Results on B Physics at CDF

University of Tsukuba
Hideki Miyake
On behalf of the CDF collaboration

CERN Joint EP/PP Seminar Apr. 27th, 2010

Outline

- Introduction
  - Brief history of Beauty
  - New mission of B physics
- Recent CDF topics
  - Rare decays
  - CPV
  - B hadrons
- Summary and prospects


Why B?
B is a pathfinder!

B physics: history

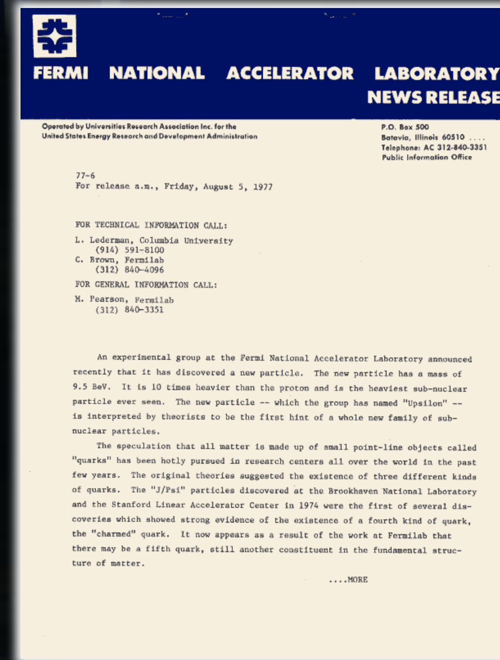
- 1977 Observation of Υ
- 1983 Observation of B (mass and lifetime)
- 1987 $B^0\bar{B}^0$ mixing
- 2001 Sin2β
- 2006 $B^0_s\bar{B}^0_s$ mixing

Observation of Υ

- In 1977 E-288 (Fermilab) observed 9.5 GeV peak in dimuon spectrum in 400GeV proton-nucleus collisions

PRL39,252 (1977)

  - Interpreted as a quarkonium of 5th quark, bottom



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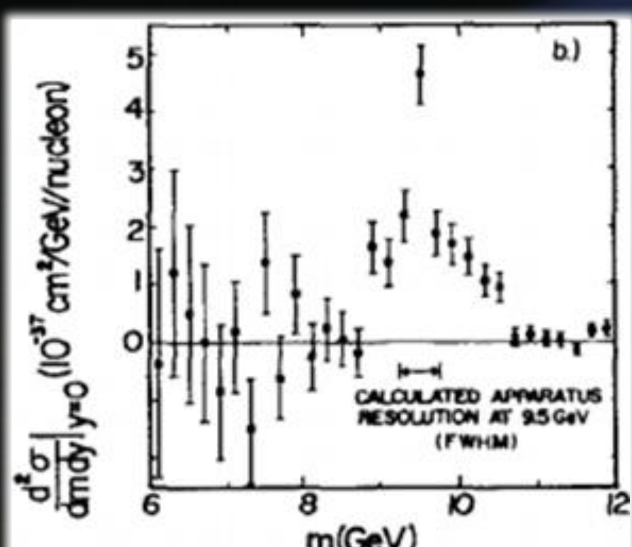
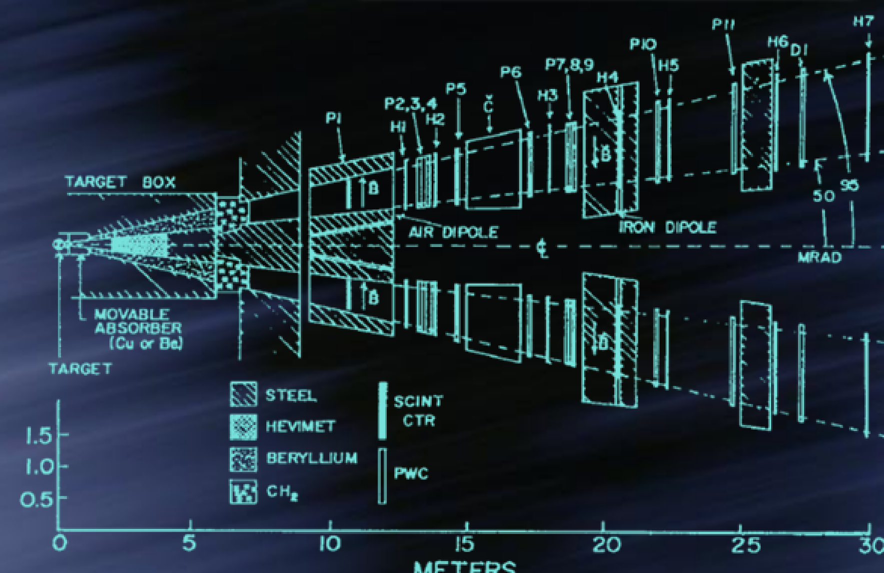
An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 BeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of sub-nuclear particles.

The speculation that all matter is made up of small point-line objects called "quarks" has been hotly pursued in research centers all over the world in the past few years. The original theories suggested the existence of three different kinds of quarks. The "J/Psi" particles discovered at the Brookhaven National Laboratory and the Stanford Linear Accelerator Center in 1974 were the first of several discoveries which showed strong evidence of the existence of a fourth kind of quark, the "charmed" quark. It now appears as a result of the work at Fermilab that there may be a fifth quark, still another constituent in the fundamental structure of matter.

....MORE

B-physics has started from hadron collisions!





Observation of Υ

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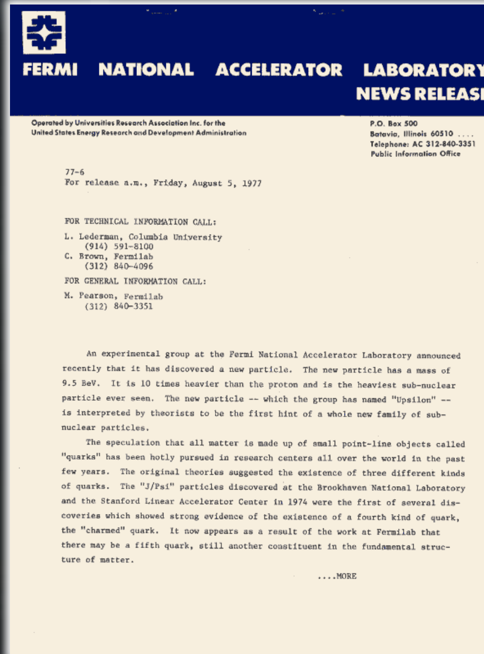

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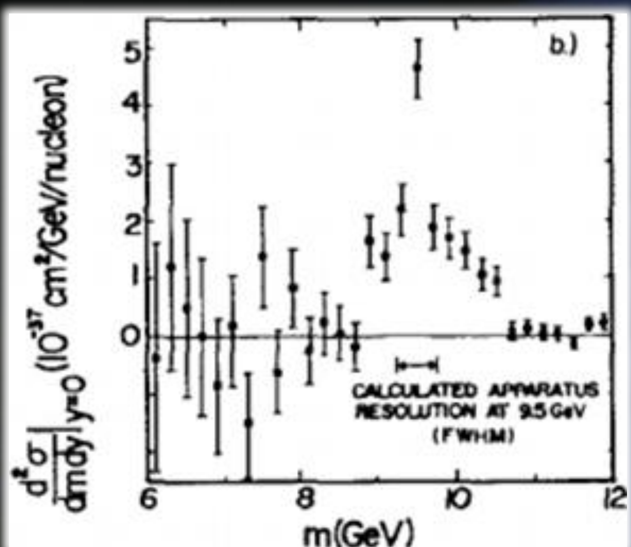
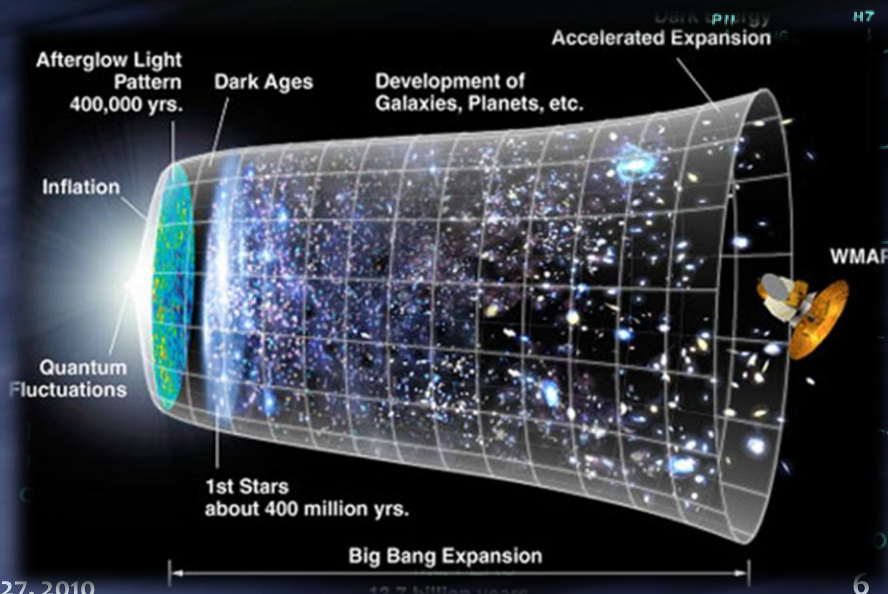
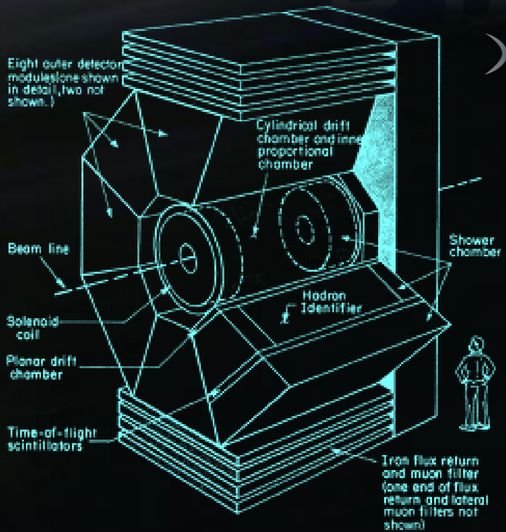




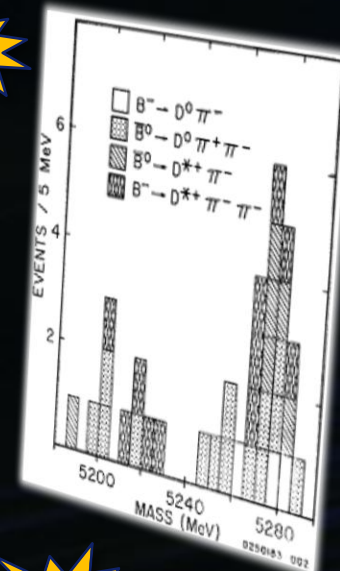
B mass and lifetime

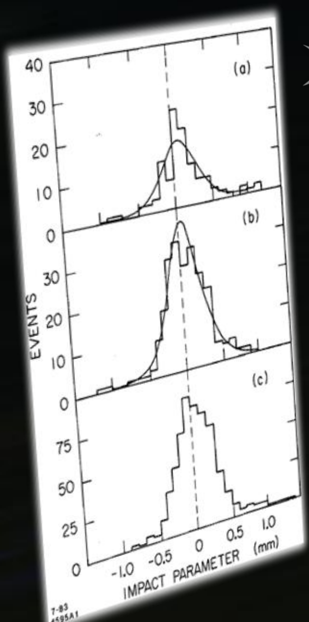


- B mesons observed by CLEO (e+e-)
  - B⁰, B⁺ masses were determined

PRL50(12),881 (1983)

M(B⁰)= 5274.2±1.9±2.0 MeV
M(B⁺)= 5270.8±2.3±2.0 MeV



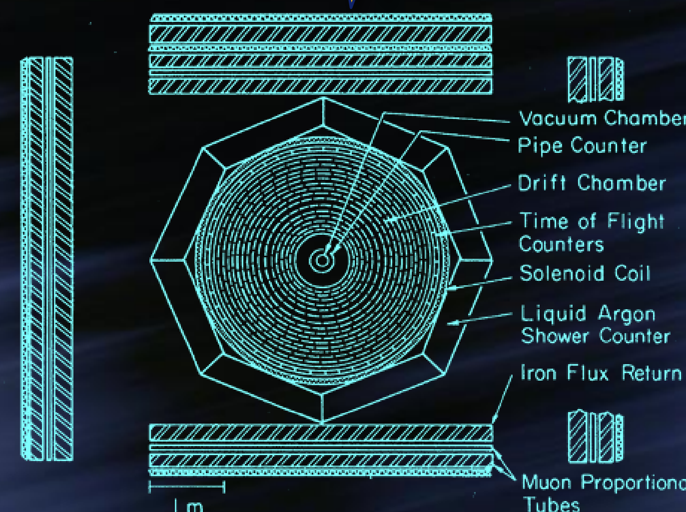


- B lifetime measured by MARKII (SLAC) (e+e-)

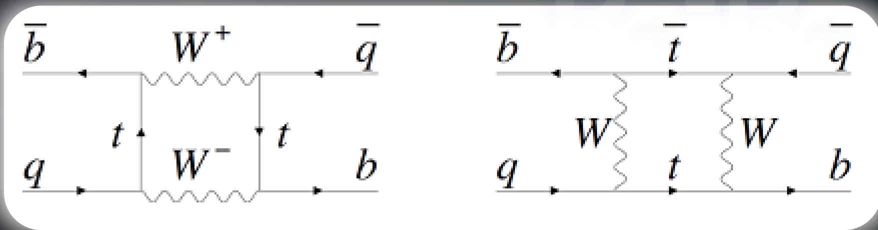
$\tau_B = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}$ sec

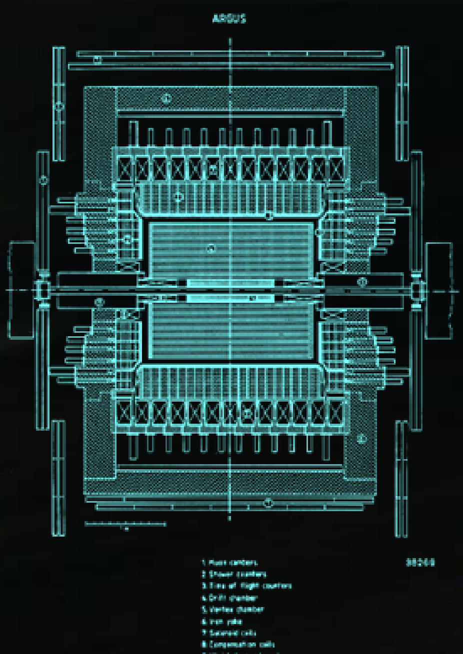
PRL51(15),1316 (1983)

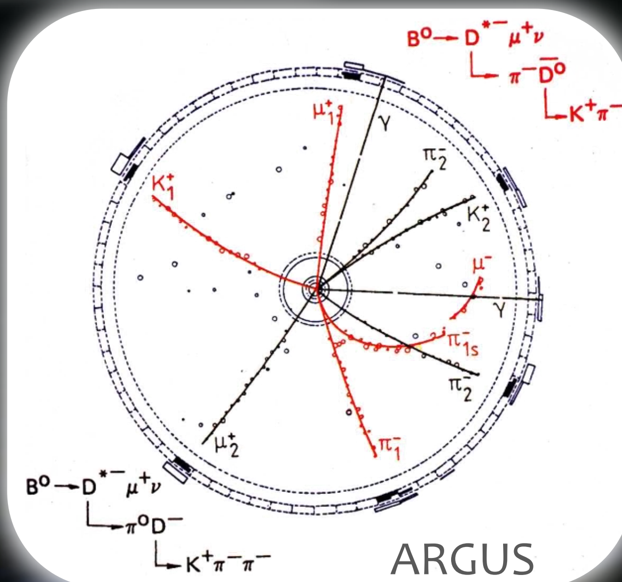
Long lifetime measured
→unexpected key feature of B

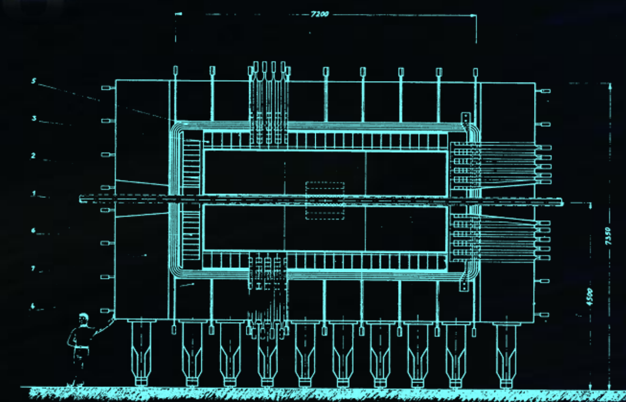


B^0-$\bar{B}^0$ mixing









$\Upsilon(4S) \to B^0\bar{B}^0 \to B^0B^0$

- UA-1 (CERN) and ARGUS (DESY) find neutral B meson mixing

$p\bar{p}$ PLB186,247 (1987)

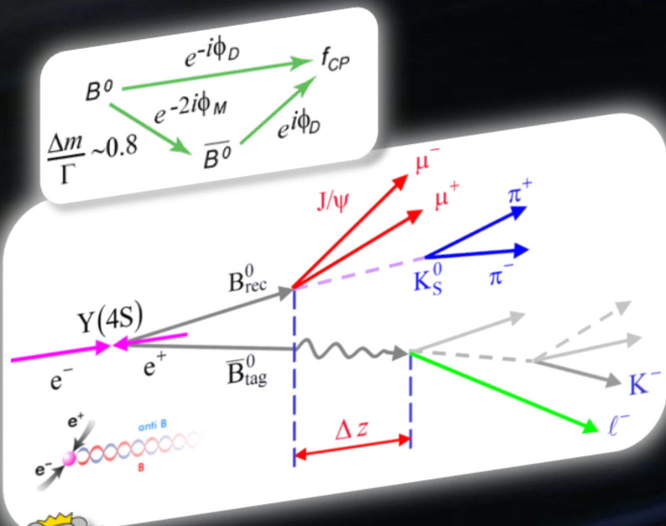
e^+e^- PLB192,245 (1987)

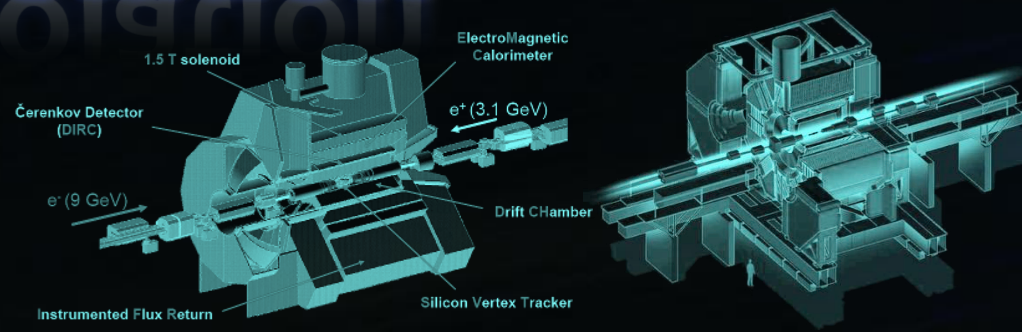
$$r = \frac{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0)} = 0.21 \pm 0.08$$

Large mixing

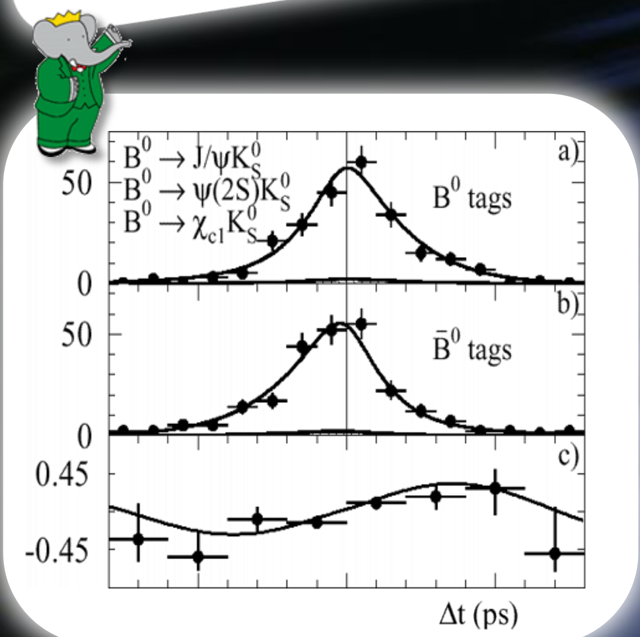
m_t>50GeV (before 1995!)

