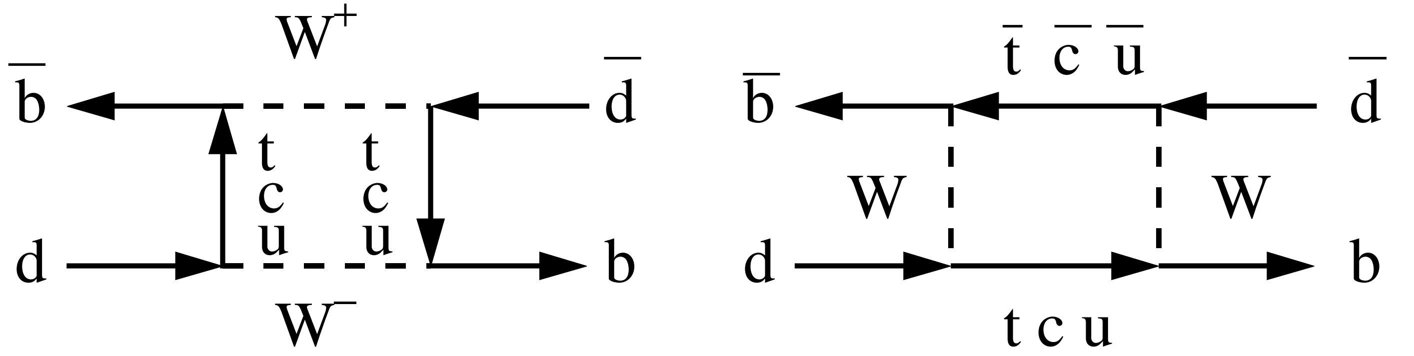
14) B-Meson System

a) Oscillations

M_{12}



very complex: t-$\bar{t}$, $\quad (V_{tb}\, V_{td}^{*})^2 \sim \lambda^6 \times \boldsymbol{m_t^2}$ ← **dominating term**

complex: t-$\bar{c}$+c-$\bar{t}$ $\quad 2 \times V_{tb}\, V_{td}^{*}\, V_{cb}\, V_{cd}^{*} \sim \lambda^6 \times m_t\, m_c$

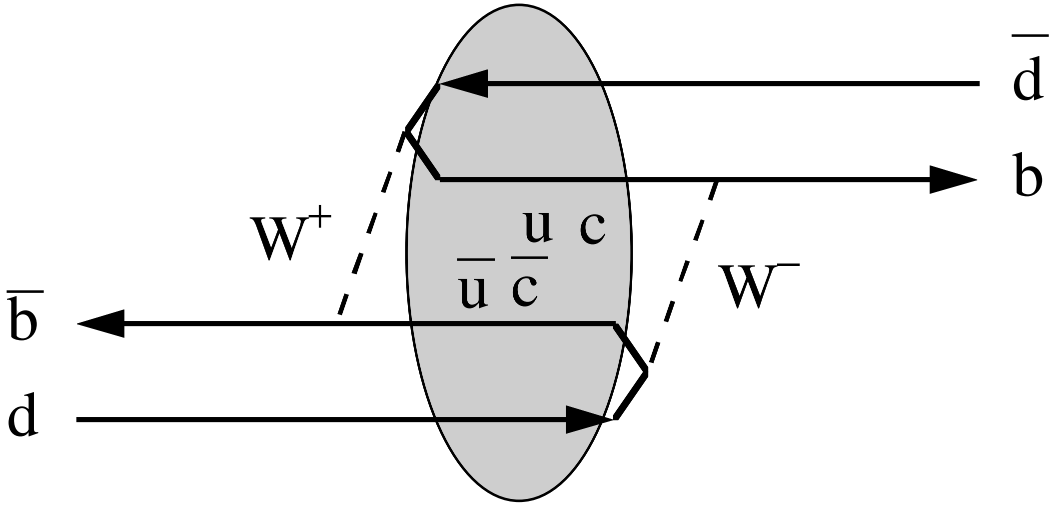
only slightly complex:c-$\bar{c}$, $\quad (V_{cb} V_{cd}^{*})^2 \sim \lambda^6 \times m_c^2$

$M_{12} \propto (V_{tb}\, V_{td}^{*})^2$ $\qquad$ i.e. $\arg M_{12} = \arg\, (V_{tb}\, V_{td}^{*})^2$

($= -2 \arg V_{td}$ in the Wolfenstein's parametrization)

M_{12} is **very** complex if $\eta \sim 1$

Γ_{12}



very complex: u-$\bar{u}$, $(V_{ub} V_{ud}^*)^2 \sim \lambda^6$

complex: u-$\bar{c}$+c-$\bar{u}$ $2 \times V_{ub} V_{ud}^* V_{cb} V_{cd}^* \sim 2 \times \lambda^6$

only slightly complex:c-$\bar{c}$, $(V_{cb} V_{cd}^*)^2 \sim \lambda^6$

CKM unitarity relation: $V_{tb} V_{td}^{*} = -V_{cb} V_{cd}^{*} - V_{ub} V_{ud}^{*}$

$$(V_{tb} V_{td}^{*})^2 = (V_{cb} V_{cd}^{*})^2 + (V_{ub} V_{ud}^{*})^2 + 2 V_{cb} V_{cd}^{*} V_{ub} V_{ud}^{*}$$

If $m_u = m_c = m_t \quad \arg M_{12} = \arg \Gamma_{12}$

No CP violation (GIM)

In reality $m_u << m_c << m_t$

$$\frac{\Delta\Gamma}{\Delta m} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \approx \left(\frac{m_b}{m_t}\right)^2 = O\left(10^{-3}\right) << 1$$

for both B_d and B_s

$$\alpha = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} + \frac{i}{2}\Gamma_{12}}} \approx \left(1 - \frac{1}{2}\underbrace{\mathrm{Im}\frac{\Gamma_{12}}{M_{12}}}_{O(10^{-3})}\right) e^{-i(\arg M_{12} + \pi)}$$

