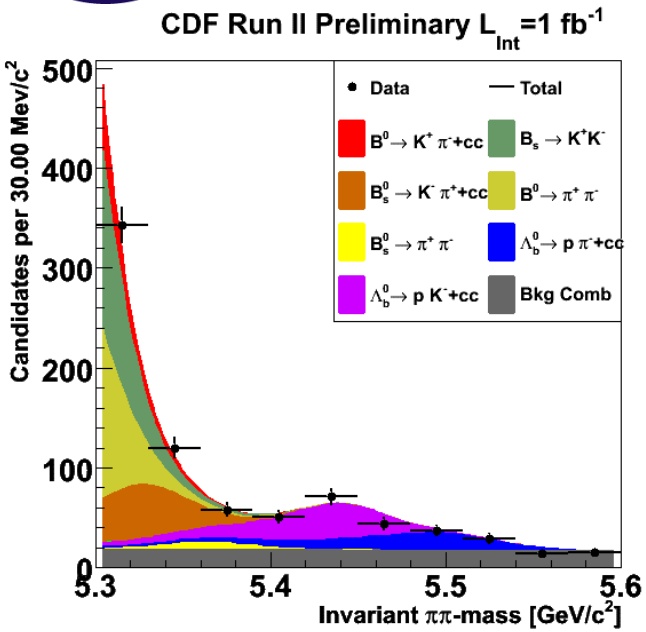
$$\tau(B^0) = 1.551 \pm 0.019(\text{stat}) \pm 0.011(\text{syst})\,\text{ps}$$

$$\tau(\Lambda_b)/\tau(B^0) = 1.018 \pm 0.062(\text{stat}) \pm 0.007(\text{syst})$$

- ~ 3 σ above theoretical prediction.
- Λ_b lifetime using the decay channel $\Lambda_b \to \Lambda_c \pi$ is work in progress.

Theory, ~ 0.87

CP Violation in $\Lambda^0_b \to pK/\pi$



$BR(\Lambda_b^0 \to pK) = (5.0 \pm 0.7 \pm 1.0) \times 10^{-6}$

$BR(\Lambda_b^0 \to p\pi) = (3.1 \pm 0.6 \pm 0.7) \times 10^{-6}$

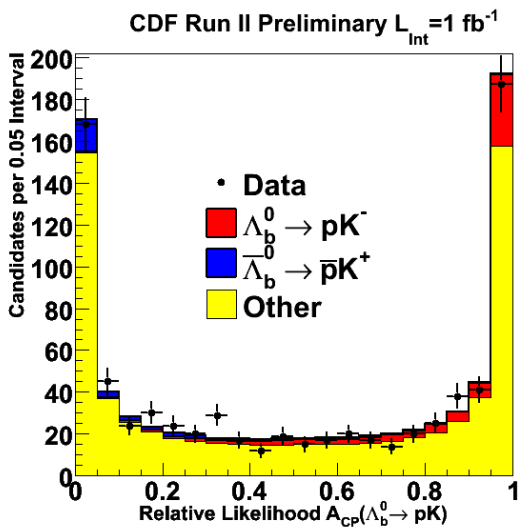
(Assuming PDG value $f_{baryon}/f_d = 0.25 \pm 0.04$)

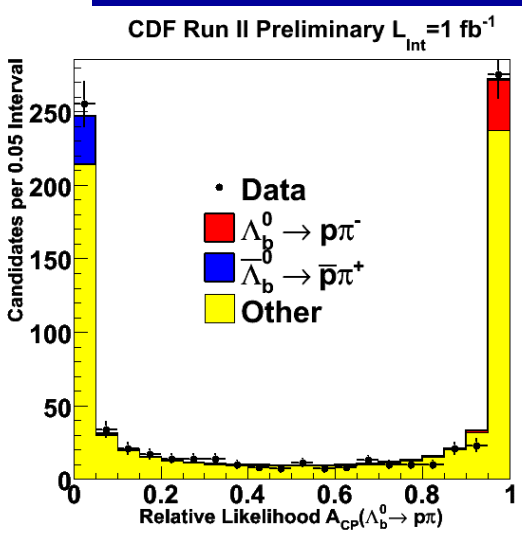
$$Br(\Lambda_b^0 \to p\pi^-)/Br(\Lambda_b^0 \to pK^-) = 0.66 \pm 0.14\,(\text{stat.}) \pm 0.08\,(\text{syst})$$

Predicted values:

$BR(\Lambda_b^0 \to pK) = 2 \times 10^{-6}$

$BR(\Lambda_b^0 \to p\pi) = 1 \times 10^{-6}$





Direct CP asymmetries:

$$A_{cp}(\Lambda_b \to p^\pm \pi^\mp) = 0.03 \pm 0.17 \pm 0.05$$

$$A_{cp}(\Lambda_b \to p^\pm K^\mp) = 0.37 \pm 0.17 \pm 0.03$$

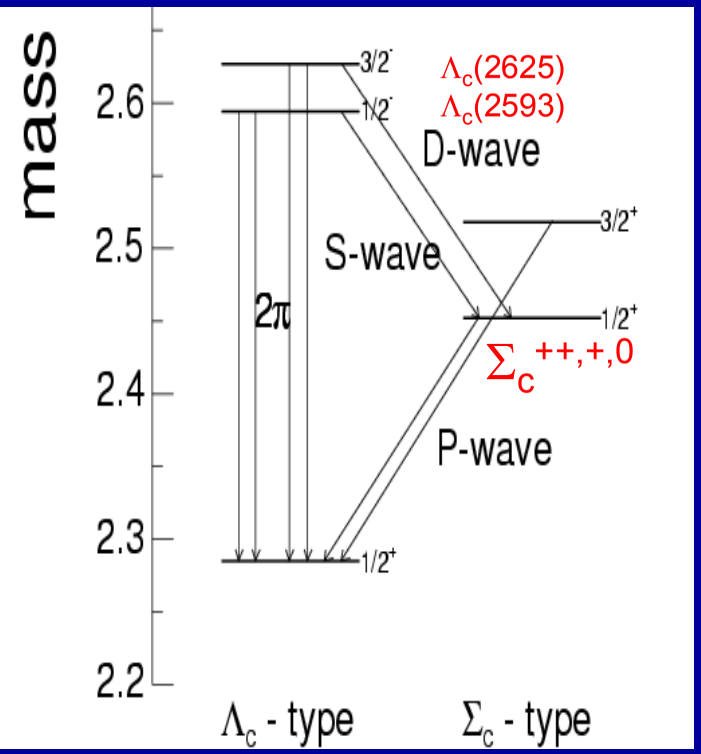
Expect an effect at least in pK.
Looking forward to more statistics

CDF contributions to Λ_b^0 Branching Ratios in PDG 2008 and beyond

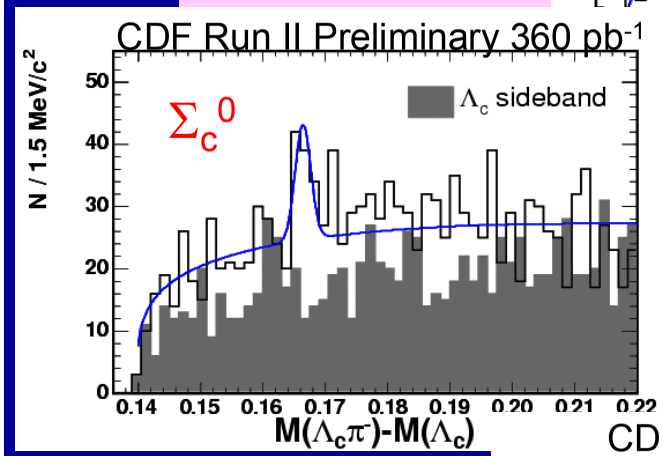
Λ_b^0 decay modes	Γ_i/Γ
$J/\psi\Lambda^0$	$(4.7 \pm 2.8) \times 10^{-4}$ (1997)
$\Lambda\gamma$	$< 1.3 \times 10^{-3}$ (90%) (2002)
$\Lambda_c^+\pi^-$	$(8.8 \pm 3.2) \times 10^{-3}$
pK	$(5.0 \pm 0.7 \pm 1.0) \times 10^{-6}$
$p\pi$	$(3.1 \pm 0.6 \pm 0.7) \times 10^{-6}$
$\Lambda_c^+l^-\nu$	$(5.0\,^{+1.9}_{-1.4})\times 10^{-2}$
$\Lambda_c^+\pi^-\pi^+\pi^-$	seen
$\Lambda_c(2593)^+l^-\,\bar{\nu}$	seen
$\Lambda_c(2625)^+l^-\,\bar{\nu}$	seen
$\Sigma_c^{++}\pi^-l^-\,\bar{\nu}$	seen
$\Sigma_c^0\pi^+l^-\,\bar{\nu}$	seen

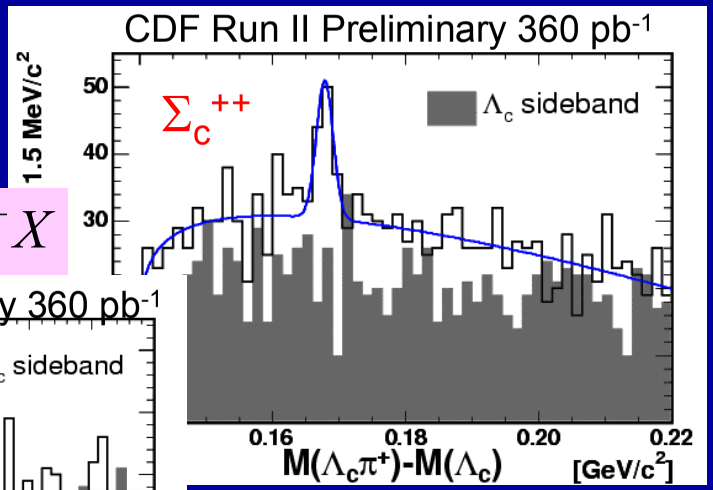
Source of semileptonic backgrounds

$$\Lambda_b \to \Sigma_c^{++}\pi^-\mu^- X$$

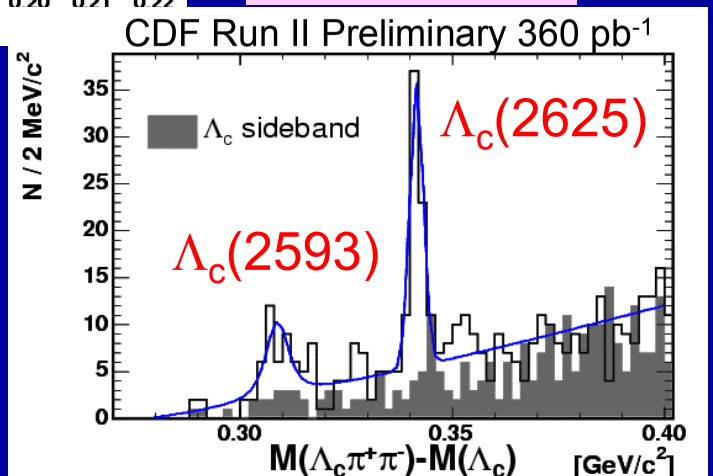


$$\Lambda_b \to \Sigma_c^{0}\pi^+\mu^- X$$





$$\Lambda_b \to \Lambda_c^{*+}\mu^- X$$



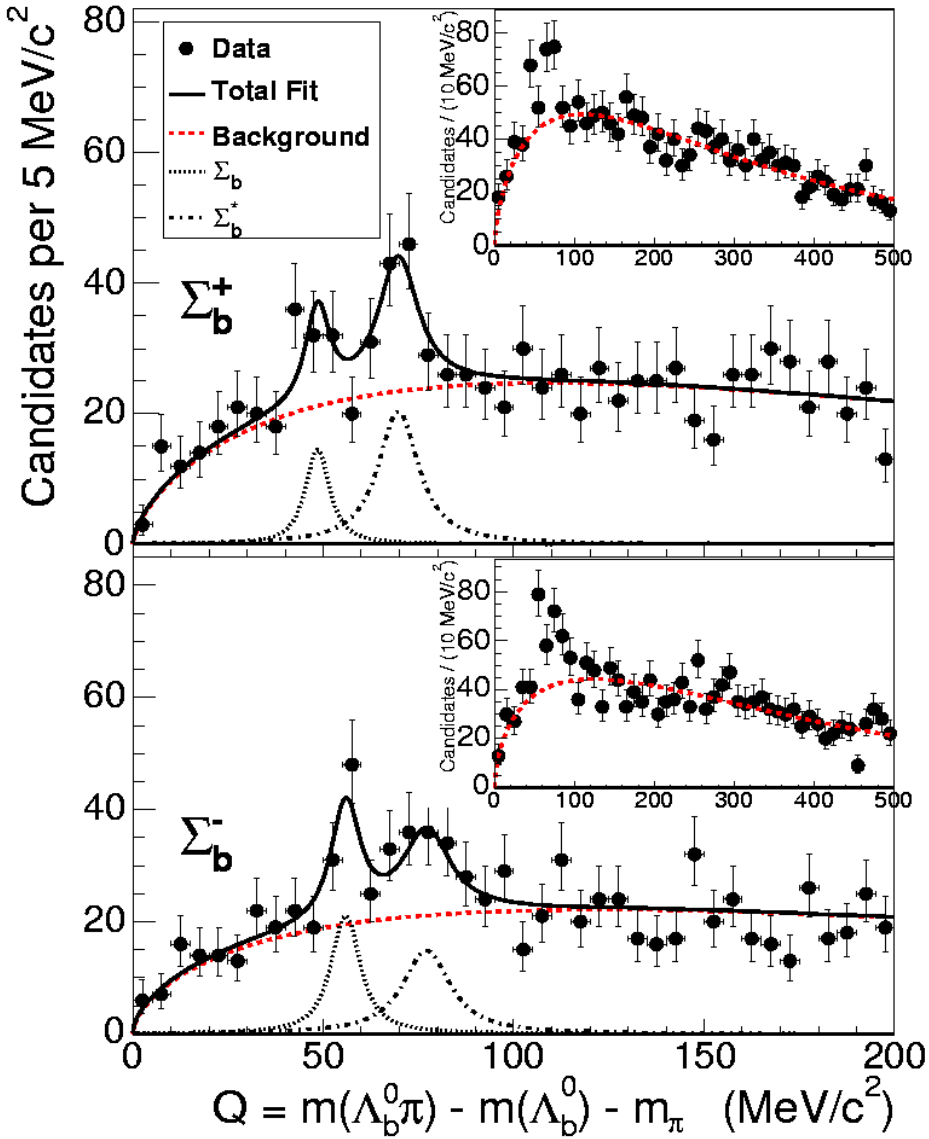
First observation of several Λ_b semileptonic decays that can 'mimic' the signal

