Flavor physics at the Tevatron

Giovanni Punzi
Pisa U. and INFN

For the CDF and D0 collaborations

Why flavor, why the Tevatron ?

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[A. Masiero, Cagliari B-physics meeting, 4/4/08]

A FUTURE FOR FLAVOR PHYSICS IN OUR SEARCH BEYOND THE SM?

- The traditional **competition** between direct and indirect (FCNC, CPV) searches to establish who is going **to see the new physics first** is no longer the priority, rather
- **COMPLEMENTARITY** between direct and indirect searches for New Physics is the key-word
- Twofold meaning of such complementarity:

i) **synergy in "reconstructing" the "fundamental theory"** staying behind the signatures of NP;

ii) **coverage of complementary areas of the NP parameter space** (ex.: multi-TeV SUSY physics)

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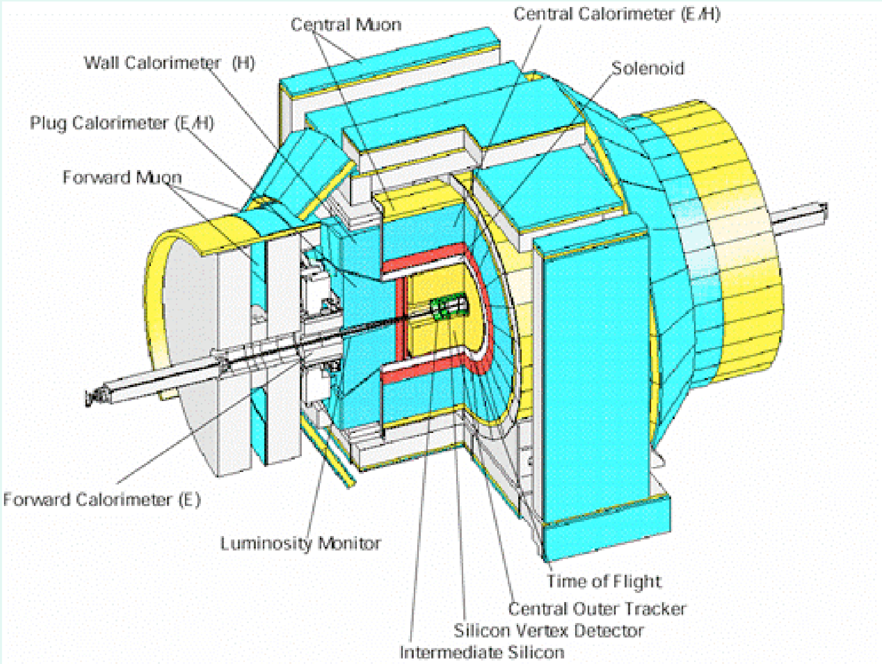
The Tevatron provides opportunities for many world-class flavor measurements

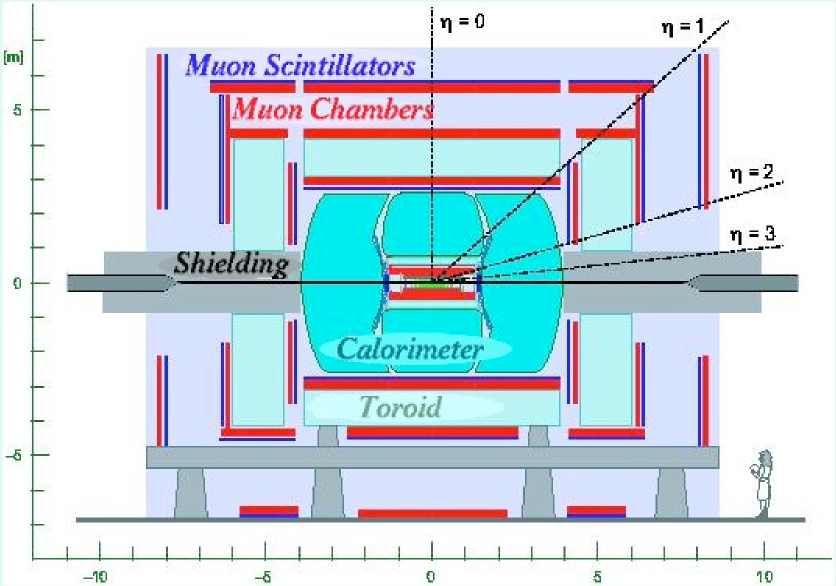
Tevatron Experiments



CDF II Detector

- Tracker: – **Silicon Vertex Detectors**
  – Drift Chambers
- **Excellent Momentum Resolution**
- **Trigger on long-lived particles**
- **Particle ID**: TOF and dE/dx
- Triggered Muon Coverage $|\eta|<1$

DØ Detector



- **Silicon Detectors – New L0** installed in 2006.
- Solenoid: 2T, weekly reversed polarity
- **Large tracking coverage**
- **Large triggered Muon Coverage** $|\eta|<2.2$
- Excellent Calorimetry and electron ID

Flavor physics menu@Tevatron

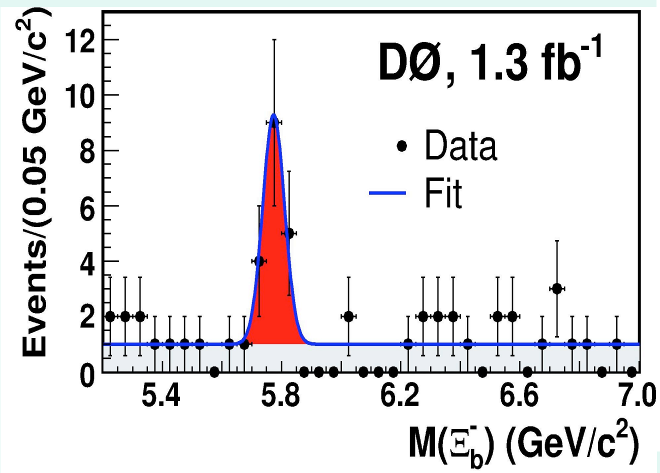
- Heavy flavor production/QCD processes
- Explore the heavy particles zoo:
  - Ground states: B_s, B_c, Λ_b, Σ_b, Ξ_b…
  - Excited states, Exotics
- Improve understanding of SM physics
  - CP violation, CKM angle gamma
  - Modeling hadronic phenomenology:
    - pQCD, HQET, SCET, factorization, U-spin…
- Search for new physics (or contribute to understand it when it is found!)
  - Rare modes -> FCNC, LFV, LQ, SUSY
  - Anomalous CP violation
  - Bs mixing parameters.
  - Charm mixing parameters

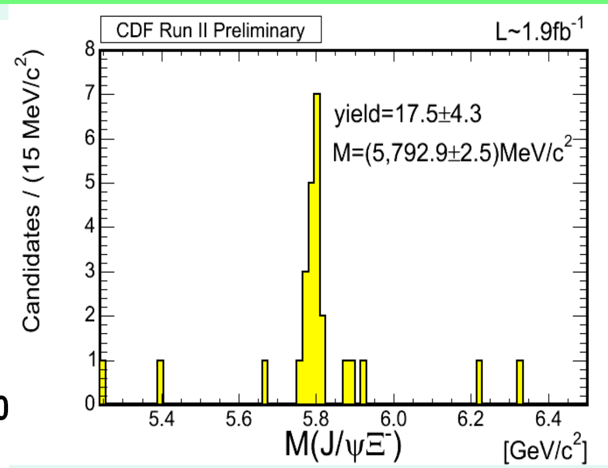
Data on tape: $3.5 fb^{-1}$/exp. – Analyses: $1 \div 2.8 fb^{-1}$

Can sample only a few topics for this talk

B hadron properties

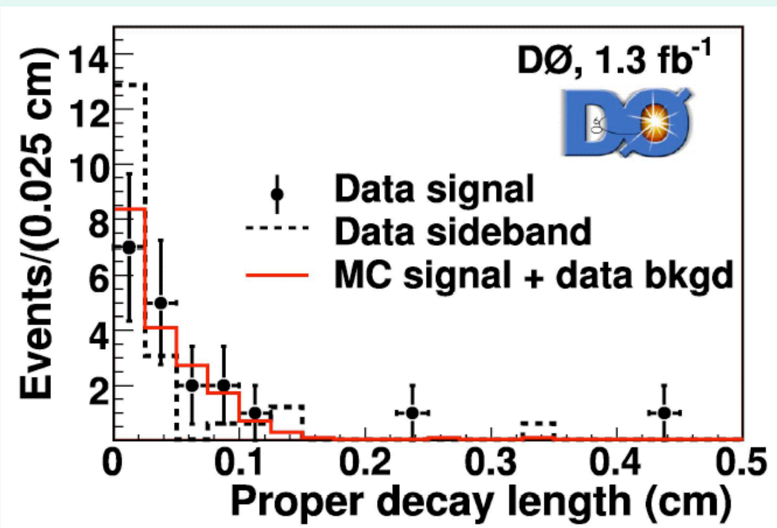
Latest entry: b-Baryon Ξ_b^- [bds]



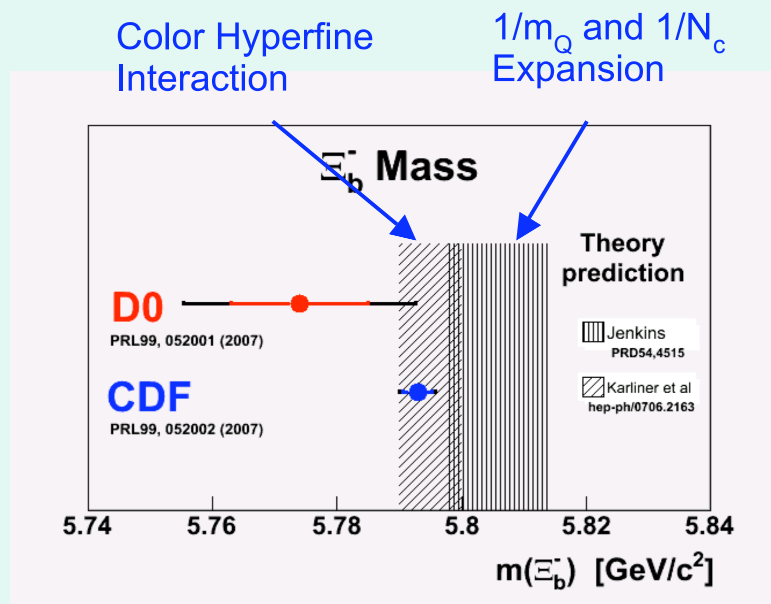


$\Xi_b^- \to J/\psi\, \Xi^-$

$\to (\mu\mu)\,(\Lambda^0\pi^-)$



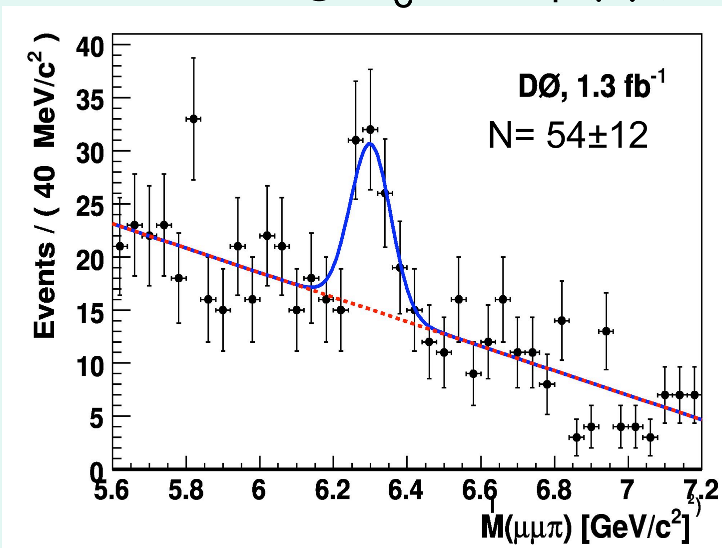
M(Ξ^-) = 5792.9 ± 2.4 ± 1.7 MeV/c^2 (CDF)
M(Ξ^-) = 5774 ± 11 ± 152 (D0)

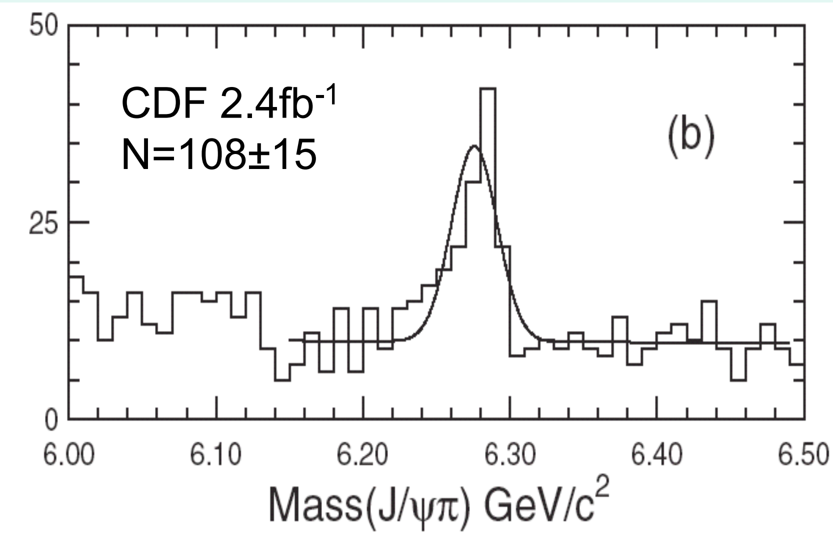


Lifetime in agreement with expectations
A better measurement would be an interesting HQET test

