Searches for New Physics in Heavy Flavor Decays at CDF

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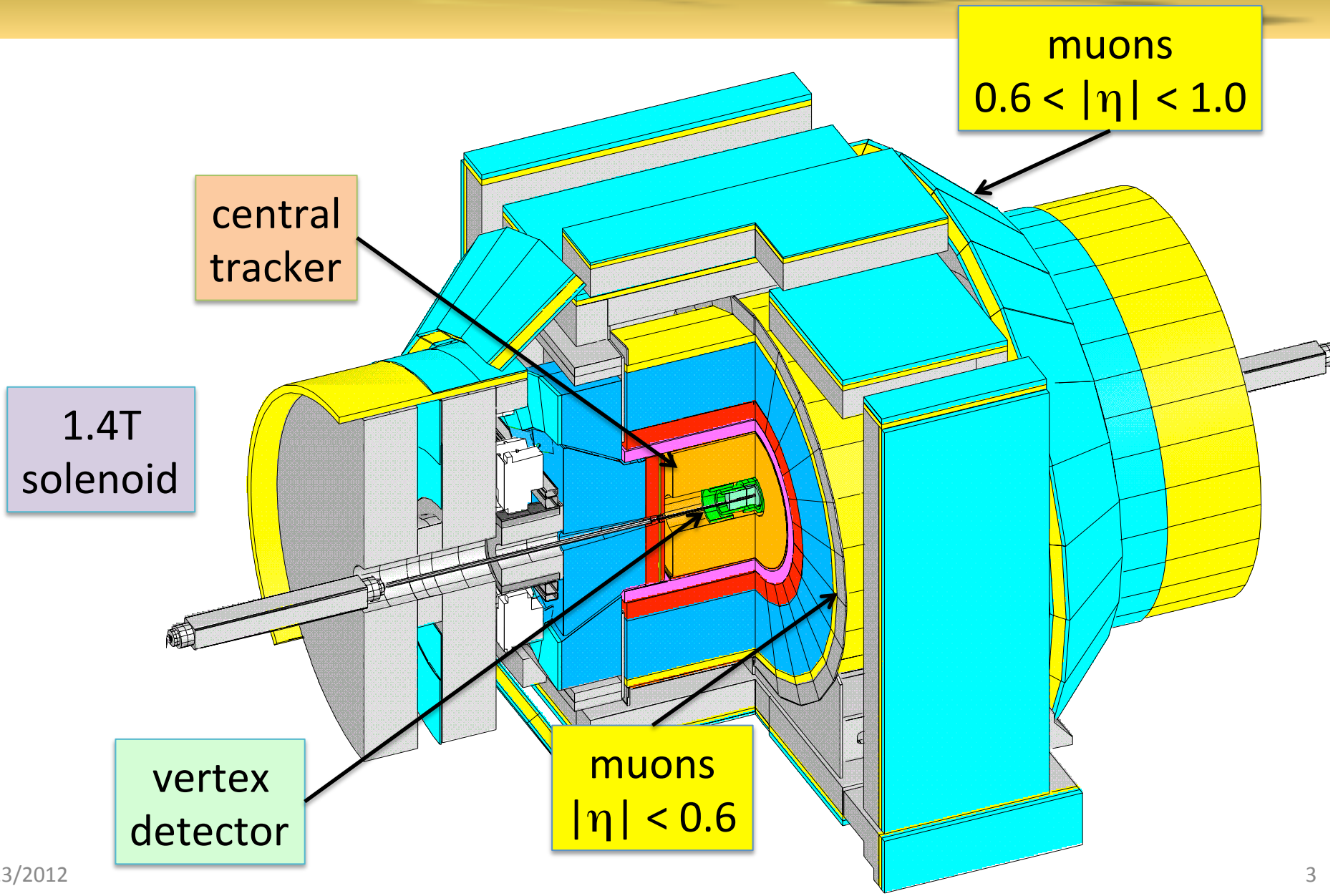
Outline

- The CDF detector
- CP violation in $B_s \rightarrow J/\psi\ \phi$
- Search for $B_{(s)} \rightarrow \mu\mu$
- $b \rightarrow s\mu\mu$
- $B \rightarrow hh$ CP asymmetries
- $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ CP asymmetries
- Summary

All results use the full Run 2 dataset.

The CDF Detector

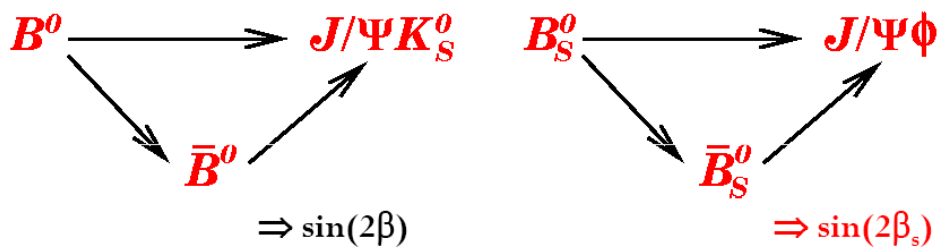


Heavy Flavor Triggers

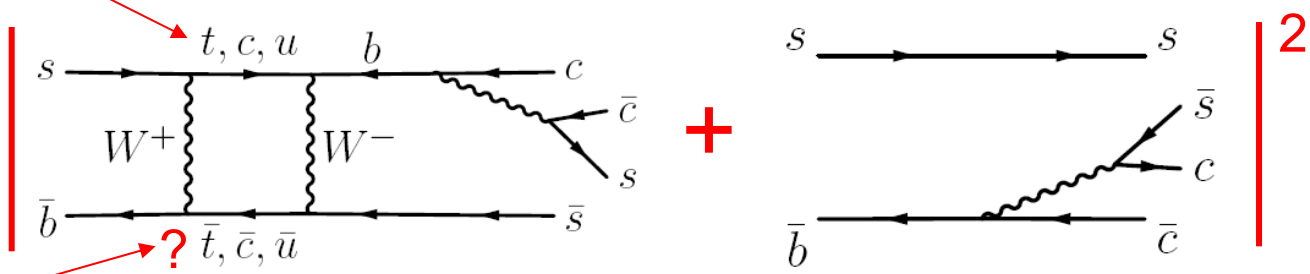
- dimuon trigger
  - for decays with $J/\psi \rightarrow \mu\mu$, and rare decays to dimuons
  - muon $p_T > 1.5$ GeV/c, $|\eta| < 1.0$
- displaced vertex trigger
  - for hadronic charm and bottom decays
  - 2 tracks, opposite charge, $p_T > 2.0$ GeV/c
  - impact parameters $100\mu m < d < 1000\mu m$

CP Violation in $B_s \rightarrow J/\psi\ \phi$ Decays

dominant contribution from top quark



Decay rate ~



New Physics particles ?

$$\beta_s^{\rm SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

SM predicts tiny CP violation in B_s mixing.

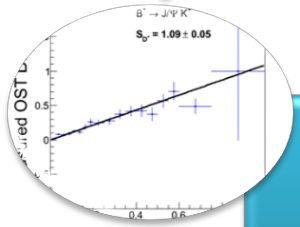
New physics can be the dominant effect.

Analysis at a Glance

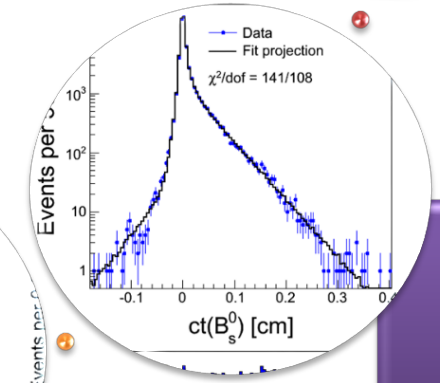
Very complex likelihood fit, 11 physical parameter 35 nuisance:
use mass, angles, decay-time and production flavor distributions

Dimuon trigger

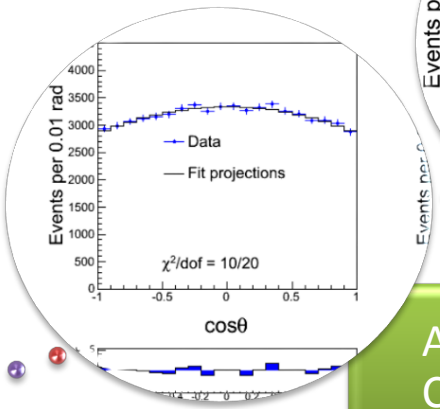
Offline selection



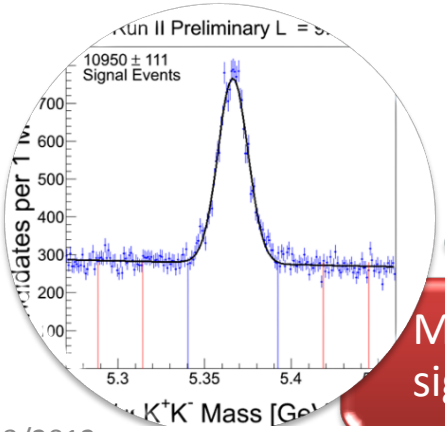
Flavor tagging to separate B from $\bar{B}$



