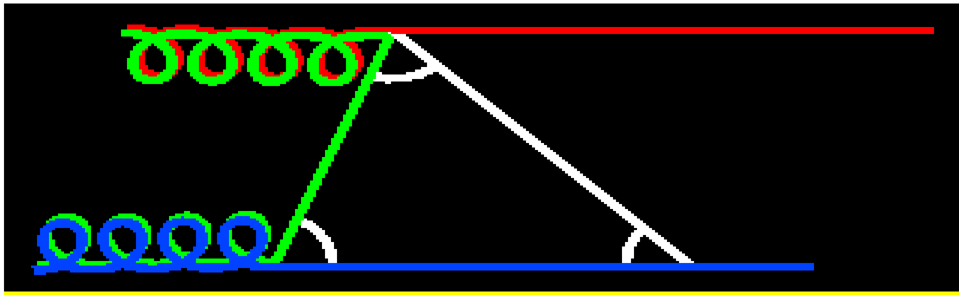
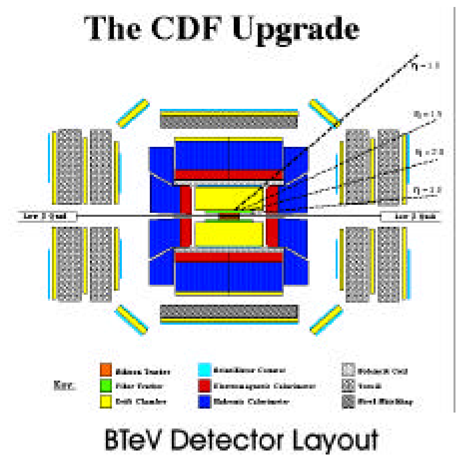
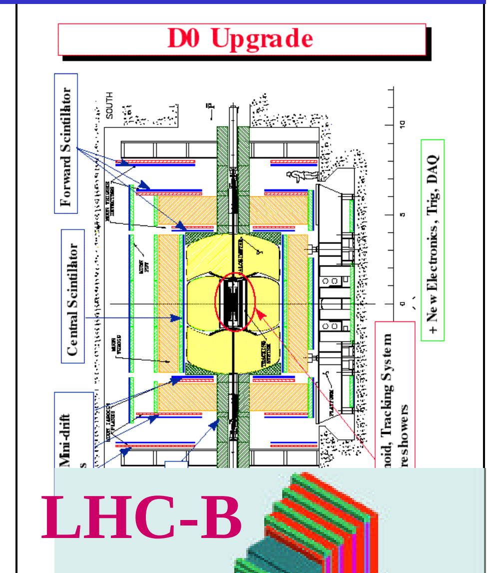
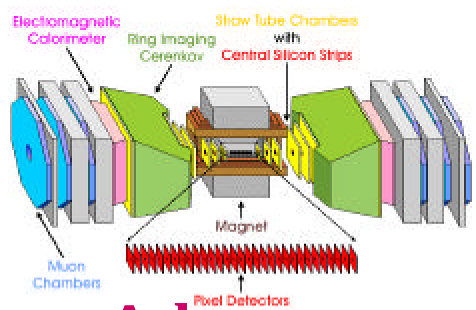


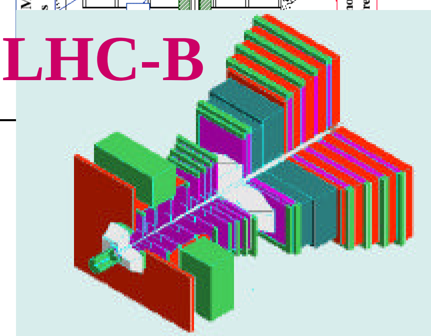
CP Violation at Hadron Colliders

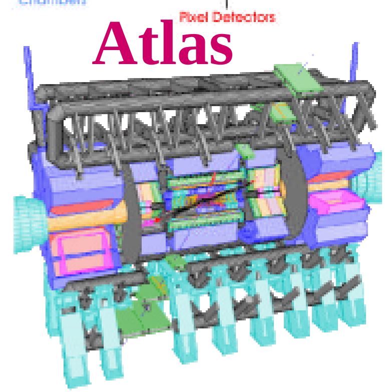
- **Introduction**
  - **CP violation**
  - **hadron colliders importance and reach**
- **Focus on key measurements:** B_s mixing, $\sin 2\beta$, $B_d \to \pi\pi$, $B_s \to KK$, $B_s \to D_s K$, $B_s \to \psi\phi$ and $B_s \to \psi\eta^{(')}$. Details in hep/ph-0201071 (FNAL) and hep/ph-0003238 (CERN)
- **Status of CDF and D0**
- **Future efforts: LHCb, BTeV, Atlas, CMS**

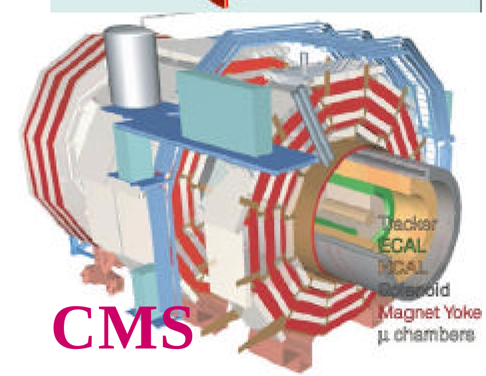












D. Bortoletto, Purdue University, Blois, June 16-22, 2002

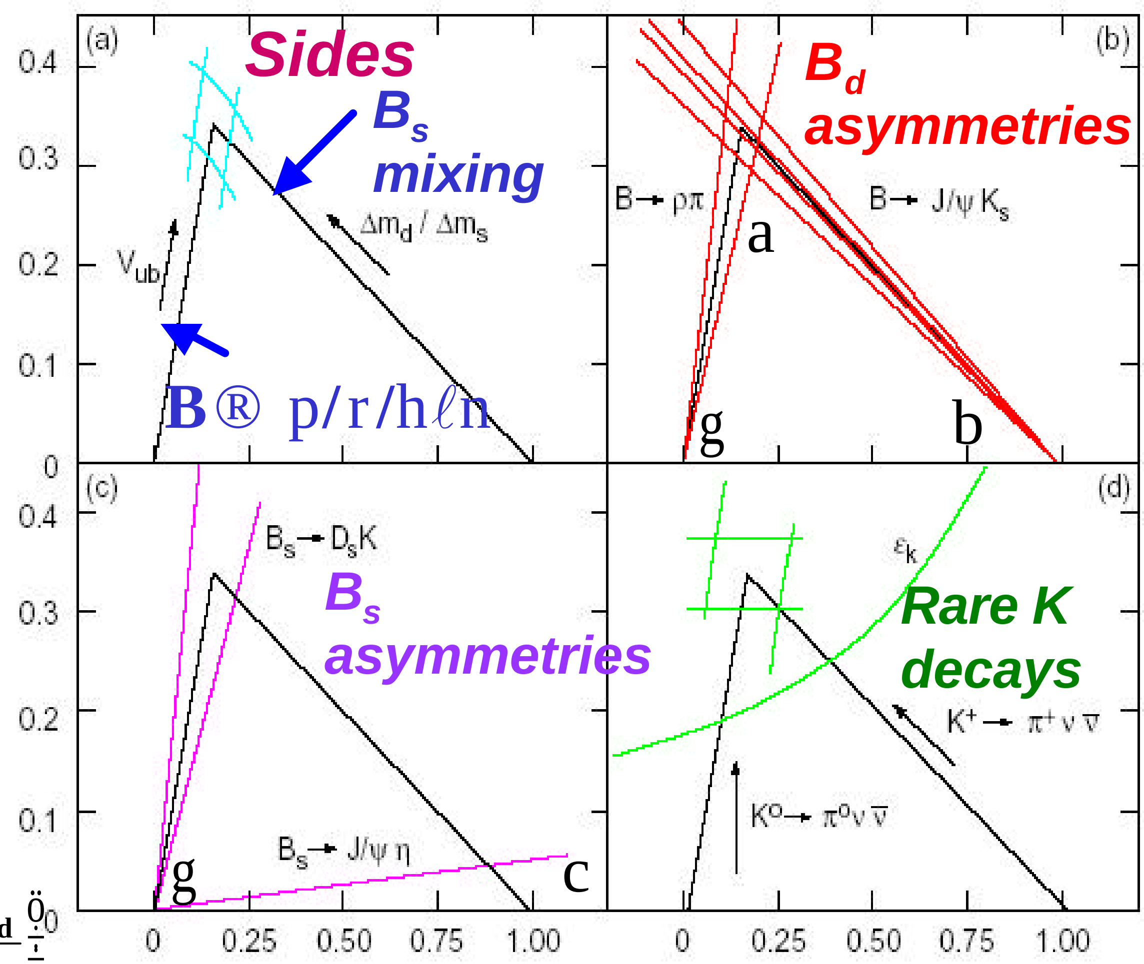
The importance of CP

- Investigation of CP violation:
  - Flavor puzzle. SM Model does not offer explanation of the structure of the CKM matrix
  - Supersymmetric flavor puzzle. Extensions of the SM need special flavor structure to achieve suppression of FCNC
  - New sources of CP violation. CP violation provides an excellent probe of NP
  - Baryon Asymmetry in the Universe. The observed CP asymmetry in the Universe in not accounted for by the CKM mechanism.
- Low energy measurements can provide insight about high mass scale physics

Checks of Unitarity

Unitarity:
$V_{ud}V^*_{ub}+V_{cd}V^*_{cb}+V_{td}V^*_{tb}=0$

- **To test CKM model of CP violation we must compare unitarity triangles determined from different CP observables**
- **B_s measurements can not be done at the B-factories**
- **Need high statistics**

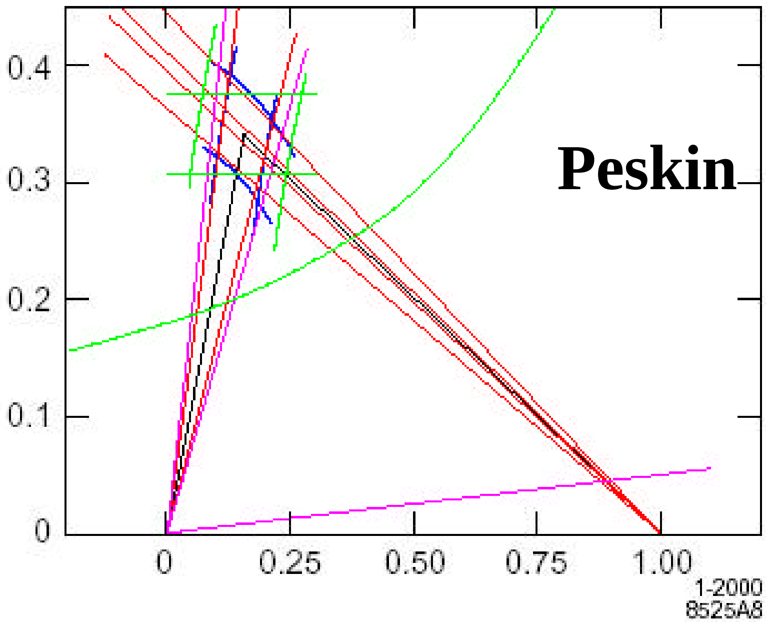


$$\beta = \arg\left(-\frac{V_{tb}V^*_{td}}{V_{cb}V^*_{cd}}\right) \qquad \gamma = \arg\left(-\frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}}\right)$$

$$\chi = \arg\left(-\frac{V^*_{cs}V_{cb}}{V^*_{ts}V_{tb}}\right) \qquad \chi' = \arg\left(-\frac{V^*_{ud}V_{us}}{V^*_{cd}V_{cs}}\right)$$

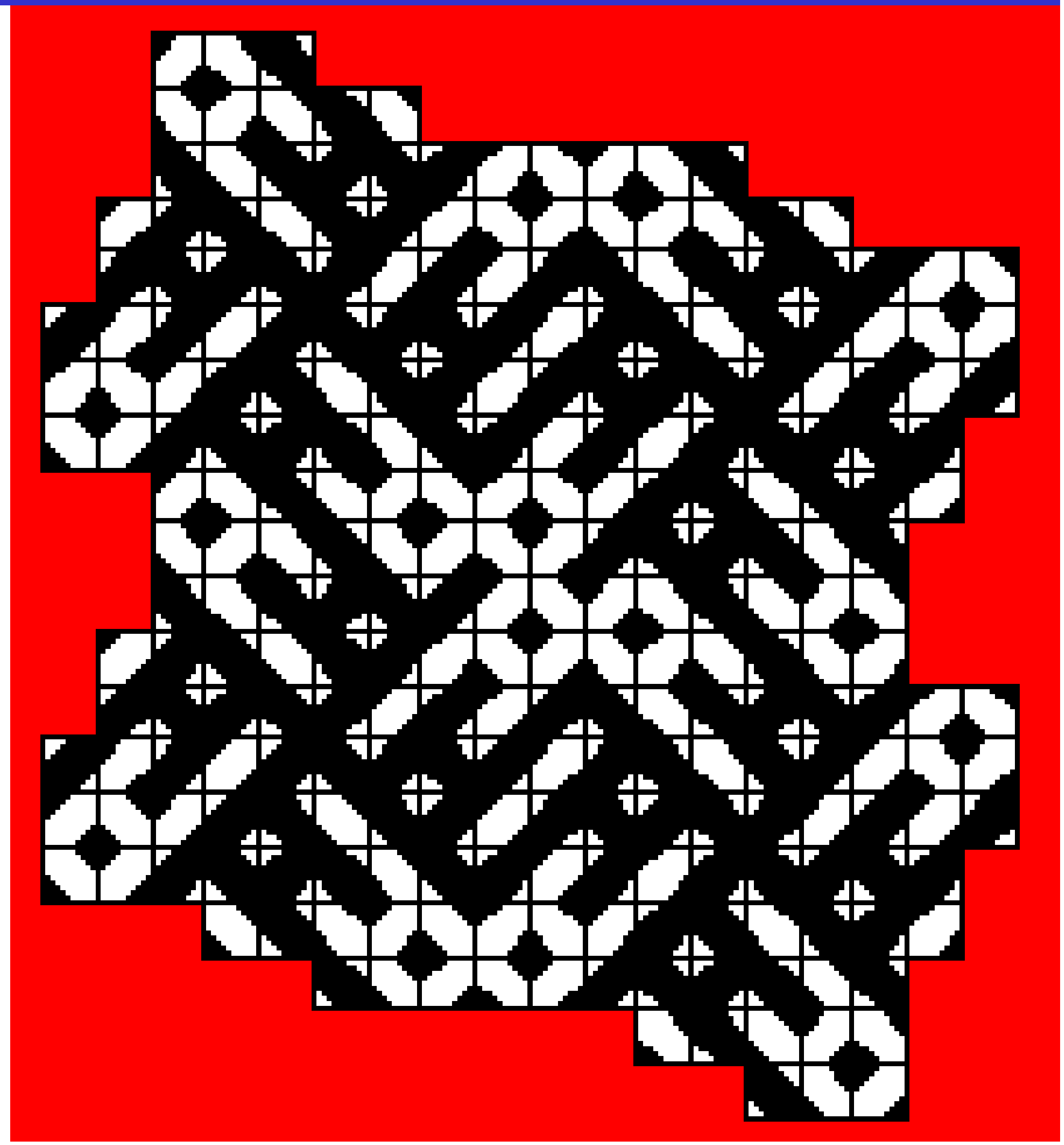
Unitarity :
$V^*_{ud}V_{td}+V^*_{us}V_{ts}+V^*_{ub}V_{tb}=0$
triangles equal $O(\lambda^3)$

