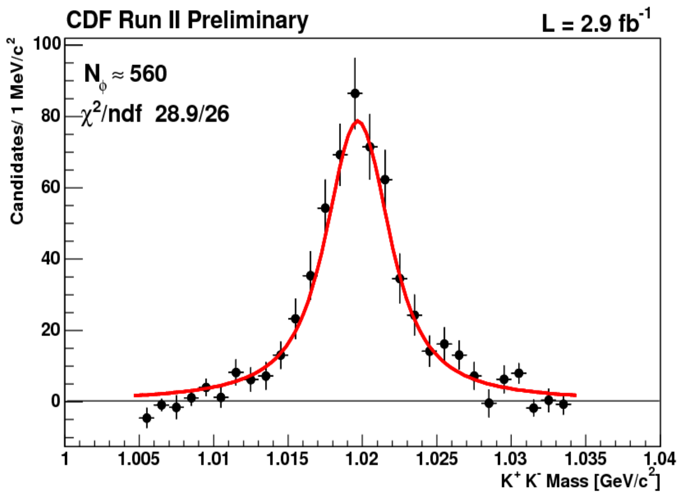
Search for non-standard model physics in rare decays at CDF

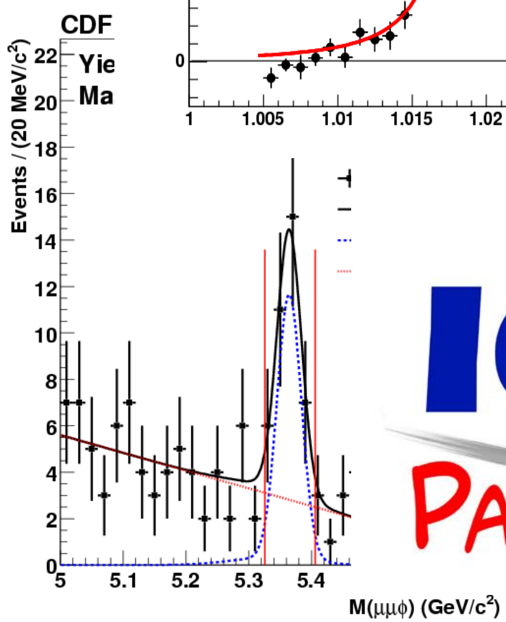
Marco Rescigno

INFN/Roma

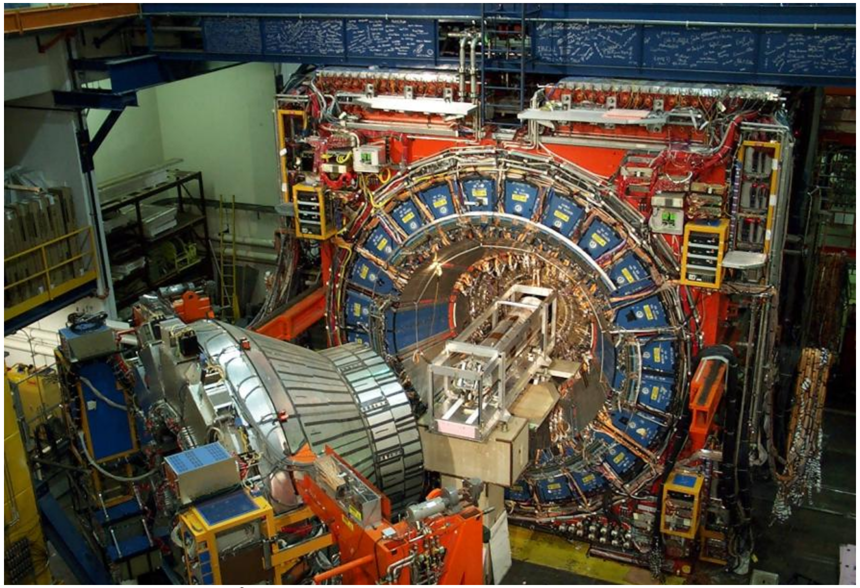
On behalf of CDF collab.

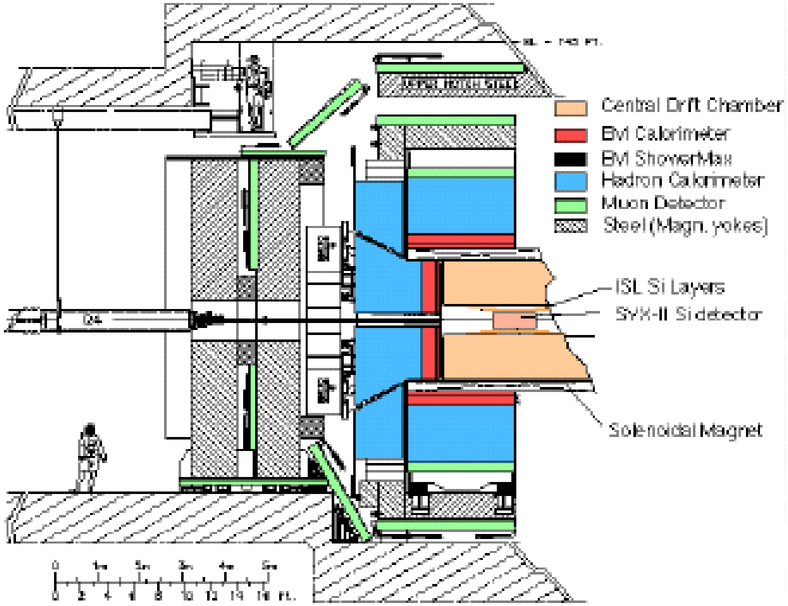
ICHEP 2010, Paris, 24-7-2010

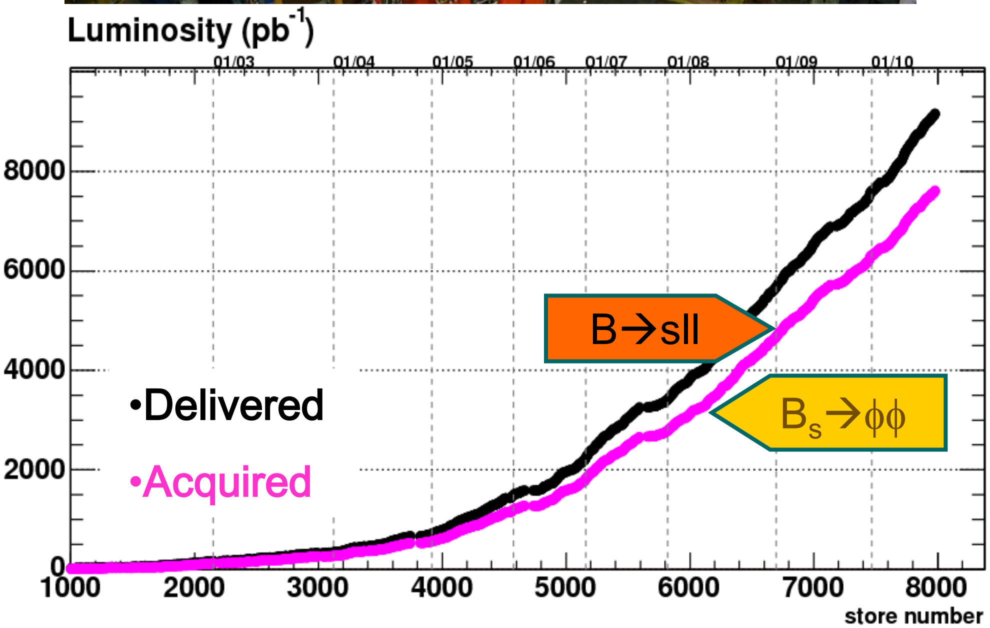




- $B_s \rightarrow \mu^+\mu^-$ search
- Exlcusive electroweak leptonic B decay
  - $B \rightarrow K(*)\ \mu^+\mu^-$ differential rate and forward-backward asymmetry
  - $B_s \rightarrow \phi\mu^+\mu^-$ observation
- $B_s \rightarrow \phi\phi$
  - First polarization measurement
- Prospects

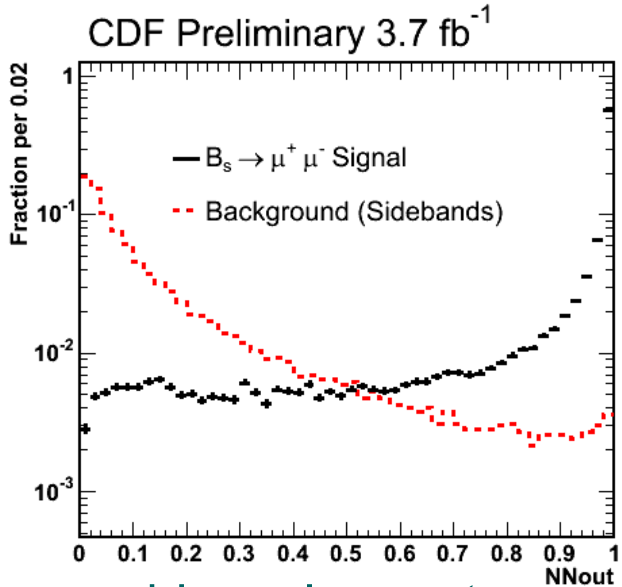


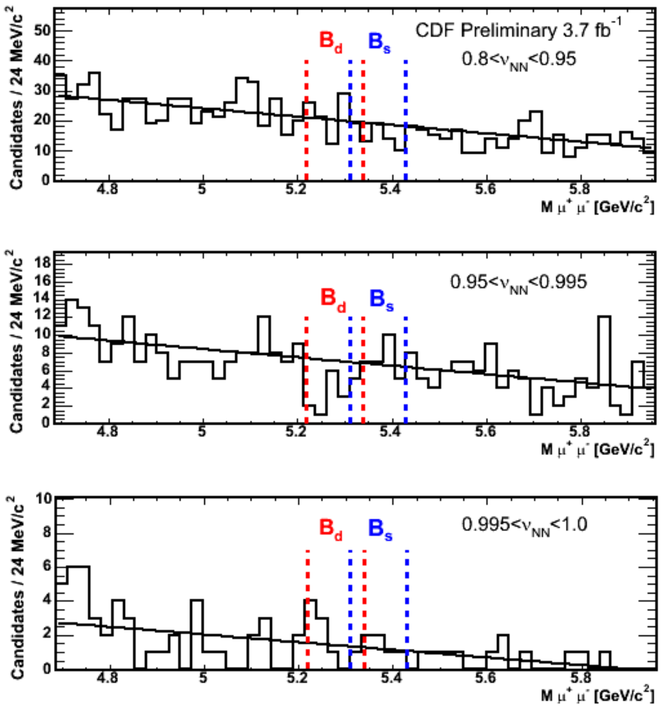




- Flexible Triggering on dimuon or displaced tracks
- Excellent p_T ($0.0015 \cdot p_T$) and vertex resolution (90-100 fs)
- Key elements for rare leptonic, semileptonic and hadronic B decays

