Rare Decays/B_s CPV: Updates from the Tevatron

Derek Axel Strom
University of Illinois at Chicago
for the CDF and DØ Collaborations

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Rare Decays and B_s CPV at the Tevatron

- Large production cross-sections and high energy collisions at the Tevatron offers the opportunity to study all species of b-hadrons. We have access to rare decays and precision CPV measurements either complementary (B_s) or competitive (B^0 and B^+) to the B factories.

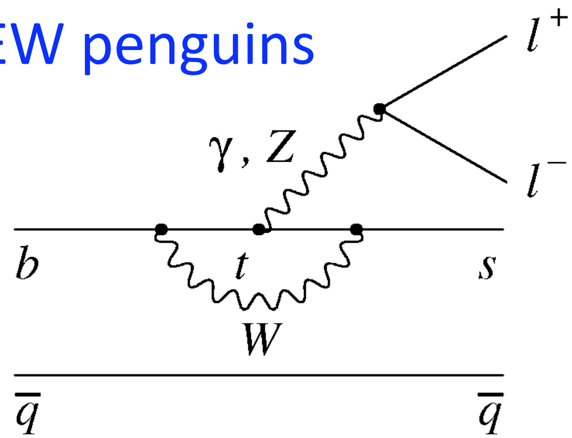
Topics

- Rare B_d and B_s decays
  - $B \to K^{(*)}\mu\mu$ and $B_s \to \phi\mu\mu$ (A_{FB} in $B \to K^{(*)}\mu\mu$)
  - $B_{(d,s)} \to \mu\mu$
  - $B_s \to \phi\phi$ branching fraction
- CPV in B_s
  - $B_s \to J/\psi(\mu\mu)\phi(KK)$ angular analysis

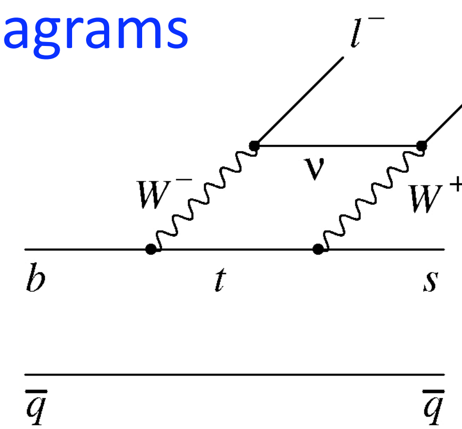
FCNC

- Highly suppressed in SM (forbidden at tree level)
- BSM physics models (SUSY, Technicolor, 4th generation) see enhanced decay amplitudes through loop diagrams
  - Promising for exploring BSM physics

EW penguins



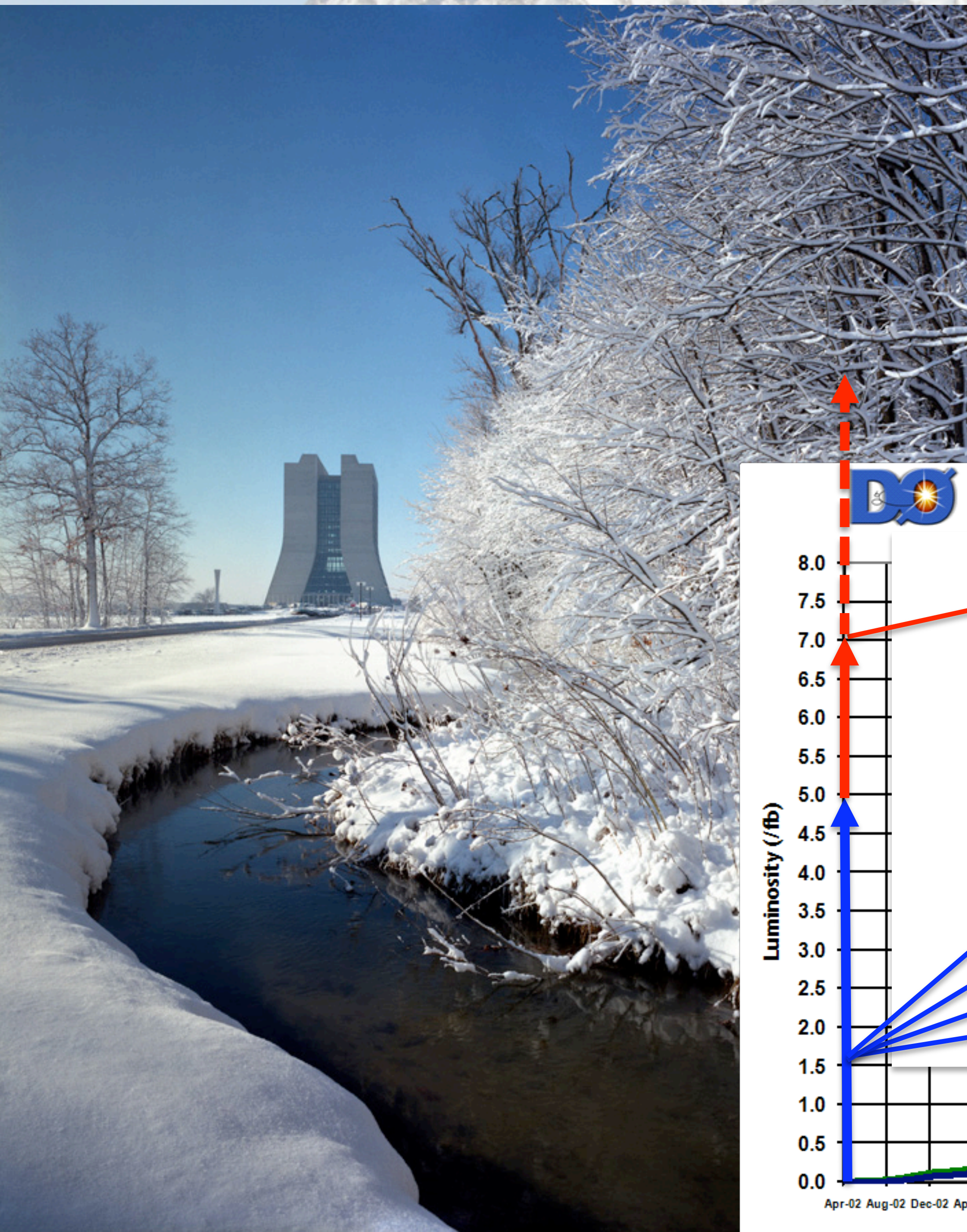
Box diagrams



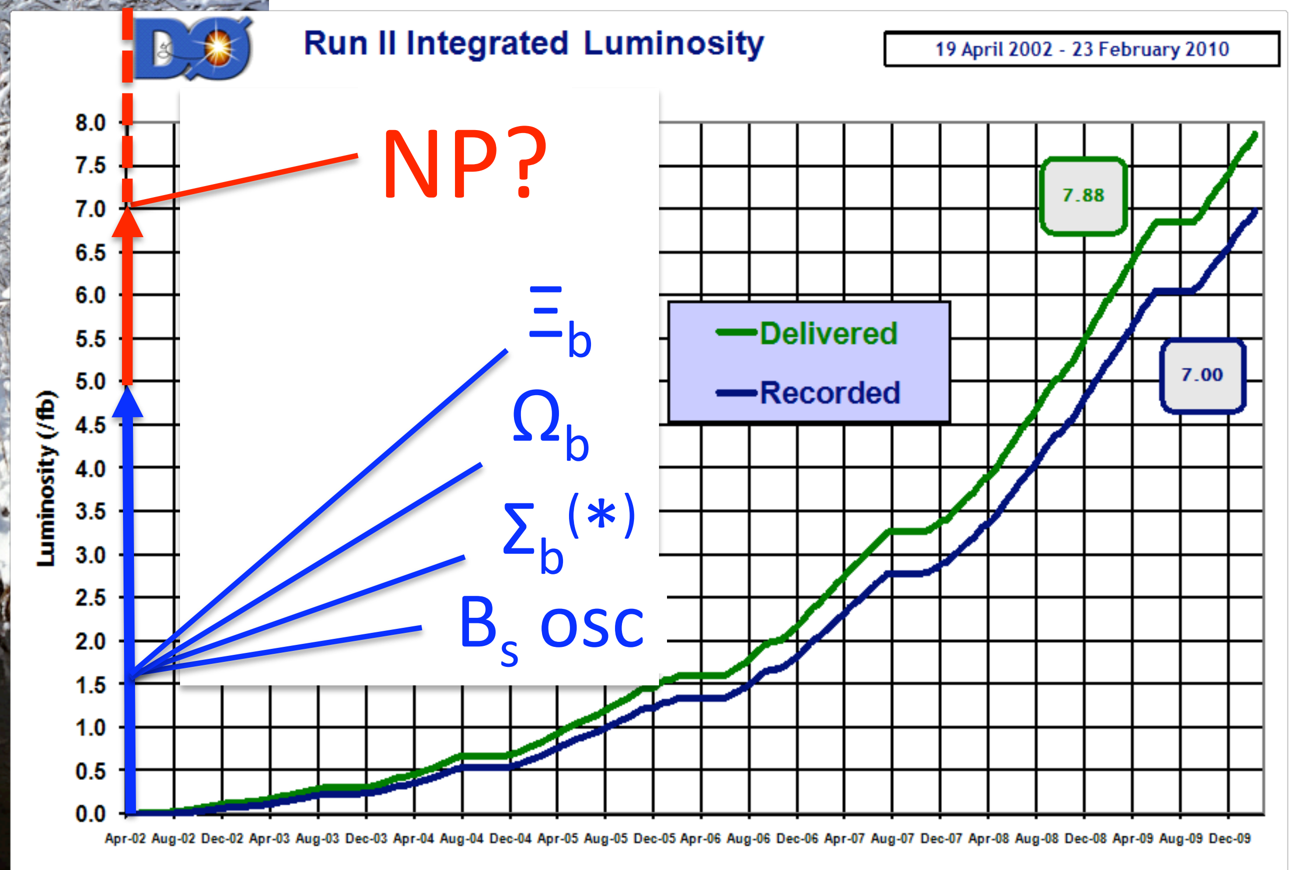
- Could enhance branching fractions (10-1000 × SM)
- Could affect angular distributions
- Would be observable at the Tevatron

