Summary of CP Violation and Rare-Decay Results from the Tevatron

LISHEP: Workshop on LHC, Present and Future

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Results Presented in this Talk

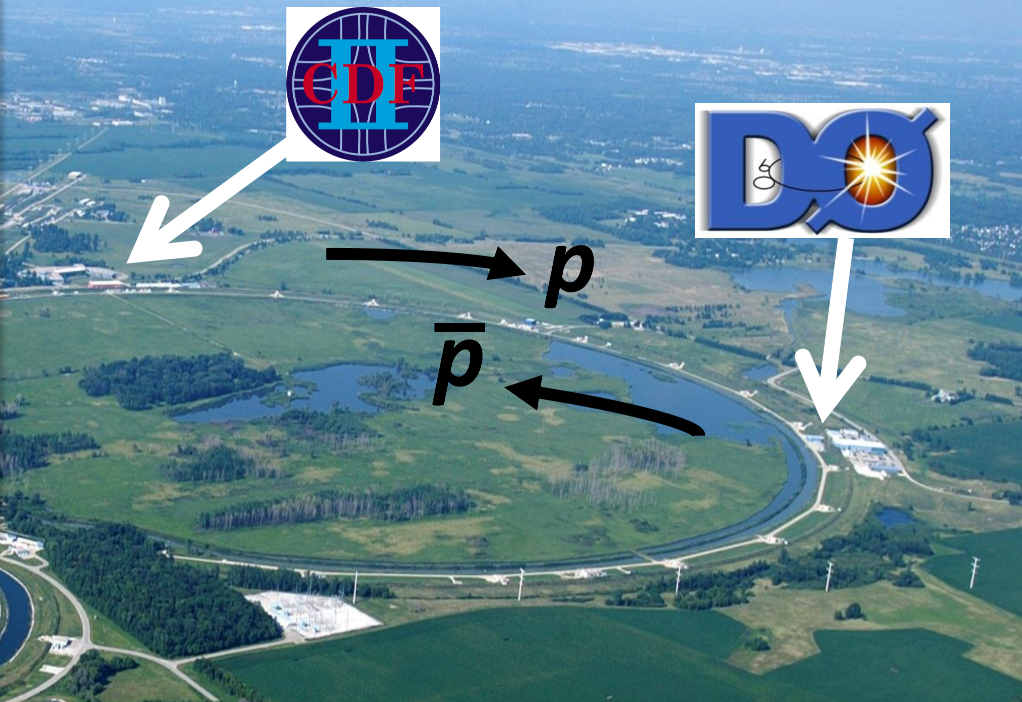
- Updated measurement of same-sign dimuon asymmetry (D0) **New!! (Last week)**
- Review of measurements of CPV phase β_s in $B^0_s \to J/\psi\varphi$ decays (CDF, D0)
- Measurement of relative BR for $B^0_s \to J/\psi f_0$ (D0, CDF) and first lifetime measurement of a B^0_s CP eigenstate (CDF) **New!! (June 2011)**
- First Evidence for pure annihilation decay $B^0_s \to \pi\pi$ (CDF) **(May 2011)**
- "ADS" analysis of doubly Cabibbo-suppressed decays $B^\pm \to D^0\pi^\pm$ $(K^\pm)$ (CDF) **(April 2011)**
- Search for CPV in $B^0_s \to \varphi\varphi$ decays (CDF) **(April 2011)**
- Measurement of CPV in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays (CDF) **(February 2011)**
- Search for rare-decay $B_s^0 \to \mu^+ \mu^-$ (CDF, D0) **(September 2010)**
- Integrated mixing probability $\chi 0$ (CDF) **(January 2011)**

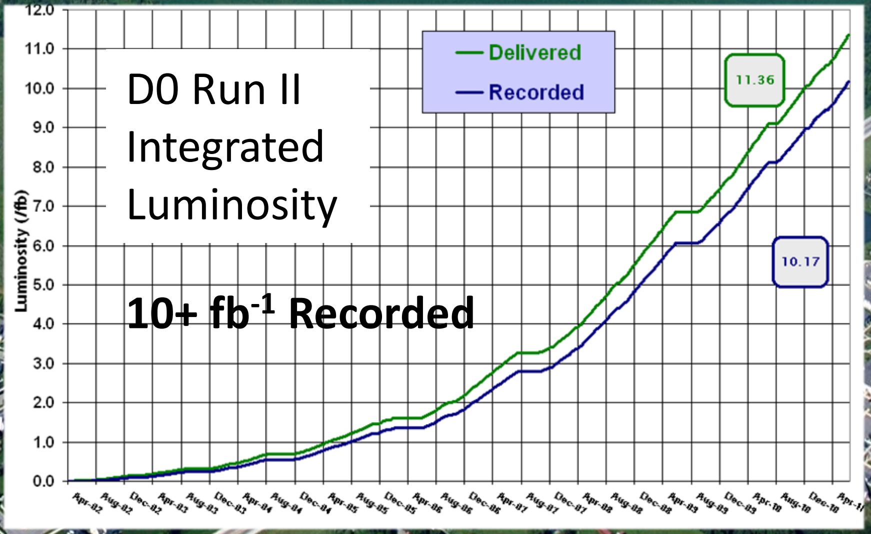
Tevatron accelerator located at the Fermilab site, 30 miles west of Chicago;

Collides protons and antiprotons at centre-of-mass energy 1.96 TeV;

Accelerator performance better than ever – learning from the past;

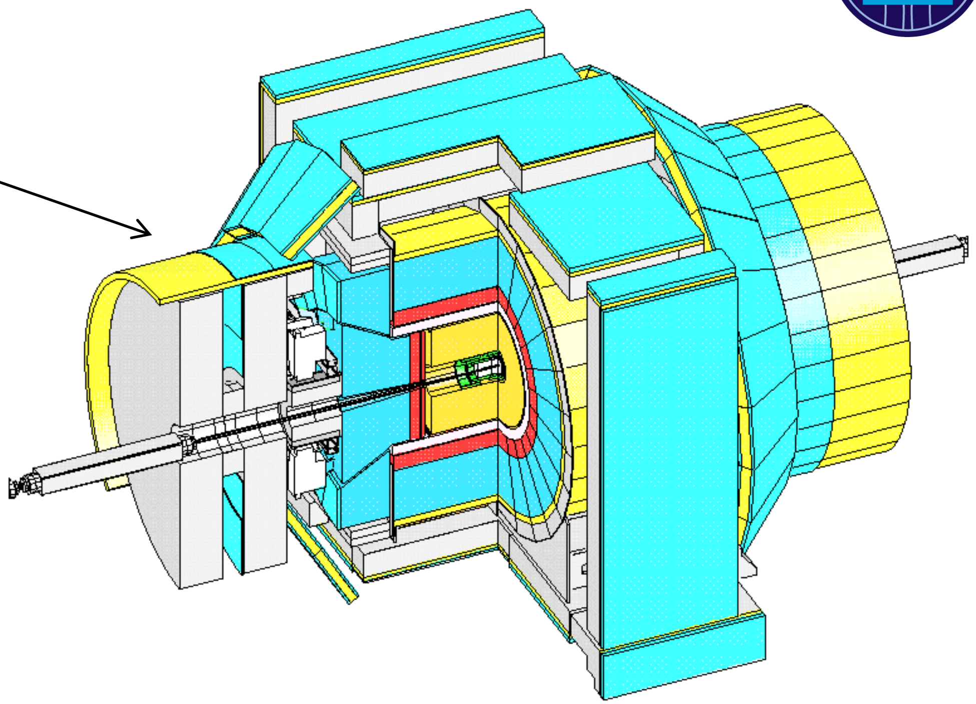
In final push before collisions stop at the end of September 2011.





Experimental Strengths

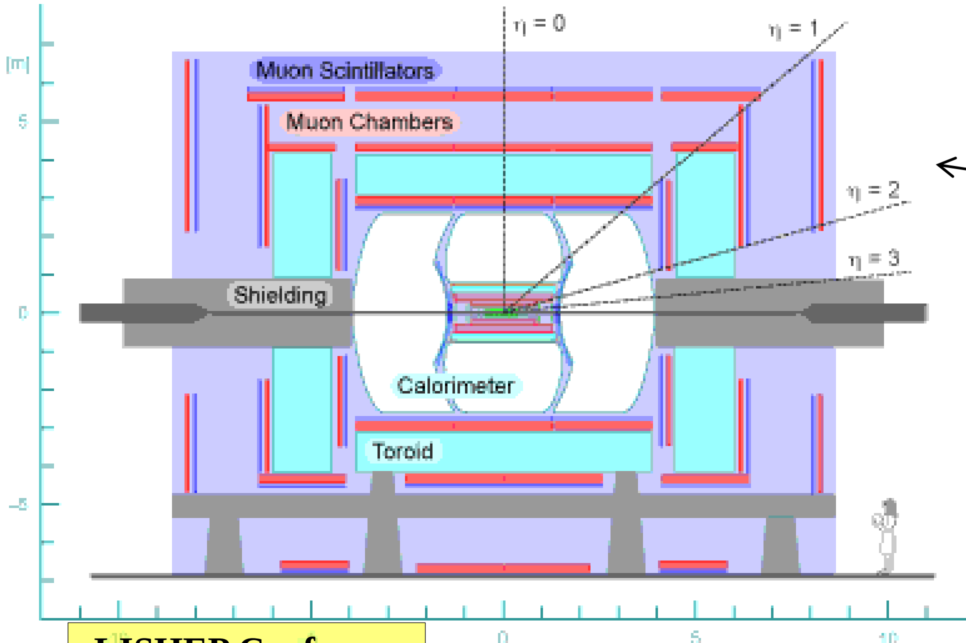
CDF Experiment



Large tracker (silicon + drift chamber) for excellent mass resolution

Particle ID: dE/dx gives good separation between kaons and pions;

Displaced-track trigger allows hadronic HF decays to be probed to high precision.



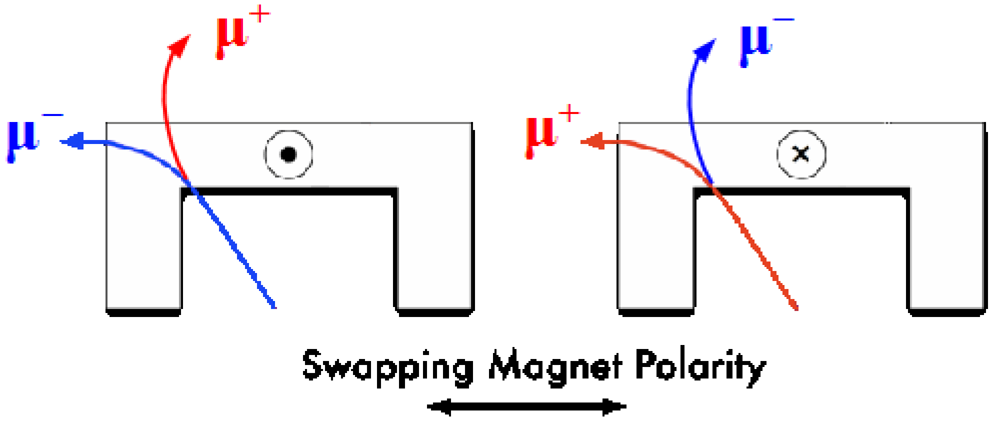
D0 Experiment

Wide acceptance in muon system (|η| < 2.5)

Regular reversal of toroid (muon-system) and solenoid (tracker) magnet polarities – cancels many detector asymmetries.

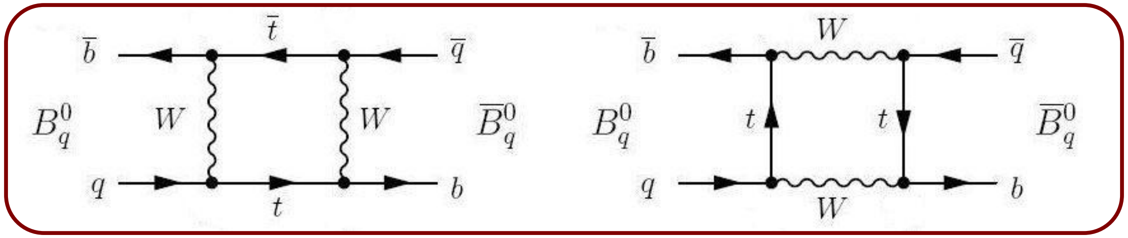
Thick shielding before muon system – hadronic punch-though suppressed.

Part I:
CPV and Rare-Decays with Dimuons



CPV in Mixing

Neutral $B^0_{(q=d,s)}$ mesons mix into their antiparticles via box diagrams:



Process **not CP symmetric** – **$R(B^0_q \rightarrow \bar{B}^0_q) \neq R(\bar{B}^0_q \rightarrow B^0_q)$** – due to complex phase $\varphi_{(d,s)}$ in quark mixing matrix, but…

…SM prediction of resulting asymmetry is **too small to explain observed matter dominance** in the universe. **New particles** entering loops can enhance this asymmetry significantly.

