

CP Violation in Dedicated Hadron Experiments

Outline

- Introduction
- Experimental issues
- Experiments
- Measurements
- Conclusions

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References

CERN yellow report, Proc. of the Workshop on Standard Model Physics (and more) at the LHC, May 2000, CERN 2000-004;

BTeV Proposal , May 2000;

LHCb Proposal, February 98;

Motivations

CP violation is one of the fundamental phenomena in particle physics

CP is one of the less experimentally constrained parts of SM

SM with 3 generations and the CKM ansatz can accommodate CP

CP asymmetries in the B system are expected to be large.

Observations of CP in the B system can:

test the **consistency** of SM

lead to the **discovery** of new physics

Cosmology needs additional sources of CP violation other than what is provided by the SM

Standard Model: CKM matrix

The quark electroweak eigenstates are connected to the mass eigenstates by the CKM matrix :

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

phenomenological applications: Wolfenstein parameterization

$$= \begin{pmatrix} 1 - \lambda^2 / 2 & \lambda & -|V_{ub}| e^{-i\gamma} \\ -\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\ -|V_{td}| e^{-i\beta} & |V_{ts}| e^{i\delta\gamma} & 1 \end{pmatrix}$$

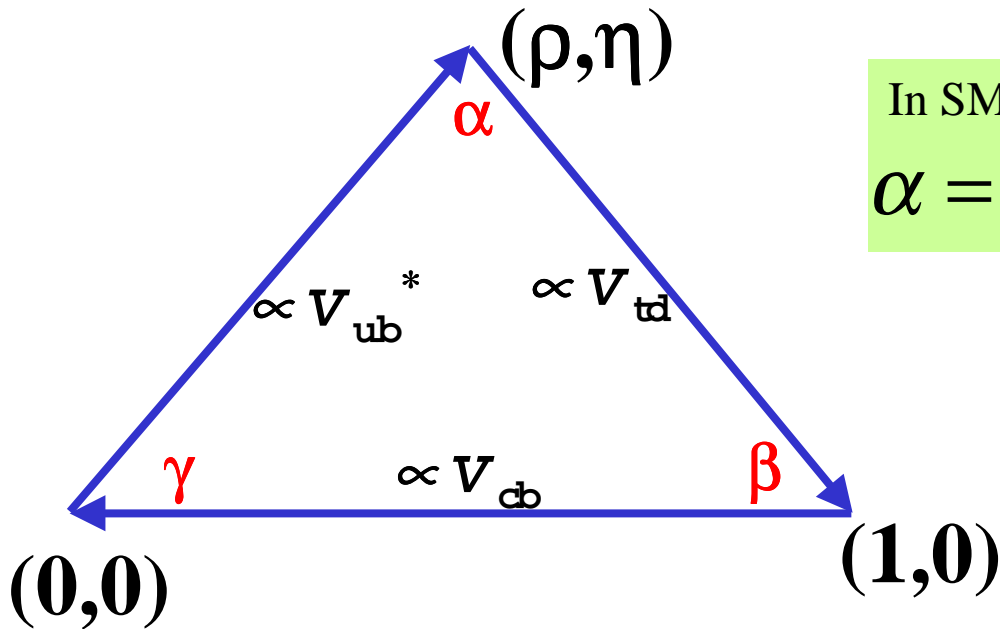
$B_d - \bar{B}_d$
mixing phase

$B_s - \bar{B}_s$
mixing phase

Weak decay
phase

Unitarity triangles

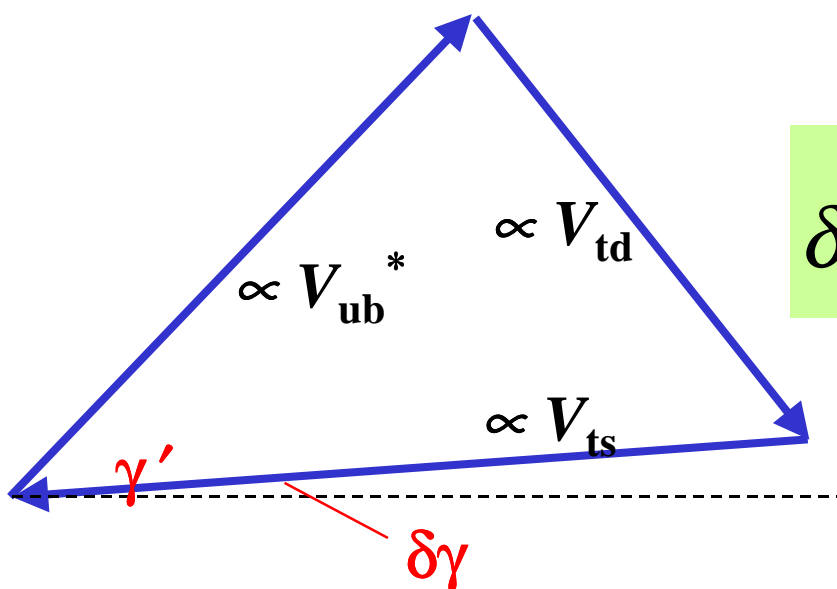
$$V_{td} V_{tb}^* + V_{cd} V_{cb}^* + V_{ud} V_{ub}^* = 0$$



In SM:

$$\alpha = \pi - \beta - \gamma$$

$$V_{td} V_{ud}^* + V_{ts} V_{us}^* + V_{tb} V_{ub}^* = 0$$

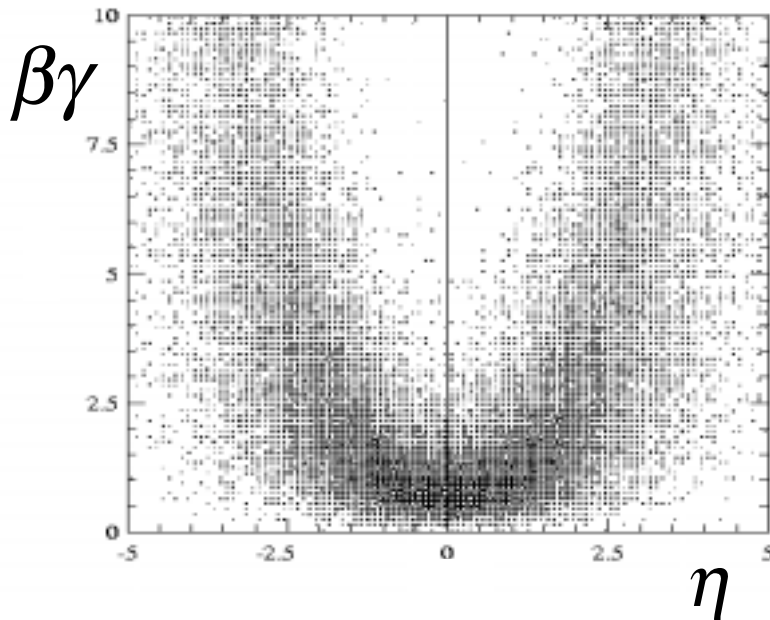


In SM:

