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

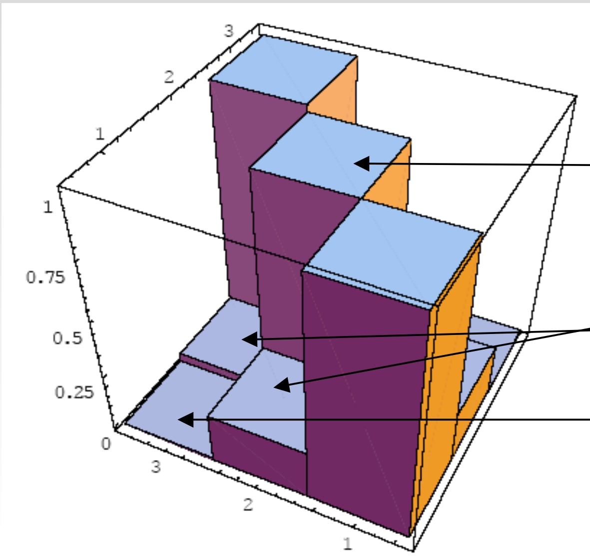
- In the SM SU(2)xU(1) quarks and leptons are assigned to be left-handed doublets and right-handed singlet
- Quark mass eigenstates are not the same as the weak egeienstates, the matrix relating these bases defined for 6 quarks and parameterized by Kobayashi and Maskawa by generalization of 4 quark case 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

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

$A, \rho, \eta \sim O(1)$

Present uncertainties:

λ~0.5%, A~4%, ρ~14%, η~4%

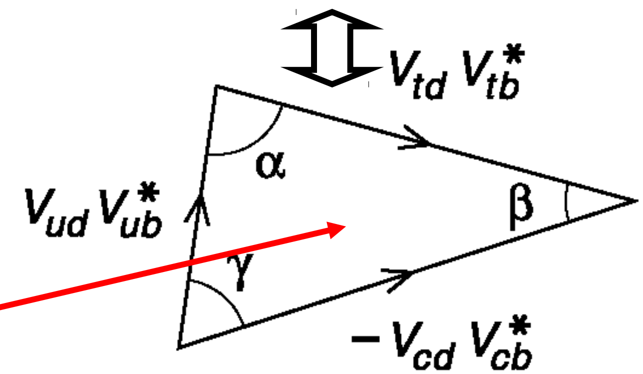
Unitarity Triangle

- 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:

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

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



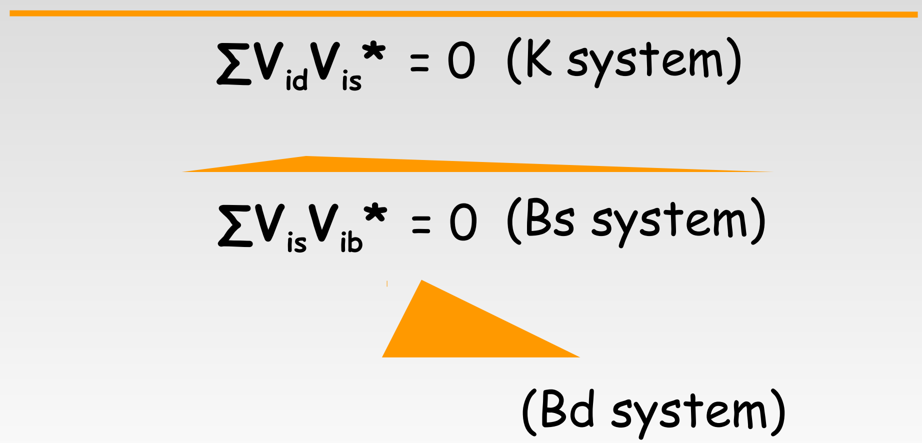
CPV in SM ∝ Triangle Area

Angles and sides are directly measurable

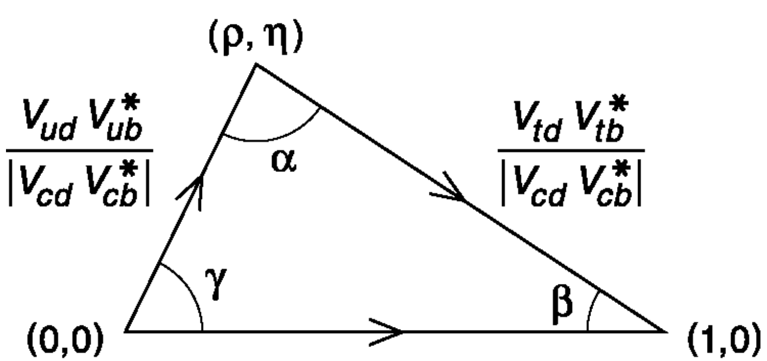
Unitarity Triangle - 2

There are 6 UT triangles
Columns and rows relations give similar results

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



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

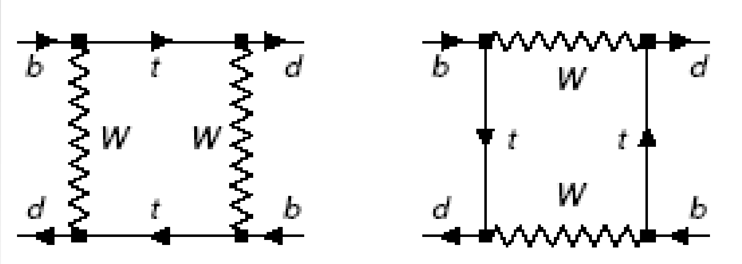


The results are shown in the ρ-η plane

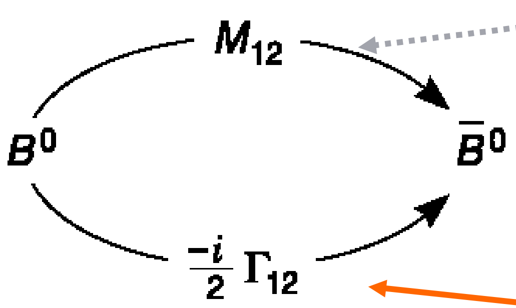
CP Violation in B System

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

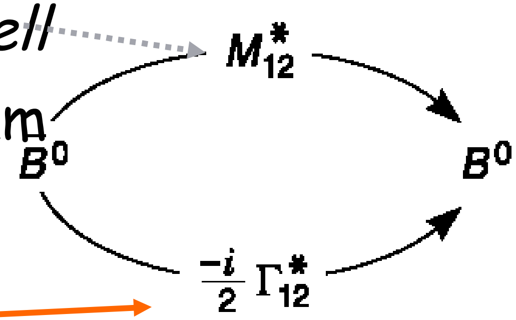
$$i\frac{d}{dt}\begin{pmatrix}|B(t)\rangle \\ |\bar{B}(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B(t)\rangle \\ |\bar{B}(t)\rangle\end{pmatrix}$$



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 $B^0 \leftrightarrow B^0$ via *off-shell* states, e.g. the weak box diagram



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

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 $|B_H\rangle$ and $|B_L\rangle$ 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

$\Delta m_s = M_H - M_L = 2|M_{12}|$ → proportional to mixing frequency

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

CP Violation in B^0 System

$\Delta m_s = 17.77 \pm 0.10 \pm 0.07 \quad ps^{-1}$ In agreement with SM

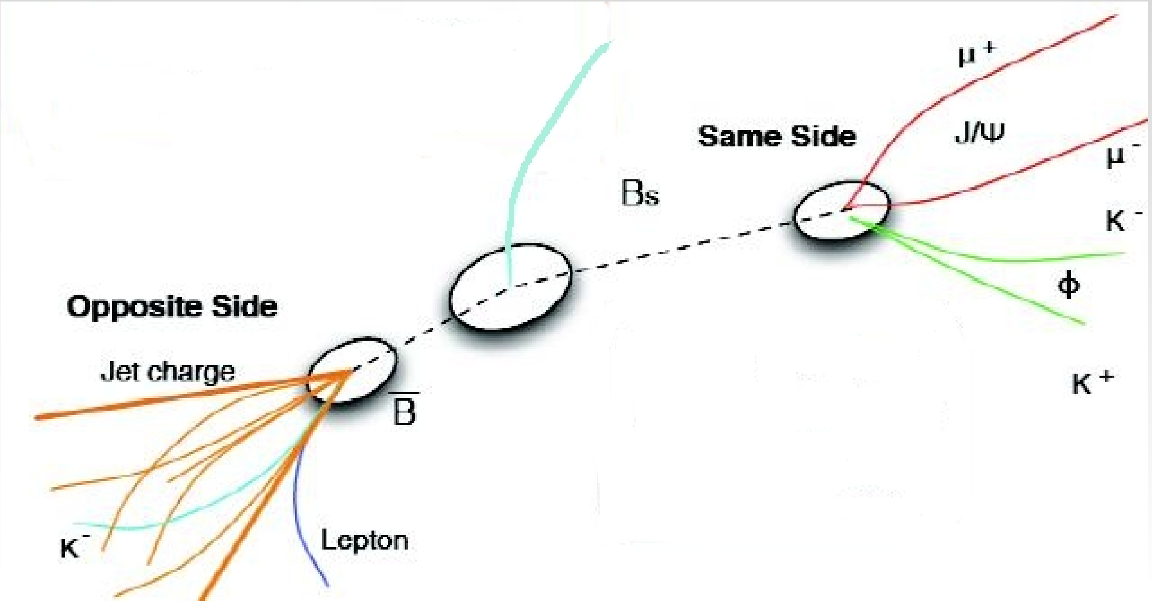
$\phi_s \approx 0.004$ In the SM no CP violation is expected in the B_s sector