$B_s \rightarrow \mu^+\mu^-$ search

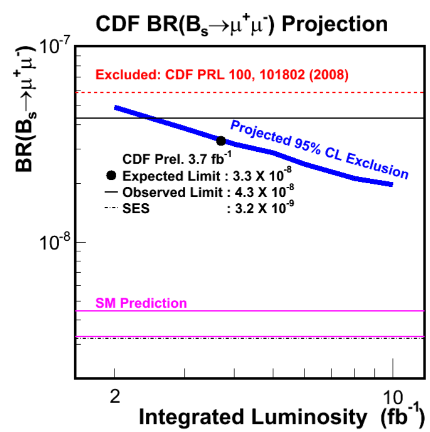




- Suppress bkg using vertex and kinematic variables in a NN trained on MC/sideband data
- CDF mass resolution allow separation of B_s and B_d signal regions
- World best limit on 3.7 fb^{-1} of data:

$$BR(B_s \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-8} \; @ \; 95\% \; C.L.$$

$$BR(B_d \rightarrow \mu^+\mu^-) < 7.6 \times 10^{-9} \; @ \; 95\% \; C.L.$$



CDF public note 9892

Exclusive $b \rightarrow s\mu^+\mu^-$

- Previous result (1 fb^{-1}): *Phys. Rev. D79, 011104(R) (2009)*
  - Observation of exclusive B_d,B^+ modes, upper limit on $B_s \rightarrow \phi\mu^+\mu^-$

- New analysis based on 4.4 fb^{-1}: *CDF public note 10047*
  - Trigger on dimuons (p_T^{μ}>2 GeV) forming a displaced vertex
  - Look for:

    $B^+ \rightarrow K^+ \mu^+\mu^-$, $B_d \rightarrow K^{*0} \mu^+\mu^- \rightarrow [K^+\pi^-] \mu^+\mu^-$, $B_s \rightarrow \phi \mu^+\mu^- \rightarrow [K^+K^-] \mu^+\mu^-$

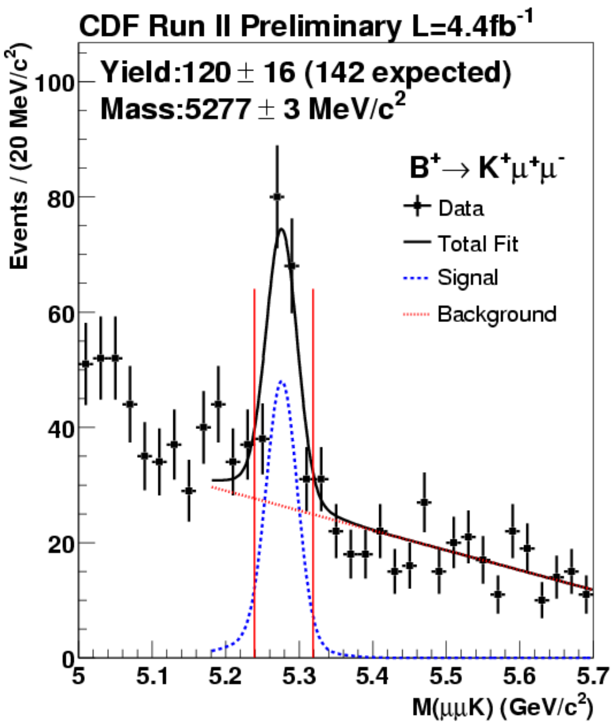
  - To reject $B \rightarrow J/\psi$ (ψ') remove:

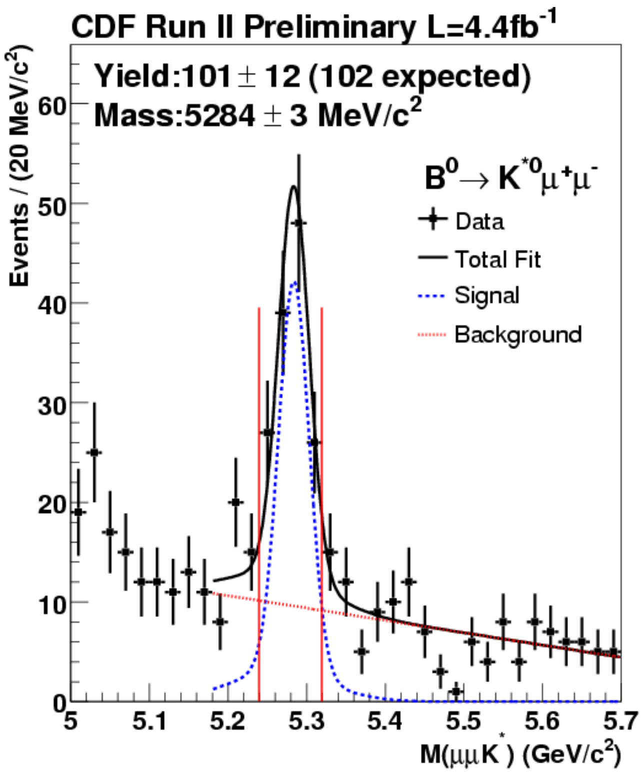
    $8.68 < M^2_{\mu+\mu-} < 10.09 \cup 12.86 < M^2_{\mu+\mu-} < 14.18$ GeV^2

  - Vertex quality, PID (dE/dx and TOF) + kinematic variables combined in a Neural Network to optimize sensitivity:
    - $S/\sqrt{(S+B)}$ for known modes
    - $S/(2.5+\sqrt{B})$ for B_s mode

  - Normalize rate to $B \rightarrow J/\psi\ h$ ($h=K,K^*,\phi$) to obtain BR

$B \to K^{(*)} \mu^+\mu^-$ signals



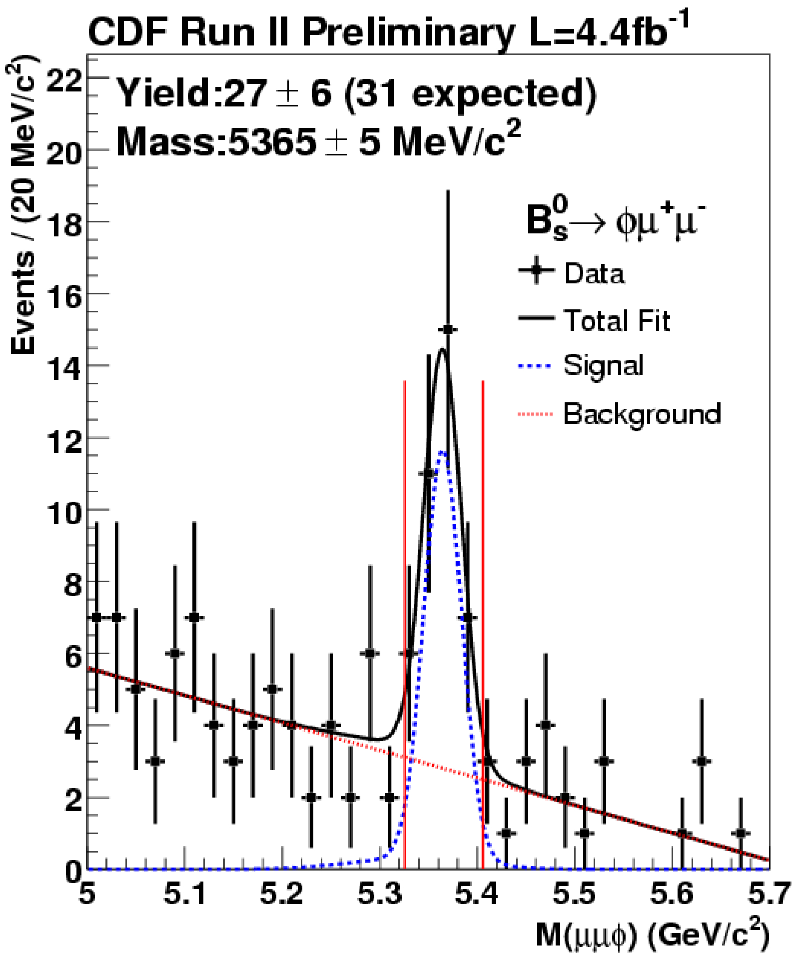


	$B^+ \to K^+\mu^+\mu^-$	$B^0 \to K^{*0}\mu^+\mu^-$
CDF	$[0.38\pm0.05\pm0.03]\times10^{-6}$	$[1.06\pm0.14\pm0.09]\times10^{-6}$
Babar	$[0.41\pm0.16\pm0.02]\times10^{-6}$	$[1.35\pm0.40-0.37\pm0.10]\times10^{-6}$
Belle	$[0.53\pm0.08(+0.07-0.03]\times10^{-6}$	$[1.06+0.19-0.14\pm0.07]\times10^{-6}$

