Search for CP Violation in Charm and Beauty Sectors

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Major research achievements

- BABAR papers with major contribution:
  - Direct CP, lepton flavor and isospin asymmetries in the Decays $B \to K^{(*)} \ell^{+} \ell^{-}$
    - Phys. Rev. Lett. 102, 091803 (2009)

  - Measurement of branching fractions and rate asymmetries in the rare decays $B \to K^{(*)} \ell^{+} \ell^{-}$
    - Phys. Rev. D 86, 032012 (2012)
  - Measurement of the $B \to Xs\, \ell^{+} \ell^{-}$ branching fraction and search for direct CP violation from a sum of exclusive final states
    - Phys. Rev. Lett. 112, 211802 (2014)
- LHCb paper with major contribution:
  - Measurement of $D^0 - \overline{D}^0$ mixing parameters and search for CP violation using $D^0 \to K^{+} \pi^{-}$ decays
    - Phys. Rev. Lett. 111, 251801 (2013)

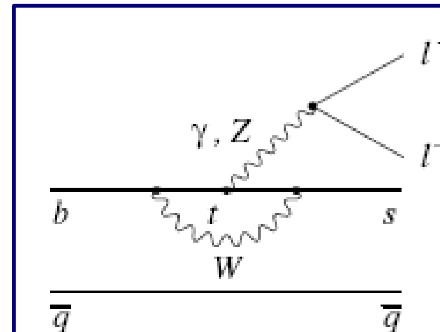
Ongoing BABAR analyses

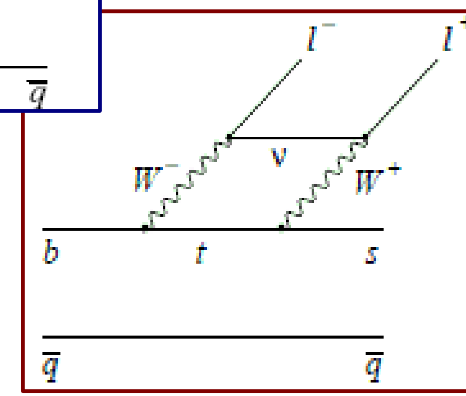
- Based on the full BABAR dataset
- Measurement of $D^0 - \overline{D}^0$ mixing parameters using a time-dependent amplitude analysis of $D^0 \rightarrow \pi^+\pi^-\pi^0$
- Measurement of the D^{*+} - D^+ mass difference using the decay chain $D^{*+} \rightarrow D^+ \pi^0$, $D^+ \rightarrow K^- \pi^+\pi^+$

$B \to X_s \ell^+ \ell^-$ decays: introduction

- The FCNC $b \to s \ell^+ \ell^-$ processes are forbidden at tree level in the SM
- $B \to X_s \ell^+ \ell^-$ decays are allowed in the **loop** and **box** diagrams with branching fractions ~ 10^{-6}
- Effective Hamiltonian H_{Eff} factorizes short-distance C_i from long-distance effects
- **N**ew **P**hysics brings in new loops:
  - May be comparable to SM contributions and alter C^{eff} values

Standard Model diagrams

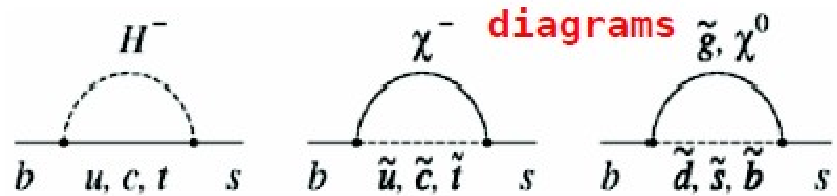




$$H_{Eff} \propto \sum_{i=1}^{10} C_i \mathcal{O}_i$$

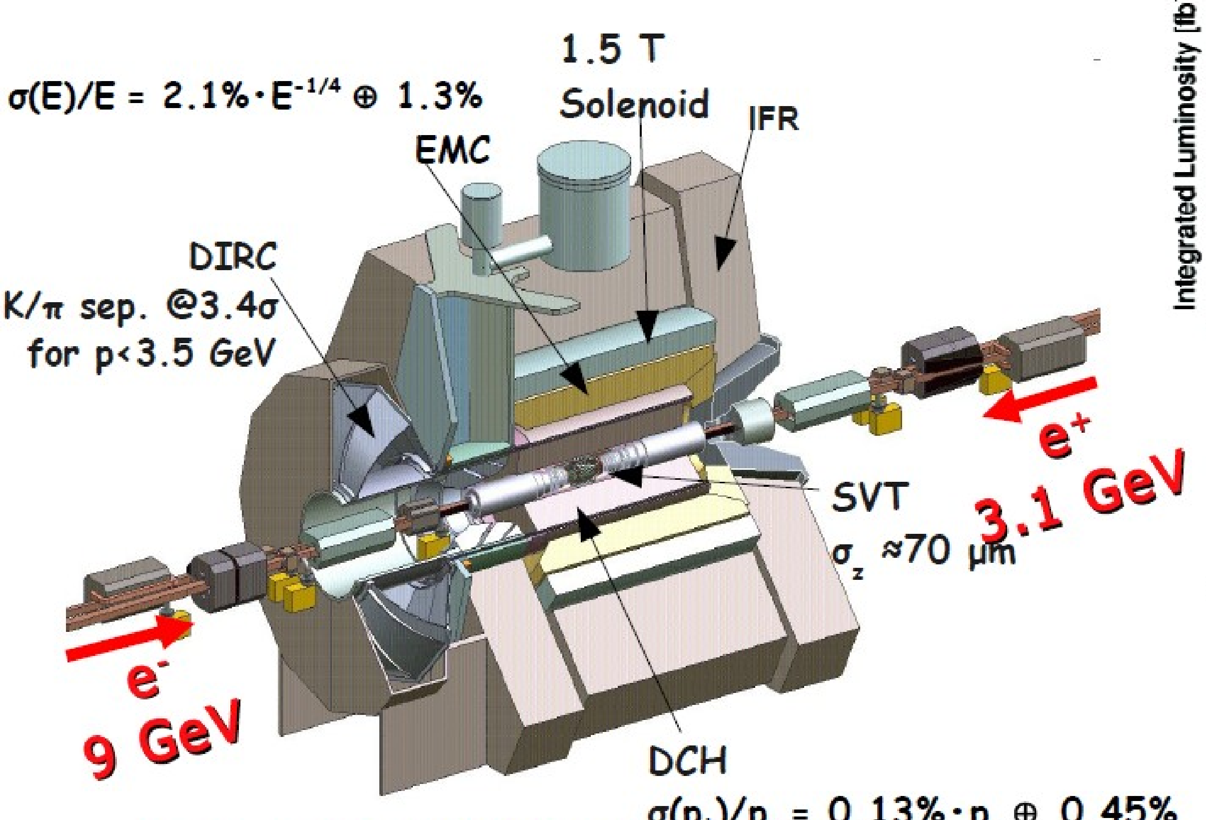
Three effective Wilson coefficients contribute:
C_7^{eff} from γ penguin (also in $b \to s\gamma$ processes)
C_9^{eff}(C_{10}^{eff}) from vector (axial-vector) part of Z penguin & W box

SUSY diagrams

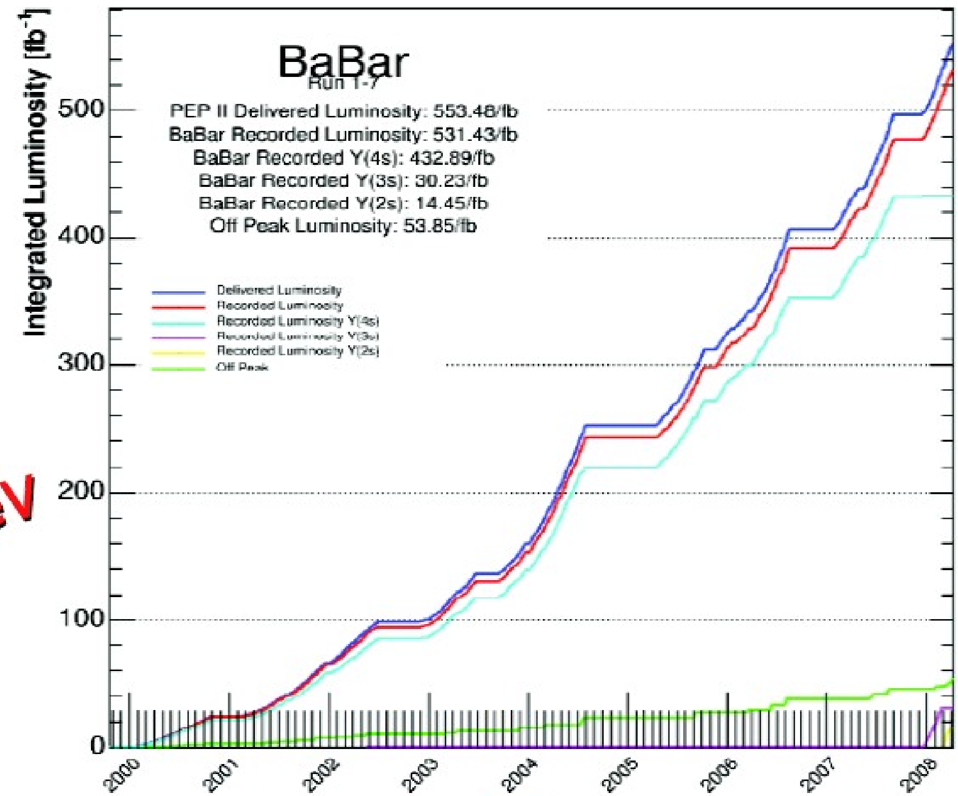


BABAR experiment

- The experimental data were collected between 1999 and 2008 with the BABAR detector at the PEP-II asymmetric energy e^+e^- collider located at SLAC



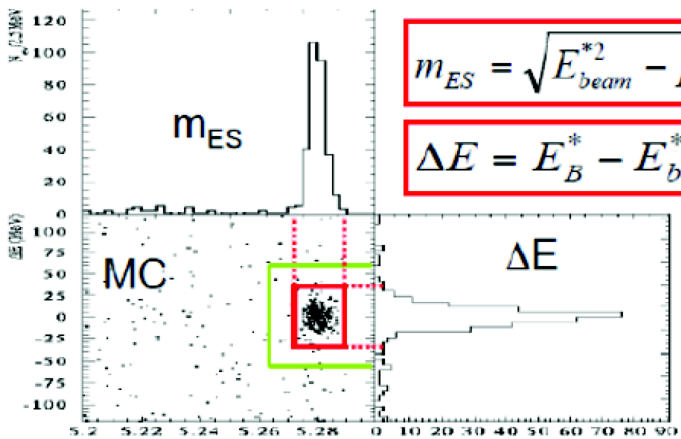
Layout of the BABAR Detector



471 x 10^6 $B\bar{B}$ pairs collected at Υ(4S) resonance: Full dataset

Common experimental techniques

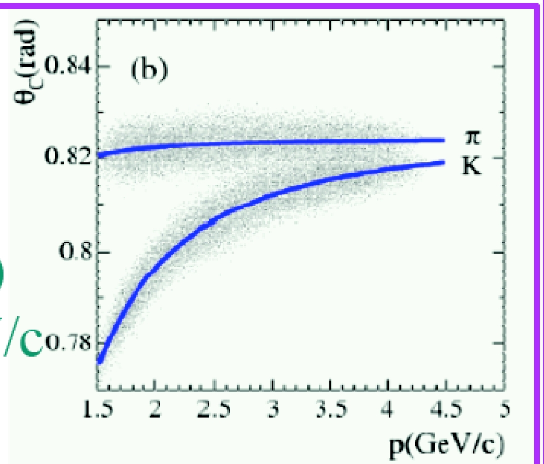
Kinematics of fully reconstructed B



$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

Good charged particle ID (in particular K/π) up to few GeV/c



Background characterization:

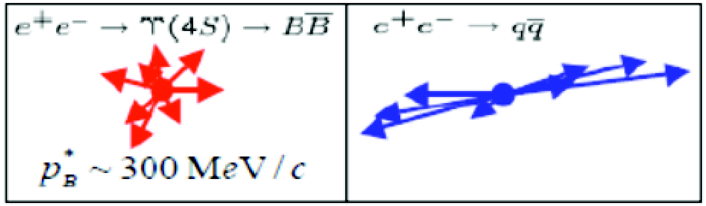
→ Mainly continuum: $e^+e^- \rightarrow q\bar{q}$ (q = u,d,s,c).

Suppression by multi-variable classifiers based on event-shape variables:

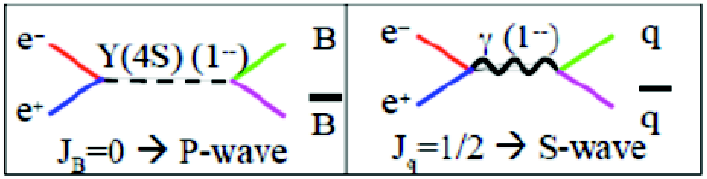
Fisher discriminant, Boosted decision trees (BDT)

…

Topology:



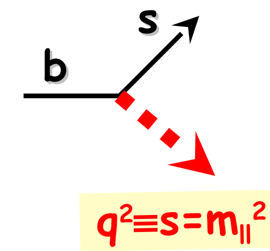
Angular distribution:



→ Background from B decays: classified by kinematic and topological properties

Variables are often combined to a likelihood function, used in a maximum likelihood fit for signal/background separation and to measure parameters of interest

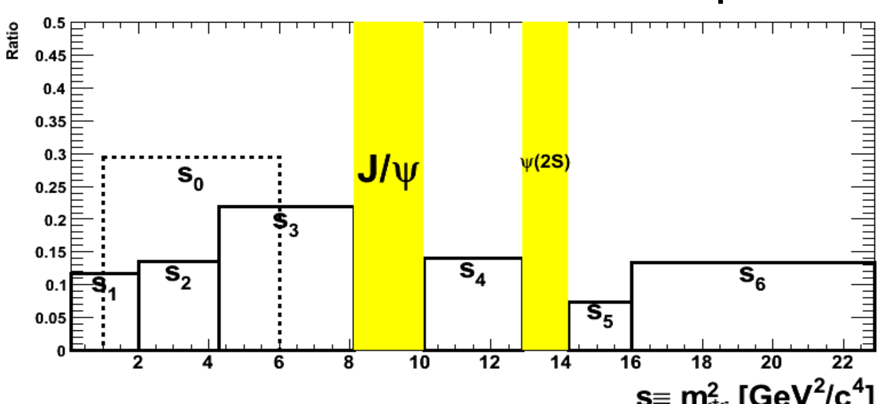
$B \rightarrow K^{(*)} \ell^+ \ell^-$ analysis details

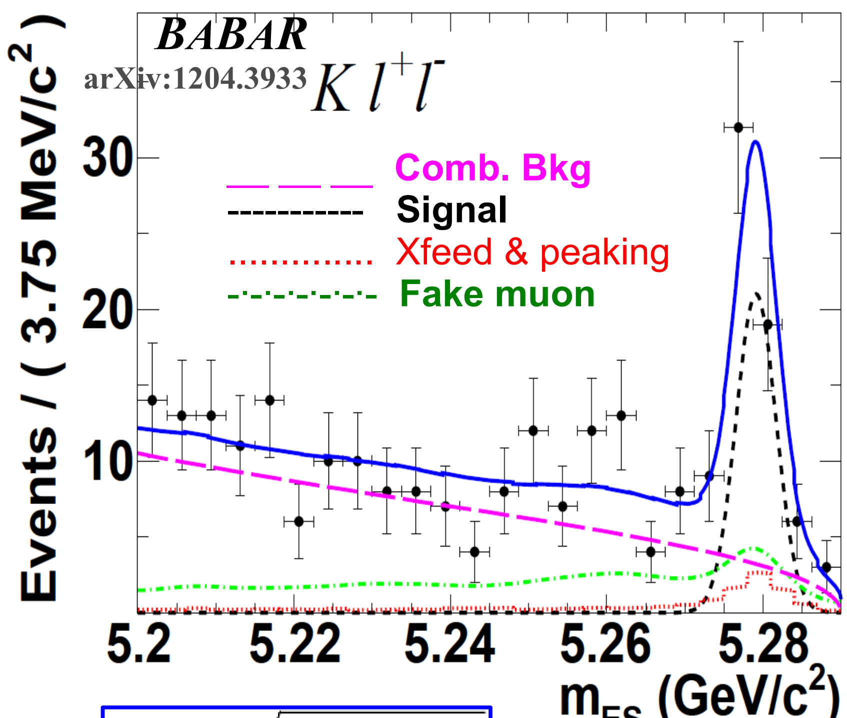


- Fully-reconstructed final states:
  - $K\ell^+\ell^-$: $K_s e^+ e^-, K^+ e^+ e^-, K_s \mu^+ \mu^-, K^+ \mu^+ \mu^-$
  - $K^*\ell^+\ell^-$: $K_s \pi^+ e^+ e^-, K^+ \pi^- e^+ e^-, K_s \pi^+ \mu^+ \mu^-, K^+ \pi^- \mu^+ \mu^-, K^+ \pi^0 e^+ e^-$ (only for angular analysis)

