Rare Decays/B_s CPV Measurements at Tevatron

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on behalf of the CDF and DØ collaborations

XXth Hadron Collider Physics Symposium
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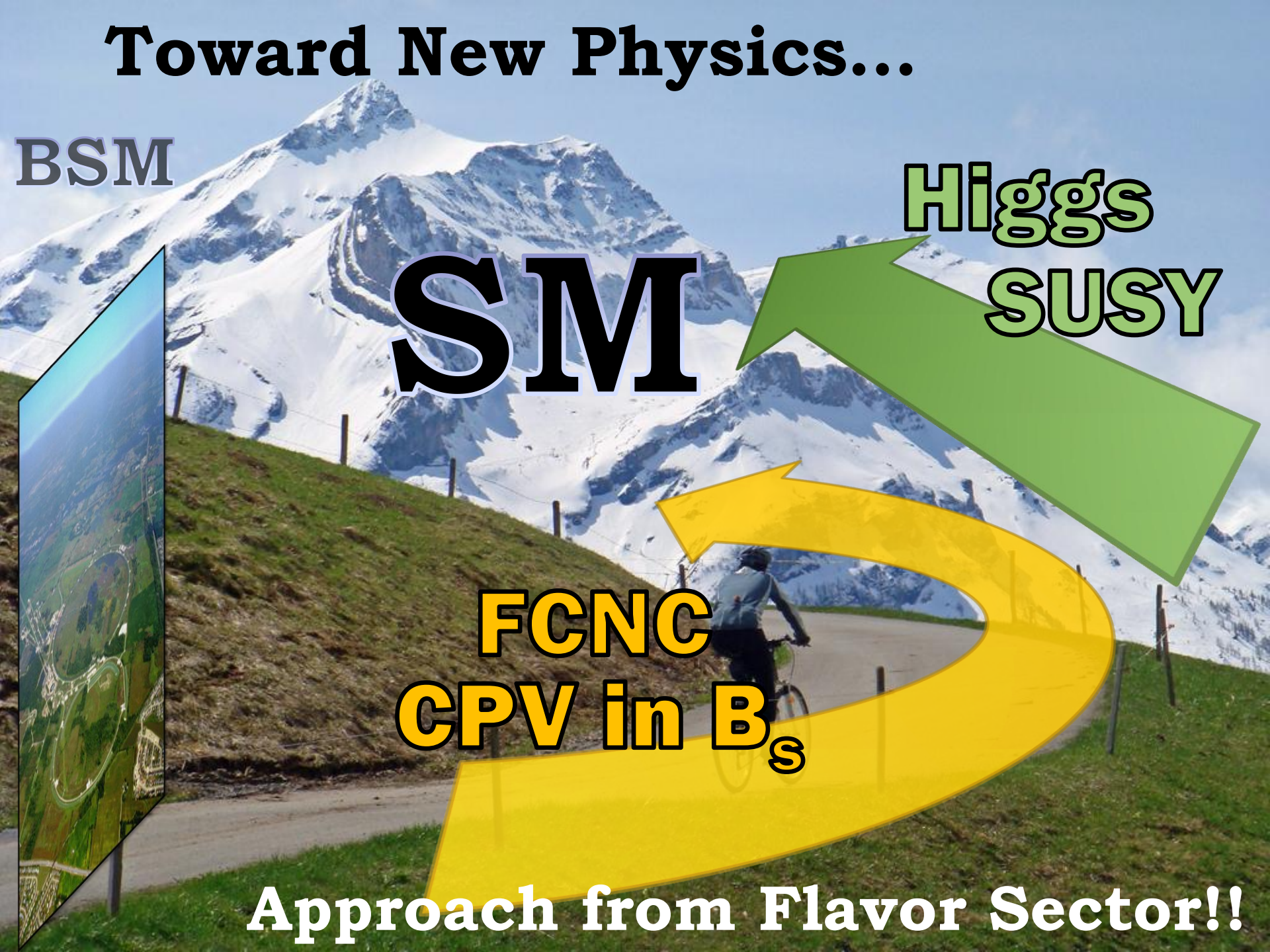
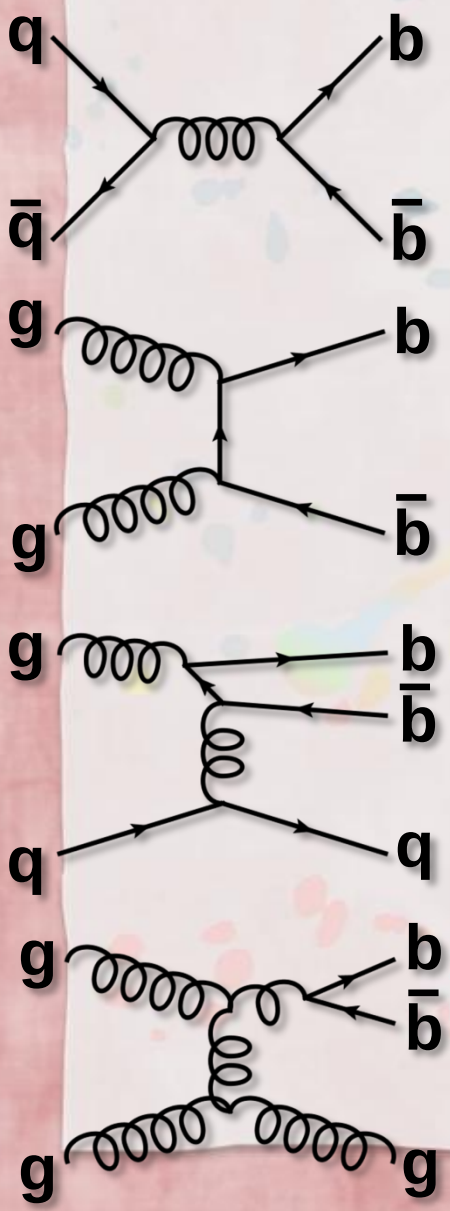

Toward New Physics...
BSM
SM
Higgs
SUSY
FCNC
CPV in B_s
Approach from Flavor Sector!!

B Physics@Tevatron



☺Pros

- ✓ Enormous cross-section
- ✓ All species of b-hadrons
  - ✓ $B_u, B_d, B_s, B_c, \Lambda_b, \Sigma_b$...

☹Cons

- ✓ QCD background x10^3 larger than $\sigma(b\bar{b})$
- ✓ Collision rate ~2MHz
  → tape writing limit ~100Hz
  - ✓ Sophisticated triggers are very important!

Much B production enables :
- explore various rare decays
- measure precise CPV parameters

Topics

- ✓ Rare decays
  - ✓ $B \to K^{(*)}\mu\mu$, $B_s \to \varphi\mu\mu$
    - ✓ $A_{FB}(K^{(*)}\mu\mu)$ measurement

New for HCP!

  - ✓ $B \to \mu\mu$

100+ citations

- ✓ β_s measurement
  - ✓ $B_s \to J/\Psi\varphi$

100+ citations

FCNC

CPV

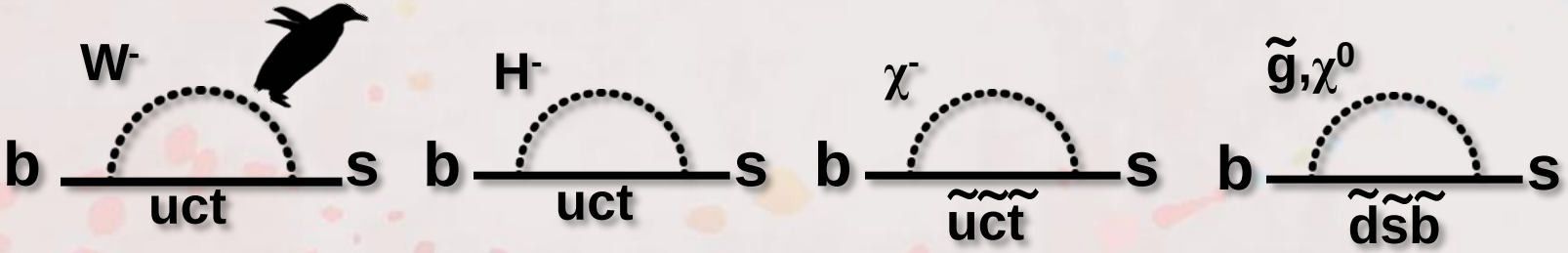
World's best or comparable results

FCNC

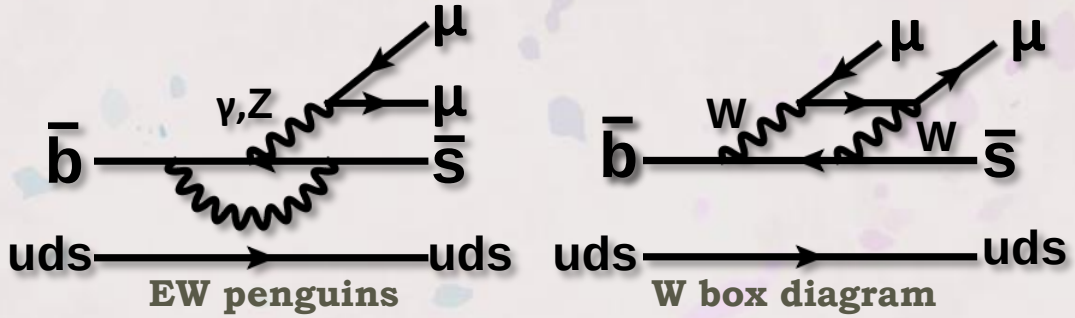
- ✓ $B \to K^{(*)}\mu\mu$
- ✓ $B_s \to \varphi\mu\mu$
- ✓ $B \to \mu\mu$

Flavor Changing Neutral Current

- ✓ **FCNC**
  - ✓ Forbidden in the tree level
  - ✓ May occur via higher order loop diagram
  - ✓ NP could enhance the amplitude
- ✓ **FCNC with dimuon**
  - ✓ Theoretically/experimentally clean



$B \to K^{(*)}\mu\mu$, $B_s \to \varphi\mu\mu$



Rare decay : $b \to sll$

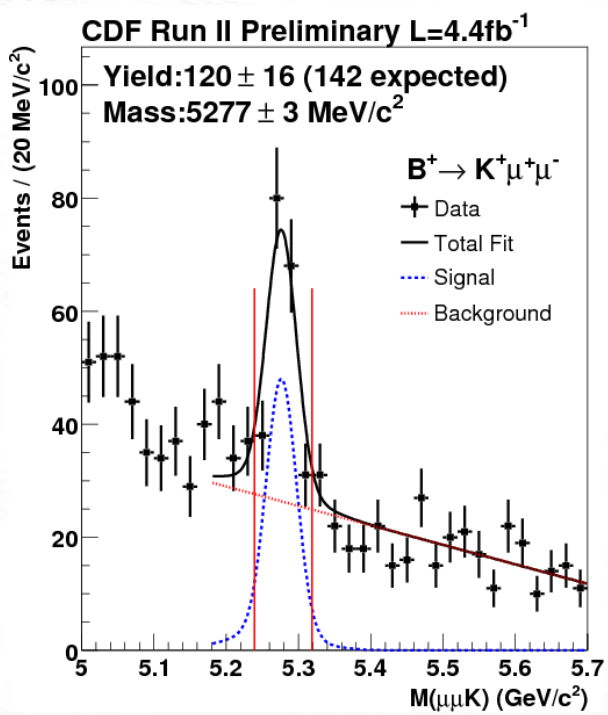
- ✓ $B^+ \to K^+\mu^+\mu^-$: $[0.52^{+0.08}_{-0.07}] \times 10^{-6}$ (HFAG)
- ✓ $B^0 \to K^{*0}\mu^+\mu^-$: $[1.05^{+0.15}_{-0.13}] \times 10^{-6}$ (HFAG)
- ✓ $B_s \to \varphi\mu^+\mu^-$: 1.61×10^{-6} (C.Q.Geng and C.C.Liu, J.Phys.G29:1103-1118,2003)
  - ✓ $BR(B_s \to \varphi\mu\mu)/BR(B_s \to J/\Psi\varphi)$
    - $< 2.3(2.6) \times 10^{-3}$ @90(95%) C.L. CDF $0.92 fb^{-1}$
    - $< 4.4 \times 10^{-3}$ @95% C.L. DØ $0.45 fb^{-1}$

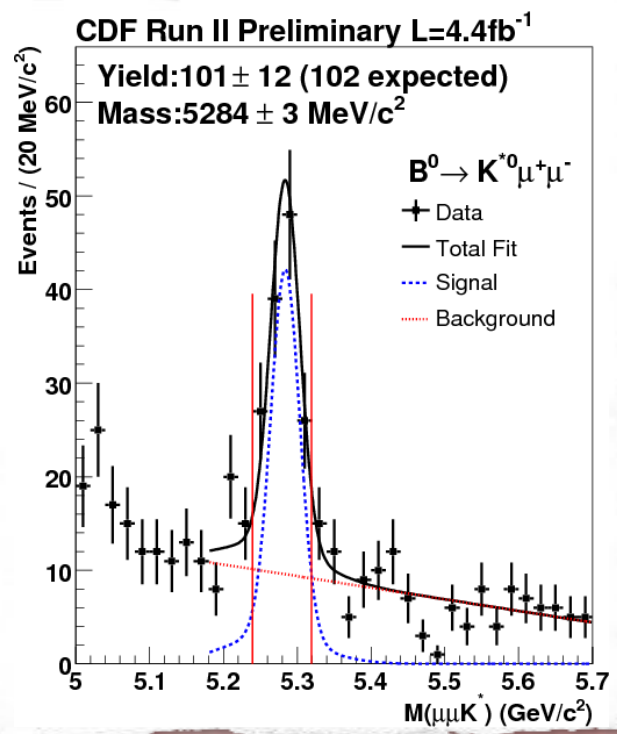
- ✓ CDF updated the analysis with $4.4 fb^{-1}$
  - ✓ BR
  - ✓ A_{FB}

New for HCP!