Observation of Σ_b at CDF

~ 1.1 fb^{-1}

$$\Sigma_b^{(*)\pm} \to \Lambda_b \pi^{\pm}; \Lambda_b \to \Lambda_c^{+} \pi^{-}, \Lambda_c^{+} \to p K^{-} \pi^{+}$$

3180±60 (stat) $\Lambda_b^0 \to \Lambda_c^+ K^-$ **cand.**



State	Yield	Mass (MeV/c²)
Σ_b^+	32^{+13+5}_{-12-3}	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}	$5836.4 \pm 2.0^{+1.8}_{-1.7}$

$$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}\ MeV/c^2$$

$$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2\ MeV/c^2$$

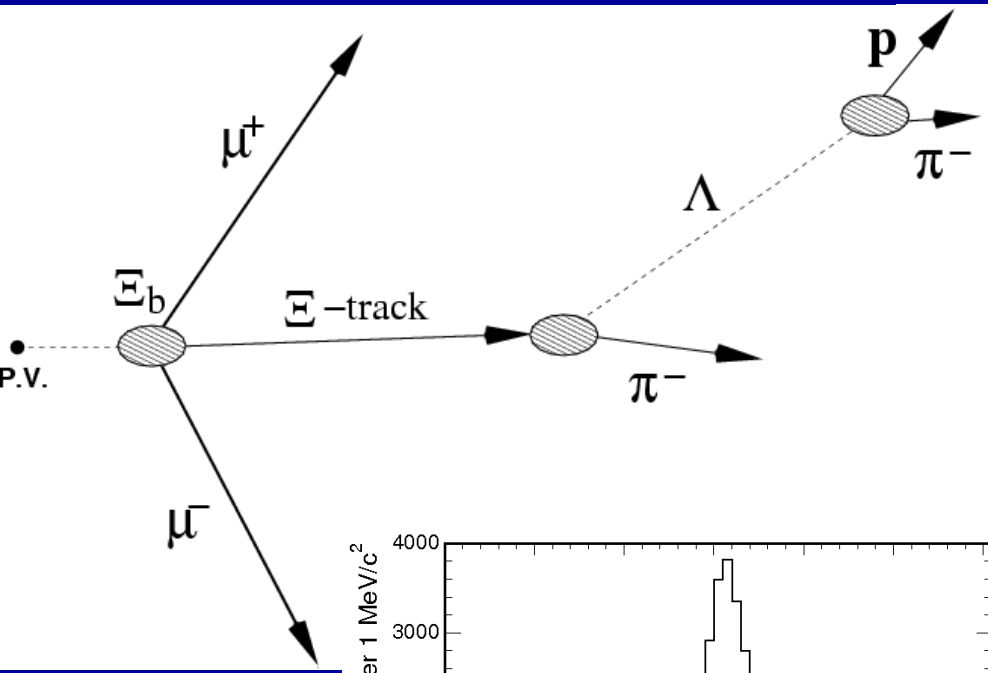
$$M(\Sigma_b^*) - M(\Sigma_b) = 21.2^{+2.0+0.4}_{-1.9-0.3}\ MeV/c^2$$

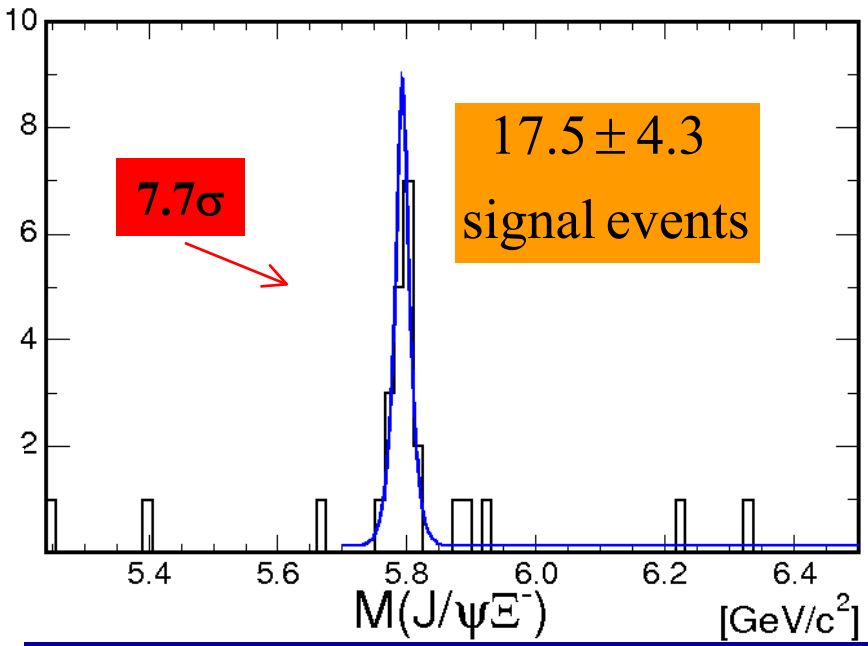
PRL 99, 202001 2007

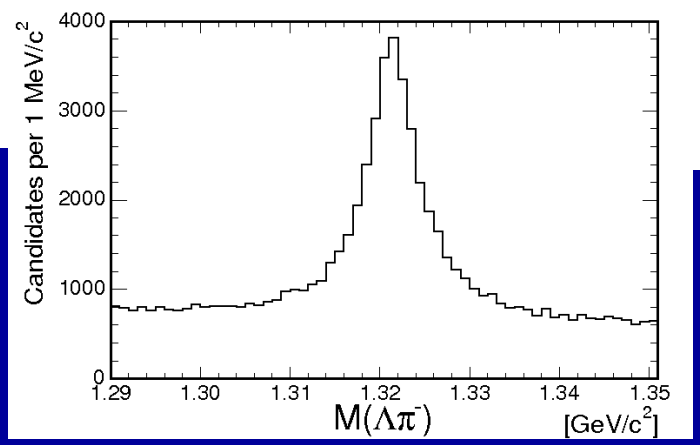
Observation of Ξ_b at CDF

Run II, 1.9 fb^{-1}

$$\Xi_b^- \to J/\psi\,\Xi^-;\ J/\psi \to \mu^+\mu^-,\ \Xi^- \to \Lambda^0\pi^-,\ \Lambda^0 \to p\pi^-$$





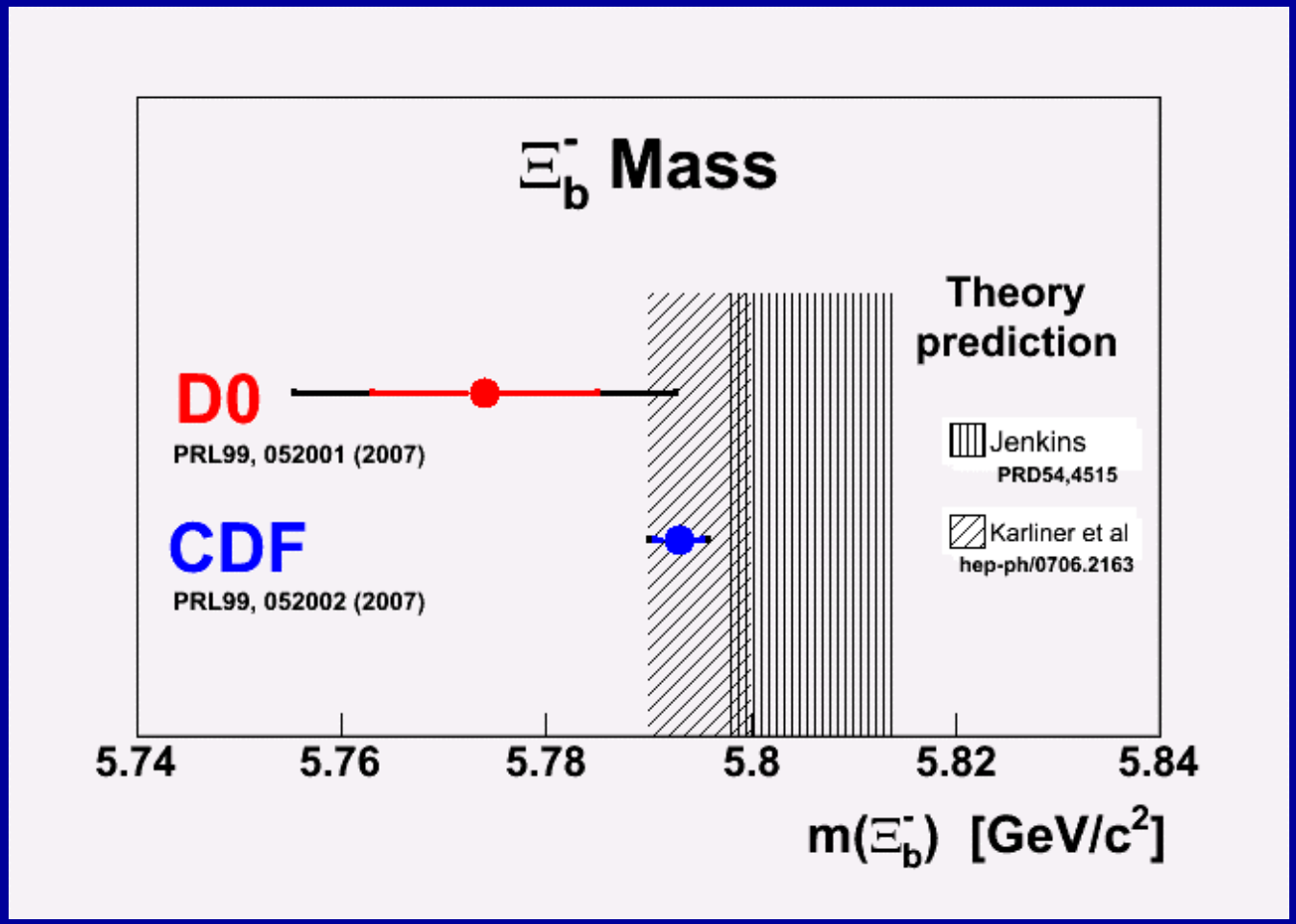


PRL 99, 052002 2007

$$M(\Xi_b^-) = 5792.9 \pm 2.5(stat) \pm 1.7(syst)\ MeV/c^2$$

Observation and mass measurement of Ξ_b by CDF and D0

$$\Xi_b^- \to J/\psi\,\Xi^-;\ J/\psi \to \mu^+\mu^-,\ \Xi^- \to \Lambda^0\pi^-,\ \Lambda^0 \to p\pi^-$$