$\boxed{K_s \rightarrow \pi^+ \pi^-}$

- Seven *s* bins to be in line with Belle/CDF/LHCb
  - Two vetoed s regions due to J/ψ & $\psi(2S)$ domination
    - Charmonium control samples





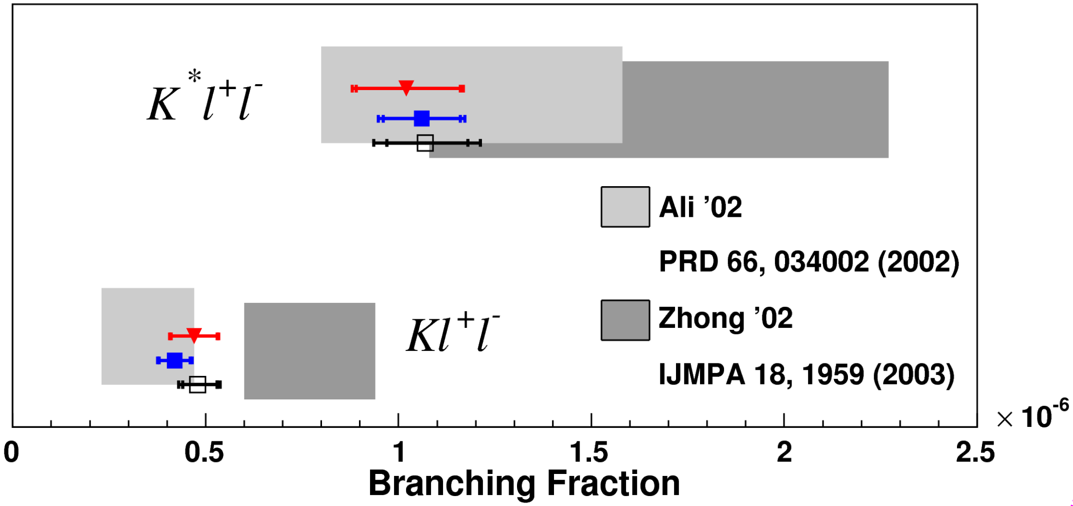
$$\boxed{m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_B}}$$

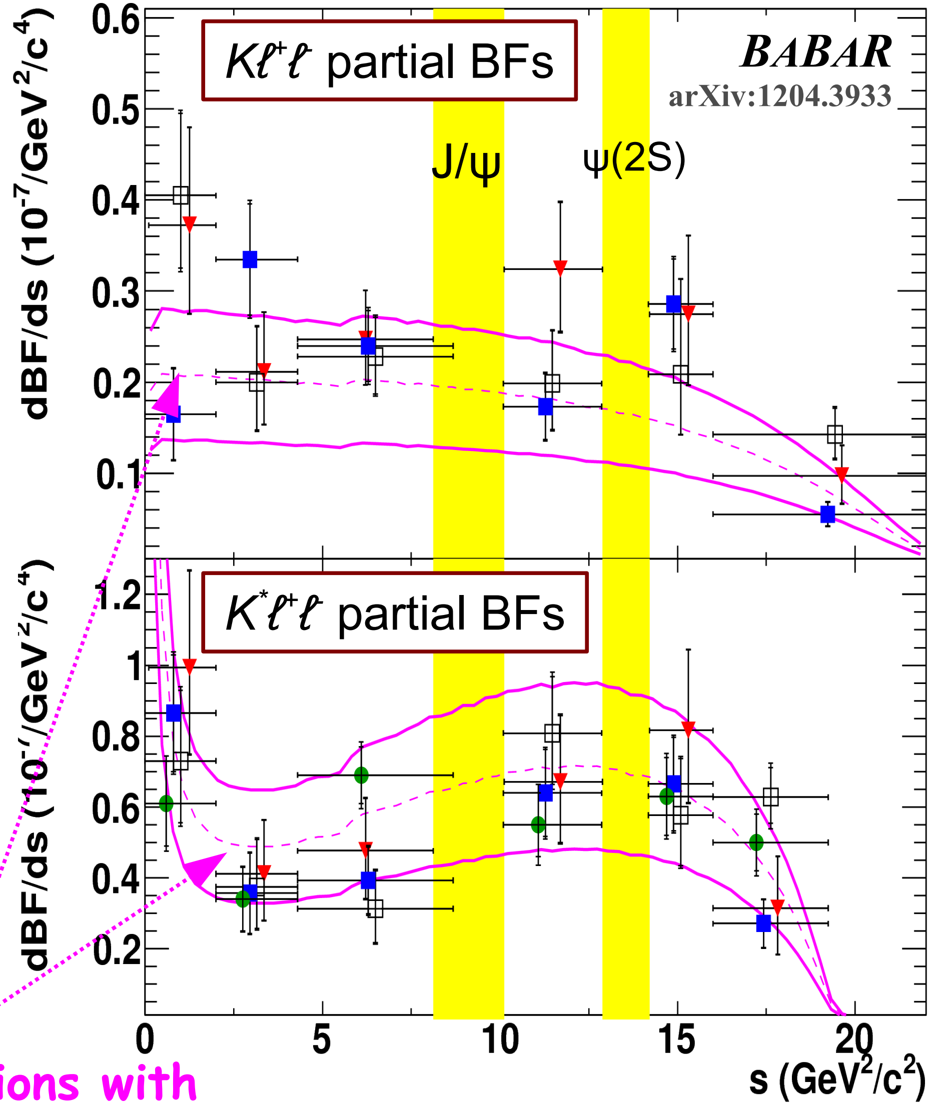
$B \rightarrow K^{(*)}\ell^+\ell^-$ rates

- ▼ *BABAR 471 M $B\bar{B}$*
- ■ CDF 6.8 fb^{-1} ($\mu^+\mu^-$ only) PRL 107, 201802 (2011)
- □ Belle 657 *M $B\bar{B}$* PRL 103, 171801 (2009)
- ● LHCb 0.37 fb^{-1}($\mu^+\mu^-$ only) arXiv:1112.3515 (2012)

- Total branching fractions

$$\mathcal{B}(B \rightarrow K\ell^+\ell^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-7},$$
$$\mathcal{B}(B \rightarrow K^*\ell^+\ell^-) = (10.2^{+1.4}_{-1.3} \pm 0.5) \times 10^{-7}.$$





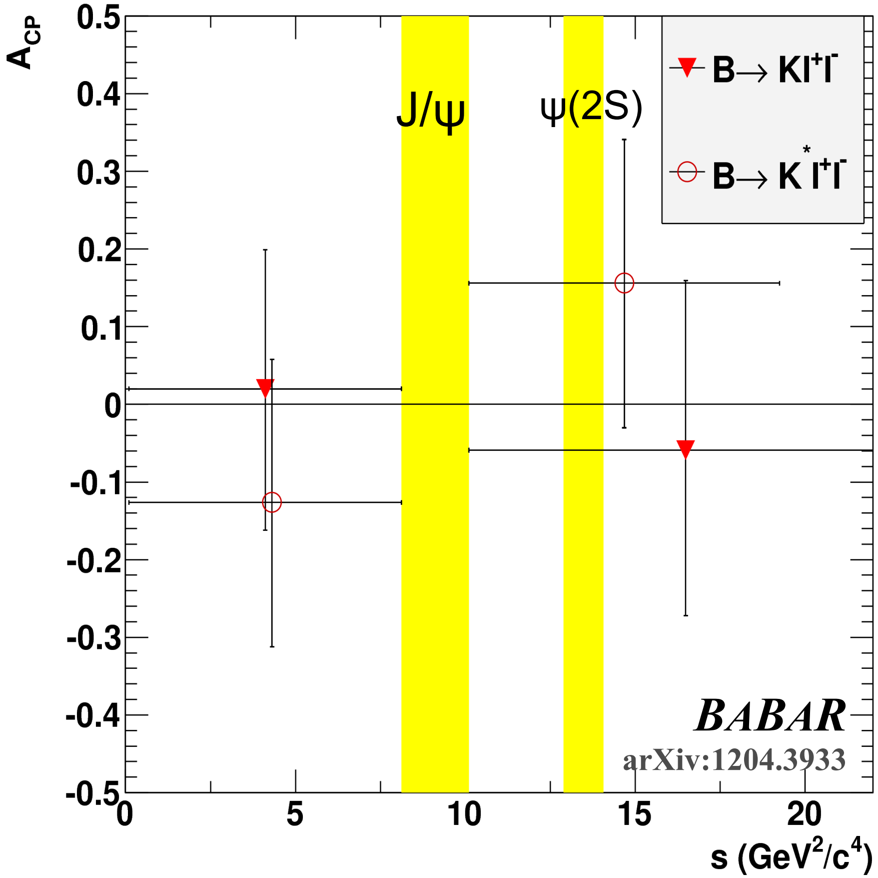
* Ball & Zwicky, PRD71, 014015(2005), PRD71, 014029(2005); Ali et al, PRD 66, 034002 (2002).

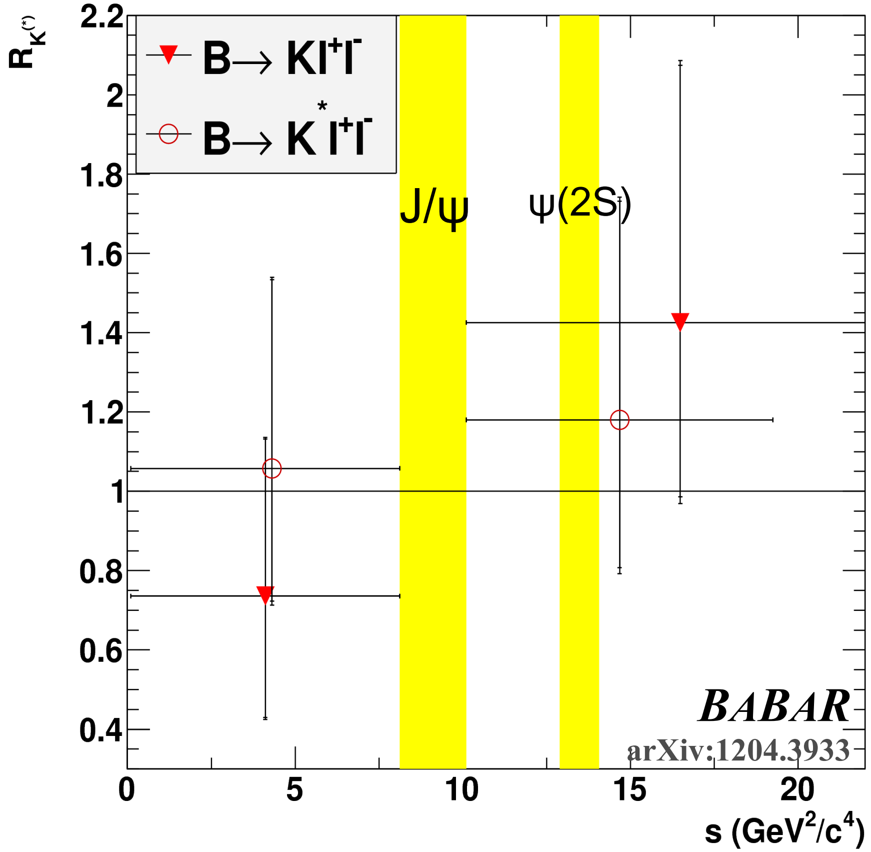
SM based predictions with Uncertainties * (solid lines)

Rate asymmetries of $B \to K^{(*)} \ell^+ \ell^-$

$$\mathcal{A}_{CP}^{K^{(*)}} \equiv \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-) - \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-) + \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}$$

$$\mathcal{R}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$





- Direct *CP* asymmetries agree with null expectation (SM)
- Lepton flavor ratios agree with unity (SM)

$B \to K^{(*)}\ell^+\ell^-$ isospin asymmetry

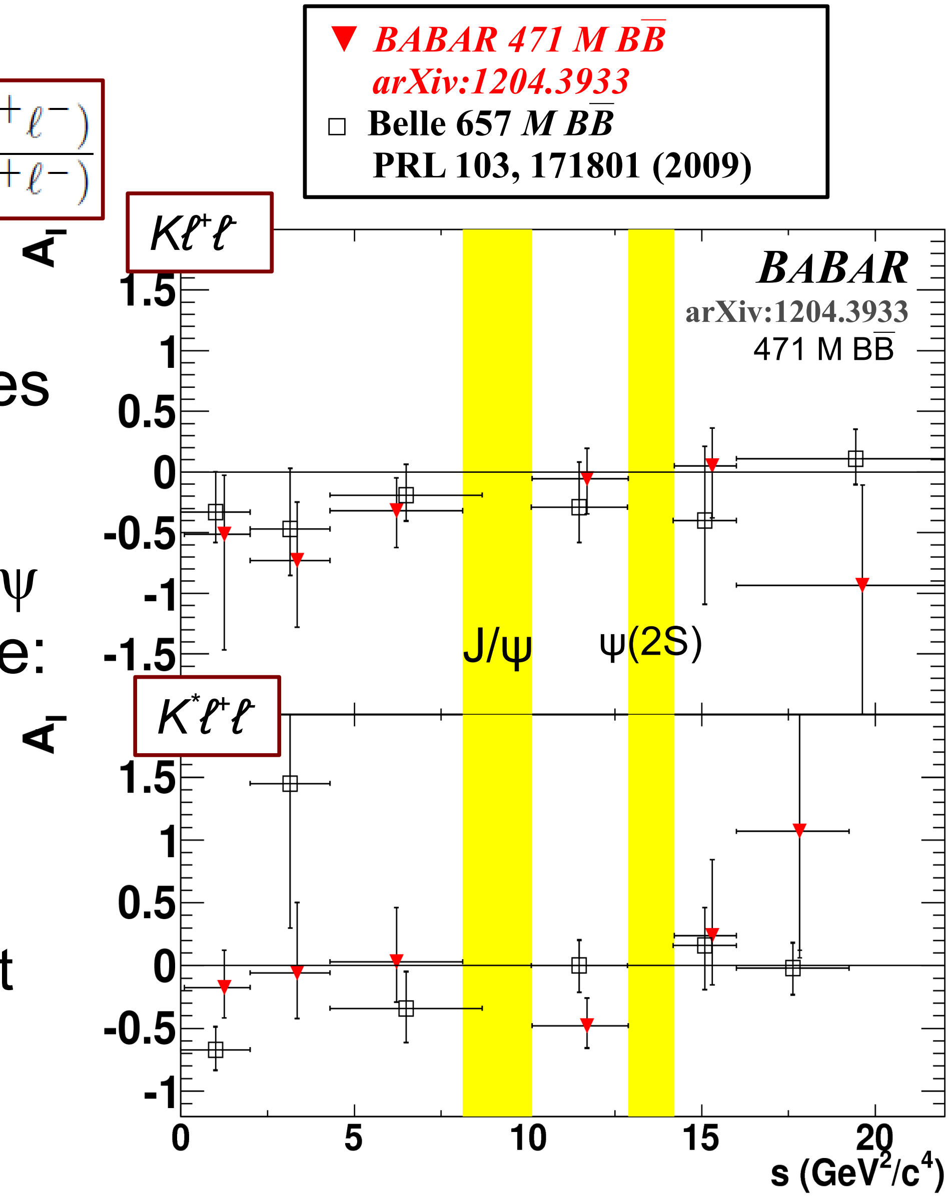
- $$\mathcal{A}_I^{K^{(*)}} \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - r_\tau \mathcal{B}(B^+ \to K^{(*)+}\ell^+\ell^-)}{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + r_\tau \mathcal{B}(B^+ \to K^{(*)+}\ell^+\ell^-)}$$

  $$r_\tau \equiv \tau_{B^0}/\tau_{B^+} = 1/(1.071 \pm 0.009)$$

- In the SM, the isospin asymmetries are expected at $O(1\%)$ *

  * *Feldmann & Matias, JHEP 0301, 074 (2003).*

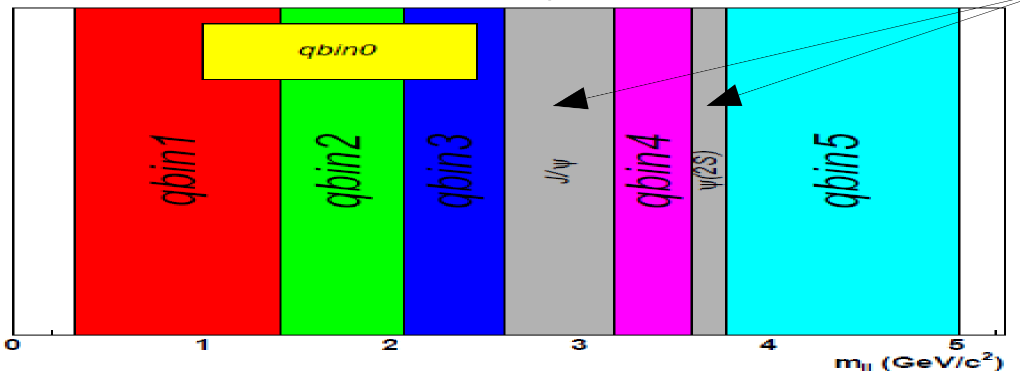
- For 471 M $B\bar{B}$ pairs, and below J/ψ (0.1 < s < 8.12 GeV^2/c^4) measure:
  - $$\mathcal{A}_I^{\text{low}}(B \to K\ell^+\ell^-) = -0.58^{+0.29}_{-0.37} \pm 0.02$$
    $$\mathcal{A}_I^{\text{low}}(B \to K^*\ell^+\ell^-) = -0.25^{+0.20}_{-0.17} \pm 0.03$$
  - Consistent with SM predictions at **2.1σ** and **1.2σ** level respectively and agree with Belle results