Decay time to know time evolution



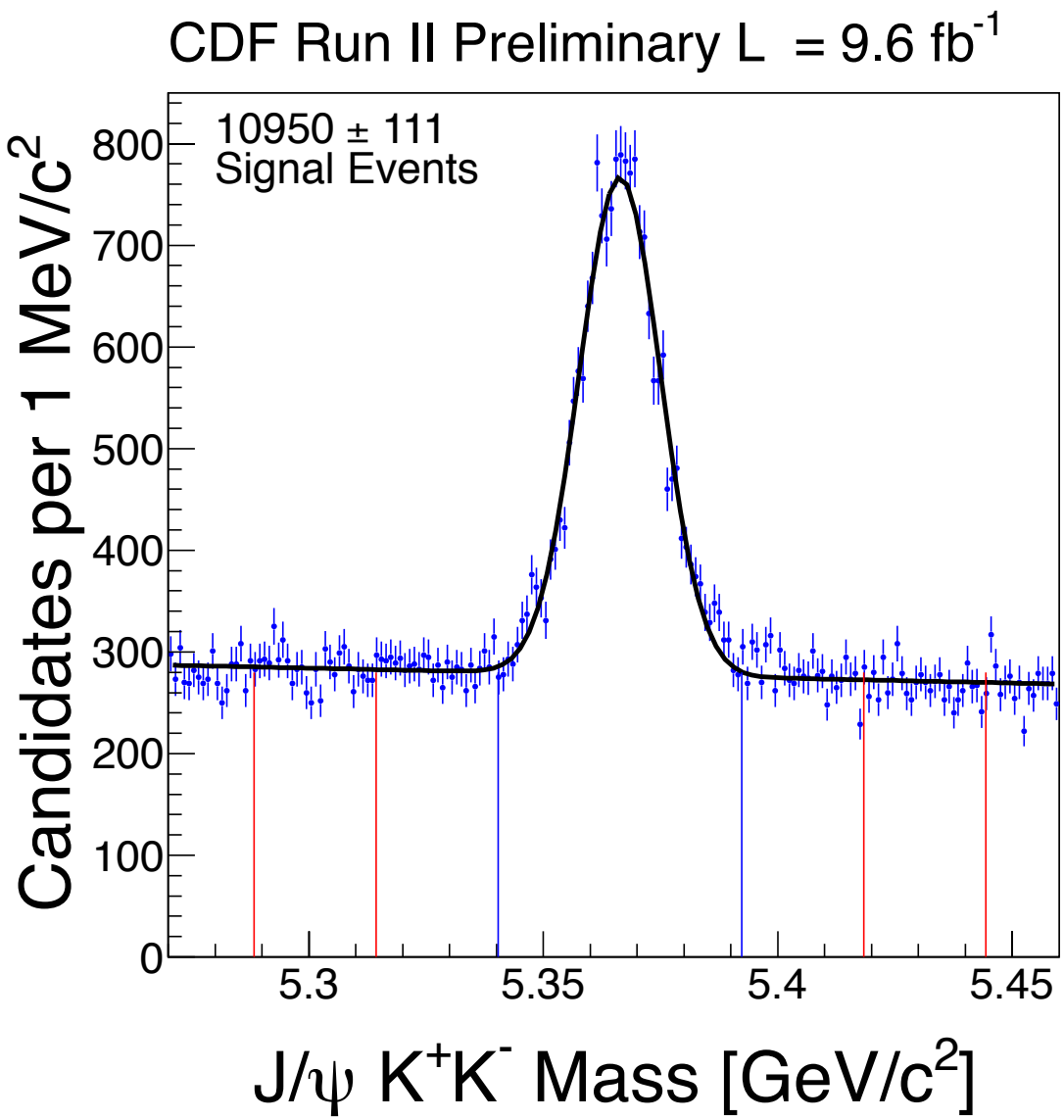
Angles to separate CP-even/odd



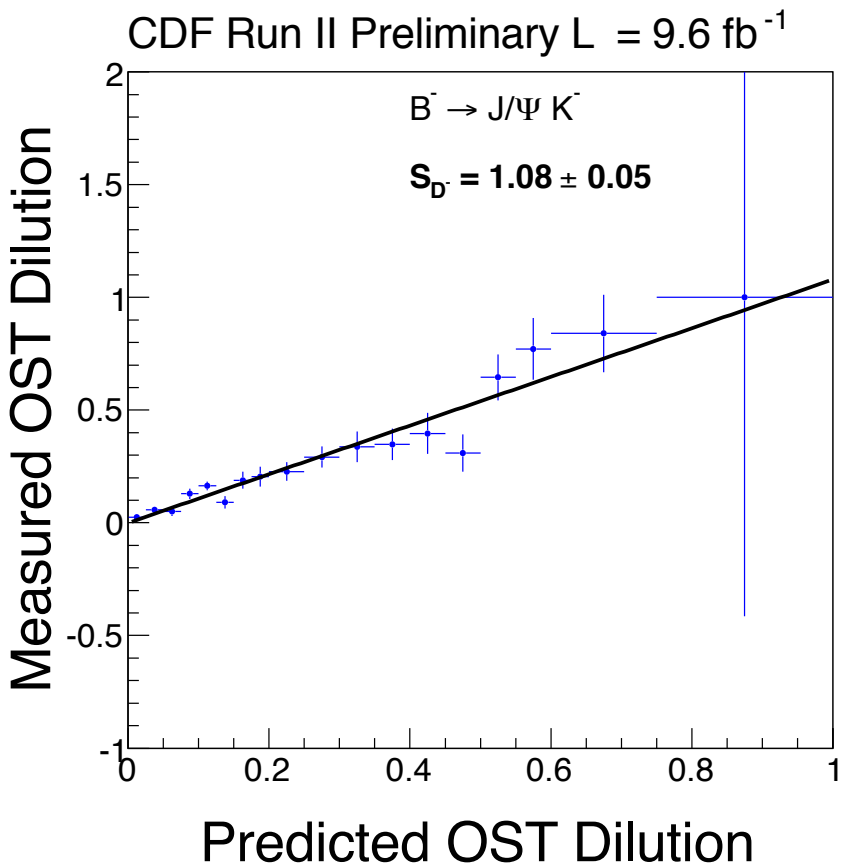
Mass to separate signal from bckg

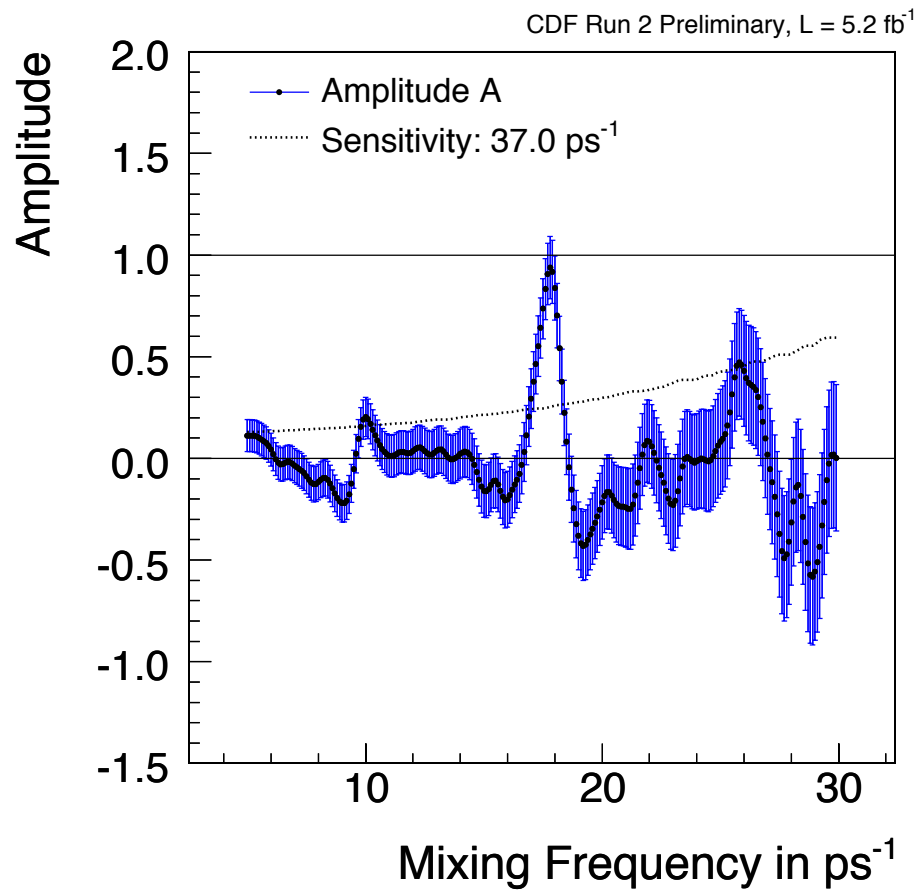
CDF Public Note 10778

Mass Projection



Tagging

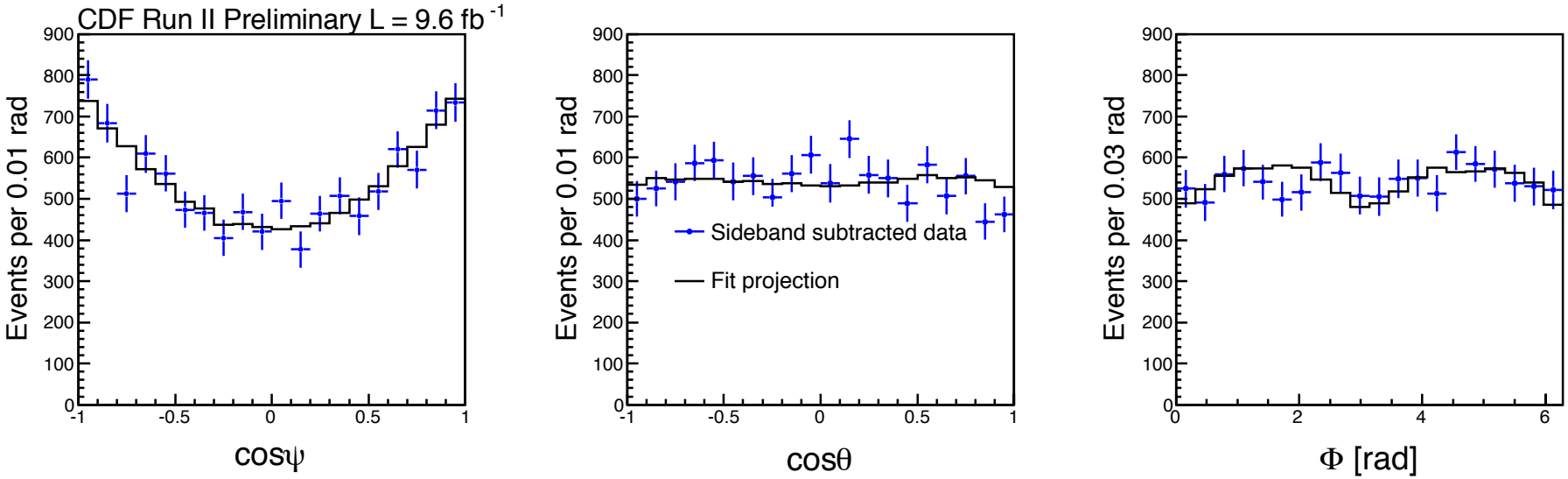




Opposite side tagging calib. for 9.6fb^{-1}

Same side kaon tagging calib for 5.2fb^{-1}

Angular Projections



Results:

$\tau_s = 1.528 \pm 0.019$ (stat) ± 0.009 (syst) ps

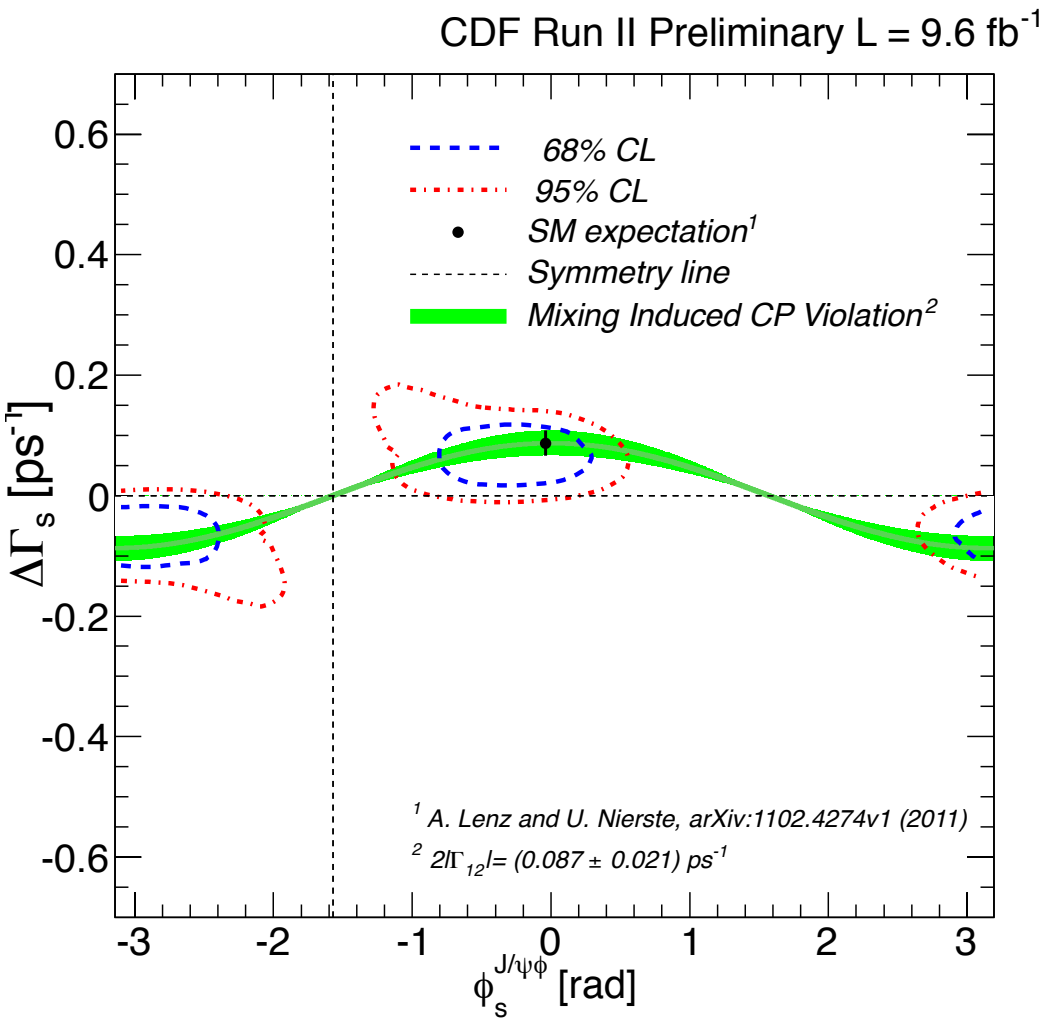
$\Delta\Gamma_s = 0.068 \pm 0.026$ (stat) ± 0.007 (syst) ps^{-1}

