Mixing, CP violation and New Physics in B and Charm

- Introduction
- CKM Matrix and CPV in the Standard Model
- CP violation and mixing in B and D system
- Rare decay

Central questions in Flavor Physics

Does the SM explain all flavor changing interactions?
If does not: at what level we can see deviations? New Physics effects?

The goal is to over constrain the SM description of flavor by many redundant measurements

Requirements for success:

Experimental and theoretical precision

CKM Matrix

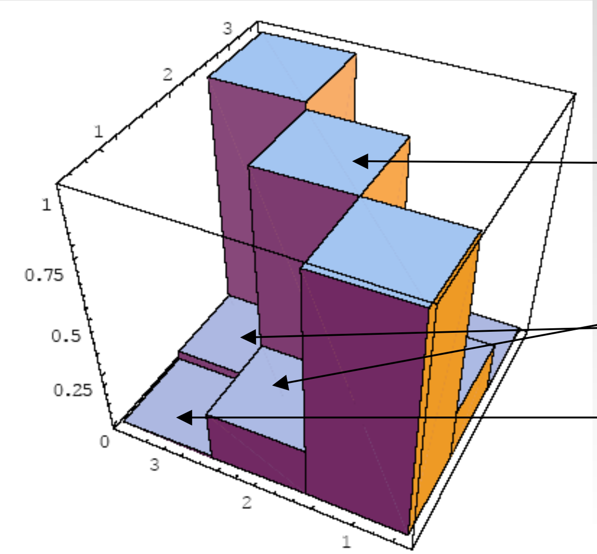
- In the SM SU(2)xU(1) quarks and leptons are assigned to be left-handed doublets and right-handed singlet
- Quark mass eigenstates are not the same as the weak egeienstates, the matrix relating these bases defined for 6 quarks and parameterized by Kobayashi and Maskawa by generalization of 4 quark case described by the Cabibbo angle
- By convention, the matrix is expressed in terms of a 3x3 unitary matrix, V, operating on the charge -1/3 quark eigenstates (d,s,b):

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

Elements depend on 4 real parameters (3 angles and 1 CPV phase)

V_{CKM} is the only source of CPV in the SM

V_{CKM}: Wolfenstein parametrization



The CKM Matrix is hierarchical

Vud, Vcs, Vtb ~ 1

Vus, Vcd ~ λ

Vcb, Vts ~ λ^2

Vub, Vtd ~ λ^3

$\lambda = |V_{us}| = \sin(\theta_c) \sim 0.22$

It is convenient to exhibit the hierarchical structure by expansion in powers of λ

$$V_{CKM}=\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+O(\lambda^4)$$

A, ρ, η ~ O(1)

Present uncertainties:

λ~0.5%, A~4%, ρ~14%, η~4%

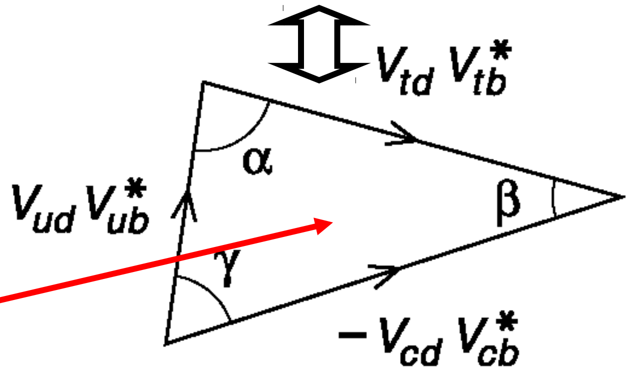
Unitarity Triangle

- A simple and vivid summary of the CKM mechanism
- V_{CKM} is unitary: $VV^\dagger = V^\dagger V = 1$
- The orthogonality of columns (or rows) provides 6 triangle equations in the complex plane:

Example: first and third column:

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

$$V = \begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix} \Rightarrow$$



CPV in SM ∝ Triangle Area

Angles and sides are directly measurable

Unitarity Triangle - 2

There are 6 UT triangles

Columns and rows relations give similar results

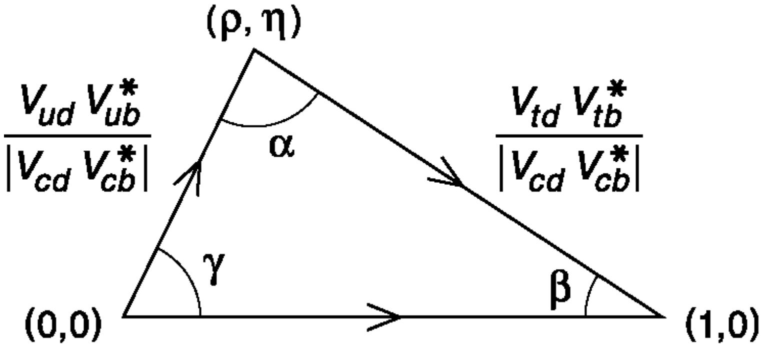
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\Sigma V_{id} V_{is}^* = 0$ (K system)

$\Sigma V_{is} V_{ib}^* = 0$ (Bs system)

$\Sigma V_{id} V_{ib}^* = 0$ (Bd system)

The "$V_{id}V_{ib}^*$" triangle is "special": all sides $O(\lambda^3)$ → large angles → large CPV in the B system

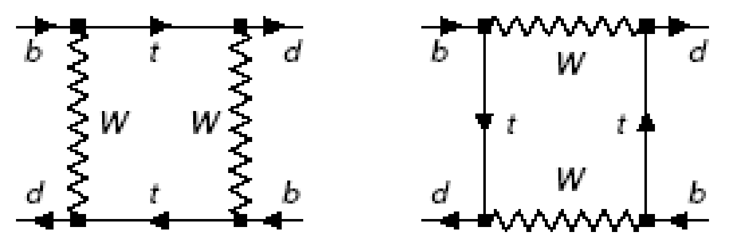


The results are shown in the ρ-η plane

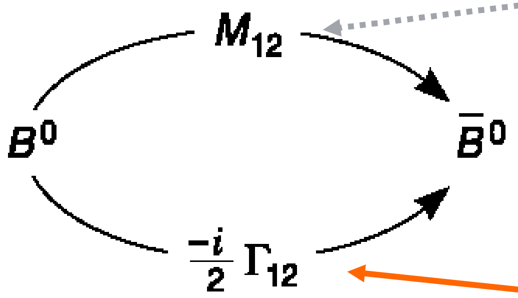
Mixing and CP Violation in B System

Time evolution and mixing of two flavor eigenstates governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle\\|\bar{B}(t)\rangle\end{pmatrix}$$

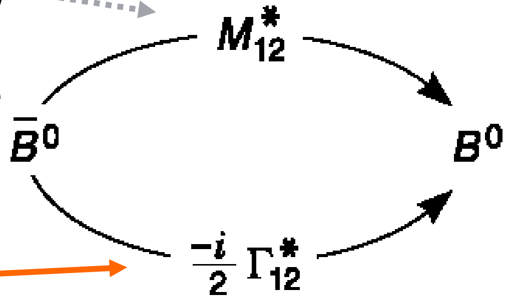


M,Γ are 2x2 time independent, Hermitian matrices; CPT invariance implies M_{11}=M_{22} and Γ_{11}=Γ_{22}, off-diagonals elements due to box diagrams dominated by top quarks are the source of mixing



M_{12} describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram

Γ_{12} describes $B^0 \leftrightarrow f \leftrightarrow \overline{B}^0$ via *on-shell* states



Mixing and CP Violation in B^0 System

Mass eigenstates are eigenvectors of H:

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$$|p|^2+|q|^2=1$$

NOTE: In general $|B_H>$ and $|B_L>$ are not orthogonal to each other

The time evolution of the mass eigenstates is governed by:

$$|B_{H,L}(t)\rangle = e^{-\left(iM_{H,L}+\frac{\Gamma_{H,L}}{2}\right)\cdot t}|B_{H,L}(t=0)\rangle$$

In the $|\Gamma_{12}|<<|M_{12}|$ limit, which holds for both B_d and B_s:

$$\Delta m = M_H - M_L = 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\varphi \qquad \varphi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\frac{q}{p} = -\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m + i\,\Delta\Gamma/2} = -e^{-i\varphi_M}\left[1-\frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$M_{12} = |M_{12}|e^{i\varphi_M}$$

Neutral meson Mixing in the SM

$$\Delta m_q = \frac{G_F^2}{6\pi^2}\left|V_{tb}\right|^2\left|V_{tq}\right|^2 M_W^2 M_{B_q^0} \underbrace{f_{B_q^0}^2 B_{B_q^0}}_{\text{non perturbative QCD}} \underset{\substack{\Big\downarrow \\ \text{perturbative QCD}}}{\eta_{B_q^0}} S\left(\frac{M_t^2}{M_W^2}\right)$$

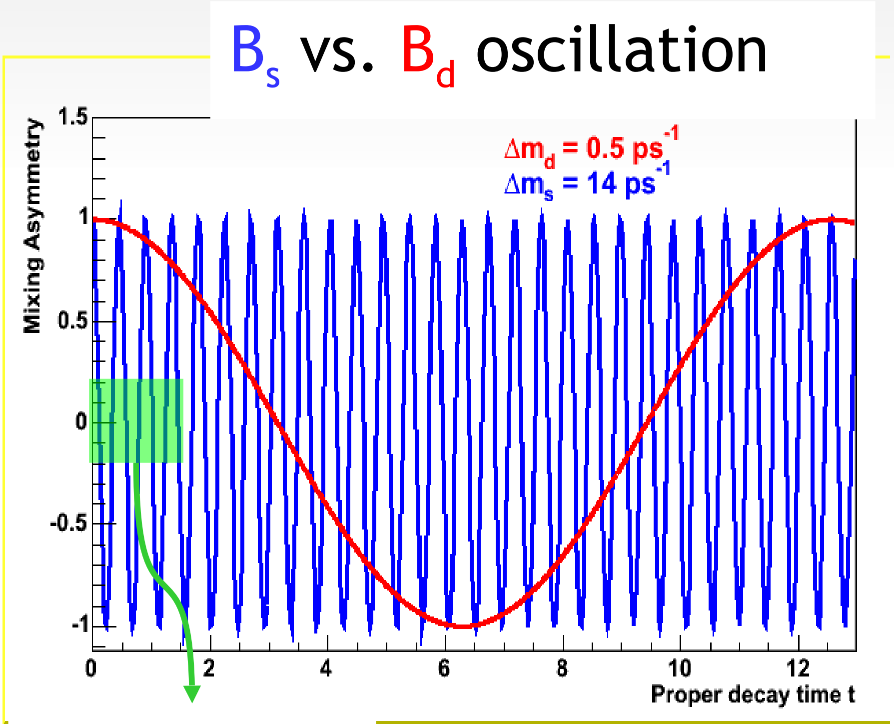
$$\frac{\Delta m_d}{\Delta m_s} = \frac{\left|V_{td}\right|^2}{\left|V_{ts}\right|^2}\frac{M_{B_d^0}}{M_{B_s^0}}\underset{\substack{\Big\downarrow \\ \cong 1}}{\frac{\eta_{B_d^0}}{\eta_{B_s^0}}}\frac{f_{B_d^0}^2 B_{B_d^0}}{f_{B_s^0}^2 B_{B_s^0}}$$