- 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 Physiscs only in the mixing part → not allowed given the mixing frequency precision.
- Other possibility: $\phi_s = \phi_s^{SM} + \phi_s^{NP} \approx \phi_s^{NP}$

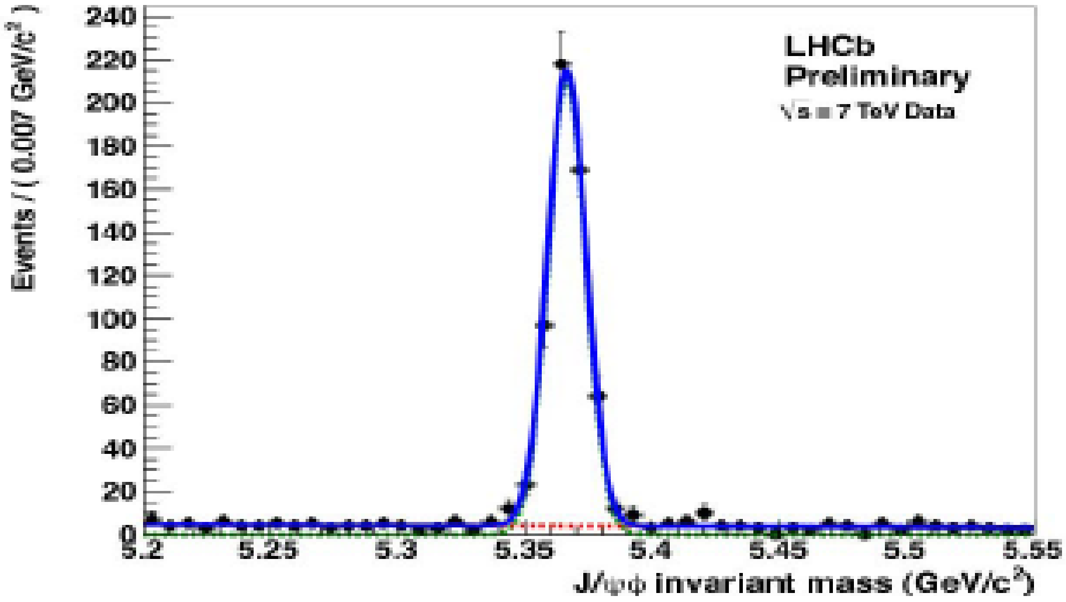
Measurement of the Φ Phase

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



1.



Measurement of the Φ Phase - 1

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

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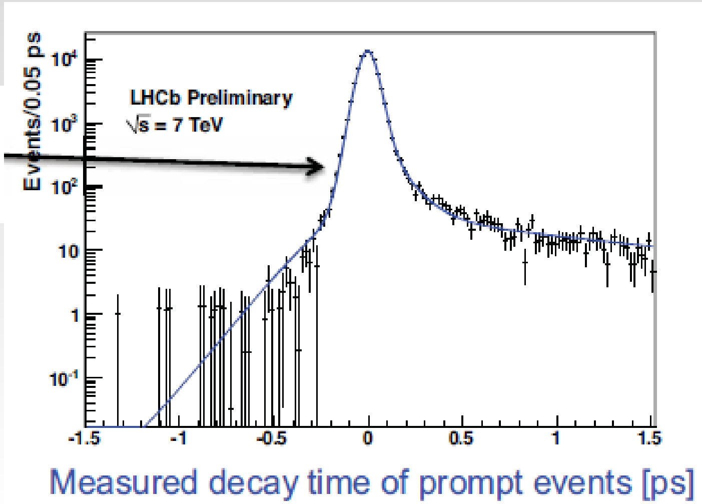
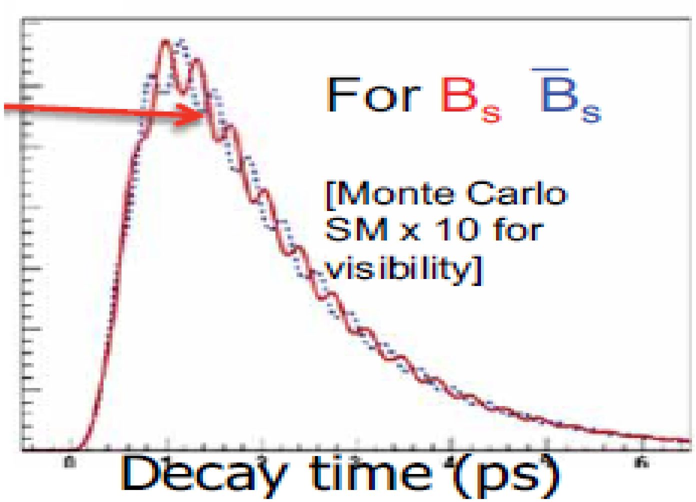
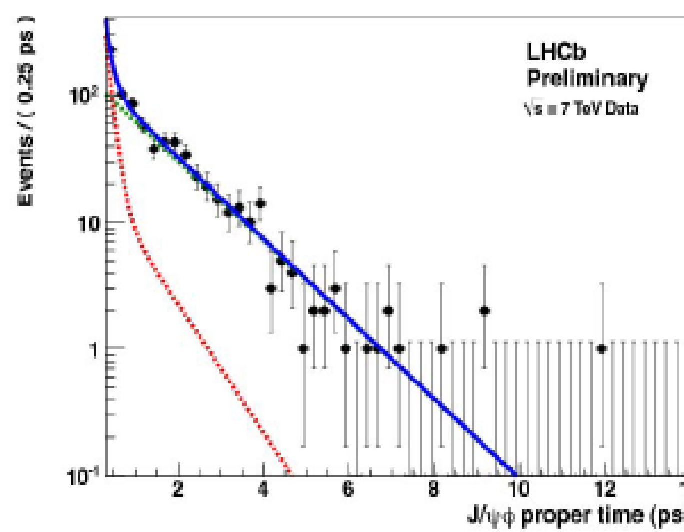


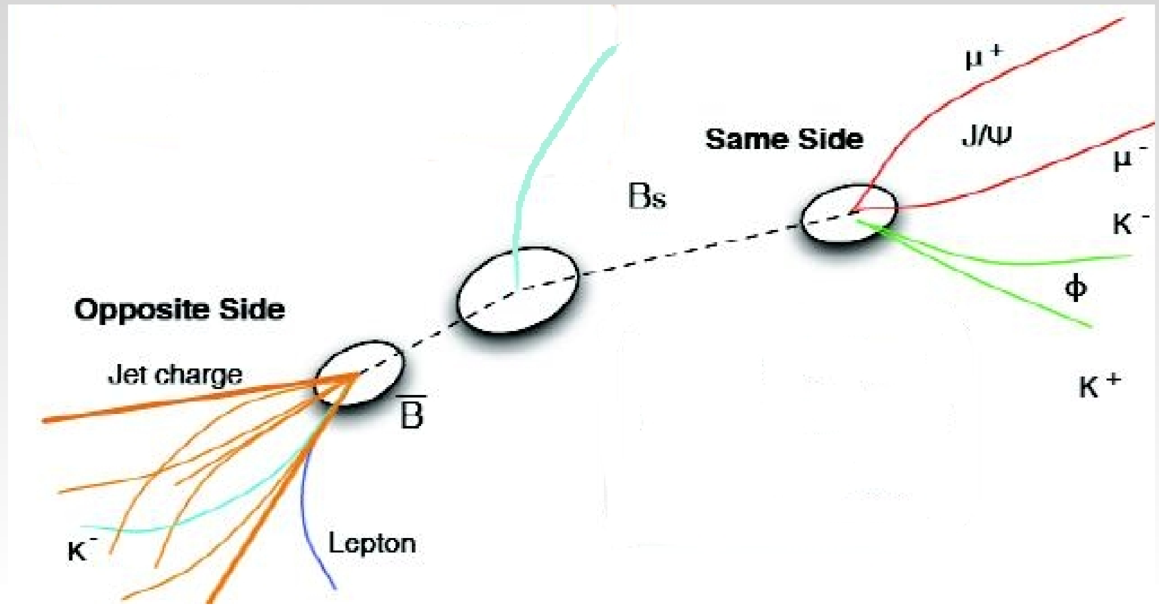
$$\Gamma(B^0) = \mathcal{N}_f e^{-\Gamma_s t}\left\{e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) - \sin(\phi_s)\sin(\Delta m_s t)\right\},$$

