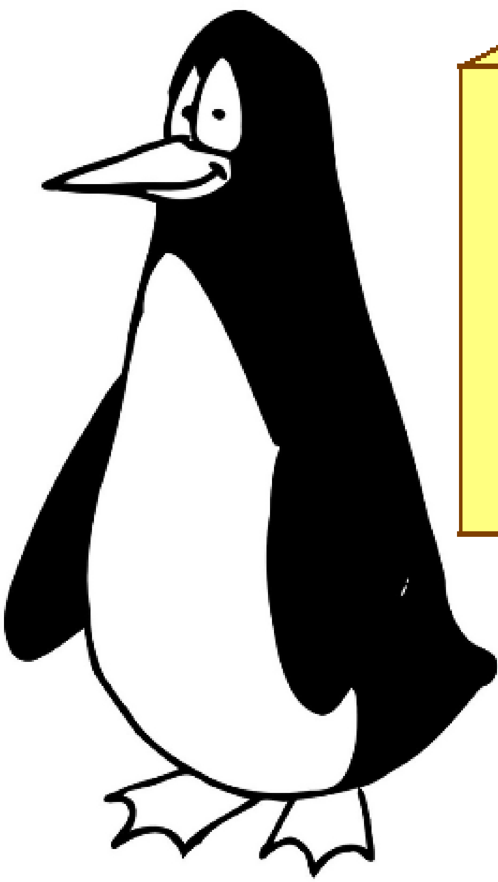
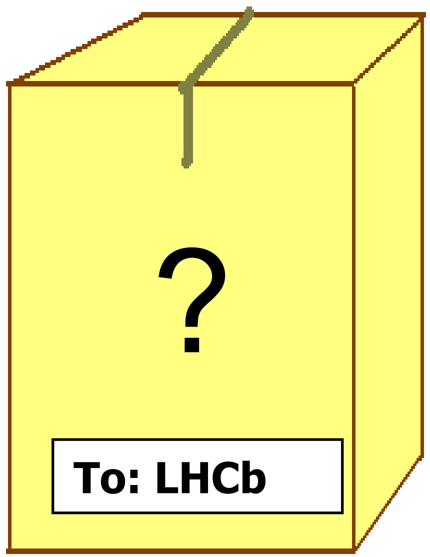
Trees, penguins and boxes at LHCb

Prospects for CP violation measurements at LHCb





Tristan du Pree (Nikhef)

On behalf of the LHCb collaboration

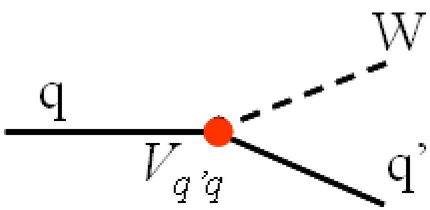
14th Lomonosov conference

19-25 Aug 2009, Moscow

B-physics

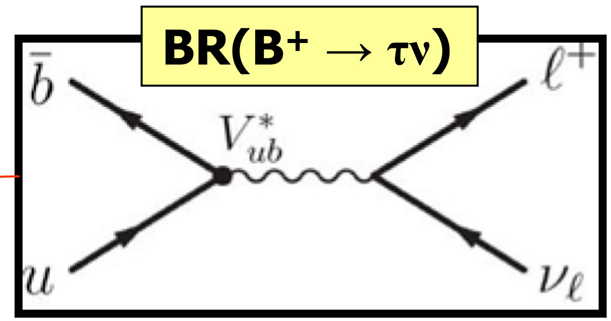
Rare B-decays at LHCb:
See (previous) talk by N. Serra

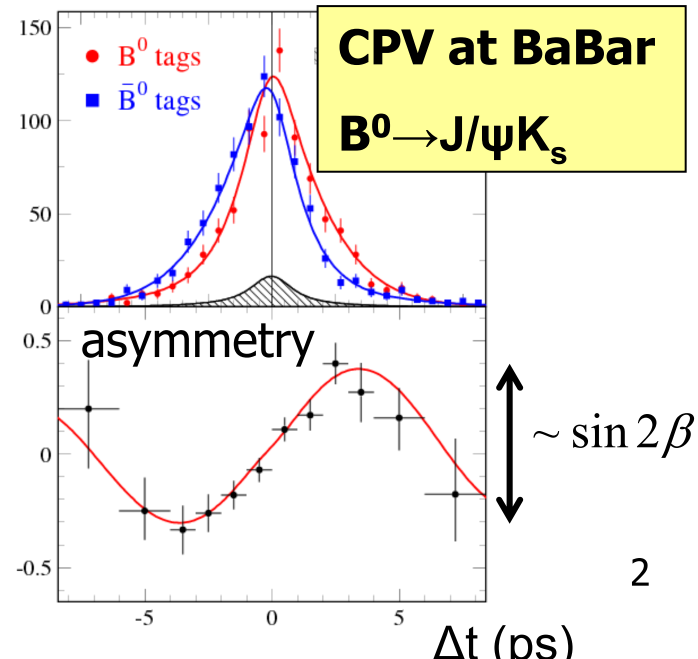
- Study CKM-matrix



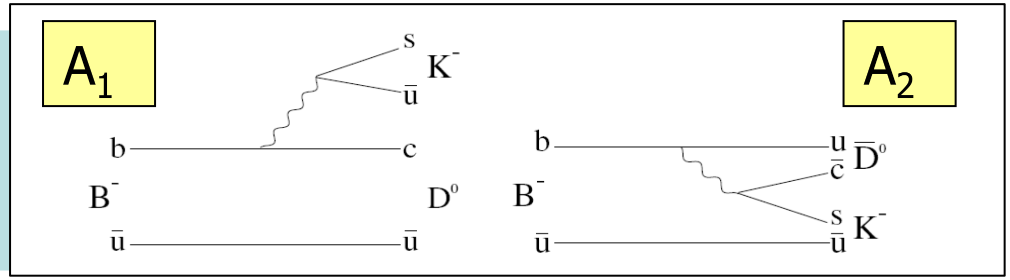
$$V_{CKM} \approx \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \end{pmatrix}$$

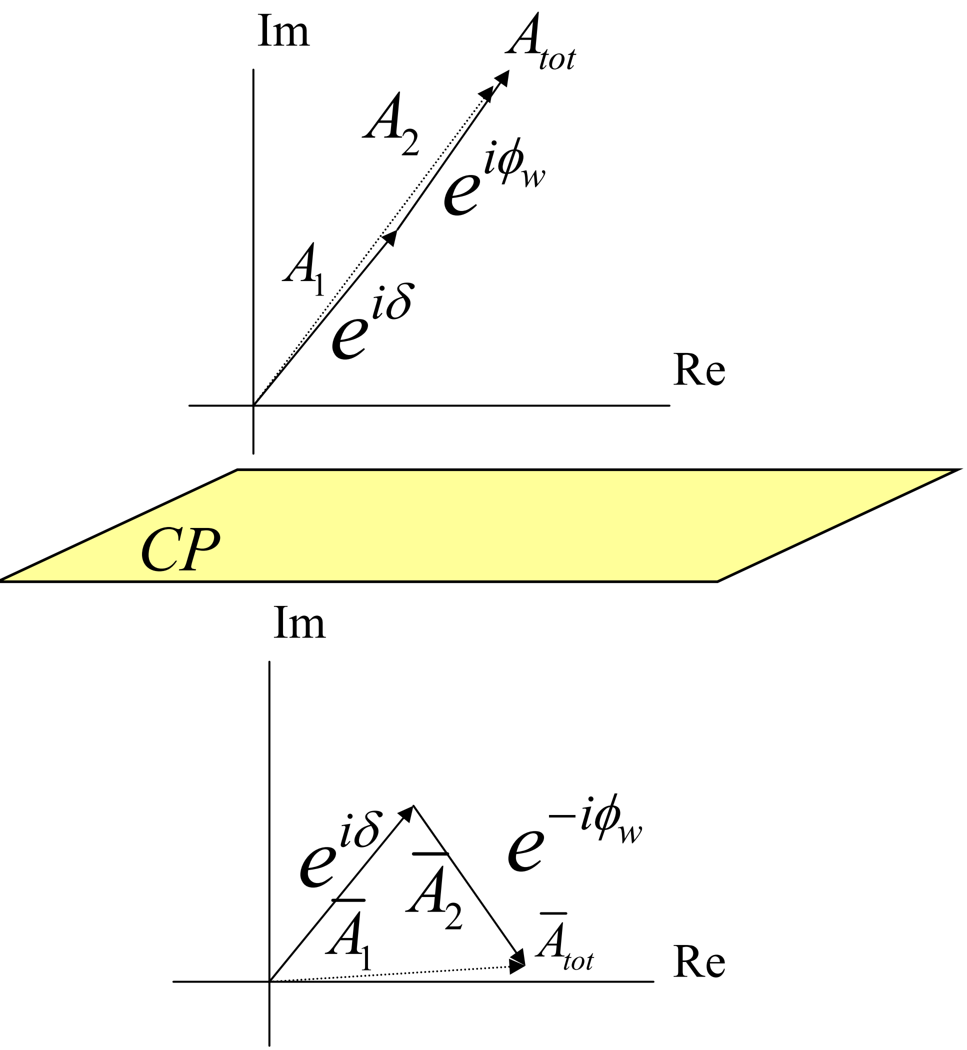
- BR's and CPV





Example
CP violation



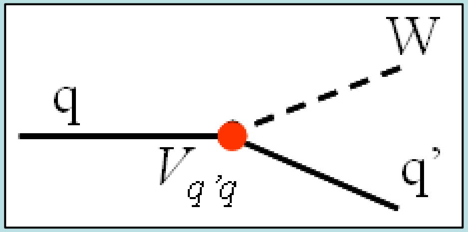


2 amplitudes

- Relative weak phase φ_w
  - Flips sign under CP
- Relative strong phase δ
  - Does not flip sign under CP
- $|A_{tot}|^2 = |A_1+A_2|^2$
- Need both nonzero δ and φ_w for CP asymmetry:

$$|A_{tot}|^2 - |\bar{A}_{tot}|^2 = -4|A_1||A_2|\sin\delta\sin\varphi_w$$

Current status CKM



$$V_{CKM} \approx \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \end{pmatrix}$$

- Unitarity: $V_{CKM} V_{CKM}^{\dagger} = \mathbf{1}$
- 4 free parameters
- Of which one complex phase
- ➢ Perform different measurements to overconstrain CKM matrix

Status:

- SM CKM mechanism explanation of CP violation
  - No significant inconsistencies
- Some interesting deviations
  - β^{eff} (penguins)
  - $|V_{ub}|(B^+ \to \tau\nu)$ vs β
  - "Kπ puzzle"
  - Φ_s (related to β_s)
- Big uncertainty in γ