CP : Complicated Puzzle



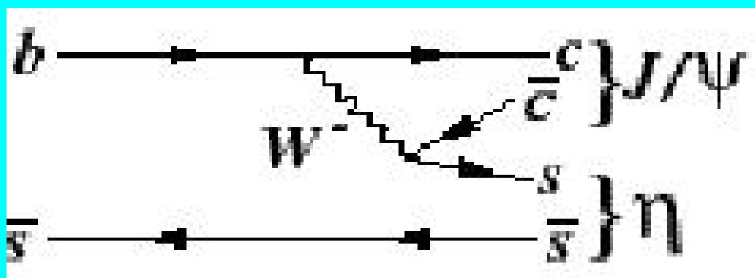
SM:side & angles measured in many processes should be consistent

Otherwise: new physics



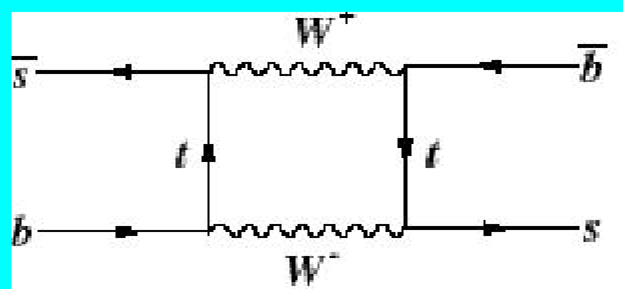
Tests of new Physics

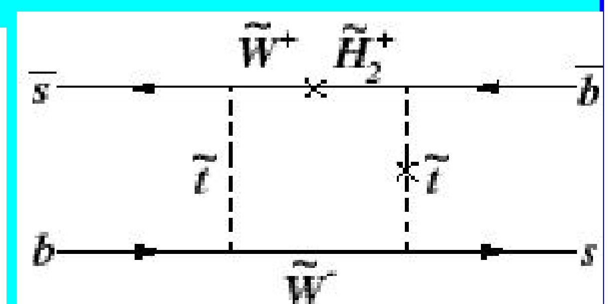
- **In SM we expect $\chi \approx 0.03$. Large asymmetries in $B_s \to \psi\phi$ and $B_s \to \psi\eta'$ $\Rightarrow$ New Physics (NP)**

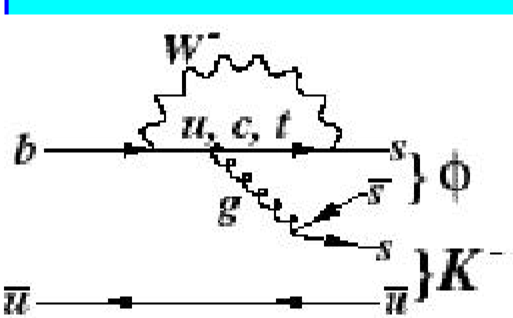


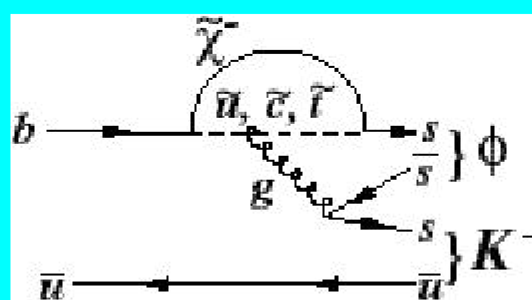
$$\chi = \arg\left(-\frac{V^*_{cs}V_{cb}}{V^*_{ts}V_{tb}}\right) = O(\lambda^2)$$

- **NP could lead to large effects in B_s mixing**





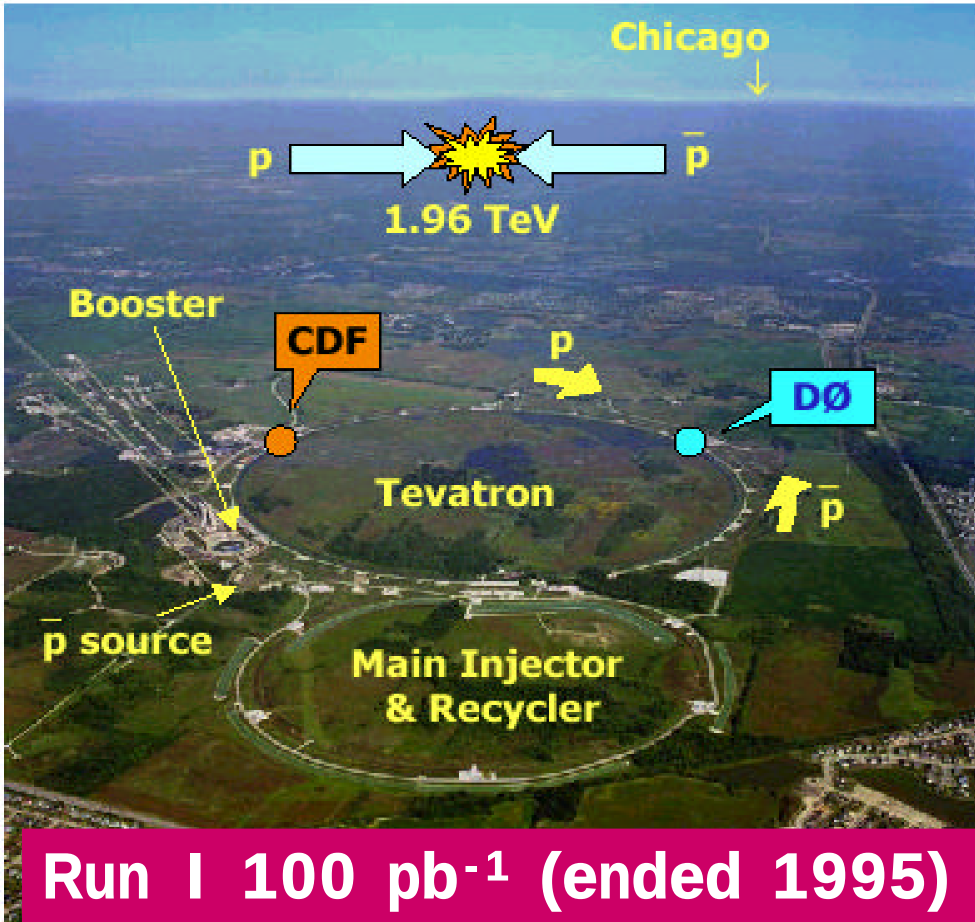




- **NP could also change BR and contribute to direct CP violation in $B^- \to \phi K^-$**

Asym=$(M_W/m_{squark})^2\sin(\phi_m)$, ~0 in SM

Hadron machines

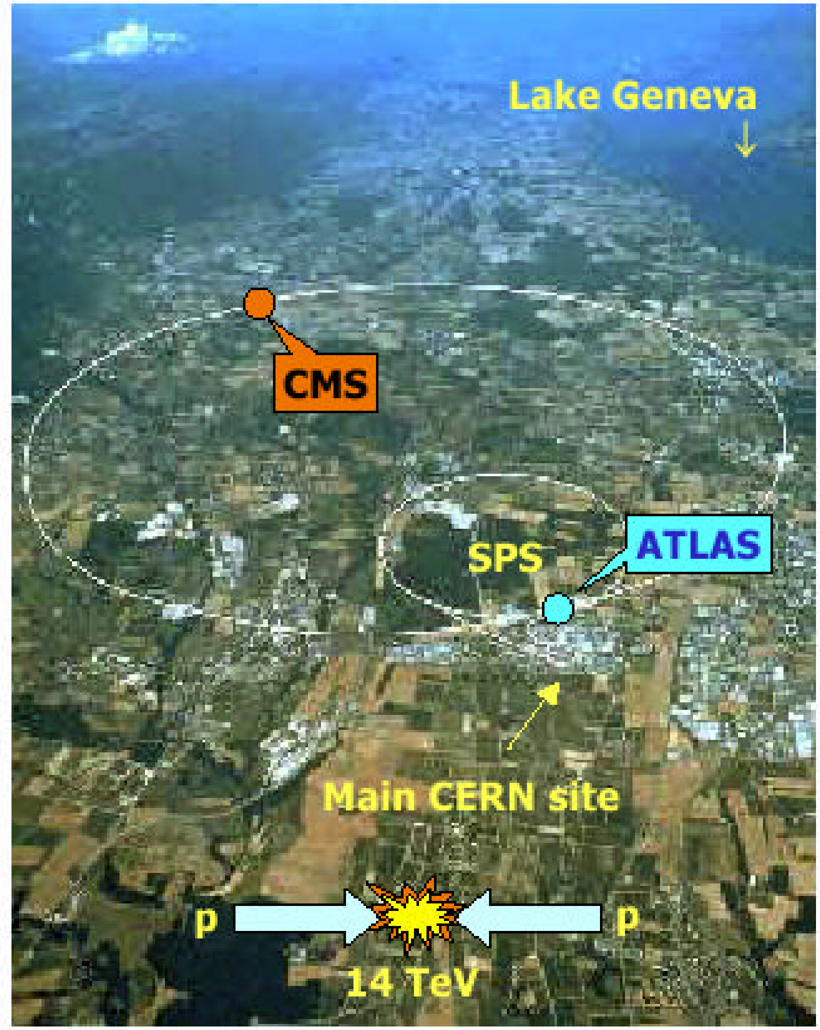


Run I 100 pb^{-1} (ended 1995)

Upgrade completed 2001

Run IIA 2 fb^{-1}

Run IIB 13 fb^{-1}



Operation 2007

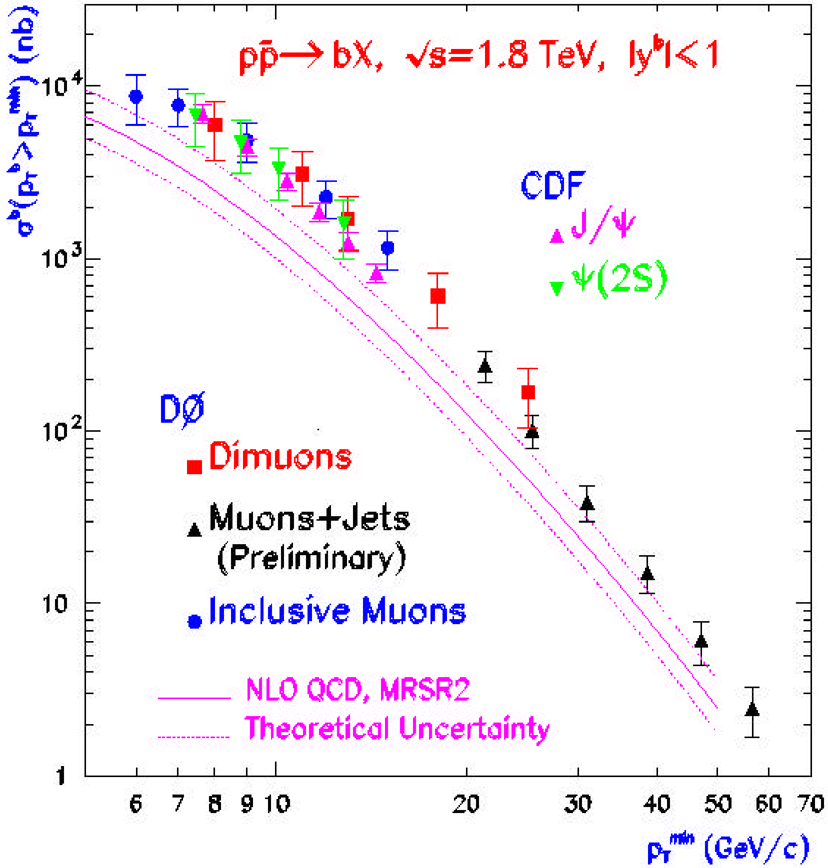
Hadron Machines

- **Large cross section:**
  s $_{\overline{bb}}$ » **100 (Tevatron)-400(LHC)** mb **for** Ös=**2.0-14** Þ » **10^{11}-10^{12} bb/year.**
- **Large QCD background:**
  s $_{bb}$/ s $_{inelastic}$ »**(0.2-0.4)% for** Ös=**2.0-14 TeV**
  - **Trigger to cut background**
- **B$_u$(40%), B$_d$(40%), B$_s$(10%), B$_c$ and** L$_b$ **are produced (at ¡(4S) only B$_u$ and B$_d$)**
- **The proper decay time**

$$t = \frac{Lm}{pc} = \frac{L}{bgc} \quad \Rightarrow \quad s\,(t) \, » \, \frac{1}{bc}$$

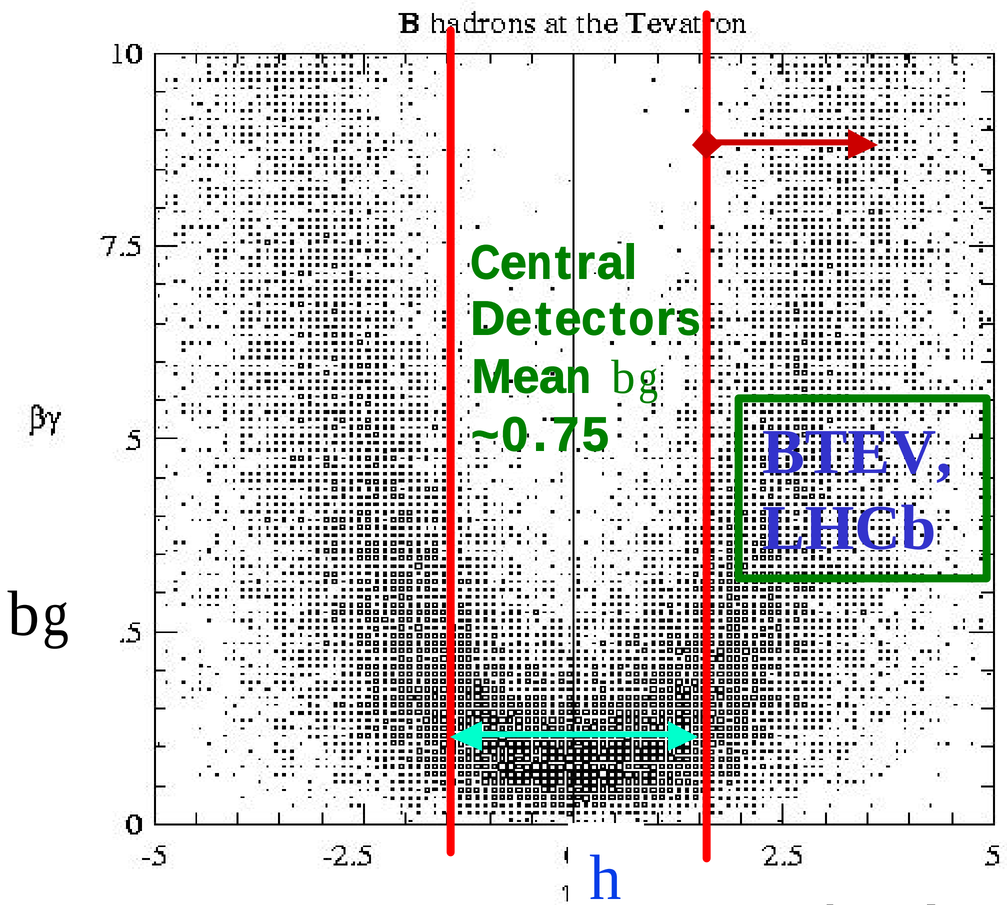
s**(t) ~900 fs at B factories, ~40-60 fs at LHC-Tevatron**