$B \to X_s \ell^+ \ell^-$ Event selection

- 20 exclusive final states with ≤ 2 pions and ≤ 1 π^0:
- $m_{ES} > 5.225$ GeV
- $-0.1\ (-0.05) < \Delta E < 0.05$ GeV for $X_s e^+ e^-$ ($X_s \mu^+ \mu^-$)
- Selection represent ~70% of the inclusive rate with $m_{Xs} < 1.8$ GeV, accounting for K^0_L modes, $K^0_s \to \pi^0\pi^0$ and π^0 Dalitz decays
- We extrapolate for the missing modes, and those with $m_{Xs} > 1.8$ GeV, using JETSET fragmentation and theory prediction
- We measure the total BF and partial BFs in 6 bins of $q^2 \equiv m^2_{ll}$, and 4 bins of m_{Xs}

Vetoed regions



$m_{Xs} < 1.8$ GeV

$B^0 \to K^0_S\ \mu^+\mu^-$
$B^+ \to K^+\ \mu^+\mu^-$
$B^0 \to K^0_S\ e^+e^-$
$B^+ \to K^+\ e^+e^-$
$B^0 \to K^{*0}\ (K^0_S\ \pi^0)\mu^+\mu^-$
$B^+ \to K^{*+}\ (K^+\ \pi^0)\mu^+\mu^-$
$B^+ \to K^{*+}\ (K^0_S\ \pi^+)\mu^+\mu^-$
$B^0 \to K^{*0}\ (K^+\ \pi^-)\mu^+\mu^-$
$B^0 \to K^{*0}\ (K^0_S\ \pi^0)e^+e^-$
$B^+ \to K^{*+}\ (K^+\ \pi^0)e^+e^-$
$B^+ \to K^{*+}\ (K^0_S\ \pi^+)e^+e^-$
$B^0 \to K^{*0}\ (K^+\ \pi^-)e^+e^-$
$B^+ \to K^0_S\ \pi^+\ \pi^0\ \mu^+\mu^-$
$B^0 \to K^+\ \pi^-\ \pi^0\ \mu^+\mu^-$
$B^0 \to K^0_S\ \pi^+\ \pi^-\ \mu^+\mu^-$
$B^+ \to K^+\ \pi^+\ \pi^-\ \mu^+\mu^-$
$B^+ \to K^0_S\ \pi^+\ \pi^0\ e^+e^-$
$B^0 \to K^+\ \pi^-\ \pi^0\ e^+e^-$
$B^0 \to K^0_S\ \pi^+\ \pi^-\ e^+e^-$
$B^+ \to K^+\ \pi^+\ \pi^-\ e^+e^-$

Requiring K_s from $K_s \to \pi^+\pi^-$, π^0 from $\pi^0 \to \gamma\gamma$

$B \to X_s \ell^+ \ell^-$ Event selection

$m_{Xs} < 1.8$ GeV

- 20 exclusive final states with ≤ 2 pions and ≤ 1 π^0:
- $m_{ES} > 5.225$ GeV
- $-0.1\ (-0.05) < \Delta E < 0.05$ GeV for $X_s e^+e^-$ ($X_s\mu^+\mu^-$)
- Selection represent ~70% of the inclusive rate with $m_{Xs} < 1.8$ GeV, accounting for K^0_L modes, $K^0_s \to \pi^0\pi^0$ and π^0 Dalitz decays
- We extrapolate for the missing modes, and those with $m_{Xs} > 1.8$ GeV, using JETSET fragmentation and theory prediction
- We separate B and $\overline{\mathrm{B}}$ samples in the 14 **self-tagging modes** to measure direct CP asymmetry

$$\boxed{A_{CP} \equiv \frac{\Gamma(\bar{b} \to \bar{s}\ell\ell) - \Gamma(b \to s\ell\ell)}{\Gamma(\bar{b} \to \bar{s}\ell\ell) + \Gamma(b \to s\ell\ell)}}$$

SM expectation well below 1% (1)

(1) Phys. Rev. D 54, 882 (1996); Eur. Phys. J. C 8, 619 (1999); JHEP 0807, 106 (2008); JHEP 0901, 019 (2009)

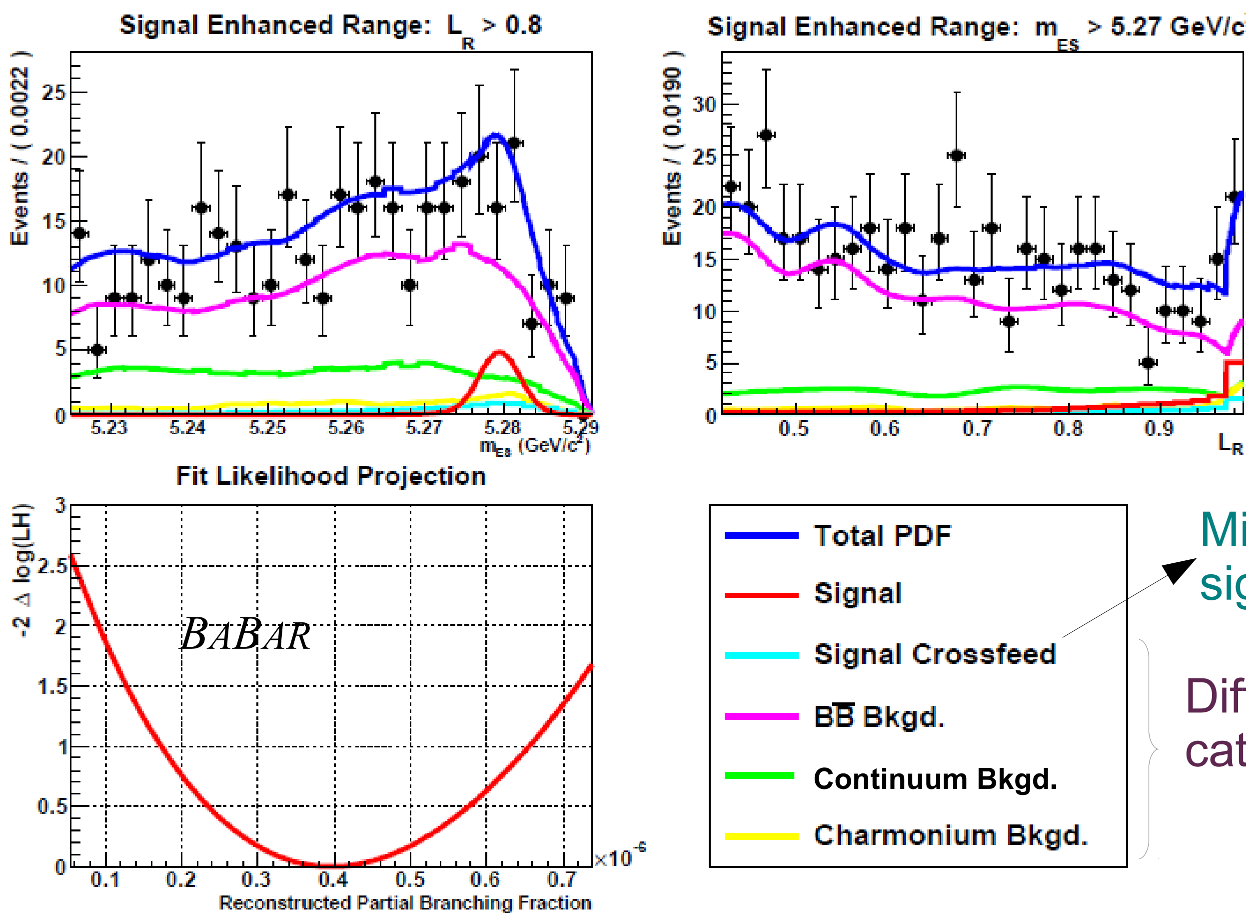
[redacted]
$B^+ \to K^+ \mu^+\mu^-$
[redacted]
$B^+ \to K^+ e^+e^-$
[redacted]
$B^+ \to K^{*+} (K^+ \pi^0)\mu^+\mu^-$ $B^+ \to K^{*+} (K^0_S \pi^+)\mu^+\mu^-$ $B^0 \to K^{*0} (K^+ \pi^-)\mu^+\mu^-$
[redacted]
$B^+ \to K^{*+} (K^+ \pi^0)e^+e^-$ $B^+ \to K^{*+} (K^0_S \pi^+)e^+e^-$ $B^0 \to K^{*0} (K^+ \pi^-)e^+e^-$
$B^+ \to K^0_S \pi^+ \pi^0 \mu^+\mu^-$ $B^0 \to K^+ \pi^- \pi^0 \mu^+\mu^-$
[redacted]
$B^+ \to K^+ \pi^+ \pi^- \mu^+\mu^-$ $B^+ \to K^0_S \pi^+ \pi^0 e^+e^-$ $B^0 \to K^+ \pi^- \pi^0 e^+e^-$
[redacted]
$B^+ \to K^+ \pi^+ \pi^- e^+e^-$

Requiring K_s from $K_s \to \pi^+\pi^-$, π^0 from $\pi^0 \to \gamma\gamma$

$B \to X_s \ell^+ \ell^-$ Fitting strategy

- Signal extraction with 2D ML fit to m_{ES} and likelihood ratio L_R which is based on boosted decision trees and peaks ~ 1 for signals

Example fit for $X_s e^+ e^-$ events with $2.0 < q^2 < 4.3$ GeV^2



$$L_R = \frac{\mathcal{P}_S}{\mathcal{P}_S + \mathcal{P}_B}$$

$\mathcal{P}_{S/B}$: signal/bkg. probability from $B\bar{B}$ BDT output

Mis-reconstructed signal events

Different background categories

$B \to X_s \ell^+ \ell^-$ Branching fraction results

- Total branching fraction ($q^2 > 0.1$ GeV^2)

$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (6.73^{+0.70+0.34}_{-0.63-0.25} \pm 0.5) \times 10^{-6}$$

$$\mathcal{B}_{SM}(B \to X_s \ell^+ \ell^-) = (4.6 \pm 0.8) \times 10^{-6} \quad (1)$$

  - < 2σ higher than the SM expectation

- In the low mass range ($1 < q^2 < 6$ GeV^2):

$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}$$

$$\mathcal{B}_{SM}(B \to X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6} \quad (2)$$

  - In good agreement with the SM

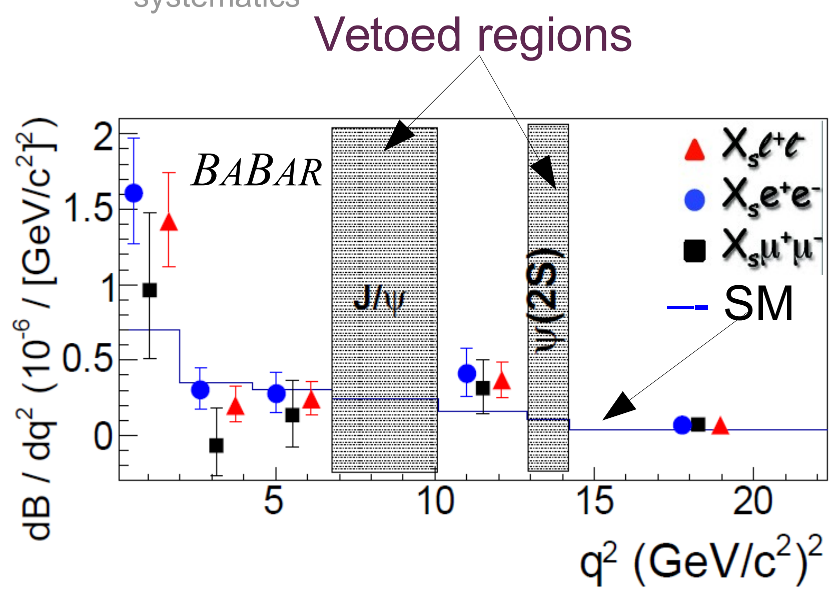
- In the high mass range ($q^2 > 14.2$ GeV^2)

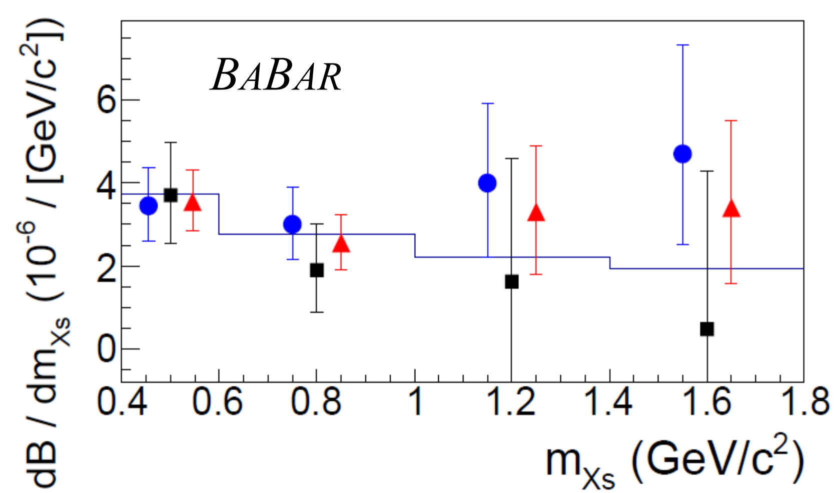
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.0) \times 10^{-6}$$

$$\mathcal{B}_{SM}(B \to X_s e^+ e^-) = (0.21 \pm 0.07) \times 10^{-6} \quad (2)$$

  - ~ 2σ higher than the SM expectation

In the listed results, the first uncertainty is statistical, the second experimental systematics and the third model-dependent systematics





(1) Nucl.Phys.B 685, 351 (2004)
(2) Nucl.Phys.B 802, 40 (2008)

$B \to X_s \ell^+ \ell^-$ Branching fraction results

In the listed results, the first uncertainty is statistical, the second experimental systematics and the third model-dependent systematics

- Total branching fraction ($q^2 > 0.1\ \mathrm{GeV}^2$)

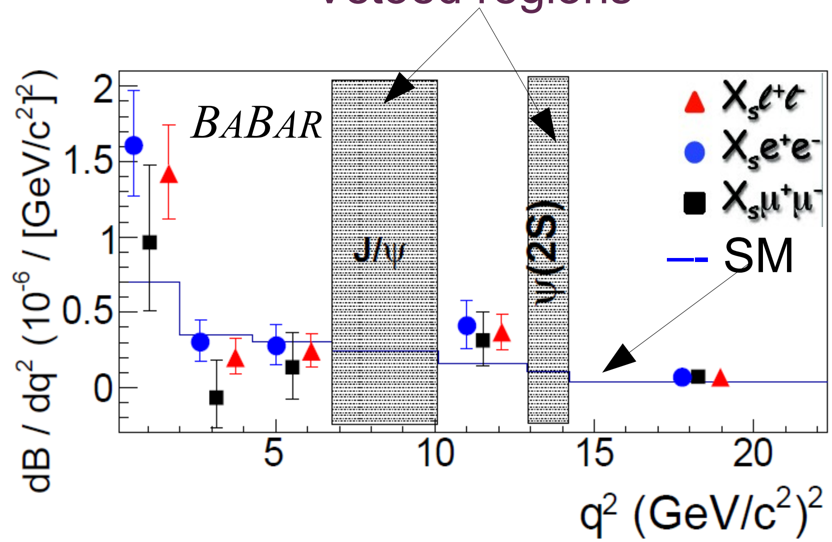
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (6.73^{+0.70+0.34}_{-0.63-0.25} \pm 0.5) \times 10^{-6}$$

$$\mathcal{B}_{SM}(B \to X_s \ell^+ \ell^-) = (4.6 \pm 0.8) \times 10^{-6} \quad (1)$$