- Dimuon signature experimentally/theoretically clean

Tevatron Performance

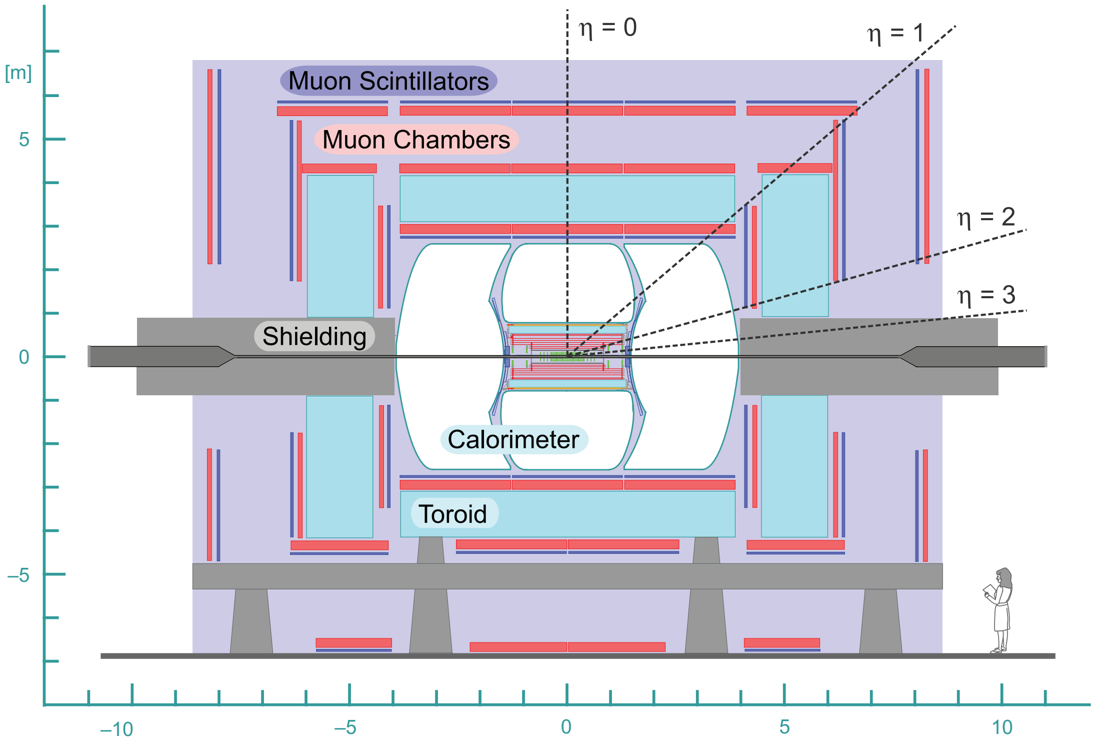


- ~8 fb^{-1} delivered
- ~7 fb^{-1} recorded/experiment
- Accelerator continually breaking records
- Regularly peak luminosities 3.5×10^{32} $cm^{-2}s^{-1}$

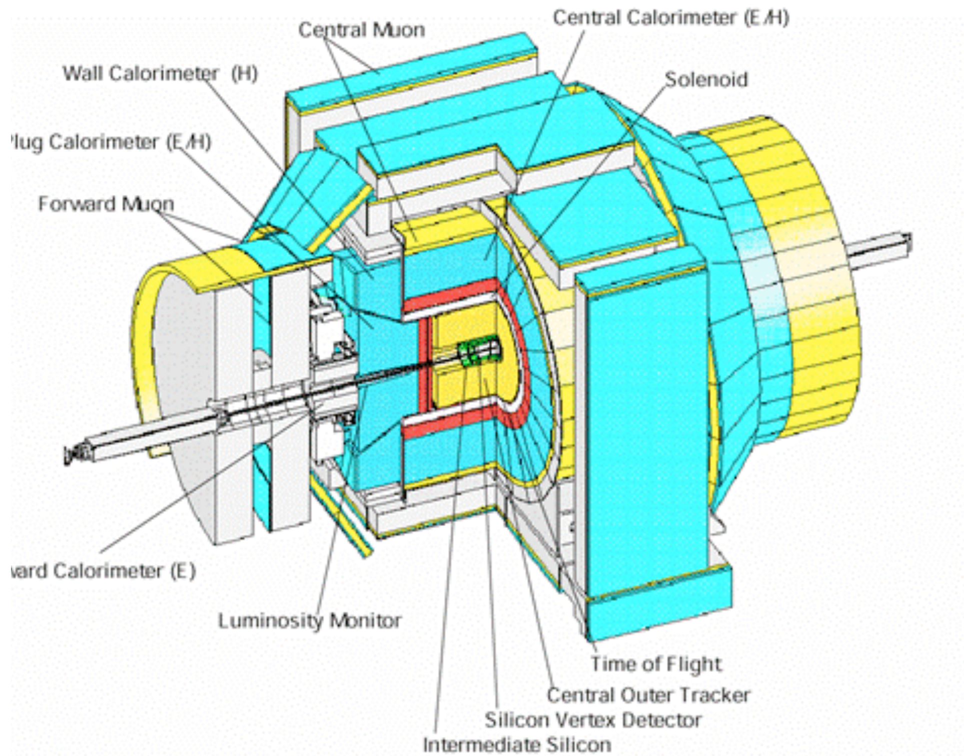


Tevatron Experiments

DØ Detector



CDF II Detector



- Excellent tracking and muon coverage
  - Extended muon system |η| < 2.0
  - Tracking up to |η| < 3.0
- Additional layer of Si on beampipe since 2006

- Excellent vertex, momentum and mass resolution
- Particle ID: p, K and π by dE/dx and TOF
- Trigger on displaced tracks

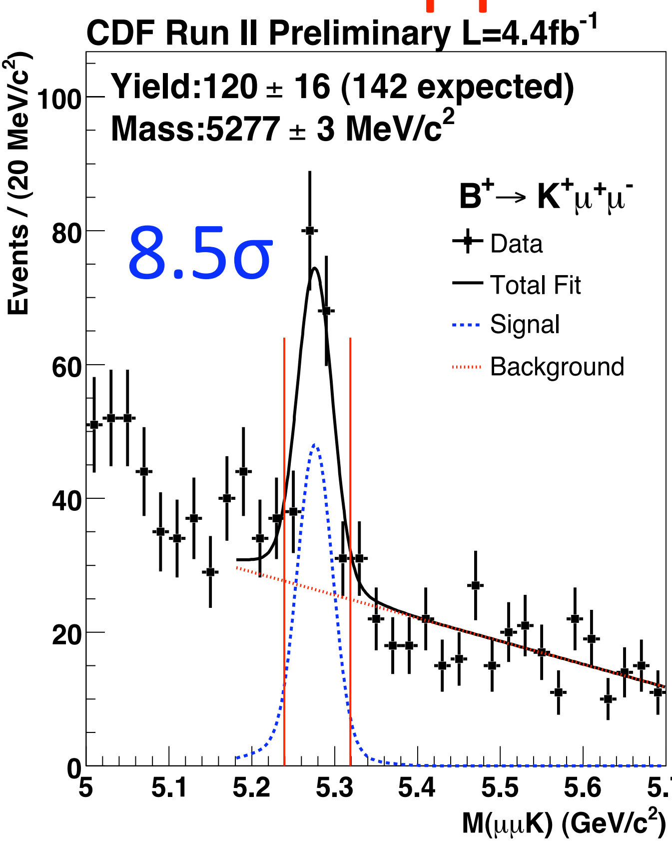
$B_{(u,d,s)} \rightarrow h\mu\mu$ Decays

- Dimuon trigger ($p_T(\mu)$>1.5 or 2.0 GeV/c)
  - Muon coverage |η| < 1.0
- Neural network optimizes event selection
- Unbinned maximum log-likelihood fit to invariant mass

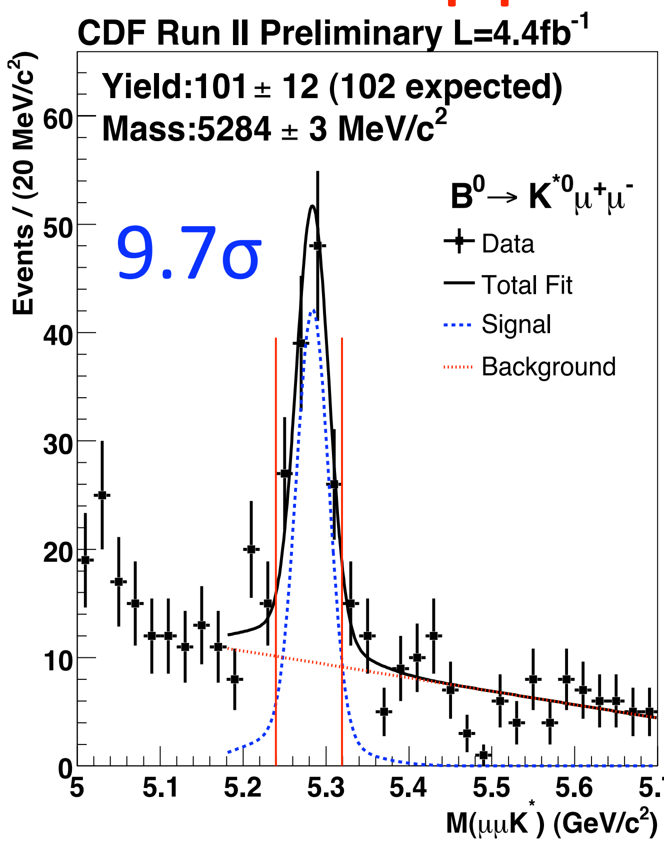
4.4 fb^{-1}

[CDF Public Note 10047]