$|A_0(0)|^2 = 0.512 \pm 0.013$ (stat) ± 0.017 (syst)

$|A_{||}(0)|^2 = 0.229 \pm 0.010$ (stat) ± 0.014 (syst)

$\delta_\perp = 2.79 \pm 0.53$ (stat) ± 0.15 (syst) rad

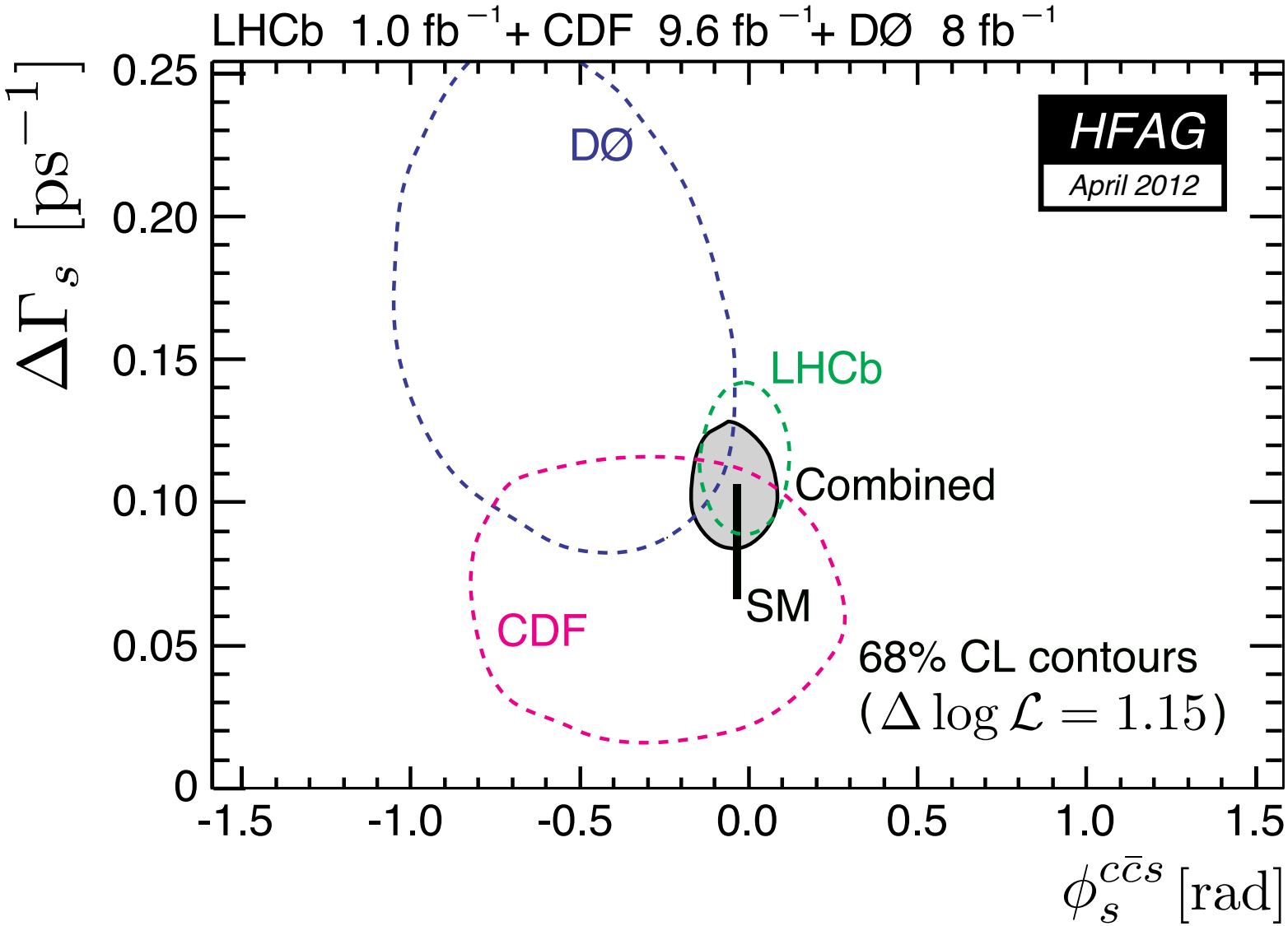
$\Delta\Gamma_s$ versus CP phase



p-value = 54%

http://www-cdf.fnal.gov/physics/new/bottom/120419.blessed-BsJpsiPhi10fb/

HFAG: $\Delta\Gamma_s$ versus CP phase



Search for $B_{(s)} \rightarrow \mu\mu$ with 9.6 fb^{-1}

- FCNC decay sensitive to NP contributing in loops.
- Predicted branching fractions are small

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

- With 7 fb^{-1} CDF observed an excess in the B_s window at the 2σ level.
- Want to see if the excess is reinforced or not.

$B_{(s)} \rightarrow \mu\mu$ Analysis Outline

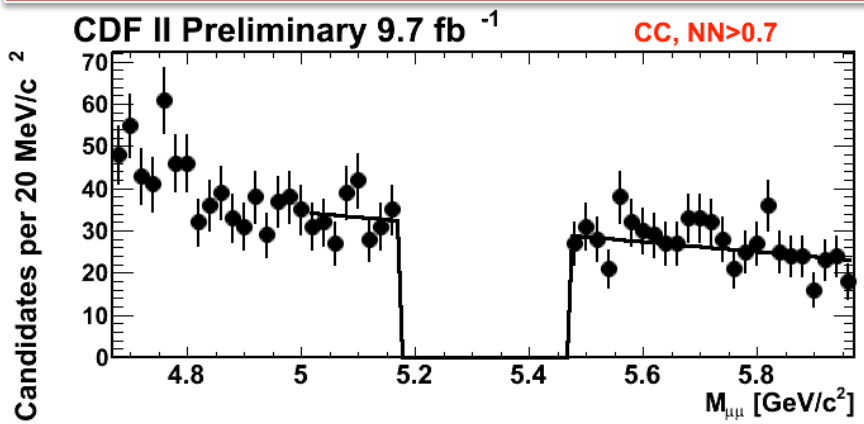
- Unbiased (blinded) analysis
- Dimuon triggered data
- Normalize to $B^+ \rightarrow J/\psi\,[\mu\mu]\,K^+$ with

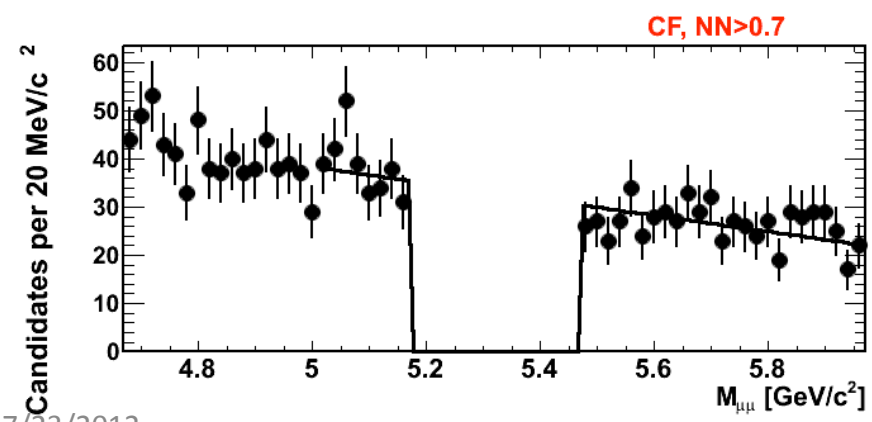
$$BR(B^0_{s(d)} \rightarrow \mu^+\mu^-) = \frac{N_{B_{s(d)}}}{N_{B^+}} \cdot \frac{\alpha_{B^+}}{\alpha_{B_{s(d)}}} \cdot \frac{\varepsilon^{total}_{B^+}}{\varepsilon^{total}_{B_{s(d)}}} \cdot \frac{1}{\varepsilon^{NN}_{B_{s(d)}}} \cdot \frac{f_u}{f_s} \cdot BR(B^+ \rightarrow J/\Psi K^+ \rightarrow \mu^+\mu^- K^+)$$

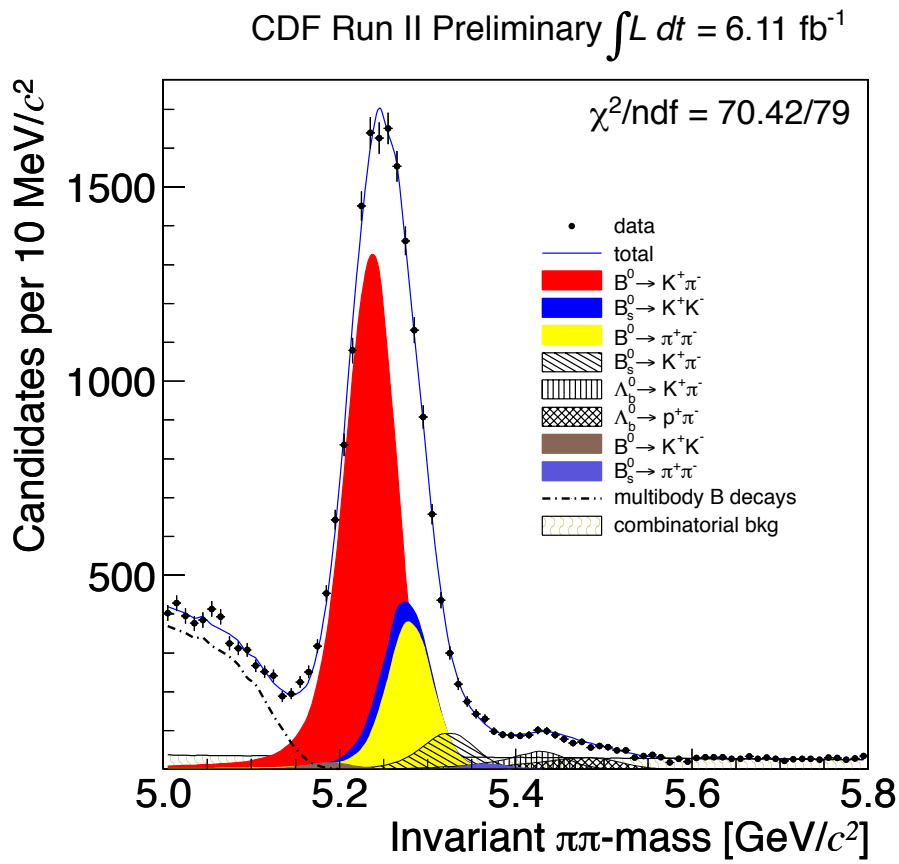
- Baseline event selection (acc. and eff.)
- Neural Net to optimize expected limit
  - Reuse NN from 7 fb^{-1} analysis without retraining
- Evaluation of backgrounds
- Unblind the signal region and evaluate

Background Estimates

Combinatoric background:
- Estimated from sidebands
- Exclude partial reconstructions