B_c mass

- Using $B_c^{\pm} \to J/\psi(\mu\mu)+\pi^{\pm}$ - fully reconstructed





M = 6275.6 ± 2.9 ± 2.5 (CDF)

[Phys.Rev.Lett. 100:182002, 2008]

M = 6300 ± 14 ± 5 (D0)

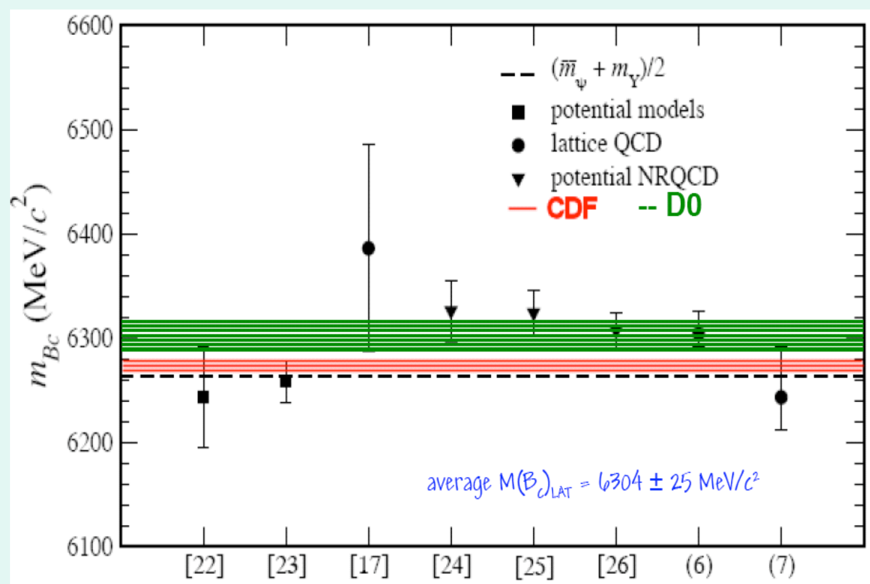
[arXiv:0802.4258 [hep-ex]]

Expectations:

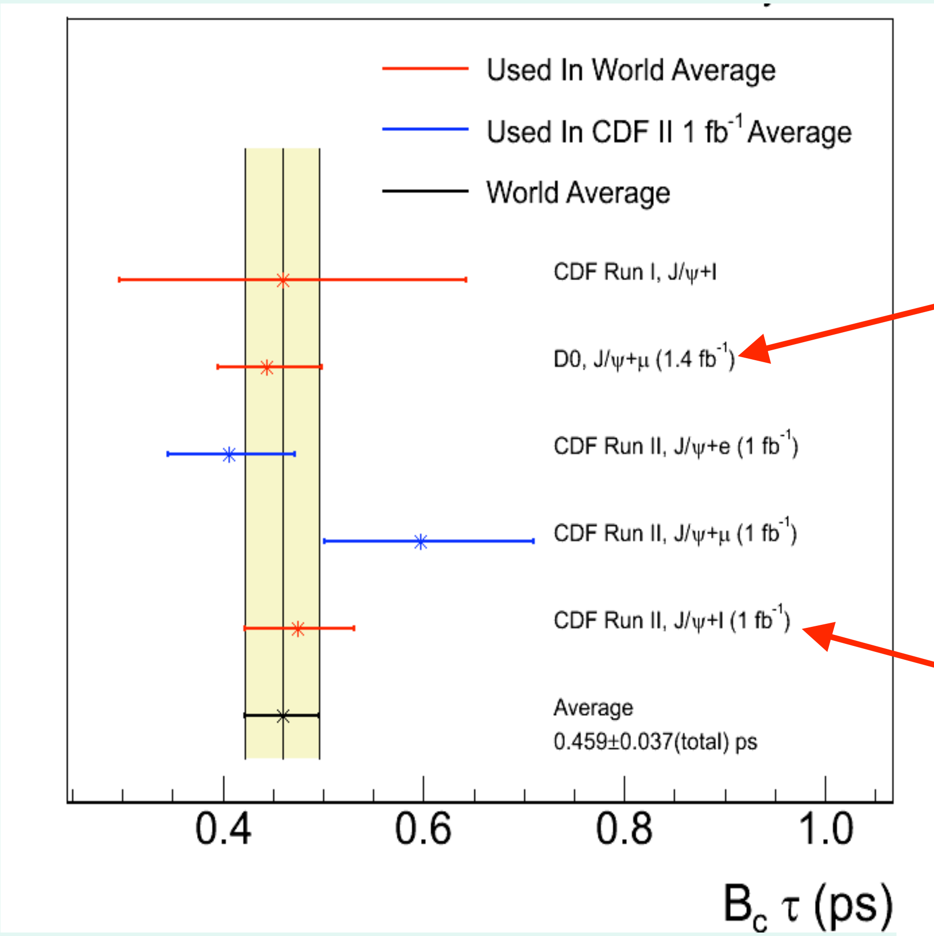
M = $6304 \pm 12^{+18}_{-0}$ MeV/c^2 (lattice QCD)

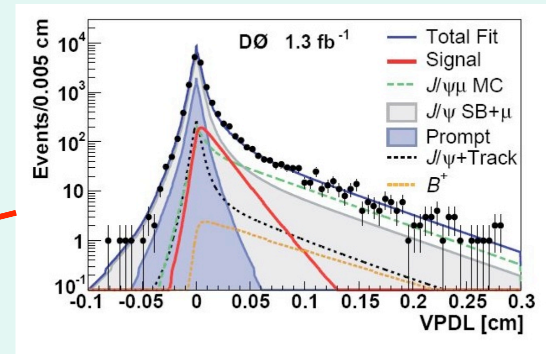
[Phys. Rev. Lett. 94, 172001 (2005)]

M = 6247-6286 MeV/c^2 [Phys. Rev. D 70, 054017 (2004)]
(non-rel. potential models)

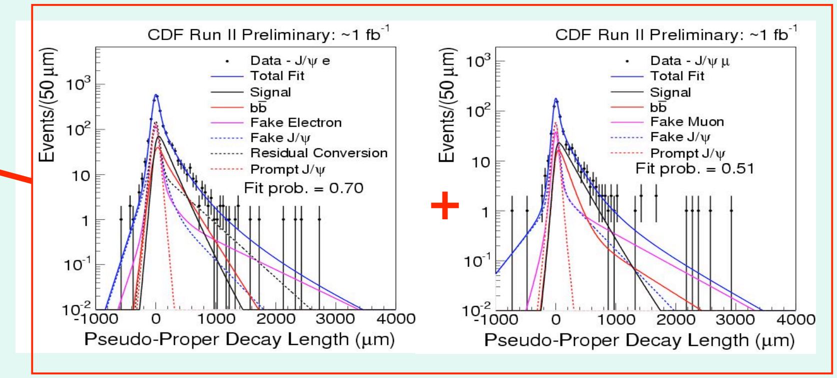


B_c Lifetime





D0 result (μ)



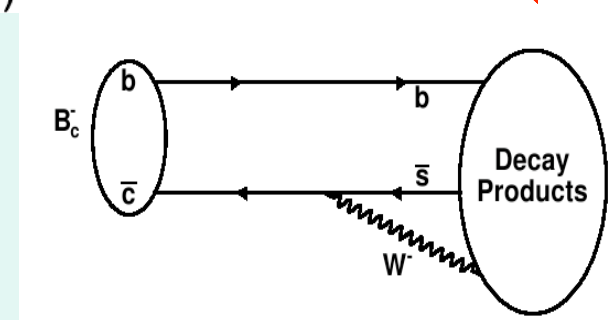
CDF result (e+μ)

τ= 0.459 ± 0.037 ps Unofficial WA

Predicted: τ= 0.47 ÷ 0.59 ps

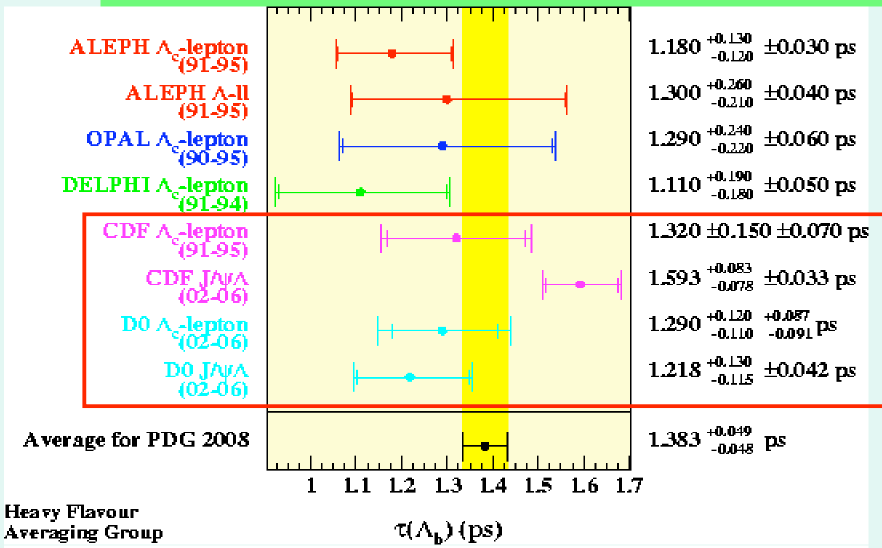
Now a good benchmark for theory

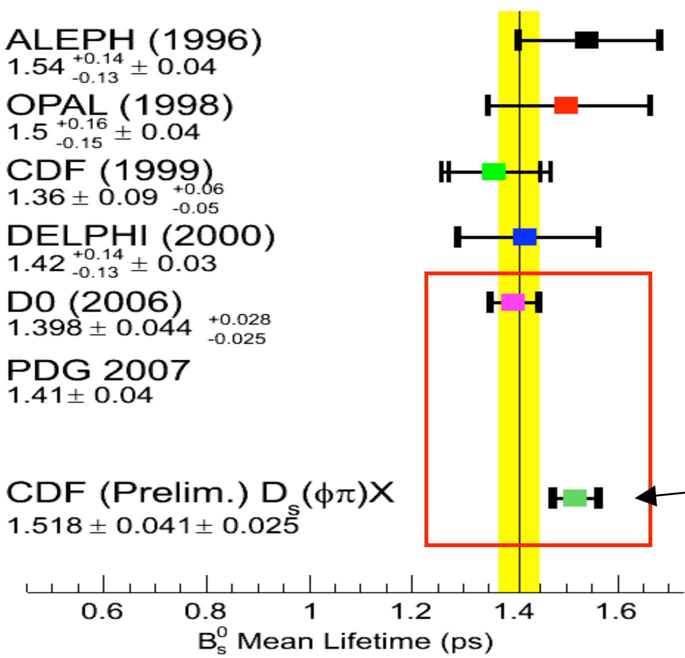
Expect further measurement from fully reconstructed



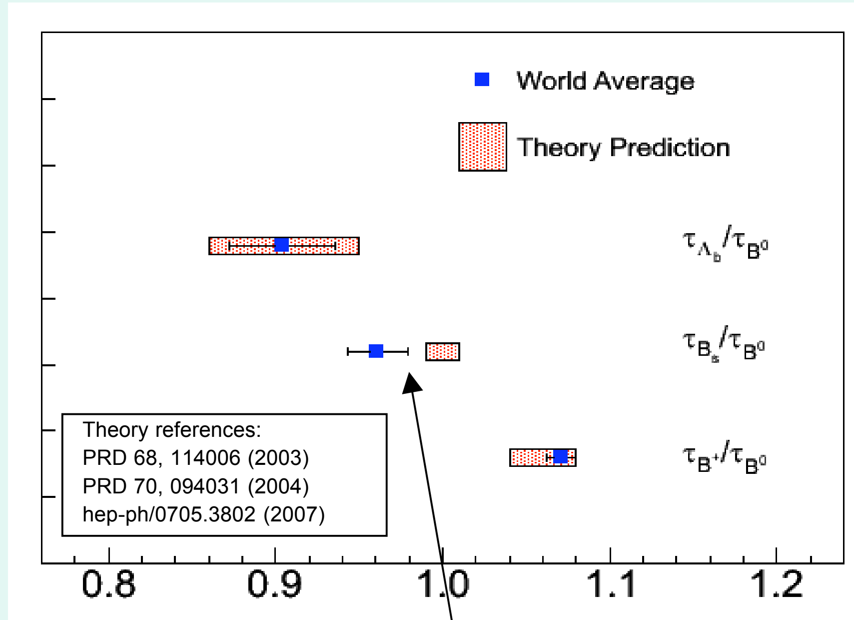
arXiv:hep-ph/0006104
Phy Rev. D 64, 14003 (2001)
Phy Lett. B 452, 129 (1999)_
hep-ph/0002127

Other hadron lifetimes





- Best existing measurements of Λ_b and B_s lifetimes. Expect more.
- Precision test HQET



Latest CDF result not yet in averages – goes in the direction of reducing $\tau(B_s)/\tau(B^0)$ discrepancy.