$$\delta\gamma = \lambda^2 \eta \approx 0.03$$

Hadronic b production

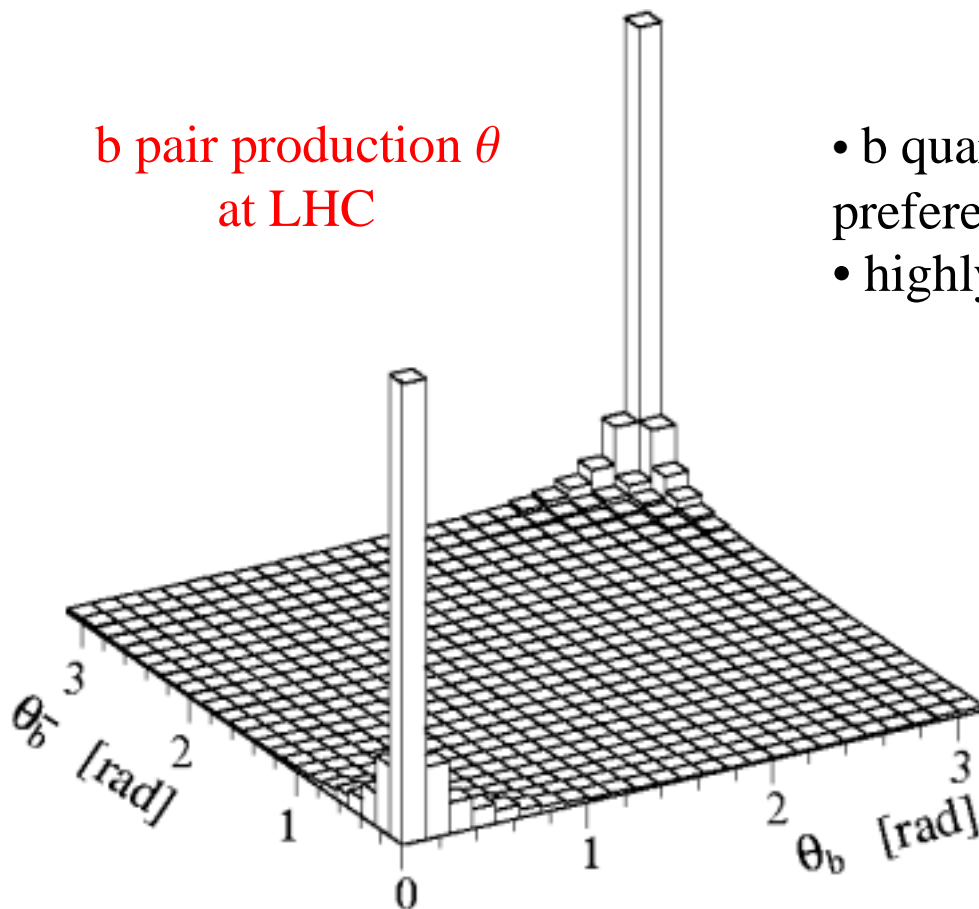
B hadrons at Tevatron



$$\eta = -\ln(\tan(\theta / 2))$$

for larger $|\eta|$ the B
boost $\beta\gamma$ increases rapidly

b pair production θ at LHC



- b quark *pair* produced preferentially at low θ
- highly correlated

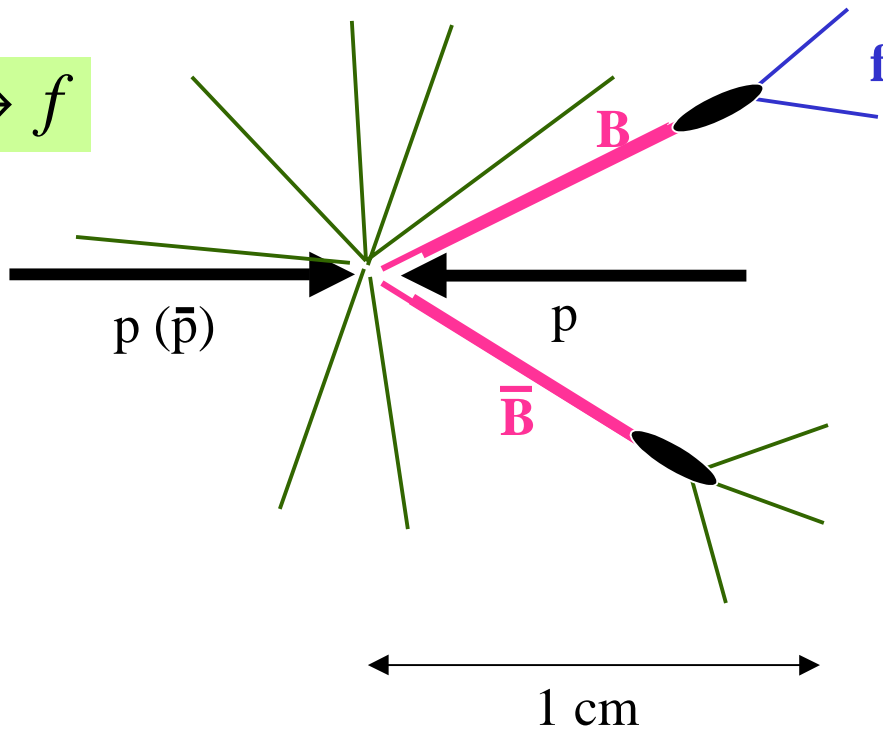
tagging
low pt cuts

LHC and Tevatron experiments

	Tevatron	LHC
Energy/collision mode	2.0 TeV $p\bar{p}$	14 TeV pp
$b\bar{b}$ cross section	$\sim 100 \mu\text{b}$	$\sim 500 \mu\text{b}$
Inelastic cross section	$\sim 50 \text{mb}$	$\sim 80 \text{mb}$
Ratio $b\bar{b}$ /inelastic	0.2%	0.6%
Bunch spacing	132 ns	25 ns
	BTeV	LHCb
Detector configuration	Two-arm forward	Single-arm forward
Running luminosity	$2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
$b\bar{b}$ events per 10^7	2×10^{11}	1×10^{12}
Interactions/crossing	~ 2.0	0.5 ($\sim 30\%$ single)
Average B momentum	40 GeV/c	80 GeV/c
Mean flight path	3.6 mm	7 mm

Generic experimental issues

$B \rightarrow f$



$$A(t) = \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow f)}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow f)}$$

triggering

decay time resolution

particle ID

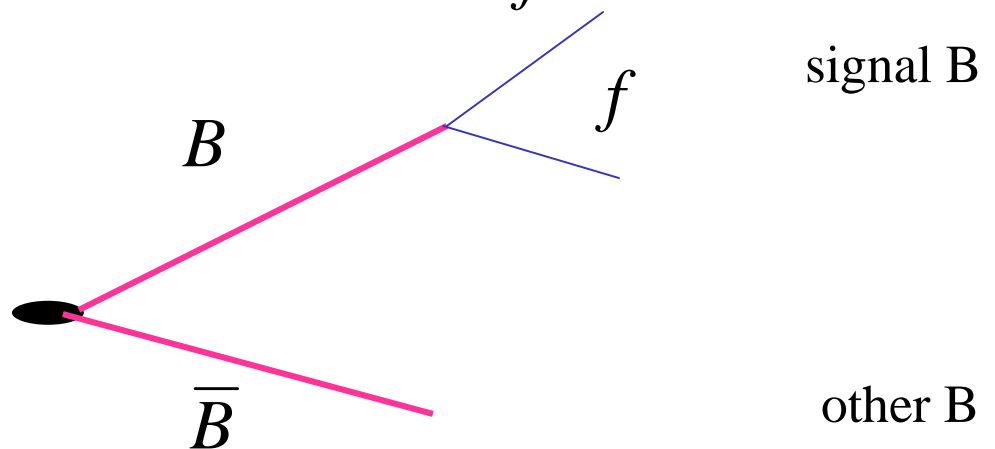
neutrals detection

flavour tagging

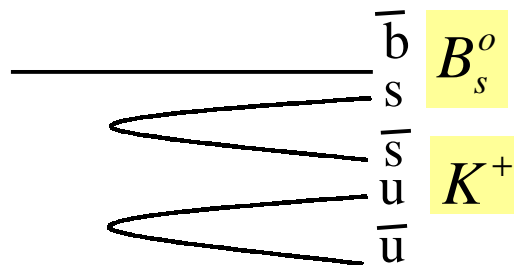
systematic effects

Flavour tagging

For a given decay channel $B \rightarrow f$



SS: look directly at particles accompanying the signal B



OS: deduce the initial flavour of the signal meson by identifying the other b hadron

semileptonic decay $b \rightarrow l$

kaon tag $b \rightarrow c \rightarrow s$

jet charge $Q_{jet} > c$

Flavour tagging

$$\epsilon = (N_R + N_W) / N$$

$$w = N_w / (N_w + N_R)$$

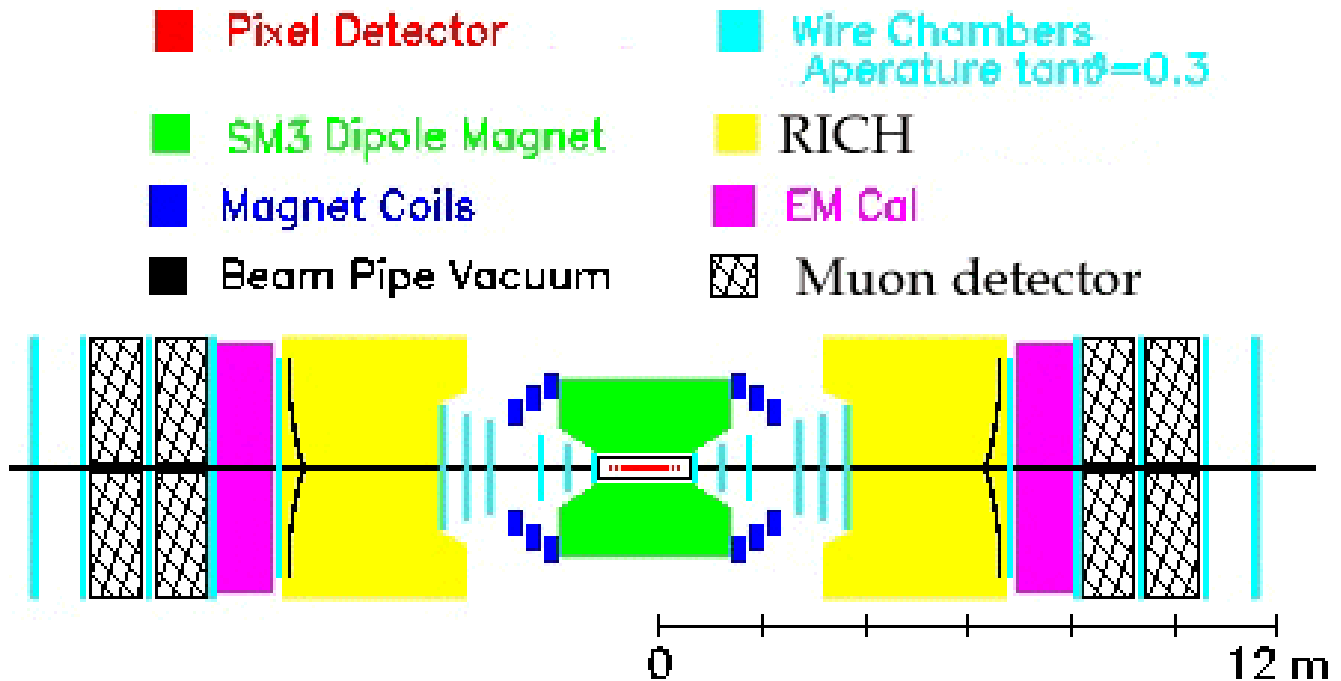
$$D = 1 - 2w$$

$$\delta A \sim \frac{1}{\sqrt{D^2 \epsilon N}}$$

- w : wrong tag fraction
- ϵ : tagging efficiency
- N : total untagged

	BTeV		LHCb	
	$\epsilon(\%)$	D	$\epsilon(\%)$	D
μ	4.5	0.66		
e	--	--	40	0.40
K	18	0.52		
Vertex charge	32	0.36	0.60	0.16
π	88	0.16	--	--
K	40	0.26	--	--
B_S	--	--	0.11	0.34

The BTeV detector

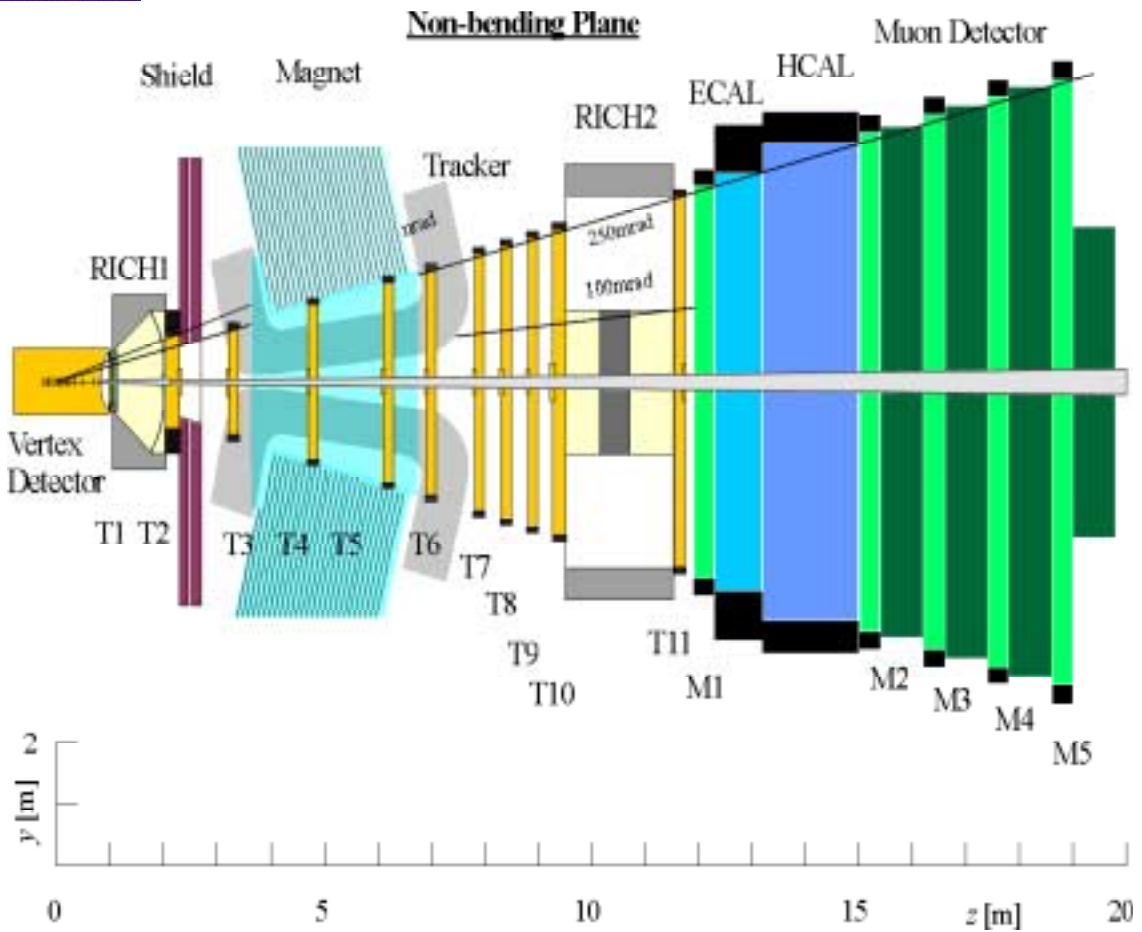


- Central **pixel vertex** detector in **dipole** magnetic field (1.6 T)
- Each of two arms:
 - tracking stations (silicon strips + straws)
 - hadron identification by RICH
 - γ/π^0 detection and e identification in lead-tungsten crystal calorimeter
 - μ triggering and identification in muon system with toroidal magnetic field
- Designed for luminosity $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
($2 \times 10^{11} \text{ bb events per } 10^7 \text{ s}$)