Quarkonia

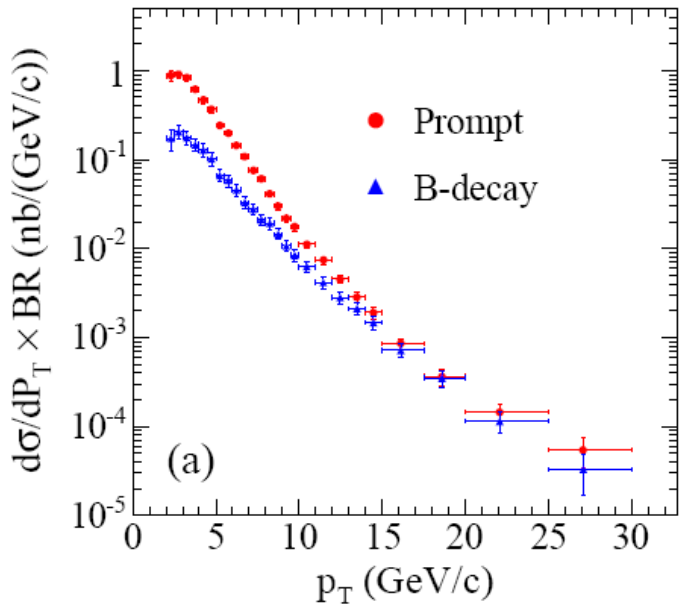
Quarkonia

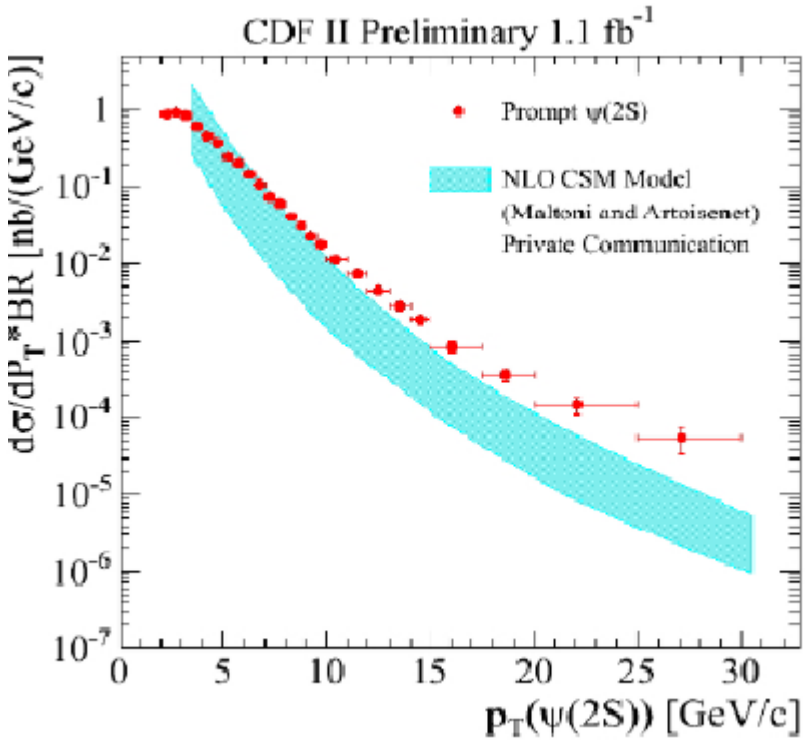
Production of ψ(2S) mesons at 1.96 TeV

Inclusive cross section for : $p_T(\psi(2S)) > 2\,\text{GeV/c}\ \&\ |y(\psi(2S))| < 0.6$

Run II, 1.1 fb^{-1}

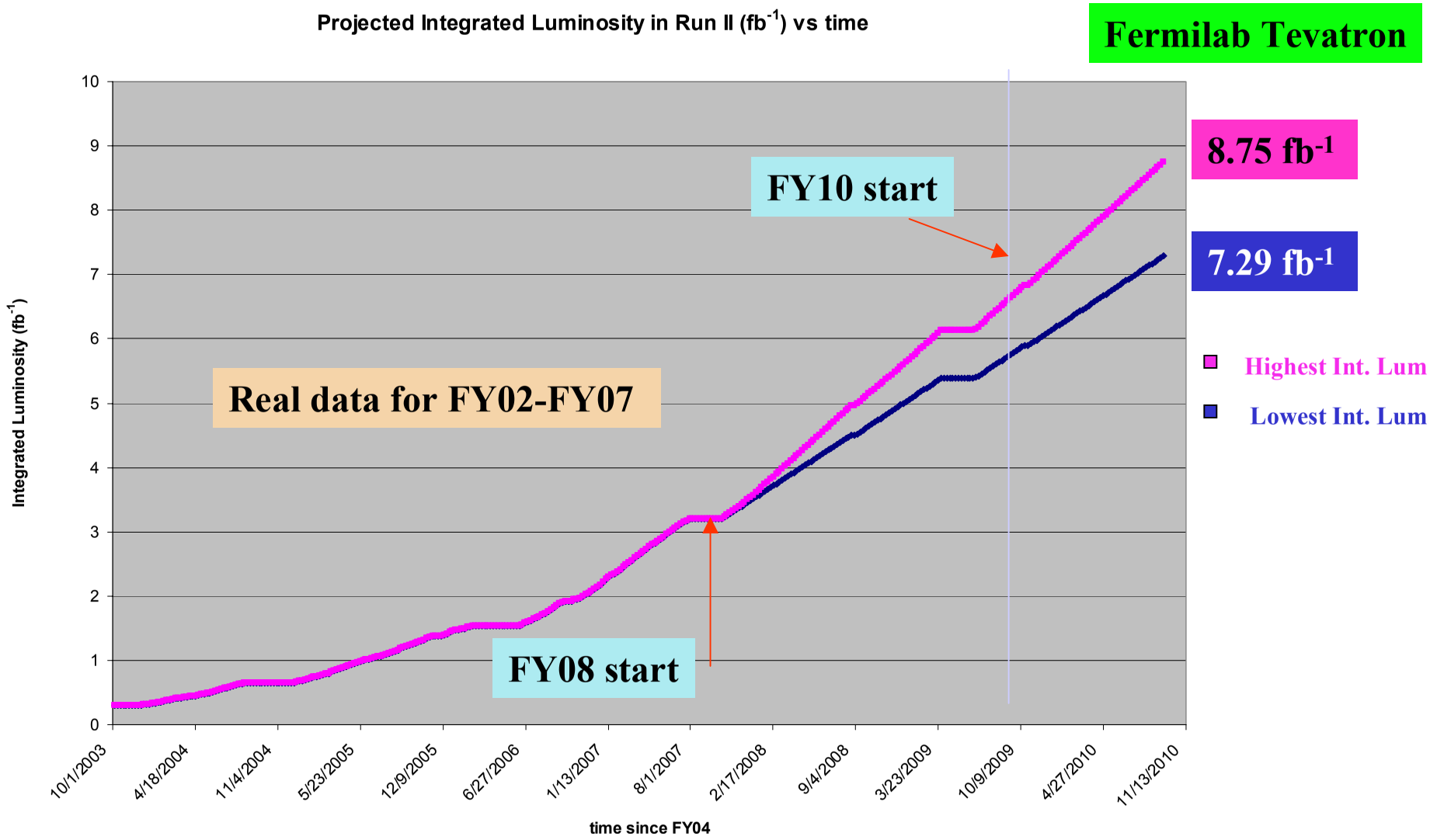
$$\sigma(p\bar{p} \to \psi(2S)X) \cdot Br(\psi(2S) \to \mu^+\mu^-) = 3.17 \pm 0.04(\text{stat}) \pm 0.28(\text{syst})\ \text{nb}$$





Important input for the update of the matrix elements in the NRQCD factorization approach.

Expected integrated luminosity for Run II



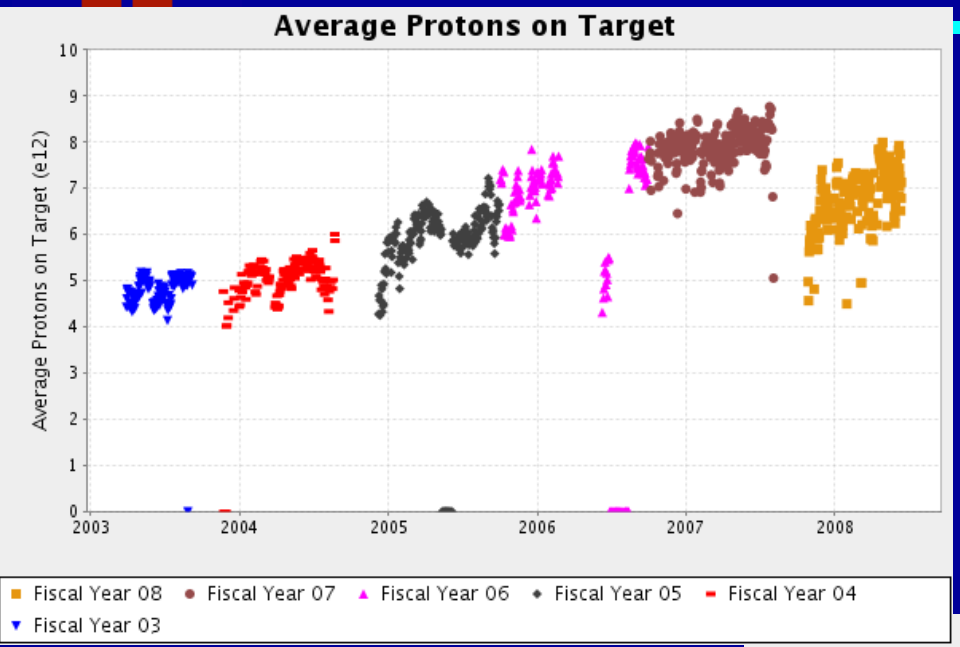
Conclusions

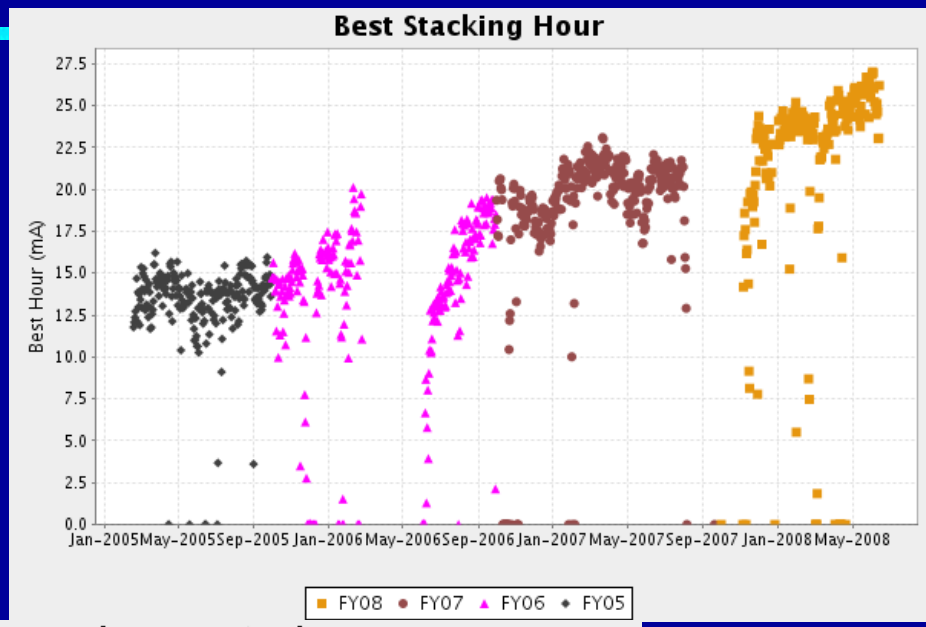
- The Tevatron is running very well.
- Many new results in B physics.
- The Tevatron is expected to provide 5.8 – 6.9 fb^{-1} by October 2009 or 7.3 – 8.8 fb^{-1} by October 2010.
- A lot of answers and surprises awaiting!!

