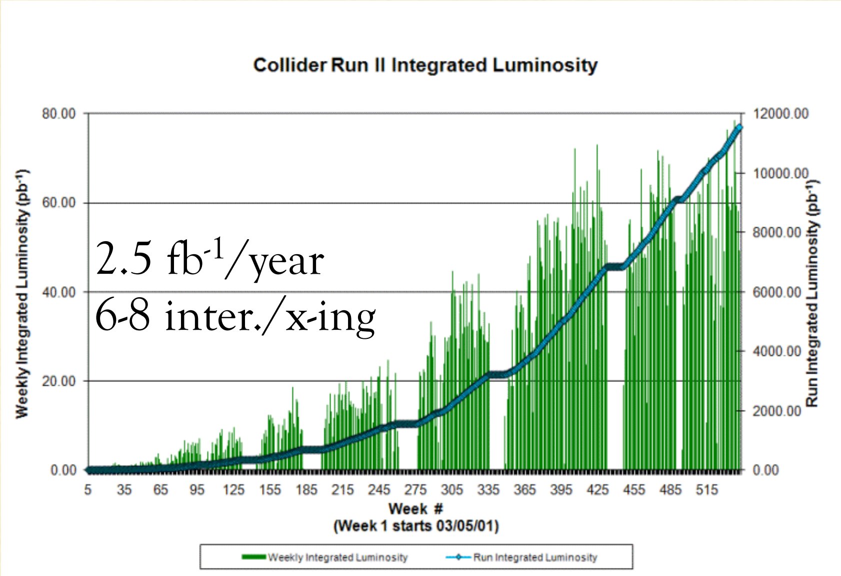
Summary of measurements from CDF

The 8th Meeting on B Physics
Genova,6-7 February 2012
Michael J. Morello - SNS and INFN Pisa
(for the CDF Collaboration)

CDF and the Flavor

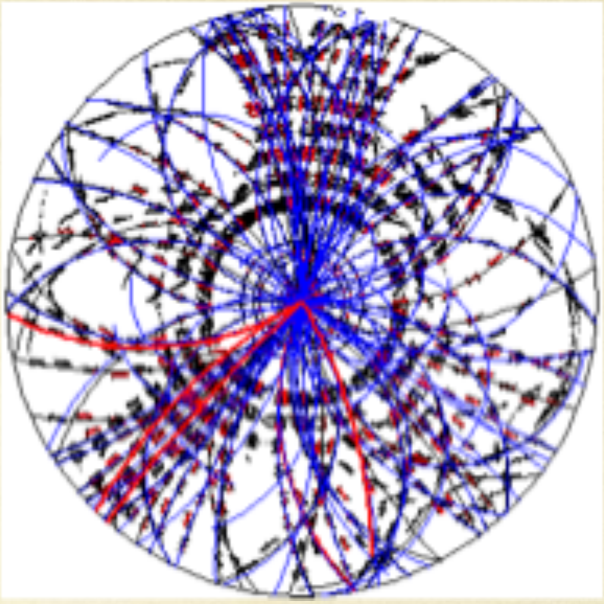
- 10 fb^{-1} final sample (Sep 30, 2011)
- 10^{13} $p\bar{p}$ collisions at 2 TeV in 10 years of operations.
- 1 KHz of reconstructable B pairs with p_T 5-10 GeV/c



CDF considered "High-P_T experiment". However...

- High-rate of all species of heavy flavors
  - actually higher than "B-Factories" (although lower than LHCb).
- Precision reconstruction capabilities.
- Symmetric detector and CP-symmetric initial state.

How do we do it?



- Tracking: $\sigma(p_T)/p_T^2$ = 0.1%.
  Usually require all-charged final state.
- Silicon close to beam, σ(i.p.) ~30 μm.
- Good muons.
- Some PID
  (1.5σ K-π separation: it's 80% of ideal)
- Efficiencies normalized to reference modes. Hard to do absolutely.
- Mostly data-driven analyses. Simulation only for kinematics.
- Typical analysis challenges:
  - Background rejection: several orders of magnitude;
  - Sample composition;
  - Tagging of HF hadron at production (D*-tag for charm and sophisticated algorithms for B).

Live or die by the trigger

- Single lepton.
- Di-lepton.
- CDF only: Secondary vertex trigger (hugely empowering)
  - Access wide range of decays.
    - Two displaced tracks.
    - One lepton + one displaced track.
  - L1 trigger on drift chamber (XFT)
    +L2 i.p. trigger on SVX(SVT)
    +L3 trigger on full reconstruction.
- Trigger philosophy @ CDF:
  - Fixed bandwidth to permanent storage ⇒ **Maximize purity**

The first CDF result was about Flavor

CDF approves first Run II paper

by Kurt Riesselmann

Scientists at CDF have announced that they will soon release the first publication based on data obtained from Fermilab's Collider Run II. An internal CDF seminar scheduled for March 7 is lik
an elaborate, six-month review process. Barring a
from members of the CDF collaboration, scientists
a mass measurement of particles containing charm
journal *Physical Review D.*

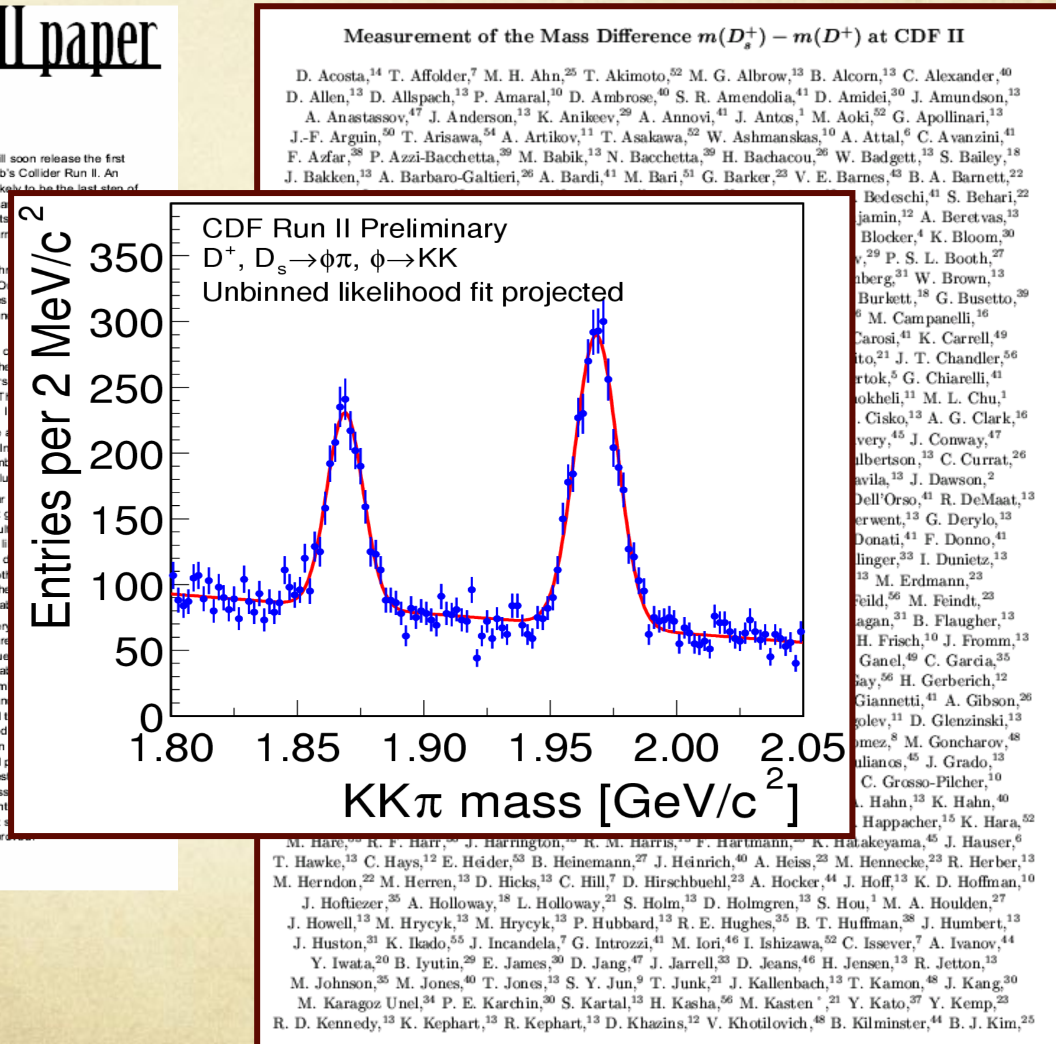
"It's not a major discovery," said CDF scientist Chr
professor at MIT. "It's bread-and-butter physics. O
mass difference between the D+ and Ds+ particles
world average. Even more important, the paper in
is back.'"

This is not to say that the CDF scientists or their c
DZero experiment had ever disappeared. Over the
collaborations have published hundreds of papers
experiments that took place from 1992 to 1996. T
first of a flood of publications expected from Run I

It often takes many months or even years before
is ready to publish results of a specific analysis. In
take almost as much time to convince other memb
that an analysis was done right and that its conclu

Graduate student Ivan Furic (left) and assistant professor Christoph Paus, both CDF scientists from MIT, carried out the analysis for the first publication of Run II results.

6 | FERMINEWS Friday, March 7, 2003

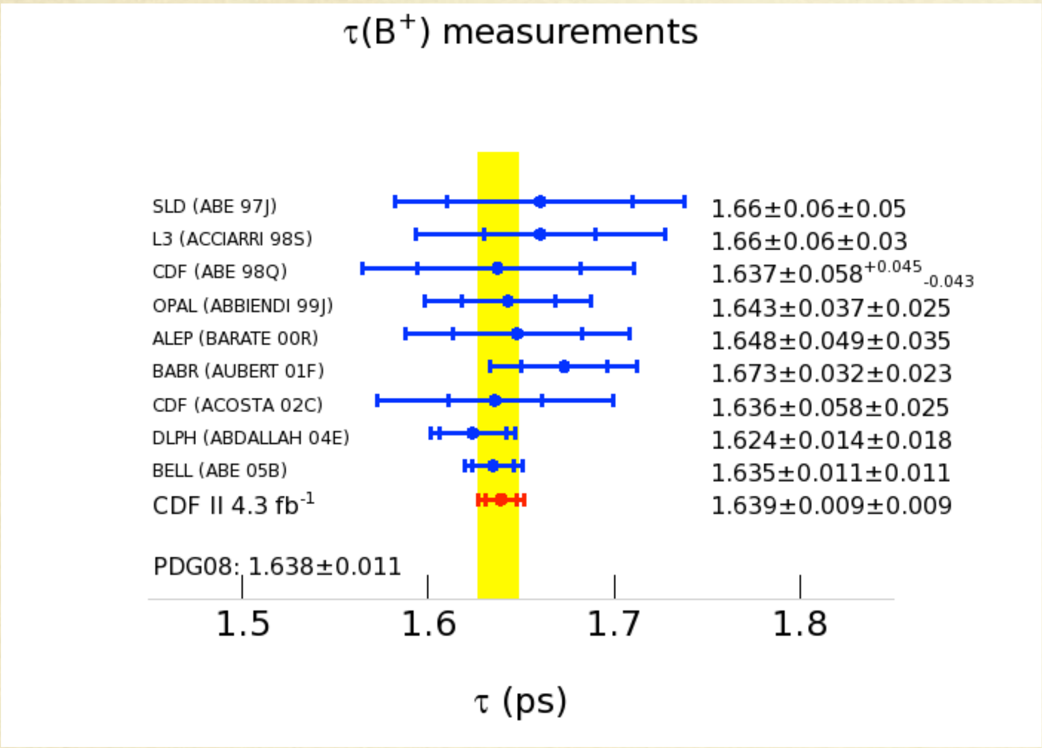


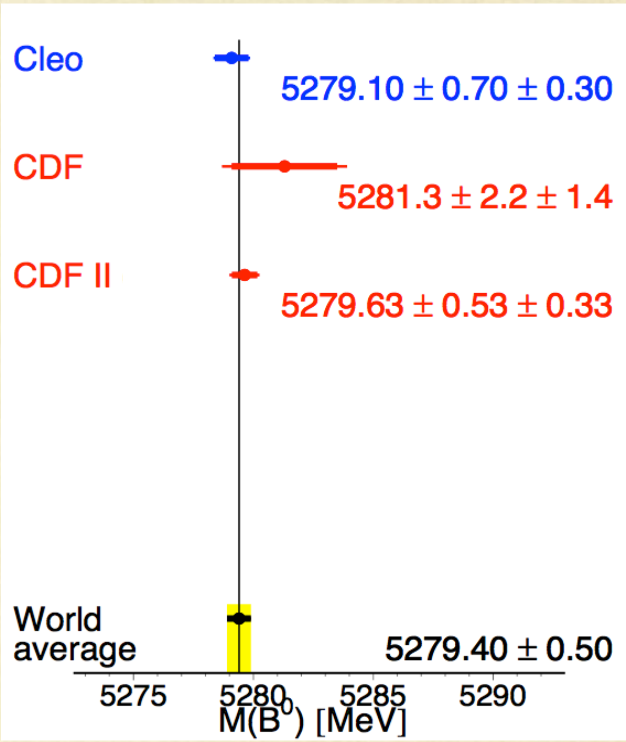
Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II

D. Acosta,[14] T. Affolder,[7] M. H. Ahn,[25] T. Akimoto,[52] M. G. Albrow,[13] B. Alcorn,[13] C. Alexander,[40] D. Allen,[13] D. Allspach,[13] P. Amaral,[10] D. Ambrose,[40] S. R. Amendolia,[41] D. Amidei,[30] J. Amundson,[13] A. Anastassov,[47] J. Anderson,[13] K. Anikeev,[29] A. Annovi,[41] J. Antos,[1] M. Aoki,[52] G. Apollinari,[13] J.-F. Arguin,[50] T. Arisawa,[54] A. Artikov,[11] T. Asakawa,[52] W. Ashmanskas,[10] A. Attal,[6] C. Avanzini,[41] F. Azfar,[38] P. Azzi-Bacchetta,[39] M. Babik,[13] N. Bacchetta,[39] H. Bachacou,[26] W. Badgett,[13] S. Bailey,[18] J. Bakken,[13] A. Barbaro-Galtieri,[26] A. Bardi,[41] M. Bari,[51] G. Barker,[23] V. E. Barnes,[43] B. A. Barnett,[22] ...

T. Hawke,[13] C. Hays,[12] E. Heider,[53] B. Heinemann,[27] J. Heinrich,[40] A. Heiss,[23] M. Hennecke,[23] R. Herber,[13] M. Herndon,[22] M. Herren,[13] D. Hicks,[13] C. Hill,[7] D. Hirschbuehl,[23] A. Hocker,[44] J. Hoff,[13] K. D. Hoffman,[10] J. Hoftiezer,[35] A. Holloway,[18] L. Holloway,[21] S. Holm,[13] D. Holmgren,[13] S. Hou,[1] M. A. Houlden,[27] J. Howell,[13] M. Hrycyk,[13] M. Hrycyk,[13] P. Hubbard,[13] R. E. Hughes,[35] B. T. Huffman,[38] J. Humbert,[13] J. Huston,[31] K. Ikado,[55] J. Incandela,[7] G. Introzzi,[41] M. Iori,[46] I. Ishizawa,[52] C. Issever,[7] A. Ivanov,[44] Y. Iwata,[20] B. Iyutin,[29] E. James,[30] D. Jang,[47] J. Jarrell,[33] D. Jeans,[46] H. Jensen,[13] R. Jetton,[13] M. Johnson,[35] M. Jones,[40] T. Jones,[13] S. Y. Jun,[9] T. Junk,[21] J. Kallenbach,[13] T. Kamon,[48] J. Kang,[30] M. Karagoz Unel,[34] P. E. Karchin,[30] S. Kartal,[13] H. Kasha,[56] M. Kasten *,[21] Y. Kato,[37] Y. Kemp,[23] R. D. Kennedy,[13] K. Kephart,[13] R. Kephart,[13] D. Khazins,[12] V. Khotilovich,[48] B. Kilminster,[44] B. J. Kim,[25]

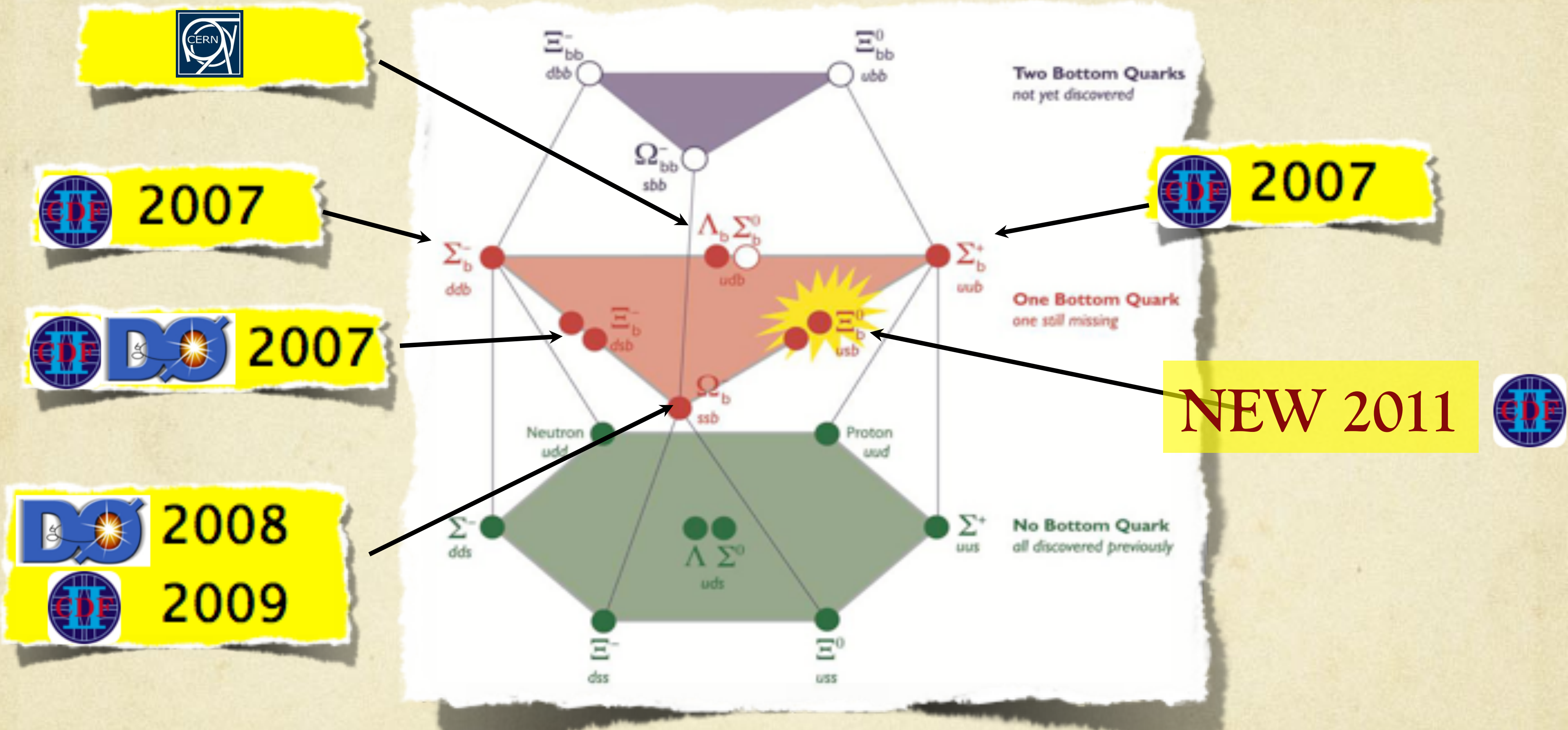
Basic parameters, important legacy





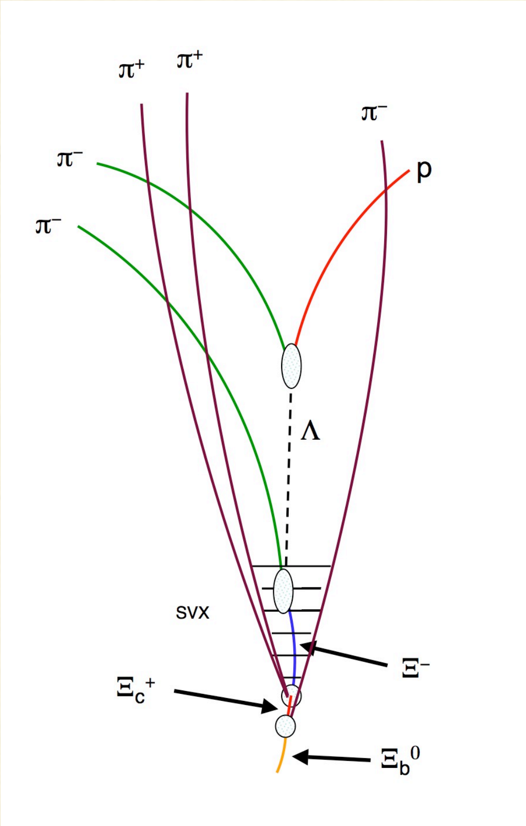
- Tevatron an important reference for basic parameters
- Still dominates world averages of masses and lifetimes - not only for Bs , but even for B^0 and B^+

