Flavor physics in the LHC era

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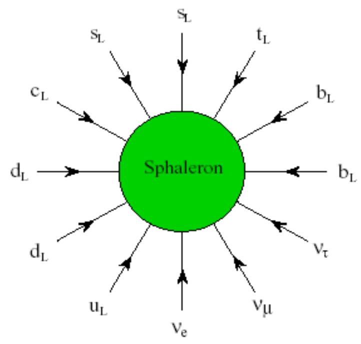
How long do they need to measure that CKM matrix?

Anonymous complaint

1. Introduction: building the Universe

★ Sakharov's conditions for matter-antimatter asymmetry of the Universe

✓ Baryon (and lepton) number - violating processes
to ***generate*** asymmetry



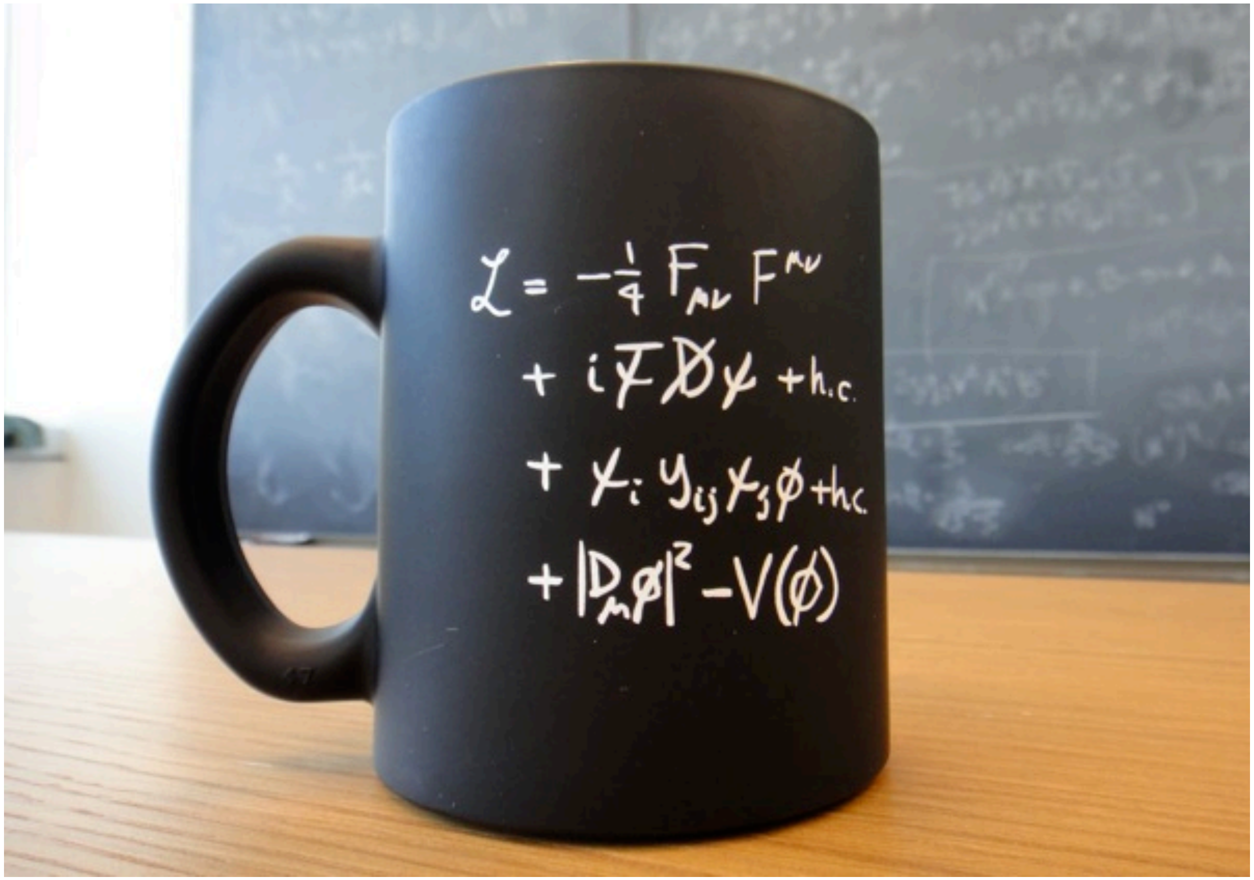
$\Delta B = 3,\ \Delta L = 3,$
$B - L$ conserved

✓ Universe that evolves out of thermal equilibrium
to ***keep*** asymmetry from ***being washed out***

✓ "Microscopic CP-violation"
to ***keep*** asymmetry from ***being compensated in the "anti-world"***

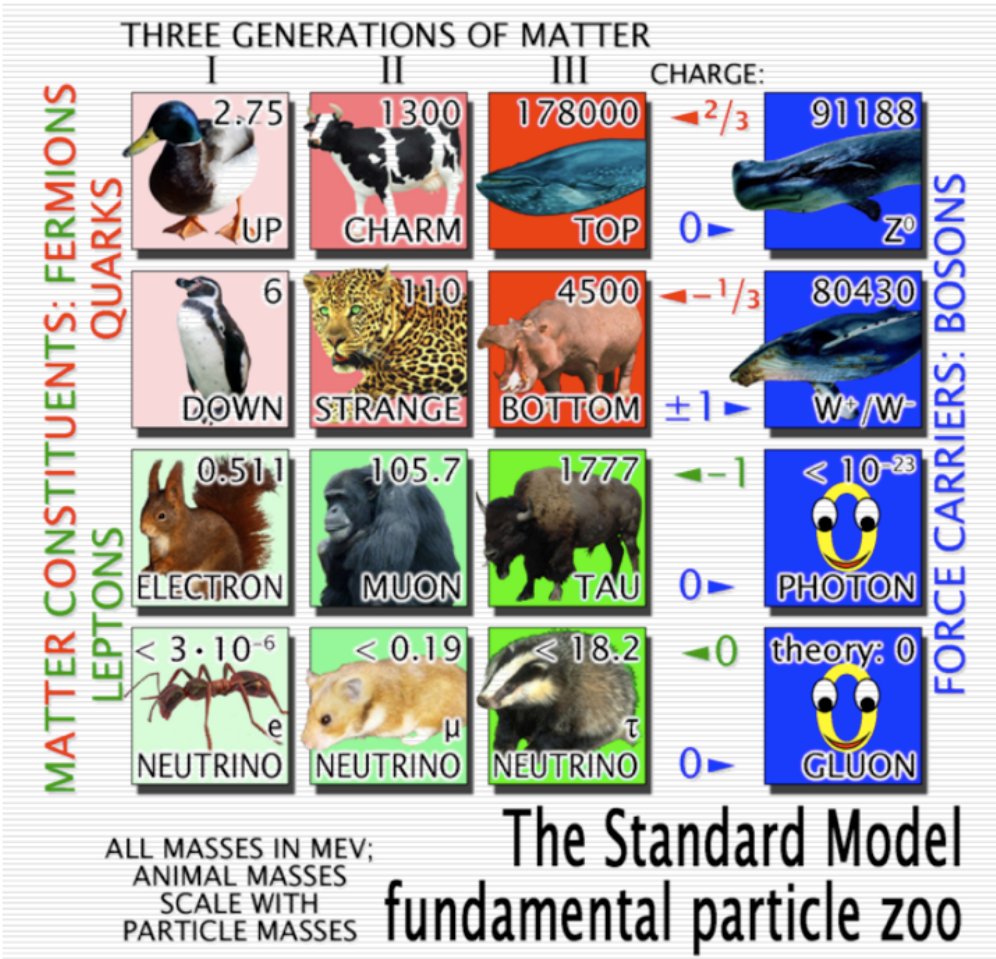
This CAN be tested experimentally

SM is a very constrained theory



CKM mechanism for SM CP-violation has been established

Matter sector: experimental data



E. Lunghi

★ Ratios of masses of quarks and leptons

- quarks

$$\frac{m_d}{m_u} \simeq 2\ , \quad \frac{m_s}{m_d} \simeq 21\ ,$$
$$\frac{m_t}{m_c} \simeq 267\ , \quad \frac{m_c}{m_u} \simeq 431\ , \quad \frac{m_t}{m_u} \simeq 1.2 \times 10^5\ .$$

- leptons

$$\frac{m_\tau}{m_\mu} \simeq 17\ , \quad \frac{m_\mu}{m_e} \simeq 207\ .$$

★ Quark mixing (Cabibbo-Kobayashi-Maskawa) matrix parameters

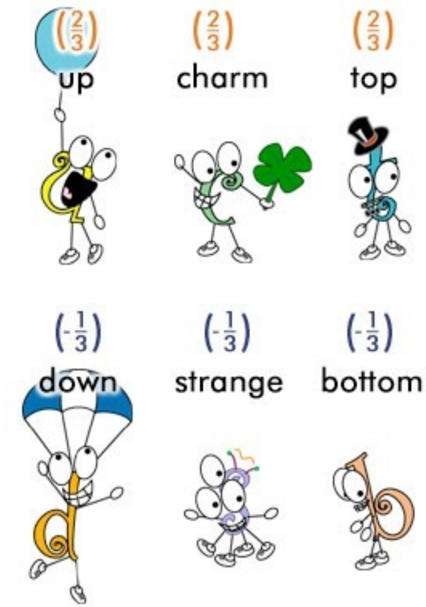
$$V_{ud} \sim 1, V_{us} \sim 0.2,\ \ V_{cb} \sim 0.04,\ \ V_{ub} \sim 0.004$$

Problem: why such hierarchy?