Measure CPV through asymmetry of decay products.

Flavor-specific semileptonic asymmetries defined for both B^0_s and B^0_d:

$$a^q_{sl} = \frac{N(\bar{B}^0_q \rightarrow B^0_q \rightarrow \mu^+X) - N(B^0_q \rightarrow \bar{B}^0_q \rightarrow \mu^-X)}{N(\bar{B}^0_q \rightarrow B^0_q \rightarrow \mu^+X) + N(B^0_q \rightarrow \bar{B}^0_q \rightarrow \mu^-X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\varphi_q$$

Physical parameters characterizing B^0_q system

Measuring CPV in Mixing

D0 experiment measures an inclusive asymmetry, with contributions from both B^0_d and B^0_s:

$$a^b_{sl} = \frac{N(\bar{\mathbf{B}}^0 \rightarrow \mu^+ X) - N(\mathbf{B}^0 \rightarrow \mu^- X)}{N(\bar{\mathbf{B}}^0 \rightarrow \mu^+ X) + N(\mathbf{B}^0 \rightarrow \mu^- X)} = \underbrace{C_d a^d_{sl} + C_s a^s_{sl}}$$

More B^0_d produced, but most decay before mixing: $C_d \approx C_s \approx 0.5$

Challenge: separate signal (semileptonic *mixed* decays of B mesons) from the many other muon-producing backgrounds.

To suppress such backgrounds, require second muon of the same charge:

$$A^b_{sl} = \frac{N(b\bar{b} \rightarrow \mu^+\mu^+) - N(b\bar{b} \rightarrow \mu^-\mu^-)}{N(b\bar{b} \rightarrow \mu^+\mu^+) + N(b\bar{b} \rightarrow \mu^-\mu^-)} = a^b_{sl} \qquad (0.028 \pm 0.006)\% \textit{ in S.M.}$$

We therefore have two ways to extract a^b_{sl}, and take advantage of the correlated backgrounds by combining the two measurements.

Analysis Strategy

1) Measure 'raw' asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

$$\underbrace{\mathrm{a} \equiv \frac{n^+ - n^-}{n^+ + n^-}}_{\text{Raw asymmetry (event counting)}} = \underbrace{\sum_{i=0}^{5} f^i_\mu}_{\text{Weighted average over bins of muon } p_T} \{ \underbrace{f_s{}^i \left(c_b a^b{}_{sl} + \right.}_{\text{Asymmetry from heavy-flavor decays}} \underbrace{\left. \delta_i\right) + f_k{}^i a_k{}^i + f_\pi{}^i a_\pi{}^i + f_p{}^i a_p{}^i}_{\text{Asymmetries from backgrounds and detector effects}} \}$$

Raw asymmetry (event counting)

Weighted average over bins of muon p_T

Asymmetry from heavy-flavor decays

Asymmetries from backgrounds and detector effects

Analysis Strategy

1) Measure ‘raw’ asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

fraction Charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i_\mu \ \{ f_s{}^i \, (c_b \, a^b{}_{sl} + \delta_i) + \underbrace{f_k{}^i a_k{}^i}_{\text{Kaon DIF and punch-through}} + \underbrace{f_\pi{}^i a_\pi{}^i}_{\text{Pion DIF and punch-through}} + \underbrace{f_p{}^i a_p{}^i}_{\text{...proton punch-through}} \}$$

Asymmetries from backgrounds and detector effects

Residual muon reconstruction asymmetries (almost entirely cancelled by magnet polarity reversal)

Analysis Strategy

1) Measure 'raw' asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i_\mu \ \{ f_s{}^i \, (c_b \boldsymbol{a^b{}_{sl}} + \ \delta_i) + f_k{}^i a_k{}^i + f_\pi{}^i a_\pi{}^i + f_p{}^i a_p{}^i \}$$

Asymmetry from heavy-flavor decays

What we want to extract

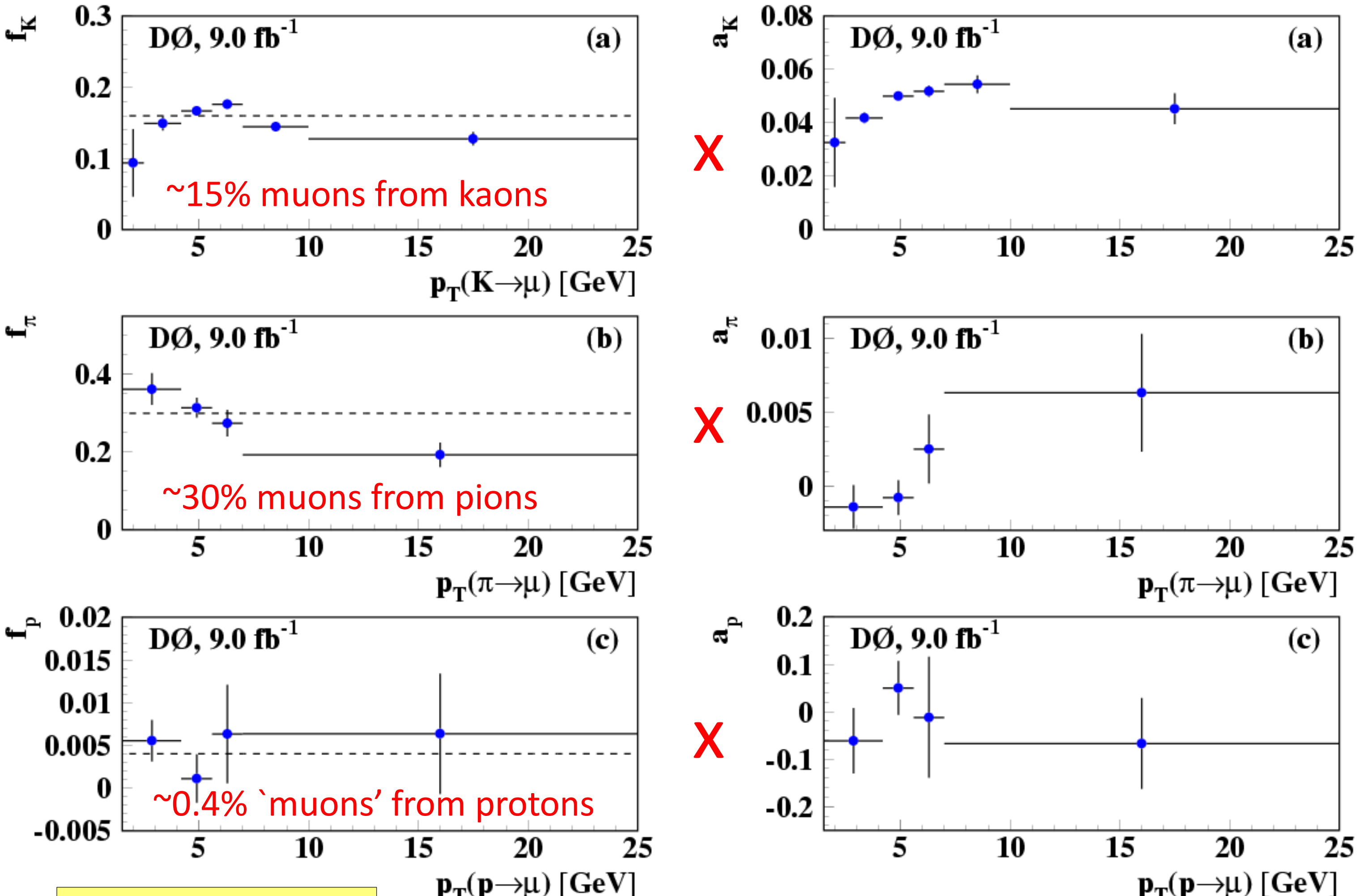
Dilution factor (muons from charge symmetric HF processes)

Remaining fraction of muons after kaon, pion, proton components taken into account: i.e. *"Heavy Flavor Fraction"*

Similar expression for dimuon case. Many BG quantities are the same, or highly correlated, e.g. presence of second muon doesn't change kaon asymmetry $a_k{}^i$.

Analysis Strategy

3) Measure all quantities $f_{k,\pi,p}{}^{i}$, $a_{k,\pi,p}{}^{i}$, δ_i in data, with limited input from simulation;



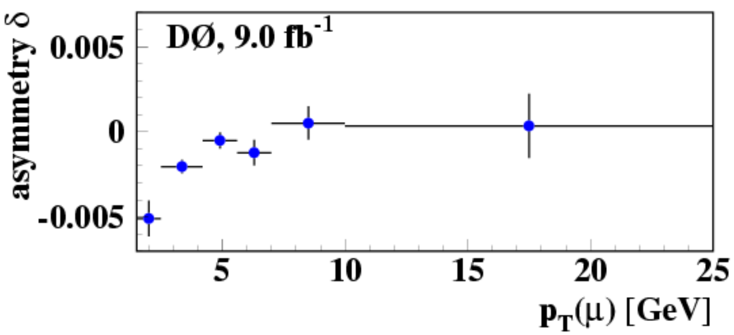
= +0.776 ± 0.021 % asymmetry from kaons

= +0.007 ± 0.027 % asymmetry from pions

= -0.014 ± 0.022 % asymmetry from protons

Analysis Strategy

3) Measure all quantities $f_{k,\pi,p}^{\;i}$, $a_{k,\pi,p}^{\;i}$, δ_i in data, with limited input from simulation;



Contribution from residual muon reconstruction asymmetry:
$\sum_i (1 - f_k^{\;i} - f_\pi^{\;i} - f_p^{\;i})\delta_i$ = -0.047 ± 0.012 %

Source	inclusive muon	like-sign dimuon
$(f_K a_K$ or $F_K A_K) \times 10^2$	$+0.776 \pm 0.021$	$+0.633 \pm 0.031$
$(f_\pi a_\pi$ or $F_\pi A_\pi) \times 10^2$	$+0.007 \pm 0.027$	-0.002 ± 0.023
$(f_p a_p$ or $F_p A_p) \times 10^2$	-0.014 ± 0.022	-0.016 ± 0.019
$[(1 - f_{\text{bkg}})\delta$ or $(2 - F_{\text{bkg}})\Delta] \times 10^2$	-0.047 ± 0.012	-0.212 ± 0.030
$(a_{\text{bkg}}$ or $A_{\text{bkg}}) \times 10^2$	$+0.722 \pm 0.042$	$+0.402 \pm 0.053$
$(a$ or $A) \times 10^2$	$+0.688 \pm 0.002$	$+0.126 \pm 0.041$
$[(a - a_{\text{bkg}})$ or $(A - A_{\text{bkg}})] \times 10^2$	-0.034 ± 0.042	-0.276 ± 0.067

Background dominated

Significantly different from zero

Analysis Strategy

4) Account for dilution from charge-symmetric processes (i.e. determine coefficients c_b, C_b):

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0) w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.096 \pm 0.012$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0) w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.064 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.002$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.675 \pm 0.101$

Weights measured using simulation
This analysis uses LEP value for χ_0, following recent CDF update.