$|a| = 1 + O(10^{-3})$ CP violation in B-$\bar{\mathrm{B}}$ oscillations SMALL

$$\boxed{\begin{array}{ll} \alpha \approx e^{-i(\pi + 2\arg V_{td})} & \mathrm{B_d} \\ \alpha \approx e^{-i(\pi + 2\arg V_{ts})} & \mathrm{B_s} \end{array}}$$

***Γ*₁₂: Unlikely to be affected by new physics**

M_{12}: Could be affected by new physics

$\Delta\Gamma/\Delta m \sim O(10^{-3})$ for both B_s and B_d

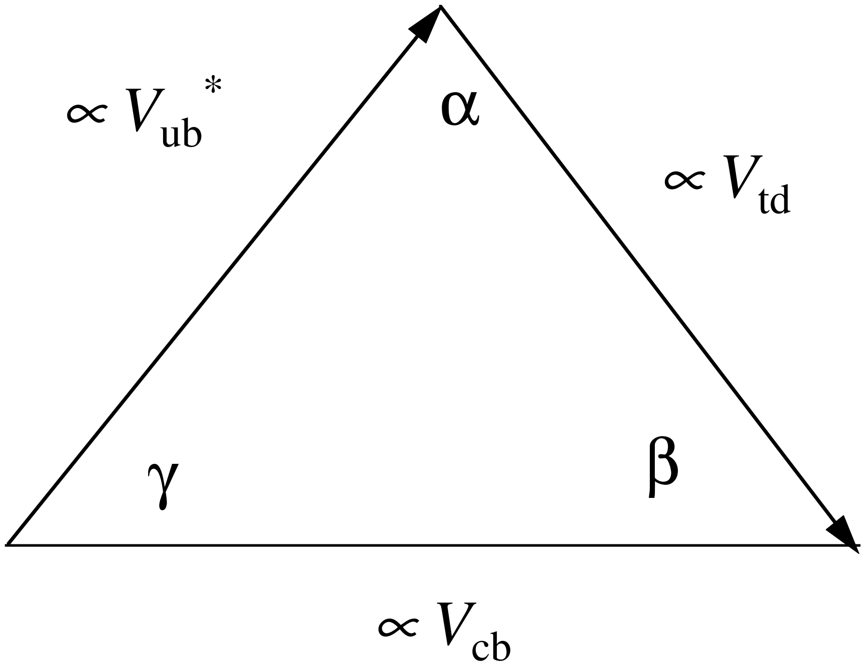
$\Delta\Gamma/(\Gamma_+ + \Gamma_-) = 10^{-3}$ for B_d (using measured B_d lifetime)

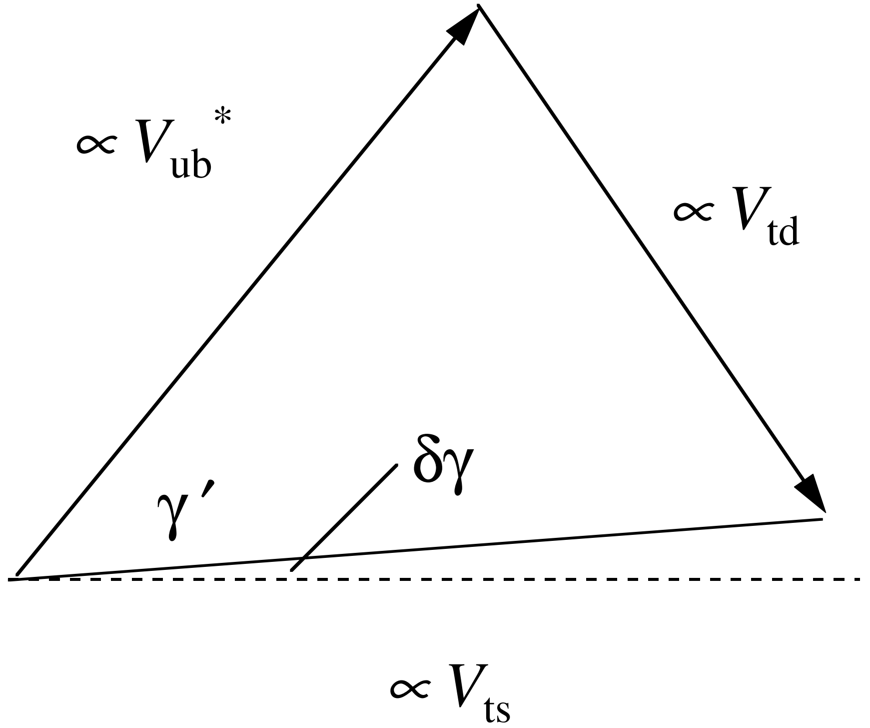
$\Delta m(B_s)/\Delta m(B_d) = |V_{ts}/V_{td}|^2 = 1/\lambda^2 \sim 20$

$\Delta\Gamma/(\Gamma_+ + \Gamma_-) \sim 0.1$ for B_s not negligible

b) Unitarity triangle

$$V_{td}\, V_{tb}^{\;*} + V_{cd}\, V_{cb}^{\;*} + V_{ud}\, V_{ub}^{\;*} = 0 \qquad V_{td}\, V_{ud}^{\;*} + V_{ts}\, V_{us}^{\;*} + V_{tb}\, V_{ub}^{\;*} = 0$$





$$\arg V_{cb} = 0\,,\ \arg V_{ub} = -\gamma,\ \arg V_{td} = -\beta\,,\ \arg V_{ts} = \pi + \gamma - \gamma'$$

$$\boxed{\mathrm{B_d}\!: \alpha \approx e^{-i\,2\,\beta} \qquad \mathrm{B_s}\!: \alpha \approx e^{\;\imath\, 2\,\delta\gamma}}$$

c) Time evolution

B^0 at $t = 0$

$$\left|B^0(t)\right\rangle = f_+(t)\left|B^0\right\rangle + e^{-i2\beta} f_-(t)\left|\overline{B}^0\right\rangle$$

$$= \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t}\left|B_l\right\rangle + e^{-im_h t}\left|B_h\right\rangle\right)$$

$$\left|B_{l,h}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B^0\right\rangle \pm e^{-i2\beta}\left|\overline{B}^0\right\rangle\right)$$

$$f_\pm(t) = \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t} \pm e^{-im_h t}\right)$$