  - $< 2\sigma$ higher than the SM expectation

The BF measurement for $q^2 > 14.2\ \mathrm{GeV}^2$ disfavors by ~2.5-3σ the δC_9 NP interpretation of the recent LHCb "anomaly" for an angular observable from $B^0 \to K^{*0} \mu^+ \mu^-$ (3)

- Expected pBF lower than SM in this interpretation



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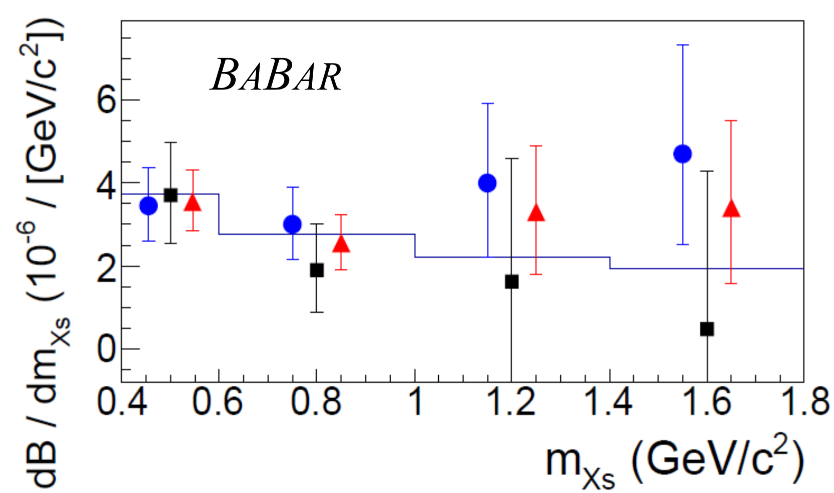
$$\mathcal{B}(B \to X_s \ell^+ \ell^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.0) \times 10^{-6}$$

$$\mathcal{B}_{SM}(B \to X_s e^+ e^-) = (0.21 \pm 0.07) \times 10^{-6} \quad (2)$$

  - ~ 2σ higher than the SM expectation



(1) Nucl.Phys.B 685, 351 (2004)
(2) Nucl.Phys.B 802, 40 (2008)
(3) PRL 111, 191801 (2013)

Results on $B \to X_s \ell^+ \ell^-$ direct A_{CP}

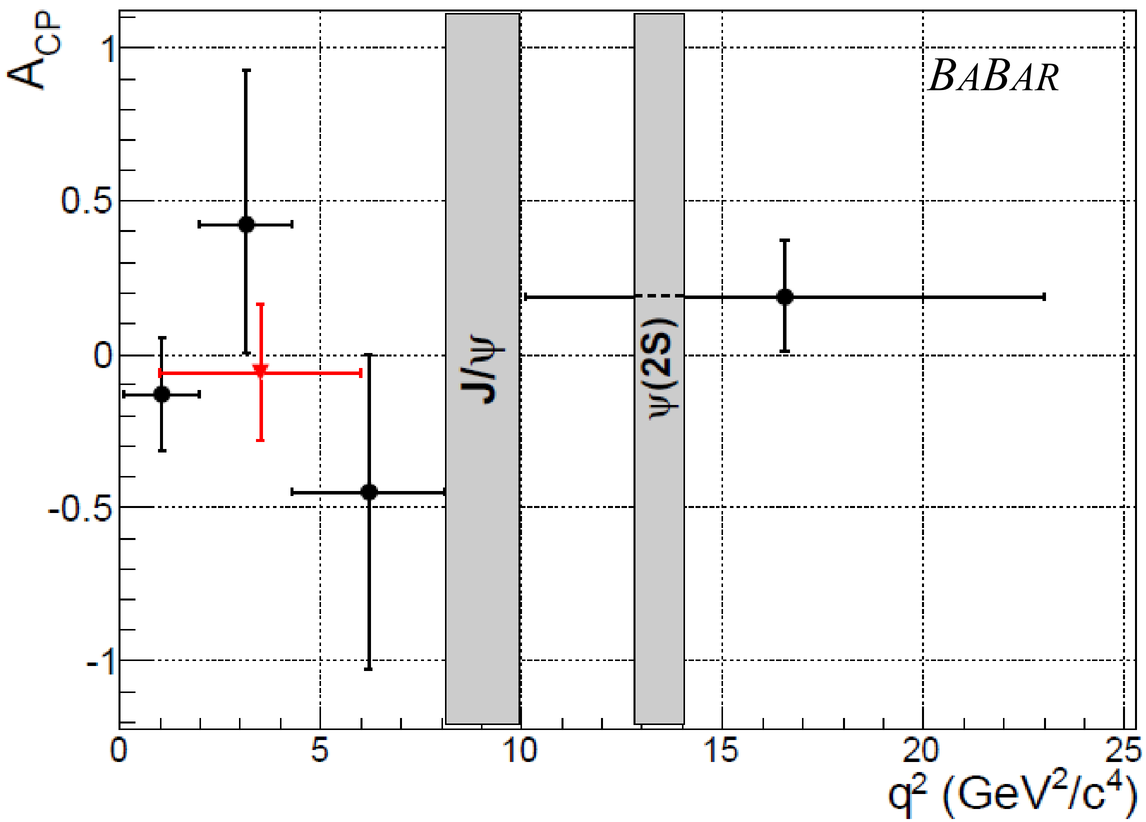
- Over the full dilepton mass range, we have:

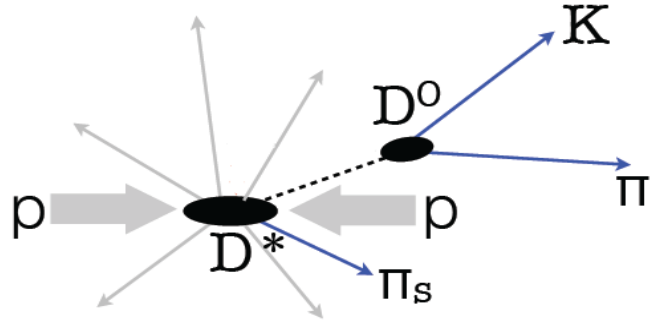
$$A_{CP}(B \to X_s \ell^+ \ell^-) = 0.04 \pm 0.11[\mathrm{stat}] \pm 0.01[\mathrm{syst}]$$

- Direct A_{CP} is measured in different regions of q^2:

$$A_{CP} \equiv \frac{\Gamma(\bar{b} \to \bar{s}\ell\ell) - \Gamma(b \to s\ell\ell)}{\Gamma(\bar{b} \to \bar{s}\ell\ell) + \Gamma(b \to s\ell\ell)}$$

- *CP asymmetry is found to be consistent with zero everywhere*





- Included $3fb^{-1}$ LHCb results on
  - $D^0 - \overline{D}^0$ mixing parameters and search for CP violation using $D^0 \rightarrow K^+ \pi^-$ decays
    - Published in 2013 and presented by myself:
      - As “new” results during the CHARM 2013 workshop as a plenary talk
      - During the Epiphany 2014 Conference

Formalism in neutral meson mixing

- Schrödinger equation describing the time evolution:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix}$$

- Mass eigenstates can be different from their flavor eigenstates: *CPT* invariance => $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$

$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle \quad \text{where} \quad \frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

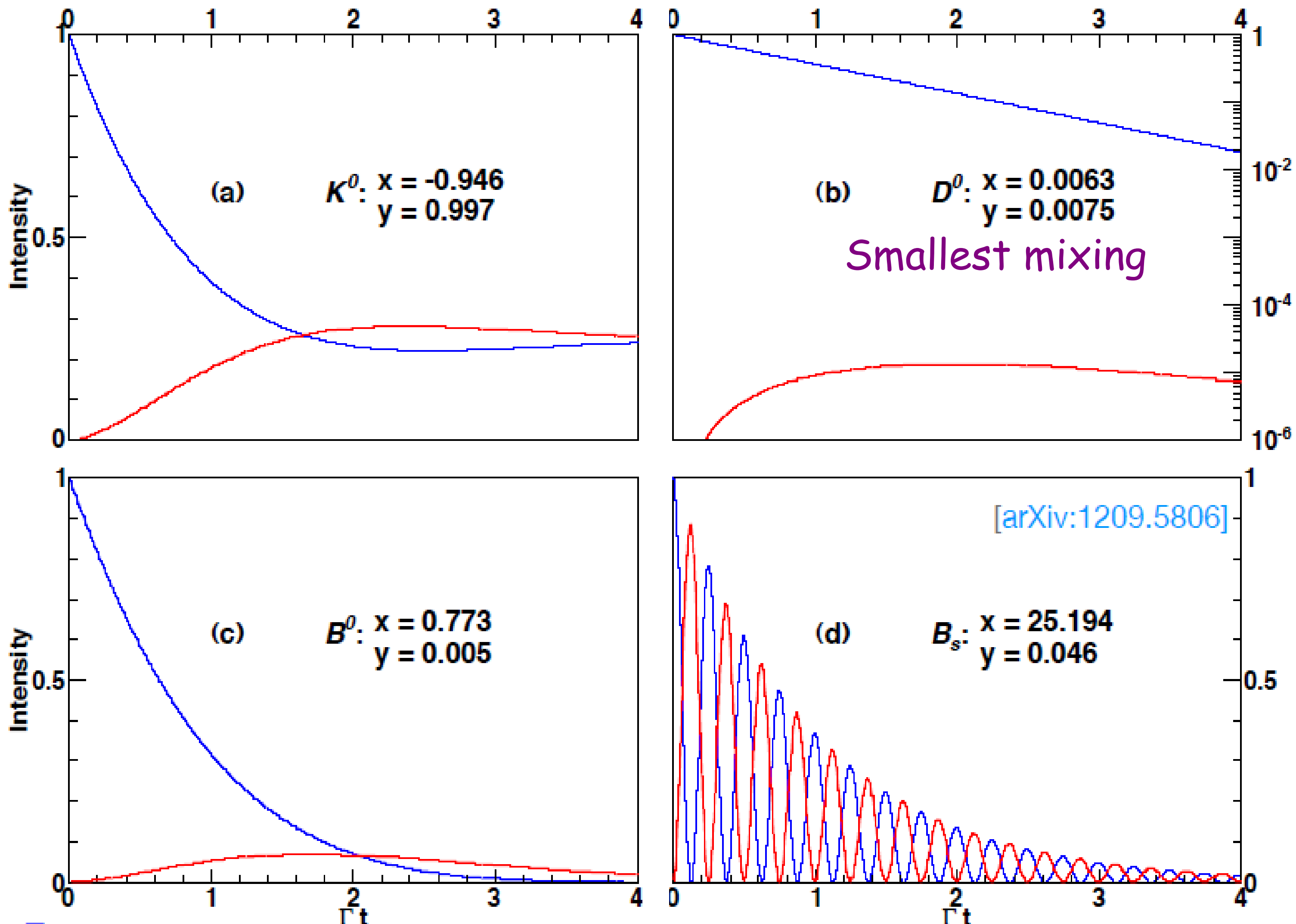
$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{(\Gamma_H + \Gamma_L)/2}, \quad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}$$

- If *CP* is conserved, q and p are real, *i.e.* |q/p| = 1 and φ = arg(q/p) = 0

Mixing of neutral mesons: phenomenology

Blue line:
given a P⁰, at t=0, the probability of finding a P⁰ at t

Red Line:
given a P⁰, at t=0, the probability of finding a $\overline{P}^0$ at t

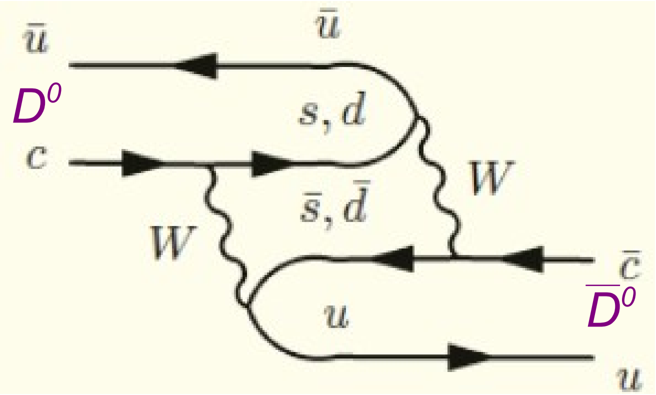


$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

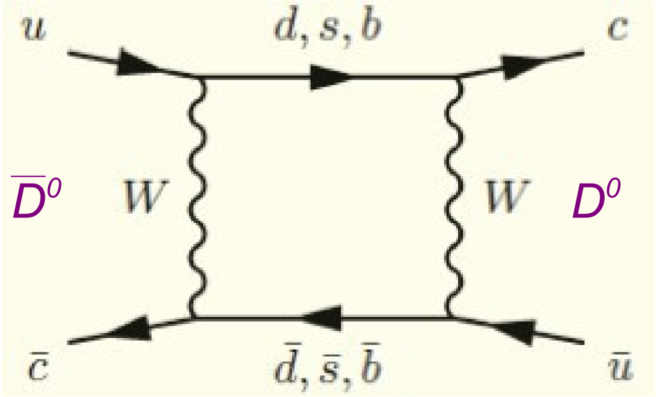
$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Motivation in measuring charm mixing & CPV

- $D^0 - \overline{D}^0$ oscillation is slow (x, y ~ 1%), and goes through two different mechanisms:
  - Long distance contribution is dominant but hard to predict
  - Short distance contribution is CKM + GIM suppressed. NP might manifest in the loop
    - FCNC processes with up-type quark, complementary to those with down quarks (K or B mesons, already studied with observed CPV)
- Observation of enhanced CPV (>> 1%) in the charm sector would be a clear indication of new physics

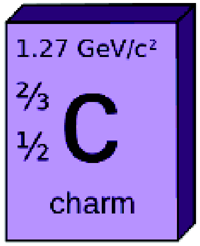


Long-distance contribution



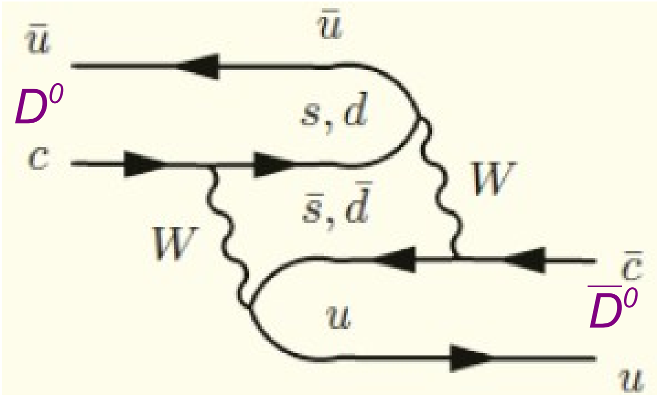
Short-distance contribution

CKM suppression: *b*
GIM suppression: *d, s*

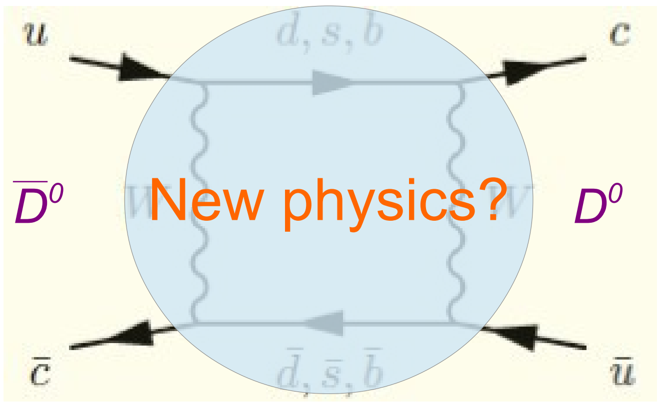


Motivation in measuring charm mixing & CPV

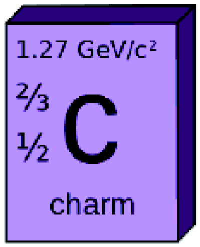
- $D^0 - \overline{D}^0$ oscillation is slow (x, y ~ 1%), and goes through two different mechanisms:
  - Long distance contribution is dominant but hard to predict
  - Short distance contribution is CKM + GIM suppressed. NP might manifest in the loop
    - FCNC processes with up-type quark, complementary to those with down quarks (K or B mesons, already studied with observed CPV)
- Observation of enhanced CPV (>> 1%) in the charm sector would be a clear indication of new physics