Trigger strategy
(three levels)

- pioneering pixel vertex trigger
- software triggers

The LHCb Detector



- 17 silicon vertex detectors
- 11 tracking stations
- two RICH for hadron identification
- a normal conductor magnet (4 Tm)
- hadronic and electromagnetic calorimeters
- muon detectors

Trigger strategy
(four levels)

- “high” p_t μ , e , γ , h
- secondary vertex
- software triggers

Calorimetry

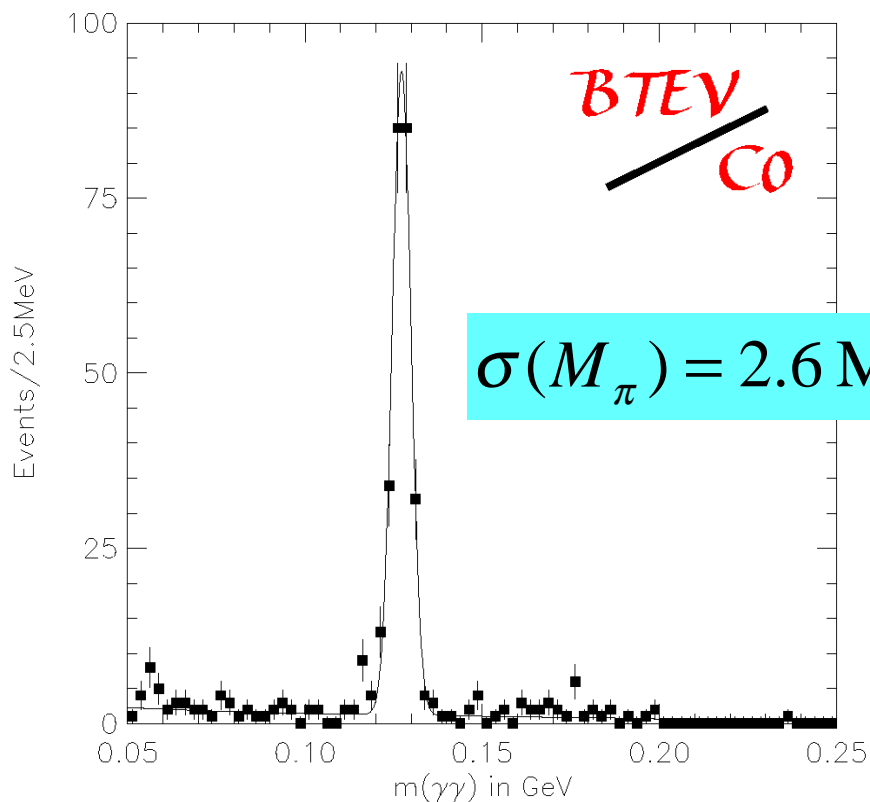
Important final states with π^0 and γ

Use 2x11,850 lead-tungsten crystals (PbWO_4)

- technology developed for LHC by CMS
- radiation hard
- fast scintillation (99% of light in <100 ns)

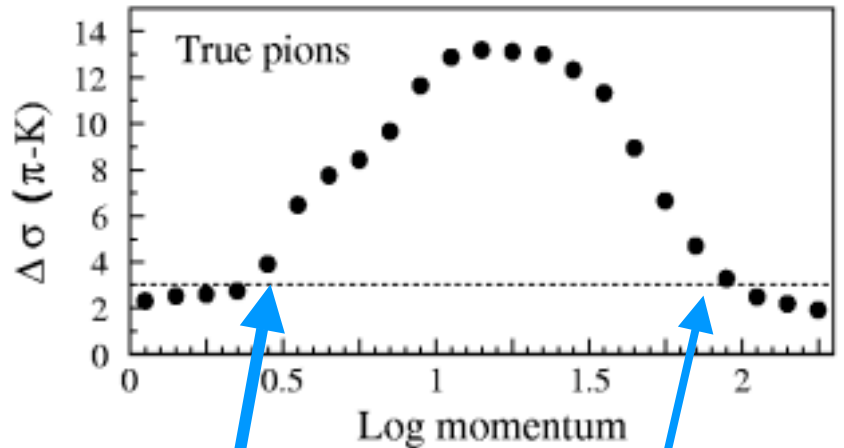
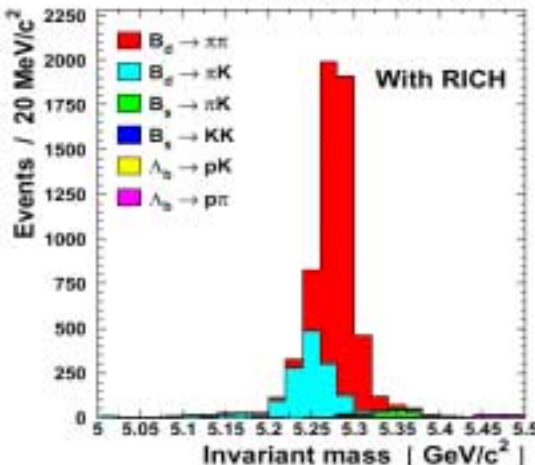
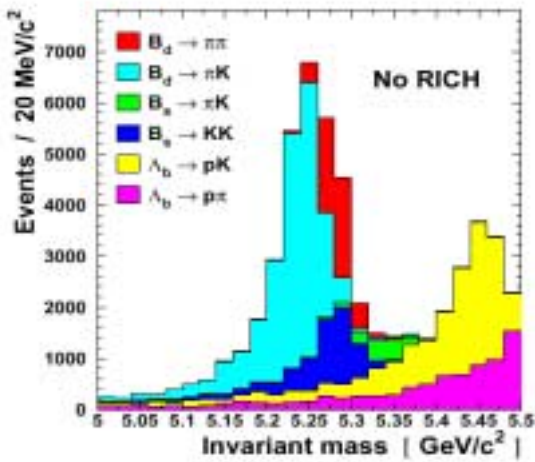
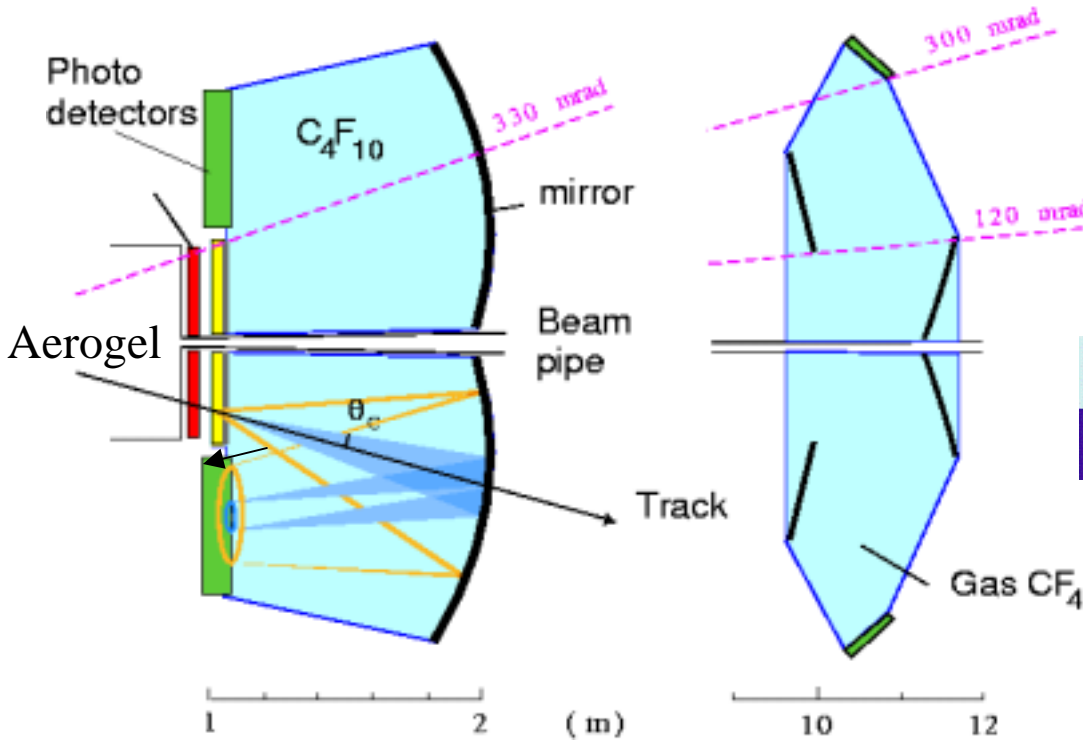
Excellent energy, angular resolution and photon efficiency

Pions with 10 GeV



Particle Id

Essential for hadronic PID



flavour tag with kaons
($b \rightarrow c \rightarrow K$)

background suppression
two body B decay products

Strategies for measurements of CKM angles and rare decays

β

$$B_d^0 \rightarrow J/\psi K_S$$

β, γ

α

$$B_d^0 \rightarrow \pi^+ \pi^- \quad (B_s^0 \rightarrow K^+ K^-)$$

$$B_d^0 \rightarrow \rho \pi$$

$$B_d^0 \rightarrow \pi^+ \pi^-$$

γ

$$B_d^0 \rightarrow DK^*$$

$$B_d^0 \rightarrow K \pi$$

$2\beta + \gamma$

$$B_d^0 \rightarrow D^{*-} \pi^+$$

$$B_{d(s)}^0 \rightarrow J/\psi K_S^0, D_{(s)}^+ D_{(s)}^-$$

$\gamma - 2\delta\gamma$

$$B_s^0 \rightarrow D_s^\pm K^\mp$$

Rare

$$B_{s(d)}^0 \rightarrow \mu^+ \mu^-$$

$$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$$

$\delta\gamma$

$$B_s^0 \rightarrow J/\psi \eta^{(\prime)}$$

$$B_s^0 \rightarrow J/\psi \phi$$

x_s

$$B_s^0 \rightarrow D_s^- \pi^+$$

β $B_d^0 \rightarrow J/\psi K_S$

$$A_{CP}(t) = \frac{\Gamma(B^0 \rightarrow J/\psi K_S^0) - \Gamma(\overline{B^0} \rightarrow J/\psi K_S^0)}{\Gamma(B^0 \rightarrow J/\psi K_S^0) + \Gamma(\overline{B^0} \rightarrow J/\psi K_S^0)}$$

$$= A_{\pi\pi}^{dir} \cos \Delta m_d t + A_{\pi\pi}^{mix} \sin \Delta m_d t$$

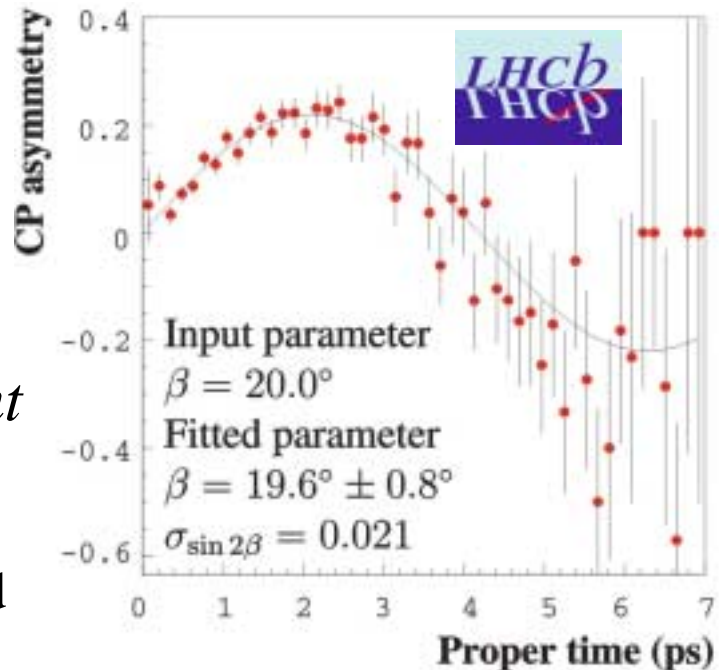
Penguins:

- expected to be small
- same weak phase as tree amplitude

$$A_{CP}(t) = D \sin(2\beta) \sin \Delta m t$$

dilution factor:

- tagging
- background



	events /1y	$\sigma(M)$ / MeV/c ²	$\sigma(\sin(2\beta))$
BTeV	88k	7	0.025
LHCb	80.5k	9.3	0.021
ATLAS	165k	18	0.017
CMS	433k	16	0.015

$$A_{CP}^{dir}(B_d^0 \rightarrow J/\psi K_S^0) \approx 0$$

Standard Model:

$$A_{CP}(B^+ \rightarrow J/\psi K^+) \approx 0$$

Observation of direct asymmetries (10% level):

strong indication of New Physics!

Systematic errors in CP measurements

asymmetries • ratios
• robust

high statistical precision

• production asymmetries

$$f_0 \quad \bar{f}_0 \quad f_s \quad \bar{f}_s \quad f_+ \quad f_-$$

• tagging efficiencies

$$\varepsilon \quad \bar{\varepsilon}$$

• mistag rate

$$\omega \quad \bar{\omega}$$

• final state acceptance

$$a(t) \quad \bar{a}(t)$$

Control channels

CP eigenstates $B_d^0 \rightarrow J / \psi K_s$

$$B^\pm \rightarrow J / \psi K^\pm \quad \left\{ \begin{array}{l} \varepsilon \quad \bar{\varepsilon} \quad \omega \quad \bar{\omega} \\ f^+ / f^- \end{array} \right.$$

$$B_d^0 \rightarrow J / \psi K^{0*} \quad \left\{ \begin{array}{l} f_0 / \bar{f}_0 \\ f_0 \varepsilon / \bar{f}_0 \bar{\varepsilon} \\ \omega \quad \bar{\omega} \end{array} \right.$$

$$B_s^0 \rightarrow D_s \pi \quad f_s / \bar{f}_s$$

$$\text{ATLAS: } \sin(2\beta) \pm 0.010 \pm 0.005$$

est sys

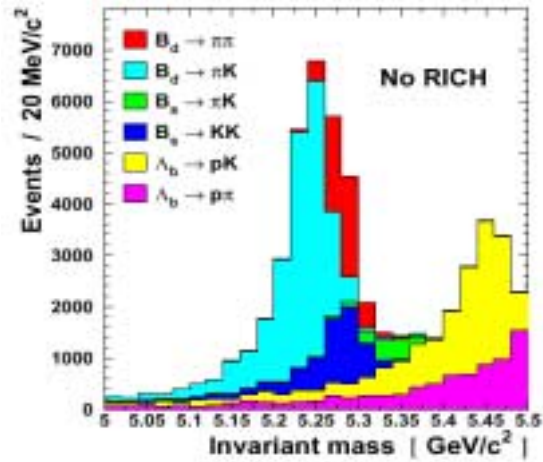
Monte Carlo

Detector cross-checks

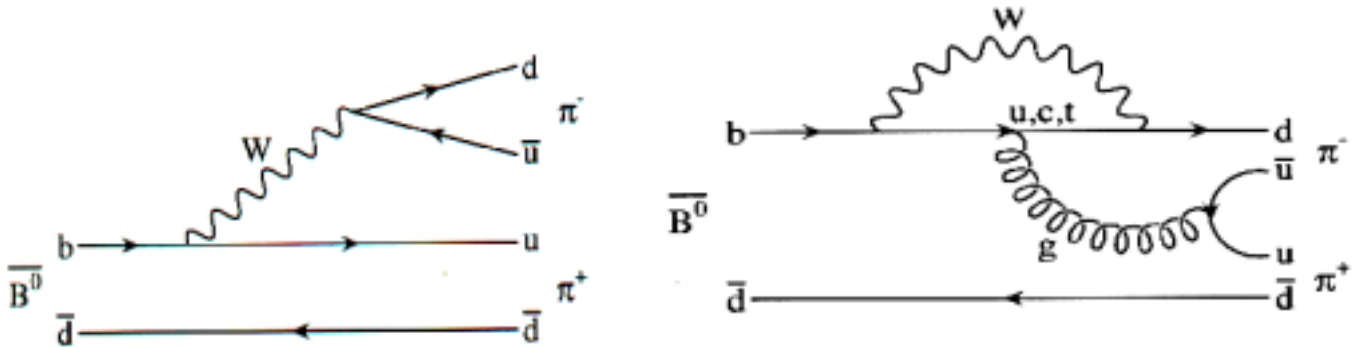
$\sin(2\alpha)$

$B_d^0 \rightarrow \pi^+ \pi^-$

- experimental: background with similar topologies



- theoretical: penguin diagrams make it harder to interpret observables in term of α



$$A(t) = \frac{\Gamma(B_d \rightarrow \pi^+ \pi^-) - \Gamma(\bar{B}_d \rightarrow \pi^+ \pi^-)}{\Gamma(B_d \rightarrow \pi^+ \pi^-) + \Gamma(\bar{B}_d \rightarrow \pi^+ \pi^-)}$$

$$= A_{\pi\pi}^{dir} \cos \Delta m_d t + A_{\pi\pi}^{mix} \sin \Delta m_d t$$

	events/ 10^7 s	σ (MeV)	$\delta A(t)$	$\delta A_{\pi\pi}^{dir}$	$\delta A_{\pi\pi}^{mix}$	C
BTeV	23.7 k	29	0.024	--	--	--
LHCb	12.3 k	17	--	0.09	0.07	-0.49

$\sin(2\alpha)$ $B_d^0 \rightarrow \pi^+ \pi^-$

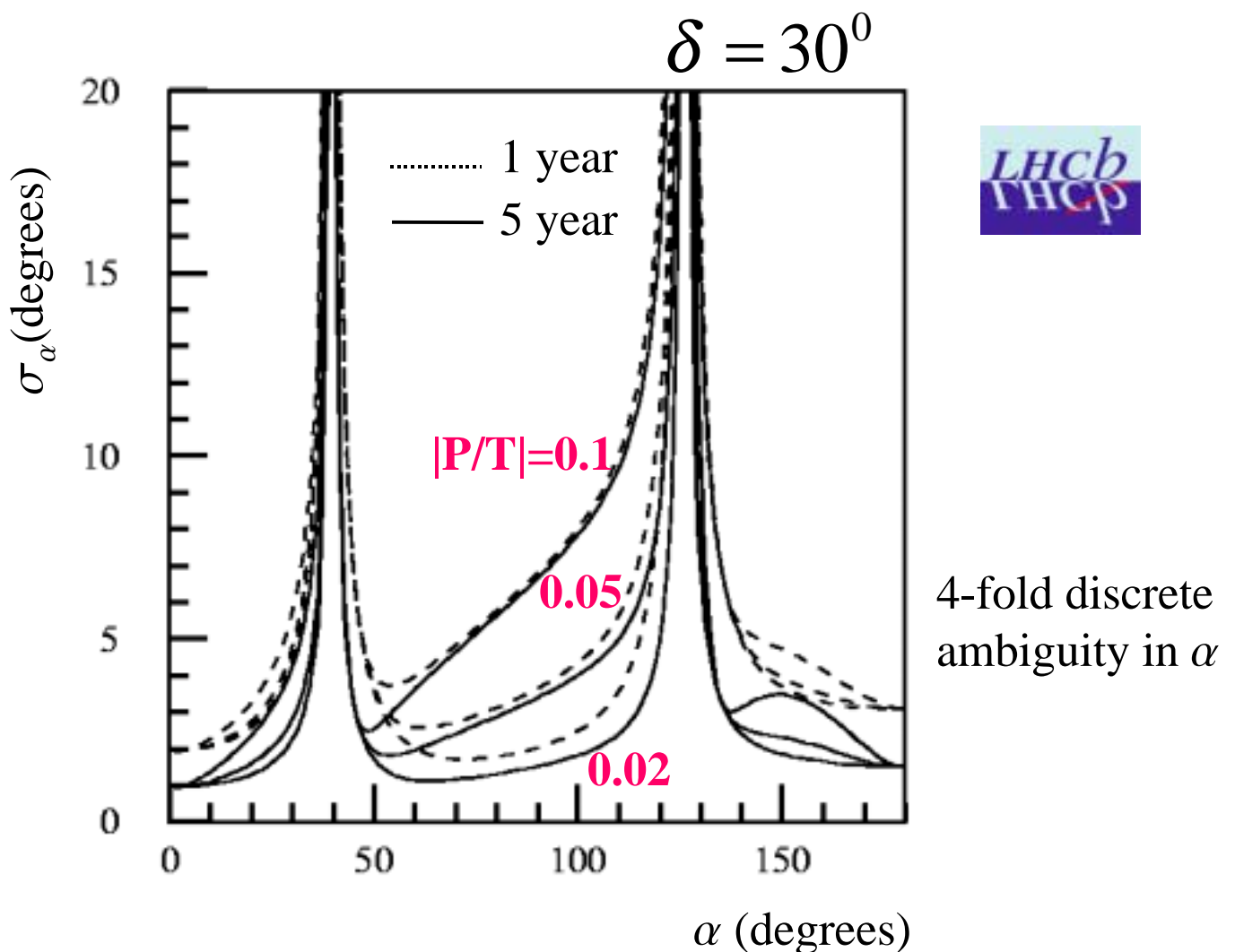
$$A(B_d^0 \rightarrow \pi^+ \pi^-) = e^{i\gamma} T + e^{-i\beta} P$$

approximately

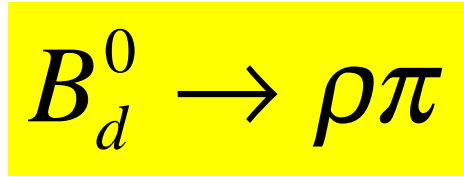
$$A^{dir}(B_d^0 \rightarrow \pi^+ \pi^-) = 2 \left| \frac{P}{T} \right| \sin \delta \sin \alpha$$

CP conserving
strong phase

$$A^{mix}(B_d^0 \rightarrow \pi^+ \pi^-) = -\sin(2\alpha) - 2 \left| \frac{P}{T} \right| \cos \delta \cos(2\alpha) \sin(\alpha)$$