SU(3) Flavor breaking
theoretical uncertainties <5%

B_s Mixing

Measurement Principle in a Perfect World

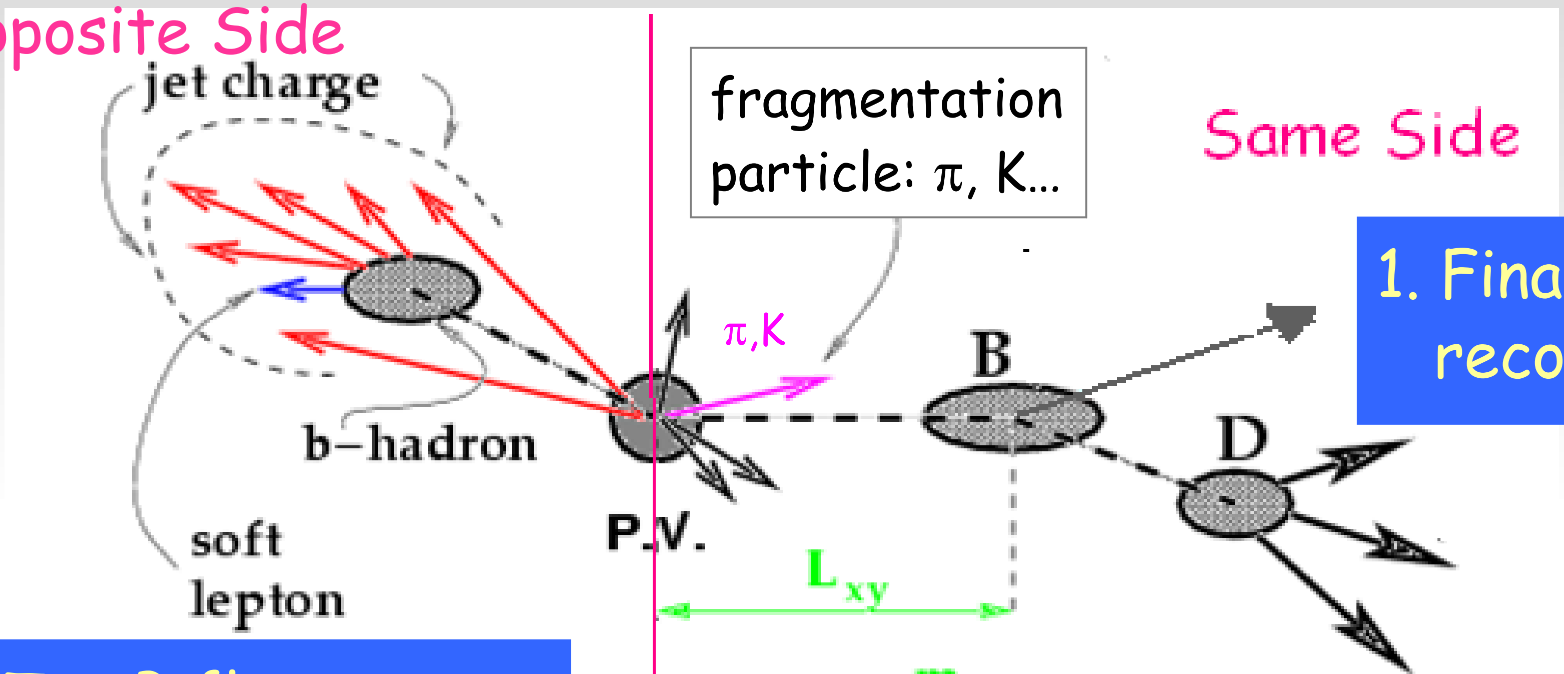
$$P(t)_{B_q^0 \to \overset{(-)}{B}_q^0} = \frac{1}{2\tau} e^{-\frac{t}{\tau}} (1 \pm \cos(\Delta m_q t)) \qquad A = \frac{N^{nomix} - N^{mix}}{N^{nomix} + N^{mix}} = \cos(\Delta m_s t)$$



B_s vs. B_d oscillation

B lifetime

Road Map to Δm_s Measurement



fragmentation particle: π, K…

Same Side

1. Final state reconstruction

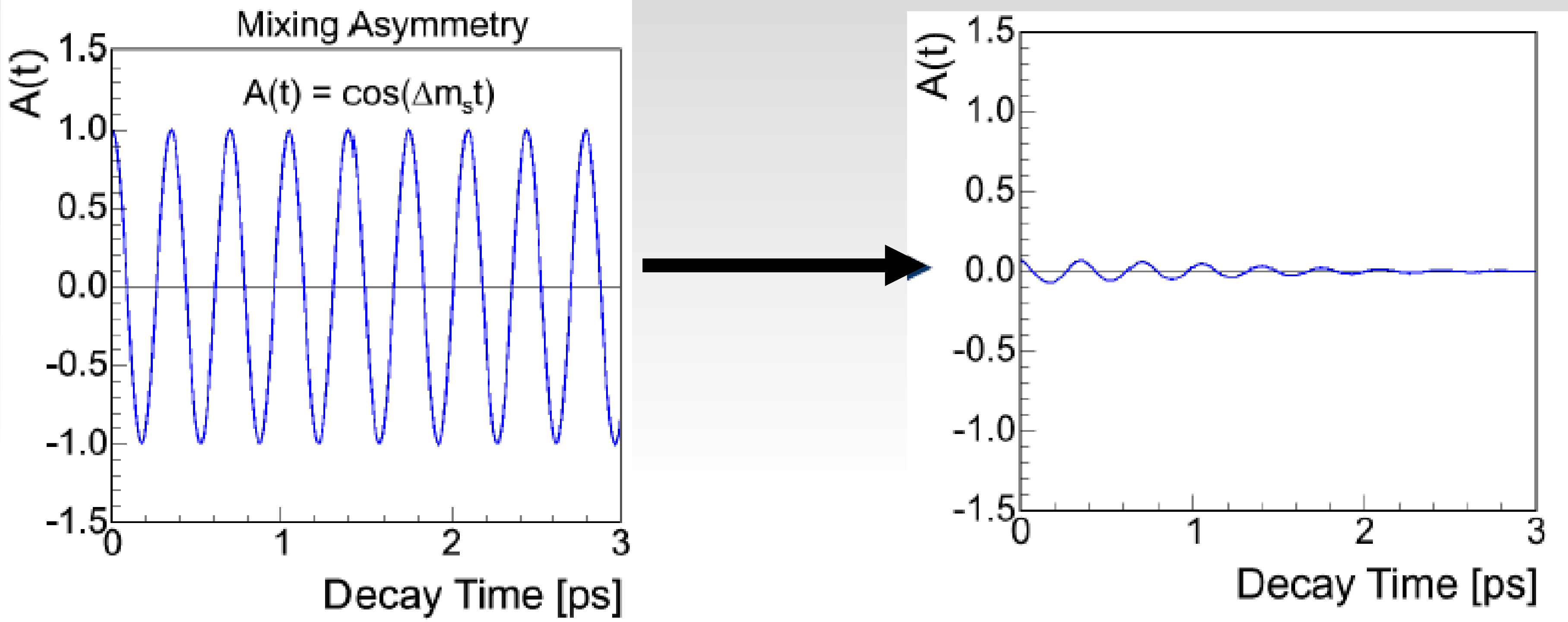
$$ct = L_{xy}\frac{m_B}{p_T}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

3. Tag B flavor at production time

2. High resolution on proper decay length

Adding all realistic effects



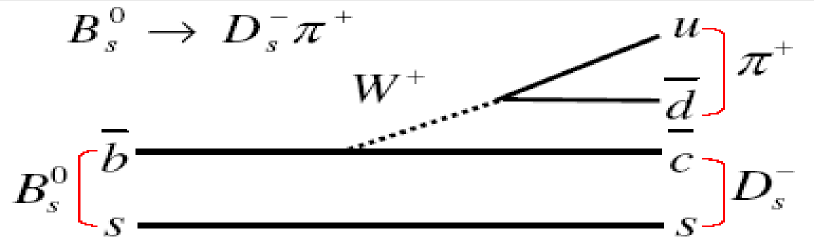
Flavor tagging power

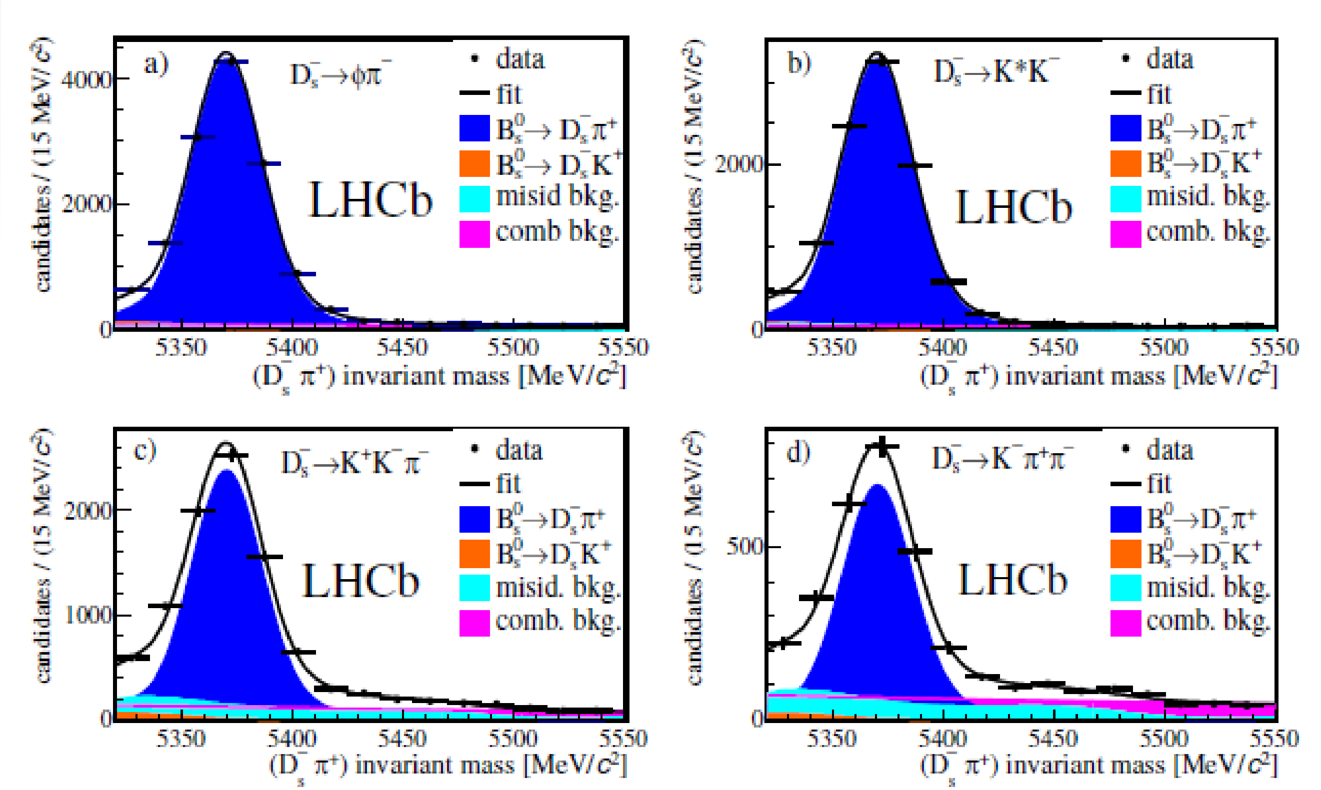
Proper time resolution

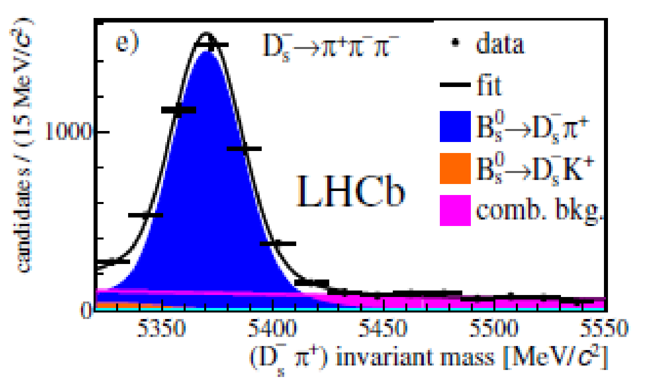
$$\frac{1}{\sigma} = \sqrt{\frac{S\boxed{\epsilon D^2}}{2}}\, e^{-\frac{(\Delta m_s \boxed{\sigma_t})^2}{2}} \sqrt{\frac{S}{S+B}}$$