CP violation





- CP violation in the B system
  - Essential part of the SM (CKM mechanism)
  - Mixing induced time-dependent CPV
    - Different behavior on differential decay rate between matter (B^0) and anti-matter ($\bar{B}^0$)



In 1999,

$\sin 2\beta = 0.79^{+0.41}_{-0.44}$ (stat+syst) **CDF RunI@110pb⁻¹** $p\bar{p}$

PRD 61,072005 (2000)

In 2001,

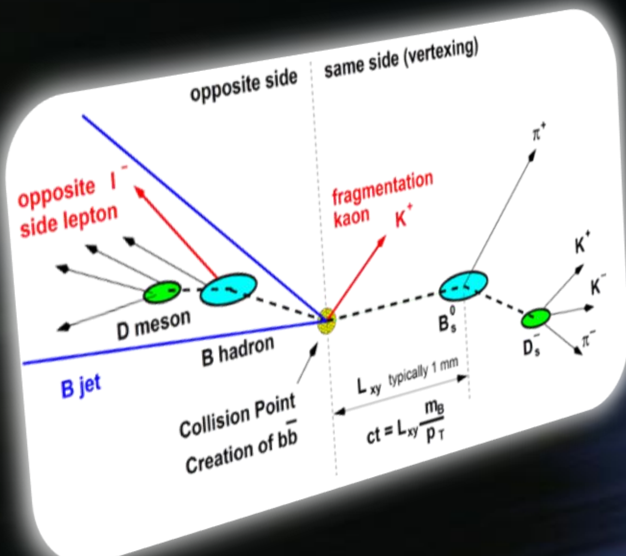
$\sin 2\phi_1 = 0.99 \pm 0.14 \pm 0.06$ **Belle@29.1fb⁻¹** e^+e^-

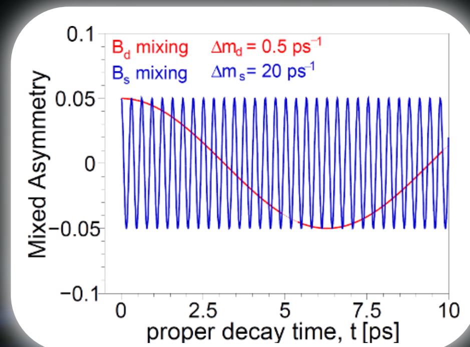
$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$ **Babar@29fb⁻¹** e^+e^-

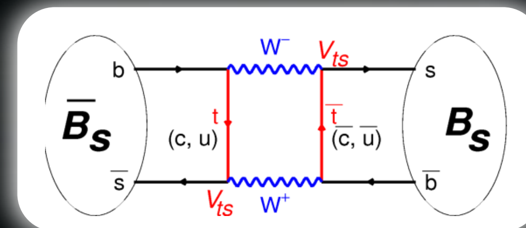
Observation of large CP violation $\phi_1 = \beta$

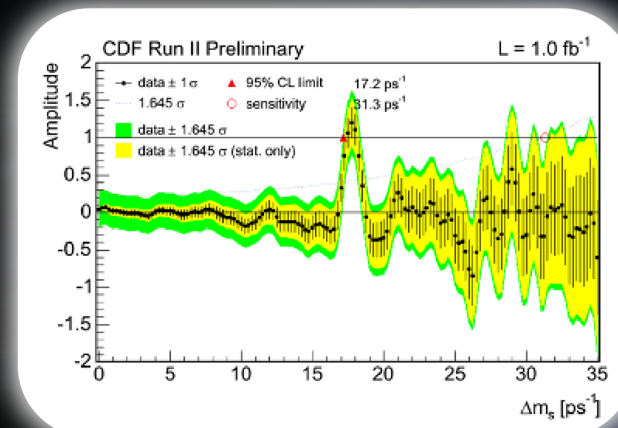
B^0_s-$\bar{B}^0_s$ mixing

- Grand challenge toward β_s
- Analogous to B^0, but ~x40 faster oscillation!









- Key techniques:
  - Good proper time resolution
  - Good flavor tagging

$p\bar{p}$ $p\bar{p}$

CDF $\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$

DØ $\Delta m_s = 18.53 \pm 0.93 \pm 0.30\ ps^{-1}$

PRL97, 242003, 2006
DØ CONF note5618, 2007

CDF contributions to HF

- CDF produced 46 TOP50+ heavy flavor papers so far!
  - Includes 6 TOP250+ papers (CDF TOP250+ papers: 16)

1. First Flavor-Tagged Determination of Bounds on Mixing-Induced CP Violation in B0(s) ---> J/psi phi Decays, Phys.Rev.Lett.100:161802,2008, TOPCITE = 100+
2. Evidence for D0 - anti-D0 mixing using the CDF II Detector, Phys.Rev.Lett.100:121802,2008, TOPCITE = 50+
3. Search for B0(s) ---> mu+ mu- and B0(d) ---> mu+ mu- decays with 2fb**-1 of p anti-p collisions, Phys.Rev.Lett.100:101802,2008, TOPCITE = 100+
4. Observation and mass measurement of the baryon Xi(b)-, Phys.Rev.Lett.99:052002,2007, TOPCITE = 50+
5. First observation of heavy baryons Sigma(b) and Sigma(b)*, Phys.Rev.Lett.99:202001,2007, TOPCITE = 50+
6. Polarization of J / psi and psi(2S) mesons produced in p anti-p collisions at s**(1/2) = 1.96-TeV, Phys.Rev.Lett.99:132001, TOPCITE = 50+
7. Analysis of the quantum numbers J**PC of the X(3872), Phys.Rev.Lett.98:132002,2007, TOPCITE = 50+
8. Observation of B0(s) - anti-B0(s) Oscillations, Phys.Rev.Lett.97:242003,2006, TOPCITE = 250+
9. Observation of B0 (s) ---> K+ K- and Measurements of Branching Fractions of Charmless Two-body Decays of B0 and B0(s) Mesons in anti-p p Collisions at s**(1/2) = 1.96-TeV, Phys.Rev.Lett.97:211802,2006, TOPCITE = 50+
10. Measurement of the B0(s) - anti-B0(s) Oscillation Frequency, Phys.Rev.Lett.97:062003, TOPCITE = 100+
11. Measurement of the dipion mass spectrum in X(3872) ---> J/psi pi+ pi- decays, Phys.Rev.Lett.96:102002,2006, TOPCITE = 50+
12. Measurement of b hadron masses in exclusive J/psi decays with the CDF detector, Phys.Rev.Lett.96:202001,2006, TOPCITE = 50+
13. Evidence for the exclusive decay B(c)+- ---> J / psi pi+- and measurement of the mass of the B(c) meson, Phys.Rev.Lett.96:082002, TOPCITE = 50+
14. Measurement of the J/psi meson and b-hadron production cross sections in p anti-p collisions at s(NN)**(1/2) = 1960-GeV, Phys.Rev.D71:032001, TOPCITE = 250+
15. Measurement of the lifetime difference between B(s) mass eigenstates, Phys.Rev.Lett.94:101803, TOPCITE = 50+
16. Pentaquark searches at CDF, Nucl.Phys.Proc.Suppl.142:374-377,2005, TOPCITE = 50+
17. Search for B0(s) ---> mu+ mu- and B0(d) ---> mu+ mu- decays in p anti-p collisions at s**(1/2) = 1.96-TeV, Phys.Rev.Lett.93:032001,2004, TOPCITE = 50+
18. Observation of the narrow state X(3872) ---> J / psi pi+ pi- in anti-p p collisions at s**(1/2) = 1.96-TeV, Phys.Rev.Lett.93:072001,2004, TOPCITE = 250+
19. Measurement of prompt charm meson production cross-sections in p anti-p collisions at s**(1/2) = 1.96-TeV, Phys.Rev.Lett.91:241804,2003, TOPCITE = 100+
20. Upsilon production and polarization in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.88:161802,2002, TOPCITE = 50+
21. Measurement of the B+ total cross-section and B+ differential cross-section d sigma / dp(T) in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.D65:052005, TOPCITE = 100+
22. Measurement of J / psi and psi(2S) polarization in p anti-p collisions at S**(1/2) = 1.8-TeV, Phys.Rev.Lett.85:2886-2891, TOPCITE = 100+
23. A Measurement of sin 2 Beta from B ---> J / psi K0(S) with the CDF detector, Phys.Rev.D61:072005, TOPCITE = 250+
24. Search for the flavor changing neutral current decays B+ ---> muon+ muon- K+ and B0 ---> muon+ muon- K*0, Phys.Rev.Lett.83:3378-3383,1999, TOPCITE = 50+
25. Measurement of the B0(d) - anti-B0(d) flavor oscillation frequency and study of same side flavor tagging of B mesons in p anti-p collisions, Phys.Rev.D59:032001,1999, TOPCITE = 50+
26. Measurement of the CP violation parameter sin(2 Beta) in B0(d)/anti-B0(d) ---> J / psi K0(S) decays, Phys.Rev.Lett.81:5513-5518, TOPCITE = 50+
27. Observation of the B(c) meson in p anti-p collisions at S**(1/2) = 1.8-TeV, Phys.Rev.Lett.81:2432-2437, TOPCITE = 100+
28. Observation of B(c) mesons in p anti-p collisions at S**(1/2) = 1.8-TeV, Phys.Rev.D58:112004,1998, TOPCITE = 100+
29. Search for the decays B(d)0 ---> mu+ mu- and B(s)0 ---> mu+ mu- in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.D57:3811-3816, TOPCITE = 100+
30. Measurement of B hadron lifetimes using J / psi final states at CDF, Phys.Rev.D57:5382-5401, TOPCITE = 50+
31. Measurement of the B0 anti-B0 oscillation frequency in p anti-p collisions using pi B meson charge flavor correlations at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.80:2057-2062, TOPCITE = 50+
32. Production of J / psi mesons from chi(c) meson decays in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.79:578-583, TOPCITE = 100+
33. J / psi and psi (2S) production in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.79:572-577, TOPCITE = 250+
34. Observation of Lambda(b)0 ---> J / psi Lambda at the Fermilab Proton - Anti-proton Collider, Phys.Rev.D55:1142-1152, TOPCITE = 50+
35. Measurement of b anti-b production correlations, B0 anti-B0 mixing, and a limit on epsilon(B) in p anti-p collisions at S**(1/2) = 1.8- Phys.Rev.D55:2546-2558,1997, TOPCITE = 100+
36. Measurement of the B meson differential cross-section, d sigma / d p(T), in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.75:1451-1455, TOPCITE = 100+
37. Measurement of the B meson and b quark cross-sections at s**(1/2) = 1.8-TeV using the exclusive decay B0 ---> J / psi K*0 (892), Phys.Rev.D50:4252,1994, TOPCITE = 50+
38. Measurement of the B+ and B0 meson lifetimes, Phys.Rev.Lett.72:3456-3460,1994, TOPCITE = 50+
39. Inclusive chi(c) and b quark production in anti-p p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.71:2537-2541,1993, TOPCITE = 100+
40. Measurement of the average lifetime of B hadrons produced in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.71:3421-3426,1993, TOPCITE = 50+
41. Measurement of bottom quark production in 1.8-TeV p anti-p collisions using semileptonic decay muons, Phys.Rev.Lett.71:2396-2400,1993, TOPCITE = 100+
42. Observation of the decay B(s)0 ---> J / psi phi in anti-p p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.71:1685-1689,1993, TOPCITE = 50+
43. Measurement of the bottom quark production cross-section using semileptonic decay electrons in p anti-p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.71:500-504,1993, TOPCITE = 100+
44. Inclusive J / psi, psi (2S) and b quark production in anti-p p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.69:3704-3708, TOPCITE = 250+
45. A Measurement of the B meson and b quark cross-sections at s**(1/2) = 1.8-TeV using the exclusive decay B+- ---> J / psi K+-, Phys.Rev.Lett.68:3403-3407,1992, TOPCITE = 100+
46. Measurement of B0 anti-B0 mixing at the Fermilab Tevatron collider, Phys.Rev.Lett.67:3351-3355,1991, TOPCITE = 50+

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Observation of B^0_s-anti-B^0_s Oscillations, Phys.Rev.Lett.97:242003, 2006 — 318 cited

Measurement of the J/ψ meson and b-hadron production cross sections in p anti-p collisions at $\sqrt{s}$=1960GeV, Phys.Rev.D71:032001, 2005 — 403 cited

Observation of the narrow state X(3872)→J/ψπ⁺π⁻ in anti-p p collisions at $\sqrt{s}$=1.96TeV, Phys.Rev.Lett.93:072001, 2004 — 316 cited

A Measurement of sin2β from B→J/ψK^0_S with the CDF detector, Phys.Rev.D61:072005, 2000 — 256 cited

J/ψ and ψ(2S) production in p anti-p collisions at $\sqrt{s}$=1.8TeV, Phys.Rev.Lett.79:572-577, 1997 — 276 cited

Inclusive J/ψ, ψ(2S) and b quark production in anti-p p collisions at $\sqrt{s}$=1.8TeV, Phys.Rev.Lett.69:3704-3708,1992 — 334 cited

44. *Inclusive J / psi, psi (2S) and b quark production in anti-p p collisions at s**(1/2) = 1.8-TeV, Phys.Rev.Lett.69:3704-3708, TOPCITE = 250+*
45. *A Measurement of the B meson and b quark cross-sections at s**(1/2) = 1.8-TeV using the exclusive decay B+- ---> J / psi K+-, Phys.Rev.Lett.68:3403-3407,1992, TOPCITE = 100+*
46. *Measurement of B0 anti-B0 mixing at the Fermilab Tevatron collider, Phys.Rev.Lett.67:3351-3355,1991, TOPCITE = 50+*

Unitarity triangle

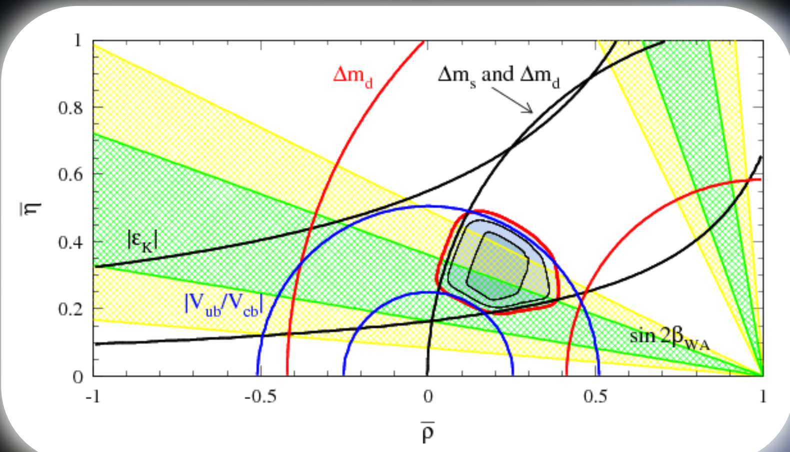
- CKM matrix: quark mixing matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

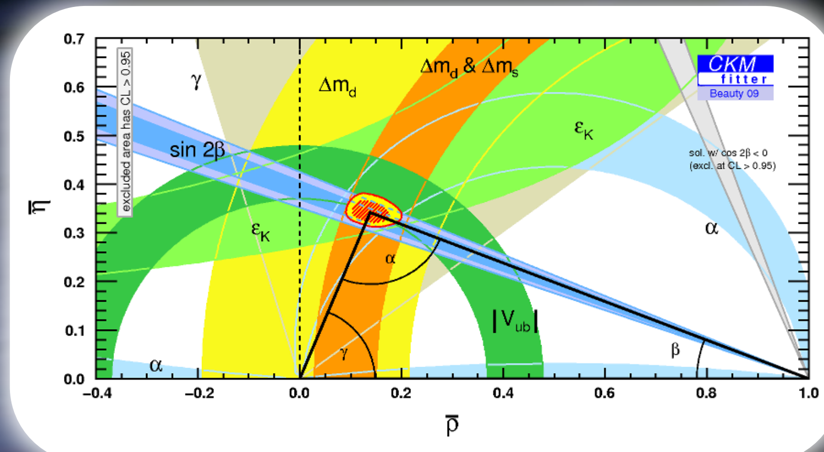
KM phase

- Unitarity:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



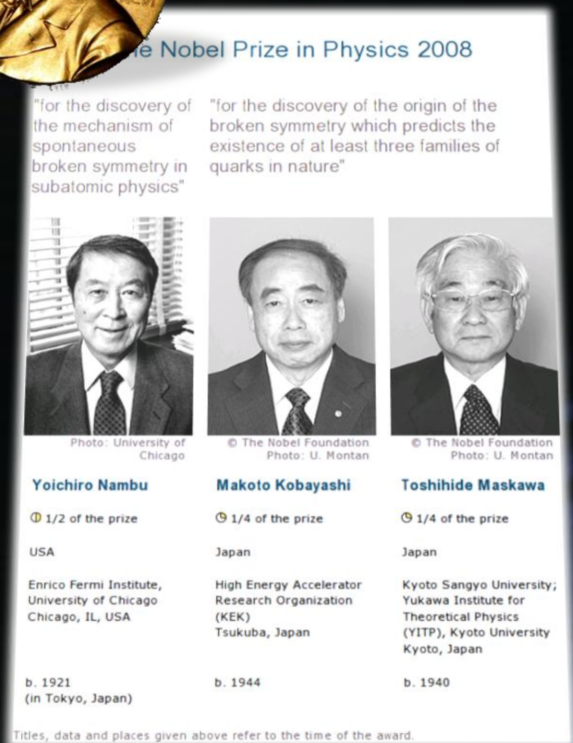
2001 w/o sin2β constraint



2009 w/ sin2β constraint

- Good agreement so far
- CKM mechanism is dominated in the SM (at EW scale)

SM is Successful



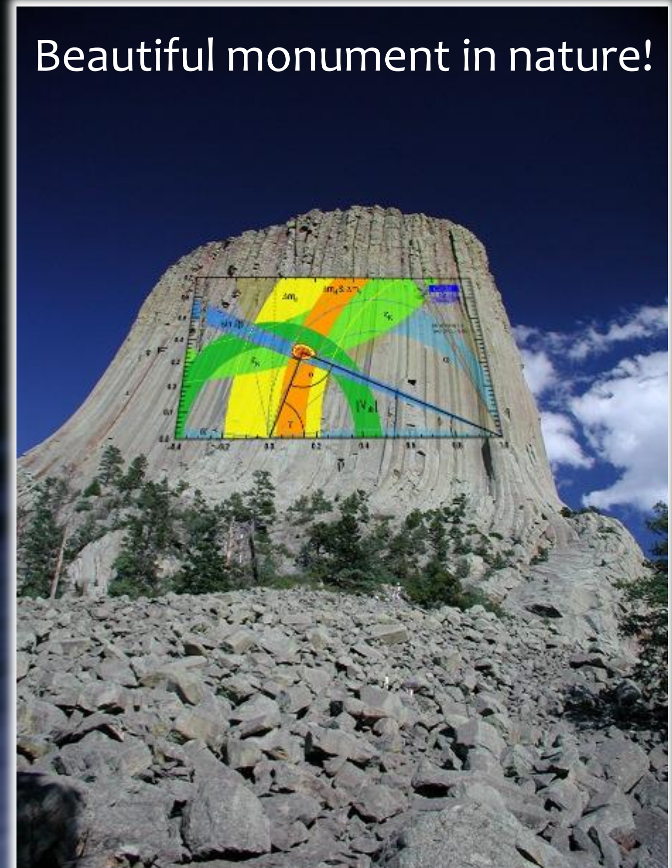
…e Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: University of Chicago	© The Nobel Foundation Photo: U. Montan	© The Nobel Foundation Photo: U. Montan
Yoichiro Nambu	**Makoto Kobayashi**	**Toshihide Maskawa**
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	Japan	Japan
Enrico Fermi Institute, University of Chicago Chicago, IL, USA	High Energy Accelerator Research Organization (KEK) Tsukuba, Japan	Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University Kyoto, Japan
b. 1921 (in Tokyo, Japan)	b. 1944	b. 1940

Titles, data and places given above refer to the time of the award.



- OK, great. Have we accomplished everything?
- **NO!**

Is SM the ultimate theory?

- We don't think so, because SM **CANNOT**:
  - explain the meaning of generation
  - explain the origin of SM free parameters:
    - Quark and lepton masses, CKM mixing angles, and KM phase…
  - explain the baryogenesis
    - KM phase is not large enough to provide the amount of CPV necessary for the matter-antimatter asymmetry
  - etc.etc…

SM should be lower energy approximation of more fundamental theory (e.g. GUT)

First approach… what is the extension theory of SM?

SUSY, technicolor, 4^{th} generation…

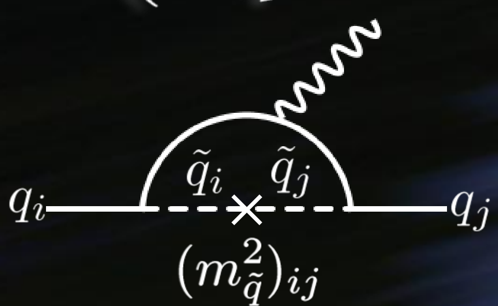
New mission of B physics

Shed light on NP from the view of flavor sector!

- **Precise measurement of SM**
  - NP contributes B particles due to the heavy mass
  - Discrepancy from the SM uncertainties (theory+exp) means NP
- **Give constraint on NP parameters**

squark/slepton mass matrix

$$(m^2_{\tilde{q}})_{ij} = \begin{bmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{bmatrix}$$



Synergy of analyses!

