Tevatron – Bottom quark

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on behalf of CDF and DØ collaborations

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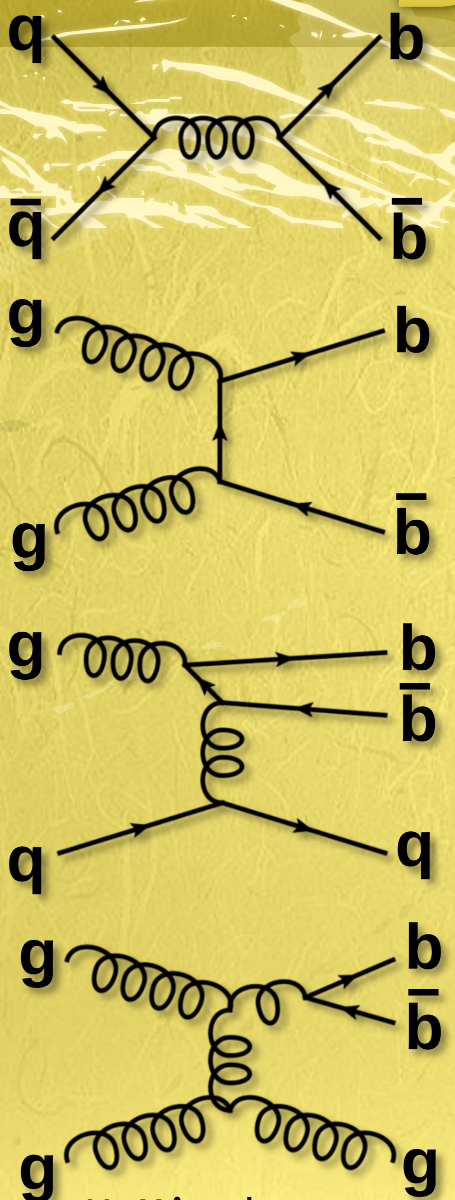
Introduction

- Tevatron as “Hadronic” B-factory
  - See Y.Takeuchi’s talk for Higgs/top

- Rich B programs are on-going
- Cover a part of Tevatron B-physics
  - Rare decay (BR, A_{FB})
    - $B \to K^{(*)}\mu\mu$, $B_s \to \varphi\mu\mu$, $B_{(s)} \to \mu\mu$, and $B_s \to \varphi\varphi$
  - CP violation (β_s)
    - $B_s \to J/\psi\varphi$
  - B hadron (BR, mass, τ, and polarization)
    - Δ_b, Ω_b, Υ(1s)

don’t cover…$B_s \to hh$, Charm mixing and so on

B production@Tevatron



☺Pros

- Enormous cross-section
- All species of b-hadrons
  - B_u,B_d,B_s,B_c,Λ_b, Σ_b...

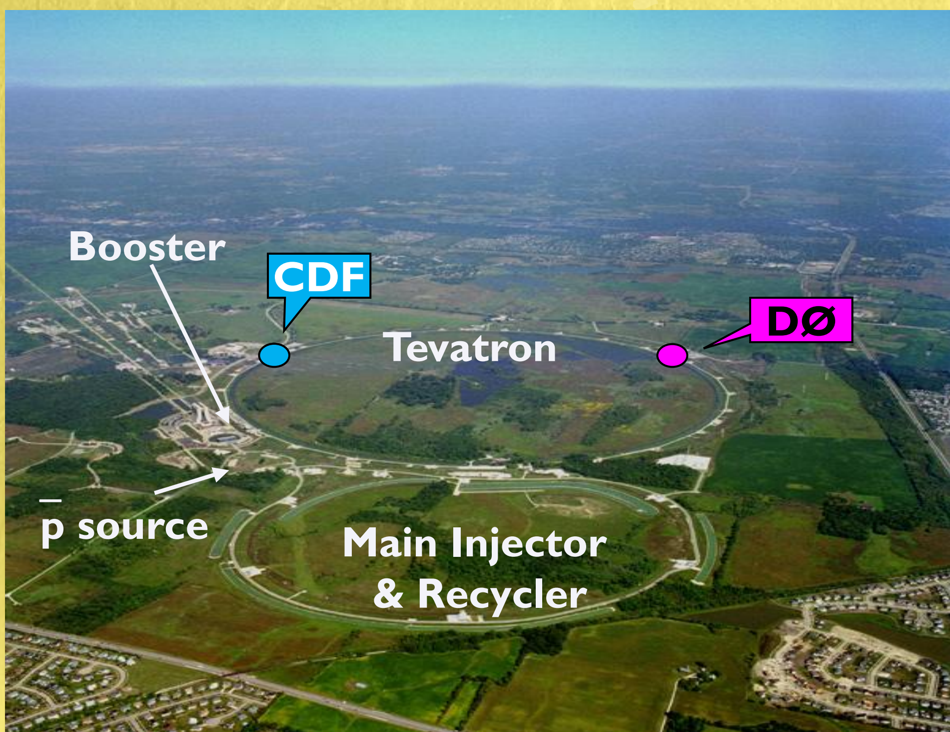
☹ Cons

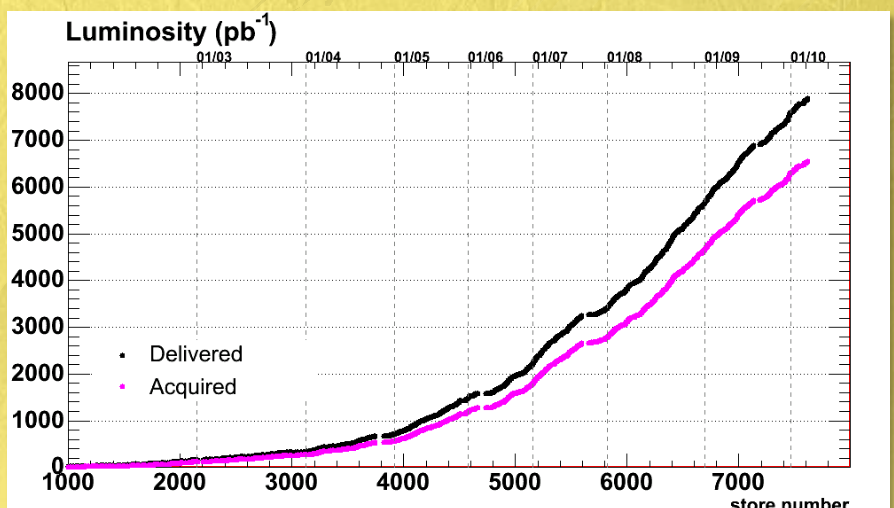
- QCD background x10^3 larger than $\sigma(b\bar{b})$
- Collision rate ~2MHz
  → tape writing limit ~100Hz
  - Sophisticated triggers are very important!

Tevatron B-production enables :
- explore various rare decays
- measure precise CPV parameters
- study wide mass range of b-hadrons

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 2.8~5fb^{-1} analysis





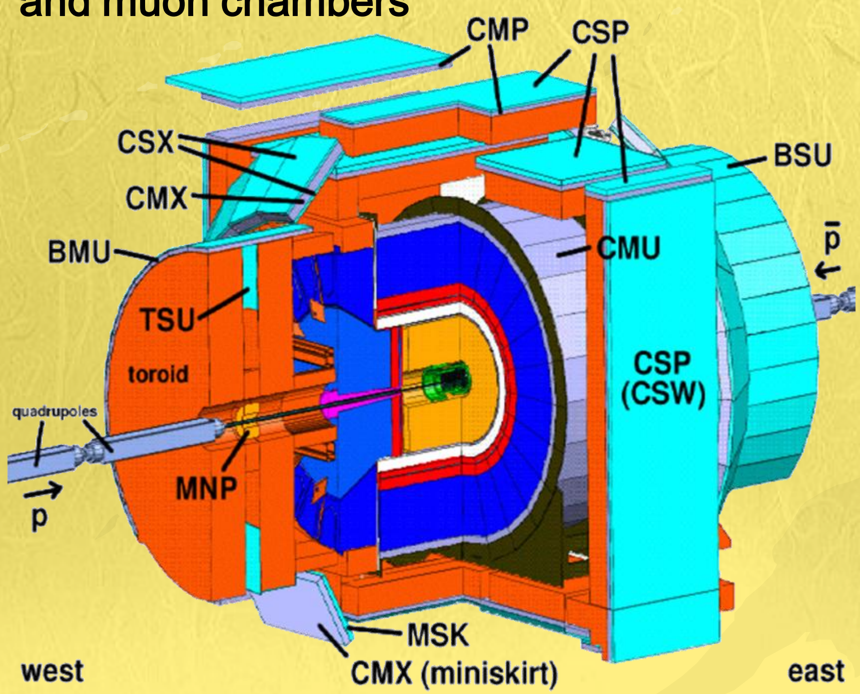
Tevatron Experiments

CDF II Detector

- Central tracking:
- silicon vertex detector
- drift chamber

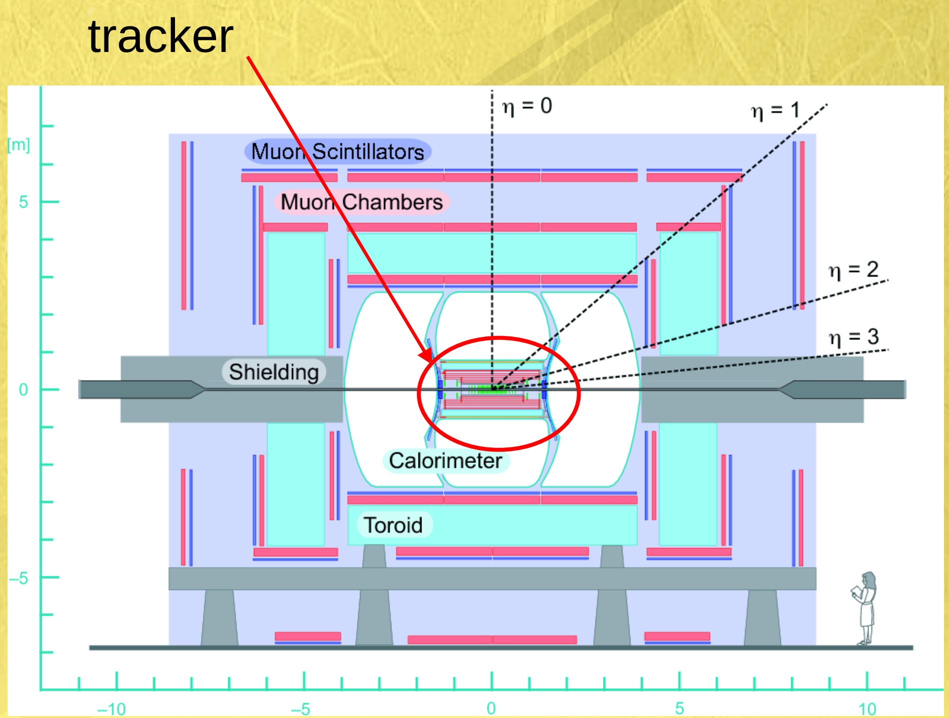
→ excellent vertex, momentum and mass resolution