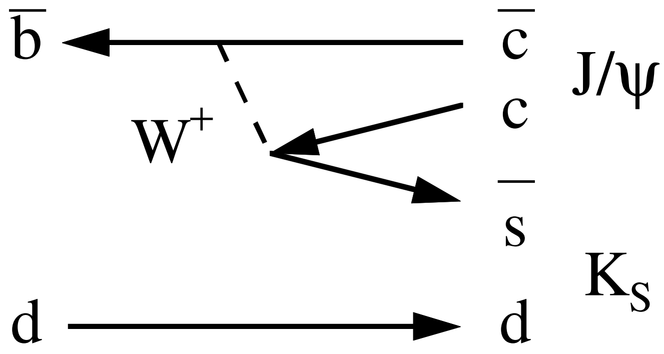
$\overline{B}^0$ at $t = 0$

$$\left|\overline{B}^0(t)\right\rangle = e^{i2\beta} f_-(t)\left|B^0\right\rangle + f_+(t)\left|\overline{B}^0\right\rangle$$

$$= \frac{e^{-\Gamma t/2}}{2}\left(e^{-im_l t}\left|B_l\right\rangle - e^{-im_h t}\left|B_h\right\rangle\right)$$

d) CP violation parameters

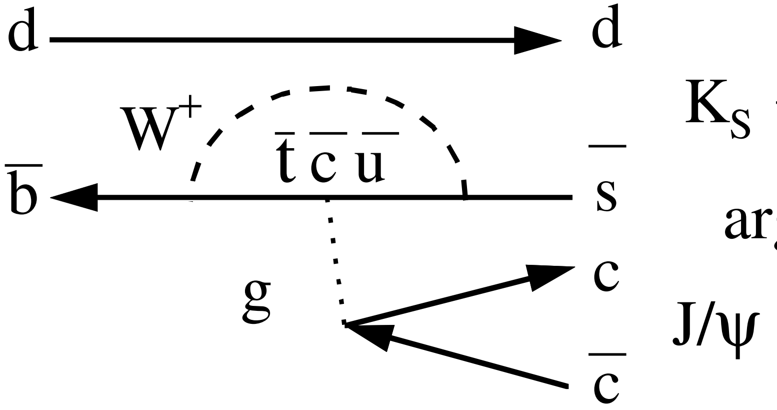
$J/\psi\ K_S$



$K_S \longrightarrow \pi\,\pi$

λ^2

$\arg\,(V_{cb}{}^* V_{cs} V_{us}{}^* V_{ud}\,) = 0$



$K_S \longrightarrow \pi\,\pi$ $\quad \lambda^2 \times \alpha_s$

$\arg\,(\,V_{tb}{}^* V_{ts} V_{us}{}^* V_{ud}\,) = -\,\delta\gamma + \pi$

very small

$\propto \lambda^2$

$\arg A_{J/\psi\,K_S} \approx 0$ with a very good approximation

$$\mathrm{CP}\,(\mathrm{J}/\psi\ \mathrm{K_S}) = -1, \qquad \overline{A}_{\mathrm{J}/\psi\ \mathrm{K_S}} \,/\, A_{\mathrm{J}/\psi\ \mathrm{K_S}} = -1$$

with absence of CP violation $\mathrm{CP(B_l)} = +1$, $\mathrm{CP(B_h)} = -1$

like K system

$$\eta_{\mathrm{J}/\psi \mathrm{K_S}} = \frac{\langle \mathrm{J}/\psi\, \mathrm{K_S} | H_{\mathrm{W}} | \mathrm{B_l} \rangle}{\langle \mathrm{J}/\psi\, \mathrm{K_S} | H_{\mathrm{W}} | \mathrm{B_h} \rangle}$$

$$= \frac{A_{\mathrm{J}/\psi \mathrm{K_S}} + e^{-i2\beta}\overline{A}_{\mathrm{J}/\psi \mathrm{K_S}}}{A_{\mathrm{J}/\psi \mathrm{K_S}} - e^{-i2\beta}\overline{A}_{\mathrm{J}/\psi \mathrm{K_S}}}$$

$$= \frac{1 - e^{-i2\beta}}{1 + e^{-i2\beta}}$$

$$= \frac{i \sin 2\beta}{1 + \cos 2\beta} \longrightarrow \text{pure imaginary}$$

$$\boxed{\text{CP violation in the interplay between the oscillation and decay}}$$

Time dependent decay rates

$$\Gamma_{J/\psi K_S}(t) = \left| \left\langle J/\psi\, K_S \middle| H_W \middle| B^0(t) \right\rangle \right|^2$$

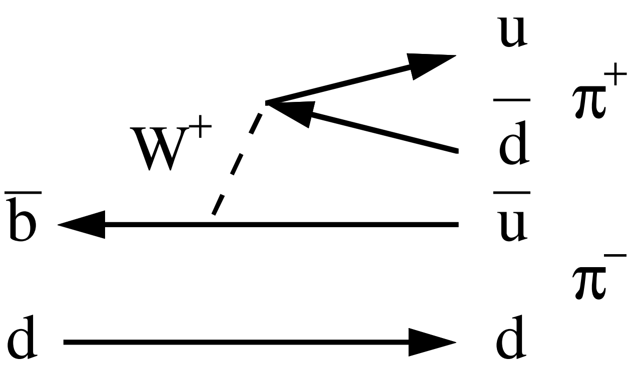
$$= \frac{e^{-\Gamma t}}{4} \left| e^{i\Delta m t} \left\langle J/\psi\, K_S \middle| H_W \middle| B_l \right\rangle + \left\langle J/\psi\, K_S \middle| H_W \middle| B_h \right\rangle \right|^2$$

$$= \frac{\left| A_h^{J/\psi\, K_S} \right|^2}{4} e^{-\Gamma t} \left| e^{i\Delta m t} \eta_{J/\psi\, K_S} + 1 \right|^2$$

$$= \frac{\left| A_h^{J/\psi\, K_S} \right|^2}{4(1+\cos 2\beta)} e^{-\Gamma t} (1 - \sin 2\beta \times \sin \Delta m t)$$