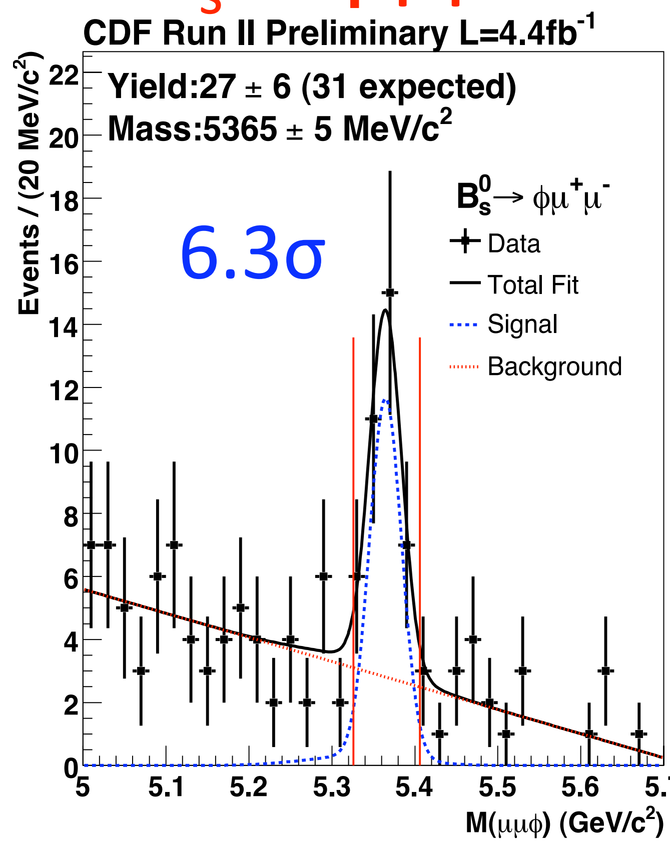
$B^+ \rightarrow K^+\mu\mu$



$B^0 \rightarrow K^{*0}\mu\mu$



$B_s \rightarrow \phi\mu\mu$



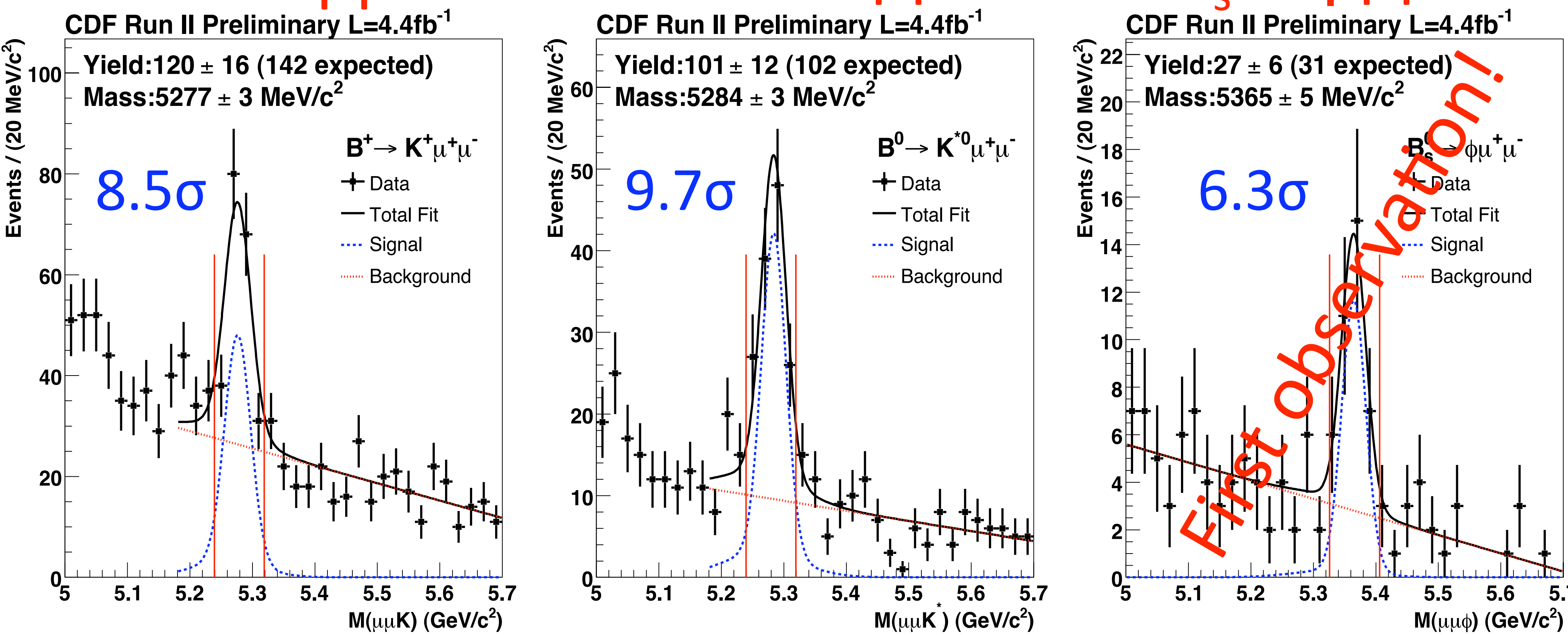
$B_{(u,d,s)} \rightarrow h\mu\mu$ Decays

- Dimuon trigger ($p_T(\mu)$>1.5 or 2.0 GeV/c)
  - Muon coverage $|\eta| < 1.0$
- Neural network optimizes event selection
- Unbinned maximum log-likelihood fit to invariant mass

4.4 fb^{-1}

[CDF Public Note 10047]

$B^+ \rightarrow K^+\mu\mu$ $B^0 \rightarrow K^{*0}\mu\mu$ $B_s \rightarrow \phi\mu\mu$



$\mathcal{B}(B_{(u,d,s)} \to h\mu\mu)$

- $B \to J/\psi h$ used as normalization channel for $\mathcal{B}(B \to h\mu\mu)$ to avoid many systematic uncertainties

  $\mathcal{B}(B^+ \to K^+\mu\mu) = [\,0.38 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst})] \times 10^{-6}$

  $\mathcal{B}(B^0 \to K^{*0}\mu\mu) = [\,1.06 \pm 0.14\,(\text{stat}) \pm 0.09\,(\text{syst})] \times 10^{-6}$

- Precision competitive to world average values:

  $\mathcal{B}(B^+ \to K^+\mu\mu) = [\,0.52\,^{+0.08}_{-0.07}] \times 10^{-6}$

  $\mathcal{B}(B^0 \to K^{*0}\mu\mu) = [\,1.05\,^{+0.15}_{-0.13}] \times 10^{-6}$

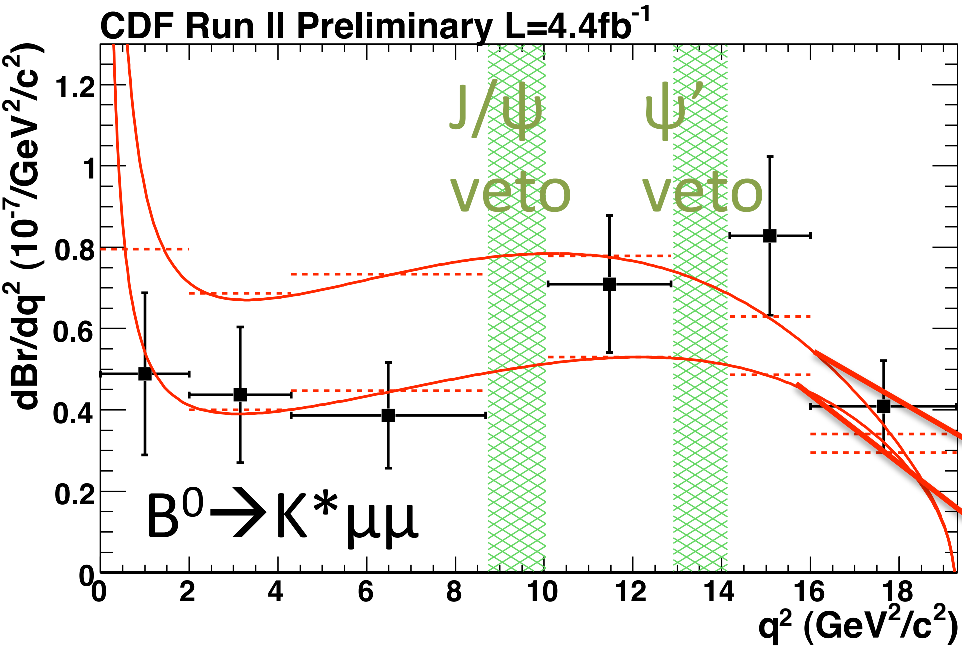
- First measurement:

  $\mathcal{B}(B_s \to \phi\mu\mu) = [\,1.44 \pm 0.33\,(\text{stat}) \pm 0.46\,(\text{syst})] \times 10^{-6}$

- The rarest observed B_s decay! [CDF Public Note 10047]
- In agreement with theoretical prediction of 1.61×10^{-6}

  [Geng, Liu, J.Phys.G29:1103-1118, 2003]

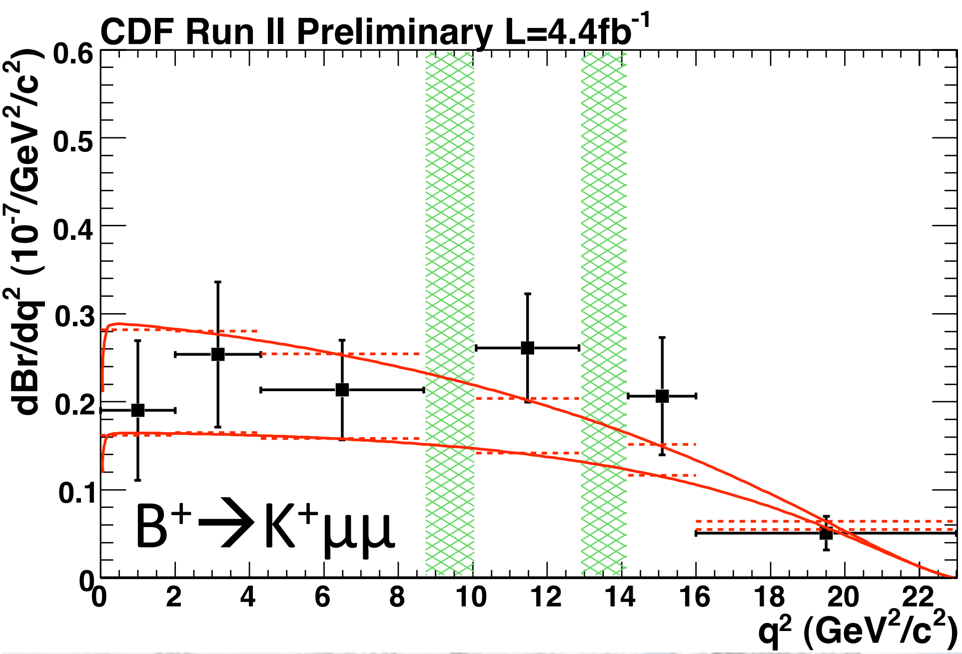
Differential $\mathcal{B}(B \to K^{(*)}\mu\mu)$



- Dimuon mass spectrum could show hints of new physics
- NP could appear in differential $\mathcal{B}$ versus $q^2 = M_{\mu\mu}^2$