- 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

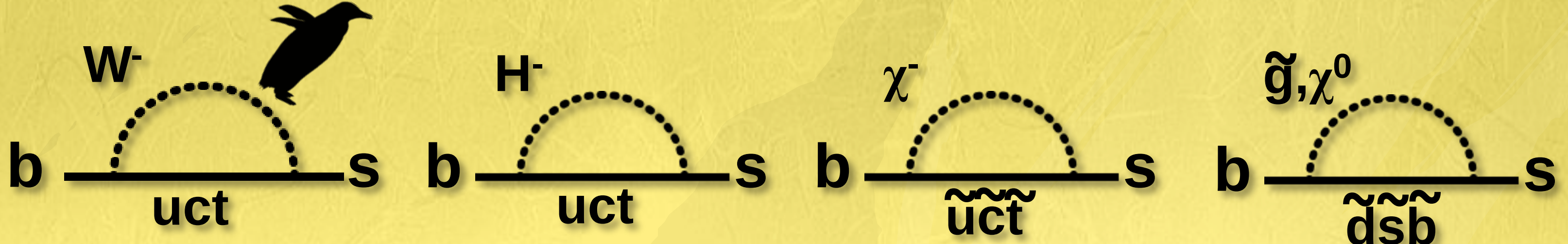


FCNC

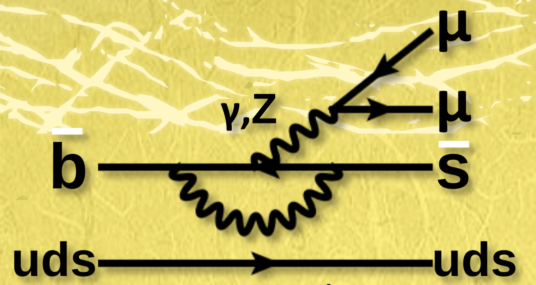
Flavor Changing Neutral Current

- b→s FCNC
  - Promising tool to search for new physics
  - Tree diagram is forbidden in the SM
  - May occur via higher order loop diagram
  - NP could enhance the amplitude
    - Interference with SM amplitude

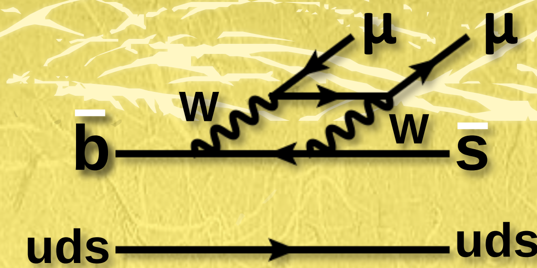
⇒
- Various observables are available
  - BR, K* polarization, and A_{FB}



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



EW penguins



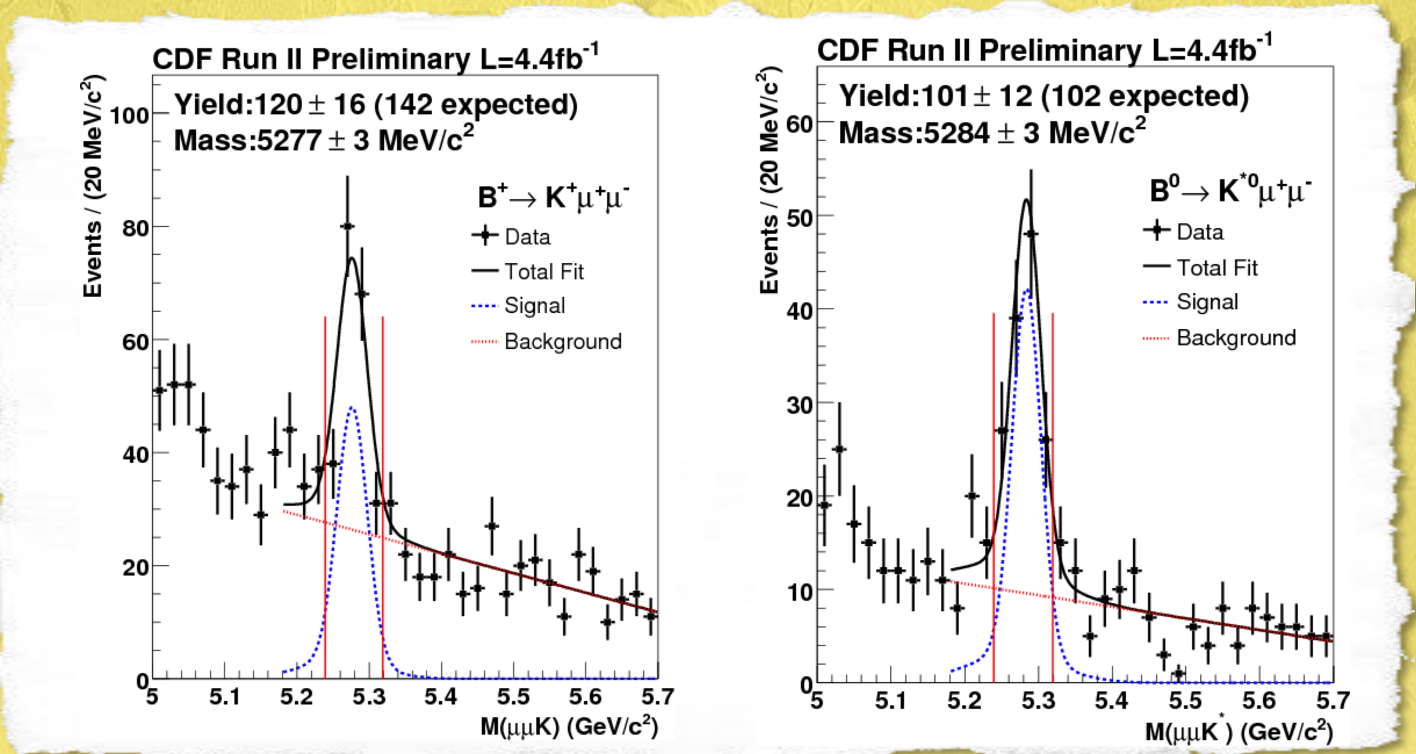
W box diagram

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}

$B \rightarrow K^{(*)}\mu\mu$: 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→K$^{(*)}$μμ : BR

- Relative BR : normalized BR by control channel (J/Ψh)

h=K,K*

Rare channel yield

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

Control channel yield

Reconstruction efficiency

- Absolute BR

(x10^{-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 $K^{*0}\mu\mu$

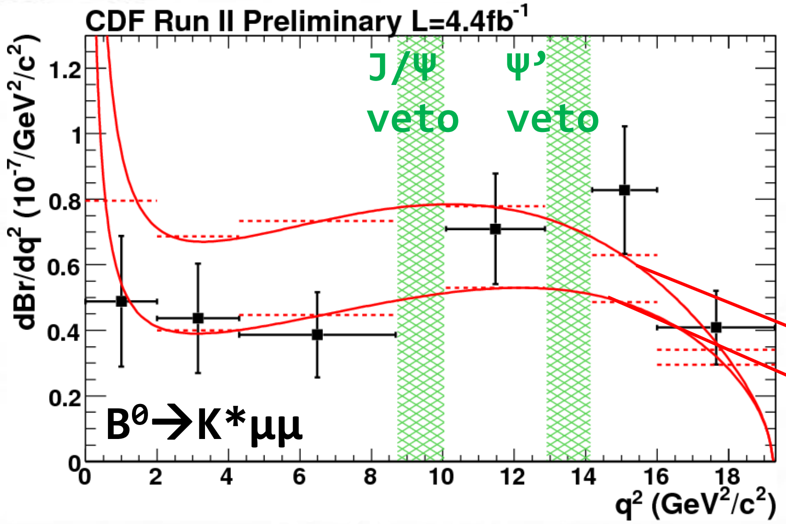
PRL102:091803 (2009) PRL103:171801 (2009)

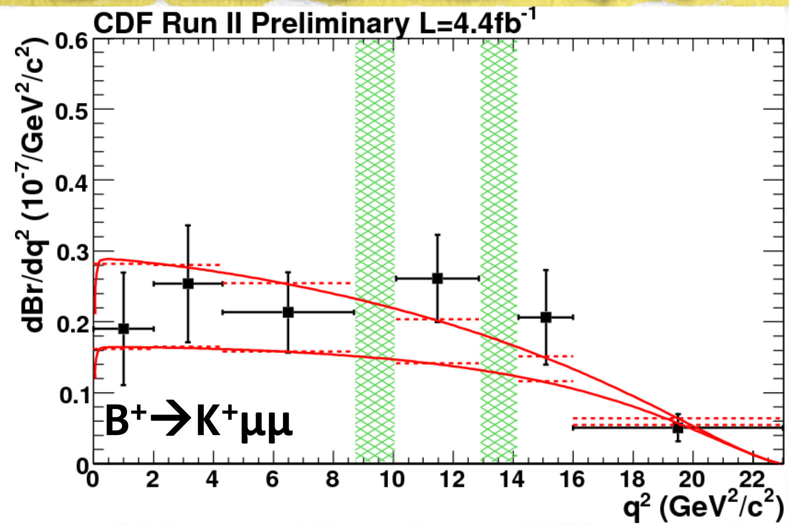
The best measurement for single final state!!