$$\sigma_{ct} = \frac{m_B}{p_T}\sigma_{L_{xy}} \oplus ct\left(\frac{\sigma_{p_T}}{p_T}\right)$$

B_s data Sample

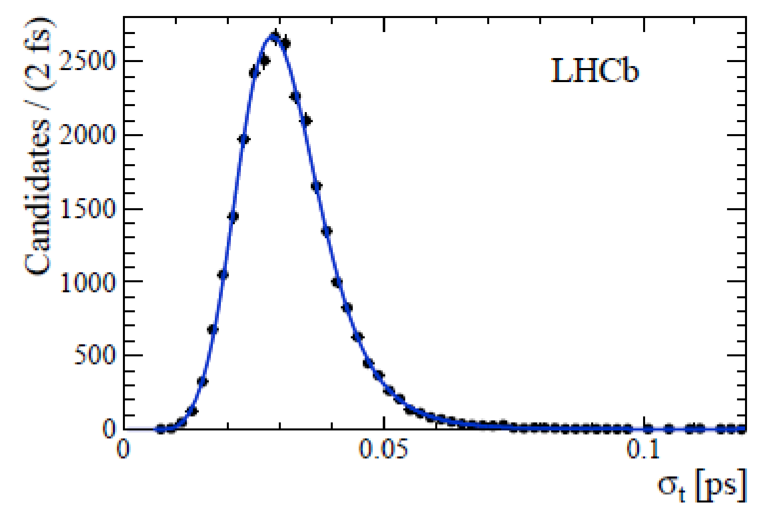


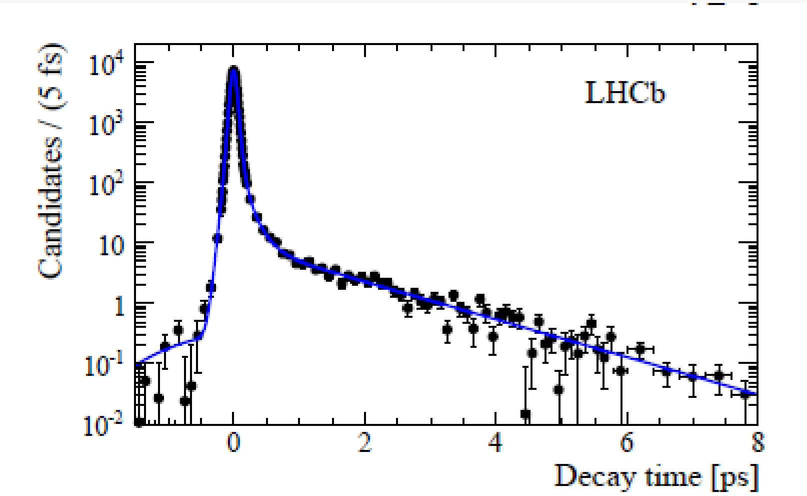




Proper decay time reconstruction

- Fully reconstructed events ct = $L_{xy}^{B} M^{B}/P_{t}^{B}$
- Measure the lifetime to establish the time scale
- Determine the time resolution
- Use events with J/Ψ+tracks





Events Tagging

Opposite Side

- Use data to calibrate taggers and to evaluate D
- Fit semileptonic and hadronic B_d sample to measure: D, Δm_d

-lepton (electron or muon)

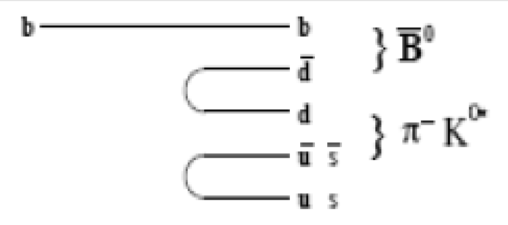
$$Q_J^{\ell} = \sum_i q^i p_T^i / \sum_i p_T^i$$

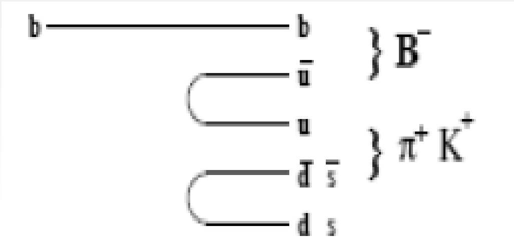
- Secondary Vertex

- $Q_{\mathrm{SV}} = \sum_i (q^i p_L^i)^{0.6} / \sum_i (p_L^i)^{0.6}$

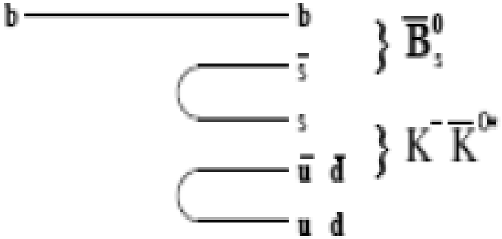
$$Q_{\mathrm{EV}} = \sum_i q^i p_T^i / \sum_i p_T^i$$

Same Side





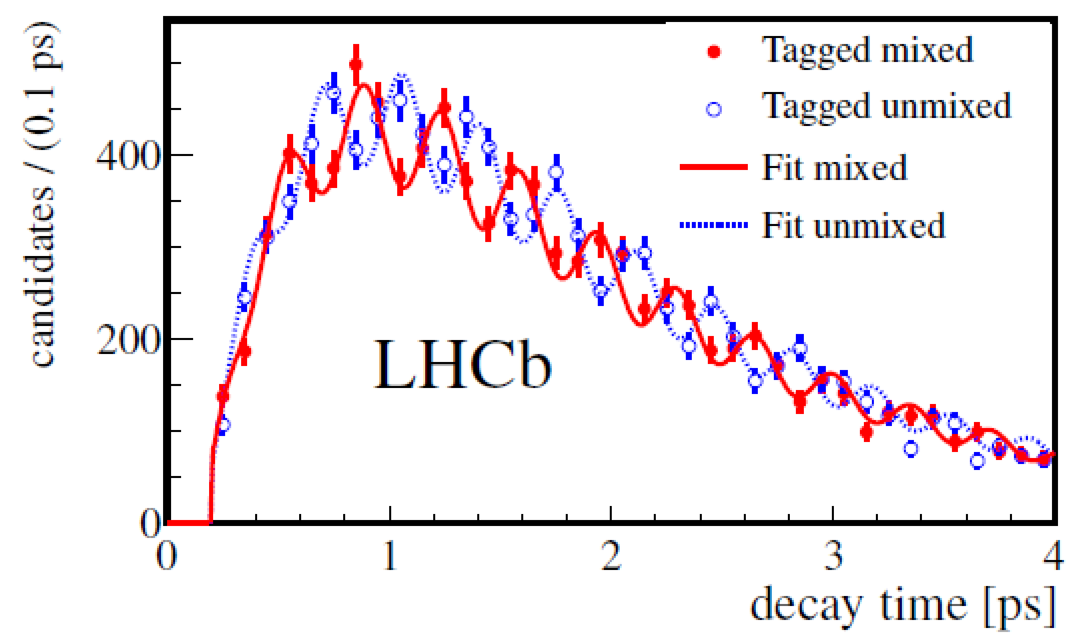
$B^0/B^\pm$ likely to have π nearby



B^0_s likely to have K

Tune Monte Carlo to reproduce B^0,B^- distributions then apply to B_s

Bs mixing results



$$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$

CP Violation in B^0 System

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$$|p|^2+|q|^2=1$$

NOTE: In general $|B_H>$ and $|B_L>$ are not orthogonal to each other

The time evolution of the mass eigenstates is governed by:

$$|B_{H,L}(t)\rangle = e^{-\left(iM_{H,L}+\frac{\Gamma_{H,L}}{2}\right)\cdot t}|B_{H,L}(t=0)\rangle$$

In the B_s system, with $\phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$

$$\Delta m_s = m_s^H - m_s^L$$

$$= 2|M_{12}^s|\left(1+\frac{1}{8}\frac{|\Gamma_{12}^s|^2}{|M_{12}^s|^2}\sin^2\phi_s + \ldots\right)$$

$$\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$$

$$= 2|\Gamma_{12}^s|\cos\phi_s\left(1-\frac{1}{8}\frac{|\Gamma_{12}^s|^2}{|M_{12}^s|^2}\sin^2\phi_s + \ldots\right)$$

In the B_s system correction the order of $\frac{M_{12}^2}{\Gamma_{12}^2}$ can be neglected

$\Delta m_s = M_H - M_L = 2|M_{12}|$ measured

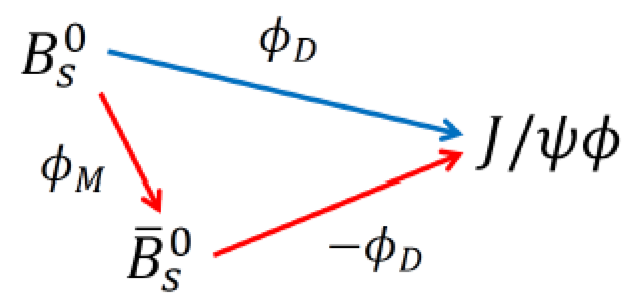
$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\varphi_s$ → related to B lifetime

CP Violation in B^0 System

In the SM no CP violation is expected in the B$_s$ sector $\phi_s \approx 0.004$

- The CP eigenstates are also the B$_s$ mass eigenstates and Γ_L is the width of the CP even state corresponding to the short lived state and Γ_H is the width of the CP odd state, the long lived one.
- Several models expected new physics in the B$_s$ sector in a such a way that $\Gamma_{12}^{s} \approx \Gamma_{12}^{s\,SM}$ $M_{12}^{s} = M_{12}^{s\,SM} \times \Delta_s$ with $\Delta_s = |\Delta_s| e^{(i\phi_s^{NP})}$
  New Physics only in the mixing part → not allowed given the mixing frequency precision.
- Other possibility: $\phi_s = \phi_s^{SM} + \phi_s^{NP} \approx \phi_s^{NP}$