SM maximum allowed

SM minimum allowed



q^2 binning

	$B^0 \to K^{*0}\mu^+\mu^-$	$B^+ \to K^+\mu^+\mu^-$
Bin#1	0.00-2.00	0.00-2.00
Bin#2	2.00-4.30	2.00-4.30
Bin#3	4.30-8.68	4.30-8.68
Bin#4	10.09-12.86	10.09-12.86
Bin#5	14.18-16.00	14.18-16.00
Bin#6	16.00-19.30	16.00-23.00

Consistent with SM

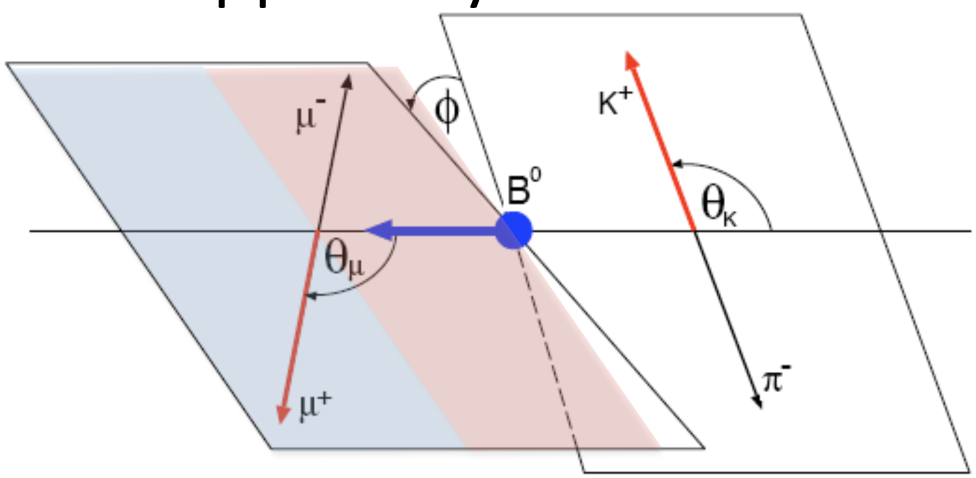
Forward-Backward Asymmetry

Forward Backward

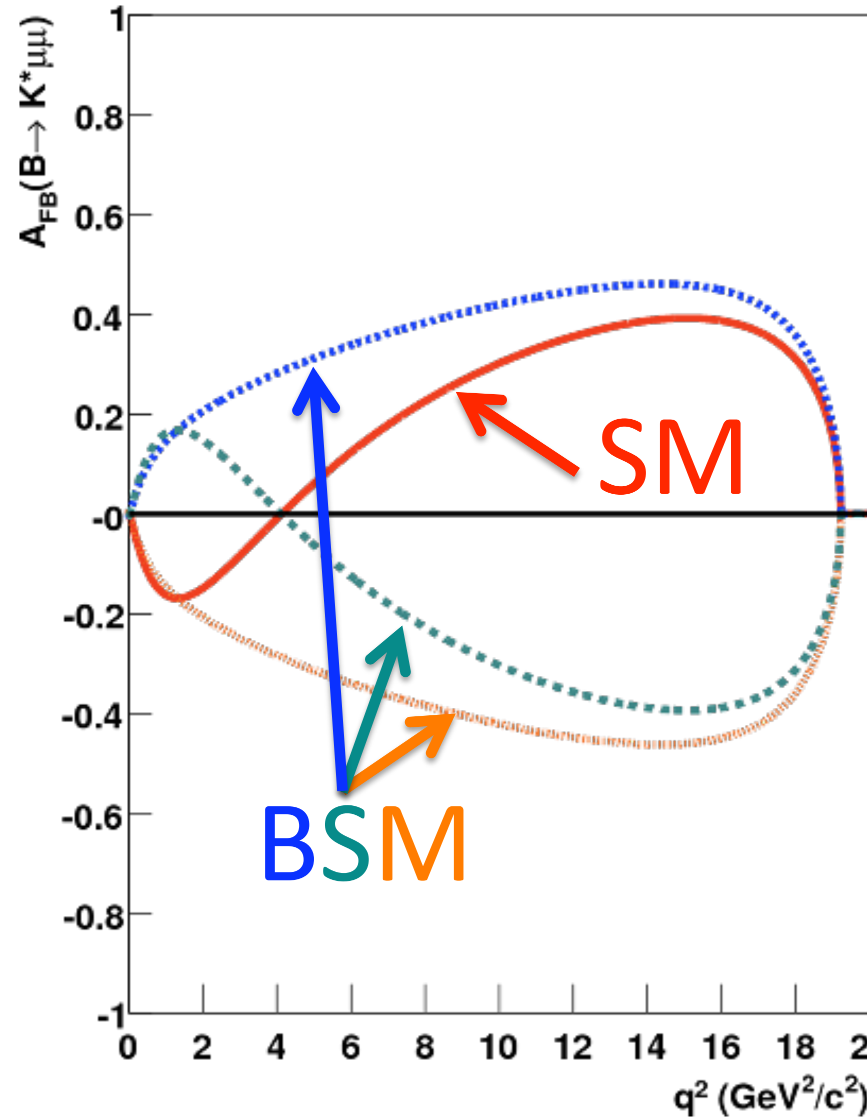
$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos(\theta_\mu) > 0) - \Gamma(q^2, \cos(\theta_\mu) < 0)}{\Gamma(q^2, \cos(\theta_\mu) > 0) + \Gamma(q^2, \cos(\theta_\mu) < 0)}$$

where $q^2 = M_{\mu\mu}^2$

$B^0 \rightarrow K^{*0}\mu\mu$ Decay Plane



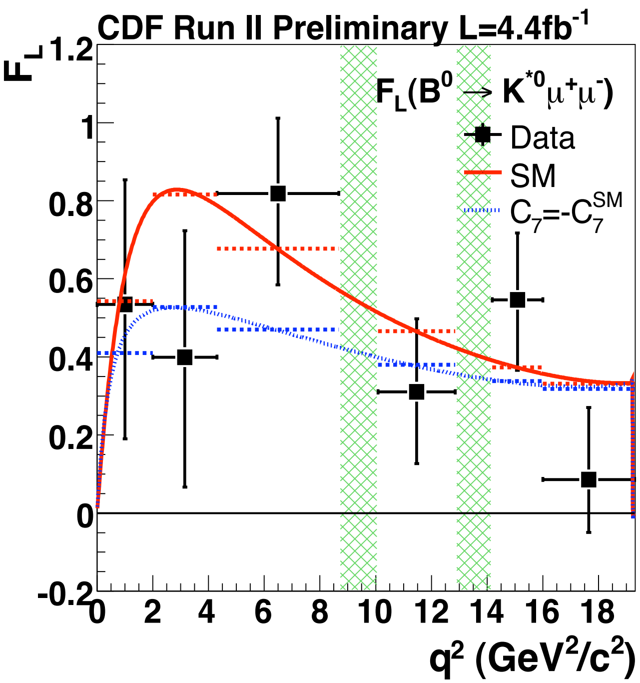
- Data divided into 6 bins of q^2
- A_{FB} may display different behavior under some BSM scenarios
- Good probe for exploring BSM