Problems, problems, problems…

- ★ Gauge forces in SM do not distinguish between fermions of different generations:
  - e, μ, τ have same electrical charge
  - quarks have same color charge

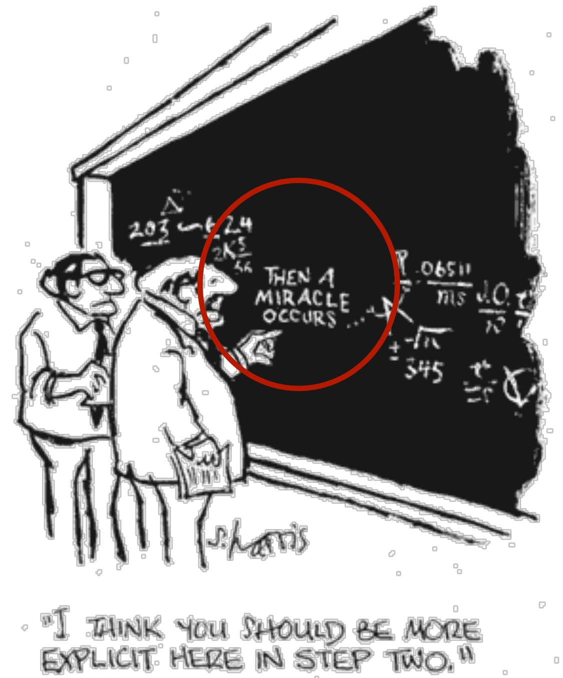
- ★ Why generations? Why only 3? Are there only 3?
- ★ Why hierarchies of masses and mixings?
- ★ Can there be transitions between quarks/leptons of the same charge but different generations?



The flavor puzzle

Standard Model "solution"

1. Why generations?
   - Why only 3?
   - Are there only 3?



S. Harris

2. Why hierarchies of masses and mixings?

$$\mathcal{L}_1 = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right),$$

$$m_\psi = y_\psi v / \sqrt{2}$$

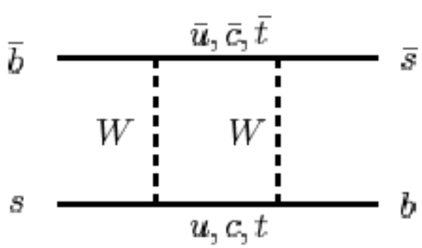
No explanation of the hierarchy, but mass hierarchy is related to hierarchy of Yukawa couplings

$$\begin{aligned} y_u &\sim 10^{-5}, \quad y_c \sim 10^{-2}, \quad y_t \sim 1, \\ y_d &\sim 10^{-5}, \quad y_s \sim 10^{-3}, \quad y_b \sim 10^{-2}, \\ y_e &\sim 10^{-6}, \quad y_\mu \sim 10^{-3}, \quad y_\tau \sim 10^{-2}. \end{aligned}$$

Solutions to the flavor problem?

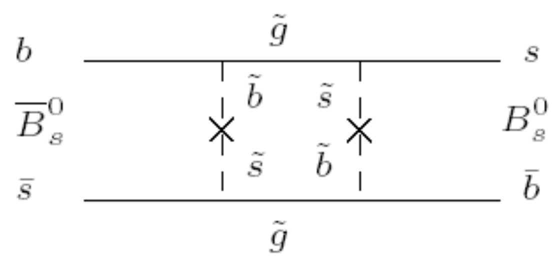
★ Standard Model adequately describes experimental FCNC data, but does not provide solution to the flavor puzzle

- BSM solution to the flavor problem?
- NP might/will affect FCNC ($\Delta F=2$ and $\Delta F=1$ processes)



Standard Model

or



Supersymmetric SM

or ???

If all of those models of New Physics affect FCNC processes, how come all of them are described by the Standard Model so well???

The "New Physics" flavor puzzle

2. "Fundamental" flavor physics: model building

★ GUT models: leptonic/quark Yukawas are related

★ Flavor symmetries

SM Lagrangian is $SU(3)^5$-invariant in the limit $y_i \to 0$

- Yukawas arise as a result of spontaneous breaking of a subgroup of $SU(3)^5$?

- continuous flavor symmetries
- discrete flavor symmetries
- accidental flavor symmetries

★ Dynamical approaches

Dynamical mechanisms: 2HDM

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Then assuming $\tan\beta \gg 1$

$$\frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

So it looks like we can solve the flavor puzzle by just having more scalar bosons, letting all Yukawa couplings be $\mathcal{O}(1)$ and $\tan\beta \gg 1$

Top quark: Das, Kao, Phys. Lett. B 392 (1996) 106.
Xu, Phys. Rev. D44, R590 (1991).
Blechman, AAP, Yeghiyan, JHEP 1011 (2010) 075

Solutions to the flavor problem?

"Frankly, I even find it hard to believe some of the things I've been coming up with."

3. "Applied" flavor physics: model testing

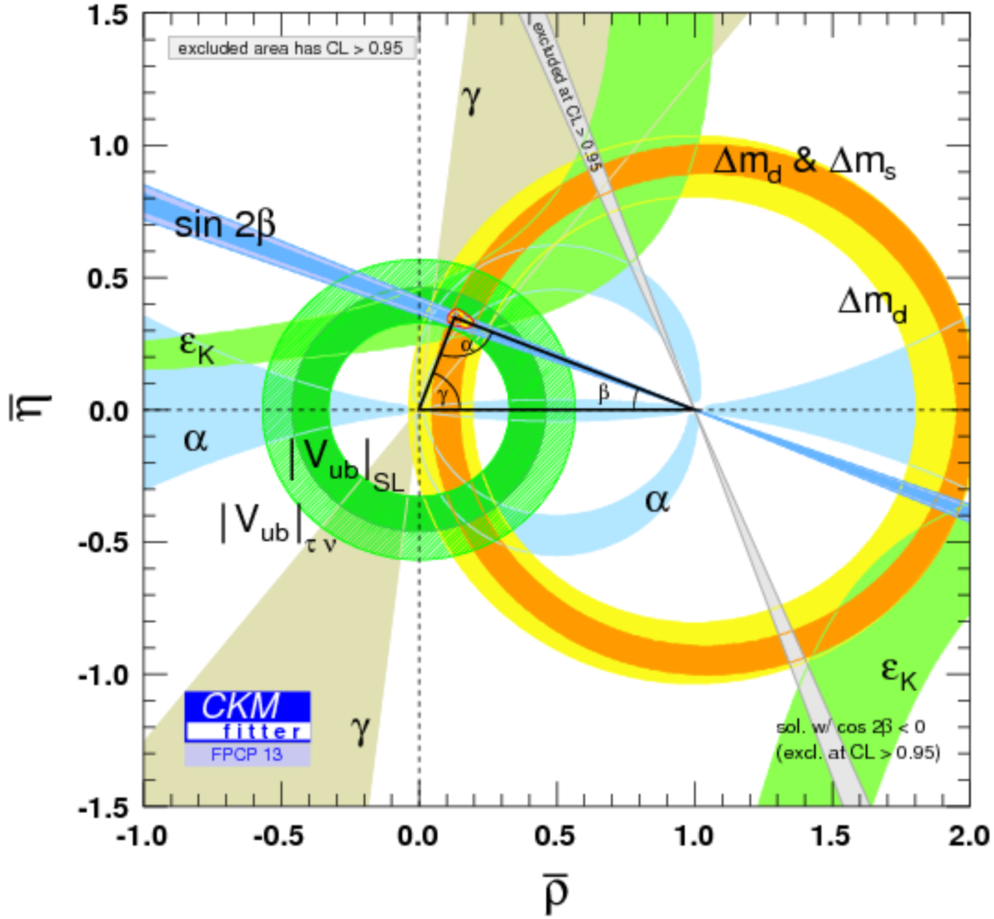
★ How can one use flavor data to test New Physics models?

1. Processes allowed in the Standard Model at tree level
   - relations, valid in the SM, but not necessarily in general
   - processes where SM rates and uncertainties are known
   - example: CKM triangle relations

2. Processes forbidden in the Standard Model at tree level
   - example: penguin-mediated decays, B(D)-mixing, etc.

3. Processes forbidden in the Standard Model to all orders
   - example: $D^0 \to p^+\pi^-\nu$

3a. Processes allowed in the SM at tree level



Some issues with exclusive/inclusive determinations of Vub…

3b. Processes forbidden in the SM at tree level

★ Let's look at some examples

★ Rare leptonic decays of Bs mesons
★ Bs mixing: SM vs New Physics
★ CP-violating asymmetries in charm

A. Rare leptonic decays of B_s mesons

- Weak effective hamiltonian for $B_s \to \mu^+\mu^-$ is simple

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \; C_{10}^{\text{eff}} \; \bar{s}\gamma_\mu(1-\gamma_5)b \; \bar{\ell}\gamma^\mu\gamma_5\ell$$

- Other operators (e.g. Q_9) do not contribute due to vector current conservation

$$\langle 0|\bar{s}\gamma_\mu(1-\gamma_5)b|B_s(p)\rangle = -if_B p_\mu$$

$$\downarrow$$

$$ip_\mu\langle\mu^+\mu^-|\bar{\ell}\gamma^\mu\ell|B_s(p)\rangle = \langle\mu^+\mu^-|\bar{\ell}\not{\partial}\ell|B_s\rangle = 0$$

$$ip_\mu\langle\mu^+\mu^-|\bar{\ell}\gamma^\mu\gamma_5\ell|B_s(p)\rangle = \langle\mu^+\mu^-|\bar{\ell}\not{\partial}\gamma_5\ell|B_s\rangle \propto m_\mu$$