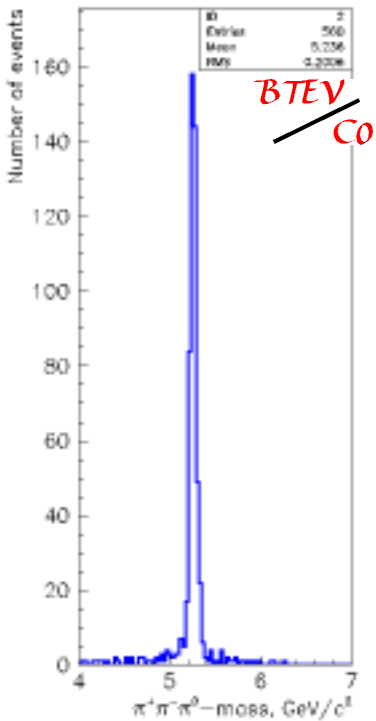


α



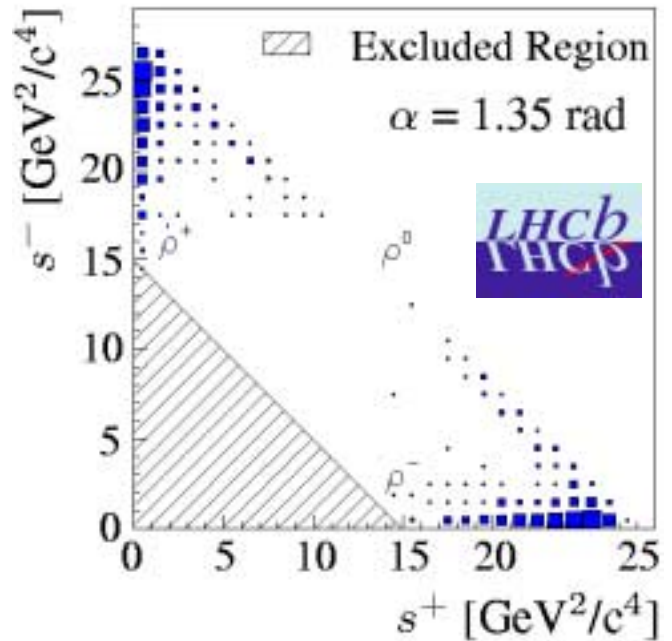
Time dependent Dalitz plot analysis

- α
- Tree terms
- Penguins



Helicity effects: corners

Cuts: lower corner eliminated



Unbinned loglikelihood analysis: 9 parameters

$\cos(2\alpha)$ and $\sin(2\alpha)$

no ambiguity

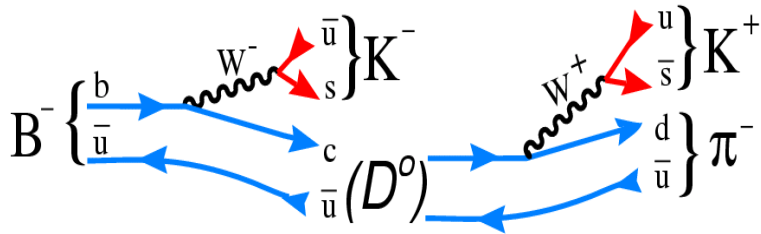
Under investigation:

- background
- Dalitz plot acceptance
- other resonances
- EW penguins

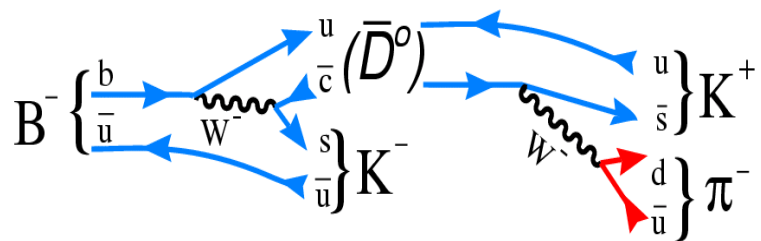
	events/1y	$\sigma(\text{MeV})$	$\sigma(\alpha)$
BTeV	10.8k	28	~ 10
LHCb	3.3k	50	$3^\circ\text{-}6^\circ$

γ $B^- \rightarrow D^0 K^-$

color allowed doubly Cabibbo suppressed



comparable decay amplitudes



- $B^- \rightarrow (K^+ \pi^-) K^-$
- $B^+ \rightarrow (K^- \pi^+) K^+$
- $B^- \rightarrow (K^+ K^-) K^-$
- $B^+ \rightarrow (K^+ K^-) K^+$

color suppressed Cabibbo allowed

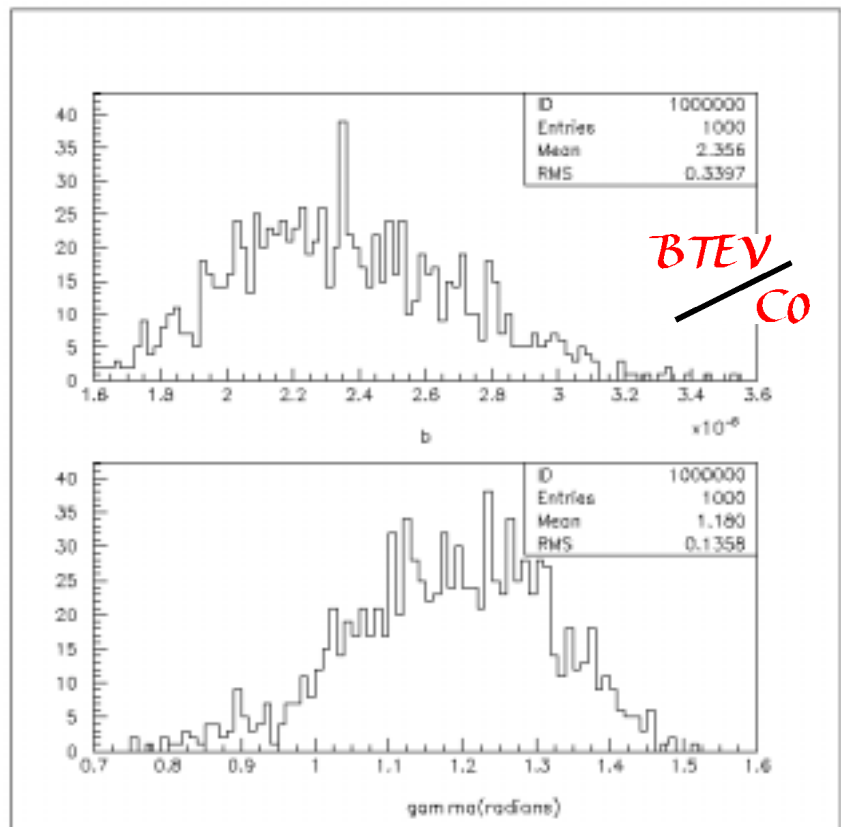
unknowns:

$$b, \xi, \delta, \gamma$$

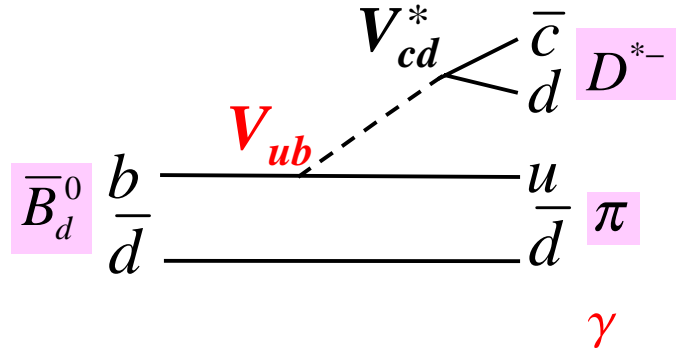
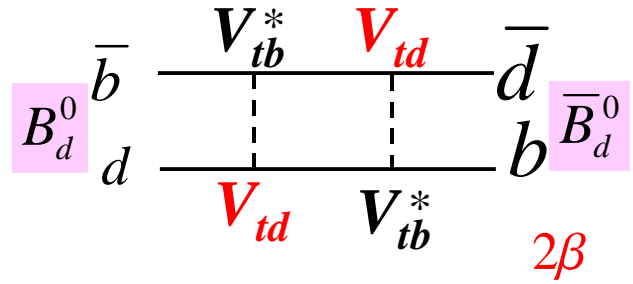
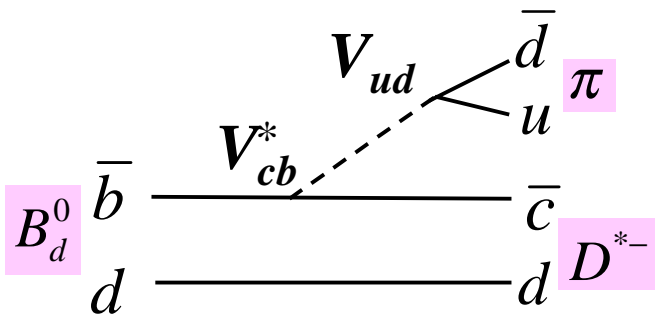
$$\gamma = 65^\circ \text{ (1.13 rad)}$$

$$b = 2.2 \times 10^{-6}$$

$$\sigma(\gamma) = 10^\circ$$



$$2\beta + \gamma \quad B_d^0 \rightarrow D^{*-} \pi^+$$



four time dependent decay rates:

$$B_d^0 \rightarrow D^{*-} \pi^+ \quad \bar{B}_d^0 \rightarrow D^{*-} \pi^+$$

$$\rightarrow D^{*+} \pi^- \quad \rightarrow D^{*+} \pi^-$$

no penguin diagrams:
clean det. of γ

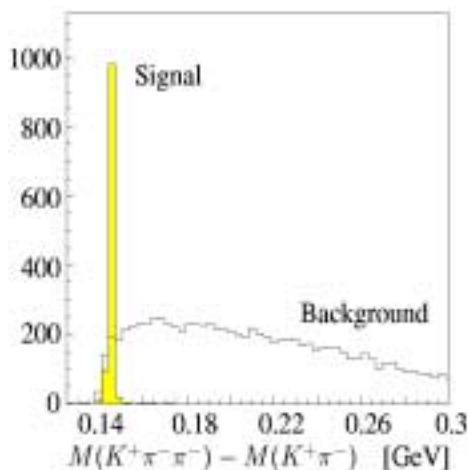
small asymmetry:
 V_{ub} suppressed

two asymmetries

- weak phase
- strong phase difference between tree diagrams

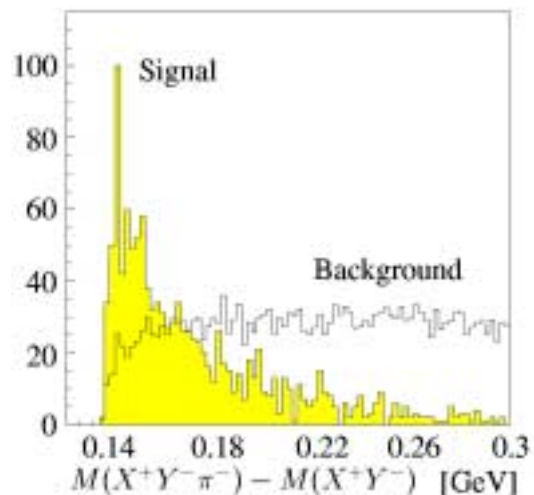
exclusive $D^* \pi$ reconstruction

~ 83k / year S/B ~ 12

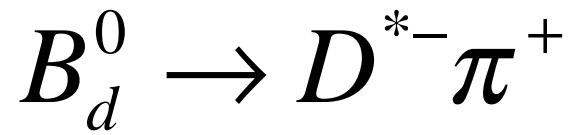


inclusive $D^* \pi$ reconstruction

~ 260k / year S/B ~ 3

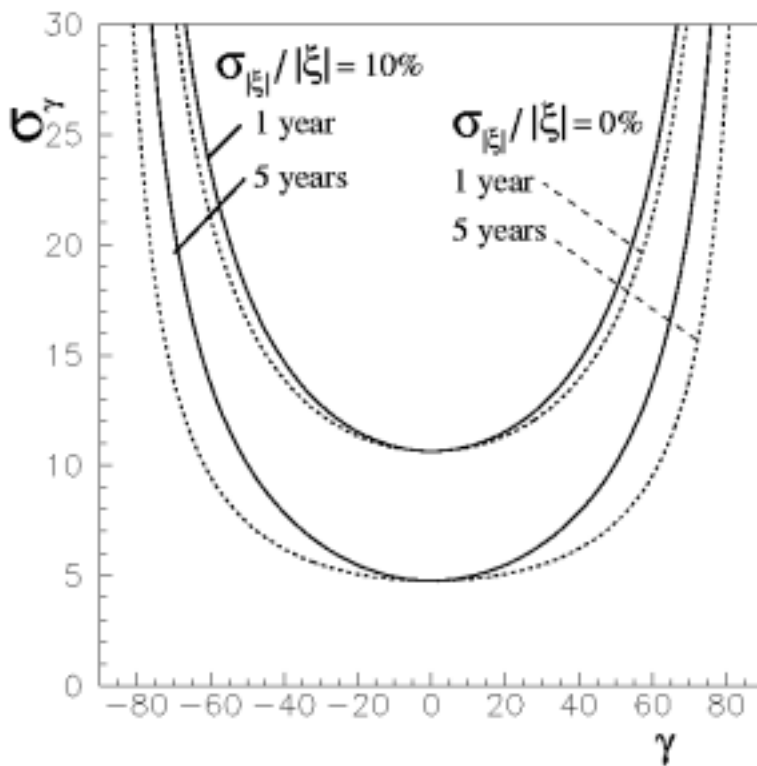


$$2\beta + \gamma$$



uncertainty due to:

$$|\xi| = \left| \frac{A(\bar{B}_d^0 \rightarrow D^{*+} \pi^-)}{A(B_d^0 \rightarrow D^{*+} \pi^-)} \right|$$



addition of $D^{*-} a_1$ channel: ~ 360k / year

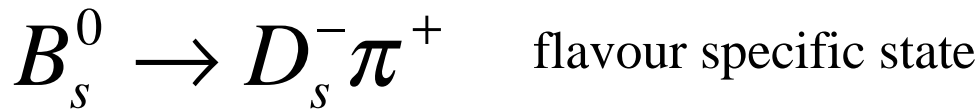
requires full
angular analysis

$B_s^0 - \bar{B}_s^0$ Mixing

- very important for flavour dynamics
- future hadron experiments: fully explore the B_s mixing

SM: $\Delta M_s = (14.3 - 26) \text{ ps}^{-1}$

$\Delta\Gamma_s / \Gamma_s = 10 - 20\%$



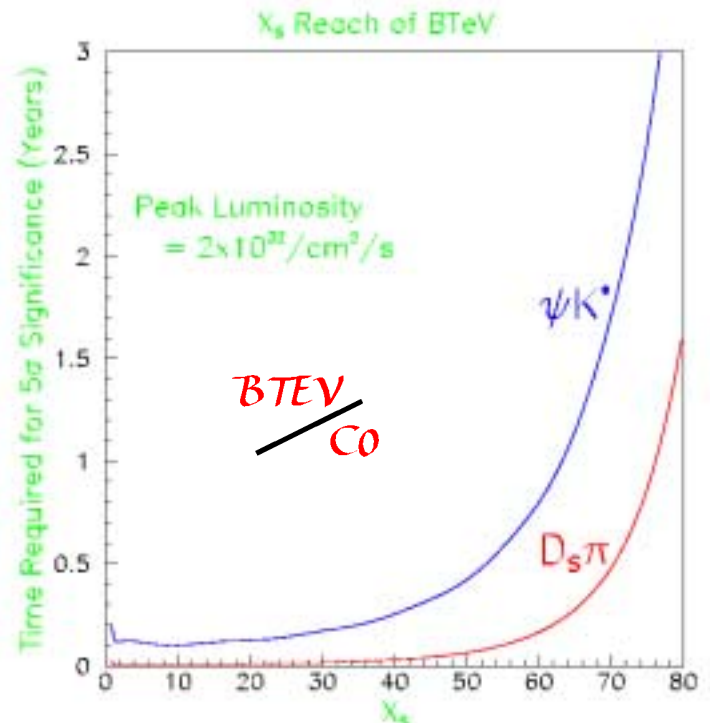
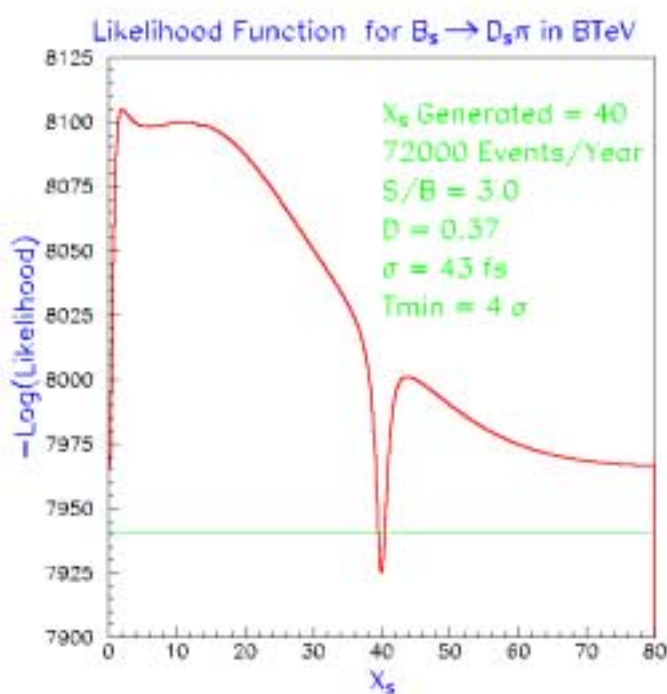
untagged: fit proper time distributions for $\Gamma_s, \Delta\Gamma_s / \Gamma_s$

tagged: ΔM_s

tagged $\sigma(\text{proper time})$

BTeV $D_s \rightarrow \phi\pi^-, K^* K^-$ 72k 43fs

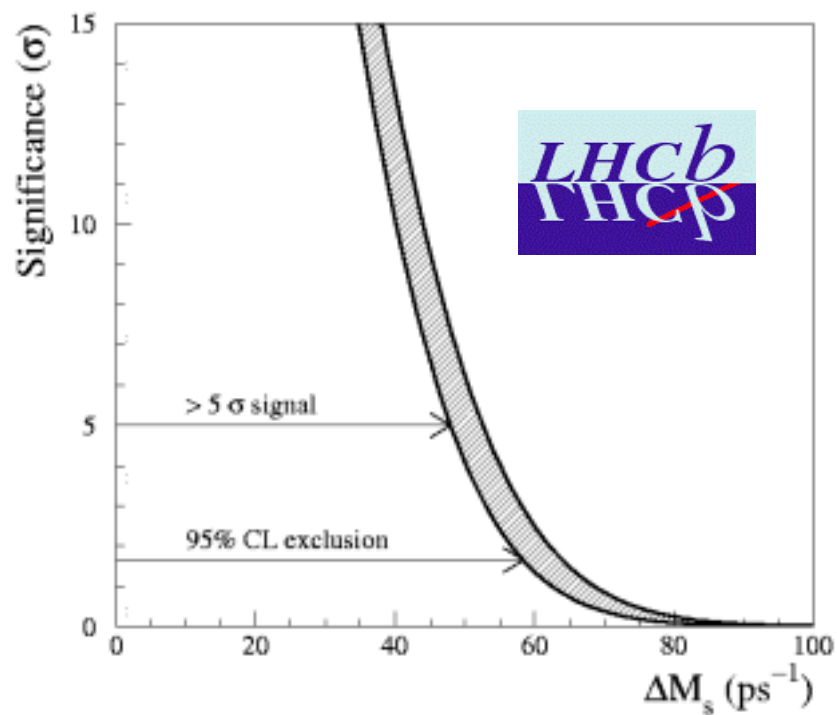
LHCb $D_s \rightarrow \phi\pi^-$ 34.5k 43fs



$B_s^0 - \bar{B}_s^0$ Mixing

Amplitude fit method: $A \cos(\Delta M_s t)$

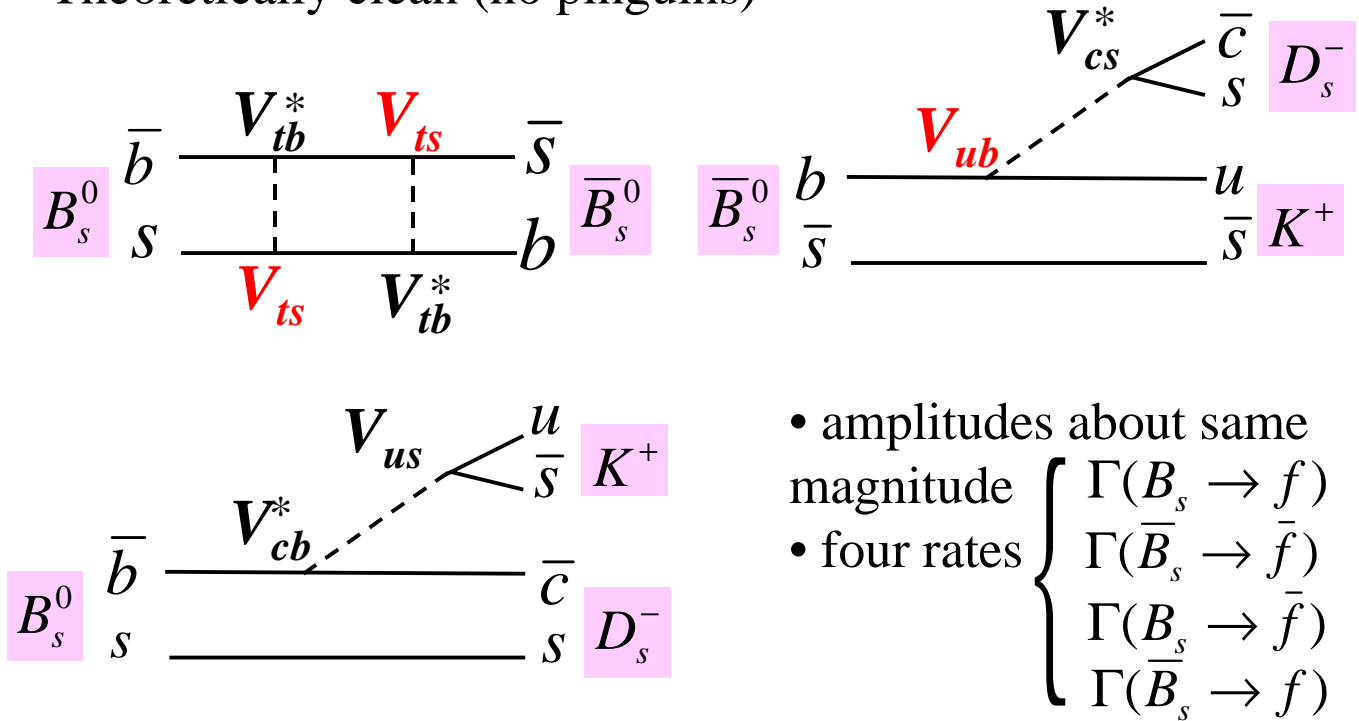
A, σ_A determined for each ΔM_s by a ML fit