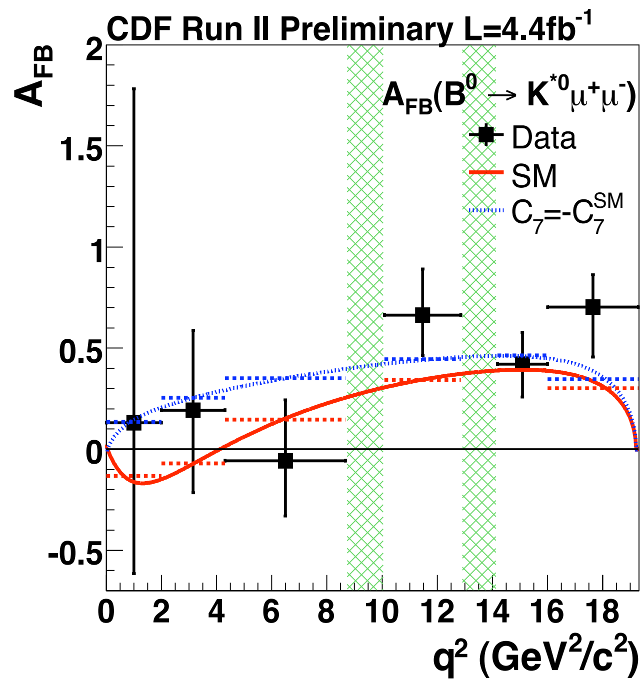


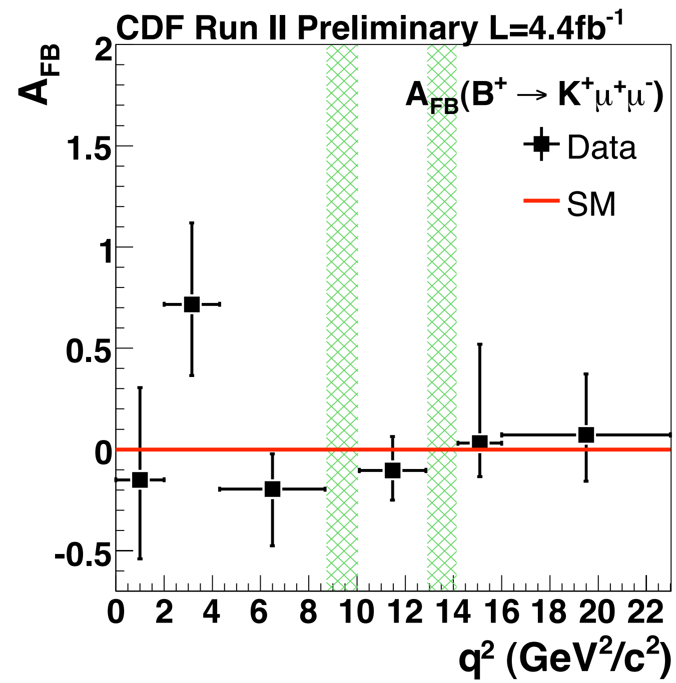
A_{FB} in $B \to K^{(*)}\mu\mu$

F_L: K* Long. Polarization

A_{FB}: μ FB Asymmetry

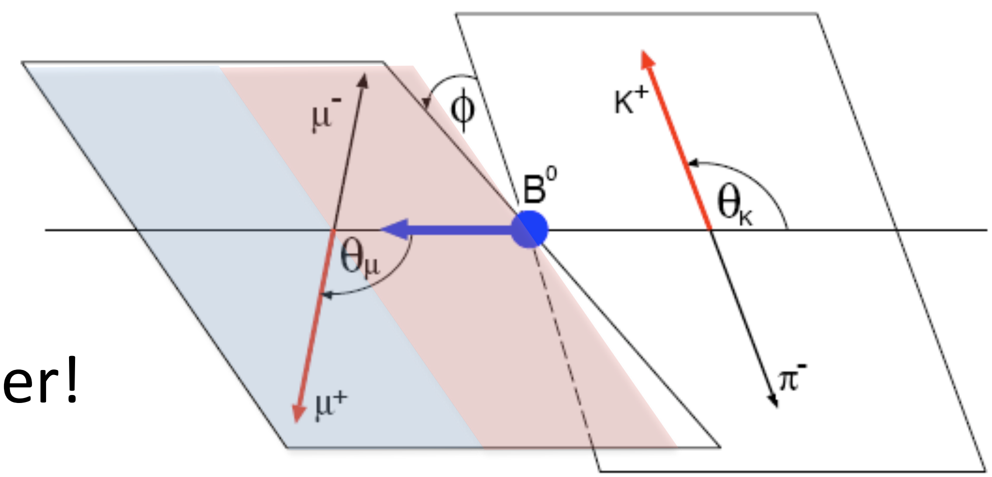






-- SM prediction

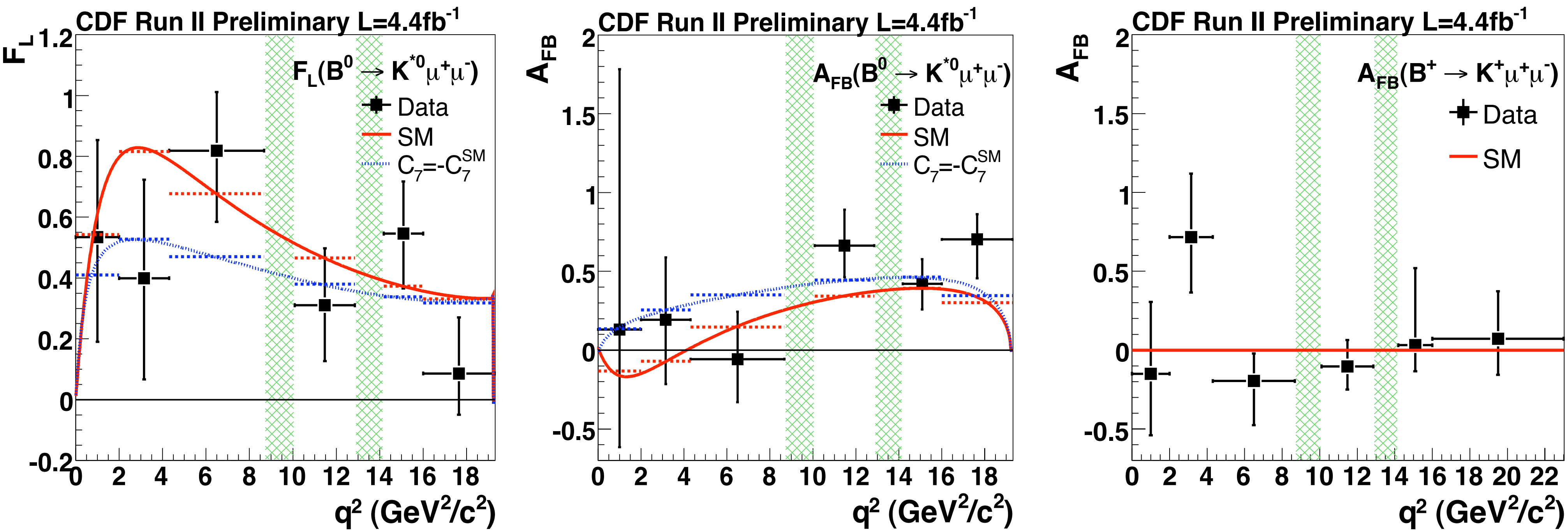
-- BSM scenario



First measurement at a hadron collider!

A_{FB} in $B \rightarrow K^{(*)}\mu\mu$

F_L: K* Long. Polarization A_{FB}: μ FB Asymmetry



-- SM prediction

-- BSM scenario

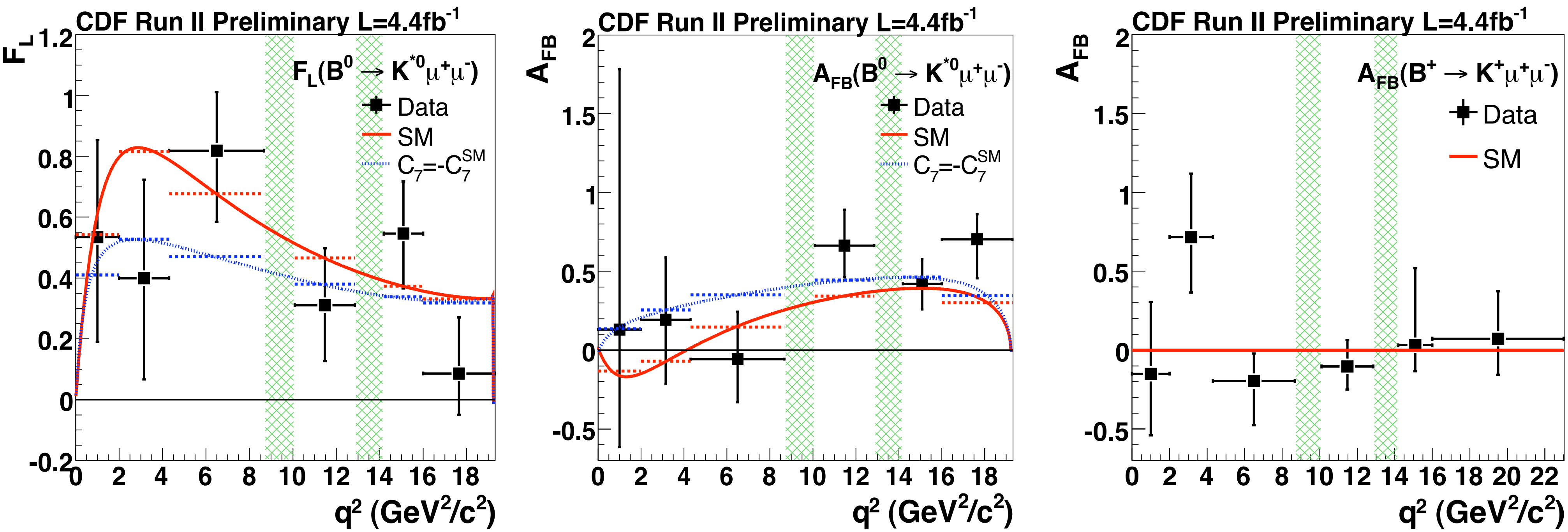
Consistent with B-factory measurements:

Babar 384M BB, PRD 79, 031102(R) (2009)

Belle 657M BB, PRL 103, 171801 (2009)

A_{FB} in $B \rightarrow K^{(*)}\mu\mu$

F_L: K* Long. Polarization A_{FB}: μ FB Asymmetry



-- SM prediction

-- BSM scenario

There is a lot of room for improvement!

Expect more precise measurements by:

- 2× more data
- additional trigger path
- additional decay channels

$B_{(d,s)} \rightarrow \mu\mu$ Rare Decays

- Highly suppressed in SM
- SM expected limits:

  $\mathcal{B}(B_d \rightarrow \mu\mu) < (1.00 \pm 0.14) \times 10^{-10} \sim |V_{td}|^2$

  $\mathcal{B}(B_s \rightarrow \mu\mu) < (3.86 \pm 0.57) \times 10^{-9} \sim |V_{ts}|^2$

  G. Buchalla, A.J. Buras Nucl. Phys. B400, 225 (1993)
  A.J. Buras PRL B 566, 115 (2003)

  – Order of magnitude below detector sensitivities

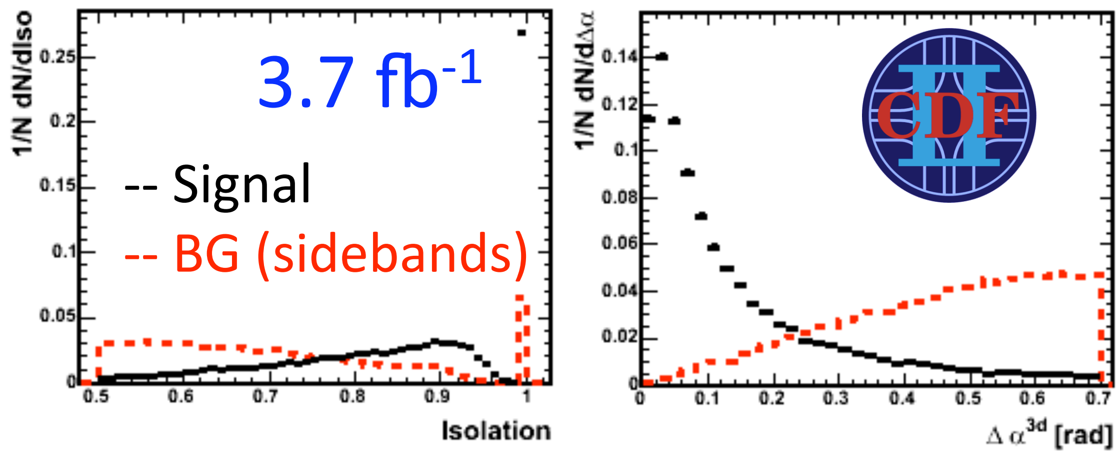
- New physics could greatly enhance $\mathcal{B}$
  – up to 100 × SM

- Observation of this decay would be an unambiguous sign of new physics!