$B \rightarrow K^{(*)}\mu\mu$: yields

- ✓ Dimuon trigger ($p_T(\mu)$>1.5 or 2.0GeV/c)
- ✓ Employ neural network to optimize event selection
- ✓ Single final state per decay channel
  - ✓ $B^+ \rightarrow K^+\mu^+\mu^-$
  - ✓ $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\ \mu^+\mu^-$





Stat. significance ~9σ **Stat. significance ~10σ**

$B \to K^{(*)}\mu\mu$: BR

- ✓ **Relative BR : normalized BR by control channel ($J/\Psi h$)**

h=K,K*

Rare channel yield

$$\frac{\mathcal{B}(B \to h\mu^+\mu^-)}{\mathcal{B}(B \to J/\Psi h)} = \frac{N^{\rm NN}_{h\mu^+\mu^-}}{N^{\rm pre}_{J/\Psi h}} \boxed{\frac{\epsilon^{\rm pre}_{J/\Psi h}}{\epsilon^{\rm pre}_{h\mu^+\mu^-}} \frac{1}{\epsilon^{\rm NN}_{h\mu^+\mu^-}}} \times \mathcal{B}(J/\Psi \to \mu^+\mu^-),$$

Control channel yield

Reconstruction efficiency

- ✓ **Absolute BR**

($\times 10^{-6}$)

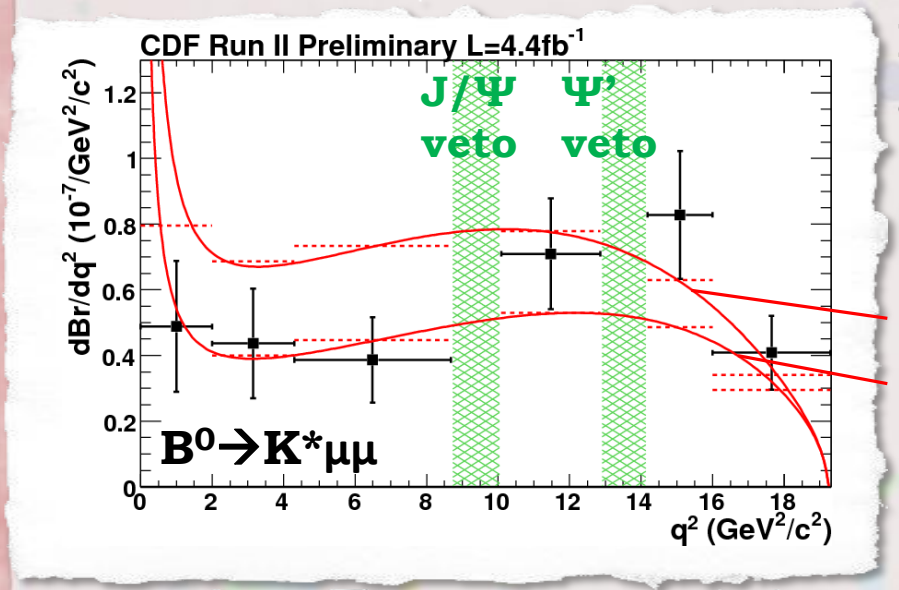
	BaBar (384M BB)	Belle (657M BB)	CDF (4.4fb^{-1})
$K^+\mu\mu$	$0.41^{+0.16}_{-0.15}$(stat)±0.02(syst)	$0.53^{+0.08}_{-0.07}$(stat)±0.03(syst)	0.38±0.05(stat)±0.03(syst)
$K^{*0}\mu\mu$	$1.35^{+0.40}_{-0.37}$(stat) ±0.10(syst)	$1.06^{+0.19}_{-0.14}$(stat) ±0.07(syst)	1.06±0.14(stat)±0.09(syst)
Kll	0.39±0.07(stat)±0.02(syst)	$0.48^{+0.05}_{-0.04}$(stat)±0.03(syst)	Same as $K^+\mu\mu$
K^*ll	$1.11^{+0.19}_{-0.18}$(stat)±0.07(syst)	$1.07^{+0.11}_{-0.10}$(stat)±0.09(syst)	Same as $K^{*0}\mu\mu$
	PRL102:091803 (2009)	PRL103:171801 (2009)	

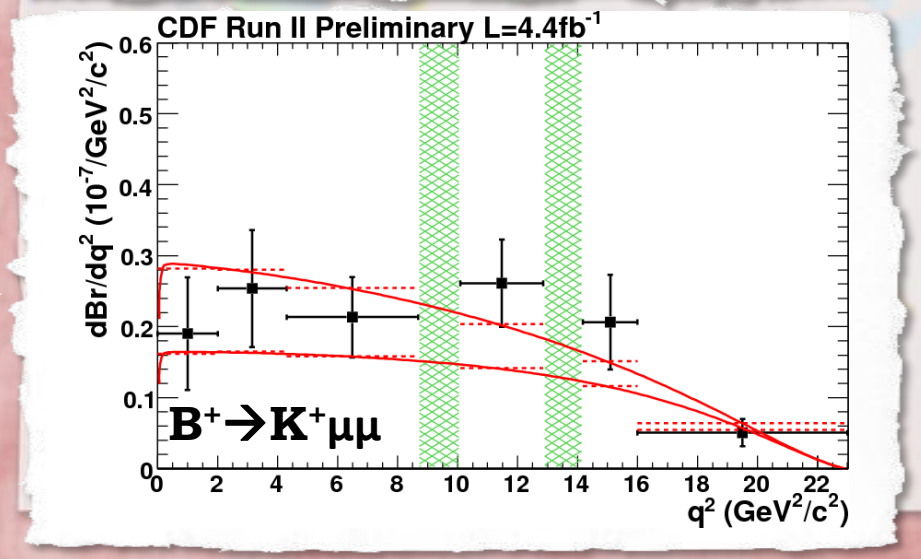
The best measurement for single final state!!

$\{K\pi, K_s\pi, K\pi^0\}*\{ee, \mu\mu\}$

$\{K, K_s\}*\{ee, \mu\mu\}$

B→K(*)μμ : differential BR





Dimuon mass spectrum could show a hint of new physics
→appears on differential BR w.r.t. q^2

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

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

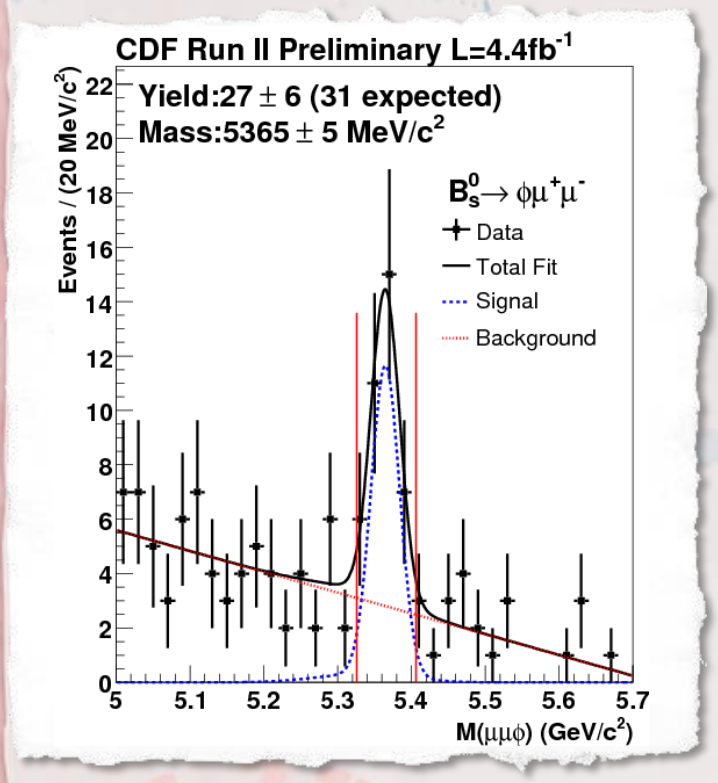
Same definition as Belle

Consistent with SM and other measurements

- **BaBar, PRL102:091803 (2009)**
- **Belle, PRL103:171801 (2009)**

B_s rare decay : $B_s \to \varphi\mu\mu$

- ✓ Similar analysis as $B \to K^{(*)}\mu\mu$
  - ✓ $B_s \to \varphi(\to K^+K^-)\mu^+\mu^-$



Stat. significance ~6σ

1st observation!

BR($B_s \to \varphi\mu\mu$)
=[1.44±0.33(stat)±0.46(syst)]×10^{-6}

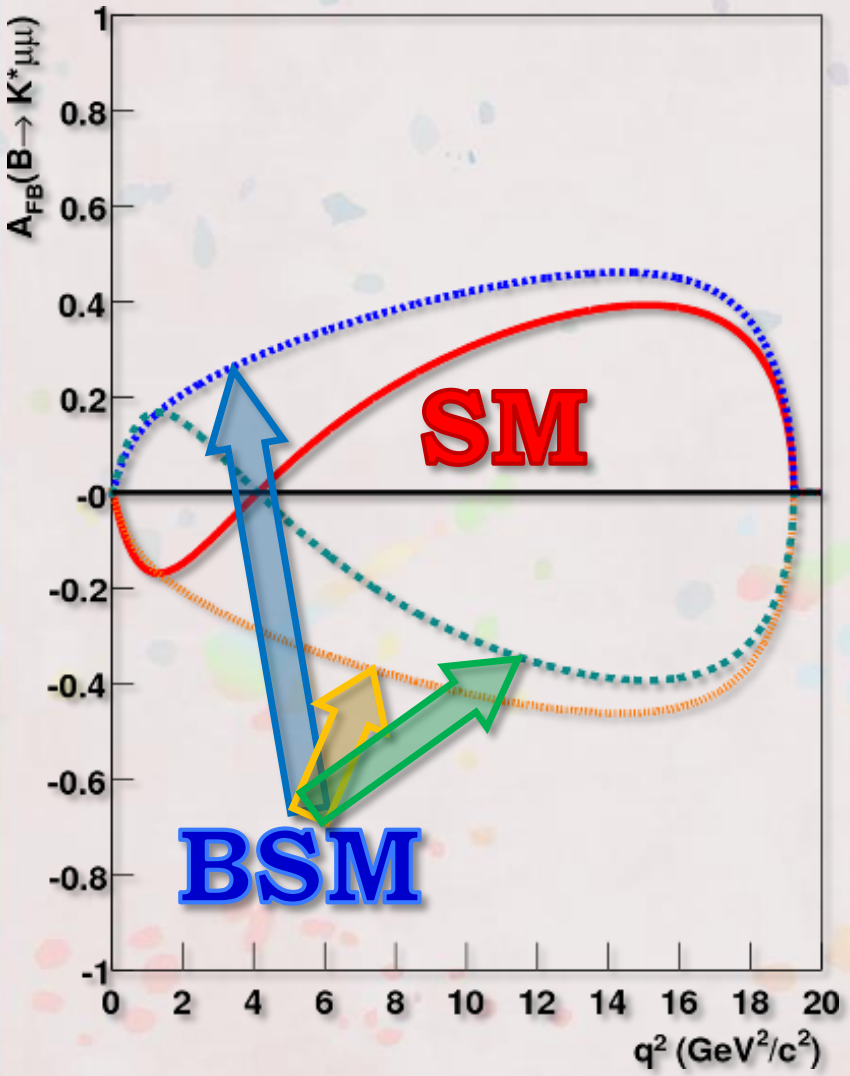
Consistent with theory ~1.61×10^{-6}

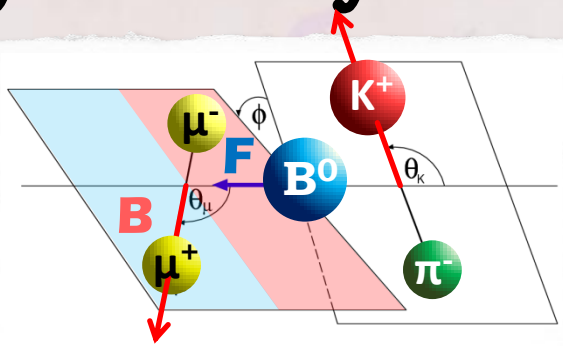
The rarest B_s decay we observed so far!!

- ✓ Yet another $B \to Vll$ decay
  - ✓ Could measure φ polarization : F_L

Brand-new probe!

Forward-Backward Asymmetry





$B^0 \to K^{*0}\mu\mu$ decay plane

Forward-Backward Asymmetry :

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

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

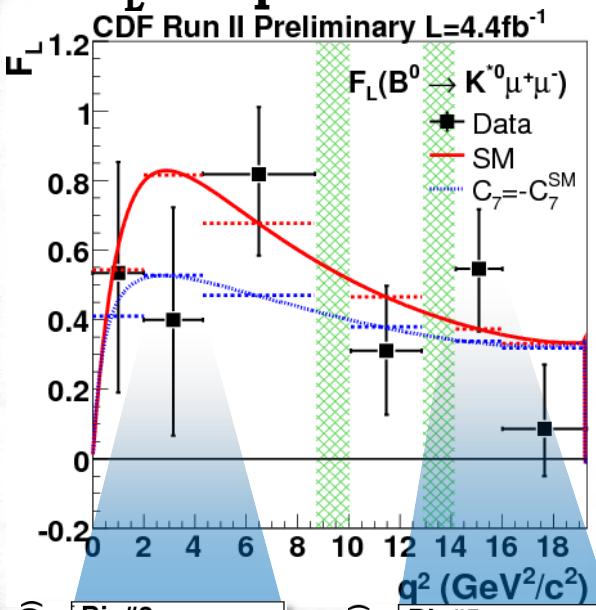
A_{FB} may show drastically different behavior under some BSM scenarios

→Good probe to explore BSM!