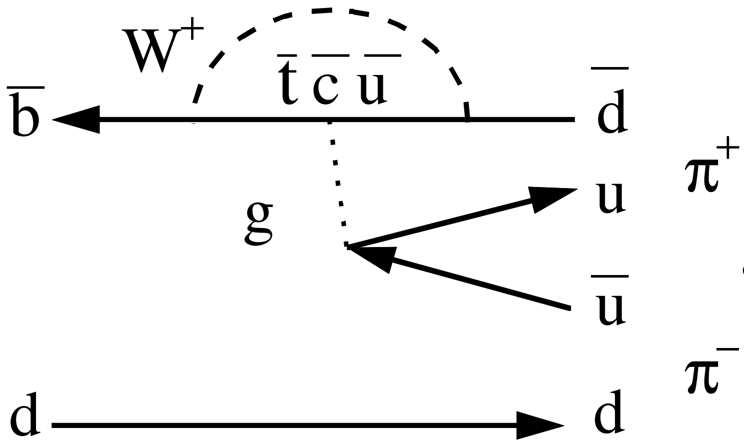
$$\overline{\Gamma}_{J/\psi K_S}(t) == \frac{\left| A_h^{J/\psi\, K_S} \right|^2}{4(1+\cos 2\beta)} e^{-\Gamma t} (1 + \sin 2\beta \times \sin \Delta m t)$$

$\pi^+\pi^-$



λ^3

$\arg\,(V_{ub}{}^{*}\,V_{ud}\,) = \gamma$



$\lambda^3 \times \alpha_s$

$\arg\,(\,V_{tb}{}^{*}V_{td}\,) = -\,\beta$

$\arg A_{J/\psi\, K_S} \approx \gamma - \beta{\times}\text{penguin}$

strong phase, rescattering, etc. etc.
wait for some more theoretical works.....

if we neglect penguin,

$$\eta_{\pi^+\pi^-} = \frac{\left\langle \pi^+\pi^- \middle| H_{\mathrm{W}} \middle| \mathrm{B_h} \right\rangle}{\left\langle \pi^+\pi^- \middle| H_{\mathrm{W}} \middle| \mathrm{B_l} \right\rangle}$$

$$= \frac{1 - e^{-i2\beta} e^{-i2\gamma}}{1 + e^{-i2\beta} e^{-i2\gamma}}$$

$$= \frac{i \sin 2(\beta + \gamma)}{1 + \cos 2(\beta + \gamma)}$$

$$= \frac{i \sin 2\alpha}{1 - \cos 2\alpha}$$

$\gamma' + \delta\gamma$ can be measured by studying the oscillation amplitudes for $B_s \to D_s^- K^+$, $D_s^+ K^-$ and $\overline{B}_s \to D_s^- K^+$, $D_s^+ K^-$

requires very good decay time resolution

background $B_s \to D_s \pi$ ~20 times larger branching fraction

particle identification

$\delta\gamma$ can be measured by studying the oscillation amplitudes for $B_s \to J/\psi\ \phi$ and $\overline{B}_s \to J/\psi\ \phi$

requires very good decay time resolution

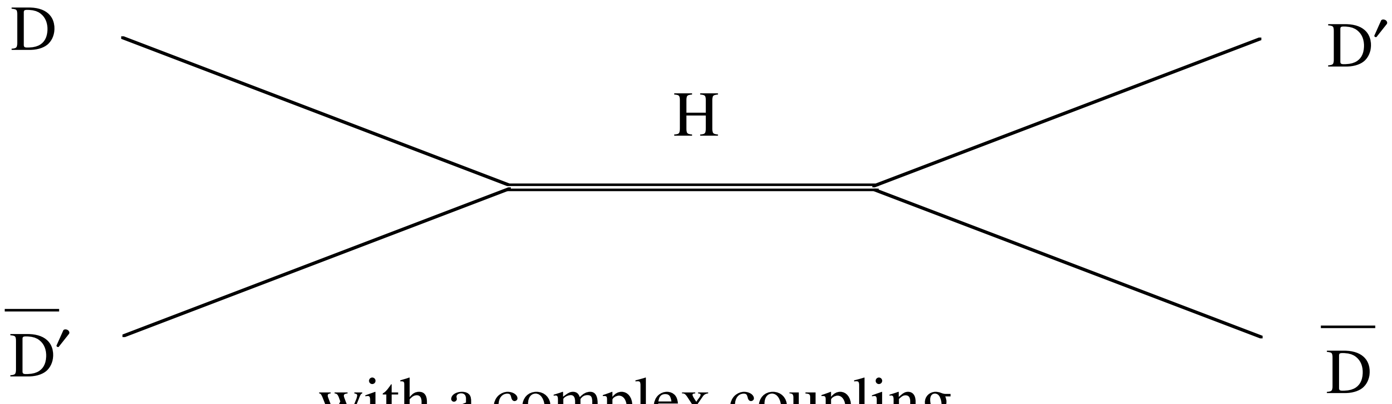
orbital angular momentum configuration needed

very small expected effect

15) An Alternative Model

A toy model

Flavour Changing Neutral Current (FCNC)
of a Higgs type



with a complex coupling
proportional to the quark mass

$$M_{12} = \mathrm{CKM}_{box} + \mathrm{H}_{tree}$$

$$\Gamma_{12} = (\mathrm{CKM}_{tree} + \cancel{\mathrm{H}_{loop}})^2$$

An extreme example: CKM = real

$$\frac{\operatorname{Im} M_{12}}{|M_{12}|} = \frac{\operatorname{Im} \mathrm{H\text{ - }tree}}{\Delta m}$$

from the observed small CP violation in $\varphi_{M-\Gamma}$ in the kaon system $\longrightarrow$ $\dfrac{\mathrm{H_{tree}(K)}}{\mathrm{CKM_{box}(K)}} << 1$

$$\frac{\mathrm{H_{tree}(B)}}{\mathrm{H_{tree}(K)}} = \frac{m_b}{m_s} >> 1$$

$$\downarrow$$

$$\frac{\mathrm{H_{tree}(B)}}{\mathrm{CKM_{box}(B)}} \approx 1$$

$$\frac{\operatorname{Im} M_{12}}{|M_{12}|} = \frac{\operatorname{Im} \mathrm{H_{tree}(B)}}{\Delta m}$$

is large due to $\mathrm{H_{tree}(B)}$

$\arg M_{12}$ = large

However..., $\mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$ is still small since Γ_{12} is small.