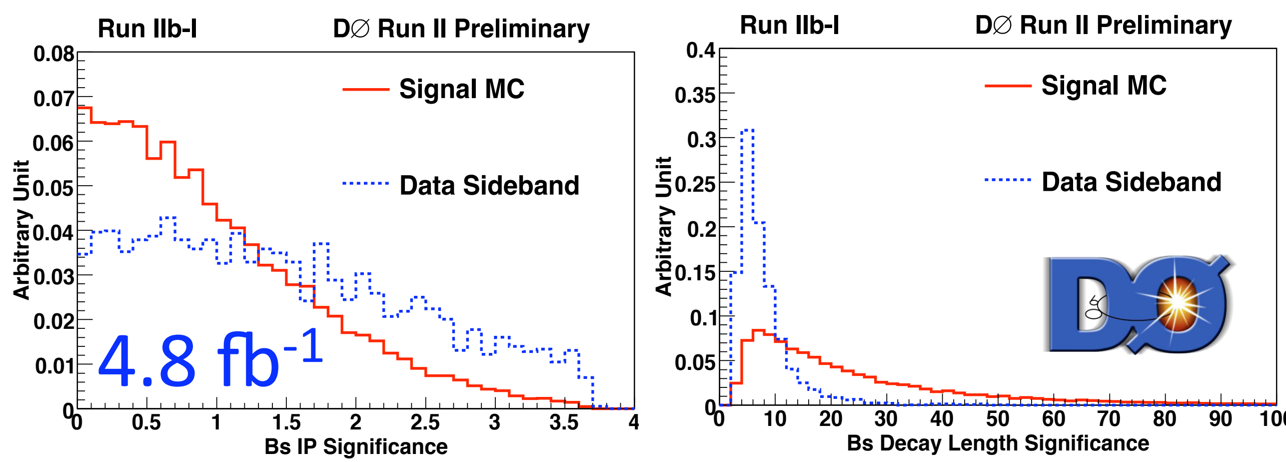
$B_{(d,s)} \rightarrow \mu\mu$

- Muons form B-candidate vertex
- 6 input variables
  - B-candidate decay length and significance
  - B-candidate track isolation
  - Opening angle between B-candidate momentum and decay length
  - $p_T(B)$ and $p_T(\mu_{LOW})$

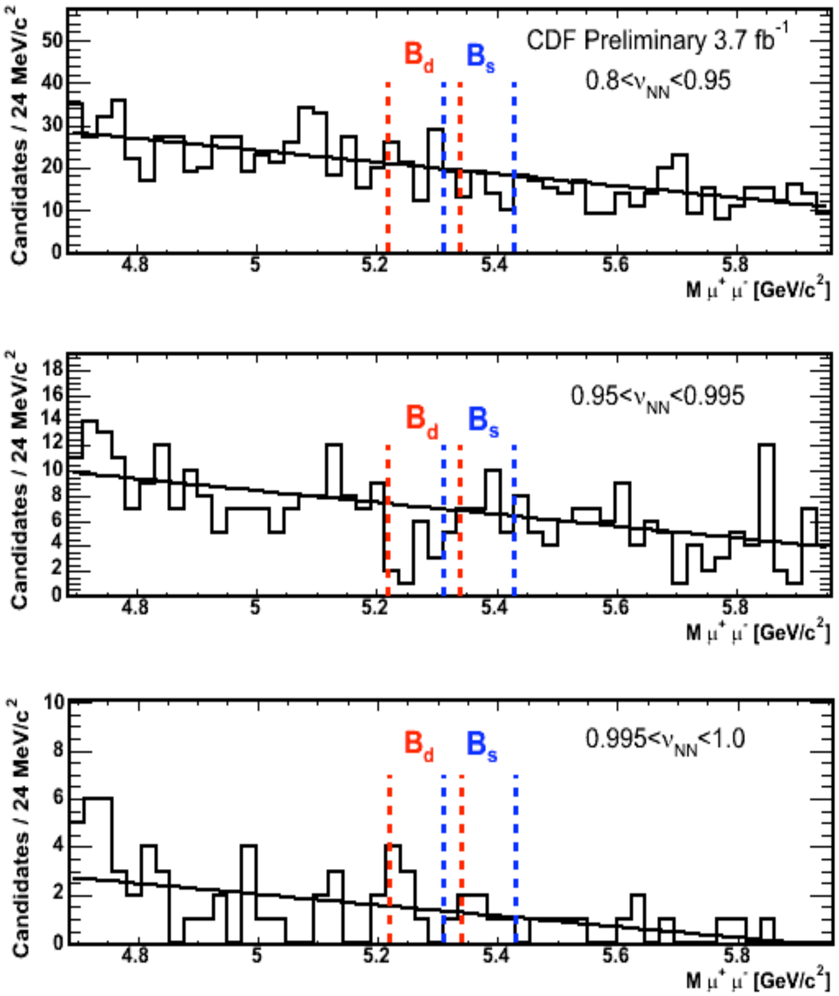
Inputs to Neural Network

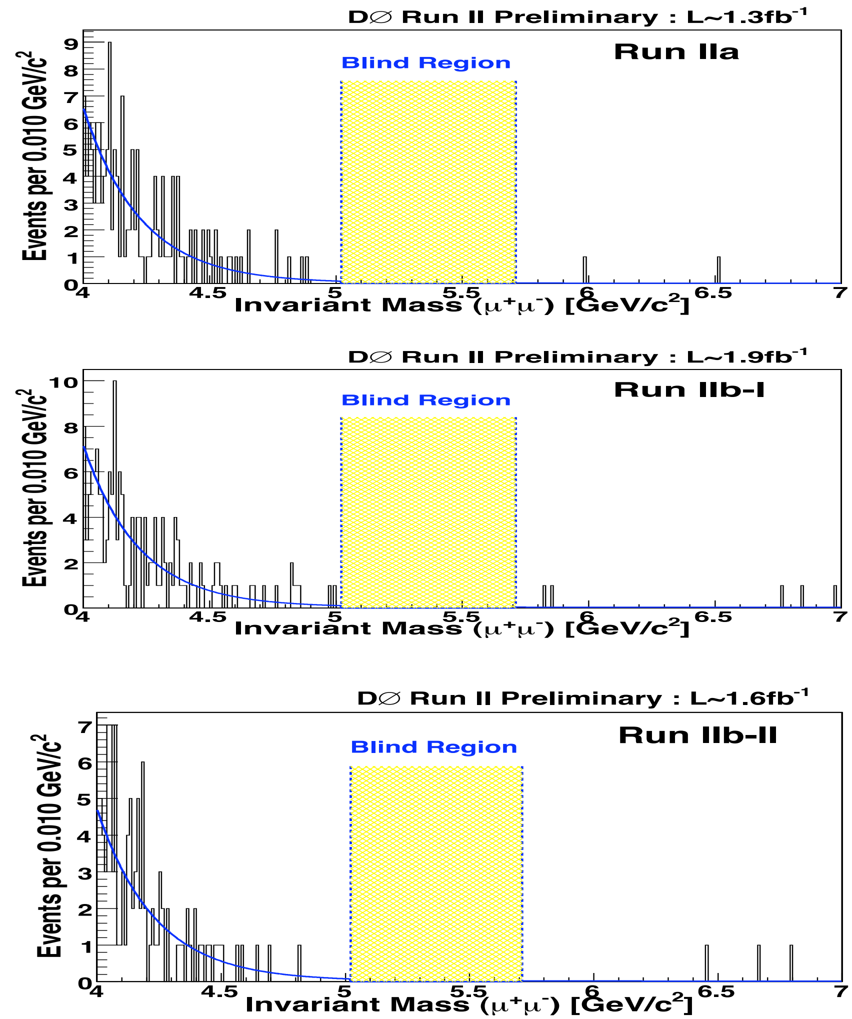


Inputs to Boosted Decision Tree



$B_{(d,s)} \rightarrow \mu\mu$





$\mathcal{B}(B_d \rightarrow \mu\mu) < 7.6 \times 10^{-9}$
$\mathcal{B}(B_s \rightarrow \mu\mu) < 4.3 \times 10^{-8}$
(95% CL in 3.7 fb^{-1})

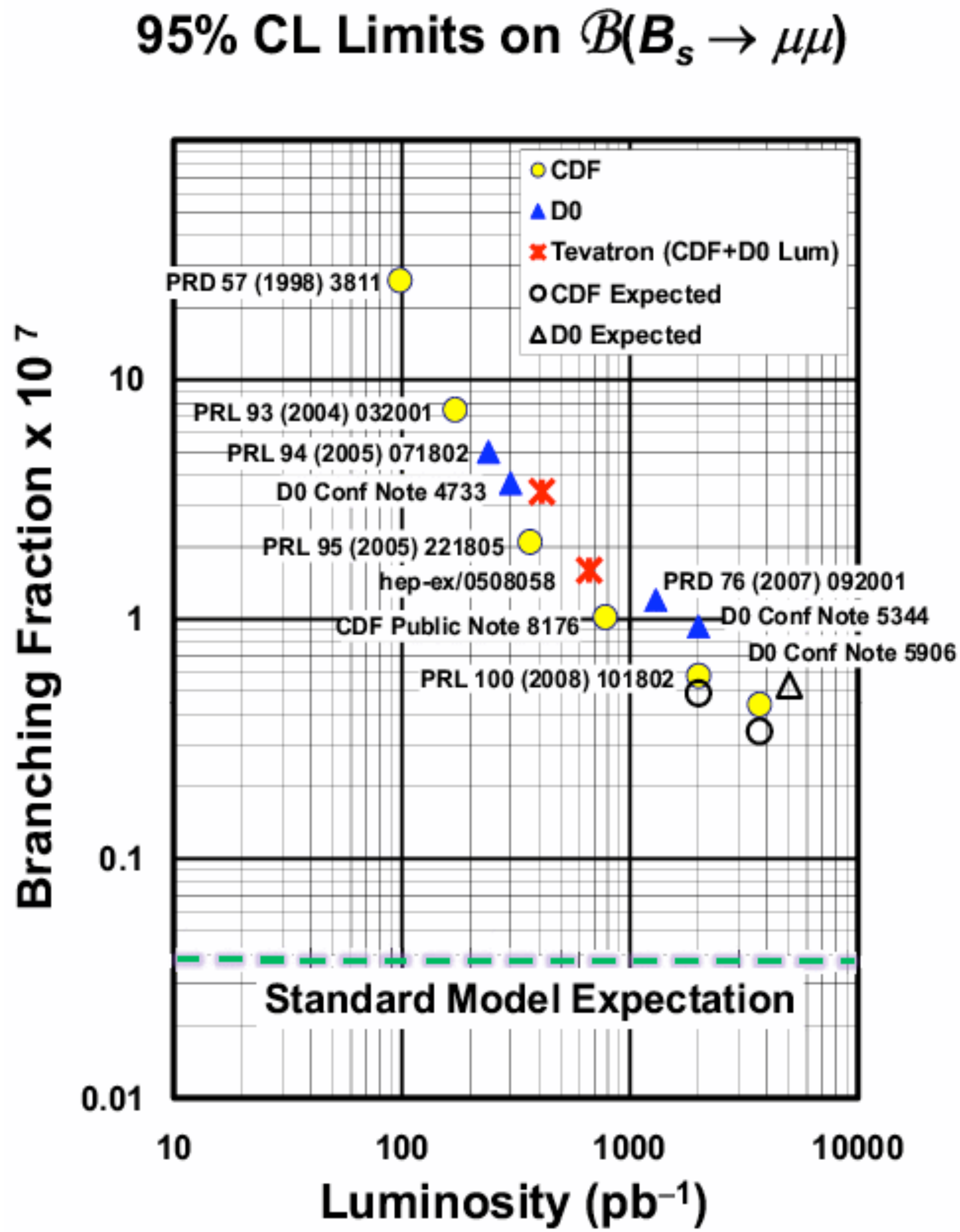
[CDF Public Note 9892]

