Heavy B Hadrons

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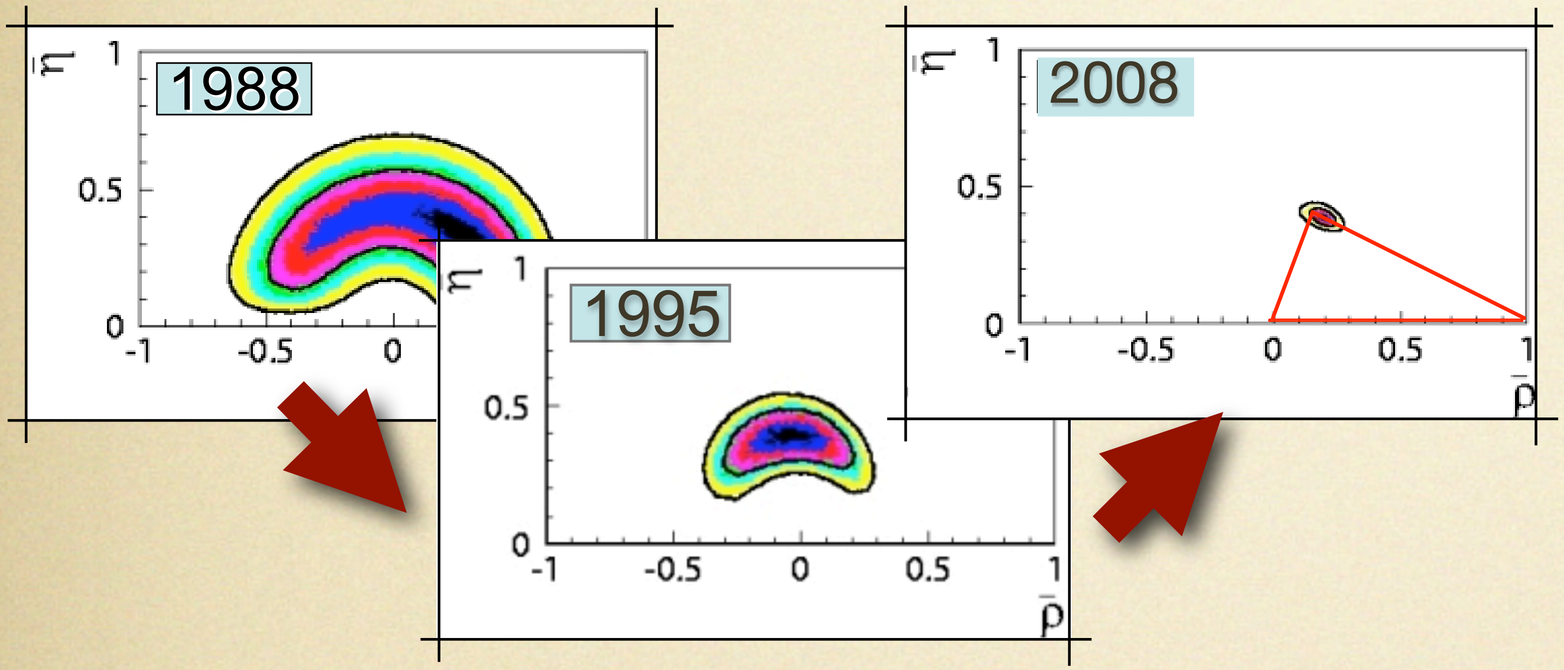
For the CDF and DO Collaborations

Prelude



10 Years of very successful experimental and theoretical progresses have strongly constrained New Physics effects in the B^0 and $B^{\pm}$ sector

... is there any remaining space to see sizable NP effects in others Heavy Flavor sectors?

.... NP in general will not obey SM relations between B and B_s decays

➡ B_s decays a priori independent chapter in nature's book on fundamental dynamics

$B_s(t) \to \psi\phi, \psi\eta, \phi\phi$ not a repetition of lessons from B_d & B_u decays!

I. Bigi, CERN Theory Institute '08

the actors of this new phase:

- today: Tevatron, B-factories@Y(5S)
- tomorrow: LHC, SuperB, ...

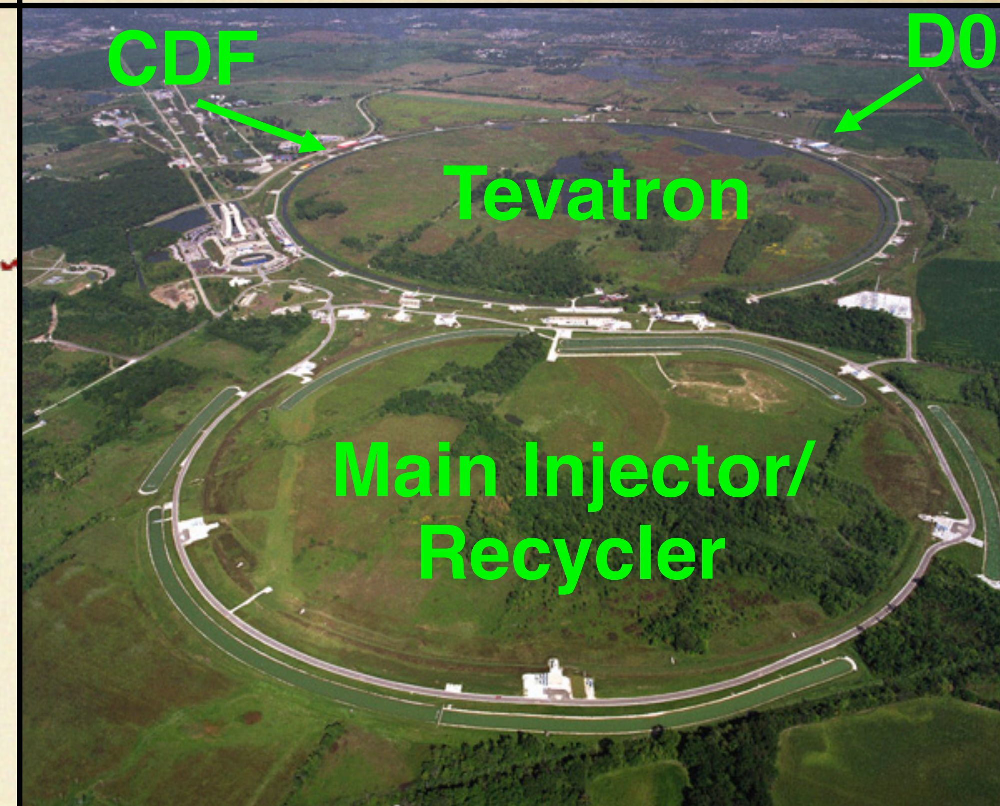
Outline

- Heavy B hadron factories
- Search for new physics in B_s mixing and CPV
- Search for new physics in Rare modes
- Outlook and Conclusions

Note: no time here to cover all the results, for a complete list:
http://www-cdf.fnal.gov
http://www-d0.fnal.gov
http://belle.kek.jp

Heavy B Hadron Factories

Tevatron

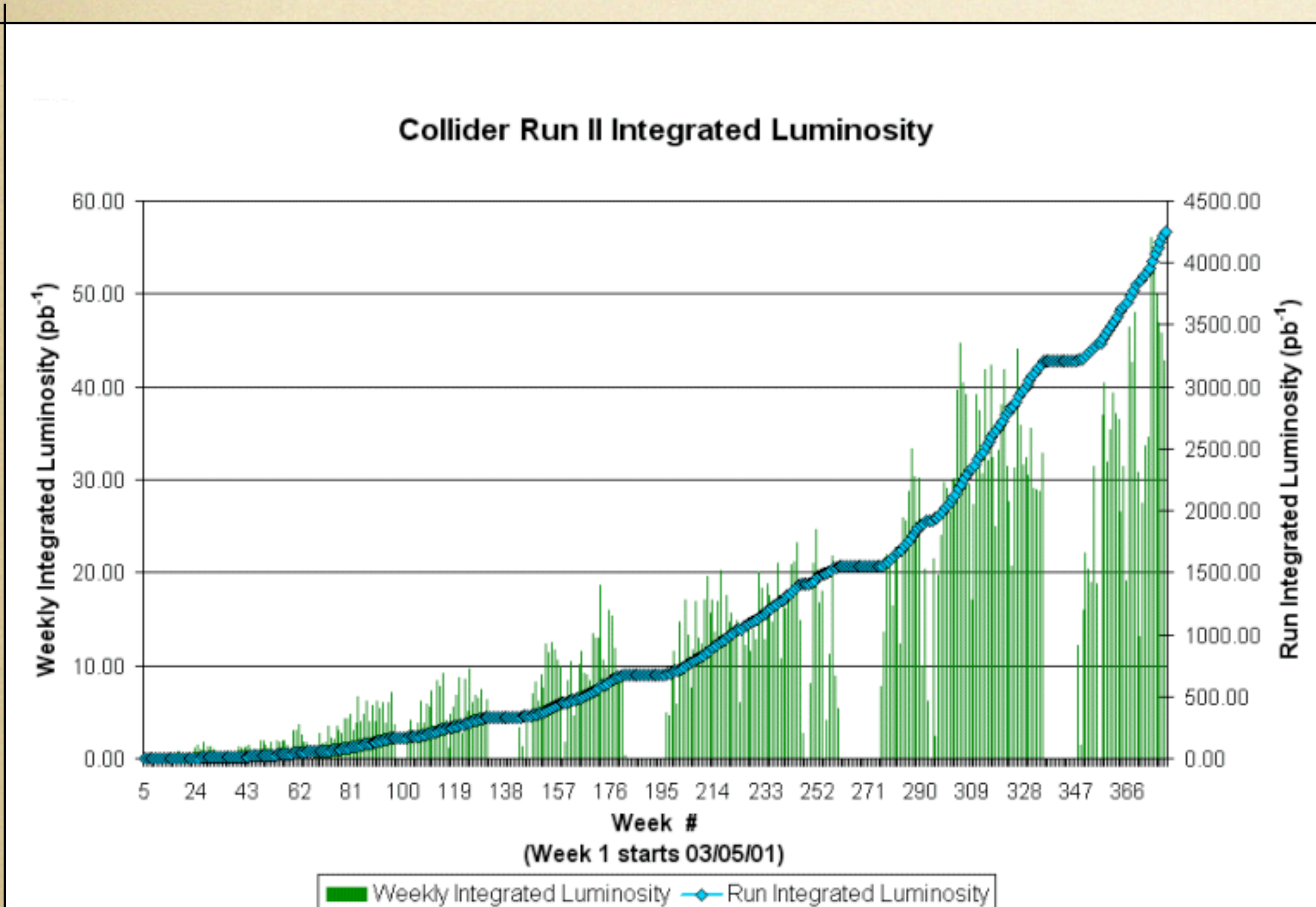


$p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

Peak instantaneous luminosities of $3.2\times10^{32}cm^{-2}s^{-1}$

>4 fb^{-1} (per experiment) delivered so far

6÷8 fb^{-1} (per experiment) by end of 2009/10



☺

Large Heavy Flavor x-sections: $\sigma(bb)\sim50\ \mu b$

All kind of B hadrons produced: B_s, B_c, Λ_b, ...

B hadrons produced with large Lorentz boost

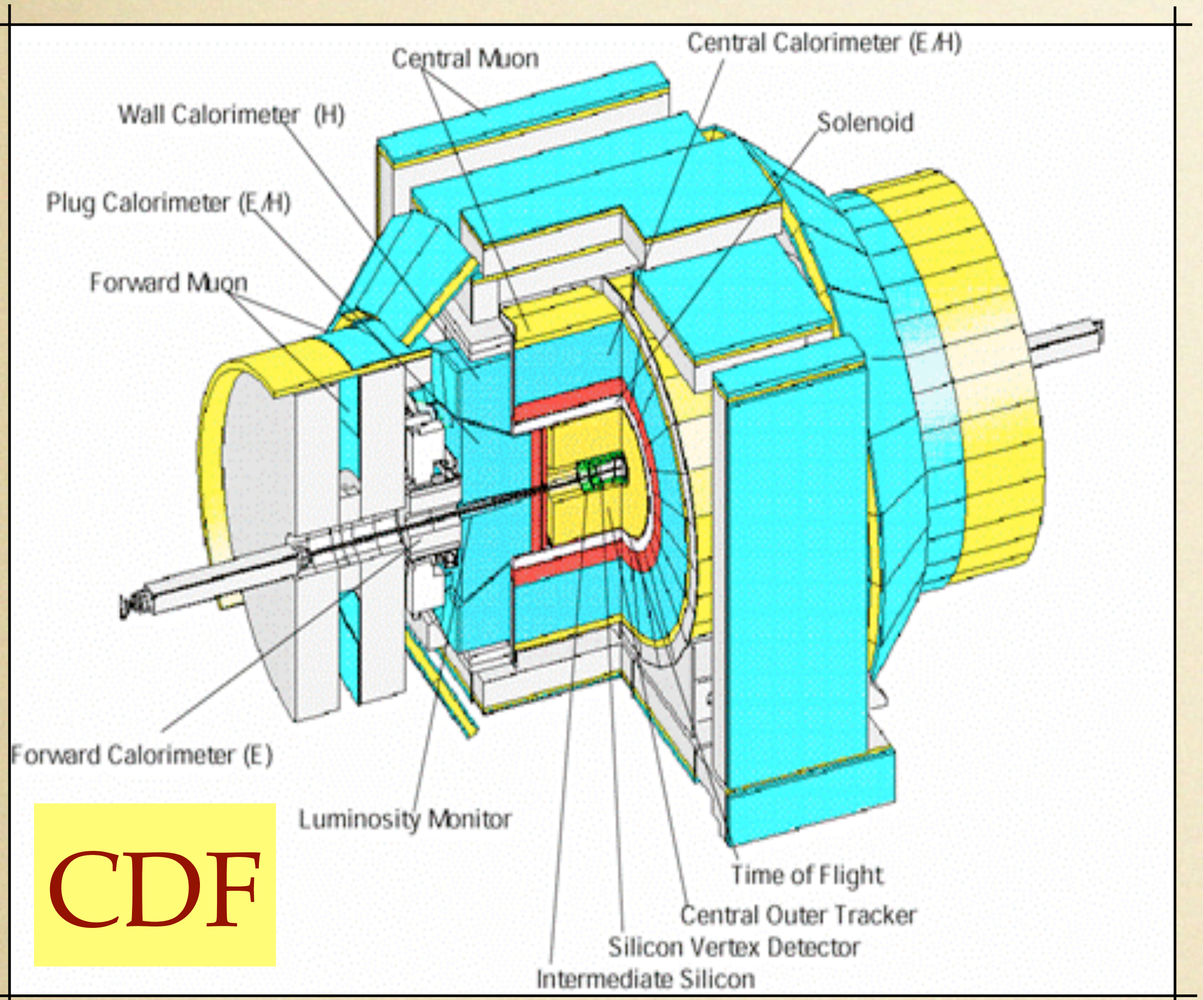
☹

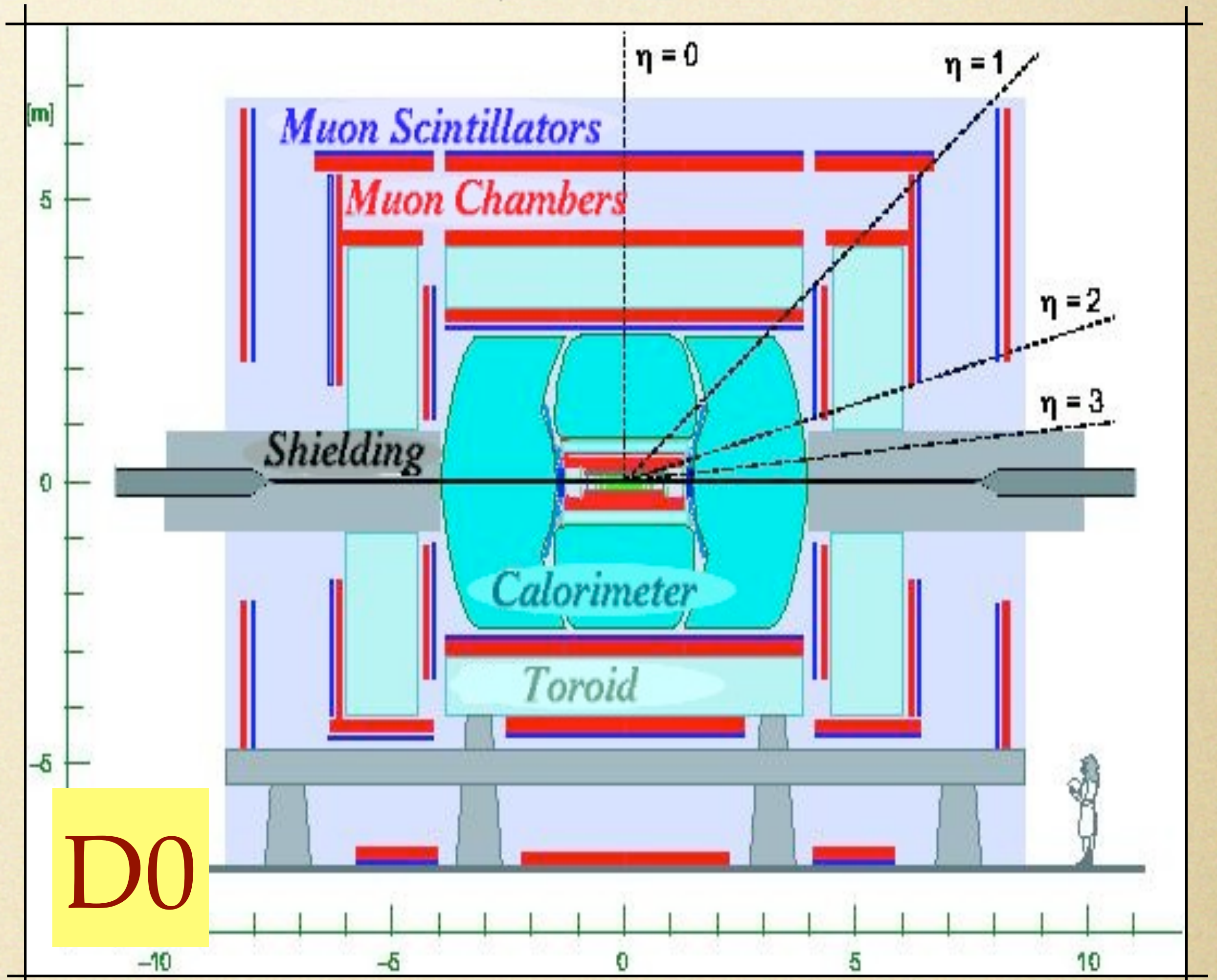
Huge total x-section: $\sim10^3\times\sigma(bb)$