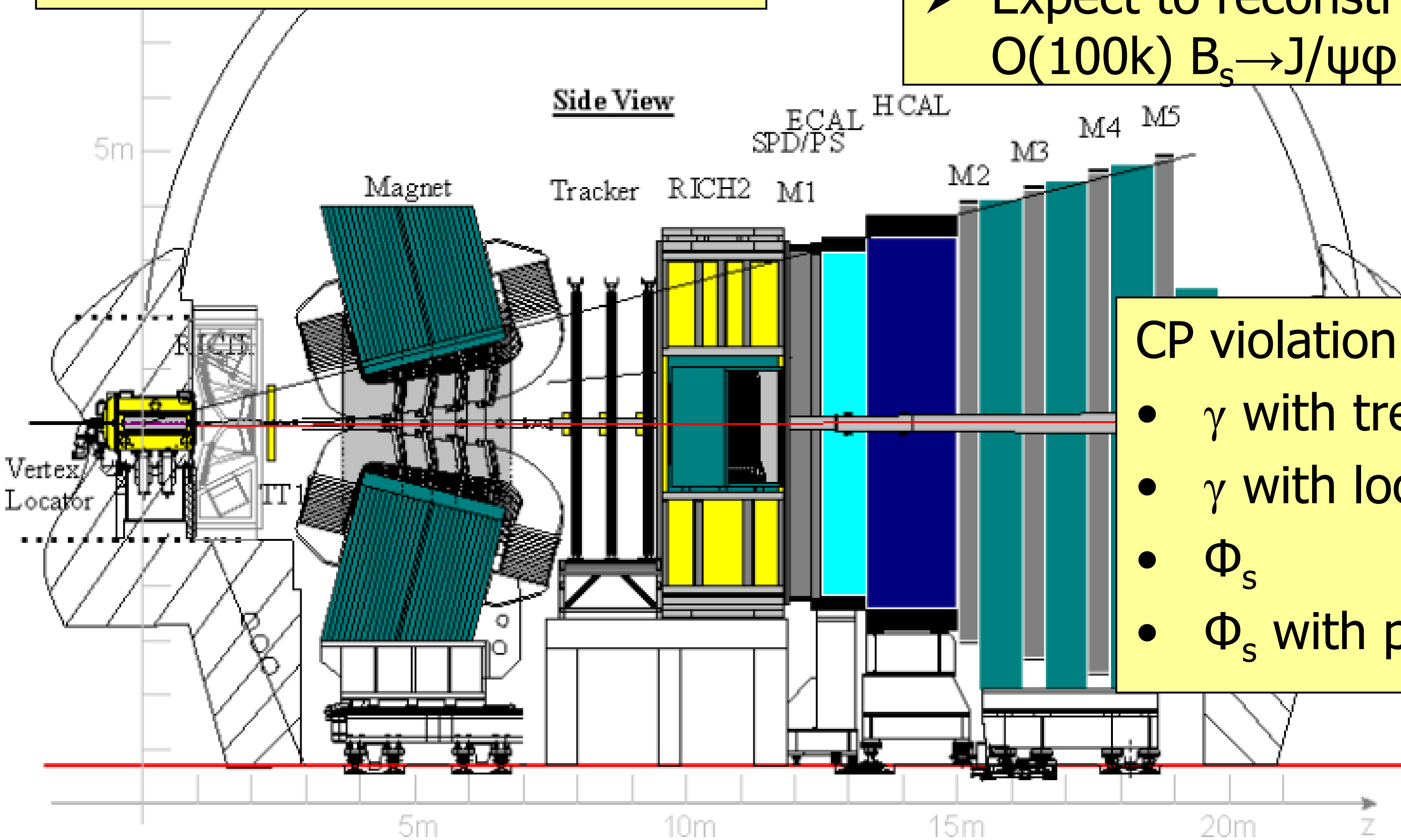
} Subject today

- ➢ Stronger constraints needed!
  - To overconstrain CKM matrix and discover New Physics

LHCb

- Forward arm spectrometer
- ~20mx10mx10m
- L = (2-5) x 10^{32} cm^{-2} s^{-1}

- σ_{bb} ~ 500 μb (10% B_s)
- '1 year' = 2.0 fb^{-1}
- ➢ Produce O(10^{11}) B_s per year
- ➢ Expect to reconstruct: O(100k) $B_s \rightarrow J/\psi\varphi$ per year



CP violation research:

- γ with trees
- γ with loops
- Φ_s
- Φ_s with penguins

CP violation at LHCb

Brown = box
Green = tree
Black = penguin

γ with time dependent osc
- $B_s \rightarrow D_s K$
- $B \rightarrow D^*\pi$

γ with direct CPV
- $B \rightarrow DK$ (glw)
- $B \rightarrow DK$ (ads)
- More bodies

γ with loops
- $B \rightarrow hh$

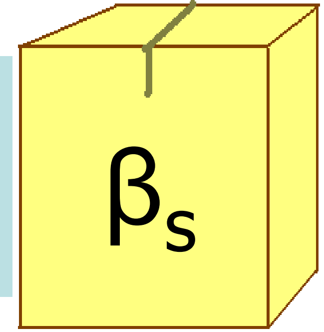
Φ_s
- $B_s \rightarrow J/\psi\phi$

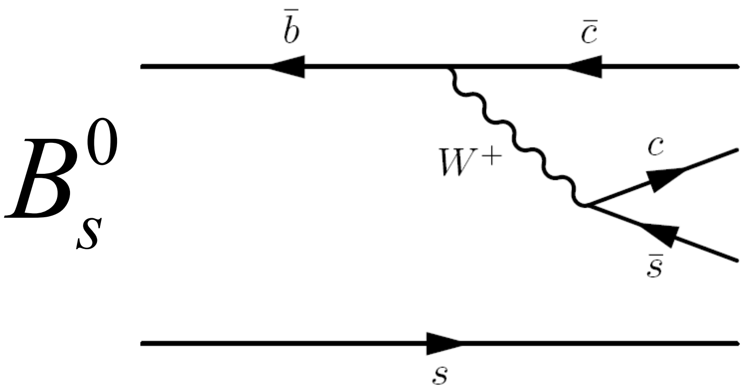
Φ_s with penguins
- $B_s \rightarrow \phi\phi$

Advantages of LHCb
- Number of B_s's
- Proper time and mass resolution
- Particle ID

The B_s mixing phase

β_s equivalent of β in B_d system



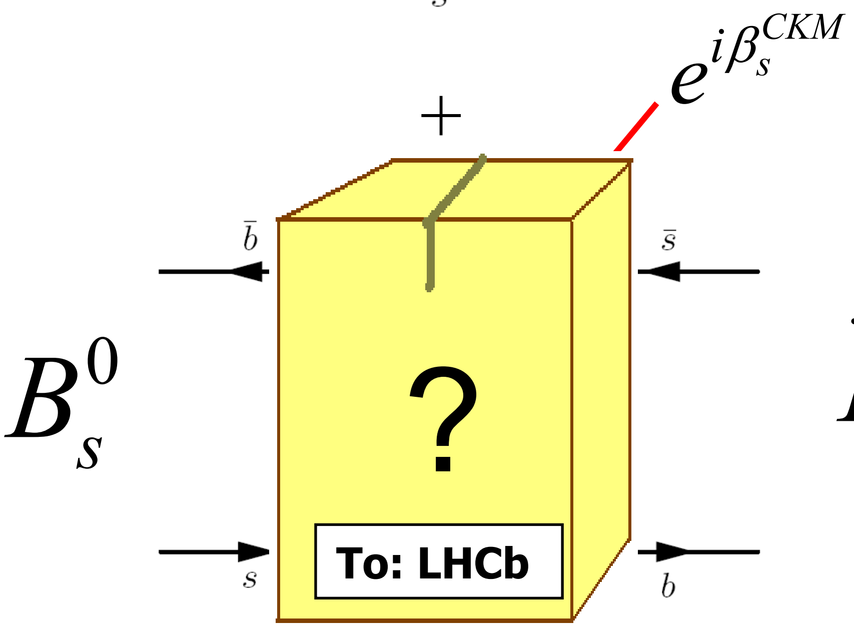


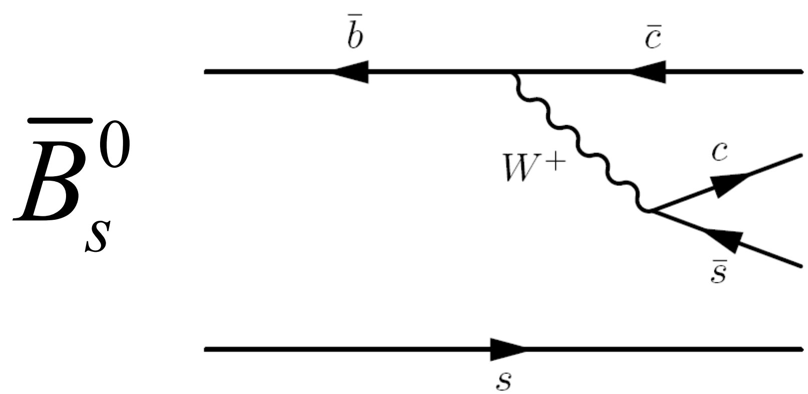
$$A_{CP} = \frac{N_{B\to f} - N_{\bar{B}\to f}}{N_{B\to f} + N_{\bar{B}\to f}}$$

If $\Delta\Gamma_s=0$:
(in general $\Delta\Gamma_s \neq 0$)

$$= \sin(-2\beta_s^{CKM} + \phi_s^{NP}) \sin \Delta m_s t$$

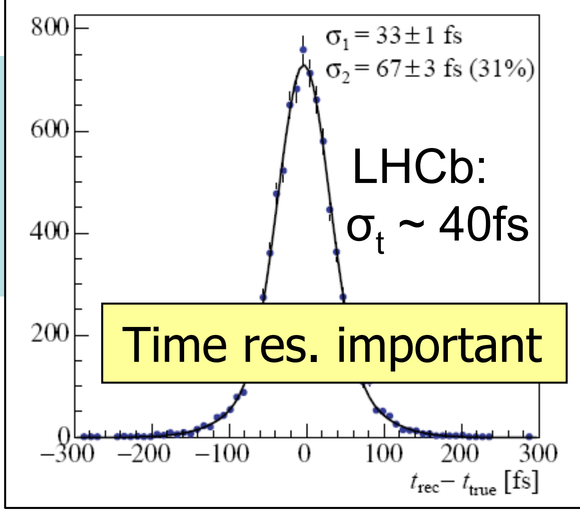
"Φ_s"