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

Kll: $\{K, K_s\}^*\{ee, \mu\mu\}$

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

→six q^2 bin (same definition as Belle)

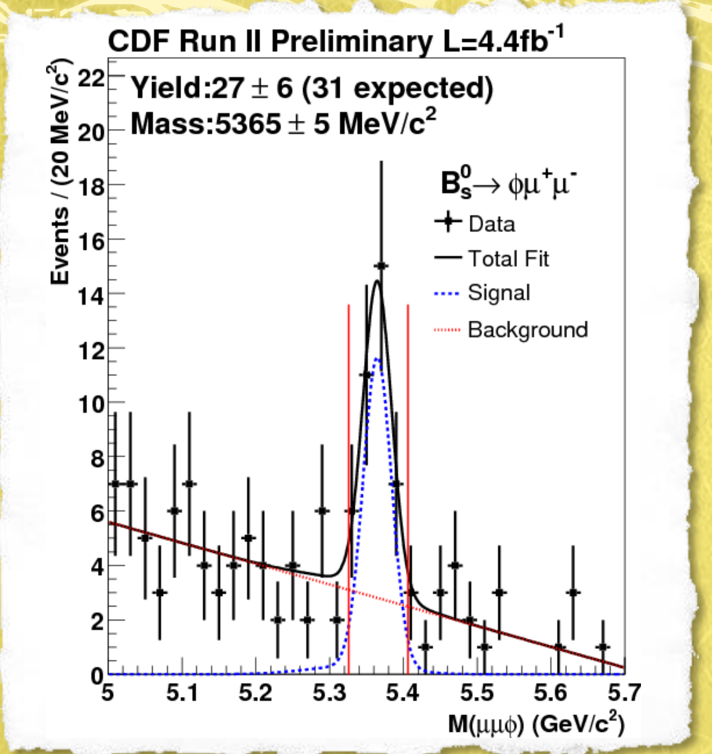
SM maximum allowed
SM minimum allowed

A. Ali, P. Ball, L. T. Handoko and G. Hiller, Phys. Rev. D61, 074024 (2000)

- **Consistent with SM**
- **Consistent and competitive with BaBar and Belle**
  - **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}

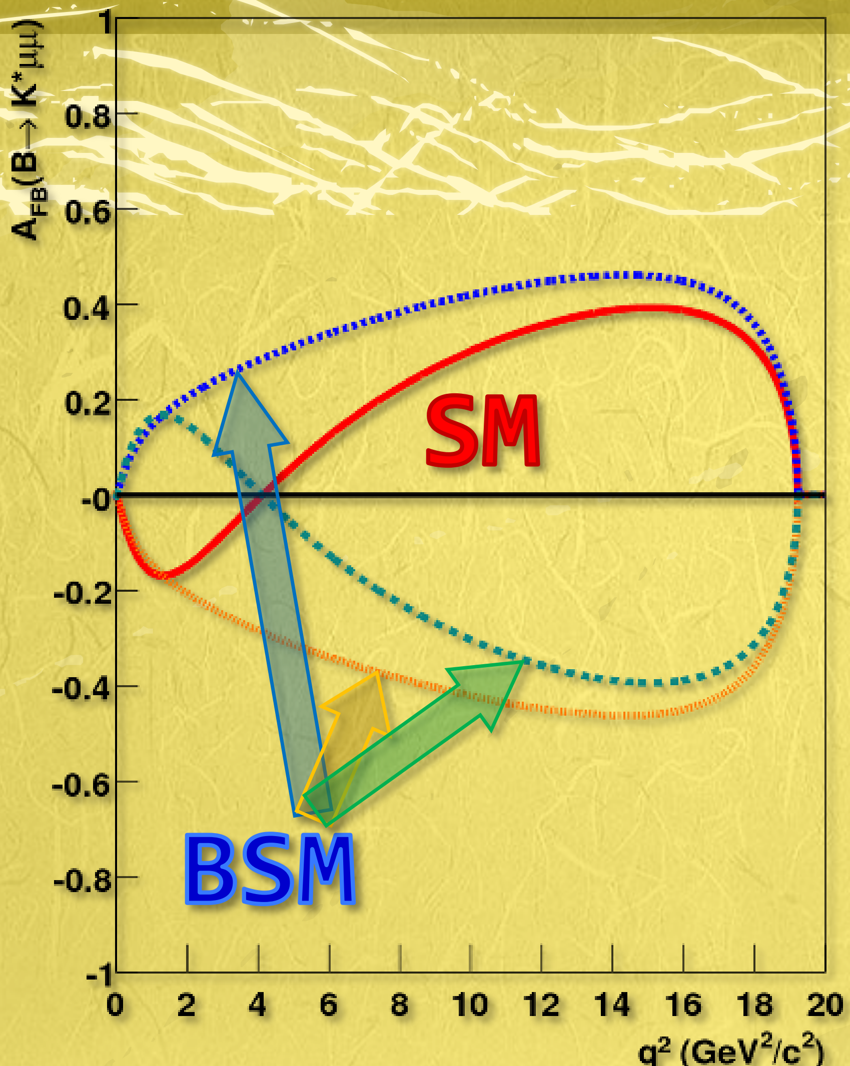
Consistent with theory ~1.61×10^{-6}

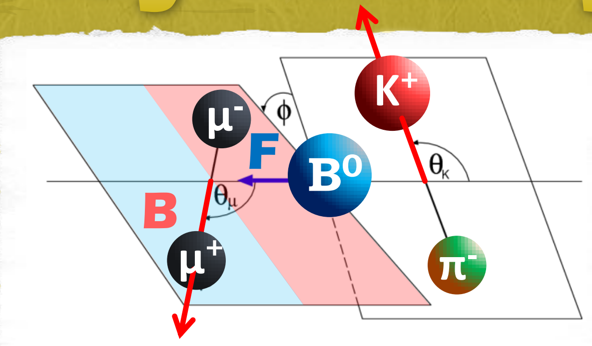
The rarest B_s decay we observed so far!!

- Yet another B→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 $q^2 = M_{\mu\mu}^2$

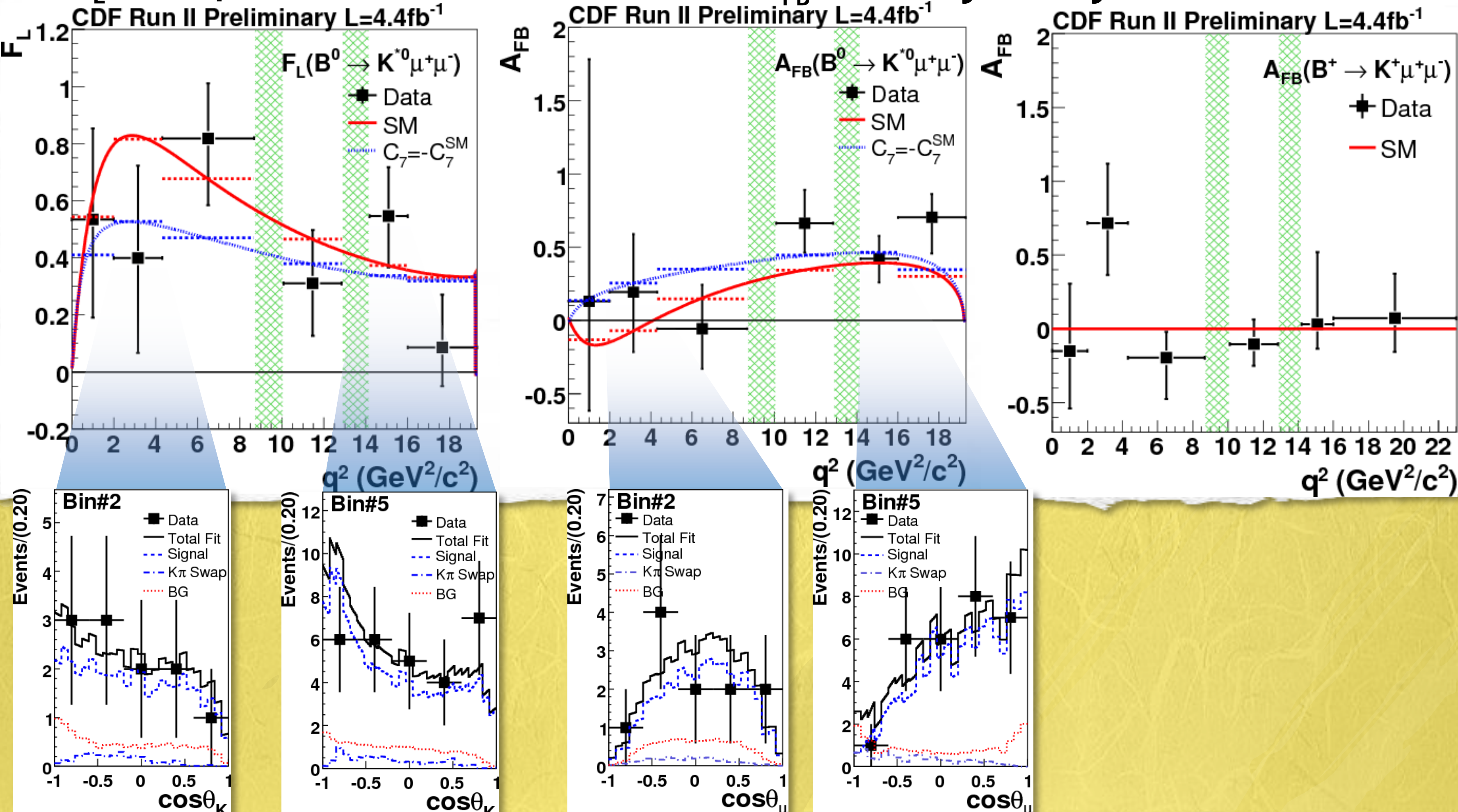
A_{FB} may show drastically different behavior under some BSM scenarios

→Good probe to explore BSM!

In case of Kμμ, A_{FB}(Kμμ)~0 is expected

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

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



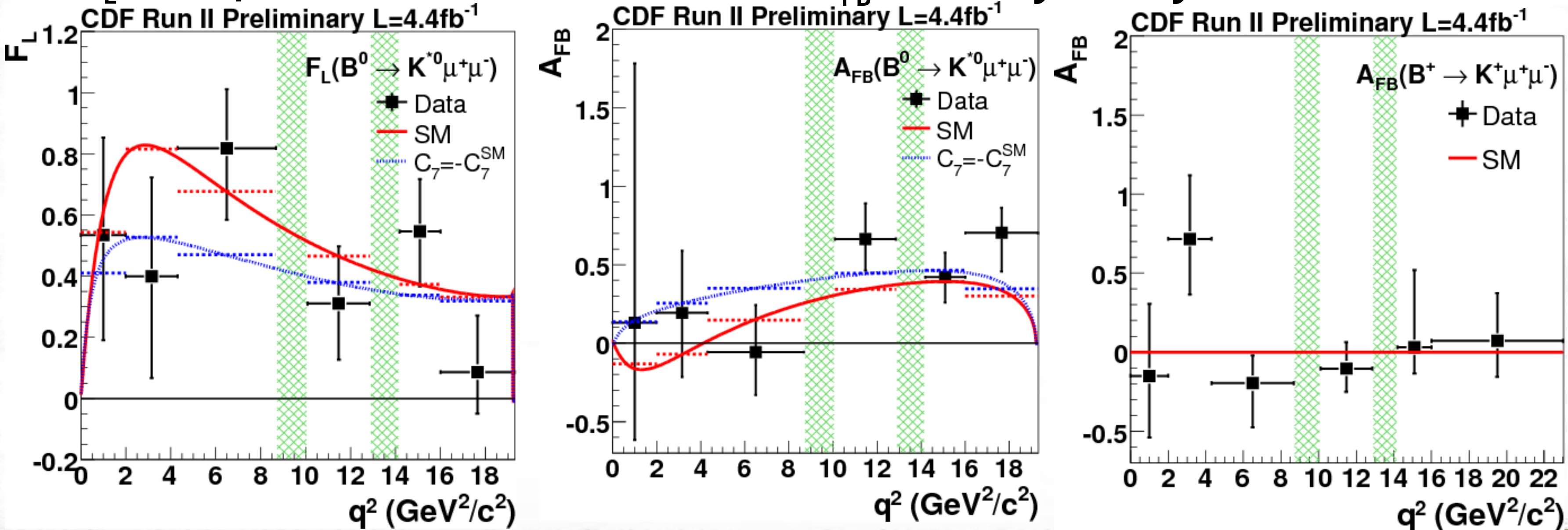
$$\frac{3}{2}F_L\cos^2\theta_K+\frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