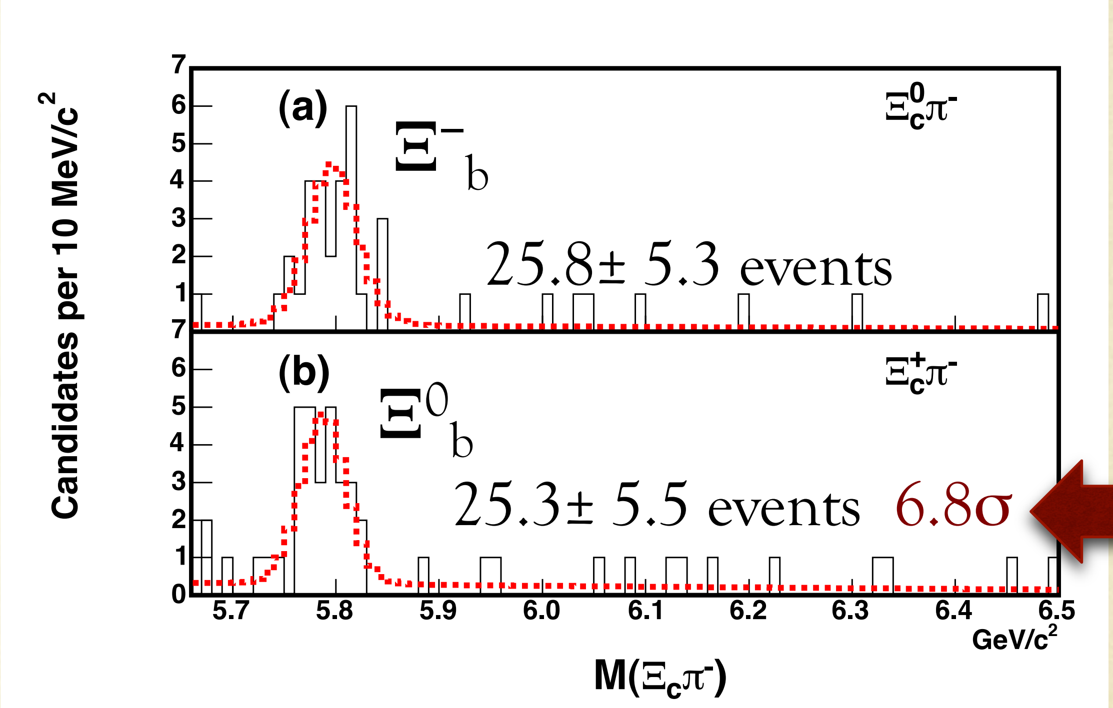
Beautiful Baryons



A whole field born at the Tevatron

Latest arrival in the family: recent observation of the Ξ^0_b





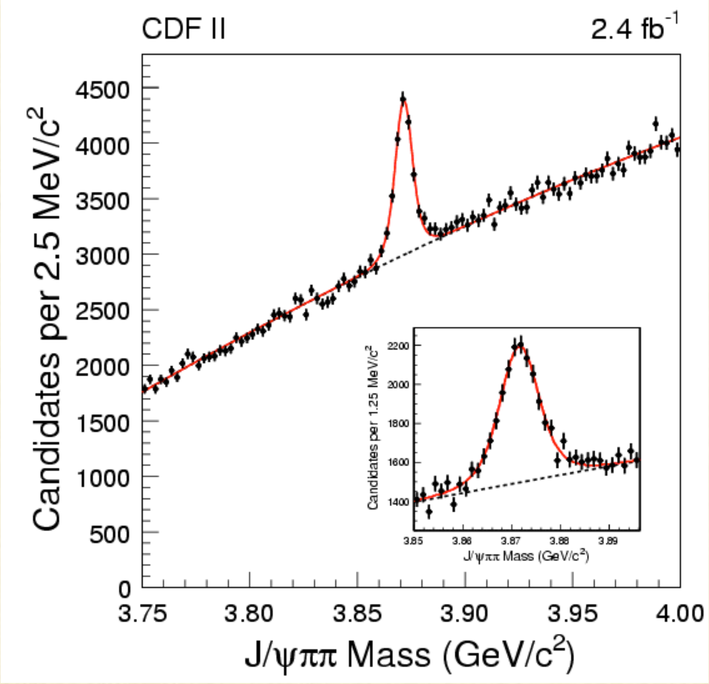
[PRL 107,102001 (2011)]

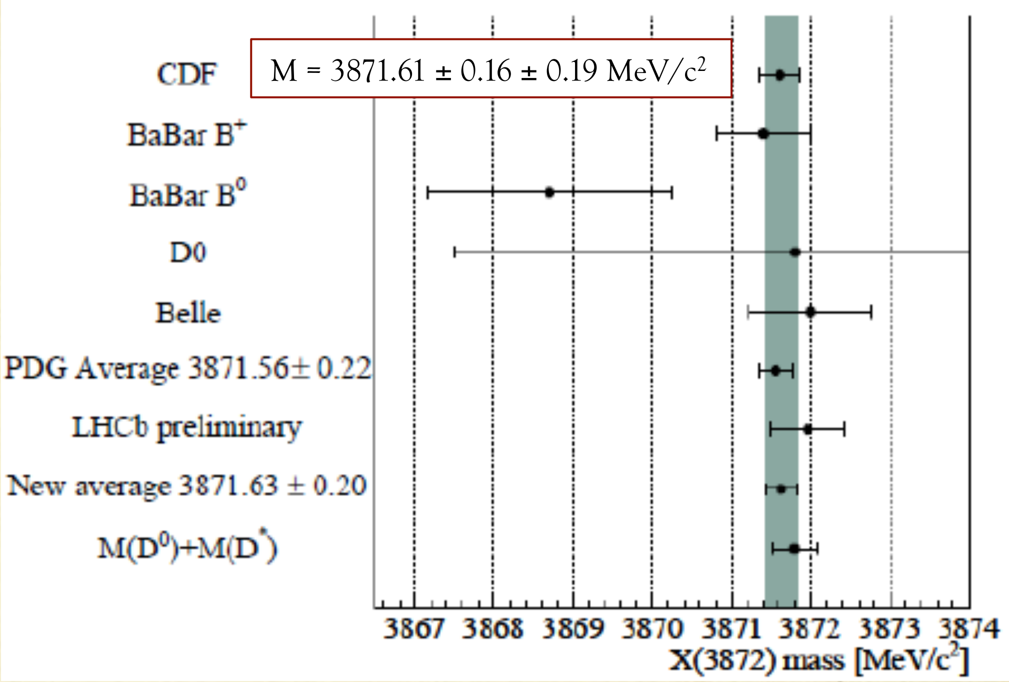
$M(\Xi^0_b) = 5787.8 \pm 5.0 \pm 1.3$ MeV

$M(\Xi^0_b) - M(\Xi^-_b) = 3.1 \pm 5.6 \pm 1.3$ MeV

Properties of X(3872)

PRL 98, 132002 (2007), PRL 103, 152001 (2009)

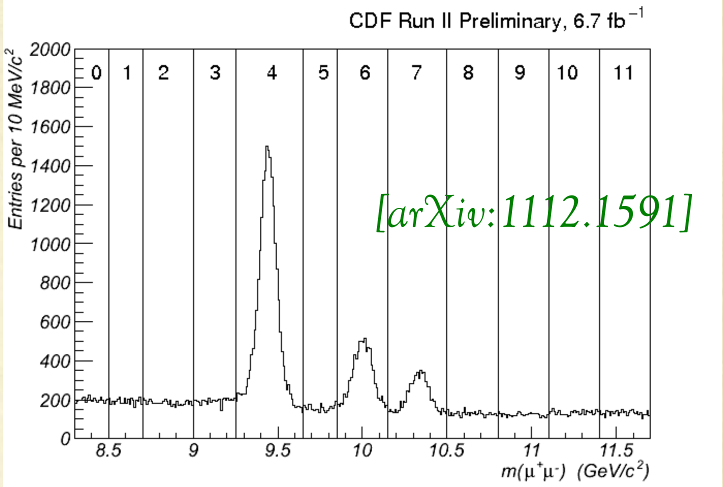




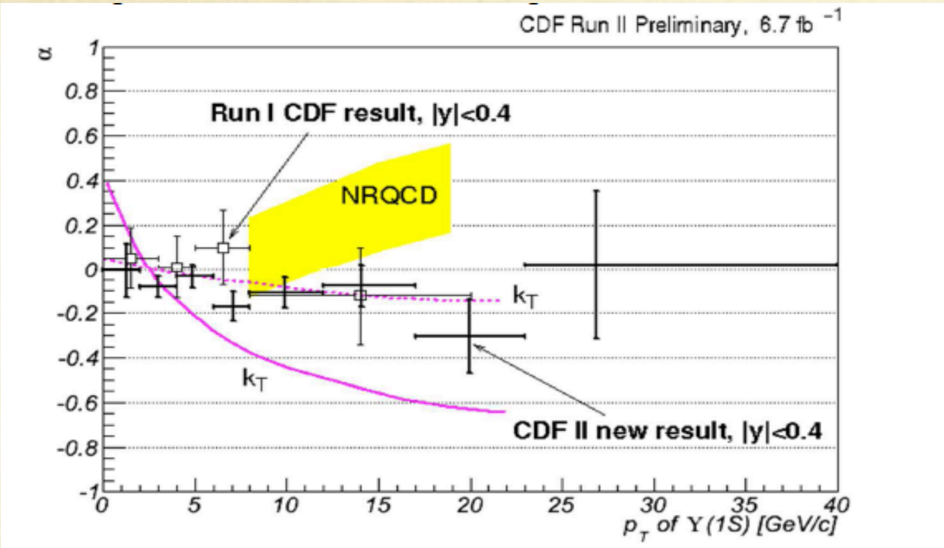
Important contributions towards understanding this exotic state

W.A. mass still dominated by CDF. Compatible with molecular model.
Now need improved D^0+D^* mass for further progress !
Limit on two-state separation <3.6 MeV/c^2 95% CL (disfavor 2-state system)
Production x-sec is important theory input (disfavor molecular model)
Quantum numbers determination.

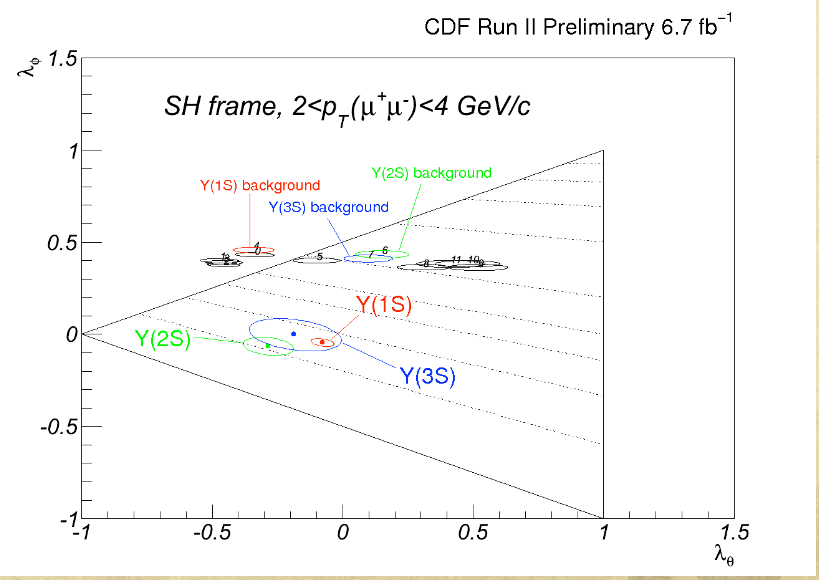
Production puzzles: full polarization analysis of **Υ**(1S,2S,3S) decays



Much improved precision.
Innovative and complex analysis.
Consistent results in different reference frames.
Serious puzzle but a huge step forward.



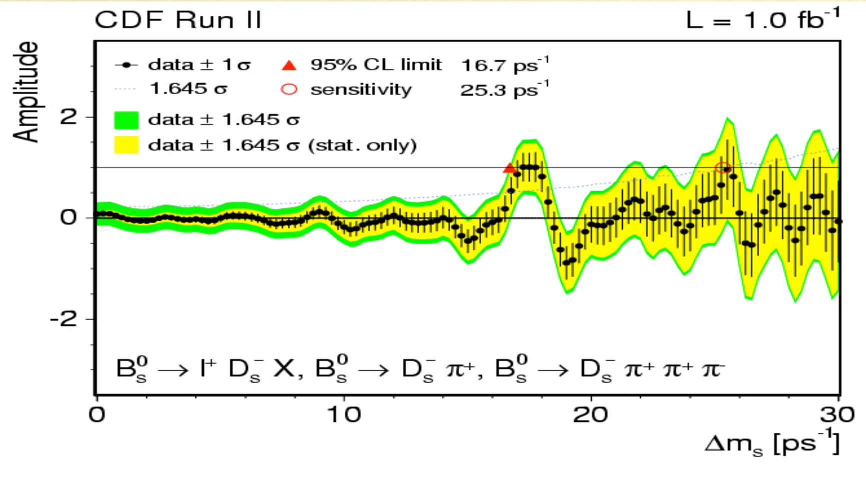
NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)



The B_s-$\overline{B}_s$ system

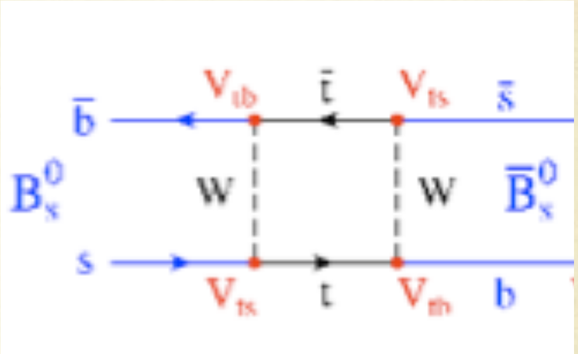
The B_s mixing phase

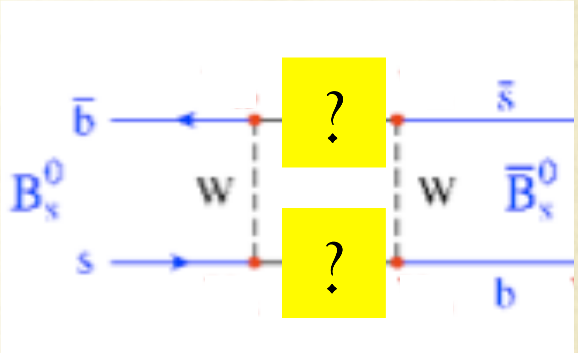
CDF/D0, 2006: magnitude of mixing amplitude consistent with SM



Mixing phase unconstrained - large NP contributions still possible.

First measurements (2008) showed intriguing 2.2σ discrepancy.

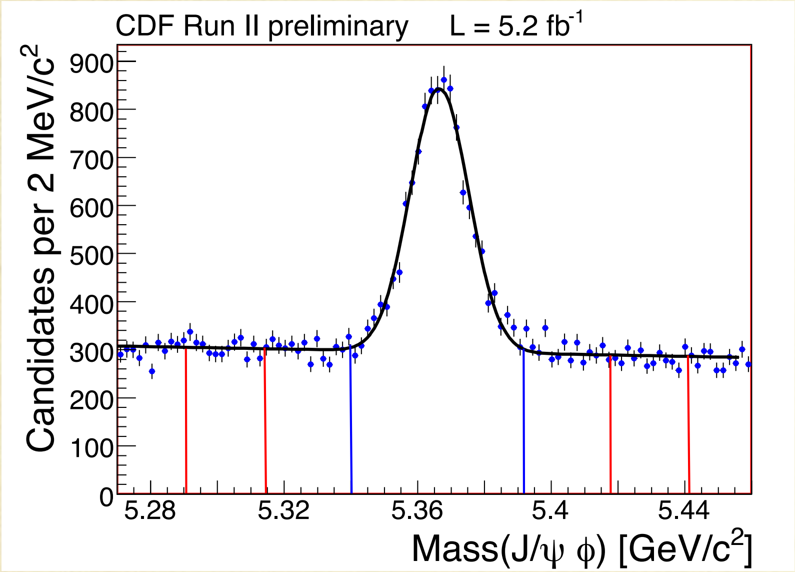


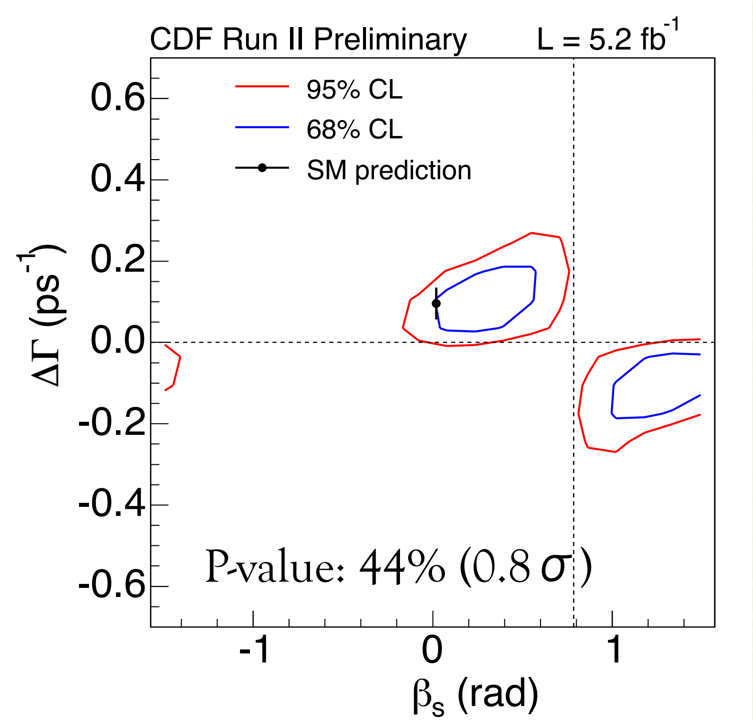


New physics accessible through interference between decay w/ and w/o flavor oscillations.

$\sin(2\beta_s)$ from $B^0_s \rightarrow J/\psi\phi$

arXiv:1112.1726

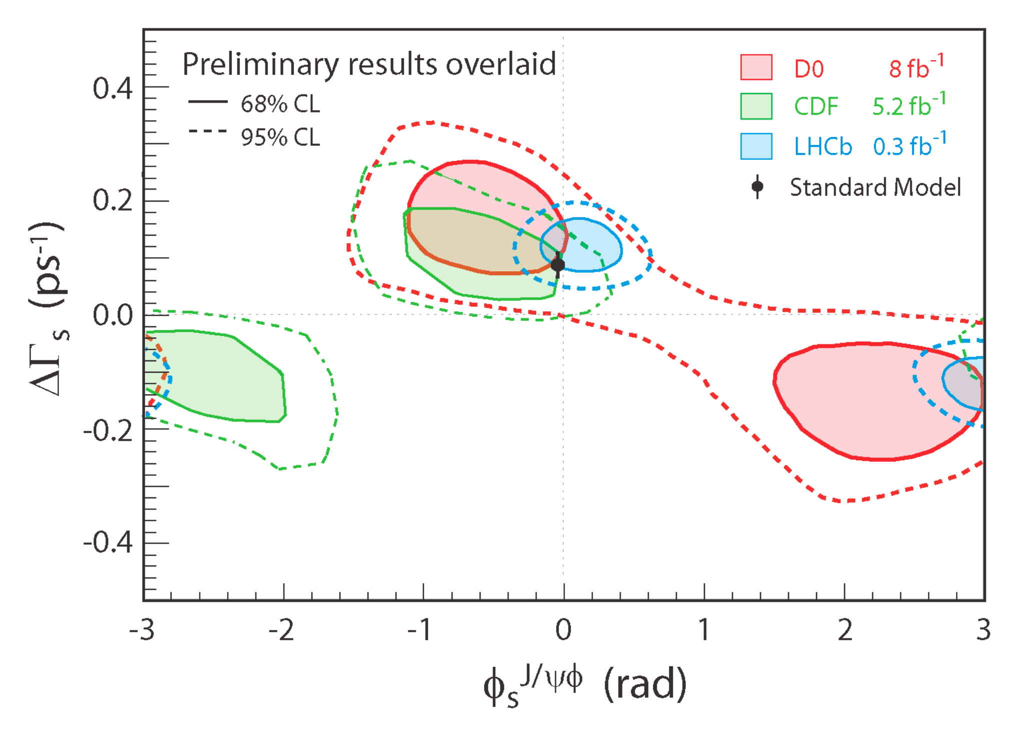




6500 events in 5.2 fb-1
Identify production flavor using whole event information
Include non-ϕ KK component in the angular analysis.

Consistent with SM expectation of very small mixing phase.

Current results for Bs mixing phase



CDF confidence region shrunk, DZero did not - both are now more consistent with SM. CDF will double statistics and combine.

LHCb result balances on the opposite side. They intersect at SM...

From a different angle: semileptonic asymmetry by DZero

$$A^b_{\rm sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}},$$

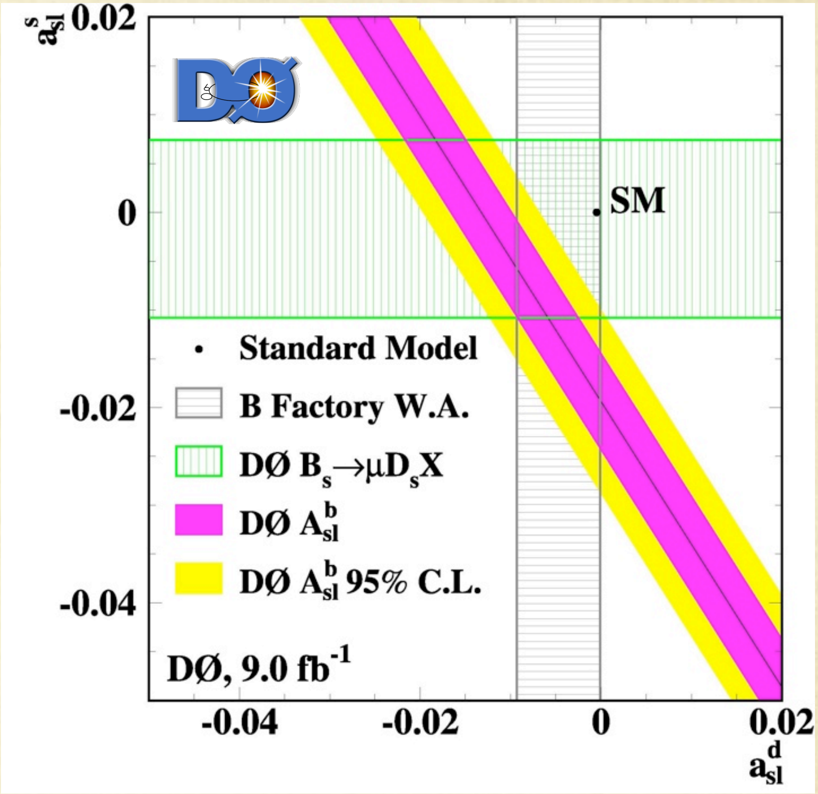
$$A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4},$$

$A_{sl}{}^{b} = (-0.79 \pm 0.17 \pm 0.09)\%$

Assuming candidate muons coming from B decays

3.9σ discrepancy

Decay-length study tells apart B^0 from B_s component



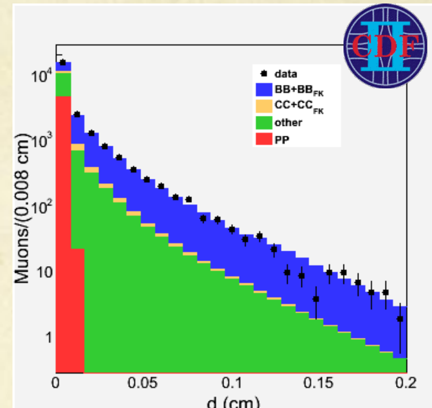
[PRD 84,052007,(2011)]

Crucial to have independent cross-check measurements.