CP violation in B-$\overline{\mathrm{B}}$ oscillations is small.

$$\boxed{\alpha \approx e^{-i(\pi + \alpha_{\mathrm{H}})} \qquad \mathrm{B_d}}$$

$$\eta_{\mathrm{J/yK_s}} = \eta_{\pi^+\pi^-} = \frac{i\sin\alpha_{\mathrm{H}}}{1+\cos\alpha_{\mathrm{H}}}$$

The reality could be a mixture of
CKM-phase + H-phase....

Need to study CP violation in different decay modes.

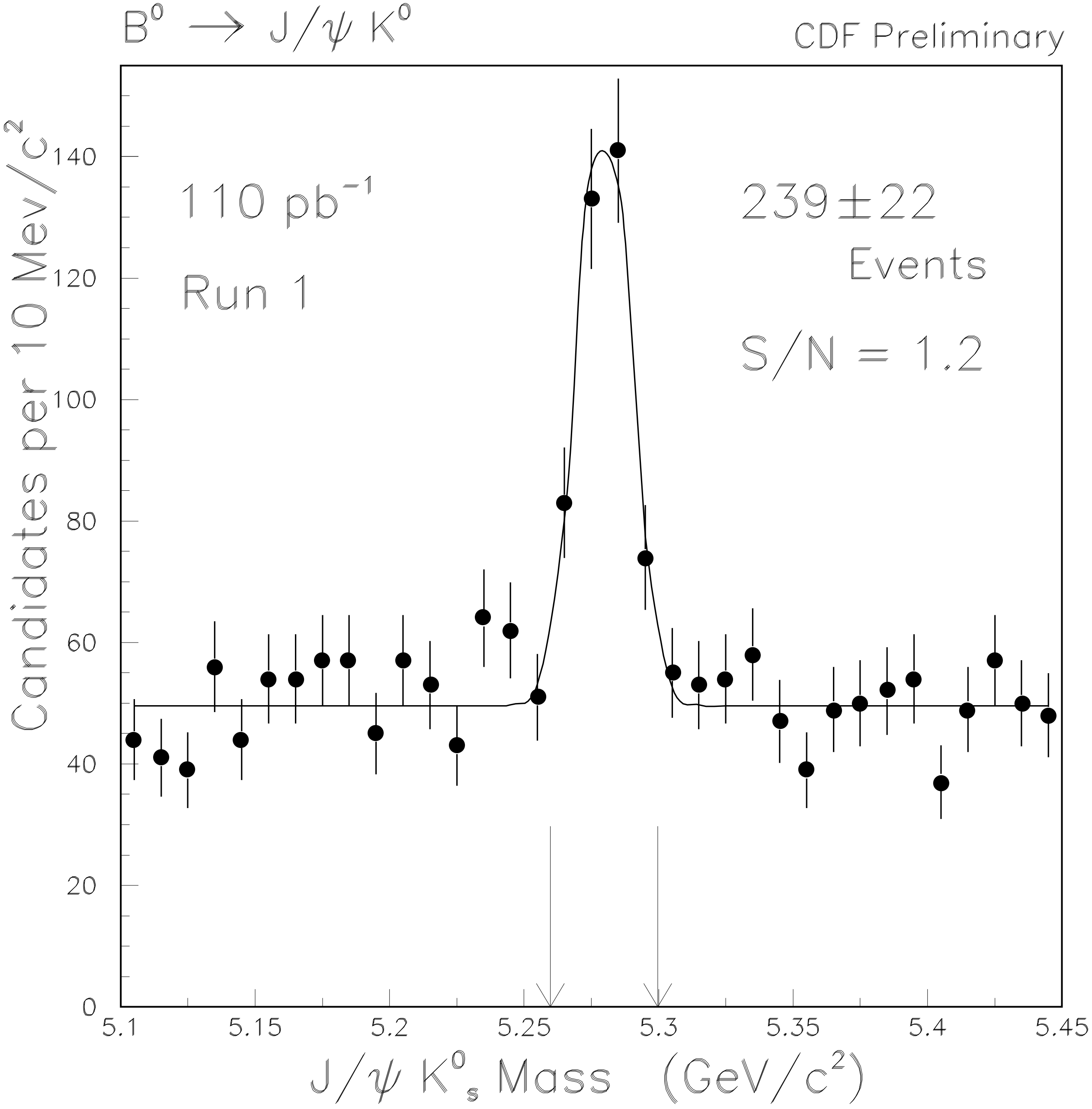
16) Future Experiments in the B-Meson System

B Physics in near future (~2000)

	electron-positron colliders	hadron machines	
	KEKB, PEP-II	Tevatron	HERA
energies	at $\Upsilon(4S)$	$p+\bar{p}$ at 1.8 TeV	p+Cu at 40 GeV
$\sigma_{b\bar{b}}$	~1 nb	~100 μb	~760 nb
$\sigma_{b\bar{b}}/\sigma_{\mathrm{inelastic}}$	2.5×10^{-1}	2×10^{-3}	10^{-6}
	No B_s unless running at $\Upsilon(5S)$ and General B physics		

Experiments by ~2000
Physics with 10^8 effective B-mesons

	BELLE BABAR	CDF D0	HEAR-B
	K/π separation	**no** K/π separation	K/π separation
		high p_t track trigger μ	high p_t track trigger μ+hadron
$\sigma_{\sin 2\beta}(J/\psi\, K_S)$	0.08	0.08	0.13
$\sigma_{\sin 2\alpha}(\pi^+\pi^-)$	0.15	0.10 (background)	0.14
$\sigma_\gamma(DK^*)$	12°	-	-
x_s	not compatible with CP	?	<17



$B^0 \to J/\psi K^0$
CDF Preliminary
110 pb^{-1}
Run 1
239±22 Events
S/N = 1.2
Candidates per 10 Mev/c^2
$J/\psi K^0_s$ Mass (GeV/c^2)
0
20
40
60
80
100
120
140
5.1
5.15
5.2
5.25
5.3
5.35
5.4
5.45