$\Gamma(B^0/\overline{B}^0)$

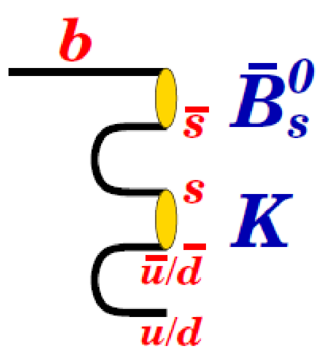




Measurement of the Φ Phase - 2



3. Flavor tagging:
   - opposite side tagging: identify the flavor of the other b-hadron of the event and the infer the B_s flavour
   - same side tagging: use the charge of the kaon produced close to the B_s



Measurement of the Φ Phase - 3

- Angular distributions:

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

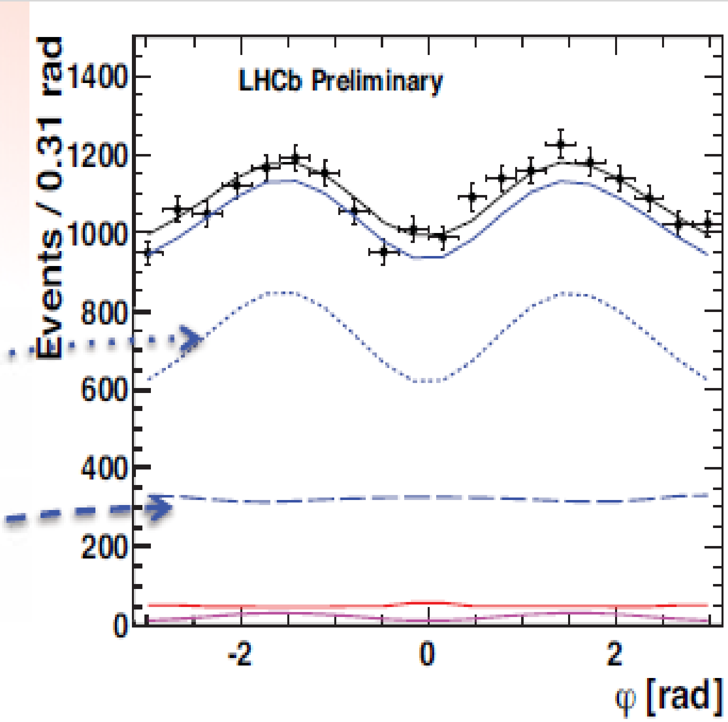
  The total spin in the final state 0,1,2. To conserve the total angular momentum, the orbital angular momentum L between the final state decay products must be either 0, 1 or 2.

  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 - 4

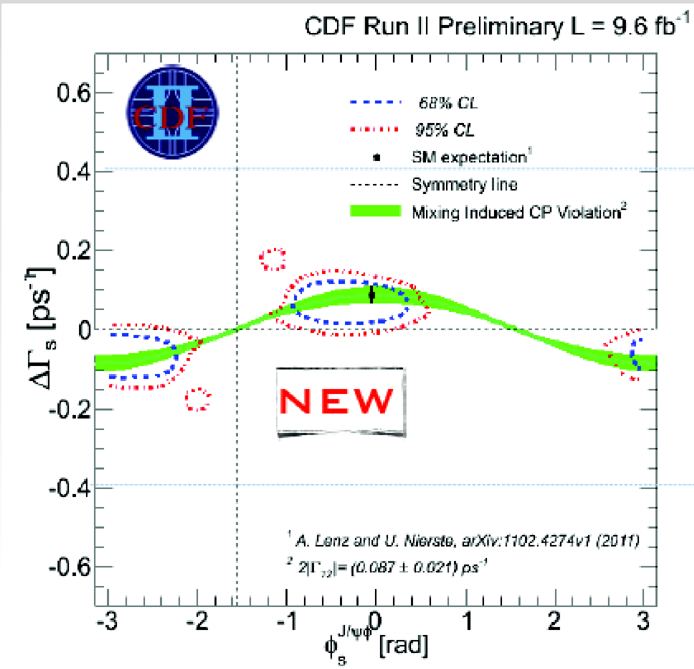
- The CP-even / CP-odd separation is very clear in all distributions.



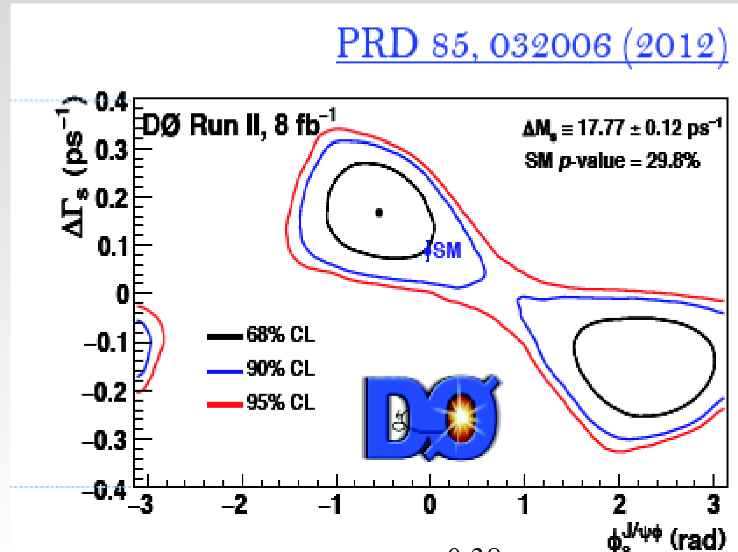
- For each event is calculated a probability and a likelihood is minimized

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

Results on Φ Phase



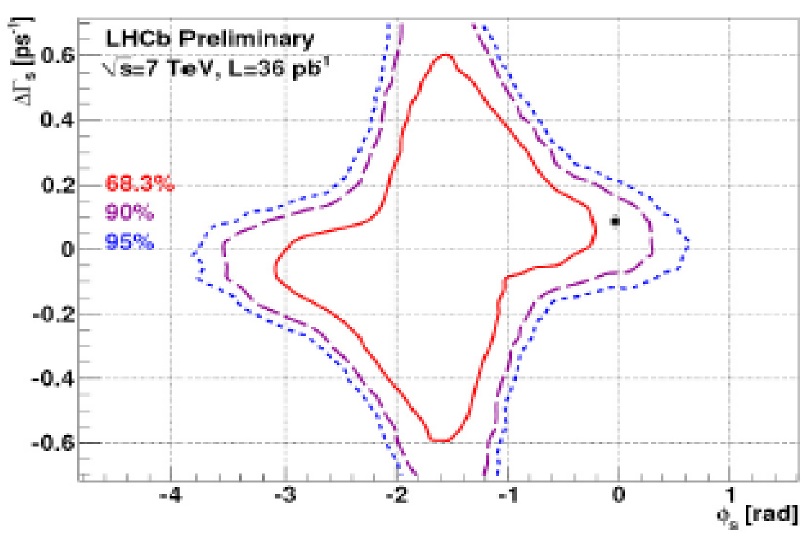
$$\phi_s \in [-0.60, 0.12] \quad rad@68\%C.L.$$



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

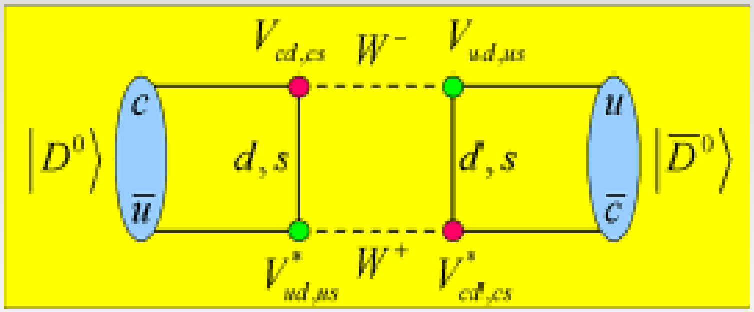
Strong phases Constrained in the fit

$$\phi_s \in [-2.7, -0.5]@68\%C.L$$



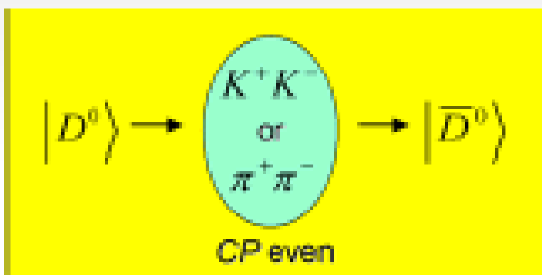
D^0-$\overline{D^0}$ Mixing

In the charm sector mixing is governed by the diagram



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

No measurements have measured mixing at 5σ, but several independent measurements have few σ.