- s **(e$^+$e$^-$ ® $\overline{\text{BB}}$)»1nb@ ¡(4S)**
- s **(e$^+$e$^-$ ® $\overline{\text{bb}}$)»7nb @Z^0**

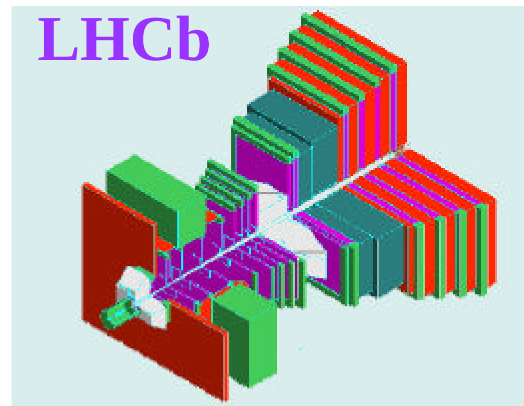


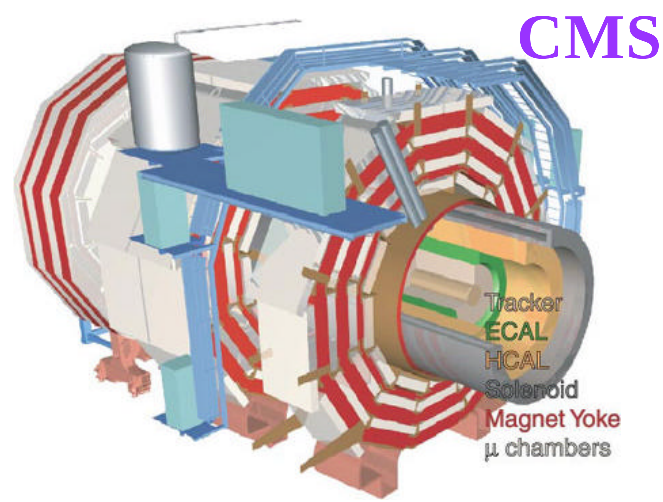
Hadronic experiments

- **Dedicated (forward »1.5<h<4.5: LHCb, BTeV) versus General (central |h|<»2.5: CDF, D0, CMS, ATLAS)**
- **Higher momentum B are at large h**



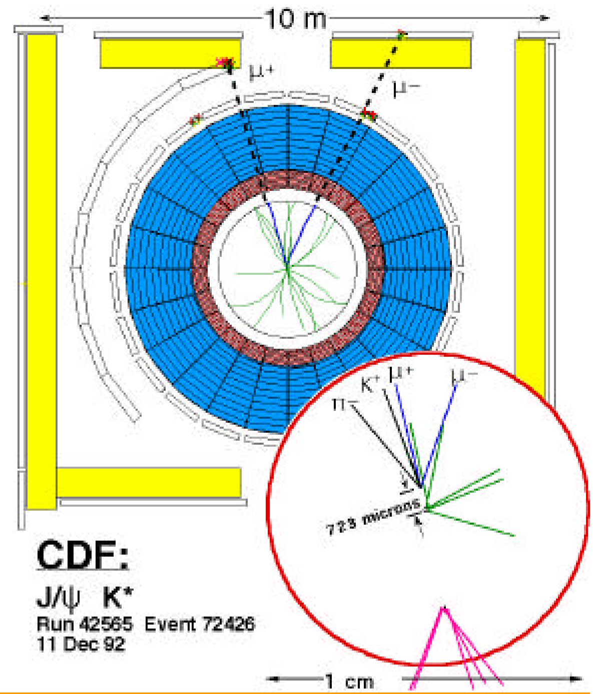
$h = -\ln\tan\left(\frac{q}{2}\right)$





Triggers

- High momentum leptons:
  B® y X and B® Xℓn
- Displaced vertices



	BTeV	CDF LHCb	Atlas,CMS CDF, LHCb	Atlas,CMS CDF, D0, LHCb
L1	Sec. Vertex	High Pt tracks	single leptons	di-leptons

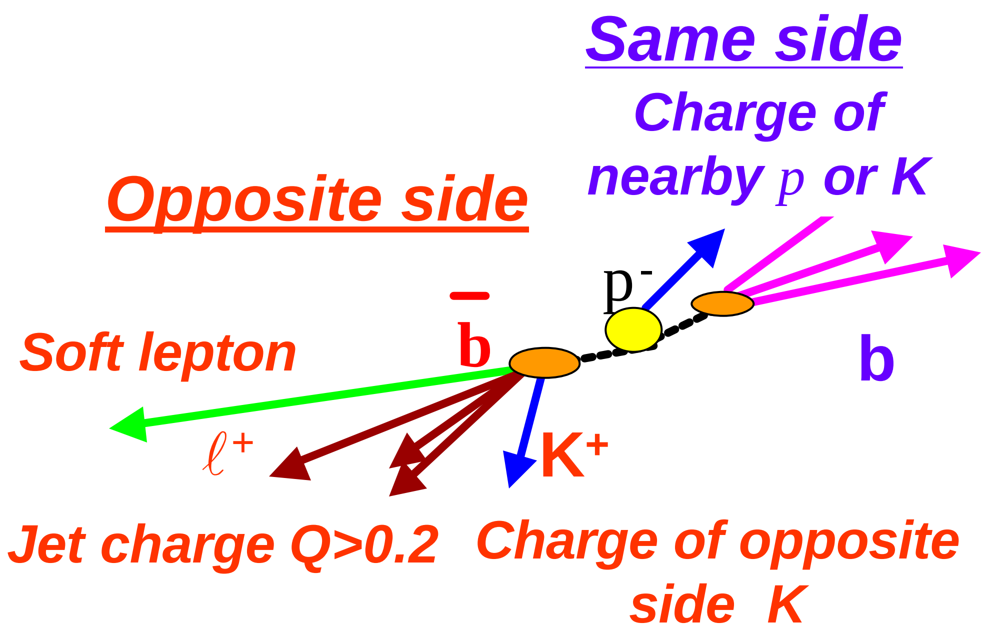
- CDF and LHCb have secondary vertex trigger at L2
- CMS and Atlas actively investigating the possibility of developing a L2 secondary vertex trigger.

Physics Requirements

- **Mixing and CP violation:**
  - **Reconstruct signal** (B ® y K_s, B_s ® D_sp etc)
    - Optimize signal/background
  - **Measure proper decay time**
    - lifetime resolution (crucial for B_s mixing)
  - **Tag B flavor at production**
    - figure of merit eD^2:
      e=efficiency=N^{tag}/N^{tot}
      D=dilution= N^R-N^W/N^R+N^W
    - Hadronic machines
      eD^2» 10%, B-factories
      eD^2»25-27%

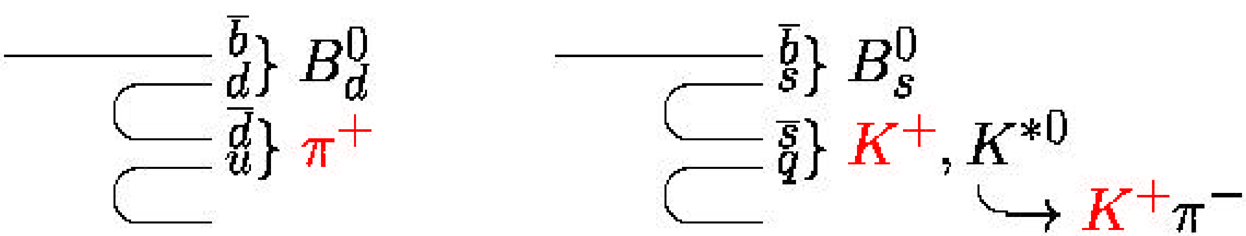
$$A(t) = \frac{N\left(\overline{B}^0(t) \circledR f_{CP}\right) - N\left(B^0(t) \circledR f_{CP}\right)}{N\left(\overline{B}^0(t) \circledR f_{CP}\right) + N\left(B^0(t) \circledR f_{CP}\right)} = D \sin 2b \sin(Dm \times t)$$

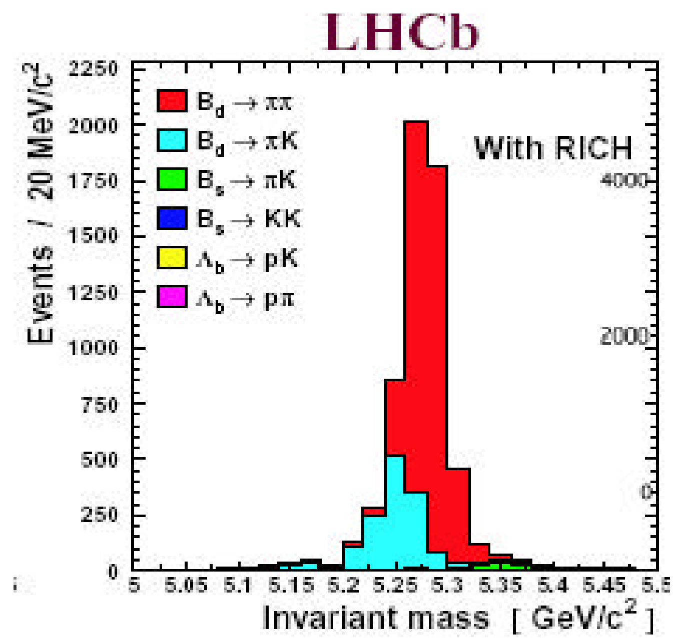
$$s(\sin 2b) » e^{x_d^2 G s_t} \sqrt{\frac{1+4x_d^2}{2x_d^2}} \frac{1}{\sqrt{eD^2N}} \sqrt{1+\frac{B}{S}}$$

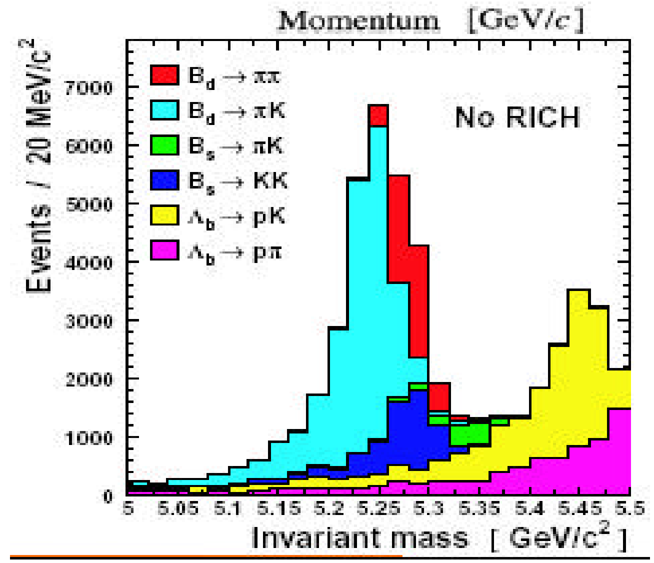


Particle Identification

- Important for many exclusive channel :
  - Distinguish B_s ® D_sK from B_s®D_sp
  - Or B®pp from B_s®KK
- Flavor tagging:
  - Opposite side tagging through:b®c ® s ®K^-
  - Same side tagging: Charge of nearest p and K tags the b flavor

