Implications of charge asymmetry in the B_s System

July 6, 2011

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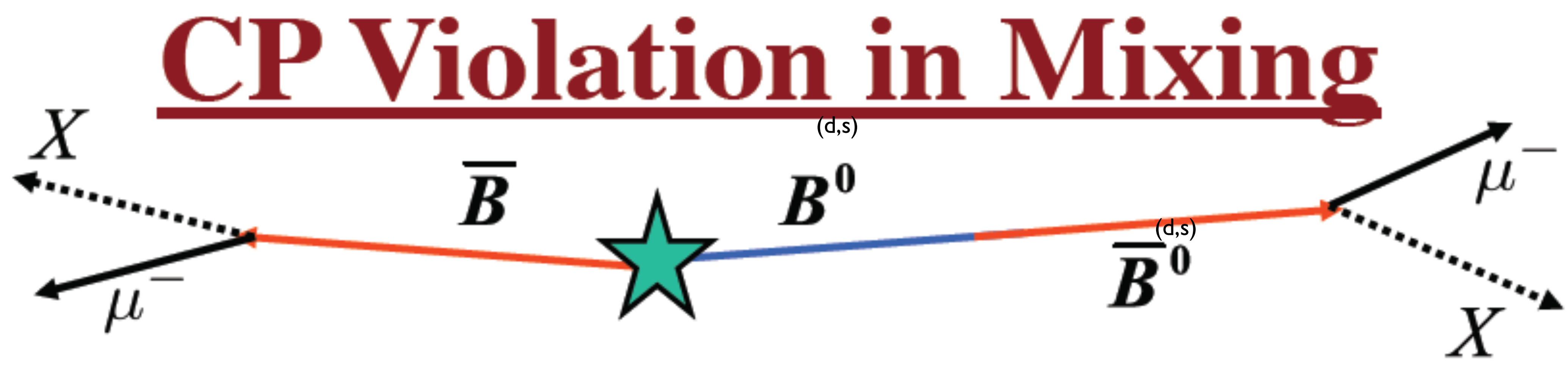
OUTLINE

- ➡ reviewing the situation:
  - ➡ recent DØ
  - ➡ upcoming LHCb
  - ➡ SM theory
- ➡ BSM theory expectations:
  - ➡ new physics in B_s mixing
  - ➡ new physics in B decay

Experiment update

“Evidence for an anomalous like sign dimuon charge asymmetry”
the DØ collaboration, arXiv:1005.2757 *6.1 fb^{-1}*

“Measurement of the anomalous like-sign dimuon charge asymmetry with 9 fb^{-1} of $p\bar{p}$ collisions”, arXiv:1106.6308



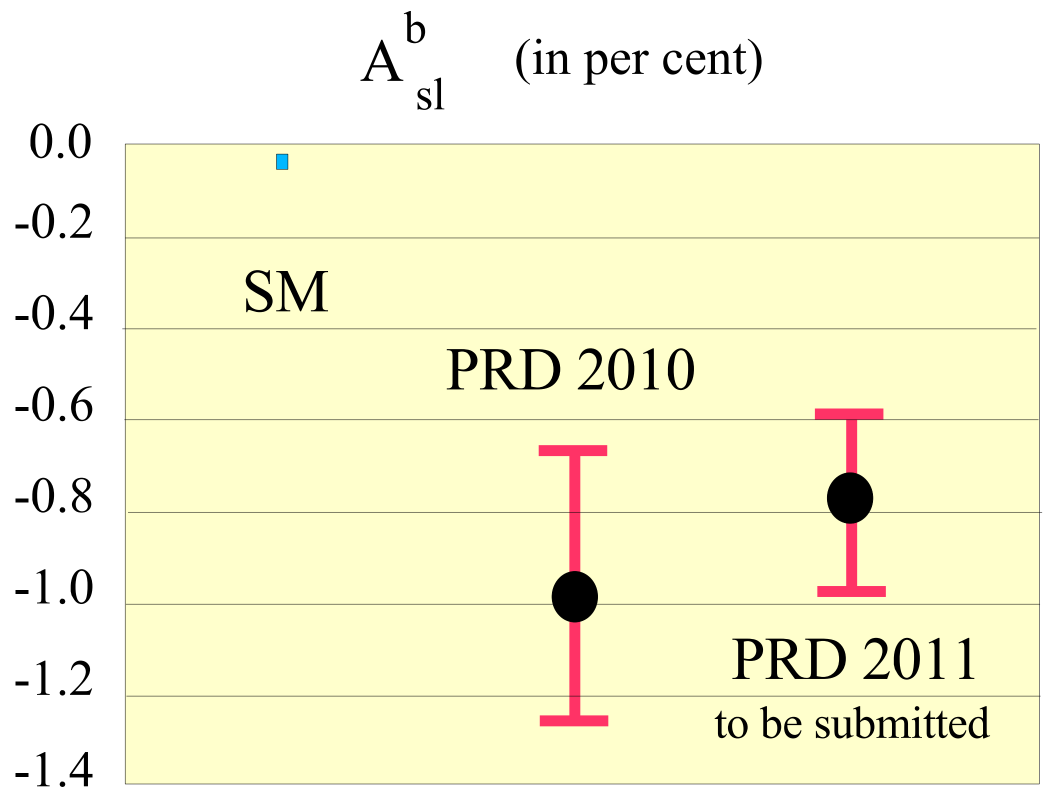
$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

“wrong sign” B decay
from oscillation
gives like sign dimuon

➡ D∅: $A^b_{sl} = (-0.00787 \pm 0.00172 \text{ (stat)} \pm 0.00093 \text{ (syst)})$

➡ differs by 3.9σ from $A^b_{sl}(SM) = -0.00028 \pm 0.00005$

Comparison with last year



from Bruce Hoeneisen
representing the
DØ Collaboration
Fermilab, 30 June 2011

Comparison of measurements of A^b_{sl}.

28

Improvements (since Phys. Rev. D 82, 032001, (2010))

- To increase the number of events, the $|p_z|$ cut is lowered from 6.4 GeV to 5.4 GeV.

- To lower the $K \to \mu$ and $\pi \to \mu$ backgrounds, the χ^2 of the match of track parameters obtained with the central detector and outer muon system is reduced from 40 to 12 (with 4 d.o.f.).

- The measurement of f_K is improved: $K_S \to \pi\pi \to \mu$ (muon required for same sample composition as $K \to \mu$).

- The measurement of $R_K \equiv F_K/f_K$ is done in two independent channels: $K^{*0} \to \pi^- K^+ \to \mu^+ X$ (with the null-fit method), and the new channel $K_S \to \pi\pi \to \mu$.

- The data set is increased from 6.1 fb^{-1} to 9.0 fb^{-1}.

from Bruce Hoeneisen
representing the
DØ Collaboration
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2. Results with 9.0 fb^{-1}

- From 1 μ (2.041×10^9 muons):
  $A^b_{\text{sl}} = (-1.04 \pm 1.30\ (\text{stat}) \pm 2.31\ (\text{syst}))\ \%$.

- From 2 μ (6.019×10^6 like-sign dimuons):
  $A^b_{\text{sl}} = (-0.808 \pm 0.202\ (\text{stat}) \pm 0.222\ (\text{syst}))\ \%$.

- $A^b_{\text{sl}} = (-0.787 \pm 0.172\ (\text{stat}) \pm 0.093\ (\text{syst}))\ \%$.
  This measurement disagrees with the prediction of the Standard Model by 3.9 standard deviations.

- The charge asymmetry of like-sign dimuon events after subtracting all background contributions from the raw charge asymmetry is:

$$\begin{aligned} A_{\text{res}} &\equiv (A - \alpha a) - (A_{\text{bkg}} - \alpha a_{\text{bkg}}) \\ &= (-0.246 \pm 0.052\ (\text{stat}) \pm 0.021\ (\text{syst}))\%. \end{aligned}$$

  This quantity does not depend on the interpretation in terms of the charge asymmetry of semileptonic decays of B mesons. This measurement disagrees with the prediction of the Standard Model by 4.2 standard deviations.