Expected upper limit in 5 fb^{-1}
$\mathcal{B}(B_s \rightarrow \mu\mu) < 5.3 \times 10^{-8}$ (95% CL)

[DØ Conf. Note 5906]

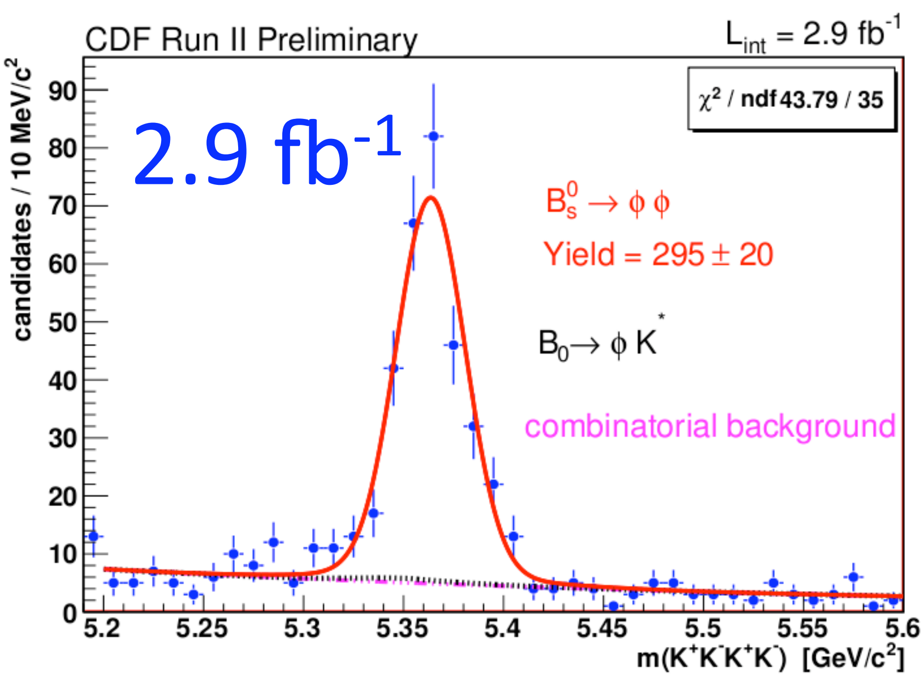
$B_s \rightarrow \mu\mu$

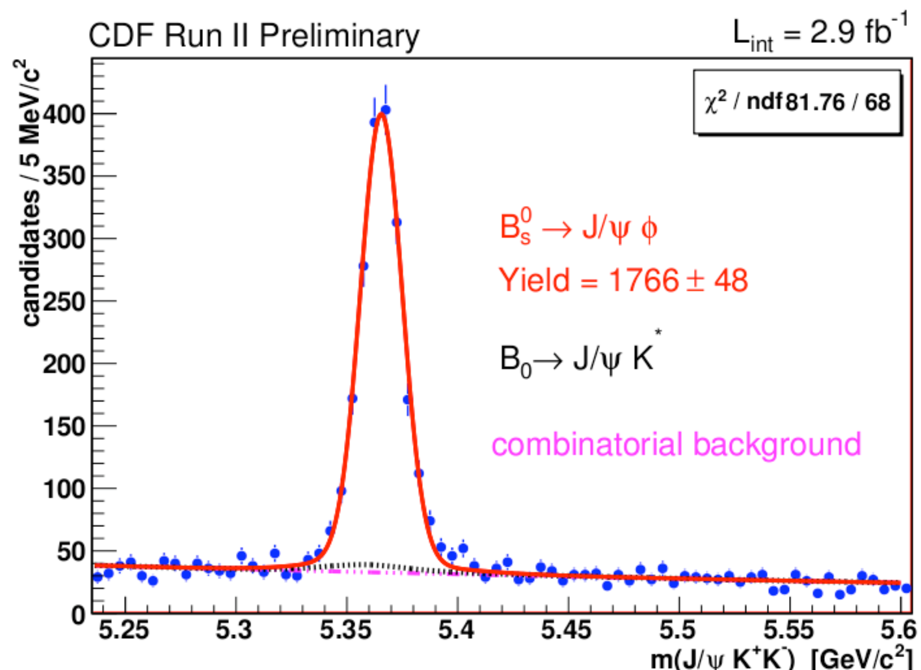
- Enhancement over SM greater than ~10× already excluded
- Combined Tevatron expected limits may reach 4× with 8 fb^{-1}
- Improvements ongoing
- Stay tuned!



$\mathcal{B}(B_s \rightarrow \phi\phi)$

- $B_s \rightarrow \phi\phi$ and $B_s \rightarrow J/\psi\phi$ (normalization) reconstructed





[CDF Public Note 10064]

$\mathcal{B}(B_s \rightarrow \phi\phi)/\mathcal{B}(B_s \rightarrow J/\psi\phi)$ = [1.78 ± 0.14 (stat) ± 0.20 (syst)] × 10^{-2}

$\mathcal{B}(B_s \rightarrow \phi\phi)$ extracted using world average value of $\mathcal{B}(B_s \rightarrow J/\psi\phi)$

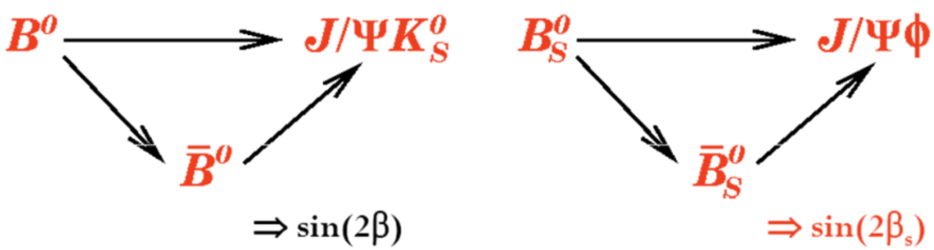
$\mathcal{B}(B_s \rightarrow \phi\phi)$ = [2.40 ± 0.21 (stat) ± 0.27 (syst) ± 0.82 (BR)] × 10^{-5}

- Measurement of amplitude analysis in progress

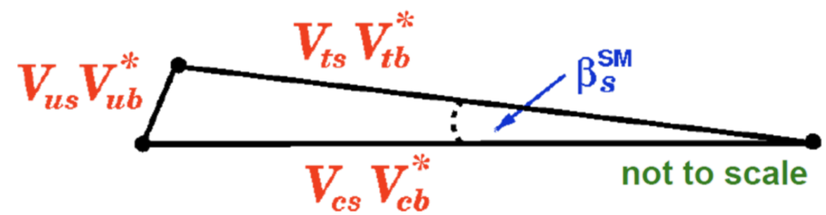
CPV in B_s System

- CPV in B_s system occurs through interference of decays with and without mixing, analogous to B_d system

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- B_s mass eigenstates B_s^L, B_s^H
  - Mass difference $\Delta m_s = m_H - m_L \sim 2|M_{12}|$
  - Width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$



- CP violating phases

$\phi_s = \arg(-M_{12}/\Gamma_{12})$ $\qquad$ $\phi_s^{SM} \sim 0.004$

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

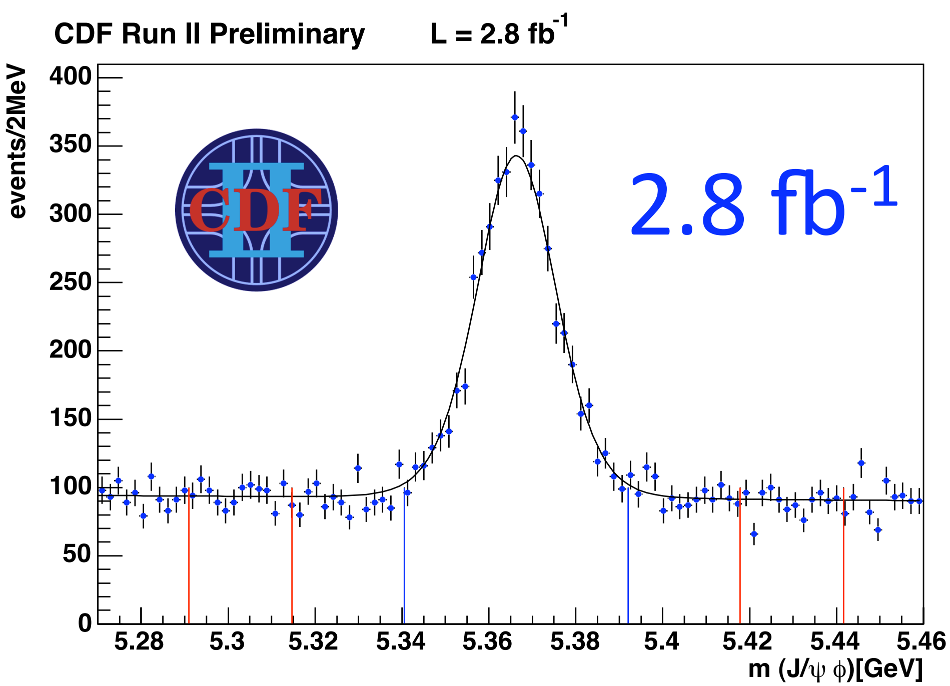
A. Lenz and U. Nierste, JHEP 06, 072(2007)