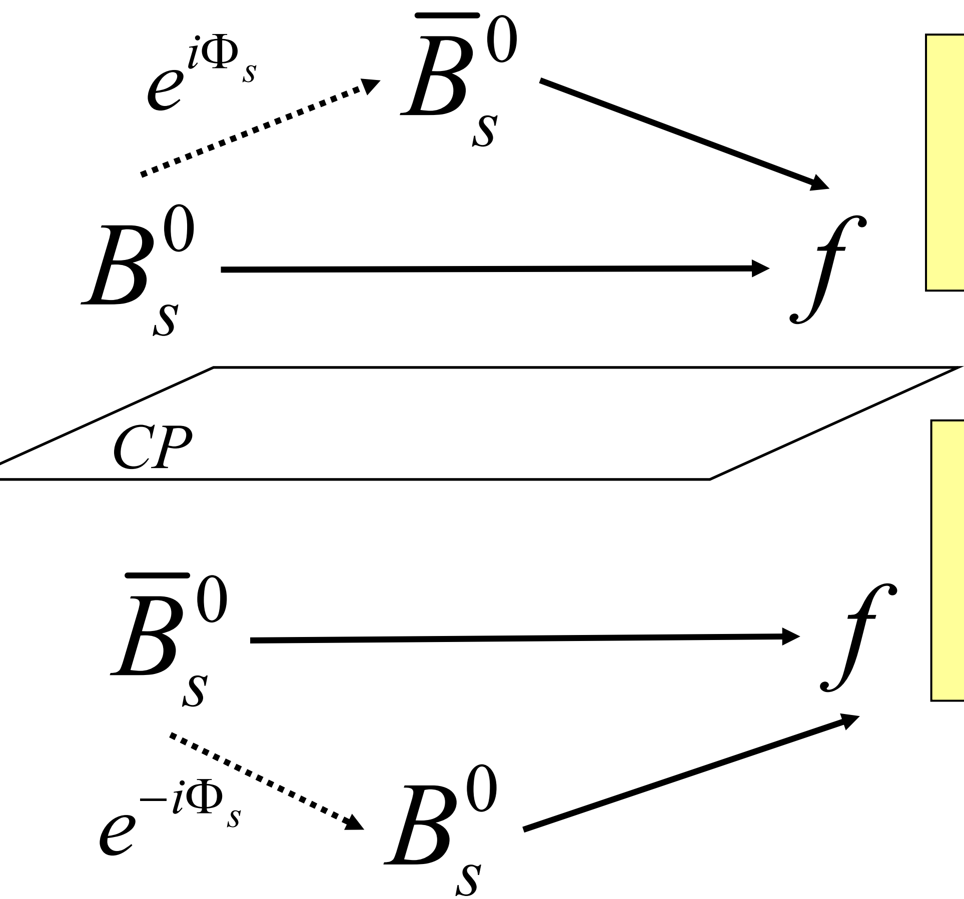


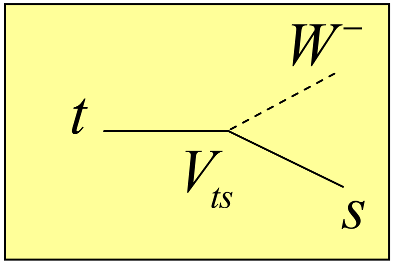


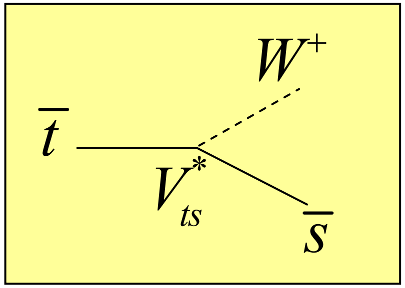
Time dependent CPV

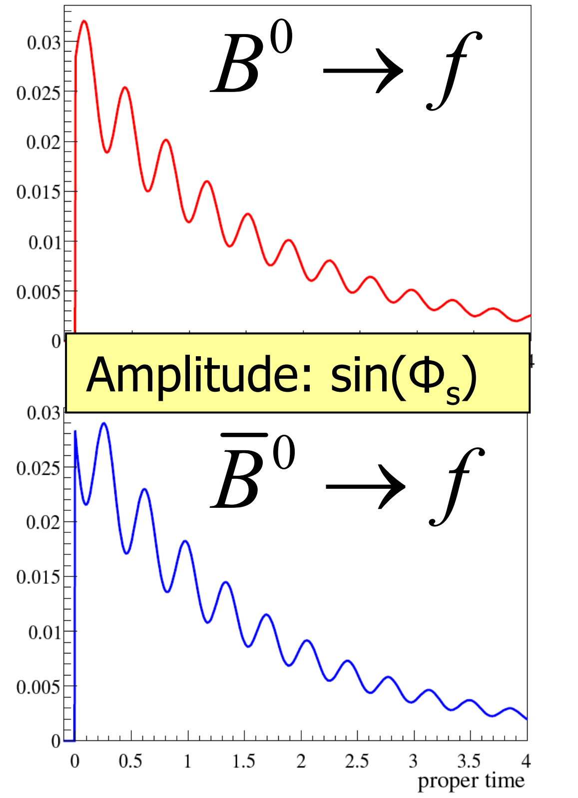
- Final state f is a $c\bar{c}s\bar{s}$ CP-eigenstate





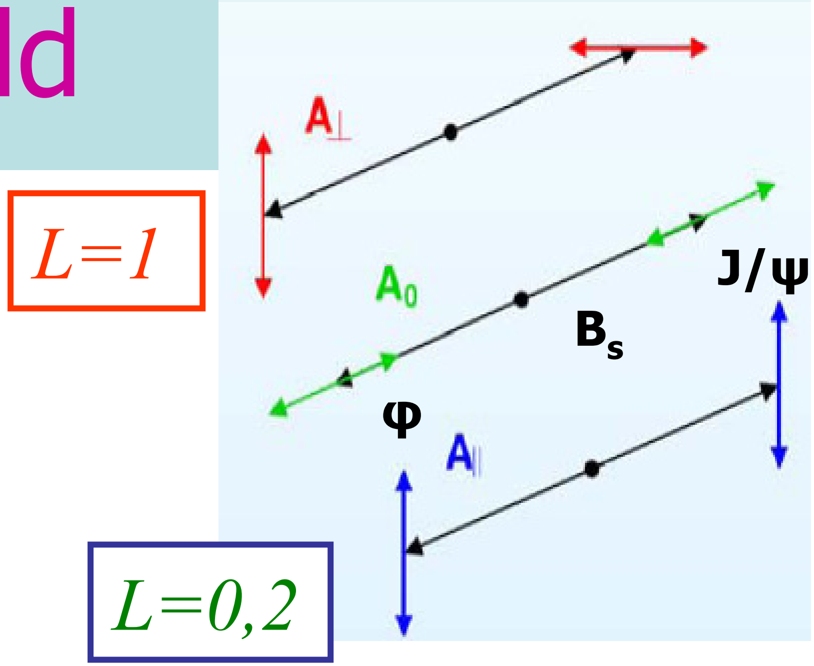






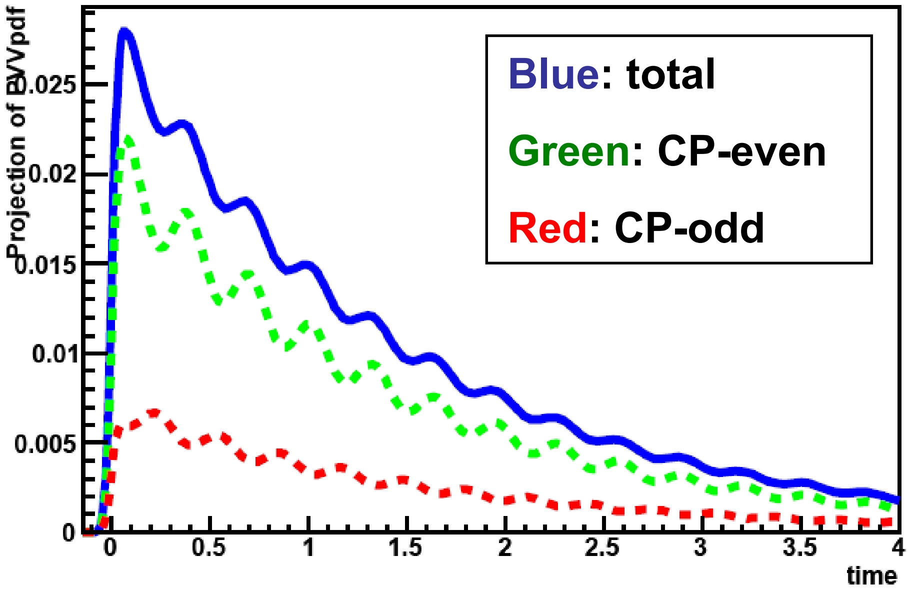
CP-even vs CP-odd

- Initial B_s: J=0
- Different final spin states
  - Different angular momenta L in final states
  - Different CP: factor $(-1)^L$
  - CP-even and CP-odd opposite proper time behaviour



If $\Delta\Gamma_s$=0:
(simplified expression, in general $\Delta\Gamma_s \neq 0$)

$$A_{CP} \sim |A_{even}|^2 \sin\Phi_s \sin\Delta m_s t - |A_{odd}|^2 \sin\Phi_s \sin\Delta m_s t$$

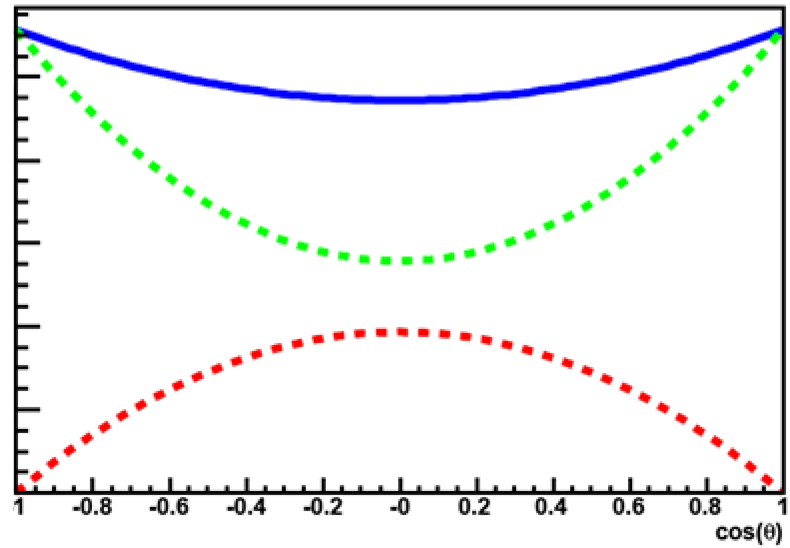


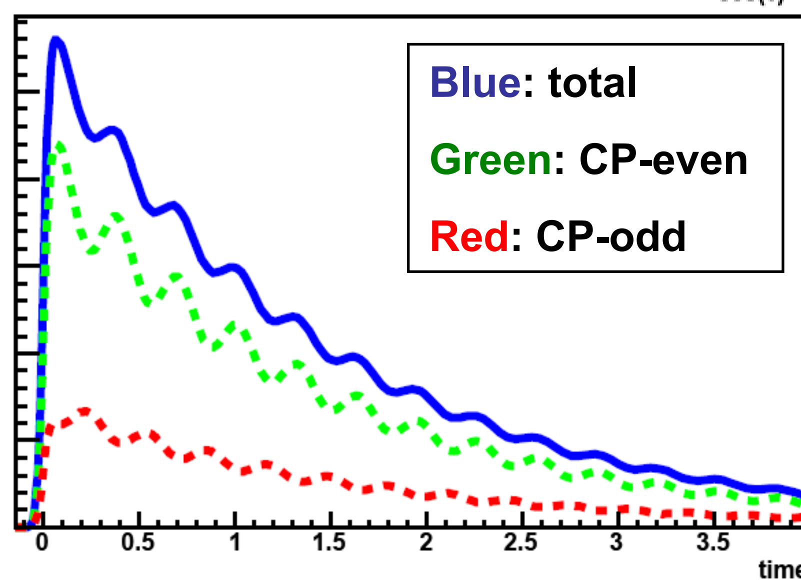
Angular analysis

- 4 particles: 3 decay angles
- Angles of daughter particles in rest frame parents
- Angular distribution: information about spin polarizations
  - ➢ CP states different angular distributions
  - ➢ Perform angular analysis to separate CP-even & CP-odd