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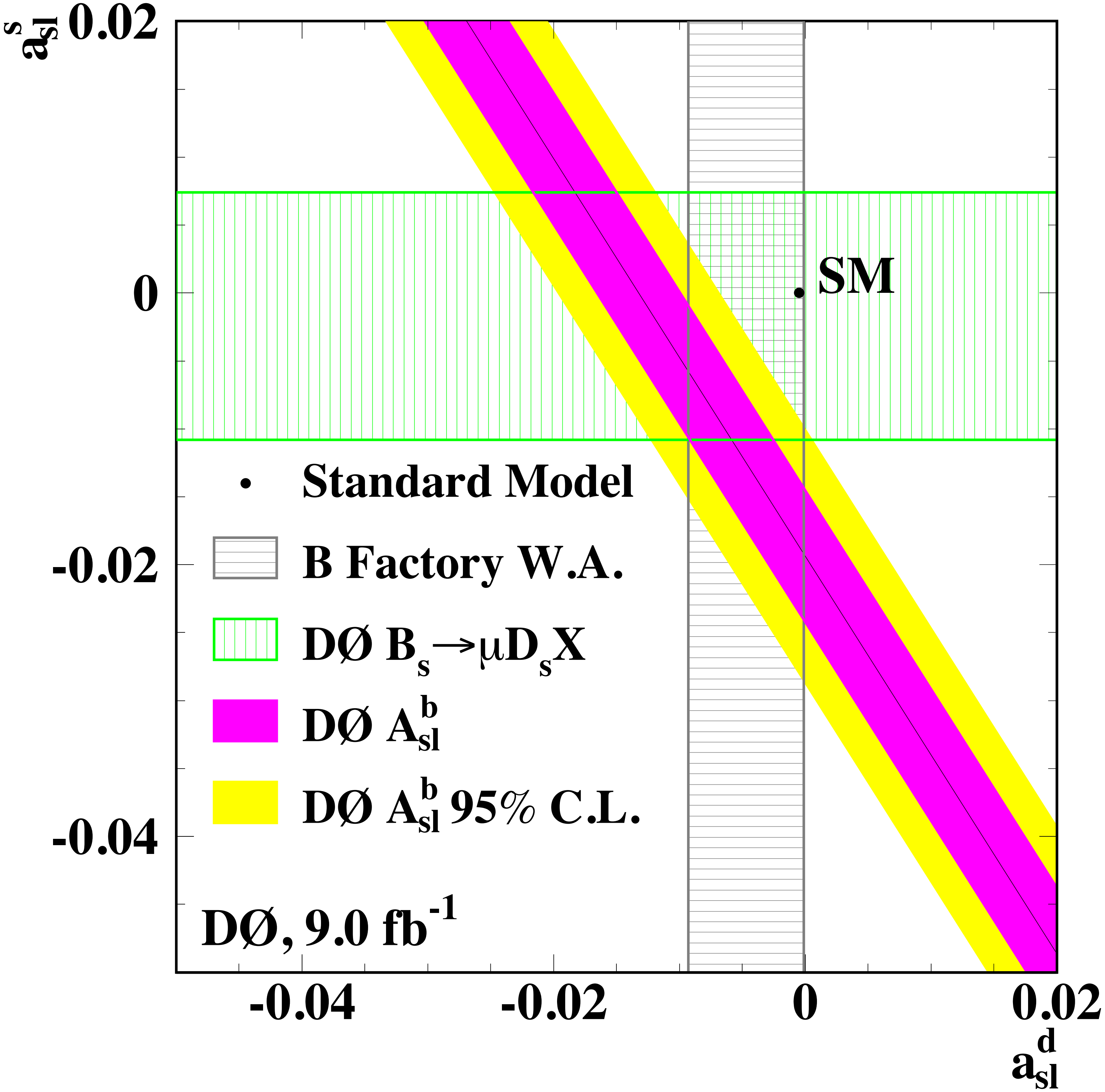

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8

4. Dependence on the impact parameter

Additional measurements are made applying an impact parameter (*IP*) cut on each muon.

IP is the distance of closest approach of the muon track to the primary vertex projected onto the plane transverse to the $p\bar{p}$ beams.

The dependence of $A^b_{\mathrm{sl}} = C_d a^d_{\mathrm{sl}} + C_s a^s_{\mathrm{sl}}$ on *IP* can reveal the origin of the asymmetry because C_d and C_s depend on *IP*.

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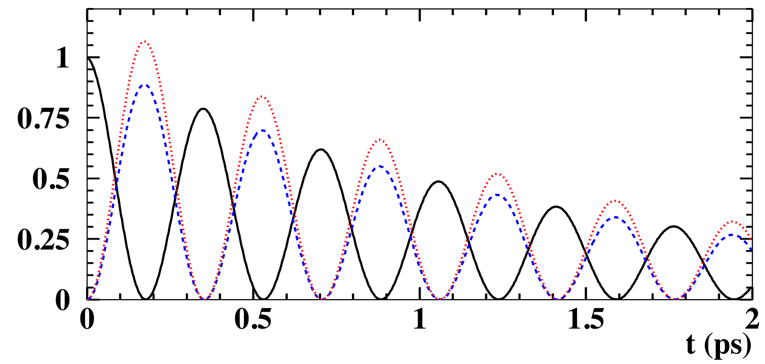

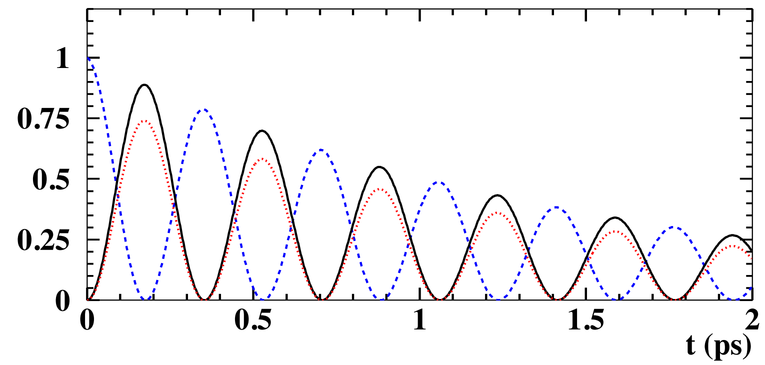

Top: Histogram of proper time of decays $B_s^0 \to \mu^+ X$ (continuous line),
$B_s^0 \to \bar{B}_s^0 \to \mu^- X$ (dashed line if no CP violation, dotted red line if CP violation).
Bottom: The same for $\bar{B}_s^0$ at $t = 0$.

36

from Bruce Hoeneisen
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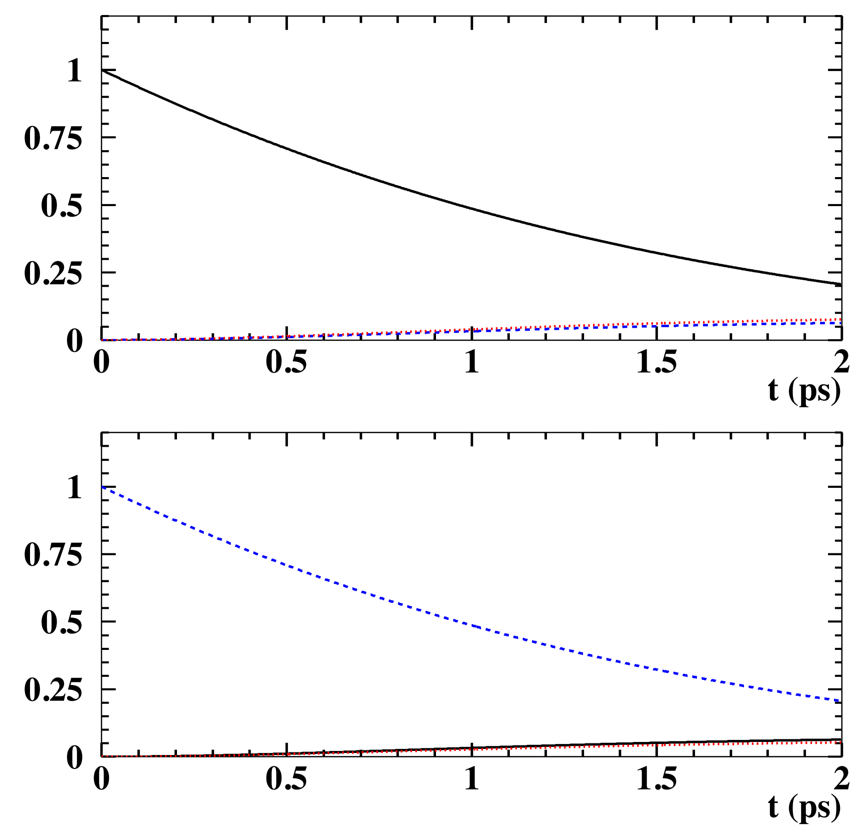

Same for B_d^0 (top) and $\bar{B}_d^0$ (bottom) at $t = 0$. Applying an IP cut can enrich the sample in oscillating B_d^0's (shown in red).

37

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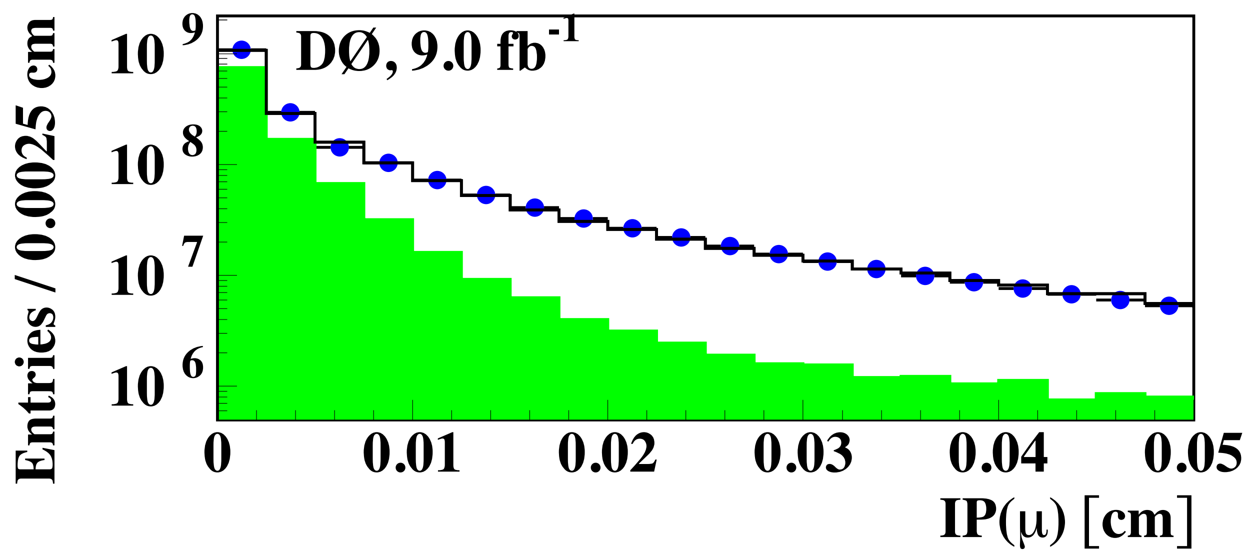

The muon impact parameter (*IP*) distribution in the inclusive muon sample (dots). The solid line represents the muon *IP* distribution in simulation. The shaded histogram is the contribution from K, π and p background muons in simulation.