LHCb

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1 \approx y\cos\phi - x\sin\phi\frac{A_m}{2}$$

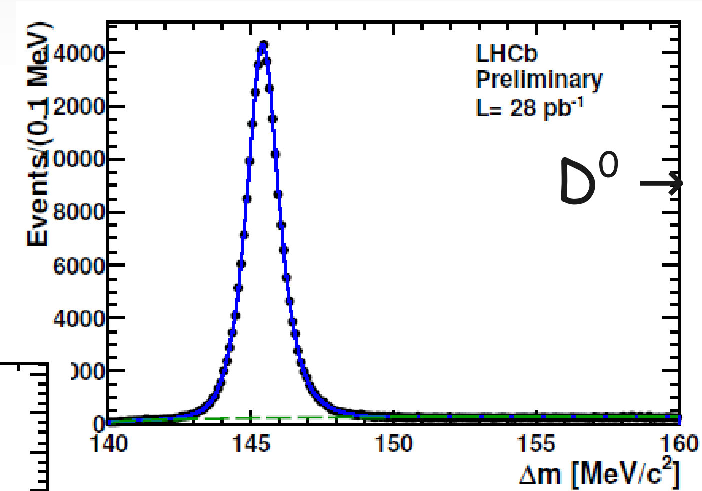
with $|q/p|^{\pm 2} = 1 \pm A_m$

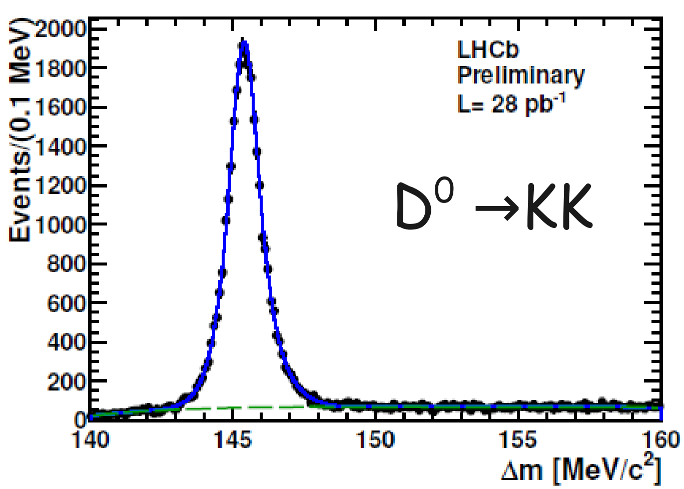
Φ CPV phase

If CPV is zero $y_{CP}=y$

Analysis procedure

$D^0 \to K^-\pi^+$ and $D^0 \to KK$ reconstructed exploiting $D^{0*} \to D^0\pi$





$$y_{CP} = (5.5 \pm 6.3_{stat} \pm 4.1_{syst}) \times 10^{-3}$$

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

CDF

$D^0 \to K^-\pi^+$ Cabibbo-favored (CF), $D^0 \to K^+\pi^-$ Cabibbo-suppressed (DCS)

R_D= A(DCS)/A(CF) in case of no mixing. In case of mixing

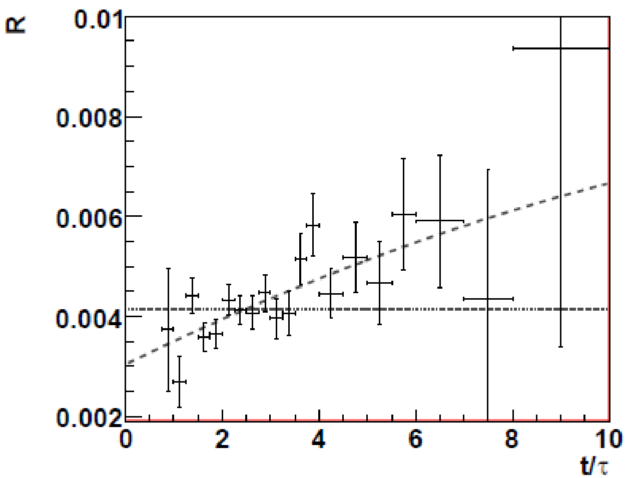
$$R(t/\tau) = R_D + \sqrt{R_D}y'\,(t/\tau) + \frac{x'^2+y'^2}{4}(t/\tau)^2,$$

t=proper time, τ= D^0 mean lifetime

$$x' = x\cos\delta + y\sin\delta \quad y' = -x\sin\delta + y\cos\delta,$$

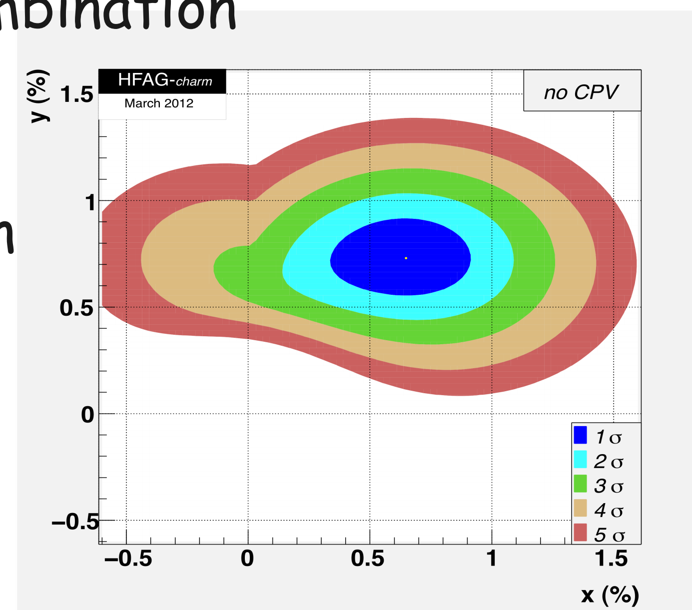
δ strong interaction phase DCS-CF

Fit of R to extract x' y'



Many other measurements determine x,y or a combination

Global fit combination exclude no mixing at 10σ



CP Violation in Charm

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

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

The time dependent asymmetry:

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

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:

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

CP Violation in Charm - 2

where:

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

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

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

Time integrated asymmetry are the integral of the previous equation

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

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 $D^0 \rightarrow \pi^-\pi^+$ $D^0 \rightarrow K^-K^+$

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

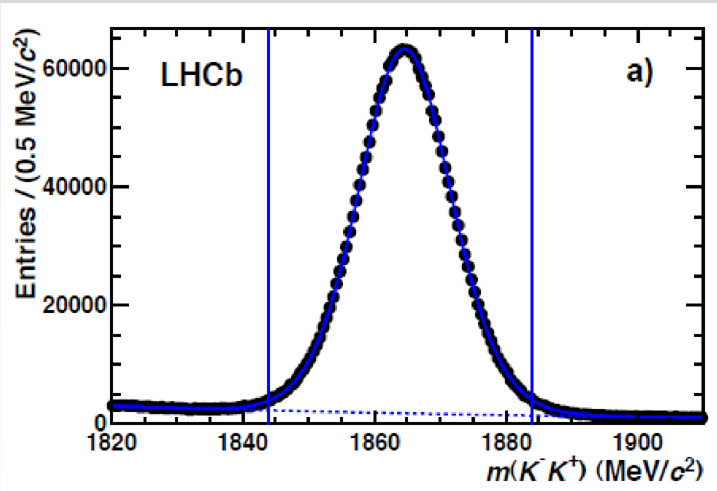
Since the difference in decay time acceptance is small, $\Delta t \approx 0$

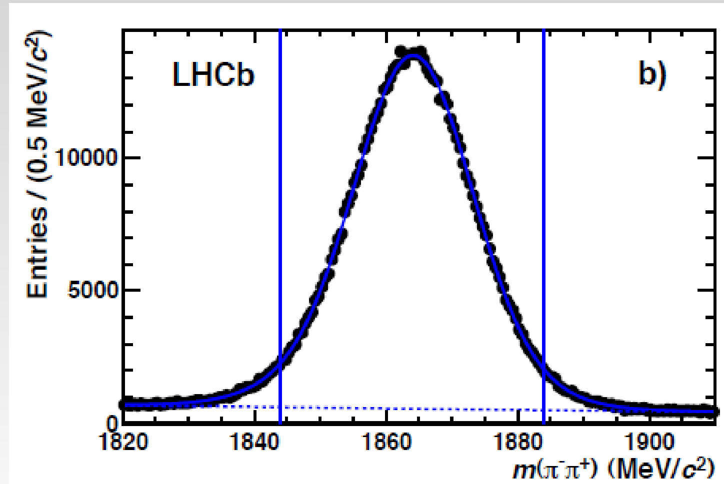
$$\Delta A_{CP}^{dir} = A_{CP}^{dir}(K^+K^-) - A_{CP}^{dir}(\pi^+\pi^-)$$