If $\Delta\Gamma_s$=0:
(simplified expression, in general $\Delta\Gamma_s \neq 0$)

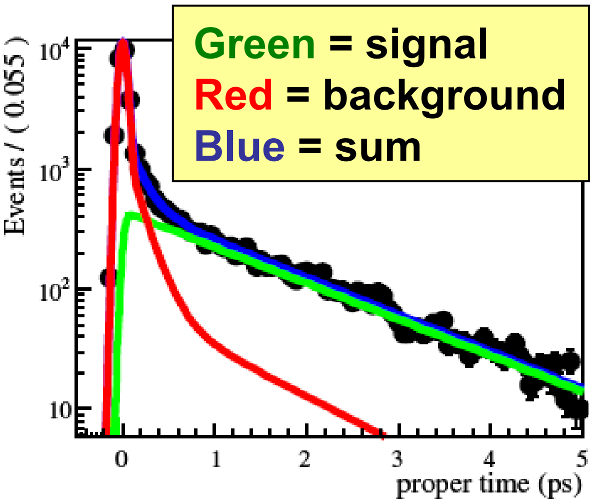
$$A_{CP} \sim |A_{\text{even}}|^2 \sin\Phi_s \sin\Delta m_s t\,(1 + \cos^2\theta)/2$$
$$- |A_{\text{odd}}|^2 \sin\Phi_s \sin\Delta m_s t\,(1 - \cos^2\theta)$$

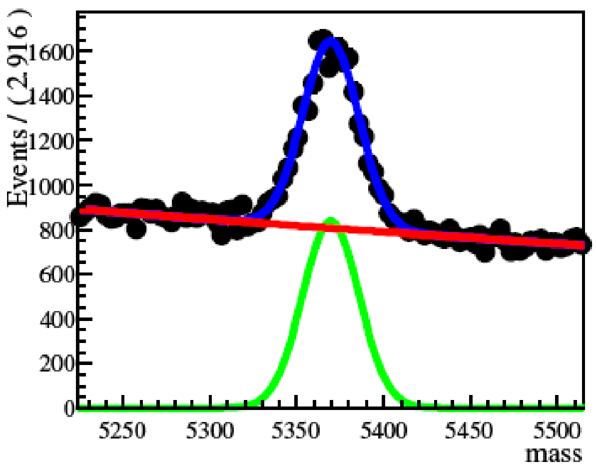




LHCb sensitivity: $\sigma(\Phi_s)$

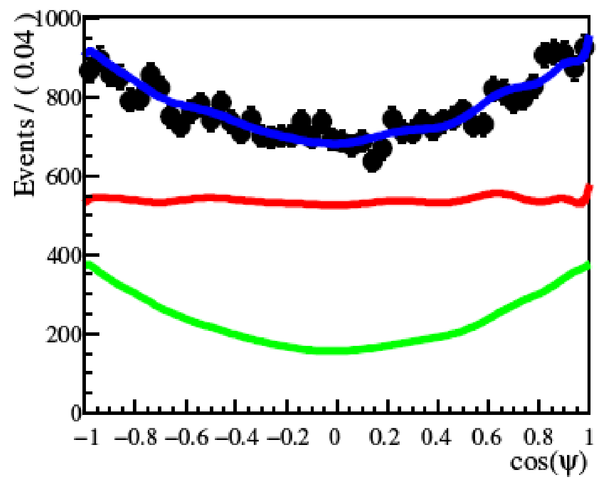
- Simultaneous likelihood analysis in mass, time, angles and tagging flavour
- Using mass sideband to model background





Expectation from toy MC

- 2.0 fb^{-1}: **$\sigma(\Phi_s) \sim 1.8^o$**



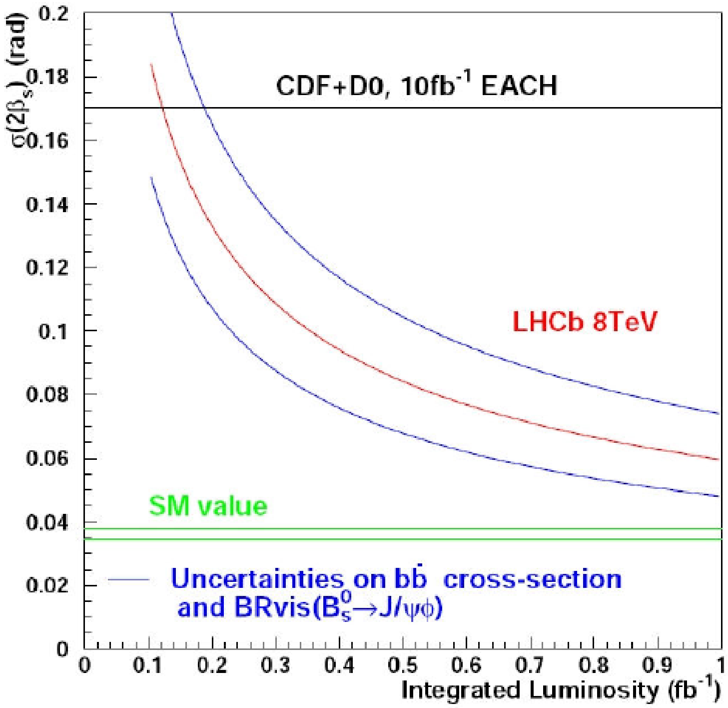
Sensitivity: $\sigma(\Phi_s)$

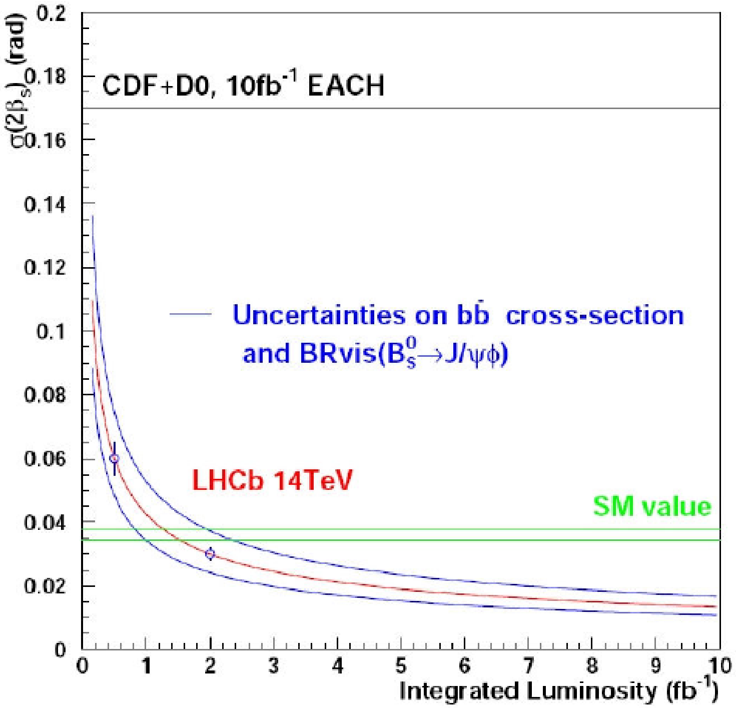
0.2 fb^{-1} (8 TeV):

- $\sigma_{LHCb}(\Phi_s) < \sigma_{TeVatron}(\Phi_s)$

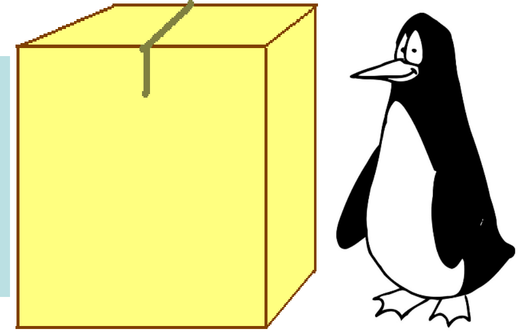
2.0 fb^{-1} (14 TeV):

- **If $\Phi_{TeVatron} = \Phi_{true}$:**
  <u>LHCb 5σ discovery!</u>

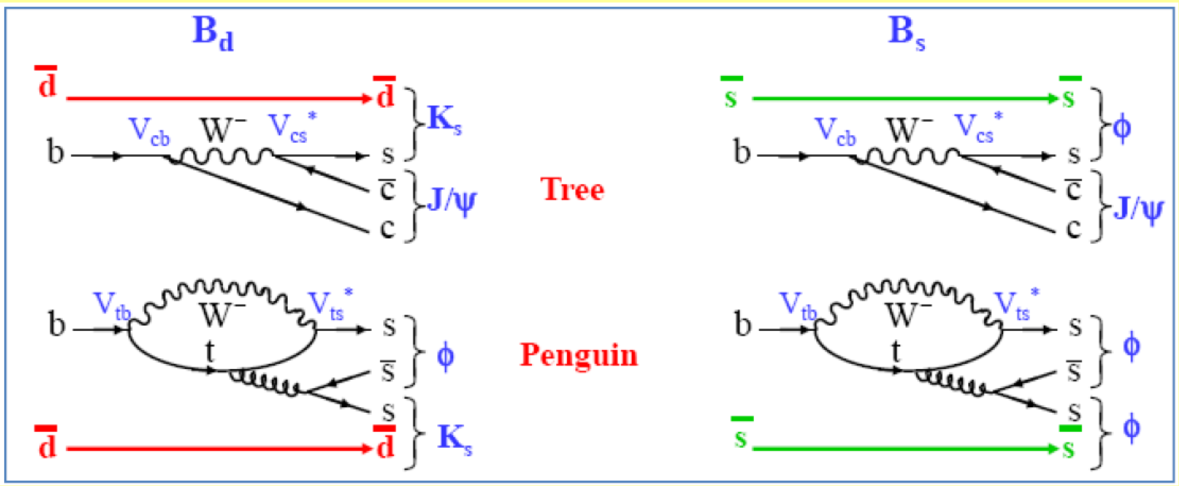




$B_s \to \phi\phi$



- Compare: phase(tree) & phase(penguin)



$$\Phi_{\phi K_s} = 2\beta^{mix} + 2\beta_s^{decay} \approx 2\beta(SM)$$

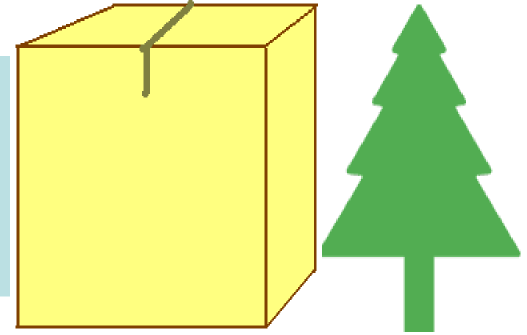
$$\Phi_{\phi\phi} = \Phi_s^{mix} + 2\beta_s^{decay} \approx 0(SM)$$