Long term future (>2005)
Physics with $>10^9$ effective B-mesons

	Tevatron	LHC
energies	$p+\bar{p}$ at 1.8 TeV	p+p at 14 TeV
$\sigma_{b\bar{b}}$	~100 μb	~500 μb
$\sigma_{b\bar{b}}/\sigma_{inelastic}$	2×10^{-3}	5×10^{-3}
Experiments	BTeV ?	ATLAS, CMS, LHC-B

LHC

General purpose high p_t detectors

ATLAS and CMS: central region

very good lepton detection

high p_t lepton trigger

ATLAS	single muon; p_t > 6 GeV/c
CMS	single muon; p_t > 9 GeV/c
	single electron: p_t > 10 GeV/c
	$B \to \pi^+\pi^+$
	dimuon; p_t > 2.6~5.4 GeV/c
	$B \to J/\psi\ K_s$

J/ψ ATLAS: $\mu + e$ CMS: μ

$B \to J/\psi\ K_s$

$B_s \to \mu^+\mu^-$

$\sigma(\sin 2\beta) = 0.02\text{~}0.06$

no particle identification

$B \rightarrow \pi\pi$, $K\pi$, KK cannot be clearly separated

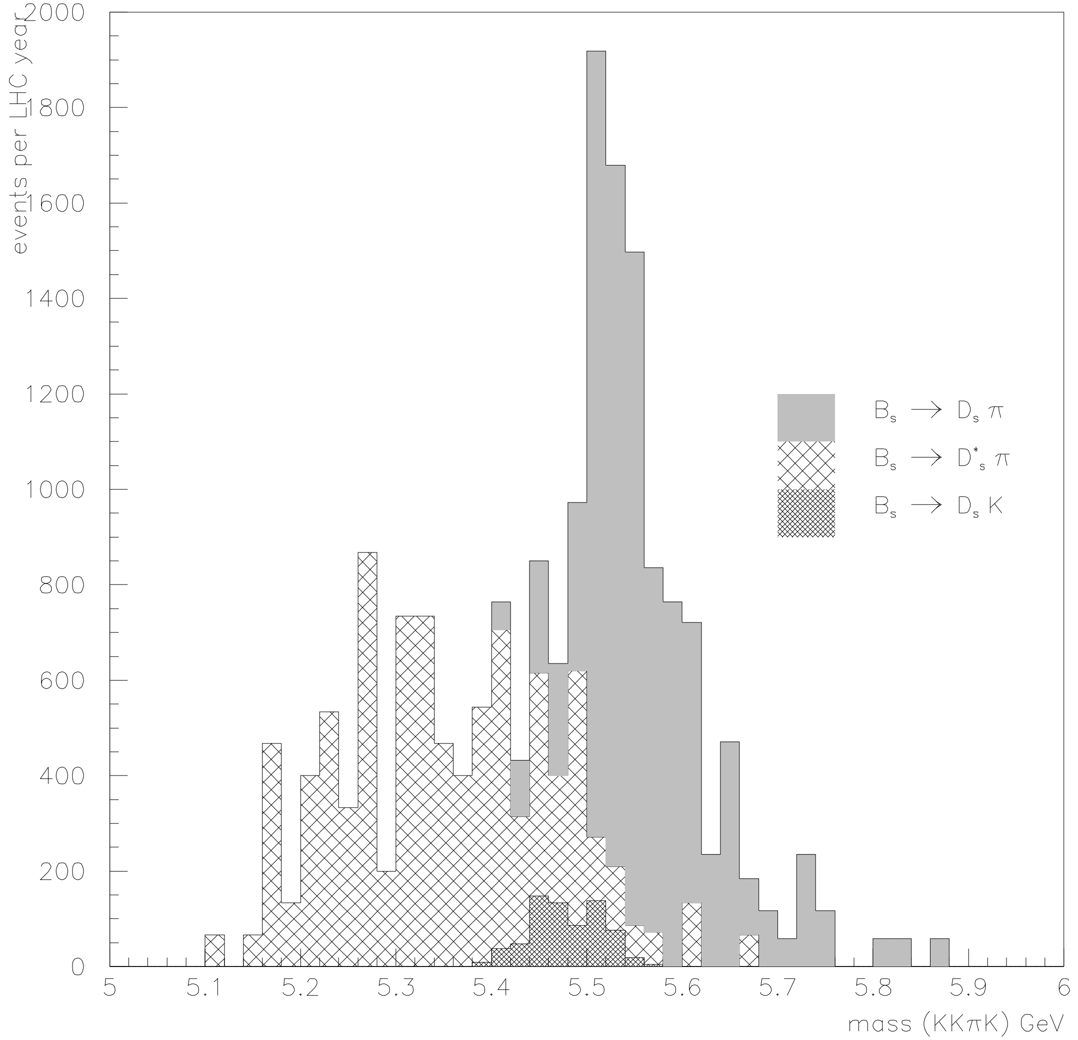
systematic uncertainty in $\sin 2\alpha$ extraction

$B \rightarrow K\pi$ allows to study the penguins
CP effect is also expected in $B \rightarrow K\pi$