$<N_{trks}> \sim 4\times$B-factories, multiple interactions

Challenge for Detectors, Triggers and Reconstruction

CDF and D0



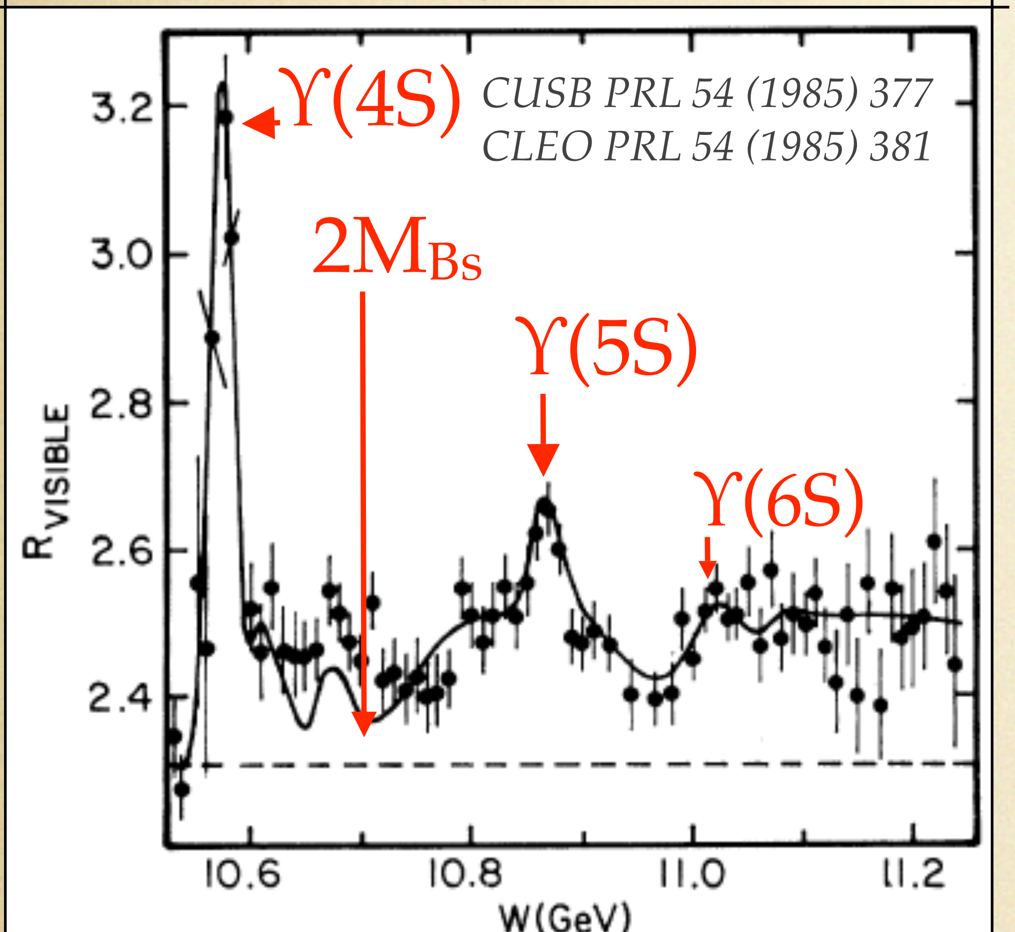


- Silicon Vertex + Drift Chamber
- Displaced Tracks trigger@L2
- Muon Trigger coverage: |η|<1
- Excellent Momentum Resolution
- Particle ID TOF and dE/dx

- Solenoid: 2T, weekly reversed polarity
- Muon Trigger coverage: |η|<2.2
- Excellent Calorimetry and electron ID
- New L0 installed in 2006

Complementary strengths

B_s @ Υ(5S)



Υ(5S) discovered by CLEO and CUSB in 1985

$$M_{\Upsilon(5S)} = (10.865 \pm 0.008)\ GeV$$
$$\Gamma_{\Upsilon(5S)} = (110 \pm 13)\ MeV$$

Massive enough to produce:

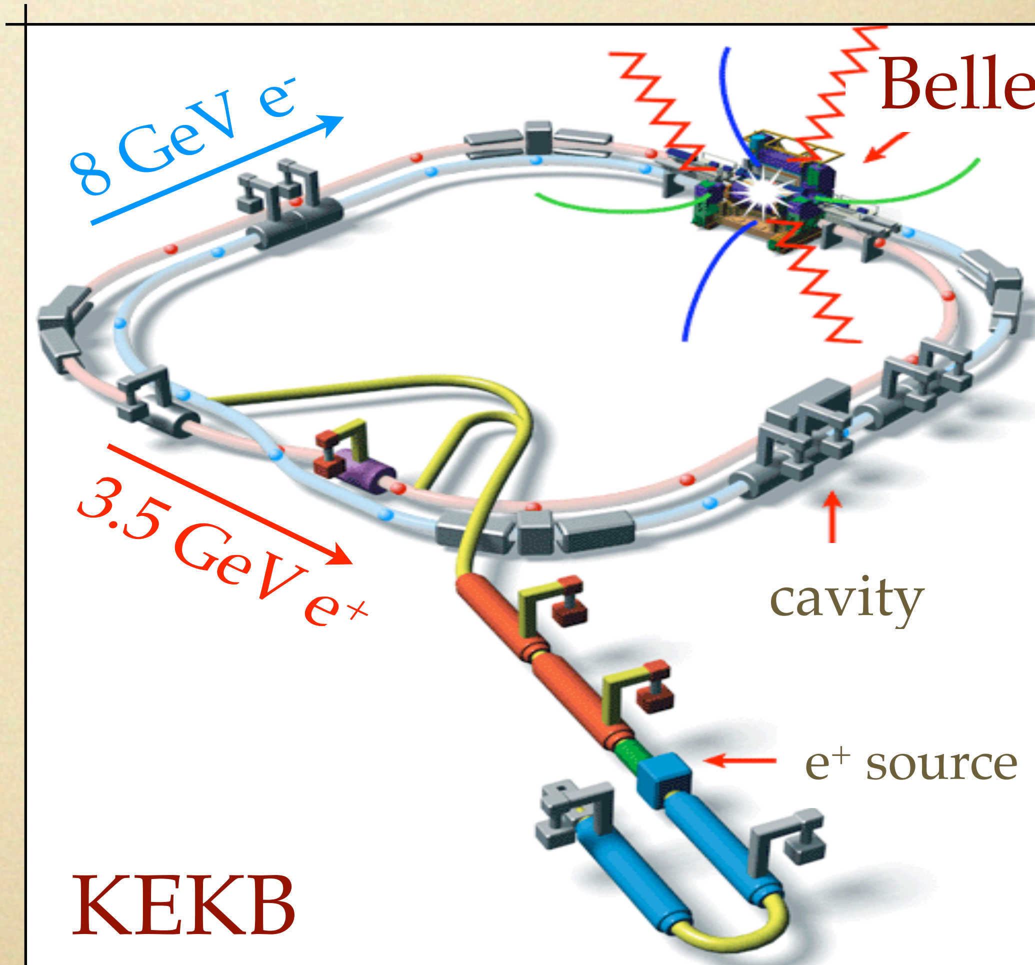
$$B_s\bar{B}_s,\ B_s\bar{B}_s^*,\ B_s^*\bar{B}_s^*$$

Υ(4S) → Υ(5S) increasing by 2.7% E_{beam}

- E_{e+}: 3.500 → 3.595 GeV
- E_{e-}: 7.996 → 8.211 GeV
- same boost βγ=0.425
- same Belle detector/trigger

$f_s = (19.5^{+3.0}_{-2.3})\% \rightarrow$ **B_s production ~ 100K B_s/fb^{-1}**

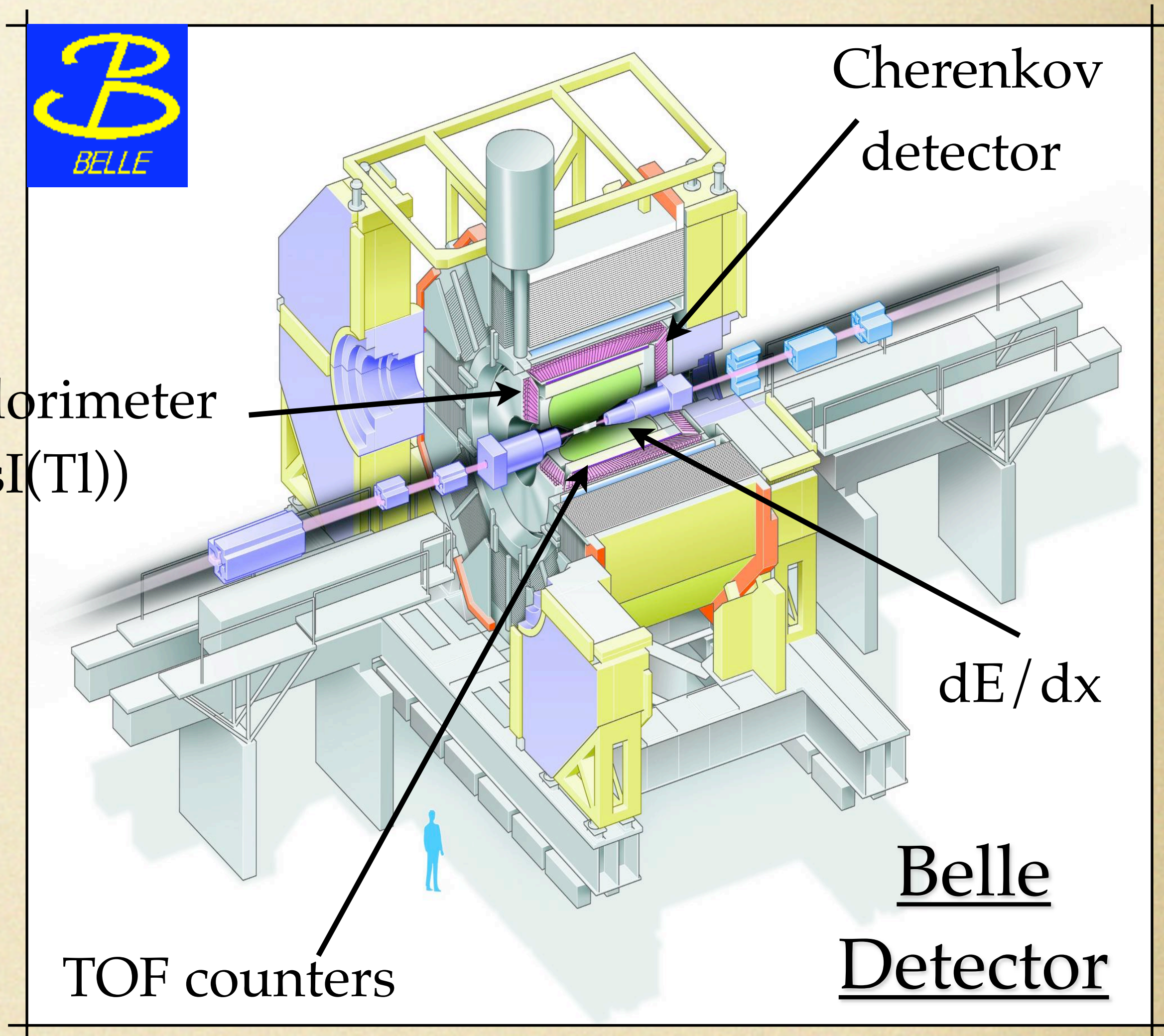
Belle Coll., PRL 98, 052001 (2007)



B_s @ $\Upsilon(5S)$

Datasets

- 1985: CESR: CLEO+CUSB ~(0.07+0.12) fb^{-1}
- 2003: CESR: CLEO III ~0.42 fb^{-1}
- 2005: KEKB: Belle ~1.86 fb^{-1}
- 2006: KEKB: Belle ~21.7 fb^{-1}



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clean source of B_s mesons

access of interesting decays hard for hadron machines:

- high trigger efficiency
- sophisticated PID
- access to neutrals (γ,π^0,η)

☹

smaller number of B_s available

B_s only (no B_c, b-baryons, ...)

no time dependent CPV B_s analysis: $\Delta z \sim \beta\gamma c\tau_{osc} \sim 46\mu m \leftrightarrow \sigma_z \sim 150\mu m$

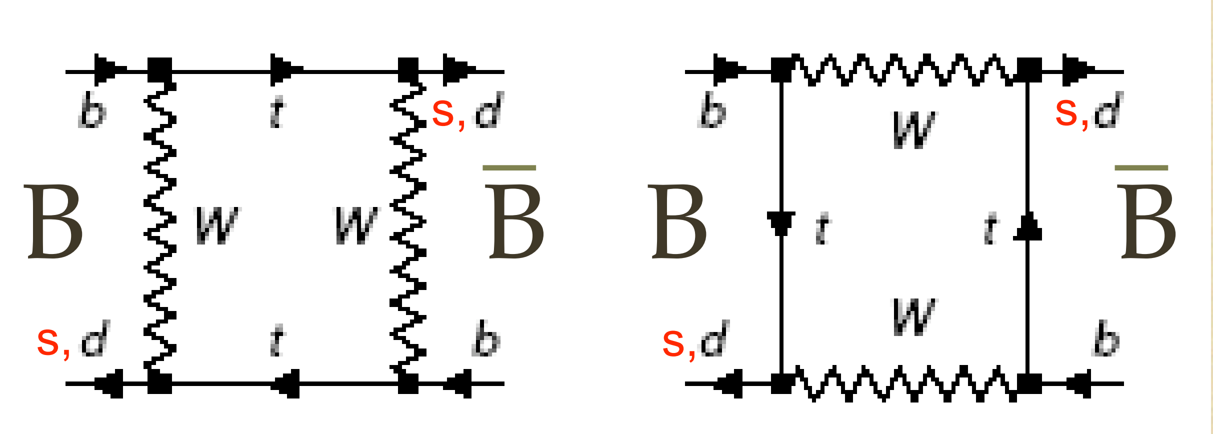
Complementarity respect to hadron machines

Search for NP in B_s Mixing and CPV

B_s Mixing

Neutral B mesons can spontaneously transform in the corresponding antiparticle

In the SM generated via $\Delta F=2$ 2nd order weak interactions, dominated by the exchange of a top quark



generators of
off-diagonal elements

New exotic particles may run in the loops mixing sensitive to NP

The time evolution of the B_s oscillations is governed by the Schrodinger equation

$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle \\ |\overline{B}(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle \\ |\overline{B}(t)\rangle\end{pmatrix}$$

$$\left.\begin{array}{ll} |B_H\rangle = p|B\rangle + q|\overline{B}\rangle & M_H = M_{11} + M_{12} \\ |B_L\rangle = p|B\rangle - q|\overline{B}\rangle & M_L = M_{11} - M_{12} \end{array}\right\}$$ Physical eigenstates

Three observable:

$$\Delta m_s = M_H - M_L = 2|M_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi_s$$

$$\phi_s = \arg\left(-M_{12}/\Gamma_{12}\right)$$

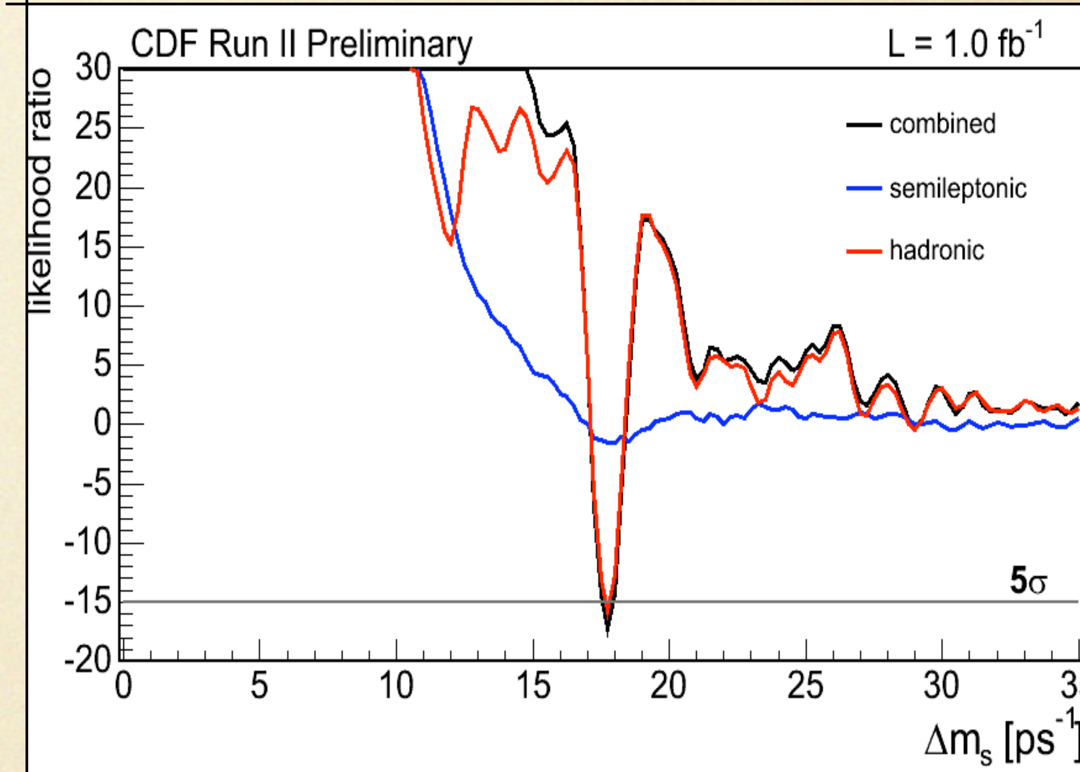
- NP can significantly affect M_{12} and ϕ_s

- Γ_{12} dominated by $b \rightarrow ccs$ tree-level decays is instead insensitive to NP

Δm_s and $|M_{12}|$

- B_s mixing observed at 5σ by CDF in 2006 with ~1fb^{-1} of data
- Δm_s measured with great precision:

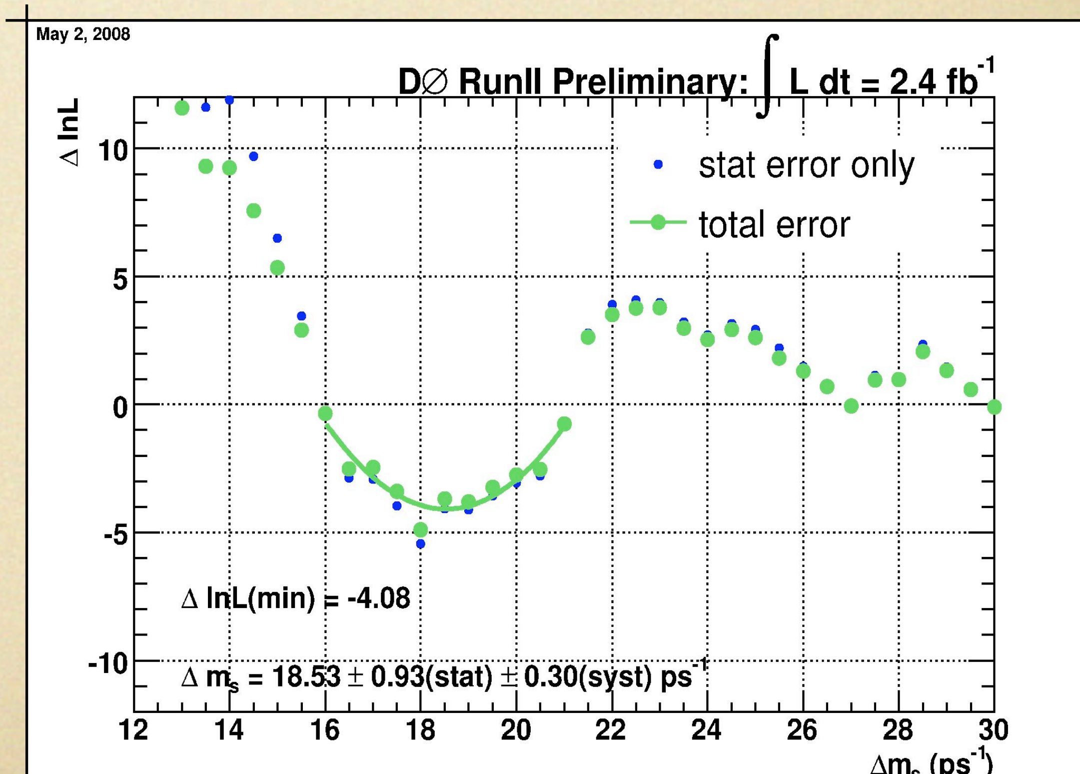
$$\Delta m_s = 17.77 \pm 0.10(stat) \pm 0.07(sys)\ ps^{-1}$$
$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(exp)^{+0.0081}_{-0.0060}(theor)$$



CDF Coll., PRL 97 242003 2006

- D0 recent update (2.4 fb^{-1}): significance up to 3σ, results consistent with CDF

$$\Delta m_s = 18.53 \pm 0.90(stat) \pm 0.30(sys)\ ps^{-1}$$



D0 Coll., D0-note 5618

- extraction of NP contributions is now dominated by theory uncertainty

known @30% from LQCD

$$M_{12} = \frac{G_F^2 M_W^2 M_{B_s} |V_{ts}^* V_{tb}|^2}{12\pi^2} f_{B_s}^2 B_{B_s} \eta_B S_0(x_t^2)$$

short-distance information (i.e. NP) is contained here

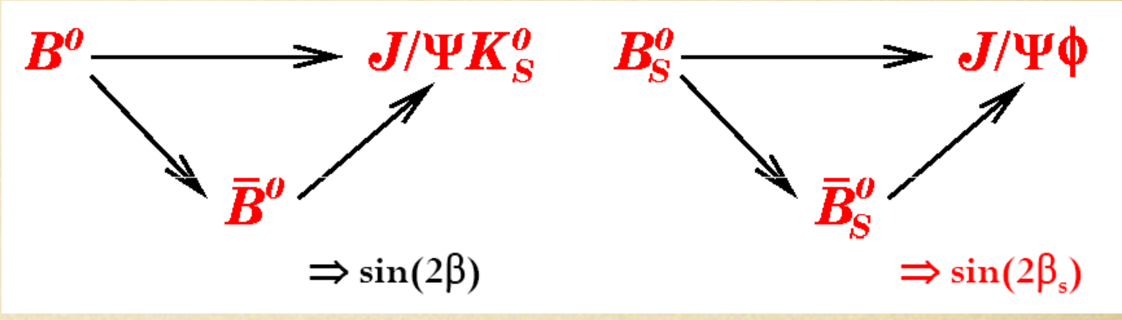
New physics and mixing phase

- B_s mixing phase small in the SM ⇒ processes depending on ϕ_s very sensitive to NP contributions

$$\phi_s = \phi_s^{SM} + \phi_s^{NP} \sim \phi_s^{NP}$$

~0.004 rad

- Experimental sensitivity on NP contributions to ϕ_s comes from two observable:
    - A_{SL}: charge asymmetry in B_s semi-leptonic decays: $A_{SL} \propto \tan(\phi_s)$
    - CKM angle β_s: CP violation in $B_s \to J/\psi\phi$ decay:



In the SM ϕ_s connected with the phases of CKM matrix elements ⇒ in presence of NP the same new physics mixing phase would add to β_s

$$2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} \sim -\phi_s^{NP}$$

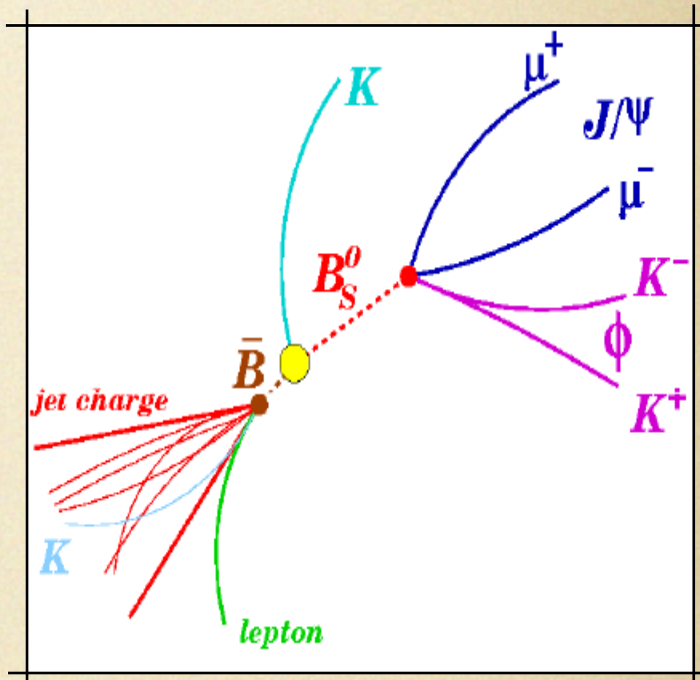
$$\beta_s^{SM} = arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$ ~0.02 rad

A large CP violation phase in $B_s \to J/\psi\phi$ unequivocal sign of physics beyond the SM

$\Delta\Gamma_s$ and β_s via $B_s \to J/\psi\phi$

- Max sensitivity to β_s retained in time dependent CP asymmetry analysis
  - similar to $B^0 \to J/\psi K_s$ in the B_d system, but:
    - B_s oscillate much more rapidly
    - final state mix of CP-even (L=0,2) and CP-odd (L=1) components

      $\Rightarrow$ angular analysis to disentangle the two contributions



Analysis flow:

1. Reconstruct decays from stable products:

   $B_s \to J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$

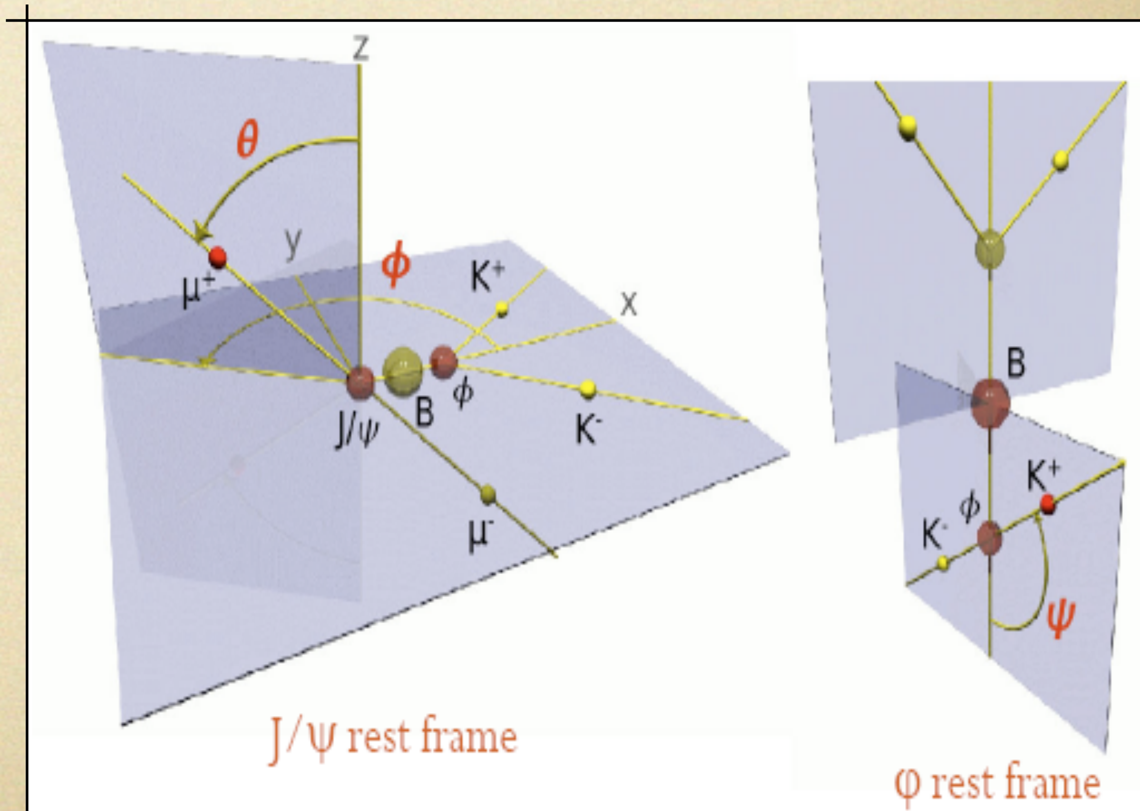
   $B^0 \to J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$ (control sample)
2. Measure proper decay time:

   $ct = m_B * L_{xy}/p_T$

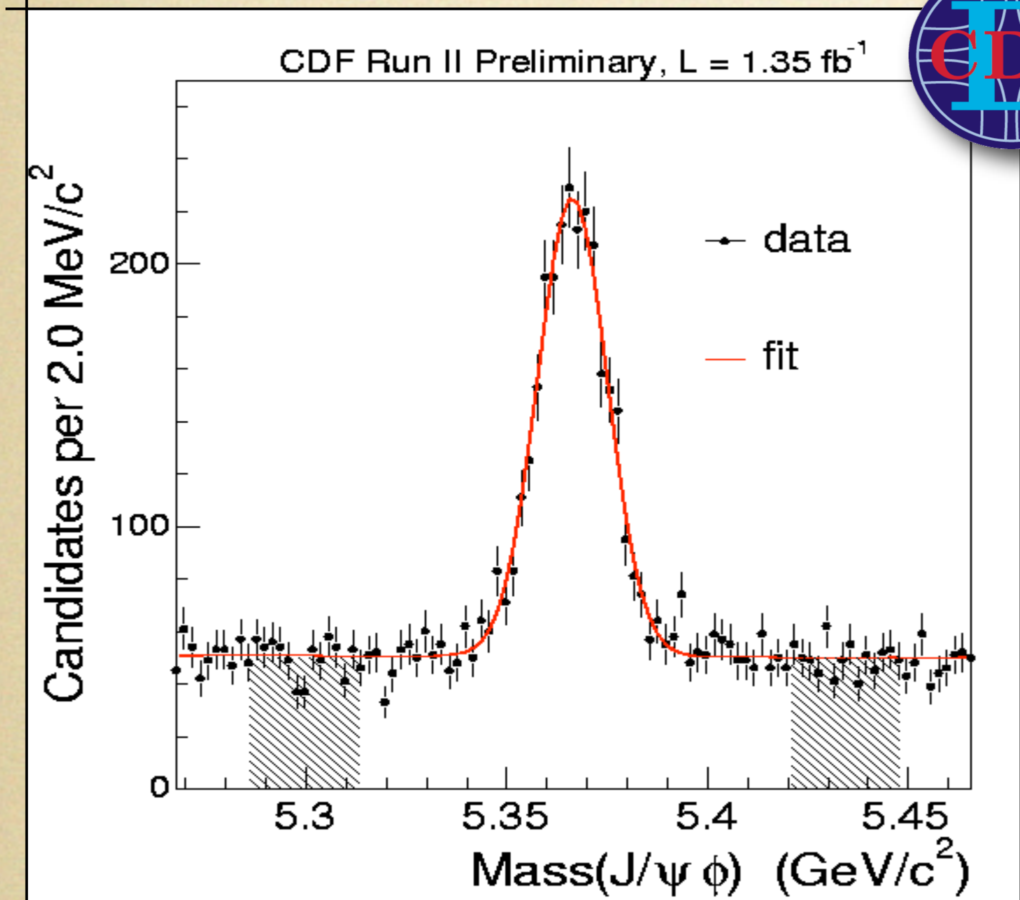
   proper time resolution essential to resolve oscillations
3. Measure decay angles in transversity base: $\vec{w} = (\vartheta, \phi, \psi)$
4. Identify B_s flavor at production time:

   flavor tagging (tag decision ξ)
5. Perform maximum likelihood fit:

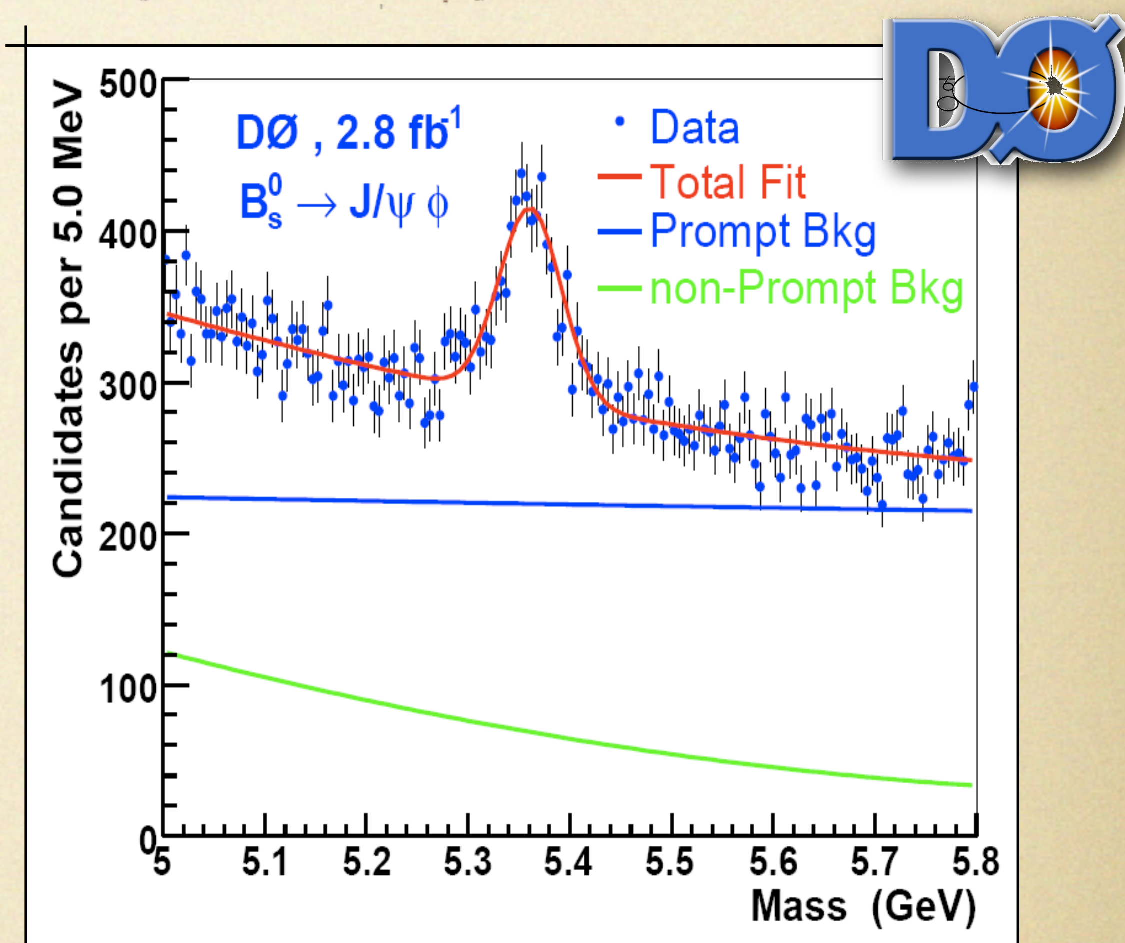
   multidimensional likelihood f(m, ct, w , ξ), 27 parameters



J/ψφ Signals



Signal ~2000 in 1.35 fb^{-1}
S/B ~ 2

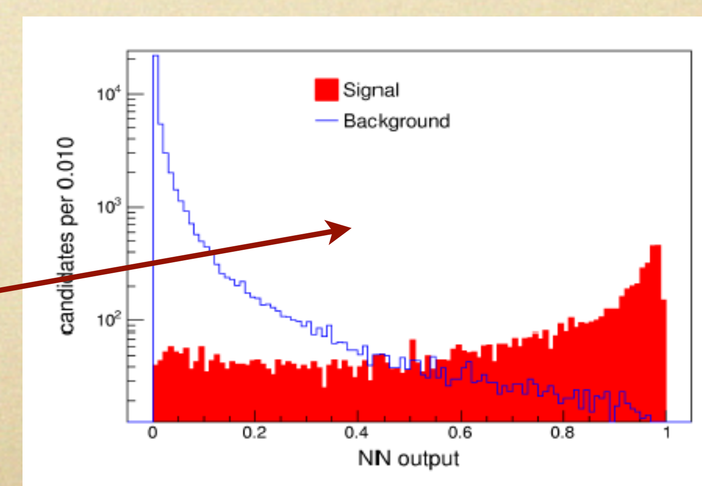


Signal ~2000 in 2.8 fb^{-1}
S/B ~ 0.5

Selection:

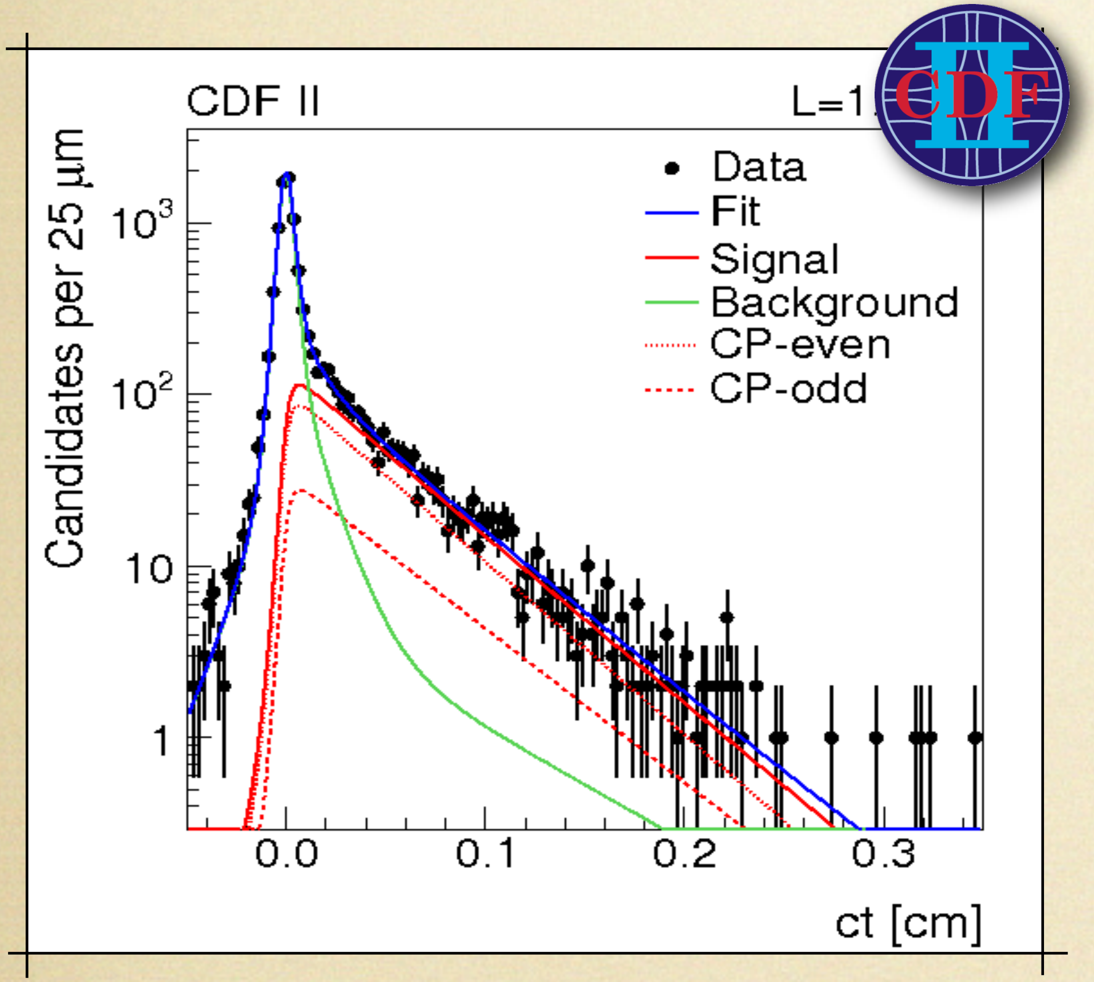
D0: "square cuts" event selection (no PID)

CDF: neural network including TOF+dE/dx PID



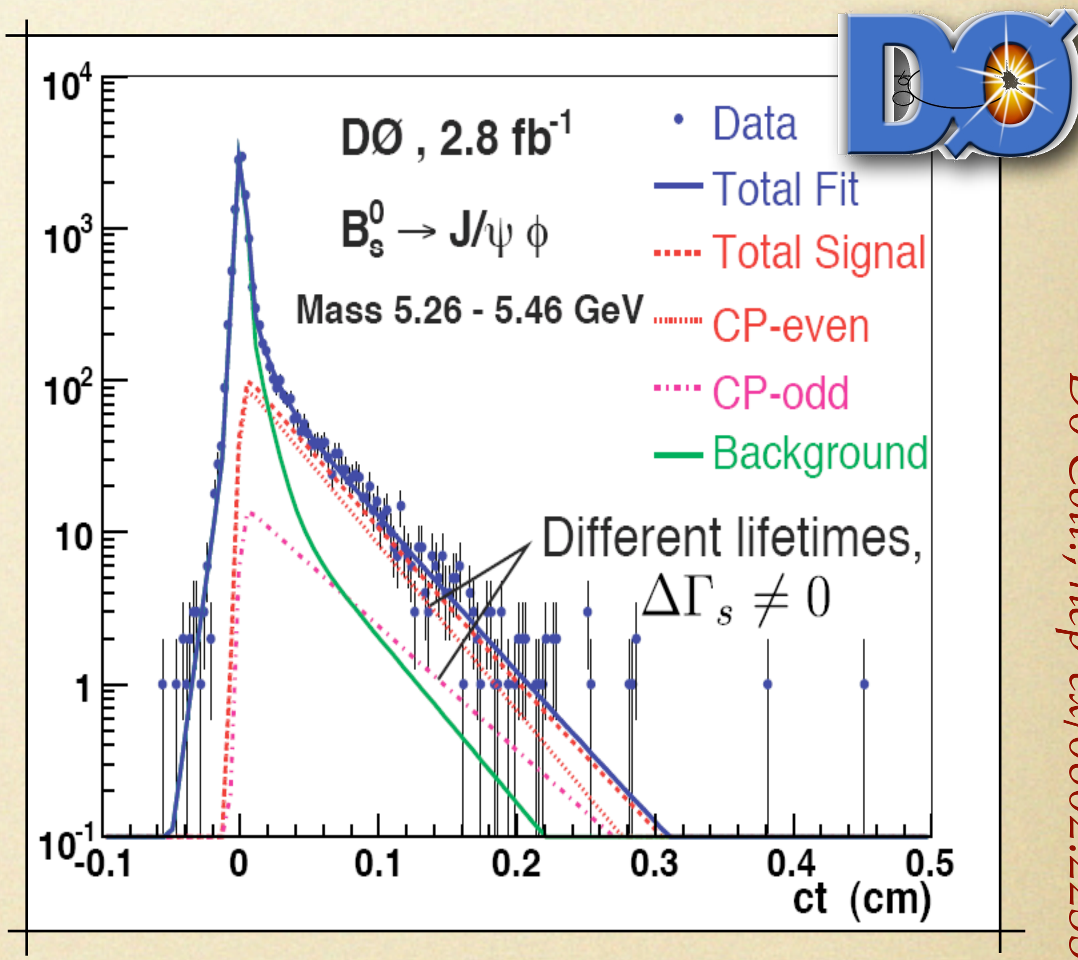
Results: average B_s lifetime ($\beta_s = \beta_s^{SM}$)

CDF Coll. , PRL 100 121803 (2008)



$$\tau_s = 1.52 \pm 0.04 \pm 0.02\ ps$$
$$\Delta\Gamma_s = 0.08 \pm 0.06 \pm 0.01\ ps^{-1}$$

D0 Coll., hep-ex/0802.2255



$$\tau_s = 1.53 \pm 0.06 \pm 0.01\ ps$$
$$\Delta\Gamma_s = 0.14 \pm 0.07^{+0.02}_{-0.01}\ ps^{-1}$$

World best measurements

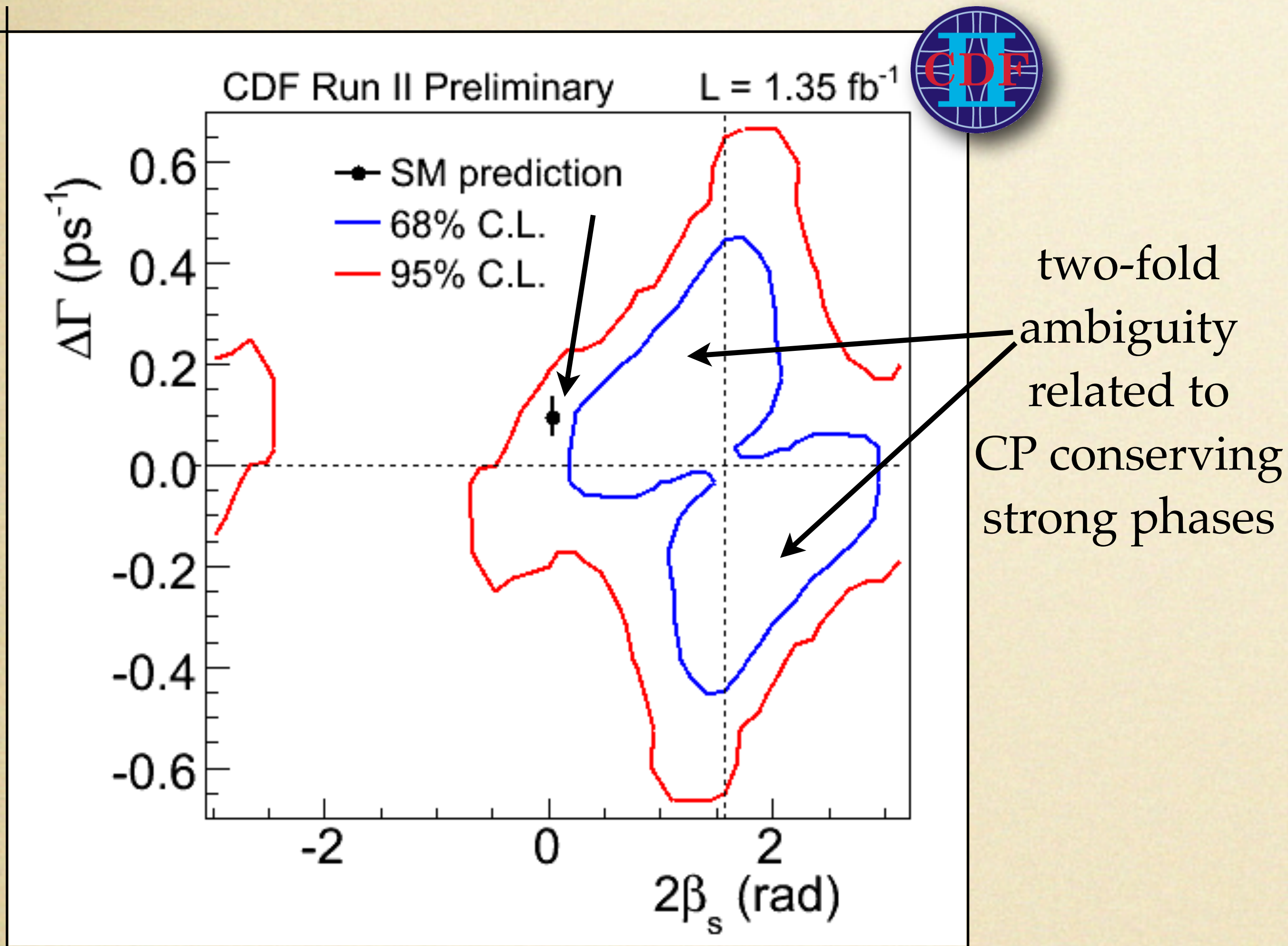
consistent with B^0 lifetime: $\tau(B^0)$ PDG08 = 1.530±0.009 ps

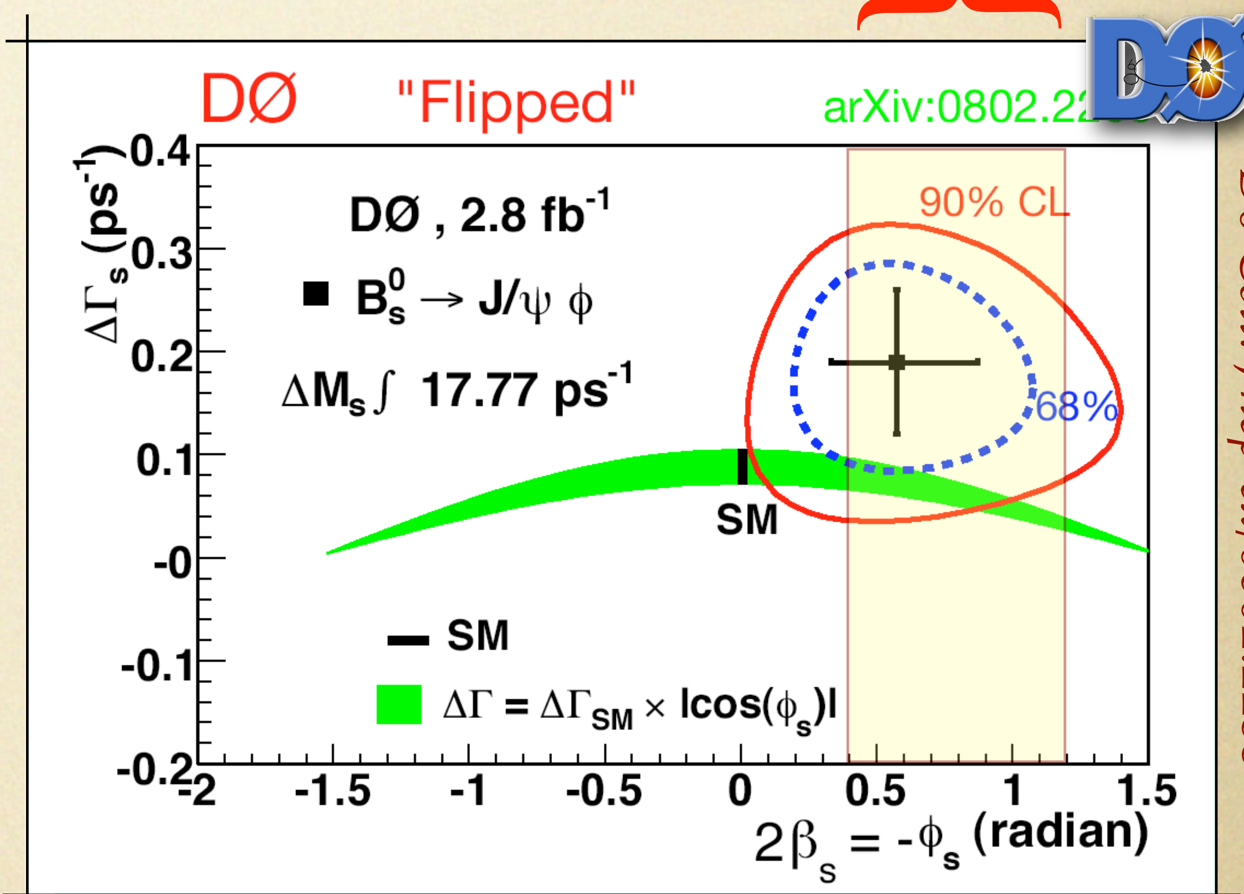
Results: fit for β_s

CDF+constr. 68% CL

Results expressed as confidence regions in the β_s–$\Delta\Gamma_s$ plane

CDF Coll. , PRL 100 161802 (2008)





D0 Coll. , hep-ex/0802.2255

Modified Feldman Cousin confidence region to include systematic uncertainties

P-value (SM): 0.15 (1.5 σ)

strong phases constrained to $B_d \to J/\psi K^*$

Point estimate:

$$\Delta\Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01}\ ps^{-1}$$

$$\phi_s = -2\beta_s = -0.57^{+0.24+0.07}_{-0.30-0.02}\ rad$$

P-value (SM): 0.066 (1.8 σ)

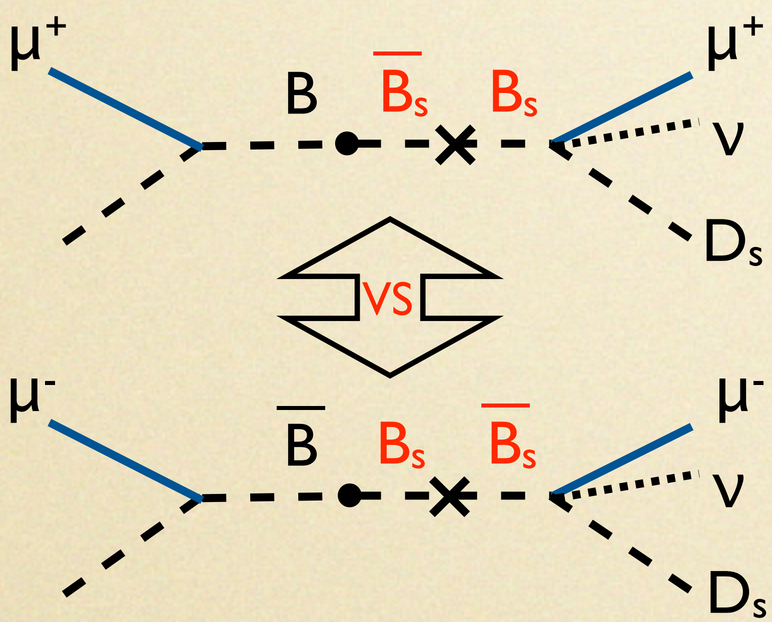
Mild tension with the SM, both experiments in the same direction