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

F_L=1 for Kμμ

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

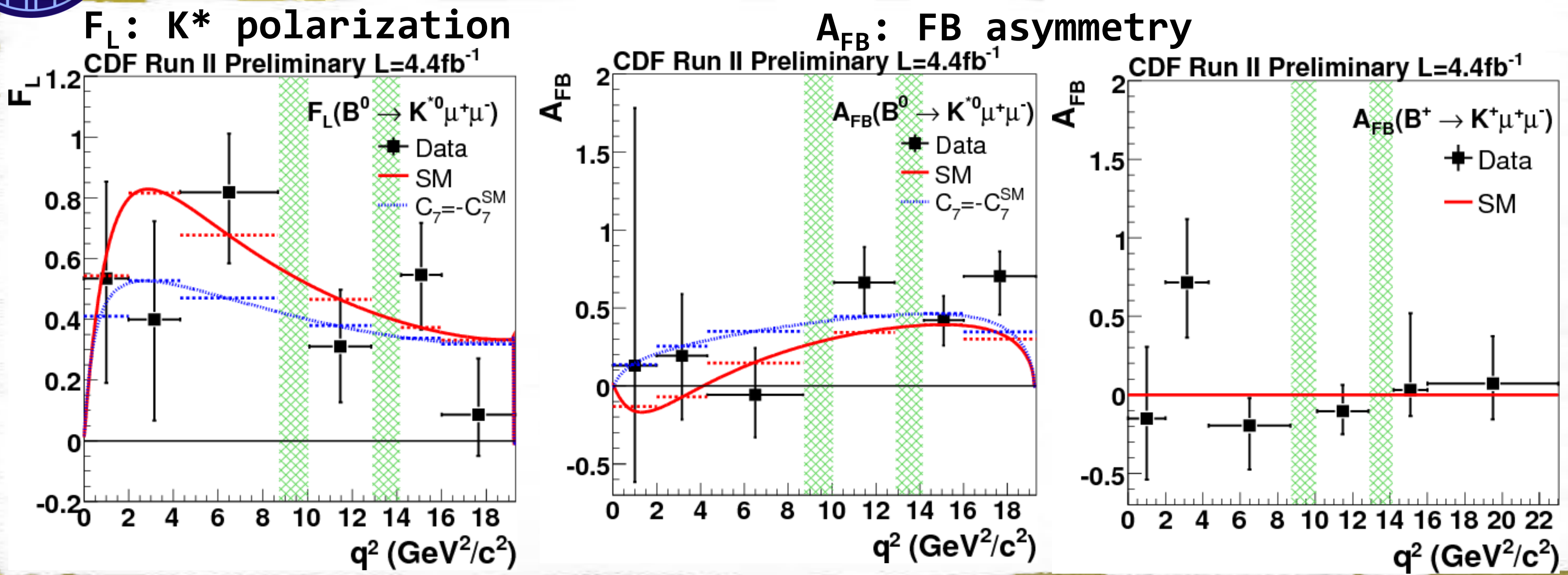
F_L: K* polarization A_{FB}: FB asymmetry



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

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

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



Expect world-leading result by end of this year:

- **doubled sample**
- **additional triggers**
- **exploit more decay channels**

Further reach if Run II extended to 2011

There is much room for improvement!

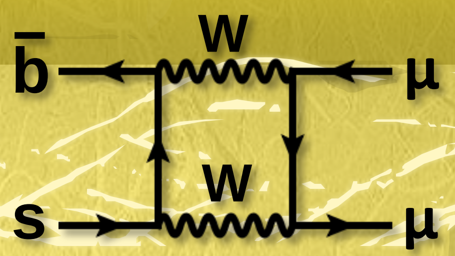
$B_{s,d} \rightarrow \mu\mu$

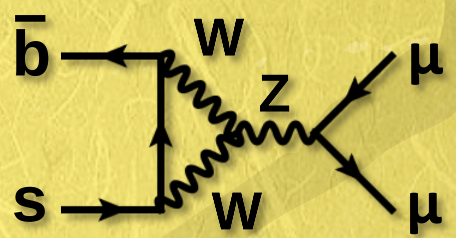
- **Highly suppressed in the SM**

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

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**



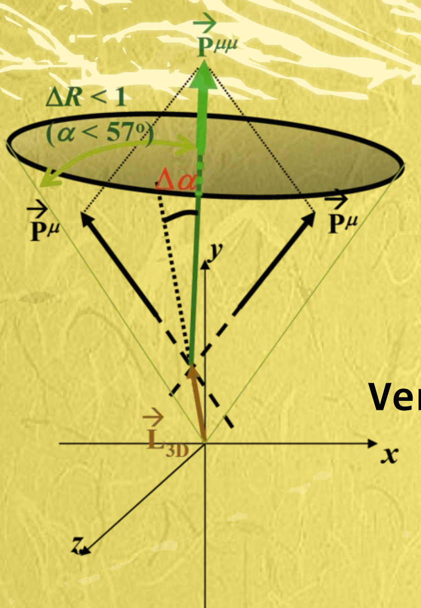


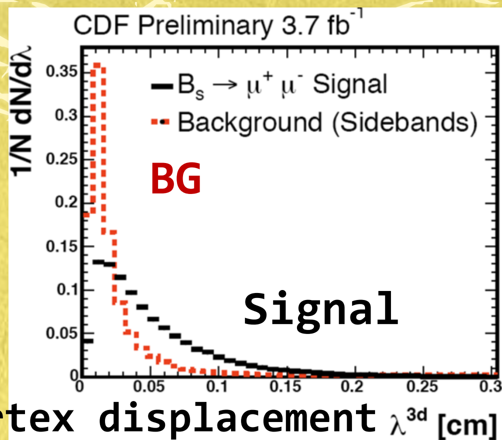
✓Current world's best upper limit:
✓$BR(B_s \rightarrow \mu\mu) < 4.7(5.8) \times 10^{-8}$
✓$BR(B_d \rightarrow \mu\mu) < 1.5(1.8) \times 10^{-8}$ 90(95)% C.L.

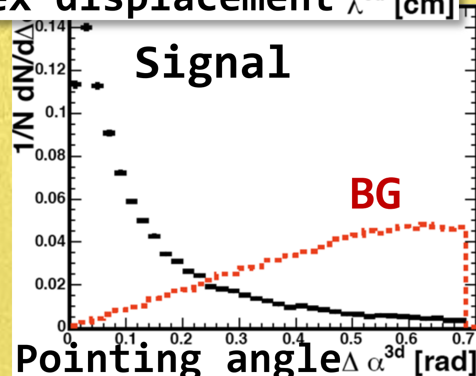
PRL 100,101802 (2008)

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

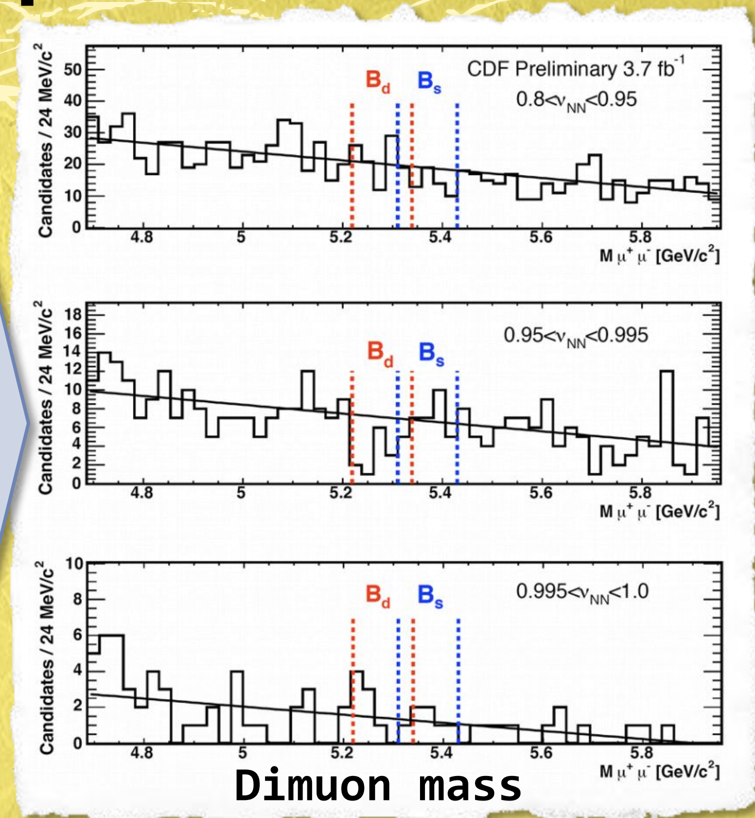
- Utilize neural network to optimize event selection







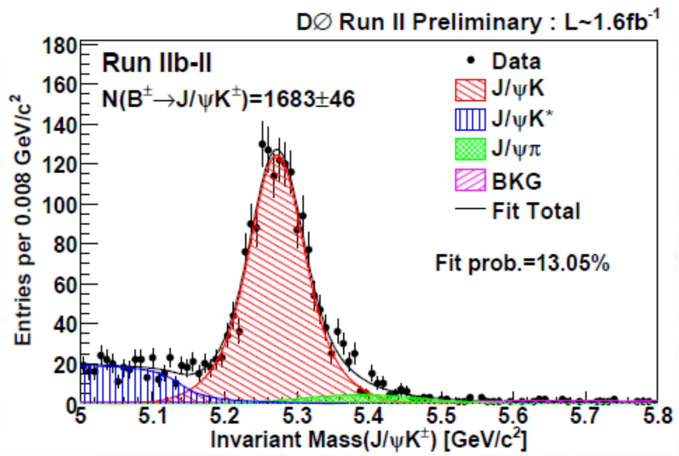
7 kinematic variables



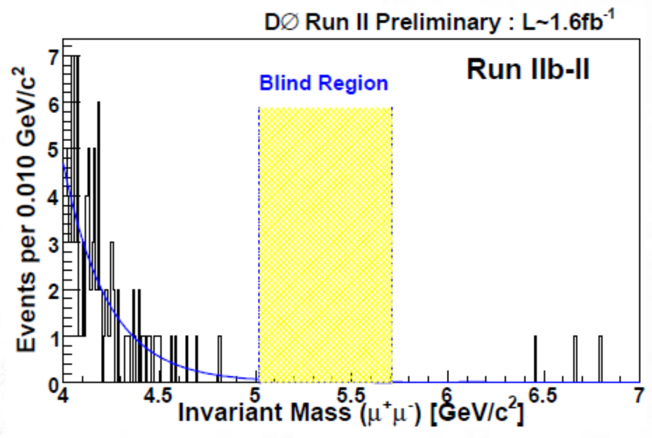
- ✓ Preliminary @3.7fb^{-1} (CDF public note 9892)
  - ✓ BR($B_s \rightarrow \mu\mu$)<3.6(4.3) x10^{-8} 90%(95%)C.L.
  - ✓ BR($B_d \rightarrow \mu\mu$)<6.0(7.6) x10^{-9} 90%(95%)C.L.