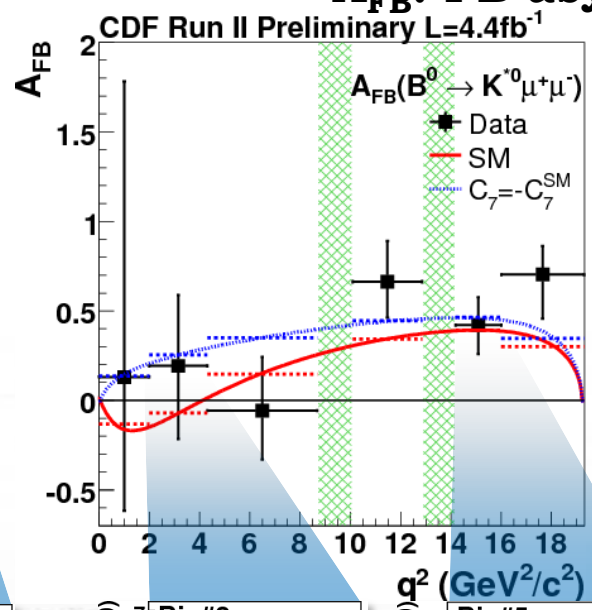
In case of $K\mu\mu$, $A_{FB}(K\mu\mu) \sim 0$ is expected

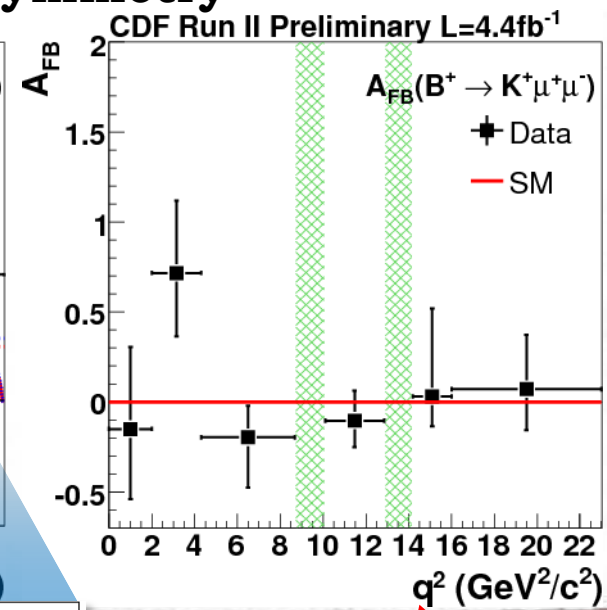
$A_{FB}(B \to K^{(*)}\mu\mu)$

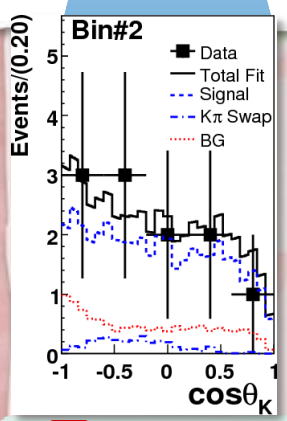
F_L: K* polarization

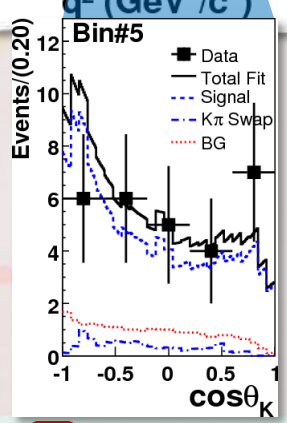


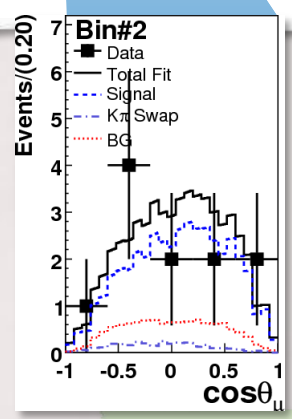
A_{FB}: FB asymmetry

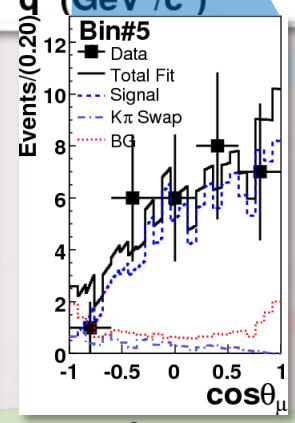


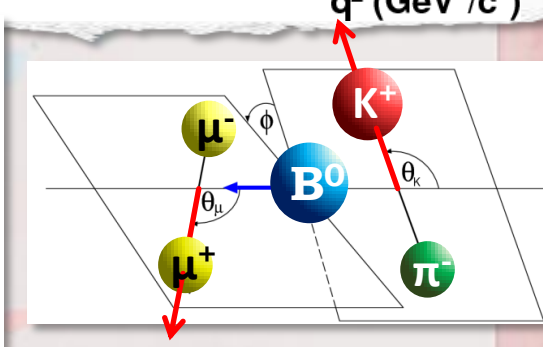












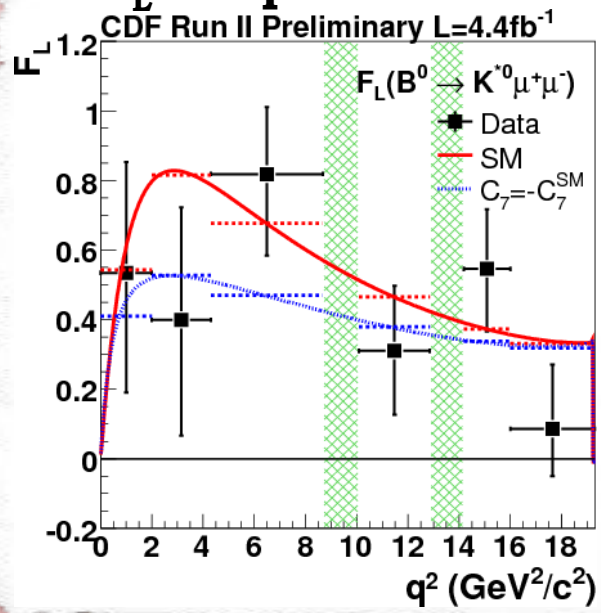
$$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

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

F_L=1 for Kμμ

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

F_L: K* polarization



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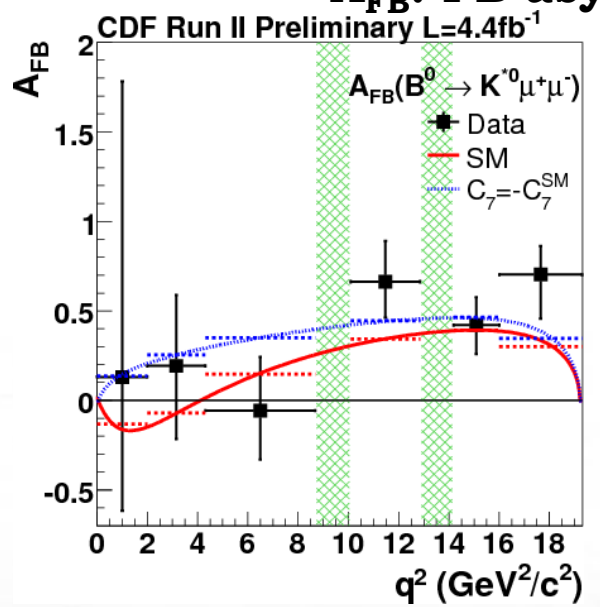
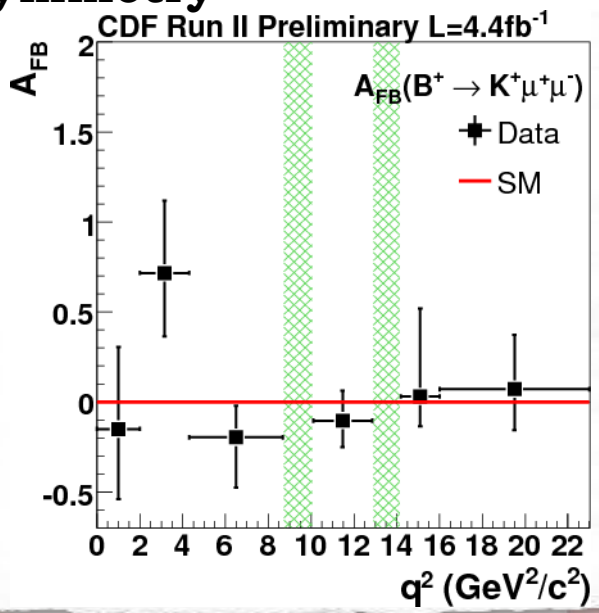


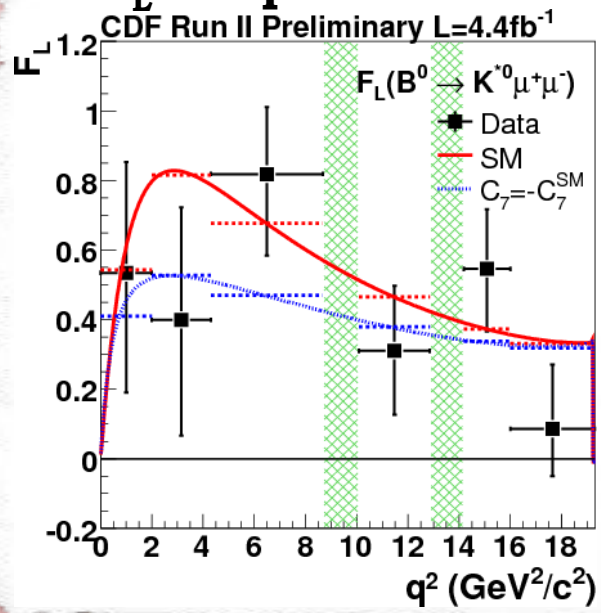


- Consistent with B-factories measurements :
BaBar 384M BB, PRD79,031102(R) (2009) and
Belle 657M BB, PRL103,171801(2009)

- Consistent with the SM and a BSM expectation...

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

F_L: K* polarization



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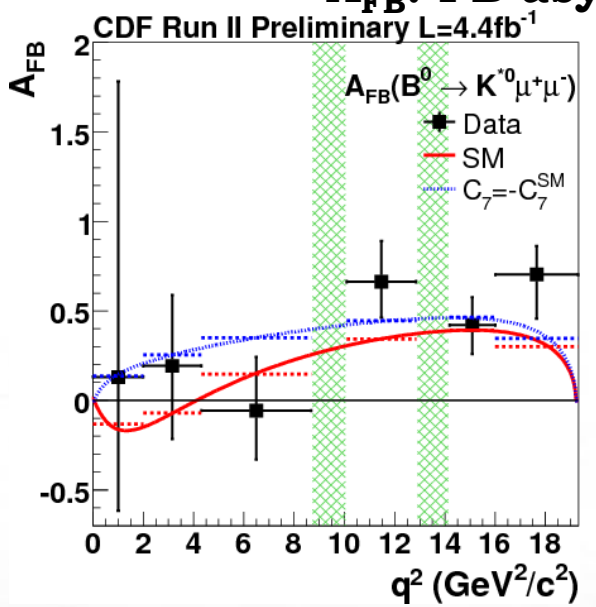

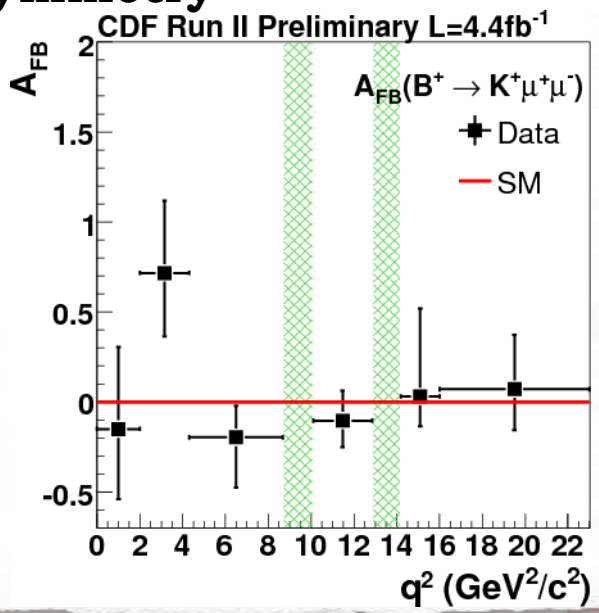

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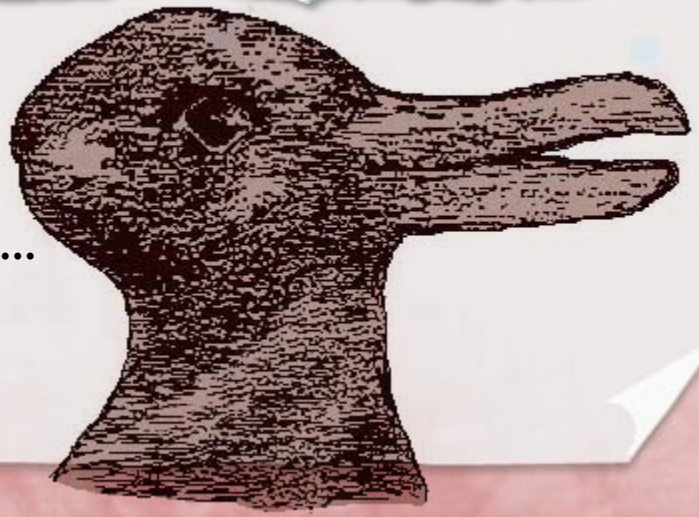
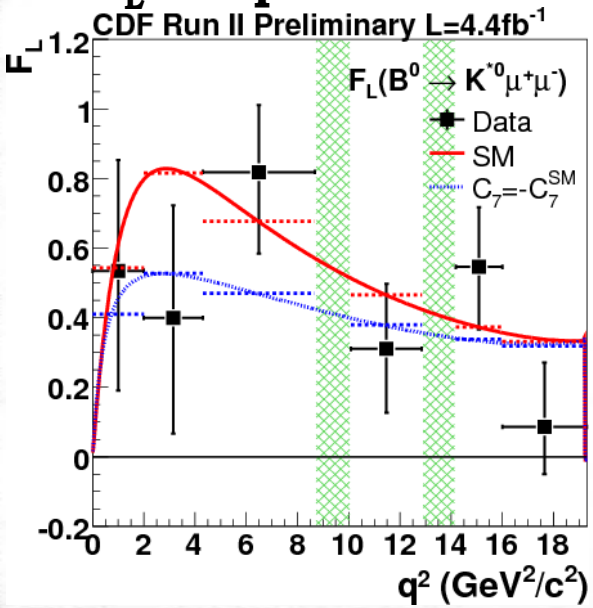


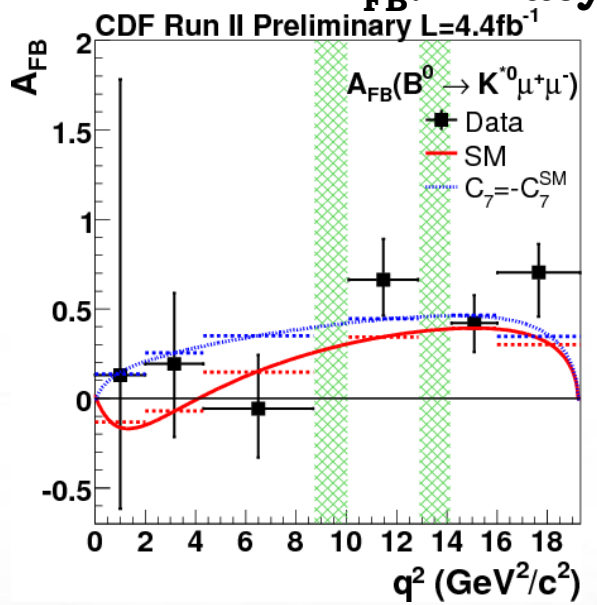
Which is it…?