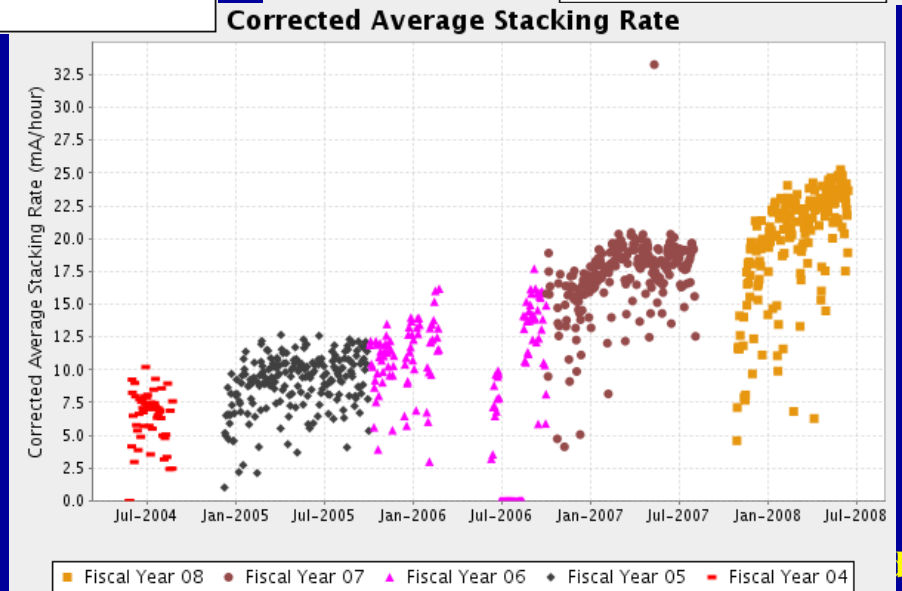
Backup

Backup Slides

Tevatron Performance

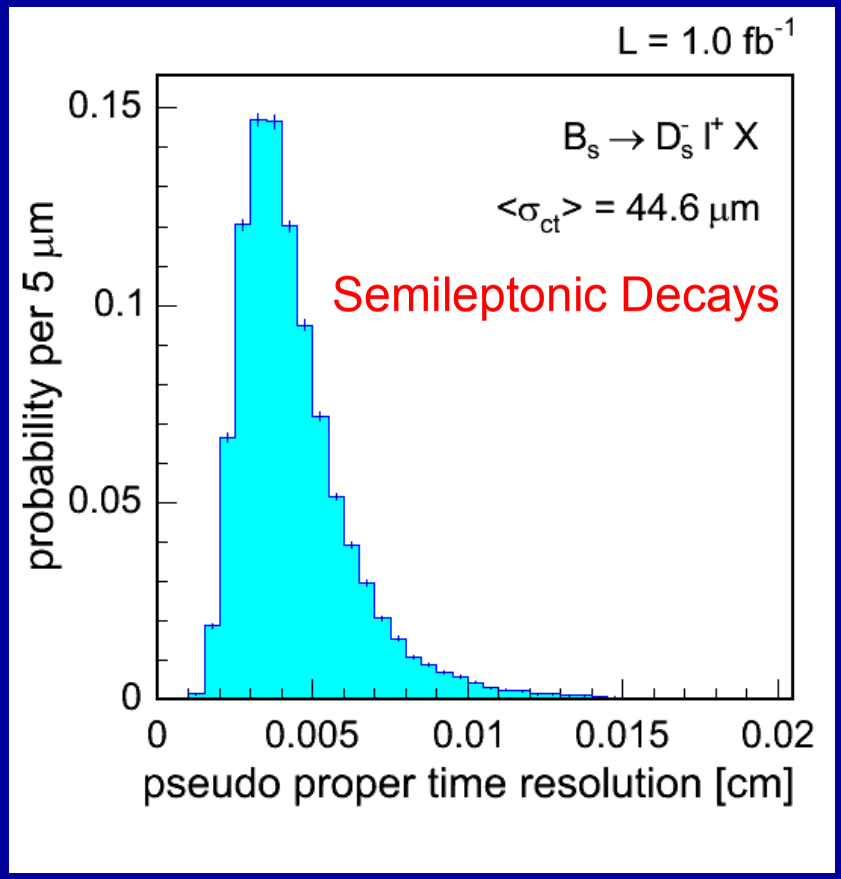


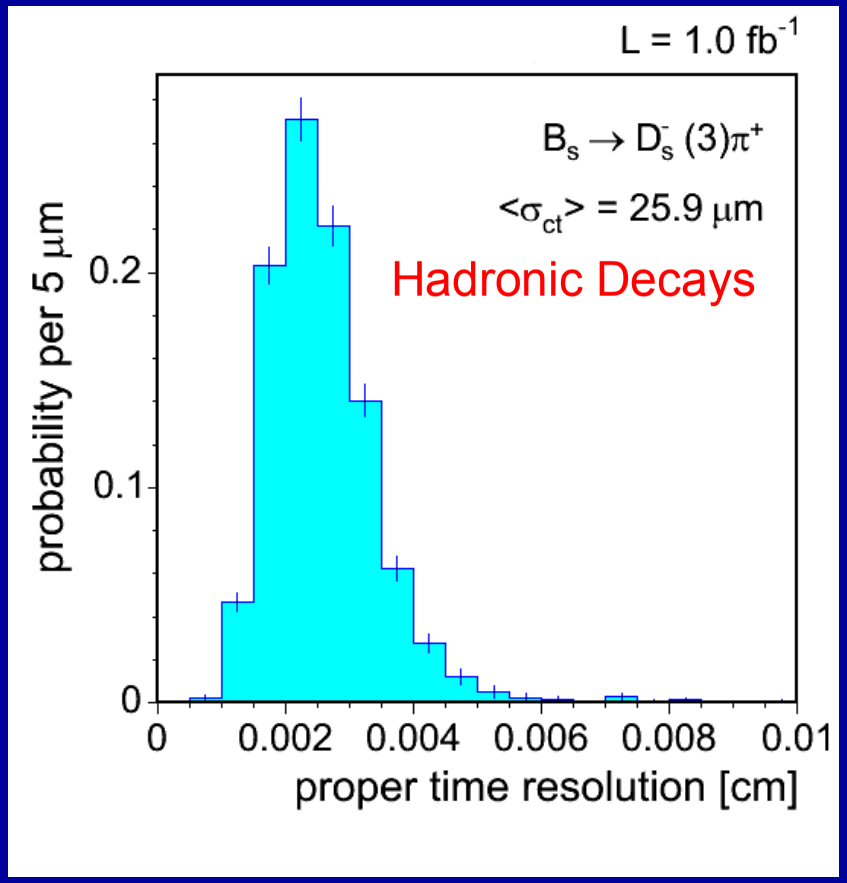




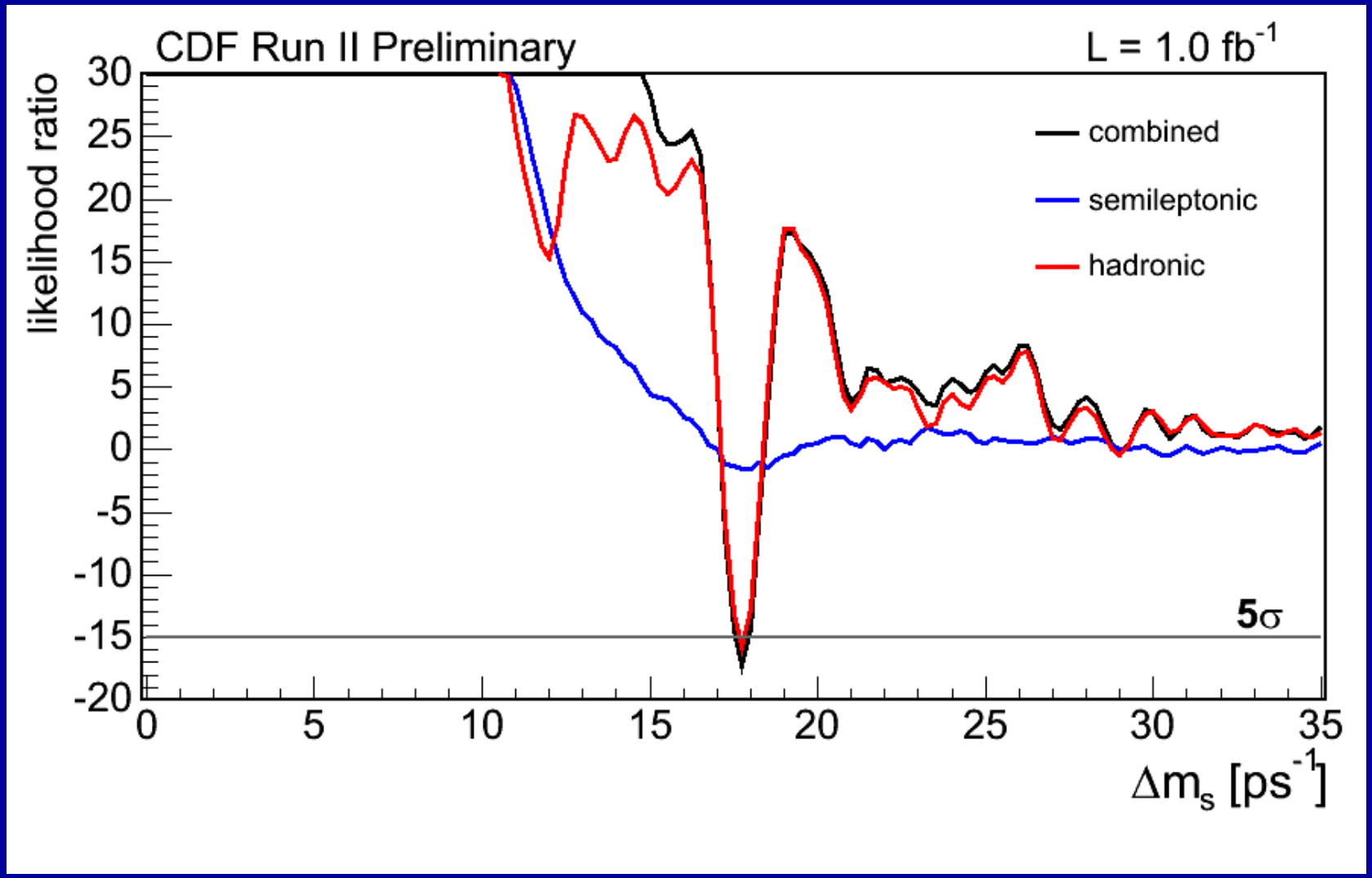
B_s Mixing: Proper Decay Time Resolution

- Hadronic decays have excellent proper time resolution





B_s Mixing

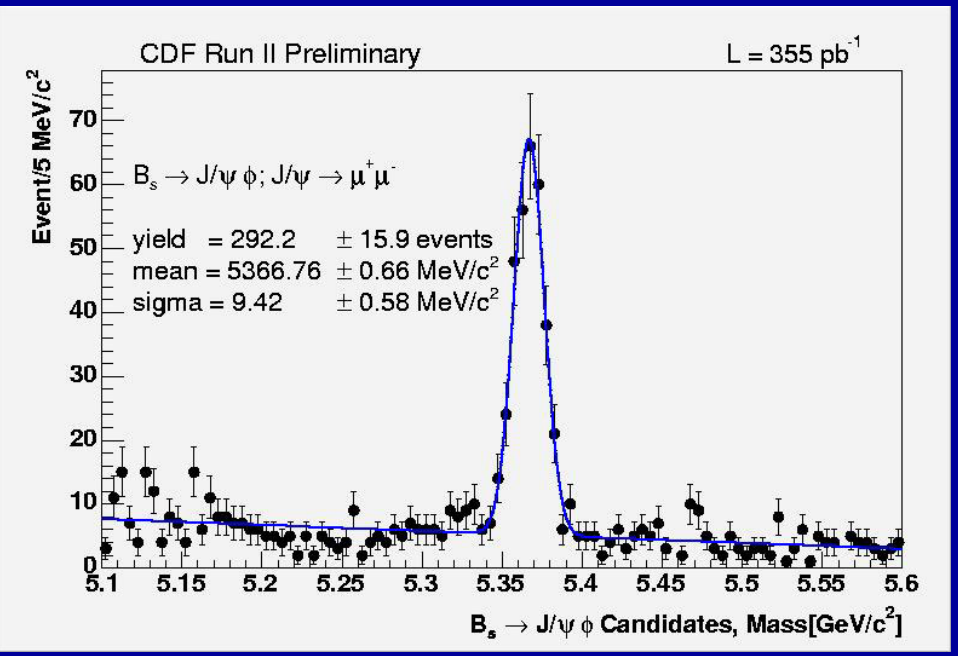

CDF Run II Preliminary
L = 1.0 fb^{-1}
likelihood ratio
30
25
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
30
35
Δm_s [ps^{-1}]
combined
semileptonic
hadronic
5σ

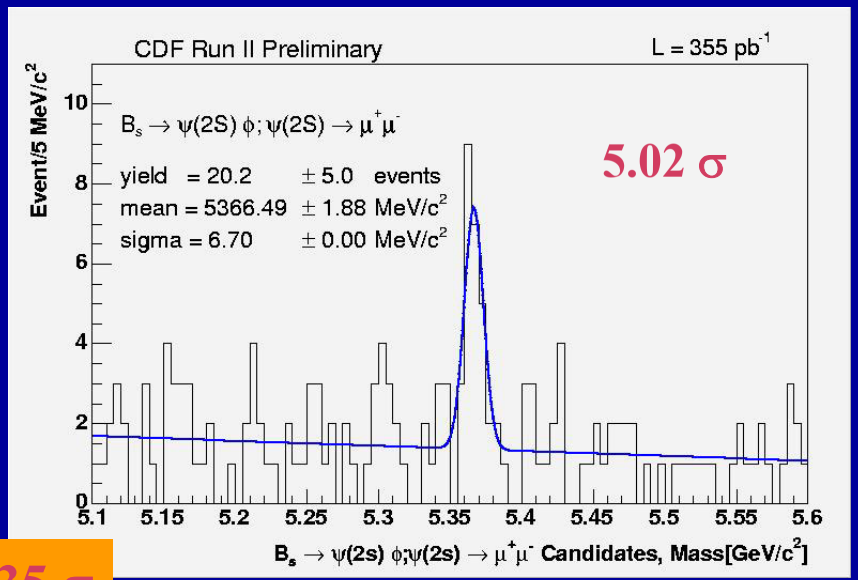
$B_s \rightarrow \psi(2S)\phi$

Run II, 355 pb^{-1}

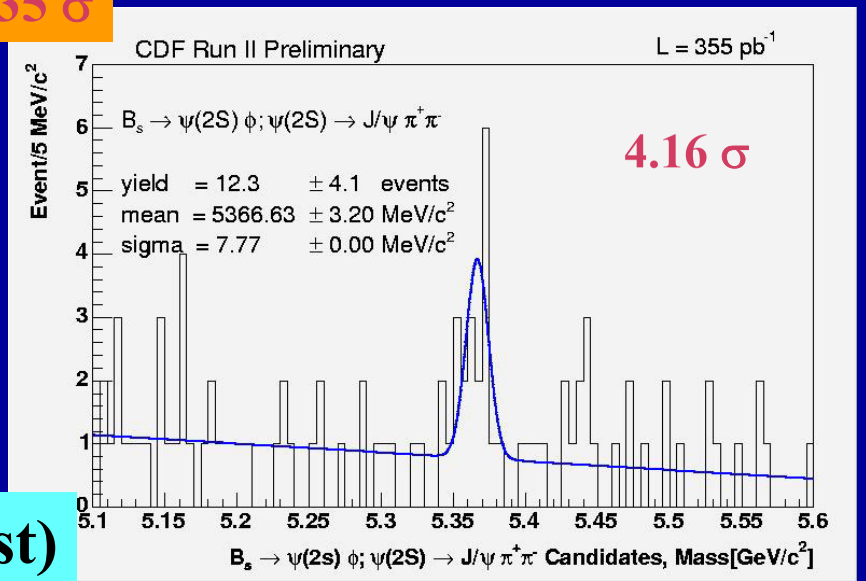
$B_s \rightarrow J/\psi\varphi\ ;\ J/\psi \rightarrow \mu\mu$

used as a control sample and for normalization





6.35 σ



$$\frac{BR(B_s \rightarrow \psi(2S)\varphi)}{BR(B_s \rightarrow J/\psi\varphi)} =$$

0.52 ± 0.13(stat) ± 0.06(BR) ± 0.04(syst)