38

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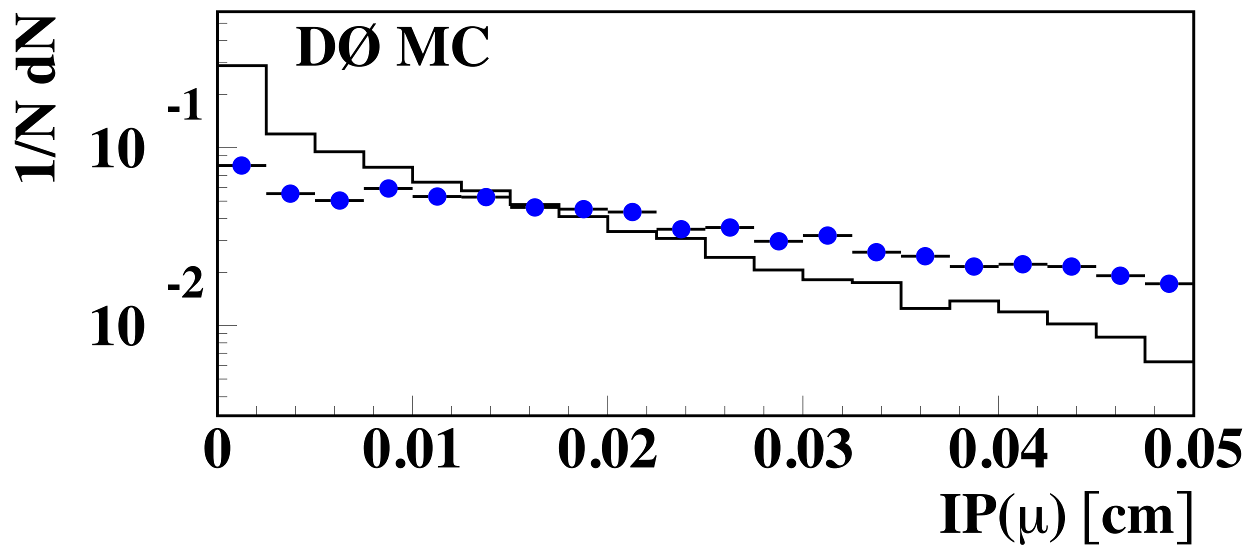

The normalized impact parameter (IP) distribution for muons produced in oscillating decays of B_d^0 mesons (dots) and B_s^0 mesons (solid histogram) in simulation.

39

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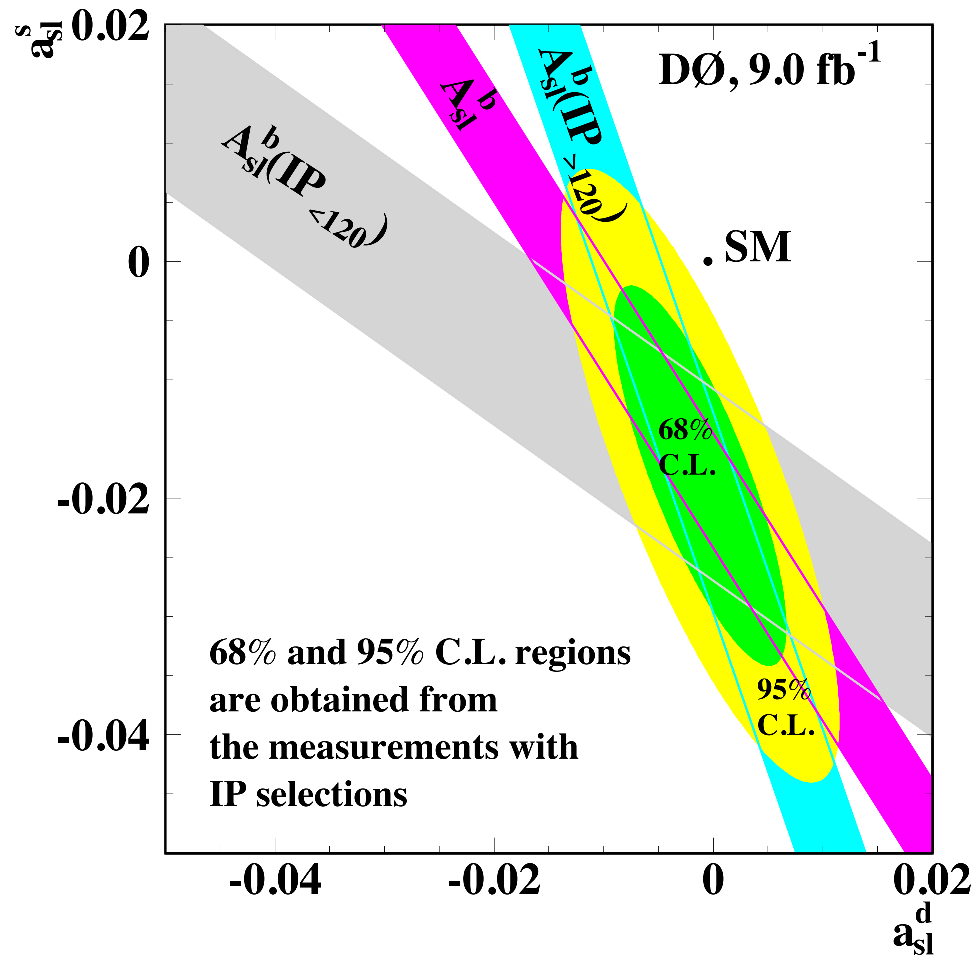

Measurements of $A^b_{\rm sl}$ with $IP > 120\mu$m and $IP < 120\mu$m, and corresponding 68% and 95% confidence level regions in the $(a^d_{\rm sl}, a^s_{\rm sl})$ plane. Also shown is the measurement with no IP cut.

from Bruce Hoeneisen
representing the
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upcoming: LHCb

LHCb and leptonic charge asymmetry

Flavour specific asymmetry: a_{fs}

- D0 charge asymmetry measurement, using bb→μμX event

$$A^b = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (0.494)a_{fs}^s + (0.506)a_{fs}^d$$

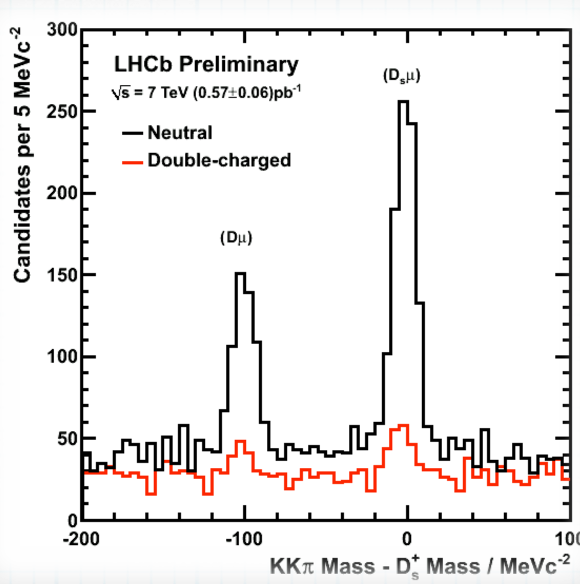
$$a_{fs}^s = \frac{\Delta\Gamma^s}{\Delta M^s} \tan\phi_s$$

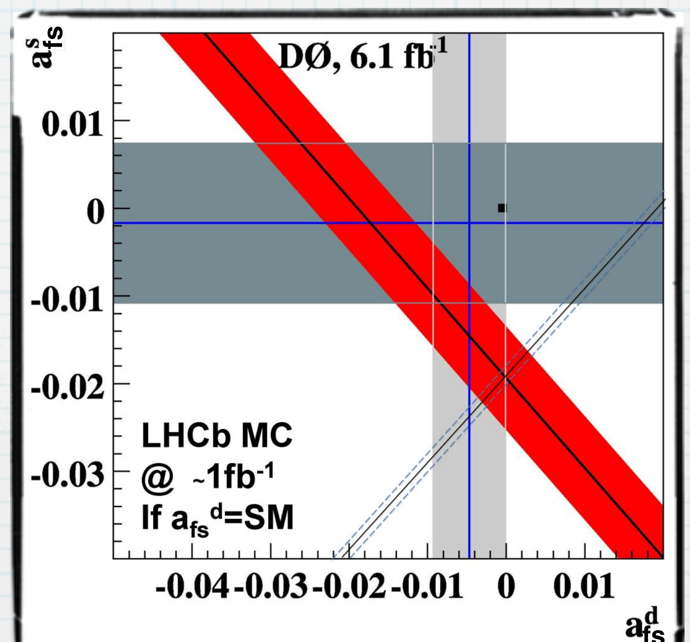
$$A_{fs}^q(t) = \frac{\Gamma(f)-\Gamma(\bar{f})}{\Gamma(f)+\Gamma(\bar{f})}$$

- LHCb plans to measure exclusive rates $B_{(q)} \to D_{(q)}\mu\nu$ in pp
- Ignore time dependent part to remove production asym (~10^{-2})
- Compute the difference in the Asymmetry between B_s, B^0 to remove detector asymmetries (~10^{-2})