Measurement of the Φ Phase



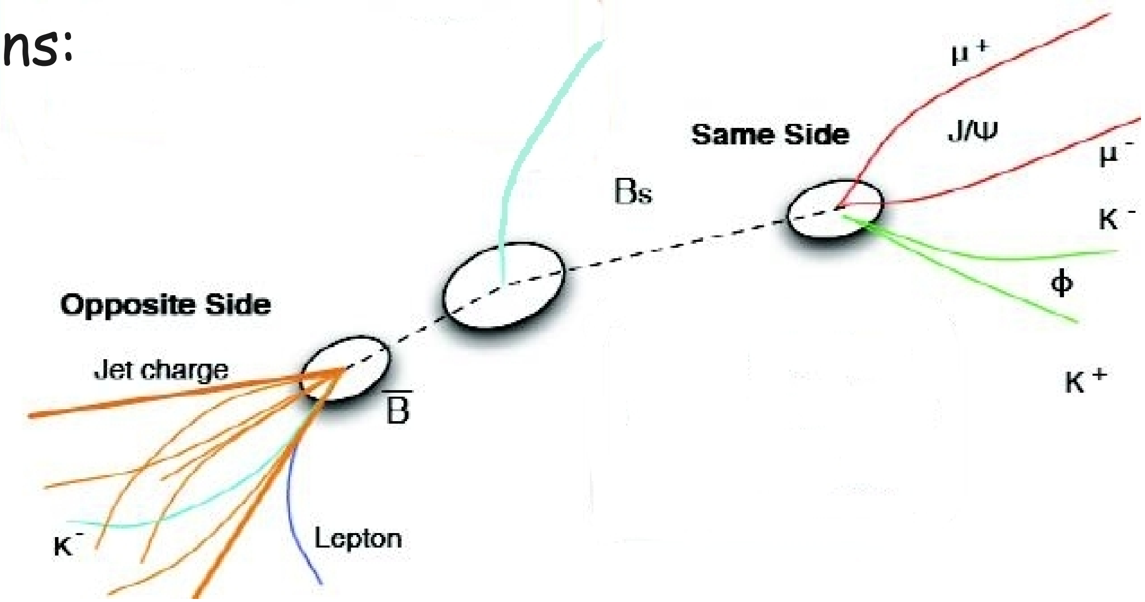
The phase Φs enter in the B → J/Ψ φ decay:
arise in the interference
between direct decay (Φ_D) and decay
via mixing (Φ_M - Φ_D).

In Standard Model:

$\Phi_{M,s}$ - $2\Phi_{D,s}$ ~$-2\beta_s$

Possible NP contributions:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP} \approx \phi_s^{NP}$$



Measurement of the Φ Phase

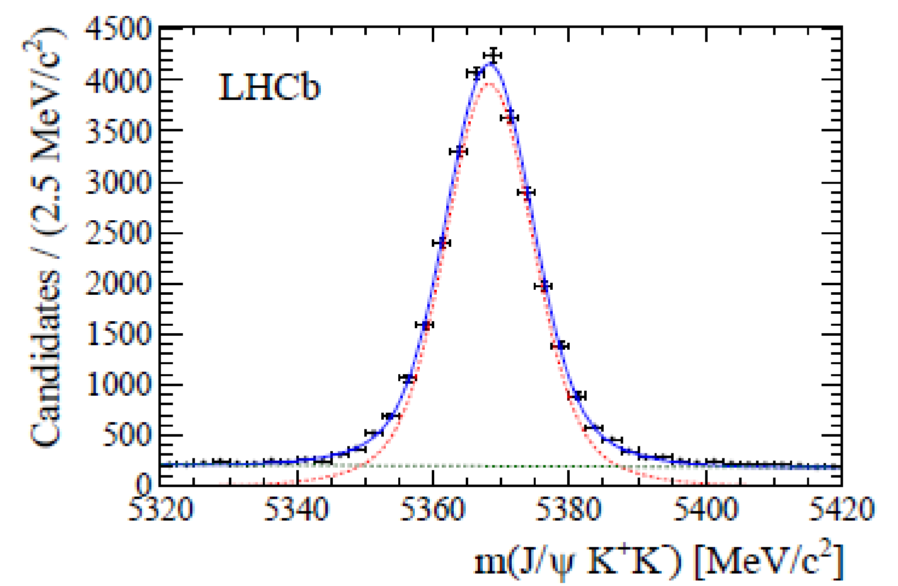
Analysis Strategy

1. reconstruct J/Ψ and Φ

2.found the secondary vertex and derive ct=Lxy/βγ

3.determine if the decay B-meson is b or $\bar{b}$

4.perform the global fit



Measurement of the Φ Phase:angular distribution

- Angular distributions:

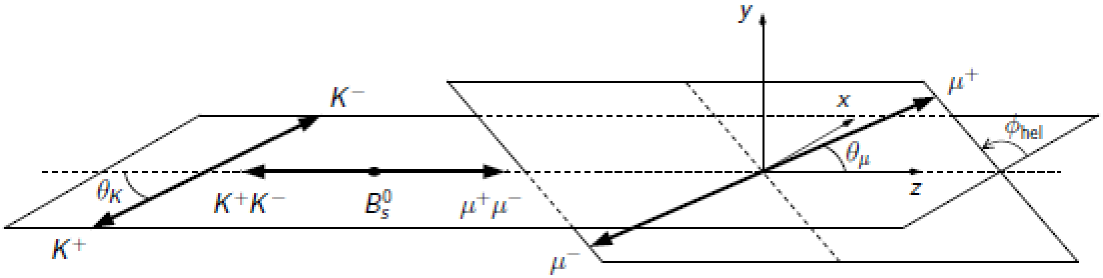
  B^0_s: pseudo-scalar   J/Ψ= vector   Φ=vector

  The total spin in the final state 0,1,2. To conserve the total angular momentum, the orbital angular momentum L between the final state decay products must be either 0, 1 or 2.

  J/ψ and φ are CP-even eigenstates, but J/ψφ final state has CP= $(-1)^L$

  States with L= 0, 2 are CP-even and L=1 is CP-odd.

- Decay time and decay angles are used to separate CP-even from CP- odd final state.

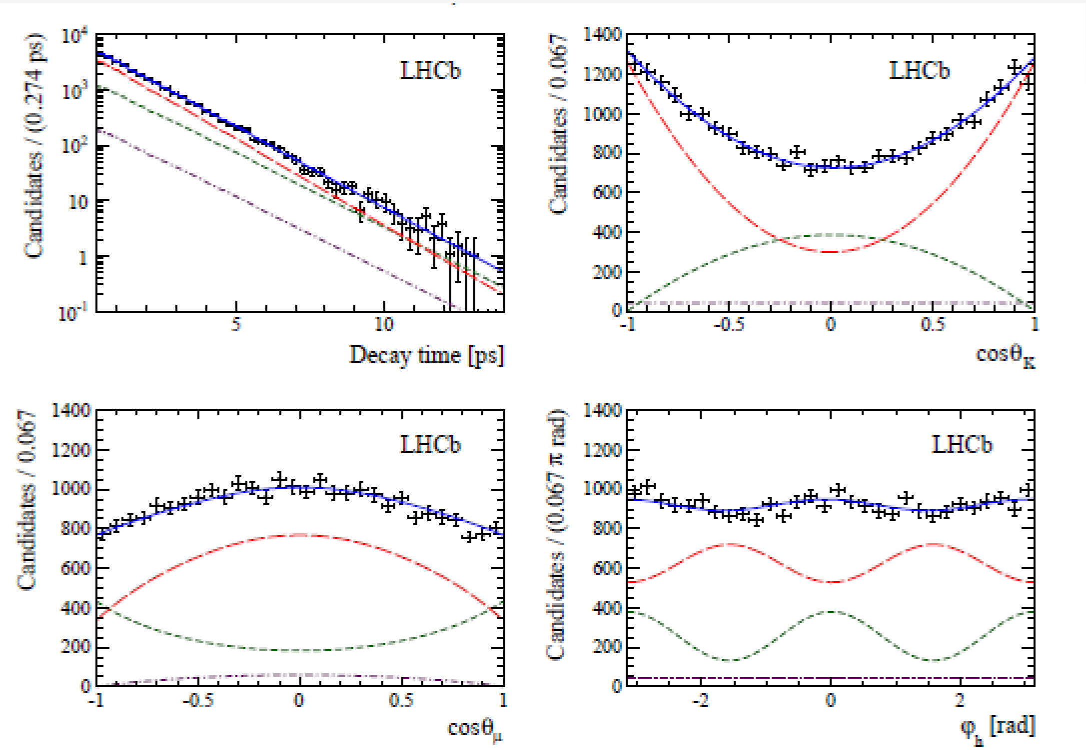


Measurement of the Φ Phase: Fit

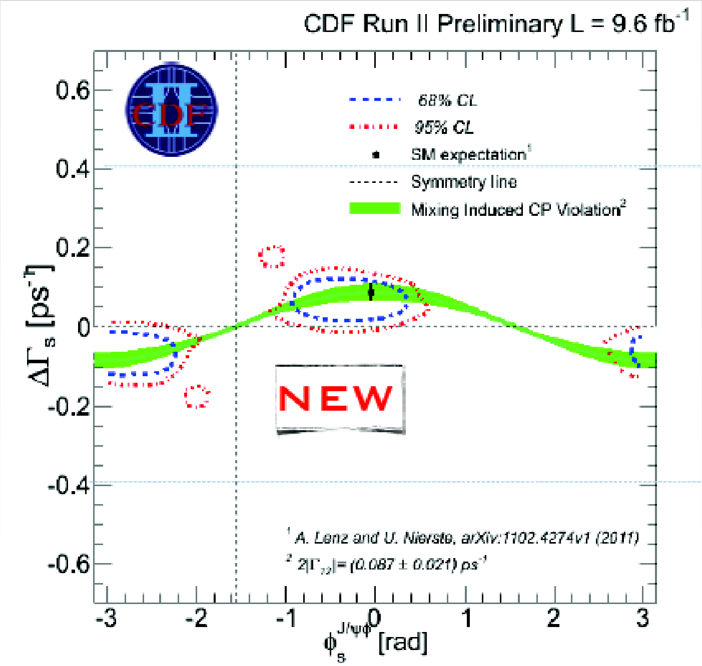
- For each event is calculated a probability and the likelihood is minimized

$$\mathcal{L} = \prod_{i=1}^{N} [f_s \cdot P_s(m|\sigma_m) \cdot P_s(\xi) \cdot P_s(\theta_T, \phi_T, \psi_T, ct|\sigma_{ct}, \xi, \mathcal{D}_p) \cdot P_s(\sigma_{ct}) \cdot P_s(\mathcal{D}_p)$$
$$+ (1 - f_s) \cdot P_b(m) \cdot P_b(\xi) \cdot P_b(ct|\sigma_{ct}) \cdot P_b(\theta_T) \cdot P_b(\phi_T) \cdot P_b(\psi_T) \cdot P_b(\sigma_{ct}) \cdot P_b(\mathcal{D}_p)]$$