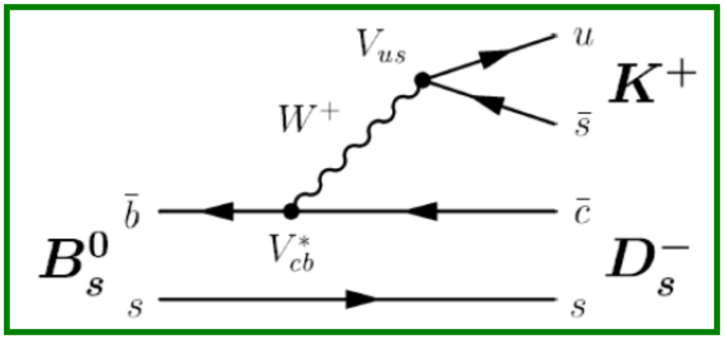
- $B_s \to \phi\phi$ angular analysis à la $B_s \to J/\psi\phi$

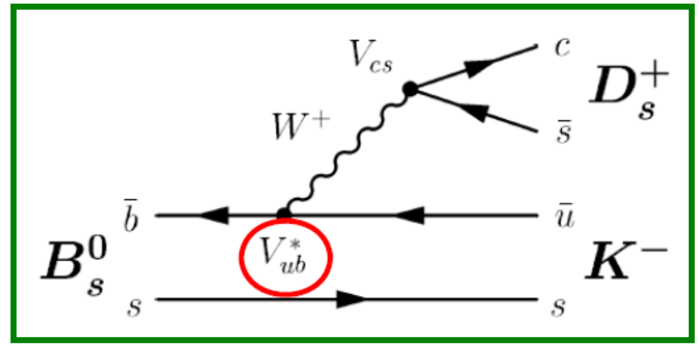
Channel	Yield (2 fb^{-1})	B/S	Weak phase precision
$B \to \phi K_s$	920	0.3 < B/S < 1.1	$\sigma(\sin(\Phi_{\phi K s}))=0.23$
$B_s \to \phi\ \phi$	3.1 k	< 0.8	$\sigma(\Phi_{\phi\phi})=4.6^o$

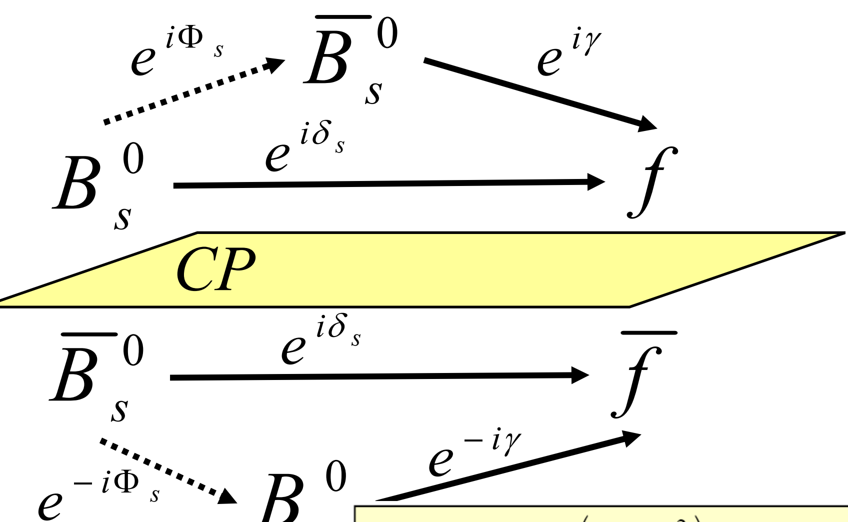
γ with trees (1)

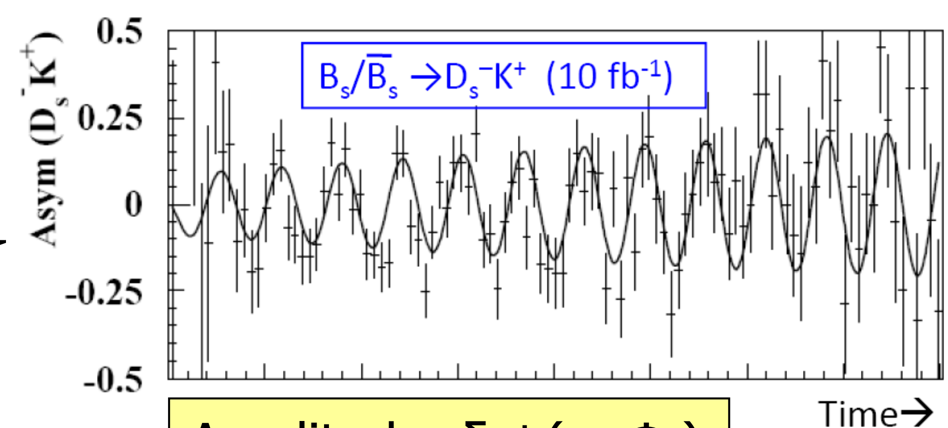
$B_s \to D_s K$: time-dependent oscillation











Amplitude: $\delta_s \pm (\gamma + \Phi_s)$

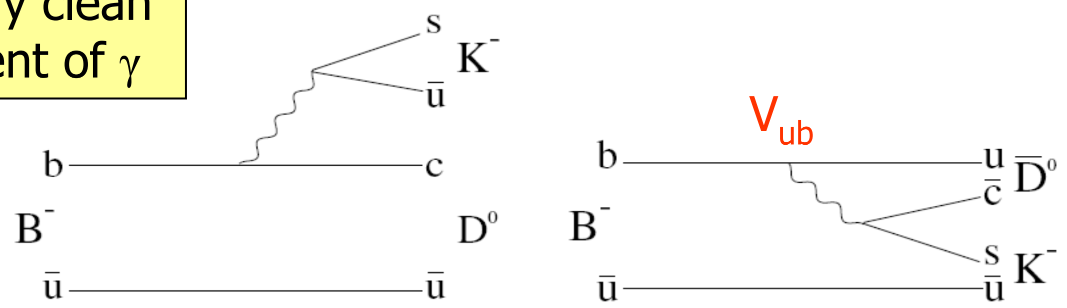
$$A_{D_s^{\mp}K^{\pm}}^{B/\overline{B}} = \frac{\left(1-|\lambda|^2\right)\cos\Delta mt - 2|\lambda|\sin\left(\delta_s \mp (\gamma+\phi_s)\right)\sin(\Delta mt)}{\left(1+|\lambda|^2\right)\cosh\frac{\Delta\Gamma t}{2} - 2|\lambda|\cos\left(\delta_s \mp (\gamma+\phi_s)\right)\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

With 2.0fb^{-1}:
$\sigma(\gamma+\Phi_s)=9^\circ$-$12^\circ$

γ with trees (2)

Decay time **in**dependent CPV in $B \to DK$

Theoretically clean measurement of γ



- $\sim V_{cb} V_{us}^*$
- D^0

- $\sim V_{ub} V_{cs}^*$
- $\overline{D^0}$

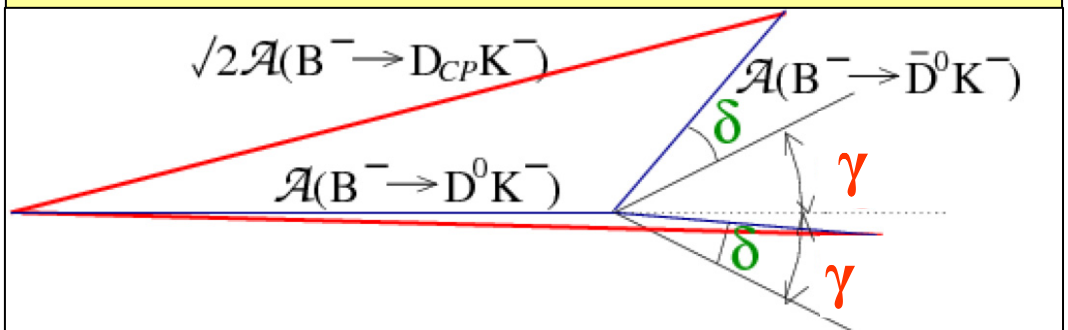
- Sum of amplitudes leads to CPV
  - Relative strong phase δ
  - Relative weak phase γ

➢ For interference: need a common final D^0&$\overline{D^0}$ state

γ with trees (2)
Decay time **in**dependent CPV

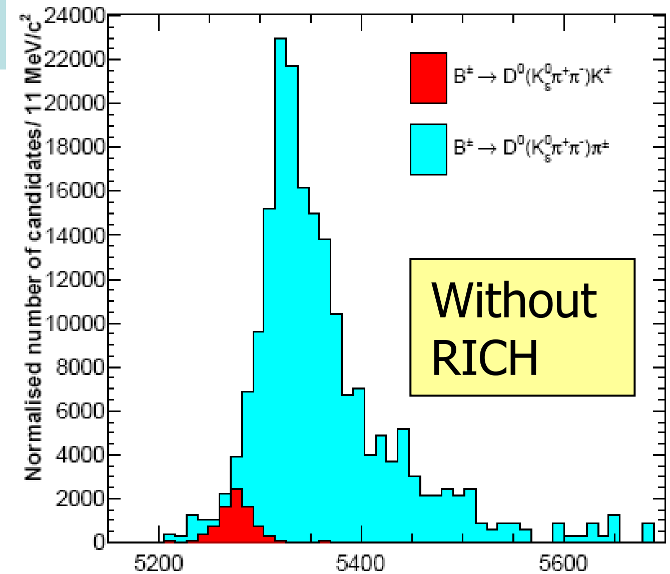
PID by RICH important

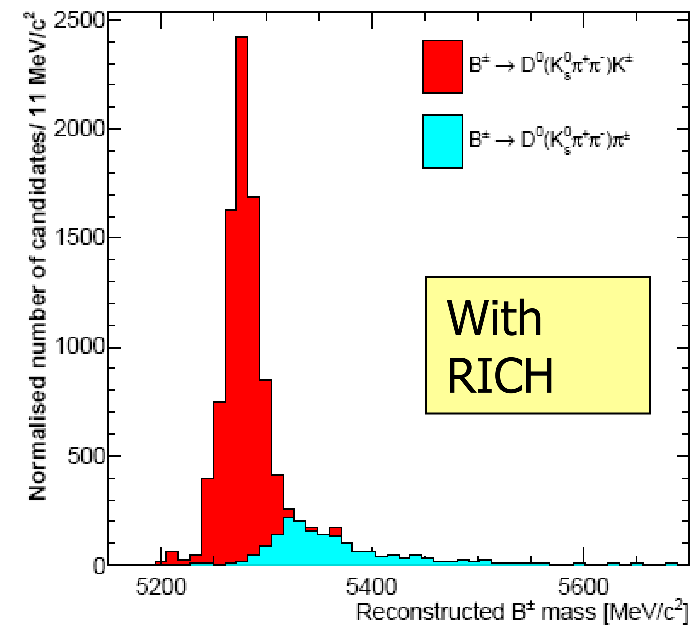
- GLW: Choose CP-even final state
  - $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
  - D_{CP} is CP-even D^0-$\bar{D}^0$ mixture



- Rates $\to$ $\delta+\gamma$
- Rates (CP-conjugated) $\to$ $\delta-\gamma$
- ➢ The combination gives two solutions of γ