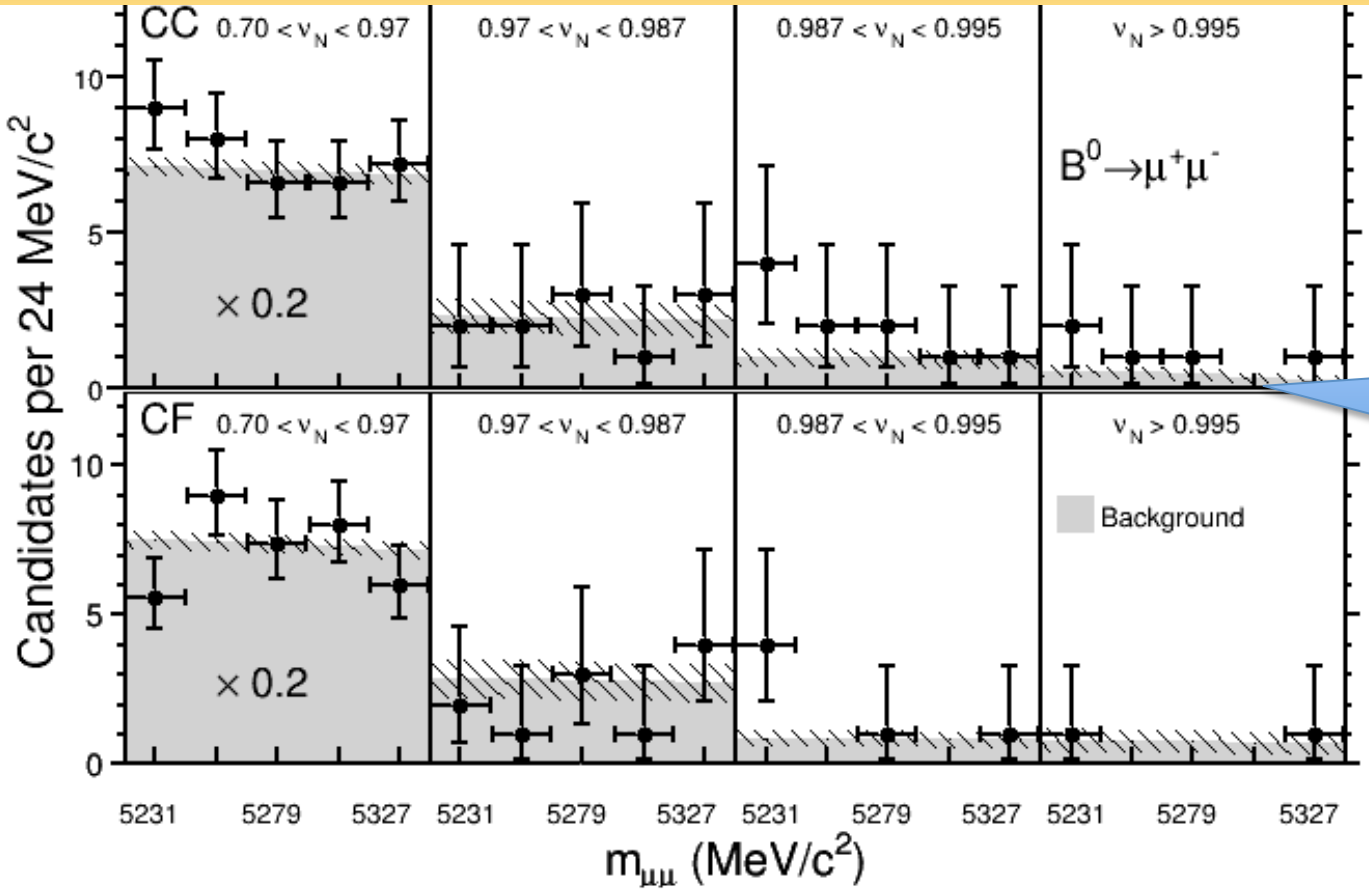






Peaking background:
- From $B \rightarrow hh'$
- MisID probs from $D^0 \rightarrow K\pi$

$B^0 \to \mu^+\mu^-$ Signal Window



CC

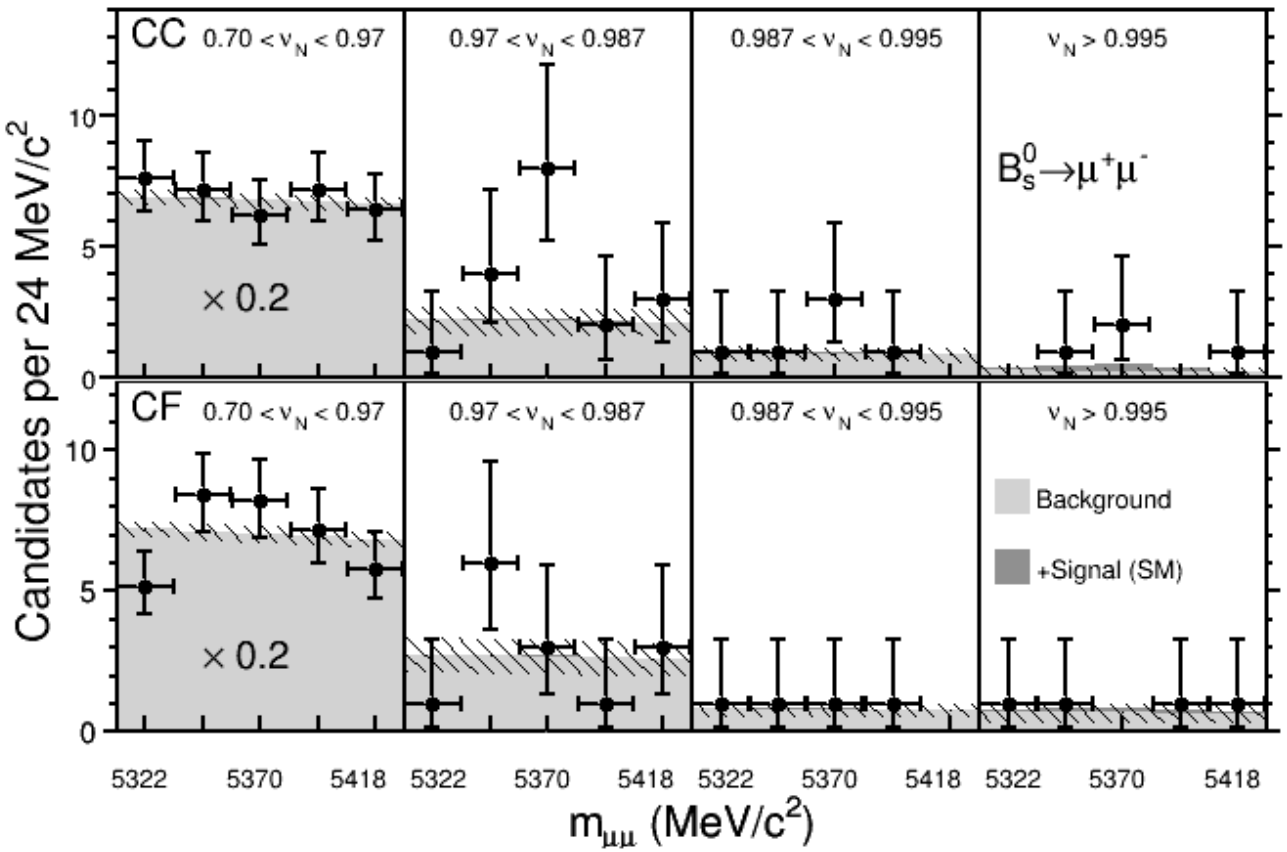
CF

Systematic uncertainty on mean background

$$\text{expected } \mathcal{B}(B^0 \to \mu^+\mu^-) < 4.0 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

$$\text{observed } \mathcal{B}(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

$B_s \rightarrow \mu^+\mu^-$ Signal Window



CC

p-value = 0.94%
(bkgd only)
p-value = 7.1%
(bkgd + SM sig.)

CF

Excess remains but is not reinforced with additional data.

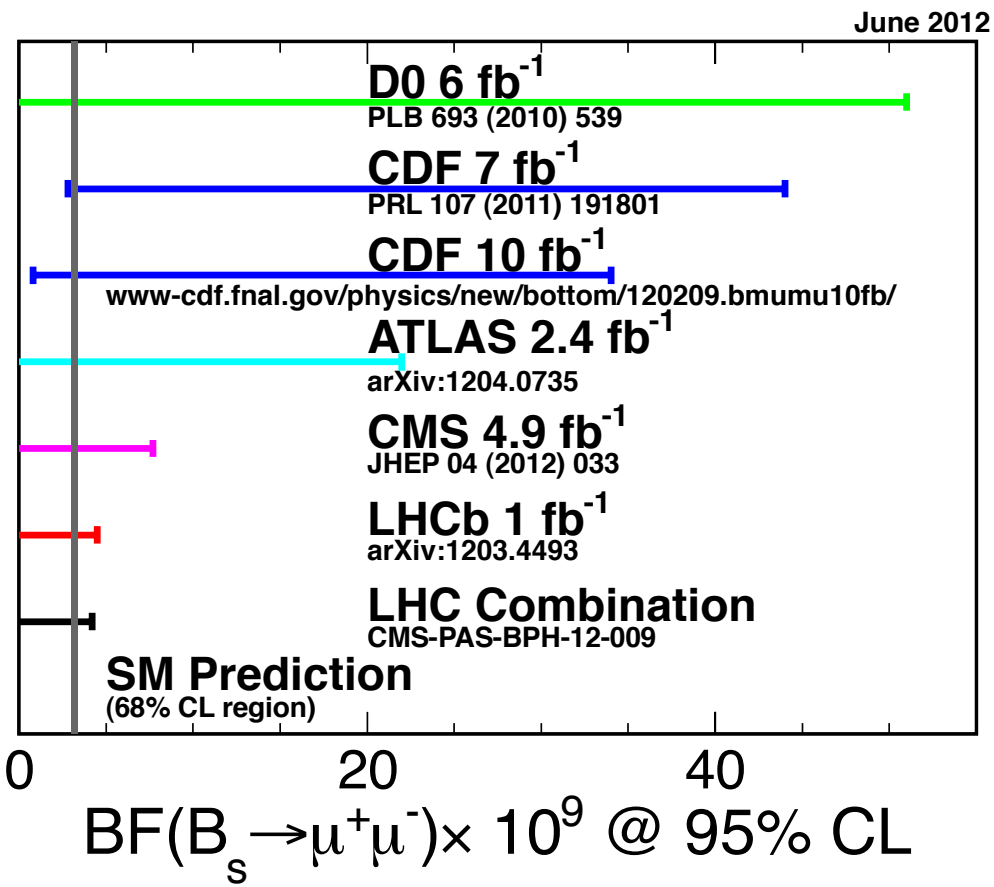
background-only fit returns p-value greater than 2σ

Comparison of Results

expected $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 13 \times 10^{-9}$ at 95% CL

observed $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 31 \times 10^{-9}$ at 95% CL

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(13^{+9}_{-7}\right) \times 10^{-9}$$

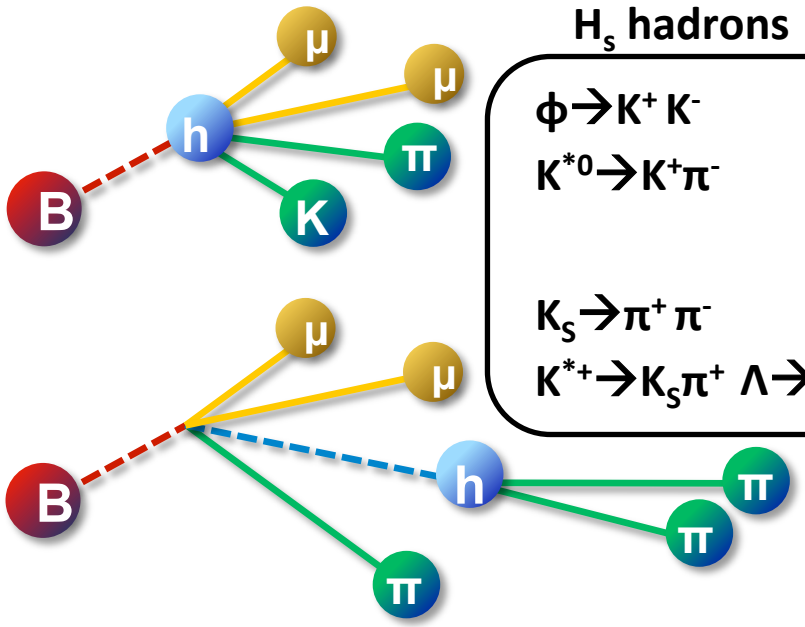


$b \rightarrow s\mu\mu$

- Also a FCNC decay.
- We observe 6 different decay modes.
  - CDF made first observation of $B_s \rightarrow \phi\mu\mu$ and $\Lambda_b \rightarrow \Lambda\mu\mu$
- Branching fractions are at the 10^{-6} level.
- Increase sensitivity to NP by looking at angular asymmetries.