CP violation

ACP($B^0 \rightarrow K^+\pi^-$) ≠ ACP($B^+ \rightarrow K^+\pi^0$)

nature Vol 452 | 20 March 2008 | doi:10.1038/nature06827

LETTERS

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

"[…] Although it is susceptible to strong interaction effects that need further clarification, this **large deviation** in direct CP violation between charged and neutral B meson decays could be an indication of **new sources of CP violation**—which would help to explain the dominance of matter in the Universe."

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beyond the standard model.

Compared to the dominant $b\rightarrow c$ decay amplitudes, the amplitude of Fig. 1a is suppressed by the smallness of $|V_{ub}/V_{cb}|$, while Fig. 1b is suppressed by the quantum loop amplitude. However, the two amplitudes are of similar magnitude, allowing for large interference (and hence appreciable CP violation) to occur. The price to pay is the small branching fractions or decay rates to be measured. For instance, out of a million neutral B^0 mesons, only about 20 will decay into $K^+\pi^-$, while for B^+ mesons, only about 13 in a million will decay to $K^+\pi^0$. Therefore, to search for CP violation, we must produce many *B* mesons and detect them with high efficiency. The Belle detector at the KEKB[11] asymmetric-energy (3.5 on 8.0 GeV) e^+e^- collider, operating on the $\Upsilon(4S)$ resonance (which decays exclusively to a $B\bar{B}$ meson pair) energy, was designed for such a purpose. The KEKB accelerator is currently the brightest collider in the world, in which the record instantaneous luminosity is equivalent to bombarding a 1 cm^2 area

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We don’t know yet if this is really new physics.
Need confirmation from other channels.

Direct CPV in the Bs

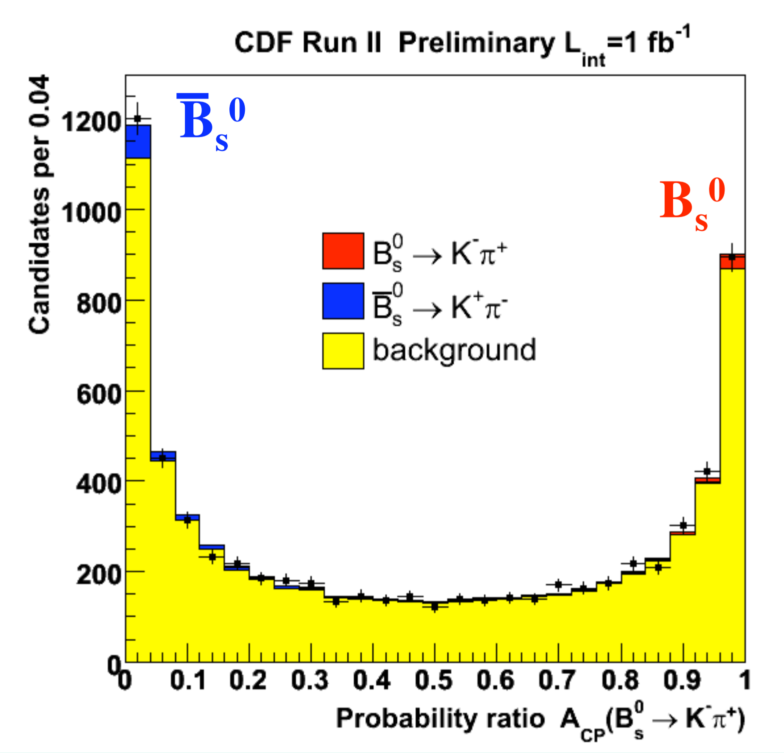
- A good, robust test available at the Tevatron is:

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

[Gronau Rosner Phys.Rev. D71 (2005) 074019, Lipkin, Phys. Lett. B621:126, .2005]]

"Is observed direct CP violation in $B^0 \to K^+\pi^-$ due to new physics ?
Check standard Model prediction of equal violation in $B^0_s \to K^-\pi^+$ "

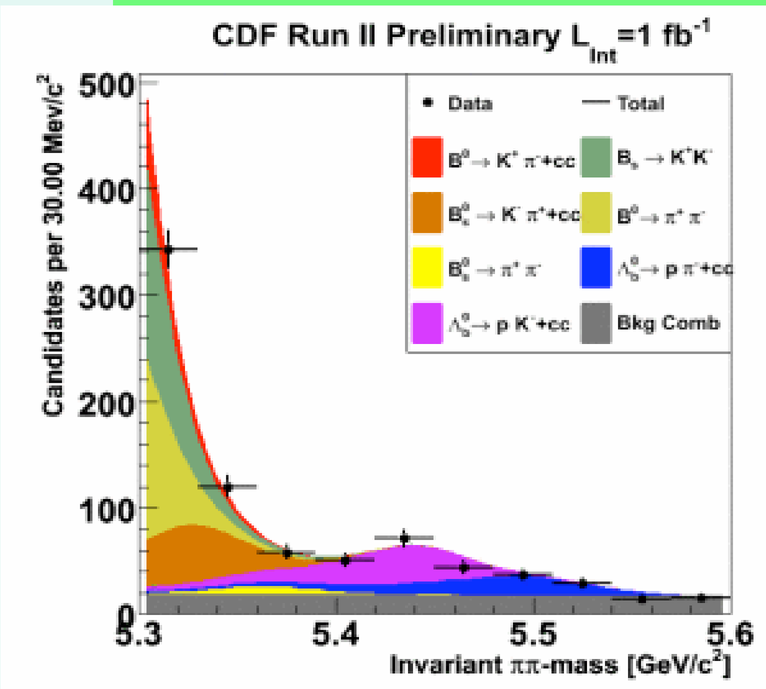
- Predicts large ACP(Bs->K-π+) = 0.37



- CDF ($1fb^{-1}$): 0.39 ± 0.15 ± 0.08 (~2.5σ from zero)
- Unique measurement of direct-CPV in Bs

Needs more data, but the sign is right: *the opposite sign would have been a 5σ-violation of SM !*

CPV in $\Lambda^0_b \to pK/\pi$

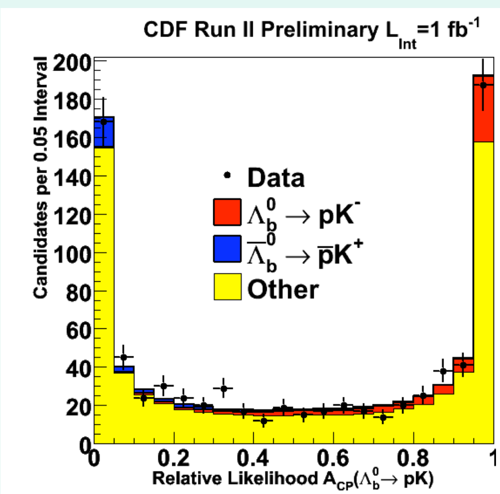


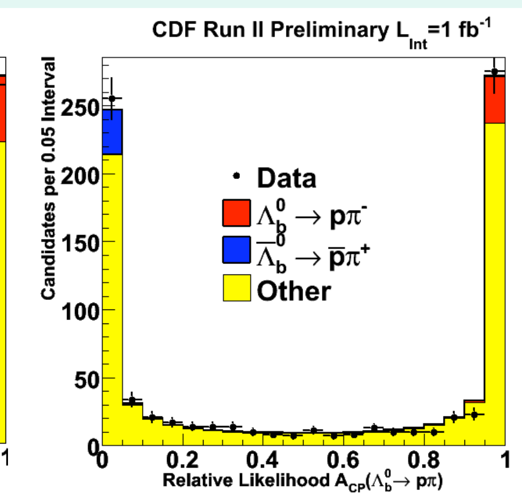
Charmless decays of a b Baryon recently observed at CDF for the first time :

$BR(\Lambda_b^0 \to pK) = (5.0 \pm 0.7 \pm 1.0) \times 10^{-6}$
$BR(\Lambda_b^0 \to p\pi) = (3.1 \pm 0.6 \pm 0.7) \times 10^{-6}$
(Assuming PDG value $f_{baryon}/f_d = 0.25 \pm 0.04$)

Predicted:

$BR(\Lambda_b^0 \to pK) = 2 \times 10^{-6}$
$BR(\Lambda_b^0 \to p\pi) = 1 \times 10^{-6}$





Direct CP asymmetries:

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

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

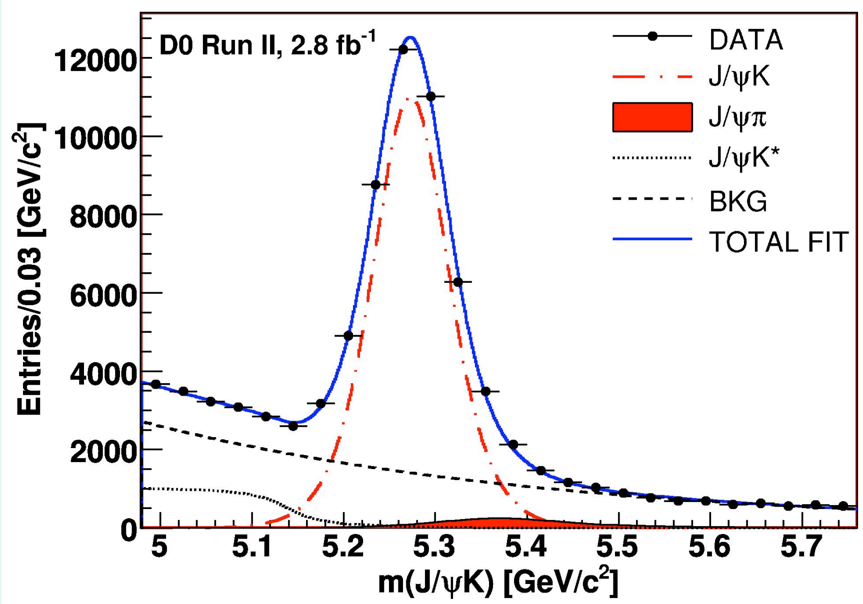
Expect an effect at least in pK. Too early to draw conclusions, but interesting in future.

These measurements unique to Tevatron, but there is more…

$B^{0/+}$ CPV at Tevatron! $B^+ \to J/\psi K^+$

- Now, with large Tevatron samples even improve precision on B^0/B^+ !
- Another good place to look for anomalous CPV is $B^+ \to J/\psi K^+$
- If $B^+ \neq B^0$ effect due to NP
  expect 1% asymmetry
- [hep-ph/0605080, PL B598, 218 (2004), PRD 62, 056005 (2000)]
- Recent D0 result improved the world average by factor 2

[arXiv:0802.3299 [hep-ex]]



$ACP(B^+ \to J/\psi K^+) = (0.75 \pm 0.61 \pm 0.27)$ %

(previous WA : (1.5 ± 1.7) %)

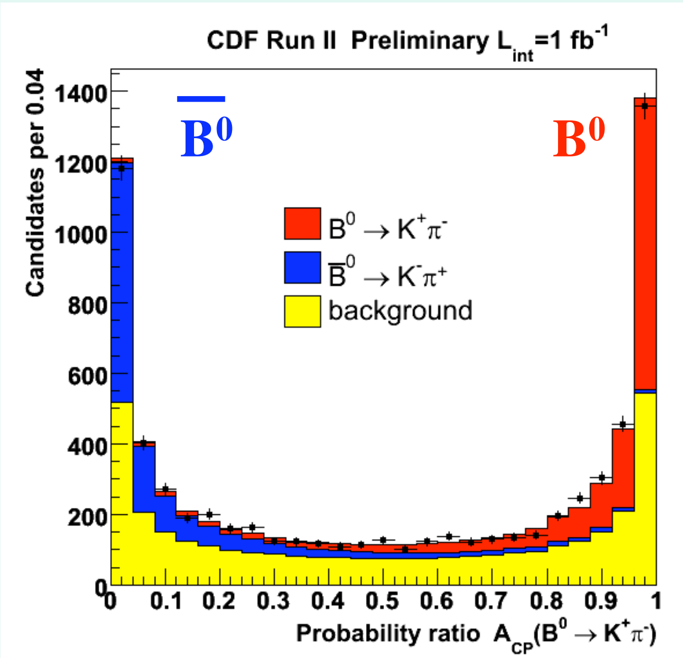
- Not conclusive yet, but important step forward

- Also measure:

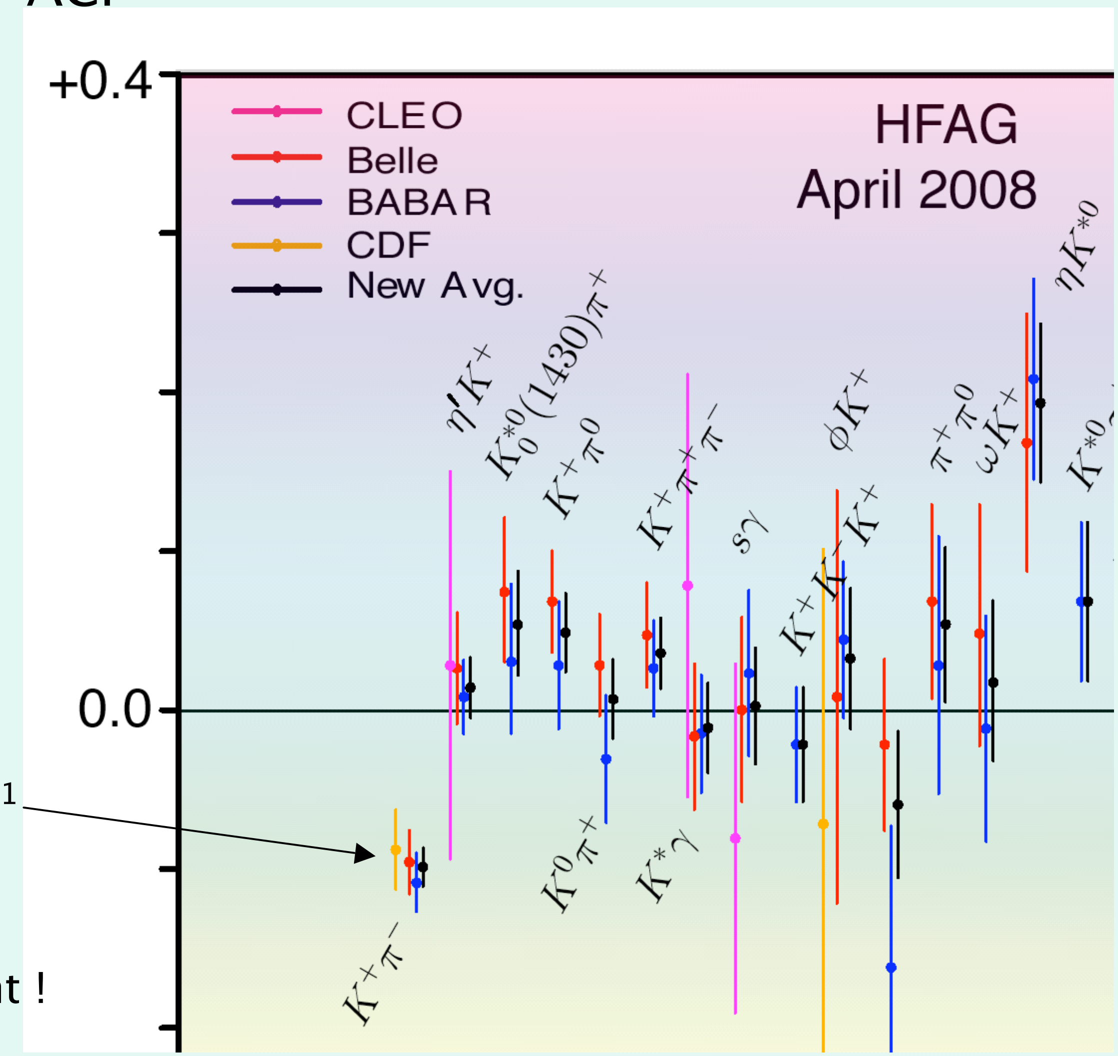
  $ACP(B^+ \to J/\psi \pi^+) = (-9 \pm 8 \pm 3)$ %

(Strictly related to the recent hint of anomalous $ACP(B^0 \to D^+D^-)$)

ACP($B^0 \to K^+\pi^-$)at Tevatron



ACP

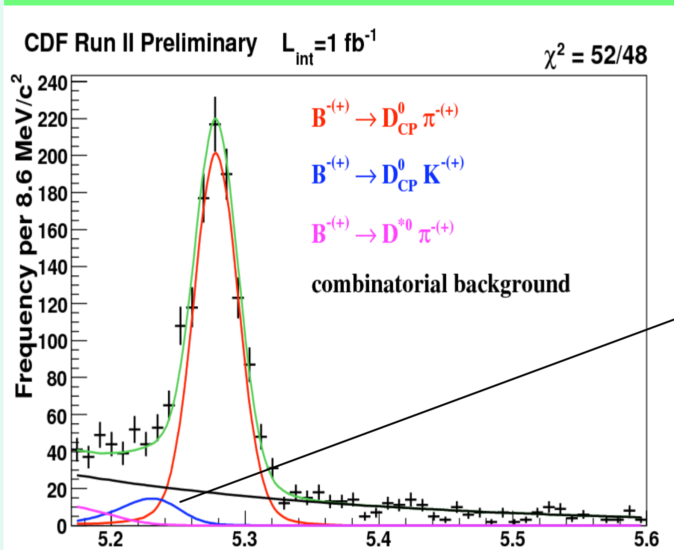


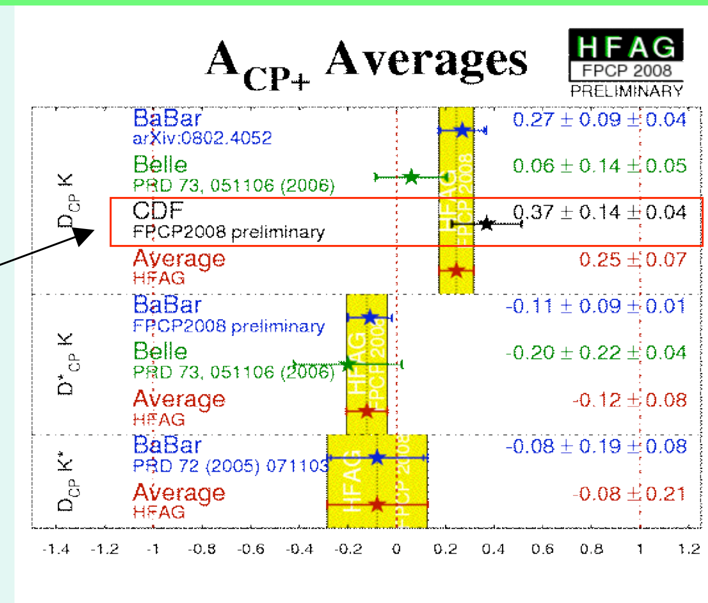
Significant contribution to
ACP(B^0->Kpi) from CDF with 1fb^{-1}

⇒ Future resolution <1%
Expect world's best measurement !

Current rates: Belle 7 ev./day
CDF 23 ev./day

CKM angles: CPV in $B^+ \to D^0_{CP} K^+$





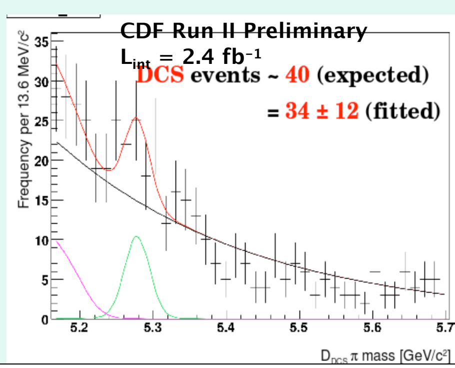
sample
~ full
~1/3 logged
~1/3 logged

- CP asymmetry in modes $D^0_{CP} \to K^+K^- / \pi^+\pi^-$
- Achieved same precision of e^+e^- with 1 fb^{-1}

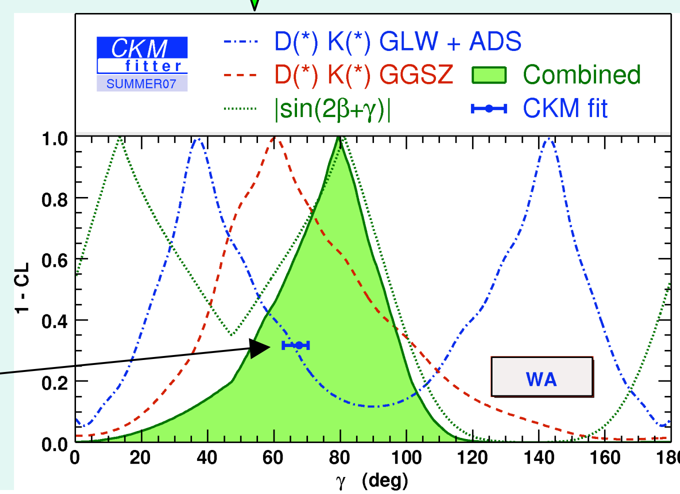
Hi-lum means will stay on track in future.

Contribute to determination of CKM angle γ (GLW method)

Moving on to ADS method: reconstruction of $B^+ \to D_{DCS}\,\pi^+$



Comparison with other determinations of γ important NP test



Bs meson

Bs meson

[I. Bigi, CERN Theory Institute, 5/26/08]

V On the Autonomy of B_s Dynamics

original paradigm: need B_d & B_s to determine all 3 angles

ϕ_2/α, ϕ_1/β from B_d vs. ϕ_3/γ from B_s

new paradigm: can get all angles from B_d

Furthermore 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!

Flavor mixing

- Flavor eigenstate ≠ Hamiltonian eigenstate
  - transition between meson and anti-meson exists
- 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 G_{12}/M_{12} <<1)

$$|B_L> = p|B_q^0> + q|\overline{B}_q^0> \qquad \Delta m_q = m_H - m_L = 2|M_{12}^q|$$

$$|B_H> = p|B_q^0> - q|\overline{B}_q^0> \qquad \Delta\Gamma_q = \Gamma_L - \Gamma_H \cong -2|\Gamma_{12}^q|\mathrm{Re}(\frac{\Gamma_{12}^q}{M_{12}^q}) = 2|\Gamma_{12}^q|\cos(\varphi_s)$$

In the Bs meson: Δm_s , $\Delta\Gamma_s$ and φ_s sensitive to New Physics ($|\Gamma_{12}|$ is not)

In particular, the phase ($\varphi_s = -2\beta_s$) is small in SM, but could be large in NP

Crucial measurements, currently possible only at Tevatron

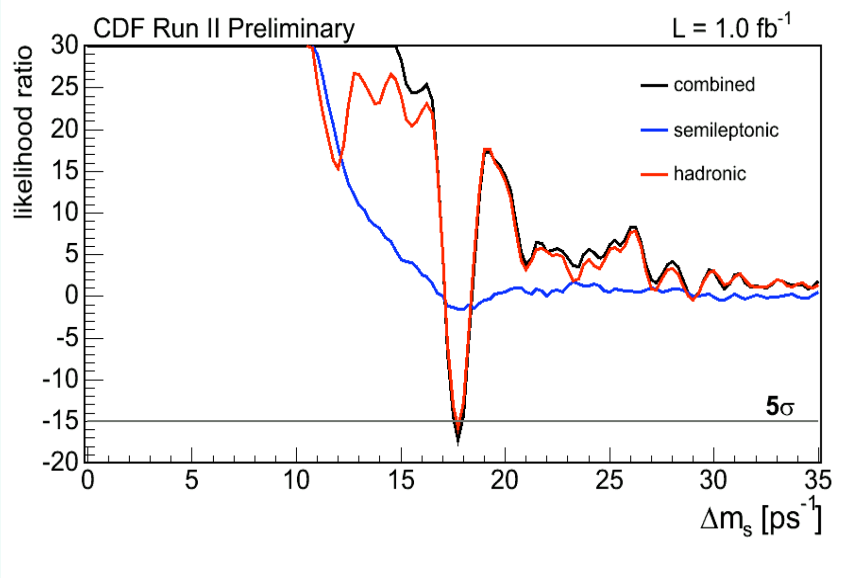
$|M_{12}|$ and Δm_s

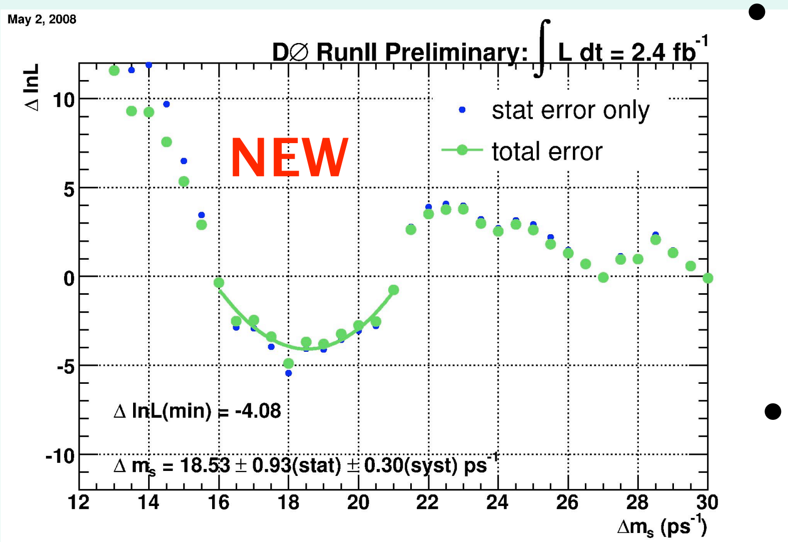
- Oscillation observed at 5σ in CDF in 2006 with $1 fb^{-1}$ of data
- Δm_s known with great precision:

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

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\exp)^{+0.0081}_{-0.0060}(theor)$$

- Comparison with SM prediction limited by lattice QCD uncertainty!