PRL 102, 091803 (2009)

PRL. 103, 171801 (2009)

$B_s \to \phi\mu^+\mu^-$ First Observation



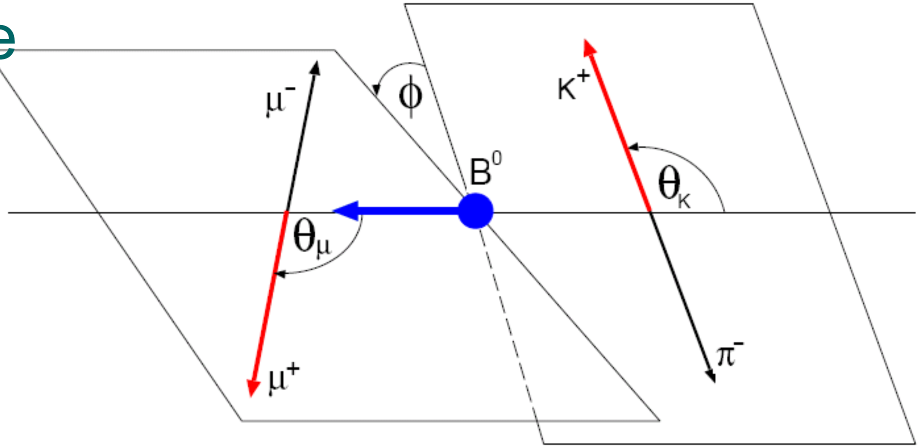
- Unbinned ML fit to B_s candidate mass
  - Signal: double Gaussian from MC (width adjusted to data)
  - Background: linear shape
- 27±6 signal events (6.3 σ)
- Normalize measured rate to BR($B_s \to J/\psi\phi$)
  - dominant syst.

$$BR(B_s \to \varphi\mu^+\mu^-) = (1.44 \pm 0.33(stat.) \pm 0.46(sys.)) \times 10^{-6}$$

Compare to $BR(B_s \to \varphi\mu^+\mu^-) \sim 1.6 \cdot 10^{-6}$ C. Q. Geng, C. C. Liu, J. Phys. G29, 1103 (2003)

$B_d \to K^{*0}\mu^+\mu^-$ angular analysis

- Kaon and muon decay angle in the B rest frame give longitudinal decay fraction and forward backward asymmetry



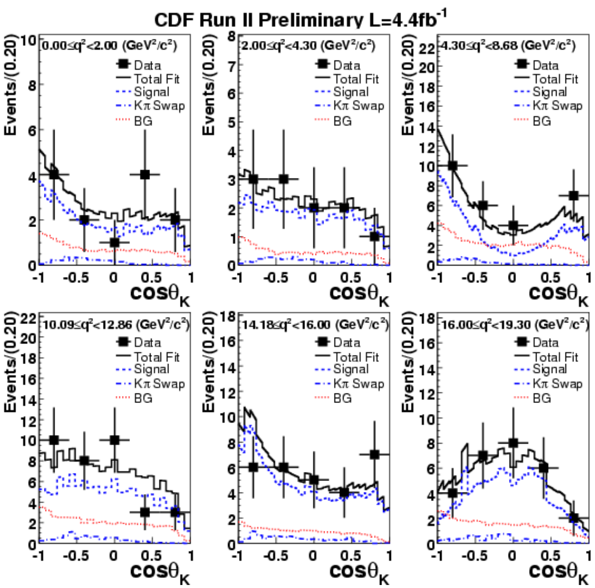
$$\frac{1}{\Gamma}\frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\cos\theta_K} = \frac{3}{2}\mathrm{F_L}\cos^2\theta_\mathrm{K} + \frac{3}{4}(1-\mathrm{F_L})(1-\cos^2\theta_\mathrm{K}),$$

Fit Parameters

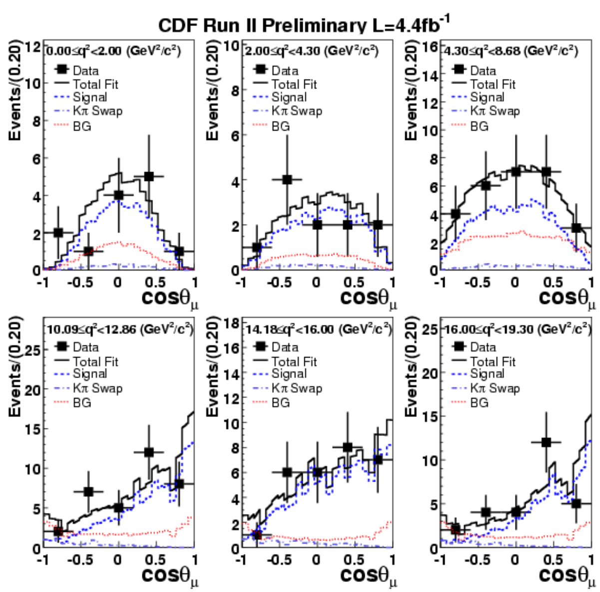
$$\frac{1}{\Gamma}\frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{d\cos\theta_\mu} = \frac{3}{4}\mathrm{F_L}(1-\cos^2\theta_\mu) + \frac{3}{8}(1-\mathrm{F_L})(1+\cos^2\theta_\mu) + \mathrm{A_{FB}}\cos\theta_\mu$$

- Correct for acceptance via detailed simulation
- 5 or 6 bin in $q^2=m_{\mu\mu}^2$ excluding ccbar resonances
- Cross check with $B \to J/\psi$ X samples