One non-perturbative parameter: lattice

Rare leptonic decays of B_s mesons: SM

★ Very clean prediction in the Standard Model (one non-perturbative parameter)

$$\mathcal{B}r^{(\mathrm{SM})}_{B_s\to\mu^+\mu^-} = \frac{1}{8\pi^5}\cdot\frac{M_{B_s}}{\Gamma_{B_s}}\cdot\left(G_F^2 M_W^2 m_\mu f_{B_s}|V_{\mathrm{ts}}^* V_{\mathrm{tb}}|\eta_Y Y(\bar{x}_t)\right)^2\left[1-4\frac{m_\mu^2}{M_{B_s}^2}\right]^{1/2}$$

Buras, Carlucci, Gori, Isidori

$$\mathcal{B}^{(SM)}_{B_s\to\mu^+\mu^-} = (3.65\pm0.06)\,R_{t\alpha}R_s\times10^{-9} = (3.65\pm0.23)\times10^{-9}$$

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser (2014)

$$R_s = \left[\frac{f_{B_s}[MeV]}{227.7}\right]^2\left[\frac{|V_{cb}|}{0.0424}\right]^2\left[\frac{|V_{tb}^* V_{ts}/V_{cb}|}{0.980}\right]^2\frac{\tau_{B_s}[ps]}{1.615} \qquad R_{t\alpha} = R_t^{3.06}R_\alpha^{-0.18}$$

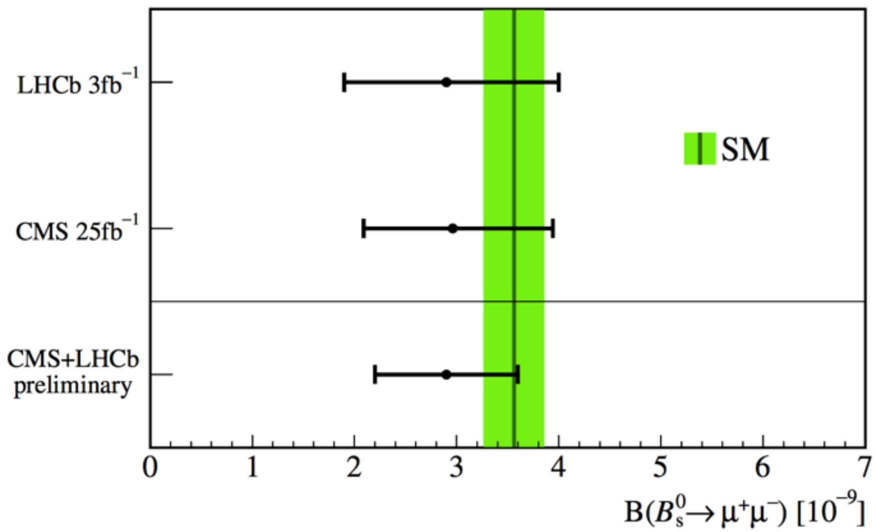
$$\mathcal{B}^{(\mathrm{LD})}_{B_s\to\mu^+\mu^-} \sim 6\times10^{-11}$$

Golowich, Hewett, Pakvasa, AAP, Yeghiyan

Experiment (LHCb/CMS): $\overline{\mathcal{B}}_{s\mu} = (2.9\pm0.7)\times10^{-9}, \quad \overline{\mathcal{B}}_{d\mu} = (3.6^{+1.6}_{-1.4})\times10^{-10}.$

Rare leptonic decays of B_s mesons: SM

- Experiment:



- Comments:

★ Standard Model rate for $B_s \to \mu^+\mu^-$ is known at NNLO in QCD + two loops in EW

★ Standard Model rate for $B_s \to \mu^+\mu^-$ is helicity suppressed

  – additional photon emission is enhanced by $\dfrac{\mathcal{B}(B_s \to \gamma \ell^+\ell^-)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \propto \alpha \dfrac{m_B^2}{m_\ell^2}$

Aditya, Healey, AAP
arXiv:1212.4166 [hep-ph]

★ $B_s \to \mu^+\mu^-$ is not sensitive to vector-like New Physics (e.g. vector Z')

Many NP models give contributions to both B_s-mixing and $B_s \to \mu^+\mu^-$ decay: correlate!!!

Mixing vs rare decays: some models

- Consider RPV SUSY: $\mathcal{W}_{R\!\!/} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c.$

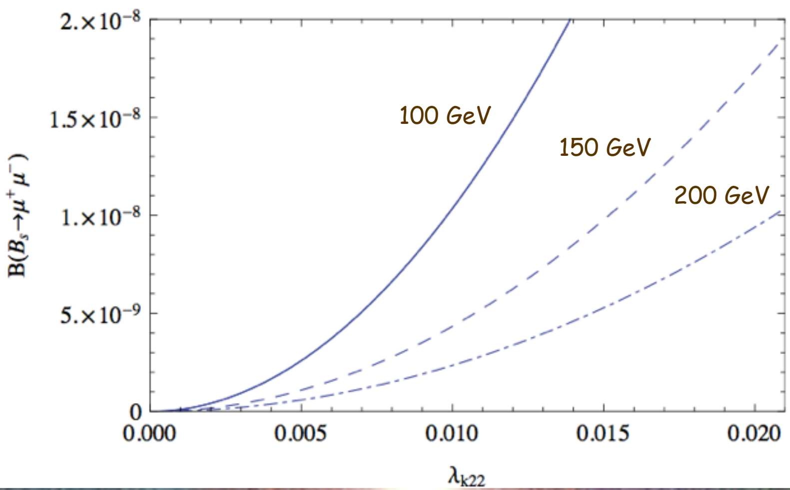
Mixing: $\mathcal{L}_R = -\lambda'_{i23}\tilde{\nu}_{i_L}\bar{b}_R s_L - \lambda'_{i32}\tilde{\nu}_{i_L}\bar{s}_R b_L + \text{H.c.},$

$$\Delta M_{B_s}^{(R\!\!/)} = \frac{5}{24} f_{B_s}^2 M_{B_s} F(C_3, B_3) \sum_i \frac{\lambda'_{i23}\lambda'^*_{i32}}{M_{\tilde{\nu}_i}^2},$$

Rare decay: $$\mathcal{B}_{B_s\to\mu^+\mu^-}^{(R\!\!/)} = \frac{f_{B_s}^2 M_{B_s}^3}{64\pi\Gamma_{B_s}}\left(\frac{M_{B_s}}{m_b}\right)^2\left(1-\frac{2m_\mu^2}{M_{B_s}^2}\right)\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}} \times\left(\left|\sum_i \frac{\lambda^*_{i22}\lambda'_{i32}}{M_{\tilde{\nu}_i}^2}\right|^2 + \left|\sum_i \frac{\lambda_{i22}\lambda'^*_{i23}}{M_{\tilde{\nu}_i}^2}\right|^2\right).$$

$$\mathcal{B}_{B_s\to\mu^+\mu^-}^{(R\!\!/)} = k\frac{f_{B_s}^2 M_{B_s}^3}{64\pi\Gamma_{B_s}}\left(\frac{\lambda_{i22}\lambda'_{i32}}{M_{\tilde{\nu}_i}^2}\right)^2\left(\frac{M_{B_s}}{m_b}\right)^2\left(1-\frac{2m_\mu^2}{M_{B_s}^2}\right) \times\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}},$$

...assume that a single sneutrino dominates, neglect possible CP-violation...



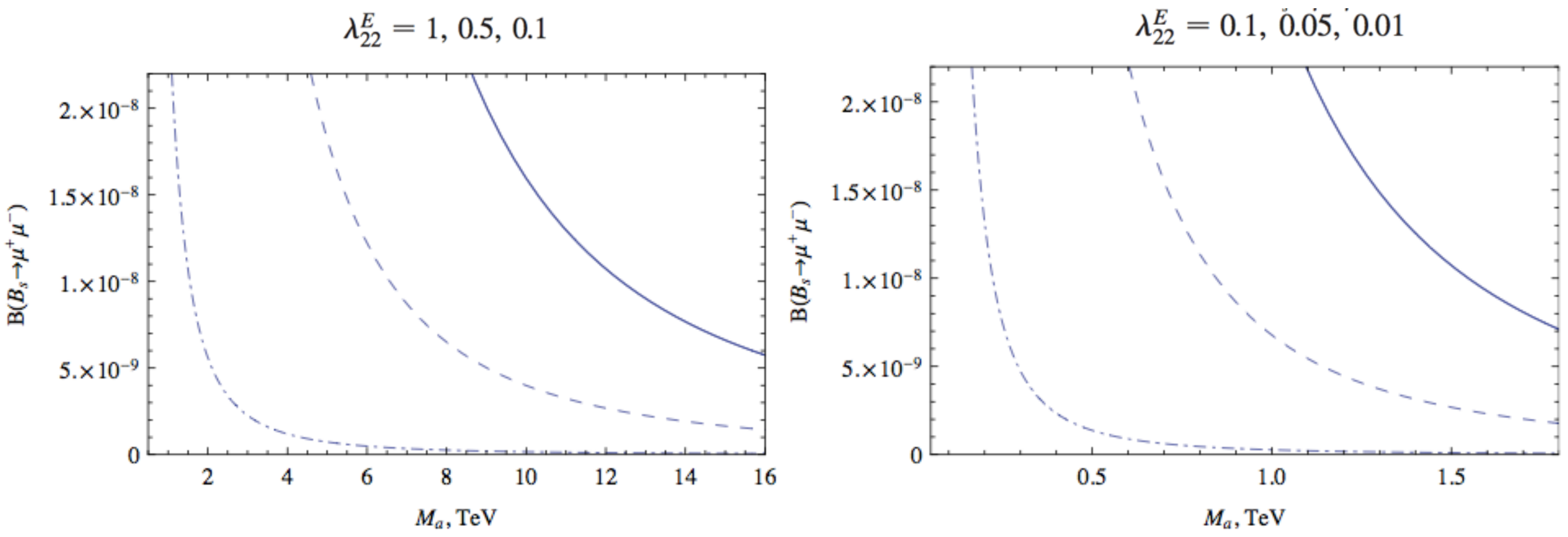
$$\mathcal{B}_{B_s\to\mu^+\mu^-}^{(R\!\!/)} = \frac{3}{20\pi}\frac{M_{B_s}^2}{F(C_3, B_3)}\left(\frac{M_{B_s}}{m_b}\right)^2\left(1-\frac{2m_\mu^2}{M_{B_s}^2}\right) \times\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}\, x_{B_s}^{(R\!\!/)}\frac{\lambda_{k22}^2}{M_{\tilde{\nu}_i}^2}.$$