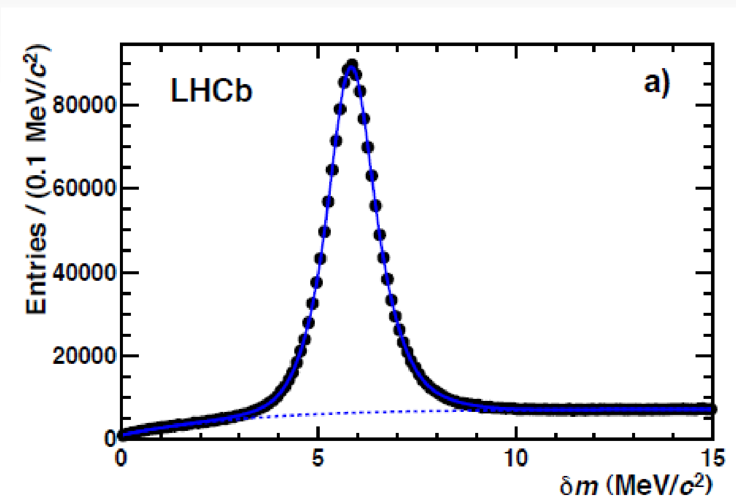
Analysis method

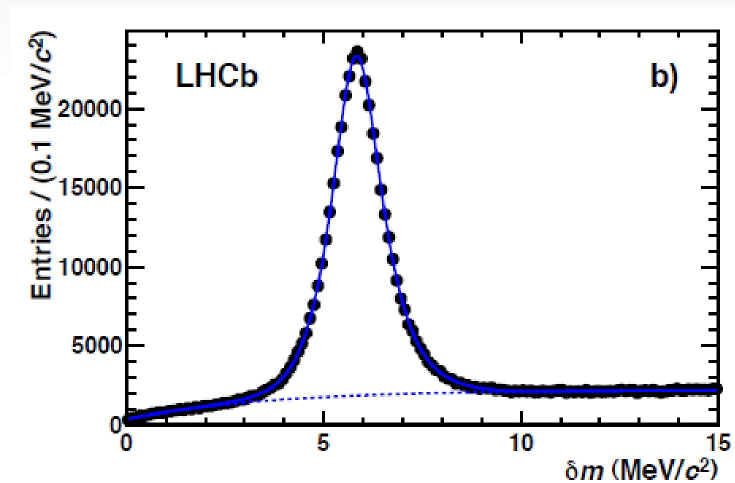
- reconstruct $D^0 \rightarrow \pi^-\pi^+$ $D^0 \rightarrow K^-K^+$
- identify a “slow” $\pi^\pm$ which form with D^0 a D^{0*}
- the charge of the π tag the flavour of of the D^0, ie if it is D^0 or $\overline{D}^0$

CP Violation in Charm - 4

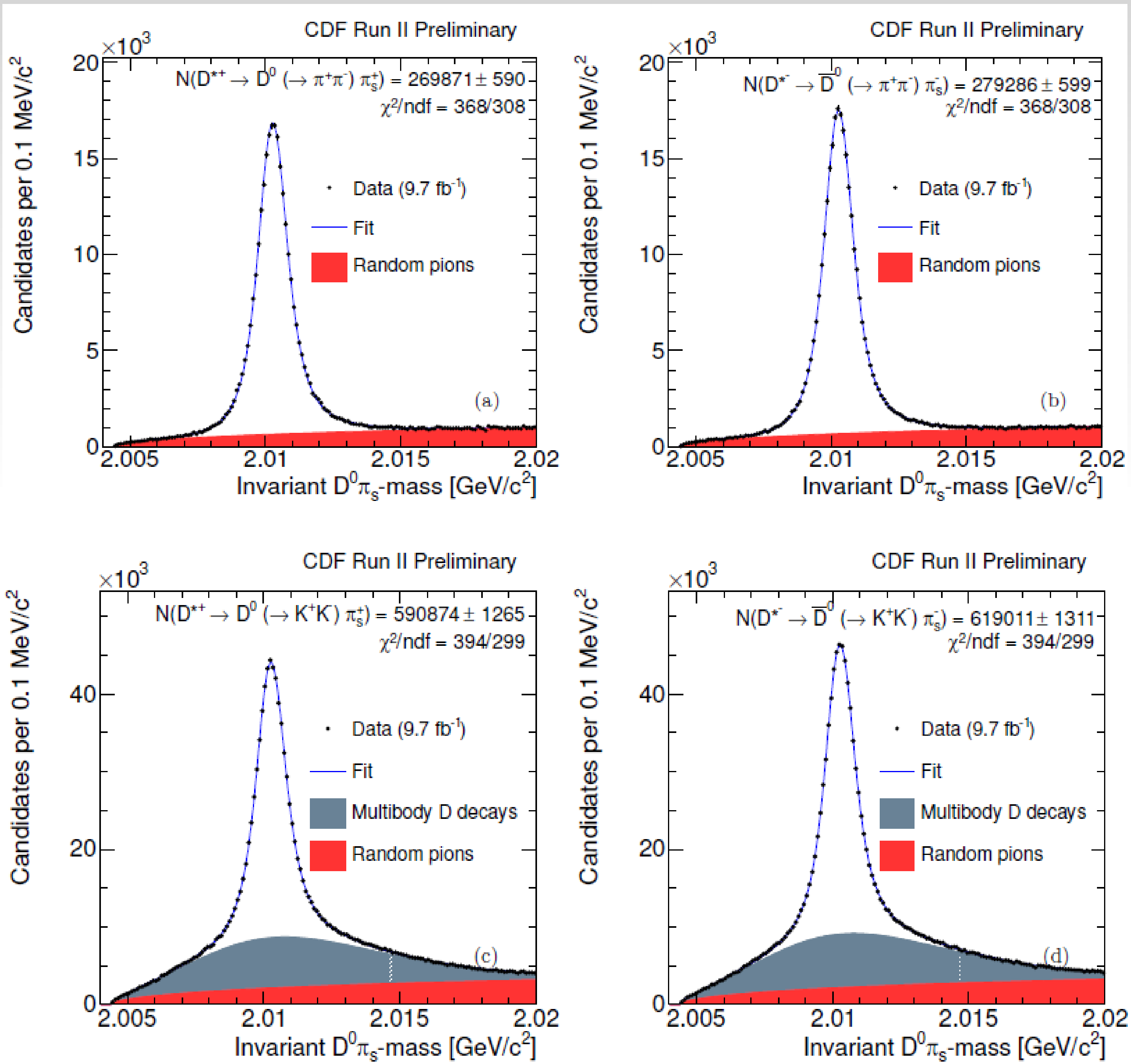








CP Violation in Charm - 5



CP Violation in Charm Results

LHCb

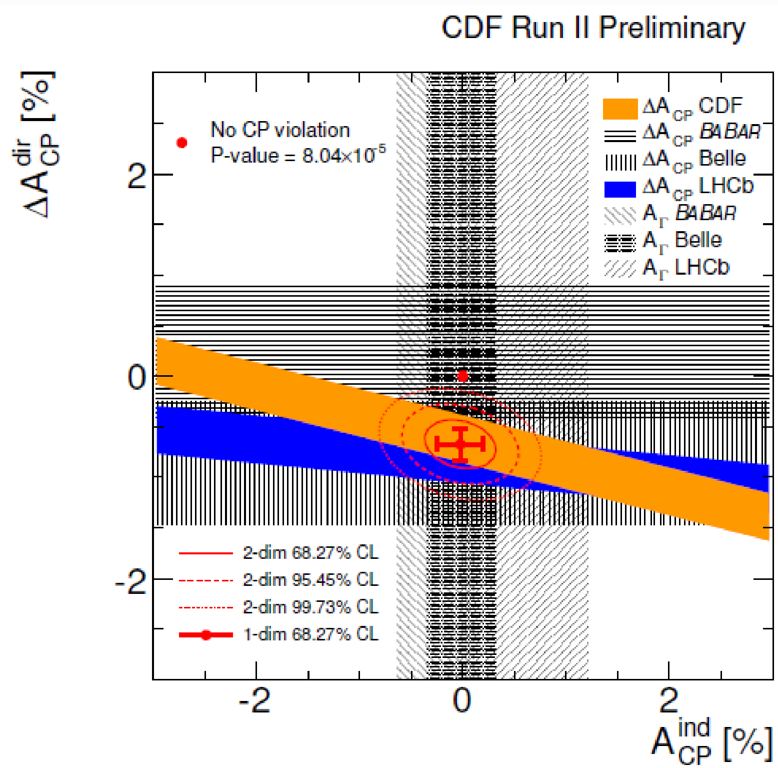
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

CDF

$$\Delta A_{\mathrm{CP}} = [-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})]\,\%$$

Combining the two results

$$\Delta A_{\mathrm{CP}}^{\mathrm{dir}} = (-0.67 \pm 0.16)\% \text{ and } A_{\mathrm{CP}}^{\mathrm{ind}} = (-0.02 \pm 0.22)\%$$