Results: $c_b = 0.061 \pm 0.007$ $C_b = 0.474 \pm 0.032$

Inclusive muon sample dominated by charge-symmetric backgrounds (94%)

Dimuon sample has a large contribution (47%) from mixed B mesons (remember: around 50% each of B^0_d and B^0_s)

Results with $9fb^{-1}$

Final asymmetry from both samples:

From inclusive muon sample: A^b_{sl} = [-1.04 ± 1.30 (stat.) ± 2.31 (syst.)] %
(2.041×10^9 muons)

From like-sign dimuon sample: A^b_{sl} = [-0.808 ± 0.202 (stat.) ± 0.222 (syst.)] %
(6.019×10^6 muons)

Now use **linear combination** of inclusive and dimuon asymmetries, $\mathbf{A' = A - \alpha a}$ with $\boldsymbol{\alpha}$**=0.89** chosen to minimise total uncertainty on A^b_{sl}:

A^b_{sl} = [-0.787 ± 0.172 (stat.) ± 0.093 (syst.)] %

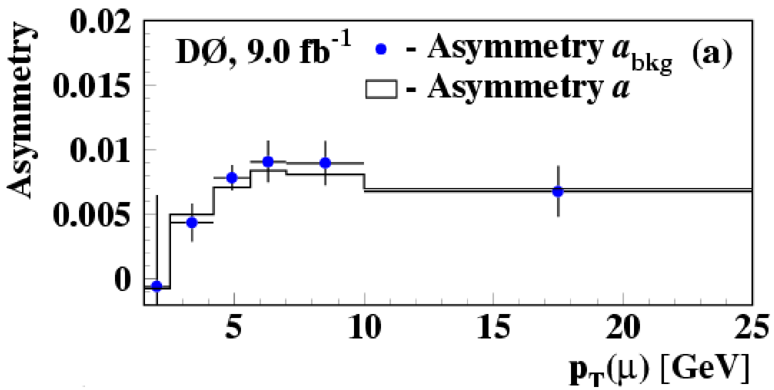
Systematic uncertainty reduces significantly due to extra information in (background dominated) inclusive muon sample

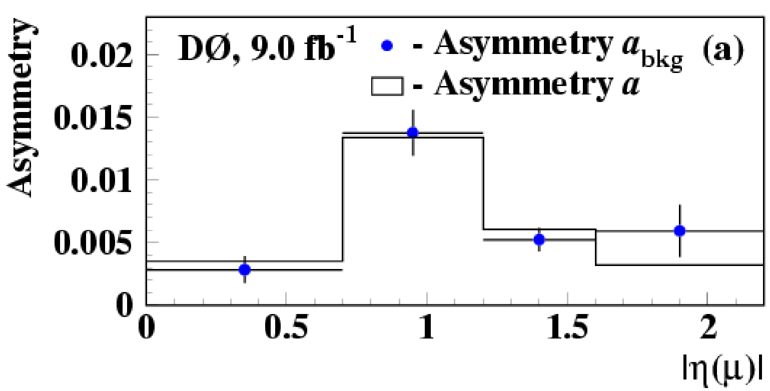
This result differs from the SM prediction by **3.9σ**

arXiv:1106.6308
(submitted to PRD)

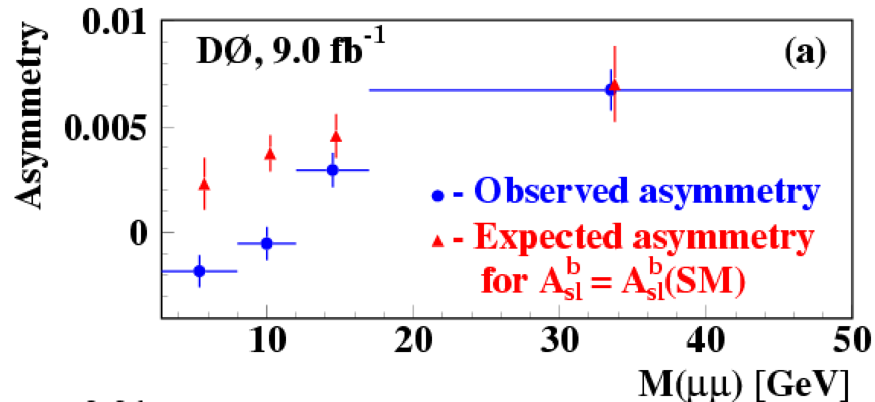
Cross-Checks

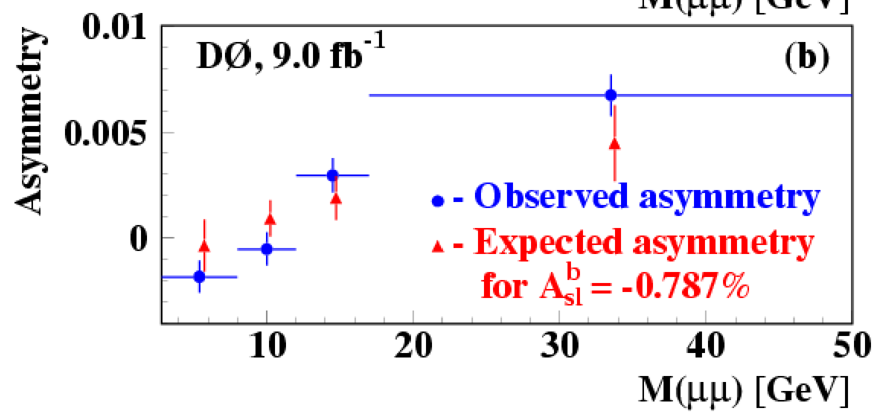
Measured inclusive muon asymmetry *a* is dominated by background: should match a_{bkg}:





Dimuon asymmetry versus M(μμ) – inconsistent with SM, but consistent with measured A^b_{sl}.



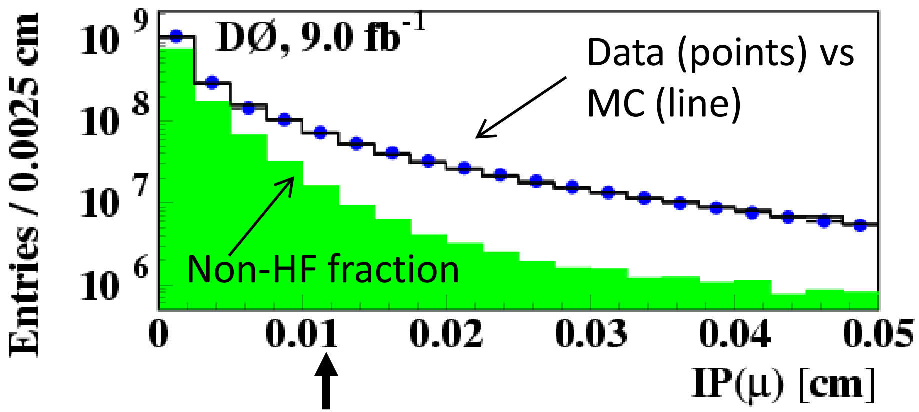


Measurement also repeated with many different requirements to enhance/suppress backgrounds. Final A^b_{sl} consistent in all samples (Total $\chi^2 = 16$ for 18 different tests)

Dependence on Impact Parameter

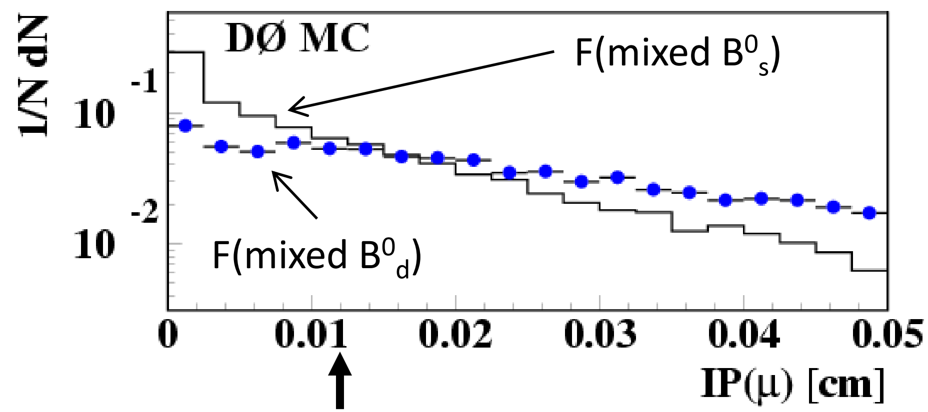
Muon impact parameter strongly influences:

Heavy flavor fraction



120μm

Fraction of \`oscillated' B^0_q mesons



120μm

By dividing into two samples corresponding to **IP(μ) < 120μm** and **IP(μ) > 120μm**, we can:

1) Confirm stable measurement in background enhanced and suppressed samples;
2) Test for larger asymmetry from B^0_d or B^0_s mesons:

for IP(μ) < 120μm: $A^b_{sl} = (0.397 \pm 0.053) a^d_{sl} + (0.603 \pm 0.053) a^s_{sl}$

IP(μ) > 120μm: $A^b_{sl} = (0.728 \pm 0.030) a^d_{sl} + (0.272 \pm 0.030) a^s_{sl}$

Dependence on Impact Parameter

Quantity	$IP_{>120}$	$IP_{<120}$
$f_K \times 10^2$	5.19 ± 0.37	17.64 ± 0.27
$f_\pi \times 10^2$	5.65 ± 0.40	34.72 ± 1.86
$f_p \times 10^2$	0.05 ± 0.03	0.45 ± 0.20
$F_K \times 10^2$	4.48 ± 4.05	21.49 ± 0.62
$F_\pi \times 10^2$	4.43 ± 3.95	40.47 ± 2.26
$F_p \times 10^2$	0.03 ± 0.05	0.59 ± 0.23
$f_S \times 10^2$	89.11 ± 0.88	47.18 ± 2.03
$F_{\rm bkg} \times 10^2$	8.94 ± 8.26	62.56 ± 3.07
$F_{SS} \times 10^2$	91.79 ± 7.65	53.66 ± 2.68
$a \times 10^2$	-0.014 ± 0.005	$+0.835 \pm 0.002$
$a_{\rm bkg} \times 10^2$	$+0.027 \pm 0.023$	$+0.864 \pm 0.049$
$A \times 10^2$	-0.529 ± 0.120	$+0.555 \pm 0.060$
$A_{\rm bkg} \times 10^2$	-0.127 ± 0.093	$+0.829 \pm 0.077$

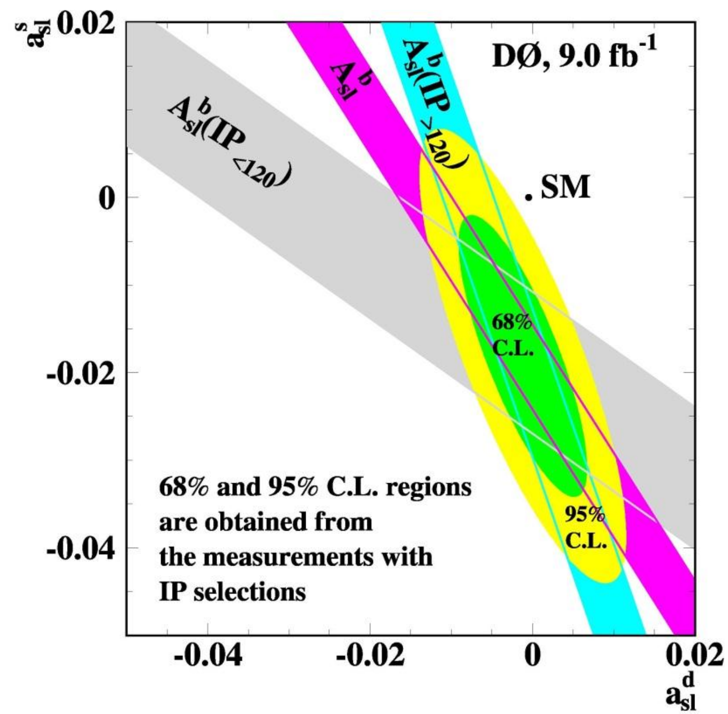
Kaon and pion fractions much lower in IP>120µm sample

HF fraction increases from ~50% → ~90%

Even inclusive muon asymmetry significantly different from BG expectation for IP>120µm

Measured asymmetry larger in B^0_d suppressed sample, but too early to make strong conclusions.

$IP < 120\mu$m	1μ	-1.654	2.774	4.962
	2μ	-1.175	0.439	0.590
	comb.	-1.138	0.366	0.323
$IP > 120\mu$m	1μ	-0.422	0.240	0.121
	2μ	-0.818	0.342	0.067
	comb.	-0.579	0.210	0.094