Further measurements

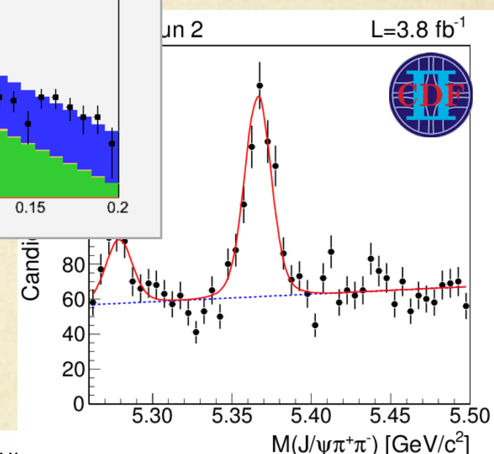
A_{SL} from sample composition fit of 2-dim impact parameter of dimuons. 1st step, time integrated mixing, consistent with LEP: $\bar{\chi}$ = 0.126 ± 0.008 (1.4 fb^{-1})

CDF Note 10335



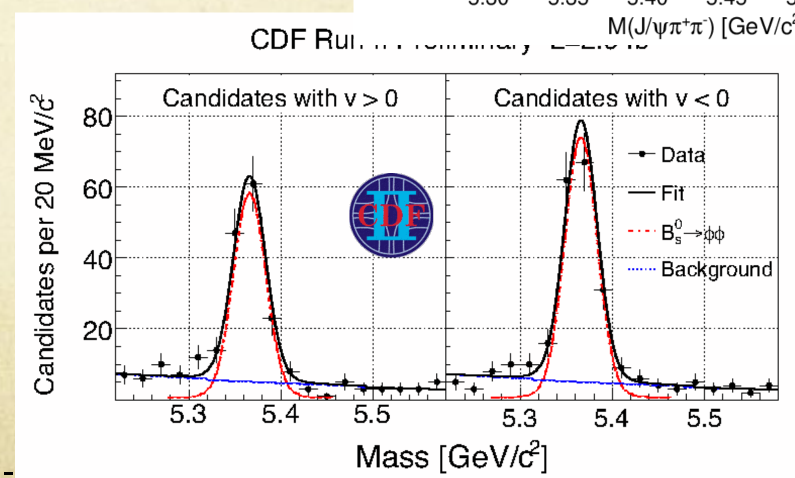
Use CP-pure $B_s \to J/\psi\ f_0$. No angular analysis.
Lifetime: τ = $1.70^{+0.12}_{-0.11}$ ± 0.03 ps (3.8 fb^{-1})

PRD 84, 052012 (2011)



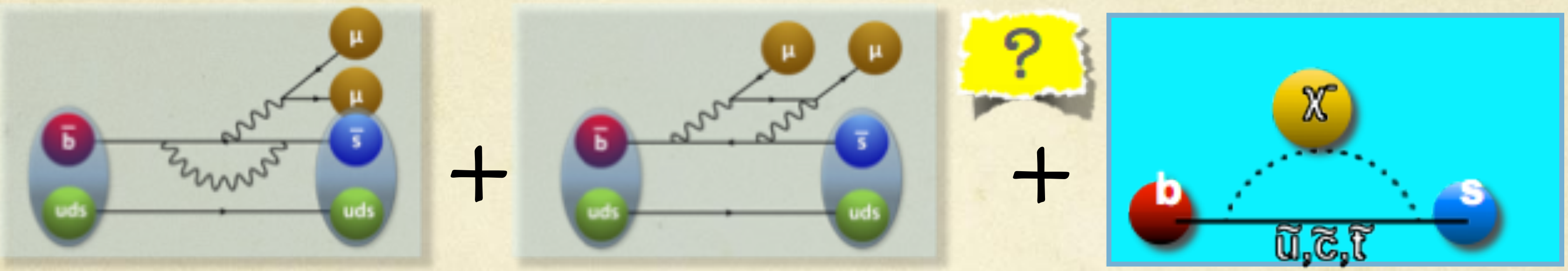
Pioneering penguin-side of B_s mixing with CPV in $B_s \to \phi\phi$
A_v = (−12 ± 6.4 ± 1.6)%
A_u = (−0.7 ± 6.4 ± 1.8)% (2.9 fb^{-1})

PRL 107,261802(2011)



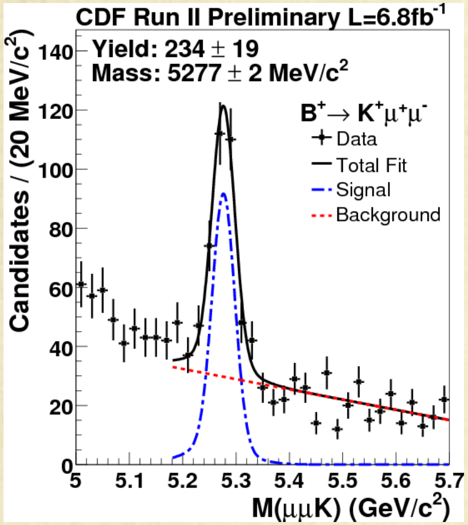
Flavor Changing Neutral Currents

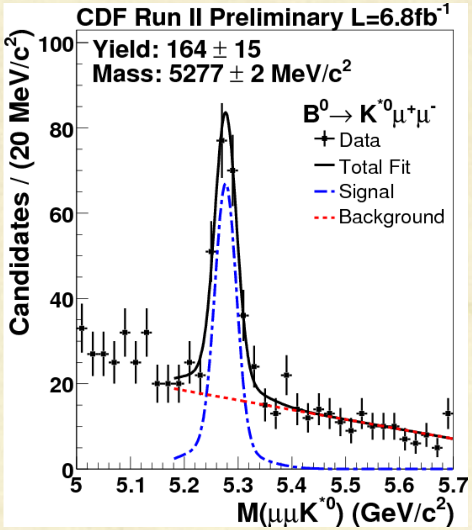
Rich dynamics

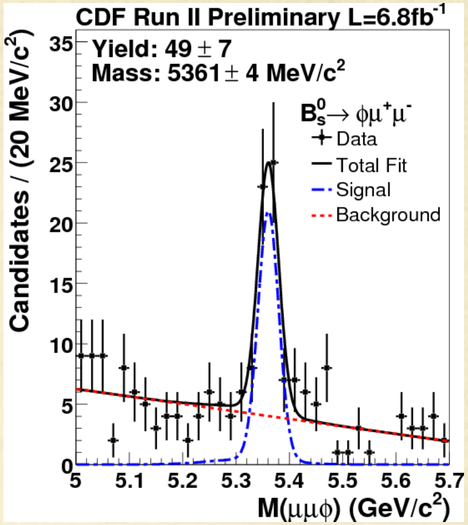


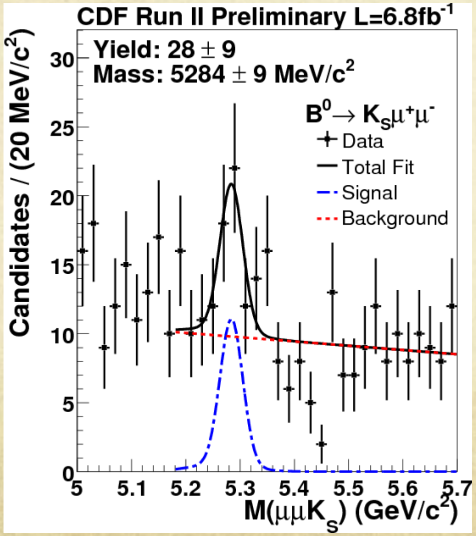
- Multiple channels:
  - $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $B^+ \rightarrow K^+\mu^+\mu^-$, $B^+ \rightarrow K^{*+}\mu^+\mu^-$, $B^0 \rightarrow K^0_s\mu^+\mu^-$, $B^0_s \rightarrow \phi\mu^+\mu^-$, $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$.
- Multiple measurements:
  - Total BR -- early access
  - BR vs squared dimuon mass
  - Full angular analysis

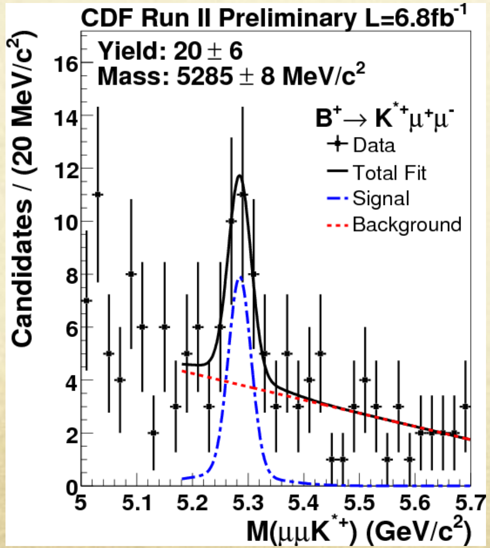
B→K(*)μμ signals











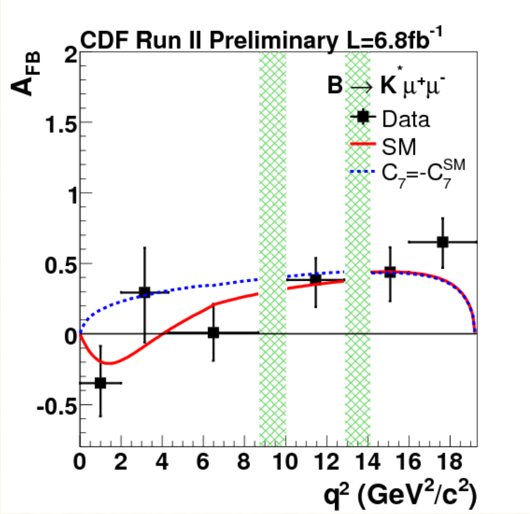
Most precise absolute and differential BR measurements to date

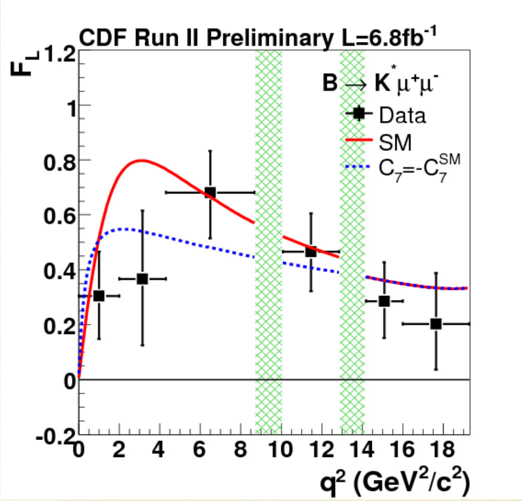
PRL 107:201802,2011

Angular analysis results

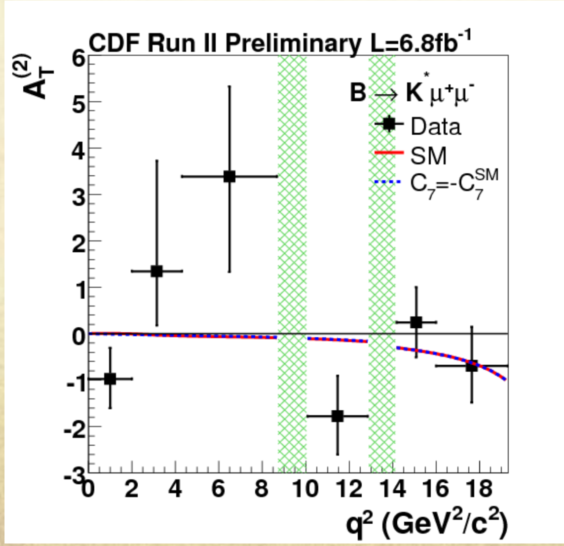
arXiv:1108.0695.

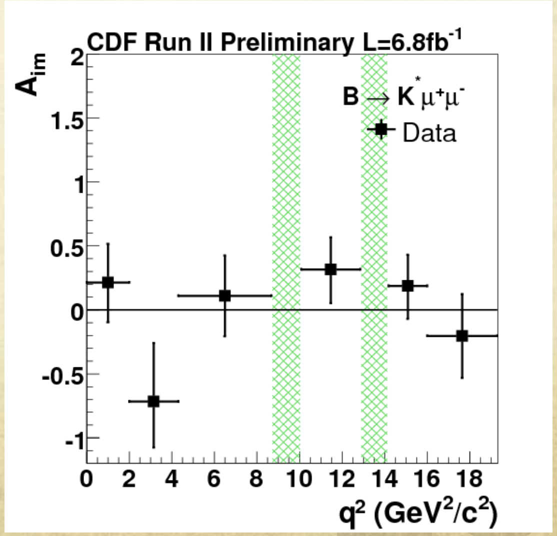
Compatible with SM
Did not confirm previous hints of deviations seen by Belle (2.7σ)





Introduce new observables in the game.
Sensitive to RH currents.
(Sorry, still no SM deviations)





Latest addition to the family

CDF Observed yet another
b->μμs process:

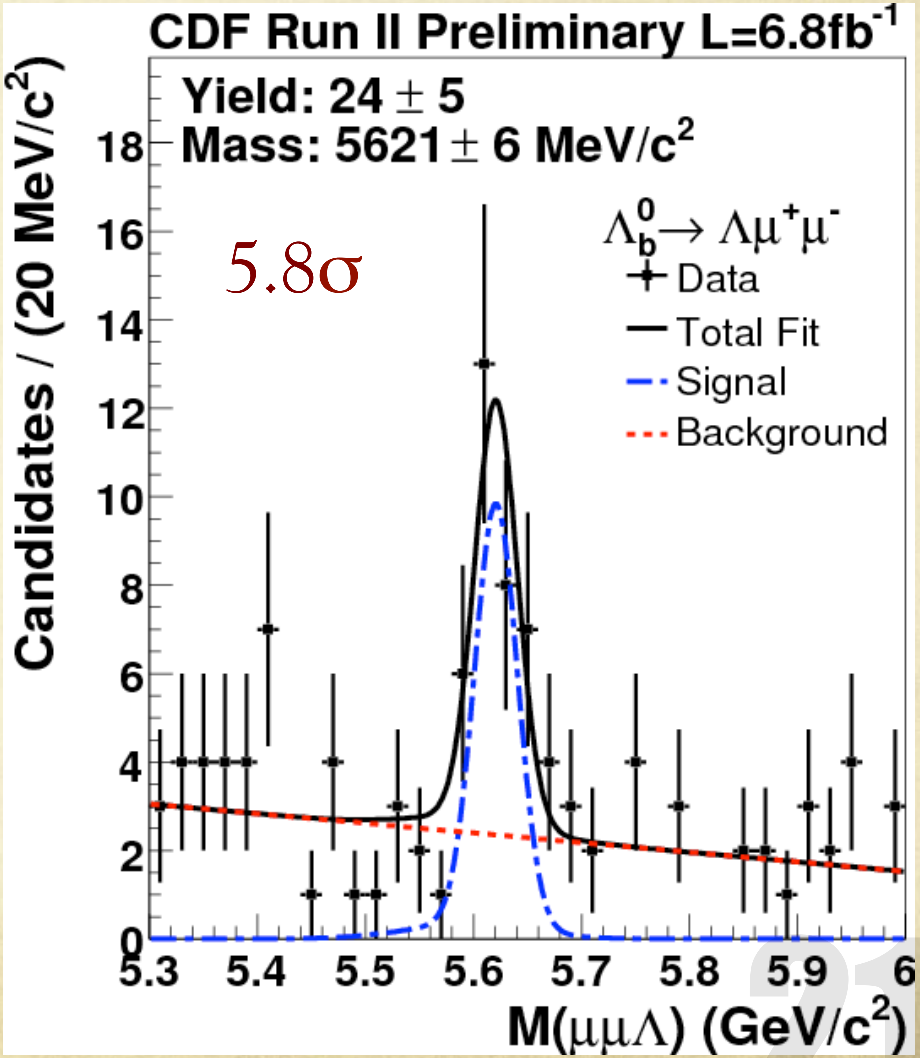
$\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$

First FCNC decay of the Λ^0_b !

BR = $(1.73 \pm 0.42 \pm 0.55) * 10^{-6}$

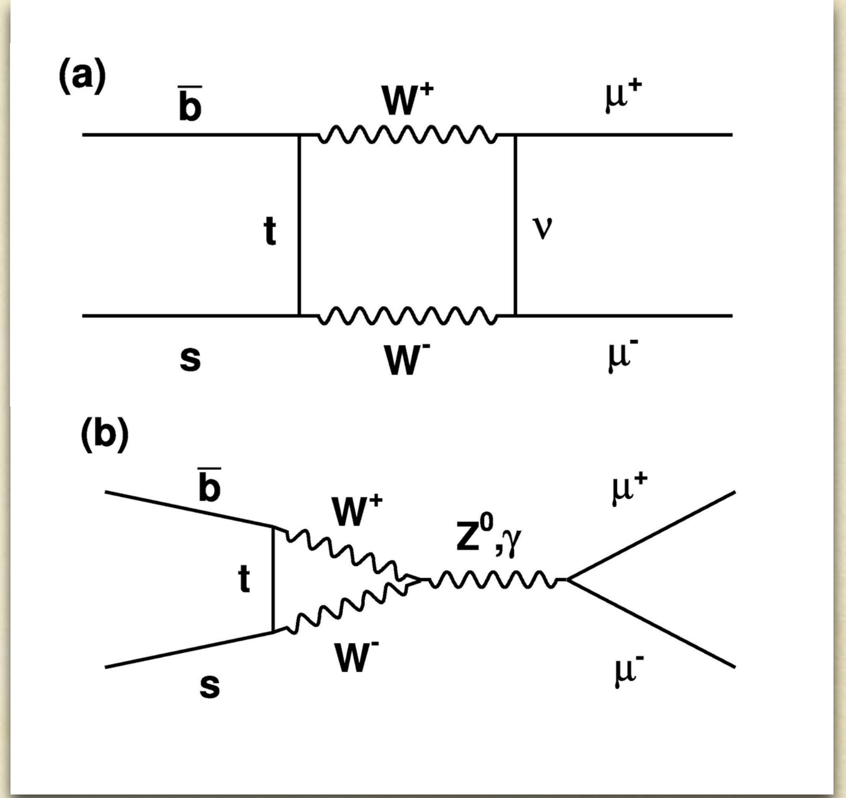
Sensitivity complementary to meson processes.

PRL 107:201802,2011



$B \rightarrow \mu^+\mu^-$

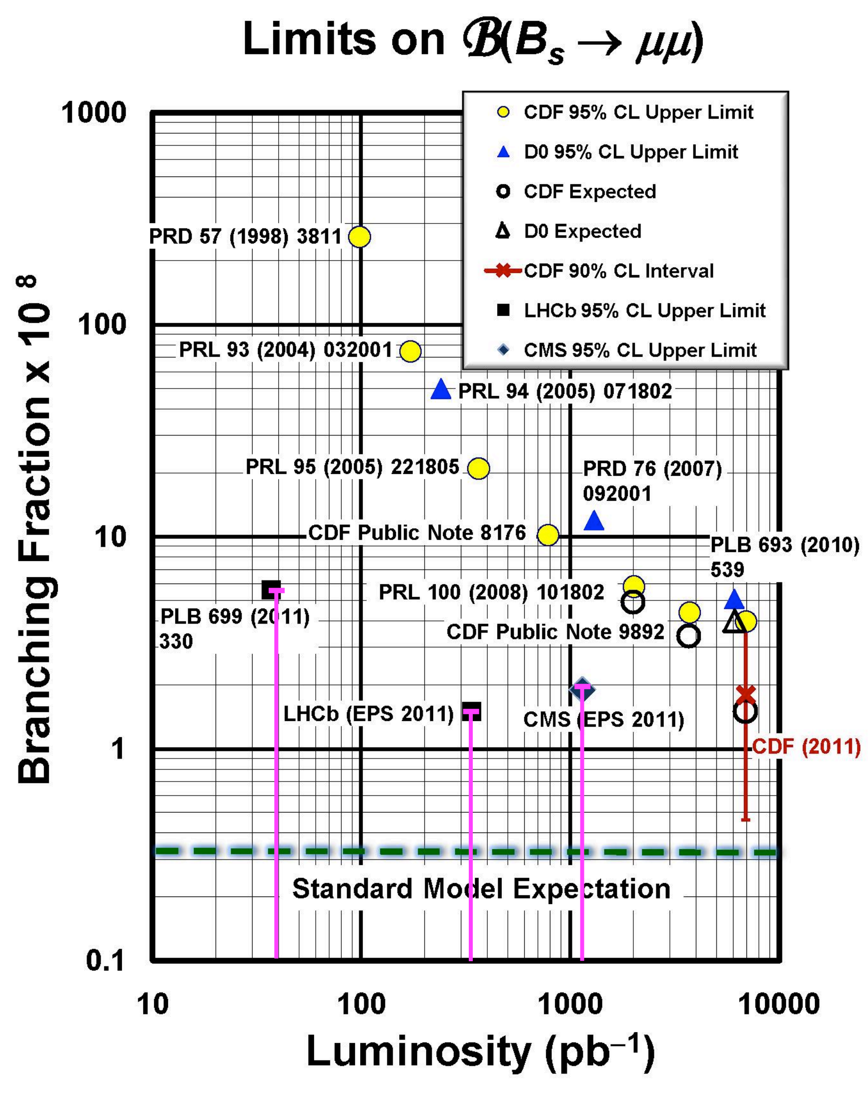
- SM rate well understood
- SM rate is small, 3.2×10^{-9}
- Broad class of NP models (scalar operators) enhance it by O(1-100)
- Clean Signature.