KKπ-Ds mass

0.57 pb-1



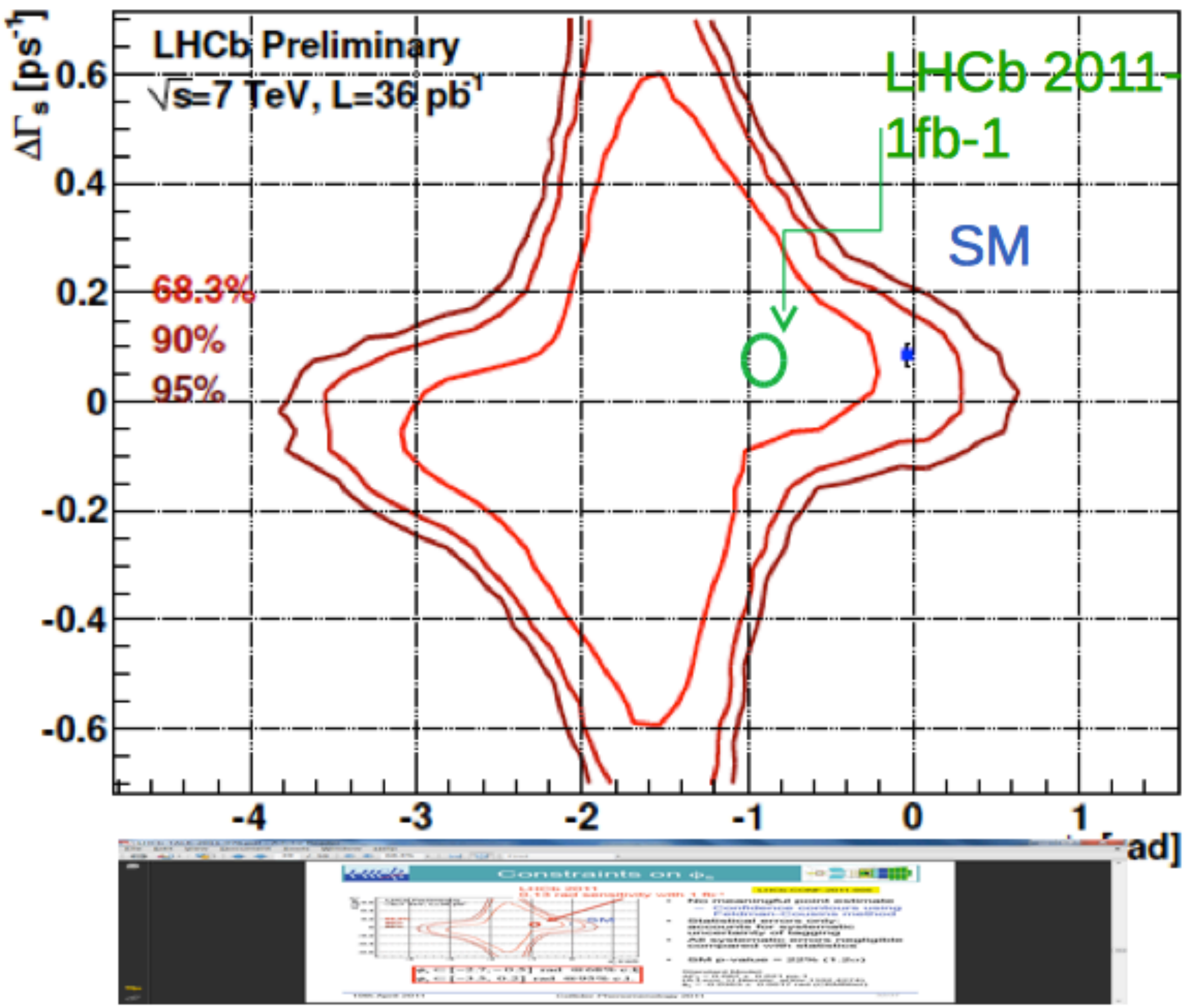


LHCb stats precision only

14

from José Ángel Hernando Morata 2010 talk

Flavour Tagged ϕs

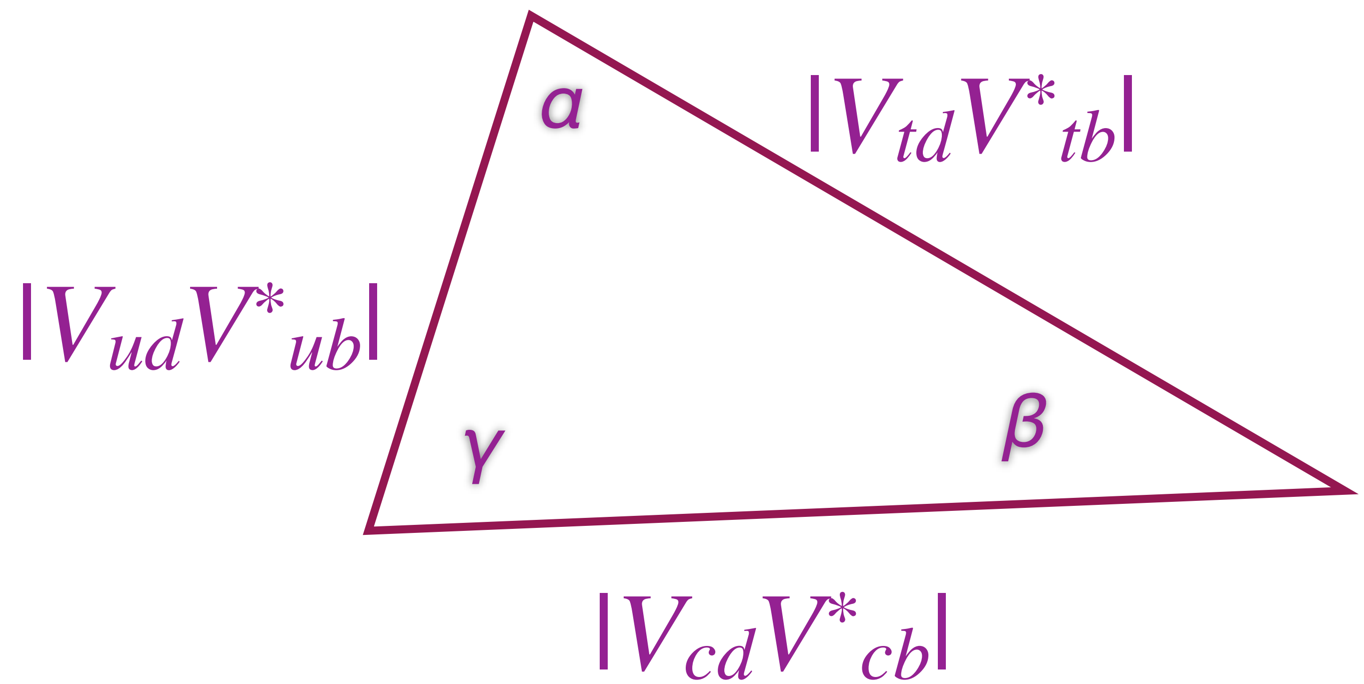


Flavour tagged fit to mass, time, and angular distributio

SM Theory

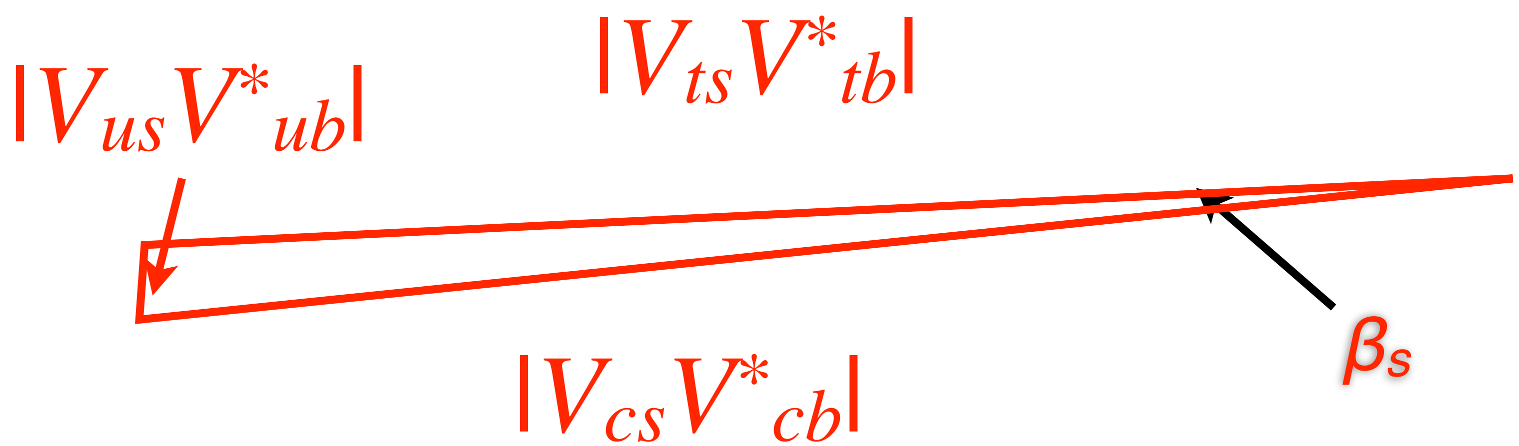
CKM parameters

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



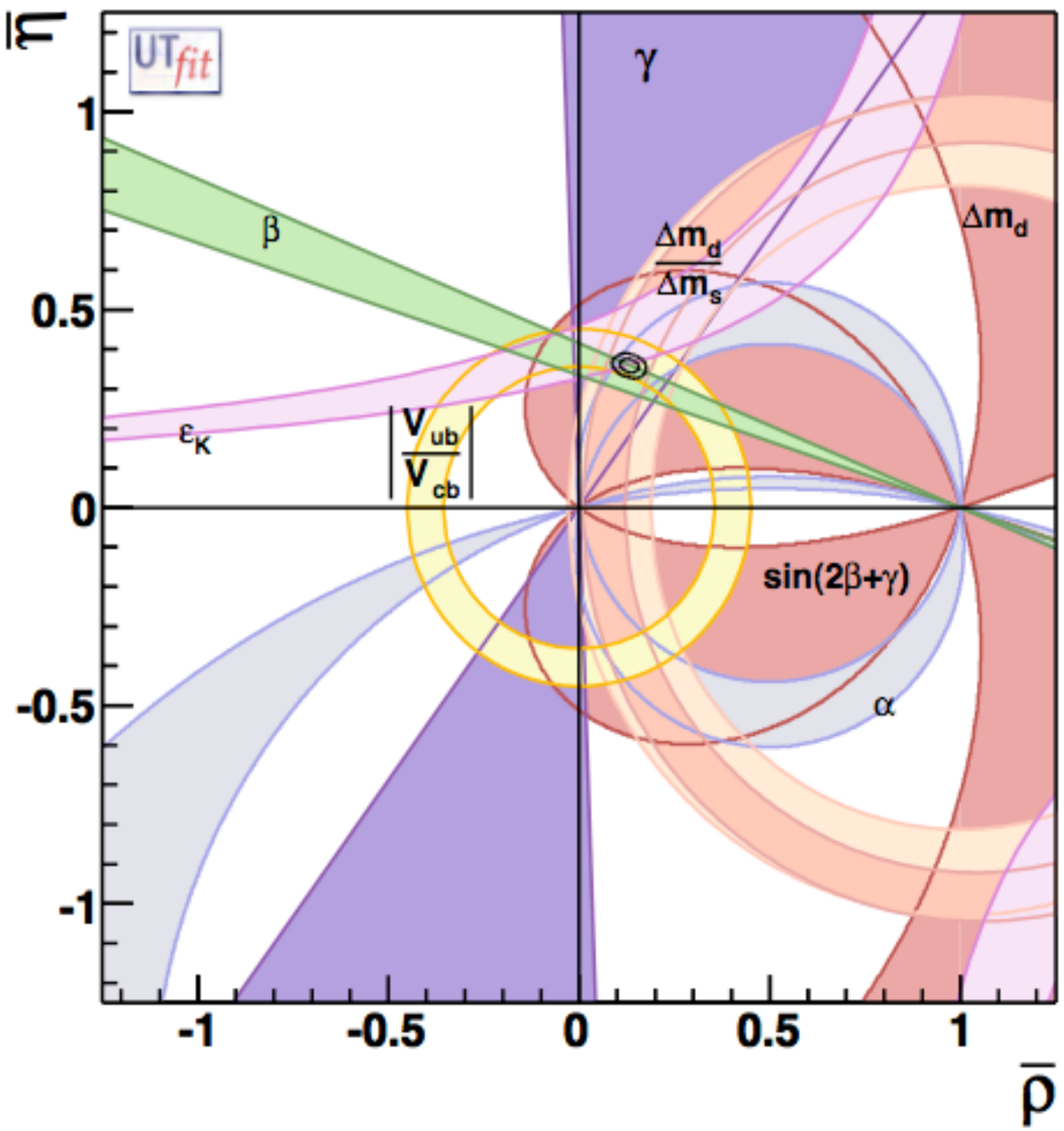
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

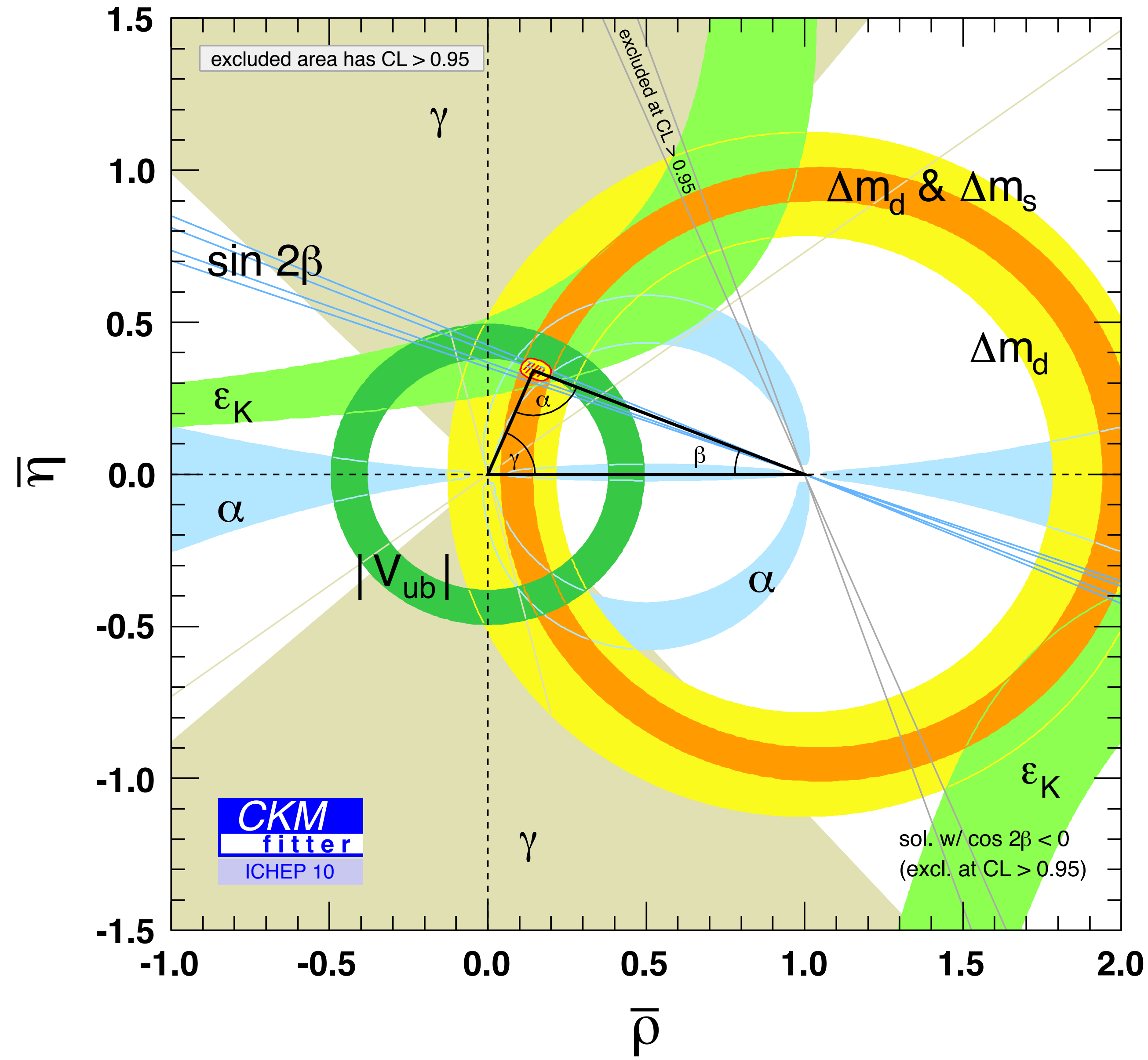
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



$$\beta_s \equiv \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \approx 0$$

The Dreaded Unitarity Triangle