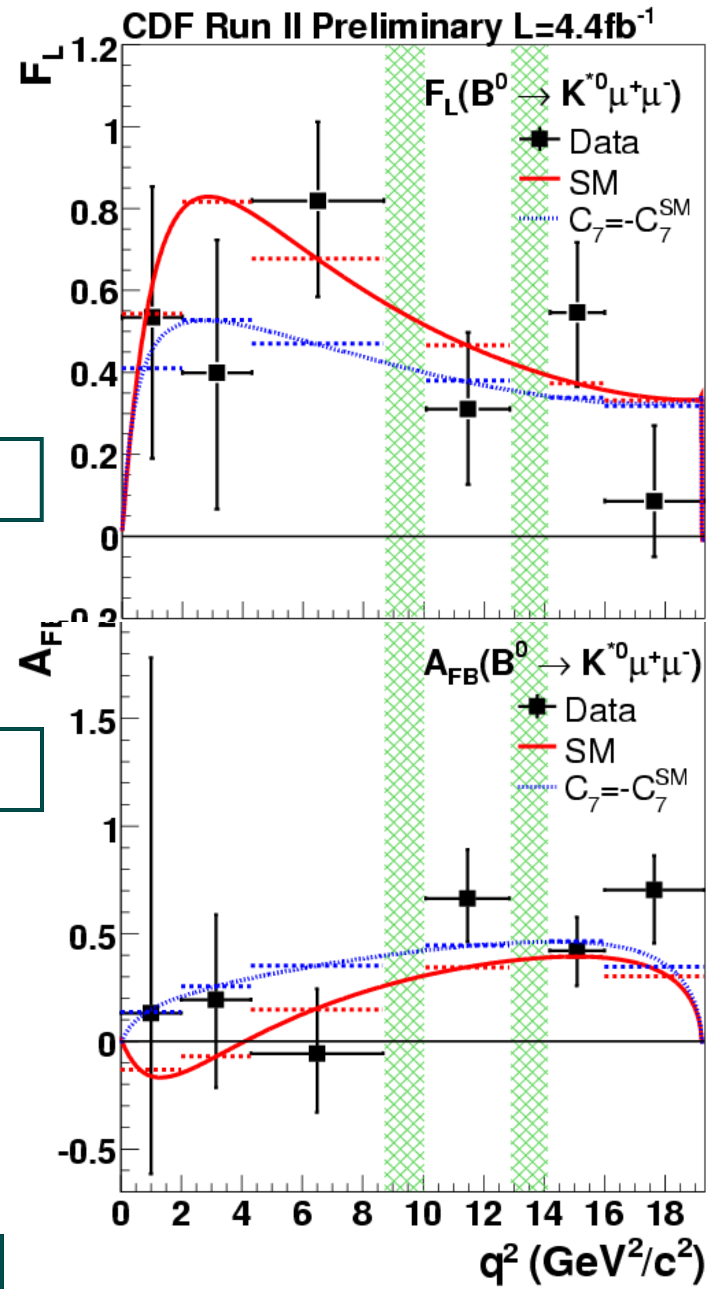
Decay Angle Analysis



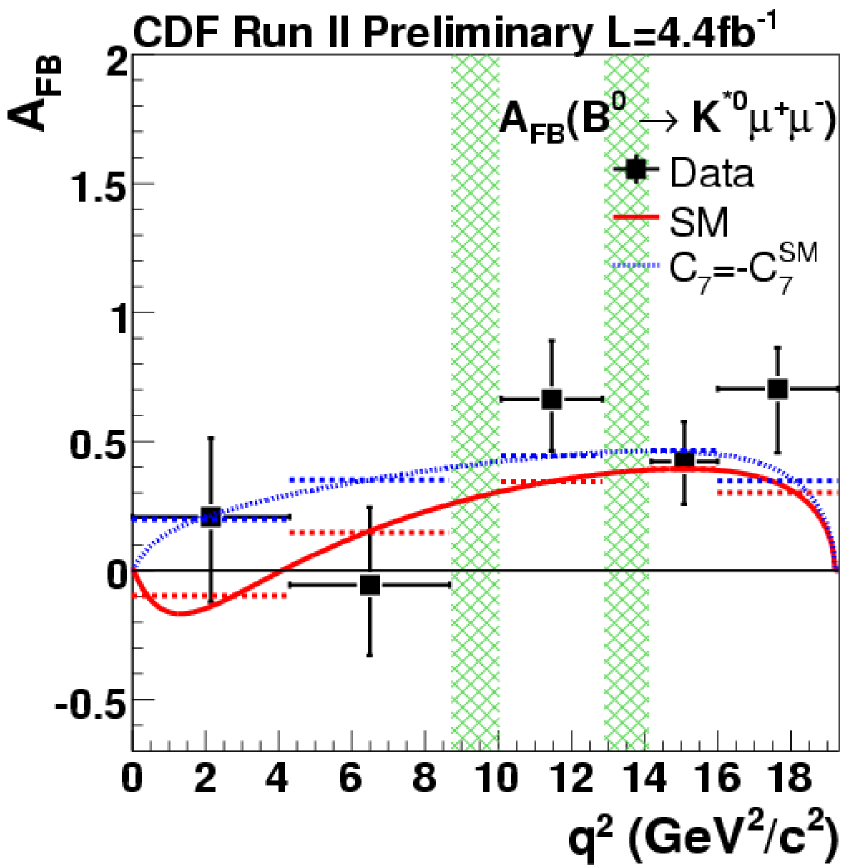
Fit $\cos(\theta_K)$



Fit $\cos(\theta_\mu)$



A_{FB} result $B_d \rightarrow K^* \mu^+ \mu^-$



- CDF provides a measurement in 5 bin and also in the theoretically cleanest range $1<q^2<6$:

$$A_{FB}^{CDF}(1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.43^{+0.36}_{-0.37} \pm 0.06$$

- Compare to Belle 660×10^6 B

$$A_{FB}^{Belle}(1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.26^{+0.27}_{-0.30} \pm 0.07$$

$$A_{FB}^{(*)}(1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.33^{+0.22}_{-0.23} \pm 0.07$$

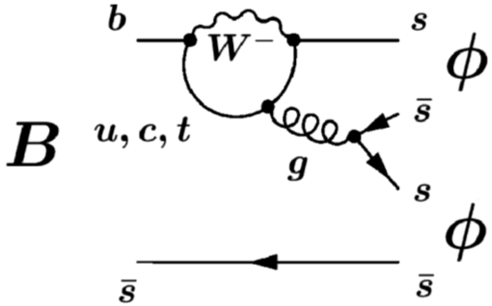
$$A_{FB}^{(th)}(1 < q^2 < 6 \text{ GeV}^2/c^4) = -0.05^{+0.03}_{-0.04}$$ C.Bobeth, et al. arXiv : 1006.5013

- Still inconclusive, wait for more data

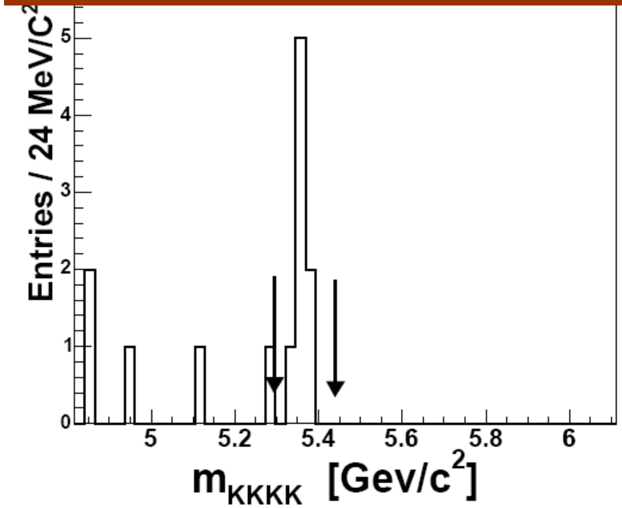
(*) speaker very naïve average !

$B_s \to \phi\phi$ at CDF

- $b \to s$ penguin dominated decay



CDF Phys. Rev. Letters **95** 031801 (2005)



- Thanks to the CDF displaced track trigger :
  - First evidence in just 180 pb^{-1} of Run II data (2004) with 8 events

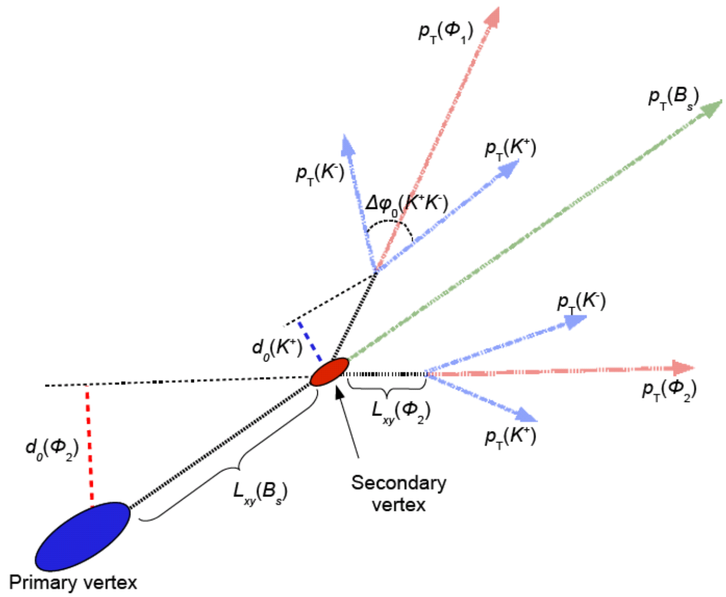
- With 2.9 fb-1 of data perform:
  - Improved BR measurement
  - Measurement of polarization amplitudes
    - First experimental data on charmless $B_s \to$ Vector–Vector : insight into the so called "polarization puzzle"

CDF public note 10064

CDF public note 10120

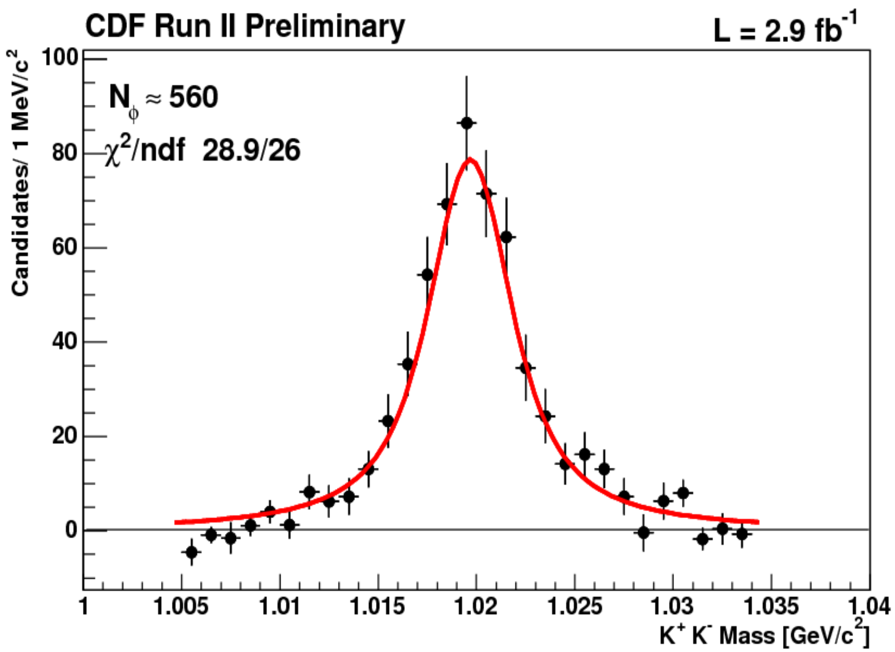
- Powerful probe for new physics in Bs mixing or in penguin decays via indirect CP violation → null SM prediction (not for today)