Long-distance contribution



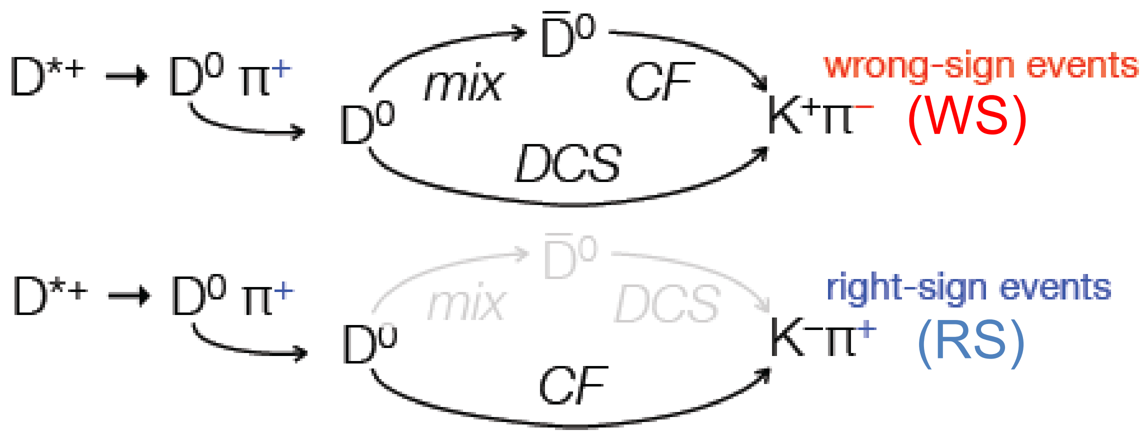
Short-distance contribution
NP might manifest in the loop

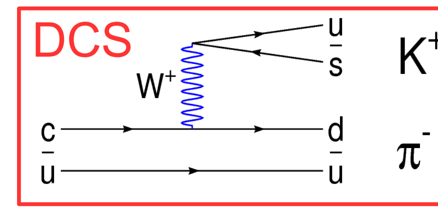


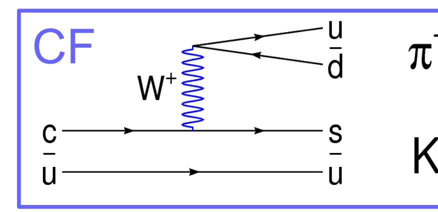
Charm mixing with $D^0 \to K\pi$

- Two-body decays with only tree-level contribution

D^0 flavor is tagged by the "soft" pion from D*







- Assuming x, y << 1 and no CPV, we have the time-dependent WS/RS ratio:

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

δ: strong phase between DCS and CF amplitudes

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

Ratio of DCS to CF decay rates

Interference of DCS and mixed decays

Mixing parameters

Measurements on R_D, x'^2, and y'

CPV in charm mixing

- Allowing for CPV, the WS-to-RS ratios are expressed separately for D^0 and $\overline{D}^0$:
  - $$R^+(t) = R_D^+ + \sqrt{R_D^+}\, y'^+ t + \frac{(x'^+)^2 + (y'^+)^2}{4} t^2,$$
    $$R^-(t) = R_D^- + \sqrt{R_D^-}\, y'^- t + \frac{(x'^-)^2 + (y'^-)^2}{4} t^2.$$

Mixing measurements on $R_D^{\pm}$, $x'^{2\pm}$, and $y'^{\pm}$ in $D^{*\pm}$, and look for the differences

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x' \cos\phi \pm y' \sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi)$$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

CPV in WS decay amplitude (**Direct CPV**)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \qquad \phi = \arg\left(\frac{q}{p}\right),$$

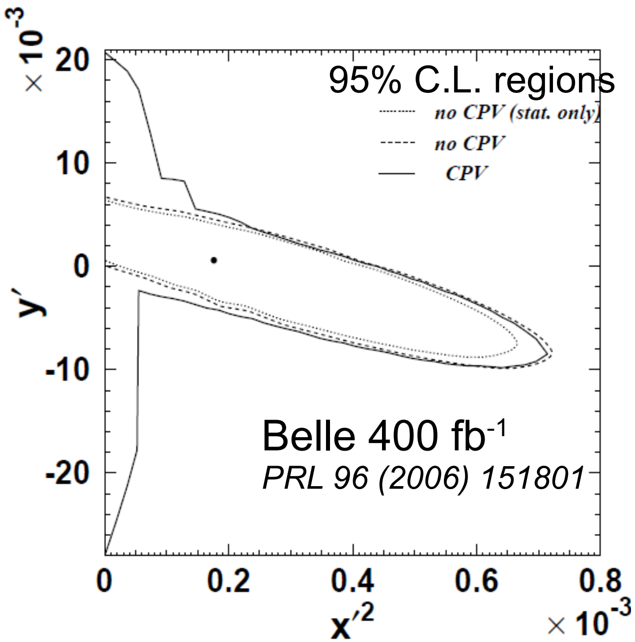
CPV in mixing / interference between mixing and decay (Indirect CPV)

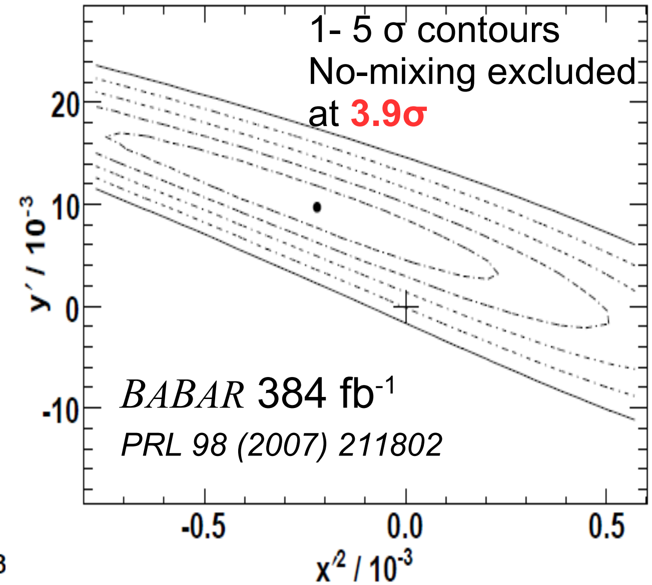
Common methods in charm mixing/CPV measurements

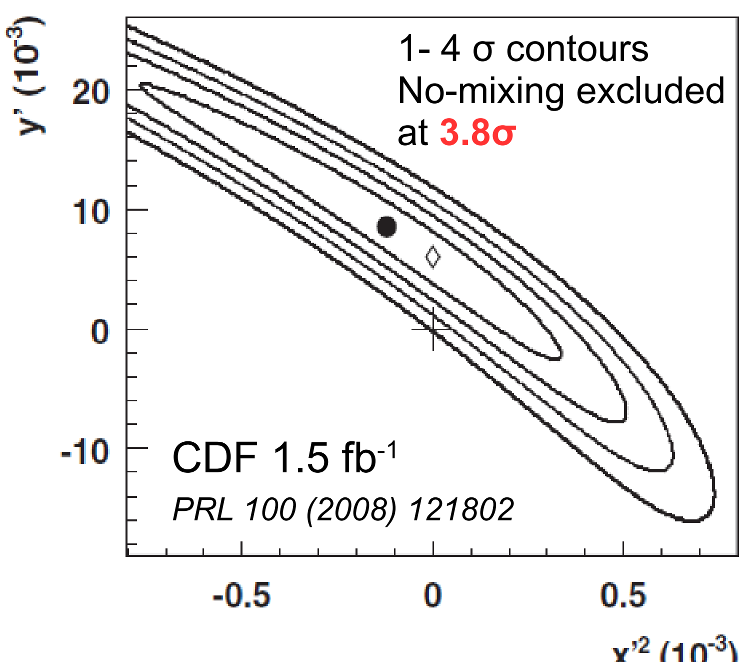
- Divide RS and WS events into a number of bins of D^0 decay time
- In each time bin, the RS and WS signal yields are collected from fits to get the WS-to-RS ratio
  - The WS signal shapes are fixed to the RS ones
- Fit the WS/RS ratio vs. D decay time to extract charm mixing parameters
- Correction to account for (secondary) D* from B decays with mis-assigned decay time
- Search for CPV: separate mixing measurements for D / $\overline{D}$

History of experimental observations

- 2006: “Improved constraints” from Belle
- 2007: Evidence for D^0-$\overline{D}^0$ mixing from BABAR
- 2008: Evidence for D^0-$\overline{D}^0$ mixing from CDF
- Observation (> 5σ) only when all the above results are combined

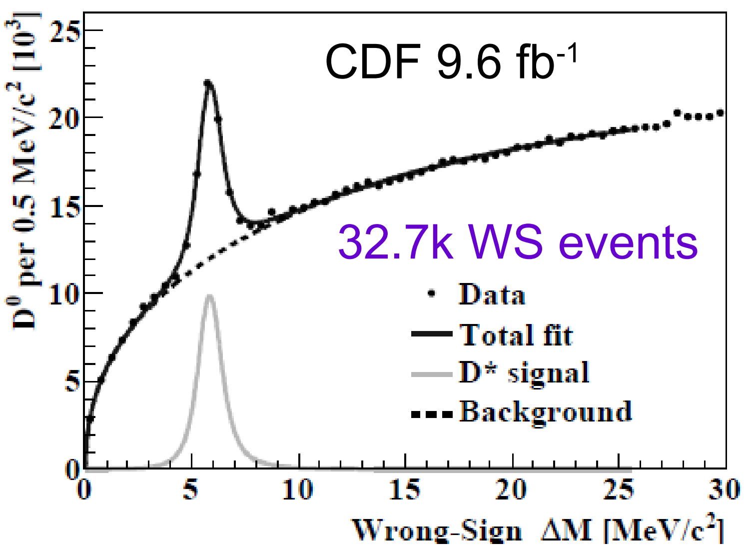




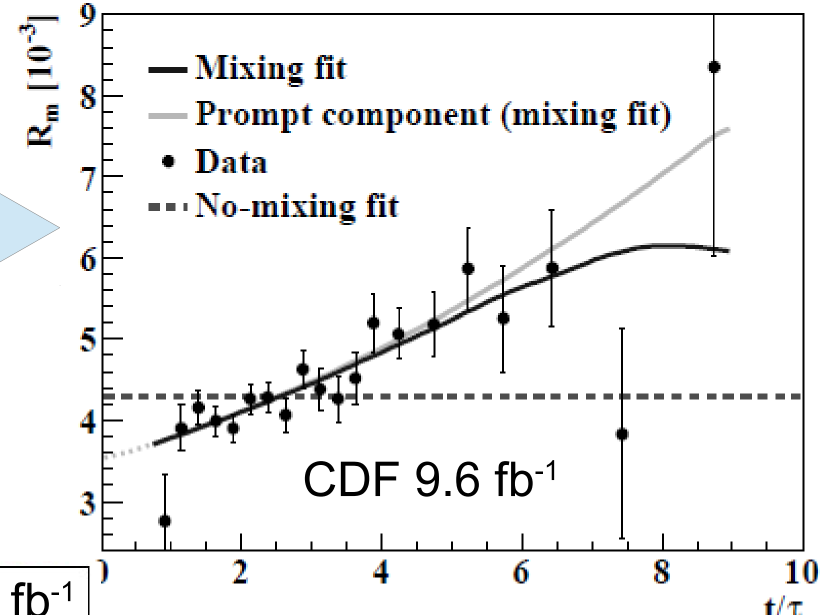


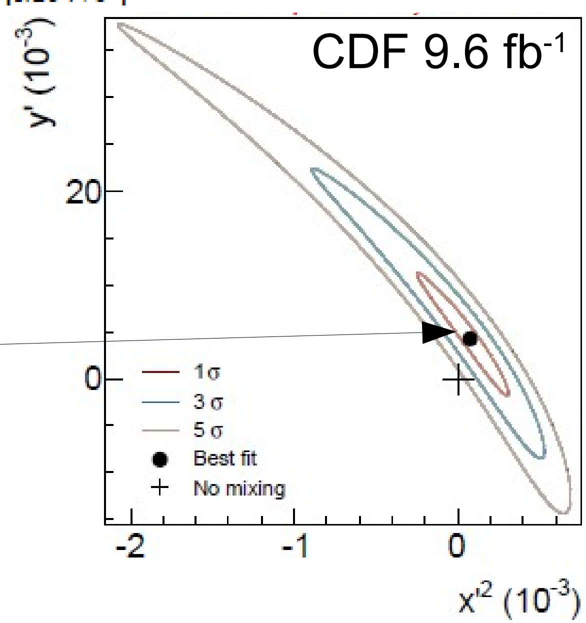
D^0 mixing @ CDF in 2013

Extraction of WS signals from the fit to the mass difference of $M(K^+\pi^-\pi^+) - M(K^+\pi^-) - M(\pi^+)$



Fit to the WS/RS ratios with different mixing hypotheses



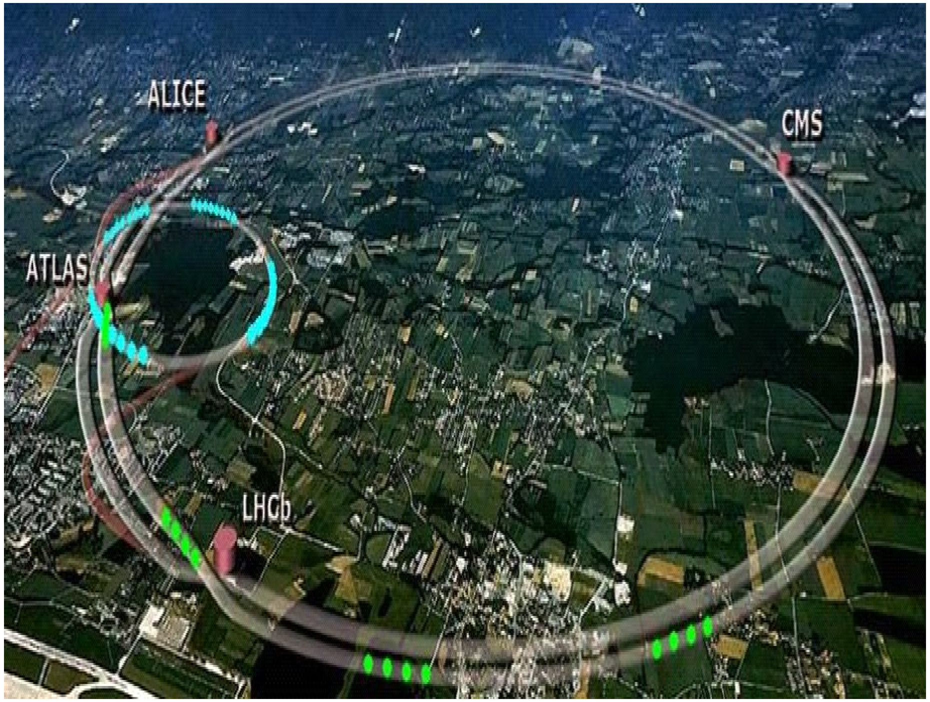


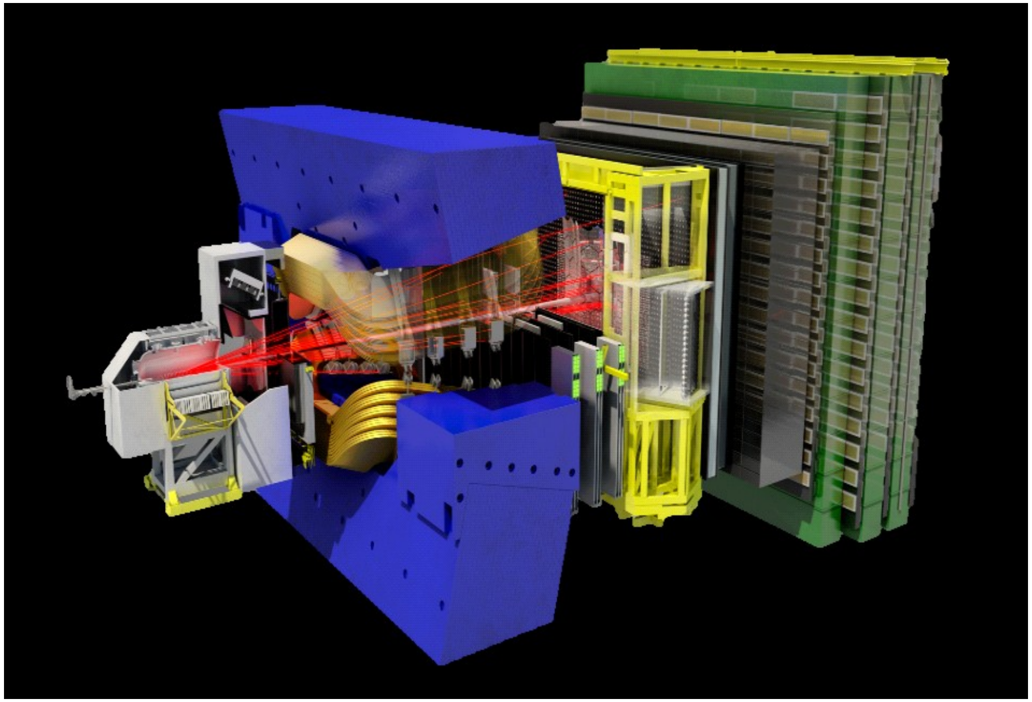
No-mixing hypothesis excluded at 6.1σ

The **second** D^0-$\overline{D}^0$ mixing observation from a single experiment after LHCb in 2012 (*PRL 110, 101802 (2013)*)