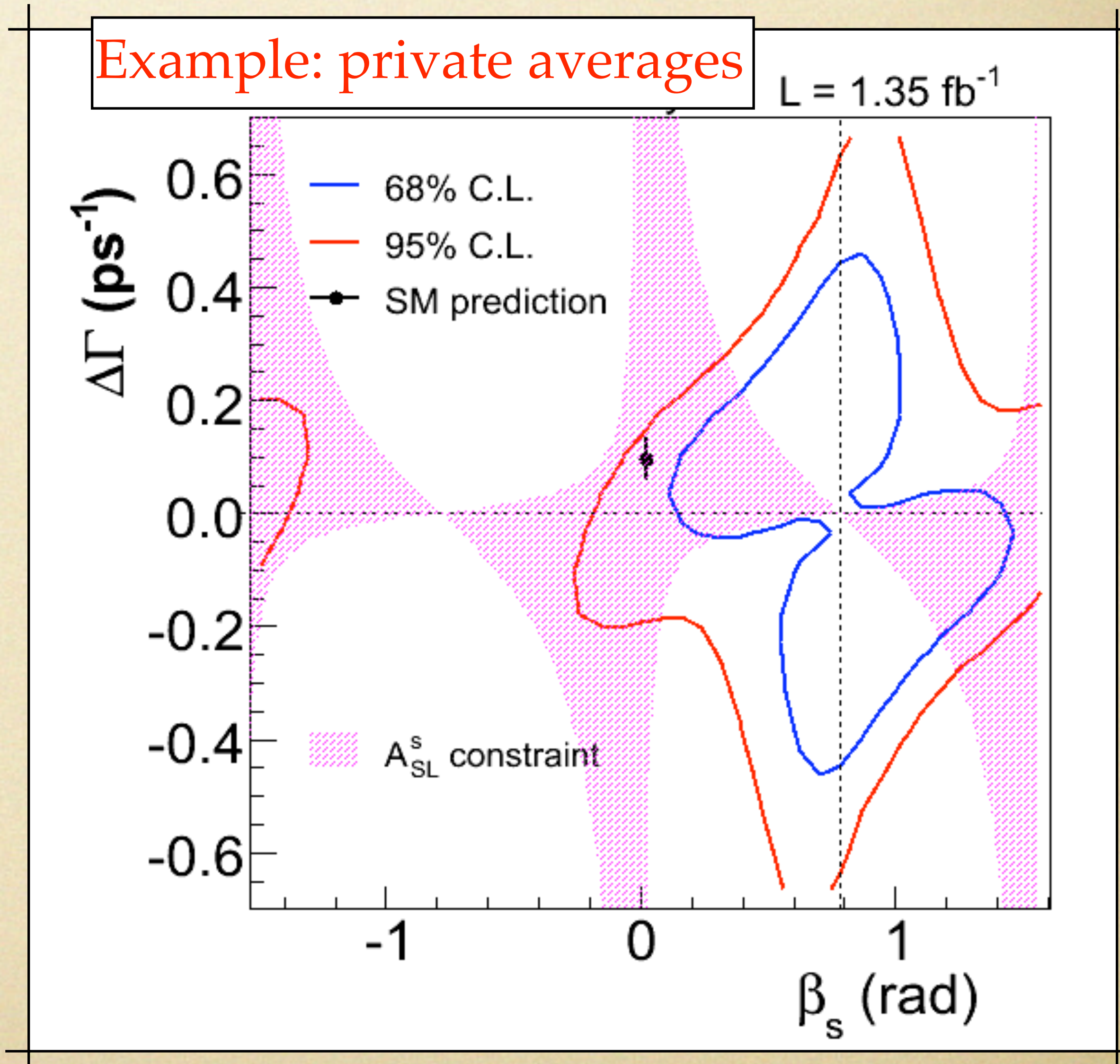
$\Delta\Gamma_s$ and ϕ_s via A_{SL}

Charge asymmetries in flavor specific decays provide combined information on $\Delta\Gamma_s$ and ϕ_s:

$M_{12}/\Gamma_{12} \gg 1$

$$A^s_{SL} \simeq \frac{\Delta\Gamma_s}{\Delta m_s}\tan(\phi_s)$$





A_{SL} measurements from both D0 and CDF:

- inclusive like-sign di-muons:

$A^s_{SL} = -0.0064 \pm 0.0101$ D0 1.0 fb^{-1} *PRD 74, 092001 (2006)*
$A^s_{SL} = -0.020 \pm 0.021 \pm 0.016(\text{sys}) \pm 0.009(\text{input})$ CDF 1.6 fb^{-1}

- exclusive semi-leptonic $B_s \to D_s \mu\nu$ decays:

$A^s_{SL} = [2.45 \pm 1.93 \pm 0.35]\ 10^{-2}$ D0 1.3 fb^{-1} *PRL 98, 151801 (2007)*

$\Delta\Gamma_s$ from Flavor Specific Decays

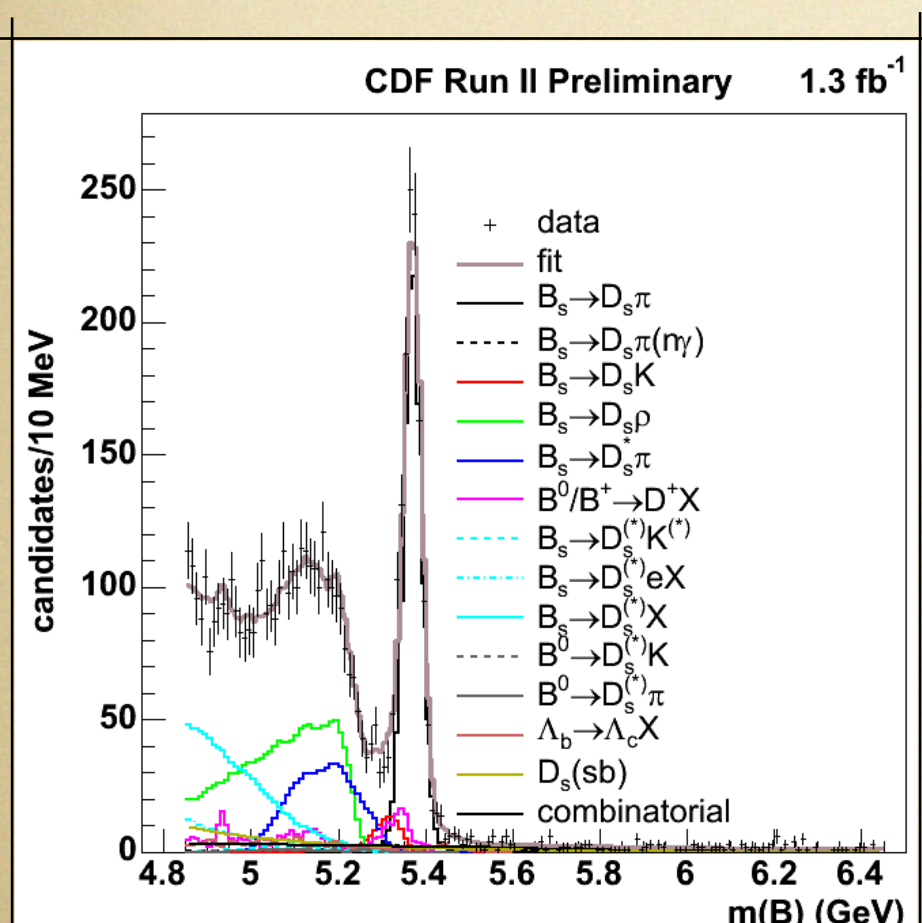
In flavor specific decays heavy and light states contribute both 50% to the time evolution

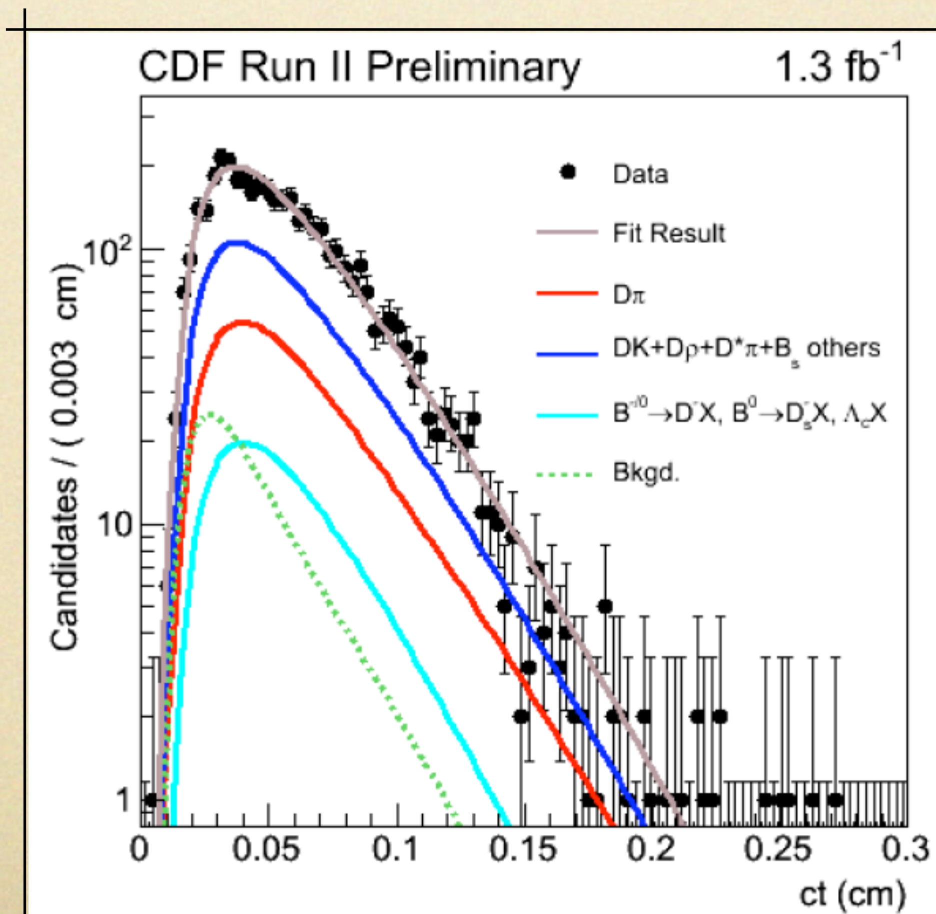
- fitting the proper decay time distribution with a single lifetime provide constraints on $\Delta\Gamma_s$

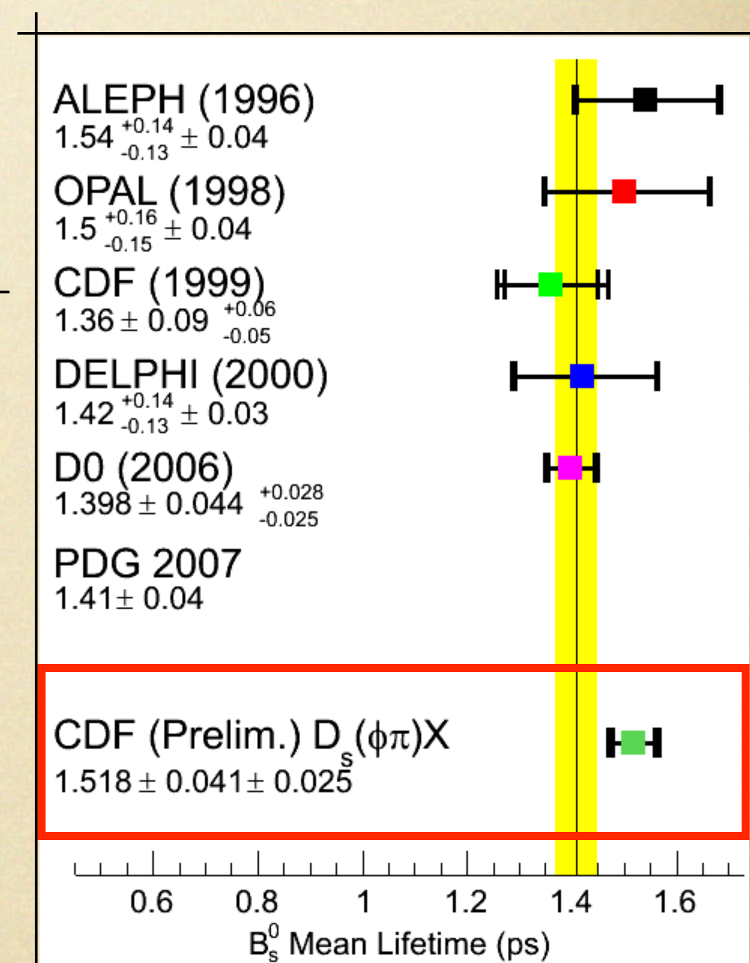
$$\tau_{fs}(B_s) = \frac{1}{\Gamma_s} \frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

New CDF measurement with 1.3 fb^{-1}:

- fully reconstructed $B_s \to D_s\pi$ decays
- partially reconstructed $B_s \to D_s\rho$, $D^*_s\pi$, ...







Better agreement with the HQET prediction $\tau_s/\tau_d = 1.0 \pm 0.02$

$\Delta\Gamma_s$ from $B_s \to D_s D_s$

Assuming the final state $D_s^{(*)} D_s^{(*)}$ mostly CP-even (expected true within few %):

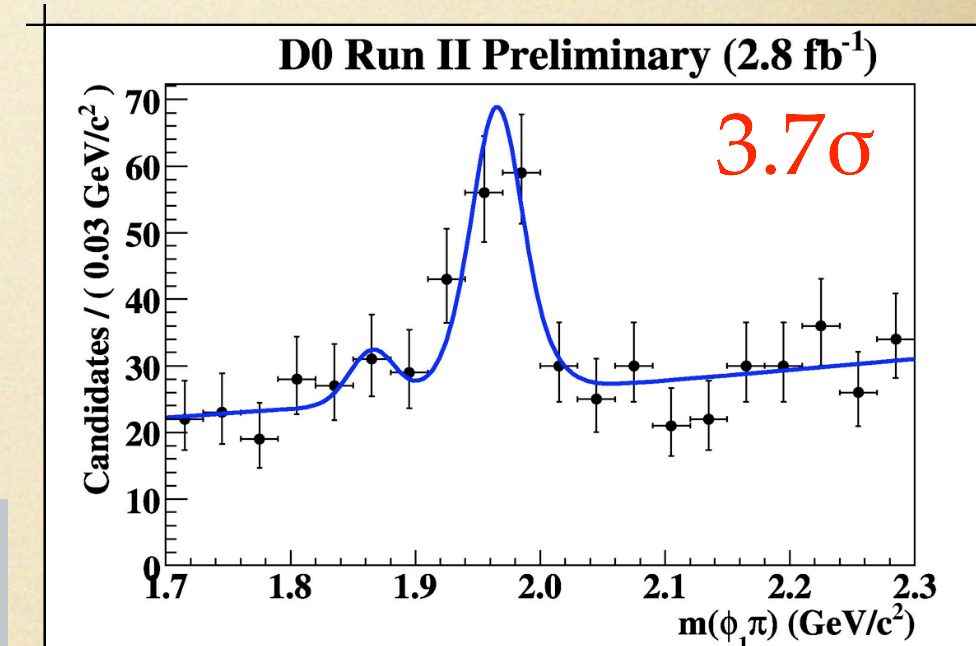
Aleksan et Al., Phys. Lett. B316 (1993) 567

$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s = \Delta\Gamma_{CP}\cos\phi_s$

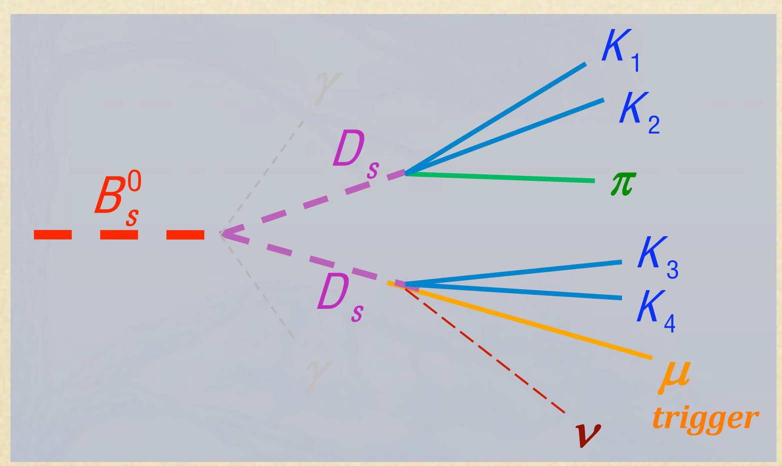
$$2BR(B_s \to D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP}\left[\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H}\right]$$

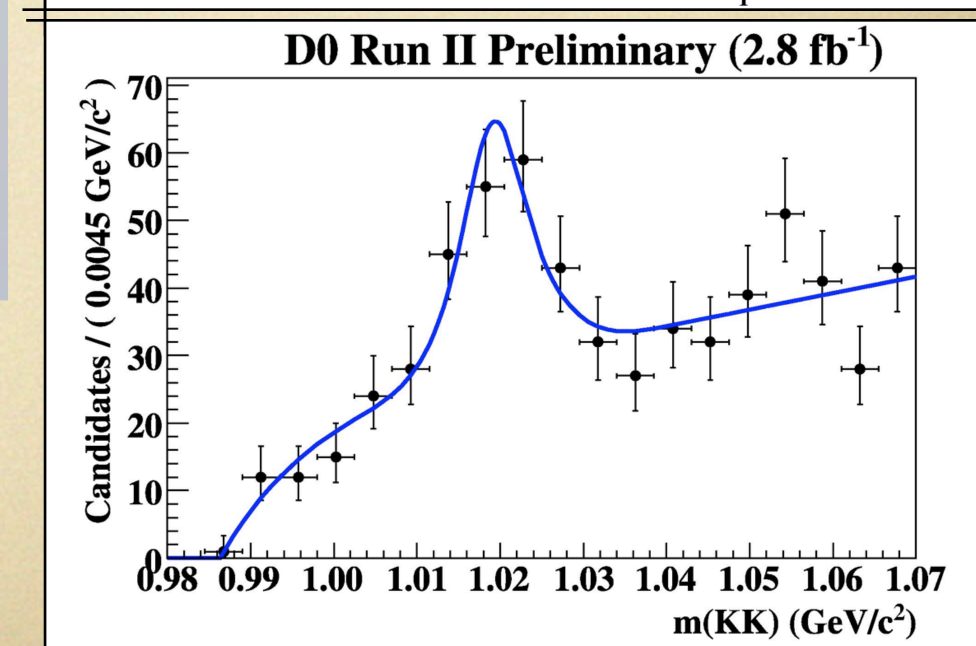
SM: $\phi_s \approx 0$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{2BR(B_s \to D_s^{(*)} D_s^{(*)})}{1 - BR(B_s \to D_s^{(*)} D_s^{(*)})}$$



NEW D0 analysis: 2.8 fb^{-1}:
- one $D_s^{(*)}$ reconstructed in $\phi\pi$
- other in $\phi\mu\nu$ (triggered D_s)