Status of SM CKM parameters from CPV in B_d mixing etc. CPV in interference between mixing and decay of B_d appears to be mostly (entirely?) from SM

20

Mixing Basics

$$i\frac{d}{dt}\begin{pmatrix}|B_q\rangle\\|\bar{B}_q\rangle\end{pmatrix}=\begin{pmatrix}m^q-\frac{i\Gamma^q}{2} & m_{12}^q-\frac{i\Gamma_{12}^q}{2}\\ m_{12}^{q*}-\frac{i\Gamma_{12}^{q*}}{2} & m^q-\frac{i\Gamma^q}{2}\end{pmatrix}\begin{pmatrix}|B_q\rangle\\|\bar{B}_q\rangle\end{pmatrix}$$

$$\phi_q\equiv arg\left(\frac{-m_{12}^q}{\Gamma_{12}^q}\right)$$

➡ Charge asymmetry ⇒$\Gamma(B\to\bar{B})\neq\Gamma(\bar{B}\to B)$⇒ $\phi_q\neq 0$

$$\left|m_{12}^q-\frac{i\Gamma_{12}^q}{2}\right|\neq\left|m_{12}^{q*}-\frac{i\Gamma_{12}^{q*}}{2}\right|$$

Note: $|\Gamma_{12}^q|\ll|m_{12}^q|$ in $B_{d,s}$ systems $\Delta m_q=2|m_{12}^q|$

dimuon asymmetry from B_s or B_d mixing?