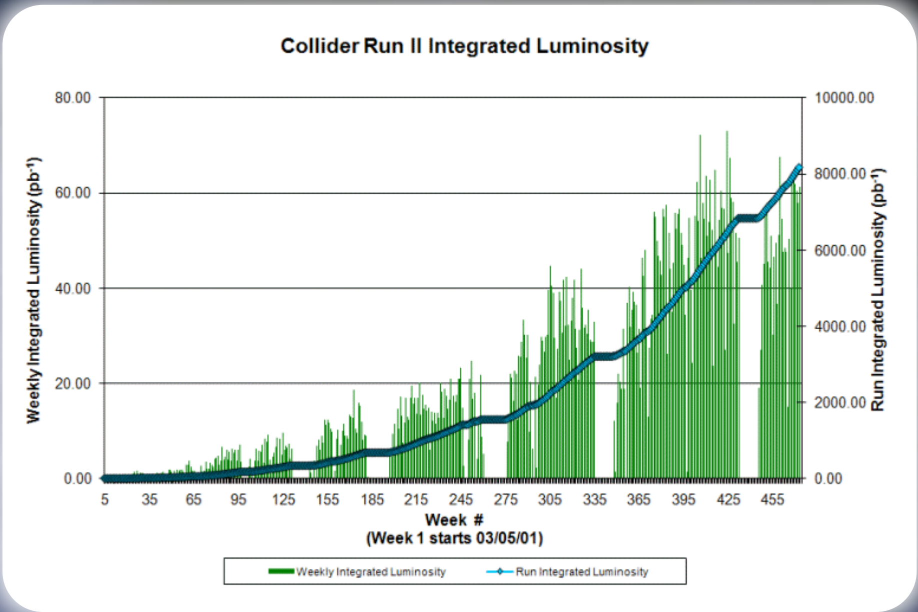
Indirect search (flavor mixing)

complementary

Direct search (mass spectrum)

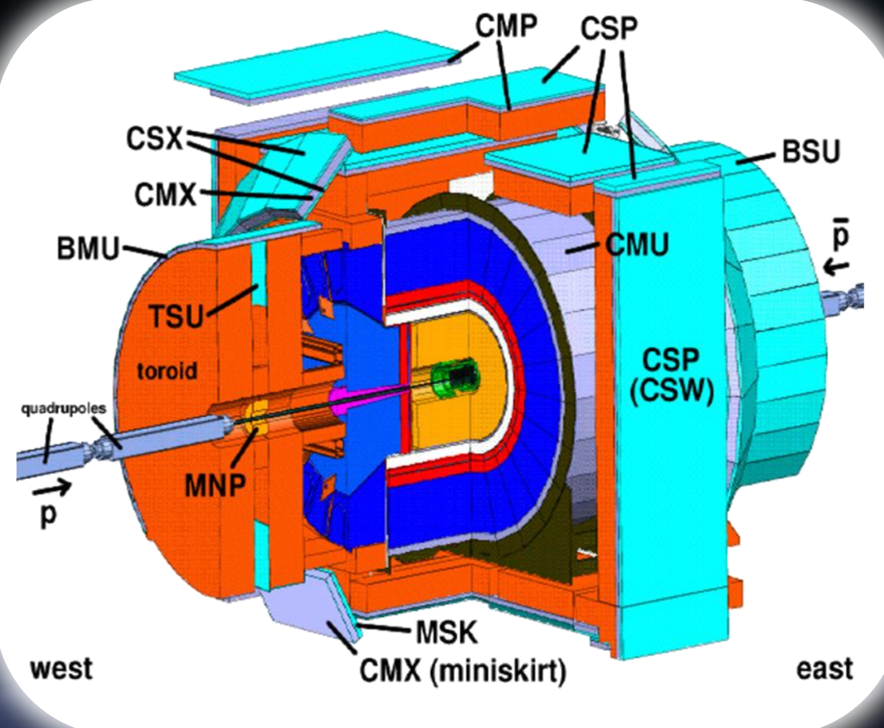
Tevatron

- $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV
  - Typical initial luminosities of $3.5\times10^{32}cm^{-2}s^{-1}$
  - >50 pb^{-1} collected per week
- >7fb^{-1} data on tape
  - Expect >10fb^{-1} until end of run in 18 months
- Today we cover 2.4-4.4fb^{-1} of data



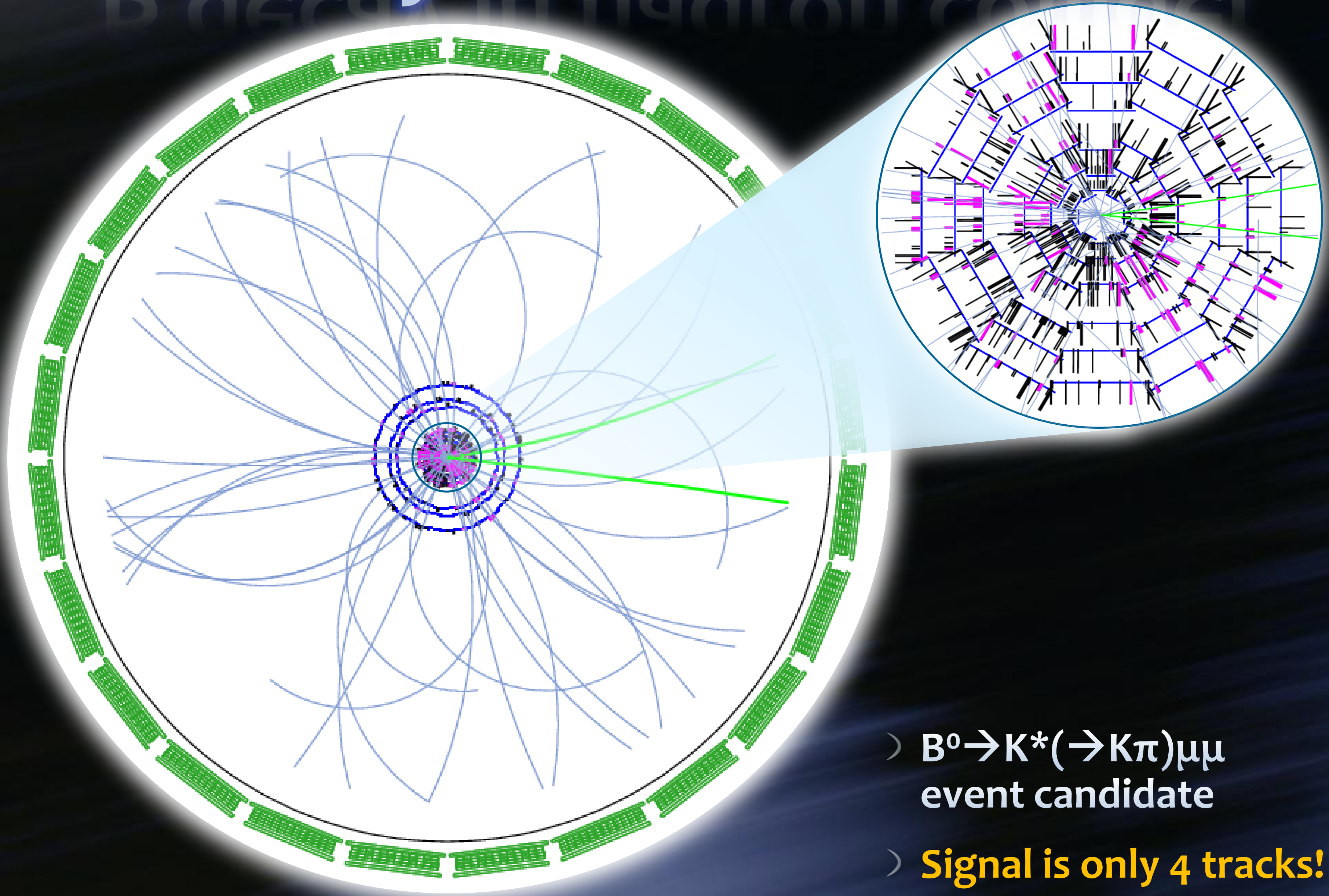
CDFII detector

- 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



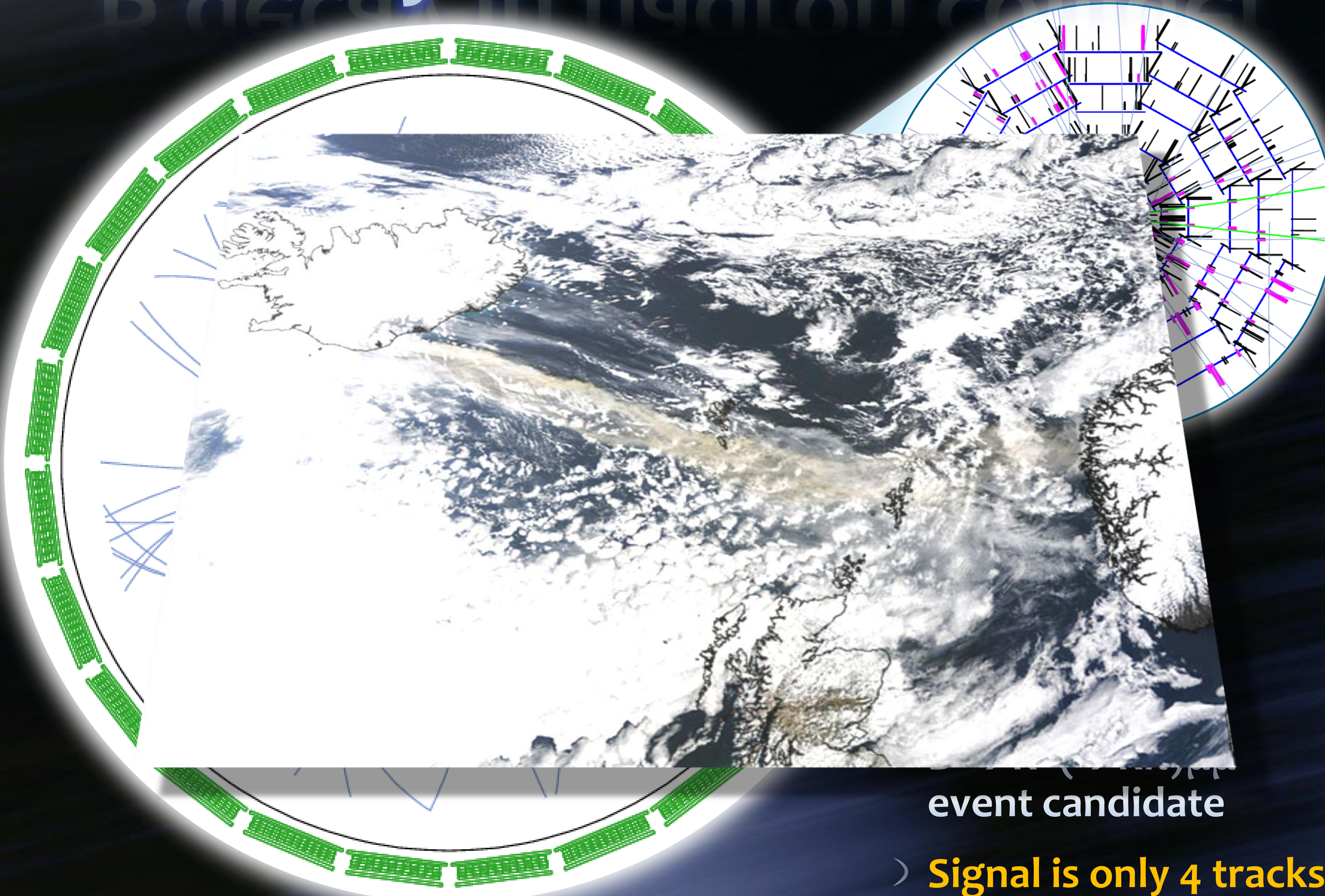
Designed in the early 80's to discover W and Z, proved very effective in doing B physics!

B decay in hadron collider



- $B^0 \rightarrow K^*(\rightarrow K\pi)\mu\mu$ event candidate
- **Signal is only 4 tracks!**

B decay in hadron collider



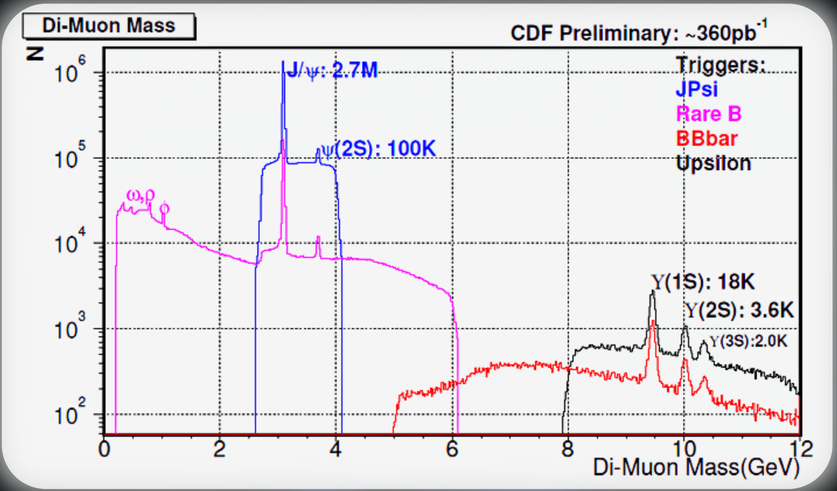
event candidate

- **Signal is only 4 tracks!**

B triggers

Di-Muon

- Conventional trigger at hadron collider
- Wide mass range



2-Displaced tracks

P_T(trk) > 2 GeV

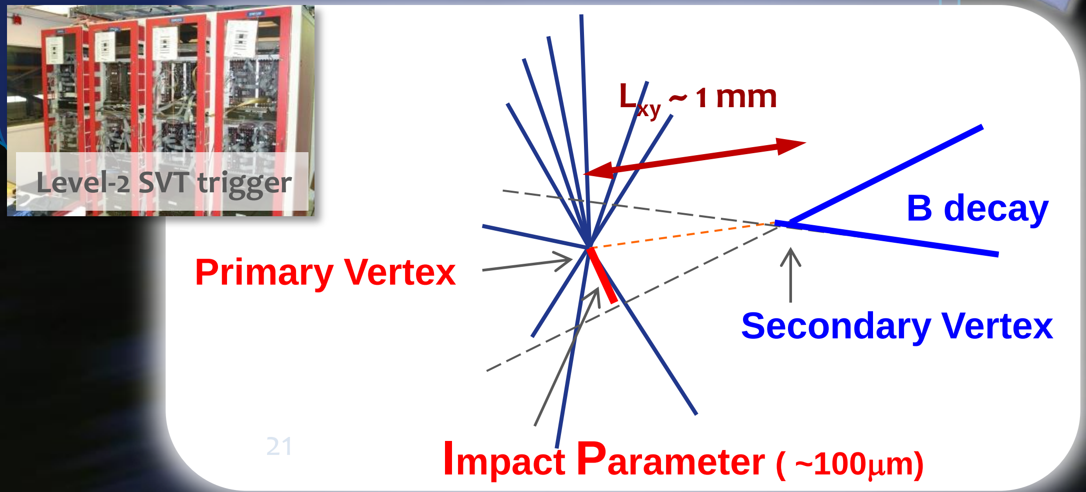
120 μm < I.P.(trk) < 1mm

Σp_T > 5.5 GeV

fully hadronic modes

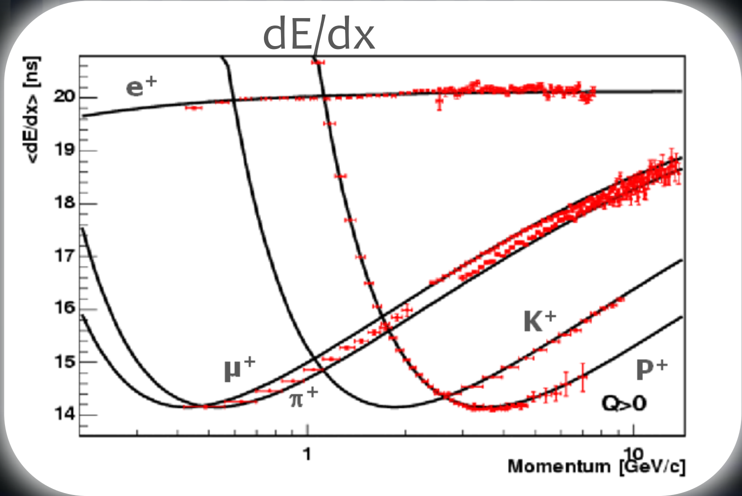
Sillicon Vertex Trigger: SVT

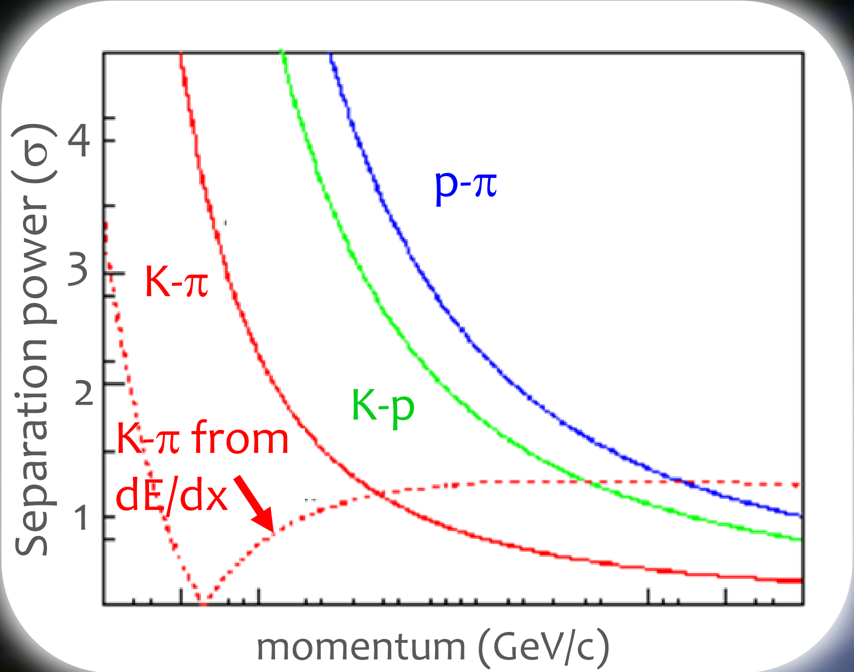
- Online selection of displaced tracks using SVX
- UNIQUE at hadron colliders

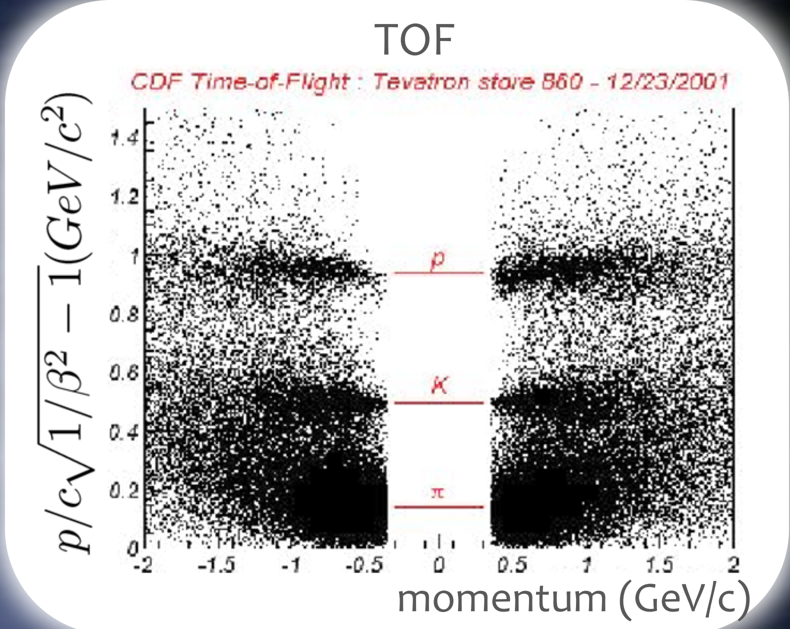


Particle Identification

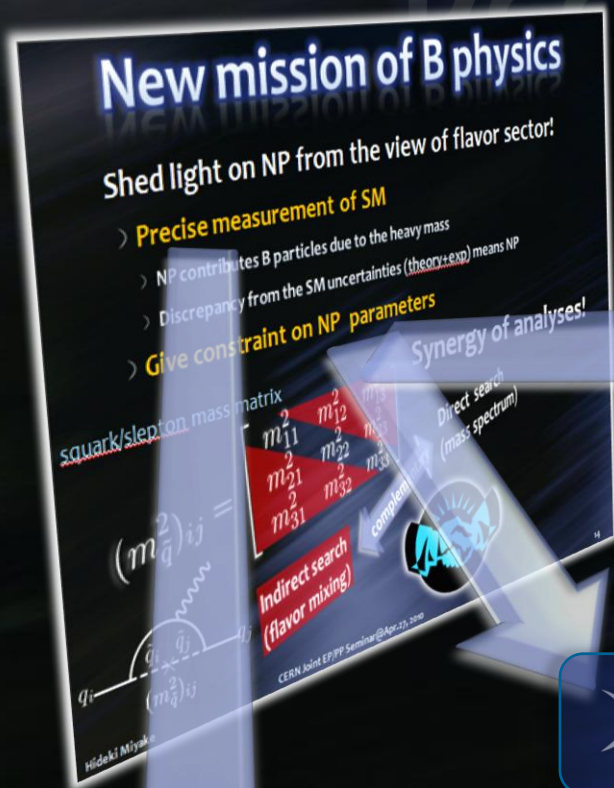
- Separate kaons from pions
  - dE/dx gives 1.5σ separation for p>2 GeV
  - TOF gives better separation at low p
- Used for:
  - Kaon/pion separation
  - Electron tagging







Recent CDF topics



SM suppressed, possible NP enhancement:

- Rare decays
  - $B \rightarrow K^* \mu\mu$, $B_{s(d)} \rightarrow \mu\mu$, $B_s \rightarrow \varphi\varphi$

b→s EW penguin   B annihilation   b→s gluon penguin

SM suppressed, possible NP enhancement:

- CPV measurements in B_s

$B_s \bar{B}_s$ mixing $b \rightarrow c\bar{c}s$ tree

SM dominant, test of theory:

- B hadron properties
  - B hadron lifetimes, Y polarization

B decay model   NRQCD

Rare decays

b→sμμ rare decays

- b→sμμ Flavor Changing Neutral Current (FCNC)

- Promising tool to search for new physics

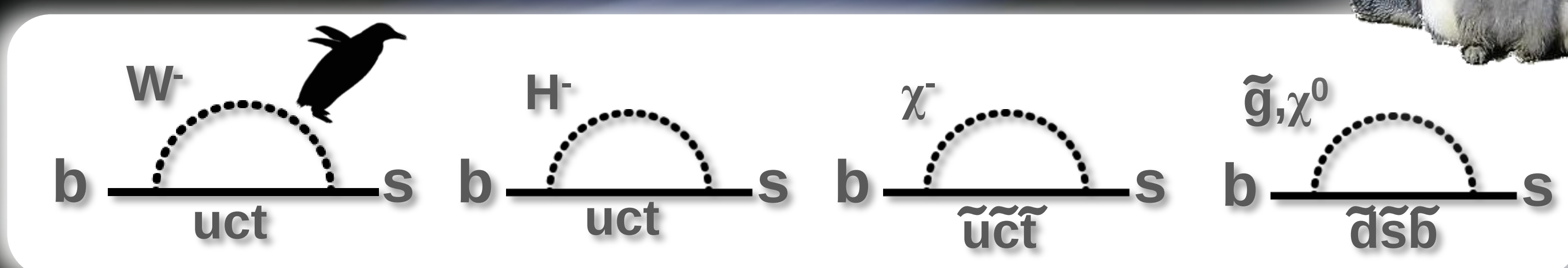
- Tree diagram is forbidden in the SM
- May occur via higher order loop diagram

BR(B→hμμ)~10^{-6} … extremely rare!