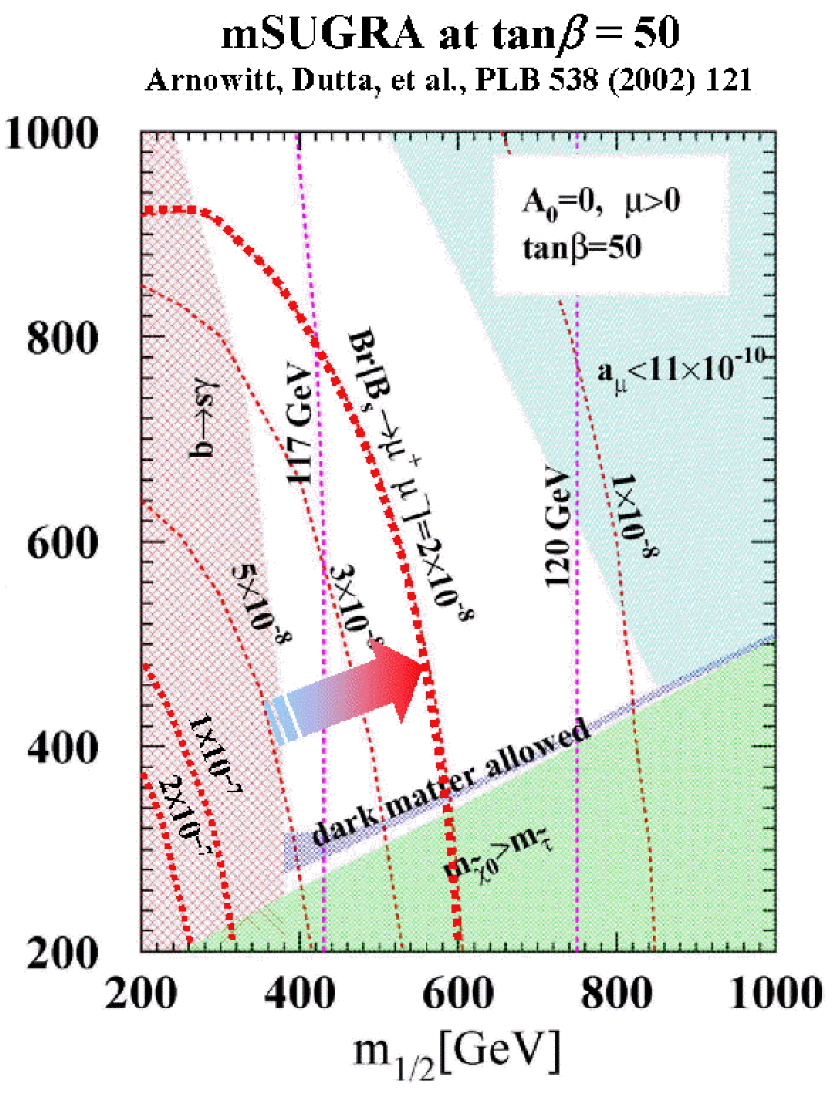


Challenge: reject 10^6 larger backg. Keep signal efficiency high.

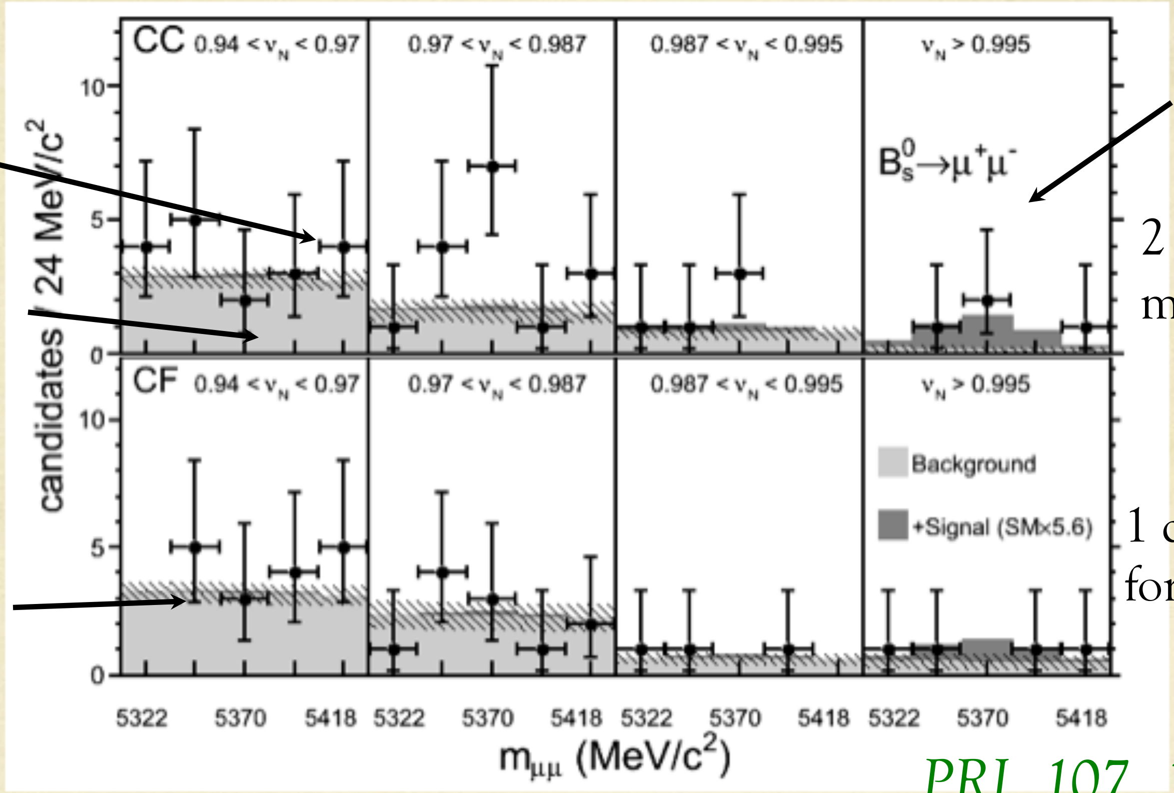
A history of exploration

Kept squeezing the space for NP for >10 years





Latest $B^0_s \to \mu\mu$ result



data

expected bckg

bckg systematic

Bckg 0.8±0.4 observed 4

2 central muons

1 central 1 forward

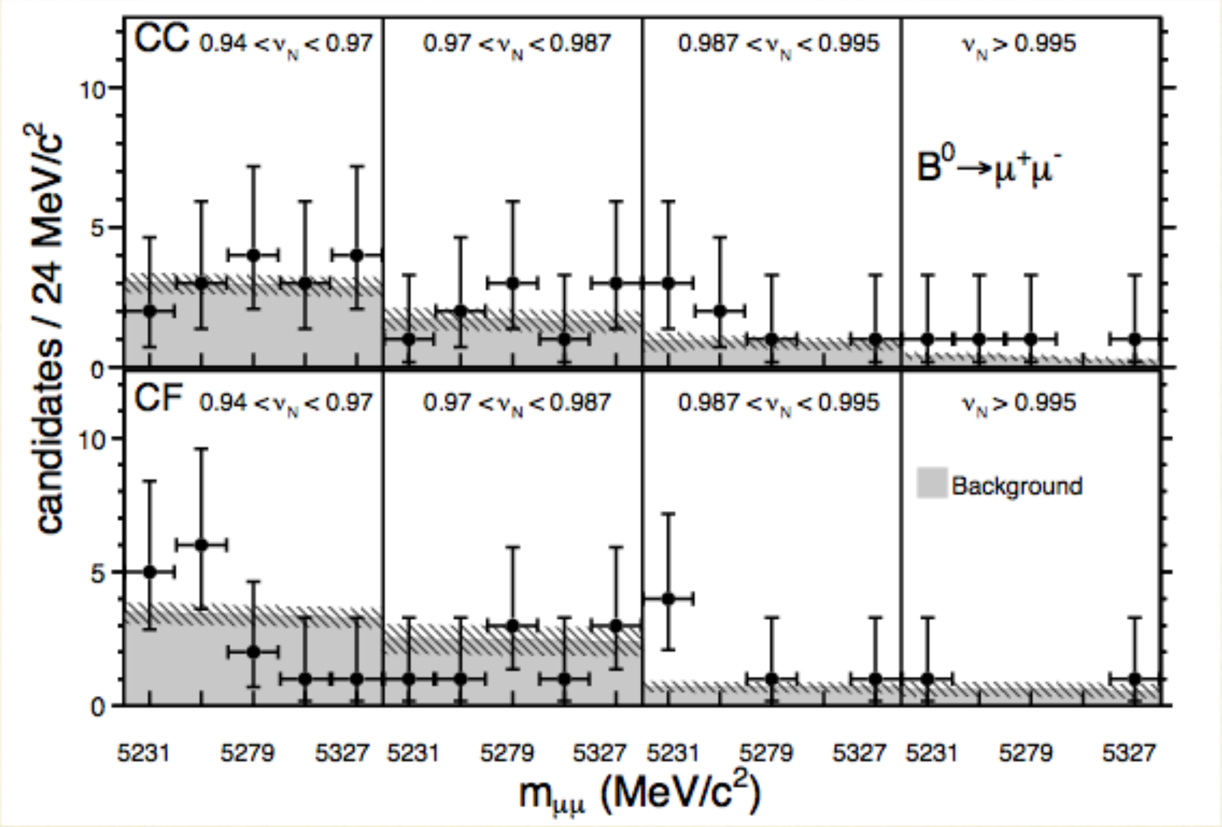
PRL 107, 191801 (2011)

Prob. that bckg (SM)produces >= fluctuation is 0.27% (1.9%)

$0.46\times10^{-8} < Br < 3.9\times10^{-8}$ at 90% CL ($Br = 1.8^{+1.1}_{-0.9}\times10^{-8}$)

A hint of a signal (not incompatible with latest LHC limits)

Don't forget the B^0



PRL 107, 191801 (2011)

Background hypothesis p-value = 0.23

BR< $6*10^{-9}$ @95%CL (expect 4.6)

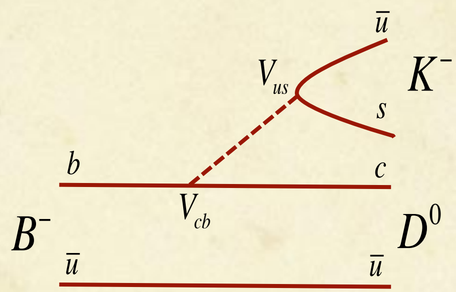
Start to become interesting (60xSM)

CKM/CPV/Hadronic modes

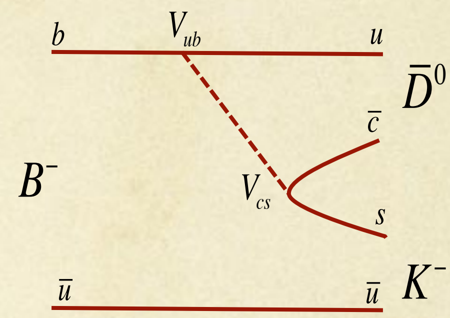
Hadronic B decays

Improve understanding of B decay strong dynamics.
Access CKM angle γ, least known phase.

γ from $B^- \to DK^-$ is theoretically-clean (tree level). Exploit interference between the favored and color-suppressed processes.
Several methods depending on D^0/ D^0 bar final state (GLW,ADS,...)

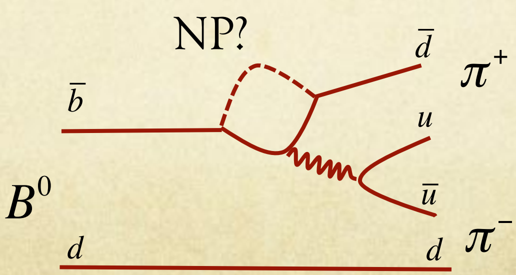


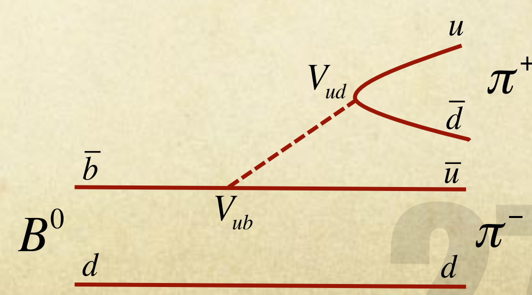
$\sim V_{cb}V^*_{us} \sim \lambda^3$



$\sim V_{ub}V^*_{cs} \sim \lambda^3 e^{i\gamma}$

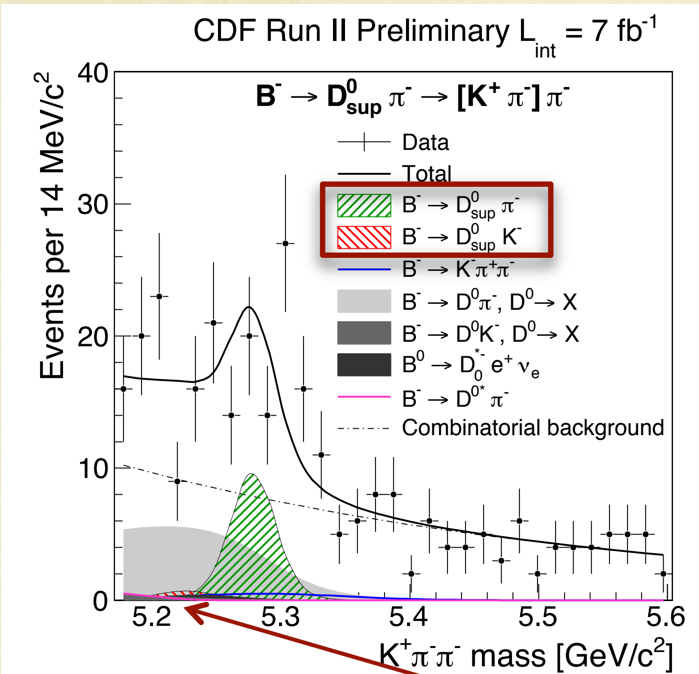
Two body charmless decays are sensitive to NP. However constrains soft because QCD uncertainties. Several simultaneous measurements needed.

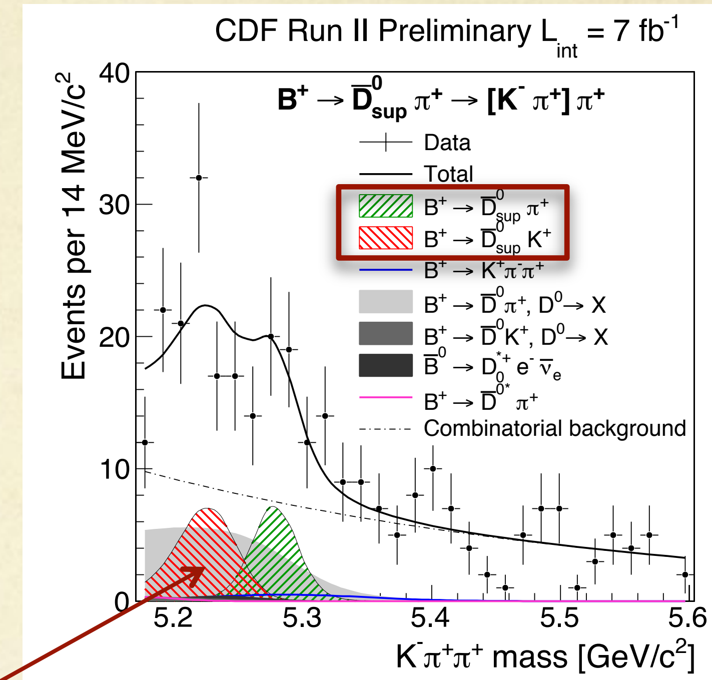




Evidence of suppressed $B^{-} \to DK^{-}$

PRD 84, 091504 (2011)





Asymmetry → $A_{ADS}(K) = -0.82 \pm 0.44(stat) \pm 0.09(syst)$

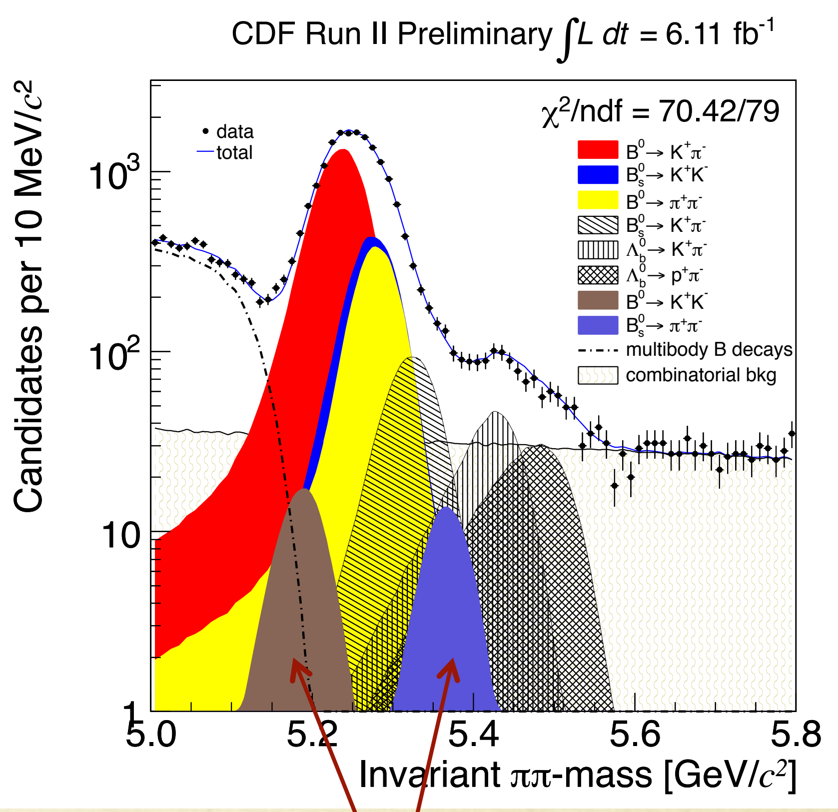
Suppresses/Favor → $R_{ADS}(K) = [22.0 \pm 8.6(stat) \pm 2.6(syst)] \cdot 10^{-3}$

Big question mark in hadronic environment. Turned out competitive with e+e- .

Charmless two-body decays

arXiv:1111.0485 [hep-ex].

- CDF pioneered the technique in hadron collisions and discovered several:
- First observations of:
  - $B^0_s \to K^+K^-$
  - $B^0_s \to K^-\pi^+$
  - $\Lambda^0_b \to p\pi^-$
  - $\Lambda^0_b \to pK^-$
- Measurements of:
  - $A_{CP}(B^0 \to K^+\pi^-)$
  - $A_{CP}(B^0_s \to K^-\pi^+)$
  - $A_{CP}(\Lambda^0_b \to p\pi^-)$
  - $A_{CP}(\Lambda^0_b \to pK^-)$



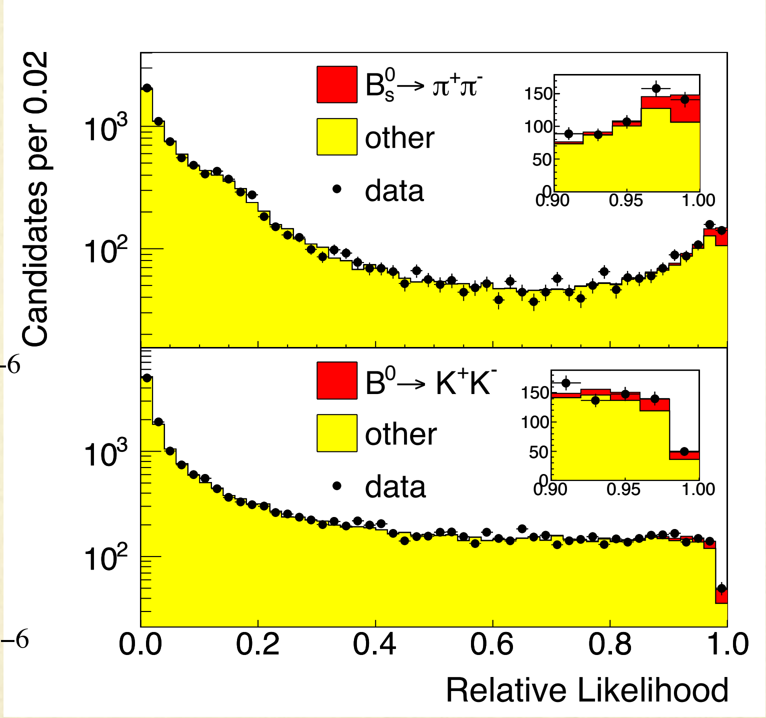
Latest arrival: annihilation-type decays $B^0_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$

Evidence for charmless annihilation

$B^0_s \to \pi^+\pi^-$

arXiv:1111.0485 [hep-ex].