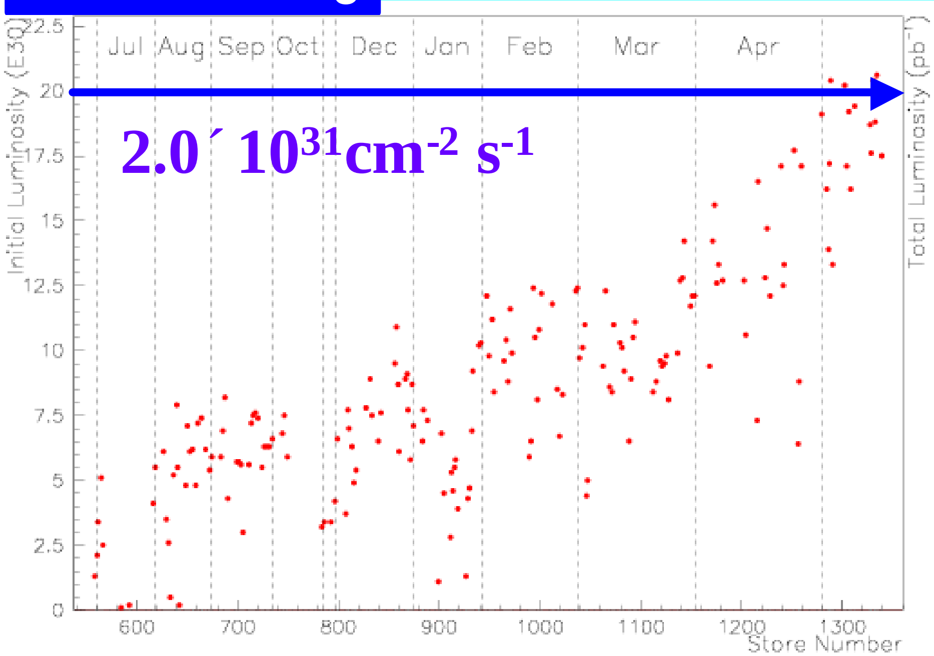


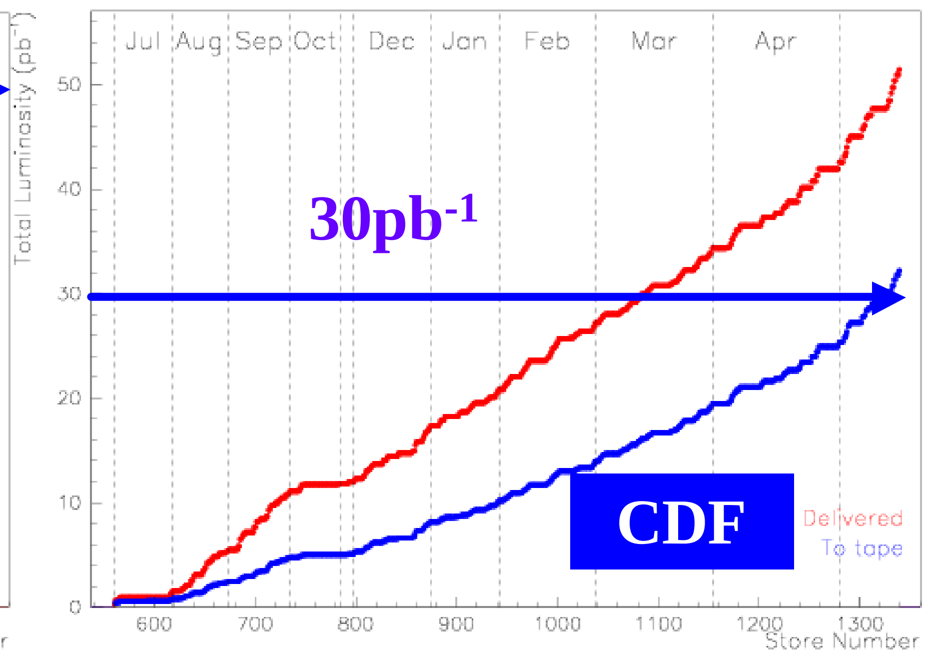




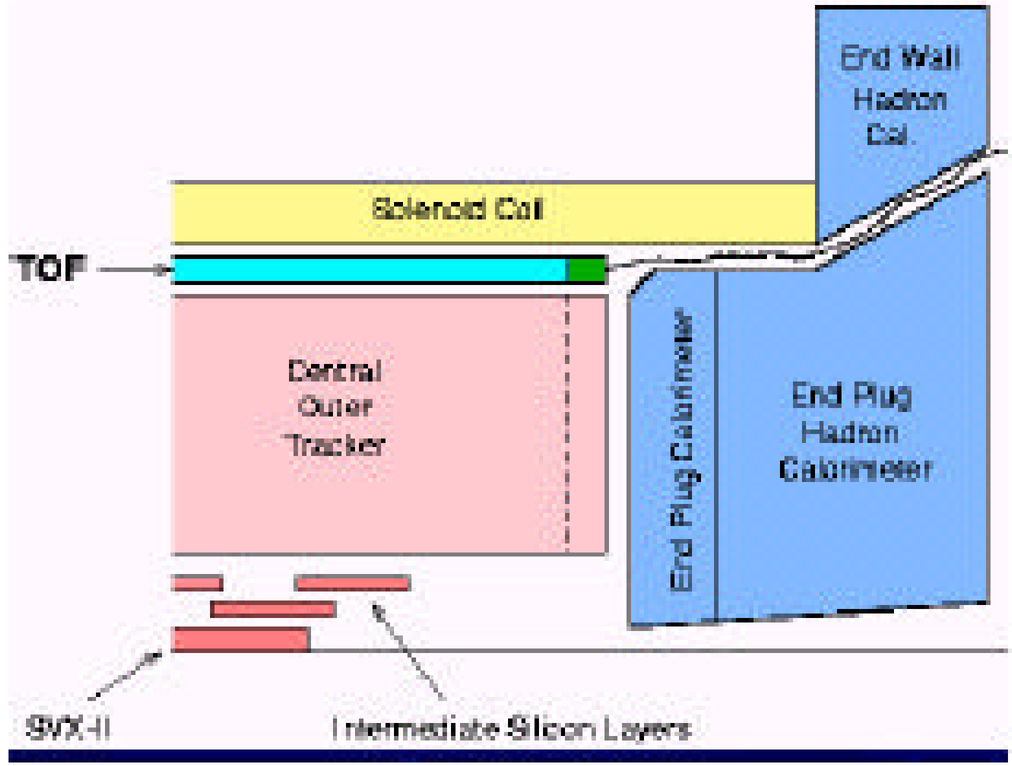
Tevatron parameters

	Run I	Run IIa	Run IIb
E_{beam}	900 GeV	980 GeV	980 GeV
L_{PEAK}	$1.6\times10^{31}cm^{-2}s^{-1}$	2×10^{32}	5×10^{32}
L_{Int}	118 pb^{-1}	2fb^{-1}	13fb^{-1}
$N_{bunches}$	6×6	36×36	140×103
Spacing	3500ns	396 ns	132 ns (Under study)
Int/crossing	2.8	5.8	4.9

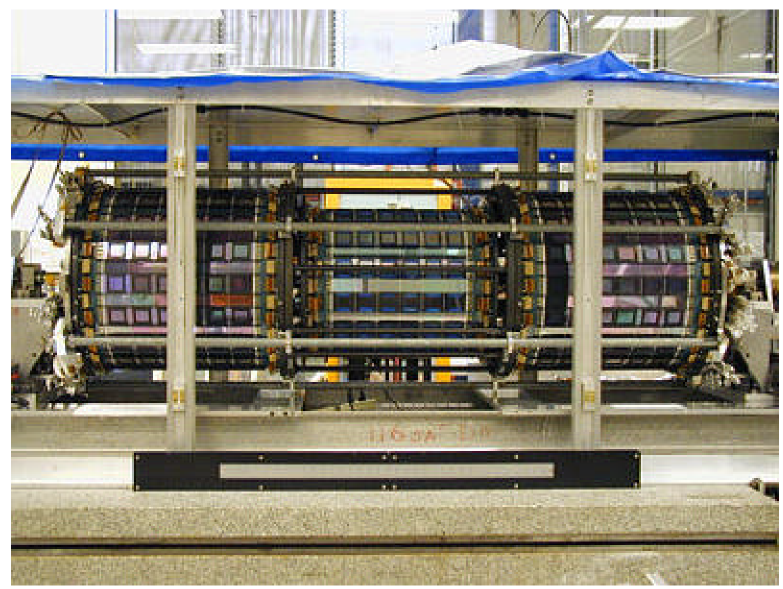




CDF II

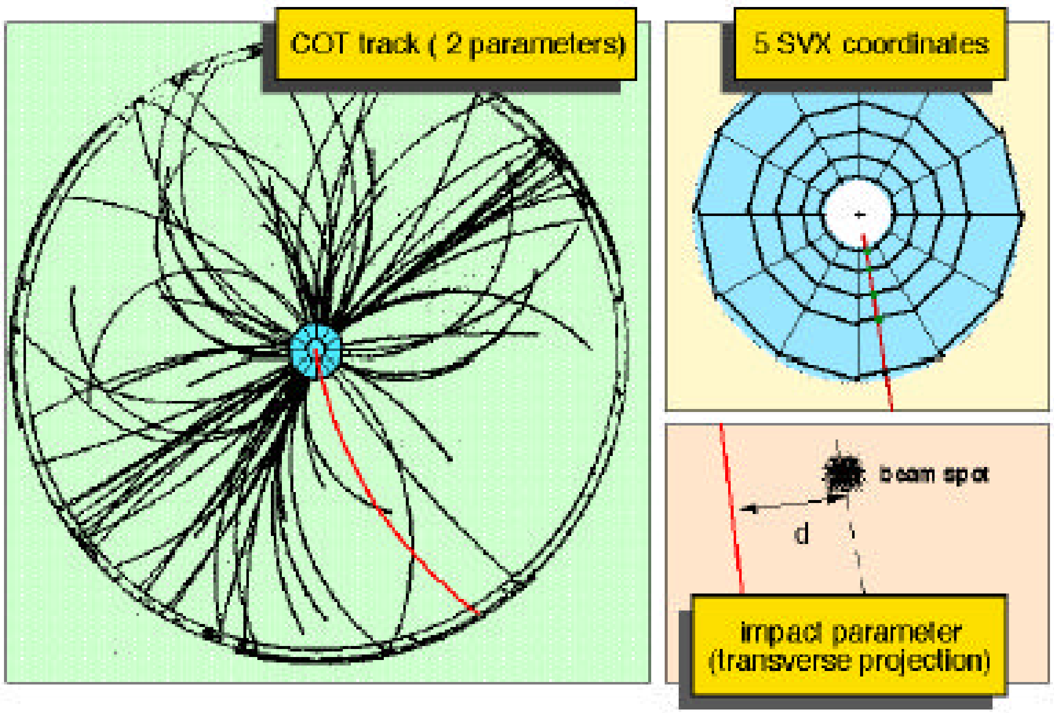


- From Run I:
  - Central calorimeter
  - Most of muon system
  - Solenoid
- New for Run II
  - Plug calorimeter
  - Time-of-Flight
  - Drift chamber
  - Silicon Microstrip Tracker with 3 D information: L00 + SVXII +ISL
  - Tracking to h of 2
- SVT: level two displaced track trigger



The SVT trigger

- Uses drift chamber tracks (f ,p_T) & 5 SVXII si layers
- 2-D reconstruction of tracks with p_T>2GeV/c with offline resolution
- Allows triggering at L2 on displaced impact parameter and vertices
  - **L2 track trigger: 100 mm <d<1 mm, 20^0<Df_0<125^0, d_B<140 mm, p_T☓X_v>0**