$$\gamma - 2\delta\gamma \quad B_s^0 \longrightarrow D_s^\pm K^\mp$$

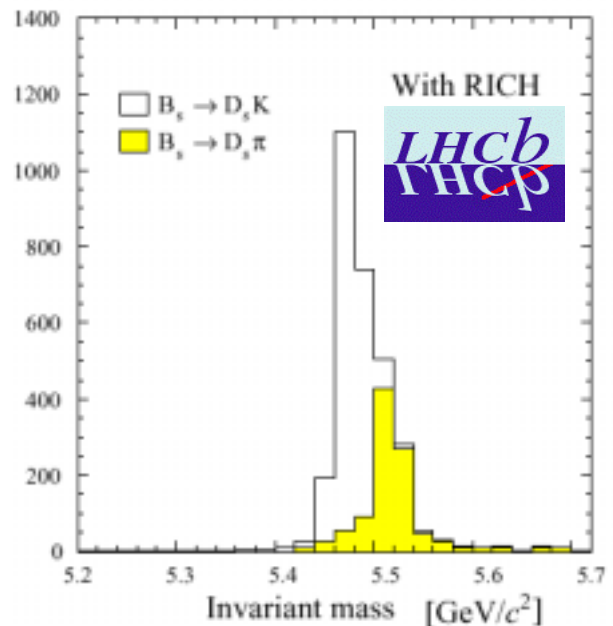
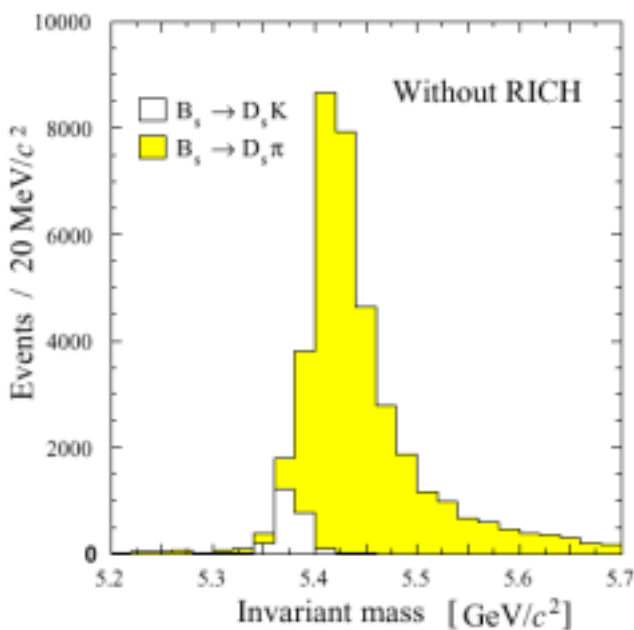
Interference of direct and mixing induced decays

Theoretically clean (no penguins)

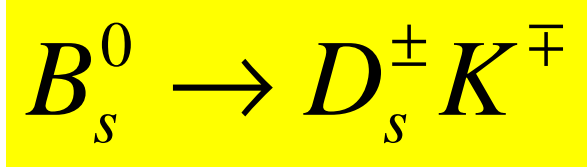


• two asymmetries

Hadron identification: $D_s \pi$ background

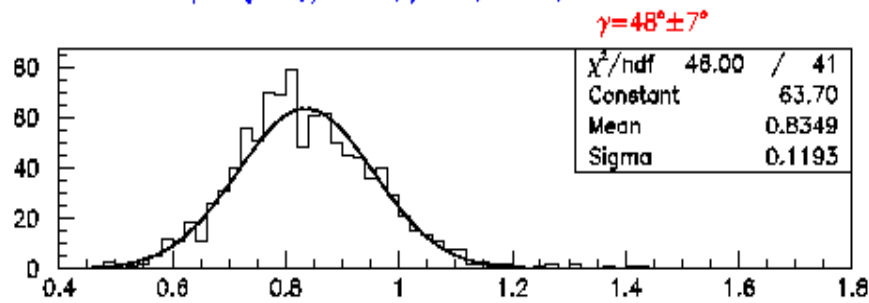


$$\gamma - 2\delta\gamma$$

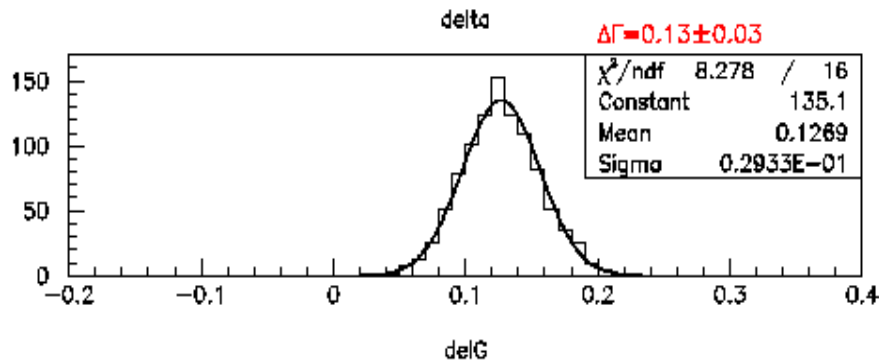
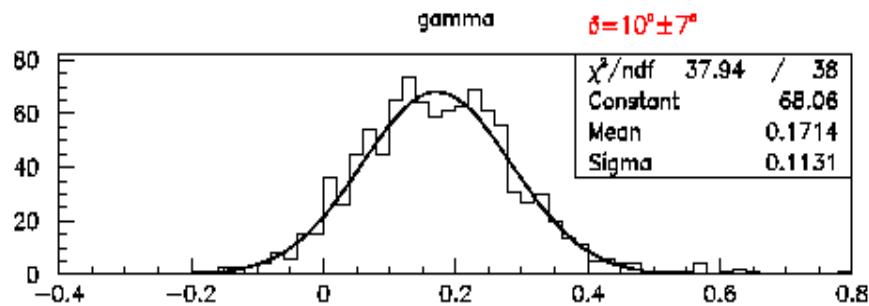


Sensitivity to: $\Delta\Gamma_s / \Gamma$ x_s δ $\rho = \left| \frac{A(B_s \rightarrow D_s^- K^+)}{A(B_s \rightarrow D_s^+ K^-)} \right|$

Input $x_s=30$, $\rho=0.71$, $\gamma=49^\circ$, $\delta=10^\circ$, $\Delta\Gamma=0.16$



BTeV
/ CO



events/1y $\sigma(\gamma - 2\delta\gamma)$

BTeV

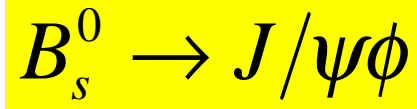
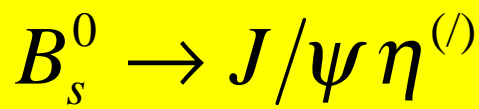
13.1k

$6^\circ - 15^\circ$

LHCb

6k

$3^\circ - 14^\circ$

$\delta\gamma$ 

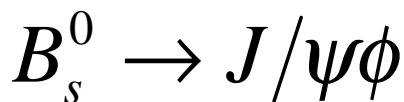
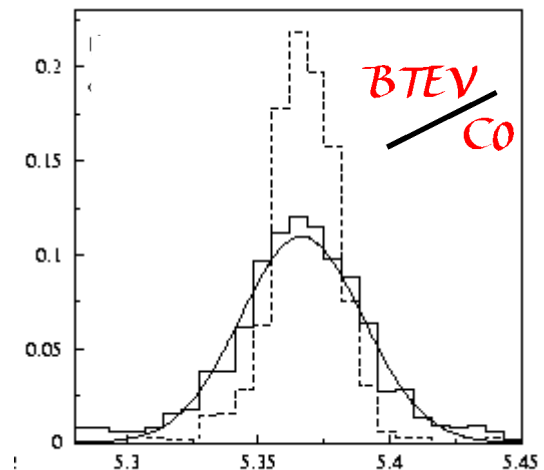
- dominated by one phase only
- very small CP violating effects (SM)
- sensitive probe for CP violating effects beyond the SM



- CP eigenstate
- direct extraction of $\sin(2\delta\gamma)$

	events/1y	$\sigma(\sin(2\delta\gamma))$
BTeV	9.2k	0.033 ($x_S=40$)