E.Golowich, J. Hewett, S. Pakvasa, A.A.P, and G. Yeghiyan PRD83, 114017 (2011)

Mixing vs rare decays: some models

- FCNC pseudoscalars:

$$\mathcal{B}^{(a)}_{B_s^0\to\ell^+\ell^-} = \frac{3}{10\pi}\cdot\frac{M_{B_s}^4 x_s^{(a)}}{m_b^2 f_a(\bar{C}_i, m_b)}\left(1-\frac{4m_\ell^2}{M_{B_s}^2}\right)^{1/2}\left(\frac{\lambda_{22}^E}{M_a}\right)^2$$



E.Golowich, J. Hewett, S. Pakvasa, A.A.P, and G. Yeghiyan PRD83, 114017 (2011)

Mixing vs rare decays: some models

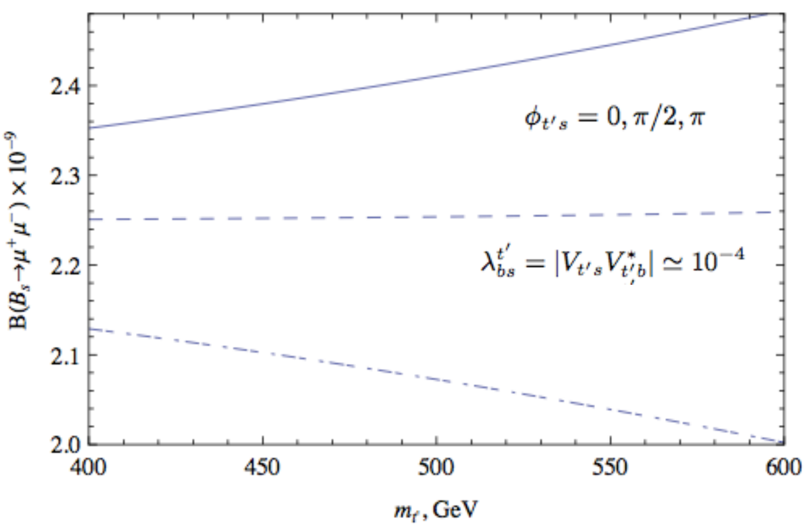
E.Golowich, J. Hewett, S. Pakvasa, A.A.P, and G. Yeghiyan PRD83, 114017 (2011)

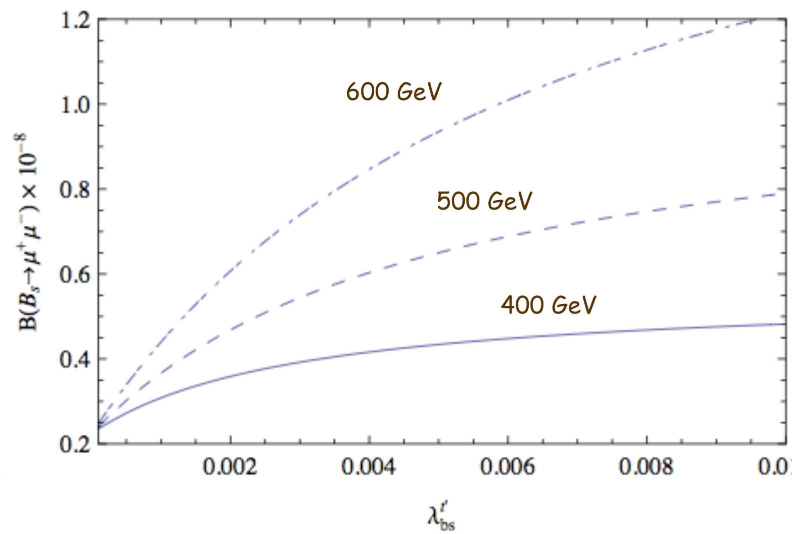
- Sequential 4th generation of quarks:

$$\mathcal{B}_{B_s\to\mu^+\mu^-} = \frac{3\alpha^2 m_\mu^2 x_{B_s}}{8\pi \hat{B}_{B_s} M_W^2}\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}\frac{|C_{10}^{tot}|^2}{|\Delta'|},$$

$$\Delta' = \eta_t S_0(x_t) + \eta_{t'} R_{t't}^2 S_0(x_{t'}) + 2\eta_{t'} R_{t't} S_0(x_t, x_{t'})$$

Soni et al





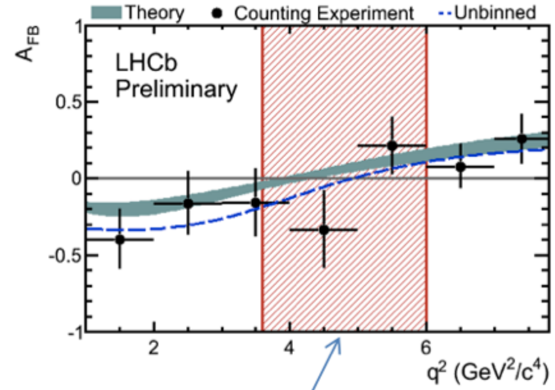
Other electroweak decays

- Important for studies of New Physics

★ the same current that generates $B_s \to \mu^+\mu^-$ decays also generates $B \to K^{(*)} \mu^+\mu^-$

- decay has three particles in the finals state: more observables: FB-, isospin, CP-asymmetries
- zero "crossing point" in A_{FB} is a probe of NP:
  SM predicts q_0^2=4-4.3 GeV^2 (Bobeth et al)
  LHCb measures: $q_0^2=4.9^{+1.1}_{-1.3}$ GeV^2
  (some SUSY models predict no crossing at all!)

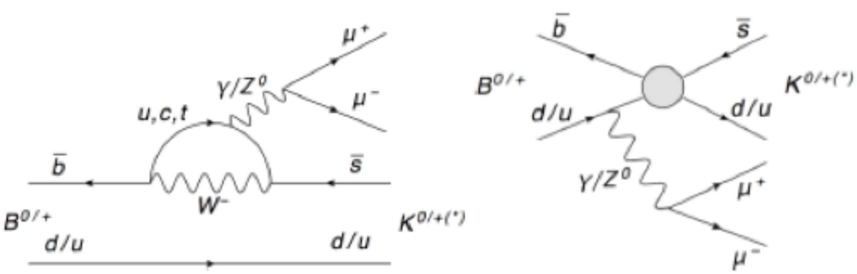
Moriond 2012 LHC-b talk
LHCb-CONF-2012-089



68% confidence interval in Zero crossing point from data.

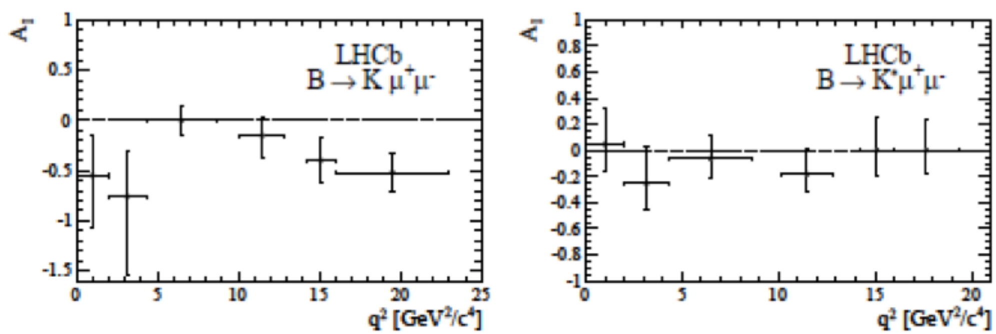
★ Isospin asymmetries in $B \to K^{(*)} \mu^+\mu^-$

- probes New Physics
- SM predicts (almost) zero
- LHCb measurement is consistent



(a) (b)

LHCb-PAPER-2012-011

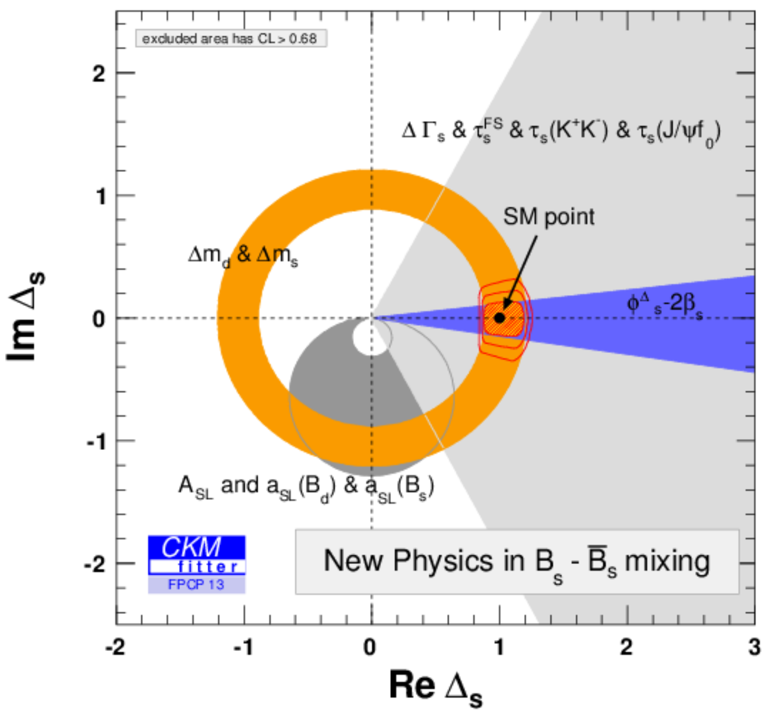


Negative with 3.0σ significance in $16<q^2<23$

consistent with zero

B. Mixing in heavy hadrons

Mixing parameters are sensitive probes of new physics



Theoretical predictions?