Required performance

s(d) »30 mm

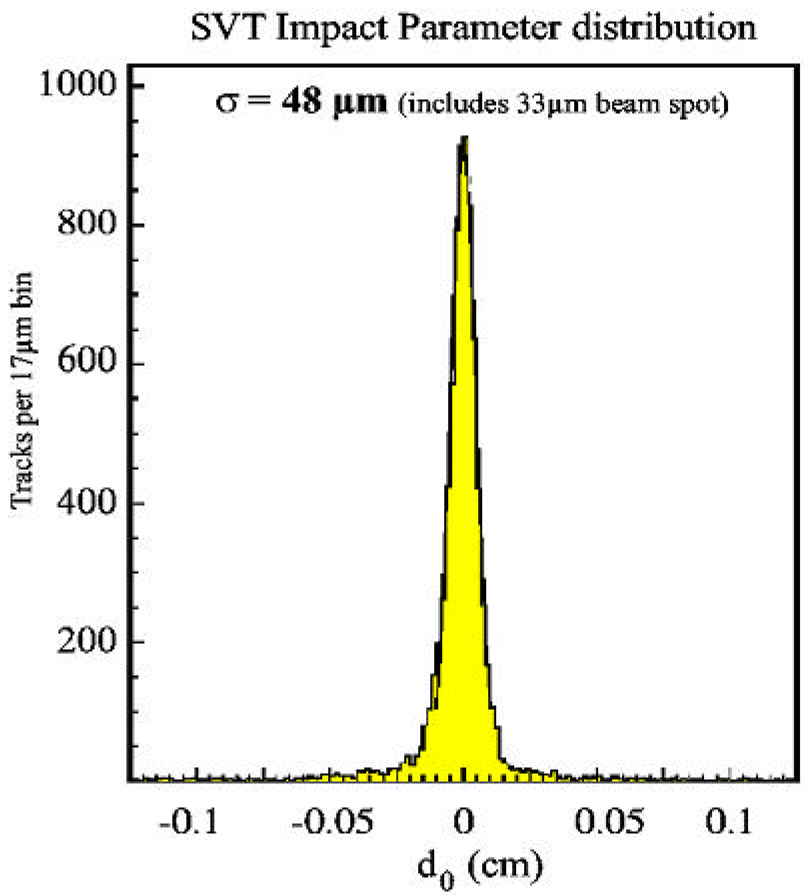
s(f) »1mR

s(P_T) »3%P_T

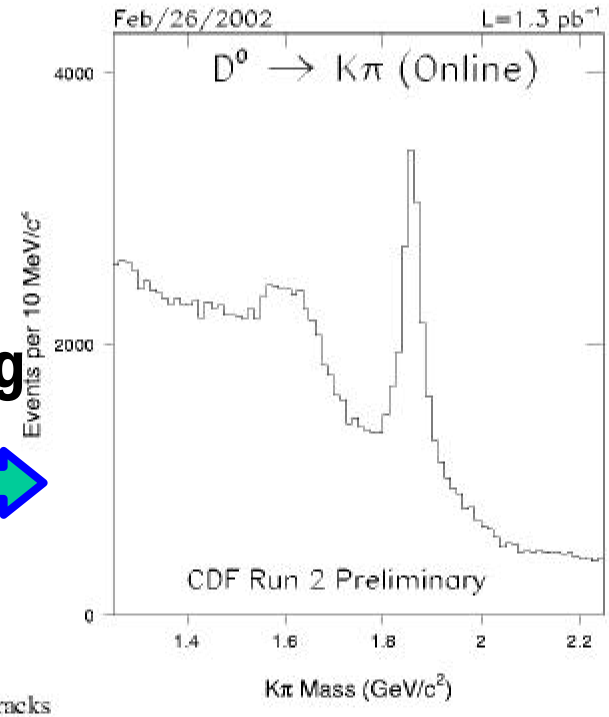
Time 10 ms

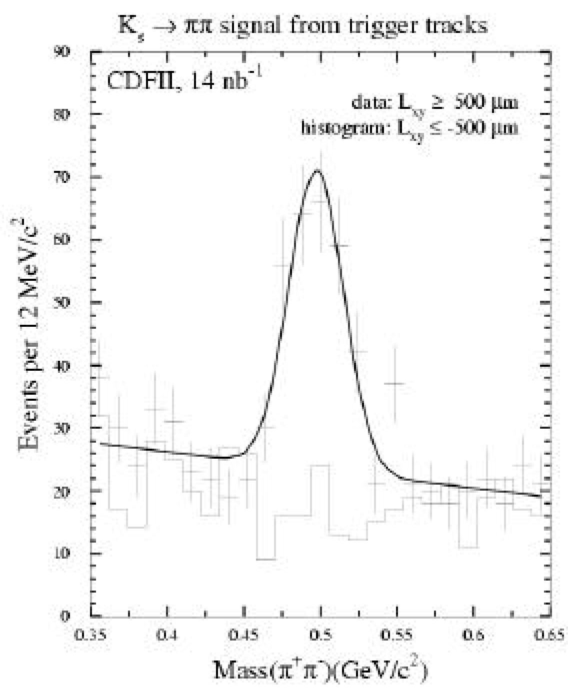
SVT Performance

- **Impact parameter resolution Þ performance is within specs**



- **D^0 signal is used for on-line monitoring of SVT trigger**

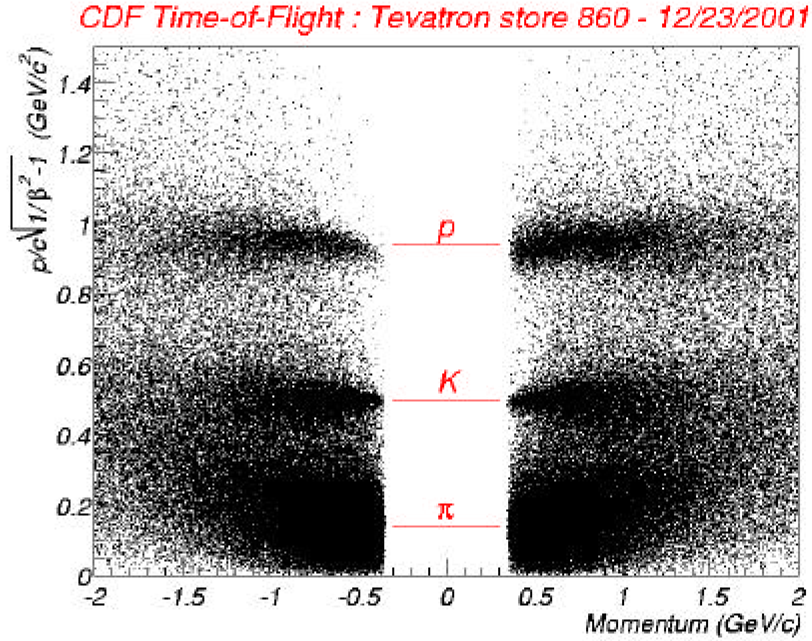


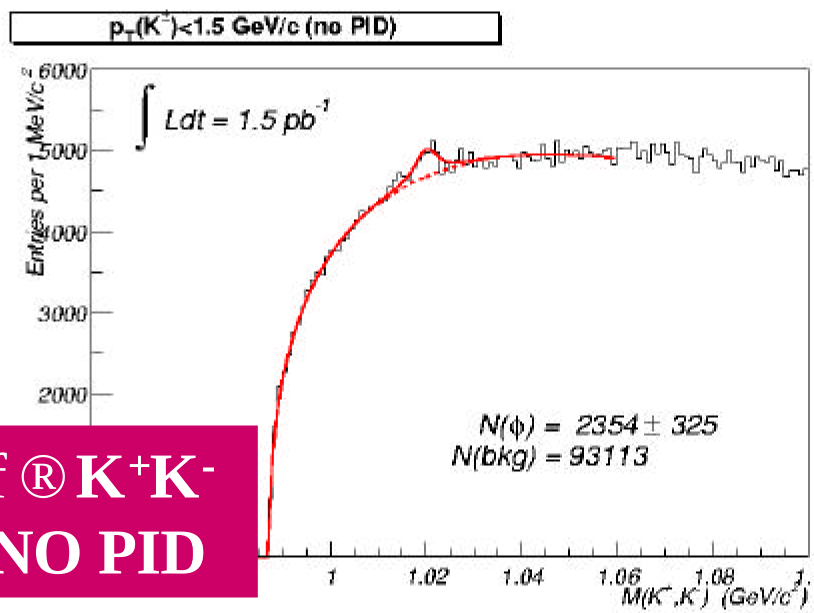


- **K_s with SVT trigger**

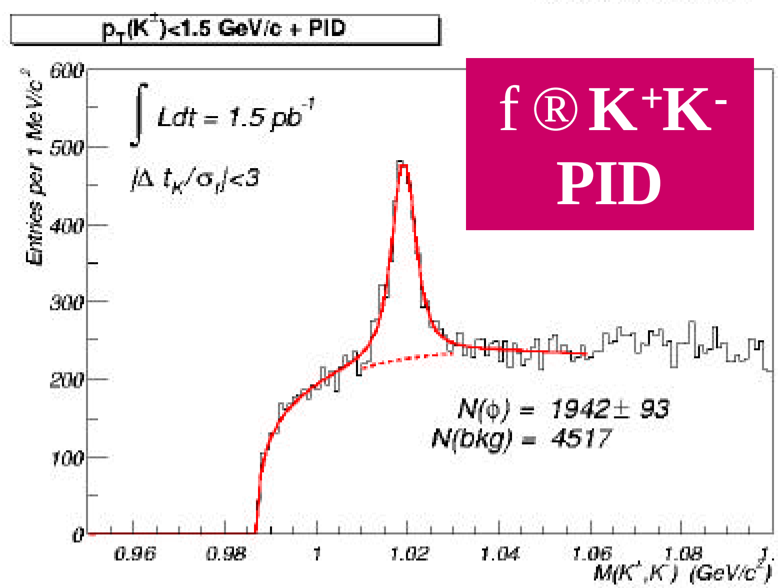
TOF Performance

- **Expected TOF resolution 100ps**
- **2σ separation of**
  - **K/π for p<1.6 GeV**
  - **p/K for p<2.7 GeV/c**
  - **π/p for p<3.2 GeV/c**





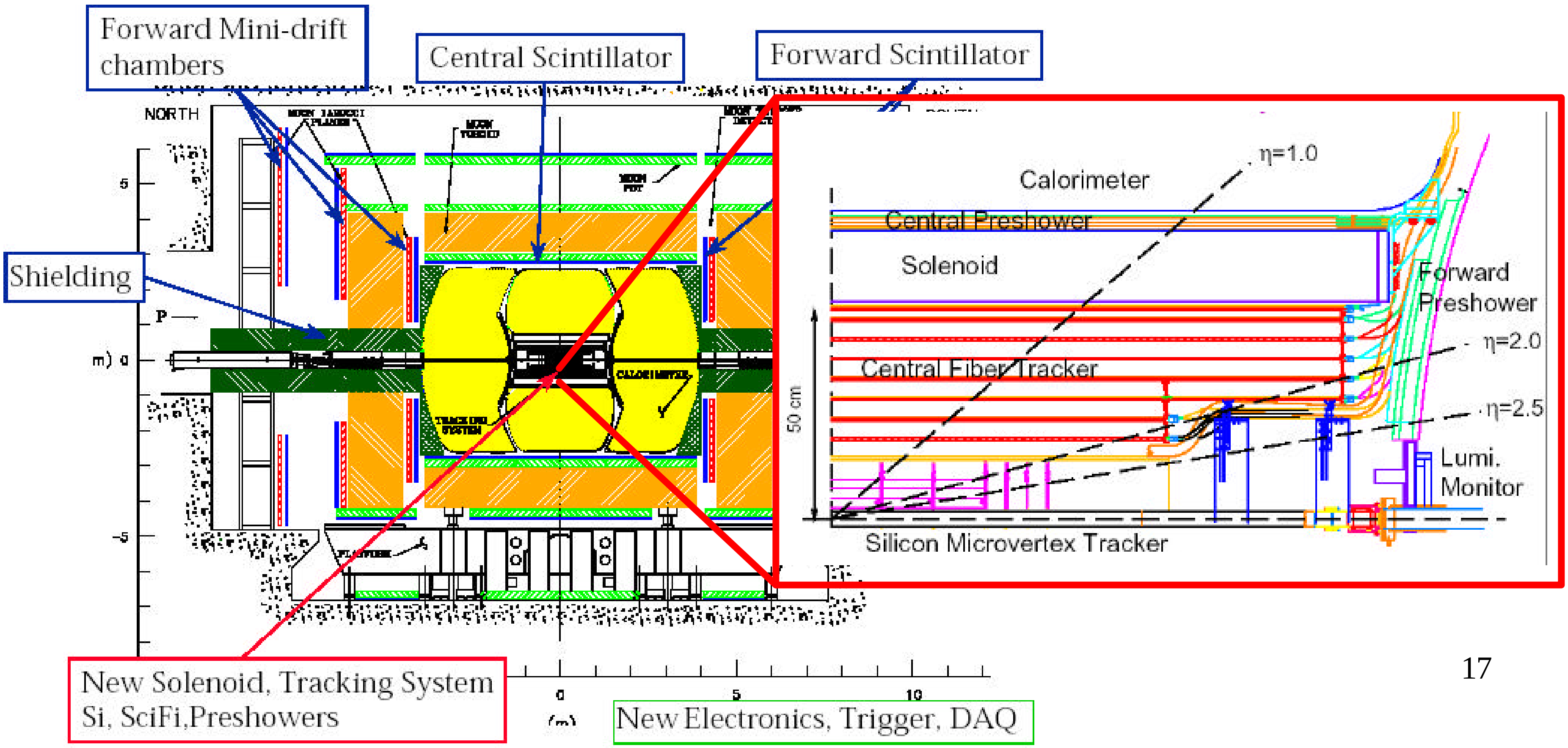
$\phi \rightarrow K^+K^-$
NO PID



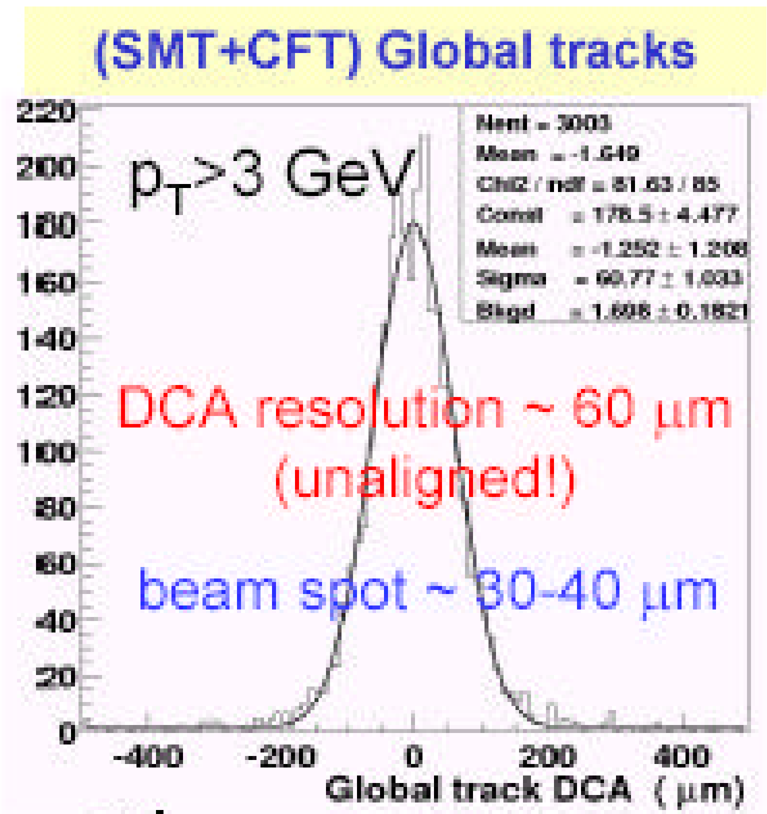
$\phi \rightarrow K^+K^-$
PID

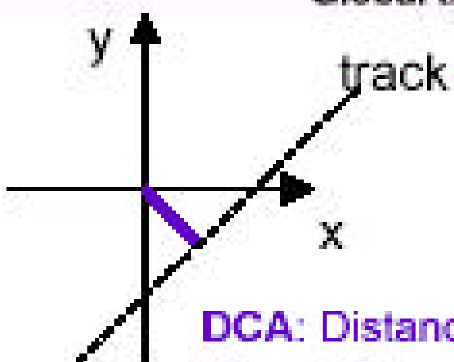
D0 UPGRADE

- **Excellent calorimetry**
- **Excellent lepton coverage**
- **Inner tracking (silicon + scintillating fibers + 2T solenoid) dp_T/p_T^2=0.002, $s^{secondary}$=40 mm (r-f), 80 mm (r-z),**
- **Pipelined level 3 trigger, impact parameter trigger at L2 starting end Summer 2002**