Data with fit results

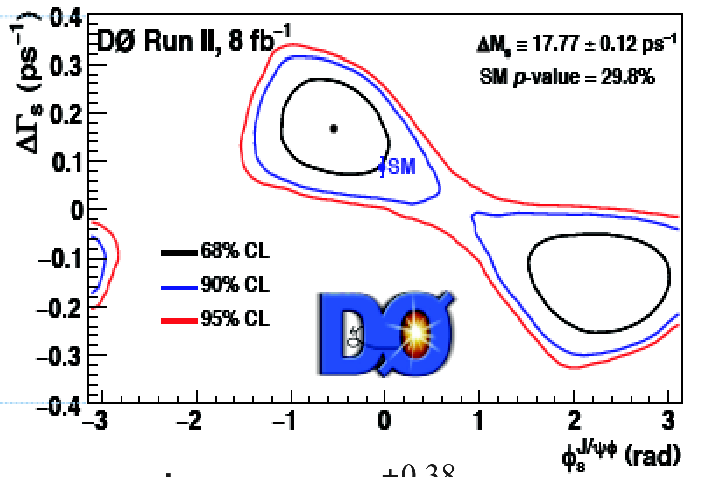


Results on Φ Phase



$$\phi_s \in [-0.60, 0.12] \quad rad @ 68\% C.L.$$

PRD 85, 032006 (2012)



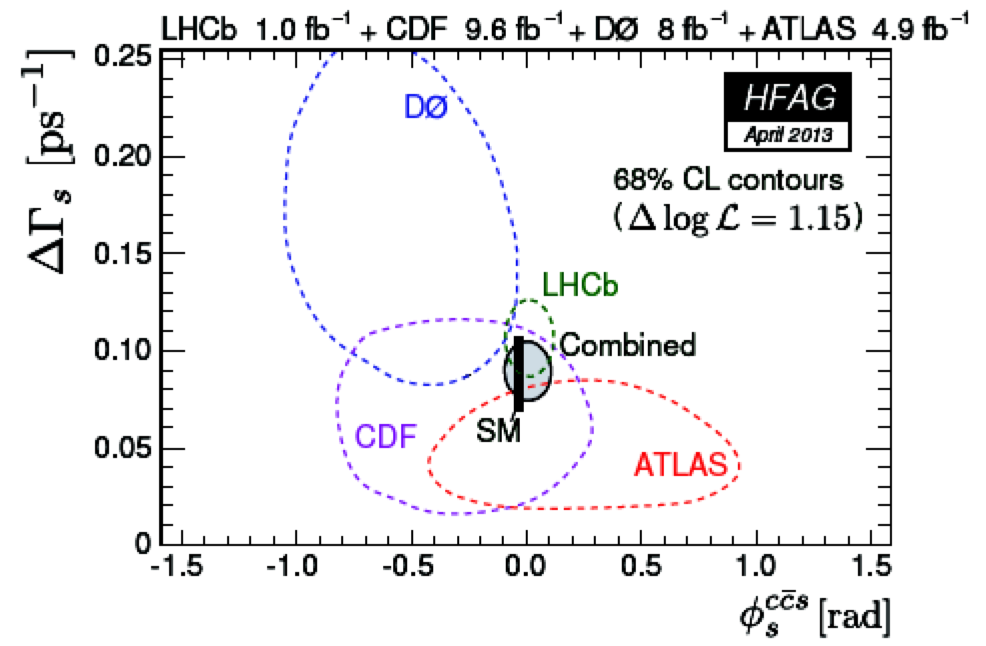
$$\phi_s = -0.55^{+0.38}_{0.36} \quad rad$$

Strong phases Constrained in the fit

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad,}$$

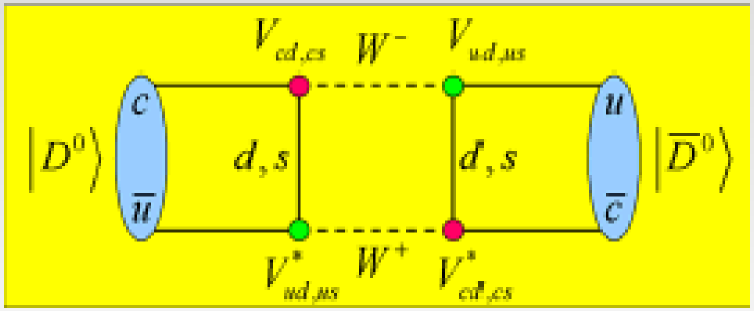
$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}$$



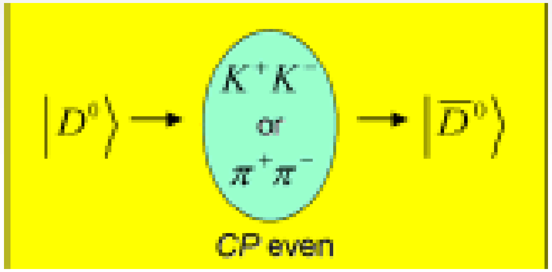
D^0-$\bar{D}^0$ Mixing

In the charm sector mixing is governed by the diagrams



dominated by strange quark -> suppressed

$$x = \frac{\Delta m}{\Gamma}$$



Long distance diagram $y = \frac{\Delta\Gamma}{\Gamma}$

$$R_{mix} = \frac{1}{2}(x^2 + y^2)$$

$$P(D^0 \to \bar{D}^0) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

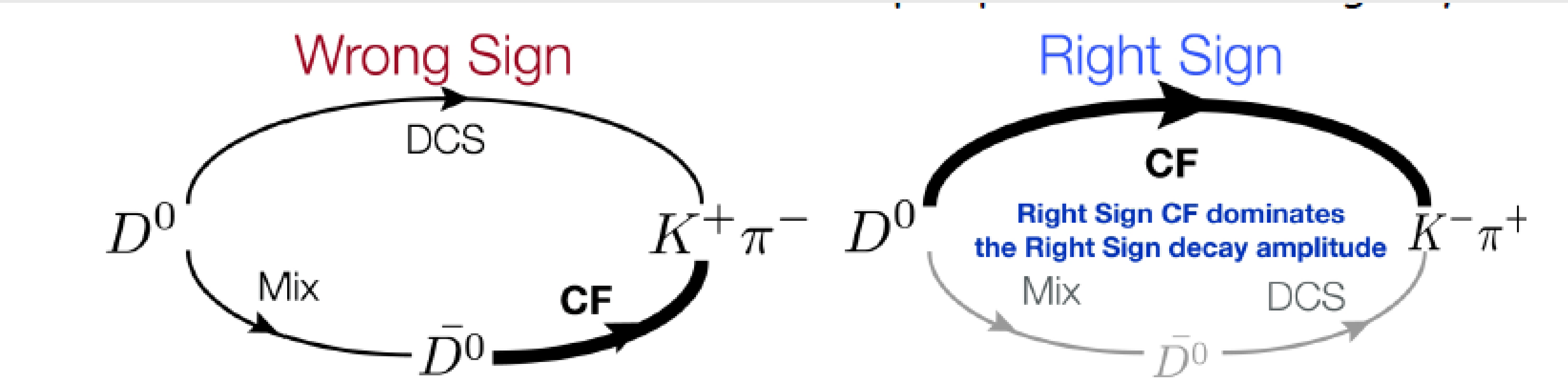
	$K^0/\overline{K^0}$	$D^0/\overline{D^0}$	$B^0_d/\overline{B^0_d}$	$B^0_s/\overline{B^0_s}$
τ (ps)	89.58 ± 0.05, 51160 ± 200	0.4101 ± 0.0015	1.530 ± 0.009	1.470 ± 0.027
Γ (s^{-1})	5.59×10^9	2.4×10^{12}	6.5×10^{11}	6.8×10^{11}
x	0.946 ± 0.002	0.0097 ± 0.0028	0.776 ± 0.008	26.1 ± 0.5
y	-0.9965	0.0078 ± 0.0019	$\|y\| < 0.04$, 90% C.L.	$[0.09, -0.03]$, 95% C.L.

K^0_S/K^0_L slow mixing fast mixing

D^0-$\overline{D}^0$ Mixing

This year LHCb has measured the mixing at 5σ

Time dependent "wrong-sign" decay rate is a cocktail of mixing and DCS decay amplitude



Assuming $|x|,|y| \ll 1$ and CP conservation,

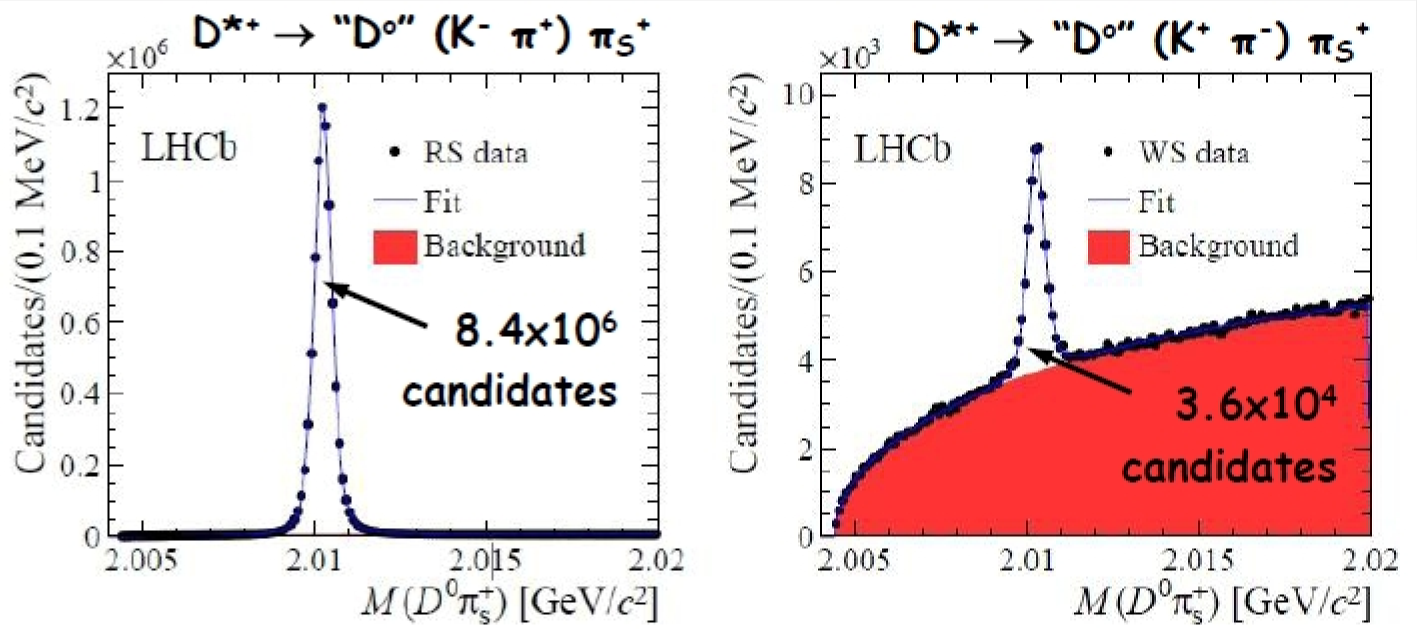
Wrong sign: $dN_{ws}/dt \approx e^{-\Gamma t}$ x [$(x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2 + D^2_{DCS} + D_{DCS} \cdot y' \cdot \Gamma t$]

mixing *DCSD* *interference*

Ratio: $N_{ws}/N_{rs}(t) \approx (x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2 + R_D + \sqrt{R_D} \cdot y' \cdot \Gamma t$

D^0-$\overline{D^0}$ Mixing

- Use prompt $D^{*+} \rightarrow D^0 \pi_S^+$
- Charge of soft pion tags the initial flavor of the D^0
- D^0 and π_S^+ required to form a vertex constrained to PV.