★ Time development of B_s system

$$i\frac{d}{dt}\begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix} = \left[M - \frac{i}{2}\Gamma\right]_{ij} \begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix}$$

★ Mixing parameters (concentrate on B_s)

$$\Delta M_{B_s} = 2\left|M_{12}\right|, \quad \Delta\Gamma_{B_s} = \frac{4Re\left(M_{12}\Gamma_{12}^*\right)}{\Delta M_{B_s}}$$

✦ NP in phase of ΔM_{Bs}:

$$\Delta\Gamma_{B_s} = 2\left|\Gamma_{12}\right| \cos 2\phi_s$$

arg(M12)

✦ "direct" NP in $\Delta\Gamma_{Bs}$:

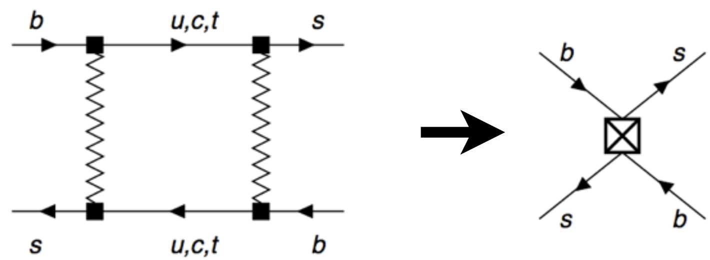
$$\Delta\Gamma_{B_s} = \Delta\Gamma_{B_s}^{SM} + \Delta\Gamma_{B_s}^{NP} \cos 2\phi_s'$$

arg(Γ12)

Standard Model contributions

Both ΔM_{Bs} and $\Delta\Gamma_{Bs}$ can be computed in the limit $m_b \to \infty$:

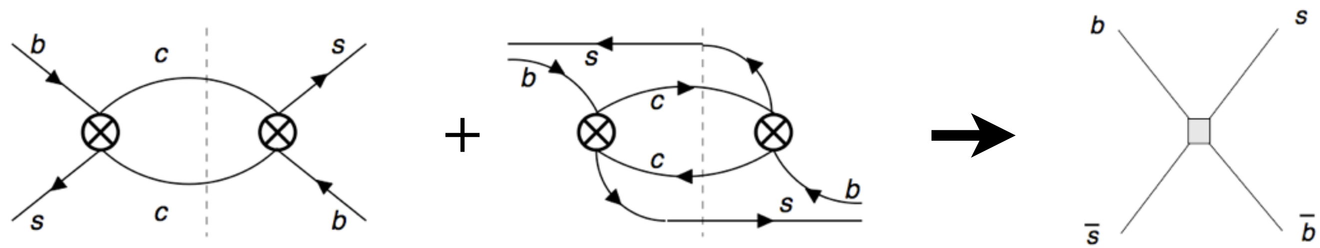
ΔM_{Bs}:



A.Buras, M.Jamin, P.Weisz

$$M_{12}(B_s) = \frac{G_F^2 M_{B_s}}{12\pi^2} M_W^2 \left(V_{tb}V_{ts}^*\right)^2 \hat{\eta}_B S_0(x_t) f_{B_s}^2 B$$

$\Delta\Gamma_{Bs}$:



$$\Gamma_{21}(B_s) = \sum_k \frac{C_k(\mu)}{m_b^k} \langle B_s | \mathcal{O}_k^{\Delta B=2}(\mu) | \overline{B}_s \rangle .$$

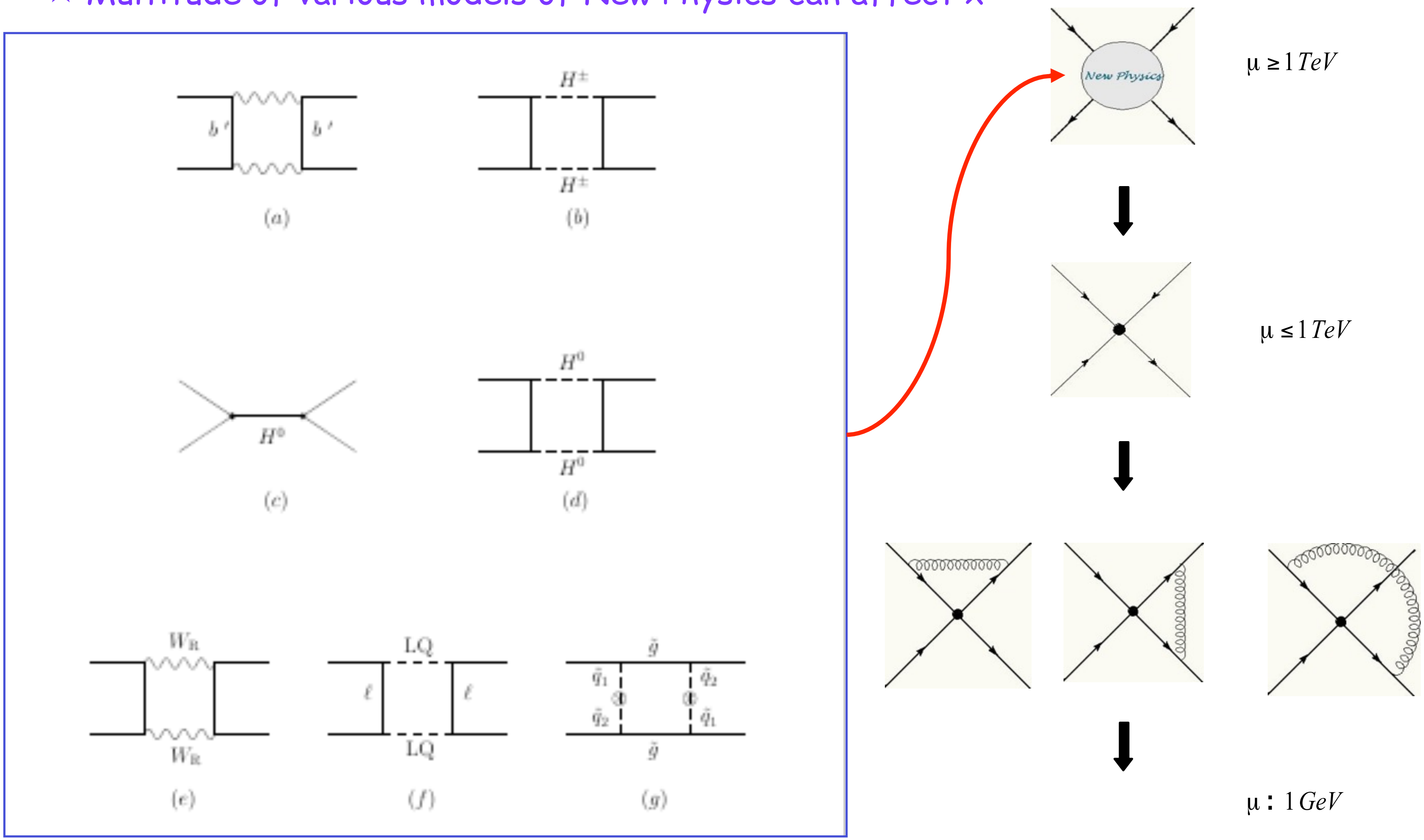
A. Lenz, U. Nierste

$$\frac{\Delta\Gamma_s}{\Gamma_s} \approx 0.137 \pm 0.027$$

Lattice estimates for matrix elements?

Constraints on NP from B(D)-mixing?

★ Multitude of various models of New Physics can affect x



Generic restrictions on NP from $D\bar{D}$-mixing

★ Comparing to experimental value of x, obtain constraints on NP models
- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2}\sum_{i=1}^{8} z_i(\mu) Q_i'$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{array}{c} L \\ \updownarrow \\ R \end{array} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$\begin{aligned} |z_1| &\lesssim 5.7\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_2| &\lesssim 1.6\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_3| &\lesssim 5.8\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_4| &\lesssim 5.6\times 10^{-8}\left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2, \\ |z_5| &\lesssim 1.6\times 10^{-7}\left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2. \end{aligned}$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10)\times 10^3\ \mathrm{TeV}$

loop level: $\Lambda_{NP} \geq (1-3)\times 10^2\ \mathrm{TeV}$

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models available

Summary: New Physics in mixing

Extra fermions

Extra gauge bosons

Extra scalars

Extra dimensions

SUSY

Model	Approximate Constraint
Fourth Generation (Fig. 2)	$\lvert V_{ub'}V_{cb'}\rvert \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$\lvert \lambda_{uc} \rvert < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed x_D
Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
Left-Right Symmetric (Fig. 9)	No constraint
Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/\lvert \Delta_{uc} \rvert > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/\lvert \Delta y \rvert > (6 \cdot 10^2$ GeV)
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$\lvert (\delta^u_{12})_{\mathrm{LR,RL}} \rvert < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\lvert (\delta^u_{12})_{\mathrm{LL,RR}} \rvert < .25$ for $\tilde{m} \sim 1$ TeV
Supersymmetric Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

★ What about particular models?