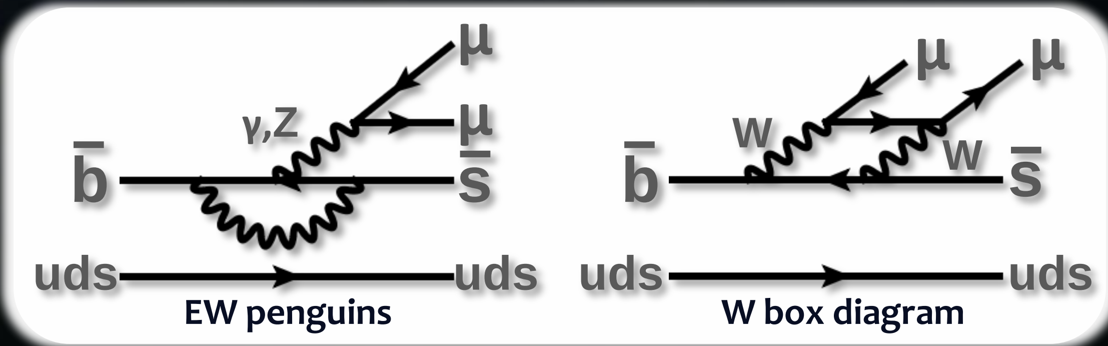
Tevatron produces huge samples of B mesons!

- NP could enhance the amplitude
  - Interference with SM amplitude

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



Current experimental status



Observed — $B^+ \to K^+\mu^+\mu^-$: $[0.52^{+0.08}_{-0.07}] \times 10^{-6}$ (HFAG)

Observed — $B^0 \to K^{*0}\mu^+\mu^-$: $[1.05^{+0.15}_{-0.13}] \times 10^{-6}$ (HFAG)

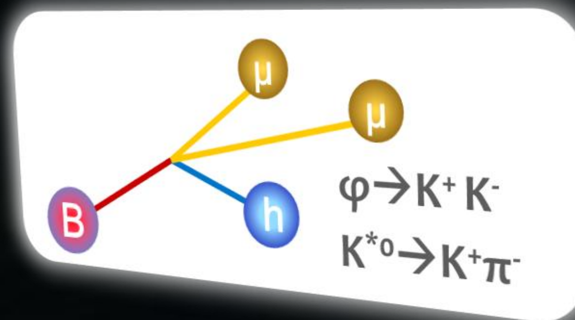
Not yet observed — $B_s \to \varphi\mu^+\mu^-$: 1.61×10^{-6} (C.Q.Geng and C.C.Liu, J.Phys.G29:1103-1118,2003)

- $BR(B_s \to \varphi\mu\mu)/BR(B_s \to J/\psi\varphi)$
  - $<2.3(2.6) \times 10^{-3}$ @90(95%) C.L. — CDF $0.92fb^{-1}$
  - $<4.4 \times 10^{-3}$ @95% C.L. — DØ $0.45fb^{-1}$

- This is the CDF update with $4.4fb^{-1}$
  - BR
  - A_{FB}

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

- $B \to h\mu\mu$ ($h = K, K^*$, and φ)
  - Reconstruct signal candidates
    - Dimuon trigger ($Pt(\mu) > 1.5$ or 2.0 GeV/c)
  - Employ neural network to optimize event selection
  - Extract signal yield from B invariant mass

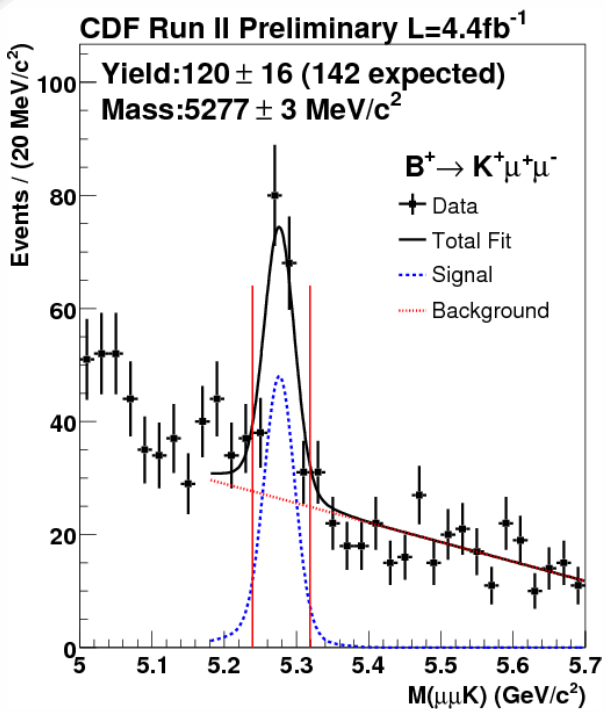


- Angular analysis
  - Kaon angle → K^* polarization: F_L
  - Muon angle → A_{FB}

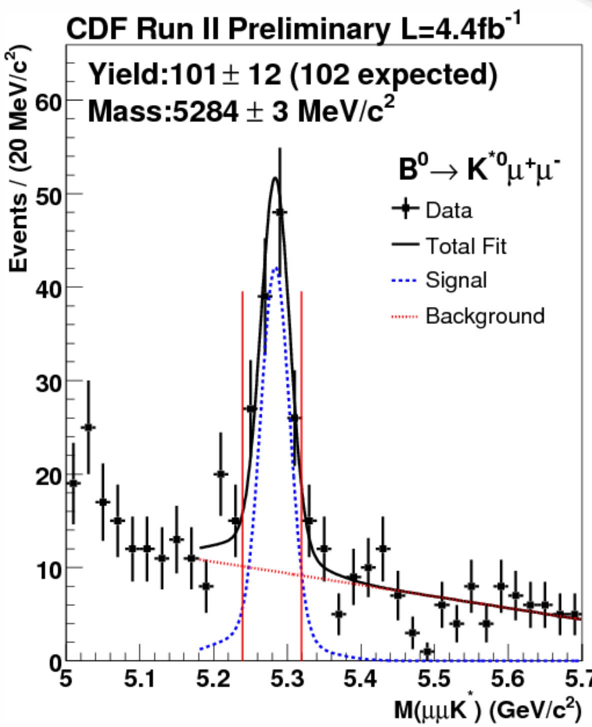
- BR measurement
  - integrated
  - differential

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

- Single final state per decay channel
  - $B^+ \to K^+\mu^+\mu^-$
  - $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$



Stat. significance ~9σ



Stat. significance ~10σ

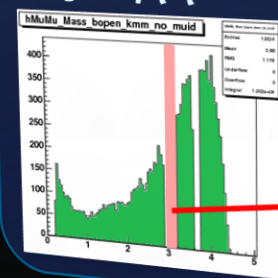
$B \to K^{(*)}\mu\mu$: BR

- **Relative BR :**
  - normalized BR by control channel ($J/\Psi h$)
  - Cancel common systematics (same final state)

h=K,K*

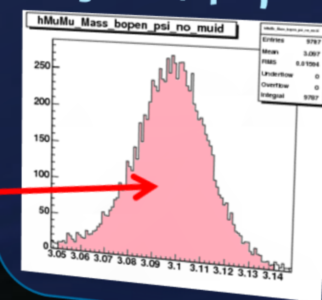
Signal mode

- $B^0 \to K^{*0}\mu\mu$
- $B^\pm \to K^\pm\mu\mu$
- $B_s \to \varphi\mu\mu$



Control sample

- $B^0 \to J/\psi K^{*0}$
- $B^\pm \to J/\psi K^\pm$
- $B_s \to J/\psi \varphi$



Dimuon mass

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

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

- Absolute BR
  - Replace J/ψ BR with PDG value

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

	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} μμ	$1.35^{+0.40}_{-0.37}$(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)

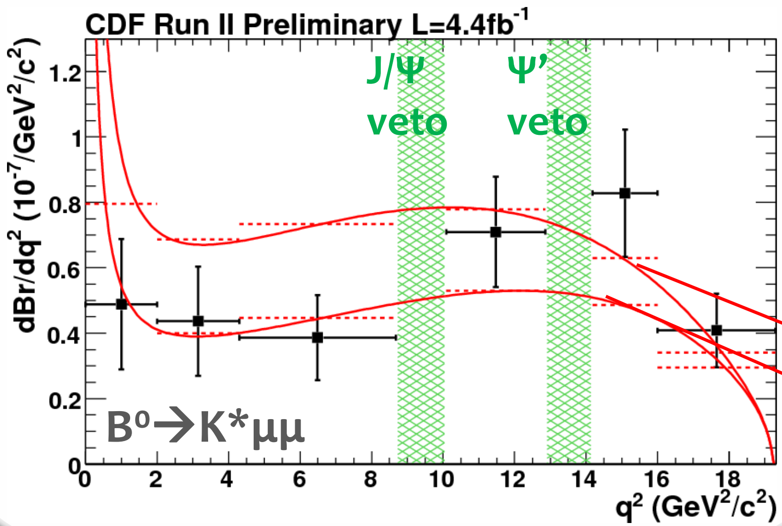
PRL103:171801 (2009)

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

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

The best measurement for single final state!!

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



Dimuon mass spectrum could show a hint of new physics

→appears on differential BR w.r.t. q^2

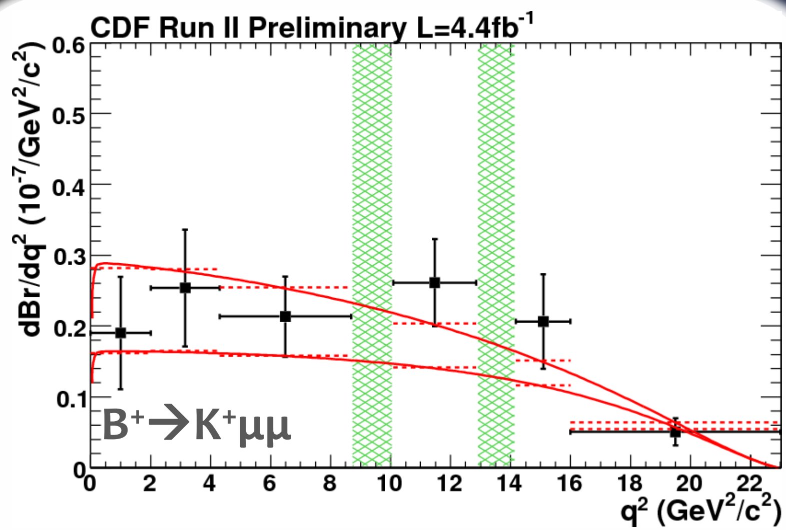
where $q^2 = M_{\mu\mu}^2$

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

SM maximum allowed

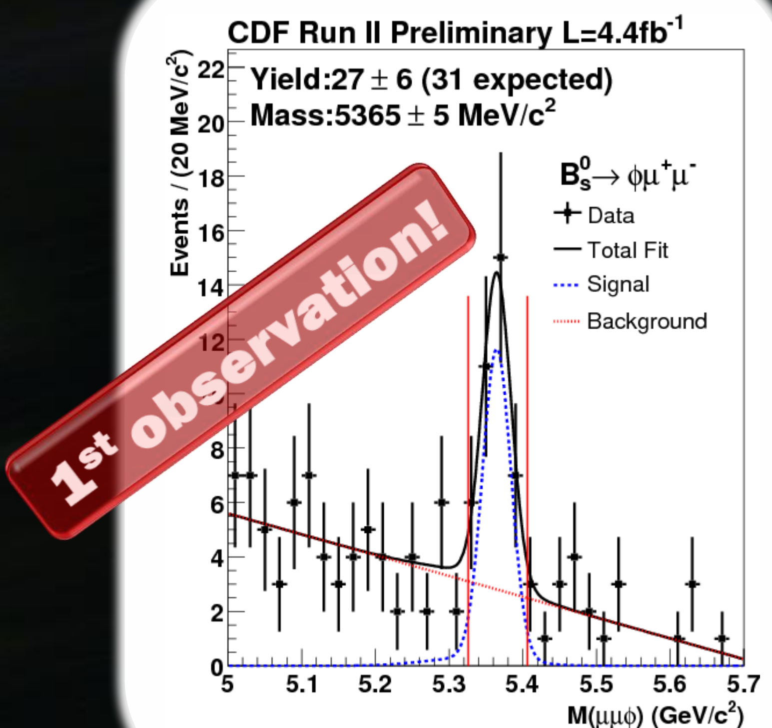
SM minimum allowed

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: $B_s \rightarrow \varphi\mu\mu$



Stat. significance ~6σ

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

$BR(B_s \rightarrow \varphi\mu\mu) = [1.44 \pm 0.33(stat) \pm 0.46(syst)] \times 10^{-6}$

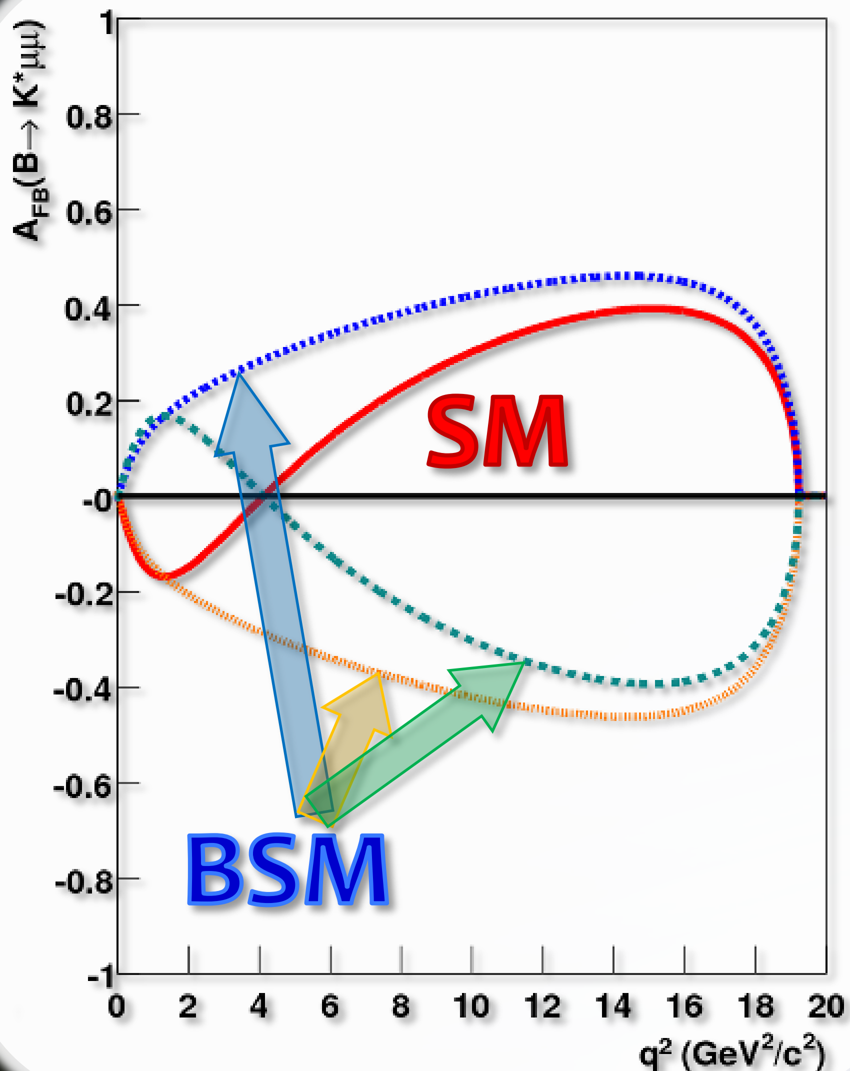
Consistent with theory ~1.61×10^{-6}

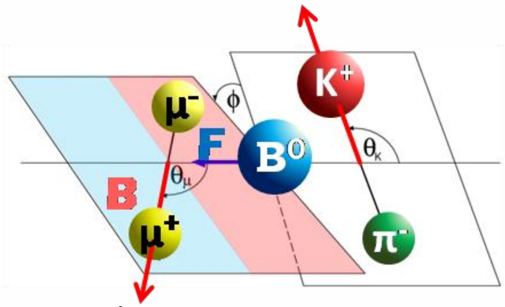
The rarest B_s decay we observed so far!!

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

Brand-new probe!

Forward-Backward Asymmetry





B⁰→K*⁰μμ 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

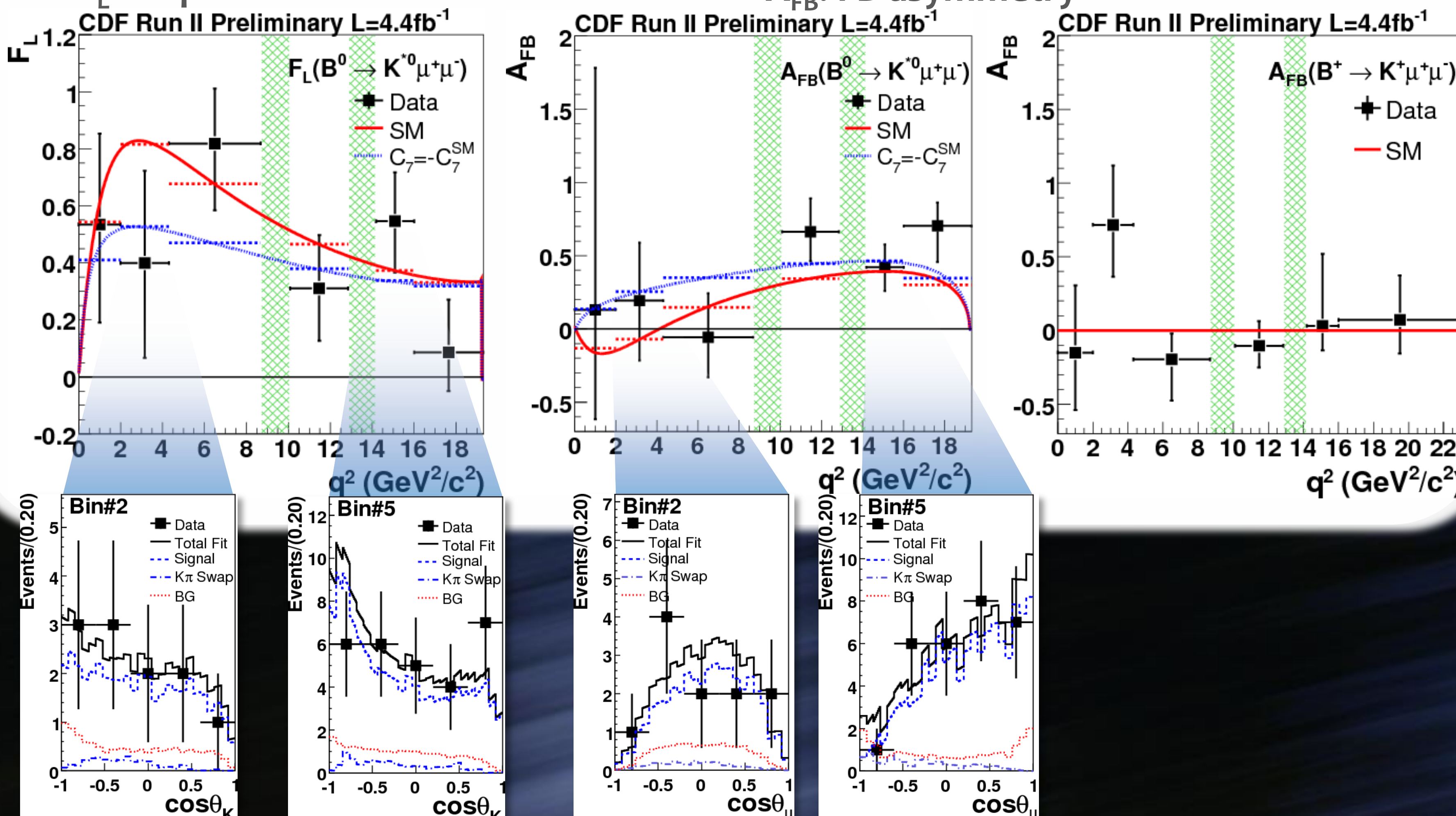
→Good probe to explore BSM!