Mode	N_s	Significance
$B^0 \to K^+K^-$	$120 \pm 49 \pm 42$	2.0σ
$B^0_s \to \pi^+\pi^-$	$94 \pm 28 \pm 11$	3.7σ



First evidence for the $B^0_s \to \pi^+\pi^-$

$$BR(B^0_s \to \pi^+\pi^-) = [0.57 \pm 0.15(stat) \pm 0.10(syst)] \times 10^{-6}$$

First two sided bound for the $B^0 \to K^+K^-$

$$BR(B^0 \to K^+K^-) \in [0.05, 0.46] \times 10^{-6} \text{ @ } 90\%CL$$

$$BR(B^0 \to K^+K^-) = [0.23 \pm 0.10(stat) \pm 0.10(syst)] \times 10^{-6}$$

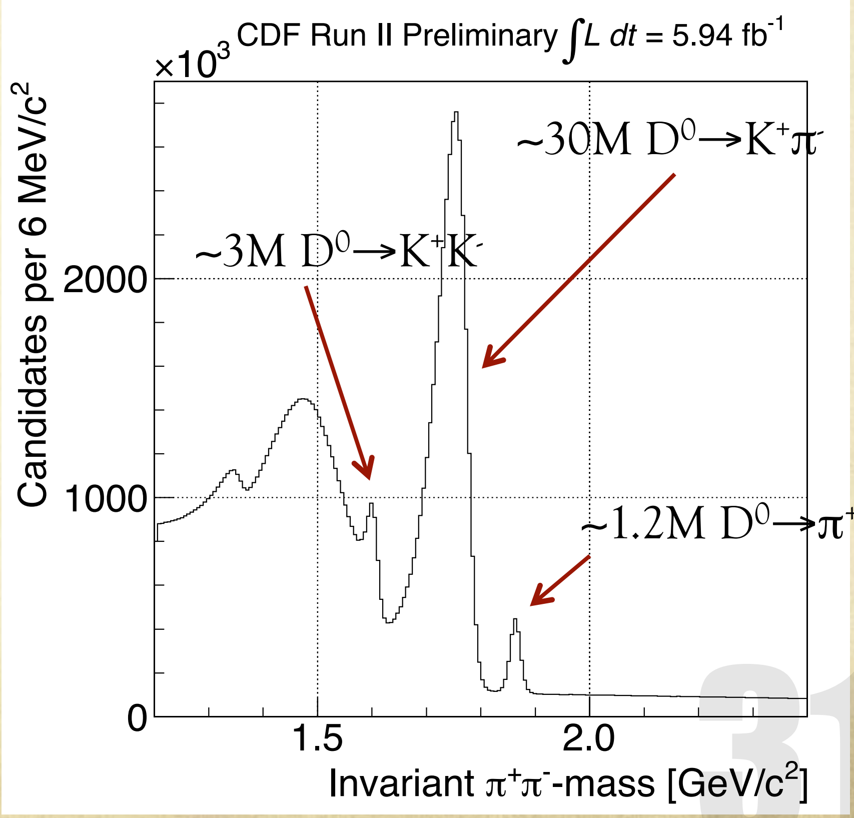
Indication of strong annihilation and important inputs into theory models

Charm Decay Factor

Trigger on displaced tracks provide huge charm samples.
Not in original CDF plans and still largely unexploited.

- Good sensitivity to charm mixing
- Exploit CP-symmetric production
- Unprecedented sensitivity to NP in up-quark sector.

Untagged decays



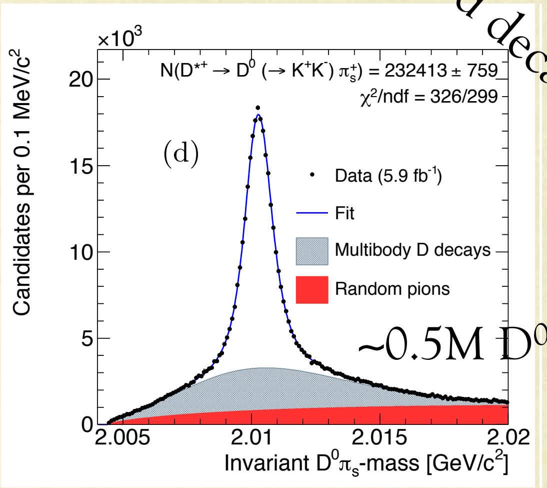
Charm Decay Factor

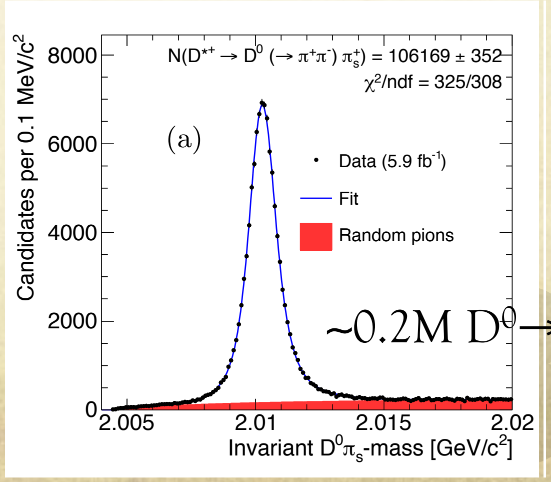
Trigger on displaced tracks provide huge charm samples.
Not in original CDF plans and still largely unexploited.

Tagged decays

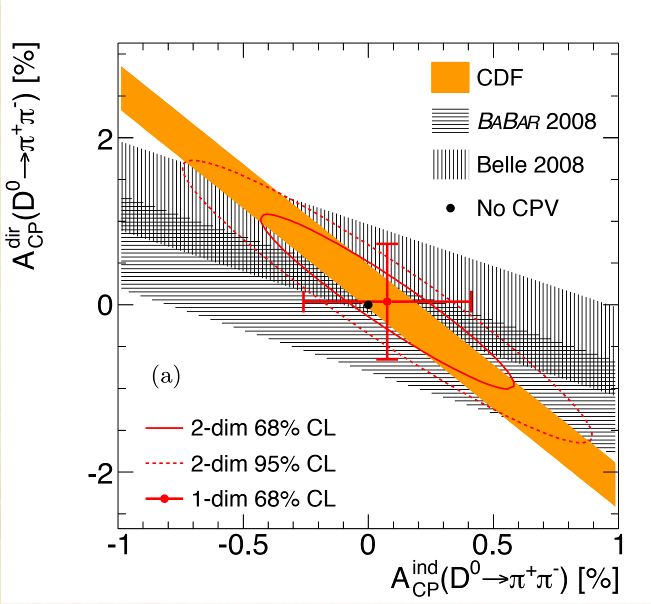
- Good sensitivity to charm mixing
- Exploit CP-symmetric production
- Unprecedented sensitivity to NP in up-quark sector.
- Time-integrated CPV:
  - $A_{CP}(D^0 \to K^+K^-)=(-0.24\pm0.22\pm0.10)\%$
  - $A_{CP}(D^0 \to \pi^+\pi^-)=(+0.22\pm0.24\pm0.11)\%$
- CPV in D^0 mixing < 0.13% @90% CL.

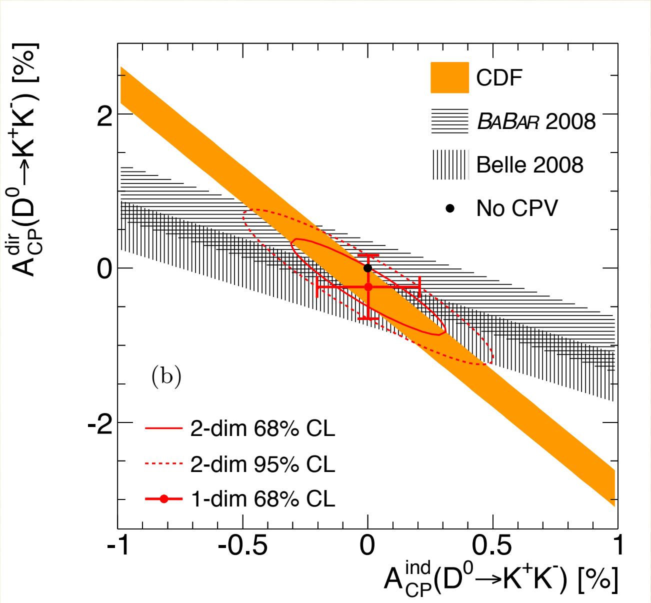
Phys. Rev. D 85, 012009 (2012)





CP violation in $D^0 \to h^+h^-$

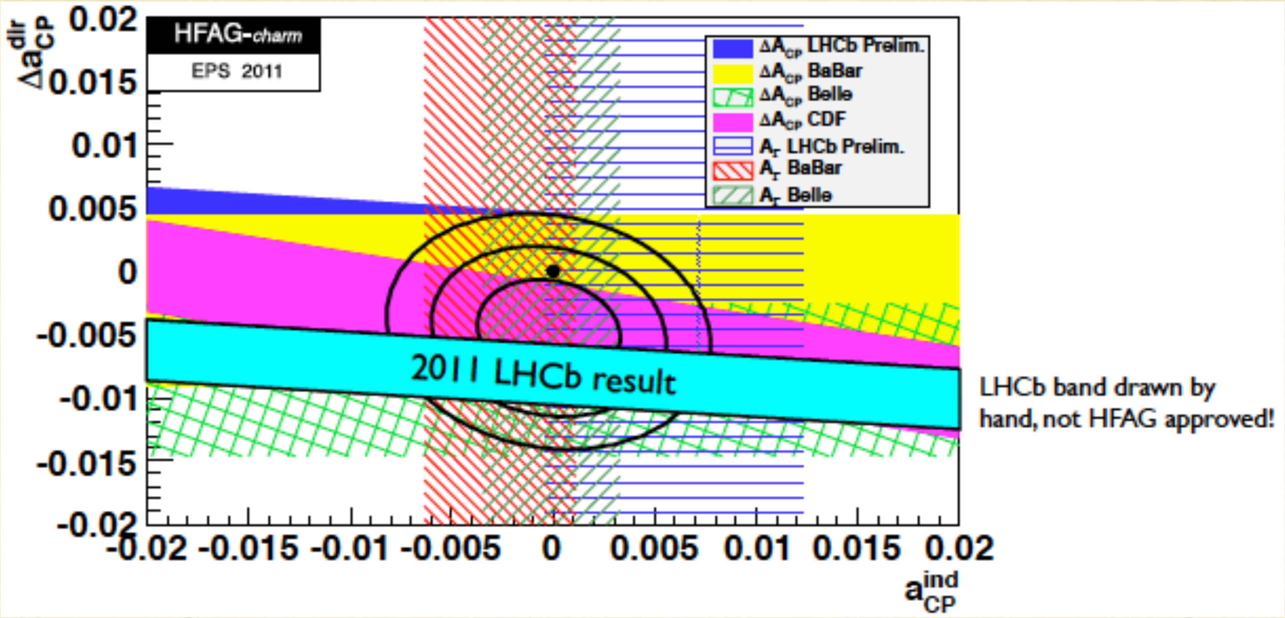




Phys. Rev. D 85, 012009 (2012)

- Complementary to e^+e^- due to different acceptance
- Best precision due to large sample and pioneering new technique - systematics <0.1% in $\pi\pi$ and KK modes
- With $6fb^{-1}$, first measurement in the sub-% region, sensitive to realistically possible effects.
- Compatible with zero in both modes, but...

DCPV difference in $D^0 \to h^+h^-$



- Recent LHCb result yields >3σ effect in DCPV difference between ππ and KK
- CDF has 1.4σ effect in same direction. Interesting to pursue with full sample.

A legacy for the future

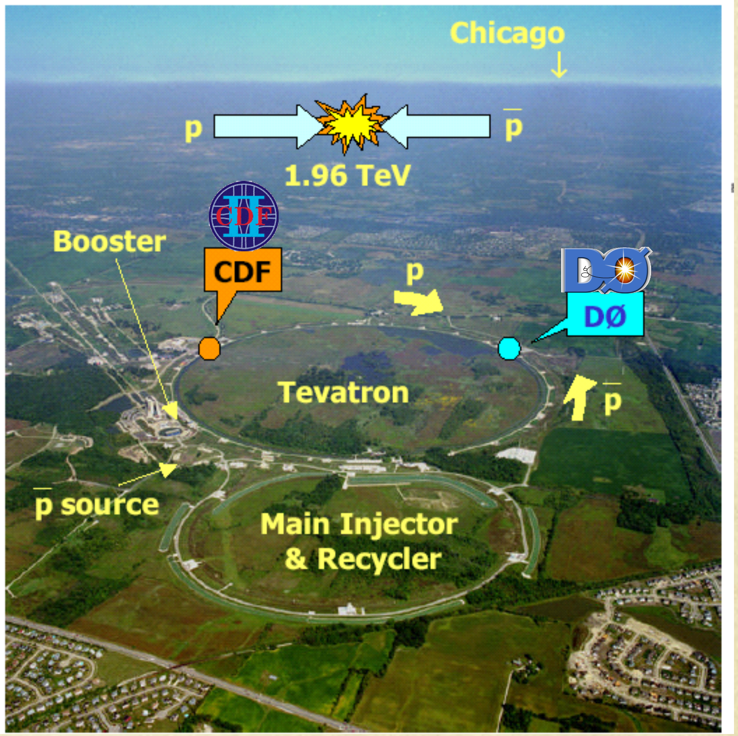
- Many first observations and precision results.
- Pioneering instruments and analysis techniques
  Explored new grounds: Bs,Bc,baryons,FCNC,charm…
- Stringent SM tests constrained possible NP.
- Set the bar high for the next generation.
- Shown feasibility HF physics in "hi-pt" environment.

Now performing final analyses with full sample…

Backup

Fermilab Tevatron

- $p\bar{p}$ collisions at 1.96 TeV
- 1.7MHz collision rate (396 ns bunch spacing)
- Peak luminosity 3.5−4 $\times 10^{32} cm^{-2} s^{-1}$
  - Average ~ 6 $p\bar{p}$ interactions per bunch crossing.
- ~8 fb^{-1} "good" data on tape per experiment.
- End of operation by September 2011.



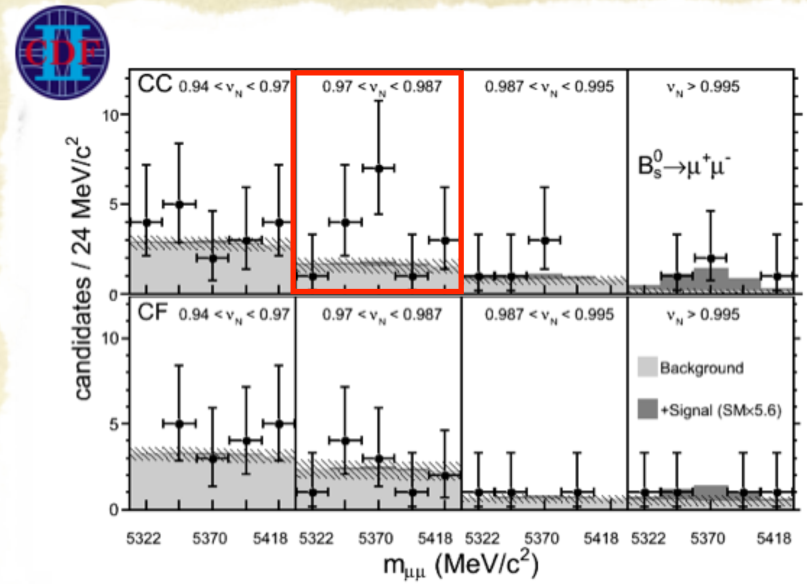
Results today on 1.6-7 fb^{-1} of data collected.

Skepticism is healthy

Unlikely to be peaking bckg. Only one is $B \rightarrow hh$. Is 10× larger in B^0 window where nothing is seen.

Unlikely to be syst. problem with combinatorial. Same procedure in B^0 where nothing is seen.

Unlikely to be NN-shape issue. Cross-check with B^+ looks good within <5%. And several cross-checks show no mass bias vs NN



We conclude this is a fluctuation (2.6σ). Not unlikely in one out of 80 bins.

Using last 2 bins only:

$Br = 1.4^{+1.0}_{-0.8} \times 10^{-8}$ ($0.33 \times 10^{-8} < Br < 3.3 \times 10^{-8}$ at the 90% CL)

p-value(bckg-only) = 0.66%

B_s oscillation parameters

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Diagonalize

CP Eigenstates: $|B_s^{odd}\rangle = |B_s^0\rangle + |\bar{B}_s^0\rangle$ $|B_s^{even}\rangle = |B_s^0\rangle - |\bar{B}_s^0\rangle$

Mass Eigenstates: $|B_s^H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ (Heavy) $|B_s^L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ (Light)

If CP conserved in mixing, $p=q$

observables

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$
$$\Delta M_s = M_H - M_L$$
$$\Gamma_s = \frac{(\Gamma_L + \Gamma_H)}{2}$$

$$a^s_{fs} = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to \bar{f})}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to \bar{f})}$$

$$\Delta M_s = 2|M_{12,s}^{SM}| \cdot |\Delta_s|$$
$$\Delta\Gamma_s = 2|\Gamma_{12,s}| \cdot \cos\left(\phi_s^{SM} + \phi_s^{\Delta}\right)$$
$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{SM}|} \cdot \frac{\cos\left(\phi_s^{SM} + \phi_s^{\Delta}\right)}{|\Delta_s|}$$
$$a^s_{fs} = \frac{|\Gamma_{12,s}|}{|M_{12,s}^{SM}|} \cdot \frac{\sin\left(\phi_s^{SM} + \phi_s^{\Delta}\right)}{|\Delta_s|} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan(\phi_s^{SM} + \phi_s^{\Delta})$$
$$\sin(\phi_s^{SM}) \approx 1/240$$

Sensitive to lots of possible New Physics:
SUSY, 4th generation, GUT, Extended Higgs, MFV, unparticle...
Really attractive hunting ground for NP

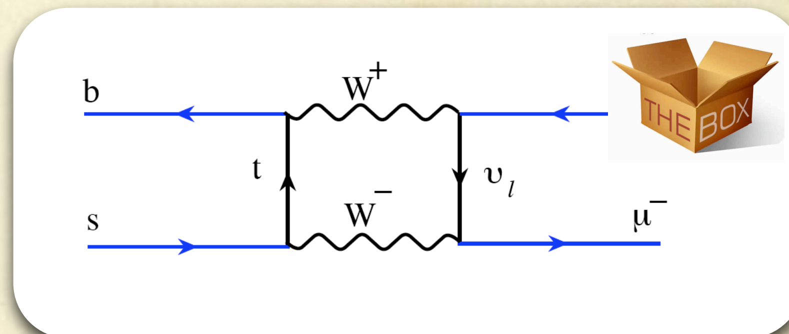
$B^0_s \to \mu^+\mu^-$

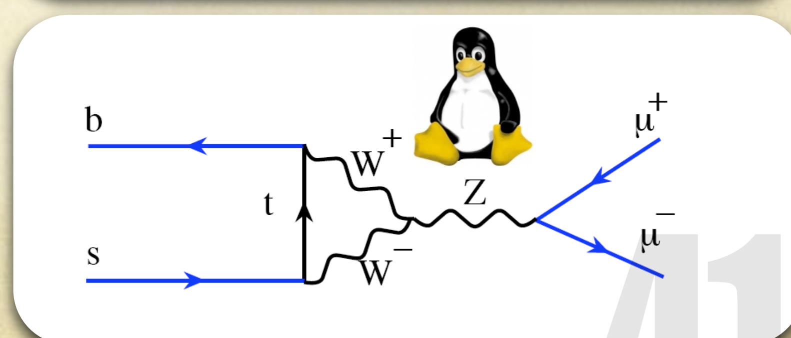
$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are the most studied FCNC processes. CKM, GIM and helicity suppression in SM lead to:

$BR(B^0_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ $(|V_{ts}|^2)$
$BR(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$ $(|V_{td}|^2)$

NP can enhance up to 100×
MSSM: $BR \propto \tan^6(\beta)$.
RPV SUSY enhances also at low $\tan(\beta)$.

Very hot! Either observation or null result provides crucial information.





The analysis@CDF

Trigger on two muons with $p_T > 1.5 - 2$ GeV/c

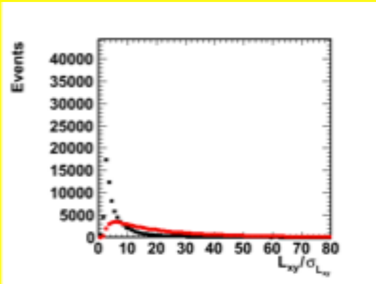
NN classifier separates S from B

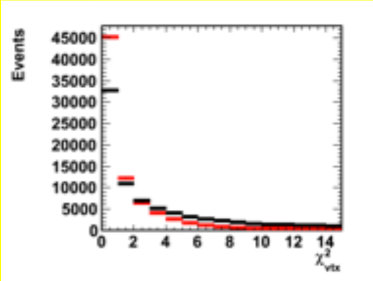
lifetime

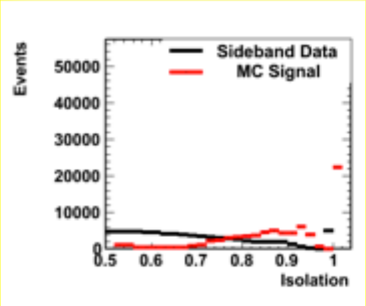
vertex quality

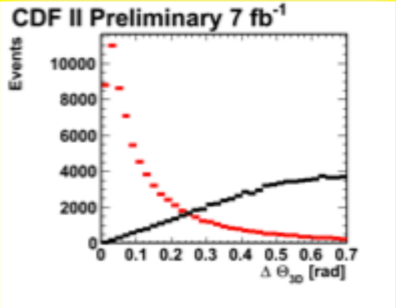
Isolation

Pointing









Bckg predicted using mass sidebands (comb.) and fake rates for B→hh. Checked on many control samples

Look at search region in bins of mass and NN.
Rate determined using $B^+ \to J/\psi K^+$ as reference

$B \to \mu^+\mu^-$ – Strategy

$BR(B^0_s \to \mu^+\mu^-)$ is obtained by normalizing to the number of $B^+ \to J/\psi K^+ \to [\mu^+\mu^-]K^+$ where $\mu^+\mu^-$ vertex is reconstructed in the "same" manner (similar for B^0).