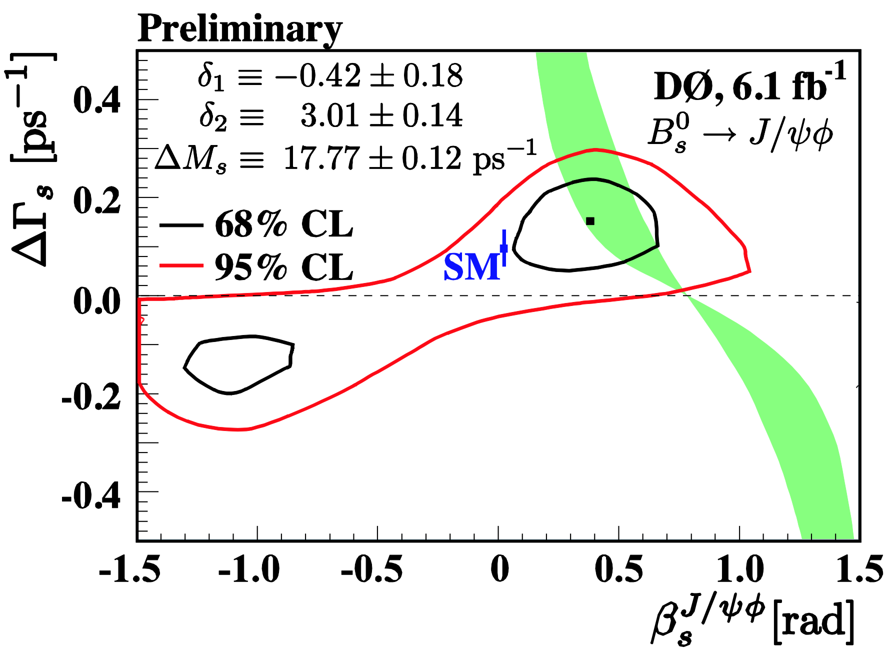


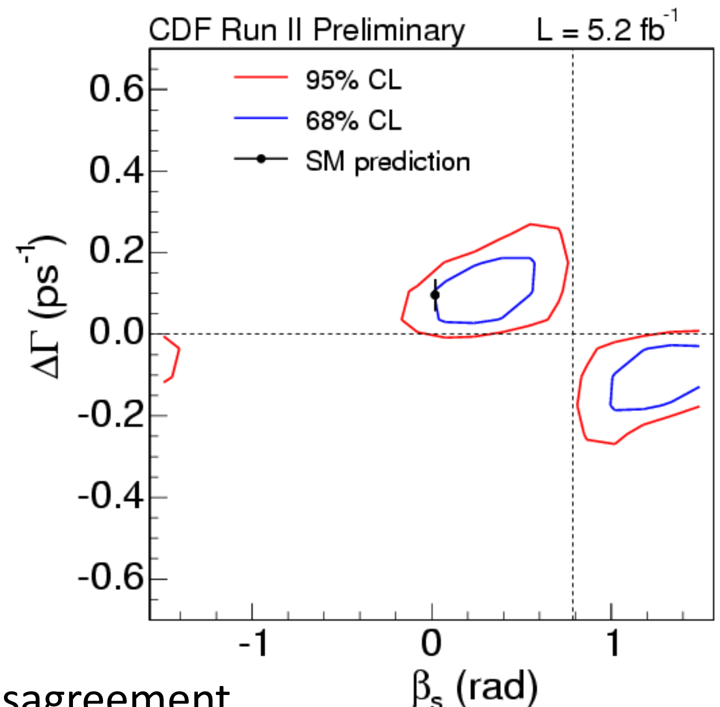
Change of Topic: **CPV in Interference**

In B^0_q decays to a common final state (e.g. $B_s \to J/\psi\varphi$), there is a relative phase between the B mixing amplitude φ_q and subsequent decay amplitudes:

$$\boldsymbol{\varphi_s^{J/\psi\varphi} = -2\beta s = 2*\arg[V_{tb}V^*_{ts}/V_{cb}V^*_{cs}]} = -0.04 \text{ in the SM}$$

New physics effects would shift $\boldsymbol{\varphi_s}$ and $\boldsymbol{\varphi_s^{J/\psi\varphi}}$ by the same amount!





Small, ($1\sigma \oplus 1\sigma$) but tantalizing suggestion of SM disagreement

Both CDF and D0 actively working on updates to their measurements in the $B_s \to J/\psi\varphi$ channel.

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

Interesting channel for several reasons

Final state is exclusively CP-odd, so:

1) No need for complicated angular analysis to disentangle CP states (as in $J/\psi\varphi$) – can potentially make **independent measurement of β_s**.

2) Can **measure lifetime of CP-odd eigenstate**:

In SM this corresponds to 'heavy' mass eigenstate;

$$\tau_s^H = (1.630 \pm 0.030)\ \text{ps} \qquad \tau_s^L = (1.427 \pm 0.023)\ \text{ps}$$

Enhancement of mixing phase φ_s causes CP and mass-eigenstates to diverge, therefore lifetime can indirectly constrain CPV.

Also, if decay $f_0(980) \rightarrow KK$ is present, it can **interfere with $B^0_s \rightarrow J/\psi\varphi$ process**; such 'S-wave' contributions need to be understood.

CDF and D0: Measurement of branching fraction of $B^0_s \rightarrow J/\psi f_0$ decay relative to the $B^0_s \rightarrow J/\psi\varphi$ decay.

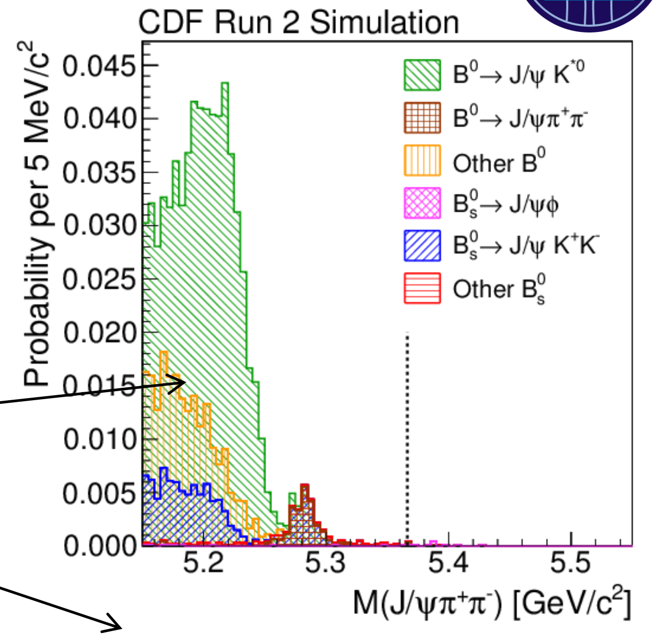
CDF: Measurement of the B^0_s lifetime in the channel $B^0_s \rightarrow J/\psi f_0$
arXiv:1106.3682

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

Neural Net event selection:

- Only use variables which are well-modelled by simulation (used to measure efficiency);
- Train on $\mathbf{J/\psi f_0}$ sample, and then use same NN for $\mathbf{J/\psi \varphi}$ sample.

Model physics backgrounds using input from simulation

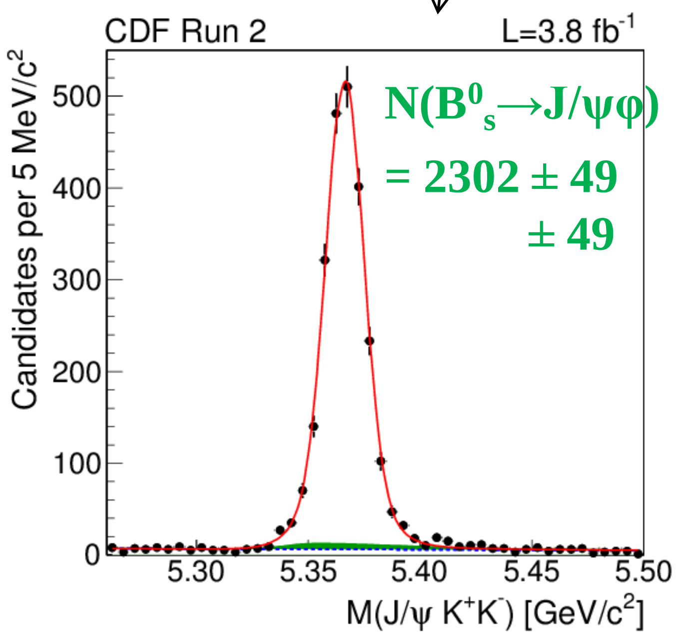


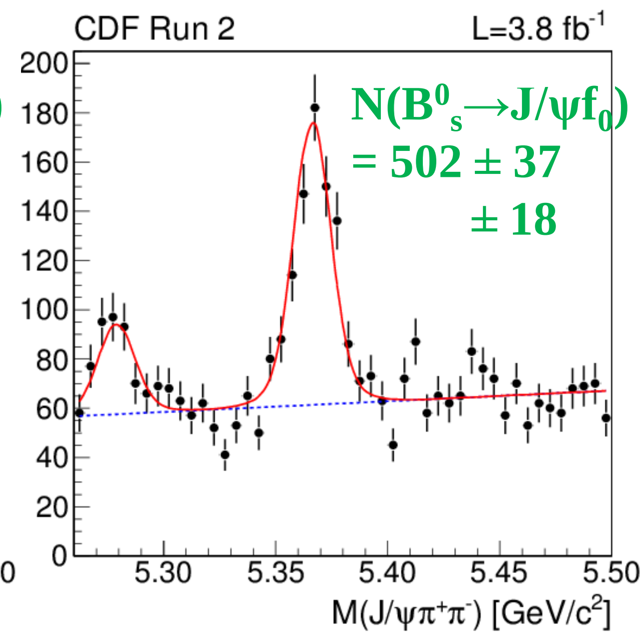
U.M.L. fits to mass distributions to extract signal size

Relative reconstruction efficiency extracted from simulation:

$$\varepsilon_{rel} = \frac{\varepsilon(B^0_s \to J/\psi\varphi)}{\varepsilon(B^0_s \to J/\psi f_0)}$$

$$= 1.178 \pm 0.040$$



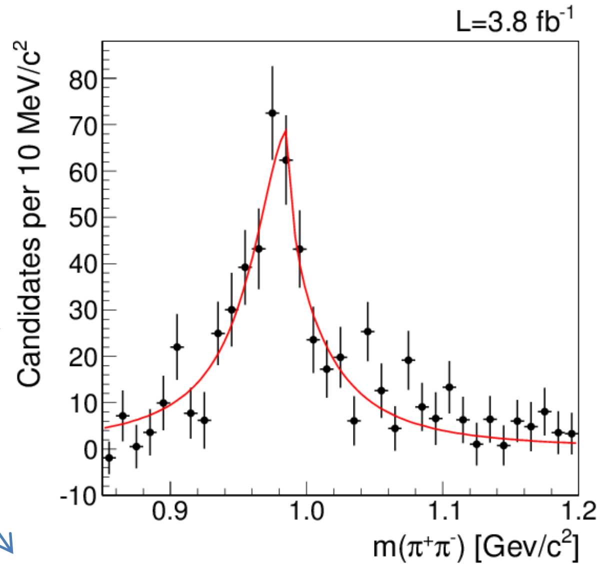


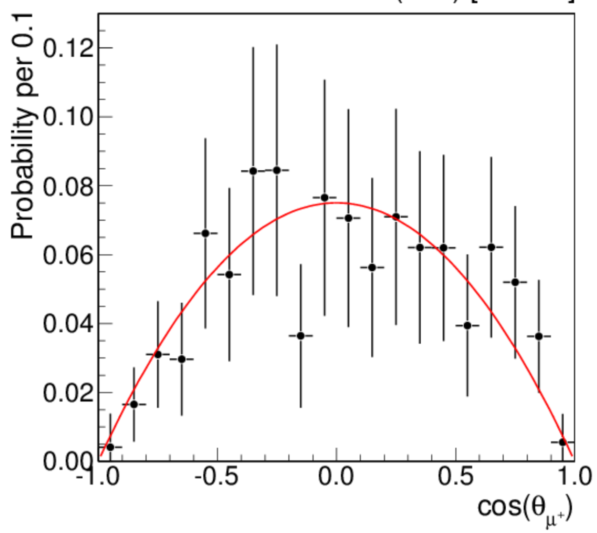
$Br[B^0_s \rightarrow J/\psi f_0(980)]$

From yields & efficiency, extract $R_{f0/\varphi} = \dfrac{\mathcal{B}(B^0_s \rightarrow J/\psi f_0)\,\mathcal{B}(f_0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B^0_s \rightarrow J/\psi\varphi)\,\mathcal{B}(\varphi \rightarrow K^+K^-)}$

$R_{f0/\varphi} = 0.257 \pm 0.020\ (\text{stat.}) \pm 0.014\ (\text{syst.})$

Plot B^0_s yield in bins of $M(\pi\pi)$, $\cos(\theta_{\mu+})$, $\cos(\theta_{\pi+})$. Results consistent with $B^0_s \rightarrow J/\psi f_0$ expectations.





Preliminary result from D0 ($8fb^{-1}$):

$R_{f0/\varphi} = 0.210 \pm 0.032\ (\text{stat.}) \pm 0.036\ (\text{syst.})$

Comparable with recent results from Belle, LHCb:

Belle: **$R_{f0/\varphi} = 0.206^{+0.055}_{-0.034}\ (\text{stat.}) \pm 0.052\ (\text{syst.})$**

LHCb: **$R_{f0/\varphi} = 0.252^{+0.046}_{-0.032}\ (\text{stat.})\ ^{+0.027}_{-0.033}\ (\text{syst.})$**

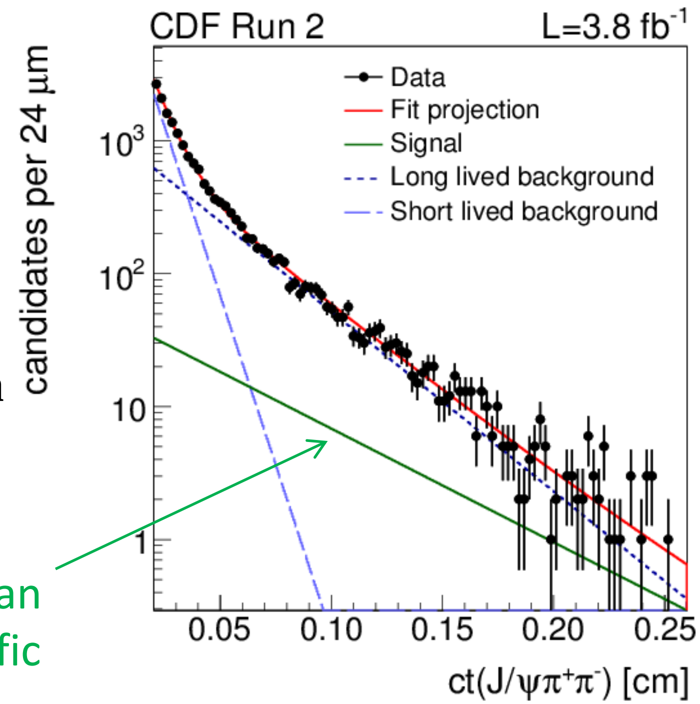
First Direct Measurement of CP-odd B^0_s Lifetime

Different NN selection:

- Remove lifetime-dependent variables;
- Add extra variables – MC/data matching not needed;
- Optimise cut value to give minimal $\sigma(\tau)$ in MC ensemble tests.