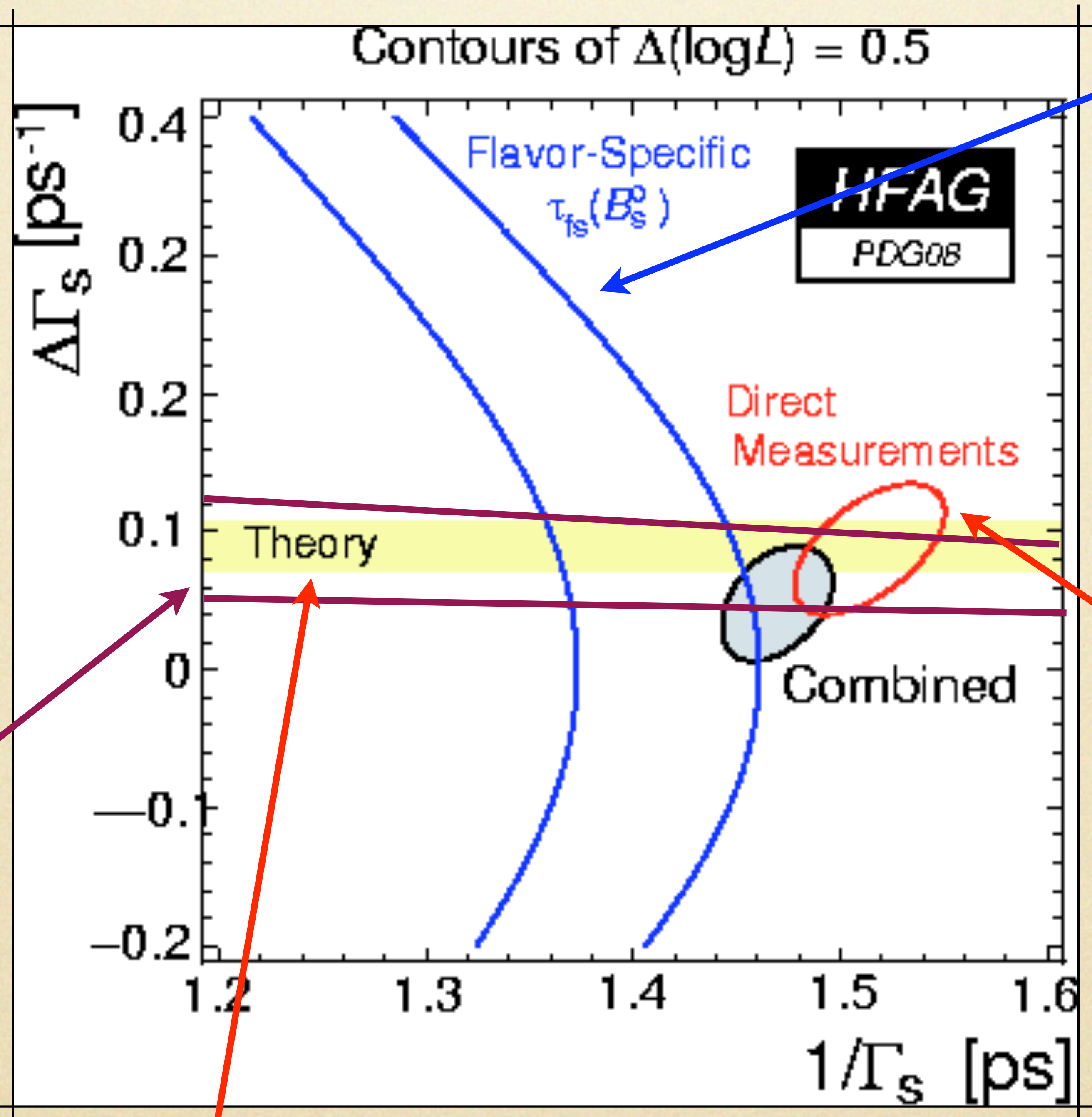
$$BR(B_s \to D_s^{(*)} D_s^{(*)}) = 0.042 \pm 0.015(stat) \pm 0.017(sys)$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.088 \pm 0.030 \pm 0.036$$

dominated by $BR(B_s \to D_s^{(*)}\mu\nu)$

Constraint on $\Delta\Gamma_s$

NOTE: assume $\phi_s = \phi_s^{SM}$



Flavor Specific: latest CDF measurement not included

$BR(B_s \to D_s^{(*)} D_s^{(*)})$
My average:
D0 + Aleph

Direct:
$J/\psi\phi$ CDF+D0

SM: $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s = 0.096 \pm 0.039\ ps^{-1}$

Good agreement with SM so far ...

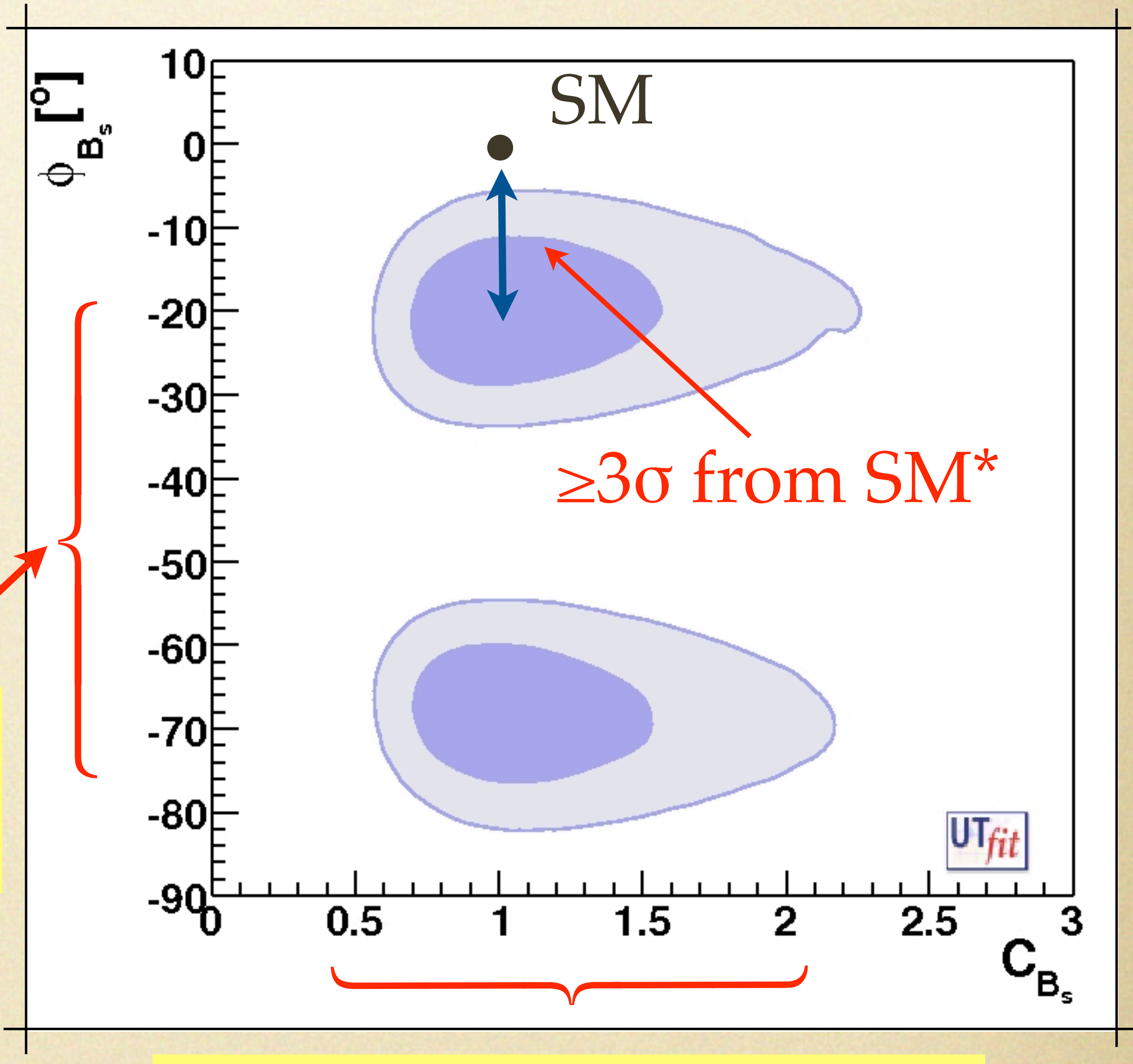
Impact on NP fits

$$C e^{2i\phi} = \frac{< B_s|H_{eff}^{SM+NP}|\bar{B}_s >}{< B_s|H_{eff}^{SM}|\bar{B}_s >}$$

$\Delta m^{exp} = C \cdot \Delta m^{SM}$

$\beta_s^{exp} = \beta_s^{SM} - \phi$

SM: C=1, ϕ=0



UT$_{fit}$ inputs:

Δm_s measurement (CDF)

Lifetime τ_s (HFAG)

$\Delta\Gamma_s$ and Φ_s (CDF and D0)

A_{SL} (CDF and D∅)

UT$_{fit}$ constraints:

$\Delta\Gamma_s \approx 2|\Gamma_{12}|\cos\beta_s$

(Γ_{12}= 0.066±0.039)

$\phi_{Bs} \in [-19.9\pm5.6]^\circ \cup [-68.2\pm4.9]^\circ$
uncertainty dominated by experiments

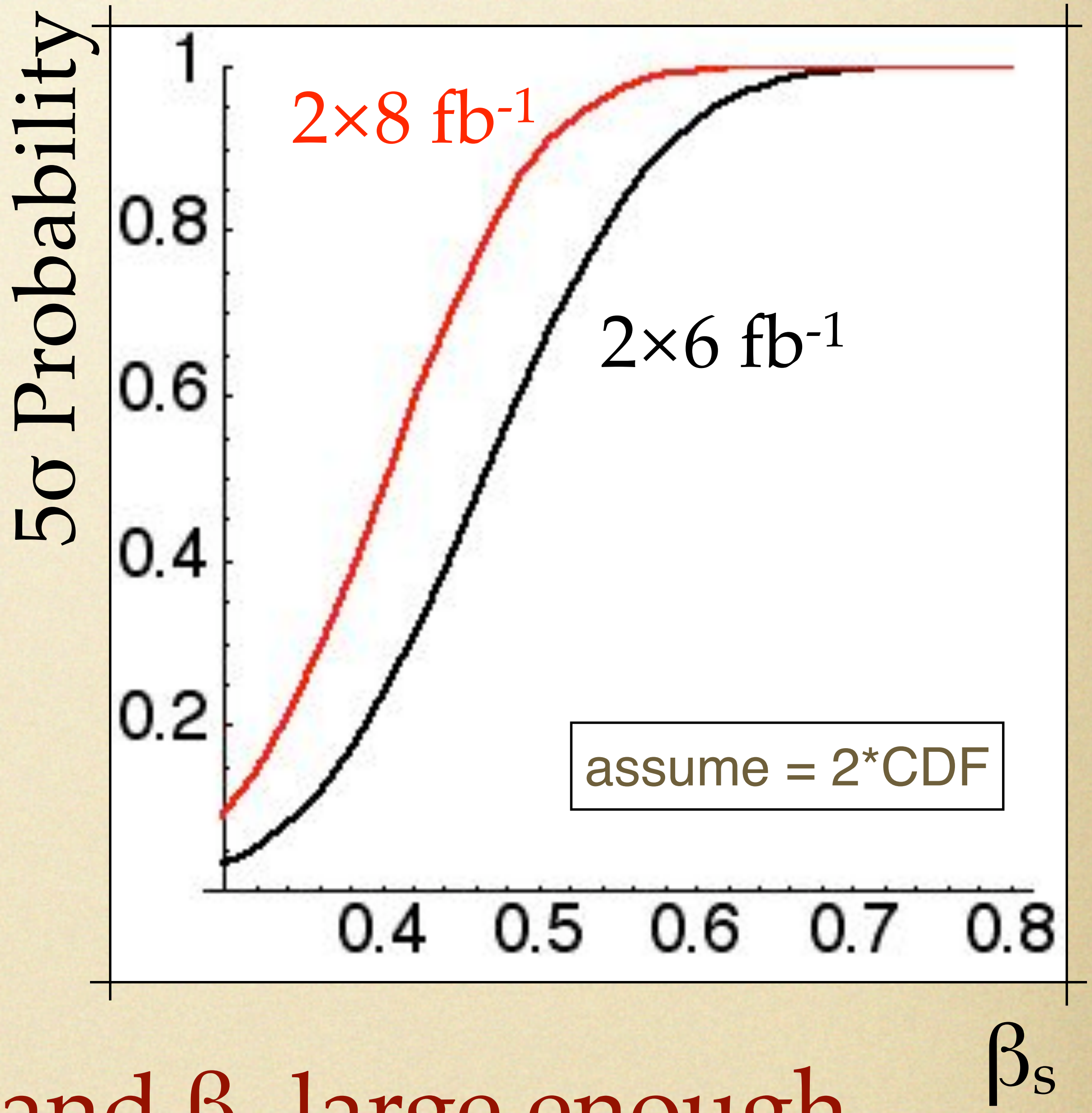
$C_{Bs} = 1.07 \pm 0.29$
strongly constrained by Δm_s
uncertainty dominated by LQCD

*NOTE: some approximations used in this analysis
A Tevatron combination is underway → results soon

ϕ_s: Perspectives

- Assumptions:
  - no analysis improvements
  - same signal yields
  - same exp. resolution

- ... may be better than that:
  - more signal (SVT trigger)
  - better tagging (underway)



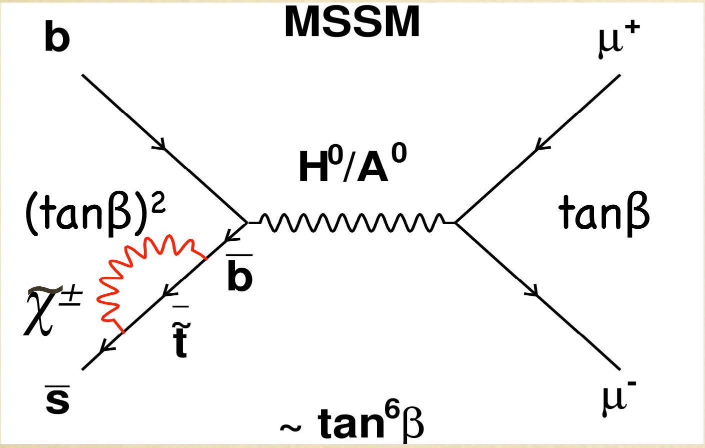
if the "fluctuation" is real and β_s large enough Tevatron can discover NP

otherwise LHCb ...

Rare Modes

Very rare decays: $B_s \to \mu^+\mu^-$

- Strategy: search for decays:
  - heavily suppressed in SM (FCNC, GIM), with BF predictions below current experimental sensitivity ⇒ any observed signal would indicate NP
  - BF's can be enhanced by orders of magnitude in new physics models



- Golden mode at Tevatron: $B_s \to \mu^+\mu^-$

Standard Model:
$BR(B_s \to \mu^+\mu^-) = (3.42 \pm 0.54)\ 10^{-9}$ (*Buras, PLB 566, 115 (2003)*)

Ex. SUSY MSSM:
$BR(B_s \to \mu\mu) \propto (\tan\beta)^6$ ~ up to x10^2 SM

Search strategy @Tevatron:
- blind optimization using signal MC and sideband data
- multivariate analysis techniques: LHR, NN
- normalize to the high statistic mode $B^+ \to J/\psi K^+$
- BG: combinatorics, $B \to hh'$

CDF limit (2 fb^{-1}):
$BR(B_s \to \mu\mu) < 4.7 \cdot 10^{-8}$ @90% C.L.
$BR(B_d \to \mu\mu) < 1.5 \cdot 10^{-8}$ @90% C.L.

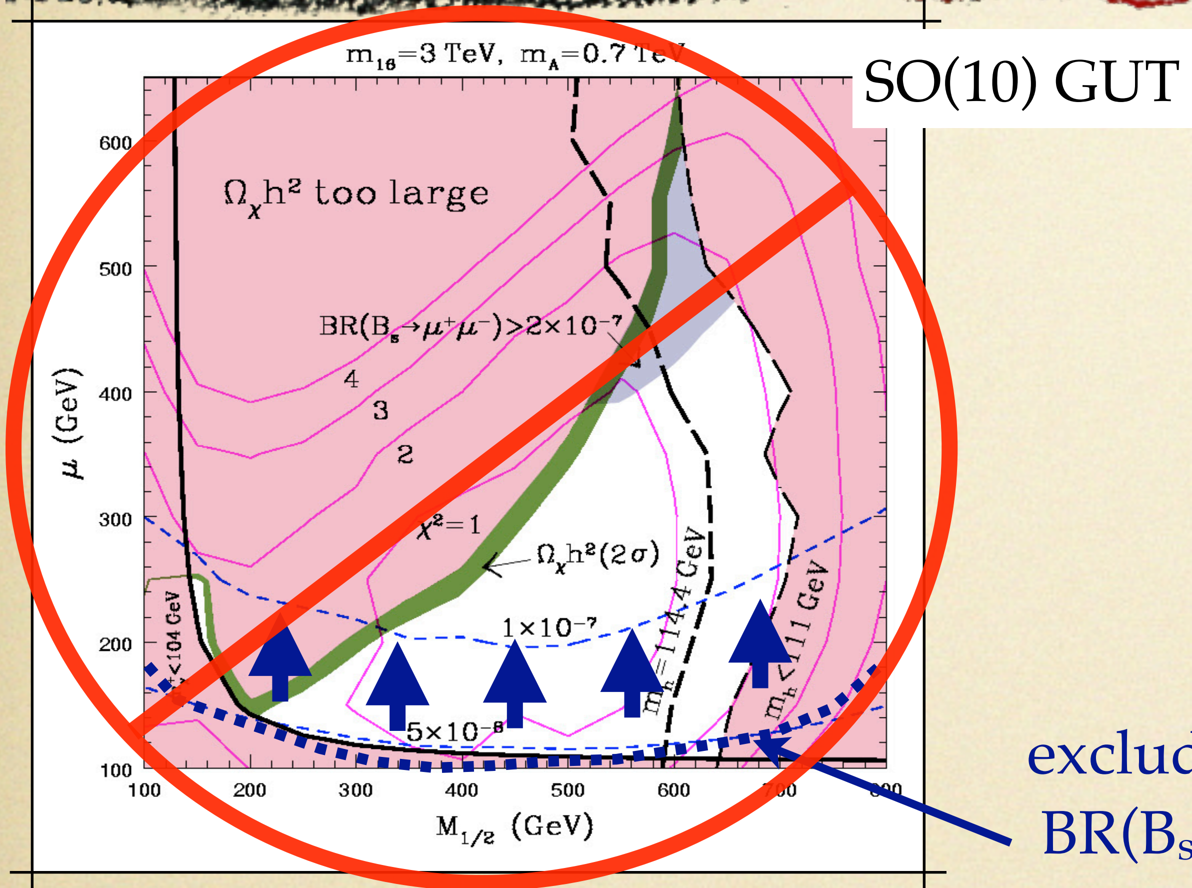
D0 limit (2 fb^{-1}):
$BR(B_s \to \mu\mu) < 7.3 \cdot 10^{-8}$ @90% C.L.