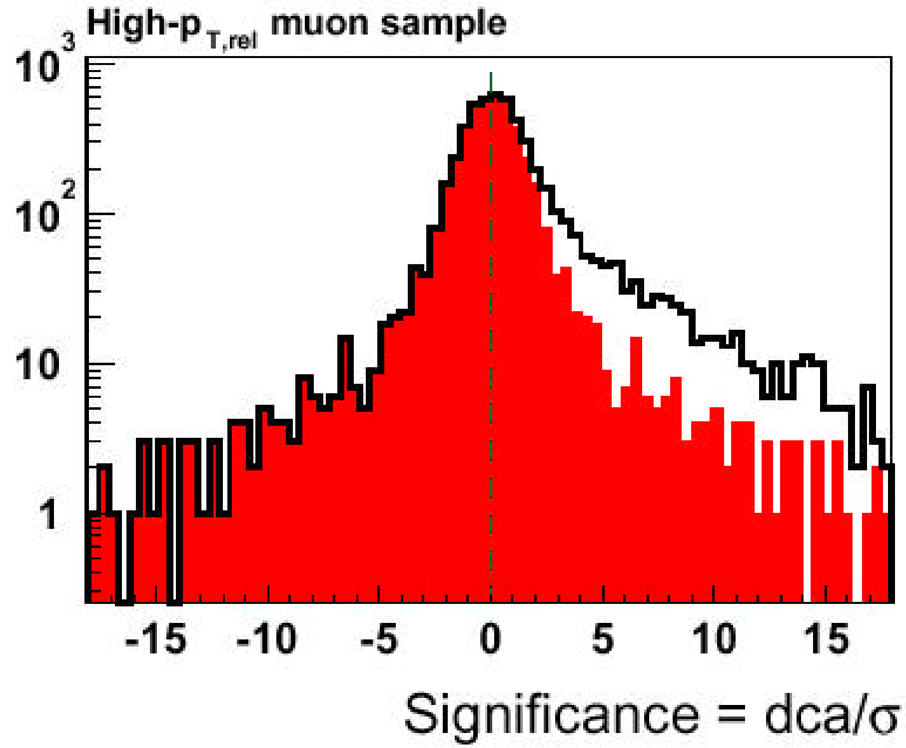
DO INNER TRACKING PERFORMANCE





DCA: Distance of Closest Approach

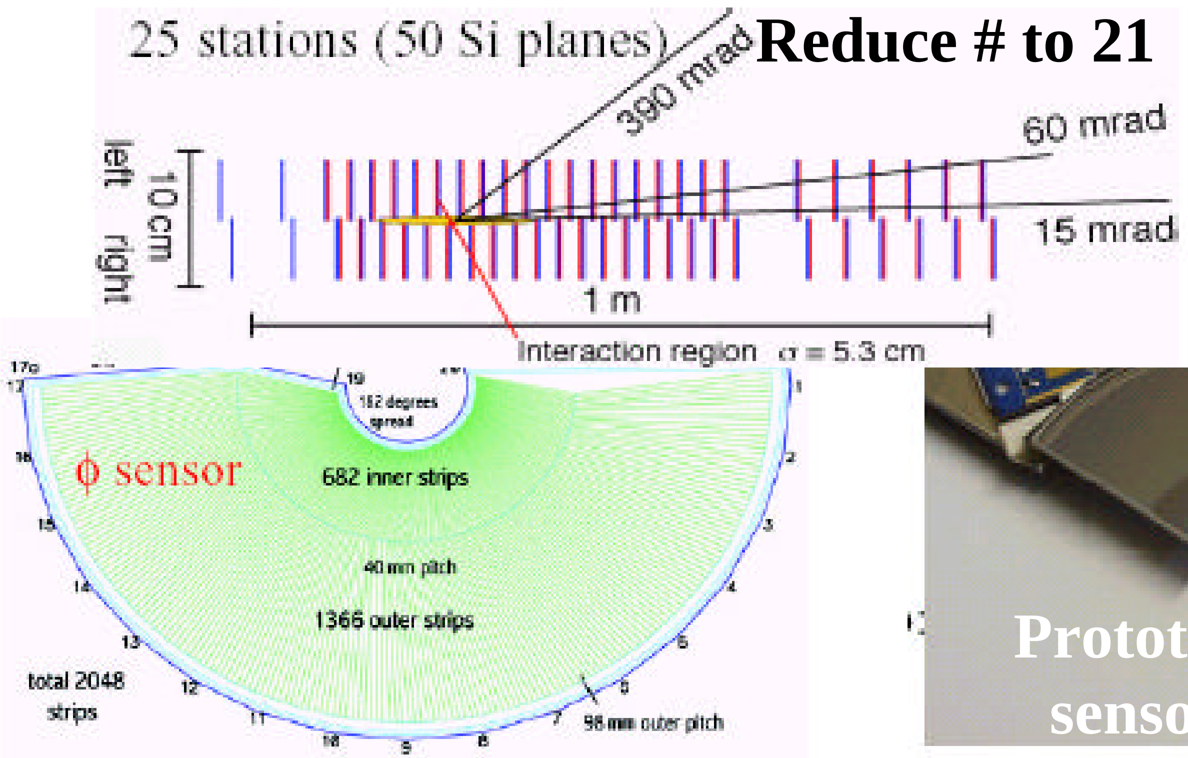
DØ Run 2 Preliminary



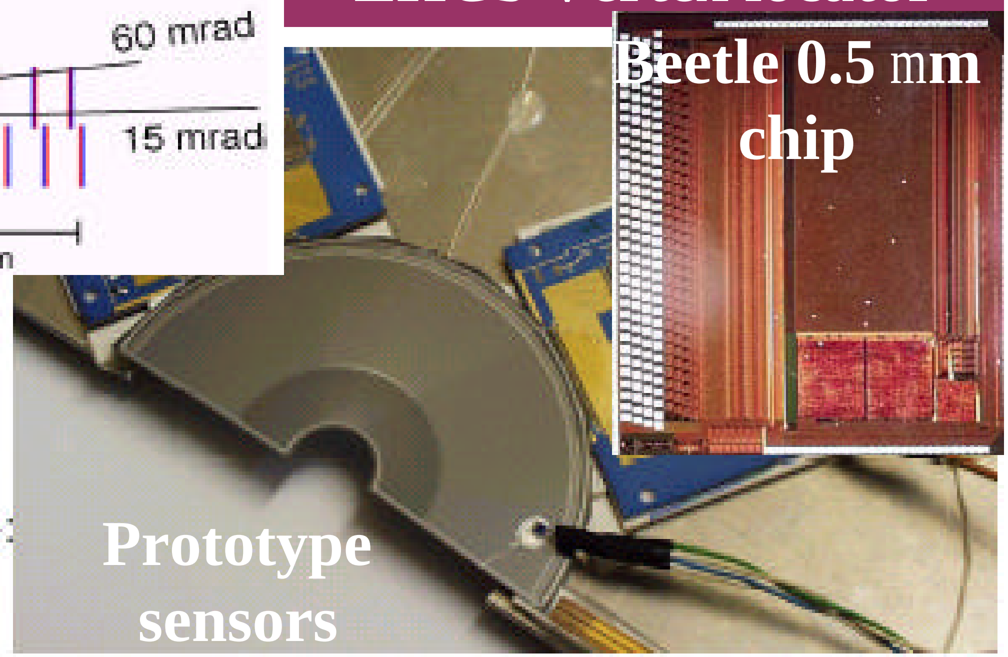
Enhanced B - content

LHCb

- **LHCb: proposed and approved in 1998, Designed for B-physics at 2×10^{32}**
  - **—Excellent PID with RICH**
  - **—Vertex detector inside the beam vacuum**
  - **—Recent optimization to reduce material budget ⇒ LHCb light TDR will be ready at the end of the year**



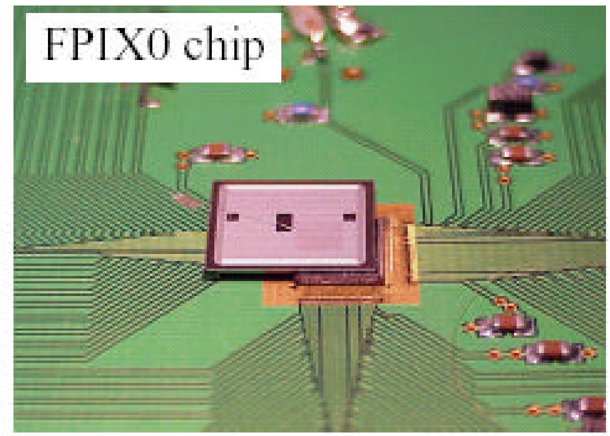
LHCb Vertex locator

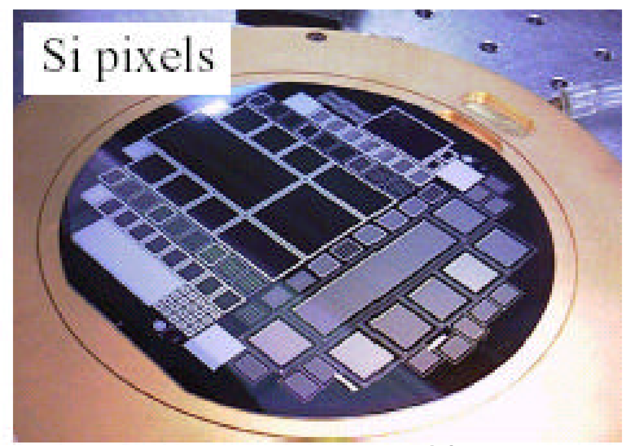


BTeV

- **BTeV proposed in 2000, approved at Stage 1, Temple review 9/2002. Updated proposal (May 2002) has single arm spectrometer.**
  - —**Excellent PID with RICH**
  - —**Pixel detector inside the beam vacuum, 30M channels, 50 mm ´400 mm pixels**
  - —**PbWO4 calorimeter (developed by CMS) with PMT readout Þ Excellent resolution**

$$\frac{s(E)}{E} = \frac{0.016}{\sqrt{E/GeV}} + 0.0055$$





31 stations (62 Si planes)

Comparison PID and g detection in Hadronic Experiments

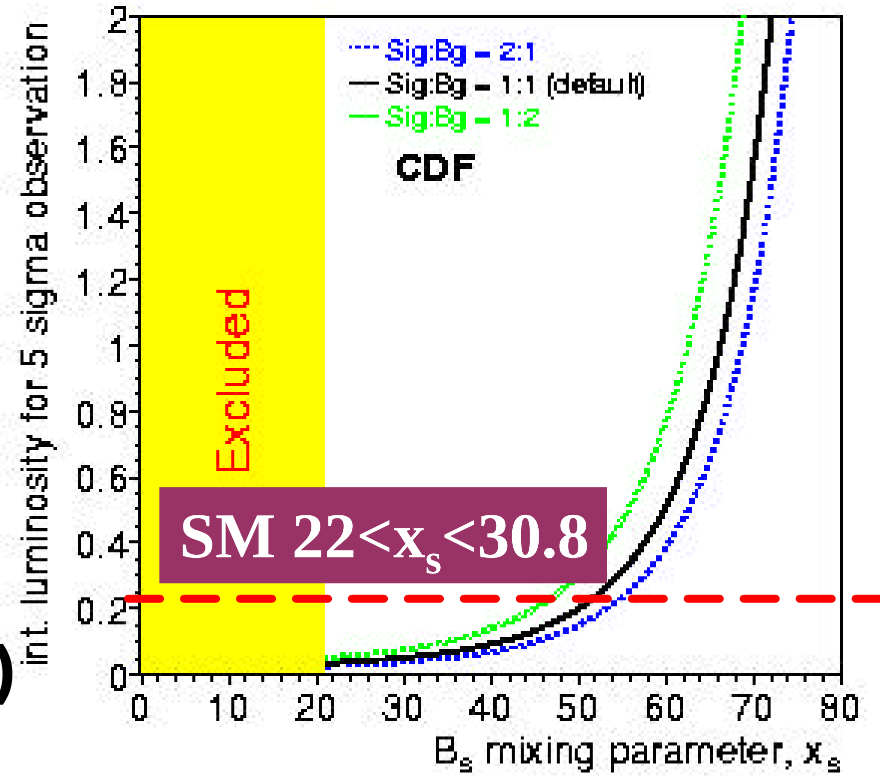
- **Particle ID and g detection can improve physics reach**

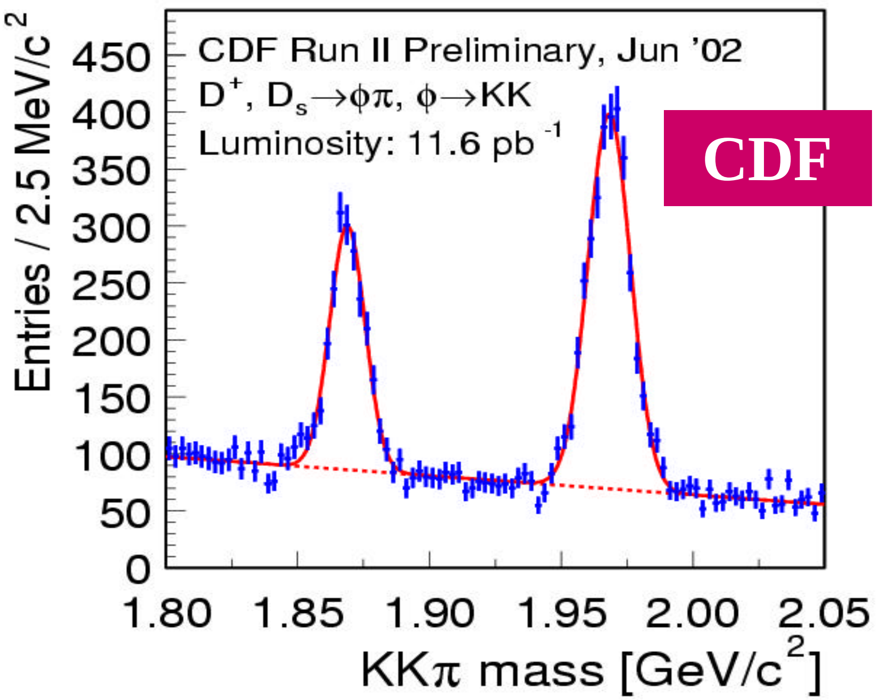
Exp	Particle ID		g Detection	
	Device	p/K p range	Device	s(E)/E (E in GeV)
CDF	TOF,dE/dx	p < 1.6(GeV/c)	Pb-scint	13.5%/ÖE
D0	None		Ur-Liquid Ar	15.7%/ÖEÅ0.3%
ATLAS	None		Pb-Liquid Ar	8%/ÖEÅ0.2/E Å0.7%
CMS	None		$PbWO_4$	2.7%/ÖEÅ0.2/E Å0.55%
BTeV	Gas RICH	» all	$PbWO_4$	1.6%/ÖEÅ0.55%
LHCb	Gas RICH	» all	Pb-scint	10%/ÖEÅ1.5%

S. Stone

B_s Mixing

- **Measurements of x_s should come from the Tevatron**
- **B^0_s ® $D^-_s p^+$, B^0_s ® D^-_s p^+ p^- p^+**
  - **SVT trigger Þ Signal 75K events ($2 fb^{-1}$)**
  - **eD^2=11.3% (TOF)**
- **S/B»0.5-2 (CDF, Run II data)**

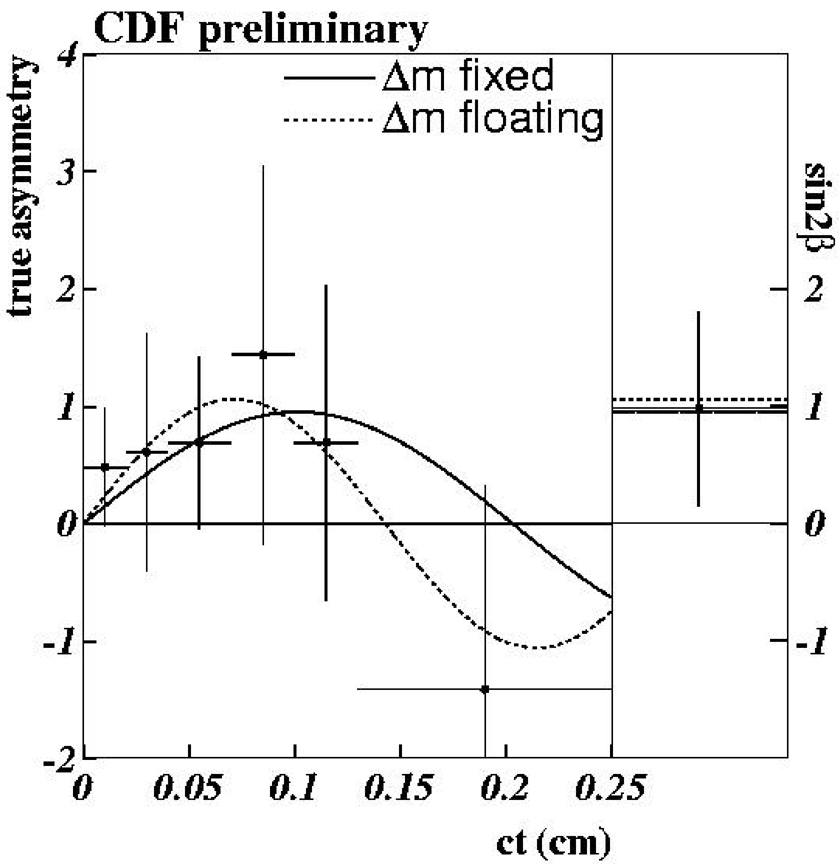


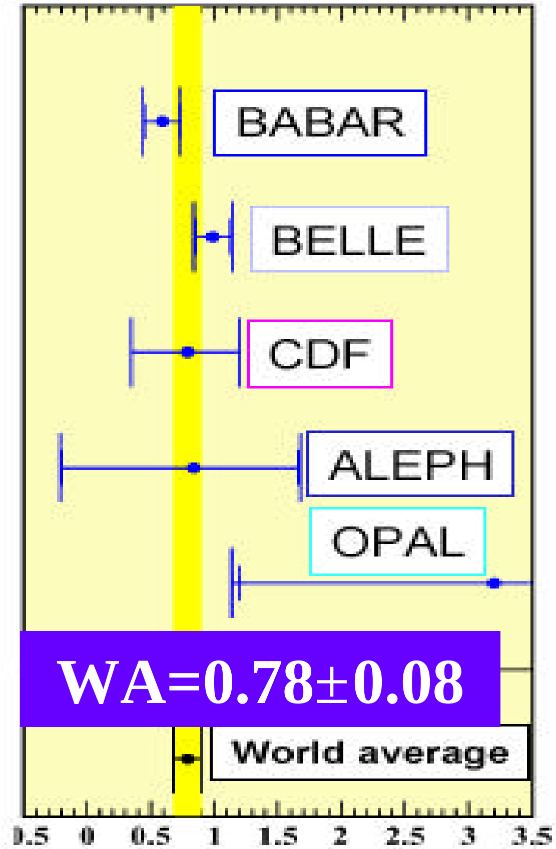


- **Excellent ct resolution**
  - **s(ct)=45fsec (L00) 60fsec (without L00)**
- **Expect to cover the SM range with 100-200 pb^{-1}.**
- **Predictions assume excellent trigger and reconstruction efficiencies**

Sin2b

- **Hadronic machines can contribute to measure sin2b**
- **CDF RUN I measurement with improved tagging, using B^0® J/yK^0_s, J/y(2S)K^0_s :**