➡impact parameter analysis favors B_s

➡$B_{d,}$ FCNC in b↔d more constrained from B-factories

➡ New contribution to B_s also hinted at from $B \to J/\psi\Phi$ time dependent CPV asymmetry

➡theory can be massaged to favor sizable (relative to SM) new contribution to B_s mixing with smaller (relative to SM) contribution to B_d mixing

New Physics vs SM backgrounds

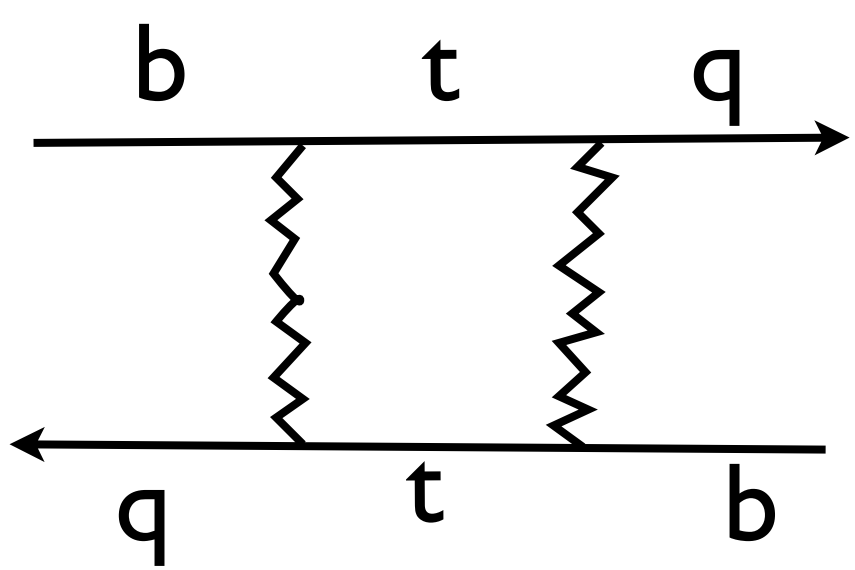
- ➡ QCD uncertainty?
  - ➡ QCD is CP symmetric (strong CPV negligible)
  - ➡ Wolfenstein parametrization: selects basis most suitable for understanding where CPV is O(1)

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}.$$

- ➡ unsuppressed CPV only in processes dominated by V_{td} and/or V_{ub}
  - ➡ e.g $B_d \bar{B}_d$ mixing, not $B_s \bar{B}_s$ mixing

SM predicts tiny semi-leptonic asymmetry in $B_{d,s}$

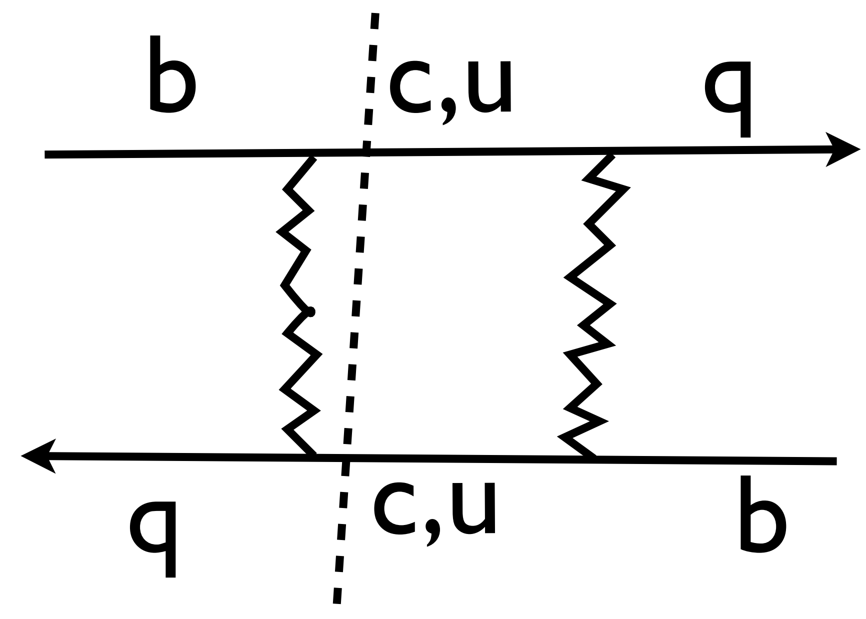
leading $m_{12}^q \propto (V_{tb}V_{tq}^*)^2$



enhancement of mass mixing by heavy top

$|\Gamma_{12}^q| \ll |m_{12}^q|$

leading$\Gamma_{12}^q \propto (V_{cb}V_{cq}^* + V_{ub}V_{uq}^*)^2$

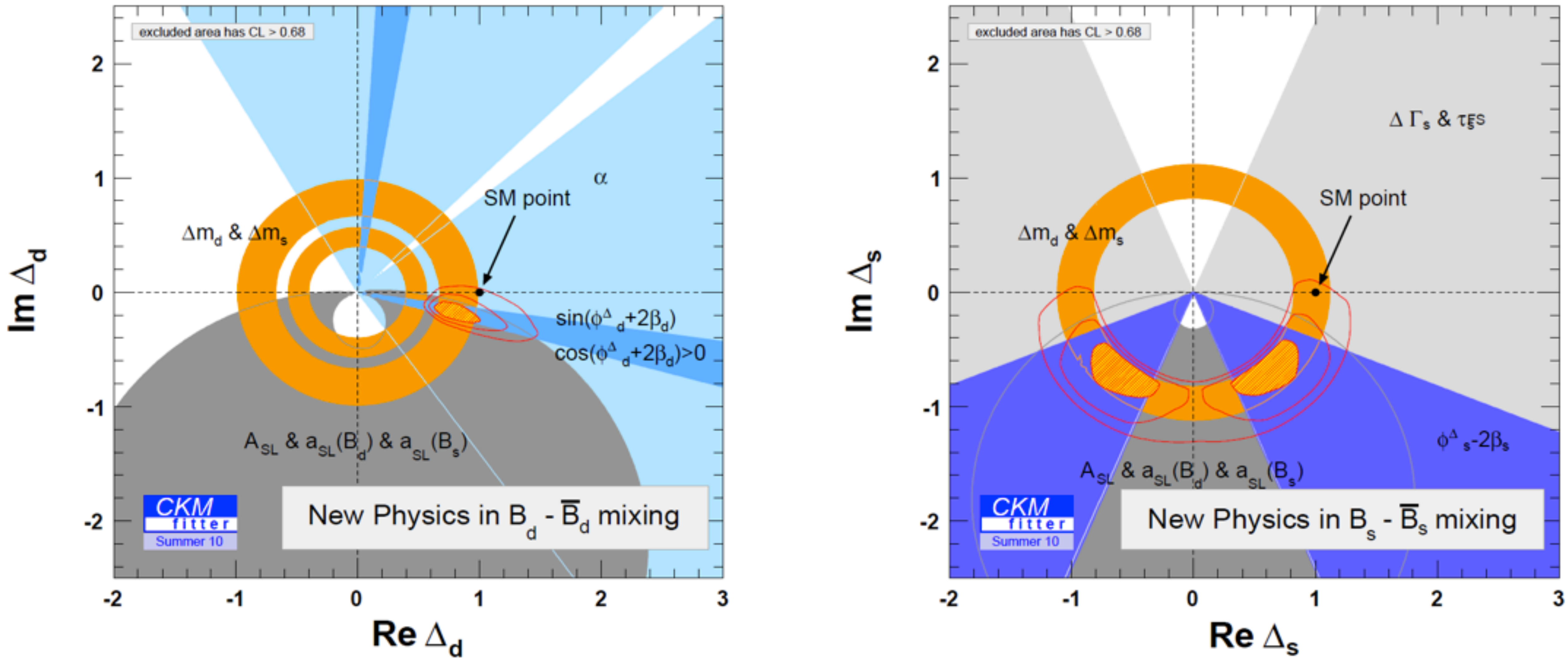


CKM unitarity + heavy b quark

$\phi^q \approx 0$

New physics in $B_{d,s}$ mass mixing?

Still room (indication?) for new CPV physics in mixing



$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q,SM}}, \qquad \Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}.$$

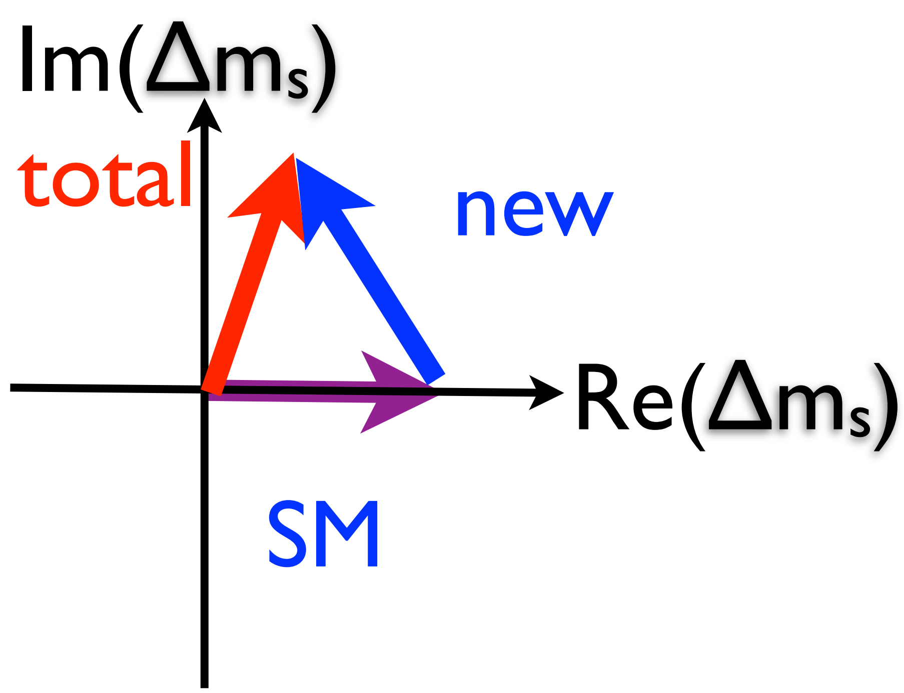
New physics in $\Delta m_{d,s}$?