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

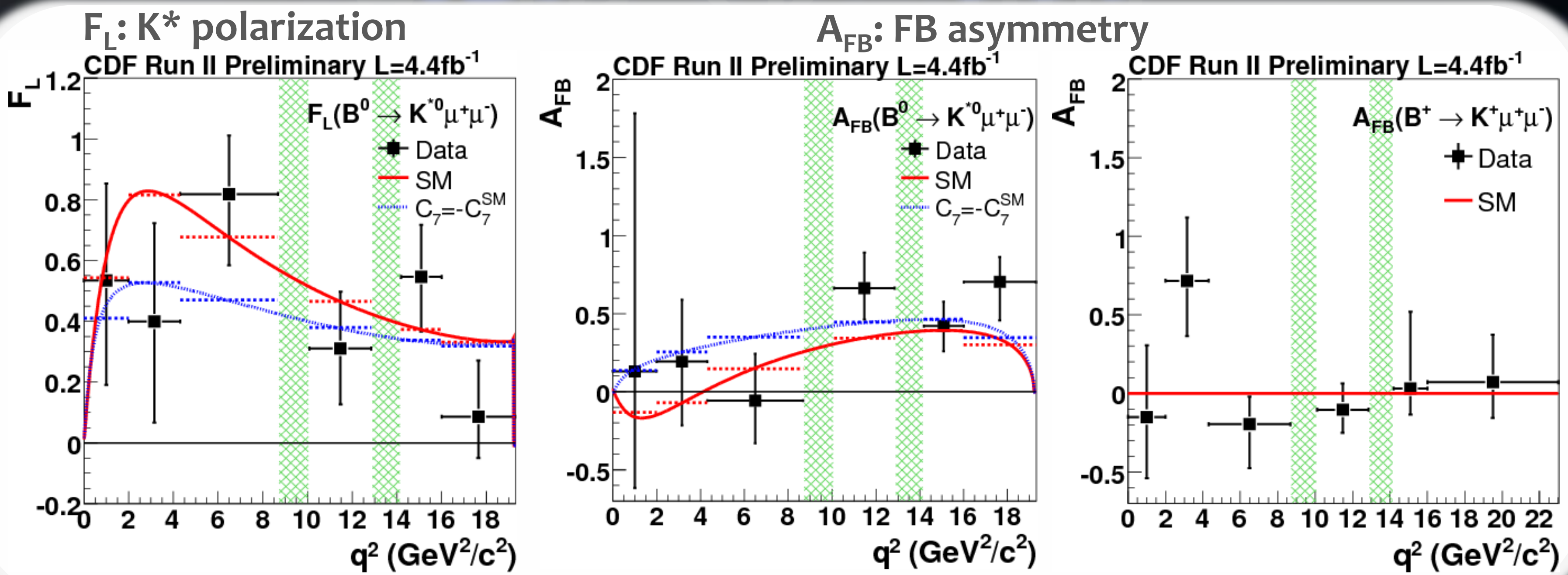


$$\frac{3}{2}F_L\cos^2\theta_K+\frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

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

F_L=1 for Kμμ

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

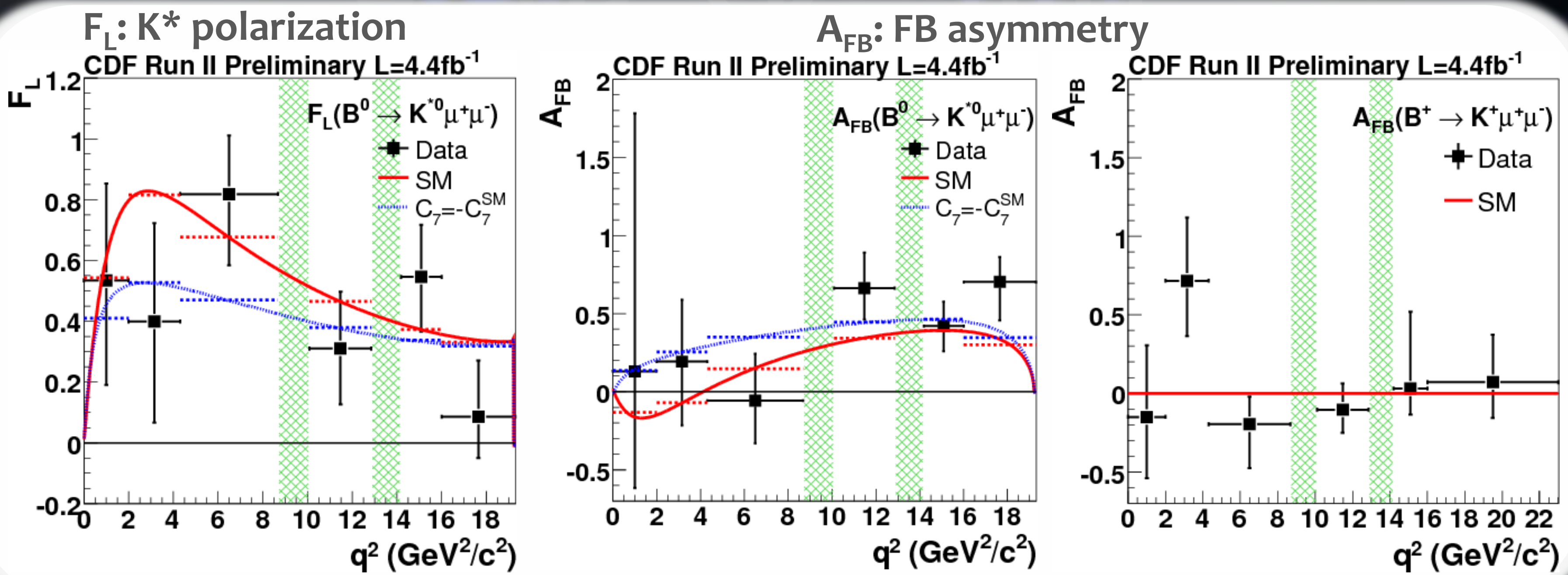


- Consistent and competitive with best B-factories results:

BaBar 384M BB, PRD79,031102(R) (2009) and
Belle 657M BB, PRL103,171801(2009)

- Consistent with the SM and a BSM expectation…

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



Expect world-leading result by end of this year:

- doubled sample
- additional triggers
- exploit more decay channels (e.g. $K_s\mu\mu$, $K^{*+}\mu\mu$…)

Further reach by the end of 2011 and more

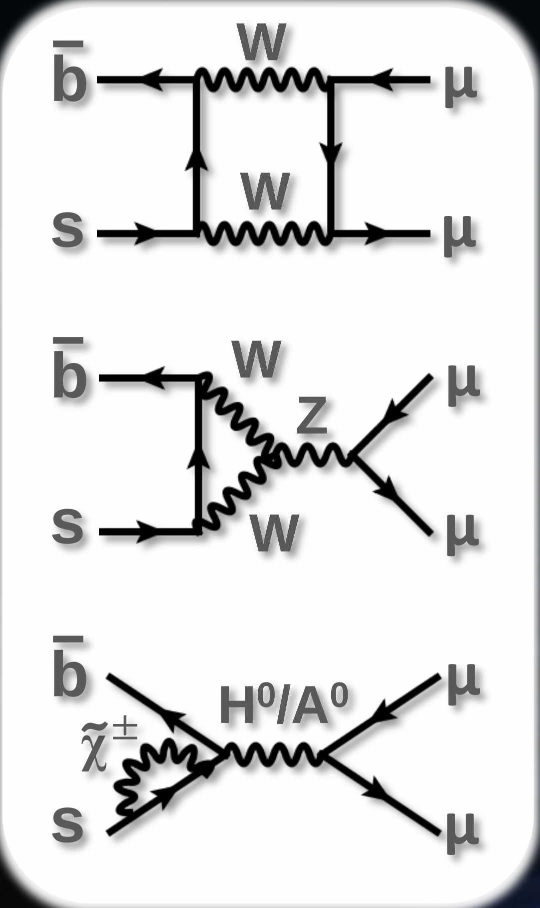
There is much room for improvement!

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

- 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:

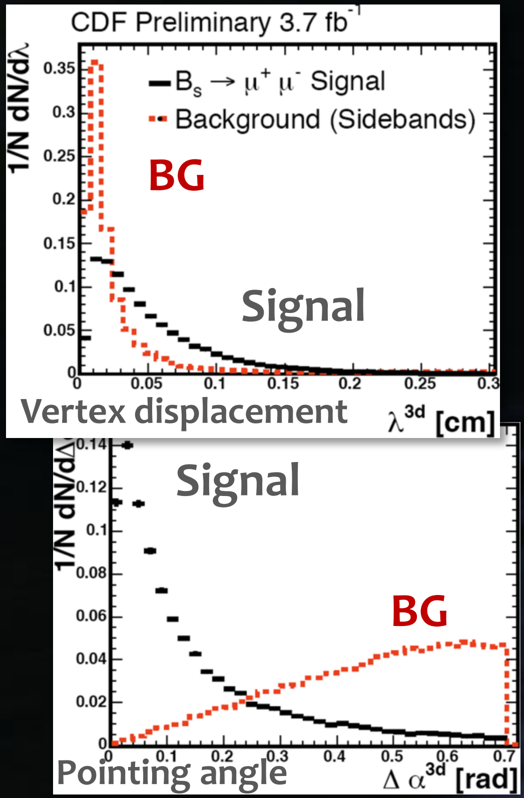
✓BR(B_s→μμ)<4.7(5.8)x10^{-8}

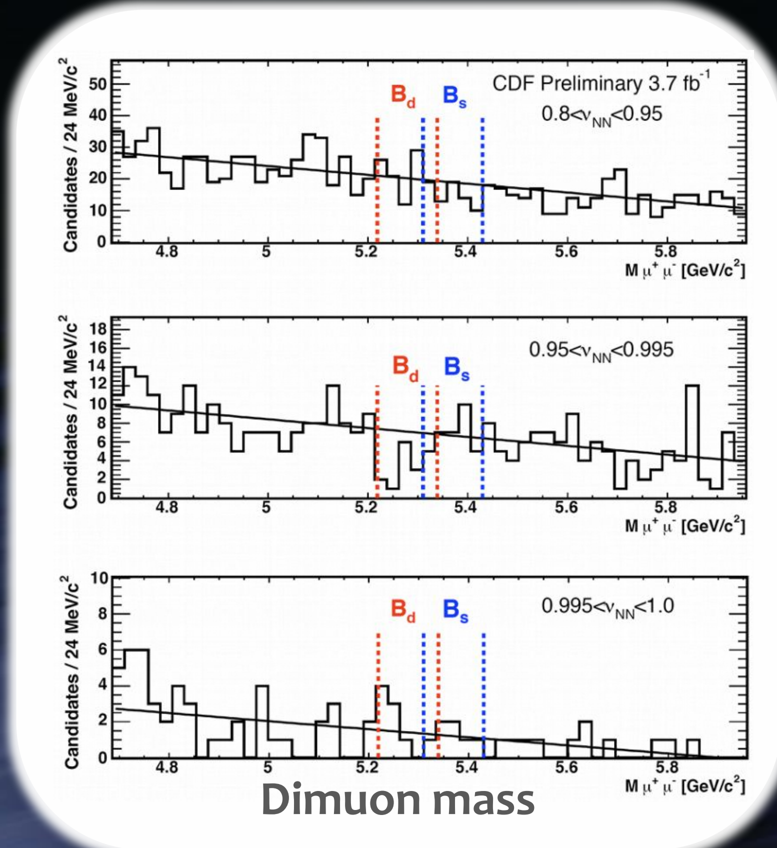
✓BR(B_d→ μμ)<1.5(1.8)x10^{-8} 90(95)% C.L.

PRL 100,101802 (2008)

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

- Utilize neural network to optimize event selection

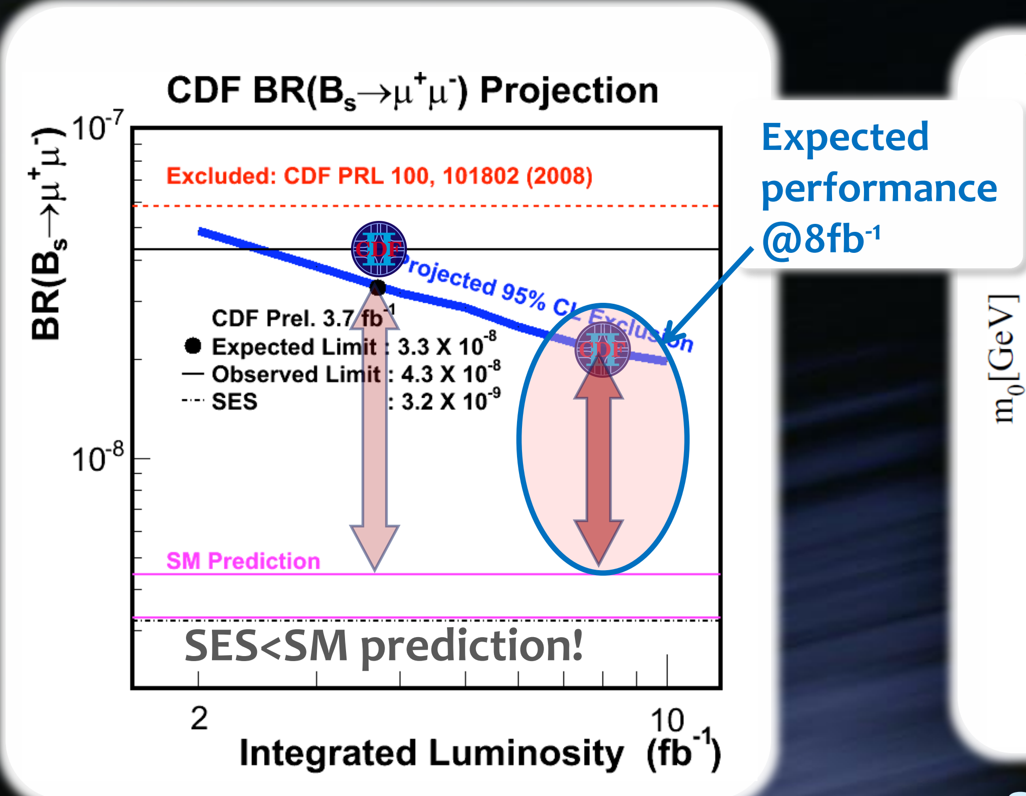




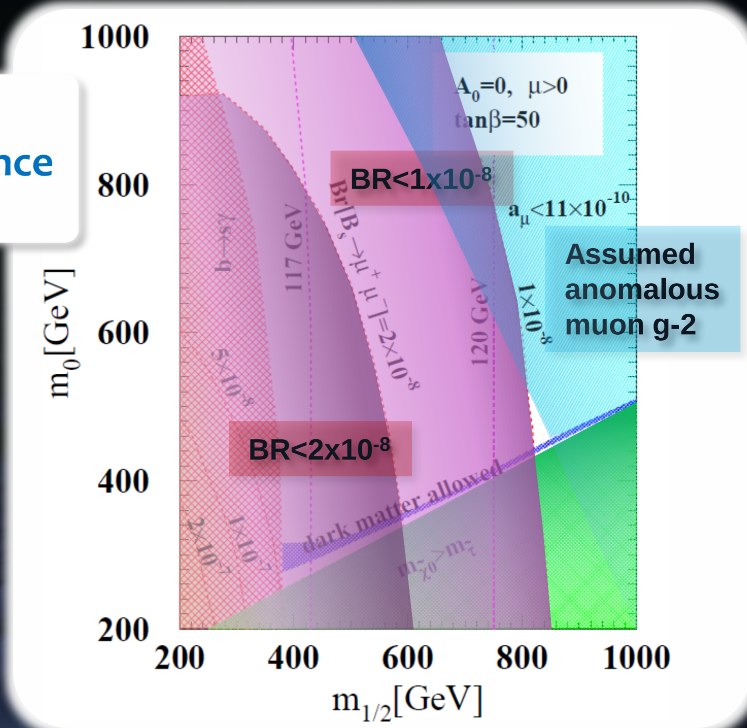
7 kinematic variables

- 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.

$B_s \rightarrow \mu\mu$: prospects



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

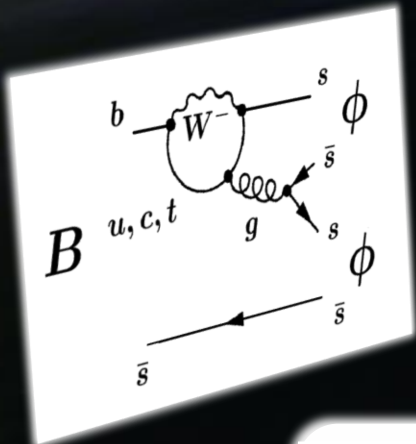


- 2010 (approved, ongoing : ~8fb⁻¹)
  - CDF Expected limit: 2×10^{-8}@8fb⁻¹ (6xSM)
  - Combined with DØ→5xSM
- 2011~ (more than 10fb⁻¹)
  - Combined limit ~$O(10^{-8})$

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

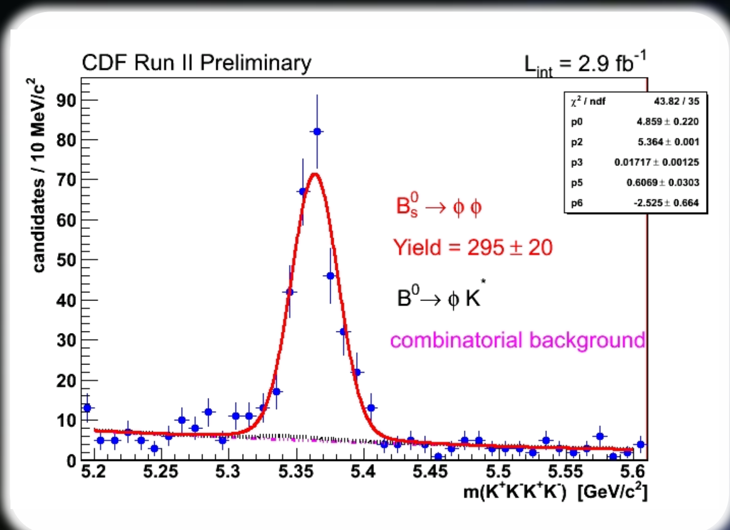
$B_s \to \varphi\varphi$: gluonic penguin

CDFnote 10064

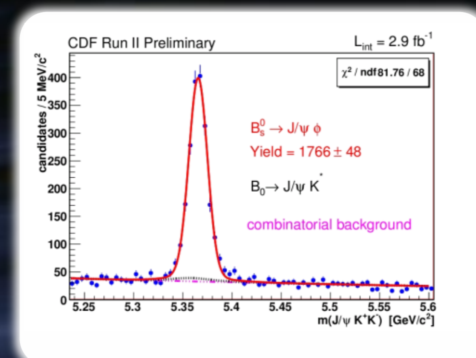


- Dominated by $b \to s\bar{s}\bar{s}$ (same as $B \to \varphi K^{(*)}$)
  - BR is sensitive to NP due to the loop diagram
    - Previous result: $(1.4^{+0.6}_{-0.5} \pm 0.6) \times 10^{-5}$ by 8 signal@180pb^{-1}
  - Theoretical BR expectation ~10^{-5}

PRD76,074018 (2007)
NPB774,64 (2007)



Control channel: J/Ψφ

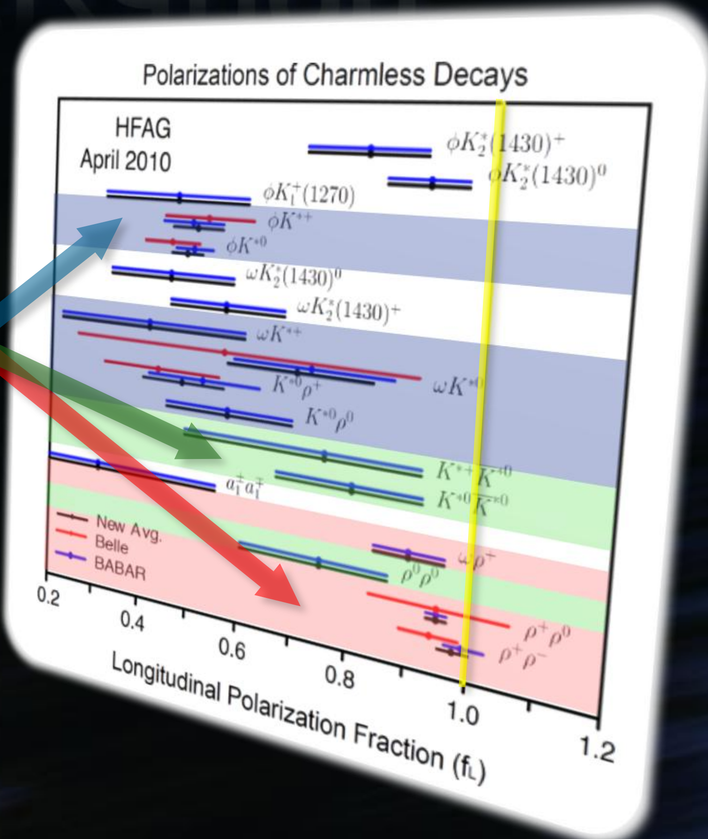


$$BR(B_s^0 \to \phi\phi) = [2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \cdot 10^{-5}$$

Significant improvement from previous results

$B_s \to \varphi\varphi$: polarization

- B→VV Polarization puzzle
  - Naïve QCD expectation: $f_L >> f_T$,
    - Confirmed b→u tree (e.g. $B^0 \to \rho^+\rho^-$)
    - Evidence b→d penguin (e.g. $B^0 \to \rho^0\rho^0$)
  - while b→s penguin: $f_L \sim f_T$
    - $f_L(B^0 \to \varphi K^{*0}) = 0.48 \pm 0.03$ (HFAG ave.)
    - $f_L(B^+ \to \varphi K^{*+}) = 0.50 \pm 0.05$ (HFAG ave.)



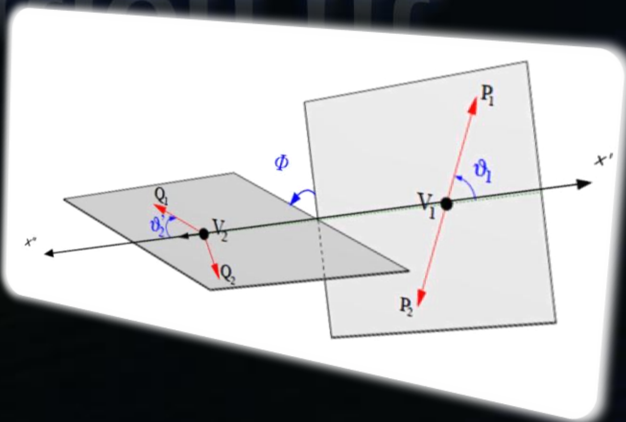
- Sign of NP?
- or within SM framework?