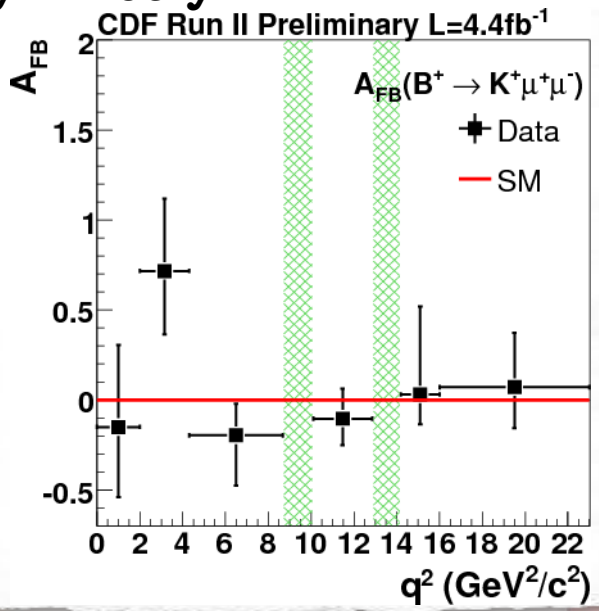
$A_{FB}(B \rightarrow K^{(*)}\mu\mu)$

F_L: K* polarization



A_{FB}: FB asymmetry





Expect more precise measurements by :

- **2x or more data in 2010 (2011) run**
- **additional trigger path**
- **additional sub-decay channels**

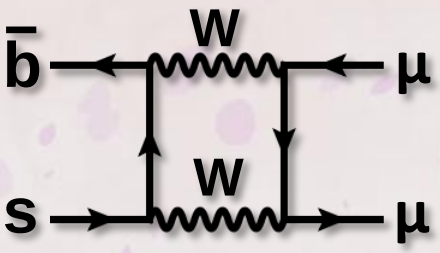
There is much room for improvement!

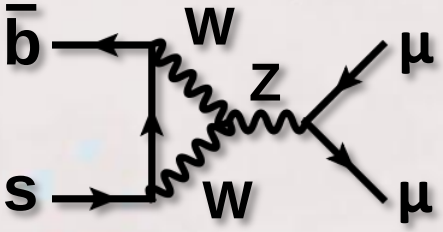
$B_{s,d} \rightarrow \mu\mu$

- ✓ **Highly suppressed in the SM**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$$
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$$

A. J. Buras, arXiv:0904.4917v1





- ✓ **Enhanced in NP (up to 100x)**
  - ✓ **Tree level:**
    - ✓ **R parity violation in SUSY**
  - ✓ **Loop level:**
    - ✓ **MFV SM extensions such as 2HDM**
    - ✓ **MSSM**
      - ✓ **BR(B→μμ) (tanβ)^6**

✓**Current world's best upper limit:**

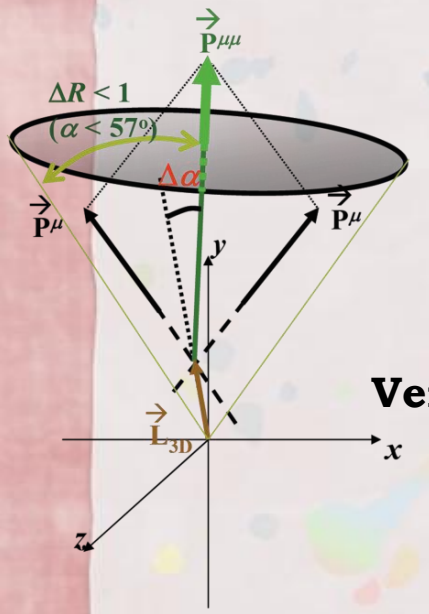
✓**BR(B_s→μμ)<4.7(5.8)x10^{-8}**

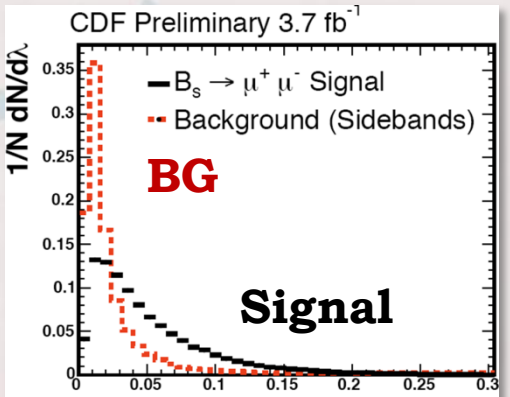
✓**BR(B_d→ μμ)<1.5(1.8)x10^{-8} 90(95)% C.L.**

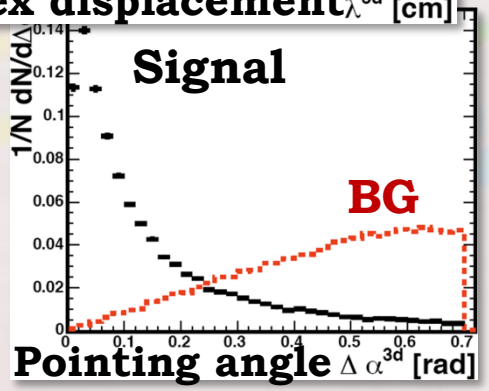
PRL 100,101802 (2008)

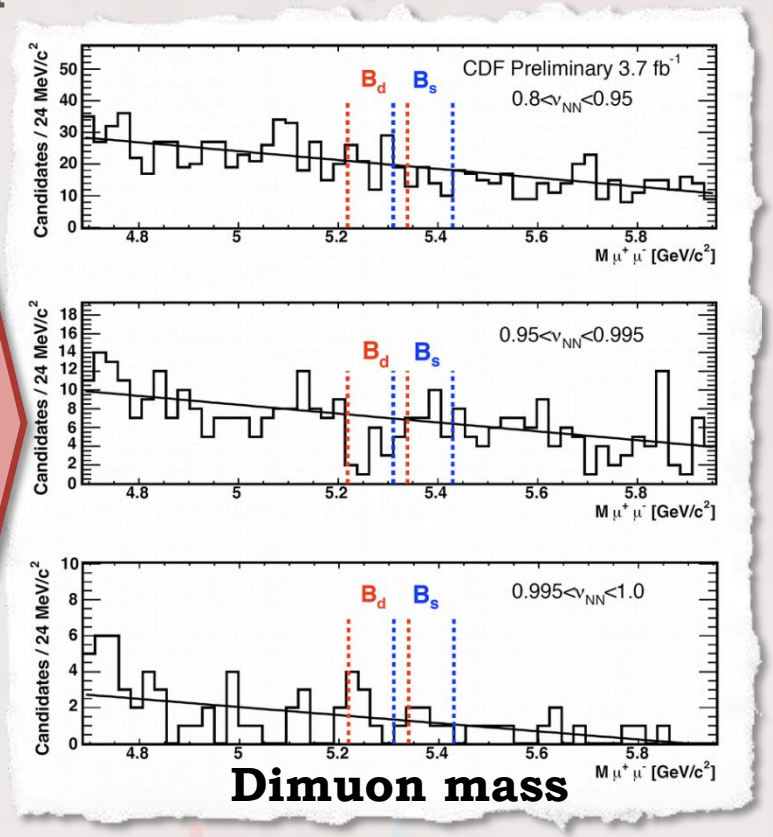
$B_{s,d} \rightarrow \mu\mu$ (CDF)

- ✓ Utilize neural network to optimize event selection







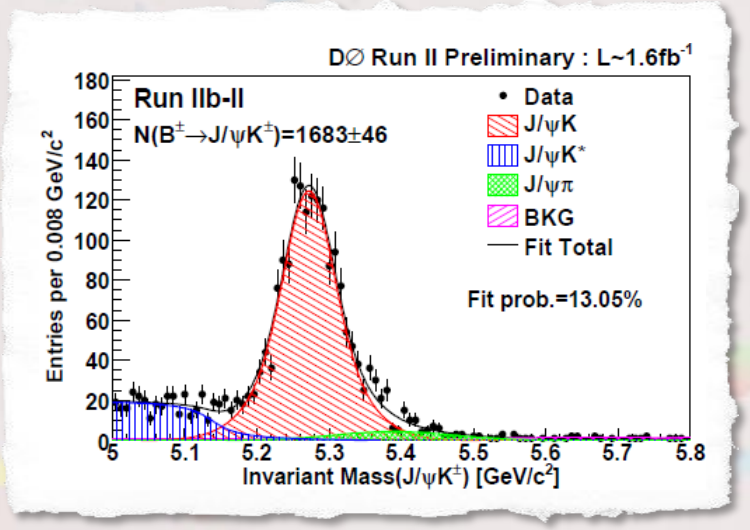


6 kinematic variables

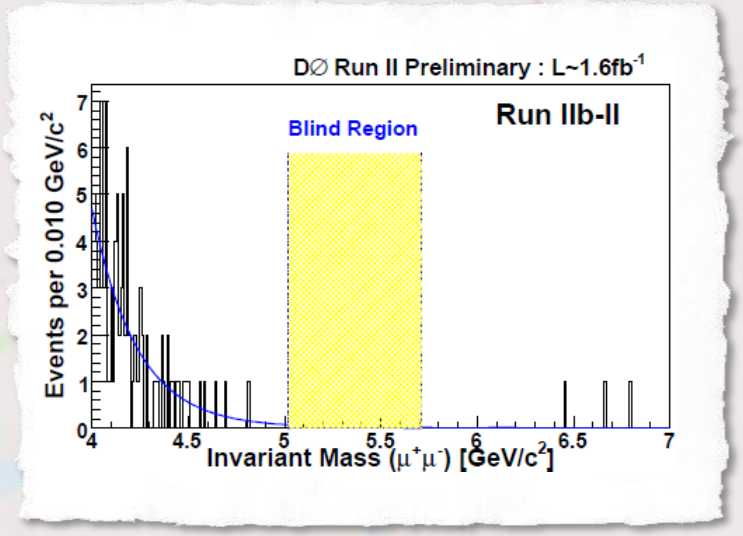
- ✓ Preliminary @3.7fb^{-1} (CDF public note 9892)
  - ✓ BR($B_s \rightarrow \mu\mu$)<3.6(4.3) x10^{-8} 90%(95%)C.L.
  - ✓ BR($B_d \rightarrow \mu\mu$)<6.0(7.6) x10^{-9} 90%(95%)C.L.

$B_s \rightarrow \mu\mu$ (DØ)

- ✓ Similar analysis method as CDF
- ✓ Utilize Boosted Decision Tree



Normalization Channel



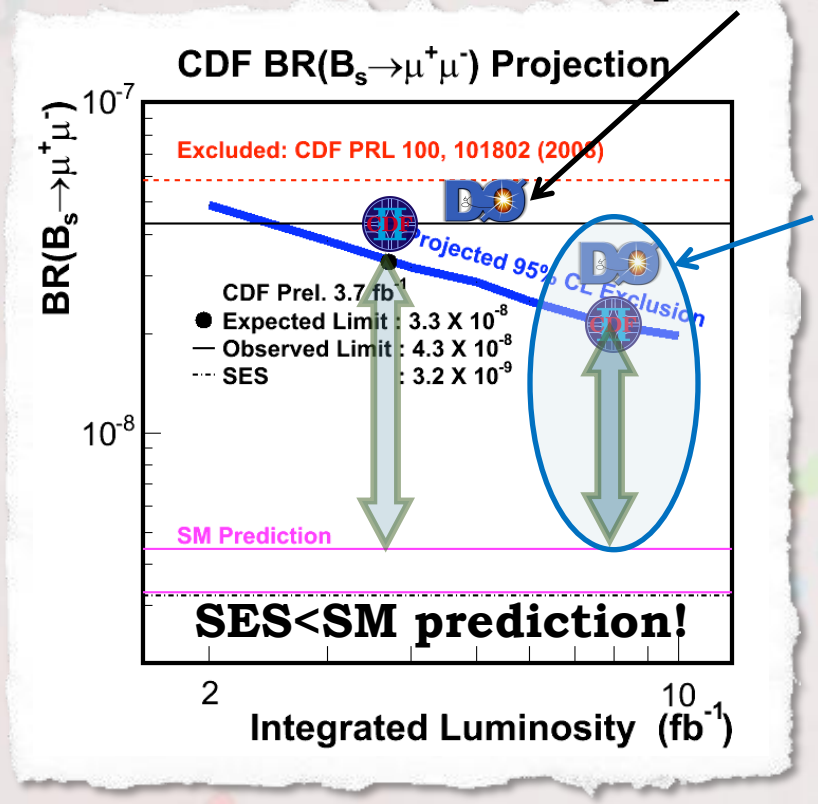
Blinded dimuon mass

- ✓ Expected limit@5fb^{-1} (DØ Conf. Note 5906)
  - ✓ BR($B_s \rightarrow \mu\mu$)<4.3(5.3) x10^{-8} 90%(95%)C.L.

Further improvements are ongoing…

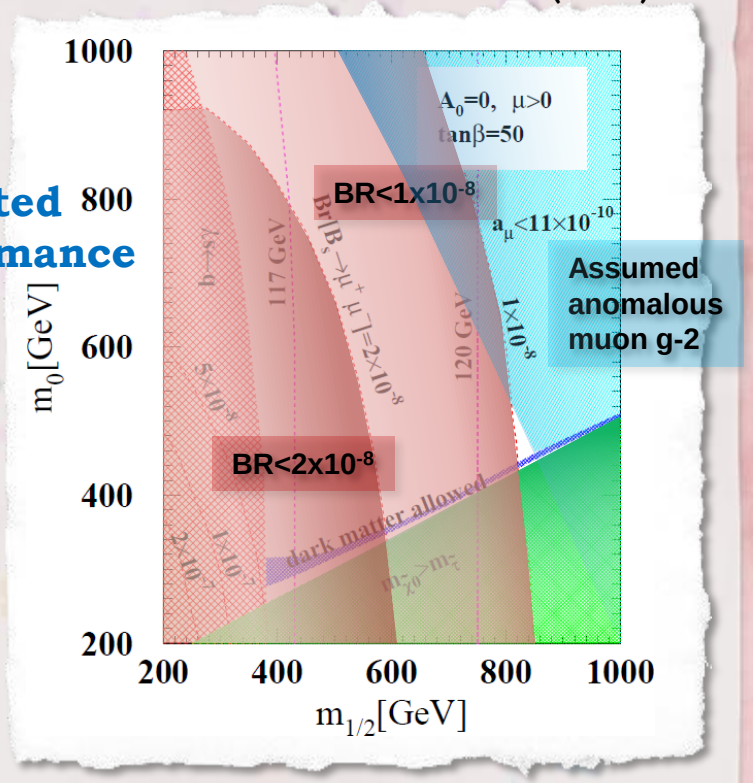
$B_s \rightarrow \mu\mu$: prospects

DØ expected@5fb^{-1}



Expected performance @8fb^{-1}

mSUGRA, D. Toback, arXiv:0911.0880v1 (2009)



- ✓ 2010 (approved, ongoing : ~8fb^{-1})
  - ✓ CDF Expected limit: 2x10^{-8}@8fb^{-1} (6xSM)
  - ✓ Combined with DØ→5xSM
- ✓ 2011 (proposal, likely 10fb^{-1})
  - ✓ Combined limit ~O(10^{-8})

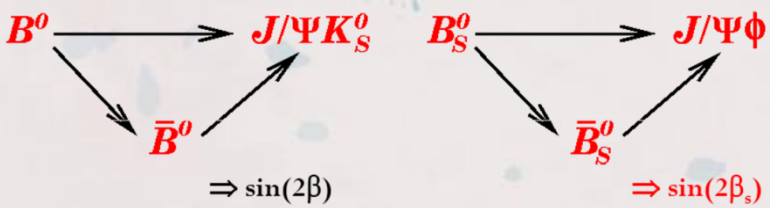
Strong constraint on NP parameters :
Could rule-out mSUGRA with Tevatron combination at 10fb^{-1}