$B^0_s \to \mu^+\mu^-$ decays at 95%CL

TriggerAcceptance ratio from MC

Rec. efficiency ratio from MC/DATA

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_s}{N_+} \cdot \frac{\alpha_+}{\alpha_s} \cdot \frac{\epsilon_+}{\epsilon_s} \cdot \frac{1}{\epsilon_N} \cdot \frac{f_u}{f_s} \cdot \mathcal{B}(B^+),$$

From PDG08

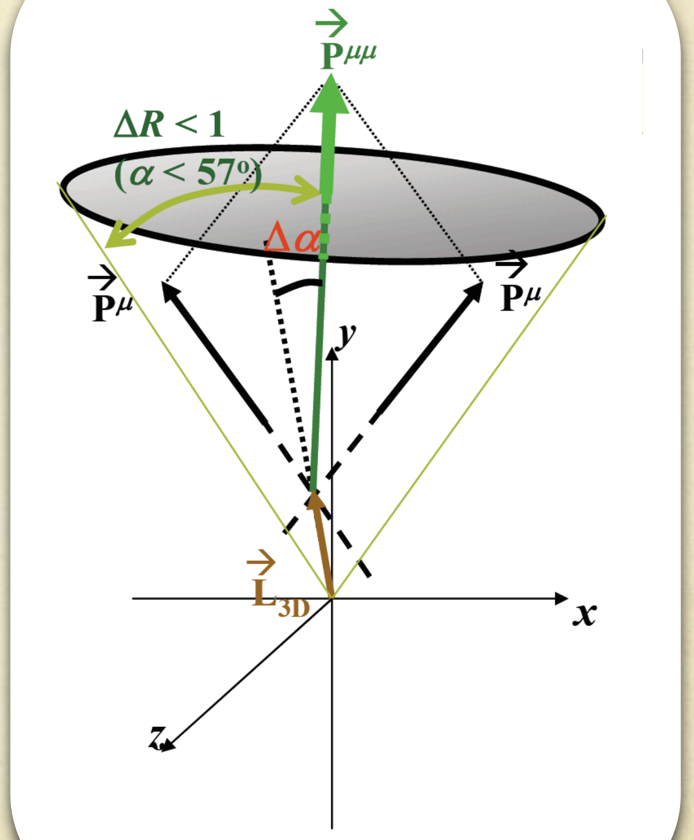
$B^+ \to J/\psi K+$ decays from data

Efficiency of NN requirement from MC

$B \to \mu^+\mu^-$ – Selection

Selection based on following kinematics discriminating variables:

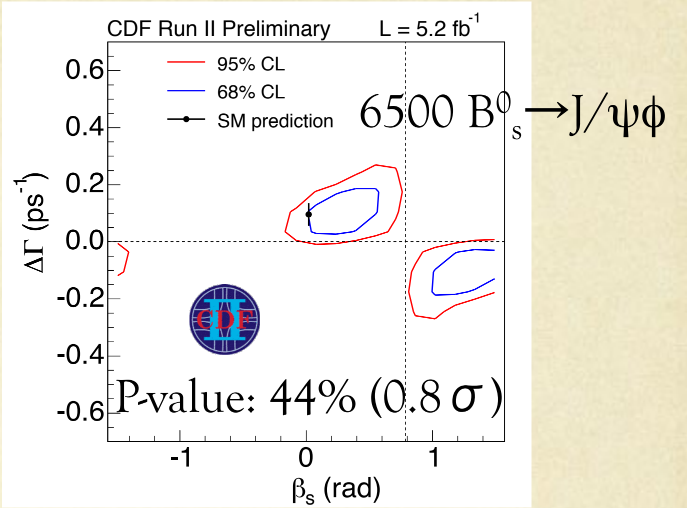
Transverse momentum of candidate $p_T^{\mu^+\mu^-}$ (>4GeV)
Transverse lower momentum of muon track p_T
Proper decay time $\lambda = L_{3D} \times M_{\mu\mu} / |p^{\mu^+\mu^-}|$
Significance of proper decay time λ/σ_λ (>2)
3D opening angle $\Delta\alpha$ (<0.7 rad)
Isolation of B candidate I (>0.5)



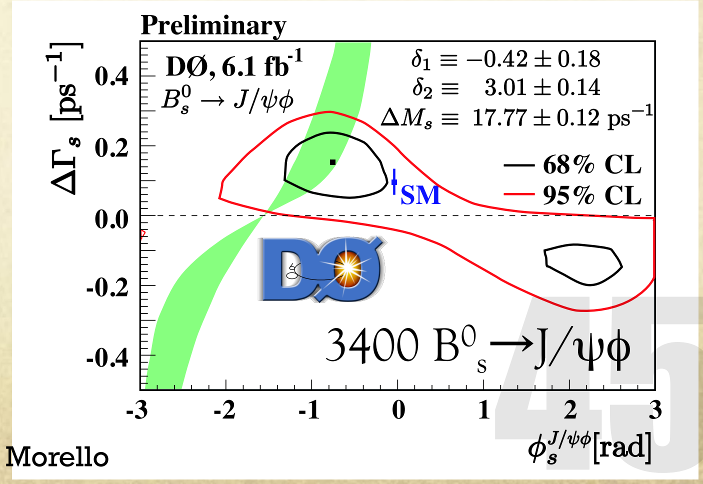
β_s from $B^0_s \to J/\psi\phi$ – status

- CP violation in $B^0_s \to J/\psi\phi$ occurs though interference of decays with and without mixing.
- SM predicts small value for the mixing phase $2\beta_s = -\phi_s$.
- New particles could enter weak mixing box diagrams and enhance CP violation
- Time evolution ($\Gamma_L, \Gamma_H, \Delta\Gamma, \beta_s$) very sensitive to NP contributions.
- Trends are the same as in the past, both experiments now see SM consistency at about 1σ level.

CDF-Pub-10206



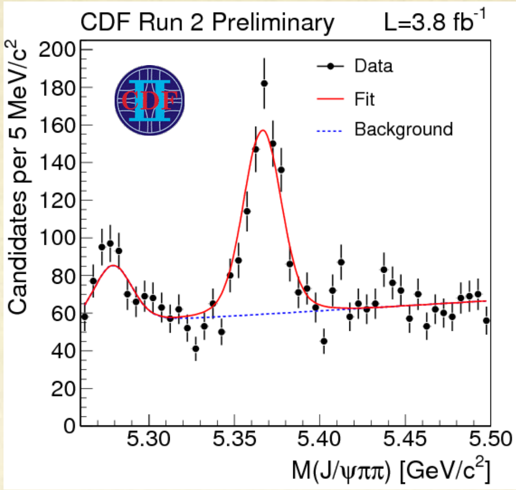
D0Note 6098-CONF



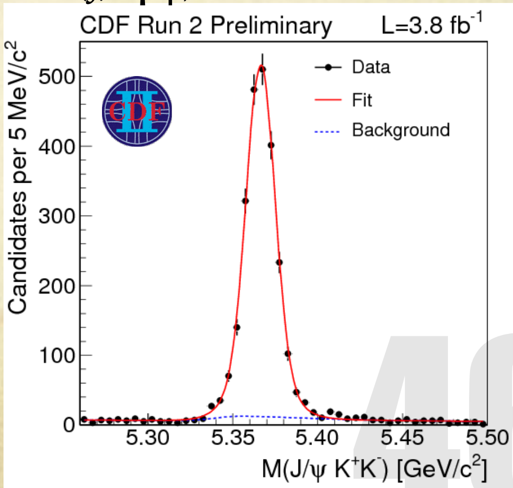
$B^0_s \to J/\psi f_0(980)$

- This is a CP=+1 eigenstate
  - Unambiguous measure of lifetime $1/\Gamma_H$
  - Clean measure B^0_s mixing phase βs
  - $B^0_s \to J/\psi\phi$ requires complex angular analysis for vector-vector final state
  - Understand S-wave contributions to βs measurement in $Bs \to J/\psi\phi$
- BR measurement
  - Neural Net Selection
  - Use identical selection for $Bs \to J/\psi\phi$ reference mode
  - Simultaneous log-likelihood fit to signal and normalization mode.

$N(J/\psi\ f_0)=571\pm37$



$N(J/\psi\phi)=2302\pm50$



BR($B^0_s \to J/\psi f_0(980)$)

~18σ significant (*CDF-Pub-10404*):

$$\frac{BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{BR(B_s^0 \to J/\psi \phi, \phi \to K^+K^-)} = 0.292 \pm 0.020(stat) \pm 0.017(syst)$$

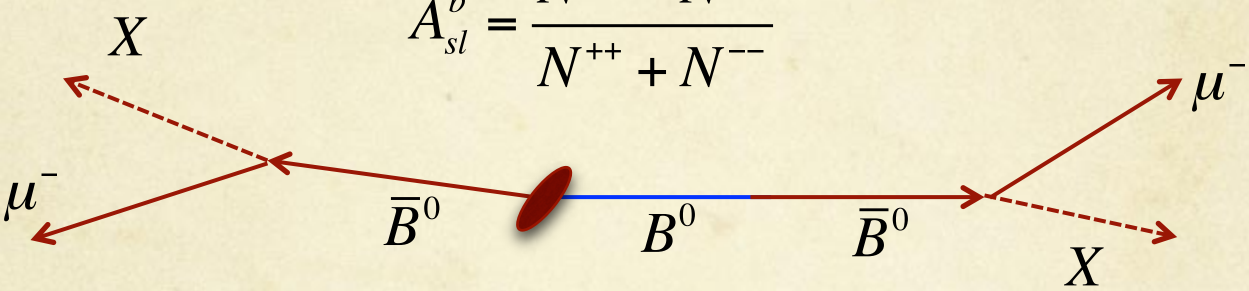
$$BR(B_s^0 \to J/\psi f_0(980)) \cdot BR(f_0(980) \to \pi^+\pi^-) = (1.85 \pm 0.13 \pm 0.57) \times 10^{-4}$$

- First observation from LHCb [PLB 698,115,2011.]
  - $\frac{BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{BR(B_s^0 \to J/\psi \phi, \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$
- Confirmed by Belle [PRL106,121802,2011]:
  - $BR(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-) = (1.15^{+0.31+0.15+0.26}_{-0.19-0.17+0.18}) \times 10^{-4}$

Di-muon charge asymmetry

- Search for CP Violation in mixing using same sign dimuon events from semileptonic B decays:

$$A_{sl}^{b} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$



- N_b^{++} and N_b^{--} are the number of events with two b-hadrons decaying semileptoncally producing two same-sign muons
  - One muon comes from direct semileptonic decay $b \to \mu^- X$
  - Second muon comes from direct semileptonic decay after mixing $\bar{b} \to b \to \mu^- X$
  - A the TeVatron, both B^0_s and B^0 contribute.

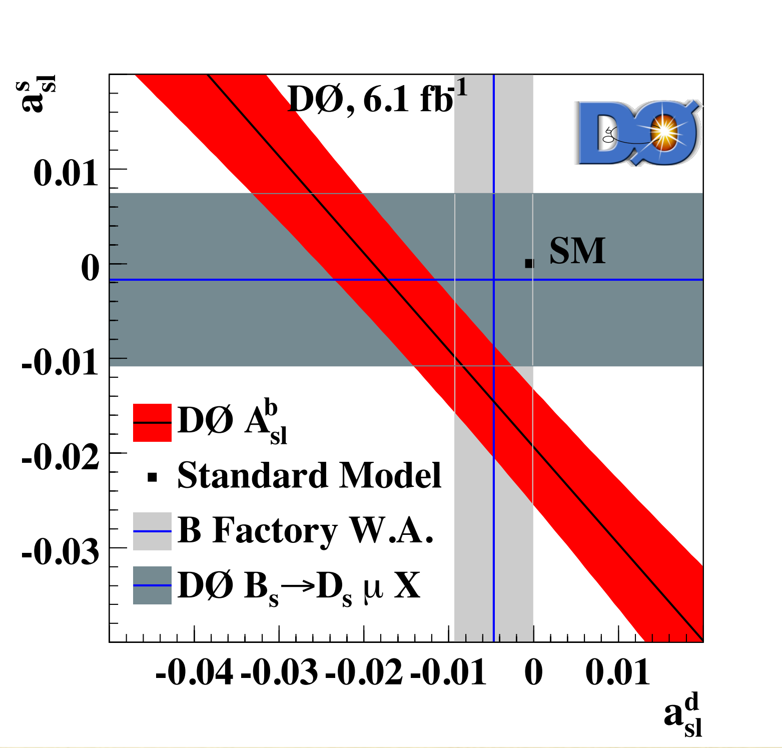
- Lots of subtleties in the analysis, but two main experimental issues:
  - Asymmetric backgrounds from kaons faking μ
  - Asymmetric μ^+ and μ^- acceptance/efficiency

Di-muon charge asymmetry

- In 6 fb^{-1} DØ measures:

$$A^b_{sl} = (-0.957 \pm 0.251 \pm 0.146)\%$$

PRD82,032001(2010)



- SM prediction is:
  - Using prediction of a^d_{sl} and a^s_{sl} from *JHEP 0706, 072 (2007)*

$$A^b_{sl} = (-0.023^{+0.005}_{-0.006})\%$$

- Differs from SM by ~3.2σ

- Results from $B^0_s \rightarrow J/\psi\phi$ consistent with dimuon asymmetry.

Di-muon charge asymmetry

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$$A_{sl}^{b} = (-0.957 \pm 0.251 \pm 0.146)\%$$

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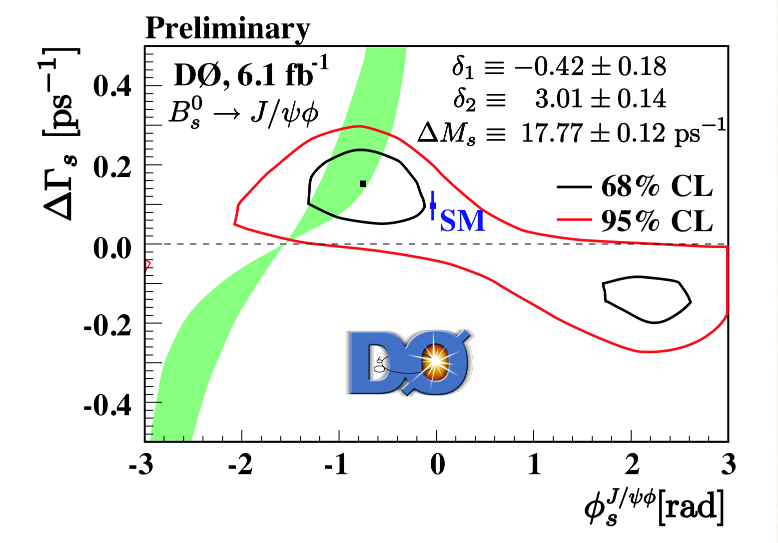
Green band from A^{b}_{sl}



What about CDF?

- CDF cannot reverse magnet polarity.
  - Probably not a major concern.
  - Dominant charge biases can be measured with data.
- DØ has better muon coverage at high $|\eta|$
- Scaling statistical uncertainty of previous CDF measurement 0.9% (*CDF-Pub-9015*) on 1.6 fb^{-1}, on 7 fb^{-1} we expect ~0.3-0.4%
- The main point is the systematic uncertainty! In the meanwhile.....

Time integrated mixing probability of B mesons

Defined as: $\bar{\chi} = \frac{\Gamma(B^0 \to \bar{B}^0 \to l^+ X)}{\Gamma(B \to l^\pm X)} = f_d \cdot \chi_d + f_s \chi_s$

where the numerator includes B^0_d and B^0_s. It derives from the measurement of the ratio R:

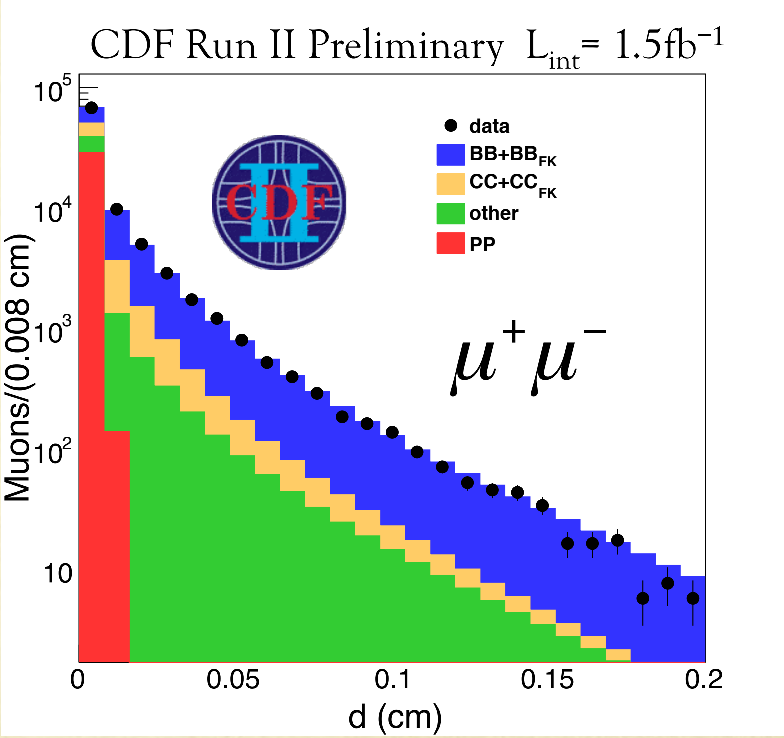
$$R = \frac{N(\mu^+\mu^+) + N(\mu^-\mu^-)}{N(\mu^+\mu^-)}$$

Use impact parameter (d) to identify source of muons: b, c, prompt components
2D fit of impact parameter using MC templates.

$$R = 0.472 \pm 0.011 \pm 0.007 \Rightarrow \bar{\chi} = 0.126 \pm 0.008$$

In agreement with LEP measurement: 0.1259±0.0042.

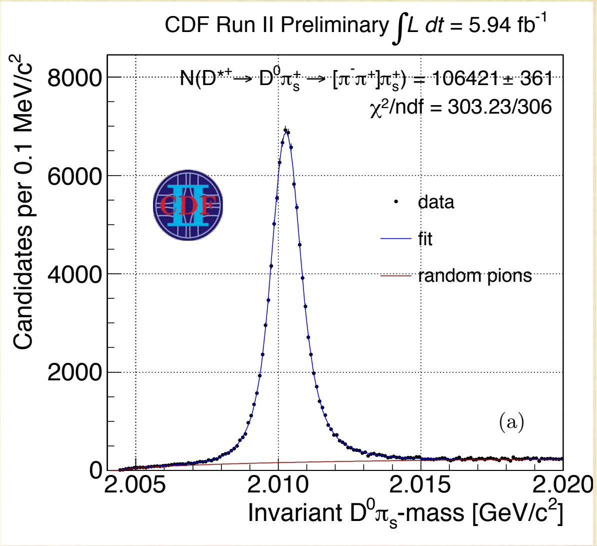
CDF-Pub-10335

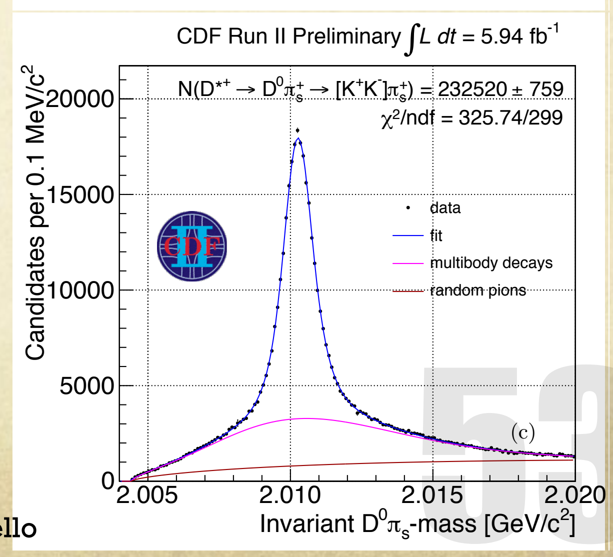


Fit projection of impact parameter

CPV in $D^0 \to h^+h^-$

- Charm is a unique because it probes up-quark sector (unaccessible through t or u quarks).
- Negligible penguin contribution the charm decays in SM
  - CPV in charm would point to NP



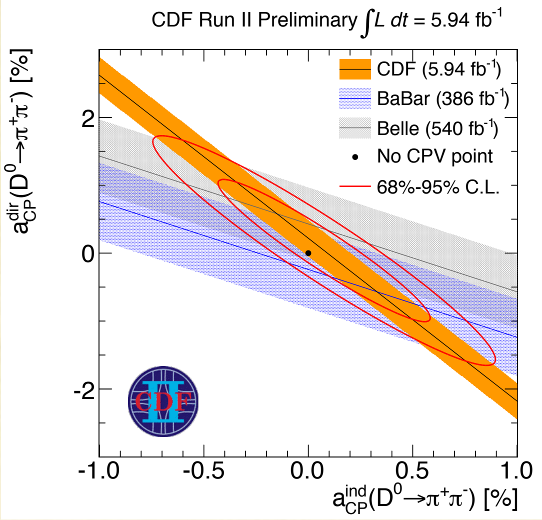


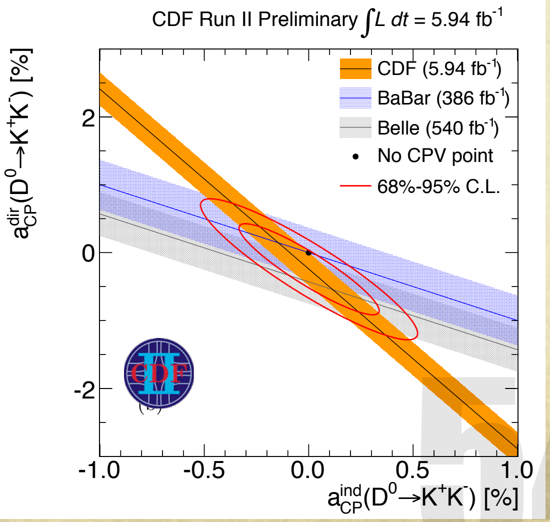
$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)}$$

Time-integrated → $A_{CP} = a_{CP}^{dir} + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$

CPV in $D^0 \to h^+h^-$

CDF-Pub-10296





- The main challenge: suppressing detector charge asymmetries at the per mille level.
- Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \to K^-\pi^+$
- Basic assumption: ppbar strong interactions are charge symmetric.