$B_s \rightarrow D_s\, \pi$, D_s K cannot be clearly separated

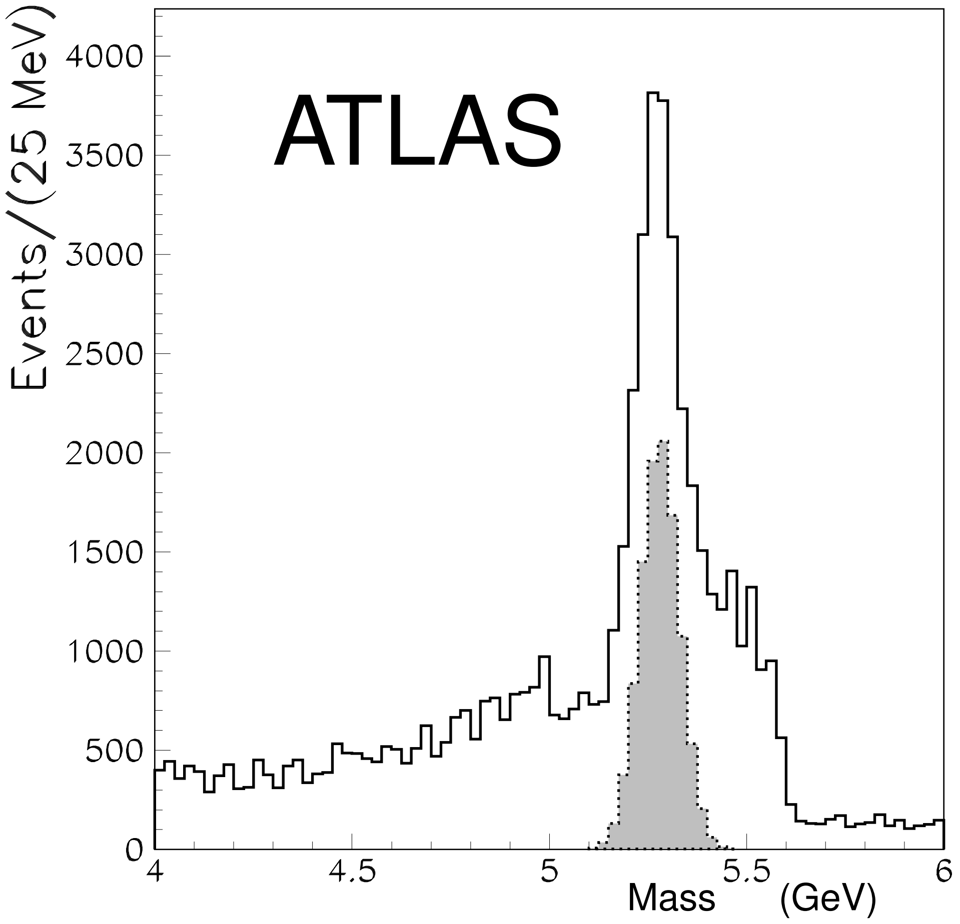
no γ extraction

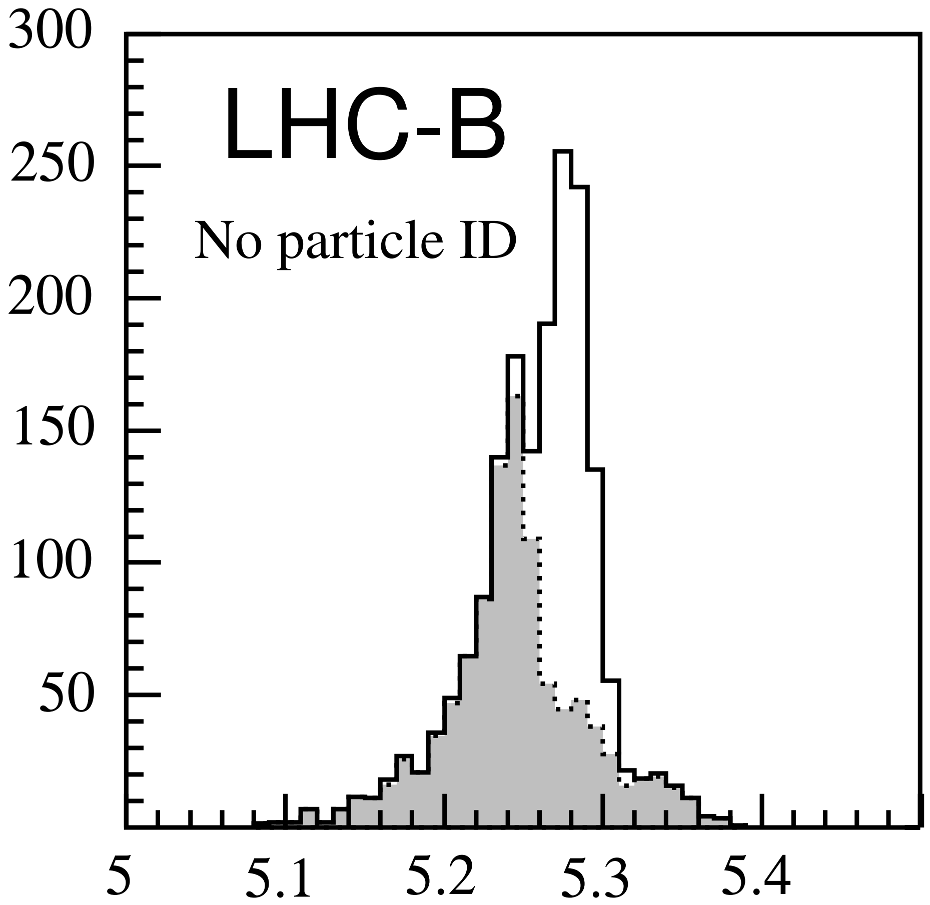
$B_s \rightarrow J/\psi\ \phi$ measures $\lambda^2\eta$ **and not** γ!!



events per LHC year
2000
1800
1600
1400
1200
1000
800
600
400
200
0
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
6
mass (KKπK) GeV
$B_s \rightarrow D_s\ \pi$
$B_s \rightarrow D^*_s\ \pi$
$B_s \rightarrow D_s\ K$

$B \to \pi^+\pi^-$


ATLAS
Events/(25 MeV)
0
500
1000
1500
2000
2500
3000
3500
4000
4
4.5
5
5.5
6
Mass (GeV)


LHC-B
No particle ID
50
100
150
200
250
300
5
5.1
5.2
5.3
5.4

LHC-B: a dedicated experiment to study
CP violation in B-meson decays
-a **forward** magnet spectrometer working in
pp **colliding mode**-

forward **efficient high p_t trigger**

muon	> 1.25 GeV/c	
electron	> 1.1 GeV/c	**low threshold values**
dihadron	> 3 and 2 GeV/c	