$B_s \rightarrow \mu\mu$ (DØ)

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



Normalization Channel



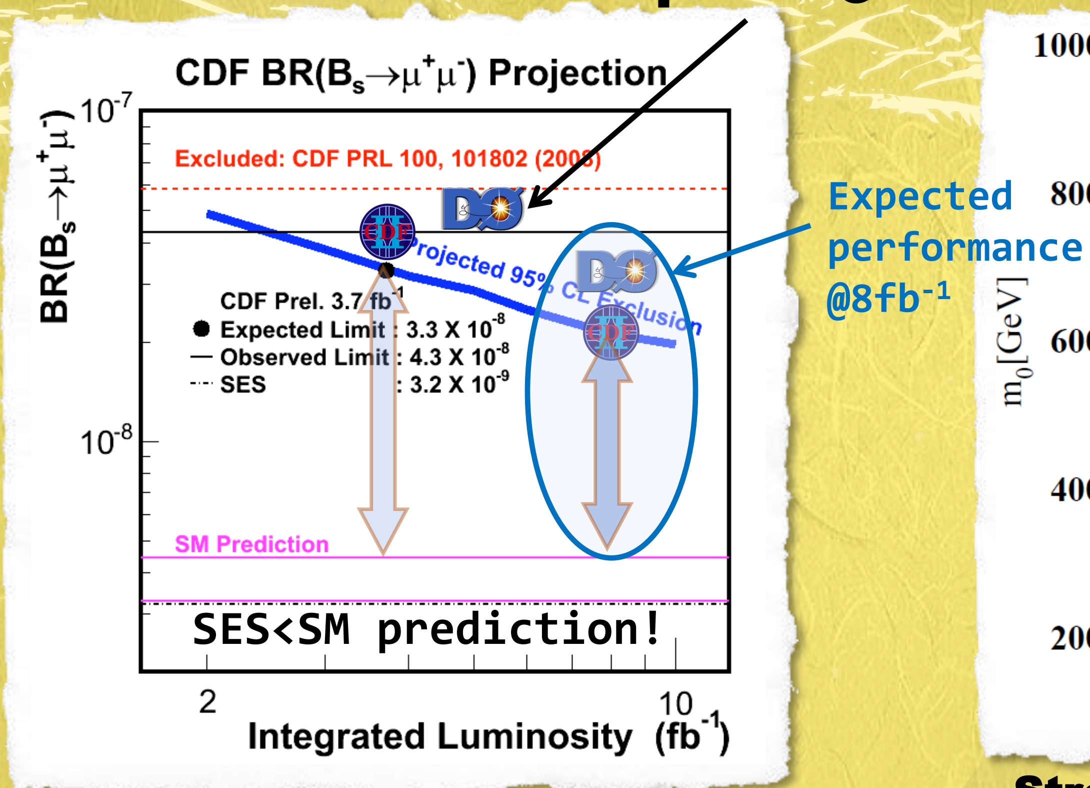
Blinded dimuon mass

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

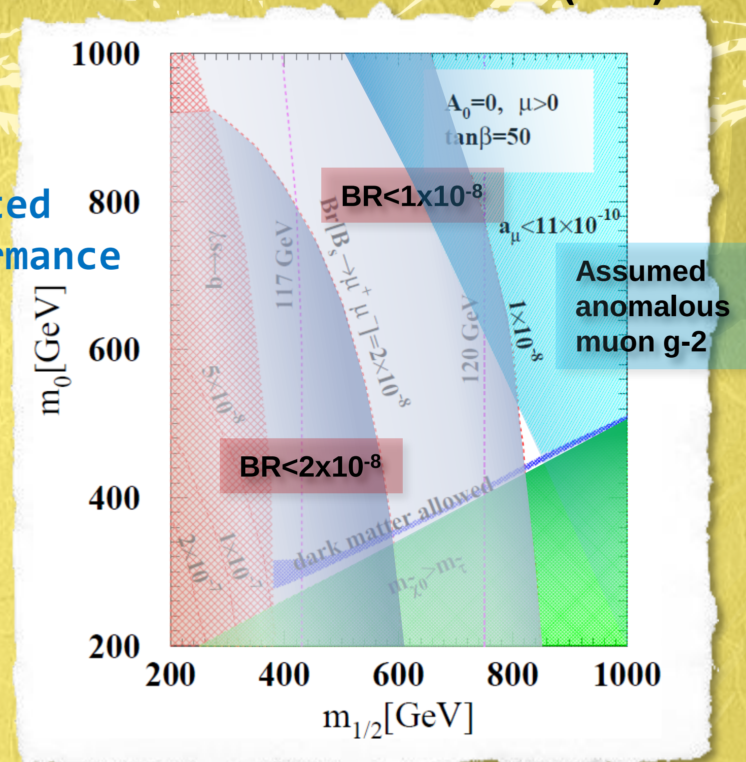
Further improvements are ongoing…

$B_s \to \mu\mu$: prospects

DØ expected@5fb^{-1}



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

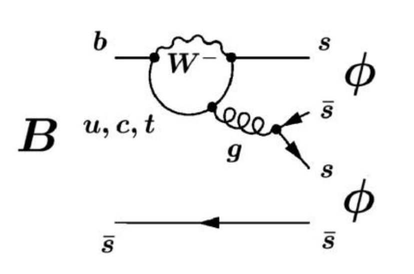


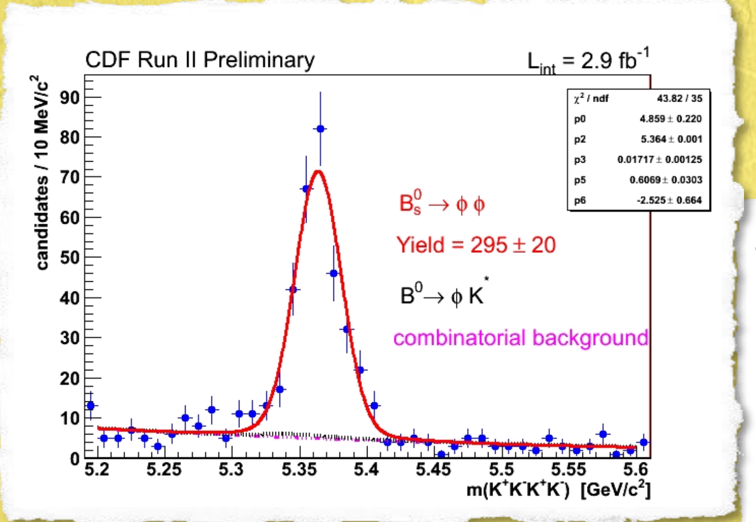
- 2010 (approved, ongoing : ~8fb^{-1})
  - CDF Expected limit: 2x10^{-8}@8fb^{-1} (6xSM)
  - Combined with DØ→5xSM
- 2011 (proposal, likely 10fb^{-1})
  - Combined limit ~O(10^{-8})

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

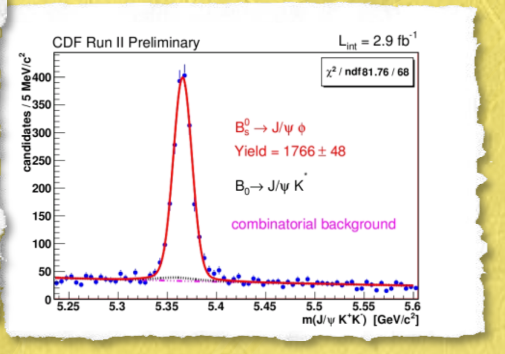
$B_s \rightarrow \phi\phi$: gluonic penguin

- **Dominated by $b\rightarrow s\bar{s}s$ (same as $B\rightarrow\phi K^{(*)}$)**
  - **BR is sensitive to NP due to the loop diagram**
    - **Previous result: $(1.4^{+0.6}_{-0.5}\pm0.6)\times10^{-5}$ by 8 signal@180pb^{-1}**
  - **Various BR expectations**
    - **QCDF: $(2.18\pm0.1^{+3.04}_{-1.78})\times10^{-5}$ NPB774,64 (2007)**
    - **pQCD: $(3.53^{+0.83}_{-0.69}{}^{+1.67}_{-1.02})\times10^{-5}$ PRD76,074018 (2007)**





Control channel: J/Ψφ



$$BR(B^0_s\rightarrow\phi\phi) = [2.40\pm0.21(stat)\pm0.27(syst)\pm0.82(BR)]\cdot10^{-5}$$

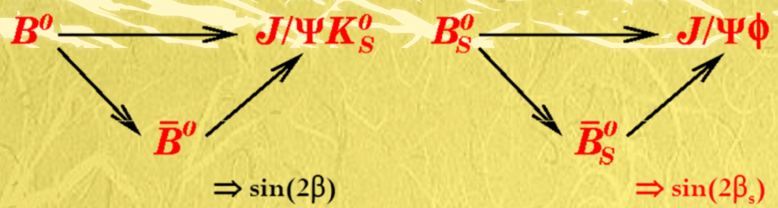
- **Updated by 2.9fb^{-1} from 180pb^{-1}~significant improvement**
- **BR: Consistent with SM**

Next step: Polarization measurement

CPV

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:

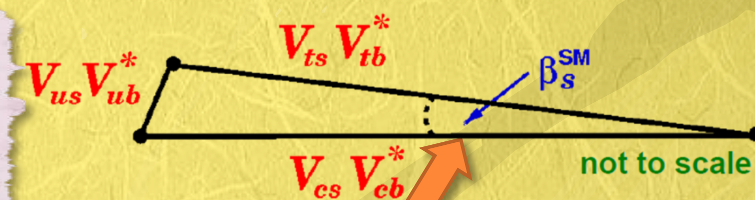


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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 :