➡ need a large order one new phase for dimuon asymmetry

➡ Don't want to change magnitude of $|\Delta m_s|$, $|\Delta m_d|$, $|\Delta m_s/\Delta m_d|$ by more than 10-20% of SM

➡ Dont want to change phase of Δm_d by more than 10-20% or lose B factory CKM fit to phase

➡ want order one change of phase of Δm_s without large change of magnitude



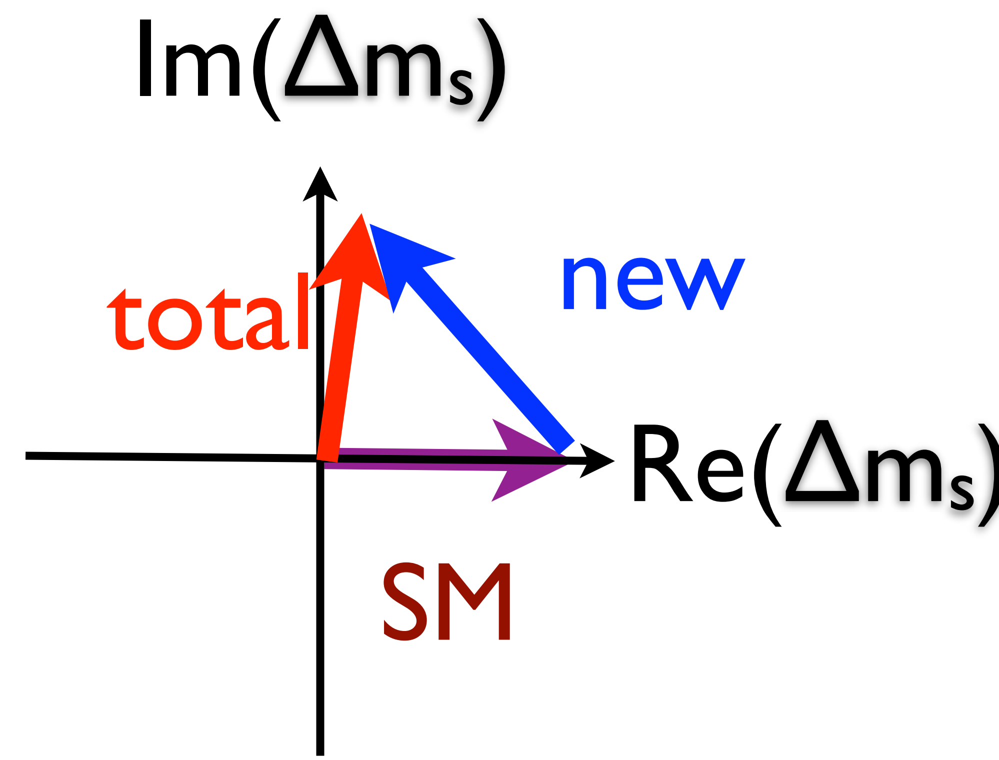
challenges for charge asymmetry via Δm_s

➡ Conspiracy to avoid large nonstandard magnitude

➡ Γ_{12}(SM) on small side, charge asymmetry prefers $\sin\phi_s > 1$

➡ Width problem: $\Delta\Gamma_s = \Delta\Gamma(SM) \cos\phi_s$

- $\Delta\Gamma(SM)$ $= 0.098 \pm 0.024\ ps^{-1}$
- $\Delta\Gamma_s(expt)$ $= 0.134 \pm 0.039 ps^{-1}$



expt preference for large $\cos\phi_s$ and large $\sin\phi_s$

Standard Model Flavor Physics:

new FCNC in $b \leftrightarrow s$ versus experiment

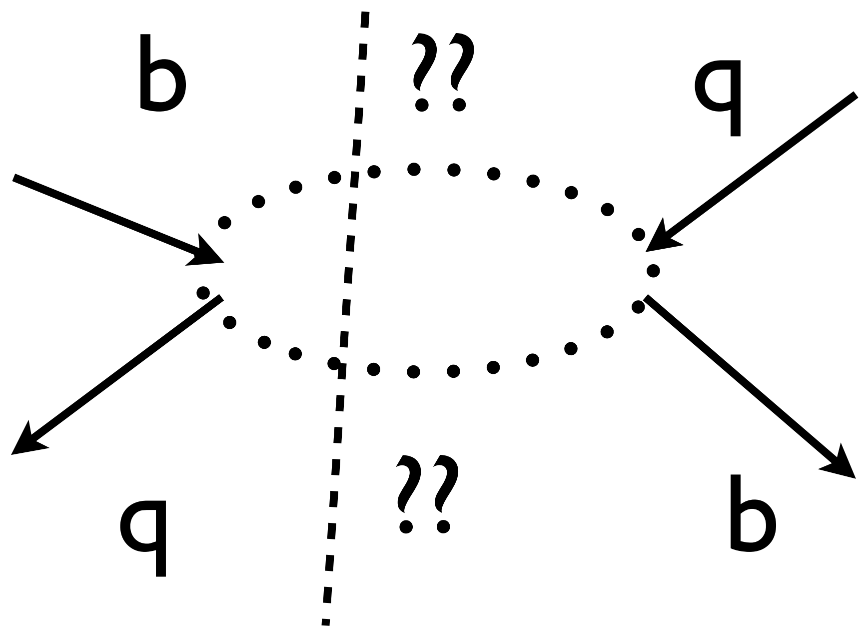
SM Theory	Current Experiment
$\Delta m_s \approx 19.6 \pm 2.2\ \mathrm{ps}^{-1}$	$\Delta m_s \approx 17.77 \pm 0.12\ \mathrm{ps}^{-1}$
$Br(B_s \to \mu^+\mu^-) \approx 3.6 \times 10^{-9}$	$Br(B_s \to \mu^+\mu^-) < 4.3 \times 10^{-8}$
$Br(B \to X_s\gamma) \approx 3.2 \pm 0.2 \times 10^{-4}$	$Br(B \to X_s\gamma) \approx 3.4 \pm 0.3 \times 10^{-4}$

Other than that...

- ➡ Clear sailing for model builders!
  - ➡ NP at TeV scale can compete with SM loops
  - ➡ similar (relative to CKM) NP contributions to B_d and B_s mixing allowed
  - ➡ must violate assumption that all CPV is in Yukawas or in spurions proportional to Yukawas (minimal flavor/CPV)
  - ➡ new flavor and/or CPV for third generation?

New physics in decay?

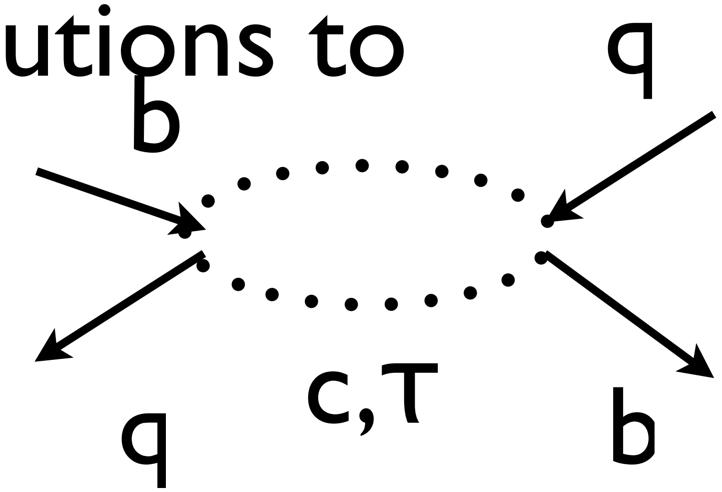
issues with new contribution to decay



➡ affects B branching fractions, requires new physics in decay comparable to SM tree

➡ Bauer and Dunn: largish new contributions to $B_s \to \tau^+\tau^-$, $c\,\bar{c}$ OK

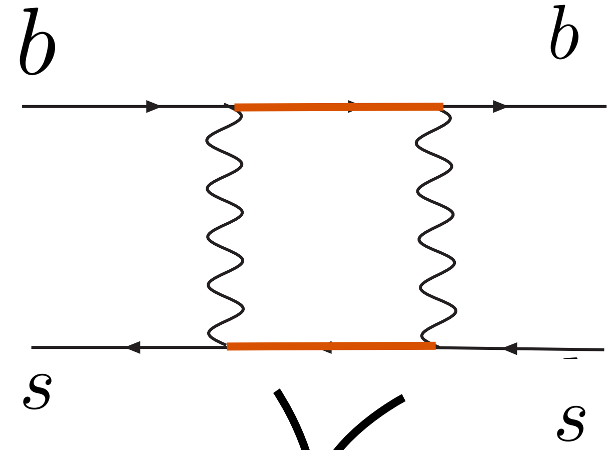
➡ potentially large contribution to Δm_s



New Physics in a^d_{SL}, a^s_{SL}

from Adam Martin
Seattle, June 8 2010

more on Γ_{12}

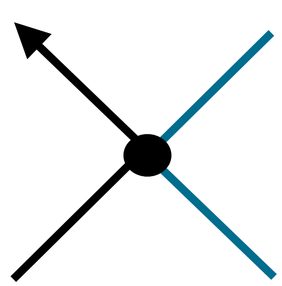
Im $\Big\{$  $\Big\}$

confusing, but rearrange slightly

so $\Gamma_{12}^{SM} \sim \Gamma_{\overline{B}\to XX} \sim \dfrac{G_F^2 f_B^2 M_B^3}{16\pi}$ from tree-level calculations

Meanwhile: $M_{12}^{SM} \sim \dfrac{G_F^2 M_W^2 f_B^2 M_B}{16\pi^2} \longrightarrow \dfrac{M_{12}^{SM}}{\Gamma_{12}^{SM}} \sim \Big(\dfrac{M_W^2}{\pi M_B^2}\Big)$

applied to new physics:

$\dfrac{1}{\Lambda^2}\Big($  $\Big)$ $\longrightarrow \dfrac{M_{12}^{NP}}{\Gamma_{12}^{NP}} \sim \Big(\dfrac{\Lambda^2}{\pi M_B^2}\Big)$

quickly generates large M_{12}

Our proposal for large contribution to Γ_{12}^{s}: a new light pseudoscalar?