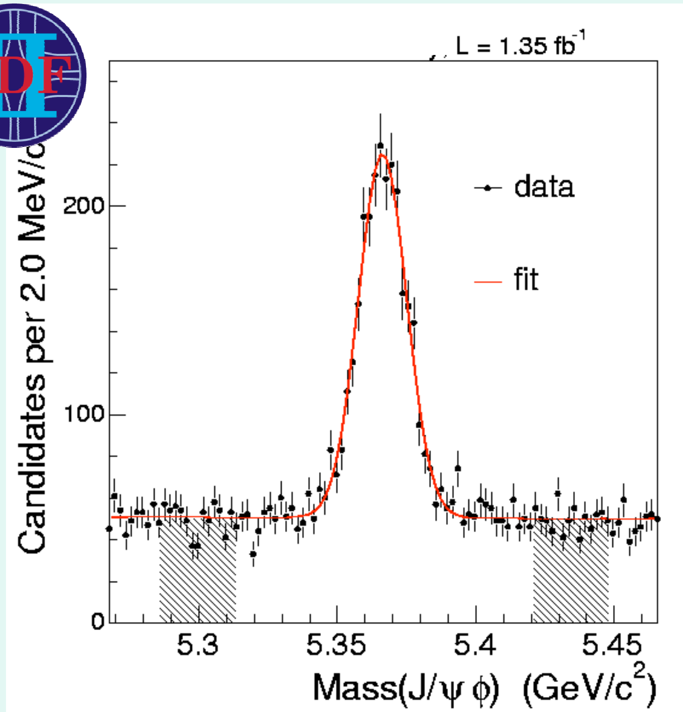
- DØ recent update ($2.4 fb^{-1}$) now gets significance up to 3σ (stat. only). Result consistent with CDF:

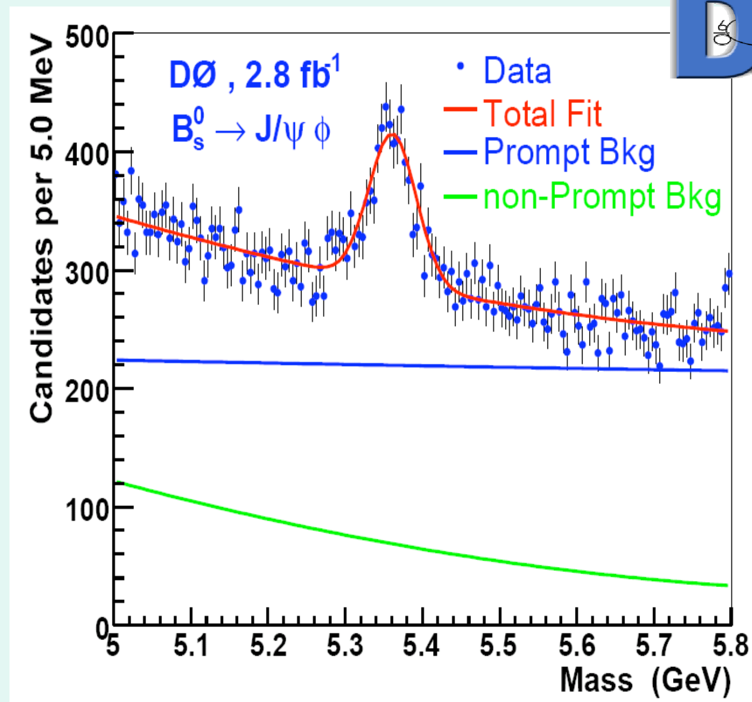
$$\Delta m_s = 18.53 \pm 0.90(stat) \pm 0.30(syst)\ ps^{-1}$$

[DØ-note 5618]

- Not much more to say on this parameter until LQCD improves considerably – But there are *two more* parameters to mixing.

$B_s \to J/\psi\ \phi$ signals



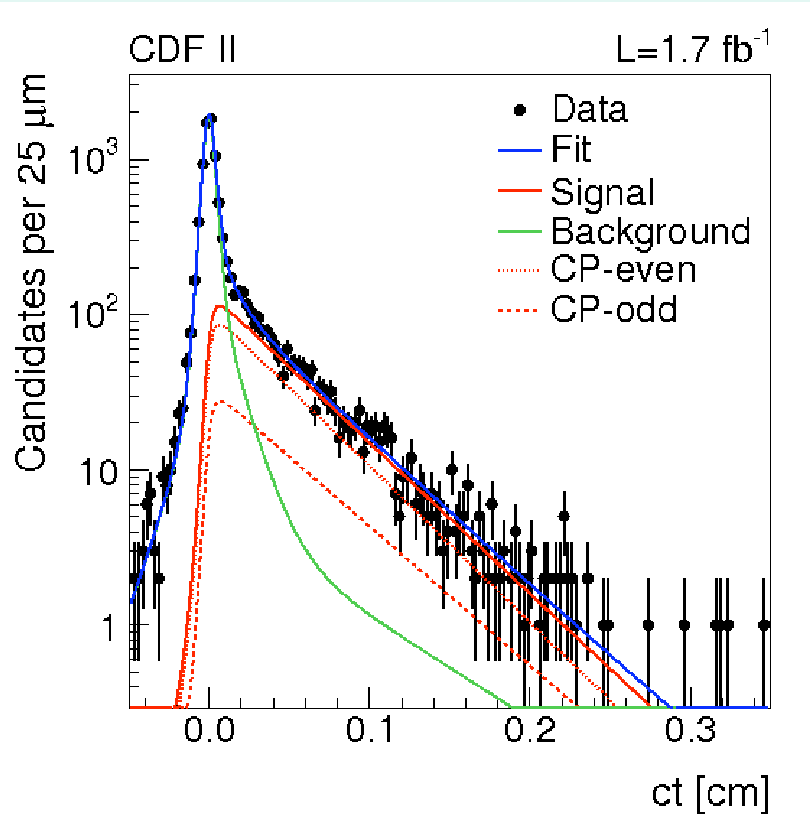


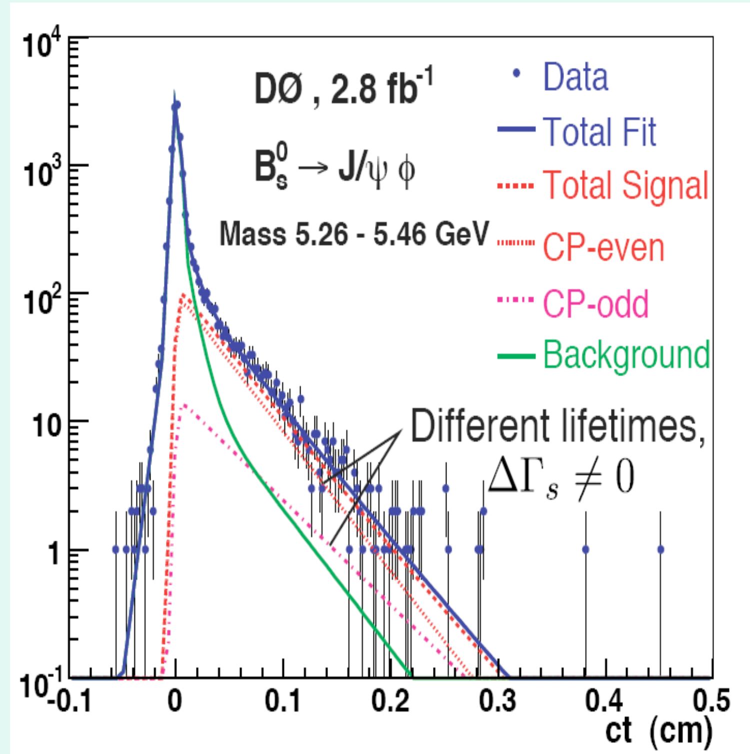
<u>Signal Candidates</u>:
~2000 in 1.35 fb^{-1}
(Separate untagged analysis uses ~2500 in 1.7 fb^{-1})

<u>Signal Candidates</u>:
~2000 in 2.8 fb^{-1}

- Bs-> $J/\psi\phi$ contains both CP components, ideal mode.
- Need to statistically separate them by their angular distribution

Results: $\tau_s(=1/\Gamma_s)$ and $\Delta\Gamma$ (assume $\beta_s=0$)





τ=1.52 ± 0.04± 0.02 ps

$\Delta\Gamma$ =0.08 ± 0.06 ± 0.01 ps^{-1}

Phys. Rev. Lett. **100**, 121803 (2008)

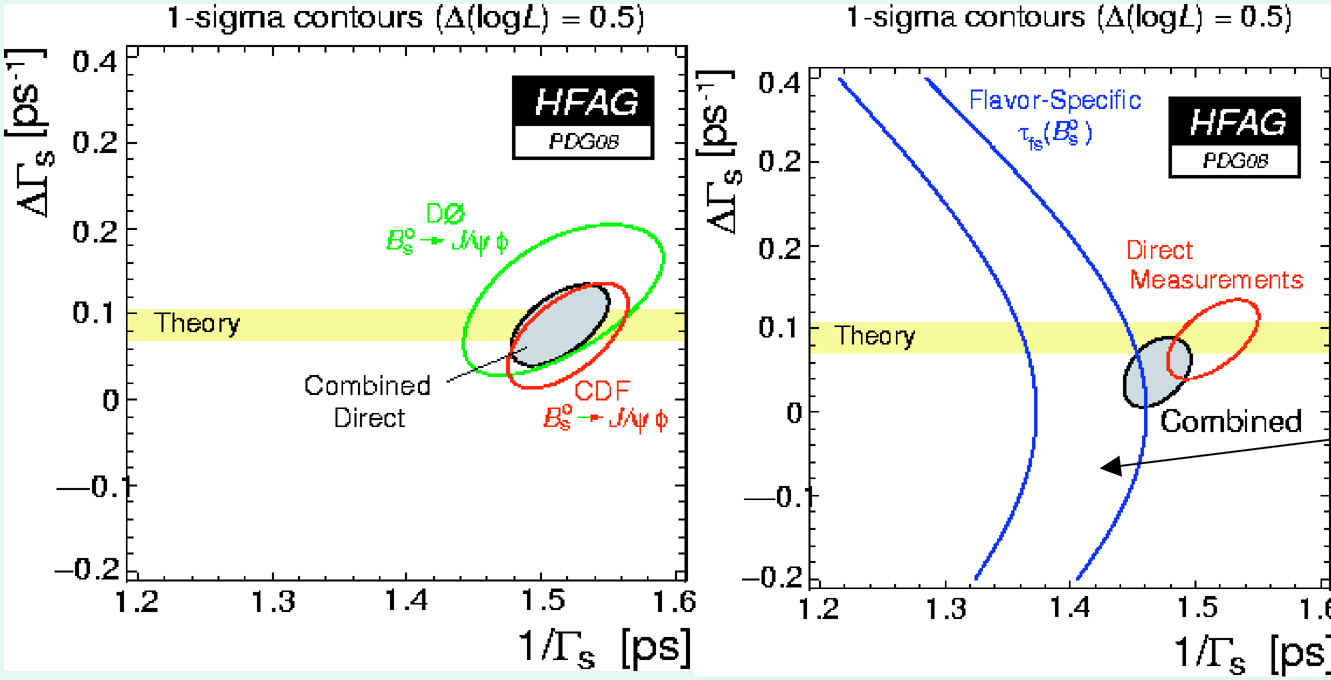
τ =1.53 ± 0.06 ± 0.01 ps

$\Delta\Gamma$ =0.14 ± 0.07 $^{+0.02}_{-0.01}$ ps^{-1}

arXiv:0802.2255[hep-ex])

World's best measurements

Status of $\Delta\Gamma$



Mostly Tevatron (Latest CDF measurement not yet included)

Predictable in SM $\Delta\Gamma_s = 2|\Gamma_{12}|\cos(2\beta_s) = 0.096 \pm 0.039\ \mathrm{ps}^{-1}$. Sensitive to NP
[Nierste, Lenz, hep-ph/0612167]

Currently good agreement with SM

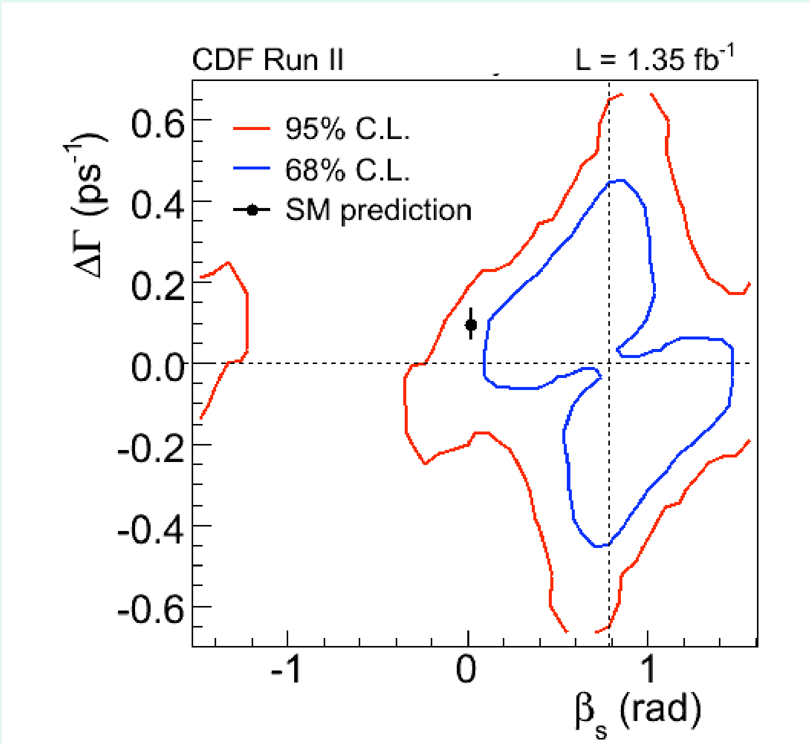
Other $\Delta\Gamma$ measurements@Tevatron:

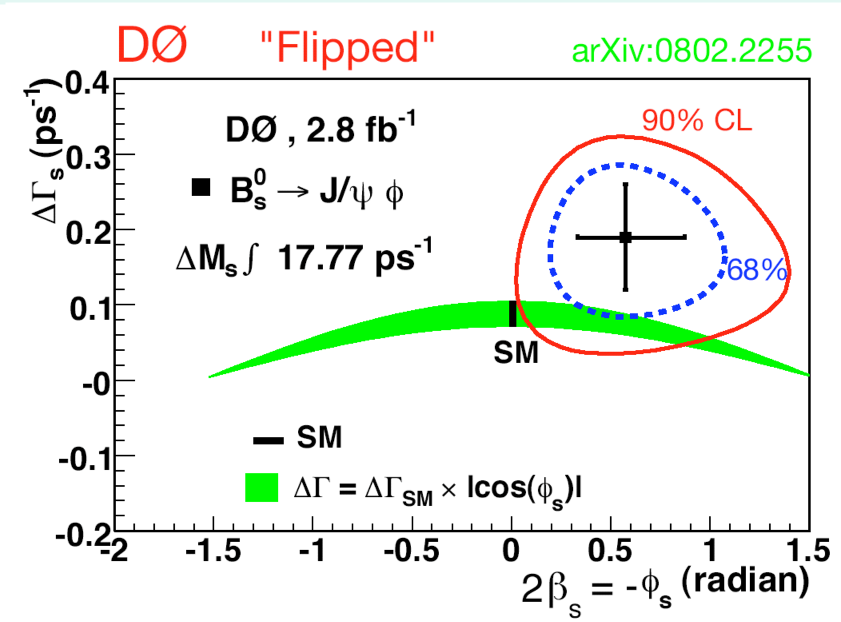
– CP-specific modes : $Bs \to K^+K^-$

– Extraction of Γ_{12} from BR(Bs → Ds(*)Ds(*)) ⇒ see talk by Youn

Almost 100% Tevatron – Looking forward to detect $\Delta\Gamma \neq 0$

Fit for β_s: limits in β_s–$\Delta\Gamma_s$ plane





	P-value(SM)
CDF	0.15 (1.5σ)
D0	0.066 (1.8σ)

Tension with SM, both experiments in the same direction.