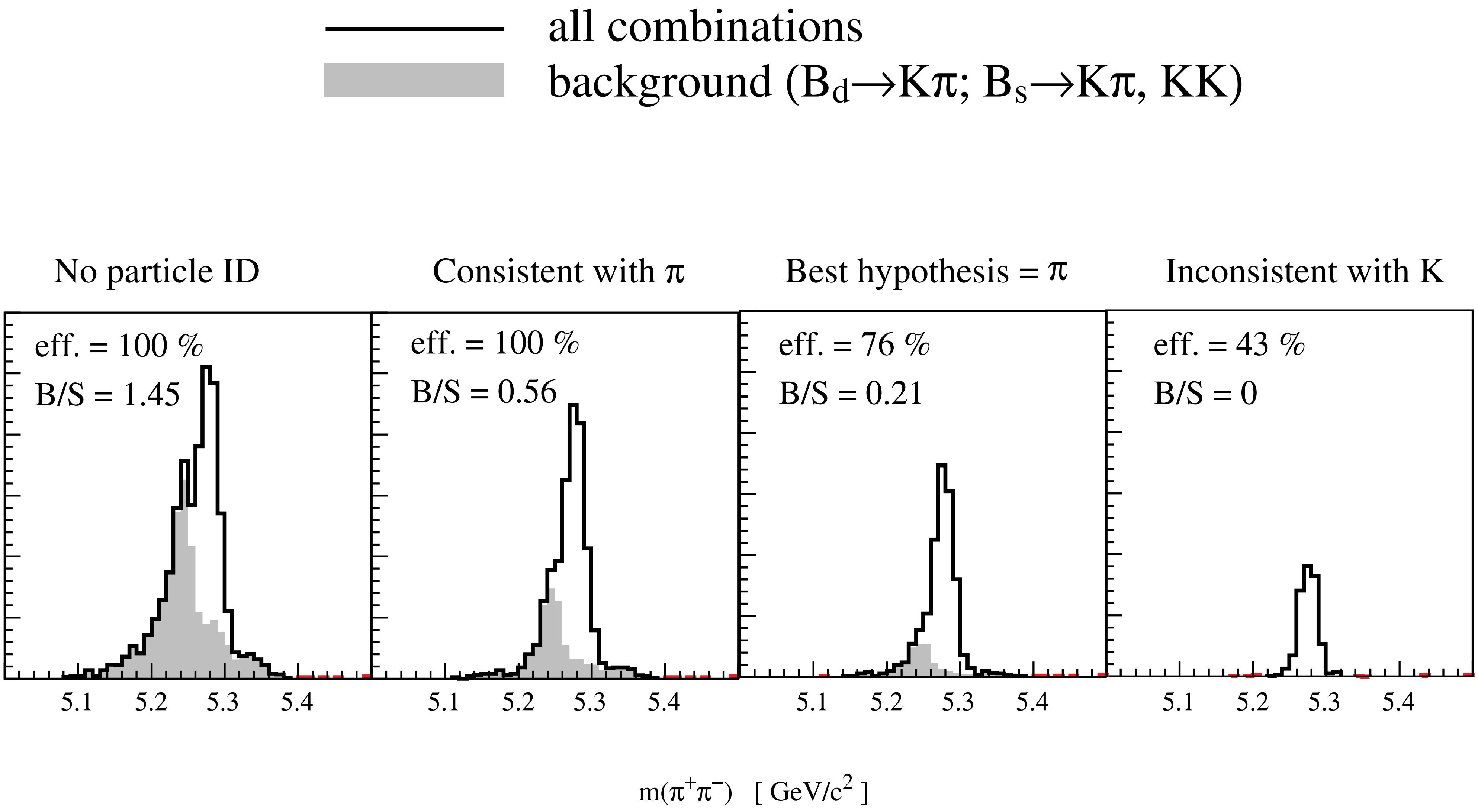
-**particle identification** over 1 to ~150 GeV/c

reconstructing separately
$B \rightarrow \pi\pi$ and $K\pi$

-**good decay time resolution** (0.04 ps)
CP violation in B_s-meson decays

Does not require high luminosity !!

$B \to \pi^+\pi^-$ reconstruction (LHC-B)



Challenges are... RICH and trigger

RICH: HPD, pattern recognition etc...
Trigger: fast vertex trigger, Level-2/3 trigger
(sensitive to many final states)

Goal is to measure, all the angles for the “two” triangles...
i.e. sensitive to λ^2 terms

17) Summary of K and B system

K-system

•domination of $2\pi(I=0)$ final states $\quad \dfrac{\Gamma_{I=0}}{\Gamma_L+\Gamma_S} \cong 0.99$

•K_S decays much faster than K_L $\quad y=\dfrac{\Delta\Gamma}{\bar{\Gamma}} \cong 2$

•K_S-K_L oscillation frequency
$\approx$ decay K_S constant $\quad x=\dfrac{\Delta m}{\bar{\Gamma}} \cong 0.95$

•CP violation in the oscillation $\quad \cong 10^{-3}$
in the oscillation-decay interplay

B-system

$m(\mathrm{B}) \cong m(\mathrm{K}) \times 10 \qquad \tau(\mathrm{B}) \cong \tau(\mathrm{K}) \times 10^{-2}$

- no dominant final states

- B_S and B_L decay constant differences

$$\mathrm{B_d} \quad y = \frac{\Delta\Gamma}{\bar{\Gamma}} \cong 5 \times 10^{-3} \qquad \mathrm{B_s} \quad y = \frac{\Delta\Gamma}{\bar{\Gamma}} \cong 0.1$$

- B_S-B_L oscillations vs. decay constants

$$\mathrm{B_d} \quad x = \frac{\Delta m}{\bar{\Gamma}} \cong 0.72 \qquad \mathrm{B_s} \quad x = \frac{\Delta m}{\bar{\Gamma}} \cong \text{big}$$

$$\Delta m(\mathrm{B_d}) \cong \Delta m(\mathrm{K}) \times 10^2$$

- CP violation in the oscillation
  expected to be $\cong 10^{-3}$

- CP violation in oscillation-decay interplay
  could be $\cong 1$

Conclusions

CP violation was, is and still will be > 2005 as one of the most mysterious and important subject of particle physics for both
theoretically
and
experimentally.
In the end, we have not yet annihilated !!!