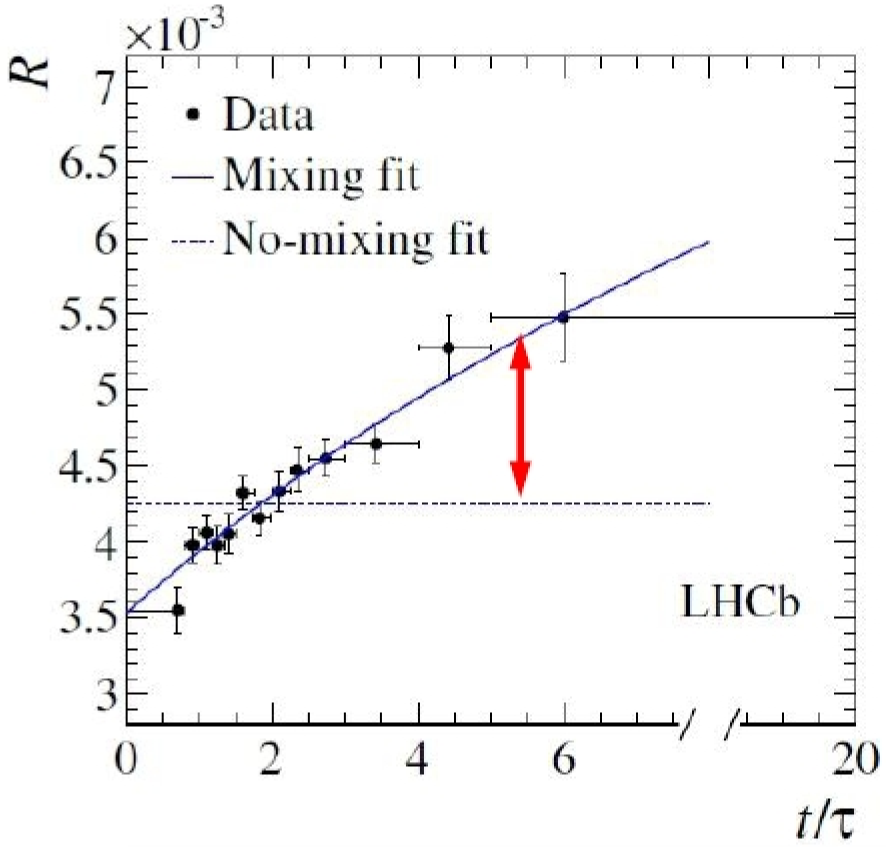
$D^{*+} \rightarrow$ "D^0" $(K^- \pi^+)\ \pi_S^+$

8.4×10^6 candidates

$D^{*+} \rightarrow$ "D^0" $(K^+ \pi^-)\ \pi_S^+$

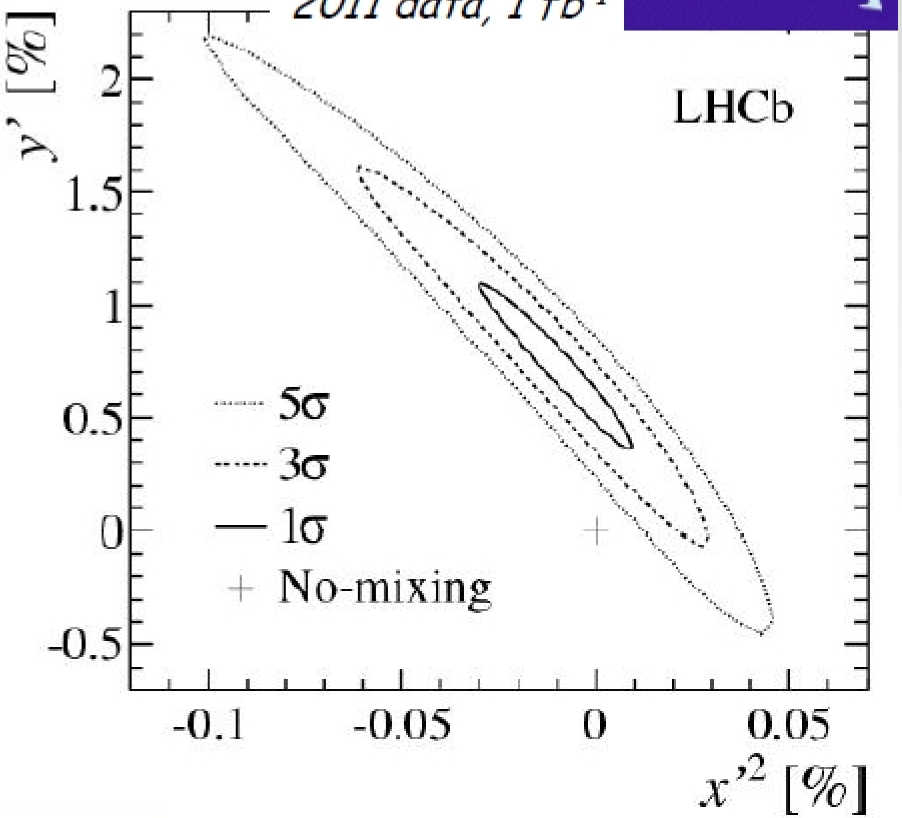
3.6×10^4 candidates

$D^0-\overline{D}^0$ Mixing



PRL 110 (2013) 101802

2011 data, 1 fb^{-1}

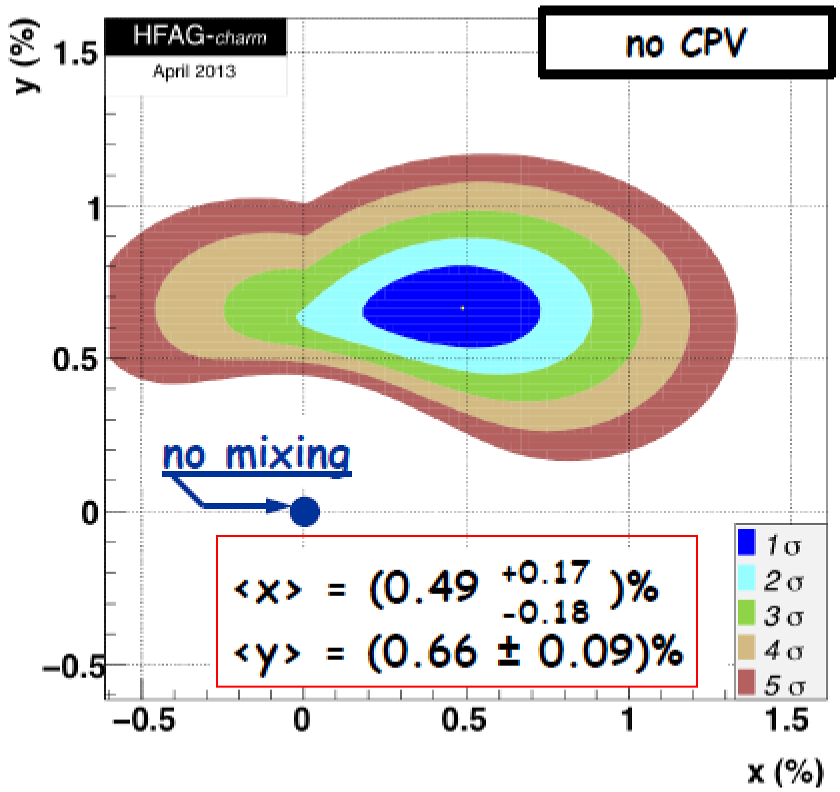


Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

No mixing hypothesis excluded at > 9σ.

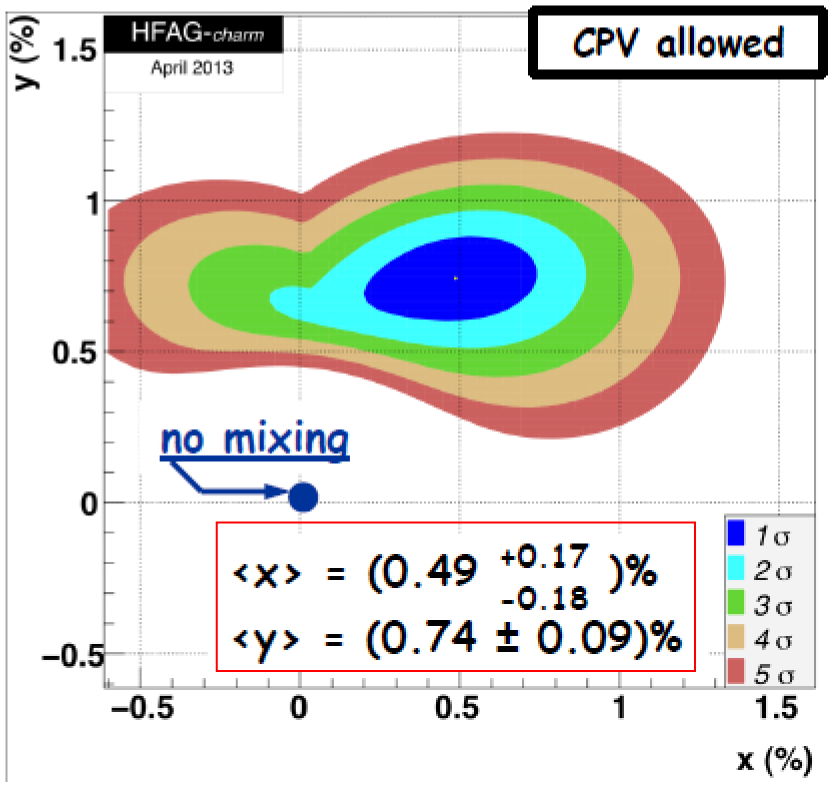
D^0-$\overline{D^0}$ Mixing

http://www.slac.stanford.edu/xorg/hfag/charm



$\langle x \rangle = (0.49\,^{+0.17}_{-0.18})\%$

$\langle y \rangle = (0.66 \pm 0.09)\%$



$\langle x \rangle = (0.49\,^{+0.17}_{-0.18})\%$

$\langle y \rangle = (0.74 \pm 0.09)\%$

Wrong sign $D^\circ \rightarrow K\pi$ latest results

	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13
Belle	3.64 ± 0.17	$0.6\,^{+4.0}_{-3.9}$	$0.18\,^{+0.21}_{-0.23}$
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

CP Violation in Charm

Several possible CP violation in Charm process, all of them expected to be small.