PRL 111, 231802 (2013)

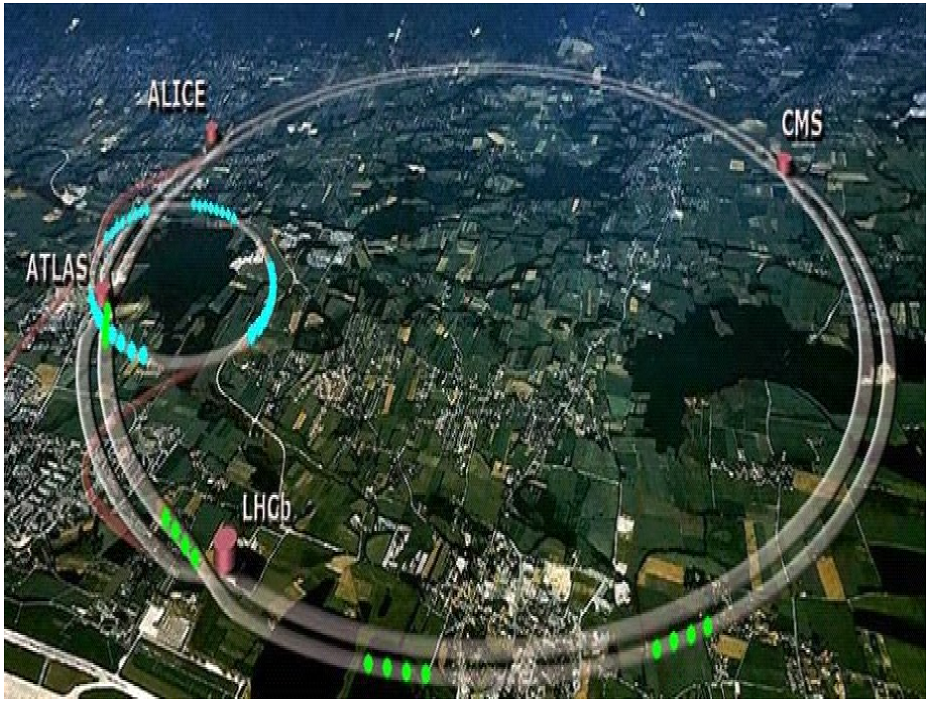
LHCb experiment

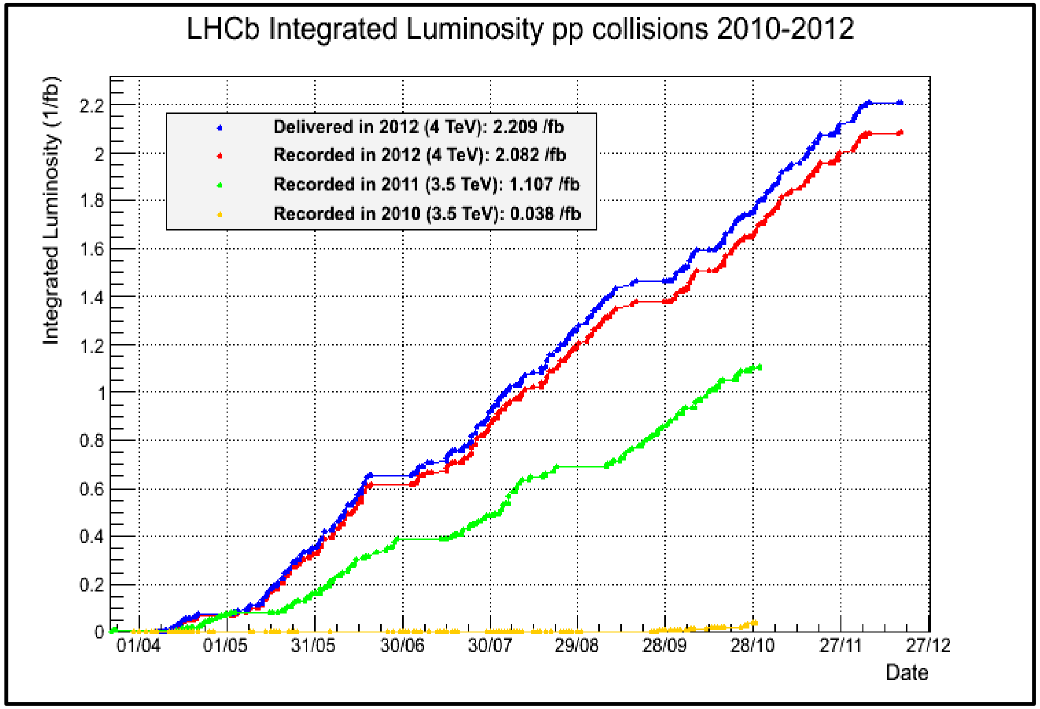




- Single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$
- Detection of particles containing *b* or *c* quarks

LHCb experiment as a charm factory





- 20x larger charm cross-section than beauty:

$\sigma(pp \rightarrow b\bar{b}X) = 75 \pm 14\ \mu b$
[PLB694:209-216]

$\sigma(pp \rightarrow c\bar{c}X) = 1419 \pm 134\ \mu b$
[arXiv:1302.2864]

→ at 7 TeV in the LHCb acceptance

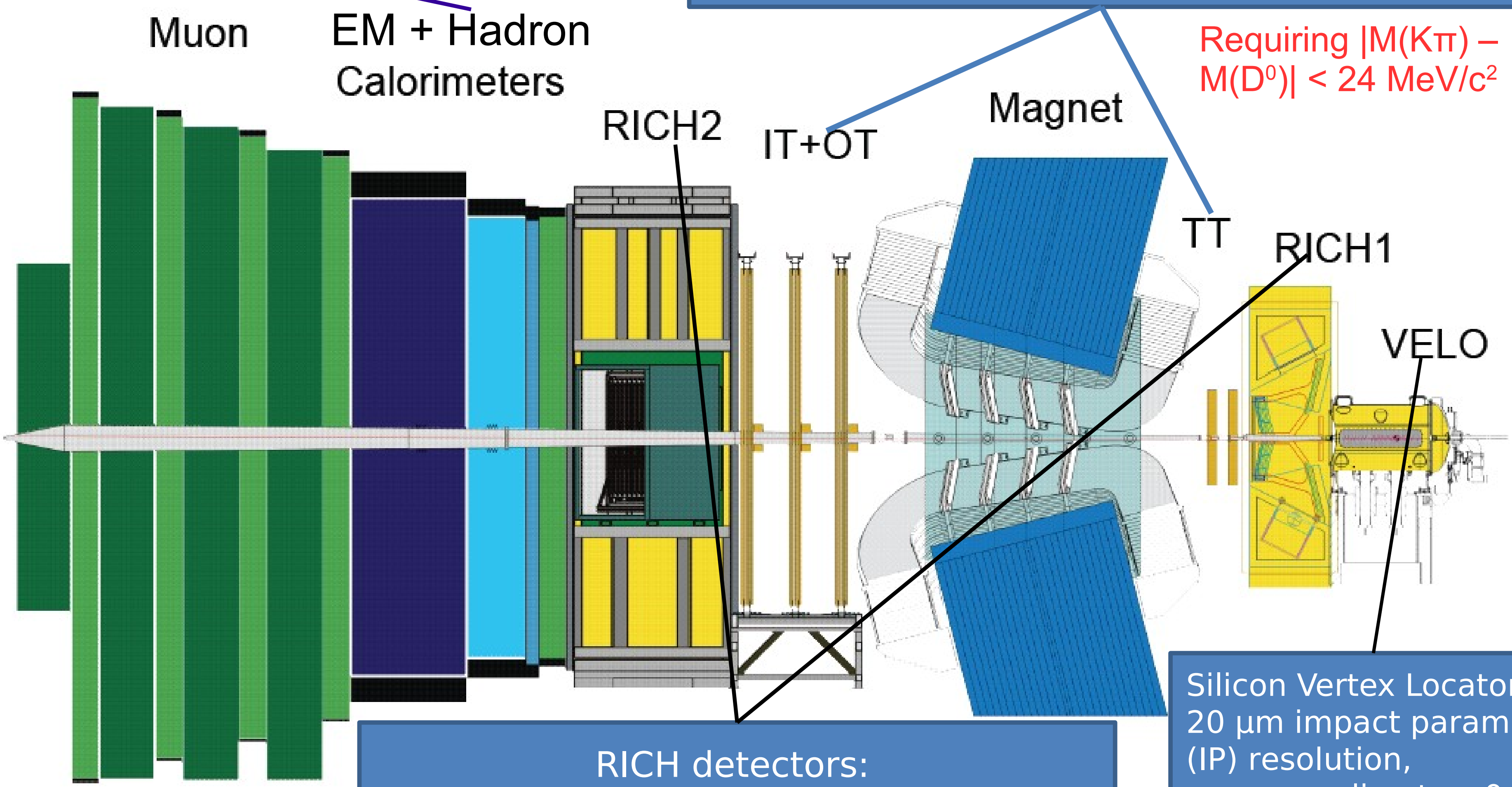
The world's largest charm samples!

LHCb detector

Hardware trigger system for hadrons: based on large E_T depositions in the hadron Cal.

Tracking system:
$\Delta p/p$ = 0.4-0.6% @ 5-100 GeV/c, corresponding to ~8 MeV/c^2 mass resolution for $D \to K\pi$

Requiring $|M(K\pi) - M(D^0)| < 24$ MeV/c^2



RICH detectors:
Good K/π separation for p < 100 GeV/c with mis-ID rate at a few percent

Silicon Vertex Locator:
20 μm impact parameter (IP) resolution, corresponding to ~0.1τ decay-time resolution for $D \to K\pi$

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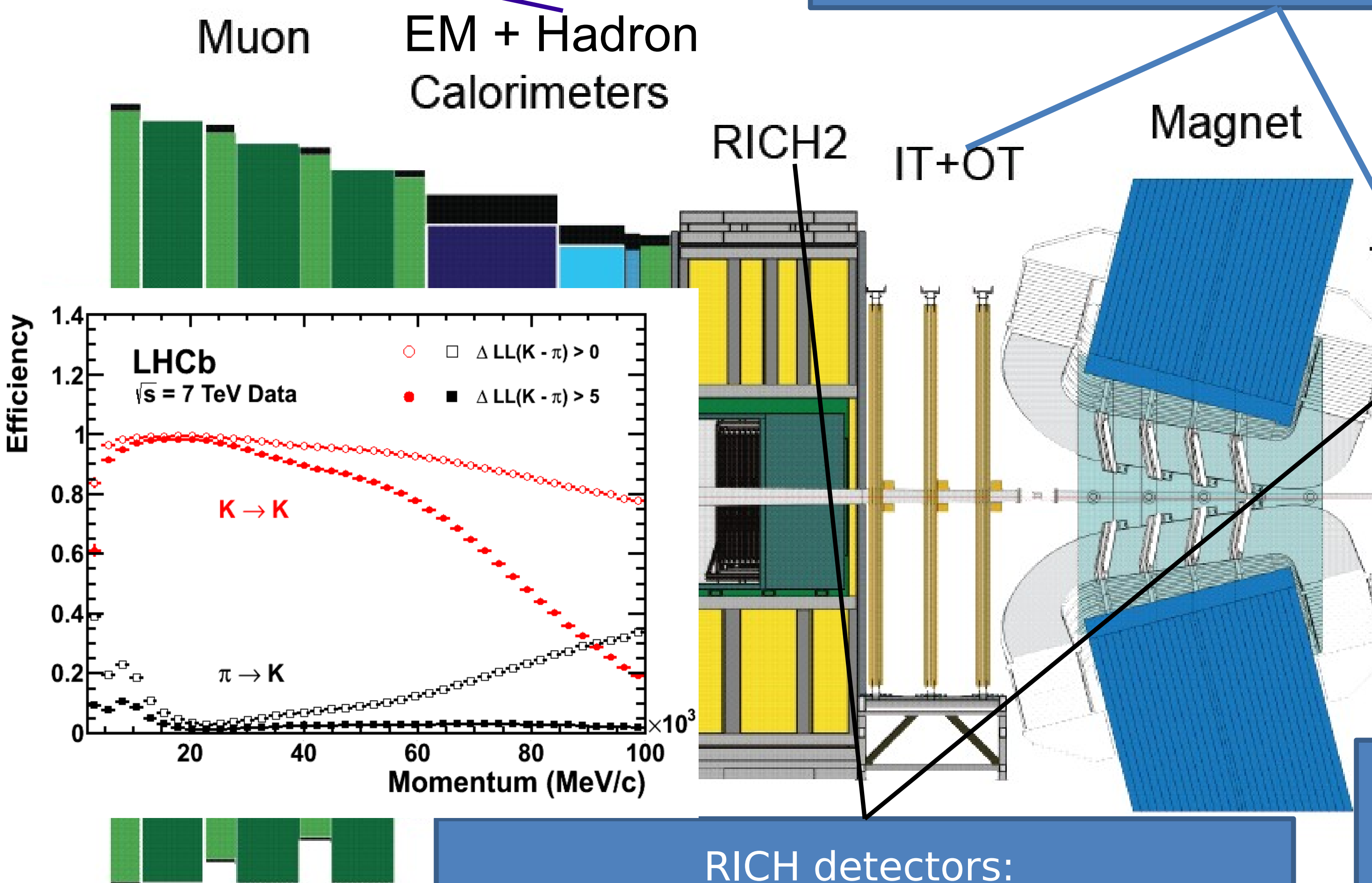