3.8σ from the no-CP violation hypothesis

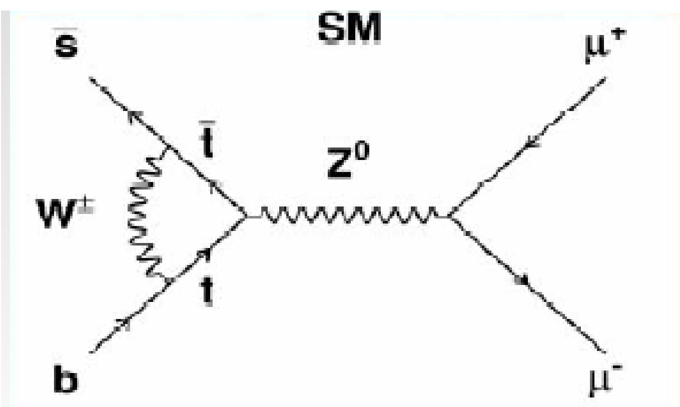
$B_s \to \mu\mu$ Decay

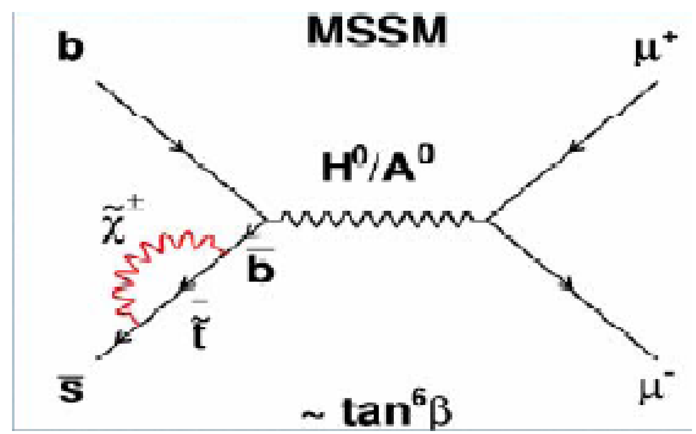
In the SM Flavor Changing Neutral Current have played an important Role in setting up the structure of the model.
At lowest order these transition are not allowed.
The decays $B^0_s \to \mu\mu$ and $B^0_d \to \mu\mu$ occur only via loop diagrams with
A branching ratio very well predicted:

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

arXiv:1005.5310
arXiv:1012.1447

Several beyond SM theories predict an enhancement of the BR





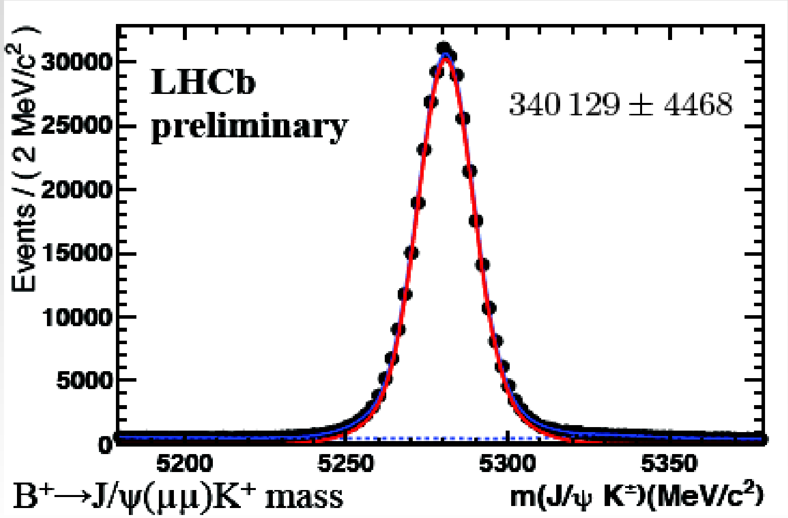
Measurements performed by all experiments at hadron collider.
Very simple idea: select events with two muon in the correct mass window.

$B_s \to \mu\mu$ Decay

Use other decay channels as normalization

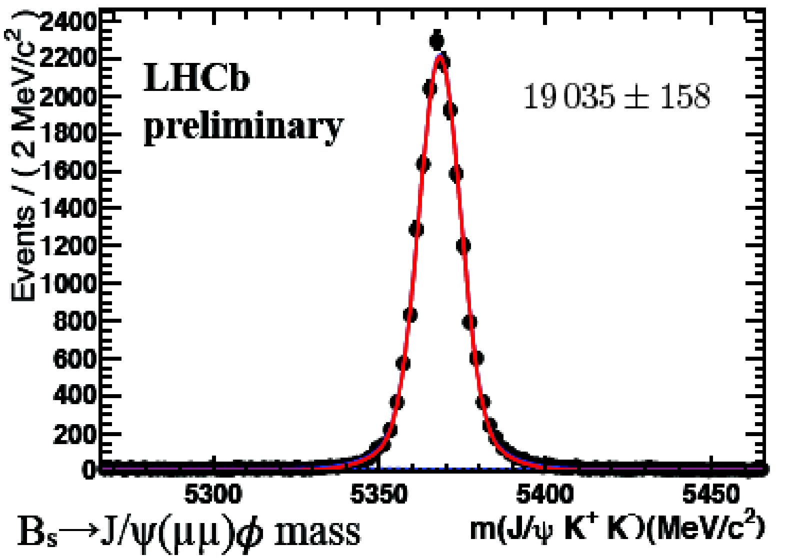
$B^+ \to J/\psi(\mu\mu)K^+$, $B_s \to J/\psi(\mu\mu)\phi$, $B \to K\pi$

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



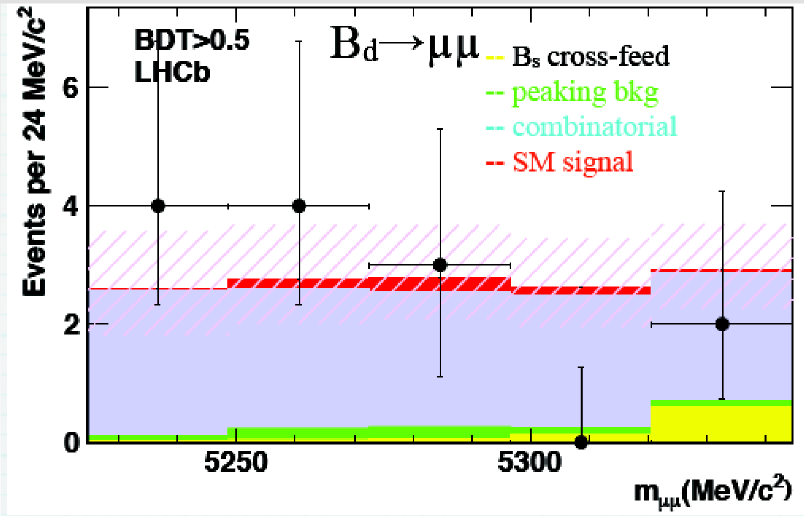
Background due mainly to combinatorial

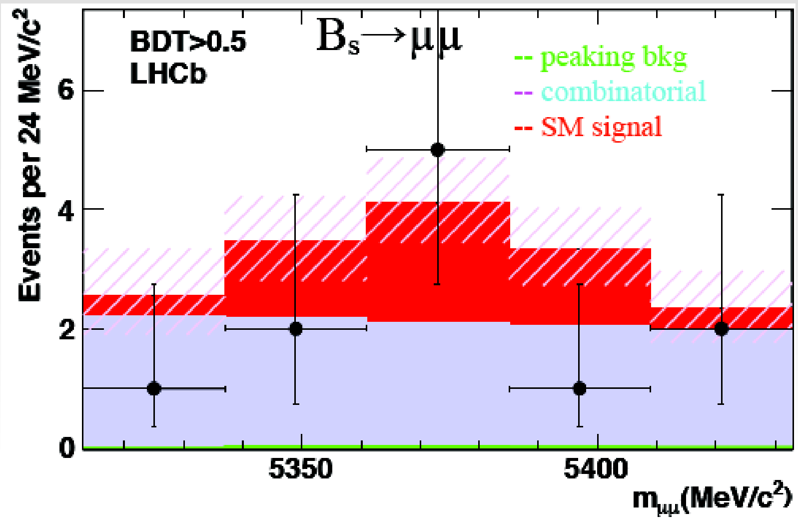
b → μμX B → hh where h is misidentified as μ