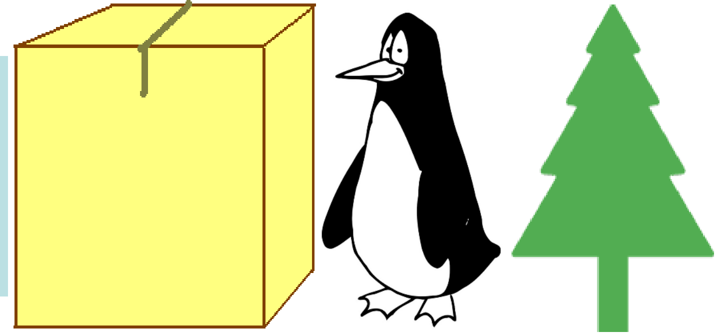
Combination of all methods after 2.0 fb^{-1}:
$\sigma(\gamma)$ = 4-5^o



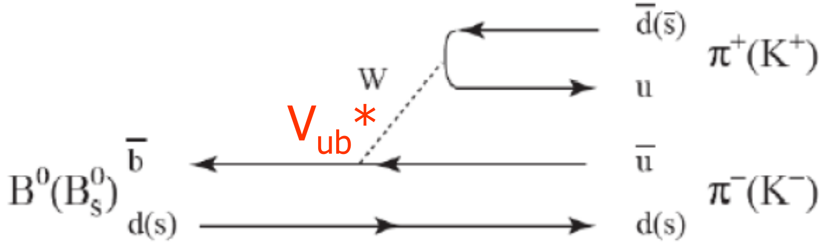


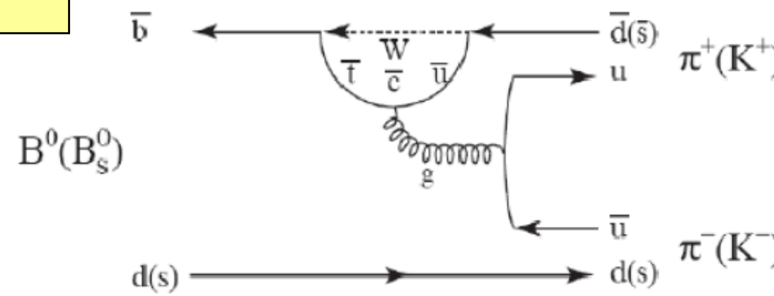
γ with loops

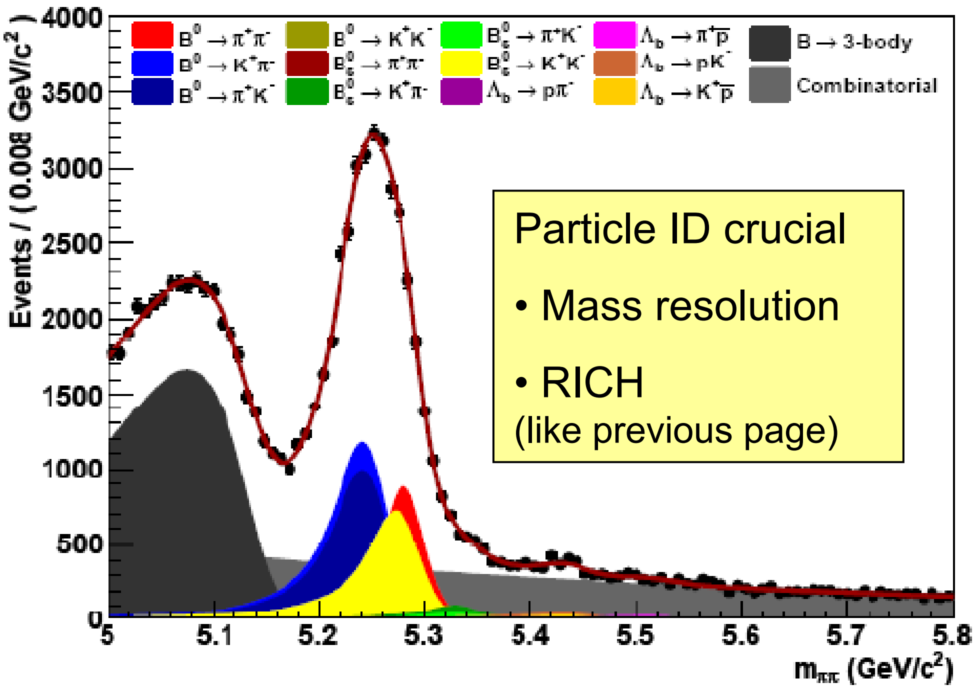
B→hh



Interfere b→u tree diagram with penguins:





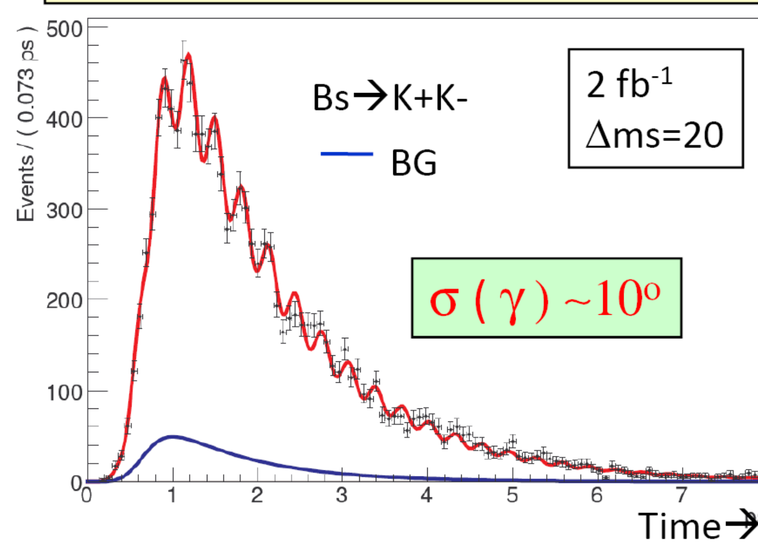


Particle ID crucial

- Mass resolution
- RICH

(like previous page)

$$A_f^{CP}(t) = \frac{A_f^{dir}\cos\Delta mt + A_f^{mix}\sin\Delta mt}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_f^{\Delta}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$



$\sigma(\gamma) \sim 10^o$

LHCb with 2 fb^{-1}

Brown = box
Green = tree
Black = penguin

γ with time dependent osc
- $B_s \rightarrow D_s K$
- $B \rightarrow D^*\pi$

$\sigma(\gamma\text{-}\Phi_s) = 9^o\text{-}12^o$

γ with direct CPV
- $B \rightarrow DK$ (glw)
- $B \rightarrow DK$ (ads)
- More bodies

$\sigma(\gamma) = 4\text{-}5^o$

γ with loops
- $B \rightarrow hh$

$\sigma(\gamma) = 7°$

$\sigma(\Phi_s) = 2.8°\text{-}3.4°$

Φ_s
- $B_s \rightarrow J/\psi\varphi$

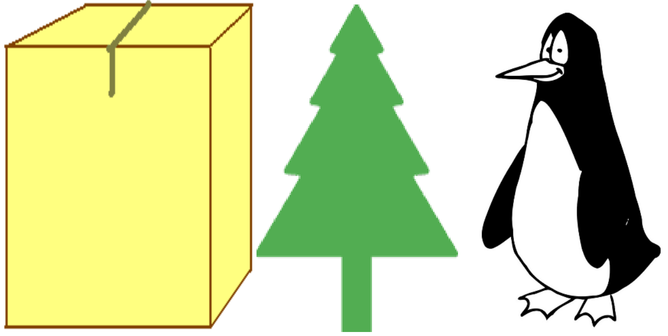
$\sigma(\Phi_s) = 1.8^o$

Φ_s with penguins
- $B_s \rightarrow \varphi\varphi$

$\sigma(\Phi_{\varphi\varphi}) = 4.6^o$

Advantages of LHCb
- Number of B_s's
- Proper time and mass resolution
- Particle ID

Conclusions



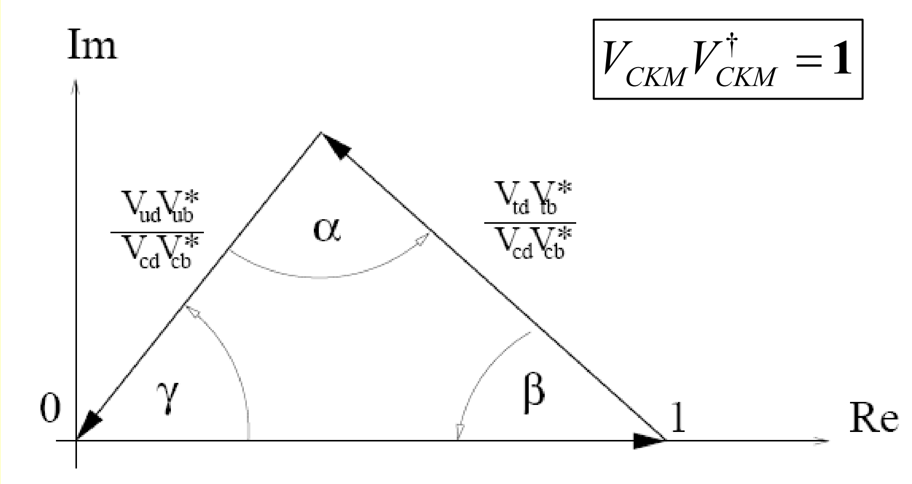
- CKM model successful in describing CP violation
  - …but γ and β_s poorly constrained
  - …and inconsistencies at the horizon?
- Many different methods to study diagrams
  - Standard model diagrams (trees)
  - Possible new physics contributions (boxes, penguins)
- LHCb will drastically improve the sensitivity to the CKM angles γ and β_s

Something new in the box of $B_s \to J/\psi\varphi$?