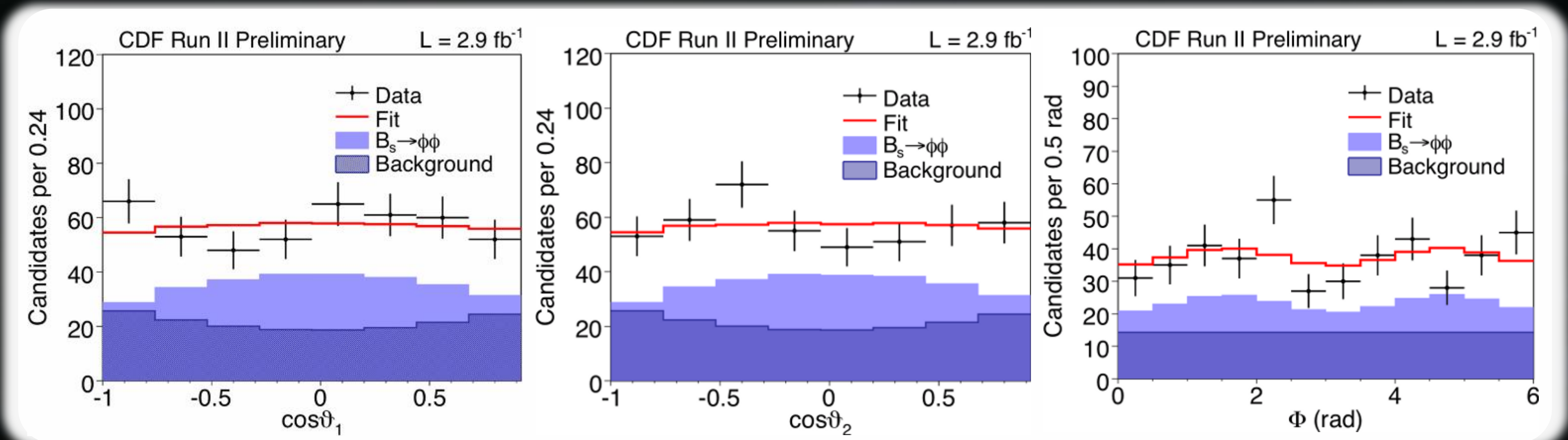
Information from penguin dominated $B_s \to VV$ is quite interesting

http://www.slac.stanford.edu/xorg/hfag/rare/index.html

$B_s \rightarrow \varphi\varphi$: polarization fit

- 3 angular distributions ($\cos\theta_1$, $\cos\theta_2$, φ)
- Unbinned maximum likelihood fit
  - Time-integrated, B_s flavor untagged, no CPV assumption
  - 3 transversity amplitudes and 1 phase difference





$$|A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}),$$
$$|A_\parallel|^2 = 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst}),$$
$$|A_\perp|^2 = 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst}),$$
$$\cos\delta_\parallel = -0.91^{+0.15}_{-0.13}(\text{stat}) \pm 0.09(\text{syst}).$$

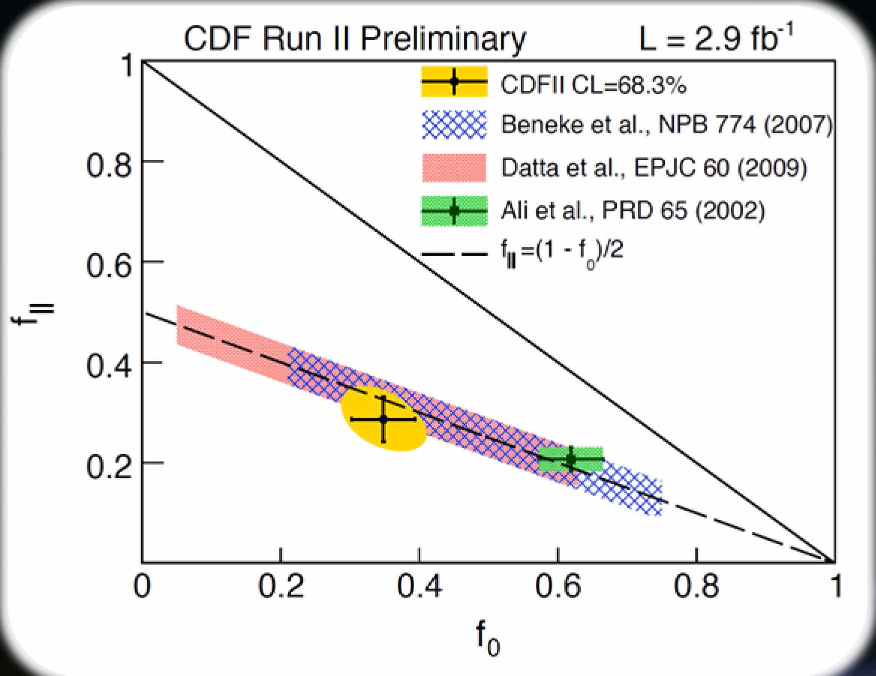
First polarization measurement of the decay!

$B_s \to \varphi\varphi$: discussion

$$|A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}),$$
$$|A_\parallel|^2 = 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst}),$$
$$|A_\perp|^2 = 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst}),$$
$$\cos\delta_\parallel = -0.91^{+0.15}_{-0.13}(\text{stat}) \pm 0.09(\text{syst}).$$

$$f_L = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}),$$
$$f_T = 0.652 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}).$$

$f_L << f_T$!!



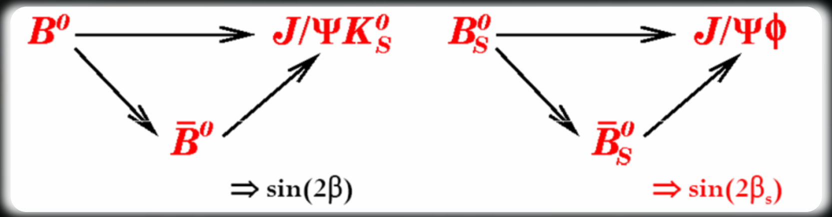
QCD factorization
QCD factorization
Perturbative QCD

This first measurement in the B_s sector seems to strengthen the puzzle!

CPV

CP Violation in $B_s \to J/\psi\varphi$

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

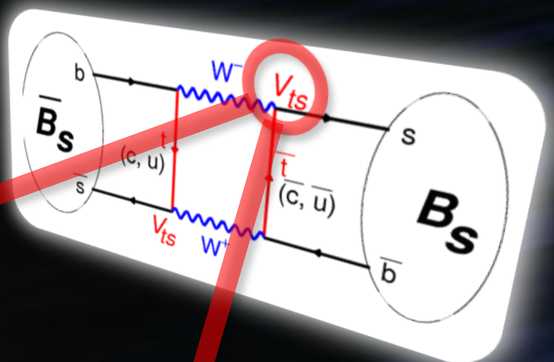


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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 $\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}| \cos\phi_s$



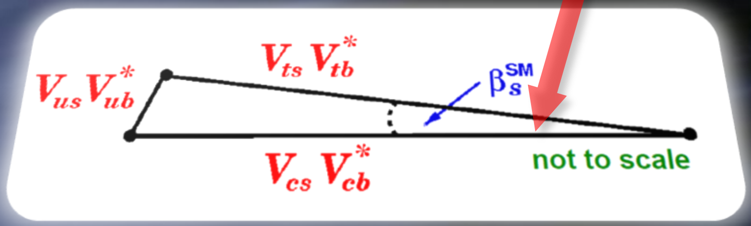
CPV phase between B_s mixing and $B_s \to J/\psi\varphi$ decay:

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

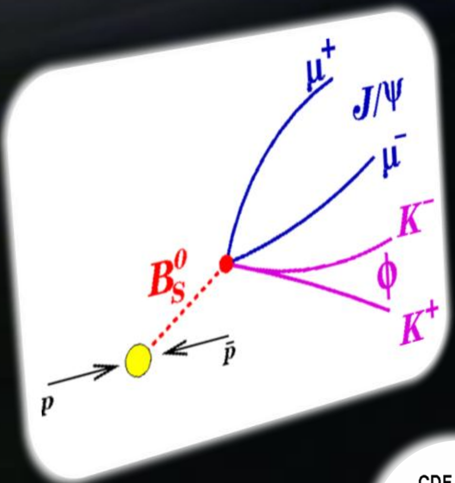
A. Lenz and U. Nierste, JHEP 06, 072(2007)

If $\varphi_s^{NP} >> \beta_s^{SM}$:

$$-2\beta_s \sim \phi_s^{NP}$$

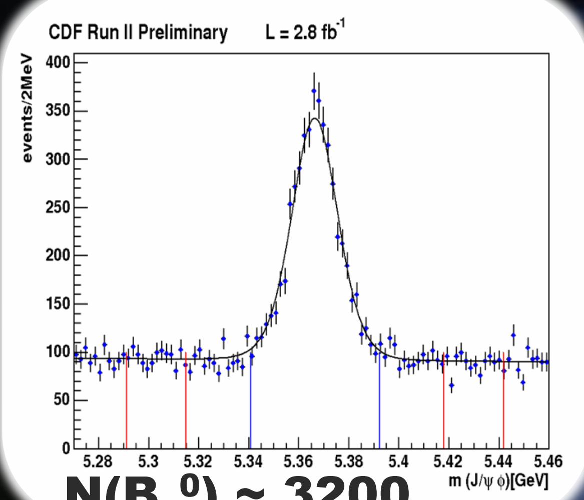


$B_s \rightarrow J/\psi\varphi$ signal

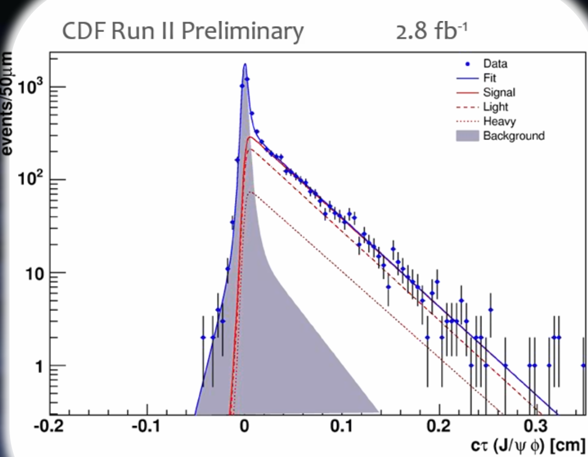


- The golden channel to measure β_s
  - dominated by b→ccs tree ~theoretically clean
- B→VV decay: three partial waves
  - L=0,2 (CP even)
  - L=1 (CP odd)

Need angular analysis



$N(B_s^0) \sim 3200$



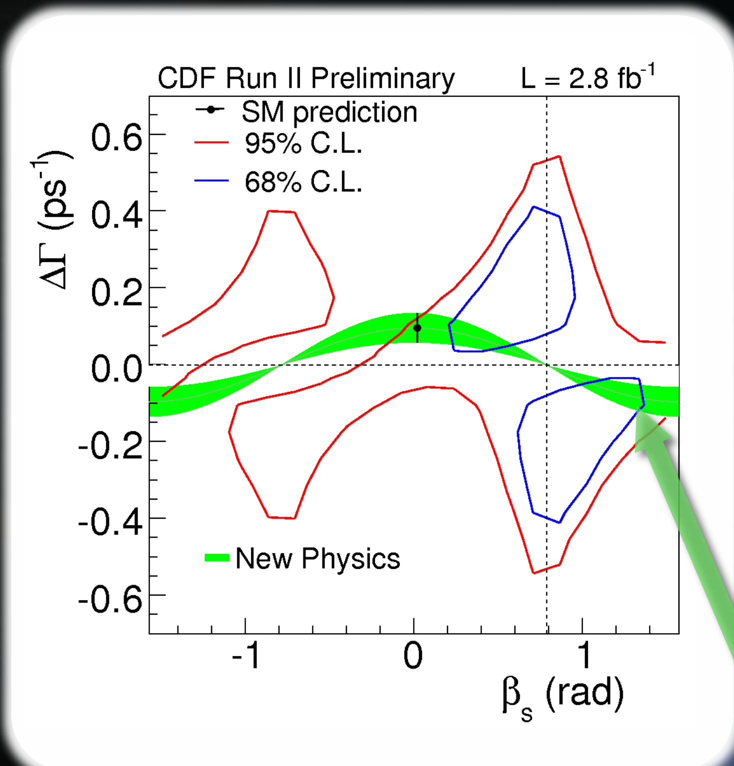
β_s=0, no flavor tag :
$\tau(B_s^0)$ = 1.53 ± 0.04 (stat) ± 0.01 (syst) ps
$\Delta\Gamma$ = 0.02 ± 0.05 (stat) ± 0.01 (syst) ps^{-1}

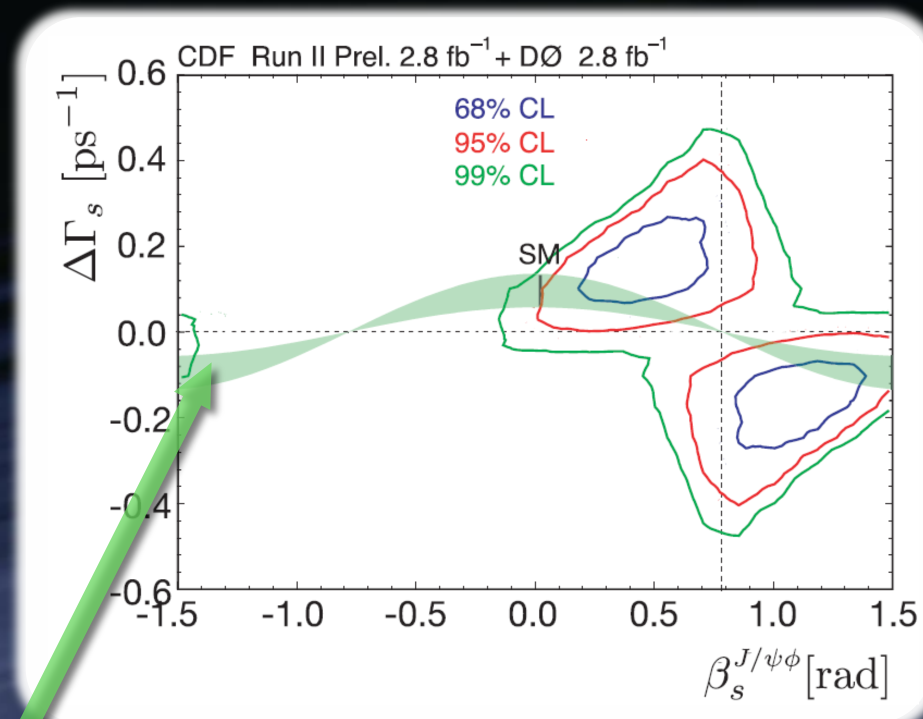
PRL 100, 121803 (2009)

β_s results@2.8fb^{-1}

CDF note 9458 (2.8fb^{-1})
PRL100,161802 (2008) (1.35fb^{-1})

DØ note 5928, CDF note 9787





$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$

SM p-value=7%

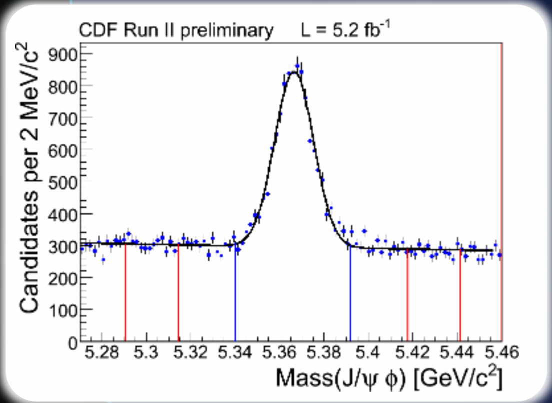
SM p-value=3.4%

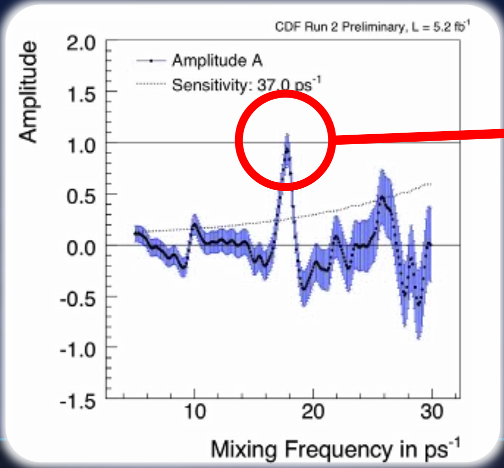
1.8σ deviation from SM

2.1σ deviation from SM

Coming improvement

- CDF update to $L=5.2fb^{-1}$
- Fully apply PID and flavor tagging
  - No PID and one of flavor tagging method (SSKT) after $1.4fb^{-1}$ data
  - Everything calibrated now→ expect significant improvement





SSKT calibration on B_s mixing

Amplitude~1 indicates accurate tagging

$\mathcal{A} = 0.94 \pm 0.15\ (\text{stat.}) \pm 0.13\ (\text{syst.})$

$\Delta m_s = 17.79 \pm 0.07\ ps^{-1}$

Good performance!

- Account for B_s→J/ψKK S-wave
  - Potential contamination from non-resonant KK or $f_0(980)$
    - Take the NR component into the likelihood for $5.2fb^{-1}$ update
    - The fraction is obtained from KK invariant mass fit

COMING SOON!

B hadrons

B hadron lifetimes

- Fundamental and important B property
- Confirmation of the B weak decay models

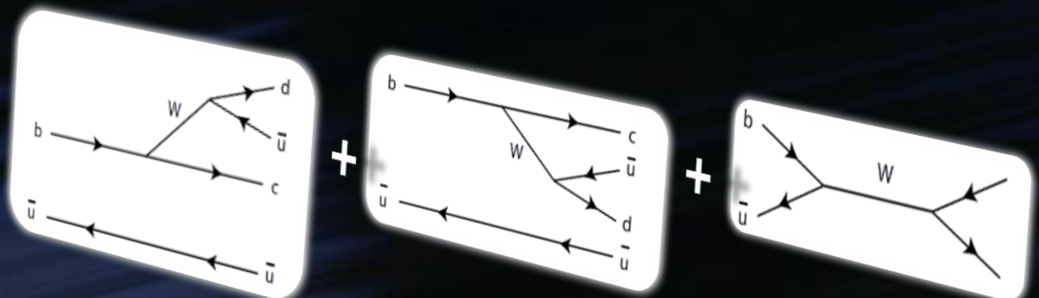
- Naïve spectator model: equal lifetimes among b hadrons

$$\tau(B_c) = \tau(\Lambda_b) = \tau(B_s) = \tau(B^0) = \tau(B^+)$$

- Experimental results:

$$\tau(B_c) < \tau(\Lambda_b) < \tau(B_s) \simeq \tau(B^0) < \tau(B^+)$$

Pauli interference, weak annihilation, weak exchange induce lifetime hierarchy



$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \cdot \left[A_0 + A_2\left(\frac{\Lambda_{QCD}}{m_b}\right)^2 + A_3\left(\frac{\Lambda_{QCD}}{m_b}\right)^3\right]$$

- Theoretical predictions:

$$\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$$
$$\tau(\Lambda_b^0)/\tau(B^0) = 0.88 \pm 0.05$$

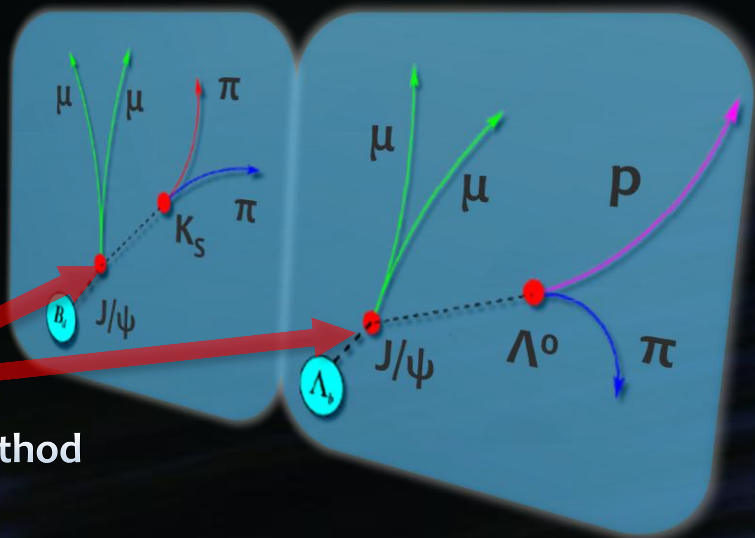
PLB667,1(2008)
Review: Production and Decay of b-flavored Hadrons

B hadrons decay into J/ψ

$B^+ \to J/\psi K^+$
$B^0 \to J/\psi K^{*0}(\to K\pi)$
$B^0 \to J/\psi K_s(\to \pi\pi)$
$\Lambda_b^0 \to J/\psi \Lambda^0(\to p\pi)$