CPV

- ✓ $\beta_s(B_s \rightarrow J/\Psi\varphi)$
  - ✓ CDF
  - ✓ DØ
  - ✓ Tevatron combination

CP Violation in B_s System

- **Analogously to the neutral B^0 system, CP violation in B_s system occurs through interference of decays with and without mixing:**

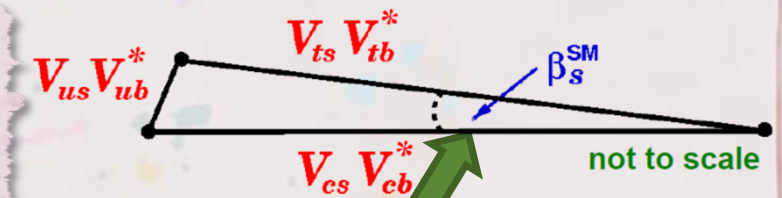


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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 :

$$\phi_s = \arg(-\frac{M_{12}}{\Gamma_{12}})$$

$$\beta_s$$

$$\phi_s^{SM} \sim 0.004$$

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

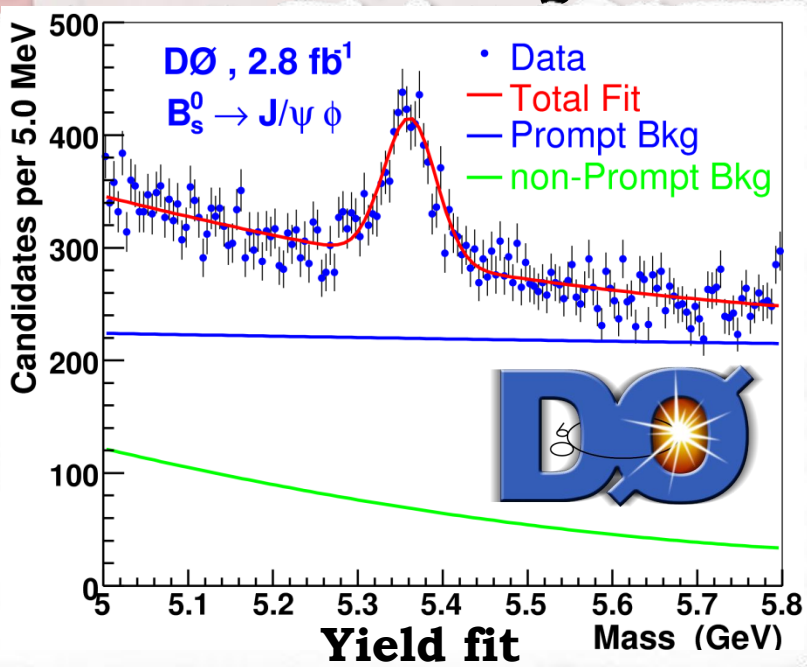
A. Lenz and U. Nierste, JHEP 06, 072(2007)

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

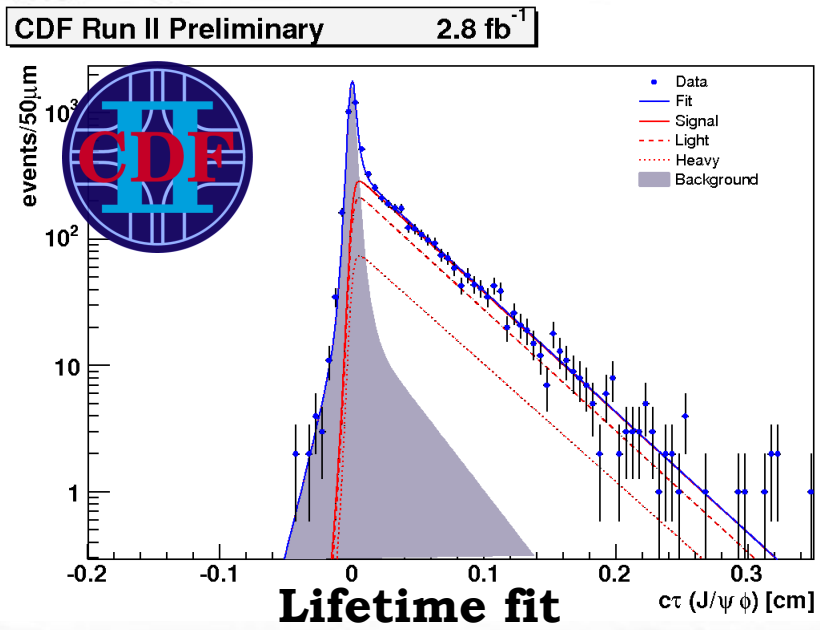
$$-2\beta_s = -2\beta_s^{SM} + \phi_s^{NP}$$

If ϕ_s^{NP} dominates : $-2\beta_s \sim \phi_s^{NP}$

$B_s \rightarrow J/\Psi\Phi$@2.8fb^{-1}



Yield fit



Lifetime fit

$N(B_s^0)^{D\emptyset} \sim 2000$

$N(B_s^0)^{CDF} \sim 3200$

β_s=0, no flavor tag :

$\tau(B_s^0) = 1.53 \pm 0.04$ (stat) ± 0.01 (syst) ps

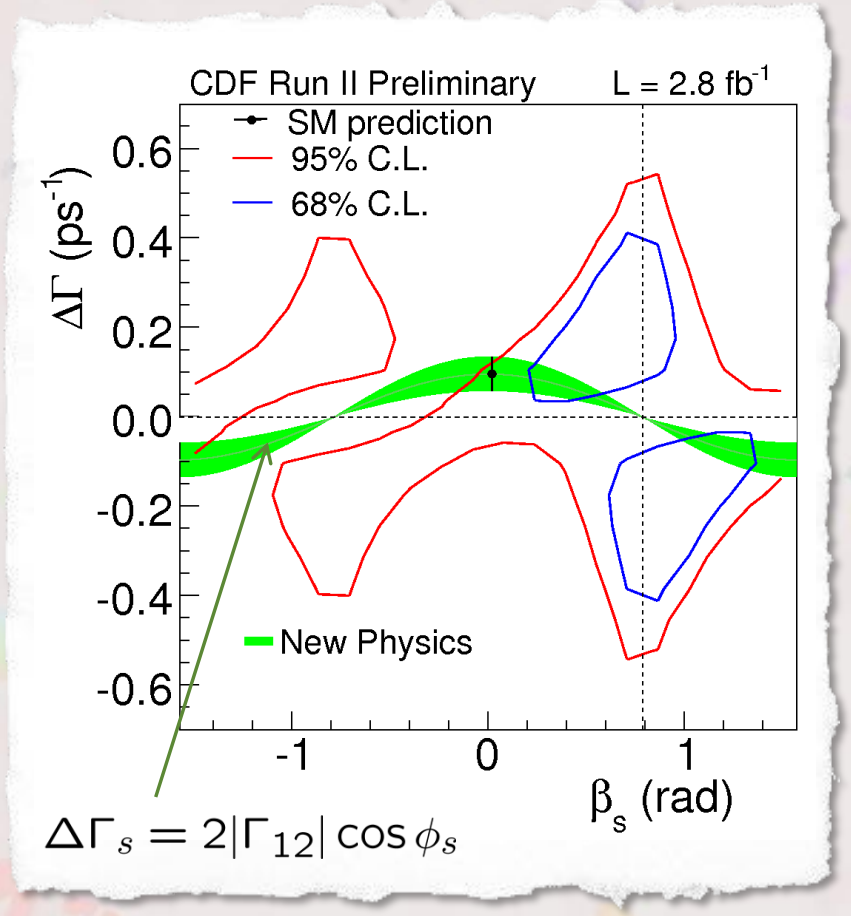
$\Delta\Gamma = 0.02 \pm 0.05$ (stat) ± 0.01 (syst) ps^{-1}

PRL 102, 032001 (2009)

$\tau(B_s^0) = 1.487 \pm 0.060$ (stat) ± 0.028 (syst) ps

$\Delta\Gamma = 0.085\ ^{+0.072}_{-0.078}$ (stat) ± 0.006 (syst) ps^{-1}

CDF β_s result@2.8fb^{-1}



CDF note 9458 (2.8fb^{-1})

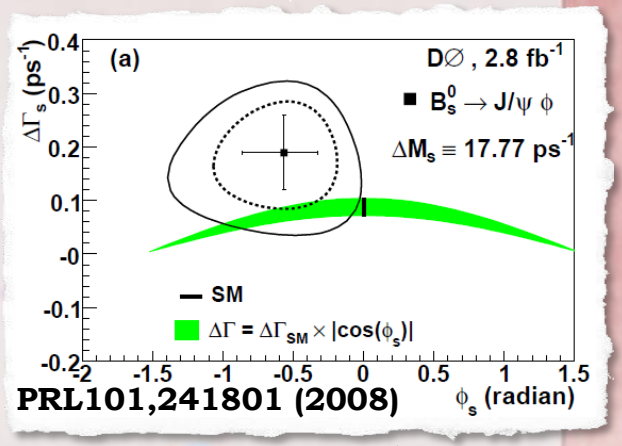
PRL100,161802 (2008) (1.35fb^{-1})

SM p-value=7%

Observe deviation from SM β_s of 1.8σ

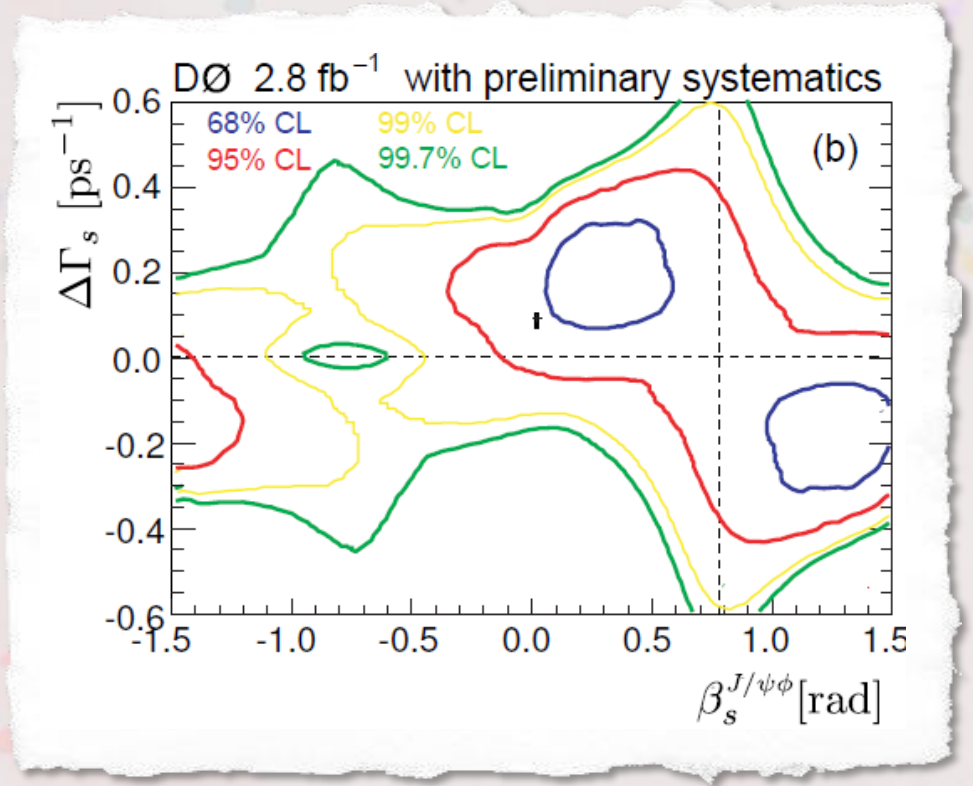
DØ β_s result@2.8fb^{-1}

Update from published result
- **Remove constraints on strong phases $\delta_\parallel$, $\delta_\perp$**
- **Include systematic uncertainties to Δm_s**



PRL101,241801 (2008)

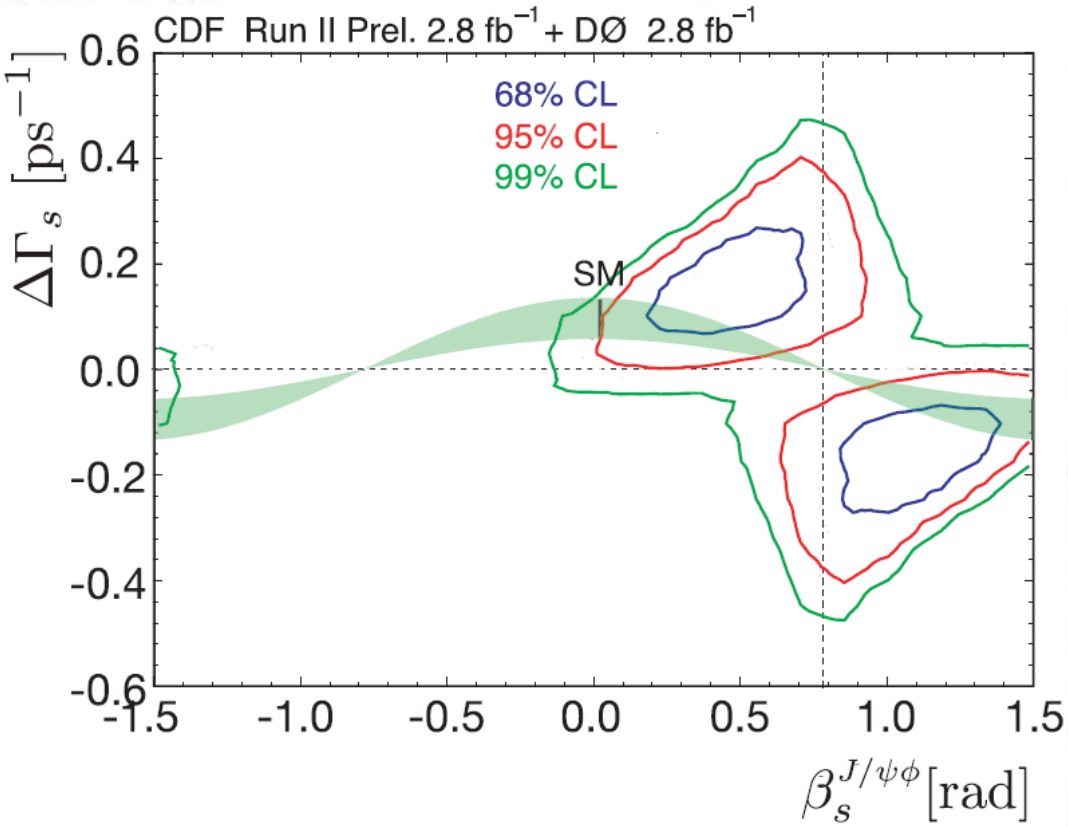
$$-2\beta_s^{J/\psi\phi} = \phi_s$$



SM p-value=24%

Tevatron combination

DØ note 5928, CDF note 9787



Combined likelihood finds 2.1σ deviation from SM

Works on new data/methods are ongoing

Conclusion

- $B_s \rightarrow \varphi\mu\mu$ ($4.4fb^{-1}$)
  - 1st observation!
- $B \rightarrow K^{(*)}\mu\mu$ ($4.4fb^{-1}$)
  - 1st measurement of A_{FB} at hadron collider
  - No significant deviation from the SM so far
- $B_{s,d} \rightarrow \mu\mu$ (3.7 and $4.8fb^{-1}$)
  - New world's best upper limit
  - Prospects for $O(10^{-8})$ limit by CDF+DØ
- β_s measurement ($2.8fb^{-1}$)
  - Updated analysis with $2.8fb^{-1}$
  - Tevatron combination
    - 2.1σ deviation from the SM

Tevatron prospects :
-2010 ~$8fb^{-1}$
-2011 ~$10fb^{-1}$

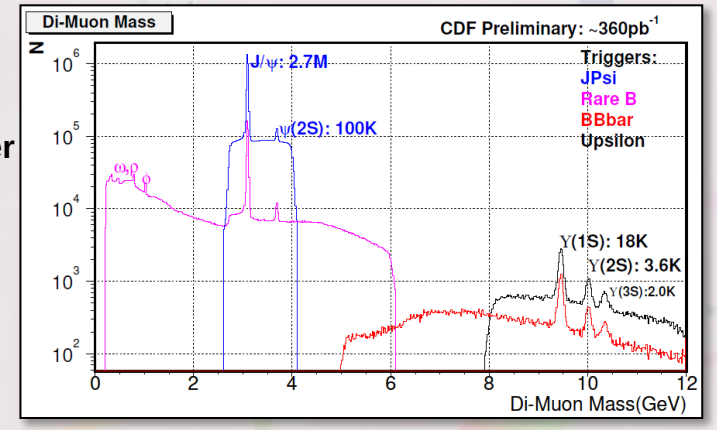
Rich B programs are ongoing…
Tevatron is our Source Cachat !!