http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-b2smumu_96/

$b \rightarrow s\mu\mu$ Analysis



H_s hadrons

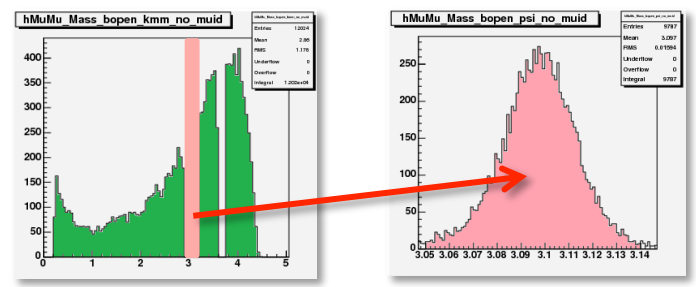
$\phi \rightarrow K^+ K^-$

$K^{*0} \rightarrow K^+ \pi^-$

$K_S \rightarrow \pi^+ \pi^-$

$K^{*+} \rightarrow K_S \pi^+$ $\Lambda \rightarrow p\pi^-$

Signal mode	Control sample
$B^0 \rightarrow K^{*0}\mu\mu$	$B^0 \rightarrow J/\psi K^{*0}$
$B^+ \rightarrow K^+\mu\mu$	$B^+ \rightarrow J/\psi K^+$
$B_s \rightarrow \phi\mu\mu$	$B_s \rightarrow J/\psi \phi$
$B^+ \rightarrow K^{*+}\mu\mu$	$B^+ \rightarrow J/\psi K^{*+}$
$B^0 \rightarrow K_S\mu\mu$	$B^0 \rightarrow J/\psi K_S$
$\Lambda_b \rightarrow \Lambda\mu\mu$	$\Lambda_b \rightarrow J/\psi \Lambda$

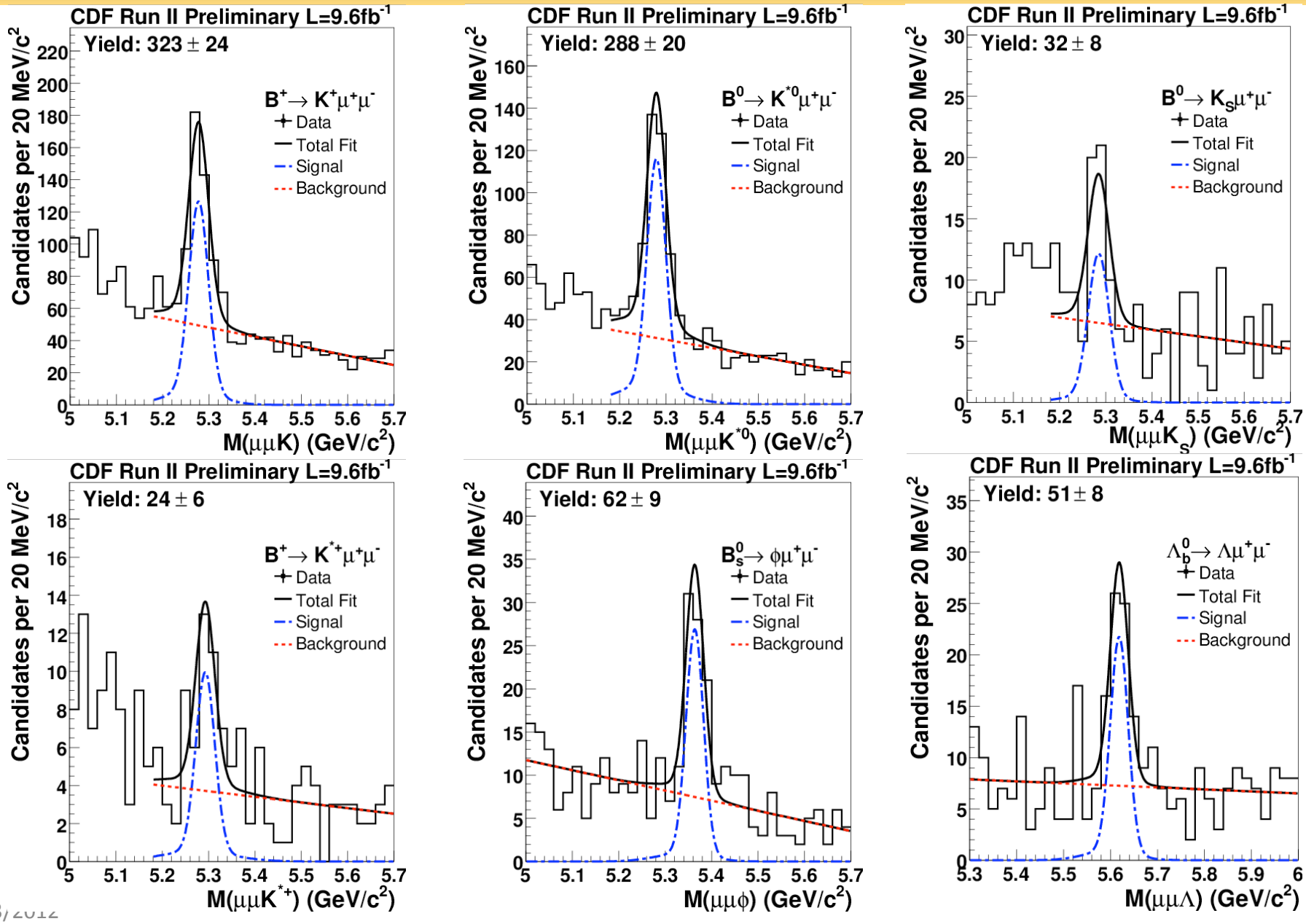


Dimuon mass

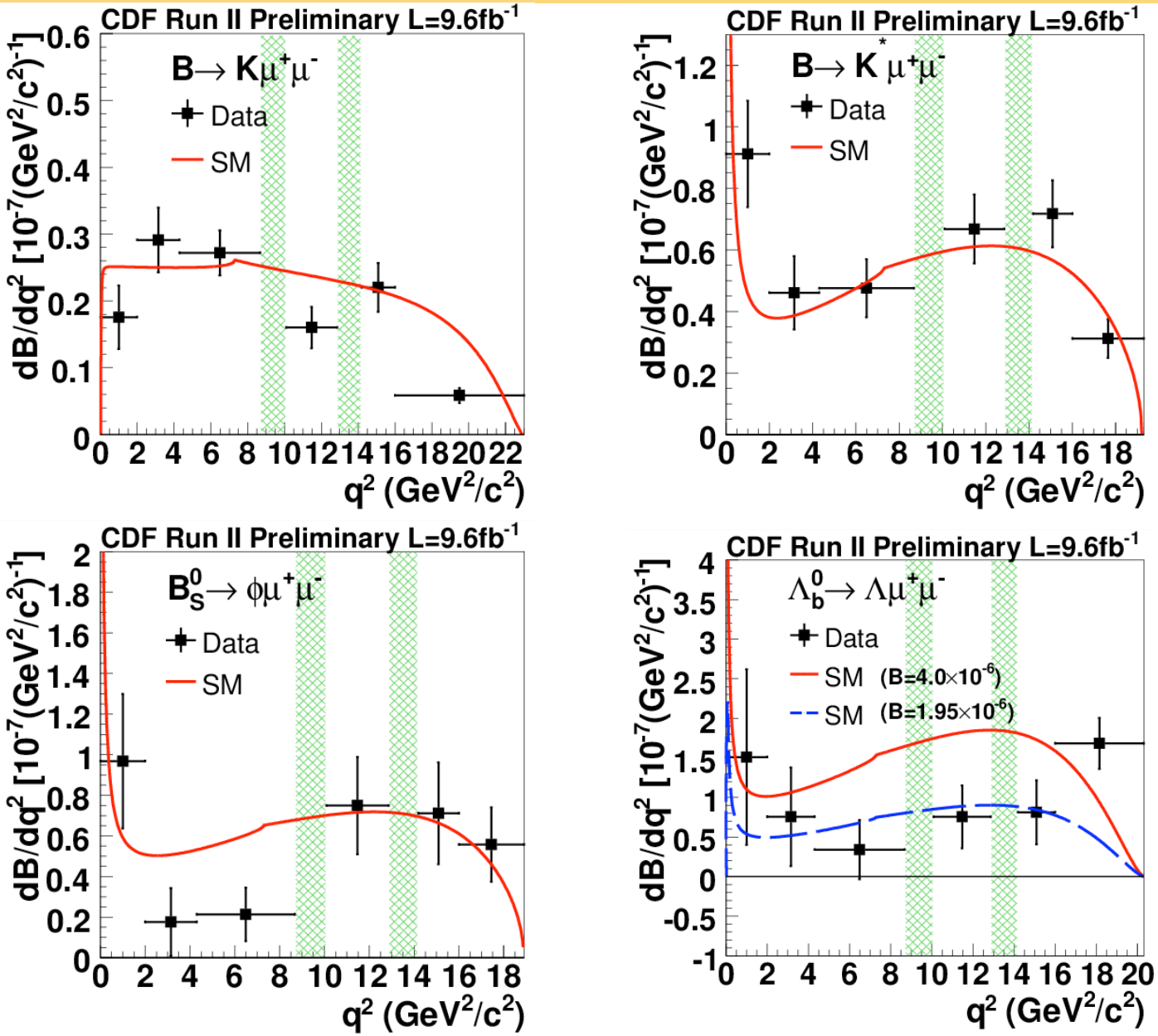
12 channel analysis!

- Start from dimuon trigger
  - Reconstruct $H_b \rightarrow H_s\mu\mu$
  - Optimize event selection with NN
- **BR measurement**
- **Angular analysis**