BACK-UP

Unitarity Triangle

- Constraints following from unitarity of CKM matrix
  - Three complex numbers add up to zero

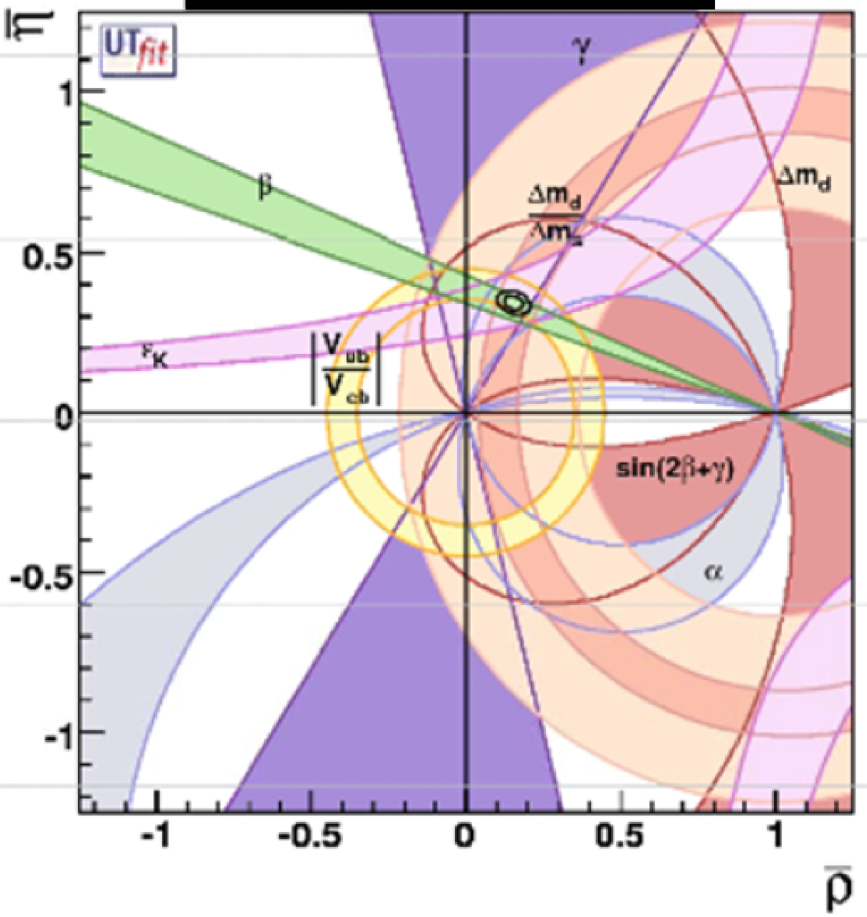


$$V_{CKM}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

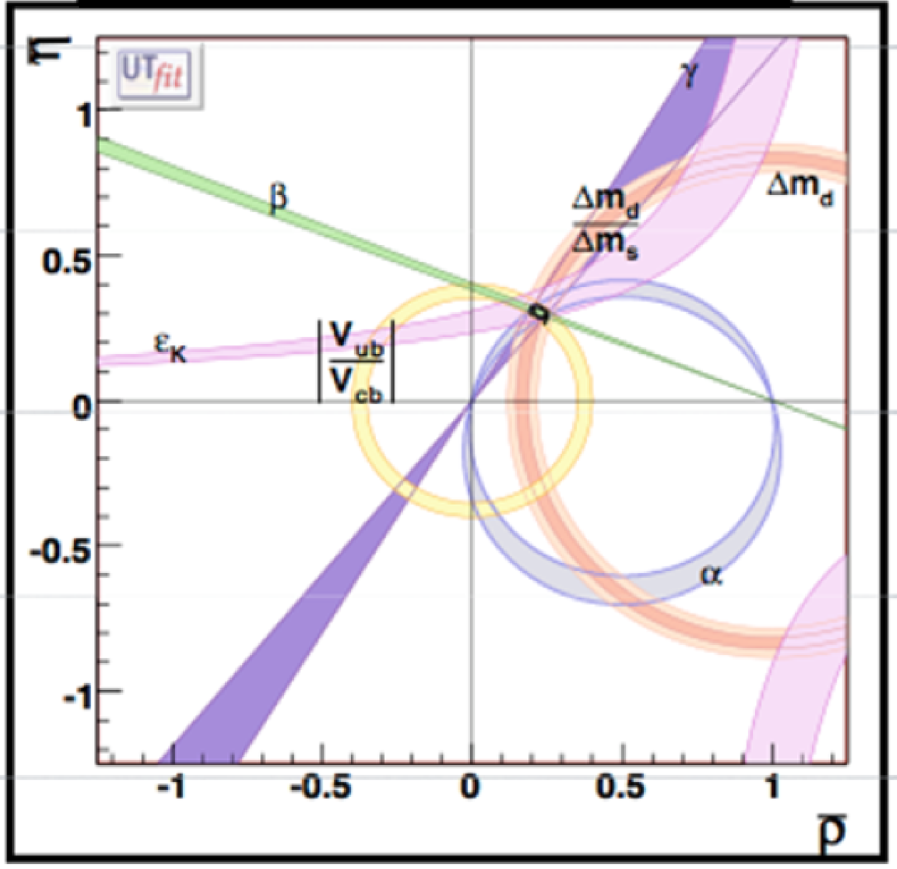
- Performing different measurements, overconstrain 4 free parameters in CKM matrix
  - To test consistency of CKM model
  - Inconsistency (e.g. triangle doesn't close) → new physics

UT after 5 years of LHCb
in case of no new physics

Winter 2009



LHCb at L=10fb^{-1}

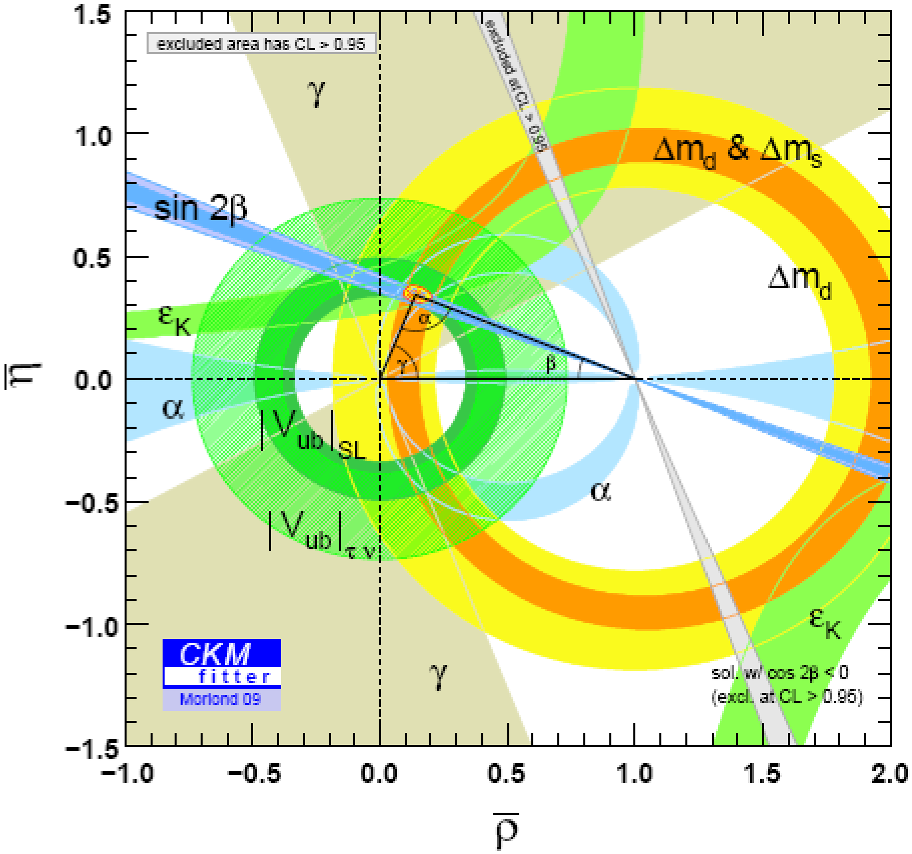


Lattice QCD improvements assumed: $\sigma(\xi)/\xi=1.5\%$

$\sigma(\sin(2\beta)) = 0.01$; $\sigma(\gamma) = 2.4°$; $\sigma(\alpha) = 4.5°$

Current status UT

experimental constraints on unitary CKM matrix

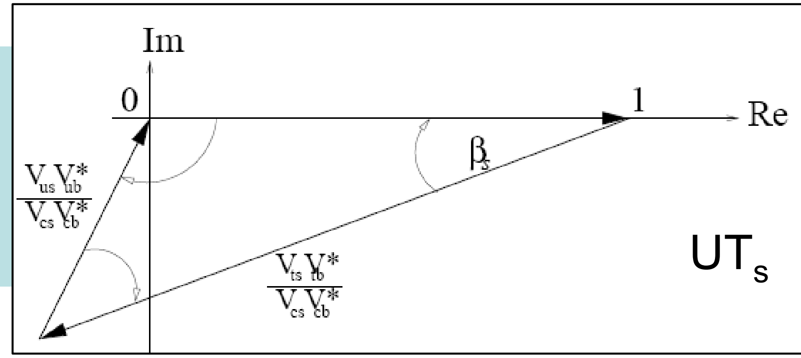


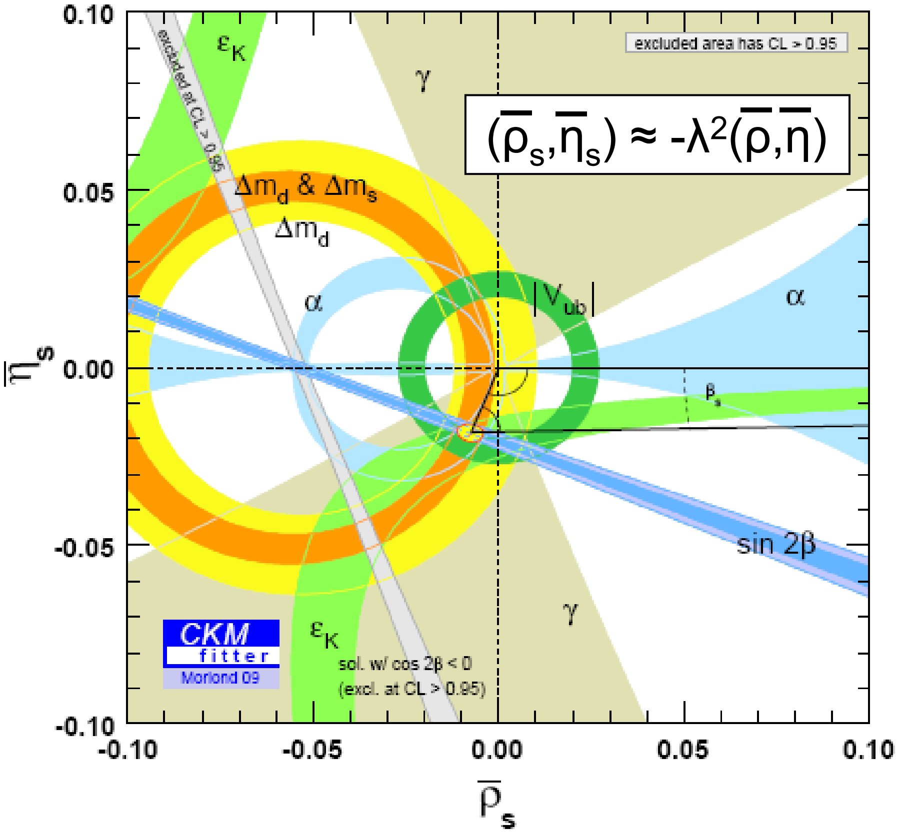
- CKM mechanism explanation of CPV
  - No significant inconsistencies
- Some interesting deviations
  - β^{eff} (penguins)
  - $B \to \tau\nu$ vs β
  - "Kπ puzzle"
  - β_s
- Biggest uncertainty in γ
- ➢ Stronger constraints needed!
  - To constrain CKM & discover NP