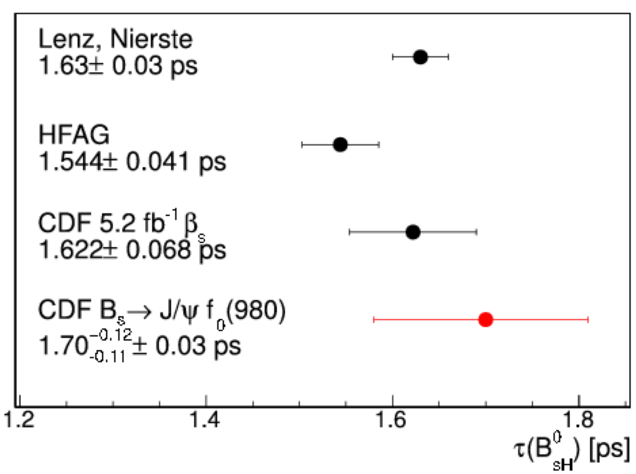
Simultaneous mass/lifetime fit in region **$c\tau(B^0_s) > 0.2$mm**

$$\tau = 1.70\,^{+0.12}_{-0.11}\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

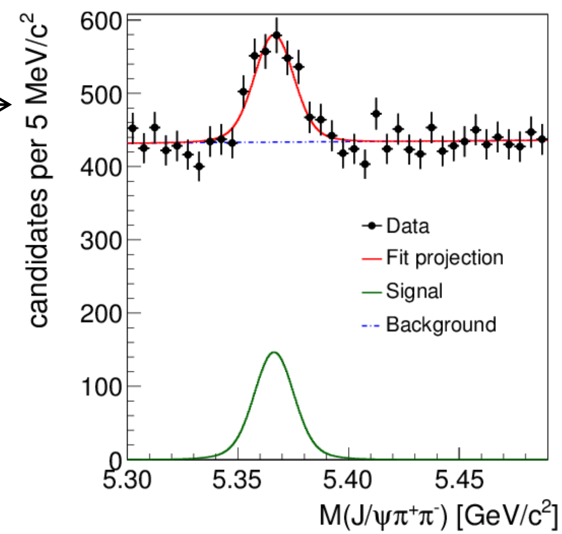


Exponential ⊗ Gaussian (with candidate-specific width)

Results Consistent with WA and SM

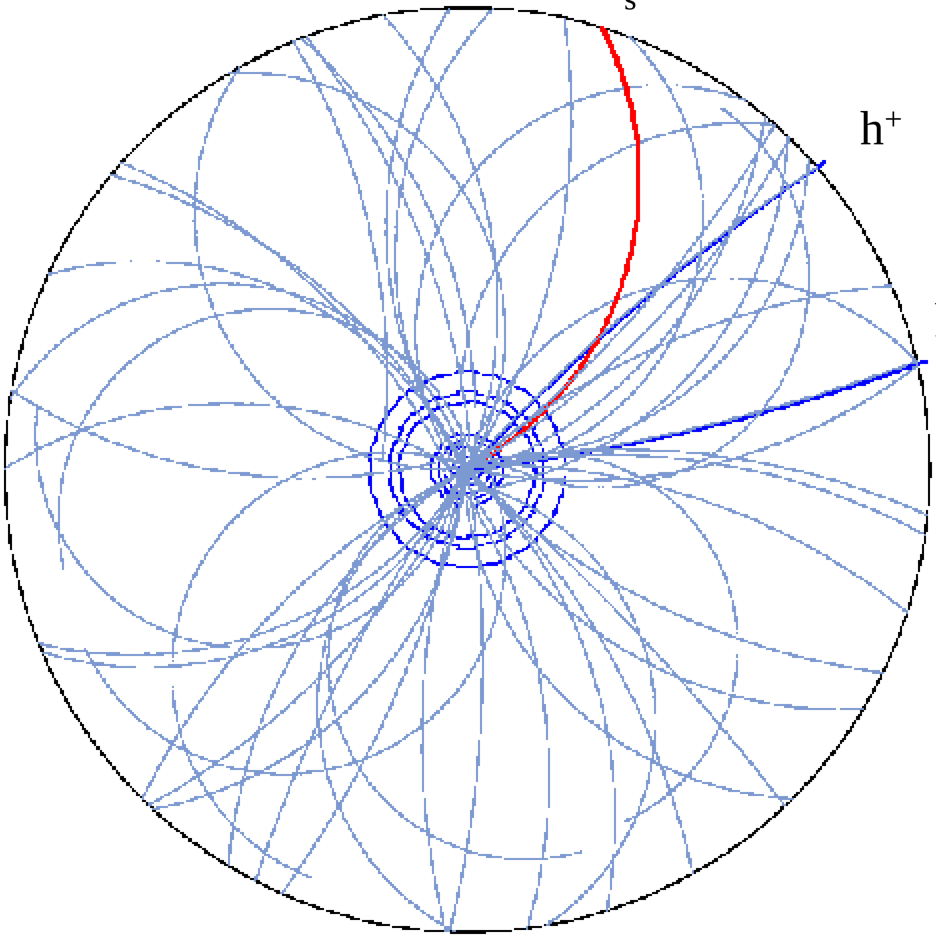


Dominated by combinatorial BG



Thorough study of systematics/biases, but statistically limited.

Part II:
CPV and Rare-Decays to Hadronic States



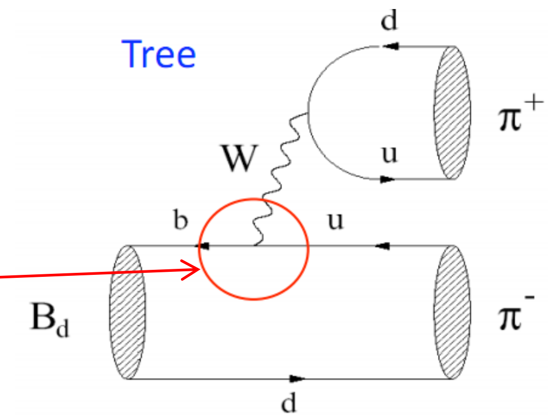
$D^* \rightarrow \pi D^0$ (CDF)

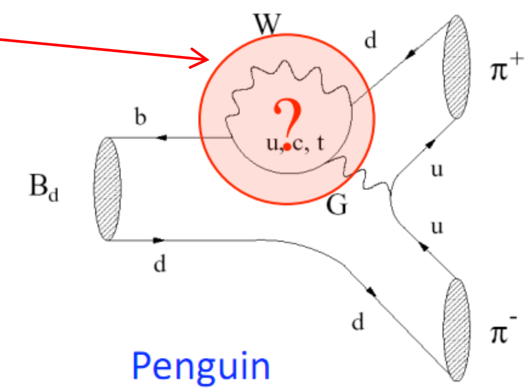
Charmless Decays $B \rightarrow h^+h'^-$

B decays into charmless pseudoscalar mesons provide important constraints on SM

Rare decays through **b→u** transition:

- Sensitive to CKM angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$
- Constrain strength of penguin-annihilation amplitudes
- Sensitive to NP contributions





$B^0_s \rightarrow K^+K^-$, $B^0_s \rightarrow K^-\pi^+$ already observed (CDF, 1fb^{-1})

$B^0_s \rightarrow \pi^-\pi^+$ and $B^0_d \rightarrow K^+K^-$ remain to be seen.

Neither initial-state quark remains – only possible via annihilation

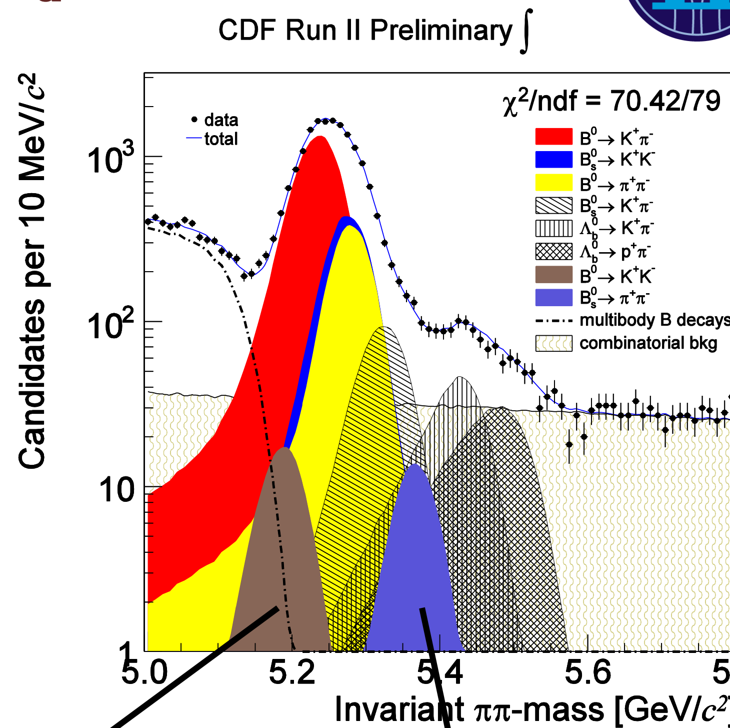
BR measurements important tests of hadronic parameters

CDF Public Note 10498 (6fb^{-1})

Search for $B^0_s \to \pi^-\pi^+$ and $B^0_d \to K^+K^-$

- Cut-based event selection to select 2-track vertex;
- Multivariate likelihood fit to extract sample composition using kinematic and PID variables:

$$m^2_{\pi\pi}, \quad \beta = (p^+ - p^-)/(p^+ + p^-), \quad p_{tot} = p^1 + p^2; \quad dE/dx$$



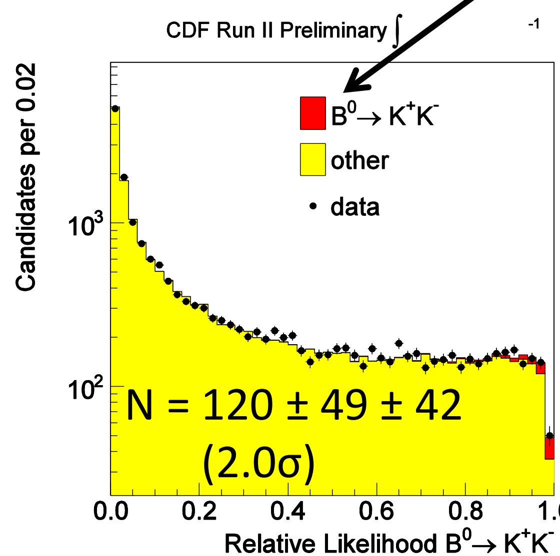
First evidence for $B^0_s \to \pi^-\pi^+$ (3.7σ);

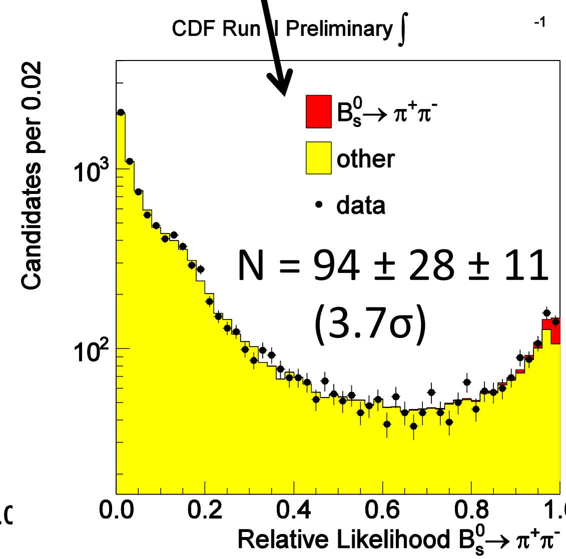
No significant signal for $B^0_d \to K^+K^-$ (2.0σ).