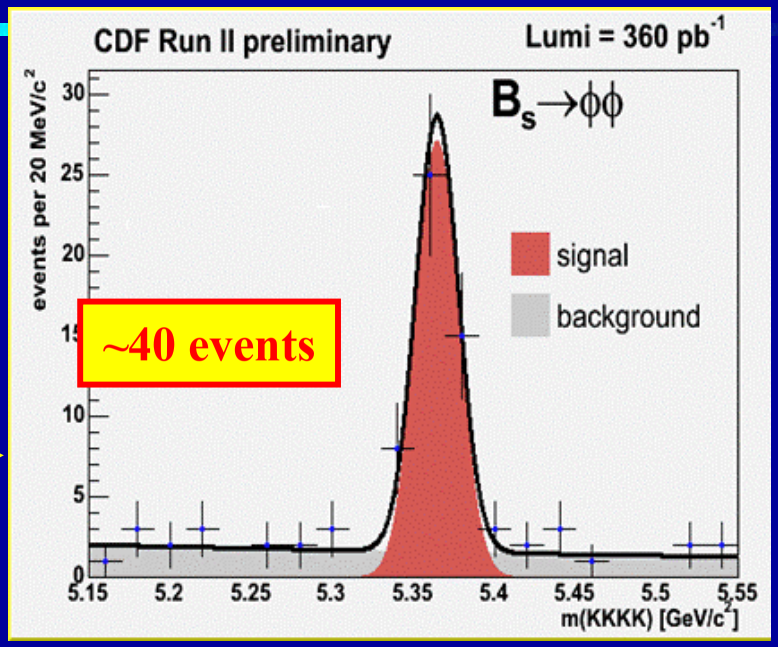
$B_s \rightarrow \phi\phi$ and $\psi(2S)\phi$

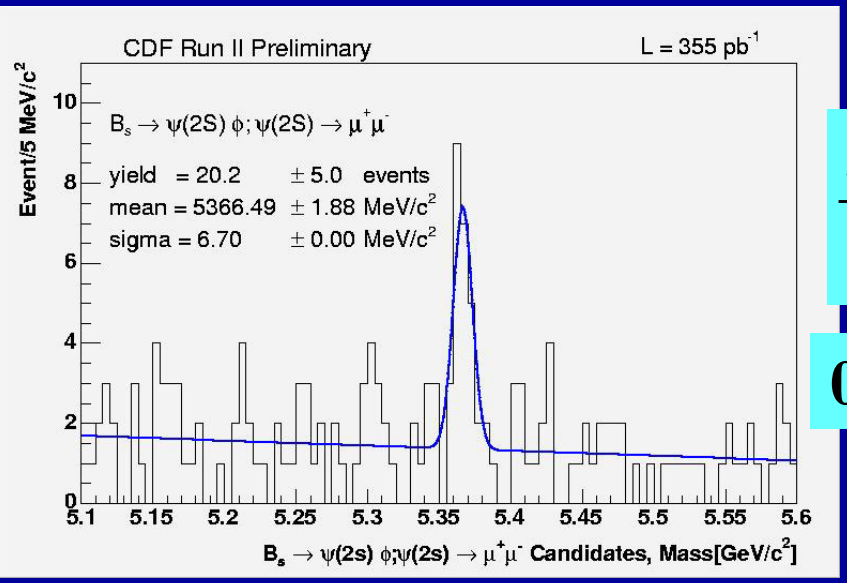
- CDF: Bs→ $\phi\phi$
  - $BR(B_s \rightarrow \phi\phi) = (1.4^{+0.6}_{-0.5} \pm 0.6) \times 10^{-5}$

QCD fact. 3.68×10^{-5}

NF fact. 1.79×10^{-5}

First observation!





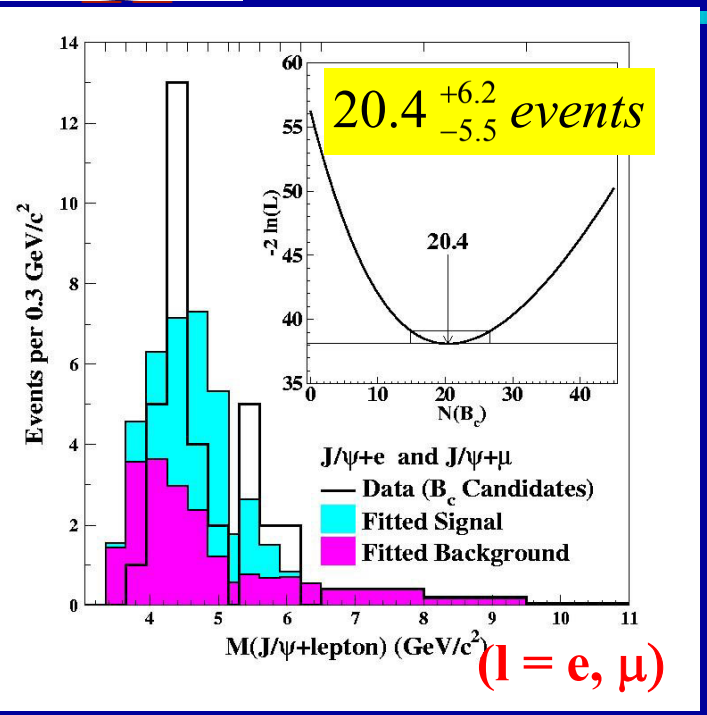
$$\frac{BR(B_s \rightarrow \psi(2S)\varphi)}{BR(B_s \rightarrow J/\psi\varphi)} =$$

0.52 ± 0.13(stat) ± 0.06(BR) ± 0.04(syst)

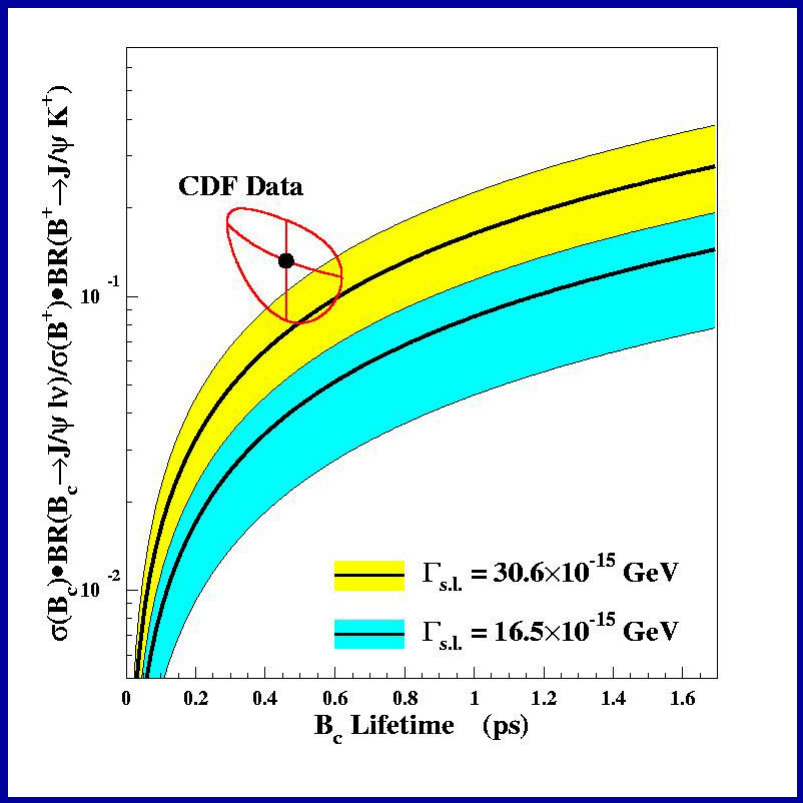
$B_c^{\pm} \rightarrow J/\Psi l^{\pm} \nu$

Run I, 110 pb^{-1}

PRL 81, 2432, PRD 58, 112004 (1998)



(l = e, μ)



$M(B_c) = 6.40 \pm 0.39\,(stat) \pm 0.13(syst)\ GeV/c^2$

$c\tau(B_c) = 0.46^{+0.18}_{-0.16} \pm 0.03\ ps$

$P_T(B) > 6\,\mathrm{GeV/c}; |\eta| < 0.6$

$\sigma(B_c) \times B(B_c \rightarrow J/\psi \ell \nu)$

$\sigma(B_u) \times B(B_u \rightarrow J/\psi K)$

$= 0.132^{+0.041}_{-0.037}\,(stat) \pm 0.031\,(syst)^{+0.032}_{-0.020}\,(c\tau)$

$B_c^{\pm} \rightarrow J/\Psi e^{\pm} \nu$

Run II, 360 pb^{-1}

Background :

63.6±4.9(stat.)±13.6(syst.)

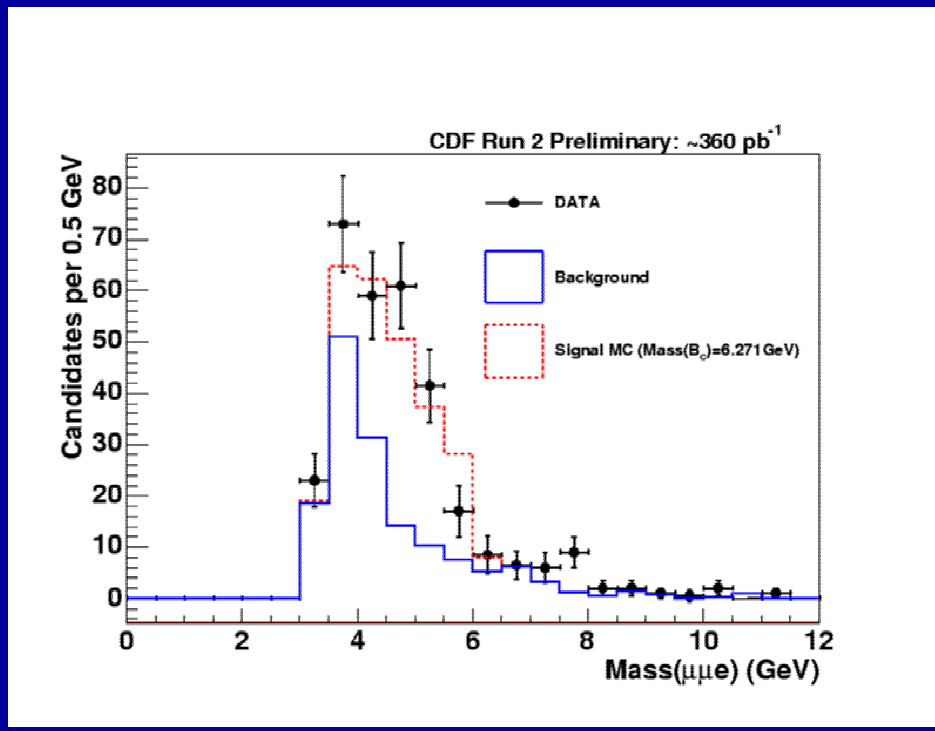
Observe :

178.5±14.7(stat.)

Excess :

114.9±15.5(stat.) ±13.6(syst.)

Significance : 5.9σ



$$\frac{\sigma(B_c^+)\times BR(B_c^+ \rightarrow J/\psi e^+ \nu)}{\sigma(B^+)\times BR(B^+ \rightarrow J/\psi K^+)}$$

- Cross section ratio is defined within the kinematical limits
  - $p_T(B) > 4.0\text{GeV}$, $|y(B)| < 1.0$

σ_{ratio}=0.282±0.038(stat.)±0.074(syst.)