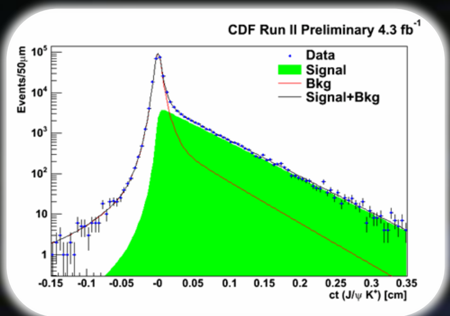
CDFnote 10071

$4.3 fb^{-1}$

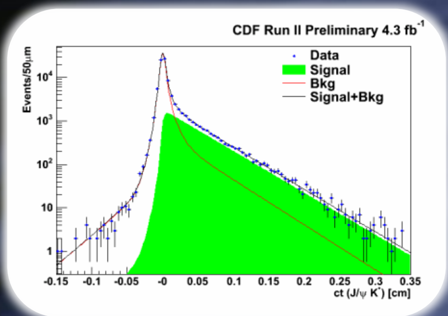


- B hadrons contain J/ψ final state:
  - Dimuon trigger
    - no biasing effects on proper time distribution
  - Proper decay length obtained from J/ψ vertex
  - Cancel BR ratio systematics with common analysis method

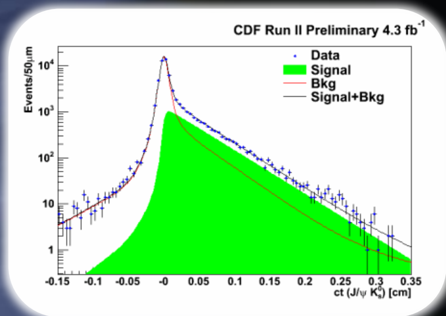
$B^+ \to J/\psi K^+$



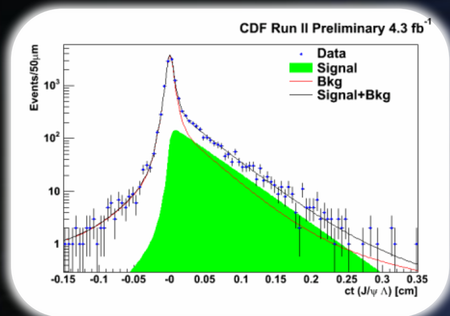
$B^0 \to J/\psi K^{*0}$



$B^0 \to J/\psi K_s$

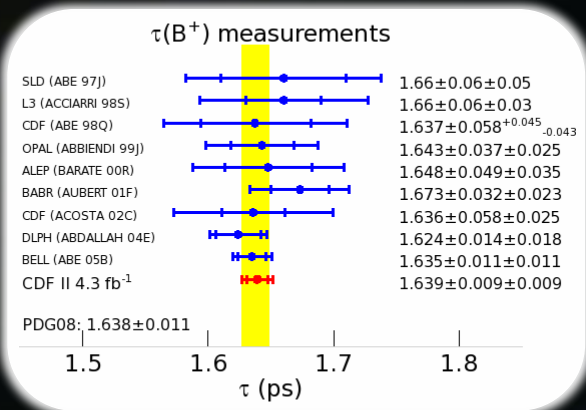


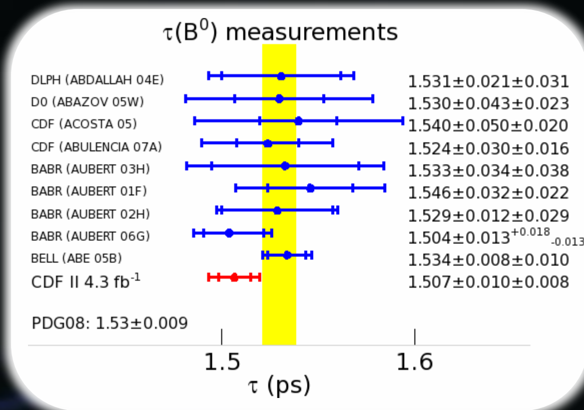
$\Lambda_b^0 \to J/\psi \Lambda^0$

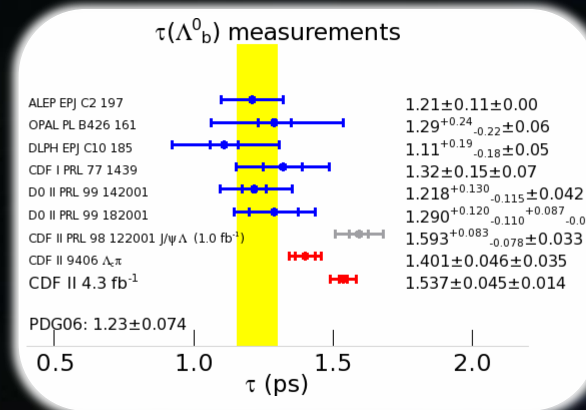


B lifetime: CDF results

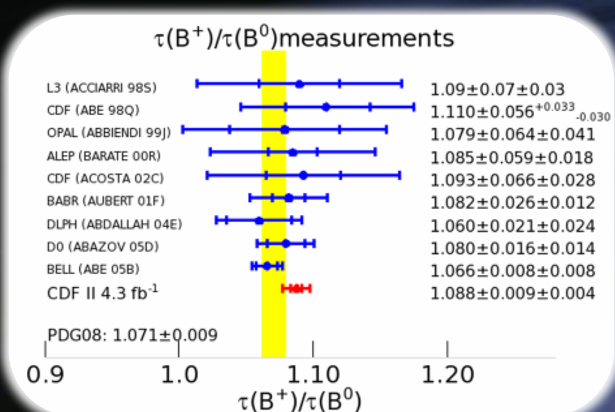
CDFnote 10071







World's most precise B hadron lifetimes!

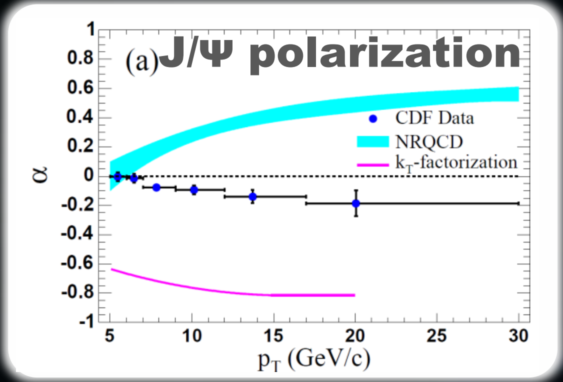


$$
\begin{aligned}
c\tau(B^+) &= 491.4 \pm 2.6\ (stat.)\ \pm\ 2.6\ (syst.)\ \mu m, \\
c\tau(B^0) &= 451.7 \pm 3.0\ (stat.)\ \pm\ 2.5\ (syst.)\ \mu m, \\
c\tau(\Lambda_b^0) &= 460.8 \pm 13.4\ (stat.)\ \pm\ 4.1\ (syst.)\ \mu m.
\end{aligned}
$$

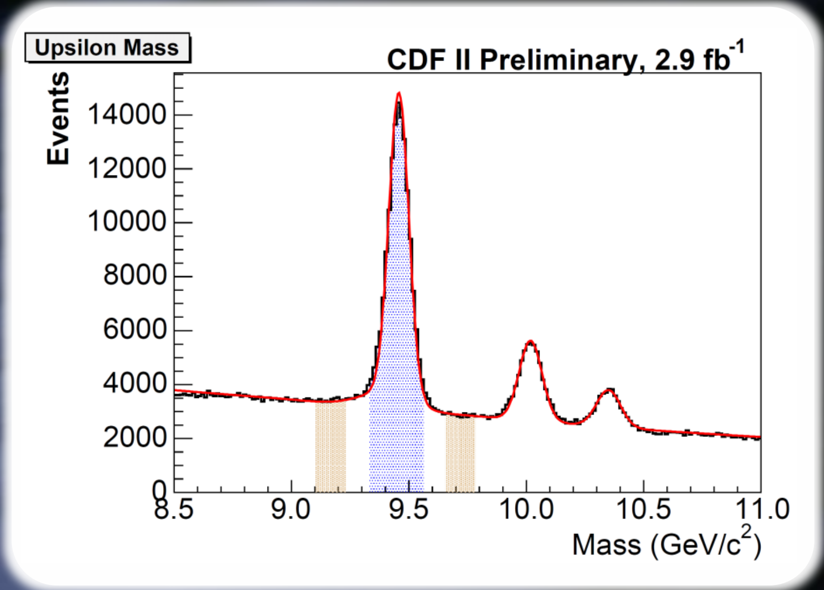
$$
\begin{aligned}
\tau(B^+)/\tau(B^0) &= 1.088 \pm 0.009\ (\text{stat.}) \pm 0.004\ (\text{syst.}) \\
\tau(\Lambda_b^0)/\tau(B^0) &= 1.020 \pm 0.030\ (\text{stat.}) \pm 0.008\ (\text{syst.})
\end{aligned}
$$

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)



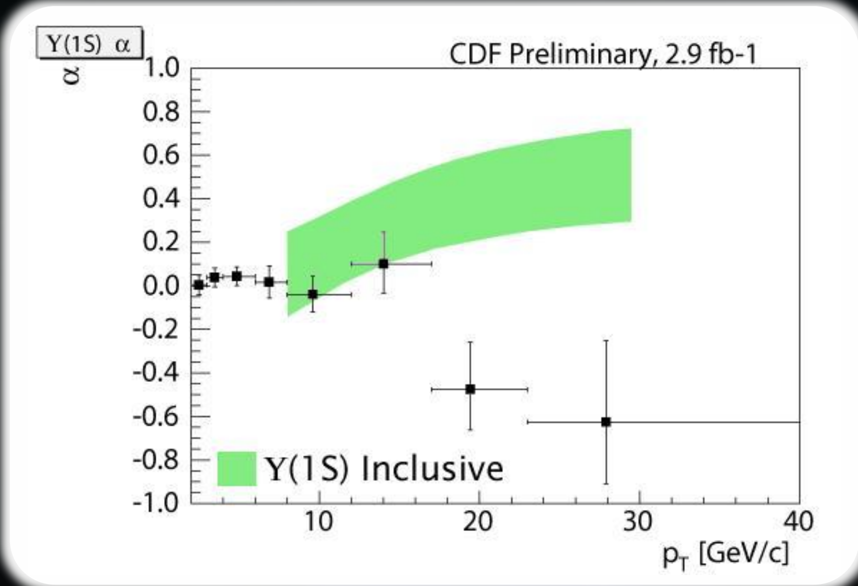
$$\frac{d\,\Gamma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^*.$$

where cosθ*: μ^+ angle

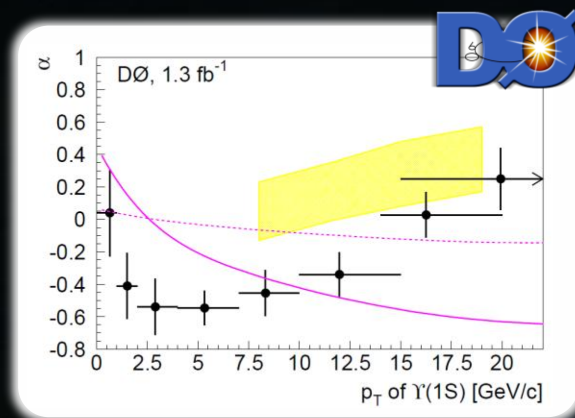
α=+1: transverse

α=-1: longitudinal

Υ polarization : result



CDF Public Note 9966



PRL101, 182004 (2008)

- CDF measures Υ(1S) polarization at 2.9fb^{-1}
  - Disagreement with NRQCD
  - Different trend between CDF and DØ
- Further test with 2x data and other Υ(nS) and Ψ(nS)

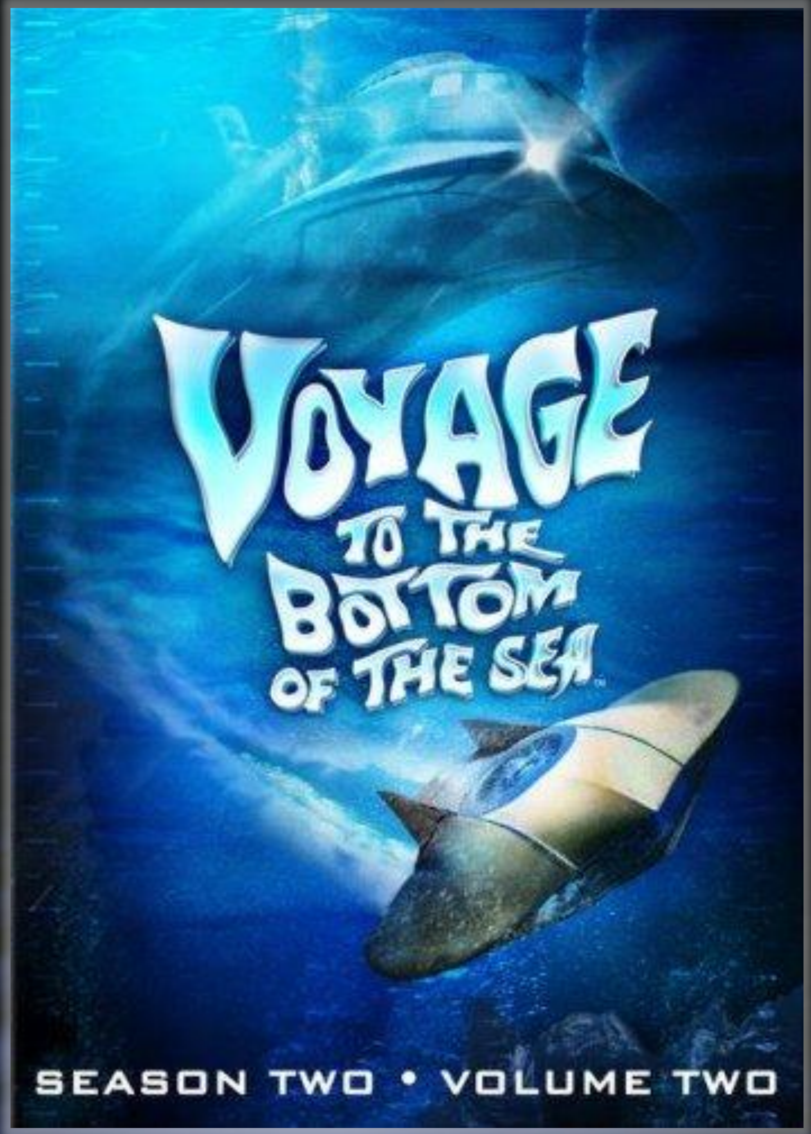
Summary

- B physics has played an important role for >30 years
  - and will do so, to pursue New Physics
- CDF heavy flavor program has reached maturity
  - Rare decays (BR, A_{FB}, polarizations)
  - CPV (β_s)
  - B-hadrons (lifetime, polarizations)
  - NOT ALL! Today we don't cover a lot of analyses…

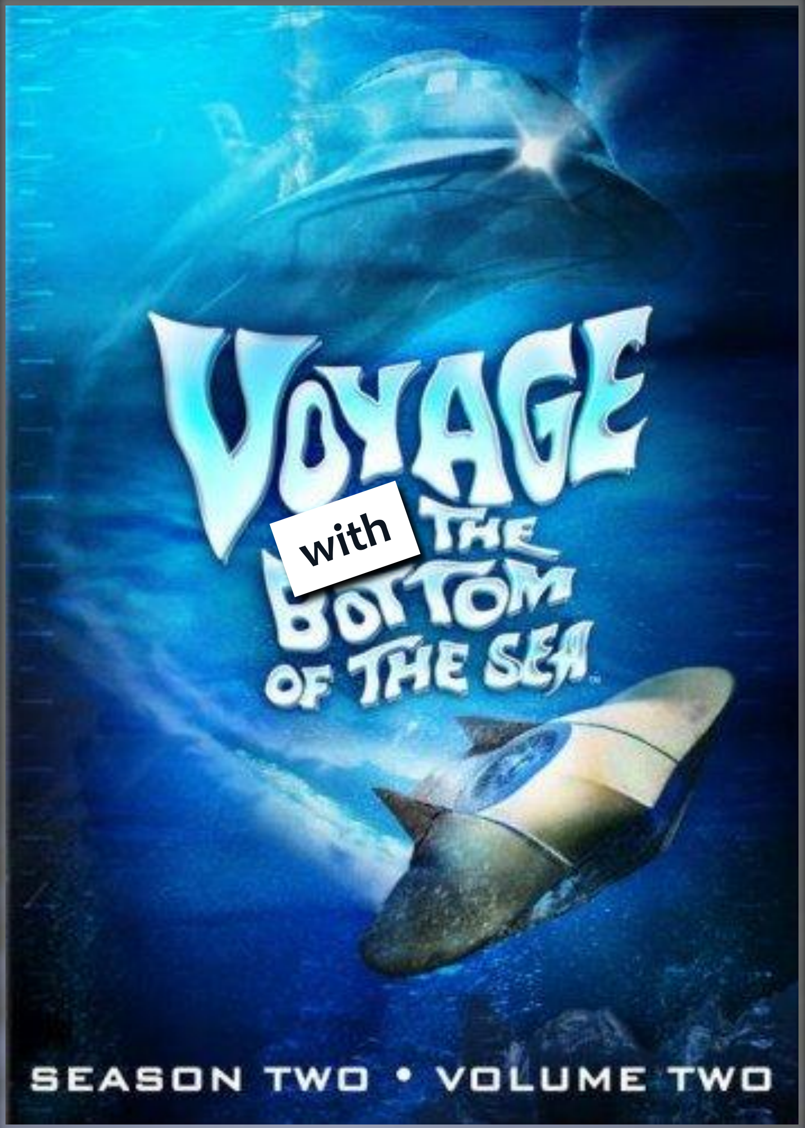
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html

Prospects

- CDF is a major player in HF physics and will be so for the next few years
  - Doubled data expected until end of the year
  - and more!
- LHC has started, congratulations!
- BaBar, Belle, and DØ continue to produce interesting B physics results
- Exciting years coming!



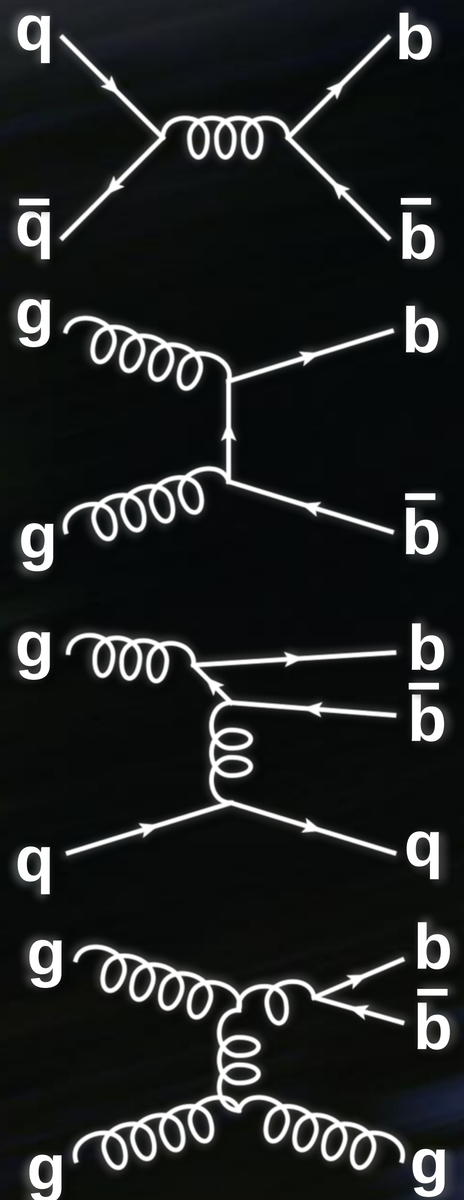
http://www.amazon.co.jp/gp/product/images/B000K7VHYG/ref=dp_image_0?ie=UTF8&n=561958&s=dvd



http://www.amazon.co.jp/gp/product/images/B000K7VHYG/ref=dp_image_0?ie=UTF8&n=561958&s=dvd

Backup

B production@Tevatron



☺Pros

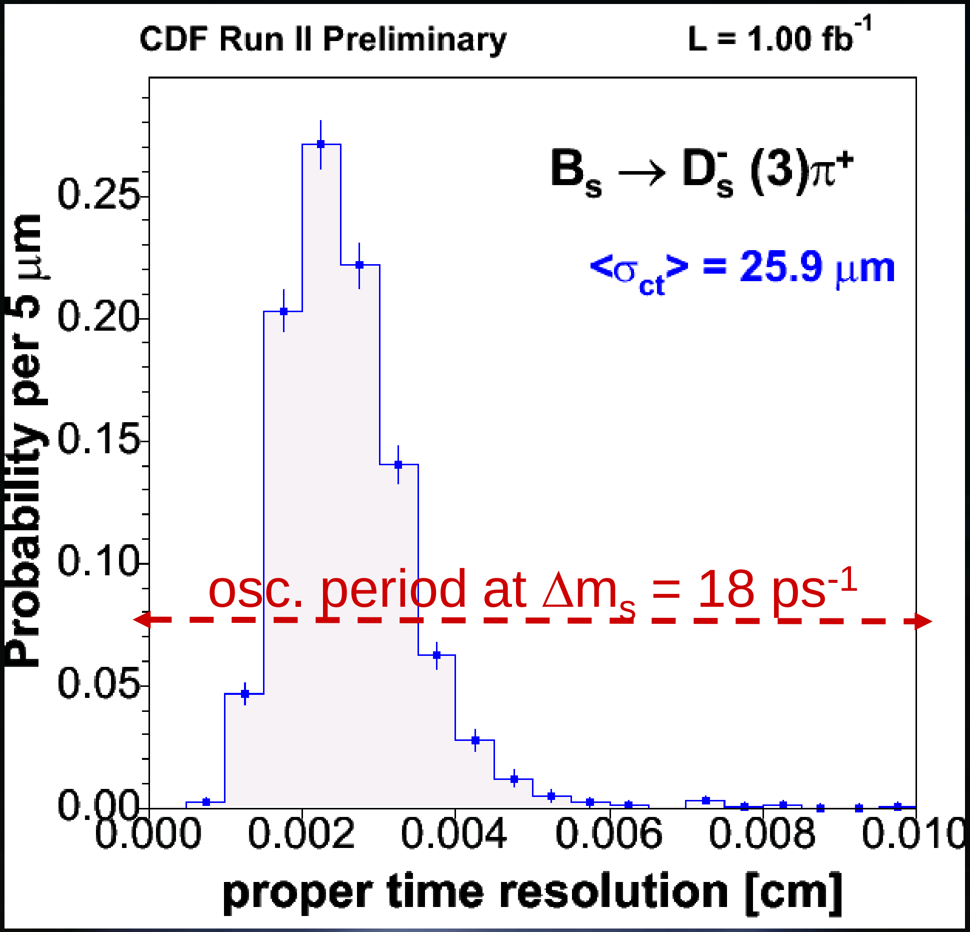
- Enormous cross-section
- All species of b-hadrons
  - B_u,B_d,B_s,B_c,Λ_b, Σ_b…