$B_s \rightarrow \phi\phi \rightarrow [K^+K^-][K^+K^-]$ Signal

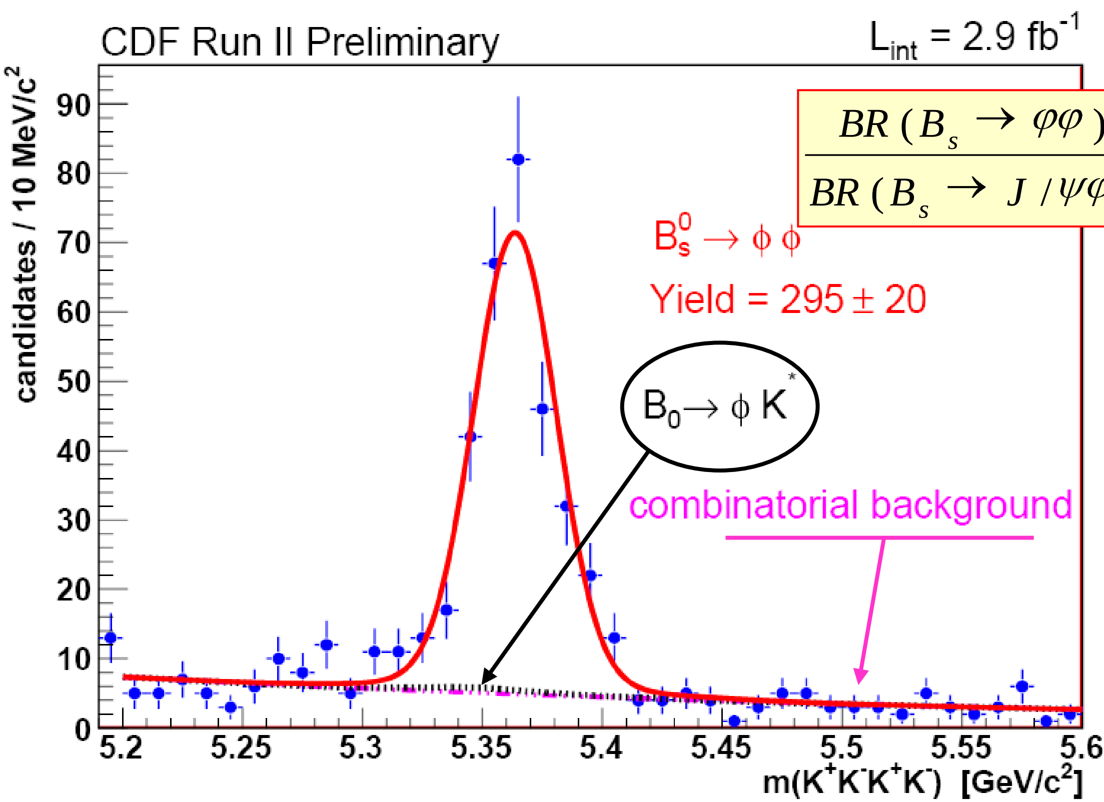


Variables		Requirements	
		$B_s^0 \to \phi\phi$	$B_s^0 \to J/\psi\phi$
L_{xy}^B	$[\mu m]$	> 330	> 290
$p_{T\,\min}^K$	$[GeV/c]$	> 0.7	
p_T^ϕ	$[GeV/c]$		> 1.4
χ_{xy}^2		< 17	< 15
d_0^B	$[\mu m]$	< 65	< 80
$d_0^{\phi\max}$	$[\mu m]$	> 85	
$p_T^{J/\psi}$	$[GeV/c]$		> 2.0

- Take $|m(KK)-m_{\phi(1020)}|<15$ MeV/c^2
- $B_d \rightarrow \phi K^*$ reflection ~ 3%, no other peaking bkg from simulation of B_s or Λ_b decays
- Use $B_s \rightarrow J/\psi\phi$ with the same trigger selection for normalization in the BR measurement and as a powerful control sample for polarization measurement



Branching Ratio $B_s \to \phi\phi$



- CDF main result:

$$\frac{BR(B_s \to \varphi\varphi)}{BR(B_s \to J/\psi\varphi)} = (1.78 \pm 0.14(stat.) \pm 0.20(sys.)) \times 10^{-2}$$

- Syst. dominated by polarization uncertainties (will be reduced)
- Use $BR(B_s \to J/\psi\phi) = [13.5 \pm 4.6] \cdot 10^{-2}$
  - updated from PDG using more recent f_s/f_d

for absolute branching ratio:

$$BR(B_s \to \varphi\varphi) = (24.0 \pm 2.1(stat.) \pm 2.7(sys.) \pm 8.2(BR)) \times 10^{-6}$$

Consistent with both QCDF and pQCD (large uncertainties):

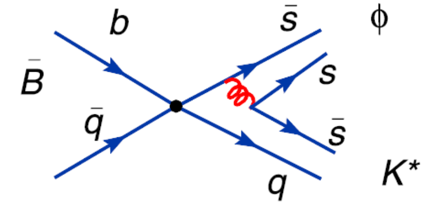
$$BR(B_s \to \varphi\varphi) = \begin{cases} (19.5 \pm 1.0(par.)^{+13.1}_{-8.0}(th.)) \times 10^{-6} & \text{M.Beneke et al., hep-ph/0612290 (QCDF)} \\ (35.3\,^{+8.3}_{-6.9}(par.)^{+16.7}_{-10.2}(th.)) \cdot 10^{-6} & \text{A.Ali et al., hep-ph/0703162 (pQCD)} \end{cases}$$

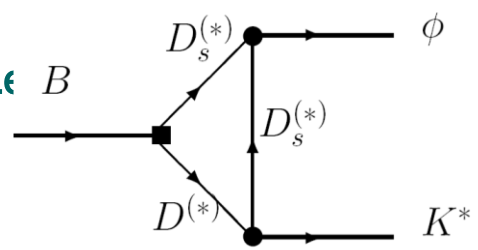
$B_s \to \phi\phi$ Polarization

- In B→VV decays 3 decay product relative angular momentum states possible:
  - 3 independent decay amplitudes
  - Best decomposed in a longitudinal and two transverse polarization amplitudes A_0,$A_{//}$(CP even), $A_\perp$(CP odd)

- Naïve expectation: $|A_0|>>|A_{//}|\sim|A_\perp|$
  - V-A nature of weak interaction and conservation helicity in qcd

- Experimentally violated in penguin decays:
  - subleading contribution (penguin annihilation) **[e.g. A. L. Kagan, Phys. Lett. B 601, 151 (2004); Beneke Nucl.Phys. B774:64-101,2007]**
  - Final State Interaction (FSI) **[P. Colangelo, et al., Phys. Le B 597, 291 (2004) + many others]**
  - New Physics ?

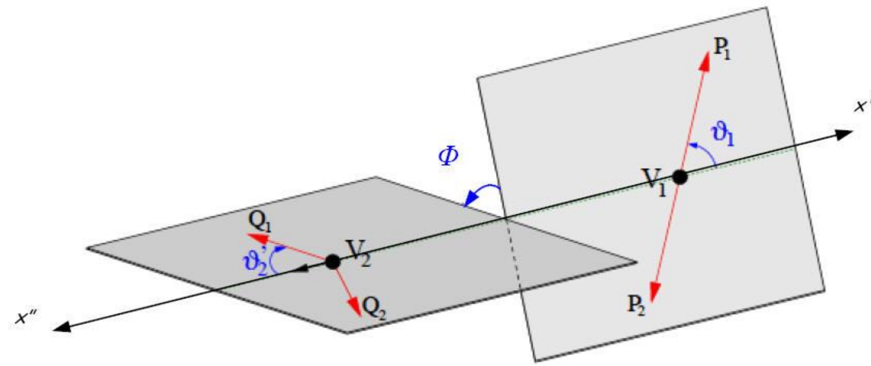




- $B_s \to \phi\phi$ Can help resolve the puzzle:
  - if PA is the reason can predict polarization in other modes e.g. $B_s \to \phi\phi$ **[A.Datta, et al. Eur.Phys.J.C60:279-284,2009]**

$B_s \rightarrow \phi\phi$ Polarization

- Measure polarization amplitudes from untagged time-integrated differential decays rate as a function of kaon decay angles (θ_1,θ_2) and the angle between the two decay planes (ϕ)



$$g_s^{(\omega)} = \frac{d^3\Lambda(\vec{\omega})}{d\vec{\omega}} = \frac{9}{32\pi}\frac{1}{\tilde{W}}\left[\tilde{\mathcal{F}}_e(\vec{\omega}) + \tilde{\mathcal{F}}_o(\vec{\omega})\right]$$

Assume SM mixing phase: $\phi_{Bs\rightarrow\phi\phi}=0$

$$\tilde{\mathcal{F}}_e = \frac{2}{\Gamma_L}\left[|A_0|^2 f_1(\vec{\omega}) + |A_\parallel|^2 f_2(\vec{\omega}) + |A_0||A_\parallel|\cos\delta_\parallel f_5(\vec{\omega})\right]$$

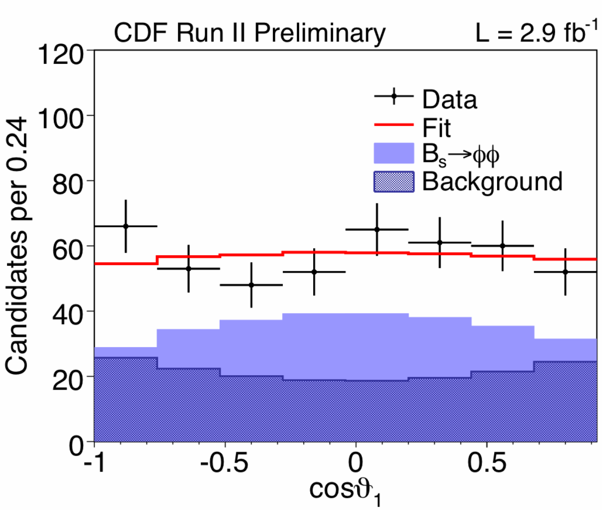
$$\tilde{\mathcal{F}}_o = \frac{2}{\Gamma_H}|A_\perp|^2 f_3(\vec{\omega})$$

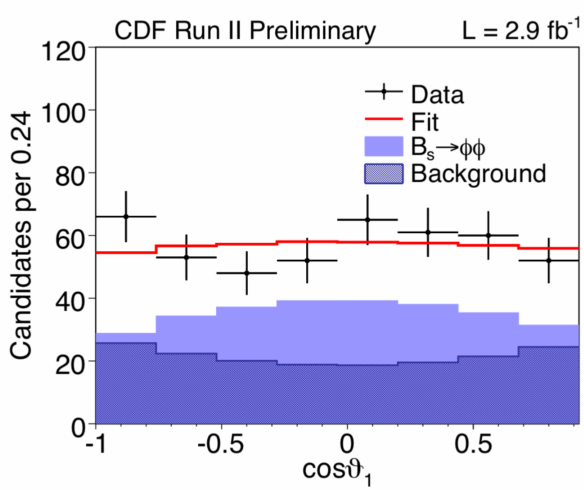
$$\tilde{W} = \frac{|A_0|^2 + |A_\parallel|^2}{\Gamma_L} + \frac{|A_\perp|^2}{\Gamma_H}$$