Use reference process $B^0 \to K^+\pi^-$ to determine BR:

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

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





CP Asymmetries in B→Dh Decays

Complementary probe of CKM angle γ in *tree-level* processes. Use "**ADS**" technique[1]:

Two decays of interest (+ c.c):

$B^- \to K^- D^0(\to \mathbf{K^-\pi^+})_{CF}$ *Cabibbo/color favored (CF)*

$B^- \to K^- D^0(\to \mathbf{K^+\pi^-})_{DCS}$ *Cabibbo/color suppressed (DCS)*

Also search for equivalent decays $B^- \to \pi^- D^0$

BR relations sensitive to γ:

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

$$A_{ADS} = \frac{\mathcal{BR}(B^- \to [K^+\pi^-]_{D^0}K^-) - \mathcal{BR}(B^+ \to [K^-\pi^+]_{D^0}K^+)}{\mathcal{BR}(B^- \to [K^+\pi^-]_{D^0}K^-) + \mathcal{BR}(B^+ \to [K^-\pi^+]_{D^0}K^+)} = C\sin(\gamma) / R_{ADS}$$

Powerful technique, but very rare process.

Take advantage of displaced-track trigger, fine mass resolution, PID to reconstruct and separate signal from BG.

[1]: Atwood, Dunietz, Soni (PRL78, 3257)

New CDF results, April 2011 ($7 fb^{-1}$)

CP Asymmetries in B→Dh Decays

Optimize cuts on CF process, and then apply to search for DCS channel;

UML Fit over 3-track invariant mass and PID variable “kaonness”:

1) Use CF sample to constrain shapes of signal and backgrounds.

2) Simultaneous fit of CF and DCS samples to reconstruct pion and kaon channels;

Use simulation to model influence of different flight-lengths of K^+ vs K^- (2% effect).

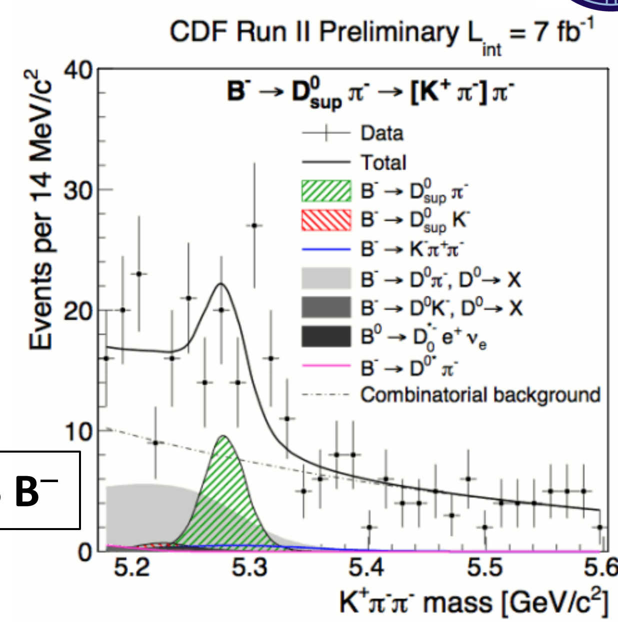
$R_{ADS}(\pi) = [2.8 \pm 0.7 \pm 0.4] \times 10^{-3}$

$R_{ADS}(K) = [22.1 \pm 8.6 \pm 2.6] \times 10^{-3}$

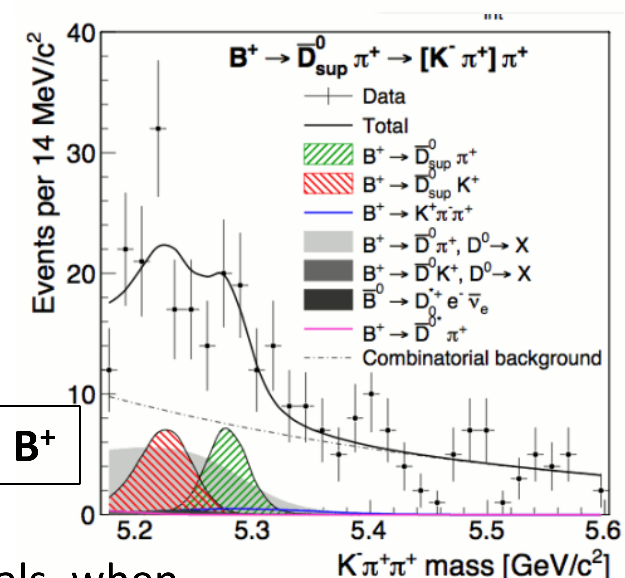
$A_{ADS}(\pi) = 0.15 \pm 0.25 \pm 0.01$

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

DCS B^-

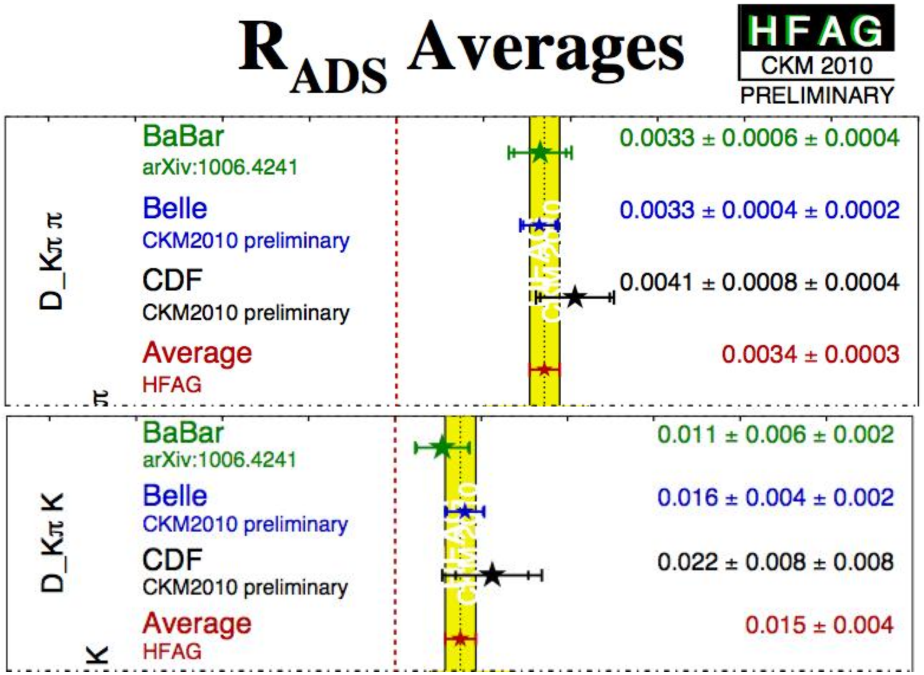


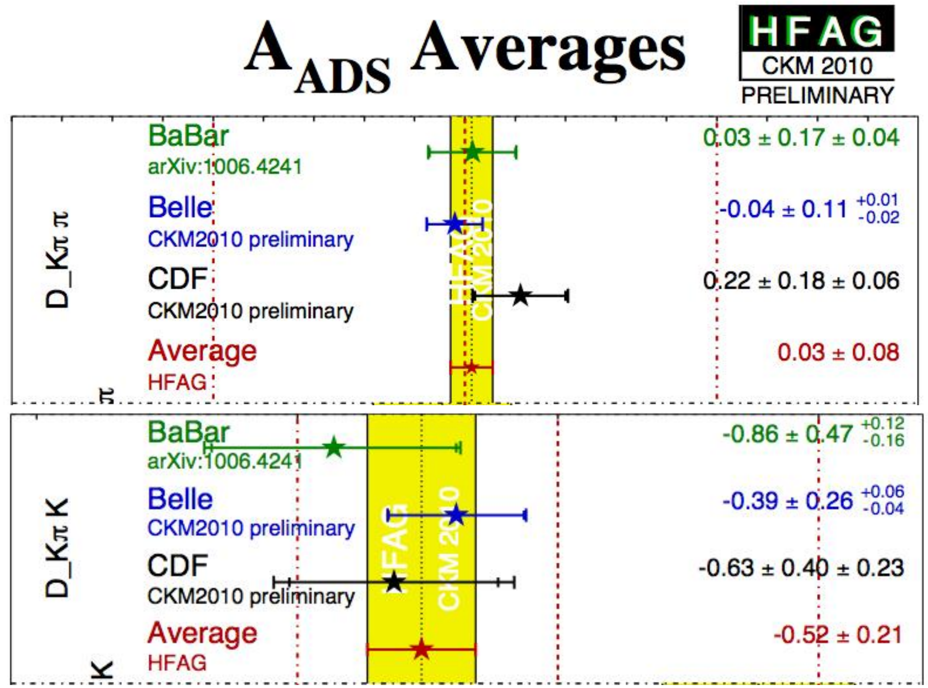
DCS B^+



>5σ significance for DCS signals, when combining kaon and pion channels.

CP Asymmetries in B→Dh Decays





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

$R_{ADS}(K) = [22.1 \pm 8.6 \pm 2.6] \text{ x } 10^{-3}$

$A_{ADS}(\pi) = 0.15 \pm 0.25 \pm 0.01$

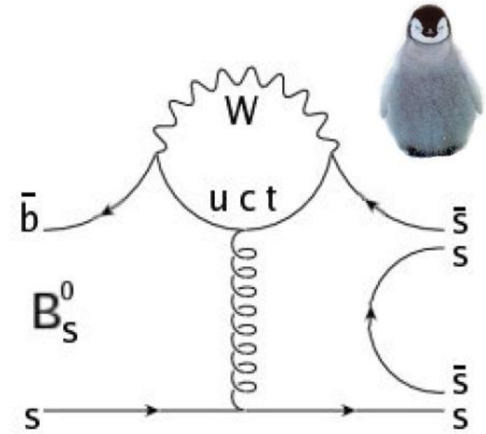
$A_{ADS}(K) = -0.82 \pm 0.44 \pm 0.09$

First such measurement in hadron collisions

Consistent with B factory measurements.

Can combine with other inputs to improve measurement of γ.

Triple-Product Asymmetries in $B^0_s \to \varphi\varphi$



Penguin-mediated process to two vector mesons.

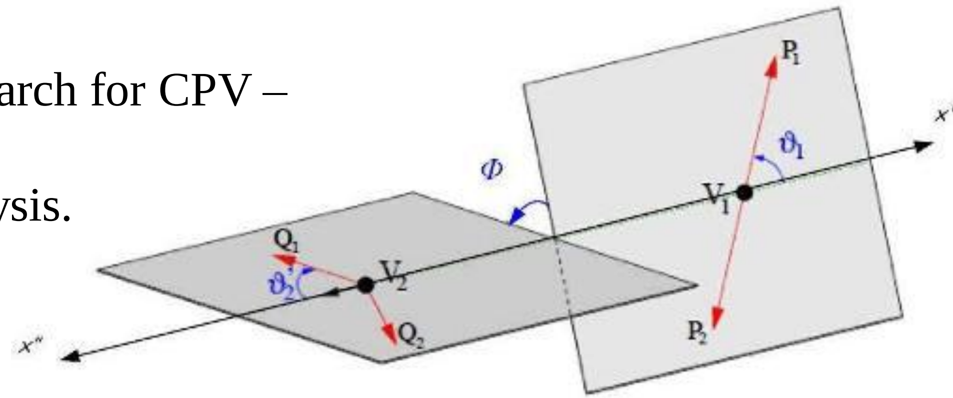
Similar to $J/\psi\varphi$ channel – mix of CP-odd and CP-even states, but… **sample too small for full angular analysis**.

Earlier CDF measured transverse polarized fraction:

$$\mathbf{f_T = (65.2 \pm 4.1 \pm 2.1)\%}$$

disagrees with naïve SM expectation.

Use **Triple-product asymmetries (A_{TP})** to search for CPV – these are small in the SM, enhanced by NP.
No need to tag B^0_s flavor, or full angular analysis.