- ζ Particle with coupling $$-\frac{1}{F}\,\partial_\mu\,\zeta\,\bar{b}\,\gamma^\mu\,(g_V^{bs} + g_A^{bs}\,\gamma_5)\,s$$
- familon?
- pseudoscalar 'Higgs' ?
- Hidden Valley?
- Mass mixing with B_s $$e^{i\alpha}\,f^2\,\zeta\,B_s + e^{-i\alpha}\,f^2\,\zeta\,\overline{B}_s$$
- Must have largish width to affect Γ $$f = 0.0026 \times \left(\frac{F/|g_A^{bs}|}{10^6\ \mathrm{GeV}}\right)^{-1/2}\ \mathrm{GeV}$$

$(B_s, \bar{B}_s, \zeta)$ mass matrix

$$M^2 = \begin{pmatrix} m_{B_s}^2 & \Delta m_{B_s} m_{B_s} & e^{i\alpha} f^2 \\ \Delta m_{B_s} m_{B_s} & m_{B_s}^2 & e^{-i\alpha} f^2 \\ e^{-i\alpha} f^2 & e^{i\alpha} f^2 & M_\zeta^2 \end{pmatrix}$$

- Cannot use perturbation theory to diagonalize mass due to near degeneracy of B_s system, fortunately mass matrix is simple to diagonalize exactly
- Width matrix may be diagonalized perturbatively in mass eigenstate basis
- obtain B_L, B_H eigenstates with small ζ mixture, fit mass, width difference

Contribution to mass, width difference

➡ Relative contribution to mass difference proportional to $M_\zeta^2 - M_{B_s}^2$

➡ Order one contribution to width difference without order one contribution to mass difference provided that

$$|M_\zeta - M_{B_s}| < \frac{m_{12}^s(SM)}{\Gamma_{12}^s(SM)} \Gamma_\zeta \approx 200 \Gamma_\zeta$$

➡ either a finetuning conspiracy in the mass, or a fairly large ζ width

2010 fit to data

	Experimental	SM prediction
$\Delta \overline{m}_s$	$(17.78 \pm 0.12)\ \mathrm{ps}^{-1}$	$(19.6 \pm 2.2)\ \mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.134 \pm 0.031\ \mathrm{ps}^{-1}$	$(0.098 \pm 0.024)\ \mathrm{ps}^{-1}$
$\overline{\Gamma}_s$	$0.680 \pm 0.012\ \mathrm{ps}^{-1}$	$(0.654 \pm 0.008)\ \mathrm{ps}^{-1}$
$\tan \phi_s^{\mathrm{sl}}$	-1.66 ± 0.64	0.0042 ± 0.0014
$\beta_s^{J/\psi\Phi}$	0.21 ± 0.12	0.018 ± 0.001

fit 5 observables to 4 variables: f, α, M_ζ, Γ_ζ

χ^2(SM)=14.0, (1.6%) χ^2 (ζ *best fit*)=2.0 (16%)

Other constraints

➡ For light ζ, we have 2 body decays $b \rightarrow s$, ruling out most of the region with m_ζ <4.8 GeV from B width

➡ Other constraints depend on the decay mode of the ζ

Allowed ζ mass for 2 widths

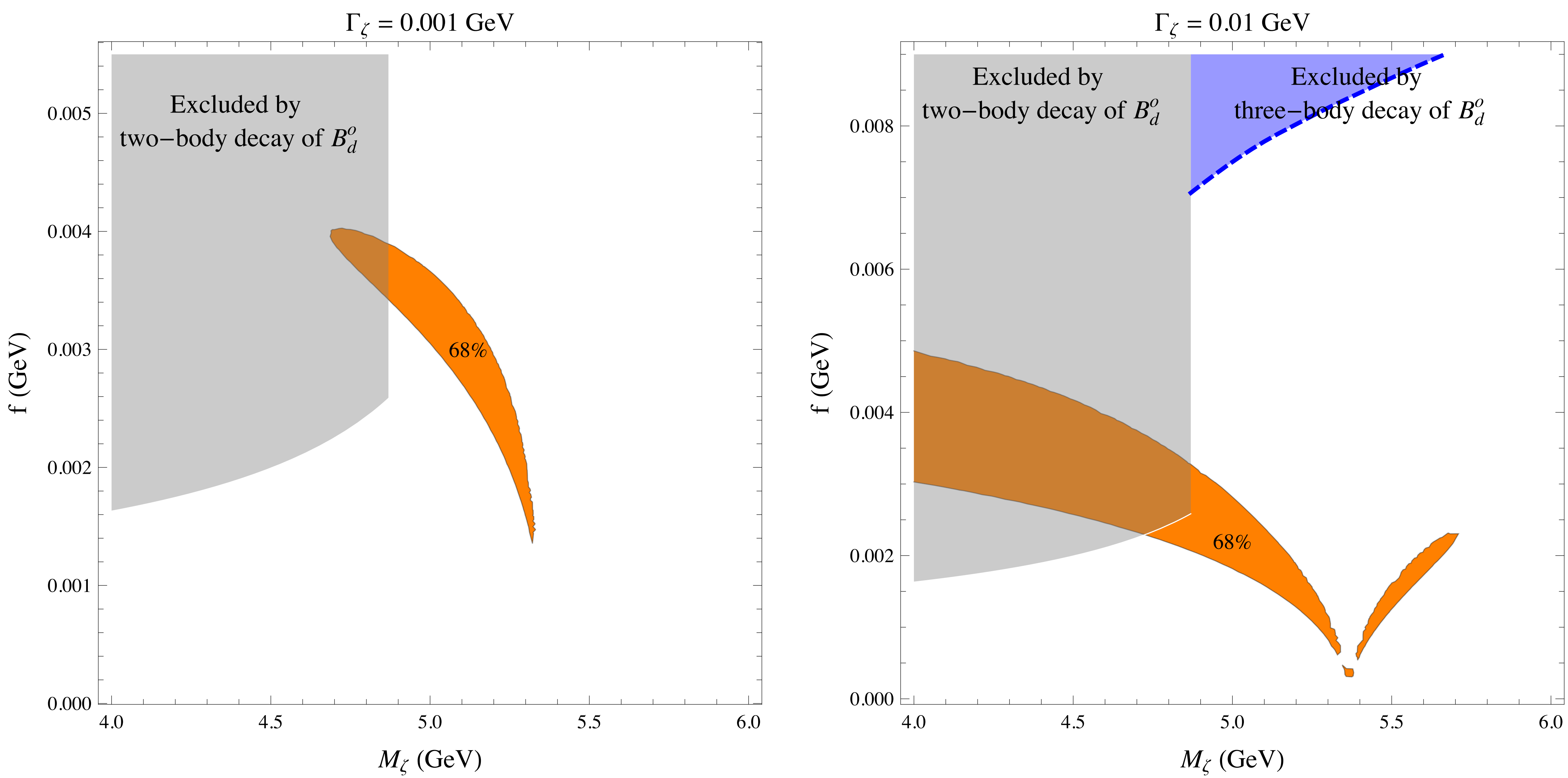


Figure 3: Left panel: the best-fit region in the M_ζ and f space for a fixed width $\Gamma_\zeta = 0.001$ GeV. The orange contour has 68% C.L. after minimizing χ^2 in terms of α. The best fit has $\chi^2 = 2.0$. The gray region is ruled out by the two-body decay width of B_d when $M_\zeta < m_{B_d} - m_K$. Three-body decays do not rule out the best-fit region. Right panel: the same as the left panel but for $\Gamma_\zeta = 0.01$ GeV. The best fit has $\chi^2 = 5.4$. The blue region is excluded by requiring the three-body decay width to be

Allowed Decay modes

➡ ζ can decay directly, or to other exotics which then decay back to SM particles, e.g.

	Decay Modes
Direct decay	$\tau^+\tau^-$, $D\bar{D}(\pi's)$, $D(\pi's)X$
$\zeta \to 2\,a$	$2\tau^+2e^-$, $2\tau^+2\mu^-$, $2D^+2\pi^-$, $2\pi^+2\pi^-$, $2\pi^+2\pi^-$, $2K^-2\pi^+$, $2K^+2K^-$
$\zeta \to a_1 + a_2$	$X + (\tau^+e^-$, $\tau^+\mu^-$, $D^+\pi^-$, $\pi^+\pi^-$, $\pi^+\pi^-$, $K^-\pi^+$, $K^+K^-)$

Something nonstandard accounts for ~1-3% of B_s decays!!

summary: light pseudoscalar

- data:largish new contribution to B_s decays, decay mixing without excessive new contribution to mass mixing
  - weakly coupled new physics below weak scale
- economical: a new pseudoscalar
  - large width, weak coupling to SM suggests a new 'sector', large $\Gamma(\zeta \to$ hidden), small Γ(hidden $\to$vis)
  - alternatively largish flavor diagonal couplings to charm or tau
    - but not 'higgs like', i.e. suppressed flavor diagonal coupling to mu ($B_{s,d} \to \mu^+ \mu^-$ constraint), top (unitarity constraint) u
      - unless largish Γ ($\zeta \to$ other 'higgses')
  - also Υ decay constraints on flavor diagonal b coupling

experimental smoking guns of hidden pseudoscalar

➡ nonstandard contribution to B_s decays at few %

➡ nonstandard contribution to B_d, B^+ decays from $b \to s$ (ζ decay products) at ~10^{-4}

➡ rare Υ decays (model dependent, from flavor diagonal coupling)

➡ $\phi_s^{sl} \neq -2\beta_s^{J/\psi\Phi}$ would indicate decay mixing, not mass mixing

Summary

★ ~ 4 σ new CPV beyond CKM indicated by A^b_{sl}

➡ theory error negligible

➡ experimental systematic claimed to be small

★ most likely in B_s mixing and/or decay

➡ new CPV in B_s mixing preferred theoretically

- SM contribution is loop suppressed
- many models of new TeV scale physics can do this
- some tuning required

➡ new physics in B_s decay allowed experimentally

- hidden pseudoscalar?