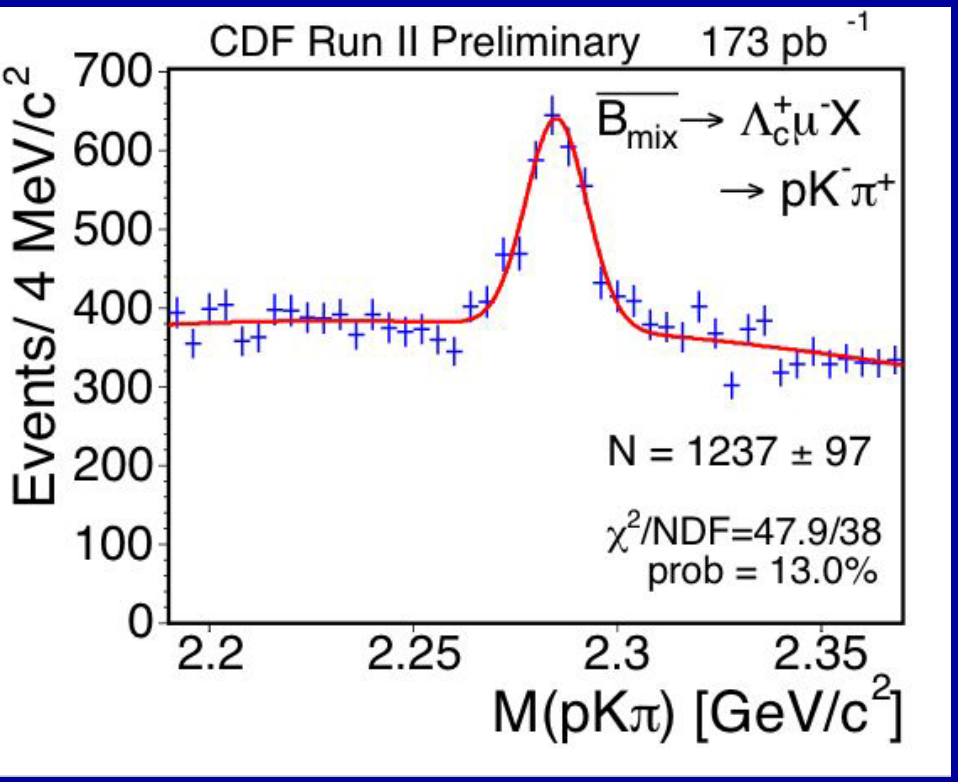
Branching Ratios

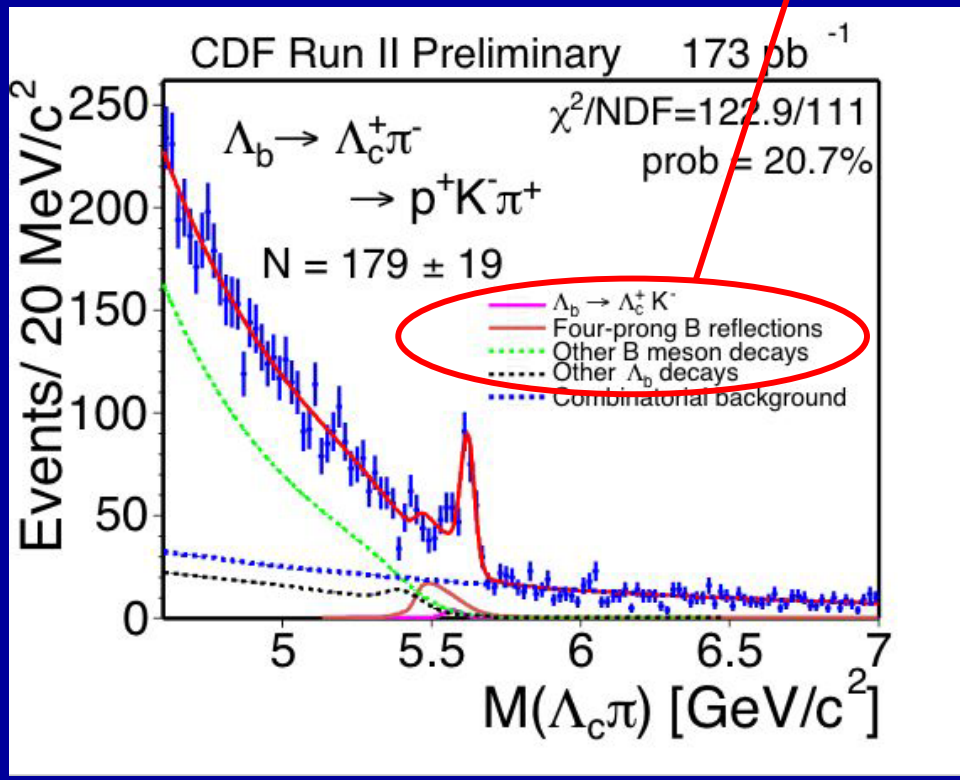
Signal Sample: $\Lambda_b \to \Lambda_c X$; $\Lambda_c \to p^+ K^- \pi^+$

Inclusive Semileptonic Signal

Hadronic Signal

from MC



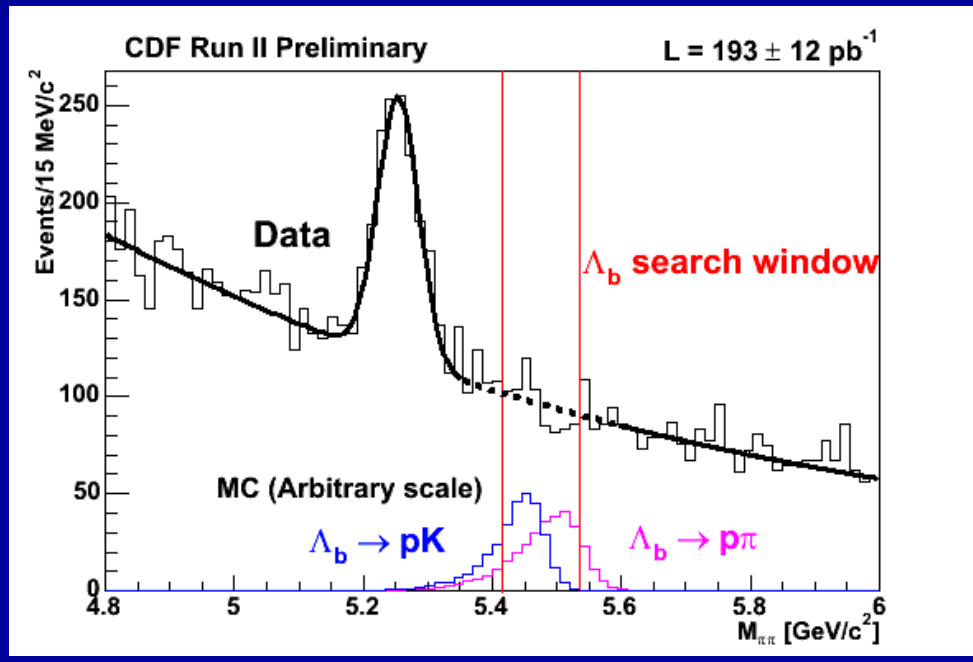


$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \pi^-)} = 20.0 \pm 3.0\ (stat) \pm 1.2\ (syst)\ ^{+0.7}_{-2.1}\ (BR) \pm 0.5\ (UBR)$$

Branching Ratios

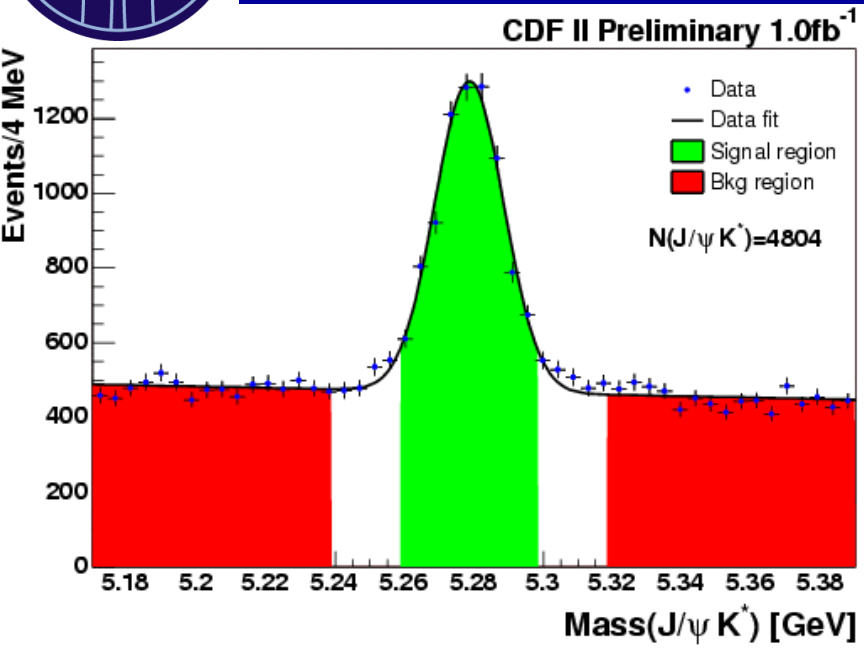
Signal Sample: $\Lambda_b \rightarrow p^+\pi^-$ and $\Lambda_b \rightarrow p^+K^-$

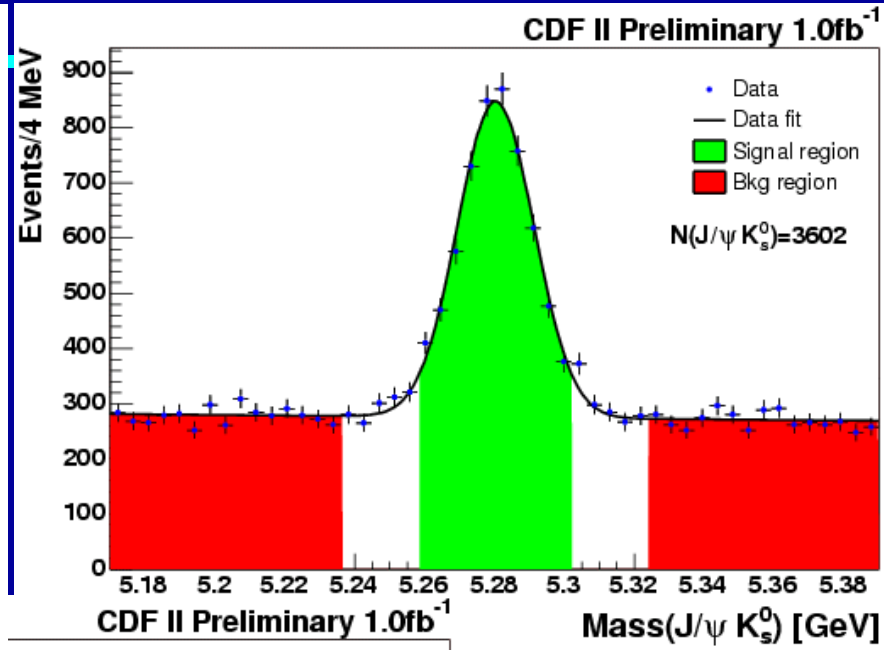
- Predictions for BR are in the range $1 \times 10^{-6} - 2 \times 10^{-6}$
- Large direct CP violation expected (Z. Phys. C56 (1992) 129)
- Exploit the two-track trigger sample
- Use $B^0 \longrightarrow K\pi$ for normalization
- Backgrounds are combinatorial and from the tail of $B \longrightarrow hh$
- $BR(\Lambda_b \longrightarrow ph) < 2.3 \times 10^{-5}$ @ 90% C.L. **h = K, π**



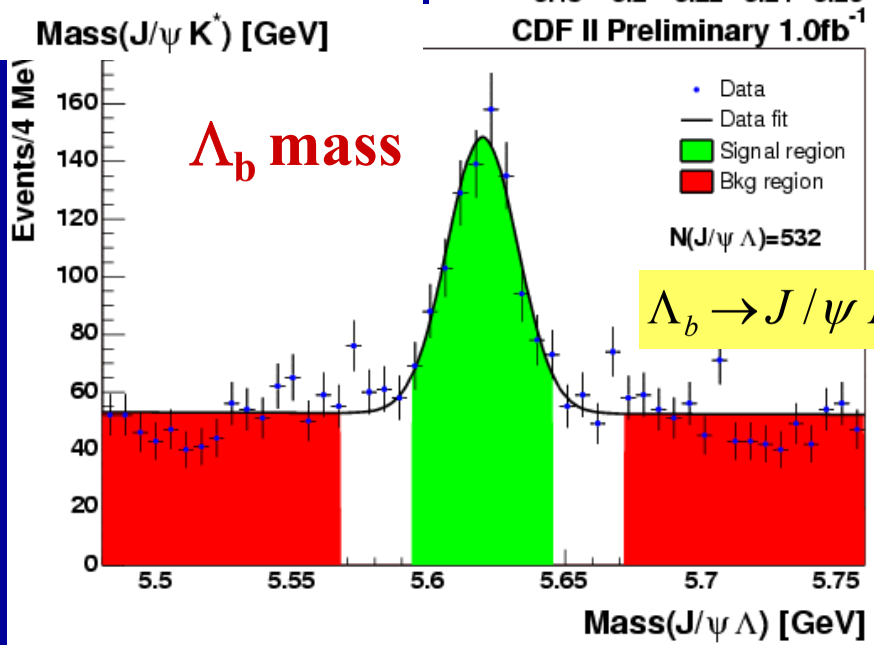
$f_\Lambda/f_d = 0.25 \pm 0.04$

Λ_b lifetime





Λ_b mass



$$\Lambda_b \to J/\psi\,\Lambda^0\,;J/\psi \to \mu\mu;\Lambda^0 \to p\pi^-$$

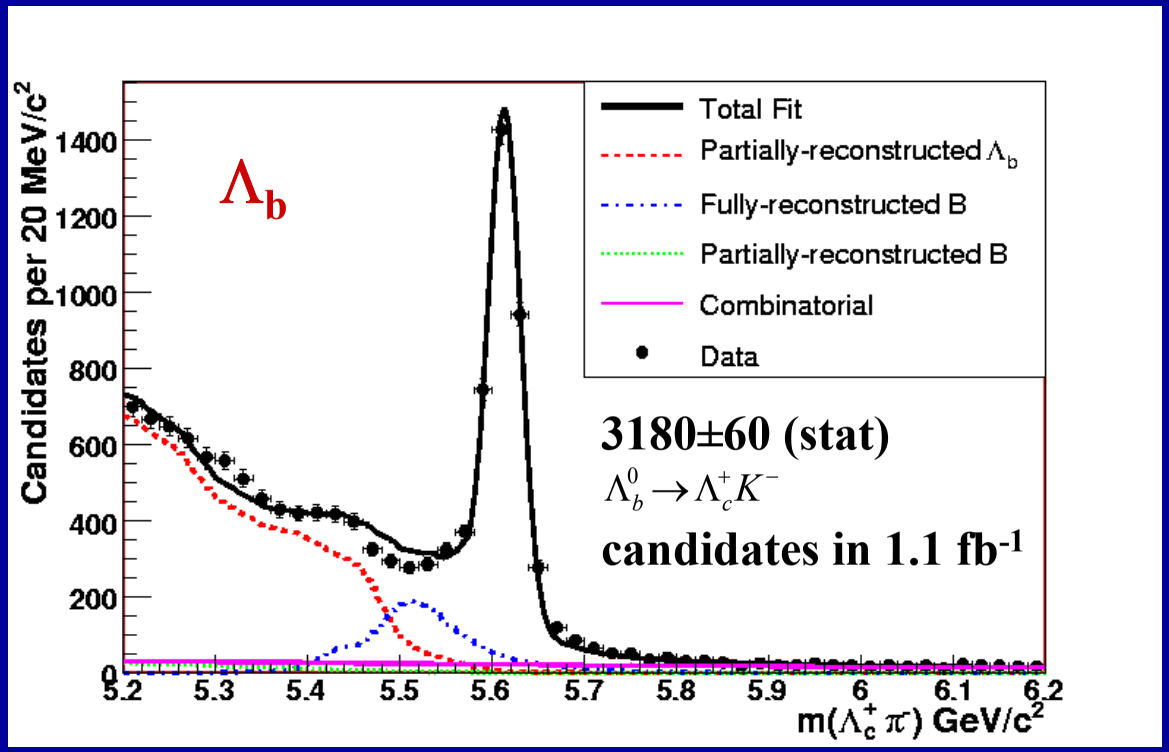
Update on:

PRL 98, 122001 2007

Observation of Σ_b at CDF

Run II, 1.1 fb^{-1}

$$\Sigma_b^{(*)\pm} \to \Lambda_b \pi^{\pm}; \Lambda_b \to \Lambda_c^{+} \pi^{-}, \Lambda_c^{+} \to p K^{-} \pi^{+}$$

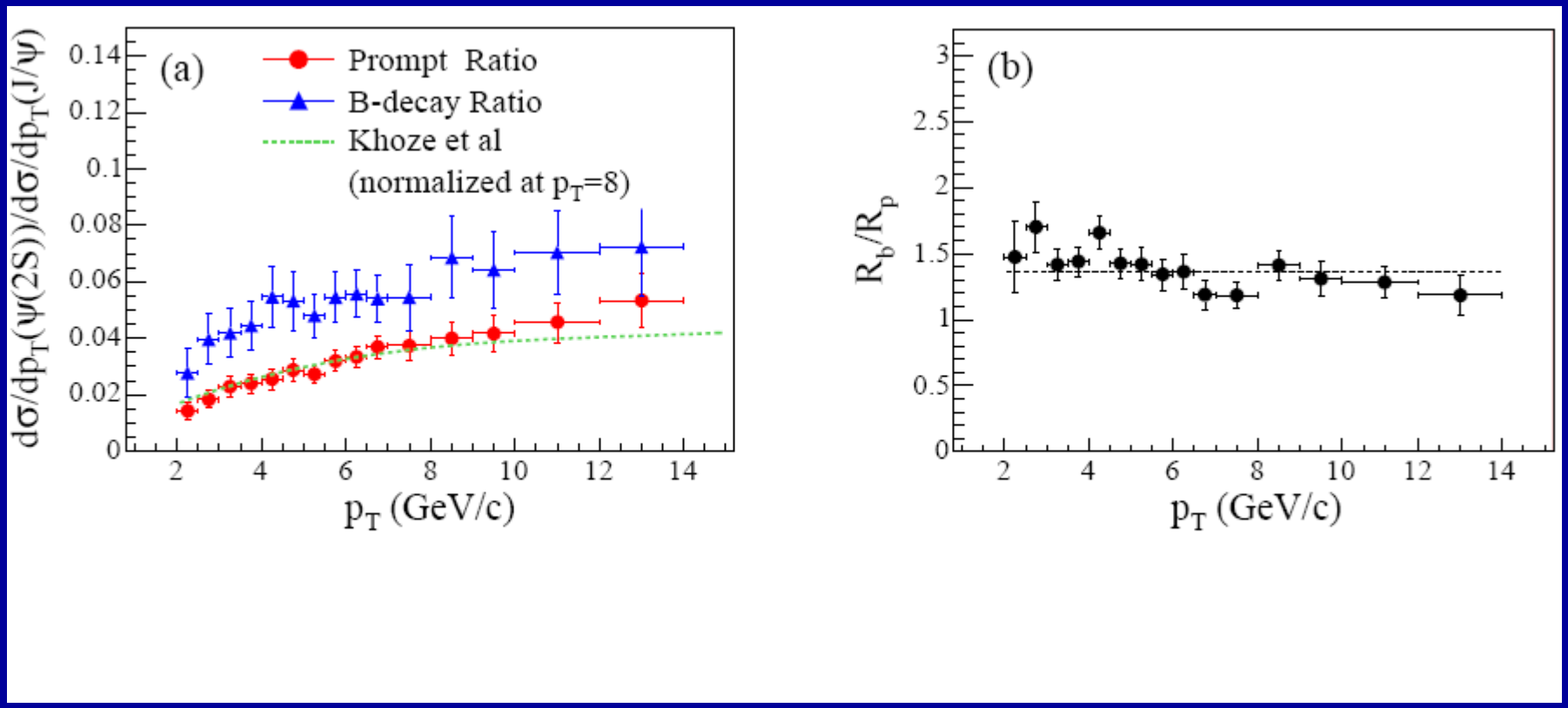


Production of ψ(2S) mesons at 1.96 TeV

Inclusive cross section for : $p_T(\psi(2S)) > 2\,\text{GeV/c}\ \&\ |y(\psi(2S))| < 0.6$

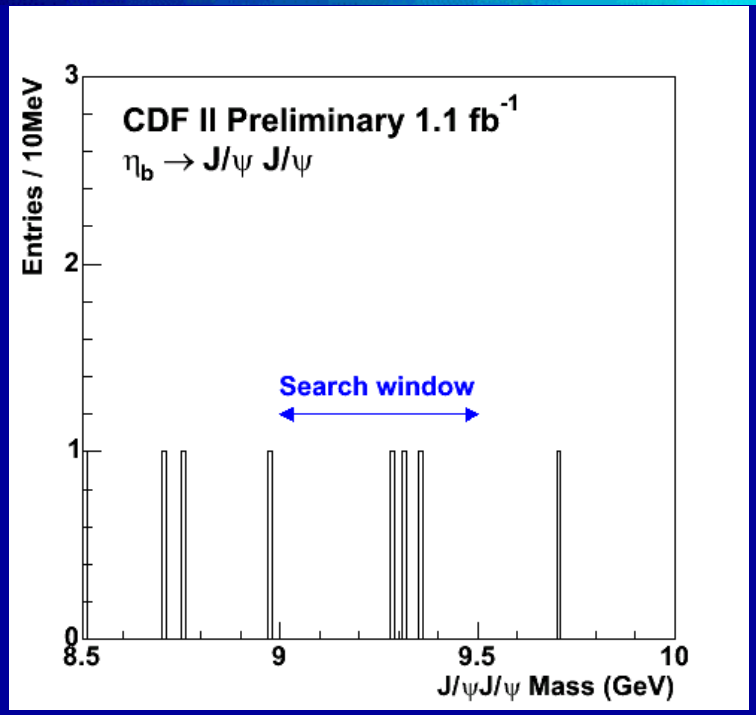
Run II, 1.1 fb^{-1}

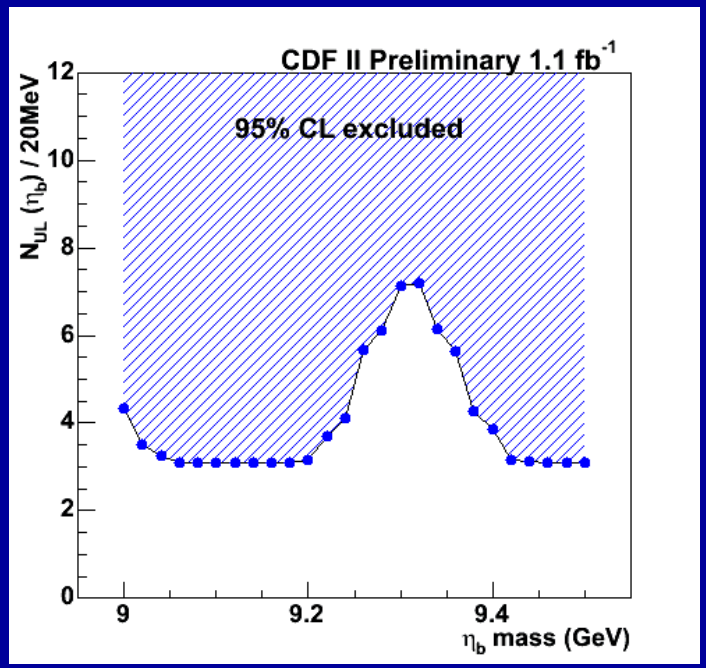
$$\sigma(p\bar{p} \to \psi(2S)X) \cdot Br(\psi(2S) \to \mu^+\mu^-) = 3.17 \pm 0.04(\text{stat}) \pm 0.28(\text{syst})\ \text{nb}$$



η_b search

Run II, 1.1 fb^{-1}





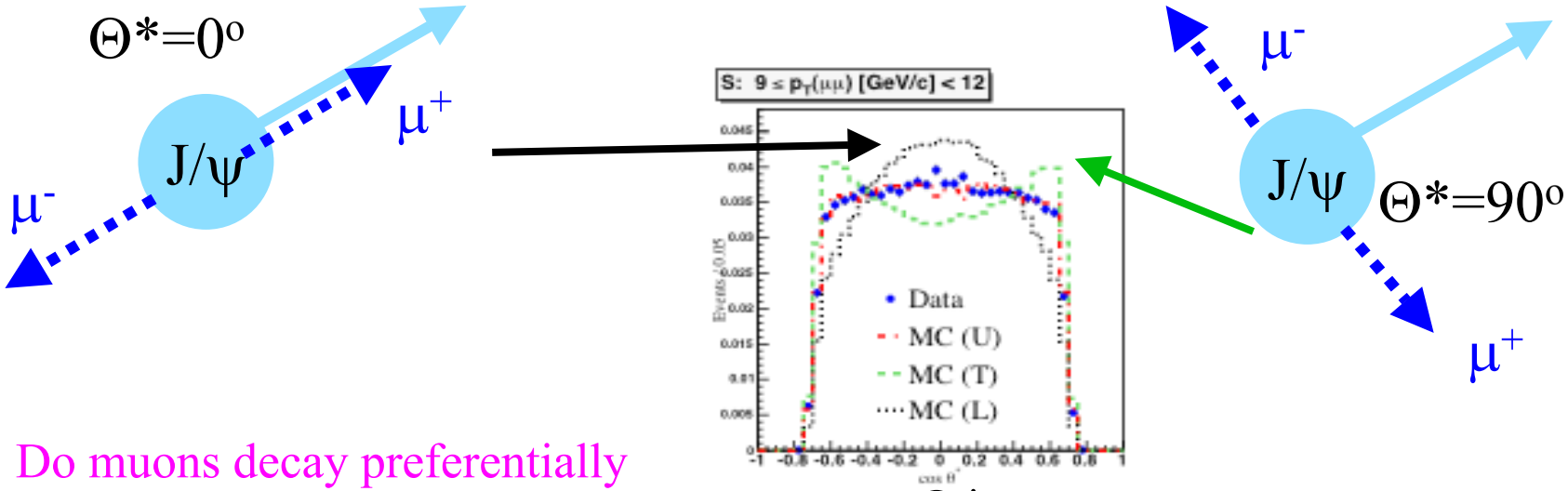
$$\frac{\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0GeV) \cdot Br(\eta_b \to J/\psi J/\psi)}{\sigma(p\bar{p} \to H_b \to J/\psi X); |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0GeV)} < 5.0 \times 10^{-3}$$

$$\sigma(p\bar{p} \to b \to J/\psi X, |y(J/\psi)| < 0.6, p_T(J/\psi) > 3GeV) = 0.152 \pm 0.005 \pm 0.015\ \mu b$$

$$\sigma(p\bar{p} \to \eta_b X, |y(\eta_b)| < 0.6, p_T(\eta_b) > 3GeV) \cdot Br(\eta_b \to J/\psi J/\psi) \cdot [Br(J/\psi \to \mu\mu)]^2 < 2.6\ pb$$