A_{TP} accessed via angular quantities:

$$\boldsymbol{u = \cos\Phi\sin\Phi}$$

$$\boldsymbol{v = \begin{cases} \sin(\Phi) & \text{if } \cos\theta_1\cos\theta_2 > 0 \\ \sin(-\Phi) & \text{if } \cos\theta_1\cos\theta_2 < 0 \end{cases}}$$

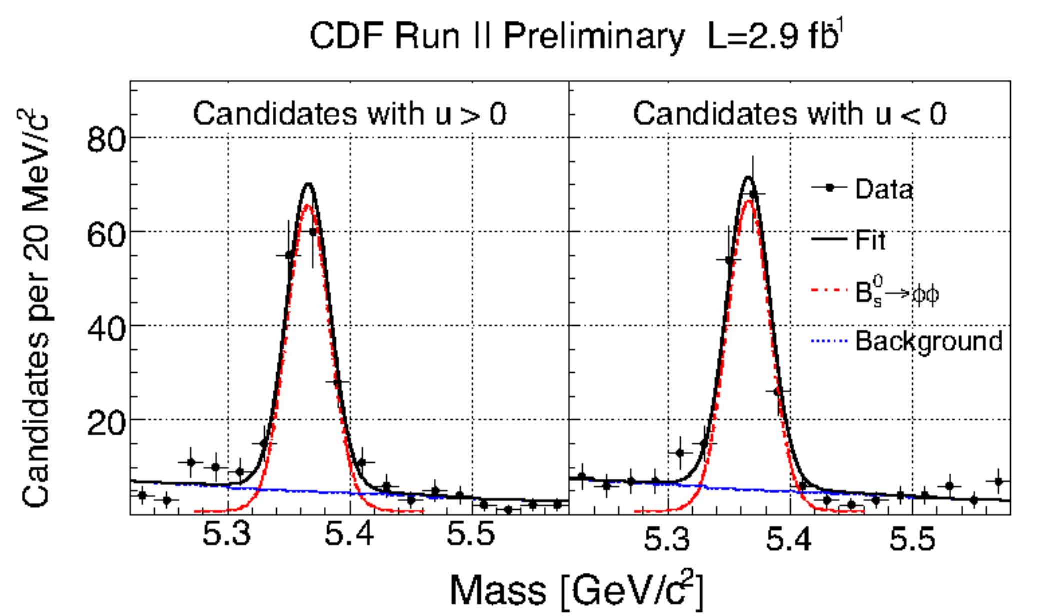
CDF Public Note 10424
CDF Public Note 10120
(2.9fb^{-1})

Triple-Product Asymmetries in $B^0_s \to \varphi\varphi$

Simultaneous fit of M(φφ) for positive and negative signs of *u* (and *v*);

Include constraint $(N^+ + N^-) = N_{tot}$;

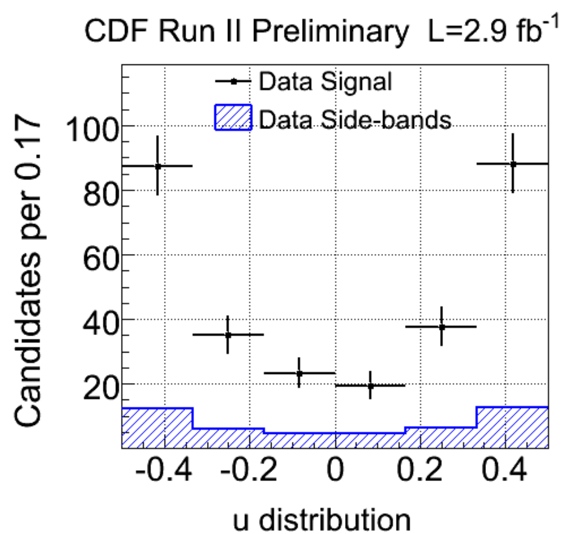
Use combinatorial BG to constrain background asymmetries.

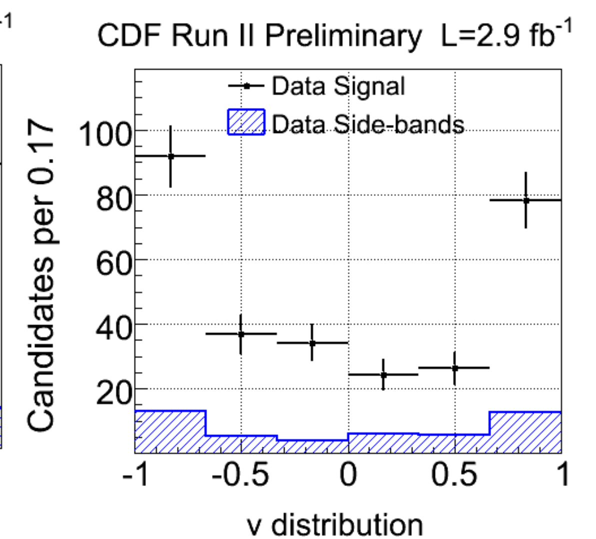


Asymmetries defined in usual way:

$$A_u = -0.007 \pm 0.064 \pm 0.018$$

$$A_v = -0.120 \pm 0.064 \pm 0.016$$





First constraints to TP asymmetries in this channel.

CVP in Charm Decays $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$

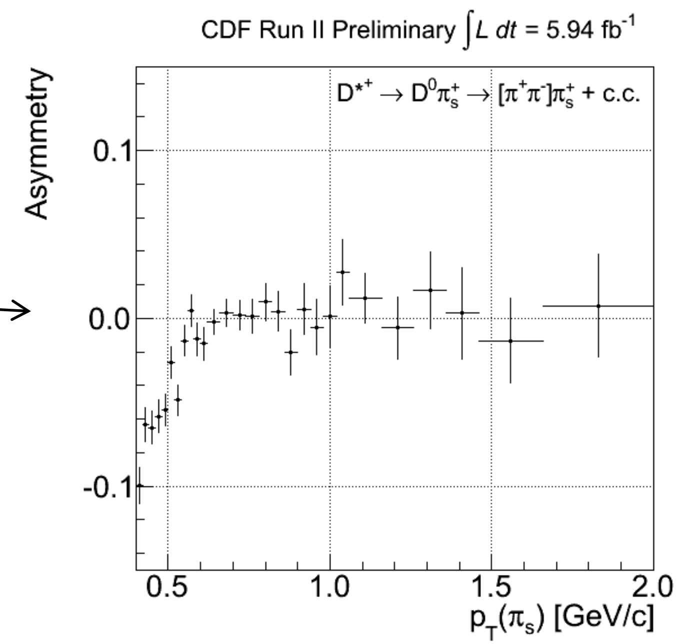
CDF measure time-integrated asymmetries in Cabibbo suppressed mode:

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

Contributions from both direct and mixing-induced CPV

Reconstruct parent $D^{*\pm}$ to tag initial D^0 flavor (i.e. look for soft pion π_s from decay)

Asymmetry dominated by detector effects of a few percent (kaon decay, asymmetric tracker)



Use reference channels with huge statistics to constrain these contributions ($D^0 \to K\pi$):

$N(D^0 \to \pi\pi) = 215{,}000$ (with D* tag)
$N(D^0 \to KK) = 476{,}000$ `` ``
} signal

$N(D^0 \to \pi K) = \sim 5M$ `` ``
$N(D^0 \to \pi K) = \sim 29M$ (no D* tag)
} reference

CDF Public Note 10296 (5.9fb^{-1})

CVP in Charm Decays $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$

Binned fit to $D^0\pi_s$ mass distributions, separately for π^+_s and π^-_s

Fit results give raw asymmetries, e.g.

$A_{CP}(K\pi)^{notag} = (-0.83 \pm 0.03)\ \%$

Combine to cancel detector effects, yielding:

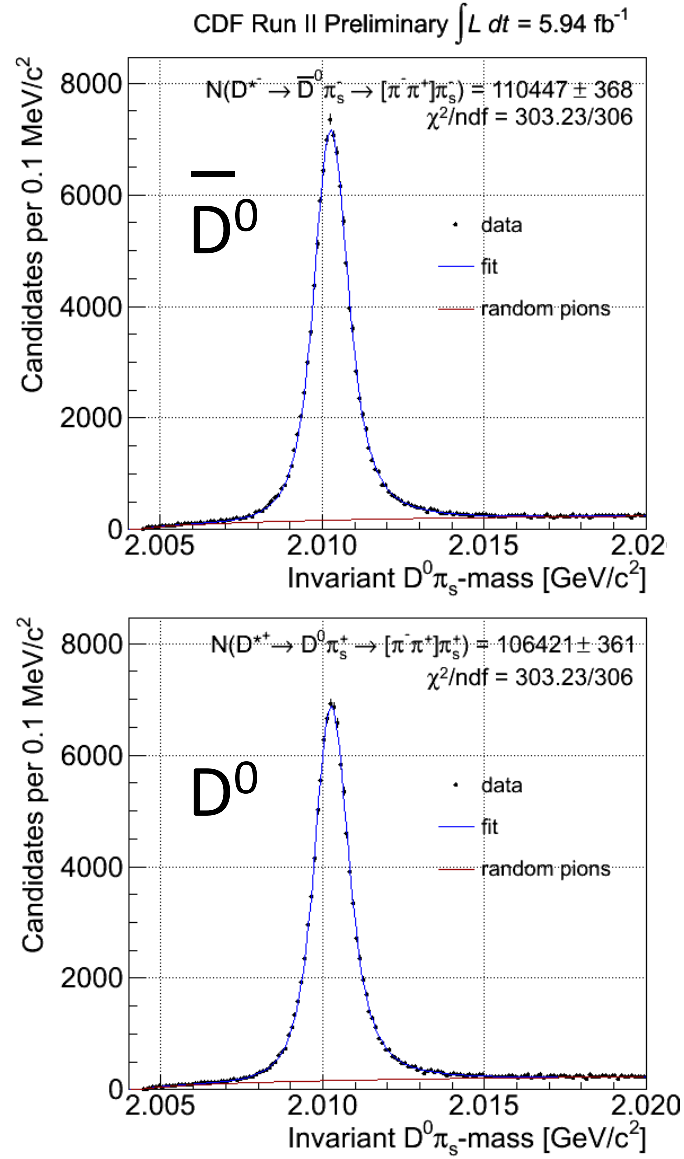
$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm 0.24 \pm 0.11)\ \%$

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

Consistent with SM predictions (and with no CPV).

Transitions between first 2 generations have real CKM parameters – any asymmetry must be from NP.

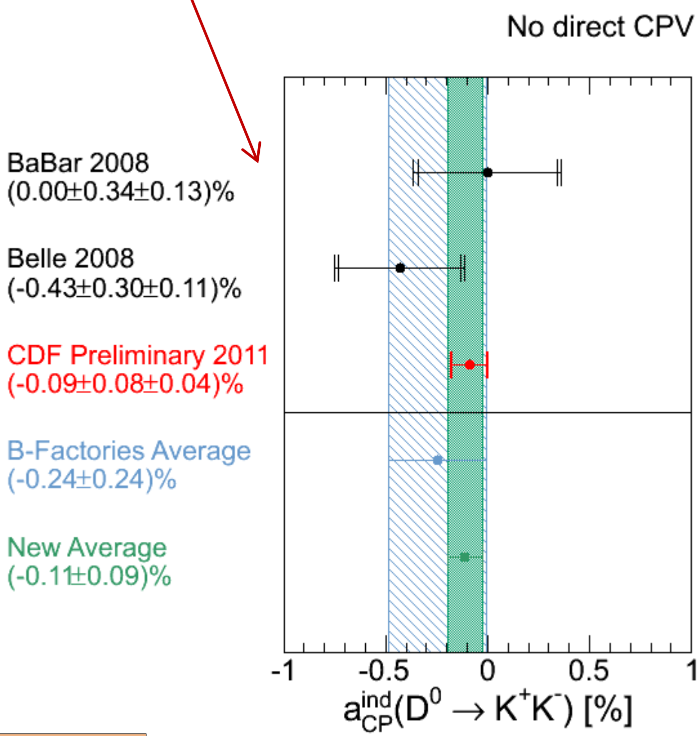
Relies on assumption that $p\bar{p}$ strong interactions are charge symmetric.