Backup

B triggers

Di-Muon

- Conventional trigger at hadron collider
- Wide mass range



1-Displaced track + *lepton* (*e*, *μ*)

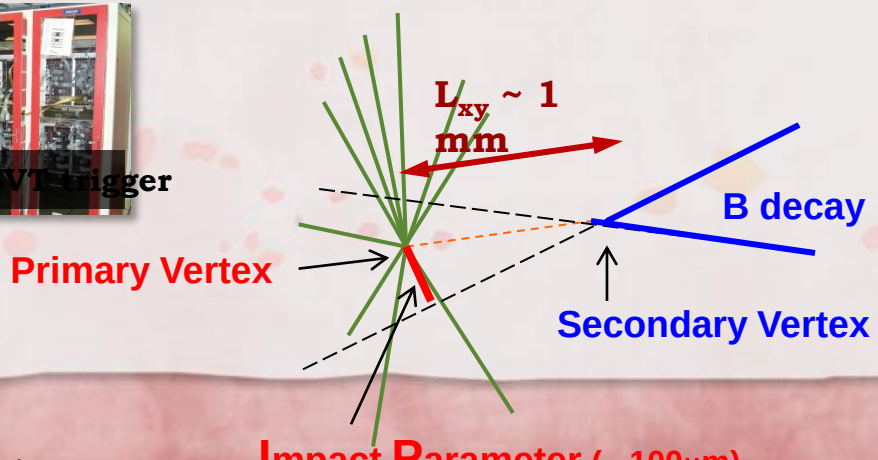
120 μm < I.P.(trk) < 1mm

P_T(*lepton*) > 4 GeV

Semileptonic modes

Sillicon Vertex Trigger: SVT

- **Online selection of displaced tracks using SVX**
- **UNIQUE at hadron colliders**



2-Displaced tracks

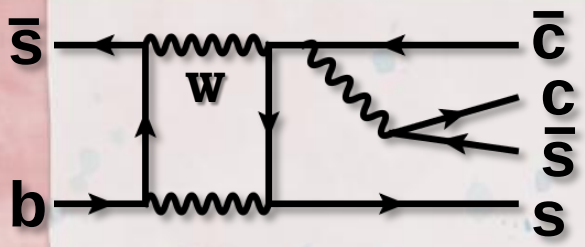
P_T(trk) > 2 GeV

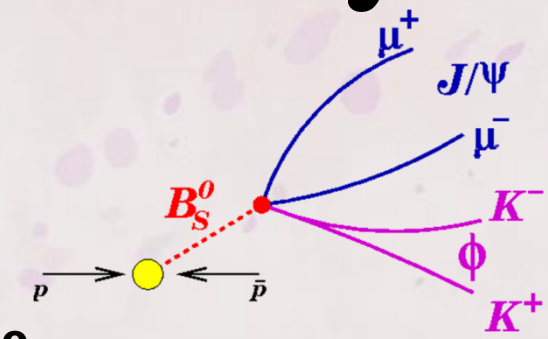
120 μm < I.P.(trk) < 1mm

Σp_T > 5.5 GeV

fully hadronic modes

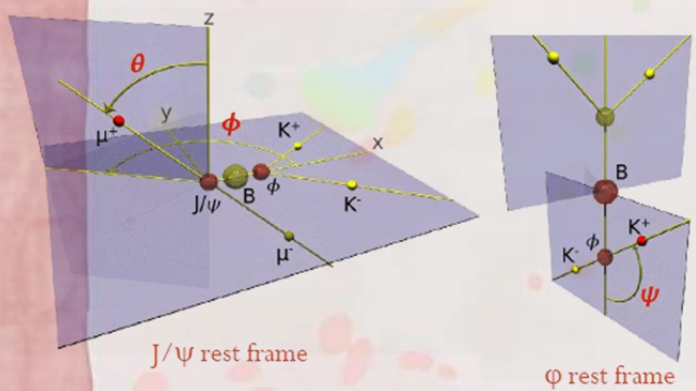
$B_s \rightarrow J/\Psi\Phi$ Decays



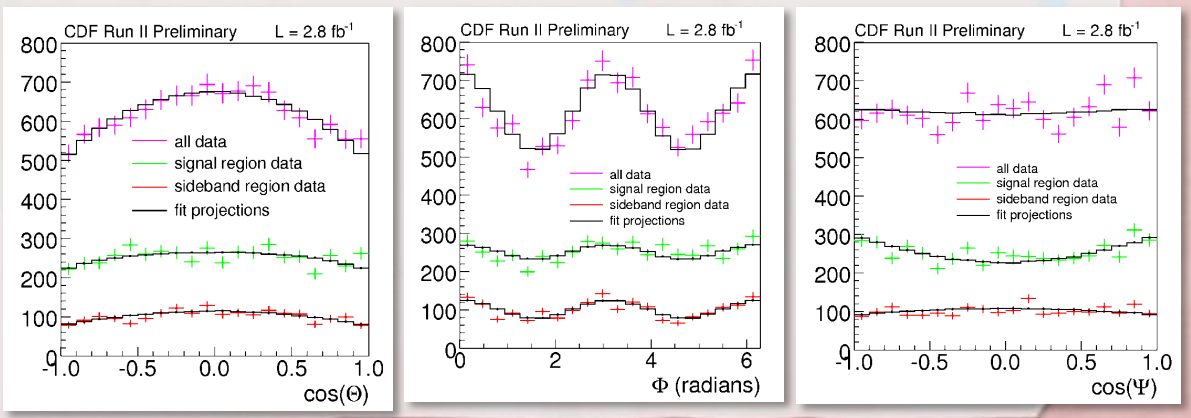


- Golden channel to measure B_s CPV
- Can measure lifetime, $\Delta\Gamma$, and β_s
- Decay of B_s (spin 0) to J/Ψ(spin 1) Φ(spin 1) leads to
  - → three different angular momentum final states:

L = 0 (s-wave), 2 (d-wave) → CP even (≈ short lived or light B_s if $\Phi_s \approx 0$)
L = 1 (p-wave) → CP odd (≈ long lived or heavy B_s if $\Phi_s \approx 0$)



Disentangle CP states by angular distributions of the decay products (angular analysis)



$B_s \to J/\Psi\Phi$ Decay Rate

- $B_s \to J/\Psi\Phi$ decay rate as function of time, decay angles and initial B_s flavor:

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho}) + |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_+ f_4(\vec{\rho}) + |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho}) + |A_0||A_\perp|\mathcal{V}_+ f_6(\vec{\rho}),$$

time dependence terms

angular dependence terms

terms with β_s dependence

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta\sin(2\beta_s)\sin(\Delta m_s t)],$$

terms with Δm_s dependence present if initial state of B meson (B vs anti-B) is determined (flavor tagged)

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].$$

'strong' phases:

$$\delta_\parallel \equiv \mathrm{Arg}(A_\parallel(0)A_0^*(0))$$

$$\delta_\perp \equiv \mathrm{Arg}(A_\perp(0)A_0^*(0))$$

- Identification of B flavor at production (flavor tagging) → better sensitivity to β_s

Non-Gaussian Regime

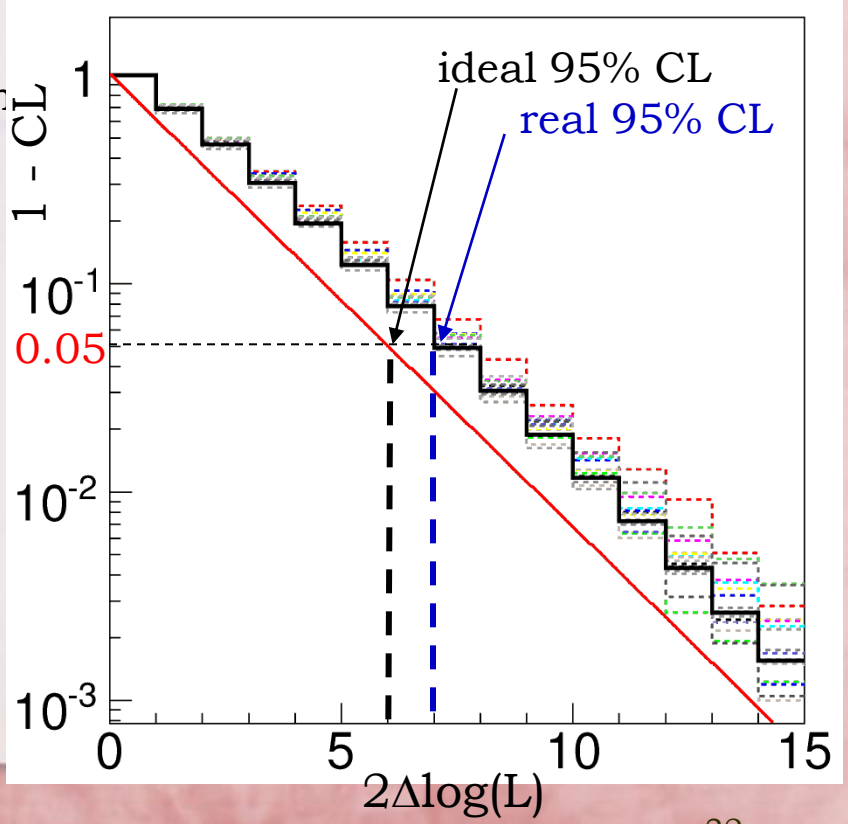
- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profile likelihood at 2.3 (6) units up from minimu

- In this analysis integrated likelihood ratio distribution (black histogram) deviates from the ideal χ^2 distribution (red continuous curve)

-To get 95% CL need to go up ~7 instead of 6 units from minimum

- Procedure used by both CDF and DØ

- From pseudo experiments find that Gaussian regime is indeed reached as sample size increases