CDF Coll., PRL 100, 101802 (2008)

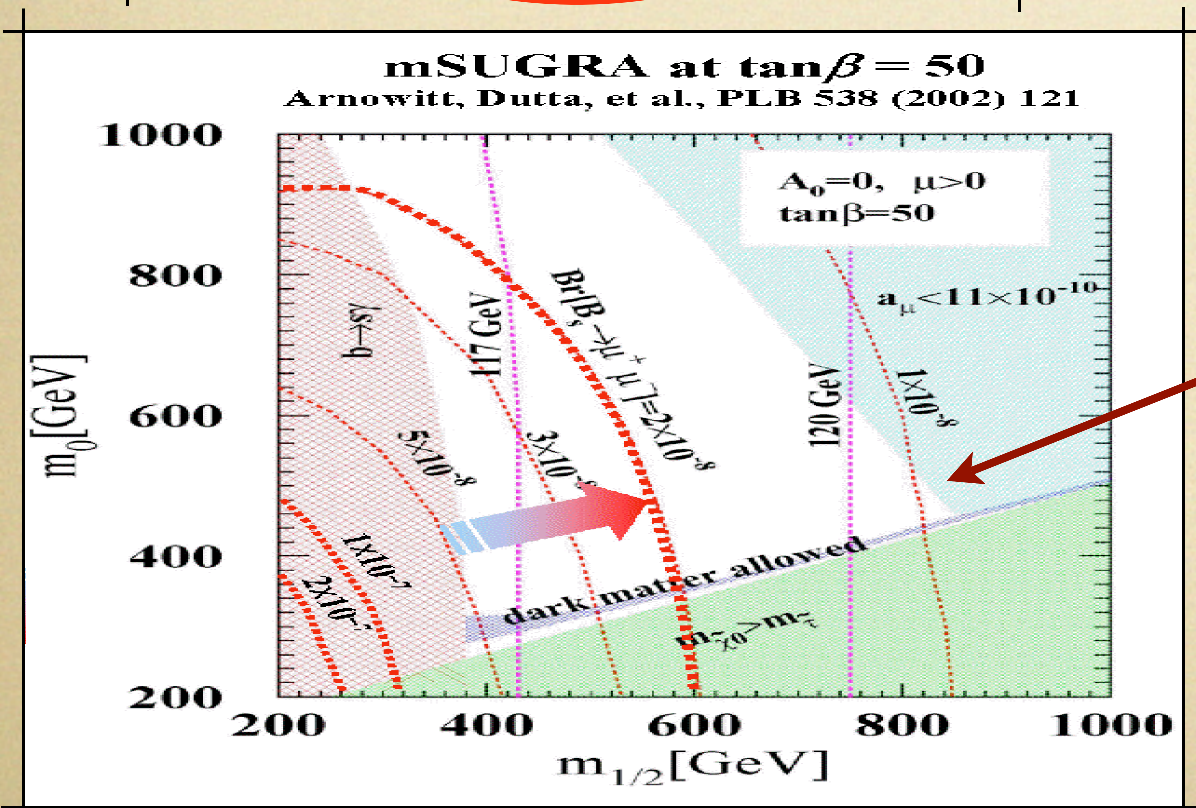
Most stringent limits to date

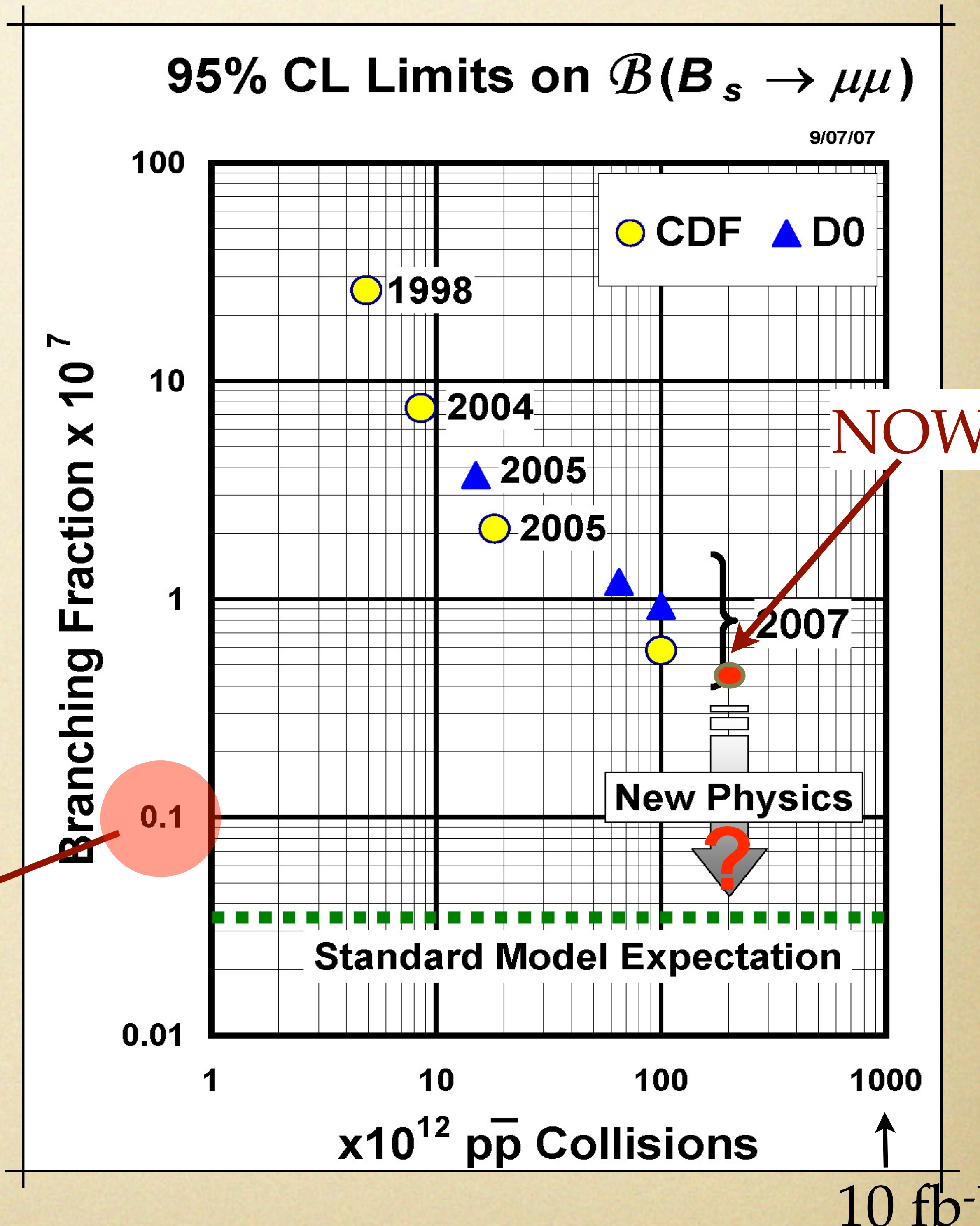
Impact on NP and Prospects

R.Dermisek et. Al., hep-ph/0507233



excluded by BR($B_s \to \mu\mu$)

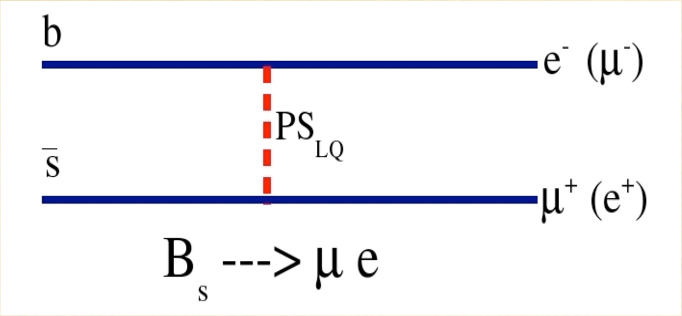


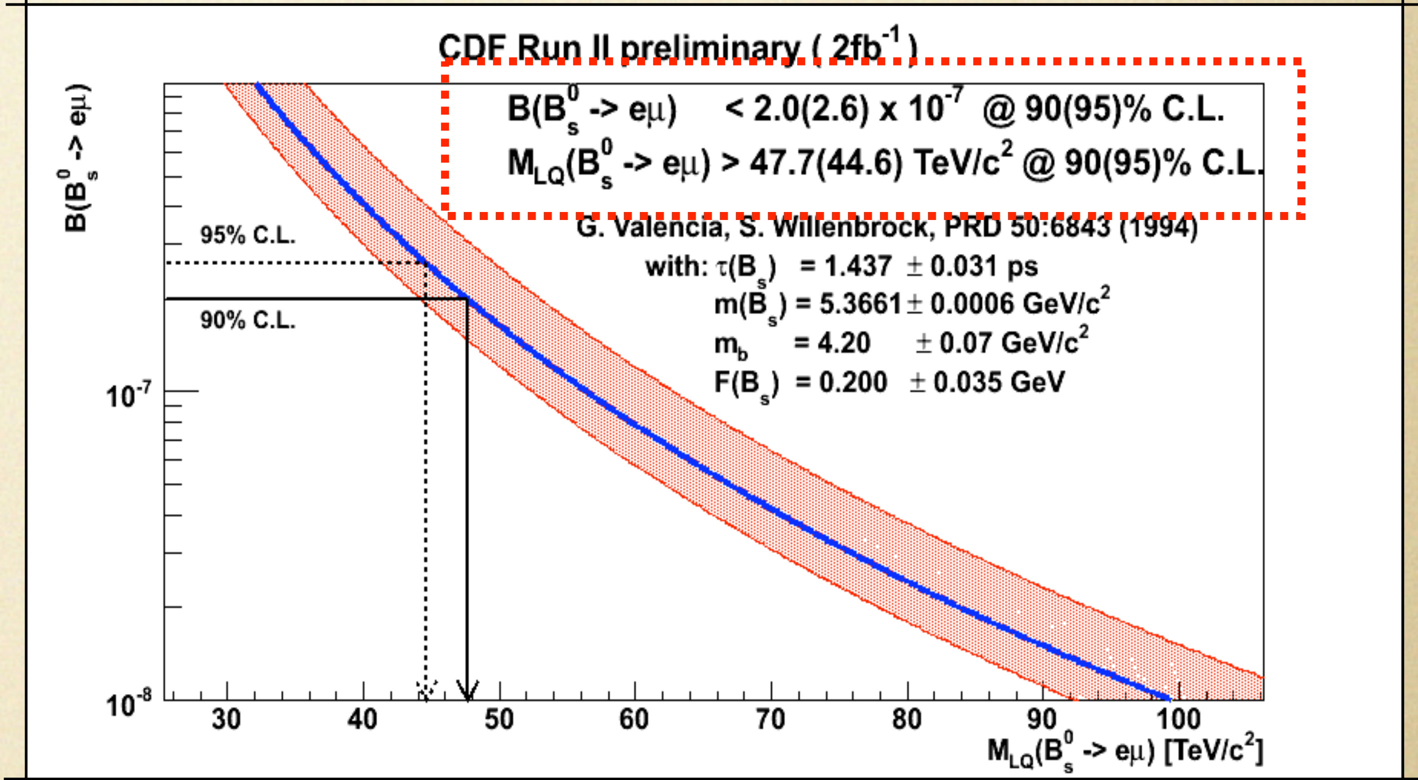


LHC is able to observe SM B→μμ ...

Just released: $B_s \rightarrow e^+\mu^-/e^+e^-$

$B_s/B_d \rightarrow e\mu$: ~forbidden in the SM BR $\leq 10^{-15}$, NP (LFV mediated by LQ, RPV SUSY, ED)





New CDF search: $2fb^{-1}$

- selected by the same trigger as $B \rightarrow hh$ decays
- e-ID based on em-calorimetry and dE/dx
- normalized to $B^0 \rightarrow K\pi$

CDF new world best limits ($2\ fb^{-1}$):

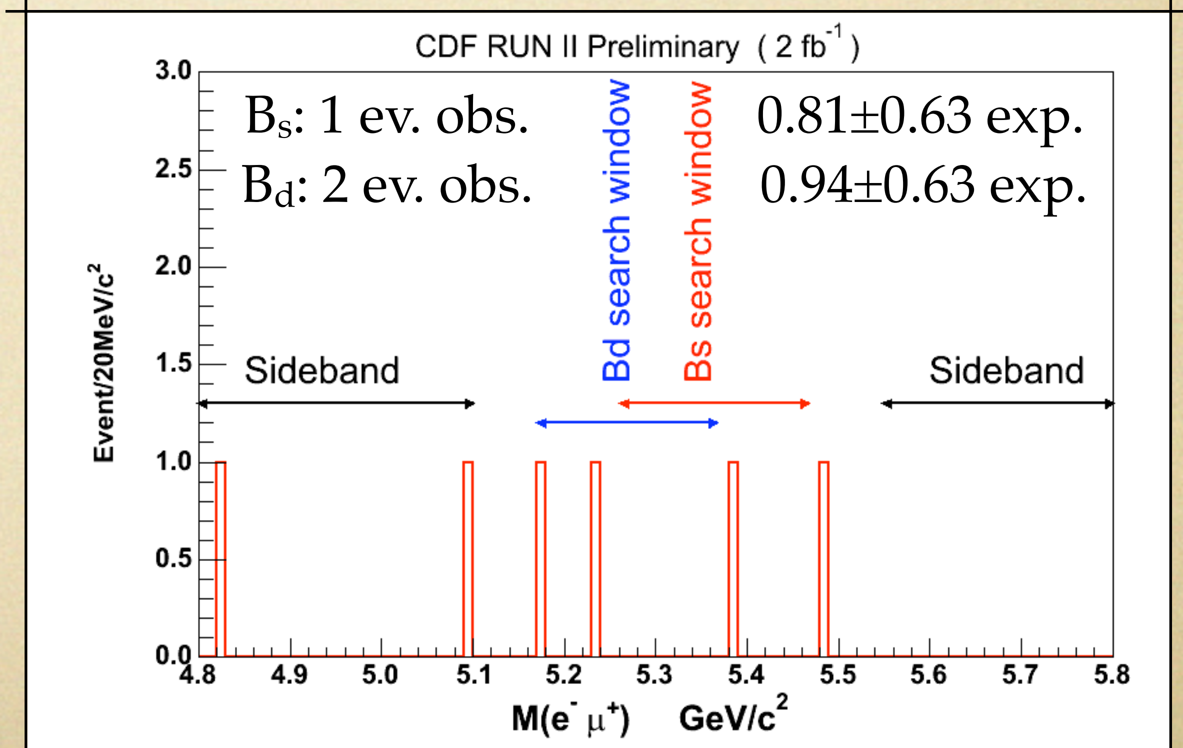
$BR(B_s \rightarrow e\mu) < 2.0 \cdot 10^{-7}$ @90% C.L.

$M_{LQ} > 47.4$ TeV/c^2 @90 C.L.

$BR(B_d \rightarrow e\mu) < 6.4 \cdot 10^{-8}$ @90% C.L.

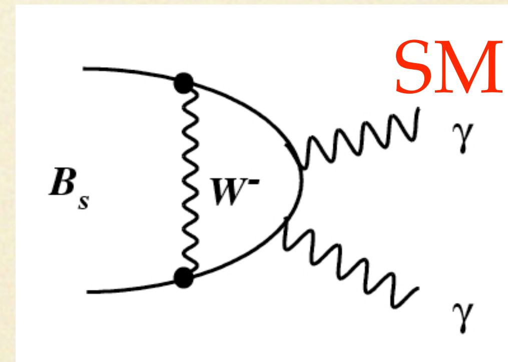
$BR(B_s \rightarrow ee) < 2.8 \cdot 10^{-7}$ @90% C.L.

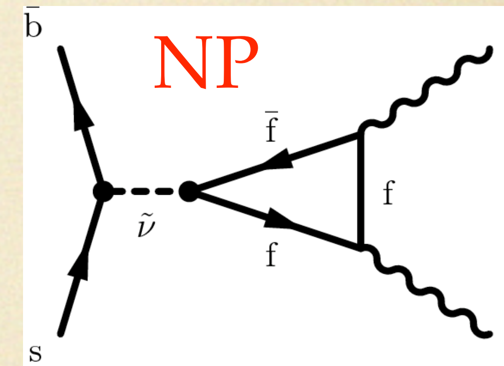
$BR(B_d \rightarrow ee) < 8.3 \cdot 10^{-8}$ @90% C.L.