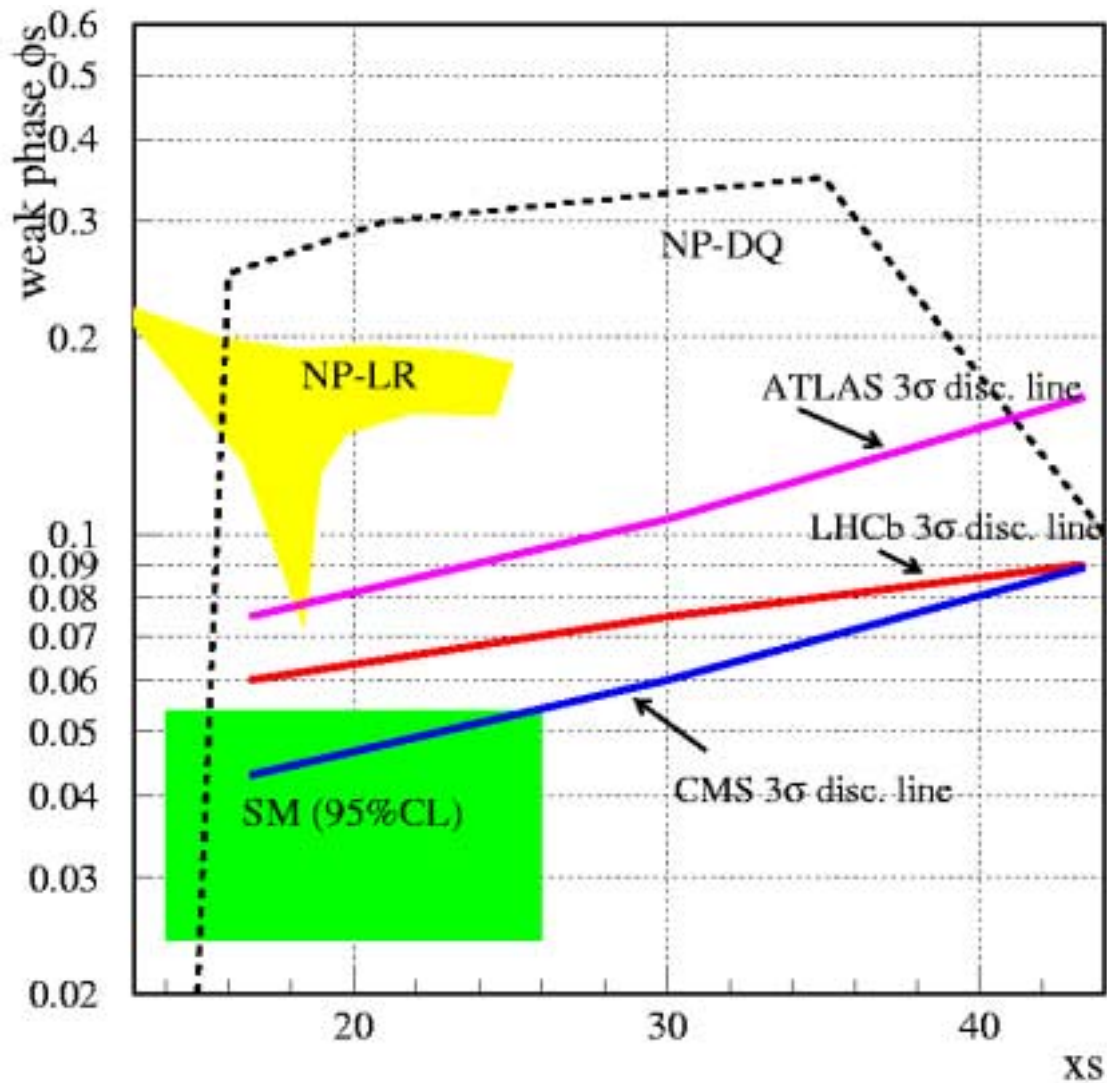
$\sigma = 19(11) \text{ MeV}/c^2$



- CP admixture
- clean experimental signature
- full angular analysis

	events	$\sigma(\sin(2\delta\gamma))$
LHCb	370k (5y)	0.03
CMS	600k (3y)	0.03 ($x_S=40$)

Sensitivity to New Physics



Transversity analysis

A. Dighe hep-ph/0102159 (CERN-TH/2001-034)

- simpler angular analysis with the transversity angle
- accuracy similar for same number of events
- if $\delta\gamma$ is large the advantage of $J/\psi\eta$ is lost

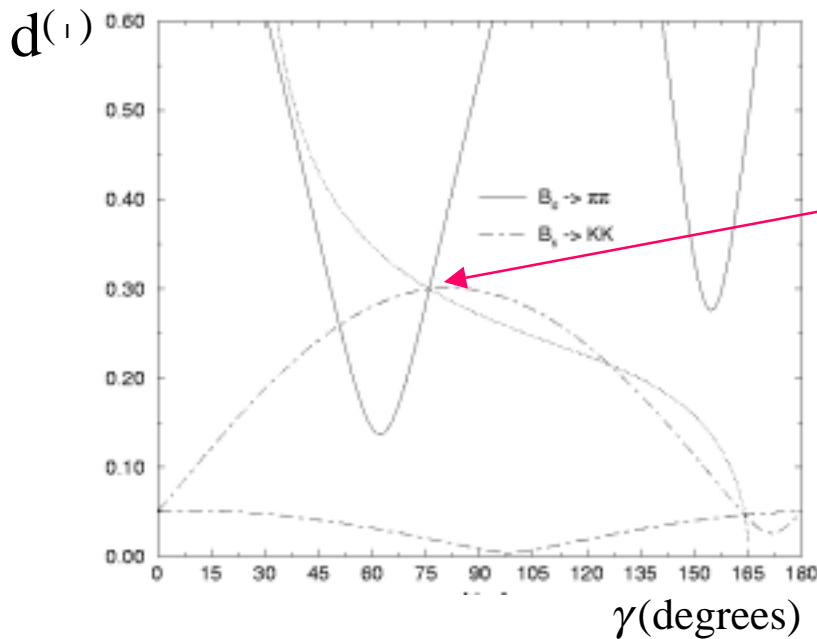
β, γ $B_d^0 \rightarrow \pi^+ \pi^-$ $B_s^0 \rightarrow K^+ K^-$

- related by U-spin symmetry ($u \leftrightarrow s$)
- makes use of penguins (sensitive to new physics...)
- four observables: $A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix}, A_{KK}^{dir}, A_{KK}^{mix}$
- seven unknowns: $\delta\gamma, \beta, \gamma, d, \theta, d', \theta'$

$$de^{i\theta} \equiv \frac{1}{R_b} \left(\frac{A_{pen}^{ct}}{A_{cc}^u + A_{pen}^{ut}} \right) \quad A_{pen}^{ut} \equiv A_{pen}^u - A_{pen}^t$$

- U-spin symmetry: $d' = d$
- input β and $\delta\gamma$

contour plots in the $\gamma - d$ and $\gamma - d'$ planes



$\gamma = 76^\circ$
 $d = d' = 0.3$
 $\beta = 53^\circ$

events/1y $\delta A_{KK}^{mix}, \delta A_{KK}^{dir}$ (5y) $\sigma(\gamma)$

BTeV

32.9k

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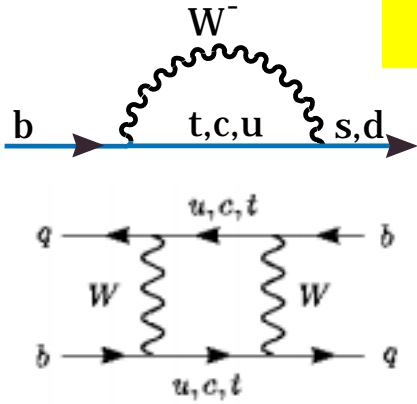
LHCb

9.5k

0.034

1.9°

Rare B decays



In the SM:

- flavour changing neutral currents only at loop level
- very small BR $\sim 10^{-5}$ or smaller

Excellent probe of indirect effects of new physics!

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

SM : BR $\sim 10^{-9}$

- observation of the decay
- measurement of its BR

	width MeV/c ²	signal	backg	
LHCb	26	33	10	(3y)
ATLAS	62	27	93	
CMS	26	21	3	

$$B_d \rightarrow \mu^+ \mu^-$$

SM : BR $\sim 10^{-10}$

- high sensitivity search

$$B_d \rightarrow \rho^0 \mu^+ \mu^-$$

- measure branching ratios
- study decay kinematics

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

$$B_d \rightarrow K^* \mu^+ \mu^-$$

	events/1y	S/B
BTeV	2.2k	11
LHCb	4.5k	16

Rare B decays

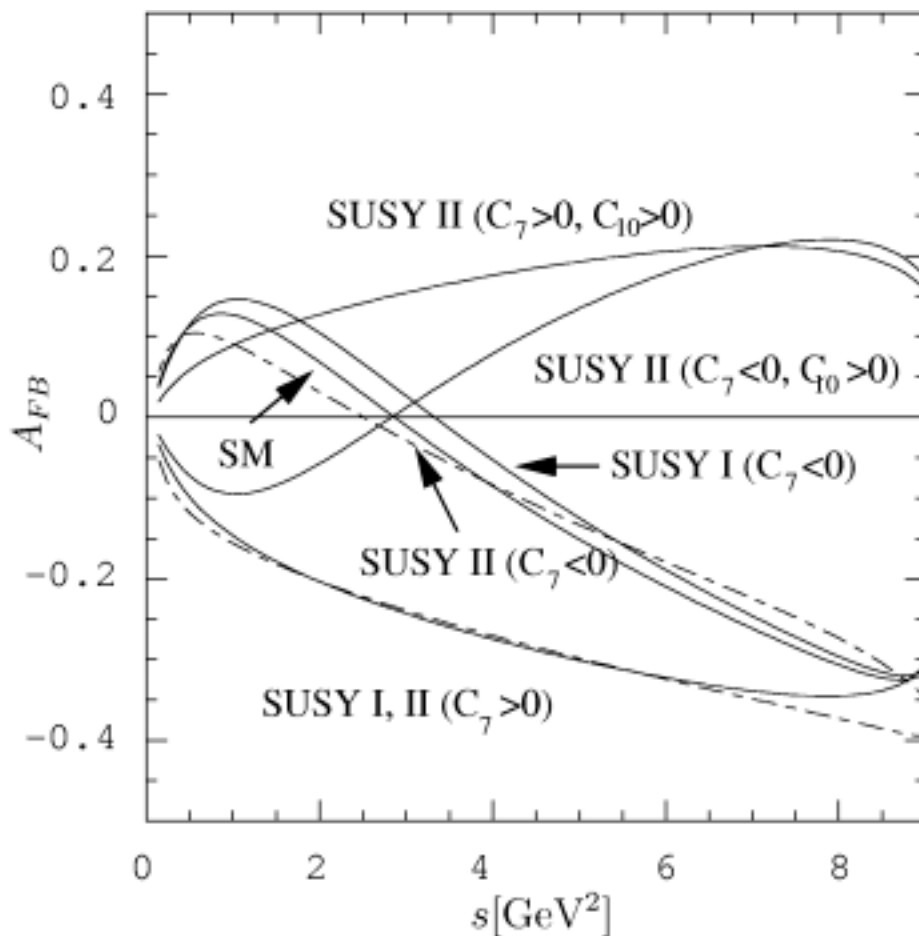
$$B_d \rightarrow K^* \mu^+ \mu^-$$

Forward-backward asymmetry $A_{FB}(s)$
 $s = (p_{\mu^+} + p_{\mu^-})^2$

can be calculated in SM and other models $A_{FB}(s_0) = 0$

$\delta A_{FB}(1y)$
LHCb 2.4% – 5.8%

A. Ali et al., Phys. Rev. D61
074024 (2000)



Physics summary (partial)

Parameter	Channels	BTeV	LHCb
$\sin(2\beta)$	$B_d \rightarrow J/\psi K_s$	0.025	0.021
α	$B_d \rightarrow \pi\pi$	$A(t)$ 0.024	--
		A^{mix} --	0.07
		A^{dir} --	0.09
$\sin(2\alpha)$	$B_d \rightarrow \rho\pi$	10°	3°- 6°
$2\beta+\gamma$	$B_d \rightarrow D^*\pi$	--	> 5°
$\gamma-2\delta\gamma$	$B_s \rightarrow D_s K$	6°-15°	3°-14°
γ	$B_d \rightarrow DK^*$	--	4° -14°
	$B^- \rightarrow D^0 K^-$	10°	--
	$B_d \rightarrow \pi\pi, B_s \rightarrow KK$	--	1.9° (5y)
$\sin(2\delta\gamma)$	$B_s \rightarrow J/\psi\phi$	--	0.03 (5y)
	$B_s \rightarrow J/\psi\eta$	0.033	--
Bs oscil.			
x_s	$B_s \rightarrow D_s\pi$	(up to) 75	(up to) 75
Rare Decays			
	$B_s \rightarrow \mu\mu$	--	11(3.3)
	$B_d \rightarrow K^* \mu\mu$	2.2k (0.2k)	22.4k(1.4k)

~~Other physics~~ topics: B_c mesons, baryons, charm, tau, b production, etc

Conclusions

BTeV and **LHCb** are second generation beauty CP violation experiments;

Both are well prepared to make crucial measurements in flavour physics with huge amount of statistics;

Impressive number of different strategies for measurements of *SM* parameters and search of **New Physics**;

Exciting times: understanding the origin of **CP violation in the SM and beyond.**