What if we combine CDF and D0…

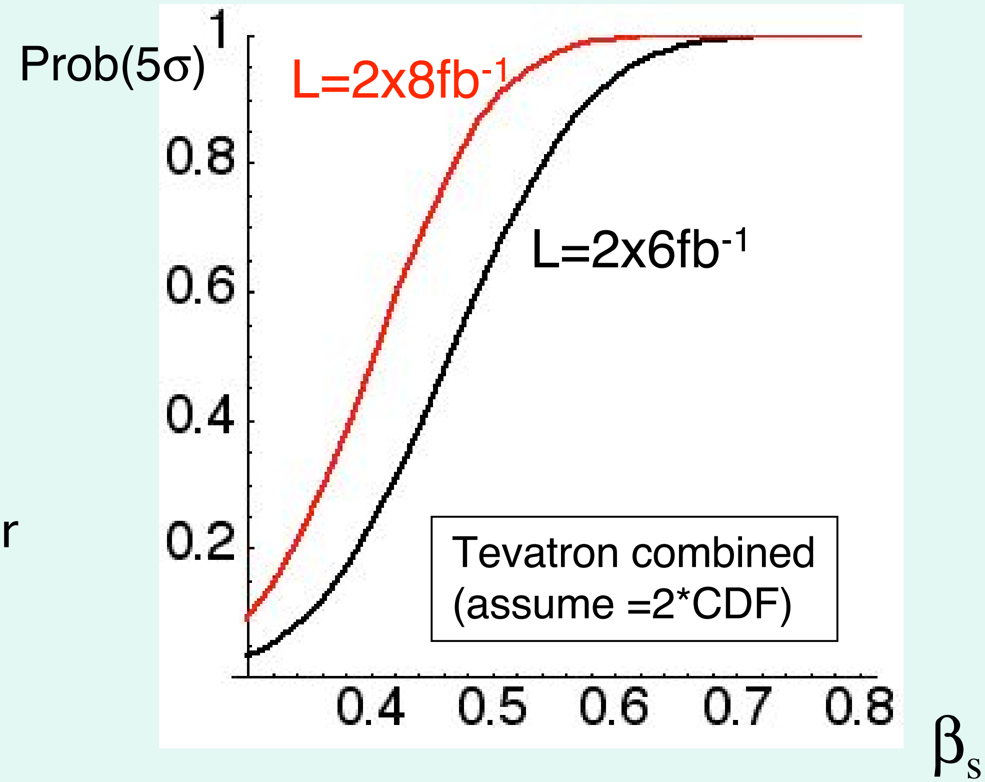
- Both experiments show a deviation of the phase in the same direction
- The UTfit collaboration made a global fit and claims a 3-sigma deviation from SM [arXiv:0803.0659v1 [hep-ph]]
- Some approximations in it:
  - Does not account for non-gaussian tails
  - Some guesswork to “remove” from D0 results the assumptions on strong phases.
- A Tevatron combination is underway – expected soon.

Could it possibly be New Physics ?

- Models predicting large βs not uncommon
- Es. based on a heavy 4th generation: [Hou at al., Phys.Rev.D76:016004,2007] Interestingly, it also predicts $A_{CP}(B^0 \to K^+\pi^-) \neq A_{CP}(B^+ \to K^+\pi^0)$, the large observed D^0 mixing, and further signals accessible at Tevatron.

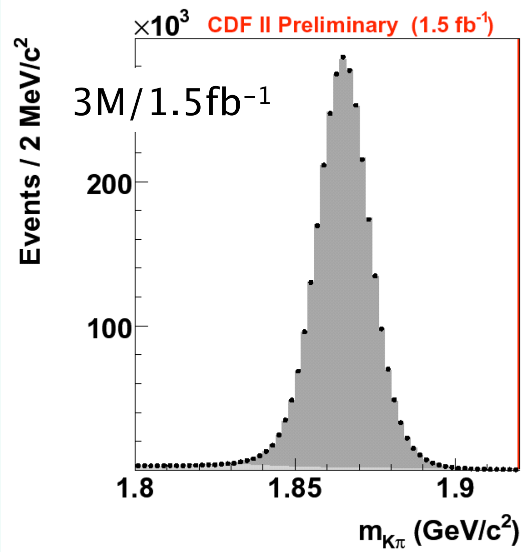
Tevatron Outlook for β_s

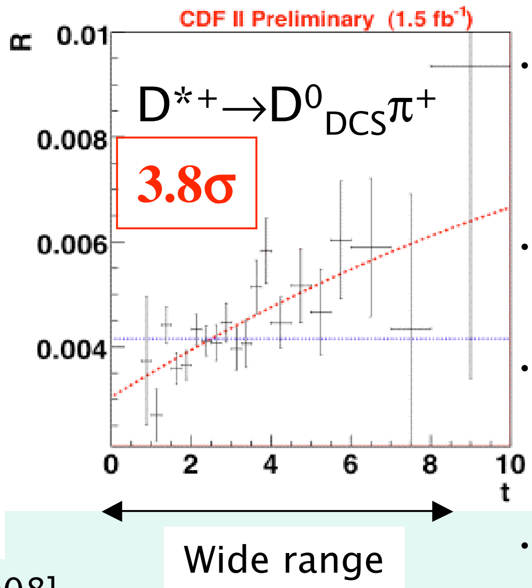
- Assumes no analysis improvements, and no external constraints, but same signal yield and experimental resolution.
- May do better adding further signals (triggers) or better tagging (underway)



If β_s is large ($\gtrsim$0.4) expect Tevatron to discover NP

A whole new territory: Charm Mixing





[Phys.Rev.Lett.100:121802,2008]

Experiment	$R_D (10^{-3})$	$y' (10^{-3})$	$x'^2 (10^{-3})$	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

- Much smaller effect than in B $\Rightarrow$ more sensitive to anomalous FCNC (**different** in *c*–quark)
- BaBar observed effect at the **very upper end** of SM expectations.
- Could it be new physics we are witnessing ? Is there CP violation ? No evidence yet.
- Huge charm samples at CDF, widest lifetime span.

CDF result@1.5fb^{-1} ≡ BaBar(0.4ab^{-1})

Expect strong Tevatron impact

Big potential for many other related measurements:

CDF dominated the WA of $A_{CP}(D^0 \to \pi^+\pi^-/K^+K^-)$ until recently with ***0.12 fb^{-1}***

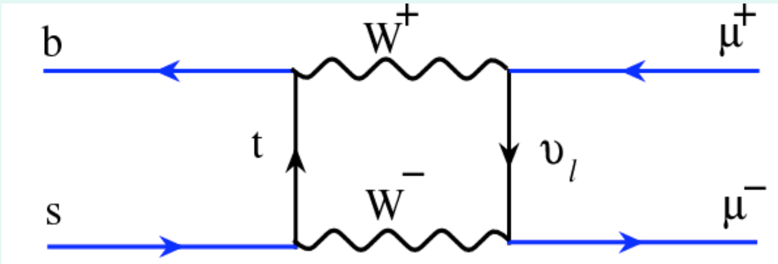
This is where significant CPV from NP can be found

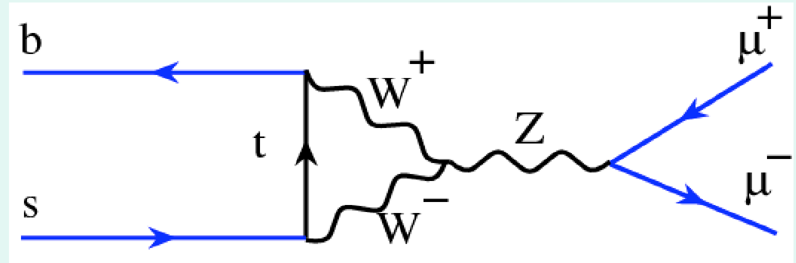
[Grossmann et al., Phys.Rev. D75 (2007) 036008]

.Unique opportunities@Tevatron for exciting new physics

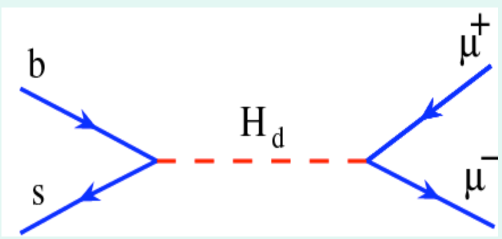
Rare modes

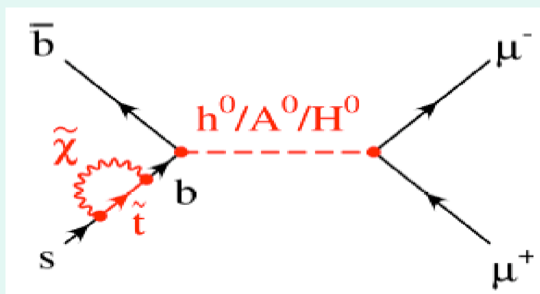
$B^0_{(s)} \to \mu^+\mu^-$

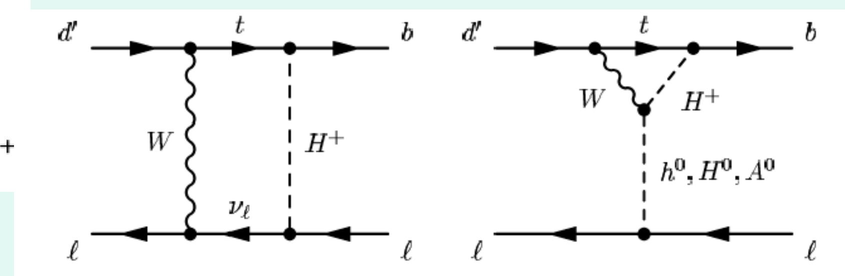




- SM: BR($B^0_s \to \mu\mu$) = $(3.42 \pm 0.54)\times10^{-9}$ *Buras, PLB 566, 115 (2003)*
- SM: BR($B^0_d \to \mu\mu$) = $(1.00 \pm 0.14)\times10^{-9}$ suppressed by $(V_{td}/V_{ts})^2$ in the SM

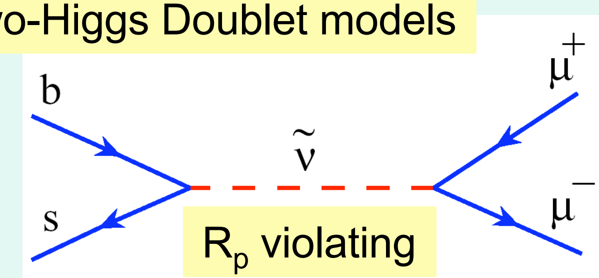




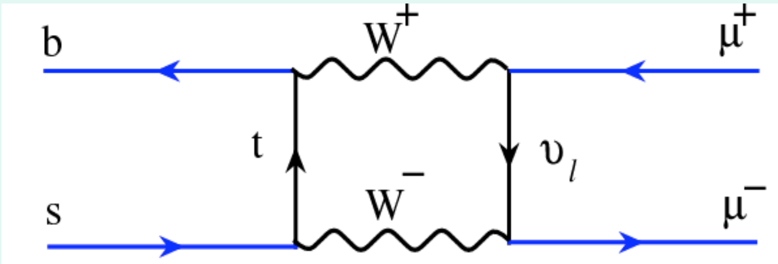


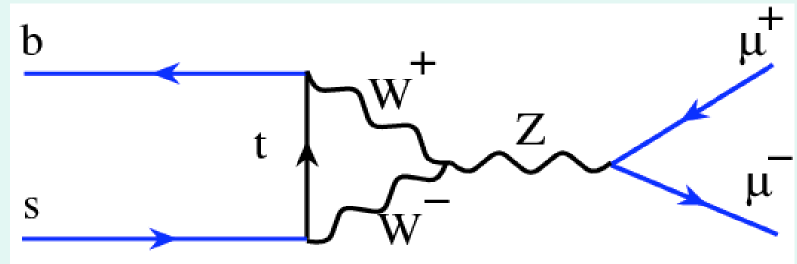
Two-Higgs Doublet models

- New Physics contributions:
  - MSSM ~$\tan^6(\beta)$, for large $\tan(\beta)$
  - SUSY with R-parity violation (RPV)
  - Z′ with off diagonal couplings
  - Almost any heavy beast…