Rare *B* Yields with 9.6 fb^{-1}



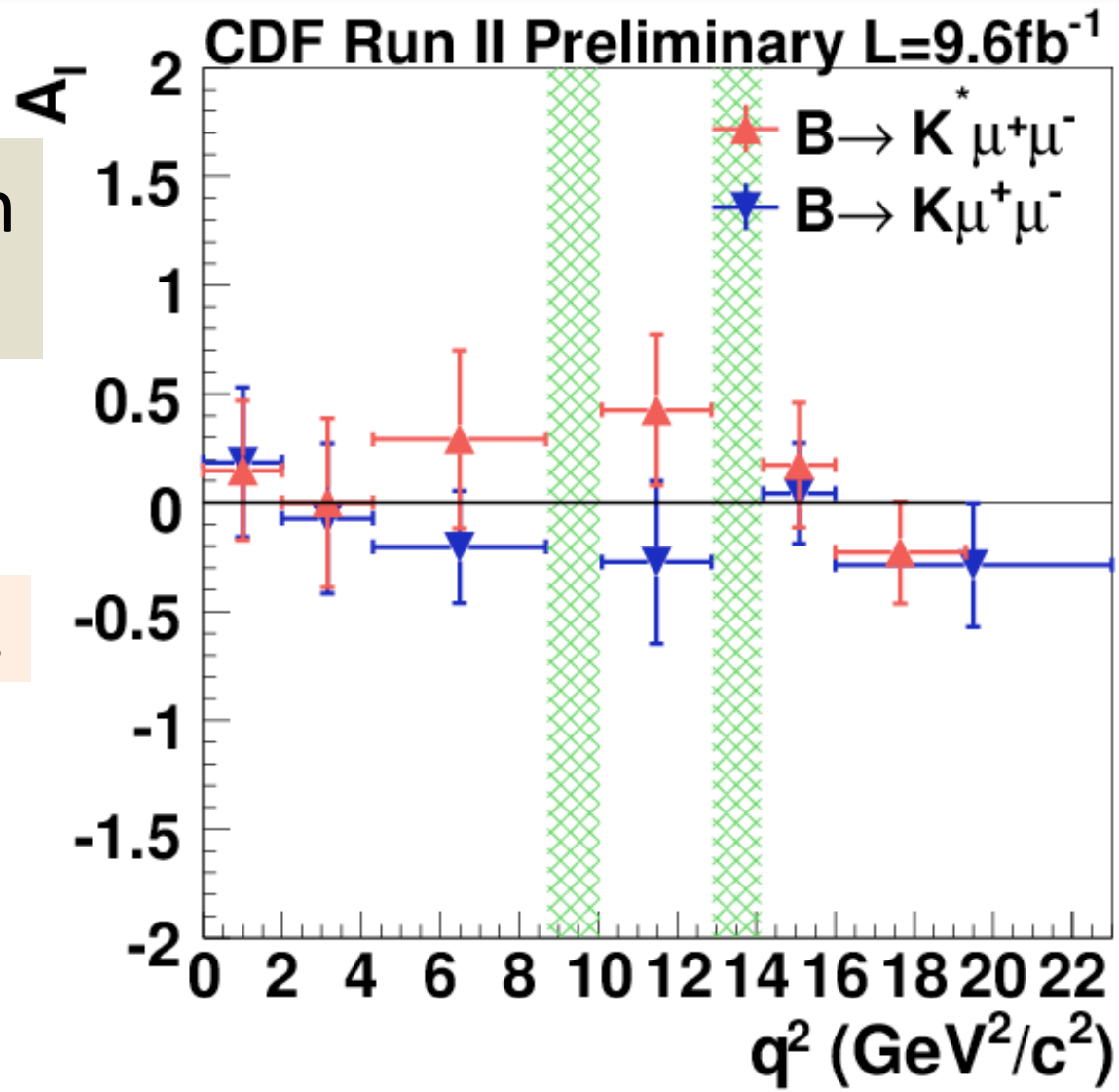
Differential Branching Ratios



Isospin Asymmetry

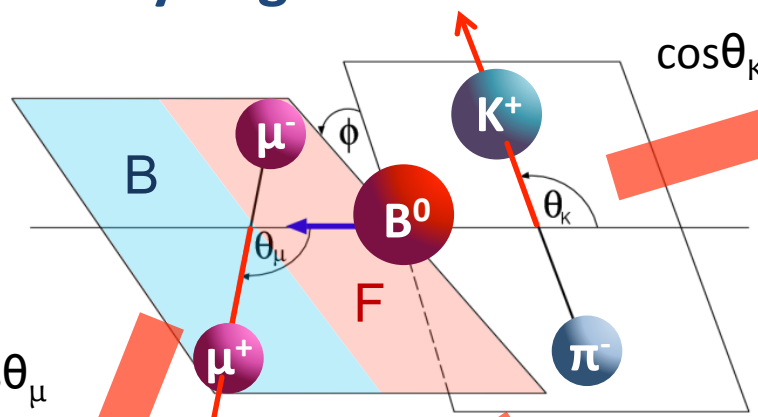
Difference between $K^{(*)+}$ and $K^{(*)0}$ rates

LHCb sees a 4σ effect.

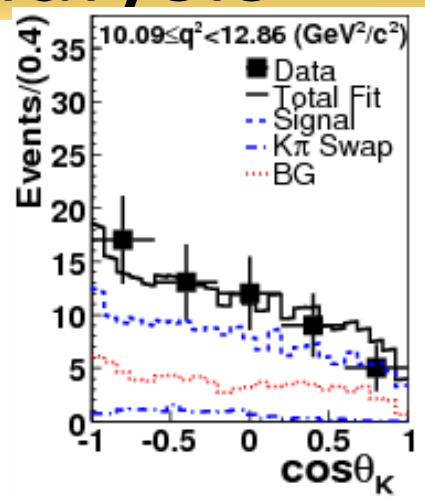


Angular analysis

- **One can extract information from the decay angular distribution**



$\cos\theta_K$

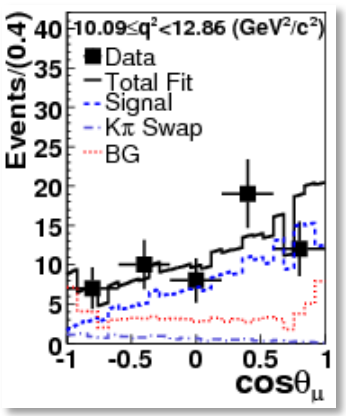


K* polarization

F_L

$$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

$\cos\theta_\mu$

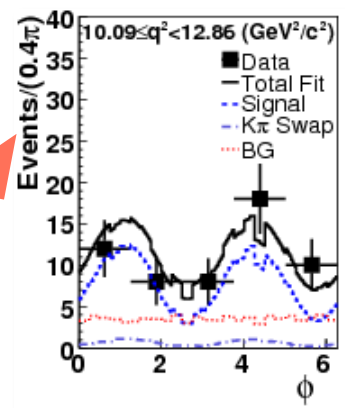


FB Asymmetry

A_{FB}

$$\frac{3}{4}F_L(1-\cos^2\theta_\mu) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\mu) + A_{FB}\cos\theta_\mu$$

ϕ



NEW

$A_T^{(2)}$ Transverse polarization asymmetry

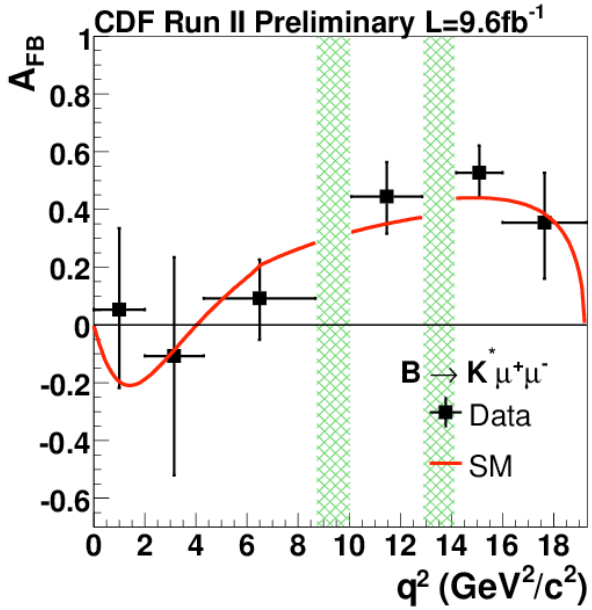
A_{im} Triple product asymmetry

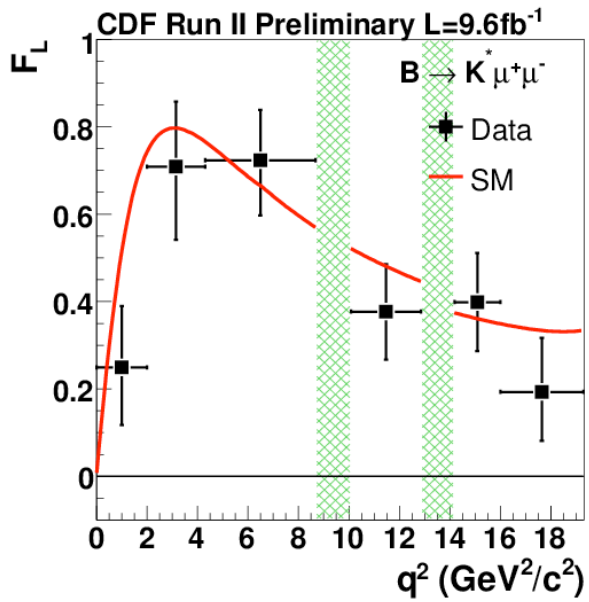
$$\frac{1}{2\pi}\left[1+\frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{im}\sin 2\phi\right]$$