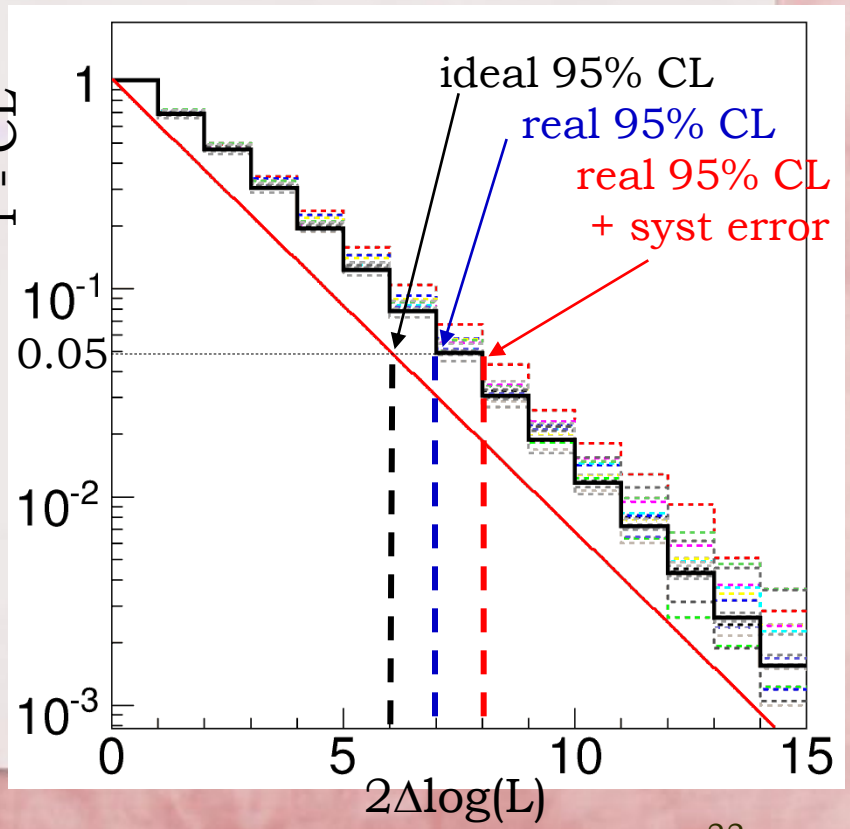


CDF Systematic Uncertainties

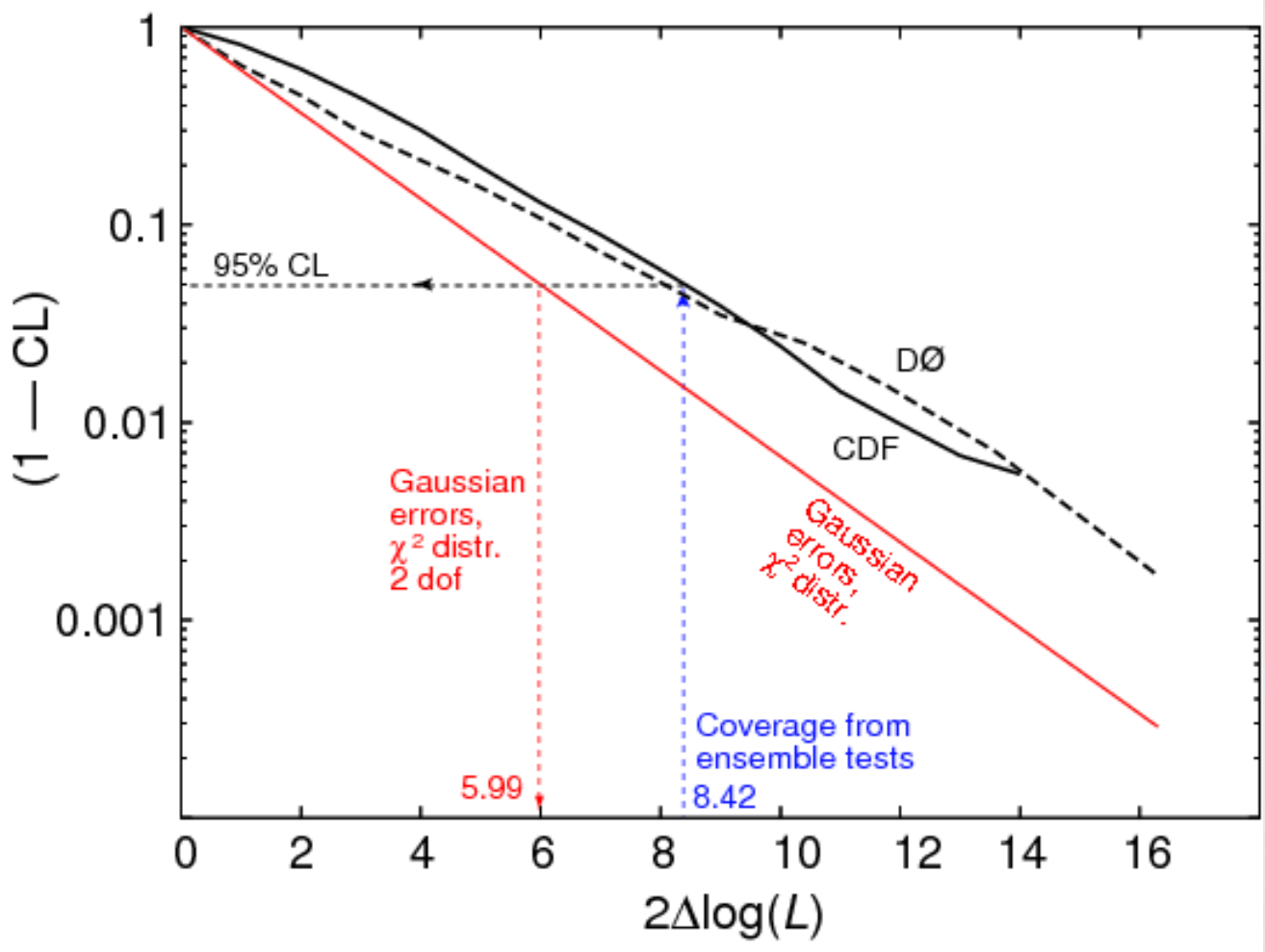
- At CDF, systematic uncertainties studied by varying all nuisance parameters +/- 5 σ from observed values and repeating LR curves (dotted histograms)

- Nuisance parameters:
  - lifetime, lifetime scale factor uncertainty,
  - strong phases,
  - transversity amplitudes,
  - background angular and decay time parameters,
  - dilution scale factors and tagging efficiency
  - mass signal and background parameters
  - …

- Take the most conservative curve (dotted red histogram) as final result



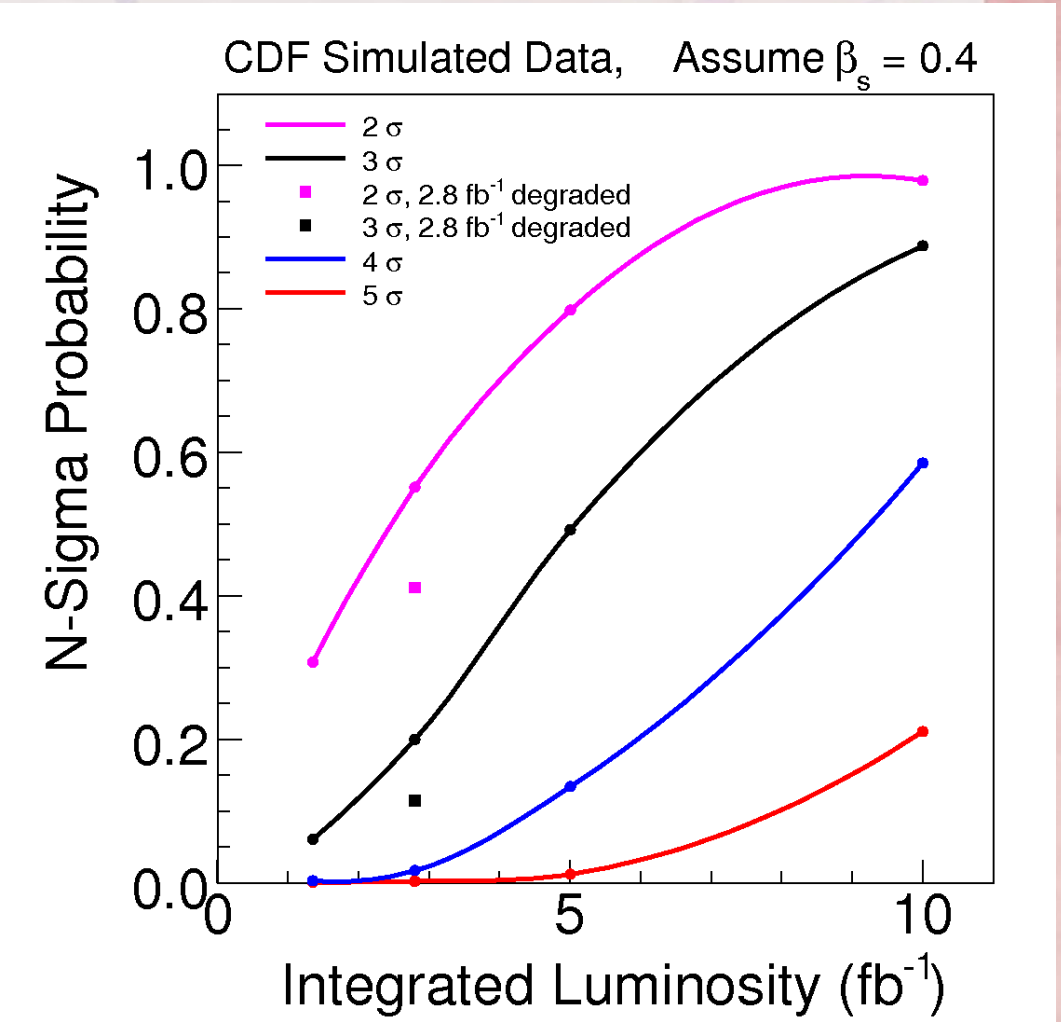
Deviation from Gaussian regime



Present CDF result doesn't fully utilize data

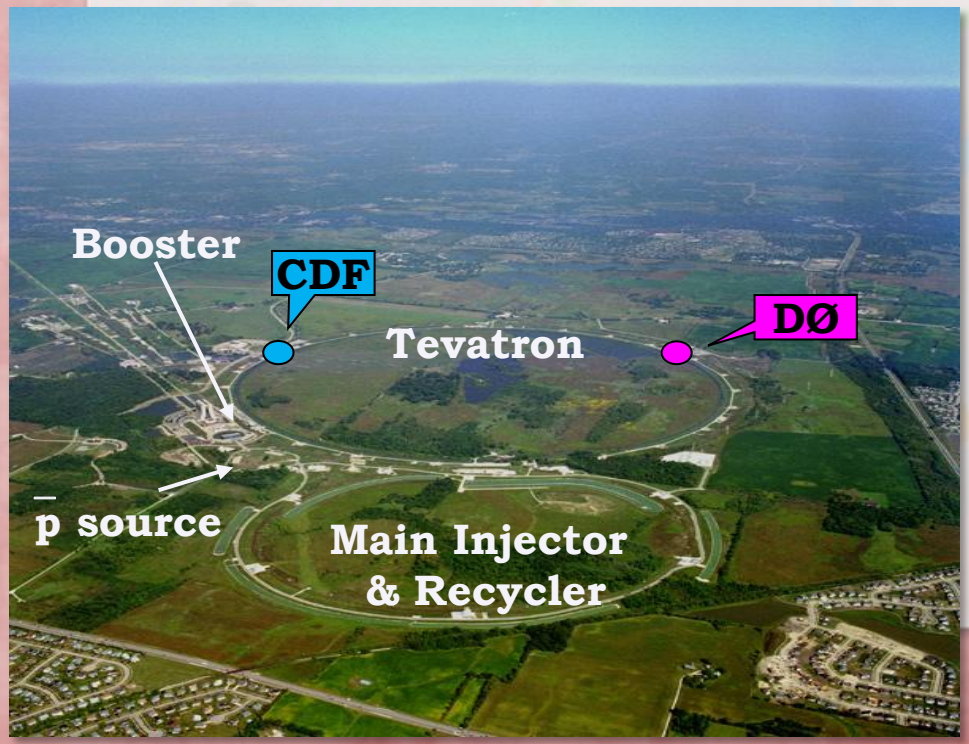
⇒ No particle ID in Neural Network selection

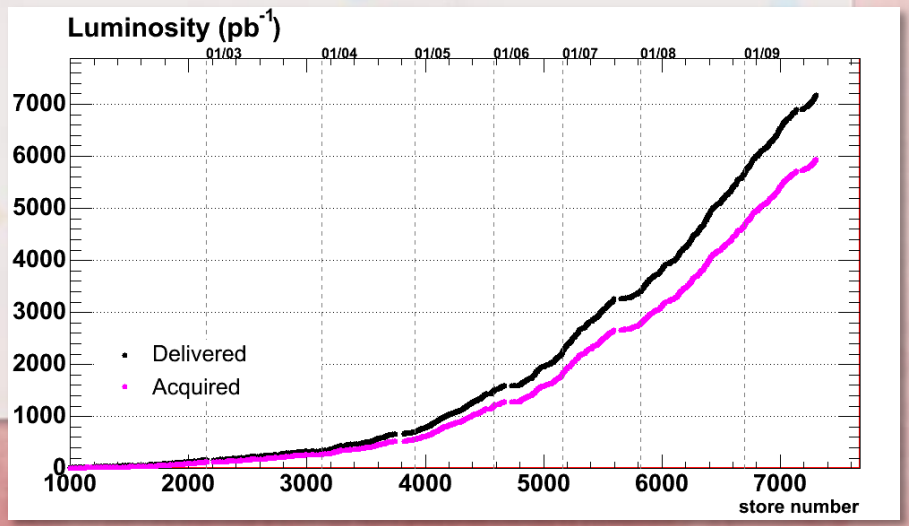
⇒ No SSKT after 1.3 fb^{-1}



Tevatron

- ✓ $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV
- ✓ 6 fb^{-1} data on tape for each experiment
- ✓ Recovery from shut down is in good status
- ✓ Today we cover 0.36~5fb^{-1} analysis

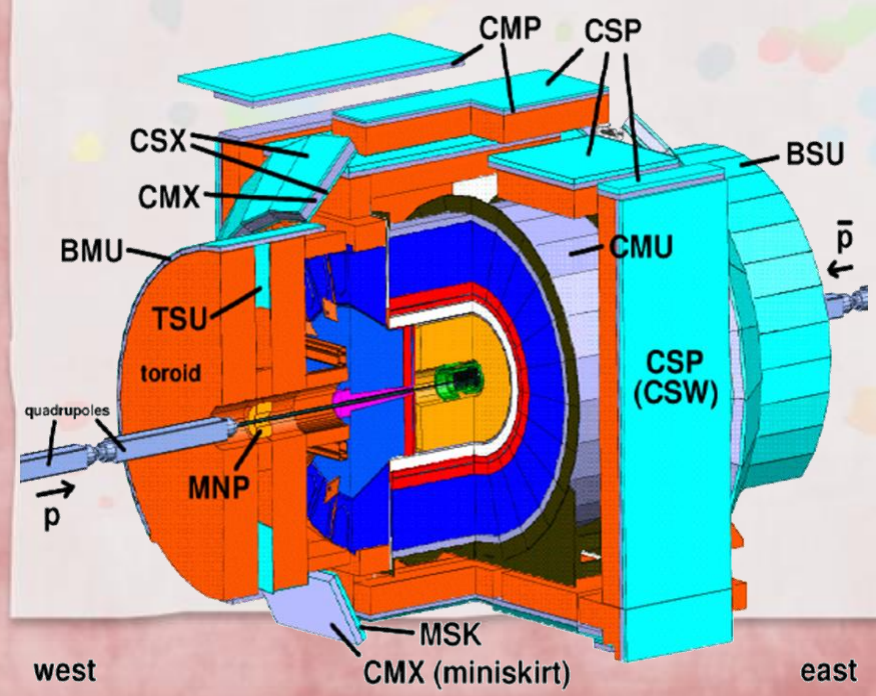




Tevatron Experiments

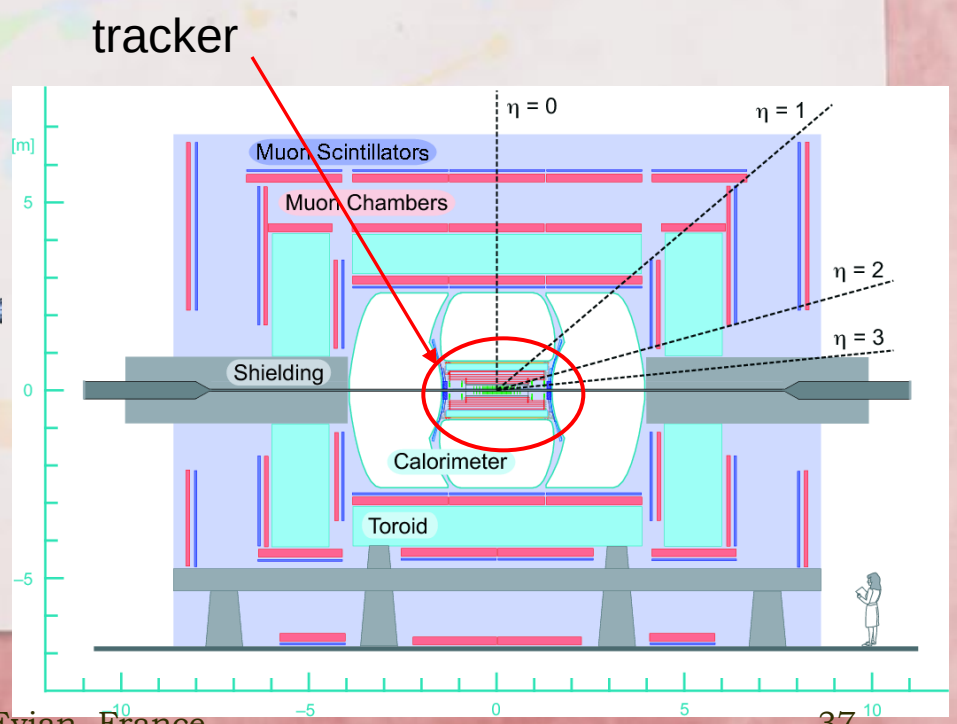
CDF II Detector

- Central tracking: - silicon vertex detector
  - drift chamber
  → excellent vertex, momentum and mass resolution
- Particle identification: dE/dX and TOF
- Electron and muon ID by calorimeters and muon chambers