- ϕ_s^{NP} contributes to both ϕ_s and β_s

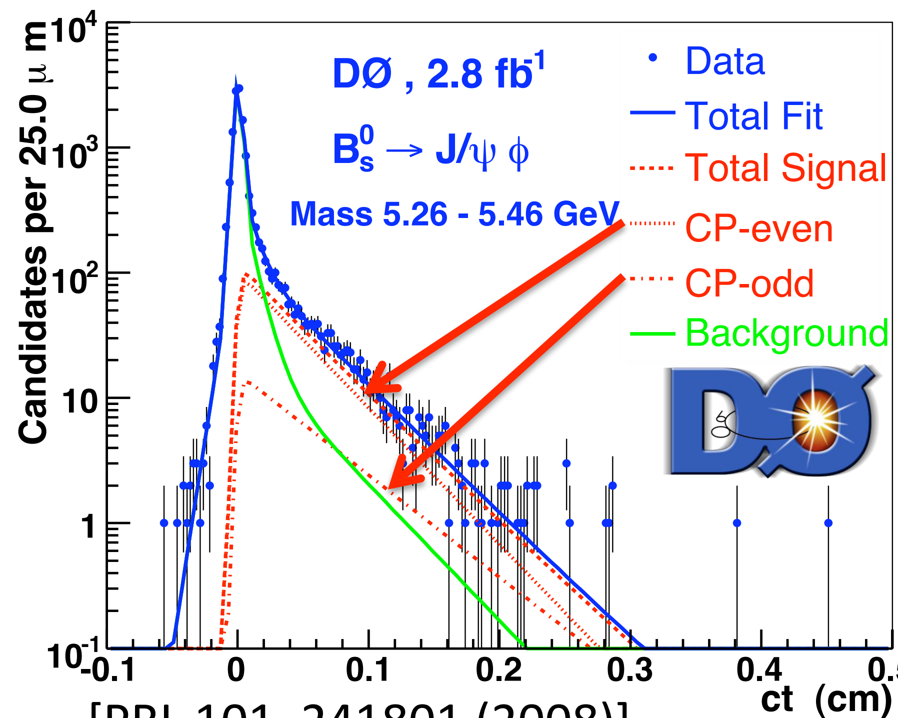
$-2\beta_s = -2\beta_s^{SM} + \phi_s^{NP}$ $\qquad$ $-2\beta_s \sim \phi_s$ if NP dominates

CPV in $B_s \to J/\psi\phi$

- CPV mixing phase in $B_s \to J/\psi\phi$ very small in SM:
  - $\phi_s^{J/\psi\phi,SM} = -2\beta_s^{J/\psi\phi,SM} = -0.04$
  - Large measured value sure sign of new physics
- Angular analysis
  - Separate into CP-even and CP-odd components



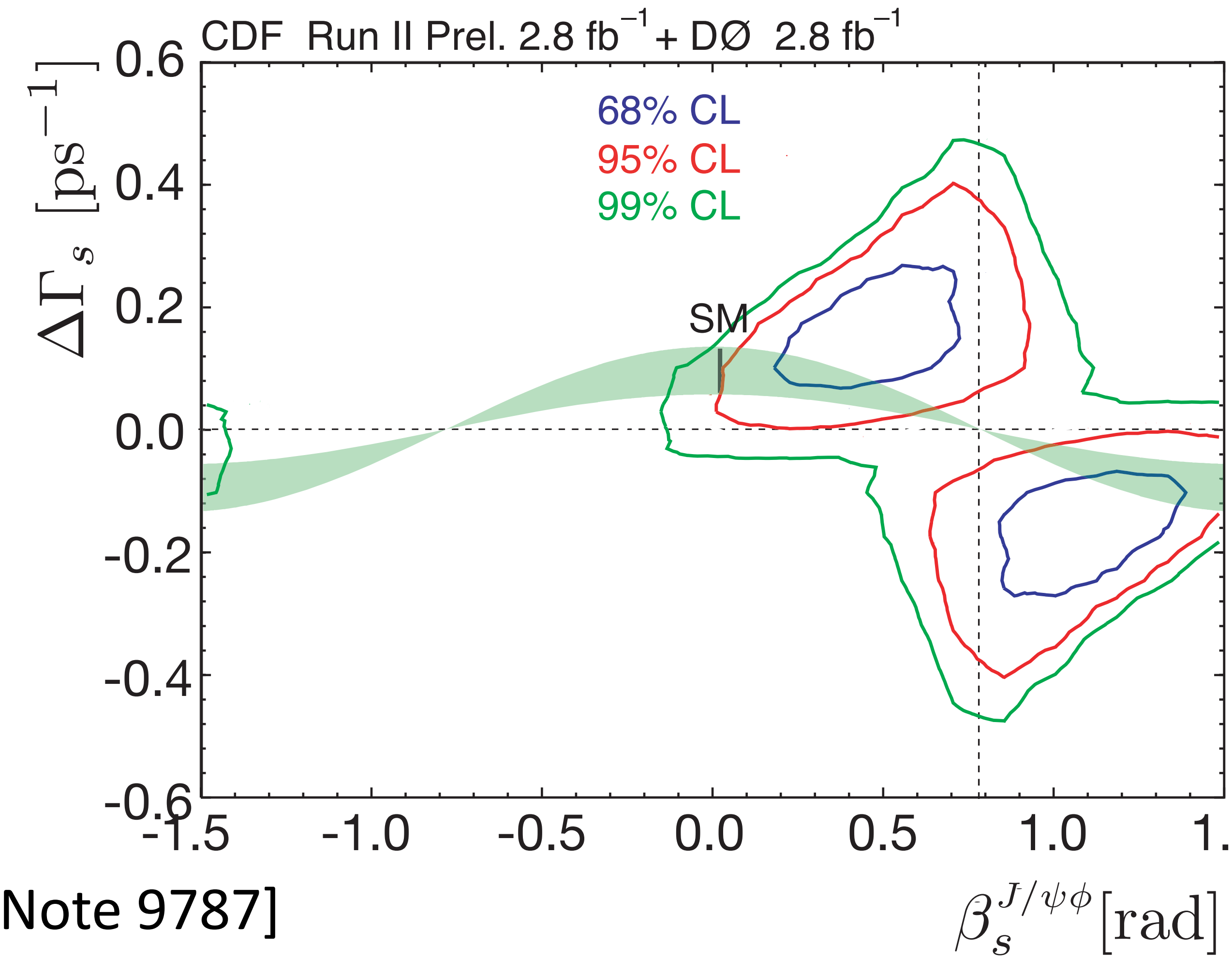
[CDF Public Note 9458]



[PRL 101, 241801 (2008)]

$B_s \rightarrow J/\psi\phi$ Combination

- Combined 2D profile likelihood
  $\Delta\Gamma_s$ vs. $\beta_s^{J/\psi\phi}$



- Region allowed by new physics models given by:
  $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$
- 2.1σ deviation from SM

[D0 Note 5928, CDF Public Note 9787]

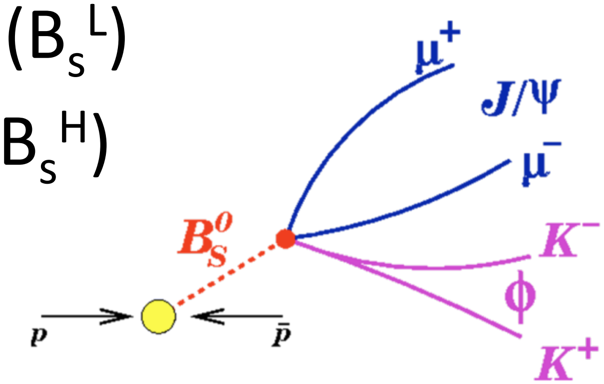
Conclusions & Prospects

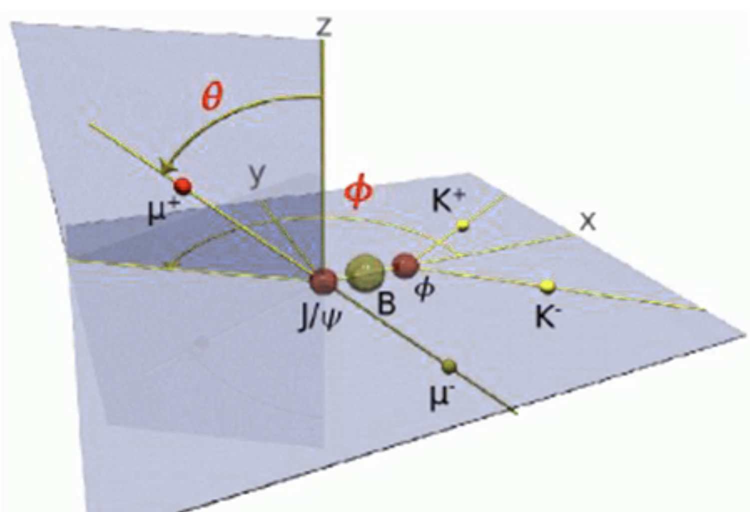
- Tevatron experiments are very active in B physics
- $B_s \rightarrow \phi\mu\mu$ (4.4 fb^{-1})
  - First observation!
- $B \rightarrow K^{(*)}\mu\mu$ (4.4 fb^{-1})
  - First measurement of A_{FB} at a hadron collider!
- $B_{d,s} \rightarrow \mu\mu$ (3.7 and 4.8 fb^{-1})
  - New world's best upper limit!
- $B_s \rightarrow J/\psi\phi$
  - Tevatron combination 2.1σ deviation from SM
- 7.9 fb^{-1} delivered to each experiment
- ~12 fb^{-1} of data expected to be delivered by the end of 2011
- Can expect many improved results and maybe new discoveries in the next two years!

Backup

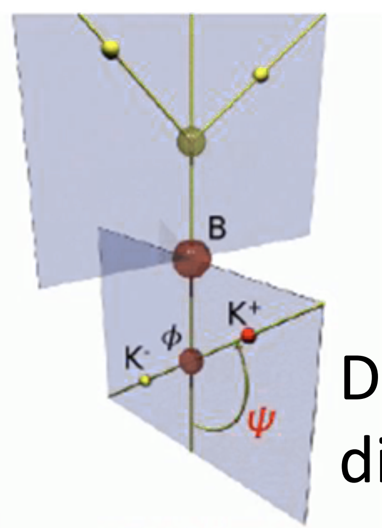
$B_s \rightarrow J/\psi\phi$

- Golden channel to measure B_s CPV
- Can measure lifetime, $\Delta\Gamma_s$, and β_s
- B_s (S=0) decay to J/ψ (S=1) and ϕ (S=1) leads to three different angular momentum final states
- L=0 (s-wave), 2 (d-wave) → CP-even (B_s^L)
- L=1 (p-wave) → CP-odd (B_s^H)





J/ψ rest frame



φ rest frame

Disentangle CP states by angular distributions of the decay products

A_{FB} in B→$K^{(*)}\mu\mu$ (5 bin)

- 1^{st} and 2^{nd} bin are merged

F_L: K* Long. Polarization A_{FB}: μ FB Asymmetry