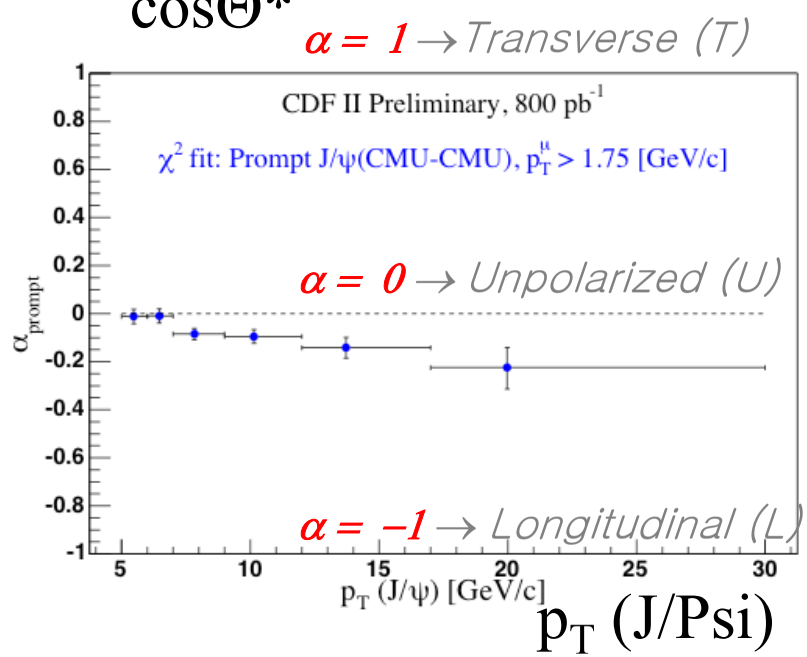
J/ψ Spin Alignment

Run II, 800 pb^{-1}

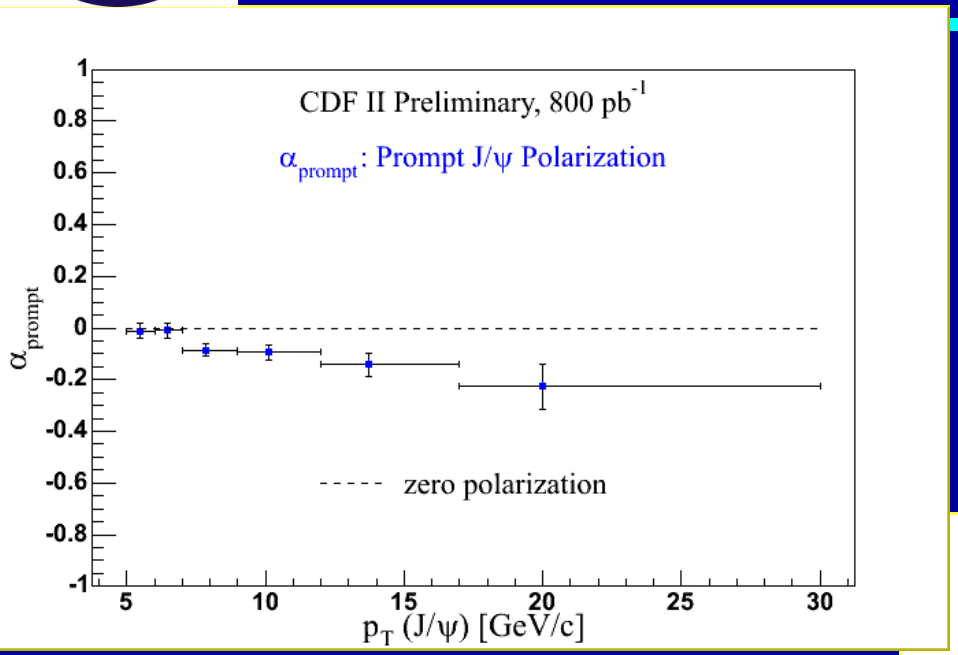


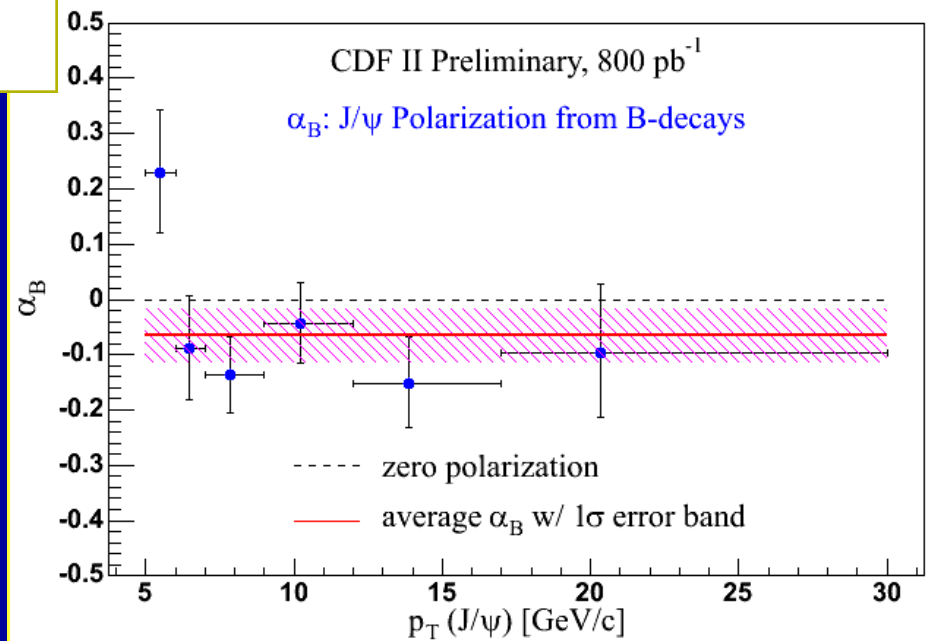
- Do muons decay preferentially into any direction?

- CDF data prefer slight longitudinal polarization:
  - Challenges color-octet models
    - NRQCD prefers transverse polarization
  - Predicted by Khoze, Martin, Ryskin, Stirling:
    - Eur. Phys. J. C39, 163 (2005)



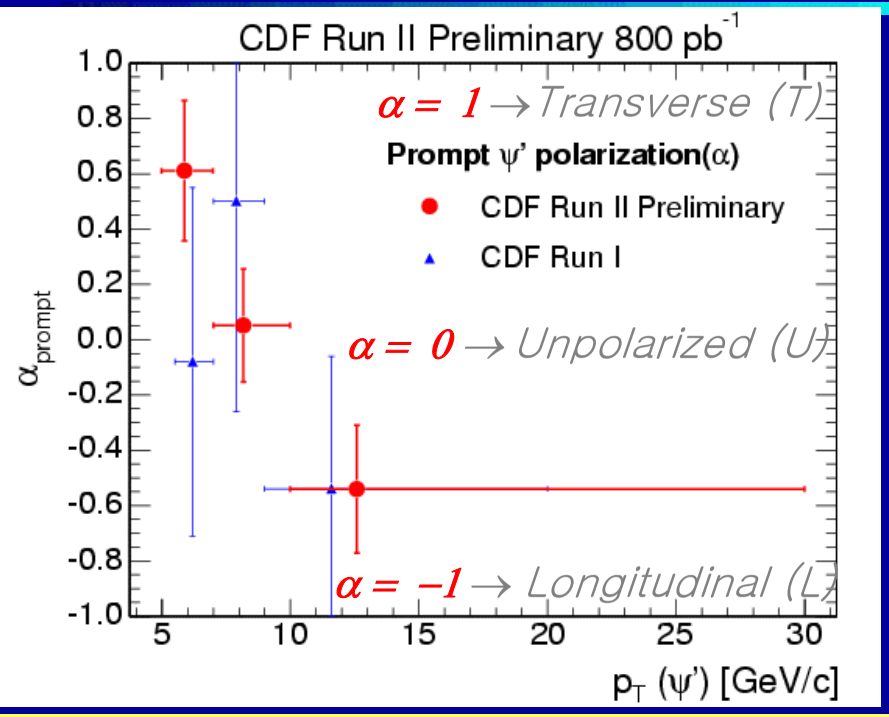
J/ψ Spin Alignment

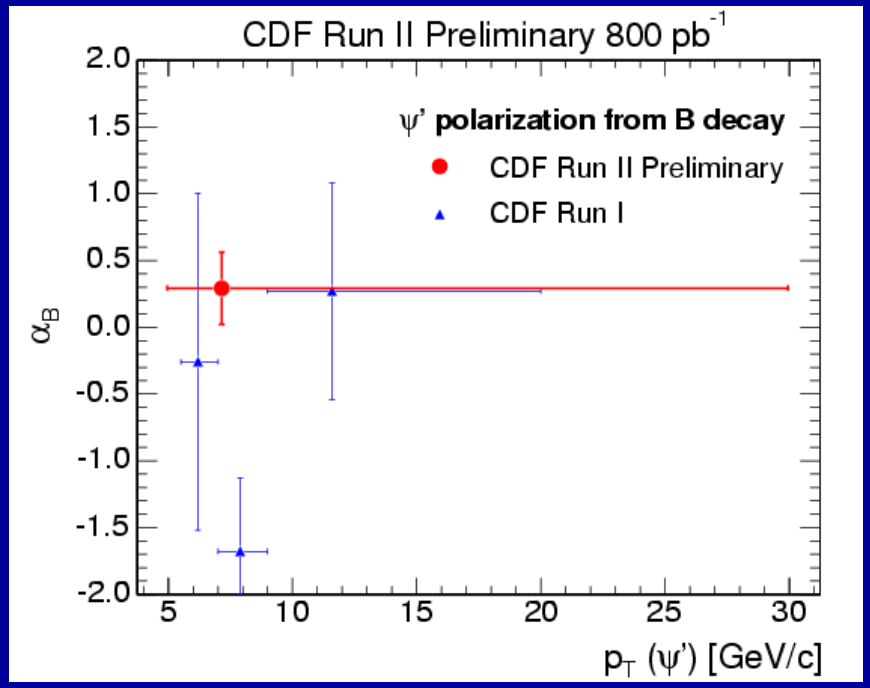




ψ(2S) Spin Alignment

Run II, 800 pb^{-1}



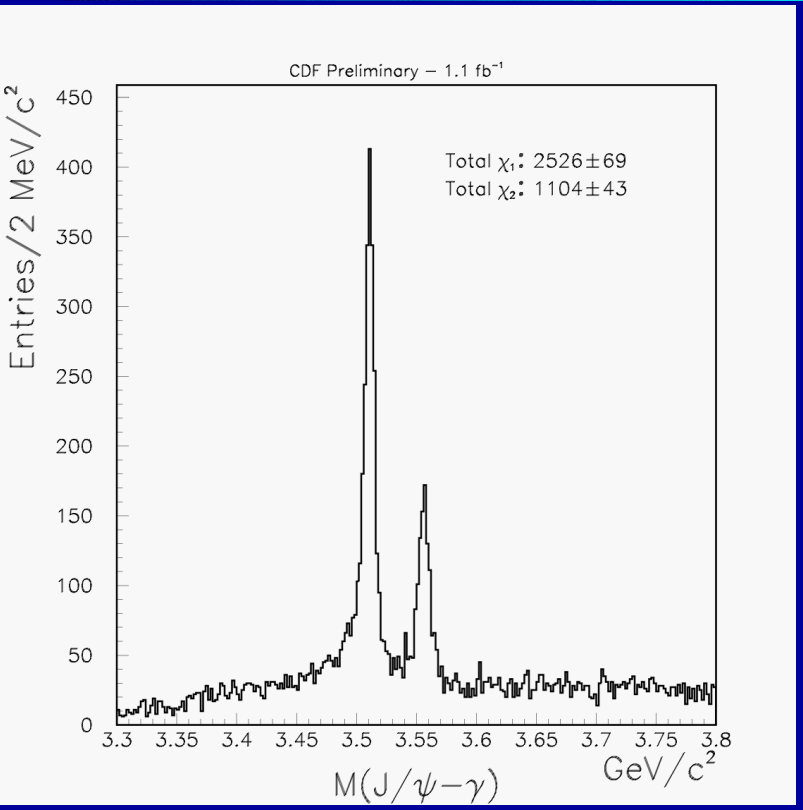


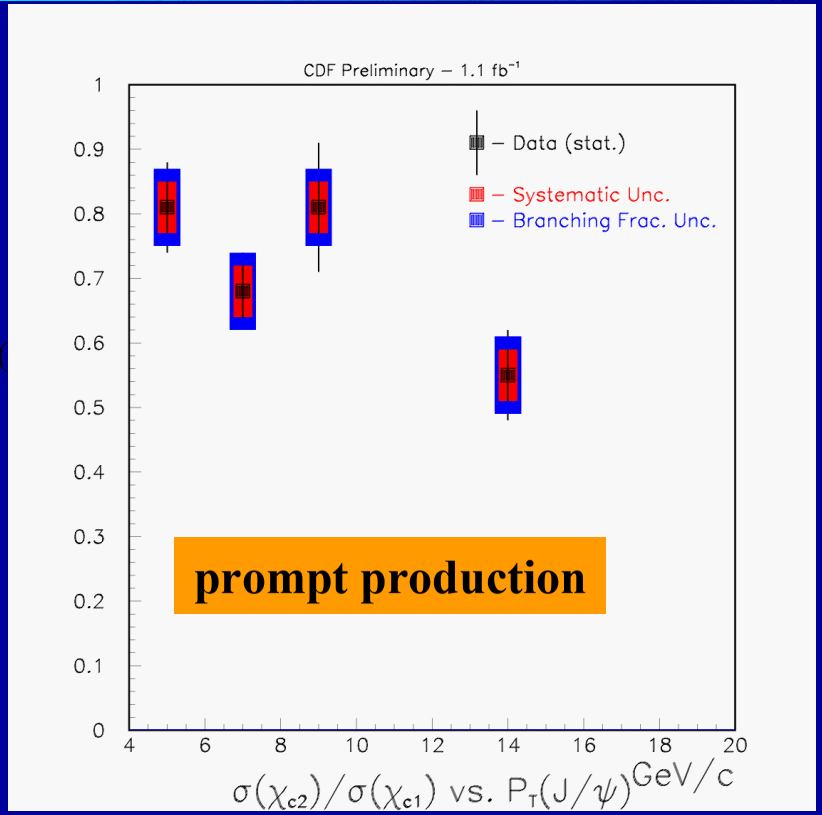
- The polarization in the highest p_T bin is longitudinal in contradiction to the NRQCD prediction of large transverse polarization

$$\alpha_B = 0.28 \pm 0.27\,(stat) \pm 0.03\,(syst)$$

χ_c Production

Run II, 1.1 fb^{-1}





$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.70 \pm 0.04(stat) \pm 0.04(syst) \pm 0.06(BR)$$

For prompt production

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.25 \pm 0.07(stat) \pm 0.01(syst) \pm 0.02(BR)$$

For production from B decay

New level of precision and good constraint for production models