Radiative B_s rare decays at Belle

- $b \to s\gamma$ penguin diagrams sensitive to contributions from new heavy exotic particles running in the loops





- Golden modes:
  - $B_s \to \phi\gamma$ (SM BR ~ 4×10^{-5})
  - $B_s \to \gamma\gamma$ (SM BR ~0.5×10^{-6}, NP (RPV SUSY, 4th quark gen., ...) BR ~5×10^{-6})
- Clean environment and superior photon-ID make these searches a perfect B_s physics topic for B-factories running at $\Upsilon(5S)$

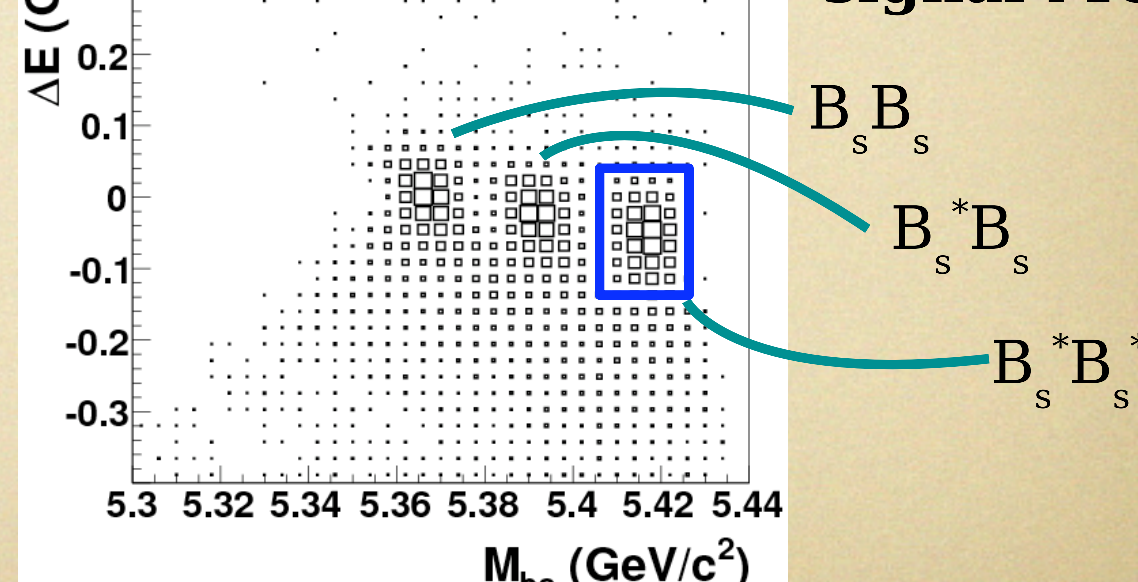
Standard B-factory analysis technique:

$$M_{bc} = \sqrt{(E_{beam}^{CM})^2 - (p_{B_s^0}^{CM})^2}$$

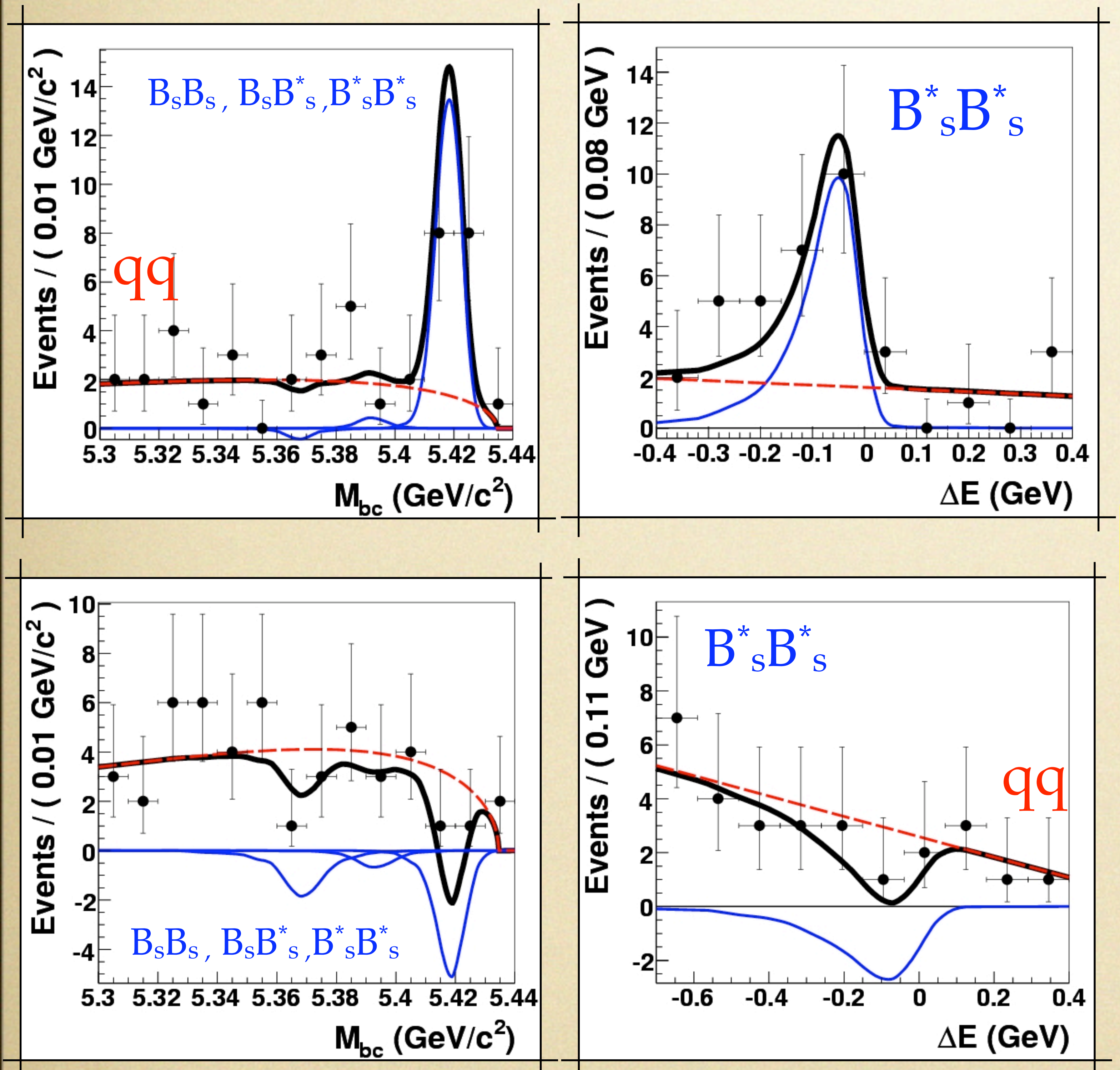
$$\Delta E = E_{B_s^0}^{CM} - E_{beam}^{CM}$$

Main background: continuum $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$
controlled by using Fox-Wolframs moments
$e^+e^- \to q\bar{q}$: jet-like shape
$e^+e^- \to \Upsilon(5S)$: spherical shape

$B_s \to \phi\gamma$ signal MC



Results: $B_s \to \phi\gamma/\gamma\gamma$



$B_s \to \phi\gamma$

first observation of a B_s radiative penguin decay

18±6 events, 5.5σ significance

consistent with SM

$$BR(B_s \to \phi\gamma) = (57^{+18+12}_{-15-11}) \times 10^{-6}$$
$$BR(B_s \to \gamma\gamma) < 8.7 \times 10^{-6} \ @90\% \ CL$$

~×6 previous best limit (Belle 2 fb^{-1})

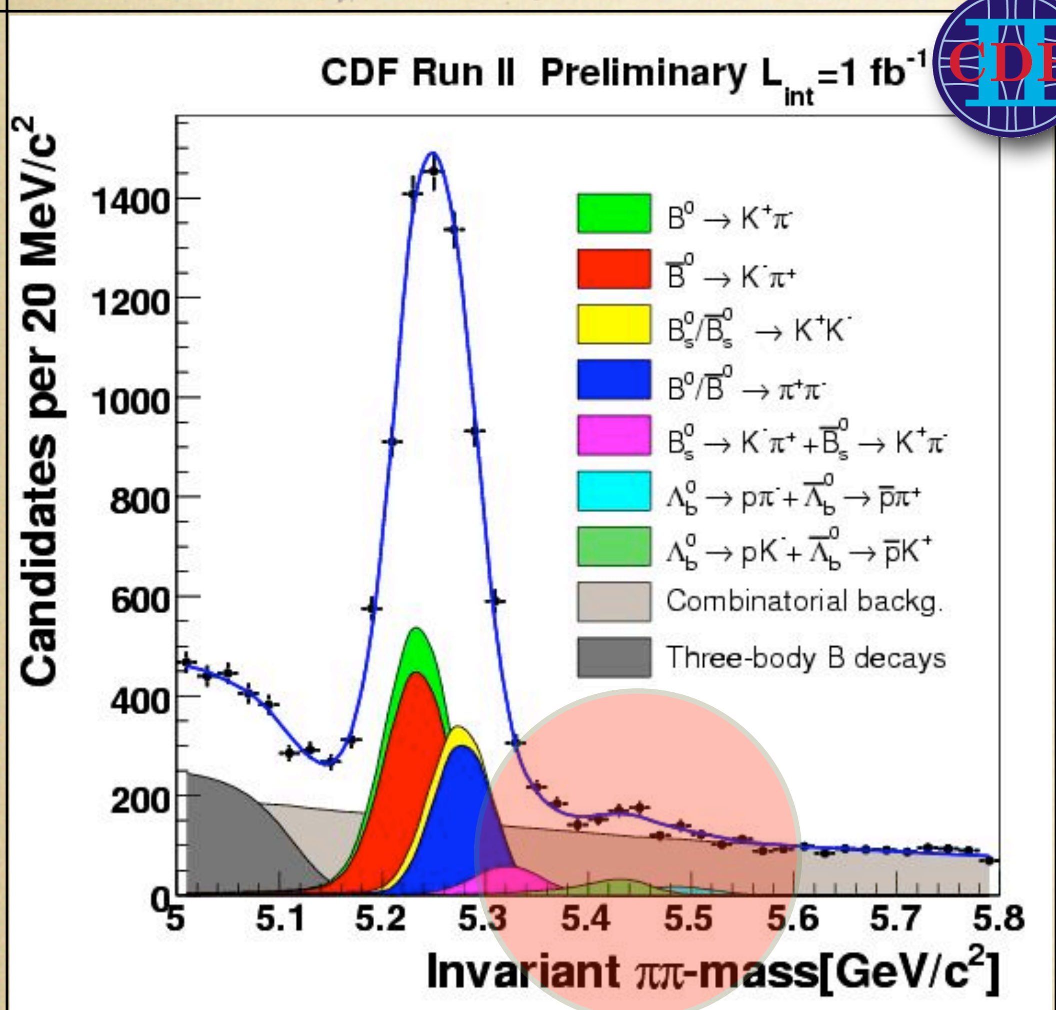
$B_s \to \gamma\gamma$

23.6 fb^{-1}

$B_s \to \gamma\gamma$ sensitivity still ×10 above SM and slightly above the interesting NP region

Belle, PRL 100, 121801 (2008)

$B_{d,s}/\Lambda_b \to hh'$ decays



CDF has unique access to fully hadronic two-body $B_{d,s} \to hh'$ and $\Lambda_b \to pK/p\pi$ decays

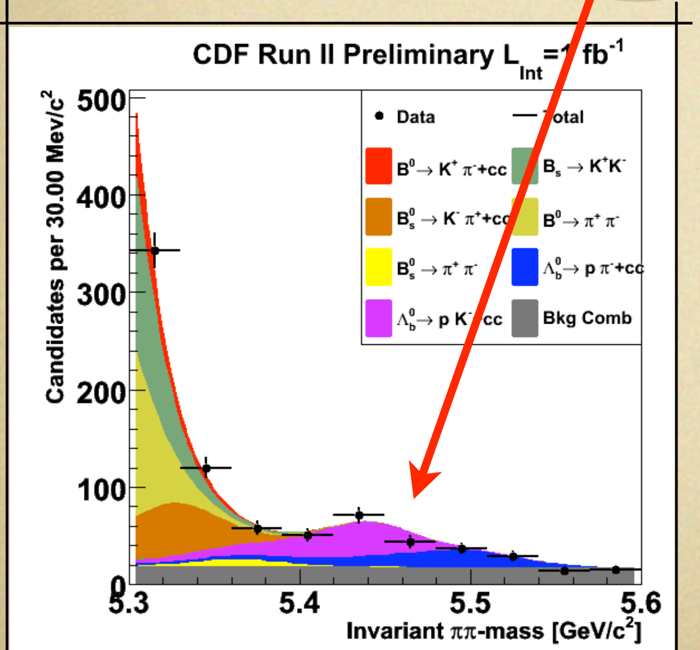
- penguin quark-level diagrams contribute → NP
- partial rates and asymmetries among various modes related by SU(2) and SU(3)

<u>Experimental challenge</u>:

- Disentangling different contributions: kinematics + PID

$B_s \to KK$ observed for the first time with 180 pb^{-1}

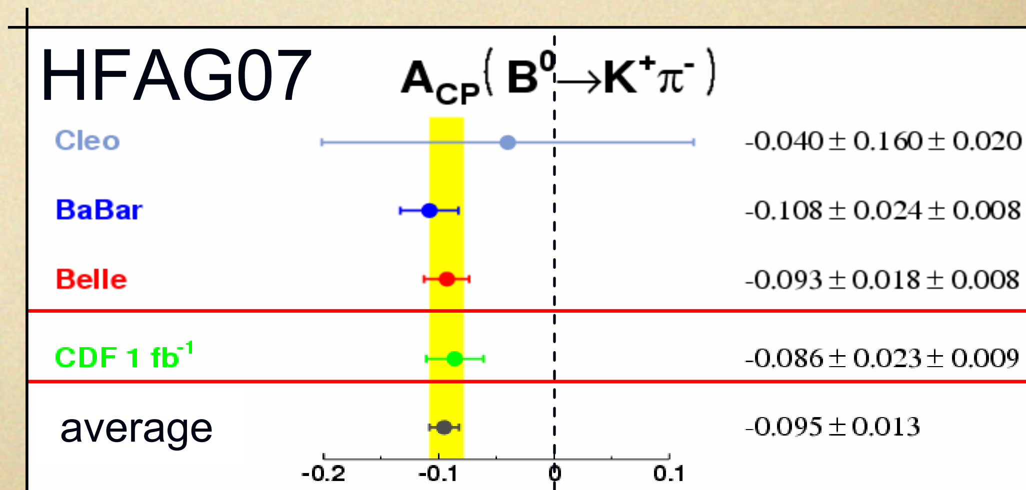
With 1 fb^{-1}: $\Lambda_b \to pK/p\pi$ observed, $A_{CP}(B^0 \to K\pi)$ measured with same precision as in B-factories



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

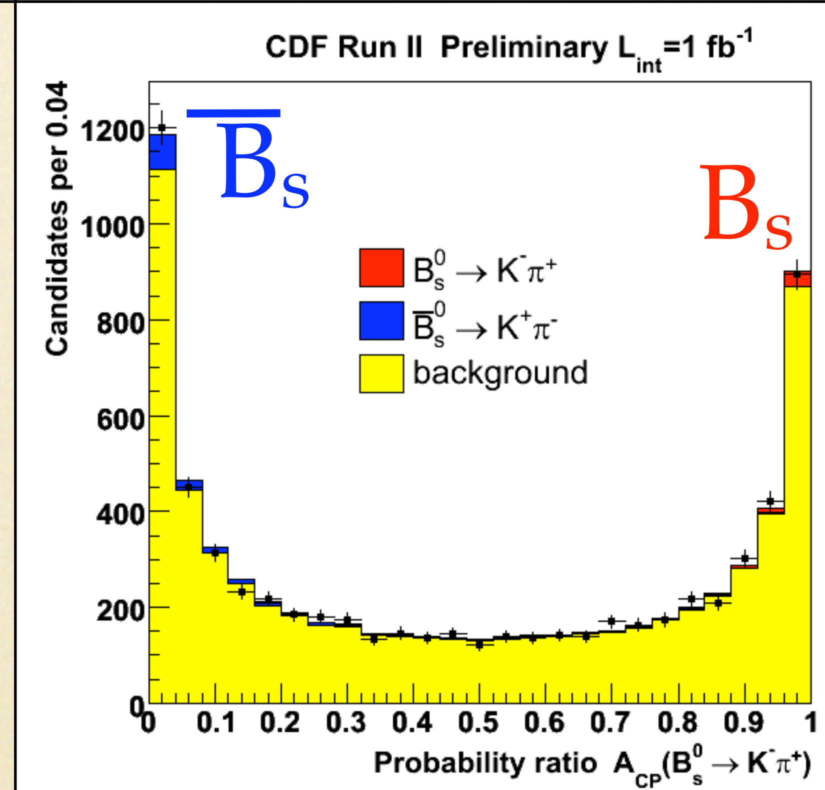
$BR(\Lambda_b \to p\pi) = (3.1 \pm 0.6 \pm 0.7)\ 10^{-6}$

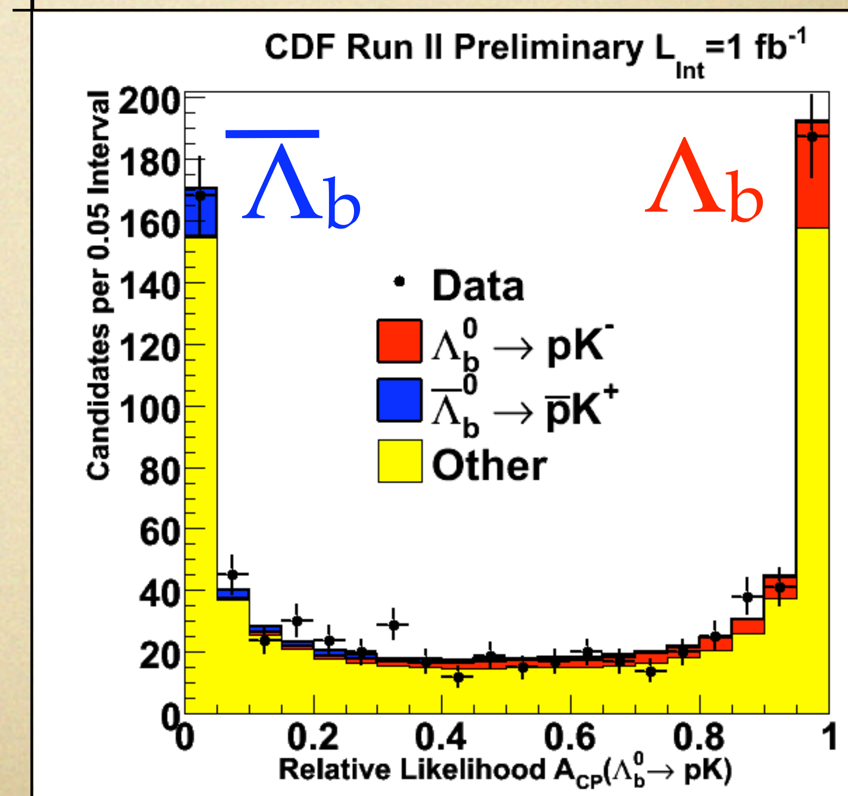
(SM BR ~$1 \div 2 \times 10^{-6}$)



B_s/Λ_b Direct CPV

CDF (1 fb^{-1})





$B_s \to K^+\pi^-$ and $\Lambda_b \to pK^-/p\pi^-$ self-tagging modes

- $B_s \to K\pi$ offers a robust test of the SM as a origin of DCPV

Gronau, Rosner ,Lipkin

$$\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) = \Gamma(B_s^0 \to K^-\pi^+) - \Gamma(\bar{B}_s^0 \to K^+\pi^-)$$

$$A_{CP}(B_s^0 \to K^-\pi^+) = -A_{CP}(B^0 \to K^+\pi^-)\frac{BR(B^0 \to K^+\pi^-)}{BR(B_s^0 \to K^-\pi^+)}\frac{\tau(B^0)}{\tau(B_s^0)} \sim 37\%$$

CDF (1 fb^{-1}): A_{CP} ($B_s \to K\pi$) = 0.39 ± 0.15 ± 0.08
(~2.5σ from zero)

- $\Lambda_b \to pK/p\pi$ quark level diagrams equivalent to $B_d \to \pi K/\pi\pi$
- useful to test if large $B_d \to K\pi$ DCPV is due to NP in mixing (Λ_b doesn't mix)

A_{CP} ($\Lambda_b \to pK$) = 0.37 ± 0.17 ±0.03 (SM $\Lambda_b \to pK$: ~O(10÷30%))

A_{CP} ($\Lambda_b \to p\pi$) = 0.03 ± 0.17 ±0.05

... will become very interesting with more statistic

Summary

- Tevatron experiments have clearly demonstrated that precision Heavy Flavor physics at an hadron machine is a reality
  - a wide array of unique measurements
  - many probes for new physics into uncharted territories
  - mild tension with SM in $\sin(2\beta_s)$, currently statistically limited
- Complementary interesting results from e^+e^- colliders @$\Upsilon(5S)$

We are in the enviable position of having at the same time a large portion of the heavy B hadron sector to explore and all the tools that are needed to perform this exploration ready ...

no doubts these are exciting times for Heavy Flavor physics ...