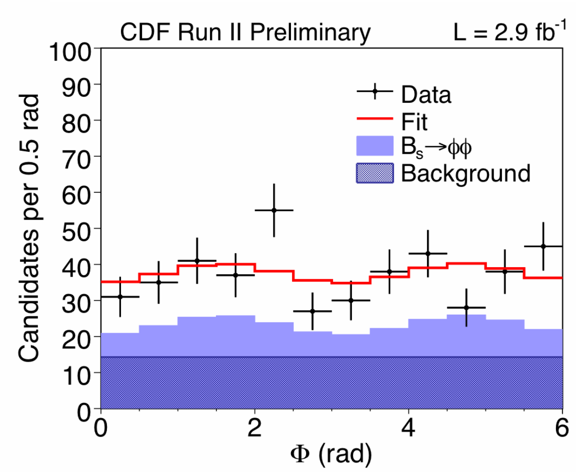
OBSERVABLES

Take Γ_L and Γ_H from PDG

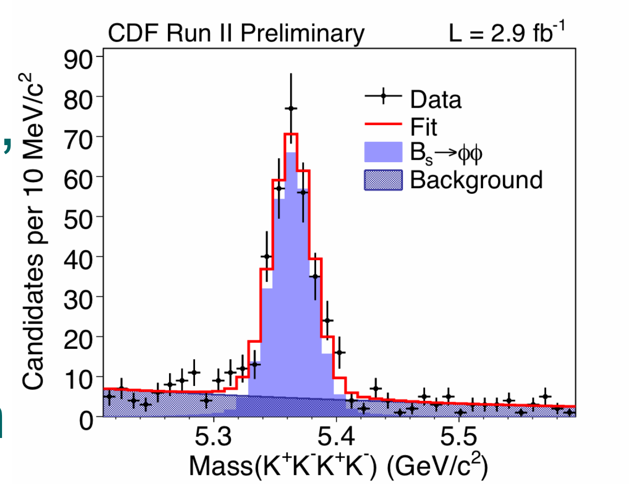
$B_s \rightarrow \phi\phi$ Polarization Fit





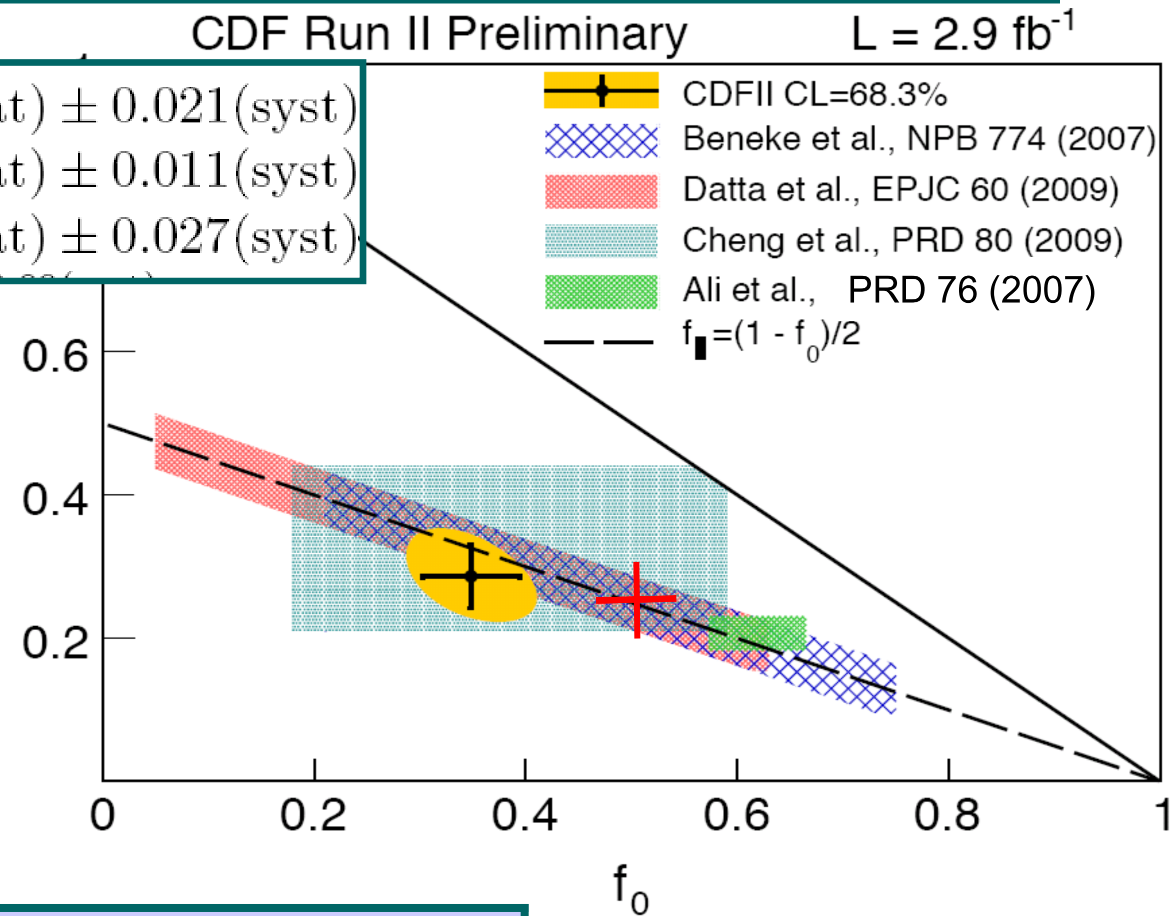


- Unbinned maximum likelihood fit to mass and decay angles
- Acceptance correction from simulation, background modeled on sideband (polinomials) and fitted in the whole mass range
- Cross check with $B_s \rightarrow J/\psi\phi$ collected in the same trigger (1700 ev.) consistent with WA within stat. uncertainties



$B_s \to \phi\phi$ Polarization Exp vs Theory

$$|A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst})$$
$$|A_\parallel|^2 = 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst})$$
$$|A_\perp|^2 = 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst})$$



Datta et. al. compare longitudinal fraction via ratio of BR with $B_d \to \phi K^*$

Beneke, Cheng (QCDf) and Ali (pQCD) all reproduce $B_d \to \phi K^*$ observables

$\cos(\delta_{//})$		
CDF	$-0.91^{+0.15}_{-0.13}(stat) \pm 0.09(syst)$	
QCDF	$-0.80^{+0.31}_{-0.16}$	NP B774:64,2007
pQCD	$0.27^{+0.09}_{-0.27}$	PRD76:074018,2007

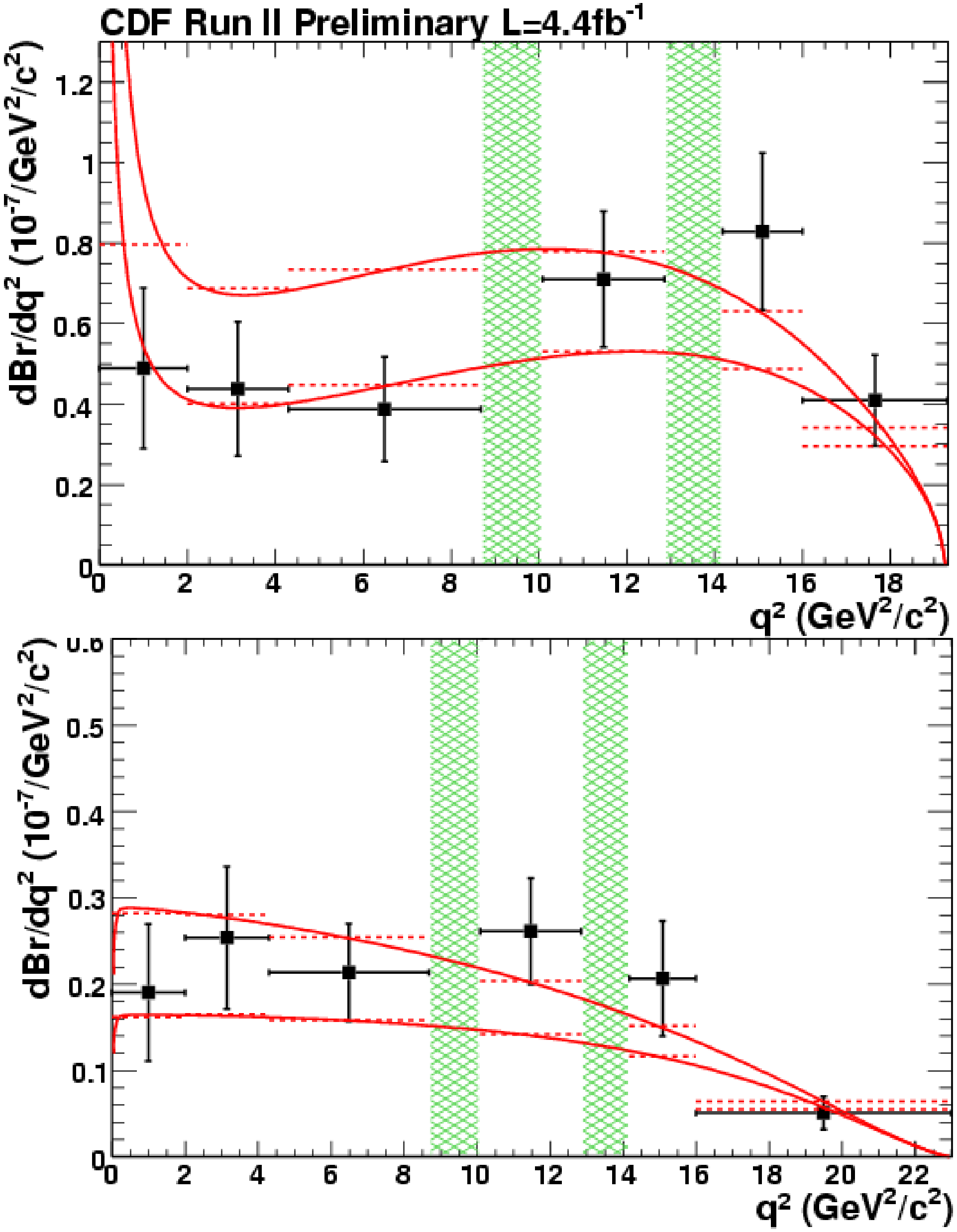
- Agreement with QCDF prediction favor polarization puzzle explanation via penguin-annihilation over FSI