CDF OLD

$$\sin 2b = 0.79^{+0.41}_{-0.44} \text{ (stat.+sys.)}$$

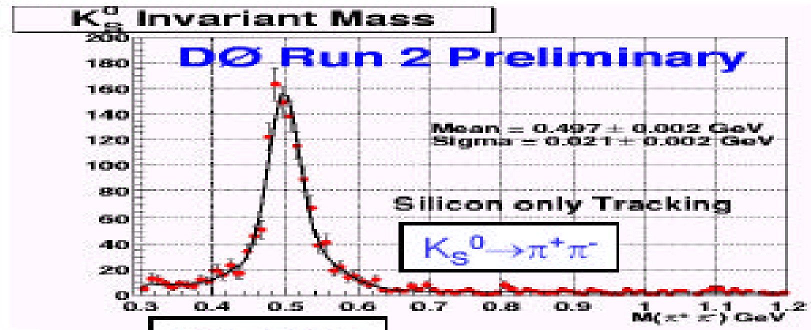
CDF NEW

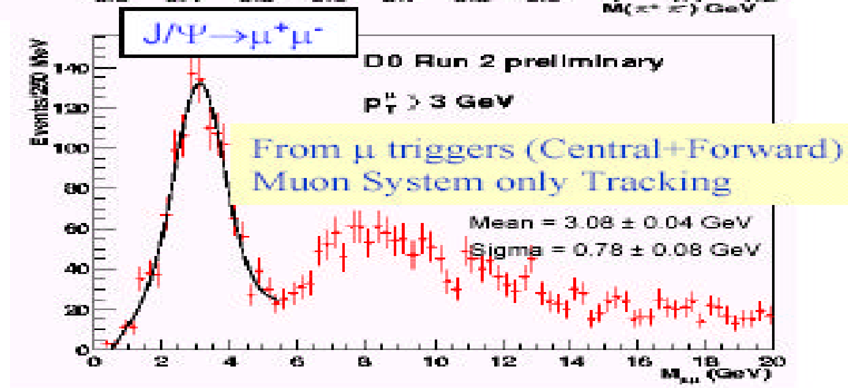
$$\sin 2b = 0.91^{+0.37}_{-0.36} \text{ (stat.+sys.)}$$

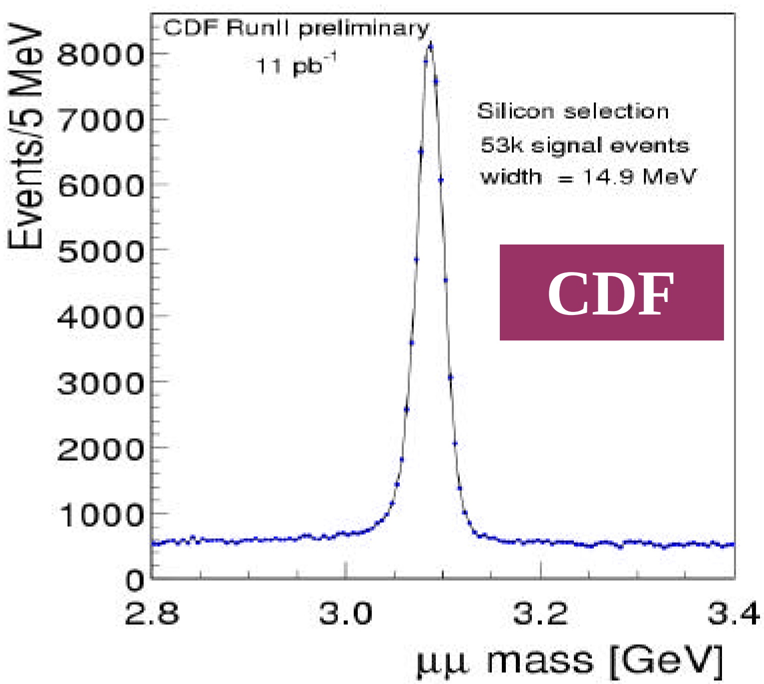
Sin2b reach

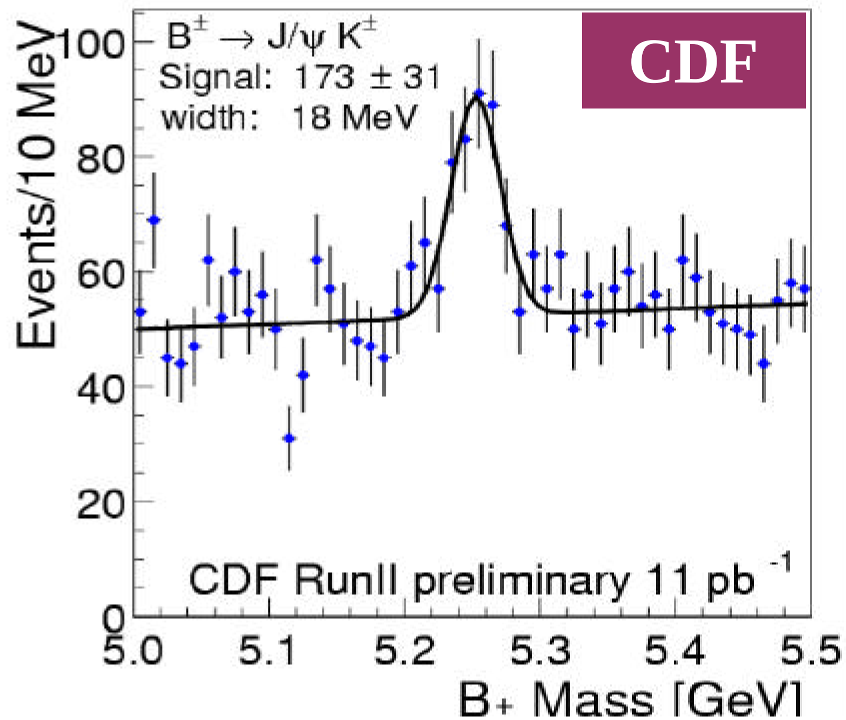
Near future

Reach in 2 fb^{-1}			
	N	eD^2	s (sin2b)
CDF	20K	0.09	0.05
D0	34K	0.10	0.04









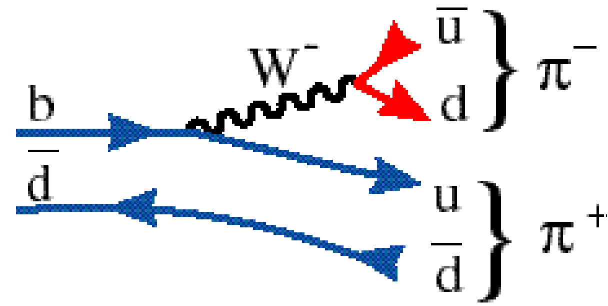
Measuring a

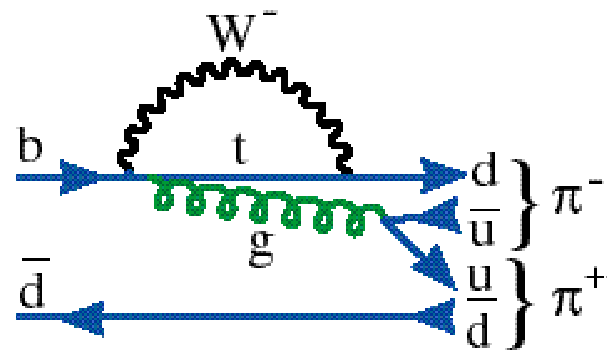
- **B® p⁺p⁻ could provide a measurement of a but we expect significant penguin pollution. CLEO, BaBar and Belle measure:**

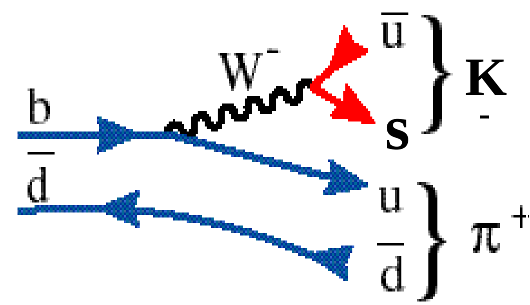
$$B(B^0 ® p^+ p^-) = (4.5 \pm 0.9) ´ 10^{-6}$$

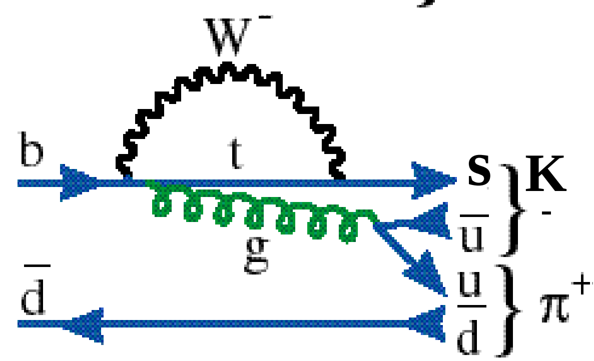
$$B(B^0 ® K^{\pm} p^{\mp}) = (17.3 \pm 1.5) ´ 10^{-6}$$

- **Measure B^0®p^+p^-, B^0®p^0p^0 B^+ ®$p^+ p^0$ (Gronau, Landon)**
- **Time dependent anlysis of B^0® r^+p^- ® $p^+p^-p^0$ Dalitz plot (Snyder & Quinn)**
- **Difficult, needs good EM calorimeter.**



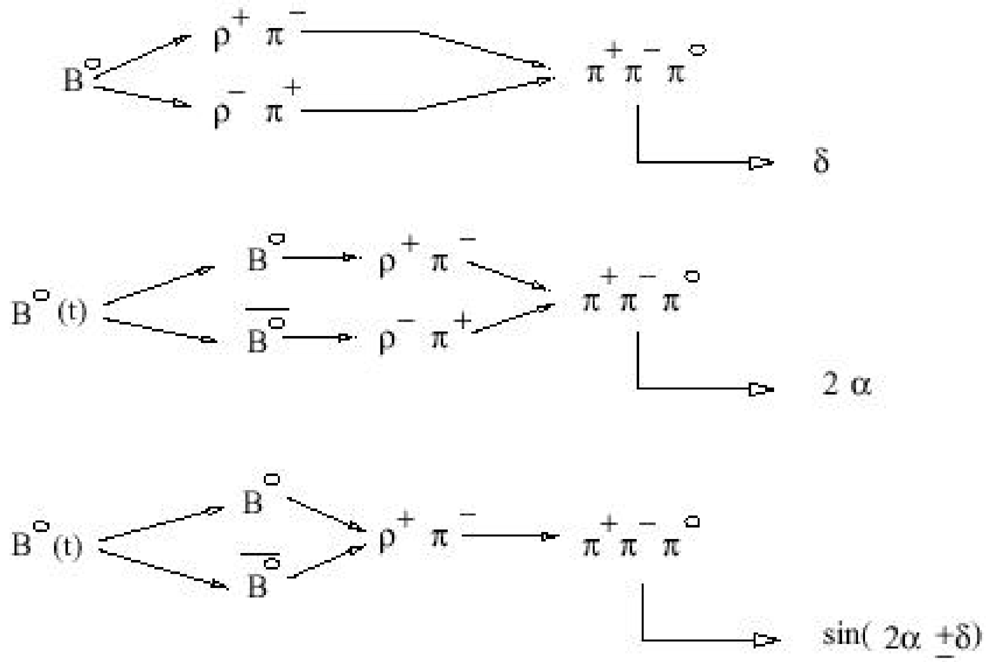


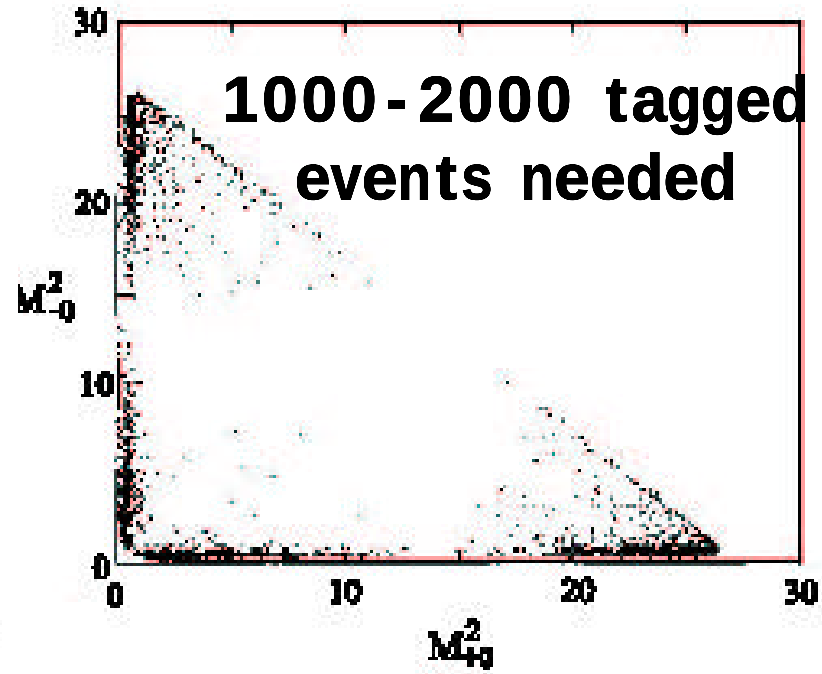




Measuring a

- **Dalitz Plot analysis of B® r p ® p⁺p⁻p⁰ yields both sin2a and cos2a (Snyder and Quinn, PRD 48, 2139 (1993))**





1000-2000 tagged events needed

B(B⁻ ® r°p⁻) ~1.5x10⁻⁵

B (B° ® r⁻p⁺ + r⁺p⁻) ~4x10⁻⁵

B (B° ® r°p°) <1.8x10⁻⁵

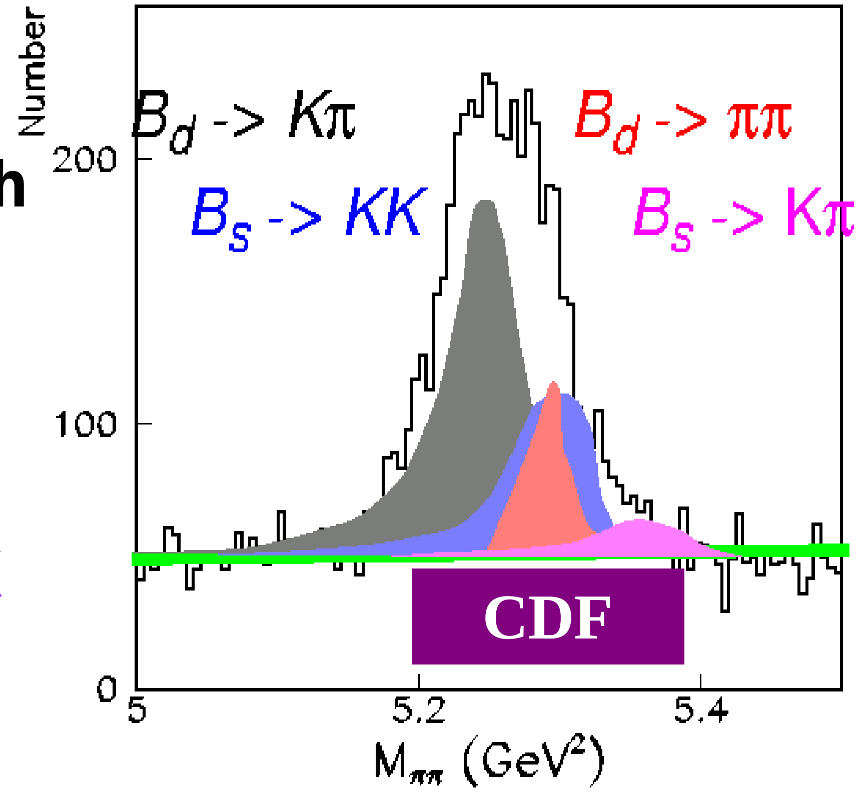
10⁷ seconds

	error on a
LHCb	**2.5-4.9°**
BTeV	**» ±4°**

Measuring g

- **Several techniques:**
  - **Time dependent B_s ® $D_s^{\pm} K^{\mp}$, large background from B_s ® D_sp. Need high statistics and PID**
  - **Time dependent rate of $B^0/\overline{B}^0$ ® $D^{*\pm}$ $p^{\mp}$ measures 2b+g but interference effect are expected to be small**
  - **Measure rate difference between B^- ® D^0K^- and B^+ ® D^0K^+**
  - **Rate measurements in $K^0p^{\pm}$ and $K^{\pm}p^{\mp}$ (Fleisher-Mannel) or rates in $K^0p^{\pm}$ & asymmetry in $K^{\pm}p^{o}$ (Neubert-Rosner, Beneke et al)**
  - **Use U spin symmetry d Û s: measure time dependent asymmetries in B^o ® p^+p^- and B_s ® K^+K^- (Fleischer)**
  - **Time dependent rate of $B_s/\overline{B}_s$ ® K^+K^- normalized to B_s ® $K^0\overline{K}^0$ (Gronau and Rosner)**
- **Several modes involve B_S decay and are ideal for hadron machines**