$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \pm 0.11]\%$$

$$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22 \pm 0.10]\%$$

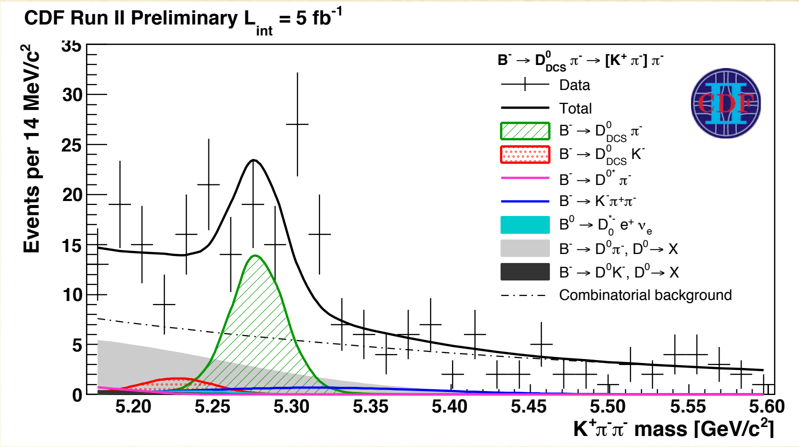
- World's best measurements.
  - CDF very sensitive to mixing induced effects, because of impact parameter requirements.
- Fully consistent with small CP violation.

γ from $B \rightarrow DK$

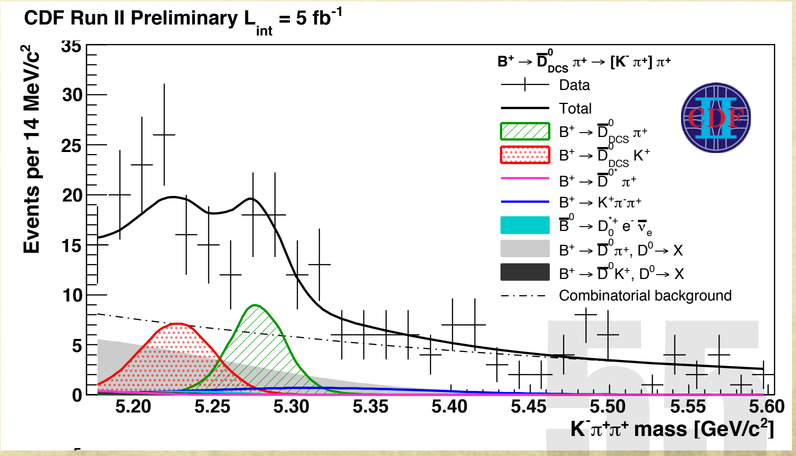
CDF-Pub-10309

- Study of $B \rightarrow DK$ is the cleanest way to access γ.
  - From the interference between $b \rightarrow c$ ubar s ($B^- \rightarrow D^0 K^-$) and $b \rightarrow u$ cbar s ($B^- \rightarrow$ anti$D^0 K^-$) with the D0 and aD0 decay in the same final state.
- Several methods to extract γ.
  - No tagging or time-dependent analysis required.
- ADS method(*PRL78,3257;PRD63,036005*) uses Doubly Cabibbo Suppressed $D^0 \rightarrow K^+\pi^-$ decays.
- Simultaneous ML fit combining mass and PID estimates:
  - $N(B \rightarrow D_{DCS}K) = 34 \pm 14$
  - $N(B \rightarrow D_{DCS}\pi) = 73 \pm 16$
  - Significance ($D_{DCS}\pi$ + $D_{DCS}K$) $> 5\sigma$

$B^- \rightarrow D\pi^- \rightarrow [K^+\pi^-]\pi^-$



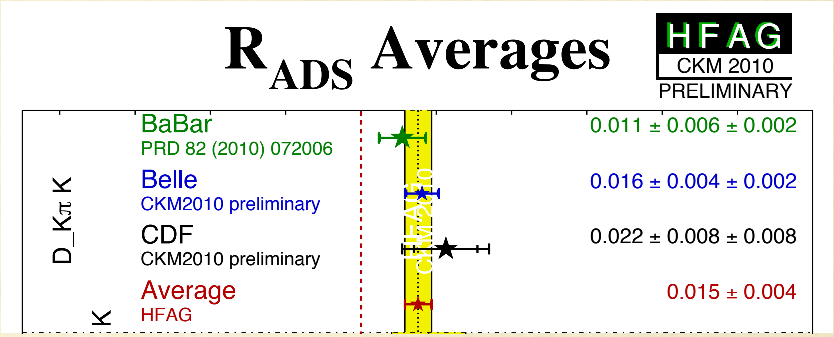
$B^+ \rightarrow D\pi^- \rightarrow [K^-\pi^+]\pi^+$



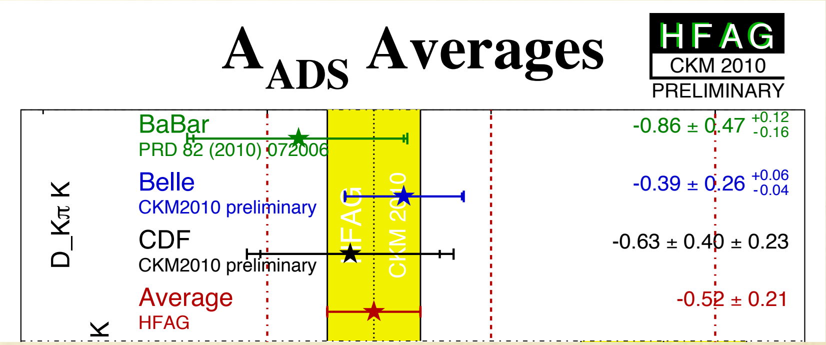
Observables: R_{ADS} and A_{ADS}

$$R_{ADS} = \frac{BR(B^- \to [K^+\pi^-]_{D^0} K^-) + BR(B^+ \to [K^-\pi^+]_{D^0} K^+)}{BR(B^- \to [K^-\pi^+]_{D^0} K^-) + BR(B^+ \to [K^+\pi^-]_{D^0} K^+)}$$

$$A_{ADS} = \frac{BR(B^- \to [K^+\pi^-]_{D^0} K^-) - BR(B^+ \to [K^-\pi^+]_{D^0} K^-)}{BR(B^- \to [K^+\pi^-]_{D^0} K^-) + BR(B^+ \to [K^-\pi^+]_{D^0} K^+)}$$



- R_{ADS} and A_{ADS} are functions of γ angle.
- First measurements of these quantities at hadron collisions.
- Results in agreement and competitive with other experiments.
- Analysis on $7 fb^{-1}$ is in progress. $D_{DCS}K$ significance $>3\sigma$.



See P. Garosi's talk for more details.

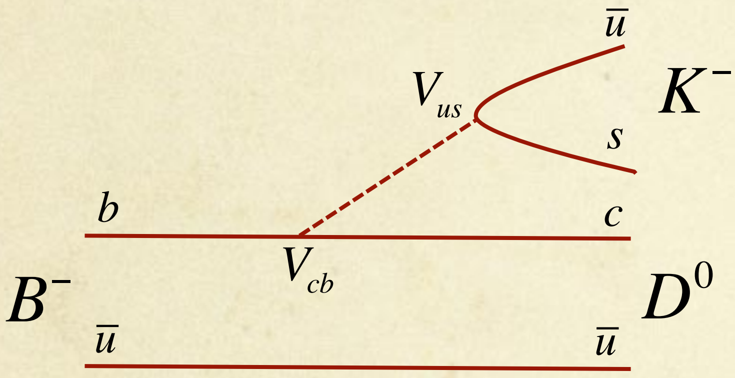
Why hadronic B-decays?

- Hadronic decays very rich field.
- Sensitive to all combinations of:
  - Cabibbo-favored and Cabibbo-suppressed decays,
  - Tree-diagrams and loop-diagrams,
  - Spectator-decays and exchange/annihilation decays,
  - Color-favored and color-suppressed decays.
- Aim: disentangle new physics from hadronic uncertainties.
  - Requires simultaneous measurements of many decays.
- Focus today on modes sensitive to the least known angle γ.
  - $B^- \rightarrow DK^-$ (ADS method)
  - $B^0_{(s)} \rightarrow h^+h'^-$ decays.

Angle γ from $B^- \to DK^-$

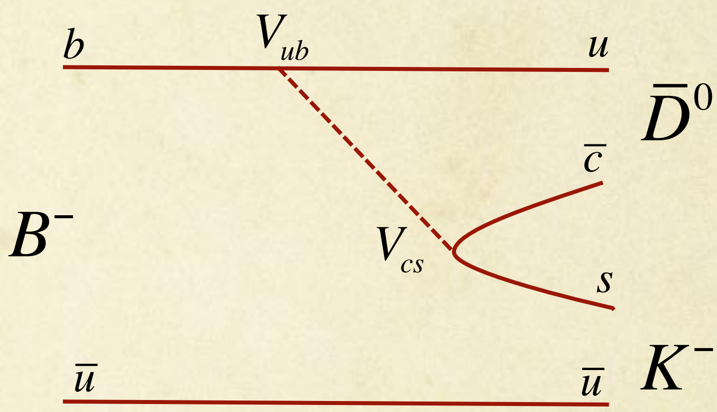
Cleanest ways to measure γ angle. Only tree-level amplitudes are involved. Tiny theoretical uncertainties. Exploit interference between the processes:

$b \to c\bar{u}s$



Favored $b \to c$ decay:
$\sim V_{cb}V^*_{us} \sim \lambda^3$

$b \to u\bar{c}s$



Color Suppressed $b \to u$ decay:
$\sim V_{ub}V^*_{cs} \sim \lambda^3 r_B\, e^{-i\delta B}\, e^{i\gamma}$

Several methods depending on $D^0 \to f$ and $\bar{D}^0 \to f$: GLW $D \to \pi\pi/KK$, ADS $D \to K\pi$ suppressed decays, etc. No tagging or time dependent analysis is needed, well suited for hadronic environment.
CDF already provided results for GLW method in $1fb^{-1}$ [*PRD81, 031105(2010)*].

ADS method

ADS method [*PRL78,3257(1997)*;*PRD63,036005(2001)*] uses the $B^- \to D K^-$ decays with D reconstructed in $D \to K^+\pi^-$:

$$B^- \to D^0 K^- \to [K^+\pi^-]K^-$$

→ Color allowed $B^- \to D K^-$ and Doubly Cabibbo Suppressed $D^0 \to K^+\pi^-$.

$$B^- \to \bar{D}^0 K^- \to [K^+\pi^-]K^-$$

→ Color suppressed $B^- \to D K^-$ and Cabibbo Favored anti$D^0 \to K^+\pi^-$.

$$\left|\frac{\mathcal{M}(B^- \to K^- D^0[\to f])}{\mathcal{M}(B^- \to K^- \overline{D}^0[\to f])}\right|^2 \approx \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 \left|\frac{a_1}{a_2}\right|^2 \frac{Br(D^0 \to f)}{Br(\overline{D}^0 \to f)} \approx 1$$

↖ color suppression

$B^- \to DK^- \to [K^+\pi^-]K^-$ suppressed by factor of about 10^{-3} wrt favored $B^- \to DK^- \to [K^-\pi^+]K^-$

The two interfering amplitudes are comparable. Large CP violation can be observed.

ADS method (cont'd)

- Expected large CP asymmetries.
- Results have to be combined with other methods to obtain γ measurement.
- Observables:

$$R_{ADS}(h) = \frac{BR(B^- \to D_{\text{sup}} h^-) + BR(B^+ \to D_{\text{sup}} h^+)}{BR(B^- \to D_{fav} h^-) + BR(B^+ \to D_{fav} h^+)}$$

$$A_{ADS}(h) = \frac{BR(B^- \to D_{\text{sup}} h^-) - BR(B^+ \to D_{\text{sup}} h^+)}{BR(B^- \to D_{\text{sup}} h^-) + BR(B^+ \to D_{\text{sup}} h^+)}$$

h = K or π
$D_{\text{fav}} \to K^- \pi^+$
$D_{\text{sup}} \to K^+ \pi^-$

From theory: $R_{ADS}(K) = r_D^2 + r_B^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$
$A_{ADS}(K) = 2 r_B r_D \sin(\delta_B + \delta_D) \sin\gamma / R_{ADS}(K)$

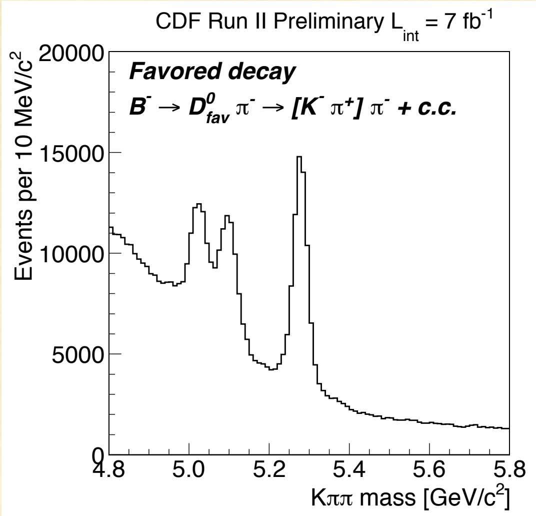
$$r_B = \left| \frac{A(b \to u)}{A(b \to c)} \right| \quad r_D = \left| \frac{A(D^0 \to K^- \pi^+)}{A(D^0 \to K^+ \pi^-)} \right|$$

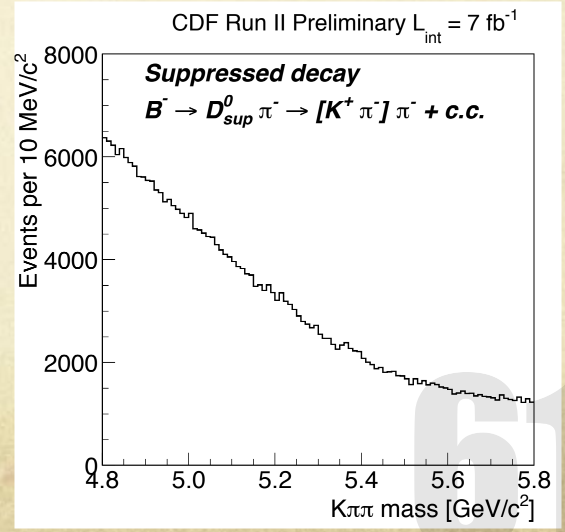
δ_B and δ_D relative strong phases of B and D decays.

$B^- \to DK^-$ ADS analysis

Before optimization

- Selection is crucial to search for highly suppressed signals.
- Optimal point chosen using large sample of favored decays (same final states).
  - Maximize the sensitivity for discovery of limit setting for an unobserved mode [*physics/0308063*].
- Simultaneous Extended Unbinned Maximum Likelihood fit on Favored and Suppressed modes.
- Using masses and particle identification (dE/dx) information to determine the signal composition.

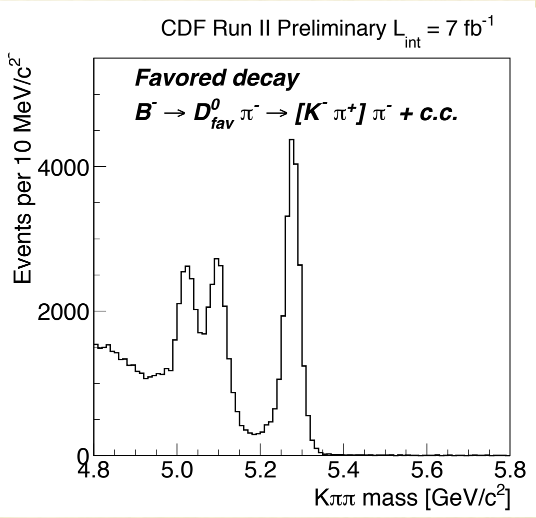


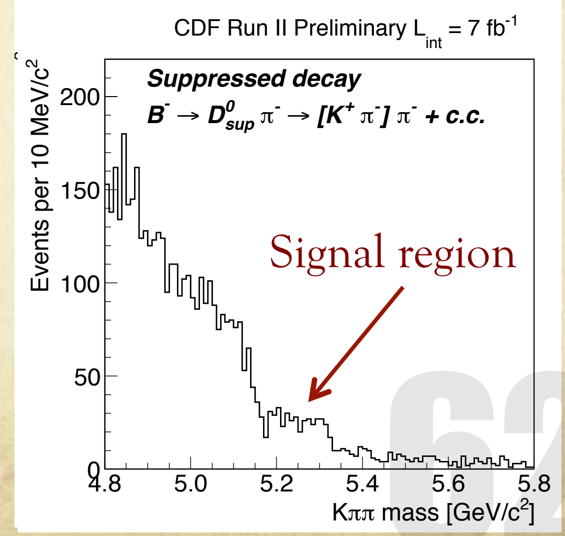


B⁻→DK⁻ ADS analysis

After optimization

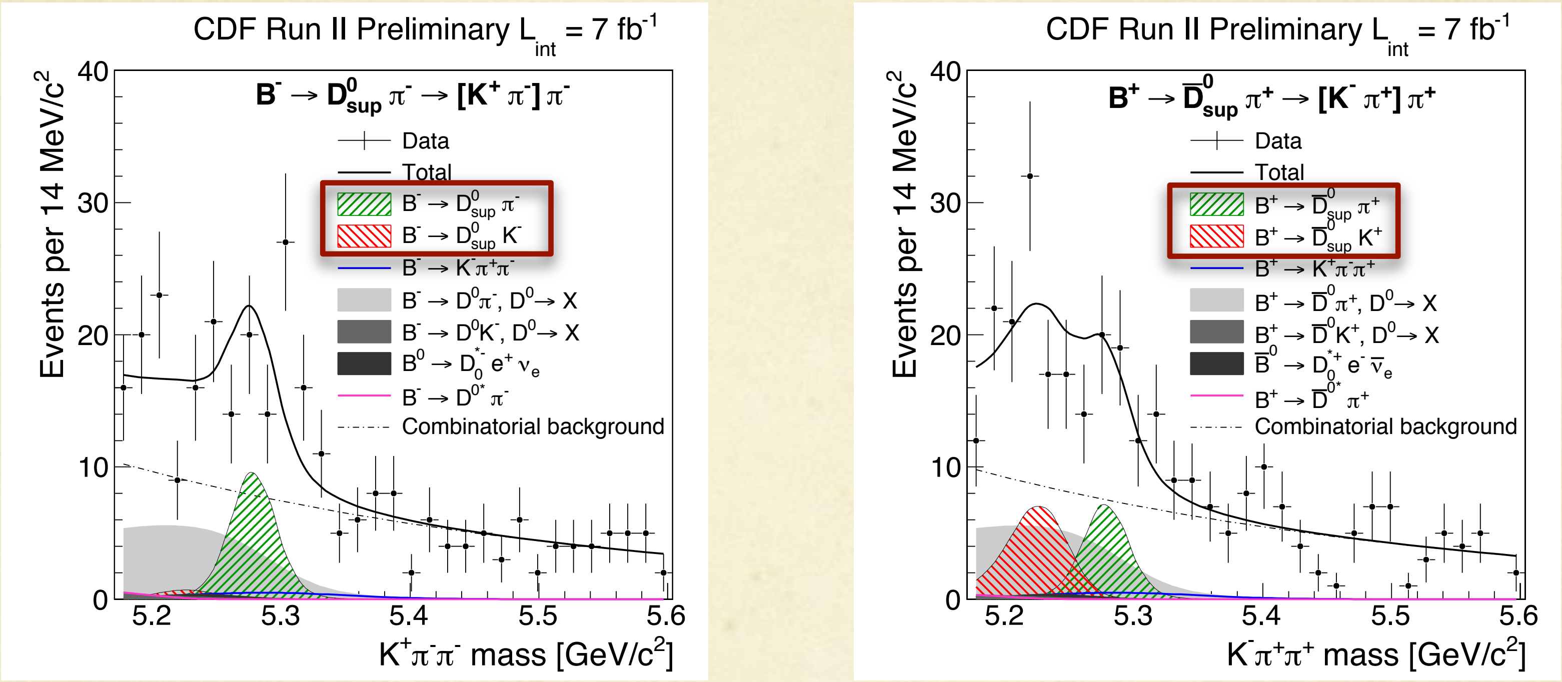
- Selection is crucial to search for highly suppressed signals.
- Optimal point chosen using large sample of favored decays (same final states).
  — Maximize the sensitivity for discovery of limit setting for an unobserved mode [*physics/0308063*].
- Simultaneous Extended Unbinned Maximum Likelihood fit on Favored and Suppressed modes.
- Using masses and particle identification (dE/dx) information to determine the signal composition.