$B_s \to \mu\mu$ Decay

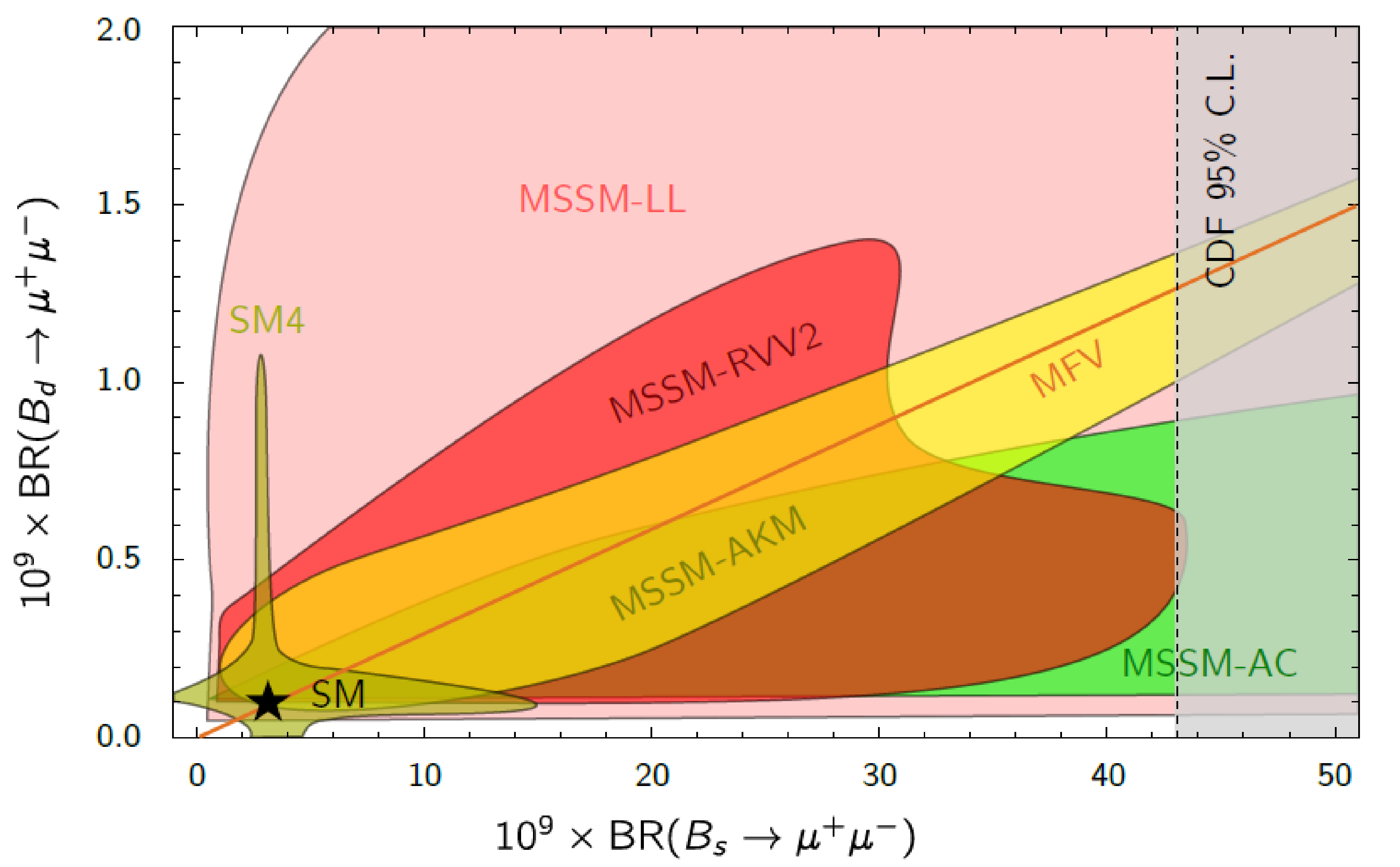
Use multivariate technique to separate signal from background



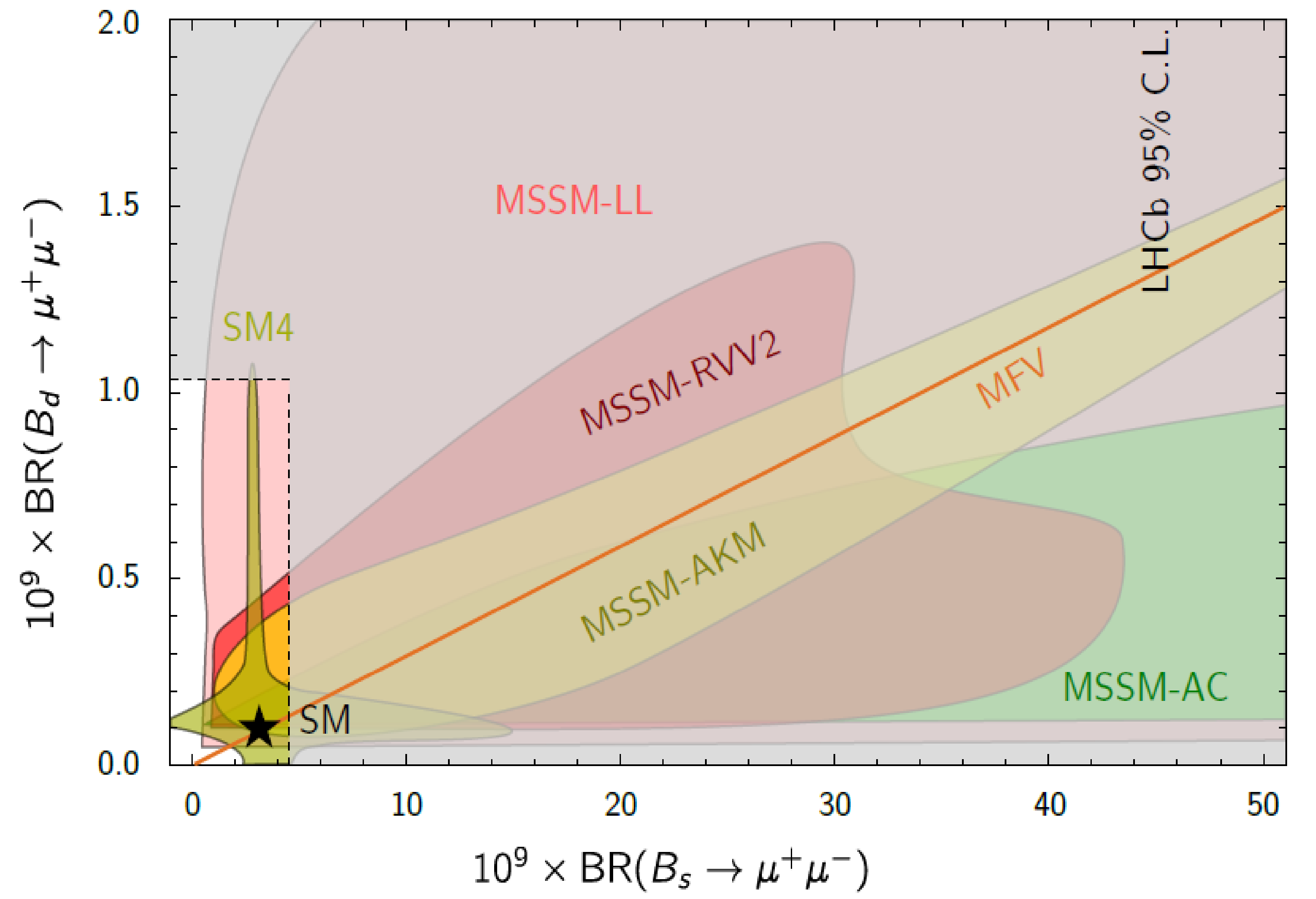


Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

$B_s \to \mu\mu$ Limit implication



$B_s \to \mu\mu$ Limit implication, Now



$B \to K^*\gamma$

In (SM), B mesons radiative decays proceed at LO through $b \to s\gamma$ one-loop electromagnetic penguin transitions, dominated by a virtual intermediate top quark coupling to a W boson.

SM extensions predict additional contributions that can introduce sizeable effects on the dynamics of the radiative transitions.

Direct CP asymmetry in $b \to s\gamma$ is sensitive to non-SM effects.

SM prediction of the direct CP violation in the $B^0 \to K^{0*}\gamma$ decay,

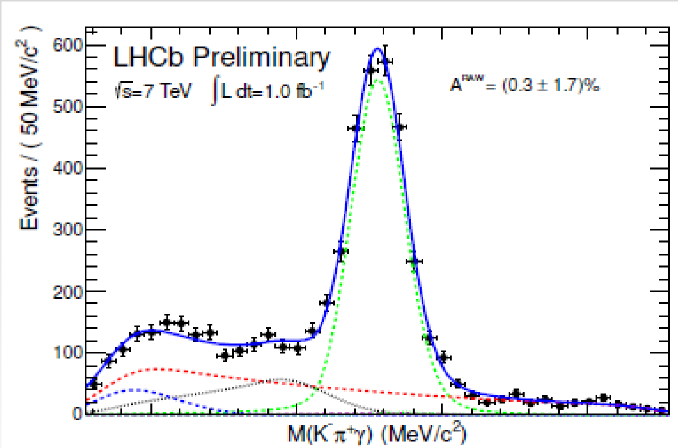
$A^{SM}_{CP} = -0.0061 \pm 0.0043$

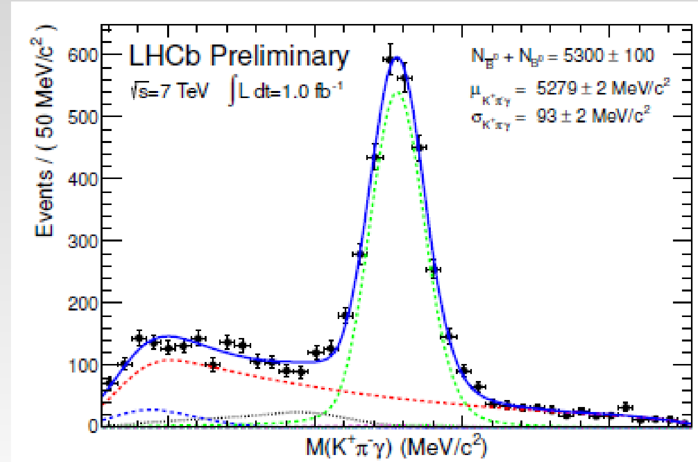
Analysis method:

- $K^{0*} \to K^-\pi^+$ and $\overline{K}^{0*} \to K^+\pi^-$ are reconstructed with an energetic photon
- Number of $B^0/\overline{B}^0$ are extracted fitting the invariant mass distribution

$$\mathcal{A}^{\mathrm{RAW}} = \frac{N_{\overline{B}^0 \to \overline{K}^{*0}\gamma} - N_{B^0 \to K^{*0}\gamma}}{N_{\overline{B}^0 \to \overline{K}^{*0}\gamma} + N_{B^0 \to K^{*0}\gamma}} = 0.003 \pm 0.017(\mathrm{stat})$$

B → K*γ





The raw asymmetry must be corrected to obtain A_{CP}

$$A_{CP}(B^0 \to K^{*0}\gamma) = A^{\mathrm{RAW}}(B^0 \to K^{*0}\gamma) - A_{\mathrm{D}}(K\pi) - \kappa A_{\mathrm{P}}(B^0)$$

$A_D(K\pi)$: detection asymmetry, given the different interaction of K^-/K^+ with the material detector

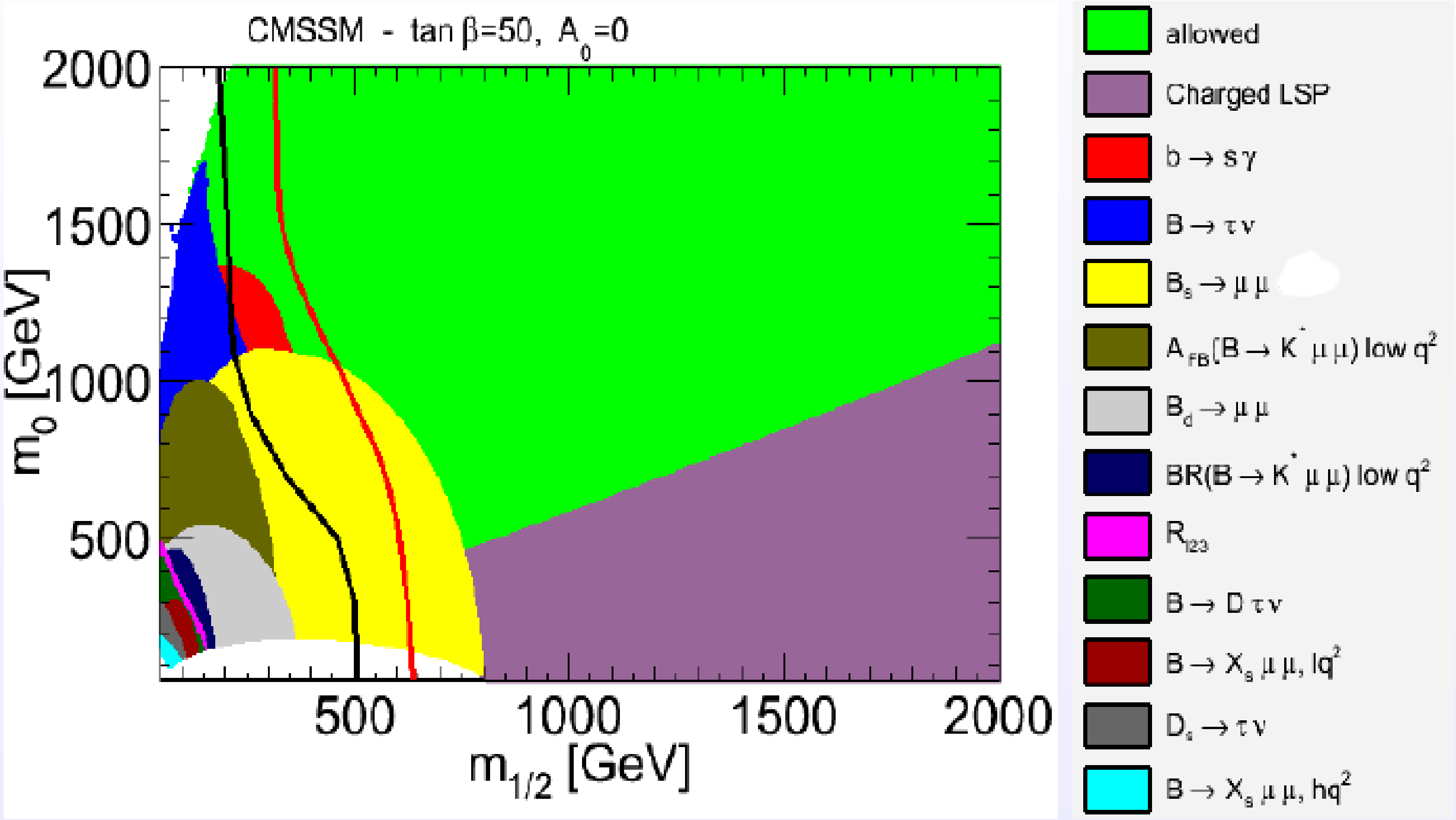
$A_P(B^0)$: production asymmetry, since we have pp there is an asymmetry between $q/\bar{q}$ and $B^0/\bar{B}^0$ are not produced at the same rate

$$A_{\mathrm{P}}(B^0) = \frac{R(\overline{B}^0) - R(B^0)}{R(\overline{B}^0) + R(B^0)} = 0.010 \pm 0.013$$

and we can extract

$$A_{CP}(B^0 \to K^{*0}\gamma) = 0.008 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst}).$$

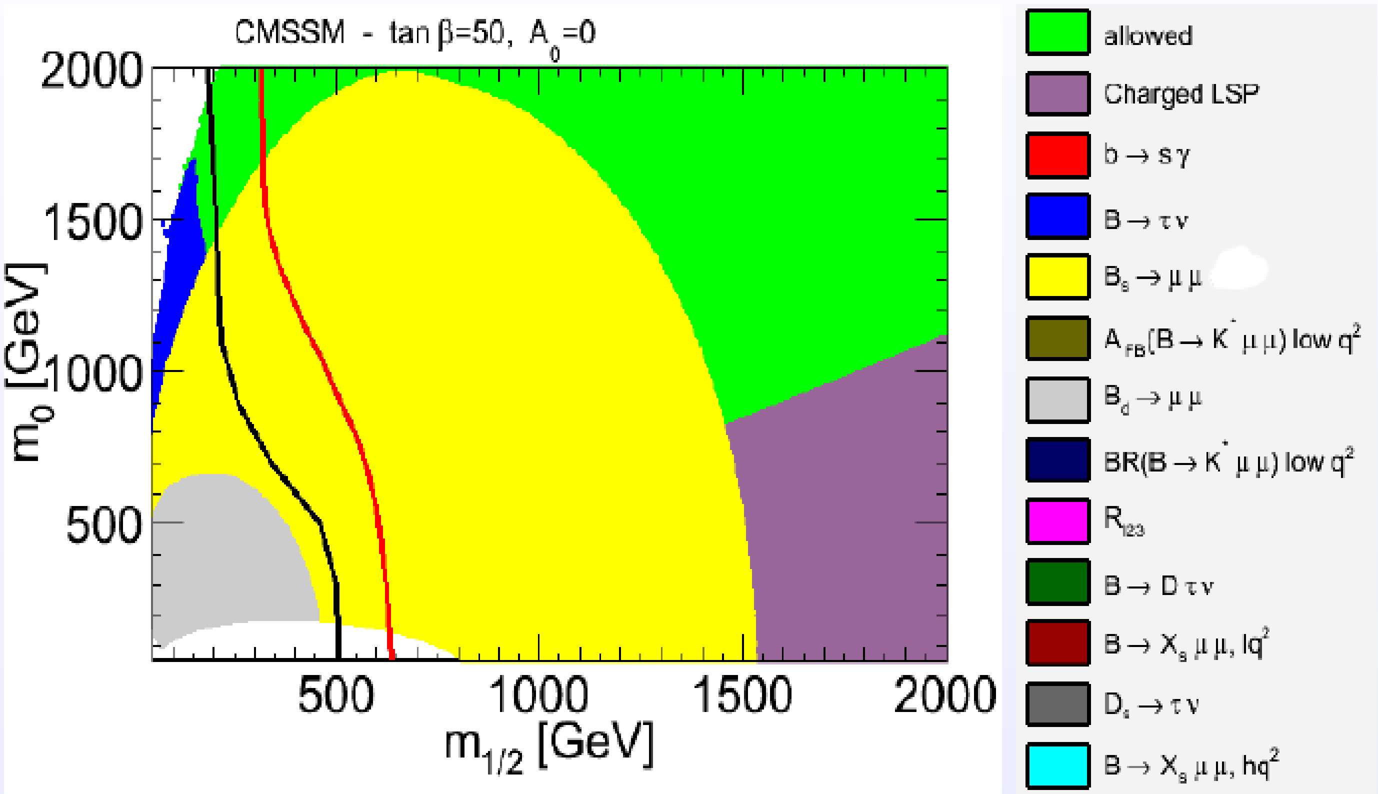
Implications of Rare Decays on cMSSM



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

Implications of Rare Decays on cMSSM



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

New LHCb limits for BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)