$B^0_{(s)} \to \mu^+\mu^-$





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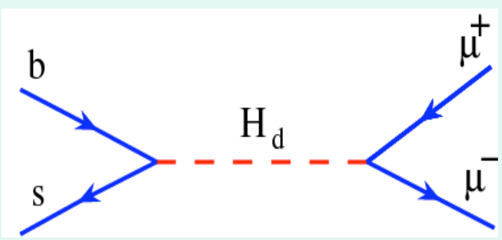

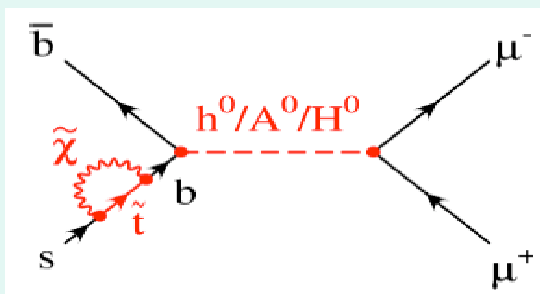

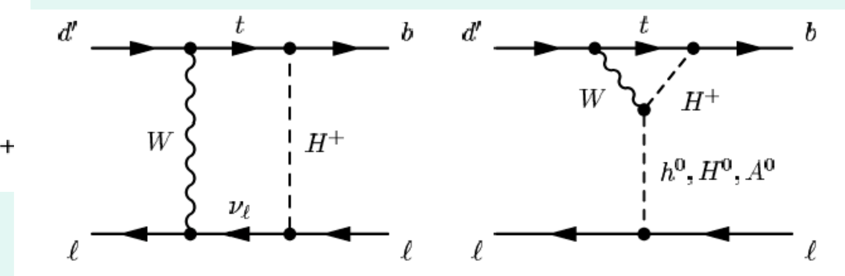

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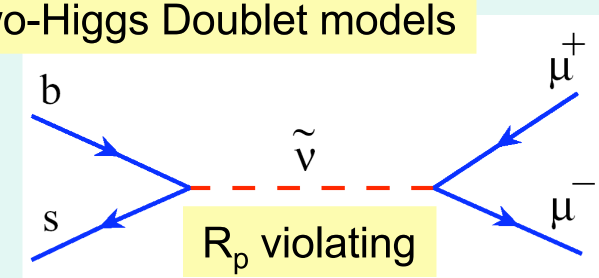
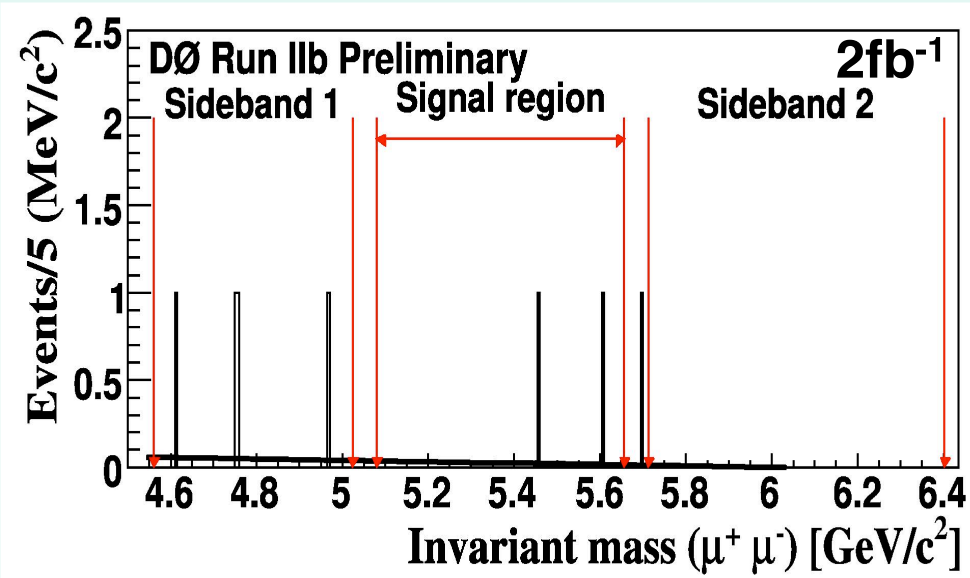
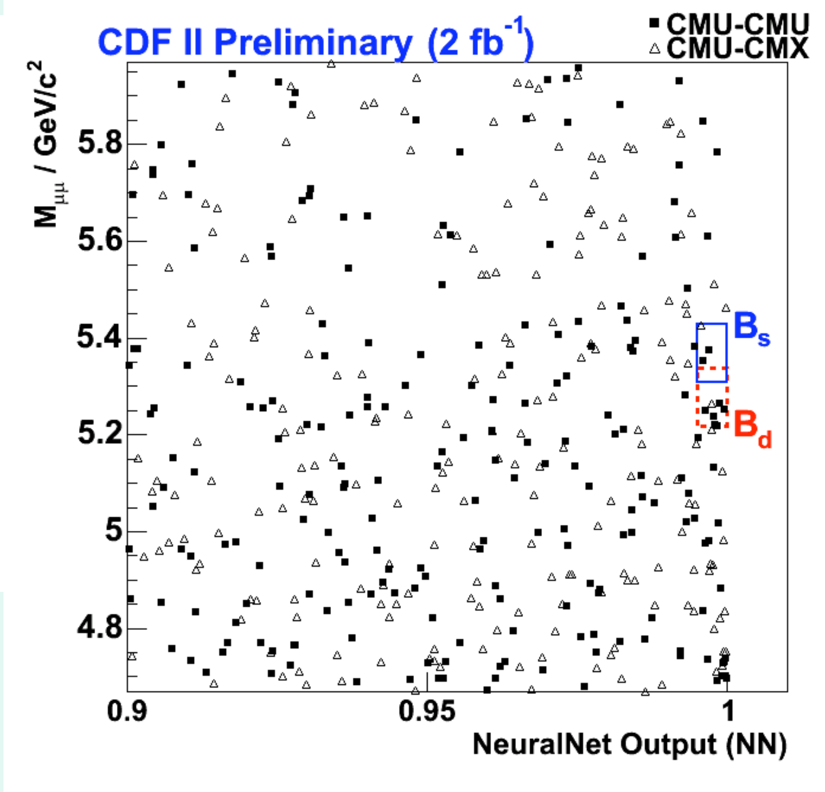


$B^0_{(s)} \to \mu^+\mu^-$ Results





2fb^{-1}/experiment

Sorry, no excess observed yet !

	$B^0_s \to \mu\mu$	$B^0_d \to \mu\mu$
CDF	$< 4.7\times10^{-8}$	$< 1.5\times10^{-8}$
D0	$< 7.3\times10^{-8}$	

PRL 100,101802 (2008)

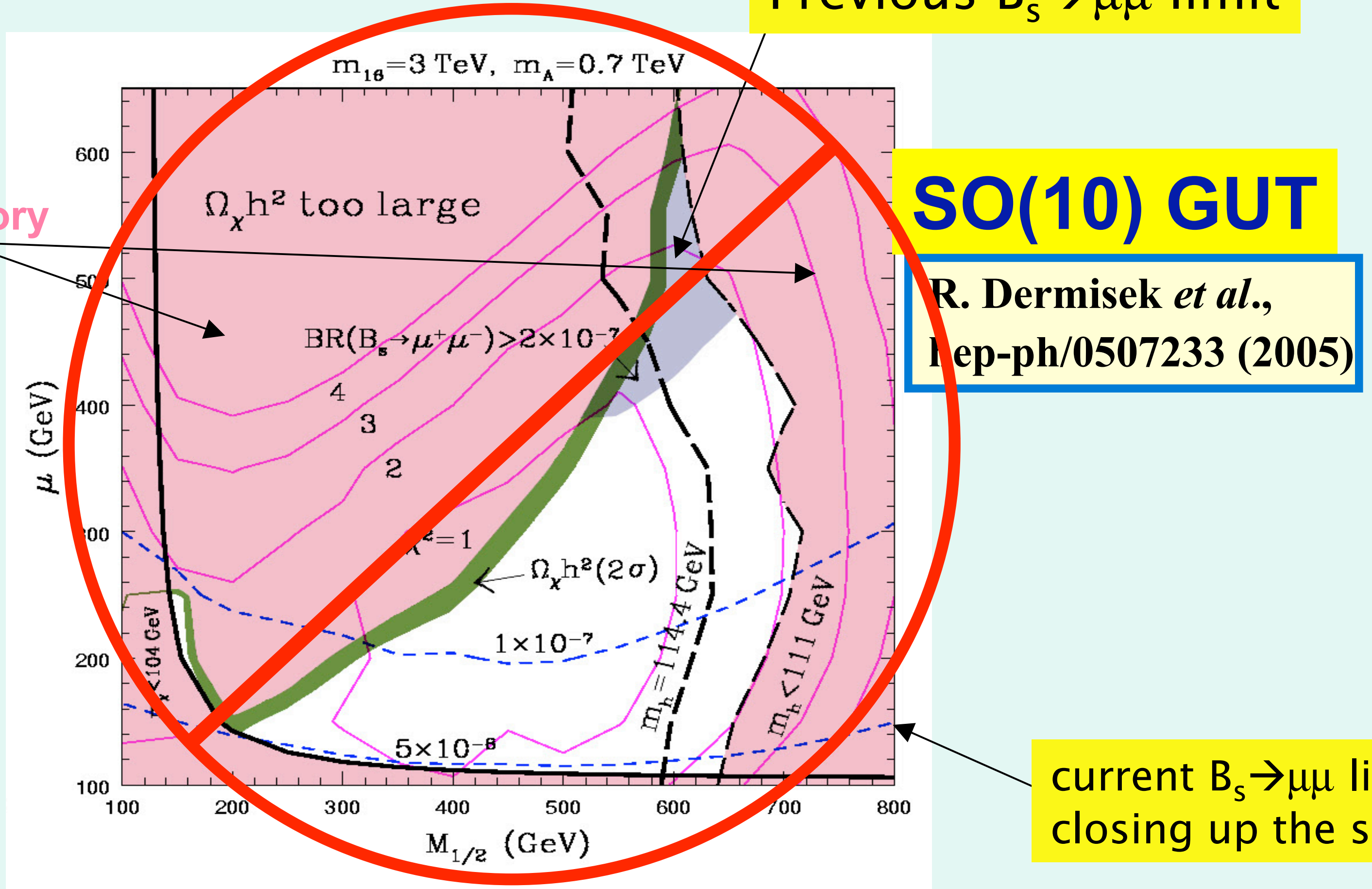
[D0 Note 5344]

- New HFAG average

  $< 4.7 \times10^{-8}$ @ 90% CL

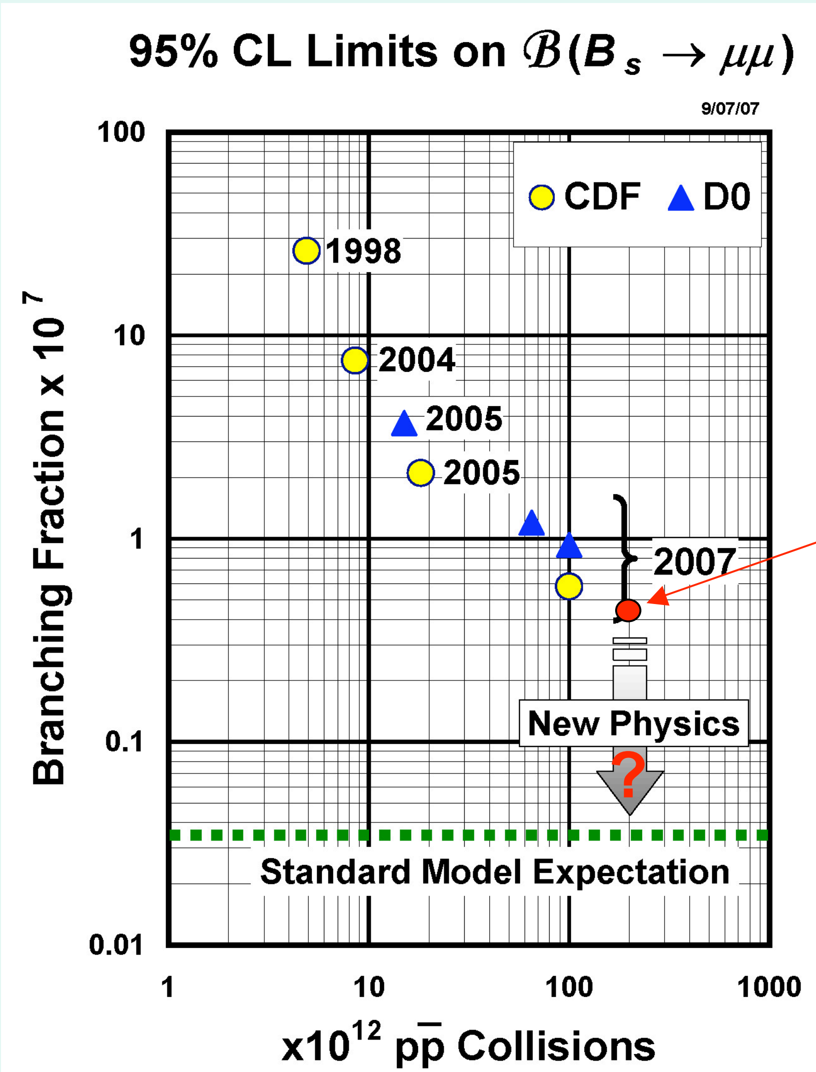
Most stringent to date!