First evidence of $B^- \to D_{sup} K^-$

CDF-note 10309



$$N(B^- \to D_{sup} K^-) + N(B^+ \to D_{sup} K^+) = 32 \pm 12$$

$$N(B^- \to D_{sup} \pi^-) + N(B^+ \to D_{sup} \pi^+) = 55 \pm 14$$

First Evidence of $B^- \to D_{sup} K^-$ signal at hadron collider (3.2σ level)

Physics observables

CDF-note 10309

$$R_{ADS}(\pi) = [2.8 \pm 0.7(stat) \pm 0.4(syst)] \cdot 10^{-3}$$

$$A_{ADS}(\pi) = 0.13 \pm 0.25(stat) \pm 0.02(syst)$$

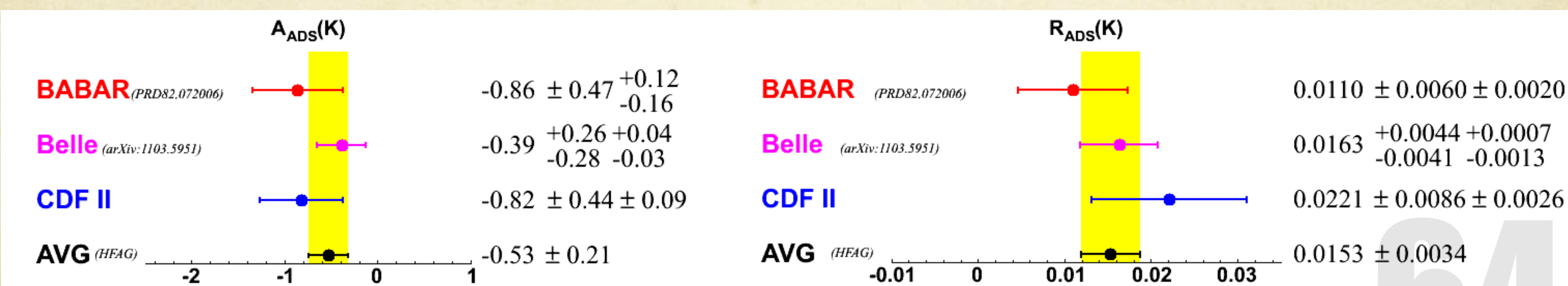
$$R_{ADS}(K) = [22.0 \pm 8.6(stat) \pm 2.6(syst)] \cdot 10^{-3}$$

$$A_{ADS}(K) = -0.82 \pm 0.44(stat) \pm 0.09(syst)$$

$B^- \to D_{fav}\pi^-$ ~19700ev
$B^- \to D_{fav}K^-$ ~1460 ev

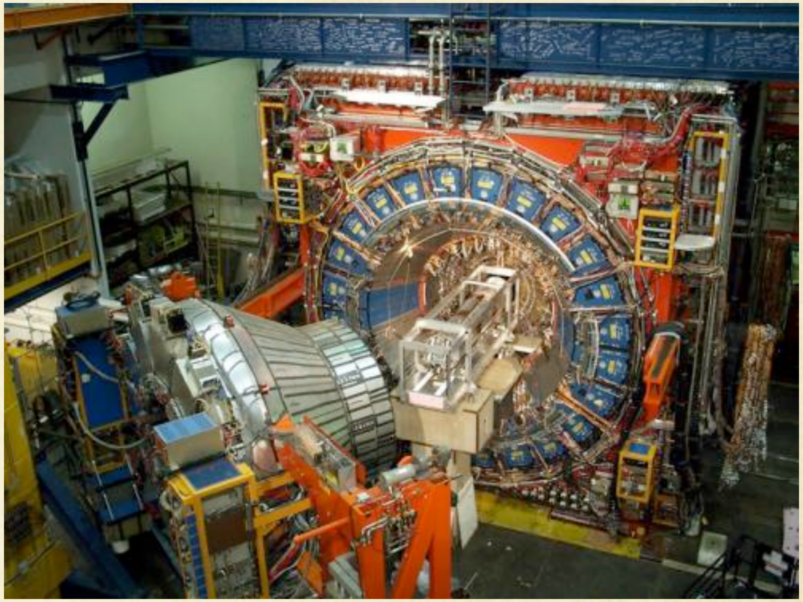
$B^- \to D_{sup}\pi^-$ ~55 ev
$B^- \to D_{sup}K^-$ ~32 ev

First measurement of A_{ADS} and R_{ADS} at hadron collider. They agree with other experiments.



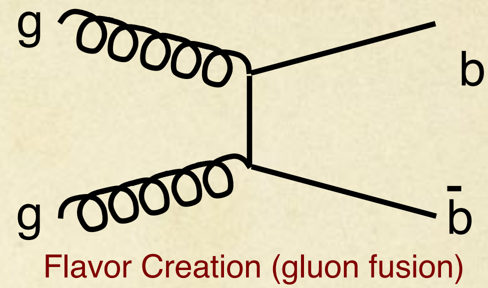
CDFII detector

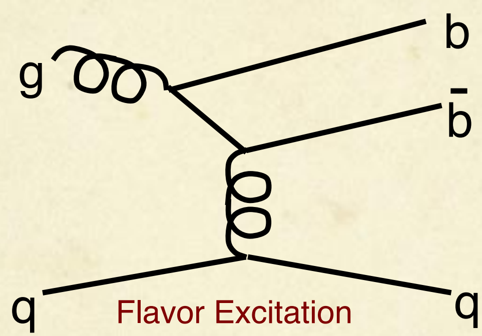
- Central Drift Chamber
  - $\delta p_T/p_T \sim 0.0015\ (GeV/c)^{-1} p_T$
- Silicon Vertex Detector
  - — Silicon Vertex Trigger
- Particle identification
  - — dE/dX and TOF
- Good electron and muon identification by calorimeters and muon chambers.

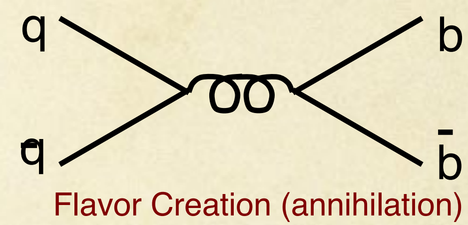


B Physics at the Tevatron

Mechanisms for b production in ppbar collisions at 1.96 TeV:





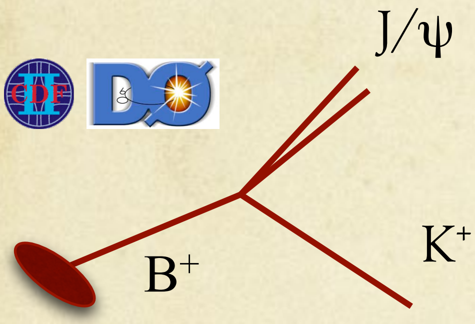


- At Tevatron, large b production cross section
- Plethora of states accessible: B^0_s, B_c, Λ^0_b, Ξ_b, Σ_b...
- Total σ(inelastic) at Tevatron is ~1000 larger that b cross section
  - large backgrounds suppressed by triggers that target specific decays.

B Triggers

J/ψ

- $p_T(\mu)>1.5$GeV
- J/ψ mass requirement
- Opposite charge



$B^0 \rightarrow J/\psi\ K^{0*}$
$B^+ \rightarrow J/\psi\ K^+$
$\Lambda_b \rightarrow J/\psi\ \Lambda$
$B_c \rightarrow J/\psi\ \pi$
$B^0_s \rightarrow J/\psi\ \phi$
Ξ_b, B^{**}

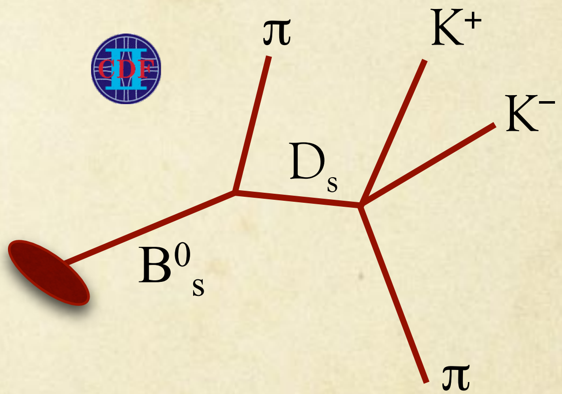
Dimuon

- $p_T(\mu)>1.5$ or 2 GeV
- Triggers with/without charge requirement

$B \rightarrow \mu\mu$+hadrons
$B \rightarrow \mu\mu$
$bb \rightarrow \mu\mu$
$cc \rightarrow \mu\mu$

Displaced Track

- p_T(track)>2 GeV
- IP(track)>80 or 120 μm
- Opposite charge



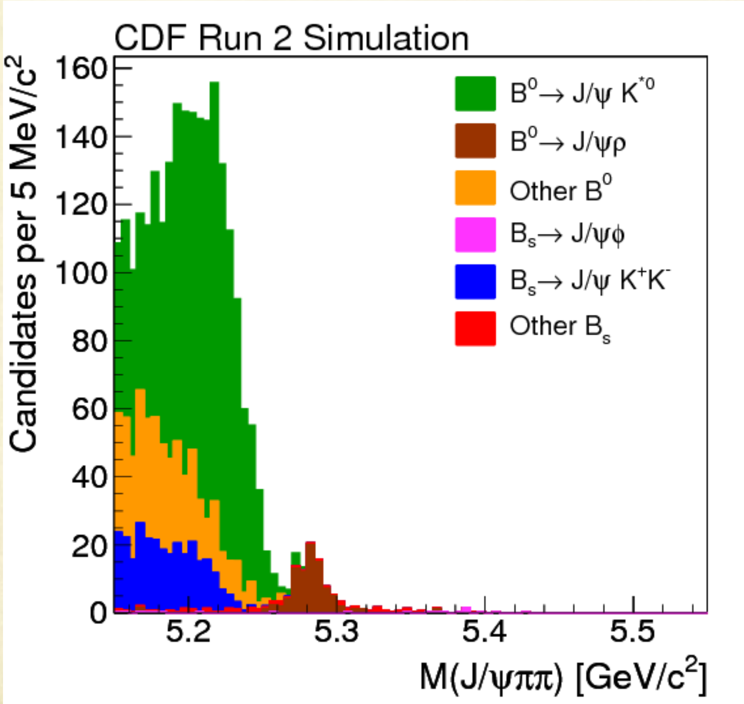
$B \rightarrow Dh$
$B \rightarrow hh$
$\Lambda_b \rightarrow ph$
$D \rightarrow hh$

$B^0_s \rightarrow J/\psi f_0(980)$

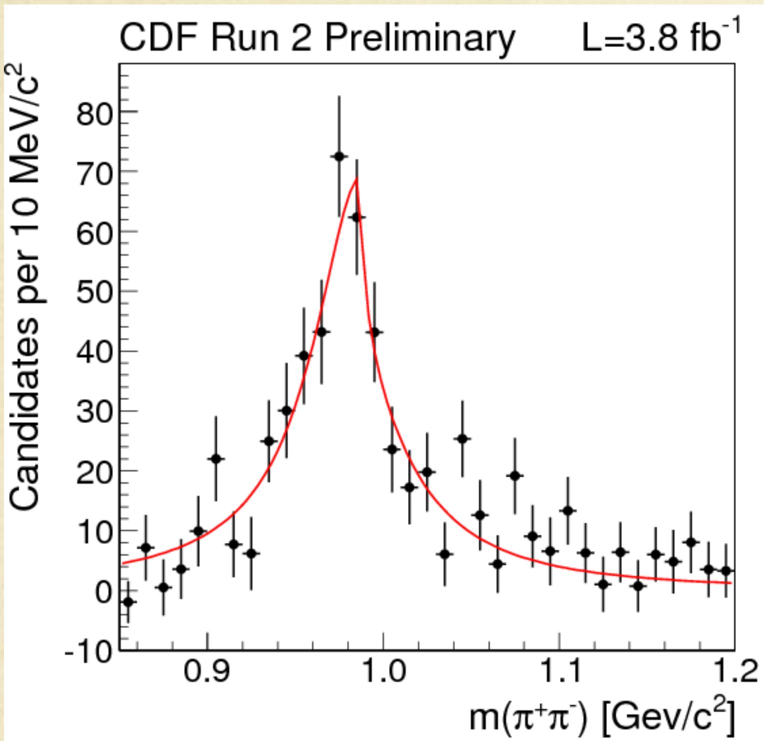
- CP=+1 eigenstate
- Unambiguous measure of lifetime $1/\Gamma_H$
- Clean measure of CP violating parameter β_s
  - $B_s \rightarrow J/\psi\,\phi$ requires complex angular analysis for vector-vector final state
- Understand S-wave contributions to β_s measurement in $B_s \rightarrow J/\psi\,\phi$

$B^0_s \rightarrow J/\psi f_0(980)$ - Analysis

- Start with loose selection of $\mu\mu\pi\pi$ candidates
  - f_0 is wide, so $0.85 < M(\pi\pi) < 1.2$ GeV
- Neural Net Selection
- Kinematic variables, track & vertex displacement, isolation
- High-mass sideband only for background model
- Use identical selection for $Bs \rightarrow J/\psi\ \phi$ reference mode
- Physics backgrounds from Monte Carlo

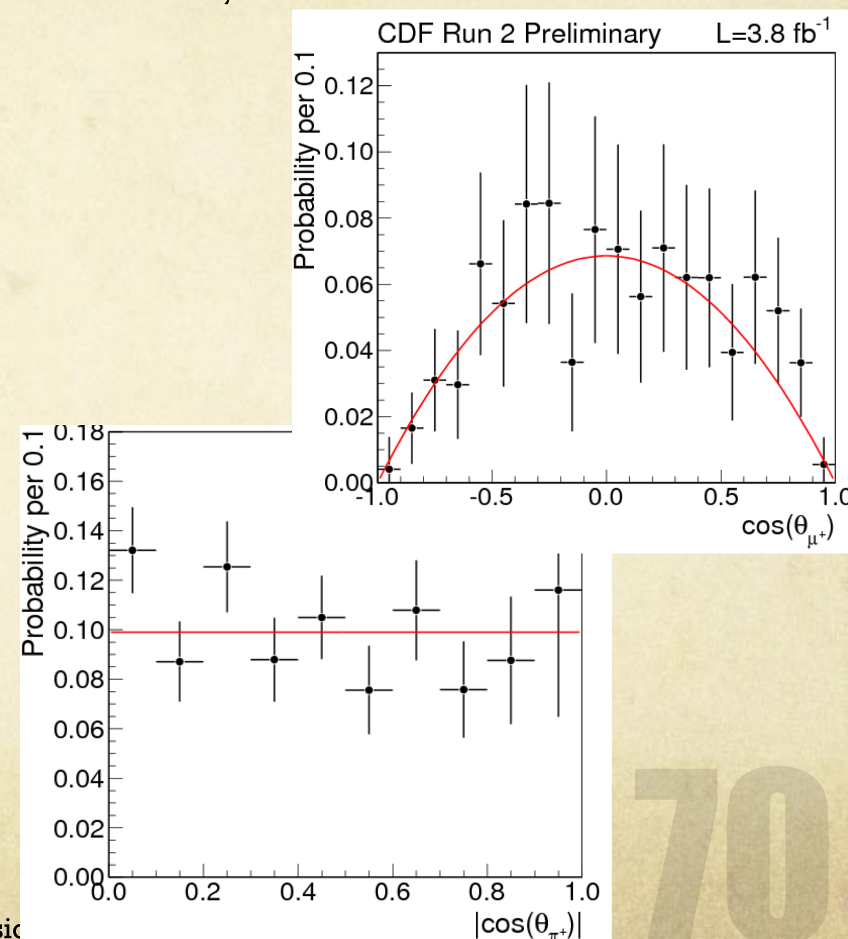


Confirmation of $f_0(980)$



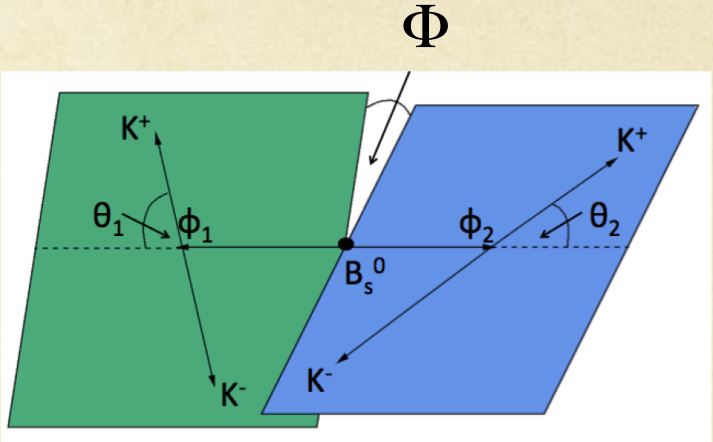
Di-pion mass distribution consistent with f_0. Shape parameters from BES.

Helicity angles consistent with P→PV decay
After efficiency correction



$B^0_s \to \phi\phi$ at the TeVatron

- First measurement of BR (*CDF-Pub-10064*) and first measurement of polarization (*CDF-Pub-10120*).
  - Found large transverse polarization $(|A_{||}|^2+|A_{\perp}|^2)/|A_0|^2 = 1.9 \pm 0.2$ in disagreement with SM, naïvely <<1
- CP violation expected very tiny, however NP could enhance it.
- The best hard way: full tagged and time-dependent analysis, but statistics still too small.
- However Triple Products (TP) Asymmetries are expected zero in SM. NP could affect those.
- Experimentally accessed by asymmetry of distribution of two angular function u and v. Theoretical details in *Int. J. of Mod. Phys. A, 19:2505 (2004) and arXiv:1103.2442*.



$$\mathcal{A}_{\rm TP} = \frac{\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)>0) - \Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)<0)}{\Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)>0) + \Gamma(\vec{p}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)<0)},$$

$$u = \cos\Phi\sin\Phi \longrightarrow A_{||}A_{\perp}$$

$$v = \begin{cases} \sin\Phi & \text{if } \cos\vartheta_1\cos\vartheta_2 > 0 \\ \sin(-\Phi) & \text{if } \cos\vartheta_1\cos\vartheta_2 < 0 \end{cases} \longrightarrow A_0 A_{\perp}$$

First measurement of CPV in $B^0_s \to \phi\phi$

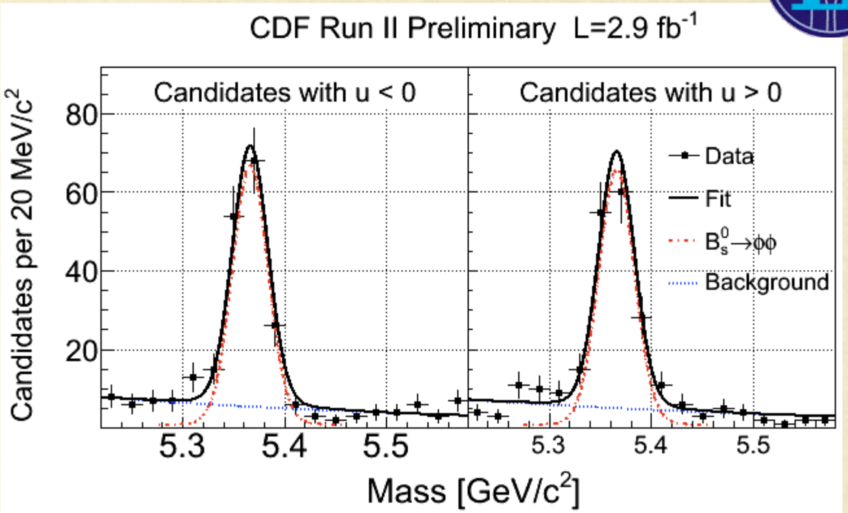
CDF-Pub-10424

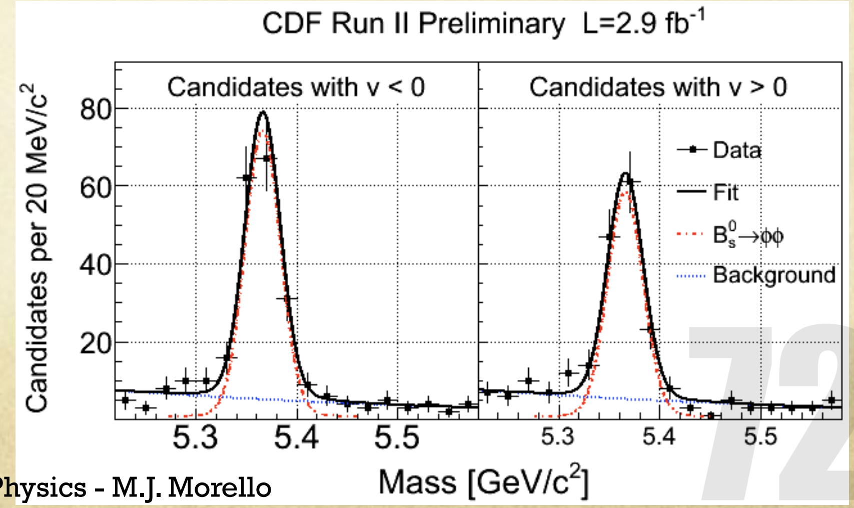
- No tagging and time-dependent analysis is required.
- Unbinned ML fit:
  - Signal asymmetry enter directly the Likelihood.
  - Backg. Asymmetry consistent with 0.

$$A_u = (-0.8 \pm 6.4 \pm 1.8)\%$$

$$A_v = (-12.0 \pm 6.4 \pm 1.6)\%$$

- Sensitive to CP Violation both in mixing and decay.





$\bar{\chi}$: New CDF Measurement

- Dimuon data sample
  - 1.4 fb^{-1}
  - Use impact parameter to identify source of muons:
    b, *c*, prompt
    - Same technique as *bb* cross-section measurement
    - 2D fit of d_0 using templates from Monte Carlo
    - Constraints on $b,c \to K,\pi \to \mu$ also from MC
    - Much tighter selection than earlier measurements
      - Requires hit in silicon layer 1.7cm far from beam

Extracting $\bar{\chi}$

- Many sources of dimuons in bb events
  - b semileptonic decay
  - $b \rightarrow c \rightarrow \mu$ sequentials
  - $b \rightarrow \psi \rightarrow \mu$
  - Hadron fakes
- Use MC to derive wrong-charge fraction
- Result: $\bar{\chi}$=0.127± 0.008
  - Includes systematic uncertainty on wrong-charge correction
  - Compare to LEP: 0.126 ±0.004

CPV in $D^0 \to h^+h^-$

- The main challenge: suppressing detector charge asymmetries at the per mille level.
- Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \to K^-\pi^+$
- Basic assumption: ppbar strong interactions are charge symmetric.

$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24 \pm 0.11]\%$$

$$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22 \pm 0.10]\%$$

- World's best measurements.
  - CDF very sensitive to mixing induced effects, because of impact parameter requirements.
- Fully consistent with small CP violation.

CDF-Pub-10296