DØ Detector

- Excellent tracking and muon coverage
- Excellent calorimetry and electron ID
- Silicon layer 0 installed in 2006 improves track parameter resolution



B→μμ : analysis strategy

- ✓ **Both CDF and DØ have similar analysis strategy**
- ✓ **Normalize to the B→J/ΨK:**

Trigger acceptance ratio

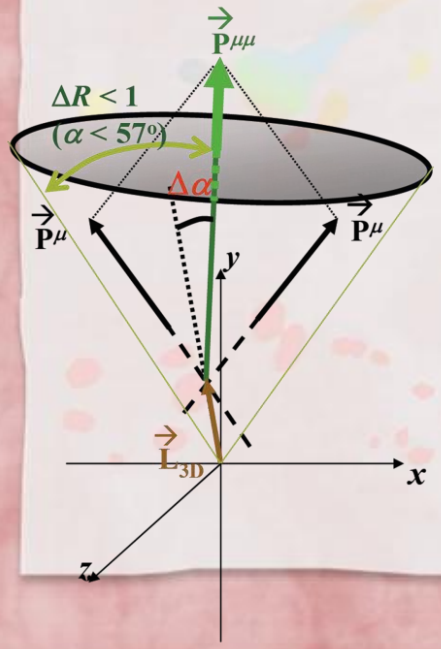
Reconstruction efficiency ratio

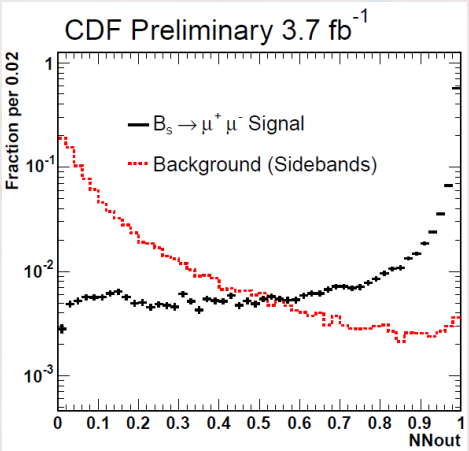
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_s}{N_+} \cdot \frac{\alpha_+}{\alpha_s} \cdot \frac{\epsilon_+}{\epsilon_s} \cdot \frac{1}{\epsilon_N} \cdot \frac{f_u}{f_s} \cdot \mathcal{B}(B^+),$$

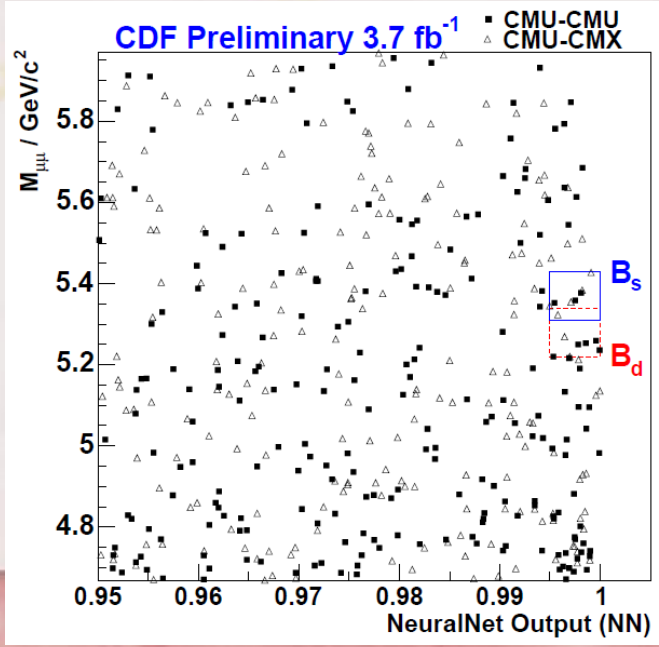
Production ratio, BR

NN requirement efficiency

- ✓ **Utilize vertex displacement, pointing angle, isolation…**

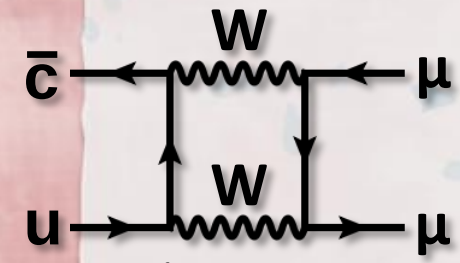




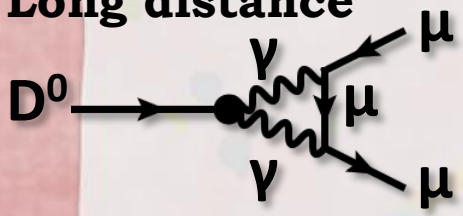


$D^0 \to \mu^+\mu^-$

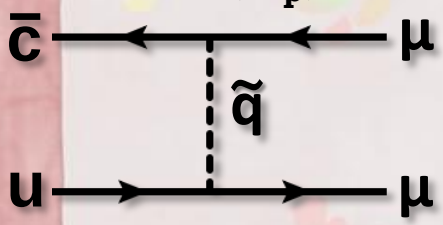
Short distance



Long distance



SUSY ($\not{R}_p$)

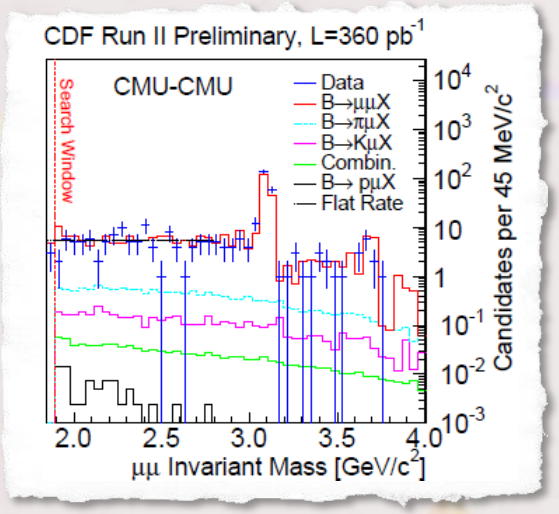


- ✓ Very suppressed in the SM (down-type loop)
- ✓ Dominated by long distance contributions

$$\mathcal{B}^{LD}_{SM}(D^0 \to \ell^+\ell^-) \sim 3 \times 10^{-13}$$

Burdman-Shipsey, Ann.Rev.Nucl.Part.Sci.53:431-499 (2003)

- ✓ NP(R-parity violation) may increase BR($D^0 \to \mu\mu$) up to O(10^{-8}~10^{-10})



CDF 360pb^{-1} analysis

(CDF public note 9226, 9899)

Observed limit :

BR($D^0 \to \mu\mu$)<2.1(3.0) x10^{-7} 90%(95%)C.L.

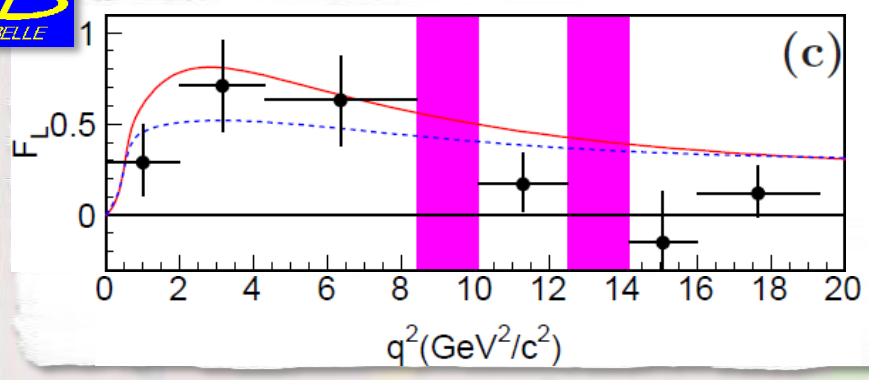
BaBar: BR($D^0 \to \mu\mu$)<1.3x10^{-6} 90%C.L. (PRL93,191801(2004))

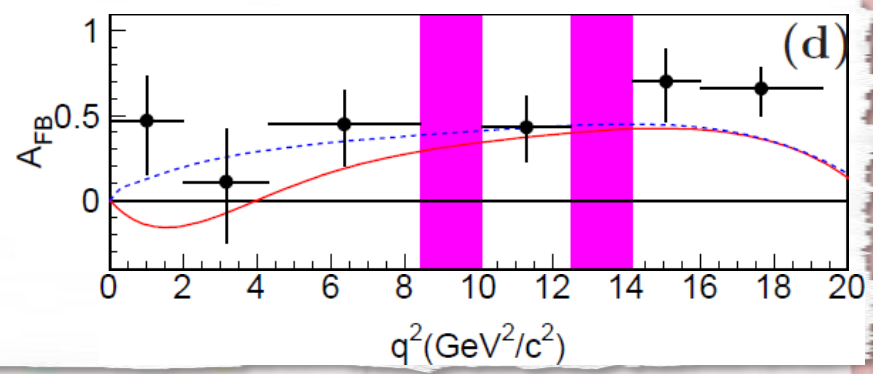
Belle: BR($D^0 \to \mu\mu$)<1.4x10^{-7} 90%C.L. Preliminary result shown at EPS09

- ✓ Tevatron has potential to improve the limit (6fb^{-1} data on tape)
  - ✓ Could reach at O(10^{-8}) by end of RunII

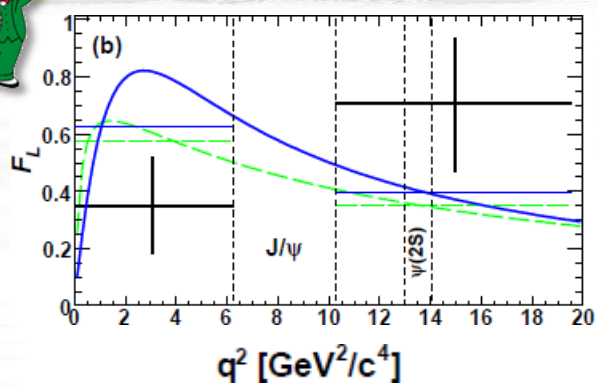
$A_{FB}(B \rightarrow K^{(*)}\mu\mu)$

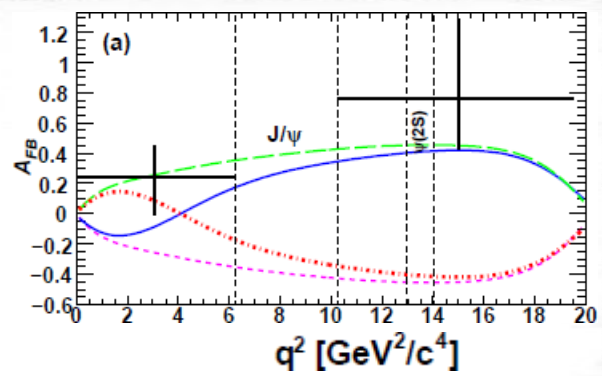
657M BB, PRL103:171801 (2009)





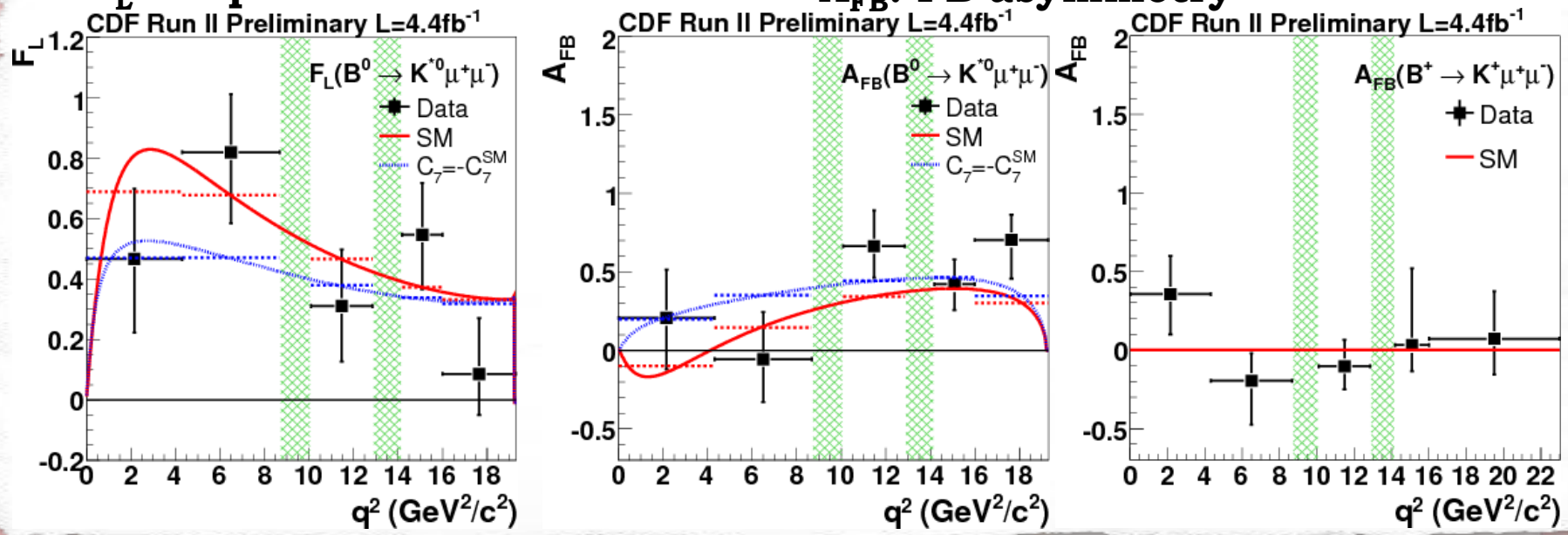
384M BB, PRD79,031102(R) (2009)





$A_{FB}(B \rightarrow K^{(*)}\mu\mu)$: 5 bin analysis

F_L: K* polarization | **A_{FB}: FB asymmetry**



- 1st and 2nd bin are merged (prior unblinding A_{FB} and F_L)