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

β_s

$\phi_s^{SM} \sim 0.004$

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

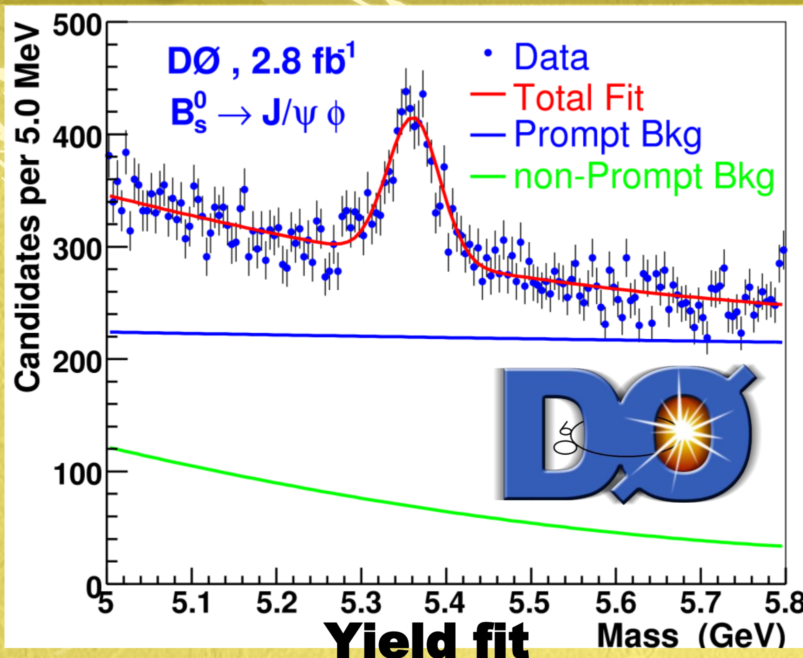
A. Lenz and U. Nierste, JHEP 06, 072(2007)

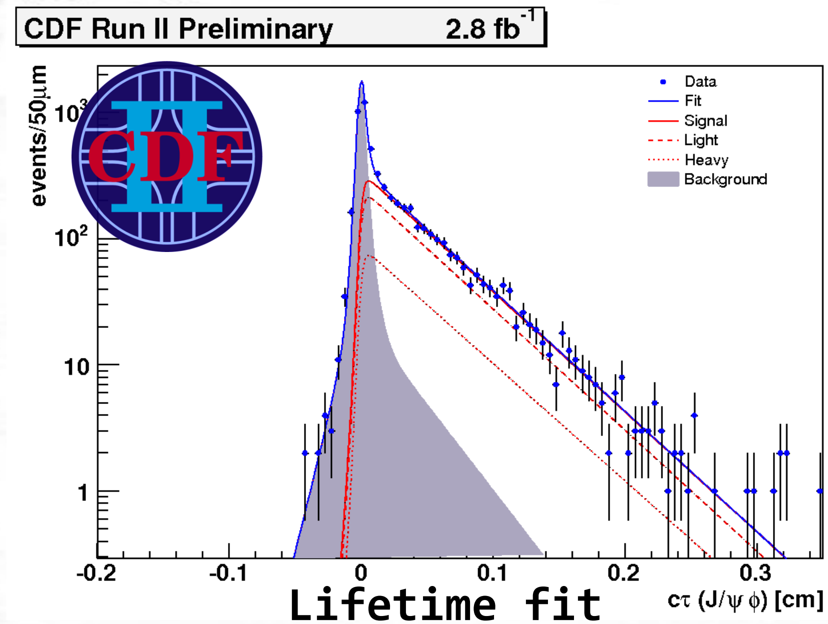
- φ_s^{NP} contributes to both φ_s and β_s

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

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

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





$N(B_s{}^0)^{DØ} \sim 2000$

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

β_s=0, no flavor tag :

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

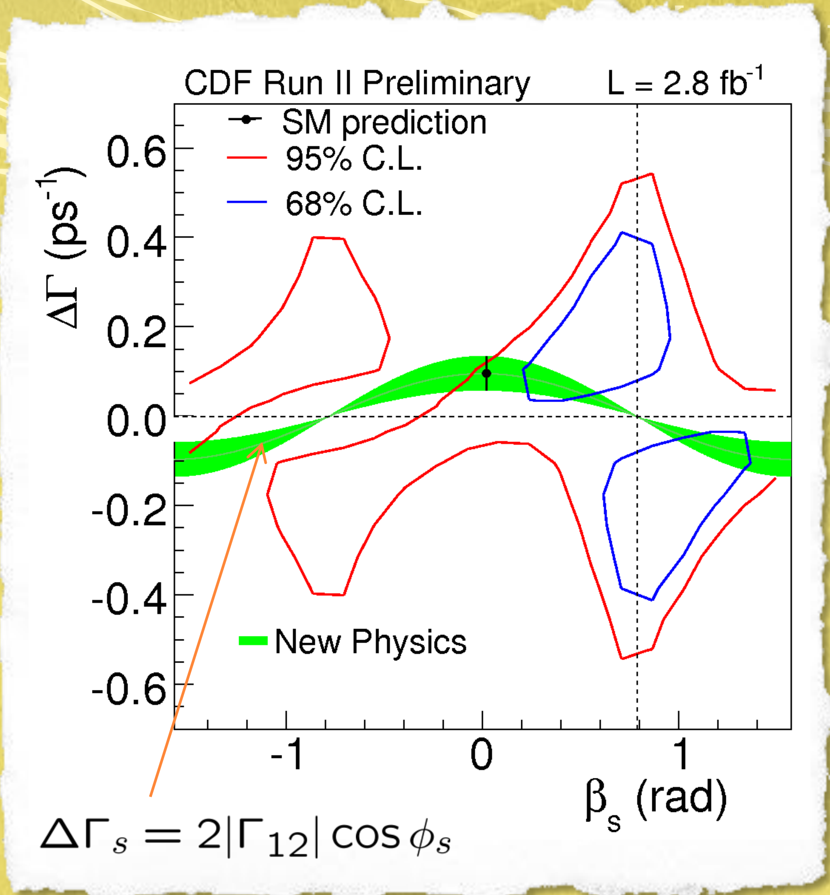
$\Delta\Gamma = 0.02 \pm 0.05\ (stat) \pm 0.01\ (syst)\ ps^{-1}$

PRL 102, 032001 (2009)

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

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

CDF β_s result@2.8fb^{-1}



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

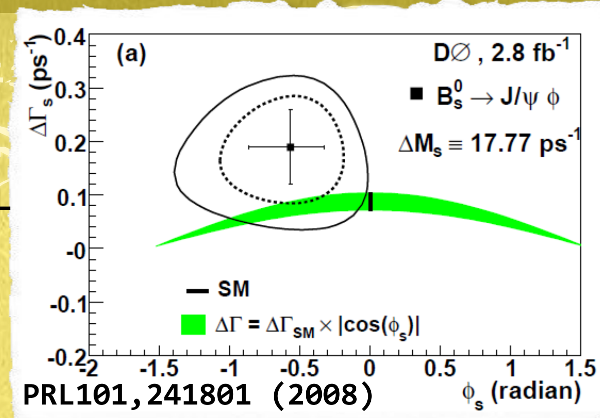
PRL100,161802 (2008) (1.35fb^{-1})

SM p-value=7%

Observe deviation from SM β_s of 1.8σ

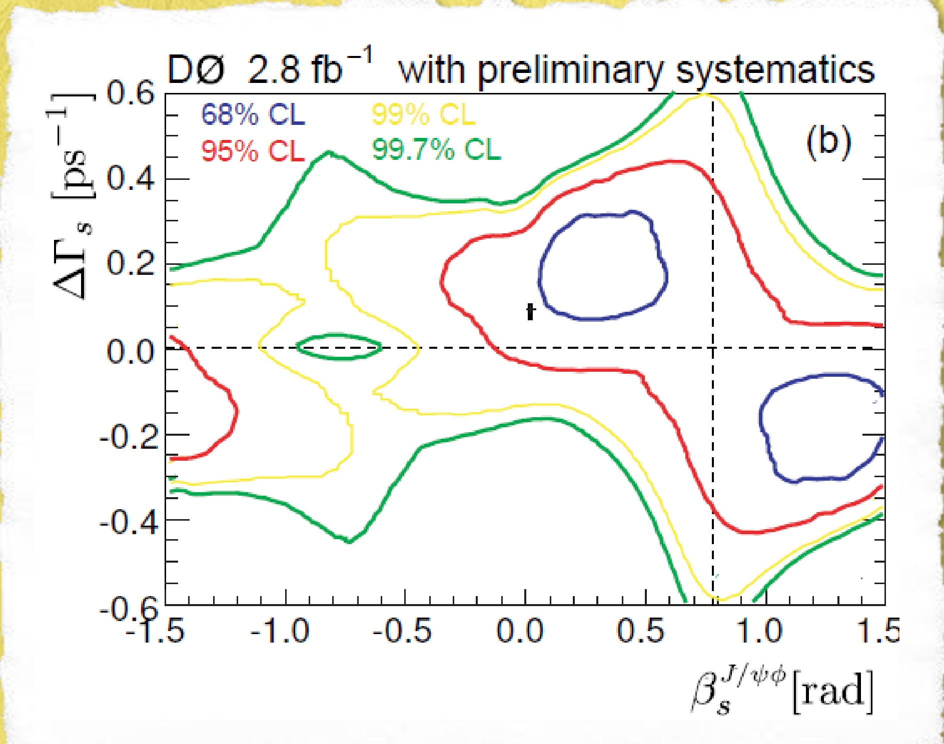
DØ β_s result@2.8fb^{-1}

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



PRL101,241801 (2008)