✓ Considered 21 well-established models

✓ Only 4 models yielded no useful constraints

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

Gedalia, Grossman, Nir, Perez
arXiv:0906.1879 [hep-ph]

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

C. CP-violation in charmed mesons

★ Possible sources of CP violation in charm transitions:

★ CPV in $\Delta c = 1$ decay amplitudes ("direct" CPV)

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f])$$

★ CPV in $D^0 - \overline{D^0}$ mixing matrix ($\Delta c = 2$):

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle \Rightarrow |D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left(|D^0\rangle \pm |\overline{D}^0\rangle\right)$$

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1$$

★ CPV in the interference of decays with and without mixing

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A}_f}{A_f}\right|$$

★ One can separate various sources of CPV by customizing observables

CP-violation I: indirect

★ Indirect CP-violation manifests itself in $D\bar{D}$-oscillations

- see time development of a D-system:

$$i\frac{d}{dt}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle$$

$$\langle D^0|\mathcal{H}|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12} \qquad \langle \overline{D^0}|\mathcal{H}|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

★ Define mixing parameters

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad x_{12} \equiv 2|M_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

Note: can be calculated in a given model

★ Assume that direct CP-violation is absent ($\mathrm{Im}\,(\Gamma_{12}^*\bar{A}_f/A_f) = 0$, $|\bar{A}_f/A_f| = 1$)

- can relate x, y, φ, $|q/p|$ to x_{12}, y_{12} and φ_{12}

$$xy = x_{12}y_{12}\cos\phi_{12}, \qquad x^2 - y^2 = x_{12}^2 - y_{12}^2,$$
$$(x^2 + y^2)|q/p|^2 = x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12},$$
$$x^2\cos^2\phi - y^2\sin^2\phi = x_{12}^2\cos^2\phi_{12}.$$

★ Four "experimental" parameters related to three "theoretical" ones

- a "constraint" equation is possible

CP-violation I: indirect

★ Relation; data fromHFAG's compilation

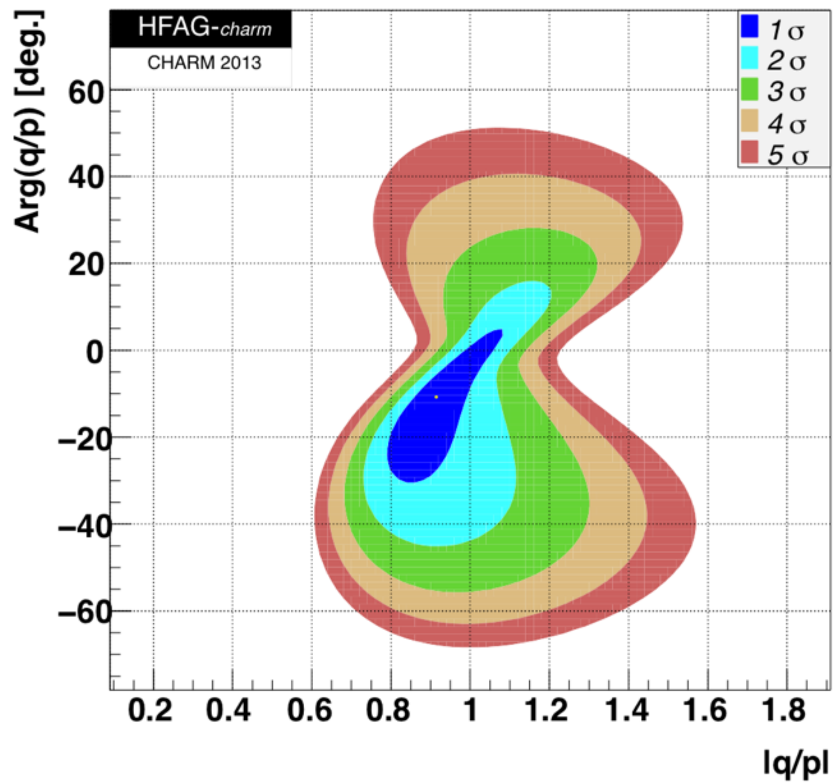
$$\frac{x}{y} = \frac{1-|q/p|}{\tan\phi} = -\frac{1}{2}\frac{A_m}{\tan\phi}$$

- $y/x \approx 0.8 \pm 0.3$ ➟ $A_m \sim \tan\,\varphi$

- CPV in mixing is comparable to CPV in the interference of decays with and w/out mixing

- aside: if $|M_{12}| < |\Gamma_{12}|$:

$$\begin{aligned} x/y &= 2\,|M_{12}/\Gamma_{12}|\cos\phi_{12}, \\ A_m &= 4\,|M_{12}/\Gamma_{12}|\sin\phi_{12}, \\ \phi &= -2\,|M_{12}/\Gamma_{12}|^2\sin 2\phi_{12}. \end{aligned}$$



Note: CPV is suppressed even if M_{12} is all NP!!!

Bergmann, Grossman, Ligeti, Nir, AAP
PL B486 (2000) 418

★ With available experimental constraints on x, y, and q/p, one can bound WCs of a generic NP Lagrangian -- bound any high-scale model of NP

CP-violation I: indirect

★ Assume that direct CP-violation is absent $(\mathrm{Im}\,(\Gamma_{12}^* \bar{A}_f/A_f) = 0, \quad |\bar{A}_f/A_f| = 1)$

- experimental constraints on x, y, φ, |q/p| exist
- can obtain generic constraints on Im parts of Wilson coefficients

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ In particular, from $x_{12}^{\rm NP} \sin\phi_{12}^{\rm NP} \lesssim 0.0022$

$$\mathcal{I}m(z_1) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$\mathcal{I}m(z_2) \lesssim 2.9 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$\mathcal{I}m(z_3) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$\mathcal{I}m(z_4) \lesssim 1.1 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$\mathcal{I}m(z_5) \lesssim 3.0 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

★ Constraints on particular NP models possible as well

CP-violation II: direct (charged D's)

★ At least two components of the transition amplitude are required

Look at charged D's (SCS): $A\left(D^+ \to f\right) \equiv A_f = |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2}$

Then, a charge asymmetry will provide a CP-violating observable

$$a_f = \frac{\Gamma\left(D^+ \to f\right) - \Gamma\left(D^- \to \overline{f}\right)}{\Gamma\left(D^+ \to f\right) + \Gamma\left(D^- \to \overline{f}\right)} = \frac{2\,\mathrm{Im}\, A_1 A_2^* \sin\left(\delta_1 - \delta_2\right)}{|A_1|^2 + |A_2|^2 + 2\,\mathrm{Re}\, A_1 A_2^* \cos\left(\delta_1 - \delta_2\right)}$$

...or, introducing $r_f=|A_2/A_1|$: $a_f = 2 r_f \sin\phi \sin\delta$

Prediction sensitive to details of hadronic model ($\delta=\delta_1-\delta_2$)

★ Same formalism applies if one of the amplitudes is generated by New Physics

- need r_f ~ 1 % for O(1%) charge asymmetry assuming that sin δ~1
- need to efficiently detect neutrals (not good for LHCb)

CP-violation II: direct

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: D →ππ vs D → KK!
For each final state the asymmetry

D^0: no neutrals in the final state!

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \Rightarrow \quad a_f = \underbrace{a_f^d}_{\text{direct}} + \underbrace{a_f^m}_{\text{mixing}} + \underbrace{a_f^i}_{\text{interference}}$$

★ A reason: $a^m_{KK} = a^m_{\pi\pi}$ and $a^i_{KK} = a^i_{\pi\pi}$ (for CP-eigenstate final states), so, ideally, mixing asymmetries cancel!

$$a_f^d = 2 r_f \sin\phi_f \sin\delta_f$$

★ ... and the resulting DCPV asymmetry is $\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2 a^d_{KK}$ (double!)

$$A_{KK} = \frac{G_F}{\sqrt{2}}\lambda\left[(T + E + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd}\right]$$
$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}}\lambda\left[(-(T + E) + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd}\right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays
e.g. Br(D → KK) ~ 3 Br(D →ππ)

Experiment?

★ Experiment: the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

★ Earlier results (before 2013):

Experiment	ΔA_{CP}
LHCb	$(-0.82 \pm 0.21 \pm 0.11)\%$
CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$
Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$
BaBar	$(+0.24 \pm 0.62 \pm 0.26)\%$

Looks like CP is broken in charm transitions! Now what?

★ Recent results (after 2013):

D^{*+} tag (this analysis): $\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\,\%$

Semileptonic analysis: $\Delta A_{CP} = (+0.49 \pm 0.30\,(\text{stat.}) \pm 0.14\,(\text{syst.}))\,\%$

Combination: $\Delta A_{CP} = (-0.15 \pm 0.16)\,\%$

LHCb-CONF-2013-003

Not so sure anymore…

Is it Standard Model or New Physics??

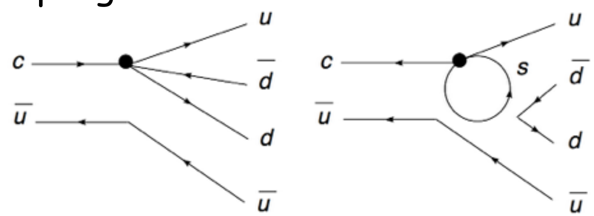
★ Is it Standard Model or New Physics? Theorists used to say...

Naively, any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$
Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

...what do you say now?