Wide regions of NP now excluded



(tan(β)~50 constrained by unification of Yukawa couplings)
Only small corners survive for other parameter choices

What's next ?



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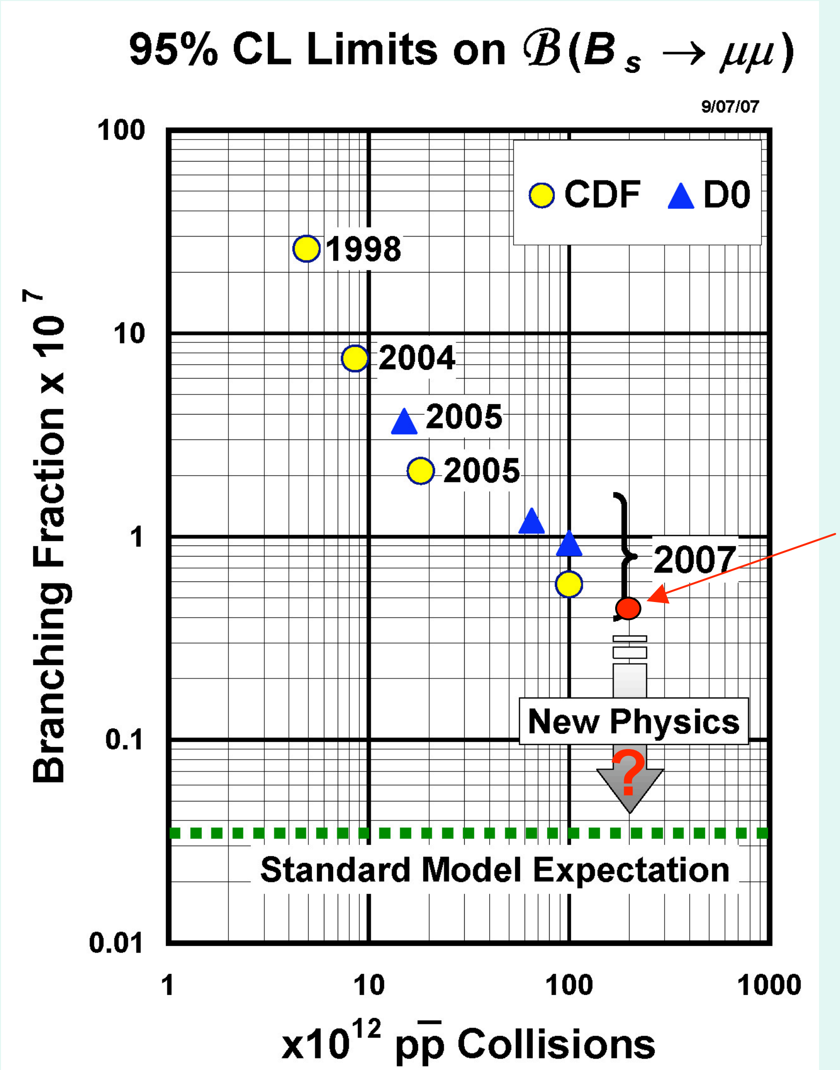
What's next ?



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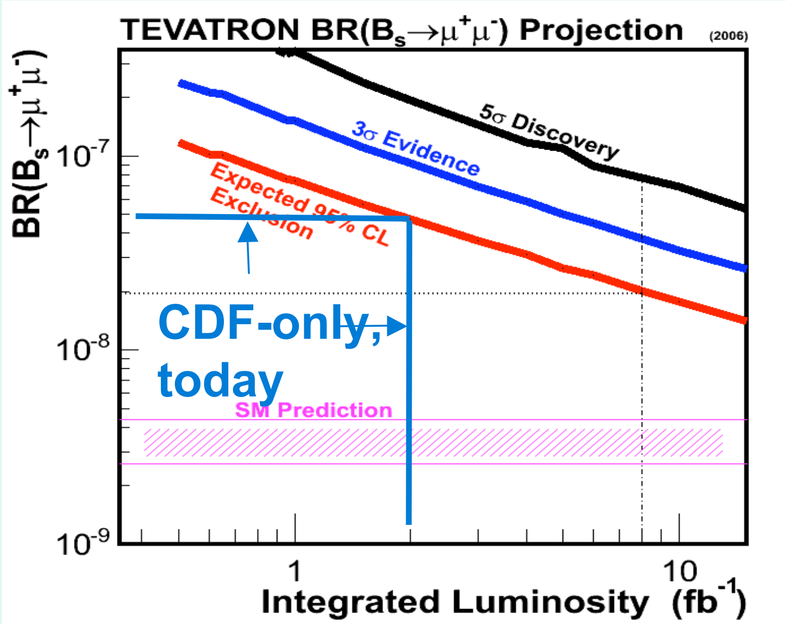
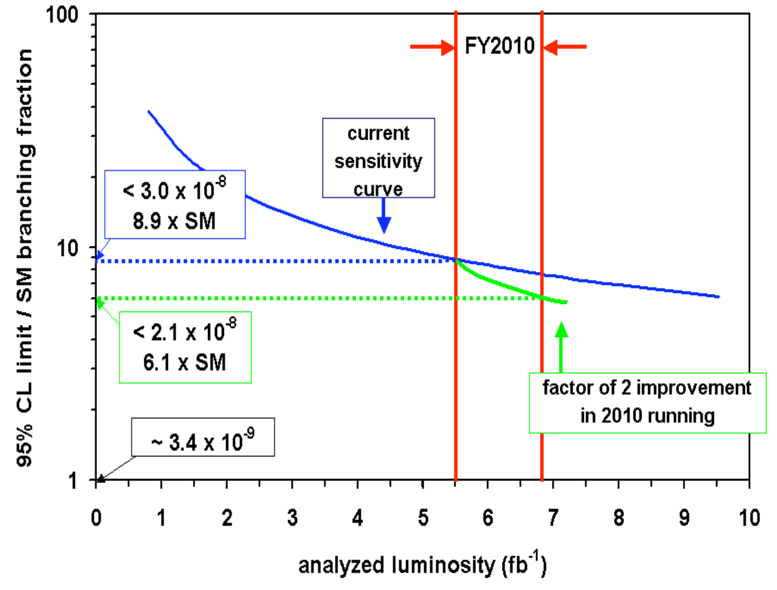
Surprises waiting in the last 10x factor ? What can Tevatron still do?

Tevatron $B_s \rightarrow \mu\mu$ Reach

- CDF extrapolates current analysis without improvements.
- D0 includes a planned increase of bandwidth allocation to this trigger
- Each exp. hits $2*10^{-8}$ at 7/8 fb^{-1}. This is just 6xSM. Corresponds to 2 SM events after all cuts (SES 1.7 10^{-9})
- Combining results expected to push the sensitivity down to 4xSM
- Past history shows results always exceeded predictions: each experiment now has the sensitivity previously predicted for the Tevatron.

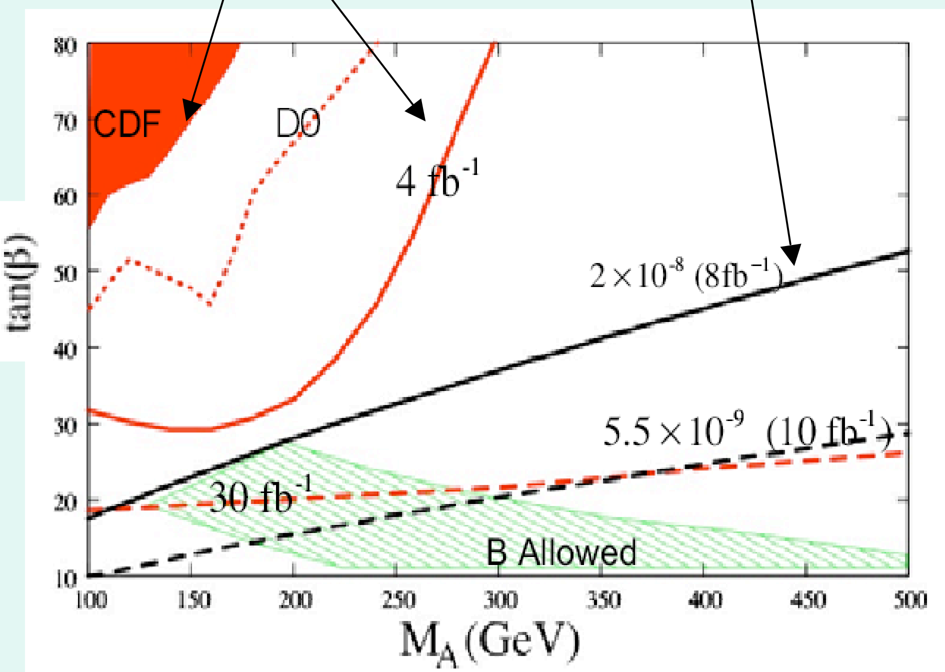




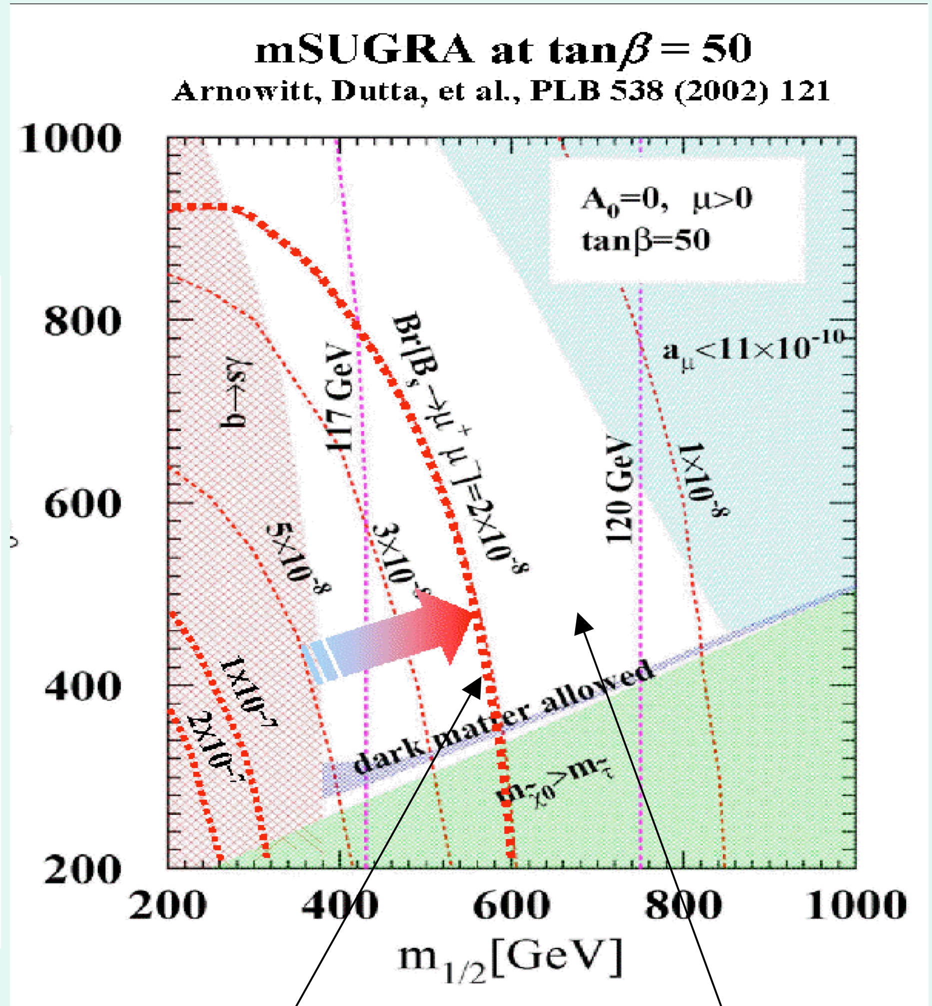
Expect some further exploration into the unknown

Red: direct searches $A/H \rightarrow \tau^+\tau^-$

Black: $B^0_s \rightarrow \mu\mu$



In some scenarios, $B^0_s \rightarrow \mu\mu$ quite more powerful than direct searches.
[Phys.Rev.D76:035004,2007]



$B^0_s \rightarrow \mu\mu$

Allowed region

Conclusions

- Very rich set of flavor results from Tevatron
  - Exploring heavy hadrons
  - CP violation
  - Rare modes
- With increase of samples, not just increase of precision, but also widening of the scope.
- Many unique measurements
- Many probes for NP into uncharted territories
- Even improving results about old friends B^0 and B^+
- Thanks to great accelerator performance, data is coming fast now.
  Exciting news may be around the corner !