Angular fit results

Simultaneous fit with K^{*0} and K^{*+}

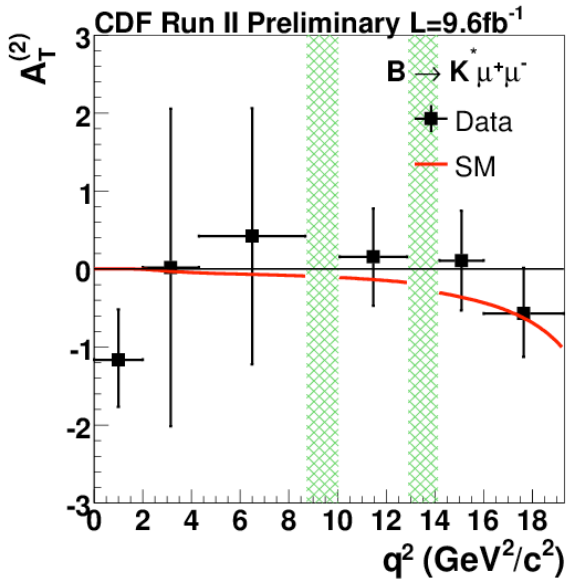
A_{FB}

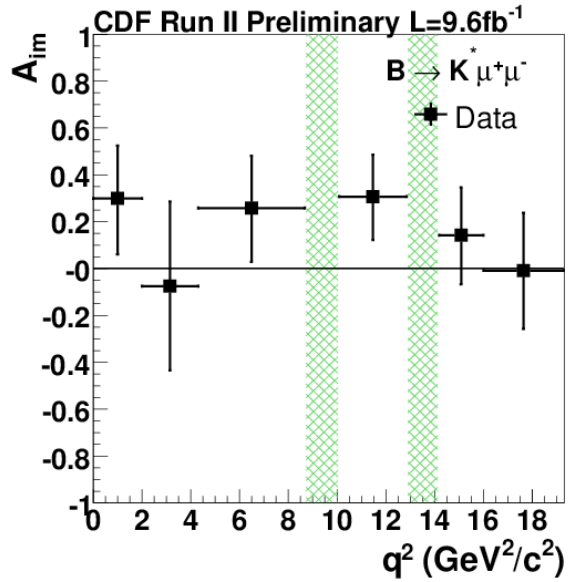




F_L

$A_T^{(2)}$





A_{im}

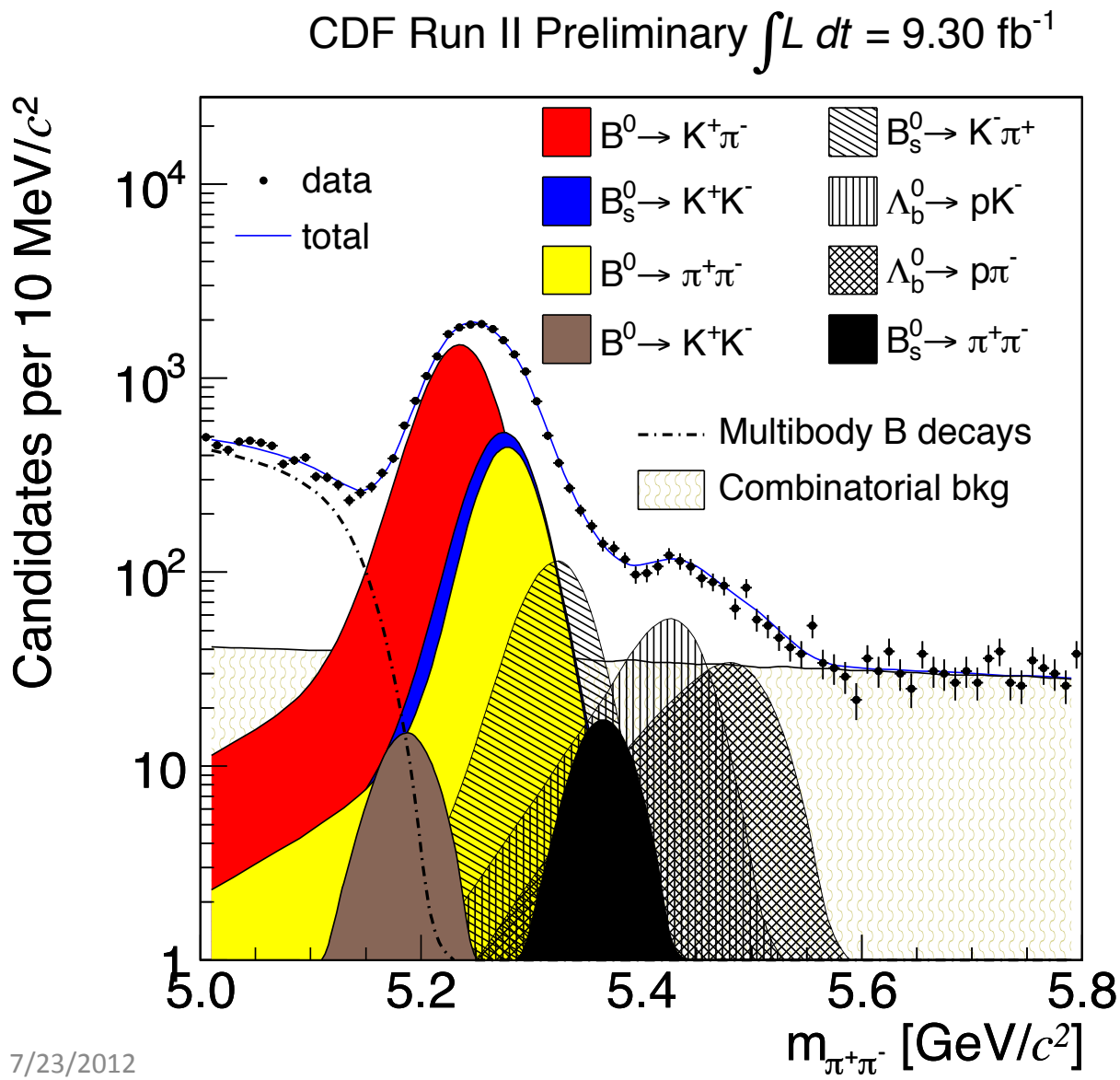
CDF Public Note 10894

$H_b \rightarrow hh'$ CP asymmetries

- Suppressed charmless decay modes
- NP can interfere with SM decay, yielding sizable asymmetries.
- $B^0_s \rightarrow K^-\pi^+$ asymmetry can be used in a model independent test of SM.
  - M. Gronau and J. L. Rosner, Phys. Lett. B 482, 71 (2000)
  - H.J.Lipkin, Phys. Lett. B 621, 126 (2005)
- Λ_b asymmetries could contain interesting physics.

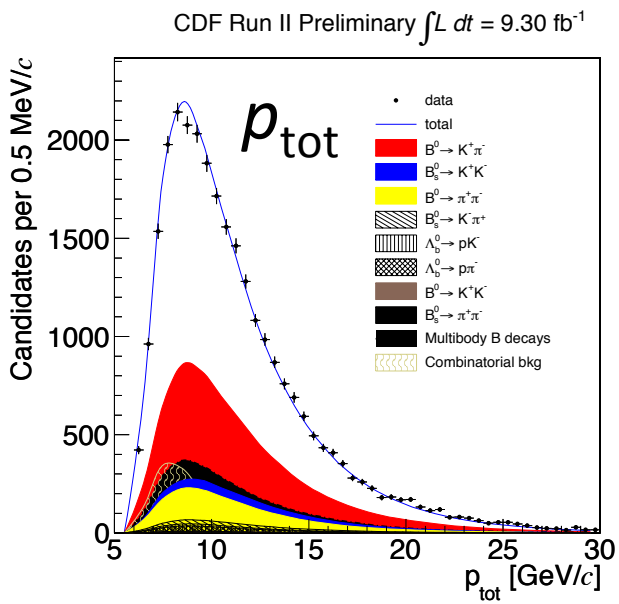
http://www-cdf.fnal.gov/physics/new/bottom/120628.blessed-Bhh9fb/

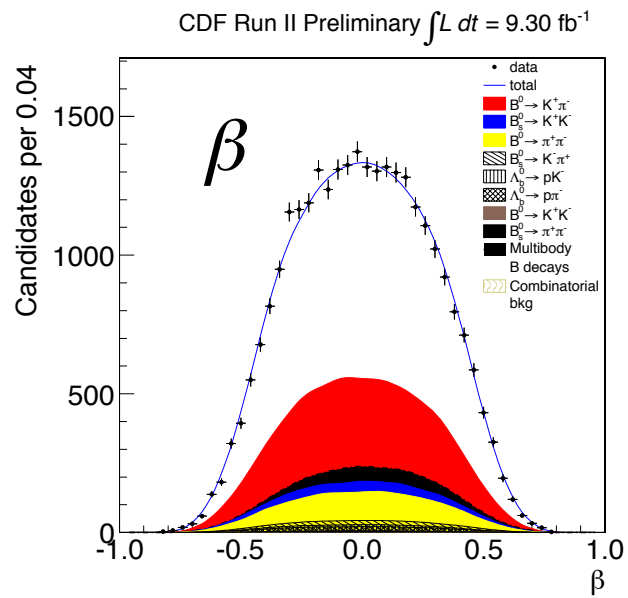
Fit to the $B \rightarrow hh'$ data

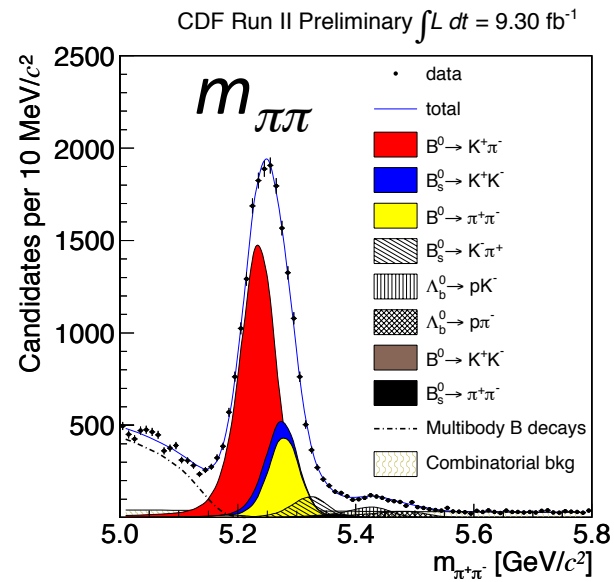


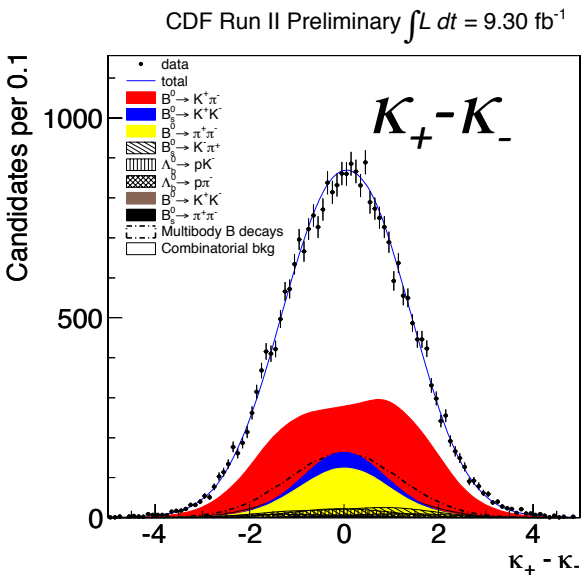
- Complex fit of
  - 8 modes
  - with complex shapes
  - and backgrounds
- Use more than just inv. mass
- Correct for det. effects

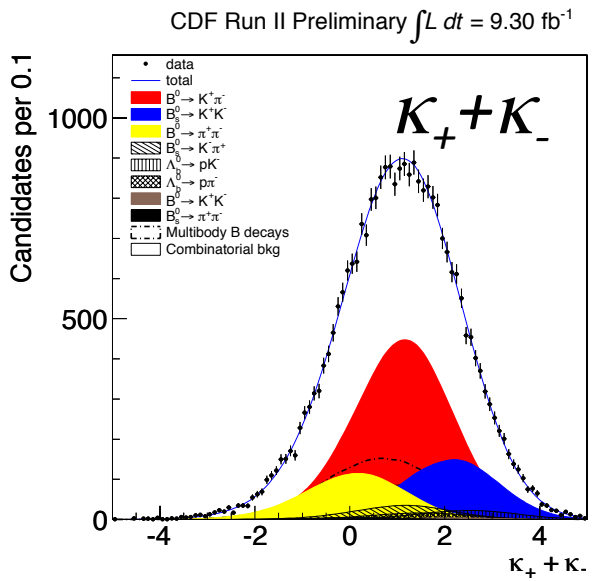
Inputs to the Fit











Tracking based

dE/dx based

Corrected *B* → *hh'* CP Asymmetries

$$
\begin{aligned}
\mathcal{A}_{\rm CP}(B^0 \to K^+\pi^-) &= -0.083 \pm 0.013\ (stat.) \pm 0.003\ (syst.), \\
\mathcal{A}_{\rm CP}(B_s^0 \to K^-\pi^+) &= +0.22 \pm 0.07\ (stat.) \pm 0.02\ (syst.), \\
\mathcal{A}_{\rm CP}(\Lambda_b^0 \to p\pi^-) &= +0.07 \pm 0.07\ (stat.) \pm 0.03\ (syst.), \\
\mathcal{A}_{\rm CP}(\Lambda_b^0 \to pK^-) &= -0.09 \pm 0.08\ (stat.) \pm 0.04\ (syst.)
\end{aligned}
$$

CDF Public Note 10726

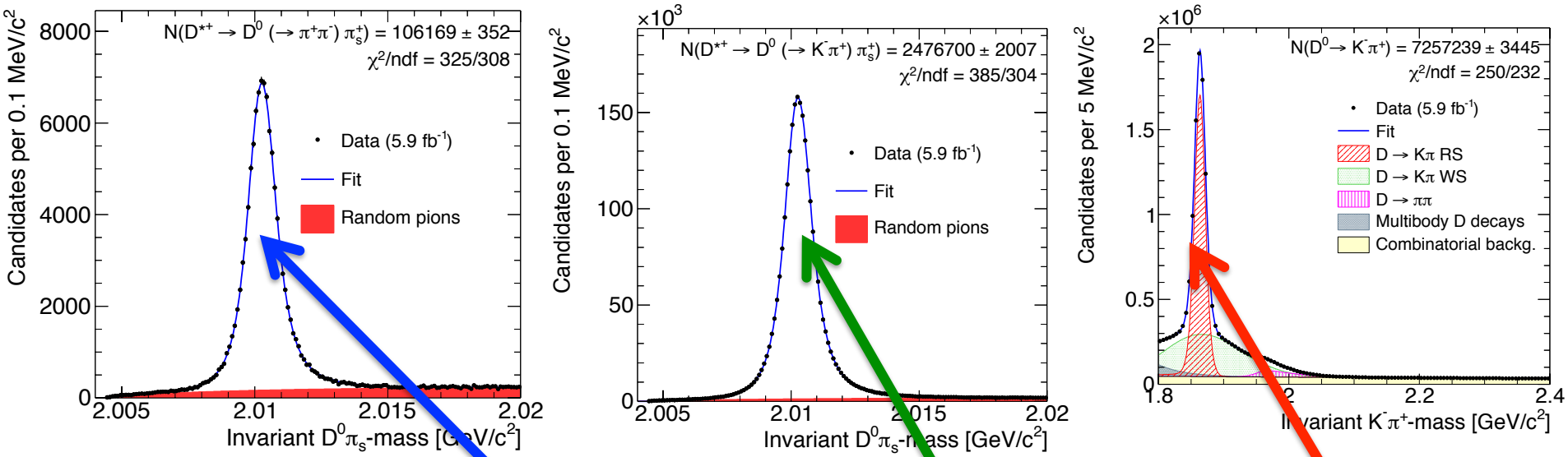
$D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$ CP asymmetries

- Predicted to be small in the SM
  - early predictions were less than 10^{-4}
  - but predictions for charm are difficult.
- Real difficulty is to cancel detector induced asymmetries.
- The KK and $\pi\pi$ asymmetries are of opposite sign in SM
  - the difference is particularly sensitive
  - and most detector asymmetries cancel in the difference
- Use $D^{*+} \rightarrow D^0 \pi^+$ and c.c. to tag D^0 production flavor.

http://www-cdf.fnal.gov/physics/new/bottom/120216.blessed-CPVcharm10fb/

http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0/

Data Driven Corrections



$$A_{\mathrm{CP}}(\pi\pi) = A_{\mathrm{CP}}^{\mathrm{raw}}(\pi\pi^*) - A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi^*) + A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi)$$

* indicates D* tagged decay.