★ assuming SU(3) symmetry, $a_{CP}(\pi\pi) \sim a_{CP}(KK) \sim 0.15\%$. Looks more or less 0.1%...
★ let us try Standard Model

- need to estimate size of penguin/penguin contractions vs. tree



- unknown penguin enhancement (similar to $\Delta I = 1/2$)
  - SU(3) analysis: some ME are enhanced

    Golden & Grinstein PLB 222 (1989) 501;Pirtshalava & Uttayarat 1112.5451
  - unusually large $1/m_c$ corrections

    Isidori et al PLB 711 (2012) 46; Brod et al 1111.5000
  - no assumptions, flavor-flow diagrams

    Broad et al 1203.6659; Bhattacharya et al PRD 85 (2012) 054014; Cheng & Chiang 1205.0580

New Physics: operator analysis

★ Factorizing decay amplitudes, e.g.

$$\mathcal{H}_{|\Delta c|=1}^{\mathrm{eff-NP}} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} \sum_q (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \frac{G_F}{\sqrt{2}} \sum_{i=7,8} (C_i Q_i + C_i' Q_i') + \mathrm{H.c.}$$

$$Q_1^q = (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A}$$

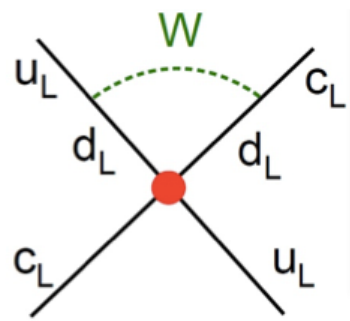
$$Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}$$

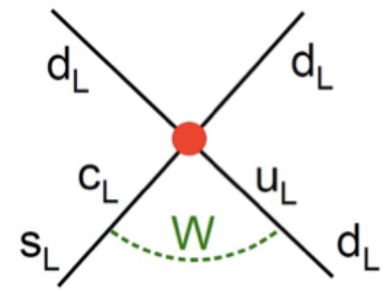
$$Q_5^q = (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A}$$

$$Q_6^q = (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A}$$

$$Q_7 = -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu} c$$

$$Q_8 = -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)T^a G_a^{\mu\nu} c$$





Z. Ligeti, CHARM-2012

★ one can fit to ε′/ε and mass difference in D-anti-D-mixing

Gedalia, et al, arXiv:1202.5038

- LL are ruled out
- LR are borderline
- RR and dipoles are possible

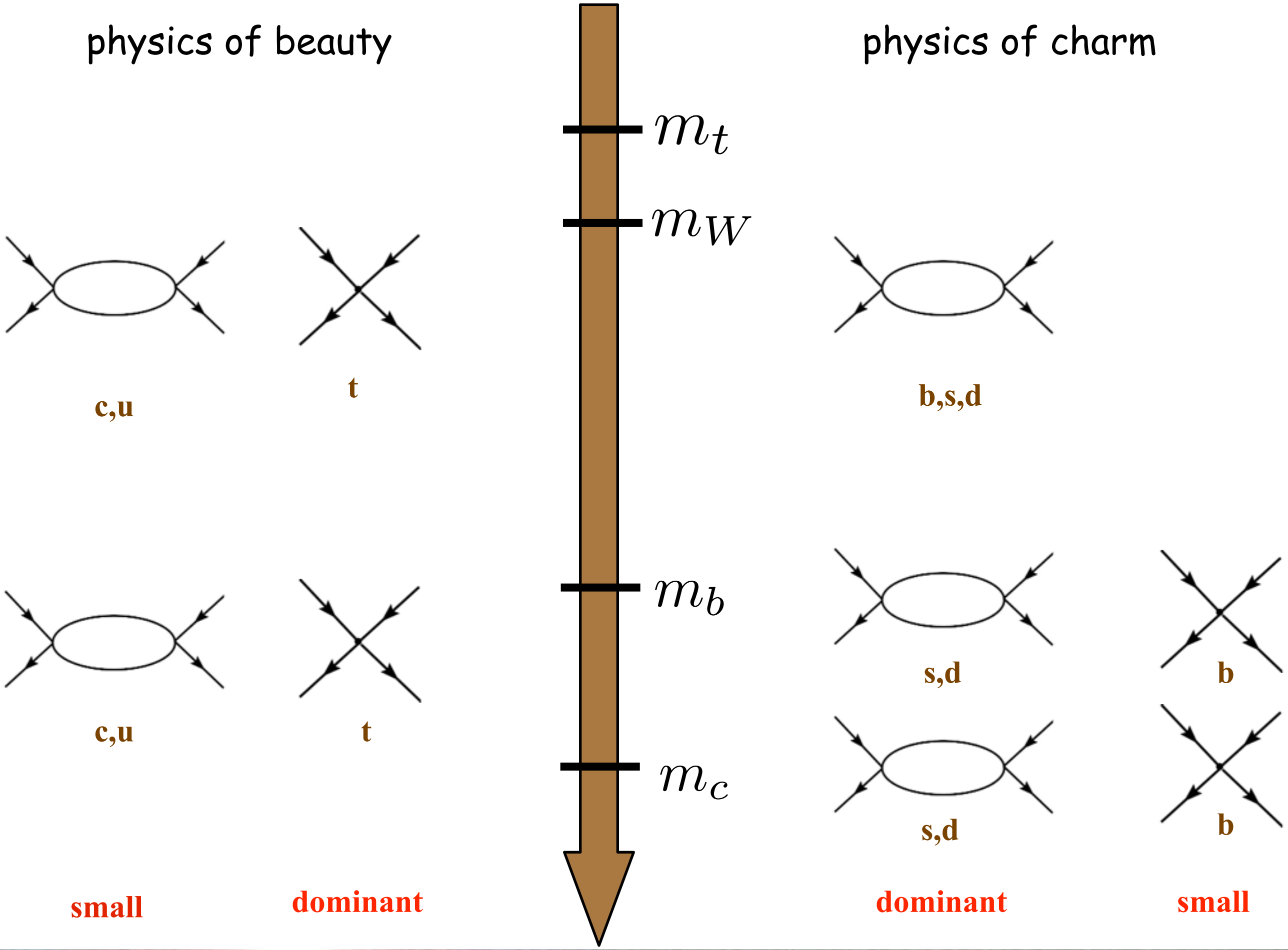
Allowed	Ajar	Disfavored
$Q_{7,8}$, $Q'_{7,8}$,	$Q_{1,2}^{(c-u,8d,b,0)}$,	$Q_{1,2}^{s-d}$, $Q_{5,6}^{(s-d)\prime}$,
$\forall f\ Q_{1,2}^{f\prime}$, $Q_{5,6}^{(c-u,b,0)\prime}$	$Q_{5,6}^{(0)}$, $Q_{5,6}^{(8d)\prime}$	$Q_{5,6}^{s-d,c-u,8d,b}$

Constraints from particular models also available

4. Testing QCD tools for flavor physics

★ Modern approach to flavor physics calculations: effective field theories

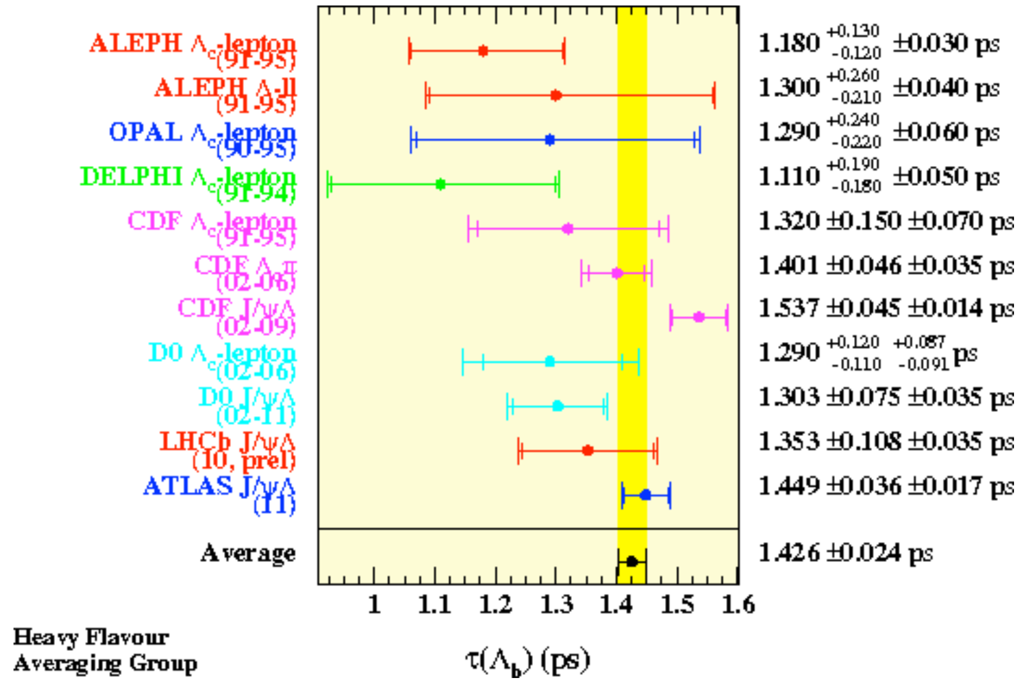
★ It is important to understand relevant energy scales for the problem at hand



Testing QCD tools for flavor physics

★ Calculations of SM observables can can help with testing the tools

1. Nice test of our understanding of non-perturbative effects in QCD
2. One of the few unambiguous theoretical predictions that are easy to test experimentally
3. Theoretical uncertainty can be estimated: precision studies



$$\Gamma\left(H_b\right)=\frac{G_F^2 m_Q^5}{192\pi^3}\left[A_0+\frac{A_2}{m_Q^2}+\frac{A_2}{m_Q^3}+\ldots\right]$$