Conclusions

- CDF accessing the largest samples of $B_{(s)}$ decays
- Second generation analysis on $b \rightarrow sll$ $B_s \rightarrow \phi\phi$ presented using 3 to 4 fb^{-1} of Run II data
  - Still holding world best limit for $B_s \rightarrow \mu^+\mu^-$
  - BR and differential decays rate and asymmetry for $B \rightarrow K^{(*)}\mu^+\mu^-$
  - First observation of $B_s \rightarrow \phi\mu^+\mu^-$
  - First polarization amplitudes measurement for $B_s \rightarrow \phi\phi$
- Tevatron excellent performances will allow at least doubling available statistics with respect to that used here by 2011
- New interesting results to come

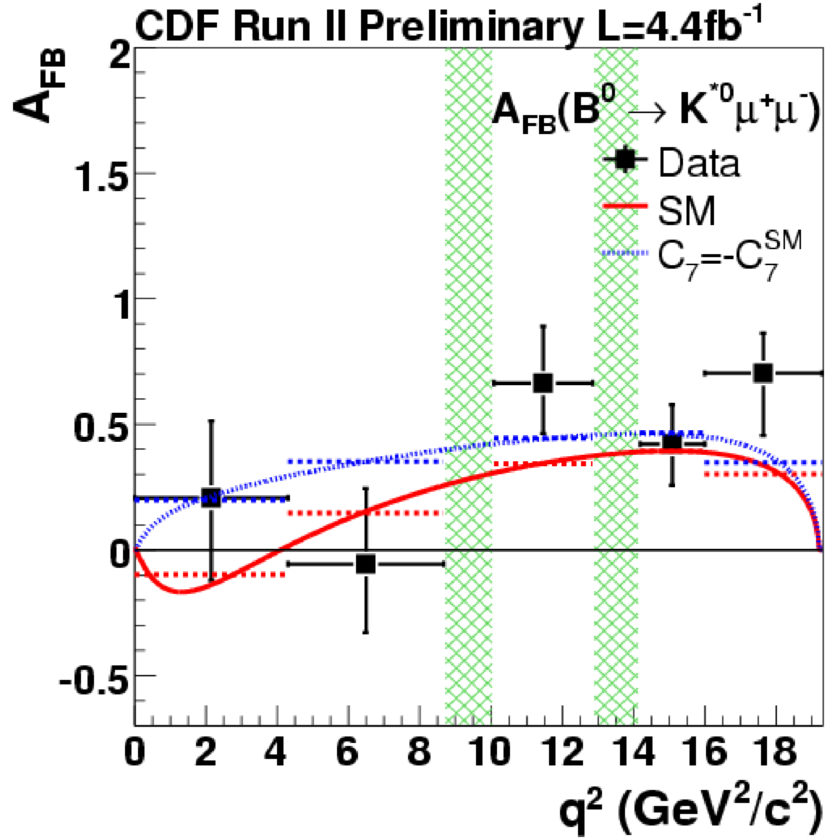
BACKUP

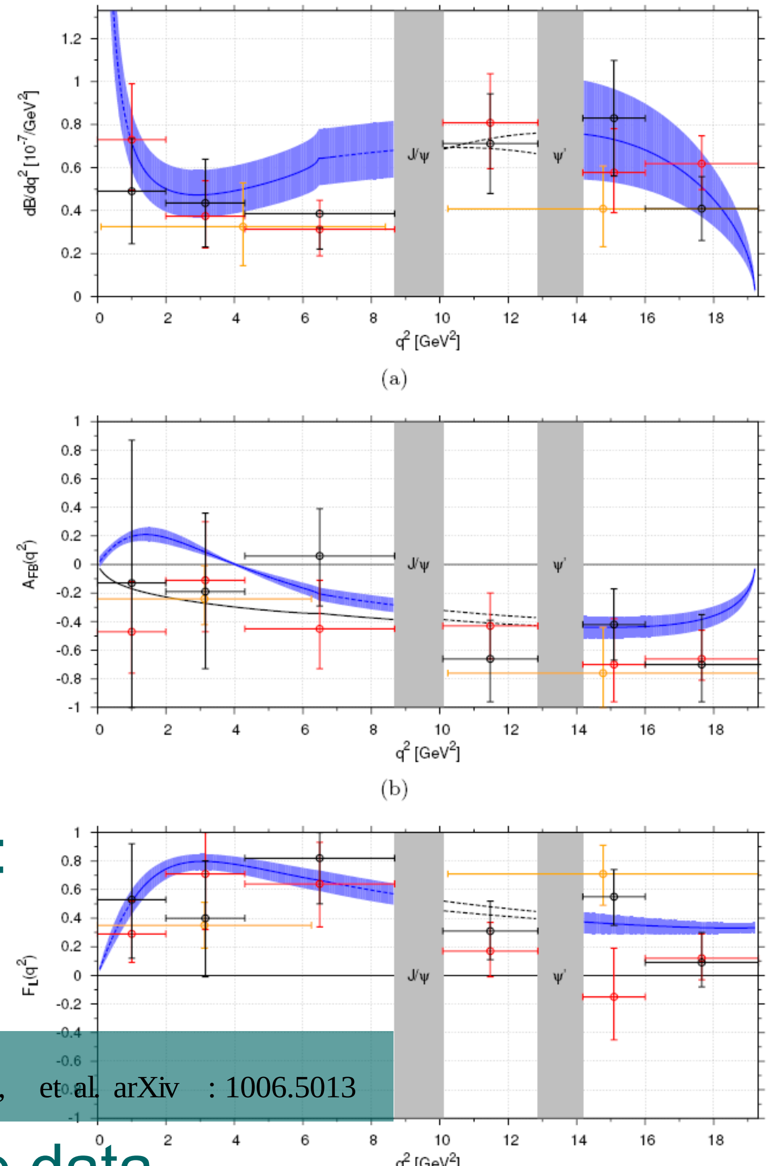
Differential Decay Rate (B_d,B^-)



- Measure differential decay rate vs q^2
- Avoid $\psi^{(\prime)}$ resonance regions
- In agreement with predictions within (large) uncertainty due to form factors

A_{FB} result $B_d \rightarrow K^* \mu^+ \mu^-$





In the theoretically cleanest range:

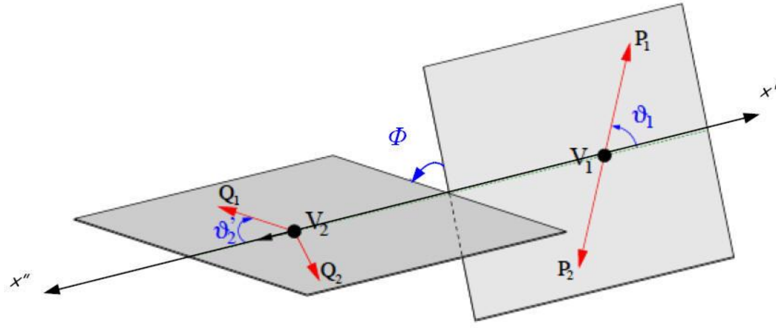
$$A_{FB}^{CDF}\ (1 < q^2 < 6\ \text{GeV}^2/c^4) = 0.43^{+0.36}_{-0.37} \pm 0.06$$

$$A_{FB}^{(th)}(1 < q^2 < 6\ \text{GeV}^2/c^4) = -0.05^{+0.03}_{-0.04}$$ C.Bobeth, et al. arXiv : 1006.5013