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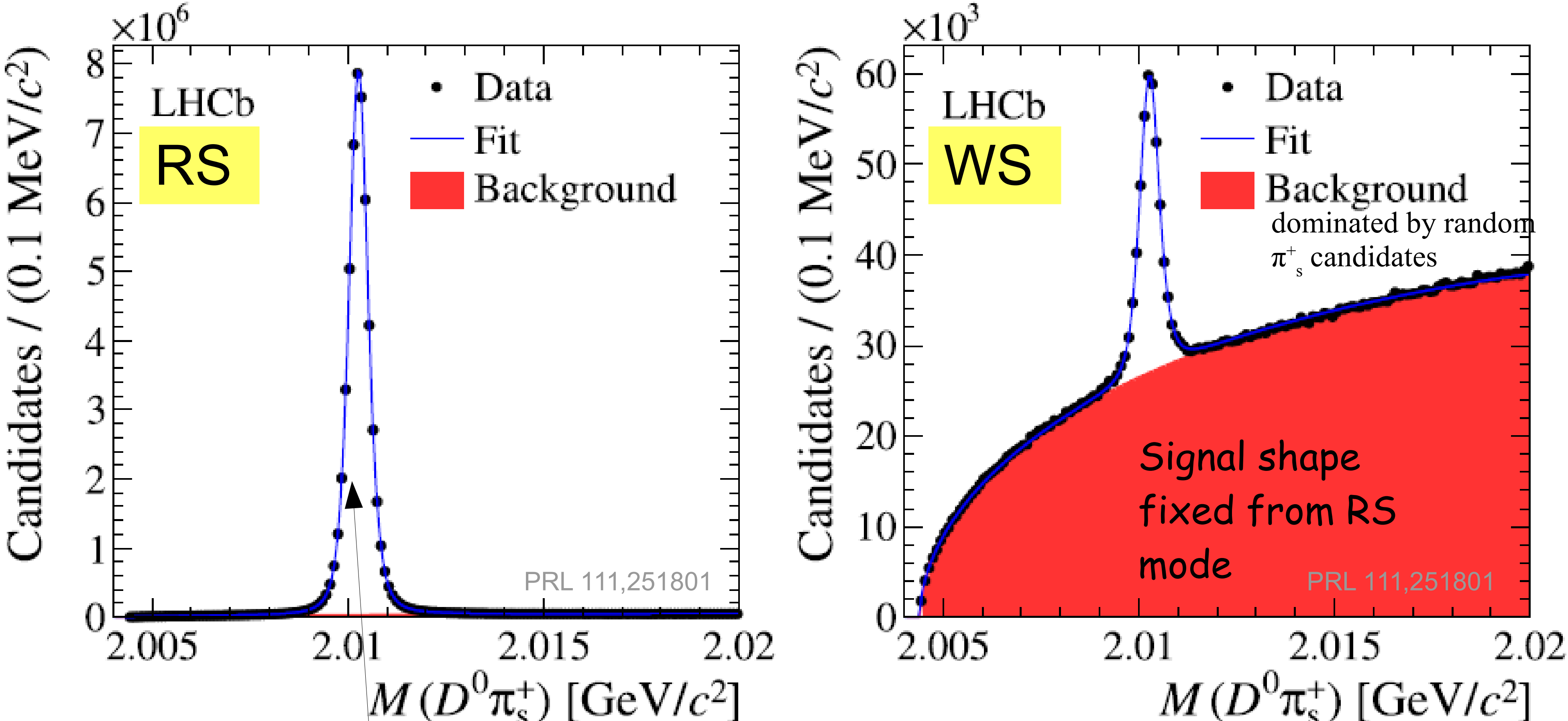
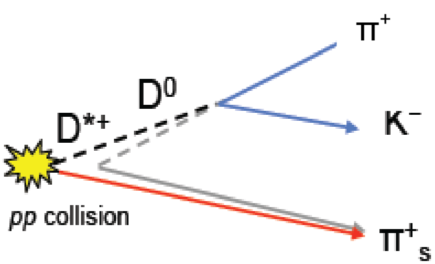
Fits to extract WS/RS signals



Computed with known D^0 and π^+ masses



Mass resolution at ~ 0.3 MeV/c^2 due to D^* vertex being well constrained to measured PV position

Time-integrated fits to 3fb^{-1} 2011+2012 data. In total ~54 M RS candidates and ~0.23 M WS candidates are collected.

Charge asymmetry in Kπ detection

- In the WS/RS ratio separated by D* charge:

$$\frac{N^{\pm}_{WS}}{N^{\pm}_{RS}} = \frac{N(D^{*\pm} \to [K^{\pm}\pi^{\mp}]_D \pi^{\pm}_s)}{N(D^{*\pm} \to [K^{\mp}\pi^{\pm}]_D \pi^{\pm}_s)} = R^{\pm} \frac{\epsilon(K^{\pm}\pi^{\mp})}{\epsilon(K^{\mp}\pi^{\pm})}$$

  – D^* production and soft pion instrumental asymmetries cancel out in the ratio

- Still needed to consider: the non-zero detection asymmetry $A_{k\pi}$:

$$\boxed{A_{K\pi} = \frac{\epsilon(K^{+}\pi^{-}) - \epsilon(K^{-}\pi^{+})}{\epsilon(K^{+}\pi^{-}) + \epsilon(K^{-}\pi^{+})}}$$

  – The efficiency ratio $\varepsilon_r^{+} = 1/\varepsilon_r^{-} = \varepsilon(K^{+}\pi^{-})/\varepsilon(K^{-}\pi^{+})$ is obtained from dedicated control samples:

$$\frac{\epsilon(K^{+}\pi^{-})}{\epsilon(K^{-}\pi^{+})} = \frac{N(D^{-} \to K^{+}\pi^{-}\pi^{-})}{N(D^{+} \to K^{-}\pi^{+}\pi^{+})} \times \frac{N(D^{+} \to K^{0}_{s}\pi^{+})}{N(D^{-} \to K^{0}_{s}\pi^{-})}$$

  – $A_{k\pi}$ is found to be at ~1% with 0.2% precision and independent of decay time

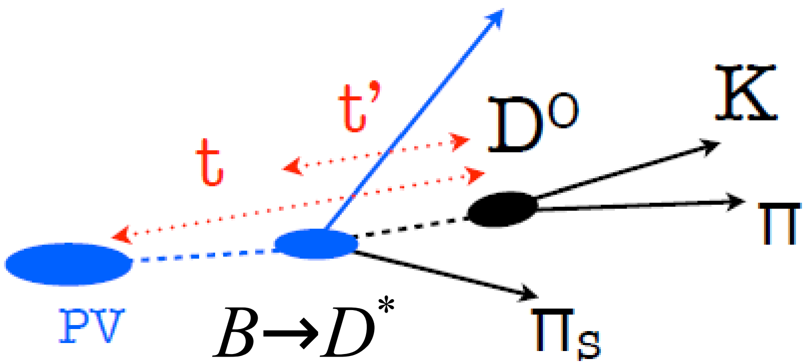
Background from secondary D decays

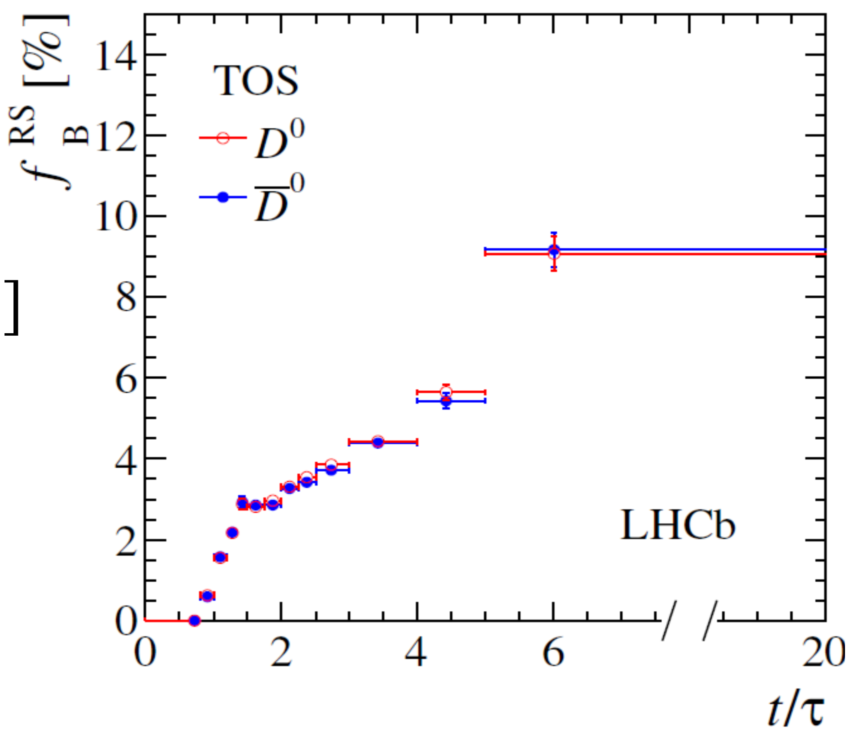
- D^0-s from B decays are assigned with wrong decay-time
- Suppressed with requirement on χ^2(IP)
- The fraction of this secondary component $f_B^{RS}(t)$ can induce bias $\Delta_B(t)$ in time-dependent WS/RS ratio. The bias is bounded by:

$$0 \le \Delta_B(t) \le f_B^{RS}(t)[1 - R_D / R(t)],$$

with observed ratio $R^m(t) = R(t)[1 - \Delta_B(t)]$

- Due to small level of contamination, we can simply assume the maximum bias
- No charge asymmetry observed, contamination assumed to be symmetric in the fit

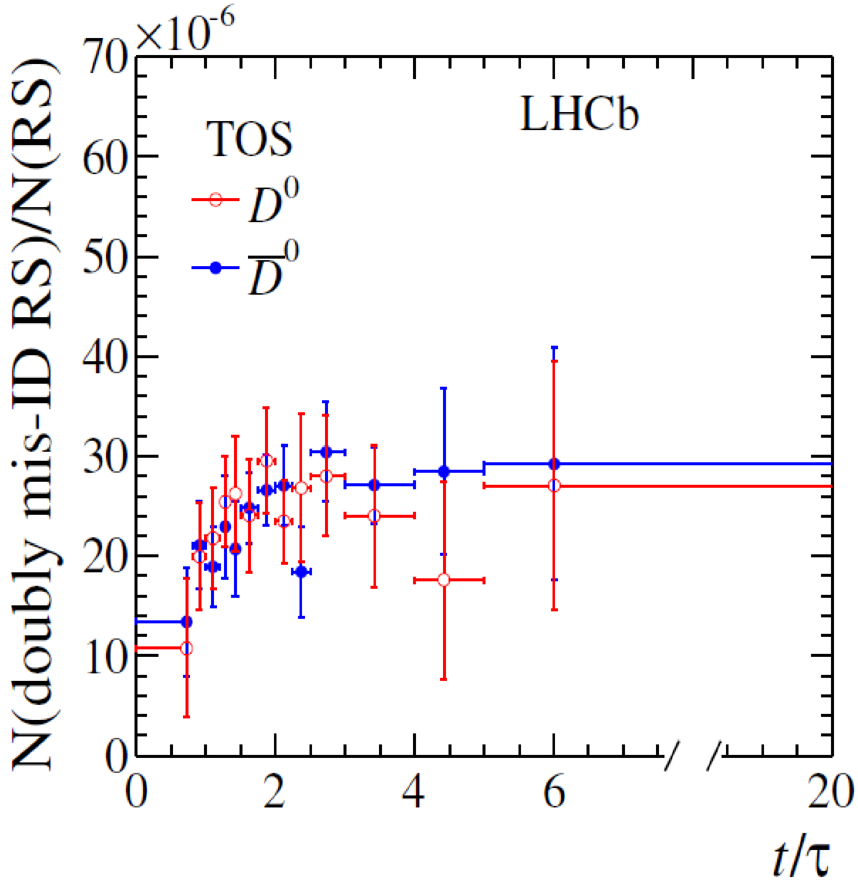




Peaking background

- RS events with both K and π being mis-IDed as each other will be indistinguishable with real WS signals in $m(D_0\pi_s)$ fits, and cause bias in the WS/RS ratio
- The overall effect is well below 1% of WS signals due to tight requirements on PID and M(Kπ) window
- No charge asymmetry observed, contamination assumed to be symmetric in the fit

$$R^m(t) = R(t) + \boxed{\frac{N^{RS}(\text{double mis-ID})}{N^{RS}}}$$



Time-dependent fit configuration

- The mixing parameters are determined by minimizing:

Predicted ratios corrected for the peaking and secondary backgrounds

$$\chi^2 = \sum_i \left[\left(\frac{r_i^+ - \epsilon_r^+ R_{i,\,\mathrm{pred}}^+}{\sigma_i^+} \right)^2 + \left(\frac{r_i^- - \epsilon_r^- R_{i,\,\mathrm{pred}}^-}{\sigma_i^-} \right)^2 \right] + \chi_\epsilon^2 + \chi_B^2 + \chi_p^2$$

Sum over 13 time bins for separately for 2011 and 2012 data, and for samples with different trigger requirements

$$\chi_\epsilon^2 = \left(\frac{a_{K\pi} - A_{K\pi}}{\sigma_{A_{K\pi}}} \right)^2$$

Constraint for detection asymmetry

$$\chi_p^2 = \sum_j \left(\frac{p_j - P_j}{\sigma_{P_j}} \right)^2$$

Constraint for peaking background:
Mainly candidates with K,π from D^0 both being mis-IDed, suppresed by tight PID requirements