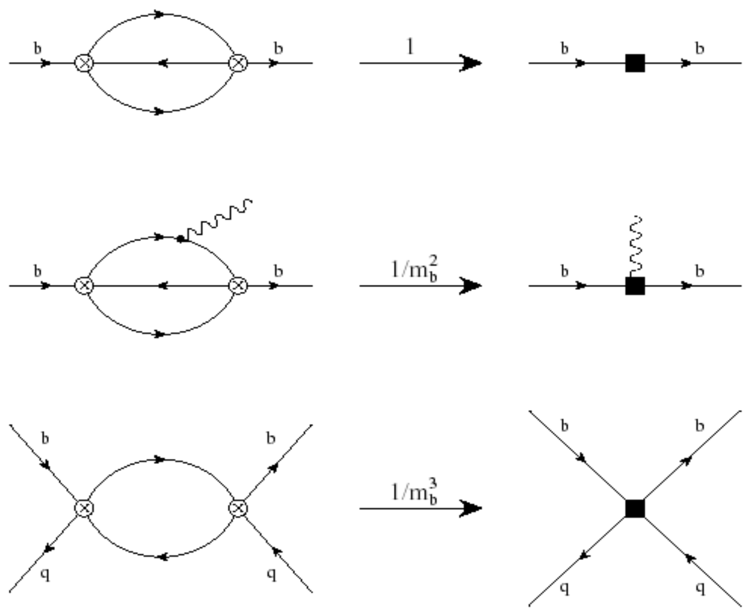
How good are theoretical predictions?

Theoretical expectations

- Assume quark-hadron duality: relate width to forward matrix element

$$\Gamma(H_b) = \frac{1}{2M_b}\langle H_b|T|H_b\rangle = \frac{1}{2M_b}\langle H_b|\mathrm{Im}\, i\int d^4x\, T\left\{H_{eff}^{\Delta B=1}(x) H_{eff}^{\Delta B=1}(0)\right\}|H_b\rangle$$

- This correlator can be expanded using OPE



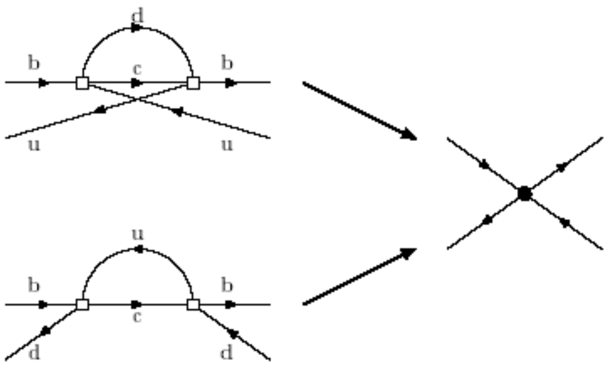
I. Bigi, M. Shifman, A. Vainshtein, M. Voloshin, N. Uraltsev, A. Falk, A. Manohar, M. Wise, M. Neubert, C. Sachrajda, P. Colangelo, F. de Fazio, …

$$\Gamma(H_b) = \sum_k \frac{C_k(\mu)}{m_b^k}\langle H_b|O_k^{\Delta B=0}(\mu)|H_b\rangle$$

What are the results?

Theoretical expectations

- Subset of $1/m_b^3$ corrections: $$\Gamma(H_b) = \sum_k \frac{C_k(\mu)}{m_b^3} \langle H_b | O_k^{\Delta B=0}(\mu) | H_b \rangle$$



$$O^q = \bar{b}_L \gamma_\mu q_L \bar{q}_L \gamma^\mu b_L, \qquad O_S^q = \bar{b}_R q_L \bar{q}_R b_L,$$
$$T^q = \bar{b}_L \gamma_\mu t^a q_L \bar{q}_L \gamma^\mu t^a b_L, \quad T_S^q = \bar{b}_R t^a q_L \bar{q}_R t^a b_L$$

Two intermediate quarks: $16\pi^2$ enhanced

For the mesons:

$$\frac{1}{2m_{B_q}} \langle B_q | Q^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} B_1, \quad \frac{1}{2m_{B_q}} \langle B_q | Q_S^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} B_2$$
$$\frac{1}{2m_{B_q}} \langle B_q | T^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} \varepsilon_1, \quad \frac{1}{2m_{B_q}} \langle B_q | T_S^q | B_q \rangle = \frac{f_{B_q}^2 m_{B_q}}{8} \varepsilon_2$$

For the baryons:

$$\langle \Lambda_b | O_1^q | \Lambda_b \rangle = -\tilde{B} \langle \Lambda_b | \tilde{O}_1^q | \Lambda_b \rangle = \frac{\tilde{B}}{6} f_{B_q}^2 m_{B_q} m_{\Lambda_b} r,$$

As a result:

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} \simeq 0.98 - \left(d_1 + d_2 \overline{B}\right) r - \left(d_3 \varepsilon_1 + d_4 \varepsilon_2\right) - \left(d_5 B_1 + d_6 B_2\right)$$

Lattice: the ONLY study of r: DiPierro, et al., 1999!

Lifetime predictions

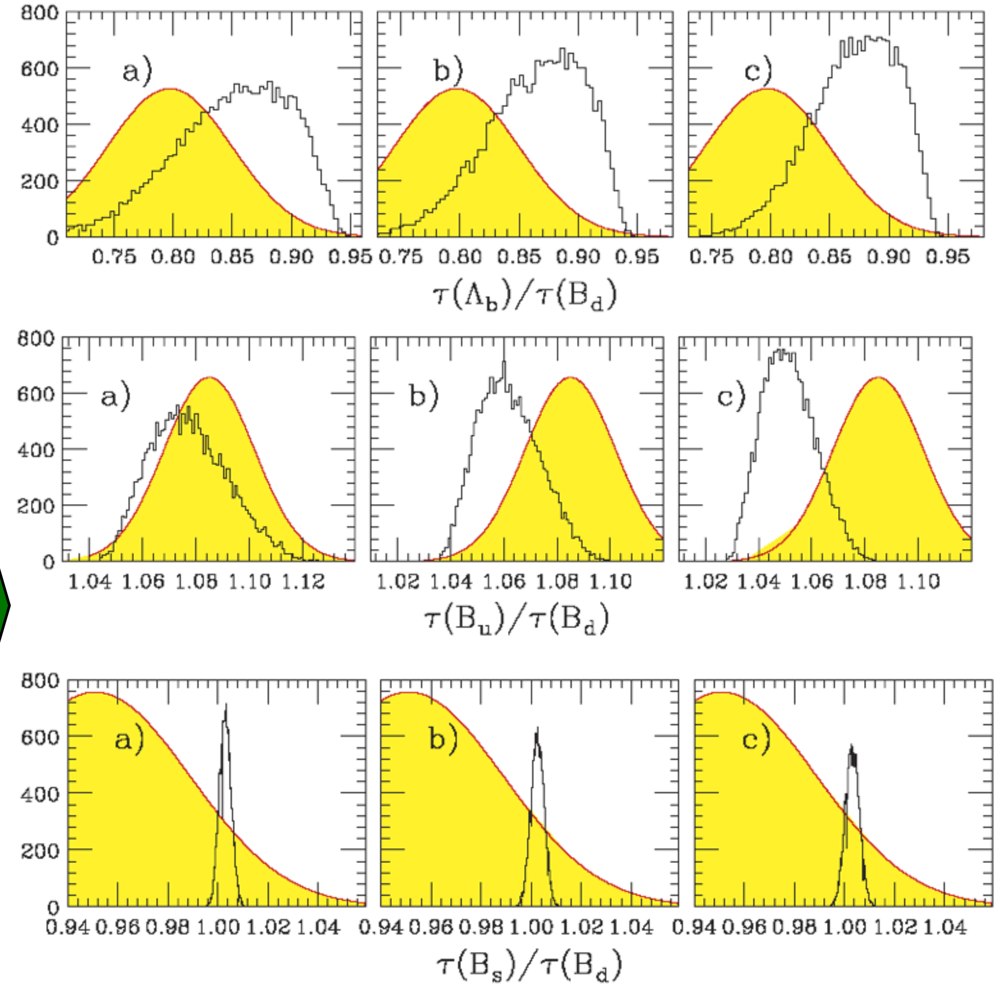
- The expansion appears well convergent for a b-quark
- Conservatively:

$$\tau(\Lambda_b)/\tau(B^0) = 0.87 \pm 0.05$$

$$\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$$

$$\tau(B_s)/\tau(B^0) = 1.00 \pm 0.01$$

Year	Exp	Ratio
2013	HFAG	0.941±0.016
2013	LHCb	0.976±0.012
2013	CMS	0.989±0.040
2012	Atlas	0.954±0.026
2003	HFAG	0.789±0.034



F. Gabbiani, A. Onishchenko, A.A.P. Phys. Rev. D70, 094031 (2004)

5. Things to take home

- Indirect probes for new physics compete well with direct searches
  - for some observables sensitive to scales way above LHC
- Calculational techniques for heavy flavors are well-established
  - but don't always work well: "heavy-quark-expansion" techniques for charm often miss threshold effects
  - "hadronic" techniques that sum over large number of intermediate states can be used, BUT one cannot use current experimental data on D-decays
- Calculations of New Physics contributions to mixing are in better shape
  - contributions of NP in $\Delta b=2$ operators are local and well-behaved
- Can correlate mixing and rare decays with New Physics models
  - signals in B/D-mixing vs B/D rare decays help differentiate among models
- Direct CP-violation in charm decays?
  - evidence for CPV in the up-quark sector looks SM-like

Rembrandt “Old Man in Military Costume”,
BNL/DESY X-ray study

Accurate analysis of flavor data might reveal hidden layers of something previously unknown.