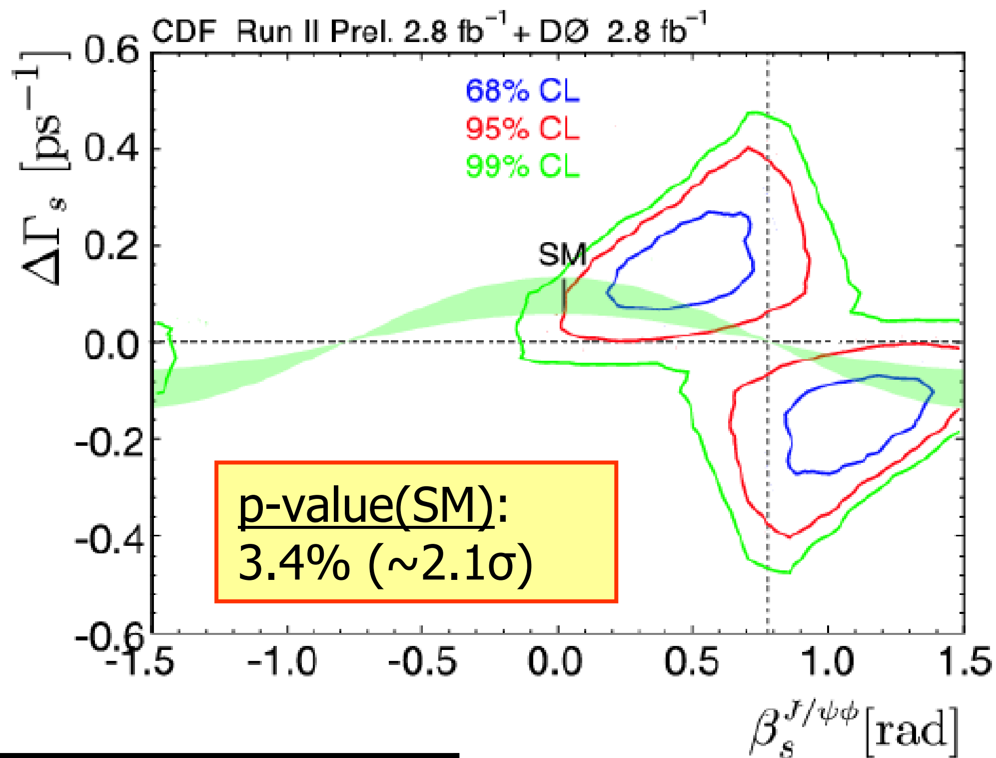
Subject today

CP angle	Indirect measurements (°)	Direct measurements (°)
α	$95.6^{+3.3}_{-8.8}$	$89.0^{+4.4}_{-4.2}$
β	$27.4^{+1.3}_{-1.9}$	$21.07^{+0.90}_{-0.88}$
γ	$67.8^{+4.2}_{-3.9}$	70^{+27}_{-30}

Present status β_s





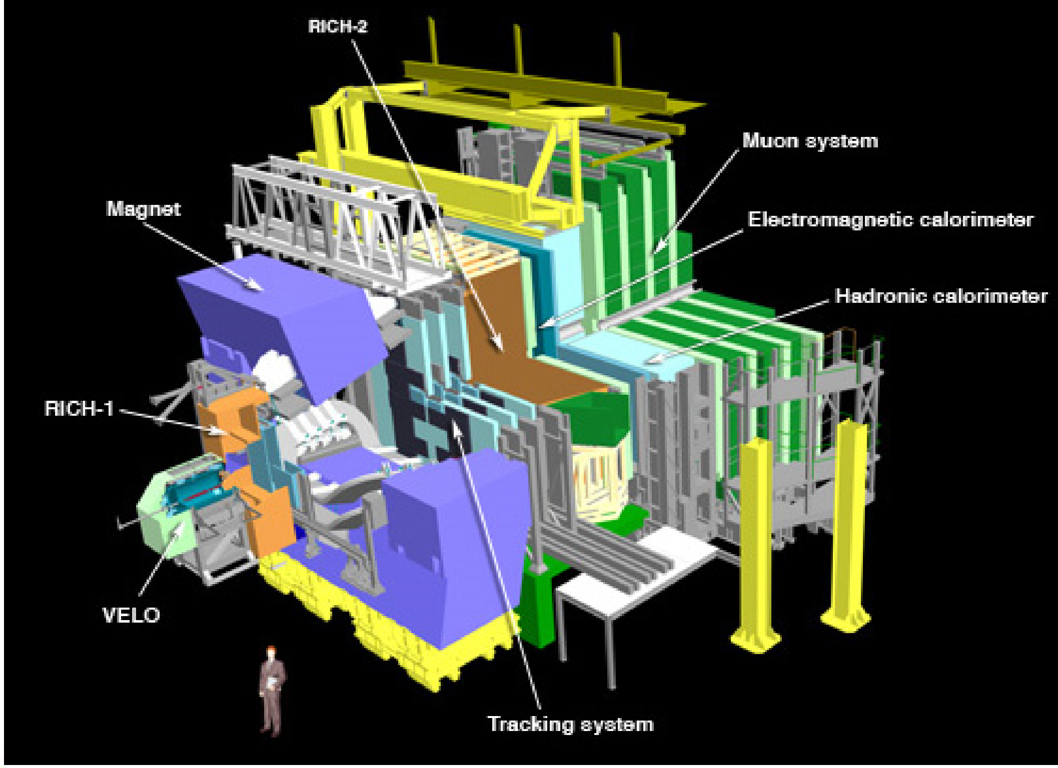


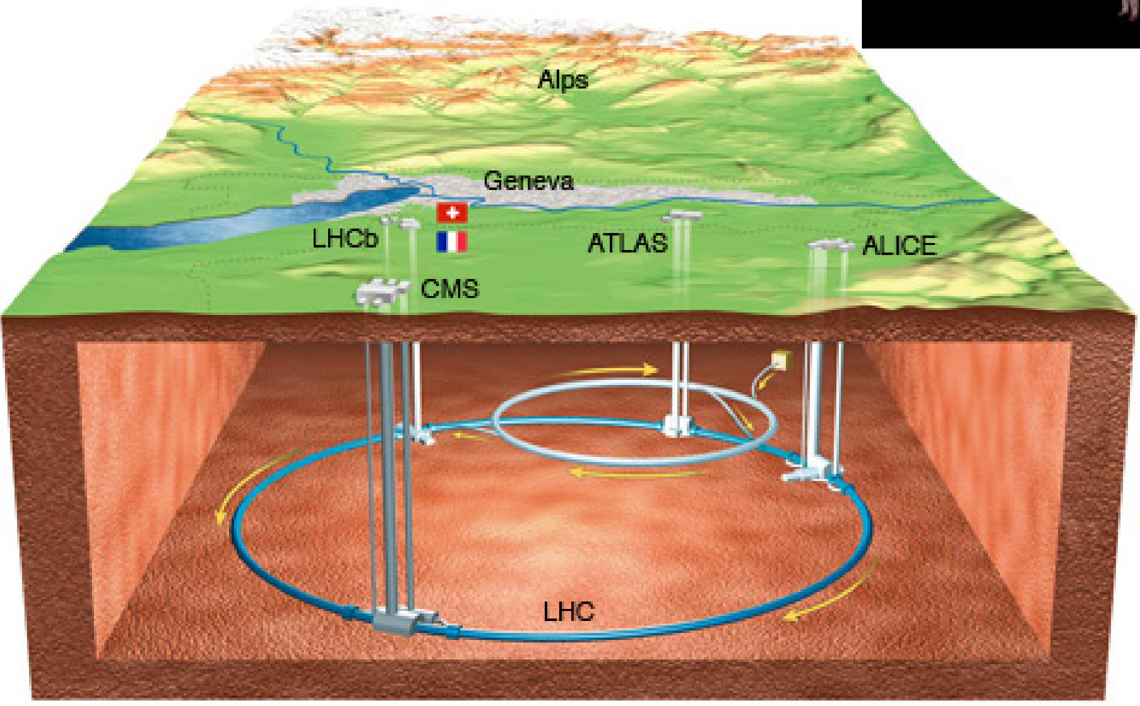
	Left: Indirect (UT_s)	Right: Direct ($B_s \rightarrow J/\psi\phi$ TeVatron)
β_s	1.03°±0.05°	[15°-34°]U[56°-75°] @68%CL

2.0 fb^{-1} LHCB:
$\sigma(\beta_s) \sim 0.9°$

LHC

- 27 km
- Proton-proton
- $\sqrt{s}$ = 14 TeV?
- Re-start this fall

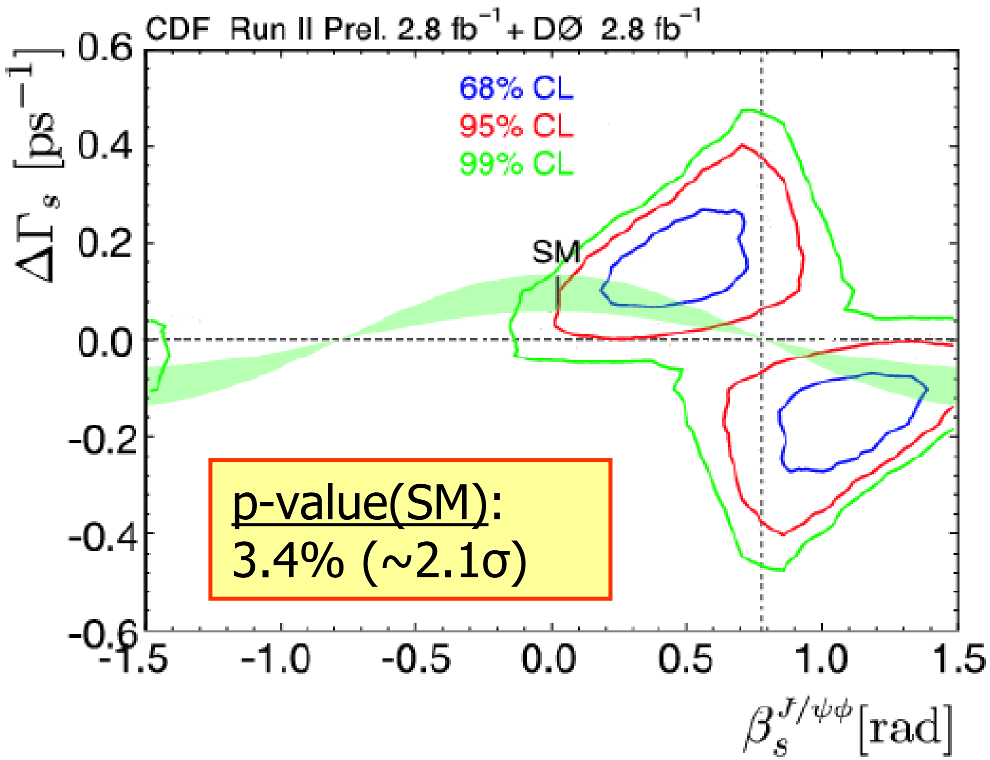




LHCb

- L = (2-5)x$10^{32}$$cm^{-2}s^{-1}$
- σ_{bb}~500μb (10% B_s)
- '1 year' = 2.0fb^{-1}
- Produce O(10^{11}) B_s per y.
- Expect to reconstruct: O(100k) $B_s \rightarrow J/\psi\varphi$ per y.

Present status Φ_s



	Indirect (CKM fit)	Direct ($B_s \to J/\psi\varphi$ TeVatron)
Φ_s	-2.1°±0.1°	[-30°,-68°]U[-112°,-150°] @68%CL

2.0 fb^{-1} LHCB:
$\sigma(\Phi_s)$ ~ 1.8°