B®h$^+$h$^-$



- **Trigger on two SVT tracks with large impact parameter.**
- **Use:** B(B_d®pp)=(4.3±1.6)´10^{-6} and B(B_d®Kp)= (17.2±2.8)´10^{-6}. Assume B_d/B_s=2.5 and SU(3) Þ

  B_d®pp: B_d®Kp: B_s®Kp: B_s®KK =1:4:0.5:2
- **CDF expects in 2 fb^{-1}:**

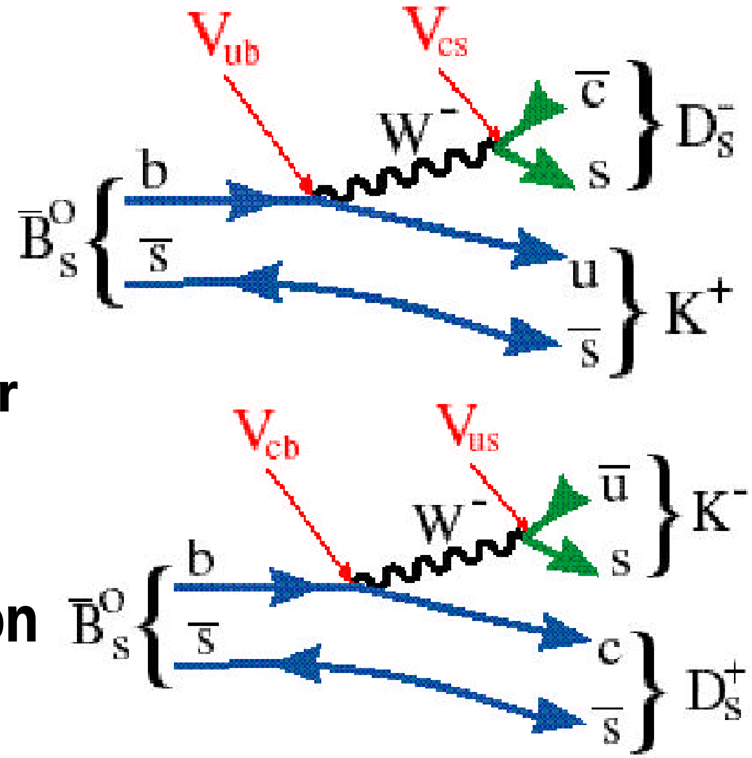
  B_d®p$^+$p$^-$ (5K) B_s®K$^+$K$^-$ (10K) B_d®K$^+$p$^-$ (20K) B_s®p$^+$K$^-$ (2.5K)

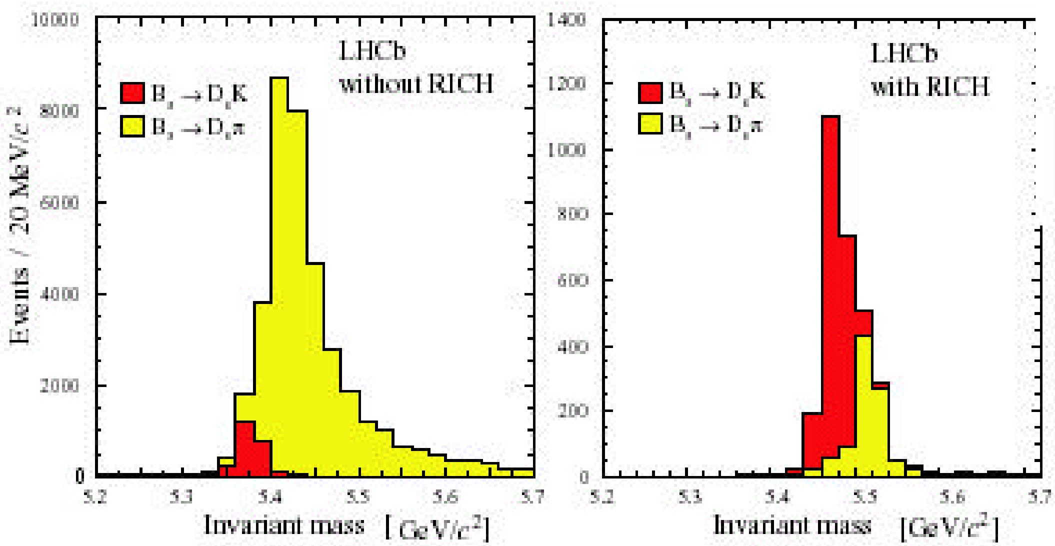
  eD^2»10% for B_d and B_s
- **Measure:** $$A_{CP} = A_{CP}^{dir} \cos(Dmt) \pm A_{CP}^{mix} \sin(Dmt)$$

  - s[A(K$^+$K$^-$)] ~ 0.08
  - s[A(p$^+$p$^-$] ~ 0.14
- **Using U-spin symmetry Þ d=d'=P/T, q=q¢=strong phase s(g) ~ 10º (stat.Å syst.)**

g From B_s ® D_sK

- **Interference between direct and mixing decays measures sin(“g-2c”±d)** Aleksan, Dunietz, Kayser
- **Expect large asymmetry because the two tree amplitudes µ l^2**
  - **Excellent proper time resolution**
  - **Excellent PID because of Cabibbo allowed B^0® D_s^-p$^+$**





	Annual yield * (untagged)	S/B	σ(m_B) MeV	σ(t_B) ps
LHCb	6.4 k	12	11	43
BTeV	9.7 k	7	17	43

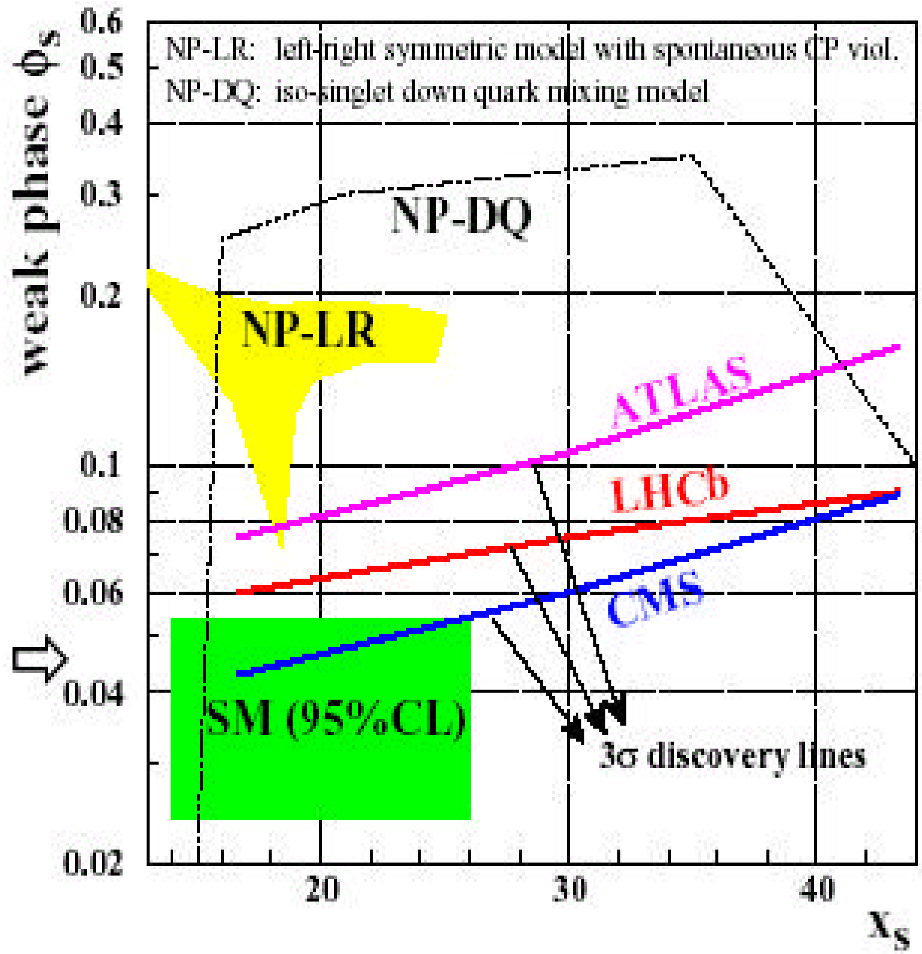
– **If Dm_s=20ps s(g)=O(10^0) after 1 year**

$B_s \to \psi\phi$ and $\psi\eta$

- **Silva & Wolfenstein, Aleksan, Kayser & London propose these modes to test new physics**
- **SM predicts the B_s mixing phase to be small**

$$\chi \approx \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{\sin\beta \sin\gamma}{\sin(\beta+\gamma)} \approx 2\lambda^2\eta$$

- **$J/\psi\phi$ is not a pure CP final state**
  - **Angular analysis required for clean extraction: Atlas, CMS 300-600K untagged events in 3 years, LHCb >370k in 5 years**
- **$J/\psi\eta^{(\prime)}$ pure CP=-1 final state**
  - **Needs excellent γ detection**
  - **BTeV: $\sigma(\chi)\approx$0.024 in 1 year**



Comparison /10^7 s

Exp	sin2b B° ® J/y K_s		a B° ® r p	g B_s ® D_sK^-	c B_s ® J/y X (m&e)	
	Error in sin2b	J/y decay	Error in a	Error in g	X=h(¢) Error in c	X=f Error in c
CDF	0.05	m^+m^-		$25-45^0$ (IIA) 6^0-17^0 (IIB)		0.08
D0	0.04	m^+m^-				
ATLAS	0.017	m&e				0.03
CMS	0.015	m&e				0.014
LHCb	0.021	m&e	$2.5-4.9^0$	8^0		0.02
BTeV	0.017	m^+m^-	$\pm 4^0$	11.5^0	0.024	

Comparison with B factories

	BTeV 10^7s	LHCb 10^7s	B-factory (2005)	SuperB-10^35 10^7s	SuperB-10^36 10^7s
sin2b	0.017	0.021	0.037	0.026	0.008
sin2a	0.05	0.05	0.14	0.1	0.032
g(B_s® D_sK)	»7^0	»8^0			
g(B® DK)	»2^0		»20^0		1-2.5 ^{0}
B(B® p^0 p^0)			»20%	»14%	»6%
V_{ub}			»2.3%	»1%	»1%

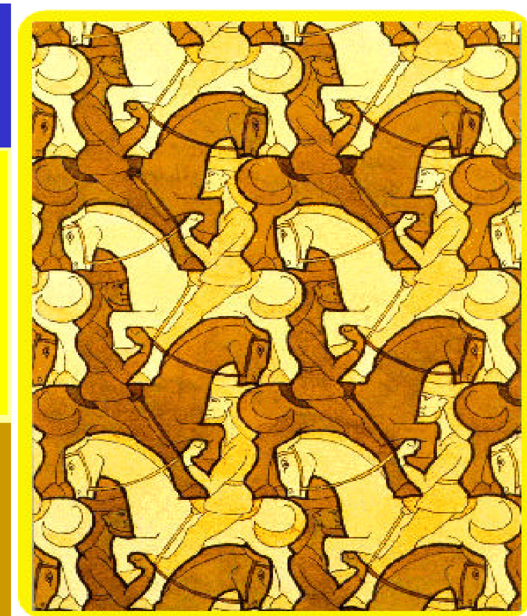
Snowmass: E2 report

New Physics Modes

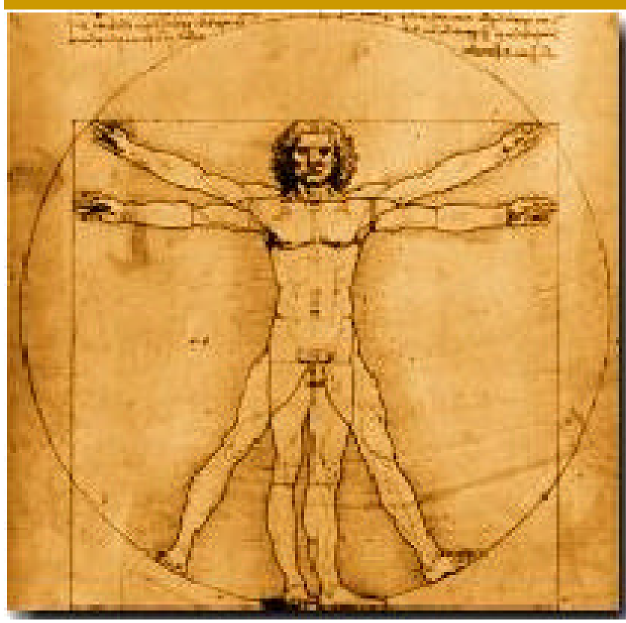
Mode	BTeV (10^7s)			B-fact ($500fb^{-1}$)		
	Yield	Tagged	S/B	Yield	Tagged	S/B
B_s® J/y h(¢)	12650	1645	>15	-	-	
B^-® fK^-	6325	6325	>10	700	700	4
B^o® fK_s	1150	115	6.5	250	75	4
B^o® K*m^+m^-	2530	2530	11	~50	~50	3
B_s® m^+m^- (10^{-9})	6	0.7	>15	-	-	-
B® tn				17	17	
D^{*+}® p^+D^o, D^o ® K^-p^+	~10^8	~10^8	large	8x10^5	8x10^5	large

´20 at 10^{36}
SuperB Factory

Conclusions



- **B Physics at hadron colliders is complementary to e^+e^- B-factories**
  - **Huge statistics 10^{12} bb/year and B_s**
- **Tevatron:**
  - **CDF is pioneering secondary vertex triggering.**
  - **Expect measurements of B_s mixing, CP asymmetries in $B \to \psi K_s$, $B \to \pi\pi$ and $B_s \to KK$ from CDF and D0.**



- **Dedicated experiments (LHCb and BTeV) with improved PID and photon reconstruction**
  - **Clean extraction of γ**
  - **Tests new physics through precision measurements and sensitivity to discrepancies with SM predictions.**