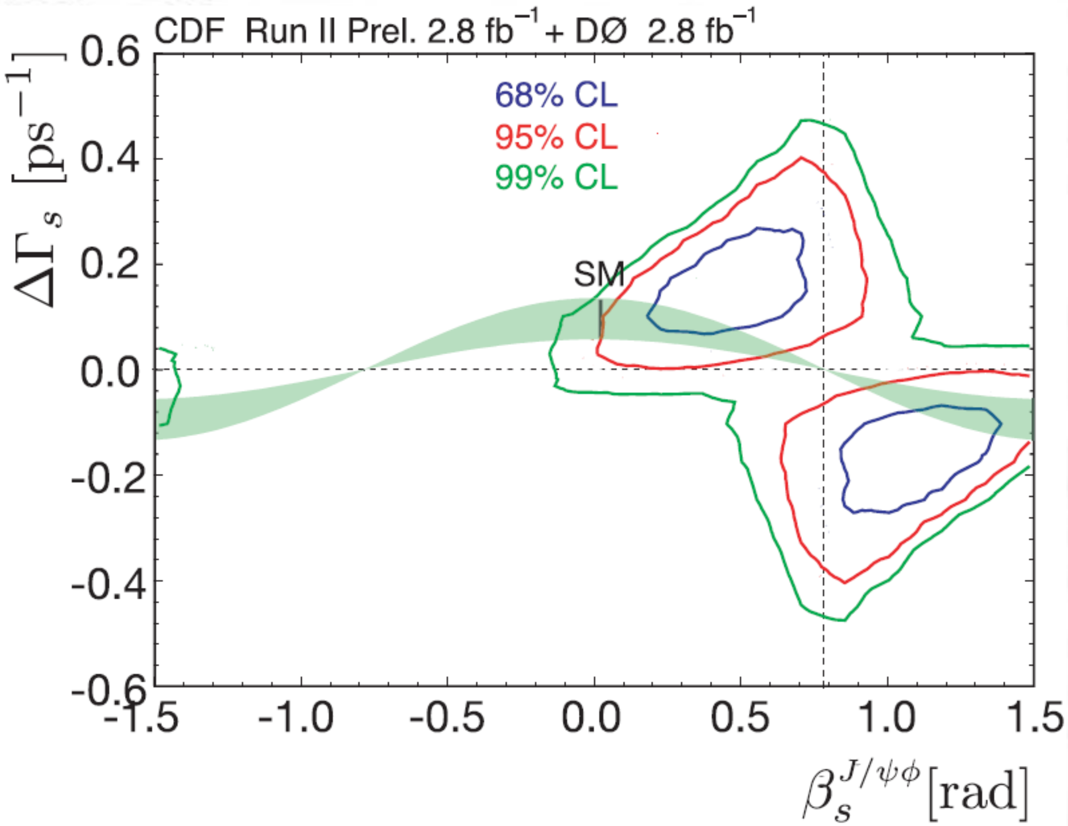
$$-2\beta_s^{J/\psi\phi} = \phi_s$$



SM p-value=24%

Tevatron combination

DØ note 5928, CDF note 9787



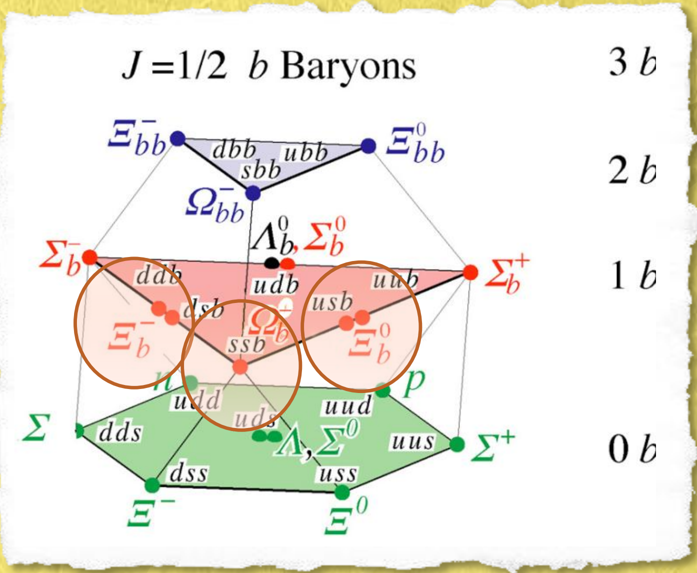
Combined likelihood finds 2.1σ deviation from SM

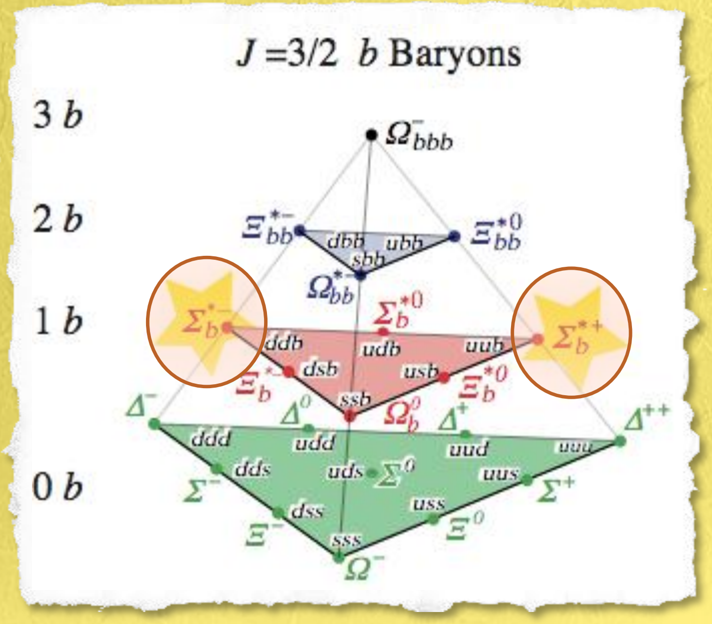
Works on new data/methods are ongoing

B hadrons

Bottom baryons

- **Our knowledge of b-hadrons greatly expanded in the last a few years**
  - **2006 $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$**
  - **2007 Ξ_b^-**
  - **2008 Ω_b^-**





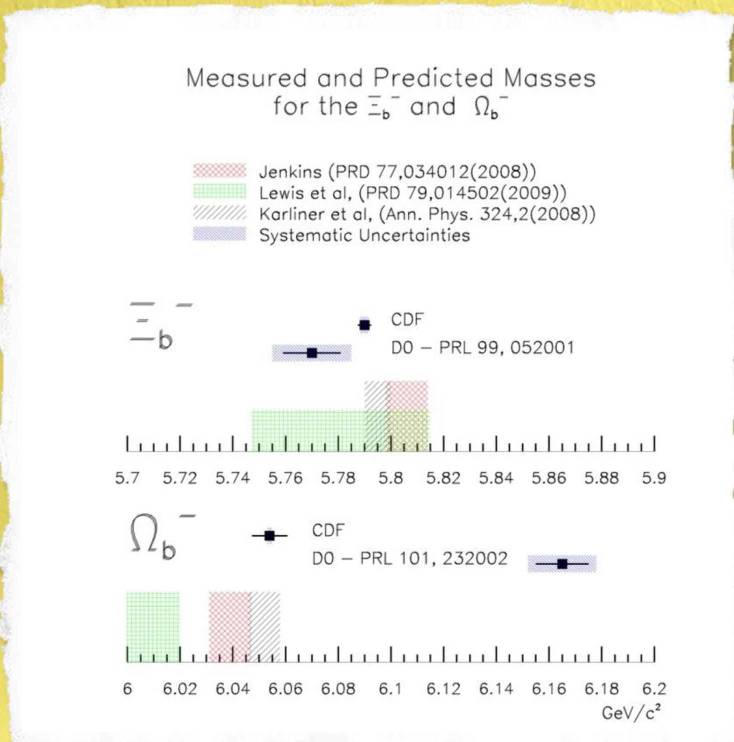
$\Omega_b \rightarrow J/\Psi\Omega$, $\Xi_b \rightarrow J/\Psi\Xi$

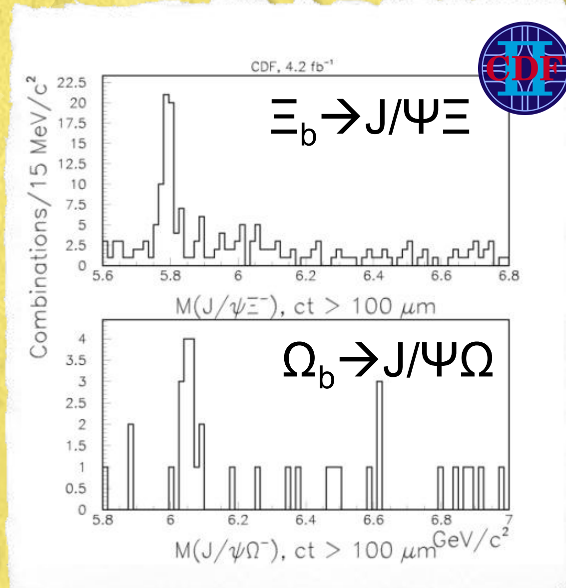
- **D0 observes 18Ω_b (15Ξ_b) signals@1.3fb^{-1}**
  - **Mass: 6165±10±13 (5774±11±15) MeV/c^2**

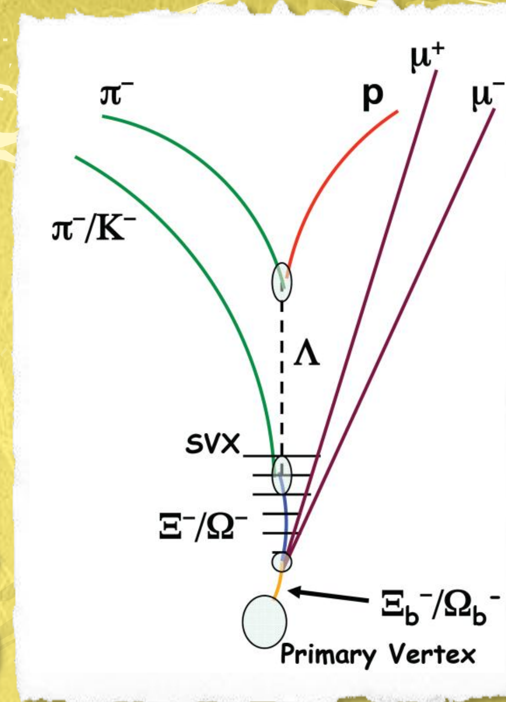
PRL101,232002 (PRL99,052001)

- **CDF observes 16Ω_b (66Ξ_b) events@4.2fb^{-1}**
  - **Mass: 6054.4±6.8±0.9 (5790.9±2.6±0.8) MeV/c^2**
  - **Lifetime: $1.13^{+0.53}_{-0.40}$±0.02 ($1.56^{+0.27}_{-0.25}$±0.02) ps**

arXiv:0905.3123







- **Ξ_b mass: agreement**
- **Ω_b mass: disagreement**

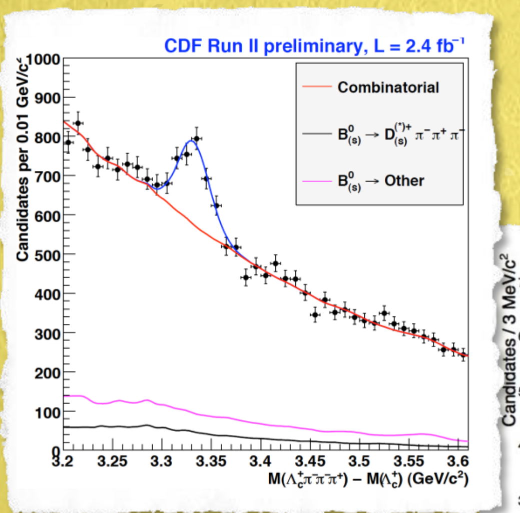
We need more data/channel!