Focus on $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow h^+h^-$. The final state are in common between D^0 and $\overline{D}^0$

The time dependent asymmetry:

$$A_{CP}(h^+h^-,t) = \frac{N(D^0 \rightarrow h^+h^-;t) - N(\overline{D}^0 \rightarrow h^+h^-;t)}{N(D^0 \rightarrow h^+h^-;t) + N(\overline{D}^0 \rightarrow h^+h^-;t)}$$

has contributions from:

- difference in decay widths between D^0 and $\overline{D}^0$ in the same finale state
- difference in mixing probabilities
- interference between direct decay and decay proceeding via mixing

Since D^0 mixing is slow time dependent asymmetry:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\text{dir}}(h^+h^-) + \frac{t}{\tau}\, A_{CP}^{\text{ind}}(h^+h^-).$$

CP Violation in Charm - 2

where:

$$A_{CP}^{\mathrm{dir}}(h^+h^-) \equiv A_{CP}(t=0) = \frac{\left|\mathcal{A}(D^0 \to h^+h^-)\right|^2 - \left|\mathcal{A}(\overline{D}^0 \to h^+h^-)\right|^2}{\left|\mathcal{A}(D^0 \to h^+h^-)\right|^2 + \left|\mathcal{A}(\overline{D}^0 \to h^+h^-)\right|^2}$$

$$A_{CP}^{\mathrm{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi\right],$$

η_{CP}=CP parity of the final state, φ is a CP violating phase

Time integrated asymmetry are the integral of the previous equation

$$\begin{aligned} A_{CP}(h^+h^-) &= A_{CP}^{\mathrm{dir}}(h^+h^-) + A_{CP}^{\mathrm{ind}}(h^+h^-)\int_0^\infty \frac{t}{\tau}\, D(t)dt \\ &= A_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t\rangle}{\tau}\, A_{CP}^{\mathrm{ind}}(h^+h^-). \qquad (4) \end{aligned}$$

These asymmetries have been measured in agreement with SM expectation

CP Violation in Charm - 3

If no large weak phases contribute to decay amplitude, A_{CP}^{ind} is independent of the finale state and a comparison between A_{CP} in the final states $D^0 \rightarrow \pi^- \pi^+$ $D^0 \rightarrow K^- K^+$

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-) = \Delta A_{\mathrm{CP}}^{\mathrm{dir}} + \frac{\Delta(t)}{\tau} A_{\mathrm{CP}}^{\mathrm{ind}}.$$

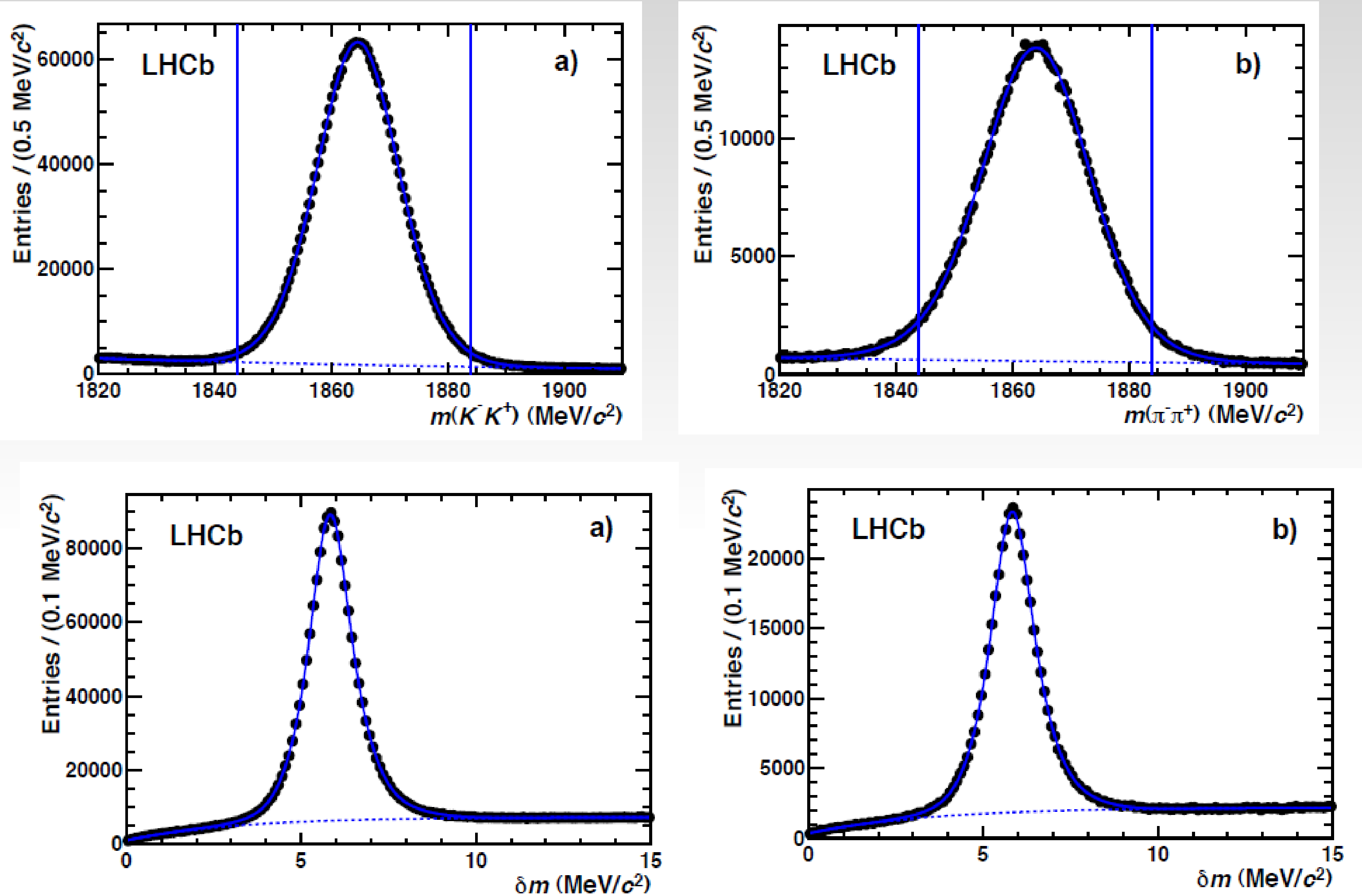
Since the difference in decay time acceptance is small, $\Delta t \approx 0$

$$\Delta A_{\mathrm{CP}}^{\mathrm{dir}} = A_{\mathrm{CP}}^{\mathrm{dir}}(K^+K^-) - A_{\mathrm{CP}}^{\mathrm{dir}}(\pi^+\pi^-)$$

Analysis method

- reconstruct $D^0 \rightarrow \pi^- \pi^+$ $D^0 \rightarrow K^- K^+$
- identify a “slow” $\pi^\pm$ which form with D^0 a D^{0*}
- the charge of the π tag the flavour of of the D^0, ie if it is D^0 or $\overline{D}^0$

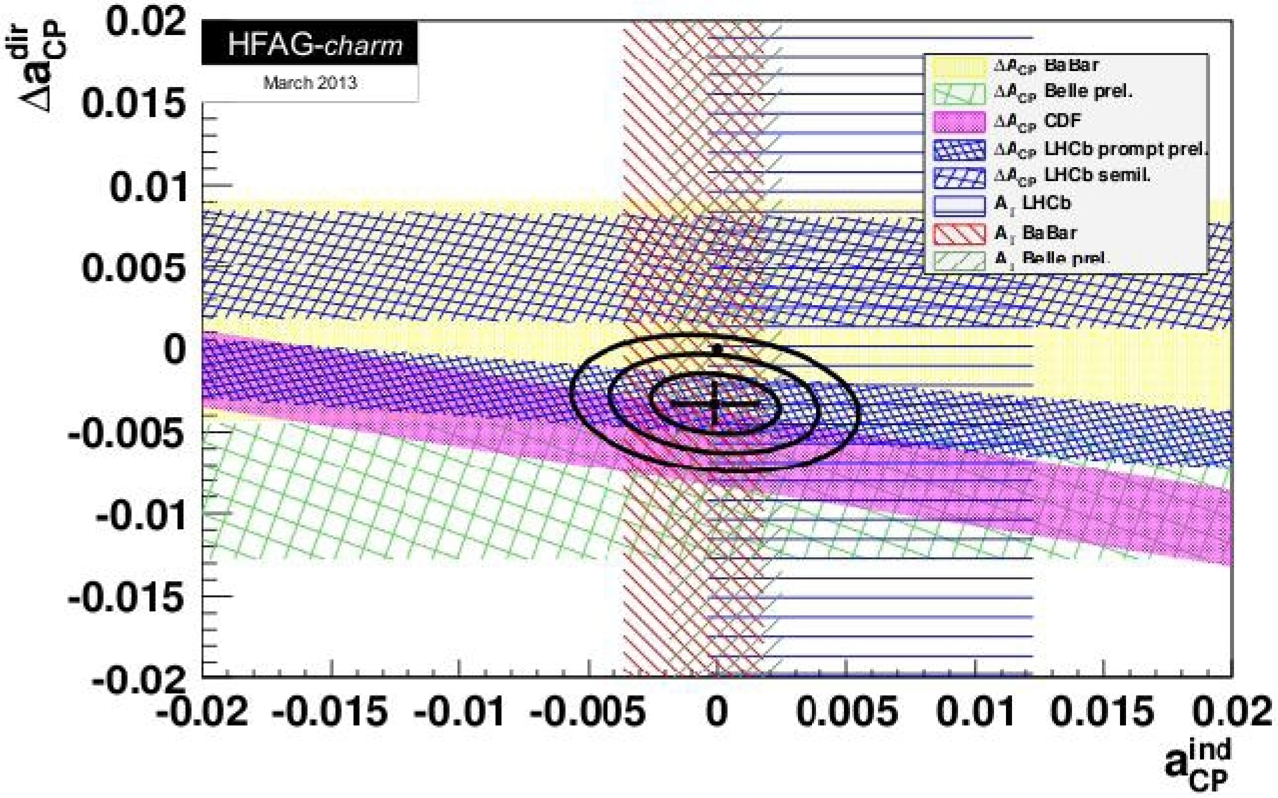
CP Violation in Charm - 4



ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%

CP Violation in Charm Results

http://www.slac.stanford.edu/xorg/hfag/charm



Data consistent with no CPV at CL = 2.1%

$\Delta a_{CP}^{dir} = (-0.329 \pm 0.121)\%$, $a_{CP}^{ind} = (-0.010 \pm 0.162)\%$

$B_s \to \mu\mu$ Decay

In the SM Flavor Changing Neutral Current have played an important Role in setting up the structure of the model.

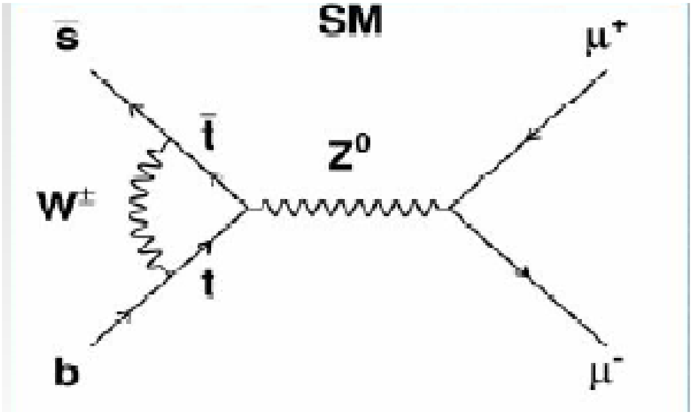
At lowest order these transition are not allowed.