$$\chi_B^2 = \sum_l \left(\frac{b_l - B_l}{\sigma_{B_l}} \right)^2$$

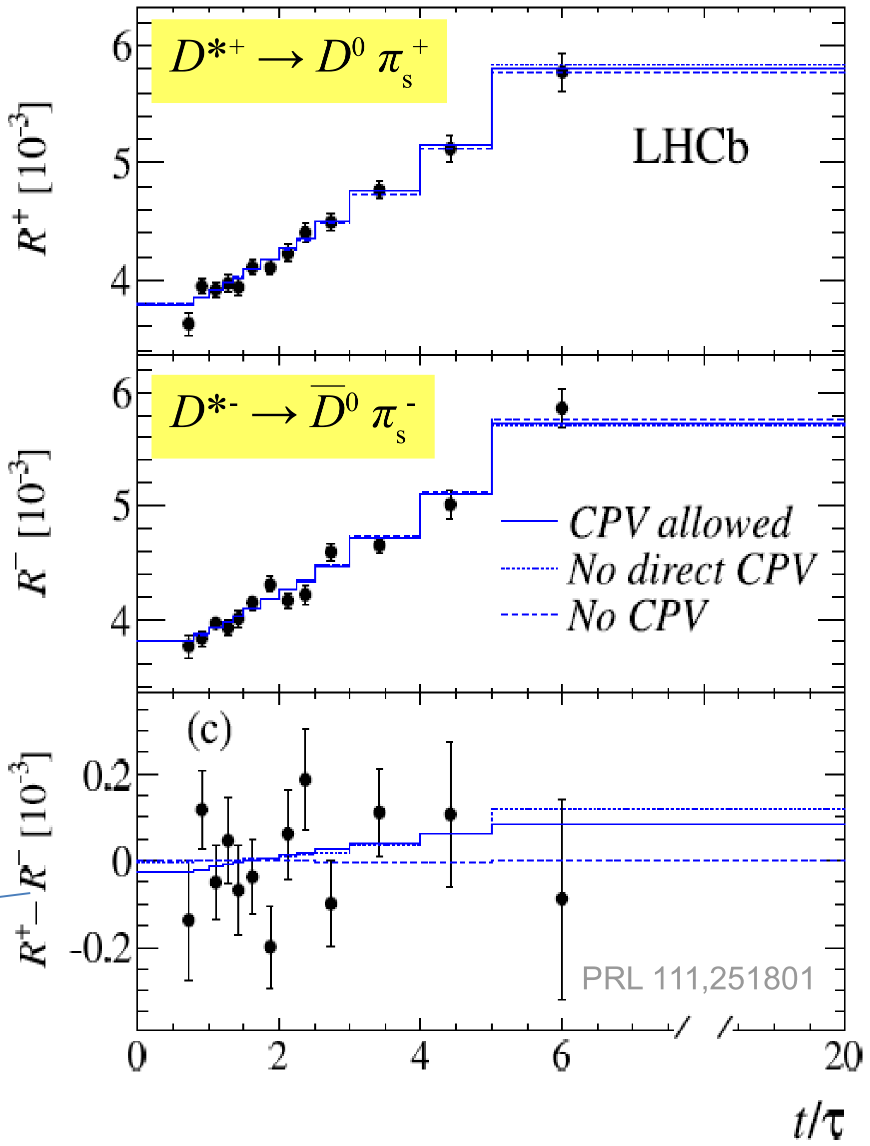
Constraint for secondary background

Systematic effects are accounted for in the final fits

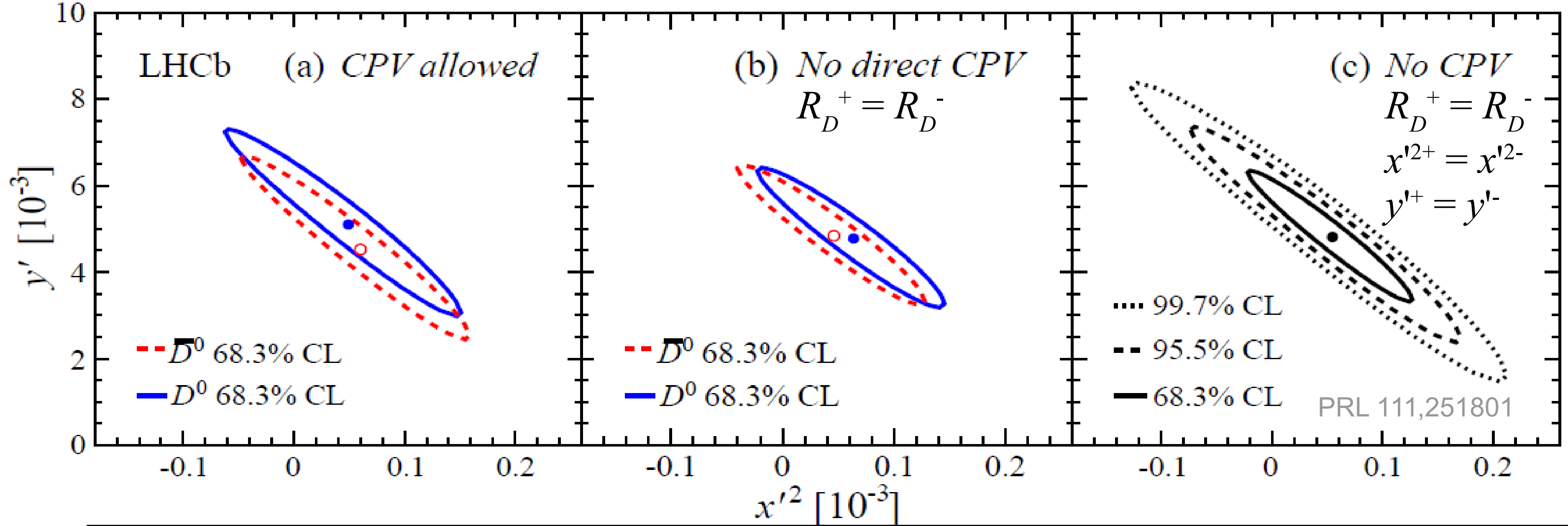
WS/RS yield ratio fits

- Fits to the $3fb^{-1}$ data for 3 different hypotheses on the CP symmetry

Efficiency corrected differences between the WS/RS ratios of $D^{*\pm}$



LHCb results



LHCb

Uncertainties are statistical and systematic combined

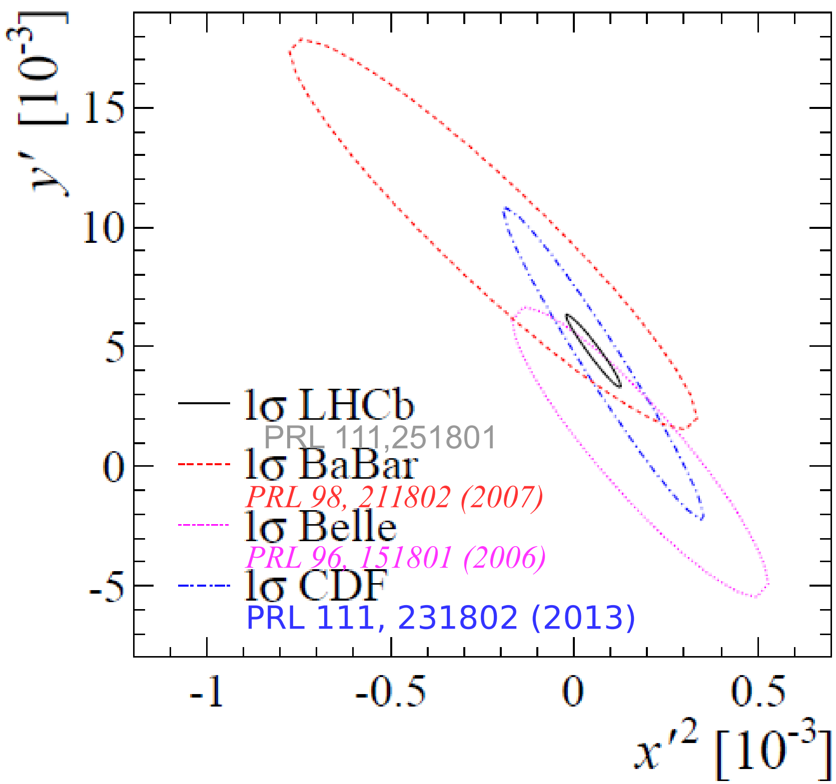
Direct and indirect CP violation			no direct CP violation			no CP violation		
R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066
A_D	$[10^{-2}]$	-0.7 ± 1.9	y'^+	$[10^{-3}]$	4.78 ± 1.07	y'	$[10^{-3}]$	4.81 ± 1.00
y'^+	$[10^{-3}]$	5.1 ± 1.4	x'^{2+}	$[10^{-5}]$	6.4 ± 5.5	x'^2	$[10^{-5}]$	5.5 ± 4.9
x'^{2+}	$[10^{-5}]$	4.9 ± 7.0	y'^-	$[10^{-3}]$	4.83 ± 1.07	χ^2/ndf		$86.41/101$
y'^-	$[10^{-3}]$	4.5 ± 1.4	x'^{2-}	$[10^{-5}]$	4.6 ± 5.5			
x'^{2-}	$[10^{-5}]$	6.0 ± 6.8	χ^2/ndf		$85.99/99$			
χ^2/ndf		$85.87/98$						

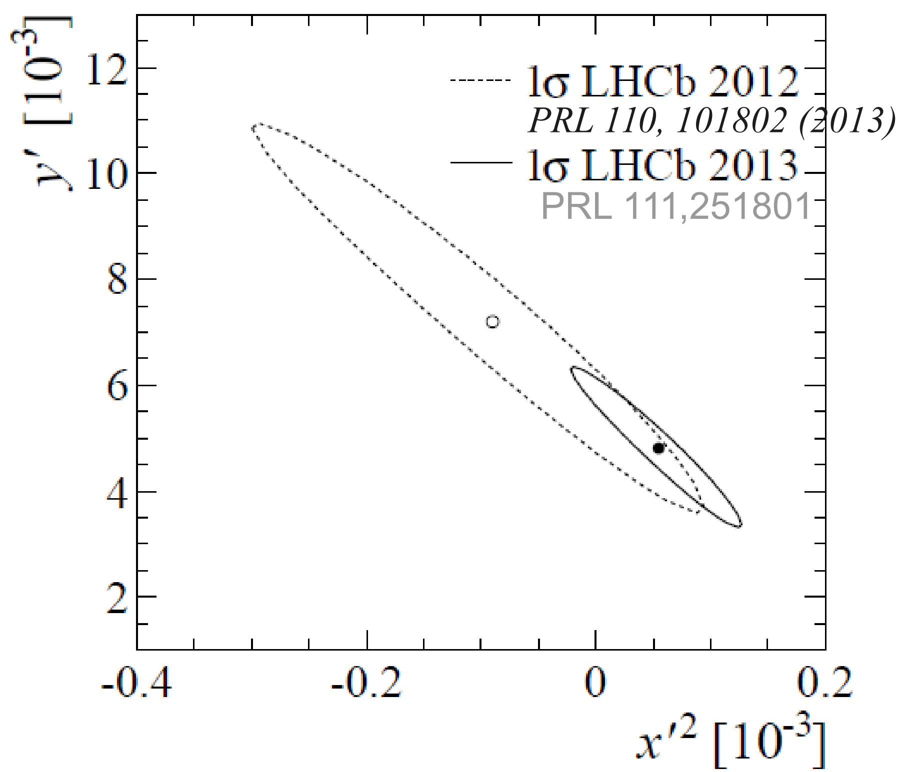
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

Results are consistent with *CP* conservation

Comparison of mixing results

- The current LHCb results are consistent with other results, and provide an update to the previous ones with 1fb^{-1} 2011 data





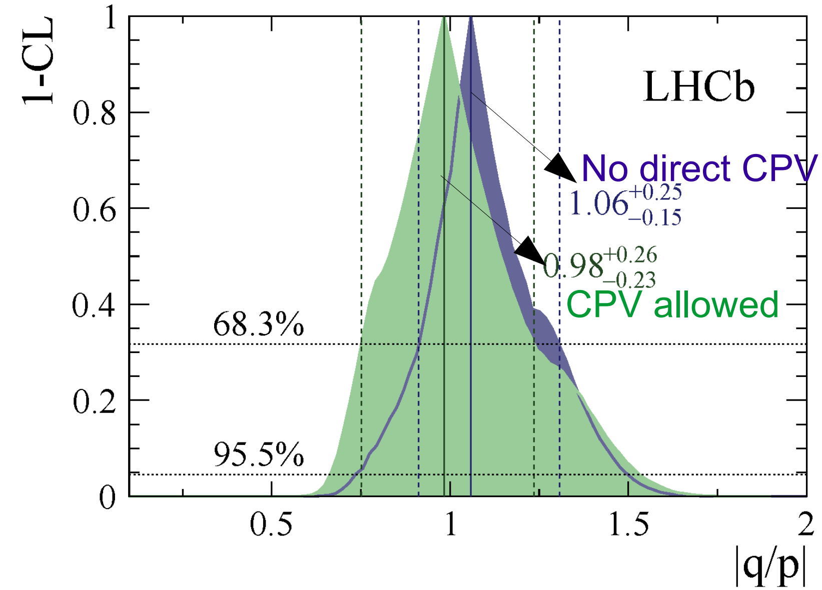
Interpretation of the LHCb results

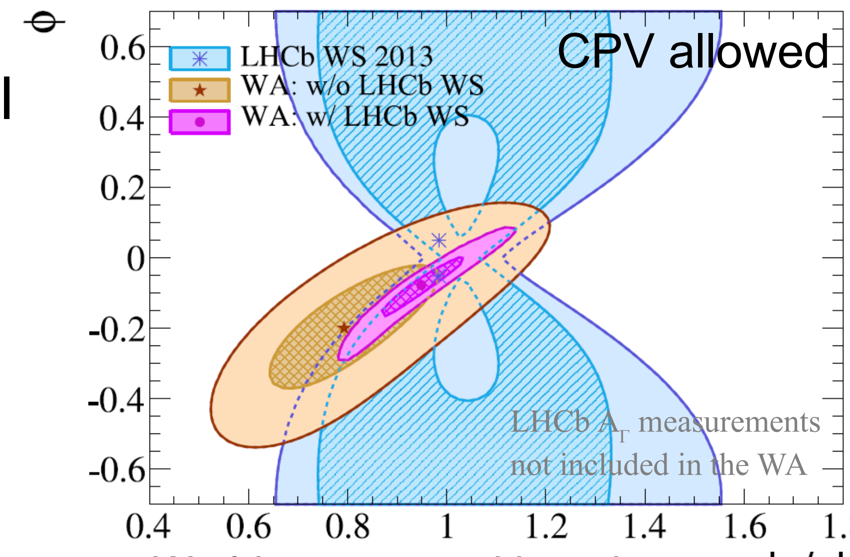
- Using only the LHCb results, and with the constraints of:

$$x'^{\pm} = (|q/p|)^{\pm 1} (x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = (|q/p|)^{\pm 1} (y' \cos\phi \mp x' \sin\phi)$$

$$\boxed{\phi = \arg\left(\frac{q}{p}\right)}$$

- The 68.3% C.L. constraints
  - 0.75 < |q/p| < 1.24 for all CPV allowed
  - 0.91 < |q/p| < 1.31 for the case without direct CPV
- The LHCb results contribute in the global fits for $D^0 - \overline{D}^0$ mixing

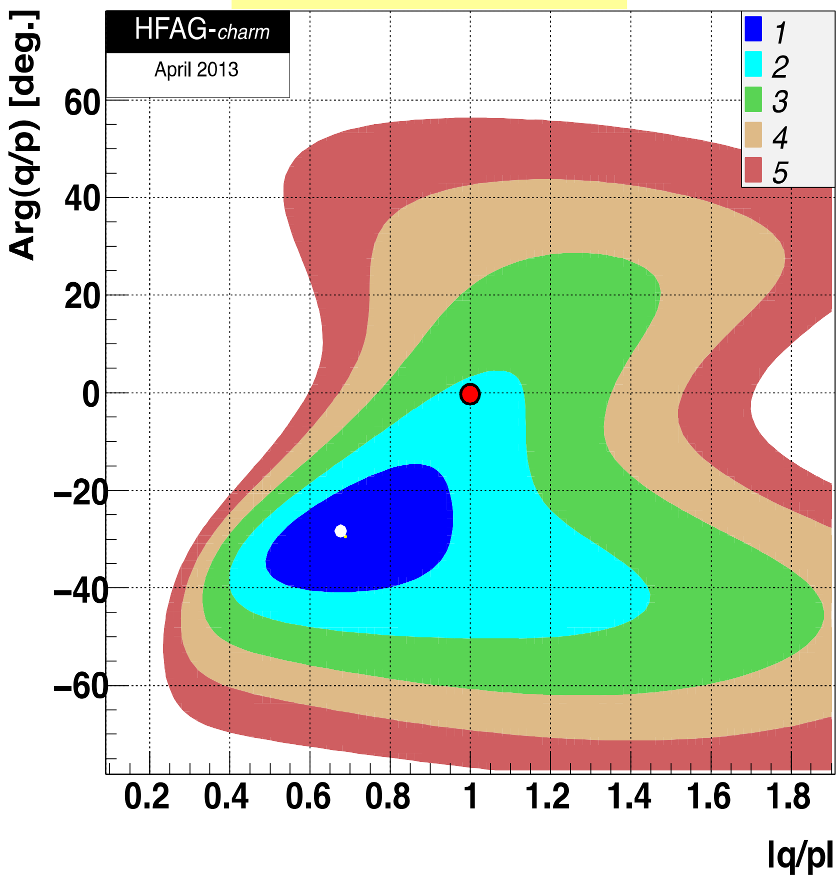




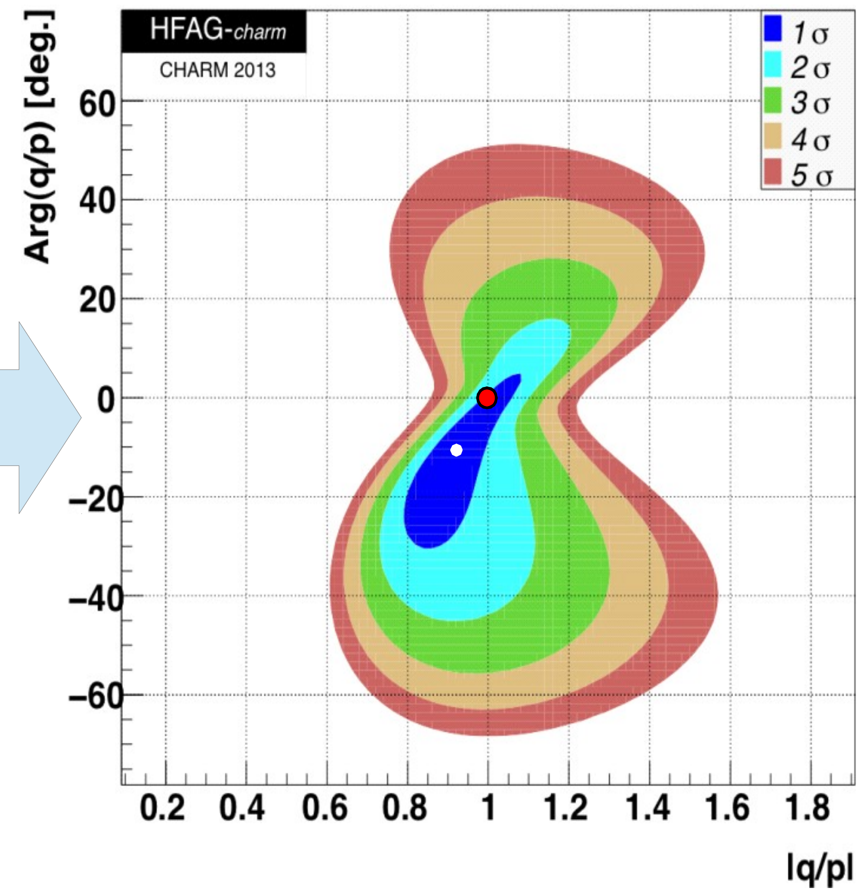
World averages with and without the LHCb results

Global Fit for D^0 - $\overline{D}^0$ Mixing (allowing for CP violation)

April, 2013



September, 2013



Much improved constraints on |q/p| and φ after the inclusion of the most recent LHCb D mixing/CPV results and CDF D mixing results, as well as the LHCb A_Γ results (*PRL 112 (2014) 041801*)

Summary

- Based on the full BABAR dataset, the decay rates and asymmetries for $B \rightarrow K^{(*)}l^+l^-$ are measured, and agree with the SM
- Also with the full BABAR dataset, the inclusive $B \rightarrow X_s\ l^+l^-$ decay rates and direct CP asymmetry are found to be consistent with the SM
- With the full Run1 LHCb data, the D0 – D0 mixing parameters are measured and CP violation is searched using $D \rightarrow K^+\pi^-$ decays
- Ongoing work on time-dependent amplitude analysis of $D^0 \rightarrow \pi^+\pi^-\pi^0$ and D^{*+} - D^+ mass difference measurement using $D^{*+} \rightarrow D^+\pi^0$ based on the full BABAR dataset

Thanks !