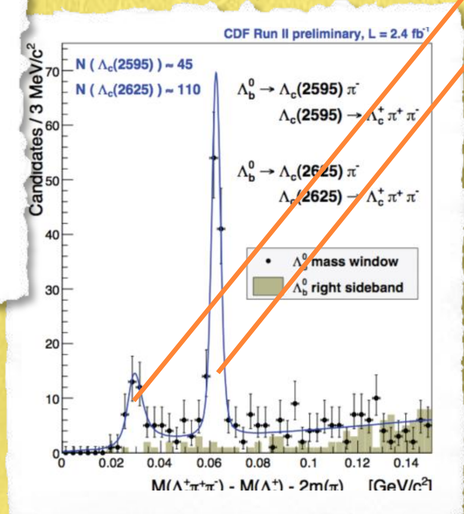
$\Delta_b \rightarrow X_c n\pi \rightarrow \Delta_c^+\pi^-\pi^+\pi^-$

- **Charm resonant decay channel**
  - **CDF observed resonant semileptonic decay channel: $\Delta_b \rightarrow X_c(\pi)\mu\nu$**

PRD 79, 032001 (2009)

- **First observation of $\Delta_b \rightarrow \Delta_c^+\pi^-\pi^+\pi^-$**





Λ_b^0 Decay Mode	Yield
$\Lambda_b^0 \rightarrow \Lambda_c(2595)^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$	46.6±9.7
$\Lambda_b^0 \rightarrow \Lambda_c(2625)^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$	114±13
$\Lambda_b^0 \rightarrow \Sigma_c(2455)^{++}\pi^-\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$	81±15
$\Lambda_b^0 \rightarrow \Sigma_c(2455)^0\pi^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$	41.5±9.3
$\Lambda_b^0 \rightarrow \Lambda_c^+\rho^0\pi^- + \Lambda_c^+3\pi(other) \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-$	610±88

848 signals@2.4fb^{-1}

Relative BR

$$\frac{BR(\Lambda_b^0 \rightarrow \Lambda_c(2595)^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (2.5 \pm 0.6(stat) \pm 0.5(syst)) \cdot 10^{-2}$$

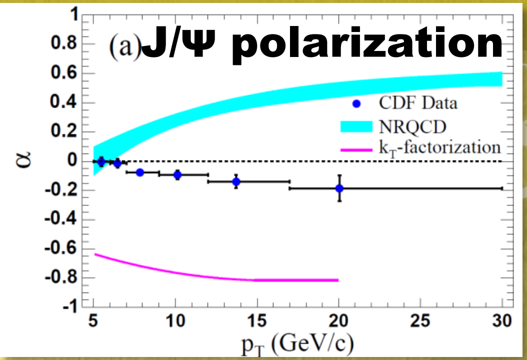
$$\frac{BR(\Lambda_b^0 \rightarrow \Lambda_c(2625)^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (6.2 \pm 1.0(stat) \pm 1.2(syst)) \cdot 10^{-2}$$

$$\frac{BR(\Lambda_b^0 \rightarrow \Sigma_c(2455)^{++}\pi^-\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-(all))} = (5.2 \pm 1.1(stat) \pm 0.9(syst)) \cdot 10^{-2}$$

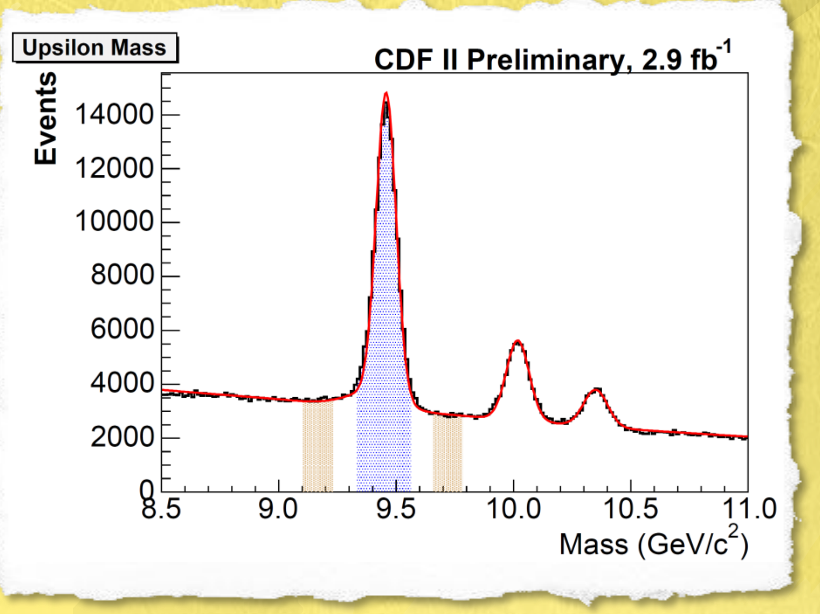
$$\frac{BR(\Lambda_b^0 \rightarrow \Sigma_c(2455)^0\pi^+\pi^- \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-\pi^+\pi^-(all))} =$$
$$(8.9 \pm 2.1(stat) + 1.5 - 1.0(syst)) \cdot 10^{-2}$$

Υ polarization

- **Vector meson polarization**
  - **Test of NRQCD (color-octet model)**
    - **Disagreement in Ψ(nS)**
      - **Both Run I and II show same trend**
    - **Υ(nS) might be better than Ψ(nS) due to heavy quark mass**



PRL99,132001(2007)



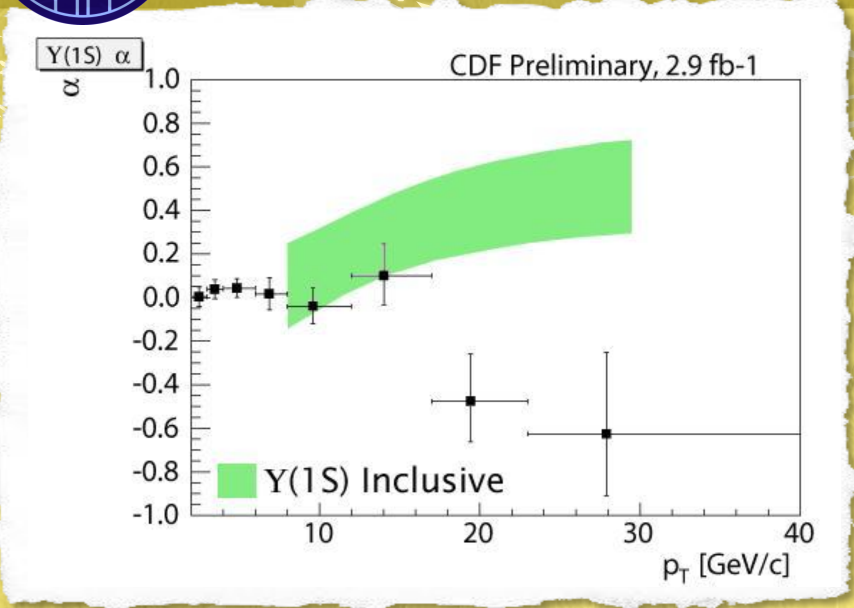
$$\frac{d\,\Gamma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^* .$$

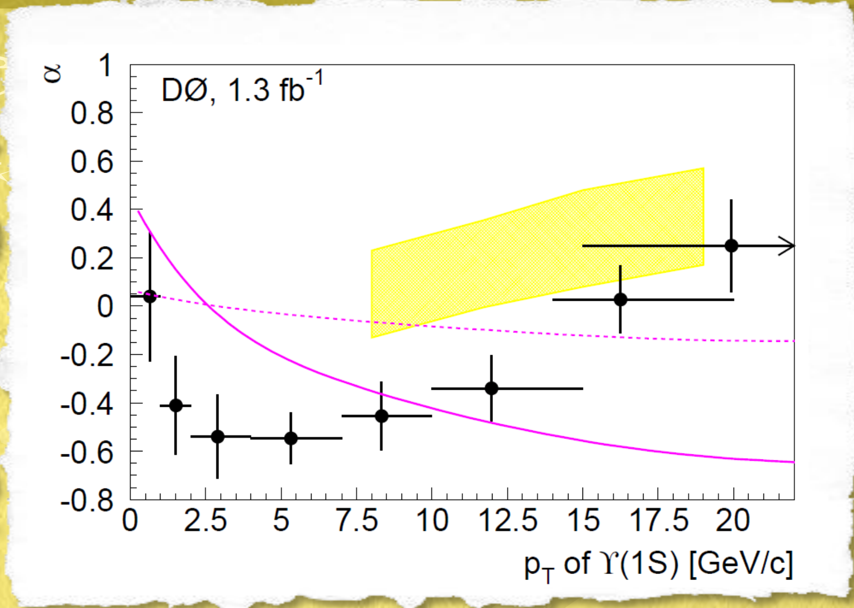
where cosθ*: μ^+ angle

α=+1: transverse

α=-1: longitudinal

Υ polarization : result





CDF Public Note 9966

PRL101, 182004 (2008)

- **CDF measures Υ(1S) at 2.9fb^{-1} while D0 measures Υ(1S) and Υ(2S) at 1.3fb^{-1}**
  - **Disagreement with NRQCD**
  - **Different trend between CDF and D0**
    - **No reason to differ...BG polarization?**
- **Further test with 2x data and other Υ(nS) and Ψ(nS)**
- **Expect D0 result for J/Ψ soon**

Summary

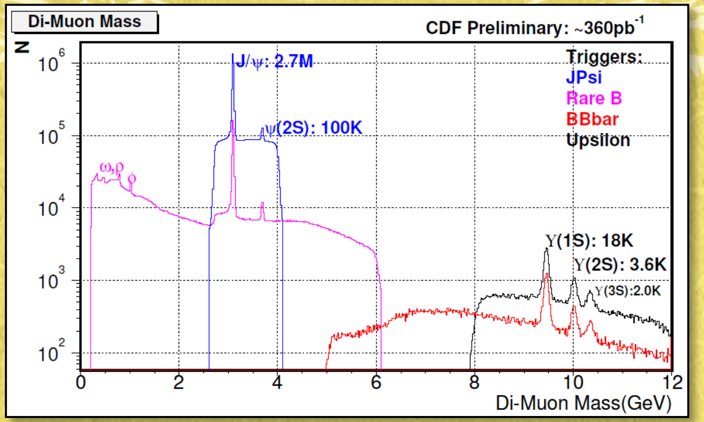
- **Various B-programs on-going at Tevatron**
  - **FCNC (BR, A_{FB})**
  - **CPV (β_s)**
  - **B-hadrons (BR, mass, life time)**
- **Doubled data expected and more if Run II extended to 2011**

Backup

B triggers

Di-Muon

- Conventional trigger at hadron collider
- Wide mass range



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

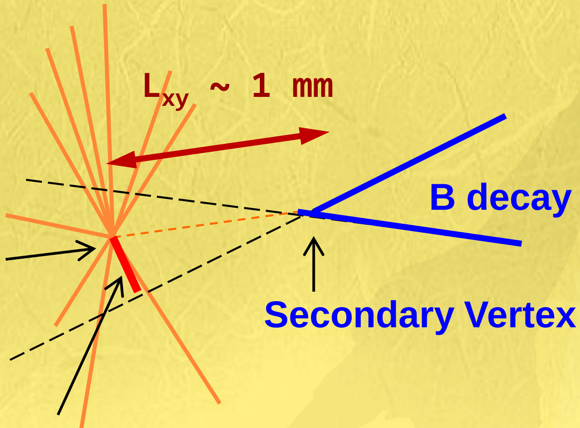
120 μm < I.P.(trk) < 1mm

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

PT(trk) > 2 GeV

120 μm < I.P.(trk) < 1mm

Σp_T > 5.5 GeV

fully hadronic modes