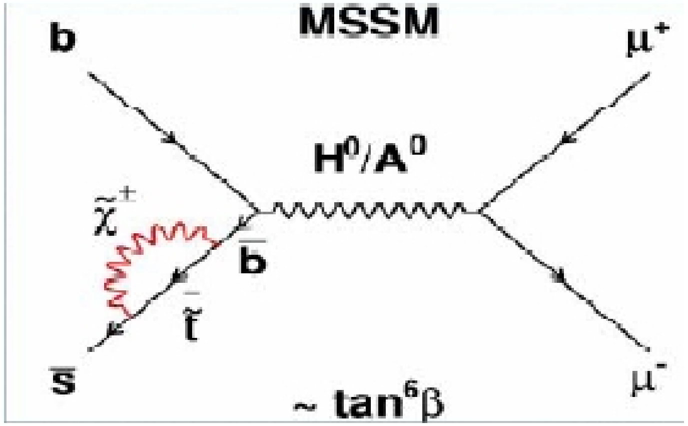
The decays $B^0_s \to \mu\mu$ and $B^0_d \to \mu\mu$ occur only via loop diagrams with A branching ratio very well predicted:

$B(Bs \to \mu\mu) = (3.2 \pm 0.2)\ 10^{-9}$ $B(B \to \mu\mu) = (0.1 \pm 0.01)\ 10^{-9}$

arXiv:1005.5310
arXiv:1012.1447

Several beyond SM theories predict an enhancement of the BR





Measurements performed by all experiments at hadron collider.

Very simple idea: select events with two muon in the correct mass window.

$B_s \to \mu\mu$ Decay

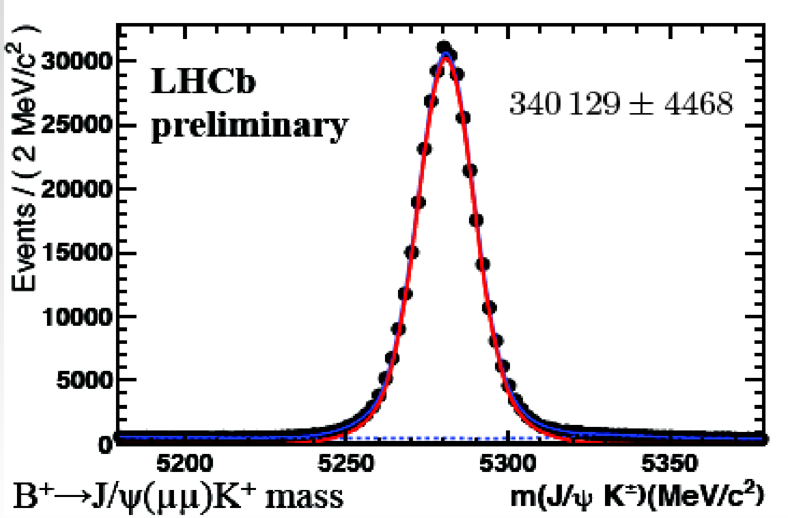
Use other decay channels as normalization

$B^+ \to J/\psi(\mu\mu)K^+$, $B_s \to J/\psi(\mu\mu)\phi$, $B \to K\pi$

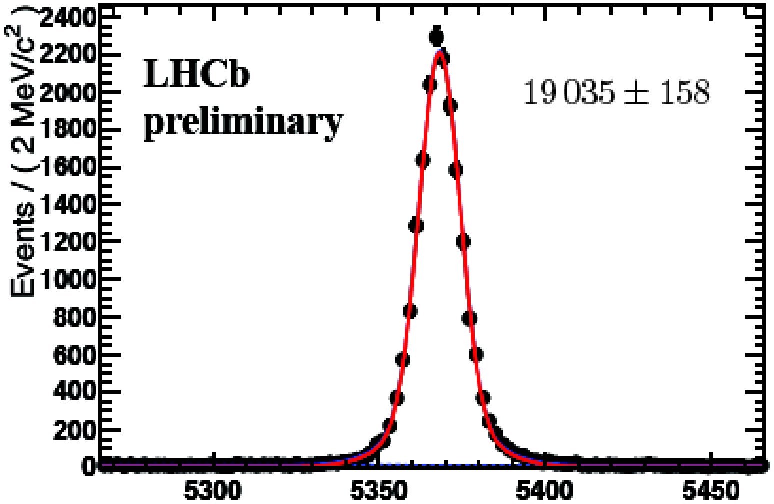
$$\mathcal{B} = \mathcal{B}_{\rm norm} \times \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}} \times \frac{f_{\rm norm}}{f_{d(s)}} \times \frac{N_{B^0_{(s)} \to \mu^+\mu^-}}{N_{\rm norm}}$$

Background due mainly to combinatorial

$b \to \mu\mu X$ $B \to hh$ where h is misidentified as μ



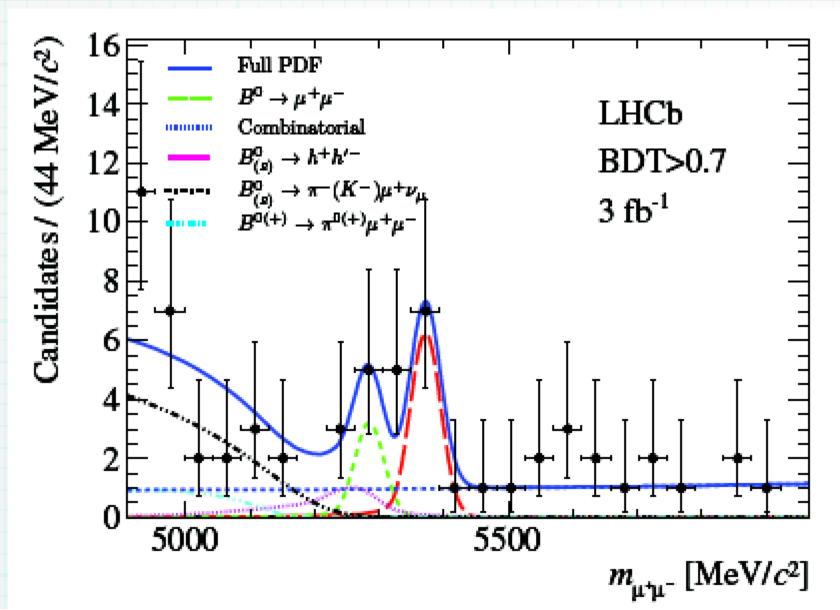
$B^+ \to J/\psi(\mu\mu)K^+$ mass

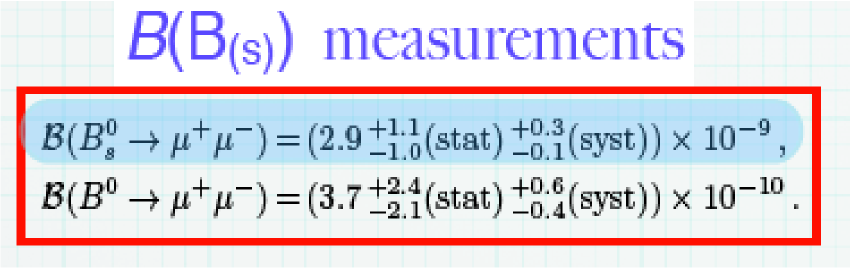


$B_s \to J/\psi(\mu\mu)\phi$ mass

$B_s \rightarrow \mu\mu$ Decay

Use multivariate technique to separate signal from background

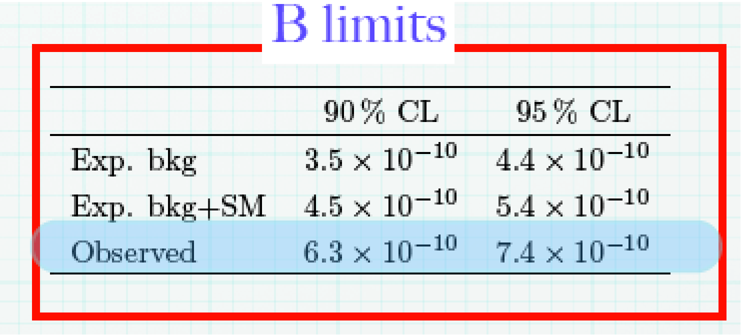




$\mathcal{B}(B_{(s)})$ measurements

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\text{stat})\,^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}\,,$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\text{stat})\,^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}\,.$$



B limits

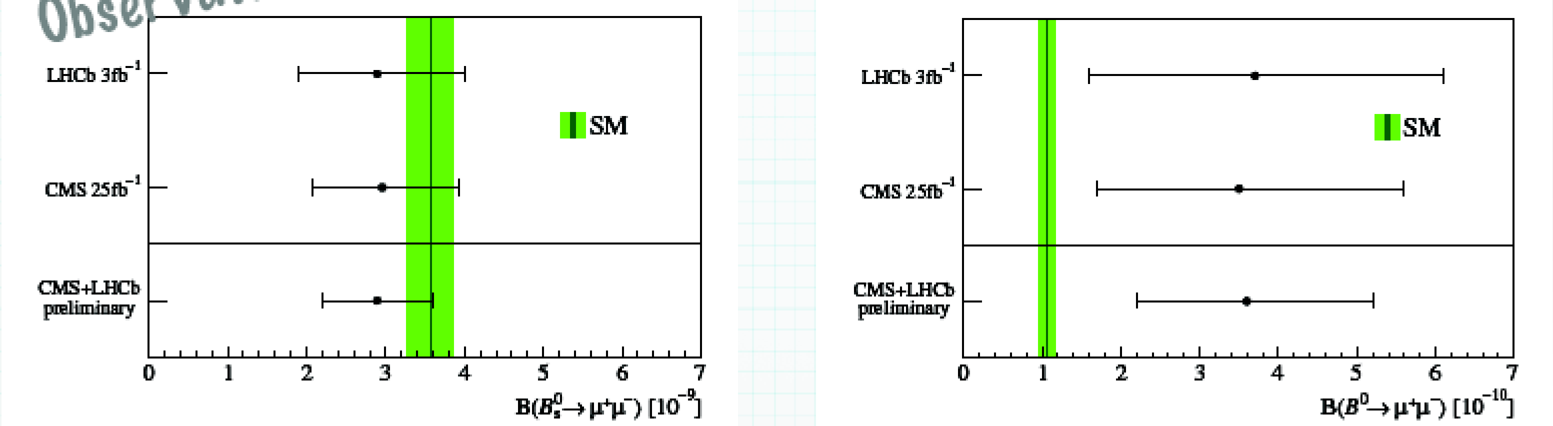
	90 % CL	95 % CL
Exp. bkg	3.5×10^{-10}	4.4×10^{-10}
Exp. bkg+SM	4.5×10^{-10}	5.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

$B_s \rightarrow \mu\mu$ Limit implication

- Combination with latest CMS result

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}\,,$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}\,,$$

Observation!



From D. Straub, arXiv:1205.6094