Weight events to match p_T and η distributions.

Individual Mode Asymmetries

$$A_{CP}(\pi^+\pi^-) = [0.22 \pm 0.24(\text{stat}) \pm 0.11(\text{sys})]\,\%$$

$$A_{CP}(K^+K^-) = [-0.24 \pm 0.22(\text{stat}) \pm 0.09(\text{sys})]\,\%$$

World's best measurements.

Measured CP asymmetry is a combination of direct and indirect CP asymmetries.

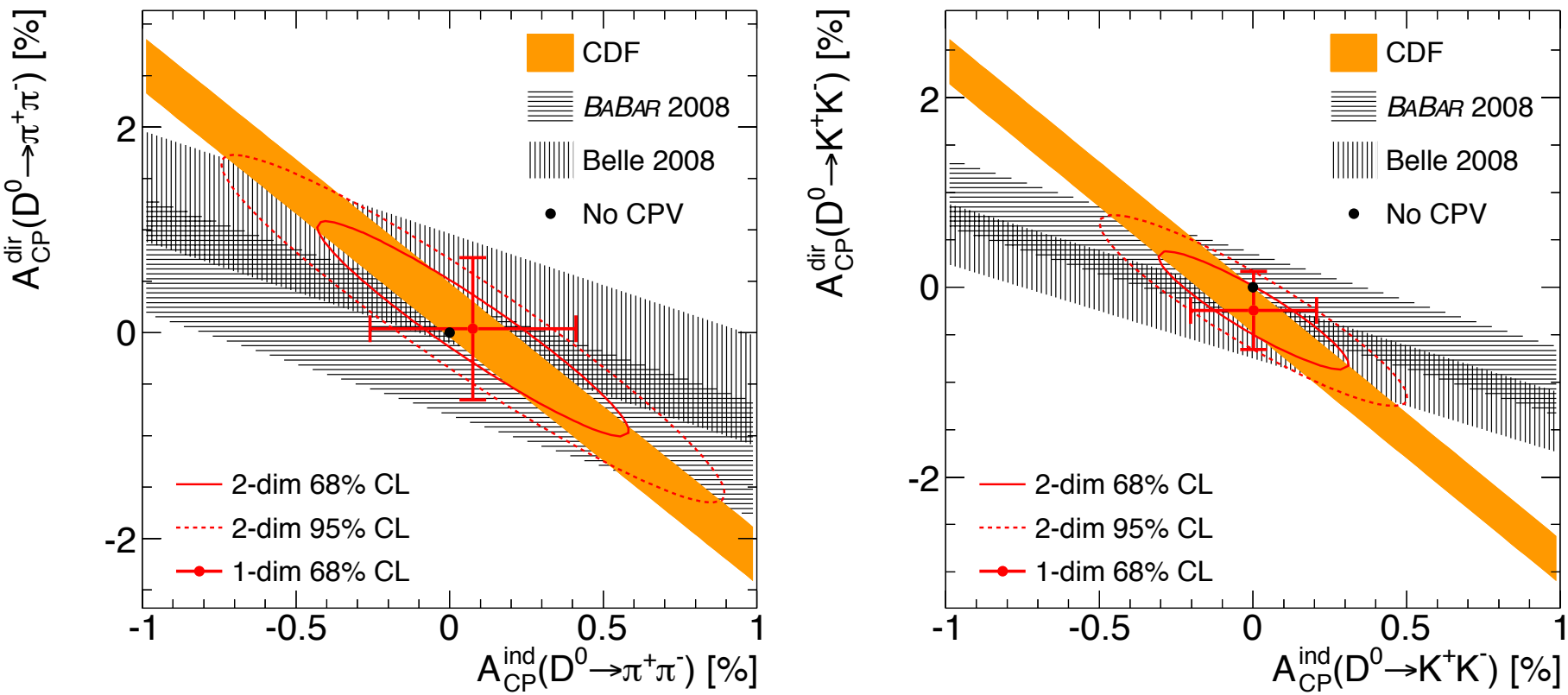
$$A_{CP} = A_{CP}^{\text{dir}} + \int_0^\infty A_{CP}(t)D(t)dt \approx A_{CP}^{\text{dir}} + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}}$$

Line in the direct-indirect asymmetry plane.

Charm Asymmetries:

- 2010 – 2011: CDF measures ACP in $D^0 \rightarrow \pi\pi$ and $D^0 \rightarrow KK$ separately

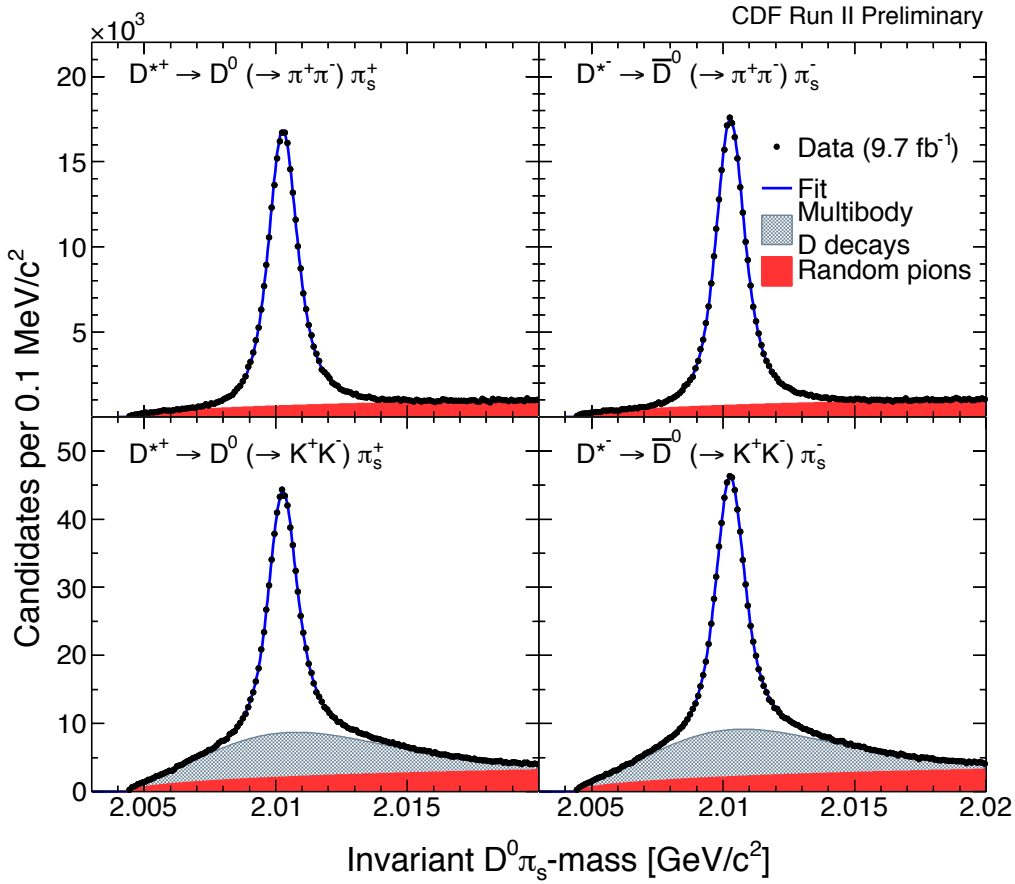
PRD 85, 012009 (2012)



CDF: Charm Detector Facility?

CDF ΔA_{CP} Measurement:

- For ΔA_{CP} measurement, selection can be loosened, and full data set used → more than doubling the statistics.
- Cross check with data binned in different η, ϕ regions.

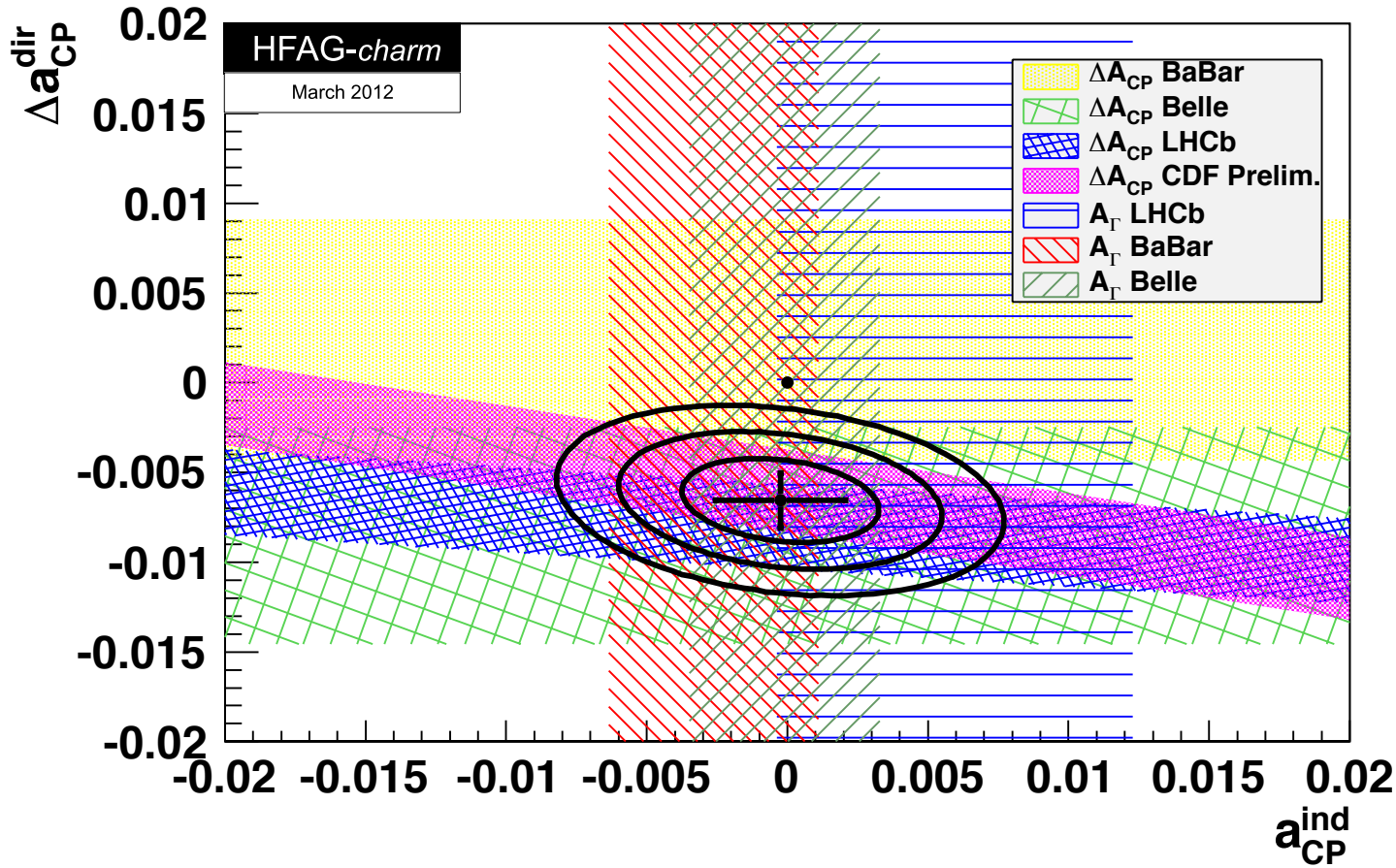


$$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$

arXiv:1207.2158

HFAG Combination of All ΔA_{CP} Results

$$A_{CP}^{\rm ind} = (-0.03 \pm 0.23)\%$$
$$A_{CP}^{\rm dir} = (-0.66 \pm 0.15)\%$$



Summary

- CDF results with the full run II dataset.
- CP violation in $B_s \rightarrow J/\psi\ \phi$ is tending to SM pred.
- Search for $B_{(s)} \rightarrow \mu\mu$ and $b \rightarrow s\mu\mu$ consistent with SM
- $B \rightarrow hh'$, $D^0 \rightarrow KK$, and $D^0 \rightarrow \pi\pi$ CP asymmetries provide tests of the SM
- More results are in the pipeline