☹ 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

Proper Time Resolution



B_s Phase and the CKM Matrix

- CKM matrix connects mass and weak quark eigenstates
- Expand CKM matrix in $\lambda = \sin(\theta_{Cabibbo}) \approx 0.23$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

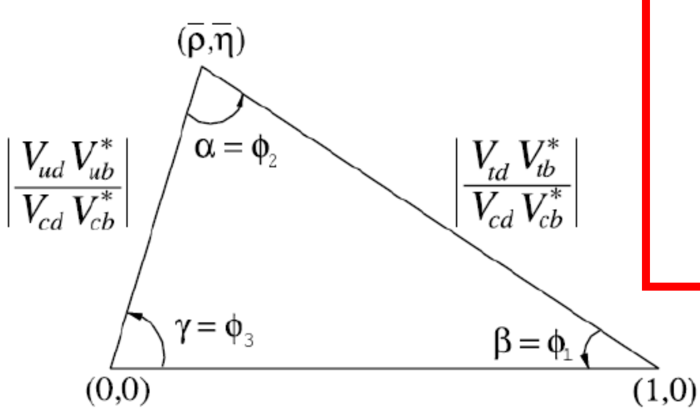
- To conserve probability CKM matrix must be unitary
  → Unitary relations can be represented as "unitarity triangles"

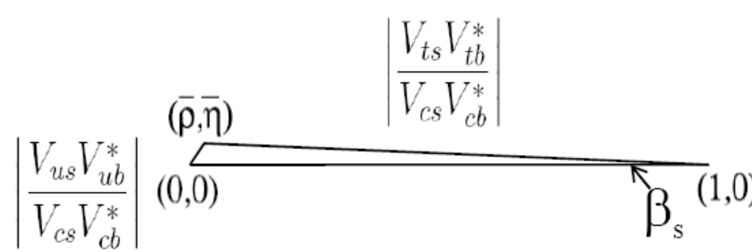
unitarity relations:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

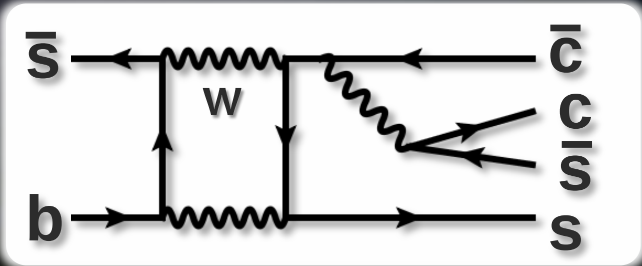
unitarity triangles:

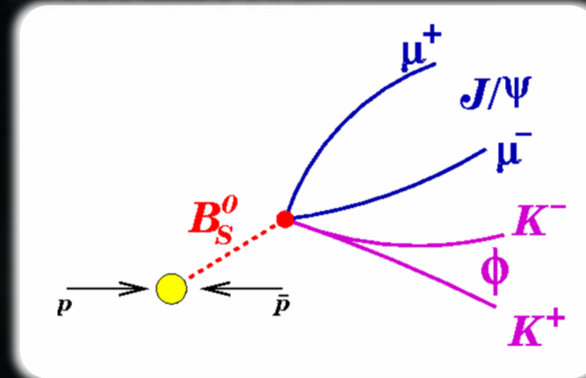




very small CPV phase β_s of order λ^2 accessible in B_s decays

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





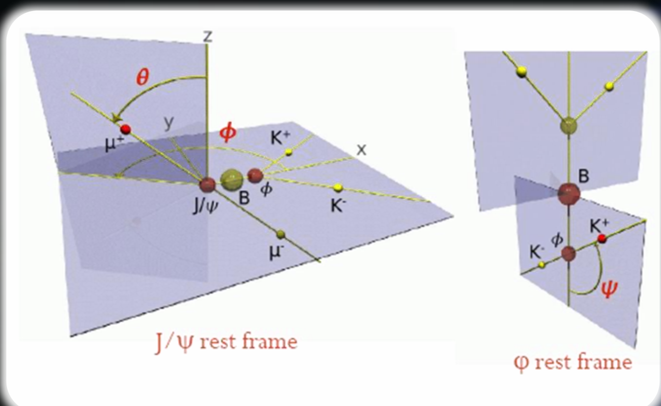
- Golden channel to measure B_s CPV
- Can measure lifetime, $\Delta\Gamma$, and β_s

-Decay of B_s (spin 0) to J/Ψ(spin 1) Φ(spin 1) leads to

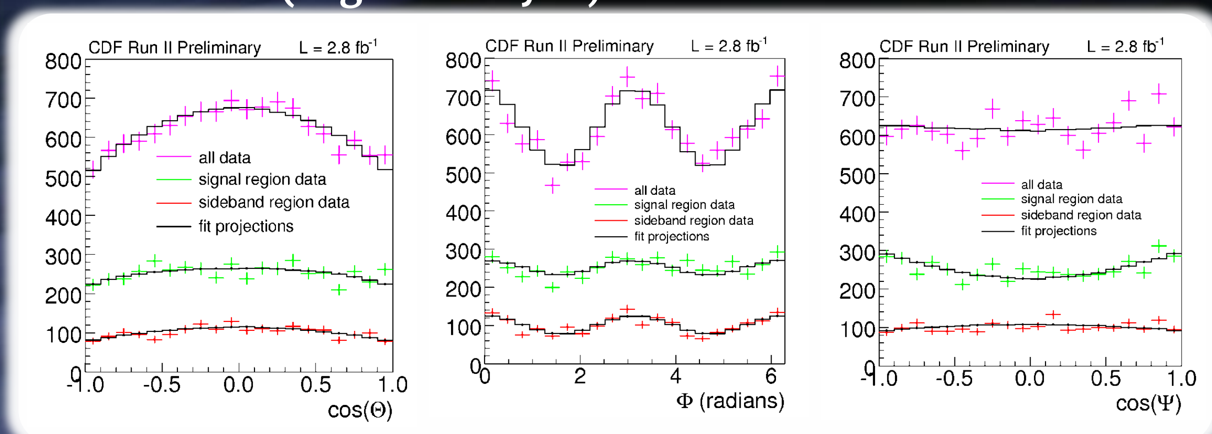
-→three different angular momentum final states:

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)



$B_s \to J/\psi\varphi$ Decay Rate

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

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

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

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

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

time dependence terms

angular dependence terms

terms with β_s dependence

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

'strong' phases:

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

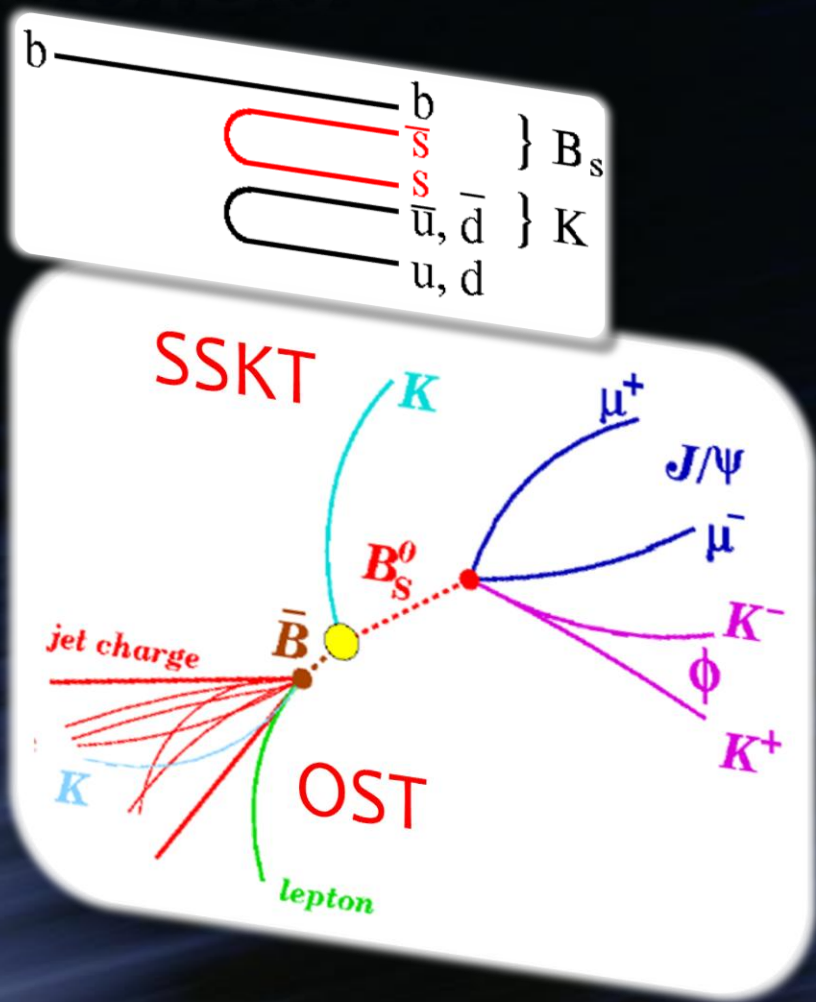
- Identification of B flavor at production (flavor tagging) → better sensitivity to β_s

Flavor tagging

- Crucial technique for both BB mixing and CP analysis
- There are two different tagging:
  - Same side kaon tagging (SSKT)
    - Identify kaon from Bs fragmentation

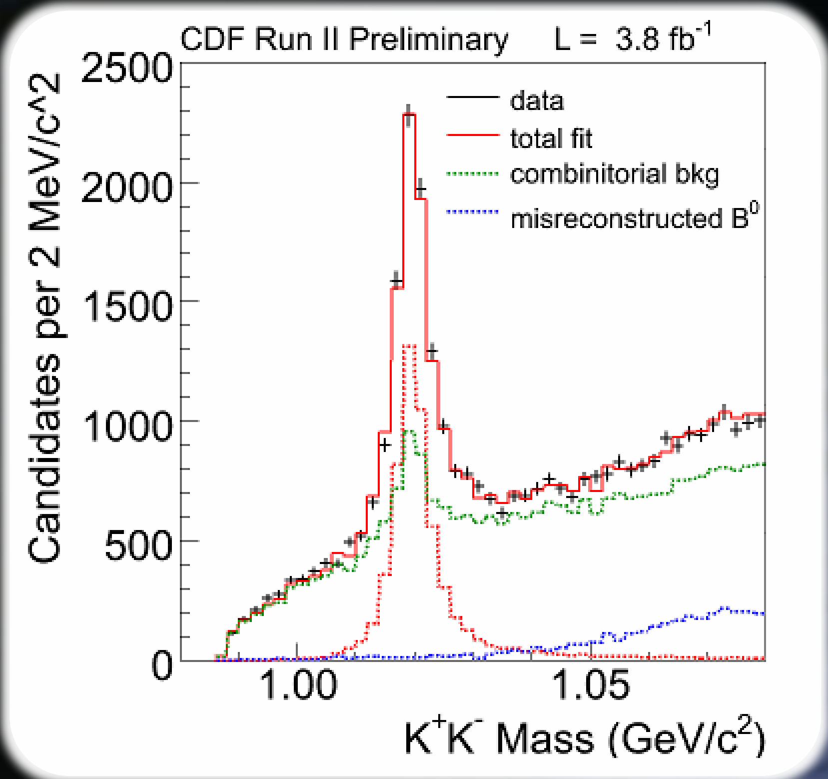
      εD^2=3.5-4.0%
  - Opposite side tagging (OST)
    - Identify lepton or jet-charge from opposite b hadron εD^2=1.5%

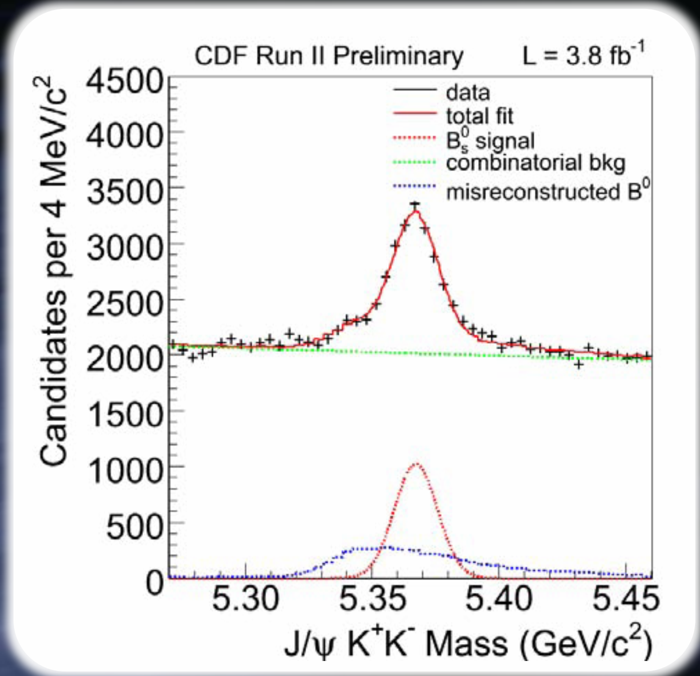
    (only works for bb pair-production)
- Powerful methods which are sophisticated for hadron collider



εD^2: product of tagging efficiency and dilution factor due to wrong tag

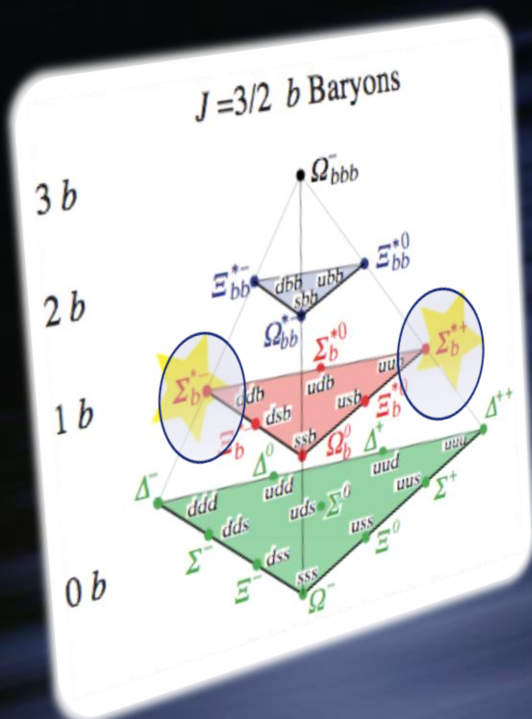
$B_s \rightarrow J/\psi KK$

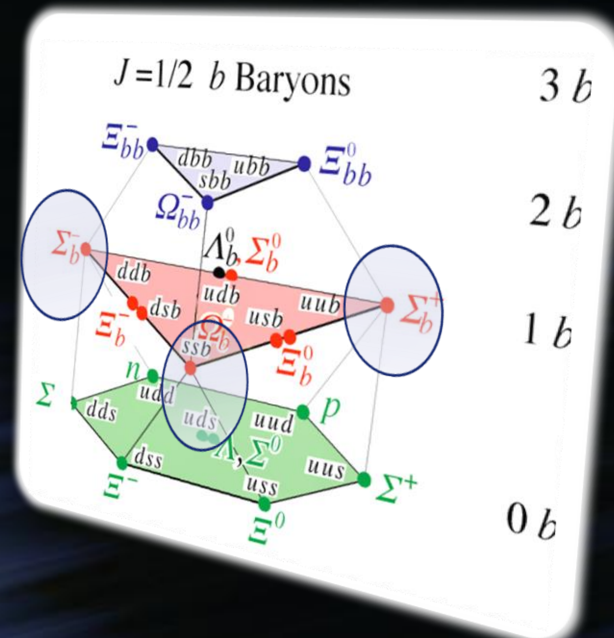




Bottom baryons

- 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^-





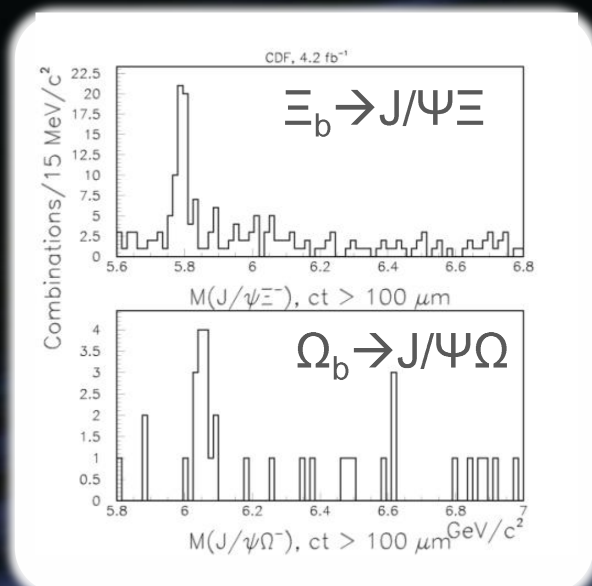
$\Omega_b \rightarrow J/\Psi\Omega$, $\Xi_b \rightarrow J/\Psi\Xi$

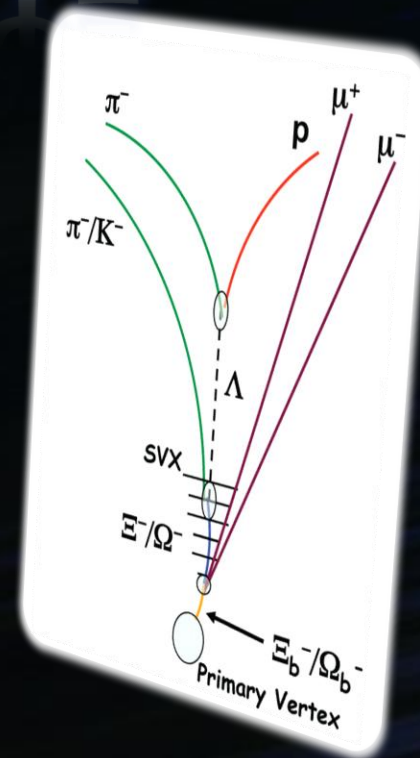
- DØ observes 18Ω_b (15Ξ_b) signals@1.3fb^{-1}
  - Mass: 6165±10±13 (5774±11±15) MeV/c^2

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!

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

- Charm resonant decay channel
  - CDF observed resonant semileptonic decay channel: $\Delta_b \to X_c(\pi)\mu\nu$
- First observation of $\Delta_b \to \Delta_c^+\pi^-\pi^+\pi^-$

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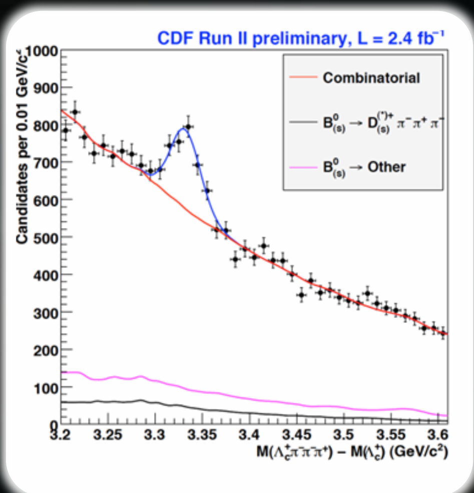

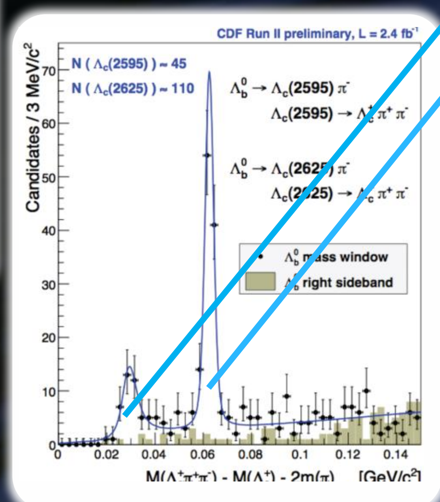

Λ_b^0 Decay Mode	Yield
$\Lambda_b^0 \to \Lambda_c(2595)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	46.6±9.7
$\Lambda_b^0 \to \Lambda_c(2625)^+\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	114±13
$\Lambda_b^0 \to \Sigma_c(2455)^{++}\pi^-\pi^- \to \Lambda_c^+\pi^-\pi^+\pi^-$	81±15
$\Lambda_b^0 \to \Sigma_c(2455)^0\pi^+\pi^-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

848 signals@2.4fb⁻¹

Relative BR

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2595)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (2.5\pm0.6(stat)\pm0.5(syst))\cdot10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2625)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (6.2\pm1.0(stat)\pm1.2(syst))\cdot10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Sigma_c(2455)^{++}\pi^-\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (5.2\pm1.1(stat)\pm0.9(syst))\cdot10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Sigma_c(2455)^0\pi^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (8.9\pm2.1(stat)+1.5-1.0(syst))\cdot10^{-2}$$