- Still inconclusive, wait for more data

$B_s \to \phi\phi$ Polarization (formulae)

$$\frac{d^4\Gamma(\vec{\omega},t)}{dt\,d\vec{\omega}} = \frac{9}{32\pi}\sum_{i=1}^{6} K_i(t) f_i(\vec{\omega})$$



$$K_1(t) = \frac{1}{2}|A_0|^2\left[(1+\cos\phi_V)e^{-\Gamma_L t} + (1-\cos\phi_V)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\phi_V\right]$$

$$K_2(t) = \frac{1}{2}|A_\parallel|^2\left[(1+\cos\phi_V)e^{-\Gamma_L t} + (1-\cos\phi_V)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\phi_V\right]$$

$$K_3(t) = \frac{1}{2}|A_\perp|^2\left[(1-\cos\phi_V)e^{-\Gamma_L t} + (1+\cos\phi_V)e^{-\Gamma_H t} - 2e^{-\Gamma t}\sin(\Delta m t)\sin\phi_V\right]$$

$$K_4(t) = |A_\parallel||A_\perp|\left[e^{-\Gamma t}\left(\sin\delta_1\cos(\Delta m t) - \cos\delta_1\sin(\Delta m t)\cos\phi_V\right) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\cos\delta_1\sin\phi_V\right]$$

$$K_5(t) = \frac{1}{2}|A_0||A_\parallel|\cos(\delta_2-\delta_1)\left[(1+\cos\phi_V)e^{-\Gamma_L t} + (1-\cos\phi_V)e^{-\Gamma_H t} + 2e^{-\Gamma t}\sin(\Delta m t)\sin\phi_V\right]$$

$$K_6(t) = |A_0||A_\parallel|\left[e^{-\Gamma t}\left(\sin\delta_2\cos(\Delta m t) - \cos\delta_2\sin(\Delta m t)\cos\phi_V\right) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\cos\delta_2\sin\phi_V\right]$$

$$f_1(\vec{\omega}) = 4\cos^2\vartheta_1\cos^2\vartheta_2$$

$$f_2(\vec{\omega}) = \sin^2\vartheta_1\sin^2\vartheta_2(1+\cos 2\Phi)$$

$$f_3(\vec{\omega}) = \sin^2\vartheta_1\sin^2\vartheta_2(1-\cos 2\Phi)$$

$$f_4(\vec{\omega}) = -2\sin^2\vartheta_1\sin^2\vartheta_2\sin 2\Phi$$

$$f_5(\vec{\omega}) = \sqrt{2}\sin 2\vartheta_1\sin 2\vartheta_2\cos\Phi$$

$$f_6(\vec{\omega}) = -\sqrt{2}\sin 2\vartheta_1\sin 2\vartheta_2\sin\Phi$$

Untagged + ϕ_V=0

$$\frac{d^4\Gamma(\vec{\omega},t)}{dt\,d\vec{\omega}} = \frac{9}{32\pi}\left[\mathcal{F}_o(\vec{\omega})\mathcal{K}_L(t) + \mathcal{F}_e(\vec{\omega})\mathcal{K}_H(t)\right]$$

Systematic Tables

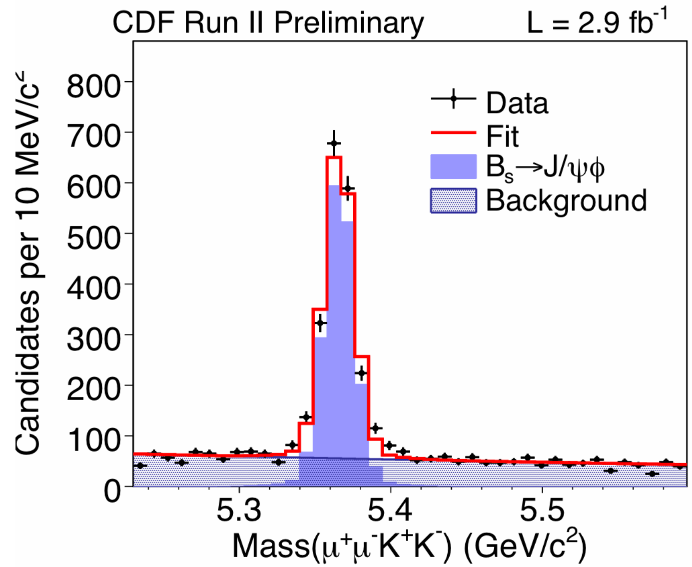
	$B_s^0 \to \phi\phi$	$B_s^0 \to J/\psi\phi$
	$\Delta N_{\phi\phi}/N_{\phi\phi}$	$\Delta N_{J/\psi\phi}/N_{J/\psi\phi}$
fit range	3%	-
signal parametrization	3%	2%
background subtraction: error on BRs	1%	1%
	$\Delta\varepsilon_{\phi\phi}/\varepsilon_{\phi\phi}$	$\Delta\varepsilon_{J/\psi\phi}/\varepsilon_{J/\psi\phi}$
polarization in MC	7%	6%
	$\Delta\varepsilon_{\phi\phi}/\varepsilon_{J/\psi\phi}$	
XFT particle dep.	4%	
p_T reweight	0.9%	
	$\Delta\varepsilon_{\mu}/\varepsilon_{\mu}$	
η parametrization & correlation	0.9%	

Table 16: *Contributions to the total relative uncertainty from the systematic uncertainty sources considered.*

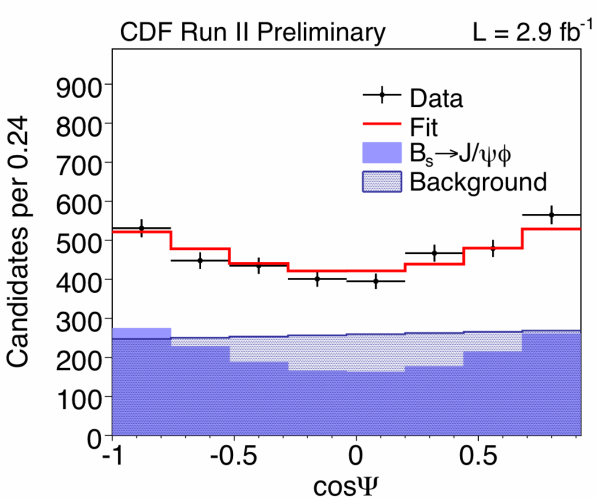
	$\|A_0\|^2$ syst	$\|A_\parallel\|^2$ syst	$\|A_\perp\|^2$ syst	$\cos\delta_\parallel$ syst
MC reweight	± 0.003	± 0.001	± 0.002	± 0.007
Acceptance binning	± 0.001	± 0.001	± 0.000	± 0.004
Acceptance Model	± 0.005	± 0.002	± 0.003	± 0.005
Background Model	± 0.001	± 0.001	± 0.002	± 0.009
Acceptance ct-dependence	± 0.000	± 0.001	± 0.001	± 0.004
Reflection component	± 0.008	± 0.002	± 0.006	± 0.019
Non-resonant contribution	± 0.013	± 0.003	± 0.010	± 0.084
Satellite peak	± 0.004	± 0.000	± 0.004	± 0.020
Acceptance $\Delta\Gamma$-dependence	± 0.009	± 0.009	± 0.016	± 0.011
$\tau_{L(H)}$ uncertainties	± 0.008	± 0.006	± 0.017	
total	± 0.021	± 0.011	± 0.027	± 0.089

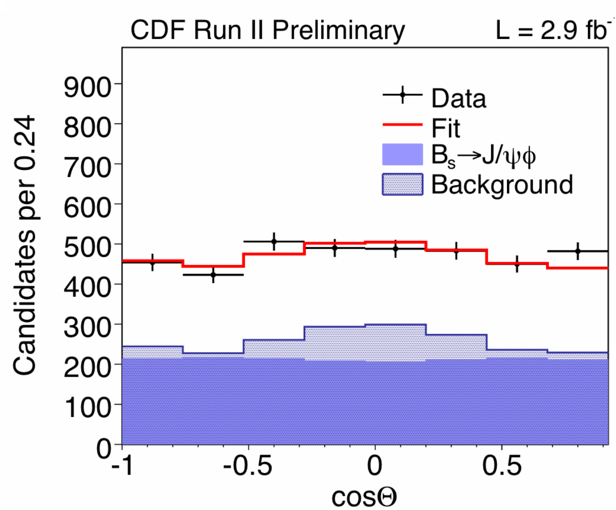
$B_s \rightarrow J/\psi\phi$ Polarization

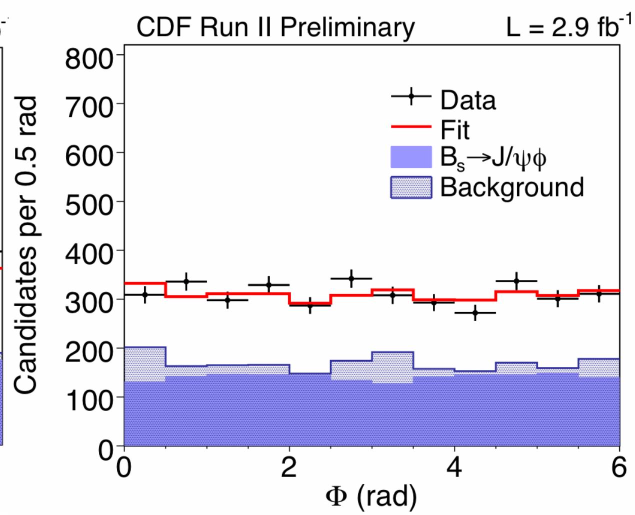
- Analysis performed in transversity basis
- Assume no CP violation: *bs = 0*
- Angular acceptance determined from simulation as in the *Bs → ΦΦ* case
- Compared to CDF measurement from di-muon trigger with 1.7 fb-1 [PRL 100, 121803 (2008)]
- and DØ measurement with 2.8 fb^{-1} [Phys.Rev.Lett.102:032001,2009]



		Dimuon sample result	
$\lvert A_0\rvert^2$	0.534 ± 0.019	$0.531 \pm 0.020(\text{stat}) \pm 0.007(\text{syst})$	0.555 ± 0.027
$\lvert A_\parallel\rvert^2$	0.220 ± 0.025	$0.239 \pm 0.029(\text{stat}) \pm 0.011(\text{syst})$	0.244 ± 0.032
		Physical Review Letters, 100:121803, 2008	







Angular Acceptance & Background