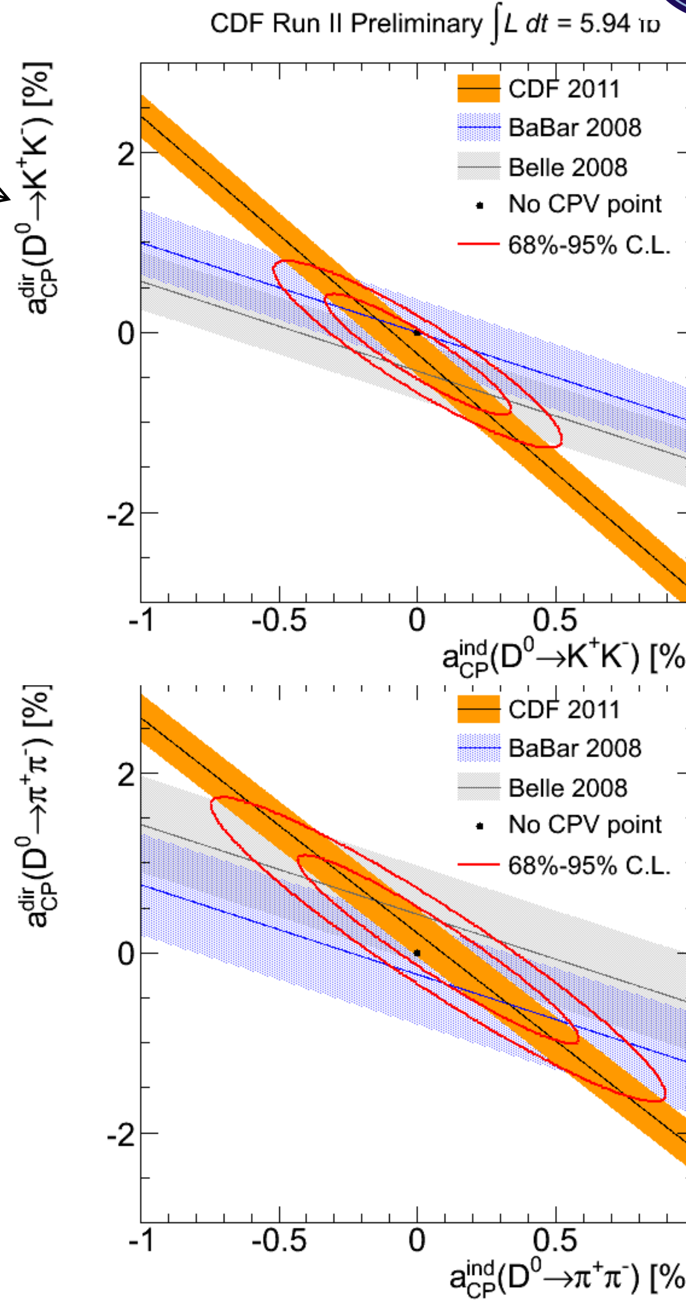


CVP in Charm Decays $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$

Measurement constrains bands in (a_{dir}, a_{mix}) consistent with B-factories.

Assuming no direct charm CPV, the indirect CPV can be constrained to world's best limits:





Conclusions

- CPV is a hot topic at hadron colliders!

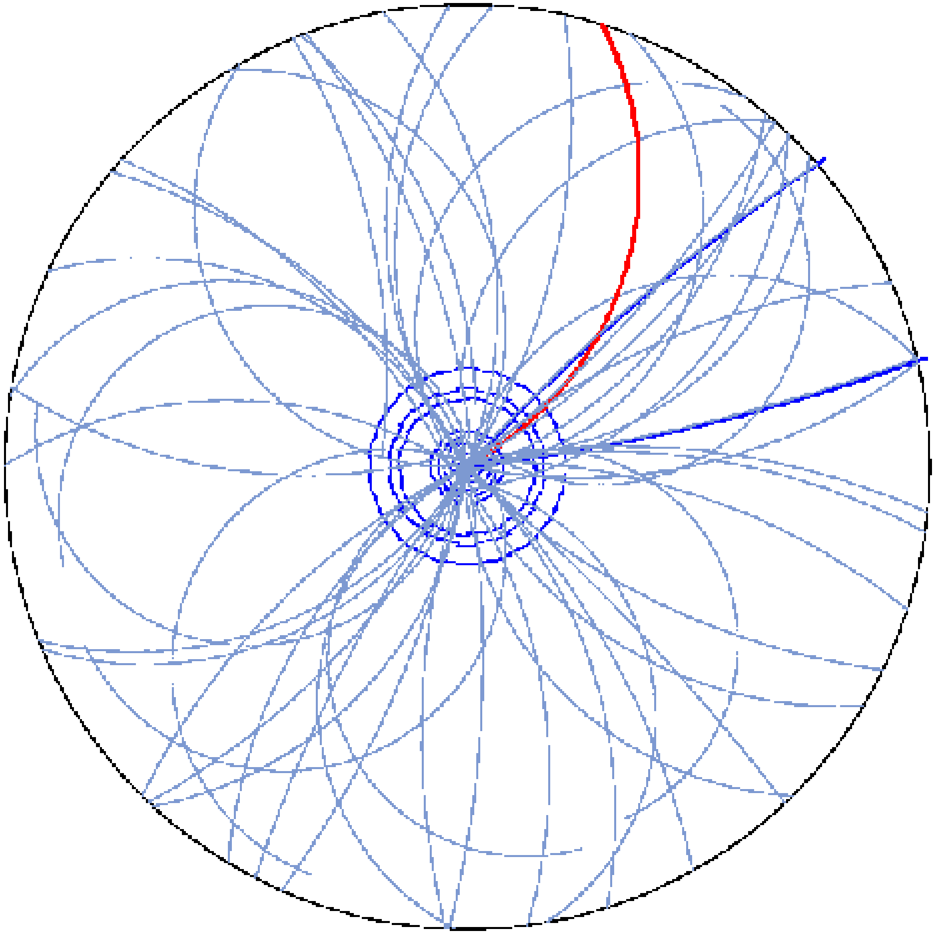
- We continue to **challenge the Standard Model**, probing quantities which are sensitive to New Physics.

- **Innovative techniques** in constant development: event selection, data-driven methods, “ADS” and Triple-product asymmetries, correlated backgrounds…

- **Dimuon asymmetry** a tantalizing possibility for BSM physics
    - D0 already planning next update with more use of IP information
    - Need independent confirmation from other experiments.

- **Tevatron legacy** will strongly influence the LHC experiments, it’s *almost* time to pass the baton, but not yet.

Extra Material



Dimuon Asymmetry: Comparison with Previous Result

Previous D0 measurement
PRD 82, 032001 (2010) ($6.1 fb^{-1}$)

A^b_{sl} = [-0.957 ± 0.251 (stat.) ± 0.146 (syst.)] %

3.2σ

First $6.1 fb^{-1}$, new technique:

A^b_{sl} = [-0.891 ± 0.204 (stat.) ± 0.128 (syst.)] %

3.6σ

Final $2.9 fb^{-1}$, new technique:

A^b_{sl} = [-0.600 ± 0.335 (stat.) ± 0.188 (syst.)] %

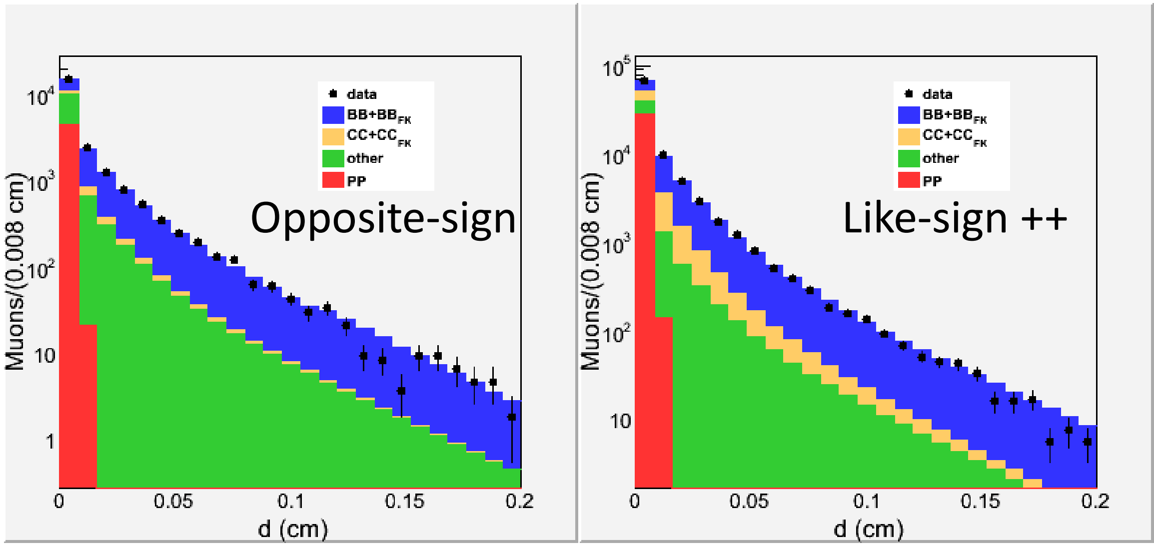
1.6σ

So what's new?

- Event selection optimized:
  - Looser minimum $|p_z|$ cut (6.4→5.4 GeV) based on new study of detector thickness;
  - Tighter match required between muon track and central track – reduces BG contribution from D.I.F.;
- New method to extract ratio of kaon fractions in two samples $\mathbf{R_k = F_k/f_k}$: eliminates dependence on mass resolution, and better quantifies correlations.
- Second, independent channel used to measure $\mathbf{R_k}$: consistent results found.

Integrated Mixing Probability χ_0

$$\chi_0 = \frac{\Gamma(B^0 \to \bar{B}^0 \to l^+ X)}{\Gamma(B \to l^{\pm} X)}$$



Important input for dimuon asymmetry interpretation;

Fit IP distributions of dimuons (+−, ++, − −) to extract heavy-flavor fraction in muon sample;

Mixing probability directly related to raw asymmetry, R:

$$R = \frac{N(b\bar{b} \to \mu^{\pm}\mu^{\pm})}{N(b\bar{b} \to \mu^{\pm}\mu^{\mp})}$$

Like-sign dimuons

Opposite-sign dimuons

R = 0.467 ± 0.008 ± 0.007
⇒ χ = 0.126 ± 0.008

(LEP: χ = 0.1259 ± 0.0042)

CDF Public Note 10335 (1.44fb^{-1})

Current $B^0_s \to \mu\mu$ Limits

Rare decay very sensitive to BSM enhancements;

Significant analysis improvements over the Tevatron era:

- Multivariate analysis;
- Background understanding;

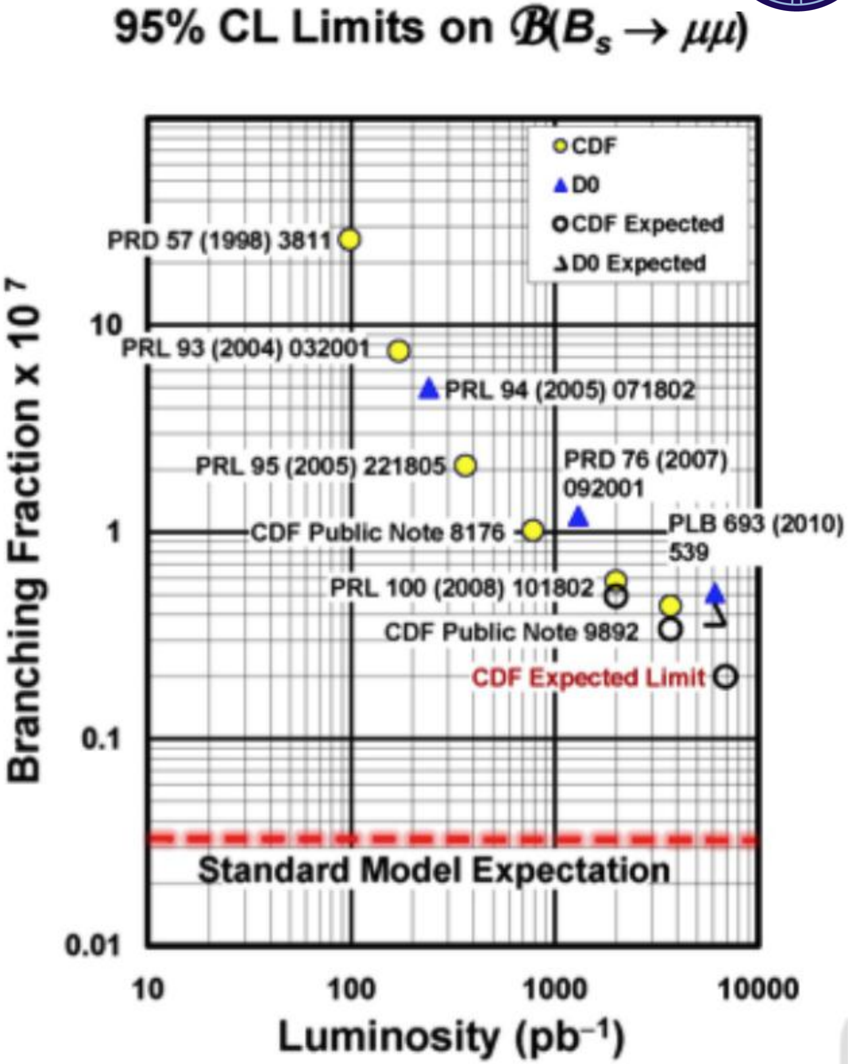
Still limited by very low expected number of events.

CDF: World's best limits (3.7fb^{-1})

$\mathcal{B}(B^0_s \to \mu\mu) < 4.3 \times 10^{-8}$ @ 95%

D0: (6.1fb^{-1})

$\mathcal{B}(B^0_s \to \mu\mu) < 5.1 \times 10^{-8}$ @ 95%



New results on their way…